Soft and Hard Probes

(selection of recent results)

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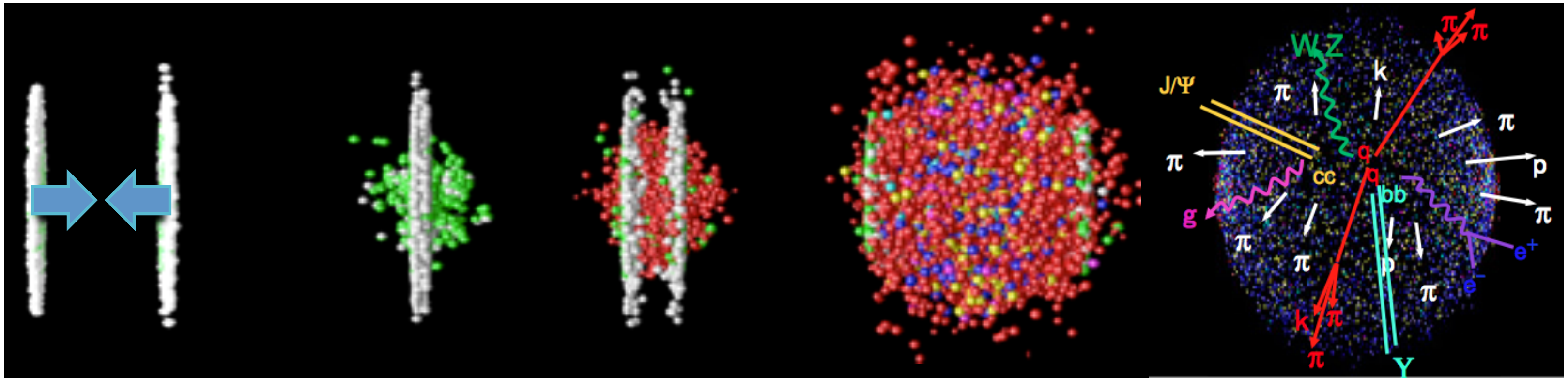
on behalf of **ALICE**, **ATLAS**, **CMS** and **LHCb** collaborations

LHCP Bologna 2018

Introduction



- Use variety of final states to provide insight into different stages of HI collisions

- **Soft** probes & bulk particle production
  - Initial conditions & geometry
  - Collective effects, thermalization
- **Hard** probes
  - Colour objects e.g. jets -> partonic energy loss in QGP
  - Colourless objects e.g. EW bosons -> ‘standard candles’, nPDFs

Also:
pp and p+Pb collisions
->reference to Pb+Pb and
to understand initial-state effects

Xe+Xe vs Pb+Pb collisions (NEW)
->role of geometry in HI collisions

Centrality estimation

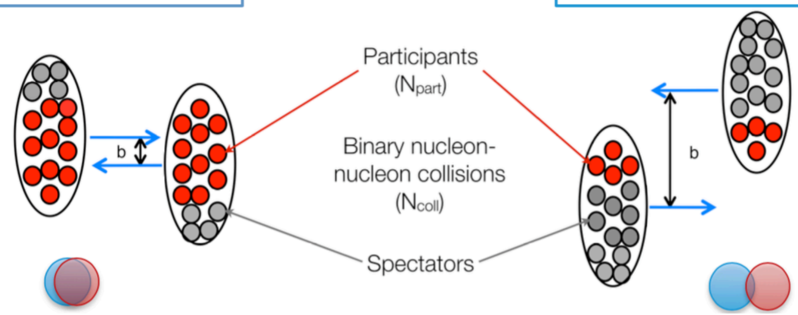
- A+A collisions can be characterized by the centrality, quantified using the energy in FCal/VZero etc.

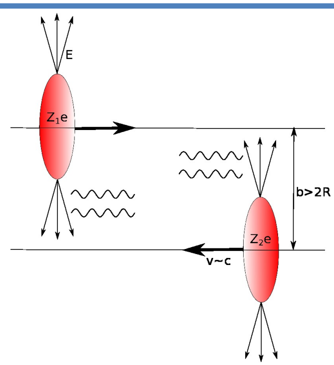
Central collisions

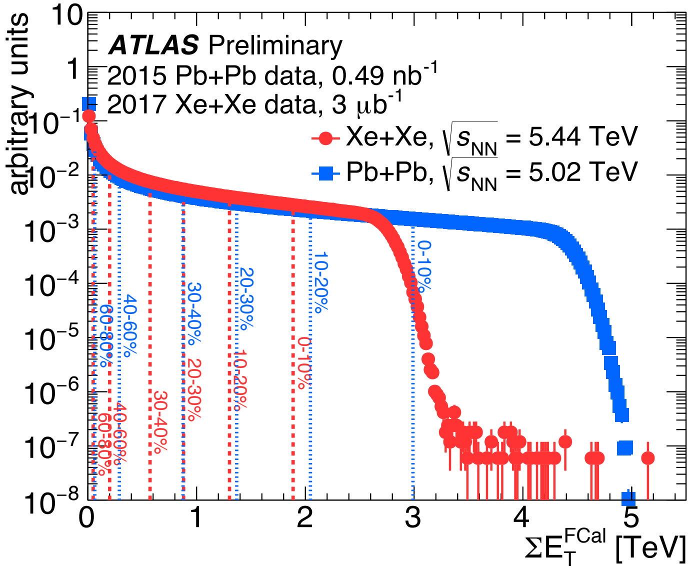
Peripheral collisions

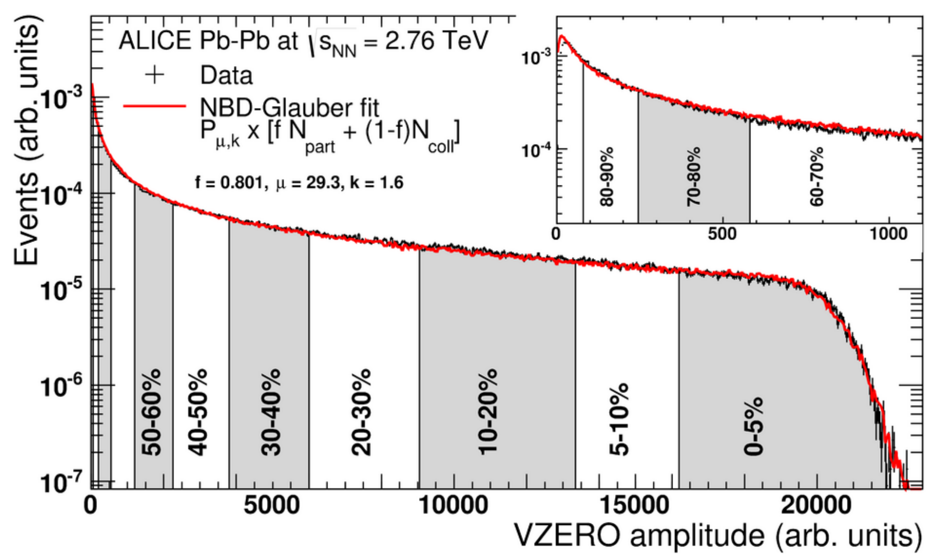
Ultra-peripheral collisions

0-10% corresponds to the most central collisions





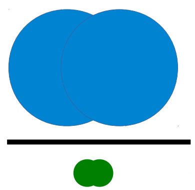




Nuclear modification factor

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

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



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

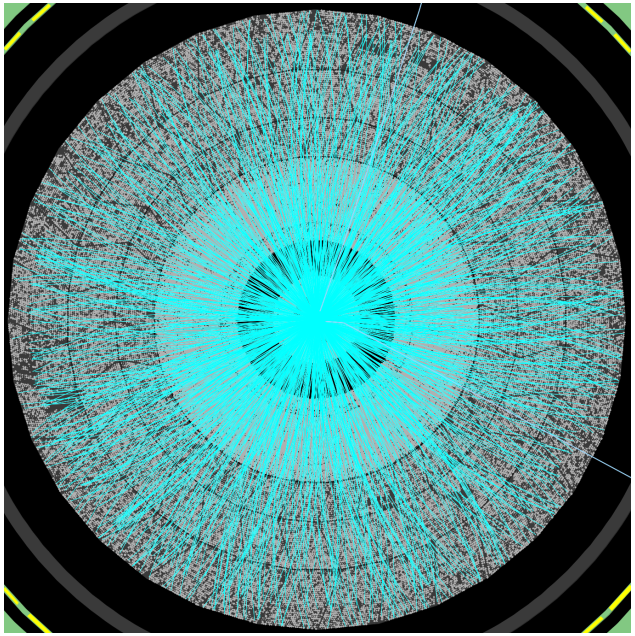
QCD in medium

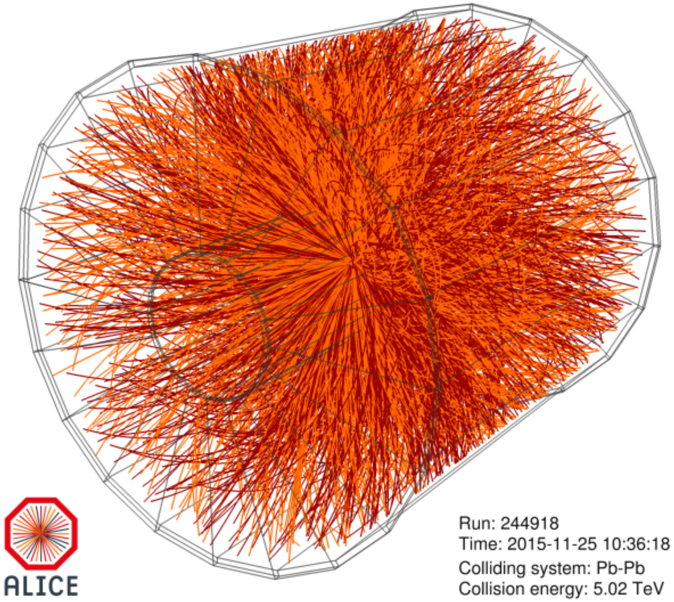
QCD in vacuum

Yields in A+A

pp reference

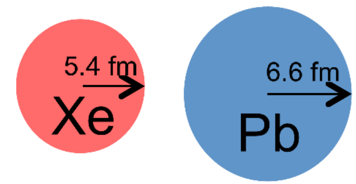
(I) Inclusive and identified hadron production



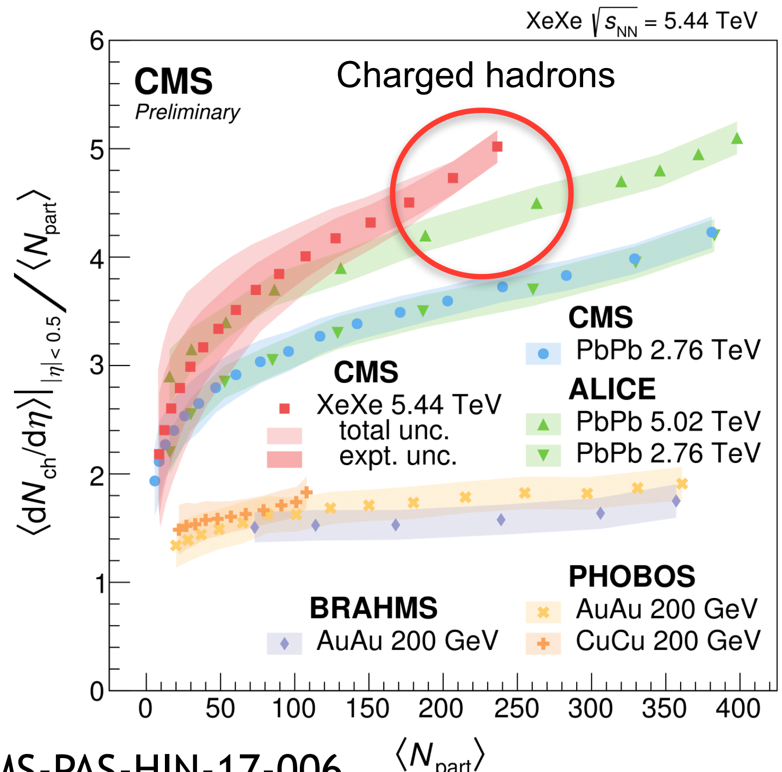


⟨dN$_{ch}$/dη⟩ in Xe+Xe

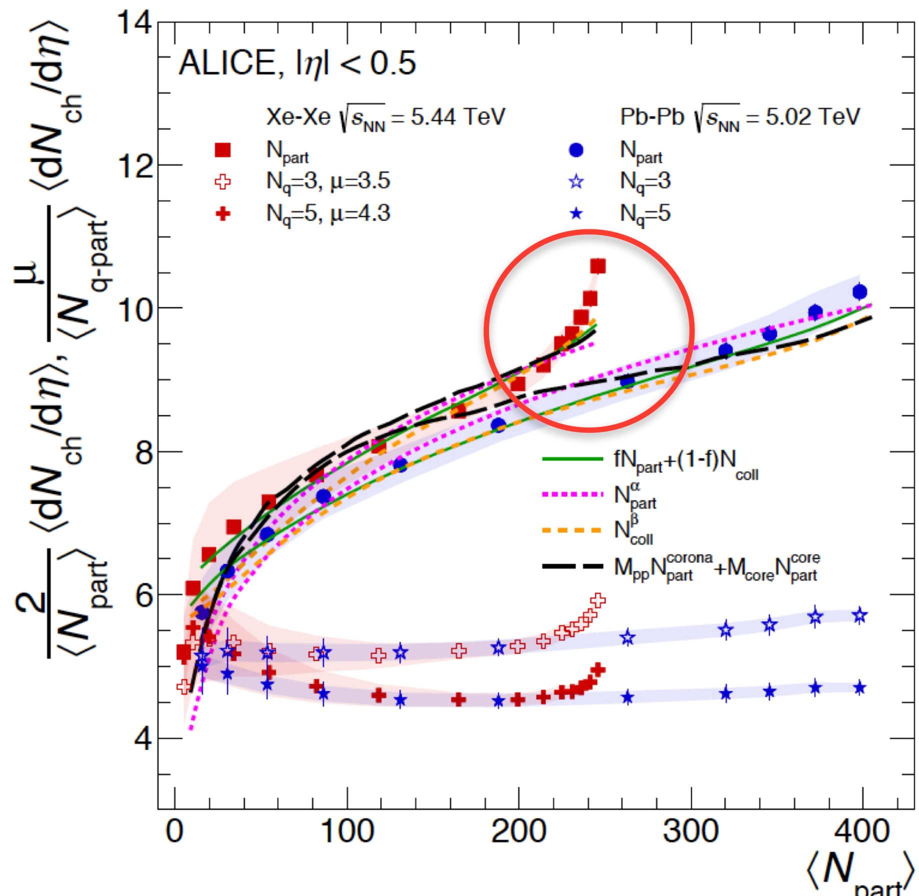
- Inclusive charged-particle multiplicity distributions
  - **<Multiplicity>/N$_{part}$ ‘scales’** (approximately) between **Xe+Xe** and **Pb+Pb**
  - **Sharper increase** for central collisions -> Origin not fully understood?



arXiv:1805.04432



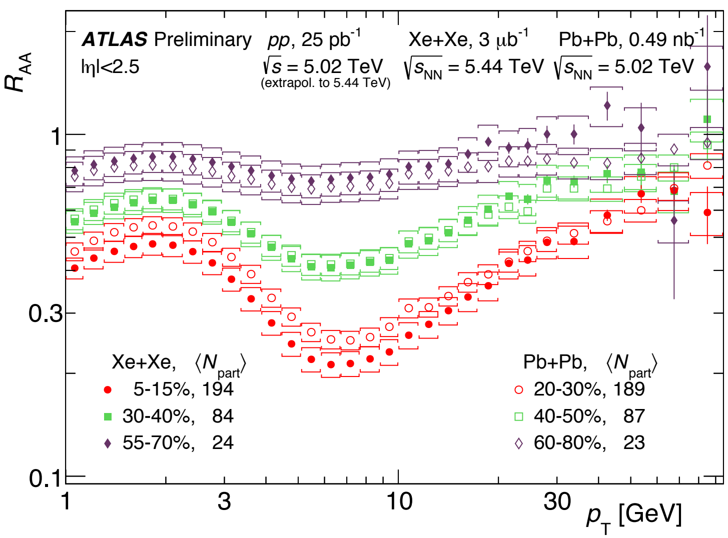
CMS-PAS-HIN-17-006



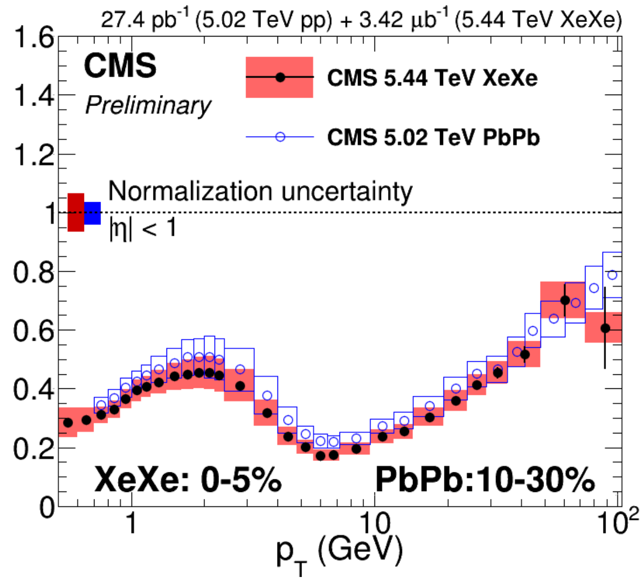
Charged-hadron R_{AA} in Xe+Xe

- R_{AA} in **Xe+Xe** collisions is **similar** to R_{AA} in **Pb+Pb** collisions at similar $\langle N_{part} \rangle$ or $\langle dN_{ch}/d\eta \rangle$

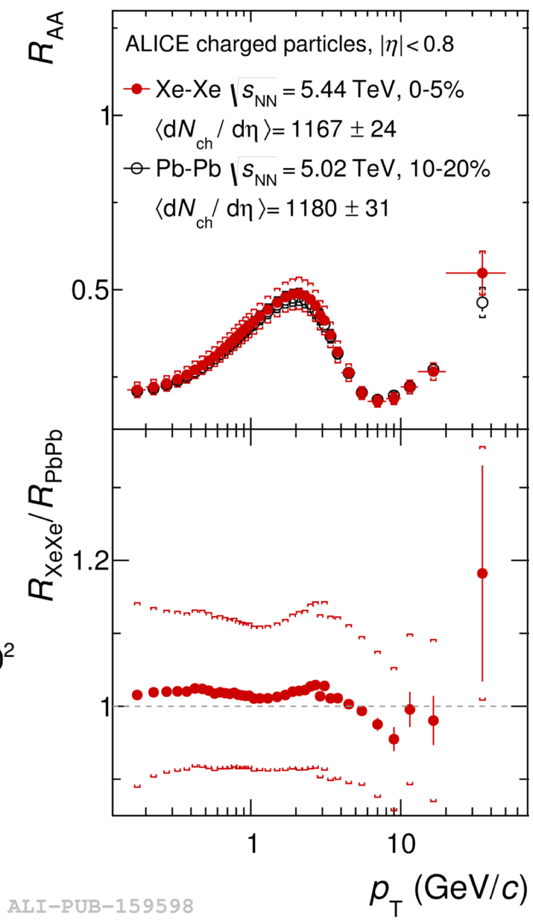
ATLAS-CONF-2018-007



CMS-PAS-HIN-18-004



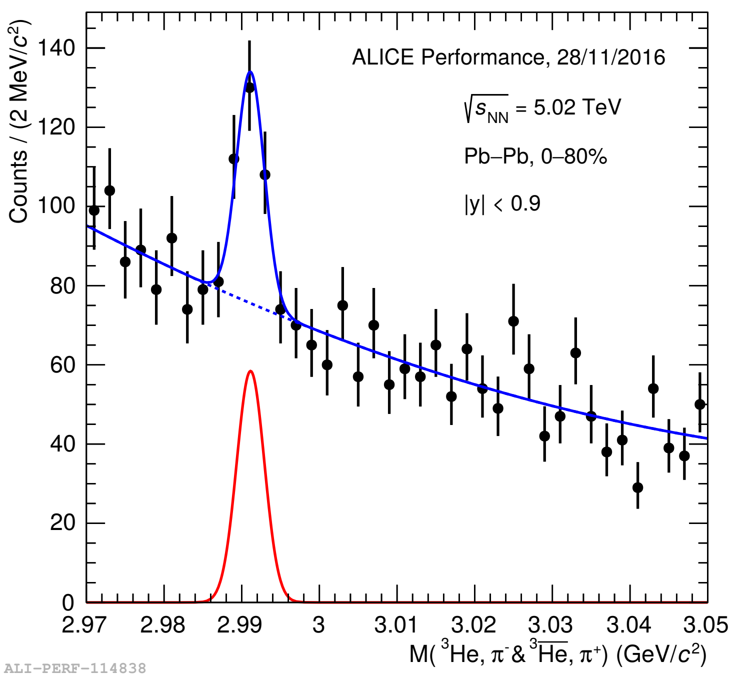
arXiv:1805.04399

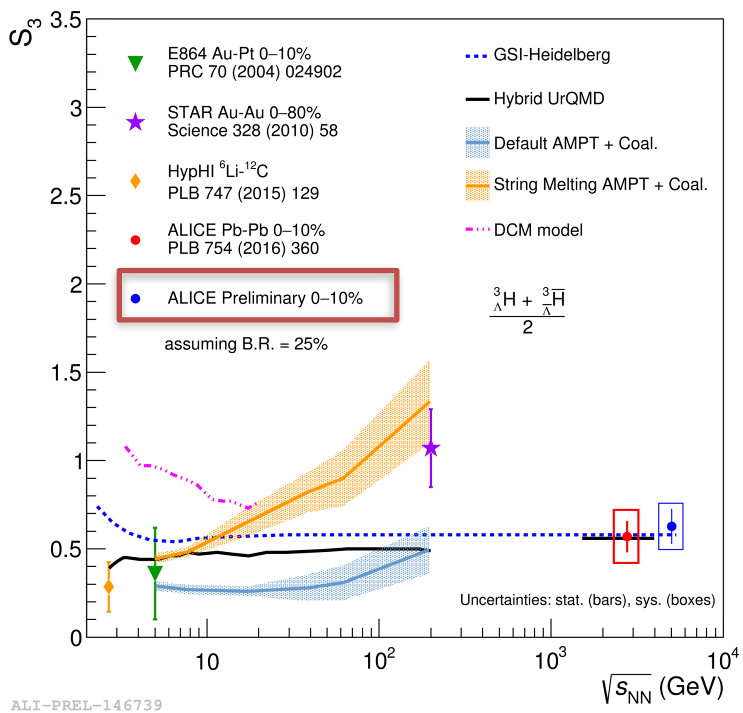


$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \equiv \frac{[medium]}{[vacuum]}$$

(Hyper-)nuclei production in Pb+Pb

- Yields of (anti-)(hyper-)nuclei are measured at 5.02 TeV
  - Hypertriton production identified via ^{3}**He + π±** decays
- Thermal model vs final-state coalescence
  - **Strangeness population factor** -> independent on the chemical potential of the particles
  - New data **compatible** with **2.76 TeV measurement** and **equilibrium thermal models**

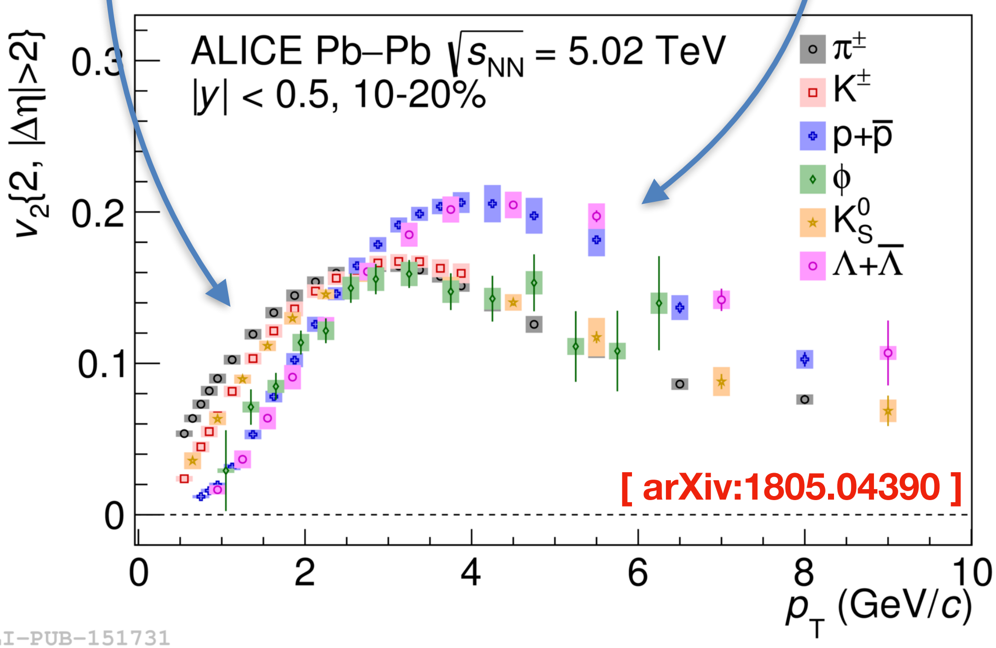


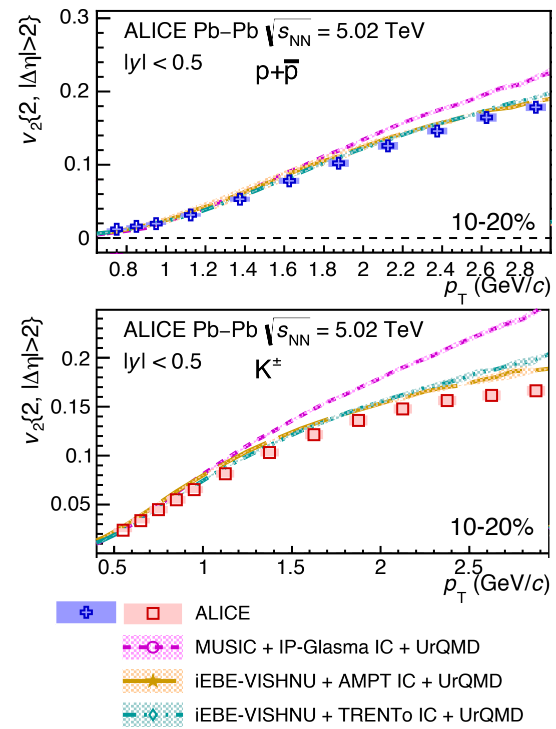


$$S_3 = \frac{^{3}_{\Lambda}\mathrm{H}}{^{3}\mathrm{He}} \times \frac{\mathrm{p}}{\Lambda}$$

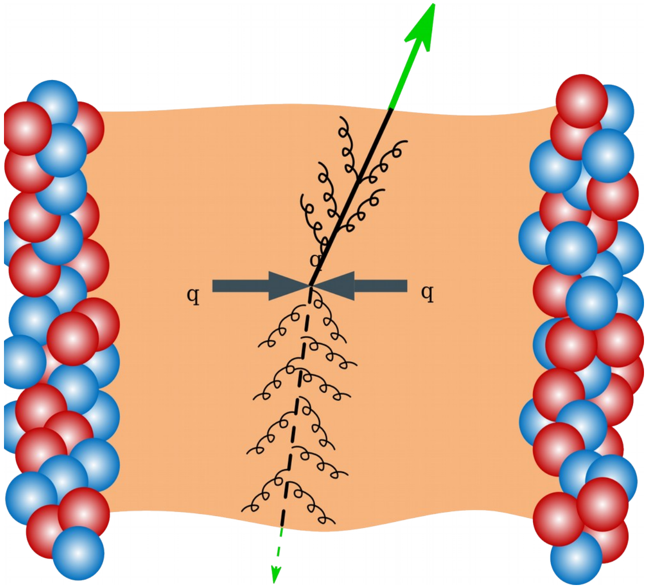
Flow of identified particles in Pb+Pb @5.02 TeV

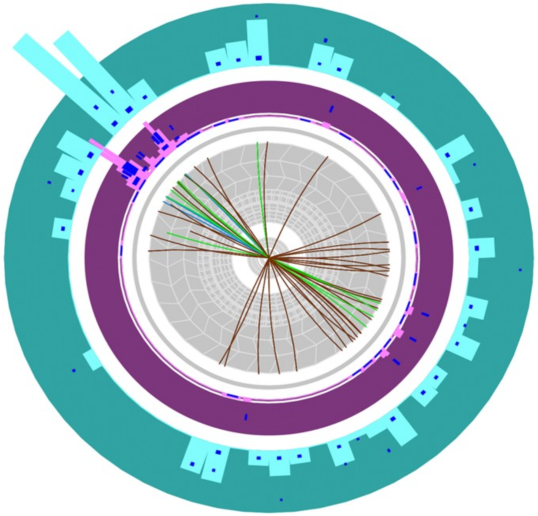
- Comprehensive measurement of flow coefficients (identified hadrons)
  - **$\pi^{\pm}$, $K^{\pm}$, p, Λ, K_0^S**, and **ϕ-mesons** are studied
  - **v_2-v_4** coefficients extracted as a function of **p_T** and **centrality**
- Mass ordering & baryon/meson grouping is observed
  - **Hydro calculations** (coupled to hadronic cascade model, UrQMD) describe the data reasonably well





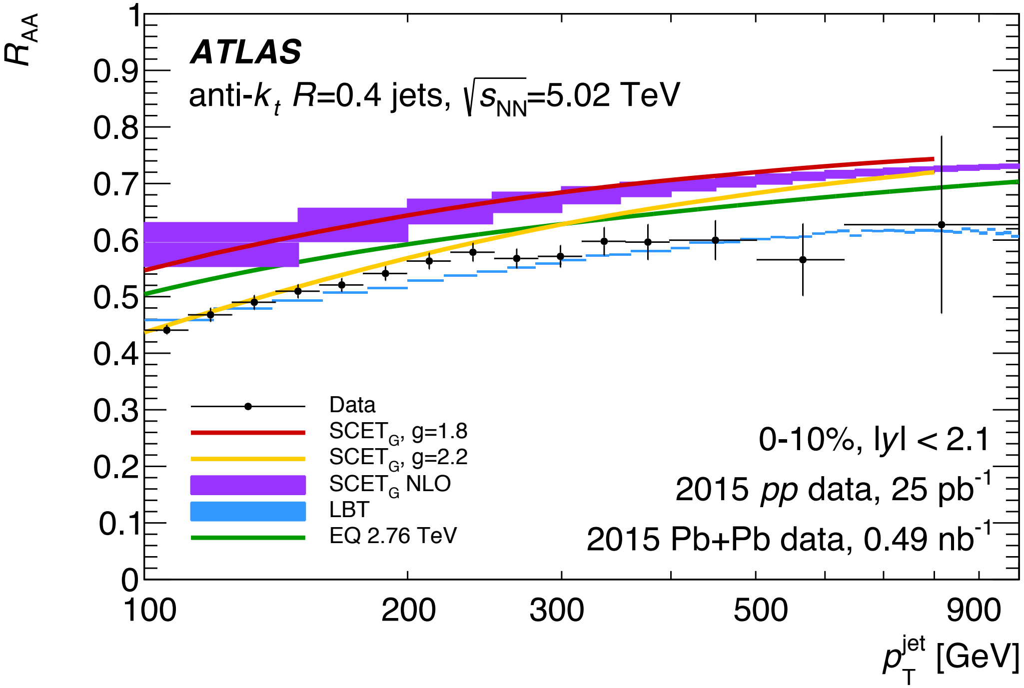
(II) Jet-medium interactions

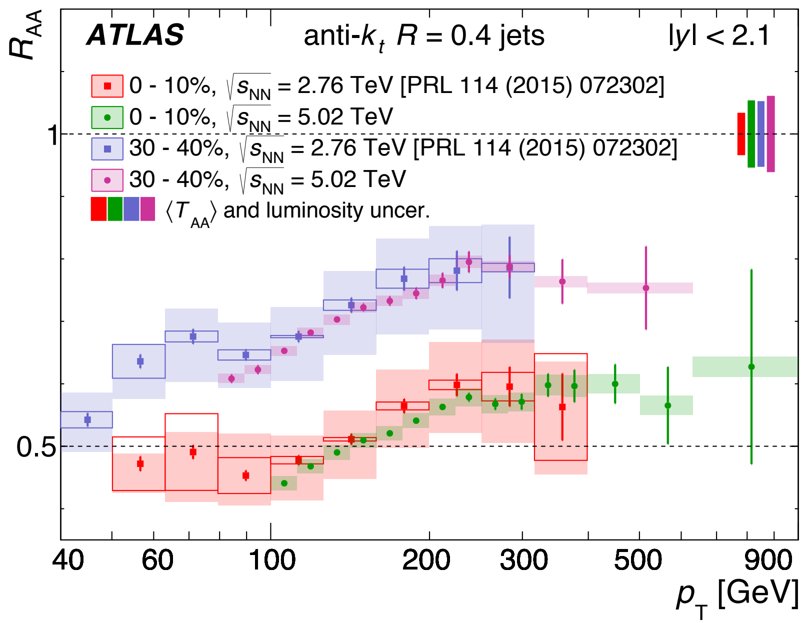




Jet R_{AA} in Pb+Pb @5.02 TeV

- "Final" ATLAS results on jet suppression from 2015 data
- Comparison with 2.76 TeV results
  - **No $\sqrt{s_{NN}}$ dependence** seen
- Comparison with theory predictions
  - **All models reproduce trends**





arXiv:1805.05635

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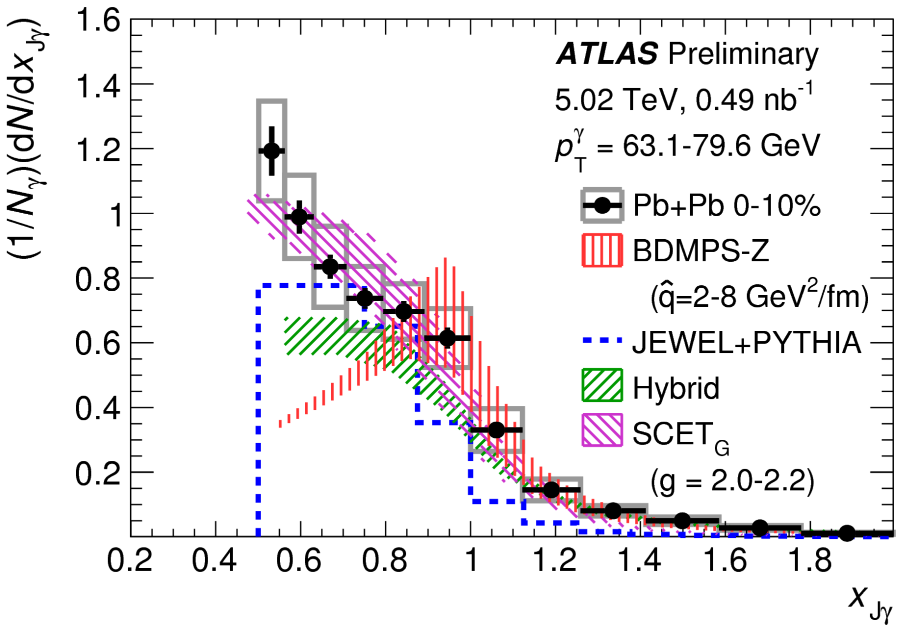
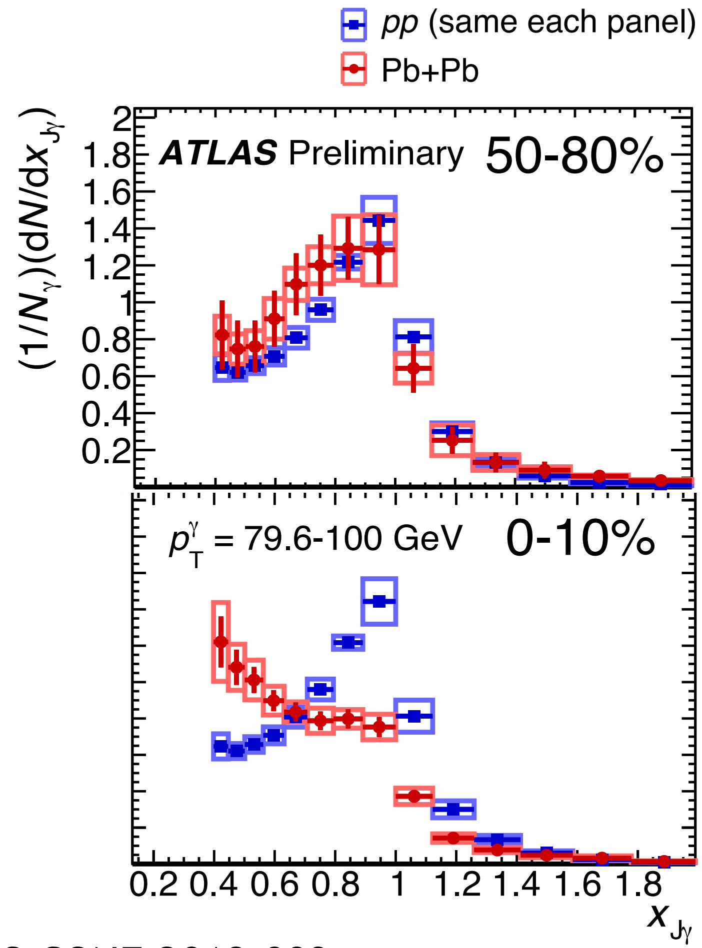
Photon-tagged jet asymmetry @5.02 TeV

- Isolated photons act as **calibration probes** in HI collisions
  - Initial parton energy constrained by E_T^γ
- Measure $\mathbf{x_{J\gamma} = p_T^j/E_T^\gamma}$ in Pb+Pb/pp
  - $x_{J\gamma}$ **fully unfolded** for detector effects
  - Centrality and E_T^γ-dependence is studied
- Data qualitatively described by models

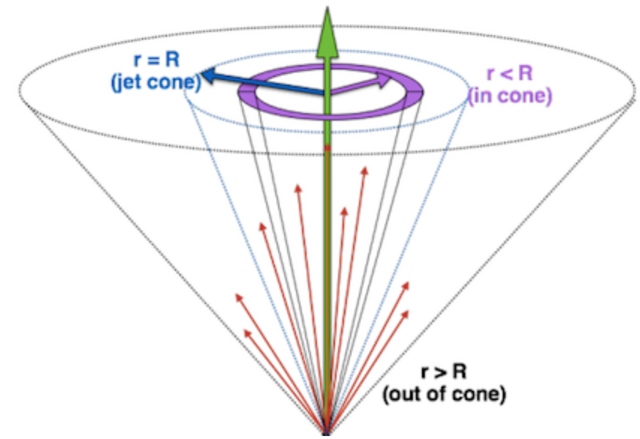


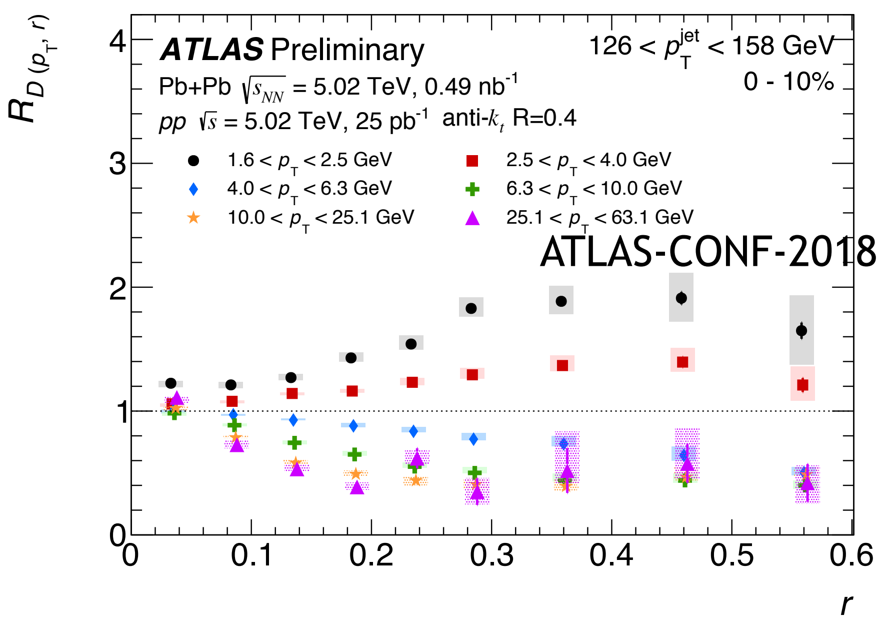


ATLAS-CONF-2018-009

Jet shapes Pb+Pb @5.02 TeV

- Charged particles **inside** and **around** a jet
  - More differential look at jet FF
- As collisions become more central:
  - p_T < 4 GeV: **enhancement**
  - p_T > 4 GeV: **depletion**
- Energy lost is transferred to particles with **p_T < 4 GeV** and **larger radial distances**





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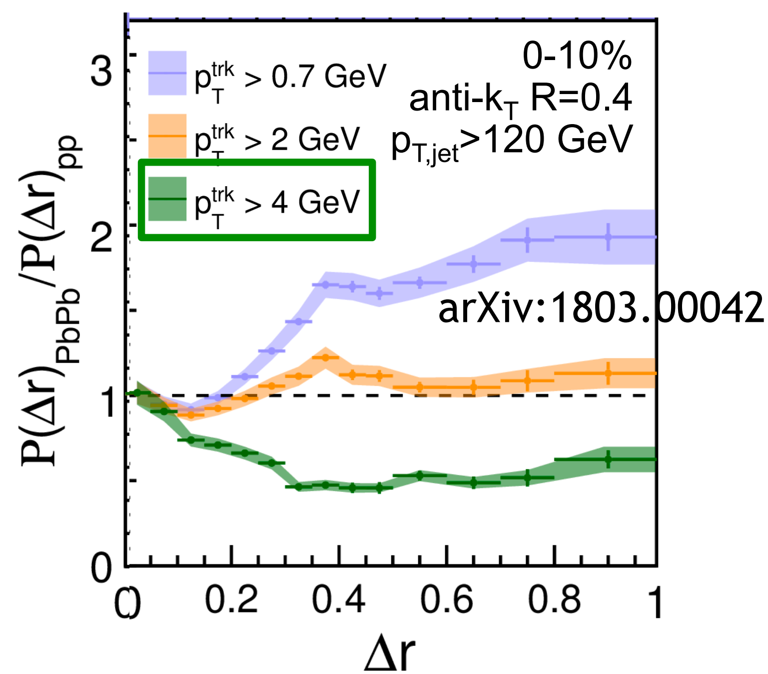
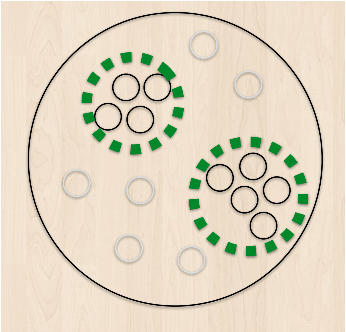


arXiv:1803.00042

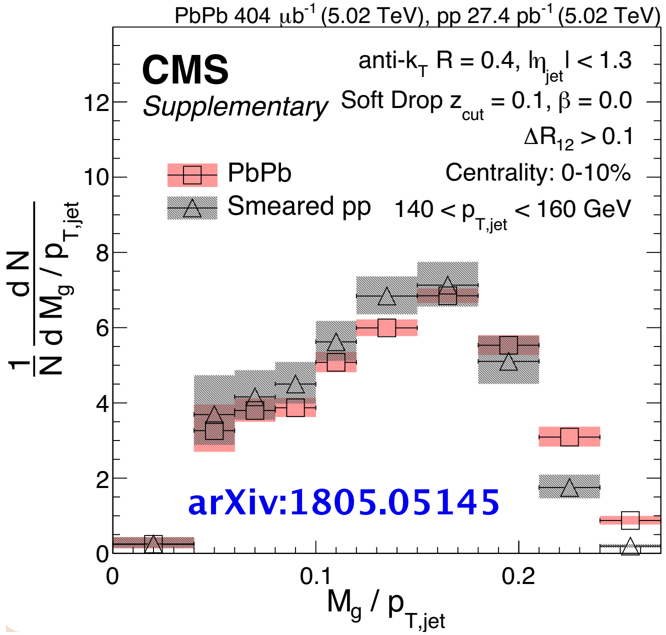
Jet substructure in Pb+Pb

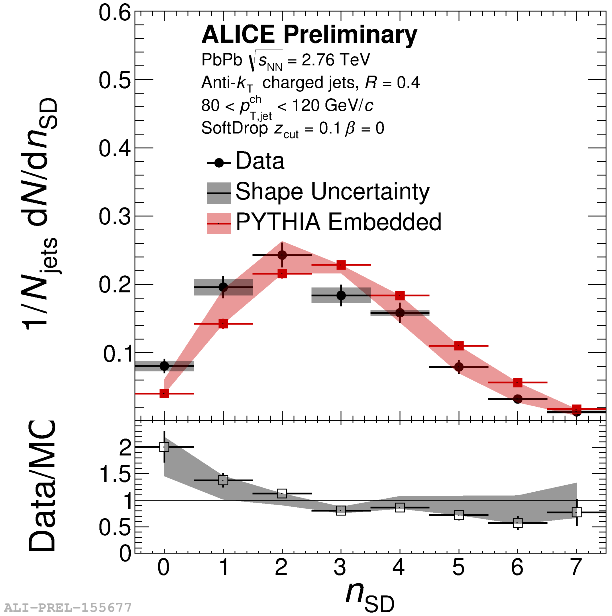
- **Jet grooming** techniques within HI environment
- Further "clean-up" of jets
  - Iterative declustering
  - **Soft drop** condition:

$$z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{cut} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$$

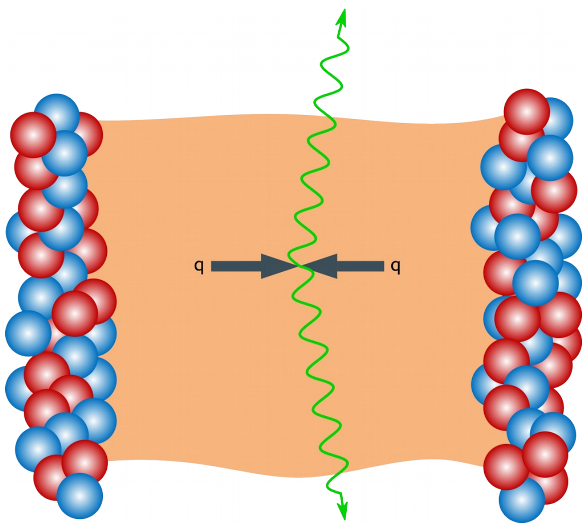


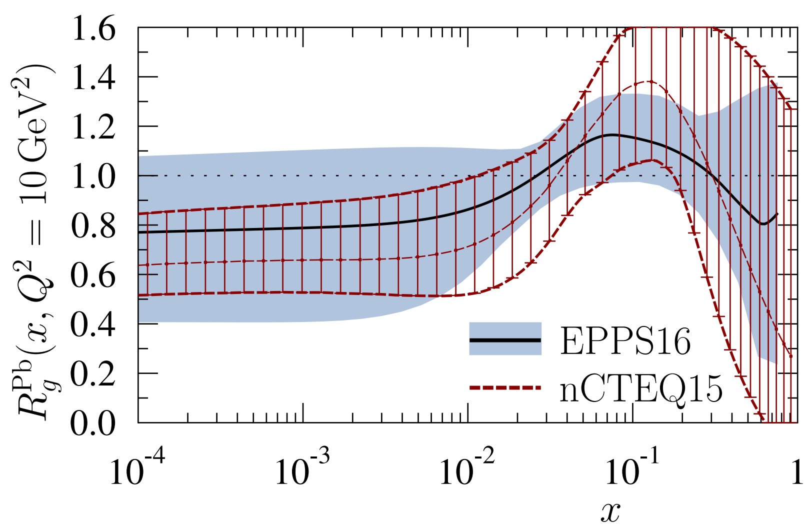
- In general:
  - No modification for the mass of the core of the jet seen
  - No enhancement in the number of splittings passing Soft drop in medium





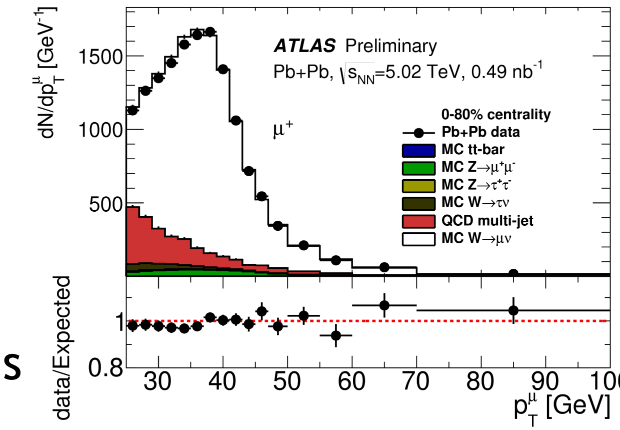
(III) Electroweak probes





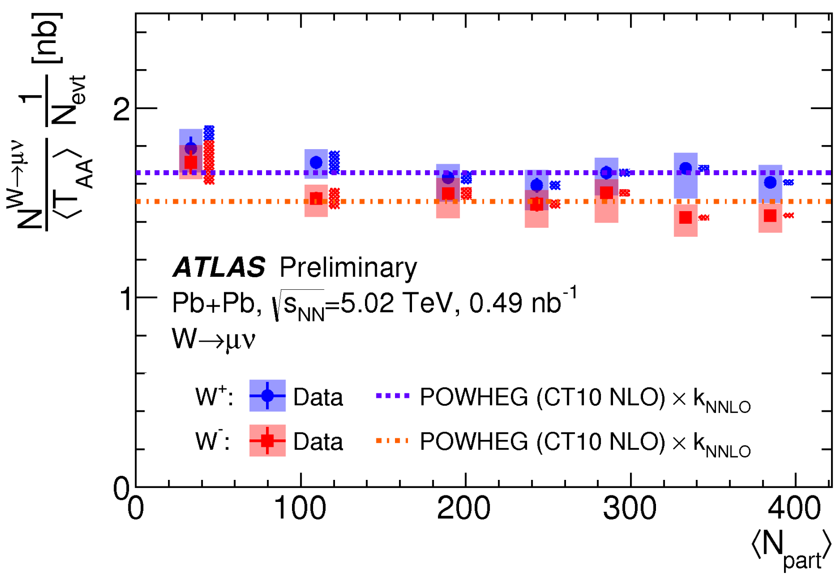
W boson production in Pb+Pb

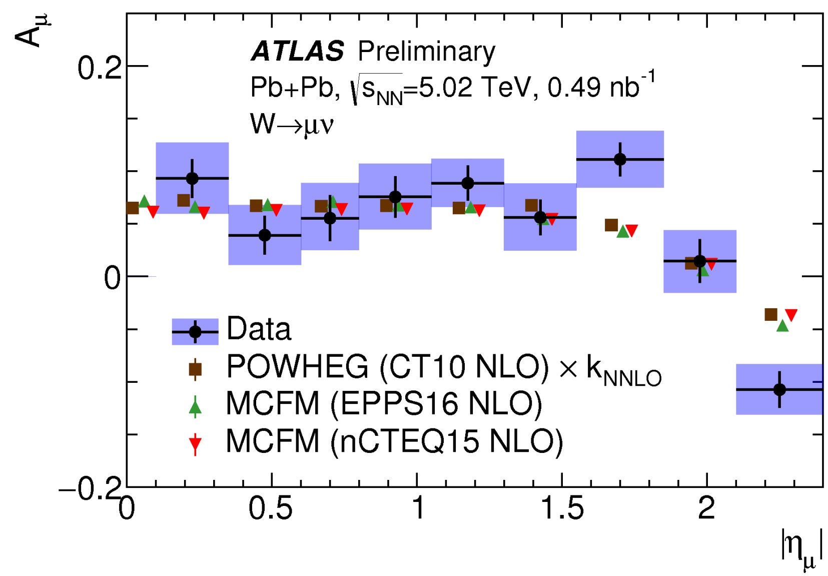
- W boson yields in μ channel @5.02 TeV
  - Statistics improved by **x4** wrt Run-1



- Yields/<T_{AA}> **flat** with <N_{part}>
  - Scaling with the number of binary collisions holds
- Lepton charge asymmetry consistent with theory
  - Some small deviations in the forward direction

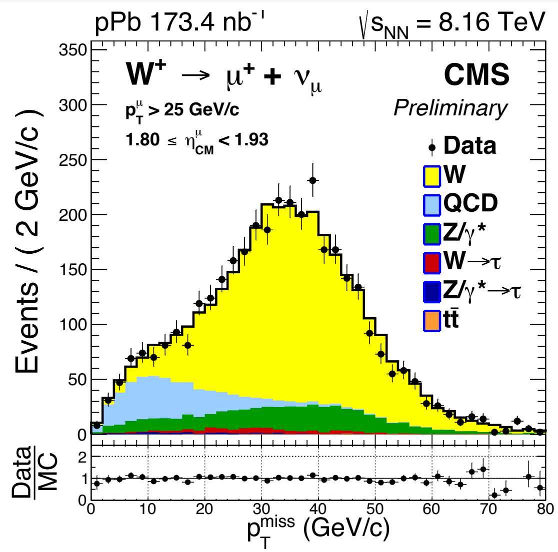
ATLAS-CONF-2017-067

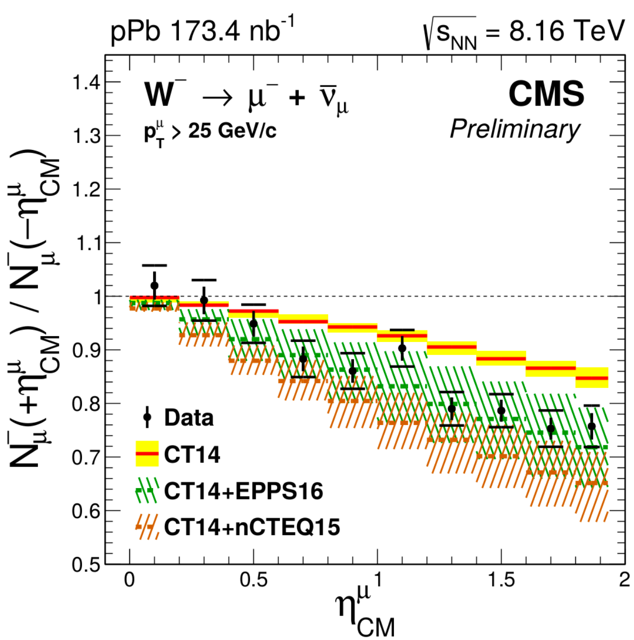


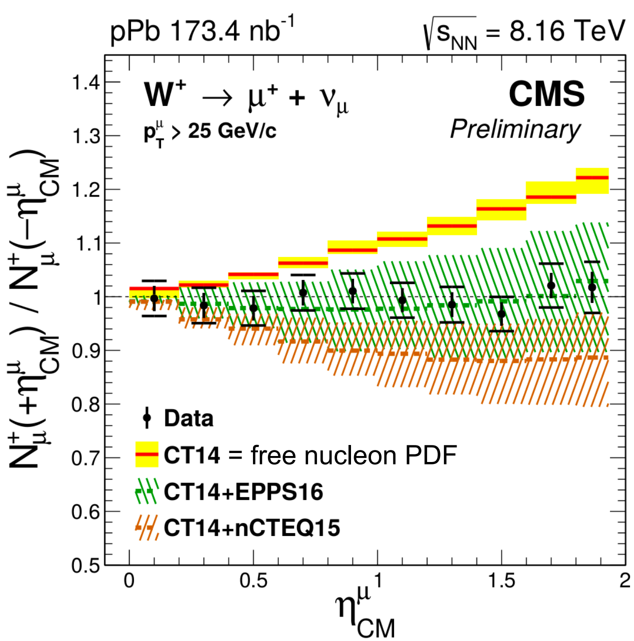


W boson production in p+Pb

- W boson yields in μ channel @8.16 TeV
- Comparison to calculations with nPDFs from EPPS16 and nCTEQ15
  - Nuclear modification needed to describe the data (free-nucleon PDF excluded at **>7σ**)
- Measurement constraints **quark** and **antiquark** nPDFs at $\mathbf{10^{-3} < x < 10^{-1}}$





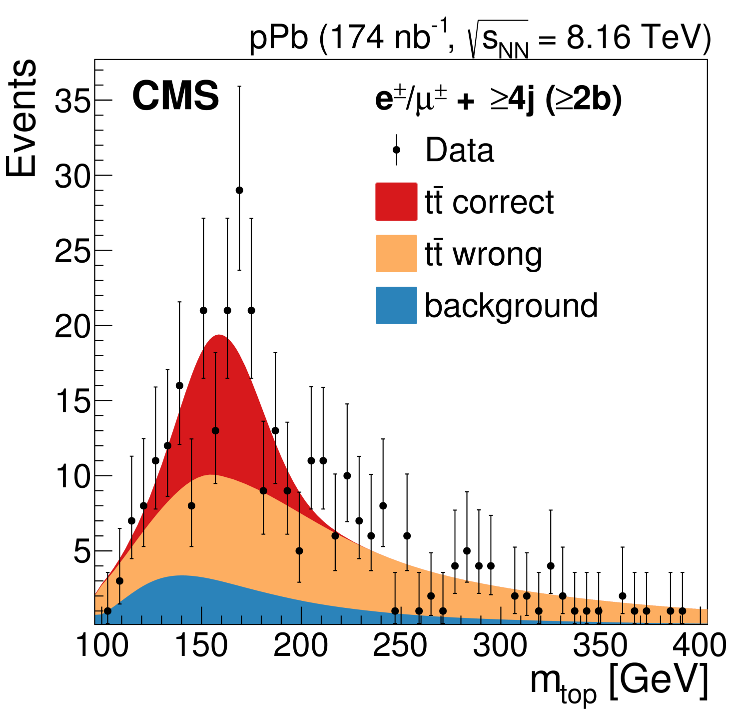


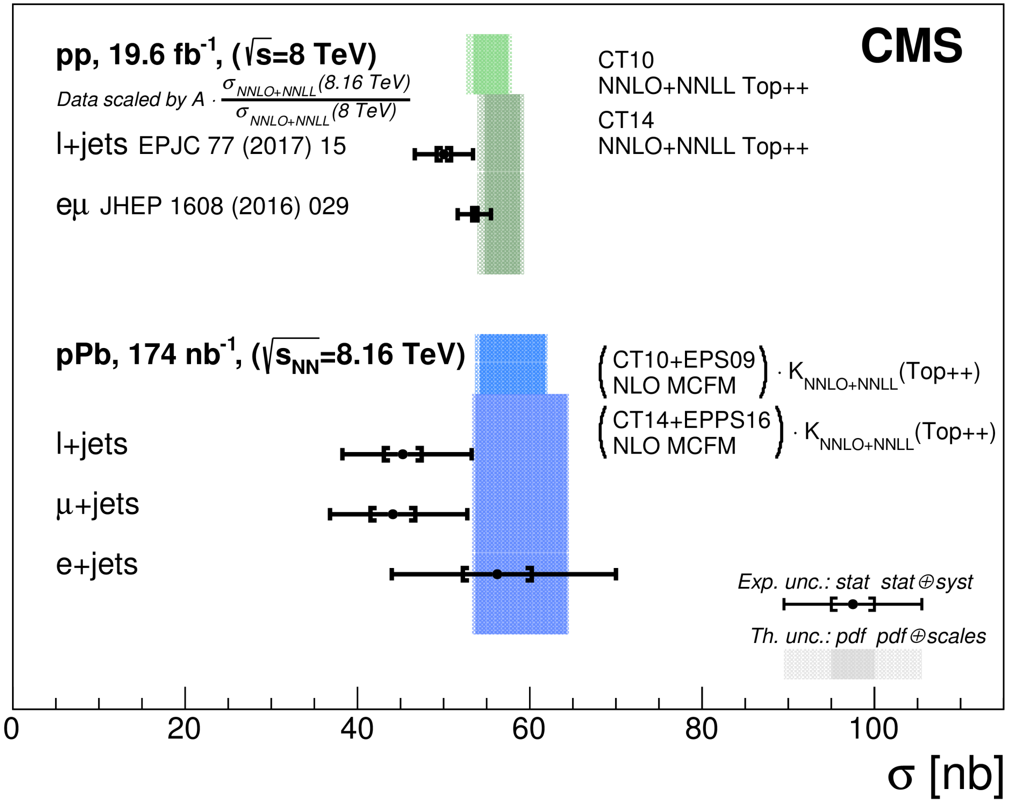
CMS-PAS-HIN-17-007

Top-quark pair production in p+Pb @8.16 TeV

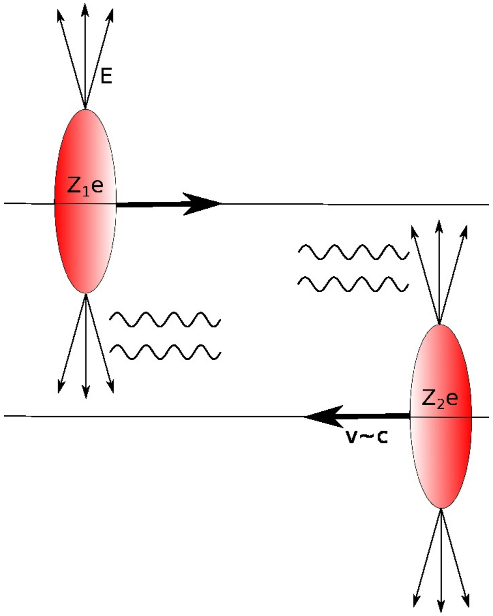
- **First observation** of the top quark production in **pA** collisions
- **Lepton+jets** channel is studied
- Cross-sections compatible with pQCD calculations including nPDFs

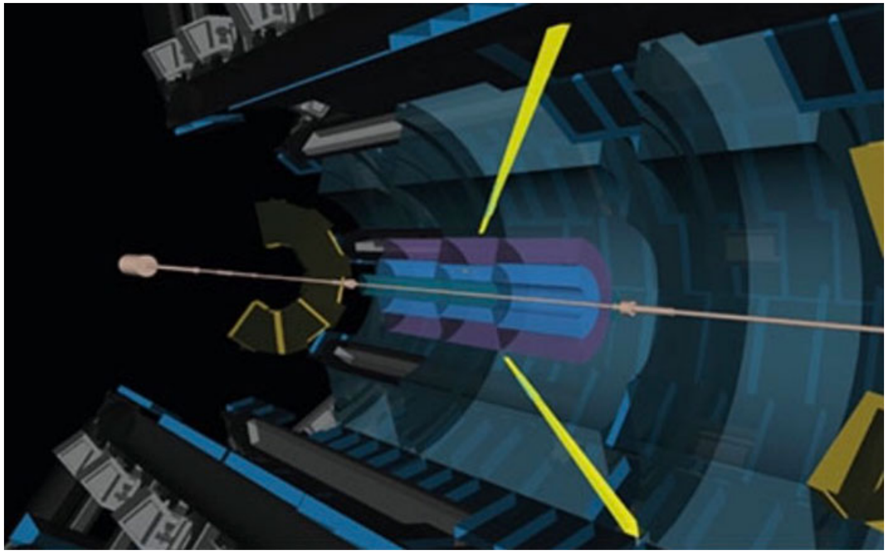
PRL 119 (2017) 242001





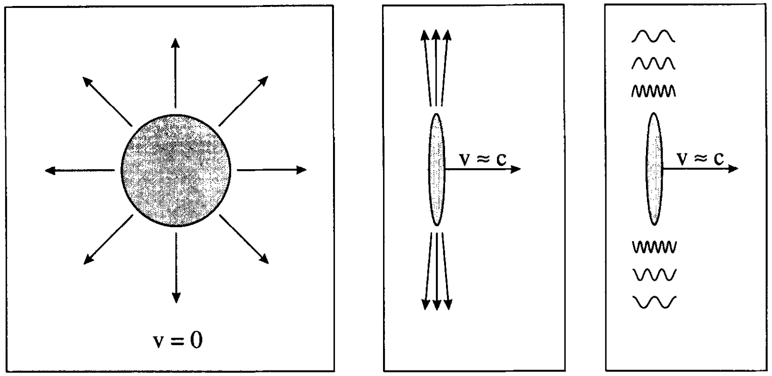
(IV) EM-induced reactions



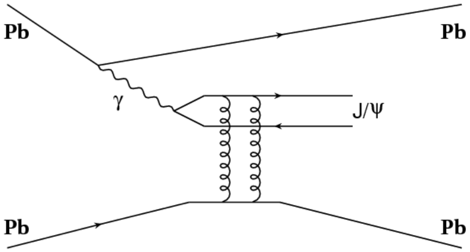


Quasi-real photons from Pb

- Boosted nuclei are intense source of quasi-real photons
- **Coherent** photon flux
  - **Q ~ 1/R ~ 0.06 GeV** for Pb @ LHC
  - **E_{max}** ≲ **γ/R ~ 80 GeV** @5.02 TeV
  - Each photon flux scales with **Z^2**



- Various types of interactions possible:



Photon-pomeron
(e.g. exclusive J/Psi)

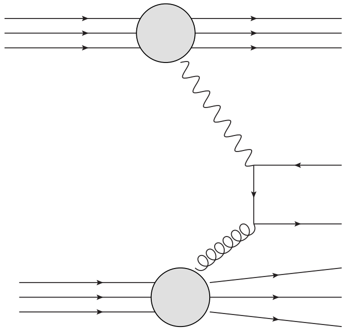
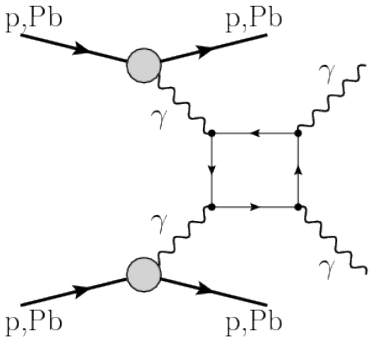


Photo-nuclear
(e.g. photoproduction of jets)



Photon-photon
(e.g. LbyL scattering)

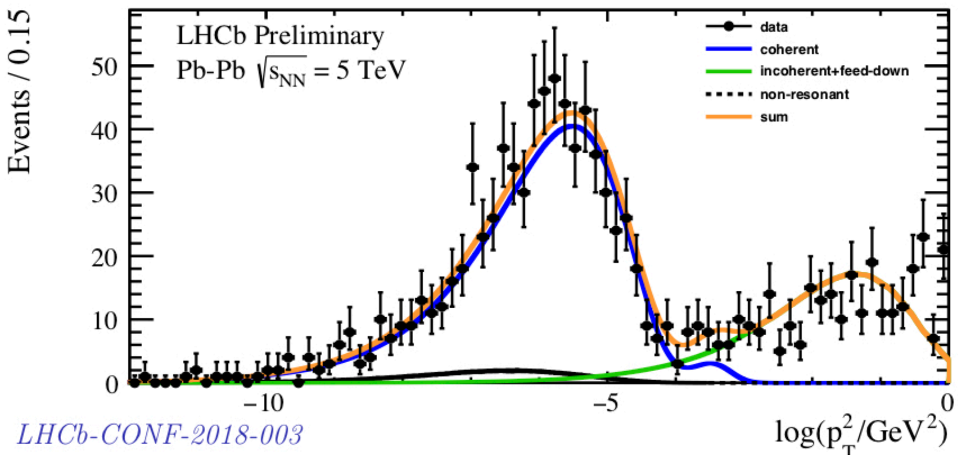
Exclusive J/ψ in Pb+Pb @5.02 TeV

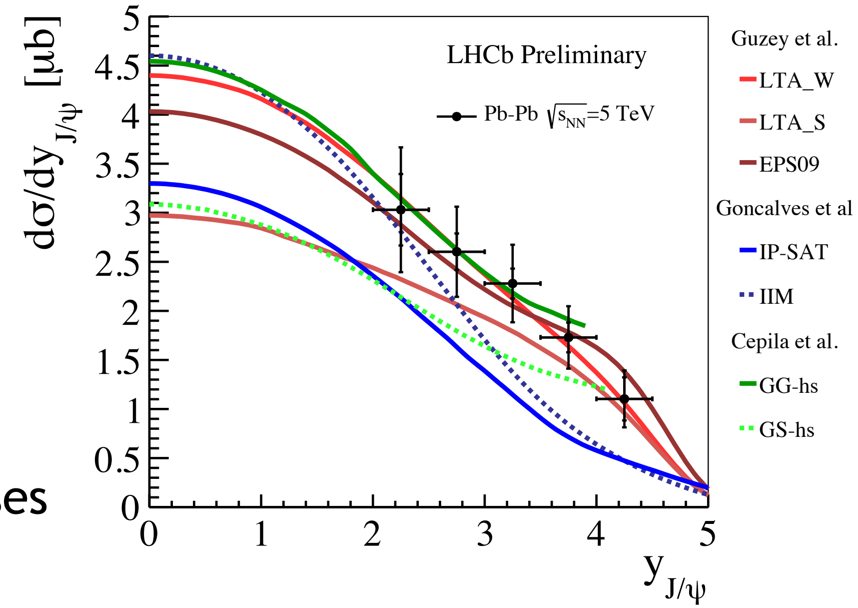
- LHCb well suited for UPC studies
  - Good forward acceptance
  - Excellent **resolution**, PID

- Dimuon events with **no extra activity** around the vertex are studied

- Cross section measured differentially in y(J/ψ)
  - Measurement acceptance interesting to discriminate between the models
  - Potential access to nuclear gluon distribution at **low-x** (down to $\mathbf{10^{-5}}$)
  - Clear extension of ALICE Run-1 analyses

LHCb-CONF-2018-003

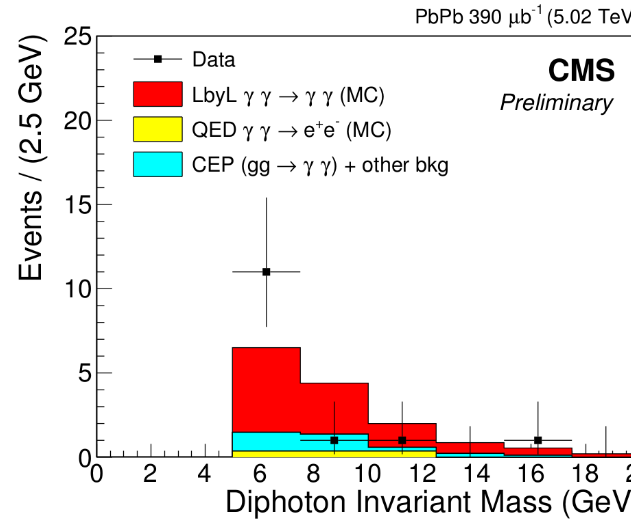


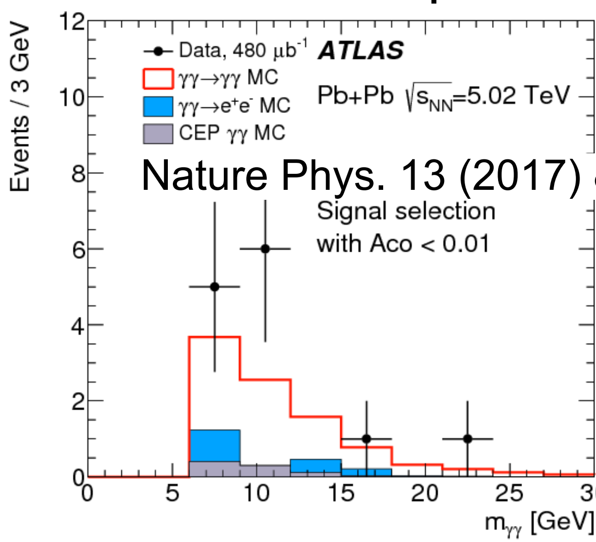


Light-by-light scattering in Pb+Pb @5.02 TeV

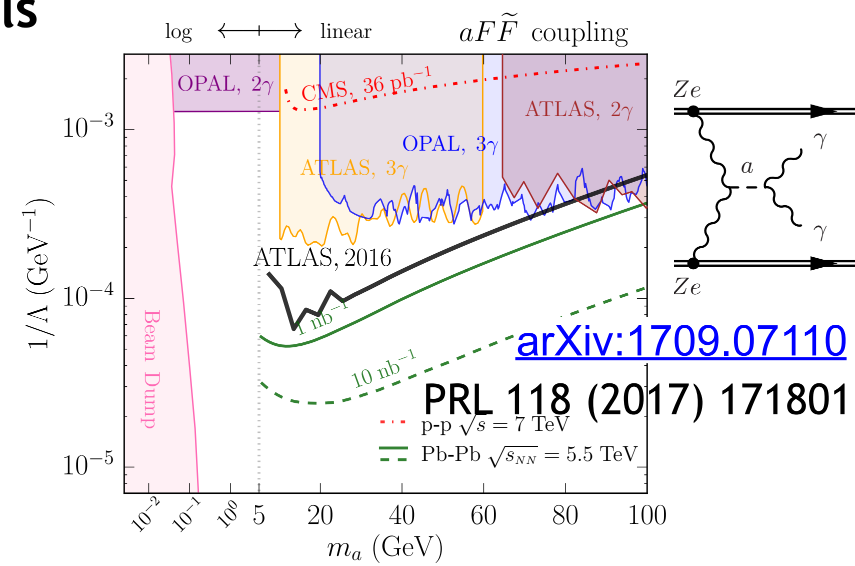
- First **direct** evidence for **γγ->γγ** interaction
  - **4.4σ** (3.8σ expected) in ATLAS
  - **4.1σ** (4.4σ expected) in CMS
- Event selection
  - Two back-to-back **low-E_T** photons and "**nothing else**" in the detector
- Fiducial cross-sections consistent with SM
- ATLAS measurement already interpreted in terms of limits on specific **BSM models**

CMS-PAS-FSQ-16-012





Nature Phys. 13 (2017) 852-858

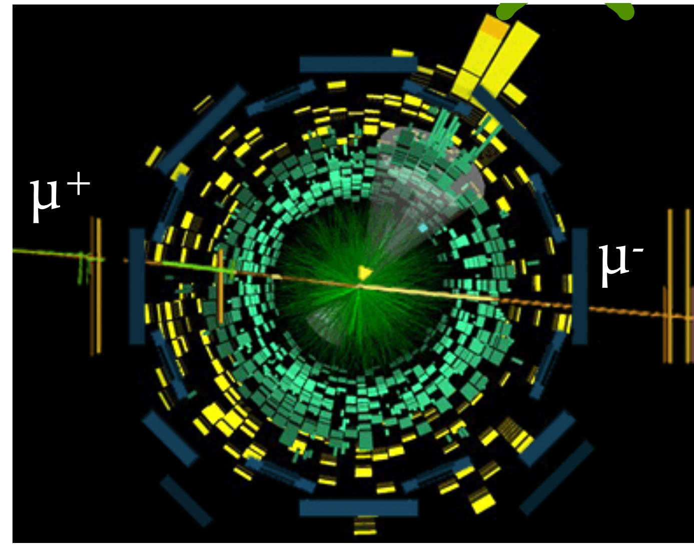


arXiv:1709.07110

PRL 118 (2017) 171801

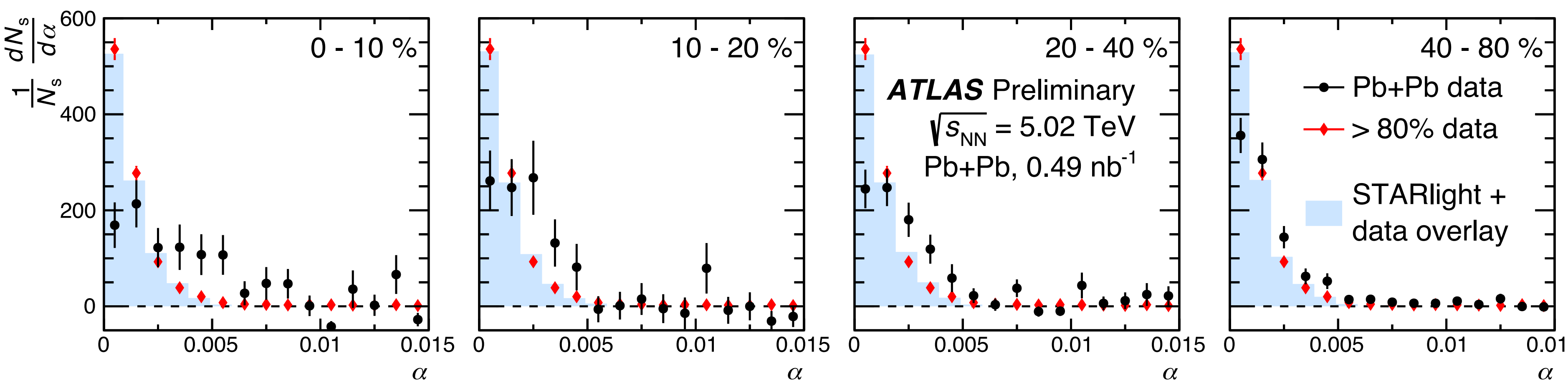
γγ->μμ in non-UPC Pb+Pb @5.02 TeV

- Ions act as a source of photons even in **non-**ultraperipheral case
- Centrality-dependent **broadening** of **dimuon acoplanarity** distribution
  - Modification possibly due to re-scattering of muons in the QGP
  - **<kT> ~70 MeV** imparted to each muon in most central events



- First observation of EM interactions with QGP?
  - Theory input needed!

ATLAS-HION-2018-11



Summary

- Many new results from all LHC collaborations
  - LHC Run-2 data analysis in full swing
  - More Pb+Pb data coming this year
- First measurements from Xe+Xe run @5.44 TeV taken in October 2017
  - Similarities between Xe+Xe and Pb+Pb
- Exploring old and new methods to probe jet quenching mechanism
  - Including photon-tagged jets, jet shapes, jet substructure, …
- New p+Pb measurements constrain nPDFs
  - Also: first observation of top-quark production in nuclear collisions
- Observation of broadening of acoplanarity distribution for muons from $\gamma\gamma \to \mu\mu$ process
  - New way to probe QGP?
- Light-by-light scattering evidenced in both ATLAS and CMS
  - LHC HI data (for first time?) sets the most stringent limit on specific BSM models (e.g. ALPs)

Summary

- More details in parallel session talks:
  - Wednesday, 11:30-13:00 (soft probes)
  - Friday, 14:30-16:30 (hard probes)

and at:

- https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN
- http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_IFT.html

Backup

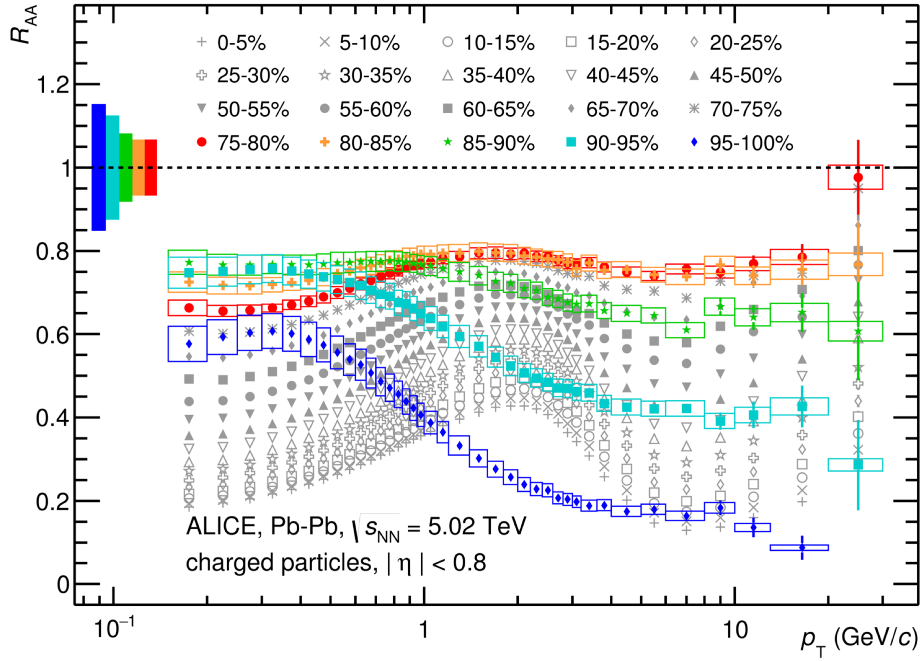
Collision systems & energies @LHC

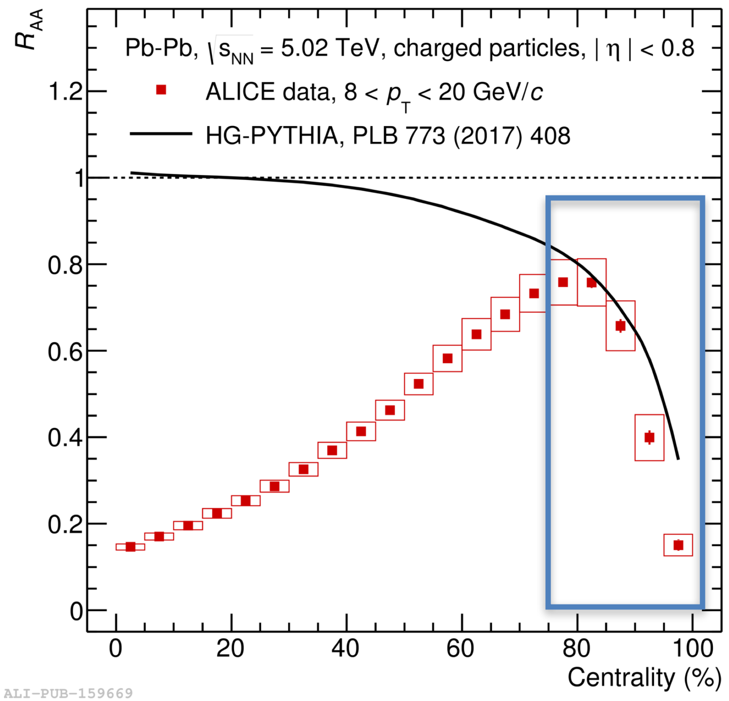
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)
Pb-Pb	2010-2011	2.76
	2015	5.02
Xe-Xe	2017	5.44
p-Pb	2013	5.02
	2016	5.02, 8.16
pp	2009-2013	0.9, 2.76, 7, 8
	2015,2017	5.02
	2015-2017	13

R_{AA} in very peripheral Pb+Pb collisions @5.02 TeV

- R_{AA} measured in **very fine** centrality bins, up to most peripheral
- Significant change of behavior found for **>80%** centrality
  - Can be explained by biases induced by event selection and collision geometry
  - Described with a simple PYTHIA-based model without nuclear modification

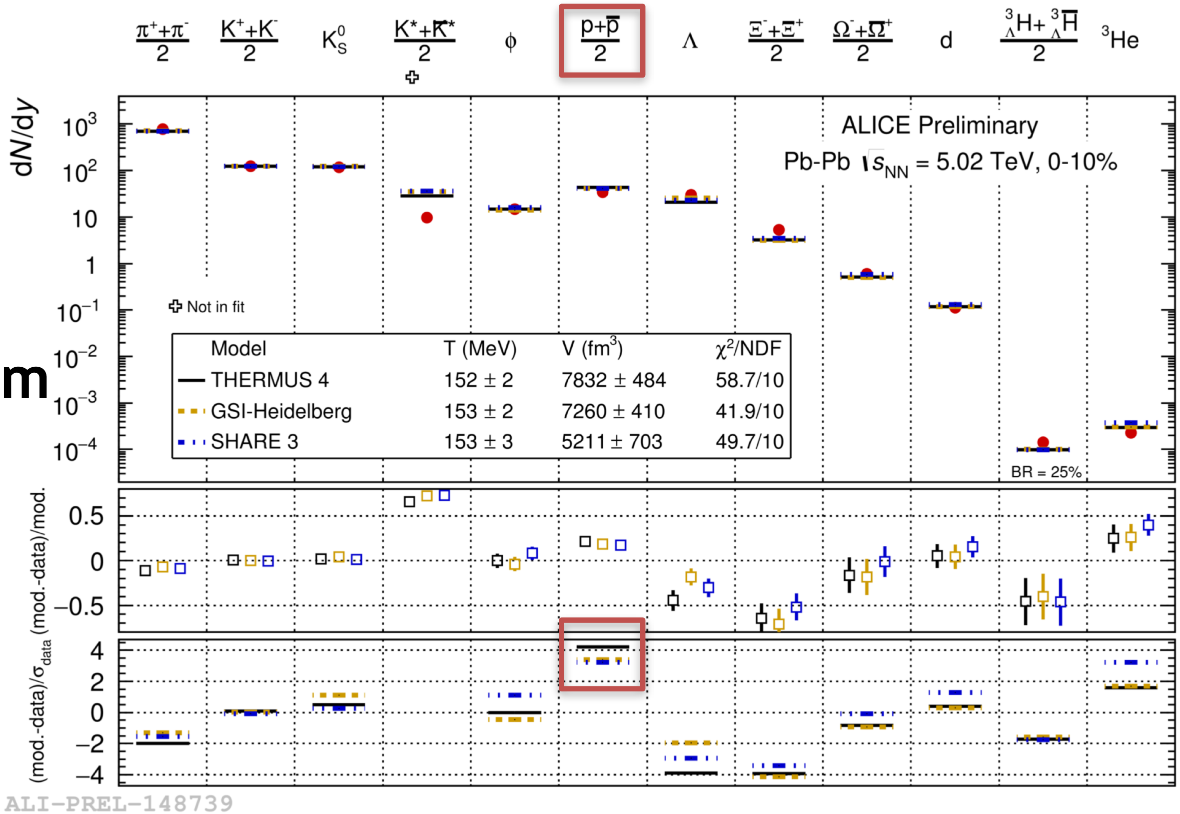
arXiv:1805.05212





Thermal statistical model fits Pb+Pb @5.02 TeV

- Measuring absolute yields (**dN/dy**)
- Also at 5.02 TeV, yields of **light flavor hadrons** are qualitatively well described by **equilibrium thermal models** over **7 orders** of magnitude



- Biggest deviations for
  - **Protons**
  - K^{*0} (not in fit)

- Fit @5.02 TeV converges to slightly lower T_{ch} than @2.76 TeV (**153 MeV vs 156 MeV**) mostly due to proton yield

Dijet asymmetry in Xe+Xe

- Xe+Xe smeared to match Pb+Pb UE fluctuations
- No clear difference between Xe+Xe and Pb+Pb

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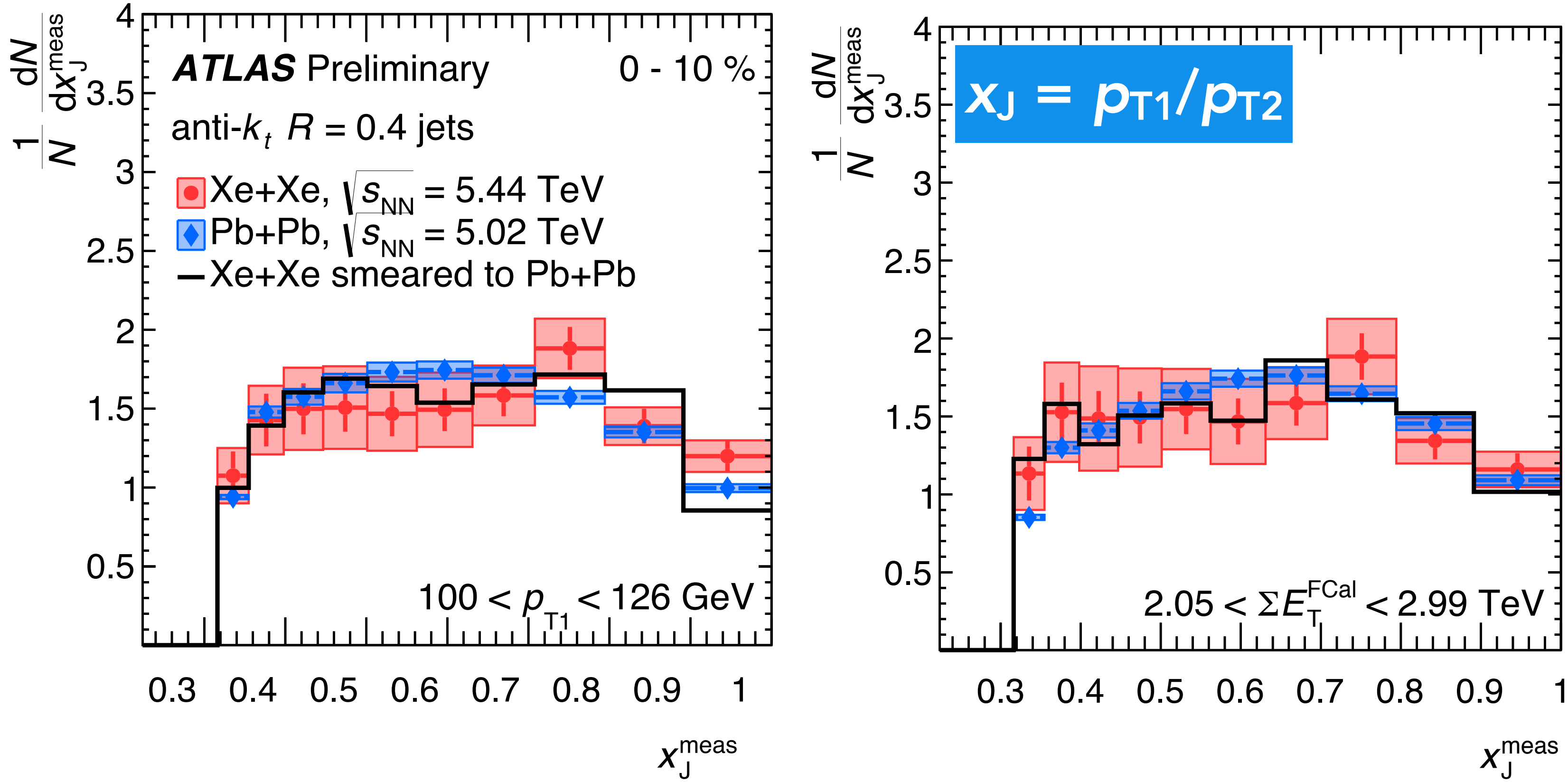

Inclusive photons in p+Pb

- Inclusive isolated prompt-photon spectrum @8.16 TeV
  - At forward and central rapidity, $\mathbf{R_{pPb}}$ consistent with **unity**
  - R_{pPb} < 1 for **η* < -2** and **large Et** -> nuclear valence region
- Comparison to JETPHOX with nPDF from EPPS16 and nCTEQ15
- With current uncertainties, the data is unable to constraint nPDFs -> work is ongoing

$$R_{\mathrm{pPb}} = \frac{\frac{d\sigma^{\mathrm{pPb}}}{dE_{\mathrm{T}}^{\gamma}}}{A \times \frac{d\sigma^{pp}}{dE_{\mathrm{T}}^{\gamma}}}$$

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