High-density QCD physics & the study of the QGP in the HL-LHC era

Florian Jonas

Workshop on High Luminosity LHC and Hadron Colliders

03.10.2024, LNF, Italy

Berkeley UNIVERSITY OF CALIFORNIA

BERKELEY LAB

Lawrence Berkeley National Laboratory

High-density QCD physics & the study of the QGP ~~in the HL-LHC era~~ at the HL-LHC

Florian Jonas

Workshop on High Luminosity LHC and Hadron Colliders
03.10.2024, LNF, Italy

Berkeley
UNIVERSITY OF CALIFORNIA

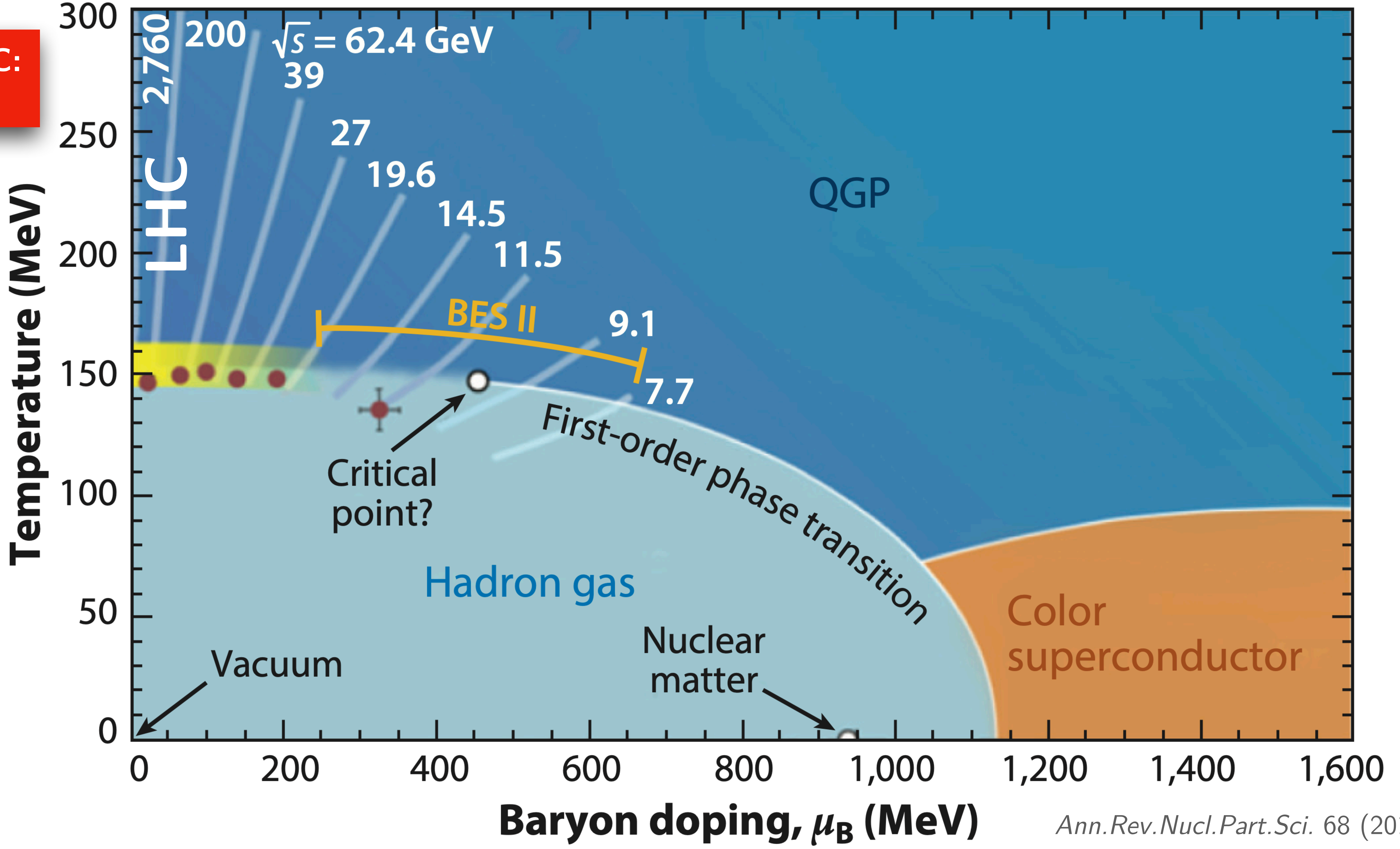
BERKELEY LAB
Lawrence Berkeley
National Laboratory

QCD phase diagram

Temp. HI collision LHC: ~2.9 trillion K

$\times 100000$

Temp. core of sun: ~27 million K



Ann.Rev.Nucl.Part.Sci. 68 (2018) 339-376

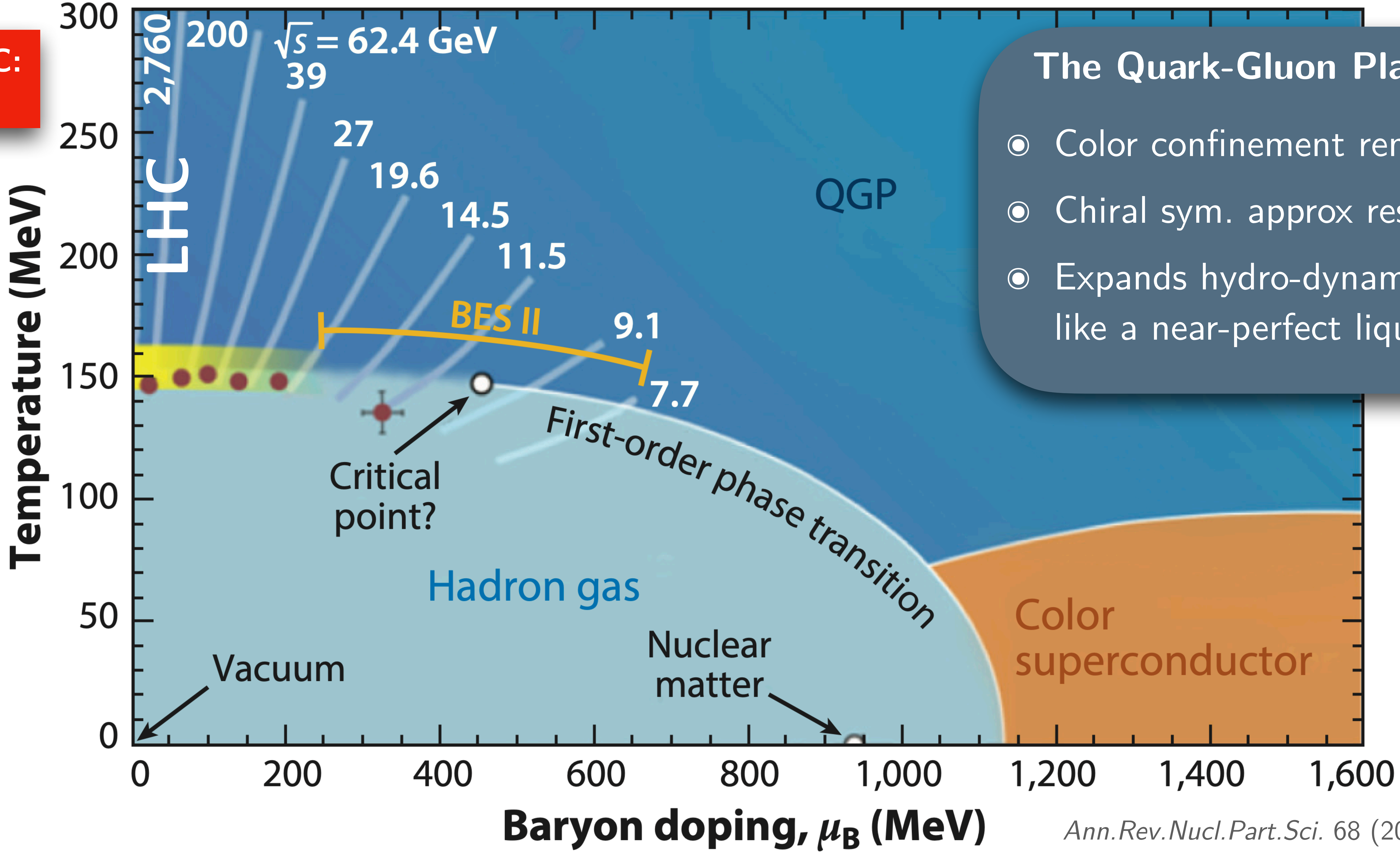
collisions of heavy-ions at the LHC produce QCD matter at unprecedented temperatures!

QCD phase diagram

Temp. HI collision LHC: ~2.9 trillion K

× 100000

Temp. core of sun: ~27 million K



Ann.Rev.Nucl.Part.Sci. 68 (2018) 339-376

The Quark-Gluon Plasma

- Color confinement removed
- Chiral sym. approx restored
- Expands hydro-dynamically like a near-perfect liquid

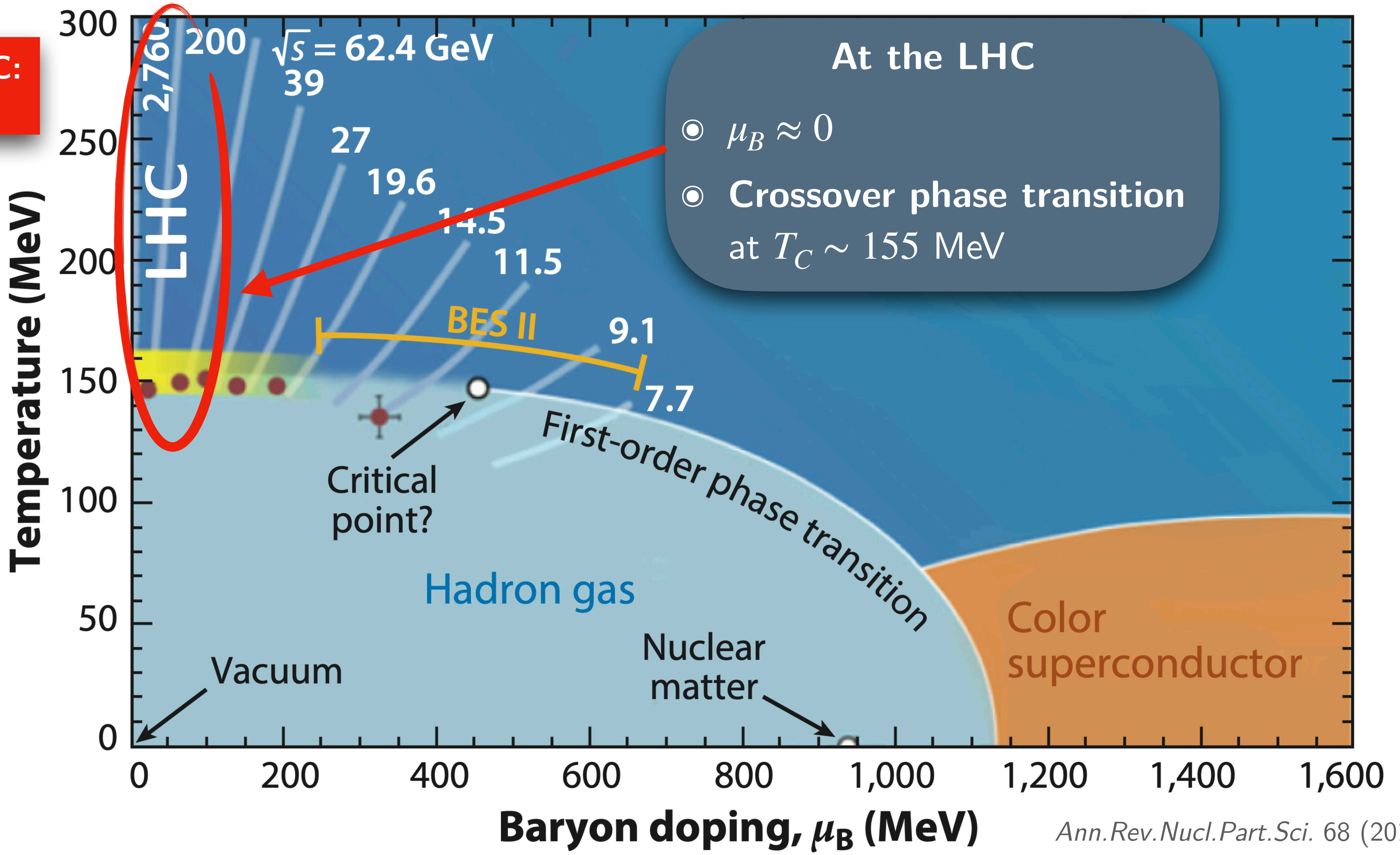
collisions of heavy-ions at the LHC produce QCD matter at unprecedented temperatures!

QCD phase diagram

Temp. HI collision LHC: ~2.9 trillion K

$\times 100000$

Temp. core of sun: ~27 million K



Ann.Rev.Nucl.Part.Sci. 68 (2018) 339-376

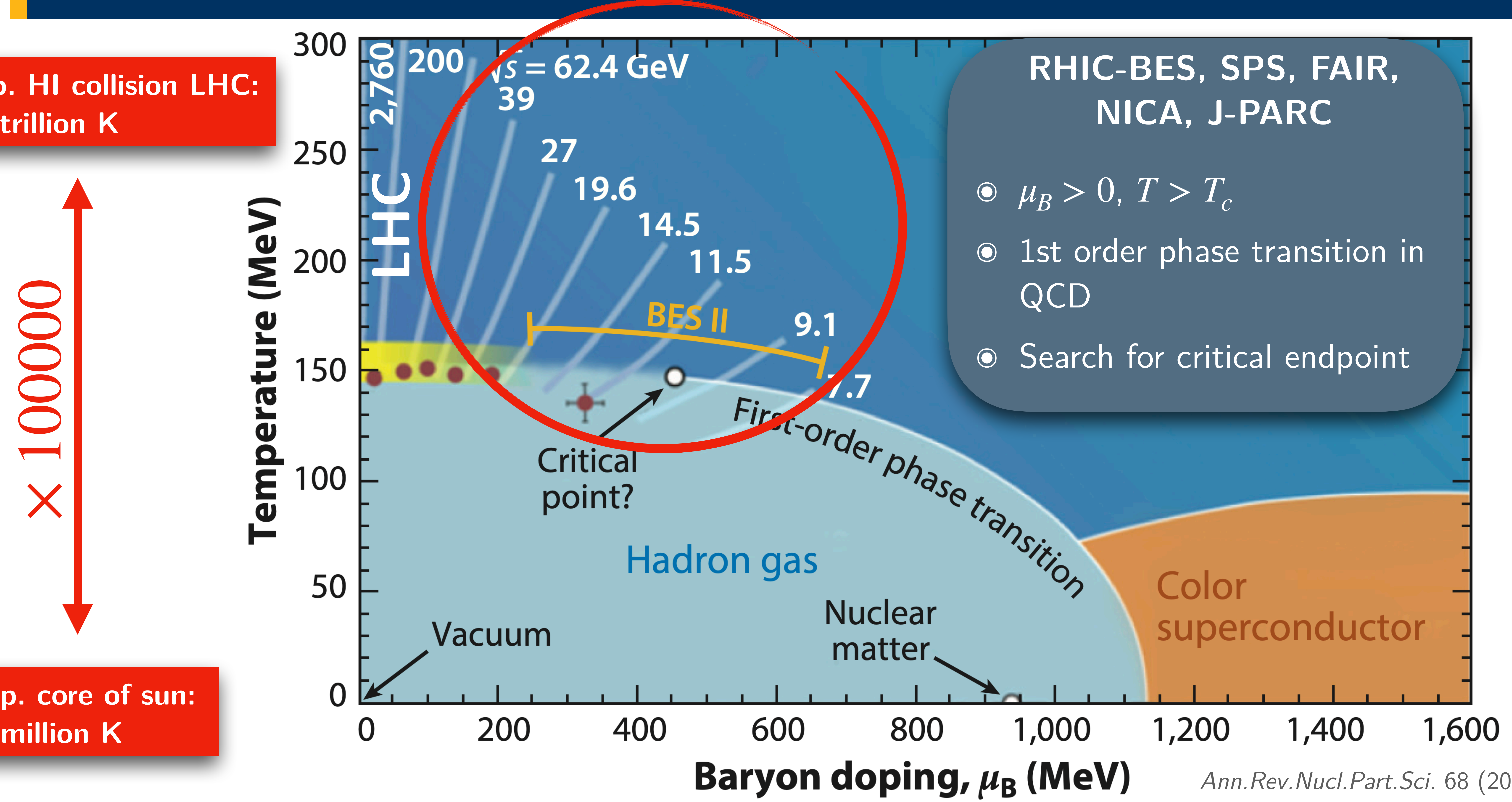
At the LHC

- $\mu_B \approx 0$
- **Crossover phase transition** at $T_C \sim 155$ MeV

collisions of heavy-ions at the LHC produce QCD matter at unprecedented temperatures!

QCD phase diagram

Temp. HI collision LHC: ~2.9 trillion K



Temp. core of sun: ~27 million K

RHIC-BES, SPS, FAIR, NICA, J-PARC

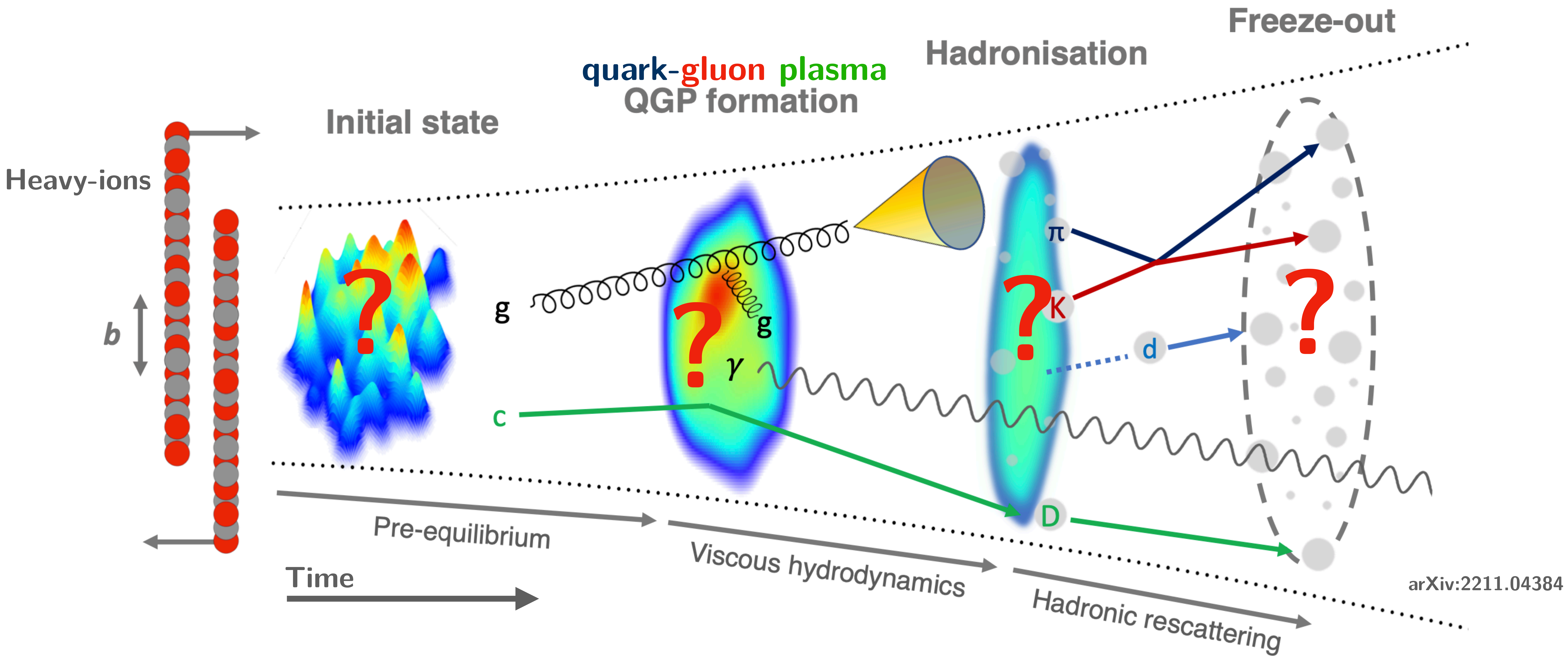
- $\mu_B > 0$, $T > T_c$
- 1st order phase transition in QCD
- Search for critical endpoint

Ann.Rev.Nucl.Part.Sci. 68 (2018) 339-376

collisions of heavy-ions at the LHC produce QCD matter at unprecedented temperatures!

By colliding heavy-ions we can learn about the evolution of QCD matter in extreme conditions (high temperature and/or high density)

using a toolbox of probes produced in all stages of collision



High-Luminosity LHC → higher precision & opportunities for new observables

The high luminosity era for heavy-ions

	2015-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2041
Run 1	Run 2	LS 2	Run 3	LS 3	Run 4	LS 4	Runs 5&6
	Pb-Pb 2.2/nb **p-Pb** 0.18/pb		**Pb-Pb** 6.2/nb **O-O** 500/μb		**Pb-Pb** 6.8/nb **p-Pb** 0.6/pb		**Pb-Pb** 35/nb (tbd)

High-Luminosity LHC (Run 4 onwards)

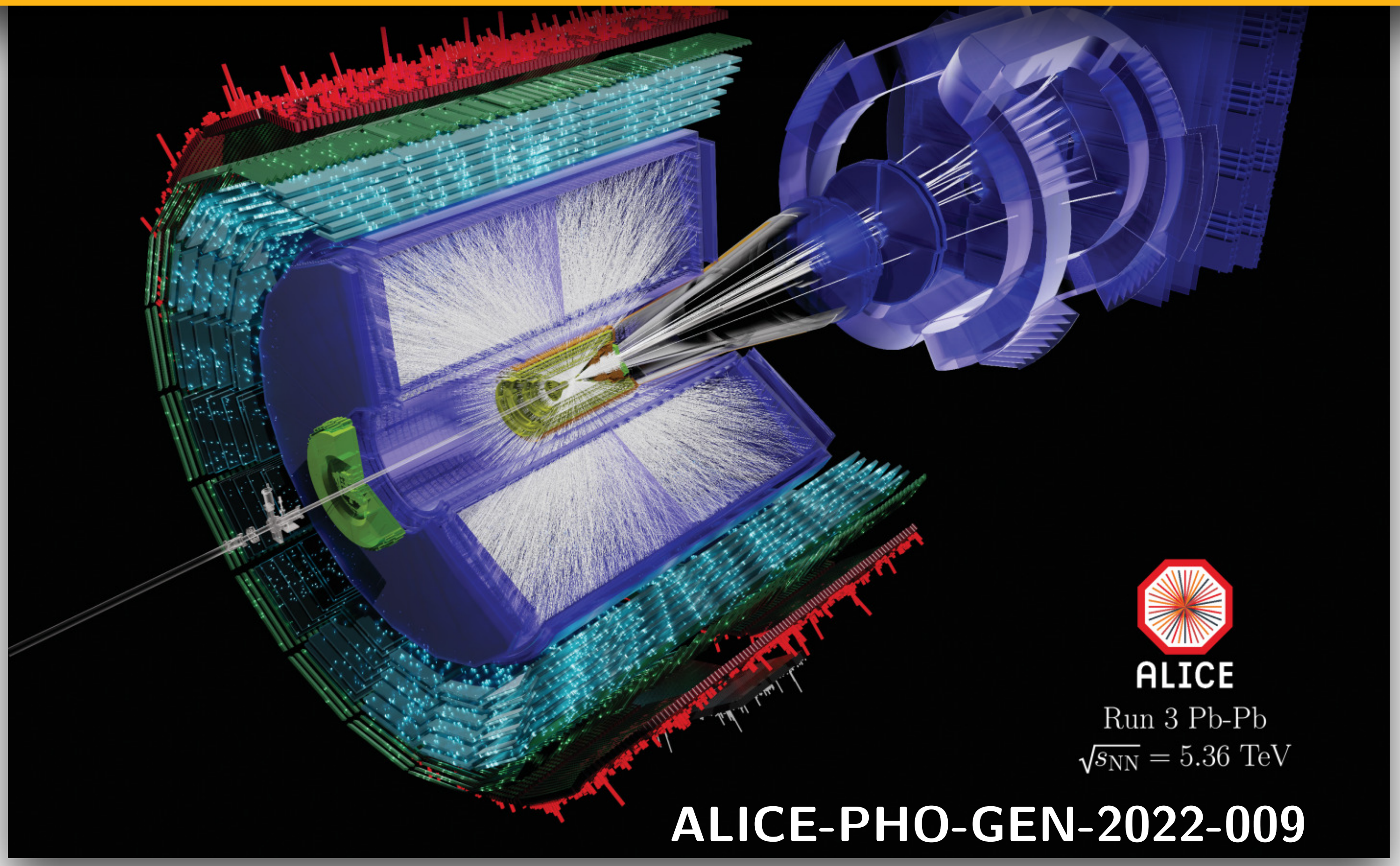
The High Luminosity LHC: CERN-2020-010

- **LS2:** LHC injector upgrades; Pb-Pb rate ~10kHz → 50kHz
- **LS3:** HL-LHC installation; pp ~460/fb → 3000/fb (HL-LHC)

Trigger/Readout compared to Run 2:

- ALICE: increase of MB Pb-Pb **x100** **compared to Run 2**
- ATLAS/CMS: increase of **MB (rare triggers)** **x5 (x10)**
- LHCb: full delivered luminosity (up to 30% central Pb-Pb in Run 3 & 4)

HL for heavy-ions is already ongoing ...



Detector upgrades (overview)

Run 1	Run 2	LS 2	Run 3	LS 3	Run 4	LS 4	Runs 5&6
	2015-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2041

High-Luminosity LHC (Run 4 onward)

ALICE:

- new ITS & new Muon Forward Tracker (MFT)
- TPC upgrade + continuous readout

LS 2

- Forward Calorimeter (FoCal)
- ITS3: ultralight cylindrical vertexer

LS 3

- ALICE 3: completely new detector

LS 4

LHCb:

- VELO & Upstream tracker upgrades
- Calorimeter. & muon upgrades

LS 2

- Smaller detector consolidation & enhancements

LS 3

- LHCb Upgrade II

LS 4

ATLAS:

- Muon New Small Wheels (MSW)
- Re-designed AFP TOF

LS 2

- Upgraded triggers & DAQ, HGTD
- New Inner Tracker + new μ chambers + lumi detectors

LS 3

CMS:

- New GEM detectors
- New innermost barrel pixel layer

LS 2

- Upgraded triggers & DAQ, MTD
- New Inner tracker + calo. endcap + μ detector

LS 3

Note: Only LHC experiments shown. Also interesting upgrades at SPS e.g. NA60+

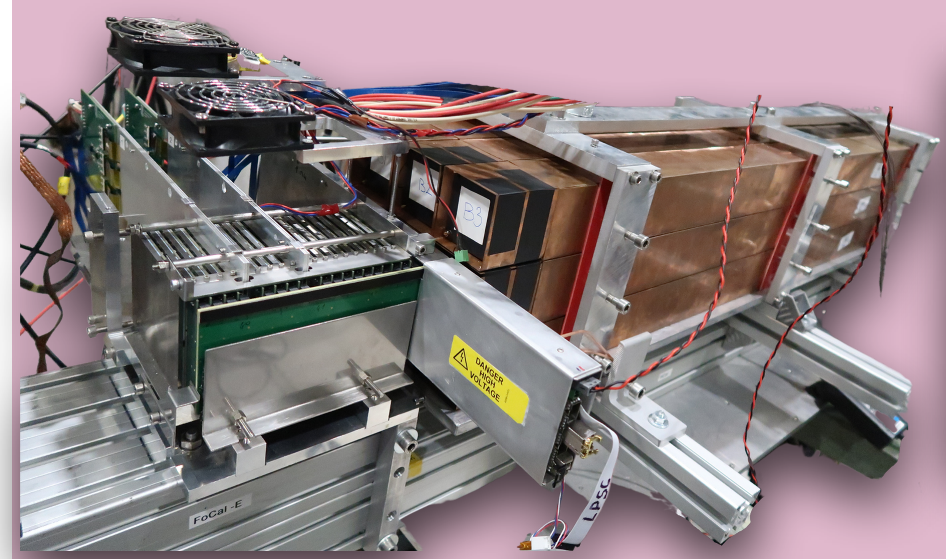
ALICE 2.1 upgrades

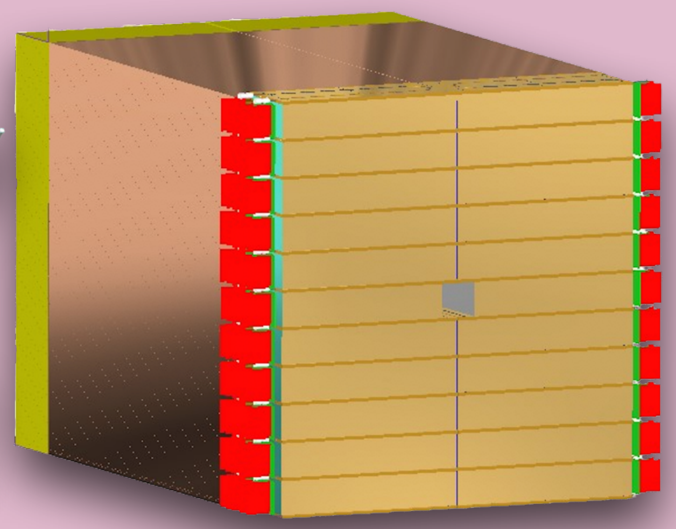
Run 1	Run 2	LS 2	Run 3	LS 3	Run 4	LS 4	Runs 5&6
	2015-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2041

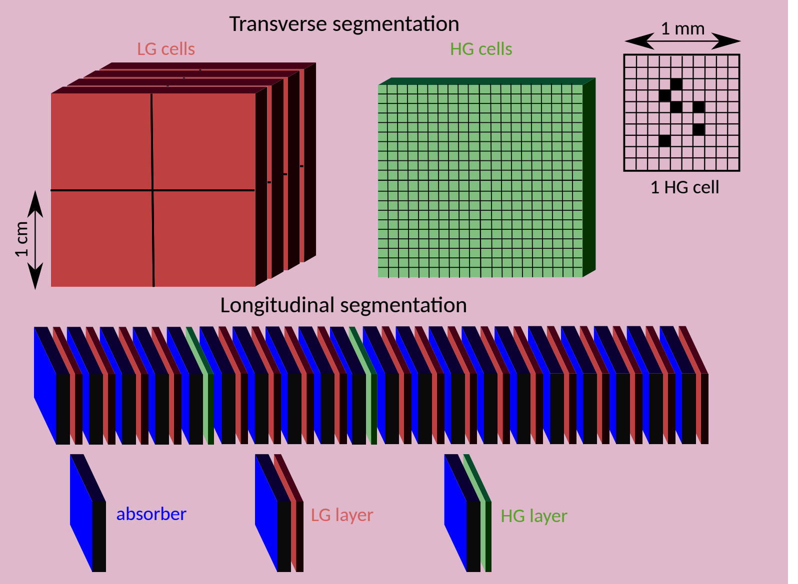
LS 3 Forward Calorimeter (FoCal) LS 3

- covering very forward rapidities $3.2 < \eta < 5.8 \rightarrow x \sim 10^{-6}$
- **FoCal-E:** highly granular Si-W calorimeter combining pixel and pad layers
- **FoCal-H:** scint. fibres embedded into Cu tubes

FoCal capabilities allow explorations of gluon saturation using a multi-messenger approach



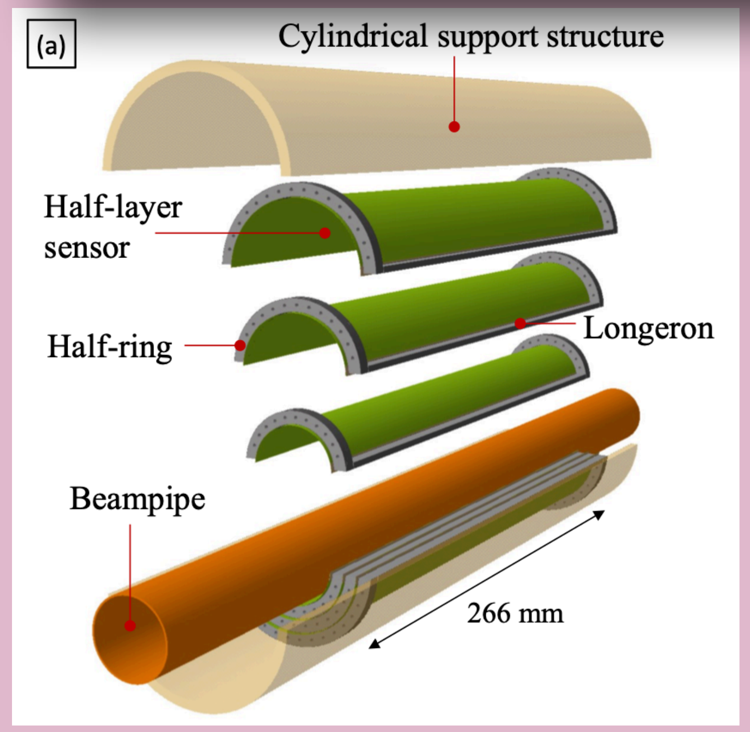


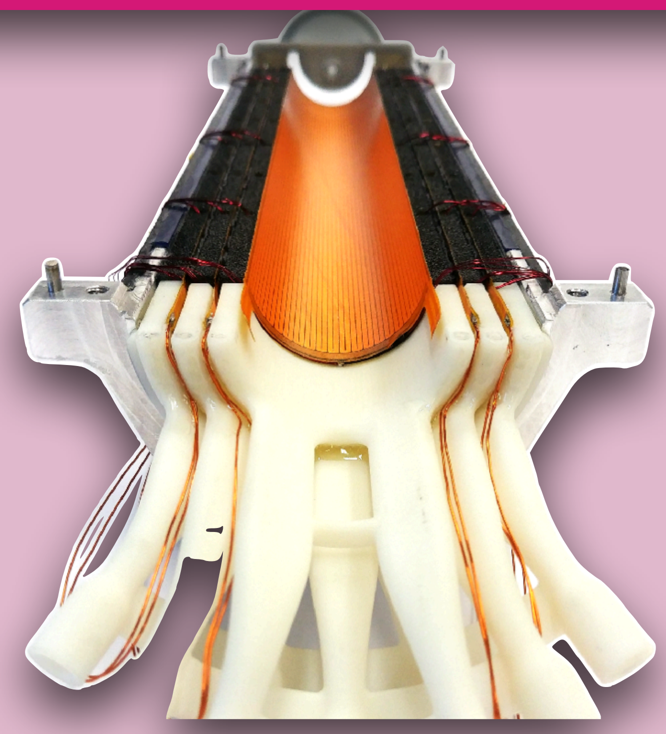


LS 3 Inner Tracking System 3 LS 3

- Replacement of ITS2 Inner Barrel with 3 layers of **ultralight & bent silicon wafer-scale MAPS**
- **Reduced material budget:** 0.09% X_0 vs. 0.36% X_0
- **Closer to interaction point:** 19mm vs. 23mm

Improvement of DCA resolution by factor 2





FoCal TDR: CERN-LHCC-2024-004

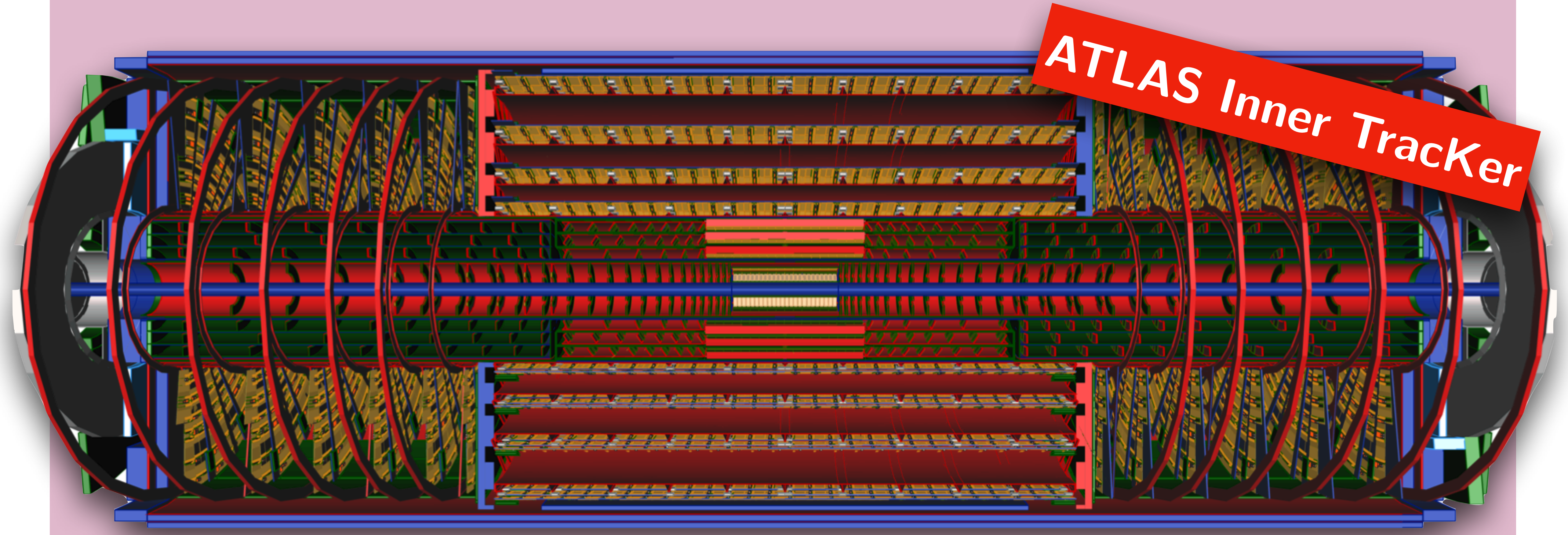
ITS3 TDR: CERN-LHCC-2024-003

ATLAS/CMS Phase 2 upgrades

Run 1	2015-2018 Run 2	2019-2021 LS 2	2022-2025 Run 3	2026-2028 LS 3	2029-2032 Run 4	2033-2034 LS 4	2035-2041 Runs 5&6

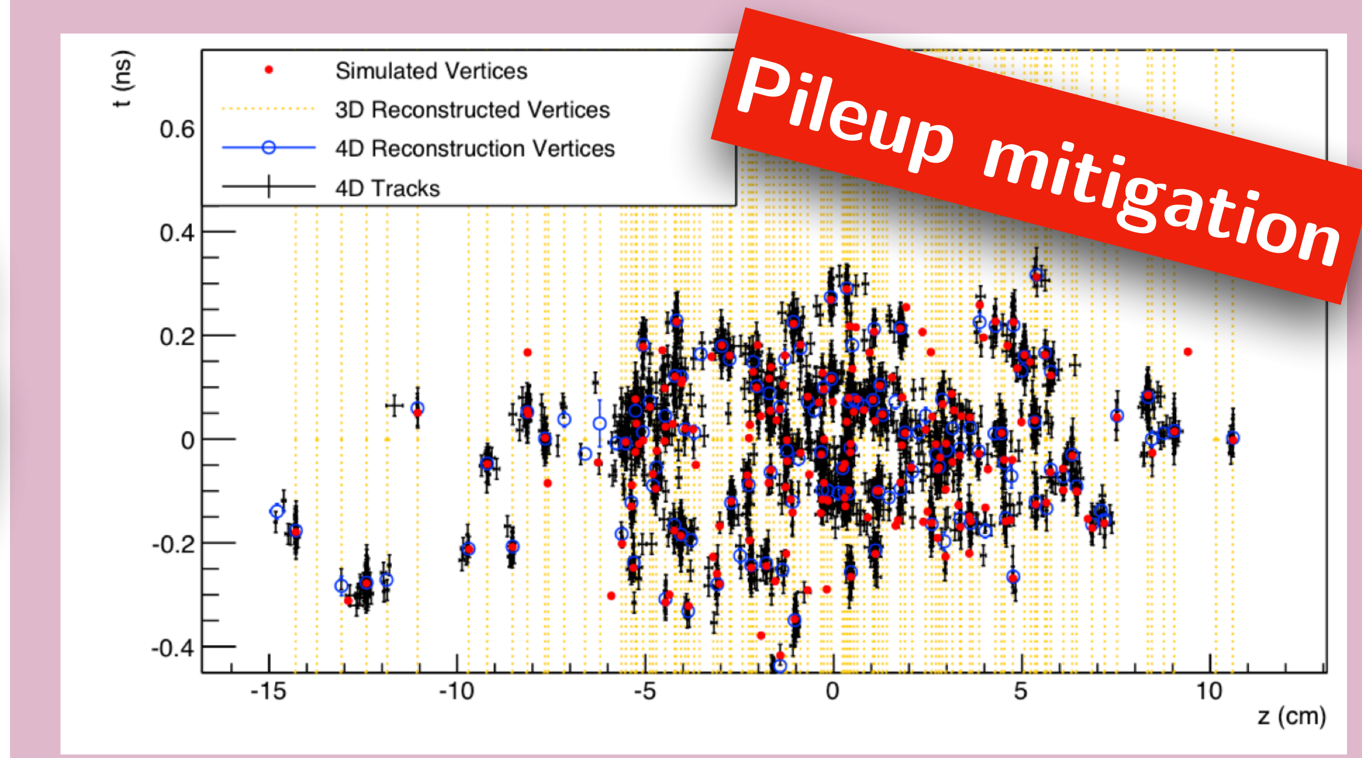
LS 3 ATLAS Phase II upgrade LS 3

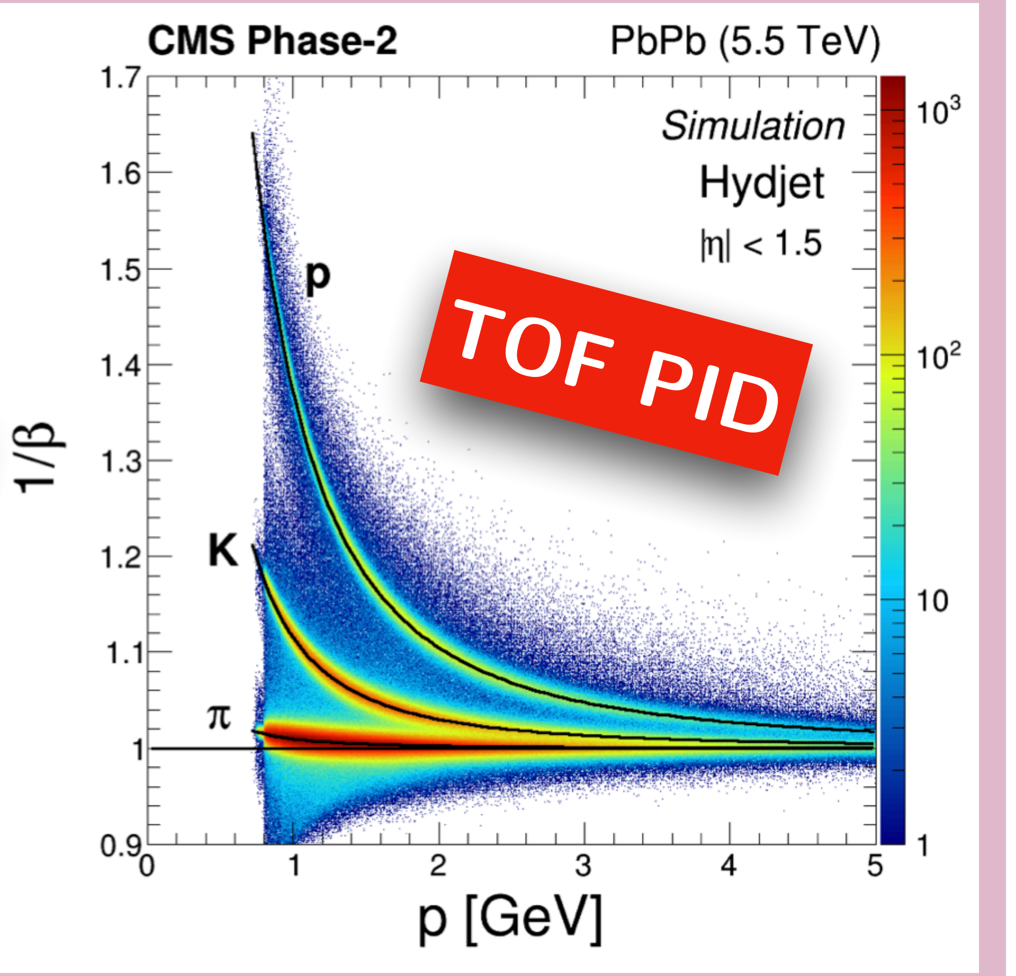
- **Completely new Inner tracker:**
  - $|\eta| < 2.5 \rightarrow |\eta| < 4$
- **New high-granularity timing detector (HGTD):**
  - Disentangle events with large pileup (30-50ps/track)
- **New muon chambers**



LS 3 CMS Phase II upgrade LS 3

- **Tracker upgrade:**
  - $|\eta| < 2.5 \rightarrow |\eta| < 4$
- **New MIP Timing Detector (MTD):**
  - TOF PID with $\sigma_t \sim$ 35ps
- **New Endcap Calorimeter**





CERN-LHCC-2012-022, CERN-LHCC-2017-005, -007 ,-017, -018, -020

CMS-TDR-14, -19, -20 & more

Run 1	Run 2	LS 2	Run 3	LS 3	Run 4	LS 4	Runs 5&6
	2015-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-2041

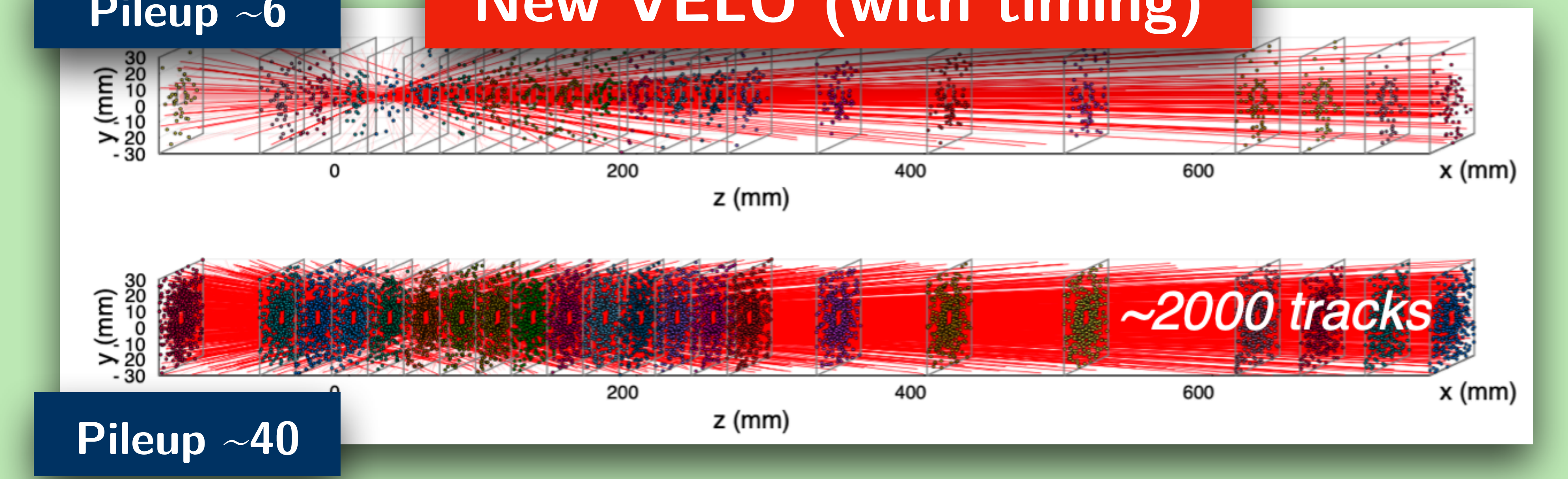
LS 4 LHCb Phase II upgrade LS 4

Target: same performance as in Run 3 but for pileup ~40 & full centrality coverage

- New VELO (4D tracking (with timing)
- Upstream Tracker + Mighty Tracker
- RICH + TOF + ECal + muon stations

Heavy-ion program for beam+beam and fixed-target collisions

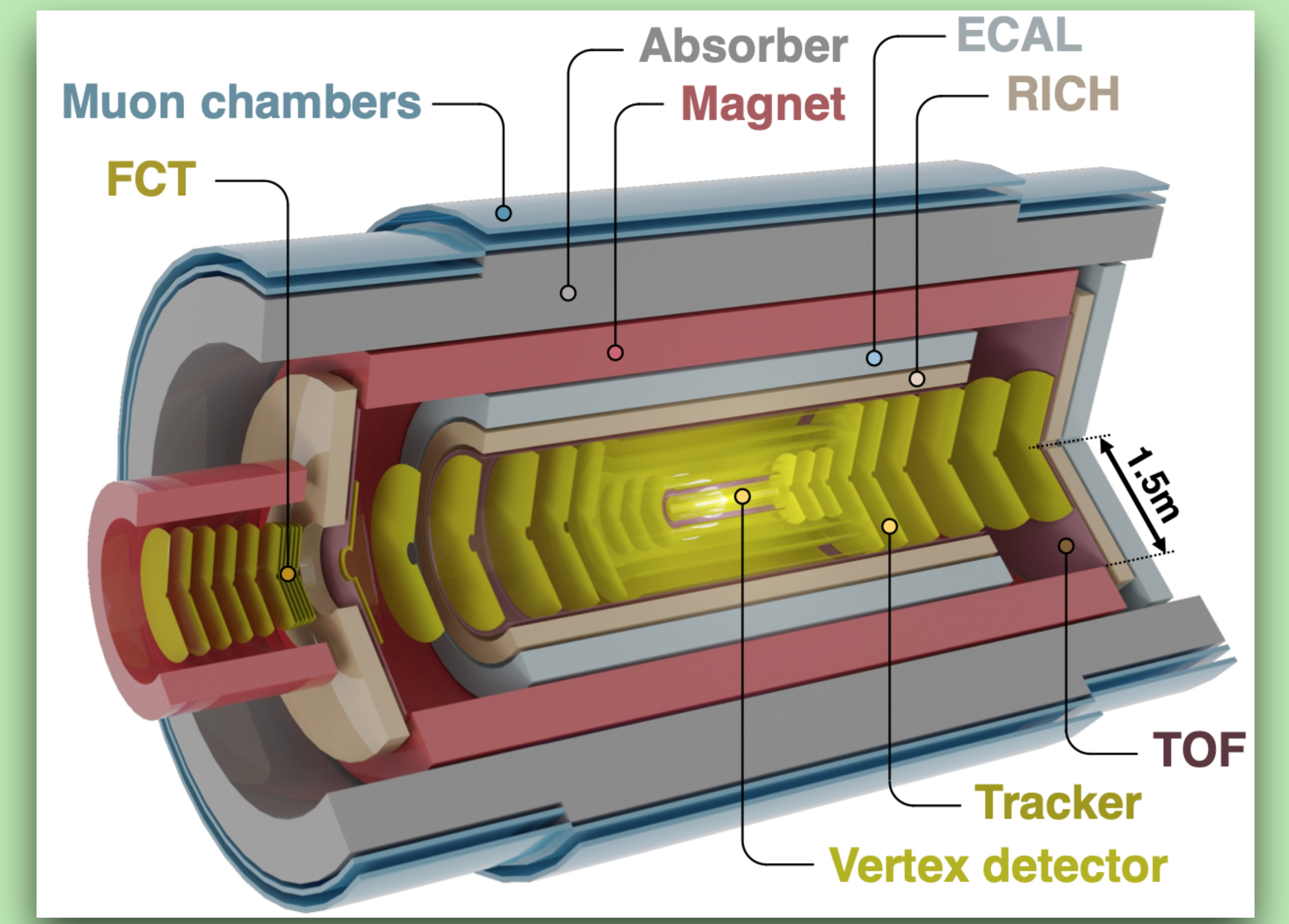
New VELO (with timing)



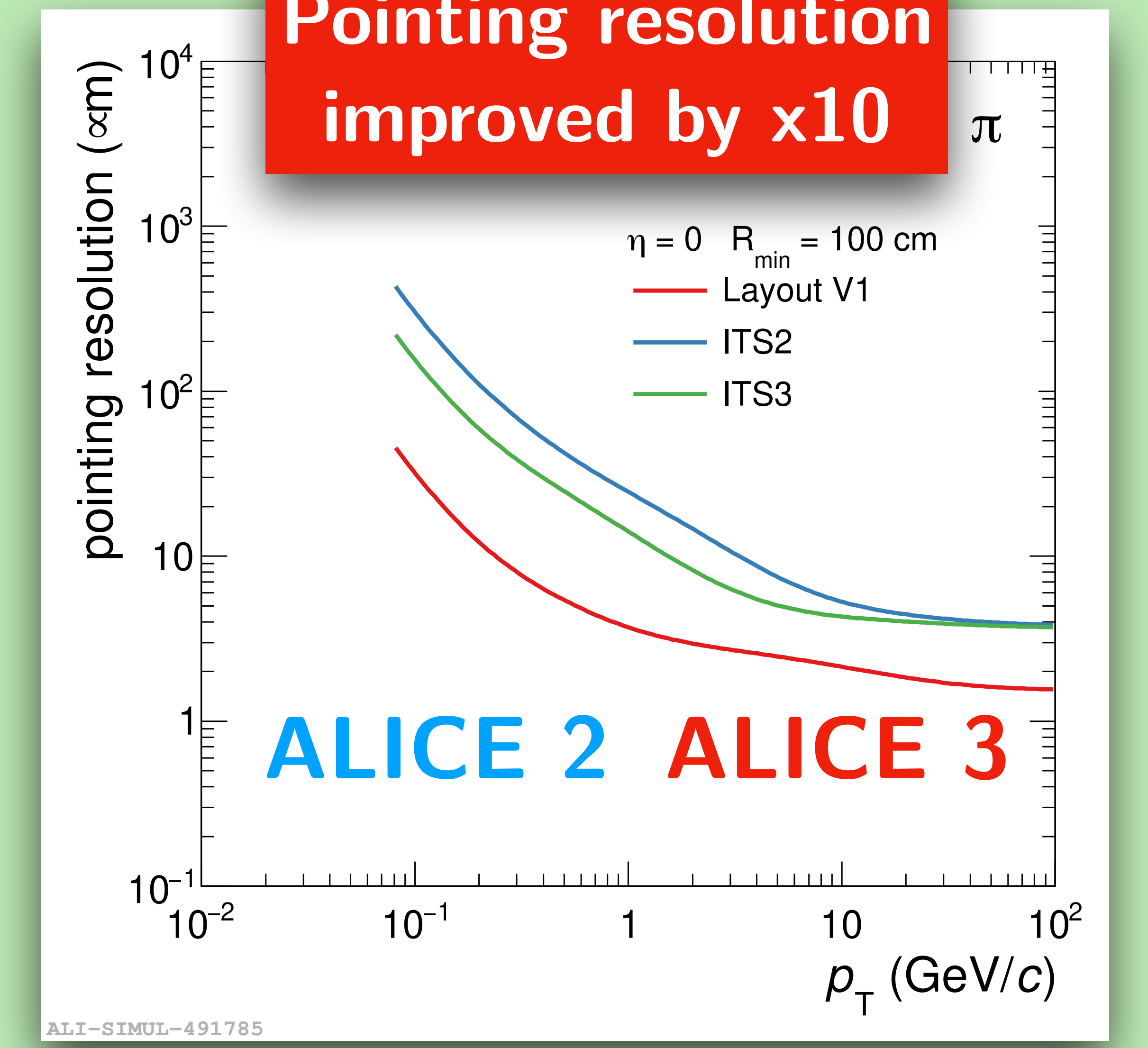
ALICE 3

All new experiment!

- **All-silicon tracker:** $|\eta| < 4$
- **Retractable vertex detector:** $r_0 = 5\text{mm}$; 2.5 μm spatial resolution!
- **PID:** TOF + RICH **Muon & Photon ID:** MID + ECal + FCT



Pointing resolution improved by x10



Detector & Interaction rate improvements

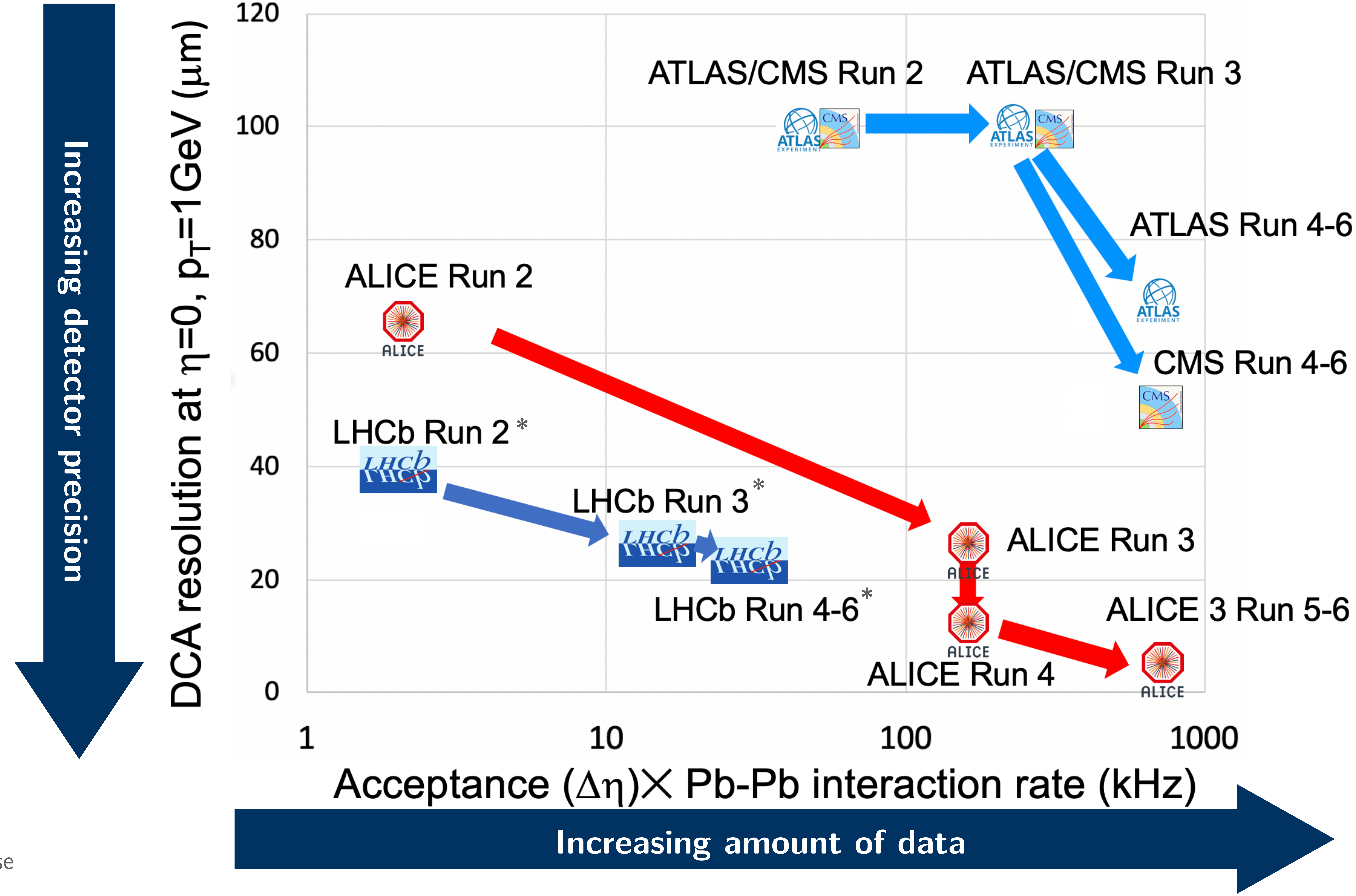
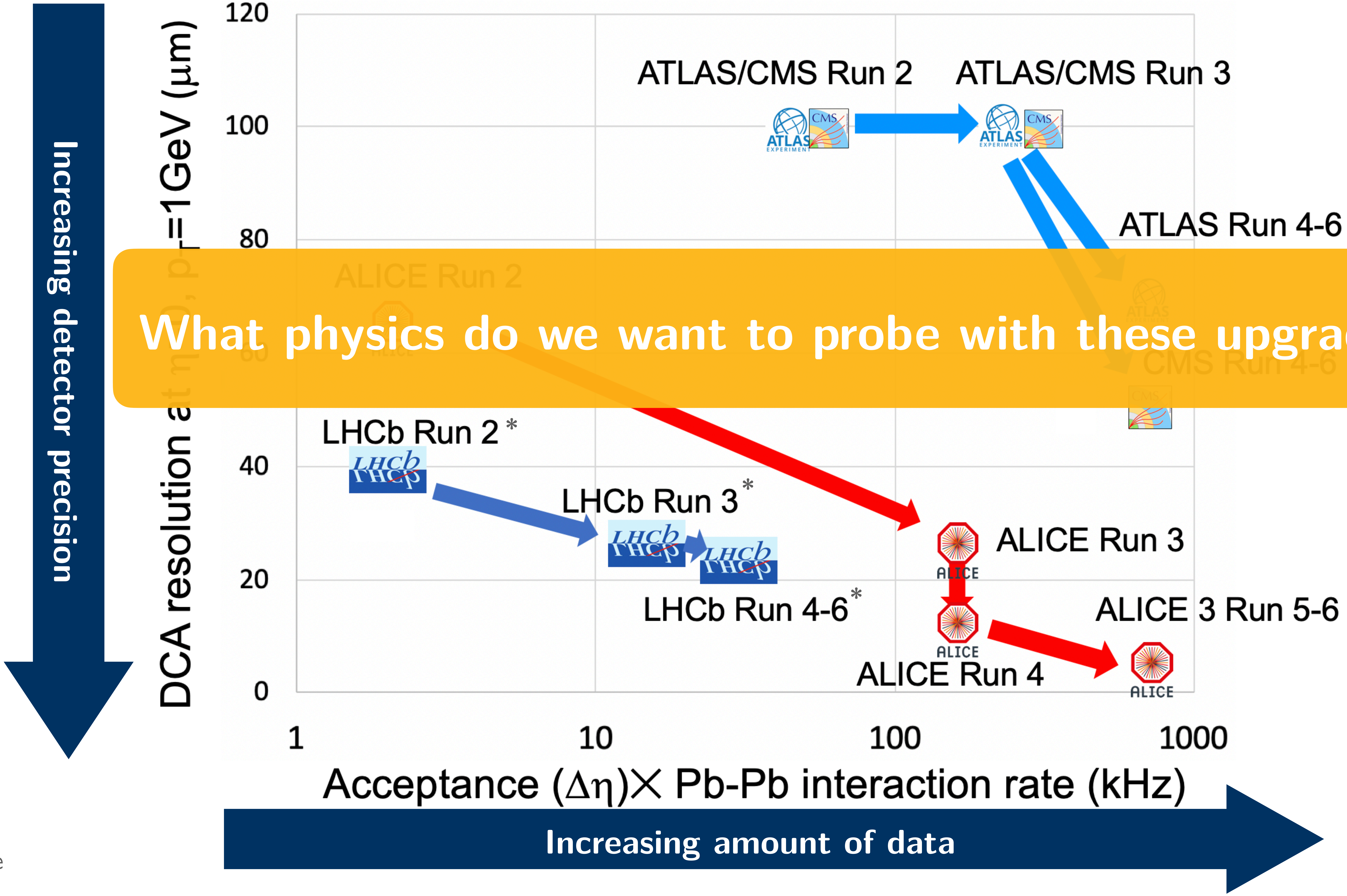


Image Credit: A. Dainese

*boost not considered

Detector & Interaction rate improvements



What physics do we want to probe with these upgrades?

Image Credit: A. Dainese

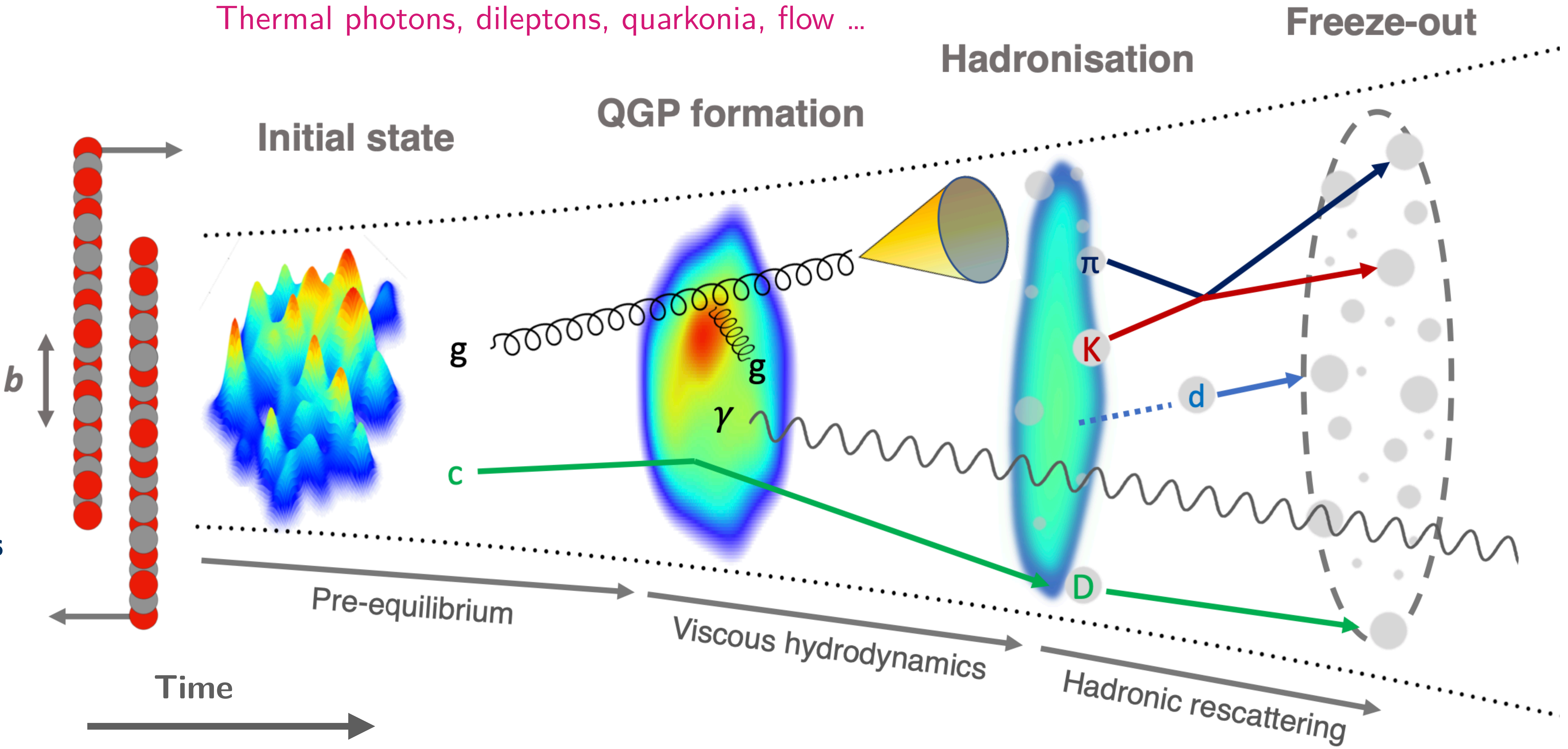
*boost not considered

Heavy-ion physics: The big questions

What are the macroscopic properties of the QGP? Temperature? Viscosity? QCD phase transition?
Thermal photons, dileptons, quarkonia, flow ...

What are the initial conditions of a collision? nPDFs & Saturation?
DY, UPC, forward LHC ...

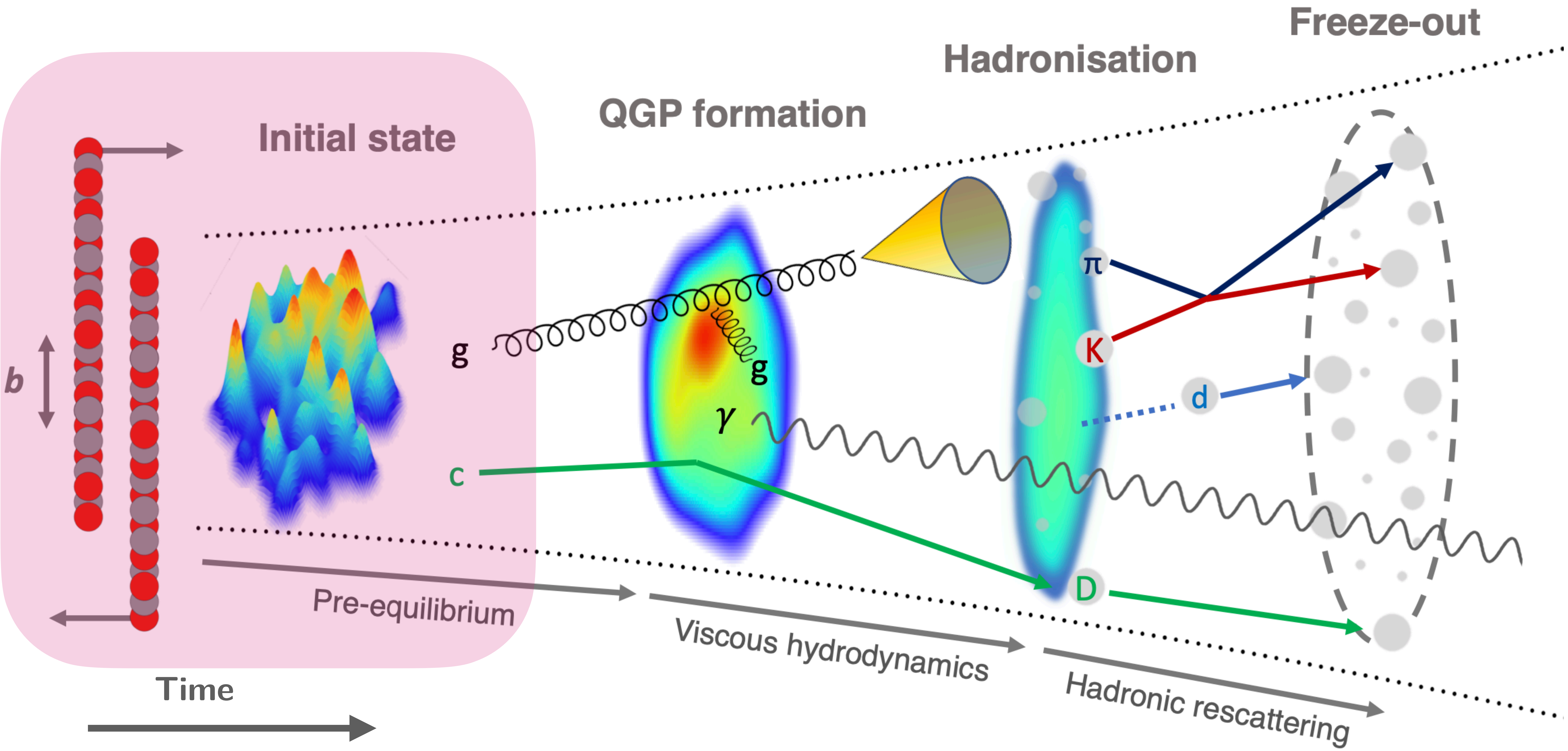
Collectivity of QCD across system sizes?
Flow in pp, p-A; strangeness production, energy loss, thermal radiation



arXiv:2211.04384

What is the microscopic dynamics of QGP at various length scales?
Jets (substructure), γ/Z-jet correlations, heavy flavour, quarkonia, hadronization

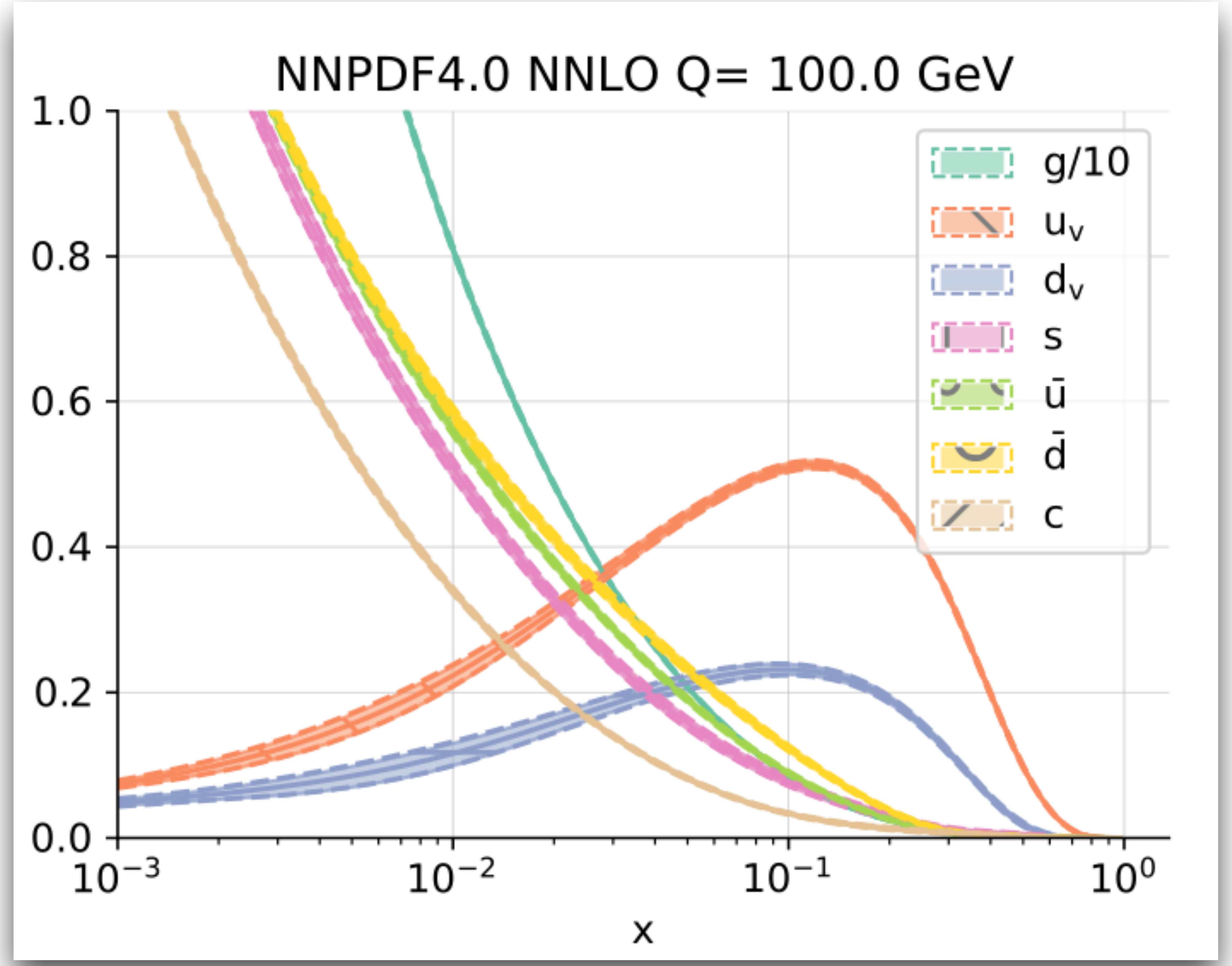
What are the initial conditions of a collision? nPDFs & Saturation?
DY, UPC, forward LHC ...



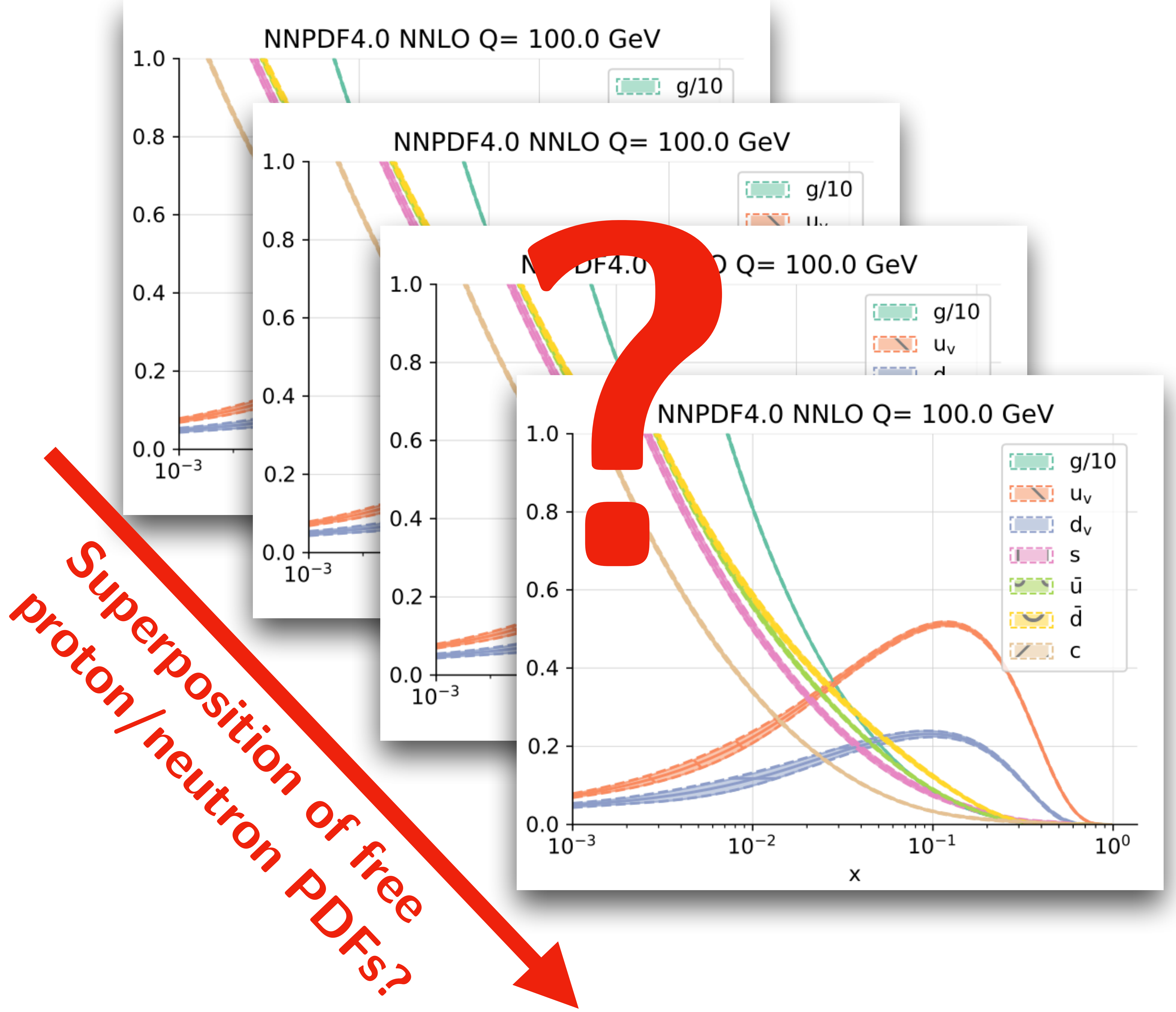
arXiv:2211.04384

How are partons distributed in a proton that is part of a bigger structure?

Proton PDF



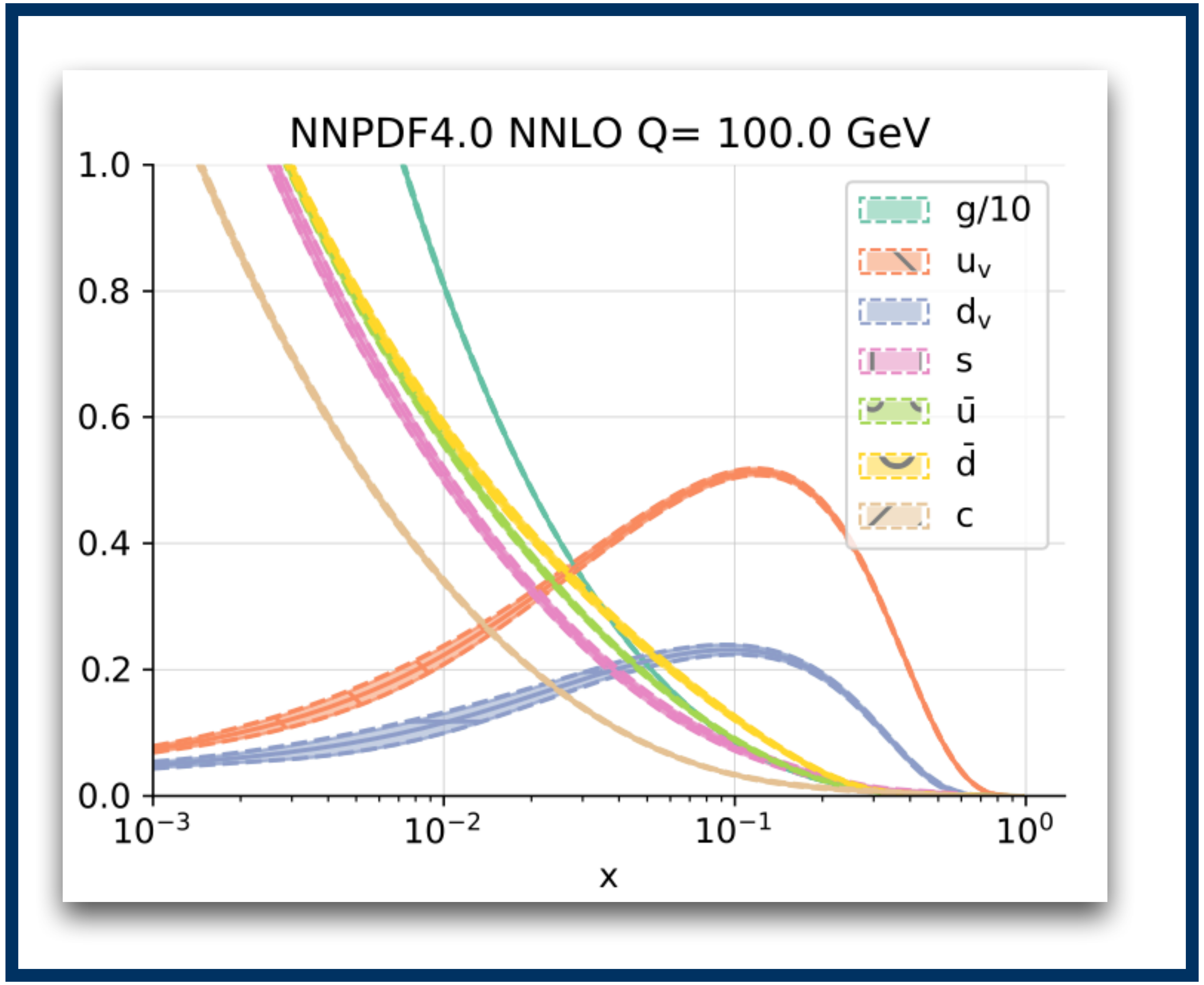
Pb PDF



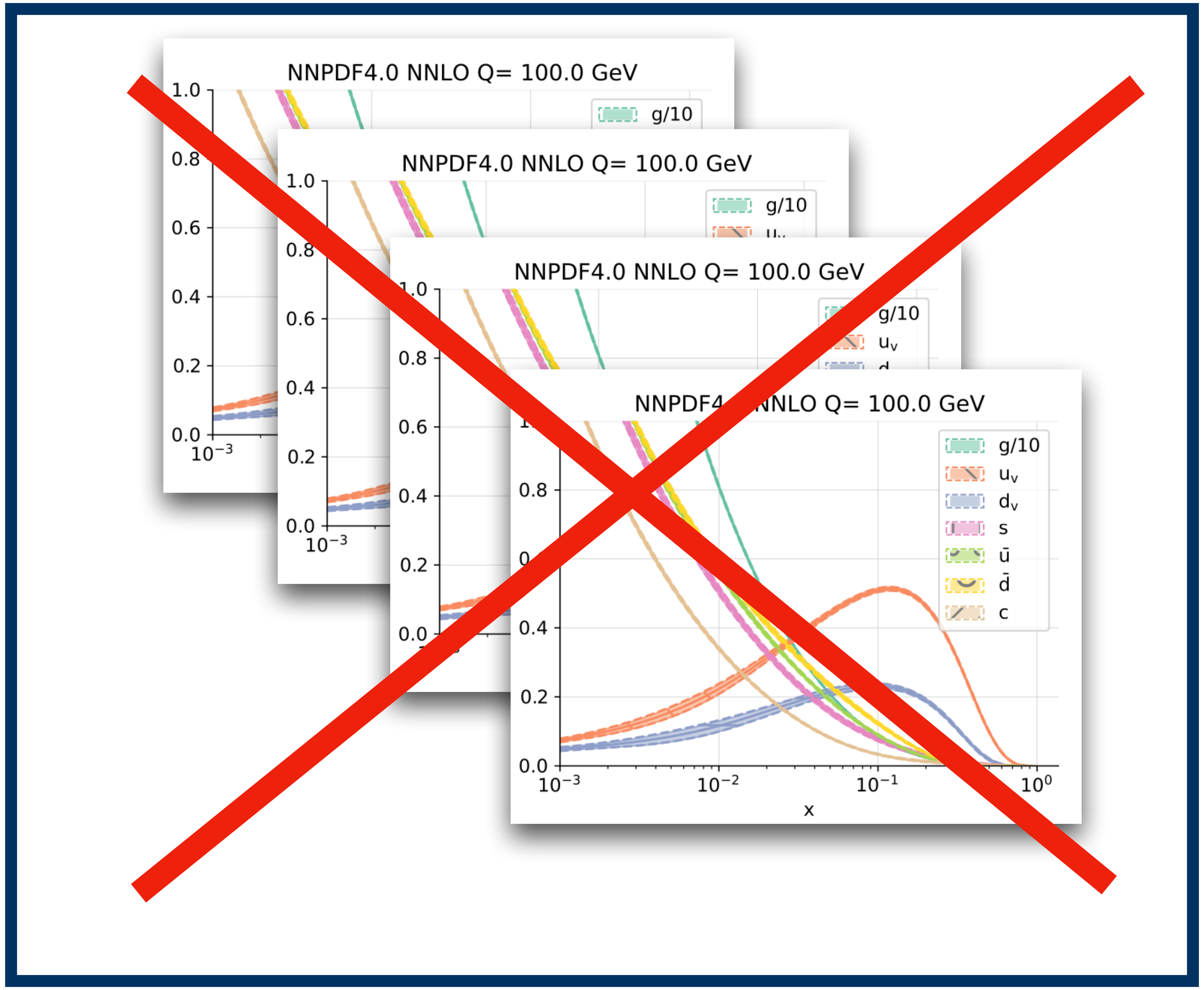
Eur.Phys.J.C 82 (2022) 5, 428

How are partons distributed in a proton that is part of a bigger structure?

Proton PDF



Pb PDF

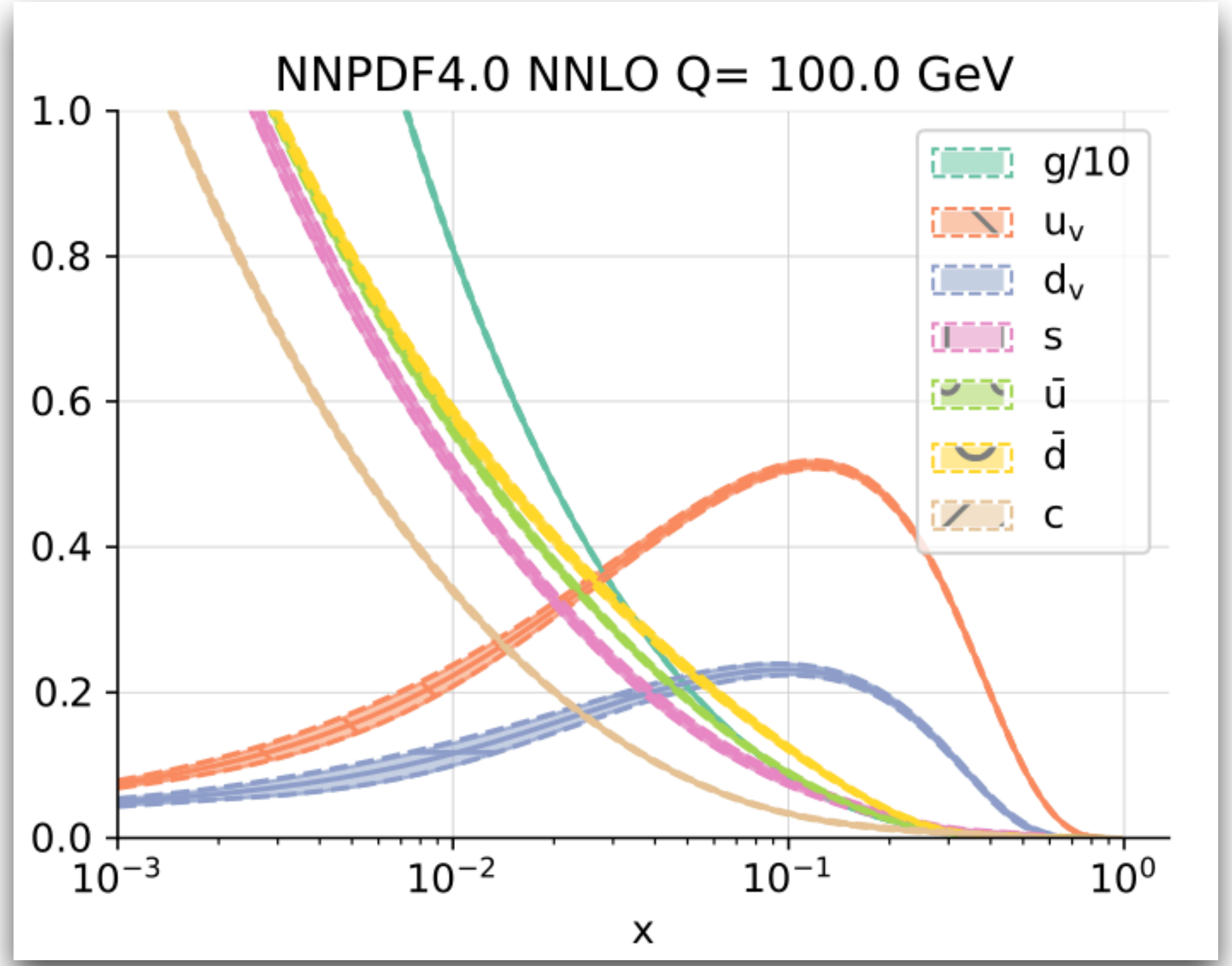


Eur.Phys.J.C 82 (2022) 5, 428

Overview: Probing partons in the incoming projectiles

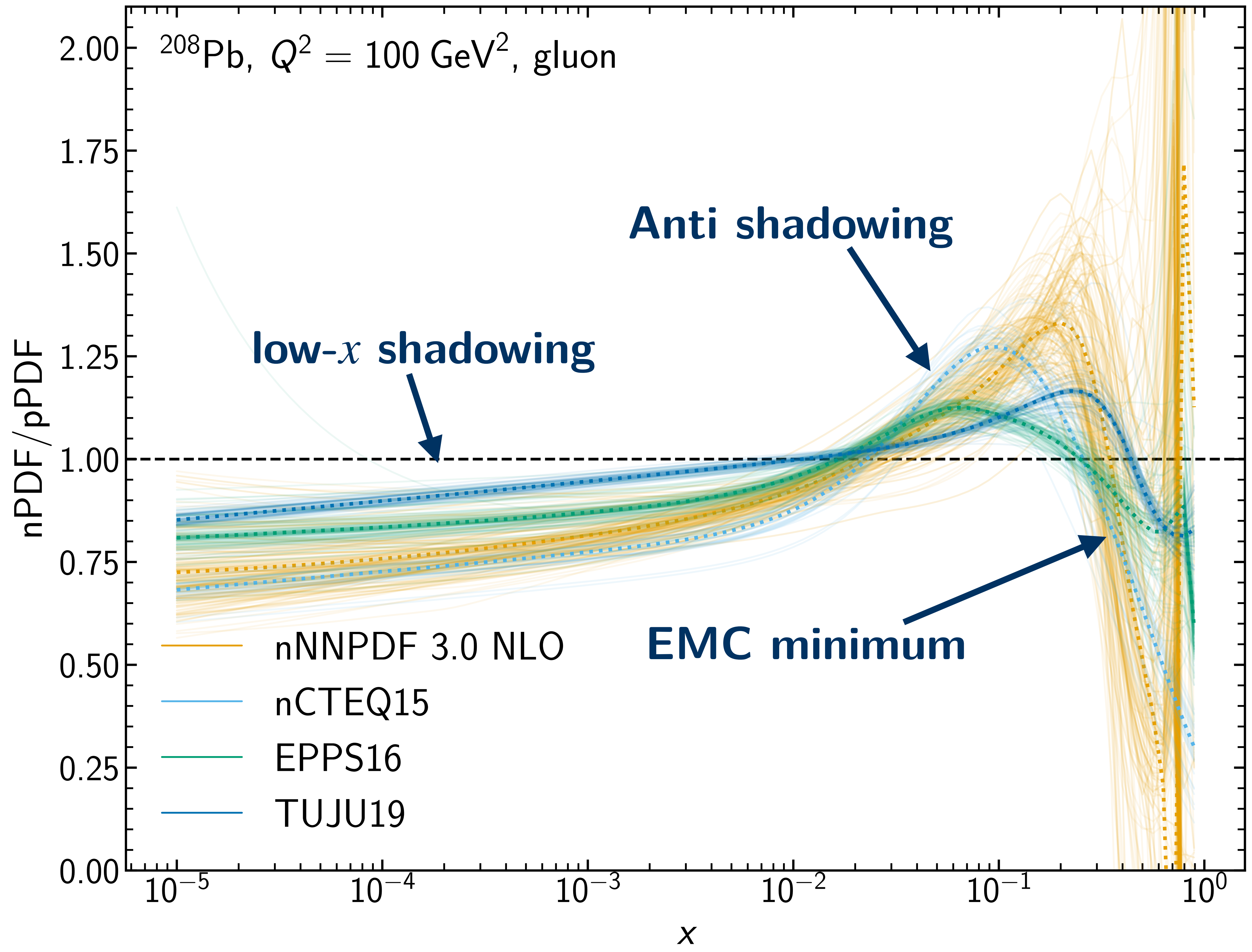
How are partons distributed in a proton that is part of a bigger structure?

Proton PDF



Eur.Phys.J.C 82 (2022) 5, 428

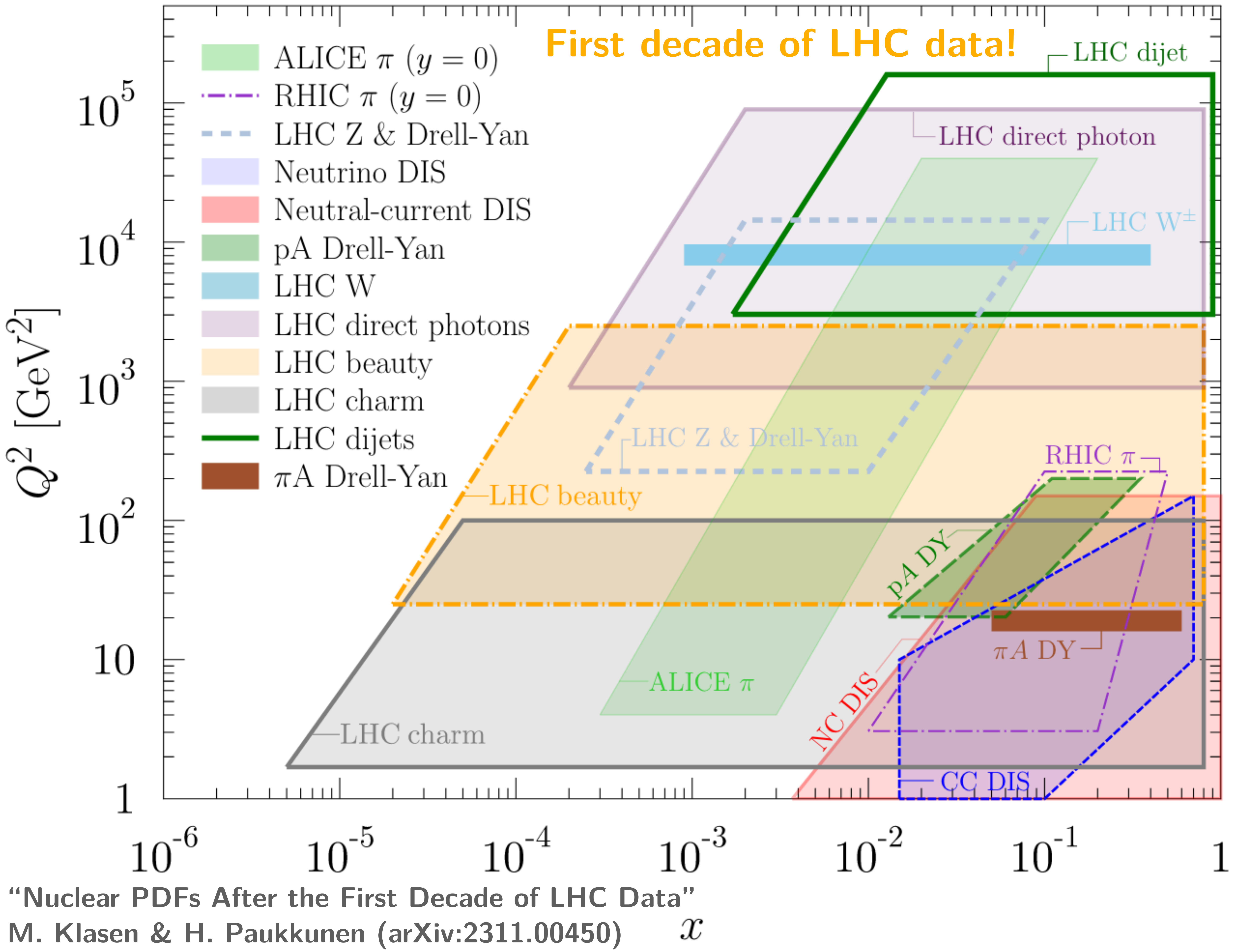
Pb PDF



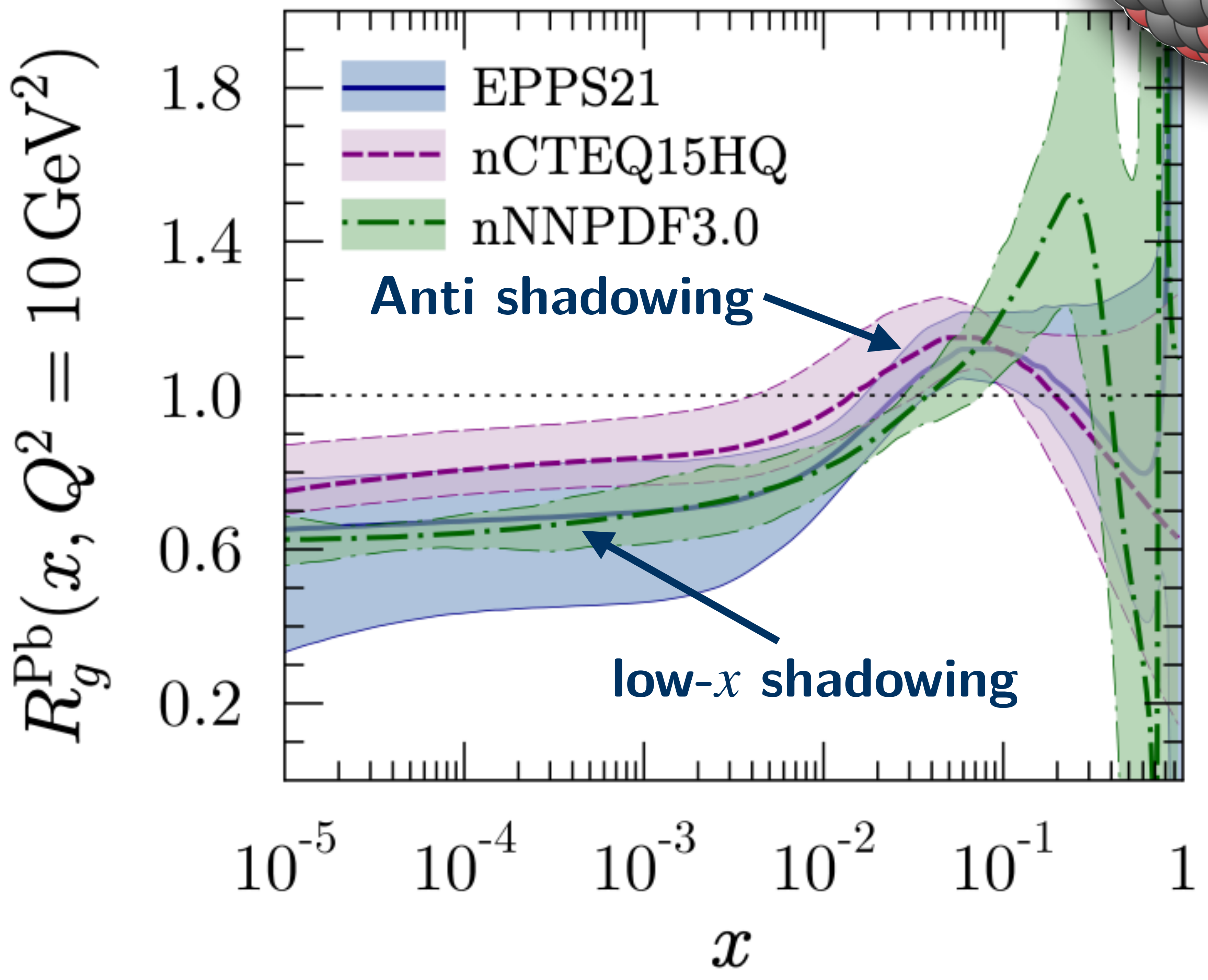
Modifications with respect to free-proton PDF!

Overview: Probing partons in the incoming projectiles

Coverage of lepton-A, pion-A and proton-A data in nPDFs

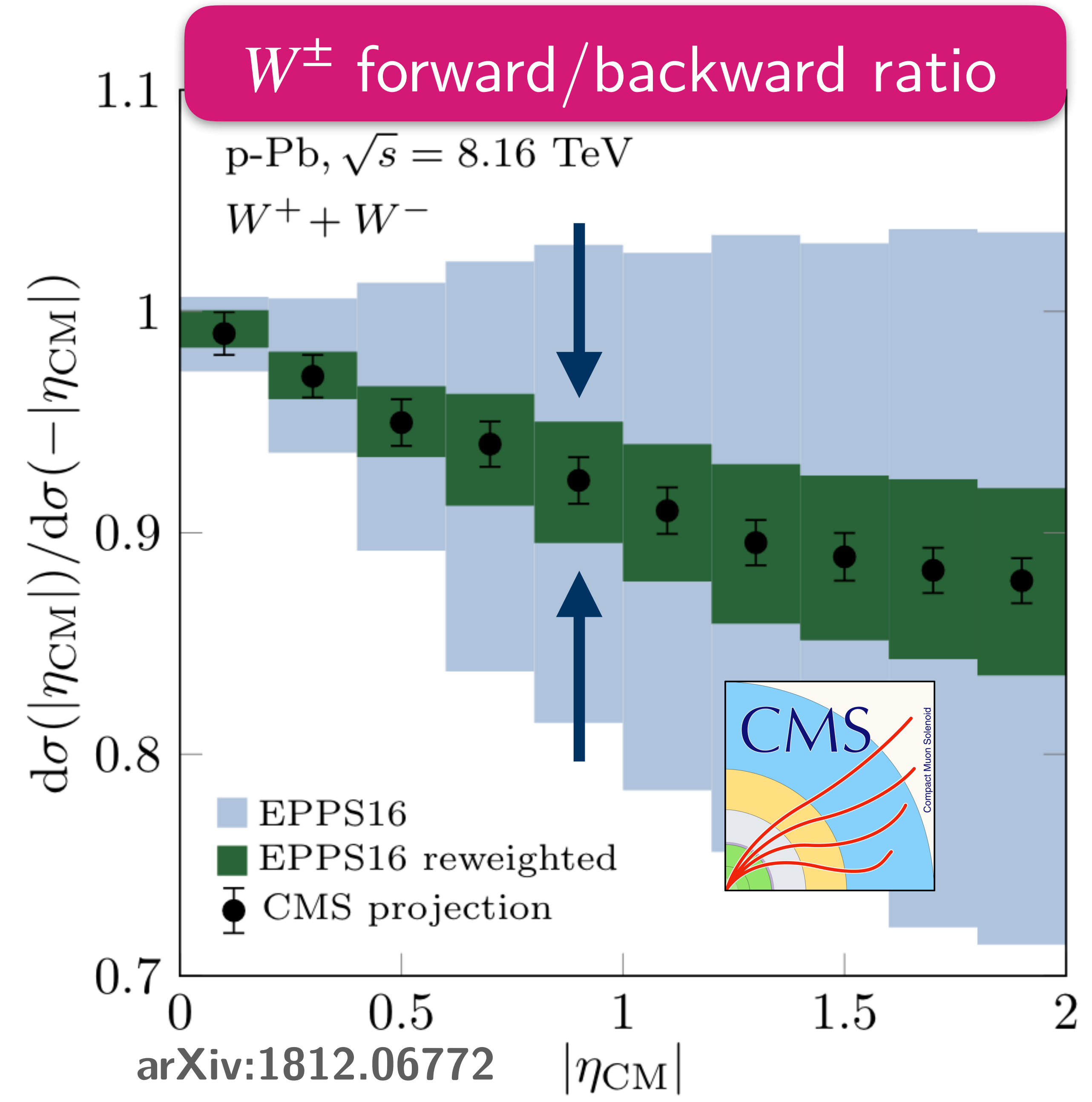


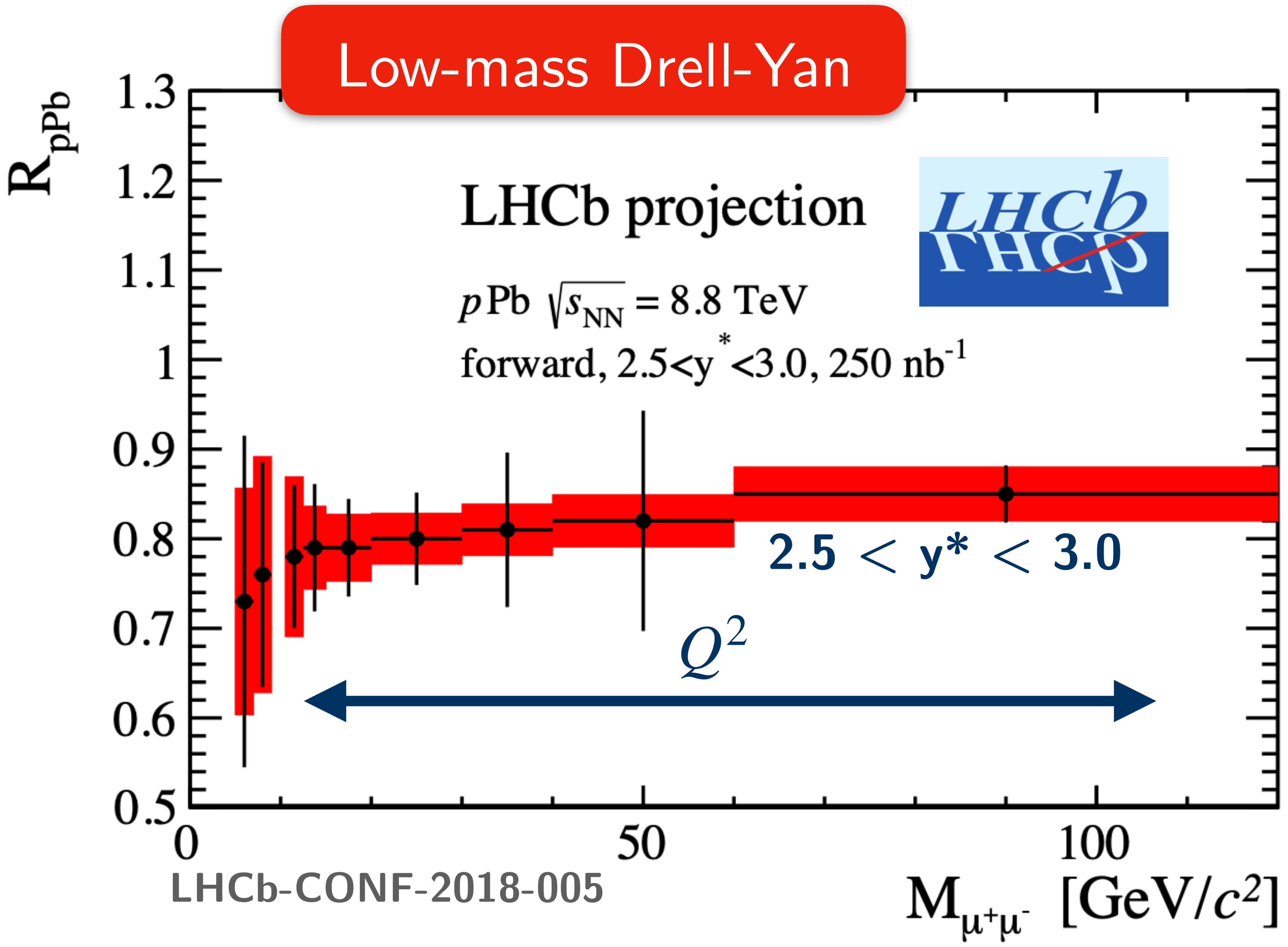
"Nuclear PDFs After the First Decade of LHC Data"
M. Klasen & H. Paukkunen (arXiv:2311.00450)

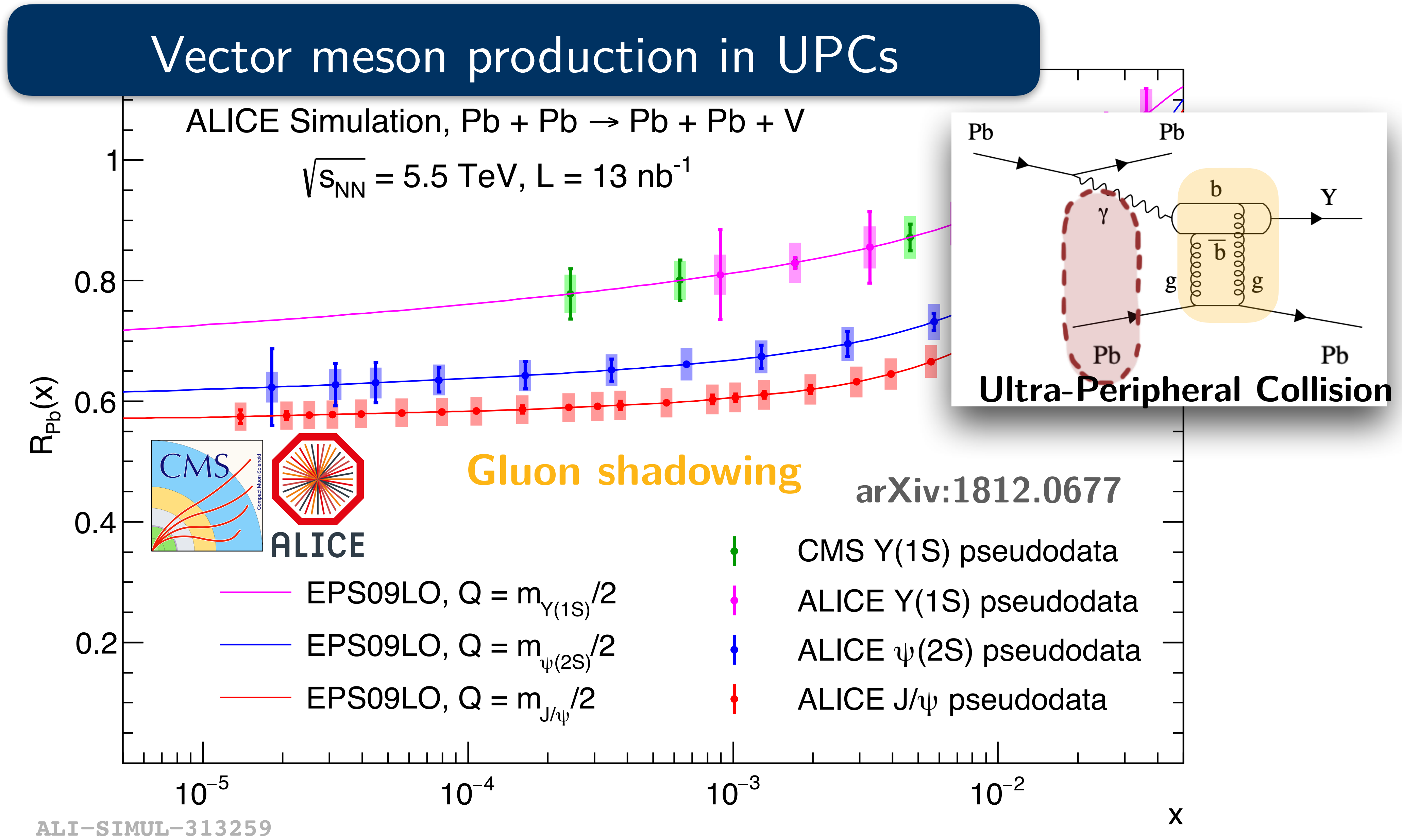


- A decade of LHC data provided significant constraints for nPDF in novel phase space
- Increase of exp. data included in global fits: EPPS09 ($N_{\mathrm{dat}} = 929$) → EPPS21 ($N_{\mathrm{dat}} = 2077$)
- Sizeable gluon shadowing at low-x, but slight tension between different global fits

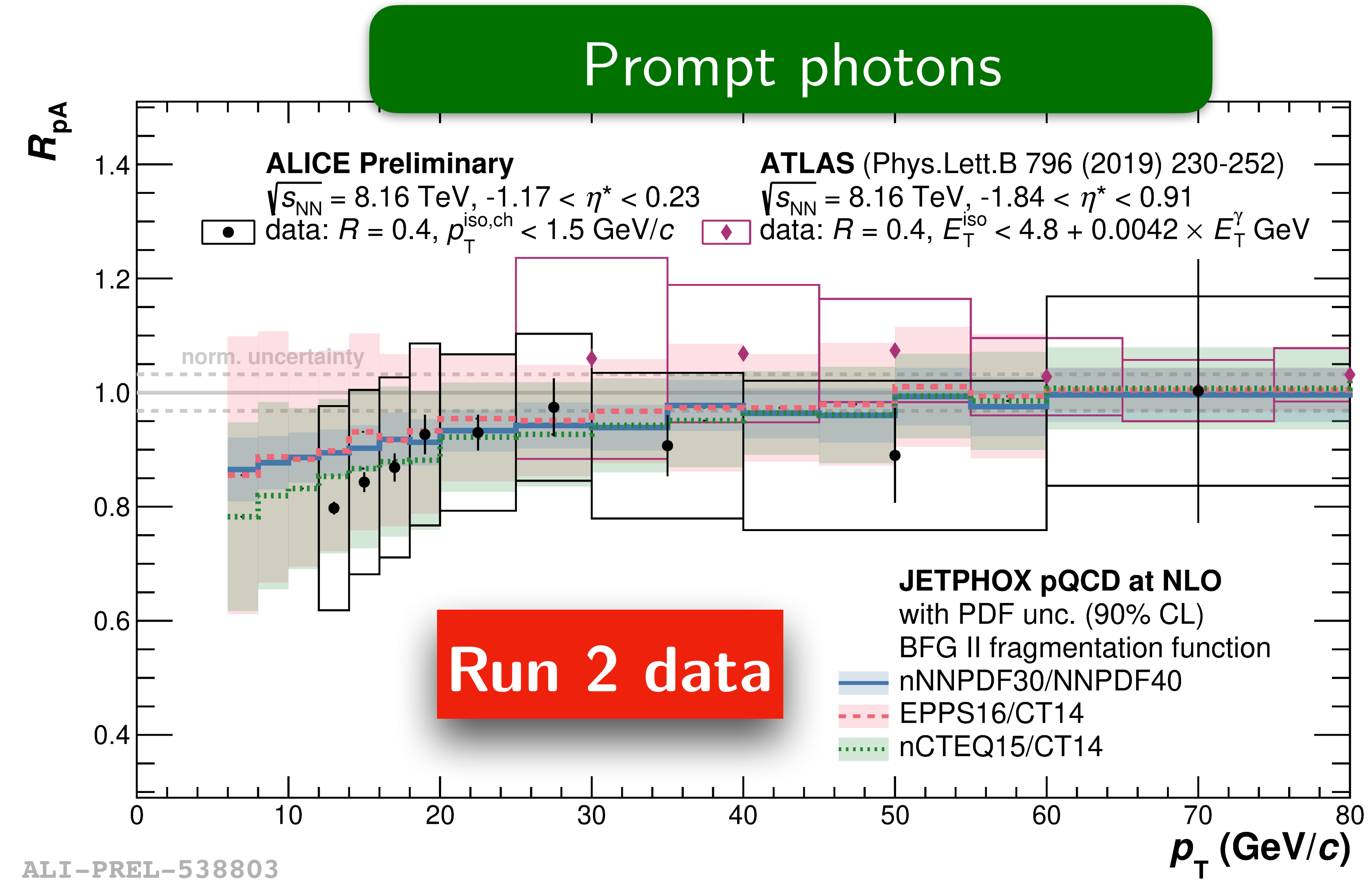
Initial state: Probing partons in the incoming projectiles

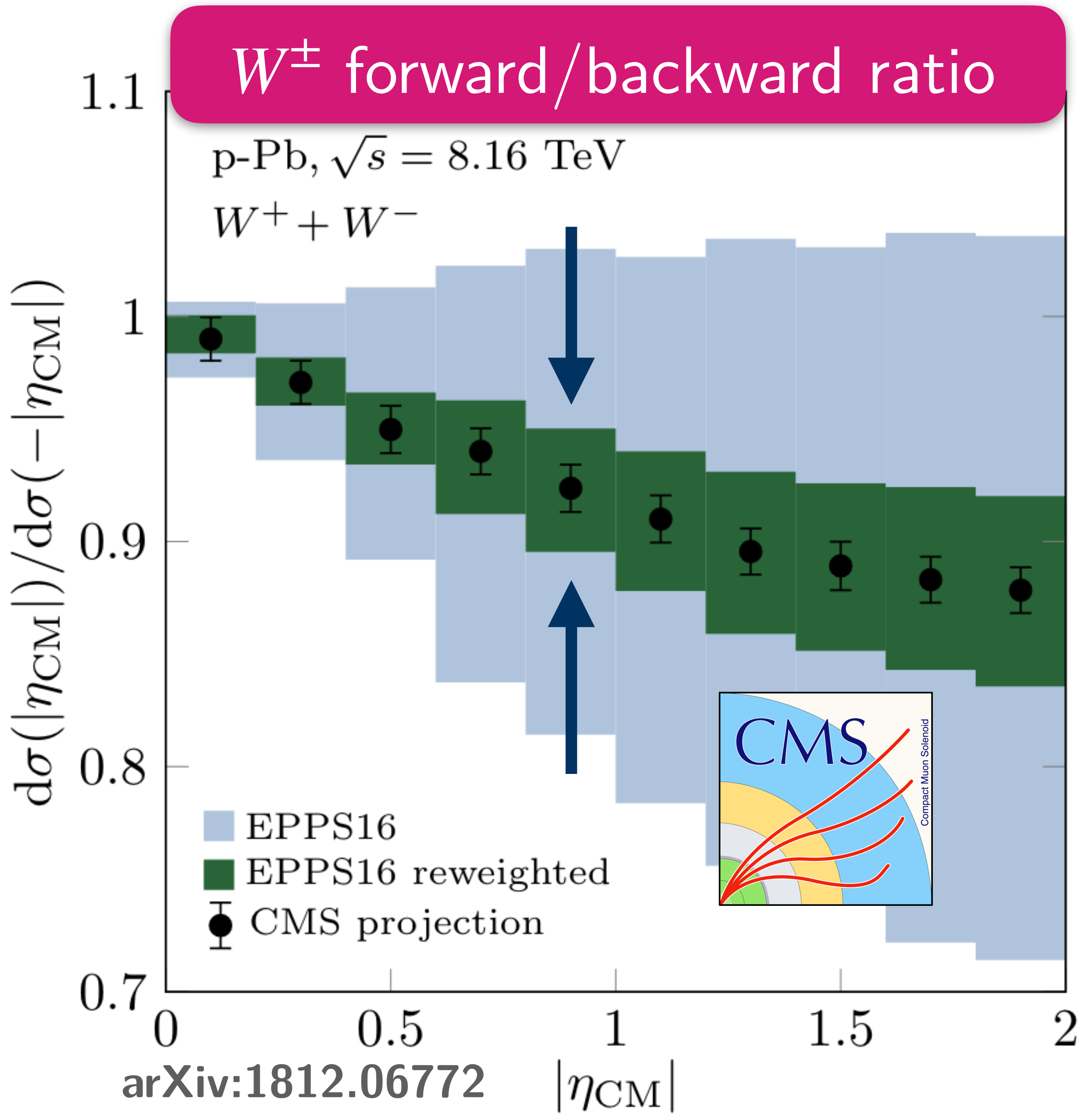






Probing (nuclear) matter in a novel phase-space with high precision:

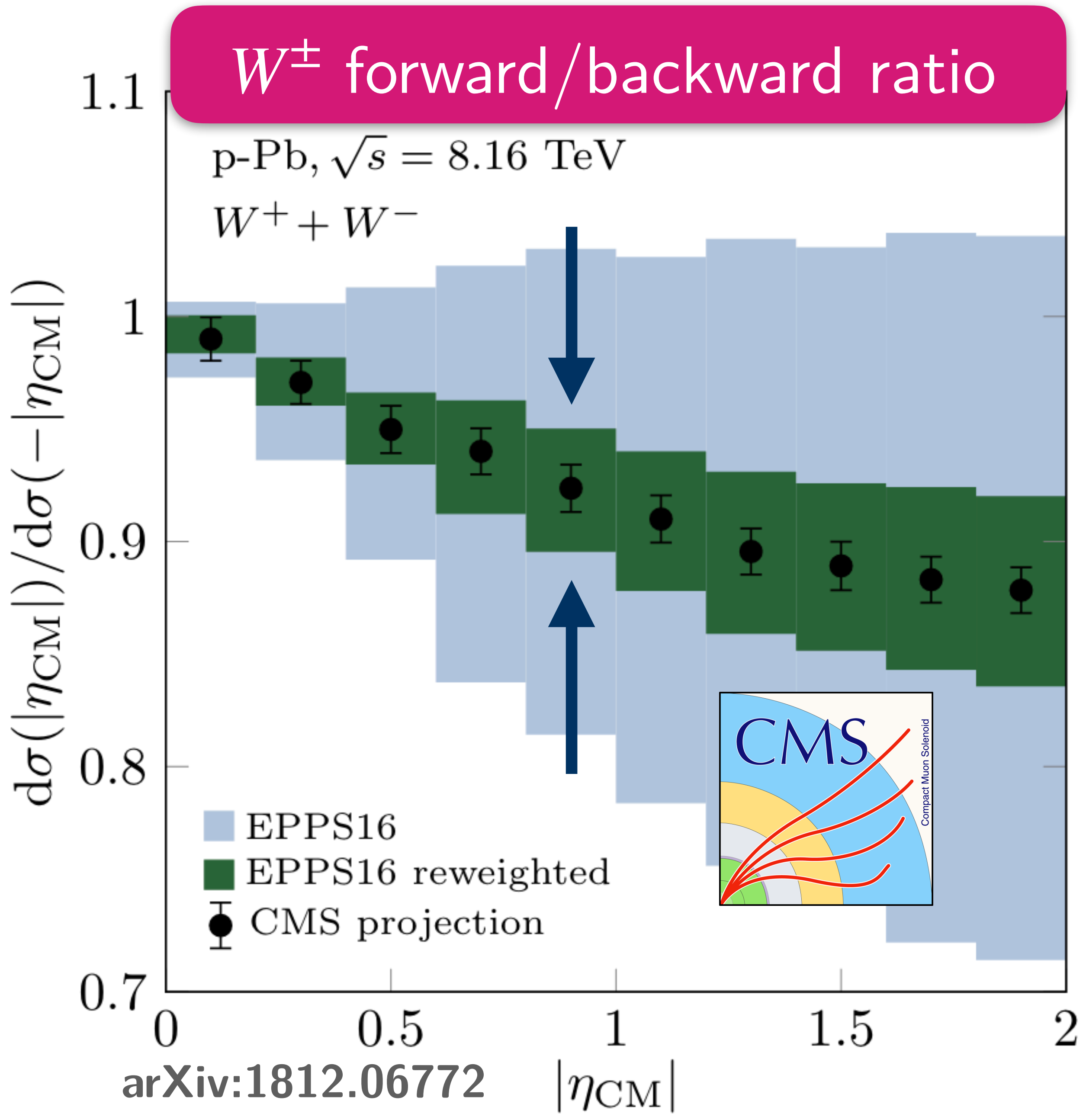


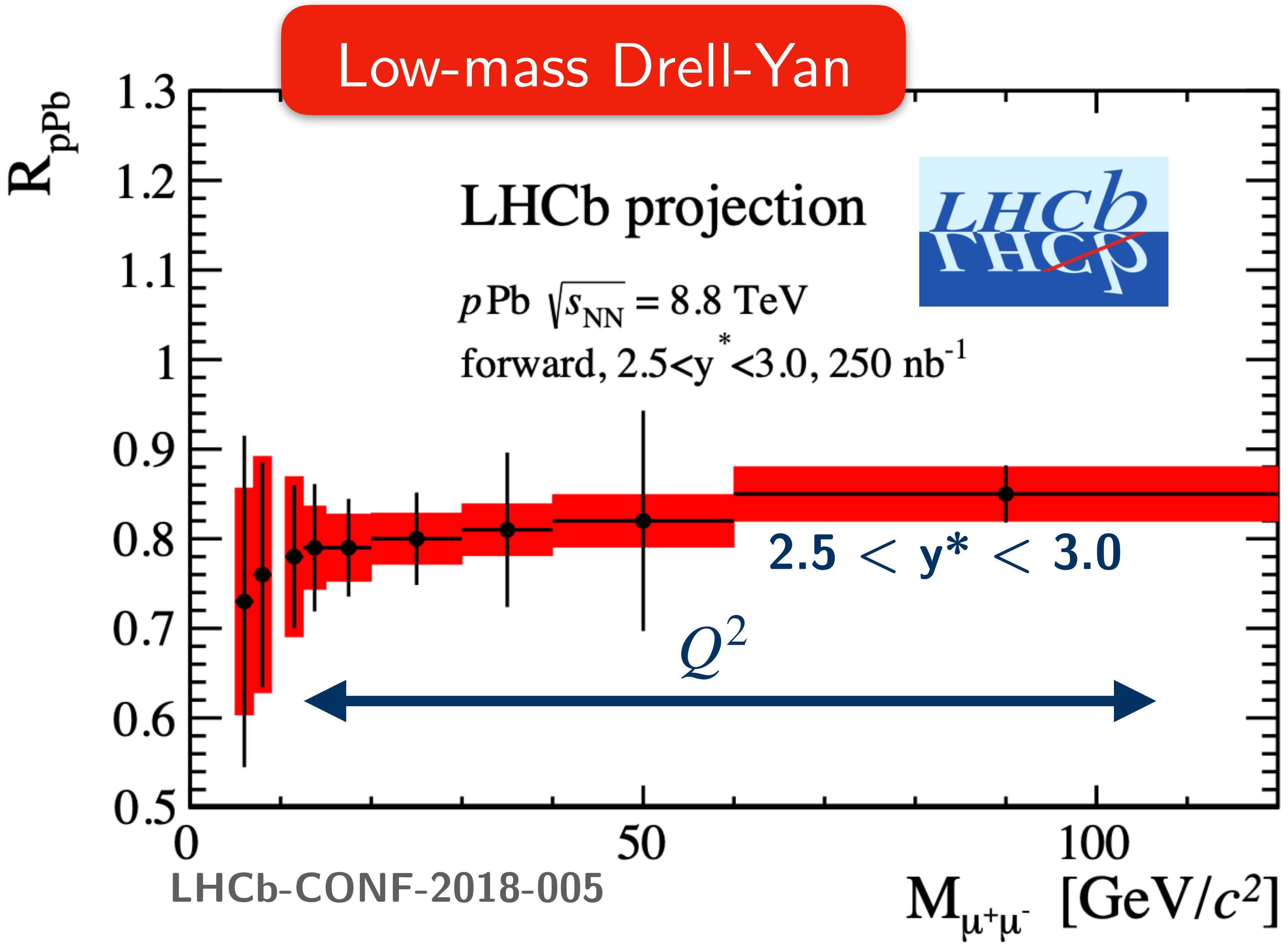


arXiv:1812.06772

Probing (nuclear) matter in a novel phase-space with high precision:

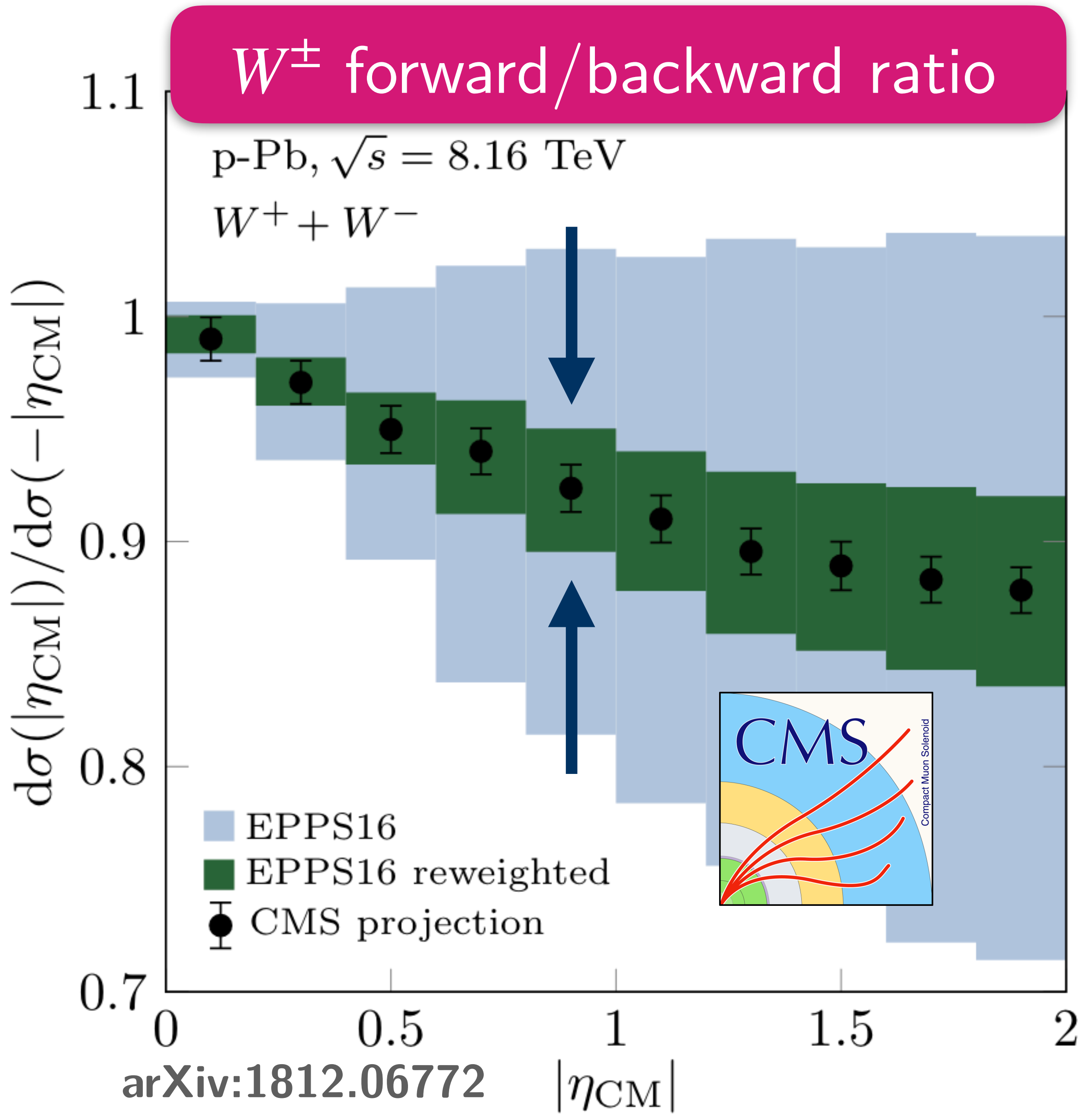
- $W^{\pm}/Z$ **production:** sensitive to quark (n)PDF and heavy flavours

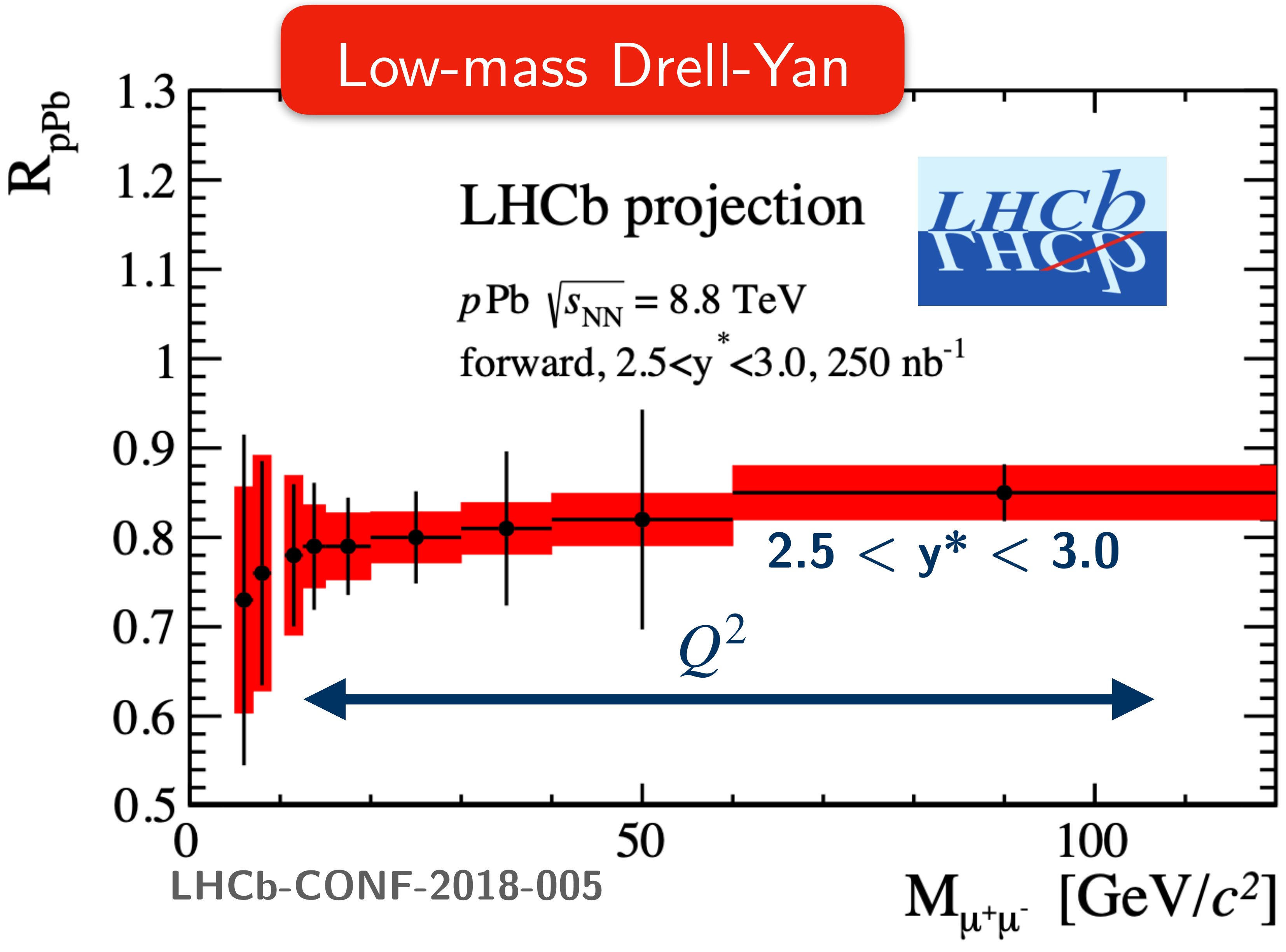


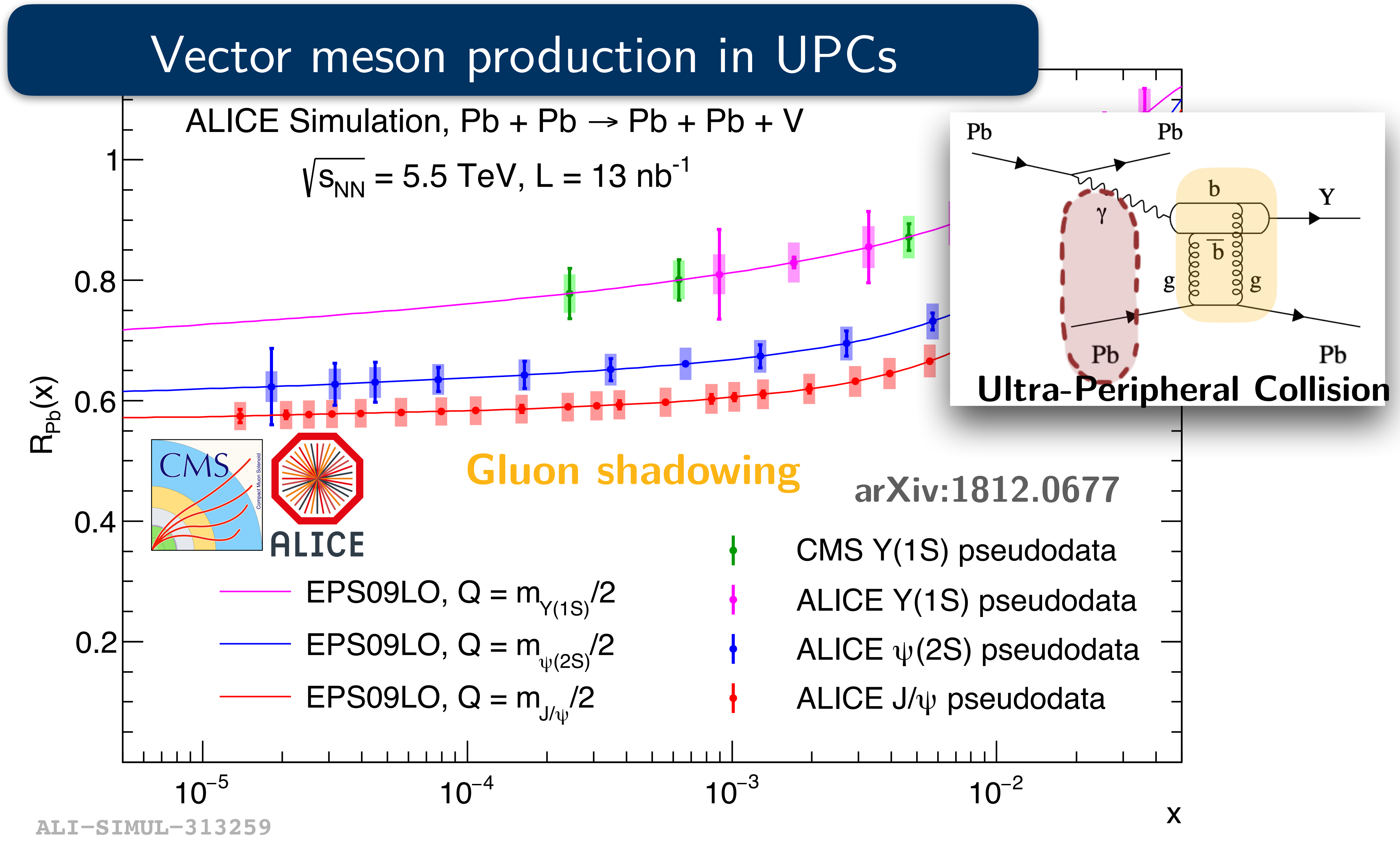


Probing (nuclear) matter in a novel phase-space with high precision:

- $W^{\pm}/\ Z$ **production:** sensitive to quark (n)PDF and heavy flavours
- **Low-mass Drell-Yan:** precision measurement over wide mass range & differential in y offer possibility to test Q^2 evolution of nPDFs



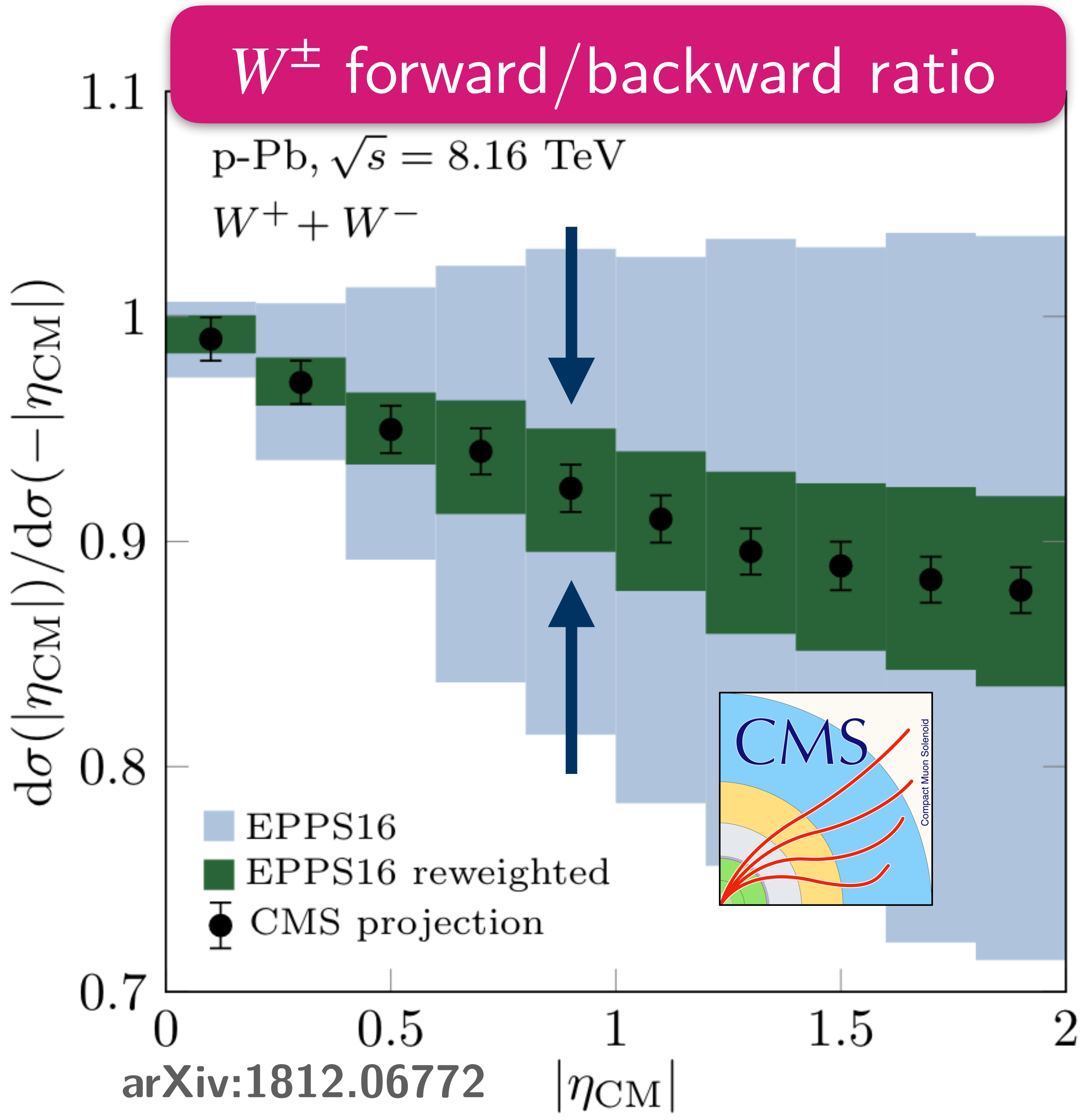


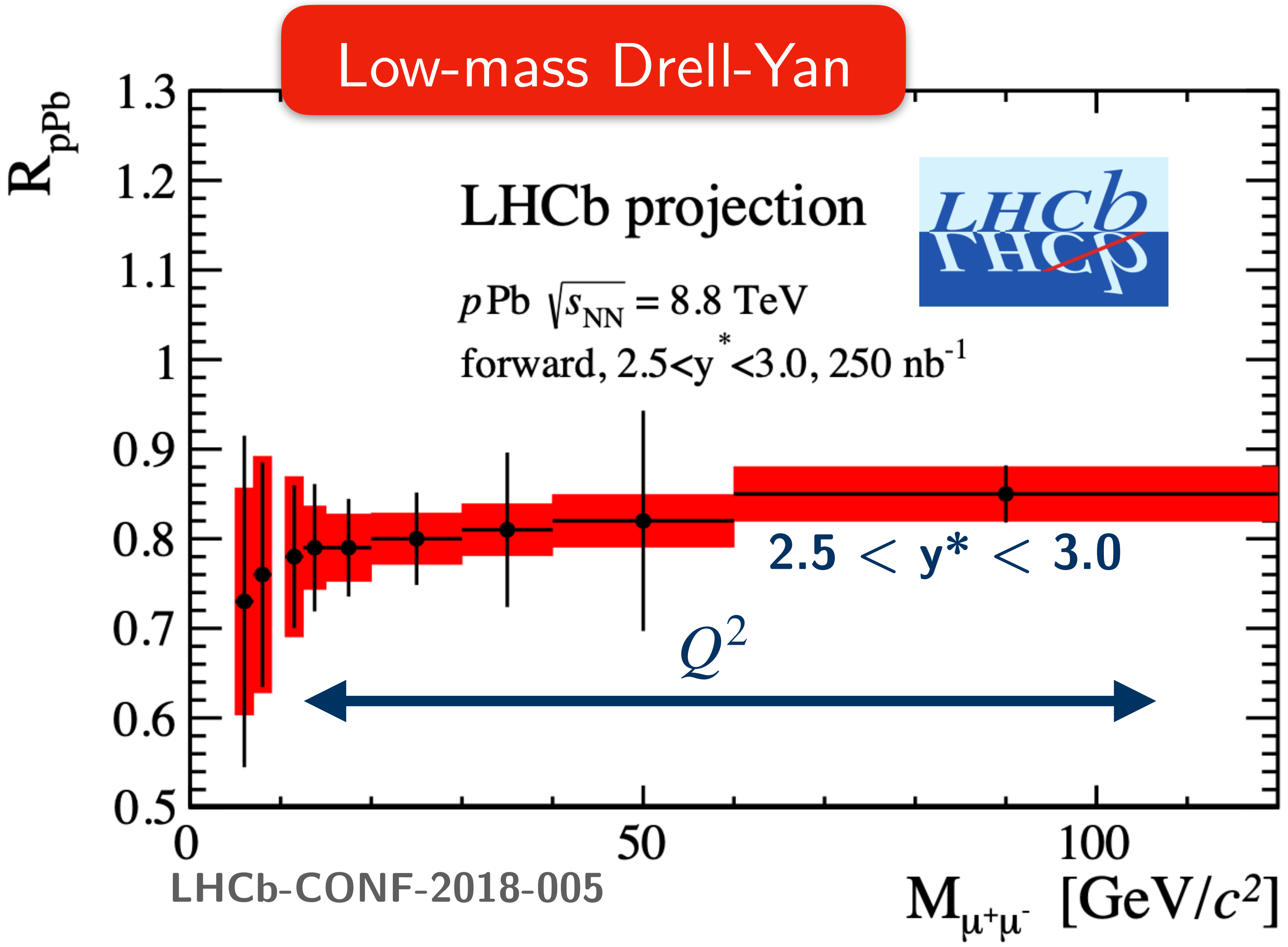


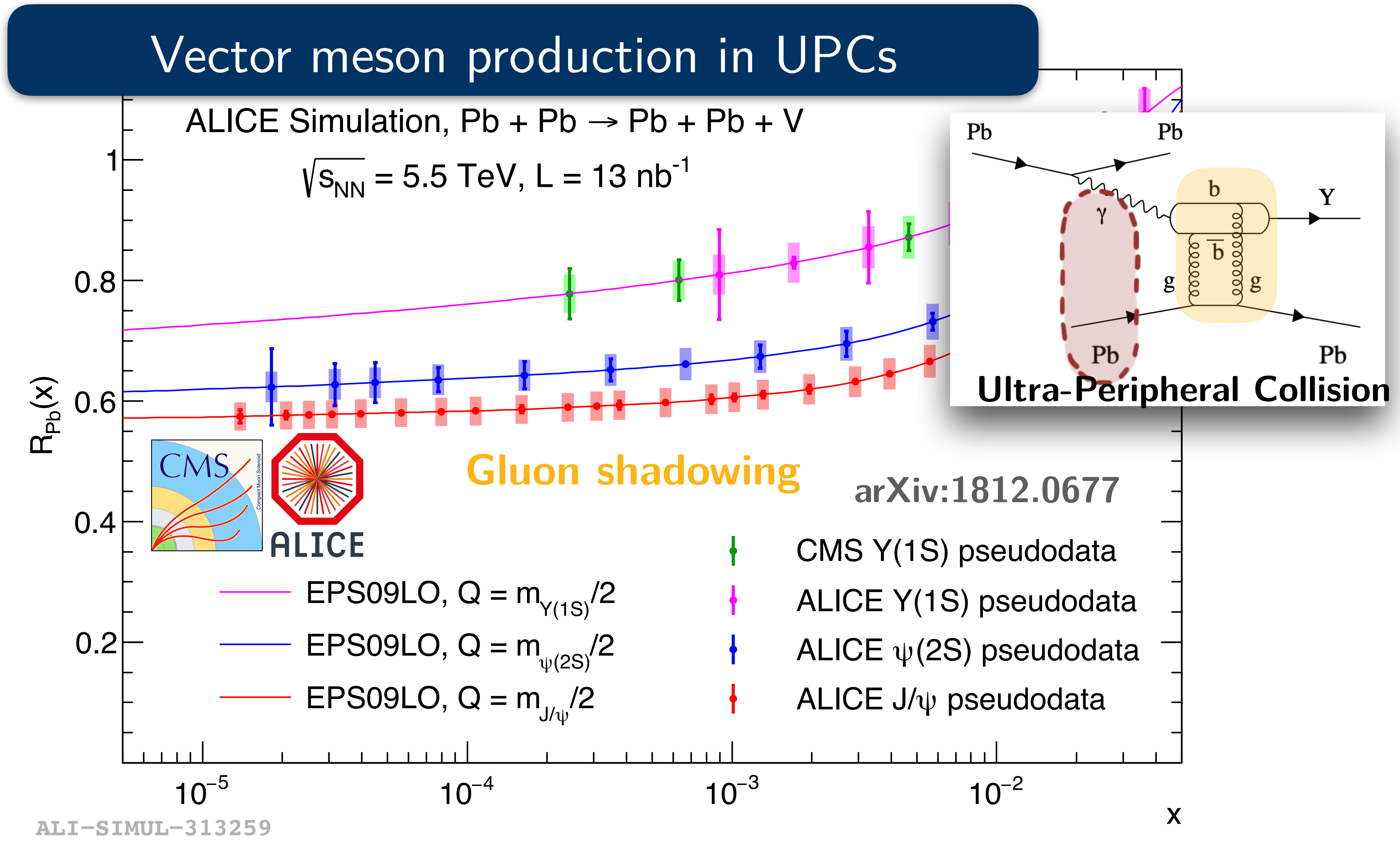
Probing (nuclear) matter in a novel phase-space with high precision:

- **$W^{\pm}$/ Z production:** sensitive to quark (n)PDF and heavy flavours
- **Low-mass Drell-Yan:** precision measurement over wide mass range & differential in y offer possibility to test Q^2 evolution of nPDFs
- **Vector meson, dijet & open charm prod. in UPCs:** gluon densities at low-x

Initial state: Probing partons in the incoming projectiles

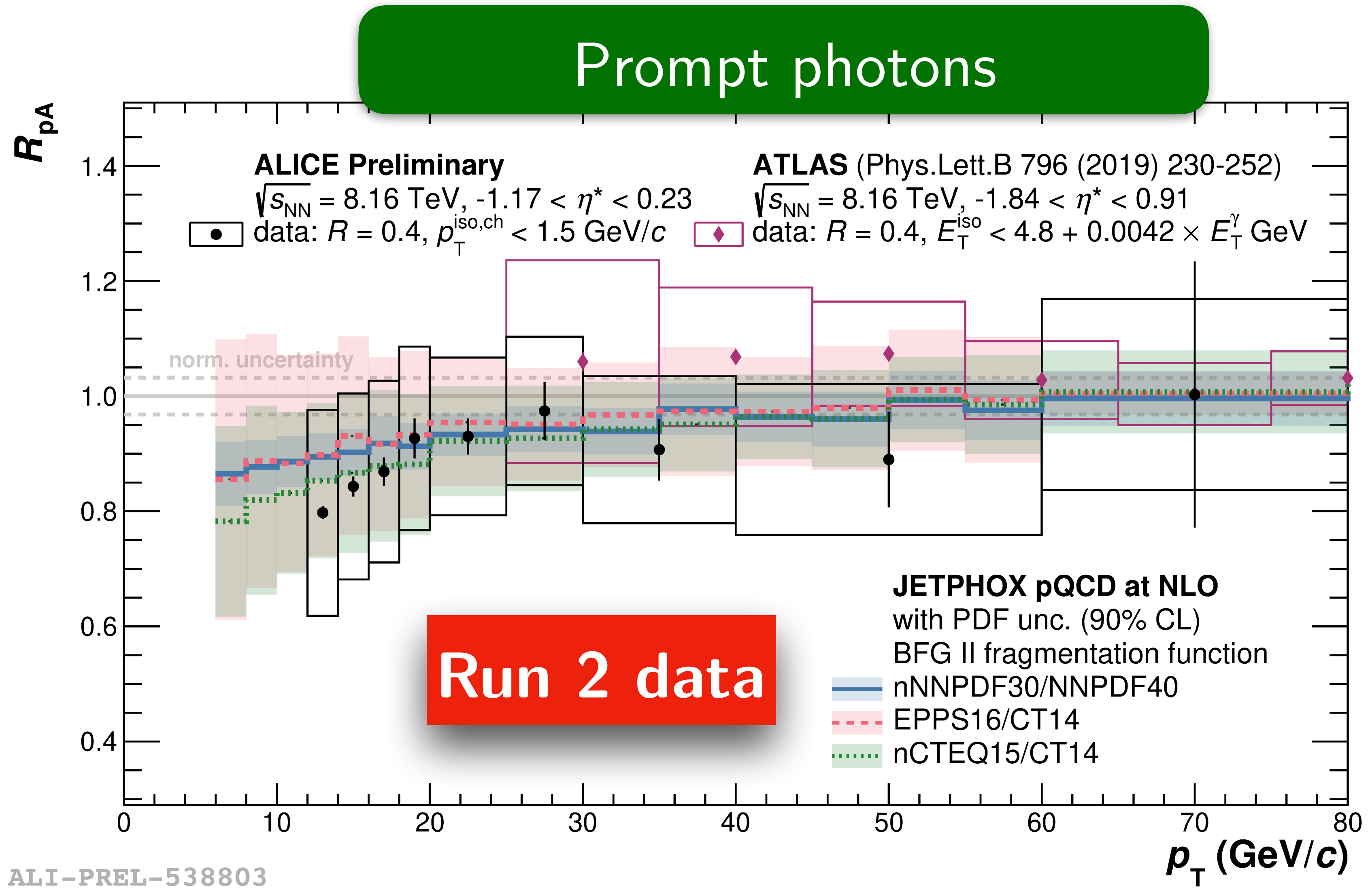






Probing (nuclear) matter in a novel phase-space with high precision:

- **$W^{\pm}$/ Z production:** sensitive to quark (n)PDF and heavy flavours
- **Low-mass Drell-Yan:** precision measurement over wide mass range & differential in y offer possibility to test Q^2 evolution of nPDFs
- **Vector meson, dijet & open charm prod. in UPCs:** gluon densities at low-x
- **Prompt γ production:** clean observable to access low-x gluons in p-Pb & Pb-Pb

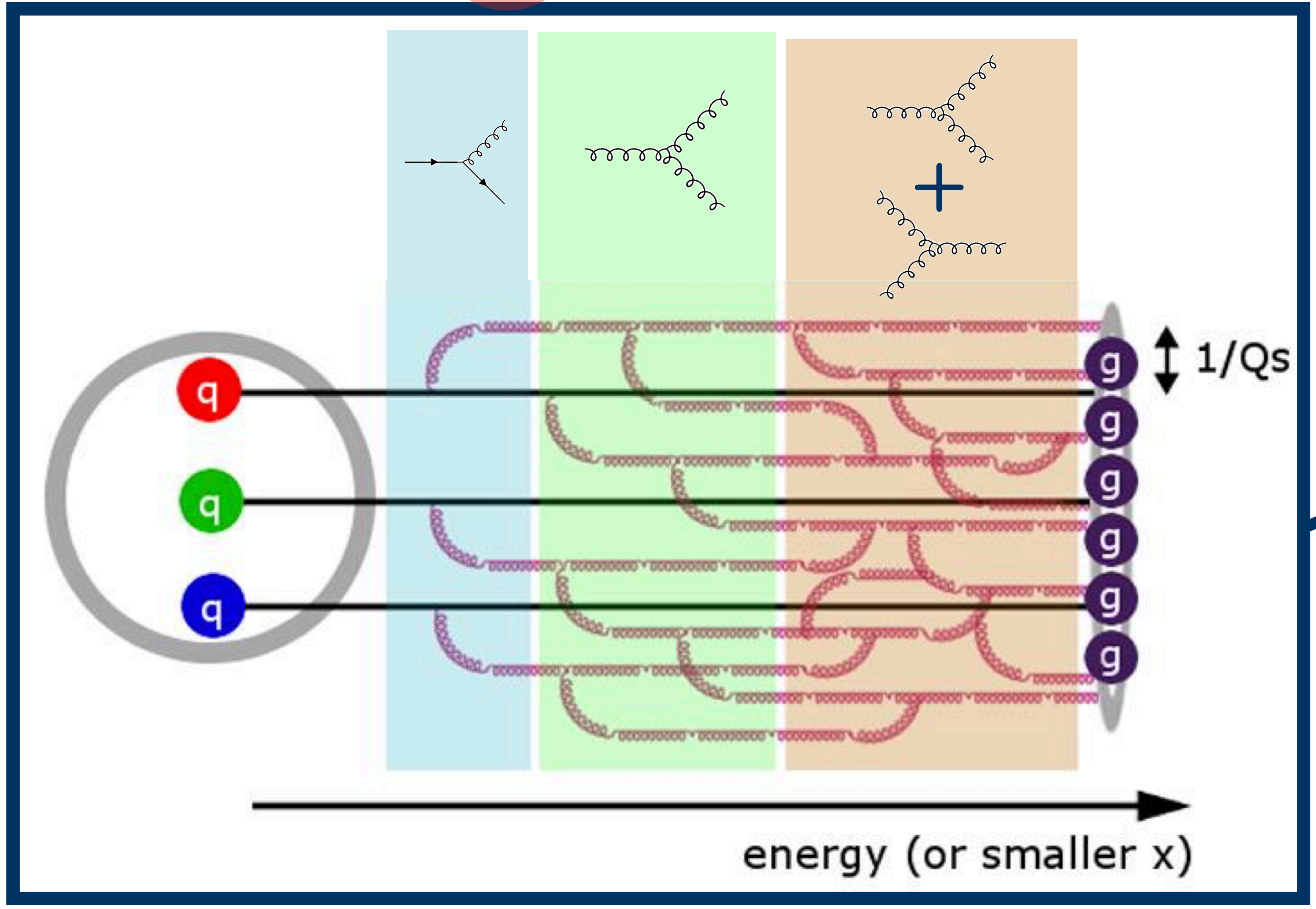


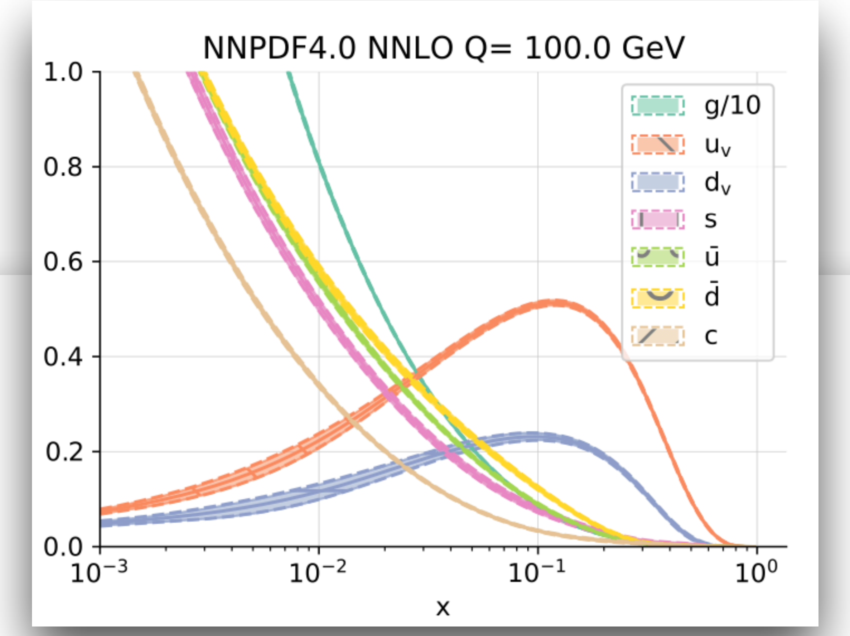
Non-linear QCD at low-x: Gluon saturation

Gluon saturation:

- Gluon increases with decreasing x (gluon splitting $g \rightarrow gg$)
- Below **saturation scale** Q_{sat} gluon fusion ($gg \rightarrow g$) and splitting ($g \rightarrow gg$) in equilibrium

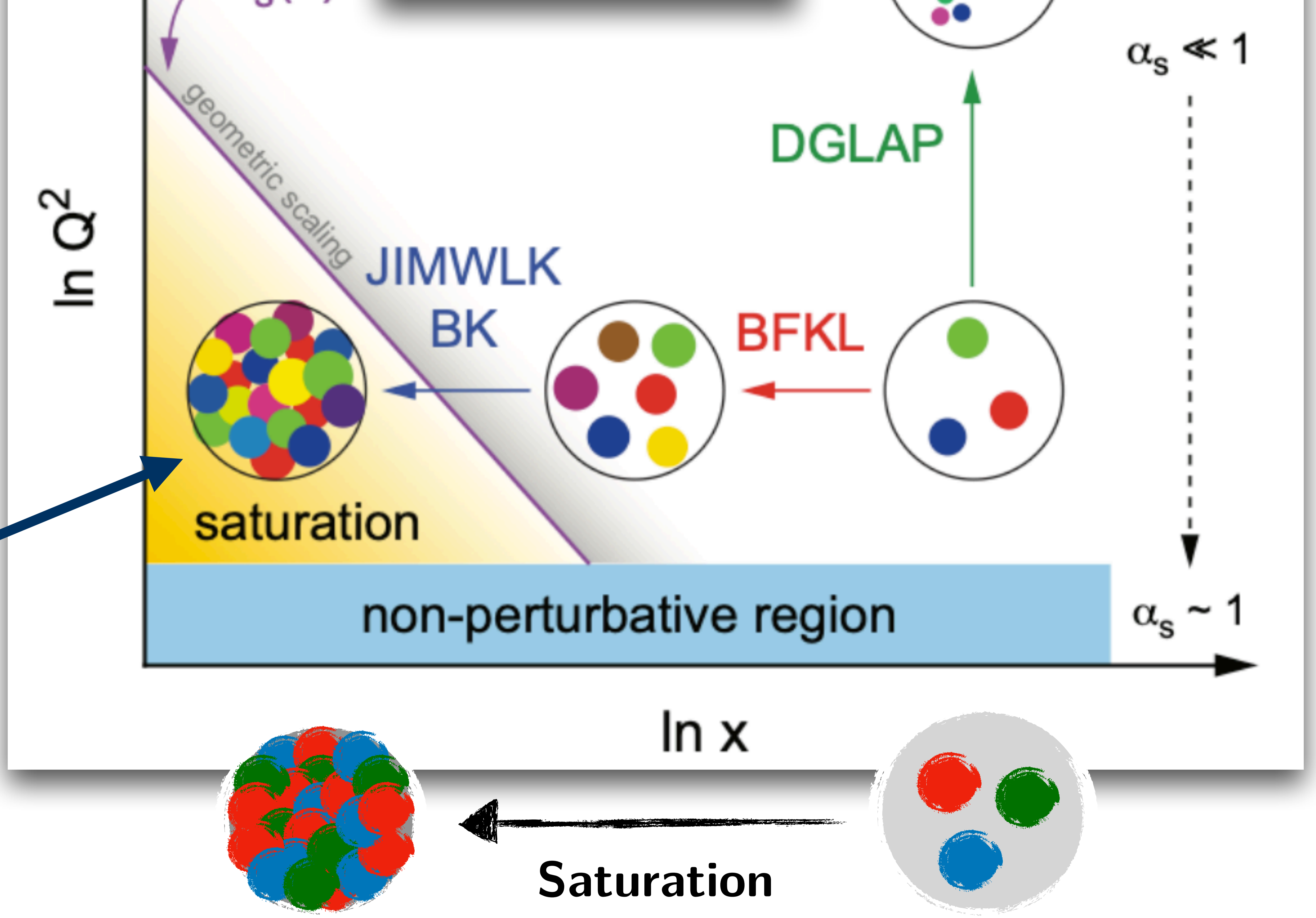
$$Q^2_{\text{sat}} \approx \frac{x g_A(x, Q^2)}{\pi R_A^2} \propto A^{1/3} x^{-\lambda} \sim \mathcal{O}(1\text{GeV})$$





ALICE-PUBLIC-2023-001

Eur.Phys.J.C 82 (2022) 5, 428



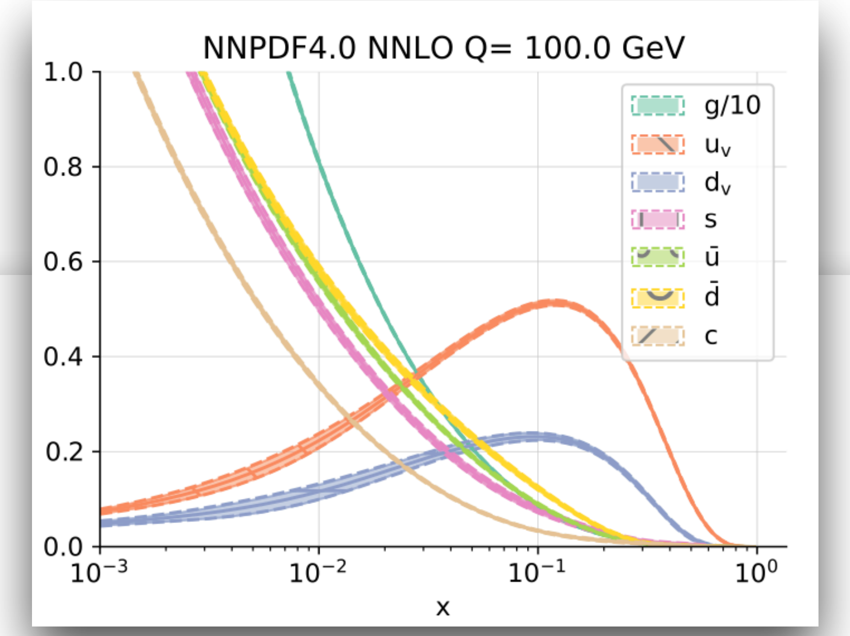
How can we probe gluon saturation experimentally in a meaningful way?

QCD phenomena evolve logarithmically in x and Q^2

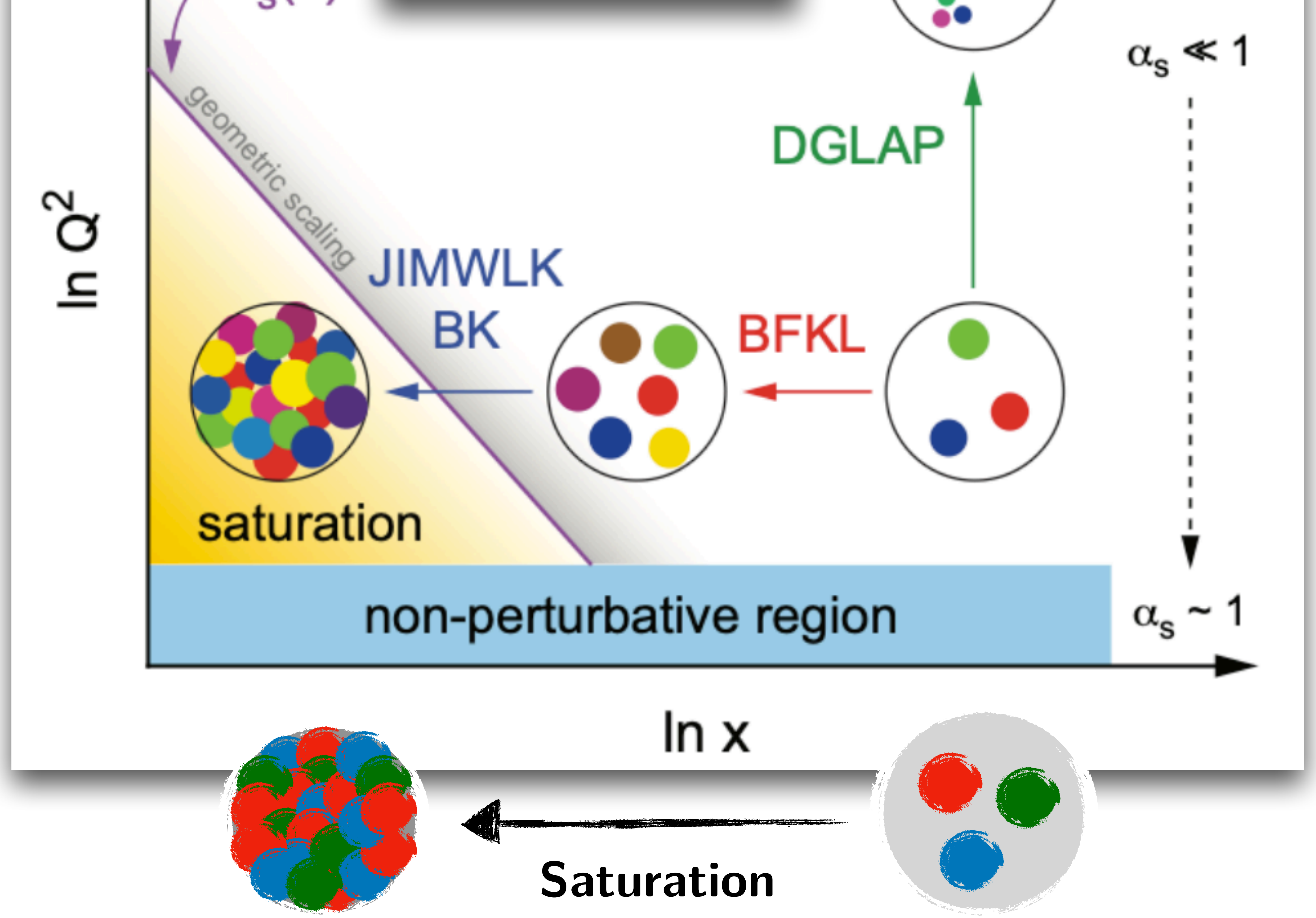
→ **logarithmically large experimental coverage in x and Q^2 desirable**

Universality: theoretical description should be able to self consistently describe multiple observables in multiple collision systems

→ **multi-messenger approach: measure multiple probes at various experimental facilities**



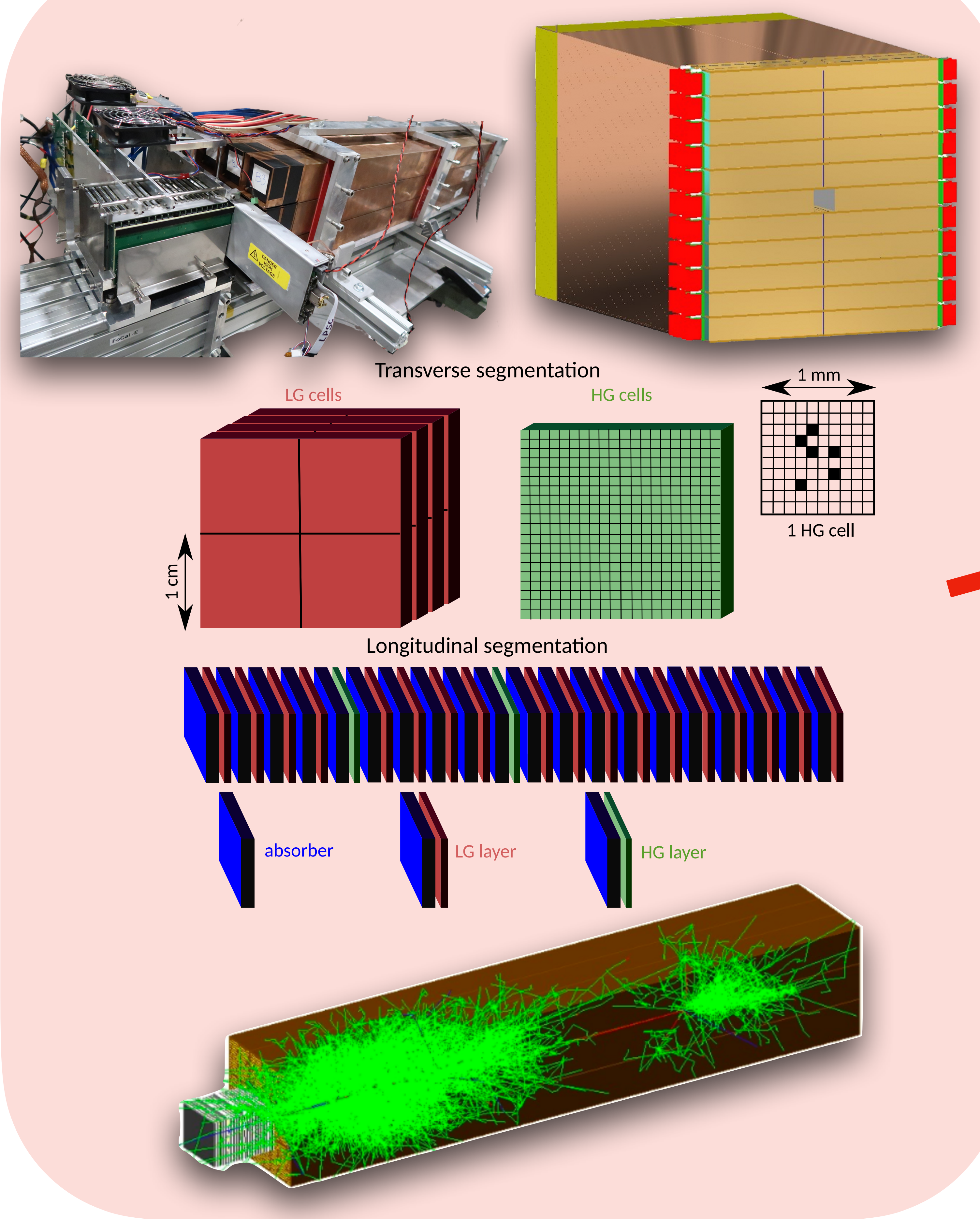
ALICE-PUBLIC-2023-001
Eur.Phys.J.C 82 (2022) 5, 428



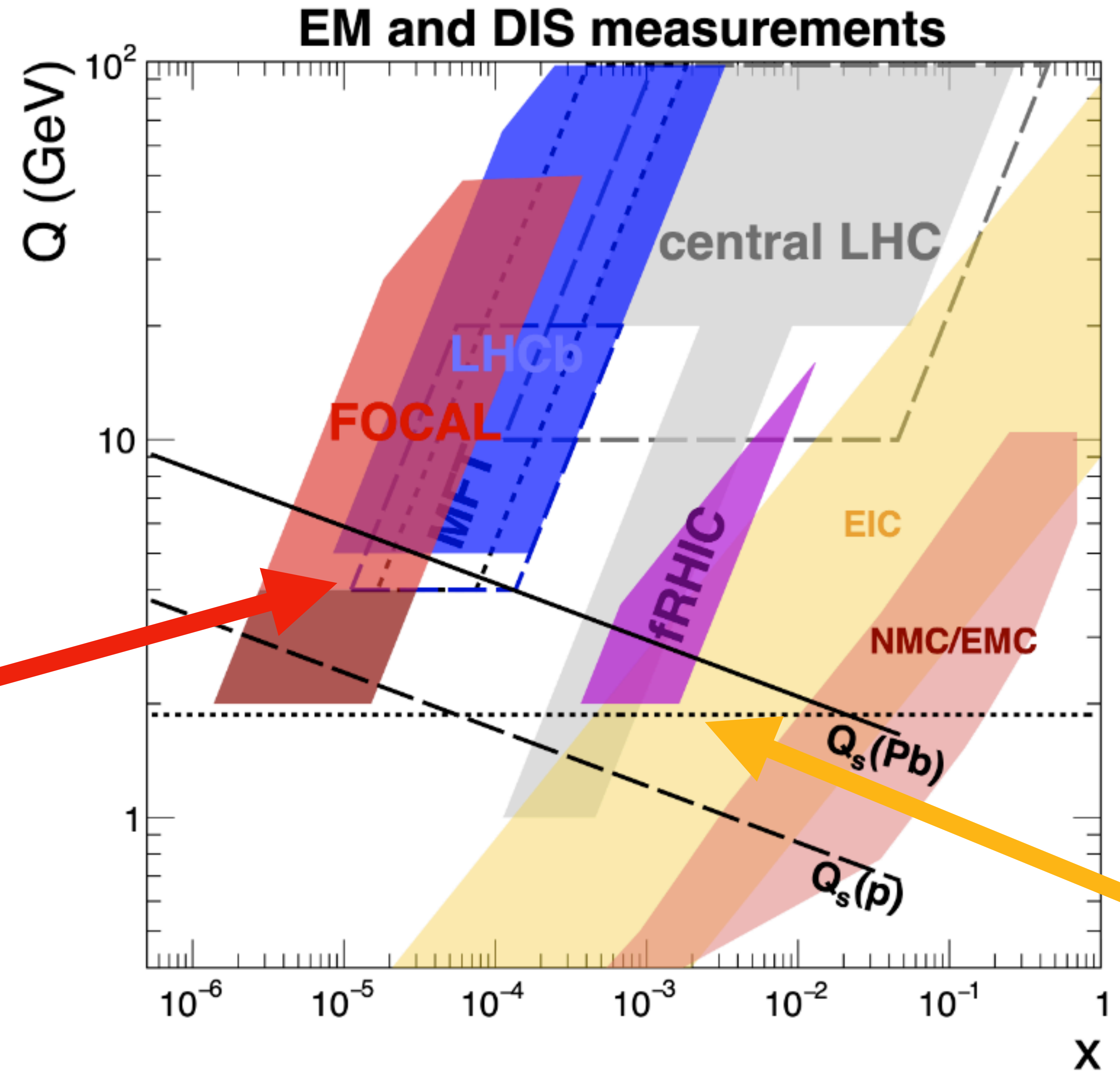
Phasespace coverage for "saturation searches"

Forward p-A collisions:

The ALICE FoCal



CERN-LHCC-2020-009, ALICE-PUBLIC-2023-001, CERN-LHCC-2024-004



Logarithmically large coverage in x and Q

Deep theoretical connection

DIS in e-A collisions:

The Electron-Ion Collider (EIC)

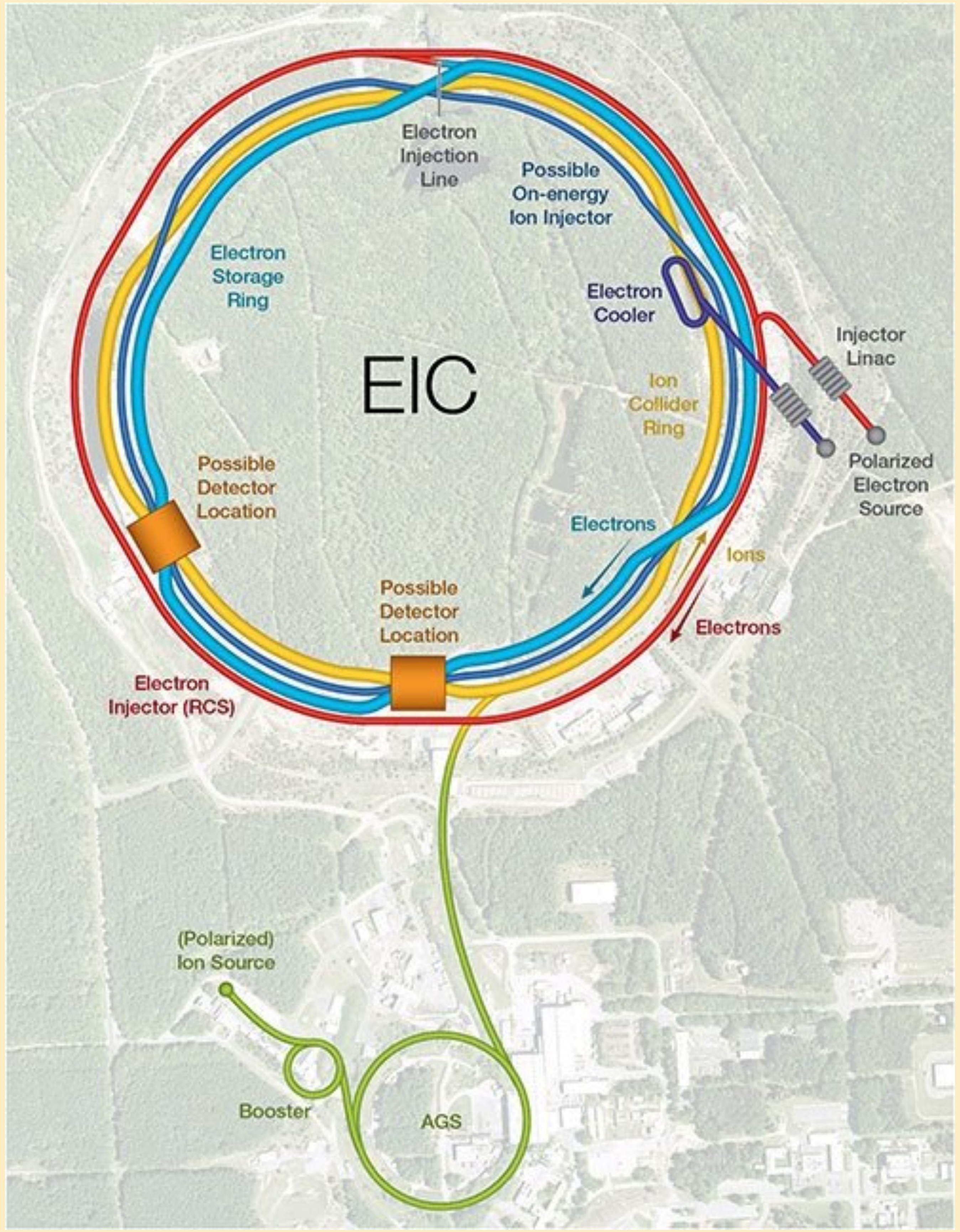


Image Credit: DOE

Theoretical connection between LHC & EIC

	Inclusive DIS	SIDIS	DIS dijet	Inclusive in p+A	γ+jet in p+A	dijet in p+A
xG_{WW}	−	−	+	−	−	+
xG_{DP}	+	+	−	+	+	+

Nucl.Phys.A 1026 (2022) 122447

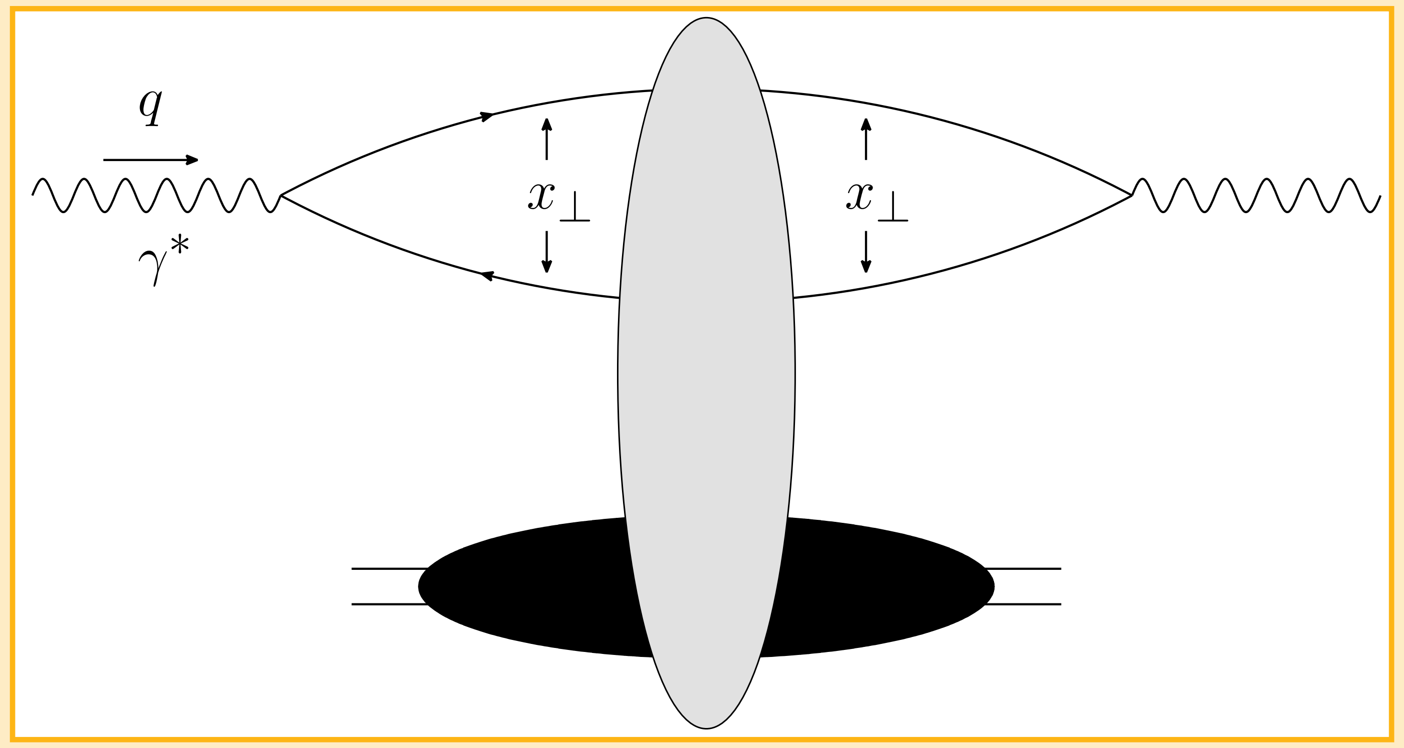
Multiple processes in **e-A DIS** and **forward p-A** collisions are theoretically described using the **same dipole/quadrupole scattering amplitudes!**

measurements in e-A DIS and forward p-A collisions
→ **test universal description of gluon saturated matter**

Bayesian inference already used successfully as a powerful tool study QGP → let's use it **in the saturation regime!**

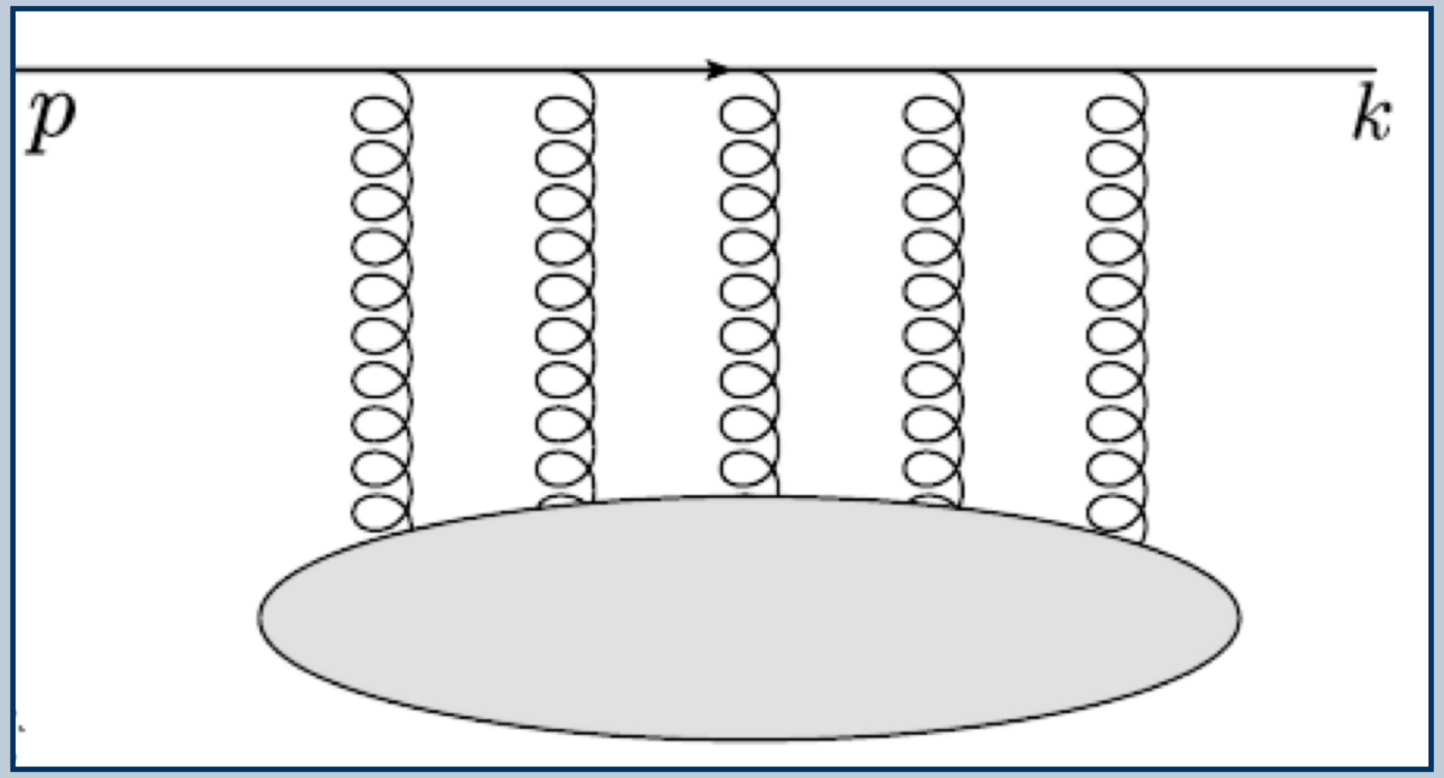
The whole picture (EIC + forward LHC/RHIC) will be more than the sum of its parts!

e+A Deep Inelastic Scattering (DIS)



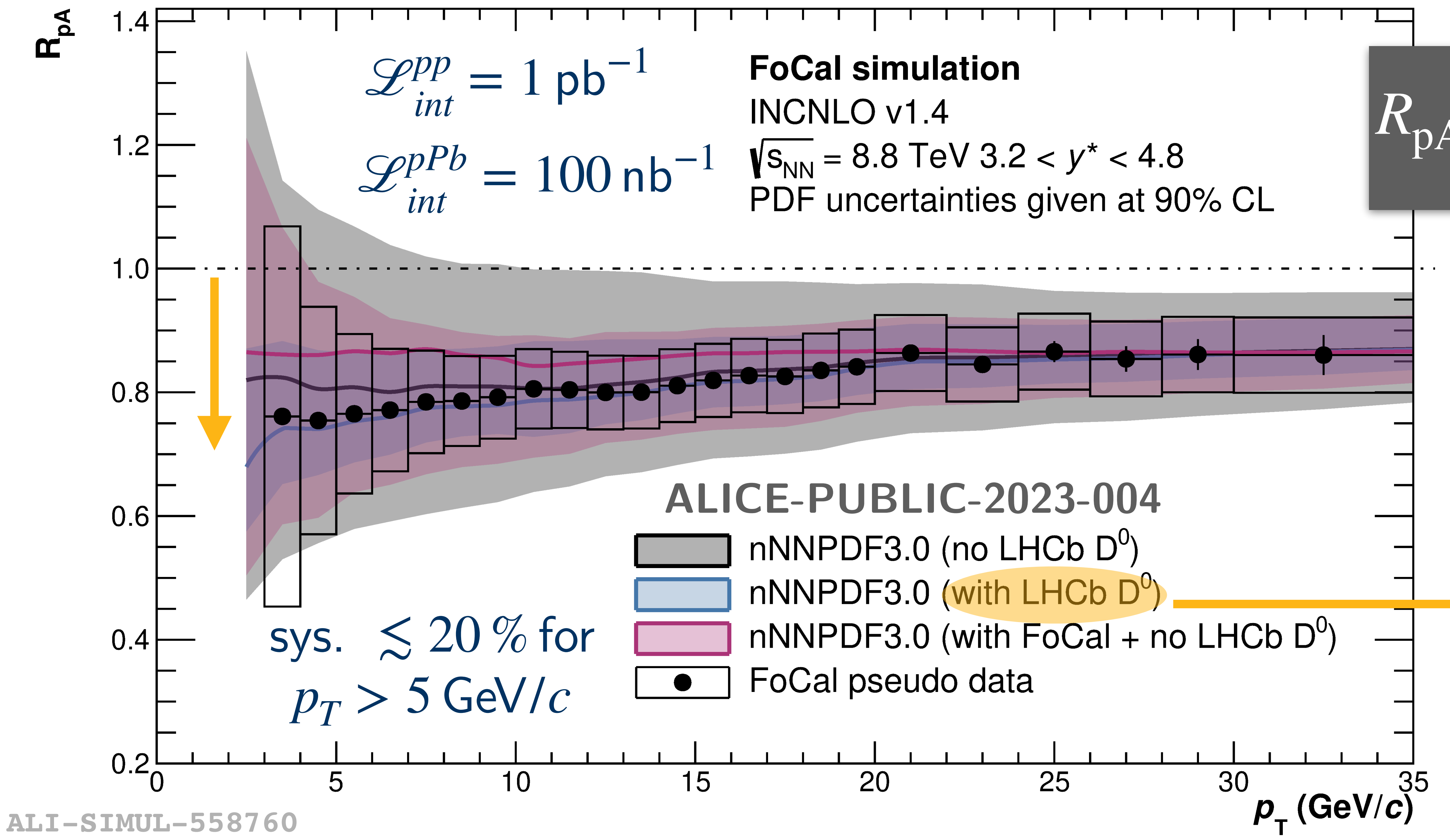
JETP 30 (1970) 709-717, Phys. Rev. D 8 (1973) 1341, Nucl. Phys. B 335 (1990) 115

Forward p+A collisions



Phys. Rev. C 59 (1999) 1609, Phys. Rev. D66 (2002) 014021, Phys. Lett. B 503 (2001) 91

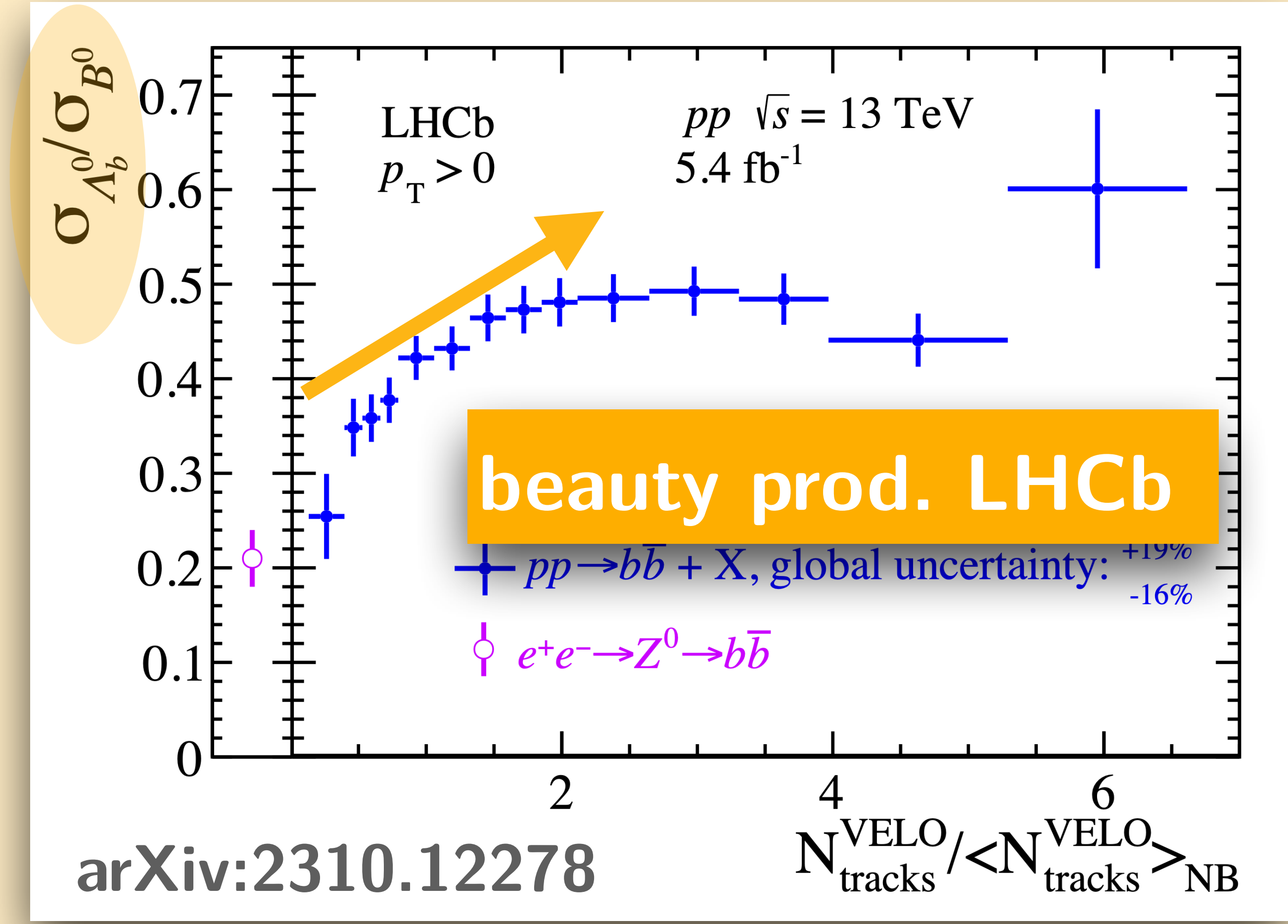
Measurement 1: Prompt photon production at forward rapidities

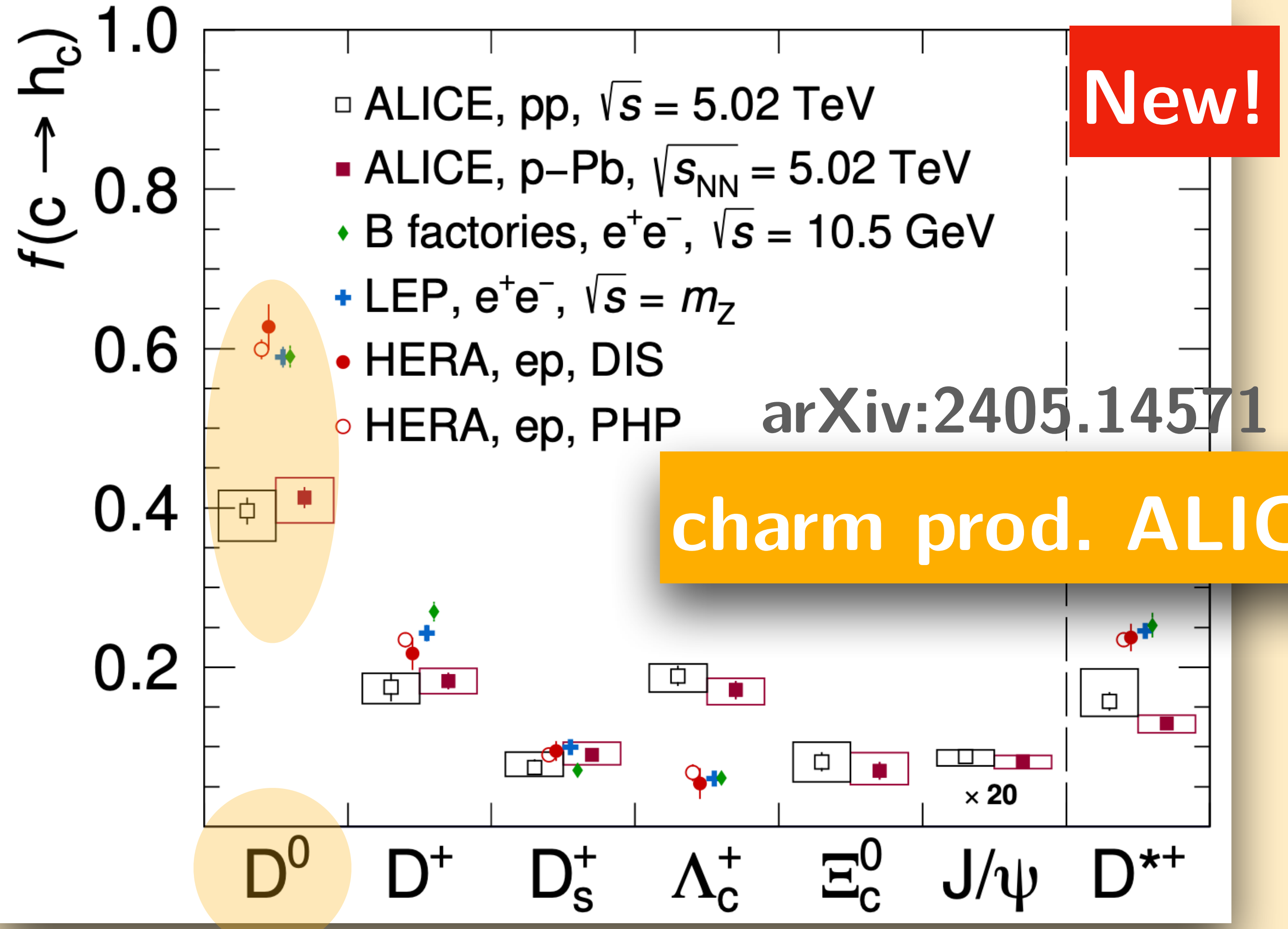


$$R_{\mathrm{pA}} = \frac{\sigma_{\mathrm{pPb}}}{A \times \sigma_{\mathrm{pp}}}$$

- **FoCal pseudo-data** of nuclear modification factor R_{pA}constructed using input from NLO+nPDF and assumptions on stat. and sys. uncertainties from perf. studies
- **Bayesian re-weighting of nNNPDF30** prediction showcases **significant reduction of nPDF uncertainties** when including FoCal data; comparable to D meson measurement by LHCb

Are fragmentation functions universal?



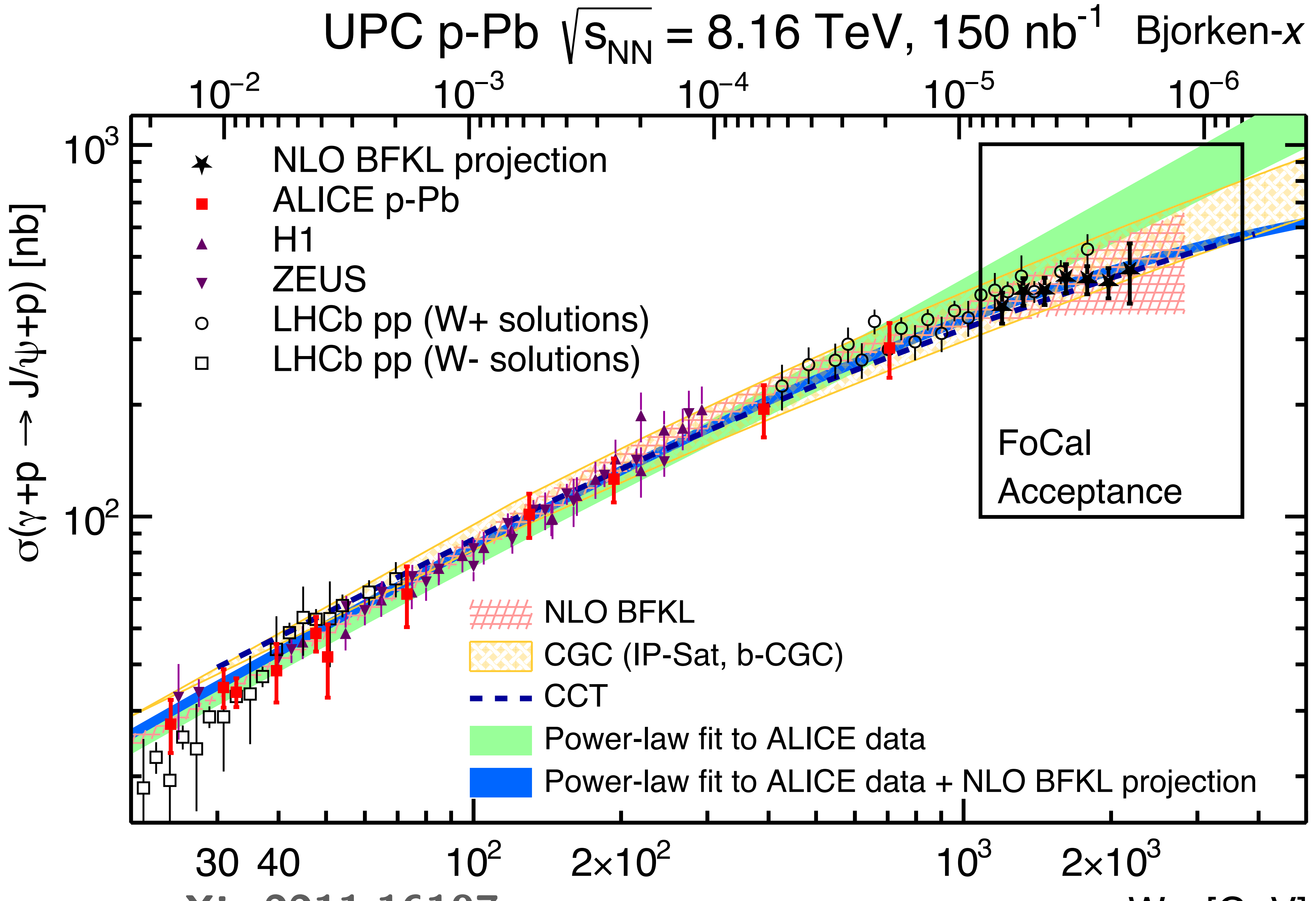


Prompt photons → no final state and hadronisation effects → universality test of low-x formalism

Measurement 2: Vector meson photoproduction in UPCs

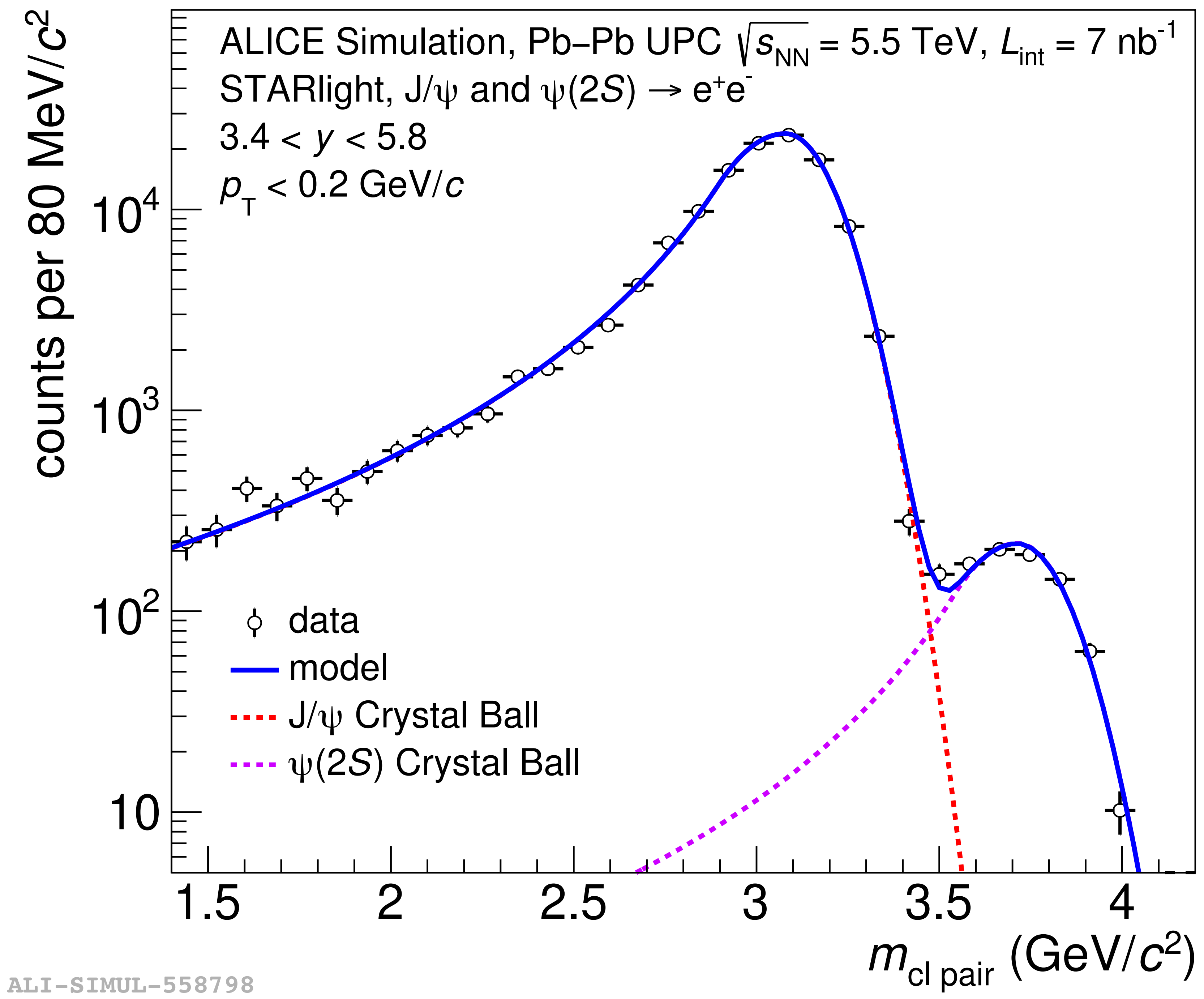
Theory:

- Photoproduction cross section of vector mesons (e.g. J/ψ) in ultra-peripheral collisions (UPCs) **proportional to gluon density squared** at LO
- **Deviation from power-law** growth of cross section with increasing $W_{\gamma p}$ expected due to **saturation effects**



arXiv:2211.16107

FoCal performance:

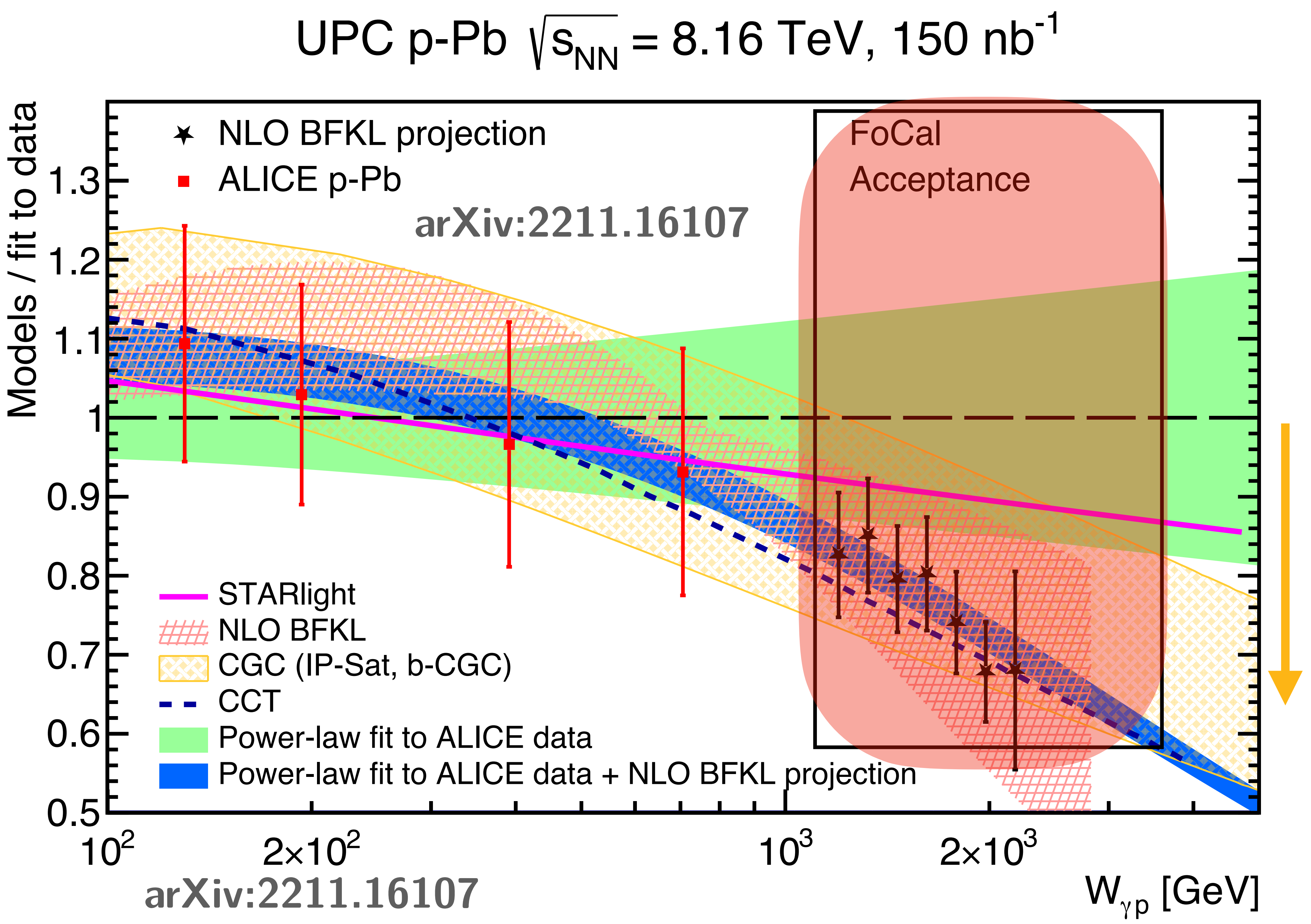


- FoCal allows to access unprecedented low-x, extending existing measurements to $W_{\gamma p} \approx 2$ TeV (10 GeV) in p-Pb (Pb-p) collisions + Pb-Pb collisions
- Studies with STARlight + GEANT show successful reconstruction of J/ψ and $\psi(2S)$

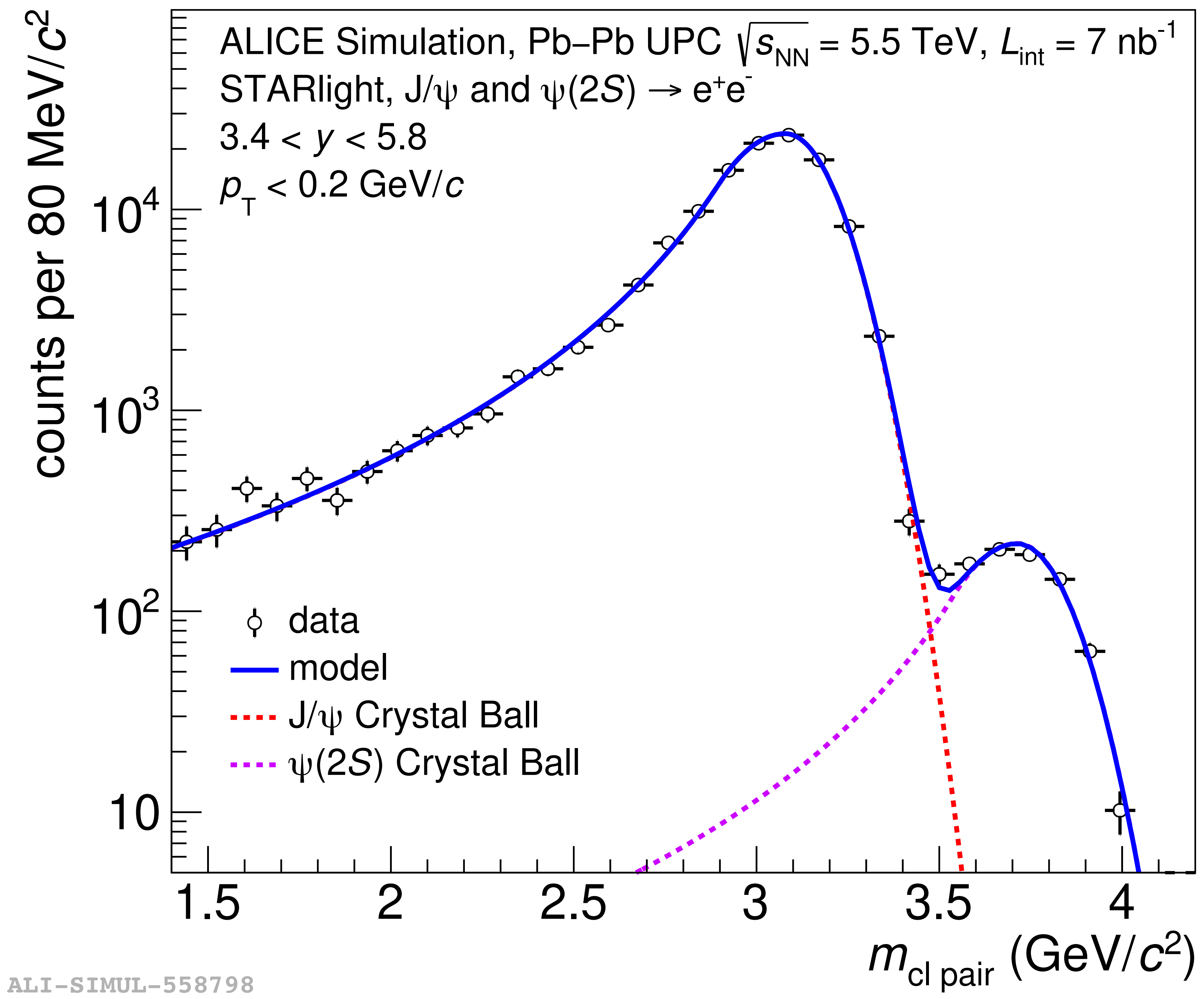
Measurement 2: Vector meson photoproduction in UPCs

Theory:

- Photoproduction cross section of vector mesons (e.g. J/ψ) in ultra-peripheral collisions (UPCs) **proportional to gluon density squared** at LO
- **Deviation from power-law** growth of cross section with increasing $W_{\gamma p}$ expected due to **saturation effects**



FoCal performance:



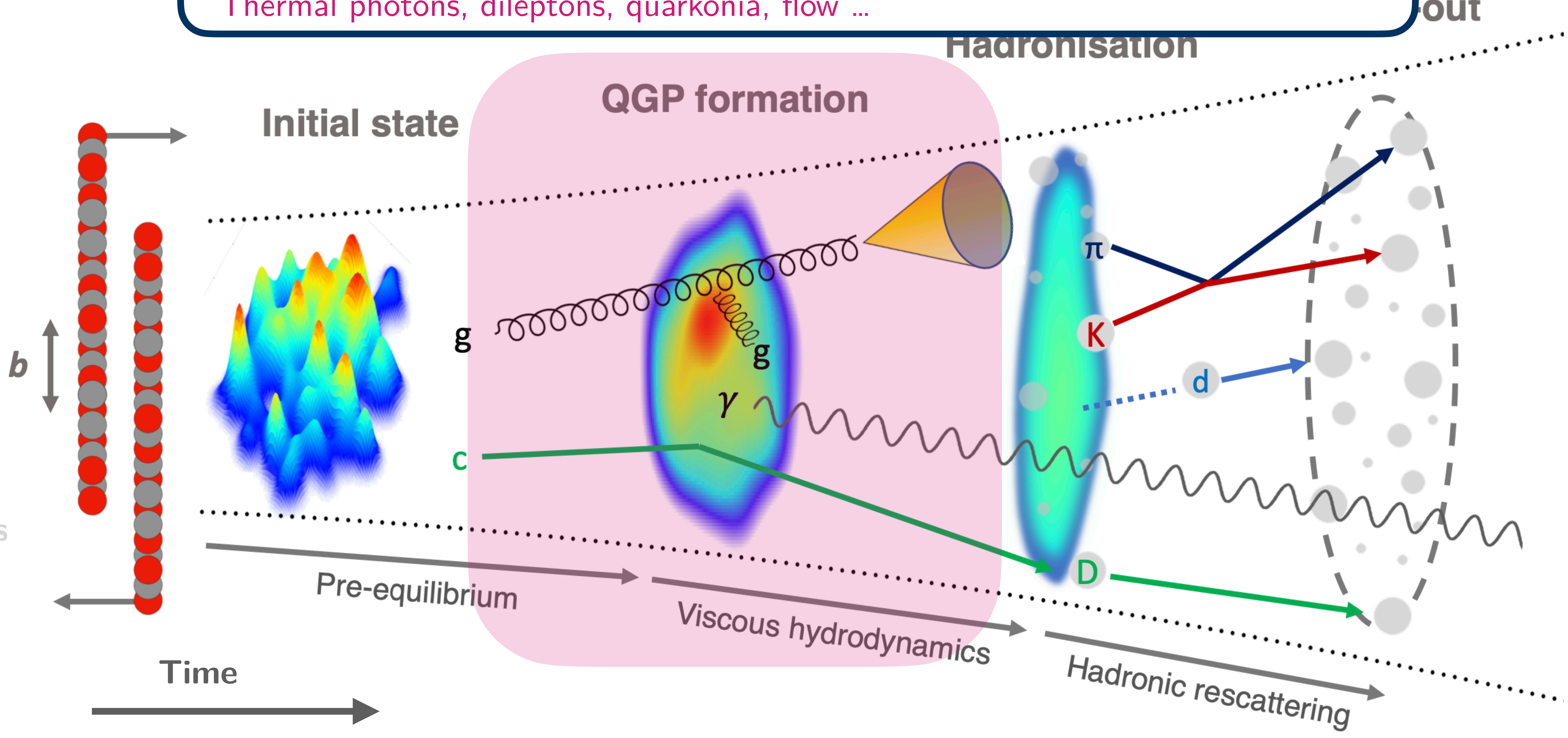
- FoCal allows to access unprecedented low-x, extending existing measurements to $W_{\gamma p} \approx 2$ TeV (10 GeV) in p-Pb (Pb-p) collisions + Pb-Pb collisions
- Studies with STARlight + GEANT show successful reconstruction of J/ψ and $\psi(2S)$

Heavy-ion physics: The big questions

What are the macroscopic properties of the QGP? Temperature? Viscosity? QCD phase transition?
Thermal photons, dileptons, quarkonia, flow ...

What are the initial conditions of a collision? nPDFs & Saturation?
DY, UPC, forward LHC ...

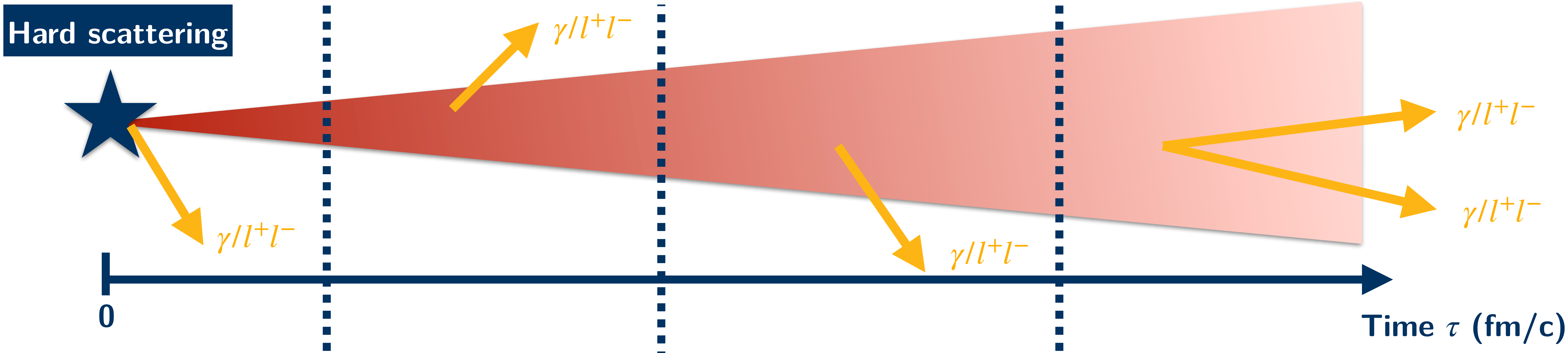
Collectivity of QCD across system sizes?
Flow in pp, p-A; strangeness production, energy loss, thermal radiation



arXiv:2211.04384

What is the microscopic dynamics of QGP at various length scales?
Jets (substructure), γ/Z-jet correlations, heavy flavour, quarkonia, hadronization

Overview: Electromagnetic probes (e.g. photons & dileptons)



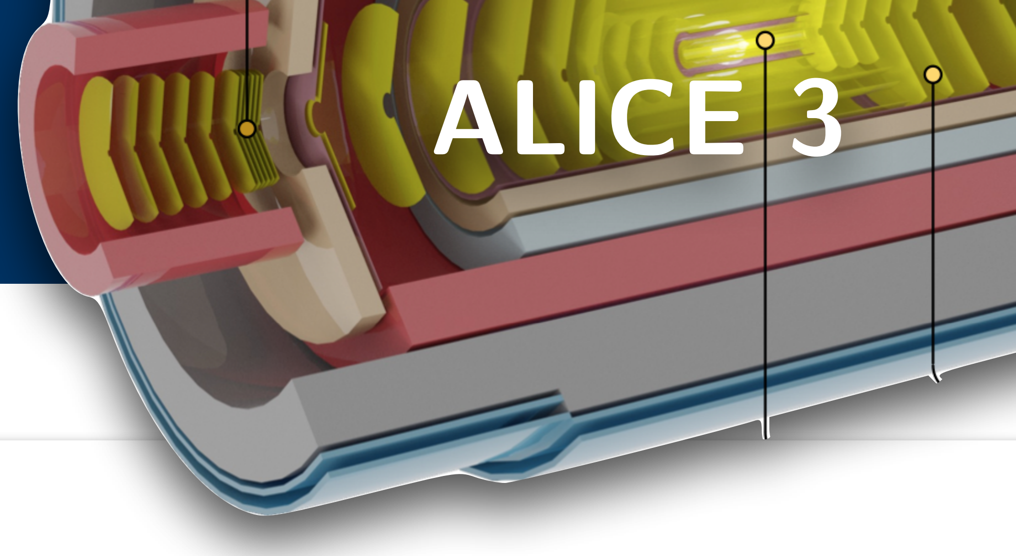
Hard Scattering	Pre-equilibrium	Thermalised QGP	Hadronic Phase
Drell-Yan Dipleptons	Thermal photons		Hadronic decays
Prompt photons	Thermal dileptons		

EM probes are produced in all stages of the collision

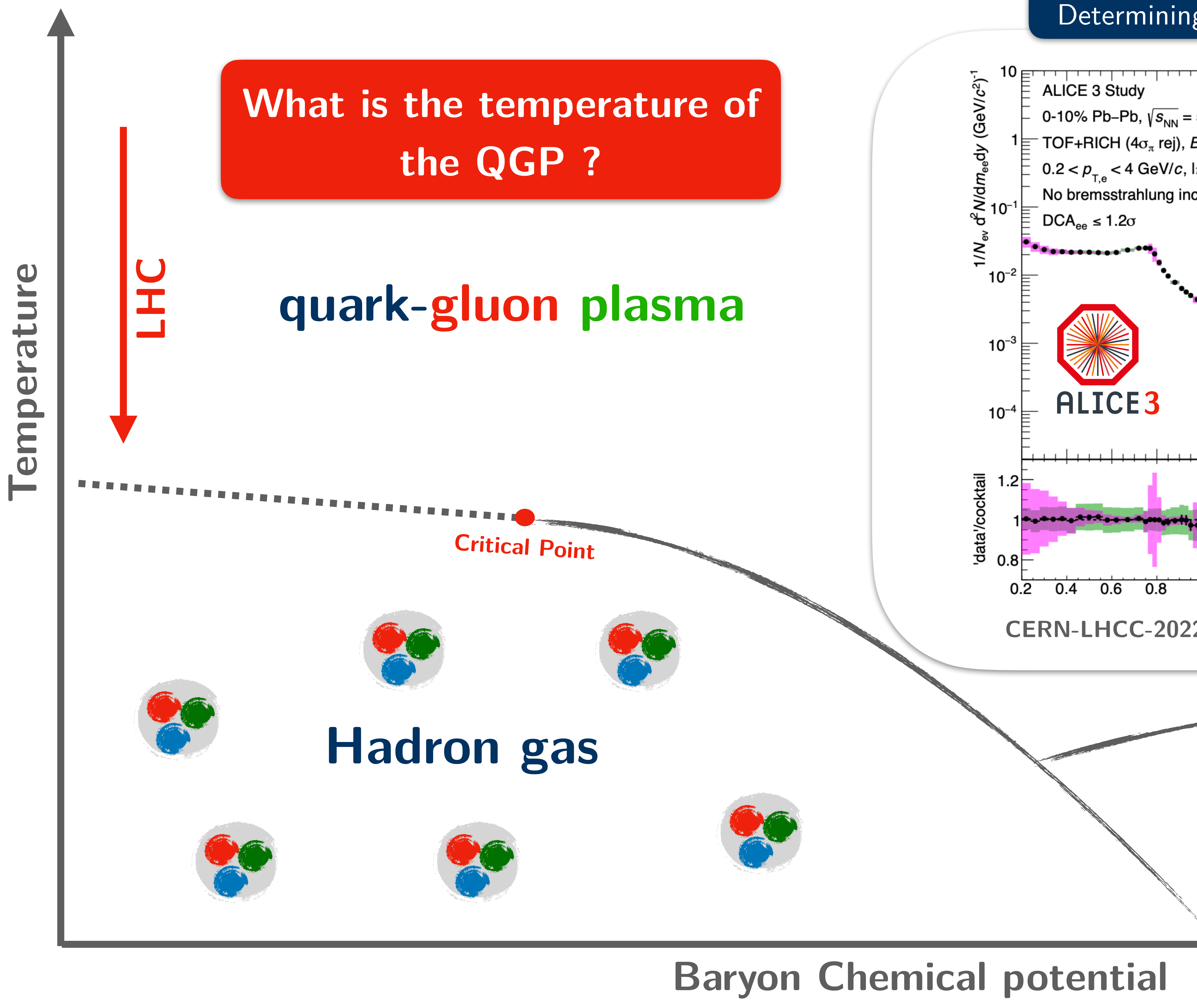
Each phase contains interesting physics!

Main challenge: We measure “all" EM probes and need to distinguish the phases

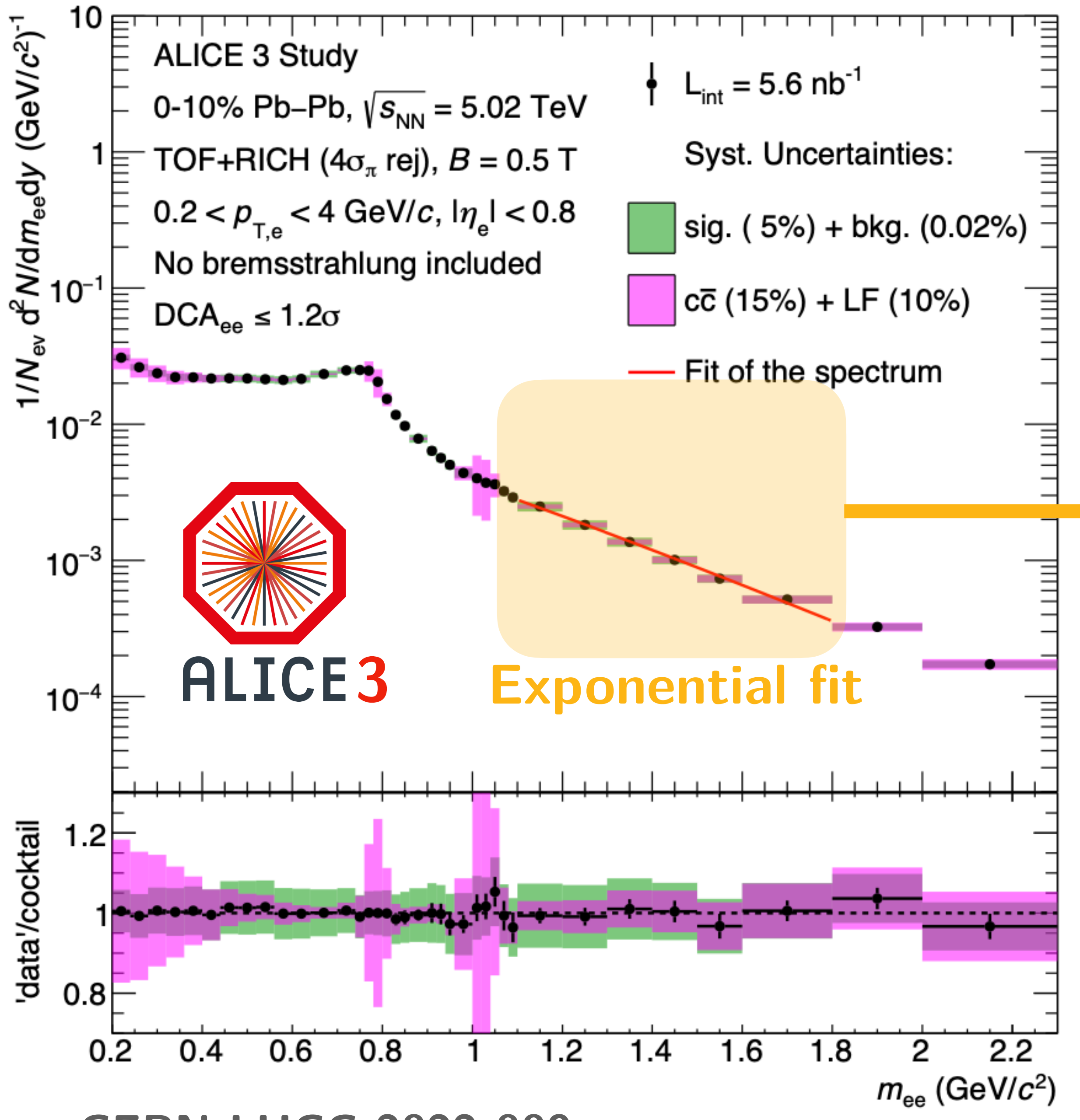
Electromagnetic probes: thermal photons & dileptons



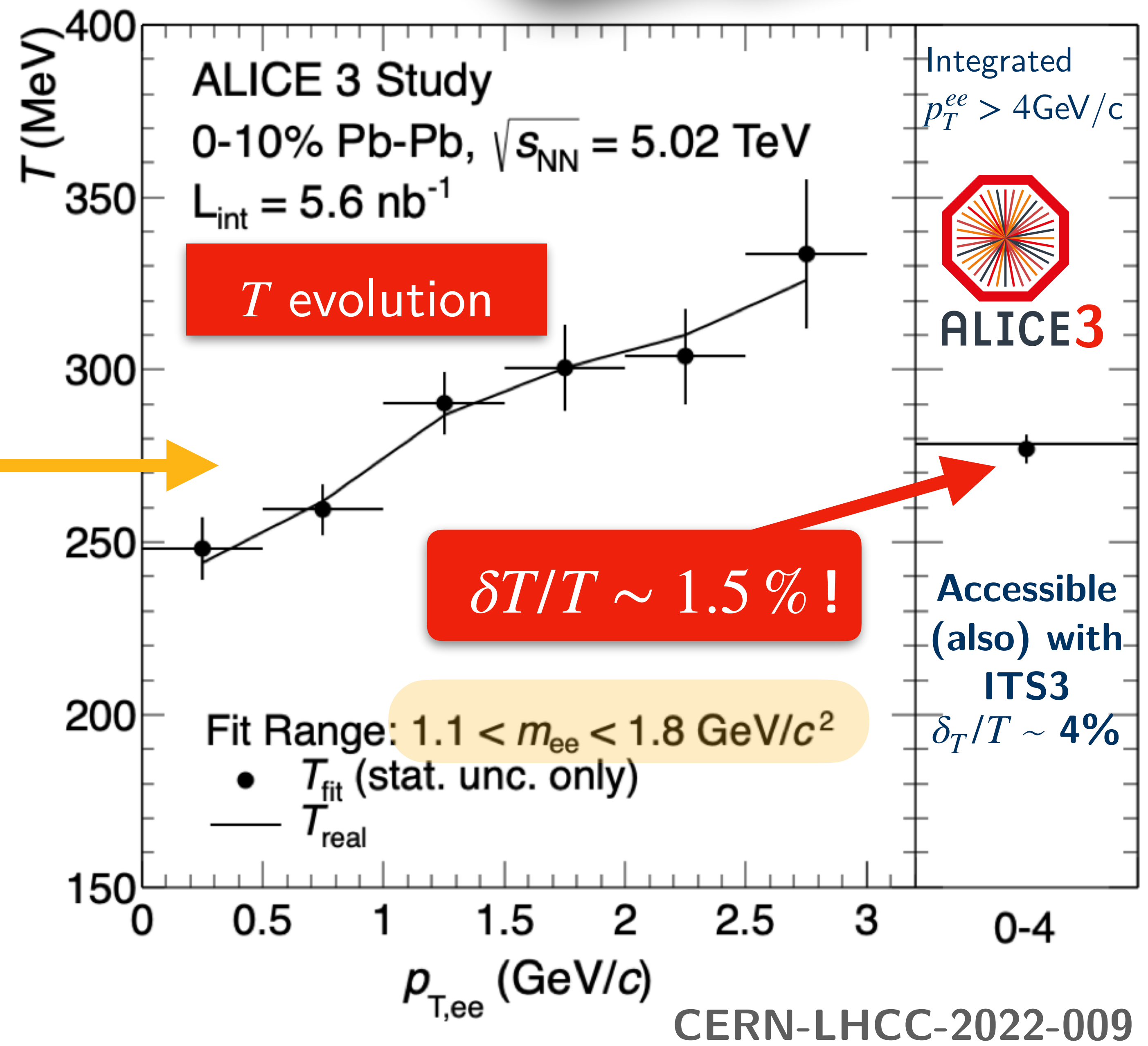
What is the temperature of the QGP ?



Determining the QGP temperature with dileptons



CERN-LHCC-2022-009

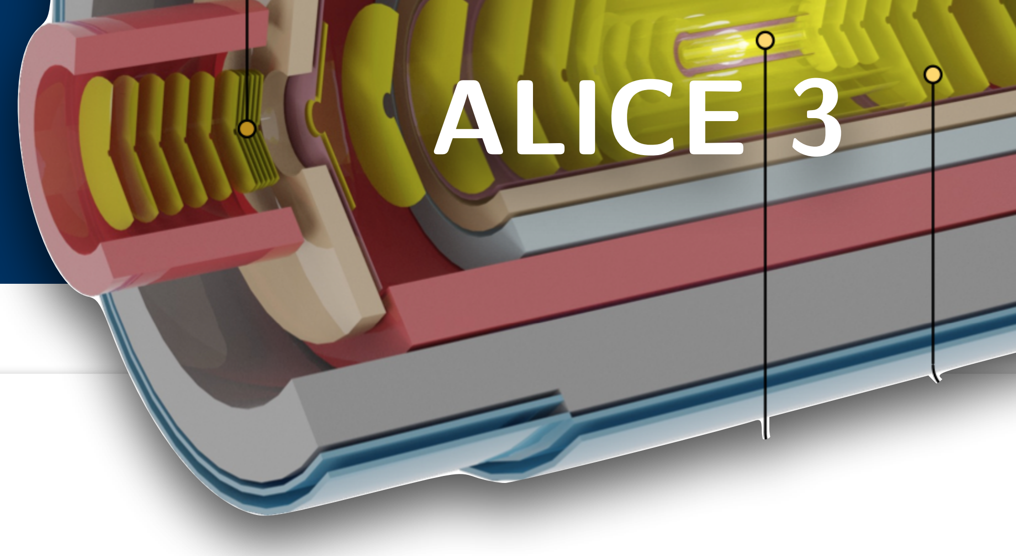


CERN-LHCC-2022-009

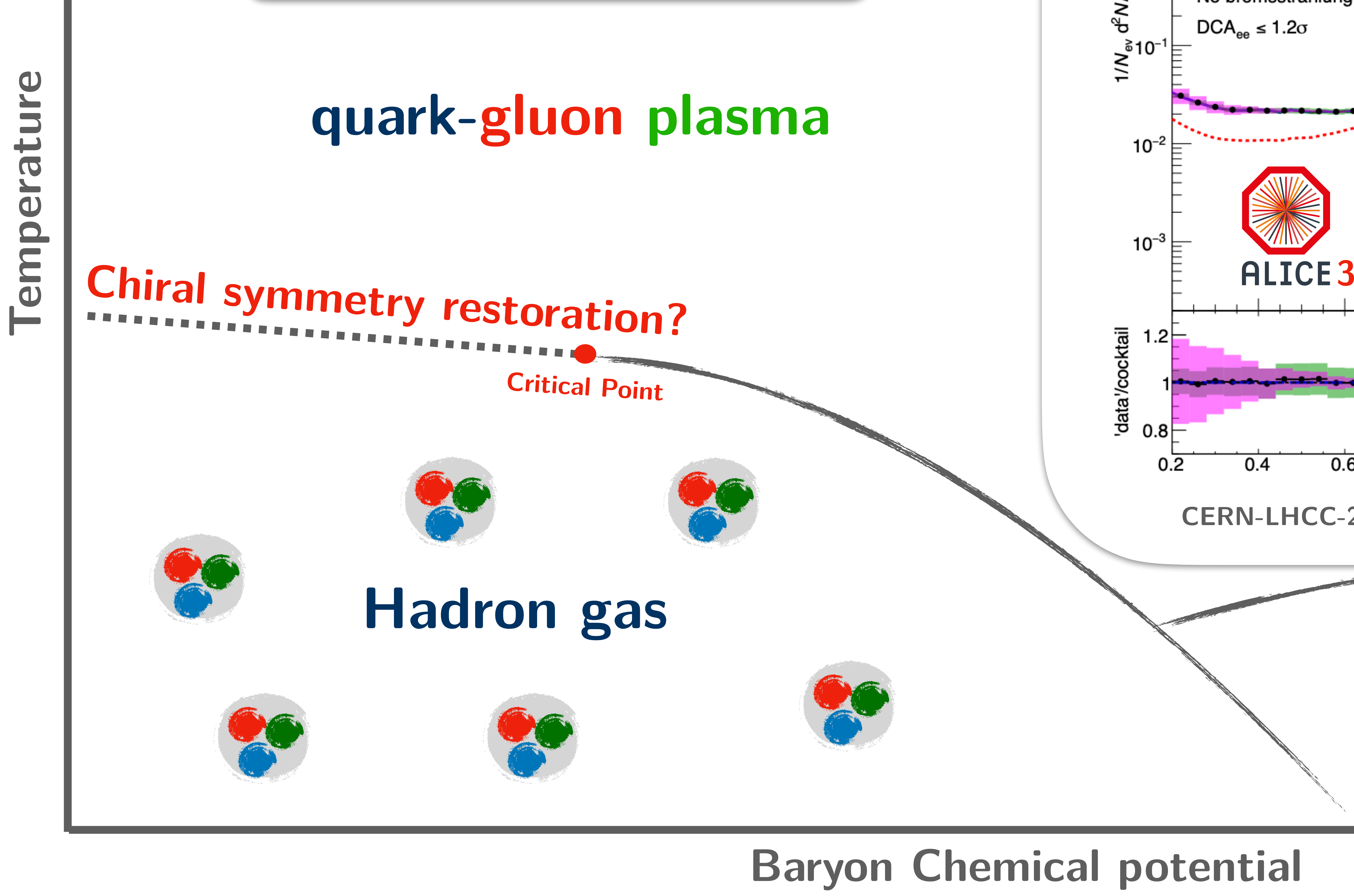
ALICE Upgrades provide:

Low p_T reach & excellent pointing resolution

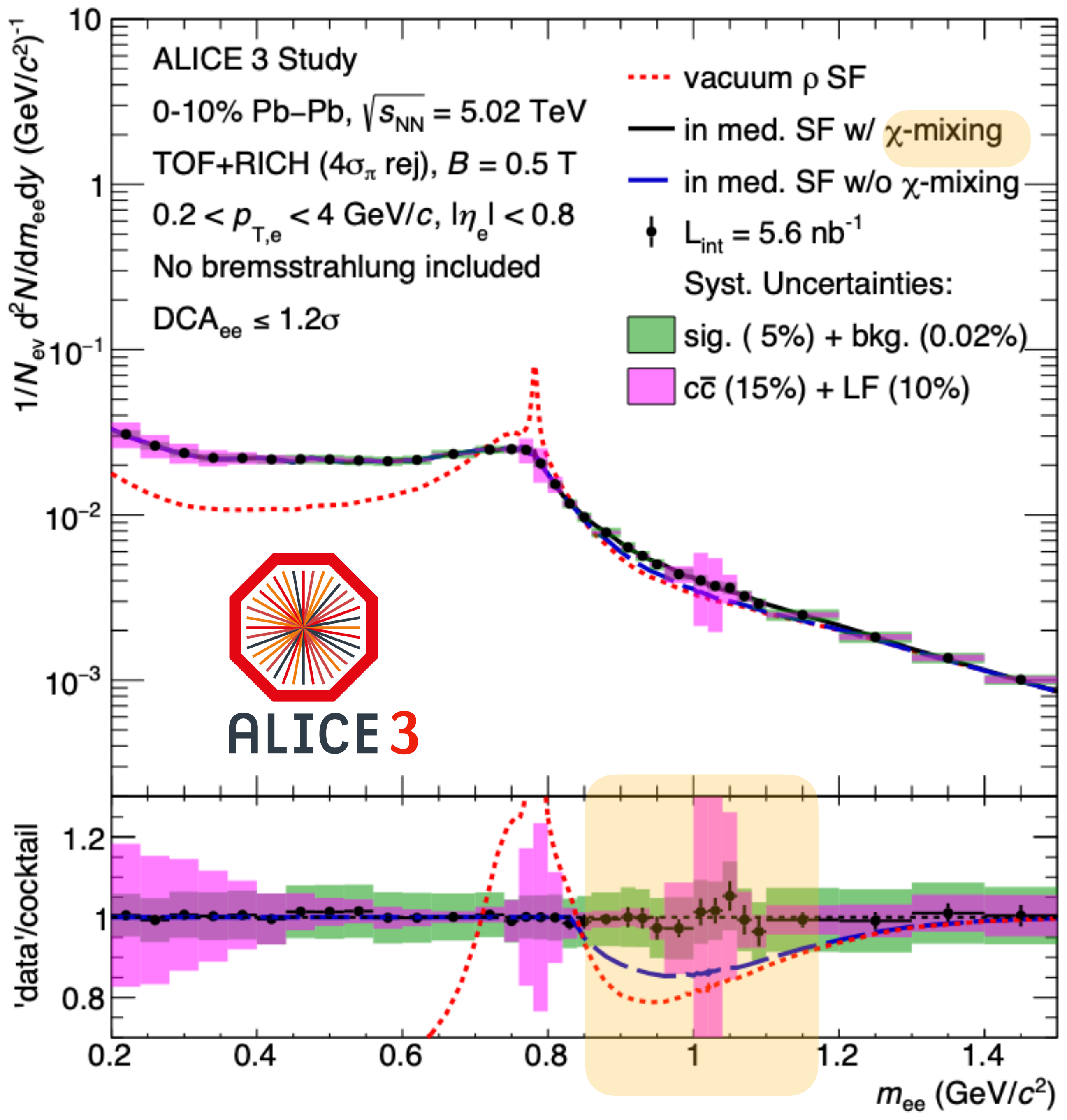
Electromagnetic probes: thermal photons & dileptons



Experimental evidence of chiral symmetry restoration?



Probing chiral symmetry restoration with dileptons



CERN-LHCC-2022-009

- Measurement of spectral shape ρ and chiral partner a_1 is **unambiguous way to measure chiral symmetry restoration.**
  $\rightarrow \rho - a_1$ mixing: enhancement of ~15% at 1 GeV (exp. unc. ~ 6-8%!)

ALICE Upgrades provide:
Low p_T reach & excellent pointing resolution

Heavy-ion physics: The big questions

What are the macroscopic properties of the QGP? Temperature? Viscosity? QCD phase transition?

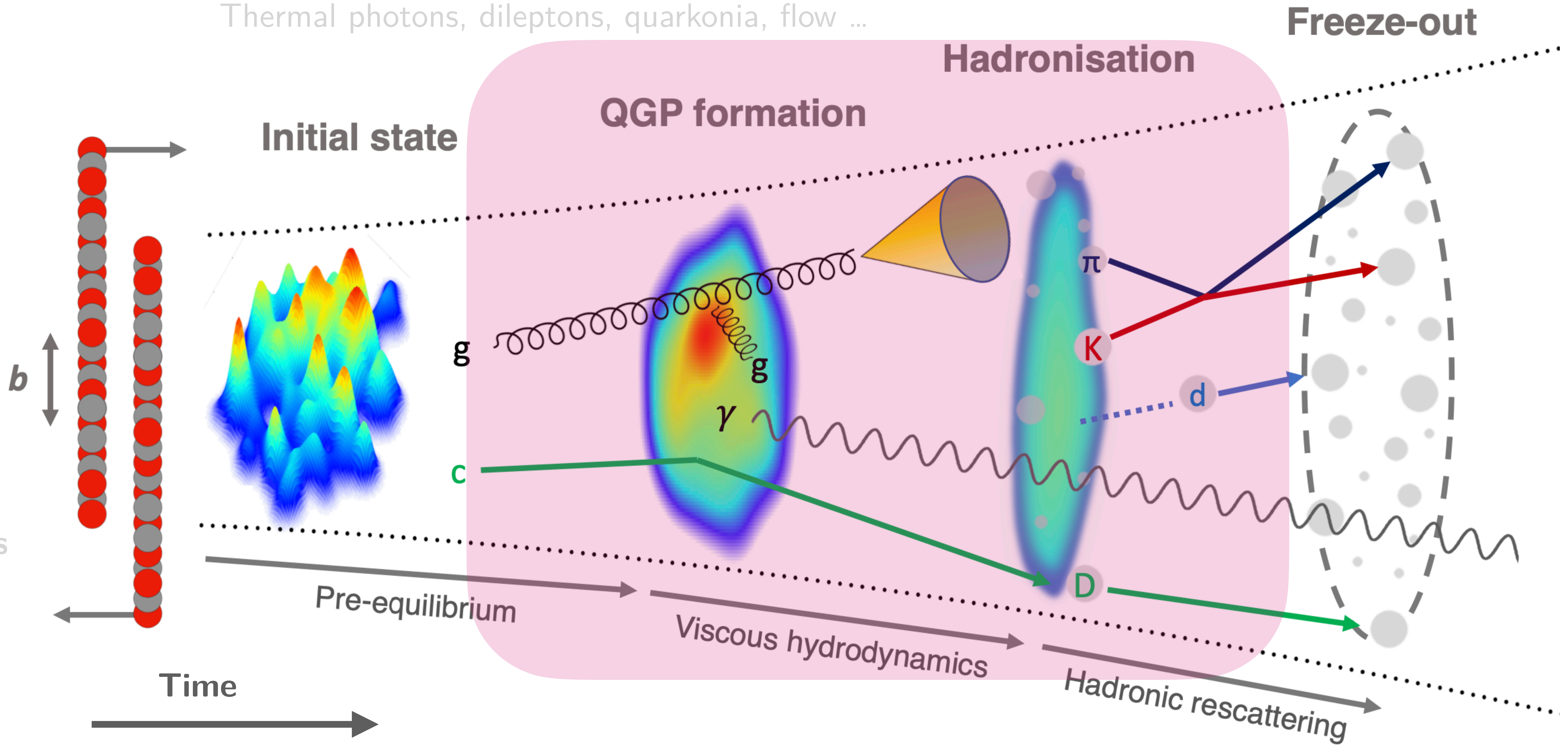
Thermal photons, dileptons, quarkonia, flow ...

What are the initial conditions of a collision? nPDFs & Saturation?

DY, UPC, forward LHC ...

Collectivity of QCD across system sizes?

Flow in pp, p-A; strangeness production, energy loss, thermal radiation



arXiv:2211.04384

What is the microscopic dynamics of QGP at various length scales?
Jets (substructure), γ/Z-jet correlations, heavy flavour, quarkonia, hadronization

Heavy flavour as a probe for the QGP

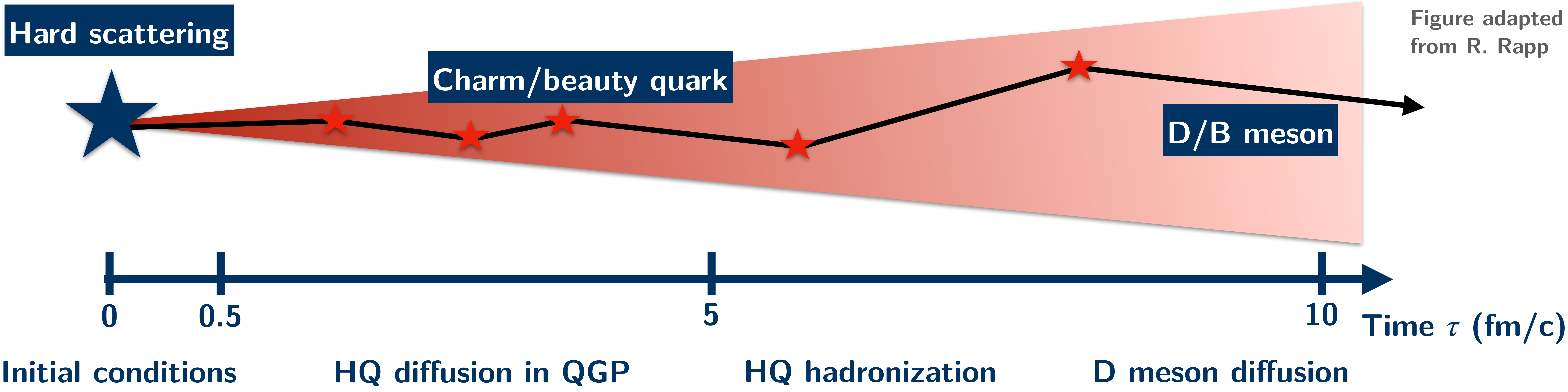
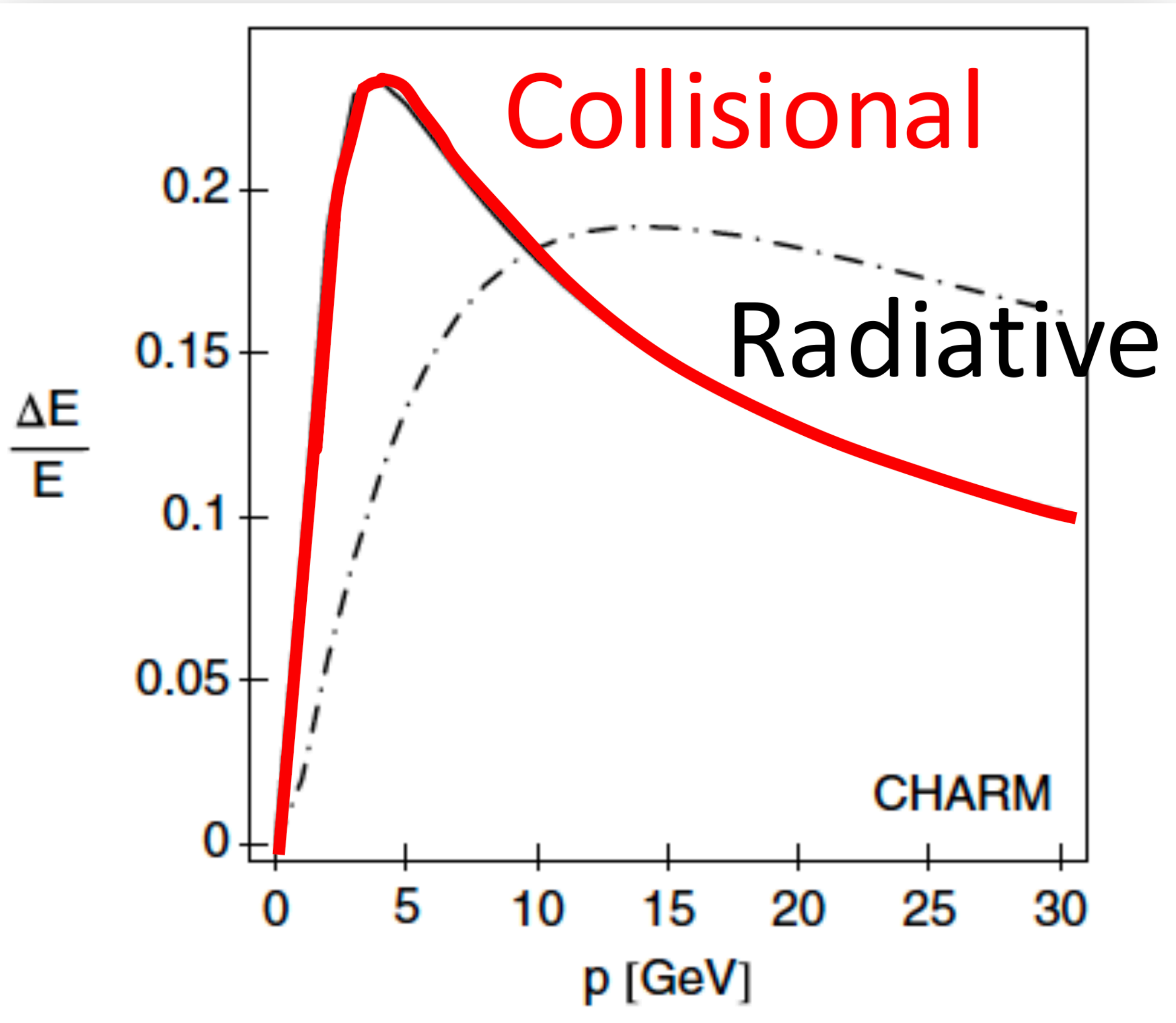


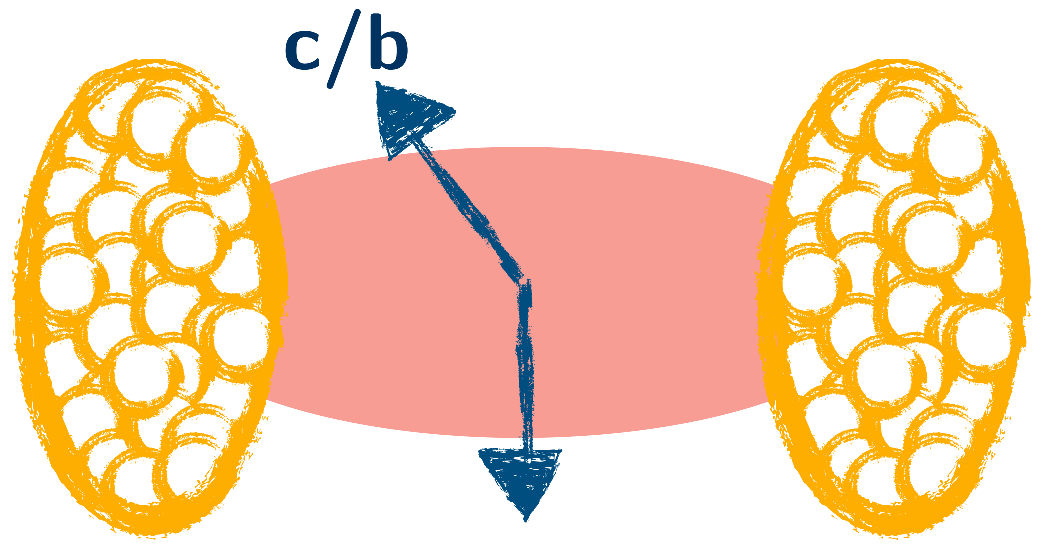
Figure adapted from R. Rapp

- Heavy flavour quarks are produced **early in the collision & allow perturbative theoretical treatment**
- **Sensitivity to:** QGP medium properties & mechanisms of medium ↔ HF interactions
- Heavy quarks interact with QGP and loose energy via:
  - Elastic collisions at low p_{T} (collectivity, diffusion etc.)
  - **Inelastic collisions at high p_{T} (main contr. to energy loss)**

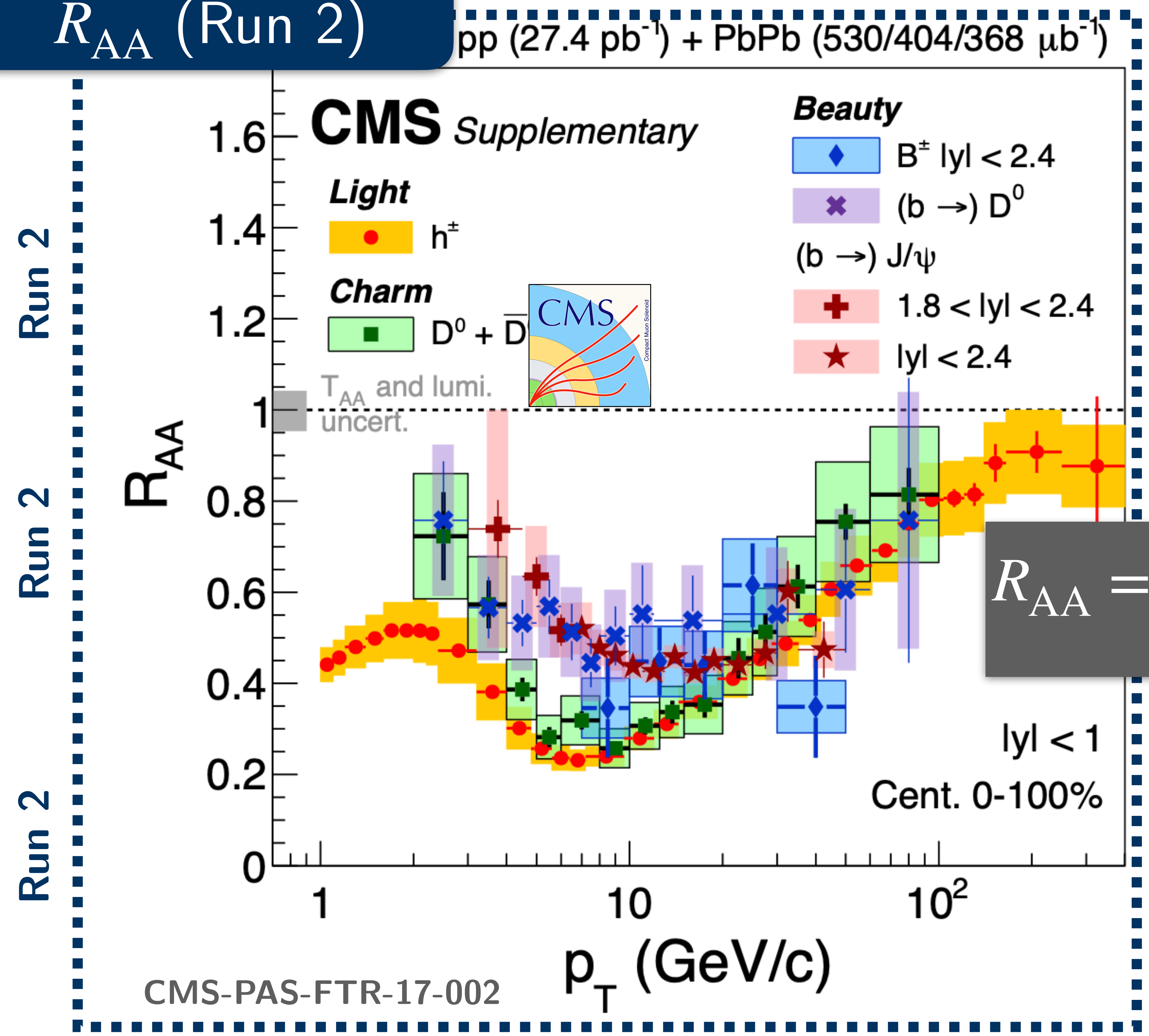


M. Djordjevic, PRC74, 064907 (2006)

- **What is the nature of the QGP on a microscopic level?**
  Insights from heavy quark interaction with QGP constituents
  → R_{AA} and flow with unprecedented precision → QGP diffusion coefficient & energy loss
  → To what degree do heavy quarks of thermalise in the QGP?

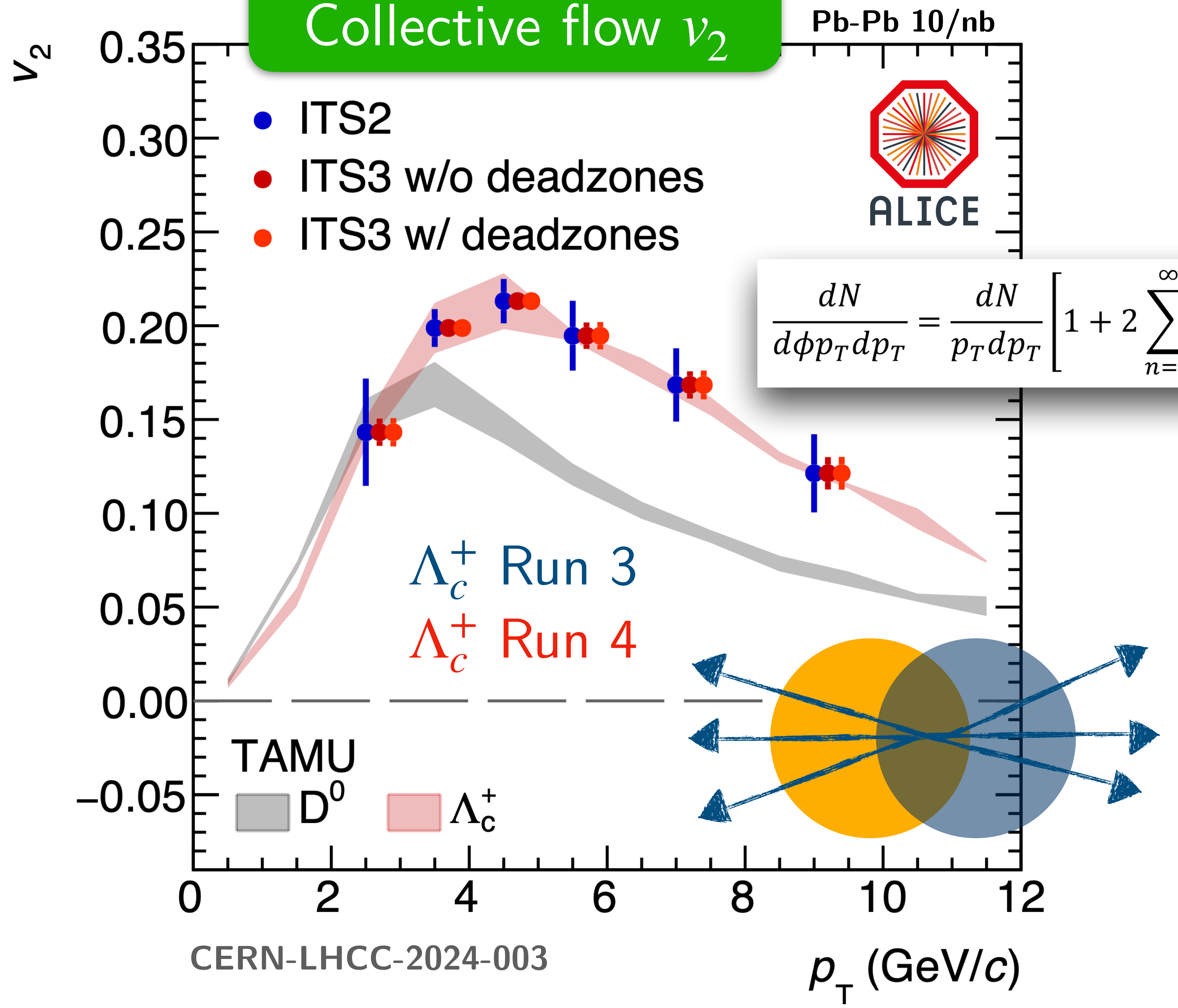


R_{AA} (Run 2)



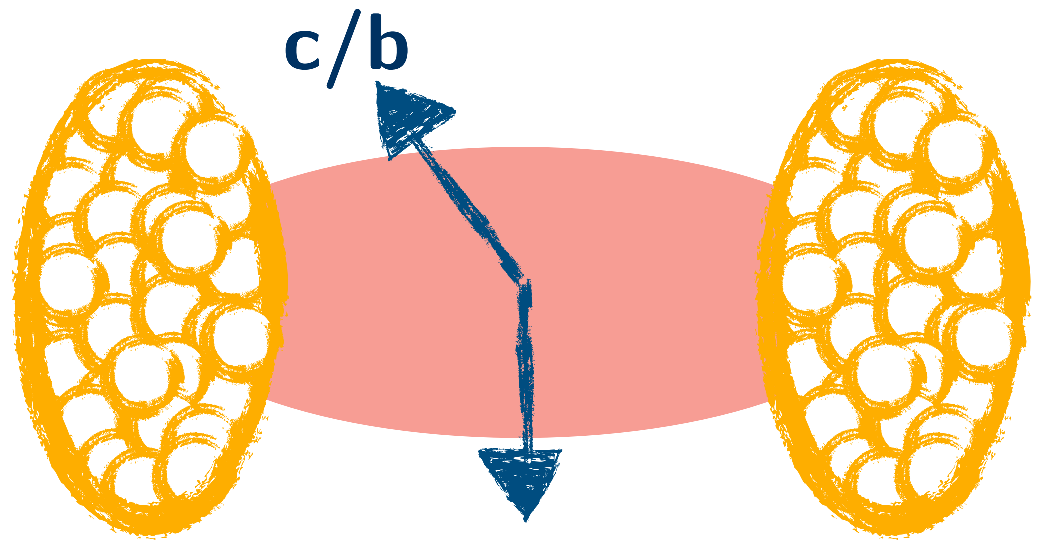
$$R_{AA} = \frac{\sigma_{AA}}{T_{AA} \times \sigma_{pp}}$$

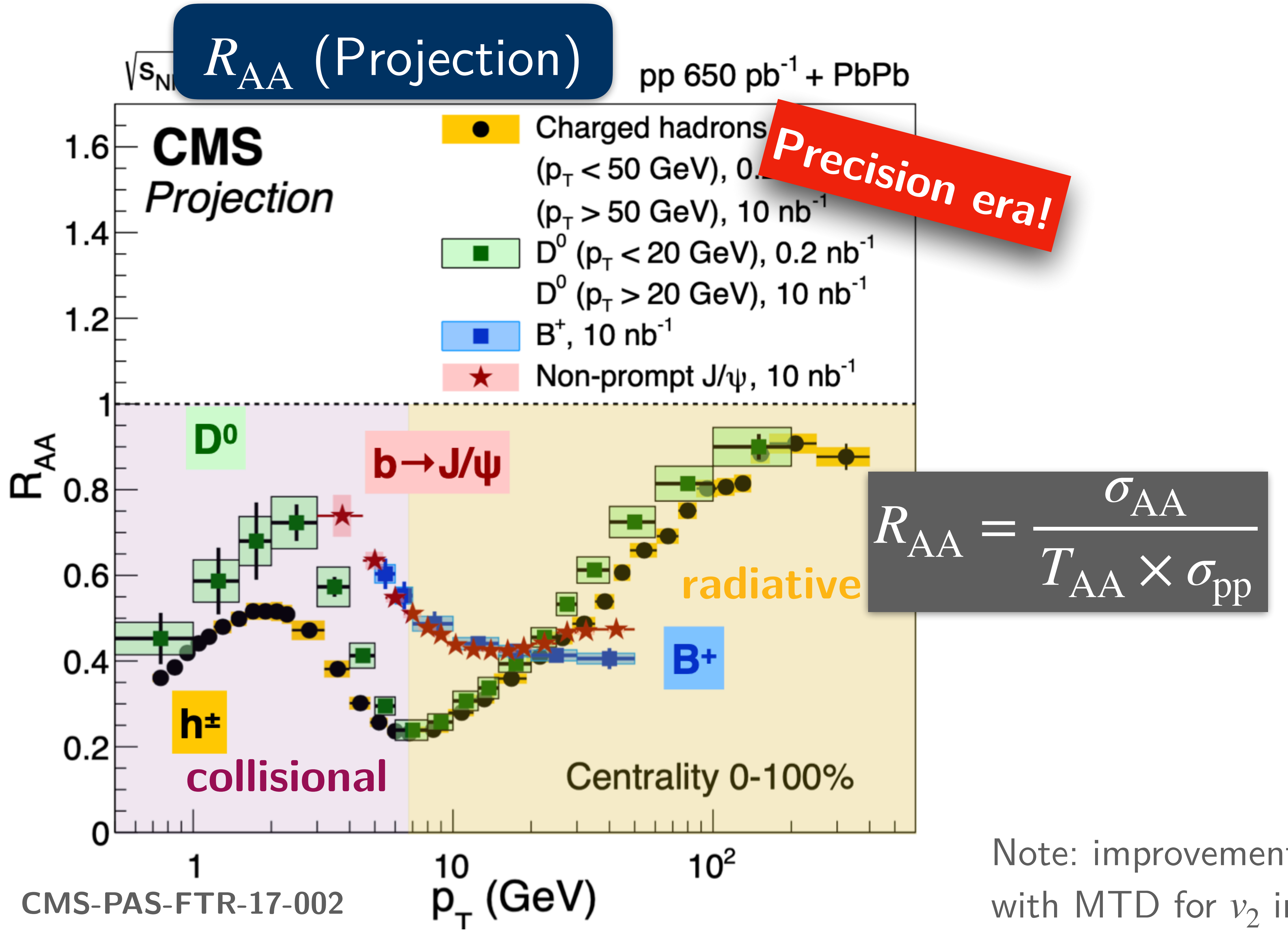
Collective flow v_2



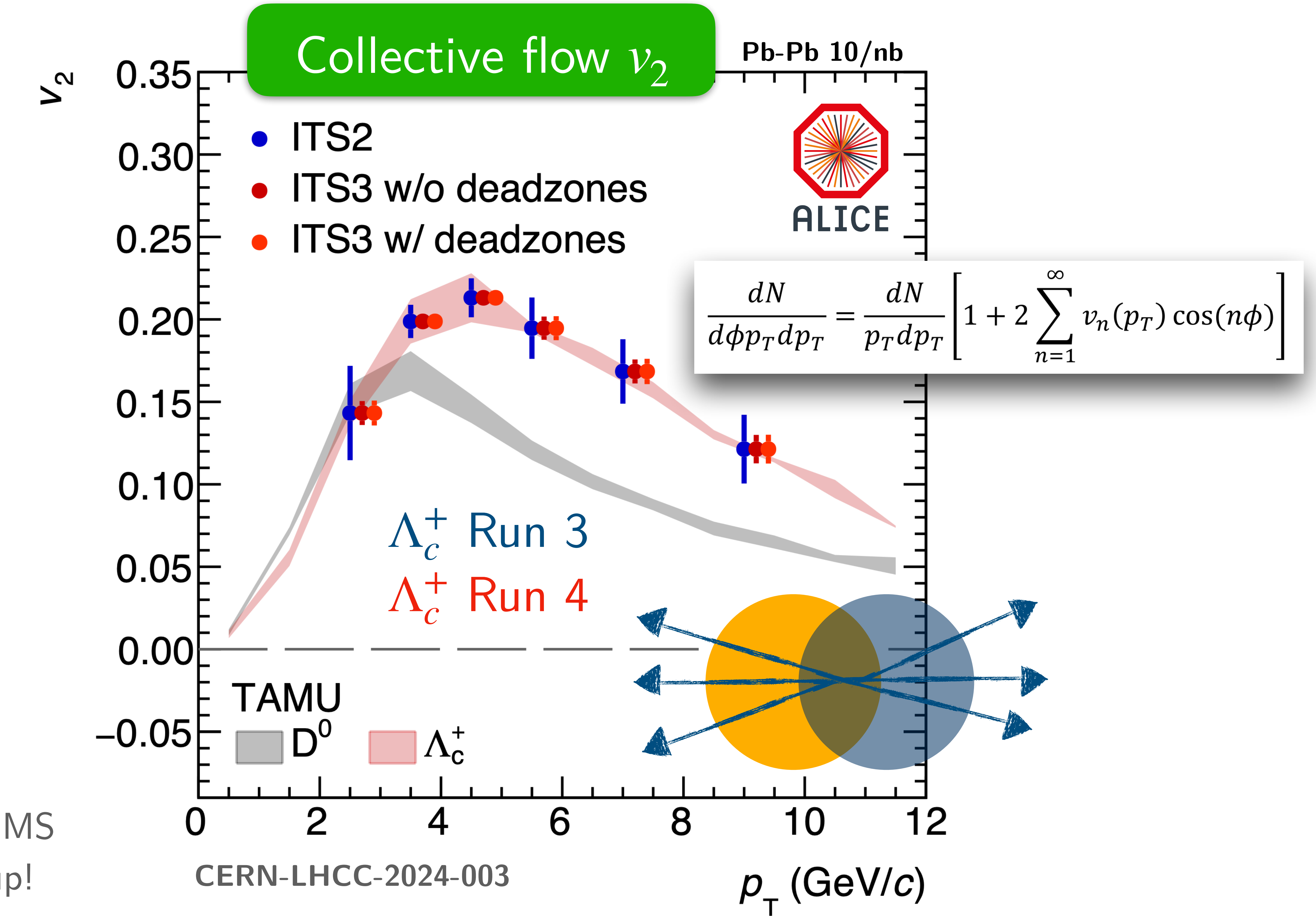
$$\frac{dN}{d\phi p_T dp_T} = \frac{dN}{p_T dp_T}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos(n\phi)\right]$$

- **What is the nature of the QGP on a microscopic level?**
  Insights from heavy quark interaction with QGP constituents
  → R_{AA} and flow with unprecedented precision → QGP diffusion coefficient & energy loss
  → To what degree do heavy quarks of thermalise in the QGP?

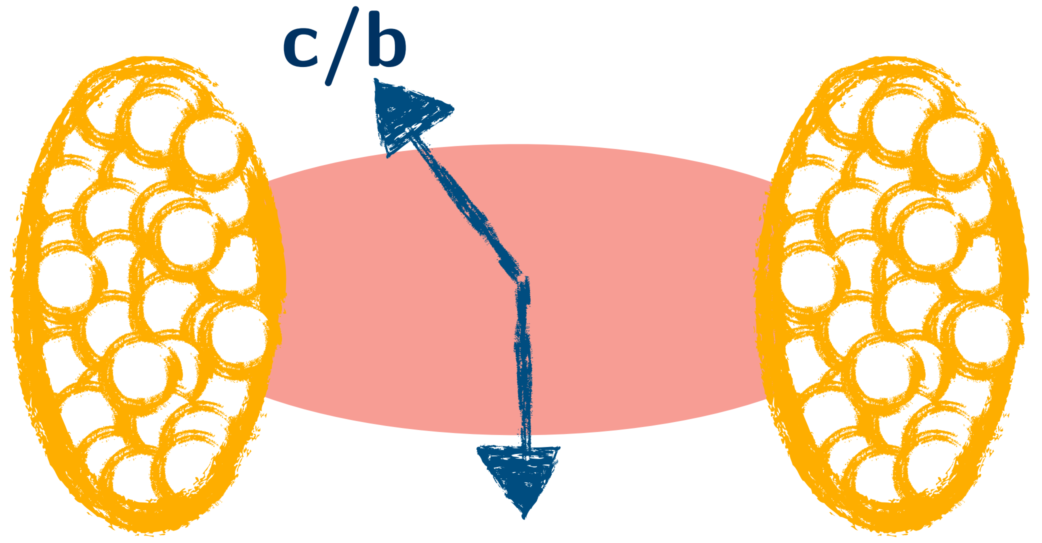




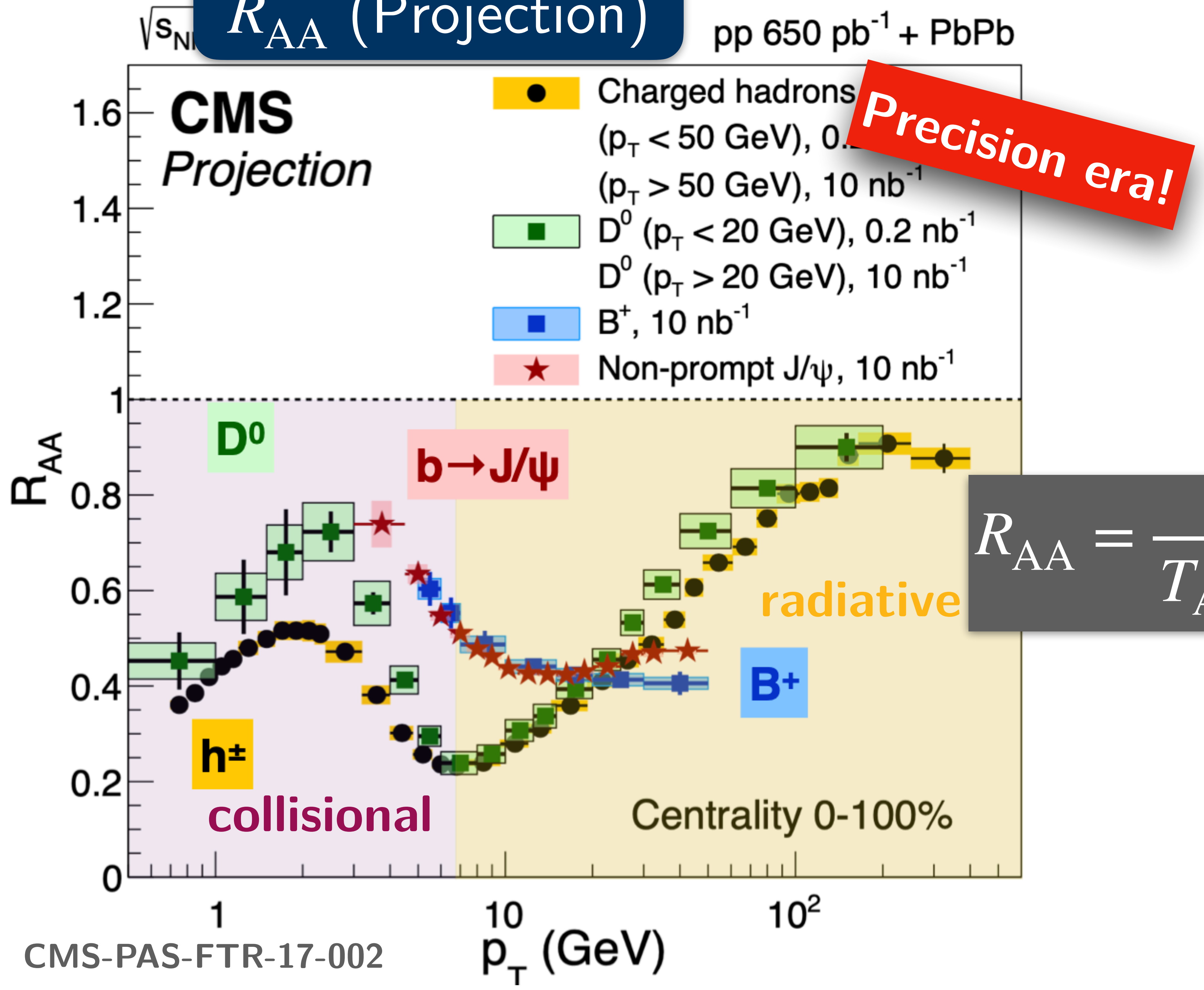
Note: improvements for CMS with MTD for v_2 in backup!



- **What is the nature of the QGP on a microscopic level?**
  Insights from heavy quark interaction with QGP constituents
  → R_{AA} and flow with unprecedented precision → QGP diffusion coefficient & energy loss
  → To what degree do heavy quarks of thermalise in the QGP?



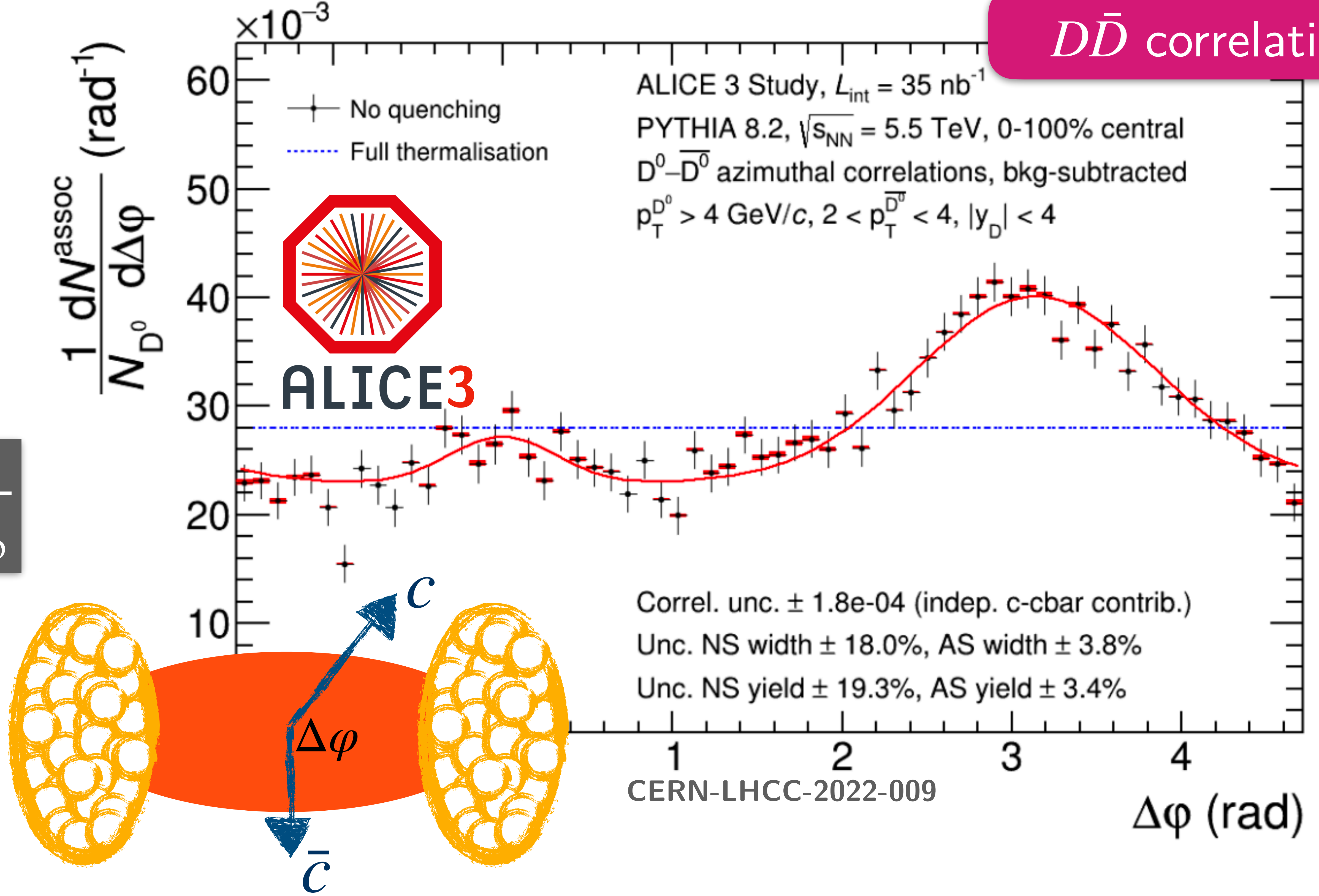
R_{AA} (Projection)



CMS-PAS-FTR-17-002

$$R_{AA} = \frac{\sigma_{AA}}{T_{AA} \times \sigma_{pp}}$$

$D\bar{D}$ correlation



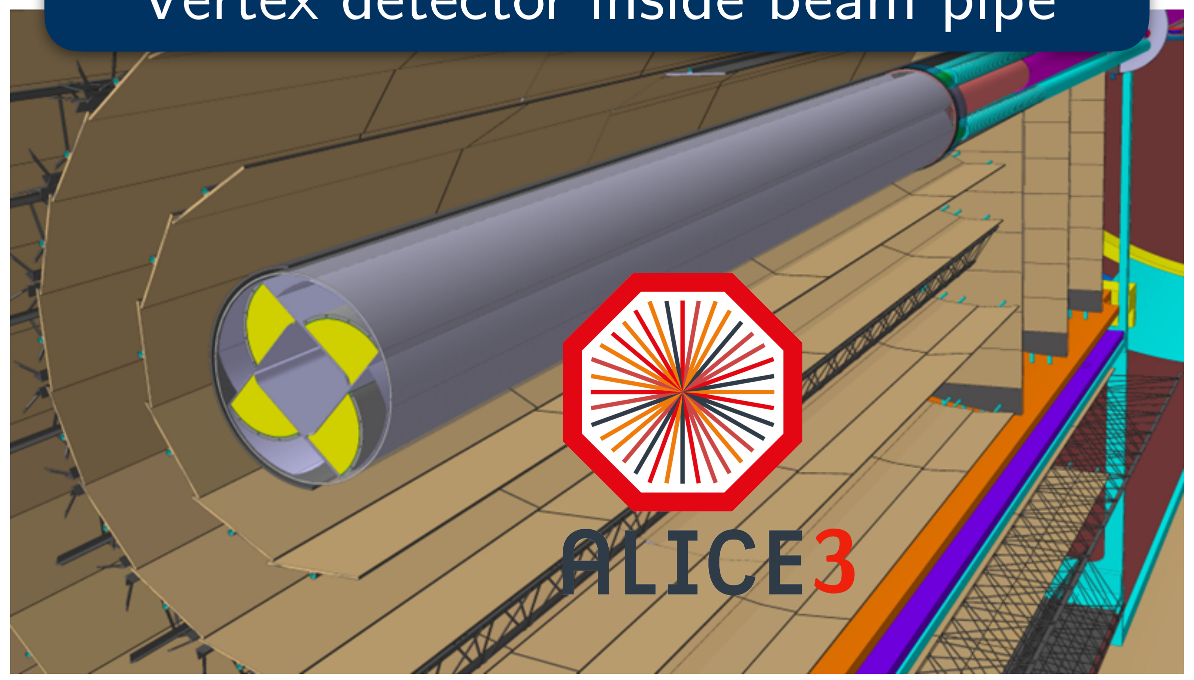
CERN-LHCC-2022-009

Novel insights into charm recombination using multi-charm hadrons

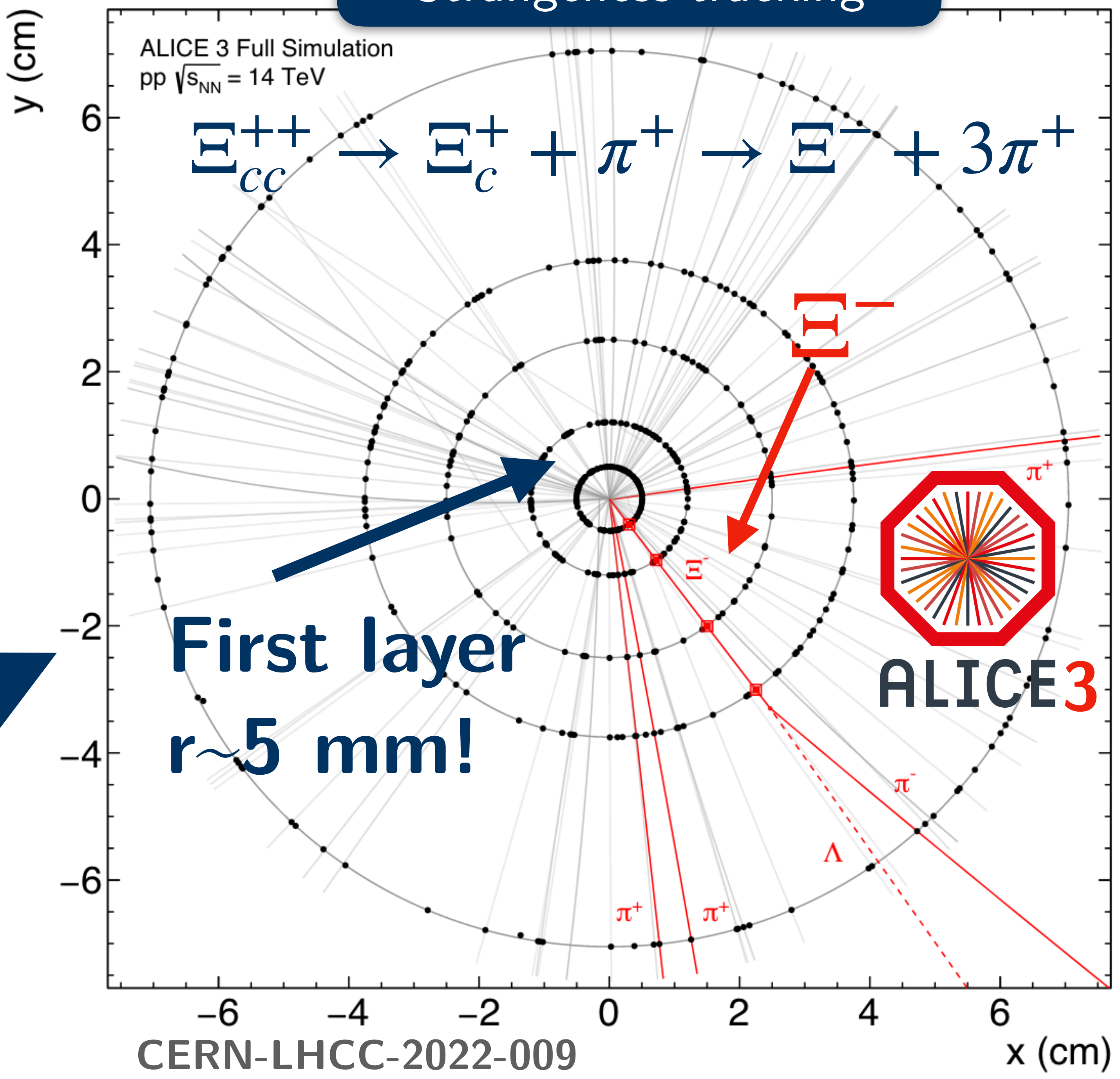
- **Present:** **multi-strange baryon yield** enhancement in Pb-Pb; first evidence Λ_C/D enhancement → **coalescence**
- **Run 3 & Run 4:** precision studies in charm sector: **single charm baryons**
- **Beyond Run 4:** **multi-charm baryons** → only produced by combination of uncorrelated charm quarks → **novel insights into production mechanism**

ALICE3: unique opportunities to study $\Xi^{+}_{cc}(ccd), \Xi^{++}_{cc}(ccu), \Omega^{+}_{cc}(ccs), \Omega^{++}_{ccc}(ccc)$ thanks to "strangeness tracking" in silicon pixel tracking layers

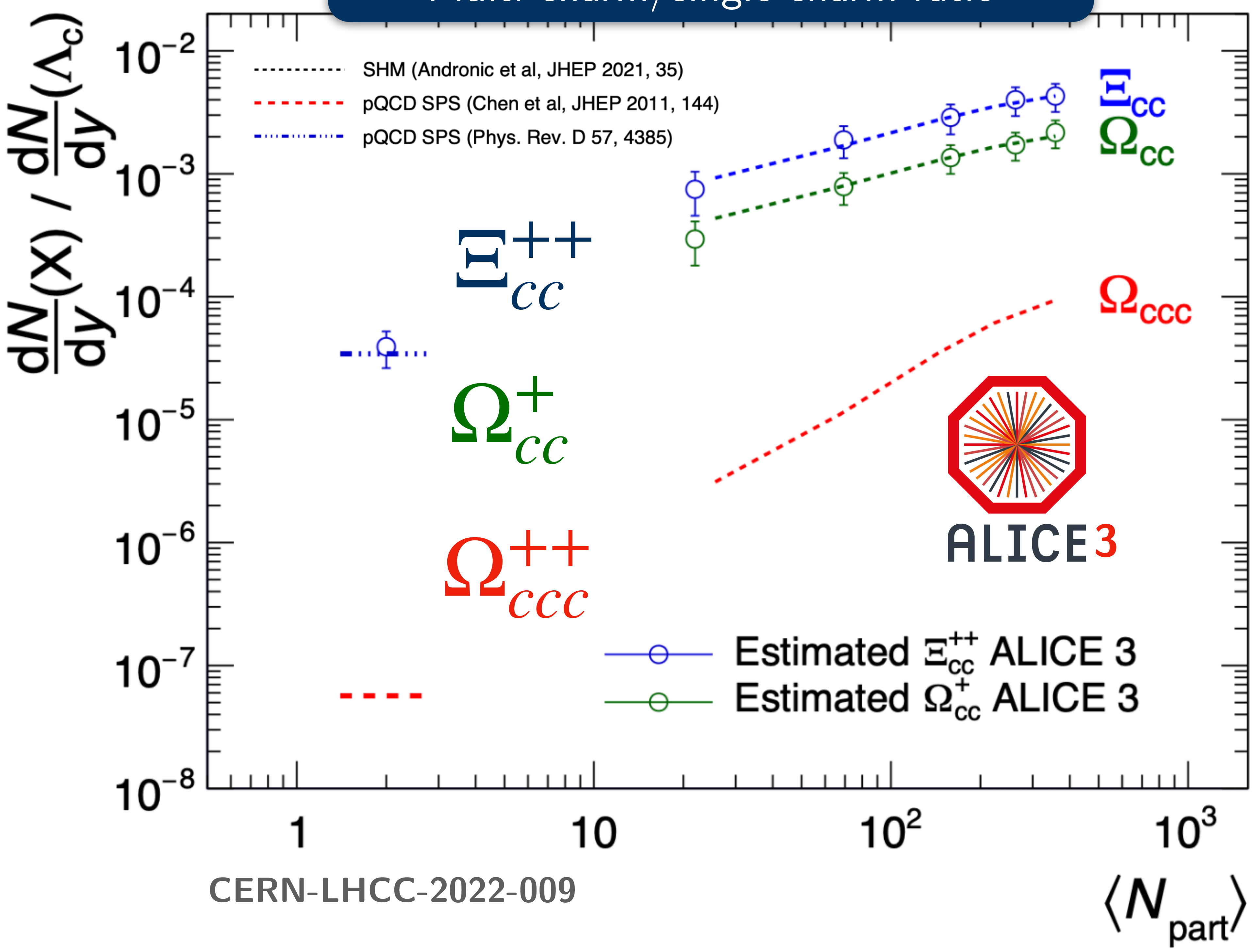
Vertex detector inside beam pipe



Strangeness tracking



Multi-charm/single charm ratio

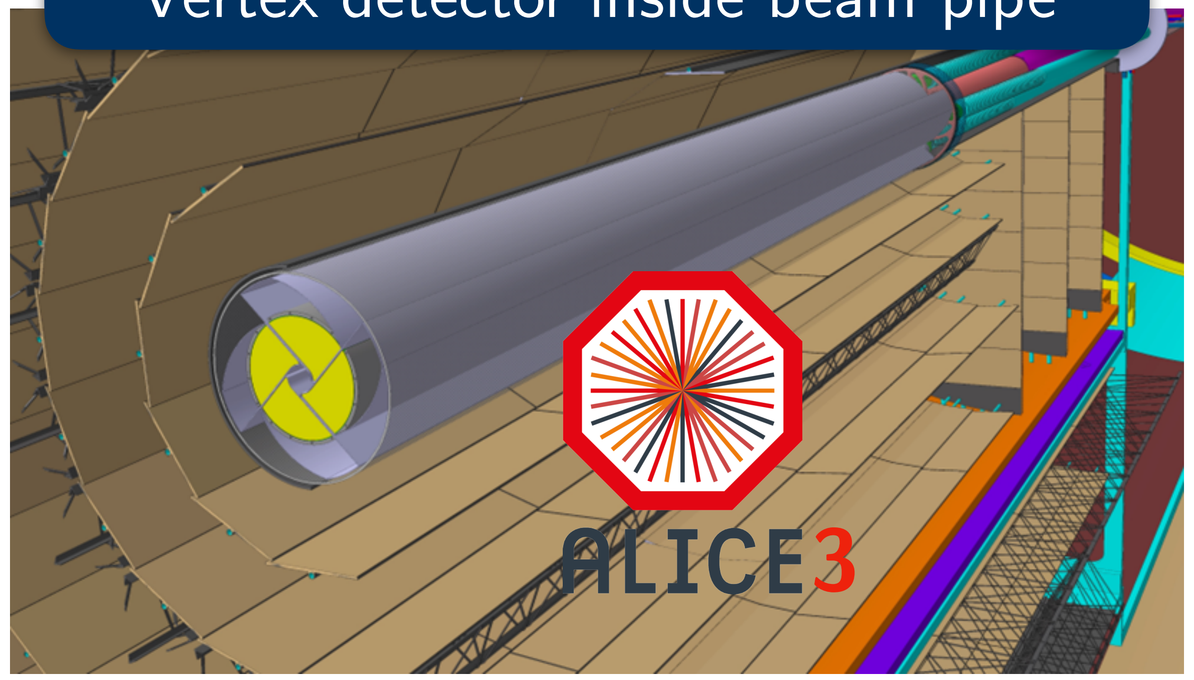


Novel insights into charm recombination using multi-charm hadrons

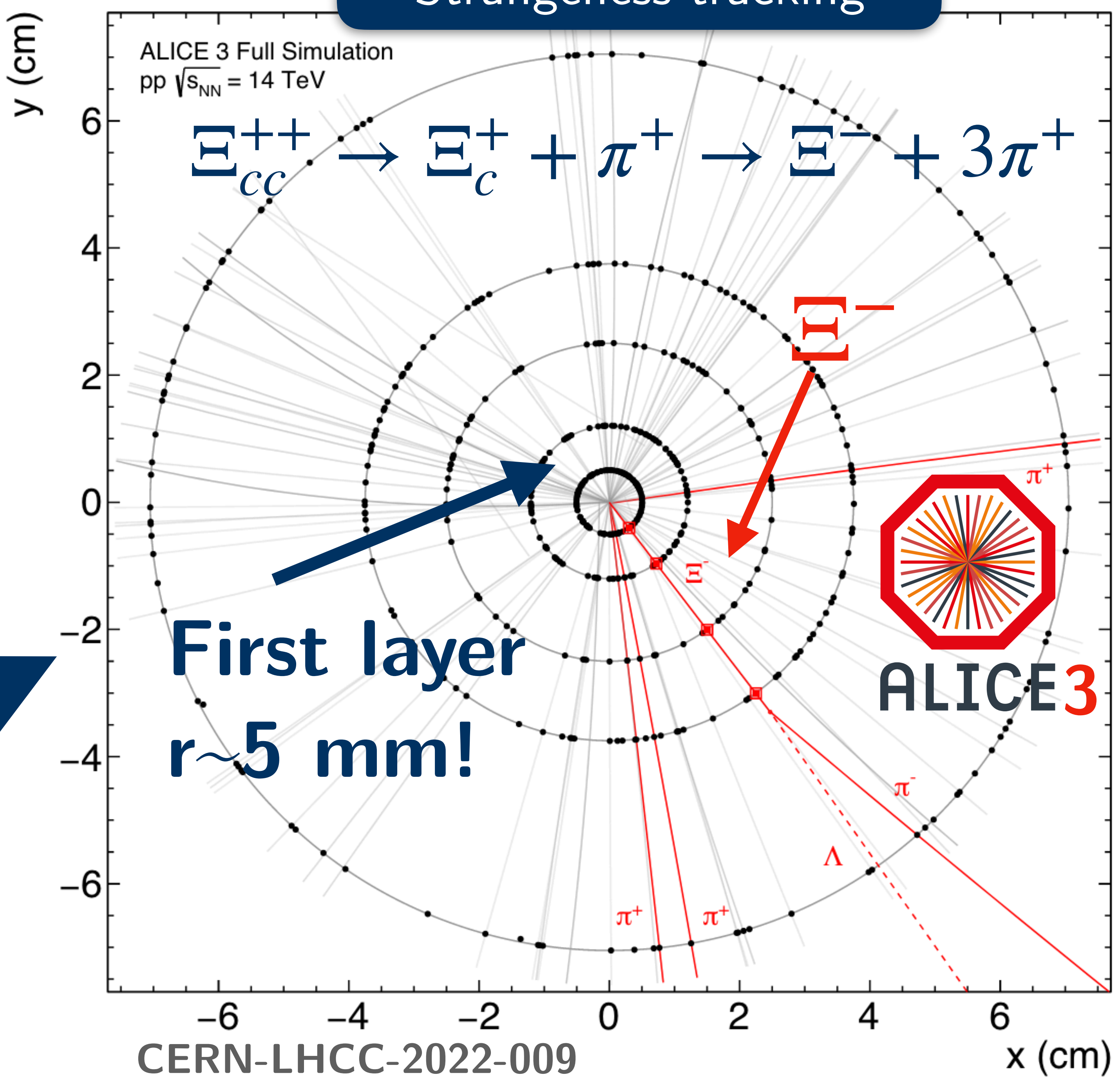
- **Present:** **multi-strange baryon yield** enhancement in Pb-Pb; first evidence Λ_C/D enhancement → **coalescence**
- **Run 3 & Run 4:** precision studies in charm sector: **single charm baryons**
- **Beyond Run 4:** **multi-charm baryons** → only produced by combination of uncorrelated charm quarks → **novel insights into production mechanism**

ALICE3: unique opportunities to study $\Xi^{+}_{cc}(ccd), \Xi^{++}_{cc}(ccu), \Omega^{+}_{cc}(ccs), \Omega^{++}_{ccc}(ccc)$ thanks to "strangeness tracking" in silicon pixel tracking layers

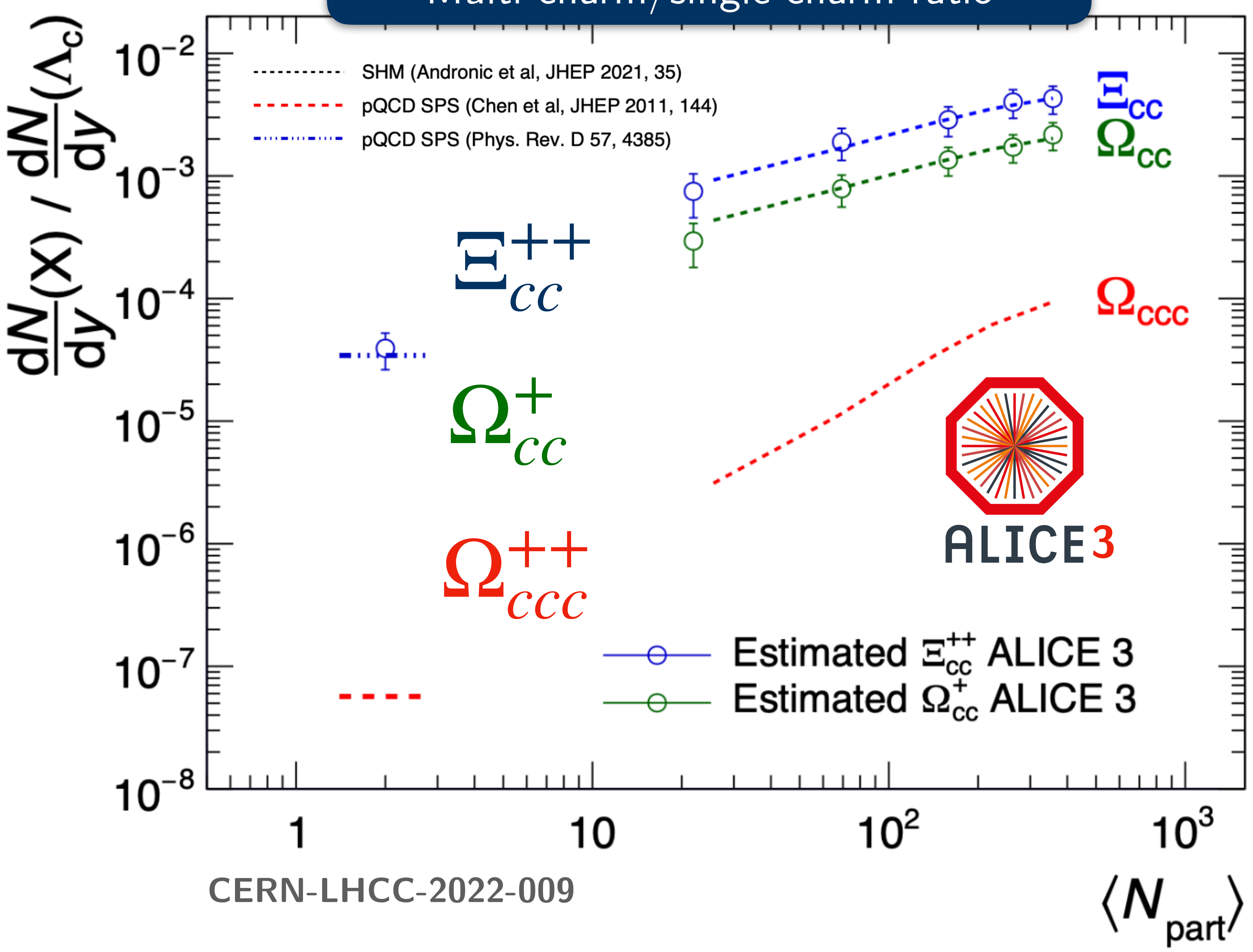
Vertex detector inside beam pipe



Strangeness tracking

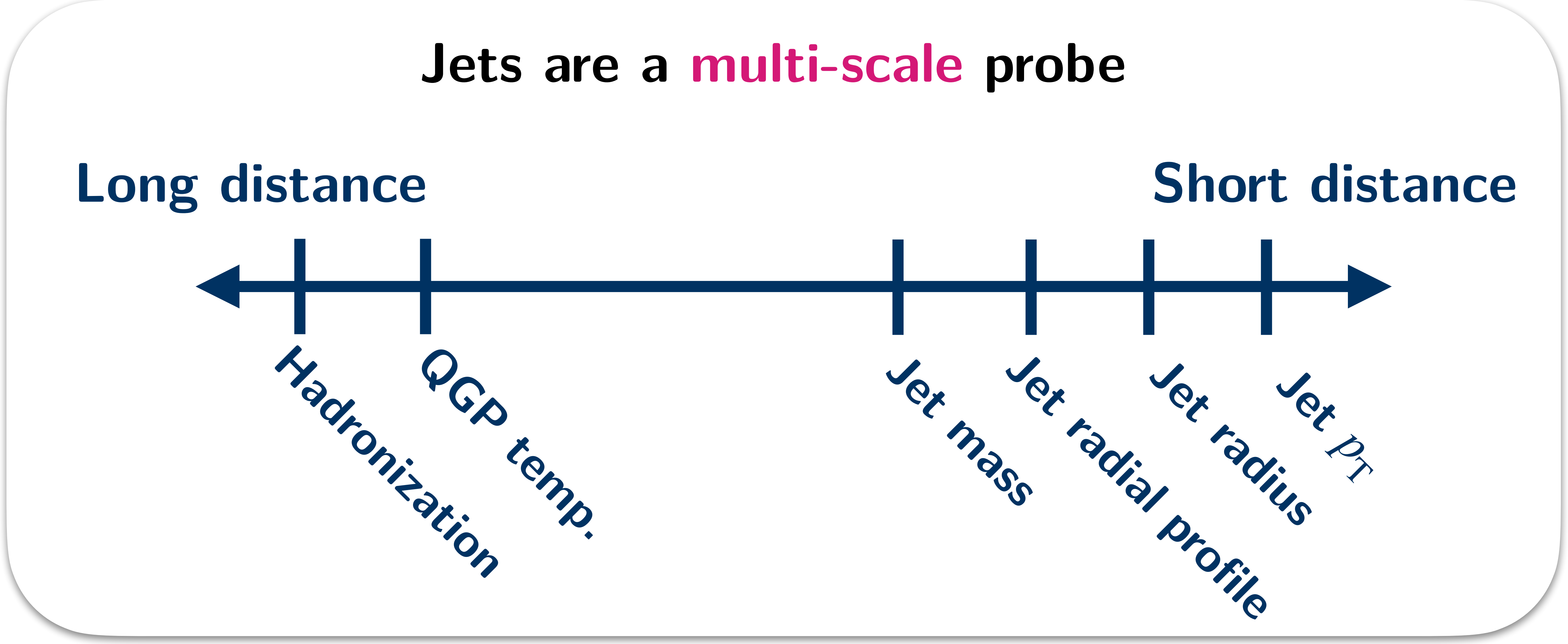


Multi-charm/single charm ratio

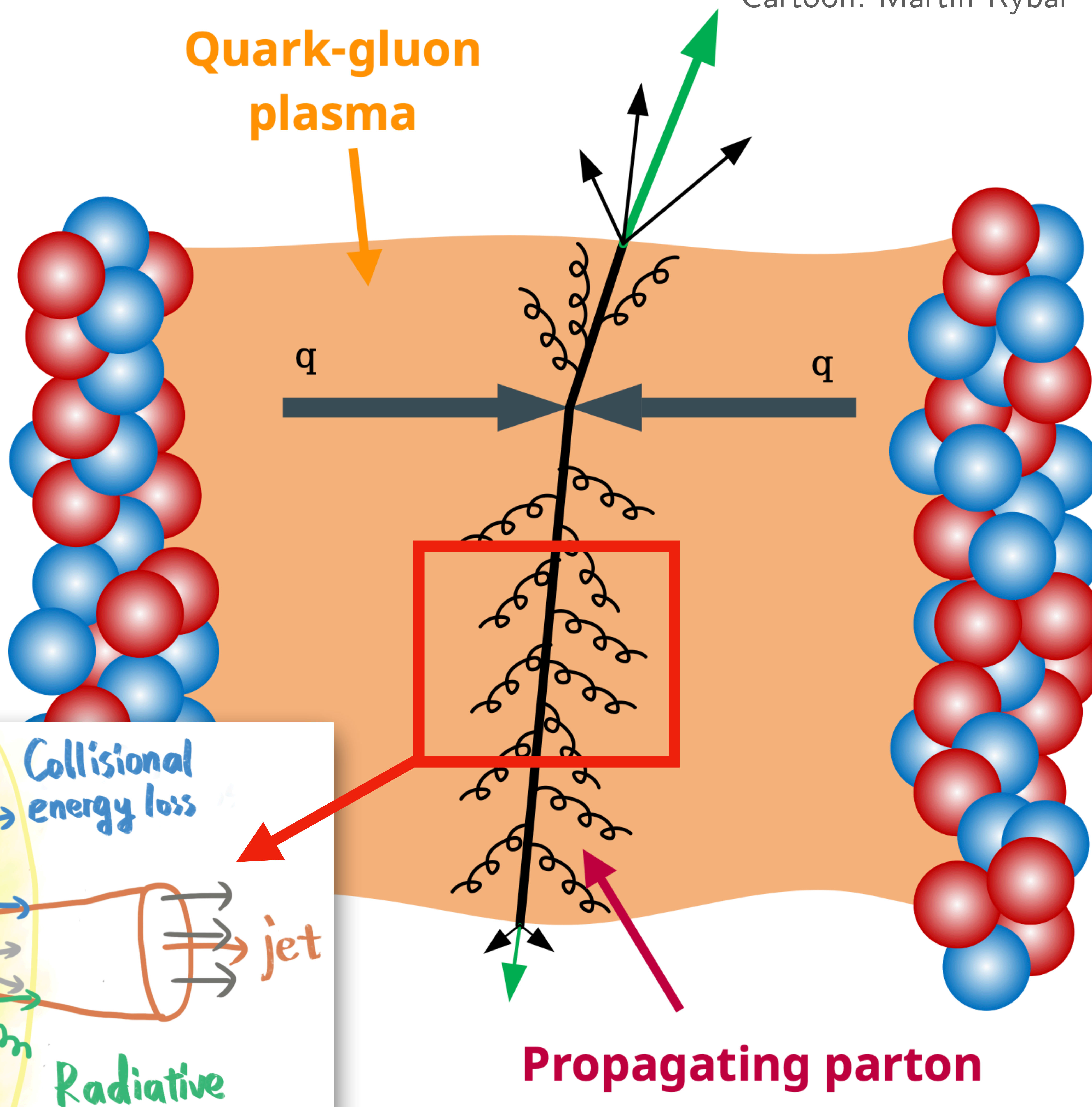


Jets as a probe for the QGP

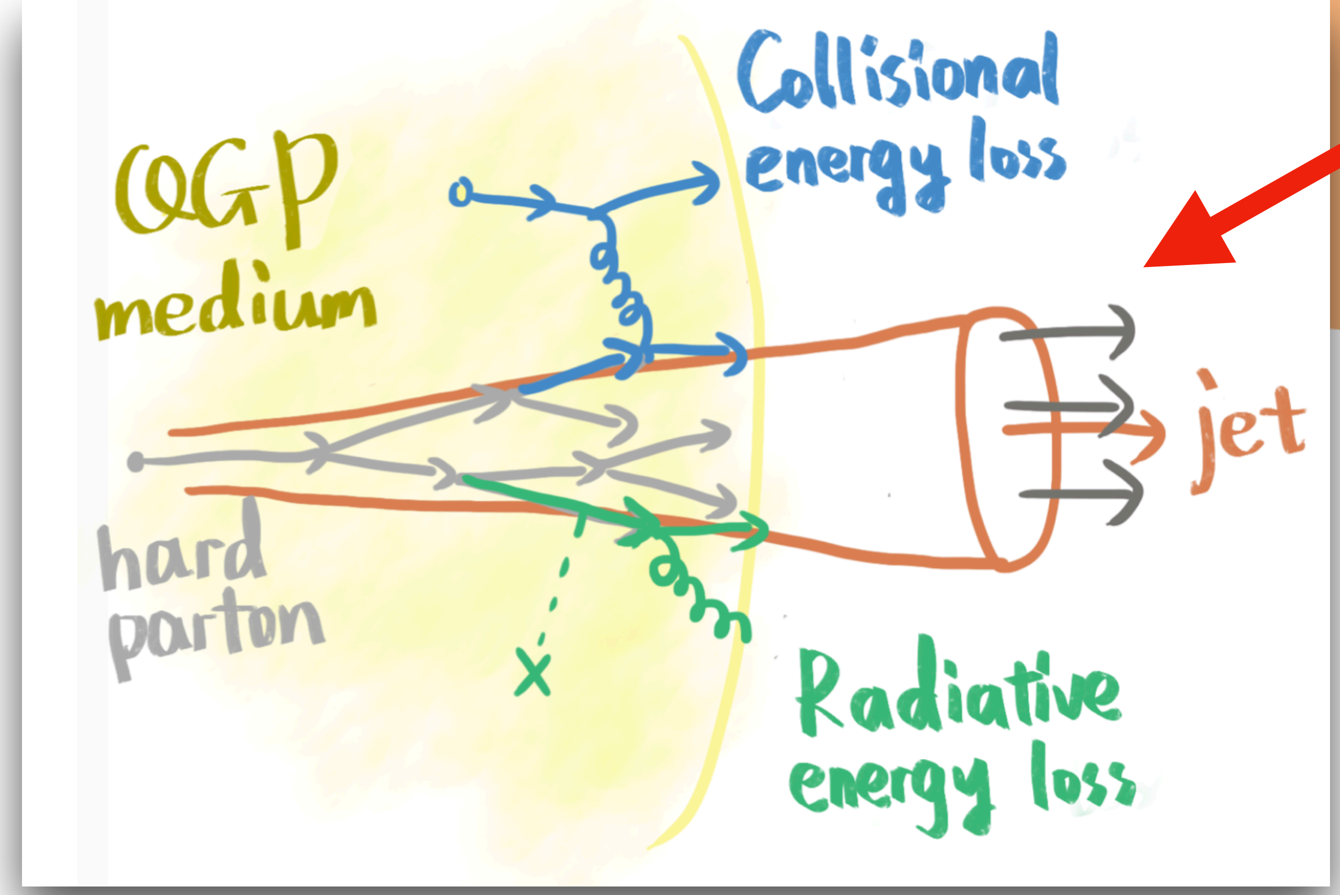
Parton traverses QGP ⇒ Interaction depend on QGP properties



Cartoon: Martin Rybar



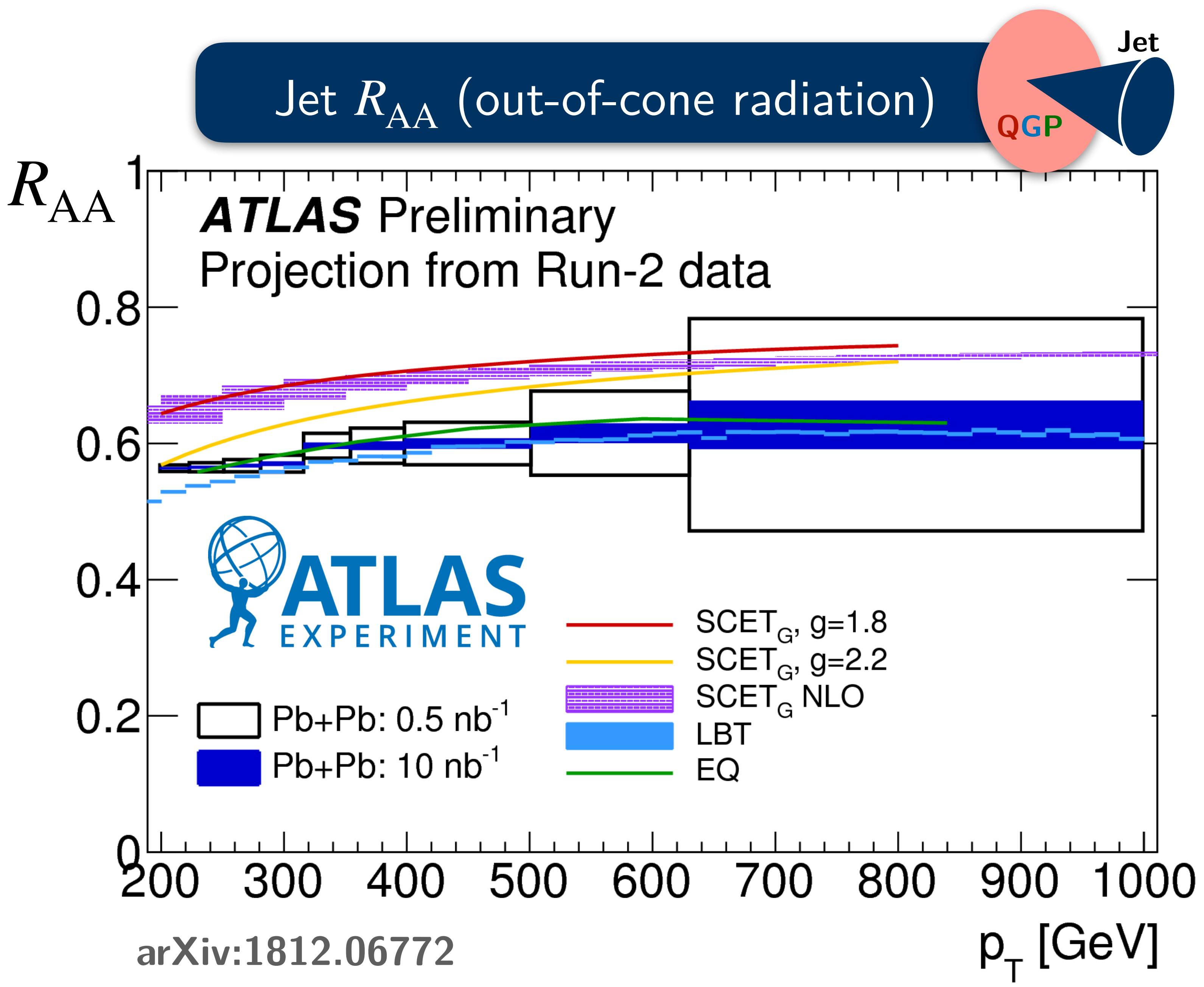
Cartoon: Jing Wang

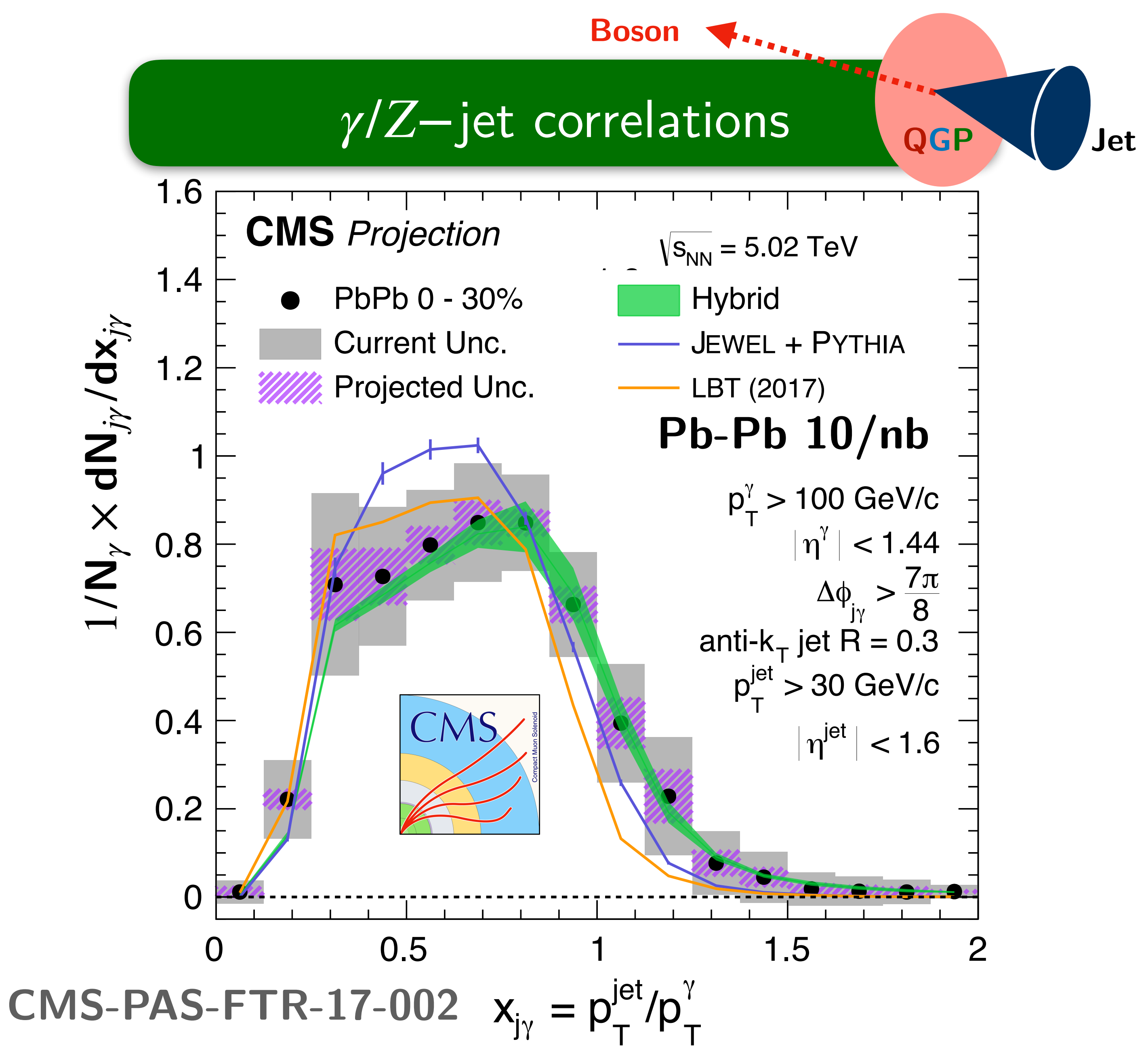


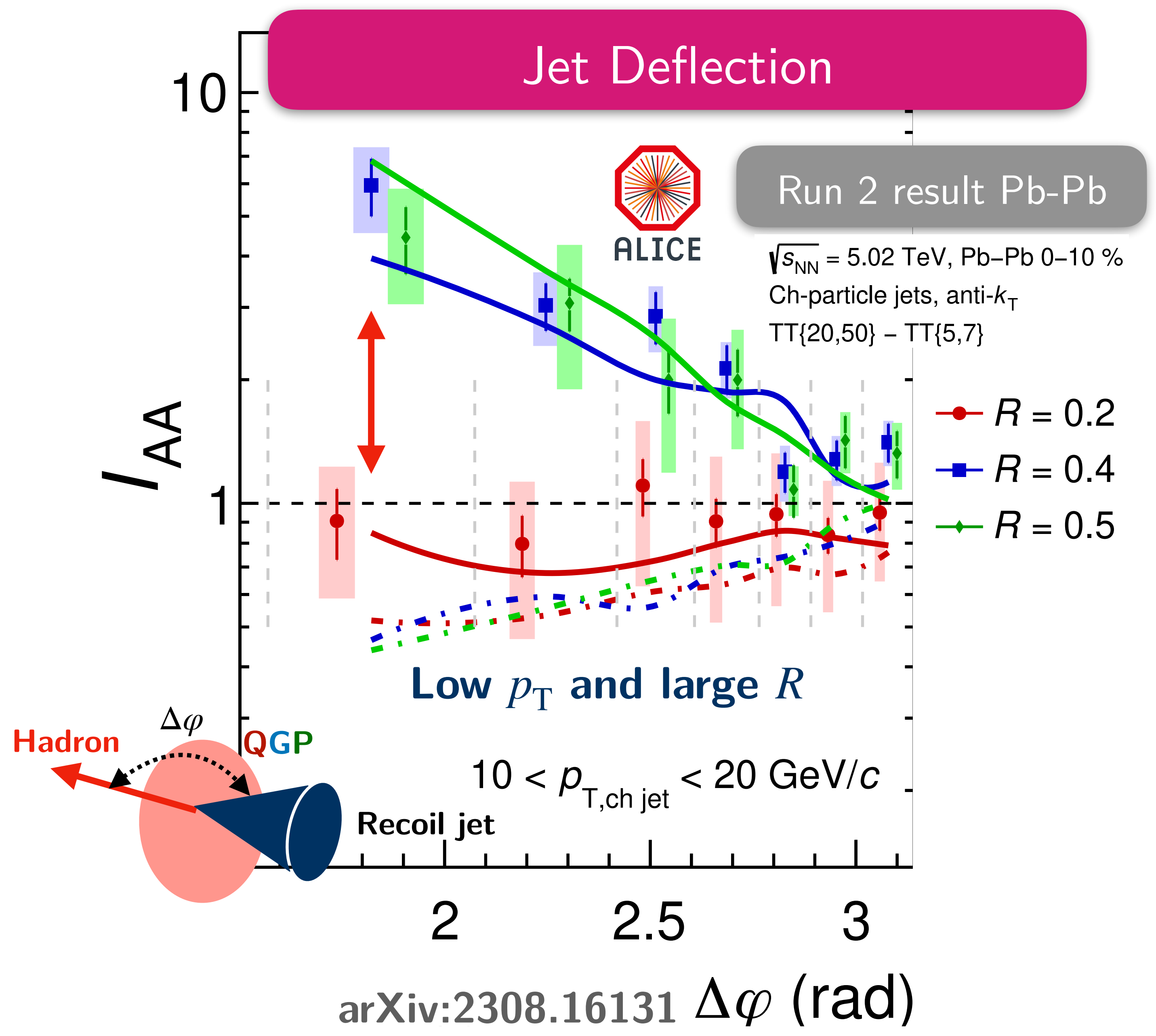
1. What does the parton resolve?
2. What does the medium resolve?
3. How does the QGP change the probe?
4. How does the probe change the medium?

Physics: Microscopic QGP properties, extraction of transport coefficient $\hat{q}$, multi-scale probe for QGP

Jet physics: probing the short distance structure of QGP through scattering of a (multi-scale) hard probe



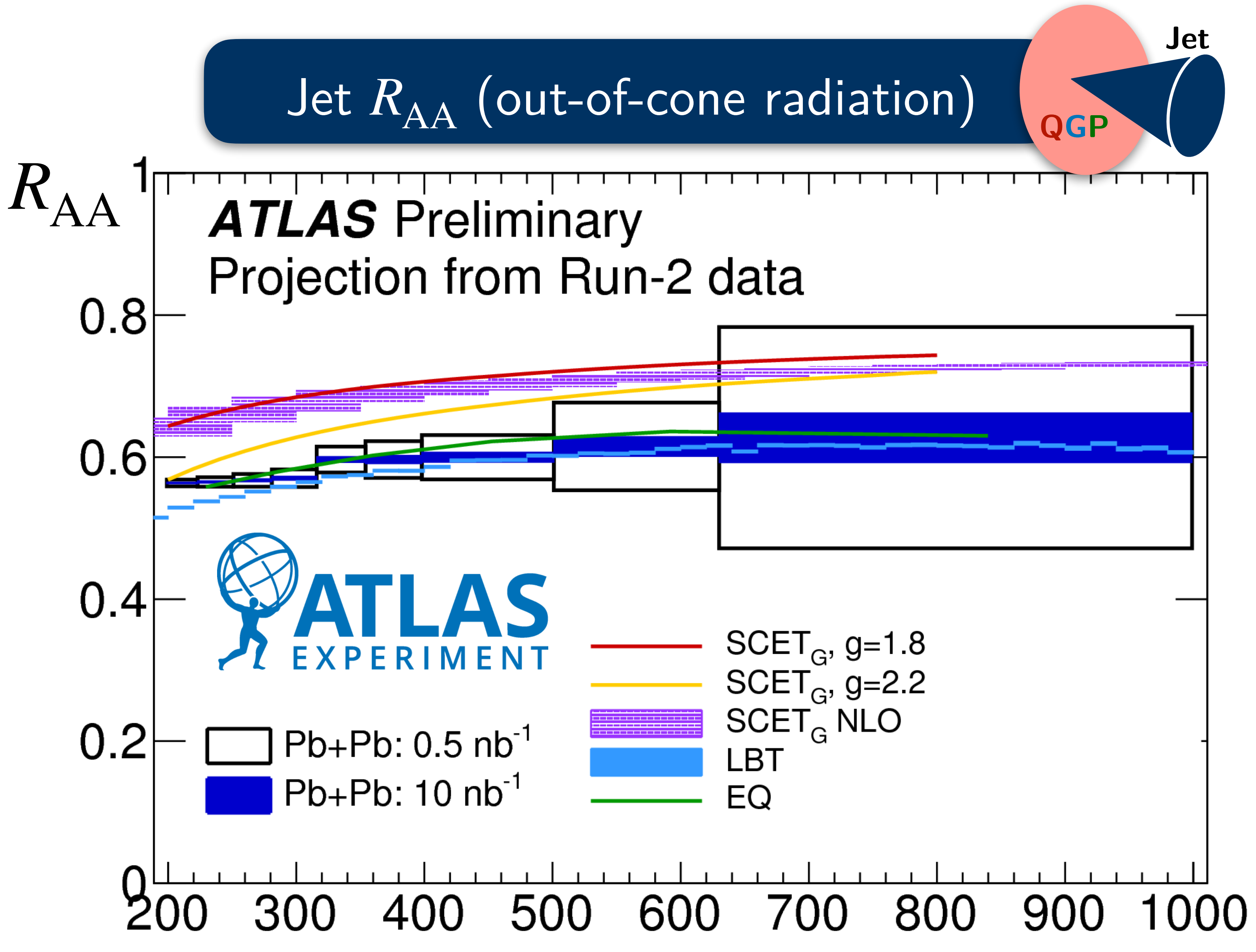




Physics: Microscopic QGP properties, extraction of transport coefficient $\hat{q}$, multi-scale probe for QGP

Jet physics: probing the short distance structure of QGP through scattering of a (multi-scale) hard probe

- ATLAS/CMS/ALICE will quantify jet suppression with unprecedented precision & kinematic reach



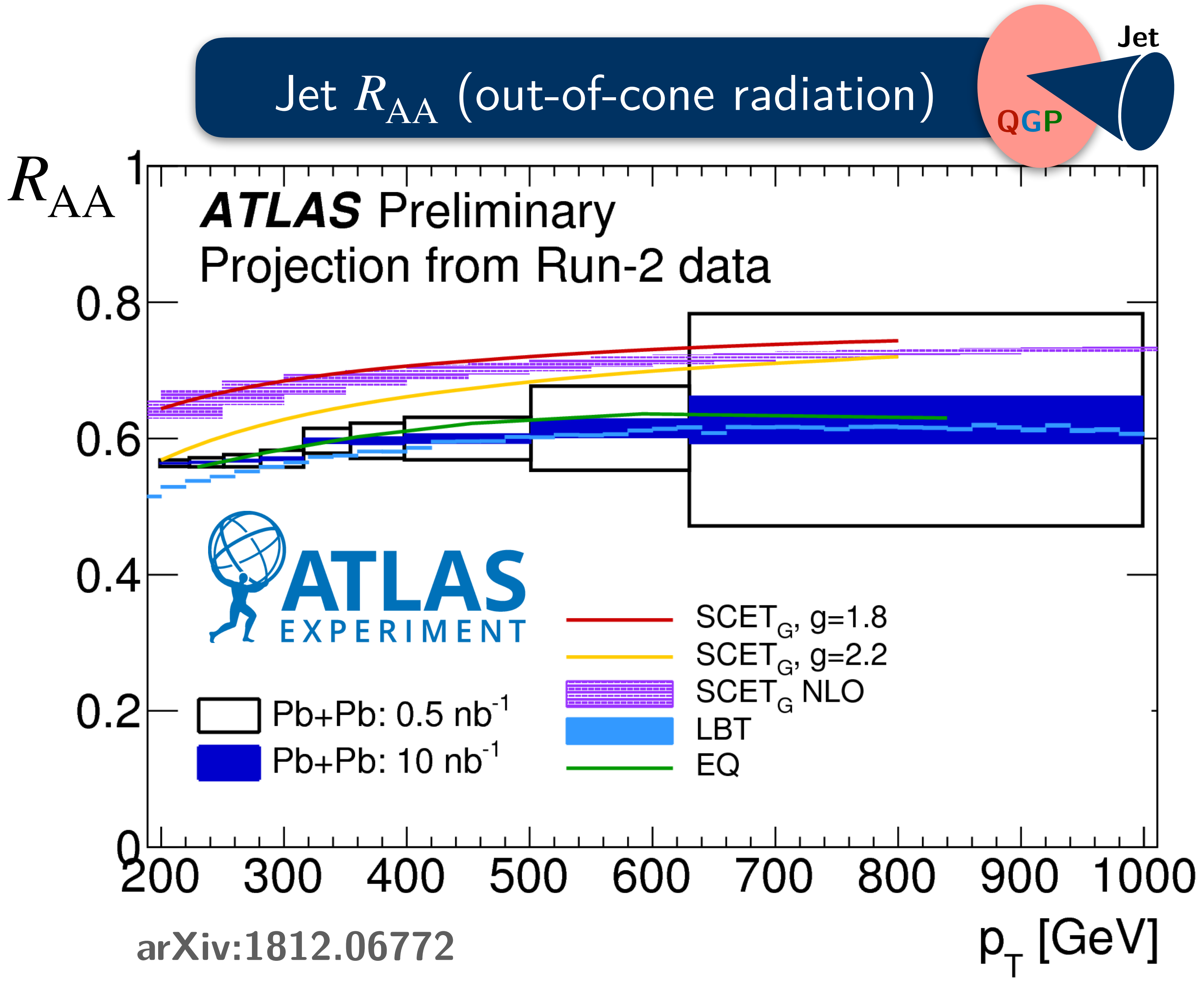
arXiv:1812.06772

arXiv:2308.16131

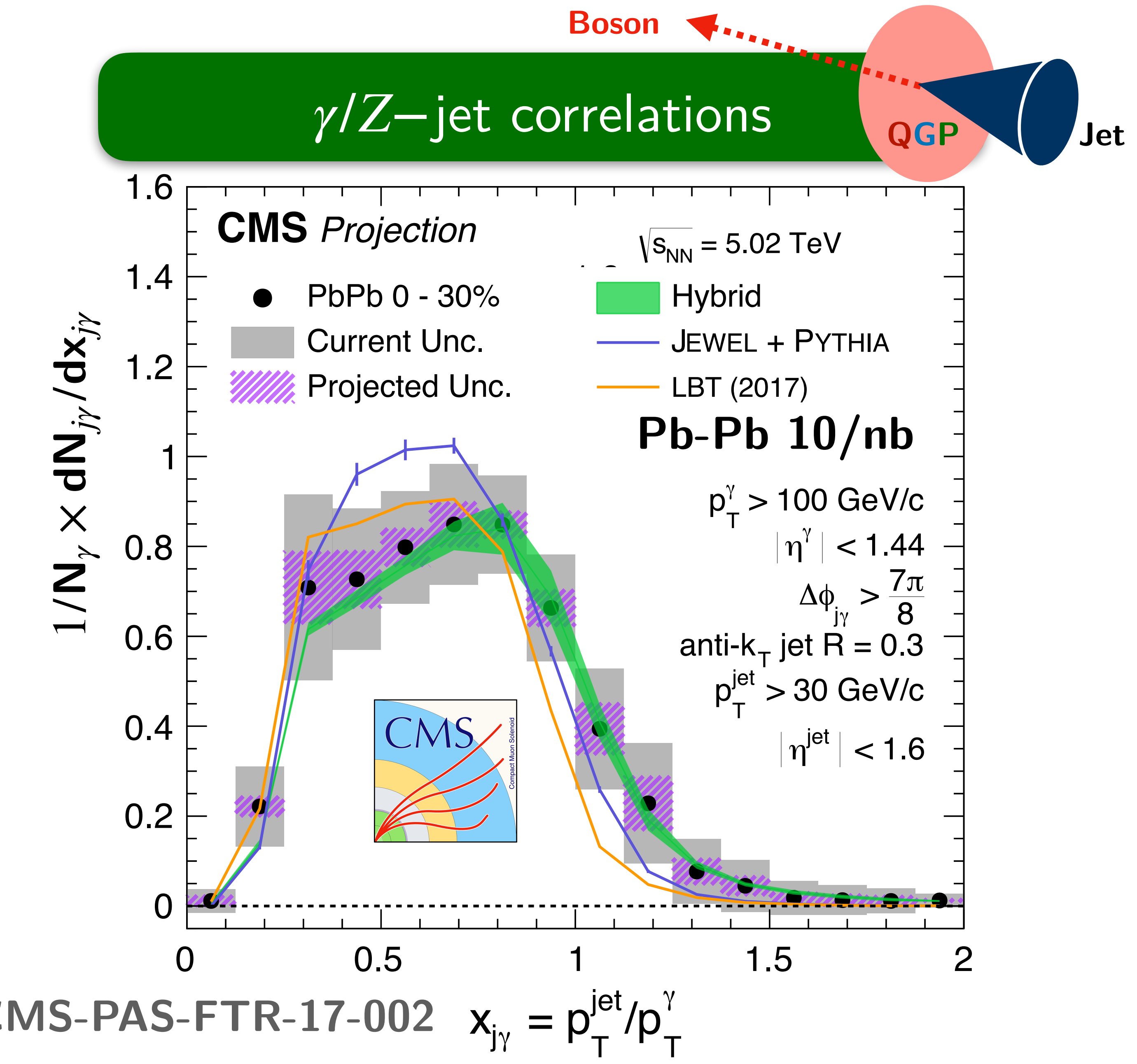
Physics: Microscopic QGP properties, extraction of transport coefficient $\hat{q}$, multi-scale probe for QGP

Jet physics: probing the short distance structure of QGP through scattering of a (multi-scale) hard probe

- ATLAS/CMS/ALICE will quantify jet suppression with unprecedented precision & kinematic reach
- γ/Z-jet corr.: calibrated probe; controlled variation of q/g fraction, path length



arXiv:1812.06772



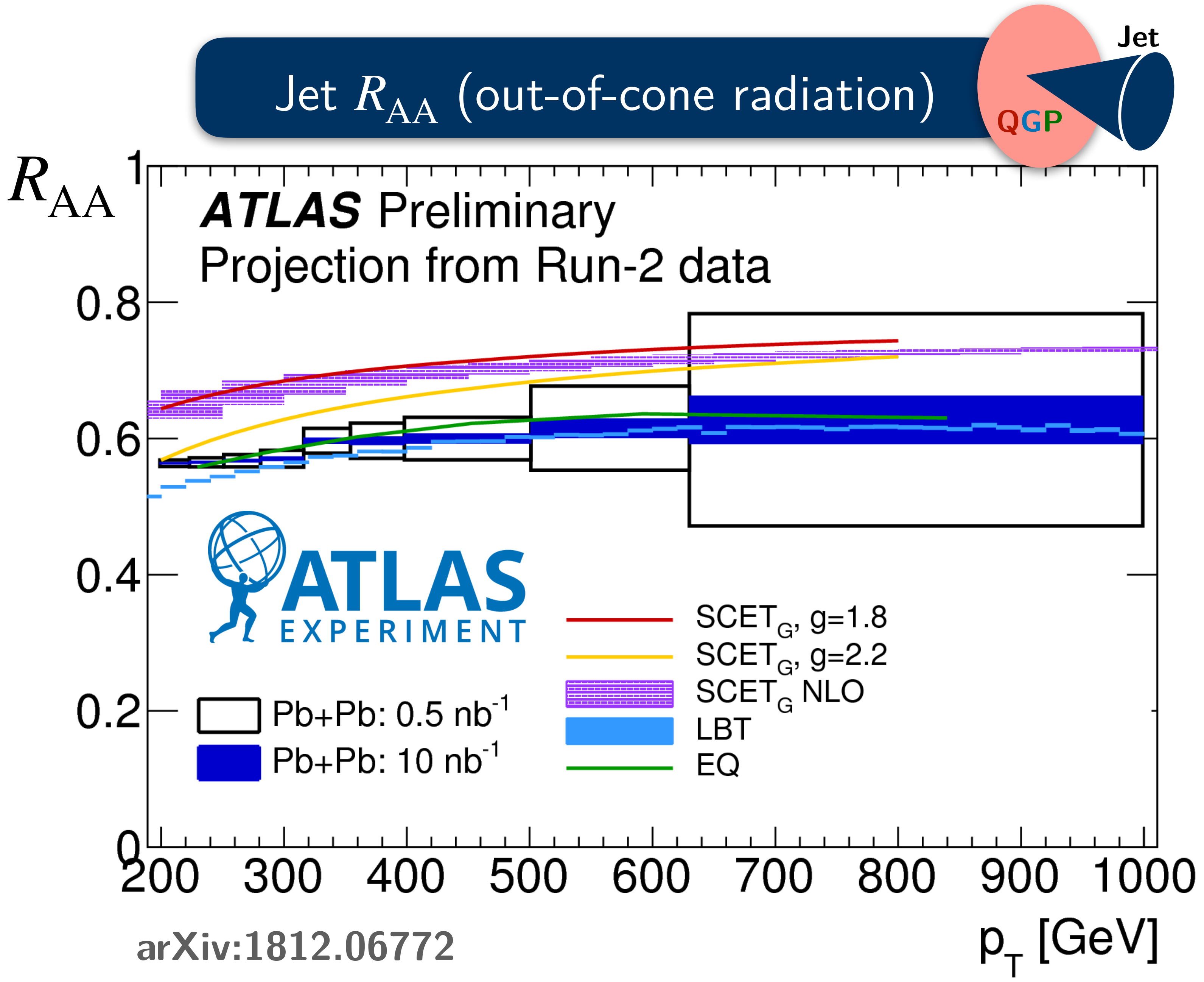
CMS-PAS-FTR-17-002

arXiv:2308.16131

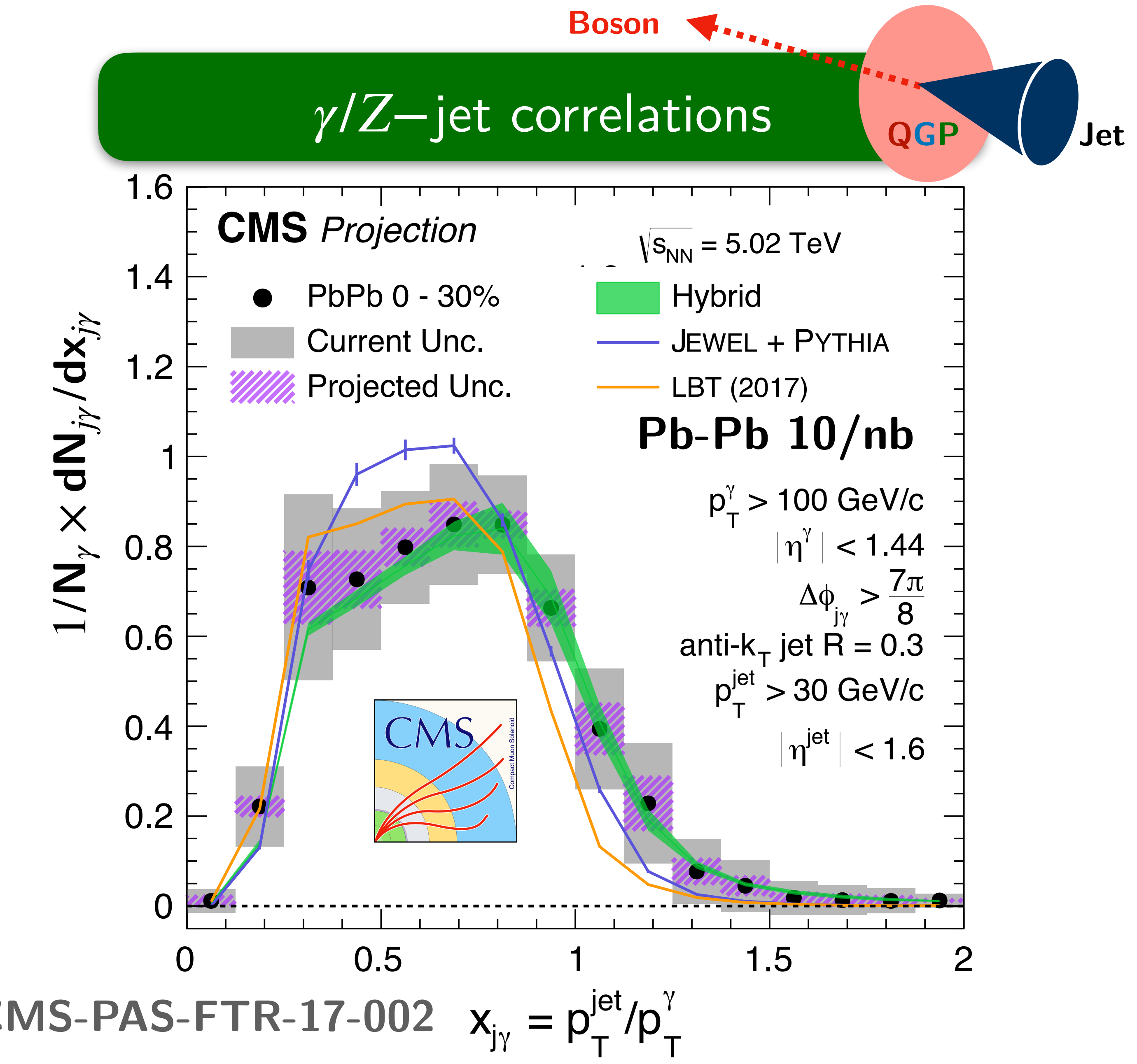
Physics: Microscopic QGP properties, extraction of transport coefficient $\hat{q}$, multi-scale probe for QGP

Jet physics: probing the short distance structure of QGP through scattering of a (multi-scale) hard probe

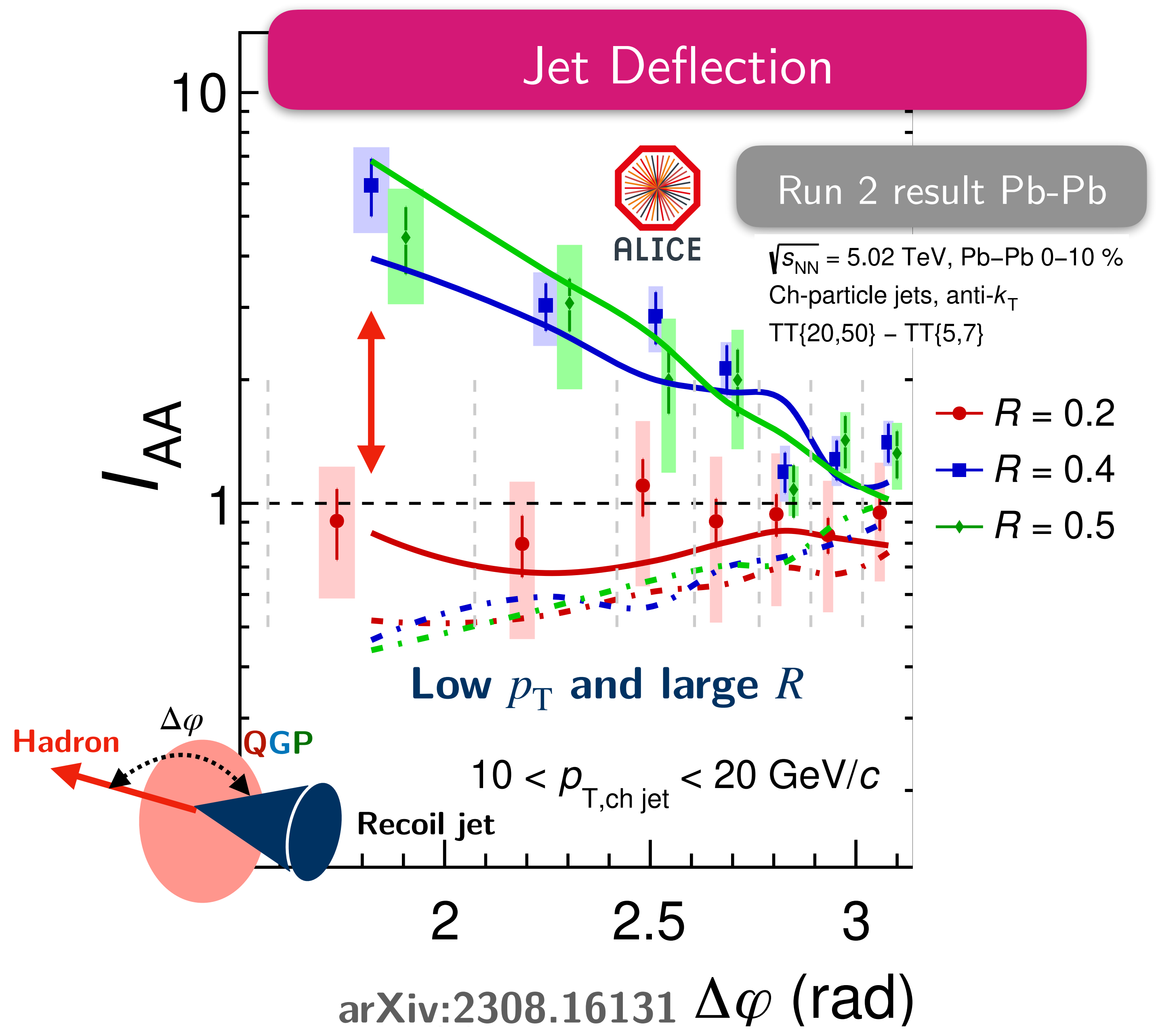
- ATLAS/CMS/ALICE will quantify jet suppression with unprecedented precision & kinematic reach
- γ/Z-jet corr.: calibrated probe; controlled variation of q/g fraction, path length
- Run 2 results show first indication of medium-induced jet deflection at low-p_{T} and large R → HL-LHC allows more differential studies in p_{T}, R ...



arXiv:1812.06772



CMS-PAS-FTR-17-002



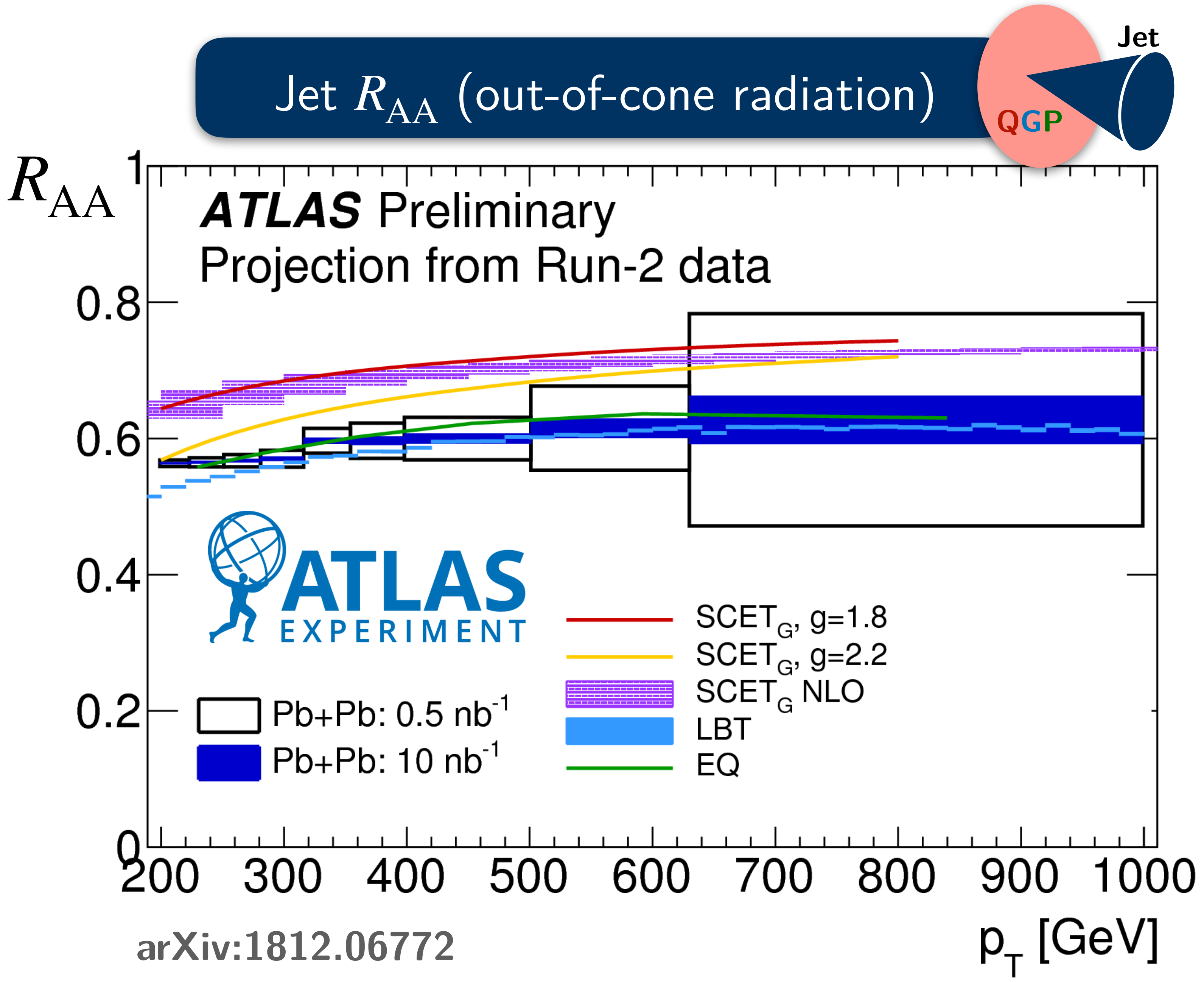
arXiv:2308.16131

Physics: Microscopic QGP properties, extraction of transport coefficient $\hat{q}$, multi-scale probe for QGP

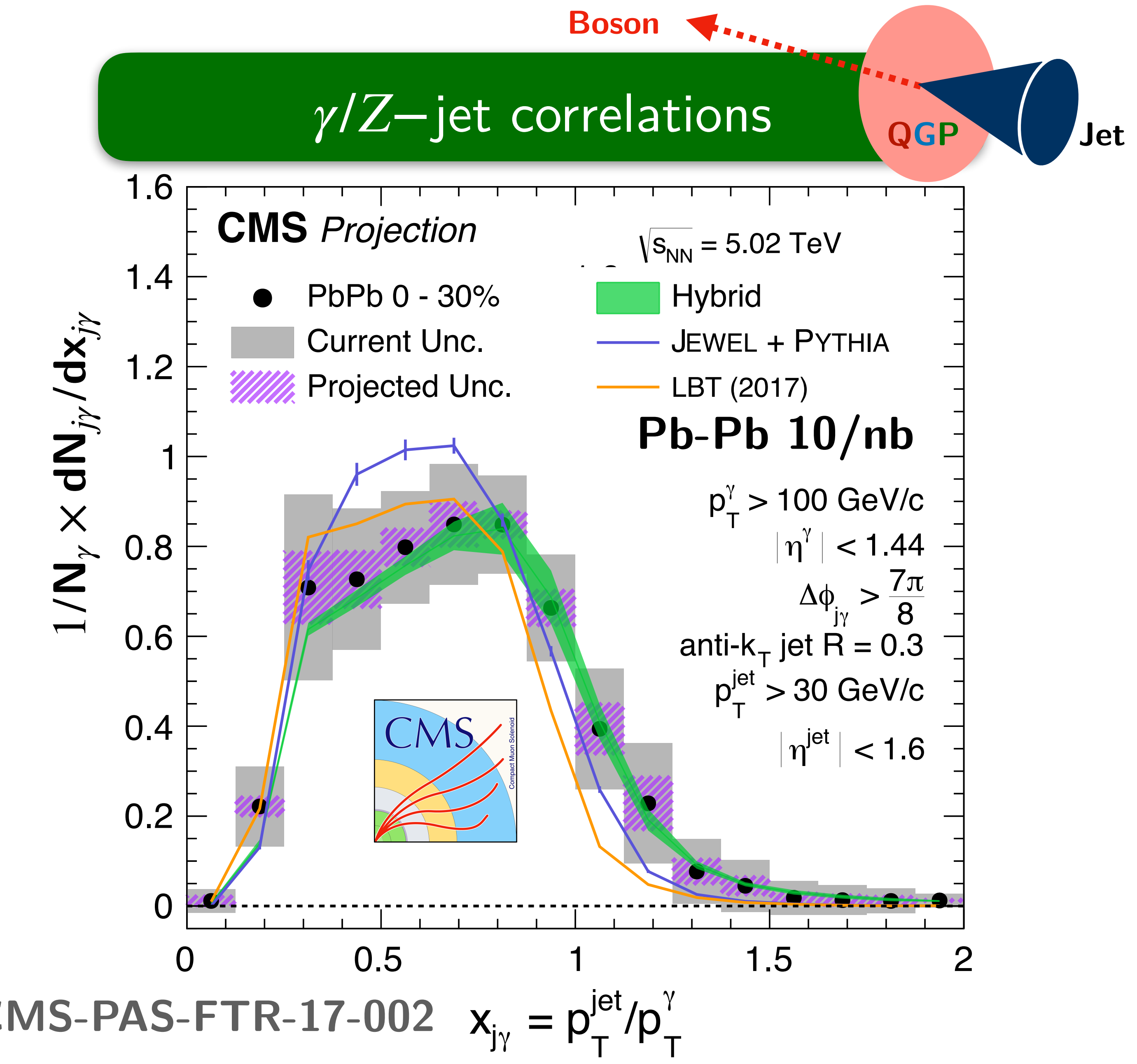
Jet physics: probing the short distance structure of QGP through scattering of a (multi-scale) hard probe

- ATLAS/CMS/ALICE will quantify jet suppression with unprecedented precision & kinematic reach
- γ/Z-jet corr.: calibrated probe; controlled variation of q/g fraction, path length
- Run 2 results show first indication of medium-induced jet deflection at low-p_{T} and large R → HL-LHC allows more differential studies in p_{T}, R ...

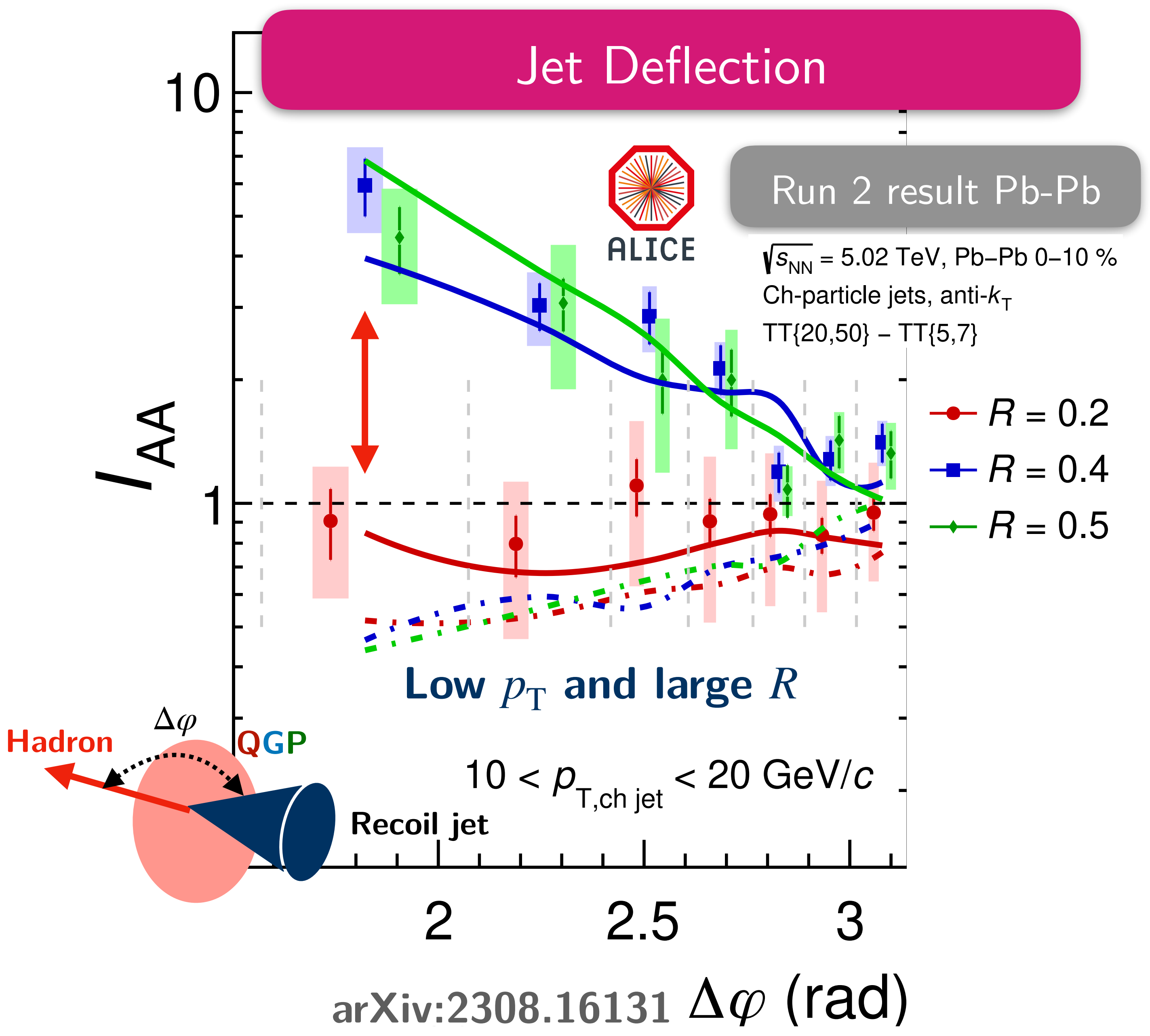
- Jet substructure: resolving energy loss on the level of parton evolution through the medium



arXiv:1812.06772



CMS-PAS-FTR-17-002



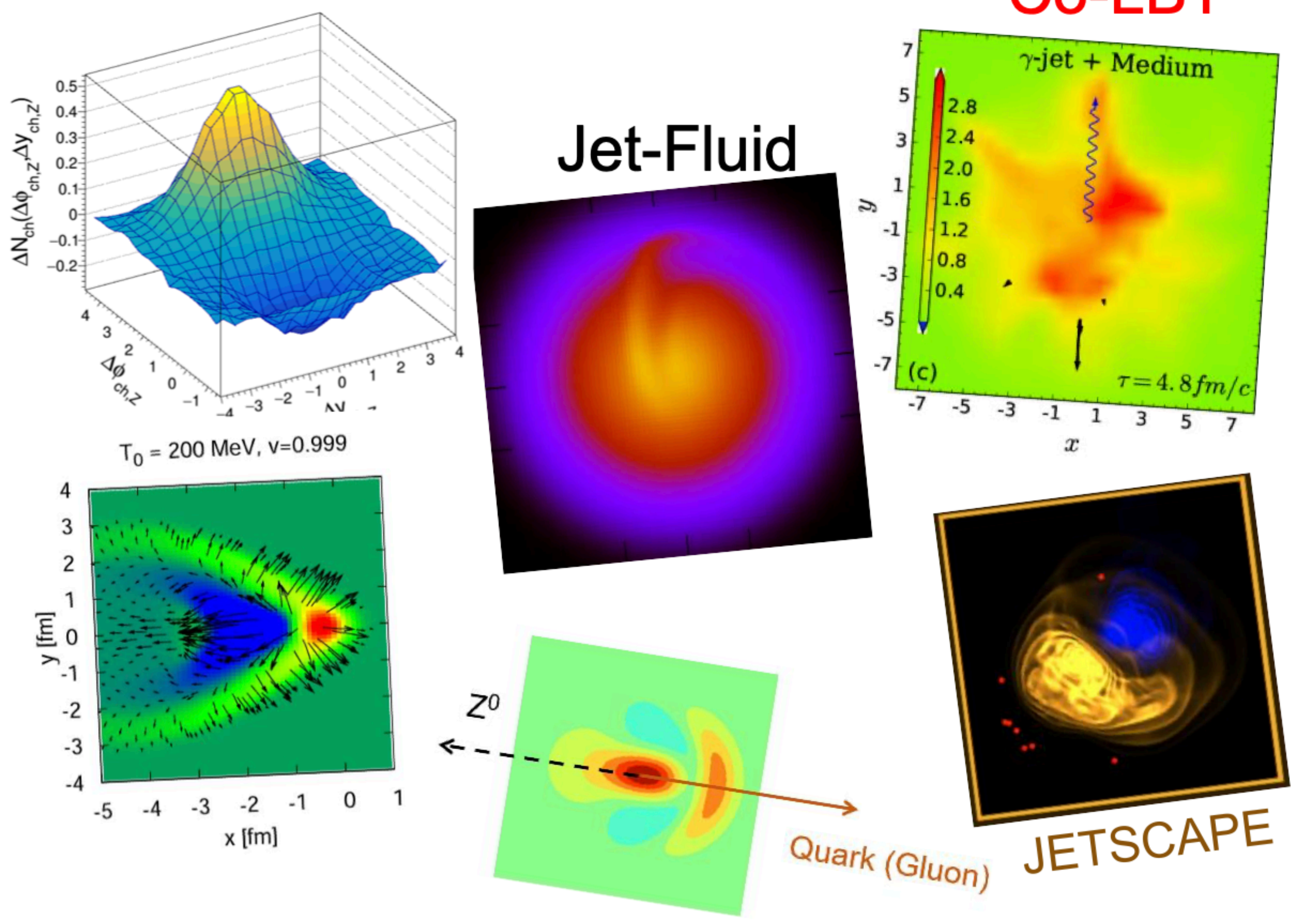
arXiv:2308.16131

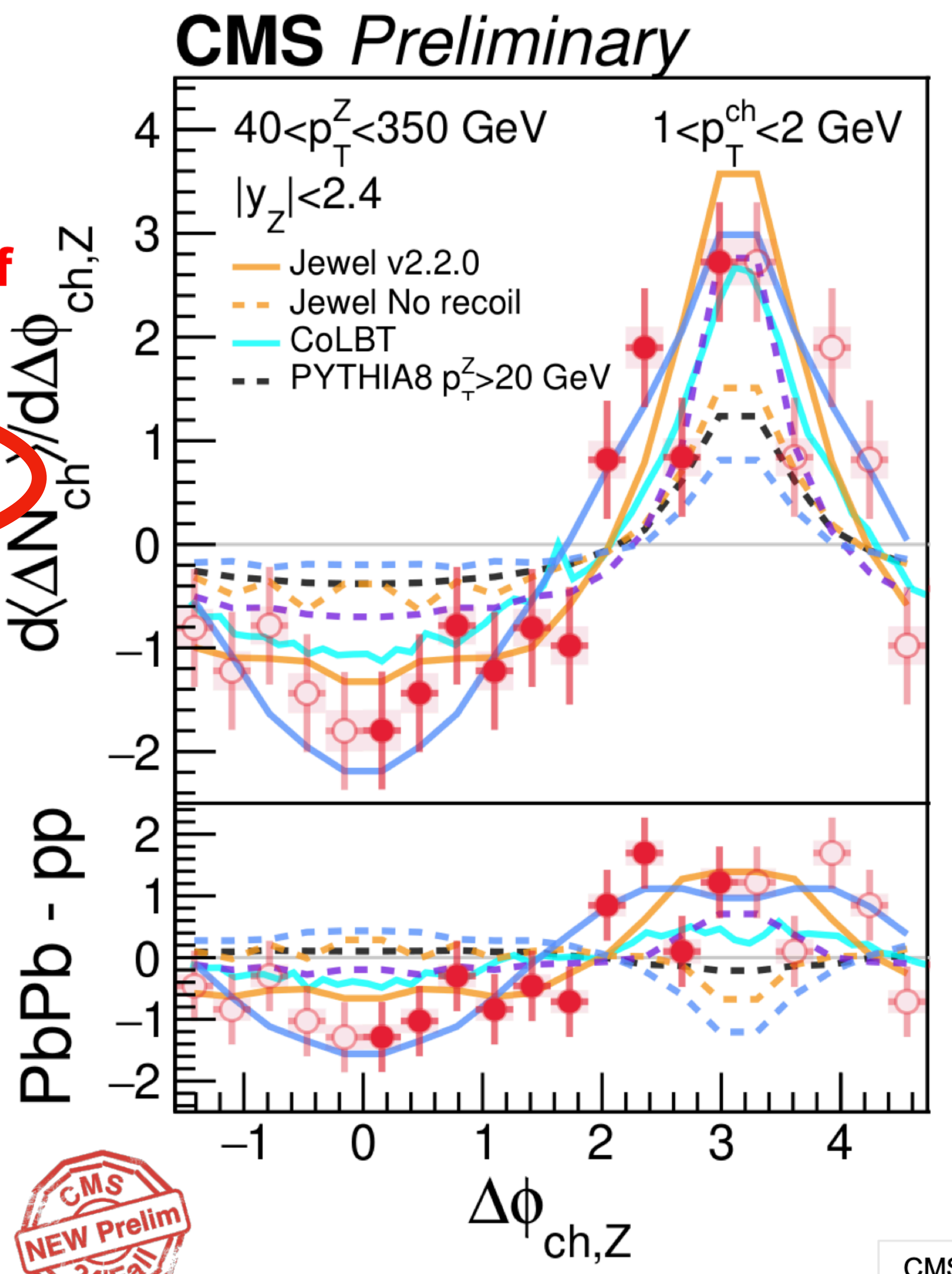
A recent example from Hard Probes 2024 where HL-LHC can help

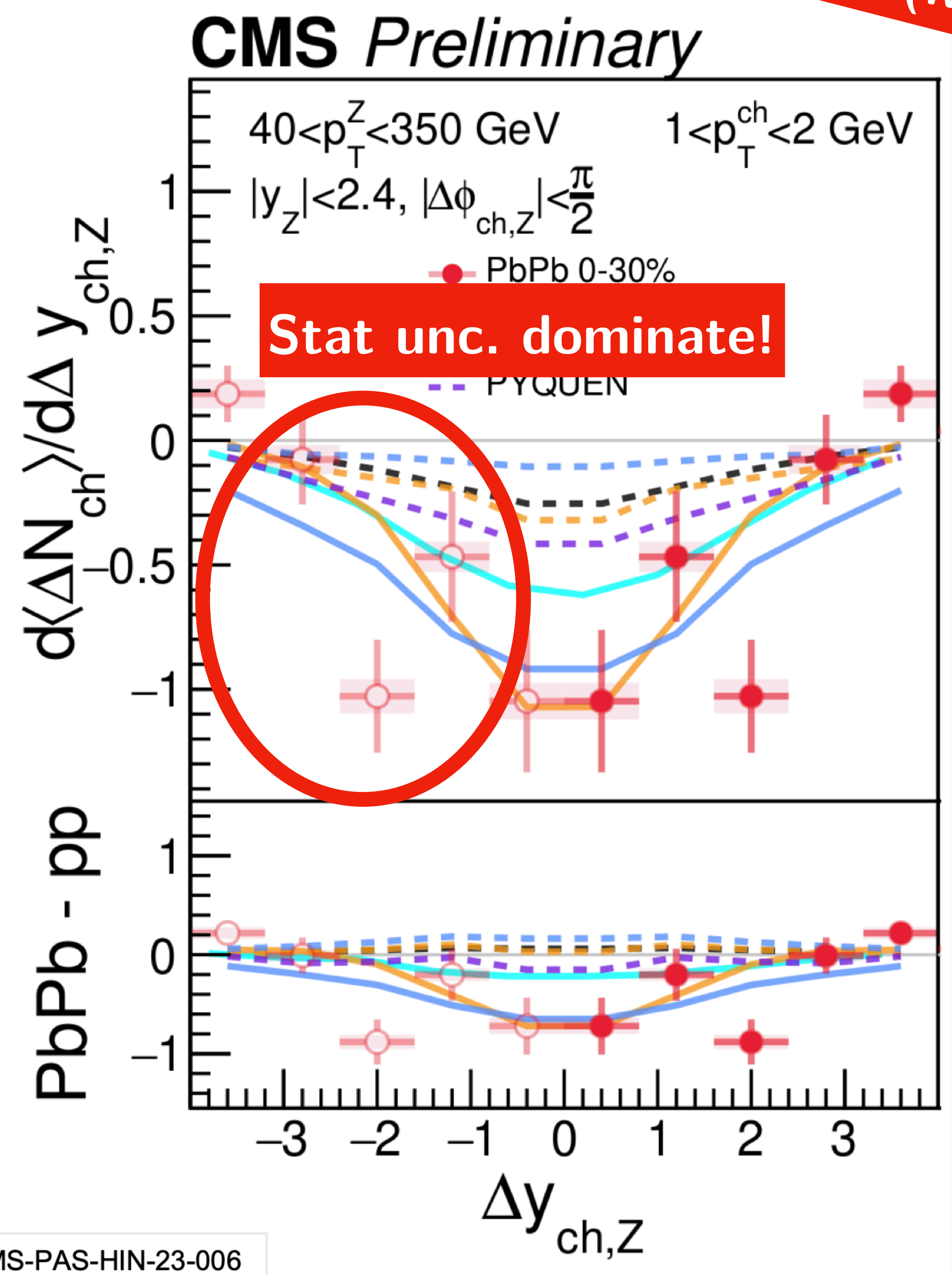
Summary and Outlook

Talk by Yen-Jie Lee (MIT)

- First p_T^{ch} differential measurement of Z^0-hadron correlation in azimuthal angle and rapidity
- We report the **first direct evidence of medium response in QGP**
- High statistics analysis with Run3+4 data in the near future



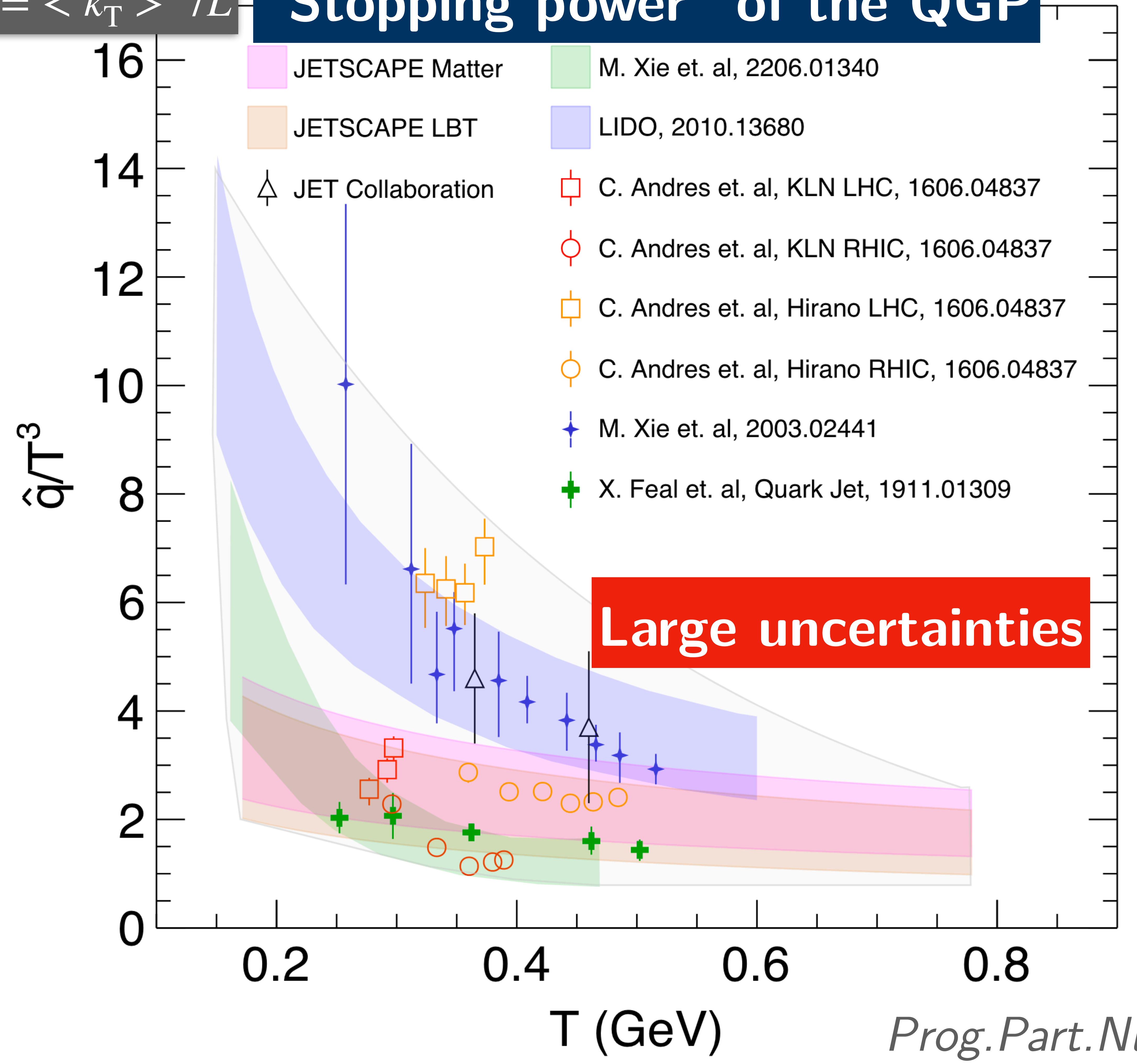




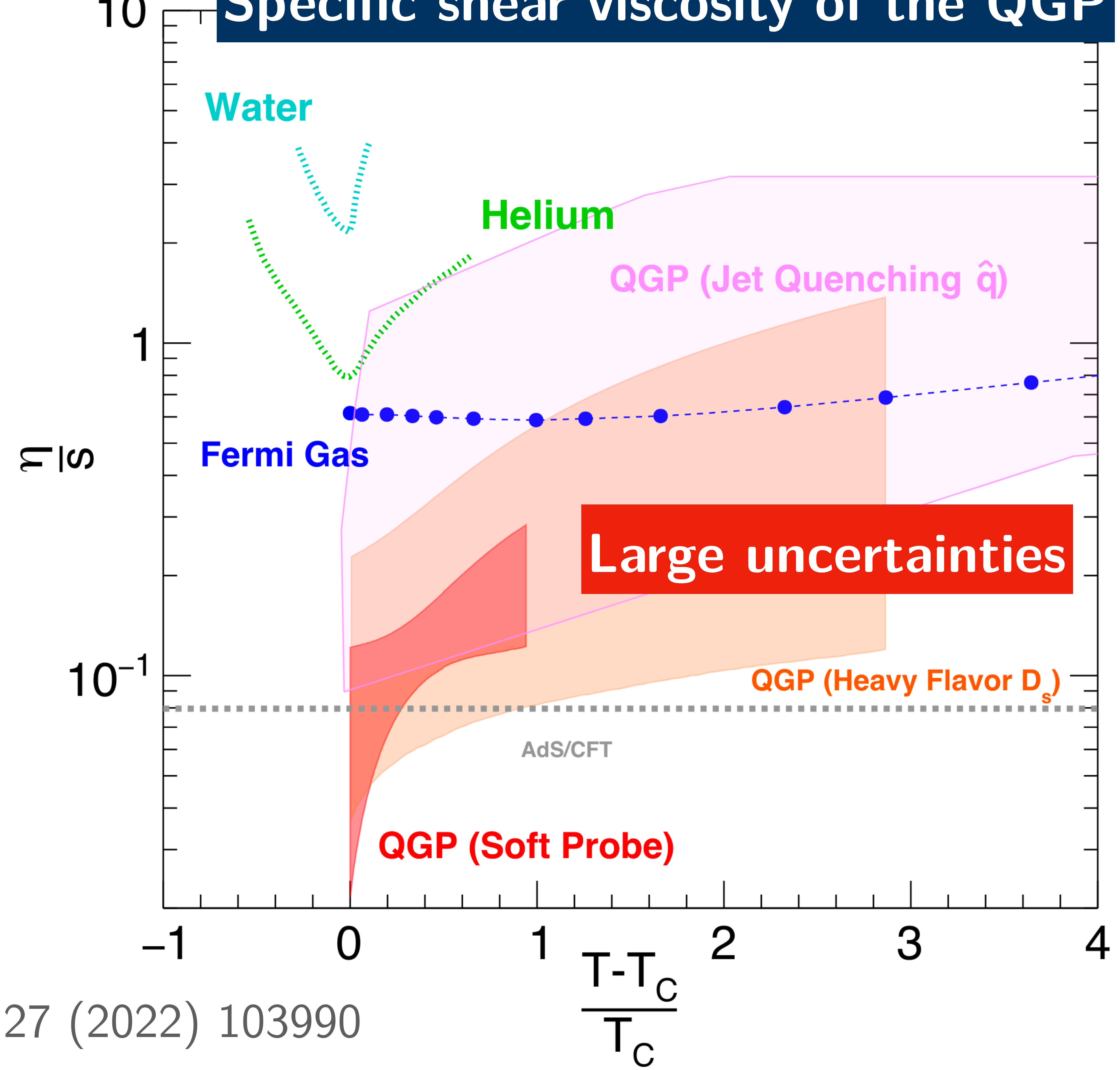
HP2024 NAGASAKI | Yen-Jie Lee (MIT) | Evidence of Medium Response to Hard Probes with Z^0-tagged Hadrons in PbPb at 5.02 TeV | 23 | MIT Laboratory for Nuclear Science | CMS

Where we are: Constraints obtained using Bayesian inference

$\hat{q} = \langle k_T \rangle^2 / L$ **"Stopping power" of the QGP**



Specific shear viscosity of the QGP

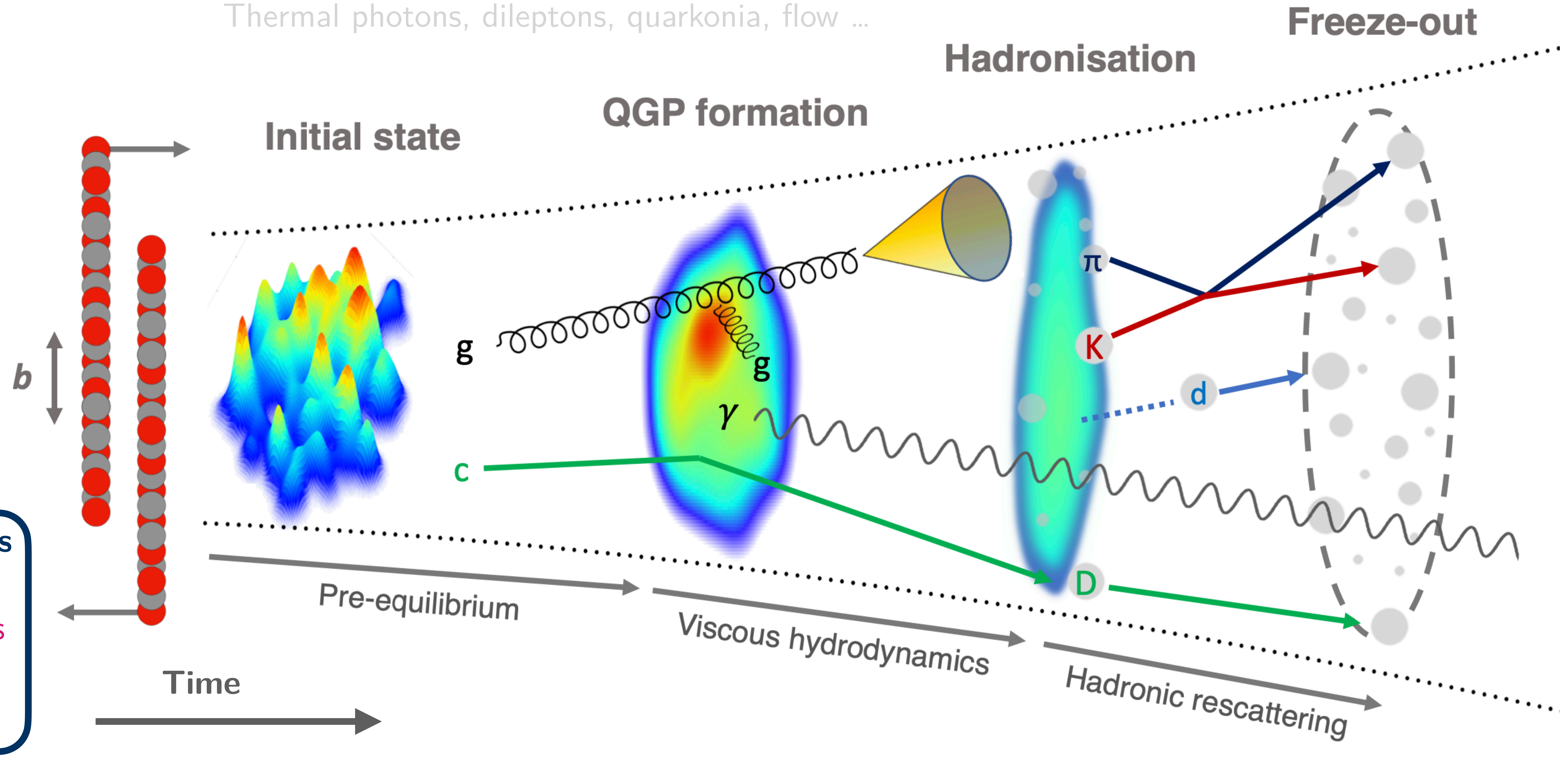


Prog.Part.Nucl.Phys. 127 (2022) 103990

We learned a lot, but precision data provided by HL-LHC (+ theory advancements) are crucial!

What are the macroscopic properties of the QGP? Temperature? Viscosity? QCD phase transition?
Thermal photons, dileptons, quarkonia, flow ...

What are the initial conditions of a collision? nPDFs & Saturation?
DY, UPC, forward LHC ...



arXiv:2211.04384

Collectivity of QCD across system sizes?
Flow in pp, p-A; strangeness production, energy loss, thermal radiation

What is the microscopic dynamics of QGP at various length scales?
Jets (substructure), γ/Z-jet correlations, heavy flavour, quarkonia, hadronization

Run 1 & Run 2: Full of surprises

1. Long-range correlations observed in high mult. pp collisions and p-Pb collisions
2. Strangeness enhancement observed in pp and p-Pb collisions → smooth as a function of multiplicity

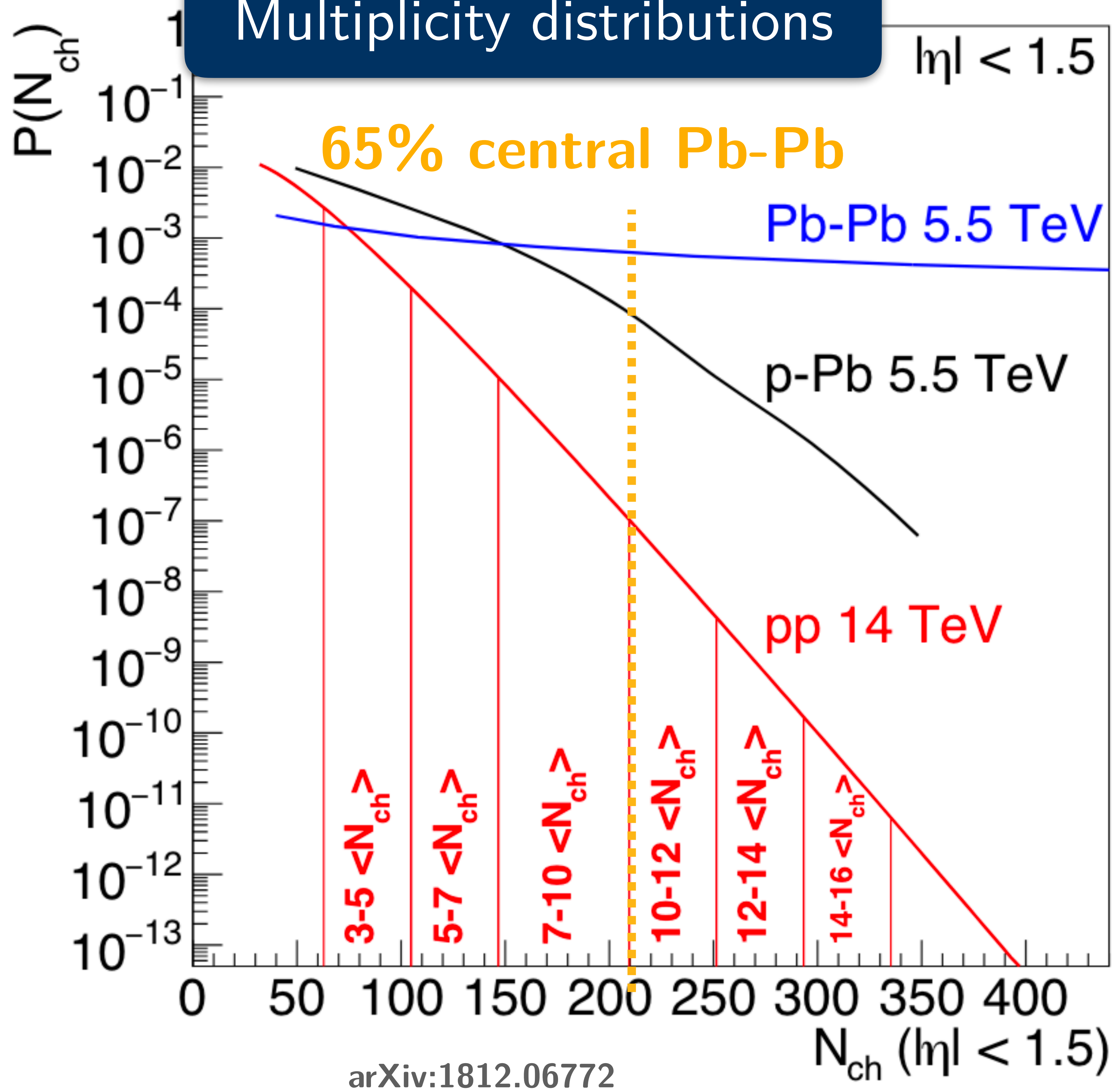
Do we have QGP in small systems?
(applying HI modelling in novel regimes?)

Is our understanding/description of pp physics still accurate?
(additions to pp modeling?)

Run 3 and beyond: systematic study of "QGP signals" in pp, p-Pb and Pb-Pb collisions but also p-O and O-O

High luminosity allows overlap of **high multiplicity pp collisions with up to 65% central Pb-Pb collisions!**

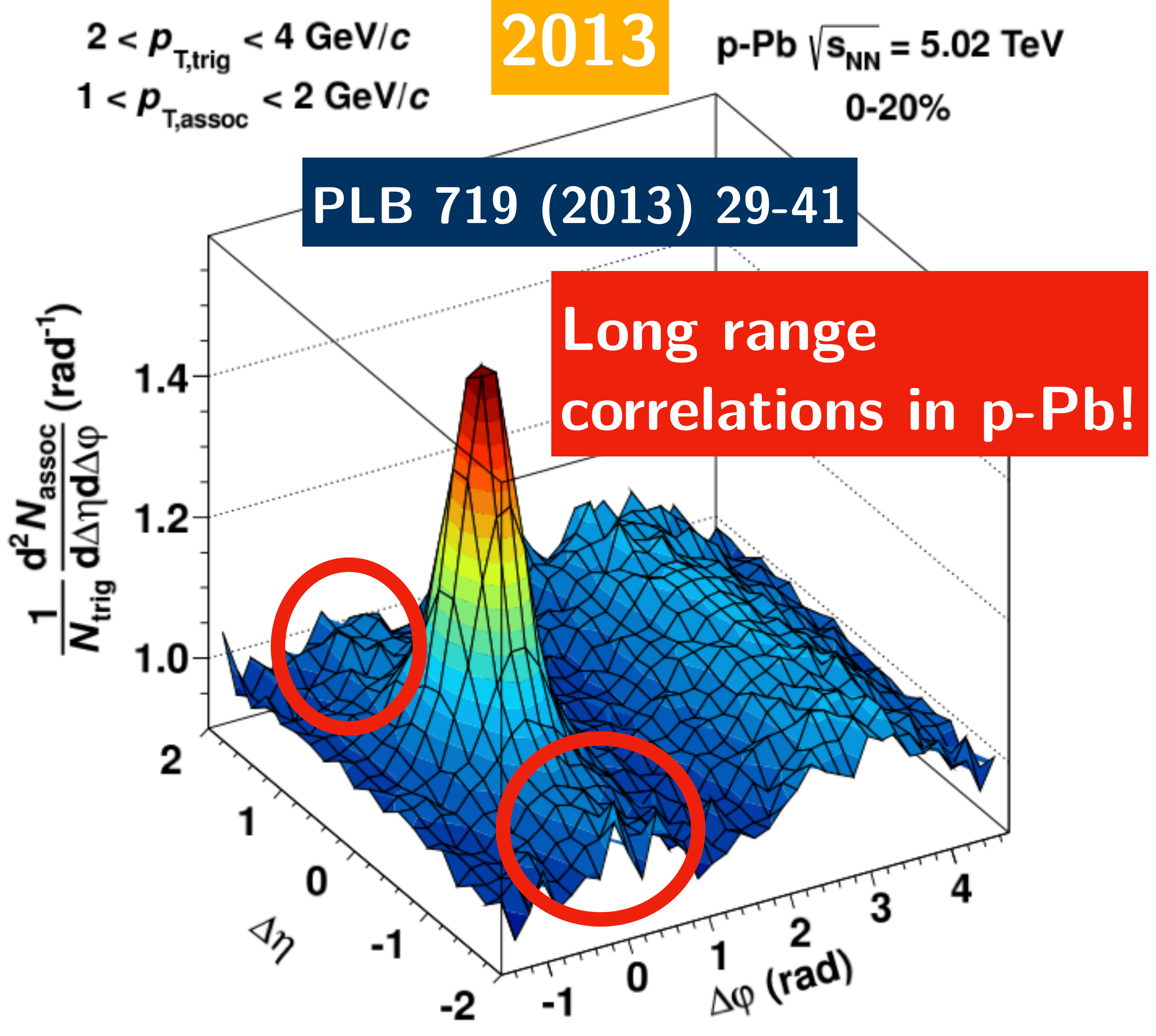
Multiplicity distributions



arXiv:1812.06772

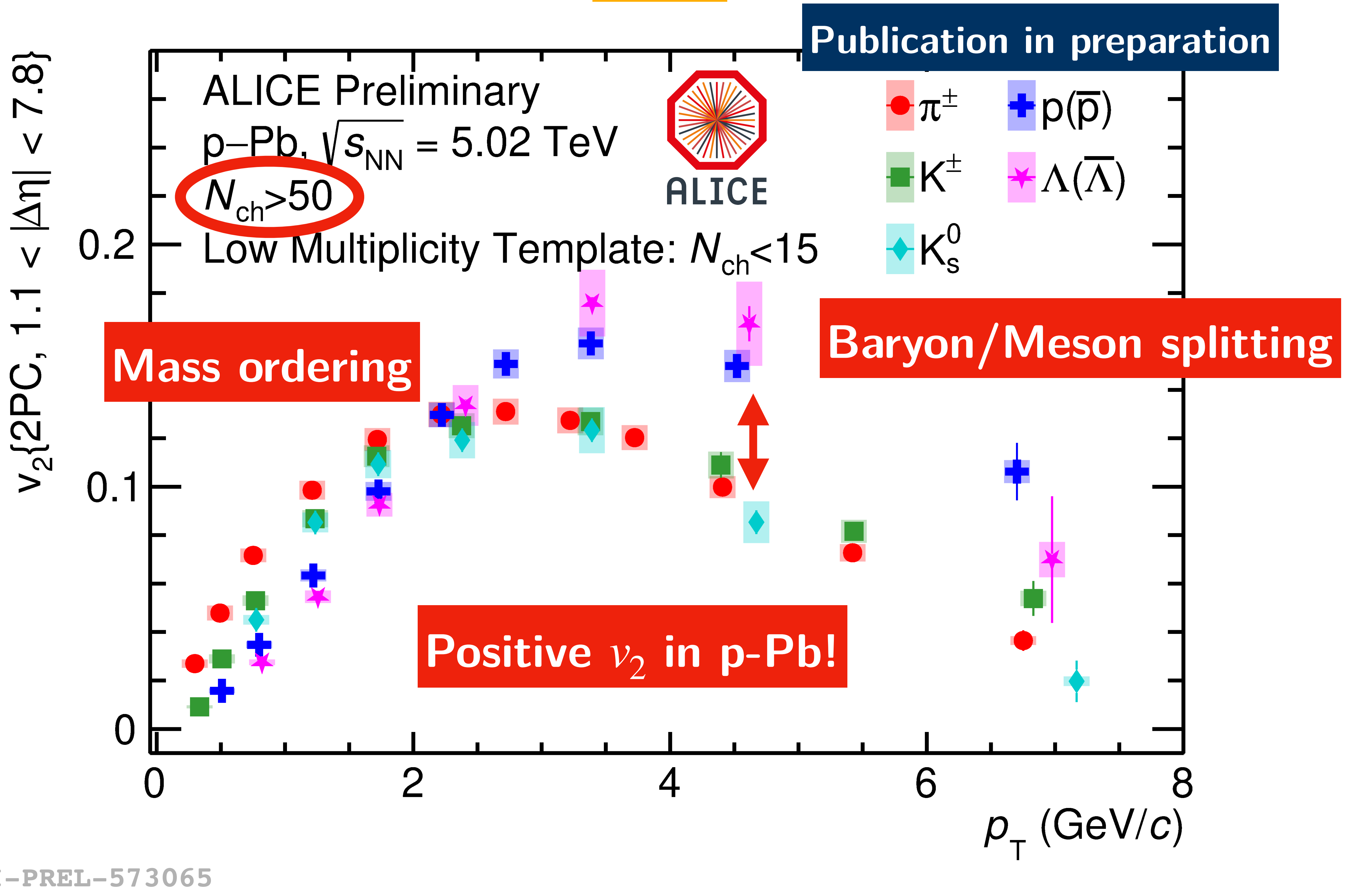
“The ridge” and (multi) anisotropic flow in p-Pb collisions

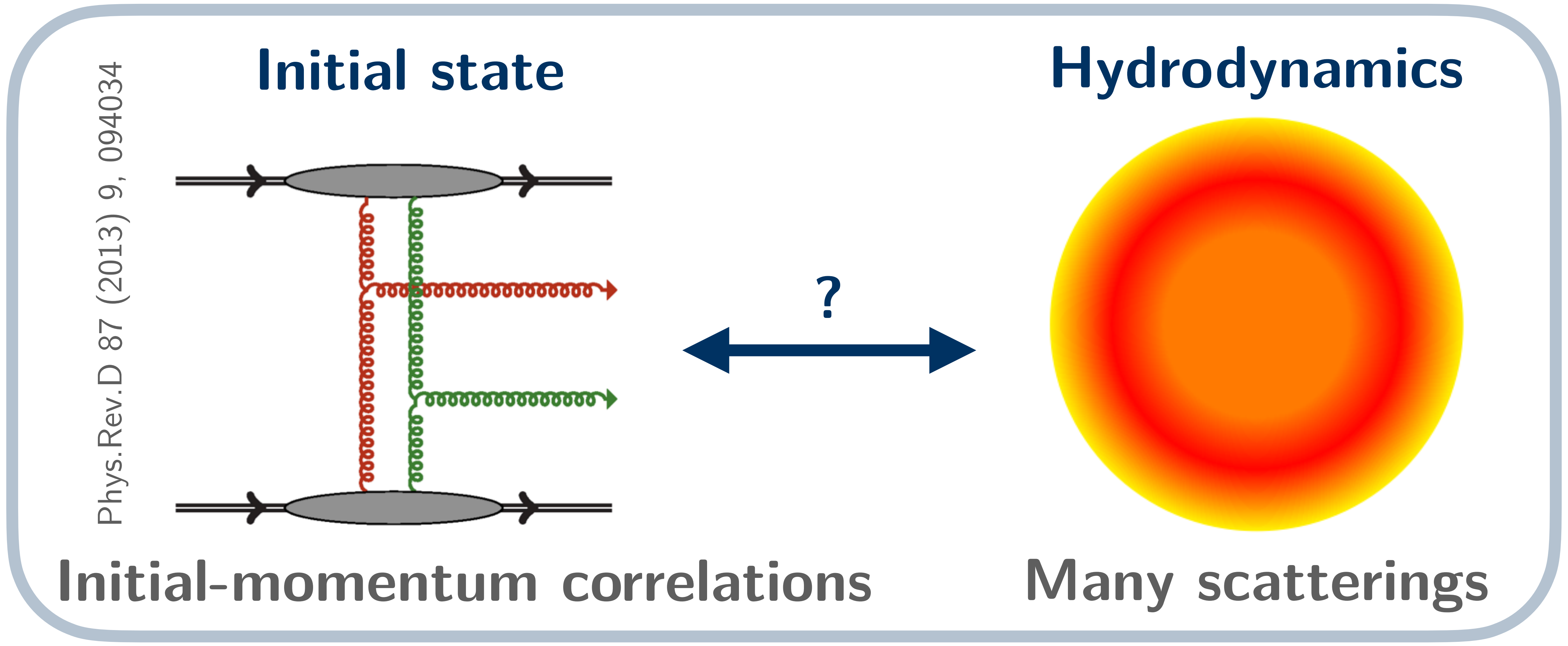
2013



~10 years

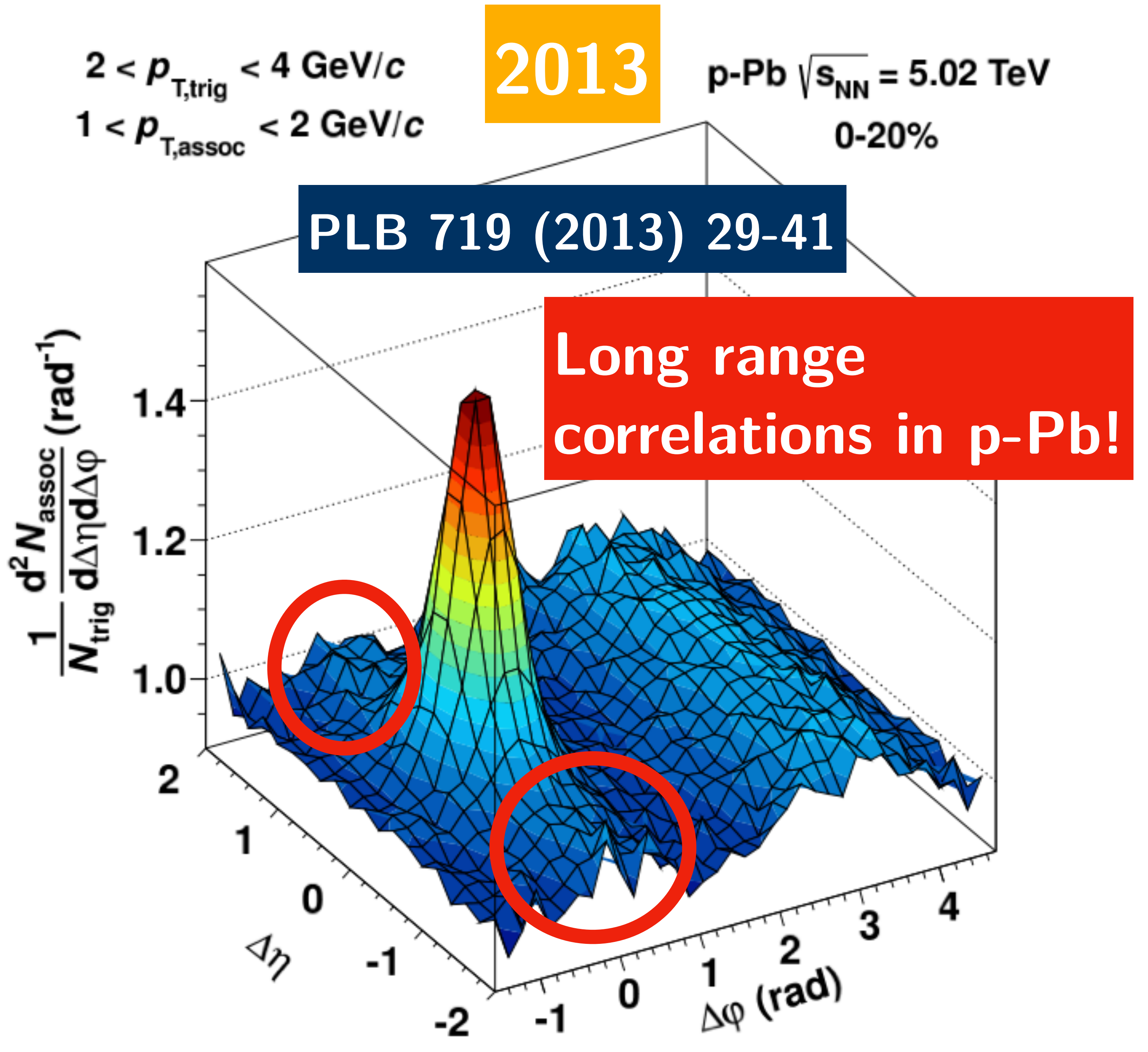
2024

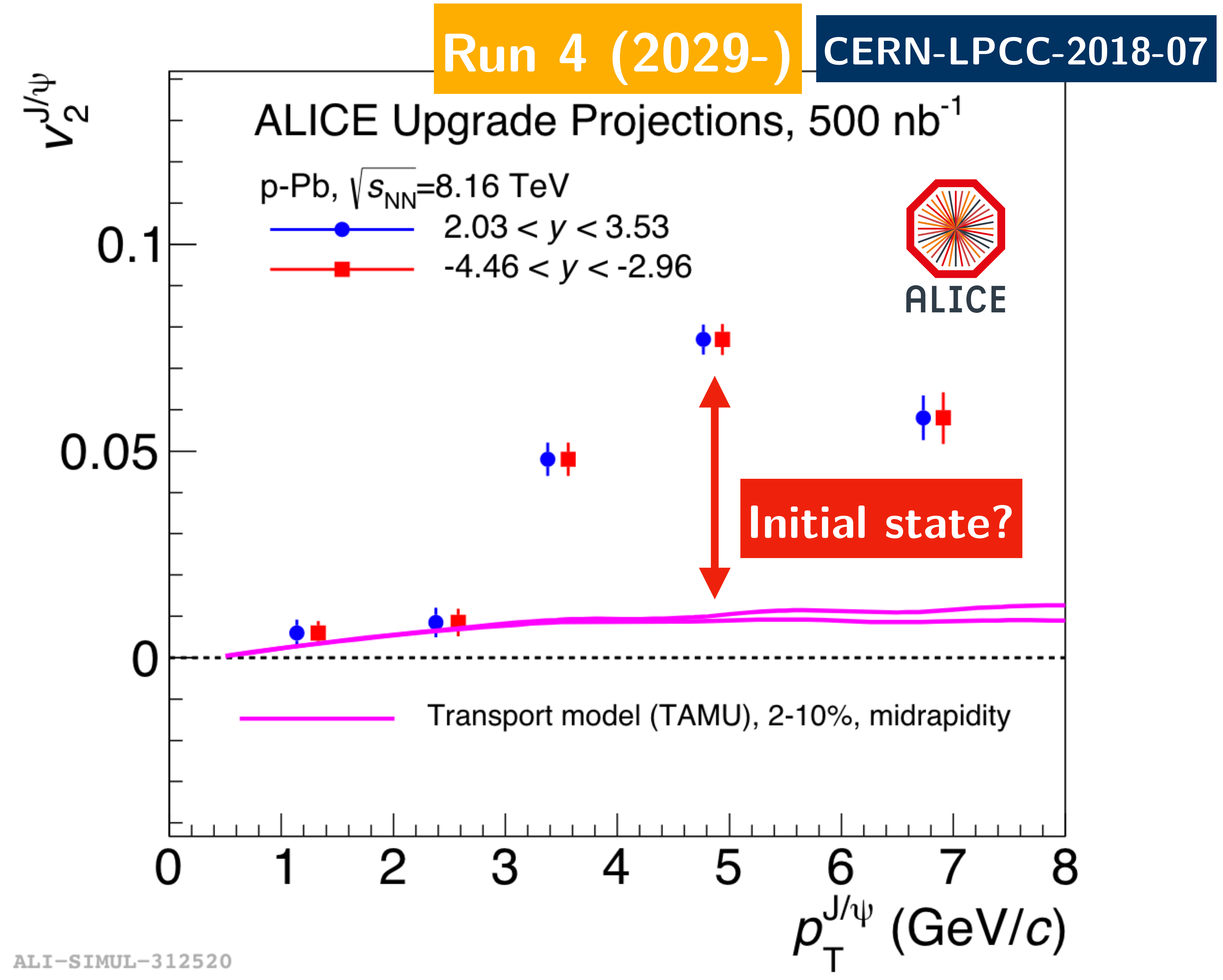


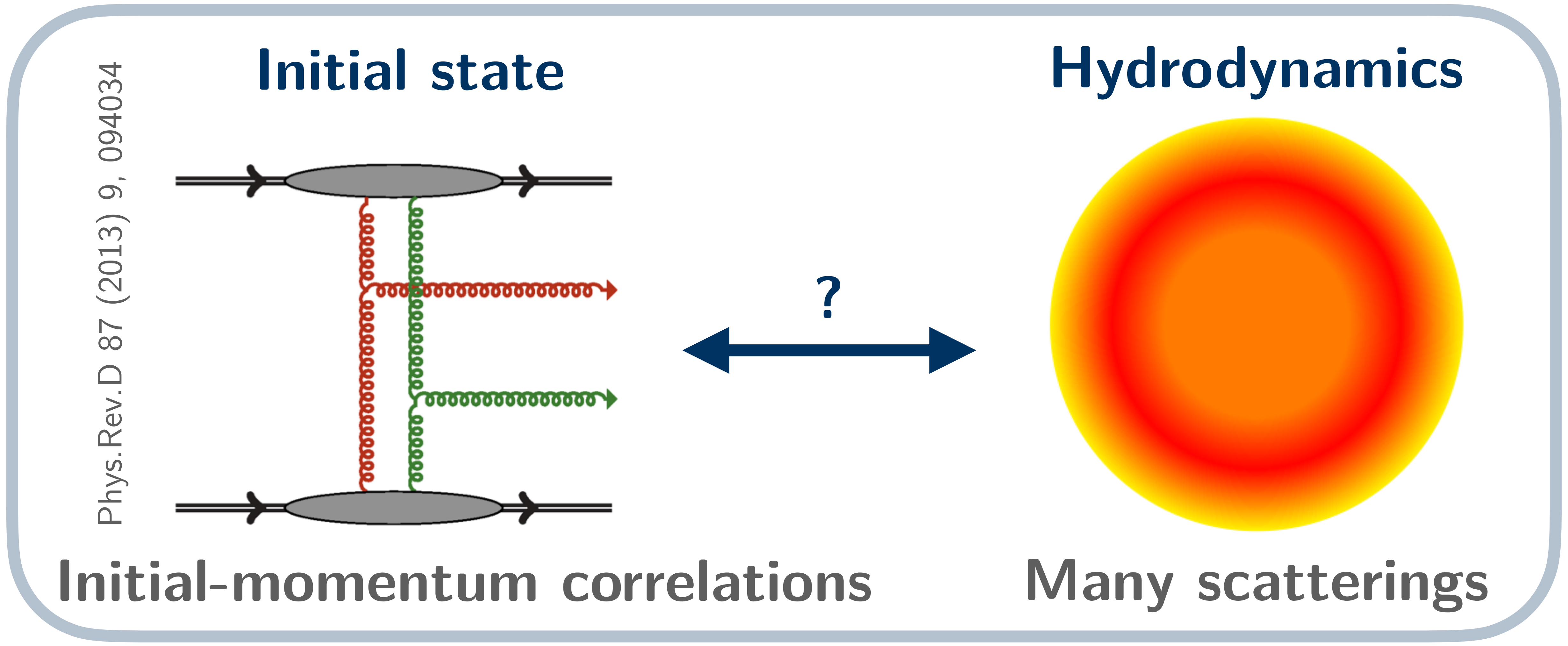


- Significant progress in precision measurement of identified charged particle v_2 since first observation of “the ridge” in p-Pb collisions (also multi-particle correlations)
- Theory has room from **momentum correlations in initial state** to **multiple scatterings in a QGP droplet**

“The ridge” and (multi) anisotropic flow in p-Pb collisions

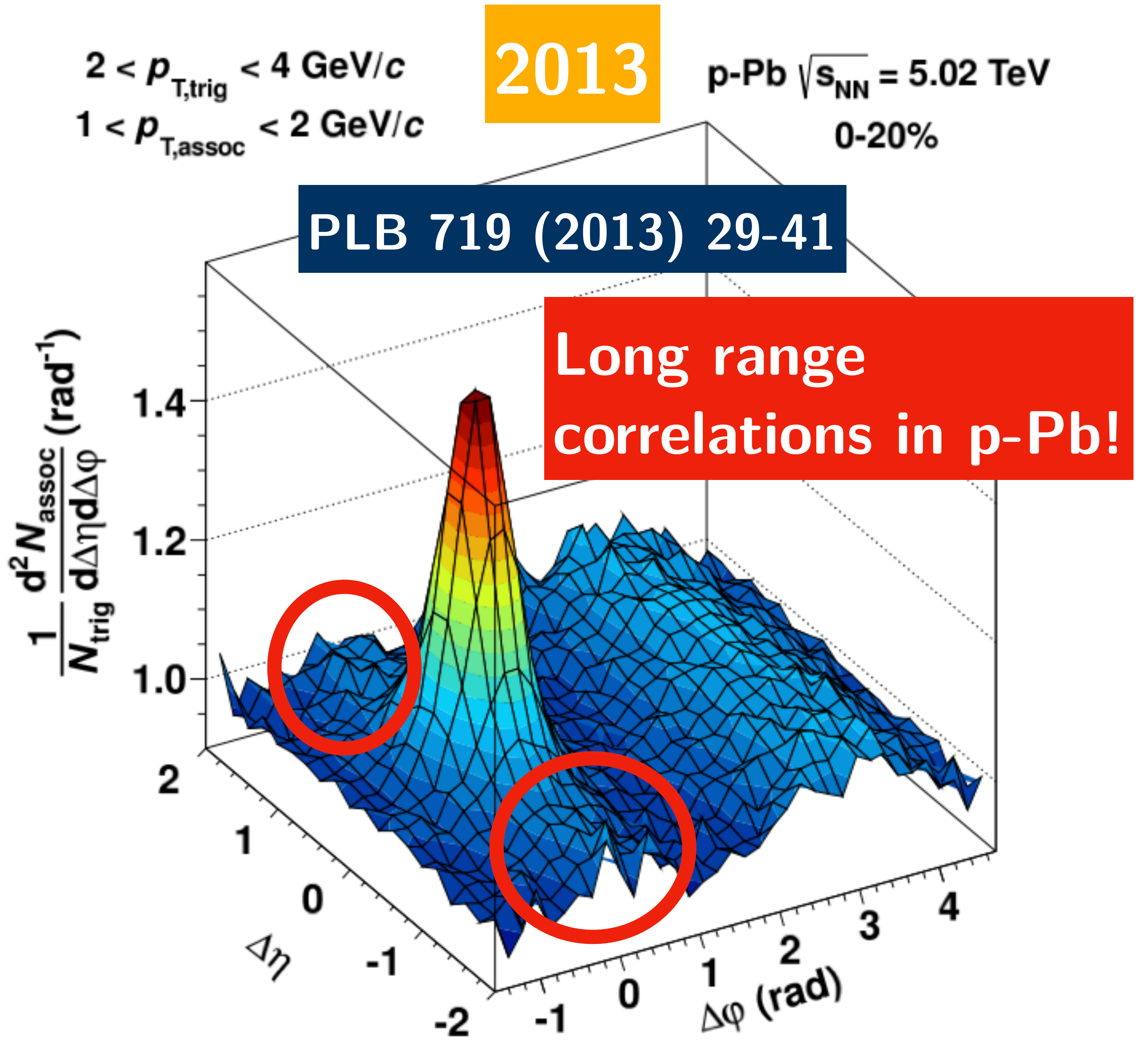


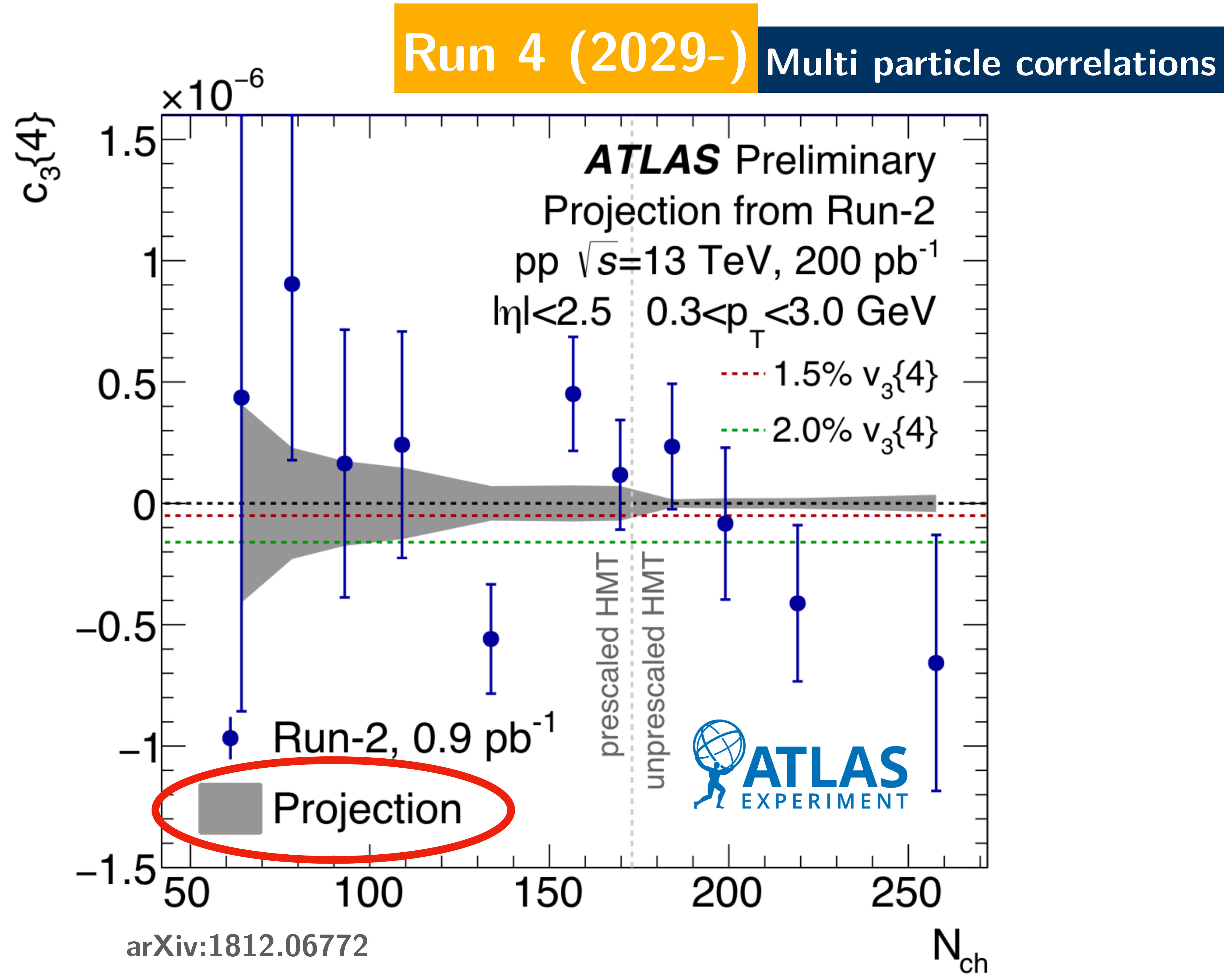


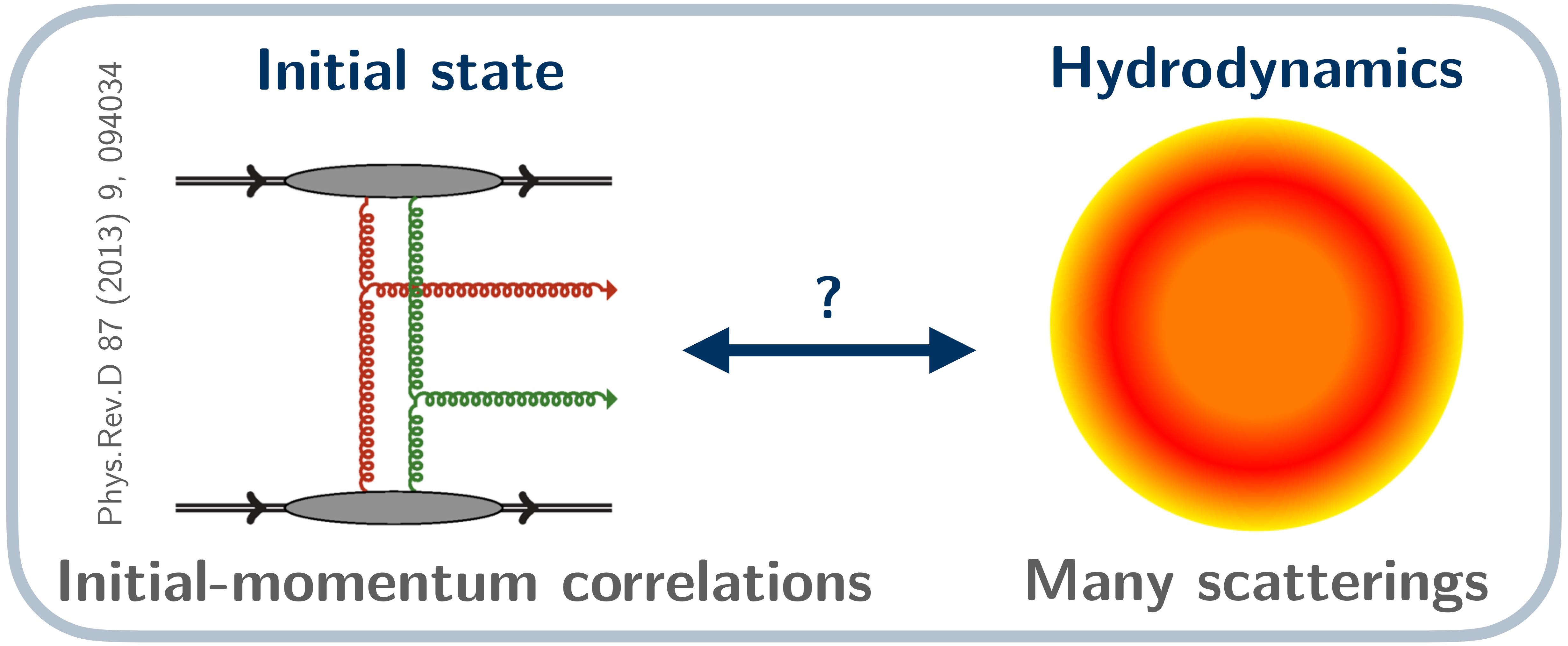


- Significant progress in precision measurement of identified charged particle v_2 since first observation of “the ridge” in p-Pb collisions (also multi-particle correlations)
- Theory has room from **momentum correlations in initial state** to **multiple scatterings in a QGP droplet**

"The ridge" and (multi) anisotropic flow in p-Pb collisions





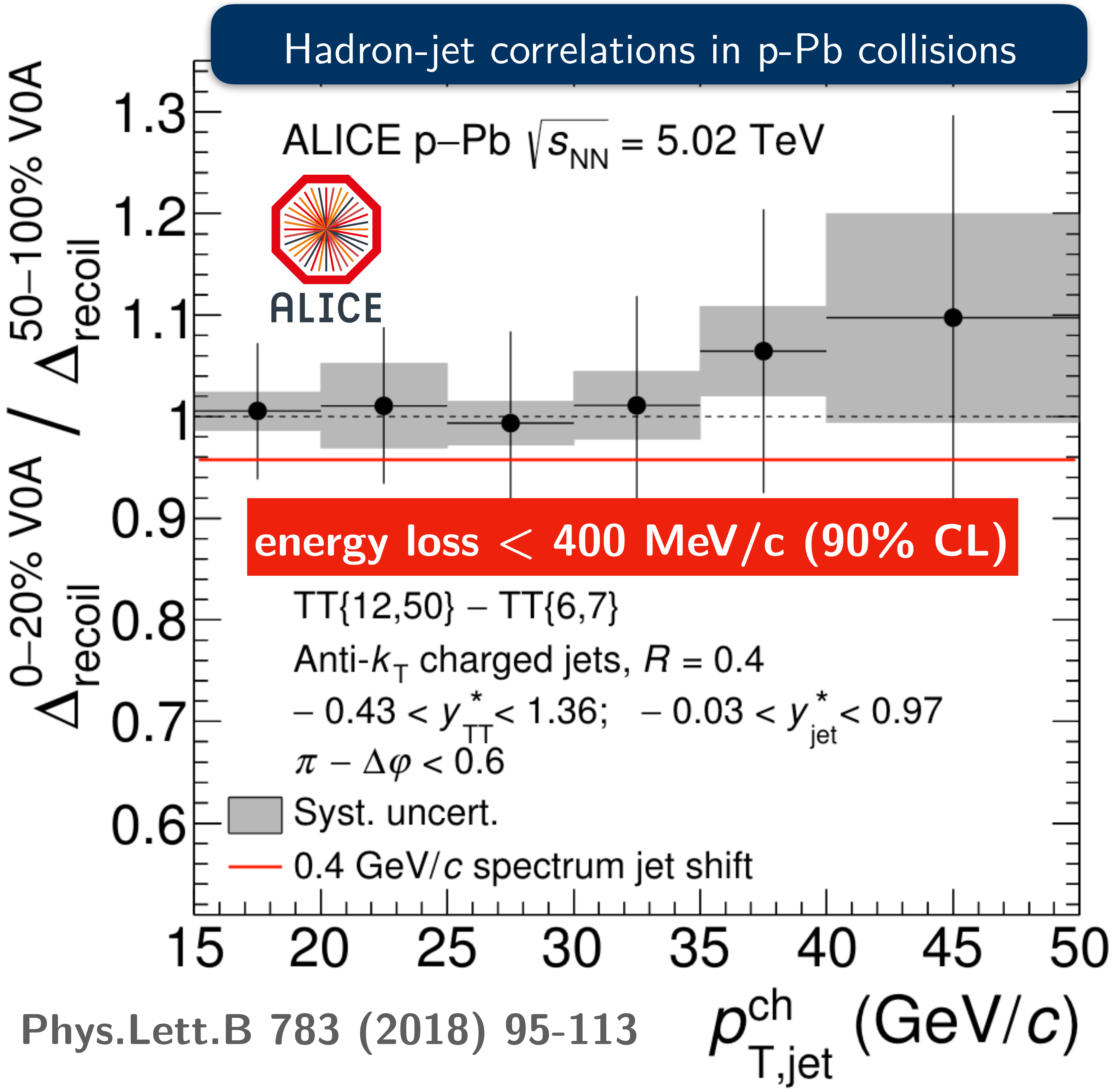


- Significant progress in precision measurement of identified charged particle v_2 since first observation of "the ridge" in p-Pb collisions (also multi-particle correlations)
- Theory has room from **momentum correlations in initial state** to **multiple scatterings in a QGP droplet**

Jet quenching in p-Pb collisions?

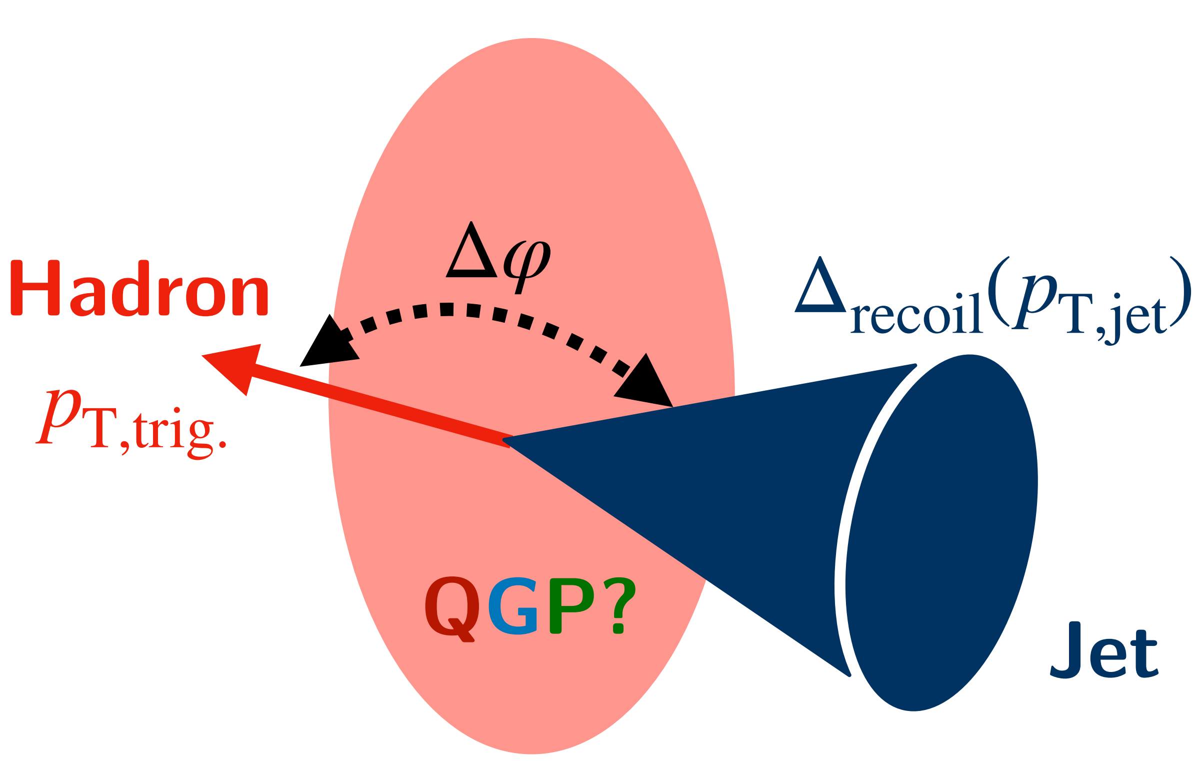
- **Jets are a key observable in heavy-ion collision**; significant jet quenching observed in Pb-Pb collisions
- BUT: so far no jet quenching observed in p-Pb collisions within experimental uncertainties
- Significant increase in p-Pb statistics at HL-LHC → higher sensitivity to energy loss in p-Pb

ALICE Run 1/2



Phys.Lett.B 783 (2018) 95-113

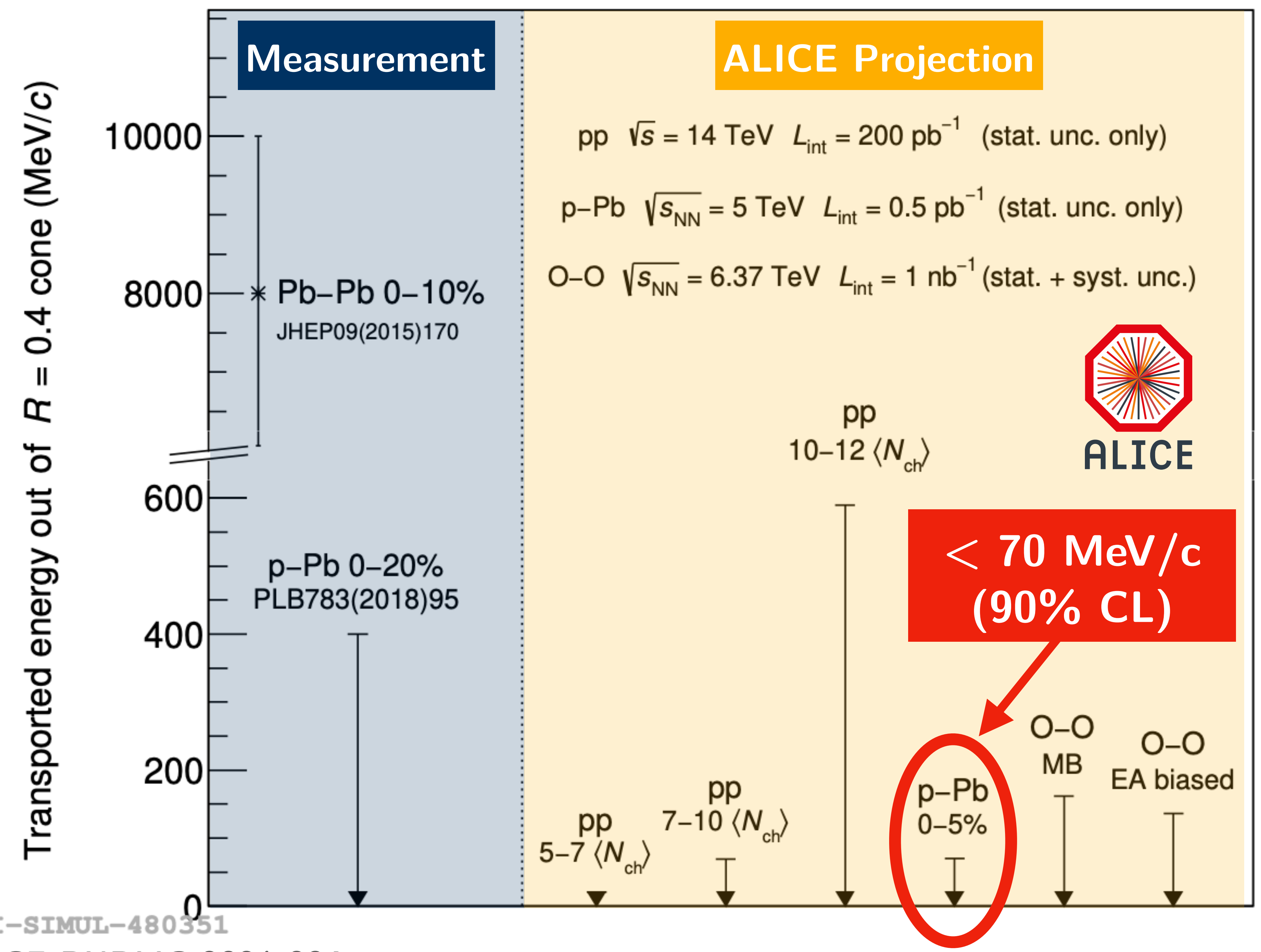
HL-LHC →



$$\Delta_{recoil}\left(p^{ch}_{T,jet}\right) = \frac{1}{N_{trig}} \frac{d^2 N_{jets}}{dp^{ch}_{T,jet}}\bigg|_{p_{T,trig} \in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}} \frac{d^2 N_{jets}}{dp^{ch}_{T,jet}}\bigg|_{p_{T,trig} \in TT_{Ref}}$$

Projection Run 3 & 4

Semi-inclusive hadron-jet correlations



ALICE-PUBLIC-2021-004

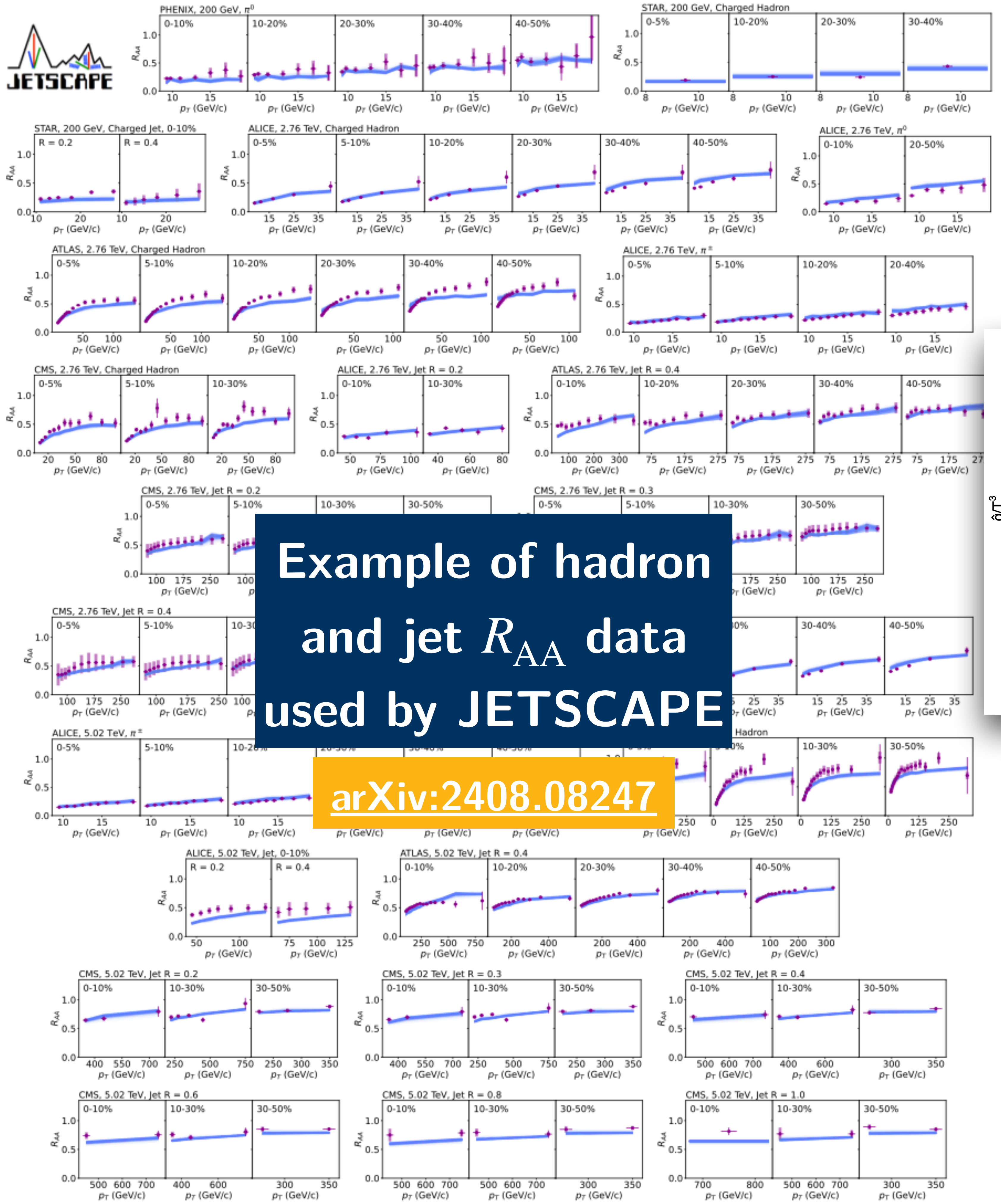
Closing thoughts

Looking at the whole picture: Bayesian inference

Experimental data

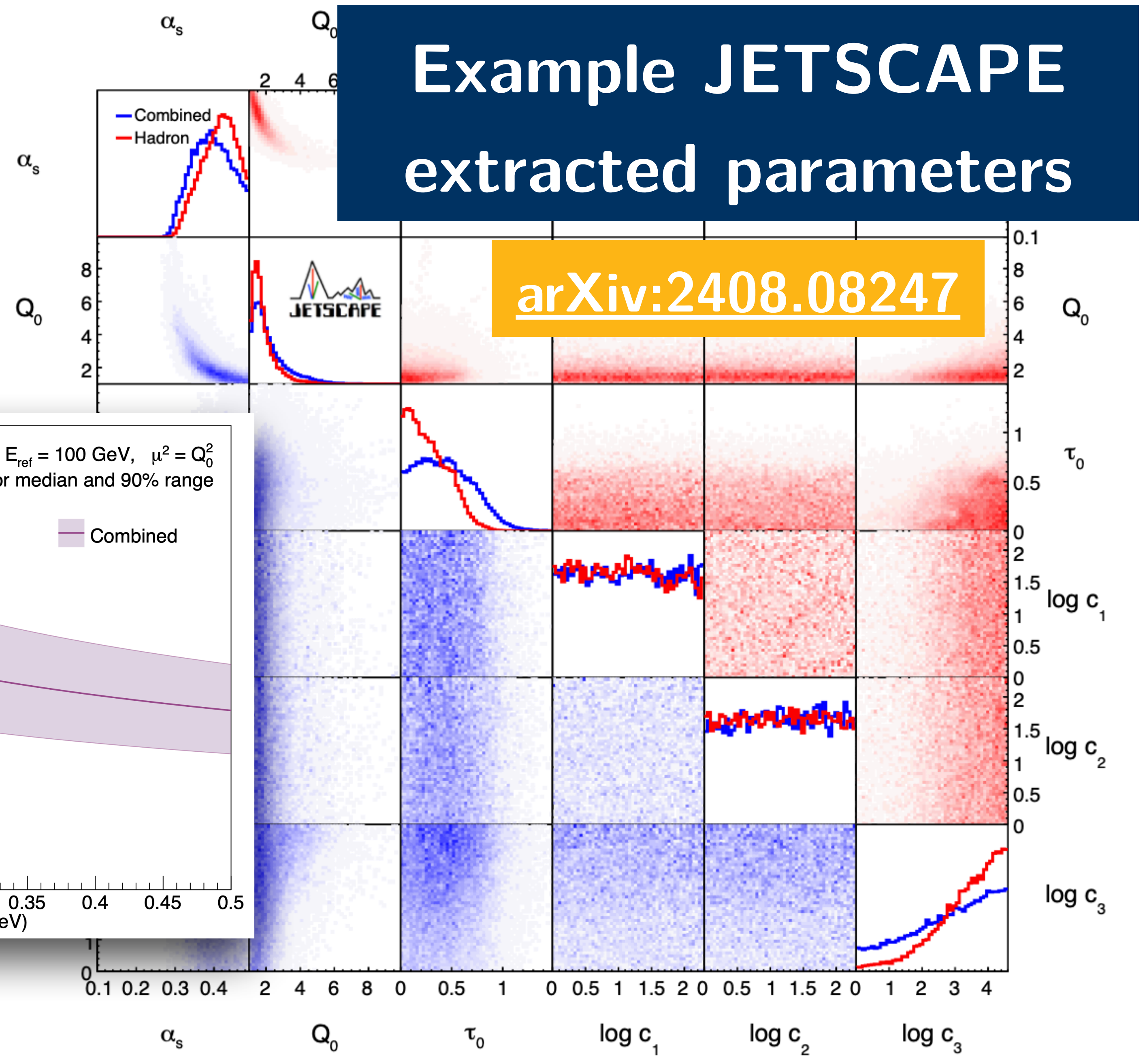
Bayesian Inference →

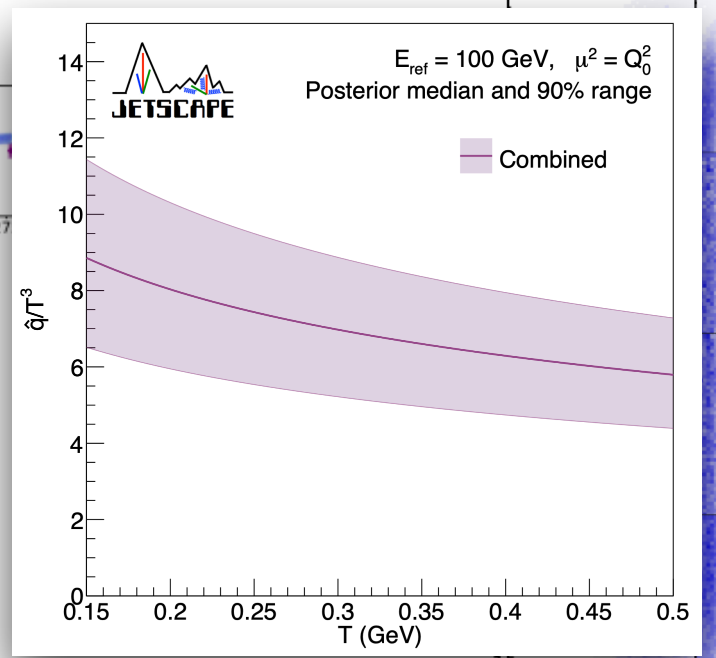
Model parameters



Example of hadron and jet R_{AA} data used by JETSCAPE

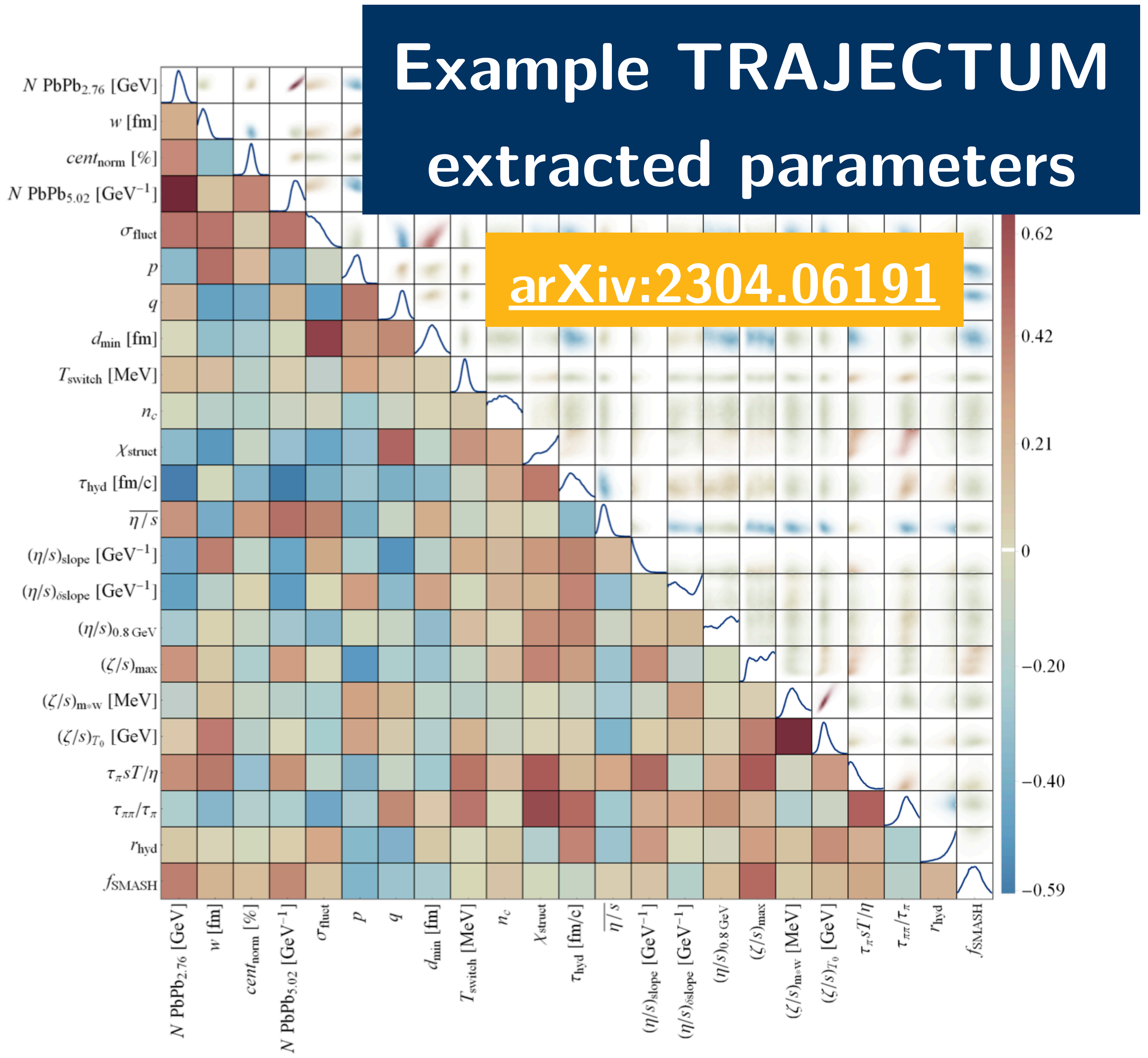
arXiv:2408.08247





Example JETSCAPE extracted parameters

arXiv:2408.08247



Example TRAJECTUM extracted parameters

arXiv:2304.06191

- Understanding the nature of the QGP requires a systematic & rigorous comparison of experimental data and models
- **Bayesian inference** has been & will be a **powerful tool** in our field

The whole picture is more than the sum of its parts!

Connections to other fields / Additional perspectives

Neutron stars
QCD Equation of State
Neutron skin thickness
Hypernuclei production
arXiv:2112.05323

Air shower modelling for cosmic rays
forward LHC and low-x constrains
arXiv:2203.08129

Hadron physics
Residual interaction in pairs and triplets of hadrons, including charm
Nature 588 (2020) 232-238

Heavy-Ion collisions

Dark-matter searches
Search for anti-nuclei in space: measurement of anti-^{3}He cross section
Nature Phys. 19 (2023) 1, 61-71

Black Holes and gravitational radiation
interesting theoretical connections between Color Glass Condensate and Black Holes
Phys.Lett.B 853 (2024) 138669

Beyond the Standard Model Physics Searches
Searches for axion-like particles in ultra-peripheral heavy-ion collisions
Phys.Lett.B 797 (2019) 134826

Summary

The HL-LHC & detector upgrades allow for up to 100 times more statistics in Pb-Pb collisions than $<$ Run 3

All four experiments will undergo major upgrades allowing to exploit this data

We have the tools to explore all stages of a heavy-ion collisions, including the QGP ...

- **... with unprecedented precision**
- **... in a wider phasespace**
- **... more differentially**
- **... with entirely new observables**

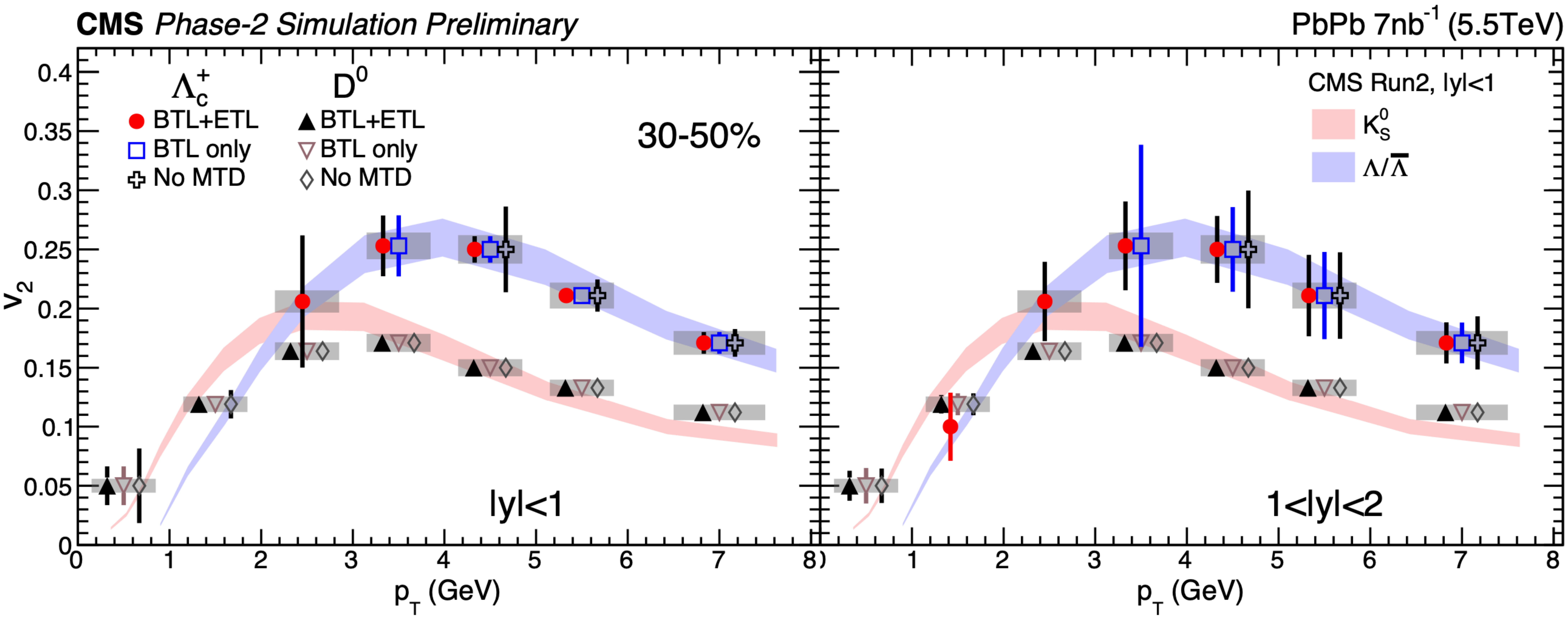
The <u>whole picture</u> painted at the HL-LHC will improve our understanding of QCD in extreme conditions

Special thanks to the people who helped me with this talk:
C. Loizides, P. Jacobs, A. Dainese

Thank you for your attention!

Backup

CMS MDT Performance Studies

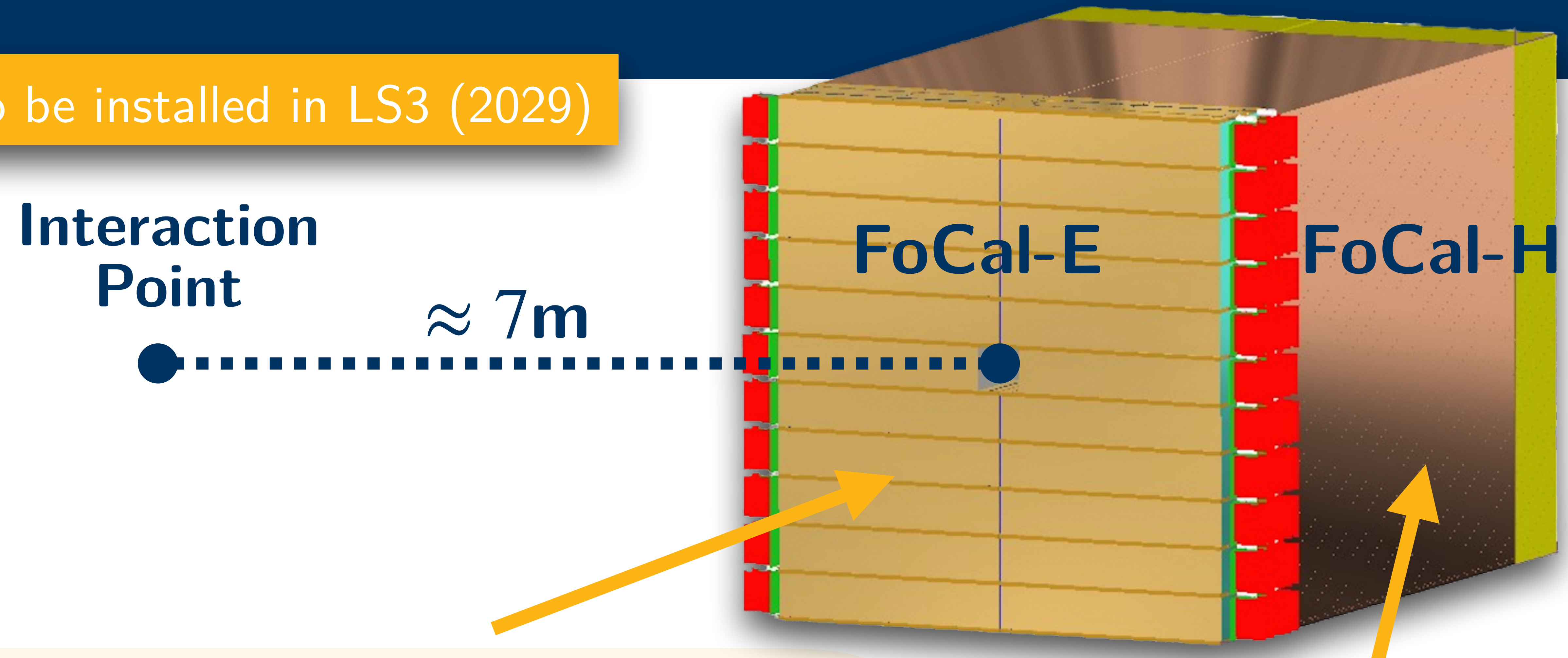


More details in CMS DP -2021/037

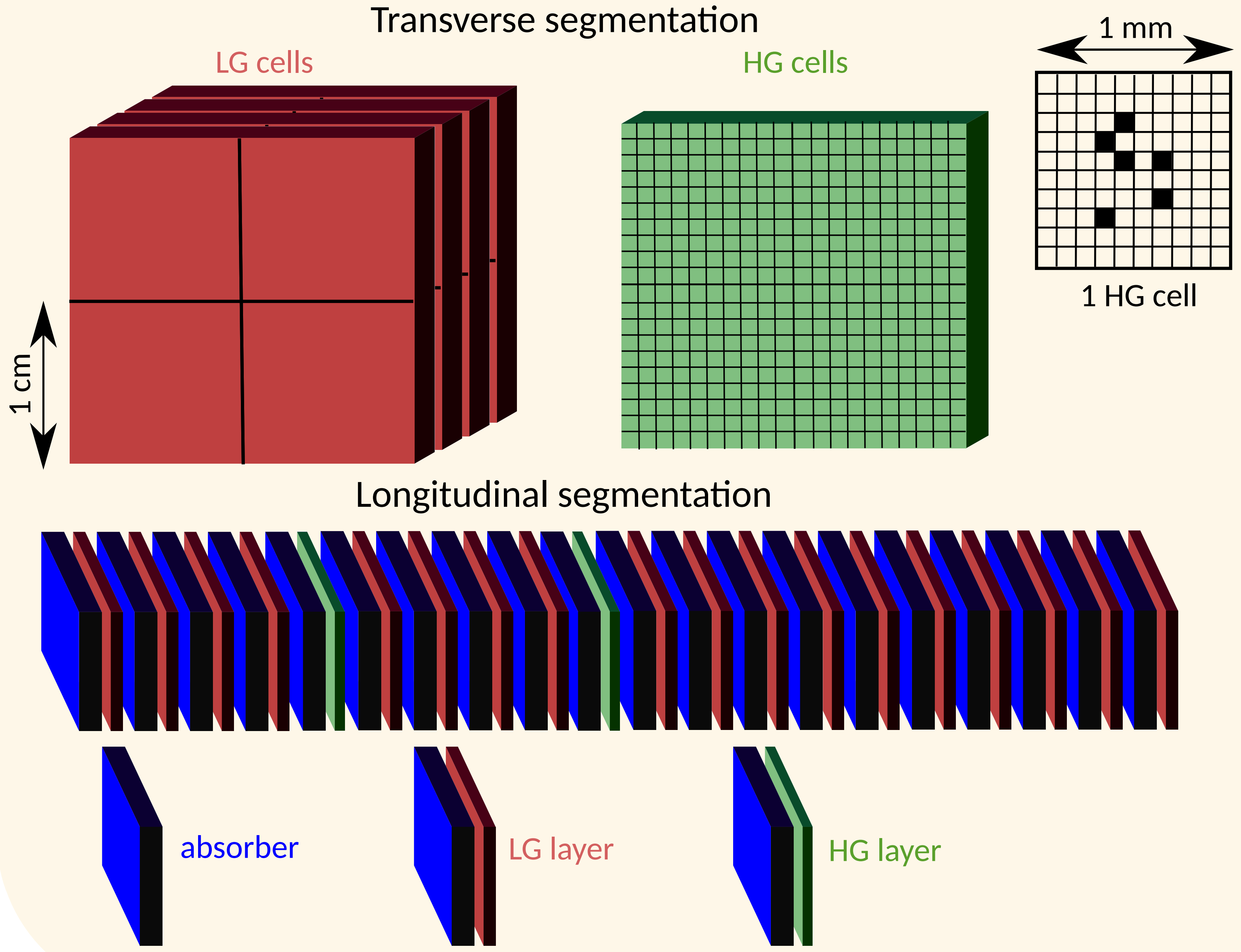
The ALICE FoCal

- upgrade to the ALICE detector covering very forward rapidities $3.2 < \eta < 5.8 \rightarrow x \sim 10^{-6}$
- **FoCal-E** is a highly granular Si-W calorimeter combining two sensor technologies: 18 silicon pad layers ($1\text{x}1\text{cm}^2$); two pixel layers ($30\text{x}30\mu\text{m}^2$)
- **FoCal-H** uses scint. fibres embedded into Cu tubes

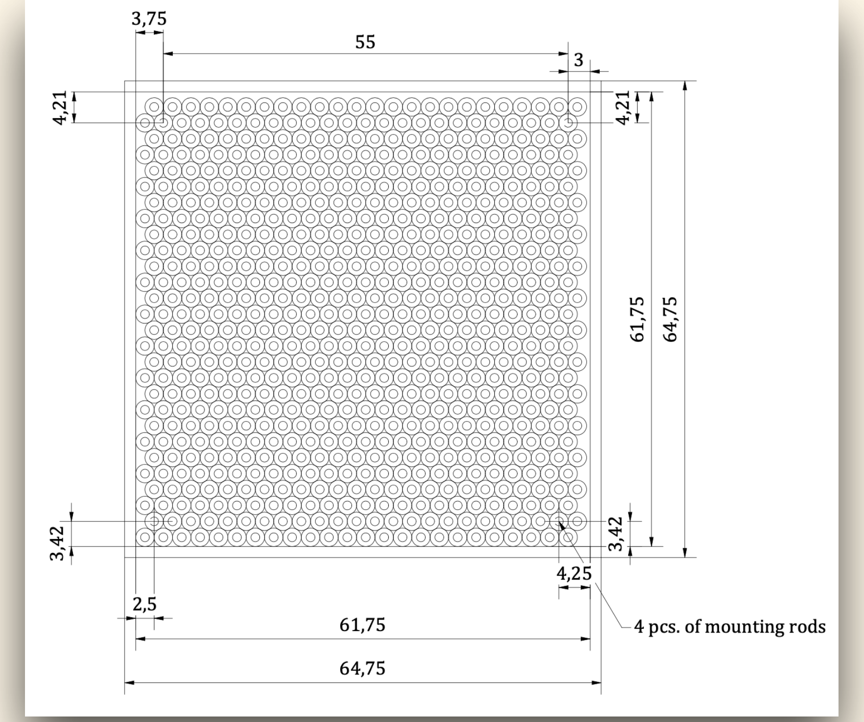
To be installed in LS3 (2029)



FoCal-E detector



FoCal-H detector



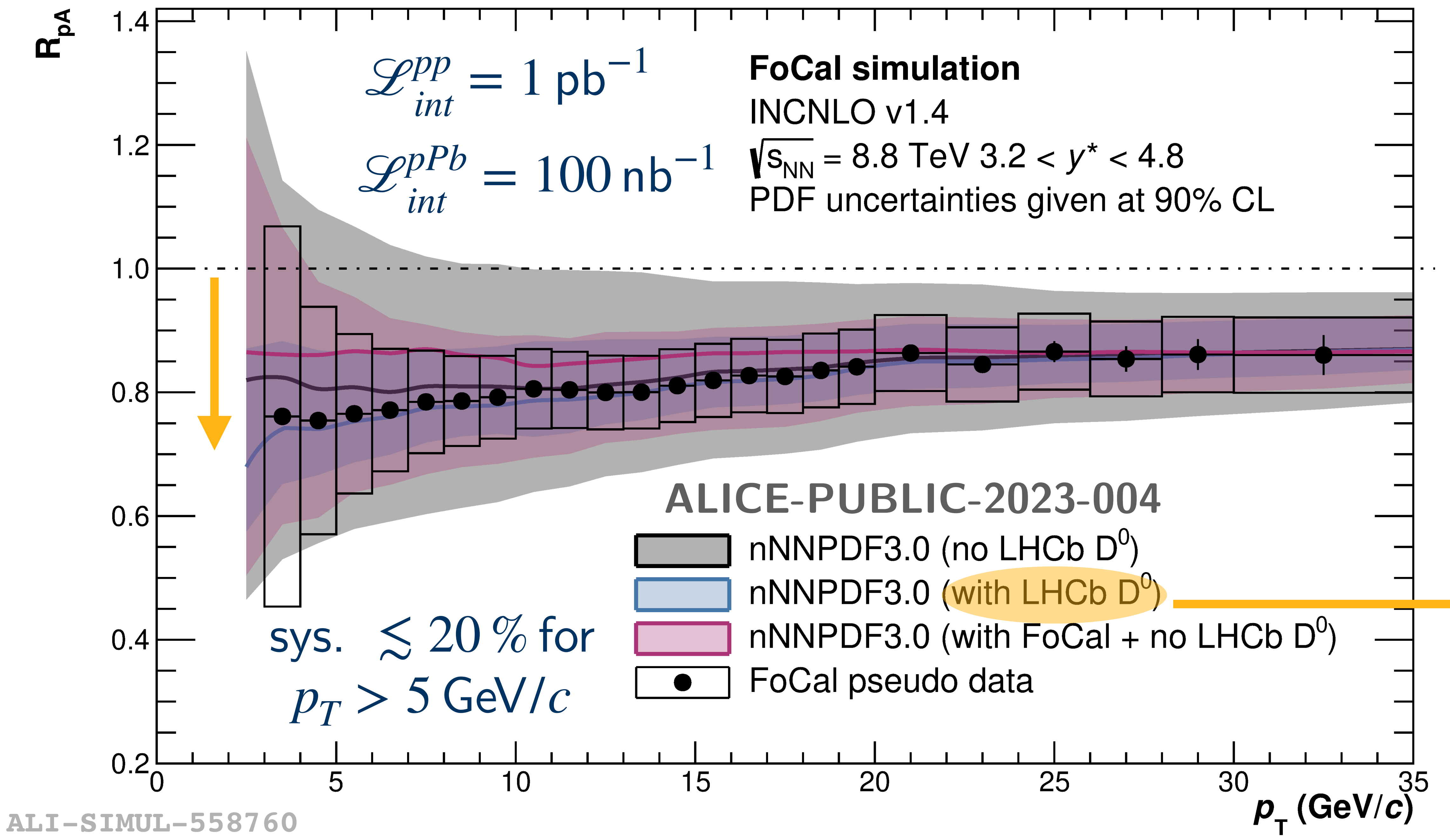
CERN-LHCC-2020-009, ALICE-PUBLIC-2023-001
ALICE-TDR-022

FoCal capabilities allow explorations of gluon saturation using a **multi-messenger approach**:

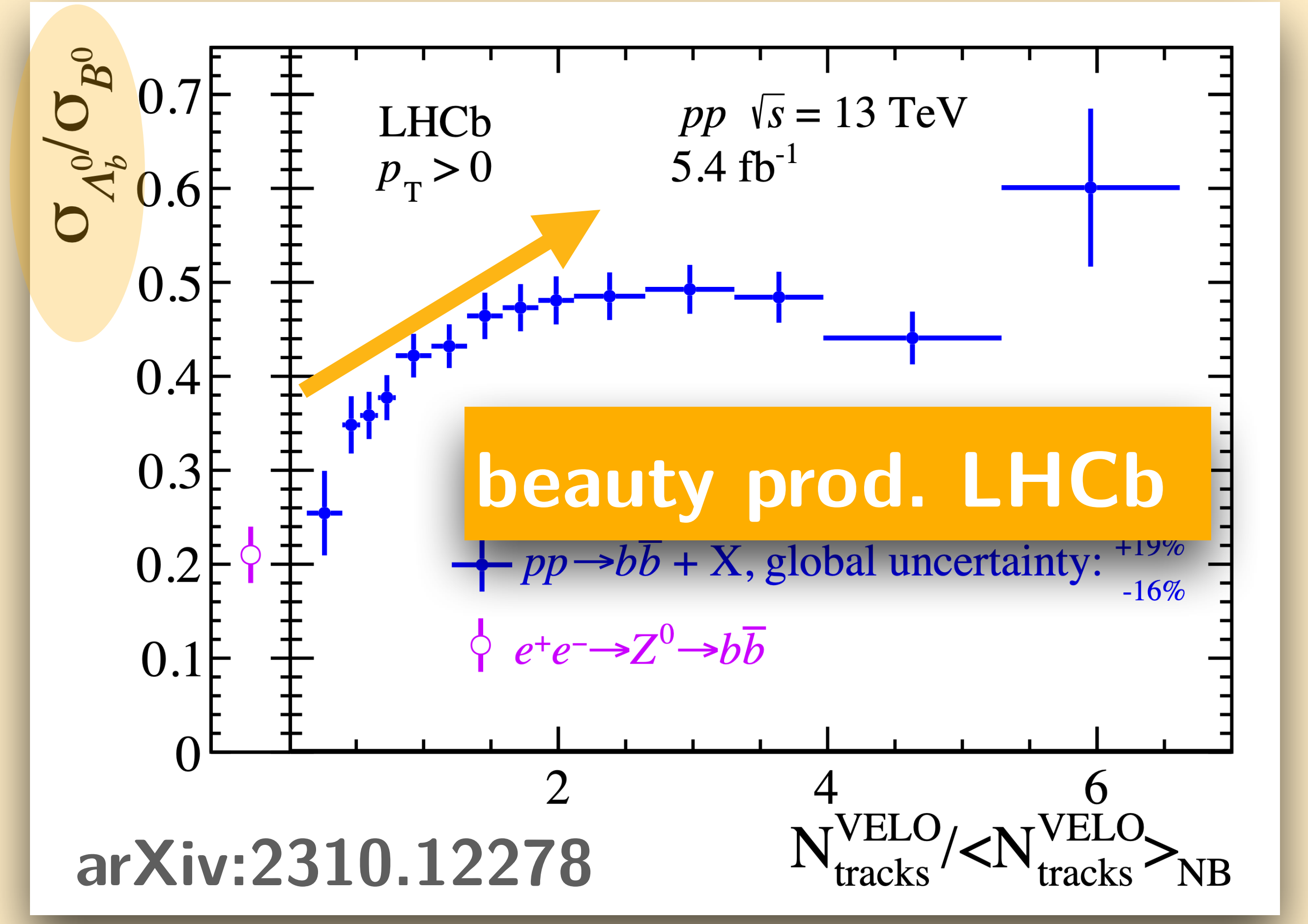
- Prompt photon production
- $\gamma-$hadron correlations
- Production of π^0, η and vector mesons
- Jet measurements (e.g. dijet production)
- Vector meson photoproduction in UPCs

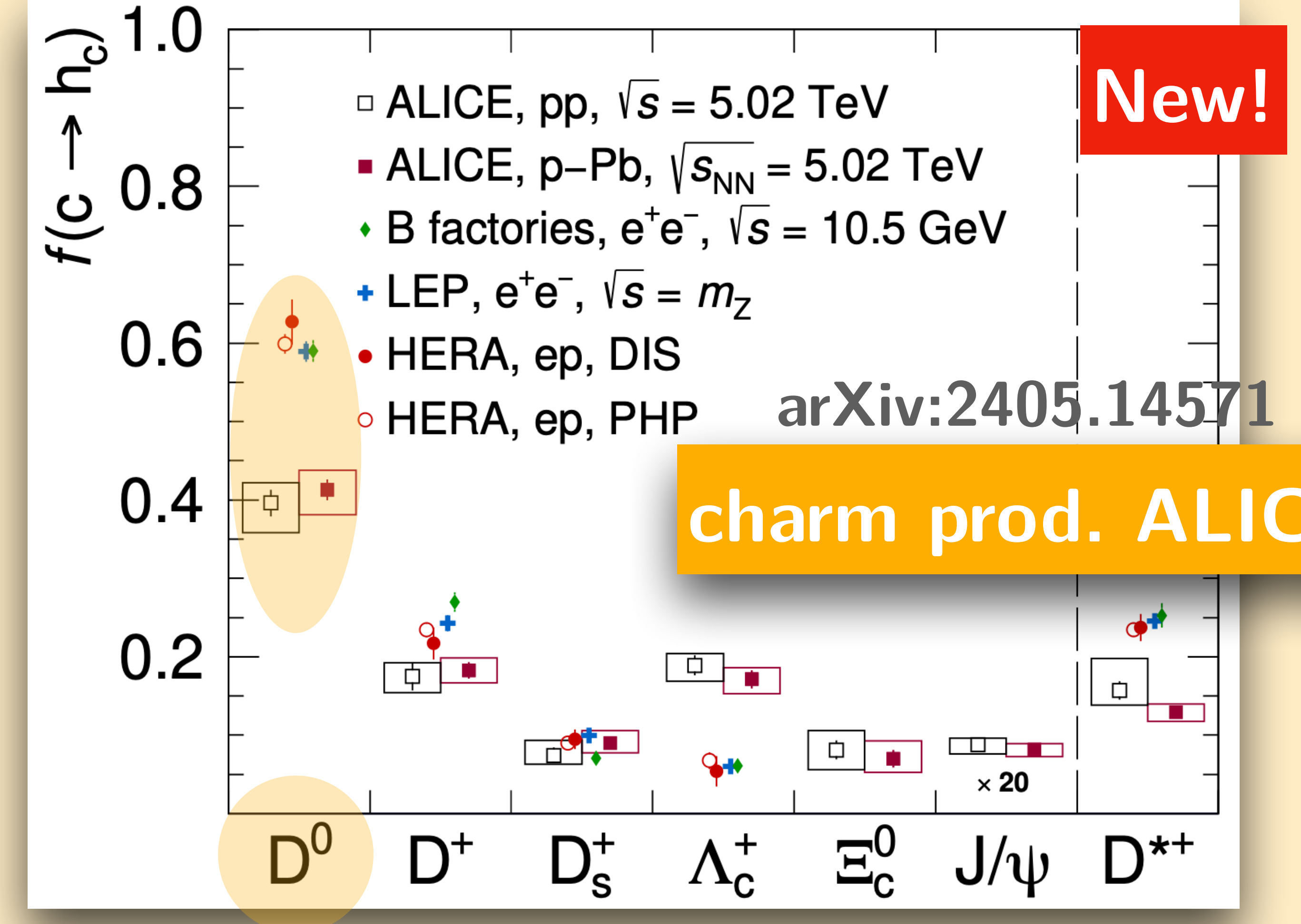
In this talk

Prompt photon production at forward rapidities



Are fragmentation functions universal?

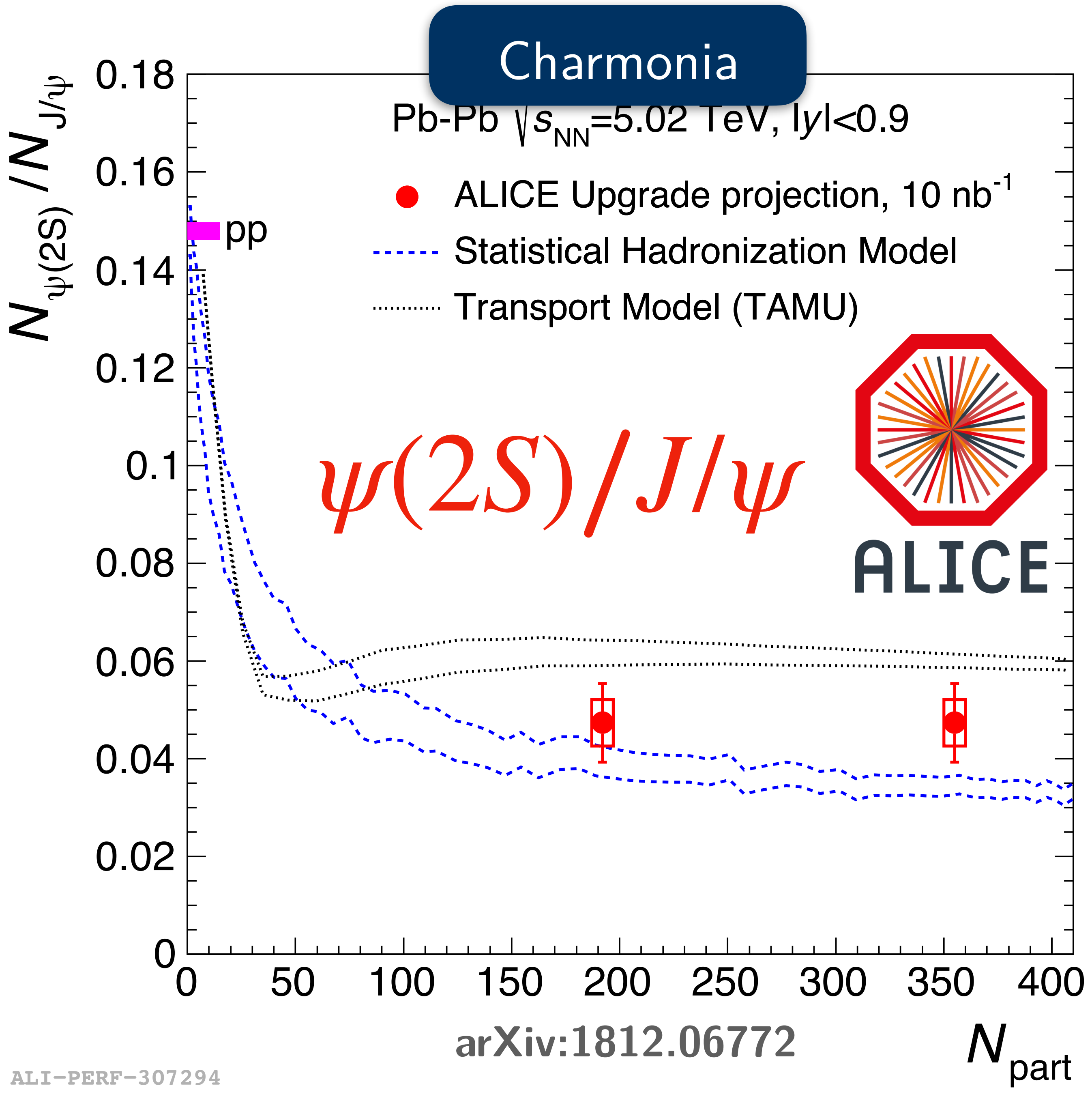


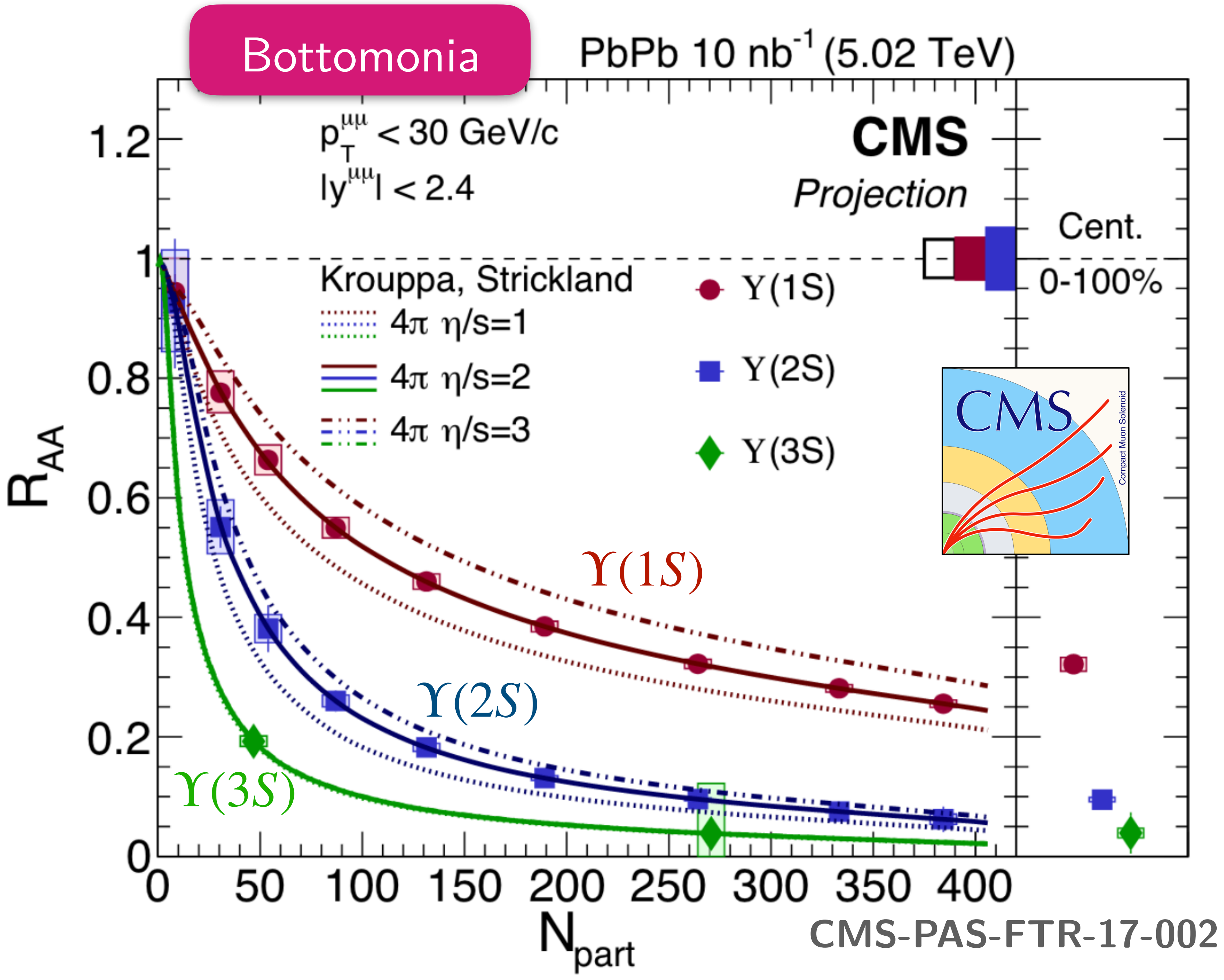


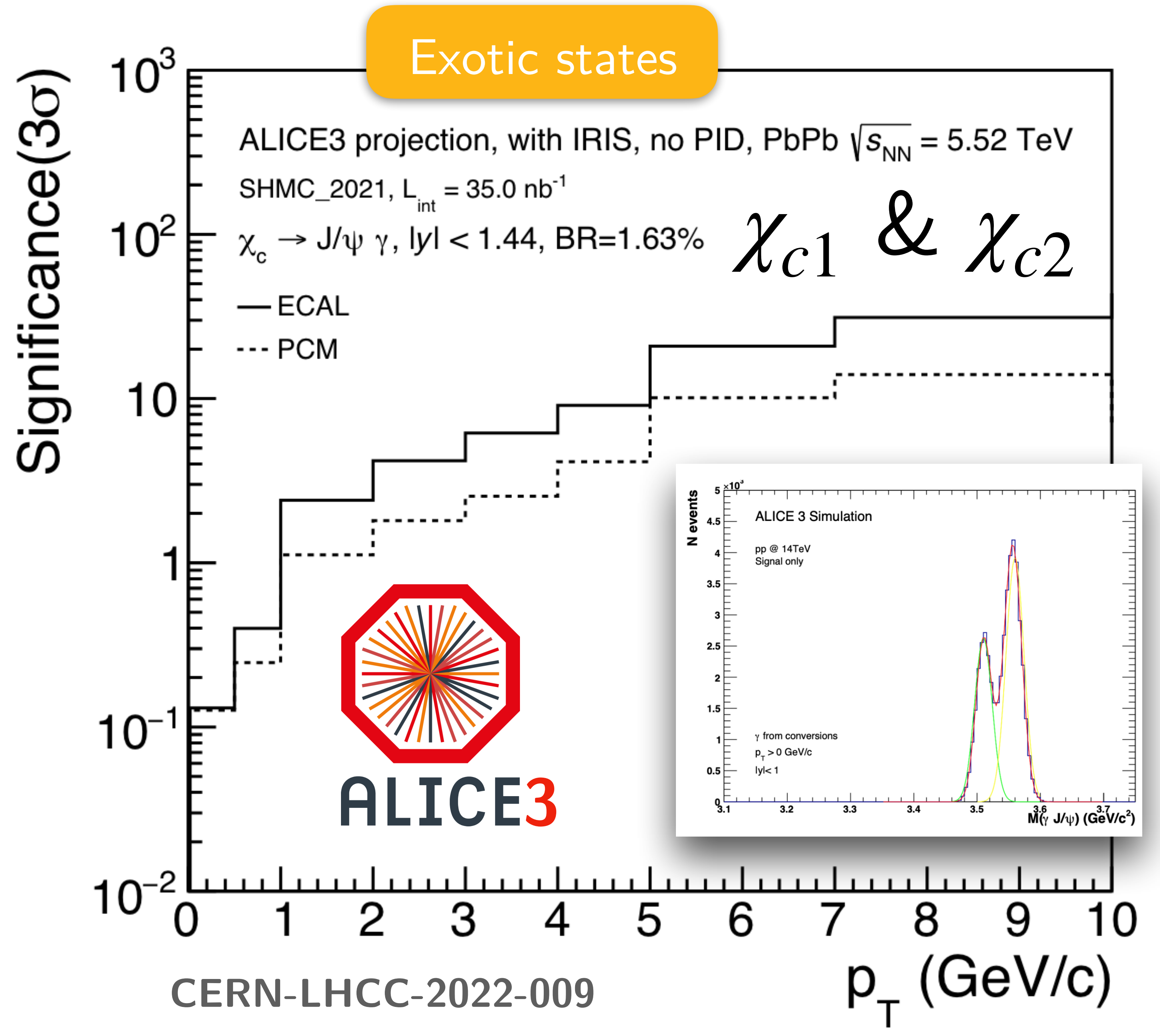
- **FoCal pseudo-data** of nuclear modification factor R_{pA}constructed using input from NLO+nPDF and assumptions on stat. and sys. uncertainties from perf. studies
- **Bayesian re-weighting of nNNPDF30** prediction showcases **significant reduction of nPDF uncertainties** when including FoCal data; comparable to D meson measurement by LHCb

Prompt photons → no final state and hadronisation effects → universality test of low-x formalism

Quarkonia







Systematic investigation of **in-medium force through spectroscopy of bound states** that dissolve/re-generate in QGP

- **Charmonia:** charm diffusion in QGP & recombination:
  → precision studies of J/ψ suppression and flow; access to rare excited states
- **Bottomonia:** lower importance of regeneration; access to $\Upsilon(3S)$ and Bottomonia flow!
- **Exotica:** access to exotic states in heavy-ion collisions in reach → properties, binding potential, hadronisation mechanism