Heavy ion physics at ATLAS and CMS

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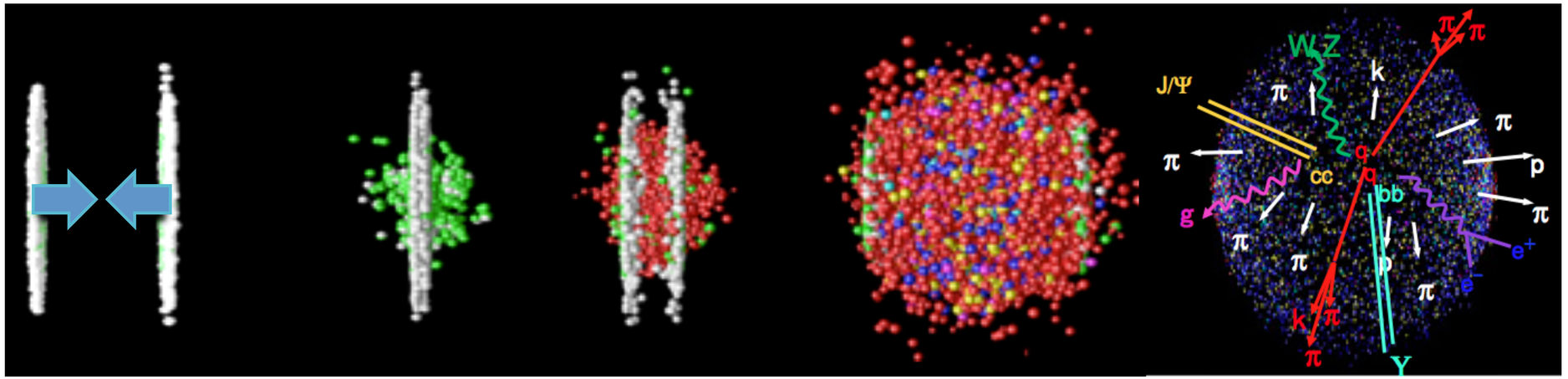
(on behalf of **ATLAS** and **CMS** collaborations)

Les Rencontres de Physique de la Vallée d'Aoste
6-12 Mar 2022

Introduction



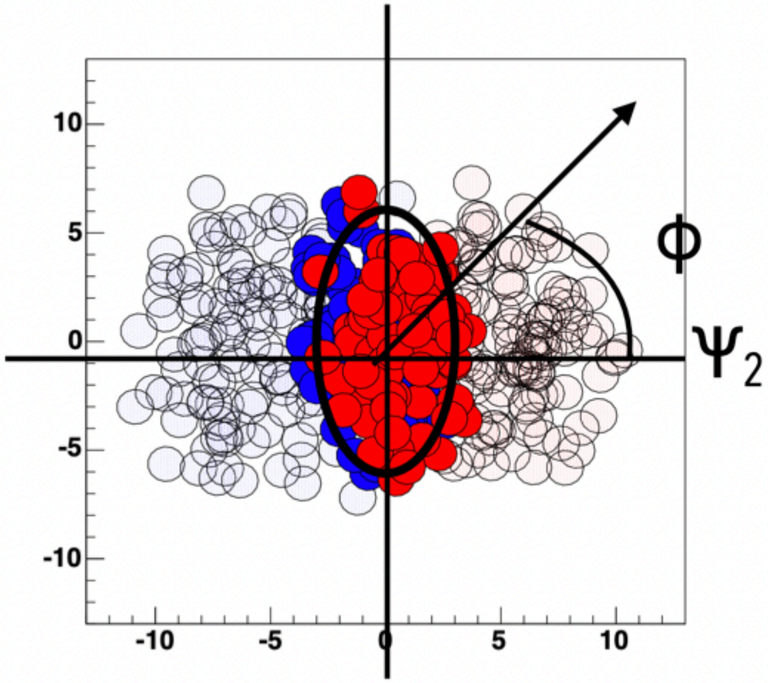
- Use variety of final states to provide insight into different stages of HI collisions
- **Soft** probes (bulk particle production)
- **Hard** probes
  - Colour objects e.g. jets → partonic energy loss in QGP
  - Colourless objects e.g. EW bosons → ‘standard candles’, nPDFs
  - Also: quarkonia & HF particles

In addition:
pp and p+Pb collisions
→ reference to Pb+Pb and
to understand initial-state effects

ATLAS & CMS detectors designed to measure high-pT objects with good precision

Heavy ion collision geometry

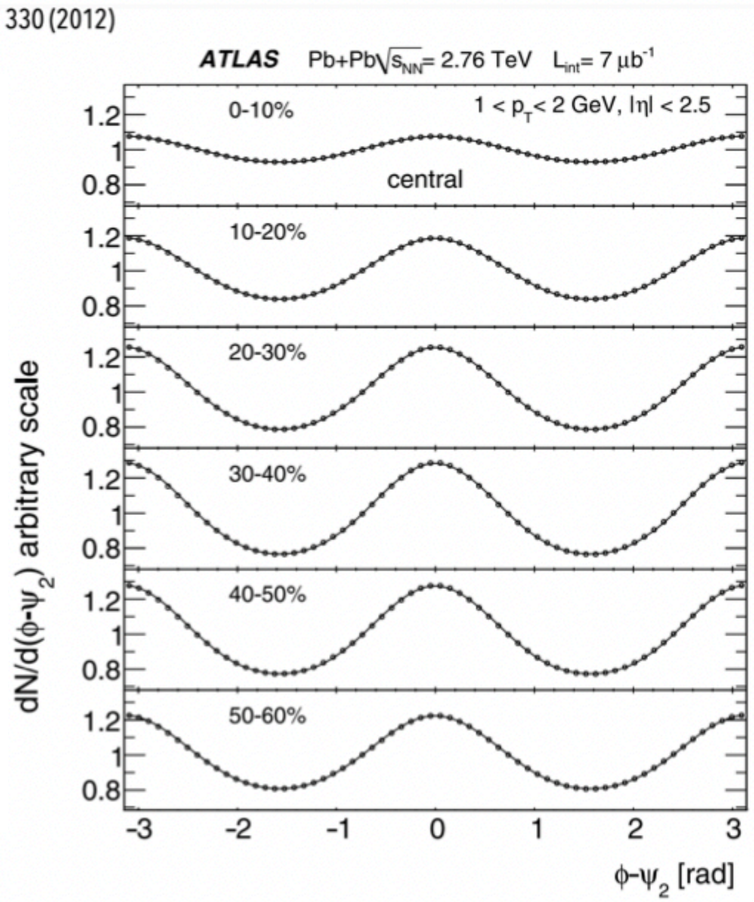
Interaction plane of nuclei

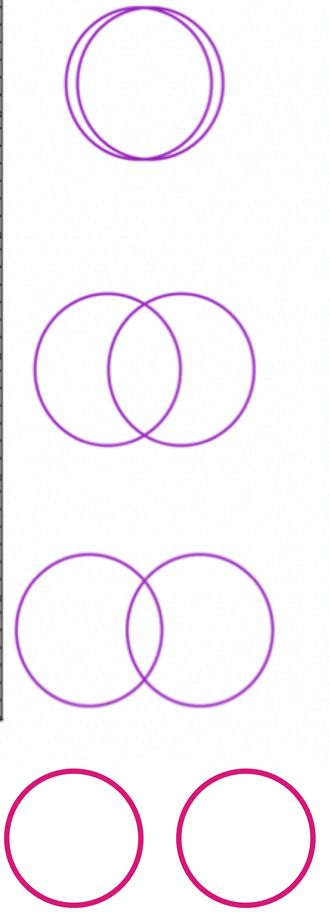


Leads to non-zero flow coefficients:

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

Distribution of particles





Central

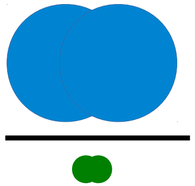
Peripheral

Ultra Peripheral Collisions (UPC)

Nuclear modification factor

- Comparing HI and pp collisions where the geometrical scaling is removed

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



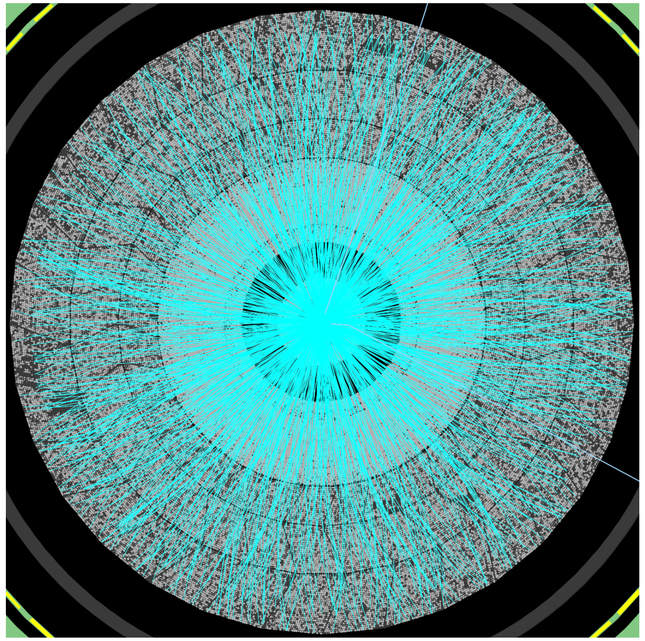
QCD in medium

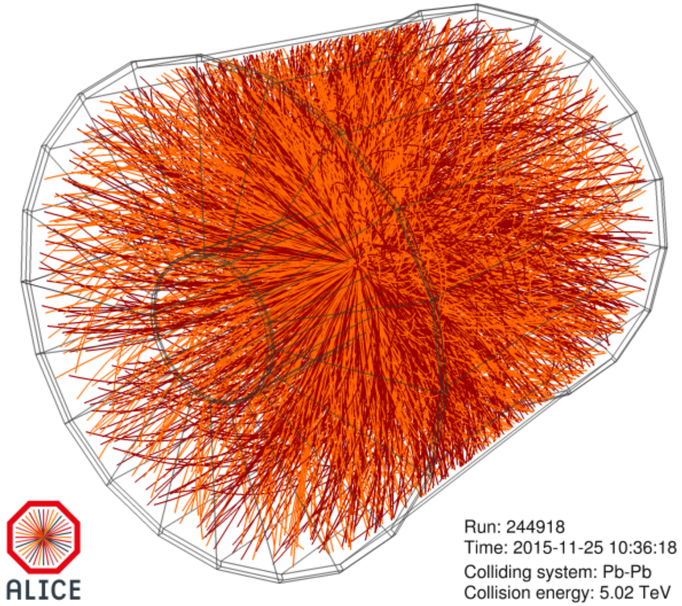
QCD in vacuum

Yields in A+A

pp reference

(I) Heavy hadron production

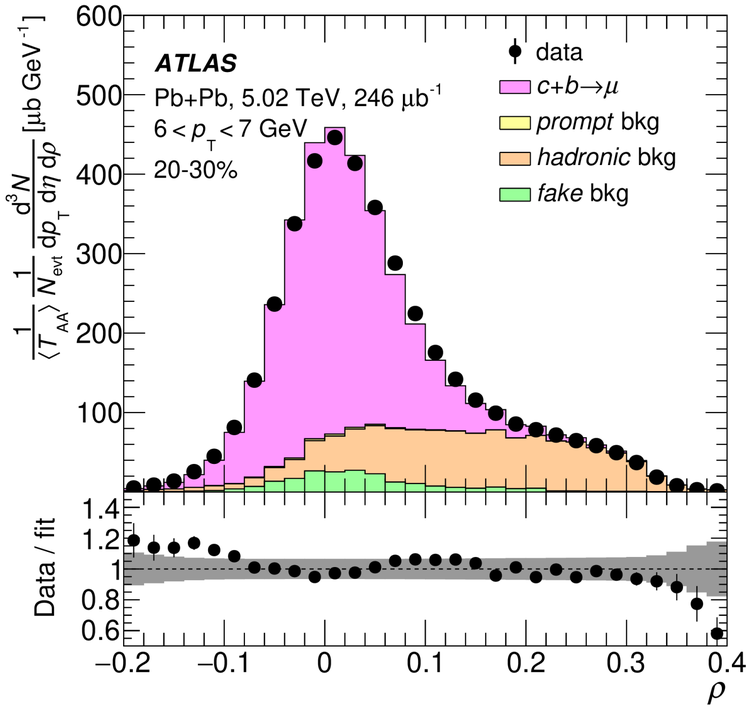


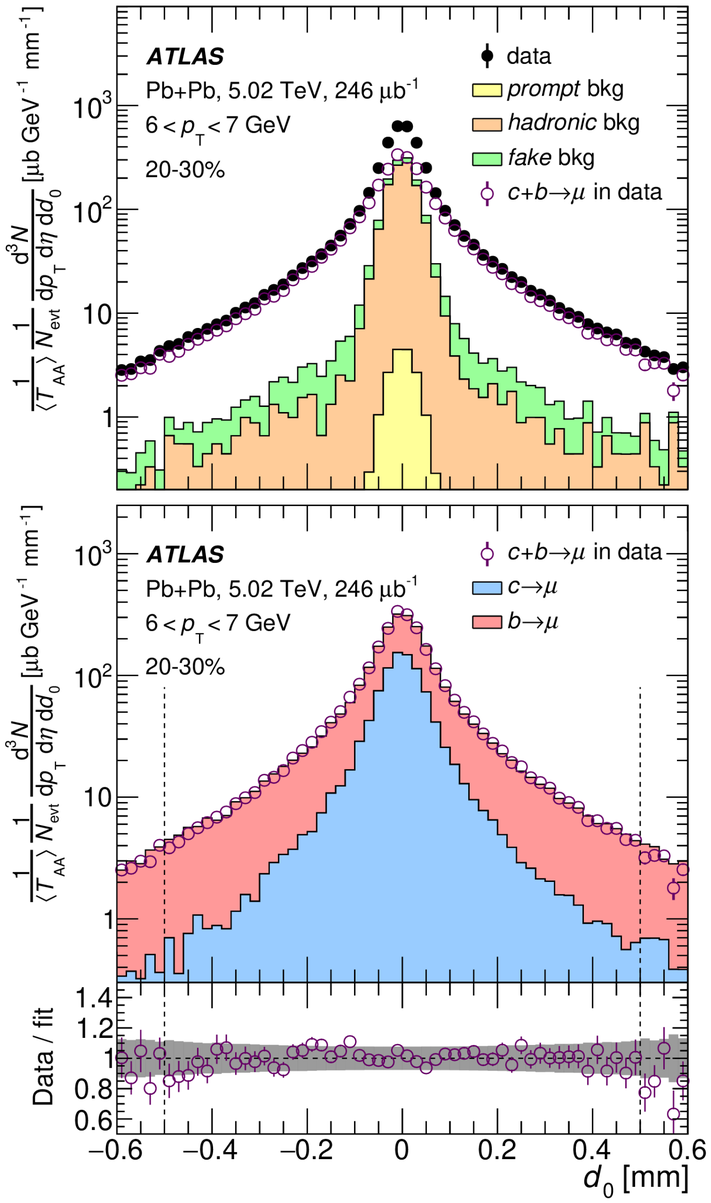


R_{AA} for muons from charm and bottom hadrons

ATLAS, arXiv:2109.00411 [nucl-ex]

- Muons from HF decays are separated from LF background using momentum imbalance between the inner detector and muon spectrometer
- Muons from c- and b-decays are further separated via the muon track's transverse impact parameter

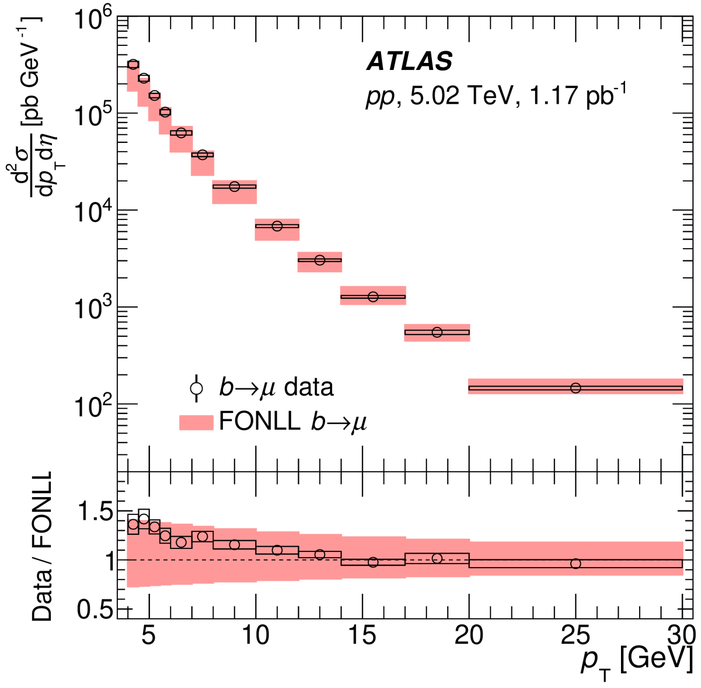


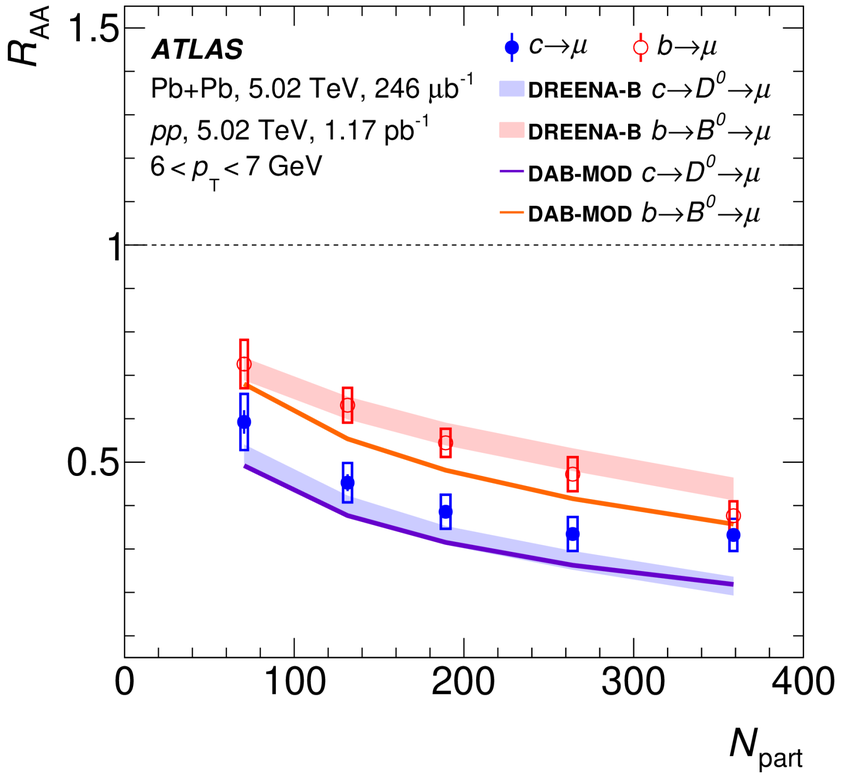


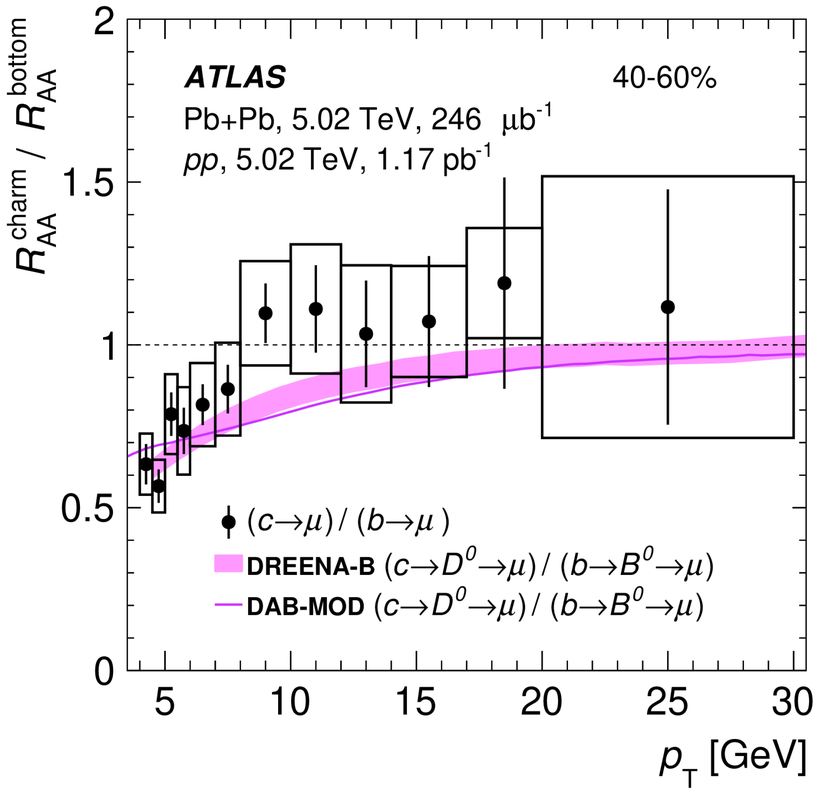
R_{AA} for muons from charm and bottom hadrons

ATLAS, arXiv:2109.00411 [nucl-ex]

- Differential cross section in pp collisions is reproduced with FONLL calculations
- R_{AA}: significant suppression is observed, stronger for c-hadron decays
  - Measurements reproduced by theory (calculations include radiative and collisional energy loss mechanisms)





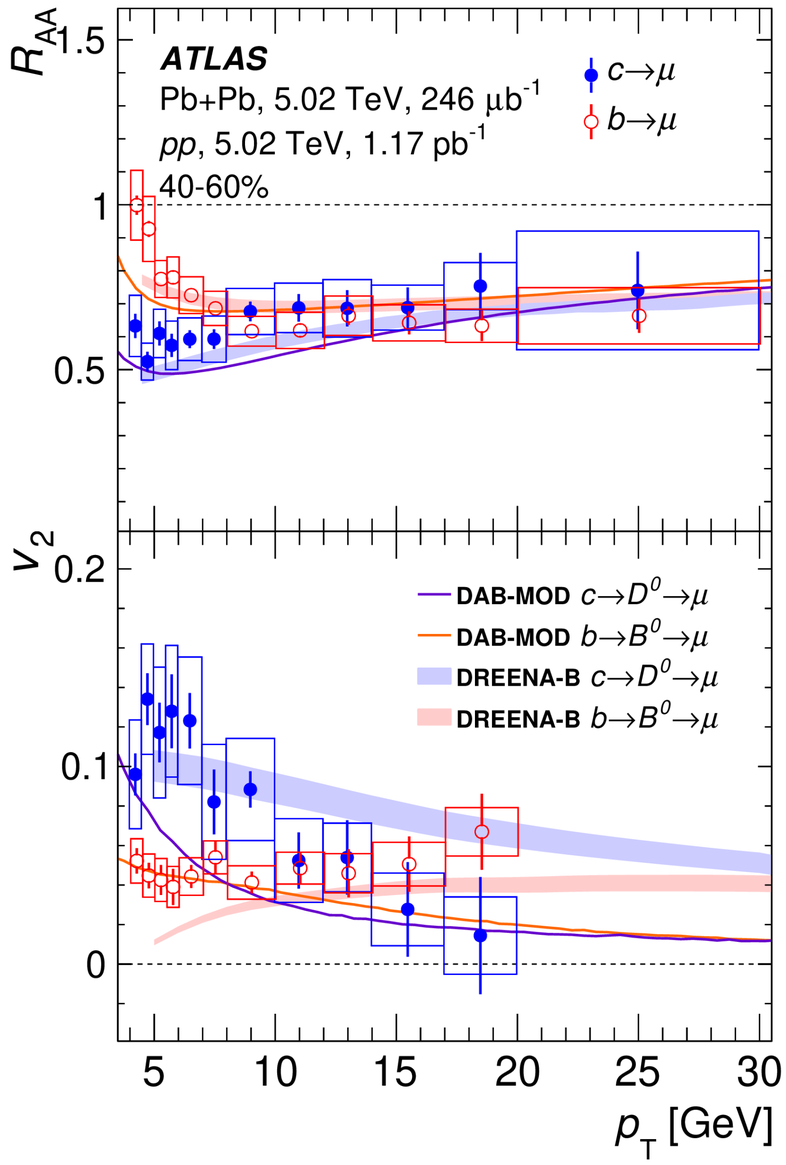


R_{AA} for muons from charm and bottom hadrons

- Simultaneous constraints imposed by R_{AA} (this measurement) and flow measurements previously published by ATLAS [Phys. Lett. B 807 (2020) 135595]
  - Provide important information for understanding heavy-quark transport and QGP properties

- Calculations (Dreena-B model) agree qualitatively with both v_2 and R_{AA}

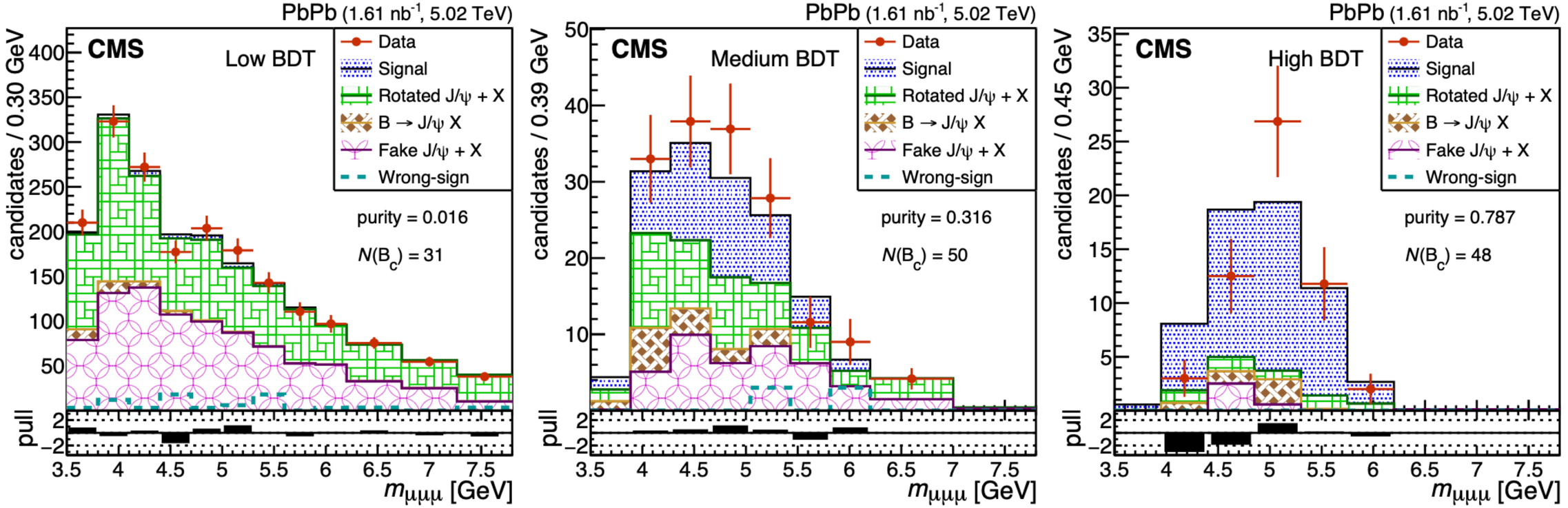
ATLAS, arXiv:2109.00411 [nucl-ex]



Observation of B_c+ meson in Pb+Pb

CMS, arXiv:2201.02659 [hep-ex]

- The signal is reconstructed from the three muons in the $B_c+ \rightarrow (J/\psi \rightarrow \mu+\mu-)\mu+\nu_\mu$ decay mode
- BDT is used to enhance the sensitivity
- Clear signal (well above 5 standard deviations) is observed



Observation of B_c+ meson in Pb+Pb

CMS, arXiv:2201.02659 [hep-ex]

- The process is also measured in pp collisions, in order to extract R_{AA}
- No hints of significant suppression → may indicate heavy-quark recombination is a significant B_c+ production mechanism in the QGP

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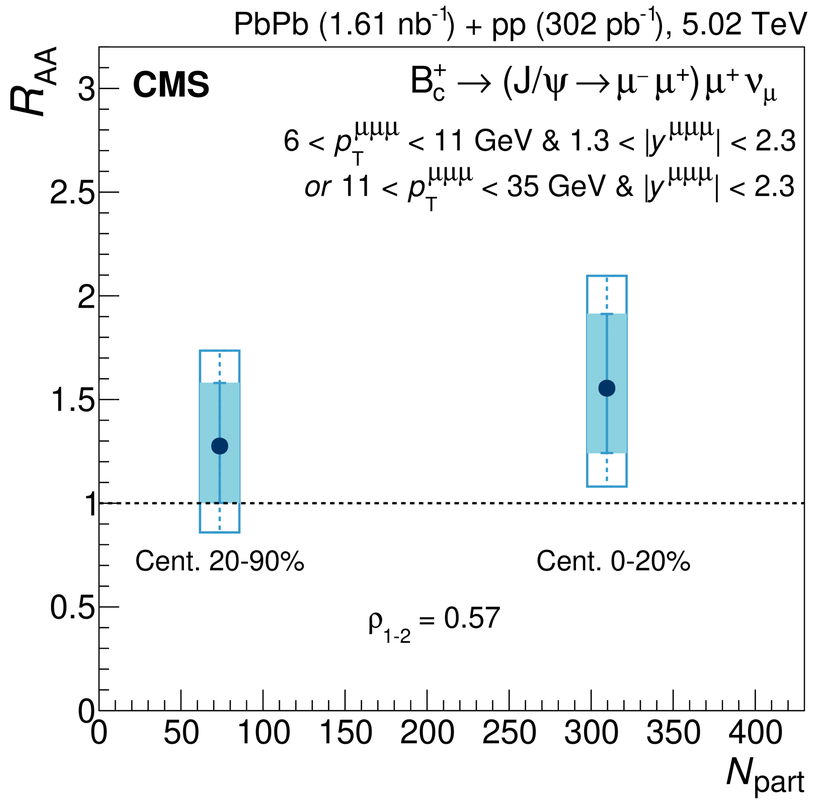
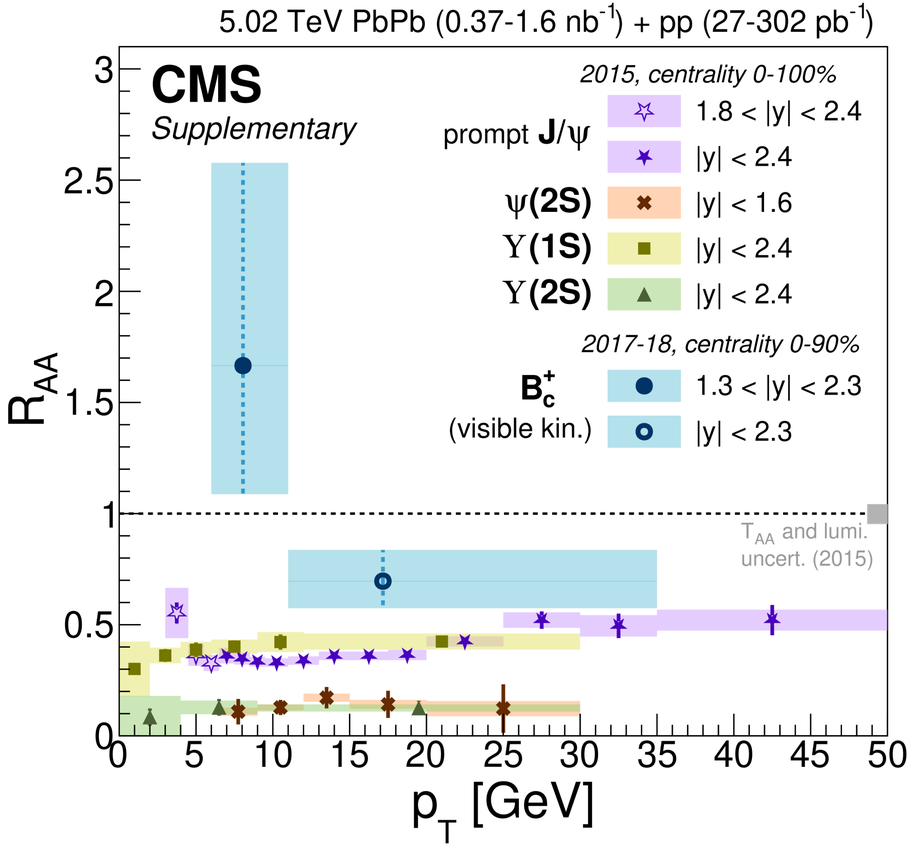
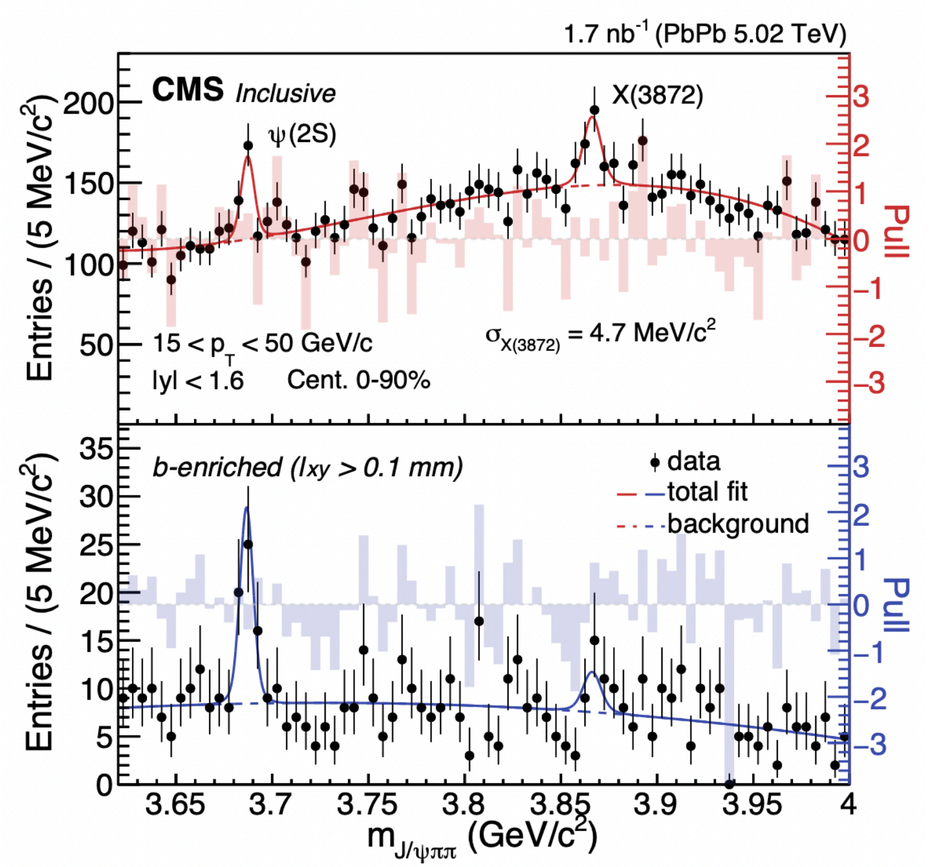


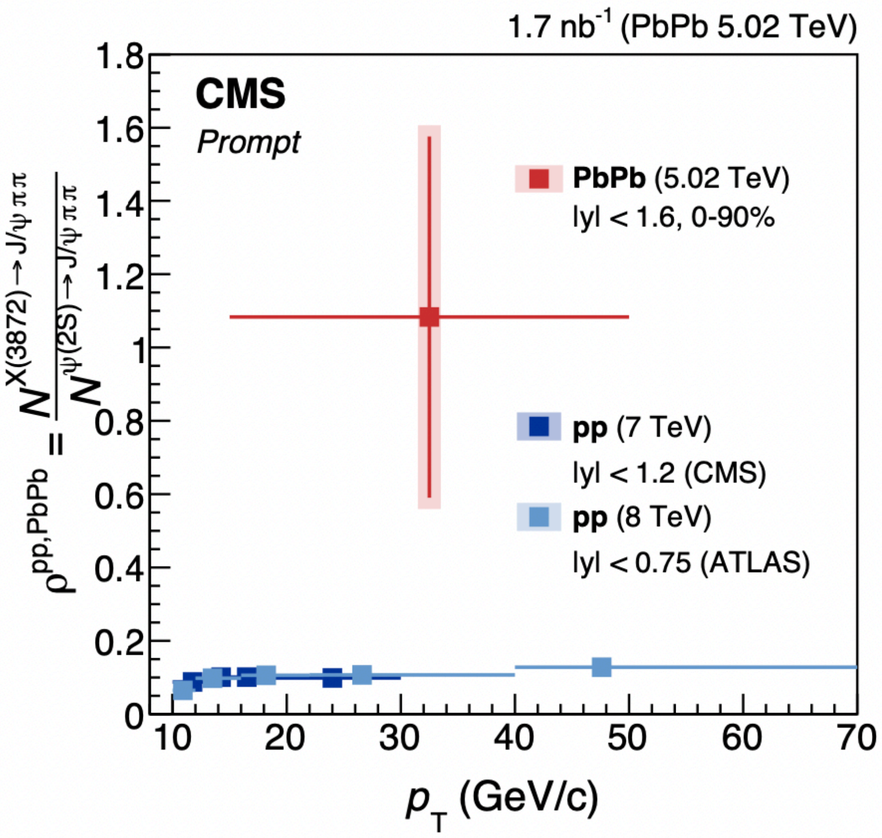


Evidence for X(3872) in Pb+Pb collisions

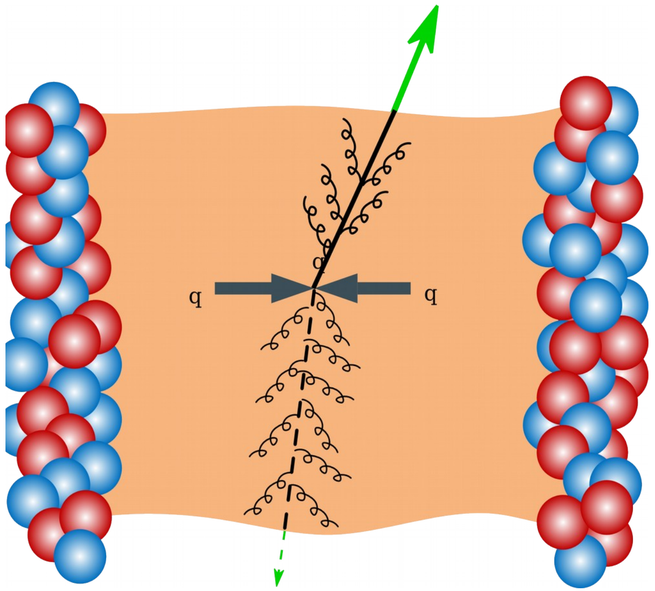
CMS, Phys. Rev. Lett. 128 (2022) 032001

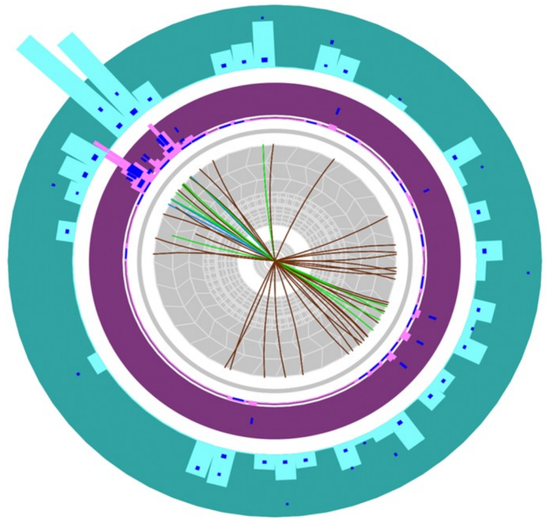
- X(3872) → J/ψπ+π−→ μ+μ−π+π- decay chain is studied
- The significance of the signal is 4.2 standard deviations
- The prompt X(3872) to ψ(2S) yield ratio is measured





(II) Jet-medium interactions

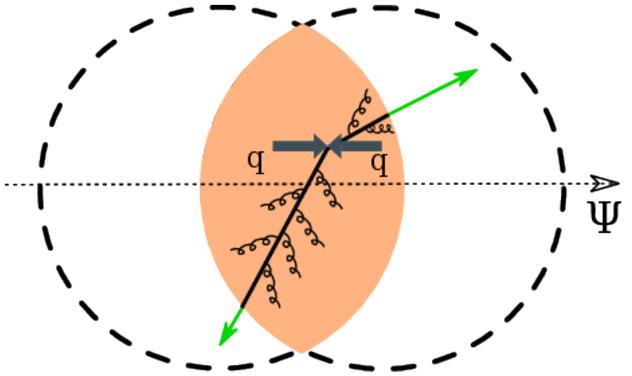


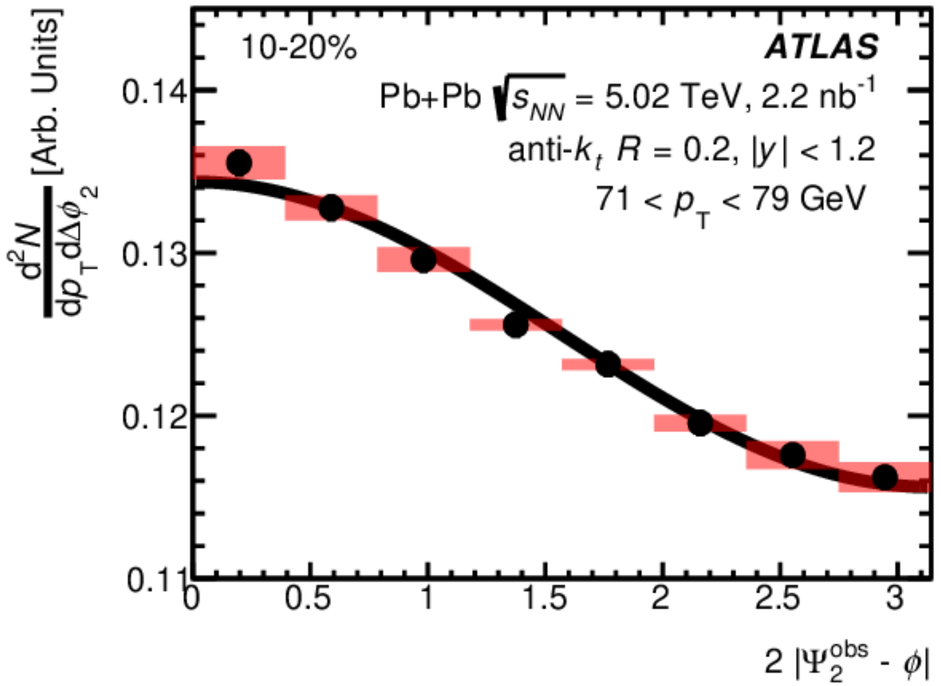


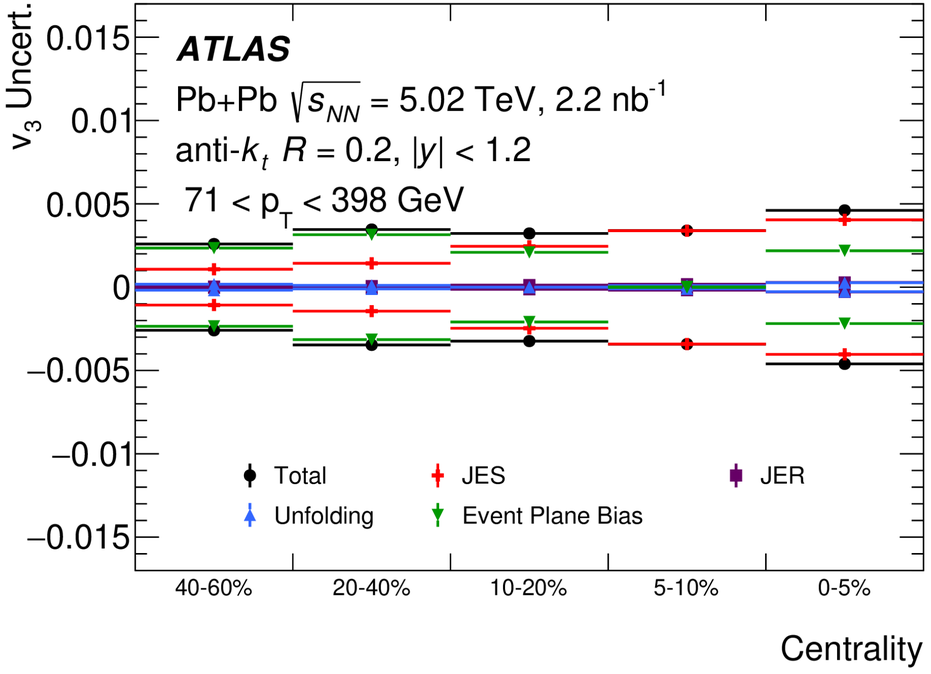
Jet Azimuthal Anisotropies in Pb+Pb

ATLAS, arXiv:2111.06606

- Comprehensive measurement of jet v_n (v_2, v_3, v_4)
- Anti-kT R=0.2 jets with |y|<1.2 are studied
- v_n values are extracted using fits to $\frac{dN_{\text{jet}}(p_T, \Delta\phi_n)}{d\Delta\phi_n} \propto 1 + 2v_n^{\text{obs}} \cos(n\Delta\phi_n)$
- Systematic uncertainties dominated by jet energy scale and event plane estimation



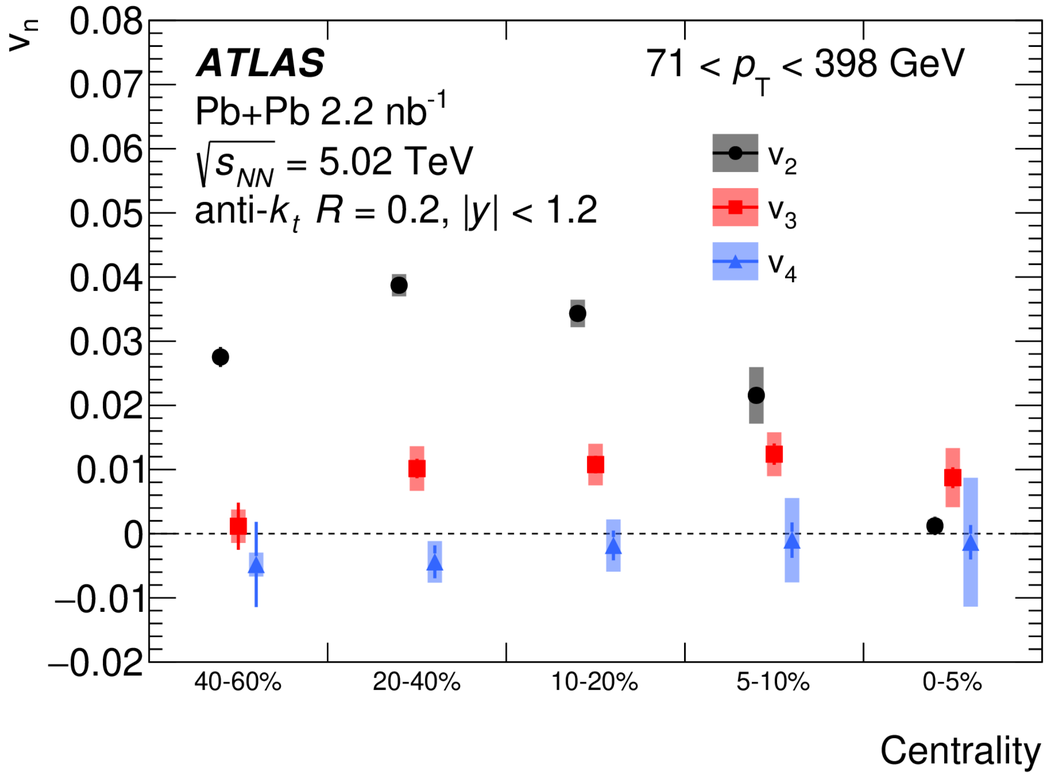


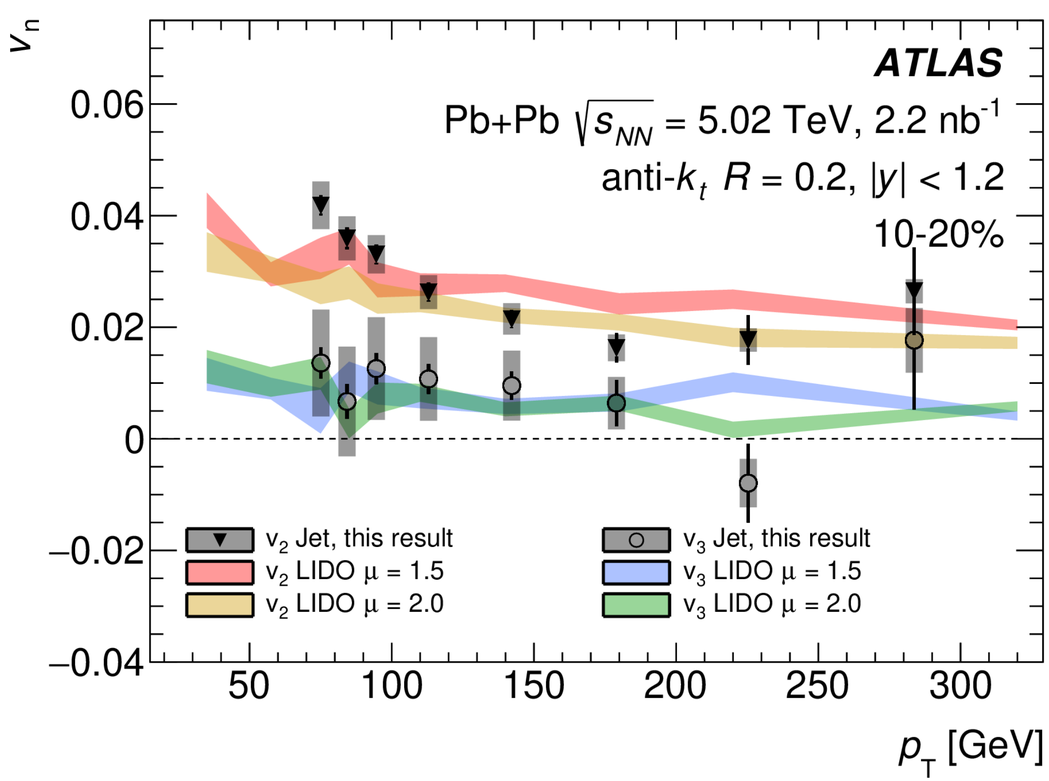


Jet Azimuthal Anisotropies in Pb+Pb

ATLAS, arXiv:2111.06606

- Nonzero values of v_2 (values up to 0.05) and **v_3 (approx. 0.01)** are measured
- No significant deviation of v_4 from zero is observed
- Theoretical calculations (transport models) in reasonable agreement with data

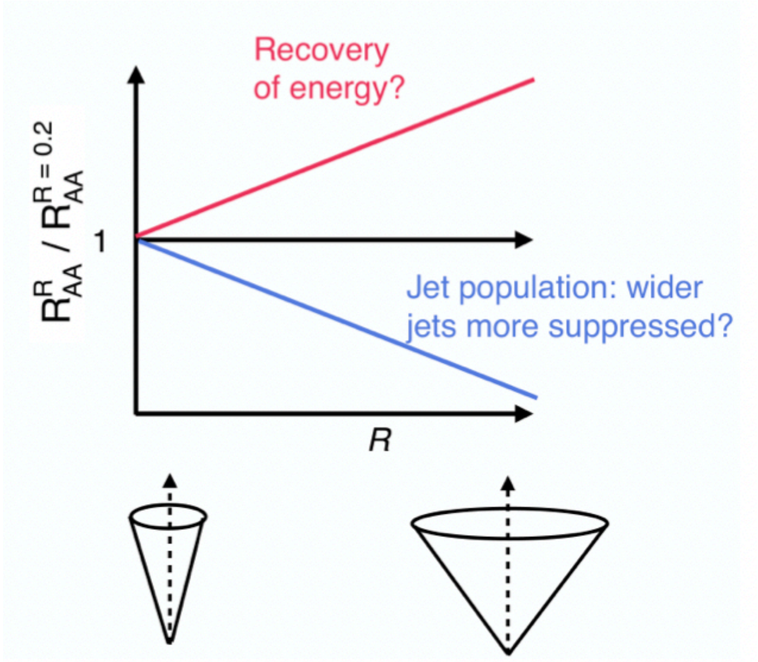


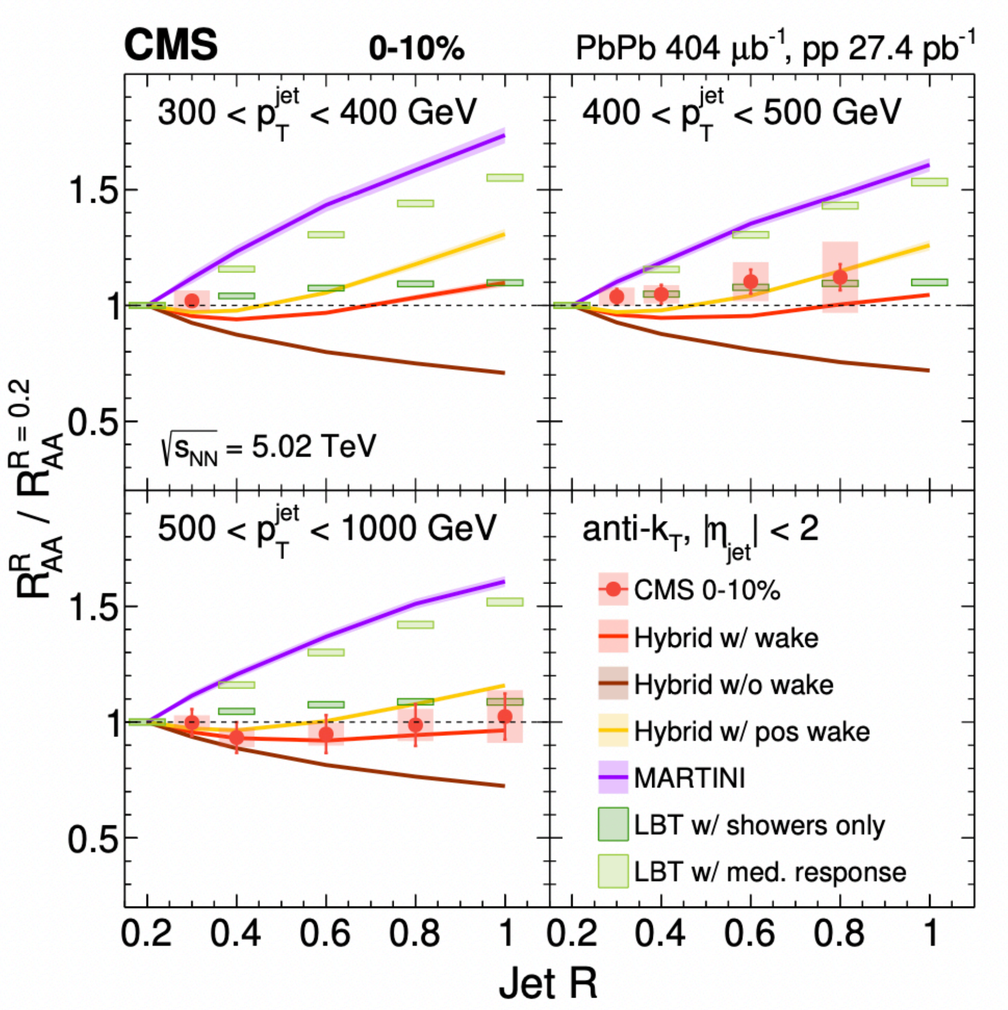


Large-radius jets in Pb+Pb

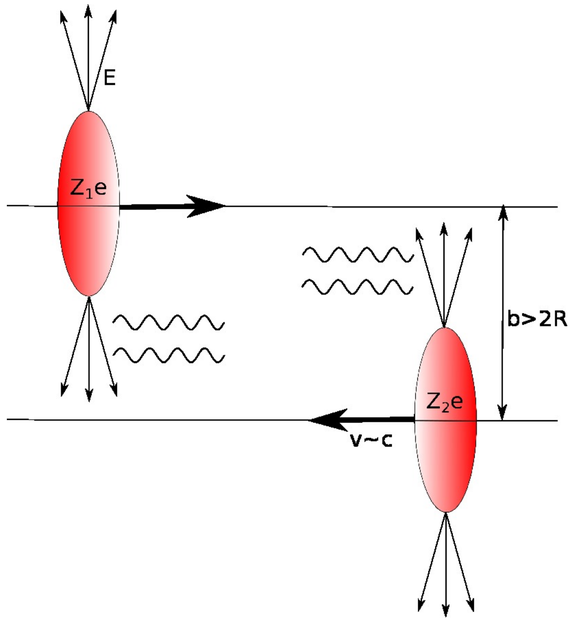
CMS, JHEP 2105 (2021) 284

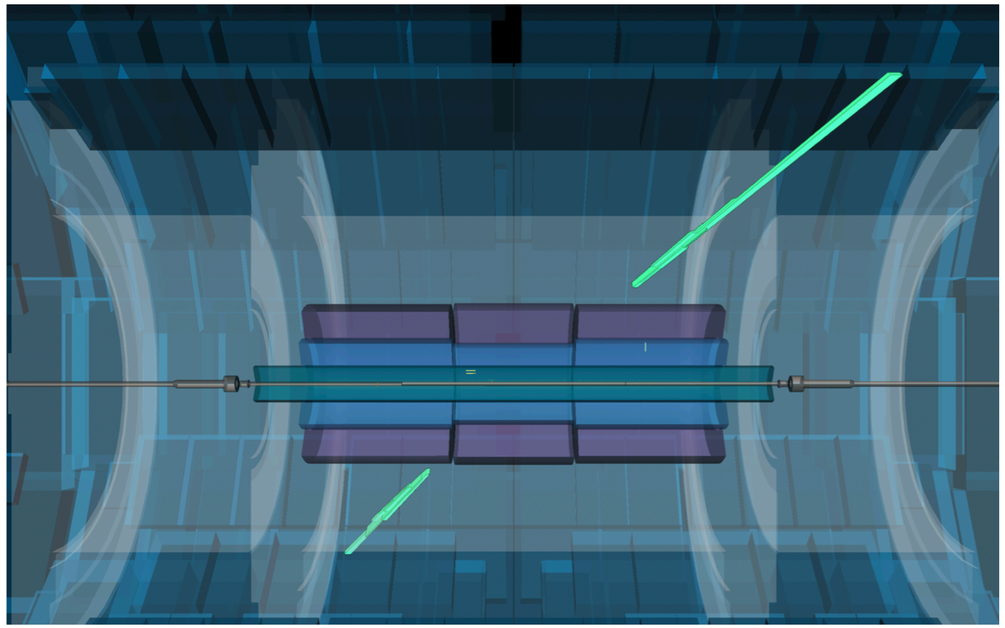
- Inclusive jet suppression: changing R=0.2 to 1.0
  - Possible recovery of the jet energy from of out-of-cone radiation
  - Possible difference in modification for larger vs smaller jets





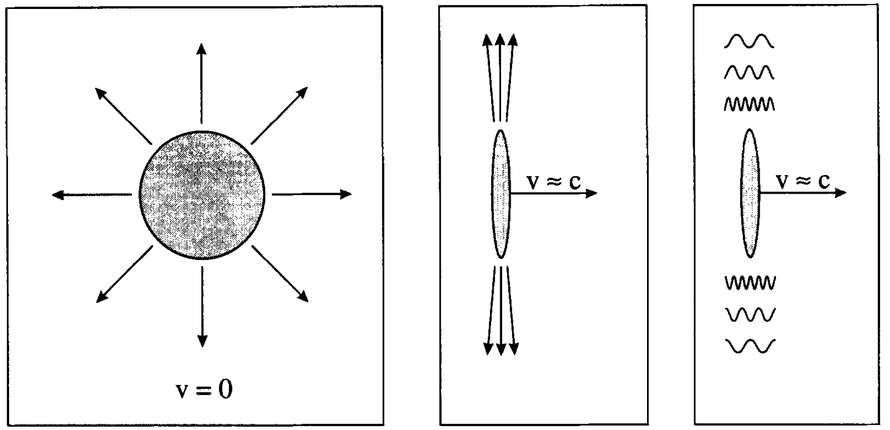
(III) Photon-induced interactions

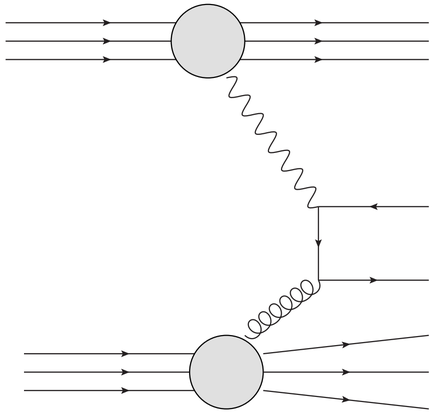




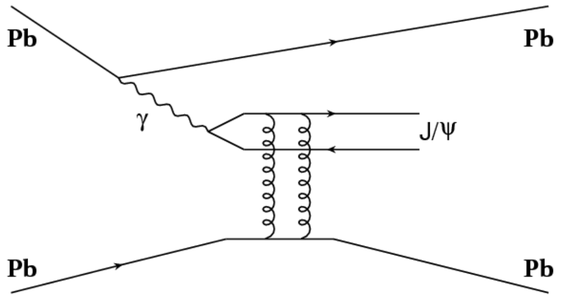
Quasi-real photons from Pb ions

- Boosted nuclei are intense source of quasi-real photons
- **Coherent** photon flux
  - **Q ~ 1/R ~ 0.06 GeV** for Pb @ LHC
  - **$E_{max} \lesssim \gamma/R \sim 80$ GeV** @5.02 TeV
  - Each photon flux scales with **~Z^2**
- Various types of interactions possible:

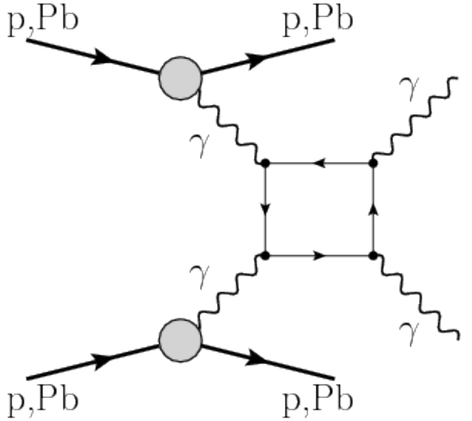




(incoherent) **Photo-nuclear**



(coherent) **Photo-nuclear**

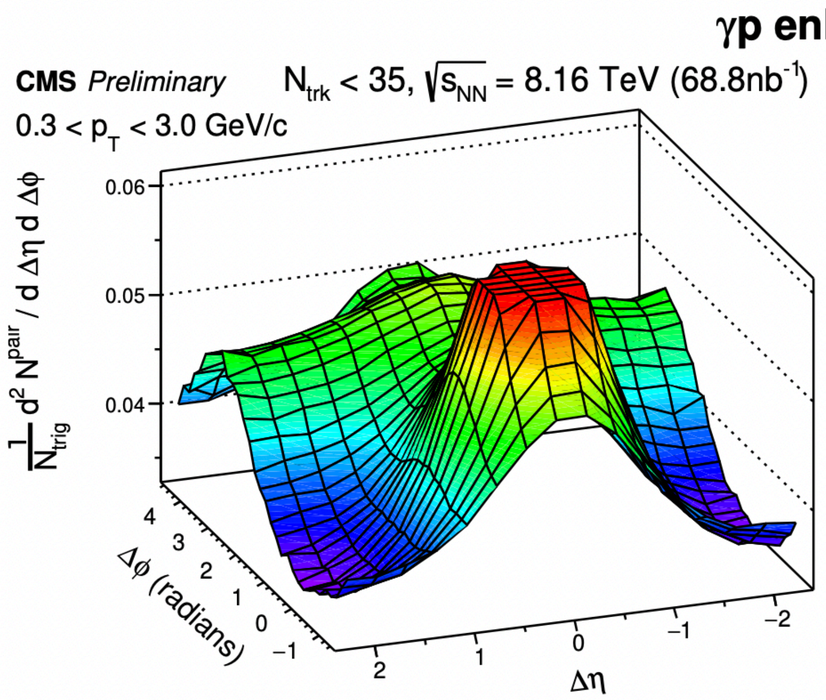


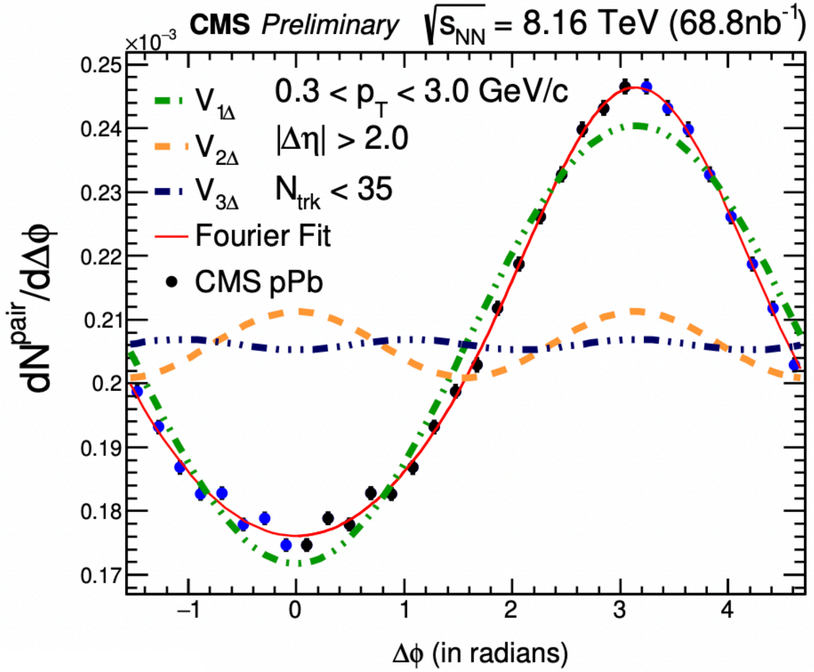
Photon-photon

Search for azimuthal anisotropies in γp interactions

CMS-PAS-HIN-18-008

- p+Pb data @8.16 TeV is used (69/nb)
- Two-particle (h+) angular correlations in γp events selected with large rapidity gaps and no n-emission from Pb, compared with minimum bias events with similar multiplicity



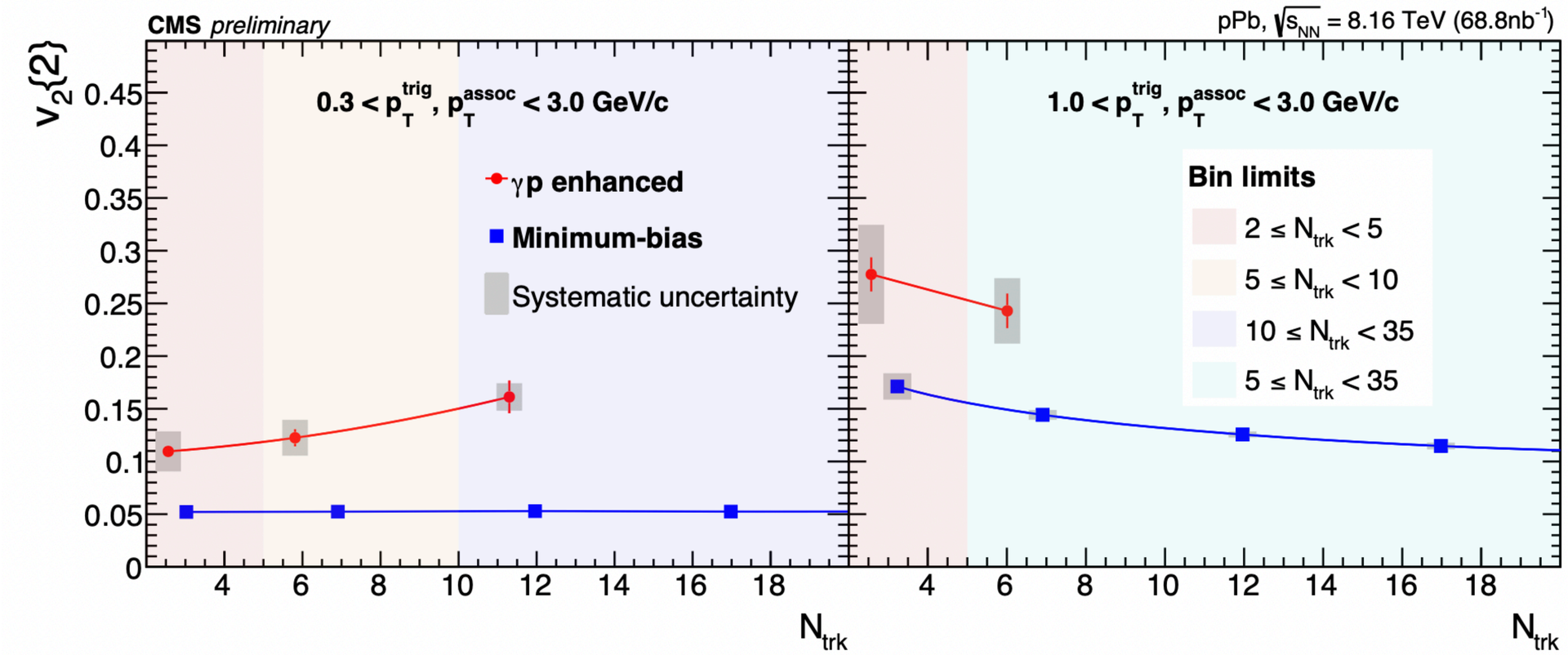


$$\frac{1}{N_{\text{trig}}}\frac{\mathrm{d}^2N^{\text{pair}}}{\mathrm{d}\Delta\eta\mathrm{d}\Delta\phi} = B(0,0)\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

Search for azimuthal anisotropies in γp interactions

CMS-PAS-HIN-18-008

- $v_2(p_T)$ increases with p_T
- larger for γp-enhanced events than for MB events at the same multiplicity
  - Likely due to the effect of jet correlations within the γp enhanced sample (note that no low-multiplicity subtraction technique is implemented due to very low-N_{trk})



Azimuthal anisotropies in γPb

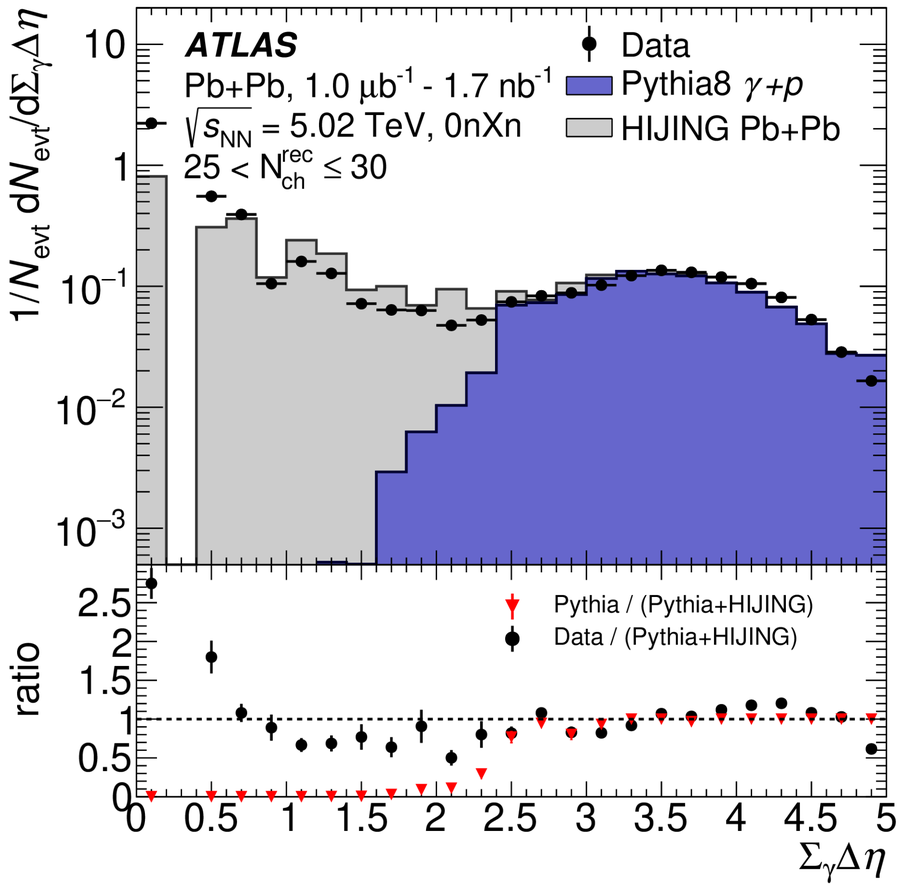
ATLAS, Phys. Rev. C. 104 (2021) 014903

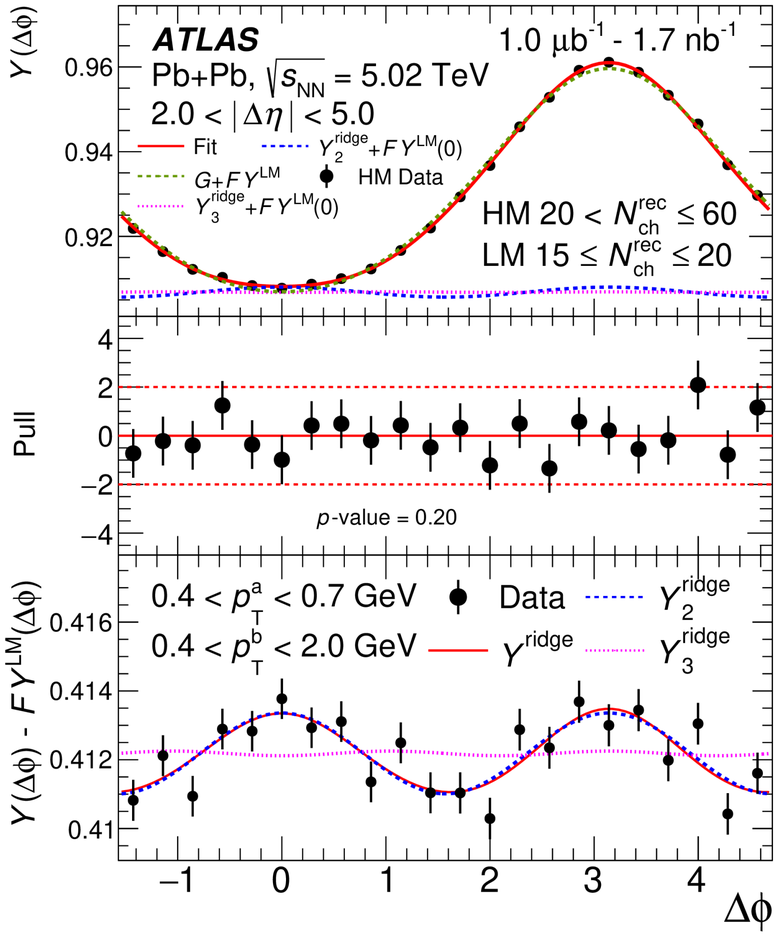
- Measurement done using photonuclear Pb+Pb UPC events

correlation function in LM events

$$Y^{\mathrm{HM}}(\Delta\phi) = FY^{\mathrm{LM}}(\Delta\phi) + G\left\{1 + 2\sum_{n=2}^{4} v_{n,n}\cos(n\Delta\phi)\right\}$$
$$= FY^{\mathrm{LM}}(\Delta\phi) + Y^{\mathrm{ridge}}(\Delta\phi). \quad (1)$$

flow coefficients

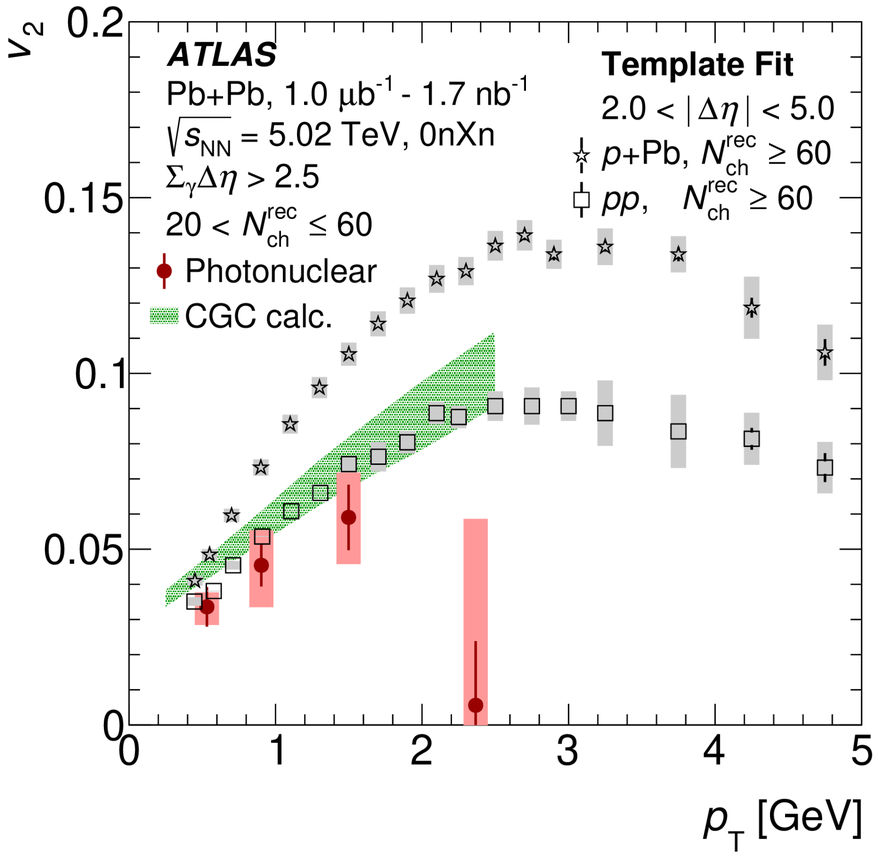


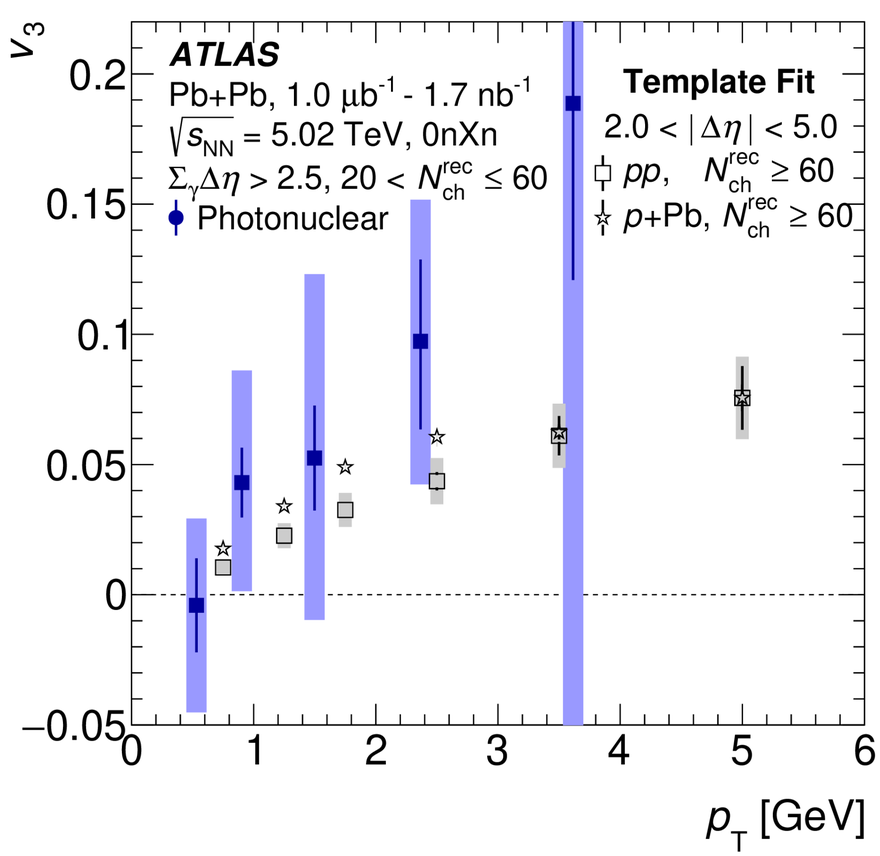


Azimuthal anisotropies in γPb

ATLAS, Phys. Rev. C. 104 (2021) 014903

- Non-zero v_2 is observed; some hints of non-zero v_3
- The v_2 values are smaller than those reported in pp and p+Pb collisions at similar particle multiplicities



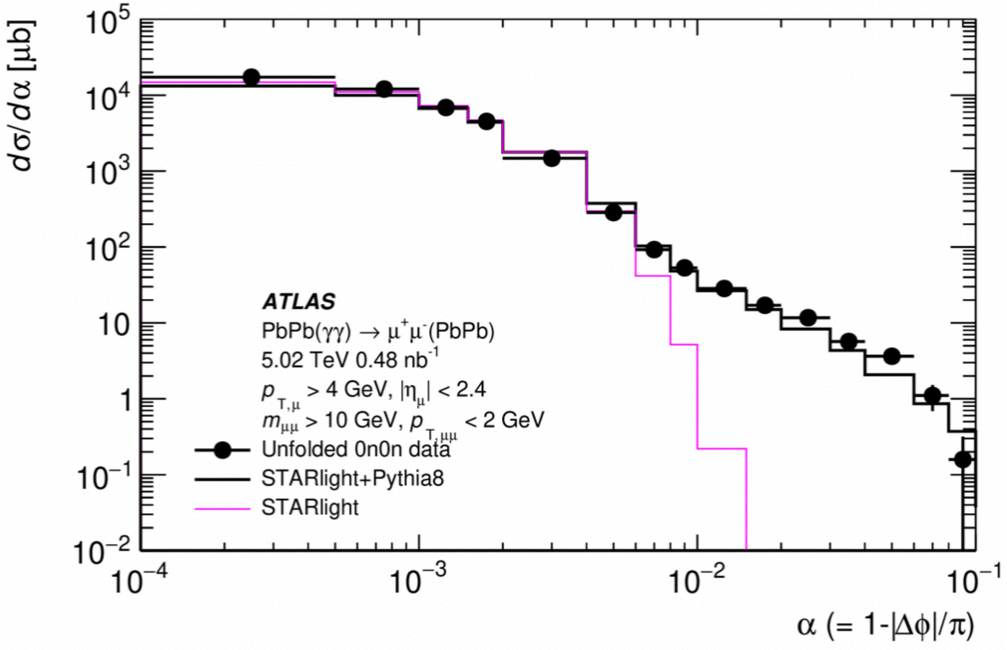


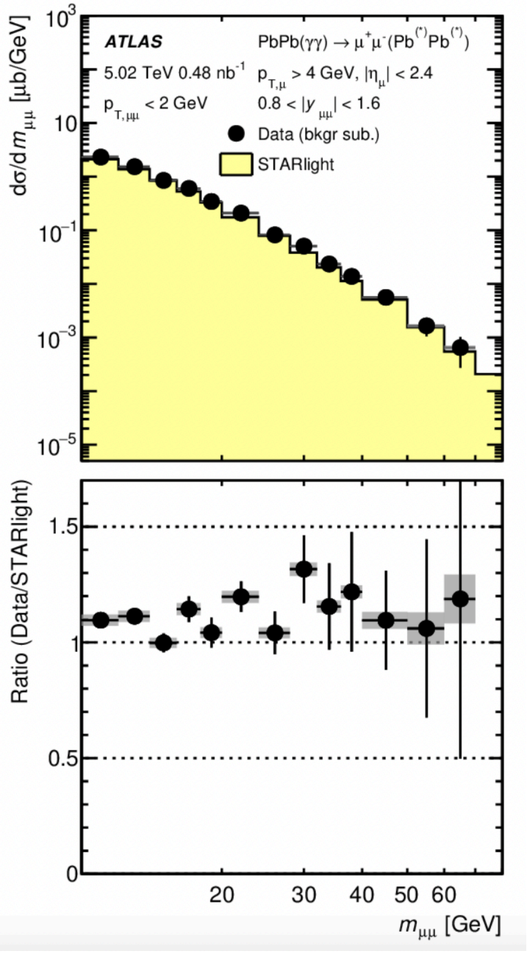
γγ→μμ production in Pb+Pb

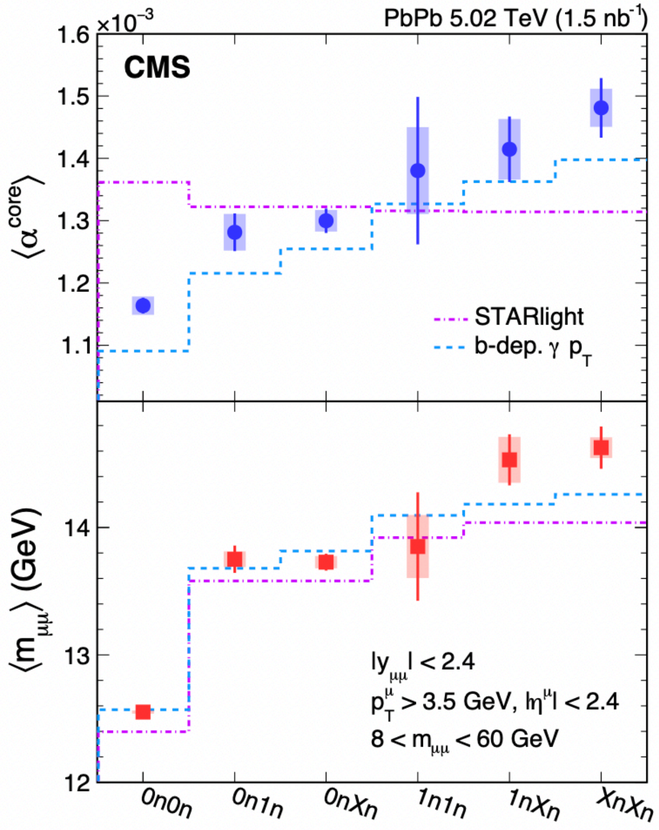
ATLAS, Phys. Rev. C 104 (2021) 024906

CMS, PRL 127, 122001 (2021)

- Abundant rate → precision test of QED and initial photon fluxes
- Comprehensive measurement of cross sections in m, y, cos(theta), acoplanarity
  - Fractions of events with singe and mutual EM dissociation → indirect probe of Pb+Pb impact parameter







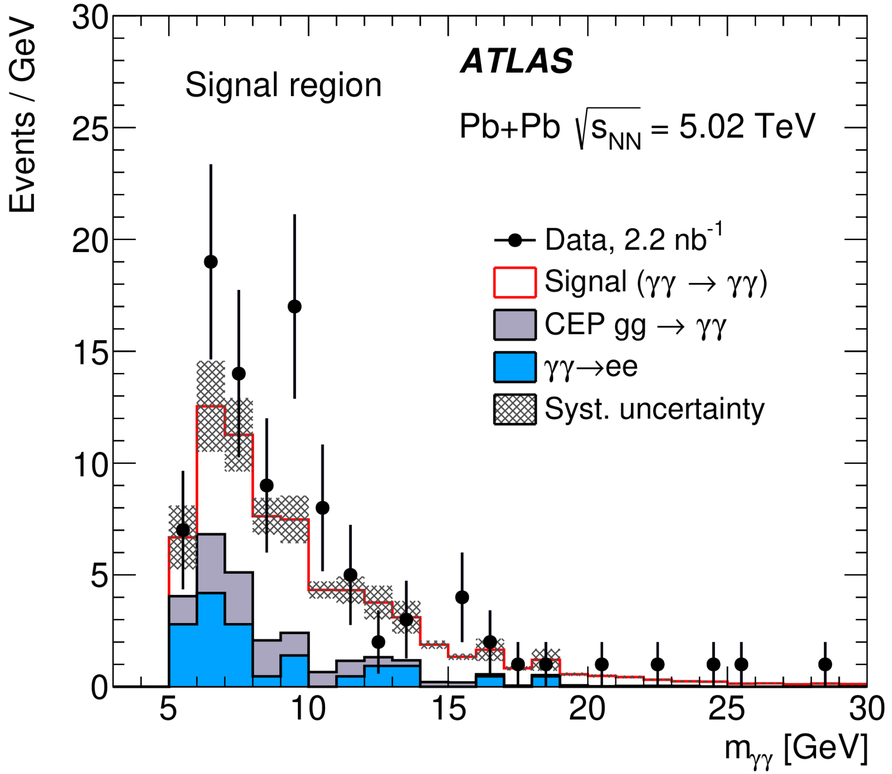
Search for axion-like particles in γγ interactions

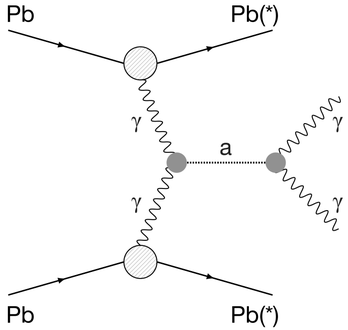
- Light-by-light scattering process signature (γγ→γγ) used to search for ALPs in Pb+Pb collisions
- ATLAS and CMS provide the most stringent limits to date on ALPs for masses in the range 5-100 GeV

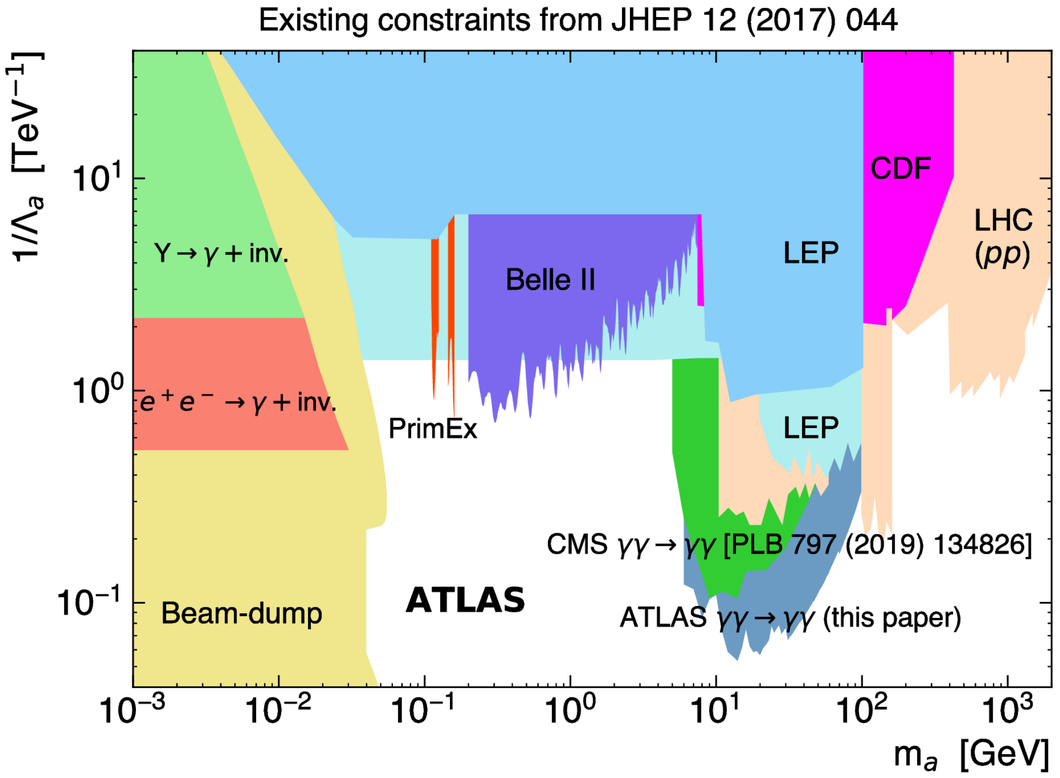
Original idea:
Knapen et al., PRL 118 (2017) 17, 171801

CMS: Phys. Lett. B 797 (2019) 134826

ATLAS: JHEP 03 (2021) 243







Summary

- Rich physics programme of HI collisions at the LHC
- Heavy hadron production
  - Experiments start to explore the production of “rare” hadrons (e.g. X(3872), B_c+)
- Production of jets
  - Precision measurements allow to test theory calculations in more detail
- Ultra Peripheral Collisions (UPC) allow to probe photon-induced interactions
  - Unique environment to test the collective phenomena in small systems
  - New testing ground for QED processes
  - Clean way to search for BSM particles that couple to photons
- Stay tuned for new results!

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Backup

Centrality estimation

- A+A collisions can be characterized by the centrality, quantified using e.g. the energy in forward calorimeters

0-10% corresponds to the most central collisions