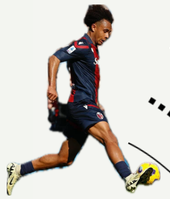
Studying the Emergence of Hot and Cold QCD Phenomena in Heavy Ions at the ATLAS experiment



Riccardo Longo
Seminar @ Università & INFN Bologna
27th February 2024

Roadmap of this talk





WHAT IS COLD AND WHAT IS HOT?

HOW DO WE UNDERSTAND THE LONG-RANGE BEHAVIOR OF THE QGP?

HOW DOES THE QGP BEHAVIOR EMERGE FROM THE MICROSCOPIC QCD THEORY?

HOW SMALL THE SYSTEM HAS TO BE TO TURN-OFF THE QGP EFFECTS?

IS THE PROTON SIZE FLUCTUATING?

HOW DIJETS MEASUREMENTS AT THE LHC CAN HELP IN CONSTRAINING INITIAL STATE EFFECTS?

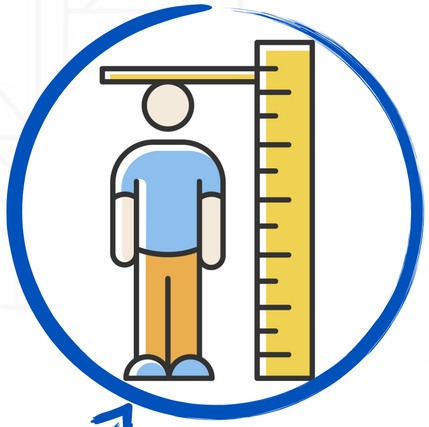
HOW DOES THE ZDC SERVE AS AN ESSENTIAL TOOL IN HEAVY-ION COLLISIONS?

What is COLD and what is HOT?

SETTING THE [COLD] LENGHT SCALE...

Human beings

h ~ 1-2 m



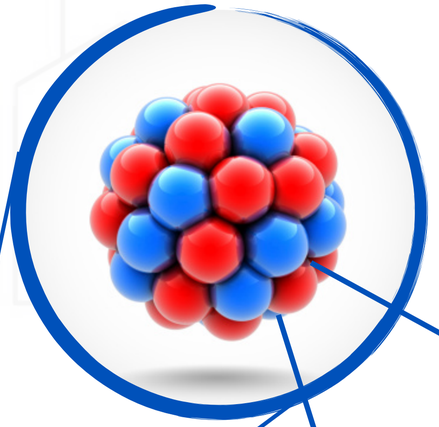
Bacteria

r ~ 10^{-6} = 1 μm



Nucleus

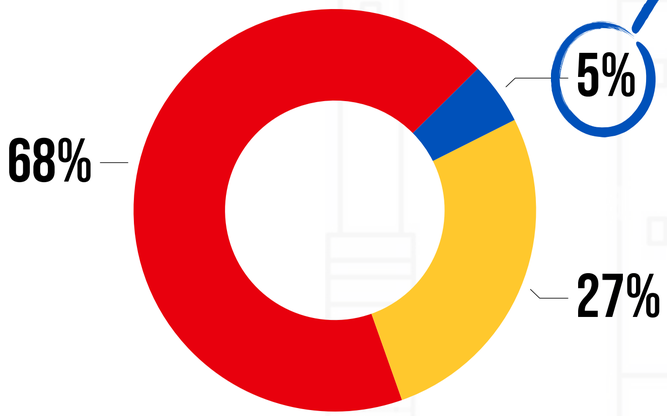
r ~ $A^{1/3} \cdot 1.2 \cdot 10^{-15}$ m = 1.2 $A^{1/3}$ fm



REGULAR MATTER

DARK MATTER

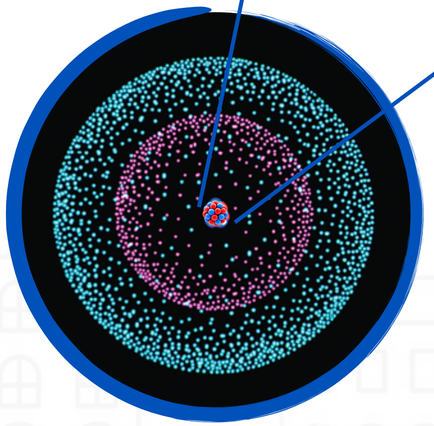
DARK ENERGY





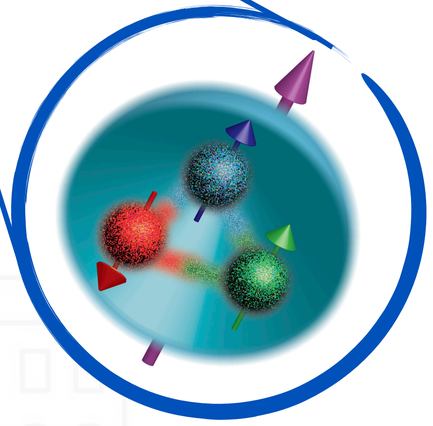
Coffee grounds

r ~ 10^{-3} m = 1 mm



Atom

r ~ 10^{-10} m = 0.1 nm

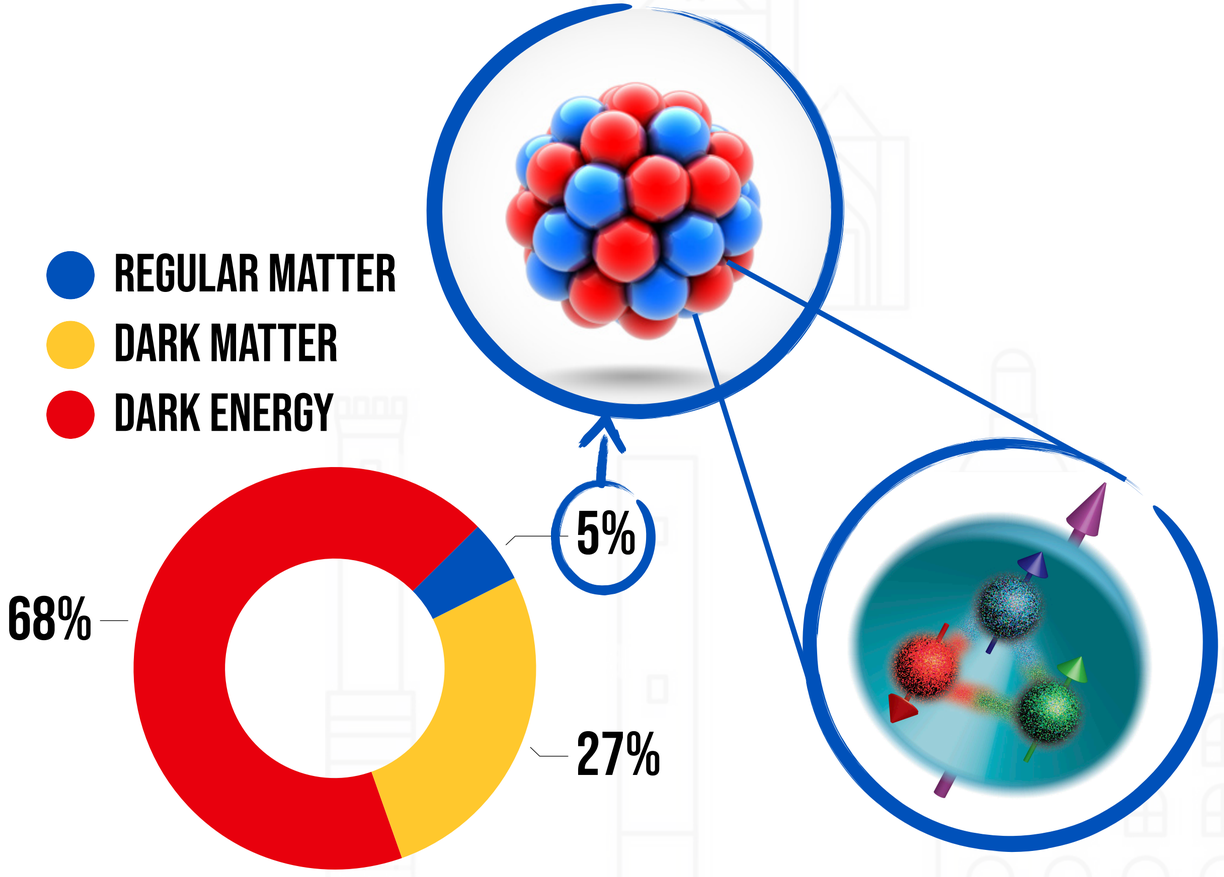


Proton

r ~ 10^{-15} m = 1 fm

...OF NUCLEAR PHYSICS: THE FEMTOSCALE

The **nucleus** constitutes **> 99% of the mass** of the atoms

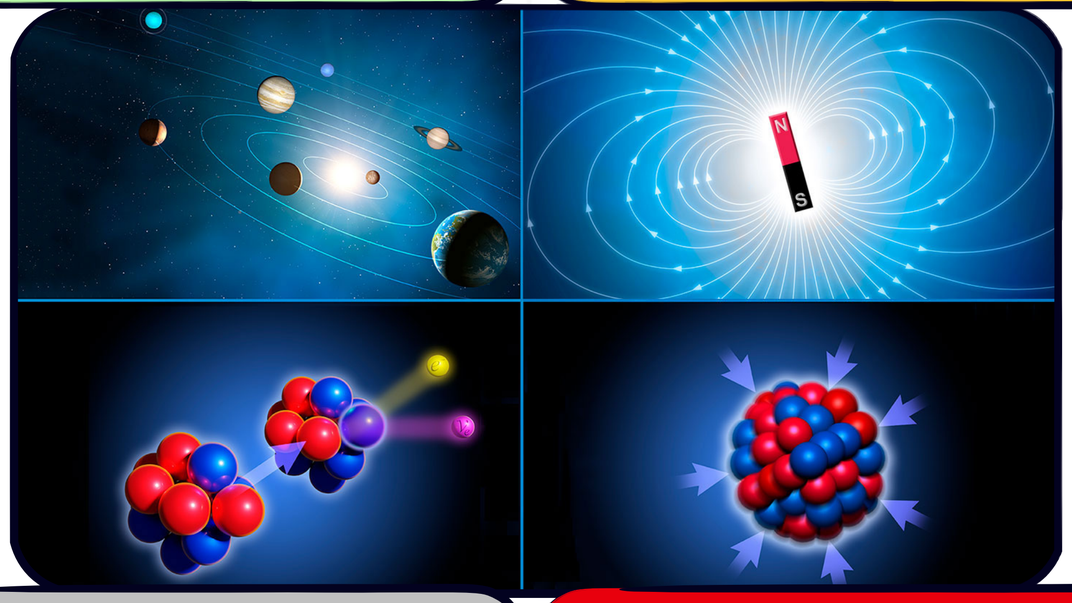


Proton

r ~ 10^{-15} m = 1 fm

Gravitational Force
~10^{-41}

Electromagnetic Force
~10^{-2}



Weak Force
10^{-9}

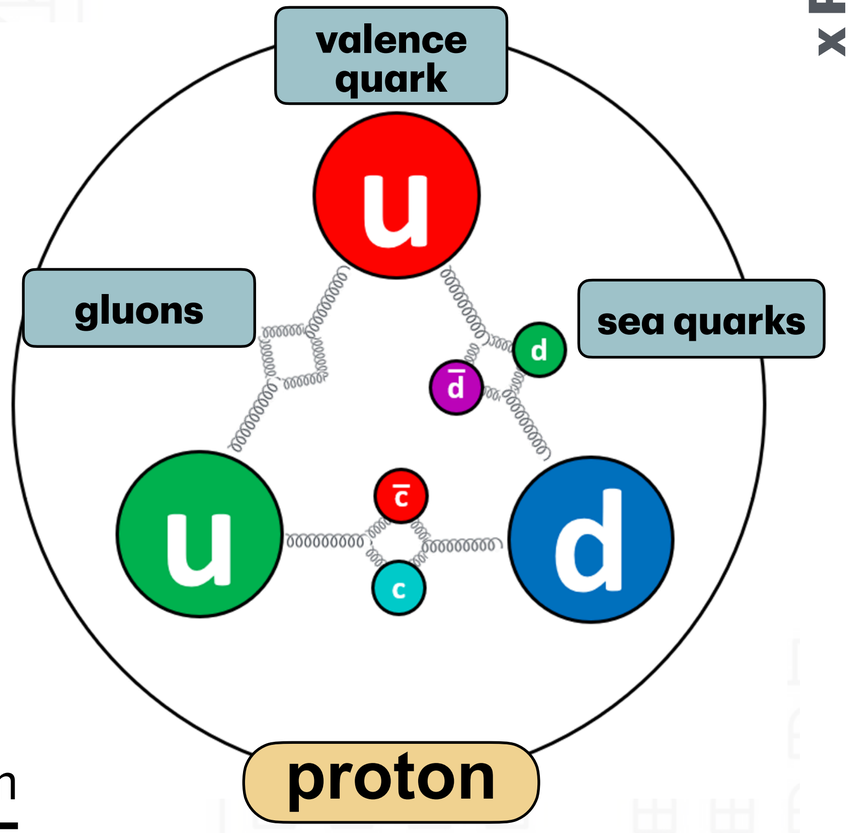
Strong Force
1

NUCLEAR DYNAMICS ARE DRIVEN BY THE STRONG FORCE!

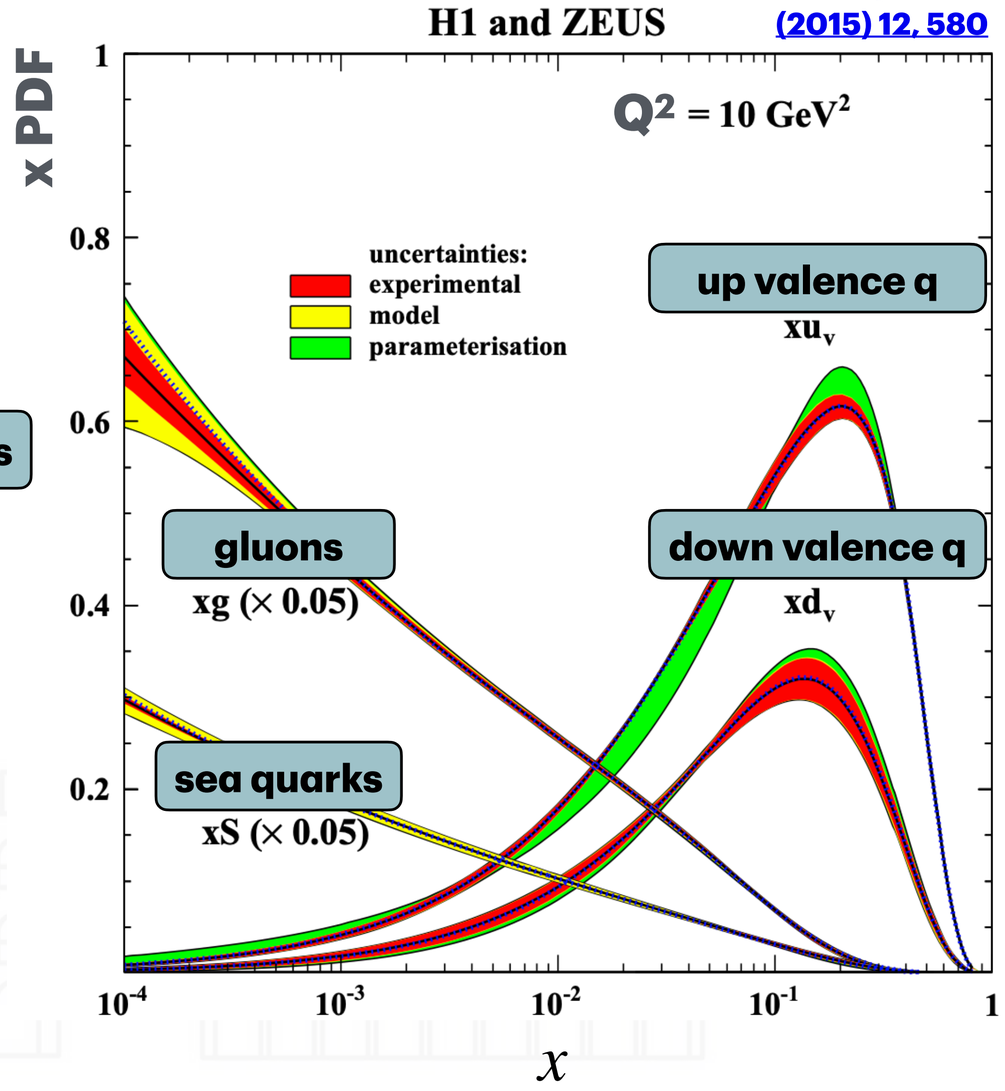
HOW DO WE DESCRIBE THE NUCLEON?

Parton distribution functions (PDFs) are used to describe the probability of finding a parton of a given species carrying a fraction *x* of the nucleon momentum.

$$x_i = \frac{\text{Parton "i" Momentum}}{\text{Proton Momentum}}$$



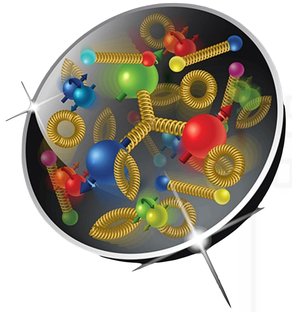
Eur.Phys.J.C 75 (2015) 12, 580



HOW DO WE DESCRIBE THE NUCLEON IN THE NUCLEUS

Are protons and neutrons bound in a nucleus still the same?

NO!



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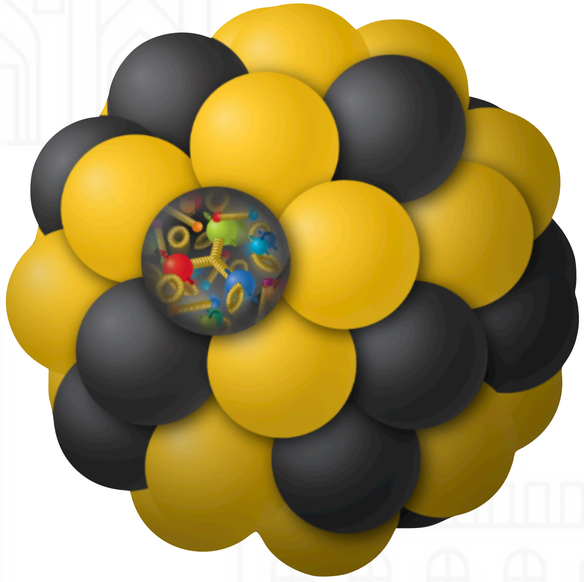
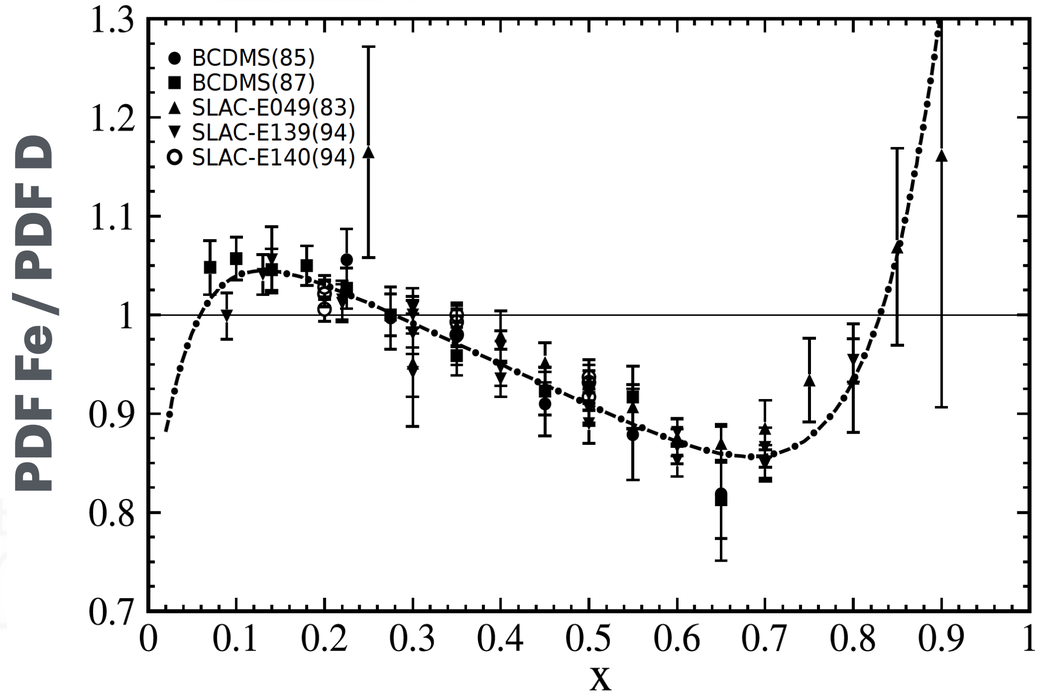


DOESN'T WORK

$$PDF^A(x,\mu) \neq Z\,PDF^p(x,\mu) + N\,PDF^n(x,\mu)$$

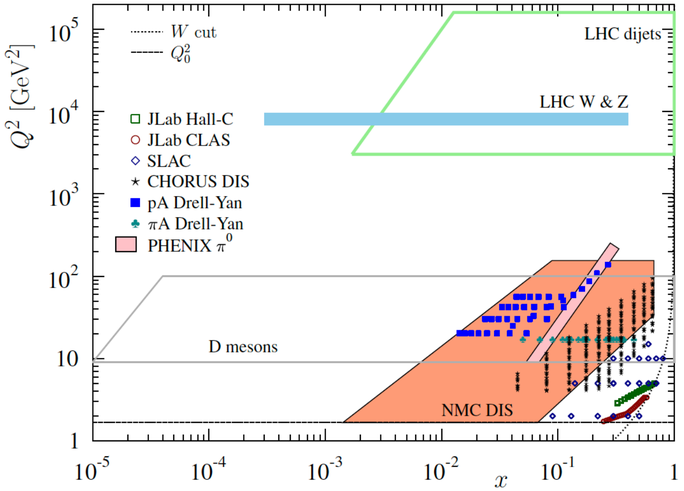
Free nucleon approximation

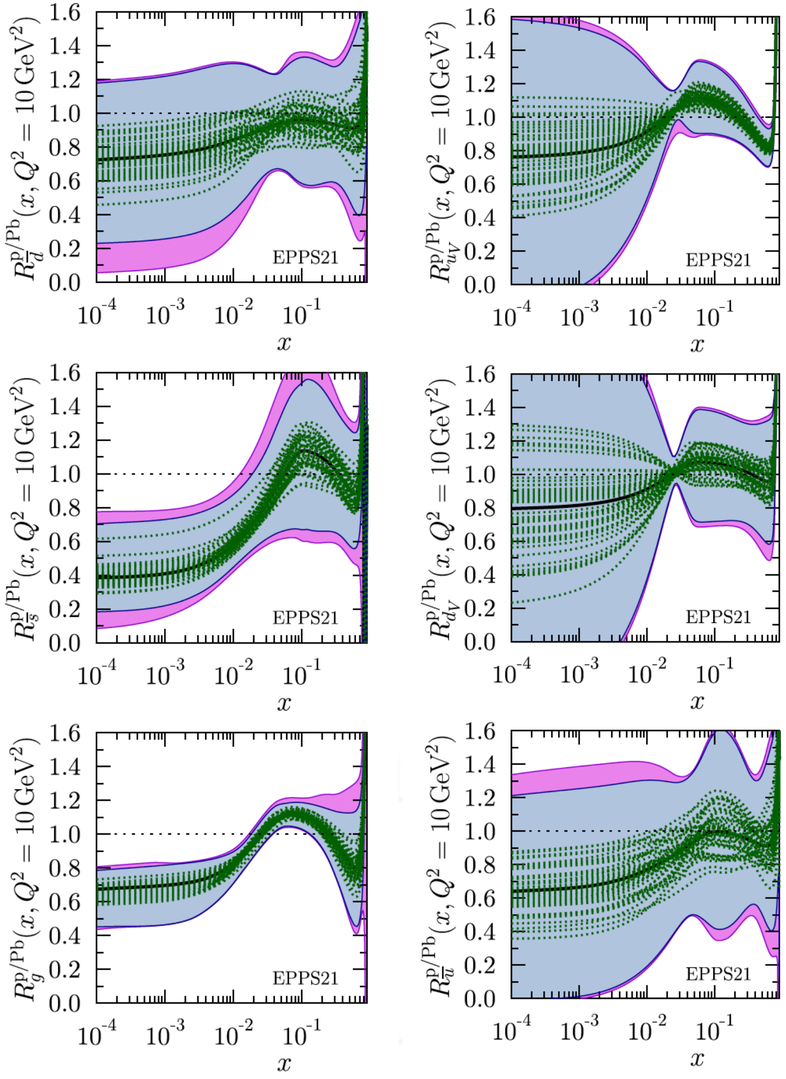


TO DESCRIBE NUCLEONS BOUND IN NUCLEI, WE NEED NUCLEAR PDFS

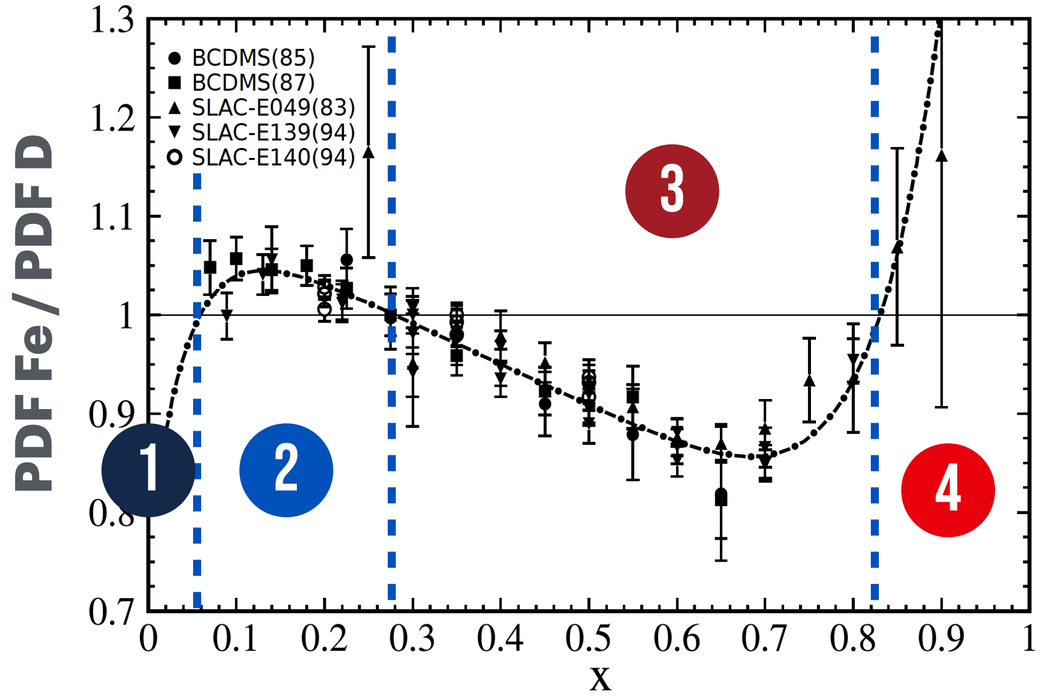
A VERY UNCERTAIN PICTURE

Eur. Phys. J. C (2022) 82:413



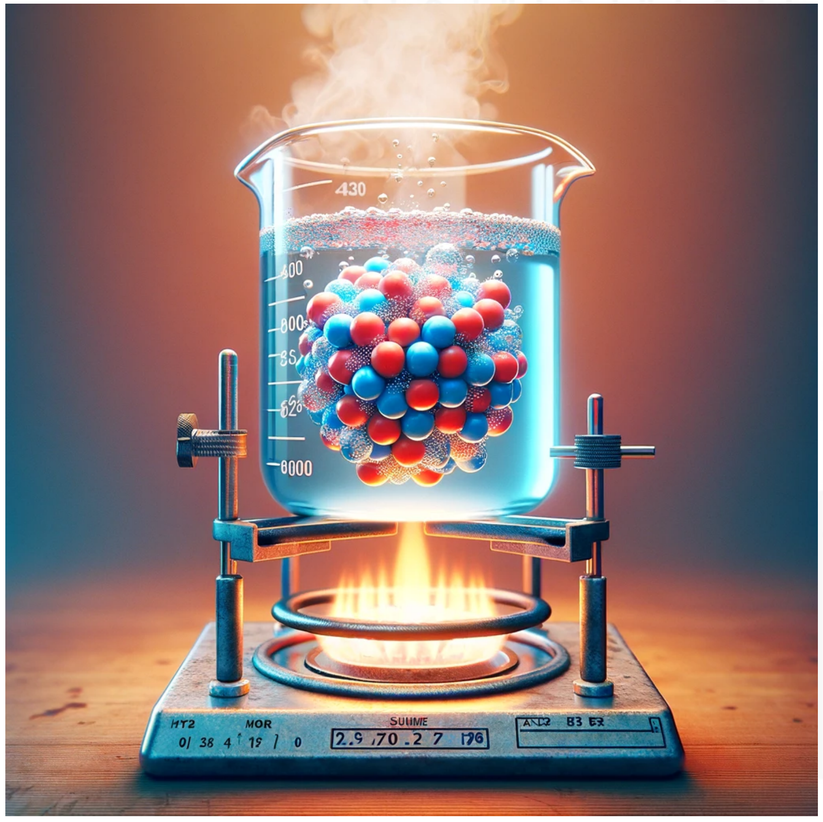


1. Shadowing
2. Anti-shadowing
3. EMC effect
4. Fermi Motion



FROM COLD TO HOT!

Let's **add more energy** to the system to bring it to a temperature where quarks and gluons can **break the chains of confinement** and create a **quark-gluon plasma (QGP)**



We definitively want to heat up the system, but unluckily is not so easy!

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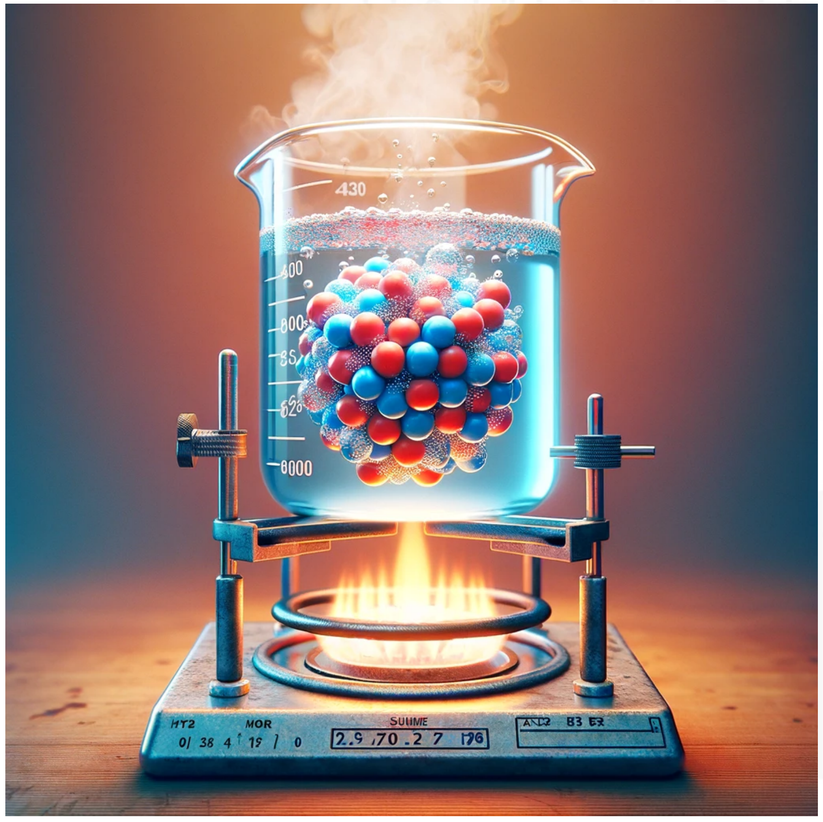

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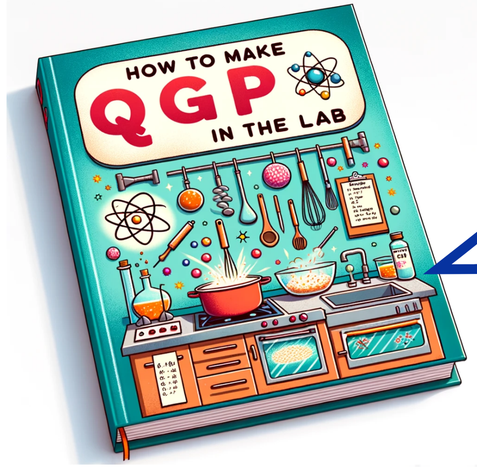
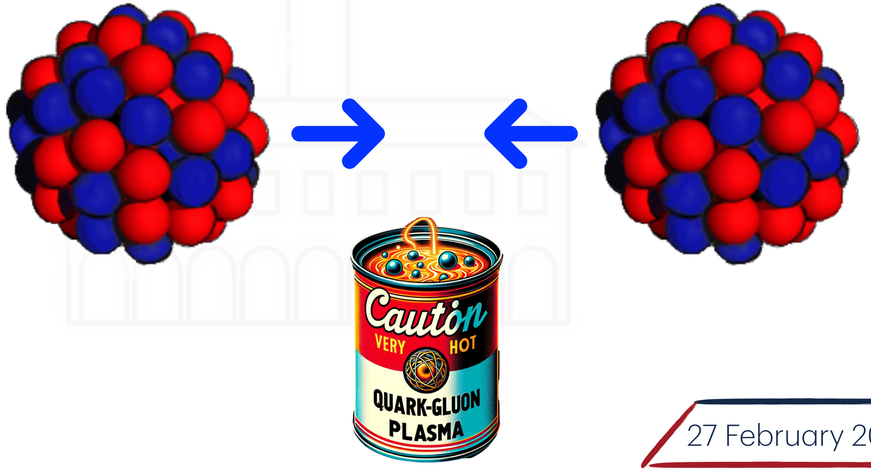


Colliding heavy nuclei is the way!

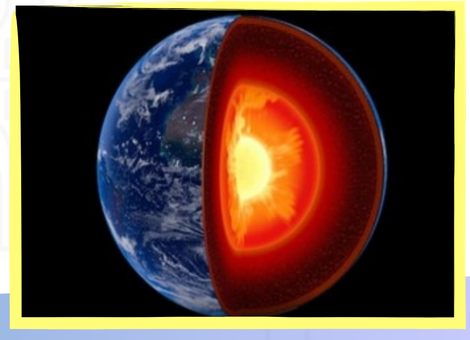


HOW HOT?

This room
68°F/20°C



Earth's core
10000°F / 5300°C



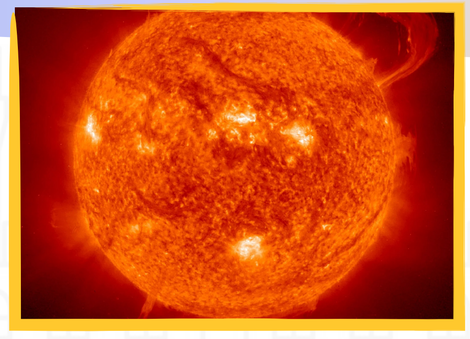
Black Hole Corona
1.8G °F / 1G °C







Boiling Water
212°F/100°C

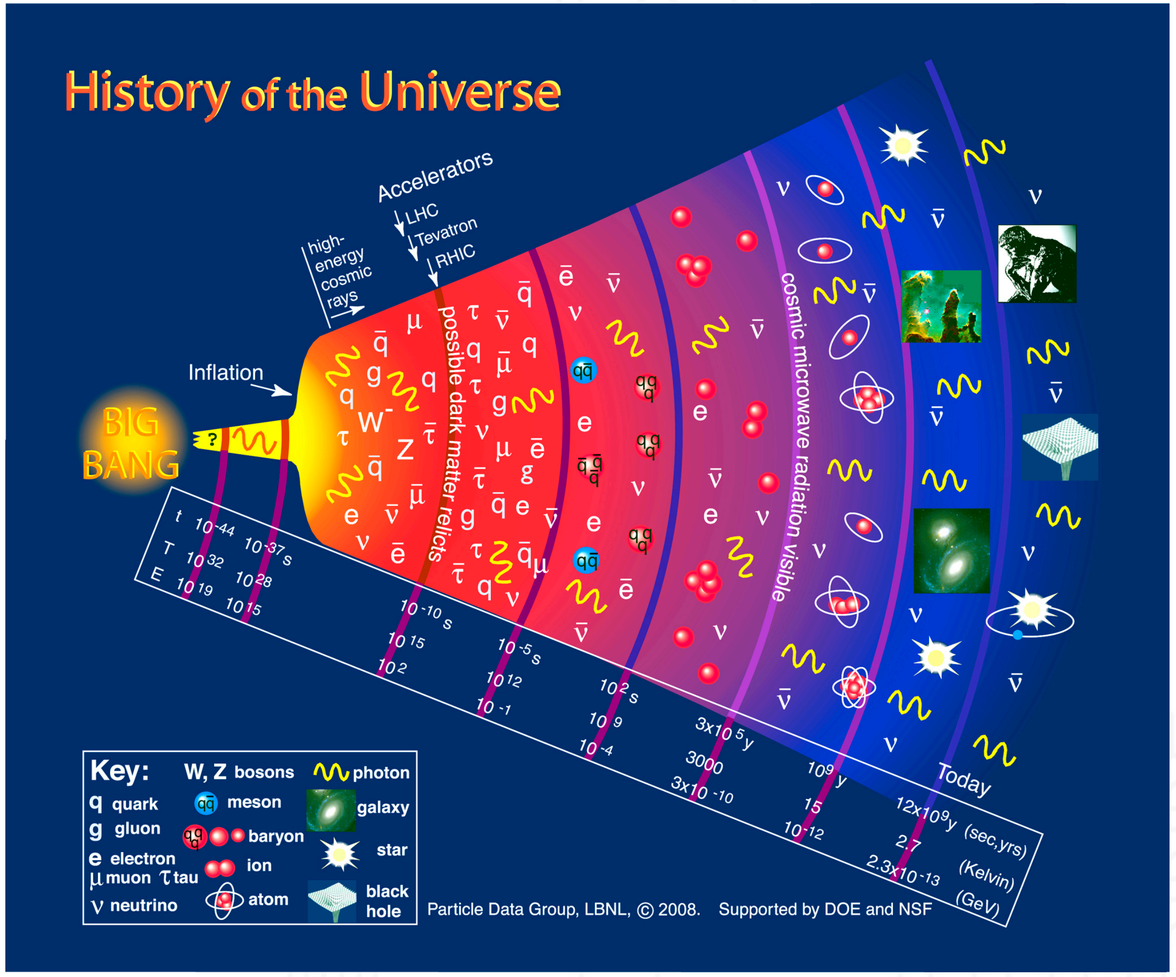


Sun's core
27M°F / 15M°C

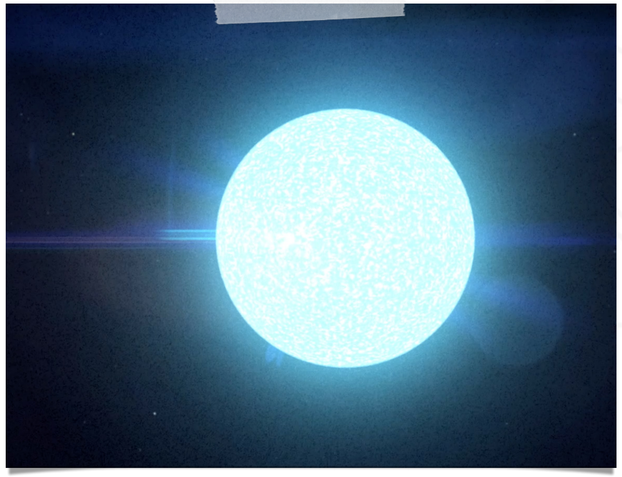


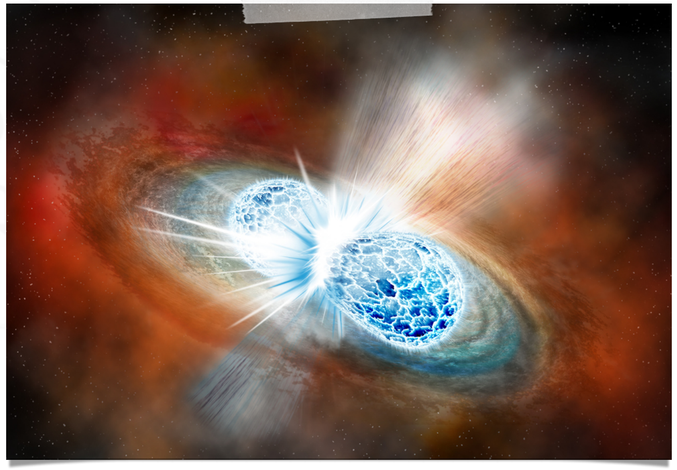
QGP
> 5.4T °F / 3T °C

QGP: WHY? WHEN? WHERE?



➡ **Early Universe** (< 10 μs from the Big Bang)





➡ Created in **neutron star merger**

➡ Potentially in **massive neutron stars (Nat Commun 14, 8451 (2023))**

➡ Understanding **QGP** ⟺ understanding **QCD**

QGP FACTORIES

RELATIVISTIC HEAVY ION COLLIDER (RHIC) @ BROOKHAVEN NATIONAL LAB



Highest Energy: 0.2 TeV/A (Gold)
Turn-off of QGP effects for nuclei at 3 GeV/A

LARGE HADRON COLLIDER (LHC) @ CERN



Highest Energy to date: 5.36 TeV/A (2023 Lead run)
Maximum Energy: 5.5 TeV/A

QGP FACTORIES

Most powerful particle accelerator in the world

Can accelerate *p* and different species of ions (Pb, Xe, O, ++) up to the multi-TeV scale

LARGE HADRON COLLIDER (LHC) @ CERN



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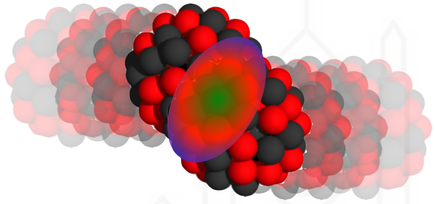
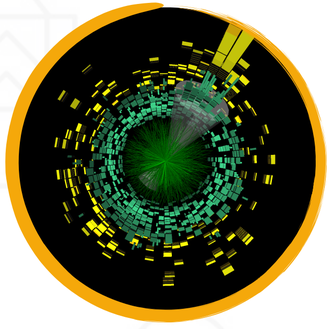
HEAVY ION COLLISIONS - IN A NUTSHELL

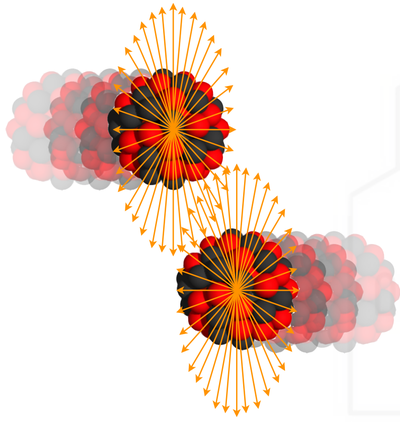
A+A Collisions (Pb, Xe, O to come...)



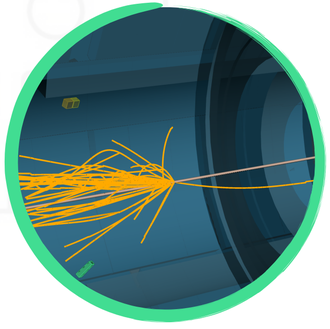
Hadronic collisions

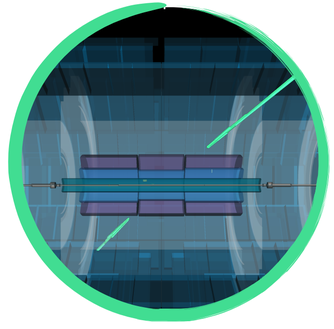




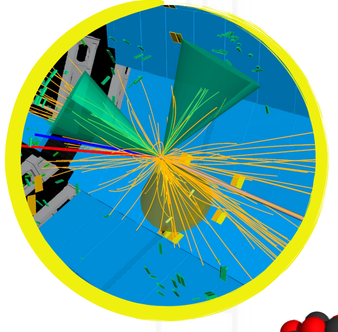


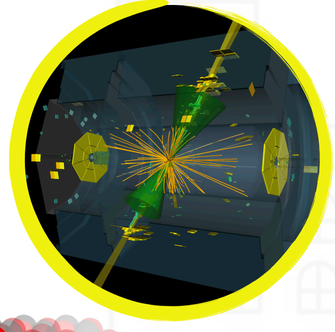
Ultra-Peripheral collisions (UPCs)

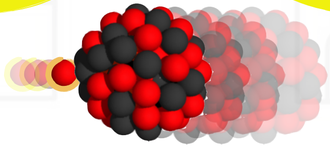




p+A collisions (p+Pb, p+O to come...)

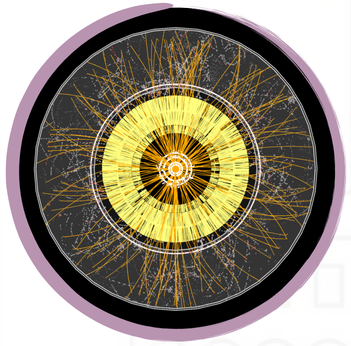






p+p collisions





HEAVY ION COLLISIONS - IN A NUTSHELL

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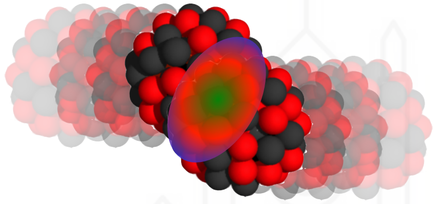

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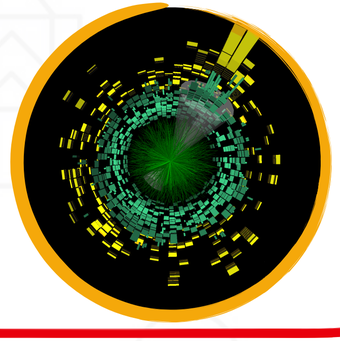

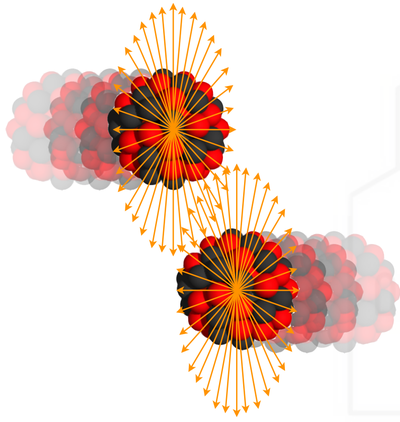

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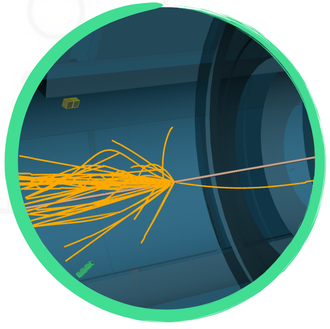

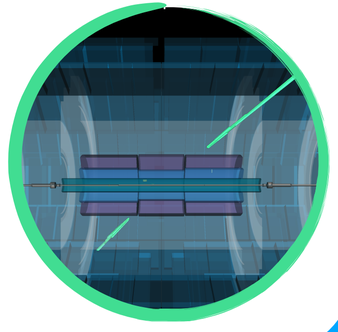

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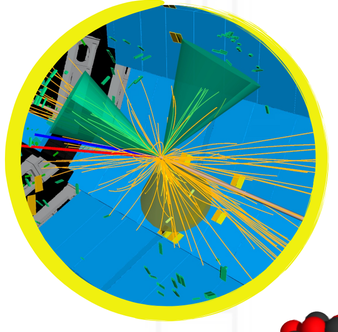

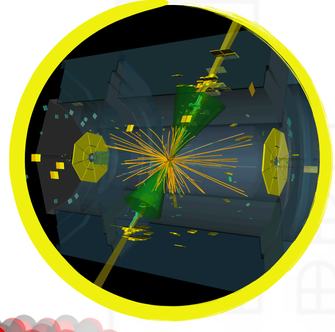

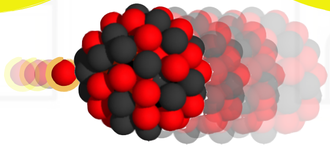

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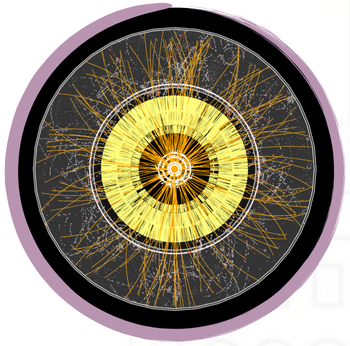
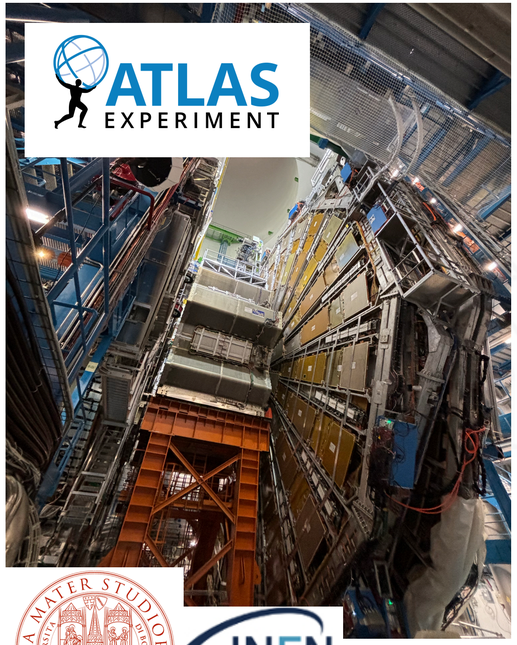


Large systems

Small systems

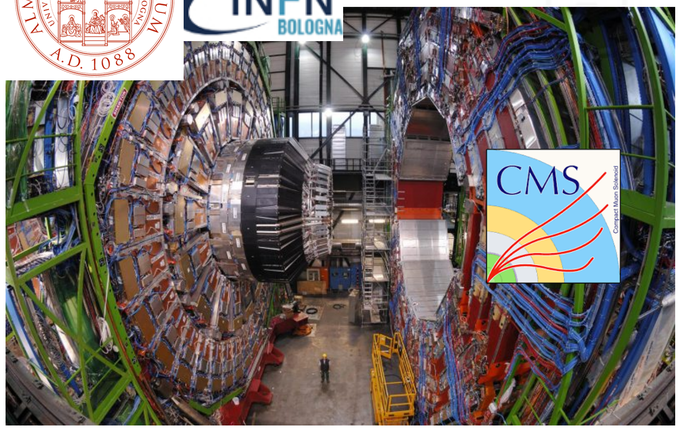
COMPLEMENTARY WAY OF DETECTING QGP SIGNATURES



High-p_T probes

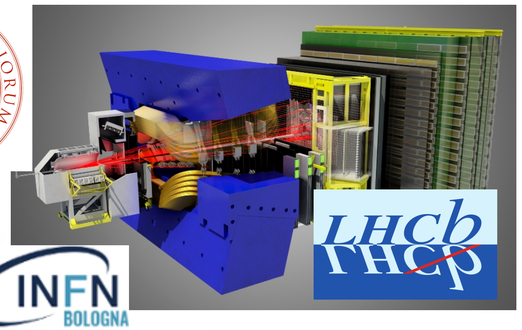
Jets

Wide η acceptance



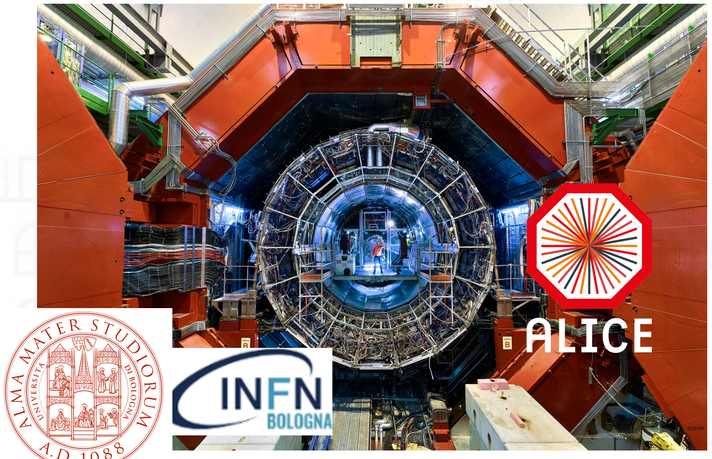
Excellent forward detection

“Fixed target” design

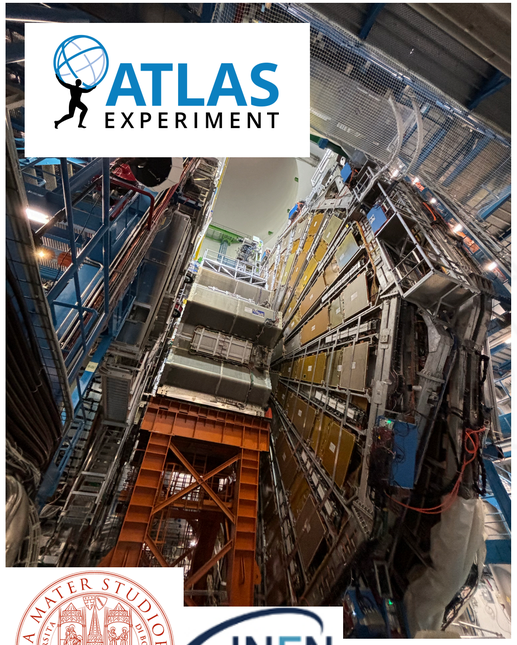


Low-p_T probes

Particle Identification



COMPLEMENTARY WAY OF DETECTING QGP SIGNATURES



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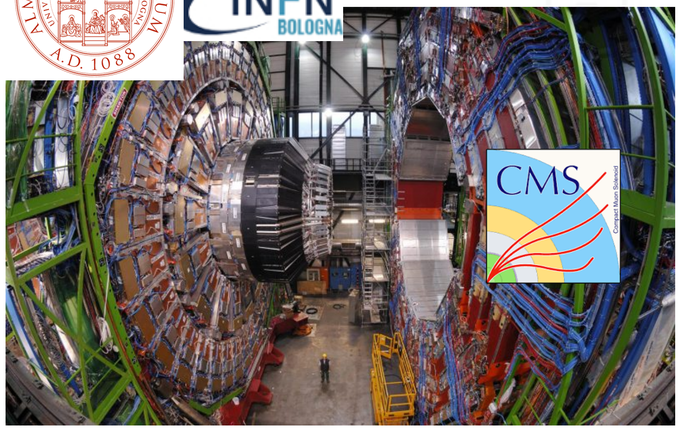
Jets

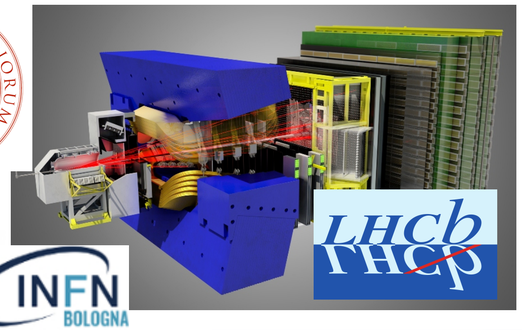
Wide η acceptance





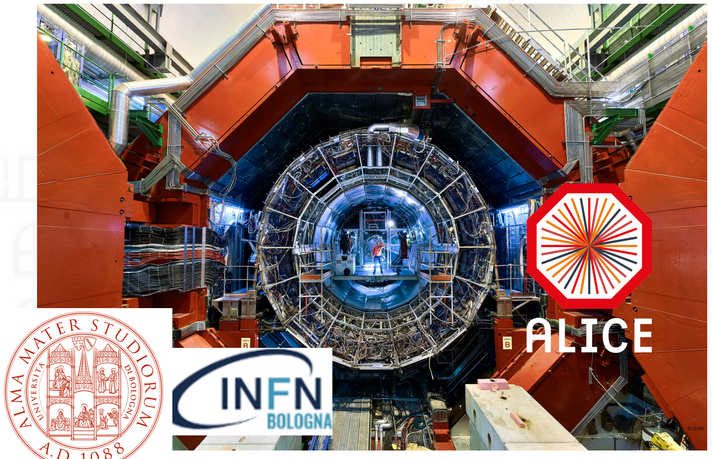
Excellent forward detection

"Fixed target" design

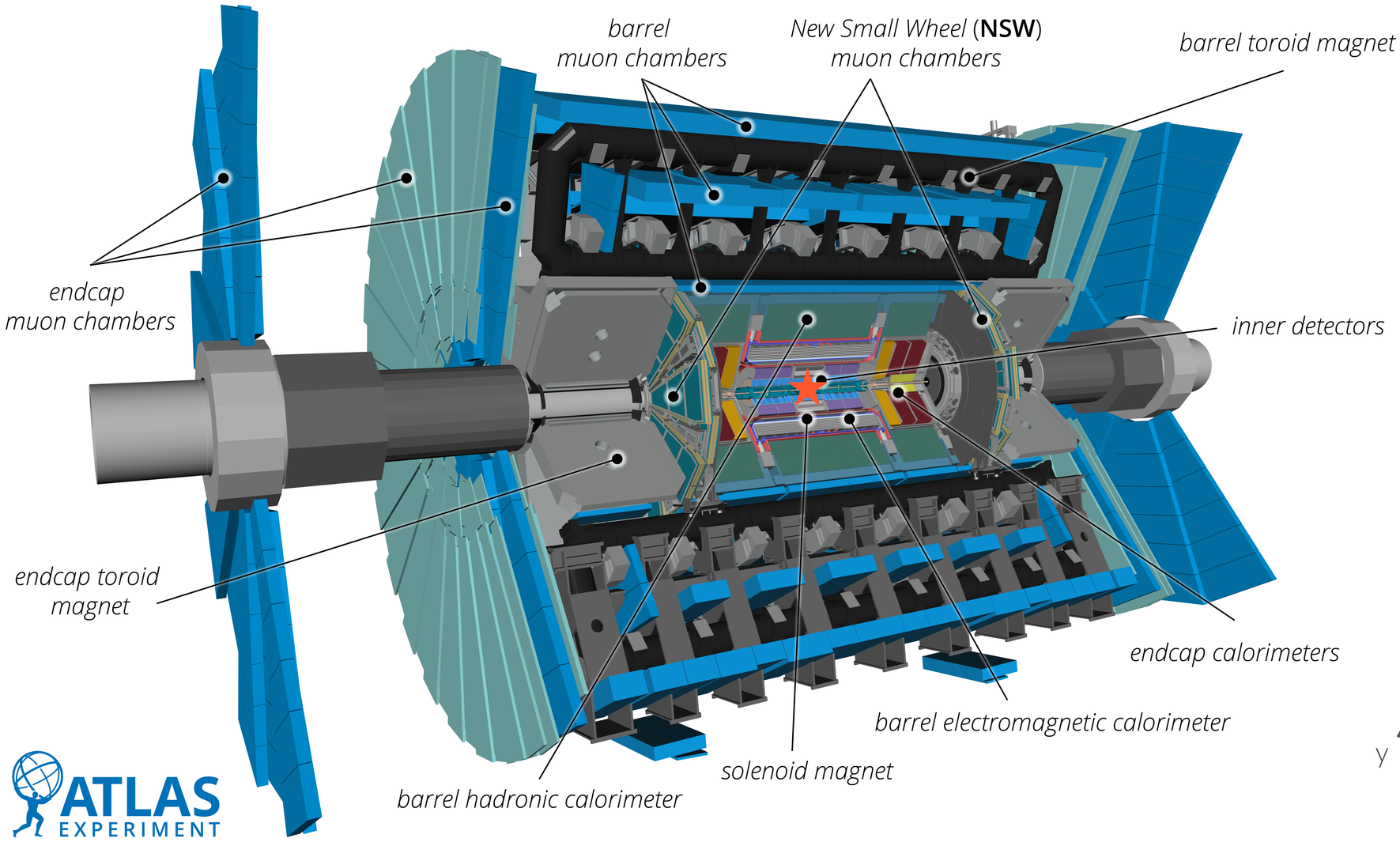


Low-p_T probes

Particle Identification



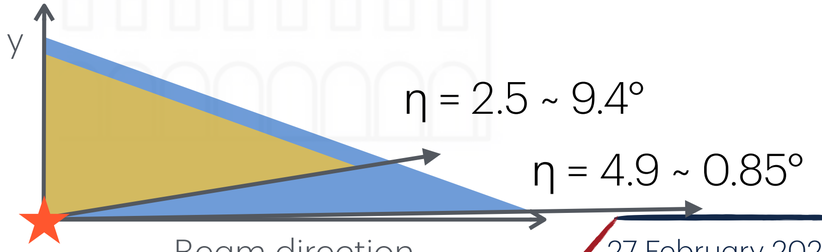
THE ATLAS EXPERIMENT



ATLAS is a **high-performance multi-purpose** detector that can detect with high efficiency both *p*+*p* and heavy-ion collisions

Tracker acceptance:
$|\eta| < 2.5$

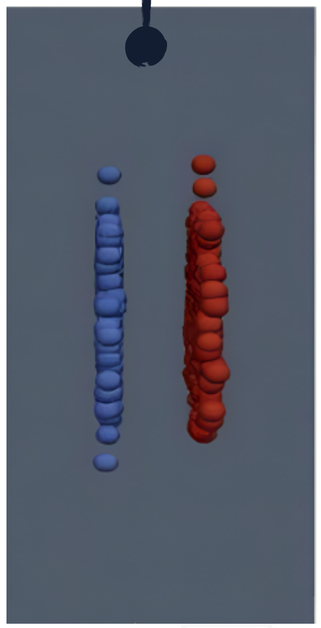
Calorimeter acceptance:
$|\eta| < 4.9$



How do we understand the long-range QGP behavior?

RECREATING QGP WITH HEAVY-ION COLLISIONS

INCOMING LORENTZ CONTRACTED NUCLEI



Collision evolution sketch from MADAI collaboration

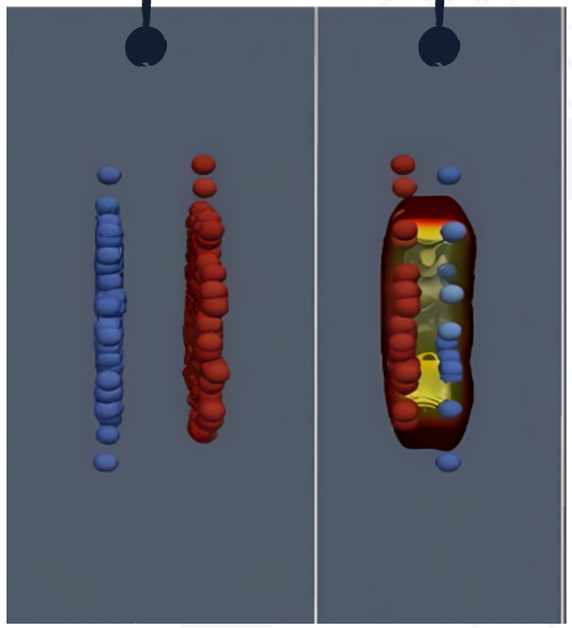
Time

Temperature

RECREATING QGP WITH HEAVY-ION COLLISIONS

Incoming Lorentz contracted nuclei

Parton scatterings



Collision evolution sketch from MADAI collaboration

Time

$\tau = 0$

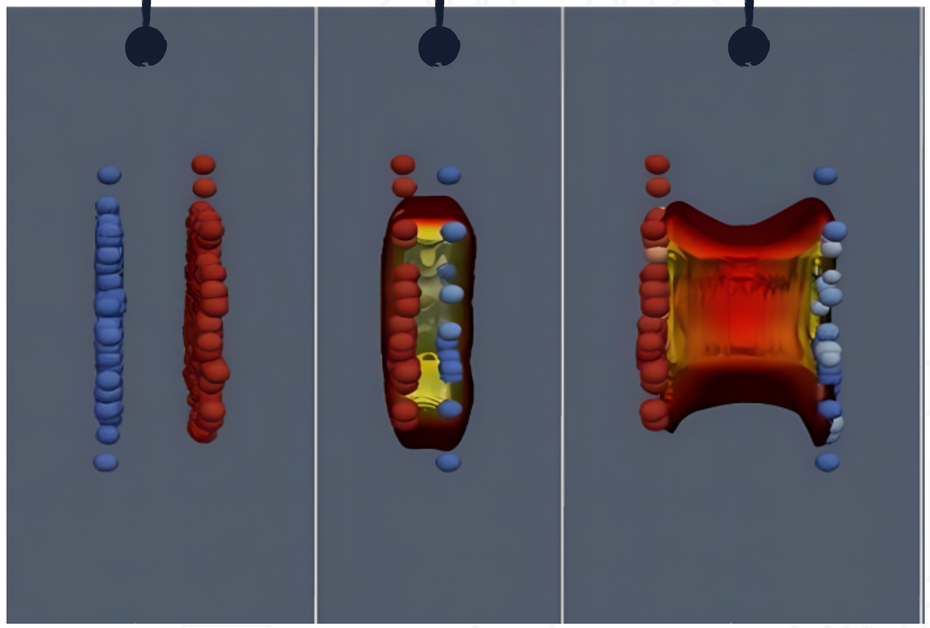
Temperature

RECREATING QGP WITH HEAVY-ION COLLISIONS

Incoming Lorentz contracted nuclei

Parton scatterings

QGP formation



Collision evolution sketch from MADAI collaboration

Time

$\tau = 0$ $\tau \sim 1$ fm/c $\sim 10^{-23}$ s

Temperature

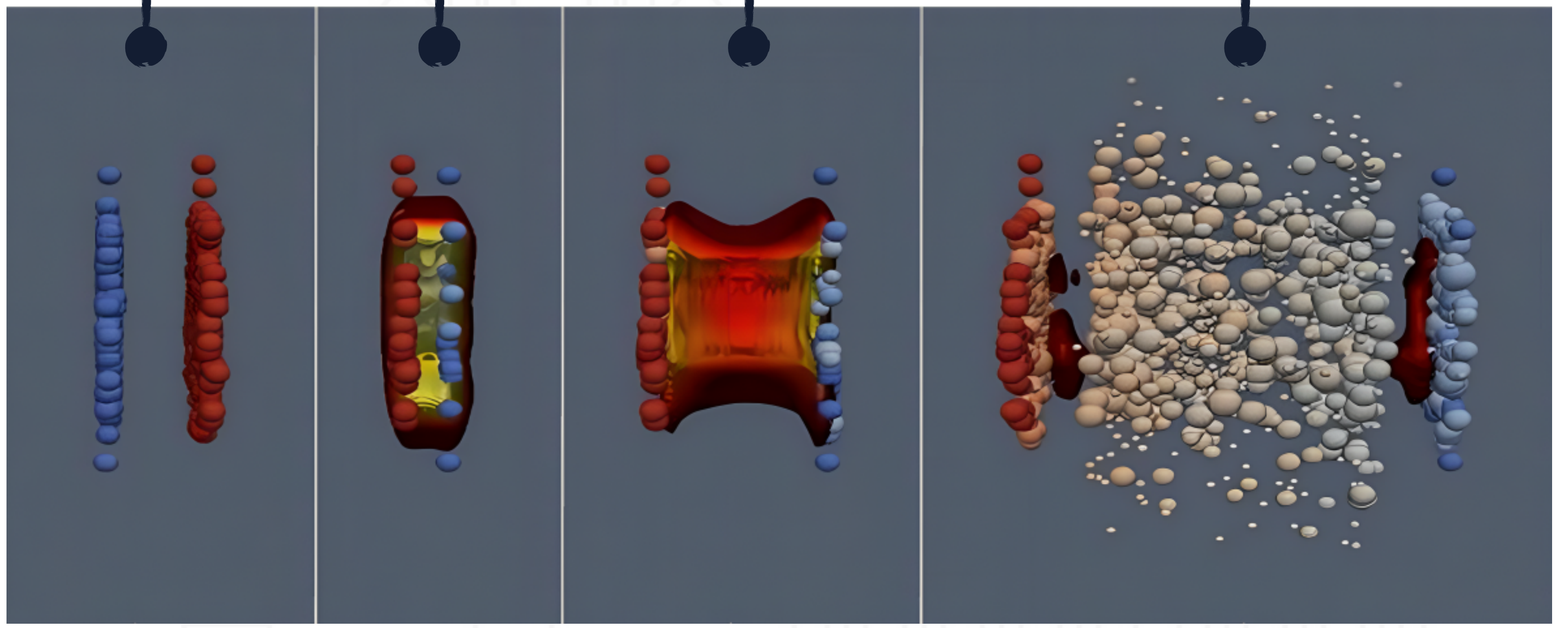
RECREATING QGP WITH HEAVY-ION COLLISIONS

Incoming Lorentz contracted nuclei

Parton scatterings

QGP formation

Hadronization and freeze-out



Collision evolution sketch from MADAI collaboration

Time

$\tau = 0$ τ ~1 fm/c ~10^{-23} s τ ~ 10 fm/c ~10^{-22} s

Temperature

RECREATING QGP WITH HEAVY-ION COLLISIONS

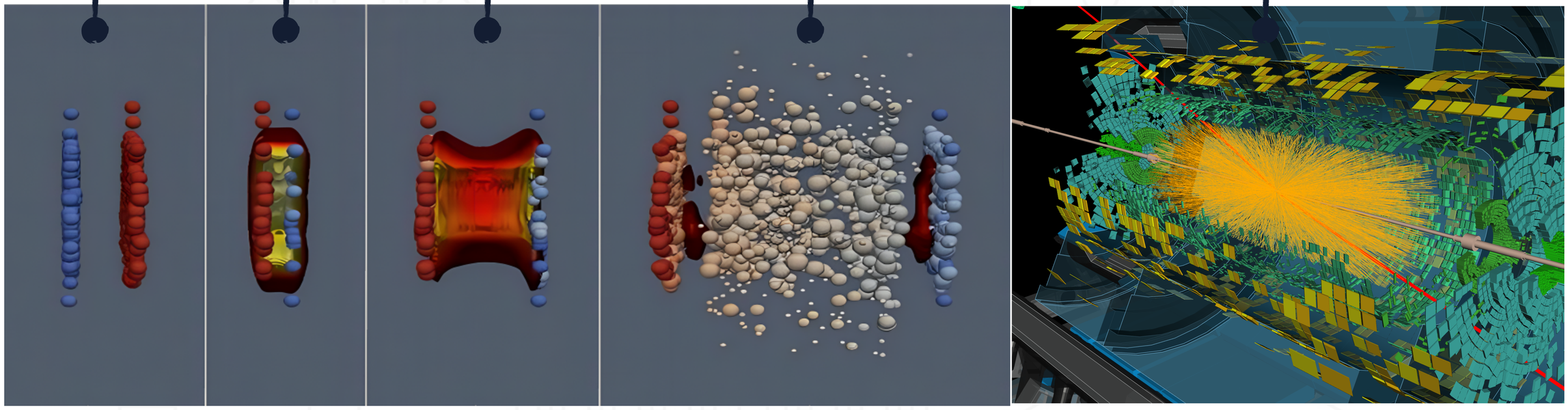
Incoming Lorentz contracted nuclei

Parton scatterings

QGP formation

Hadronization and freeze-out

Particle detection!



Collision evolution sketch from MADAI collaboration

Time

$\tau = 0$ τ ~1 fm/c ~10^{-23} s τ ~ 10 fm/c ~10^{-22} s τ > 10 cm/c ~10^{-11} s

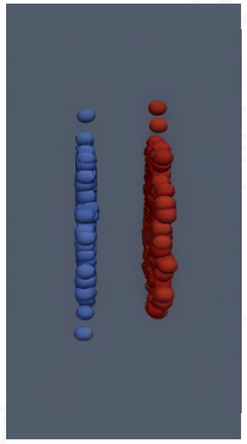
Temperature

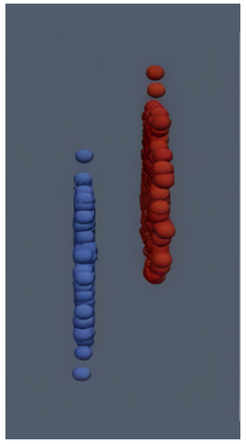
HOW MUCH QGP?

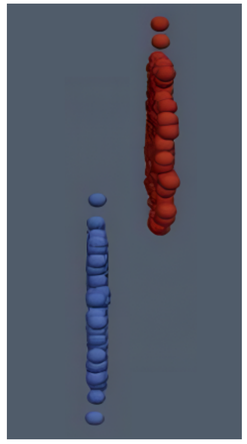
CENTRAL

PERIPHERAL

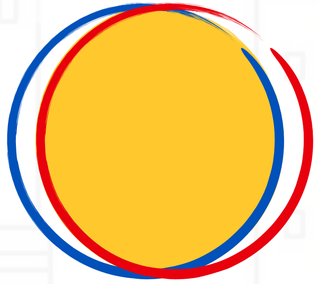
Side view

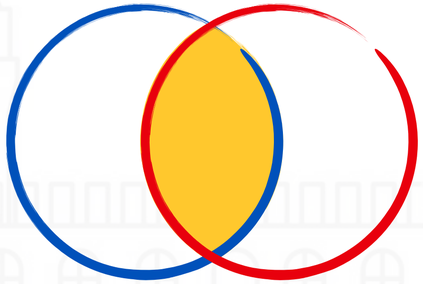


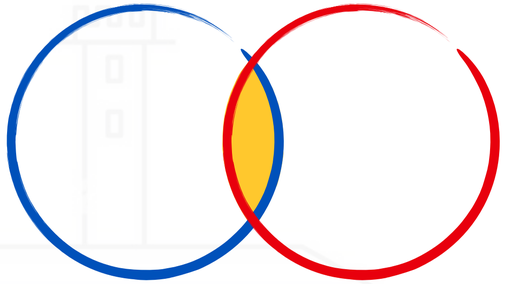




Front view







→ different collisions correspond to different amounts of nuclear overlap

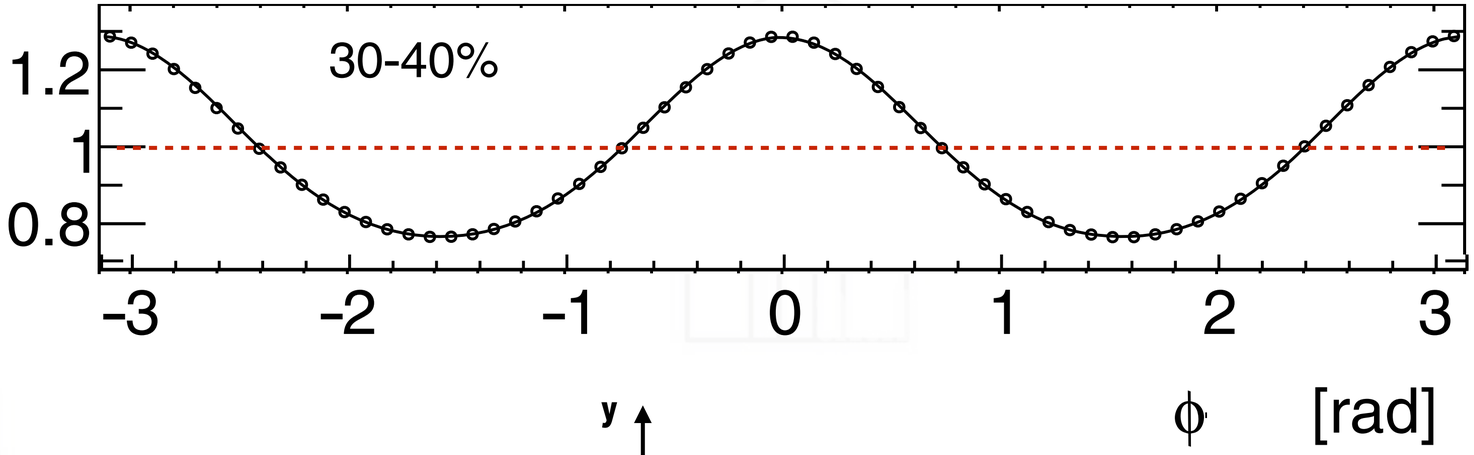
We quantify this via "centrality" determination

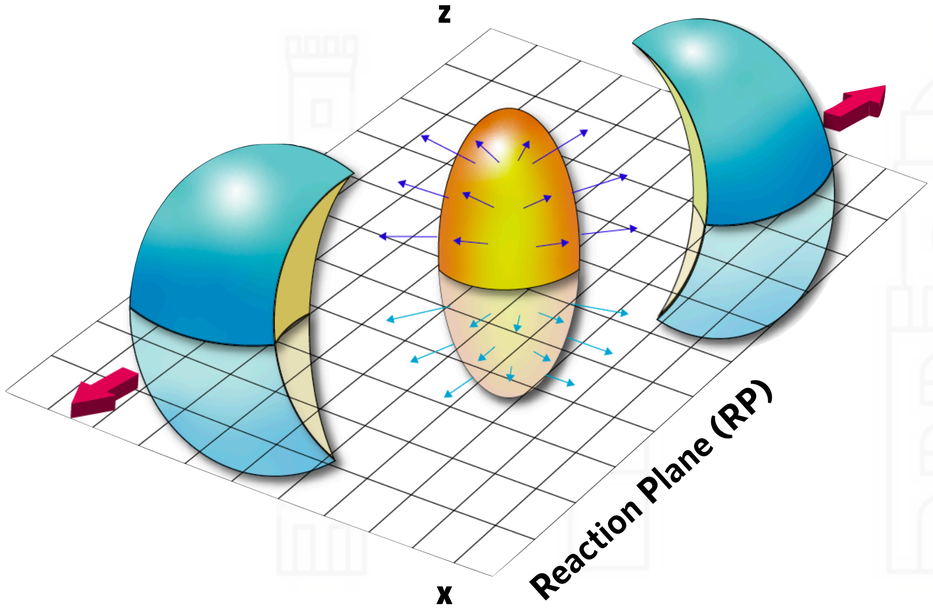
COUNTING OUTGOING PARTICLES [LONG RANGE BEHAVIOR]

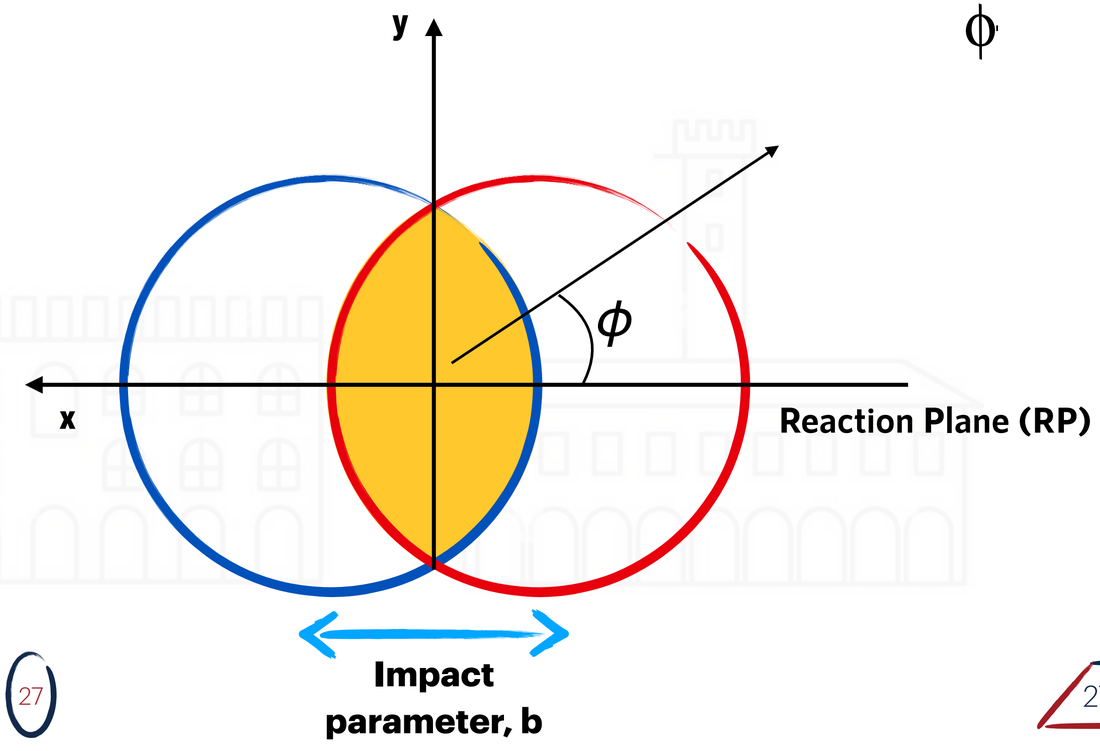
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{i=1}^{\infty} v_n \cos(n\phi)\right)$$

number of particles

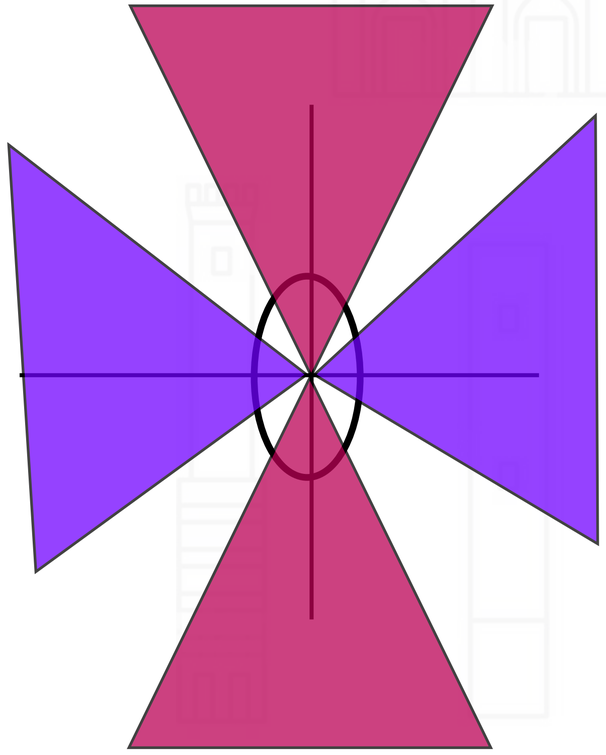
PLB 707 330 (2012)

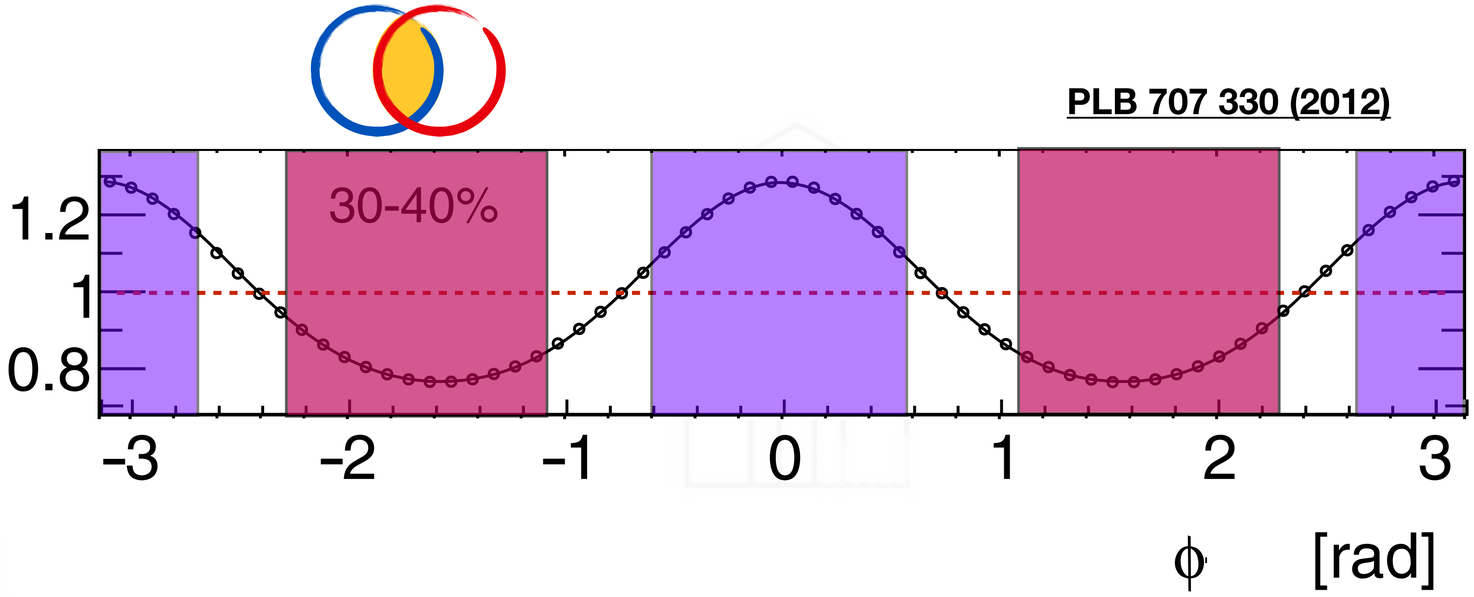






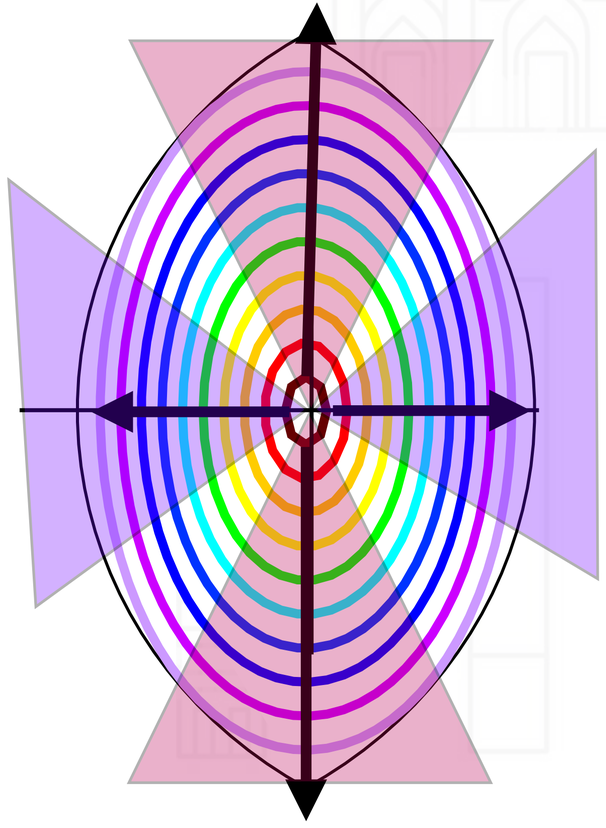
AZIMUTHAL ANISOTROPY - IN A NUTSHELL

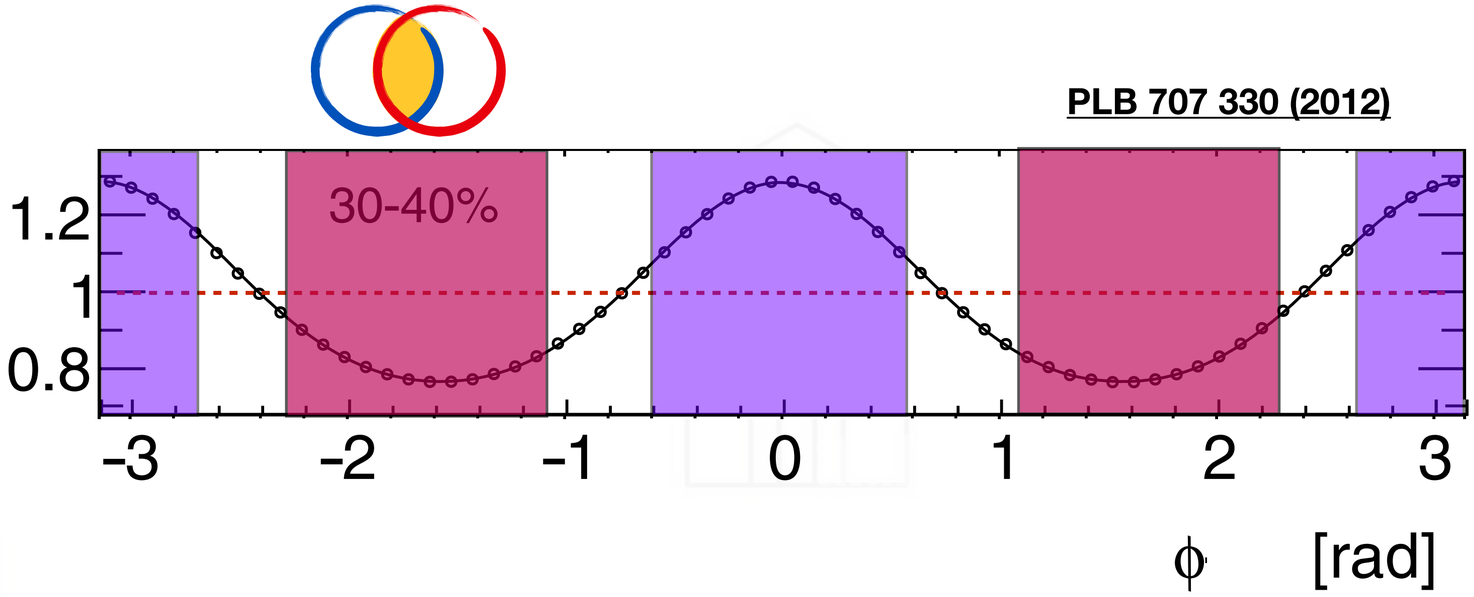




more particles come out the short side than the long side!

FLOW - IN A NUTSHELL

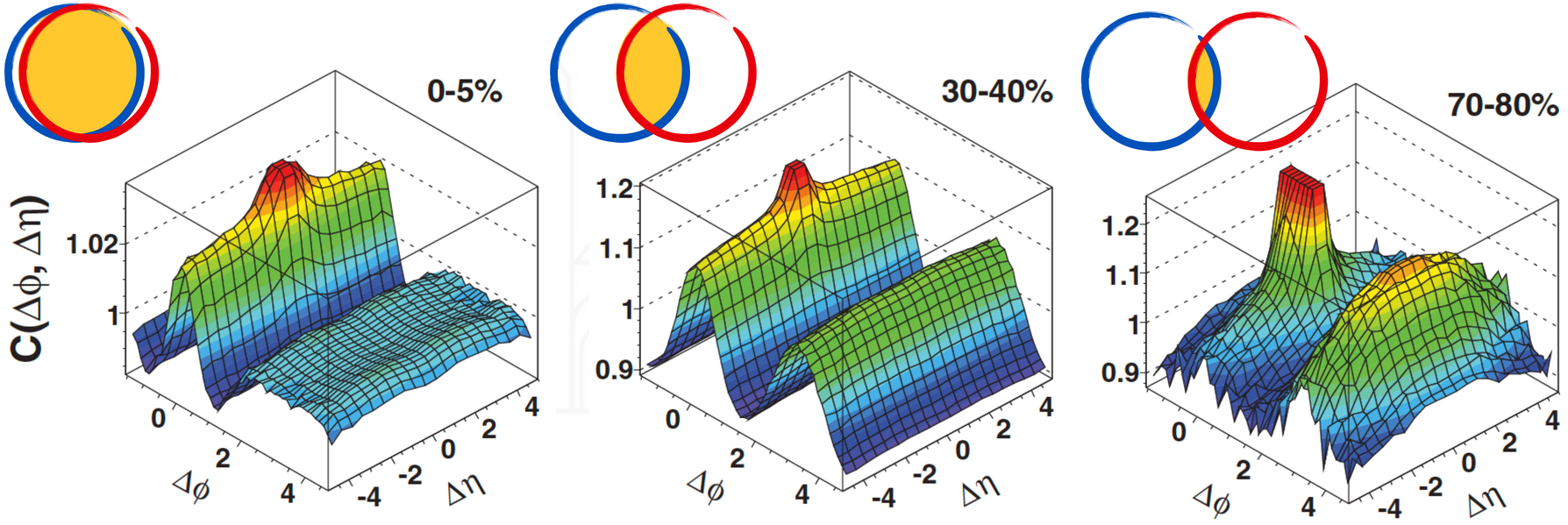




gradual pressure change

steep pressure change

FLOW - MORE IN DETAIL



ATLAS

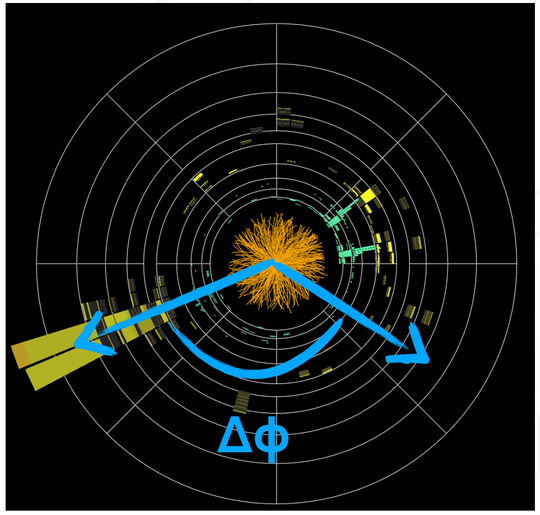
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV

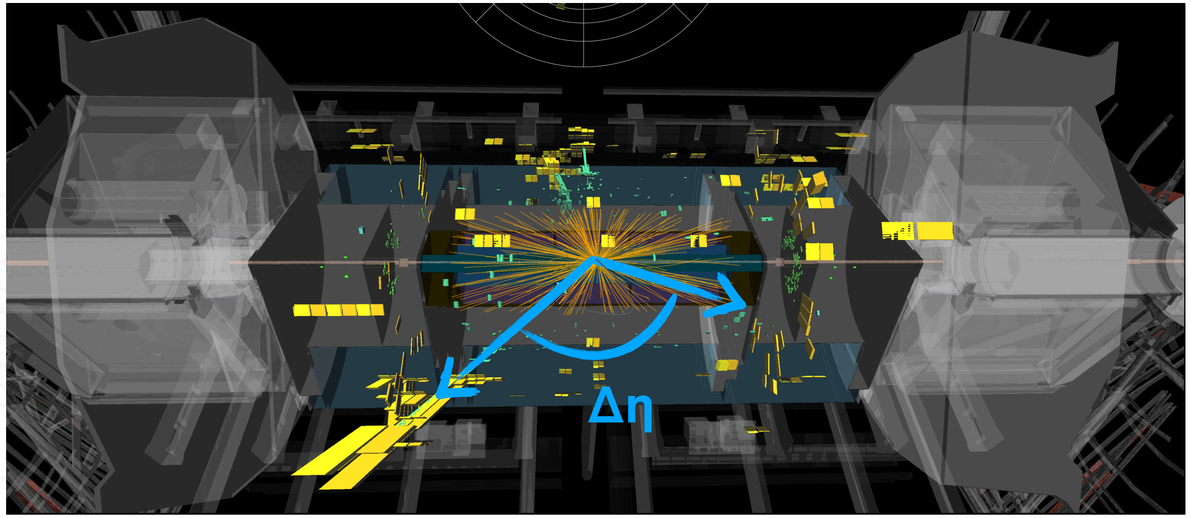
L_{int}= 8 μb^{-1}

$2 < p_T^a, p_T^b < 3$ GeV

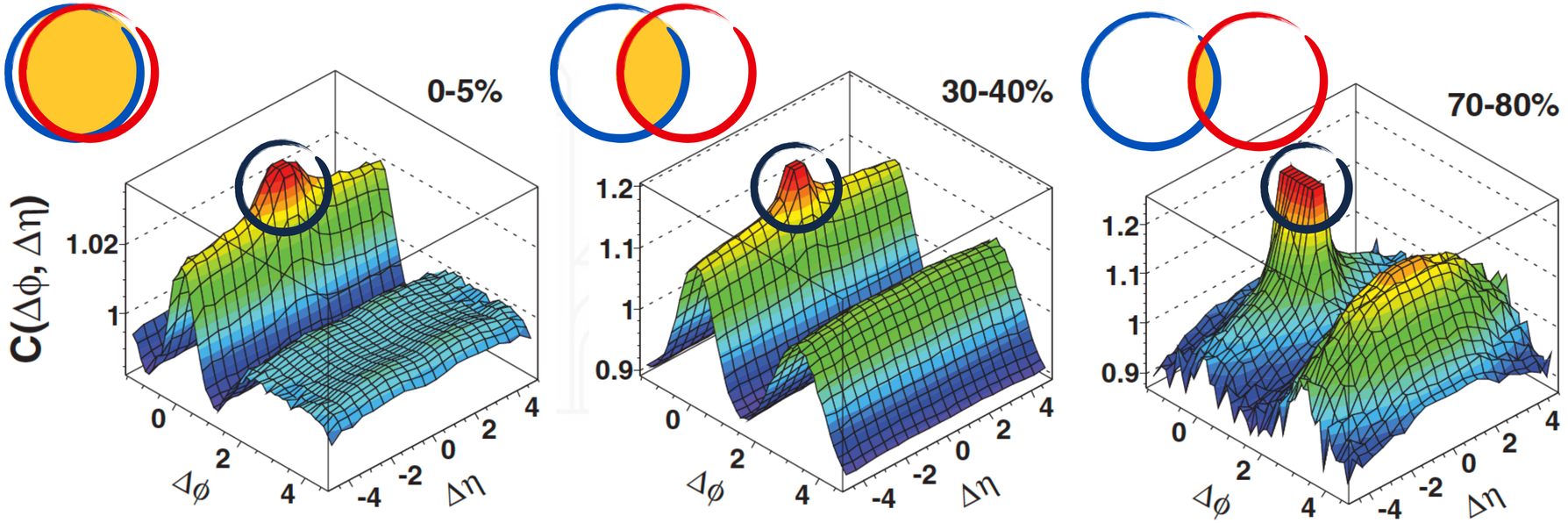
2-particle correlations

To study azimuthal (Δϕ) and longitudinal (Δη) correlations between pairs of particles





2PC INTERPRETATION



PRC 86, 014907 (2012)

ATLAS

Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV

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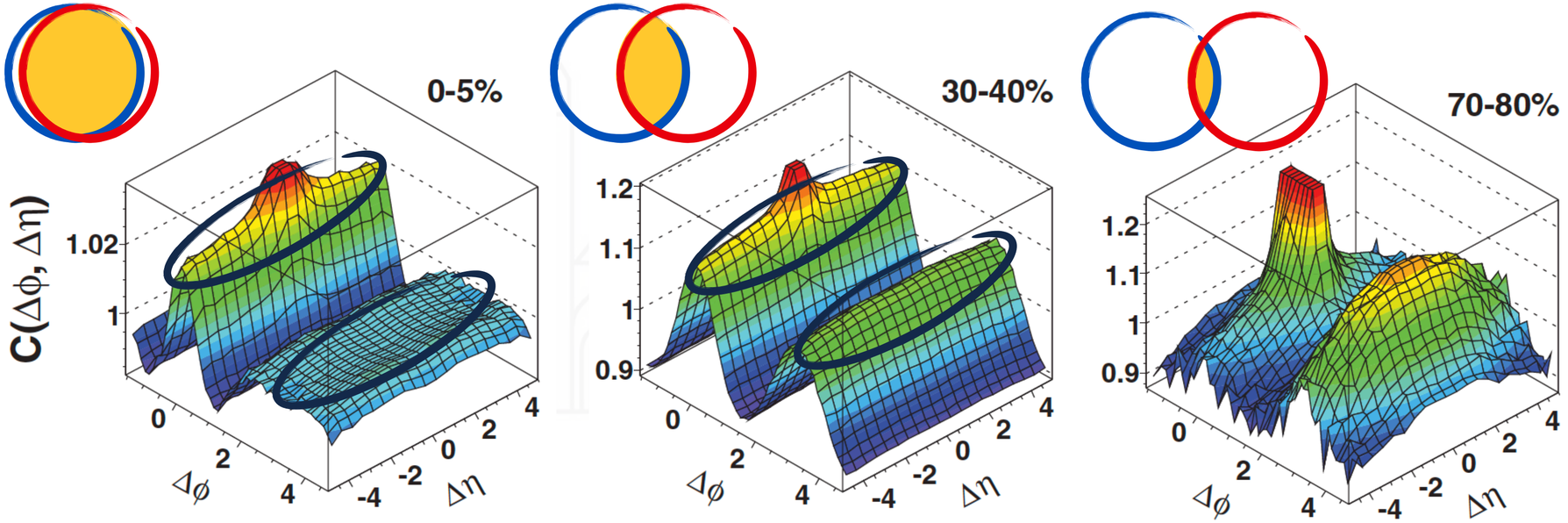
➡**Clear near-side contribution from jets for all centralities**

2PC INTERPRETATION



PRC 86, 014907 (2012)

ATLAS

Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV

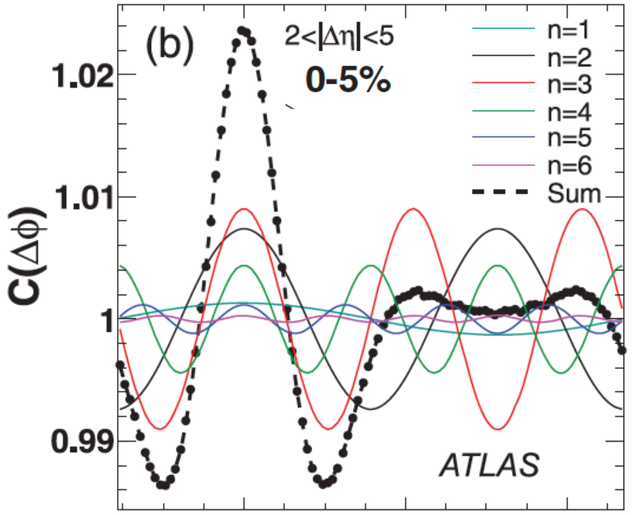
L_{int}= 8 μb^{-1}

$2 < p_T^a, p_T^b < 3$ GeV

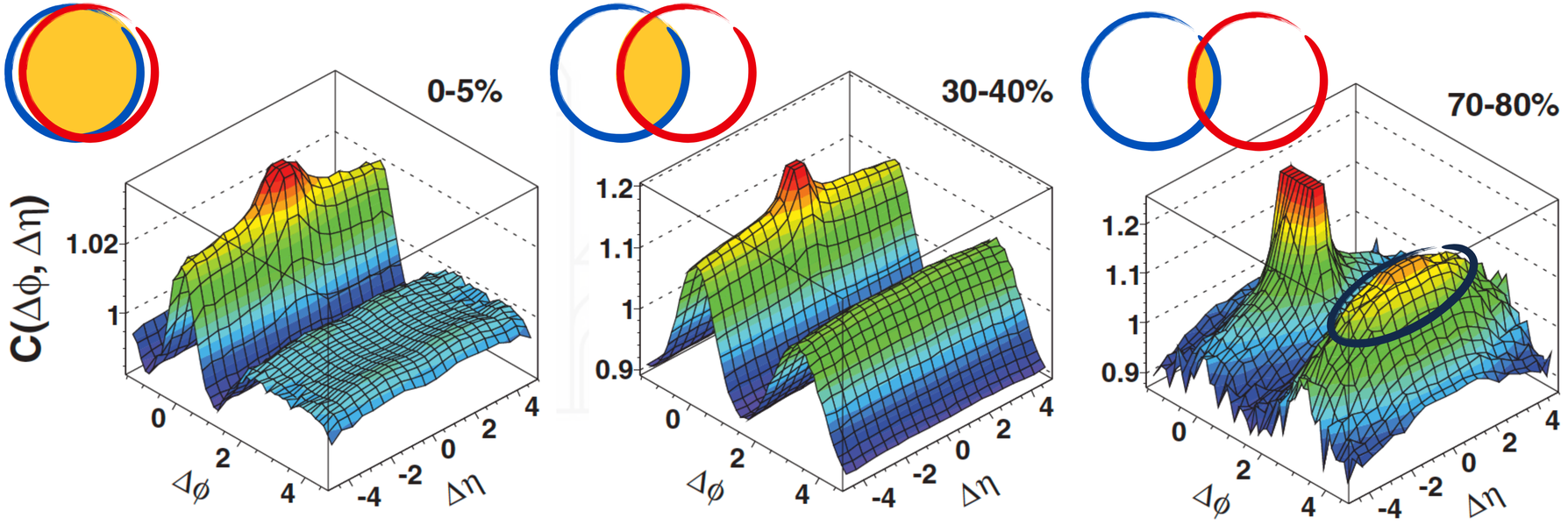
➡Clear near-side contribution from jets for all centralities

➡**Long-range correlations (in Δη) appear in central and mid-central events (not in peripheral)**

Alll harmonics for different n all contribute positively to the correlation function at $\Delta\phi = 0$



2PC INTERPRETATION



PRC 86, 014907 (2012)

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➡Clear near-side contribution from jets for all centralities

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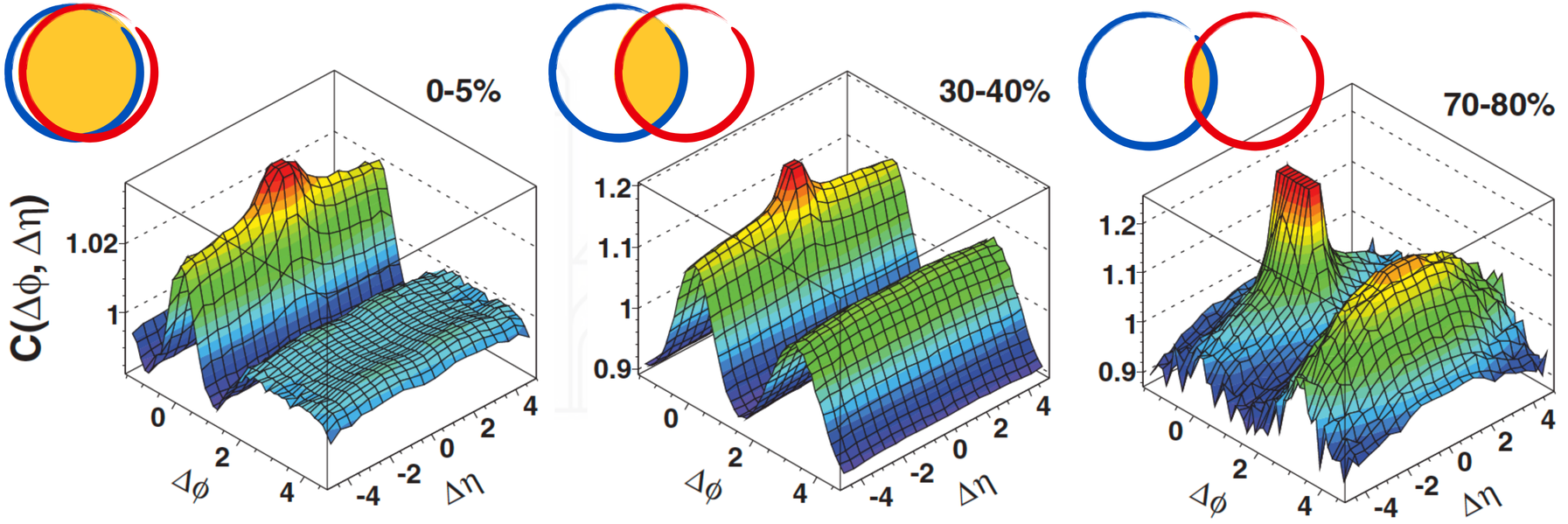
➡**No long-range correlations in peripheral collisions & emergence of away side (di)jet peak**

2PC INTERPRETATION



PRC 86, 014907 (2012)

ATLAS

Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV

L_{int}= 8 μb^{-1}

$2 < p_T^a, p_T^b < 3$ GeV

- Clear near-side contribution from jets for all centralities
- Long-range correlations (in Δη) appear in central and mid-central events
- No long-range correlations in peripheral collisions & emergence of away side (di)jet peak

COLLECTIVE, STRONGLY COUPLED, LONG-DISTANCE BEHAVIOR!

How does the long-range QGP behavior emerge from the microscopic QCD theory?

LONG VS SHORT RANGE QGP BEHAVIOR

AZIMUTHAL ANISOTROPY

Strongly-coupled long distance behavior

Hydrodynamic evolution of perfect fluid to describe it

How does the long range QGP behavior emerge from the microscopic QCD theory?

MODIFICATION OF HARD PROBES

Short distance

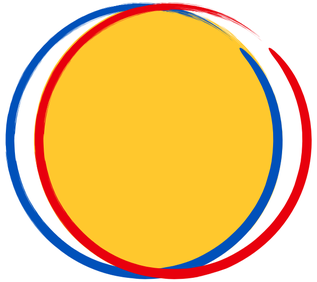
Probes asymptotically free quarks and gluons

AN INSIDER WORK

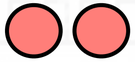
HARD PROBES

Generated in the early stage of the collisions - they experience QGP effects while escaping from it

NUCLEAR MODIFICATION FACTOR

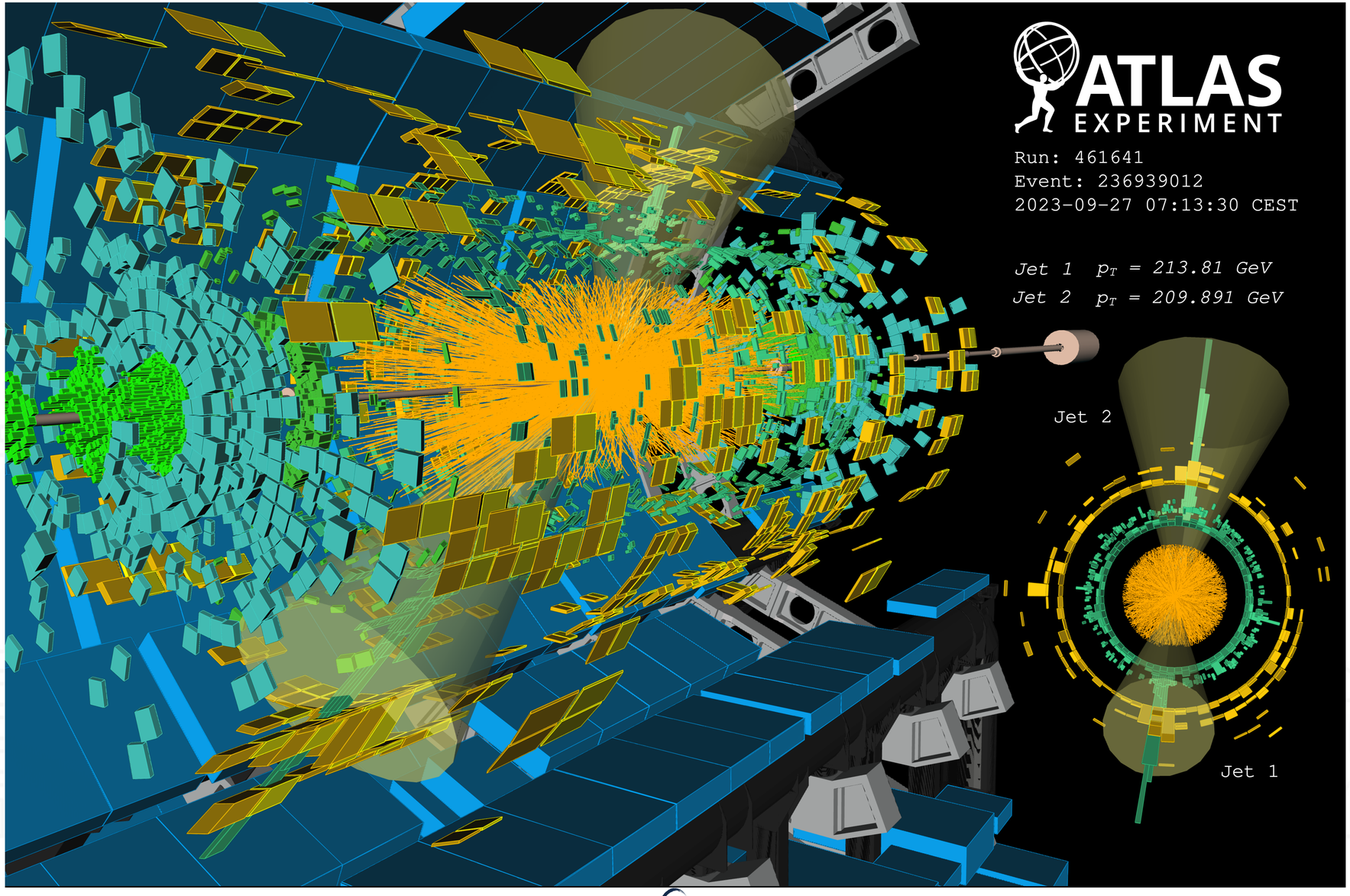


Probe in QGP

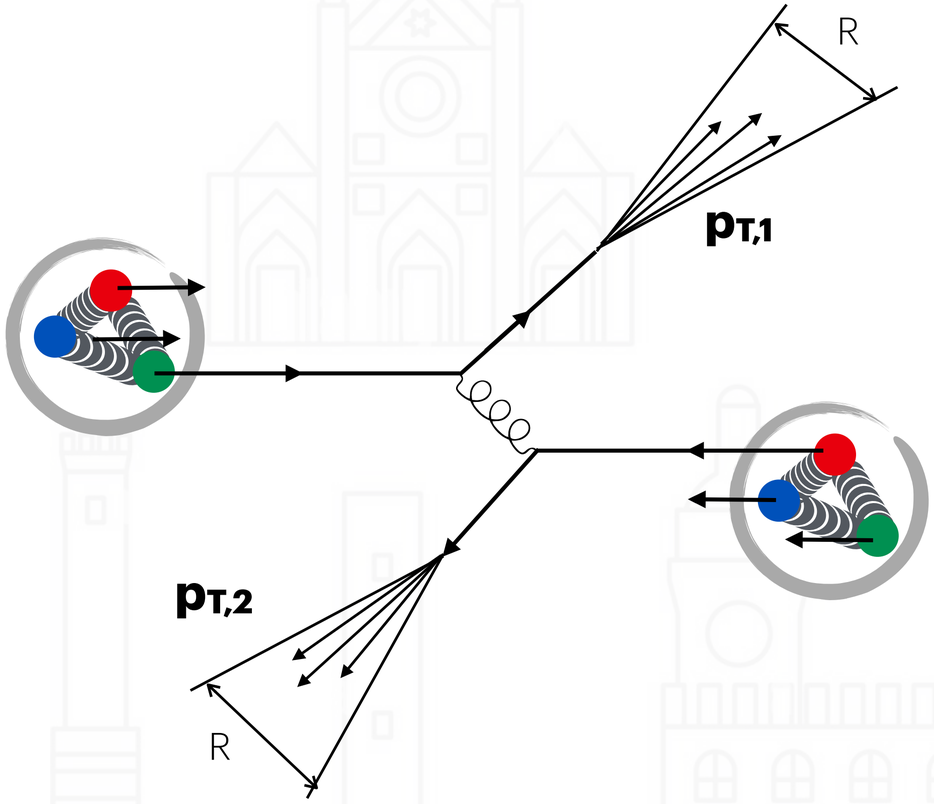


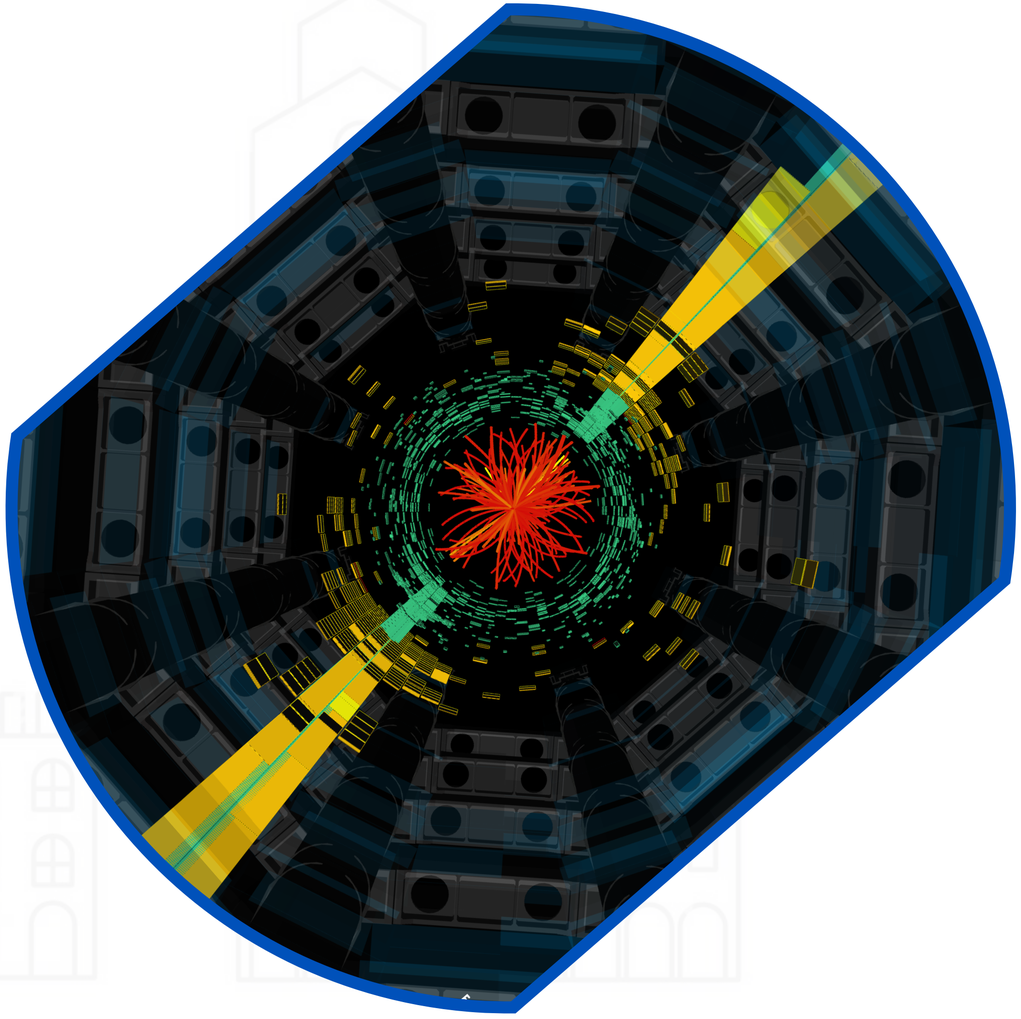
Probe w/o QGP

DIJETS AS MICROSCOPE FOR THE QGP

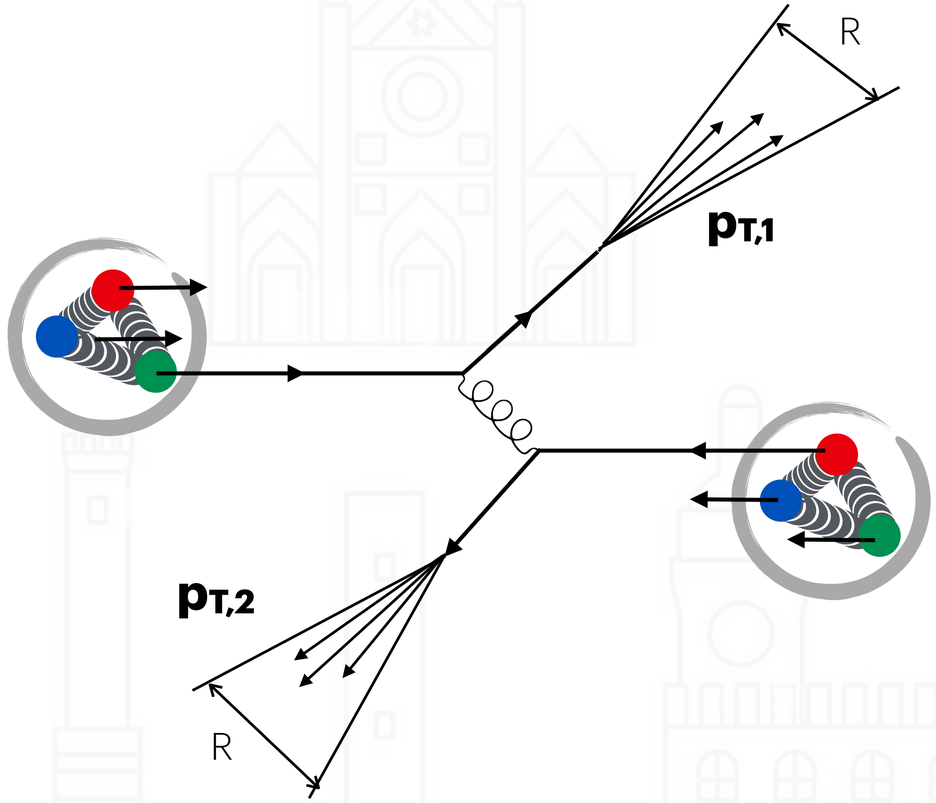


PROTON-PROTON BASELINE



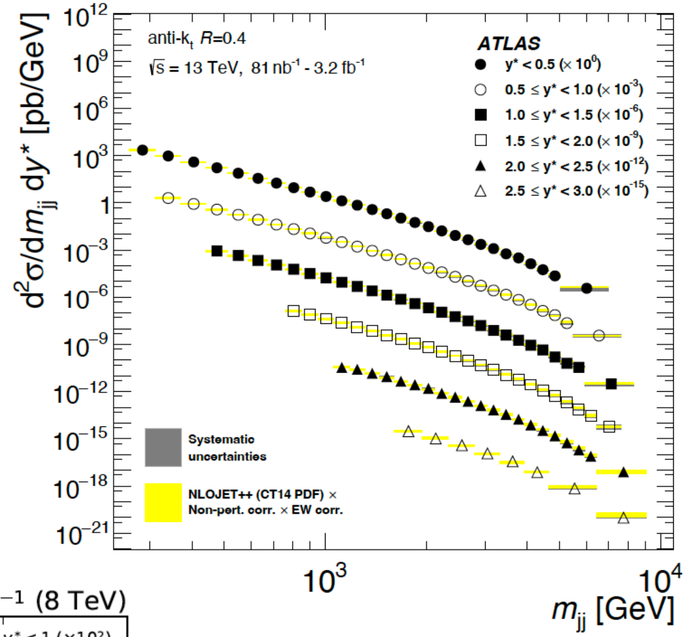


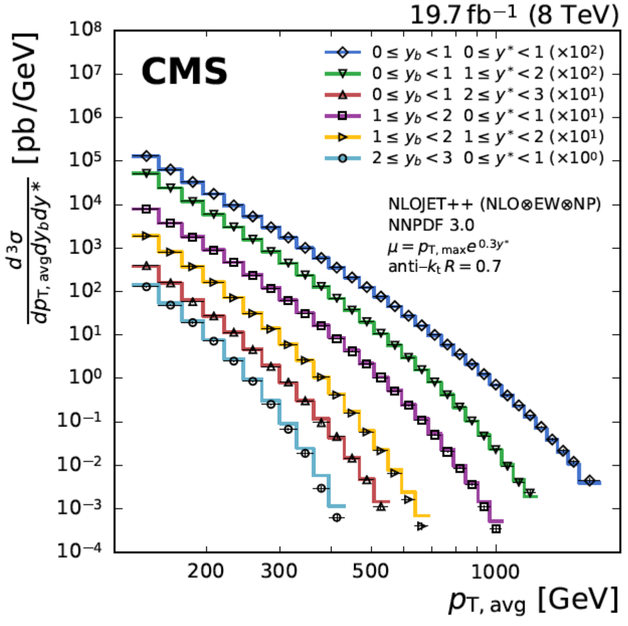
PROTON-PROTON BASELINE



Very well understood
several measurements @ various energies

[JHEP 05 (2018) 195]

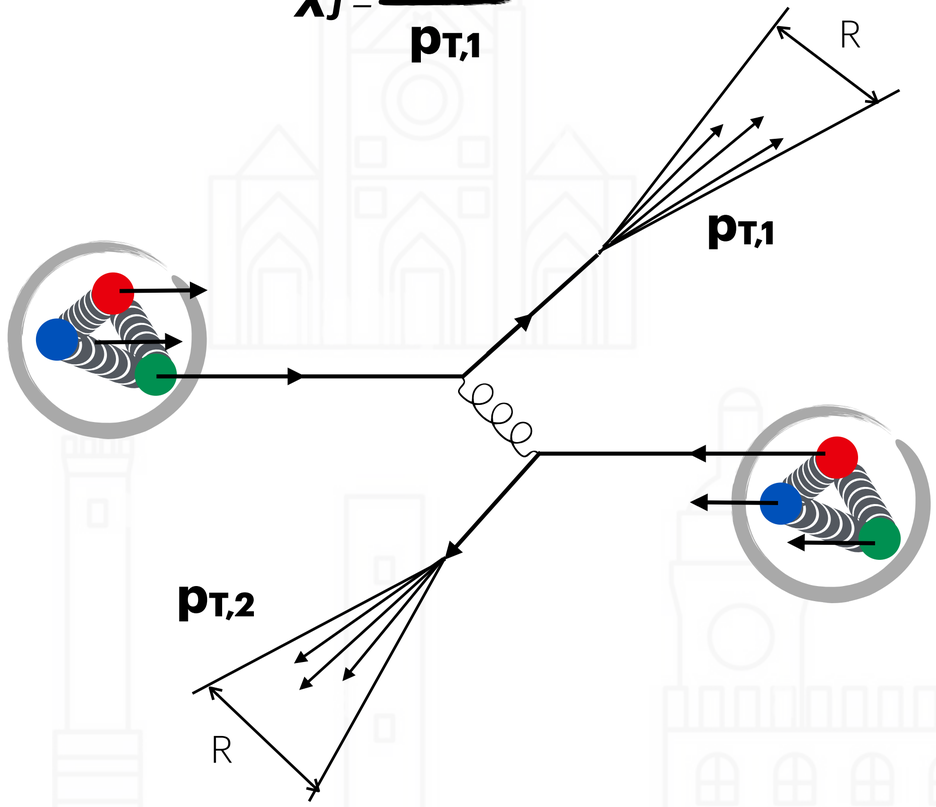




[Eur. Phys. J. C 77 (2017) 746]

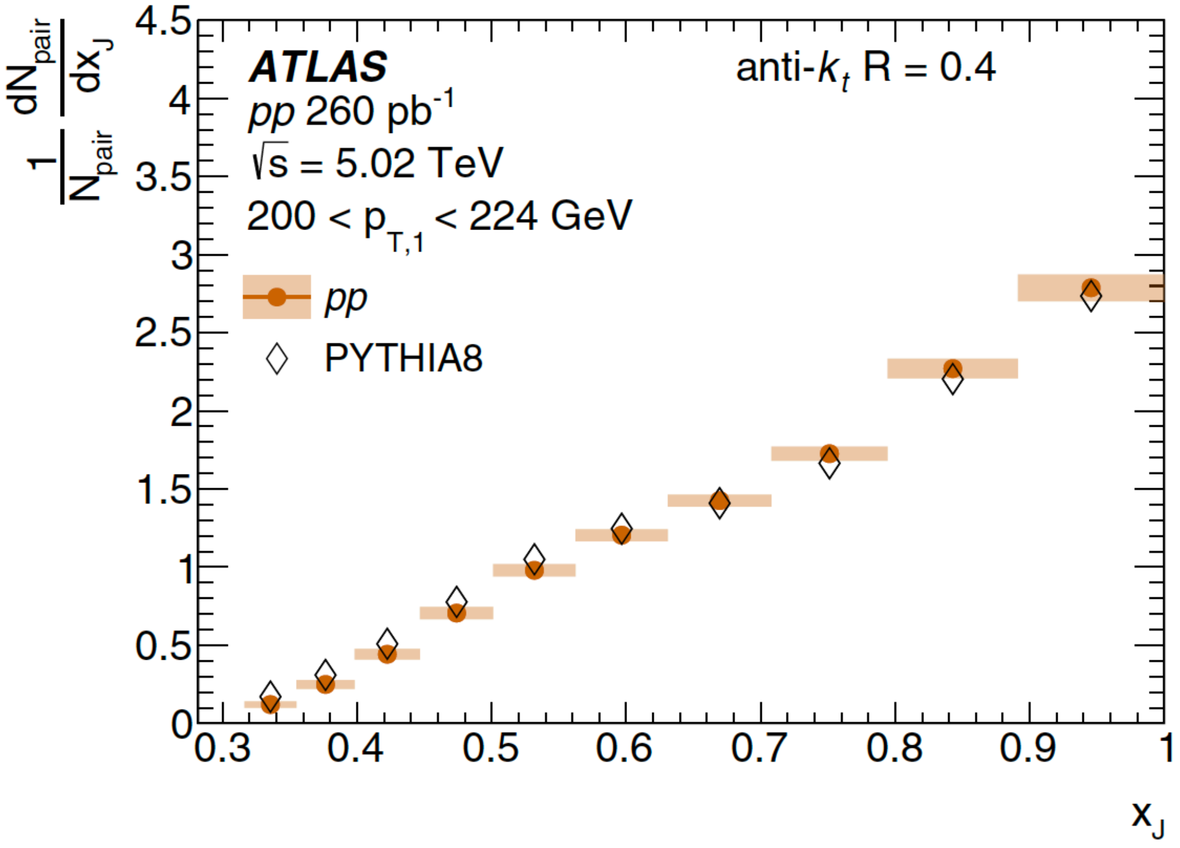
PROTON-PROTON BASELINE

$$x_J = \frac{p_{T,2}}{p_{T,1}}$$



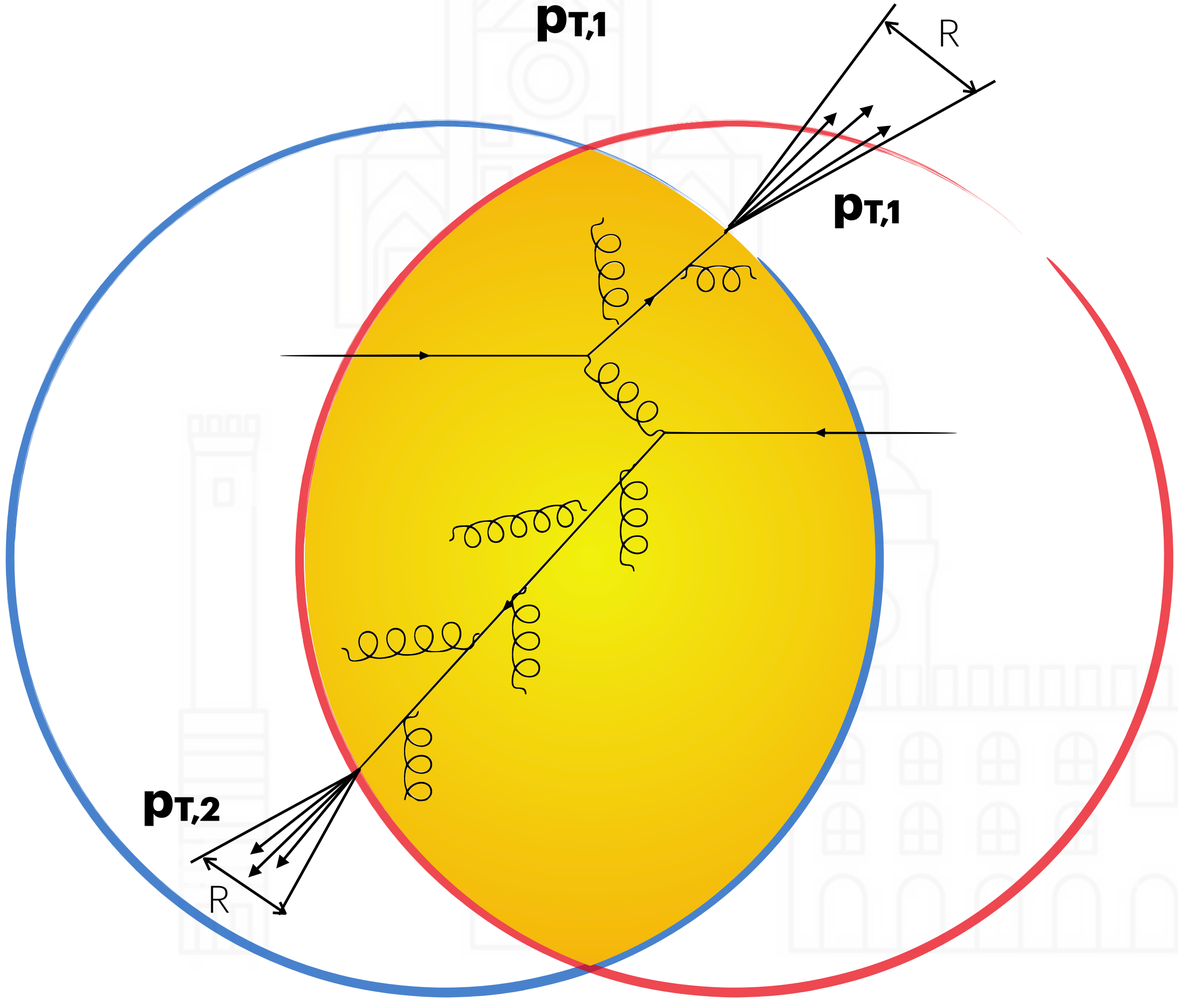
Very well understood
several measurements @ various energies

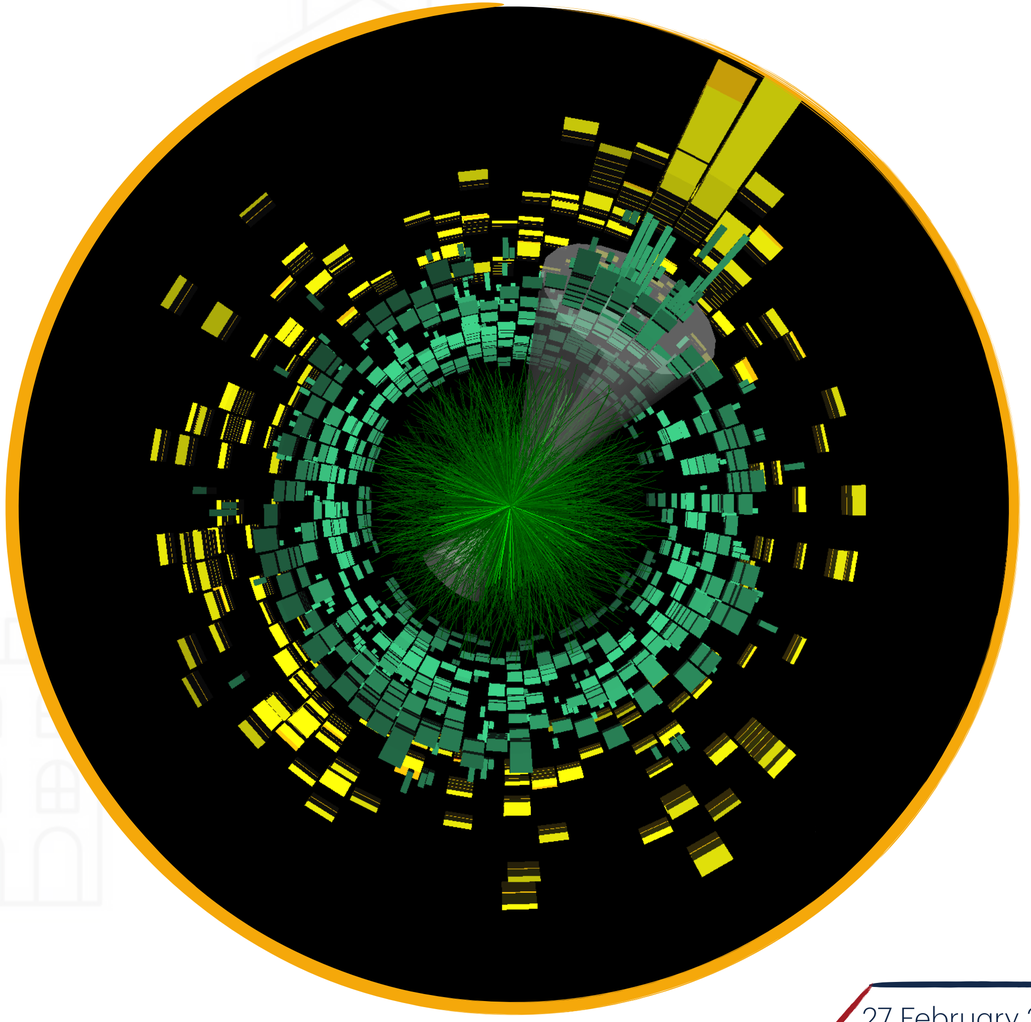
Dijets in p+p are likely to be balanced



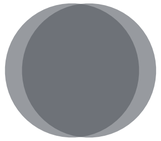
HOW THAT CHANGES IN HEAVY IONS?

$$x_J = \frac{p_{T,2}}{p_{T,1}}$$

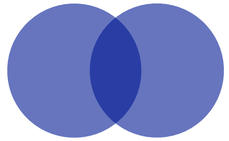


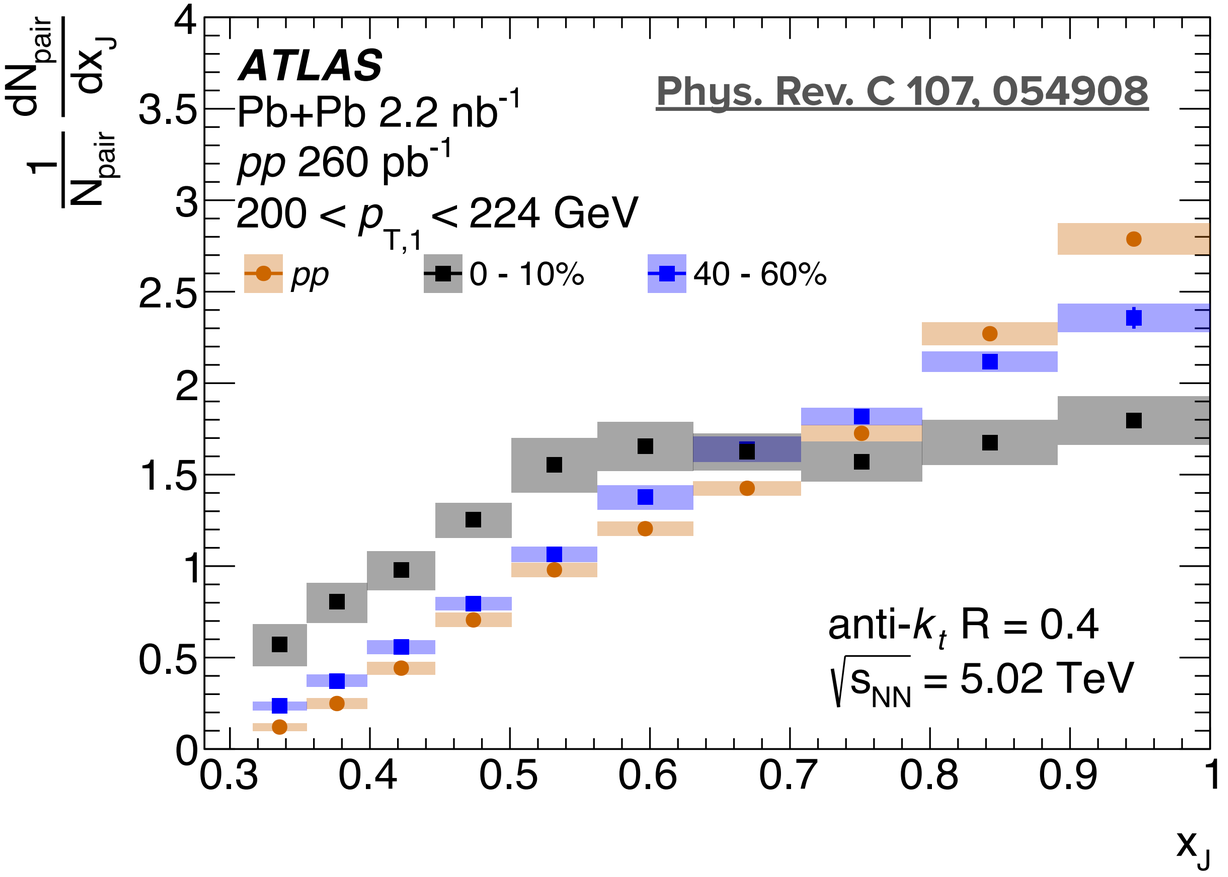


QUANTIFYING THE MEDIUM EFFECT



$$x_J = \frac{p_{T,2}}{p_{T,1}}$$

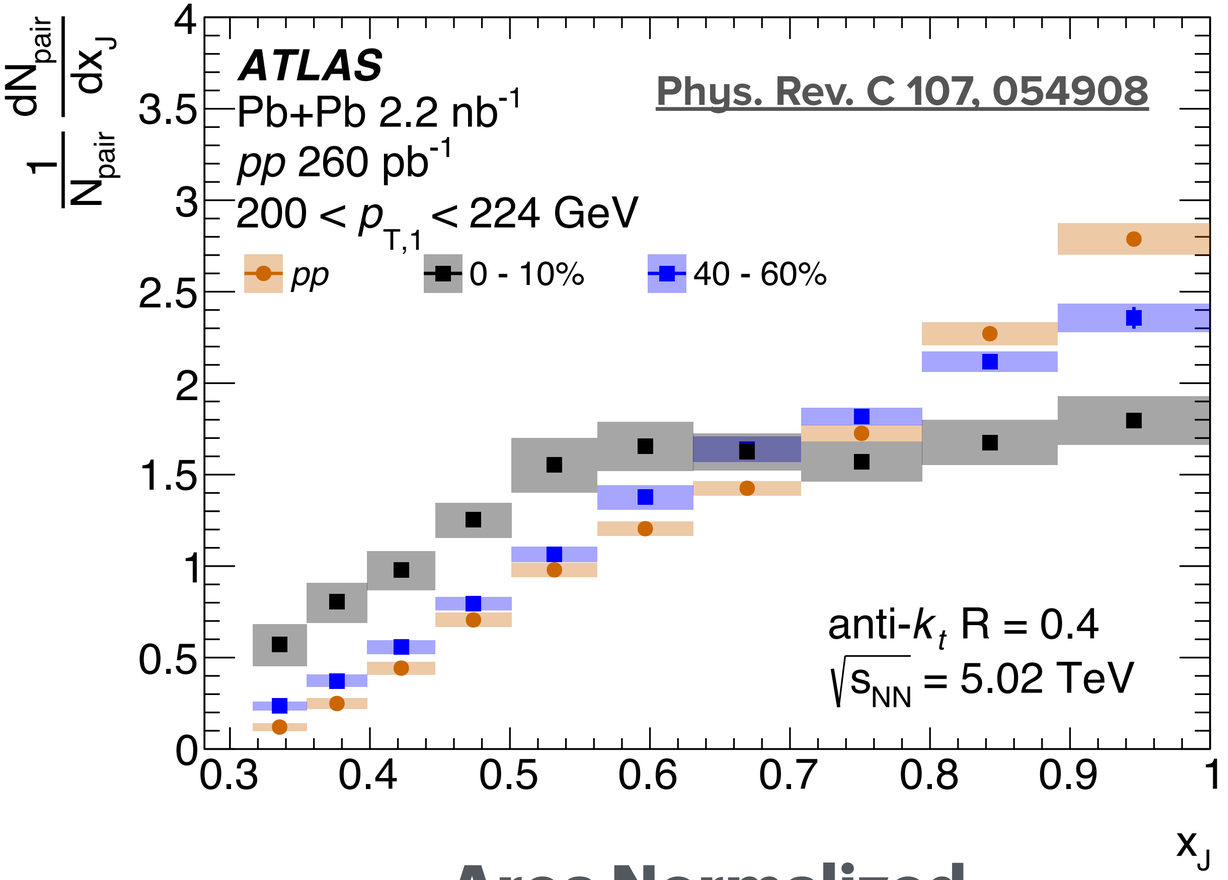




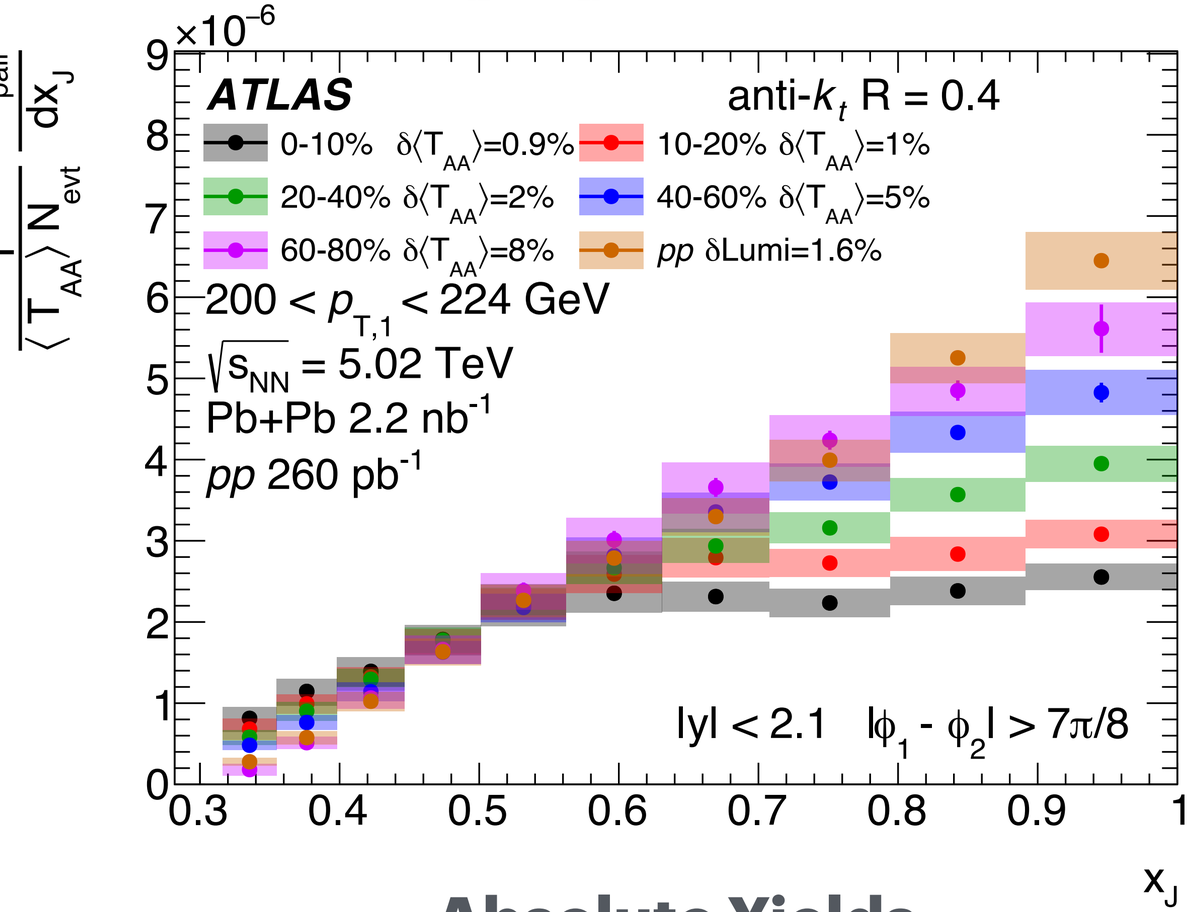
increasing the size of the QGP increases the amount of imbalanced jets

QUANTIFYING THE MEDIUM EFFECT

Rate of imbalanced jets barely changes from pp collisions
Balanced jets are preferentially suppressed



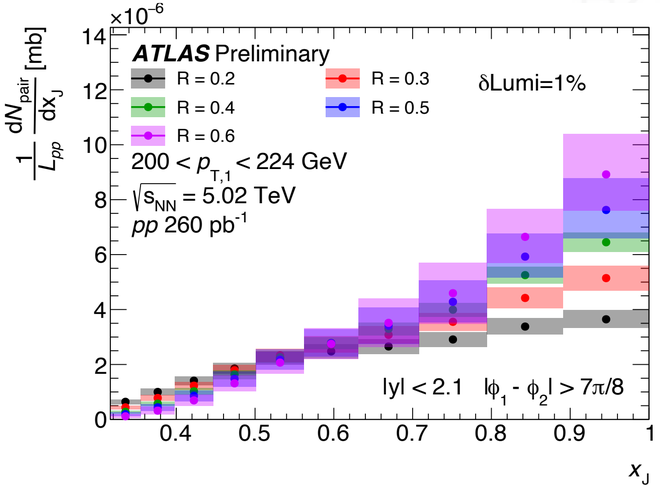
Area Normalized



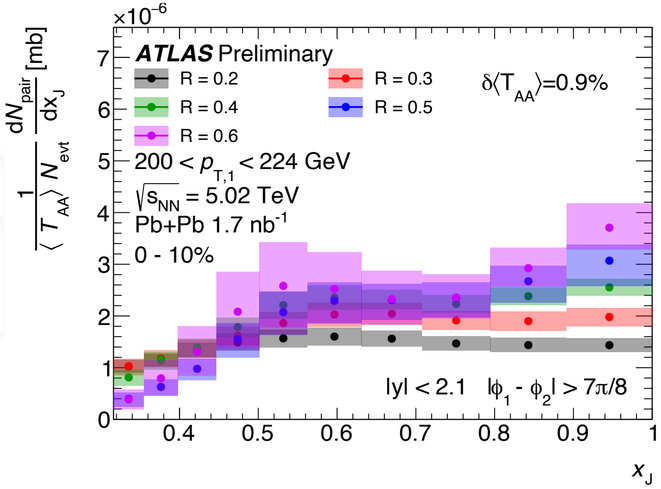
Absolute Yields

QUANTIFYING THE MEDIUM EFFECT [MORE DIFFERENTIALLY]

pp

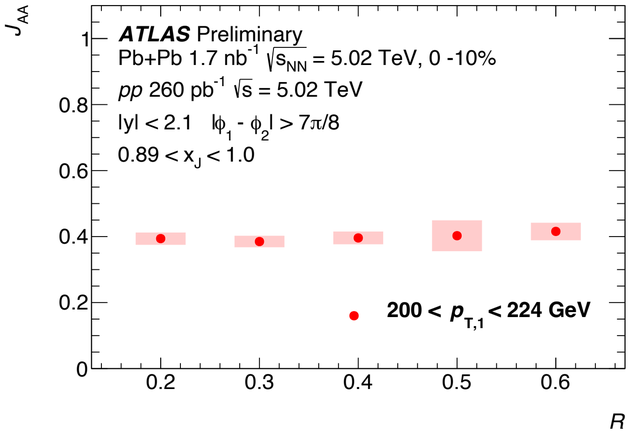


Pb+Pb
0-10%

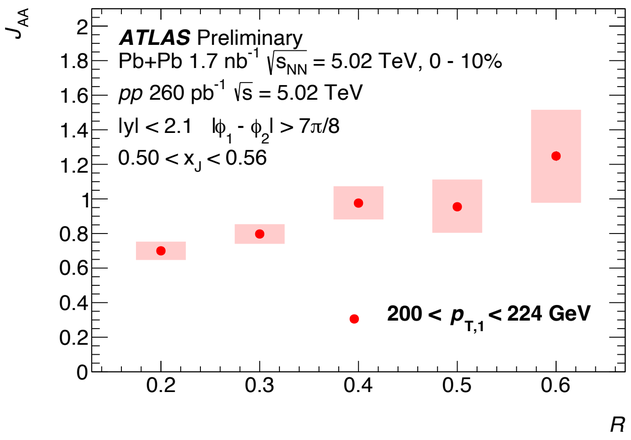


$$J_{AA} = \frac{\text{Pb+Pb 0-10%}}{pp}$$

Balanced jets



Unbalanced jets



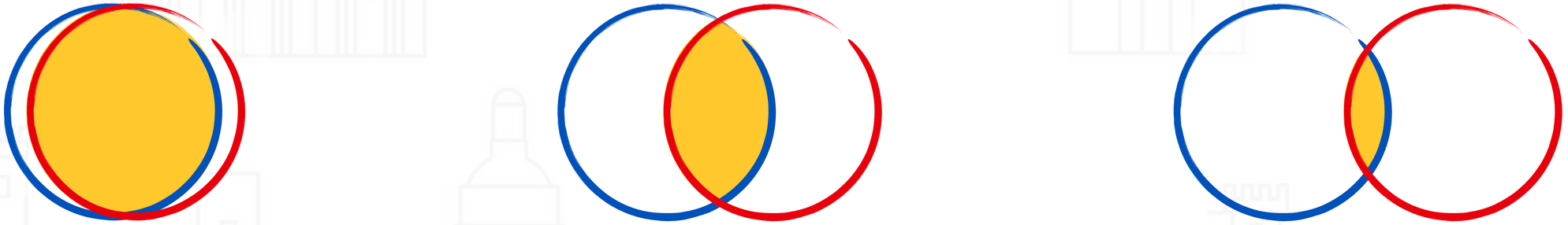
Imbalanced dijets are less suppressed for larger radius

ATLAS-CONF-2023-060

IS IT JUST ABOUT THE FINAL STATE?

Final State (FS) Effects: introduced between the collision and the particle detection (e.g. by the QGP) => **Jets as a microscope for them!**

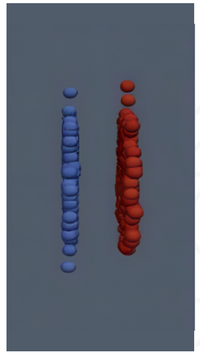
Front view

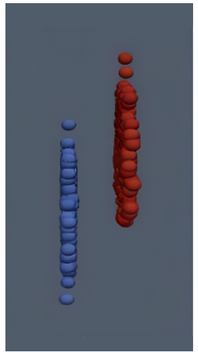


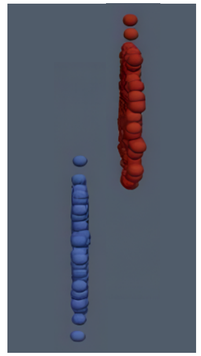
Initial State (IS) Effects: introduced by conditions that can influence the status of the collision and its products (e.g. **geometry of the collision**, ...)

INITIAL STATE EFFECTS

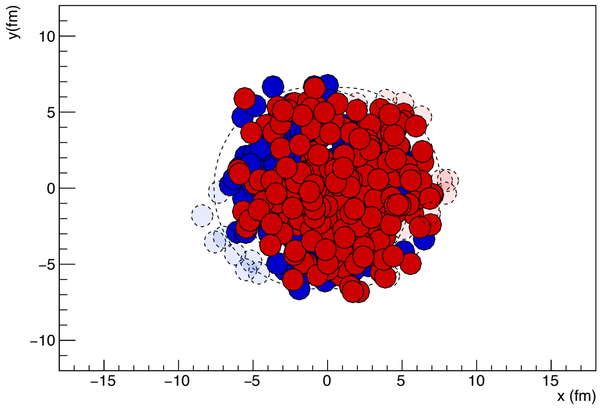
Side view

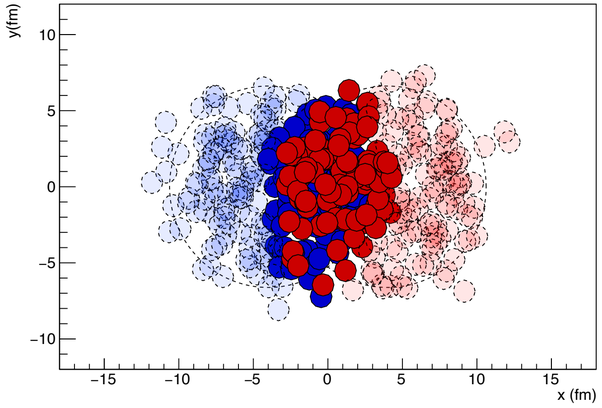


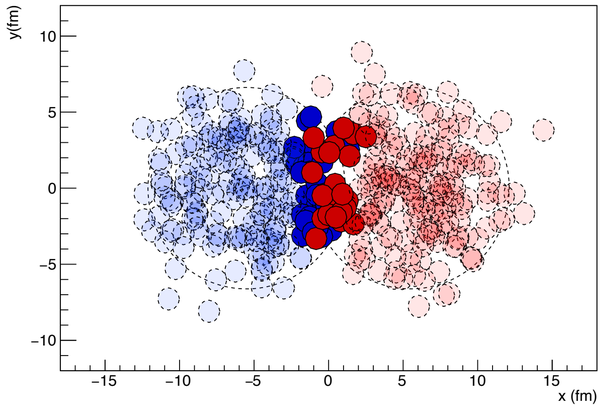




Front view







Nucleus 1

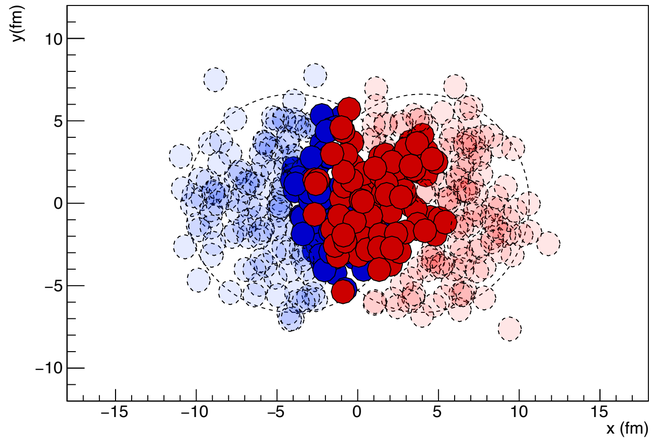
Nucleus 2

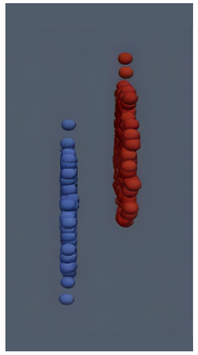
"Spectators"

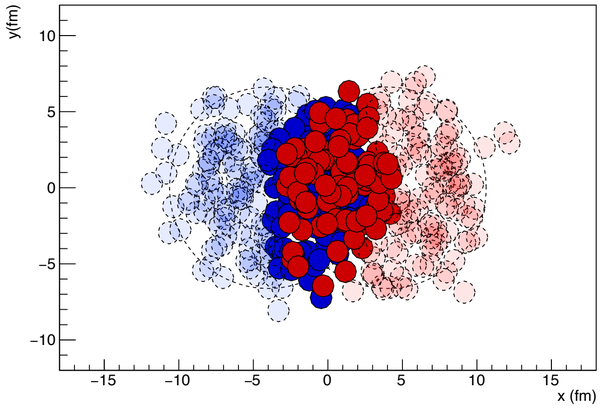
"Participants"

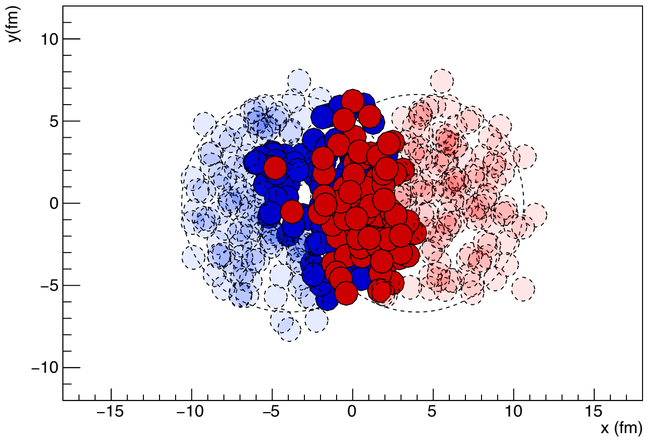
Initial State (IS) Effects: introduced by conditions that can influence the status of the collision and its products (e.g. geometry of the collision, **nucleus configuration**…)

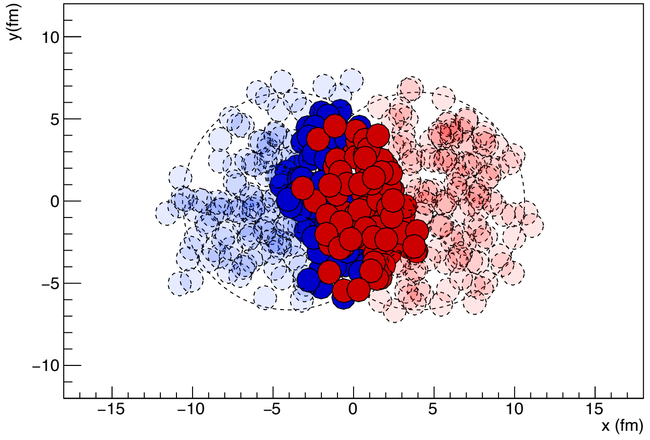
INITIAL STATE EFFECTS











Nucleus 1

Nucleus 2

"Spectators"

"Participants"

Examples of different collisions at same impact parameter generated using the MC Glauber approach

What is the nucleus configuration at the time of the collision?

P+A COLLISIONS TO ACCESS INITIAL STATE EFFECTS

$\sqrt{s_{NN}} = 5.02\,\text{TeV}$

2013, ~30 nb^{-1}

$\sqrt{s_{NN}} = 8.16\,\text{TeV}$

2016, ~165 nb^{-1}

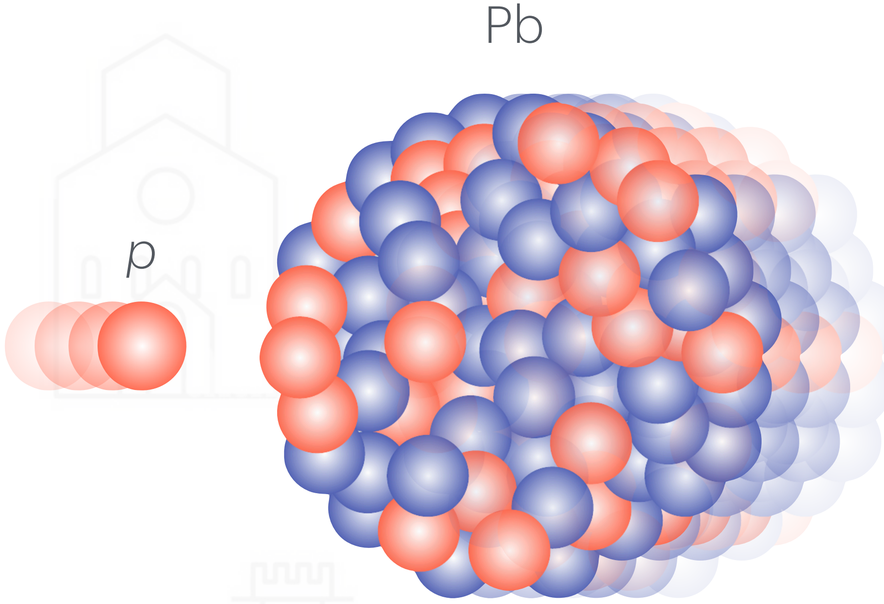
$\sqrt{s_{NN}} = 8.8\,\text{TeV}$

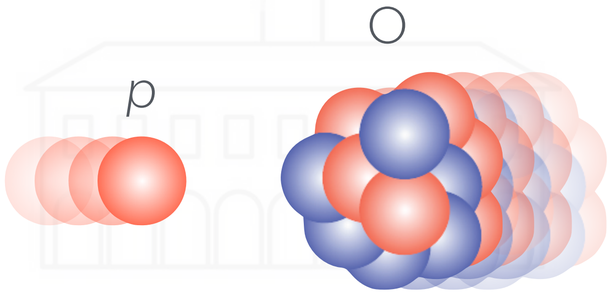
Run 4++ (2029++)



$\sqrt{s_{NN}} = 9.9\,\text{TeV}$

2025 bonus track: p+O collisions!





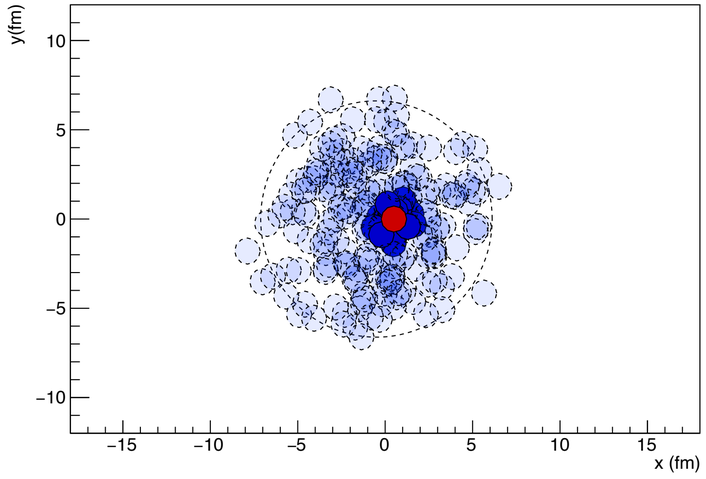
How small the system has to be to turn-off the QGP effects?

QGP EFFECTS IN P+A?

We can use the proton as a probe for the nuclear structure [**cold QCD**]

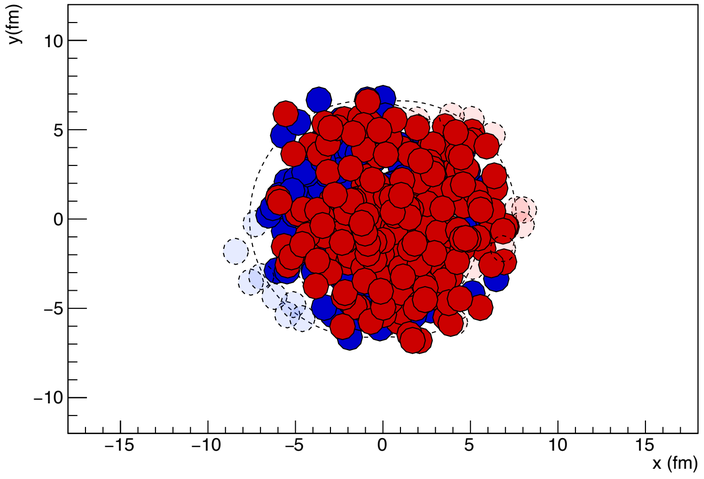
Are there [**hot QCD**] final state effects to be accounted for?

➡**Is QGP formed in p+A collisions?**



p+Pb

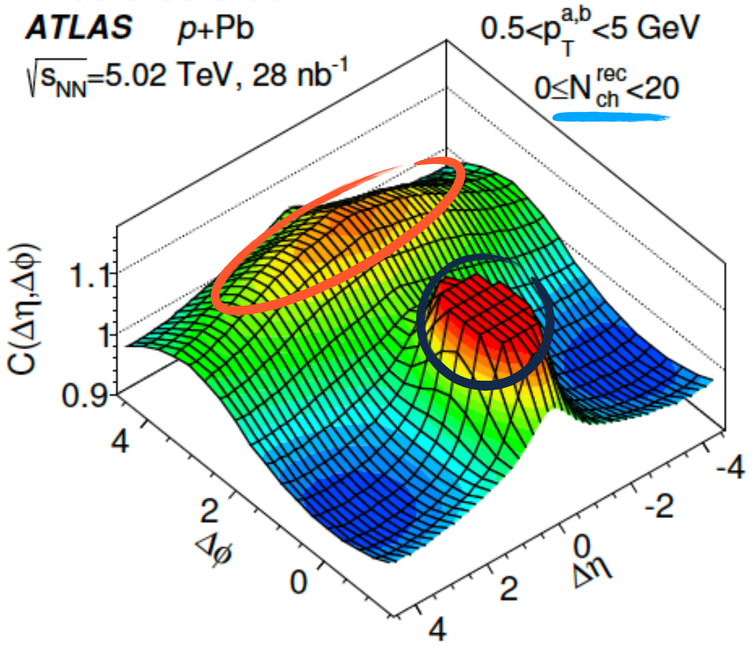
VERY DIFFERENT COLLISION SYSTEM SIZE!



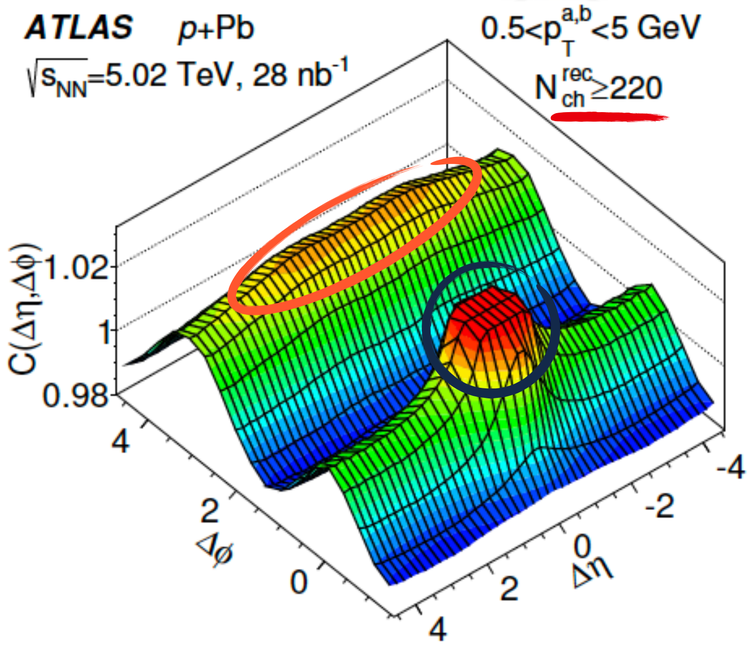
Pb+Pb Central

FLOW IN SMALL SYSTEMS: P+PB

“Low" Multiplicity



“High” Multiplicity



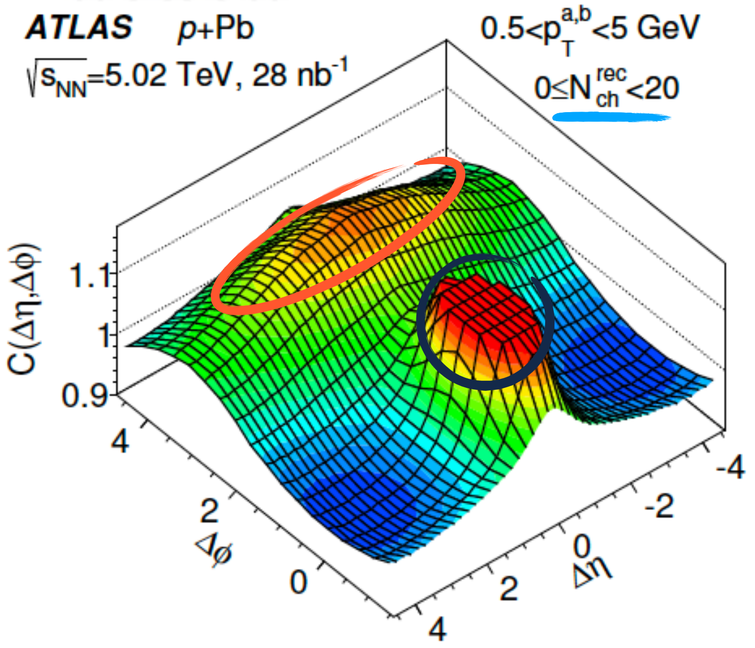
Phys. Rev. C 96 (2017) 024908

Similar behaviors as observed in Pb+Pb!

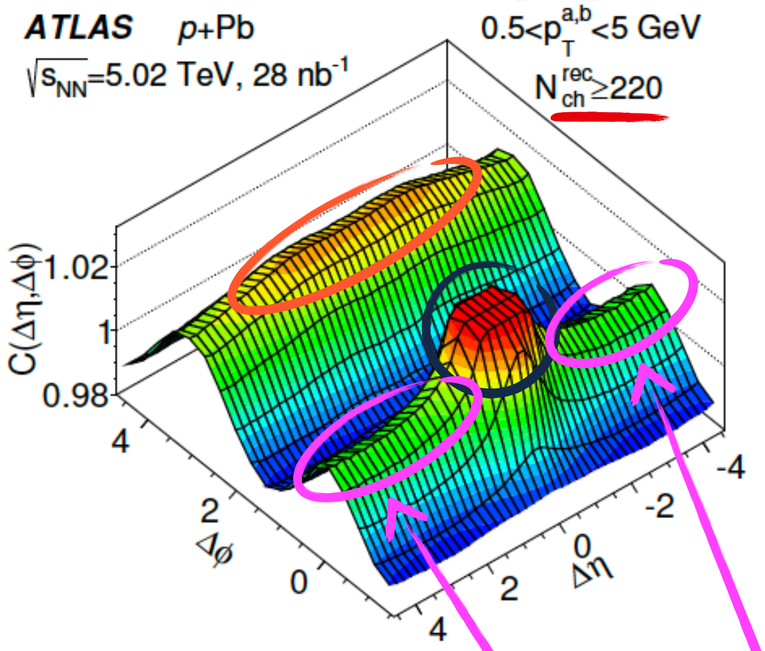
- ➡Jets contribution
- ➡Dijets contribution
- ➡Low-multiplicity events similar to peripheral Pb+Pb

FLOW IN SMALL SYSTEMS: P+PB

“Low" Multiplicity



“High” Multiplicity



Phys. Rev. C 96 (2017) 024908

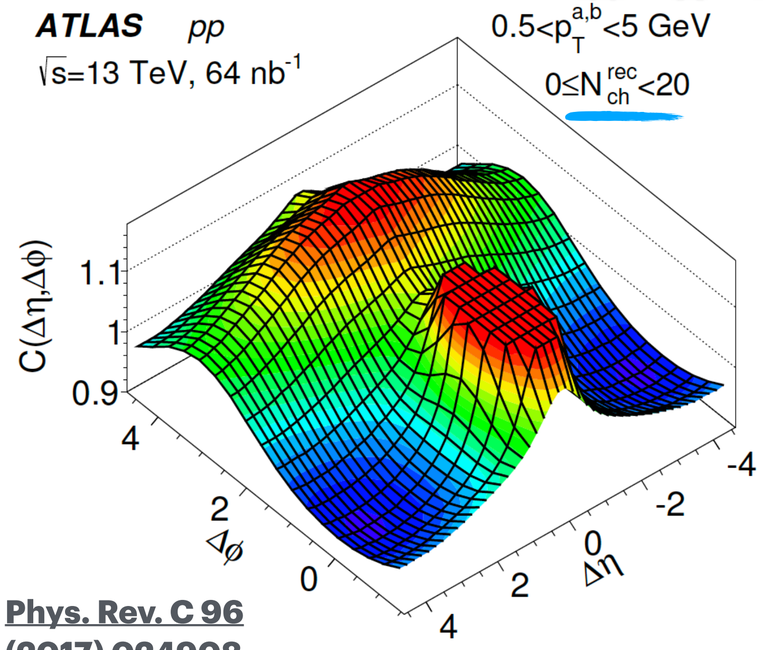
Similar behaviors as observed in Pb+Pb!

- ➡Jets contribution
- ➡Dijets contribution
- ➡Low-multiplicity events similar to peripheral Pb+Pb

Additional near-side“ridge” in high multiplicity events: unexpected!

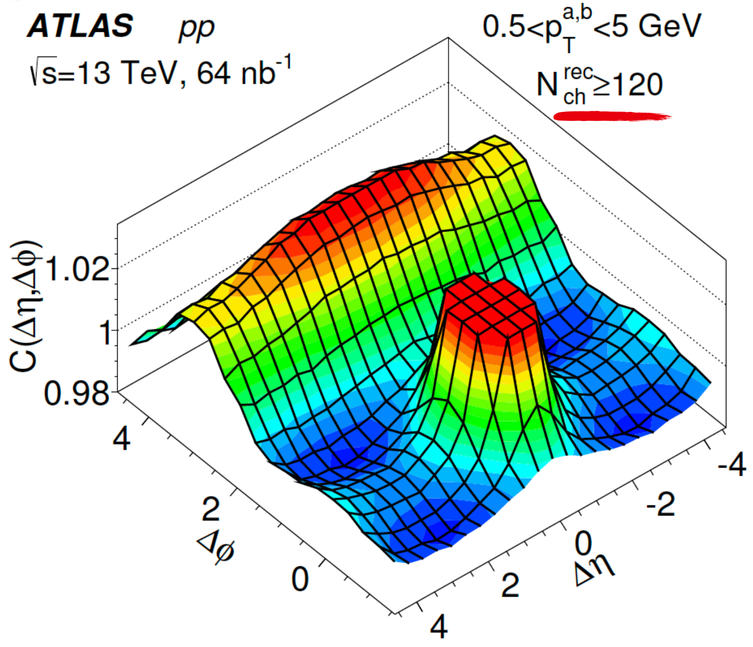
FLOW IN EVEN SMALLER SYSTEMS: P+P !

"Low" Multiplicity



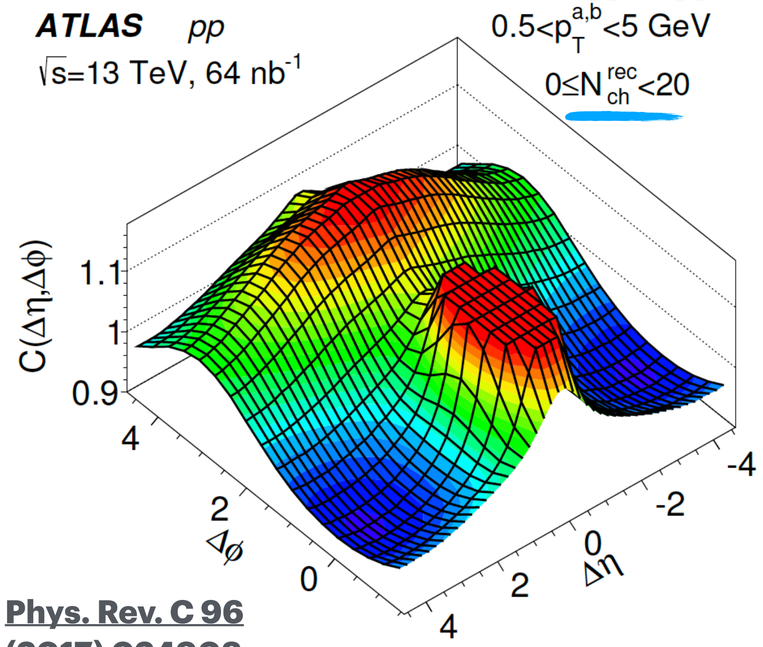
Phys. Rev. C 96 (2017) 024908

"High" Multiplicity

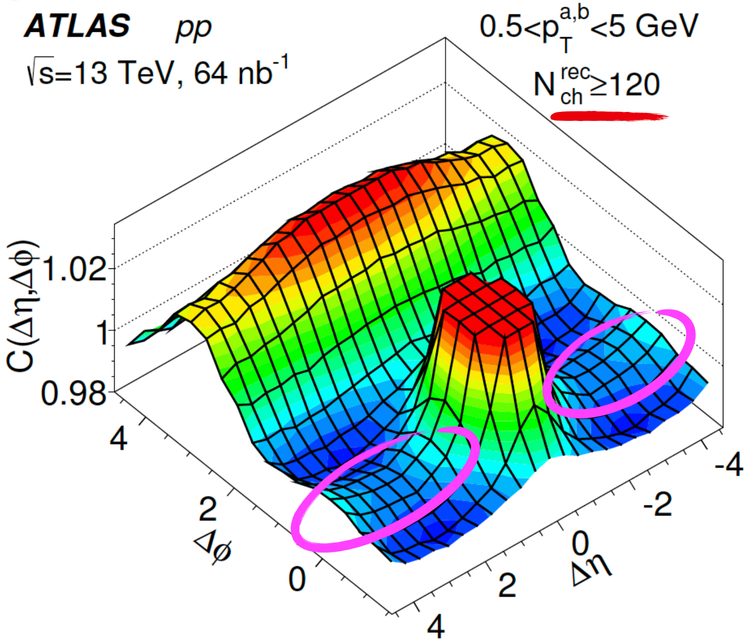


FLOW IN EVEN SMALLER SYSTEMS: P+P !

"Low" Multiplicity

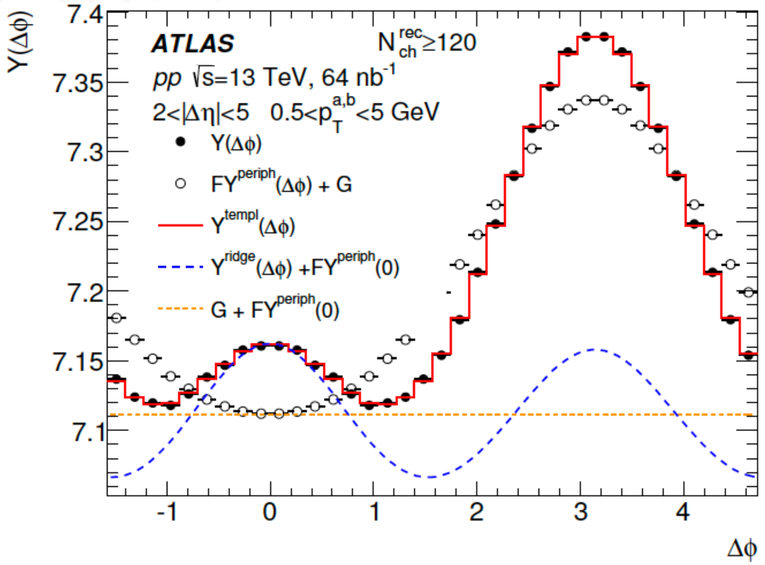


"High" Multiplicity



Phys. Rev. C 96 (2017) 024908

Additional near-side "ridge" in high multiplicity events also in *pp*!

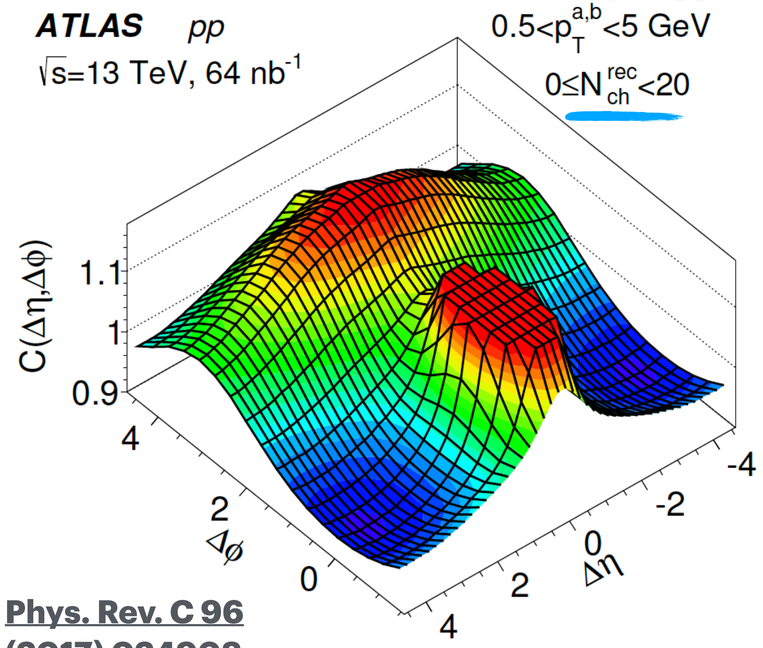


- **Assume 2-particle correlation is a super-position of "intrinsic" (hard?) correlation + sinusoidal harmonics**
  - ➡ intrinsic measured in low-multiplicity (peripheral) events

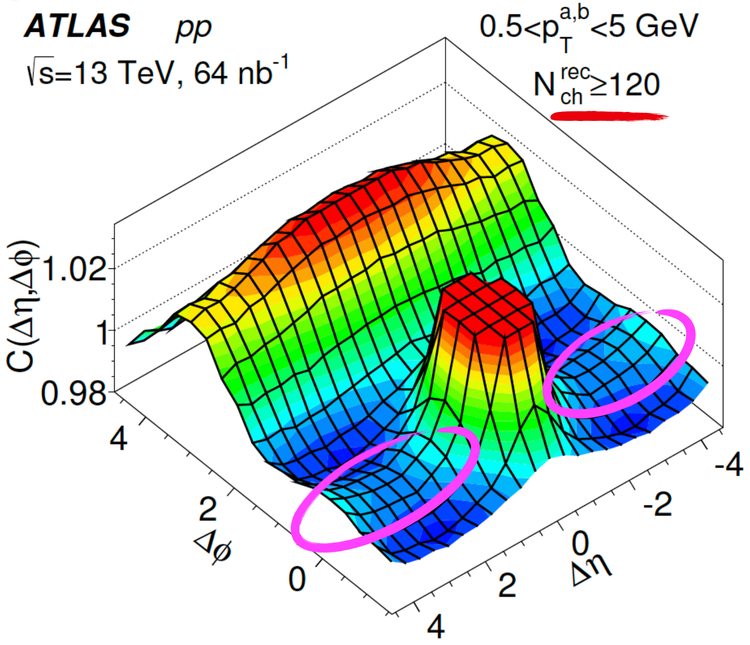
$$Y^{\text{templ}} = FY^{\text{templ}}_{\text{periph}} + G\left(1 + 2\sum_{n} v_{n,n}\cos\Delta\phi\right)$$

FLOW IN EVEN SMALLER SYSTEMS: P+P !

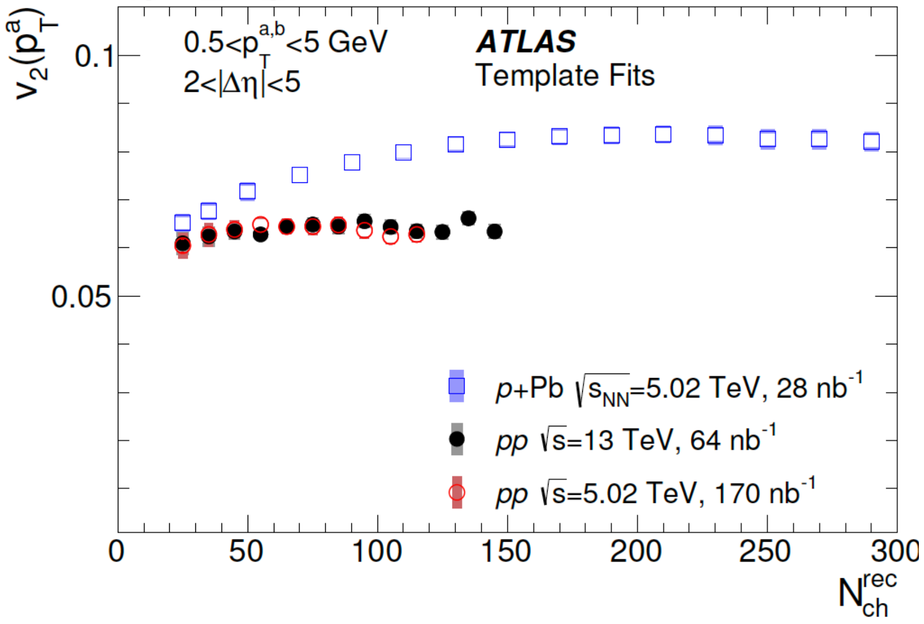
"Low" Multiplicity



"High" Multiplicity



Phys. Rev. C 96 (2017) 024908

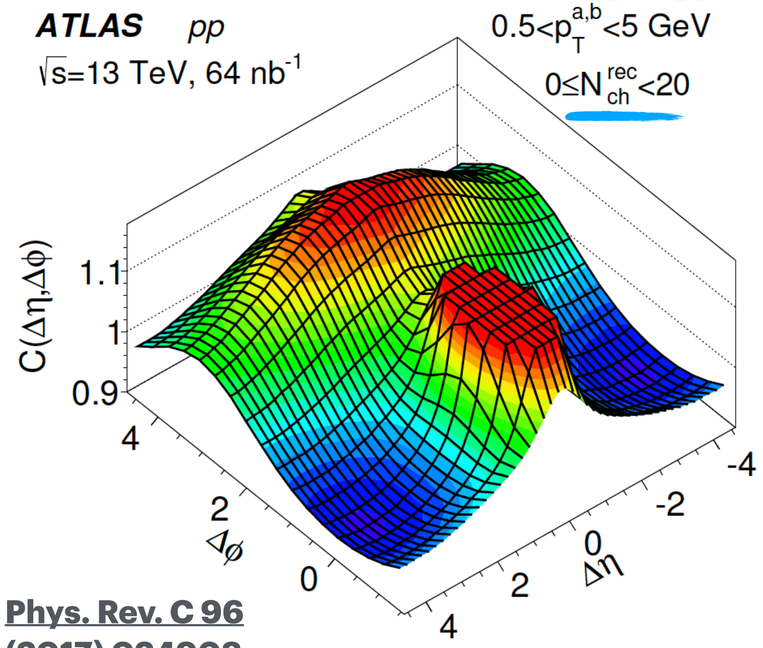


- **v_2 coefficients do not change as a function of the number of particles or beam energy!**

➡Universal behavior of QCD at high-energies and long wavelengths?

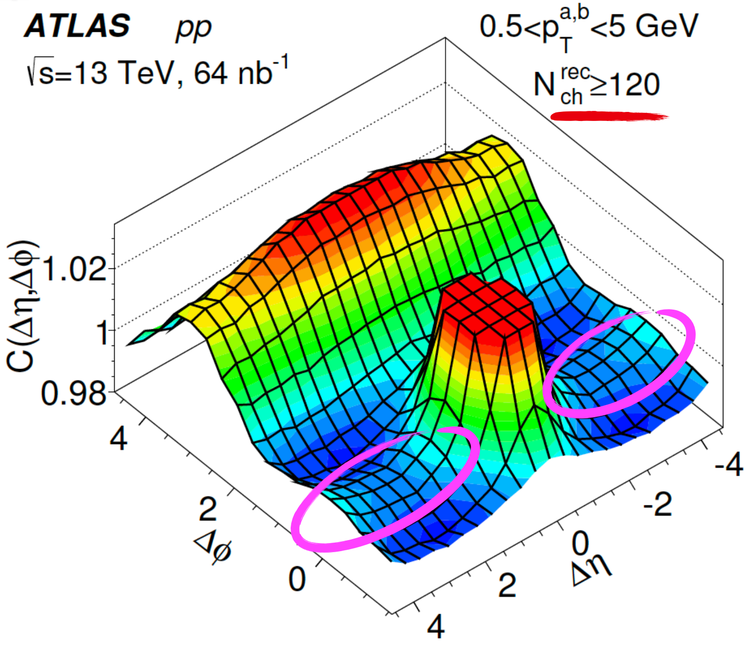
FLOW IN EVEN SMALLER SYSTEMS: P+P !

"Low" Multiplicity

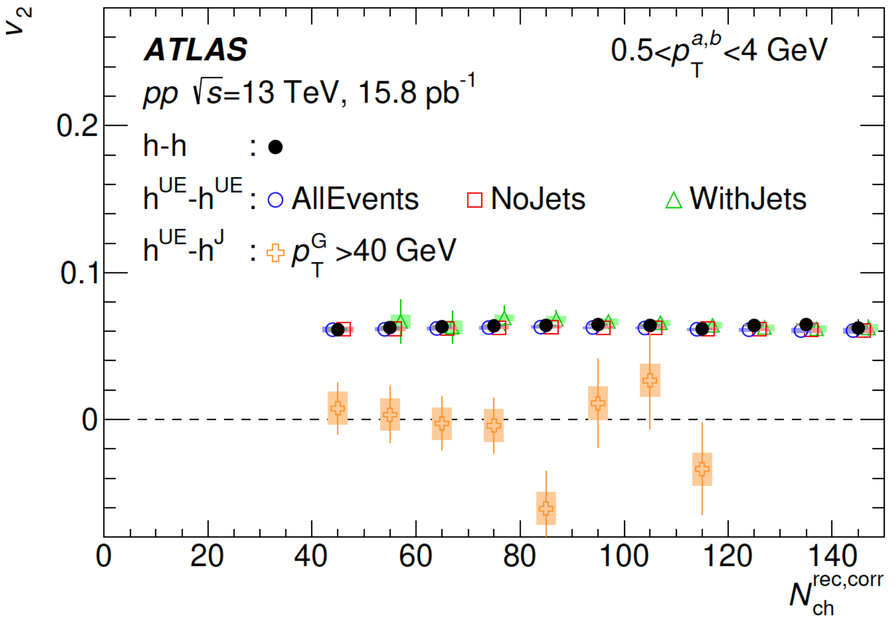


Phys. Rev. C 96 (2017) 024908

"High" Multiplicity



Phys. Rev. Lett 131 (2023) 162301

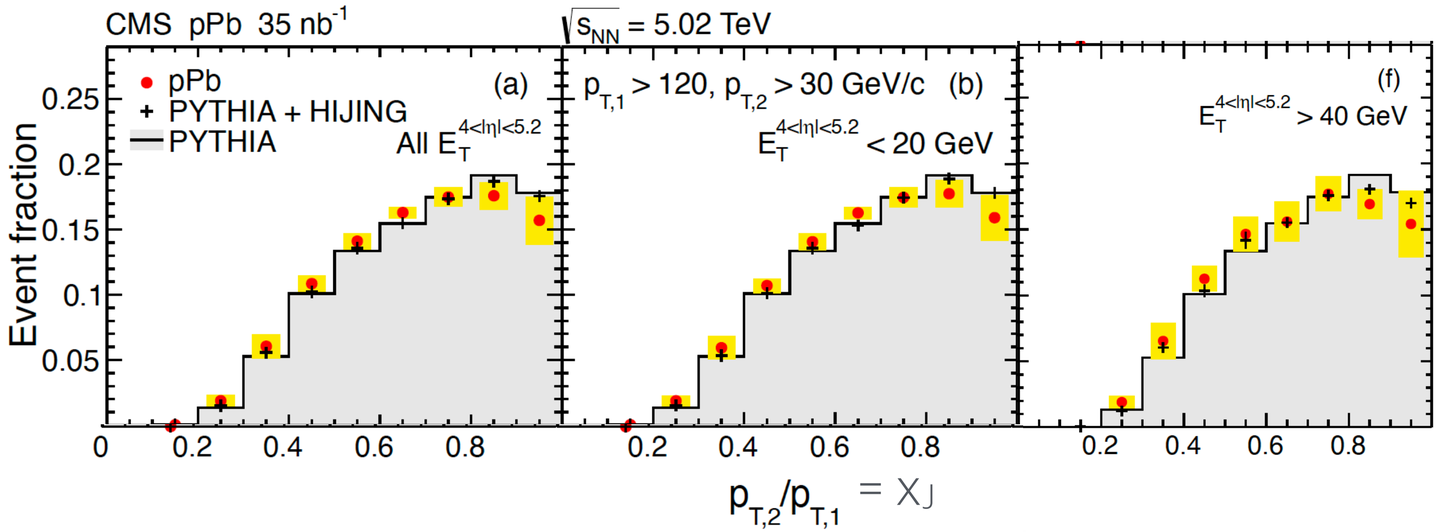


- **Excluding particles associated with jets does not affect the measured correlations**
- **Particles associated with jets do not exhibit any significant azimuthal correlations with the underlying event**

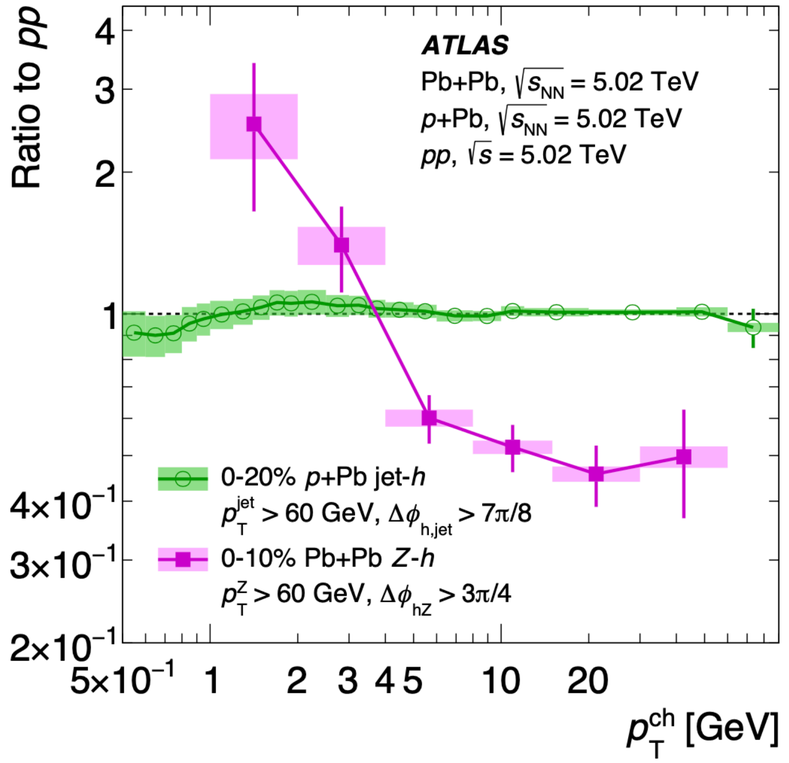
➡ hard processes do not contribute to the ridge.

JET QUENCHING IN P+A?

CMS, Eur. Phys. J. C 74 (2014) 2951



PRL 131 (2023) 072301



All Centralities



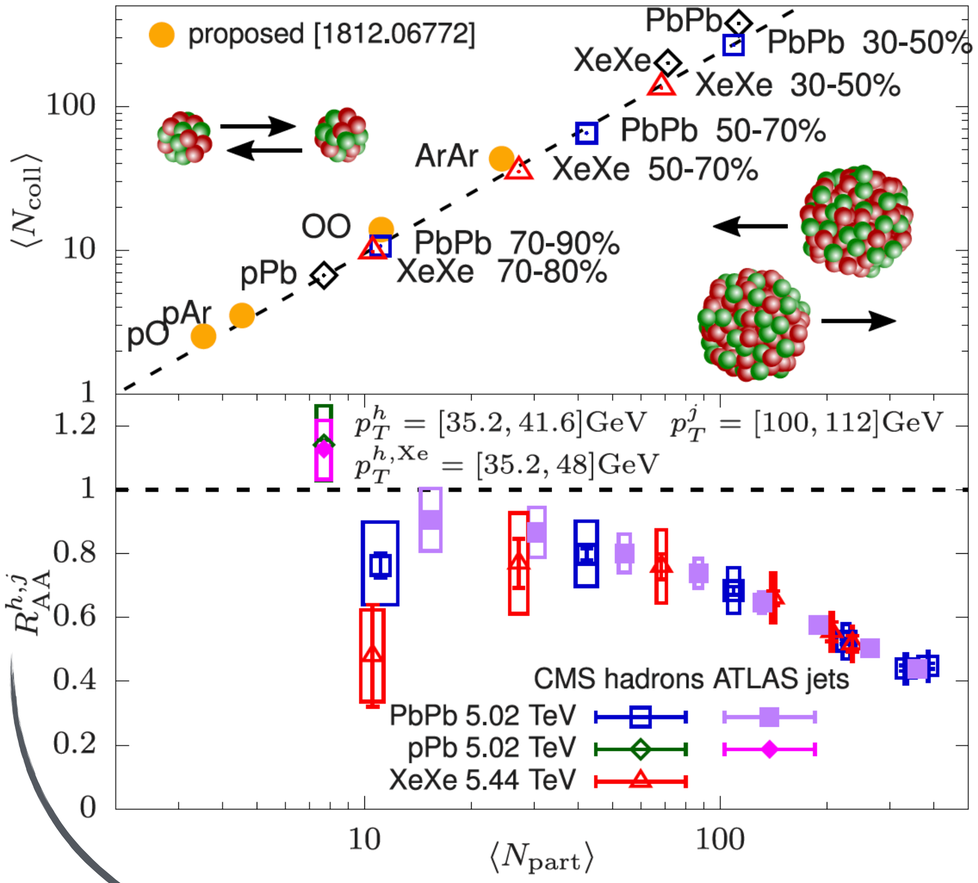
No evidence of jet quenching in p+Pb

No energy loss = no QGP? But large collectivity signal…

Energy loss scales w/ path length → not much pathlength to traverse in p+Pb

QGP SIGNATURES: [PART OF] THE PUZZLE

PRL 126, 192301 (2021)



Nuclear modification factor for hadrons or jets

Need further experimental effort to characterize emergent QCD properties of the QGP as a function of the collision system size @ LHC energies

➡No significant evidence of jet quenching in current measurements in p+Pb

➡Consistent long-range correlations observed throughout different system size

At what system size can we observe the onset of energy loss effects?

OXYGEN @ LHC IS THE NEXT STEP!



JETS IN P+PB TO ACCESS INITIAL STATE EFFECTS

The absence of jet quenching makes jet measurements in p+A fantastic tools to investigate:

- **Proton color fluctuations**

  ➡ Understand the role of p configurations in p+A interactions

- **Cold nuclear matter initial state effects**

  ➡ Further constrain nuclear PDFs (nPDFs), in particular in the low-x regime

Is the proton size fluctuating?

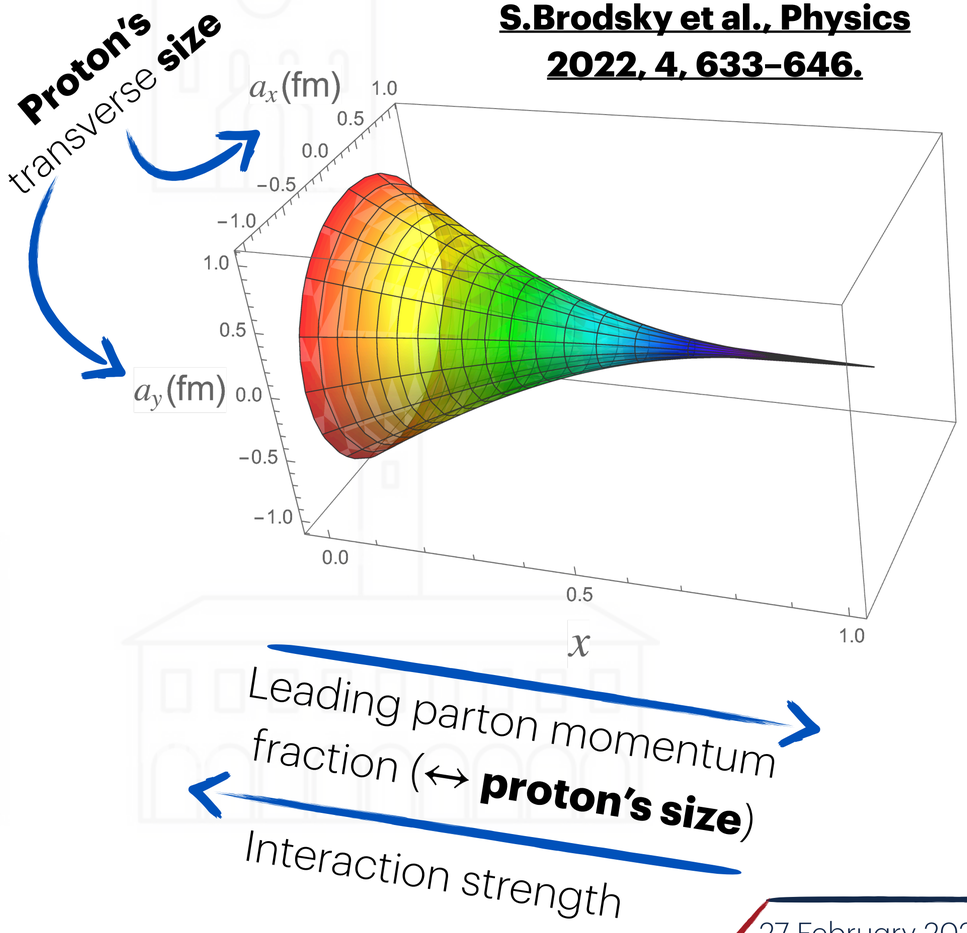
SMALL, WEAK PROTONS



SMALLER QCD OBJECTS ARE EXPECTED TO HAVE SMALLER INTERACTION STRENGTH

The color field of a small color-neutral object is suppressed because the color fields of closely separated quarks and gluons cancel each other **(color transparency)**

S.Brodsky et al., Physics 2022, 4, 633–646.



PLOT TWIST: FROM PROBE TO "PROBED"!

G.Baym et al,
Nuclear Physics A566 (1994), 149-156c

Properties subject to changes in a rapidly moving hadron (e.g. transverse area occupied by the color fields) change from collision to collision **(color fluctuations)**

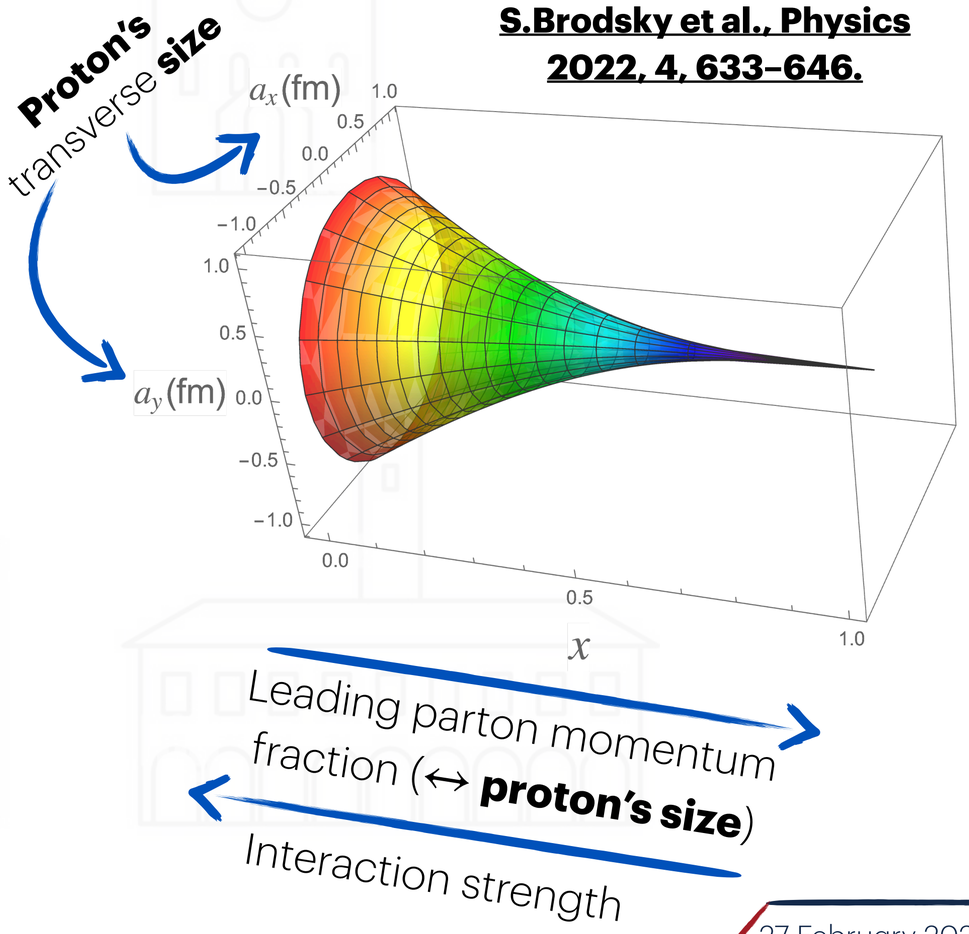
+

Spatial and momentum configuration of quark and gluons in hadrons remain "**frozen**" **during** the time of the p+A **collision**

⬇

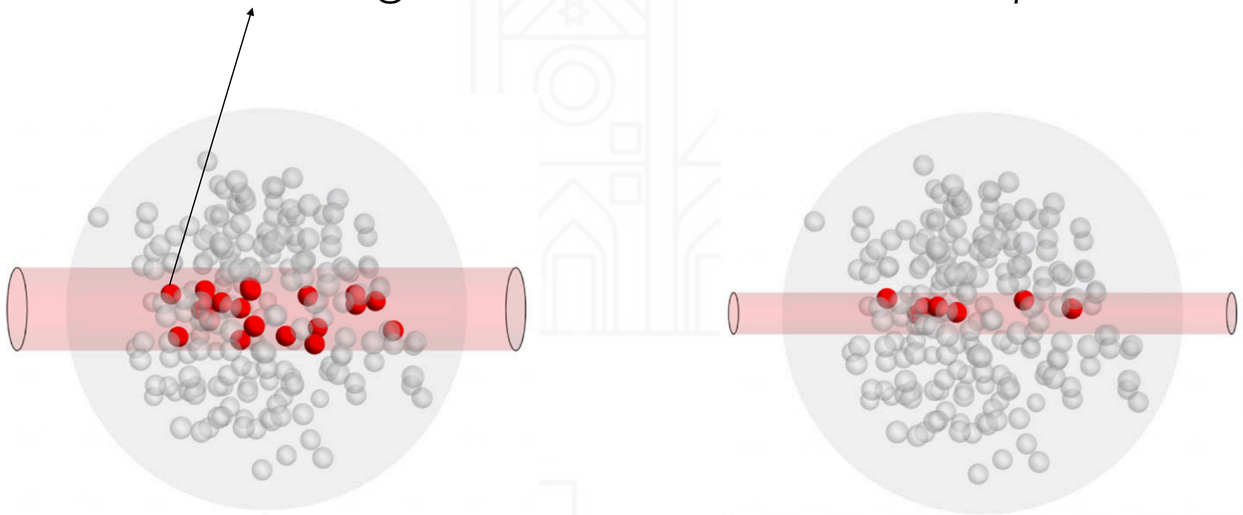
in p+A collisions, we can use the **nucleus as a filter** to access different **proton configurations** on a collision basis.

S.Brodsky et al., Physics 2022, 4, 633–646.



IS THE PROTON SIZE FLUCTUATING?

- Single NN interaction of the *p* in the nucleus



***p* w/ average configuration**



***p* w/ high-x parton**



Model proposed by Alvioli et al,
PRD 98 (2018) 071502

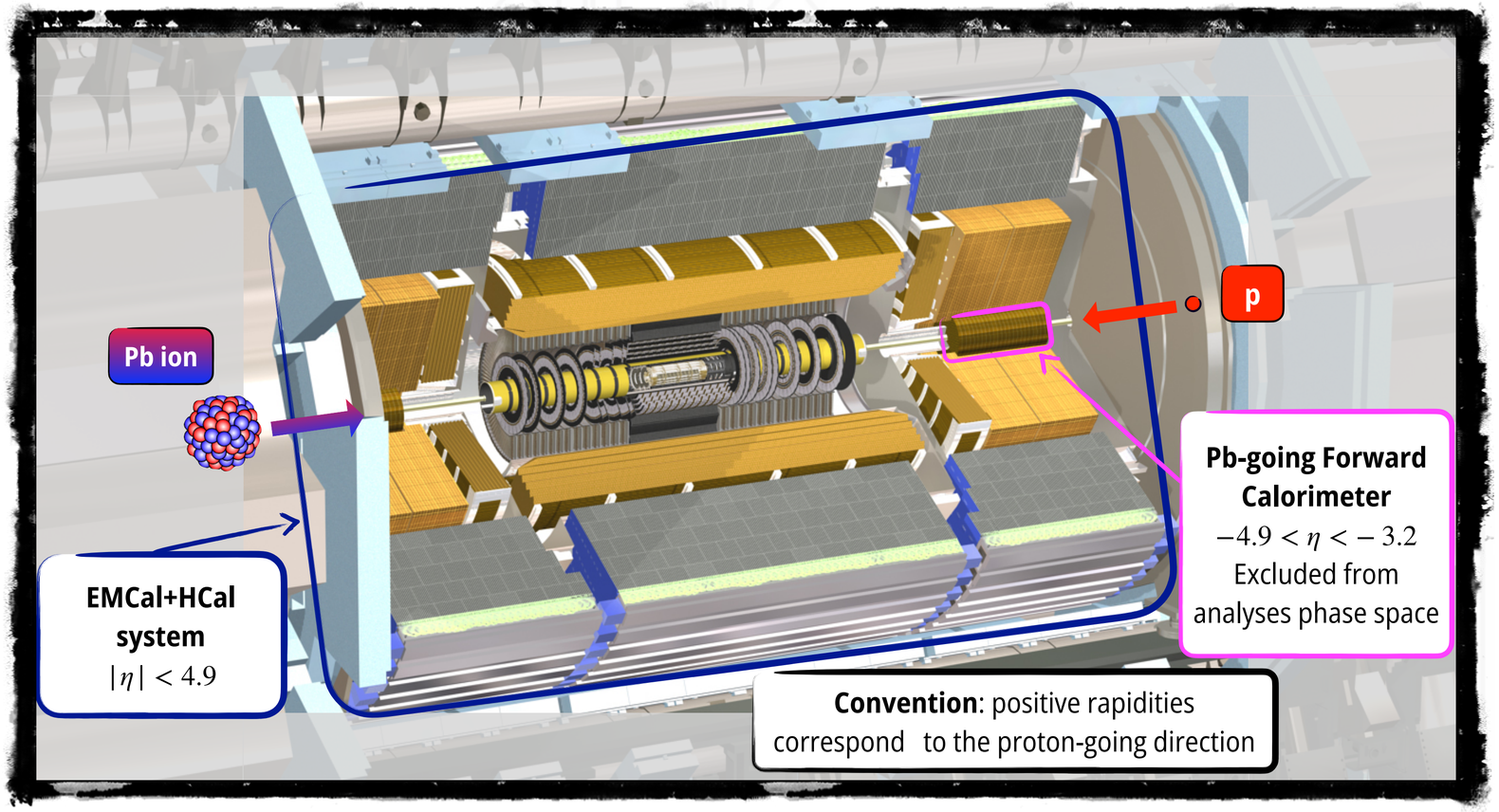
p w/ a high-*x* parton are characterized by less # of NN interactions (nucleus more '**transparent**' to the proton)

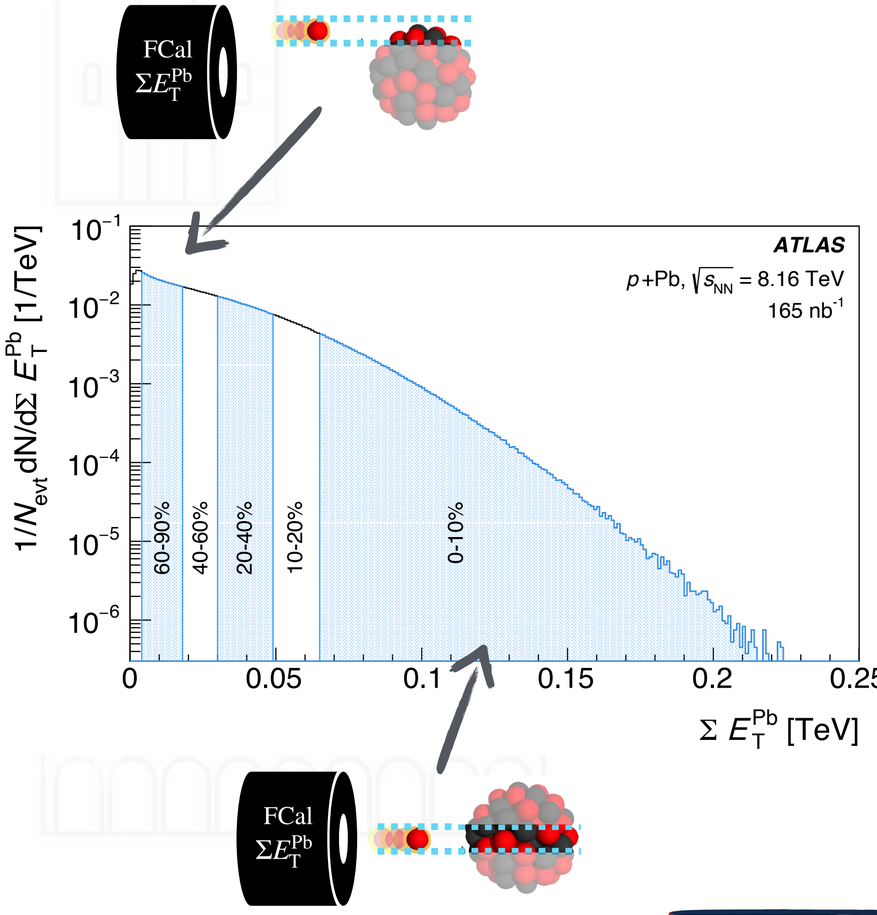
less activity produced in the detector

Event activity bias

EVENT ACTIVITY CHARACTERIZATION IN P+A @ ATLAS

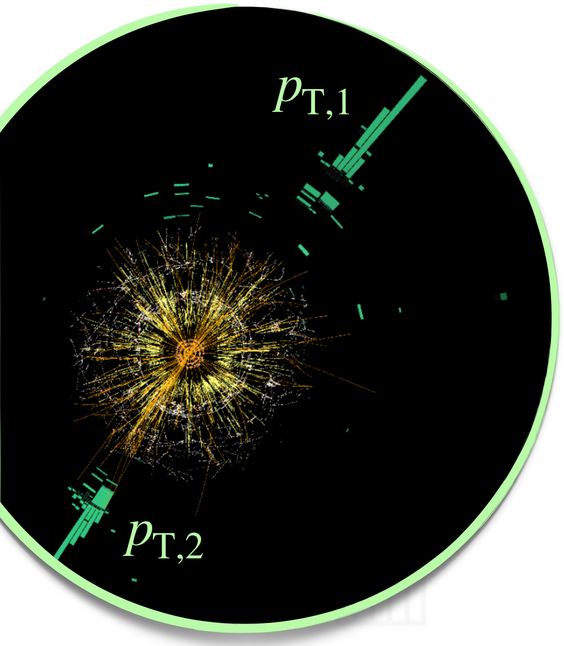
In ATLAS, the transverse energy (E_T) deposited in the **Forward Calorimeter** facing the nuclear debris provides great sensitivity to event activity

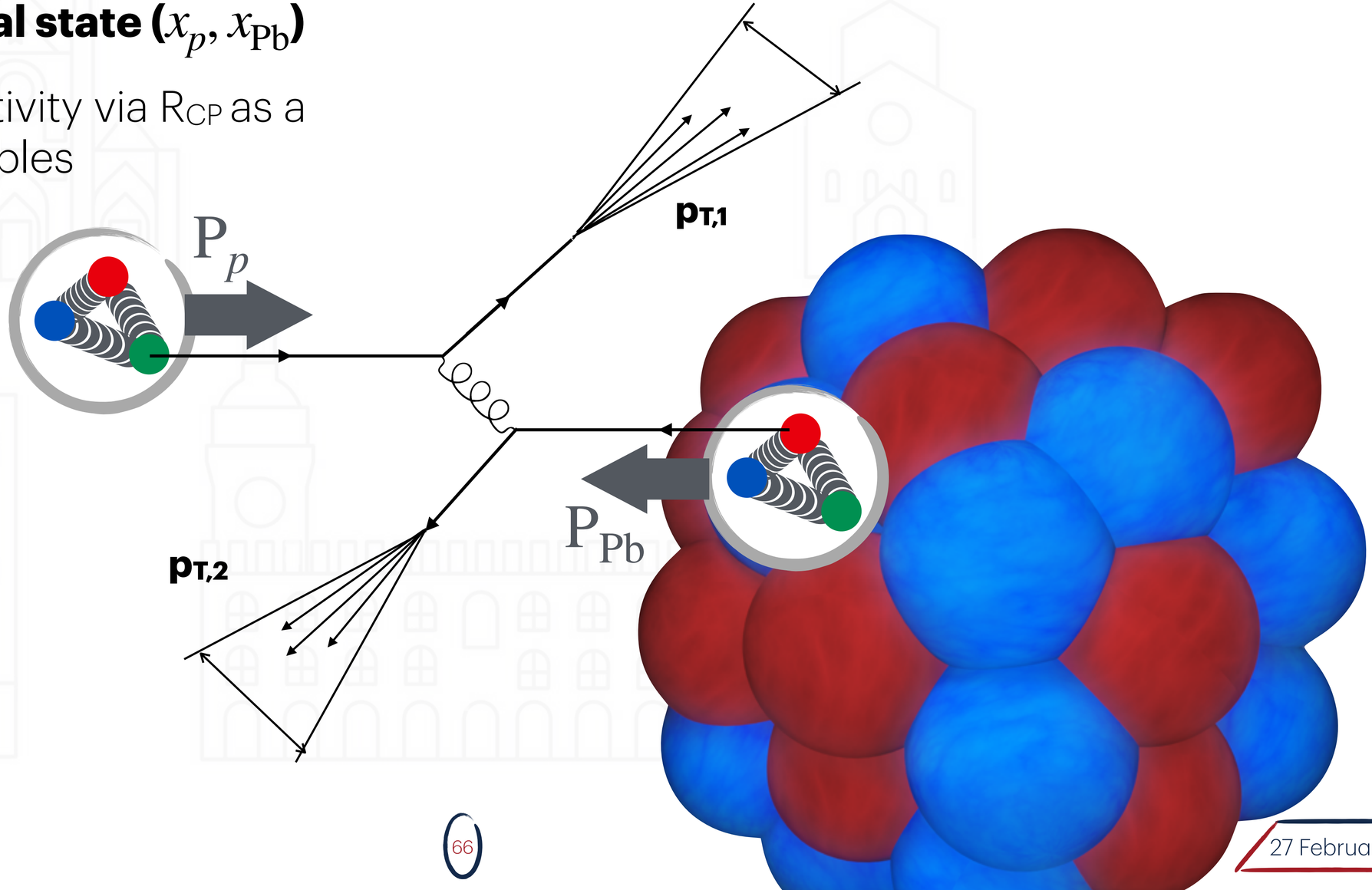




DIJETS AS PROXIES TO THE INITIAL STATE

- We measure transverse momentum and angular coordinates of the **dijets to access the kinematic of the initial state (x_p, x_{Pb})**
- We study the event activity via R_{CP} as a function of these variables





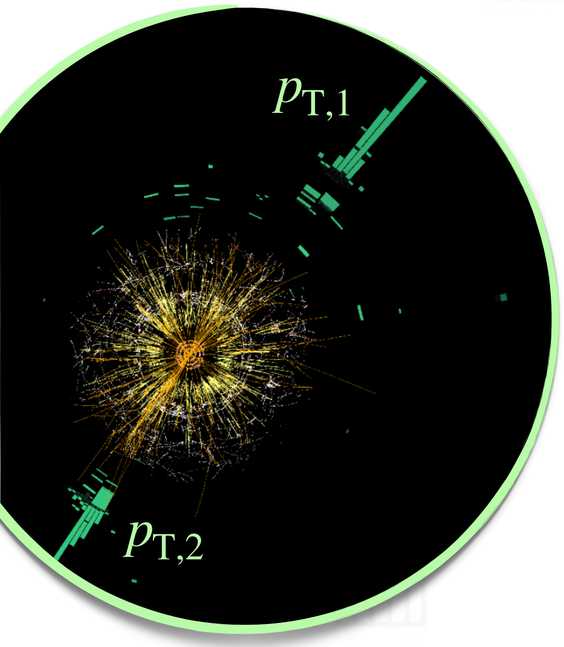
DIJETS AS PROXIES TO THE INITIAL STATE

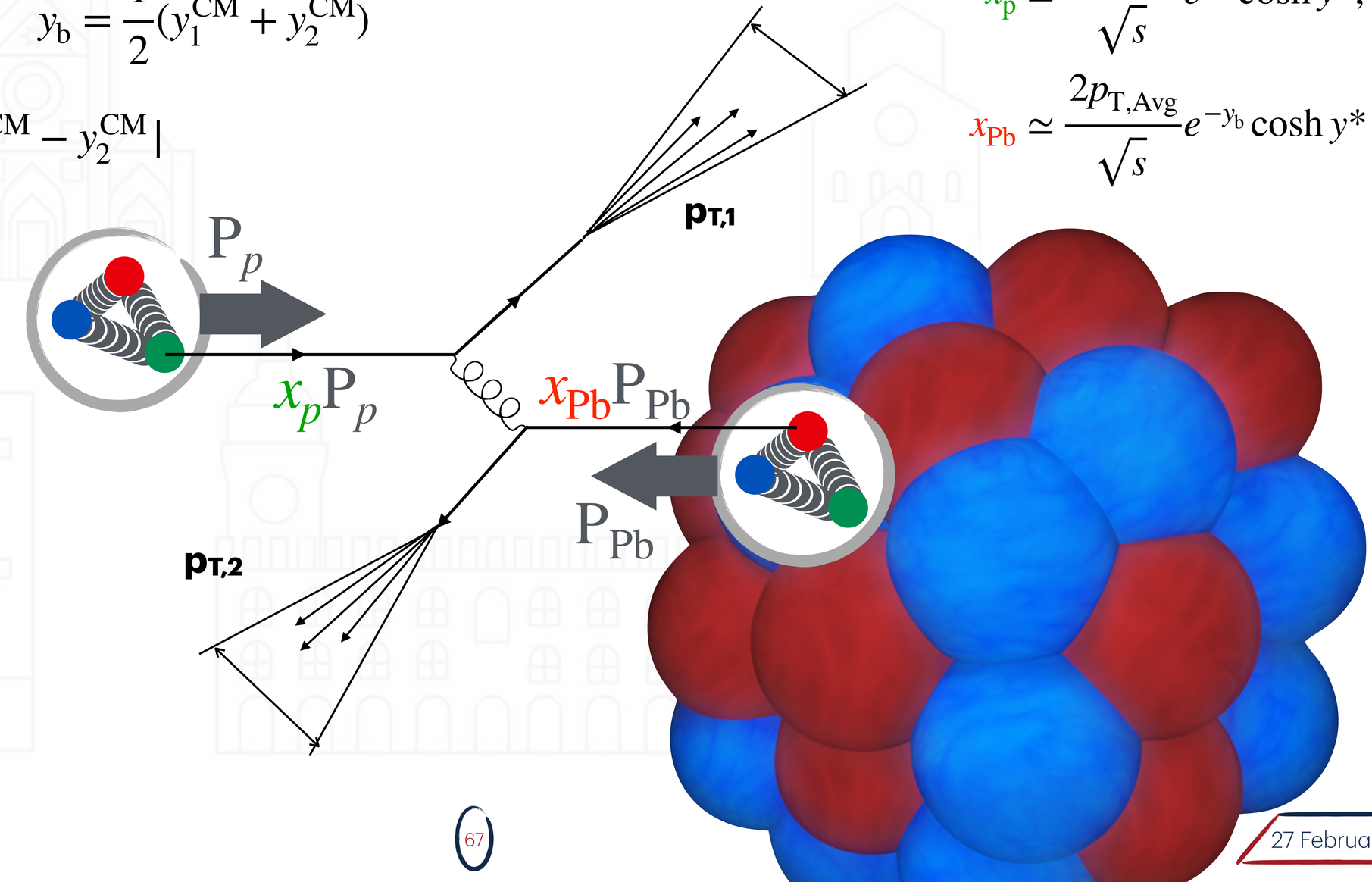
$$p_{\mathrm{T,Avg}} = \frac{p_{\mathrm{T},1} + p_{\mathrm{T},2}}{2} \qquad y_{\mathrm{b}} = \frac{1}{2}(y_1^{\mathrm{CM}} + y_2^{\mathrm{CM}})$$

$$y^* = \frac{1}{2}|y_1^{\mathrm{CM}} - y_2^{\mathrm{CM}}|$$

$$x_{\mathrm{p}} \simeq \frac{2p_{\mathrm{T,Avg}}}{\sqrt{s}} e^{y_{\mathrm{b}}} \cosh y^*,$$

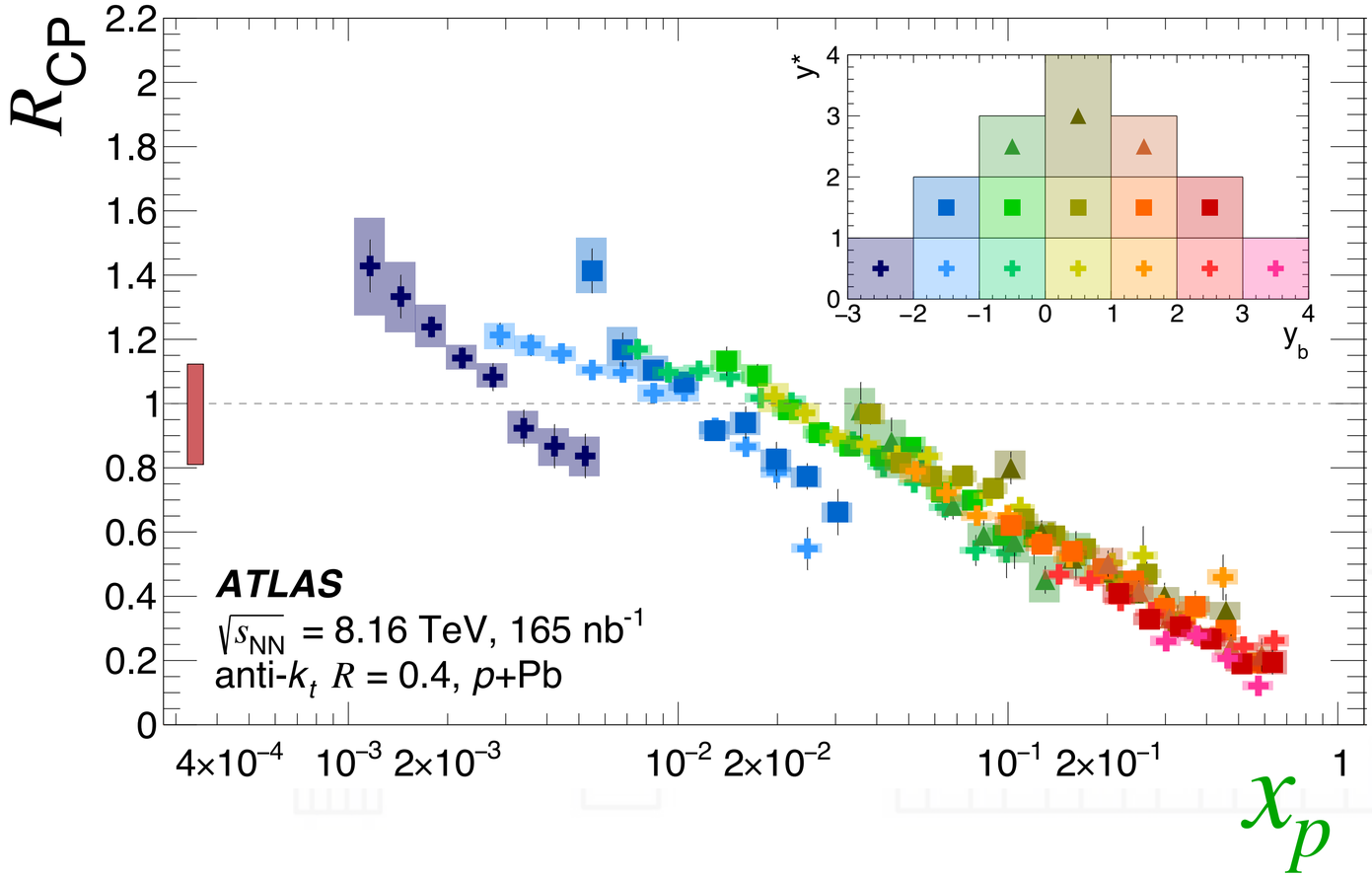
$$x_{\mathrm{Pb}} \simeq \frac{2p_{\mathrm{T,Avg}}}{\sqrt{s}} e^{-y_{\mathrm{b}}} \cosh y^*$$





EVENT ACTIVITY VS PROTON CONFIGURATION

$$R_{CP} = \frac{\text{Absolute number of events w/ highest activity (0-10\%)}}{\text{Absolute number of events w/ lowest activity (60-90\%)}} = \frac{\frac{1}{T_{\text{dijet}}^{0-10\%}} Y_{\text{dijet}}^{0-10\%}}{\frac{1}{T_{\text{pA}}^{60-90\%}} Y_{\text{dijet}}^{60-90\%}}$$



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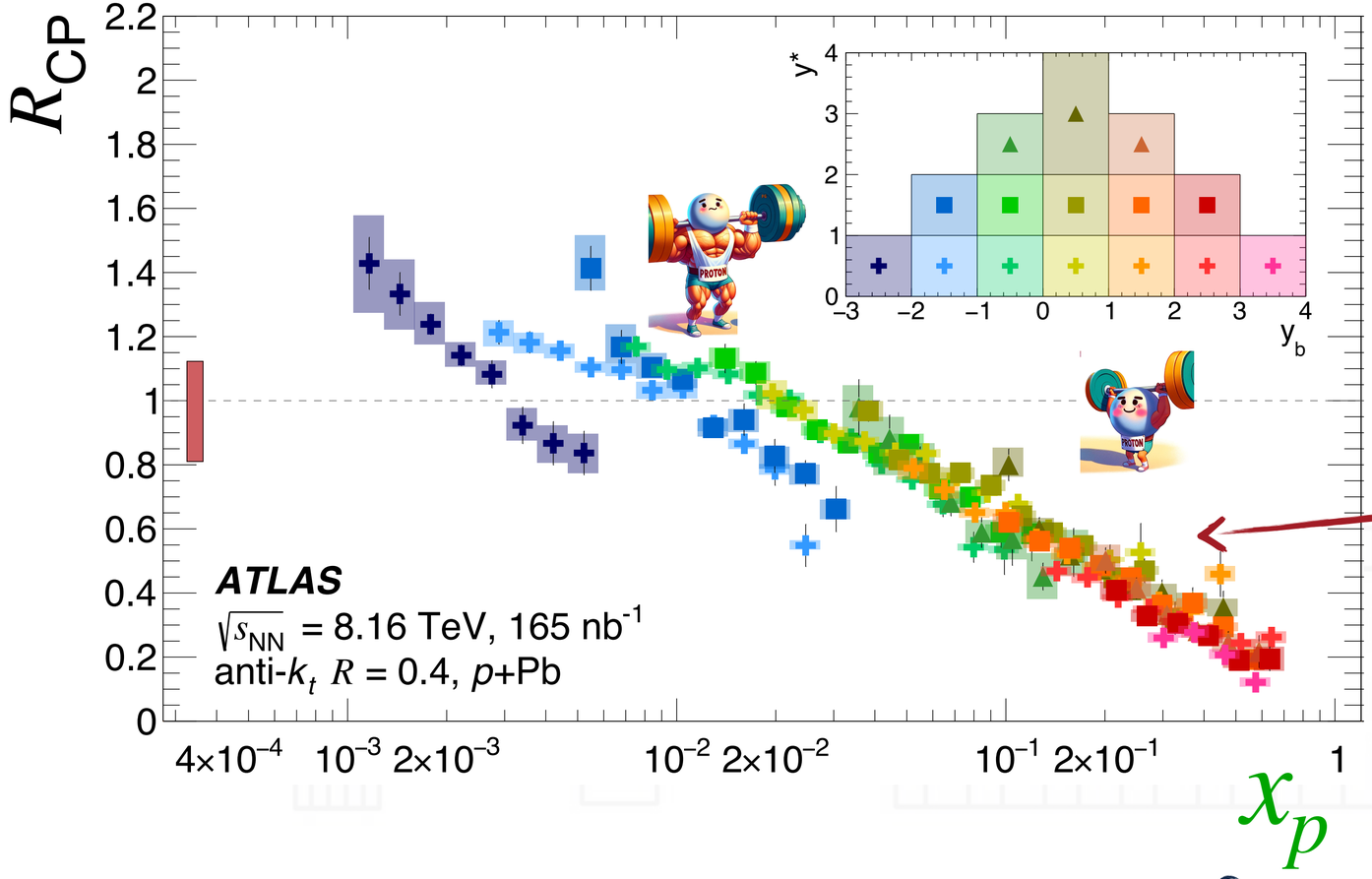
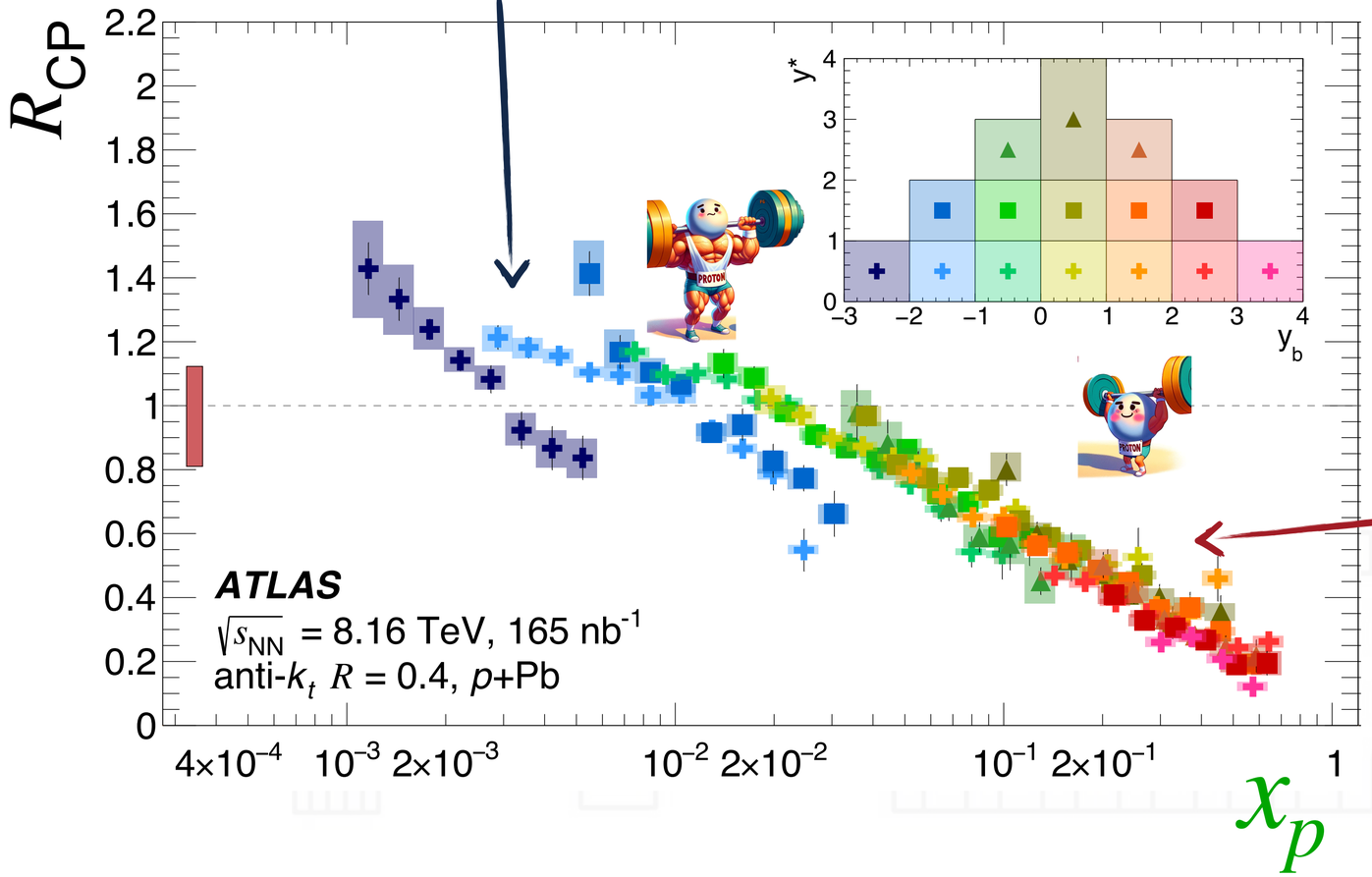


Striking **scaling with x_p** observed for $x_p \gtrsim 0.03$! R_{CP} suppression increasing log-linearly with x_p: **qualitatively in agreement** with color transparency interpretation of jet suppression in p+Pb

SCALING BREAKING

The **scaling breaks** when approaching **low-x_p region**, corresponding to backward dijets (and high x_{Pb})

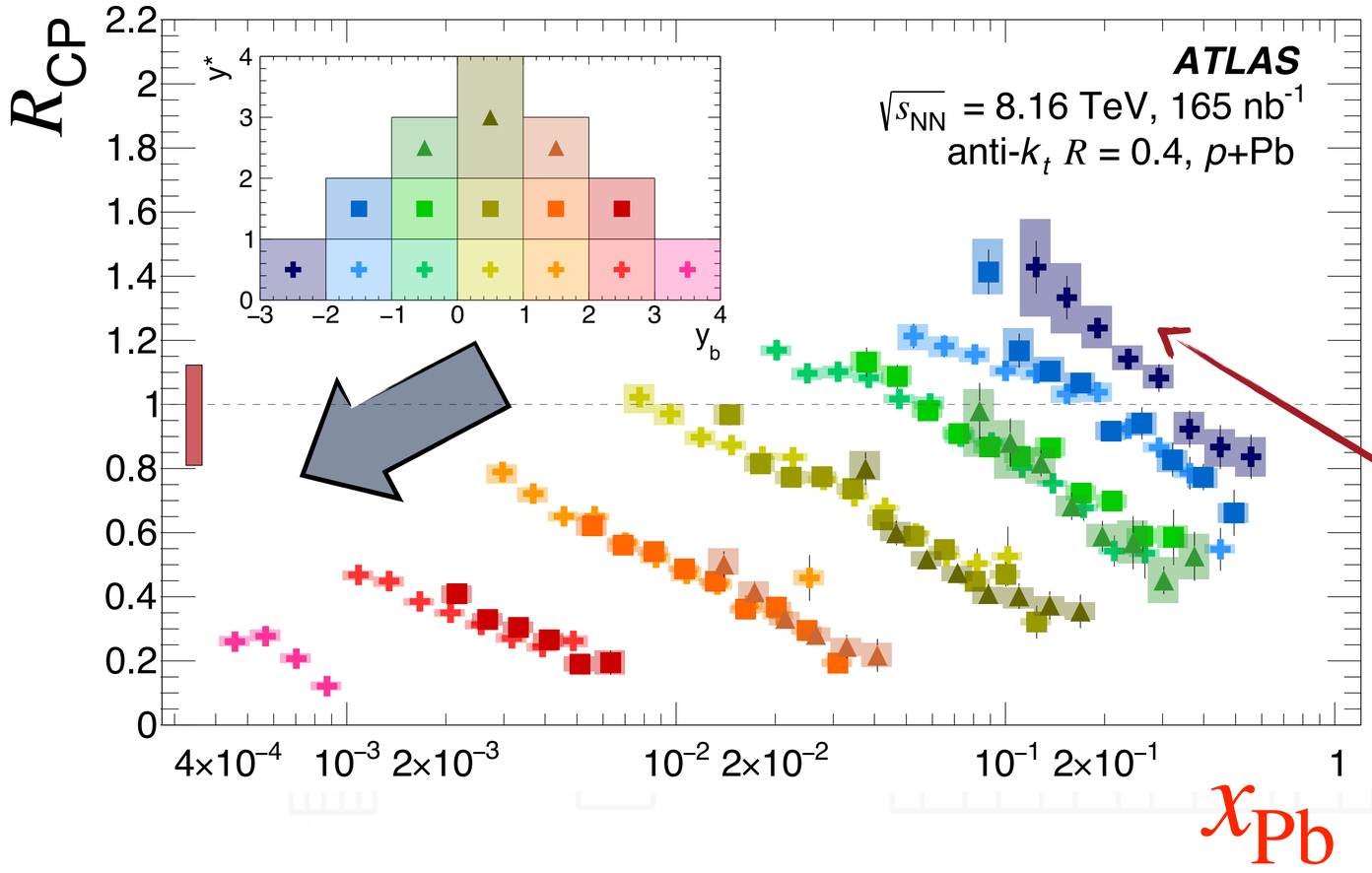


Striking **scaling with x_p** observed for $x_p \gtrsim 0.03$! R_{CP} suppression increasing log-linearly with x_p: **qualitatively in agreement** with color transparency interpretation of jet suppression in p+Pb

arXiv:2309.00033, acc. PRL

POV CHANGE!

Overall, an increasing R_{CP} suppression while moving towards low-x_{Pb} is observed



No common scaling observed when results are displayed as a function x_{Pb}

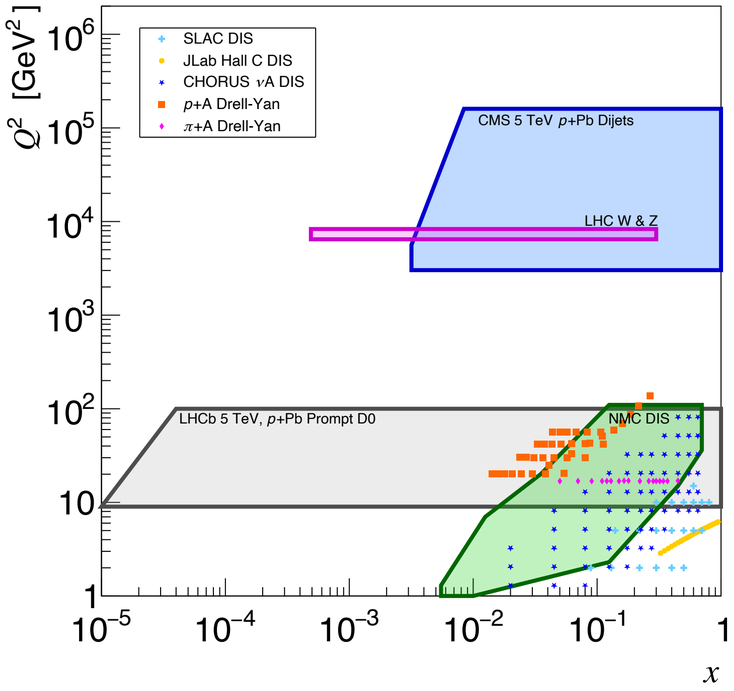
Values of $R_{\mathrm{CP}} > 1$ interestingly localized where anti-shadowing effects in the nucleus are expected (and out of the x_p -scaling region)

How dijets measurements at the LHC can help in constraining initial state effects?

DIJETS TO EXPLORE THE NUCLEAR STRUCTURE

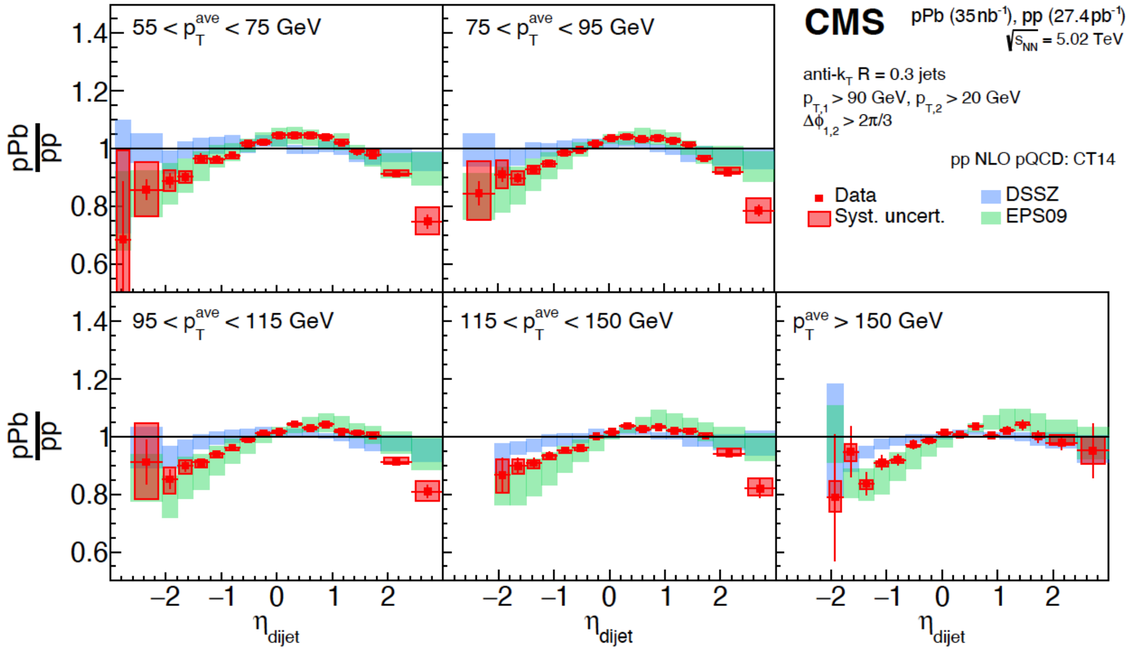
Dijets measurements are excellent to constrain nuclear PDFs over a broad kinematic range

Adapted from Eur. Phys. J. C (2022) 82:413 w/ B. Gilbert



- **Dijets in *p*+Pb** @ ATLAS and CMS can explore a **broad (x,Q²) phase space**
- CMS data @ 5.02 TeV only one published so far

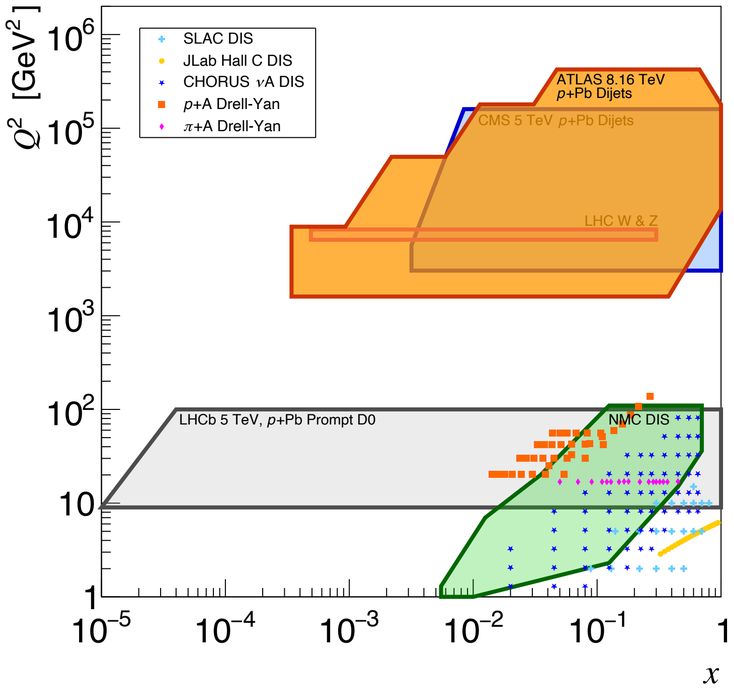
PRL 121, 062002 (2018)



NEXT IN LINE: DIJET CROSS-SECTION FROM ATLAS P+PB DATA

Dijets measurements are excellent to constrain nuclear PDFs over a broad kinematic range

Adapted from Eur. Phys. J. C (2022) 82:413 w/ B. Gilbert



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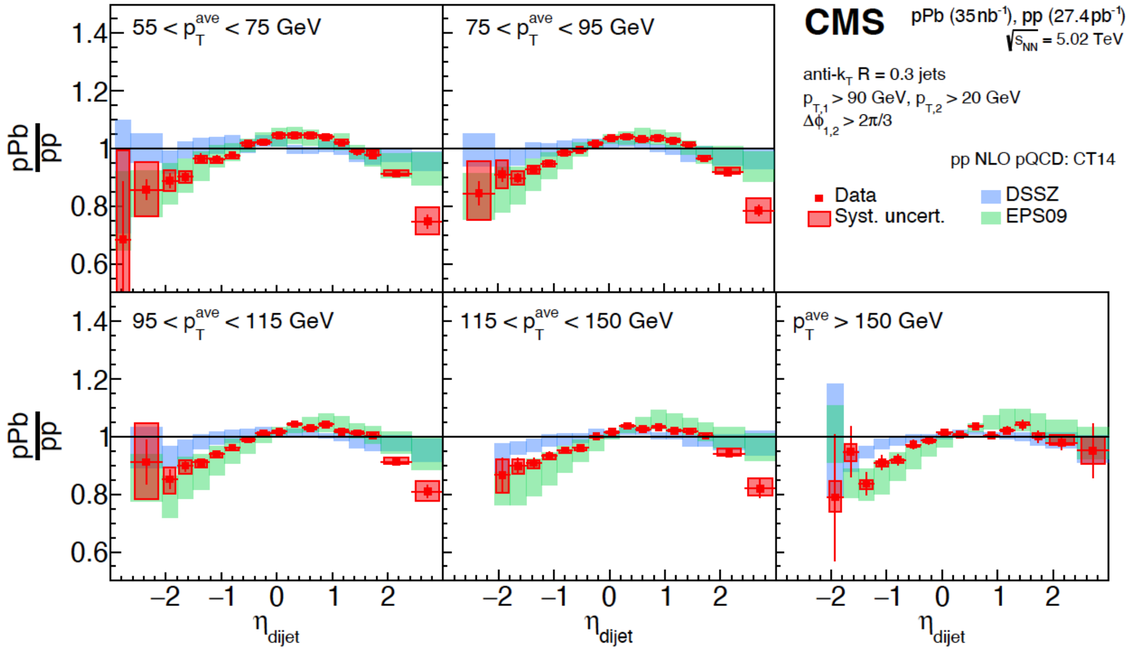
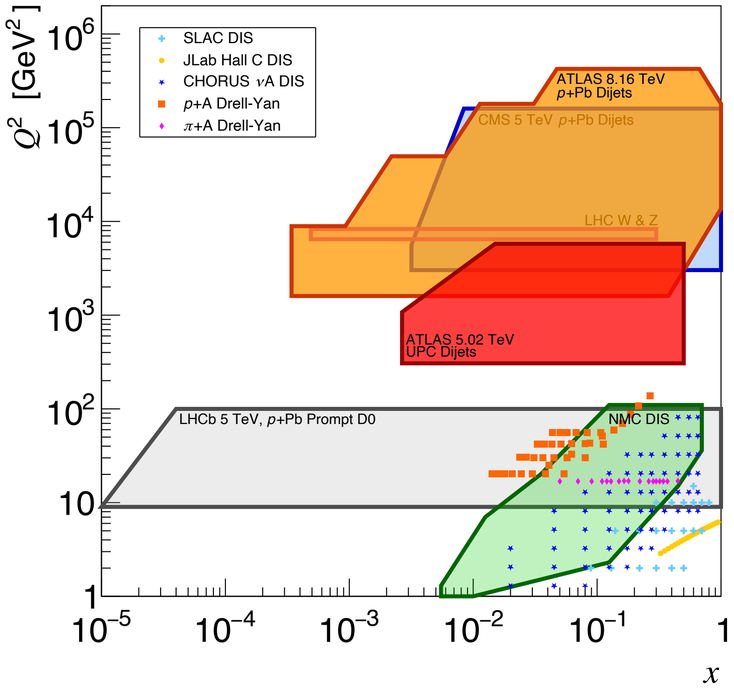


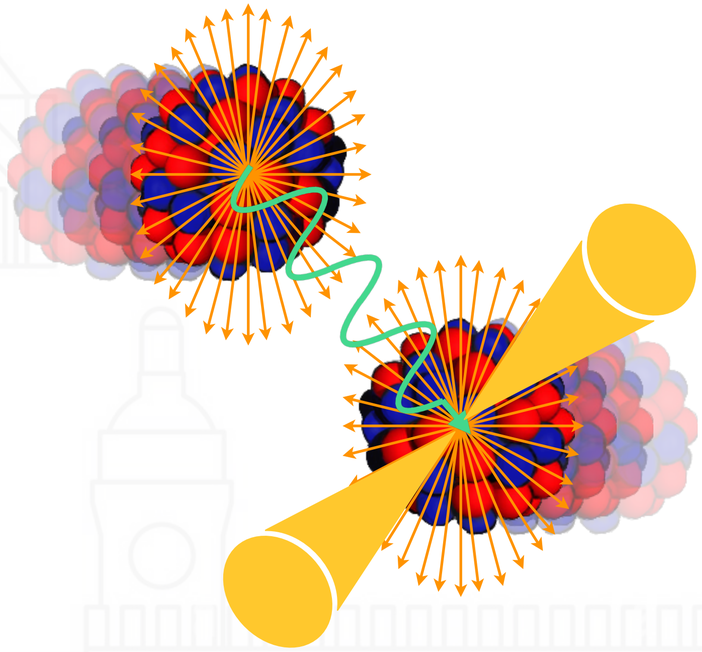
MultiD extraction of dijet cross-section from ATLAS 8.16 TeV data ongoing

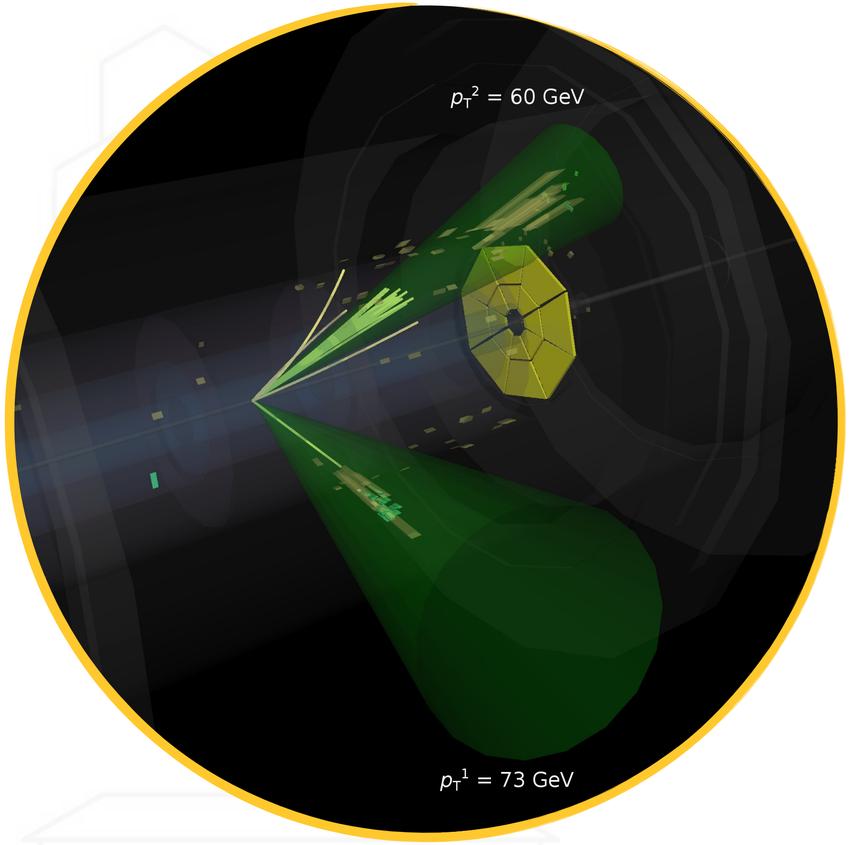
➡Will be impactful for nPDFs of different partons!

EM PROBES FOR THE NUCLEUS AT THE LHC: UPC DIJETS!

Adapted from Eur. Phys. J. C (2022) 82:413 w/ B. Gilbert





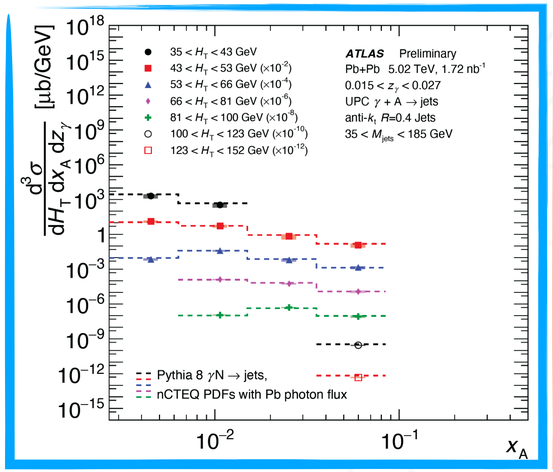


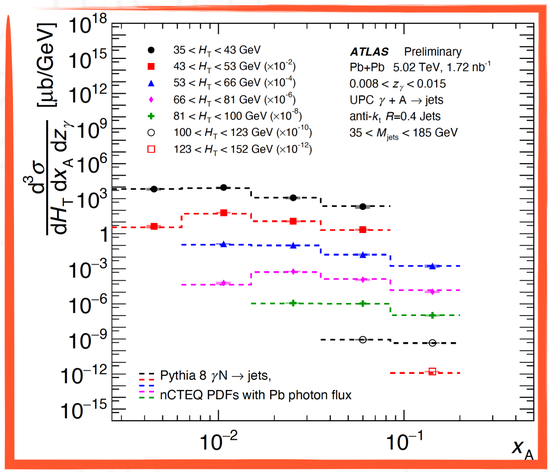
UPC dijets @ ATLAS explore a unique (x,Q^2) phase space

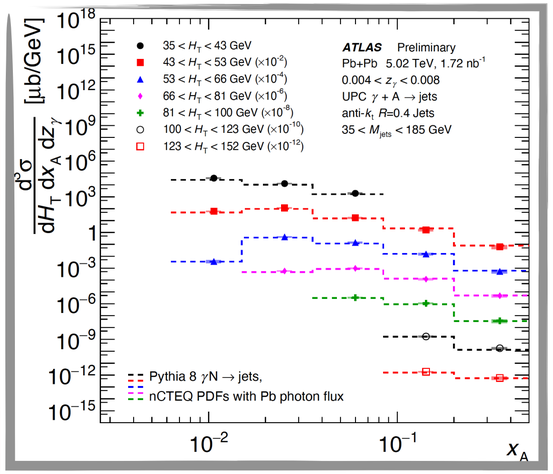
SHINING LIGHT ON THE NUCLEAR STRUCTURE

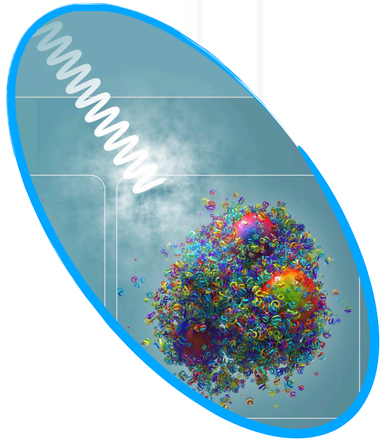
3 dimensional fully-unfolded UPC dijet cross-section measurement

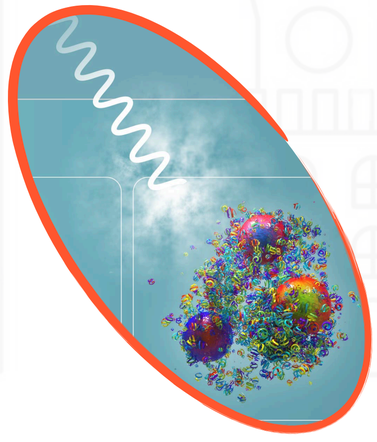
Scan in photon energy ⟺ scan w/ different resolution power

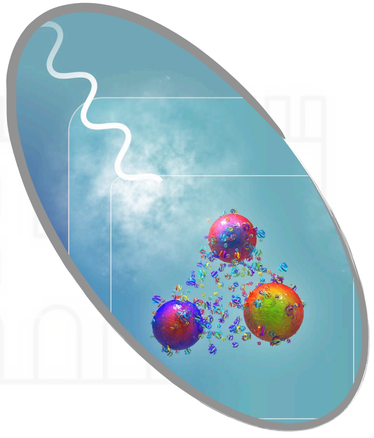


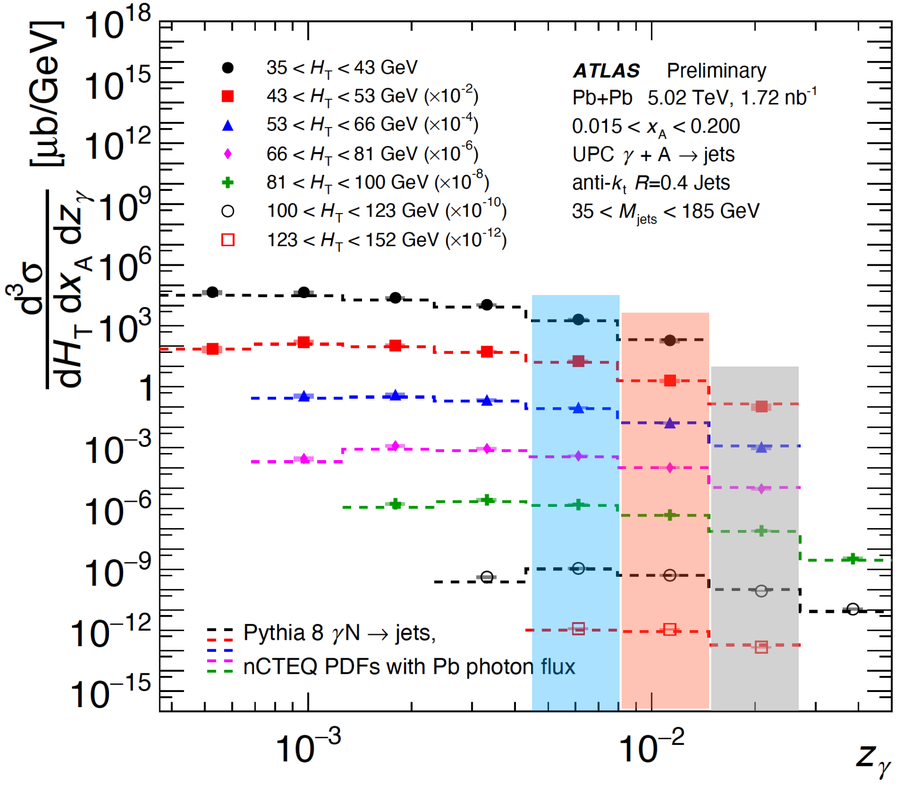










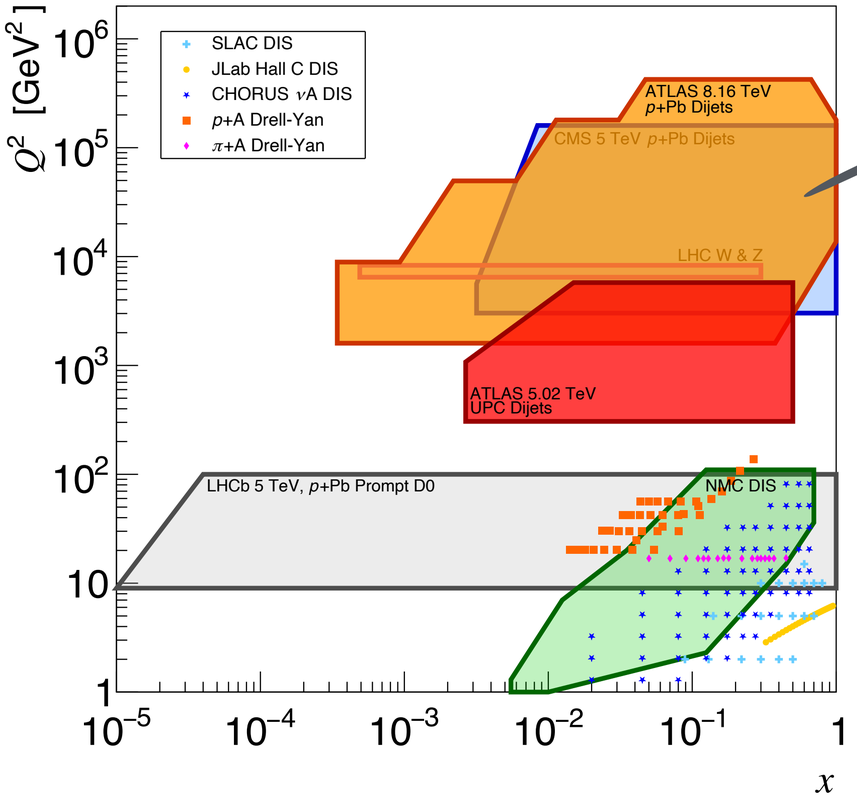


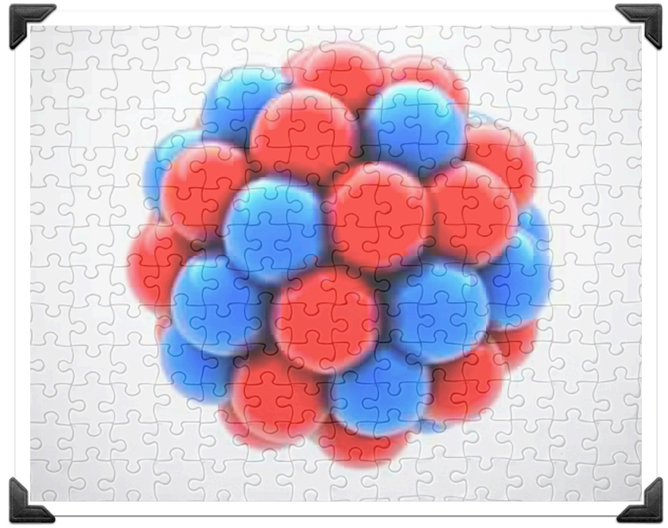
ATLAS-CONF-2022-021

Final results close to publication!

ADDING PIECES TO THE NUCLEAR STRUCTURE PUZZLE...

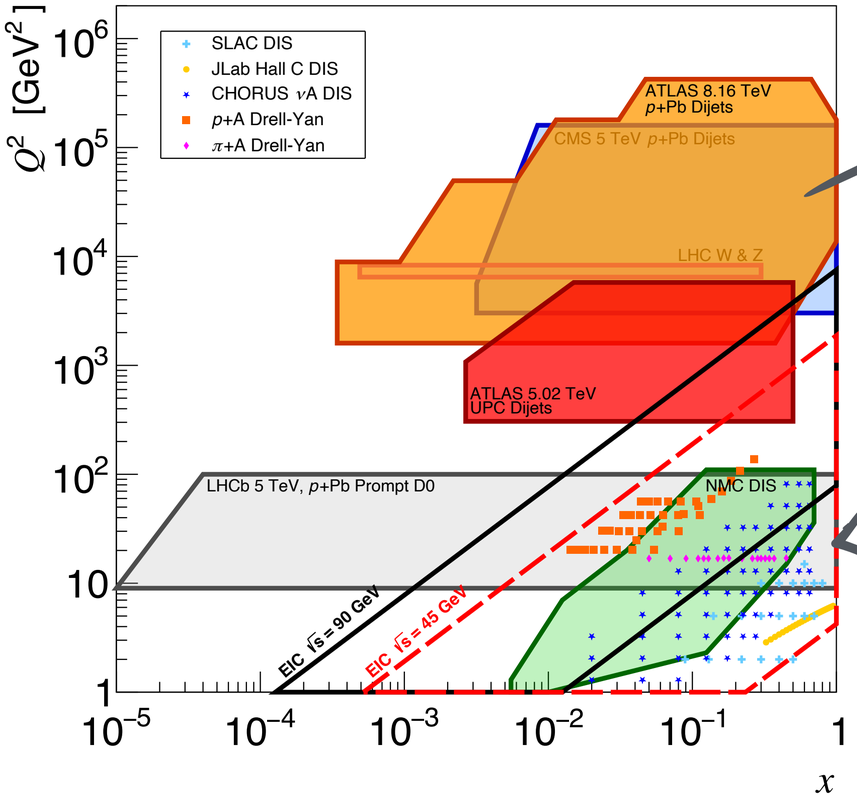
UPCs studies are one of the major focus of the HI physics program @ (HL-)LHC

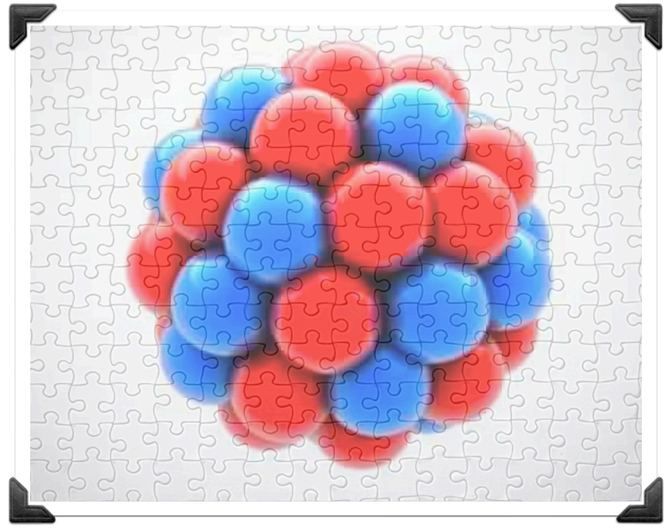


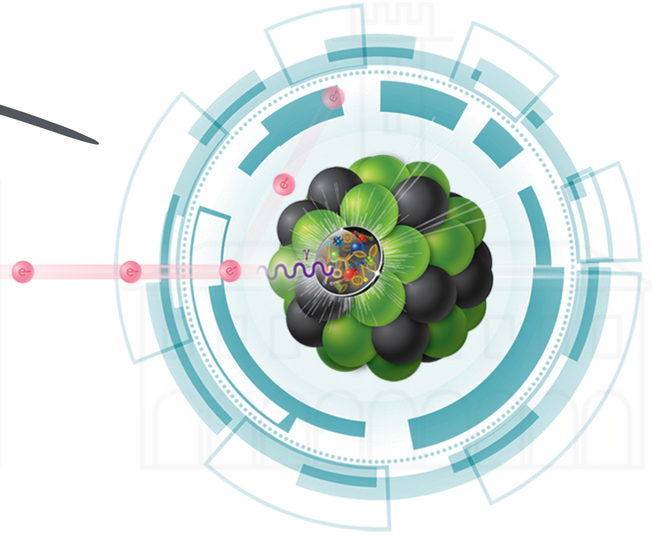


...WAITING FOR THE THE EIC!

UPCs studies are one of the major focus of the HI physics program @ (HL-)LHC





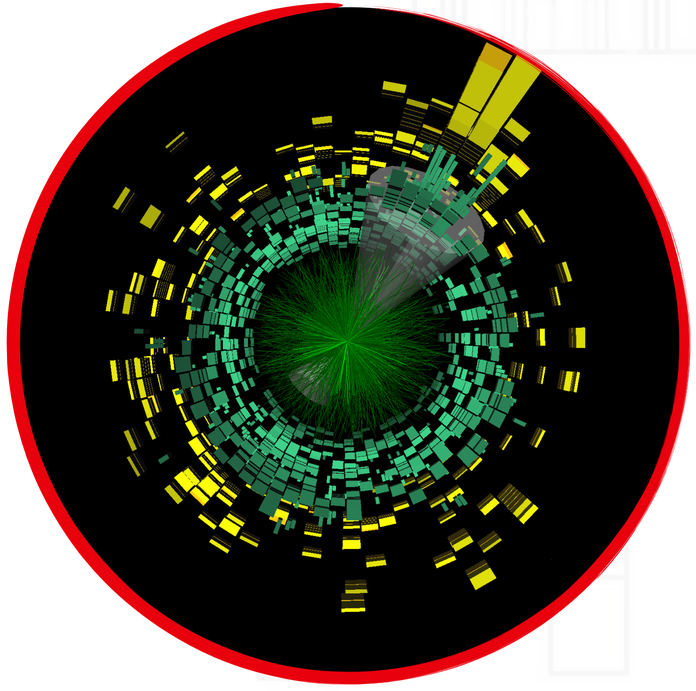


UPC dijets represent a direct bridge between the Electron-Ion Collider and LHC

BOTTOM LINE: DIJETS ARE FANTASTIC TOOLS!

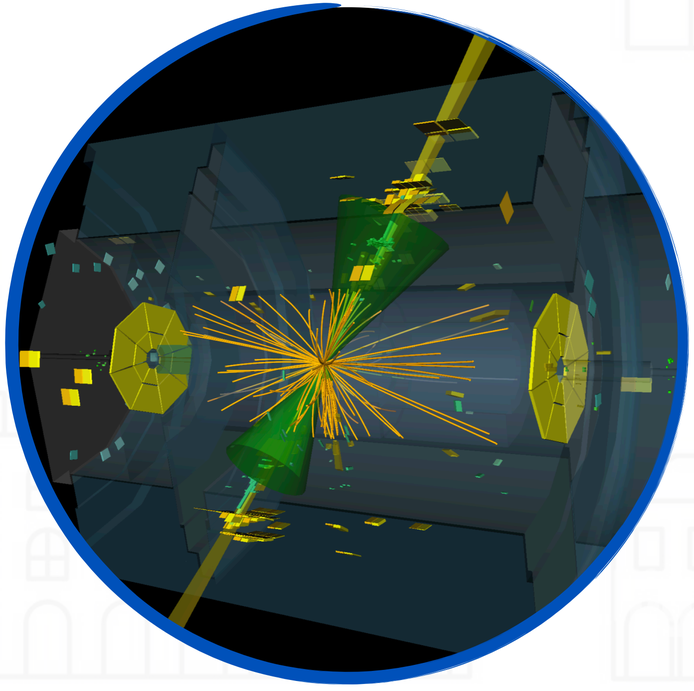
HOT QCD

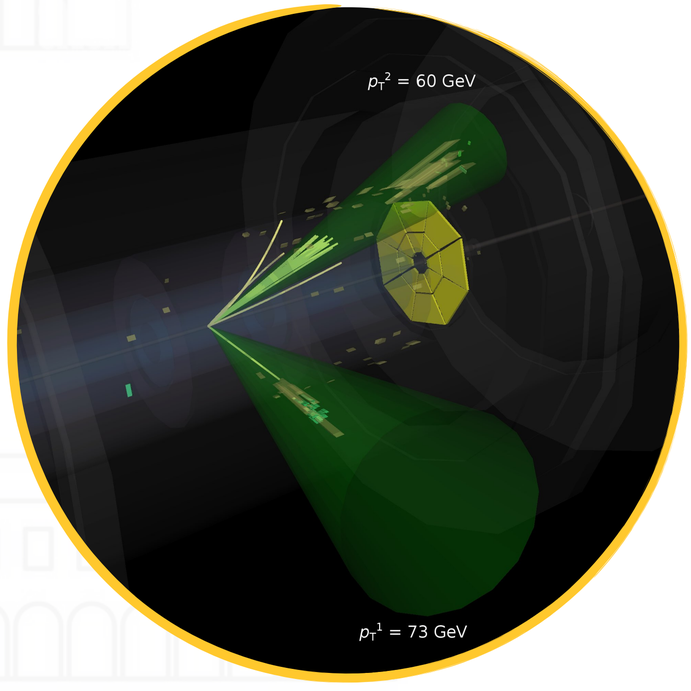
Powerful microscopes for QGP properties in **A+A**



COLD QCD

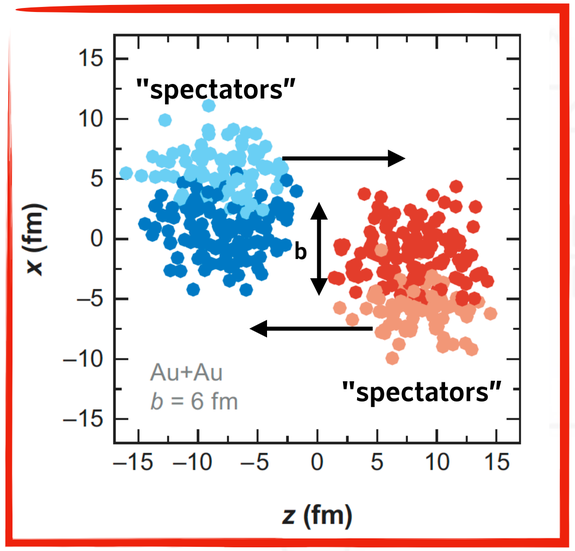
Fantastic proxies to access nuclear and nucleon properties in **p+A** and **UPCs in A+A**





How does the ZDC serve as an essential tool in heavy-ion collisions?

HOW TO TAG DIFFERENT TYPE OF HI EVENTS?



HADRONIC EVENTS

Nuclear debris in both beam directions (**XnXn**)

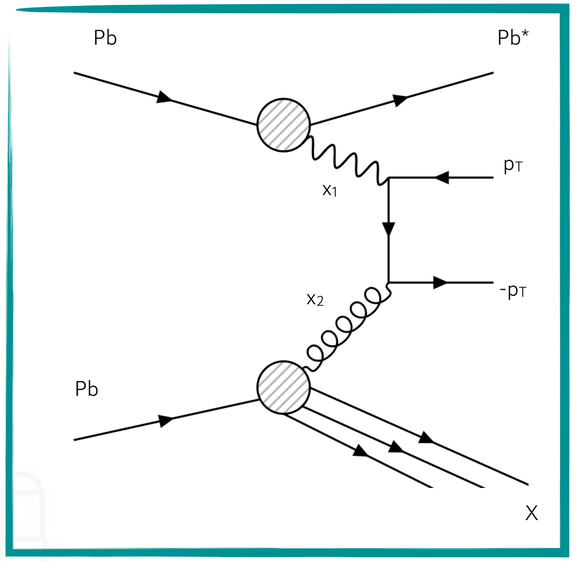
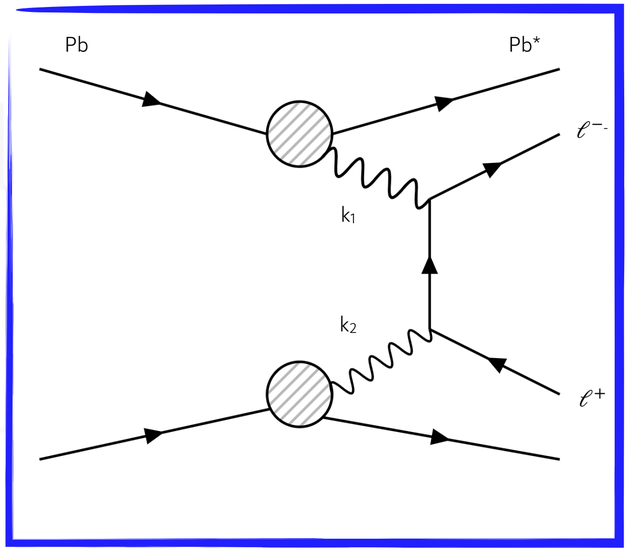


PHOTO-NUCLEAR EVENTS

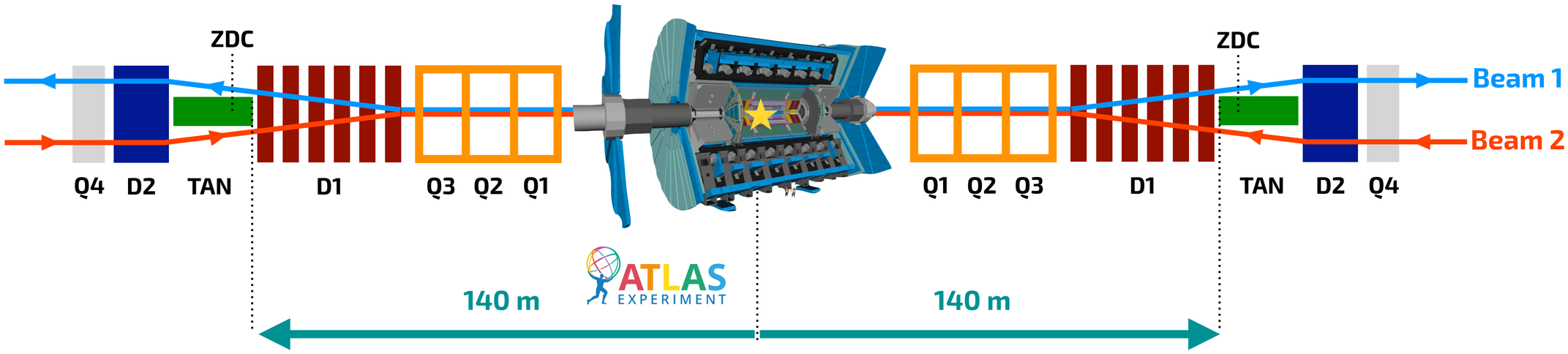
Nuclear debris in one beam direction (**XnOn**)

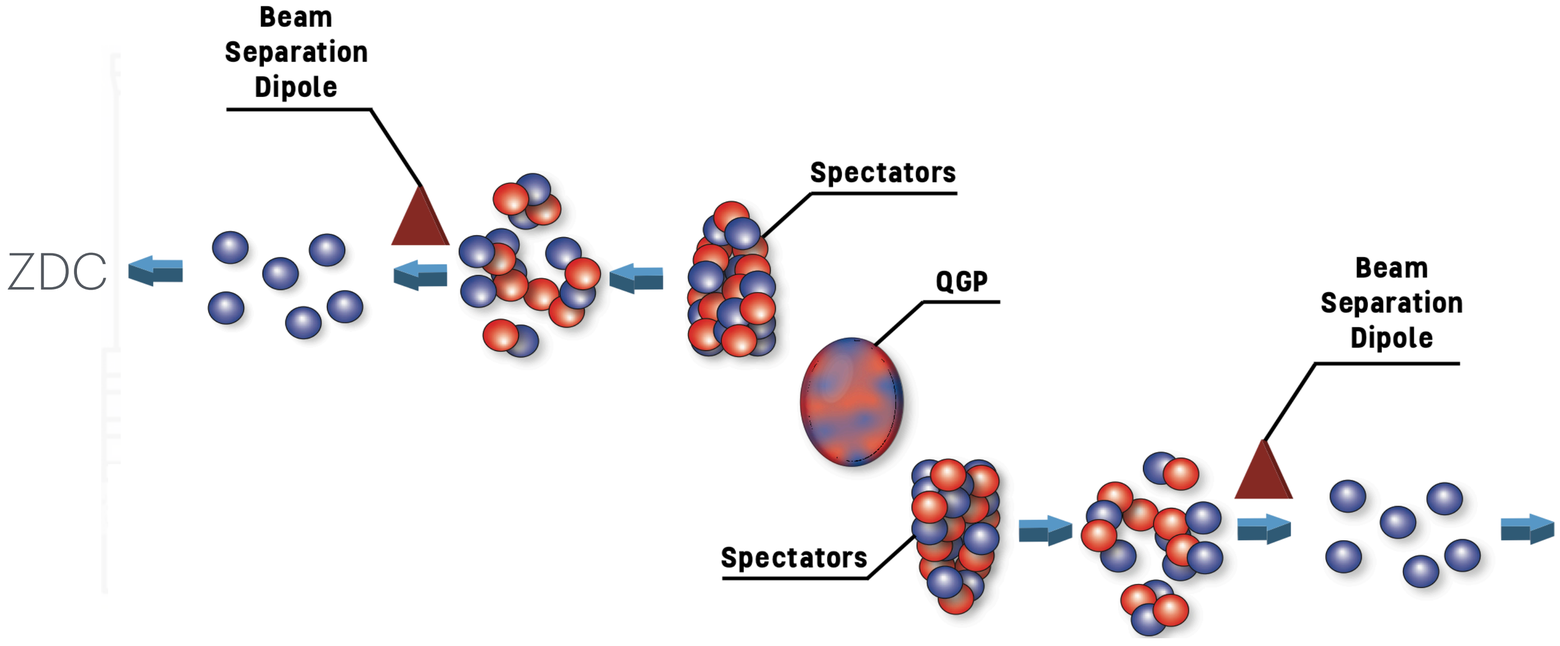


LIGHT-BY-LIGHT EVENTS

No nuclear debris (**OnOn**)

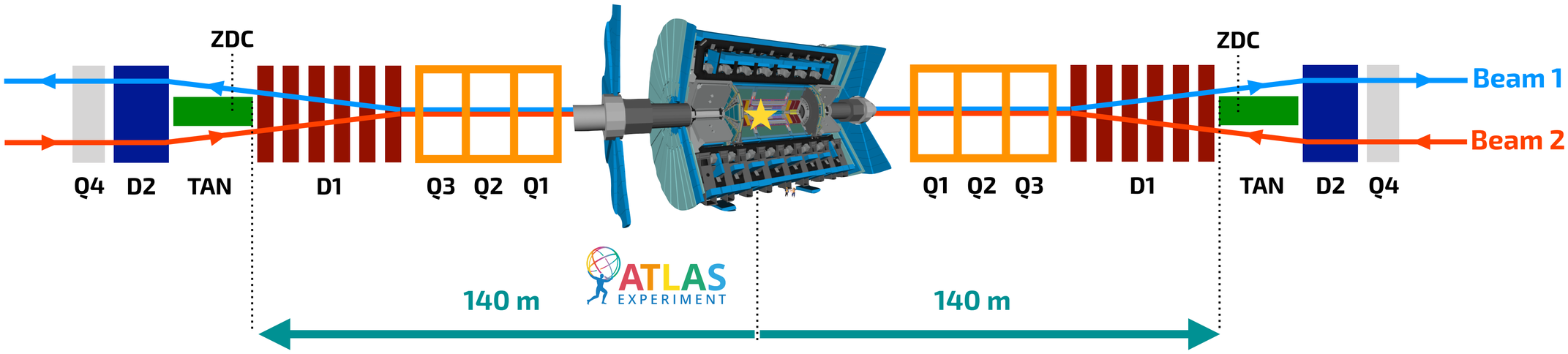
EVENT TAGGING WITH THE ZDC

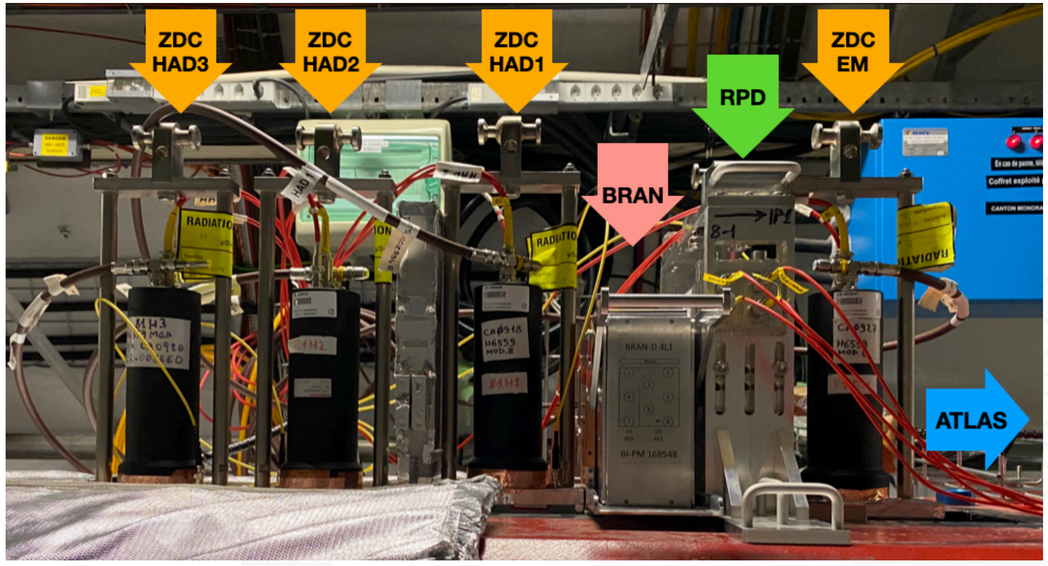


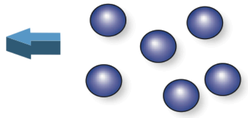


We can classify different types of Heavy Ion collisions by looking at different **spectator neutron topologies** detected in the **Zero Degree Calorimeters (ZDC)**

EVENT TAGGING WITH THE ZDC

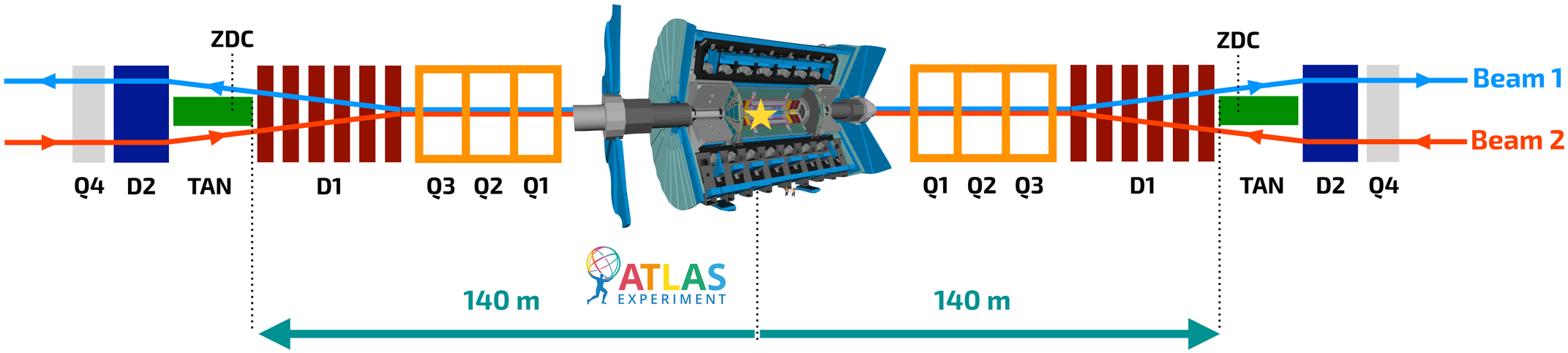


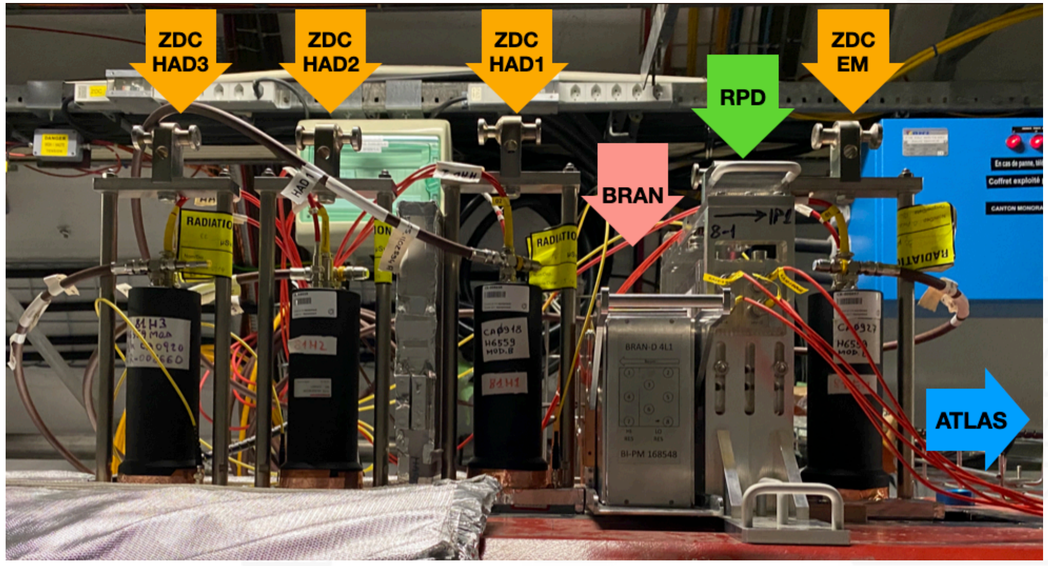


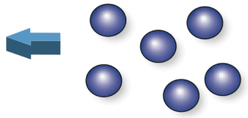


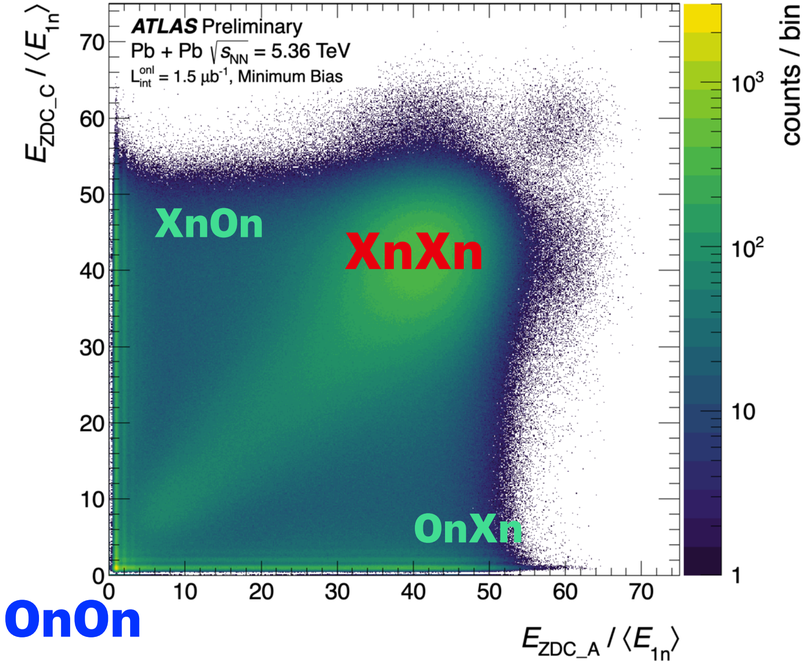
- W-fused silica sampling calorimeter
- 1 Electromagnetic (EM) + 3 Hadronic modules (HAD)
- New Reaction Plane Detector (RPD)

EVENT TAGGING WITH THE ZDC



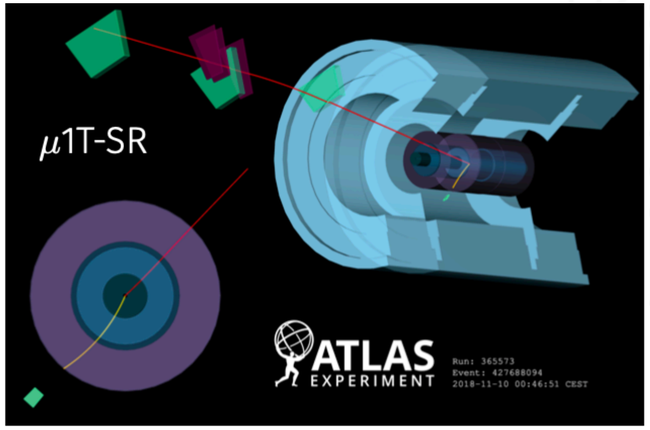






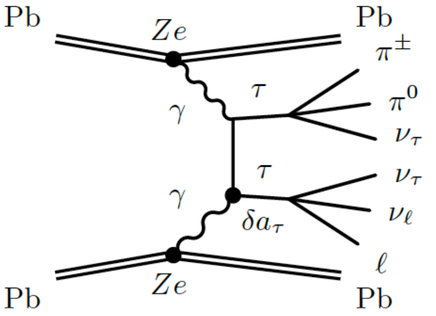
NOT JUST EVENT TAGGING...

Several Run 2 analyses used ZDC event selection / tagging, including several beyond the standard model (BSM) searches. τ g-2 example:



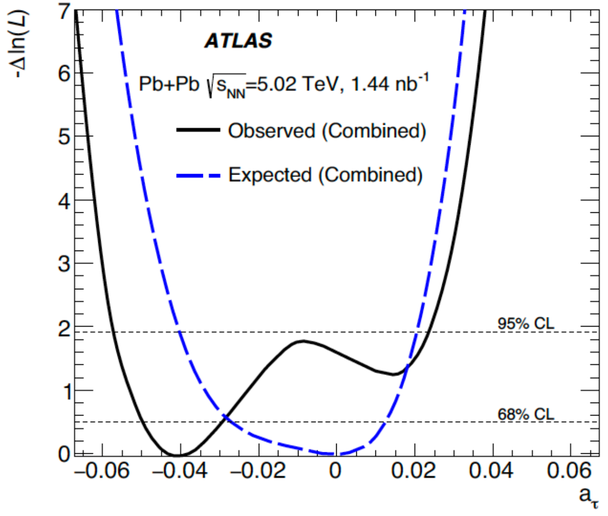
Anomalous magnetic moment of tau leptons $a_\tau=(g_\tau-2)/2$ sensitive to physics BSM

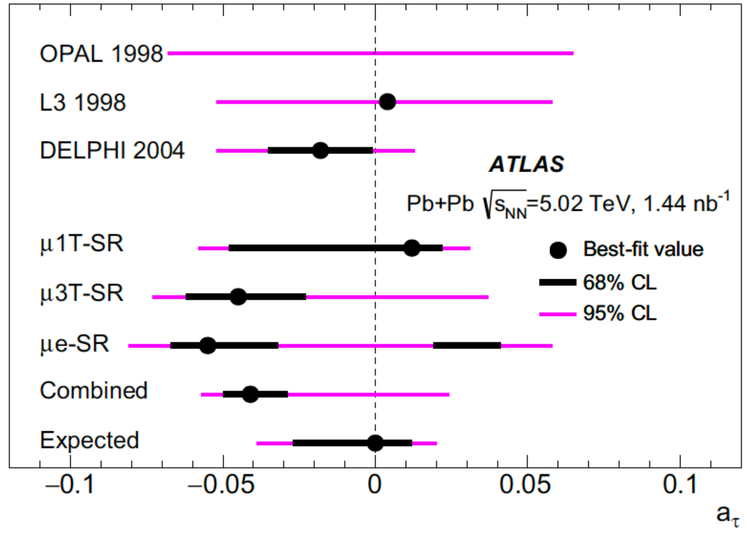
Large m_τ increases sensitivity to new physics by $(m_\tau/m_\mu)^2$ relative to μ g-2 (e.g. at BNL & FNAL)



Three channels available: eμ, μ+track, μ+3 tracks

- CMS only uses μ+3 tracks in 2015 data (404 μb^{-1}), with no ZDC selections
- ATLAS uses all 3 channels in 2018 (1.44 nb^{-1}), requiring 0n0n and cluster veto to suppress dissociative and hadronic backgrounds



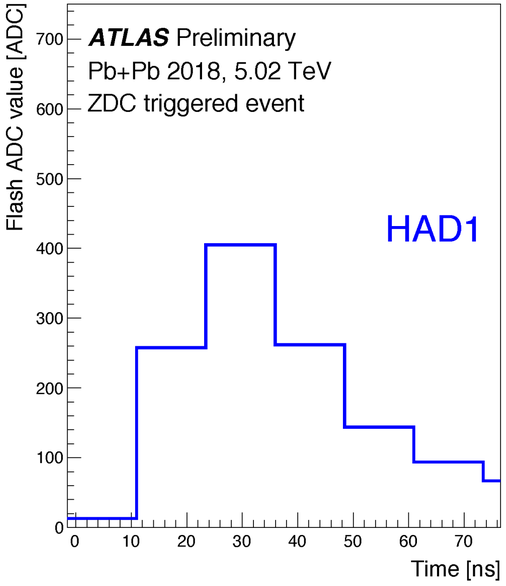


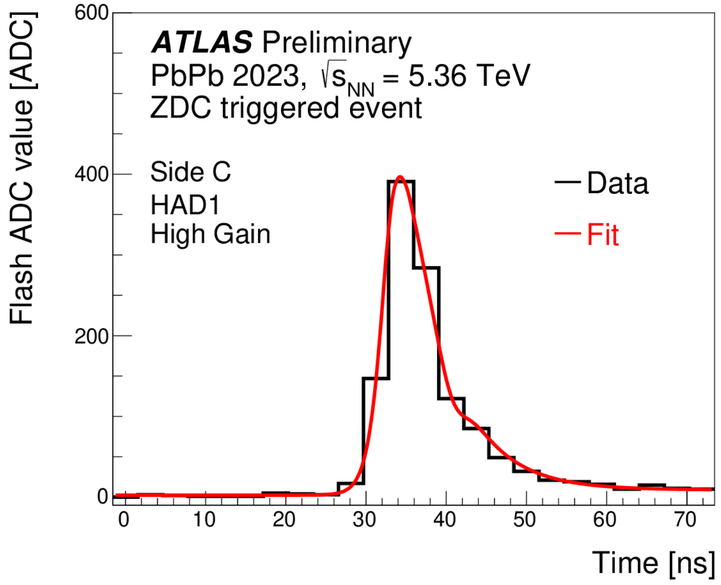
PRL 131, 151802

RUN 3 ZDC UPDATES: NEW ELECTRONICS & CABLES



- New low-dispersion **air-core cables** to tame OOT pile-up contribution
- New **LUCROD**-based readout - adapted from LUCID
  - Flash ADC recording @ 320 MHz (was 80 MHz in Run 2)





Stefano Meneghini



Giulio Avoni



Antonello Sbrizzi



RUN 3 ZDC UPDATES: NEW ELECTRONICS & CABLES



- New low-dispersion **air-core cables** to tame OOT pile-up contribution
- New **LUCROD**-based readout - adapted from LUCID
  - Flash ADC recording @ 320 MHz (was 80 MHz in Run 2)
  - New 3 bit fully digital trigger

Run2 - NIM based

Xn	γA	Hadronic
0n	γγ	Aγ
↑C A→	0n	Xn

Run3 - LUCROD based

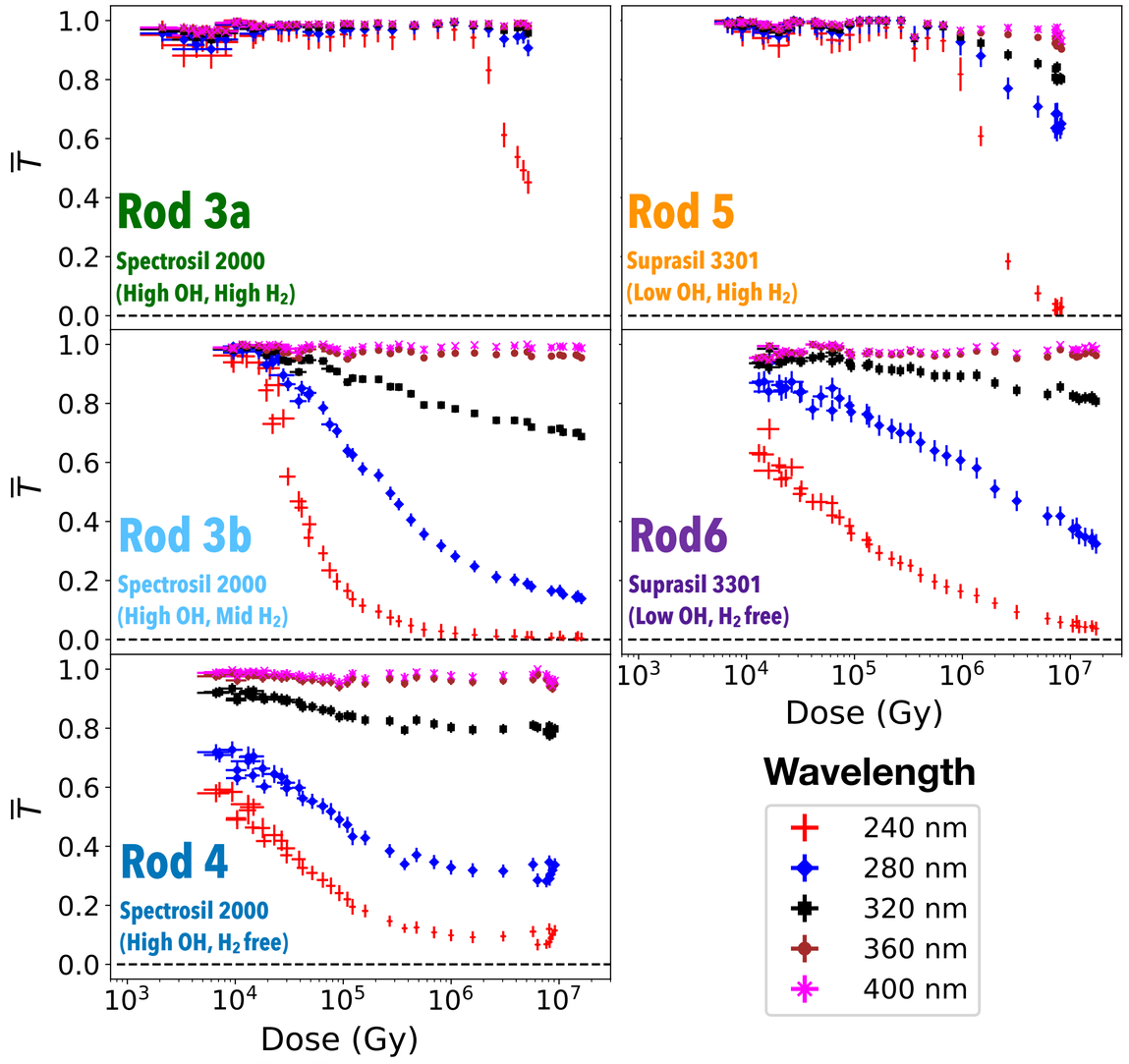
Xn	γA 7	γA 2	Hadronic 3
1-4n	γA γγ 6	γA Aγ γγ 1	Aγ 2
0n	γγ 0	Aγ γγ 4	Aγ 5
↑C A→	0n	1-4n	Xn

Stefano Meneghini **Giulio Avoni** **Antonello Sbrizzi**





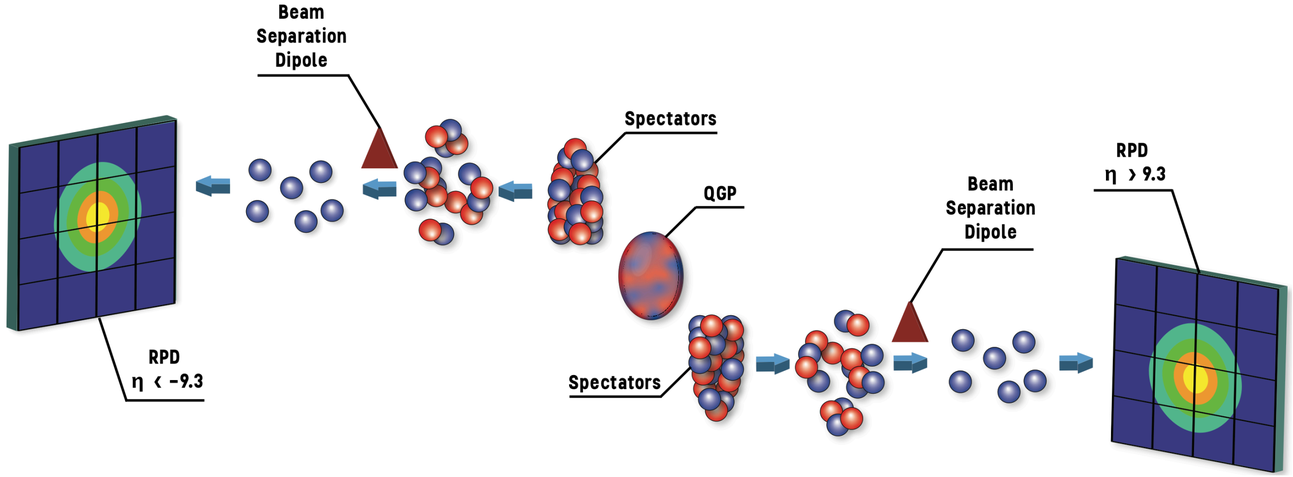
RUN 3 ZDC UPDATES: FUSED SILICA RODS & LED CALIBRATION

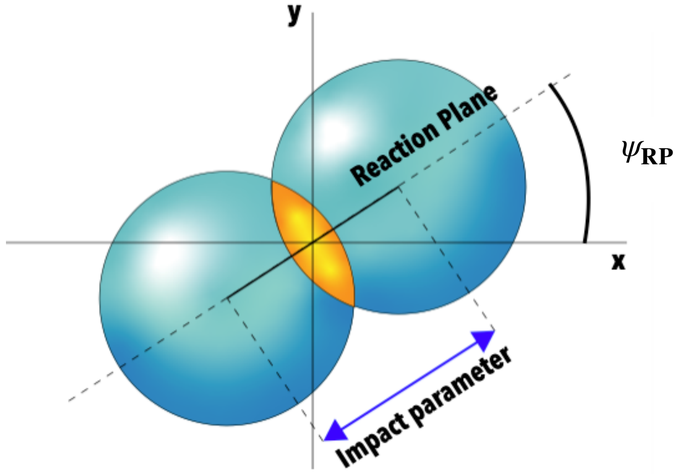


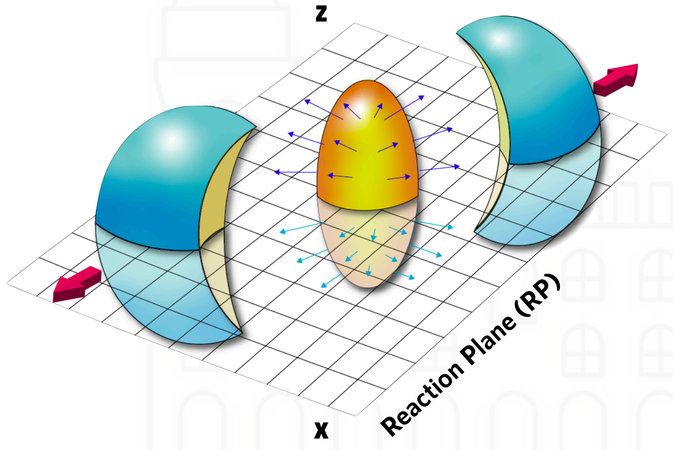
- **Refurbishment of Cherenkov radiator w/ new rad-hard H2 doped fused silica material**
  - Studies done for HL-ZDC upgrade (collaboration with CERN **FLUKA** and **BRAN** teams)
  - Great performance during 2023 HI run
- **New LED-based calibration system**
  - Allows for precise independent tracking of radiation damage of the PMT window

Nucl.Instrum.Meth.A 1055 (2023) 168523

RUN 3 ZDC UPDATES: REACTION PLANE DETECTOR !





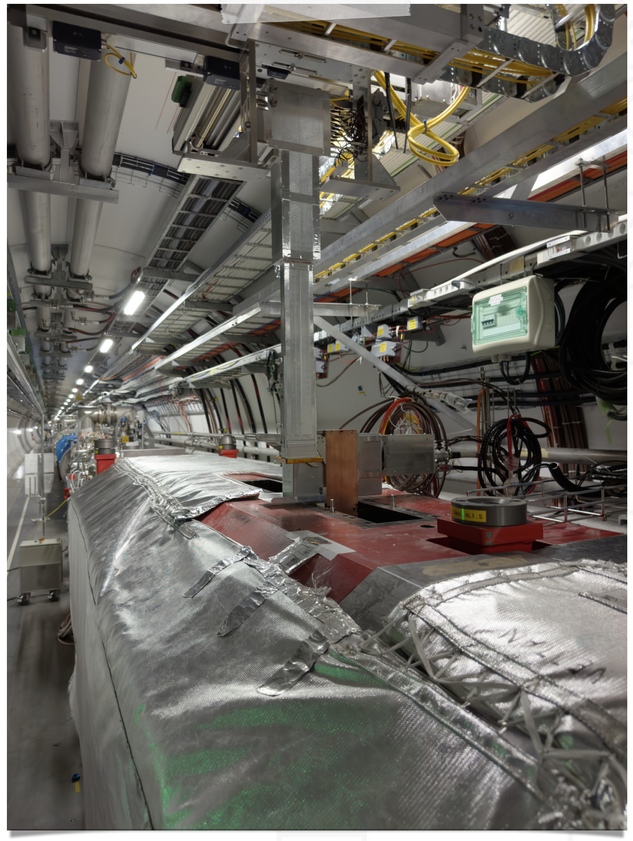


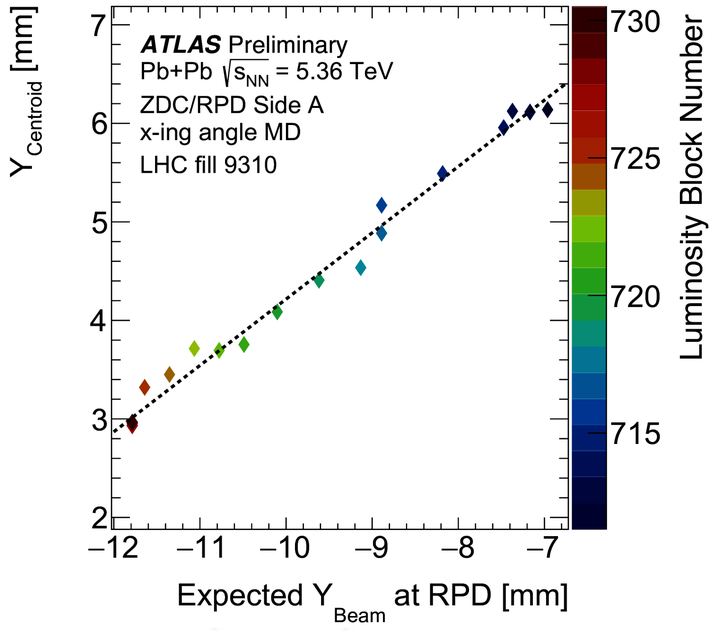
The Reaction Plane Detector is a new addition planned for the HL-ZDC

The RPD measures the **reaction plane** of HI collisions by looking at the **correlated deflection of spectator neutrons**

Detector designed to detect multiple neutrons at TeV scale - can't be easily tested outside of the LHC...

REACTION PLANE DETECTOR: RUN 3 PREVIEW!





RPD successfully tracking the LHC vertical beam position !

A pair of new radiation-hard RPDs for ATLAS was constructed at UIUC during LS2

Successfully operated in Sept/ Oct 2023, first Run 3 Heavy Ion run! Channel calibration ongoing

ML-based reconstruction being developed to enhance detector resolution

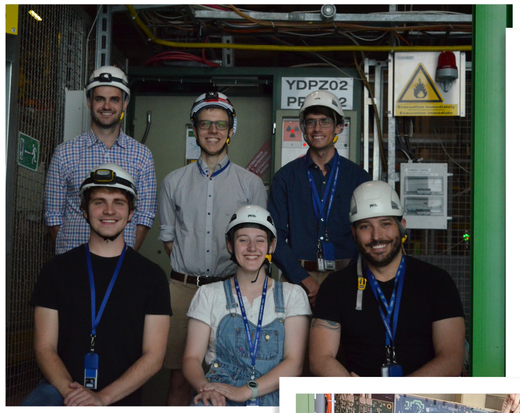
BIG CREDITS TO THE YOUNG PEOPLE WHO BUILT THE RPD!



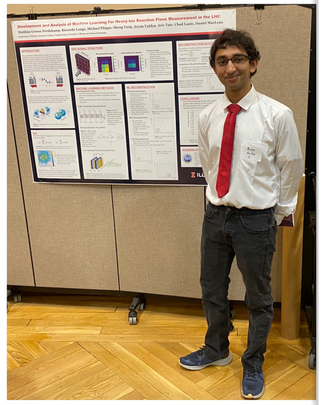


DaRin Butz Foundation

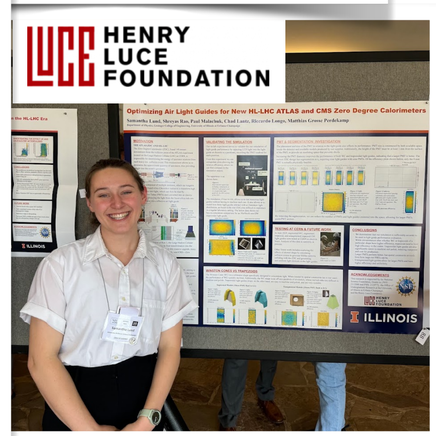












UIUC Students involved in the RPD project

A.Przbyl
A.Tate
A.Vaidya
B.Liu
C.Lantz
D.MacLean
F.Rafee
J.Fritchie
K.Young
M.Hoppesch
M.Housenga
N.Santiago
P.Malachuk
S.Lund
S.Yang
Y.Liu
X.Ma

...AND TO THOSE WHO OPERATED THE ZDC AND THE RPD LAST FALL!

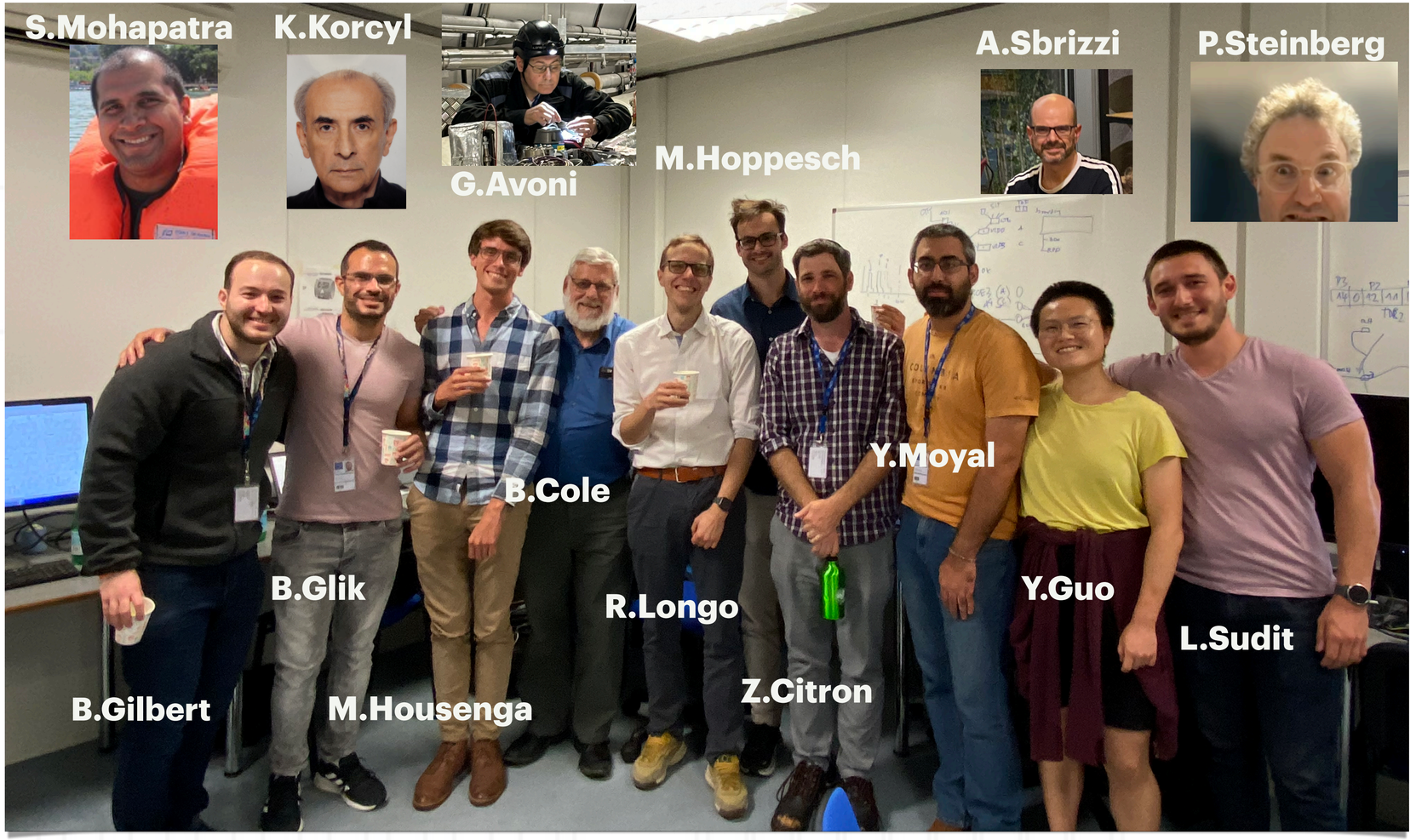
Ben-Gurion University of the Negev

Columbia University in the City of New York

University of Illinois Urbana-Champaign

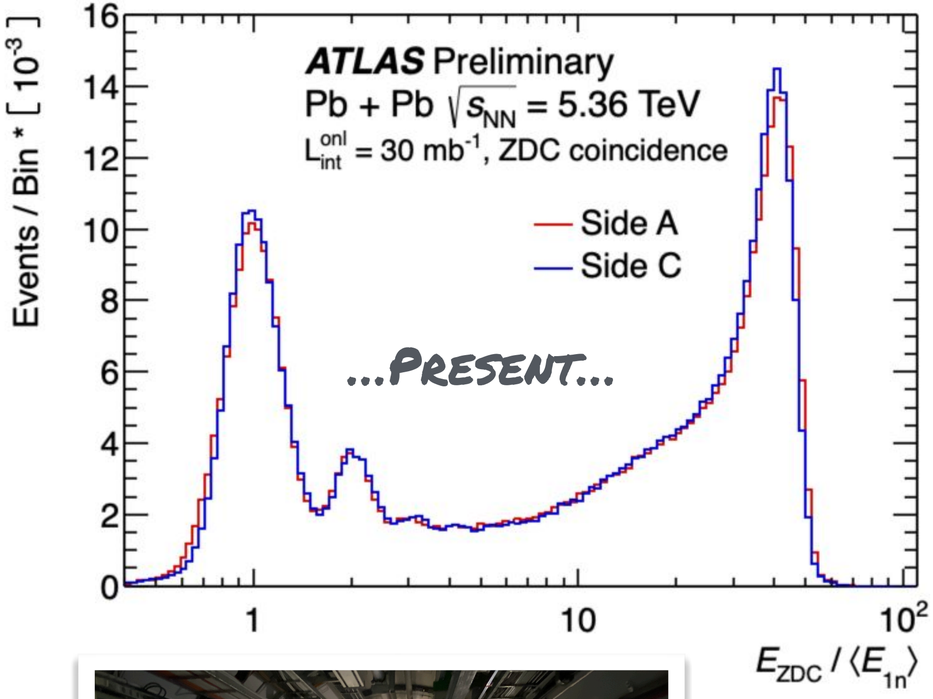
Brookhaven National Laboratory

INFN Bologna



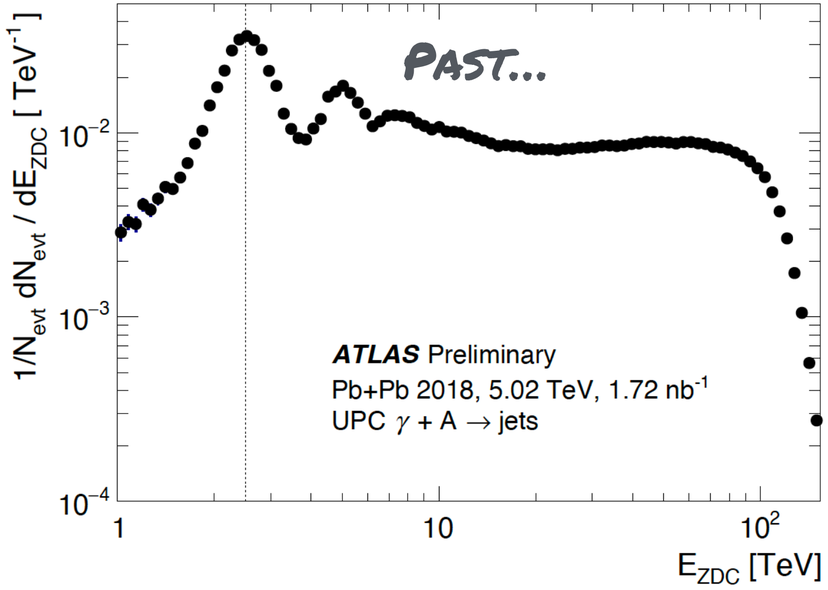
HI PROGRAM ⟺ ZDC

Run 3 ZDC: preliminary performance





A high-performance ZDC is a must for a successful HI program!



... and Future!

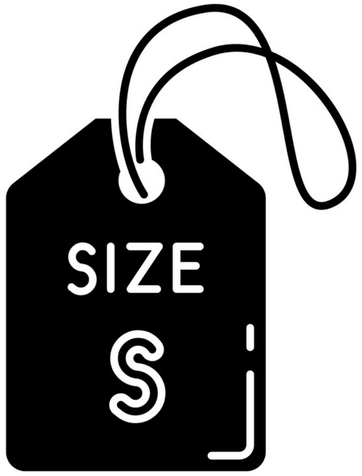
2029 - 2032

Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

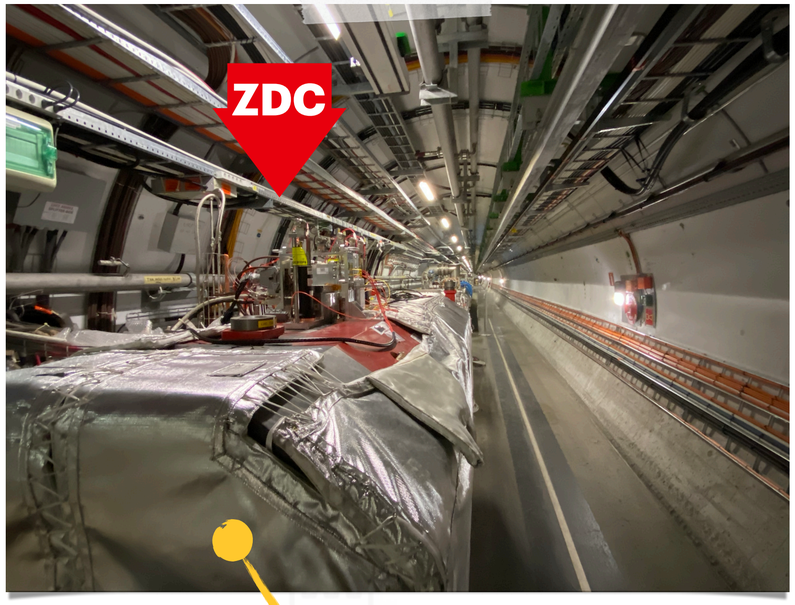
ZDC UPGRADE CHALLENGES



Harsh radiation environment
~MGy/nb^{-1} deposited in detector during operation
Expected to worsen in Run 4



Very limited amount of space
(10 cm in Run 3, 4.6 cm(!!) in Run 4++)



TAN absorber
20 mSv/h in the core after 1 year of *pp* run in Run 3

ZDC UPGRADE CHALLENGES



Harsh radiation environment
~MGy/nb^{-1} deposited in detector during operation
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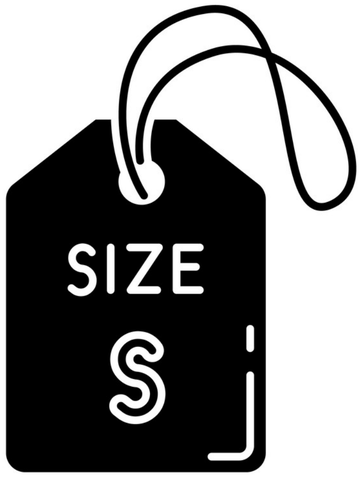


Very limited amount of space
(10 cm in Run 3, 4.6 cm(!!) in Run 4++)

SAME CHALLENGES FOR BOTH ATLAS AND CMS!



TAN absorber
20 mSv/h in the core after 1 year of *pp* run in Run 3

ATLAS-CMS JOINT HL-ZDC UPGRADE PROJECT

ATLAS EXPERIMENT

Ben-Gurion University of the Negev

Columbia University in the City of New York

Brookhaven National Laboratory

University of Illinois Urbana-Champaign

CMS Compact Muon Solenoid

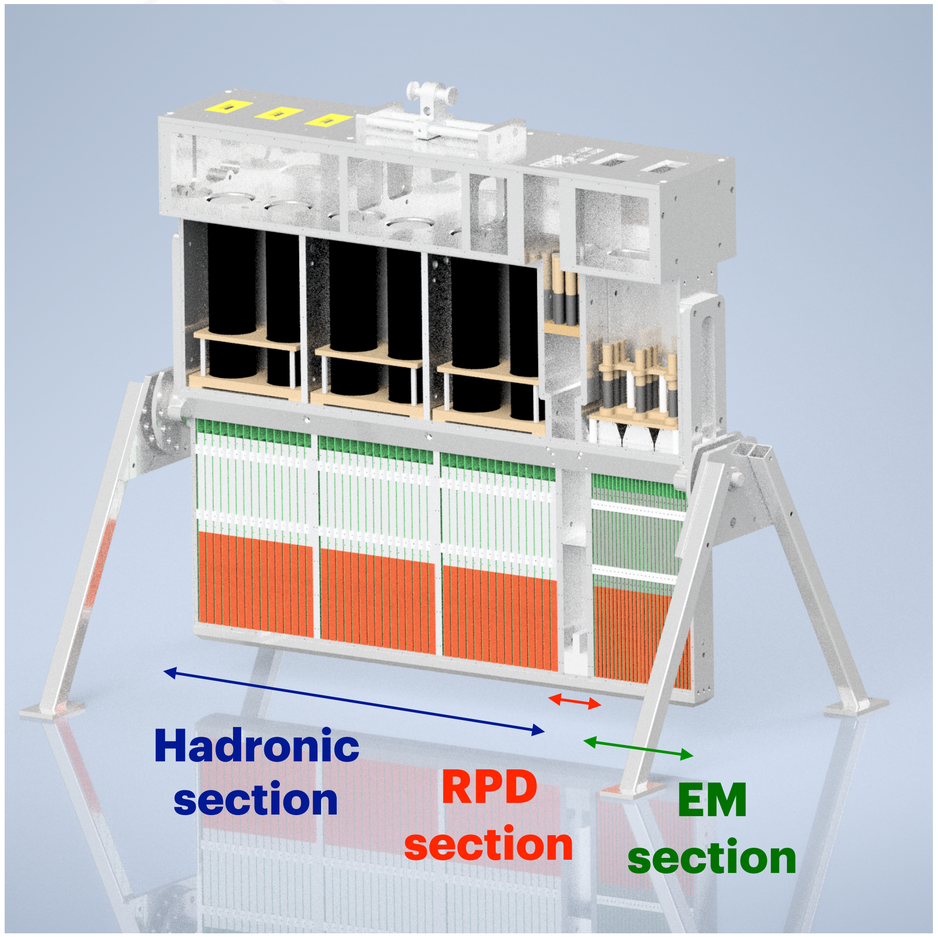
KU The University of Kansas

University of Maryland

First joint hardware project between ATLAS and CMS!

Will enable the heavy ion program for both the experiments for run 4 and beyond!

Run 4 HL-ZDC design



ATLAS-CMS JOINT HL-ZDC UPGRADE PROJECT

ATLAS EXPERIMENT

Ben-Gurion University of the Negev

Columbia University in the City of New York

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University of Illinois Urbana-Champaign

CMS Compact Muon Solenoid

KU The University of Kansas

University of Maryland

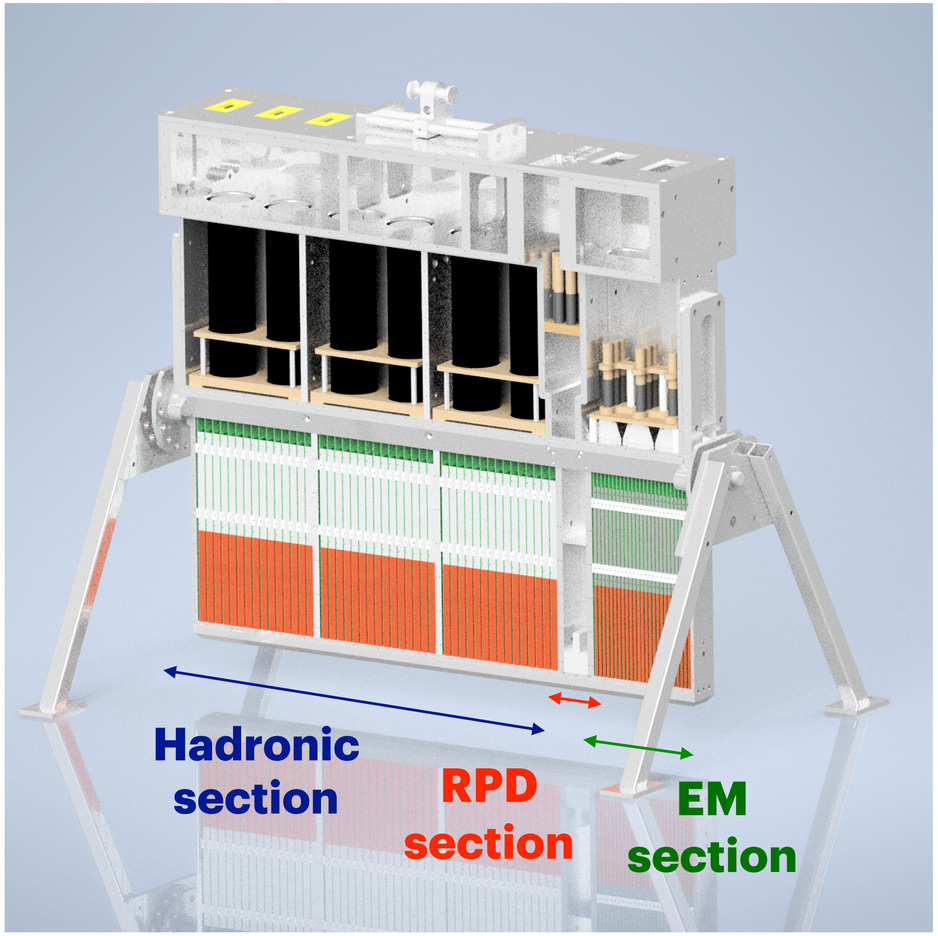
ATLAS ZDC electronics still LUCROD based!

INFN Bologna

First joint hardware project between ATLAS and CMS!

Will enable the heavy ion program for both the experiments for run 4 and beyond!

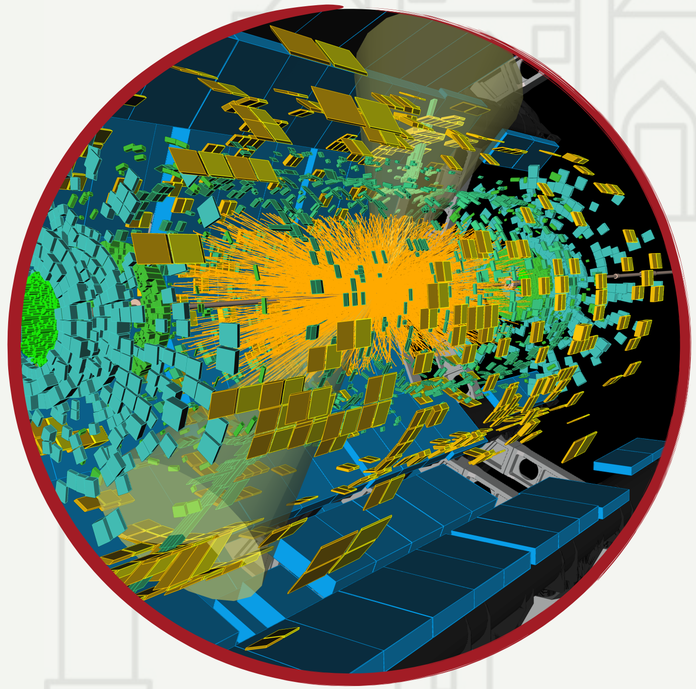
RUN 4 HL-ZDC DESIGN

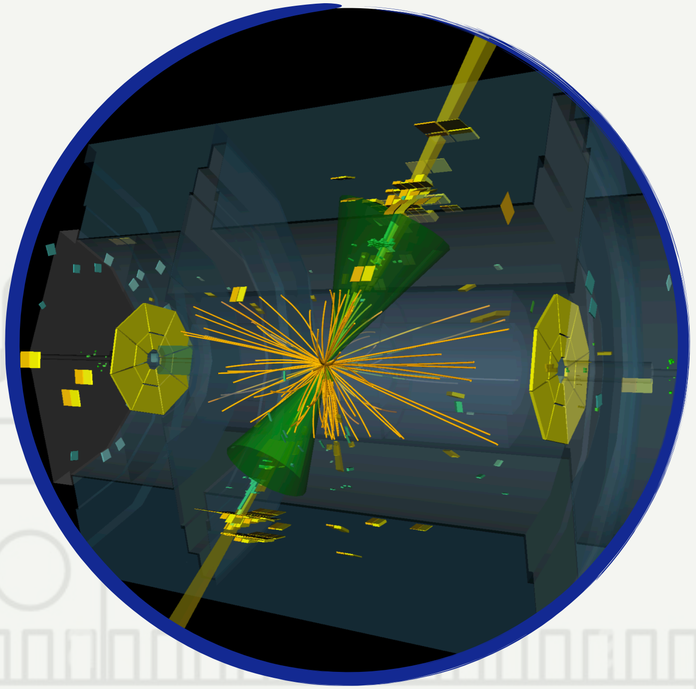


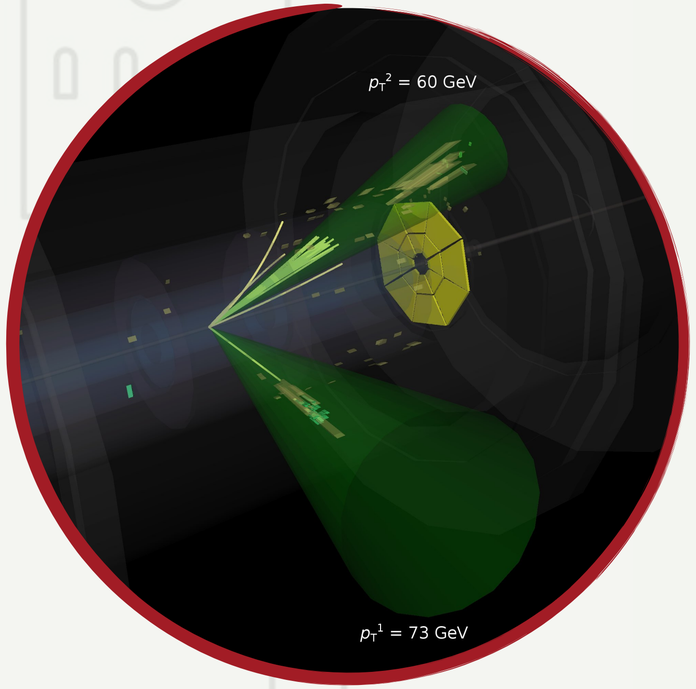
Summary

- The high versatility of the ATLAS detector offers great opportunities to investigate hot & cold QCD effects emerging in heavy ion collisions
- Several advancements in answering some of the key questions in the last decade - but still a lot to be understood to connect short and long-range behavior of the QGP (Run 3 and Run 4 data to the rescue!)
- 2025 oxygen data taking will shed new light on energy loss onset in small systems
- Dijets @ ATLAS are an incredible tool to study both hot & cold QCD effects
- ZDC detectors are an irreducible part of a successful heavy ion program! Will also be needed for HL-LHC (together w/ the LUCROD)

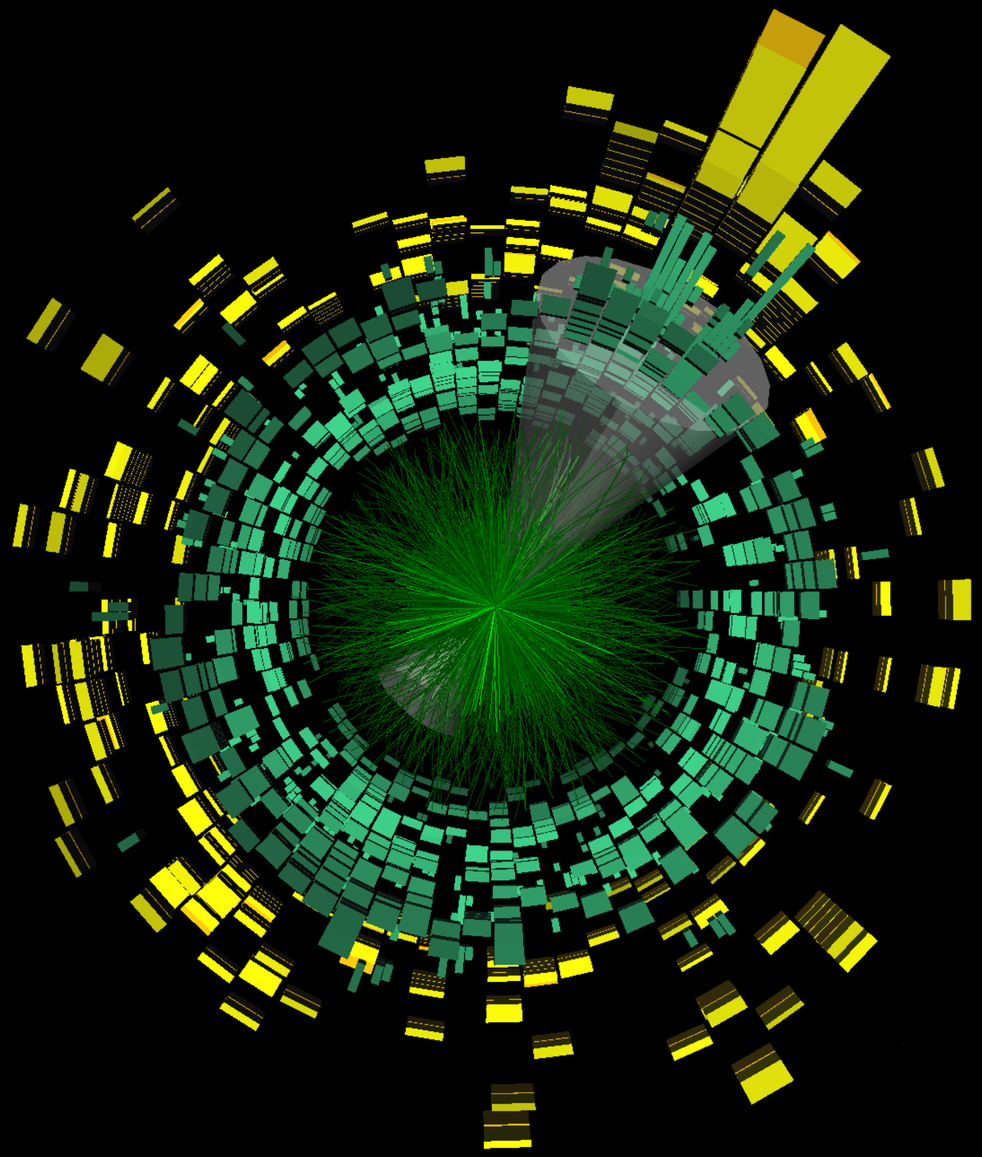
Thank you for your attention!







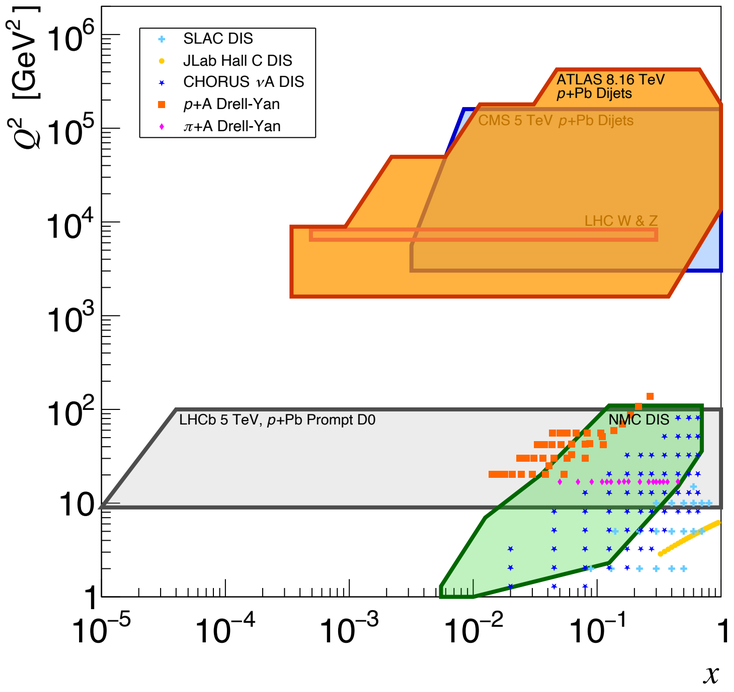
Thanks to B.Cole, P.Steinberg, and A.Sickles for insightful discussions during the preps of this talk



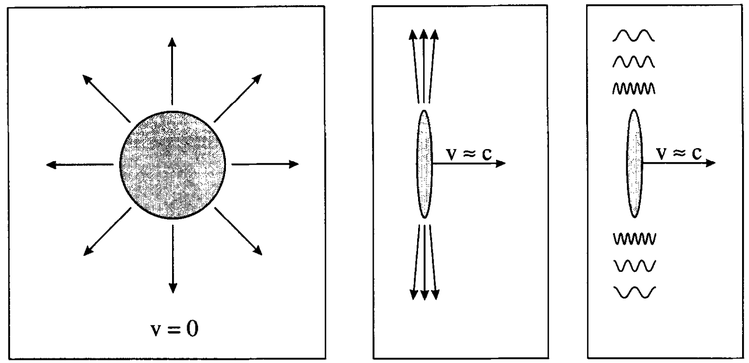
Backup slides

EM PROBES FOR THE NUCLEUS AT THE LHC

Adapted from Eur. Phys. J. C (2022) 82:413 w/ B. Gilbert



Fermi, Landau, von Weiszacker, Williams



Equivalent photon approximation

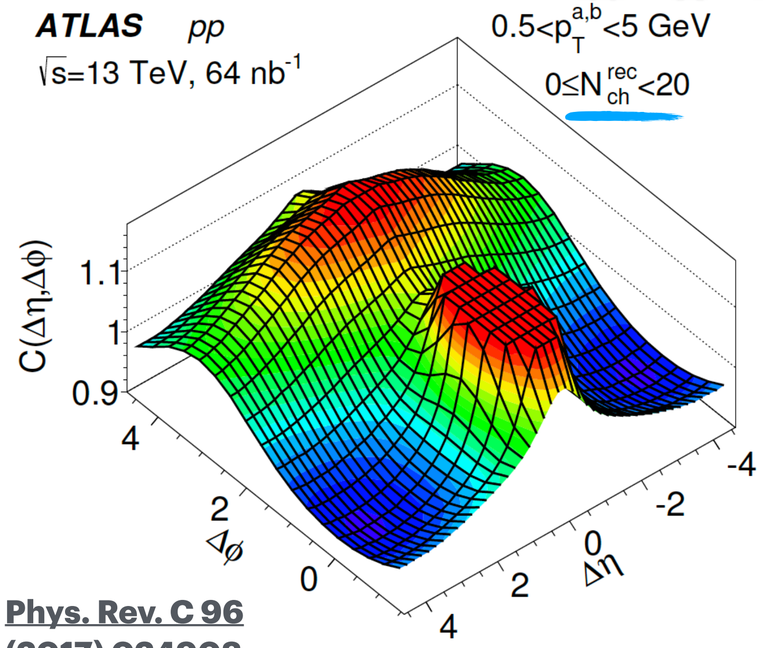
$E_{\gamma,max} \sim \gamma(\hbar c/R)$	80 GeV in Pb+Pb @ LHC
$p_{Tmax} \sim \hbar c/R$ ($\Longleftrightarrow$virtuality)	O(30) MeV @ LHC
Coherent rates scale as Z^2: nuclei >> protons	Flux of photons on other nucleus ~ Z^2, flux of photons on photons ~ Z^4 (45M!)

Table courtesy of P.Steinberg

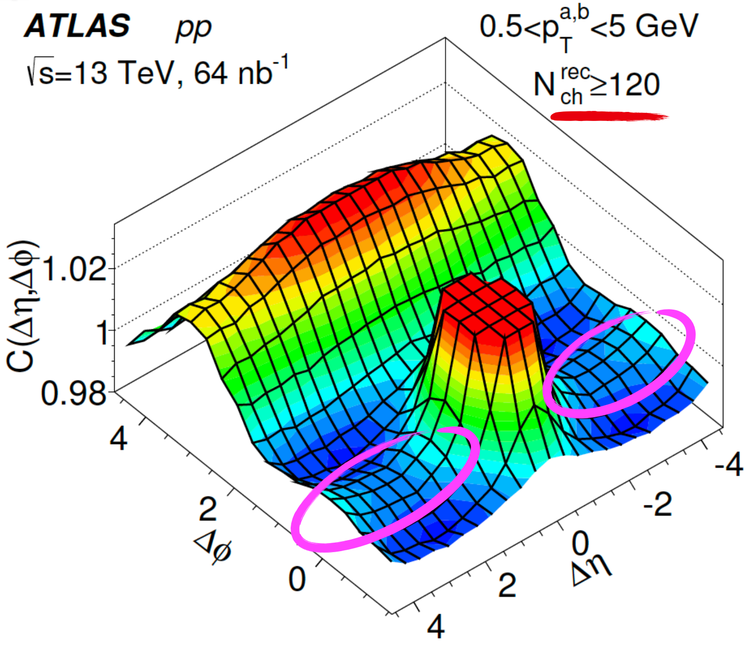
Heavy ions running @ LHC are also fantastic photon sources!

FLOW IN EVEN SMALLER SYSTEMS: P+P !

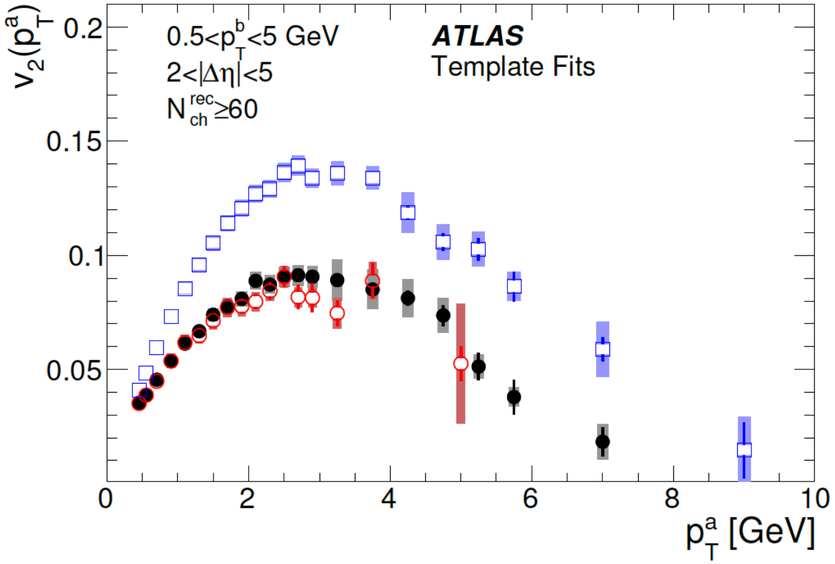
"Low" Multiplicity

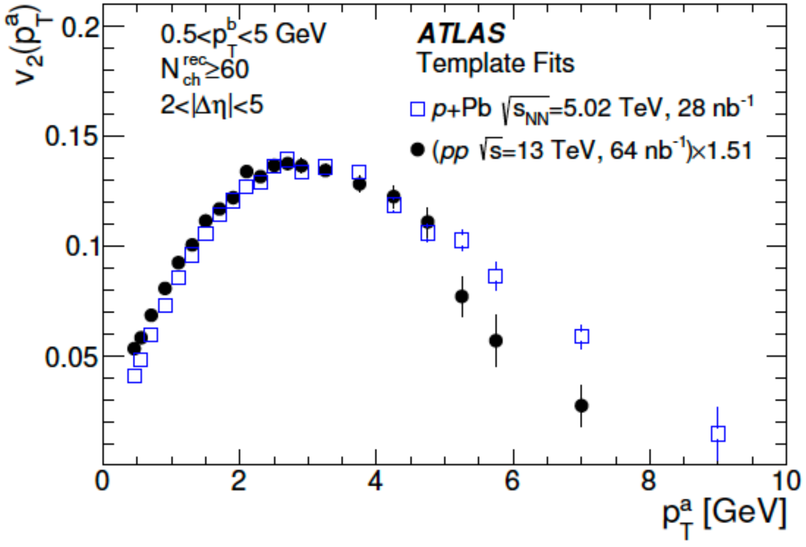


"High" Multiplicity



Phys. Rev. C 96 (2017) 024908

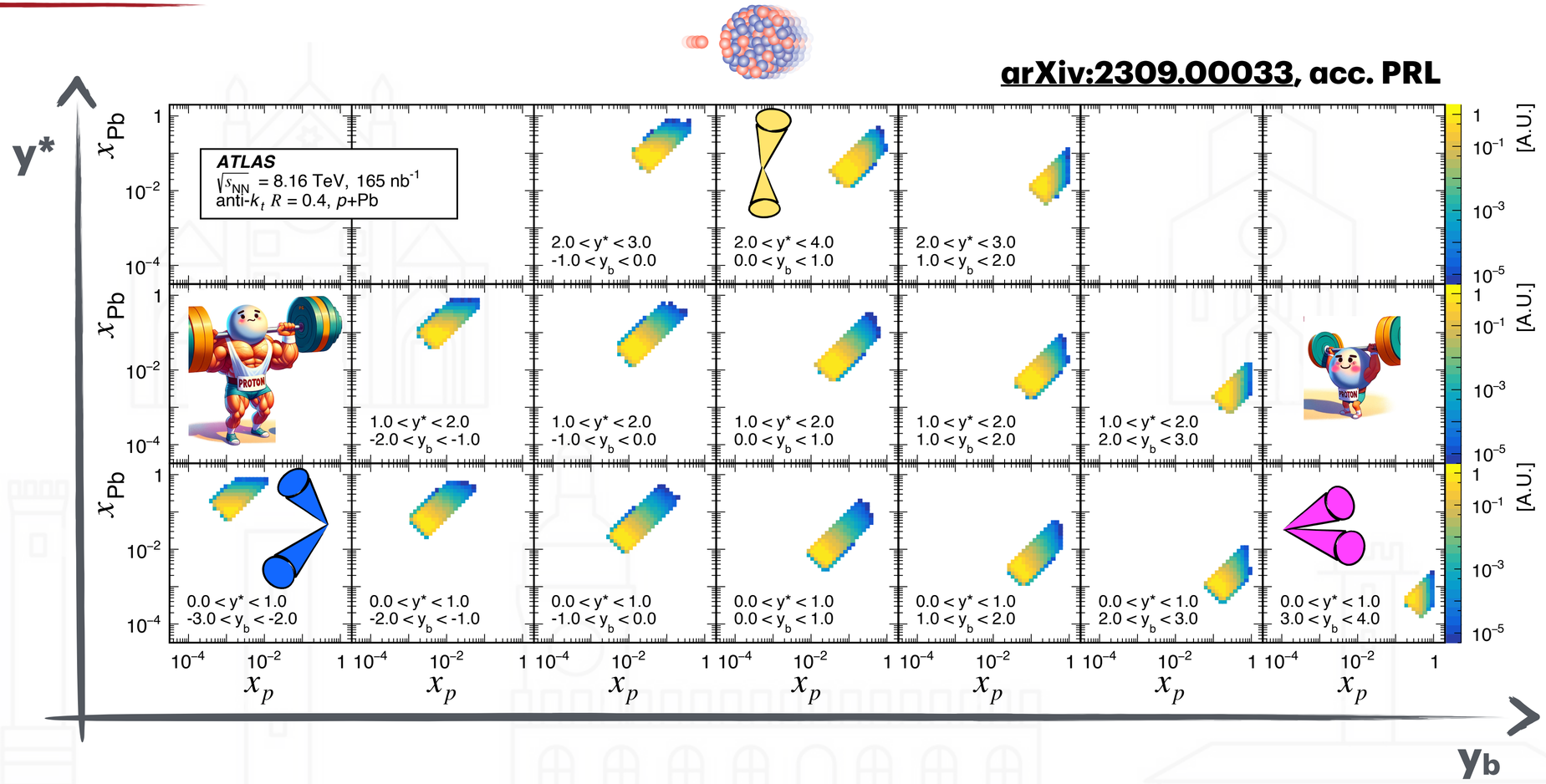




- Compare the (transverse) momentum dependence of the p+Pb and pp cos(2ϕ) Fourier coefficients

➡ **Results rescaled by ratio of maxima agree, except where jets start to contribute at high-energies and long wavelengths?**

BROWSING PROTON CONFIGURATIONS WITH ATLAS CALORIMETER

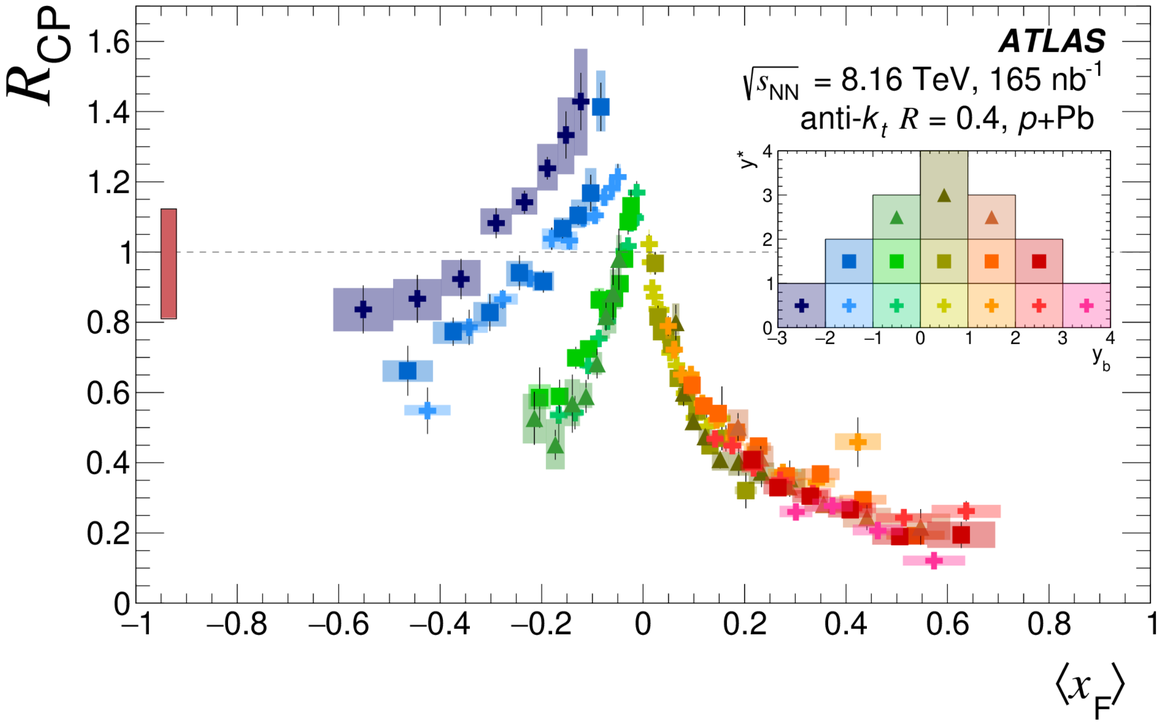


High statistics dataset + wide acceptance of ATLAS calorimeter

=

access to a wide array of proton configurations

R_{CP} AS A FUNCTION OF X_F



- We can try to draw a connection with the inclusive measurement using a kinematic variable that carries information from both initial state parton kinematics: the **Feynman variable**, x_F
- x_F can be seen as a property of the final state particle or, equivalently, of the two-party system

Final state particle definition:

$$x_F = \frac{2p_z}{\sqrt{s}}$$

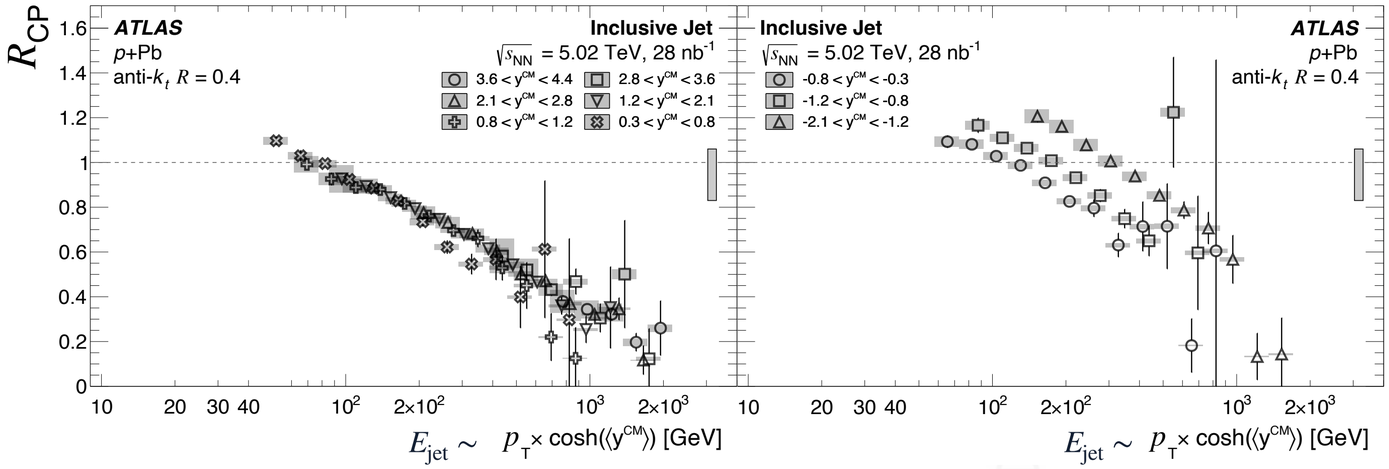
Two parton system definition:

$$x_F = x_1 - x_2 = x_p - x_{\mathrm{Pb}}$$

arXiv:2309.00033, acc. PRL

SAME PHYSICS EFFECT AS FOR INCLUSIVE JETS?

Run 1 [**PLB 748 (2015) 392–413**] inclusive jet data - plotted as a function of $p_T \times \cosh y^{\mathrm{CM}}$



$$p_z = m_T \sinh y^{\mathrm{CM}} = \sqrt{m^2 + p_T^2} \sinh y^{\mathrm{CM}} \sim p_T \sinh y^{\mathrm{CM}}$$

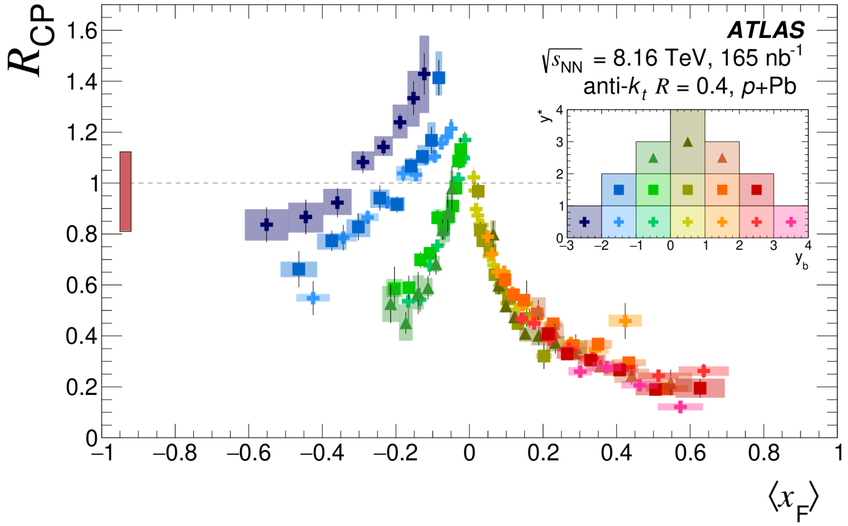
Assuming $\sinh y^{\mathrm{CM}} \sim \pm \cosh y^{\mathrm{CM}}$ if $|y^{\mathrm{CM}}| > 0$

Initial state definition

$$x_p - x_{\mathrm{Pb}} = x_{\mathrm{F}} = \frac{2p_z}{\sqrt{s_{\mathrm{NN}}}} \sim \pm 2\frac{p_{\mathrm{T}} \times \cosh y^{\mathrm{CM}}}{\sqrt{s_{\mathrm{NN}}}}$$

Final state definition

$$\pm\frac{\sqrt{s_{\mathrm{NN}}}}{2} \times x_{\mathrm{F}} \sim p_{\mathrm{T}} \times \cosh y^{\mathrm{CM}}$$



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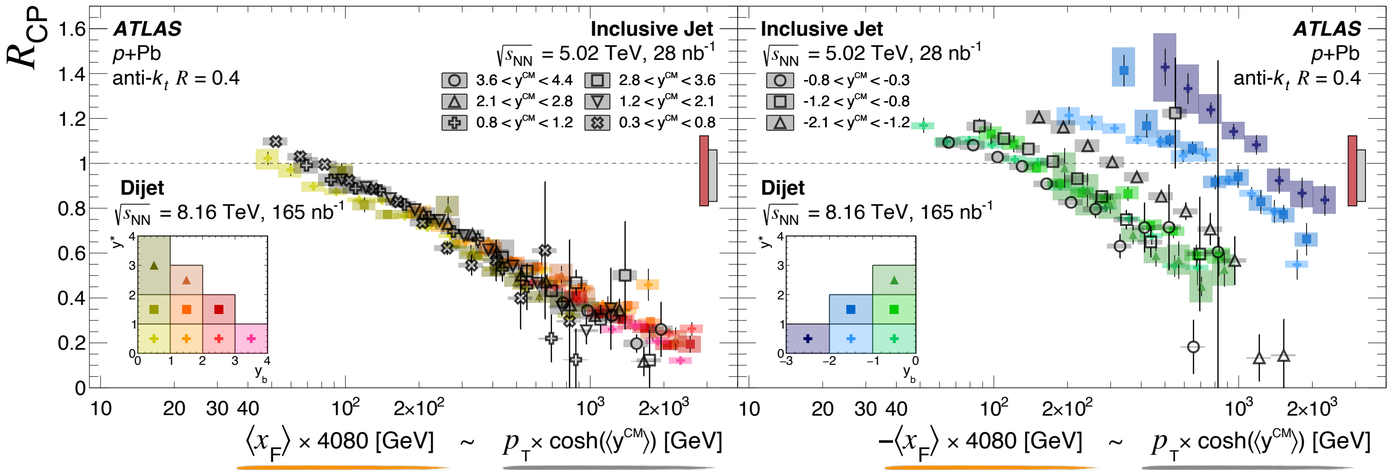

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Assuming $\sinh y^{\mathrm{CM}} \sim \pm \cosh y^{\mathrm{CM}}$ if $|y^{\mathrm{CM}}| > 0$

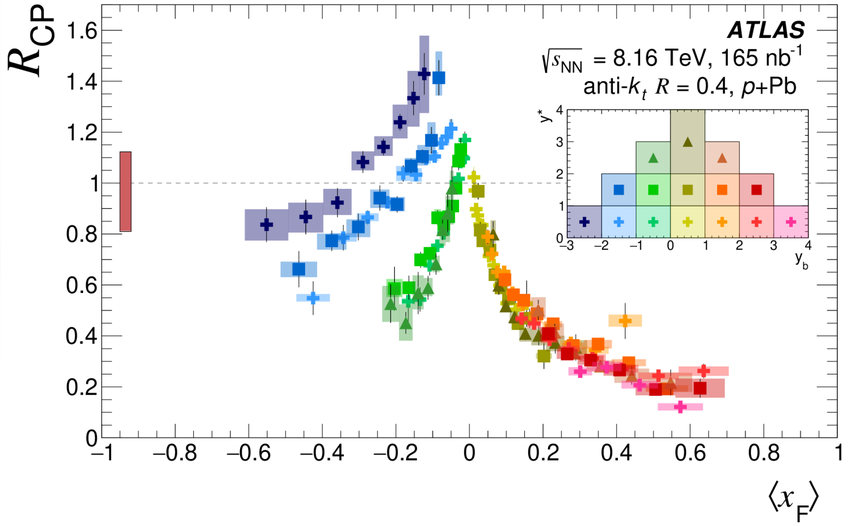
Initial state definition

$$x_p - x_{\mathrm{Pb}} = x_{\mathrm{F}} = \frac{2p_z}{\sqrt{s_{\mathrm{NN}}}} \sim \pm 2\frac{p_{\mathrm{T}} \times \cosh y^{\mathrm{CM}}}{\sqrt{s_{\mathrm{NN}}}}$$

Final state definition

$$\pm\frac{\sqrt{s_{\mathrm{NN}}}}{2} \times x_{\mathrm{F}} \sim p_{\mathrm{T}} \times \cosh y^{\mathrm{CM}}$$

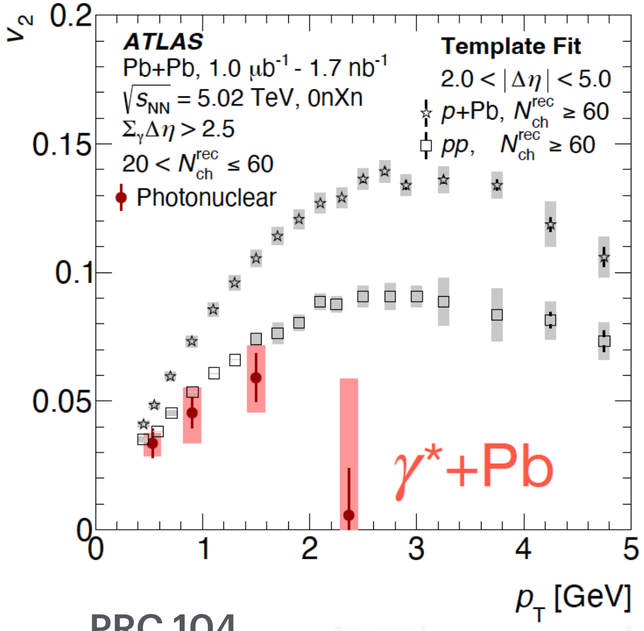
NEW POWERFUL DATASET FOR MORE DETAILED GLOBAL ANALYSES OF CT EFFECTS



SAME PHYSICS EFFECT, DRIVEN BY THE INITIAL STATE PROTON KINEMATICS!

FLOW IN EVEN SMALLER SYSTEMS: UPCs!

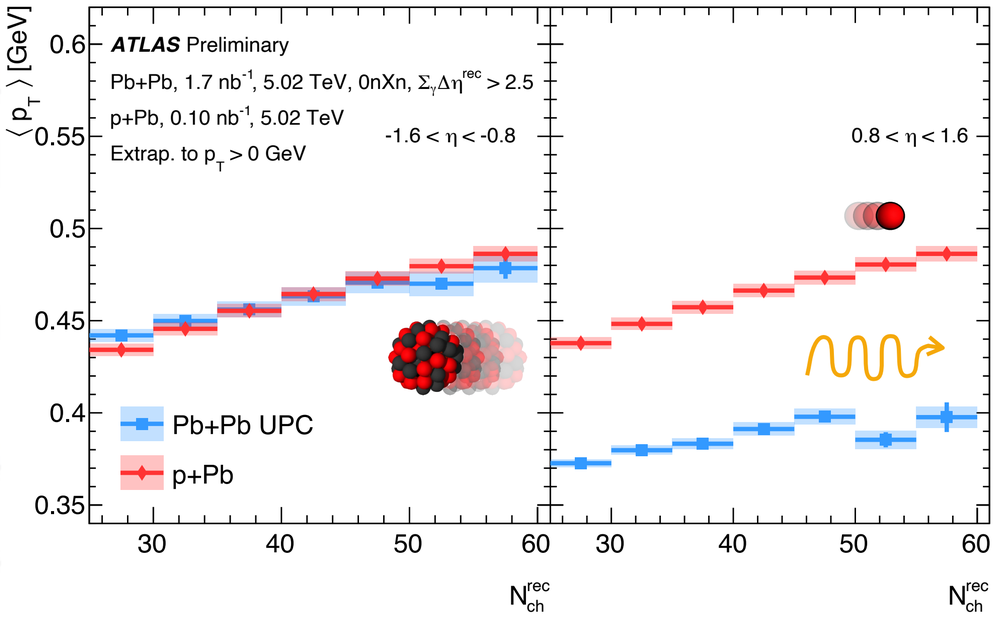
QGP-like signature in UPCs!

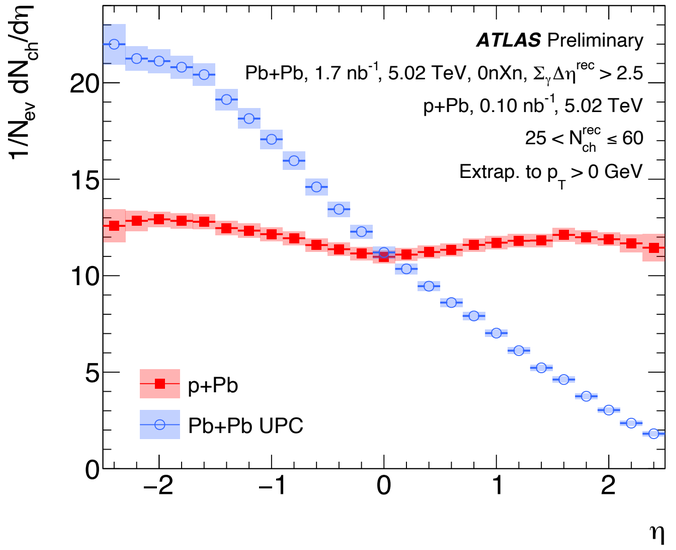


PRC 104, 014903 (2021)

- Theory (**PRL 129, 252302**) predicts that both p+Pb and γ^*+Pb should have the same radial flow, e.g. same $\langle p_T \rangle$, at backward rapidities!
- Analysis in the same multiplicity region for both UPC and p+Pb

ATLAS-CONF-2023-059





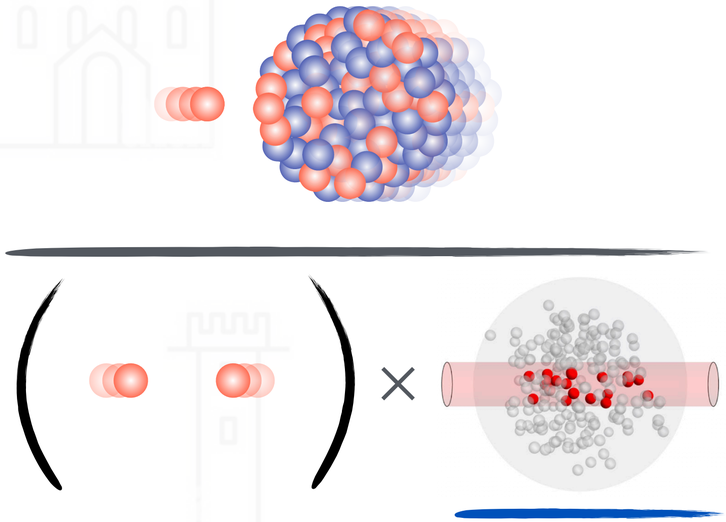
- Comparable $\langle p_T \rangle$ at backward rapidities - hint of hydrodynamic behavior in UPC
- Analysis being extended to K^S_0, λ, Ξ, more sensitive to radial flow

JET NUCLEAR MODIFICATION IN P+A

Nuclear modification typically studied via analysis of the **nuclear modification factor**, R_{pA}, for a specific jet final state channel of interest, X

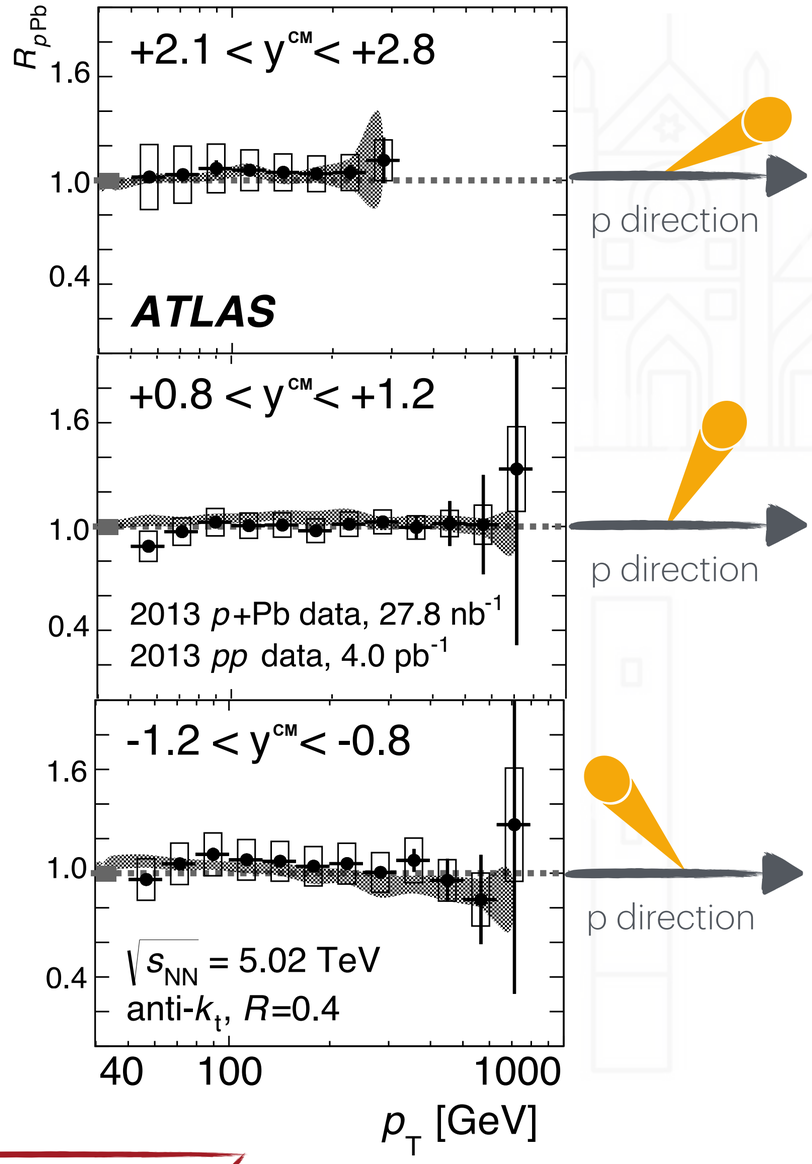
SHOULD BE UNITY IF NO NUCLEAR MODIFICATION

$$R_{\mathrm{pA}} = \frac{1}{T_{\mathrm{pA}}} \frac{\sigma_{X,\mathrm{pA}}}{\sigma_{X,\mathrm{pp}}}$$



Ratio between production in p+A and production in *p+p* rescaled by the **nuclear thickness function**, T_{pA}

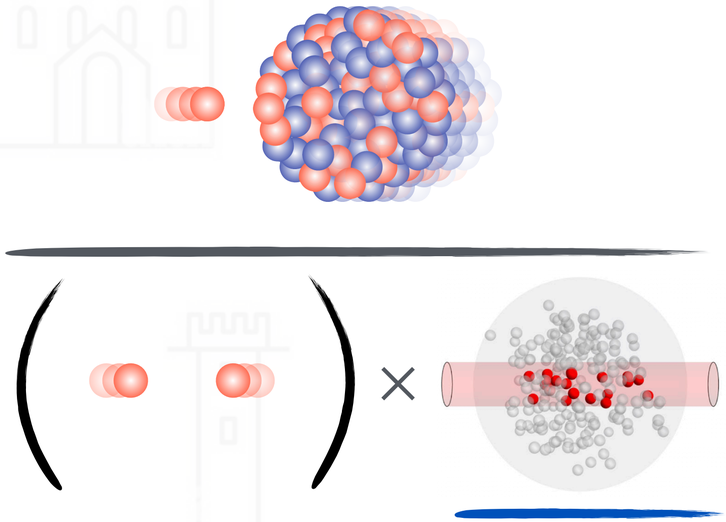
NUCLEAR MODIFICATION IN P+A COLLISIONS



ATLAS, inclusive jet, p+Pb @ 5.02 TeV

PLB 748 (2015) 392–413

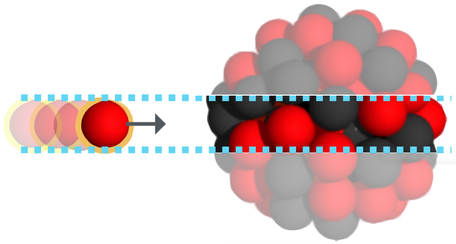
$$R_{\mathrm{pA}} = \frac{1}{T_{\mathrm{pA}}} \frac{\sigma_{X,\mathrm{pA}}}{\sigma_{X,\mathrm{pp}}}$$



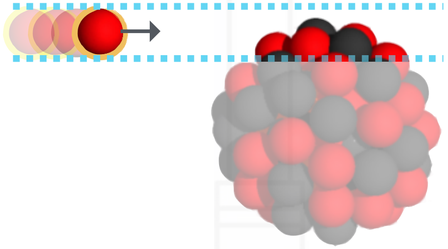
No evidence for large modification of the jet yield relative to the geometric expectation

GEOMETRY DEPENDENCE OF NUCLEAR EFFECTS?

Does event geometry affect the nuclear modification of jet production in p+Pb?



‘Central’ p+Pb collision

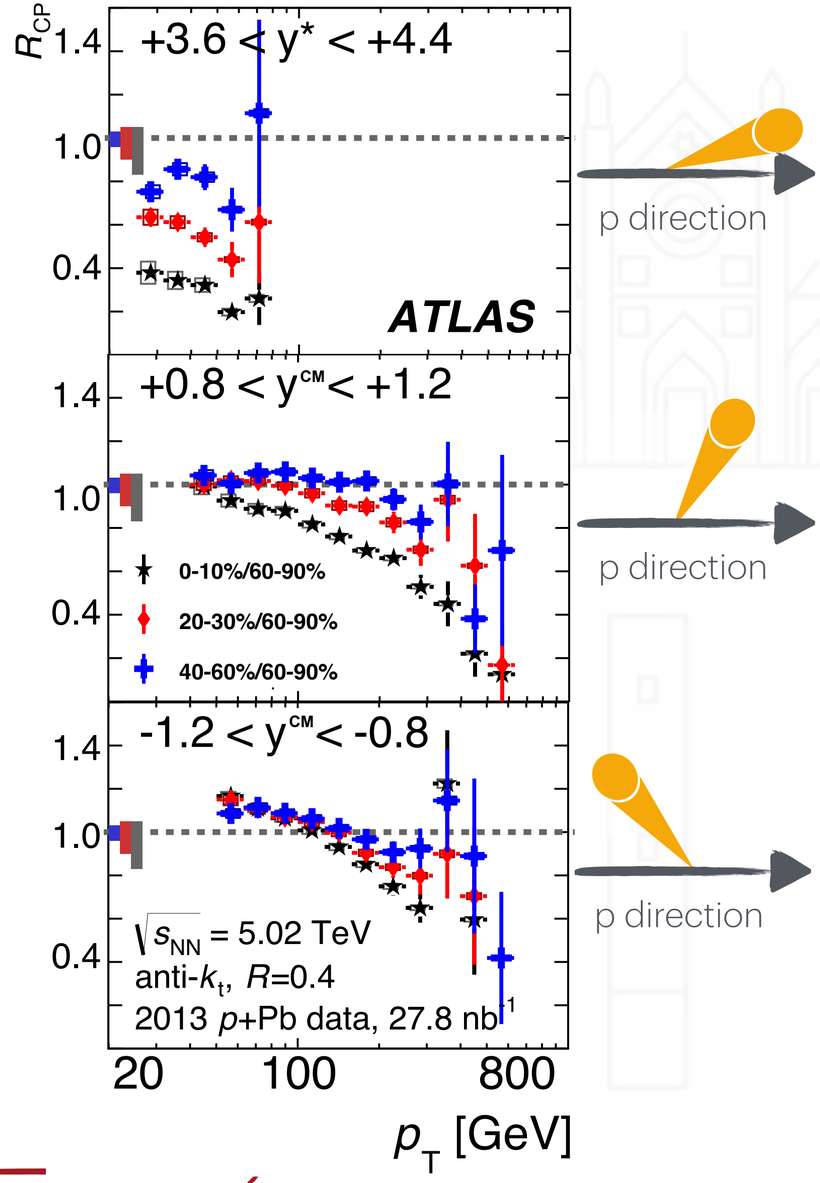


‘Peripheral’ p+Pb collision

$$R_{\mathrm{CP}} = \frac{R_{\mathrm{pA}}^{\mathrm{Cent.}}}{R_{\mathrm{pA}}^{\mathrm{Periph.}}} = \frac{\frac{1}{T_{\mathrm{pA}}^{\mathrm{Cent.}}}\sigma_{\mathrm{pA}}^{\mathrm{Cent.}}}{\frac{1}{T_{\mathrm{pA}}^{\mathrm{Periph.}}}\sigma_{\mathrm{pA}}^{\mathrm{Periph.}}}$$

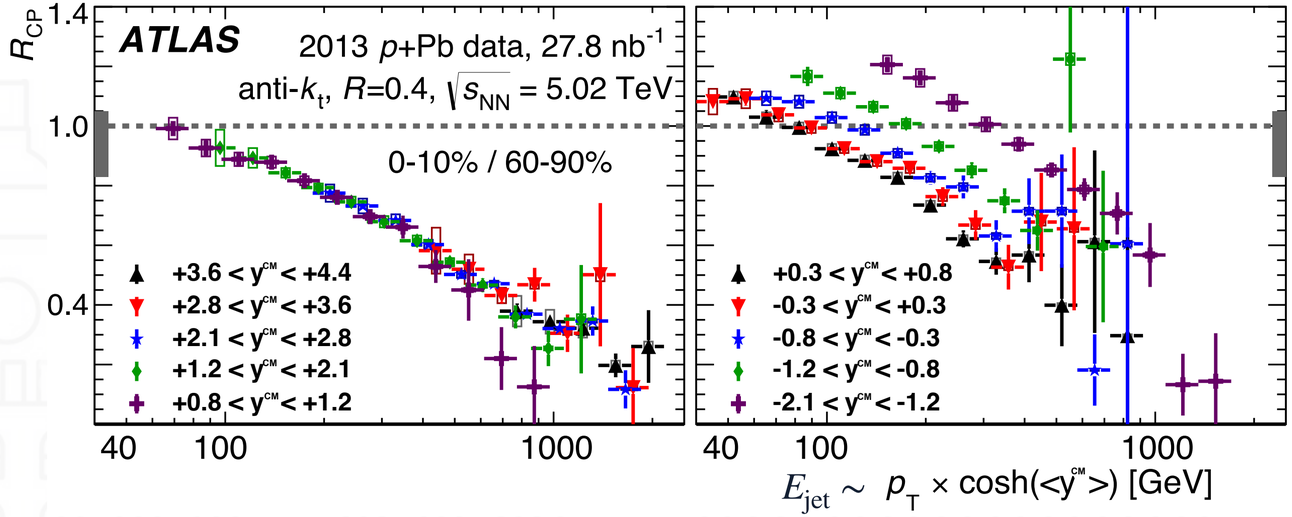
Ratio Central to Peripheral: quantifies deviations in the observed process between central collisions and geometric expectations built from peripheral collisions

ANOTHER SURPRISE IN SMALL SYSTEMS



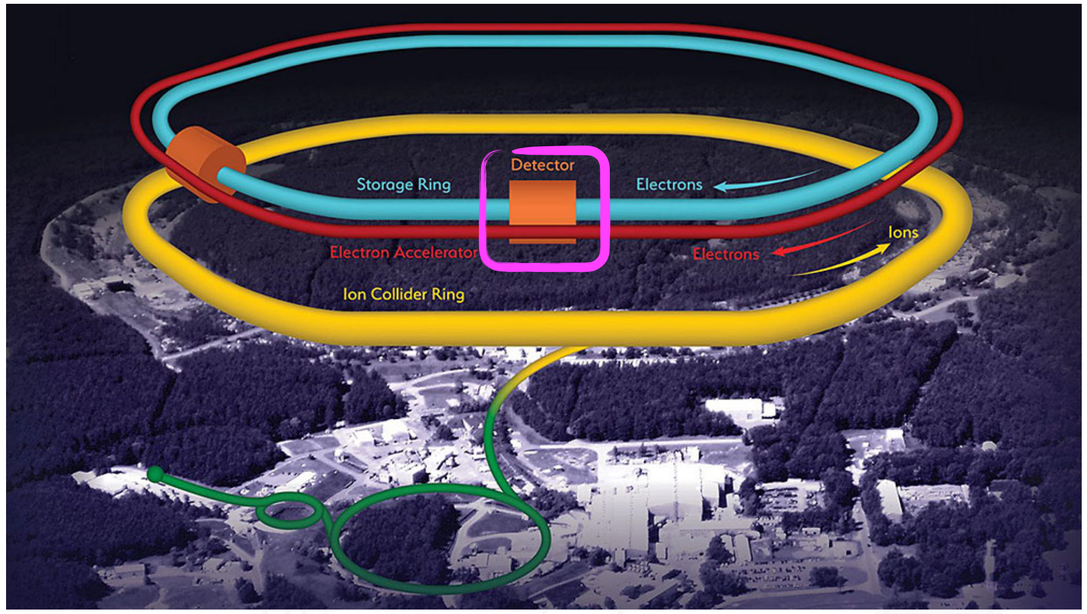
Large suppression of jet production in central events compared to peripheral ones!

- Effect dependent on both y^{CM} and p_T
- Forward jets are more suppressed than those at mid-rapidity



RESULTS FOUND TO SCALE WITH THE JET ENERGY AT MID-FORWARD RAPIDITIES!

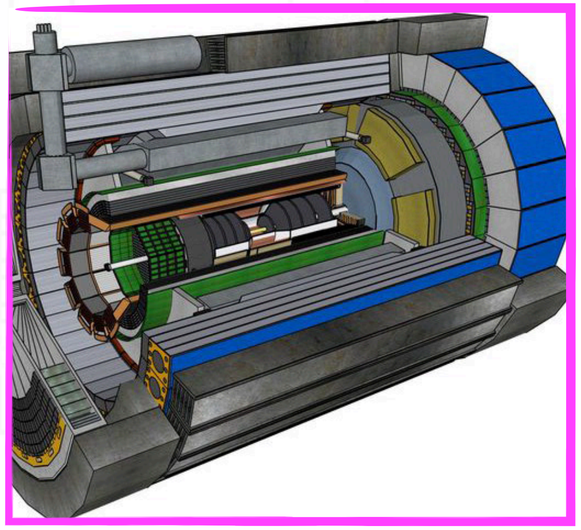
THE ELECTRON-ION COLLIDER



The EIC will be built at Brookhaven National Laboratory - using and upgrading RHIC

High luminosity and versatility

- *e*+*p* and *e*+A
- Variable center of mass energies (20-140 GeV)
- Beams with different A (up to Uranium)
- Polarized *e* and *p* beams



DATA TAKING: 2034++

A HOT & COLD EXCITING FUTURE AHEAD FOR QCD!

HOT & COLD QCD @ LHC

Only High-energy Heavy Ion Lab after RHIC conversion

HL-LHC to start in 2029 [Run 4: 2029-2032]

Facility/Year	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
LHC	LS2		Run 3				HL-LHC Upgrade			Run 4				LS4	
EIC			R&D and Design Phase							Construction & Installation				Commissioning & start of Operations	

COLD QCD @ EIC

Major advancement in the understanding of nucleons and nuclei structure

EIC to start data taking around 2034

A HOT & COLD EXCITING FUTURE AHEAD FOR QCD!

HOT & COLD QCD @ LHC

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Facility/Year
LHC
EIC



HOT & COLD QCD HAS A POP FUTURE AHEAD: TAKE PART!

COLD QCD @ EIC

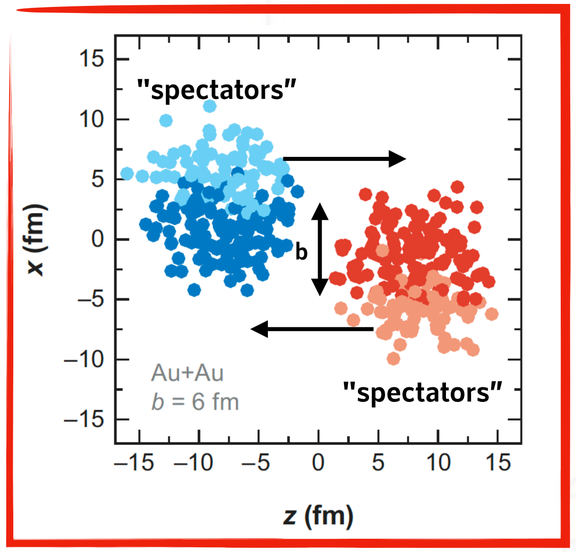
Major advancement in the understanding of nucleons and nuclei structure

EIC to start data taking around 2034

HOW TO TAG DIFFERENT TYPE OF HI EVENTS?

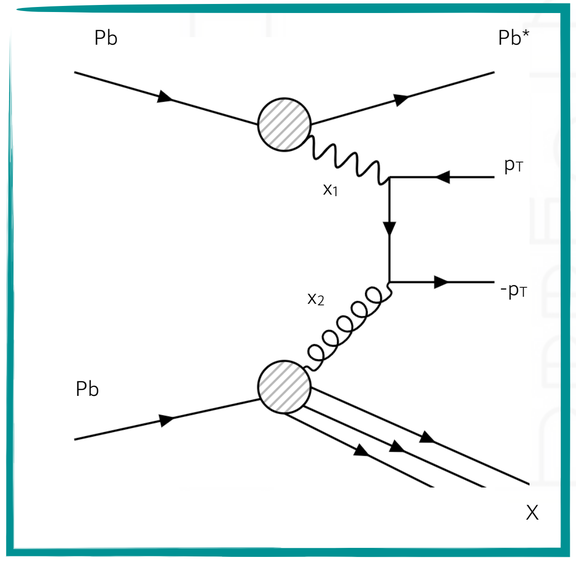
HADRONIC EVENTS

Nuclear debris in both beam directions (XnXn)

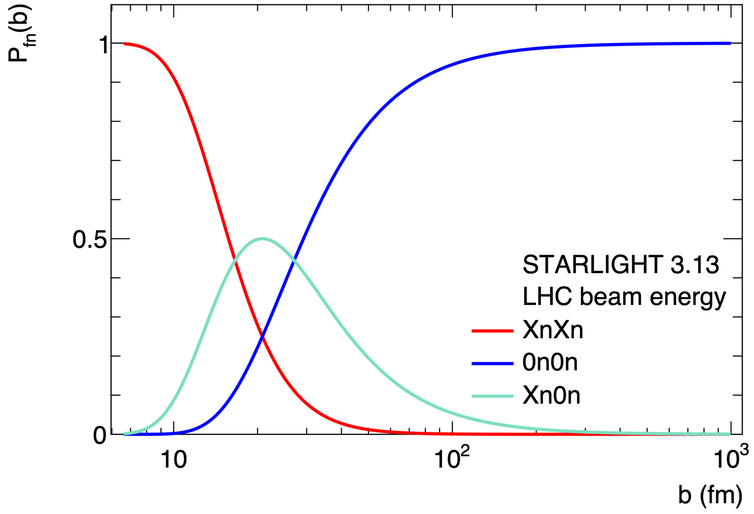


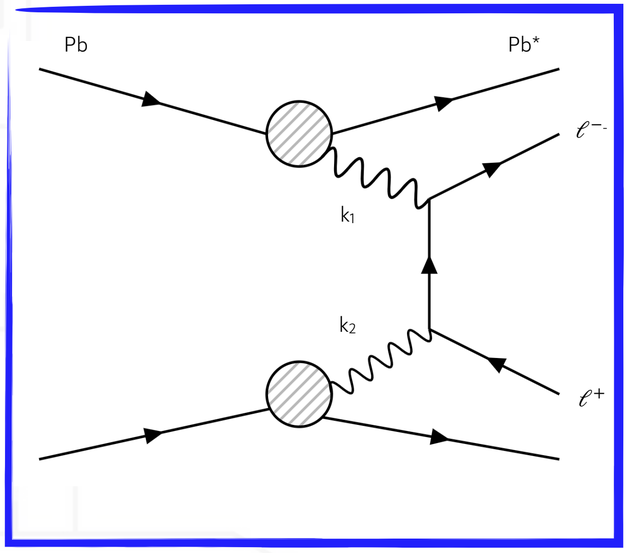
UPC EVENTS

Nuclear debris in one beam direction (XnOn)



S.Klein and P.Steinberg,
Ann.Rev.Nucl.Part.Sci. 70 (2020) 323-354

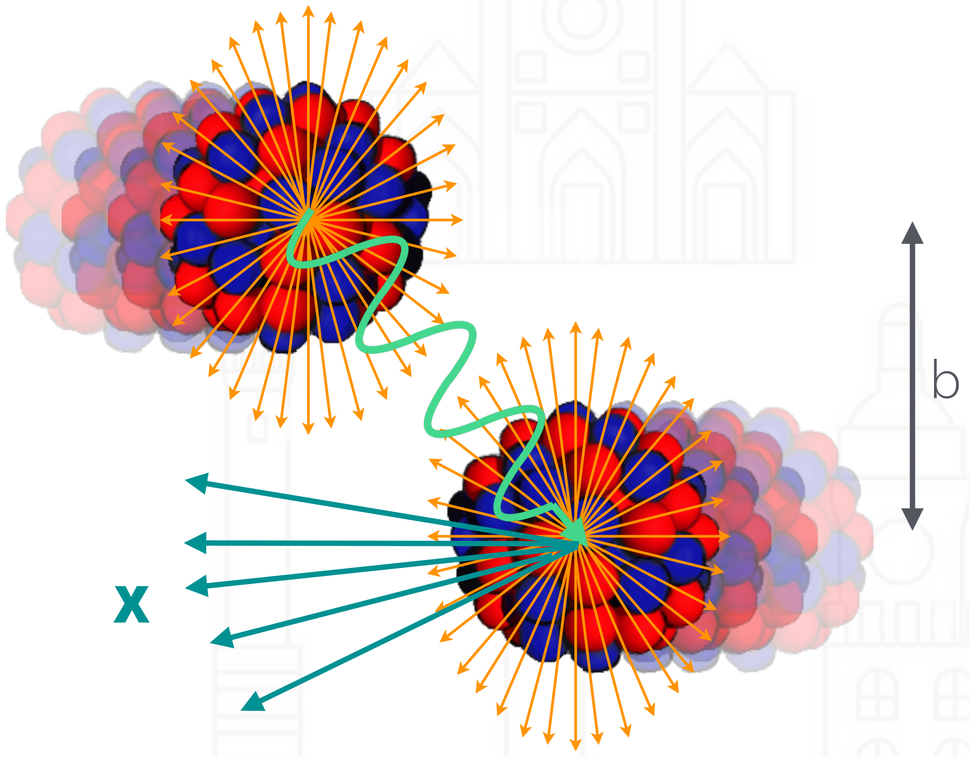




LIGHT-BY-LIGHT EVENTS

No nuclear debris (0n0n)

Heavy ions running @ LHC are also fantastic photon sources!



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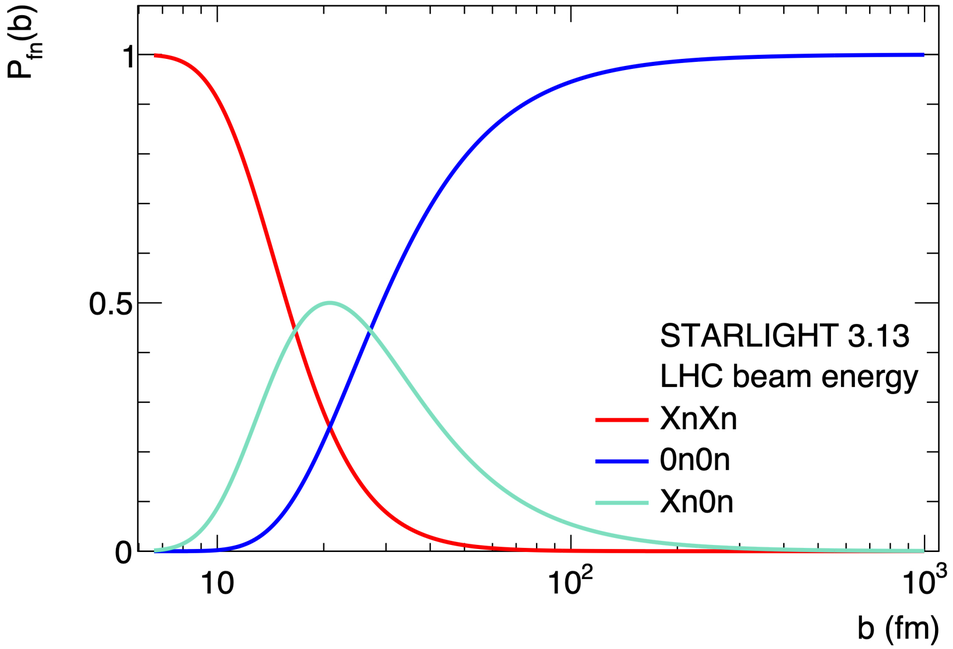
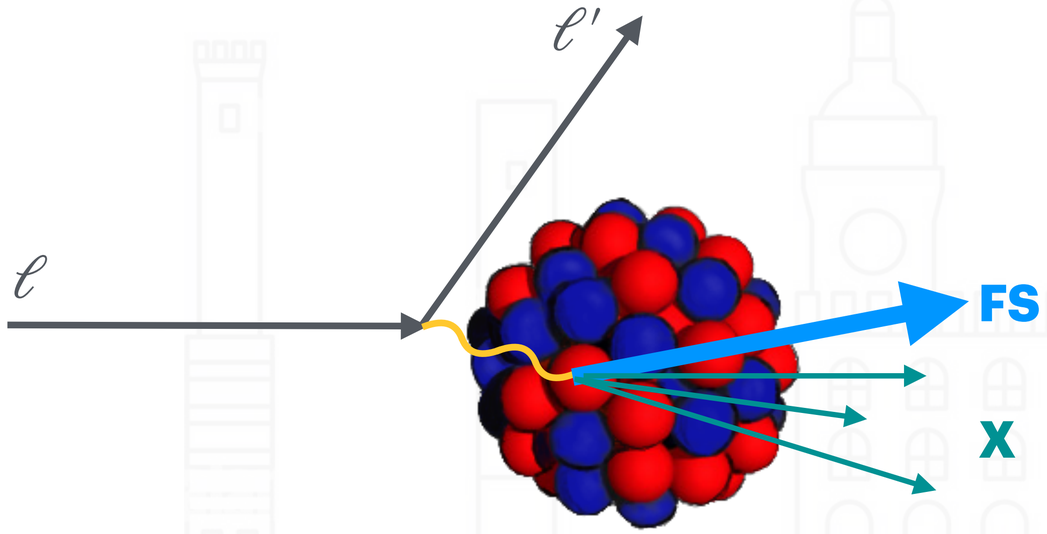


Quasi-real photon flux generated by each ion $\propto Z^2$

HADRONIC PROBE

Results at fixed target experiments were obtained using leptonic probes ($e^{\pm}$ or $\mu^{\pm}$)

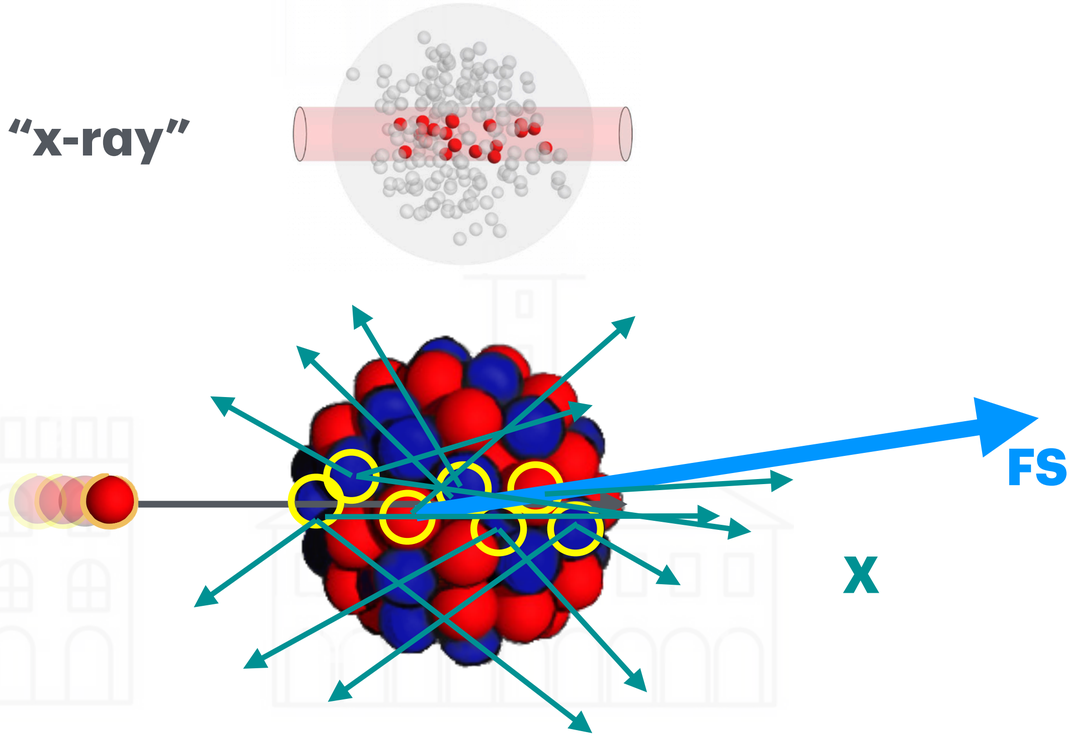
- **Low energy → high-x structure**
- **Only EM & Weak interactions**



$\ell + A$

LHC offers proton probes

- **Higher energy → access to low-x**
- **Multiple collisions between the projectile and the nucleus**



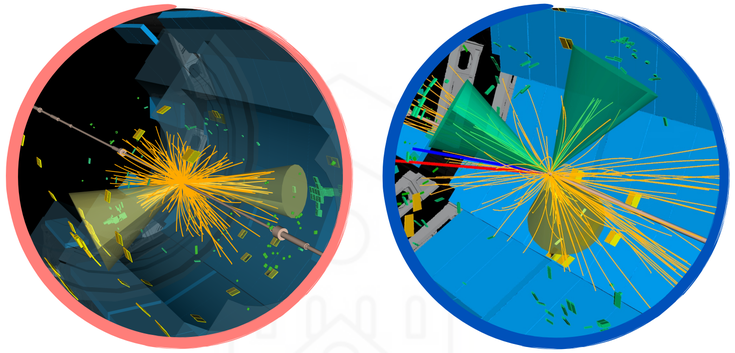
$p + A$

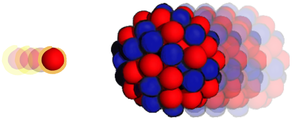
P+PB PHYSICS - IN A NUTSHELL

Lower underlying event compared to Pb+Pb, way closer to *p+p*



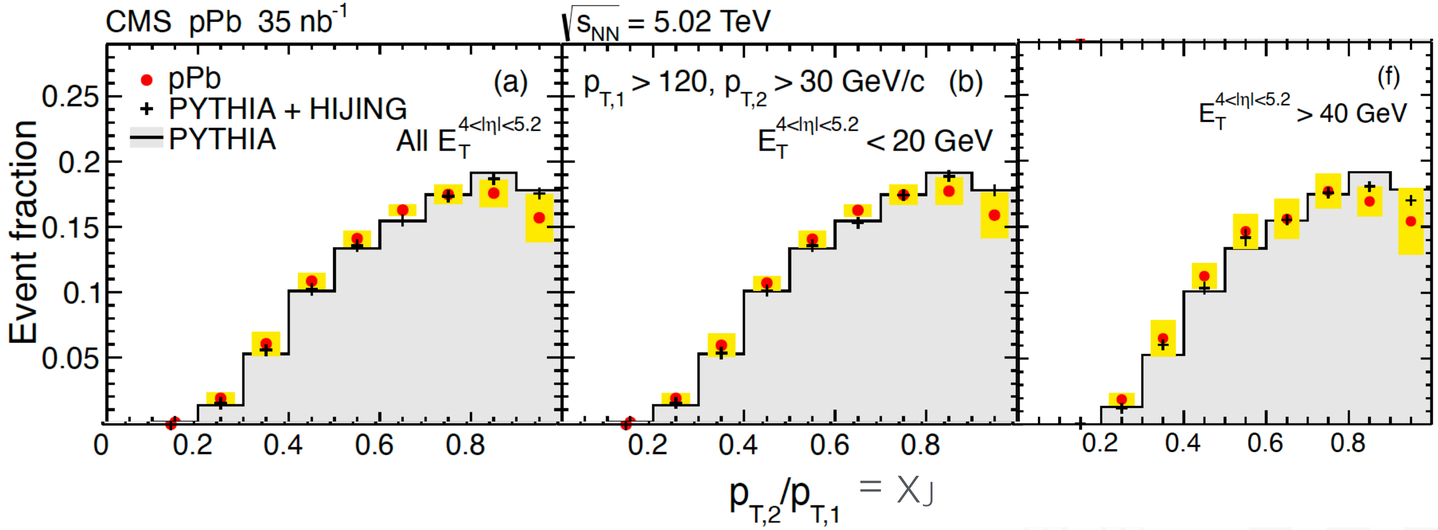
p+p @ 13 TeV





p+Pb @ 8.16 TeV

CMS, Eur. Phys. J. C 74 (2014) 2951



All Centralities

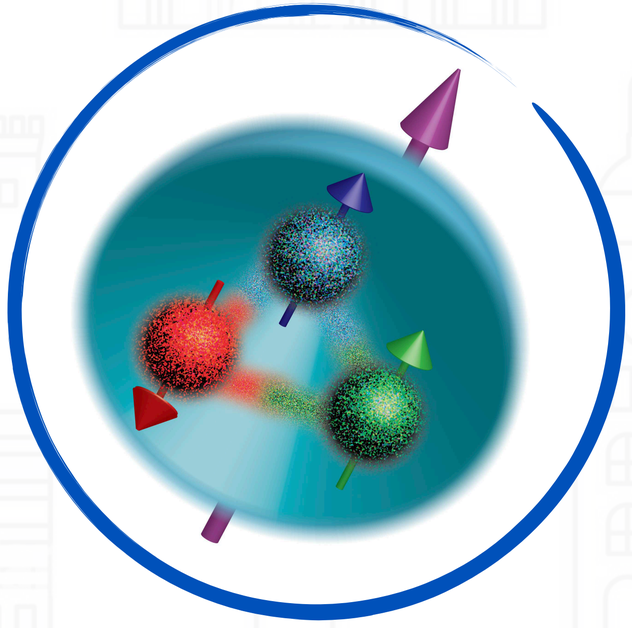


No sizable jet quenching signature observed

We can use the p as a probe for the nucleus w/o significant contamination of FS effects

THE PROTON: A QCD LABORATORY

We know very well the properties of the proton (charge, mass, size, spin etc), but how this relates to what is inside it?



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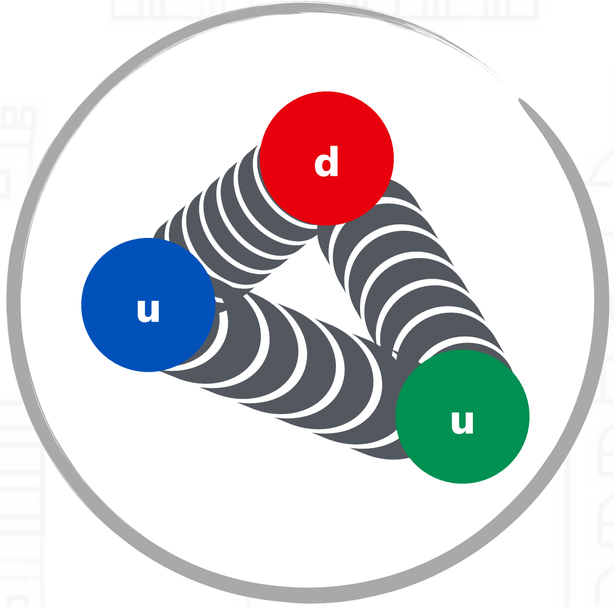

What if we try to knock off partons from the proton (e.g. with a high-energy EM probe)?

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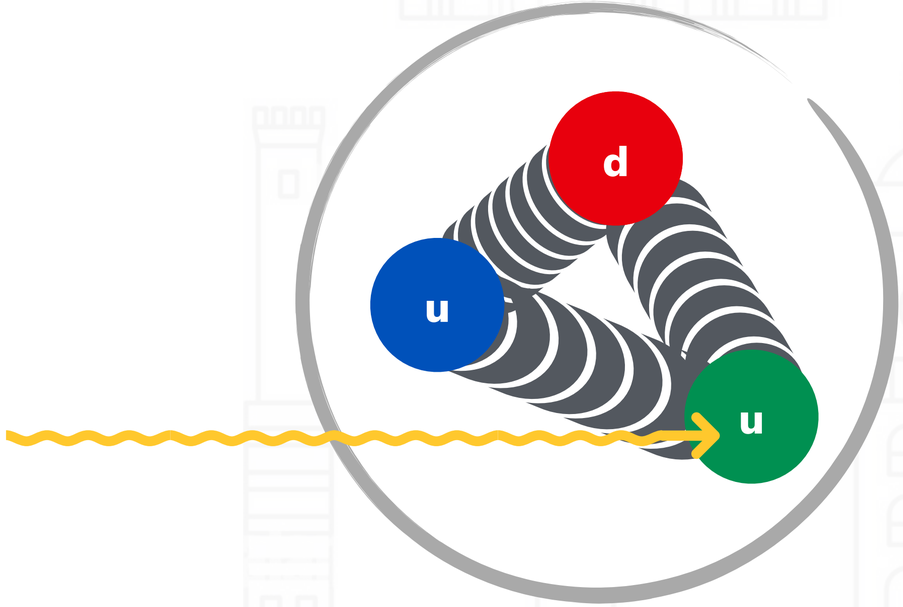

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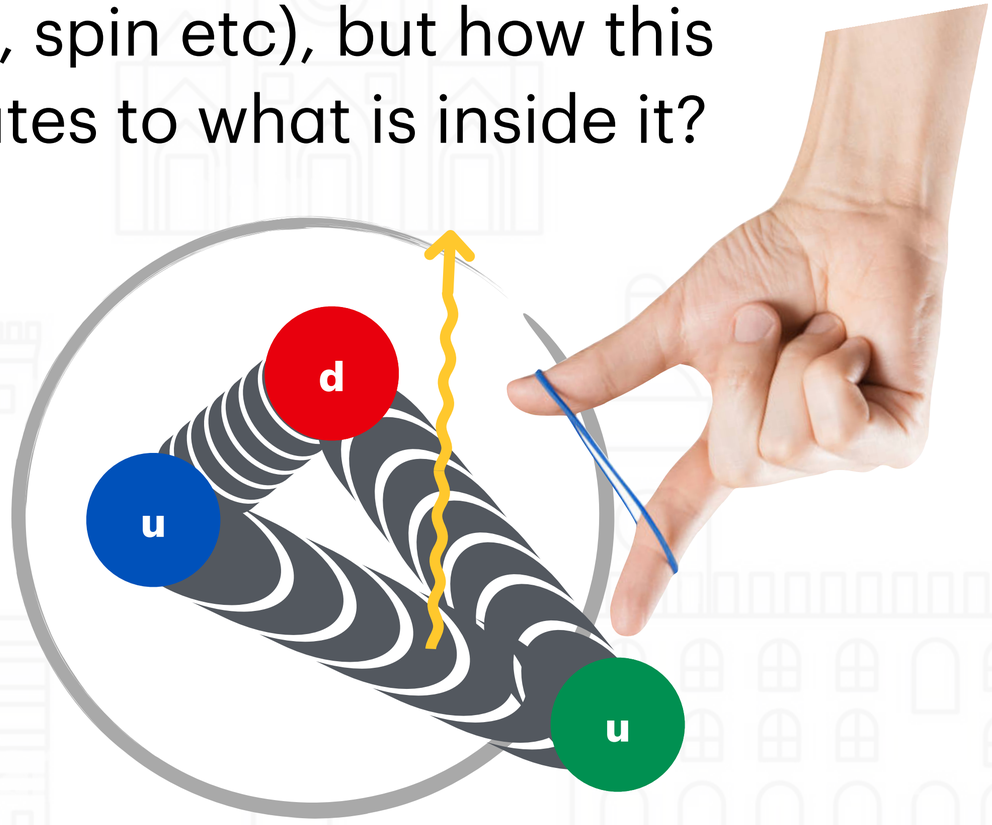

When the struck quark gets farther from the proton, energy increases ~ linearly with the distance

THE PROTON: A QCD LABORATORY

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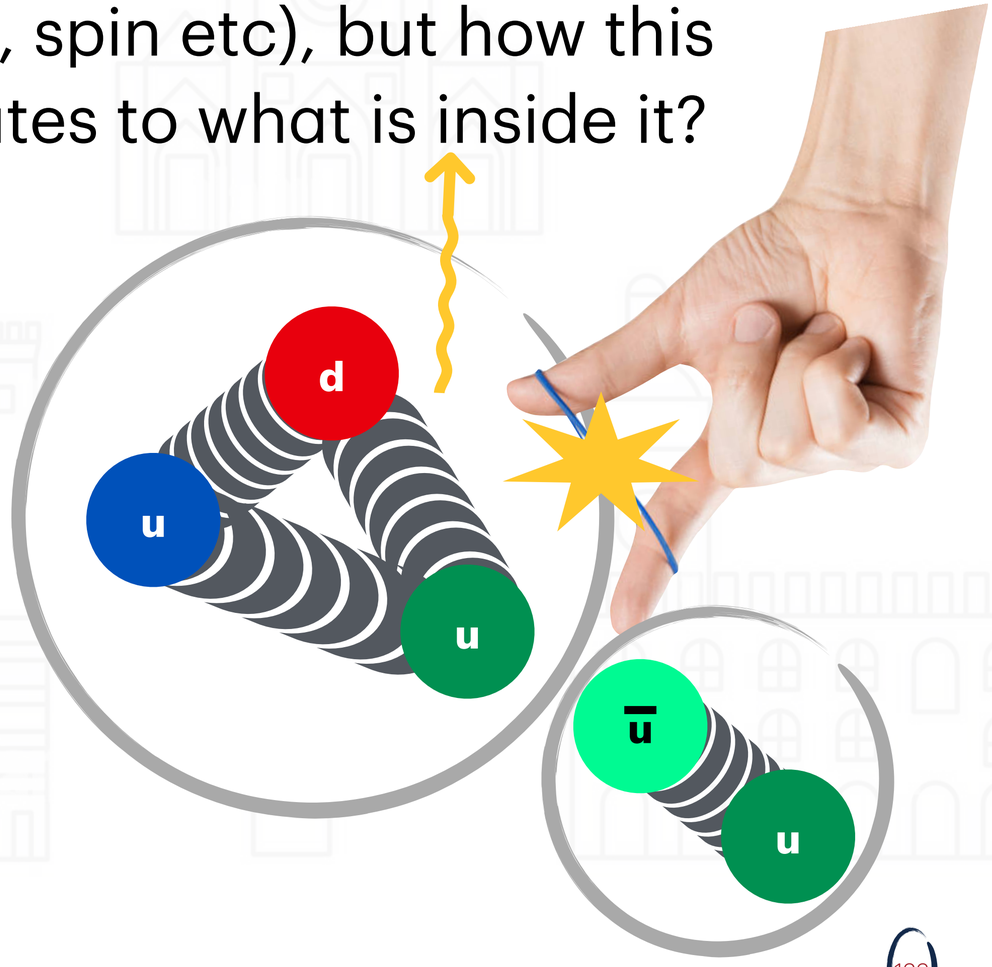


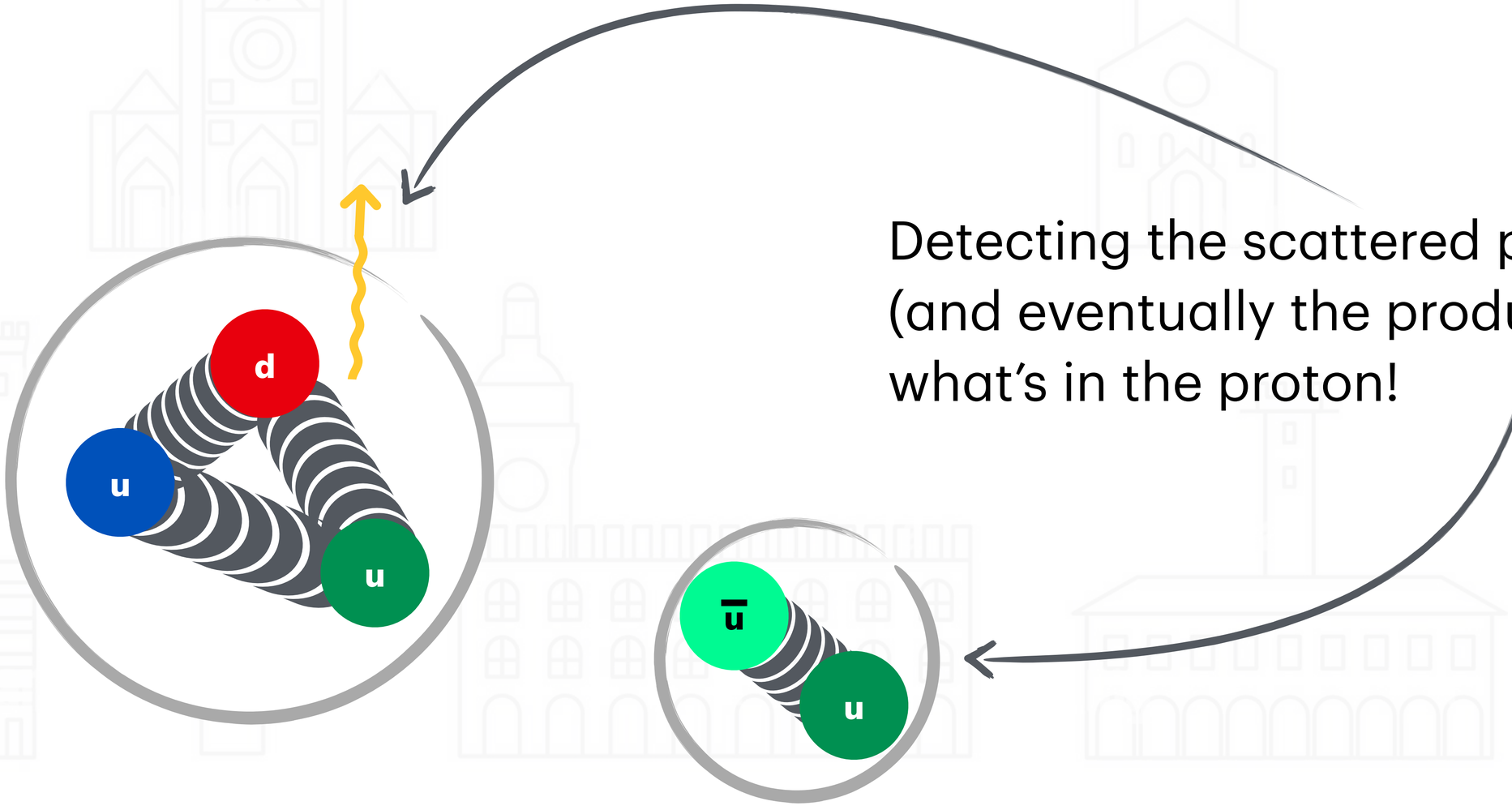
When the struck quark gets farther from the proton, energy increases ~ linearly with the distance

$E = mc^2$

Too much energy → convenient to extract a quark-anti quark pair from the vacuum!

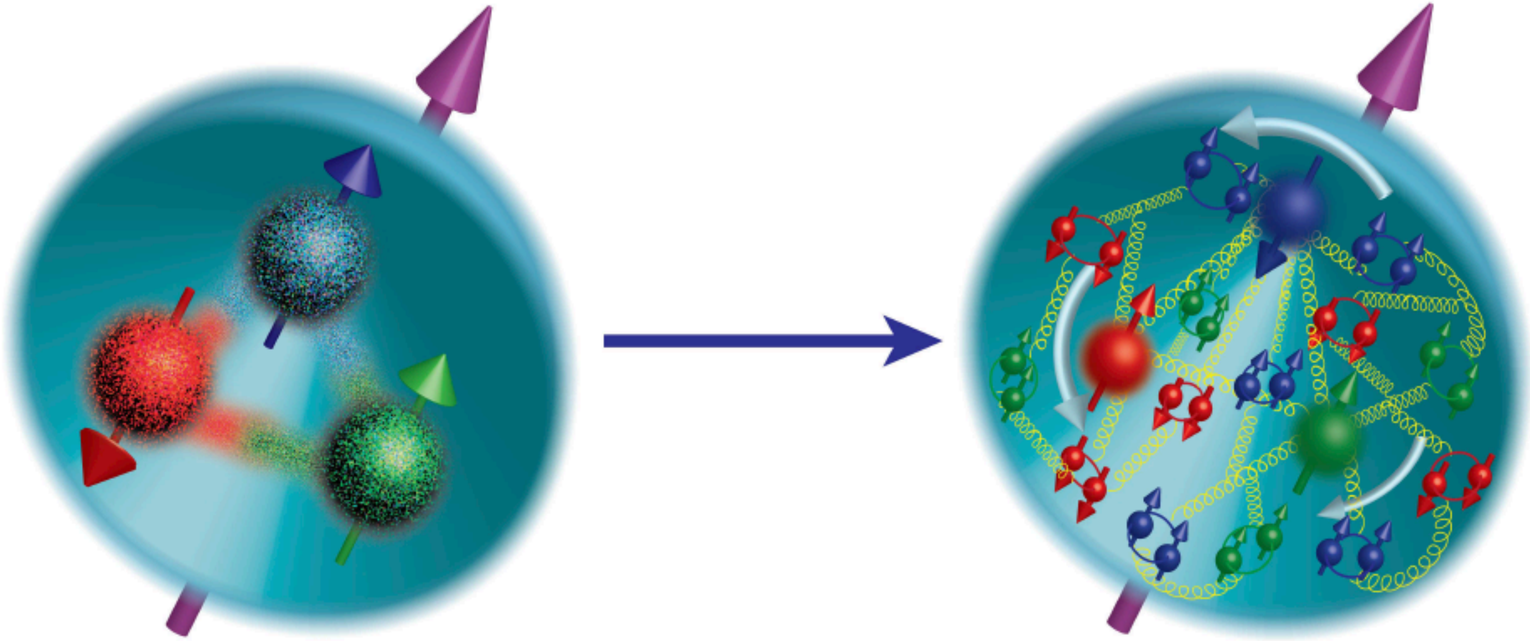
CONFINEMENT

THE PROTON: A QCD LABORATORY



Detecting the scattered probe (and eventually the products) we what's in the proton!

THE PROTON: WAY MORE THAN 3 QUARKS



Increasingly complex internal picture involving gluons, sea quarks, spin, angular momentum

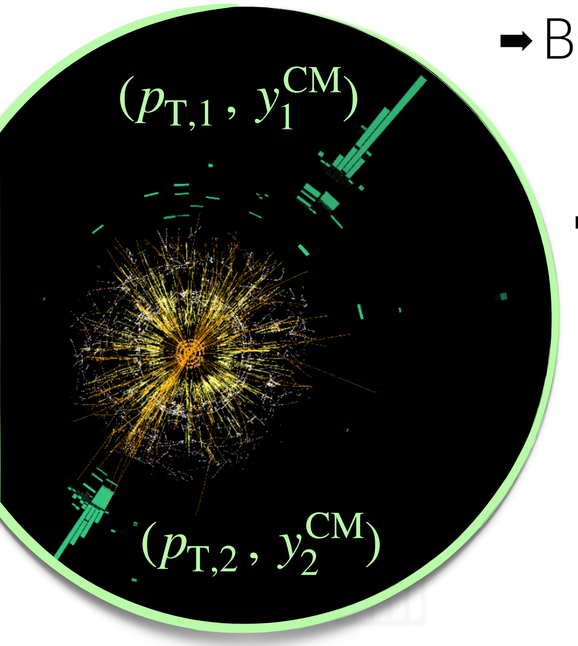
DIJETS AS PROXIES TO THE INITIAL STATE

- Measurement of the centrality-dependence of the **triple differential** per-event dijet yield using ATLAS $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV data

$$\frac{1}{N_{\mathrm{evt}}^{\mathrm{cent}}} \frac{\mathrm{d}^3 N_{\mathrm{dijet}}^{\mathrm{cent}}}{\mathrm{d}p_{\mathrm{T,Avg}} \mathrm{d}y_{\mathrm{b}} \mathrm{d}y^*}$$

➡ Average transverse momentum: $p_{\mathrm{T,Avg}} = \dfrac{p_{\mathrm{T},1} + p_{\mathrm{T},2}}{2}$

➡ Boost of Dijet System: $y_{\mathrm{b}} = \dfrac{1}{2}(y_1^{\mathrm{CM}} + y_2^{\mathrm{CM}})$



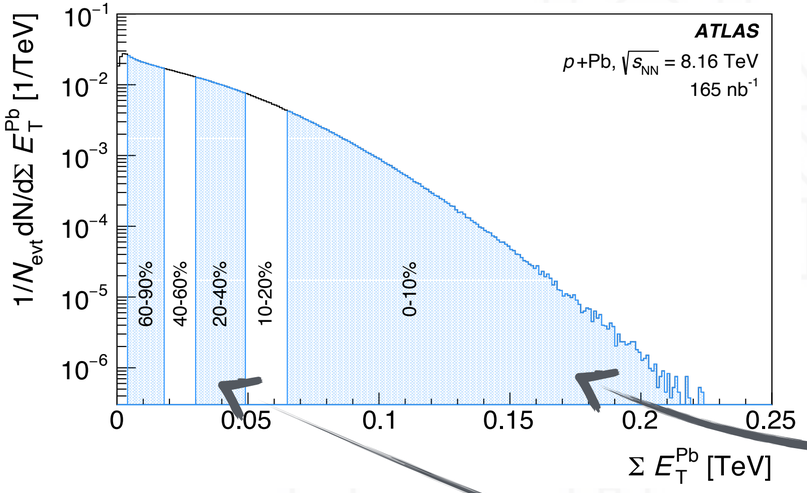
➡ Dijet Half Rapidity Separation: $y^* = \dfrac{1}{2}|y_1^{\mathrm{CM}} - y_2^{\mathrm{CM}}|$

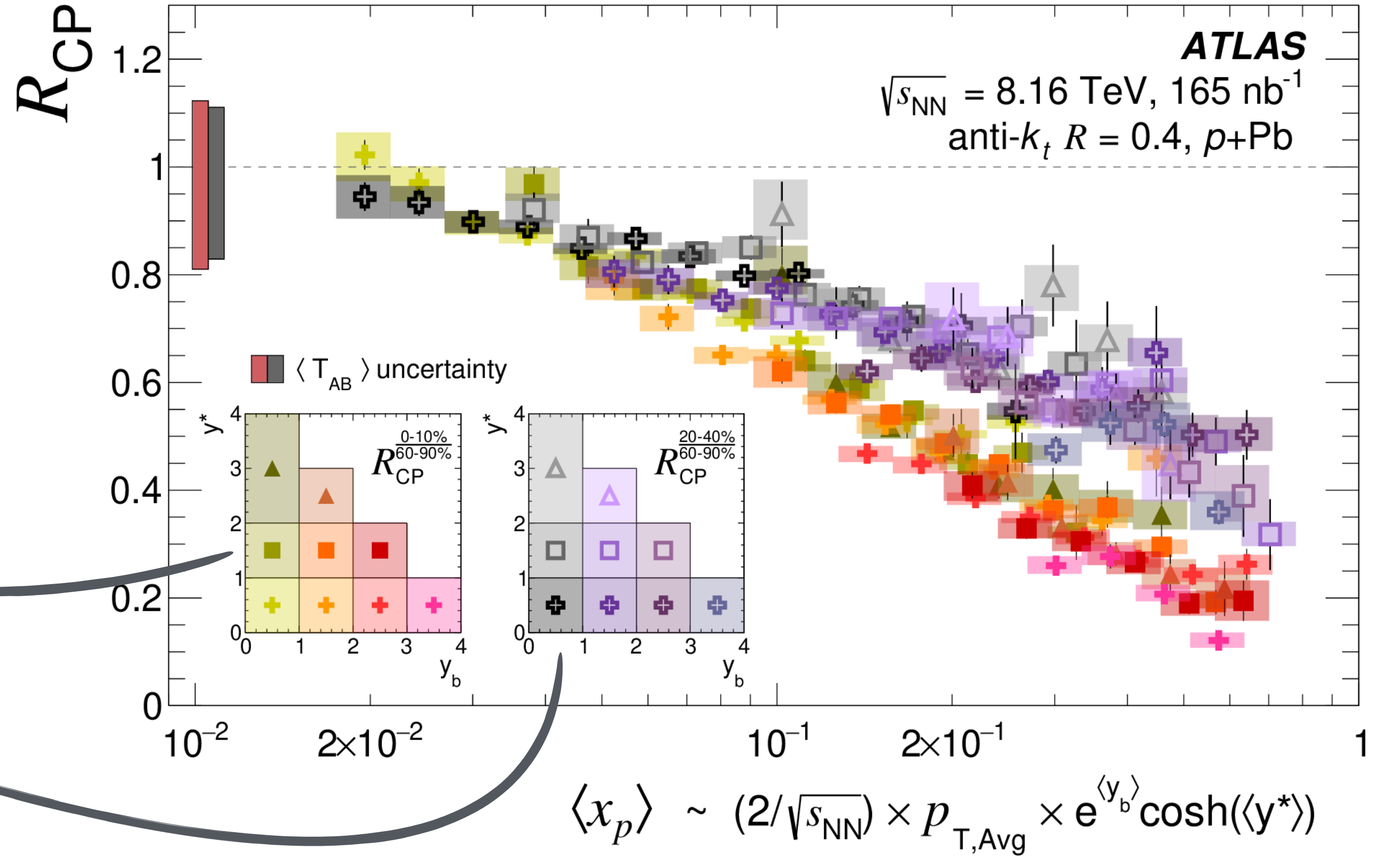
- 3D measurement provides **access to partonic system kinematics**

$$x_{\mathrm{p}} \simeq \frac{2p_{\mathrm{T,Avg}}}{\sqrt{s}} e^{y_{\mathrm{b}}} \cosh y^*,$$

$$x_{\mathrm{Pb}} \simeq \frac{2p_{\mathrm{T,Avg}}}{\sqrt{s}} e^{-y_{\mathrm{b}}} \cosh y^*$$

DIJET IN P+PB: BONUS TRACKS



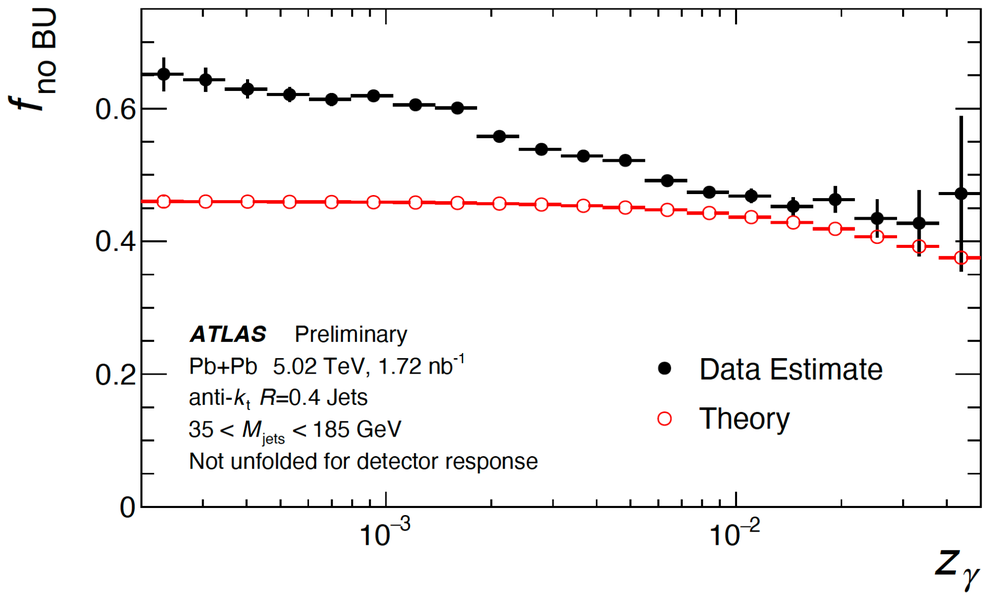


$$\langle x_p \rangle \sim (2/\sqrt{s_{NN}}) \times p_{T,Avg} \times e^{\langle y_b \rangle} \cosh(\langle y^* \rangle)$$

- R_{CP} also extracted for mid-central collisions to peripheral
- Trend confirms log-linear dependence from x_p but with a more tamed slope (as expected)

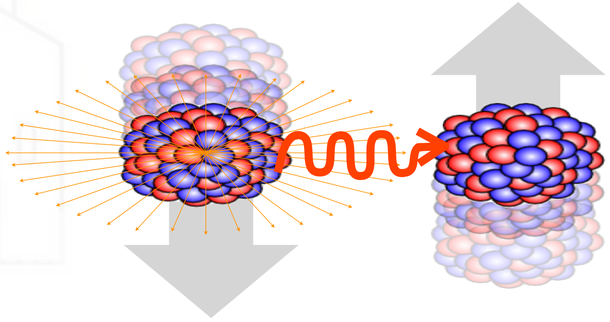
XN XN EVENTS

- Photo-nuclear jet events requirements select events with high-energy photons
  - $E_\gamma \propto 1/b$ ➡ Bias toward lower impact parameter of the collisions

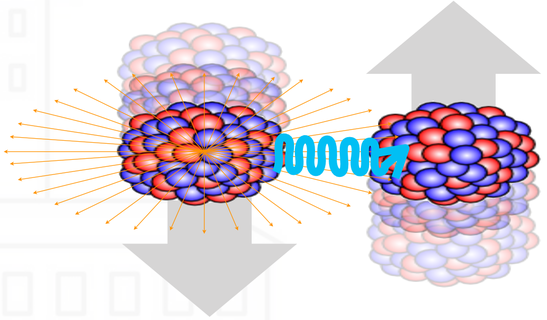


$$f_{\text{no BU}} \equiv \frac{\mathrm{d}\sigma/\mathrm{d}z_\gamma|_{0nXn}}{\mathrm{d}\sigma/\mathrm{d}z_\gamma|_{XnXn} + \mathrm{d}\sigma/\mathrm{d}z_\gamma|_{0nXn}}$$

Studies of dijet events with large gaps on one side estimate about 50% of photo-nuclear jet production breaks up!

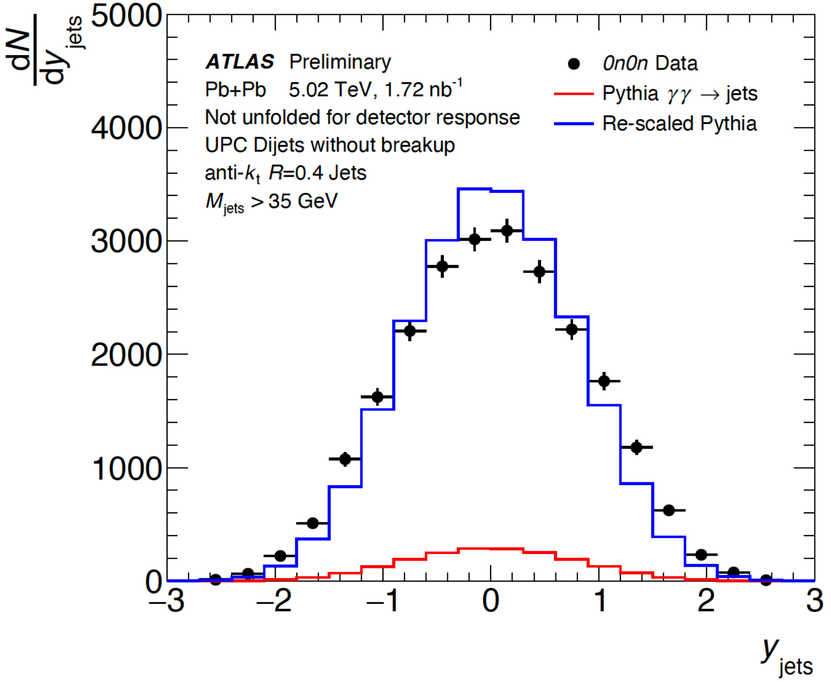


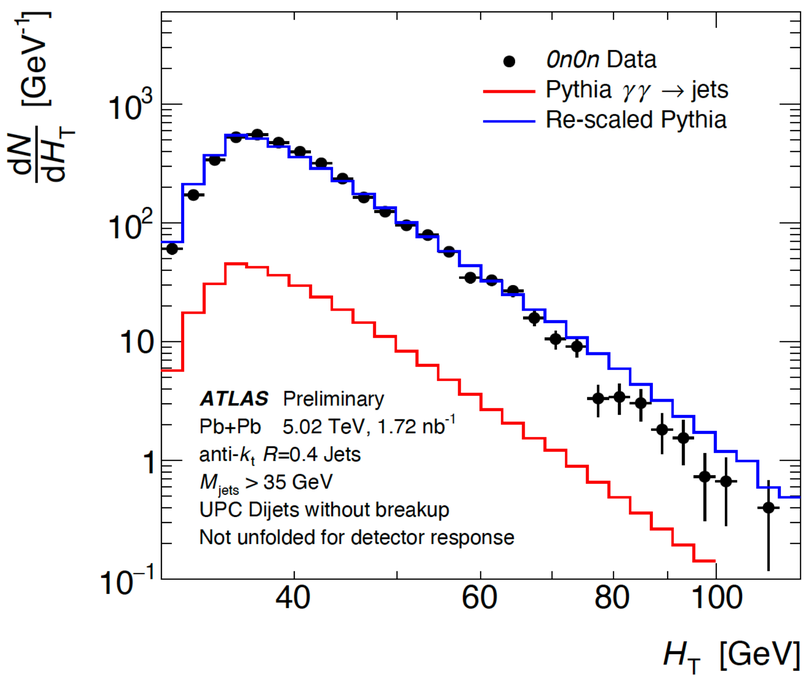
Basic theoretical modeling predicts an even higher rate

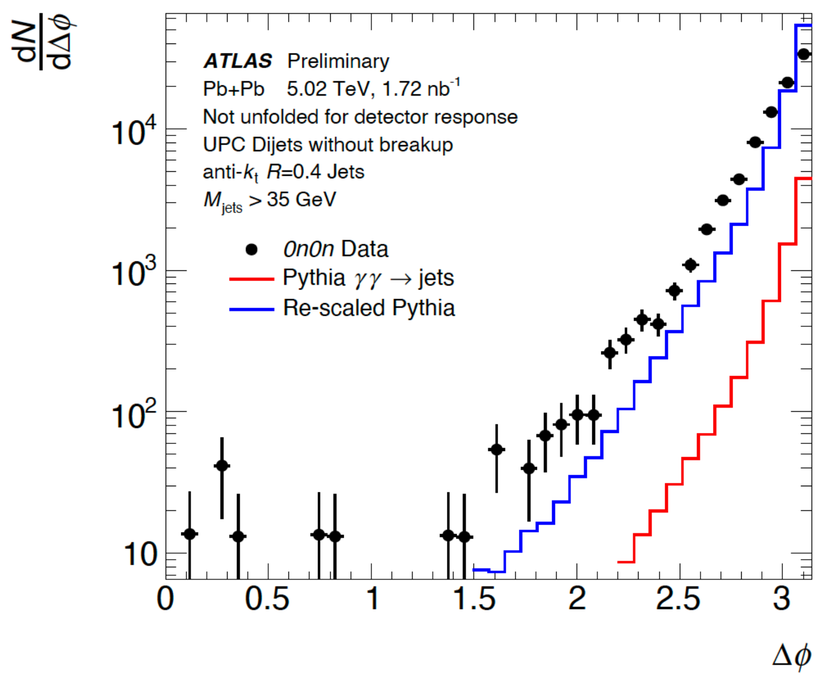


DIJET PRODUCTION W/O NUCLEAR BREAKUP

- Tagged requiring 0n0n pattern in the ATLAS ZDC and gaps on both side of the detector
- Originated by $\gamma\,\gamma$ scattering or diffractive photo-production
- A factor of 10 more events are observed in data than are predicted from $\gamma\,\gamma$ →jets, estimated by Pythia







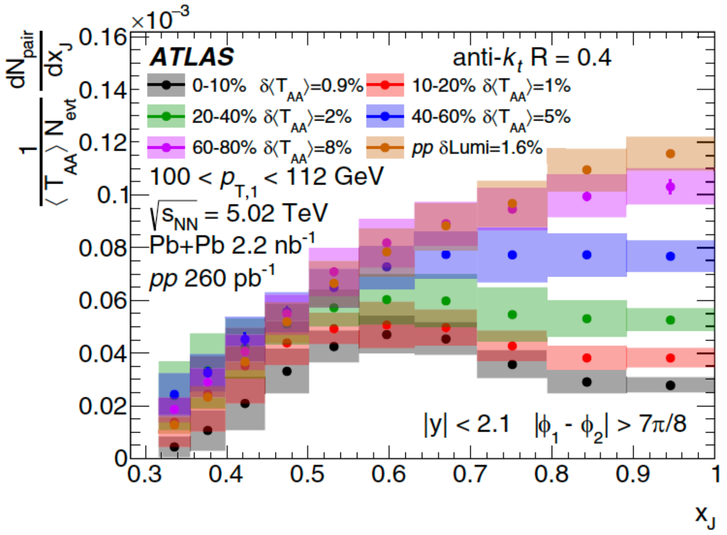
MODELING OF NUCLEAR BREAKUP

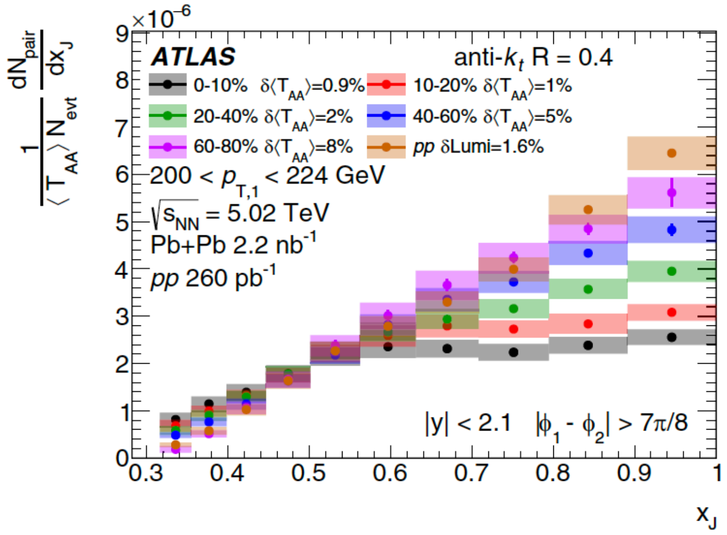
- Pythia8 allows for generation of γ+A collisions
  - The photons is taken from the equivalent flux of a lepton or a nucleon beam
  - Photon energy distribution treated as an attribute of one of the incident beams and not a feature of the full collision system → can't fully describe UPC

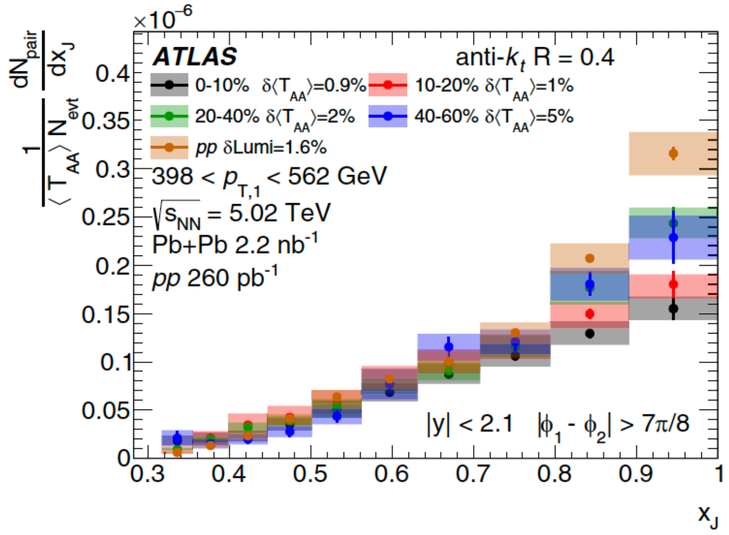
$$F^{\text{eff}}_{\gamma/A}(E_\gamma) \equiv \int \mathrm{d}^2 b \mathrm{d}^2 s_A P_{\text{no had}}(b) P_{\text{no EM}}(b) f_{\gamma/A}(E_\gamma, s) T_B(\vec{s}_A - \vec{b})$$

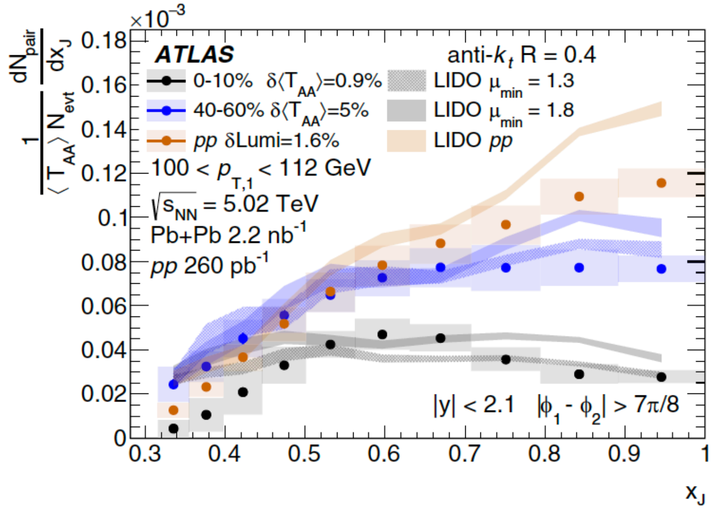
- New integrated flux factor introduced to improve comparison with data. It includes:
  - **Integration over** A-A impact parameter (***b***) and impact parameter relative to the photon emitting nucleus ($\mathbf{s_A}$)
  - Correction for the probability of no **hadronic** or **electromagnetic breakup** occurs (from STARlight)
  - Correction to Pythia8 point source treatment to turn it into **coherent nuclear emission.**
  - **Nuclear thickness function**

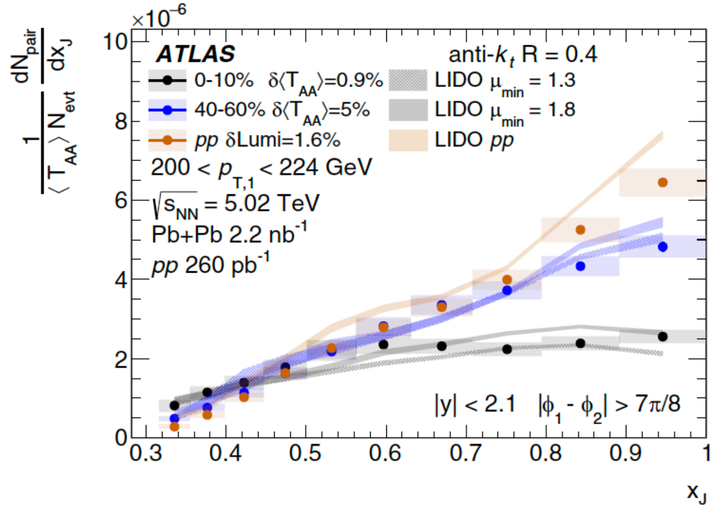
DIJET ASYMMETRY

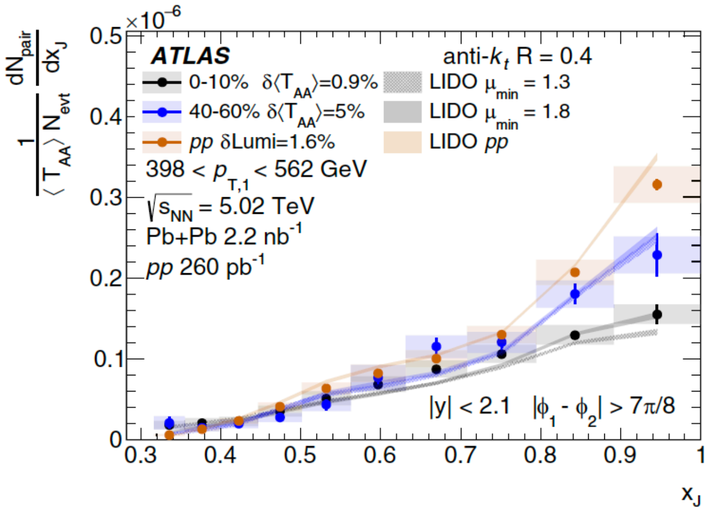








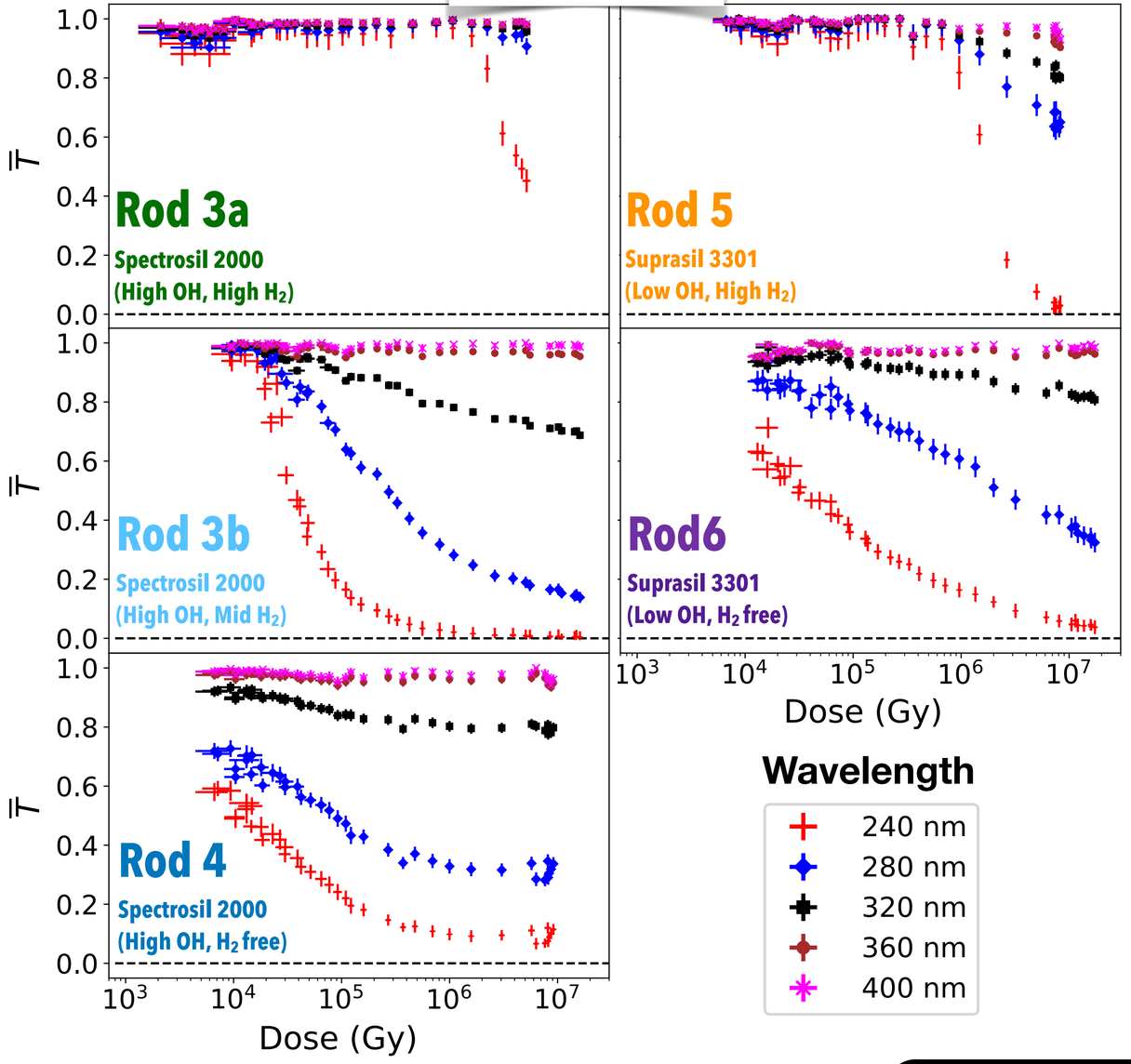




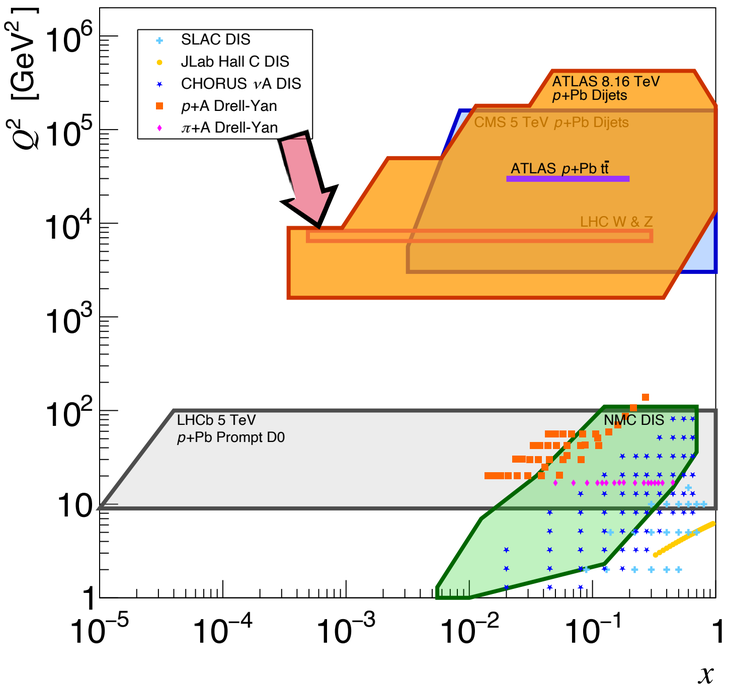
R&D PAPERS



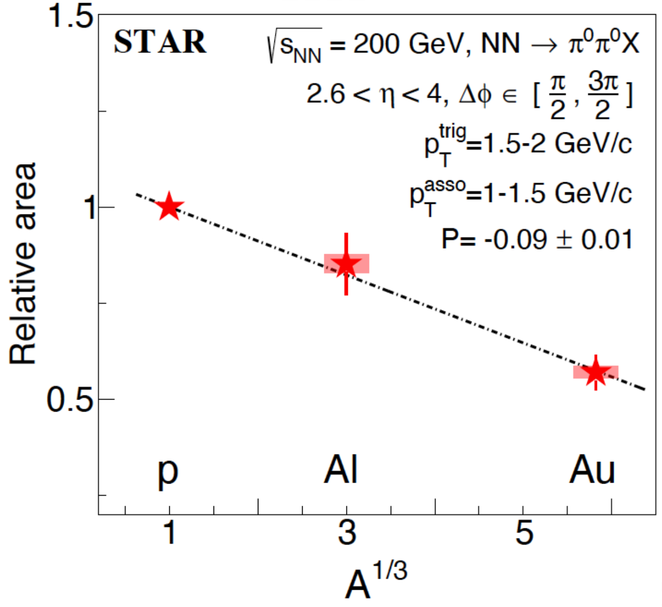
- Collaboration between joint ZDC upgrade project, **CERN FLUKA and BRAN groups**, and **Heraeus Conamics** to investigate radiation hardness of Run 4 forward detector components:
  - First characterization of radiation hardness of different fused silica materials up to MGy scale vs wavelength, dose, and material doping **Nucl.Instrum.Meth.A 1055 (2023) 168523** ⟶
  - First benchmarking of the description of ^{22}Na activation in FLUKA simulations, **Phys.Rev.Accel.Beams 25 (2022) 5, 053001**
- New irradiation campaign (x10++ increase) ongoing in Run 3 and at Soreq reactor [Israel]
  - 2-3 additional publications expected in 2-3 years



DIJETS AS PROBES FOR GLUON SATURATION

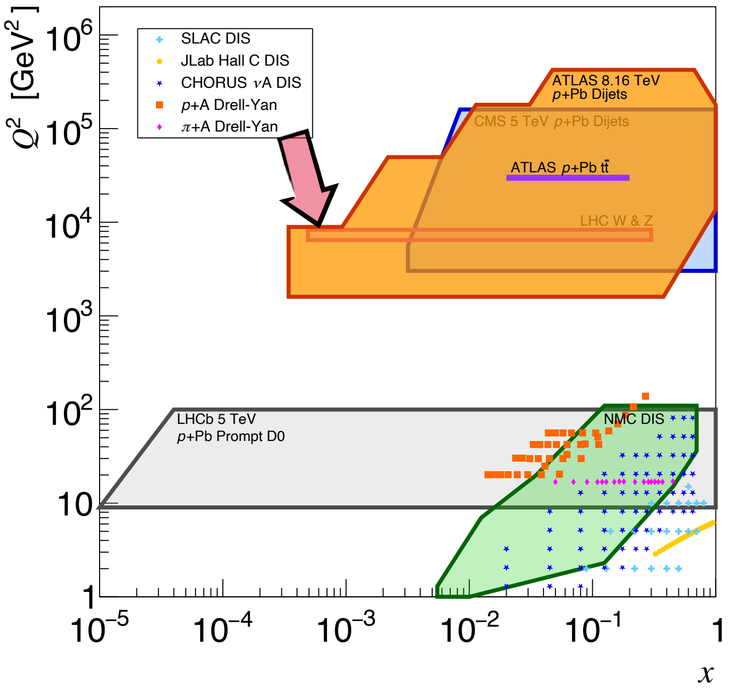


- **Dijets in *p*+Pb** @ ATLAS explore a **broad (x,Q²) phase space**
- MultiD extraction of dijet cross-section from the 8.16 TeV data sample would bring major advancements to nPDFs parametrization
- The dijet cross-section extracted at forward rapidities can also be used to search for onsets on gluon saturation
  - The strength of the non-linearity responsible for taming the gluon distribution is supposed to depend on the size of the target (~$A^{1/3}$)



PRL 129, 092501 (2022)

DIJETS AS PROBES FOR GLUON SATURATION



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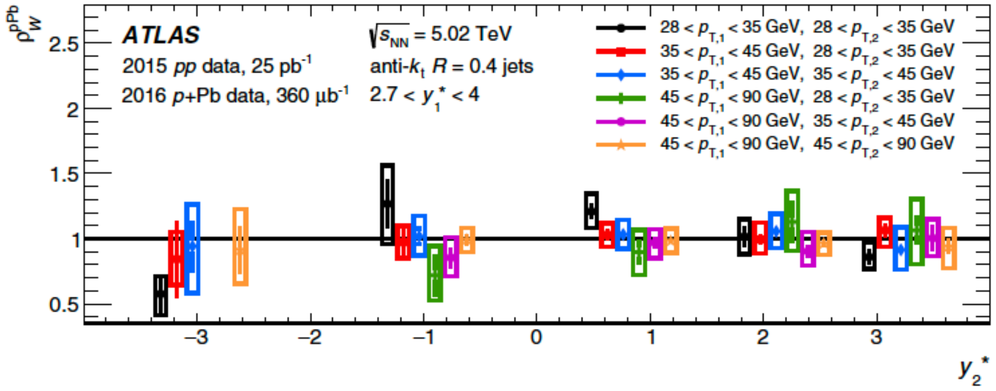
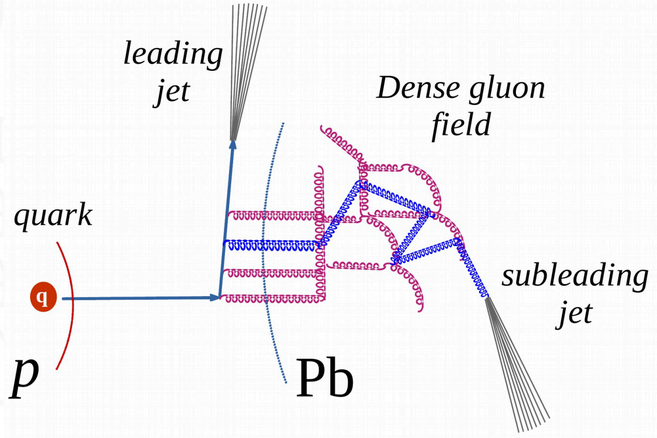
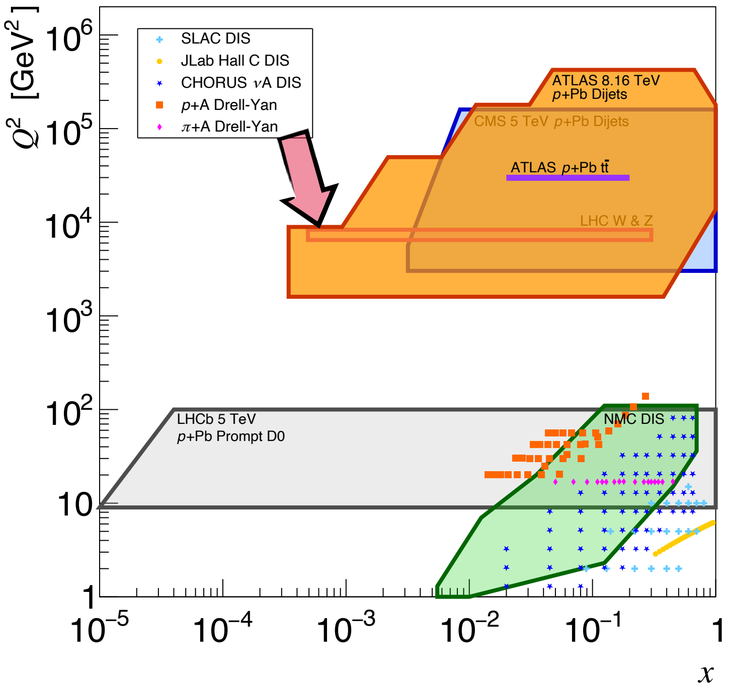




- **Azimuthal broadening** due to the interaction of the knock-out gluon w/ the dense gluon field before emerging and forming the jet [**arXiv:2210.06613**]

DIJETS AS PROBES FOR GLUON SATURATION



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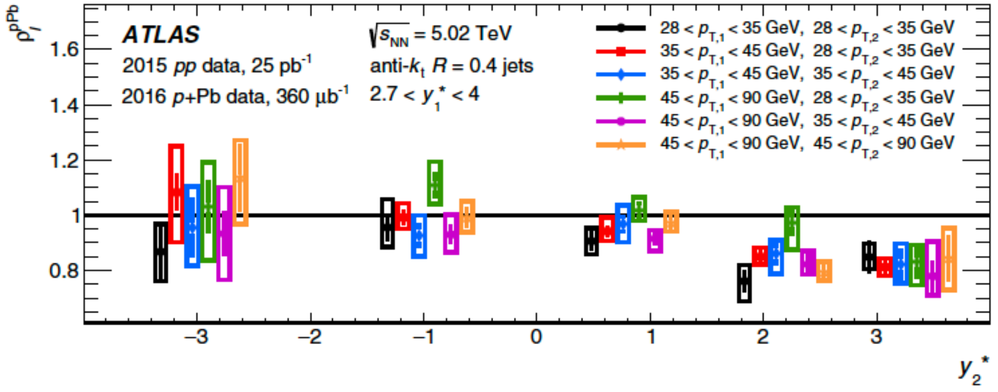
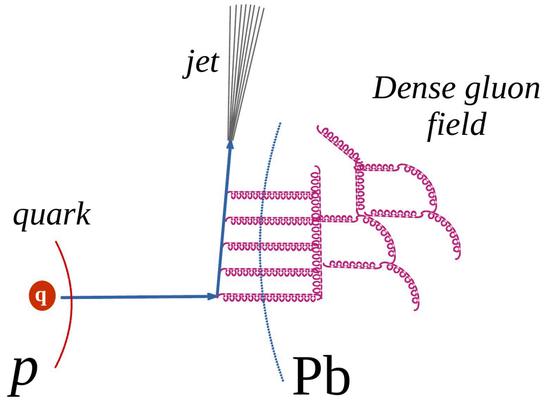




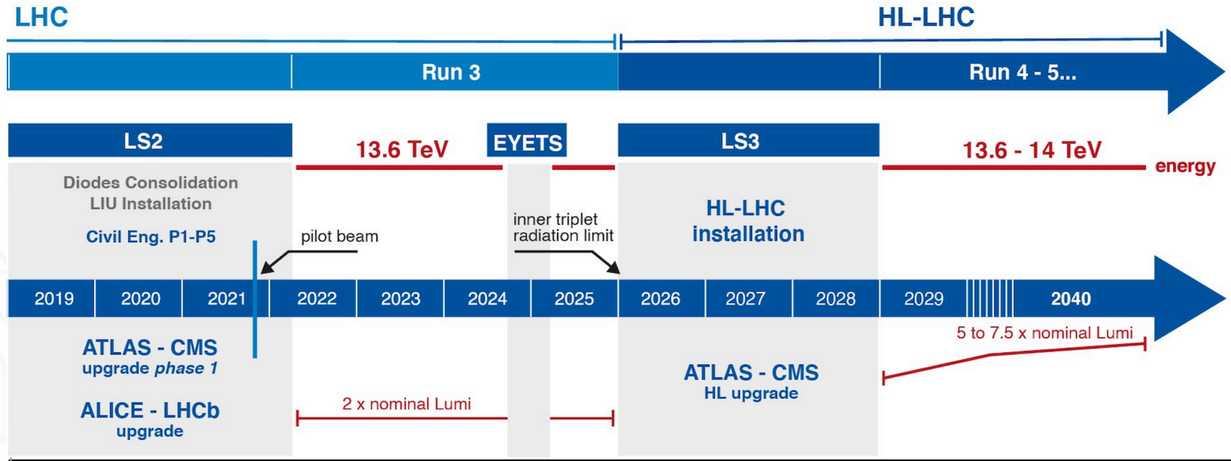
- **Monojet signature** due to coherent scattering of the incoming parton over the dense nucleon field [**Nuc.Phys.A, Volume 748, Issues 3–4**]

Phys. Rev. C 100, 034903

A HOT N COLD AND EXCITING FUTURE AHEAD...

HOT QCD

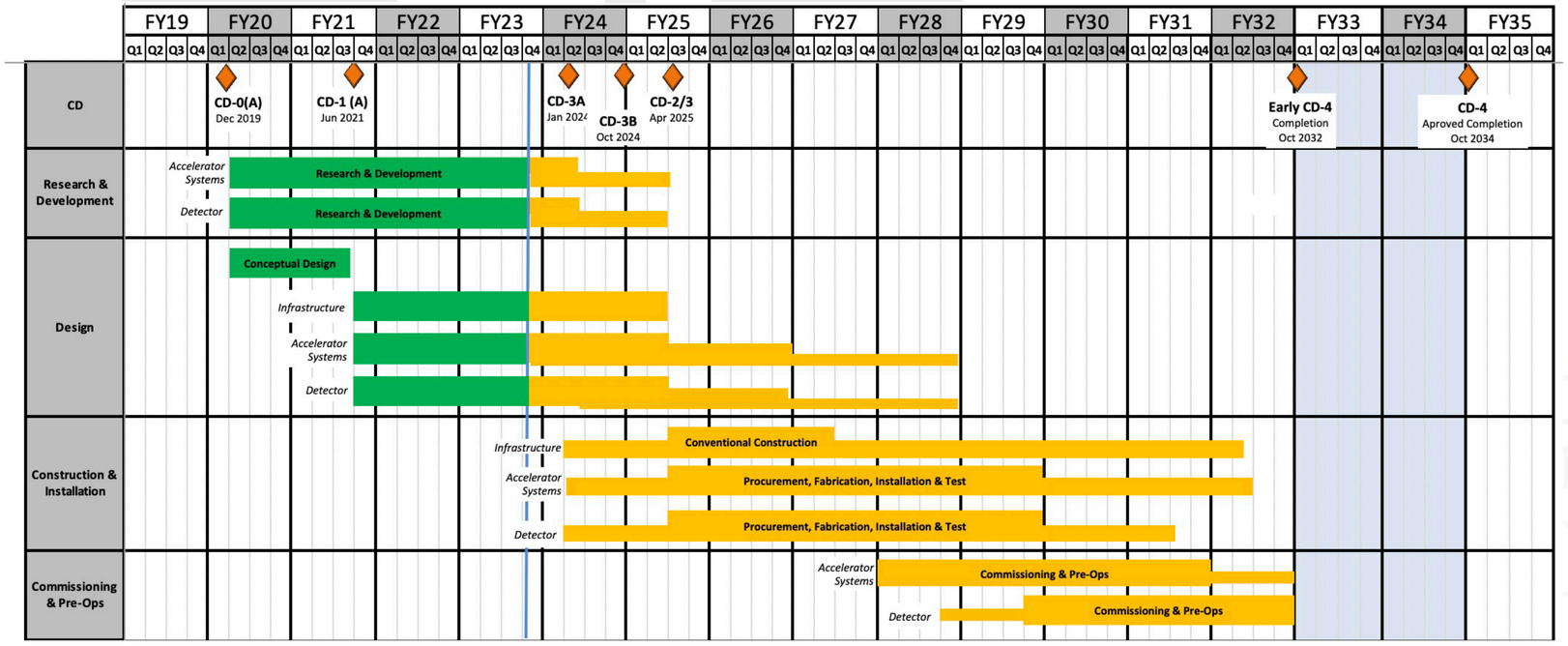
Only High-energy HI Lab after RHICH conversion



HL-LHC to start in 2029 [Run 4: 2029-2032]

COLD QCD

Major advancement in the understanding of nucleons and nuclei structure



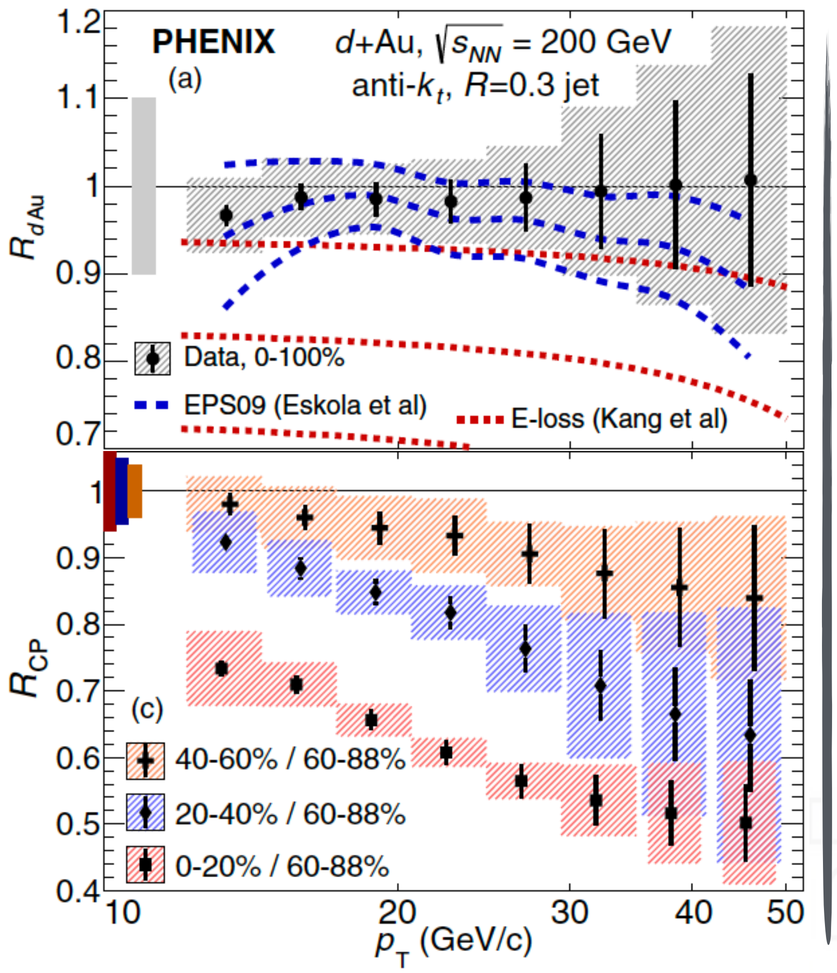
EIC to start data around 2034

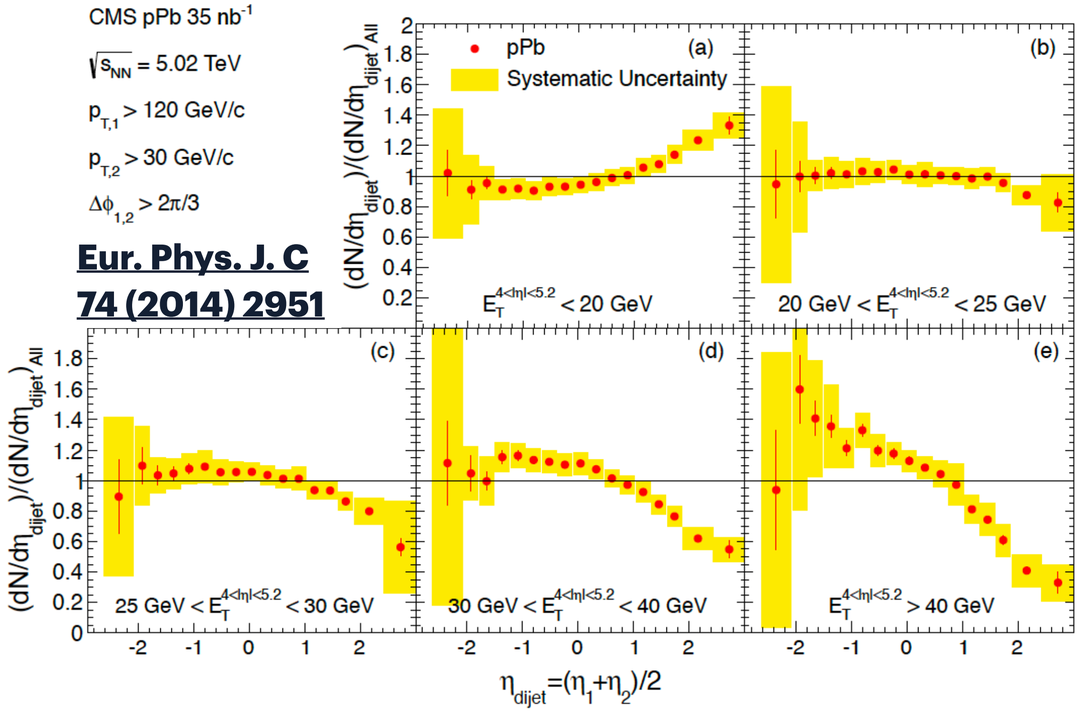
SIMILAR OBSERVATIONS BY OTHER EXPERIMENTS

PHENIX

d+Au @ 200 GeV

PRL 116, 122301 (2016)





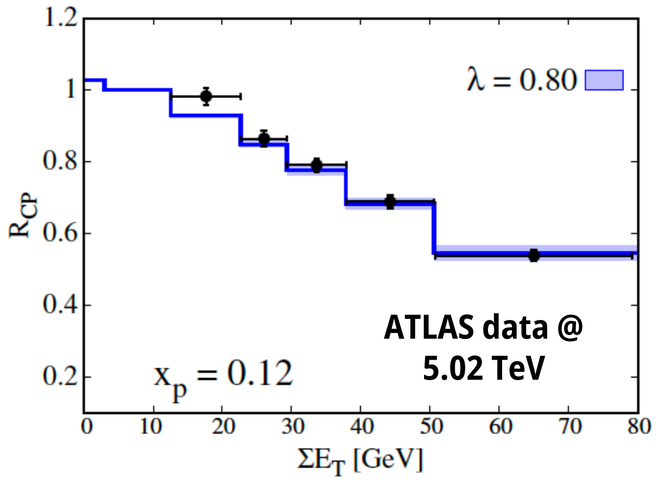
CMS

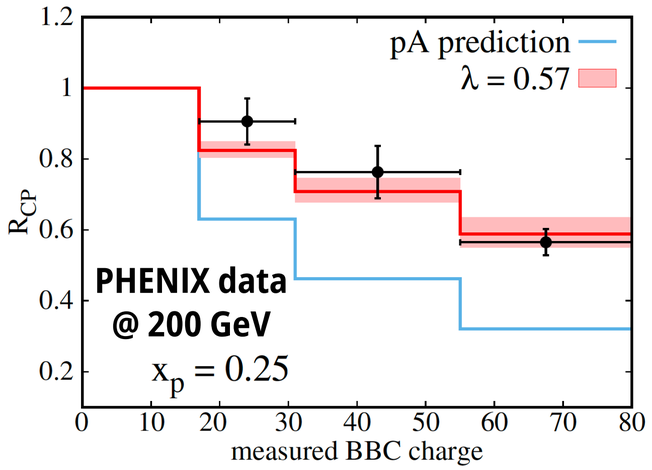
- Dijet measurement, but only 1D → **no access to the initial state kinematics**
- Not conventional R_{CP} definition

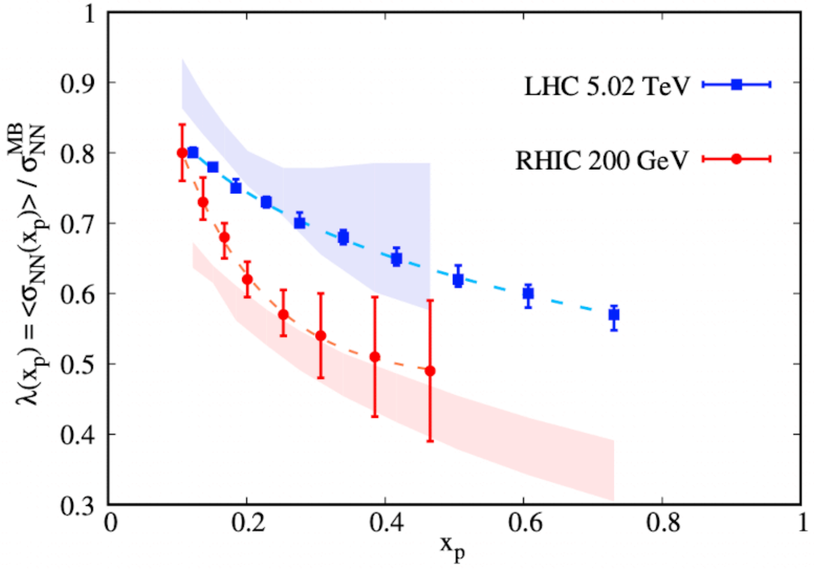
Both measurements qualitatively compatible w/ ATLAS' one. No additional breakthroughs

IS THE PROTON SIZE FLUCTUATING?

- Alternative approach to explain the results proposed by Alvioli et al., **PRD 98 (2018) 071502**
- ***Manifestation of color fluctuations:*** *p* containing a parton with large x are characterized by smaller-than-average configurations, associated to **smaller than average interaction strength**
- Successful modeling of both ATLAS and PHENIX data introducing an x_p-dependent shrinking of the average interaction strength at a given collision energy: $\lambda(x_p) = \langle\sigma_{NN}^{MB}\rangle(x_p)/\sigma_{NN}^{MB}$

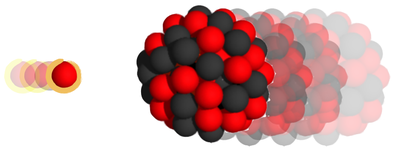






ATLAS JETS IN p+Pb @ 5.02 TEV

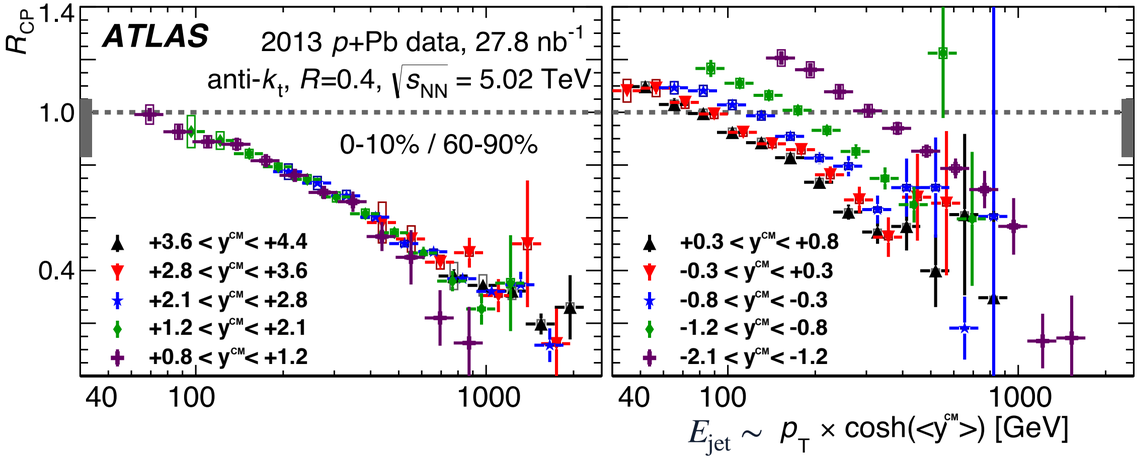
4 TeV p → ← 1.57 TeV/N Pb



Asymmetric collision system

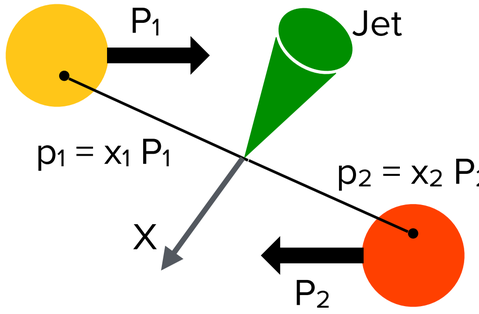
CM system != Lab

$y^{CM} = y_{Lab} - 0.465$



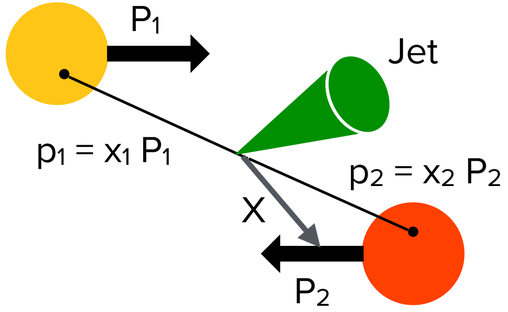
Results found to scale with the jet energy at mid-forward rapidities!

The Observed scaling suggests relation to initial state kinematics



CM system if $x_1 \sim x_2$

High-energy forward jets are more likely to be produced by high x_p events

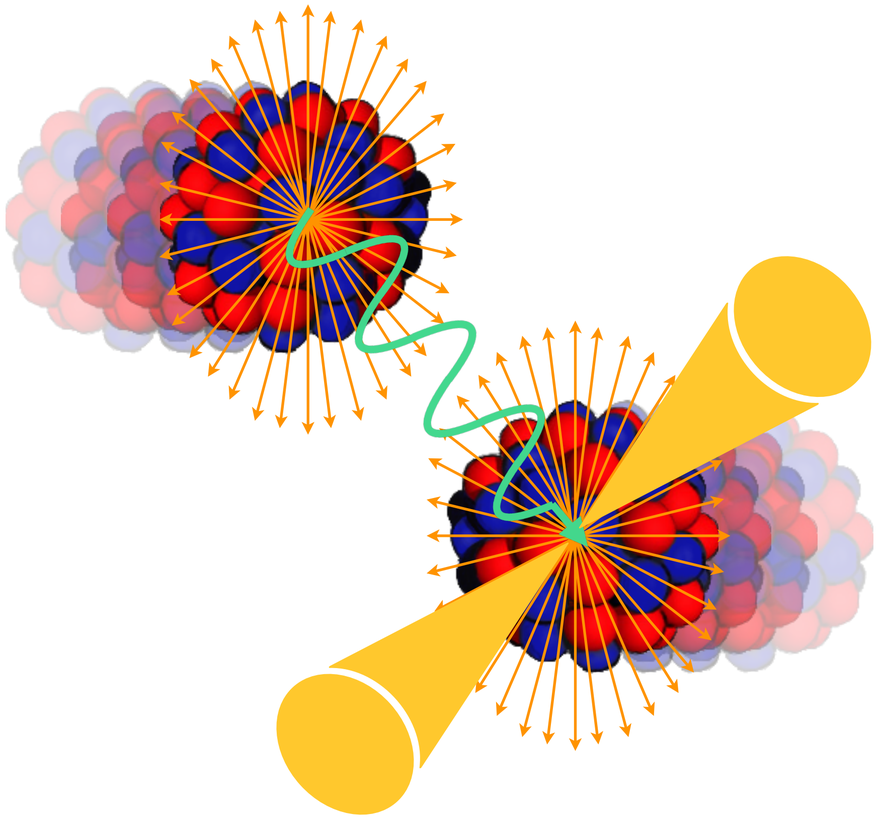


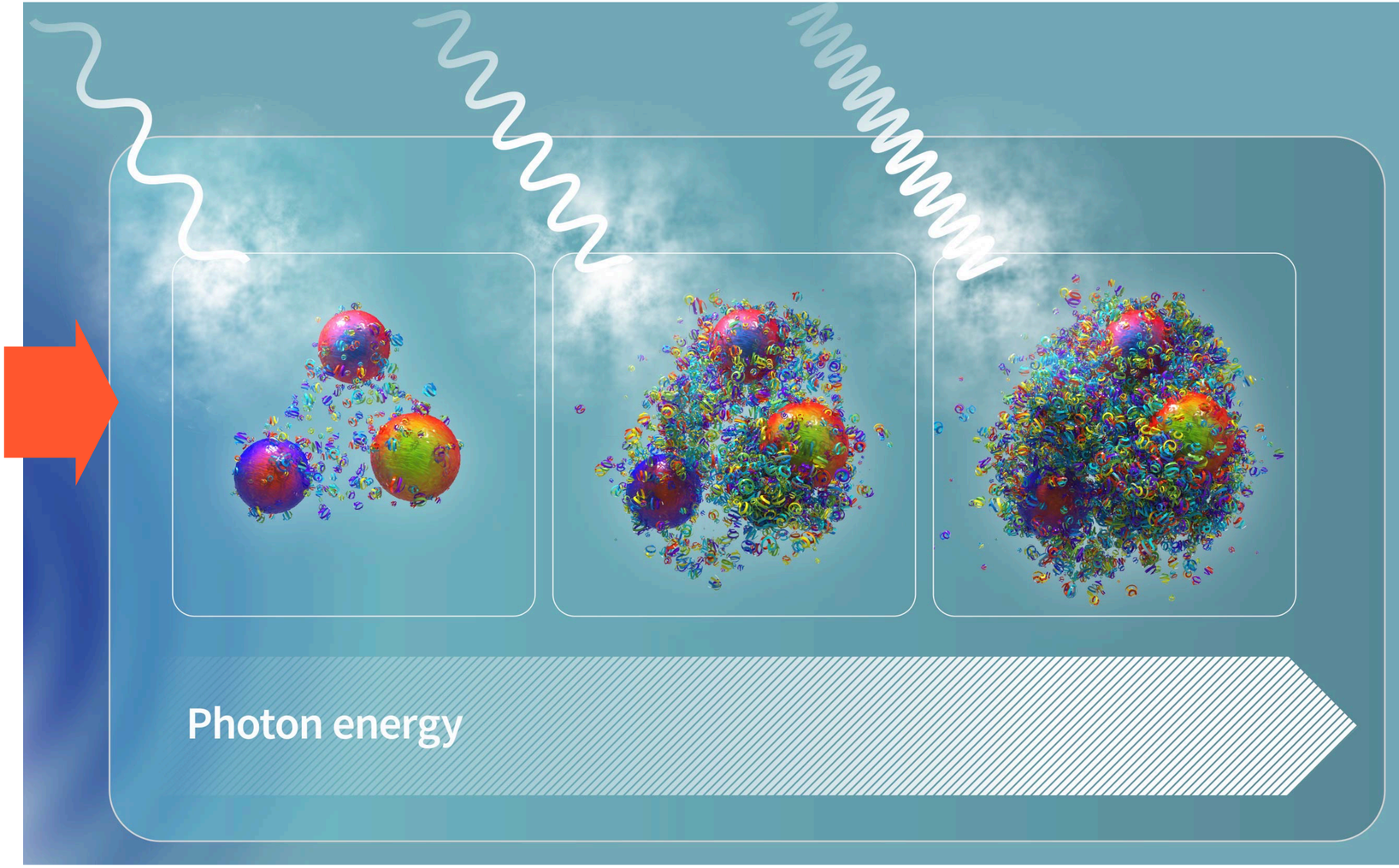
CM system if $x_1 >> x_2$

Dijet probes, analyzed in a triple differential fashion, allow for fully constraining the kinematics of the initial state

PLB 748 (2015) 392–413

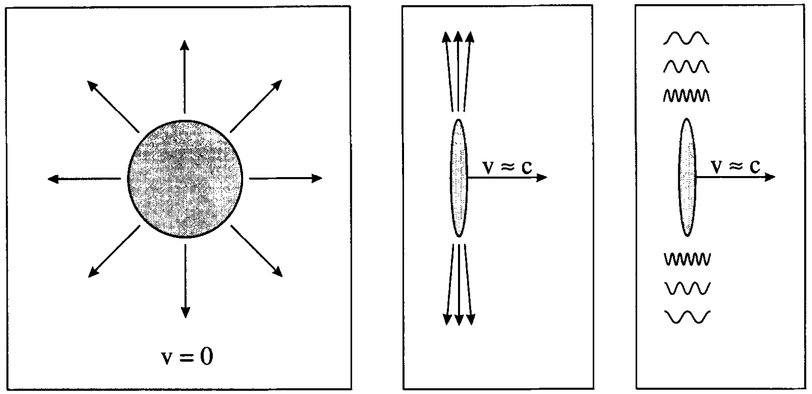
DIFFERENT PHOTON ENERGIES PROVIDE DIFFERENT RESOLUTION





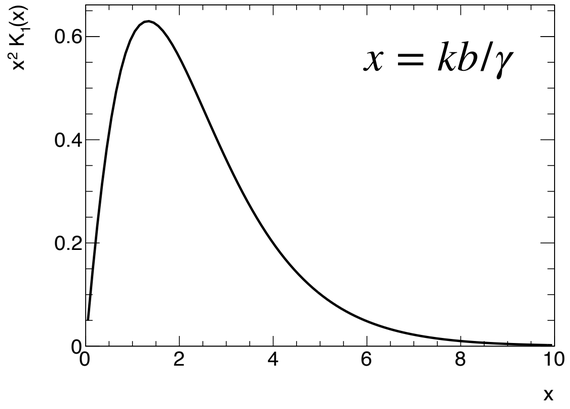
Picture from D.Tapia Takaki's talk @ QM2023

EQUIVALENT PHOTON APPROXIMATION



For a point charge:

$$n(k,b) = \frac{d^3N_\gamma}{d^2b\,dk} \propto \frac{\alpha Z^2}{kb^2} f(kb/\gamma)$$



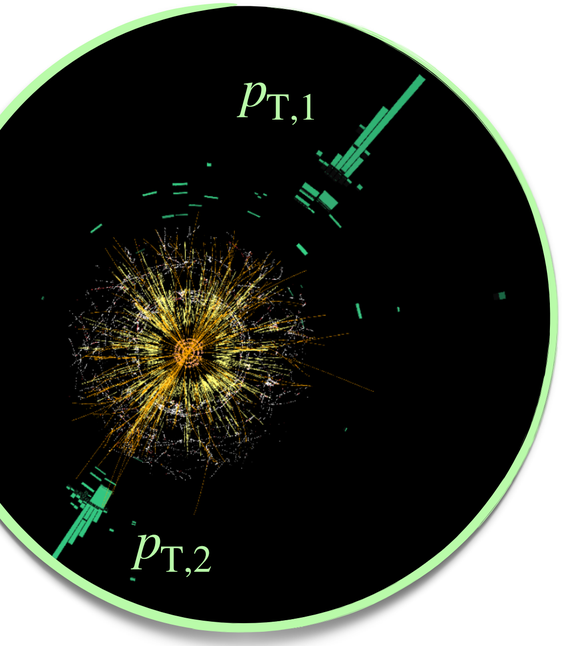
maximum energy $E_{\gamma,max} \sim \gamma(\hbar c/R)$	**80 GeV in Pb+Pb@LHC** **3 GeV in Au+Au@RHIC**
typical p_T (& virtuality) $p_{Tmax} \sim \hbar c/R$	**O(30) MeV @ RHIC & LHC**
Coherent strengths (rates) scale as **Z^2**: nuclei >> protons	Flux of photons on other nucleus ~ **Z^2**, flux of photons on photons ~ **Z^4 (45M!)**

Slide courtesy of P.Steinberg

KINEMATIC DOMAIN

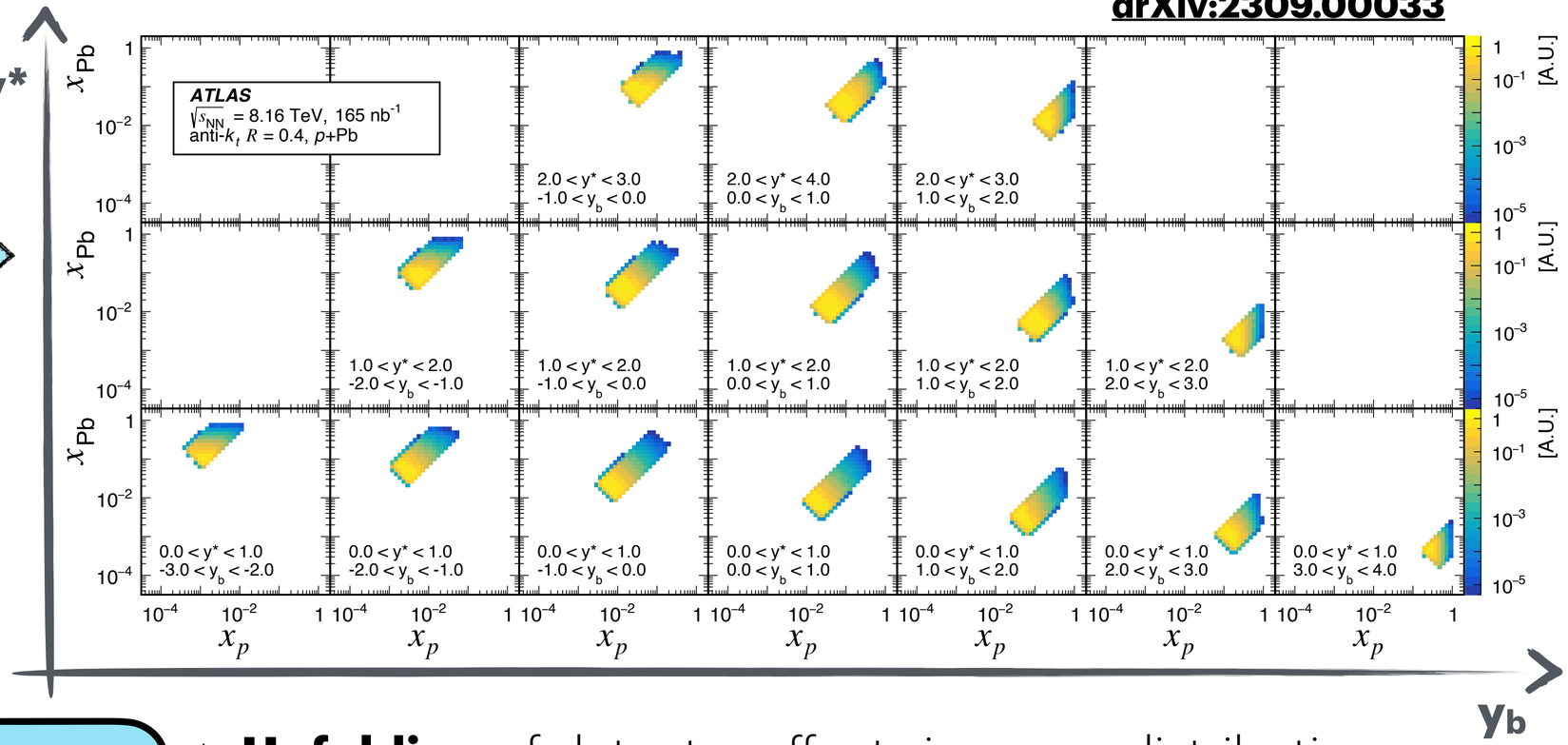
$$x_{\mathrm{p}} \simeq \frac{2p_{\mathrm{T,Avg}}}{\sqrt{s}} e^{y_{\mathrm{b}}} \cosh y^*,$$

$$x_{\mathrm{Pb}} \simeq \frac{2p_{\mathrm{T,Avg}}}{\sqrt{s}} e^{-y_{\mathrm{b}}} \cosh y^*$$



$$p_{\mathrm{T},1} > 40\,\mathrm{GeV}$$
$$p_{\mathrm{T},2} > 30\,\mathrm{GeV}$$
$$-2.8 < \eta_1 < 4.5$$
$$-2.8 < \eta_2 < 4.5$$

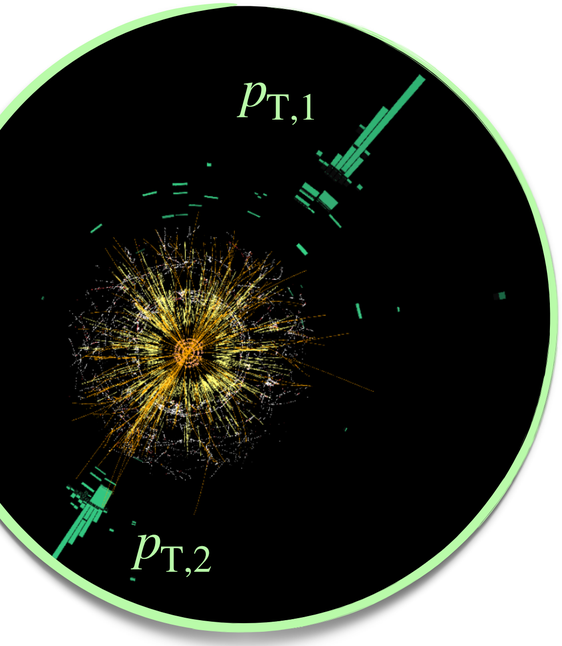
arXiv:2309.00033



- **Unfolding** of detector effects in $p_{\mathrm{T,Avg}}$ distributions using 1D bayesian approach
- Allowed by limited migration in y_{b} and y^* (also corrected for during unfolding)
- The measurement is **not directly carried out in parton system kinematic variables**

KINEMATIC DOMAIN

MEASUREMENT THAT PROBES INTERNAL STRUCTURE OF P AND PB OVER FOUR ORDERS OF MAGNITUDE OF X



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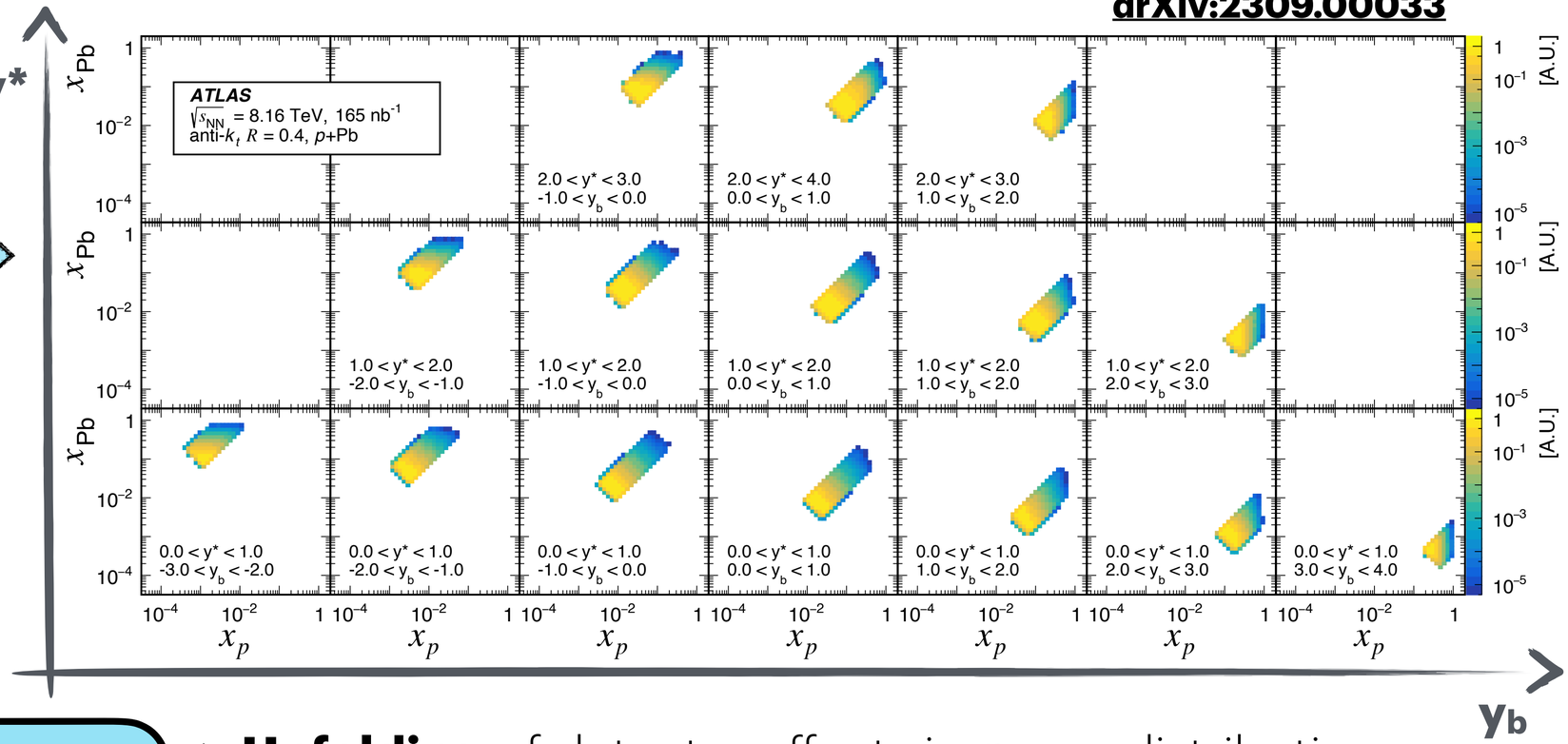

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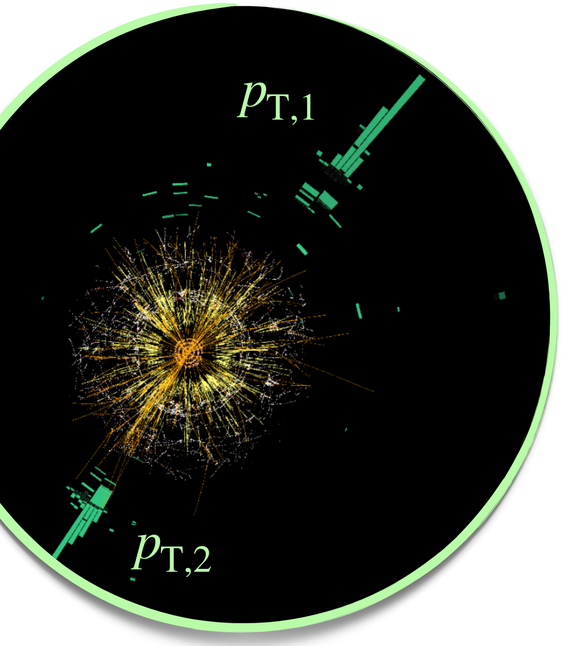

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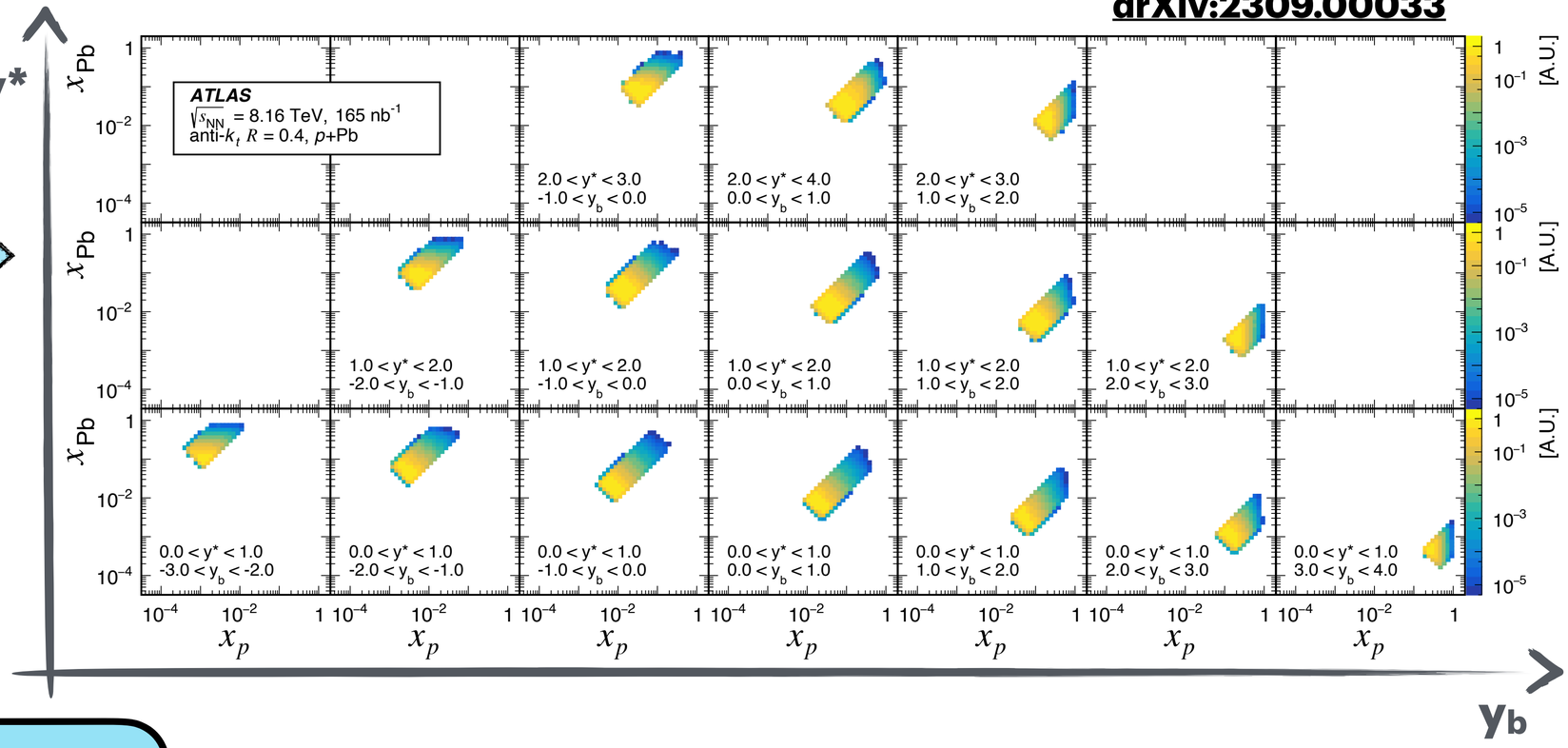
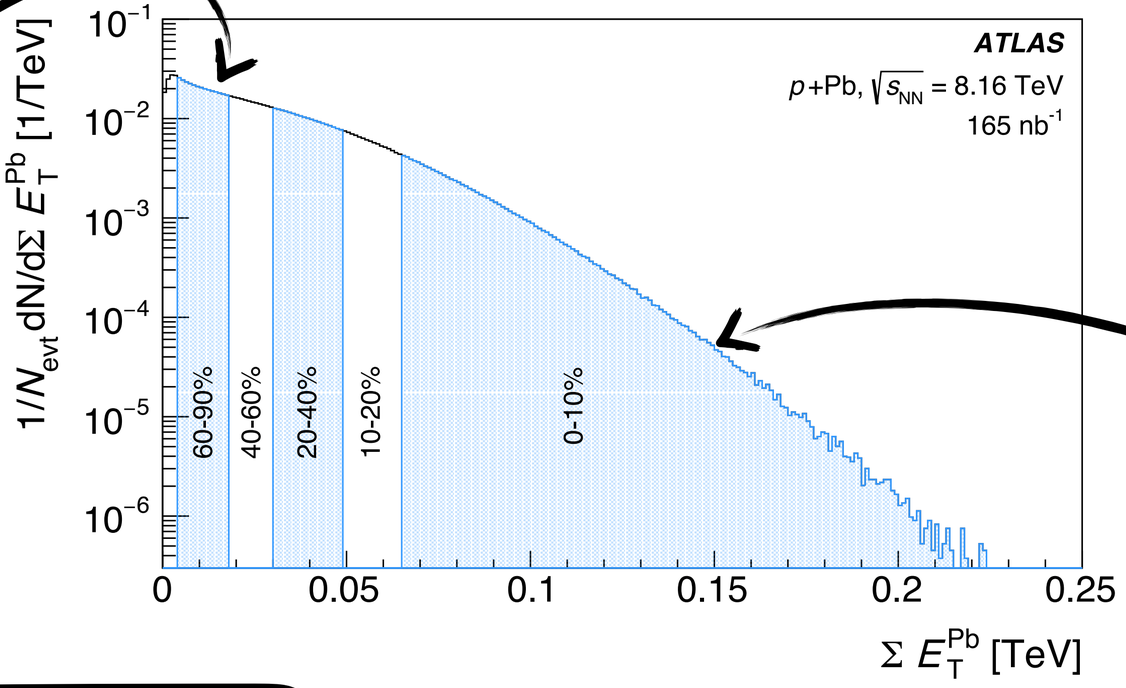


- Using full-acceptance of the ATLAS calorimeter (padding on edges to fully contain R=0.4 jets)
- Centrality determination fully separated from analysis thanks to fiducial cut on η

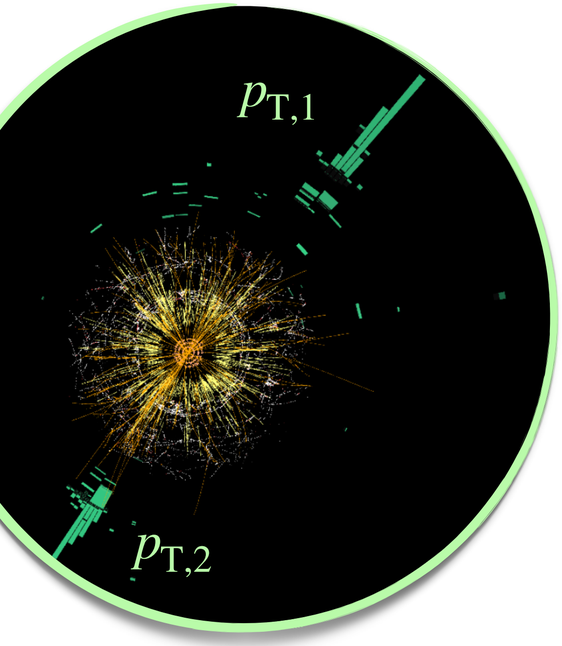
CENTRALITY INTERVALS

Peripheral events
60–90%



Centrality intervals chosen to **match inclusive jet data-analysis** and simplify comparison

Central events
0–10%



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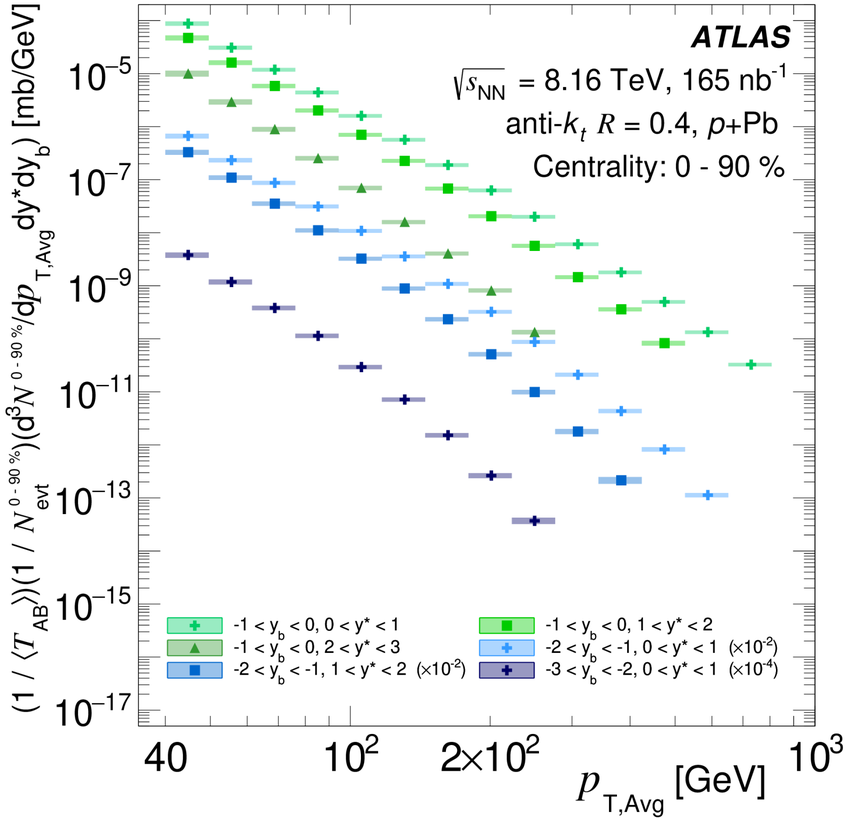
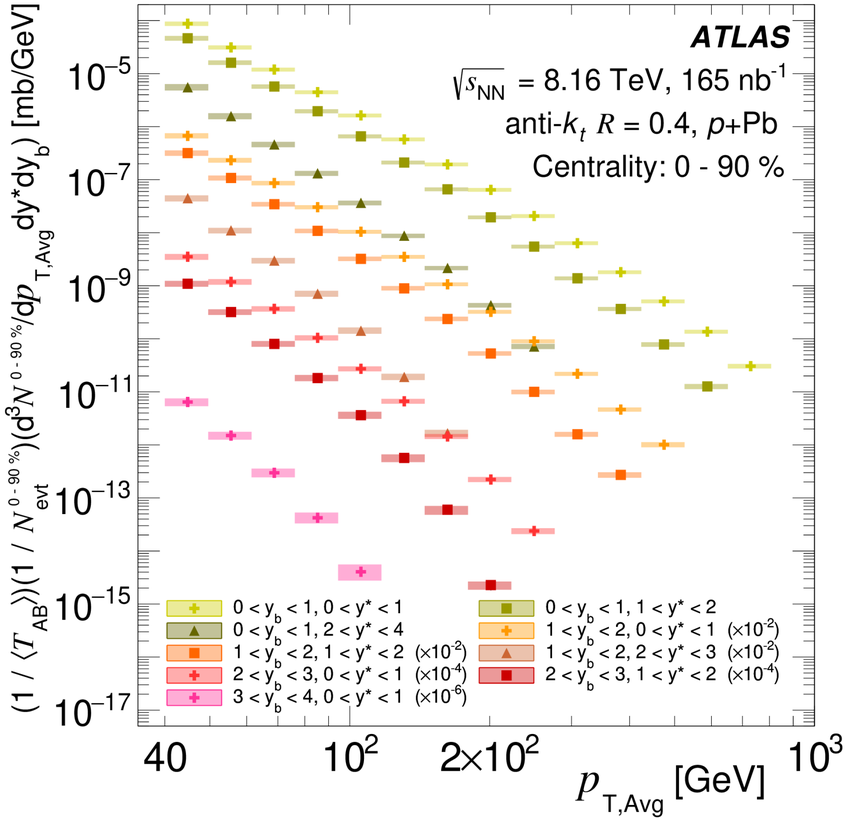
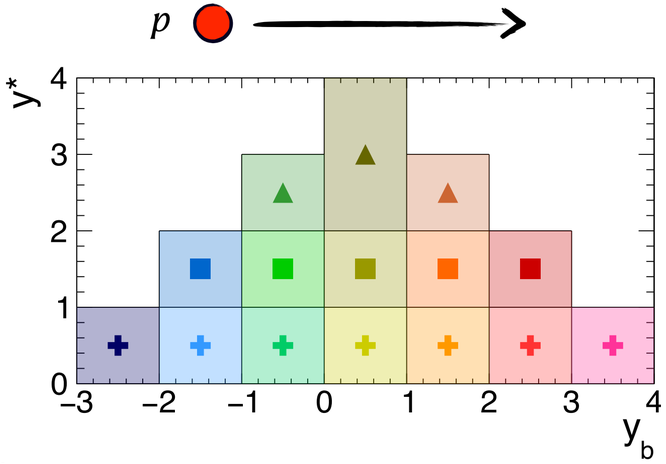
DIJET PER-EVENT YIELDS: 0-90%





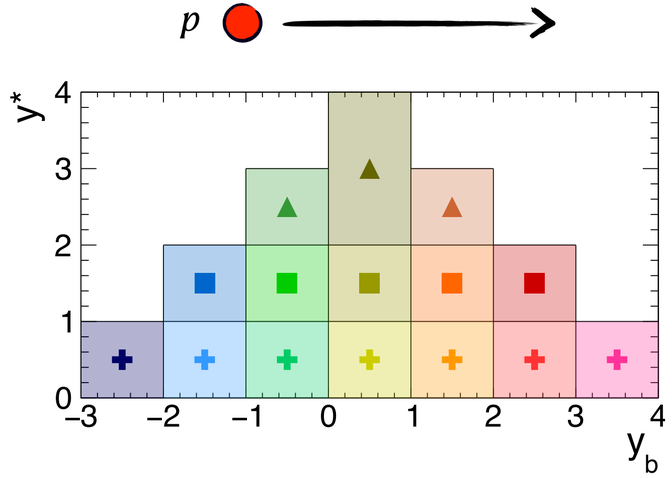


- y^* bins ⟺ different markers
- y_b bins ⟺ different colors

$$Y^{0-90\%} = \frac{1}{\left\langle T_{\mathrm{AB}}^{0-90\%} \right\rangle} \frac{1}{N_{\mathrm{evt}}^{0-90\%}} \frac{\mathrm{d}N_{\mathrm{dijet}}^{0-90\%}}{\mathrm{d}p_{\mathrm{T,Avg}}\mathrm{d}y_{\mathrm{b}}}$$

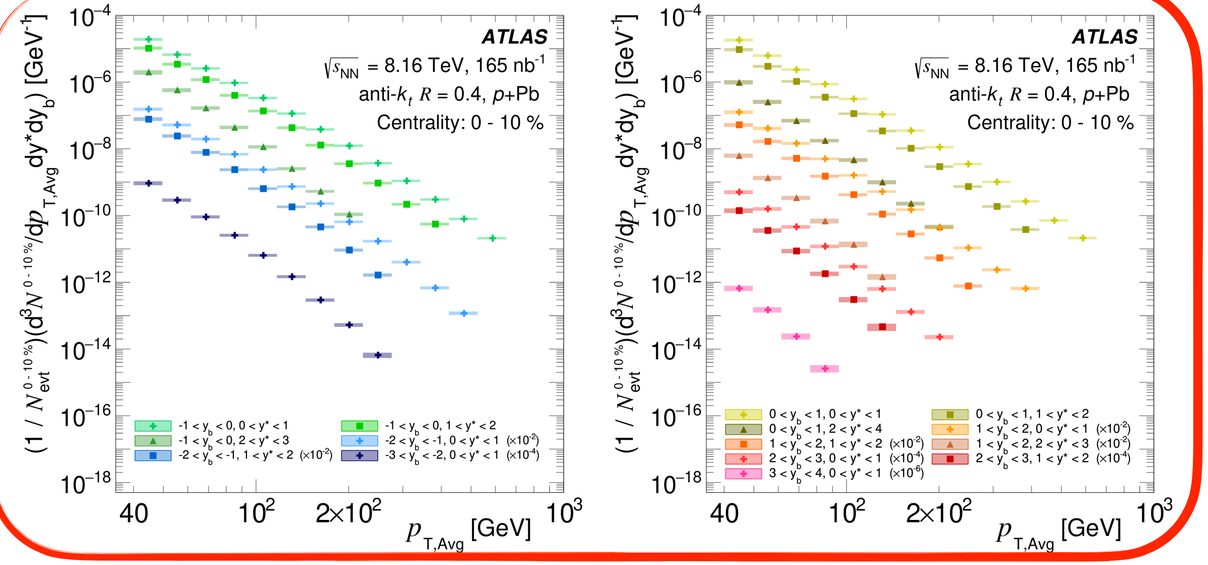
- Per-event dijet yields, **normalized to the nuclear thickness function T_{AB}**
- Here displayed over the full range of centrality considered for the analysis [0-90%]

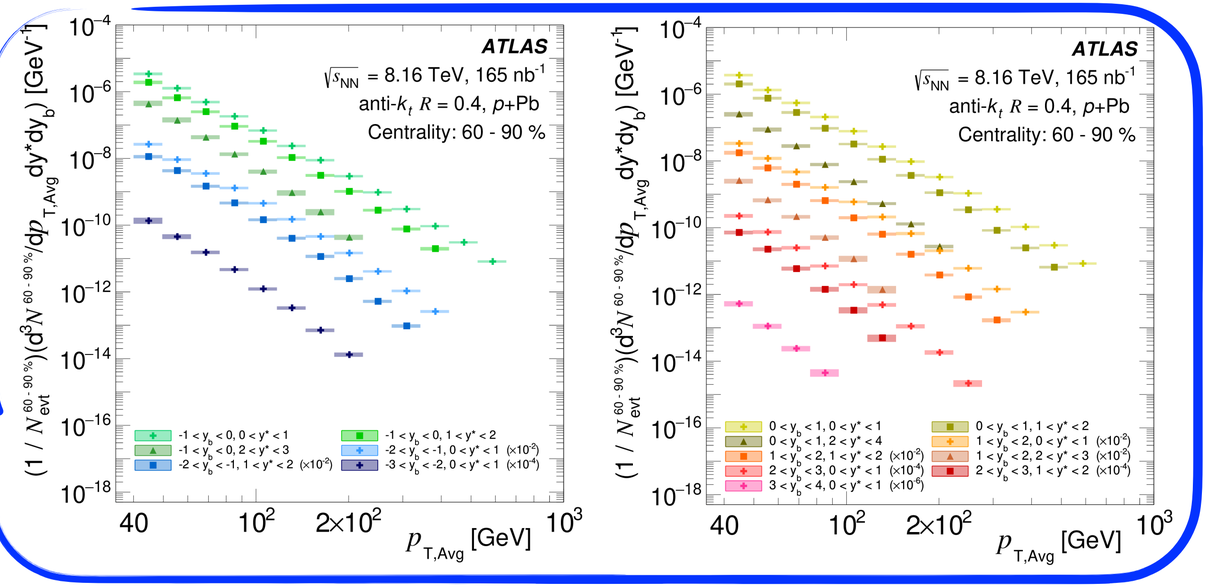
R_{CP} CONSTRUCTION



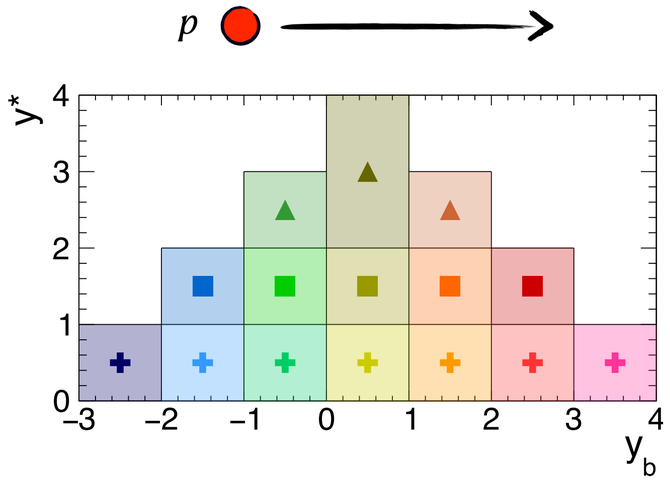
$$R_{\mathrm{CP}}^{\frac{0-10\,\%}{60-90\,\%}}(p_{\mathrm{T,Avg}}, y_{\mathrm{b}}, y^{*}) = \frac{\frac{1}{\langle T_{\mathrm{AB}}^{0-10\%}\rangle}\frac{1}{N_{\mathrm{evt}}^{0-10\%}}\frac{\mathrm{d}N_{\mathrm{dijet}}^{0-10\%}}{\mathrm{d}p_{\mathrm{T,Avg}}\mathrm{d}y_{\mathrm{b}}\mathrm{d}y^{*}}}{\frac{1}{\langle T_{\mathrm{AB}}^{60-90\%}\rangle}\frac{1}{N_{\mathrm{evt}}^{60-90\%}}\frac{\mathrm{d}N_{\mathrm{dijet}}^{60-90\%}}{\mathrm{d}p_{\mathrm{T,Avg}}\mathrm{d}y_{\mathrm{b}}\mathrm{d}y^{*}}}$$

Nuclear overlap function, computed using a standard Glauber Monte Carlo [**SoftwareX 1-2 (2015) 13-18**]

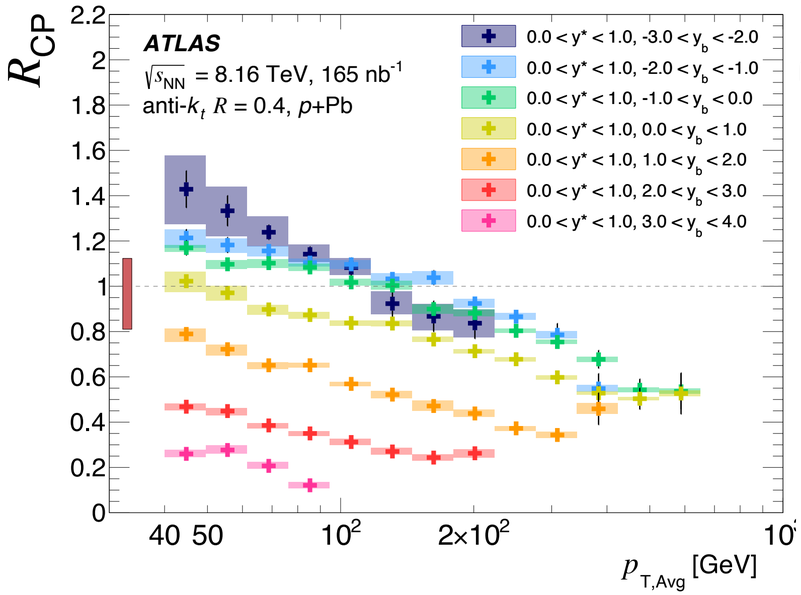


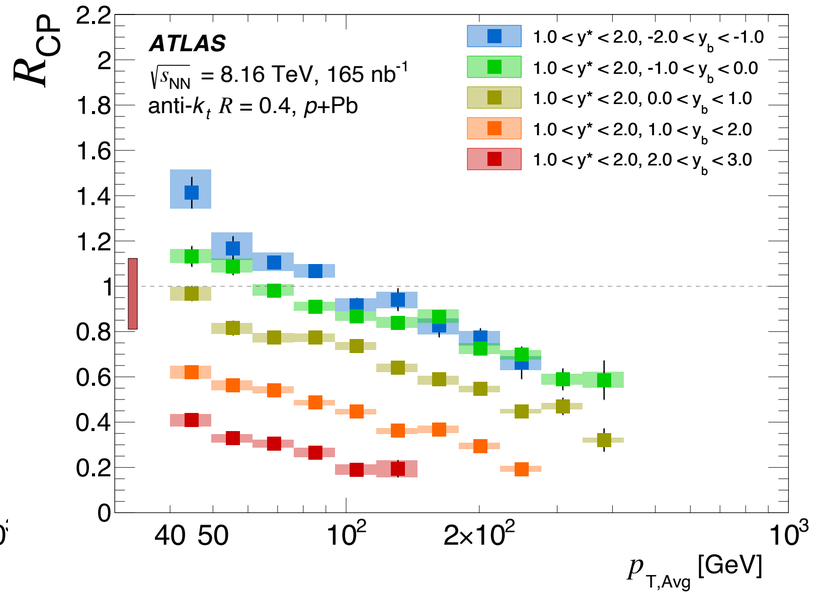


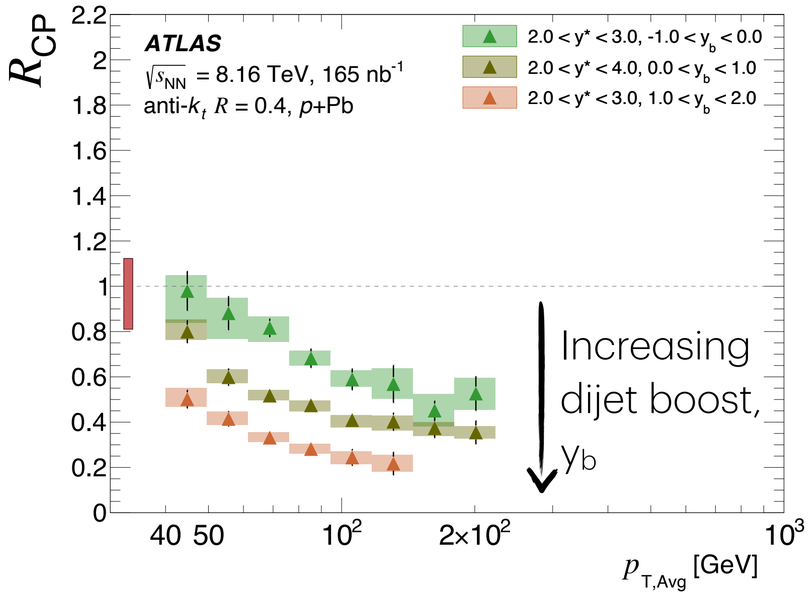
R_{CP} RESULTS



Increasing suppression w/ the hard-scale of the process ($p_{T,Avg}$) and with y_b, i.e. R_{CP} of dijets with a more forward boost is more suppressed







Increasing dijet half separation, y*

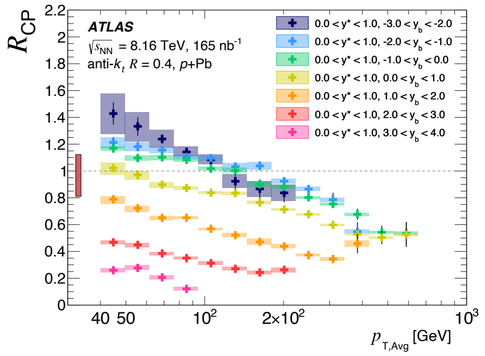
MAPPING R_{CP} RESULTS ON INITIAL STATE KINEMATICS

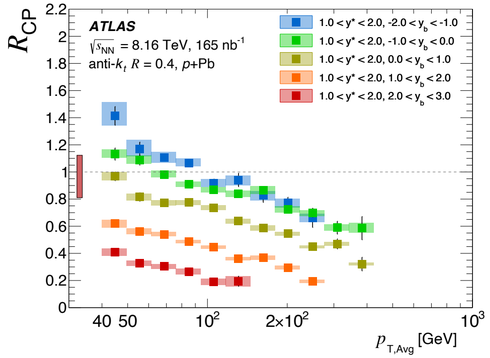
Approximated parton-level kinematics in each bin

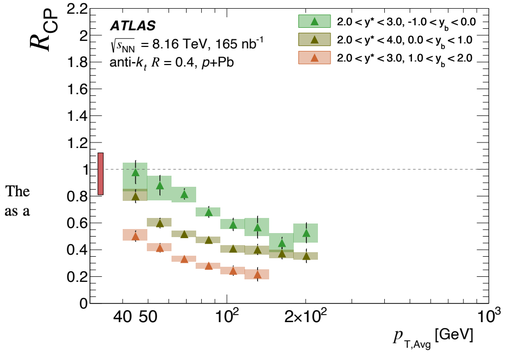
- The parton-level kinematics in each bin can be approximated by using the average value of y_b and y^* in each kinematic bin
- For $p_{T,Avg}$, the center of the bin is used

$$x_p \simeq \frac{2p_{T,Avg}}{\sqrt{s}} e^{\langle y_b \rangle} \cosh\langle y^* \rangle, \quad x_{Pb} \simeq \frac{2p_{T,Avg}}{\sqrt{s}} e^{-\langle y_b \rangle} \cosh\langle y^* \rangle$$

$$m_{1,2} = \sqrt{x_p x_{Pb} s} \simeq 2p_{T,Avg} \cosh\langle y^* \rangle$$







y^* \ y_b	[-3.0:-2.0]	[-2.0:-1.0]	[-1.0:0.0]	[0.0:1.0]	[1.0:2.0]	[2.0:3.0]	[3.0:4.0]
[2.0:3.0]	-	-	(-0.42,2.29)	(0.50,2.42)†	(1.33,2.26)	-	-
[1.0:2.0]	-	(-1.39,1.32)	(-0.50,1.37)	(0.48,1.40)	(1.45,1.41)	(2.30,1.30)	-
[0.0:1.0]	(-2.33,0.43)	(-1.45,0.49)	(-0.49,0.49)	(0.46,0.49)	(1.44,0.52)	(2.44,0.0.51)	(3.24,0.37)

Table 1: The average value of the dijet boost, $\langle y_b \rangle$, and the half rapidity separation, $\langle y^* \rangle$, in each bin of (y_b, y^*). The values are used to rescale the $p_{T,Avg}$ axis, according to Equations 2 and 3 in order to display the R_{CP} results as a function of the x_p and x_{Pb}, respectively. The bin denoted by "†" has a maximum y^* of 4.0.

MAPPING R_{CP} RESULTS ON INITIAL STATE KINEMATICS

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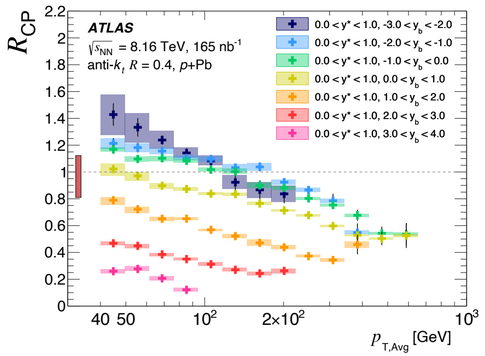

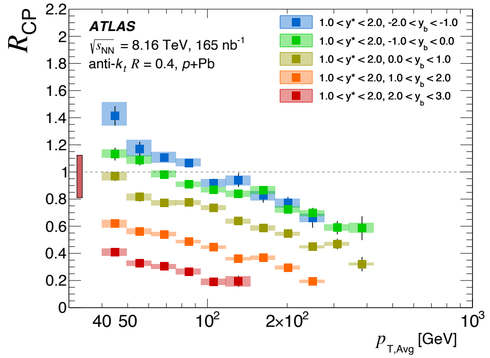

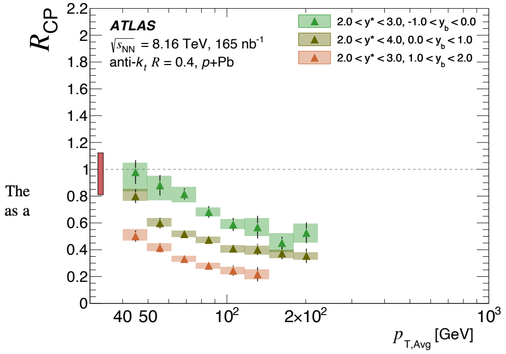

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[0.0:1.0]	(-2.33,0.43)	(-1.45,0.49)	(-0.49,0.49)	(0.46,0.49)	(1.44,0.52)	(2.44,0.0.51)	(3.24,0.37)

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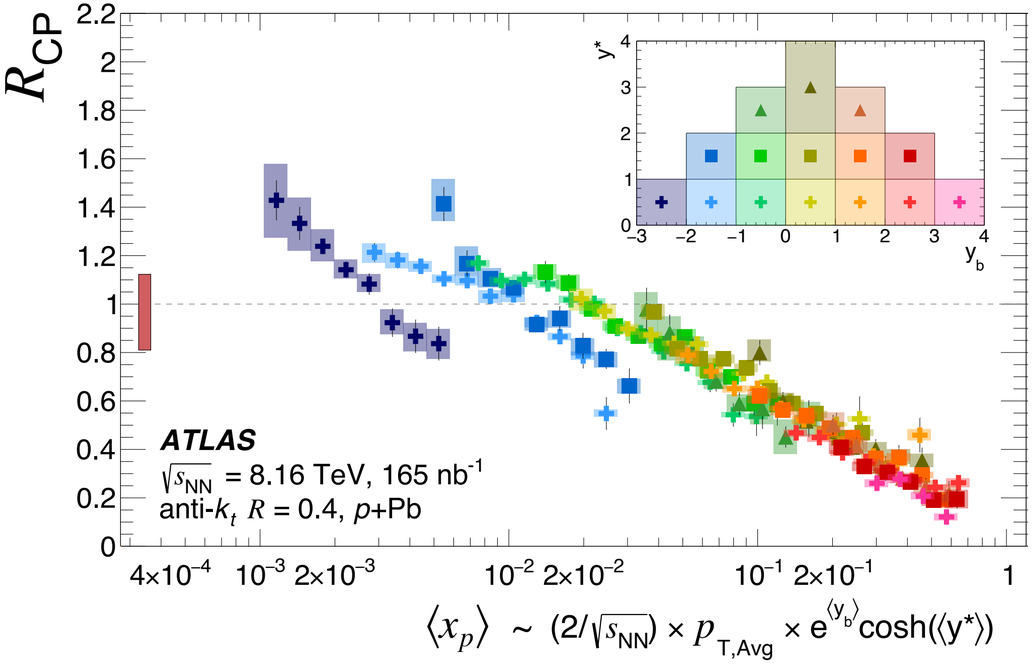
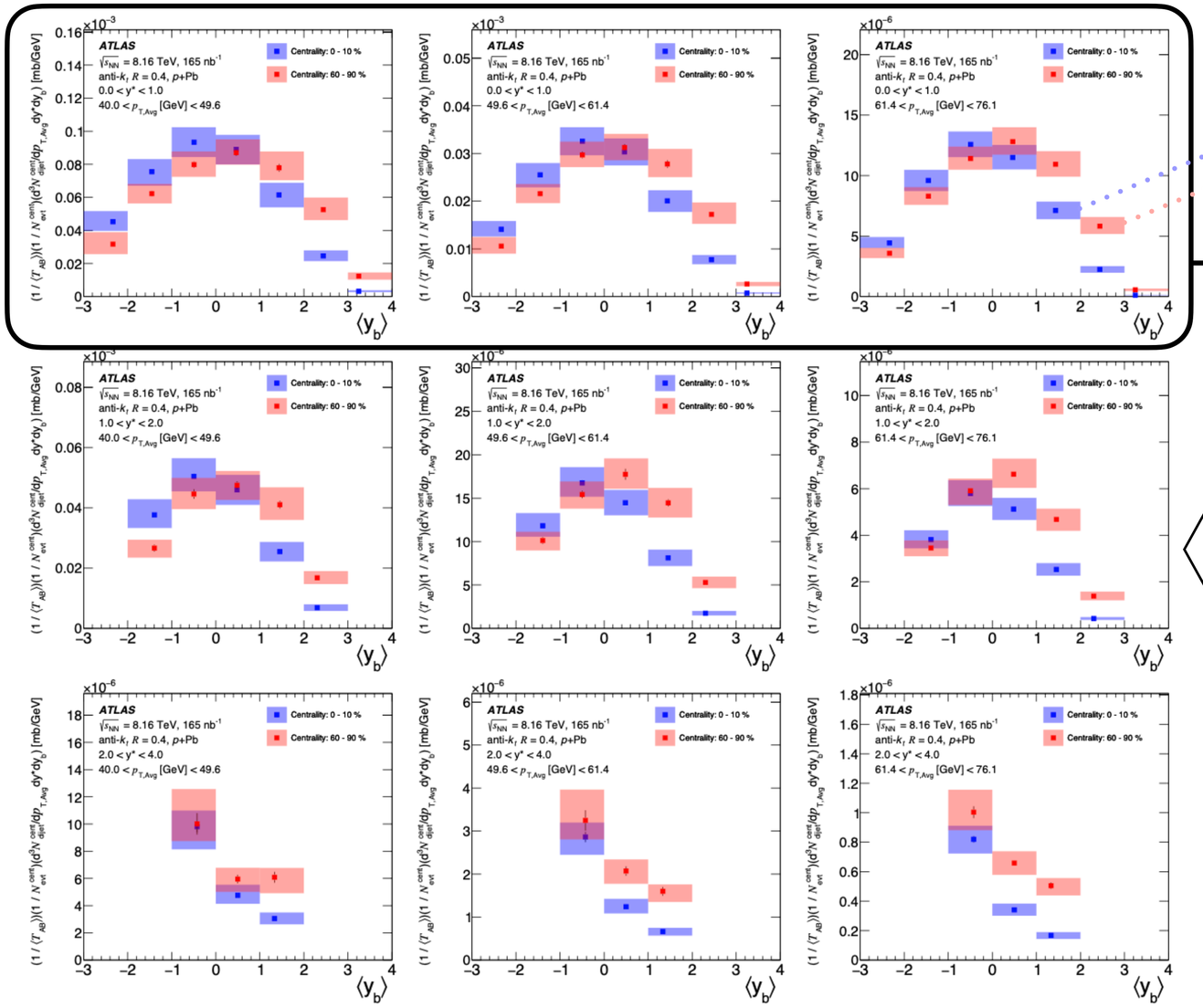
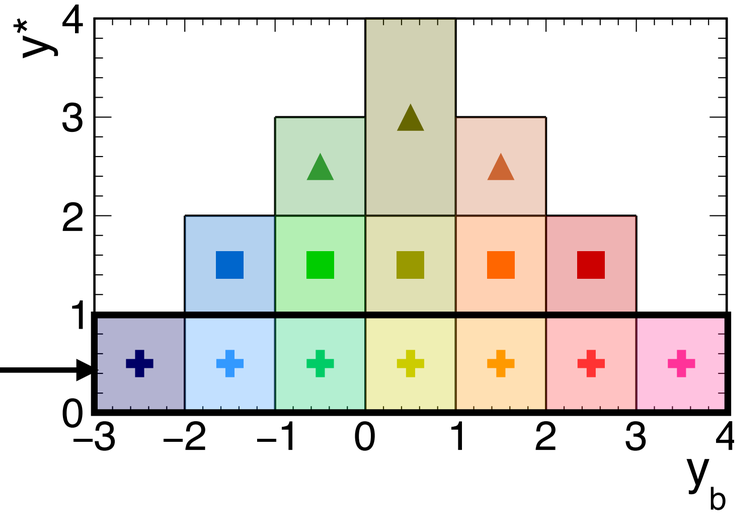


RECASTING CMS RESULTS ON INITIAL STATE KINEMATICS

- Map of dijet yield centrality dependence on y_b and y^*

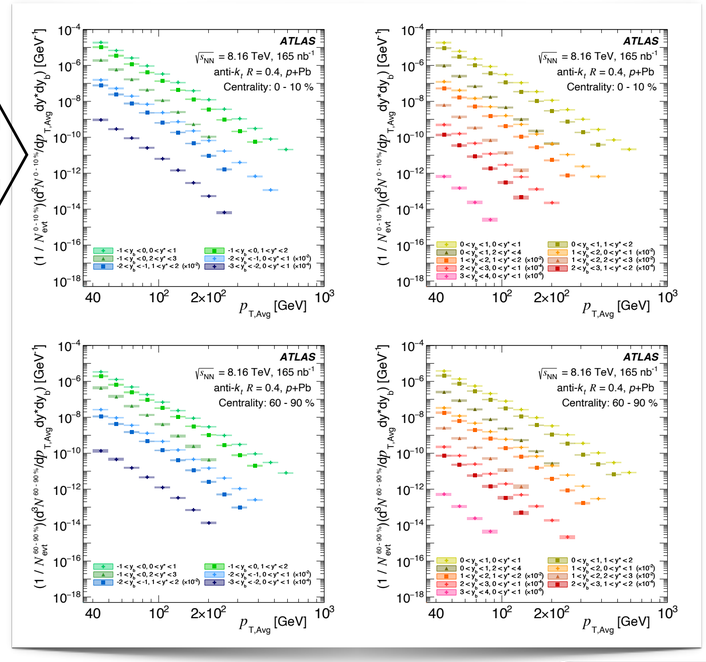


CENTRAL
PERIPHERAL



Same information as shown in previous yields!

Just **plotted** in a **different** way



RECASTING CMS RESULTS ON INITIAL STATE KINEMATICS

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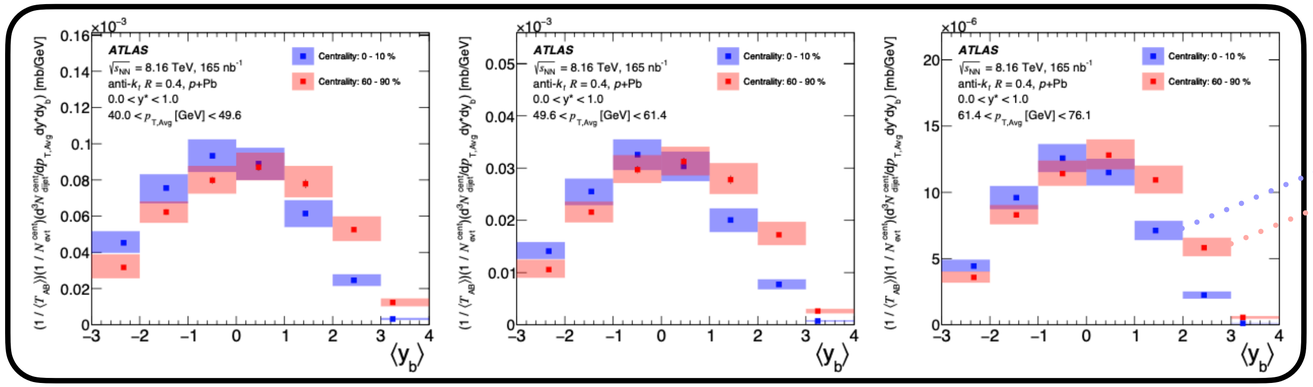
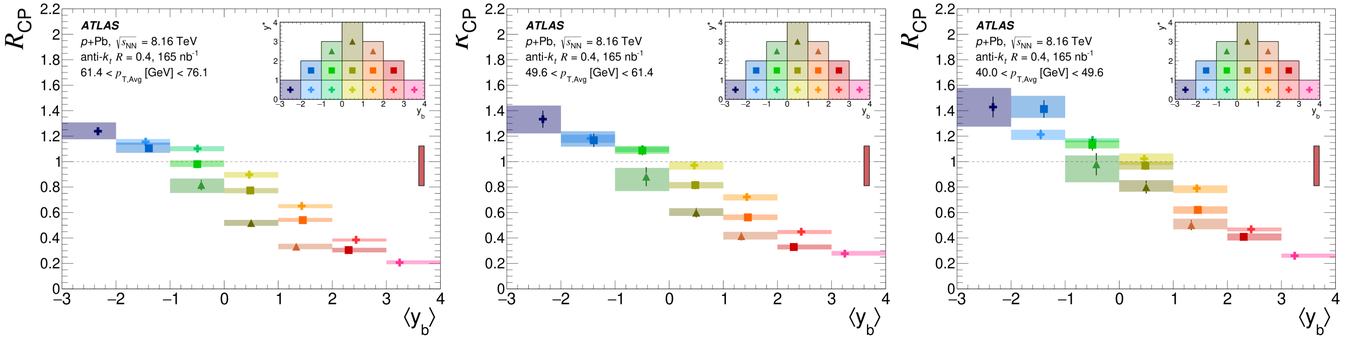
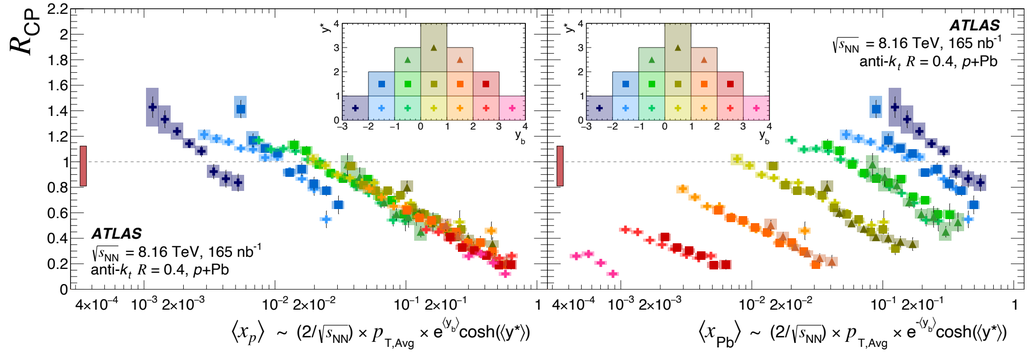
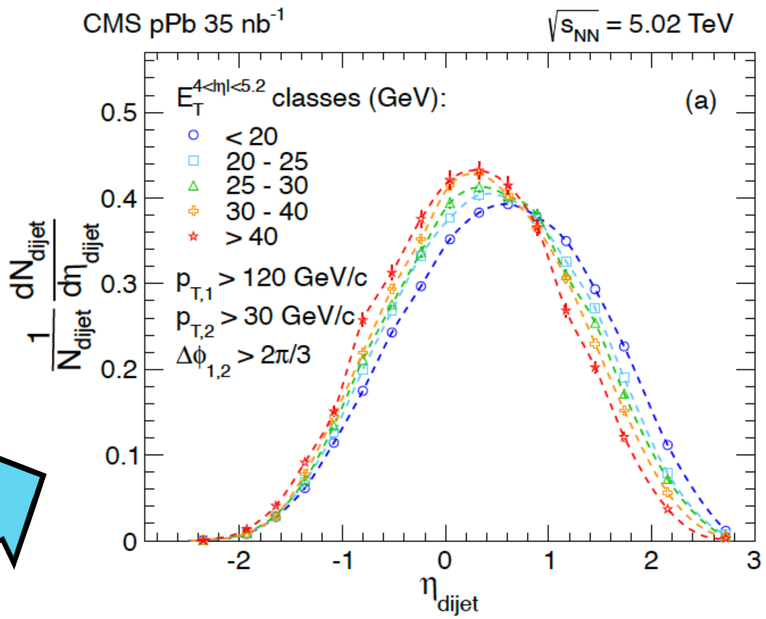


CENTRAL
PERIPHERAL







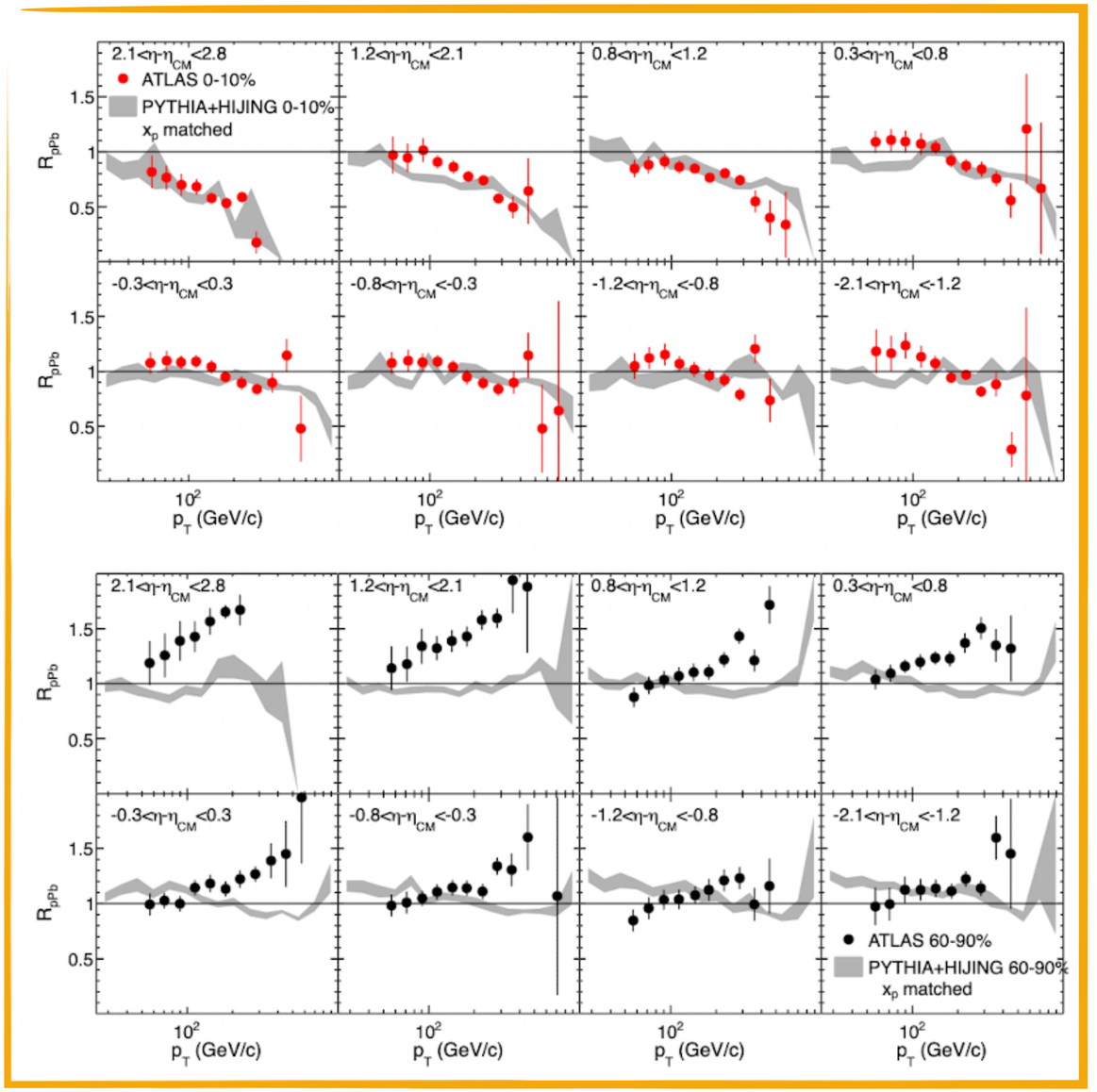
Centrality dependent dijet rapidity shift observed by CMS

Eur. Phys. J. C 74 (2014) 2951

SAME PHYSICS EFFECT, CAN NOW BE INTERPRETED AS A FUNCTION OF THE INITIAL STATE KINEMATICS

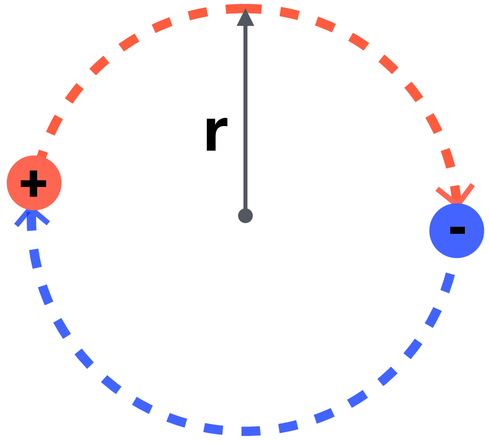
PROPOSED INTERPRETATIONS

- Wave of theoretical works inspired by the observed jet centrality dependence. Many focused on the energy removed from the proton in events with a high-*x* parton participating in the hard scattering
  - **PRC 93 (2016) 044901**: Suppression of soft particle production dependent on the amount of energy removed from the projectile proton
  - **PLB 747 (2015) 441**: Kinematic bias introduced by energy momentum conservation between the hard process and the production of soft particles
  - **PRC 97 (2018) 5, 054904**: Suppression of soft particle production away from the jet, caused by the depletion of energy available in the proton after the production of a hard jet



A QED ANALOGY: CHARGE TRANSPARENCY

- **Positronium is a bound state of an electron and positron**
  - Distance parameter "r" can fluctuate such that r~0
  - For r~0, the electron and positron wave-functions effectively cancel, resulting in a point-like neutral configuration (QED prediction!)
  - Excitation energy ΔE from ground state is ~5 eV



Heisenberg's Uncertainty Principle $\rightarrow \Delta t \sim \frac{\hbar}{\Delta E} \sim 0.1 \text{ fs}$

Time Dilation $\rightarrow \Delta t' = \gamma \cdot \Delta t, \quad \gamma = \frac{E_{+-}}{2m_e \cdot c^2}$

A positronium with E_{+-}= 1 GeV has a lorentz factor: $\gamma \sim 10^3$

Positronium can travel $\rightarrow c \cdot \Delta t' \sim 30\ \mu m$
in same configuration

Theoretical calculation from 1981
V. L. Lyuboshitz et al, Zh. Eksp. Teor. Fiz. 1981, 81, 1556-1566

Experimentally challenging to produce positronium, but there are alternatives!