Status and prospects of heavy-ion physics at the LHC

Evgeny Shulga on behalf of ATLAS and CMS Collaborations

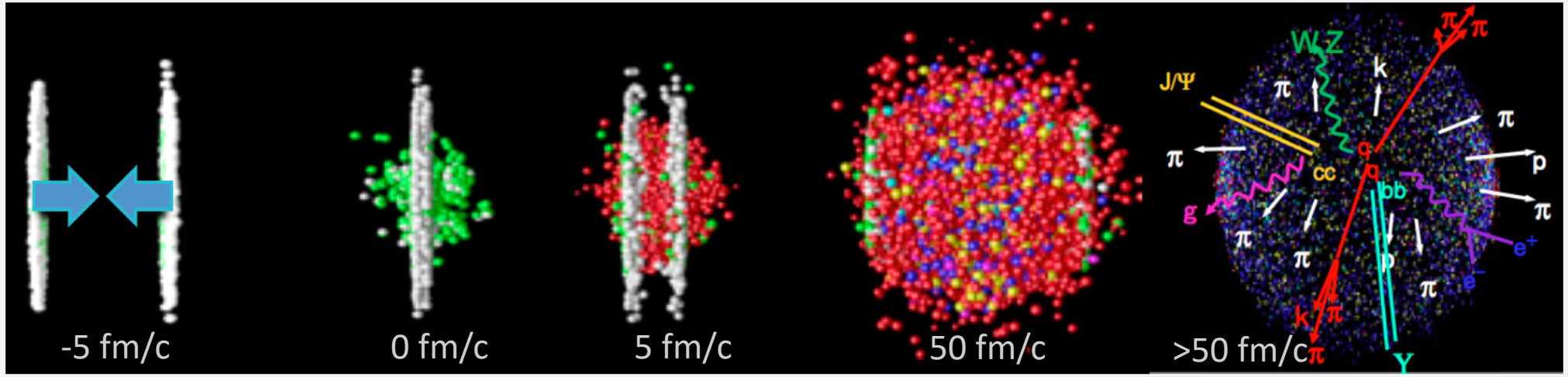
New Trends in High-Energy Physics

May 12-18, 2019

מכון ויצמן למדע

WEIZMANN INSTITUTE OF SCIENCE

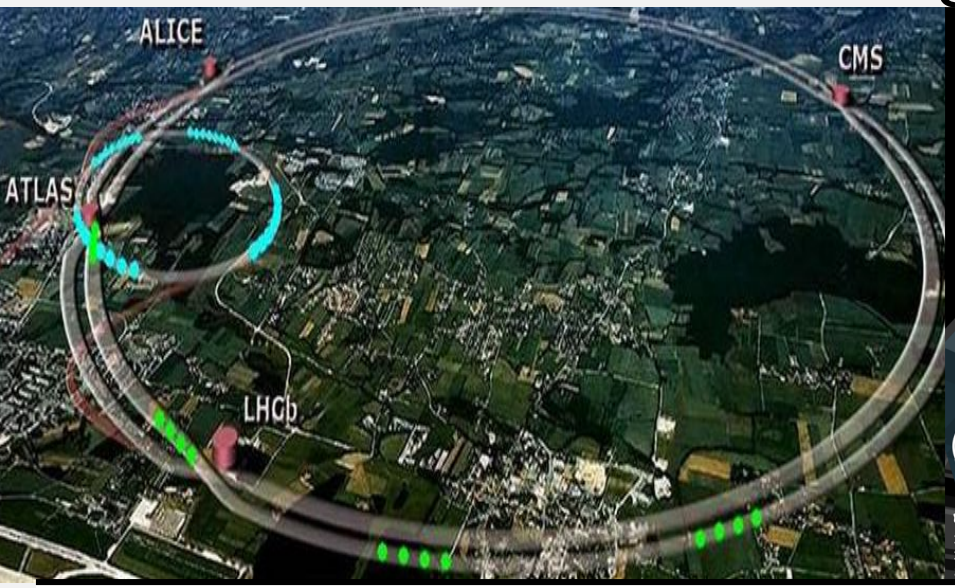
Introduction

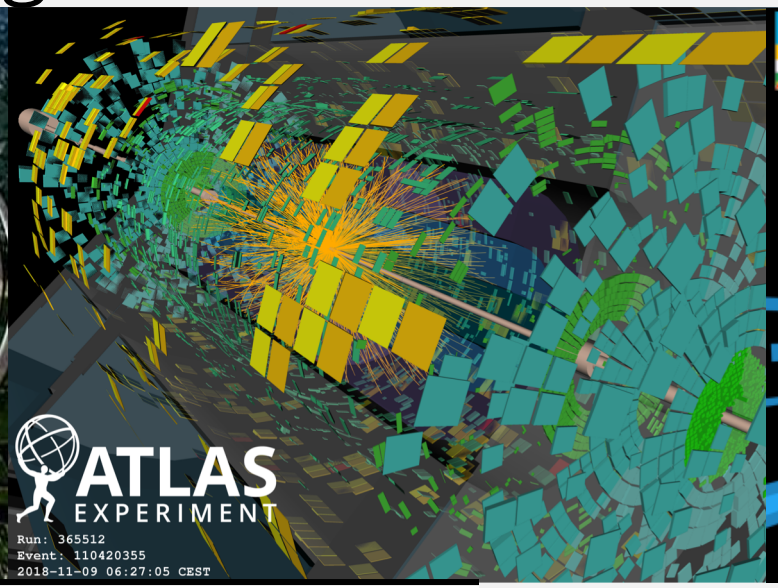


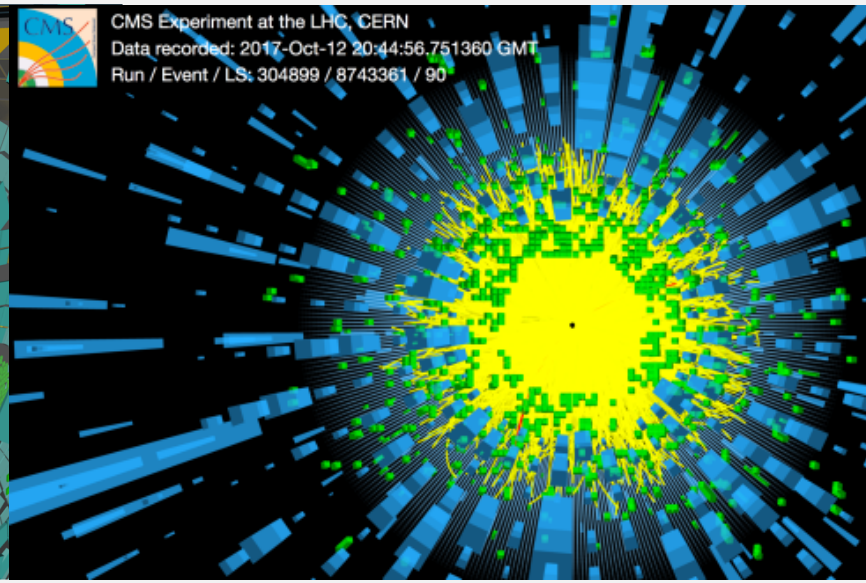
One of the main goals of the ultra relativistic Heavy Ion collisions is to study strongly interacting quark-gluon plasma (QGP).

- Variety of final state probes in AA collisions are used for this purpose:
  - Bulk particle production:
    - Initial geometry, initial conditions, collective behavior, ridge etc
  - Hard probes:
    - Colorless objects e.g. electroweak bosons (nPDFs)
    - Color objects e.g. jets, hadrons, quarkonia (partonic energy loss and transport properties in the QGP)
- pp and pA collisions are used to disentangle initial and final state effects

The Large Hadron Collider (LHC)







System	Years	$\sqrt{s_{NN}}$, [TeV]	$L^{ATLAS}_{int} \approx L^{CMS}_{int}$
Pb-Pb	2010-2011	2.76	~0.14 nb^{-1}
	2015	5.02	~0.49 nb^{-1}
	2018	5.02	~1.7 nb^{-1}
Xe-Xe	2017	5.44	~3 μb^{-1}
p-Pb	2013	5.02	~29 nb^{-1}
	2016	5.02, 8.16	~0.5 nb^{-1}, ~0.16 pb^{-1}
pp	2011-2013	2.76, 8	~4 pb^{-1}, ~19.4 fb^{-1}
	2015, 2017	5.02	~270 pb^{-1}

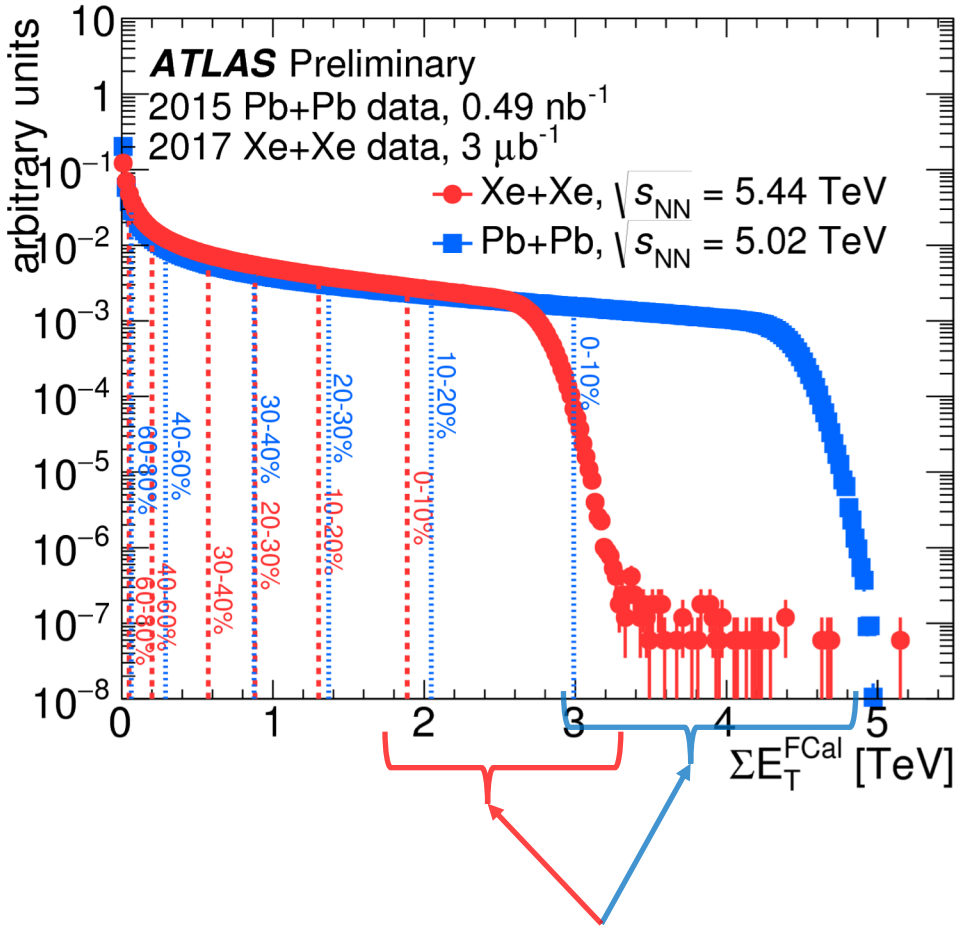
It is already eight years of data taking

- LHC Run 2 data analysis is running
- Recent significant increase in integrated luminosity in p-Pb, and Pb-Pb collisions allows more precise investigation of probes requiring statistics

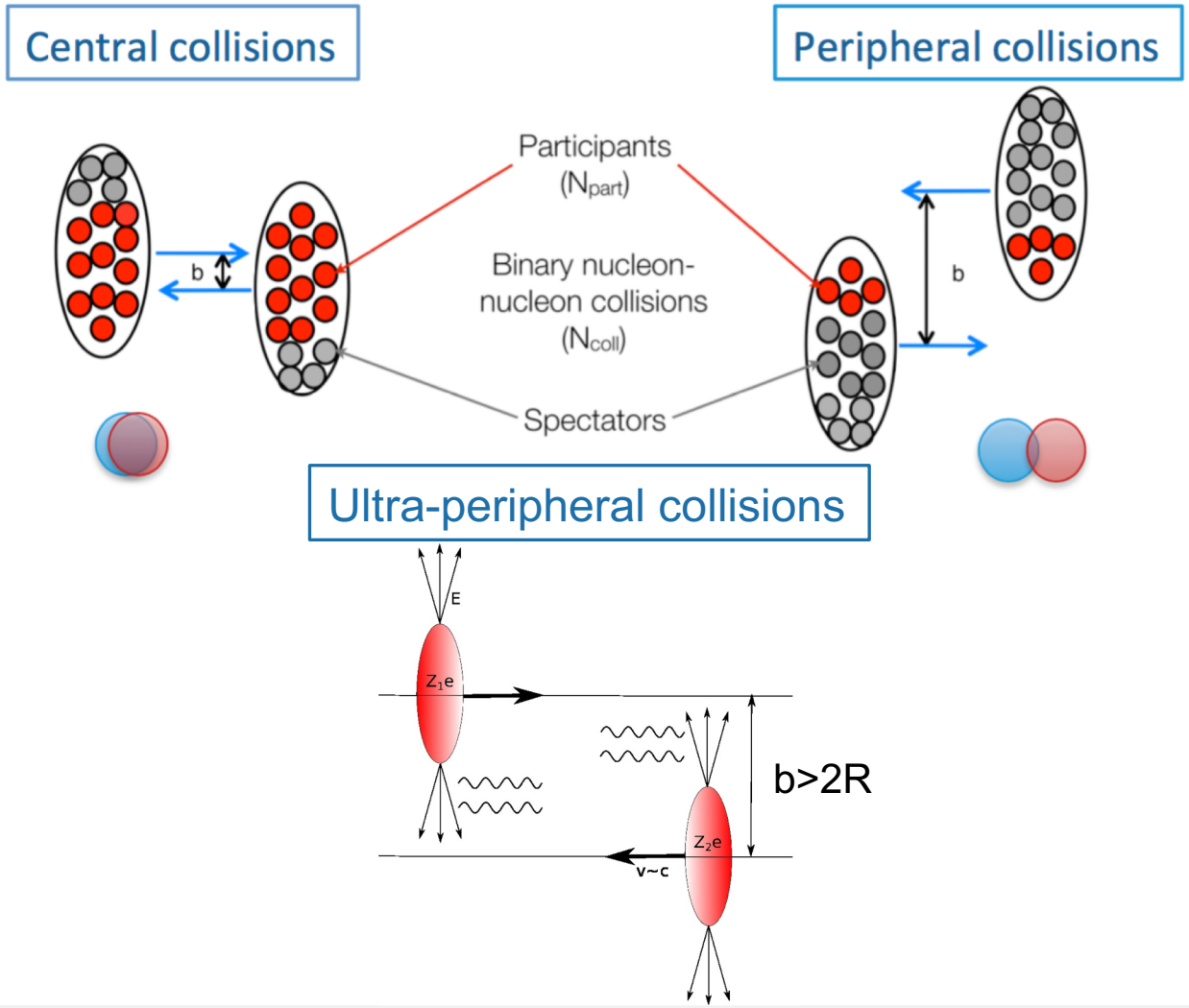
Centrality definition

- A+A collisions are characterized by the centrality, quantified using the energy in forward calorimeters

ATLAS-CONF-2018-007



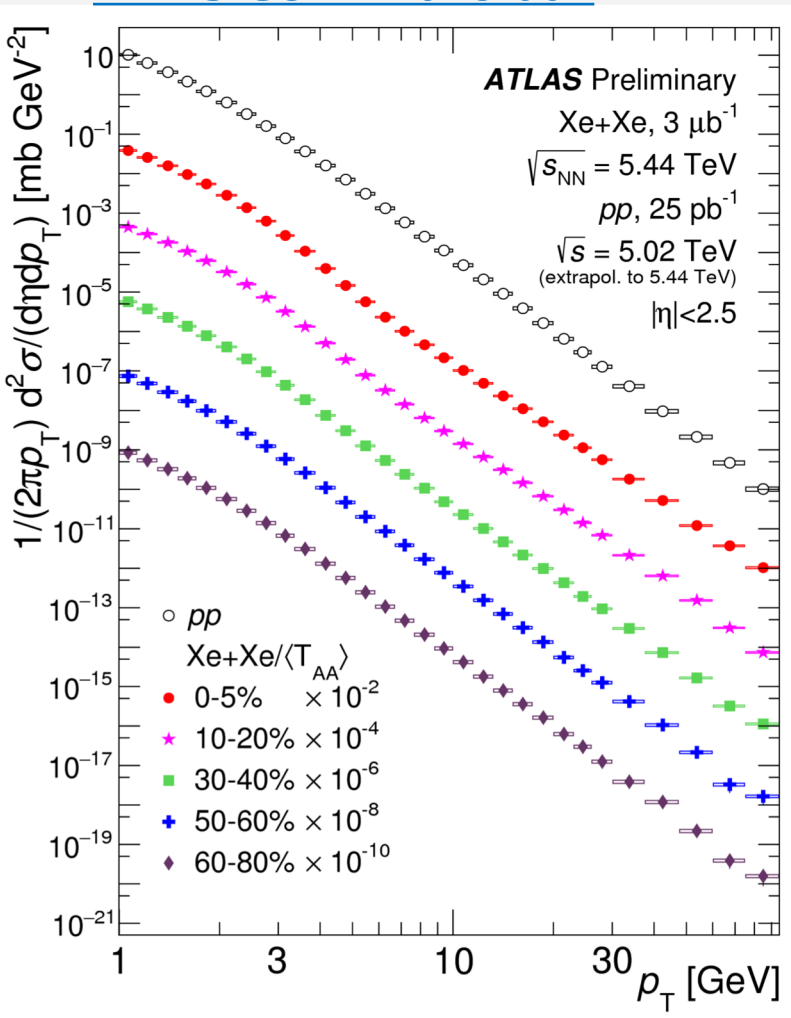
0-10% corresponds to the most central collisions



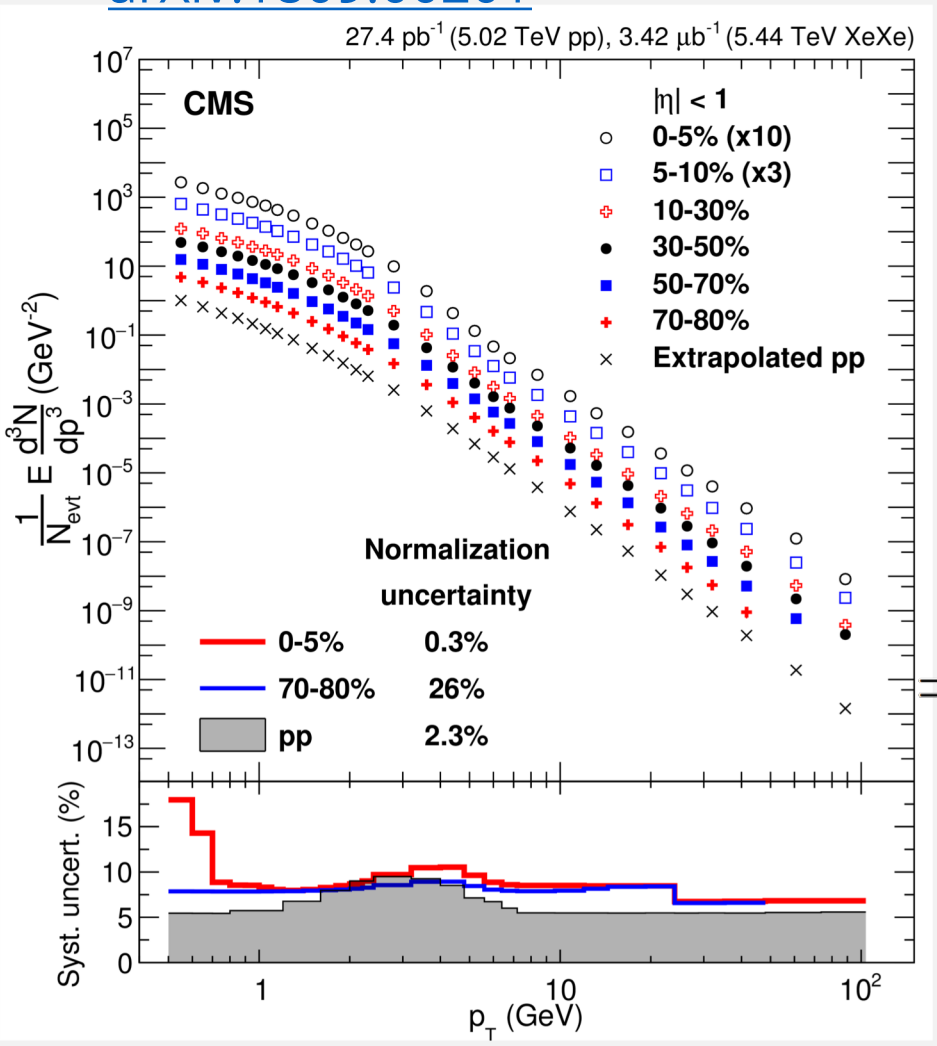
Bulk particle production

Nuclear modification factor

ATLAS-CONF-2018-007



arXiv:1809.00201



Comparing HI and pp collisions where the geometrical scaling is removed

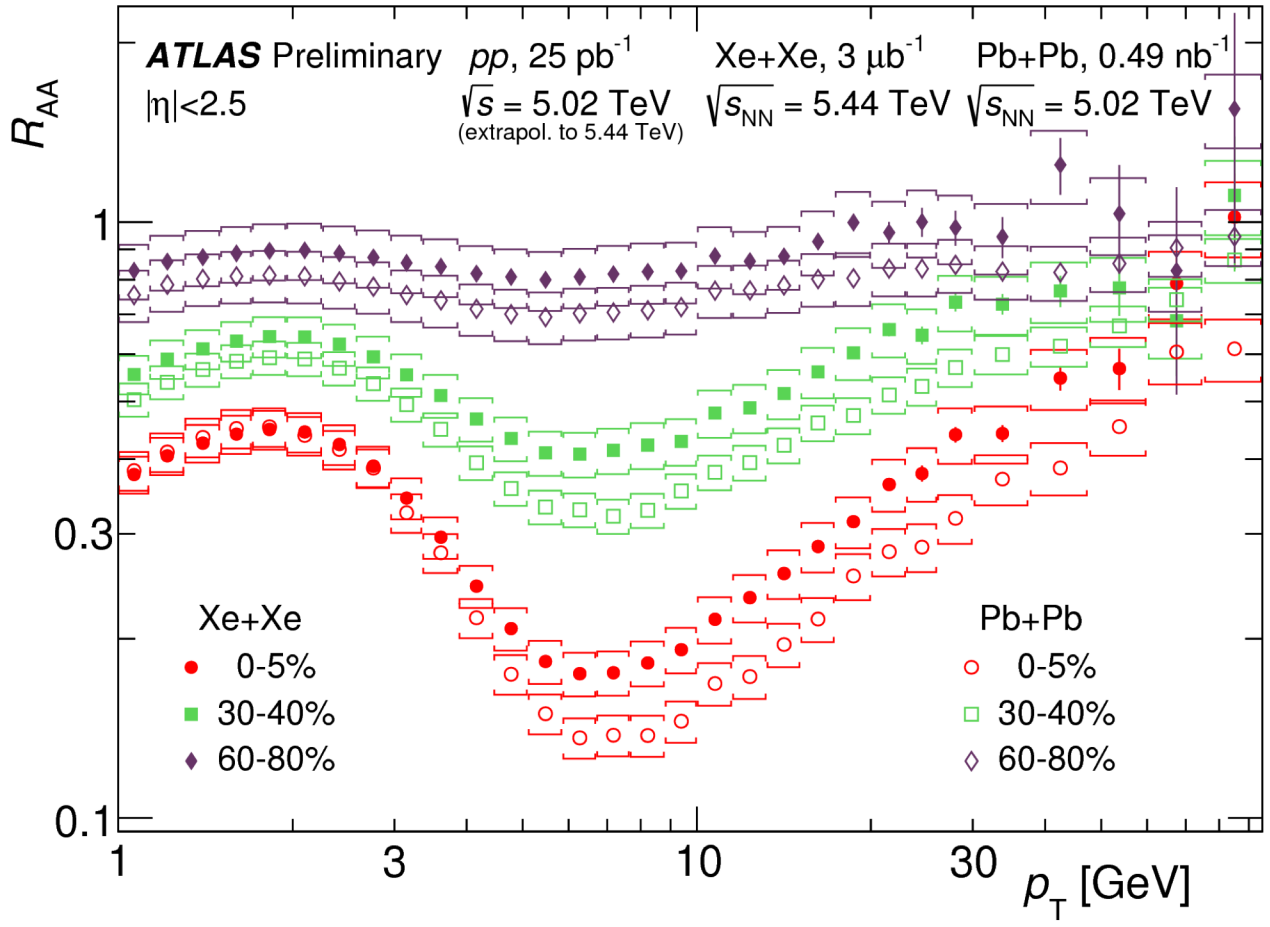
$$R_{AA} = \frac{1}{N_{\mathrm{coll}}} \frac{\text{Yields in A+A}}{\text{Yields in pp}} =$$

$$= \frac{\text{QCD in medium}}{\text{QCD in vacuum}} = \frac{\dfrac{1}{N_{\mathrm{coll}}} \dfrac{dN_{AA}}{dp_T}}{\dfrac{dN_{pp}}{dp_T}} = \frac{1}{T_{AA}} \frac{\dfrac{dN_{AA}}{dp_T}}{\dfrac{d\sigma_{pp}}{dp_T}}$$

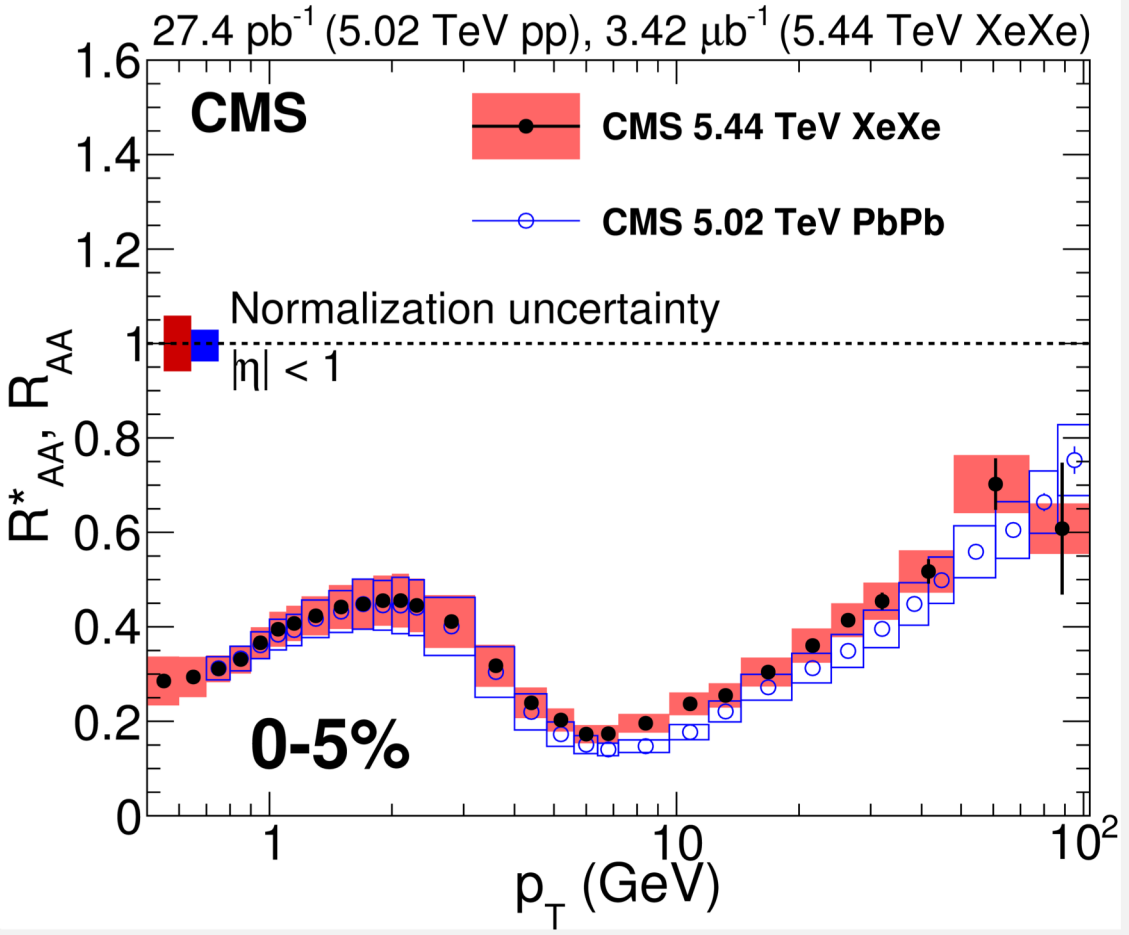
pp reference

Particle production

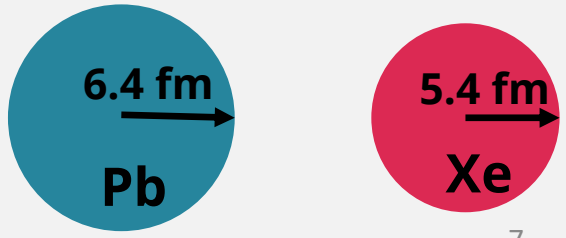
ATLAS-CONF-2018-007



arXiv:1809.00201

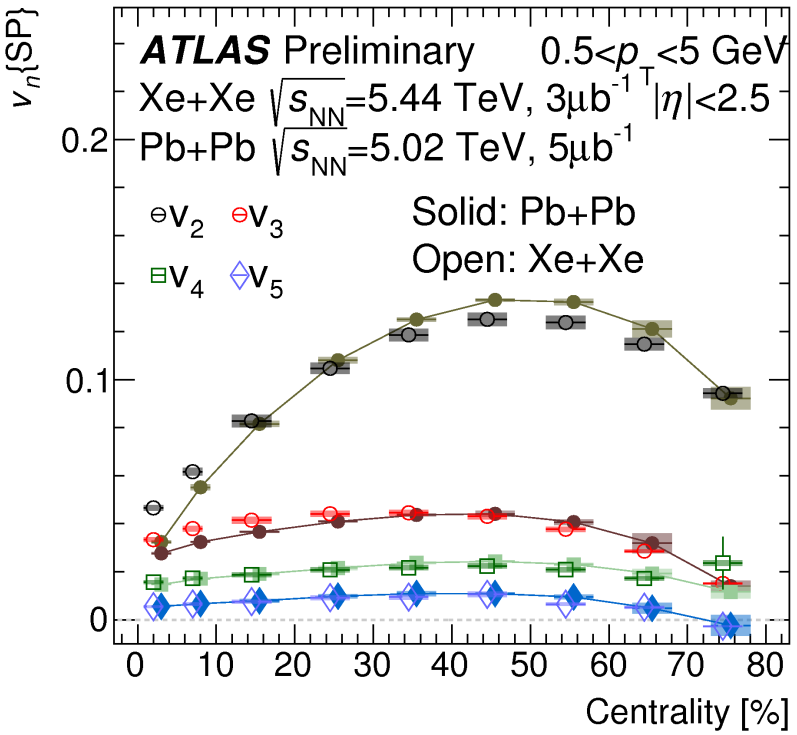


- Significant suppression is observed in AA systems
- R_{AA} is similar in both collision systems in events with a similar $\langle N_{part} \rangle$ values

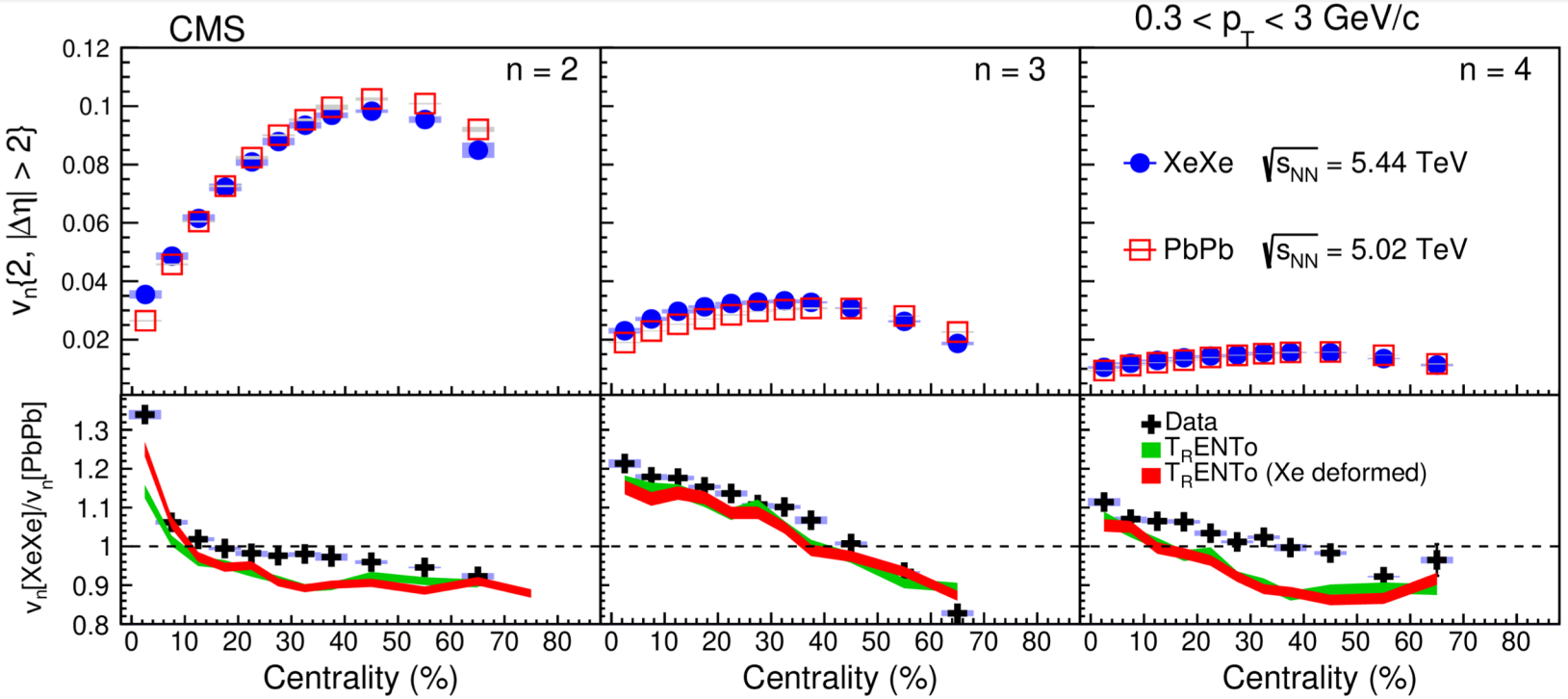


Charged-particle angular correlations in XeXe & PbPb

ATLAS-CONF-2018-011



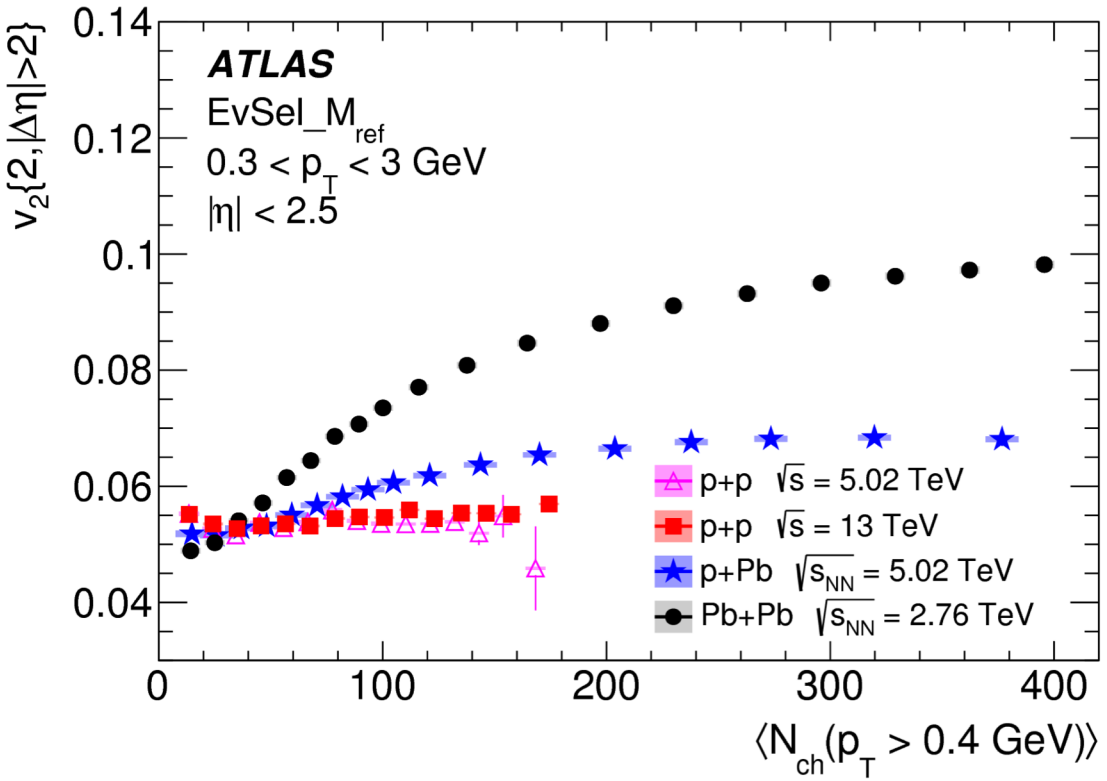
arXiv:1901.07997



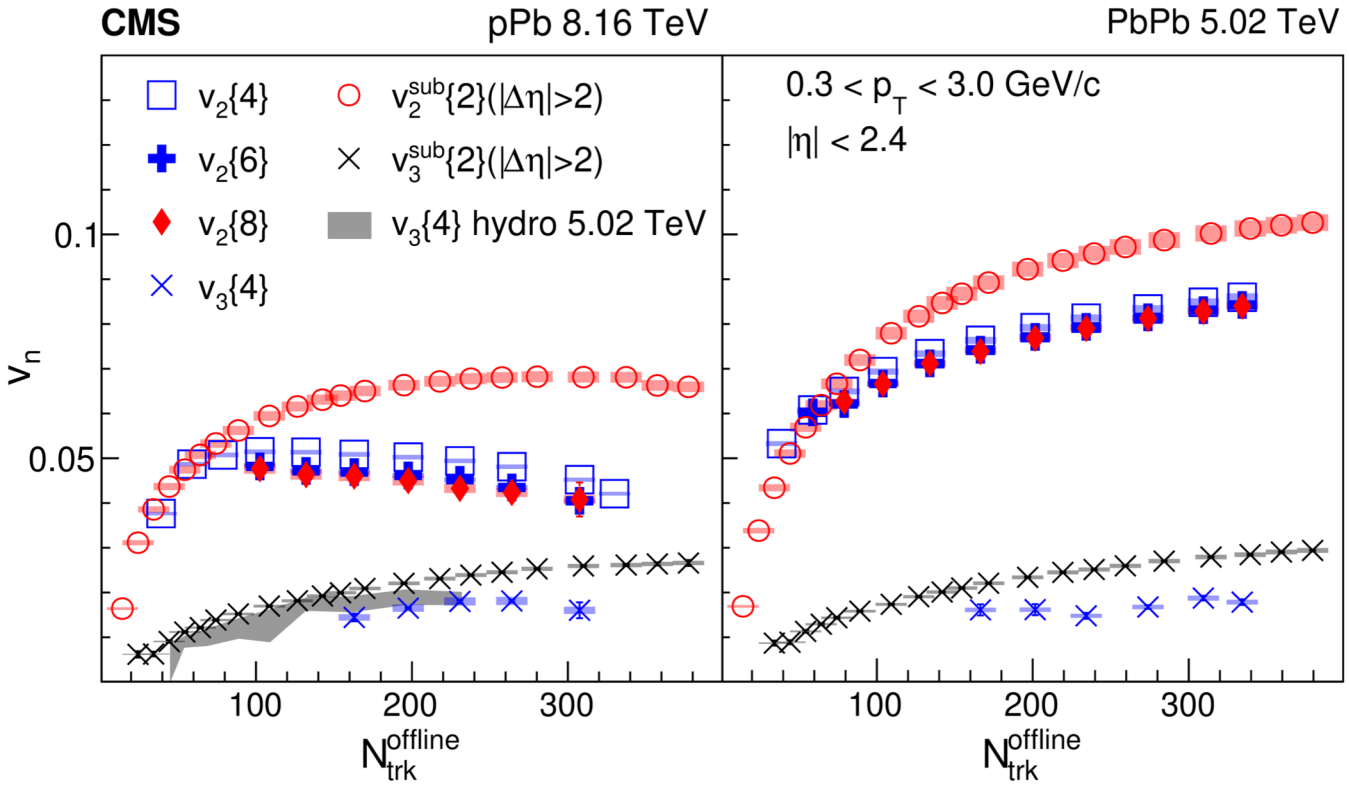
- For the central collisions v_2 for XeXe collisions are larger than those found in PbPb collisions
- This behavior is qualitatively consistent with expectations from hydrodynamic models
- Hydrodynamic models that consider the xenon nuclear deformation are able to better describe the ratio

Charged-particle angular correlations in pp & pPb

arXiv:1705.04176



arXiv:1904.11519



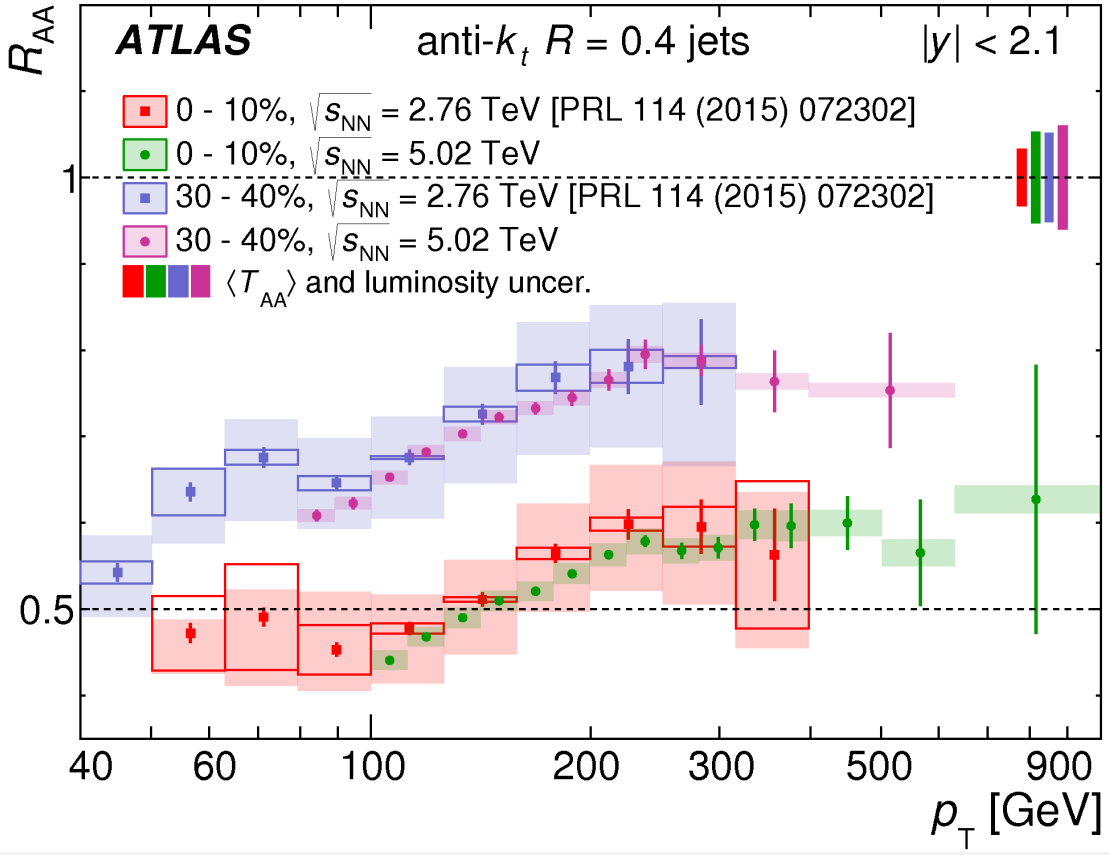
- The pPb and PbPb systems have very similar coefficients, indicating a similar initial-state geometry
- Even smallest system (pp) show flow effects

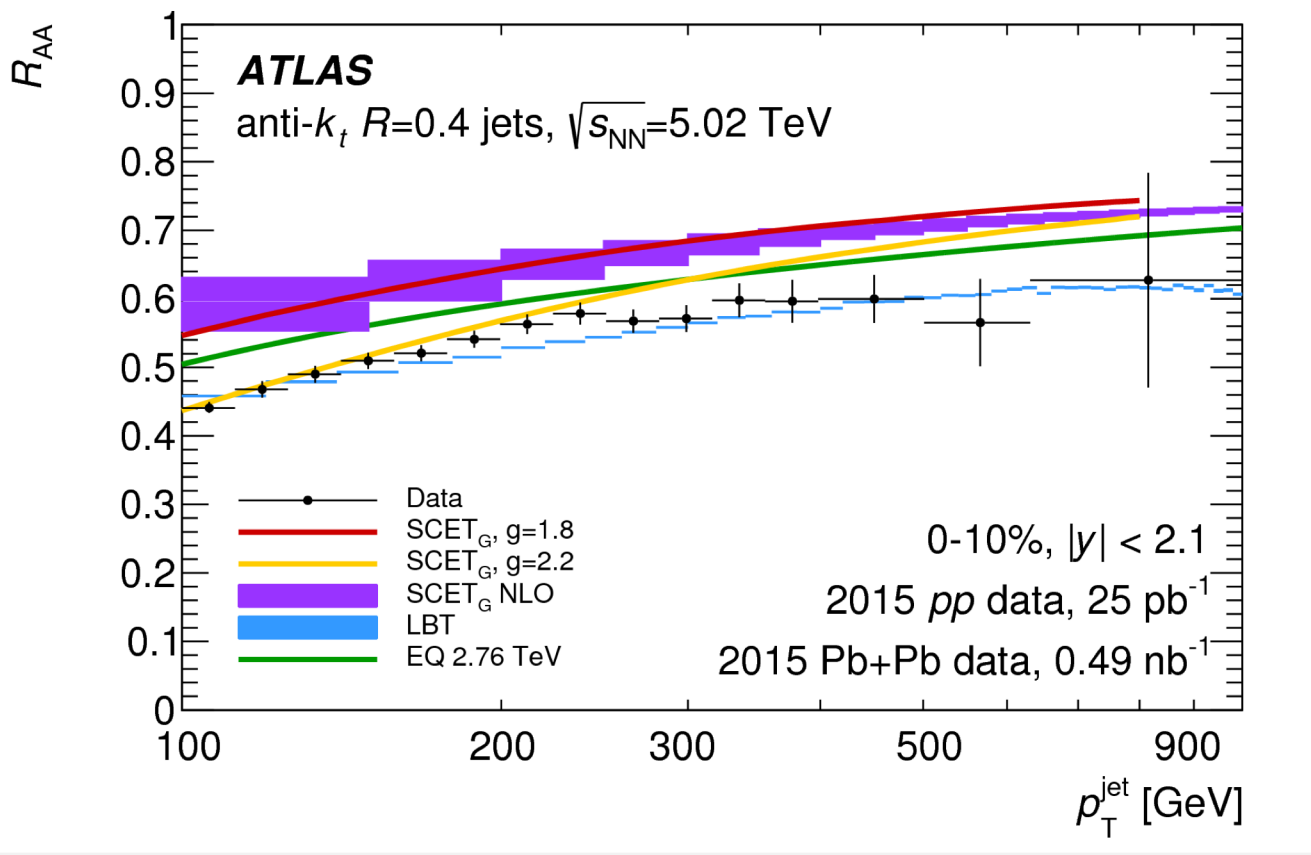
Hard probes:

- Jet-medium interactions
- Electroweak
- Quarkonia & Heavy Flavor

Jet R_{AA}

arXiv:1805.05635

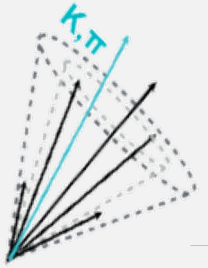




- Strong suppression is observed by all LHC experiments
- No significant $\sqrt{s_{NN}}$ dependence is observed
- Comparison with theory predictions shows that models reproduce trends

Photon-tagged jet fragmentation

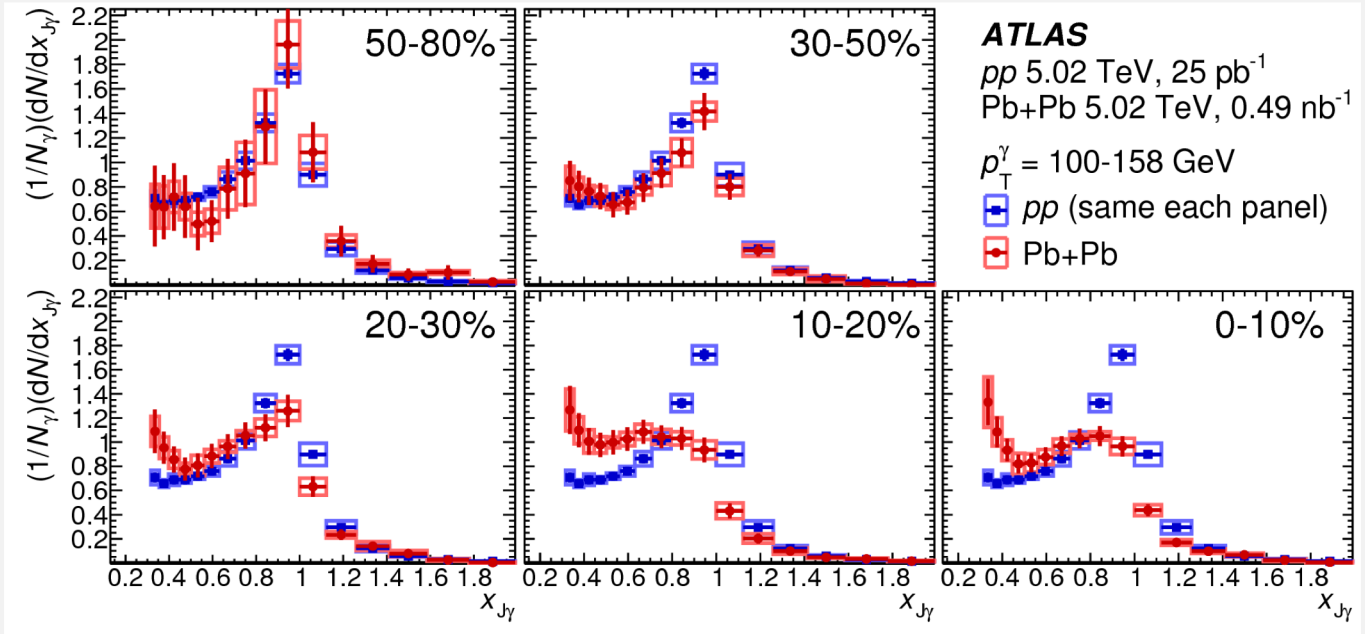
arXiv:1809.08602

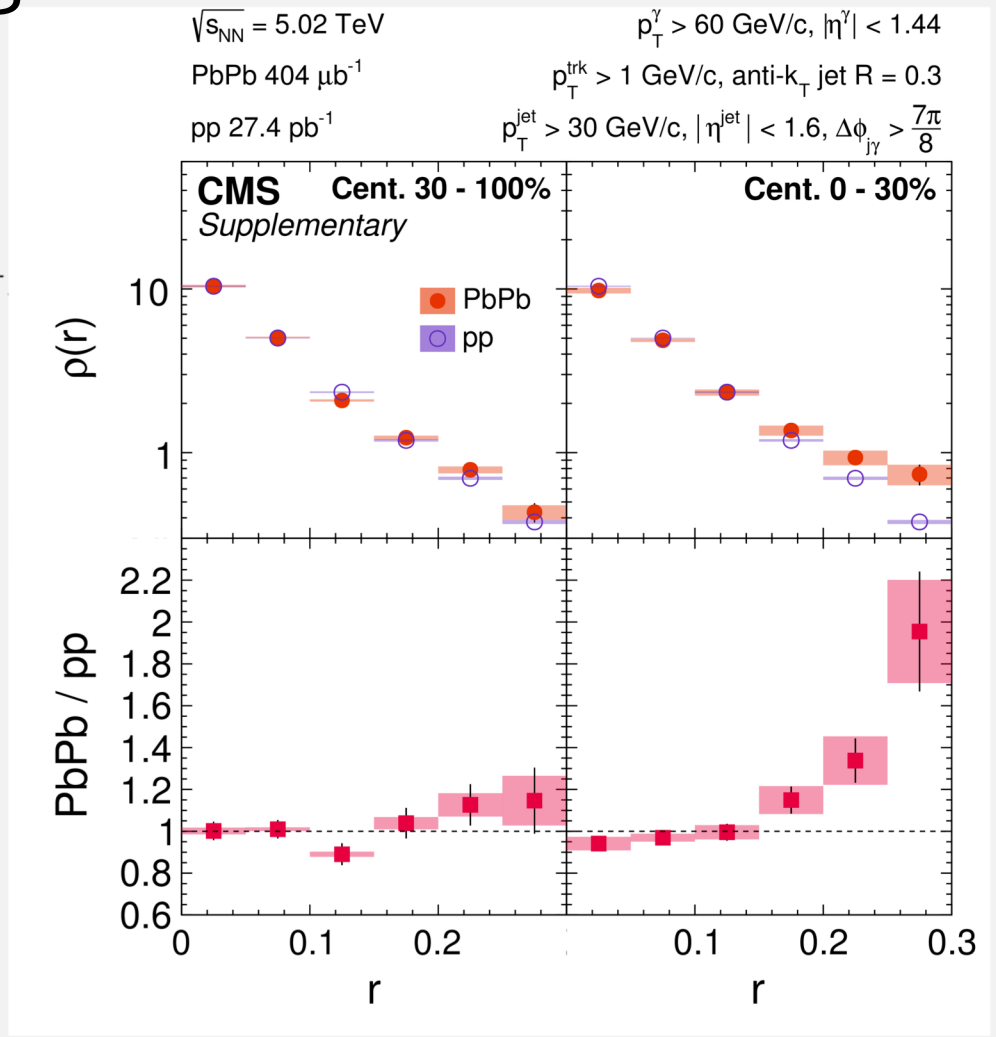


photon

arXiv:1809.07280

$$x_{J\gamma} = \frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}}^{\gamma}};\ \rho(r) = \frac{1}{\delta r}\frac{\sum_{\mathrm{jets}}\sum_{r_{\mathrm{a}}<r<r_{\mathrm{b}}}(p_{\mathrm{T}}^{\mathrm{trk}}/p_{\mathrm{T}}^{\mathrm{jet}})}{\sum_{\mathrm{jets}}\sum_{0<r<r_{\mathrm{f}}}(p_{\mathrm{T}}^{\mathrm{trk}}/p_{\mathrm{T}}^{\mathrm{jet}})}$$





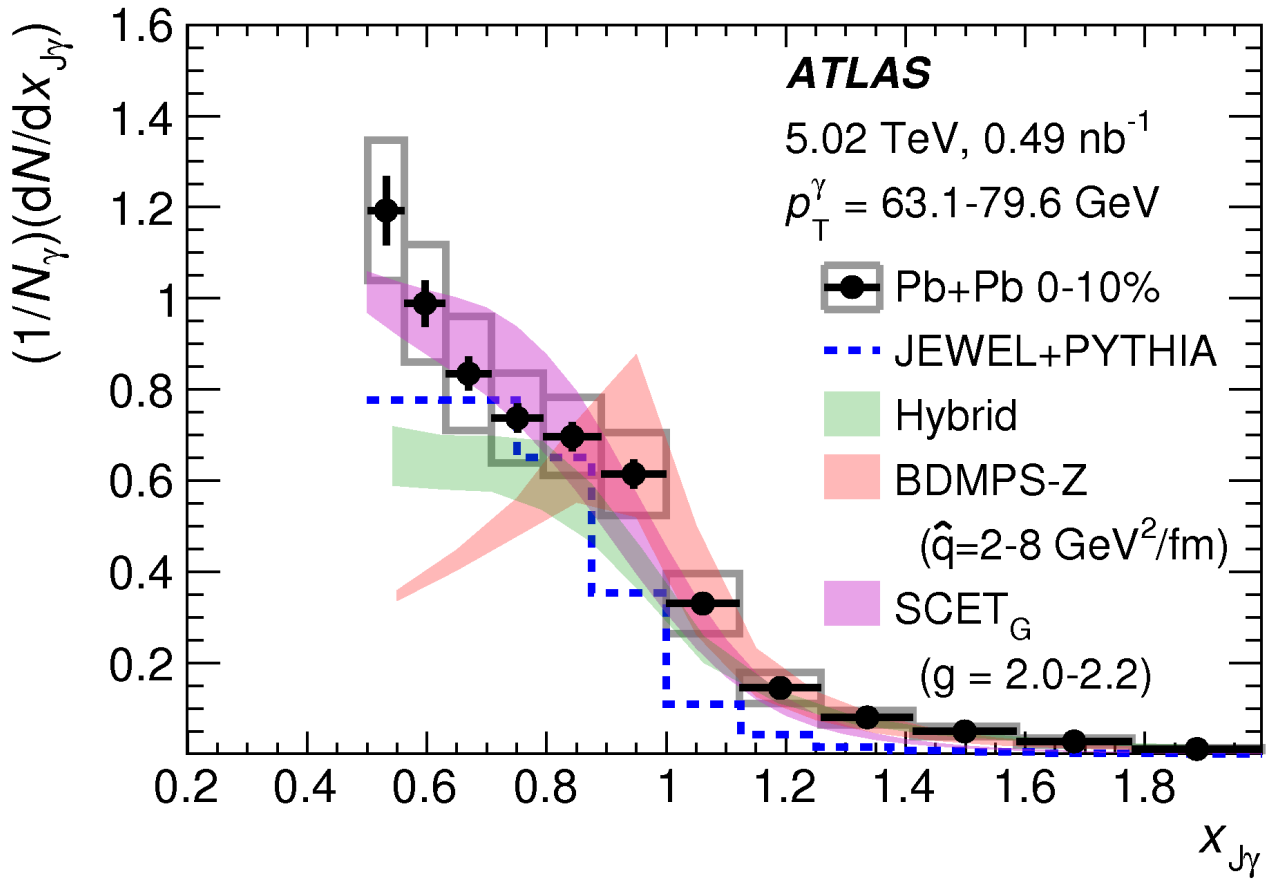
- Photons act as calibration probes in HI collisions
- For peripheral - comparable to pp, for central - not anymore
- The jet momentum is redistributed to larger radial distance in PbPb collisions

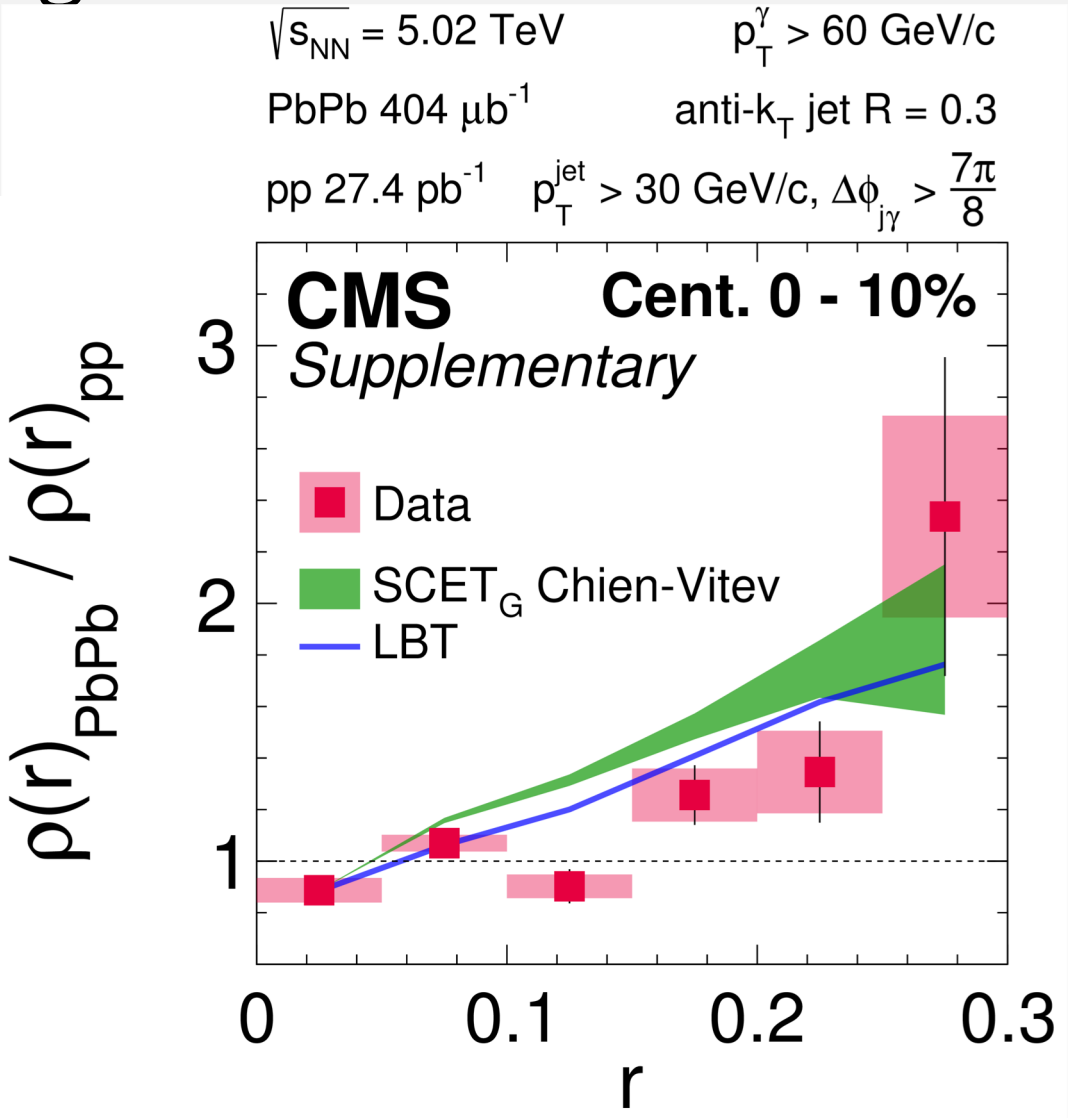
Photon-tagged jet fragmentation

arXiv:1809.08602

arXiv:1809.07280

$$x_{J\gamma} = \frac{p_{\mathrm{T}}^{\mathrm{jet}}}{p_{\mathrm{T}}^{\gamma}} \qquad \rho(r) = \frac{1}{\delta r} \frac{\sum_{\mathrm{jets}} \sum_{r_a<r<r_b} (p_{\mathrm{T}}^{\mathrm{trk}}/p_{\mathrm{T}}^{\mathrm{jet}})}{\sum_{\mathrm{jets}} \sum_{0<r<r_f} (p_{\mathrm{T}}^{\mathrm{trk}}/p_{\mathrm{T}}^{\mathrm{jet}})}$$





- Main features of the data are described by models

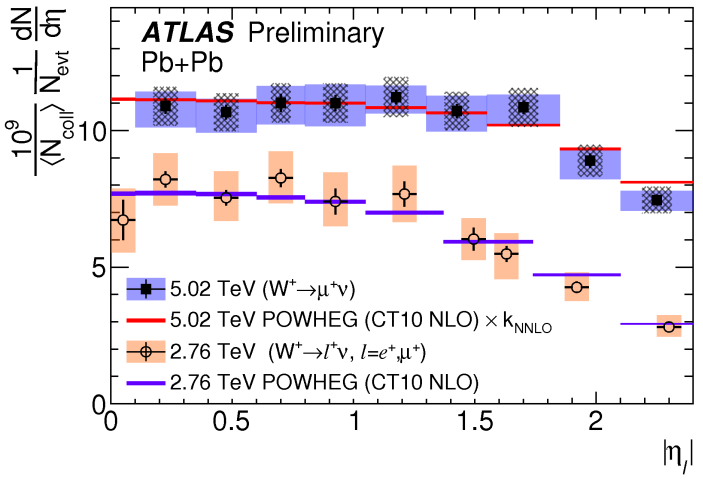
Hard probes:

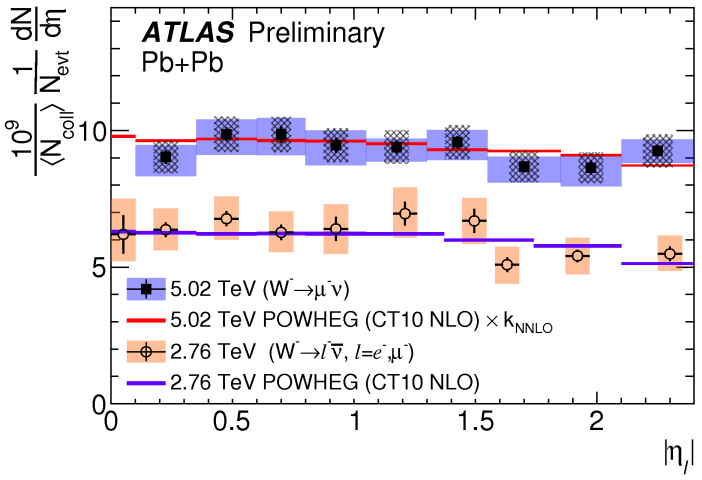
- Jet-medium interactions
- Electroweak
- Quarkonia & Heavy Flavor

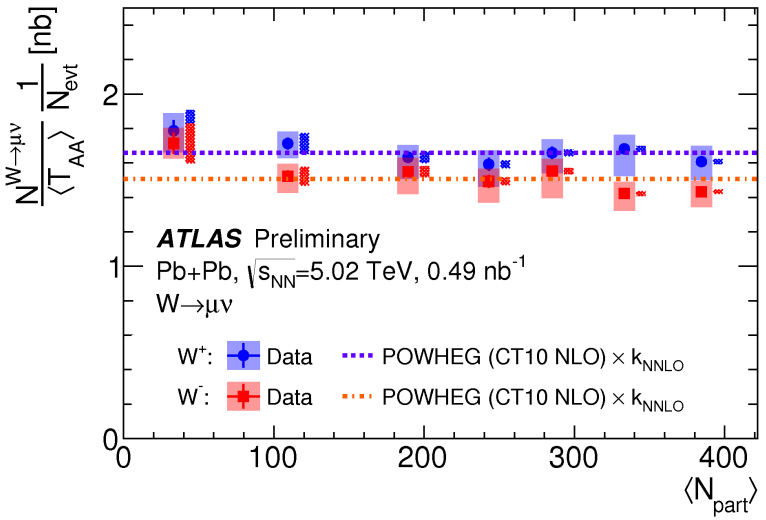
W production

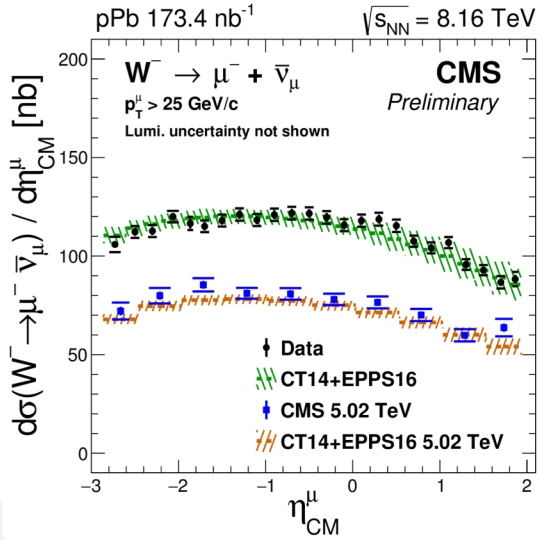
ATLAS-CONF-2017-067

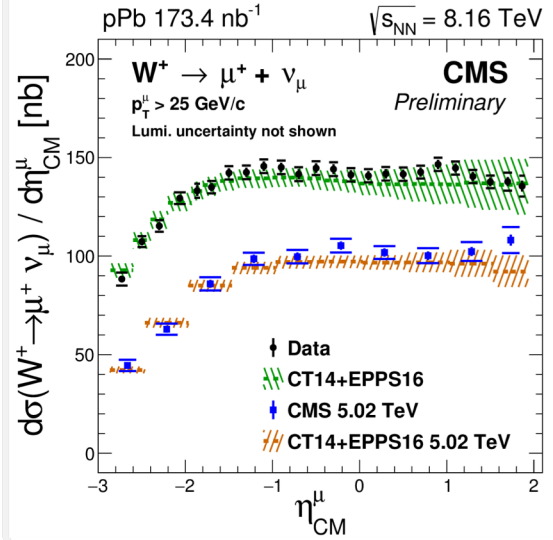
CMS-PAS-HIN-17-007

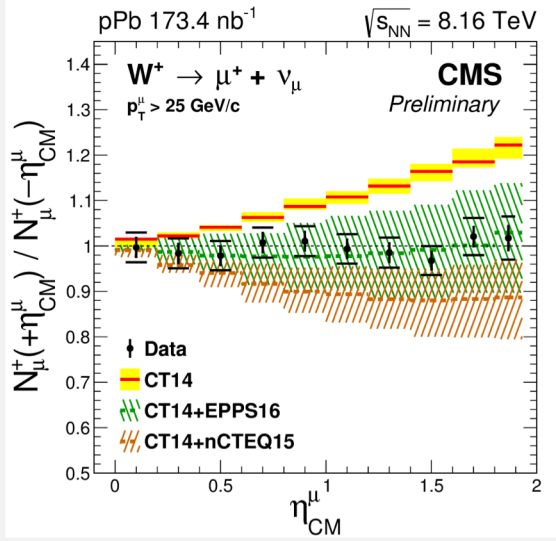


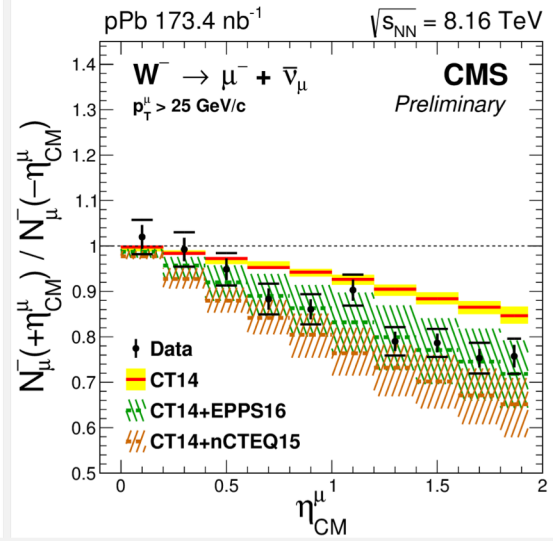












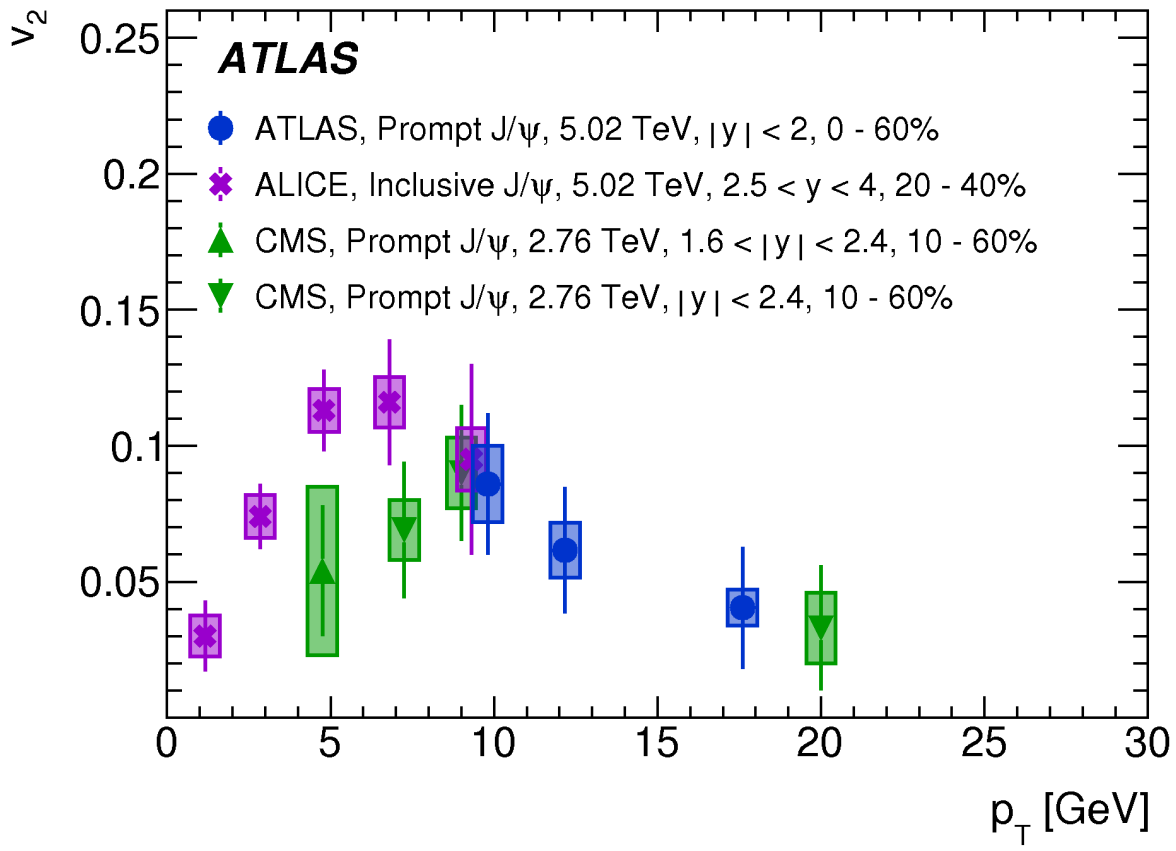
- Scaling with the number of binary collisions holds
- Lepton charge asymmetry consistent with theory with small deviations in the forward direction
- W measurements could constrain the quark and antiquark distributions in nuclei

Hard probes:

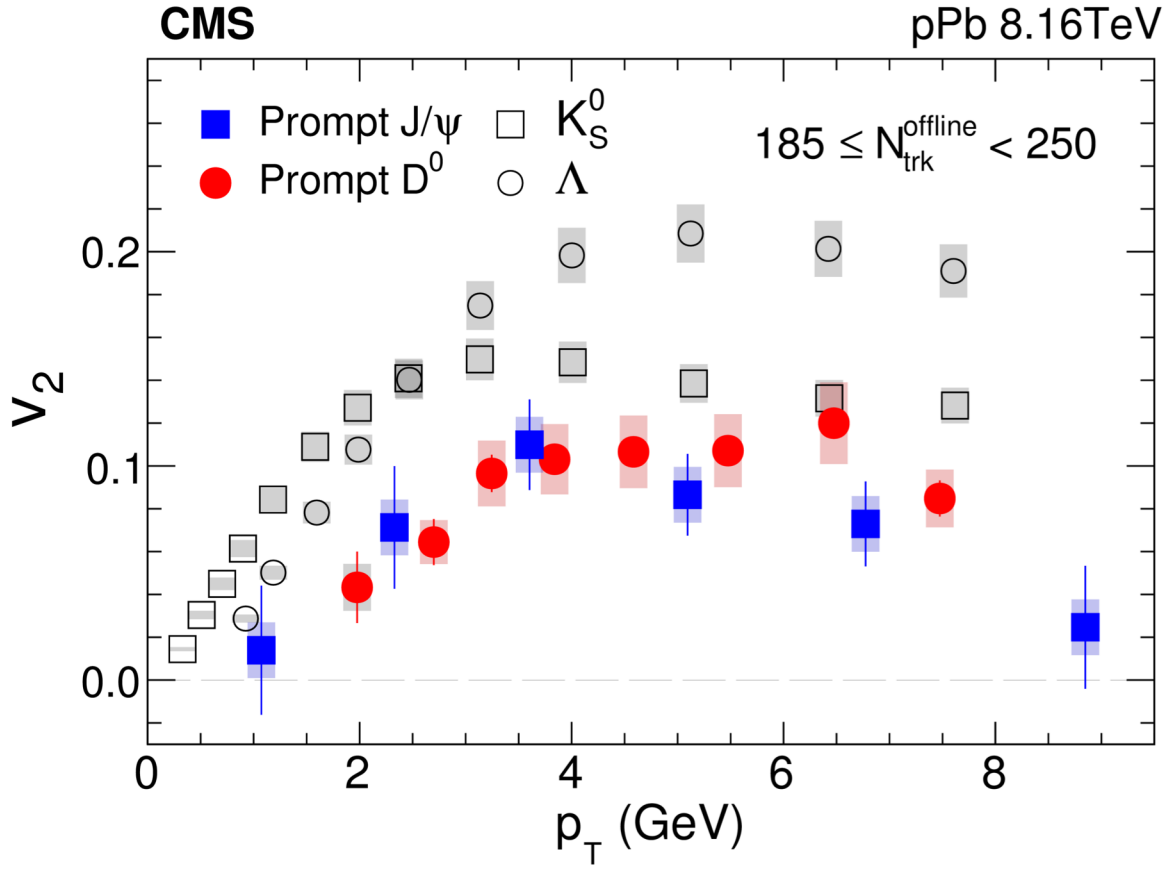
- Jet-medium interactions
- Electroweak
- Quarkonia & Heavy Flavors

Quarkonia elliptic flow

arXiv:1807.05198 PbPb



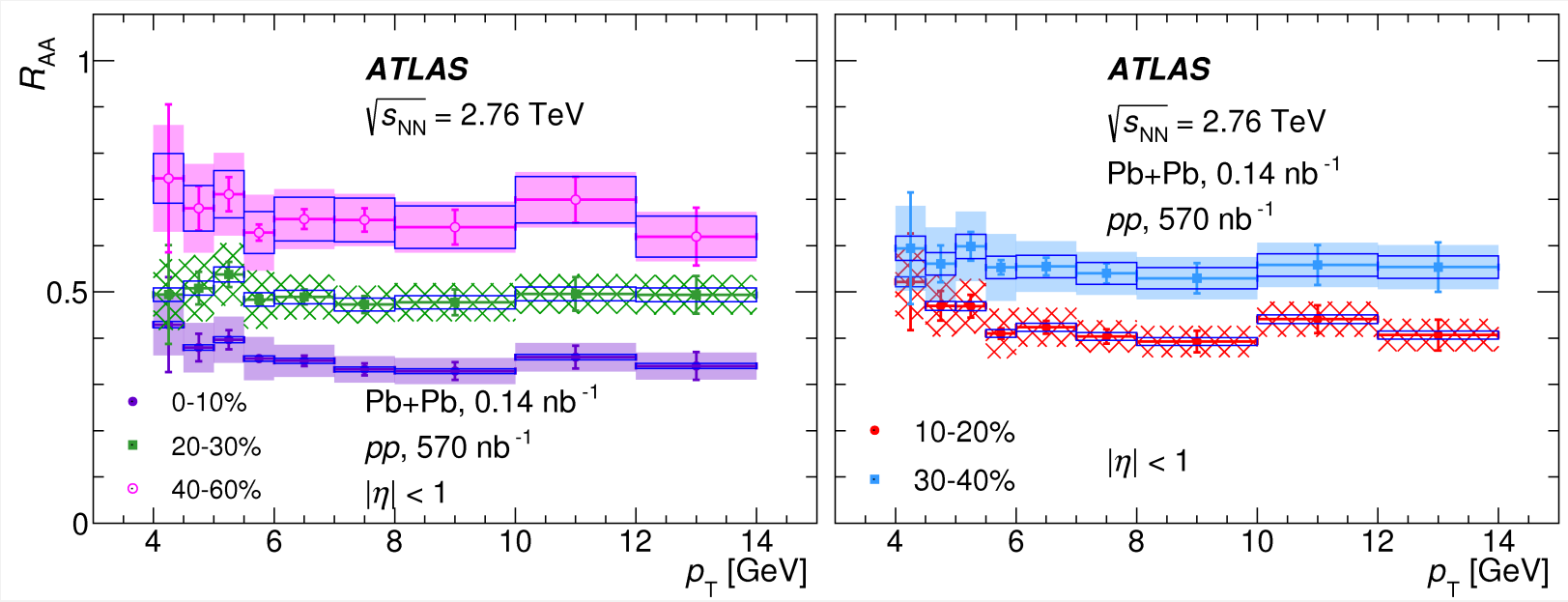
arXiv:1810.01473

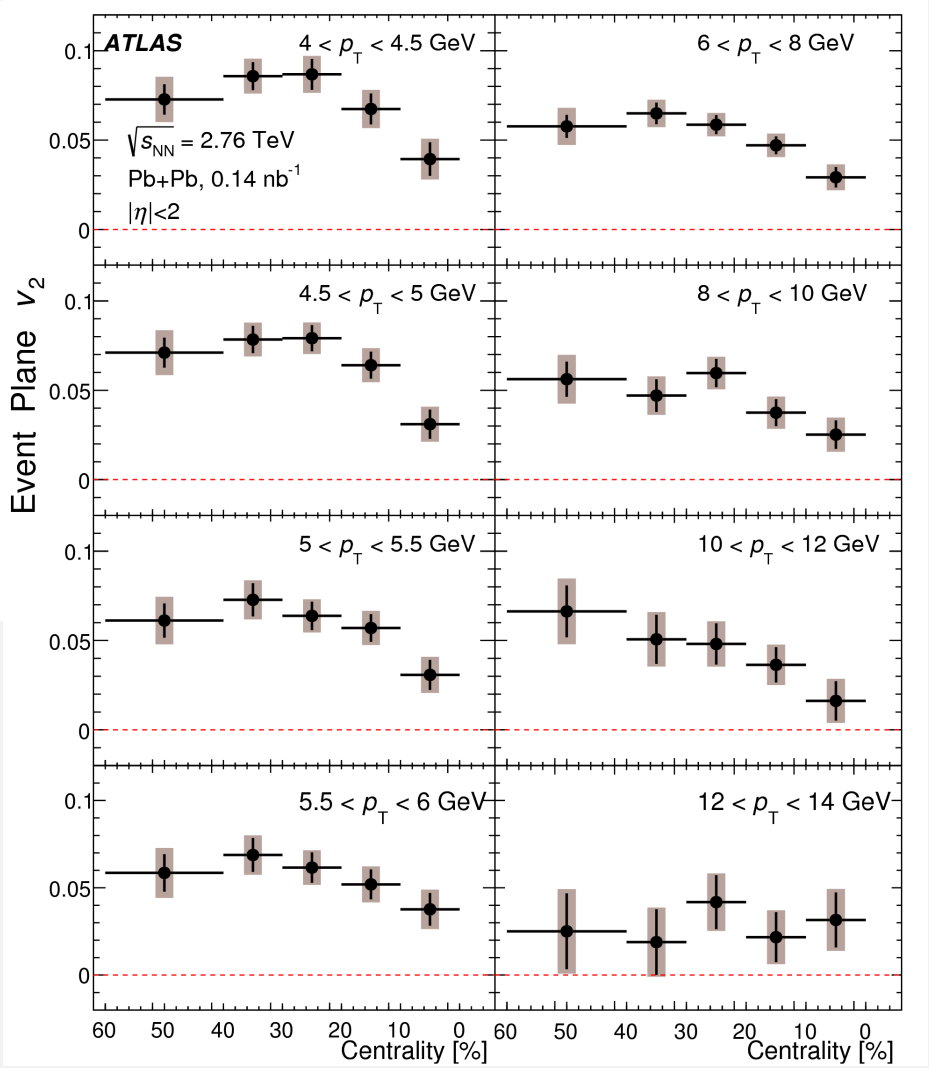


- A significant flow signal is found in Pb Pb for prompt J/ψ
- Flow coefficients are similar for PbPb and pPb systems
- In pPb heavy quarks exhibit weaker collective behavior than light quarks or gluons in small systems

Heavy flavor muons

arXiv:1805.05220

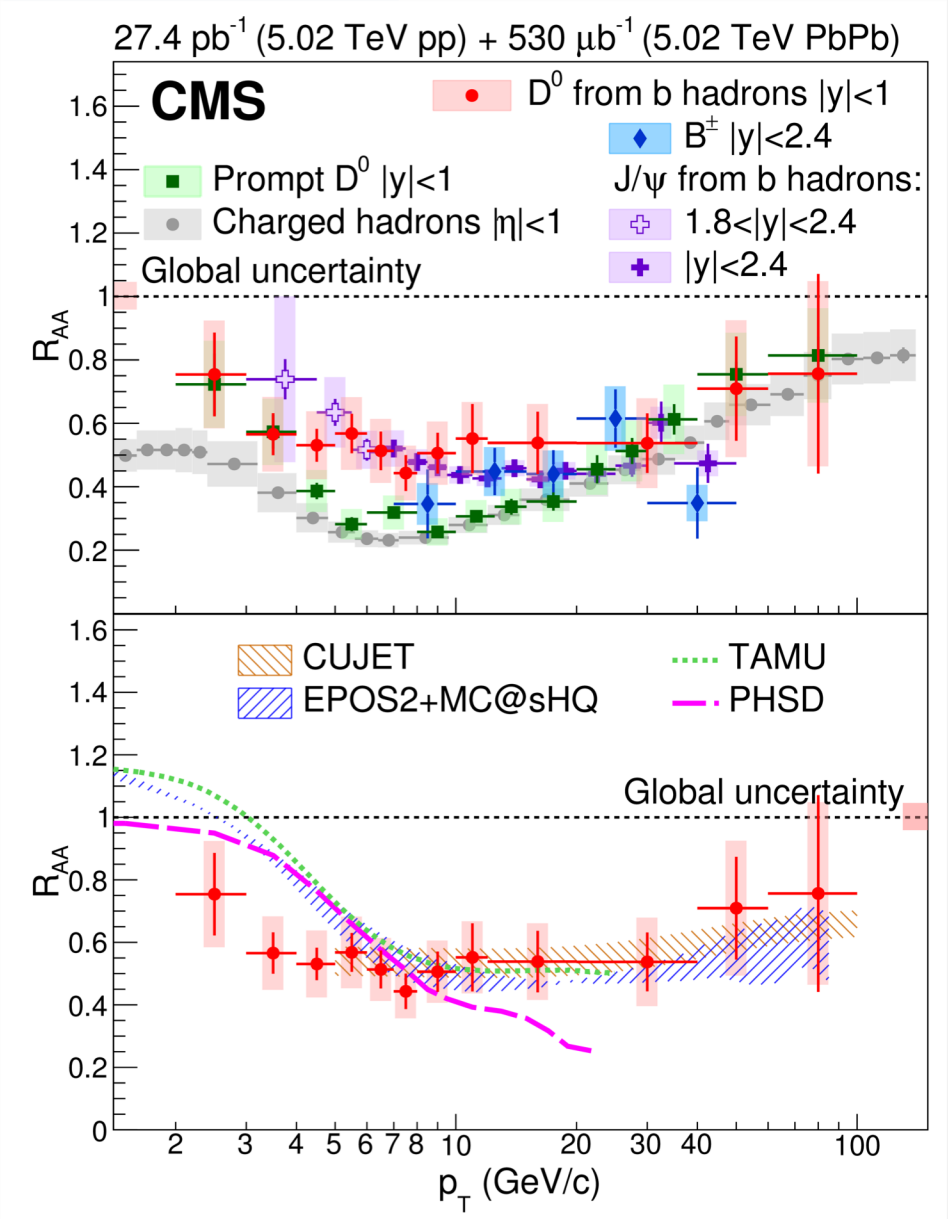




- R_{AA} is independent of pT and decreases with centrality
- v_2 is non-zero and shows a systematic variation with centrality

D^0 from b hadrons

arXiv:1810.11102

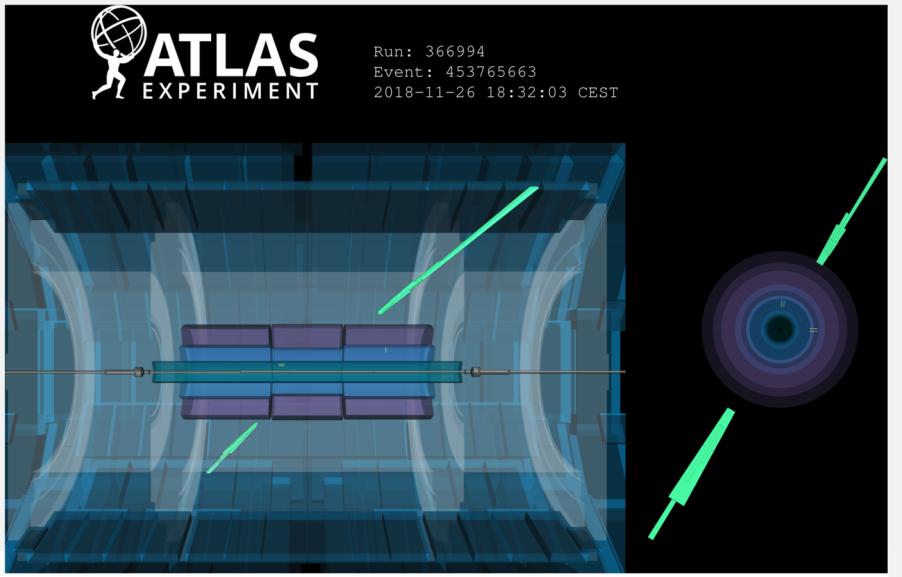


- $B \rightarrow D^0$ yield is suppressed in PbPb
- R_{AA} is higher than for prompt D^0, which is in line with a quark mass ordering of suppression
- Compared to theoretical predictions, the measured R_{AA} is consistent with some models at higher p_T

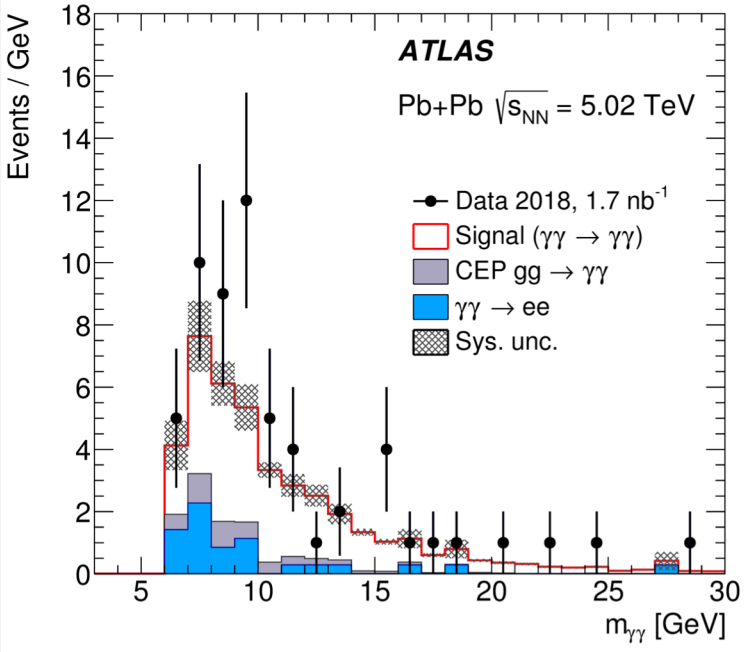
EM-induced reactions

Light-by-light scattering in Pb+Pb collisions

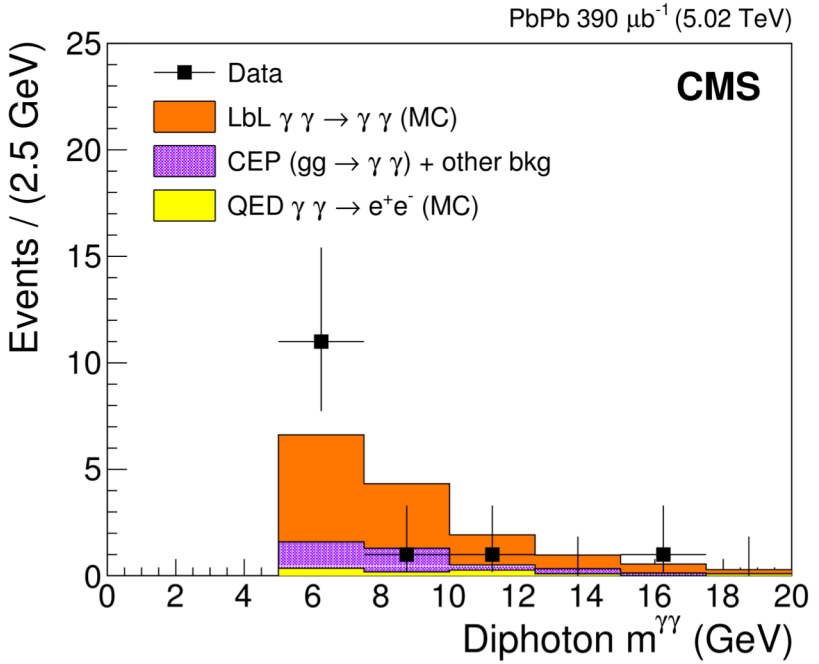
- First direct evidence for $\gamma\gamma \to \gamma\gamma$ by ATLAS (Nature Phys. 13 (2017) 852-858) updated results are presented
  - 4.4σ (3.8σ expected) in ATLAS
  - 4.1σ (4.4σ expected) in CMS
- Only two back-to-back low E_T γ are present in the detector
- Fiducial cross-sections consistent with SM

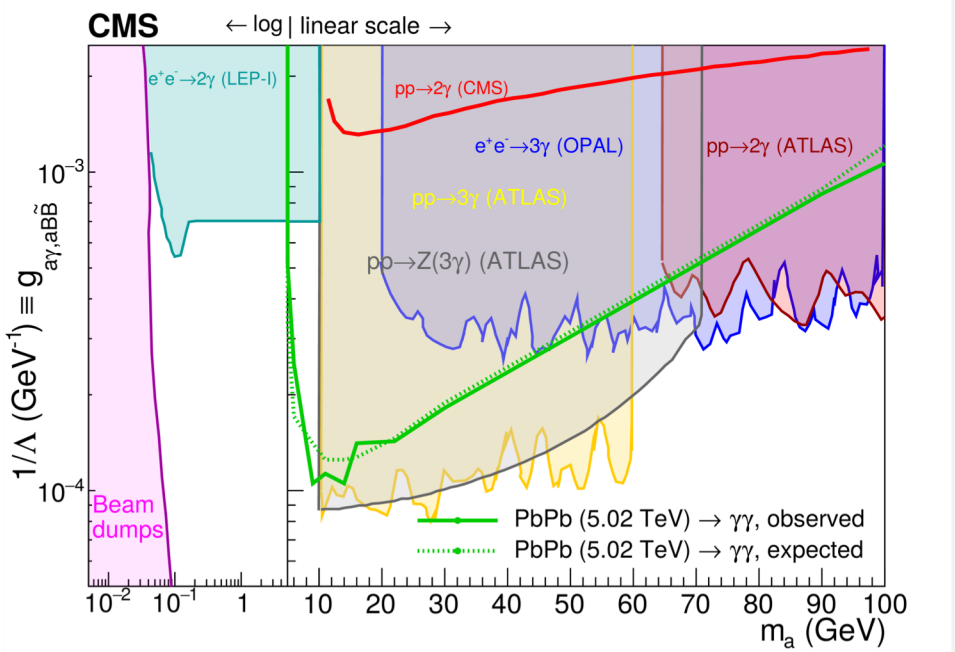


arXiv:1904.03536



arXiv:1810.04602



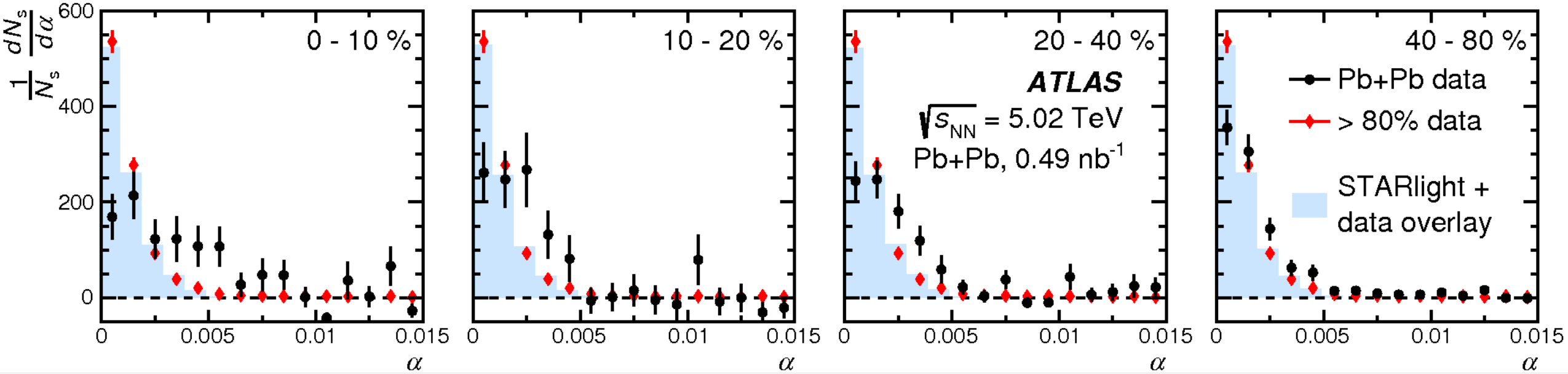


Non-UPC dimuons in Pb+Pb collisions

Ions are incredible source of photons: each photon flux scales with Z^2

$$\alpha \equiv 1 - \frac{|\phi^+ - \phi^-|}{\pi}$$

arXiv:1806.08708



- Centrality dependent broadening of dimuon acoplanarity
- Modification due to re-scattering of muons in the QGP?
- First observation of EM interactions with QGP?

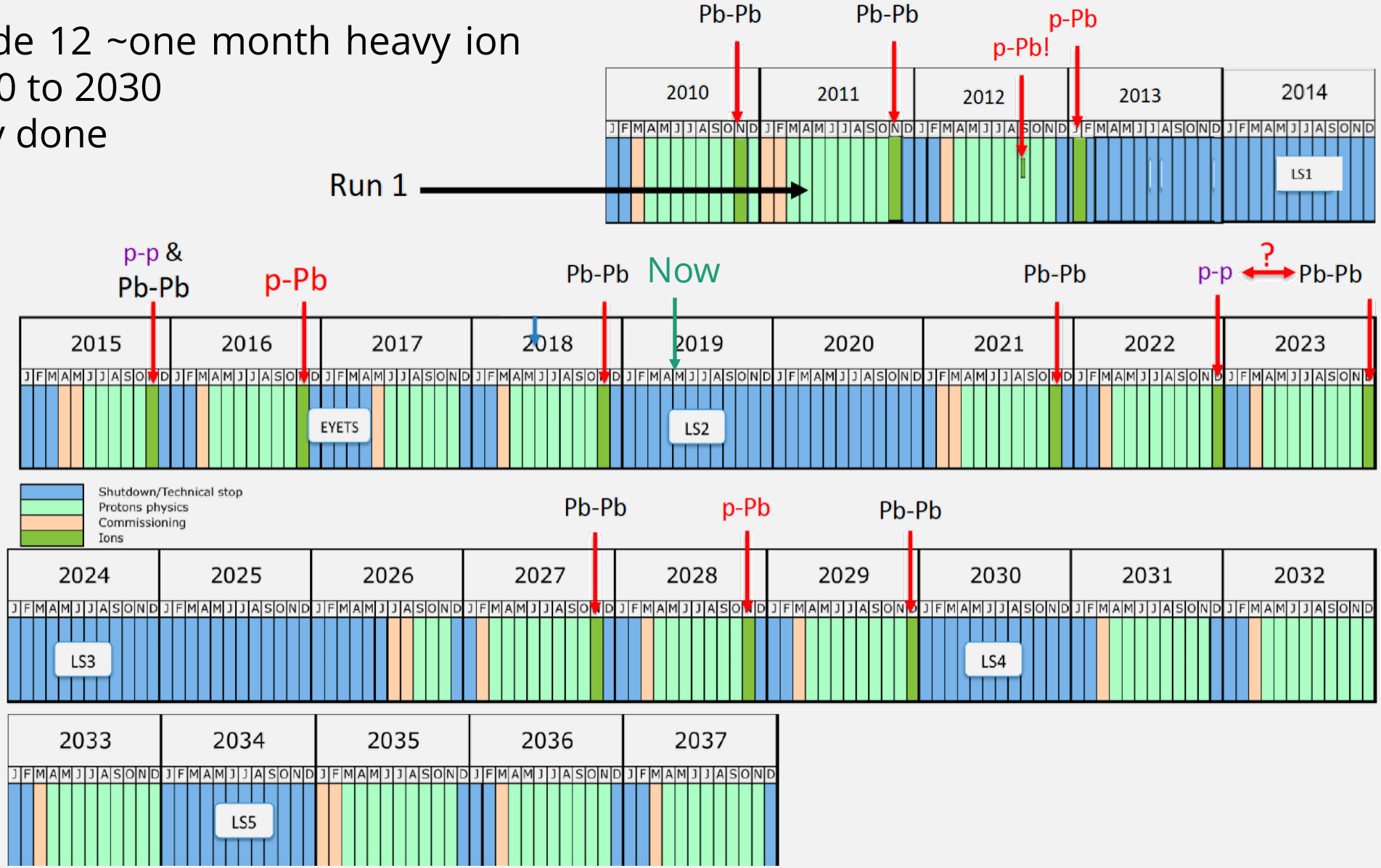
Summary

- A brief overview of heavy ion results is present
- Outline:
  - observation of flow-like phenomena in essentially all measured soft particle spectra, even in small systems;
  - observation of quantitatively-large quenching phenomena in essentially all measured hard hadronic observables in A–A collisions

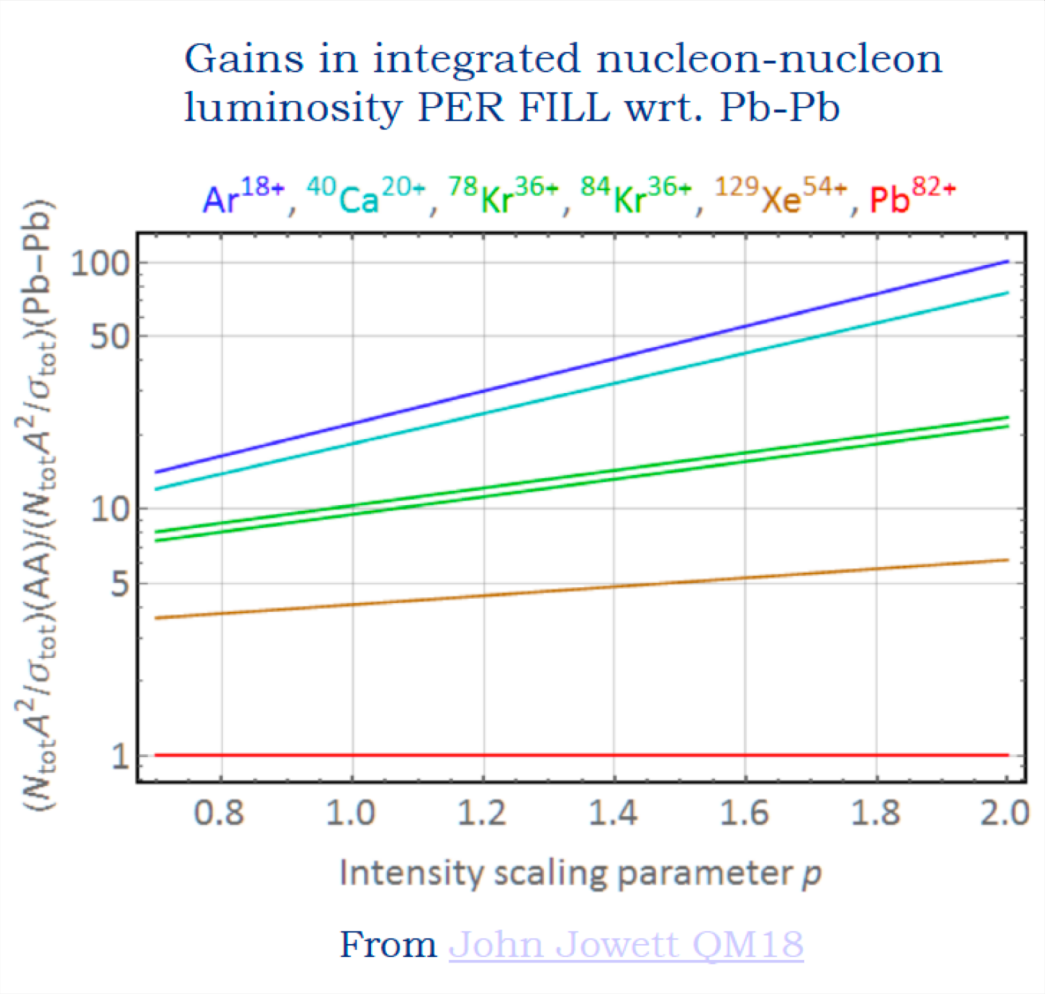
Future prospects

LHC HI runs

- LHC will provide 12 ~one month heavy ion runs from 2010 to 2030
- 6 of 12 already done



Light ions @ LHC



- Successful Xe+Xe run in 2017
  - Few hours of data taking
  - Precise measurements of bulk and jets
- Runs with small ions (like O+O)
  - Better constrains on small systems
  - Measurable energy loss
- Lighter ions - source of statistics for hard probes
  - Detailed studies of energy loss

Future HI physics @ LHC

Future HI running (Run-3 and Run-4):

- Factor ~20 more data for CMS and ATLAS
- Precise differential measurements

High Luminosity LHC documents:

- **Yellow report - "**Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams ": arXiv:1812.06772
- **ATLAS :**
  i. Nuclear PDFs in Run 3 and 4: ATL-PHYS-PUB-2018-039
  ii. Bulk properties of heavy ion collisions in Run 3 and 4: ATL-PHYS-PUB-2018-020
  iii. Jet energy loss in heavy ion collisions in Run 3 and Run 4: ATL-PHYS-PUB-2018-019
  iv. UPC with photons in Run 3 and 4: ATL-PHYS-PUB-2018-018
- **CMS :**
  i. Projected Heavy Ion Physics Performance: CMS-PAS-FTR-17-002
  ii. Open heavy flavor and quarkonia: CMS-PAS-FTR-18-024
  iii. Jet quenching measurements in pp & PbPb collisions : CMS-PAS-FTR-18-025
  iv. Predictions for small system flow observables : CMS-PAS-FTR-18-026
  v. Constraining nuclear parton distributions: CMS-PAS-FTR-18-027

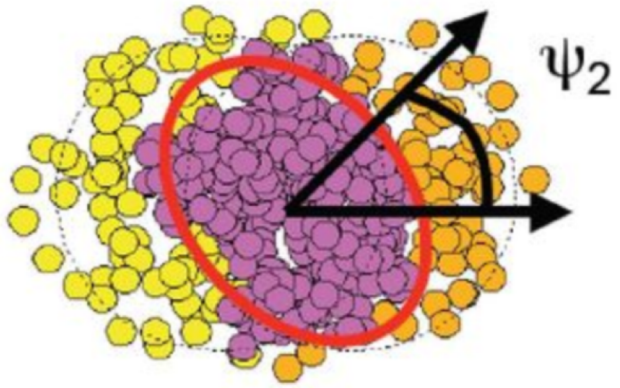
Summary

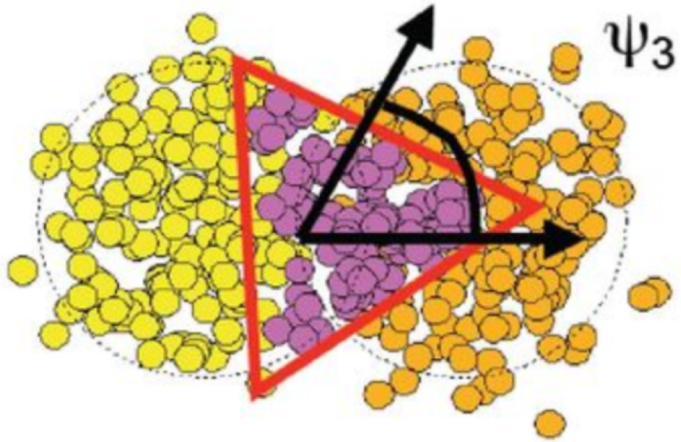
- A brief overview of heavy ion results is present
- Outline:
  - observation of flow-like phenomena in essentially all measured soft particle spectra, even in small systems;
  - observation of quantitatively-large quenching phenomena in essentially all measured hard hadronic observables in A–A collisions
- Prospects:
  - future improved measurements of flow and transport phenomena (i.e. measurements of soft heavy flavour and electromagnetic radiation);
  - improved experimental control over the system-size dependence of flow phenomena to better constrain under which conditions and in which kinematic regime ultra-relativistic p–A and A–A collisions show fluid dynamic behavior and where this picture fails;
  - analysis of hard probes in p–A and A–A collisions with the greater precision and kinematic reach accessible in future LHC runs;
  - probing the inner workings of the QGP by resolving its properties at shorter and shorter length scales is one of the main motivations for future experimentation with hard probes;
- Many more exciting results ahead of us!

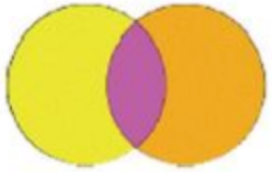
Backup

Charged-particle angular correlations in XeXe & PbPb

B. Alver and G.Roland, PRC 81 (2010) 054905



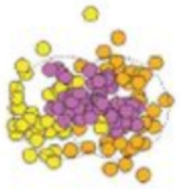




$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_R)\right)\right)$$

$$v_2 = \left\langle \cos\left(2(\phi - \psi_R)\right)\right\rangle$$

$$v_3 = 0$$

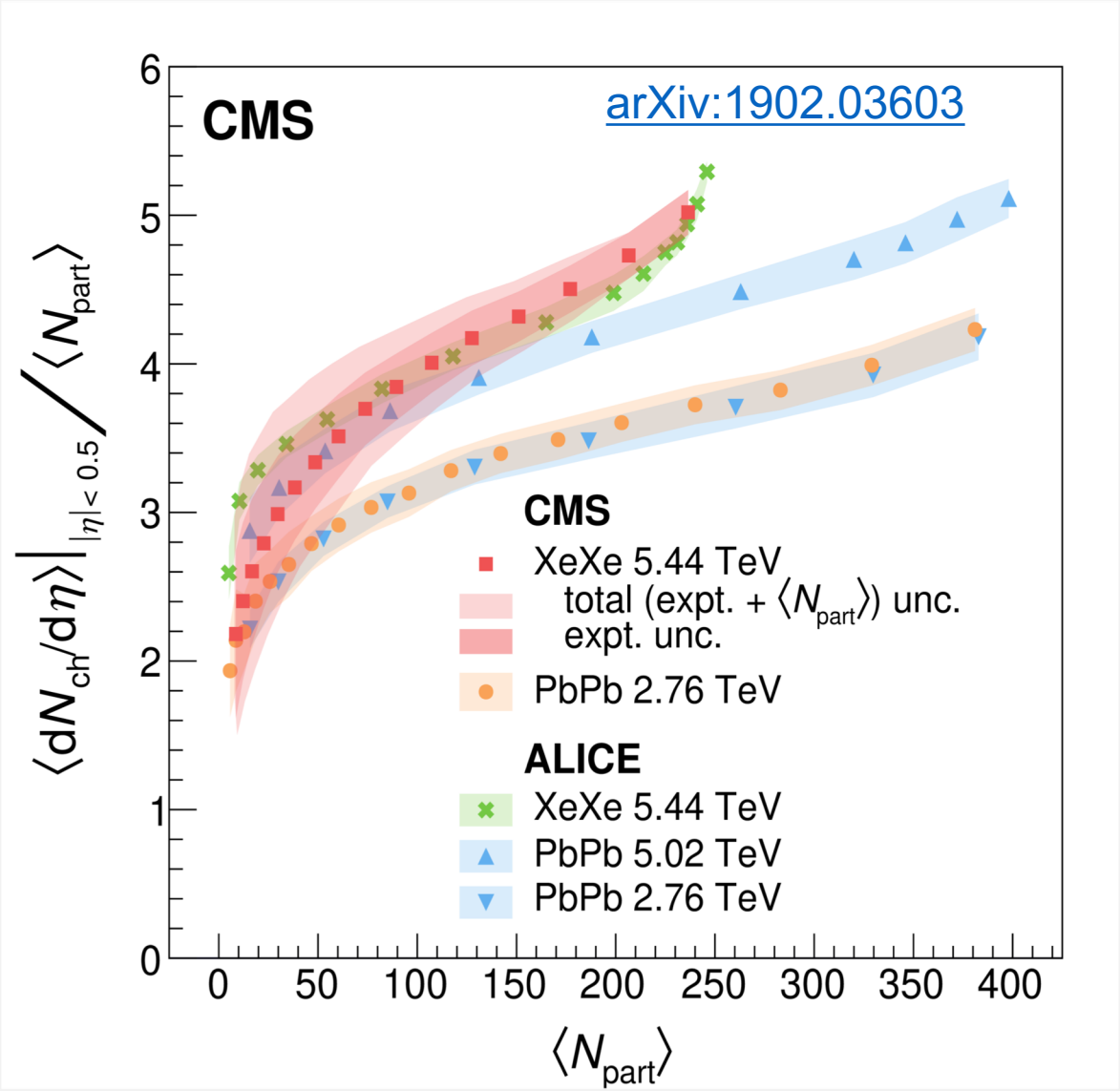


$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_n)\right)\right)$$

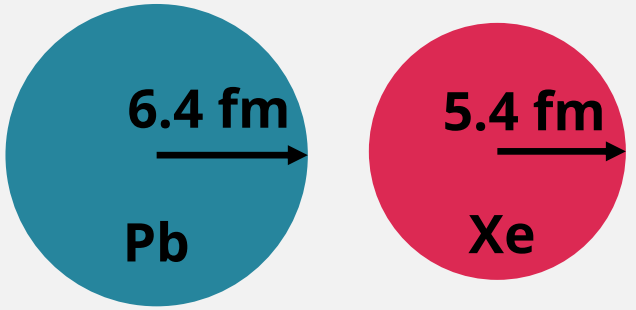
$$v_2 = \left\langle \cos\left(2(\phi - \psi_2)\right)\right\rangle$$

$$v_3 = \left\langle \cos\left(3(\phi - \psi_3)\right)\right\rangle$$

<dN/dη>



- N_{part} scaling is not describing bulk particle production: confirmed by Xe-Xe data
- More particles produced in central Xe-Xe collisions than in Pb-Pb with the same N_{part}
- N_{part} estimation procedure could be imperfect

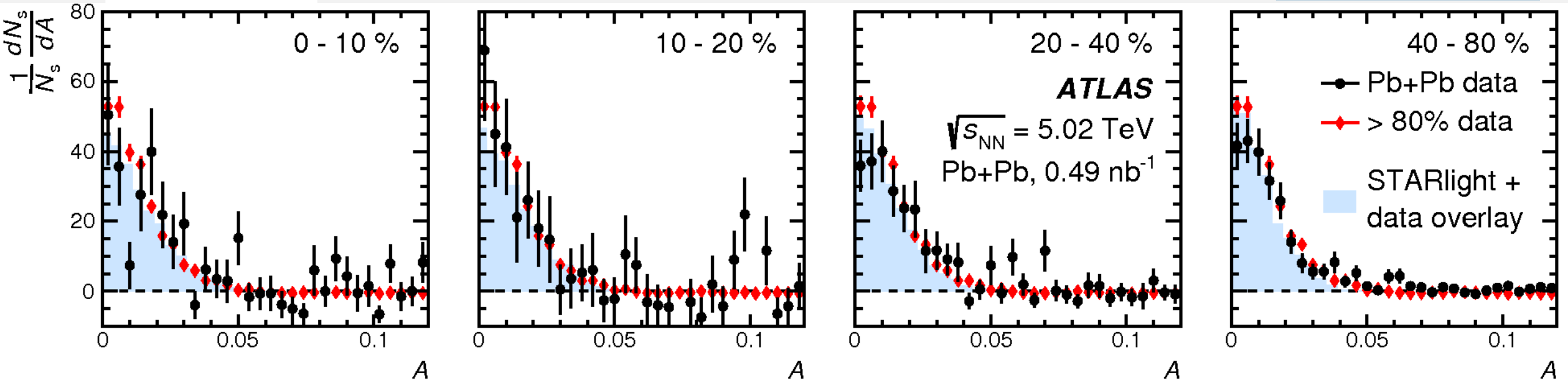


Non-UPC dimuons in Pb+Pb collisions

Ions are incredible source of photons: each photon flux scales with Z^2

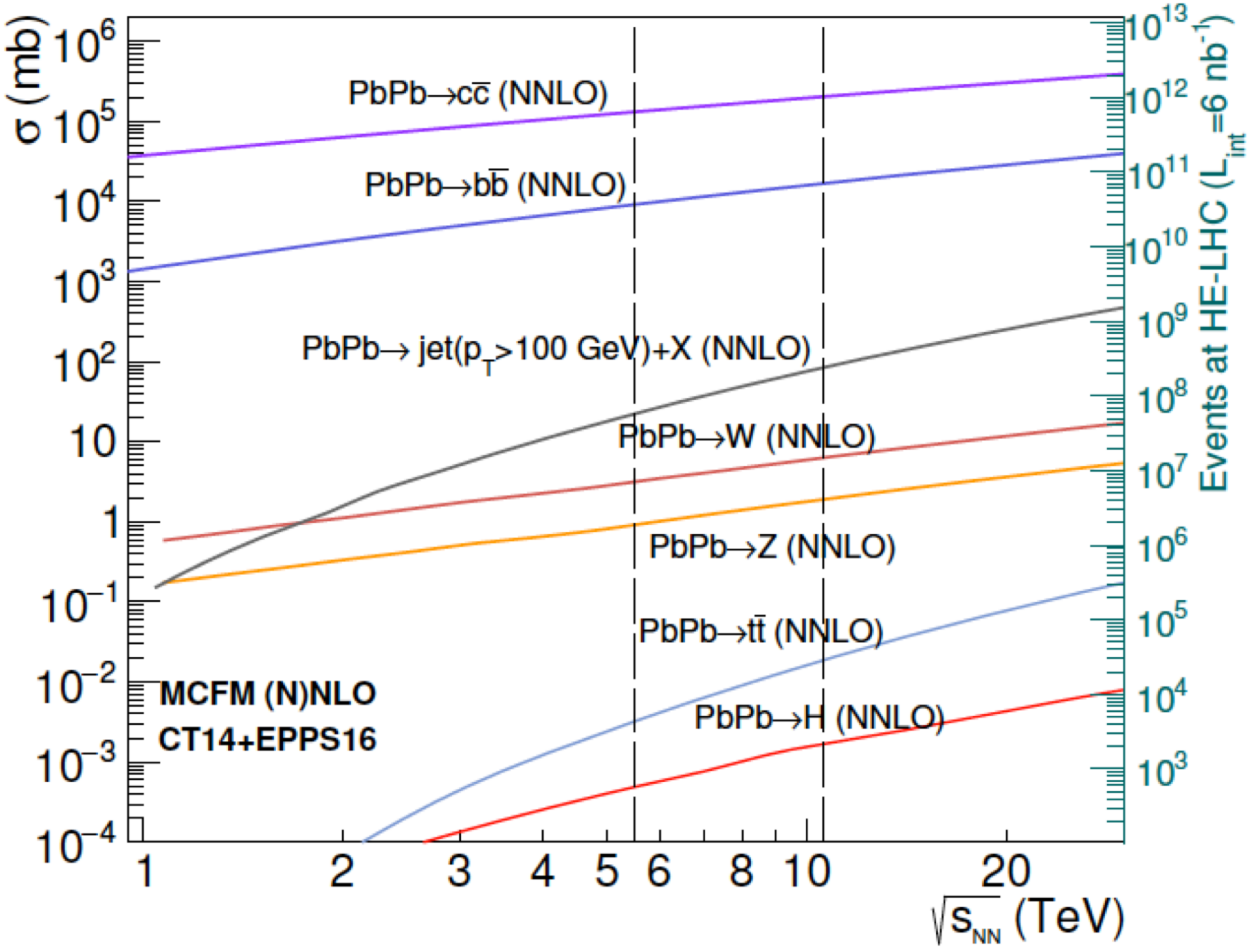
$$A \equiv \left| \frac{p_{\mathrm{T}}^{+} - p_{\mathrm{T}}^{-}}{p_{\mathrm{T}}^{+} + p_{\mathrm{T}}^{-}} \right|$$

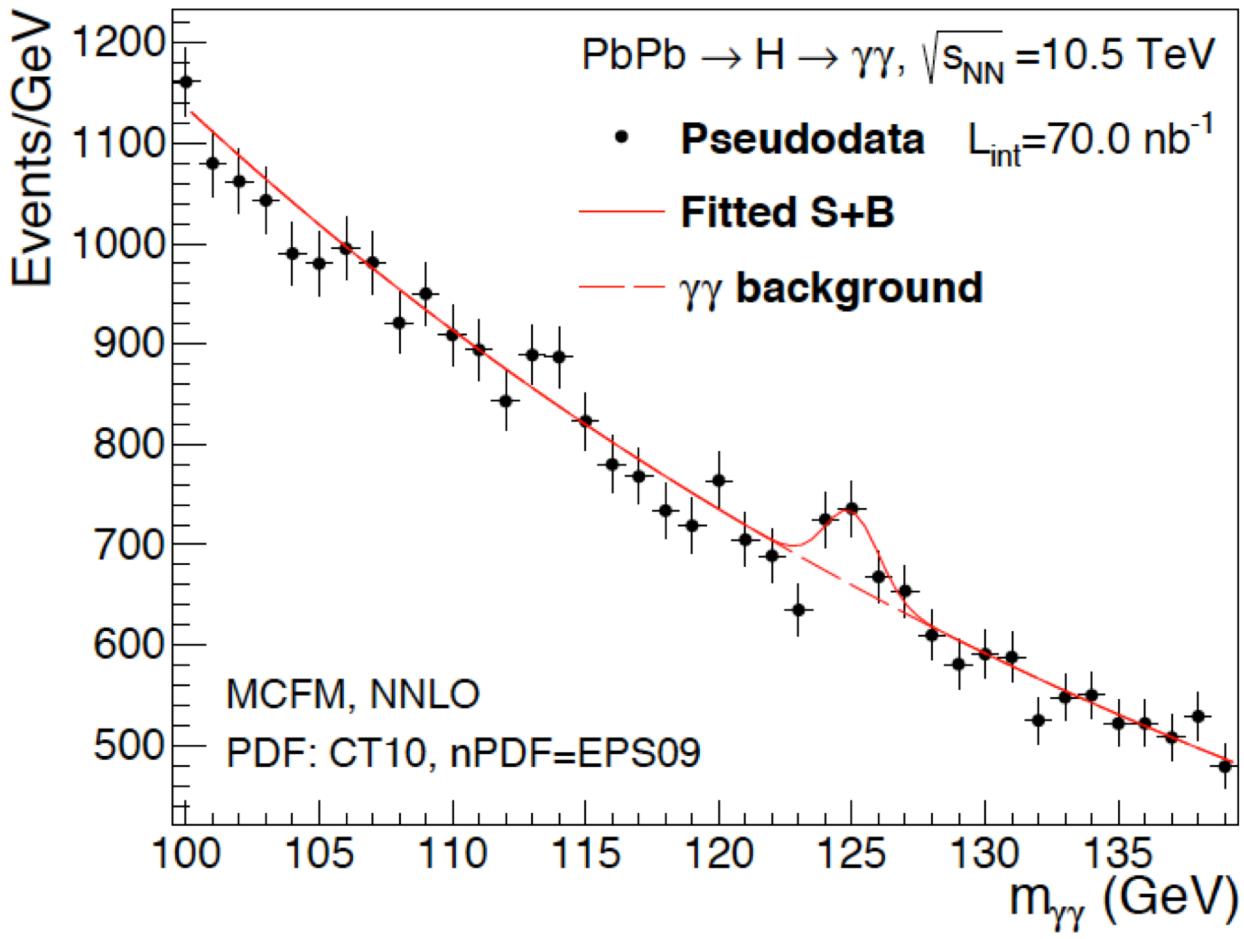
arXiv:1806.08708



- Centrality dependent broadening of dimuon acoplanarity
- Modification due to re-scattering of muons in the QGP?
- First observation of EM interactions with QGP?

AA collisions @ HE-LHC ($\sqrt{s_{NN}}$=10.6 TeV)





- Nucleus program at future HE-LHC can provide $t\bar{t}$ and Higgs boson measurements