Aspects of an e+p/A program relevant to the LHC heavy ion program and vice versa

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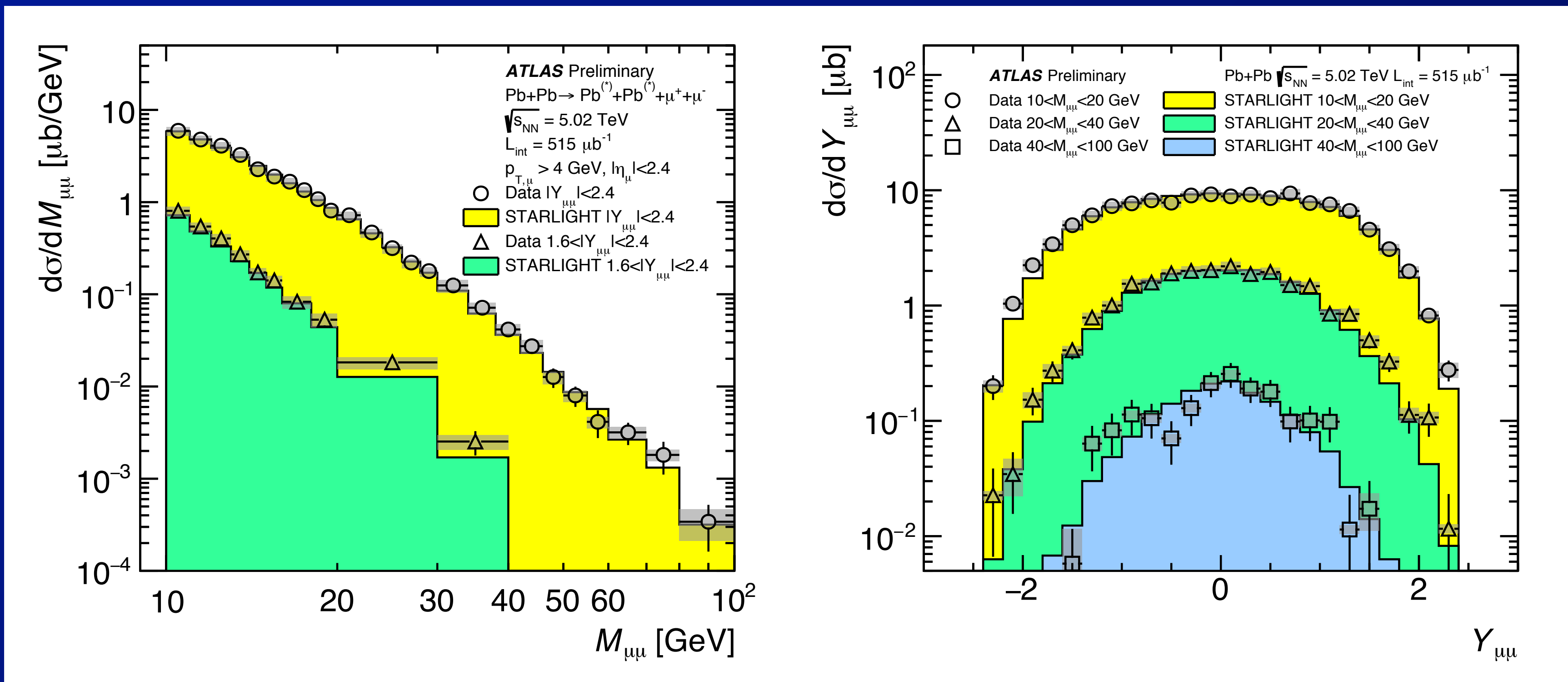
Workshop on the LHeC, FCC-eh and PERLE

Overview

- Nuclear parton distribution functions
  - Measurements in p+Pb collisions
  - Exclusive vector mesons in Pb+Pb
  - Ultra-peripheral photoproduction in A+A
- Azimuthal anisotropies (AKA "ridge")
  - Persistence to small systems (p+A, pp)
  - Presence in ultra-peripheral photoproduction
- $\gamma+\gamma$ processes
  - $\gamma+\gamma \rightarrow \mu^+\mu^-$ in hadronic Pb+Pb collisions
  - Light-by-light

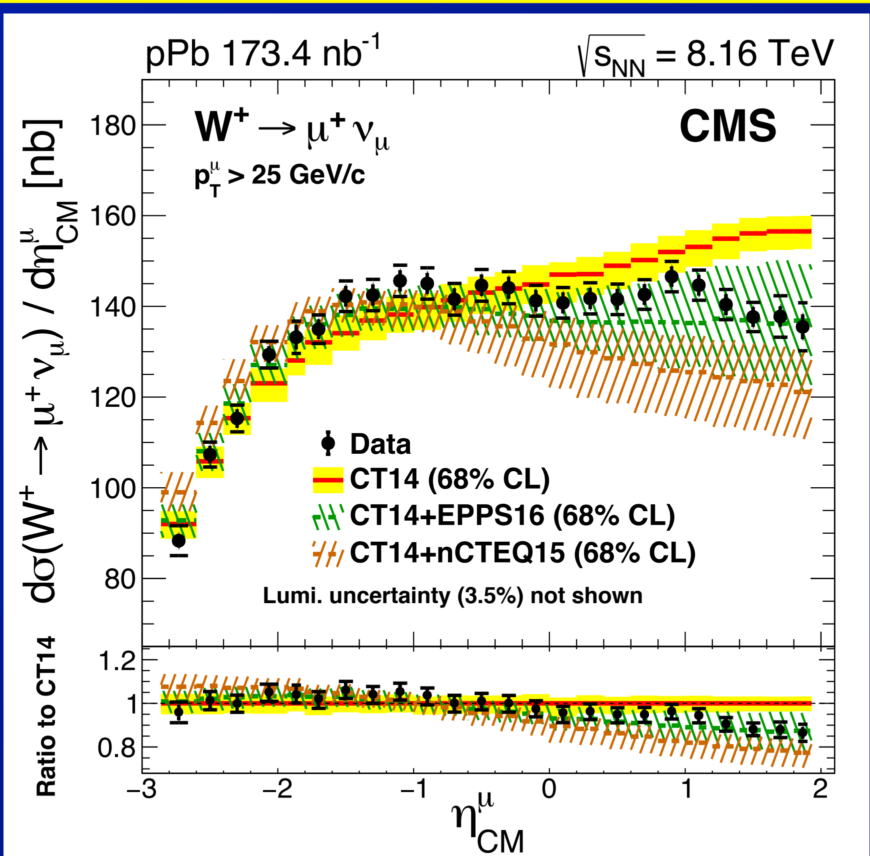
Ultra-peripheral Pb+Pb collisions

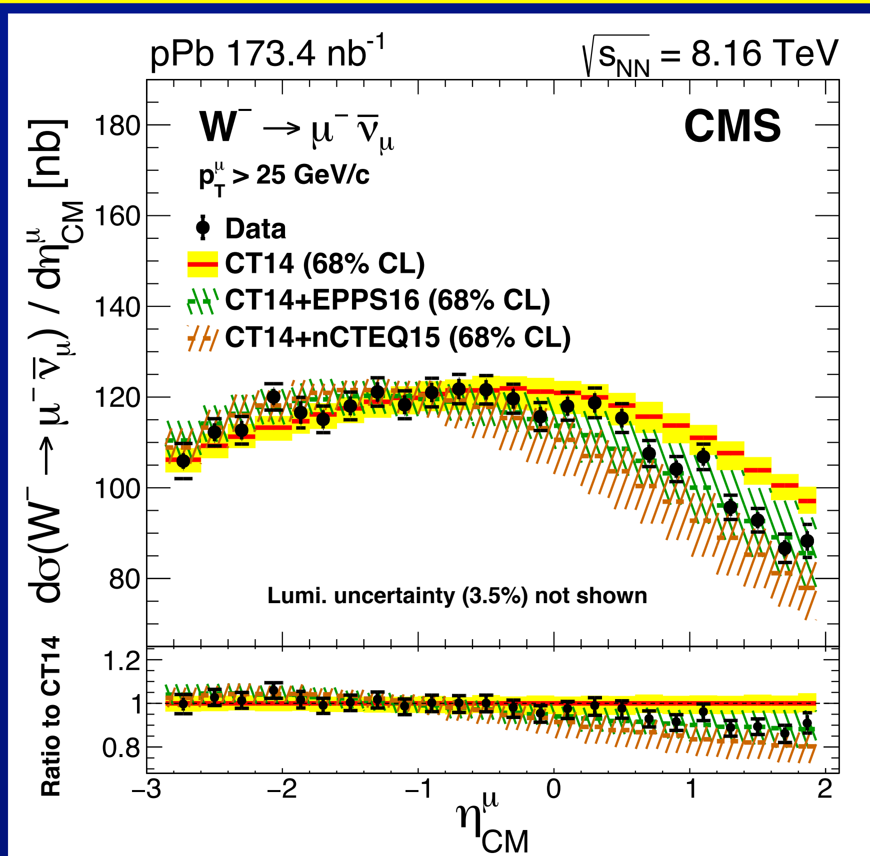
- **Ultra-peripheral Pb+Pb collisions (UPC)**
  - either γ+A, or γ+γ ⇒ nominally, b > 2R
- **Significant rates:**
  - coherent photon flux ∝ Z^2 — applies for $E_\gamma \lesssim 50$ GeV
- **e.g. ATLAS (preliminary) $\gamma\gamma \rightarrow \mu^+\mu^-$**



Measurements sensitive to nuclear PDF, saturation

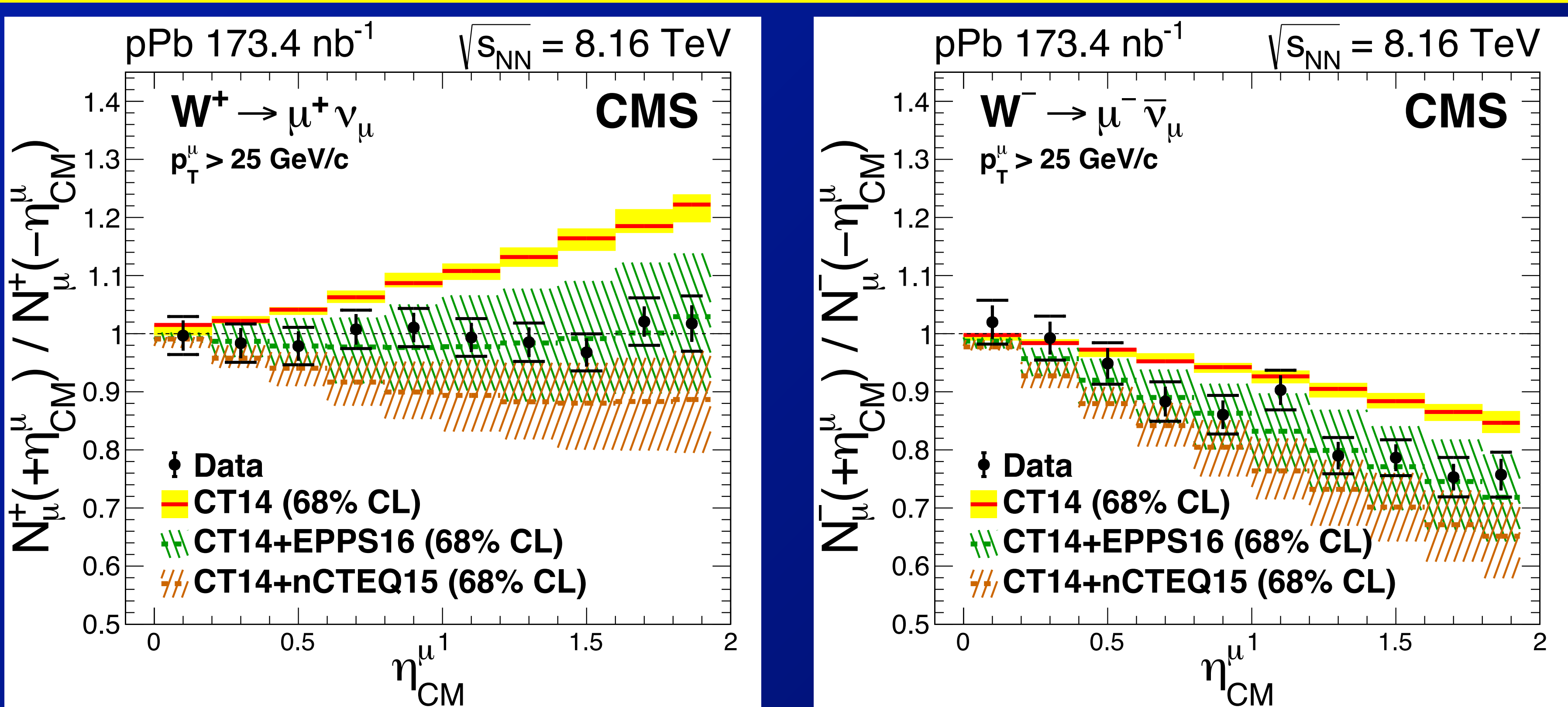
p+Pb W production (CMS)





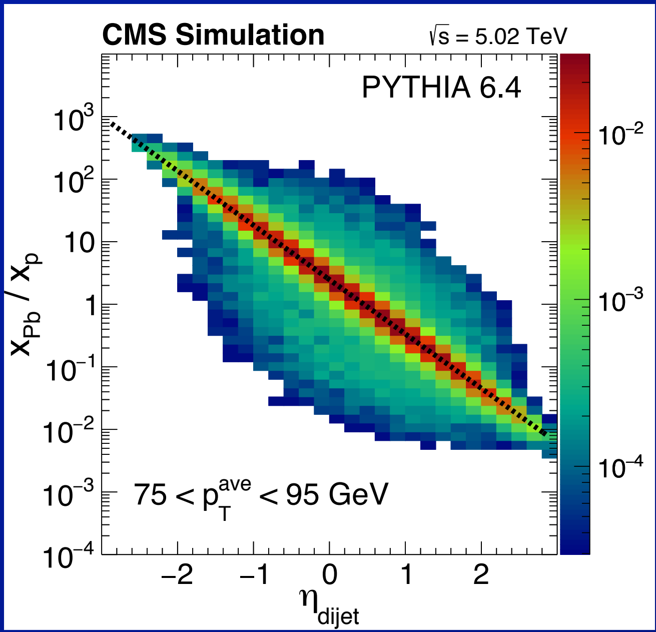
- W $\rightarrow \mu^{+/-}$ yields vs μ rapidity (- in Pb direction)
  - forward production sensitive to low x_{Pb}
    - ⇒ comparisons with NNLO calculations show evidence for shadowing, prefer EPPS16 over nCTEQ
    - ⇒ But issues with CT14 (in)consistency w/ pp data

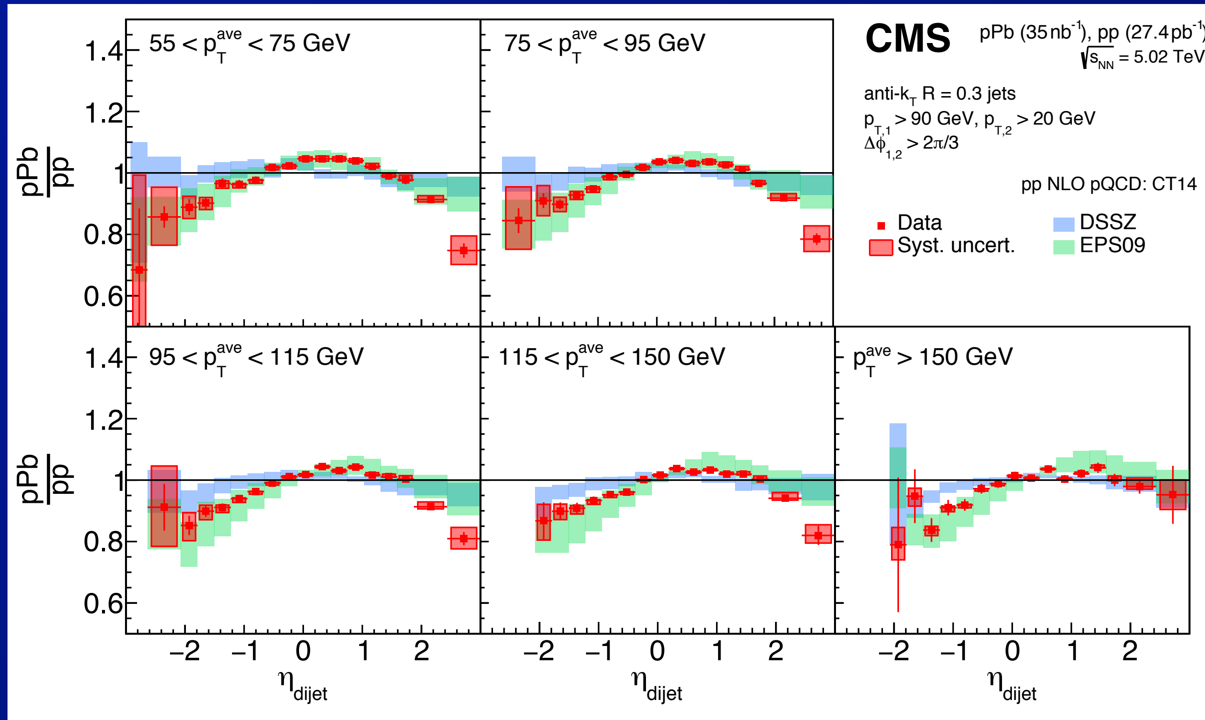
p+Pb W production (CMS)



- W forward/backward asymmetry vs $|\eta^{\mu}|$
  - ⇒ Clear(er) demonstration of nuclear PDF effects
  - ⇒ As on previous slide, data prefer EPPS16 central values, but only 1-2σ from nCTEQ15

Dijet probes of nPDFin p+Pb (CMS)

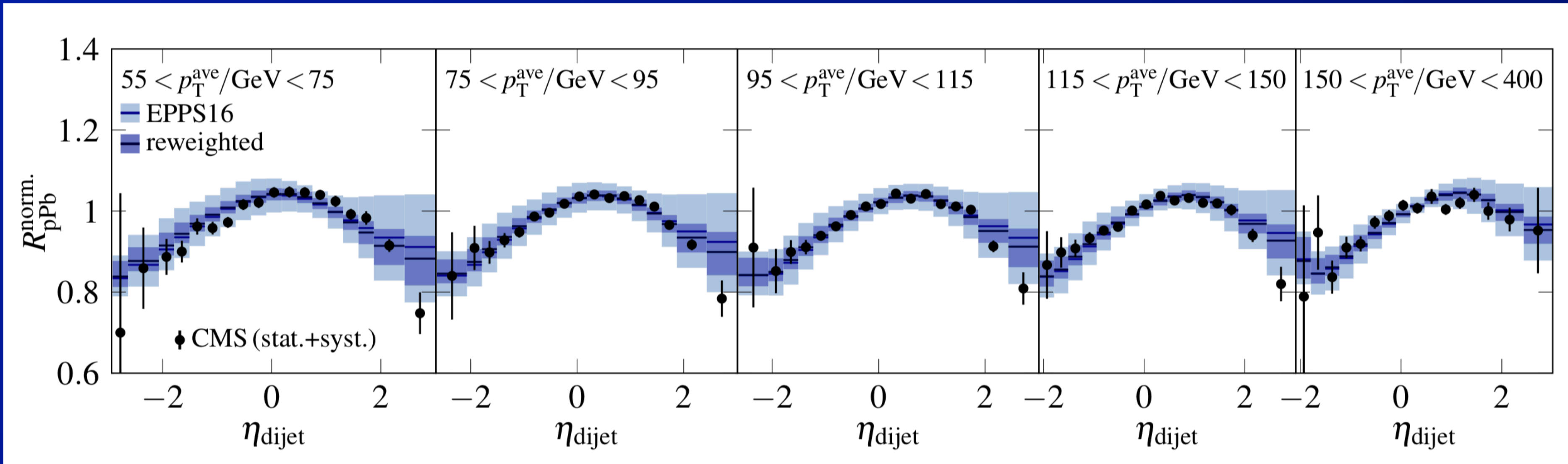




- Correlation between x_{Pb}/x_p and dijet η used to indirectly probe nuclear PDF modifications
  - compare ratio of p+Pb/pp to calculations

p+Pb dijets: impact on nPDF fits

Eskola *et al*. Eur. Phys. J. C79 (2019) arXiv:1903.09832

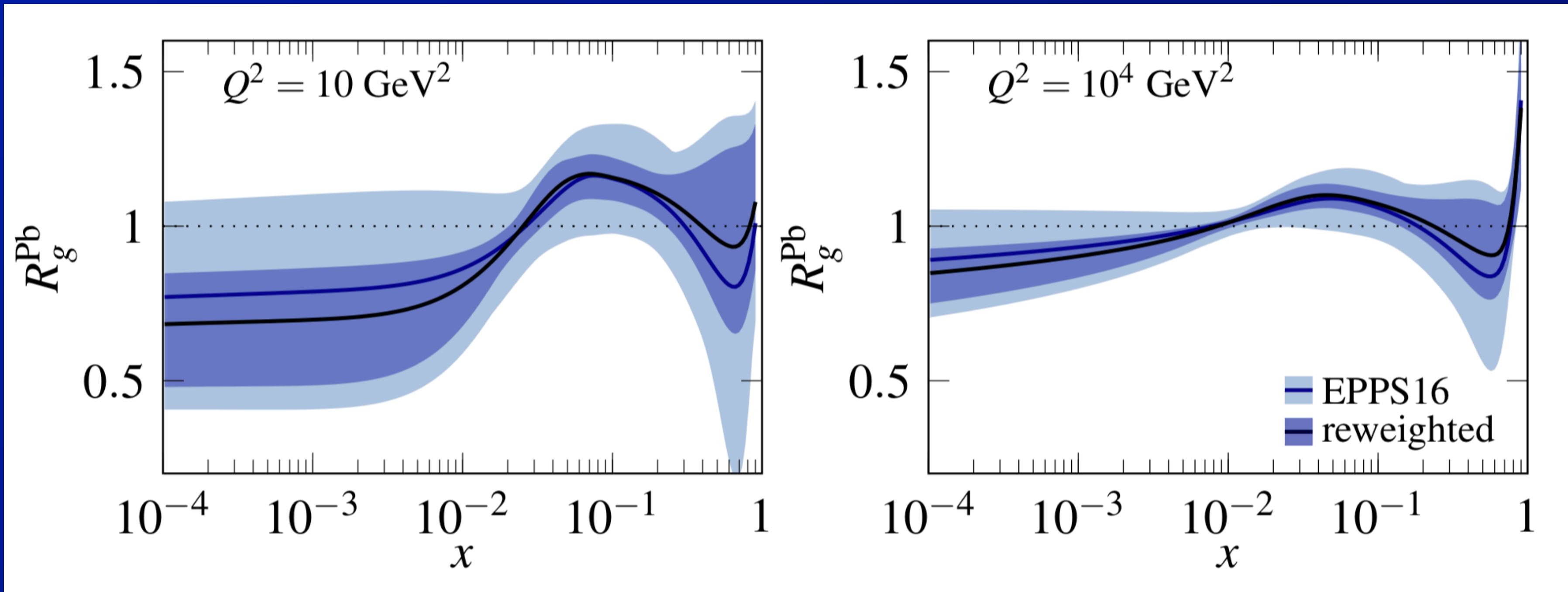


- **Effect of incorporating the CMS p+Pb dijet data into EPS nPDF fits**
  - after re-weighting proton PDFs to match pp data

  ⇒substantial improvement in the description to the experimental data

p+Pb dijets: impact on nPDF fits

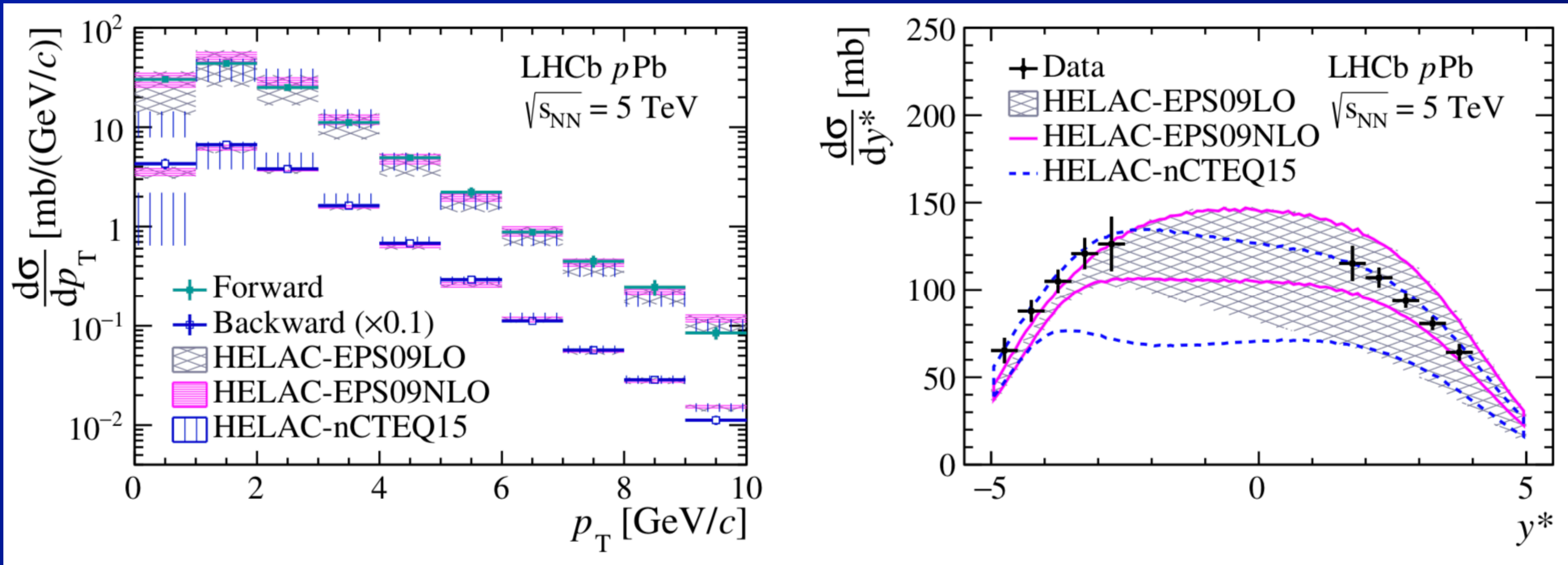
Eskola *et al*. Eur. Phys. J. C79 (2019) arXiv:1903.09832



- **Effect of incorporating the CMS p+Pb dijet data into EPS nPDF fits**
  - after re-weighting proton PDFs to match pp data

  ⇒ substantial reduction in gluon PDF uncertainties over the full *x* range

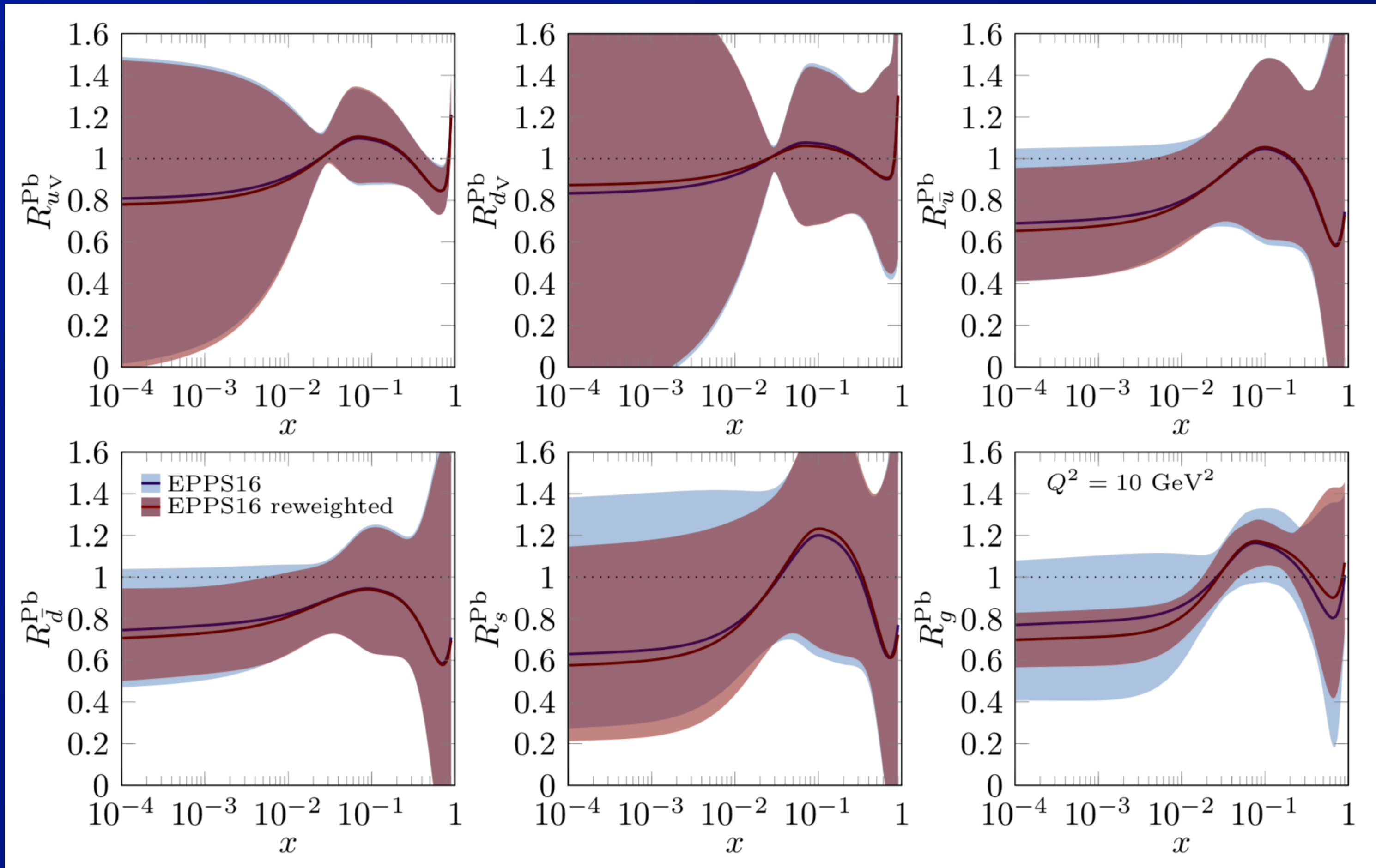
LHCb p+Pb D^0 meson production



- **LHCb D^0 differential cross-sections vs p_T, y^***
  - compared to theoretical calculations using different nPDF sets
  - forward and backward (swapped beam directions) measurements probe both low and high x

nPDF fits including LHCb data

Eskola *et al*, arXiv:1906.02512

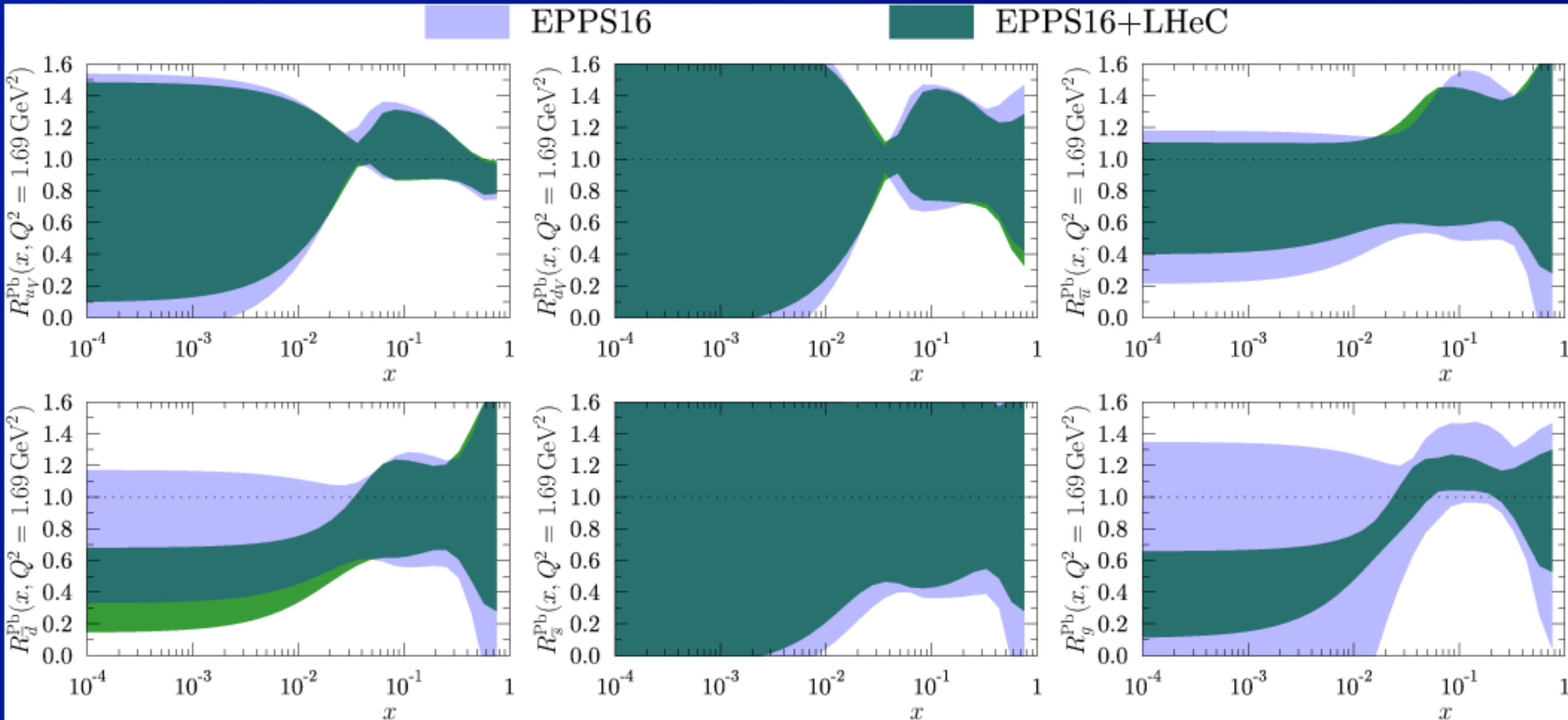


- **EPPS16 nPDFs nominal and w/ re-weighting to account for LHCb D0 data**

  ⇒**substantial reduction in gluon uncertainties**

What about LHeC nPDF constraints

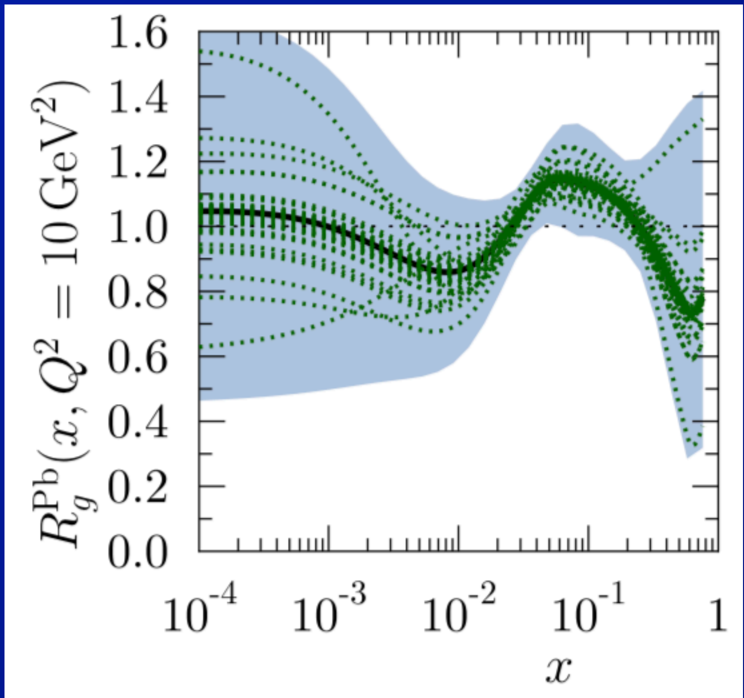
Paukkunen, arXiv:1709.08342

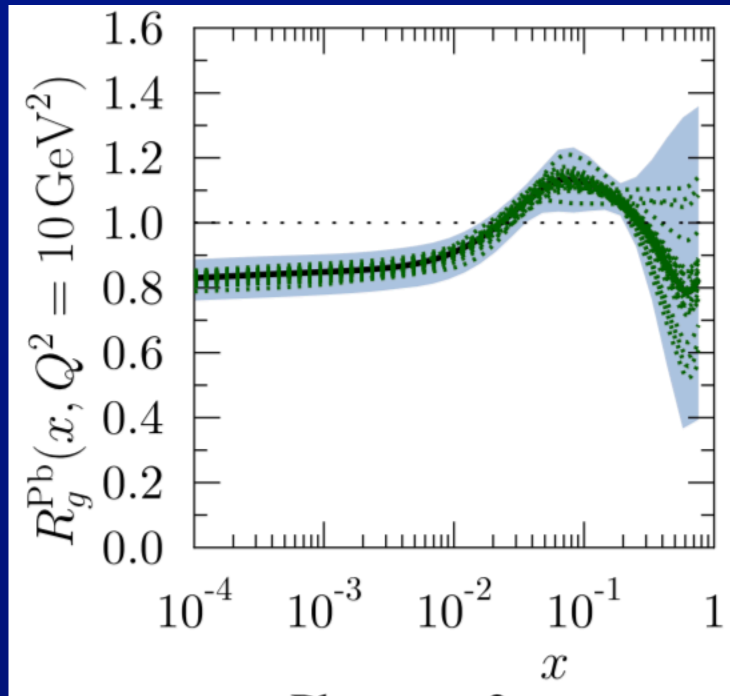


- Impact of including LHeC e+Pb (pseudo) data (1 fb^{-1}) on EPPS16 nPDFs

What about LHeC nPDF constraints

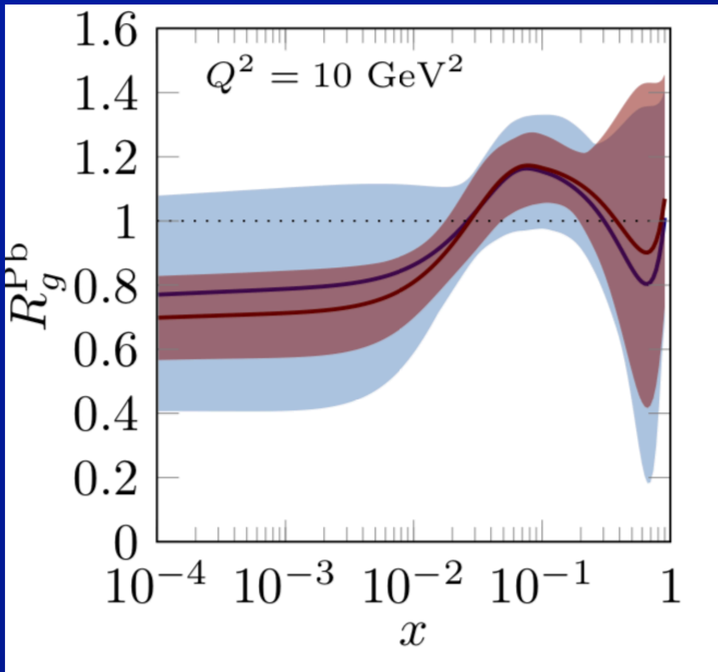
Paukkunen, arXiv:1709.08342

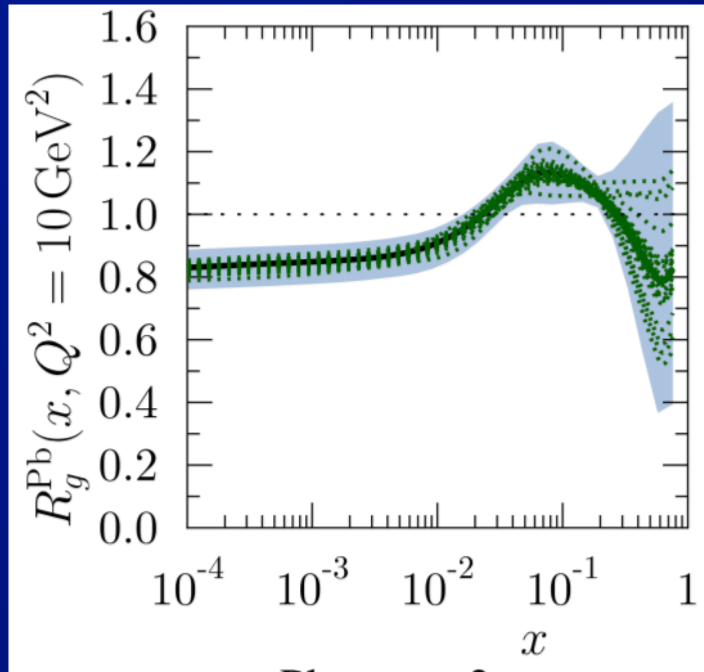




- Impact of including LHeC e+Pb (pseudo) data (1 fb^{-1}) on EPPS16 nPDFs

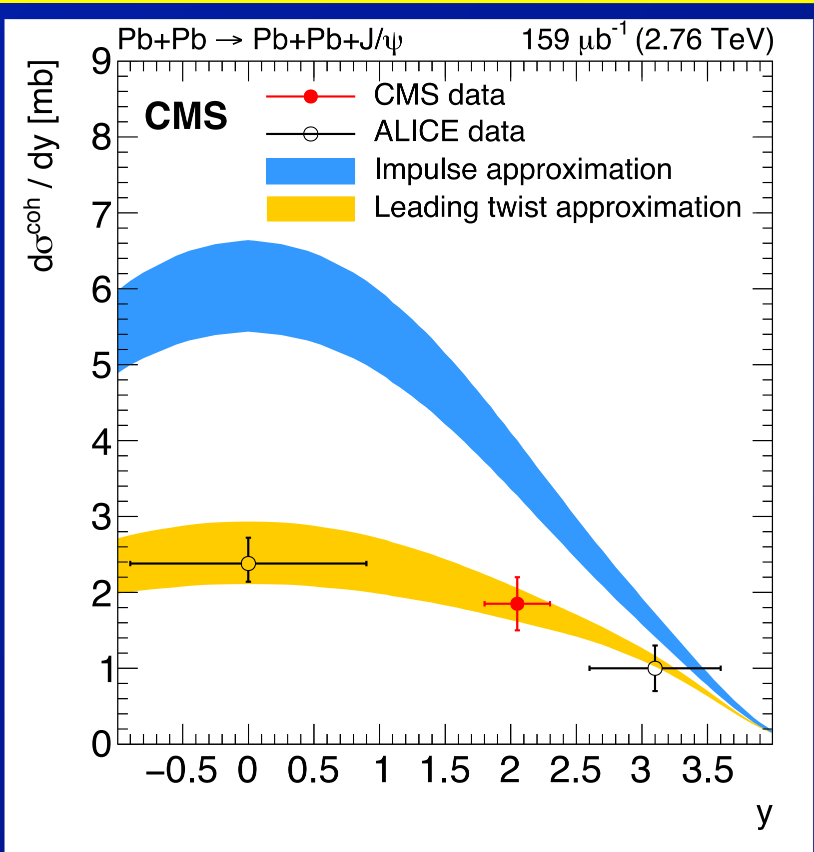
LHC p+Pb vs LHeC



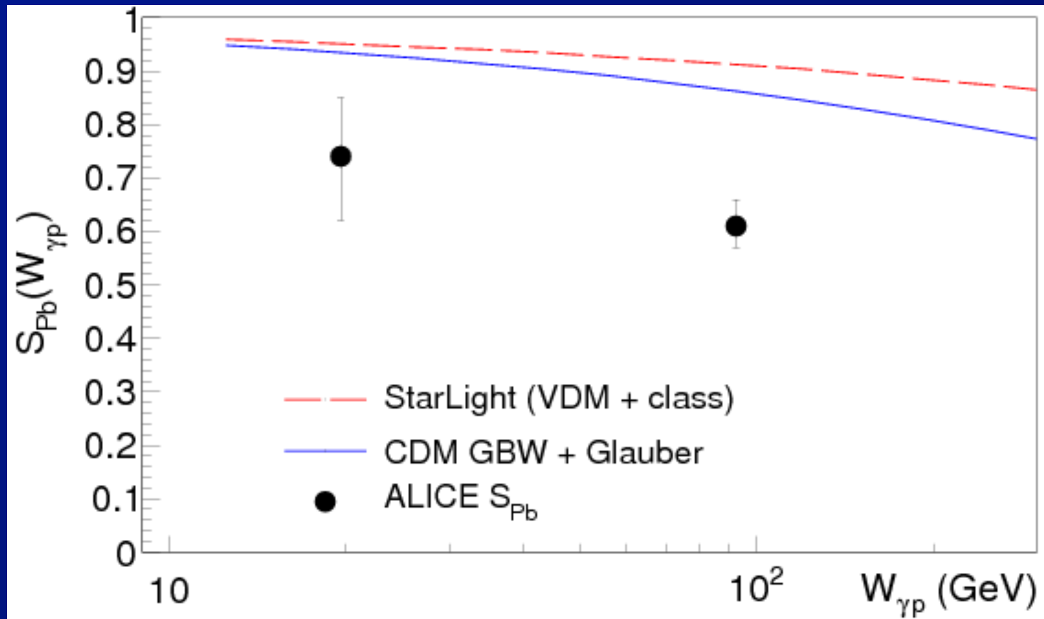


- Compare constraints from e.g. LHCb D^0 data — left and LHeC — right
  - ⇒(obviously) LHeC produces much better constraints on the gluon distribution
- But this is the wrong "question"
  - ⇒Instead with improvements in nPDFs from LHeC much improved experimental tests of p+Pb theory.

Exclusive vector mesons (J/ψ), Pb+Pb



Guzey *et al*, PLB726 (2013) 290



- @LO∝g², so sensitive to shadowing/saturation

  ⇒ observe factor of ~ 3 suppression relative to IA
- Guzey et al, characterize using (gluon density) suppression factor:

$$S(W_{\gamma p}) \equiv \left[\frac{\sigma^{\exp}_{\gamma Pb \to J/\psi Pb}(W_{\gamma p})}{\sigma^{\rm IA}_{\gamma Pb \to J/\psi Pb}(W_{\gamma p})} \right]^{1/2}$$

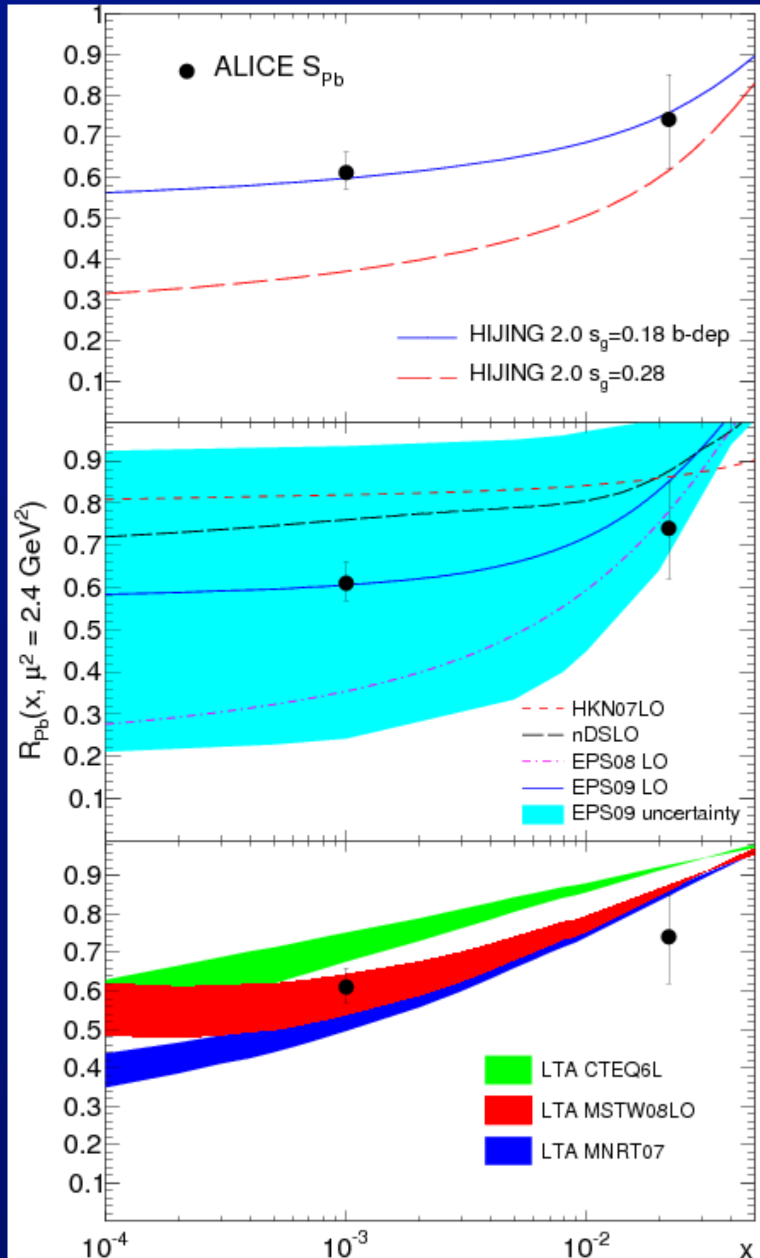
Exclusive vector mesons

- Guzey: comparison of suppression factors to different shadowing models / nPDF sets
  - suppression factors compatible with nPDFs having significant (~0.6) shadowing @ 10^{-3}
  - data compatible with leading-twist shadowing

  ⇒modulo uncertainties in proton PDFs

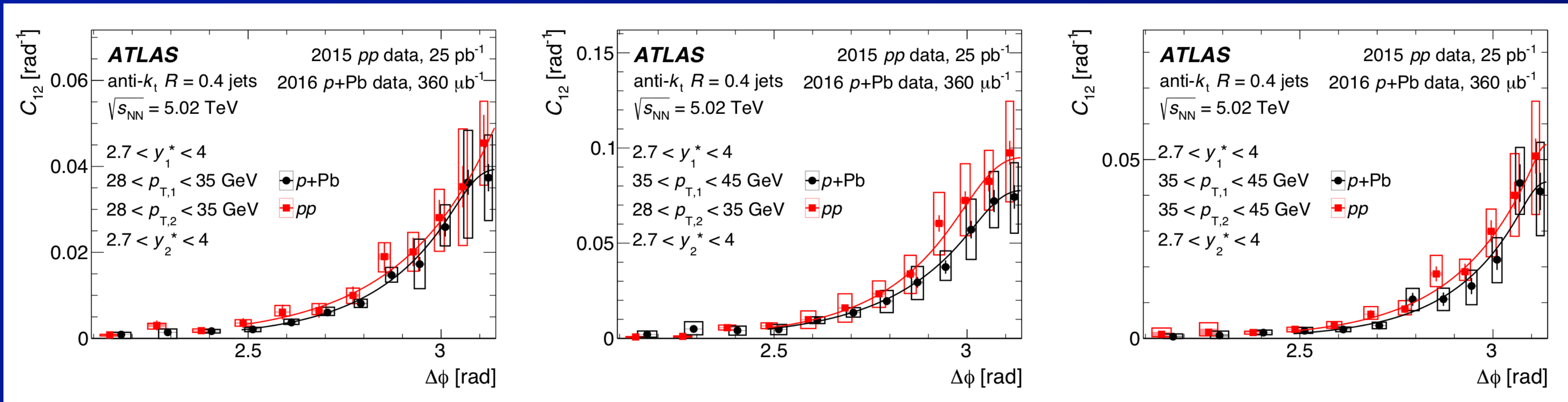
  ⇒need for saturation?

Guzey *et al*, PLB726 (2013) 290



Forward dijet production in p+Pb

ATLAS, Phys. Rev. C 100 (2019) 034903, arXiv:1901.10440



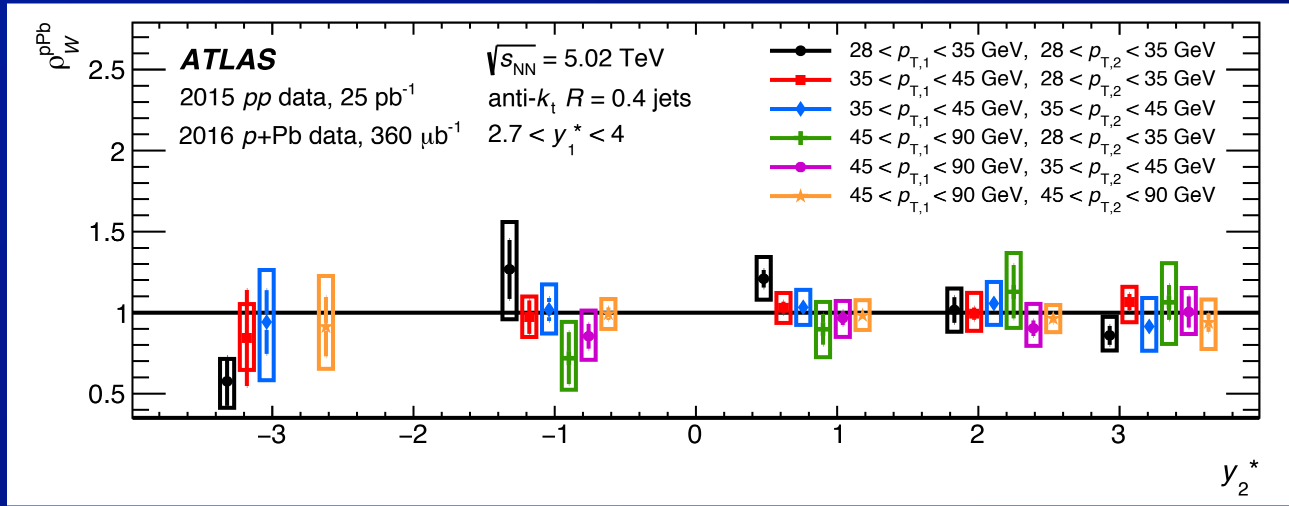
- dijet Δφ distributions in 5.02 TeV p+Pb, pp
  - jet p_T > 28 GeV, forward jet 2.4 < y < 4
  - dijet correlation function $$C_{12}(p_{T,1}, p_{T,2}, y_1^*, y_2^*) = \frac{1}{N_1}\frac{dN_{12}}{d\Delta\phi}$$
- Quantify using RMS width, W, and conditional yields:

$$I_{12}(p_{T,1}, p_{T,2}, y_1^*, y_2^*) = \frac{1}{N_1}\frac{d^4N_{12}}{dy_1^* dy_2^* dp_{T,1} dp_{T,2}}$$

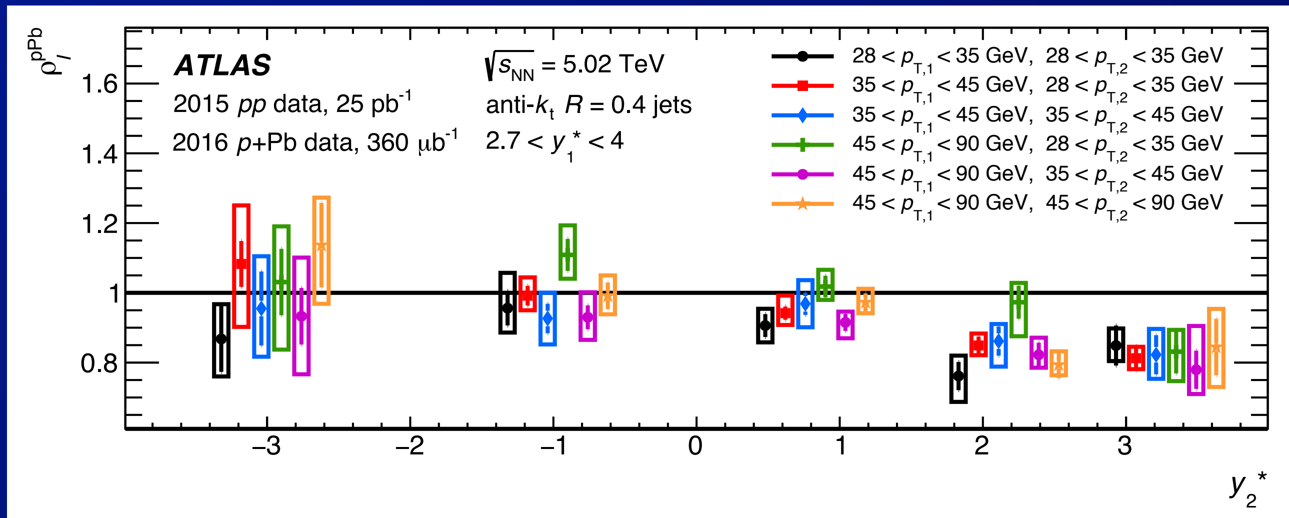
- Evaluate ratios: ρ≡ p+Pb/pp

Forward dijet production in p+Pb

- Ratios of RMS widths



- Ratios of conditional yields

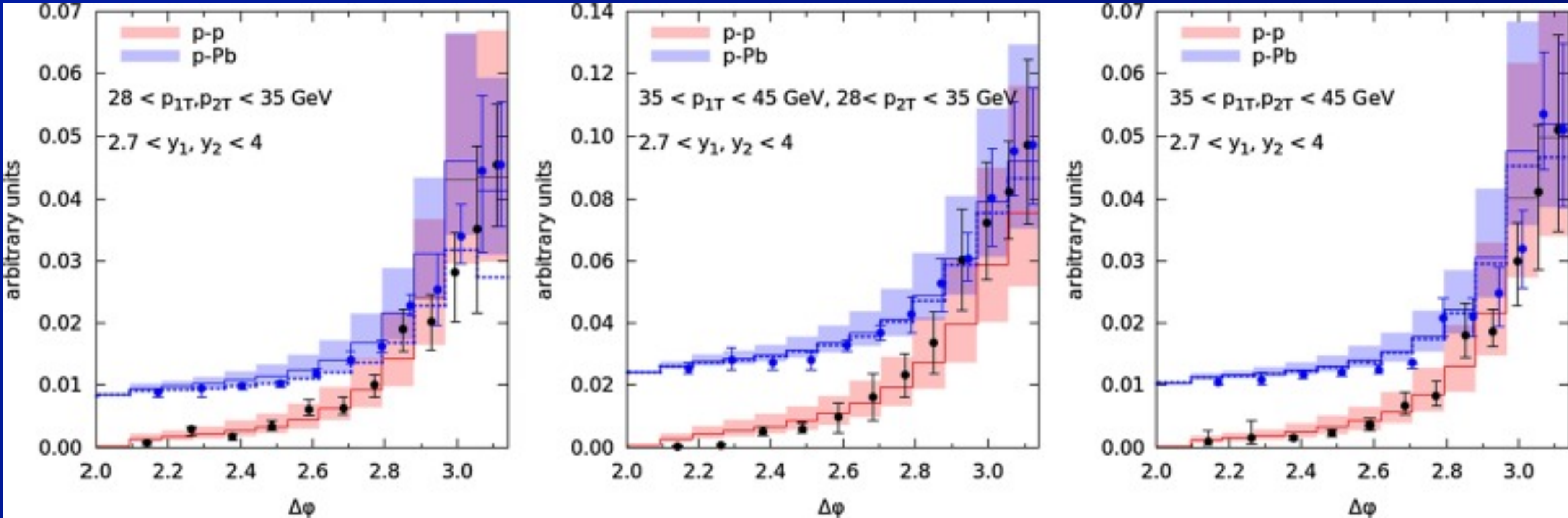


⇒ No significant broadening observed in p+Pb

⇒ Forward-forward dijet (conditional) yields smaller in p+Pb than pp

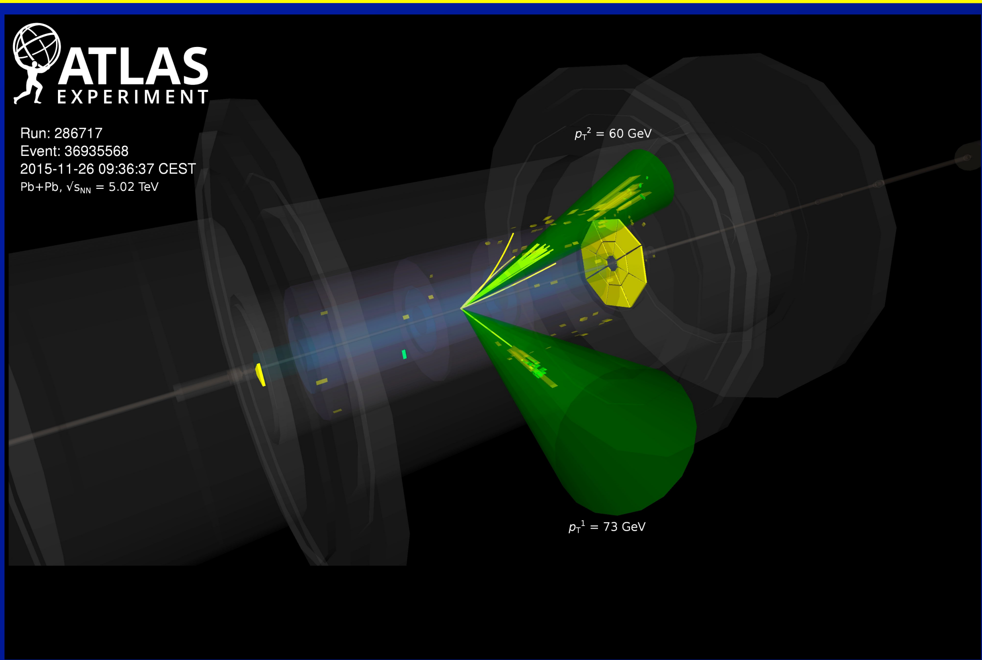
Forward dijets: theory

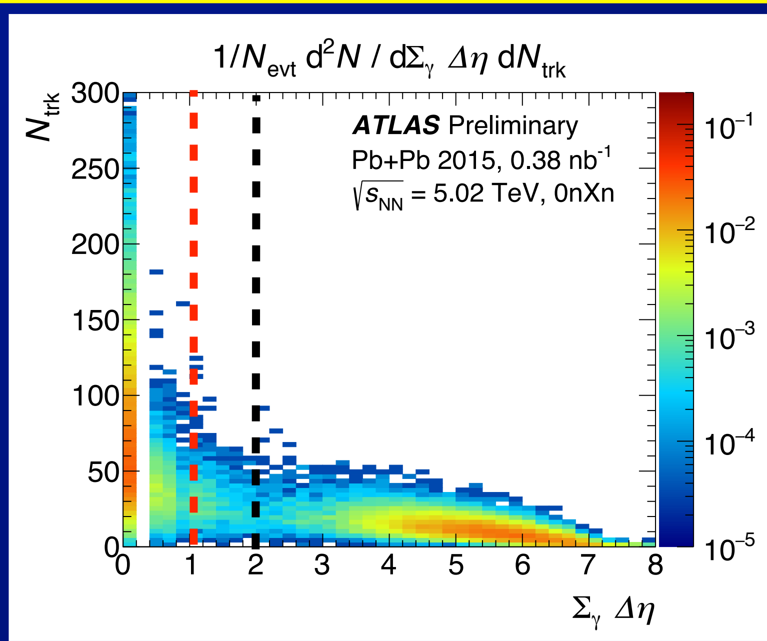
Hameren *et al*, Phys. Lett. B795 (2019) 511-515

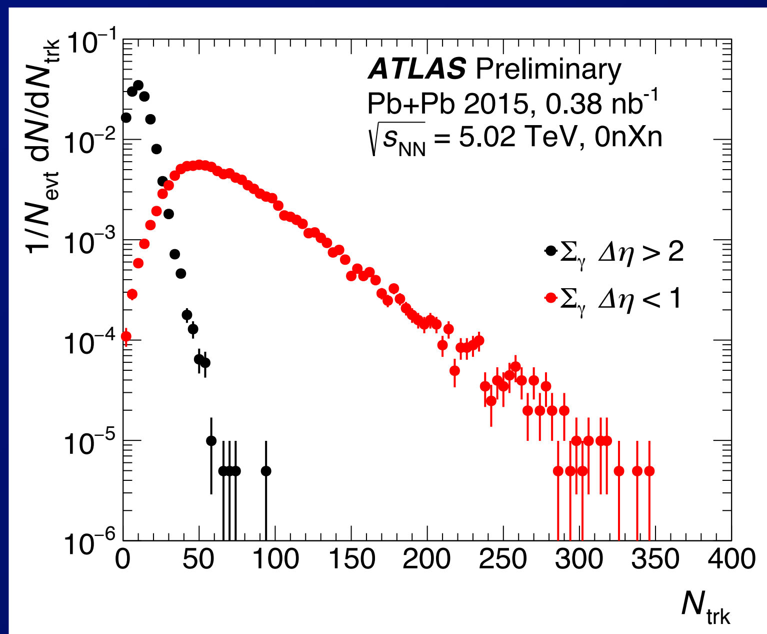


- **Recent analysis by Kutak et al:**
  - Using ITMD + Sudakov resumption
    - ⇒Saturation and Sudakov effects needed to describe both pp and p+Pb data
    - ⇒where do we see larger Q_s in Pb?

di/multi-jet photoproduction in Pb+Pb



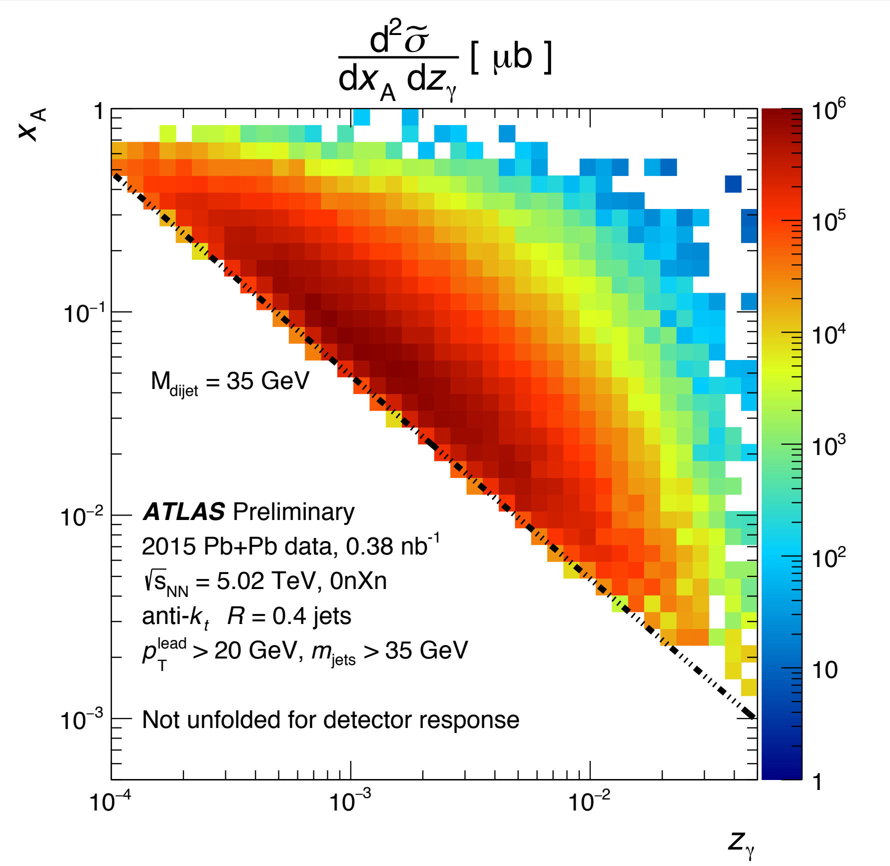


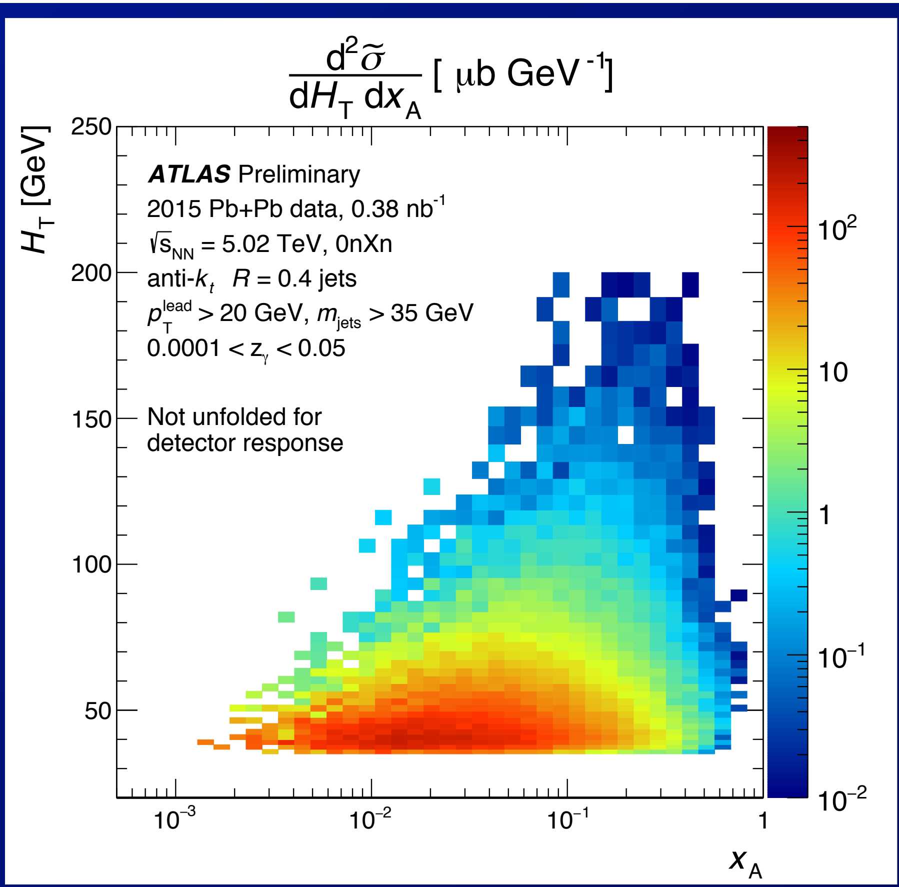


- Measure ≥ 2 jet events in ultra-peripheral γ+Pb
  - Zero-degree calorimeter (0nxn) and gap selections
  - Partonic kinematics from jet system mass, rapidity, H_T

Jet photoproduction: 2-D cross-sections

$$H_\mathrm{T} \equiv \sum p_{\mathrm{T}\,i} \qquad x_\mathrm{A} = \frac{m_\mathrm{jets}}{\sqrt{s}} e^{-y_\mathrm{jets}} \qquad z_\gamma = \frac{m_\mathrm{jets}}{\sqrt{s}} e^{+y_\mathrm{jets}}$$





Jet photoproduction kinematic range

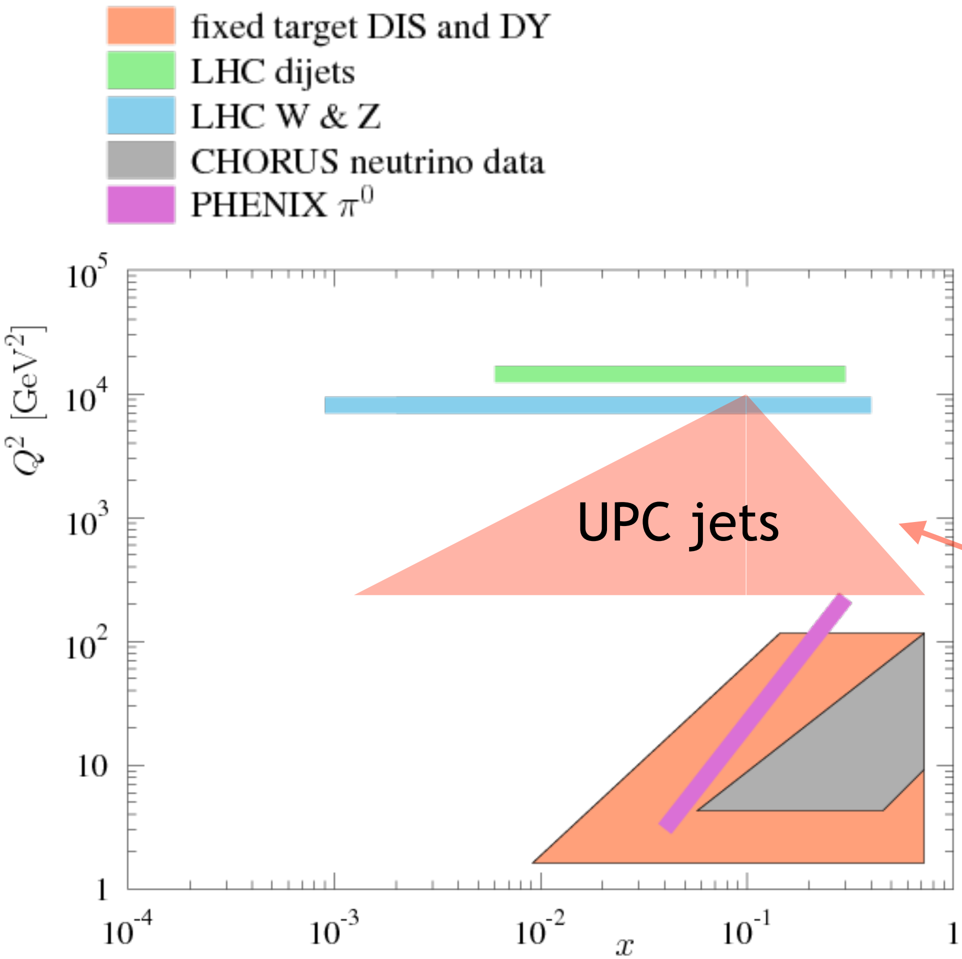
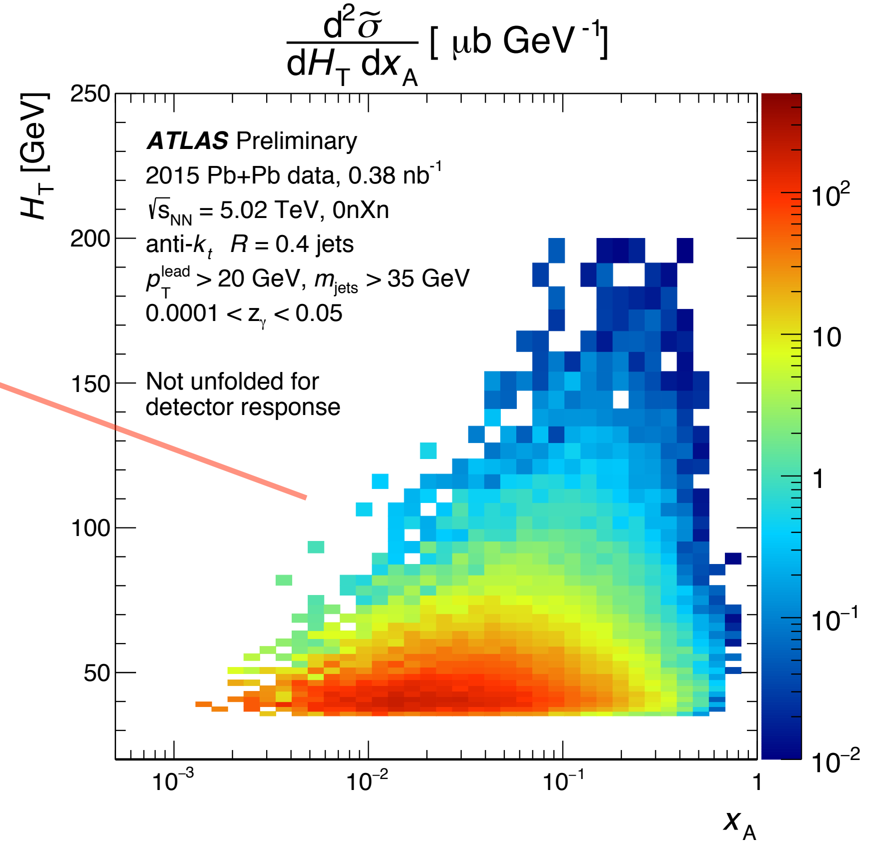


Figure adapted from EPPS16
1612.05741 [hep-ph]

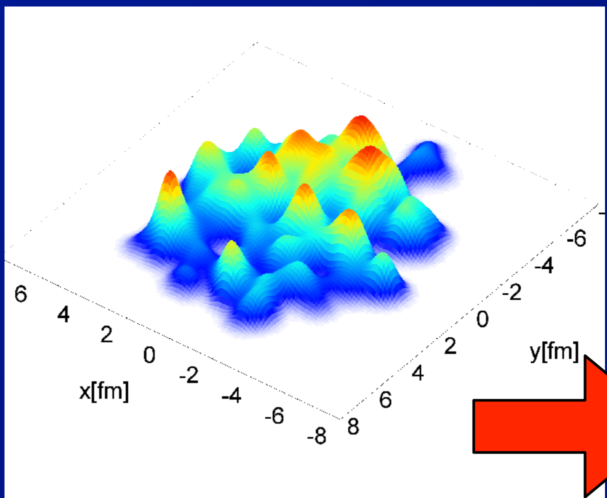


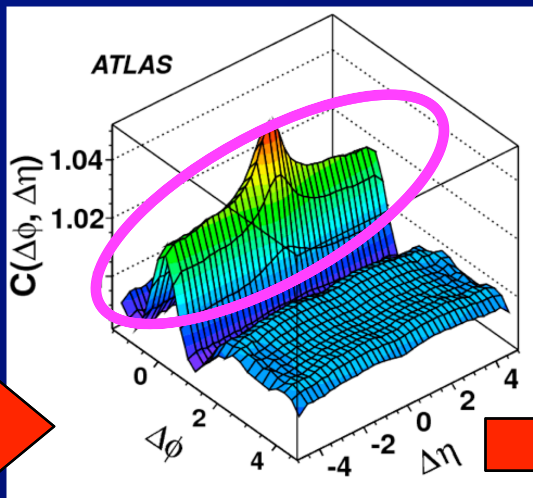
Ridge in pp, p+Pb, …

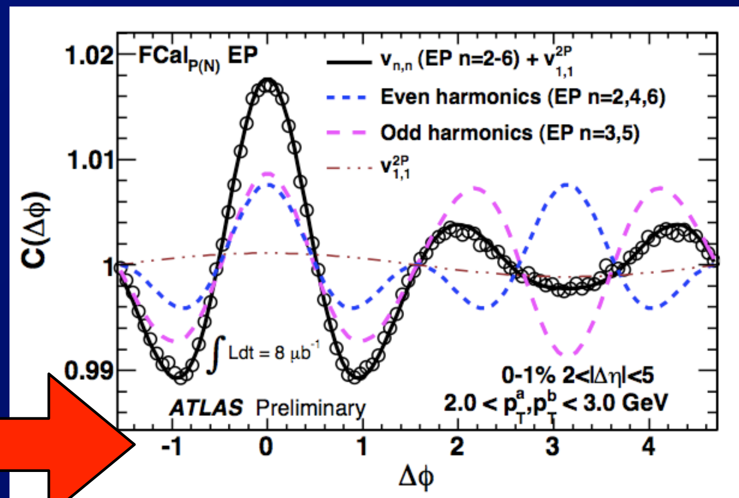
“ridge” in Pb+Pb collisions

- Spatial anisotropies in the initial state
  - get converted to azimuthal anisotropies by the nearly ideal hydrodynamic evolution of the plasma
- Measure using 2-particle (η,φ) correlations
  - characterize the anisotropies by (relative) Fourier coefficients of the single-particle φ distribution

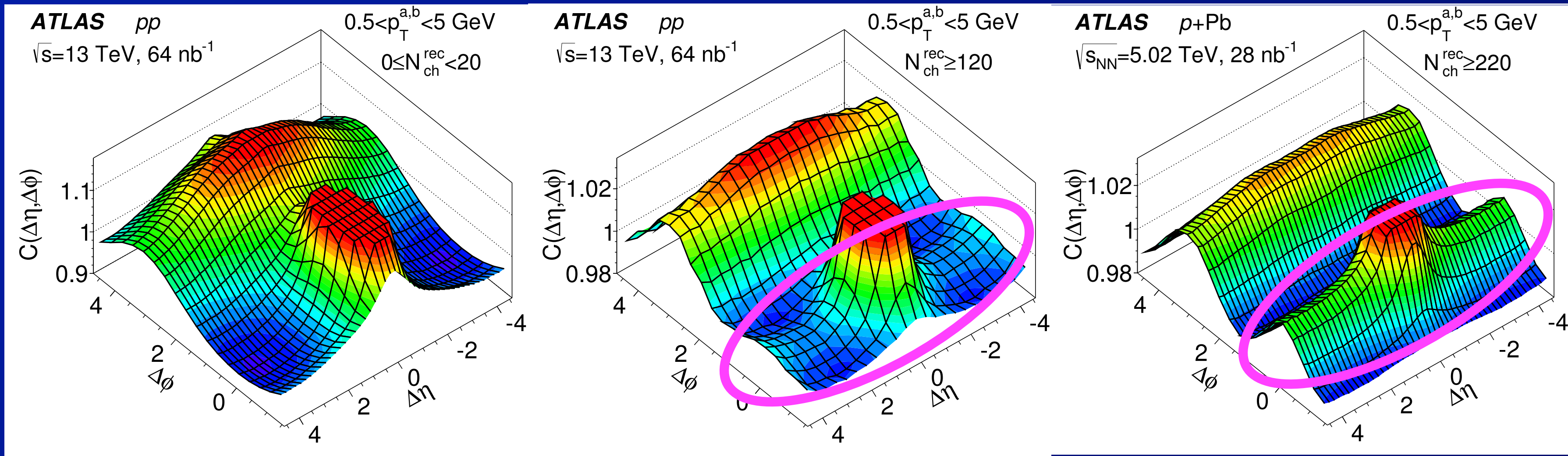
$$\Rightarrow \quad \frac{dN}{d\phi} = \left\langle \frac{dN}{d\phi} \right\rangle \left(1 + \sum_n 2\underline{v_n} \cos\left[n\left(\phi - \Psi_n\right)\right] \right)$$







ridge in small (pp, p+Pb) systems



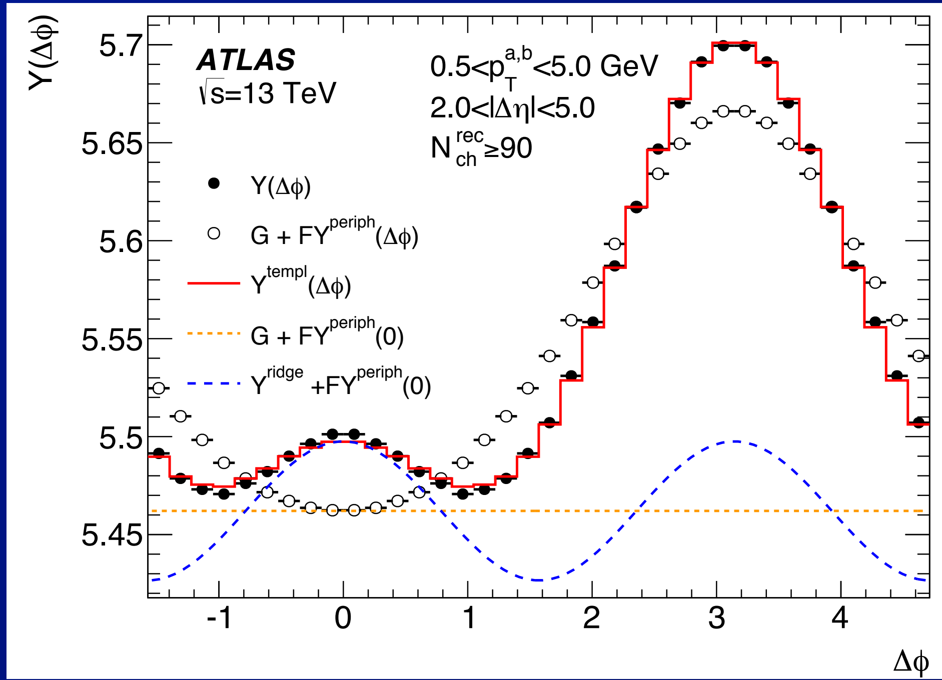
- **Measurements of two-particle angular (η,φ) correlations in pp and p+Pb collisions**
  - also show the ridge
  - most visible in high-multiplicity events
- **Also associated with azimuthal harmonics?**

  ⇒i.e. similar to Pb+Pb collisions?

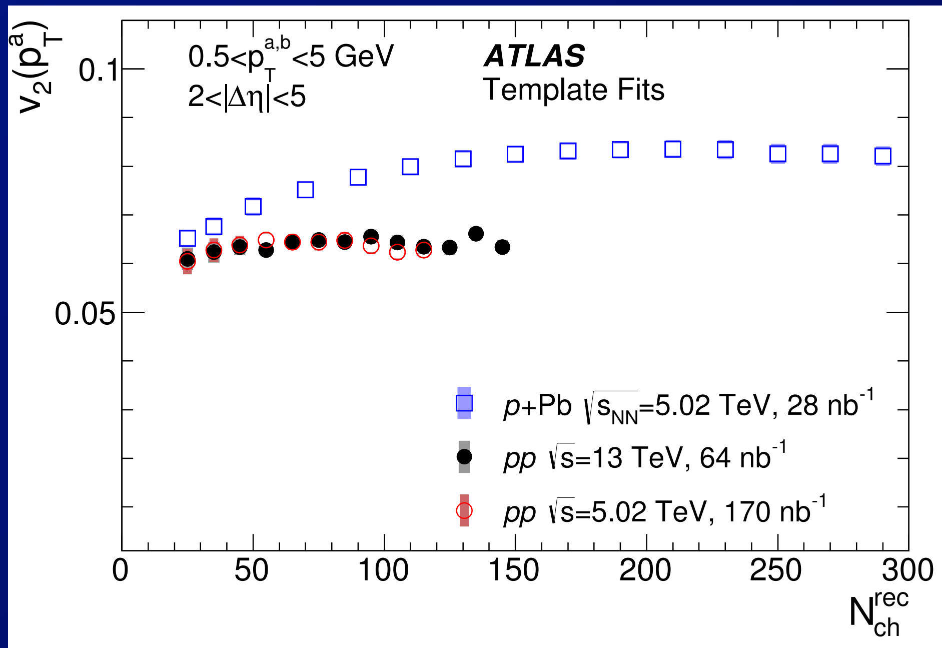
"ridge" in small systems

- ATLAS template fit:
  - assume 2-particle correlation function is sum of hard & modulated soft contributions

  ⇒ it is ?!



- Extracted v_2 values in pp independent of multiplicity, √s
  - weak mult. dependence in p+Pb



“ridge” in small systems

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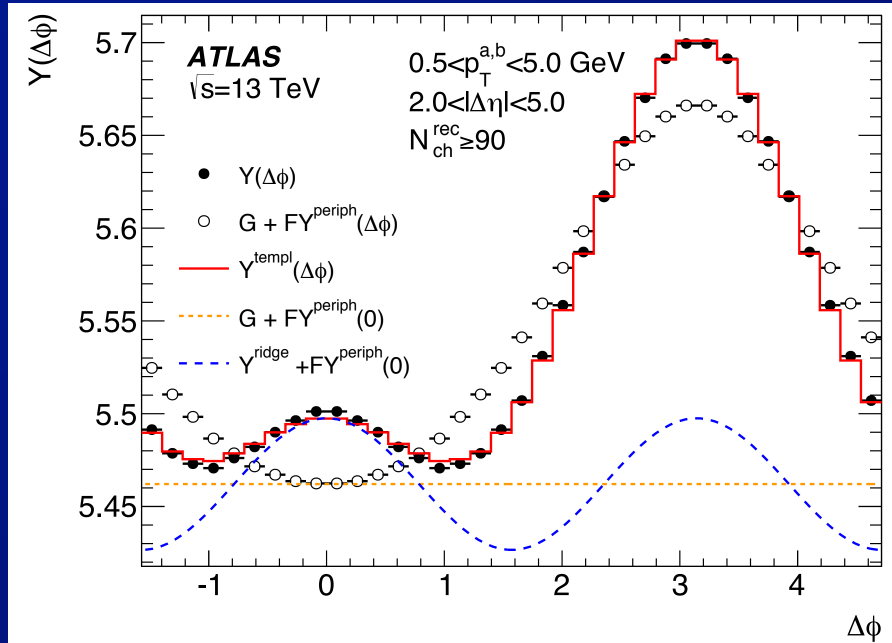
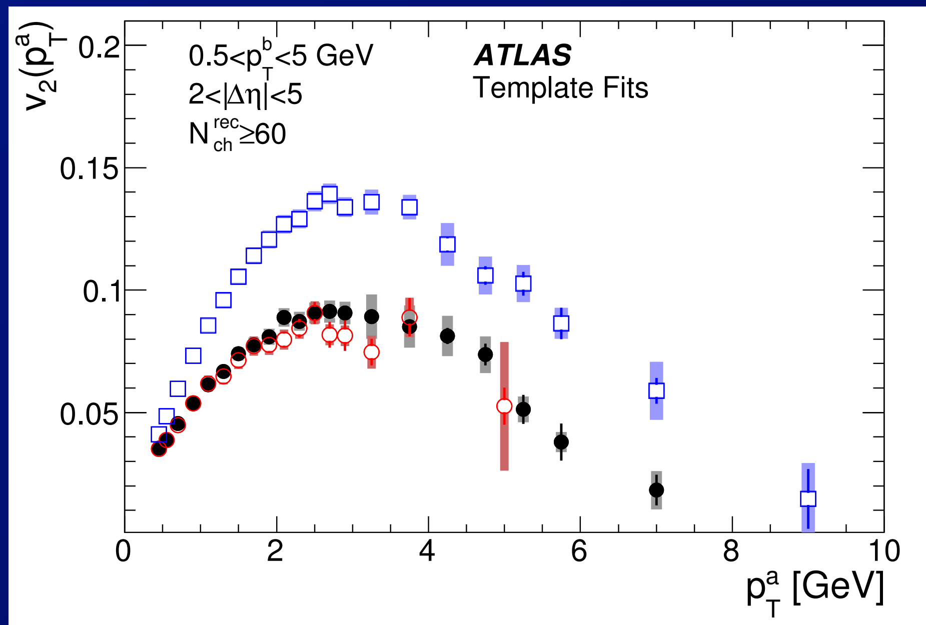
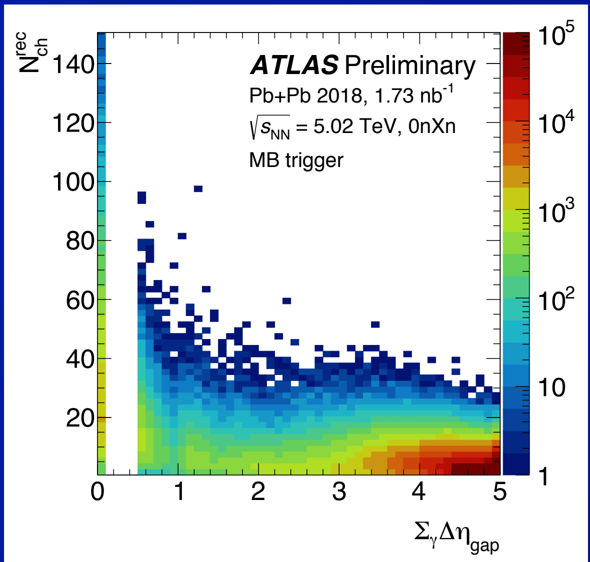


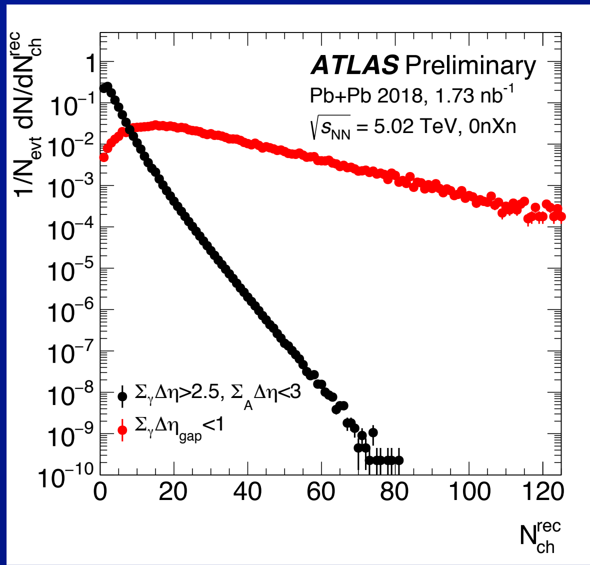
- **p_T dependence of v_2 ~ identical in pp, p+Pb, and Pb+Pb (not shown)**
  - ⇒universal behavior of soft particle production?

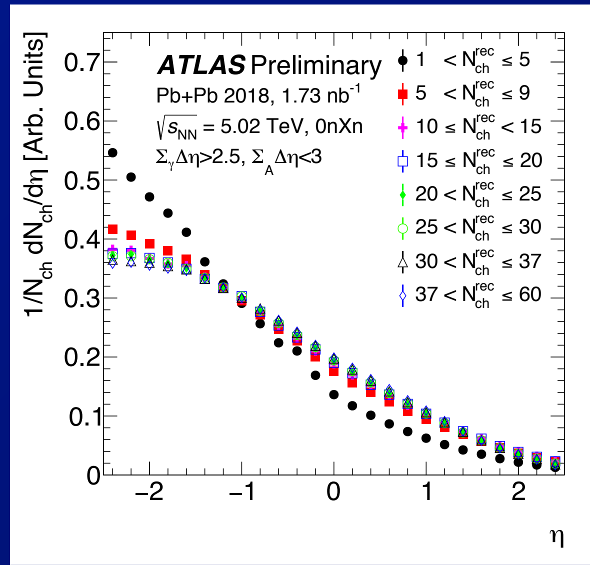


Ridge in UPC photoproduction?

ATLAS-CONF-2019-022





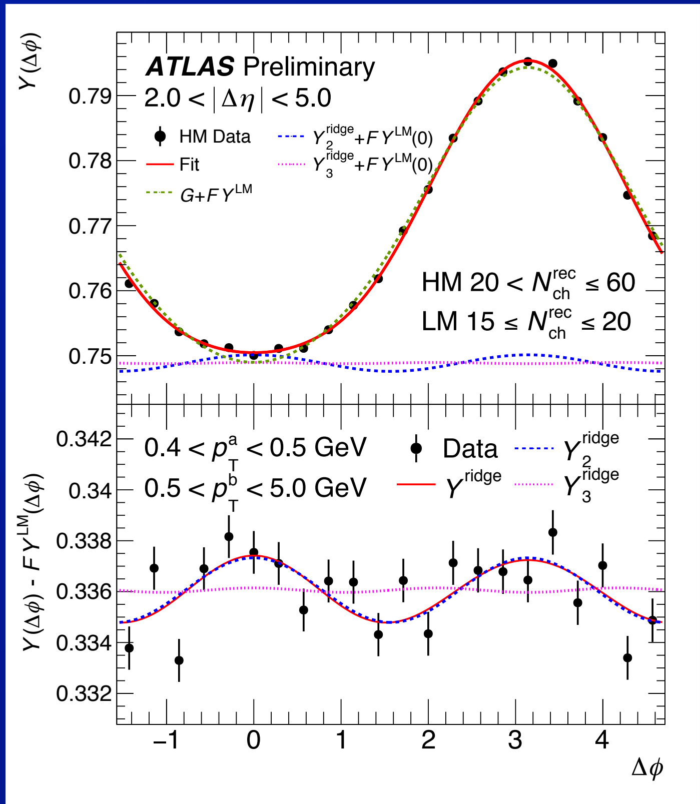


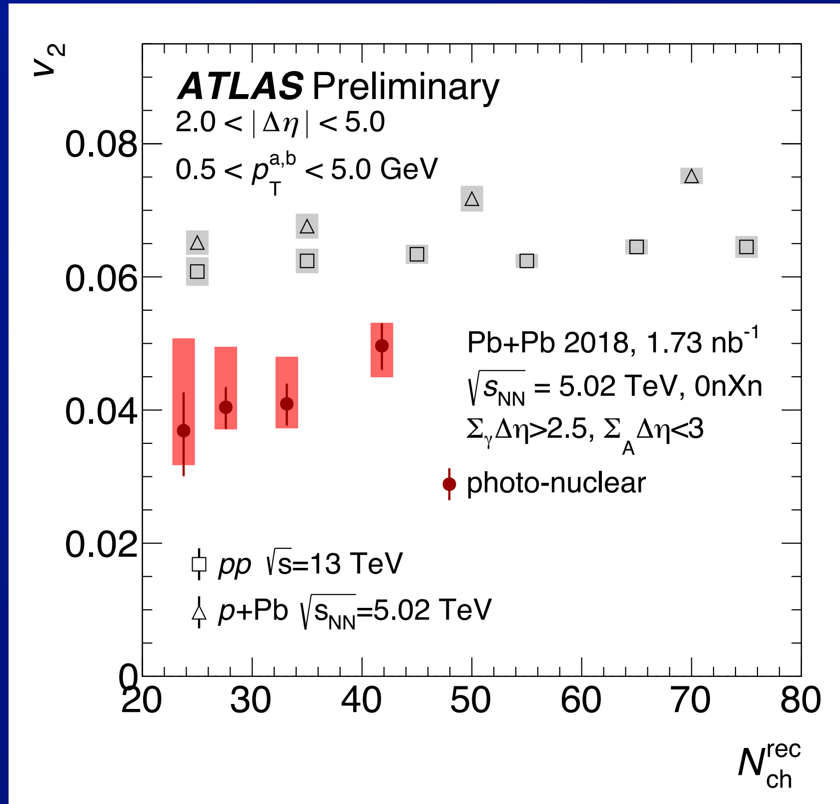
- (inclusive) photoproduction events selected using zero-degree calorimeters (0NxN) and gap requirements.
  - clear difference in multiplicity distributions between photoproduction and “hadronic” events

    ⇒ photoproduction dominated by low-multiplicities

    ⇒ absolute amplitude of any modulation likely small

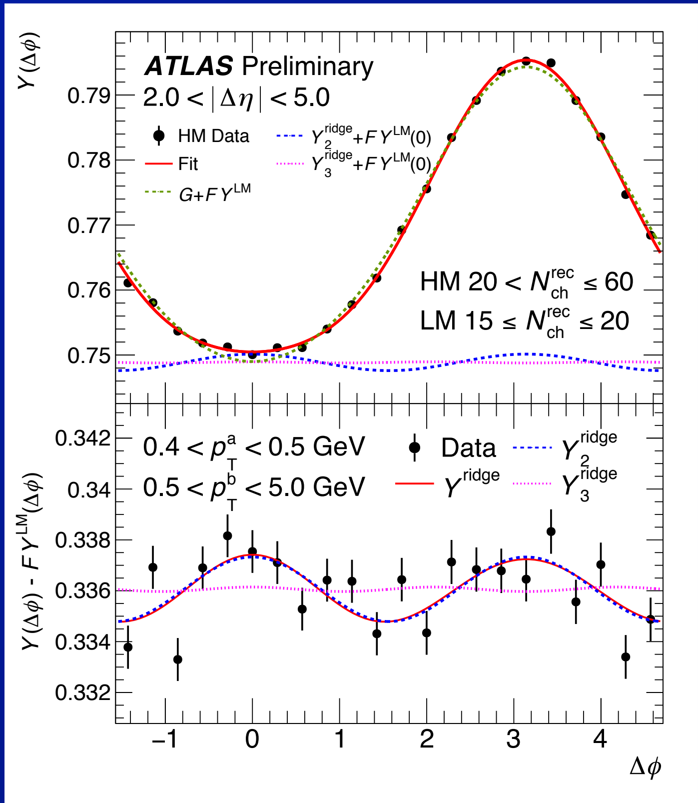
Ridge in UPC photoproduction?

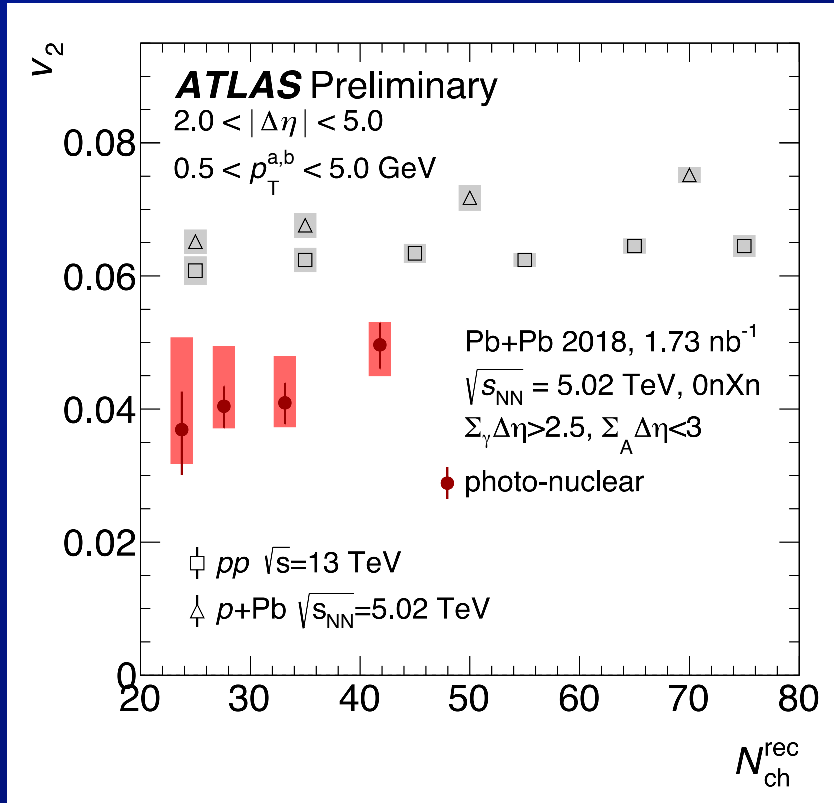




- Apply template-fitting procedure used in pp
  - observe small-amplitude modulation in CF
    - ⇒relative amplitudes (v_2) ~ 2/3 pp v_2 values
- Apparently the ridge is present in γ+Pb
    - ⇒surprising? probably not given VMD (ρ+A ~ p+A)

Ridge in UPC photoproduction?

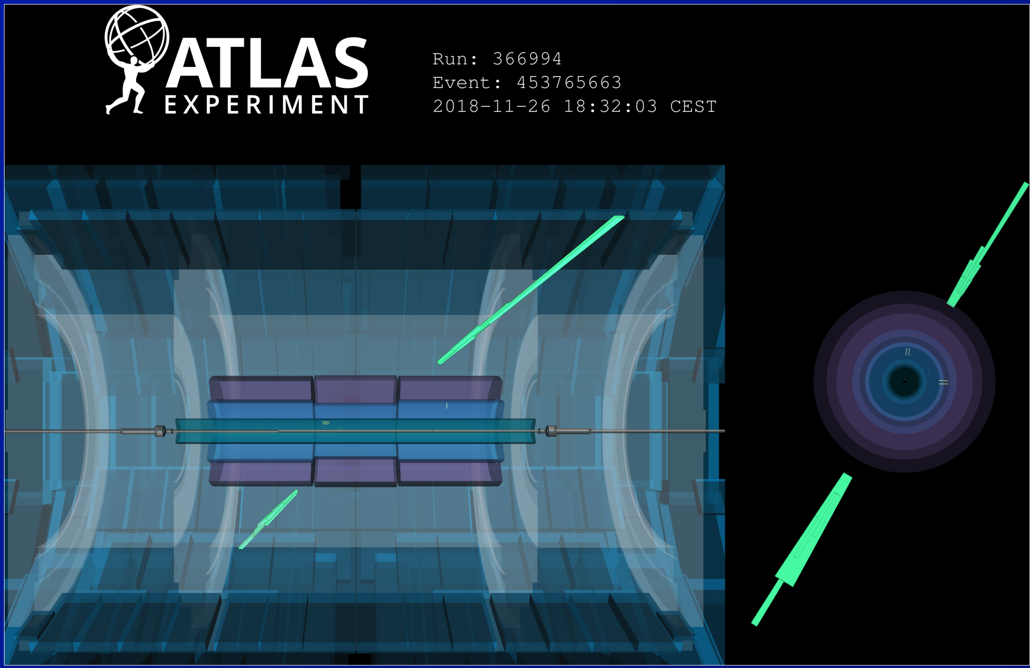


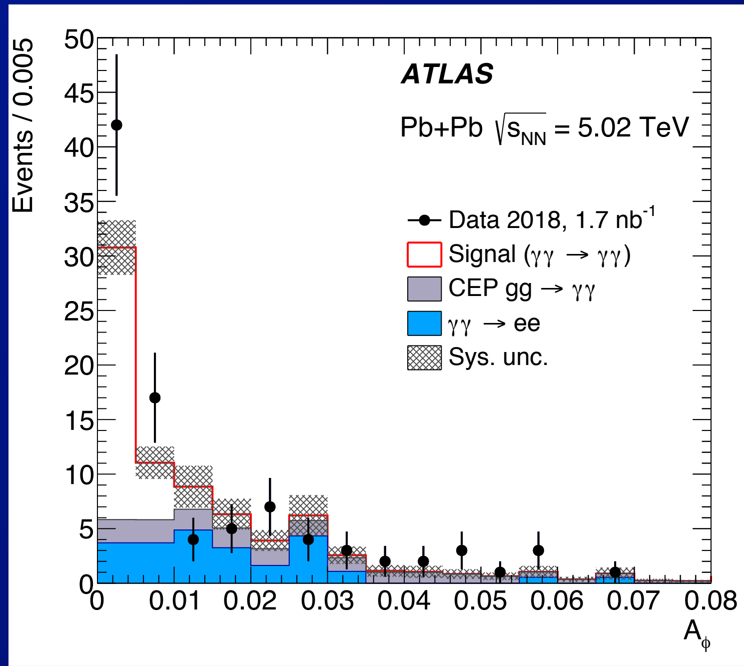


- I predict the ridge will be present in e+p/A DIS
  - recent attempts to analyze HERA data inconclusive
- If it is
  - does it disappear with increasing Q^2?
  - how does it depend on x?
  - in diffractive final states?

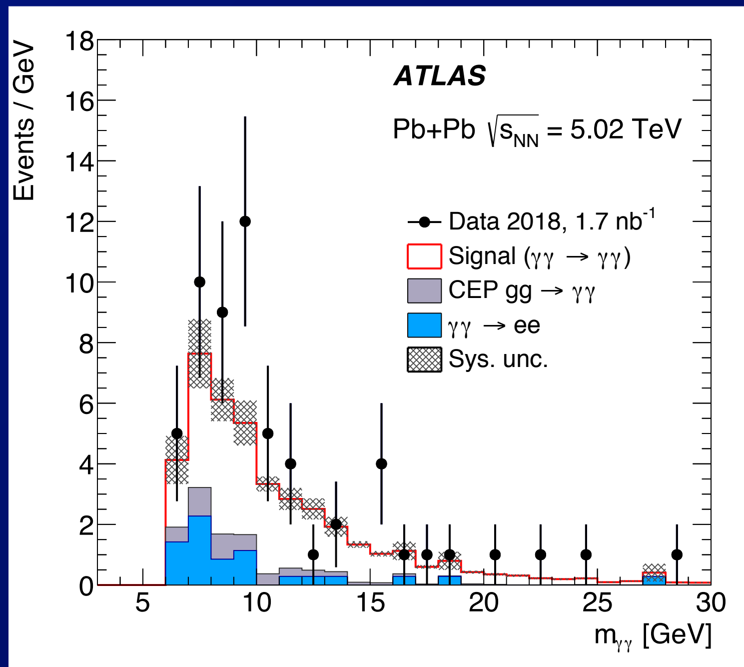
Ultra-peripheral $\gamma+\gamma$

Pb+Pb Light-by-light ($\gamma\gamma \rightarrow \gamma\gamma$)





- Using 2018 Pb+Pb data set
  - σ_{LbyL} = 78 ± 13 (stat.) ± 7 (syst.) ± 3 (lumi.) nb
  - 8.2σ significance
- New arena for BSM tests
  - e.g. ALP $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$
  - rates for e+A $\gamma\gamma$ @ LHeC?

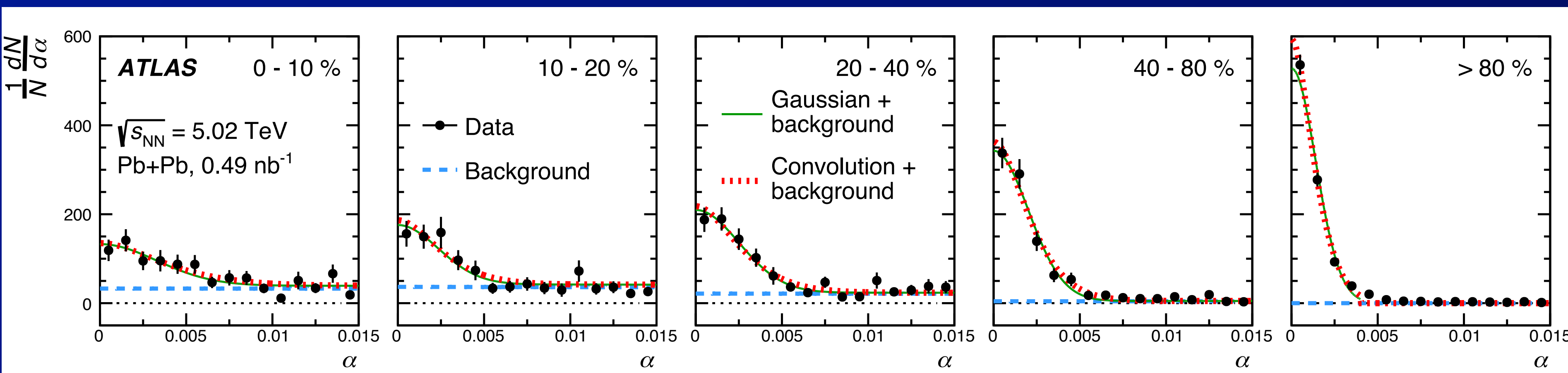


Non-ultra-peripheral $\gamma\gamma \rightarrow \mu^+\mu^-$

- Unexpectedly, we are able to observe $\gamma\gamma \rightarrow \mu^+\mu^-$ processes in hadronic Pb+Pb collisions
  - essentially because of the tight $\Delta\varphi$ distribution
  - in hind-sight, not really a surprise

  $\Rightarrow \gamma\gamma \rightarrow \mu^+\mu^-$ processes must be there
- The real surprise:

  $\Rightarrow$ observe a centrality-dependent $\Delta\varphi$ broadening, express in terms of acoplanarity $\alpha = 1 - \Delta\varphi/\pi$



ATLAS, Phys. Rev. Lett. 121 (2018) 212301

Non-ultra-peripheral $\gamma\gamma \rightarrow \mu^+\mu^-$

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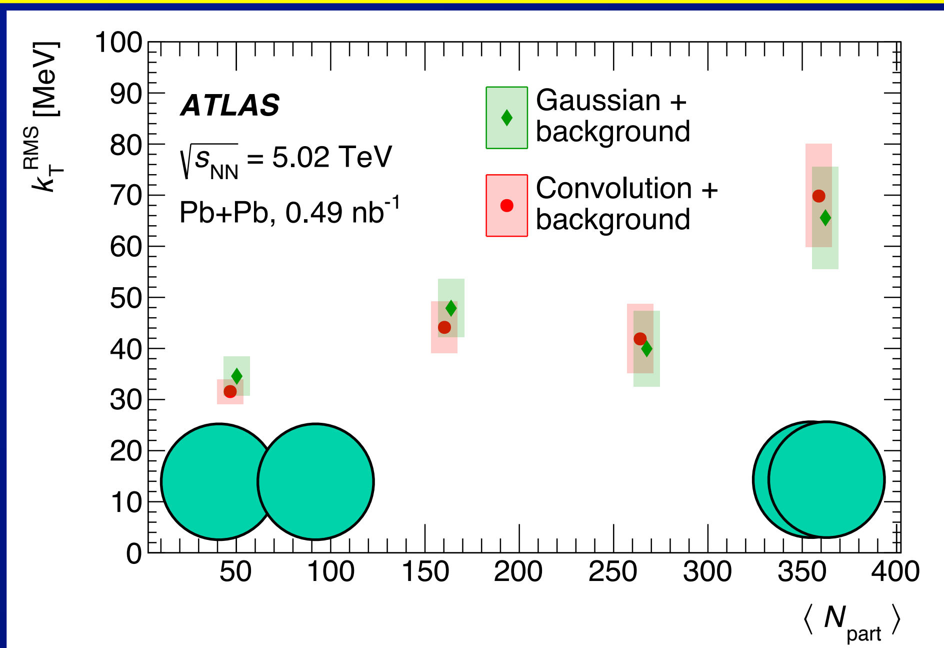

- **Estimate the momentum scale associated with broadening → ~ 70 MeV in most central Pb+Pb**
- **Possible physics mechanism(s):**
  - QED interactions in quark-gluon plasma
  - deflection of muons in magnetic field of plasma
  - initial-state: photon p_T at small b *wrt* nucleus

⇒need calibration of nuclear photon p_T distribution

⇒p+Pb cross-sections too small, e+A $\gamma\gamma$?

Summary

∃ many places where LHC heavy ion and LHeC QCD/low x/e+A programs overlap

- "Standard" examples
  - Hard processes & nPDFs (p+Pb & Pb+Pb)
  - Forward physics & low x/saturation
  - Exclusive diffraction
  - photoproduction
- Some not-so-standard examples here
  - Ridge in e+p/e+A

    ⇒ using DIS kinematics to control initial geometry
  - $\gamma+\gamma$ processes (rates calculated?)
  - other opportunities provided by high Pb γ flux?

Backup

“ridge” in small systems, interpretation

- There has been significant controversy over the interpretation of the ridge measurements
  - similarity of many results to Pb+Pb data
    - ⇒seeing collective dynamics even in pp collisions?!
  - or, due to glasma/saturation/cgc
    - ⇒can qualitatively explain many features in data
    - ⇒but quantitatively?
- My personal opinion is that the most natural interpretation of a large set of data is that we are seeing evidence for universal collective dynamics in soft particle production
  - but observed anisotropies (v_n) depend on initial state
    - ⇒e.g. “ridge” should be present in e+p/A final states
    - ⇒what about ultra-peripheral Pb+Pb γ+A?