JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Heavy Ion Physics with ATLAS and CMS

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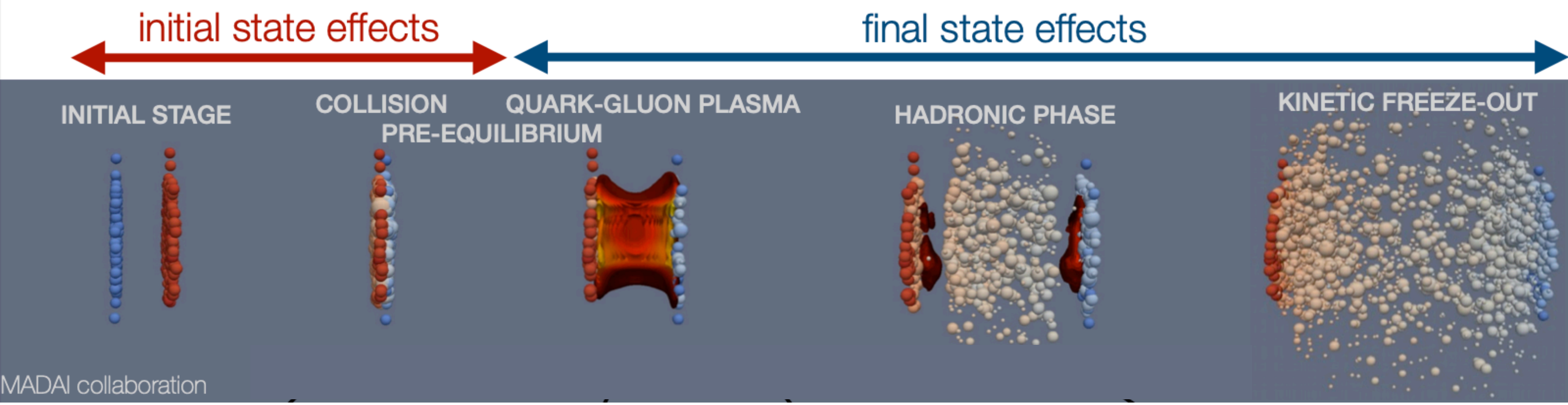
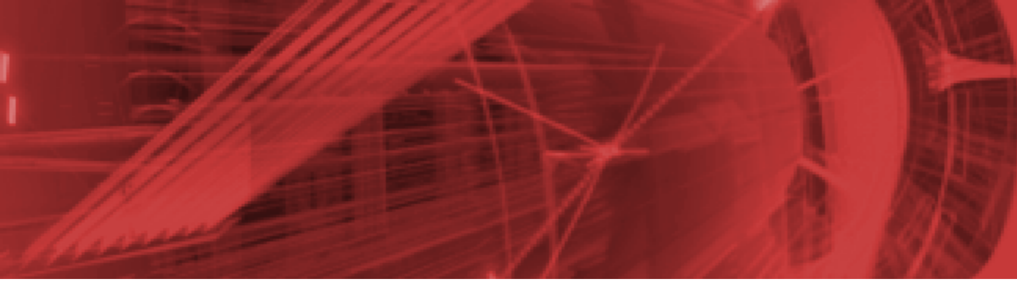
on behalf of the ATLAS and CMS Collaborations

Introduction to Heavy Ion Physics

- Quark-gluon plasma (QGP) = deconfined strongly-interacting QCD matter with color degrees of freedom

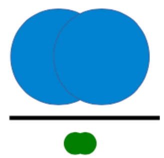


- Use variety of final states to provide insight into different stages of HI collisions
  - Soft probes (bulk particle production)
  - Hard probes
    - Colour objects e.g. jets → partonic energy loss in QGP
    - Colourless Objekts, e.g. EW Bosons
    - Also: Quarkonia and HF particles



Nuclear Modification Factor

- It is useful to compare (or normalize) HI collisions to proton-proton collision
  - Nuclear modification factor: Comparing HI and pp collisions where the geometrical scaling is removed

$R_{AA} = \frac{1}{N_{\mathrm{coll}}}$ 

$$= \frac{1}{N_{\mathrm{coll}}} \frac{\frac{\mathrm{d}N_{AA}}{\mathrm{d}p_{\mathrm{T}}}}{\frac{\mathrm{d}N_{pp}}{\mathrm{d}p_{\mathrm{T}}}} = \frac{1}{T_{AA}} \frac{\frac{\mathrm{d}N_{AA}}{\mathrm{d}p_{\mathrm{T}}}}{\frac{\mathrm{d}\sigma_{pp}}{\mathrm{d}p_{\mathrm{T}}}}$$

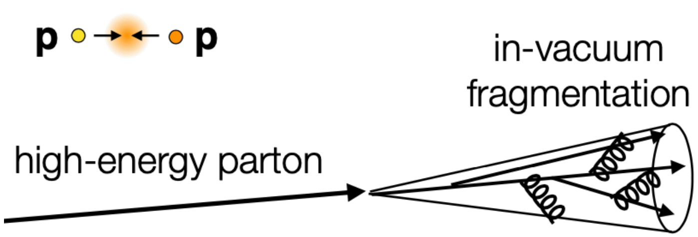
QCD in Medium

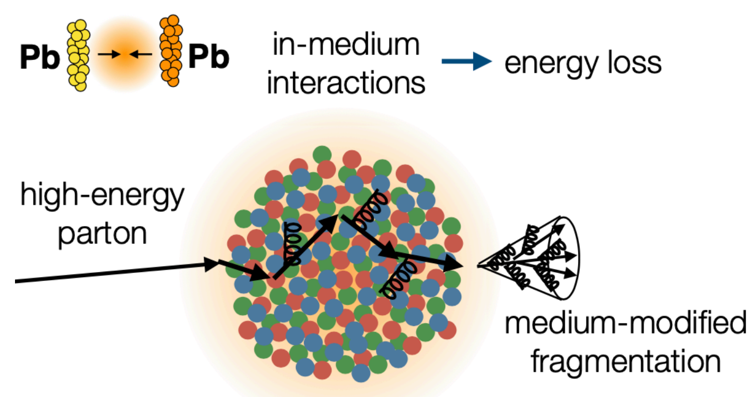
QCD in Vacuum

Yield in PbPb

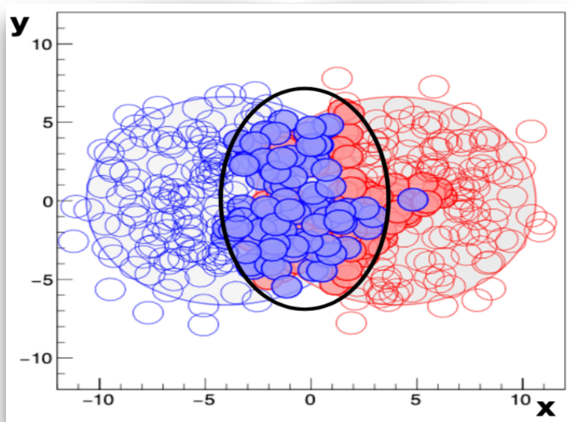
pp reference

- However, interaction of final state objects is very different

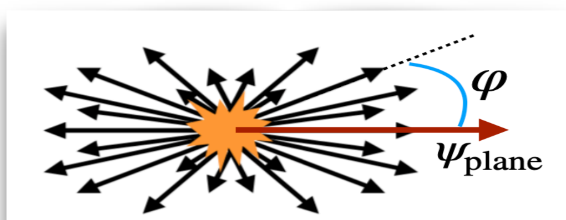




Heavy Ion Collision Geometry and the Physics Case

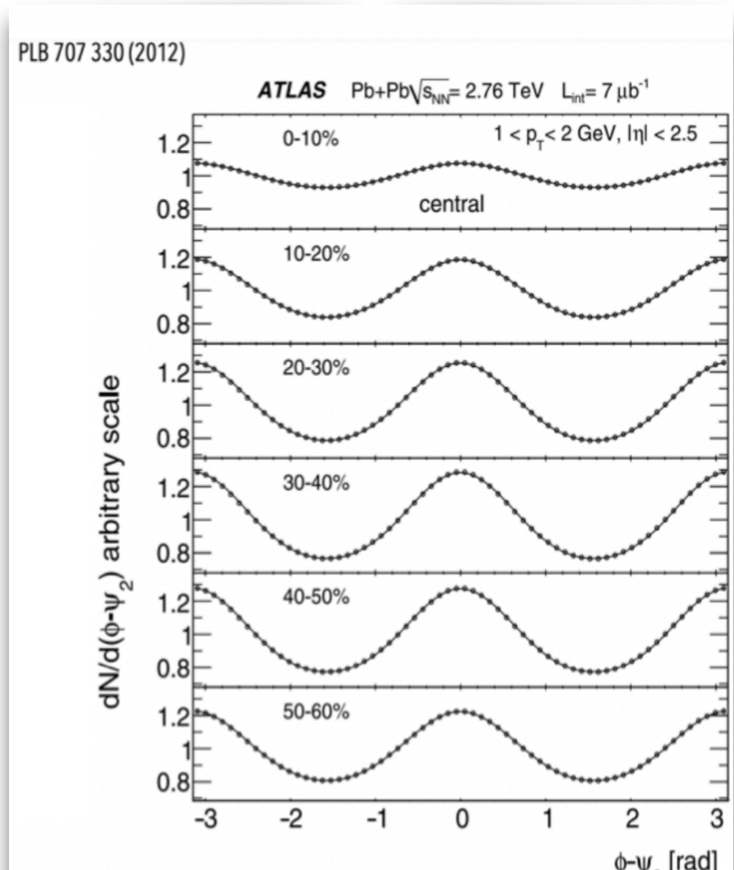


- Anisotropic particle emission
- Angular modulation of their distribution

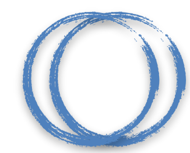


- Leads to non-zero flow coefficients

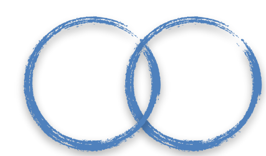
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}[1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi_R))]$$



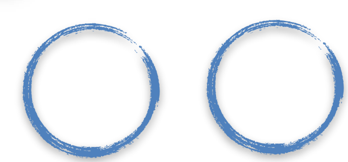
Central



Peripheral



Ultra Peripheral



What happened since LaThuille 2022?

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Dijet asymmetry in 5.44 TeV Xe+Xe
Large-R jets yields and substructure in Pb+Pb and pp
Charged hadrons in pPb, PbPb, XeXe
Jet substructure and suppression
Exclusive two-photon production of electron pairs in Pb+Pb
Non-exclusive production of dimuon pairs via gamma gamma scattering in 5.02 TeV Pb+Pb collisions
Jet-hadron correlations in p+Pb 5.02
Upsilon in pp and PbPb collisions
Dijet Asymmetry in Pb+Pb and pp collisions at 5.02 TeV
Measurement of v_n-p_T correlations in Xe+Xe collisions
b-jets in Pb+Pb and pp at 5.02 TeV
γγ→tautau and tau g-2 interpretation

Discussed Today

Study of ordered hadron chains in p-p, p-Pb and Pb-Pb
Measurements of jet production in ultra-peripheral collisions
Flow decorrelations in pp and per XeXe
Photon-tagged jet RAA in 5 TeV PbPb

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

First measurement of the forward rapidity gap distribution in pPb collisions at 8.16 TeV
K0S and Λ two-particle femtoscopic correlations in PbPb collisions at 5.02 TeV
Measurements of azimuthal anisotropy of nonprompt D0 mesons in PbPb collisions at
Search for medium effects using jets from bottom quarks in PbPb collisions at 5.02 TeV
Azimuthal anisotropy of dijet events in PbPb collisions
Observation of τ lepton pair production in ultraperipheral lead-lead collisions at 5.02 TeV
Strange hadron collectivity in pPb and PbPb collisions
Azimuthal correlations within exclusive dijets with large momentum transfer in photon-lead collisions
Two-particle azimuthal correlations in γp interactions

Photon-nucleus energy dependence of coherent J/ψ cross session in ultraperipheral PbPb collisions
Multiplicity and transverse momentum dependence of charge balance function in pPb and PbPb collisions
Probing hydrodynamics and the moments of the elliptic flow distribution in 5.02 TeV lead-lead collisions
Observation of the Y(3S) meson and sequential suppression of Y states in PbPb collisions

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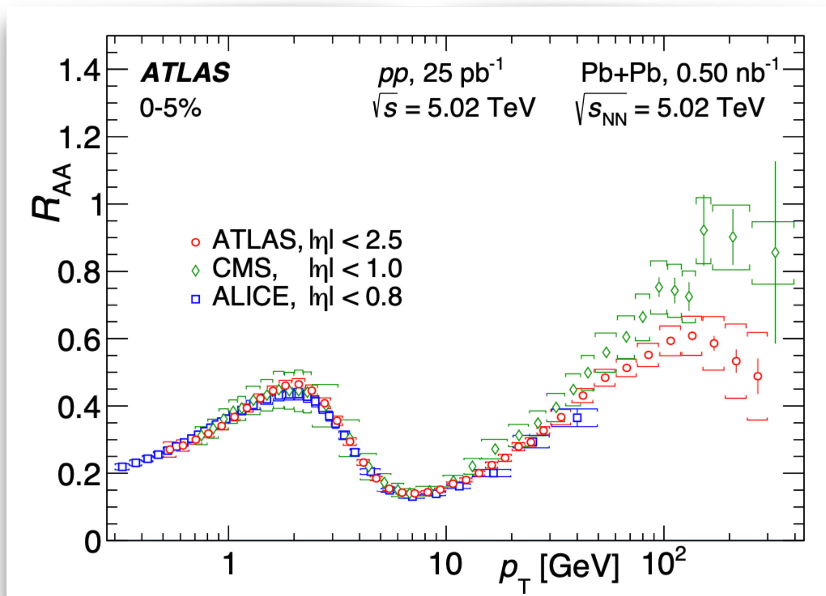
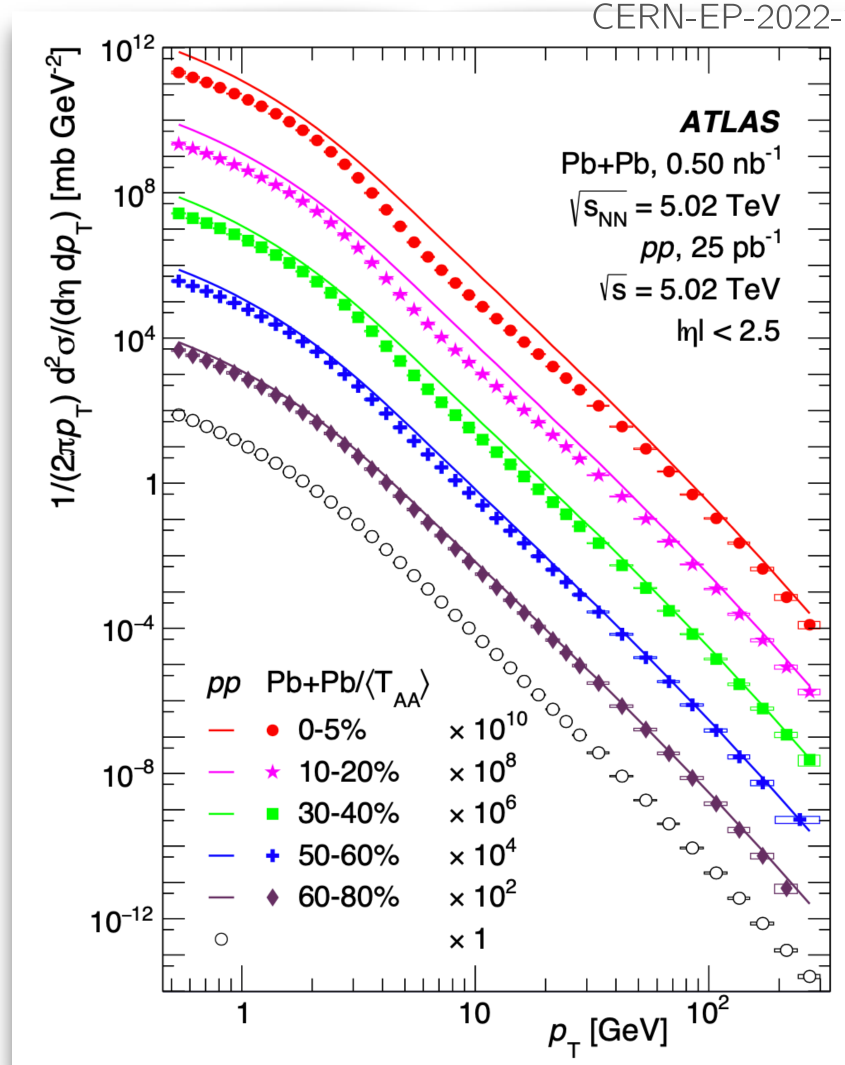
Soft Probes and Particle Flow

ATLAS: Charged-hadron production in pp, pPb,PbPb and XeXe collisions (1/2)

- Measurements of charged-hadron spectra
  - Differential nuclear modification factors by comparing the spectra in HI and pp collisions
- Consistent results between ATLAS, CMS and ALICE

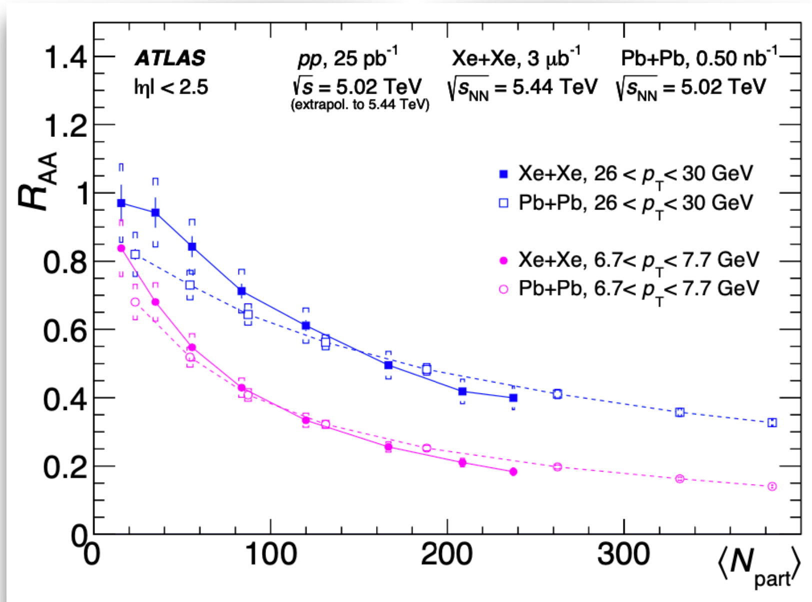
CERN-EP-2022-221

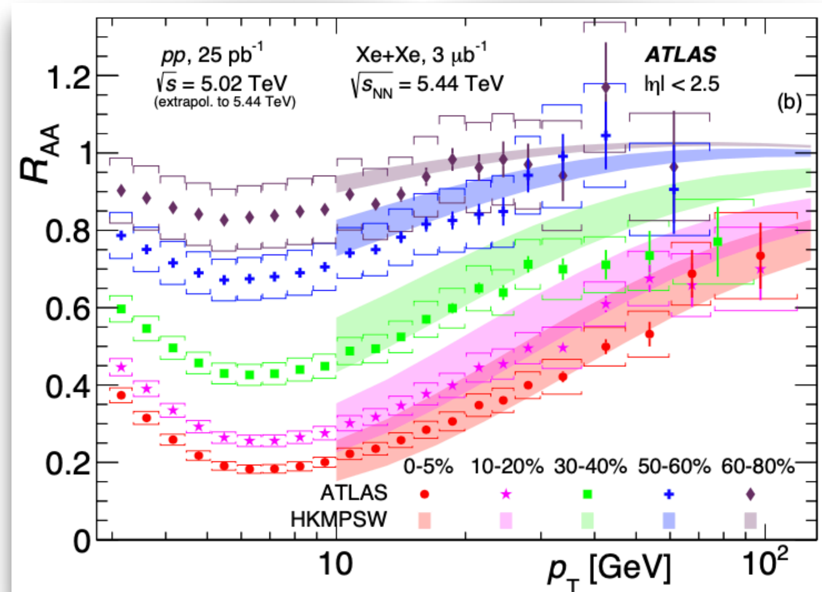




ATLAS: Charged-hadron production in pp, pPb,PbPb and XeXe collisions (2/2)

CMS: CERN-EP-2018-228





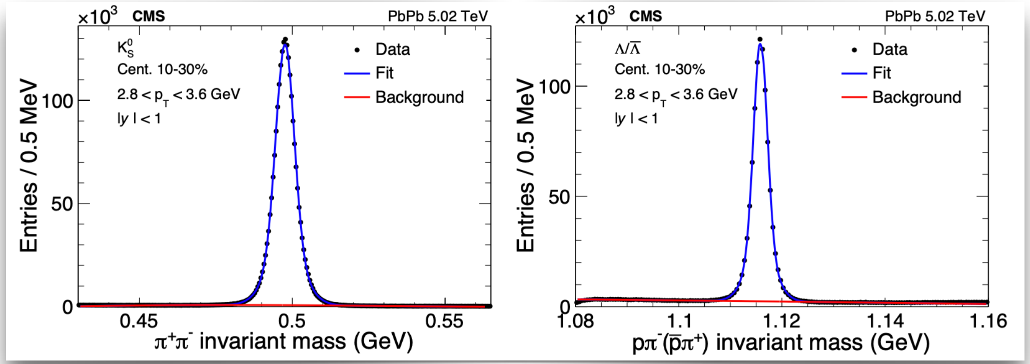
- Characteristic Shape of R_{AA}
  - Local maximum at $p_T \approx$ 2 GeV,
  - Decrease to local minimum at $p_T \approx$7 GeV
  - Rise towards higher p_T

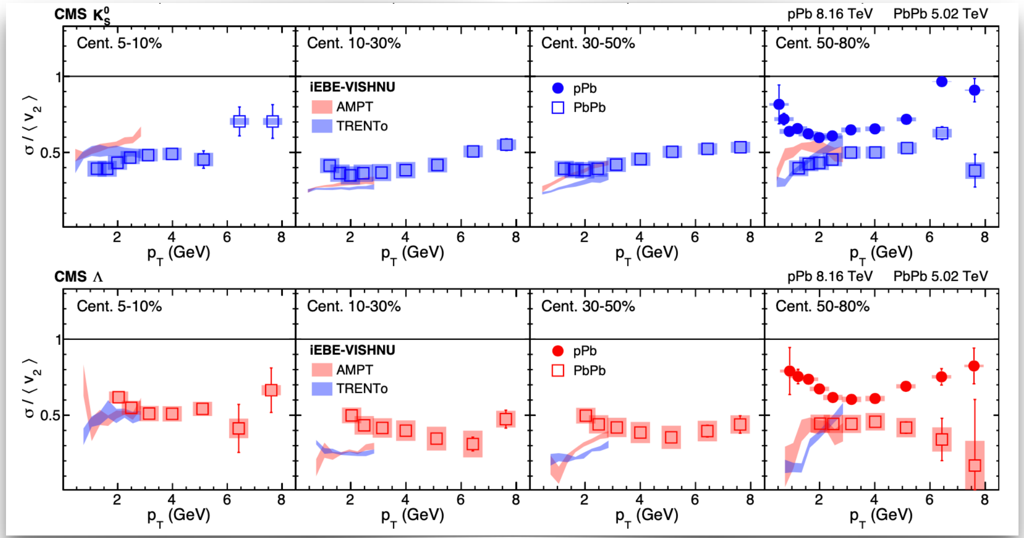
- The suppression of charged-hadron production is strongest in the most central collisions
- No theoretical model is able to describe R_{AA} dependence over the full kinematic range

CMS: Strange hadron collectivity in pPb and PbPb collisions

- HI collisions: strong collective azimuthal correlations between particles
  - Explained by formation of QGP with hydrodynamic behavior
- Azimuthal correlation characterized by Fourier coefficients
  - Second Fourier coefficient, known as elliptic flow (v_2): reflects medium response to initial collision geometry
- New CMS measurement: v_2 for K_0 mesons, Λ baryons, and charged hadrons in PbPb and pPb
  - Hydrodynamic models qualitatively consistent data
  - No dependence of v_2-fluctuations on particle species observed
  - Confirm that v_2 fluctuations come from initial-state geometry

CERN-EP-2022-036



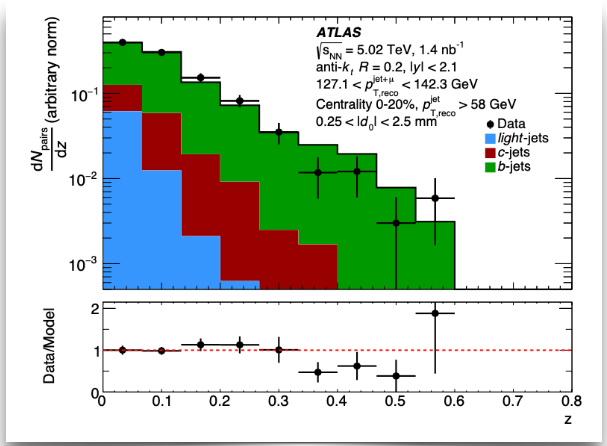


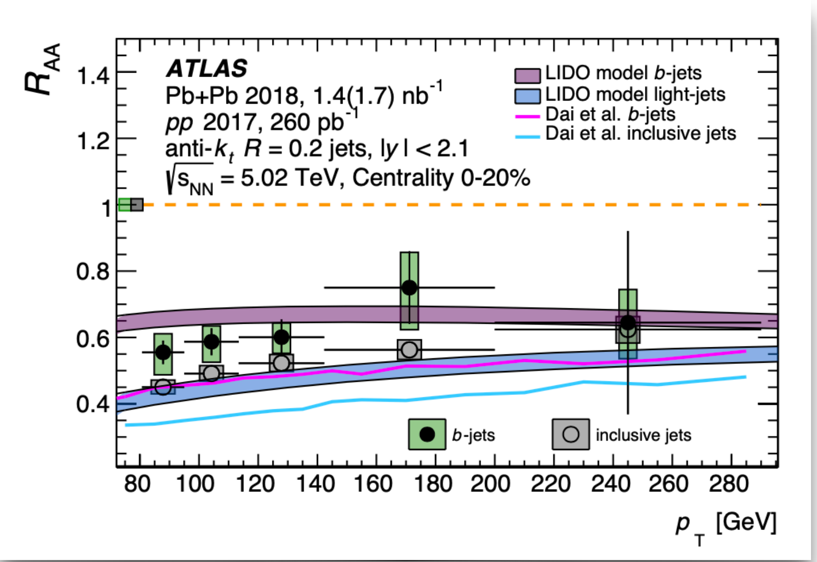
Hard and Heavy Probes

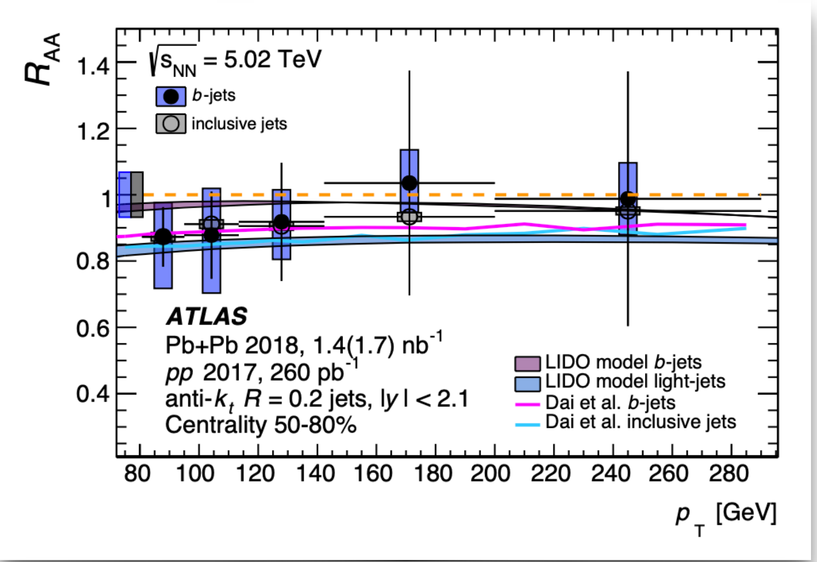
ATLAS: Measurement of the nuclear modification factor of b-jets

- B-jets behave differently in QGP due to quark mass
  - Medium-induced gluon radiation suppressed
  - Overlay quark jets are expected to lose a smaller amount of energy wrt gluon due to color factor.

- B-jets ID: Use jets with muonic b-decays + template fits of the muon momentum relative to the jet axis.
  - R_{AA} decreases with larger centrality for all jets
  - R_{AA} seems to be larger for b-jets than light-jets

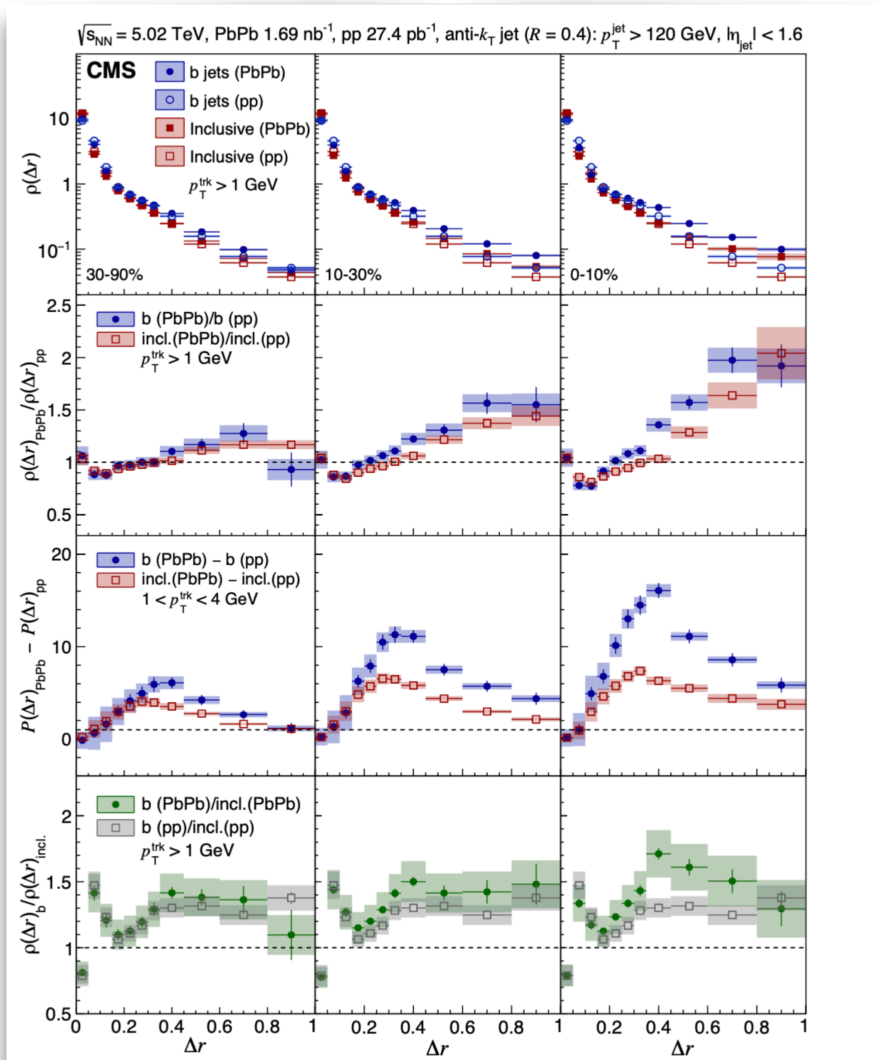






CMS: CERN-PH-EP-2013-228 ATLAS: CERN-EP-2022-043

CMS: Search for medium effects using jets from bottom quarks

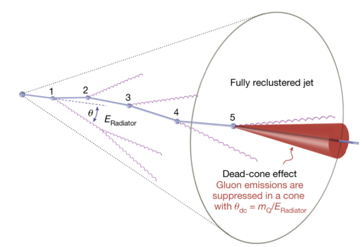


CERN-EP-2022-190

- Jet Shape: Measure of how pT of charged particles is distributed with respect to the jet axis.

$$\rho(\Delta r) = \frac{P(\Delta r)}{\Sigma_{\text{jets}} \Sigma_{\text{trk} \in (\Delta r < 1)} p_T^{\text{trk}}}$$

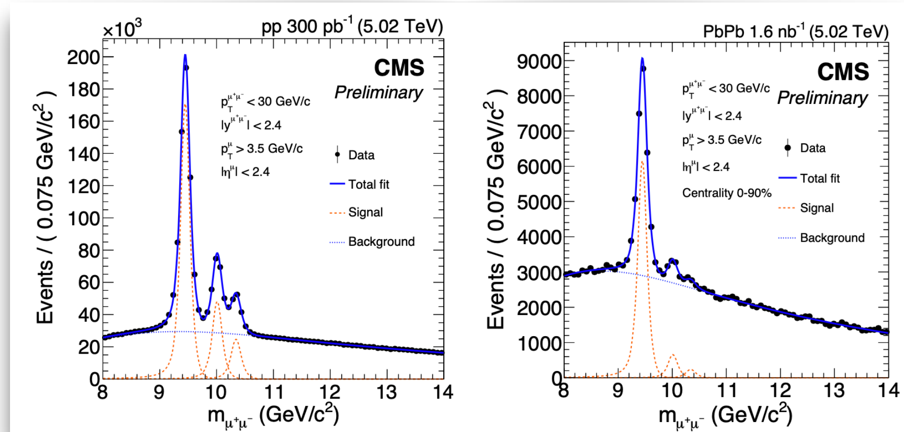
- B jet shapes show depletion of pT at small radial distances from the jet axis compared to inclusive jet shapes.
  - already present in pp
  - maybe a quantitative measurement of the expected dead-cone effect for b jets.

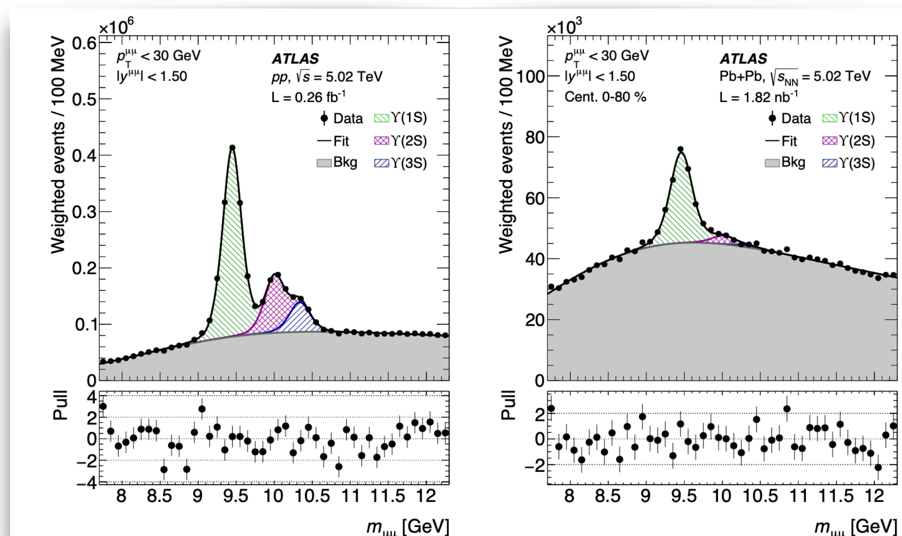


- QGP modifies the energy flow around b jets
  - depletion of the transverse momenta in the range of about Δr<0.4 and an enhancement at larger radial distances from the jet axis.

ATLAS and CMS: Observation of the Υ(3S) meson and sequential suppression of Upsilon states (1/2)

- Modification to the heavy-quark potential in QGP leads to „sequential suppression“
  - Different quarkonium states dissolve at different temperatures of the medium
  - Excited states dissociate just above the transition temperature T_C~155 MeV needed to form the QGP
  - Ground states melt far above that value
  - Creation of a hierarchy in the measured suppression of quarkonium states.
- Predictions based on lattice calculations:
  - Υ(1S) persists well above T_C,
  - Υ(2S) dissociates at about 1.1 T_C
  - Υ(3S) cannot exist at temperatures above T_C

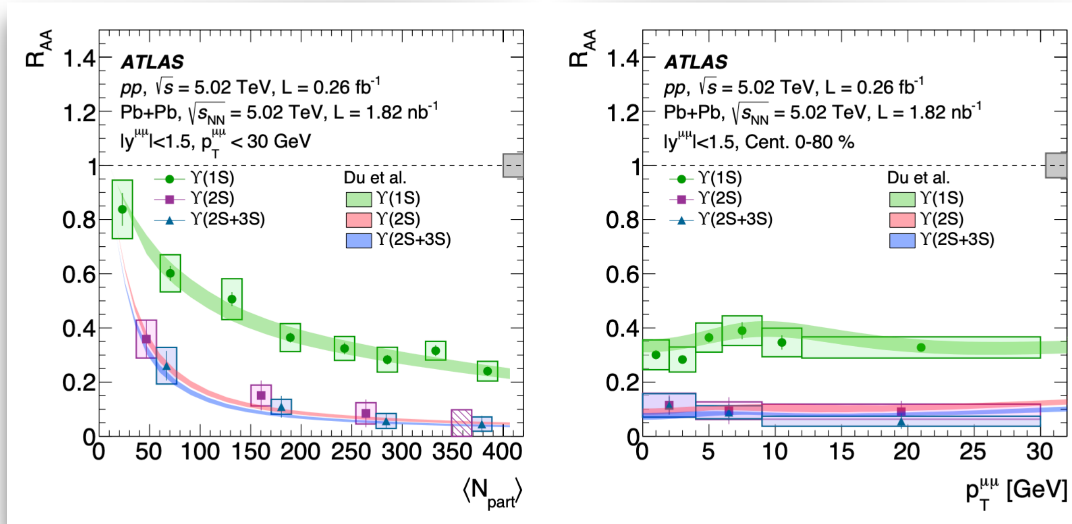


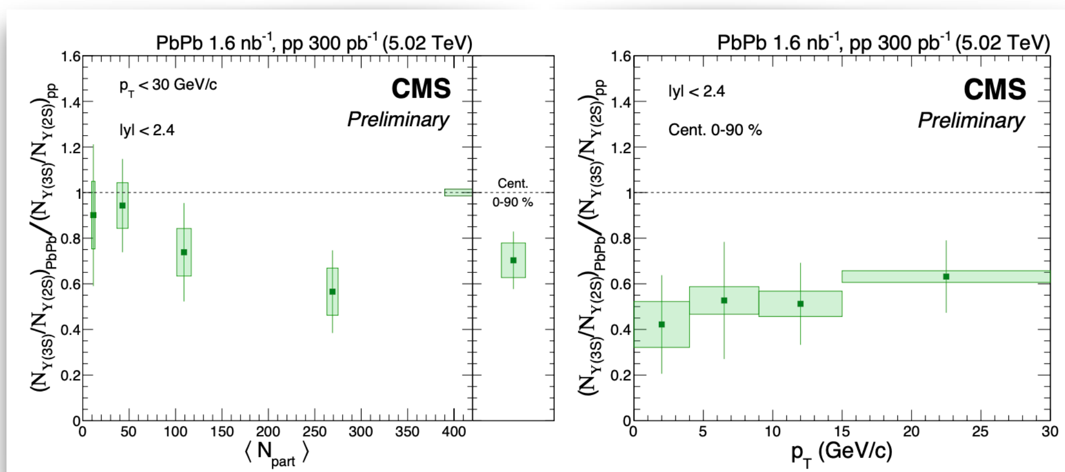


CMS PAS HIN-21-007
CERN-EP-2022-045

ATLAS and CMS: Observation of the Υ(3S) meson and sequential suppression of Upsilon states (2/2)

- The Υ(3S) meson is observed for the first time in PbPb collisions, and the amount of suppression is found to be stronger than for the Υ(2S) meson
- The values of R_{AA} for both Υ(2S) and Υ(3S) are observed to decrease gradually for more central collisions
- No significant p_T dependence is observed
- New constraints on the understanding of quarkonium suppression in HI collisions

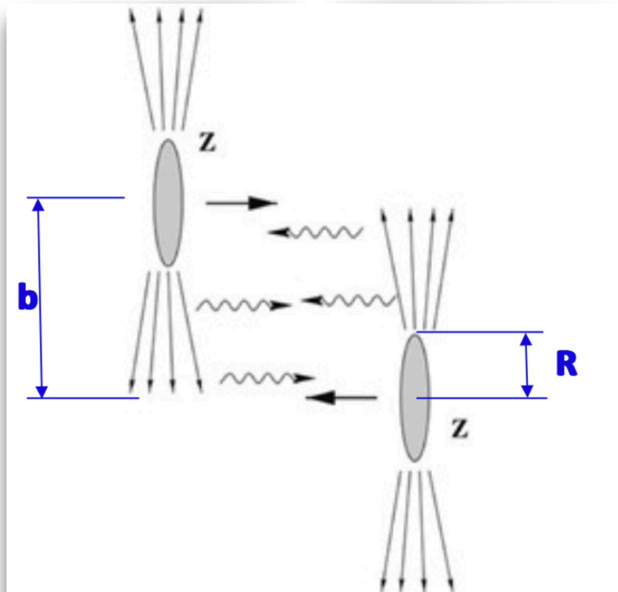


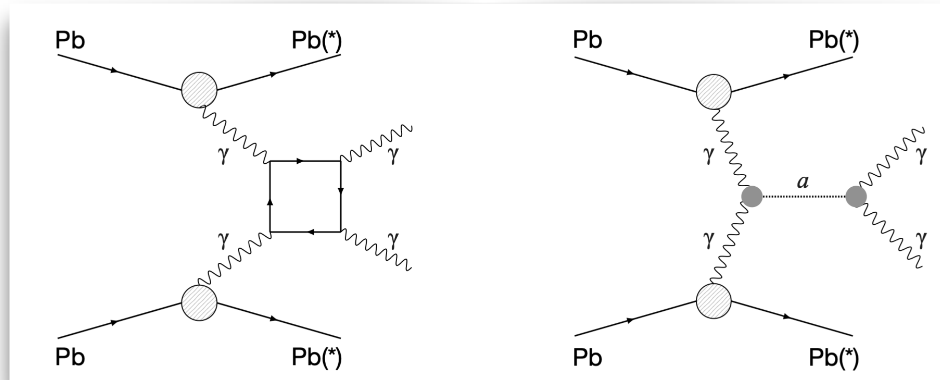


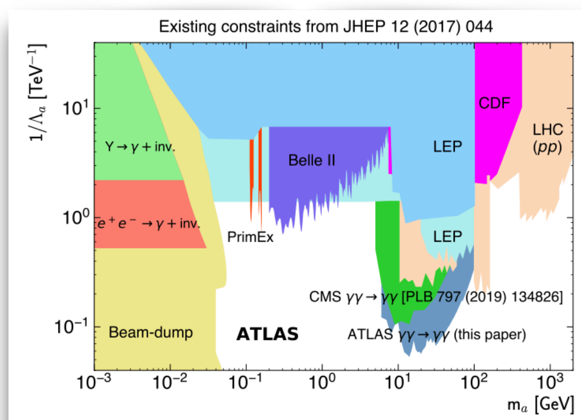
Ultra-peripheral Collisions

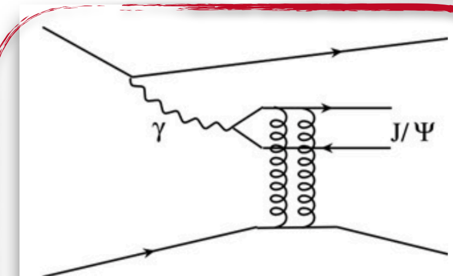
CMS: Photon-nucleus energy dependence of coherent Jψ cross session in ultraperipheral PbPb collisions

CERN-EP-2016-098









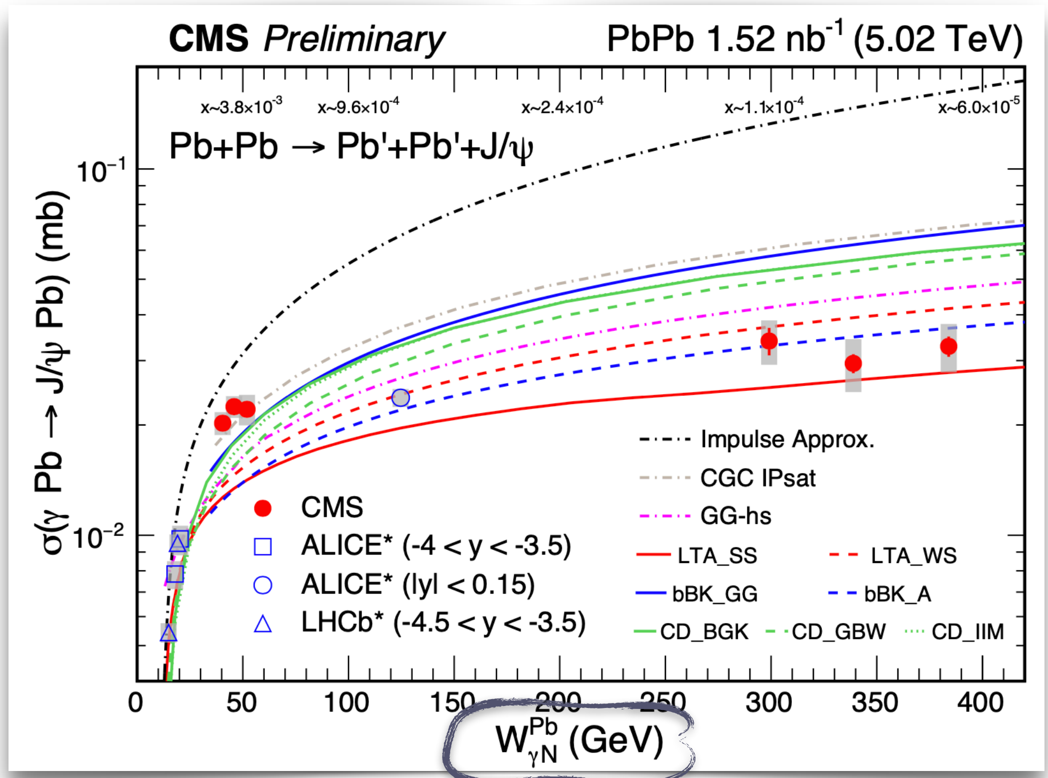
- Ultra-peripheral (UPC) collisions:
  - Hadronic interactions strongly suppressed
  - High photon flux (Z^2)
  - High cross sections for γ-induced reactions (e.g. exclusive vector meson production)

- Coherent vector meson production
  - Photon couples coherently to all nucleons
  - No neutron emissions in 80% of cases
  - Probe gluon PDF at very small x (6×10^{-6})

CMS: Photon-nucleus energy dependence of coherent J/ψ cross session in ultraperipheral PbPb collisions

- Experimental Challenge: distinguish between low and high photon-nucleon center-of-mass energy
  - Use forward-emitted neutron multiplicities from electro-magnetic dissociation of ions
  - Tag neutrons with ZDC |η| > 8.3
- Selection:
  - Suppress hadronic activity in the forward region
  - Two muons with $2.6 < m_{\mu\mu} < 4.2\,\text{GeV}$
- Conclusion:
  - Either: first experimental evidence of black disk limit
  - Or: Indication of a gluon density suppression significantly larger than QCD predicts

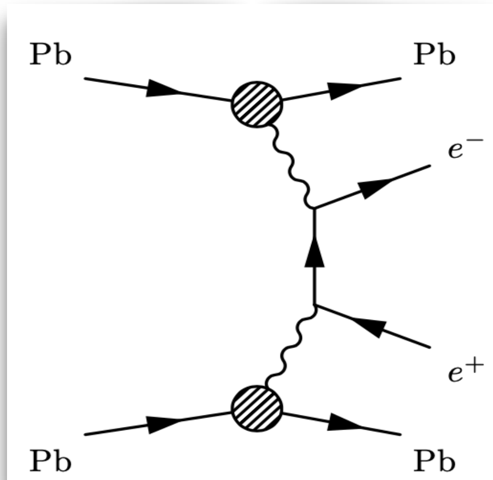
CMS PAS HIN-22-002

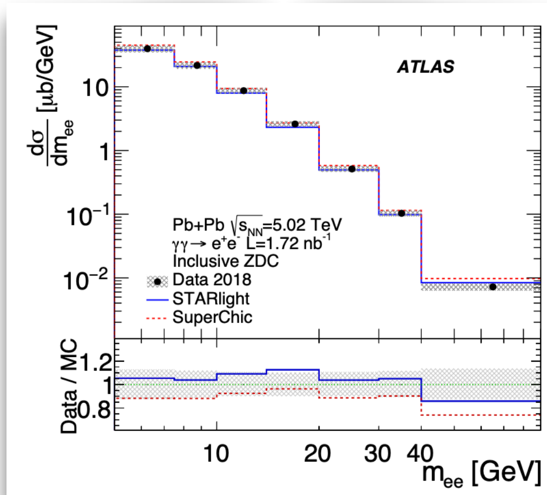


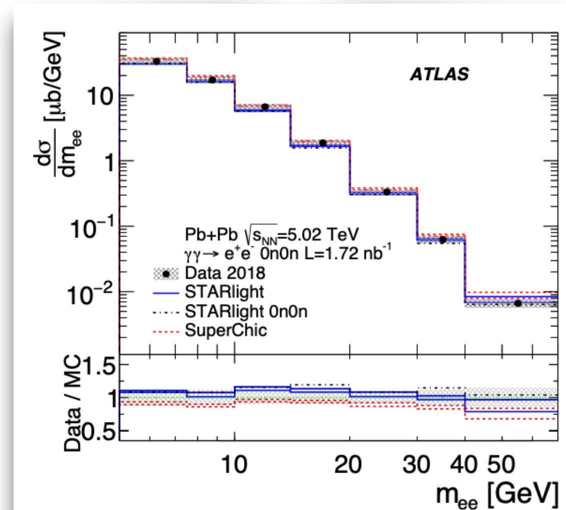
Center of mass of the γ-Pb System

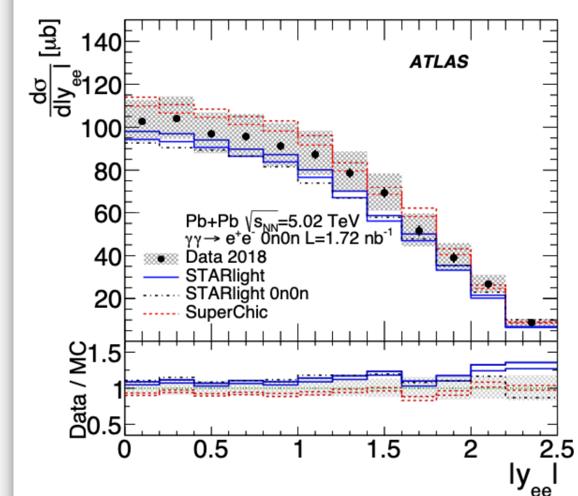
ATLAS: Exclusive dielectron production in ultraperipheral Pb+Pb collisions

ATLAS: CERN-EP-2022-130 CMS: CERN-EP-2020-196





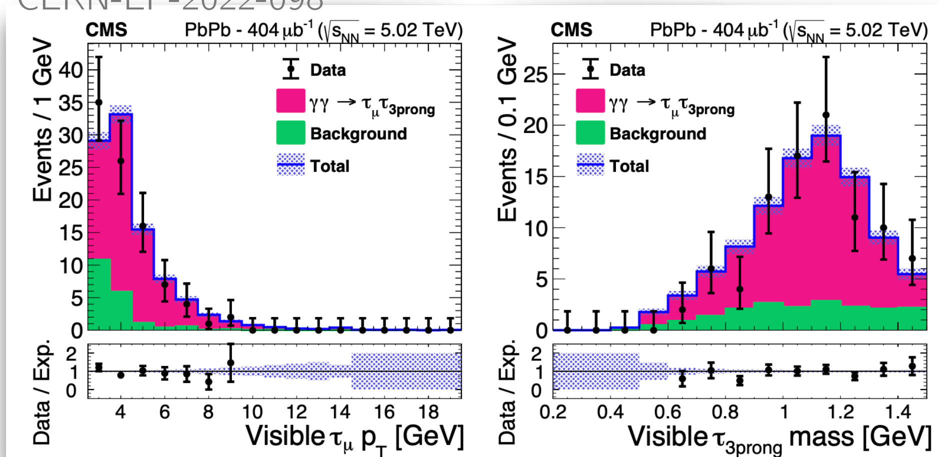




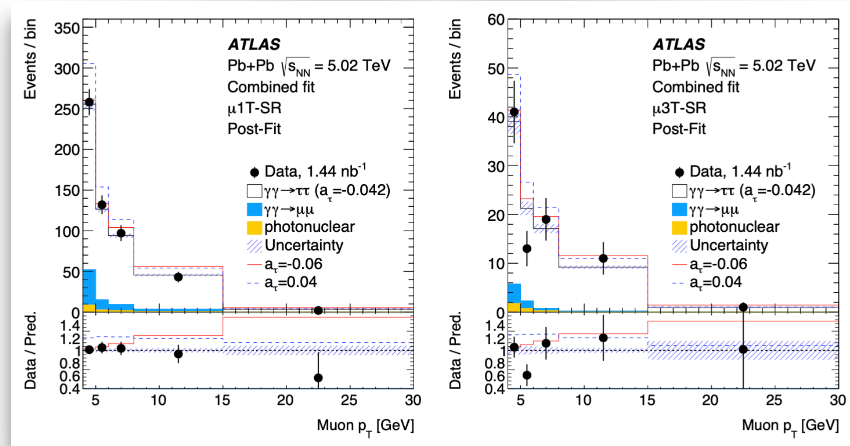
- Signal Selection: two electrons with p_T>2.5 GeV
  - Three cases: 0n0n (no neutron is registered in either ZDC), Xn0n, XnXn
- Cross section uncertainty at 10%
  - Discrepancy between data and the Starlight prediction rises with higher $|y_{ee}|$, similarly to what ATLAS observed previously in $\gamma\gamma \to \mu\mu$

ATLAS and CMS: Observation of τ lepton pair production in UPC Collisions

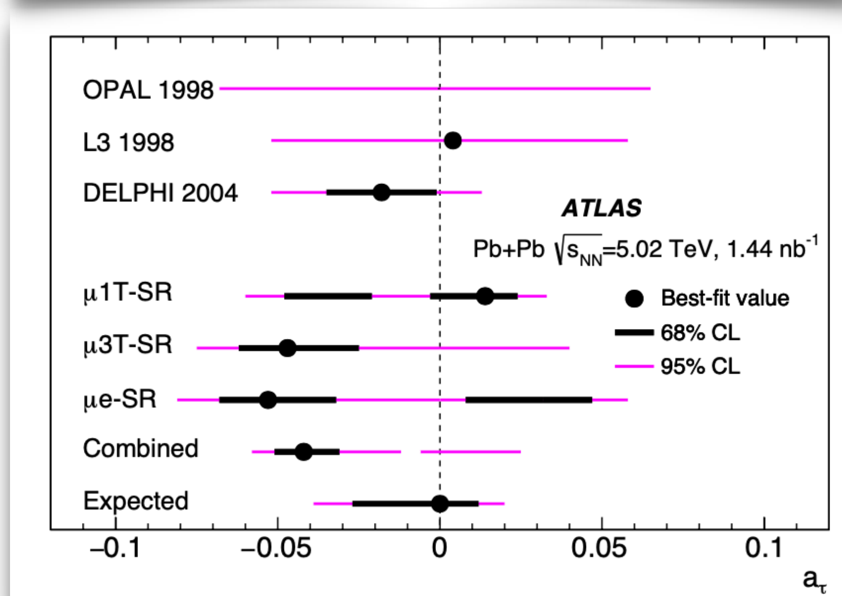
CERN-EP-2022-098



CERN-EP-2022-079



- Signal selection: Two tau decays
  - One muonic τ-decay
  - Second τ-decay: electron, 1-track, 3-tracks
- Differential cross section can be reinterpreted to give a constrain on $(g-2)_\tau$
  - Similar precision as DELPHI
  - CMS/ATLAS will surpass this limit in the future (new channels, higher lumi)

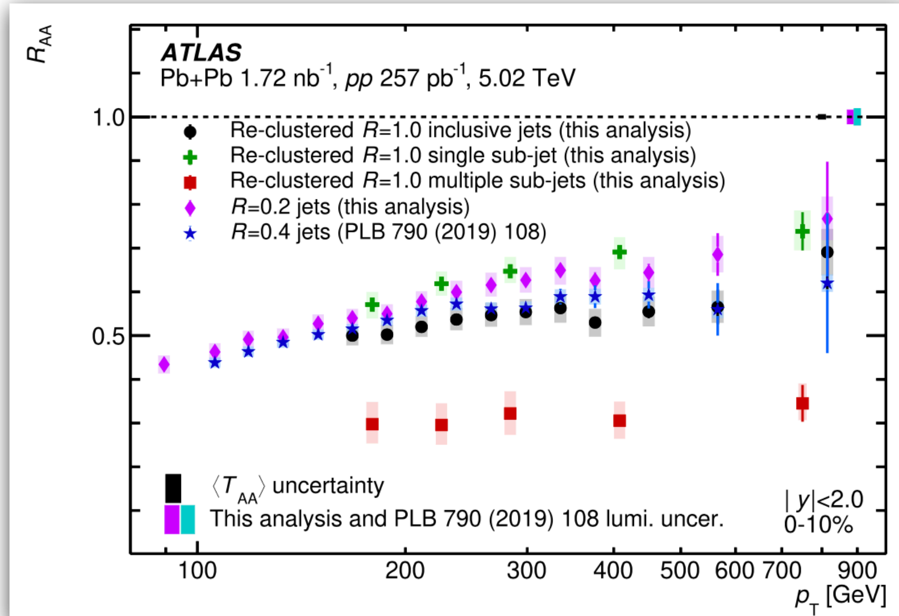


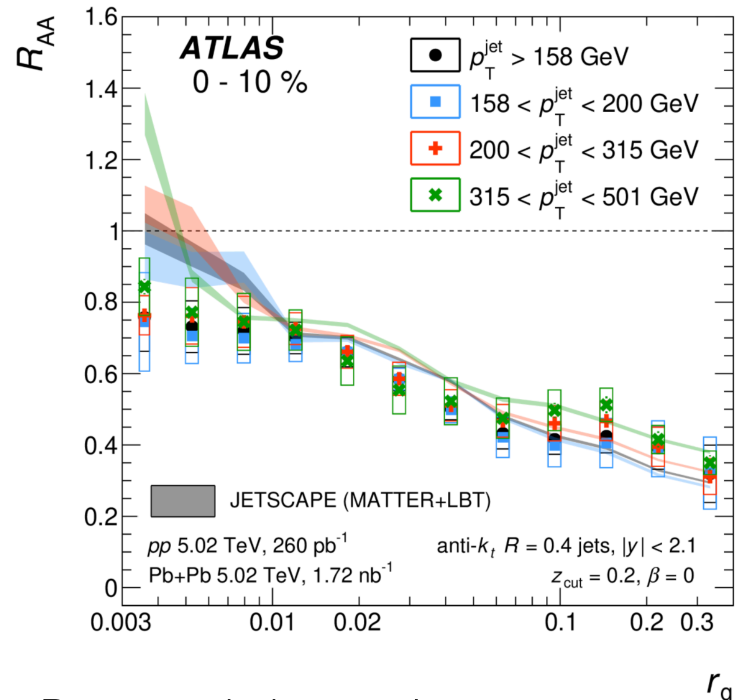
Summary

- Heavy Ion Physics is not only QCD at low energies, but reaches out to searches for new physics
  - LHC as photon collider!
- Rich physics programme of HI collisions at the LHC also with the ATLAS and CMS detectors
- New and exciting results every year
  - Strong interest within the community to continue Heavy Ion runs also during the High Luminosity Phase of the LHC

ATLAS: Measurement of suppression of large-radius jets and its dependence on substructure

ATLAS: CERN-EP-2022-250, CMS: CERN-EP-2020-226





- Substructure to study jet quenching: distinguishing sub-jets resulting from hard splittings in the parton shower from soft medium-induced radiation, soft particles resulting from jet-induced medium excitations
- Presented observations are qualitatively consistent with the hypothesis that jets with hard internal splittings lose more energy, and provide a new perspective for understanding the role of jet structure in jet suppression in the QGP.

CMS: Charge balance function in pPb and PbPb collisions (1/2)

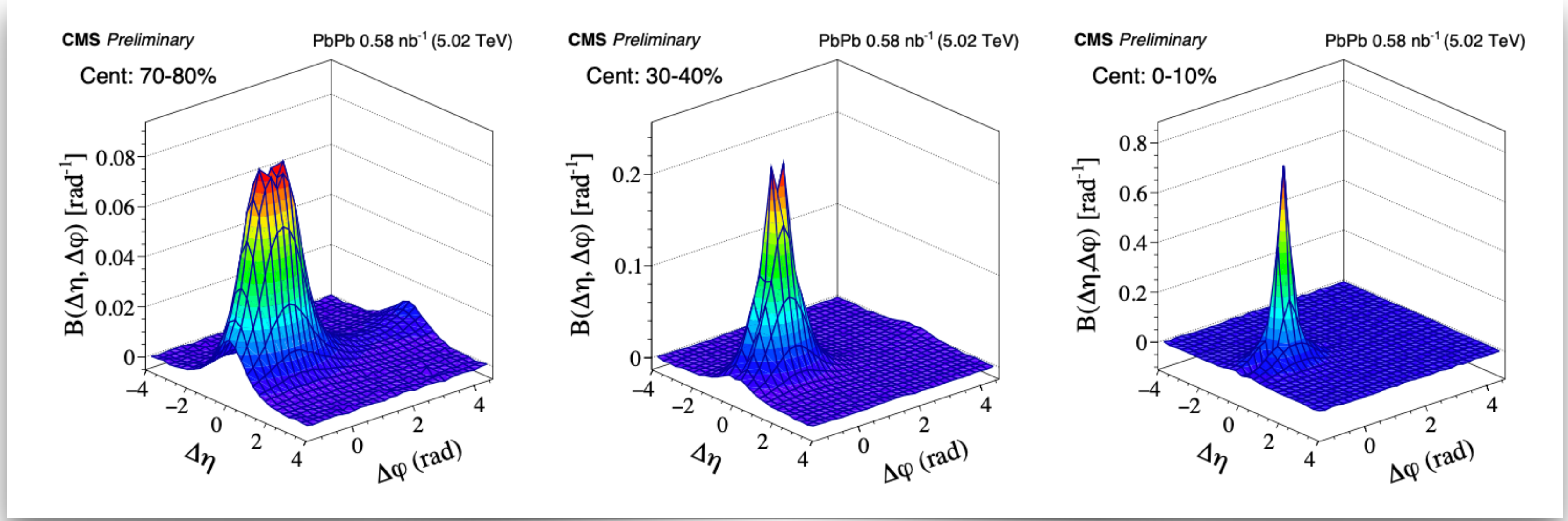
CMS PAS HIN-21-017

- Reminder on particle correlations

$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{same}}}{d\Delta\eta\Delta\varphi} \qquad M(\Delta\eta,\Delta\varphi) = \frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{mix}}}{d\Delta\eta\Delta\varphi} \qquad C_2(\Delta\eta,\Delta\varphi) = M(0,0)\frac{S(\Delta\eta,\Delta\varphi)}{M(\Delta\eta,\Delta\varphi)}$$

- Definition of balance function

$$B(\Delta\eta,\Delta\varphi) = \frac{1}{2}[C_2(+,-) + C_2(-,+) - C_2(+,+) - C_2(-,-)]$$



- A narrower balance func. distribution is observed as final state particles are produced at the later stages of the collisions and are separated longitudinally smaller in Δη.

CMS: Charge balance function in pPb and PbPb collisions (2/2)

- The balance function width distribution quantifies how tightly the balancing partners are correlated.
- Model comparisons cannot reproduce the multiplicity dependence of the width in $\Delta\eta$
- AMPT, which incorporates collective effects, can reproduce the narrowing of the width