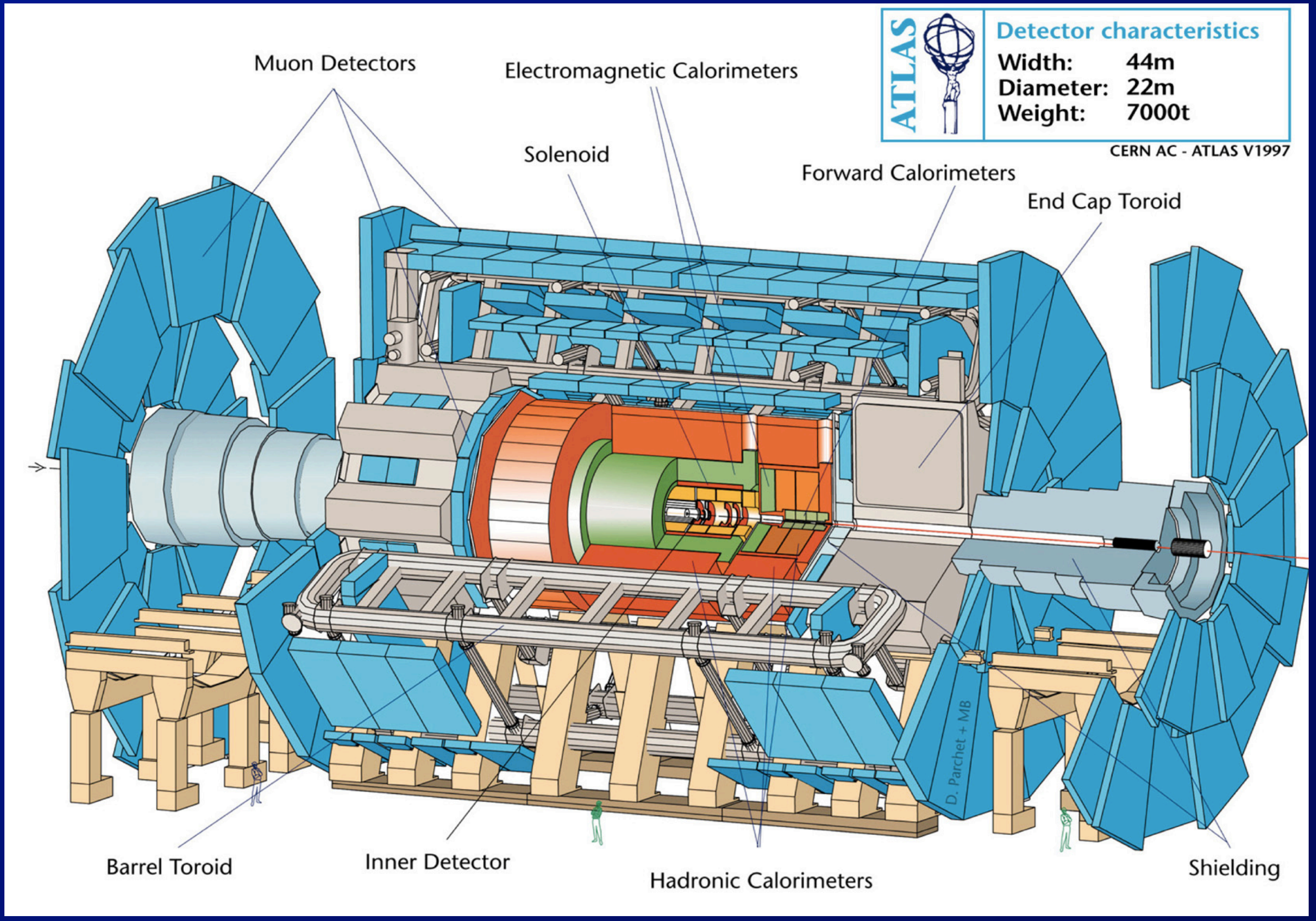
Overview of recent results from the ATLAS experiment

Prof. Brian Cole
Columbia University
on behalf of ATLAS



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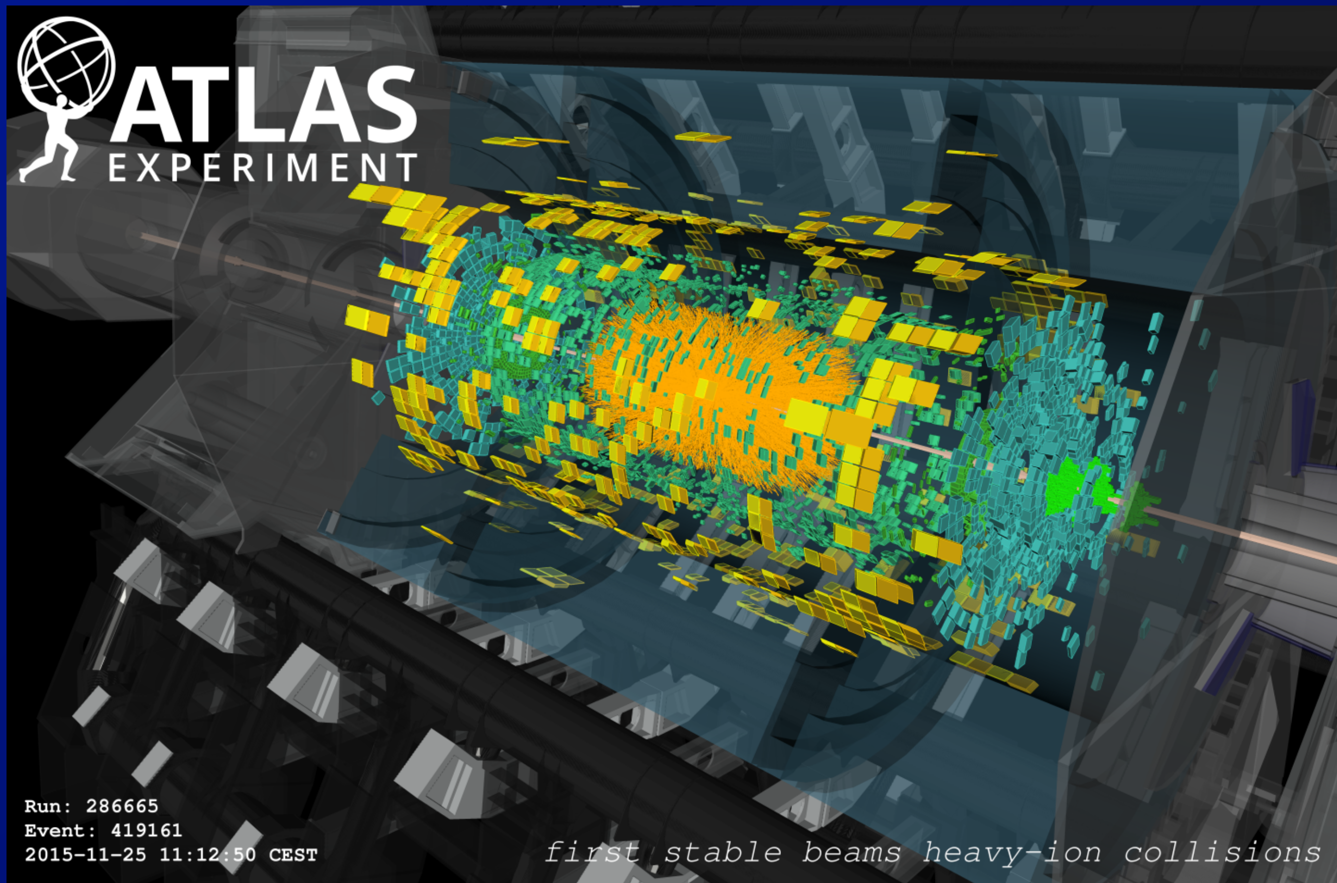

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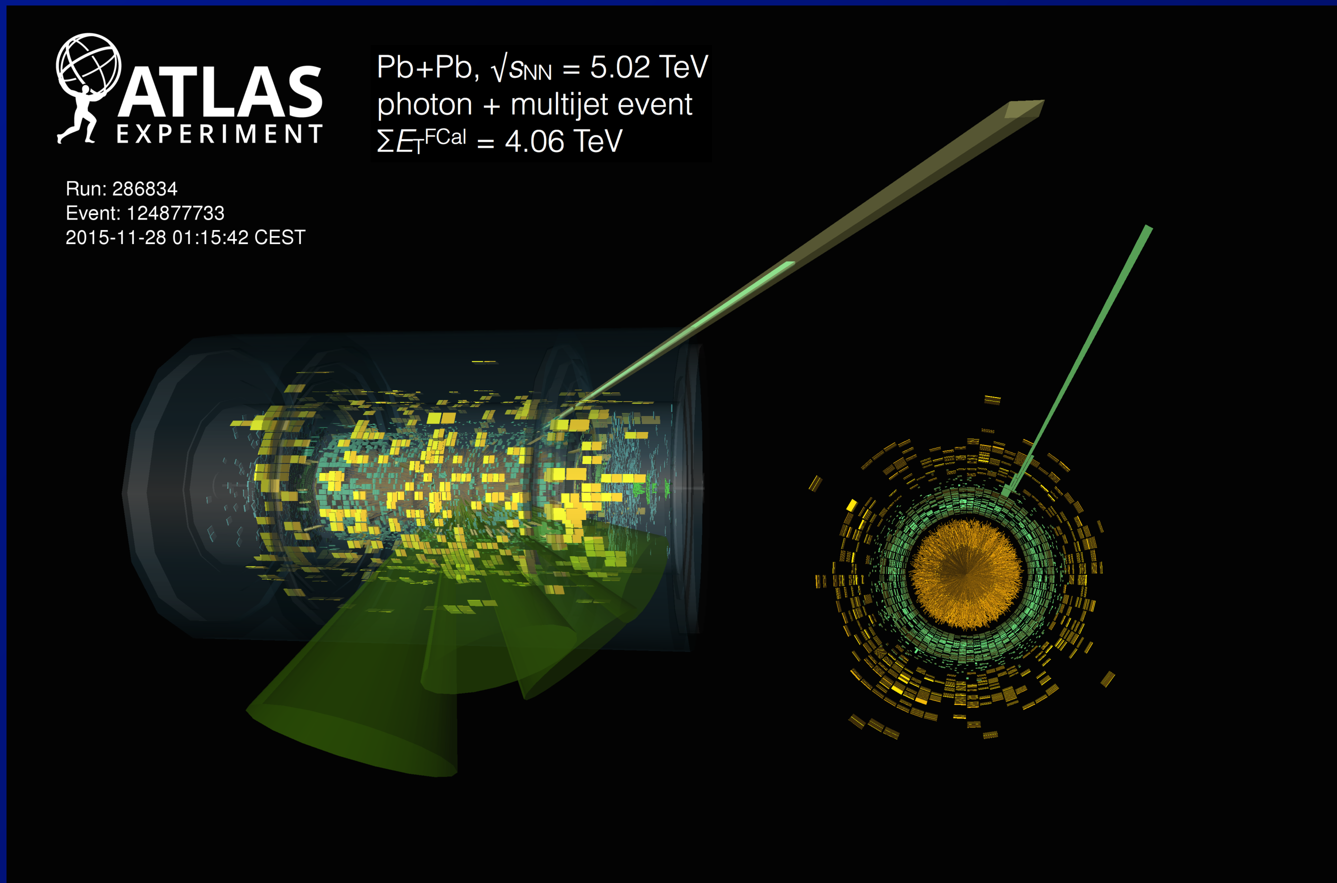
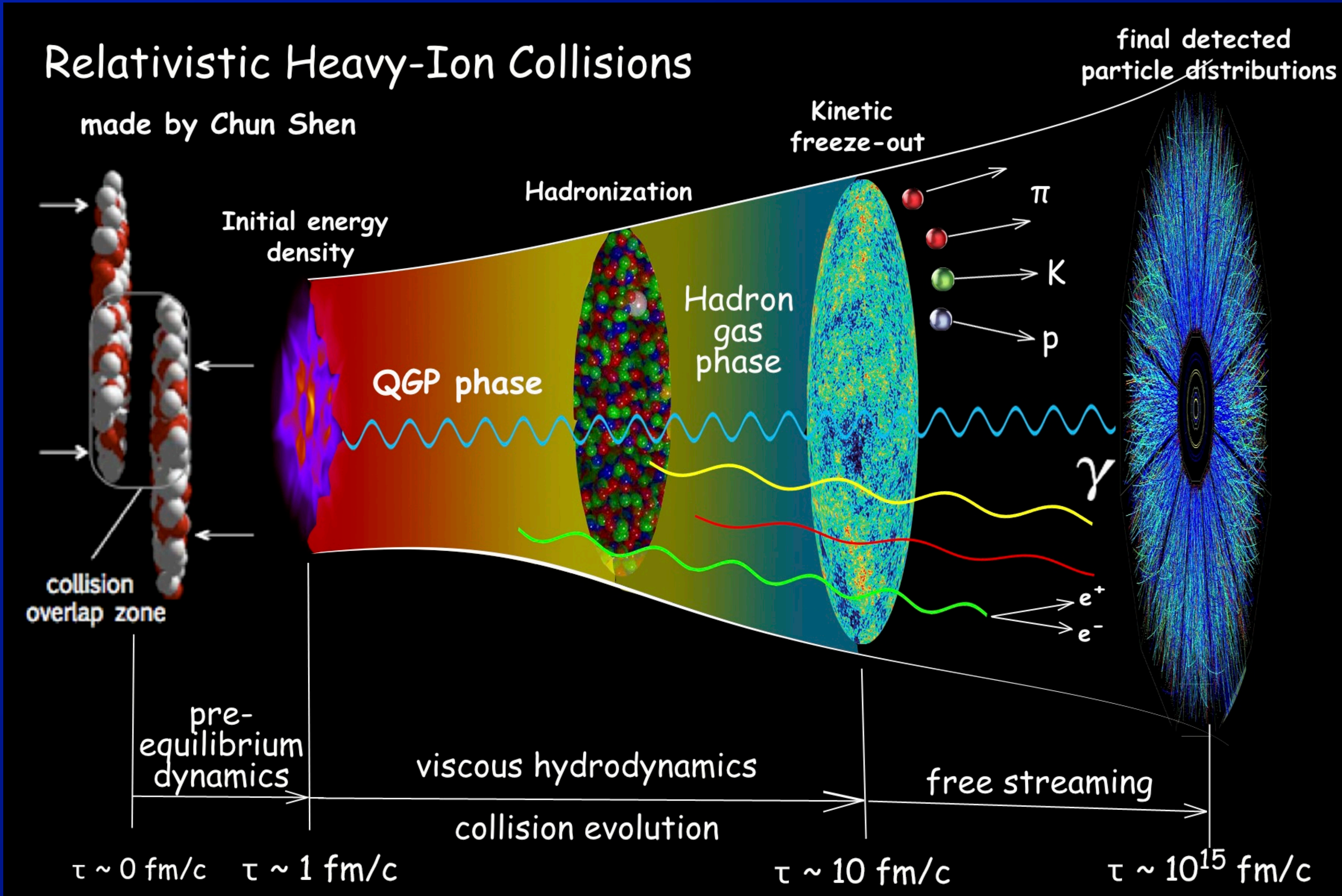
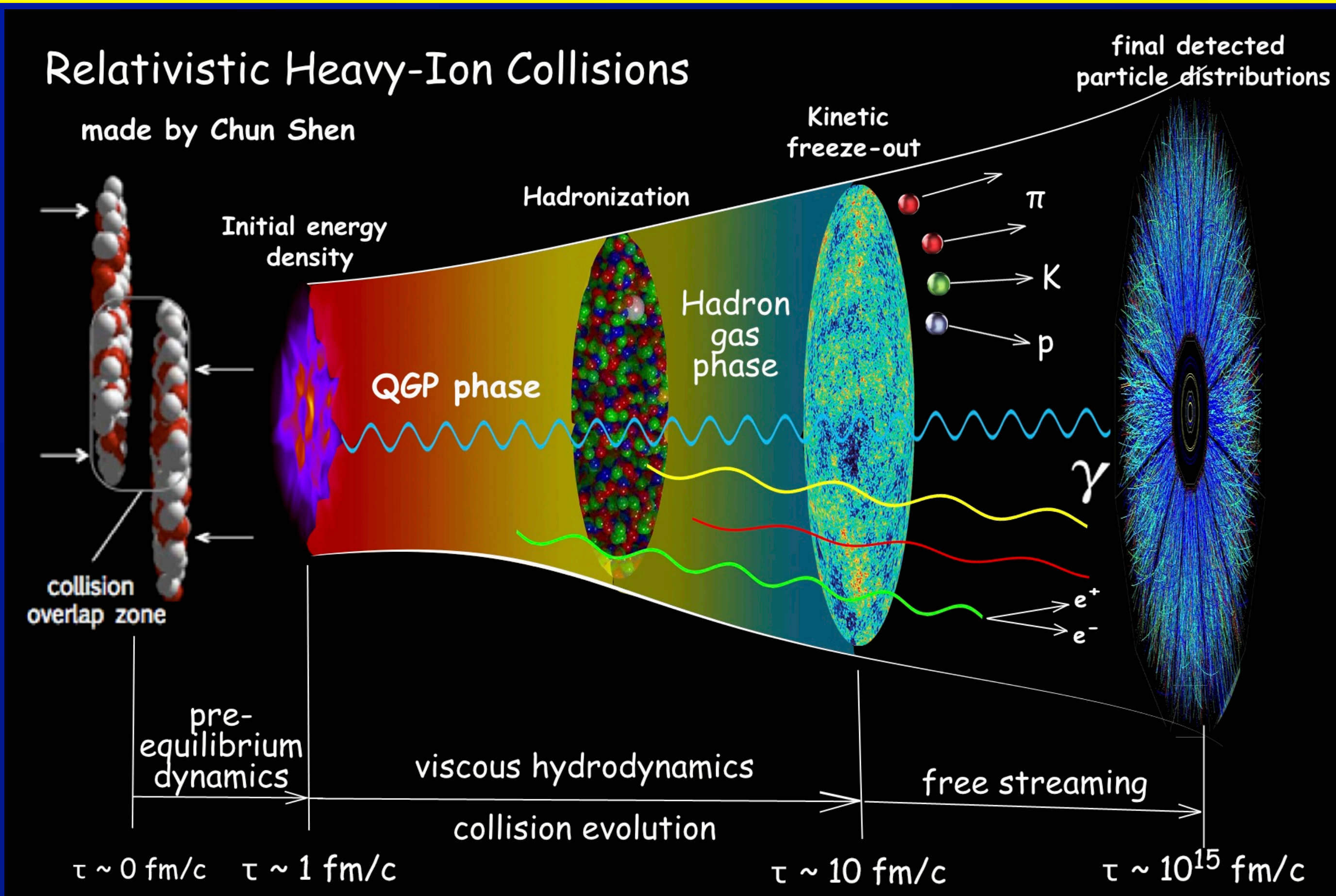


Physics overview

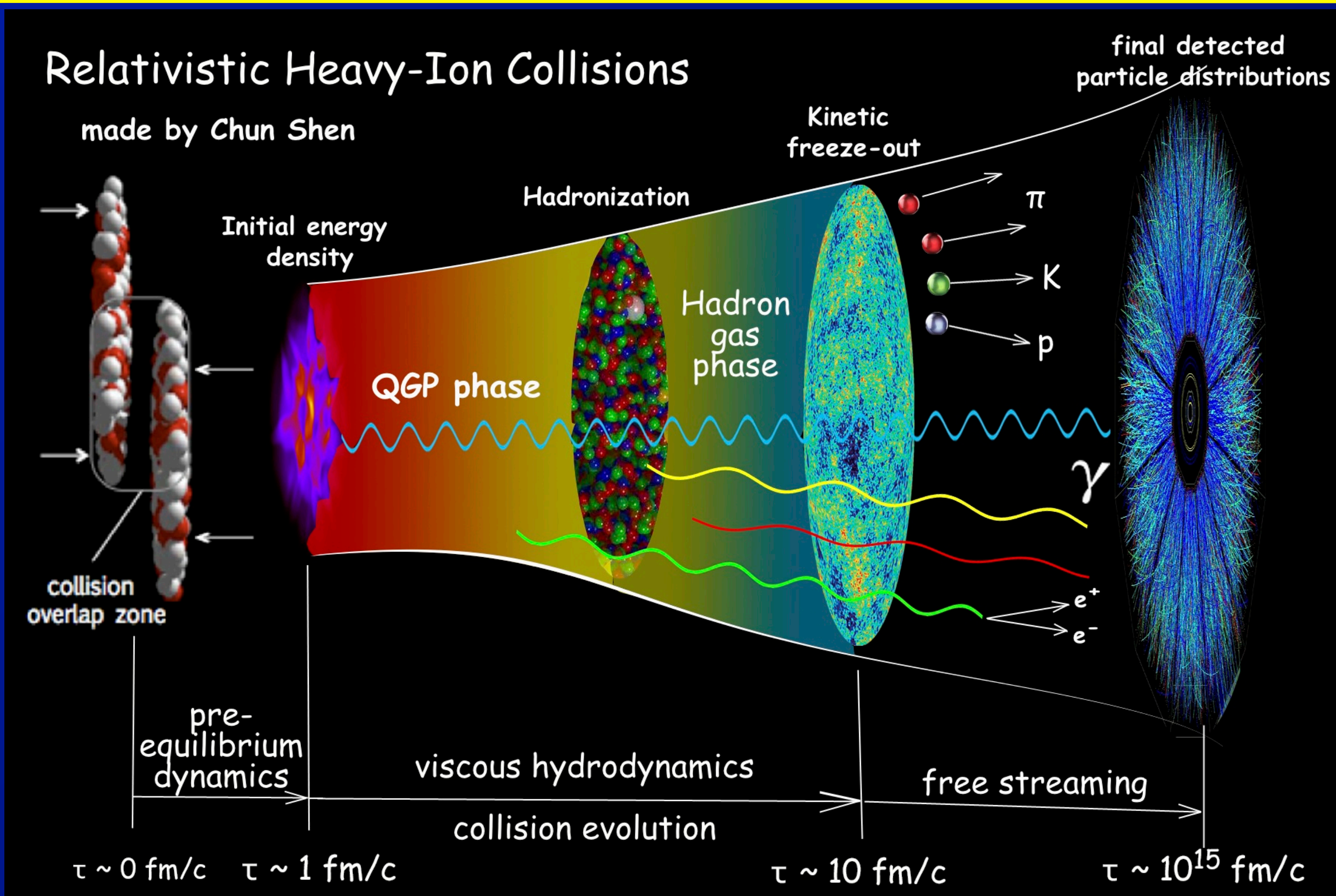


This talk



- How well do we understand "hydrodynamics"?
  - controlling uncertainties re: initial state
  - persistence in small systems?

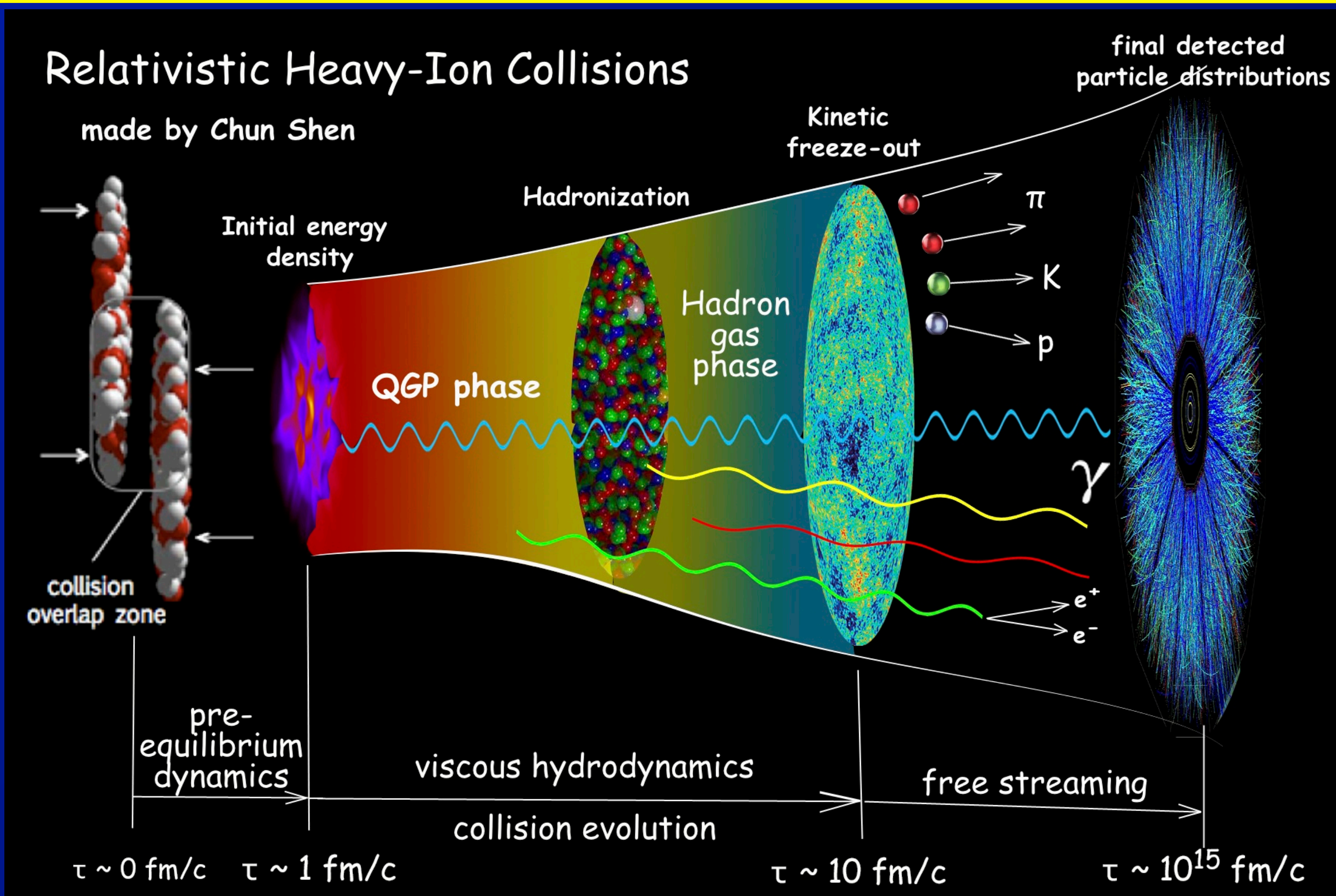
This talk



- **How do QGP properties depend on scale?**
  - **Use multi-scale probe of plasma**

  ⇒ **hard processes/jets**

This talk



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  ⇒ **EM probes??**

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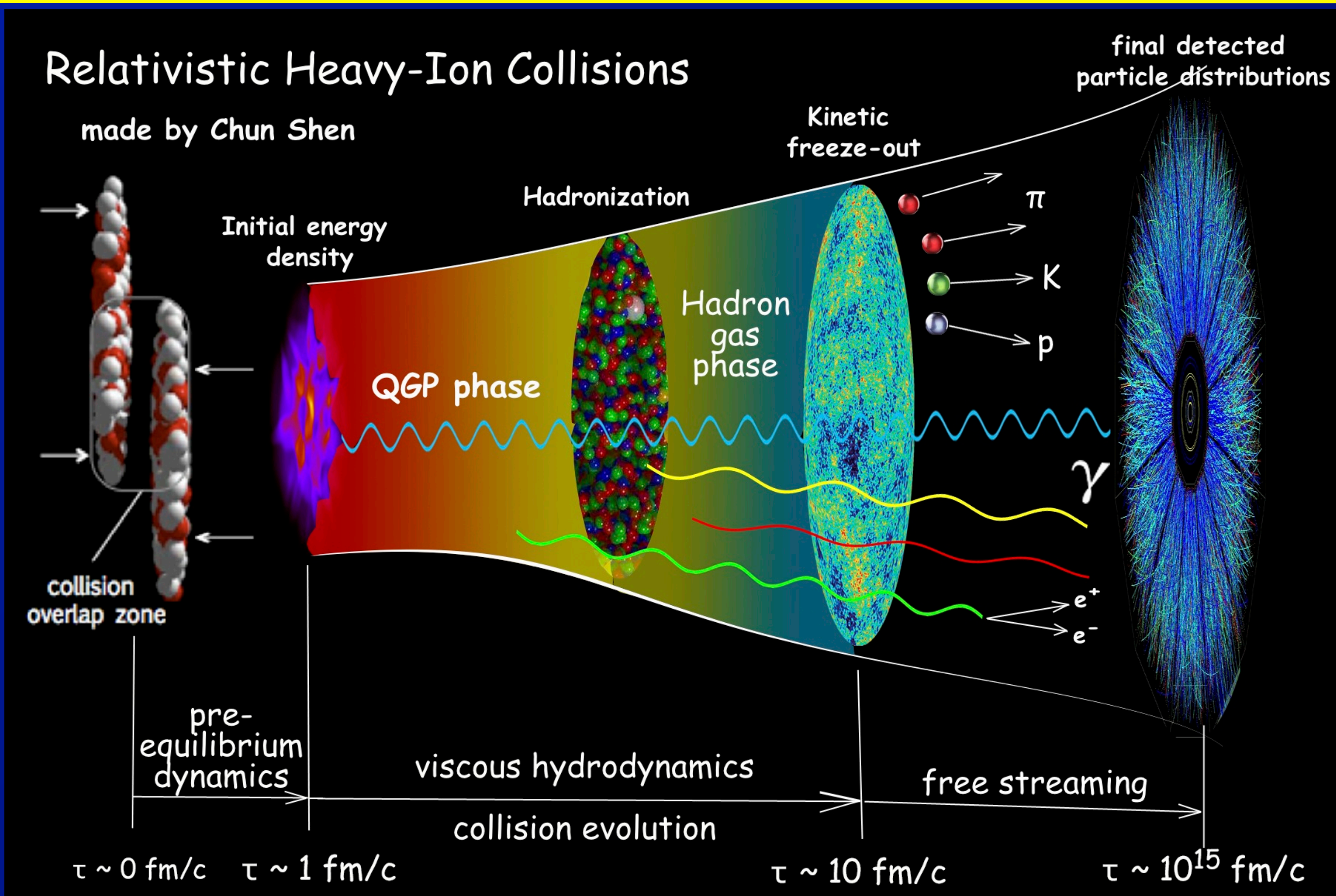
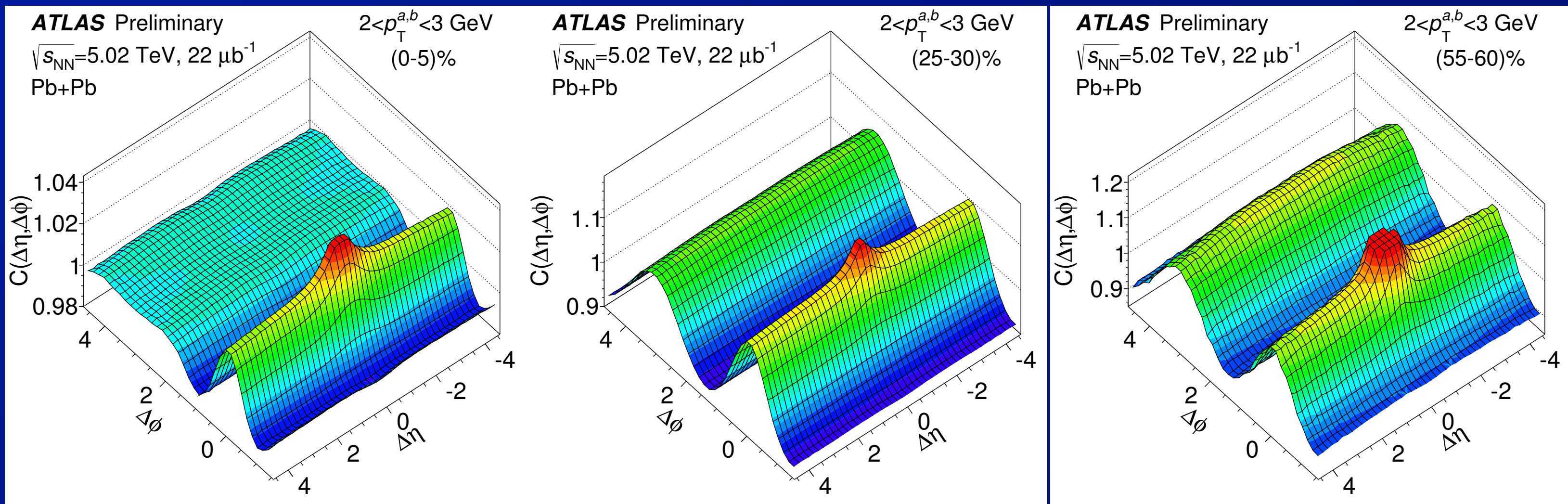


- **Constraining the initial state**
  - **Probing the parton distributions in nuclei**
  - **origin of "ridge" in small systems?**

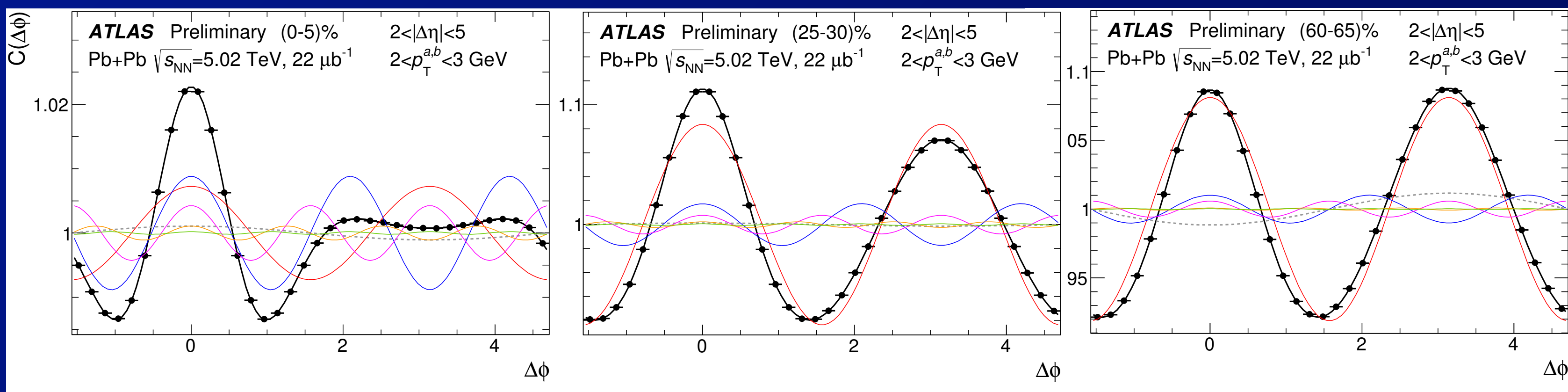
Collective dynamics in nucleus-nucleus (Pb+Pb, Xe+Xe) collisions

Collective dynamics: how?

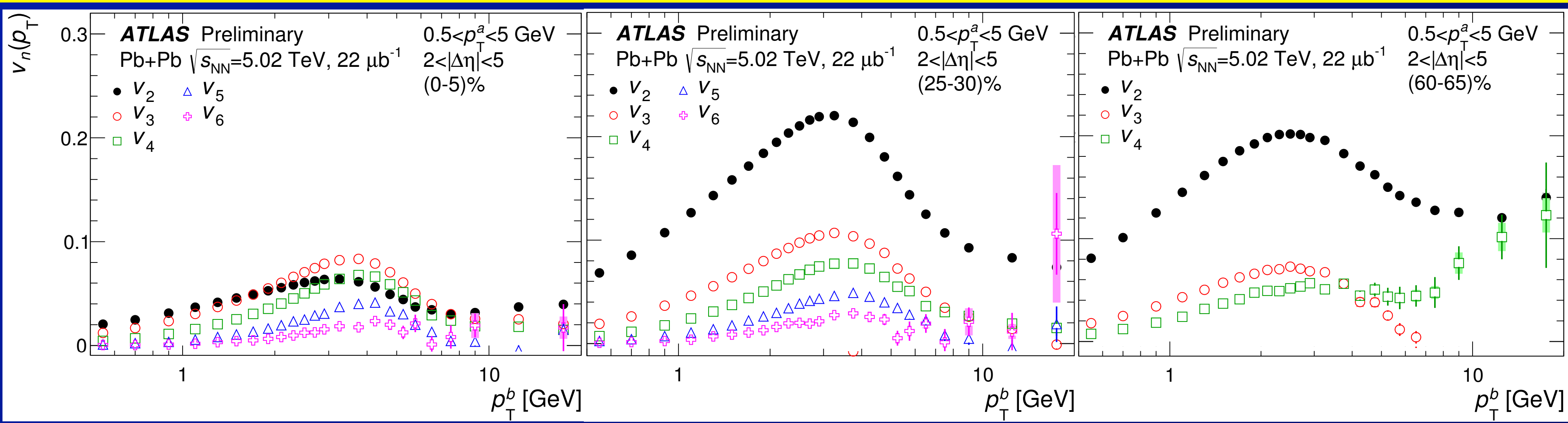
- **One method: 2-particle correlations**
  - Measure two-particle correlation function, C_2, as a function of Δφ and Δη (η is pseudo-rapidity)



  - Project to Δφ requiring |Δη| > 2 to excludes jet peak
  - Fourier decompose

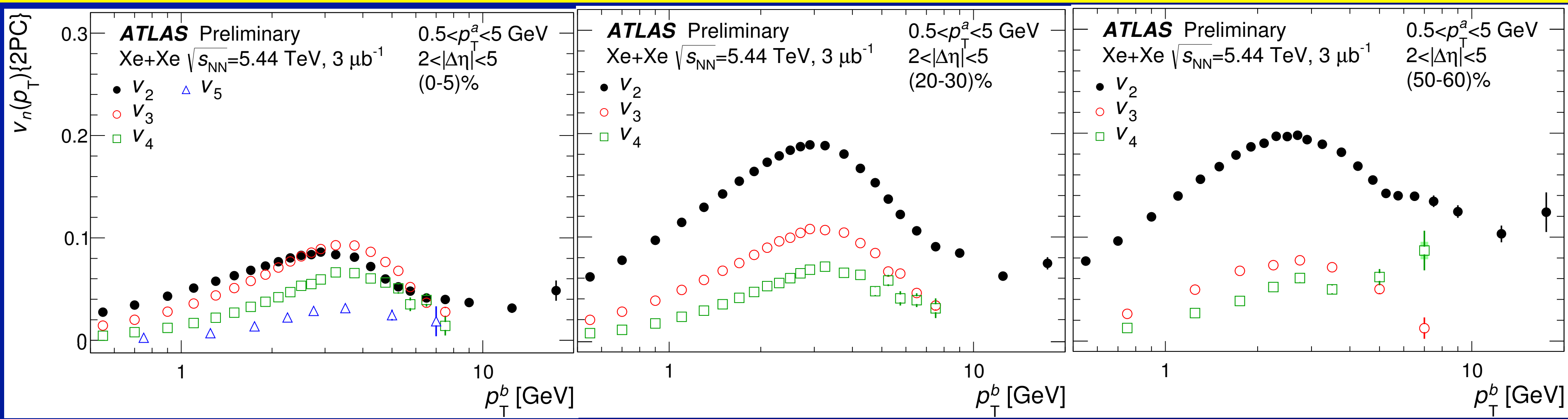


Pb+Pb v_n measurements



- p_T dependence of v_2 - v_6 for three centralities

Pb+Pb and Xe+Xe v_n measurements



- Xe+Xe & Pb+Pb v_ns very similar

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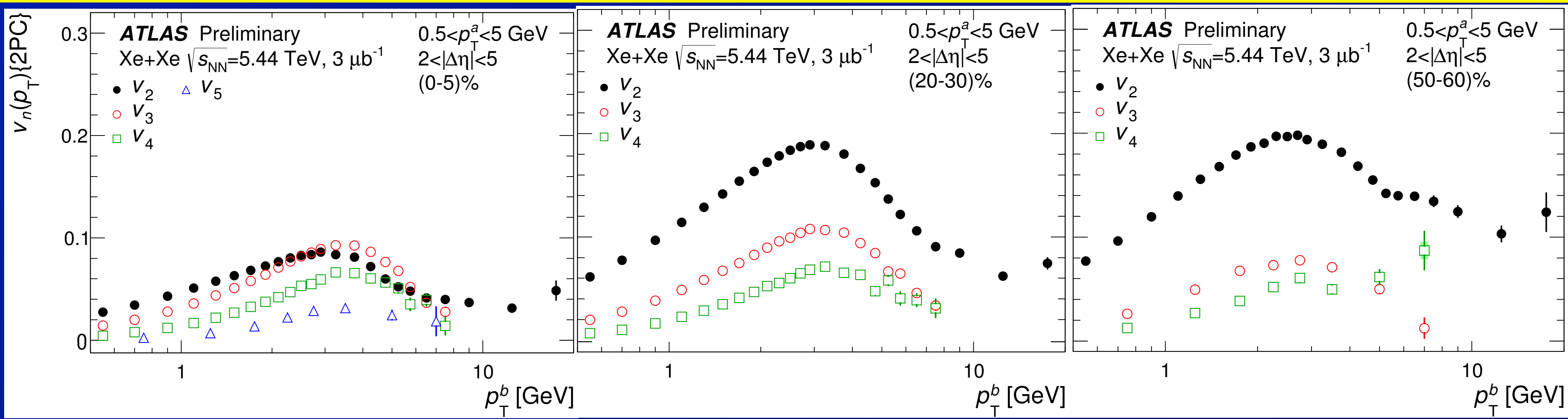
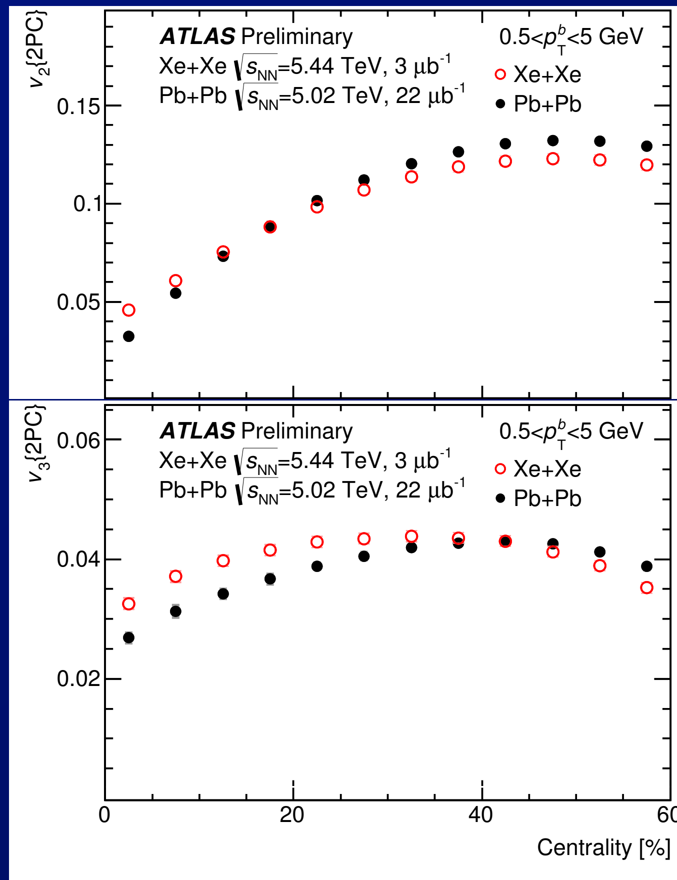


- Xe+Xe & Pb+Pb v_ns very similar
  ⇒both p_T and centrality dependence



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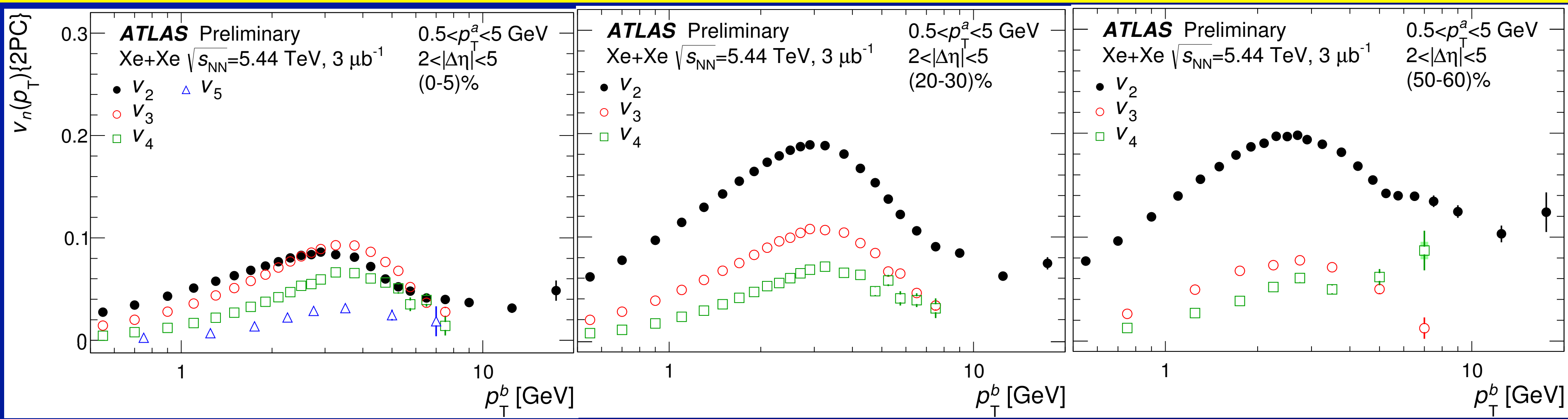
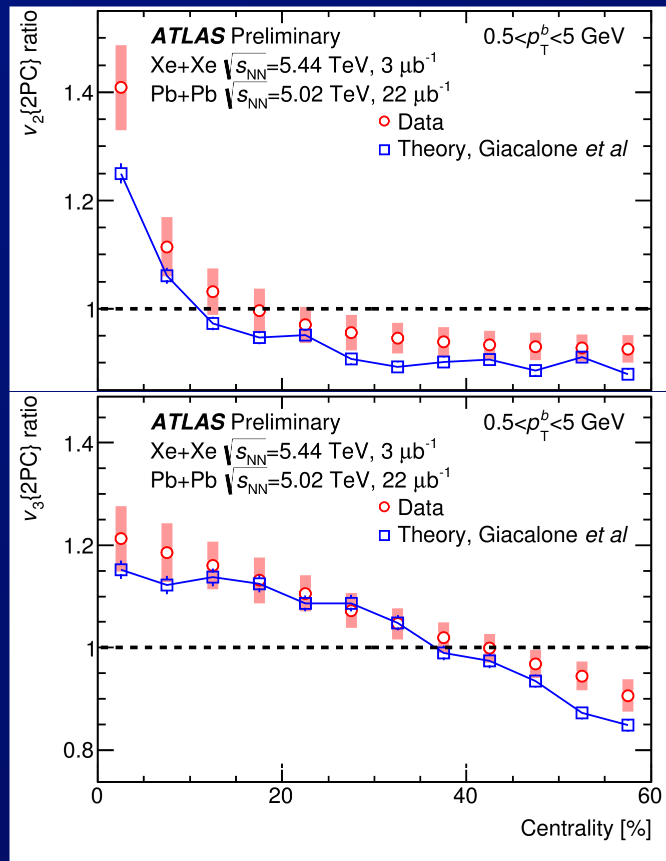


- **Xe+Xe & Pb+Pb v_ns very similar**
  - ⇒both p_T and centrality dependence
- **Take ratios vs centrality**
  - Compare ratios vs centrality to results of hydrodynamics
  - ⇒good agreement



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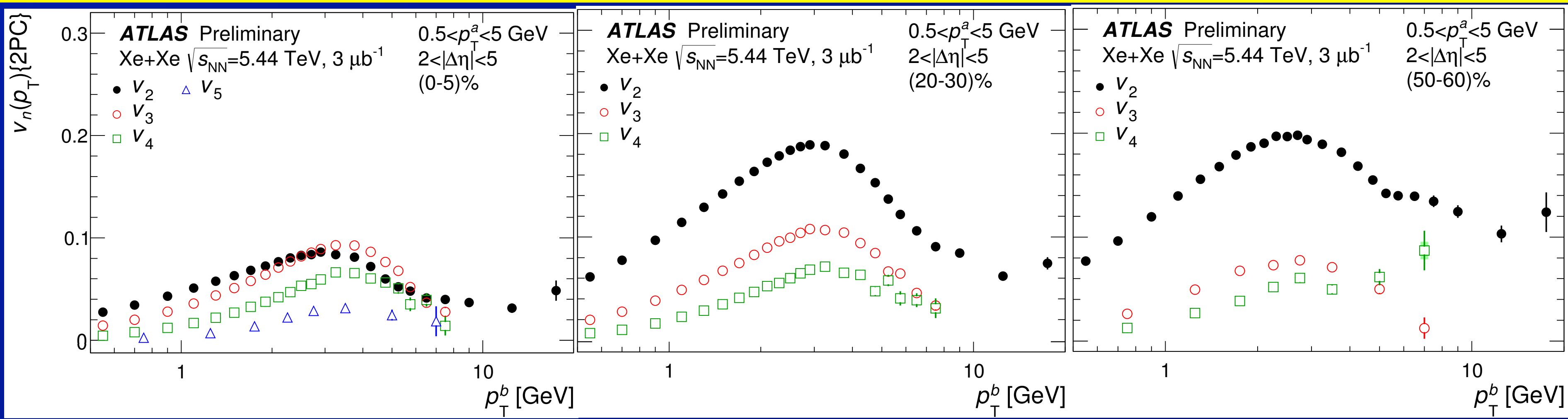

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  - ⇒both p_T and centrality dependence
- Take ratios vs centrality
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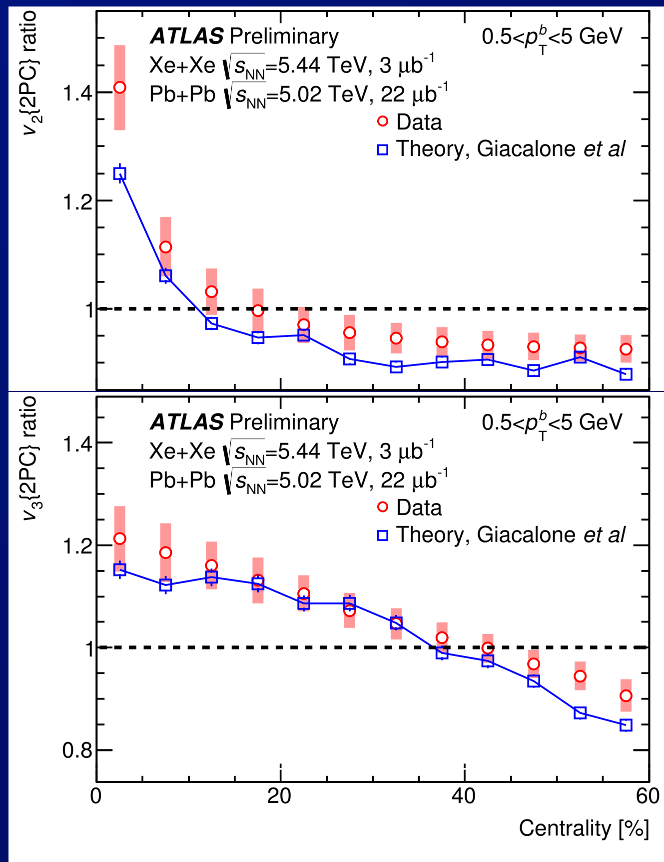
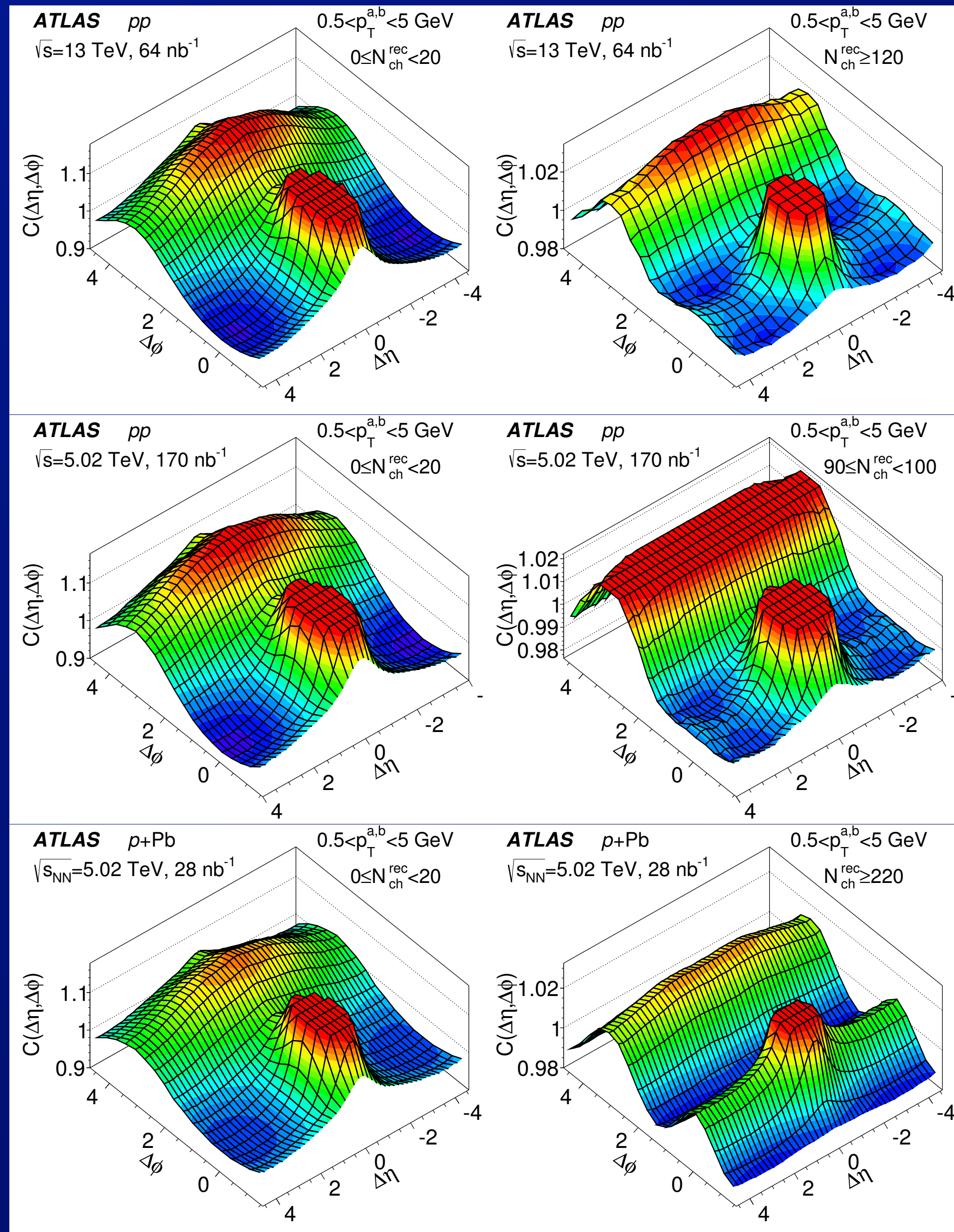
  - ⇒good agreement
  - ⇒similar modeling of initial state but different results from hydrodynamic evolution



Small systems: pp and p+Pb

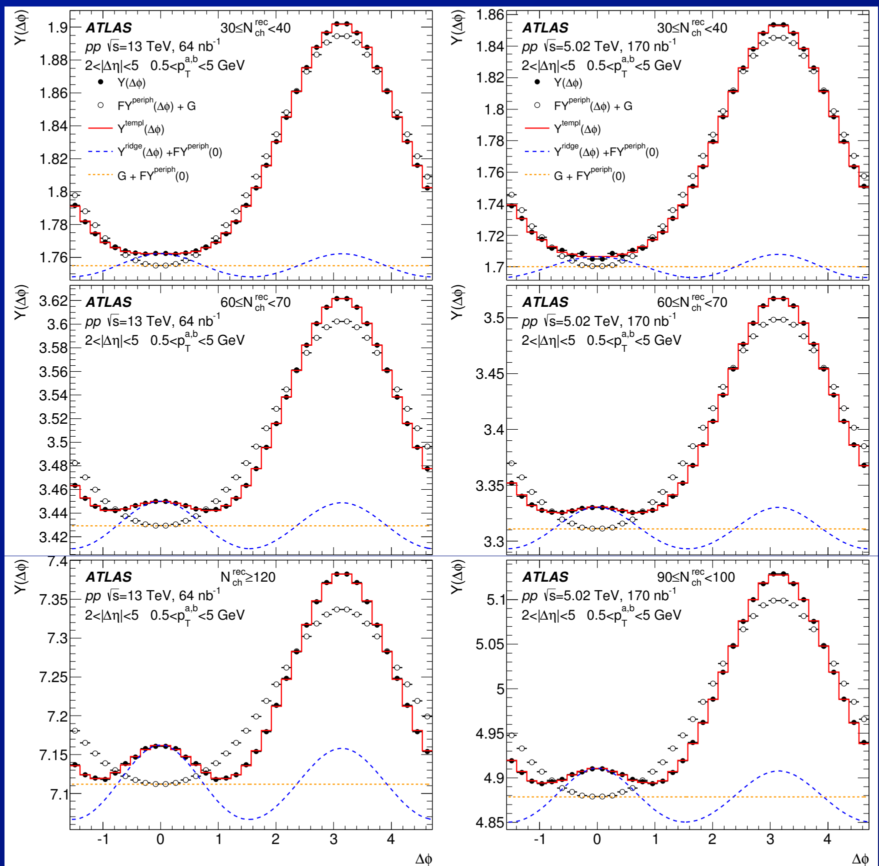
- pp and p+Pb collisions show similar azimuthal anisotropy as Pb+Pb
  - e.g. 2-part. correlations



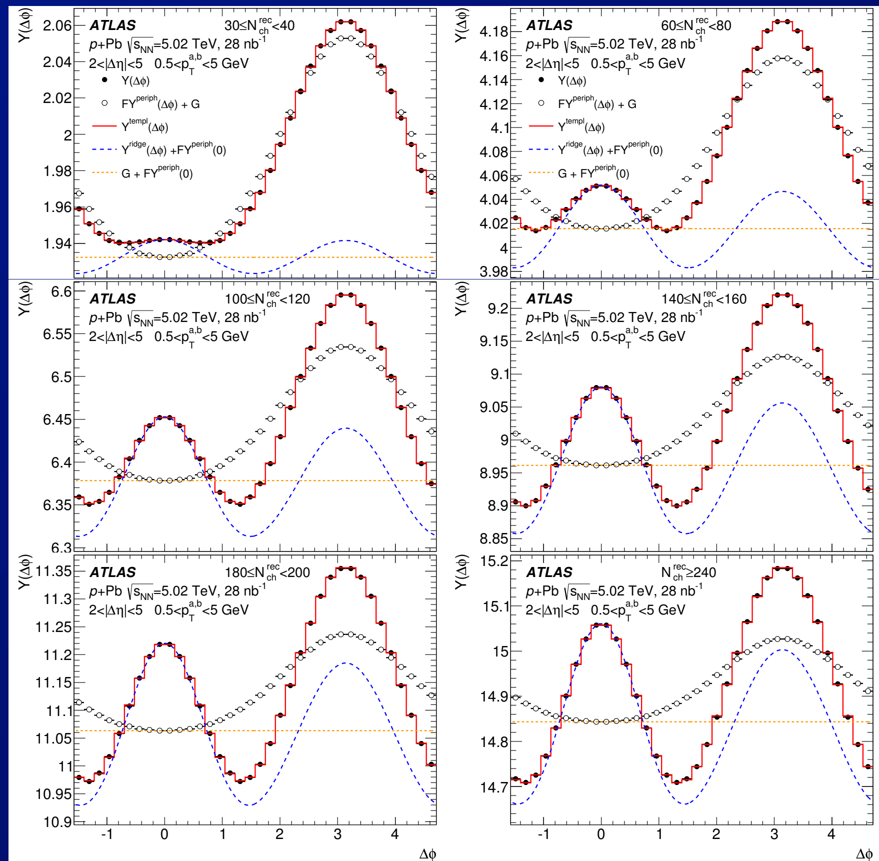
Small systems: template fits

- **Assume 2-particle correlation is a super-position of "intrinsic" (hard?) correlation + sinusoidal harmonics**
  - intrinsic measured in low-multiplicity (peripheral) events

$$Y^{\mathrm{templ}} = F Y^{\mathrm{templ}}_{\mathrm{periph}} + G\left(1 + 2\sum_{n} v_{n,n}\cos\left[n\left(\Delta\phi\right)\right]\right)$$



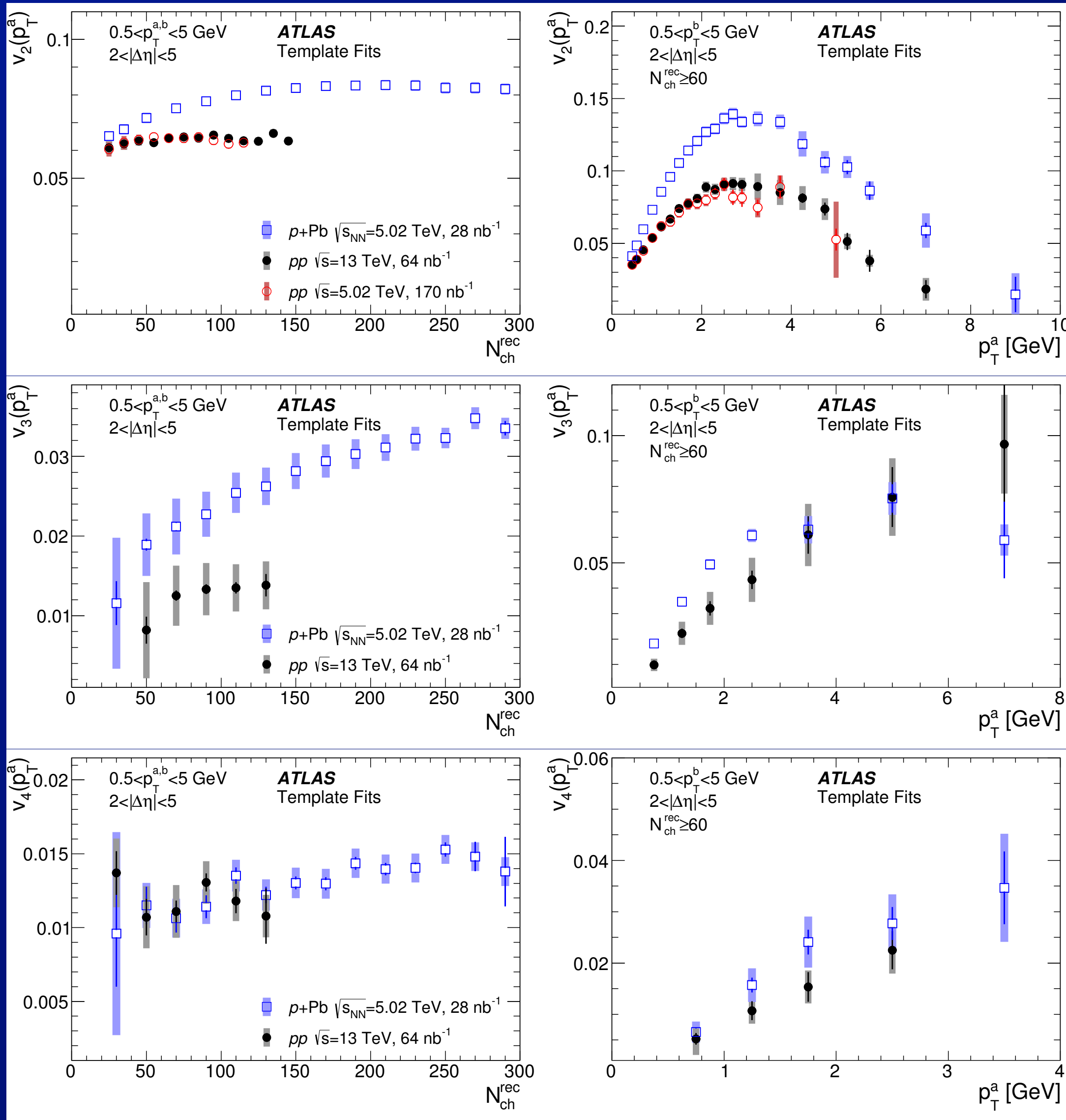
pp



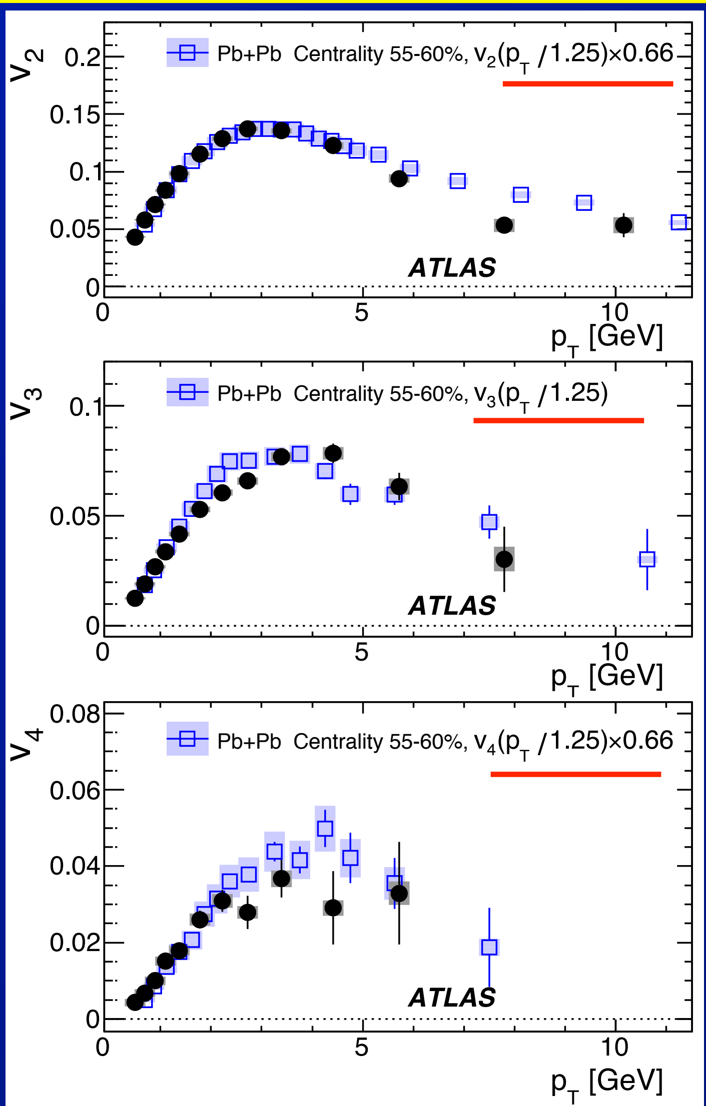
p+Pb

Small systems: template fits, results

- Observe non-zero v_2, v_3, v_4 in both pp, p+Pb
  - different multiplicity dependence
    - ⇒pp v_n's ~ constant
      - » vs N_{ch} and $\sqrt{s}$
    - ⇒p+Pb v_n's rise with N_{ch}
  - geometry different between pp and p+Pb
- Observe similar p_T dependence for v_2
  - uncertainties on v_3, v_4 too large to judge

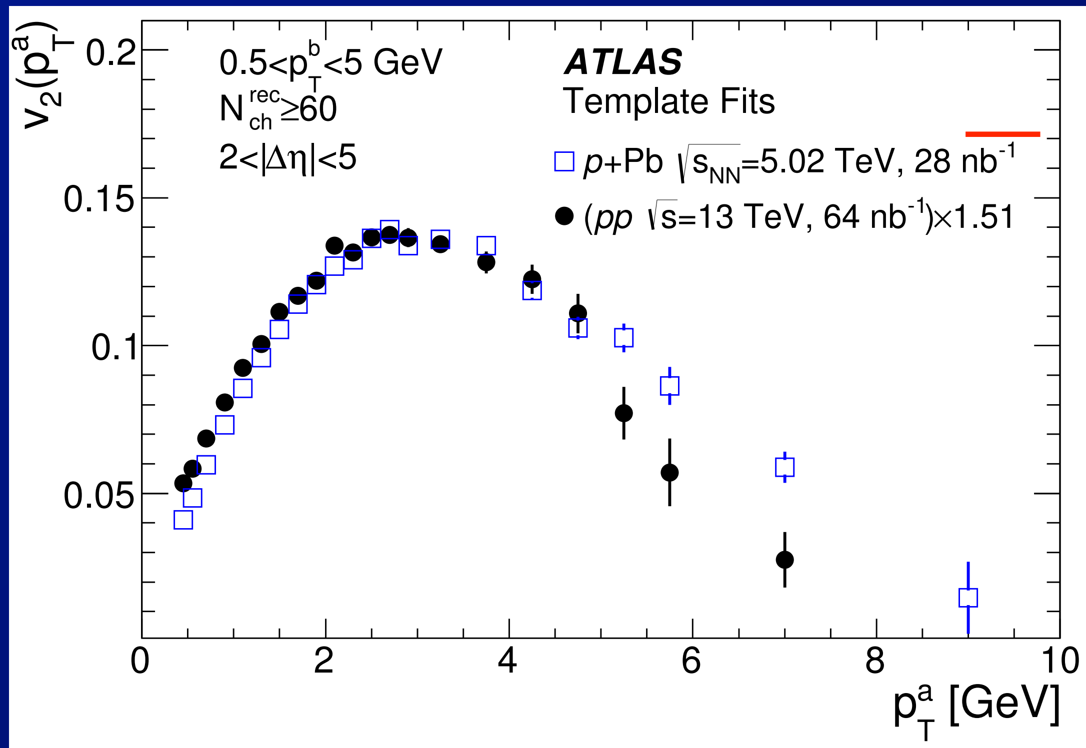


v_2 p_T dependence



p+Pb & Pb+Pb

pp & p+Pb



- When re-scaled to match maximum v_2
  - and mean p_T (for p+Pb ↔ Pb+Pb)

  ⇒ p_T dependence of v_n's ~ same for Pb+Pb, p+Pb, pp

Multi-particle correlations: pp, p+Pb

- >2 particle correlations (e.g. 4) important for showing global azimuthal correlations in pp, p+Pb

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

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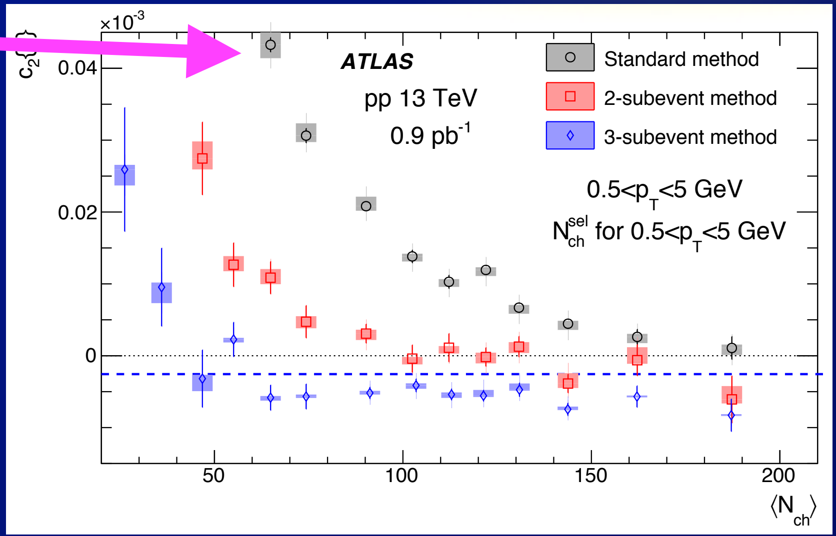
⇒ positive $c_2\{4\}$



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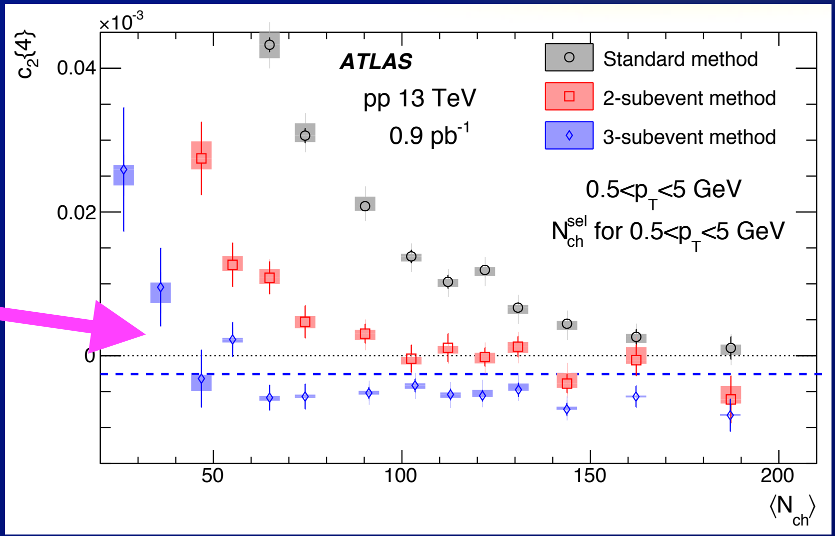
  - divide detector into 2, 3 η intervals, restrict {4}



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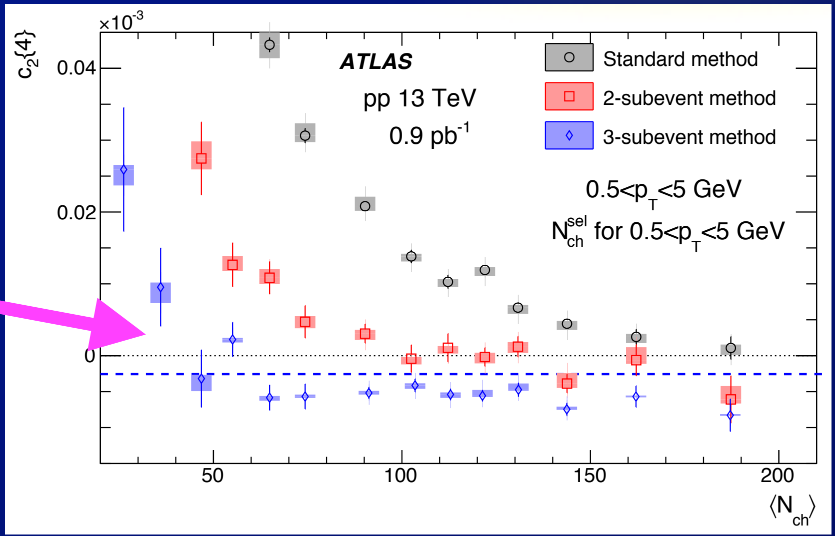

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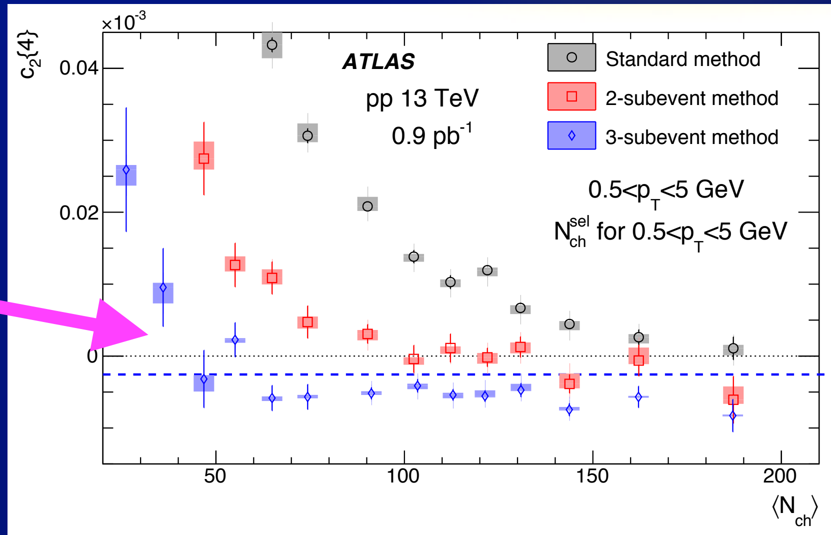

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$\Rightarrow$ global correlations in pp!

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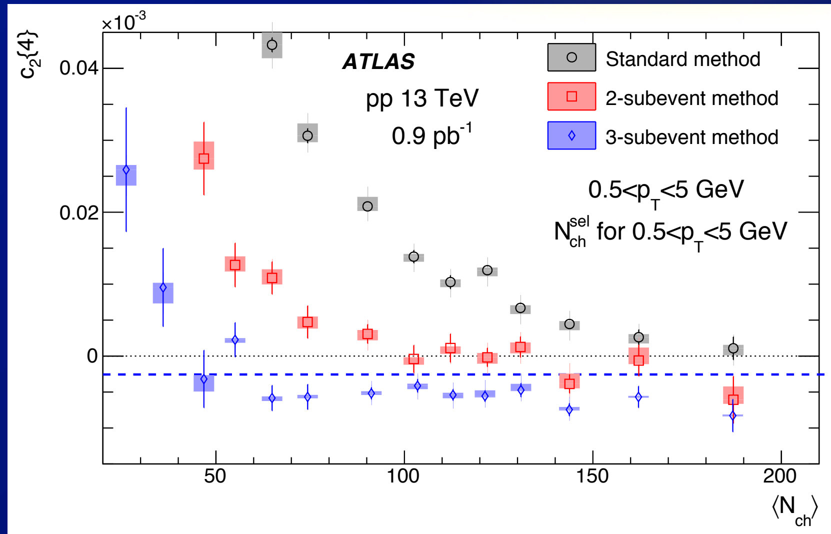

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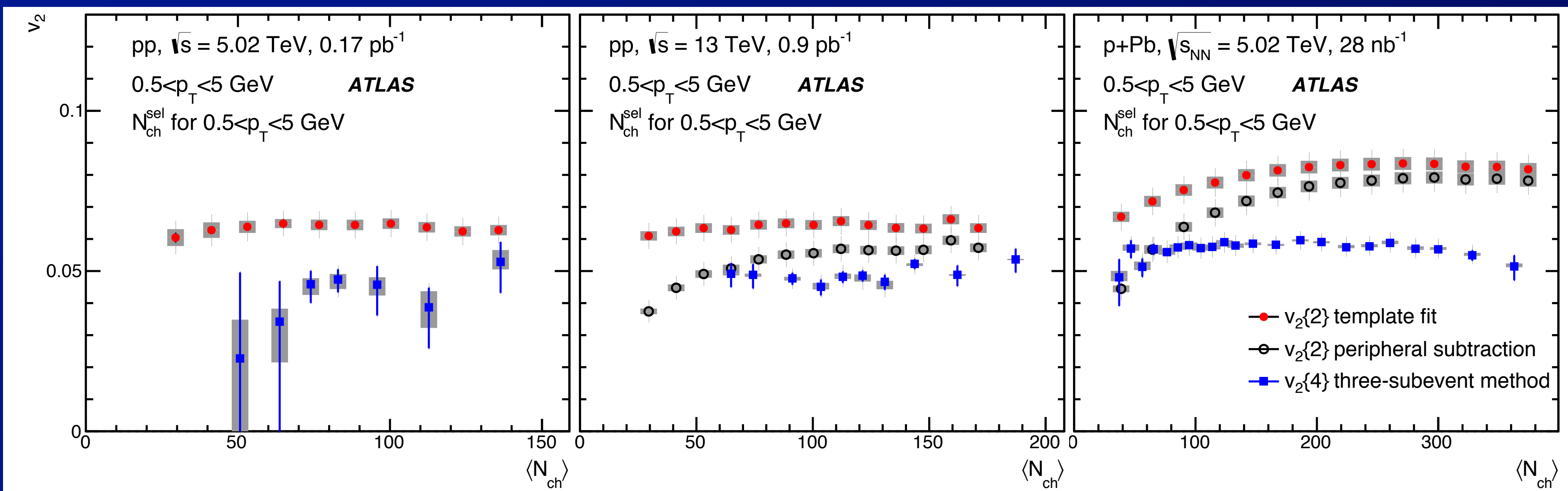

p+Pb HBT measurements

- Identical particle correlations probe the spatial geometry of particle production:

$$C(\mathbf{p}_1, \mathbf{p}_2) \equiv \frac{\frac{dN_{12}}{d^3p_1 d^3p_2}}{\frac{dN_1}{d^3p_1}\frac{dN_2}{d^3p_2}}$$

$$C_{\mathbf{k}}(\mathbf{q}) = \int d^3r \, S_{\mathbf{k}}(\mathbf{r}) \left|\psi_{\mathbf{q}}(\mathbf{r})\right|^2 \; .$$

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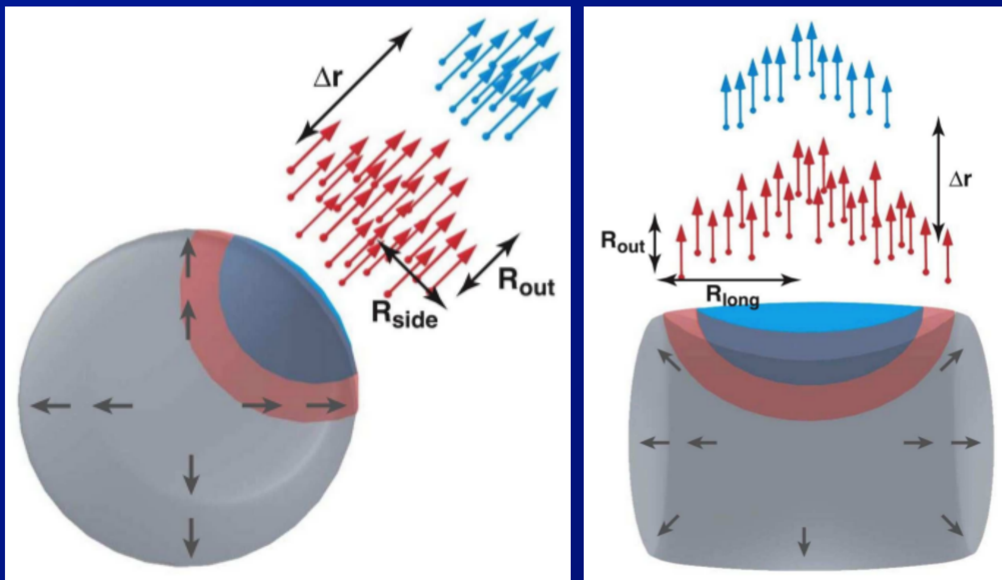
- Use Bertsch-Pratt decomposition (q_{out}, q_{side}, q_{long})
  - in pair longitudinal co-moving frame



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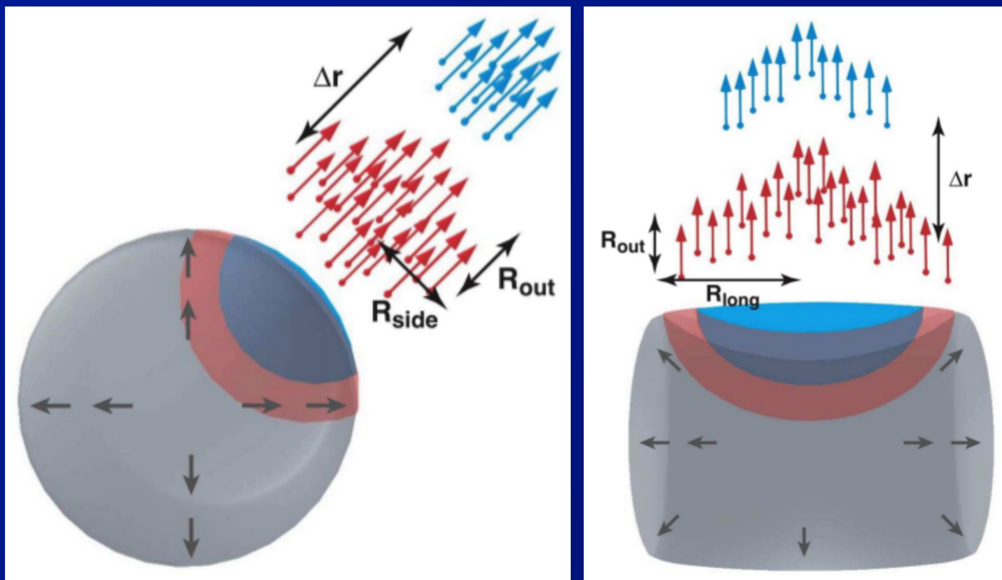

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$$C_{\text{BE}}(\mathbf{q}) = 1 + \exp\left(-\|R\mathbf{q}\|\right)$$

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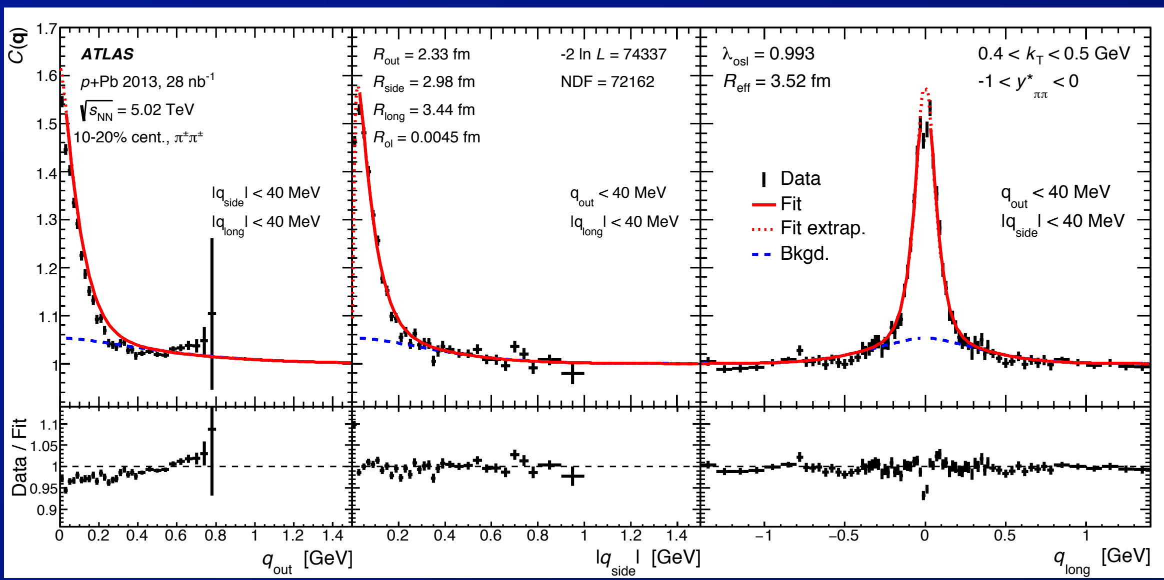

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out side long

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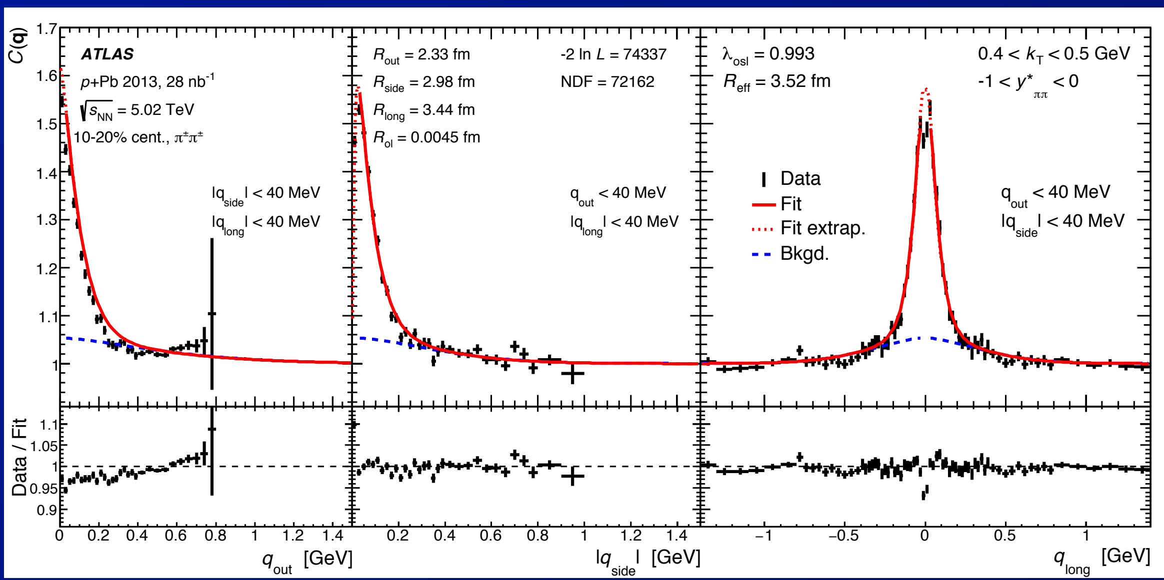

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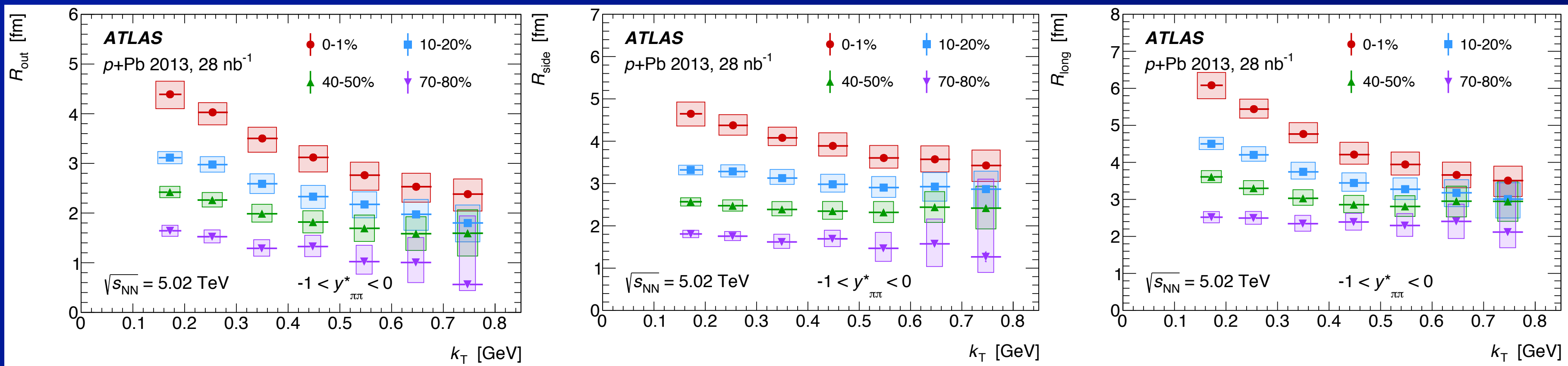
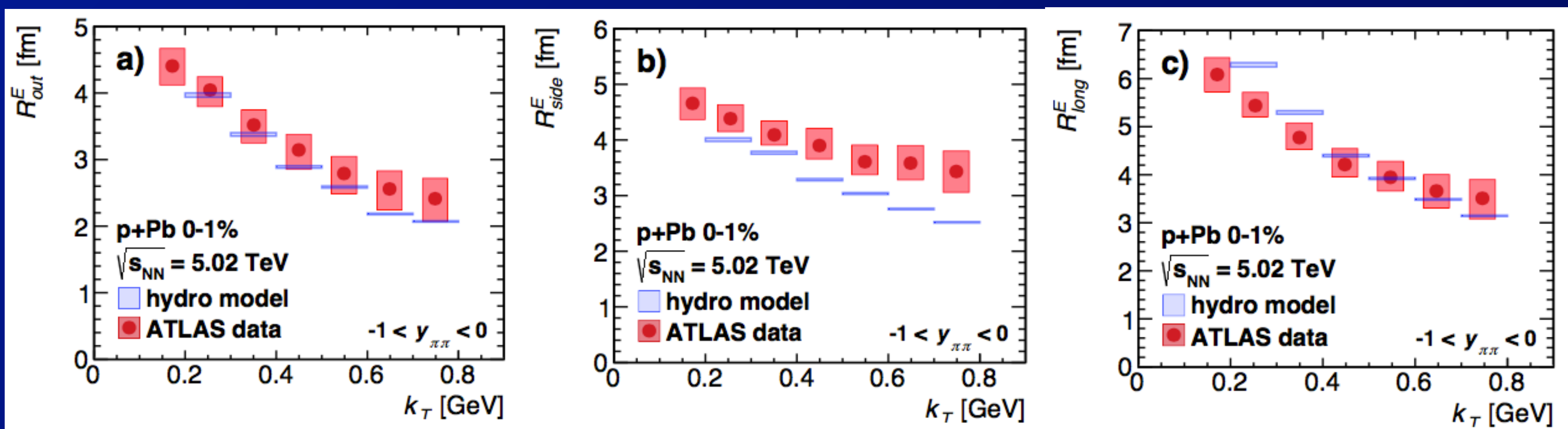
out side long

p+Pb 2-pion HBT analysis

- Observe dependence of radii on pair k_T
  - ⇒ characteristic of collectivity/hydrodynamics



- From recent talk by S. Bysiak at 2018 Workshop on Particle Correlations and Femtoscopy
  - ⇒ hydrodynamics qualitatively describes trends in data



p+Pb 2-pion HBT: hydro comparisons

- Out-long cross-term:

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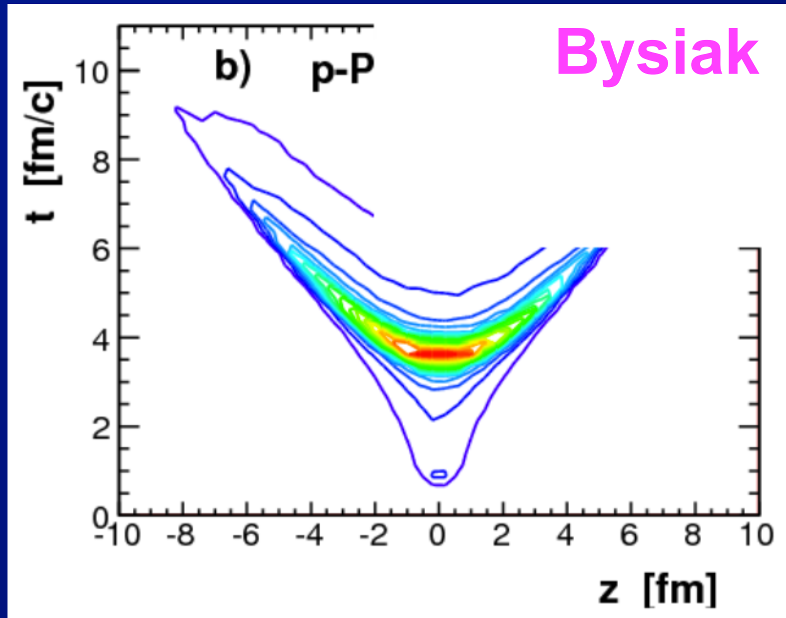
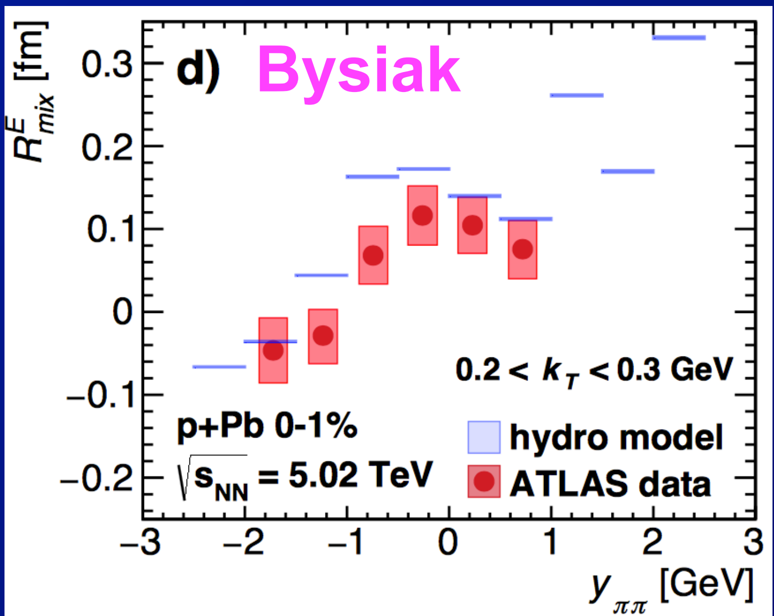
  – Can be non-zero in p+Pb collisions

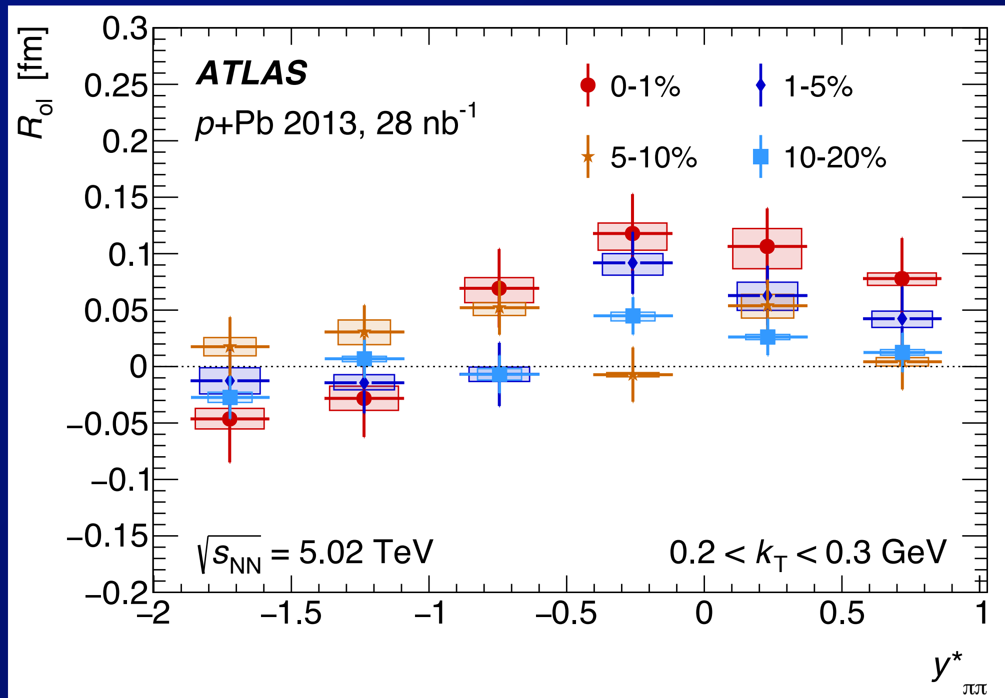
  ⇒ due to rapidity asymmetry



- Observed in ATLAS data

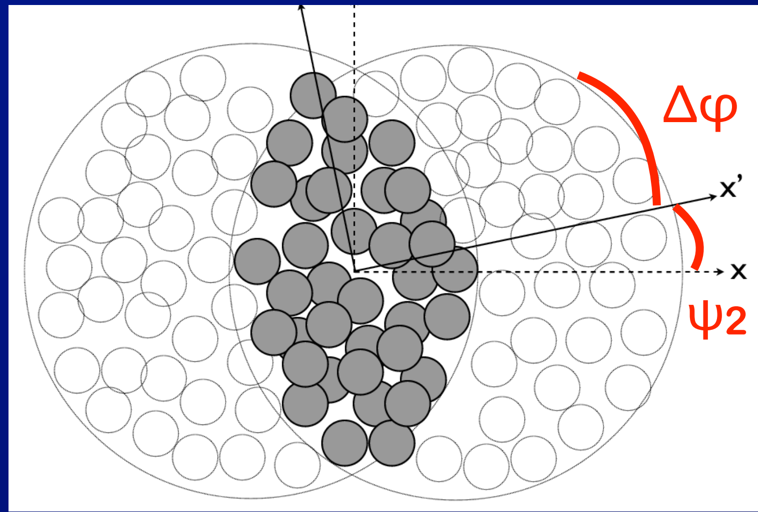
  ⇒ well described by hydro





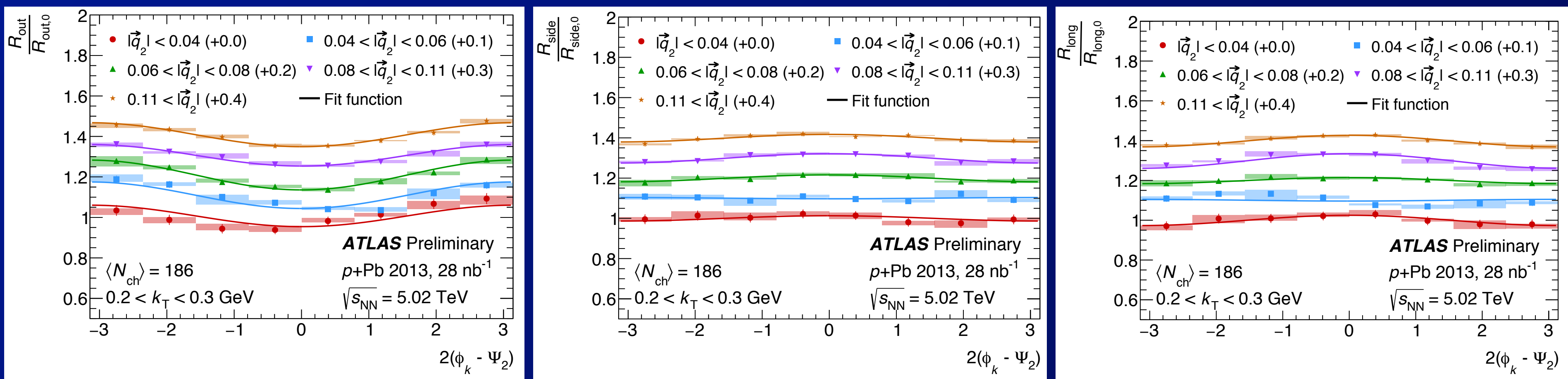
Δφ dependent HBT measurement: p+Pb

- Perform HBT measurements as a function of pair angle relative to the elliptic event plane
  - Measure event plane angle, ψ_2, and flow vector magnitude, q_2, using calorimeters, $\Delta\varphi \equiv \varphi_k - \psi_2$
  - In highest 1% of multiplicity dist.
  - C_2 corrected for ψ_2 resolution



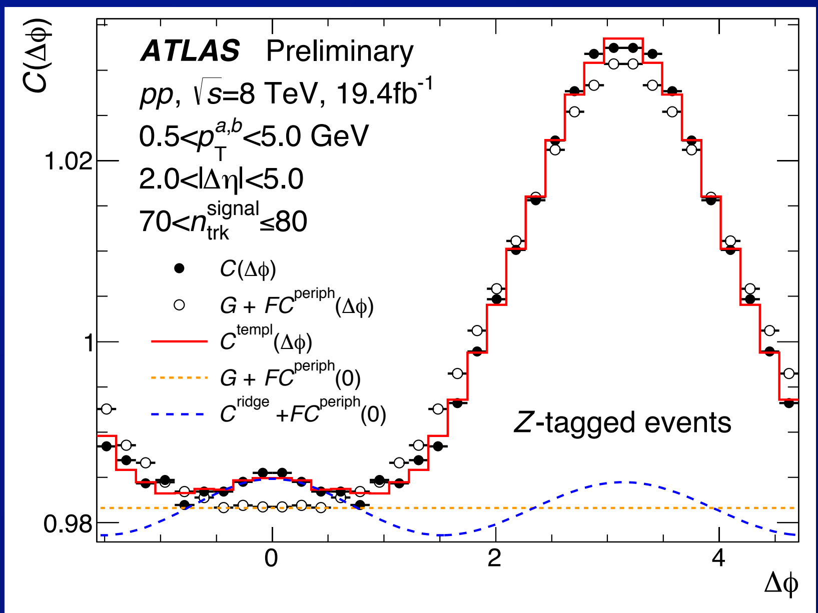
⇒ observe pattern of radii modulation similar to that seen in A+A collisions

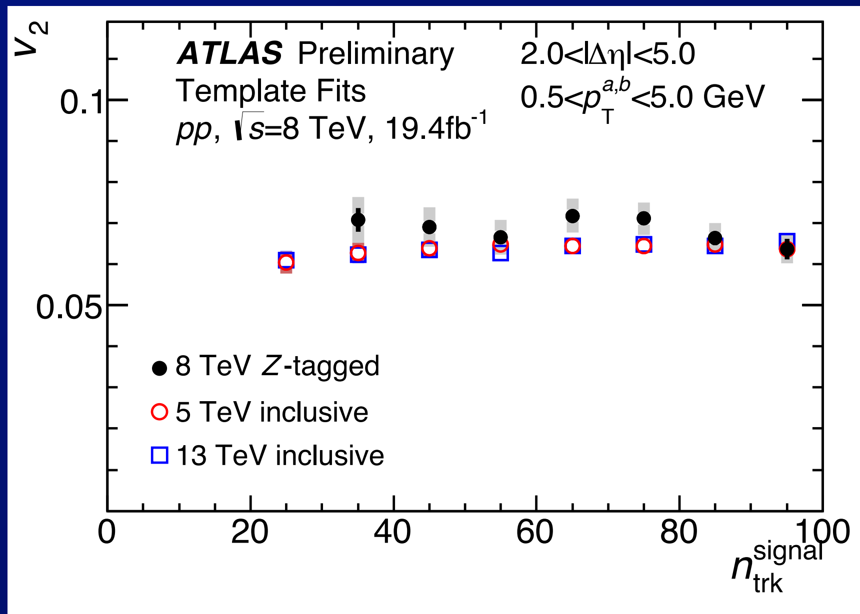
⇒ (qualitatively) consistent with collectivity



Z-tagged pp 2-particle correlations

- **Do we really understand the origin of the ridge?**
  - e.g. is there any correlation/connection with hard processes?
    - ⇒ study in pp collisions containing Z boson
  - similar analysis as above but @ high luminosity
    - ⇒ correct for pileup background
- **Result:**
  - ⇒ similar to minimum-bias pp but 8±6% larger v_2 values
  - ⇒ Likely a result of larger hadron <pT> in Z-tagged events

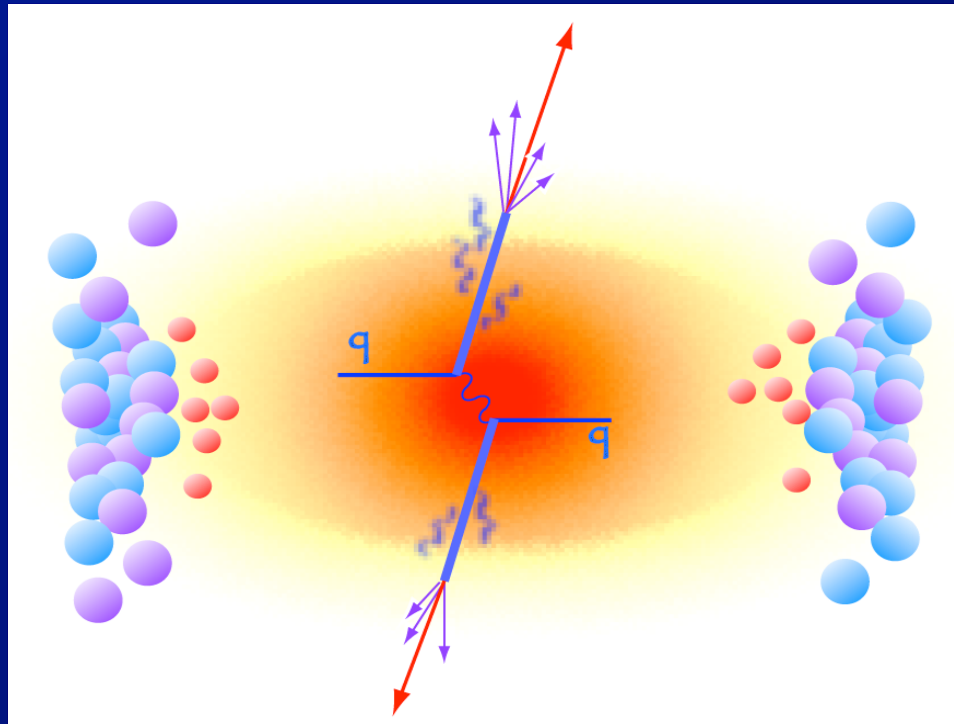




Hard scattering and Jet Quenching

Jet probes of the quark gluon plasma

- Use jets from hard scattering processes to directly probe the quark gluon plasma (QGP)



- Key experimental question:
  - How do parton showers in quark gluon plasma differ from those in vacuum?

  ⇒ important: not all jets the same (q/g/c/b)

Jet Suppression

- Energy loss of hard-scattered quarks & gluons reduces the yield of high-p_T jets

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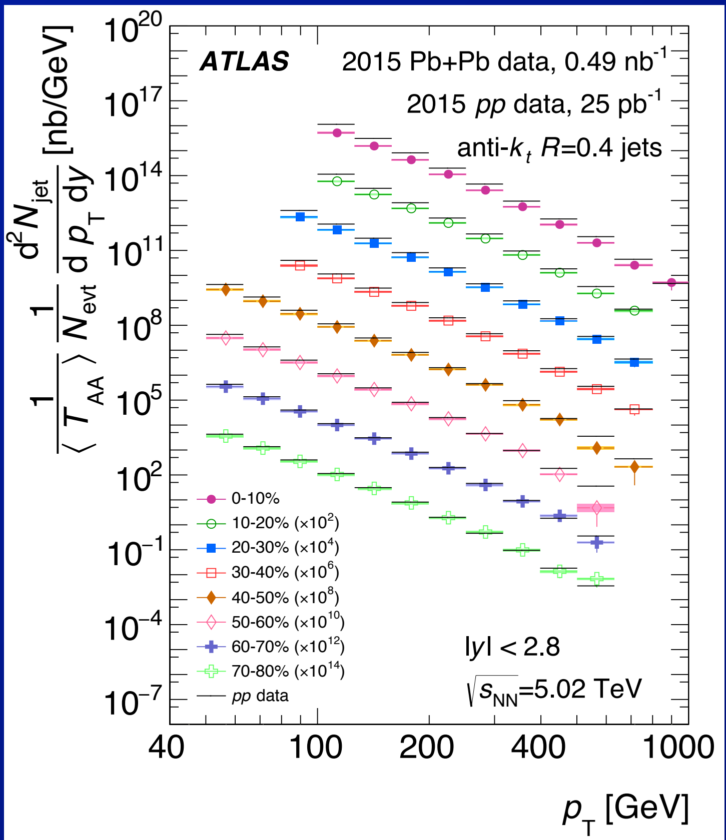

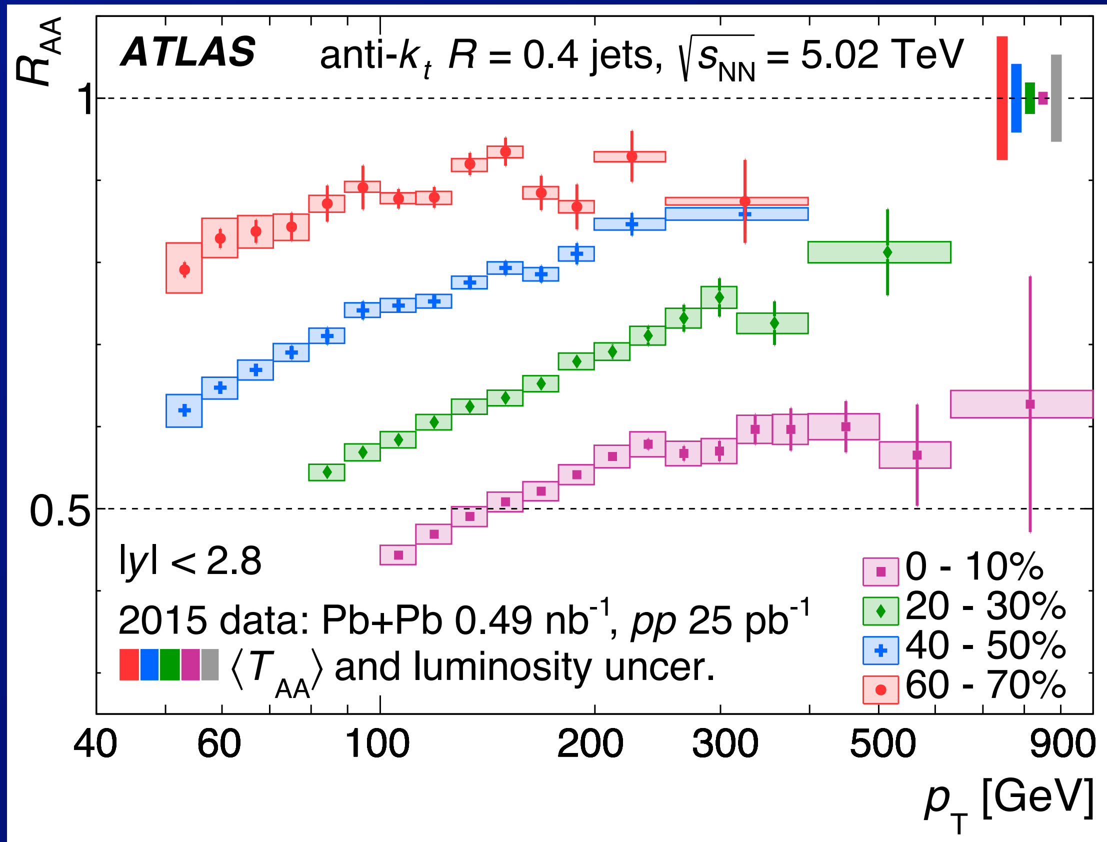

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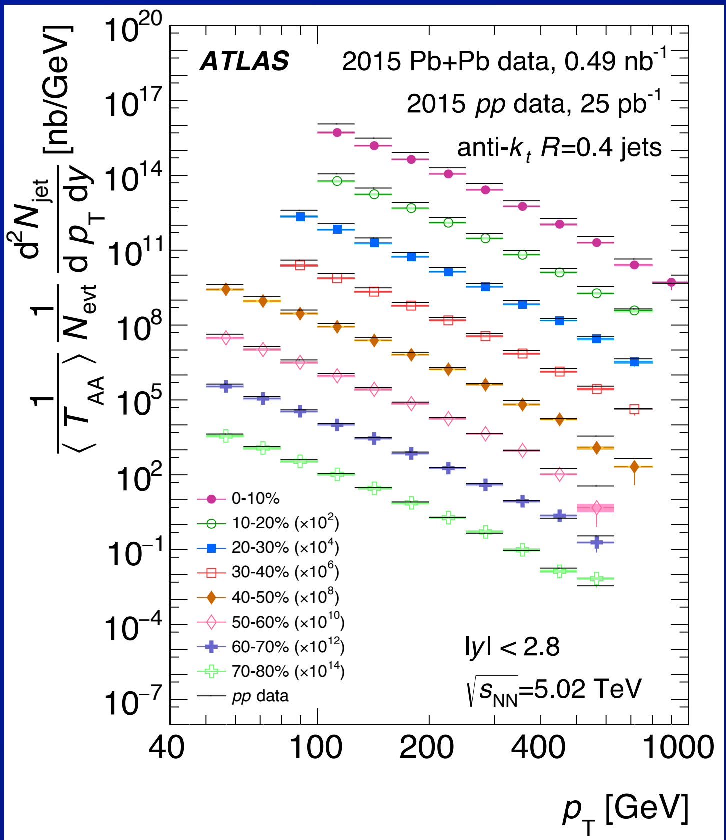
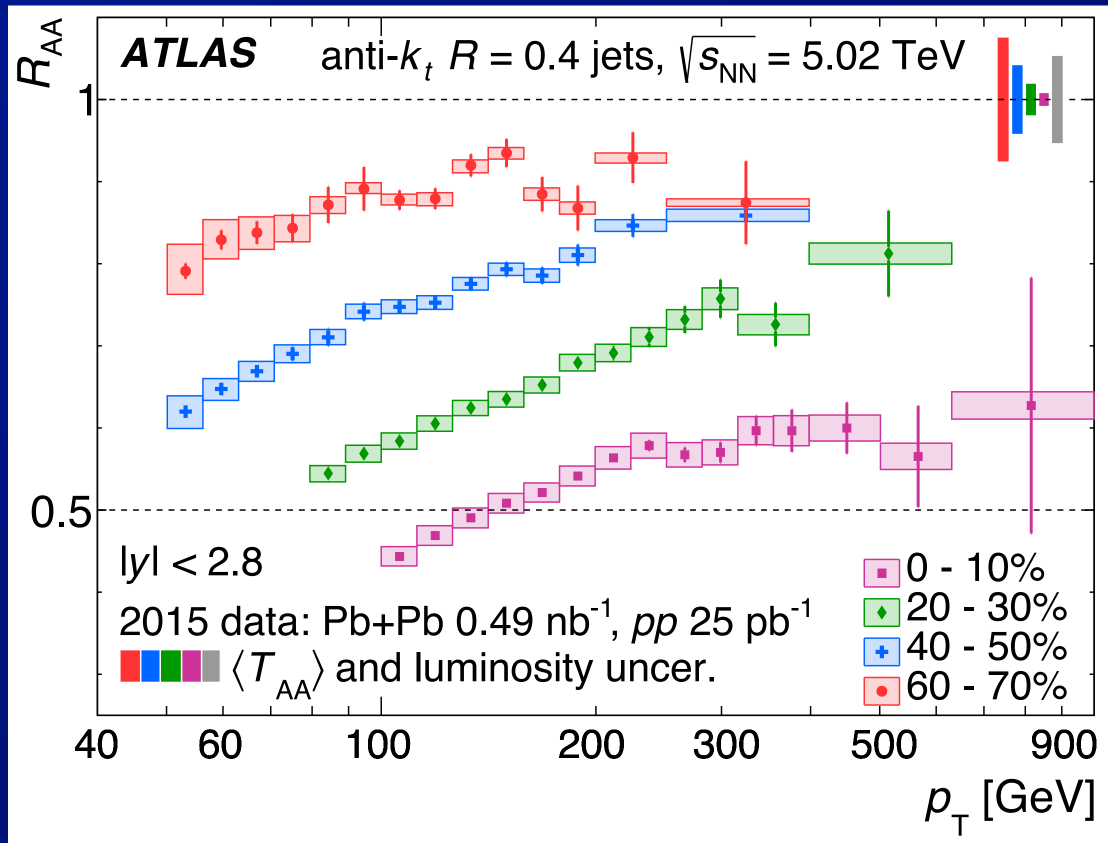




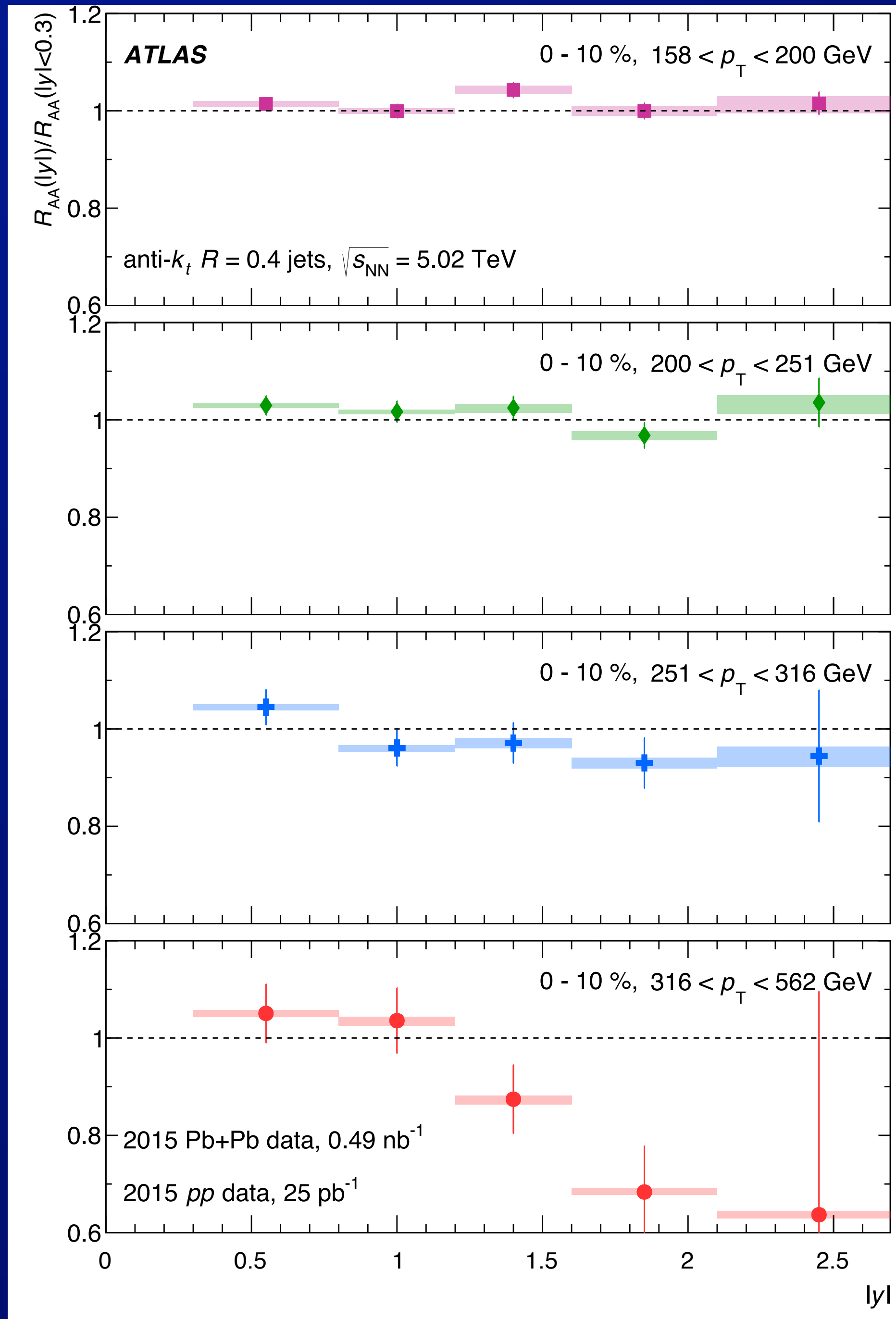
⇒ observe substantial suppression out to ~ 900 GeV

⇒ p_T dependence from interplay between ΔE, spectrum

Jet R_{AA}: rapidity dependence

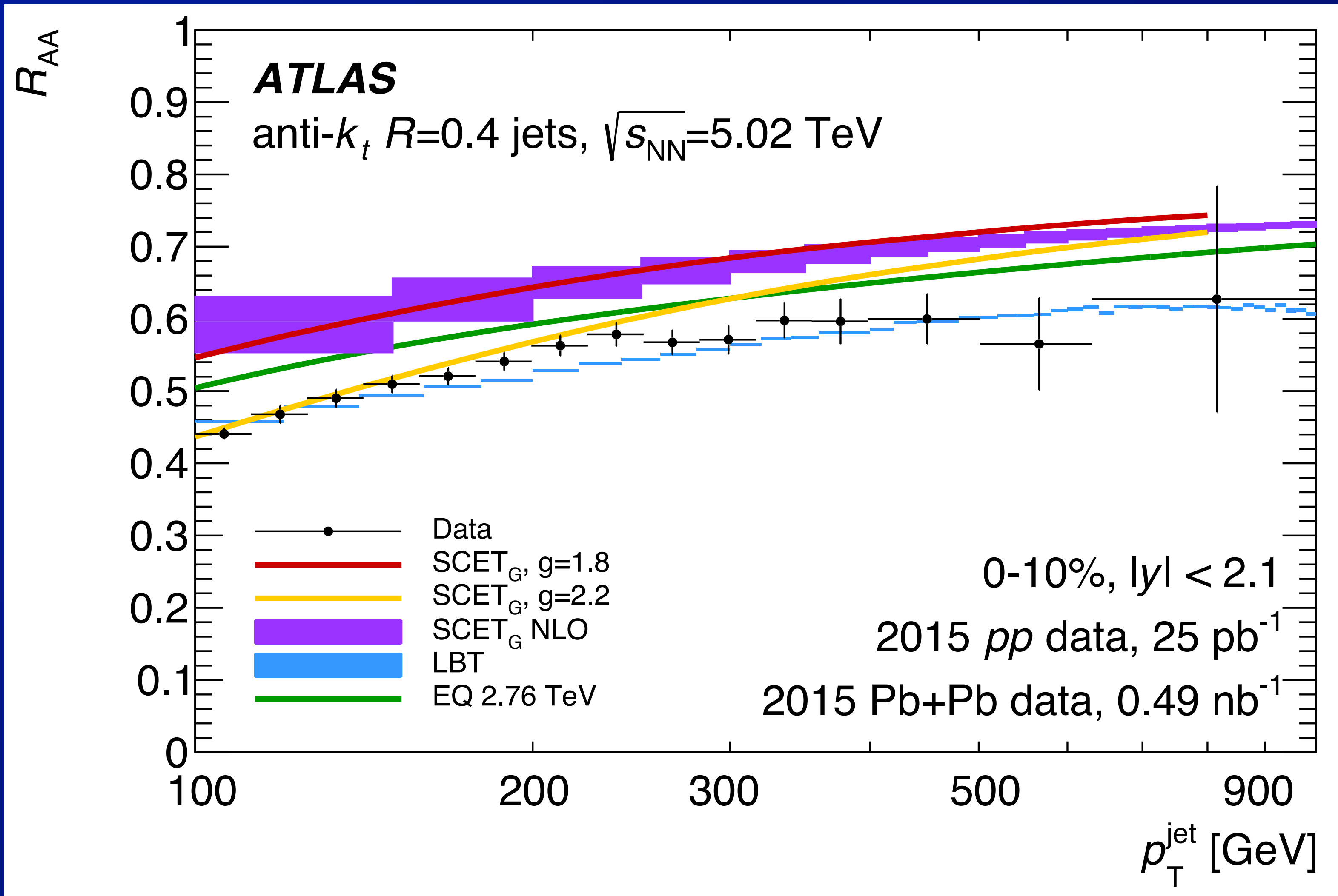
- With increasing rapidity, the jet spectrum becomes steeper @ high p_T
  - Expect energy loss to yield greater suppression at larger y & higher p_T

  ⇒ can now observe this effect using high-statistics Pb+Pb and pp data

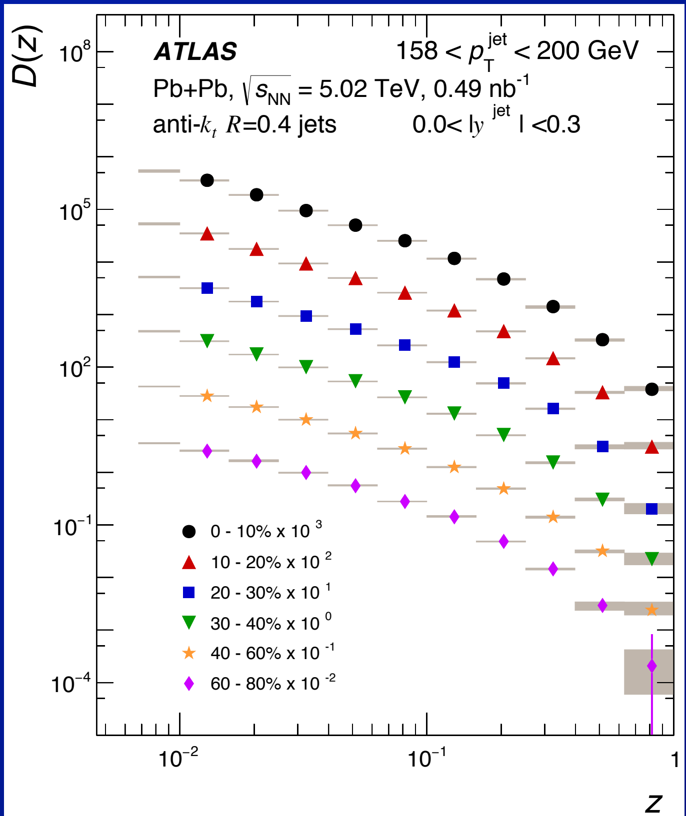


Jet R_{AA}, theory comparisons

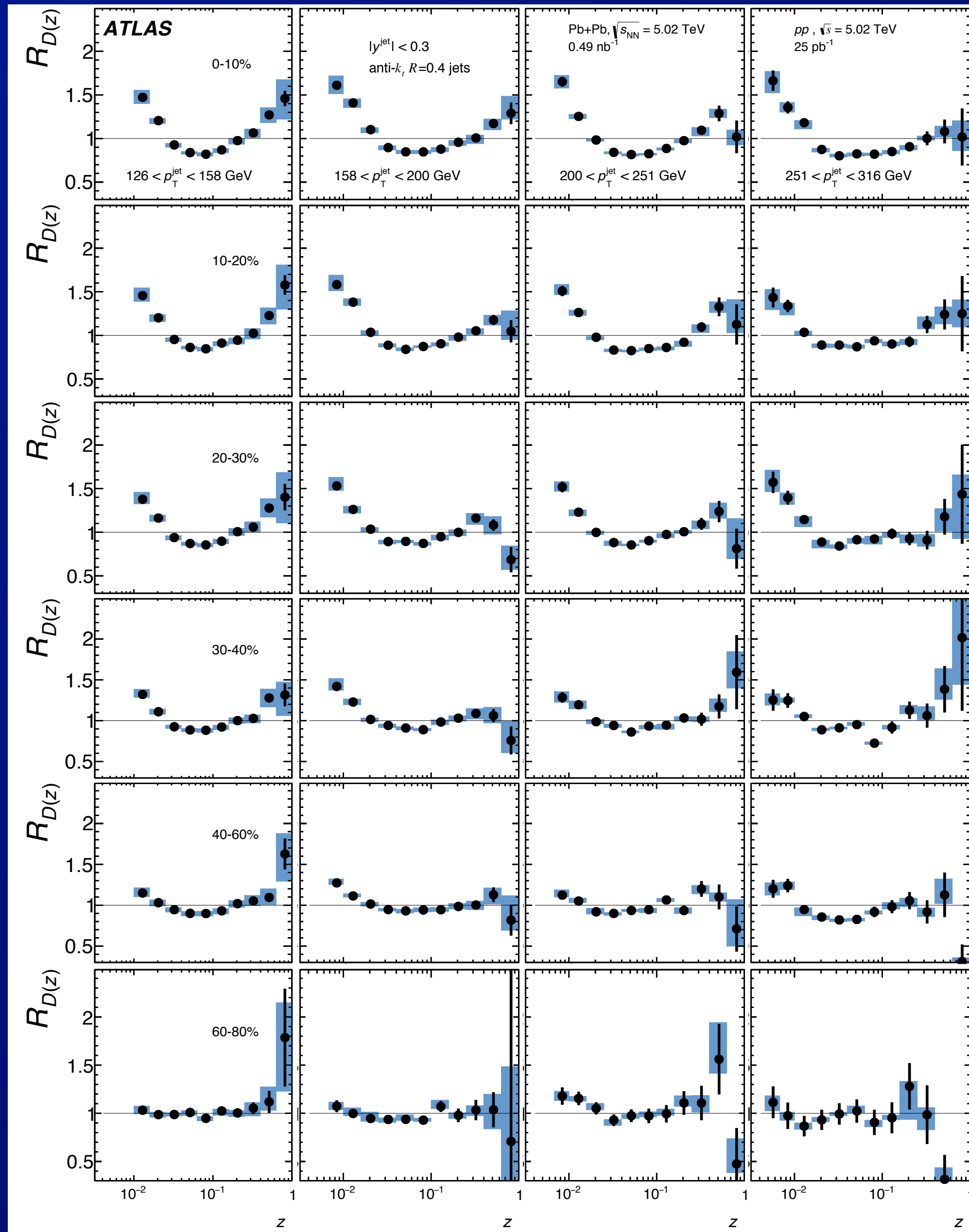
- Jet R_{AA} measurements are (now) providing stringent tests of jet quenching calculations
  - only the LBT model describes full p_T dependence



Pb+Pb Jet Fragmentation



centrality



$$D(z) = \frac{1}{N_{jet}} \frac{dN_{chg}}{dz}$$

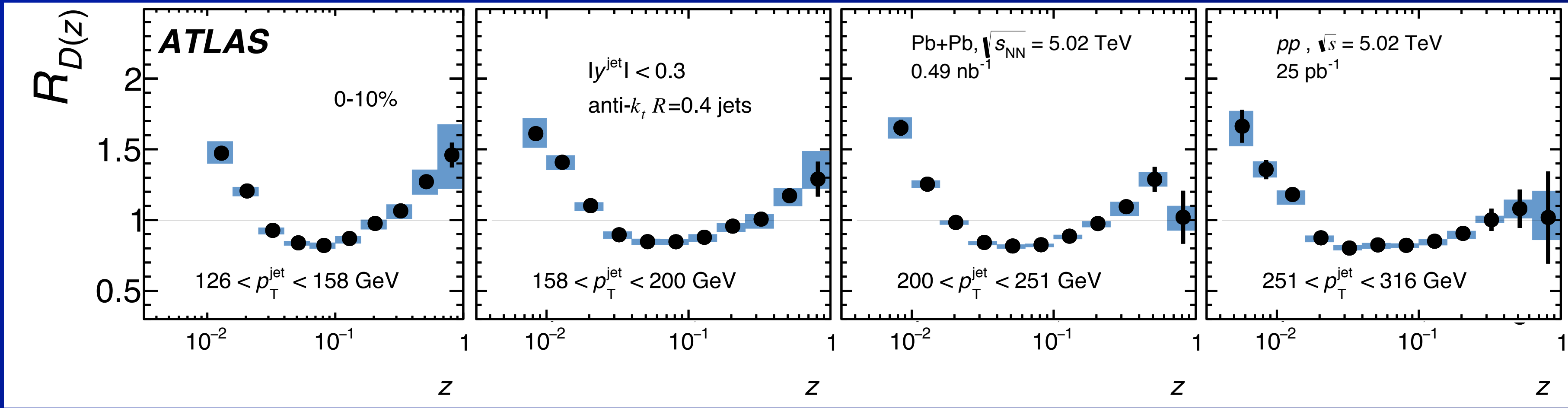
$$z = \vec{p}_{chg} \cdot \vec{p}_{jet} / \left|\vec{p}_{jet}\right|^2$$

- **Measure D(z) in Pb+Pb**
  - Take ratio w/ pp $R_{D(z)}$

⇒ Versus centrality, jet p_T

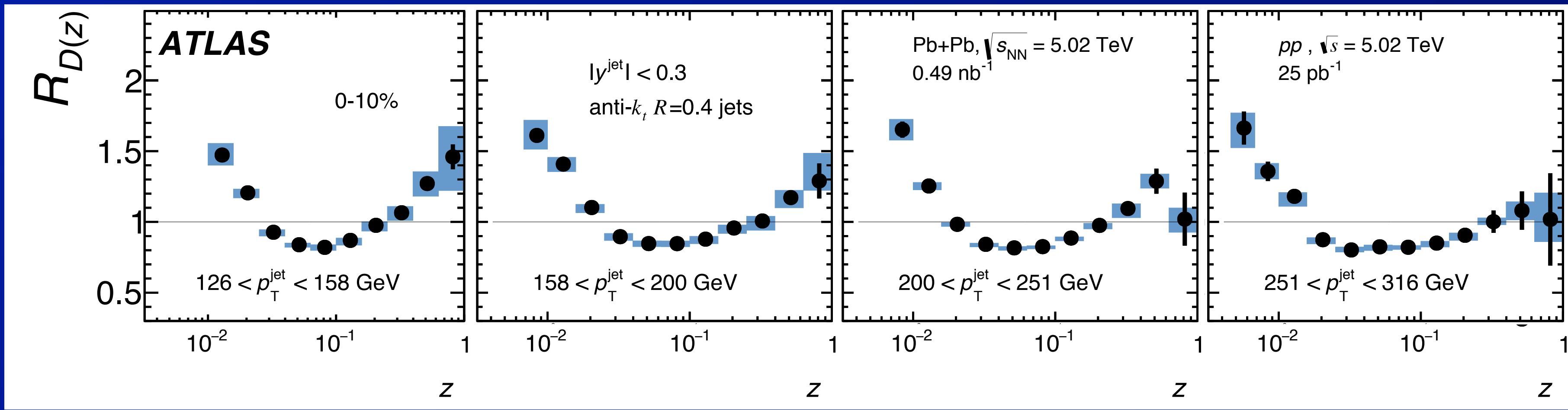
jet p_T

Pb+Pb Jet Fragmentation: 0-10%

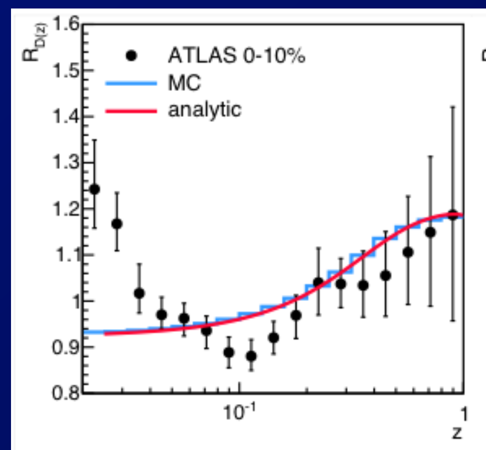


- **Observe complicated pattern of modification:**
  - ⇒ Enhanced production of low-z fragments
  - ⇒ Enhanced production of high-z fragments
  - ⇒ Suppressed production at intermediate

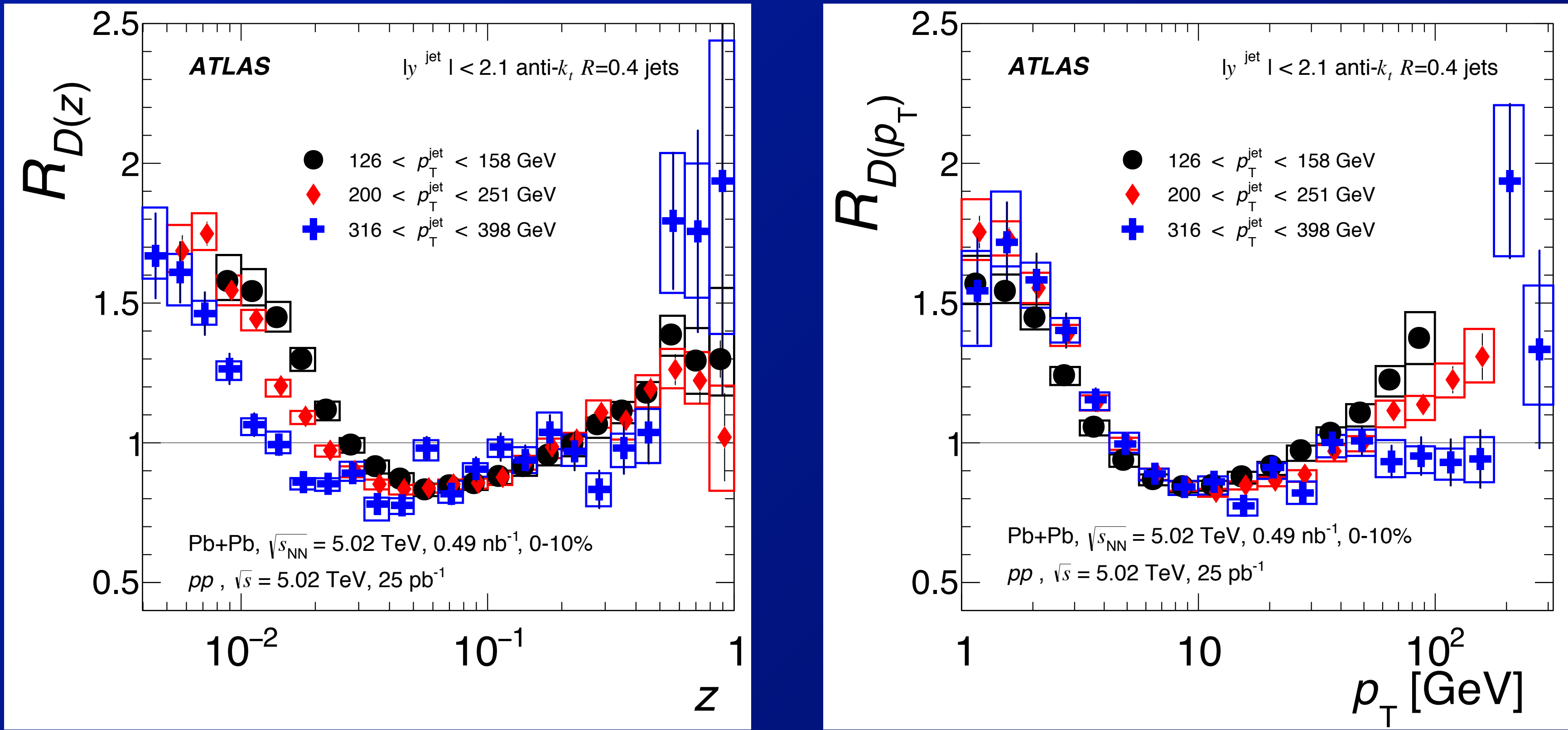
Pb+Pb Jet Fragmentation: 0-10%



- Observe complicated pattern of modification:
  - ⇒ Enhanced production of low-z fragments
  - ⇒ Enhanced production of high-z fragments
  - ⇒ Suppressed production at intermediate z
- An analysis of 2.76 TeV data by BAC and Spousta:
  - ⇒ large-z behavior may result from change in quark/gluon fraction
  - ⇒ But not all the mid-z suppression and not the enhanced production @ low z.
    - » How do the modifications vary with jet p_T?



Jet fragmentation vs jet p_T

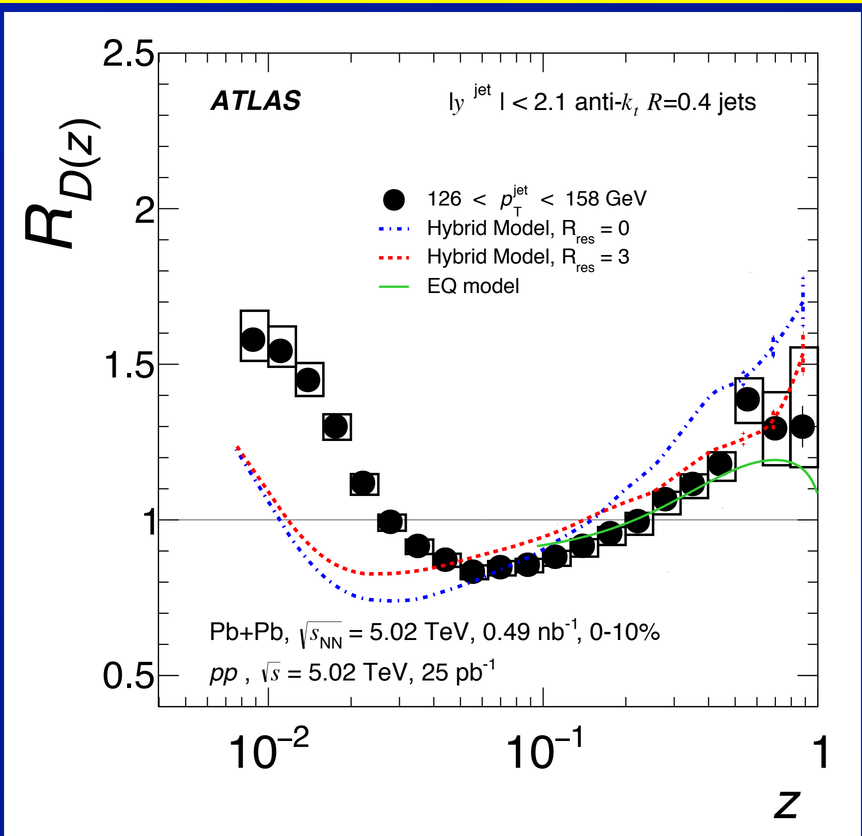


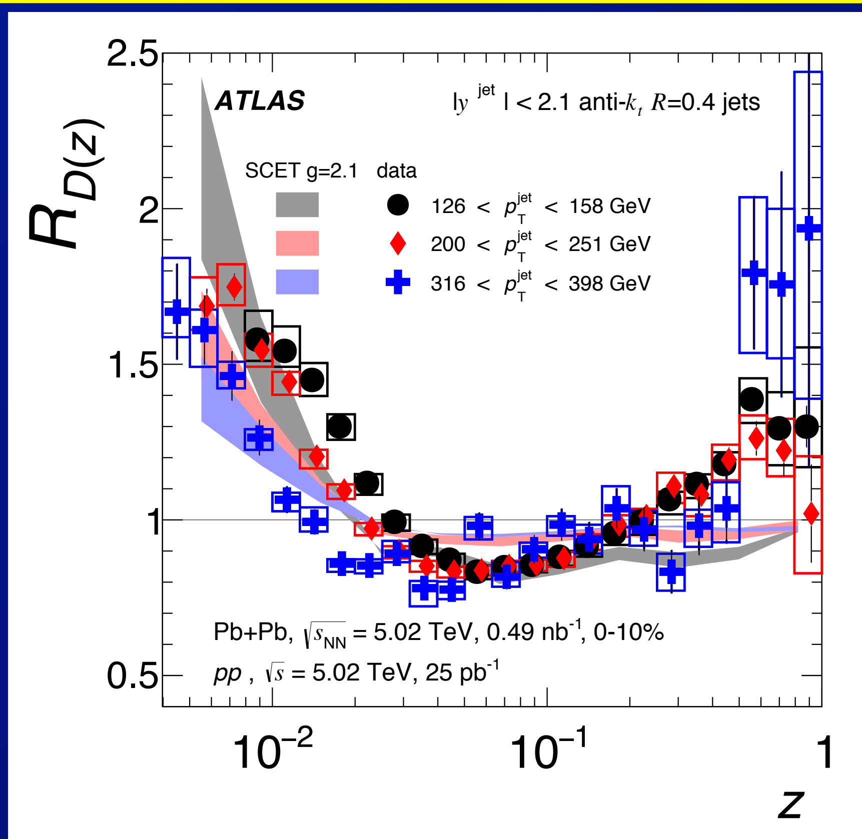
- Compare results from different jet p_T intervals
  - versus z or p_T

  ⇒ large-z enhancement depends on z

  ⇒ low-z enhancement depends on p_T, not z

Jet fragmentation: theory comparisons





- Two of the most studied models of jet quenching:
  - Strong/weak coupling hybrid and SCET

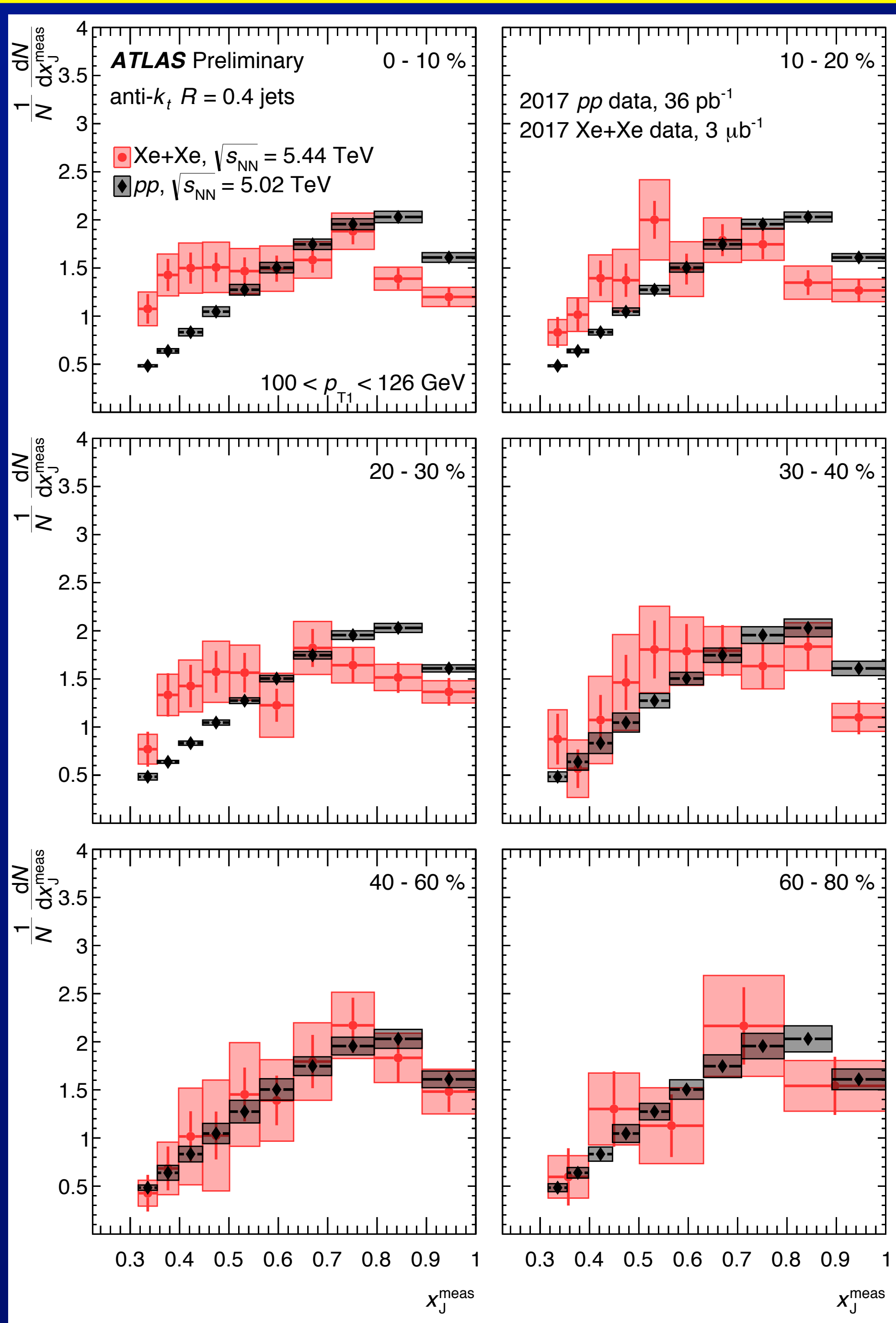
⇒ cannot simultaneously describe both the low-z and high-z modifications to the fragmentation function

Dijet balance

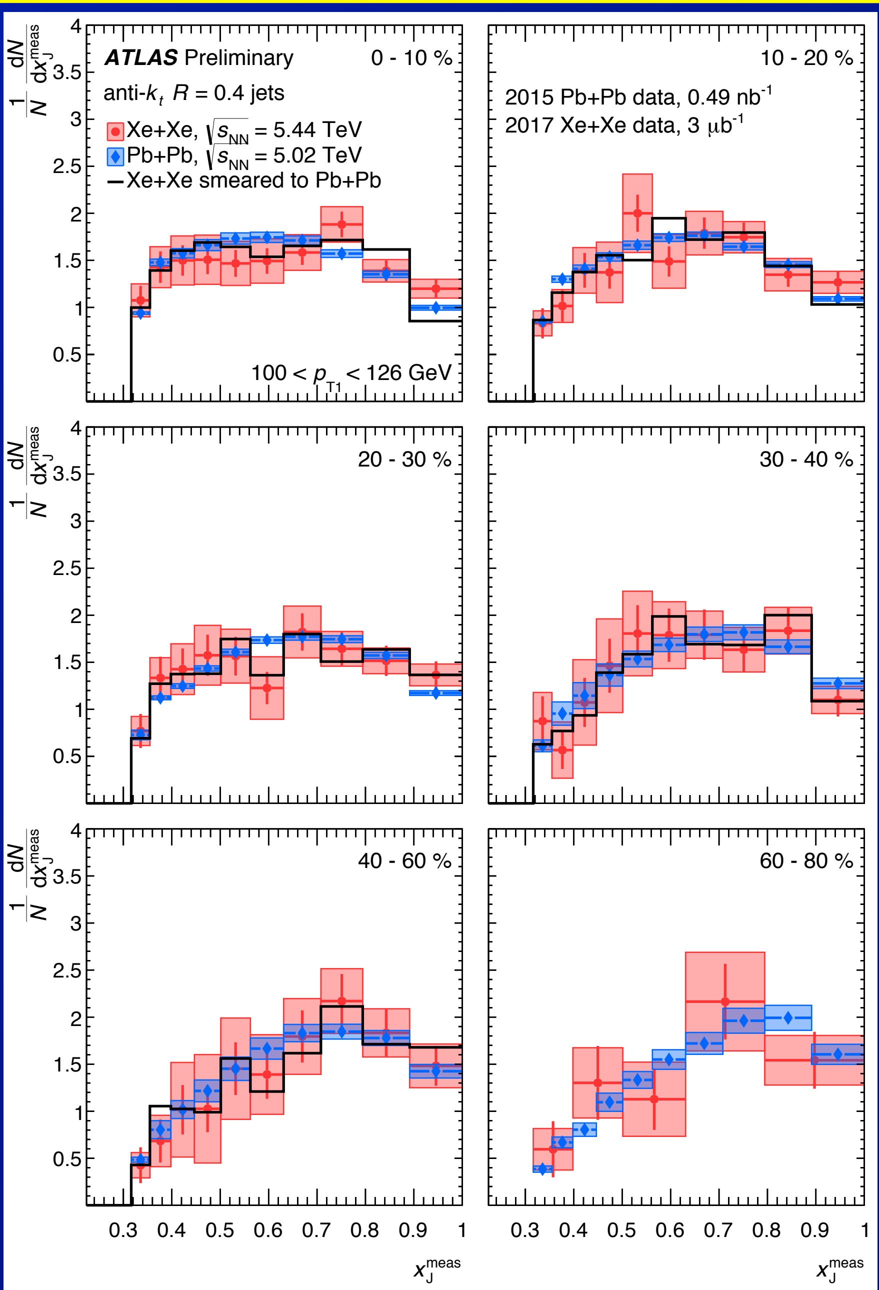
- **ATLAS has measured dijet balance in 2.76 TeV Pb+Pb unfolded for jet response**
  - not shown here for brevity
- **Xe+Xe data sufficient for low-statistics measurement**
  - distributions of dijet x_J

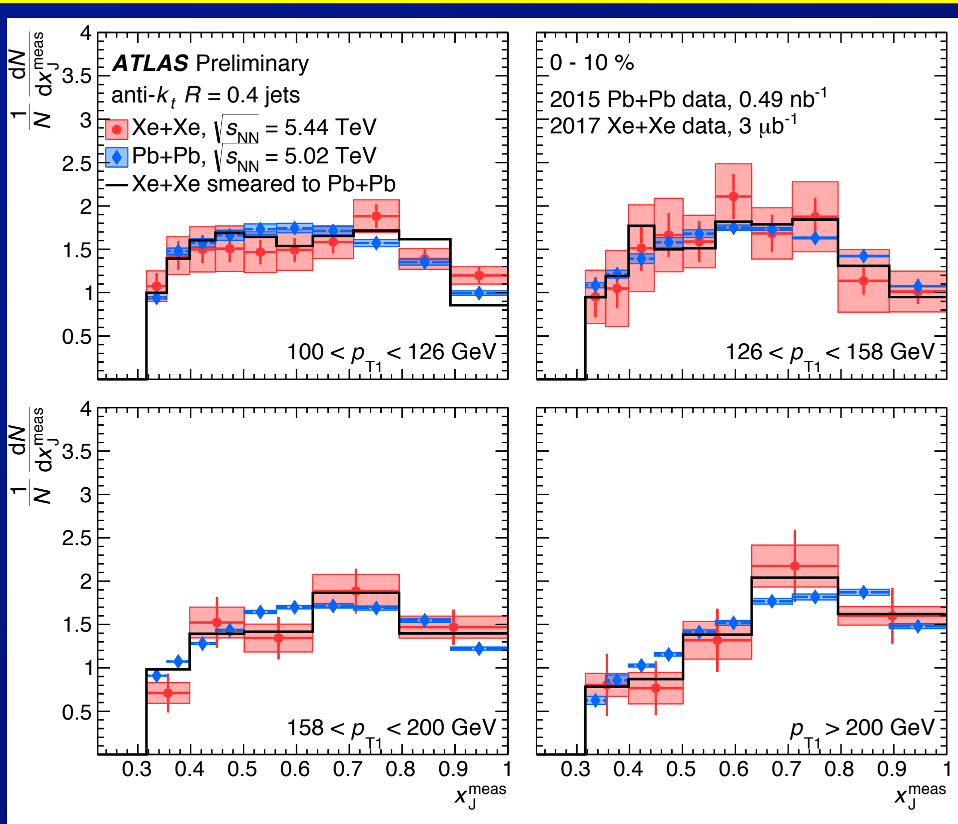
    $\Rightarrow \; x_J \equiv p_{T2}/p_{T1}$
  - not unfolded for jet response
  - here for $100 < p_{T1} < 126$ GeV
  - compared to 5.02 TeV pp

    ⇒ see shift of x_J distributions similar to first ATLAS result



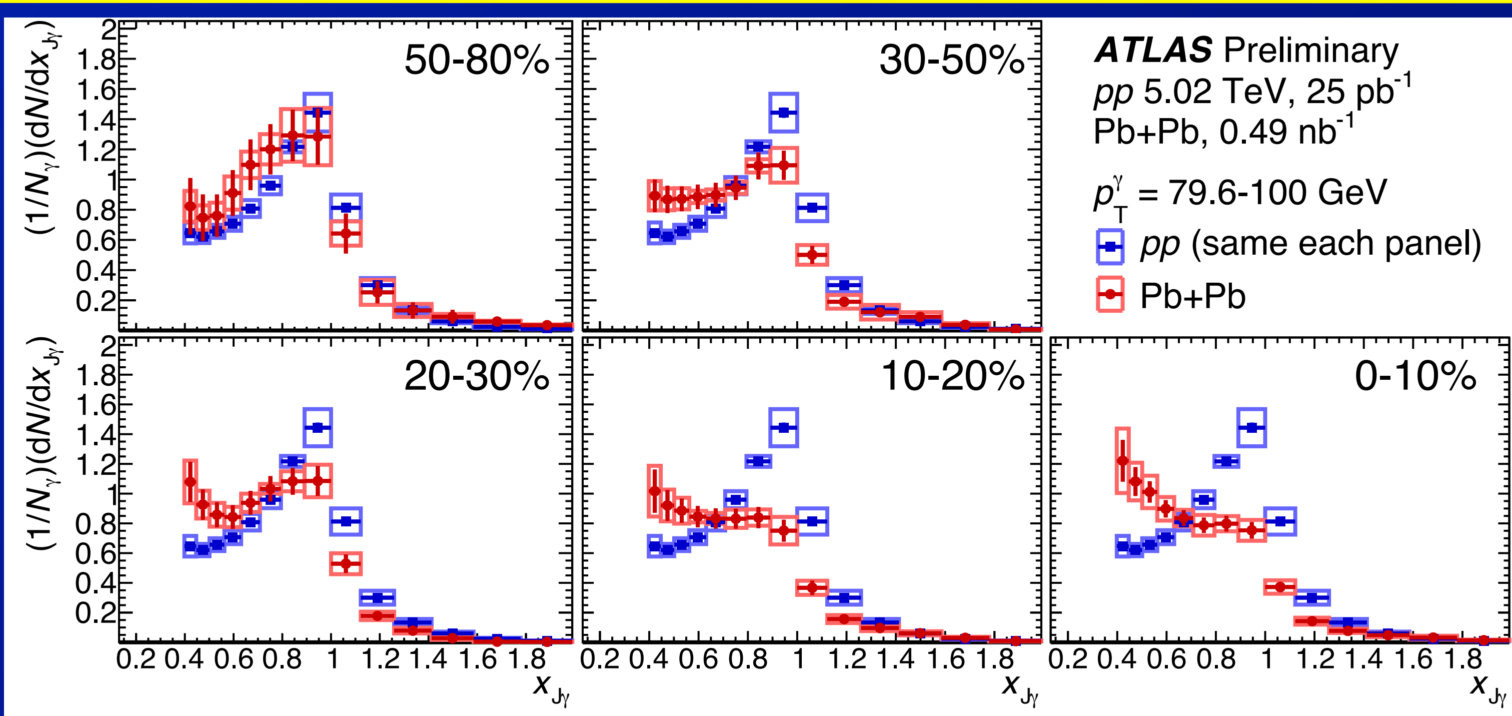
Dijet balance





- Compare x_J distributions between Xe+Xe, Pb+Pb
  - ⇒ identical within uncertainties
  - ⇒ versus centrality and p_{T1}
    - » dominance of fluctuating energy loss (vs geometry) ?

Photon-jet balance



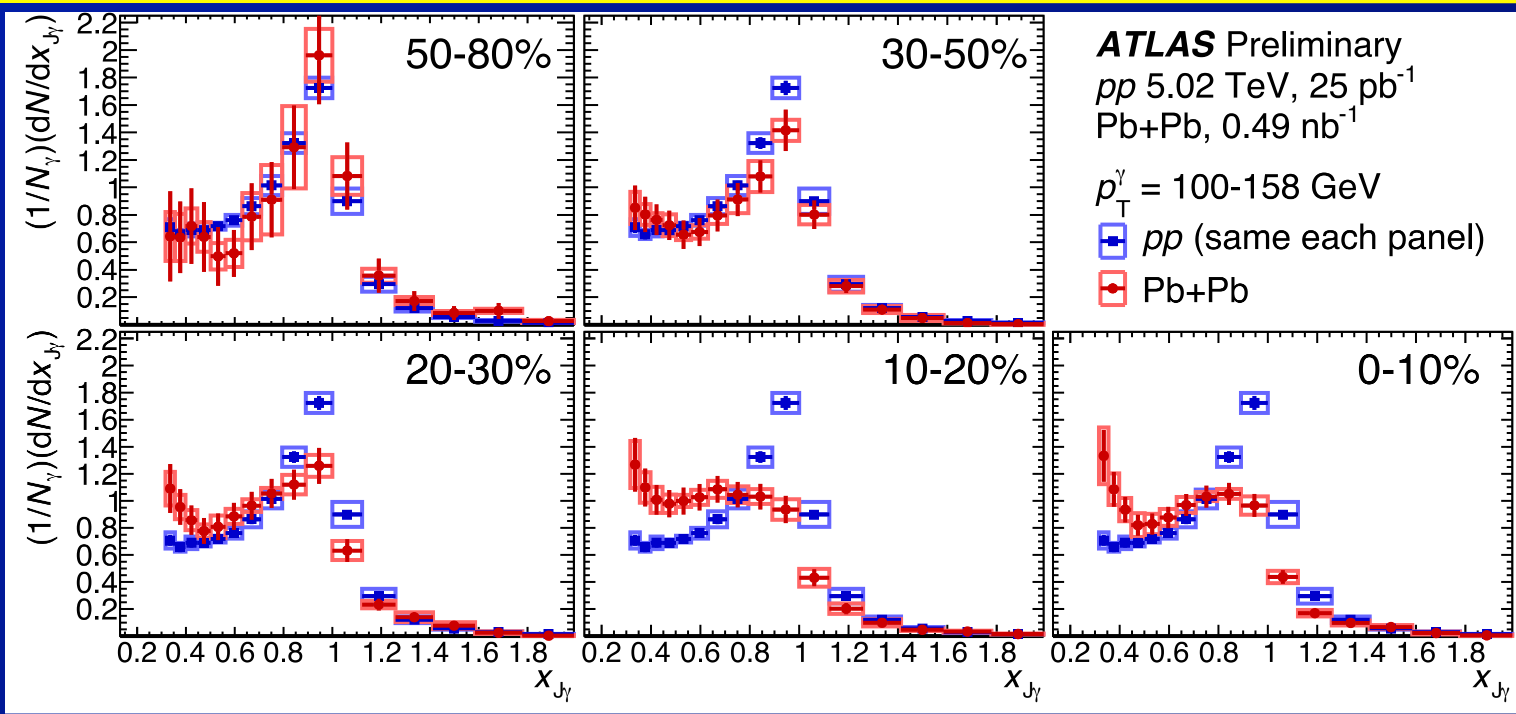
$p_{\mathrm{T}}^{\mathrm{jet}} > 31.6\ \mathrm{GeV}$

$|\Delta\phi| > 7\pi/8$

- **Measure p_{T} distribution of jets opposite prompt photons**
  - inclusive, not just the leading jet
  - unfolded for jet response
  - here for photons having $79.6 < p_{\mathrm{T}}^{\gamma} < 100\ \mathrm{GeV}$
  - balance expressed in terms of $x_{\mathrm{J}\gamma} \equiv p_{\mathrm{T}}^{\mathrm{jet}}/p_{\mathrm{T}}^{\gamma}$

$\Rightarrow$ observe centrality-dependent shift of jets to lower x_{J}

Photon-jet balance, high γ p_T



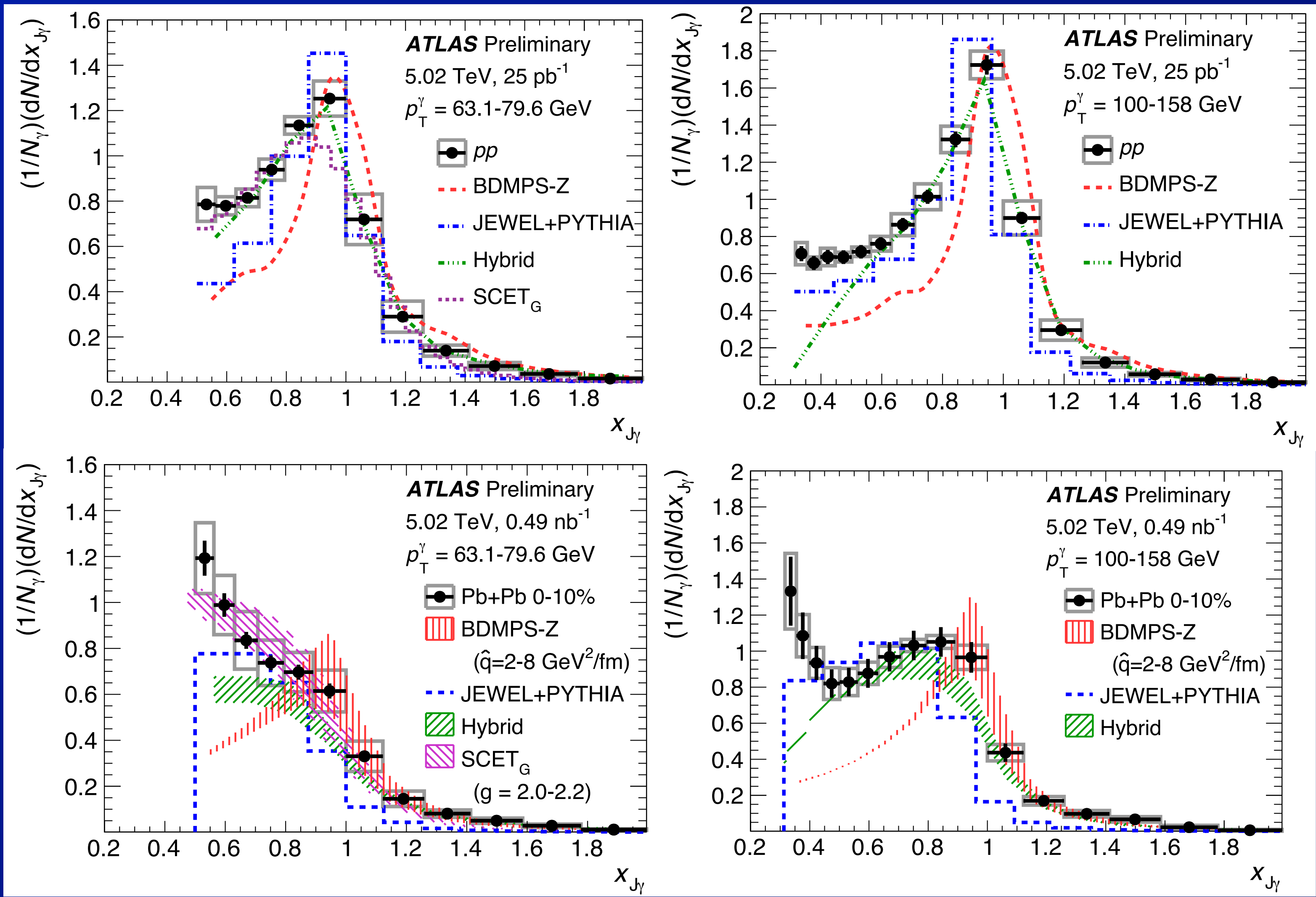
$p_T^{jet} > 31.6$ GeV

$|\Delta\phi| > 7\pi/8$

- **Measure p_T distribution of jets opposite prompt photons**
  - inclusive, not just the leading jet
  - unfolded for jet response
  - here for photons having $100 < p_T^{\gamma} < 168$ GeV
  - balance expressed in terms of $x_{J\gamma} \equiv p_T^{jet}/p_T^{\gamma}$

⇒ observe similar centrality-dependent shift of jets to lower x_J

Photon-jet balance, theory comparisons

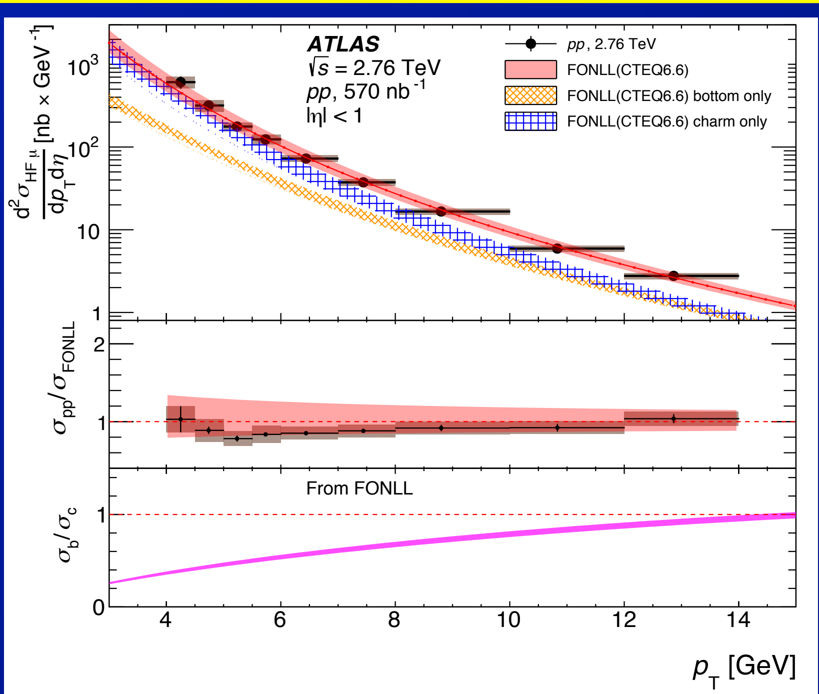


pp

Pb+Pb 0-10%

- **SCET and hybrid weak/strong coupling models do best**
  - **but hybrid model does not describe lower-x_J part of spectrum**
    - **⇒ in pp or Pb+Pb**

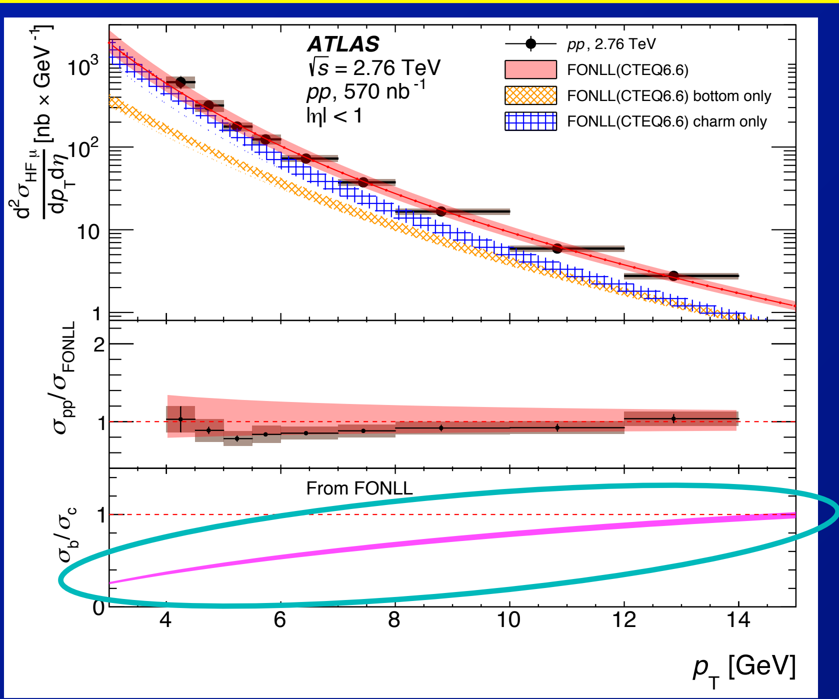
Heavy flavor suppression



- **Measured using semi-leptonic decay muons**
  - separated from π/K decays via muon spectrometer/inner detector momentum balance, template fitting procedure
- **pp cross-section compared to FONLL calculation**

  ⇒ good agreement

Heavy flavor suppression



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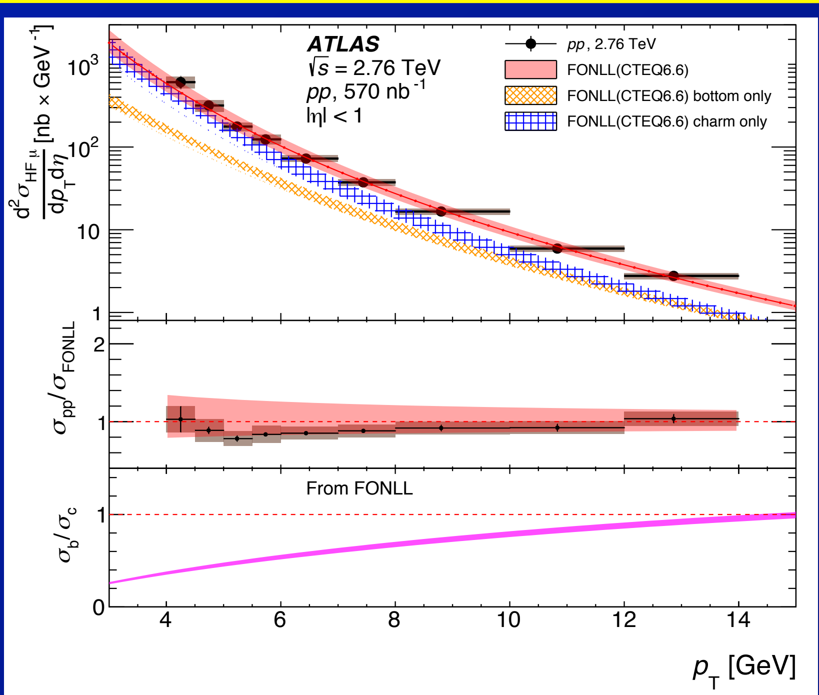
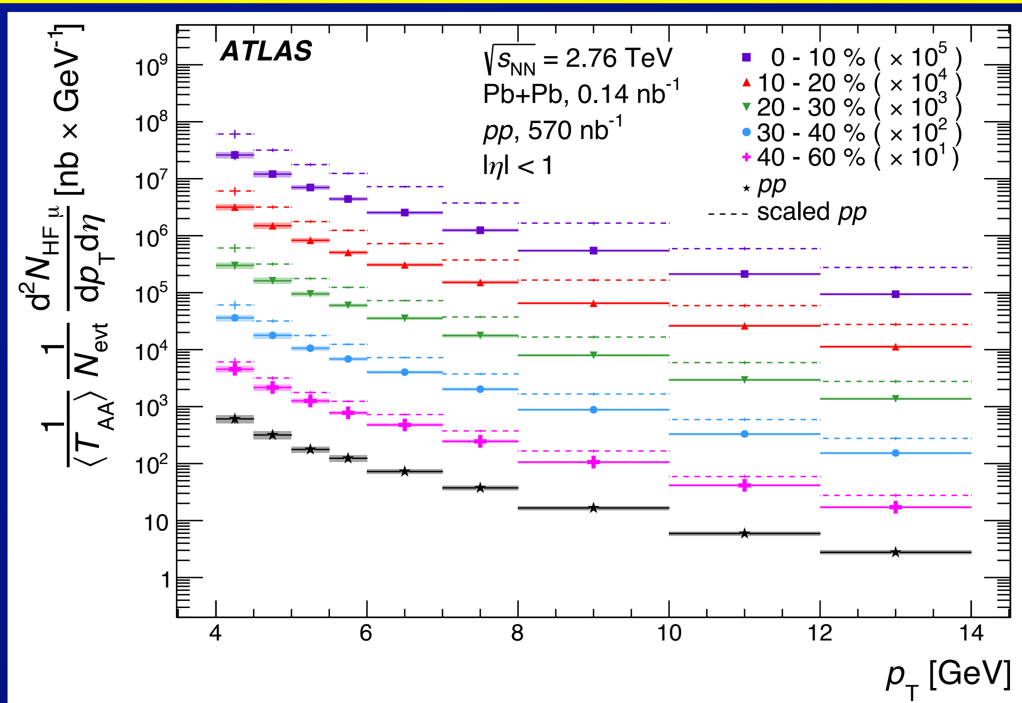
  - **separated from π/K decays via muon spectrometer/inner detector momentum balance, template fitting procedure**
- **pp cross-section compared to FONLL calculation**
  - ⇒ **good agreement**
  - ⇒ **ratio of b/c cross-sections (FONNL) varies with p_T**

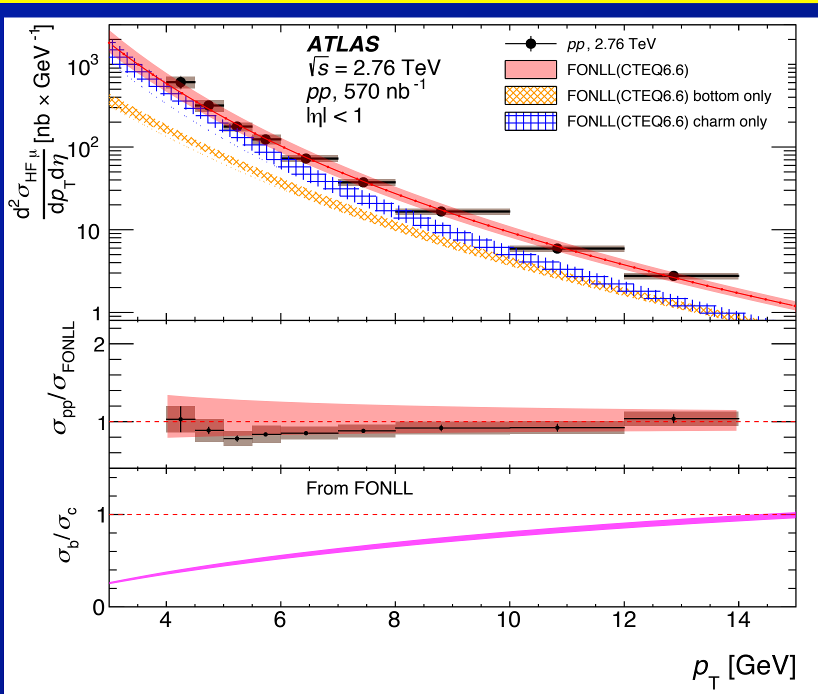
Heavy flavor suppression

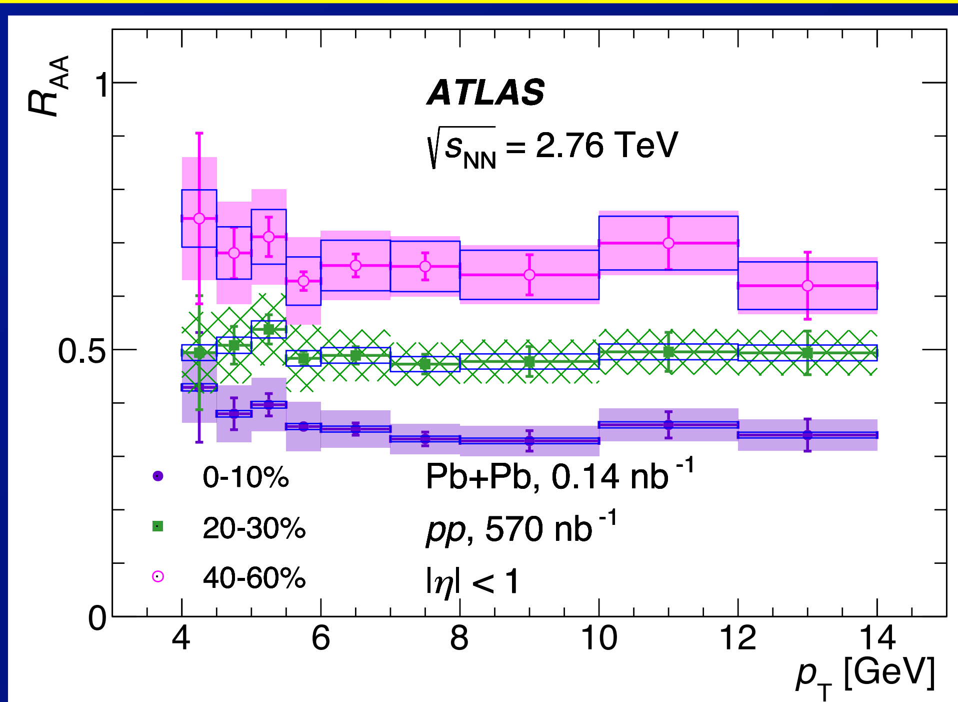




- **Measured using semi-leptonic decay muons**
  - separated from π/K decays via muon spectrometer/inner detector momentum balance, template fitting procedure
- **Pb+Pb spectra divided by T_{AA} (nucleon luminosity)**
  - ⇒ suppressed compared to pp

Heavy flavor suppression



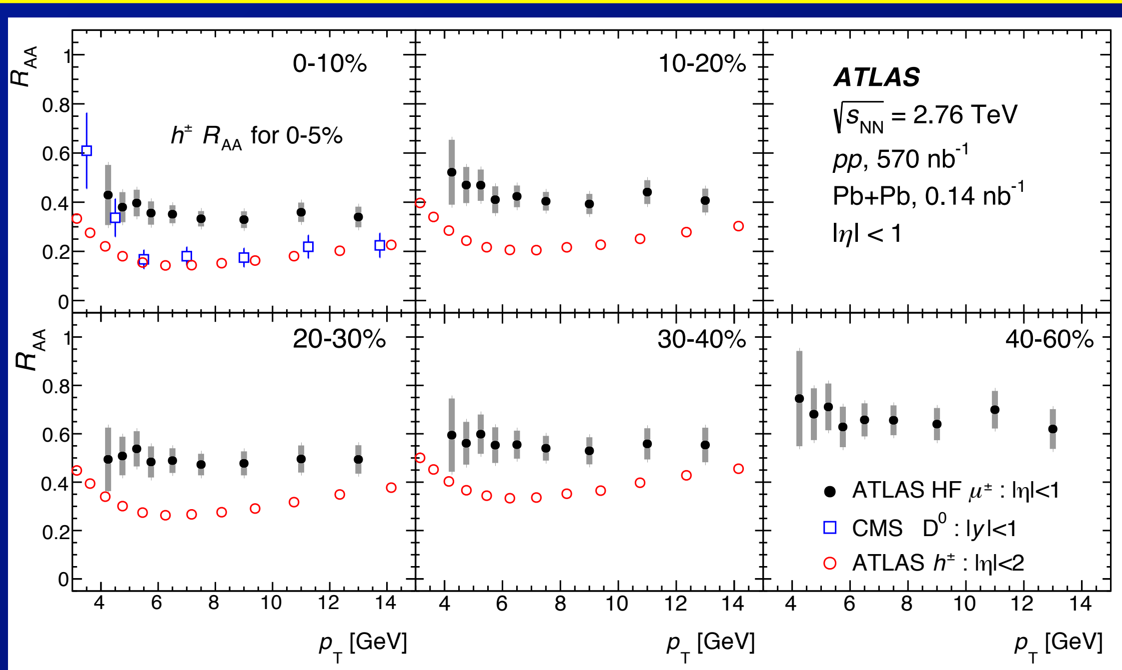


- **Measured using semi-leptonic decay muons**
  - separated from π/K decays via muon spectrometer/inner detector momentum balance, template fitting procedure
- **R_{AA} vs p_T for (subset) of measured centrality bins**

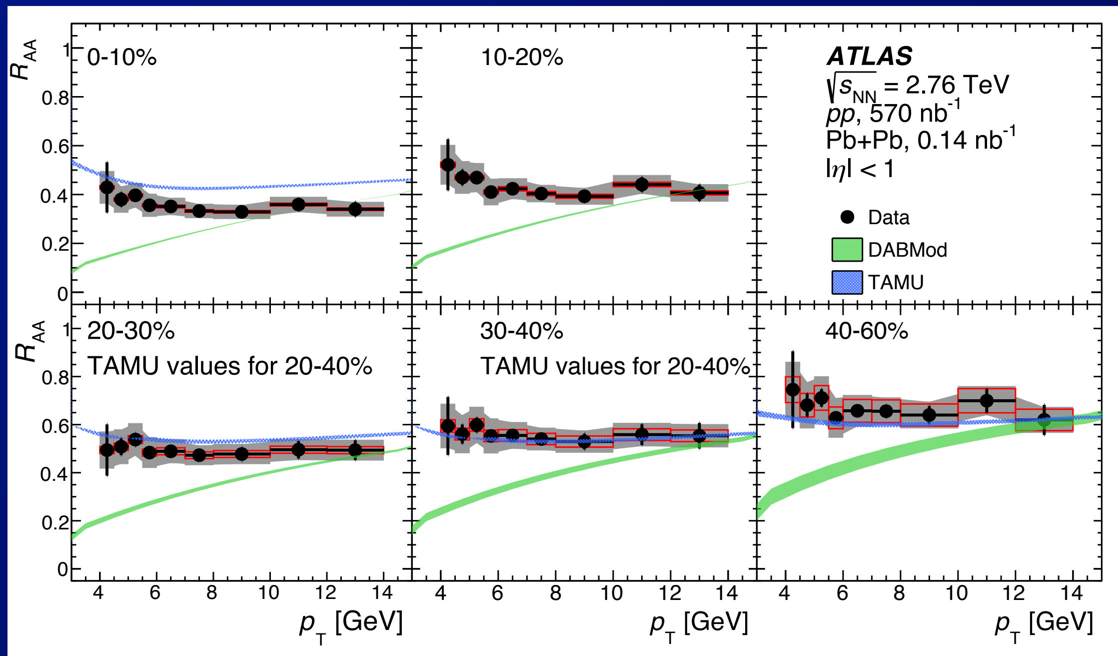
  ⇒ in spite of different b/c energy loss & p_T-dependent b/c ratio?

Heavy flavor suppression

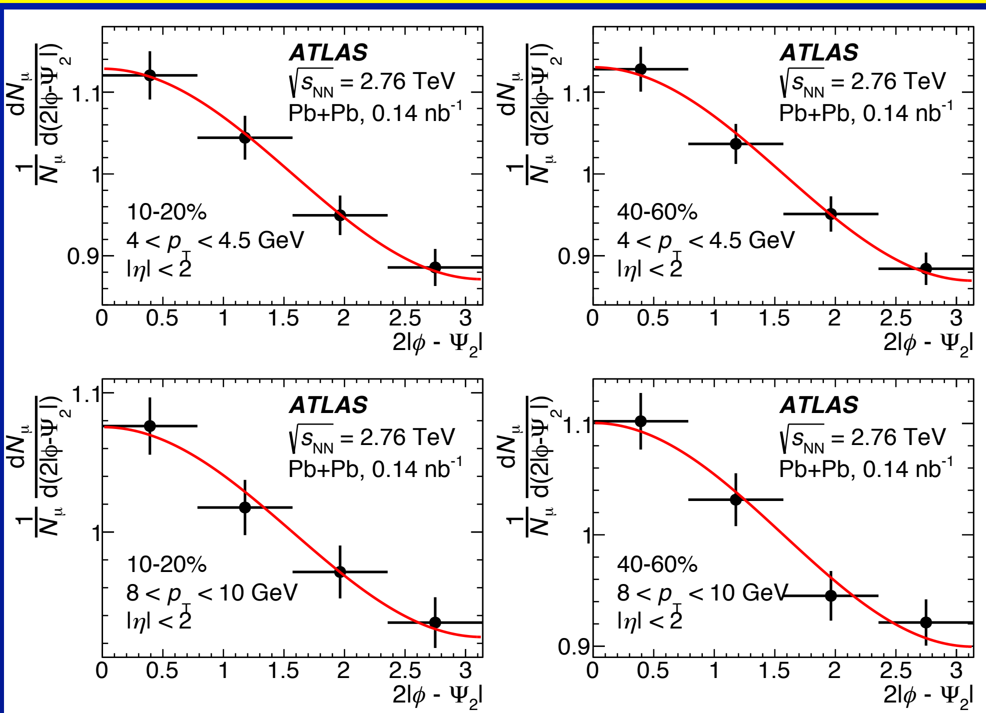
- Heavy flavor muon R_{AA} compared to hadron, D meson
  - – beware different kinematics for D, μ
    - ⇒ less μ suppression → less b suppression

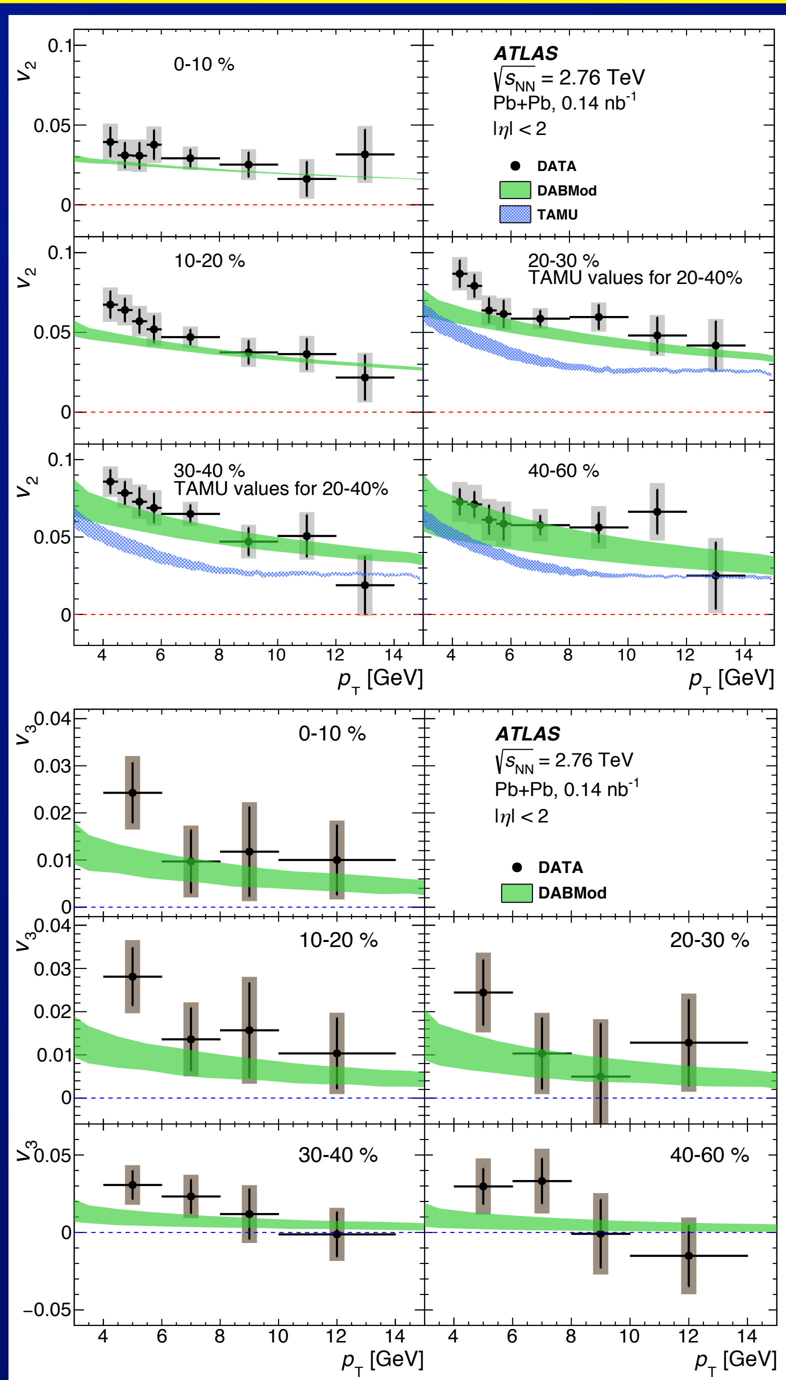


- Theory comparisons
  - ⇒ TAMU (diffusion + energy loss) describes data well, centrality dependence too weak
  - ⇒ DABMod (energy loss) doesn't reproduce p_T dependence



Heavy flavor v_n



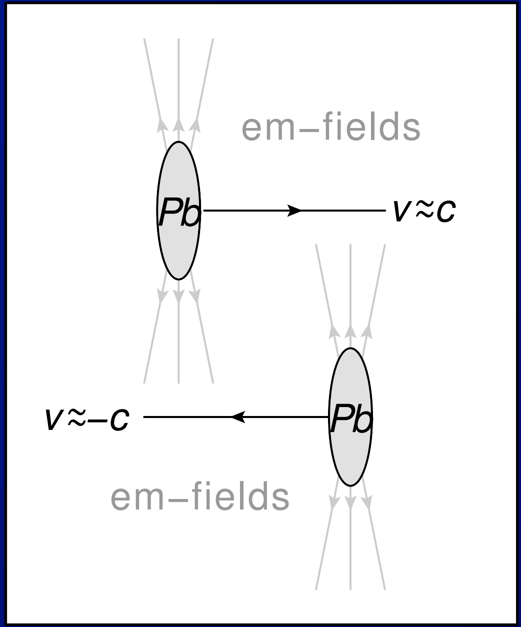


- **Measure semi-leptonic muon yield vs angle with respect to ψ_n**
  - using event plane and scalar product methods
  - ⇒ v_2, v_3, v_4 (not stat. significant)
  - ⇒ data well described by DABmod not by TAMU

Probing the initial state with electromagnetic processes

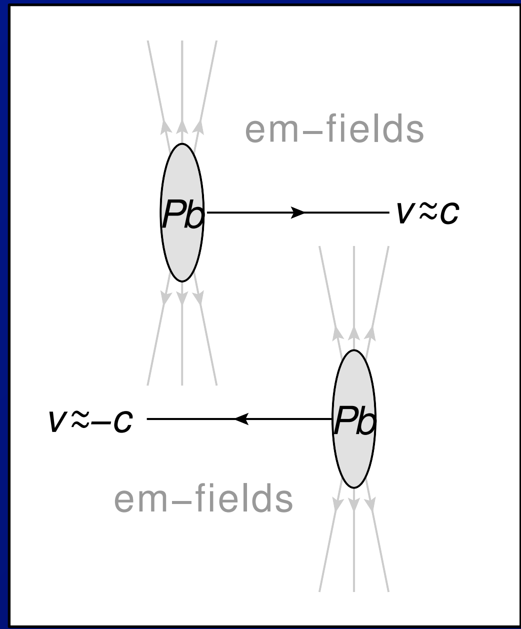
Ultra-peripheral Pb+Pb collisions

- Ultra-relativistic nuclei are sources of very strong coherent EM fields



Ultra-peripheral Pb+Pb collisions

- Ultra-relativistic nuclei are sources of very strong coherent EM fields
  - Equivalently, sources of photons w/ high flux extending to >~ 50 GeV



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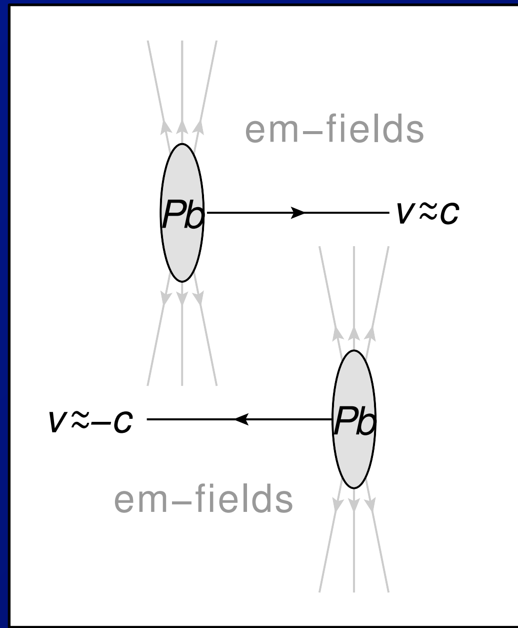
  ⇒ Use to probe "initial state" of Pb+Pb collisions using γ+A collisions



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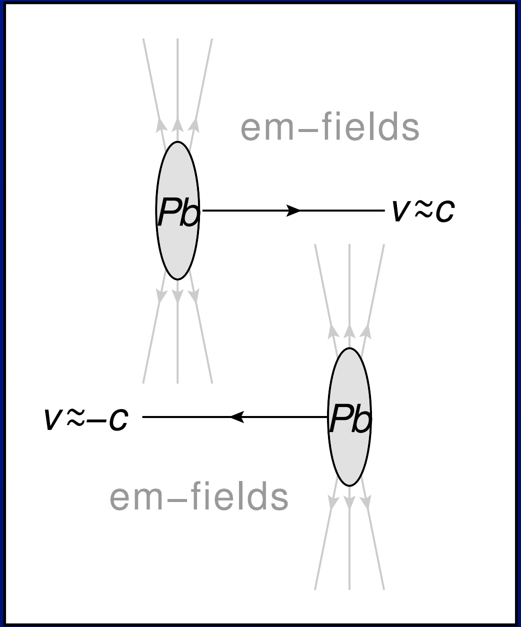
  - ⇒ e.g. γ+A→di-/multi-jets



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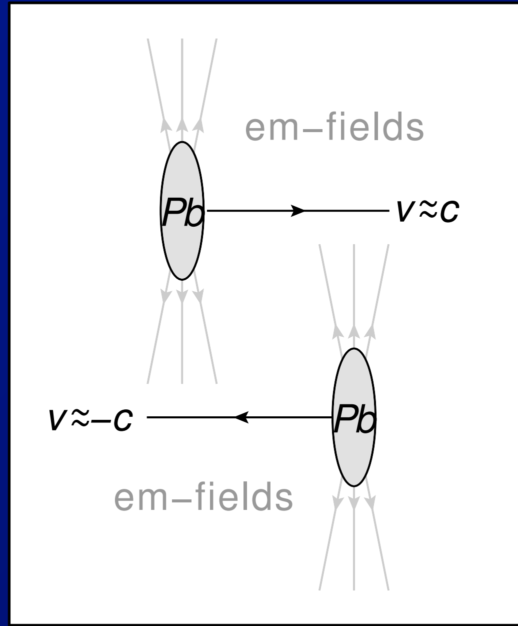
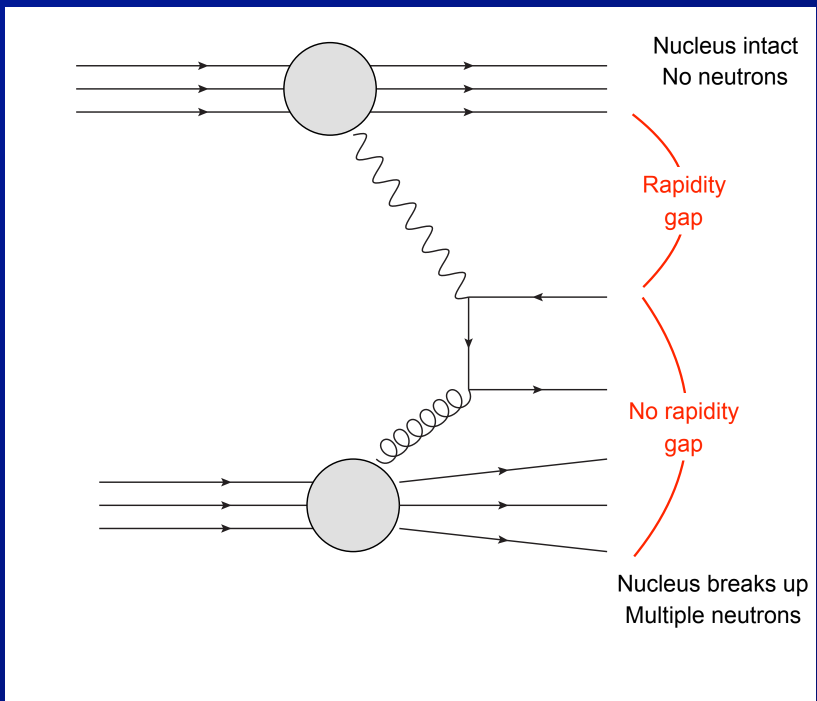
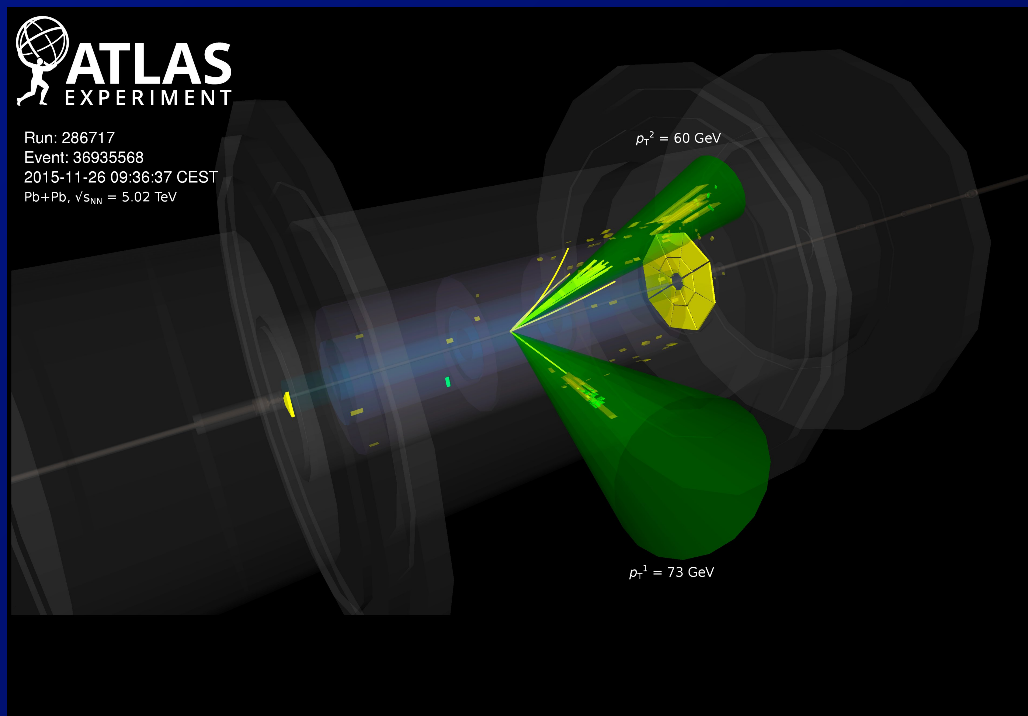
  - ⇒ Use to probe “initial state” of Pb+Pb collisions using γ+A collisions
  - ⇒ e.g. γ+A→di-/multi-jets
    - » probe nuclear PDFs



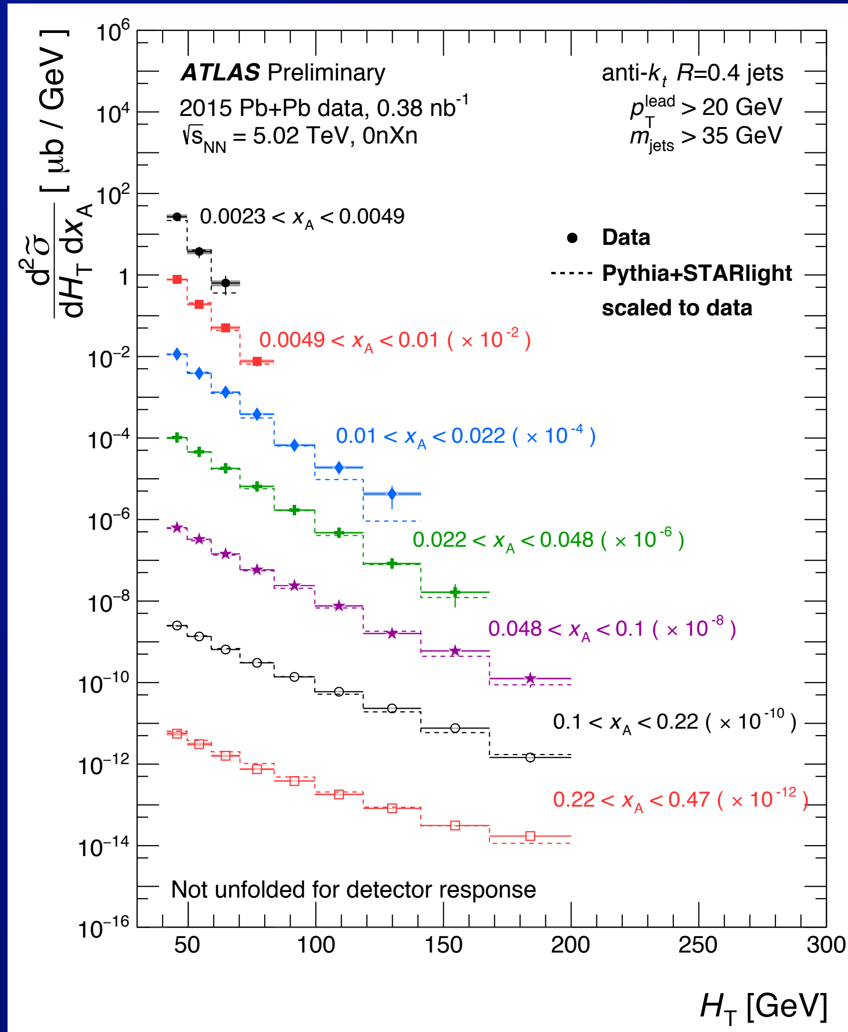


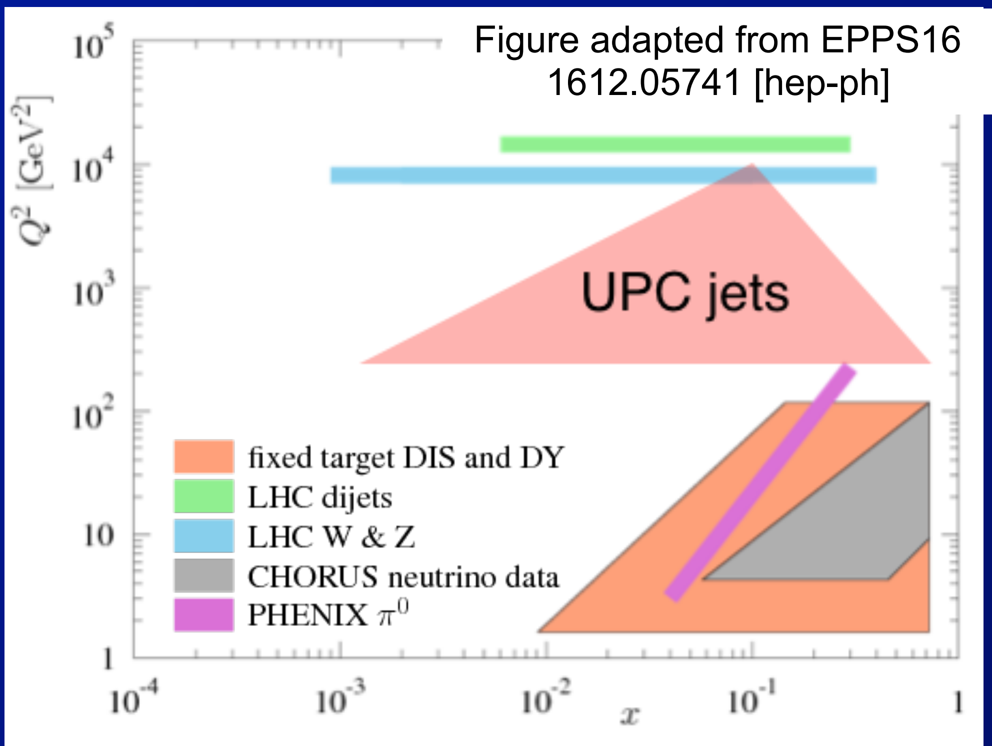


Ultra-peripheral Pb+Pb collisions

- Preliminary measurement of γ+A→di-/multi-jets:
  - tagged w/ forward neutron (ZDC) and forward gap requirement
  - uncorrected for jet response
  - compared to Pythia

⇒ agreement → proof of principle





kinematic coverage in (x, Q^2)

Ultra-peripheral Pb+Pb collisions

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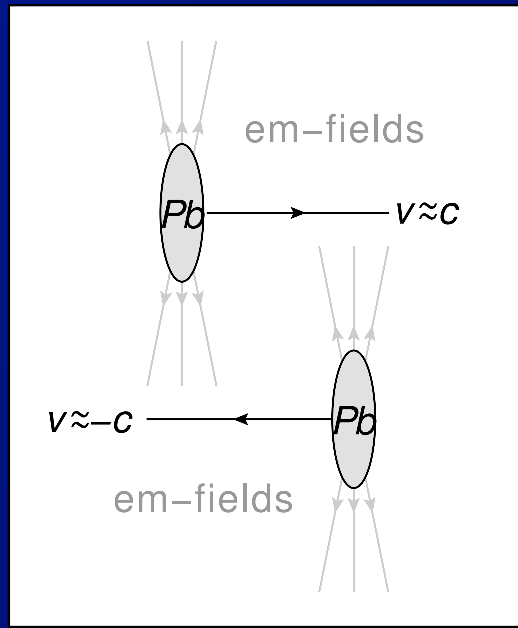
  - Equivalently, sources of photons w/ high flux extending to >~ 50 GeV



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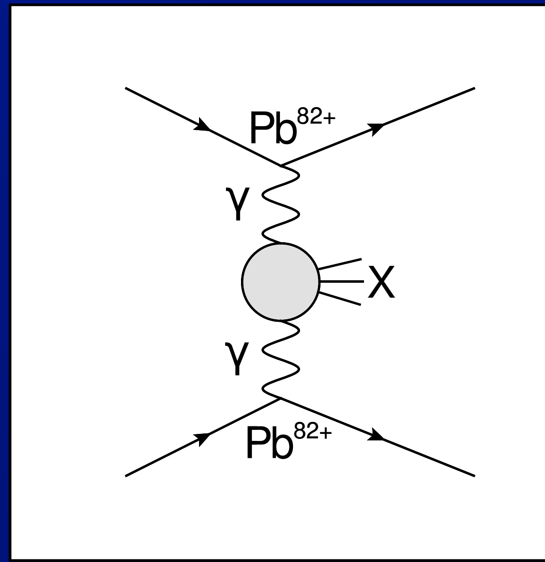

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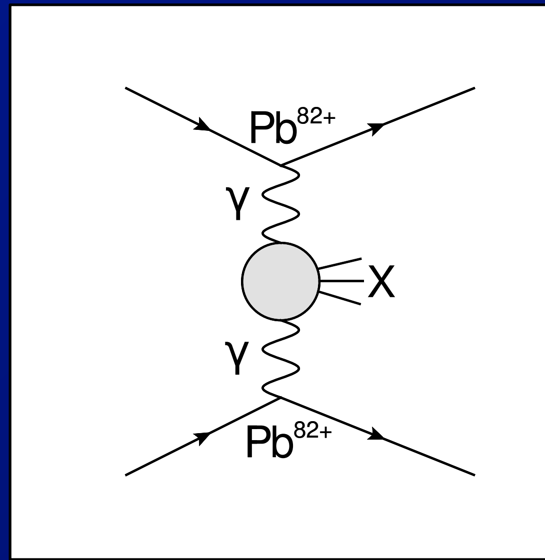

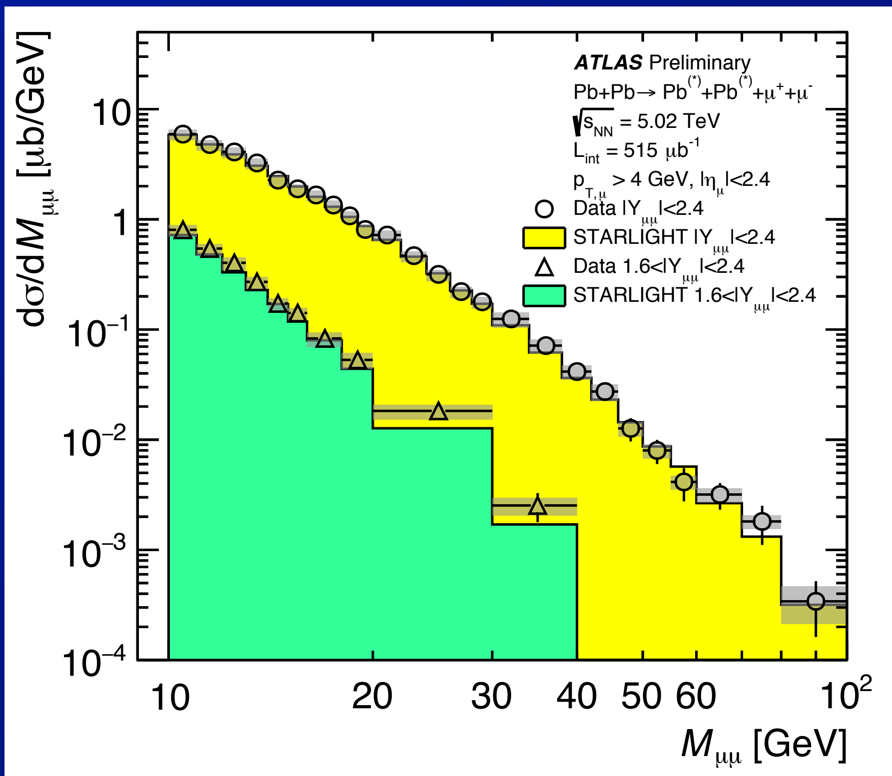

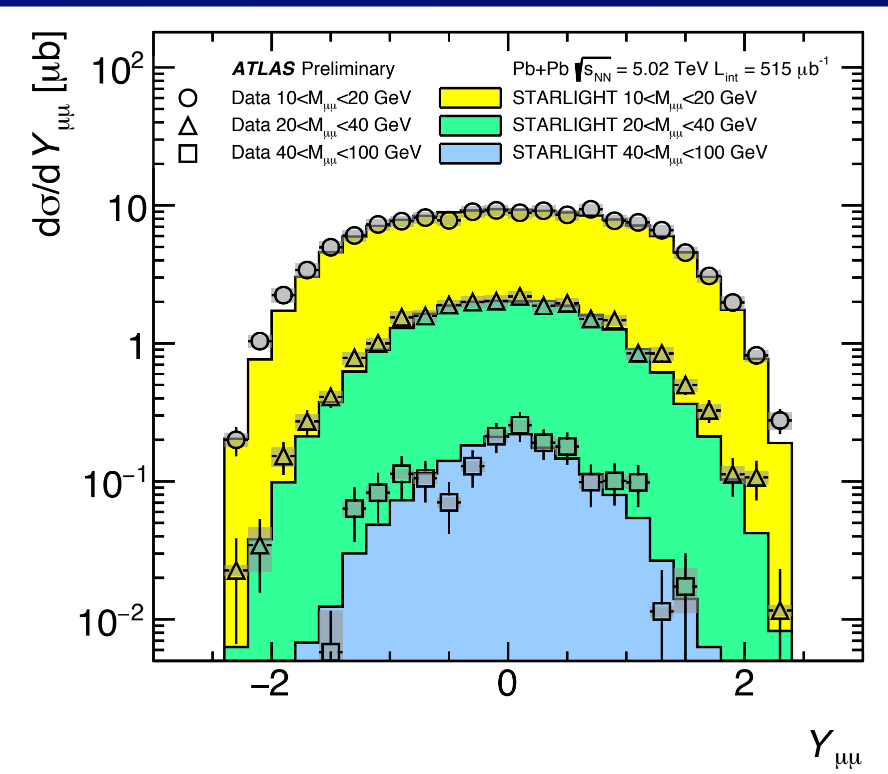

Ultra-peripheral Pb+Pb collisions

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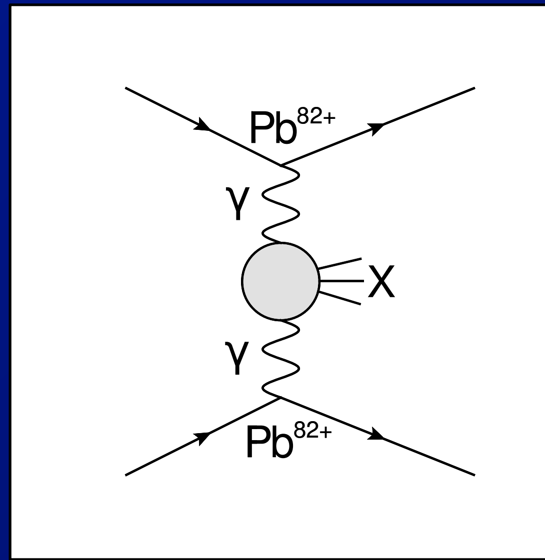
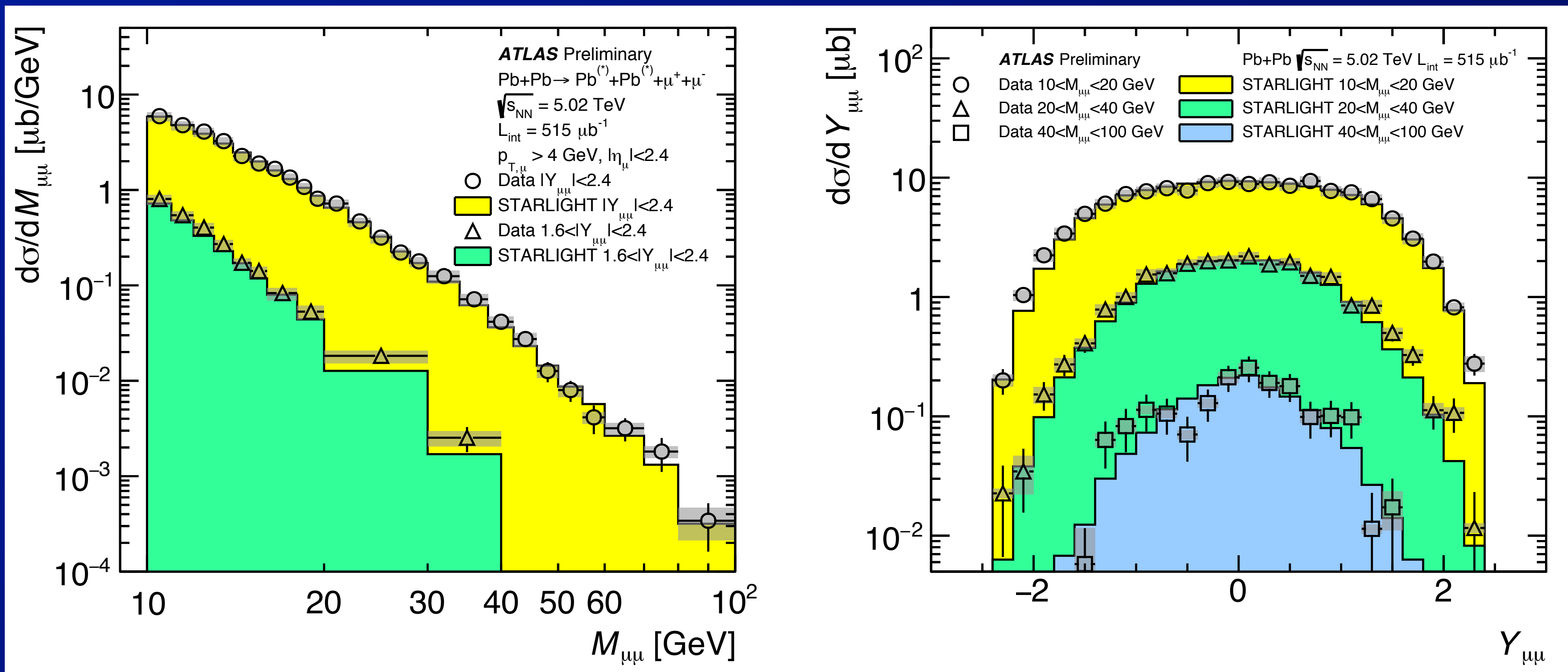
  - Equivalently, sources of photons w/ high flux extending to >~ 50 GeV
- **Calibrate using (e.g.) $\gamma+\gamma \rightarrow \mu^+\mu^-$**
  - ⇒ good agreement with STARLIGHT model (nuclear photon flux + LO QED)





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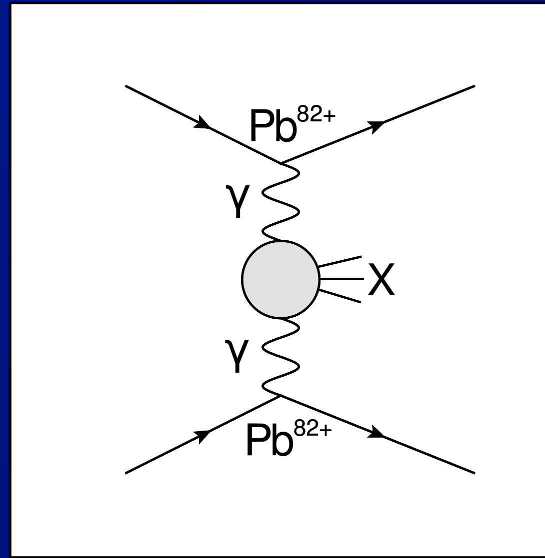

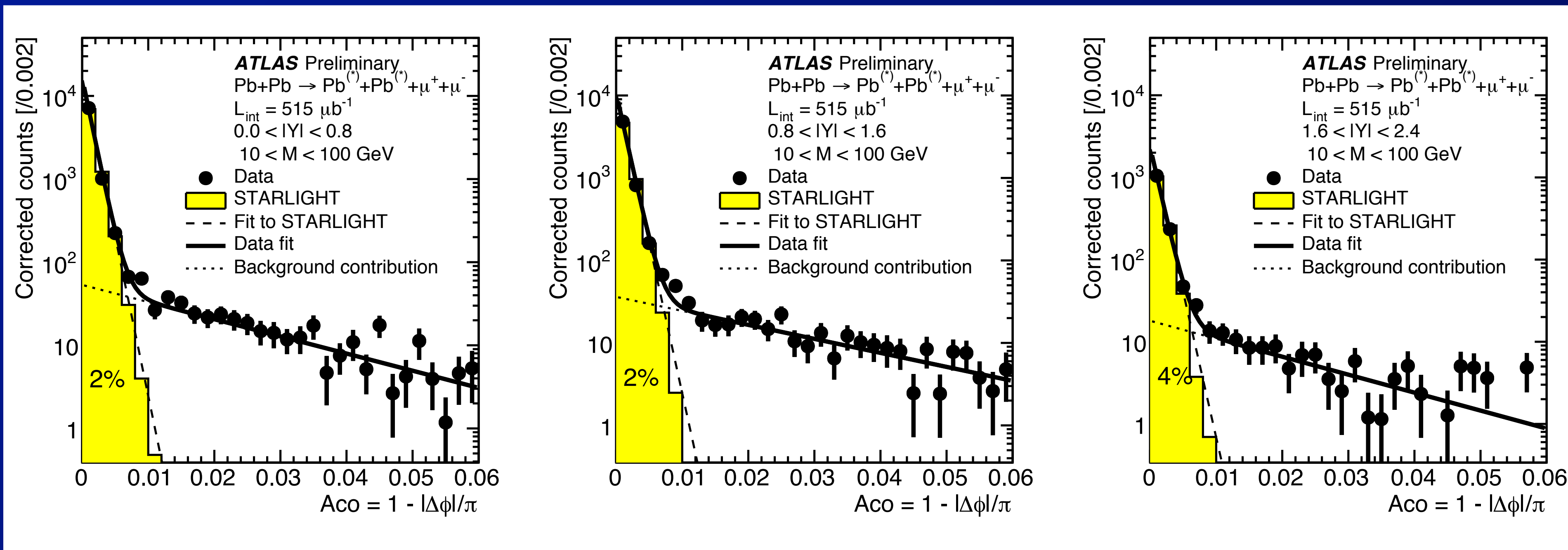

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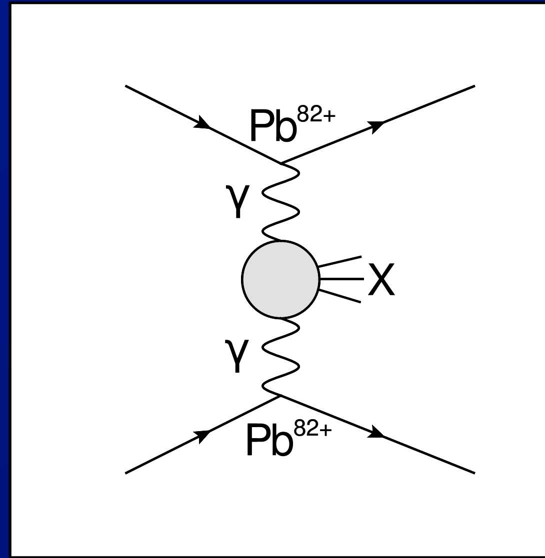
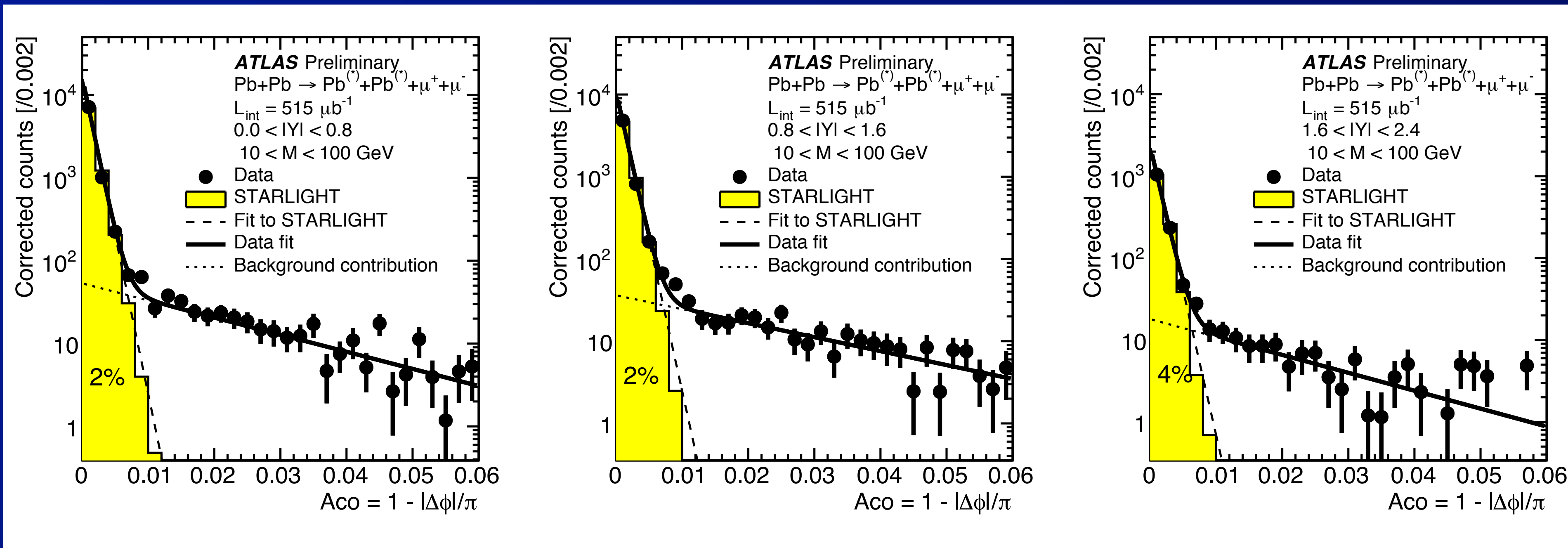
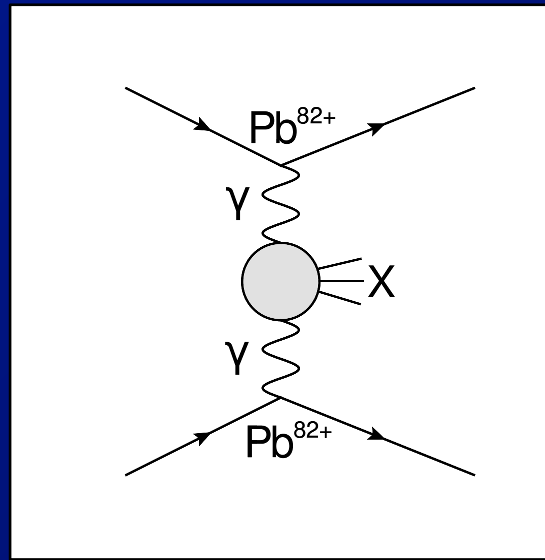
  ⇒ muons are highly aligned (coherent γ)

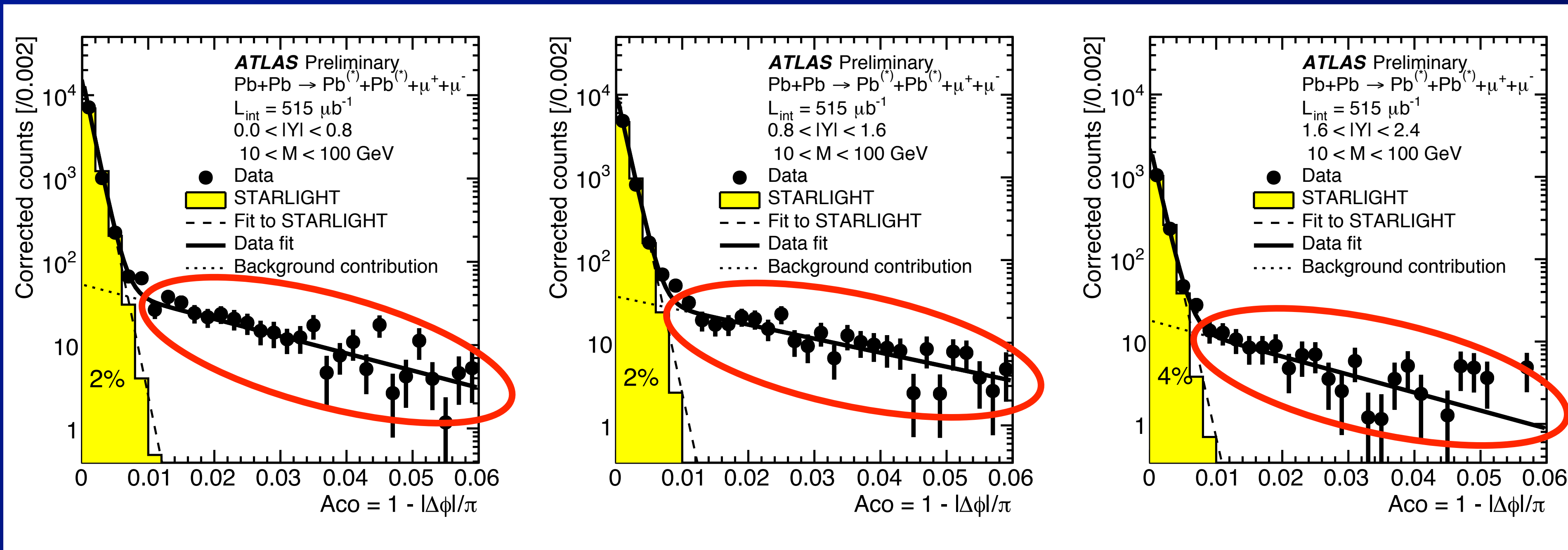




Ultra-peripheral Pb+Pb collisions

- **Ultra-relativistic nuclei are sources of very strong coherent EM fields**
  - Equivalently, sources of photons w/ high flux extending to >~ 50 GeV
- **Calibrate using (e.g.) $\gamma+\gamma \rightarrow \mu^+\mu^-$**
  - ⇒ muons are highly aligned (coherent γ)
  - ⇒ except when they aren't





Ultra-peripheral Pb+Pb collisions

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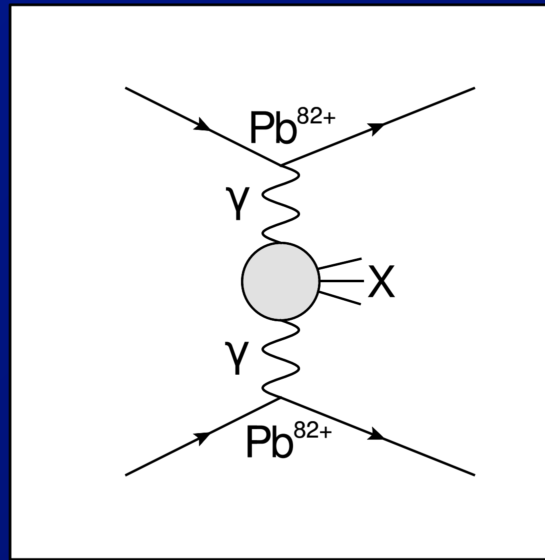
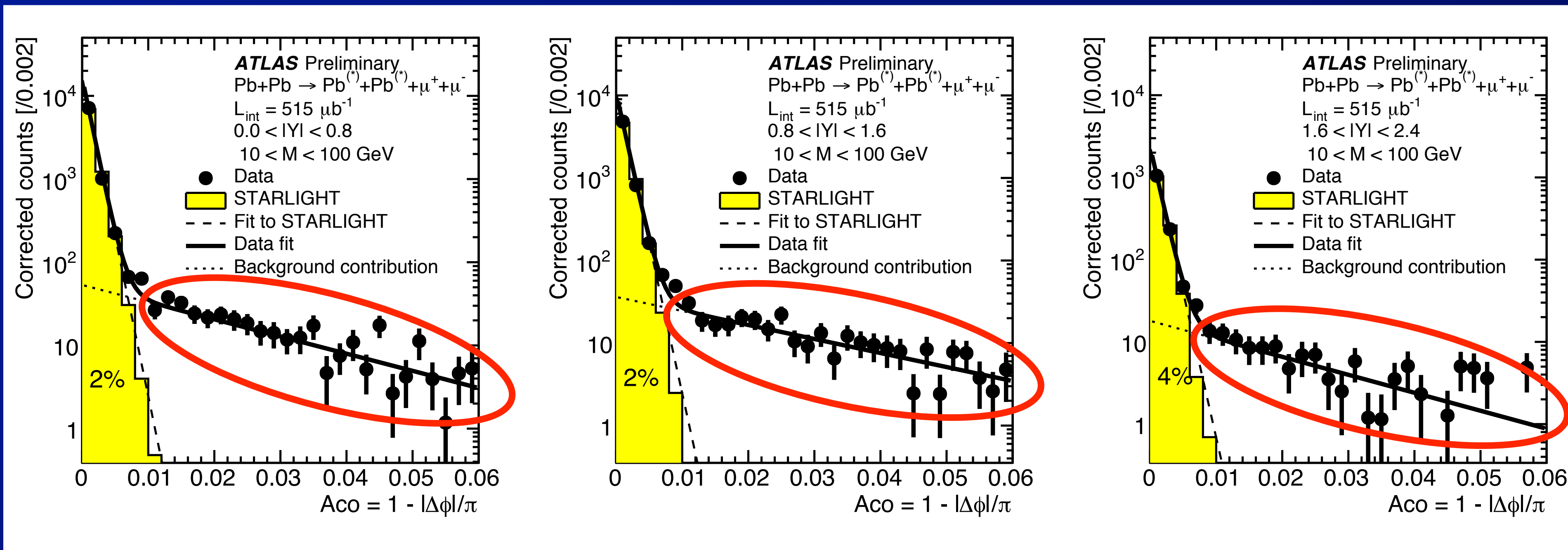
  - Equivalently, sources of photons w/ high flux extending to >~ 50 GeV
- Calibrate using (e.g.) $\gamma+\gamma \rightarrow \mu^+\mu^-$
  - ⇒ muons are highly aligned (coherent γ)
  - ⇒ except when they aren't
    - » few % QED & incoherent





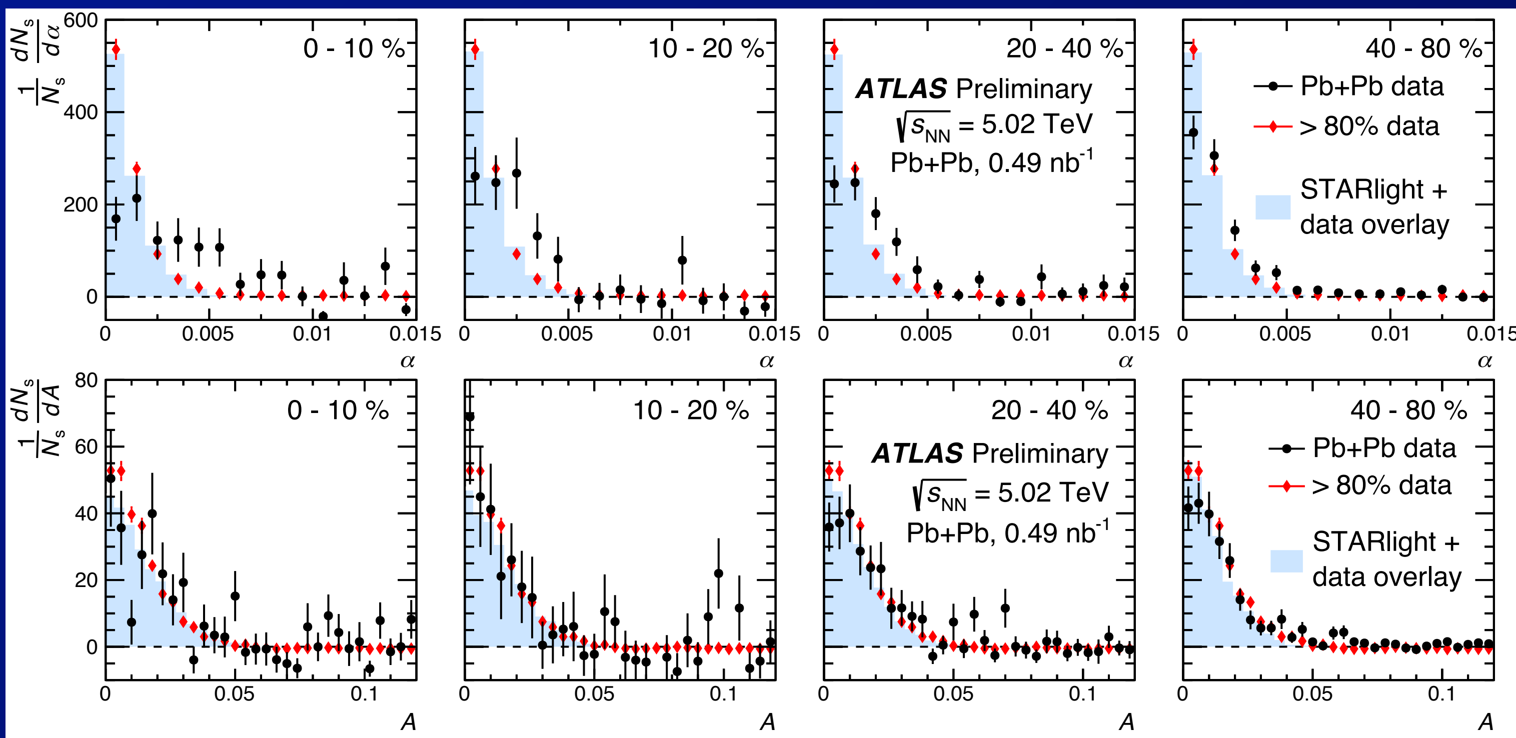
Non-UPC $\gamma\gamma \rightarrow \mu^+\mu^-$

- The tight alignment of $\gamma\gamma \rightarrow \mu^+\mu^-$ pairs makes detection possible in non-UPC Pb+Pb collisions
  - Background from heavy flavor decays subtracted
  - other physics backgrounds (Drell-Yan, dissociative) ~ flat over the measured acoplanarity range.
- Plot acoplanarity (α) and asymmetry, $A \equiv \left| \frac{p_T^+ - p_T^-}{p_T^+ + p_T^-} \right|$

$\Rightarrow$ observe a centrality-dependent acoplanarity broadening!

α

A



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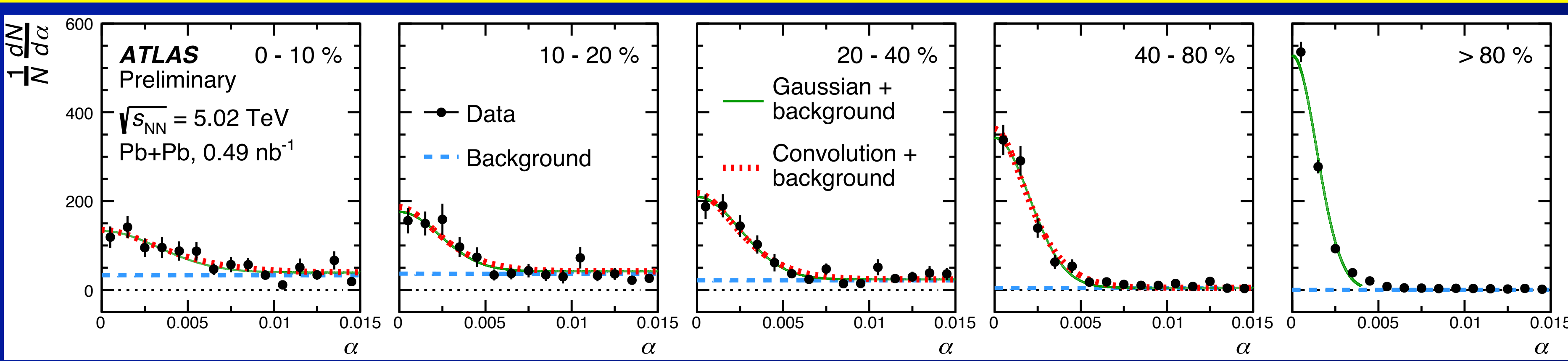
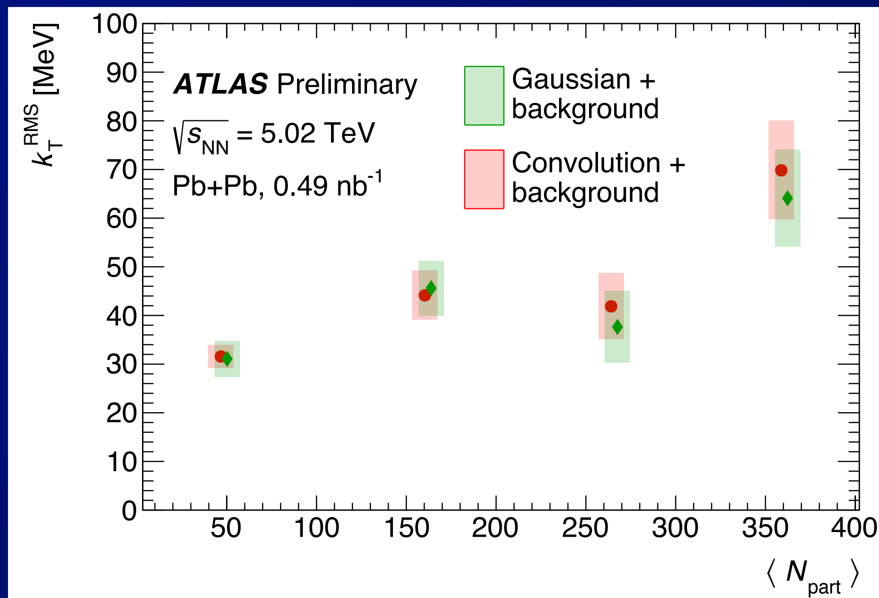


- **Fit α distributions to Gaussians to quantify broadening**
  - estimate momentum scale for broadening:

$$\langle \alpha^2 \rangle = \langle \alpha^2 \rangle_0 + \frac{1}{\pi^2} \frac{\langle \vec{k}_T^2 \rangle}{\langle p_{T\,avg}^2 \rangle}$$

  - two different fit methods
    - ⇒ use simple Gaussian fits
    - ⇒ convolute over $p_{T\,avg} \equiv \frac{1}{2}\left(p_T^+ + p_T^-\right)$
  - use >80% to determine $\langle \alpha^2 \rangle_0$
- **Plot RMS k_T vs N_{part}**
  - ⇒ slow growth with N_{part}
    - » from ~30 MeV to ~70 MeV
  - ⇒ Asymmetry resolution too poor to see such effects



Summary

- Measurements of collectivity in A+A collisions
  - ⇒ e.g. using new Xe+Xe data to help disentangle initial state modeling from hydrodynamics
- Measurements of collectivity (?) in small systems
  - – 2 particle correlations
  - – 4 particle correlations
  - – HBT measurements of production geometry
  - – Z-tagged pp collisions
  - ⇒ all empirical evidence points to presence of collective/ strong-coupling dynamics in small systems (even pp!)
- Jet quenching
  - – single jet suppression
  - – jet fragmentation
  - – dijet balance: Pb+Pb and Xe+Xe
  - – photon-jet balance

Summary

- Jet quenching (cont.)
  - single jet suppression
  - jet fragmentation
  - dijet balance: Pb+Pb and Xe+Xe
  - photon-jet balance

  ⇒ just a subset of available measurements probing our understanding of jet quenching physics

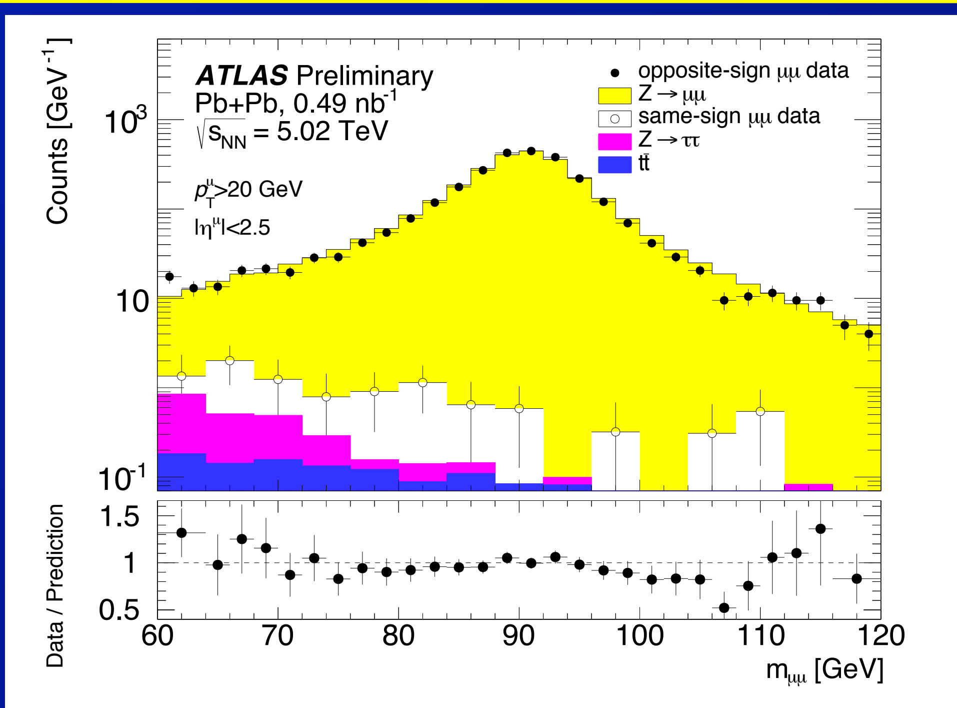
  ⇒ high-statistics data from LHC now allowing us to study the quark gluon plasma with probe energies varying by ~ x100
- Initial state
  - using γ+A→di-/multi-jets (e.g.) to probe nuclear PDFs

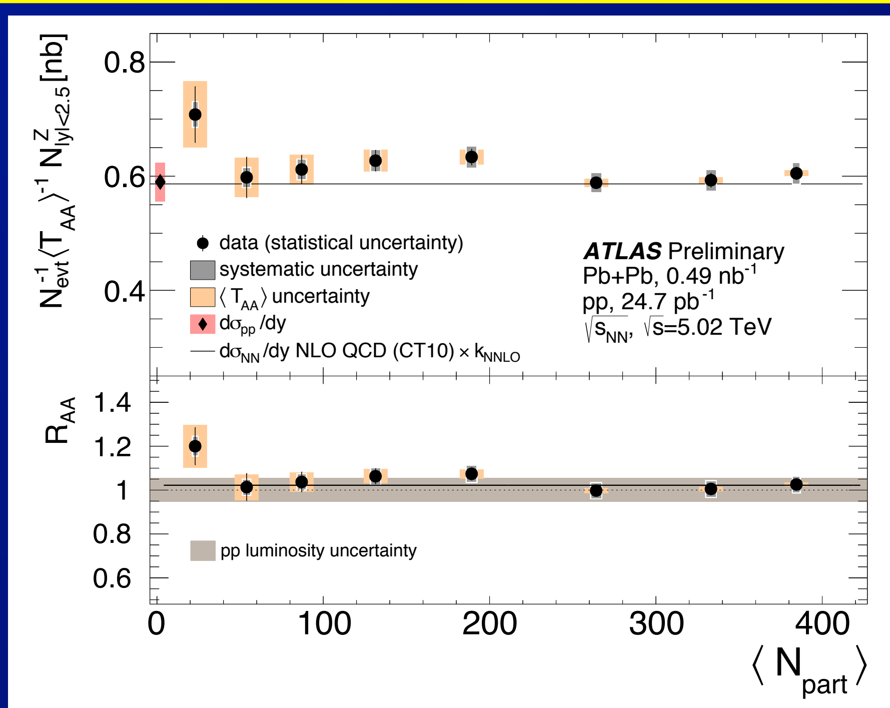
  ⇒ just the start of a long program
  - calibrating photon fluxes using di-leptons
- Surprise:

  ⇒ Non-UPC $\gamma\gamma \rightarrow \mu^+\mu^-$ processe provide EM probe of plasma?

Backup

Calibrating Pb+Pb hard-scattering rates





- Use vector bosons e.g. $Z \rightarrow \mu^+\mu^-$
  - easily measured even in Pb+Pb collisions
  - ⇒ Z R_{AA} equal to unity within uncertainties

p+Pb 2-pion HBT: hydro comparisons

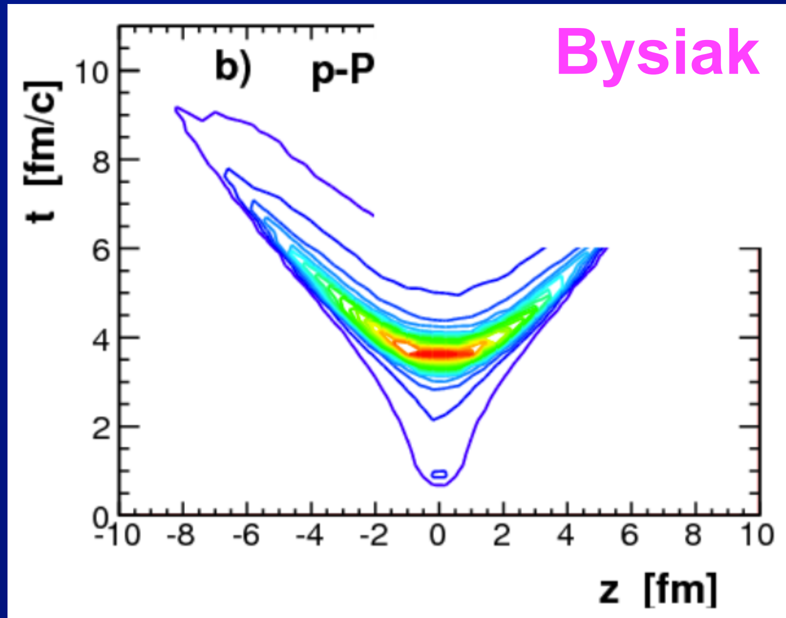
- Out-long cross-term:

$$C_{\rm BE}(\mathbf{q}) = 1 + \exp\left(-\|R\mathbf{q}\|\right)$$

$$R = \begin{pmatrix} R_{\rm out} & R_{\rm os} & R_{\rm ol} \\ R_{\rm os} & R_{\rm side} & 0 \\ R_{\rm ol} & 0 & R_{\rm long} \end{pmatrix}$$

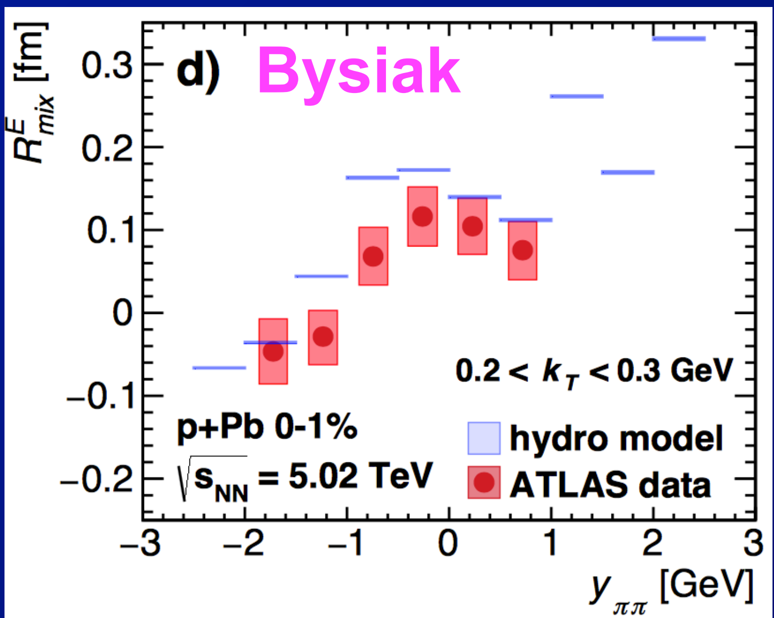
  – Can be non-zero in p+Pb collisions

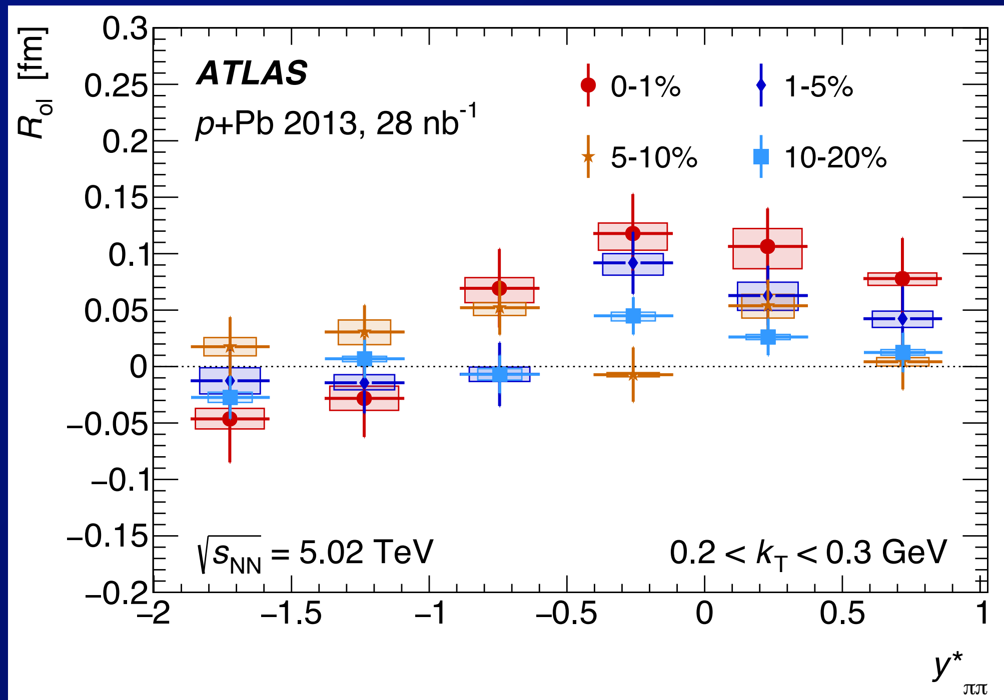
  ⇒ due to rapidity asymmetry



- Observed in ATLAS data

  ⇒ well described by hydro

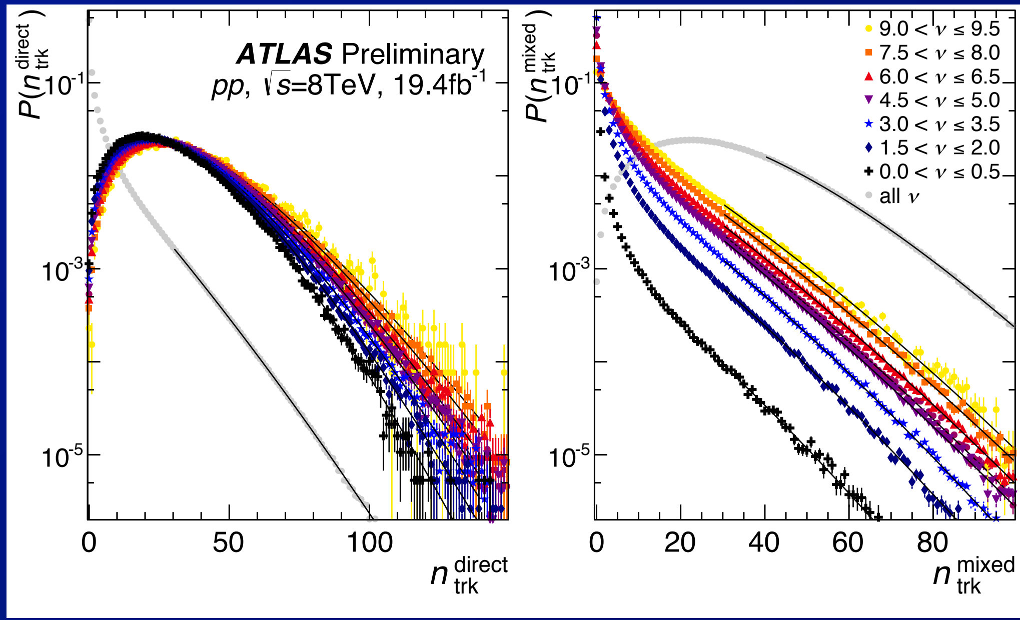


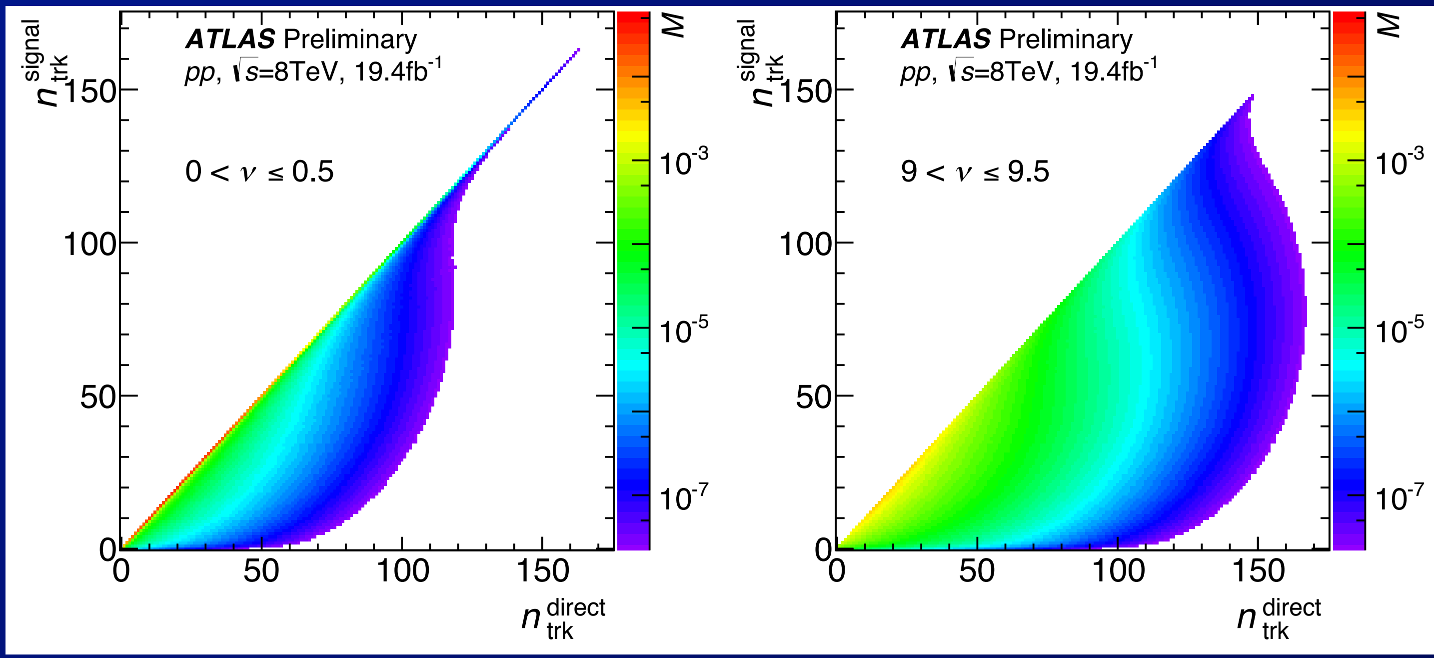


Pileup background

- Use mixed events to obtain distribution of # background tracks
  - as a function of Z-event (direct) N_{trk}
  - and $\nu \equiv \langle N_{trk}^{bkgd} \rangle$

$\Rightarrow N_{trk}$ response matrices





Pileup background

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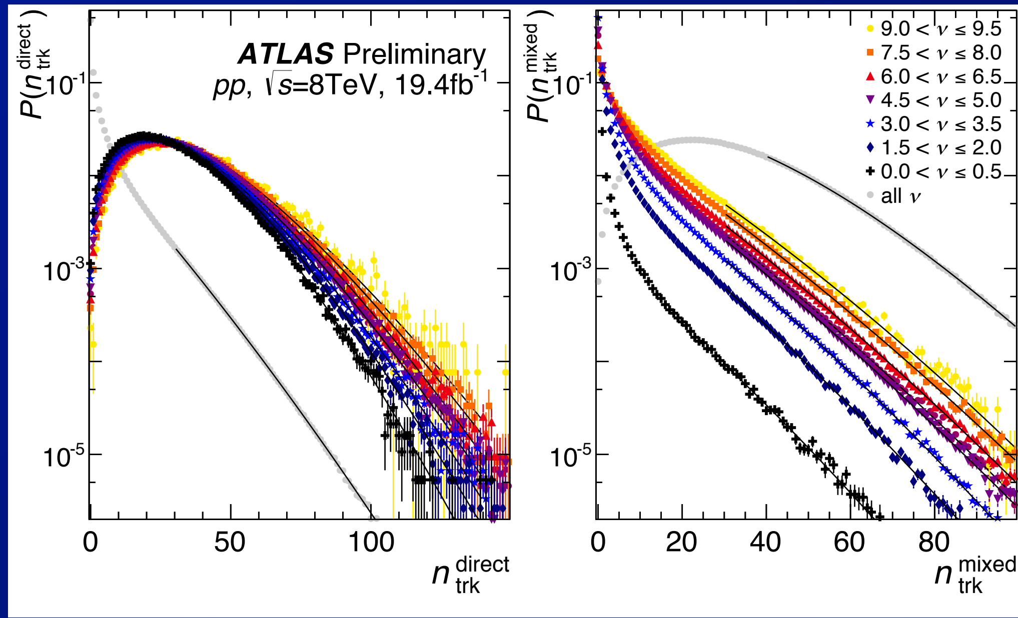
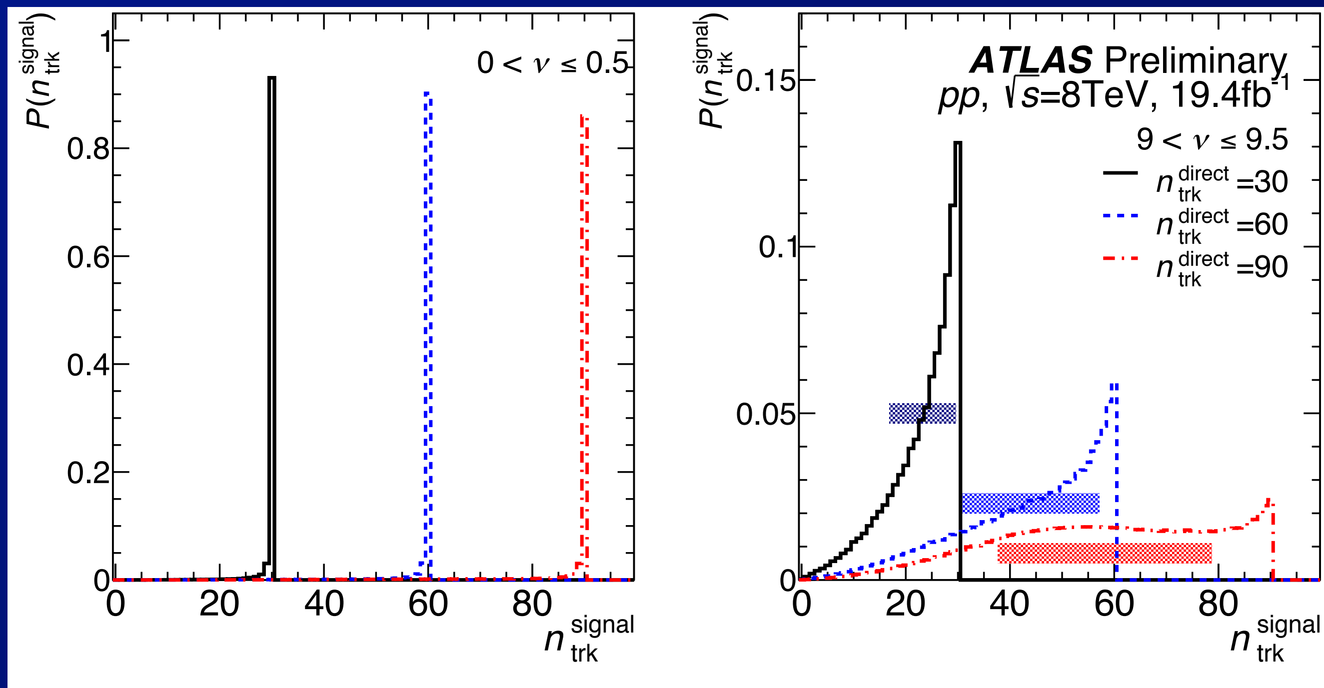
  $\Rightarrow$ Unfold N_{trk} distributions



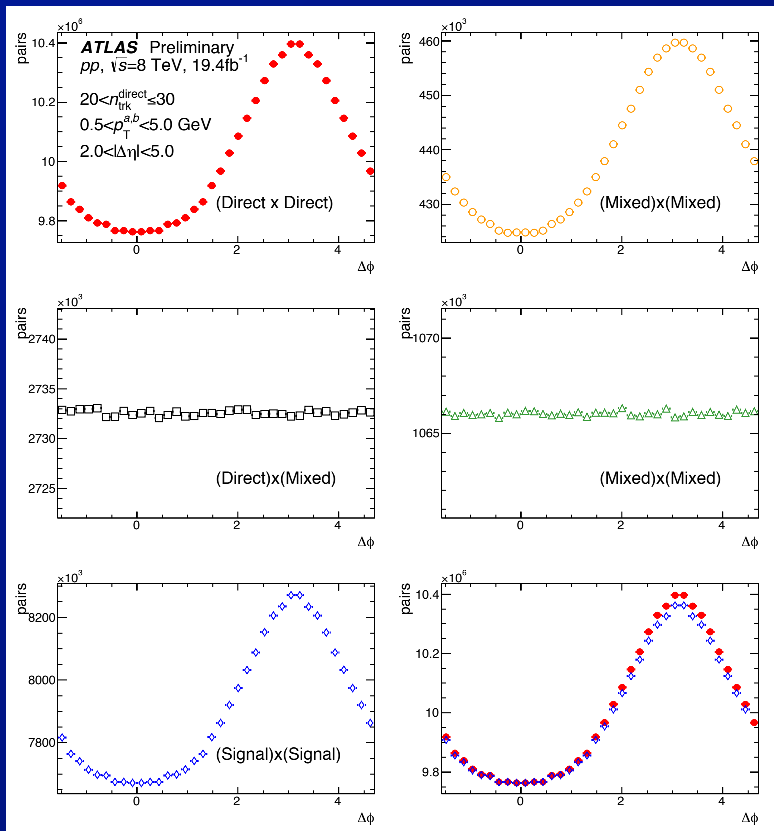


Two-particle correlation analysis

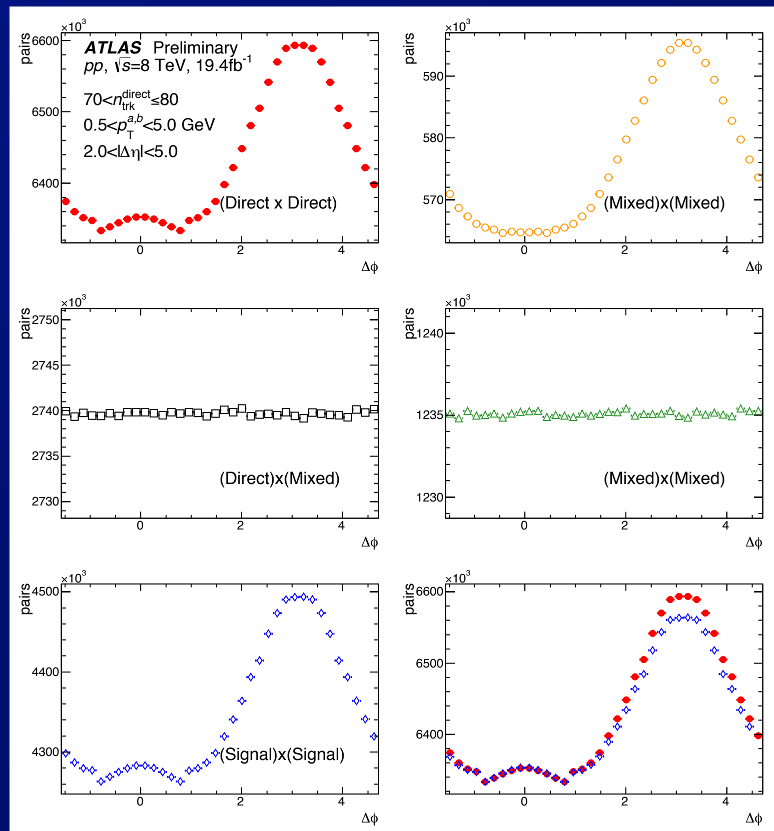
- **Pileup can add multiple tracks from same collision**
  - background not flat in $\Delta\varphi$
- **Pileup has different η distribution than Z events**
  - due to ν-dependent effect of $\Delta z \sin\theta$ cut applied to tracks

$\Rightarrow$ **Need to measure two-particle correlations for both correlated and uncorrelated pileup & subtract**

N_{trk}^{dir} 20-30



N_{trk}^{dir} 70-80



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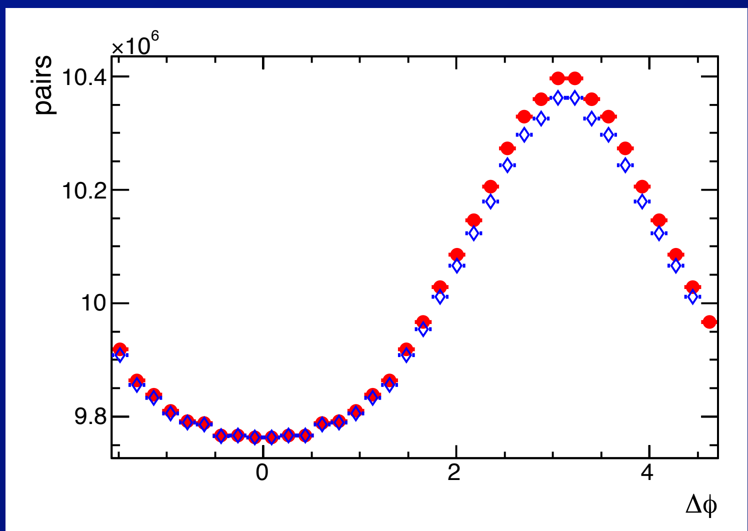
N_{trk}^{dir} 20-30

subtracted



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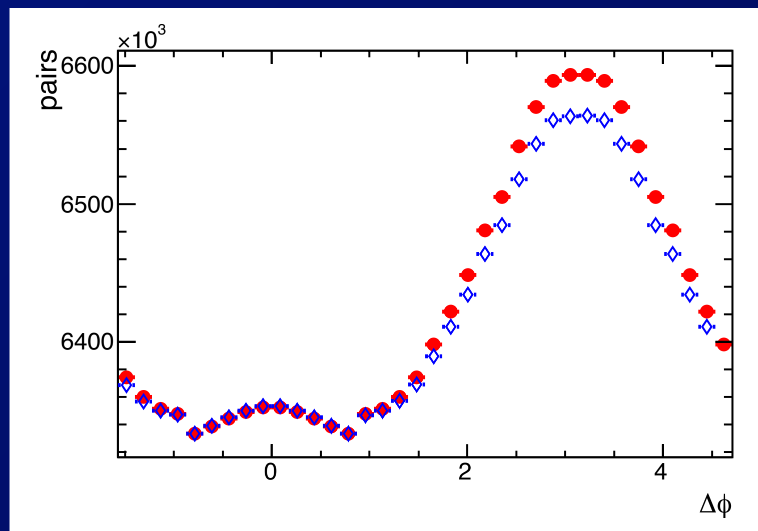
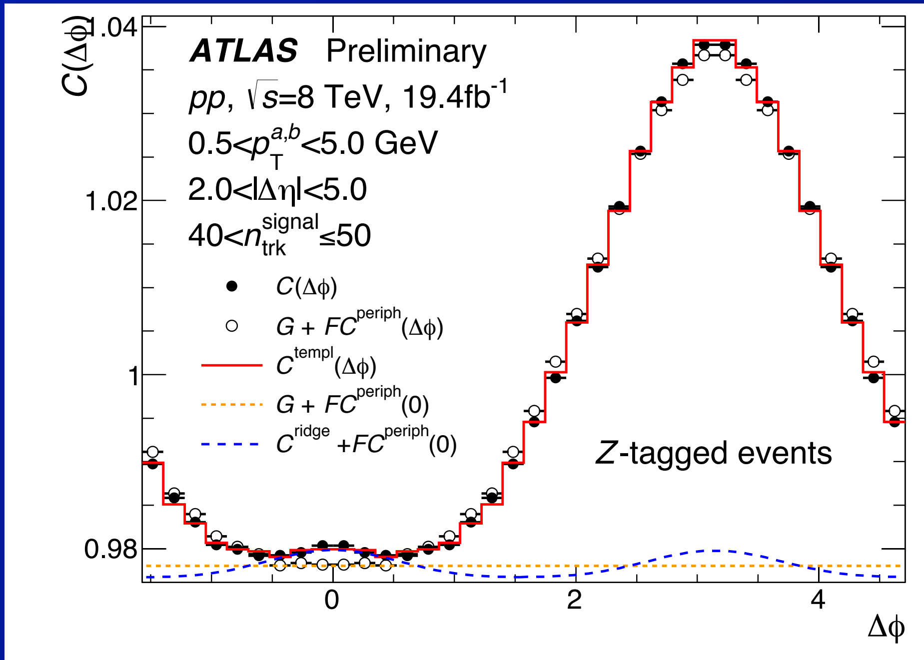
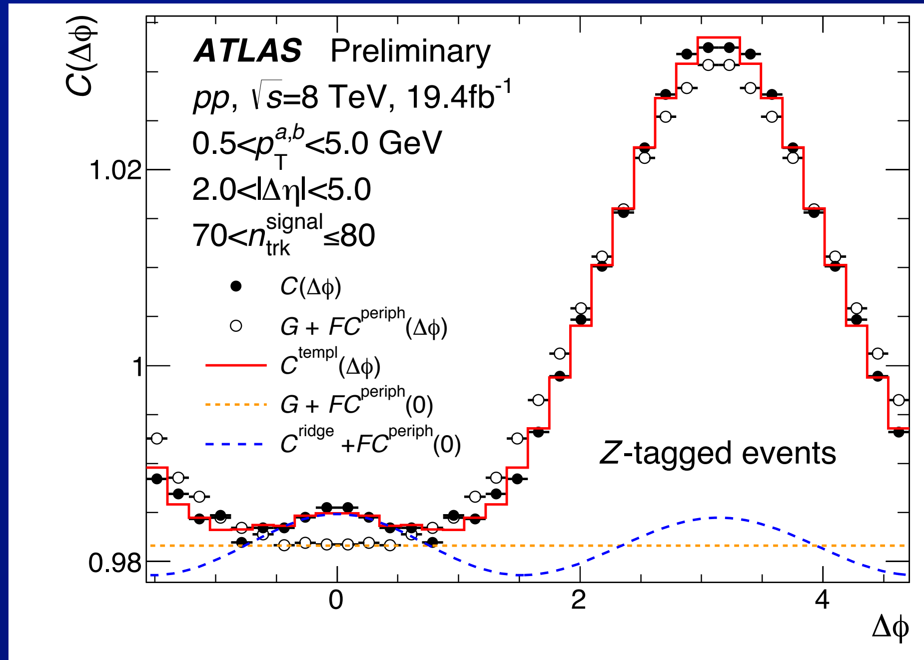


Two-particle correlation analysis



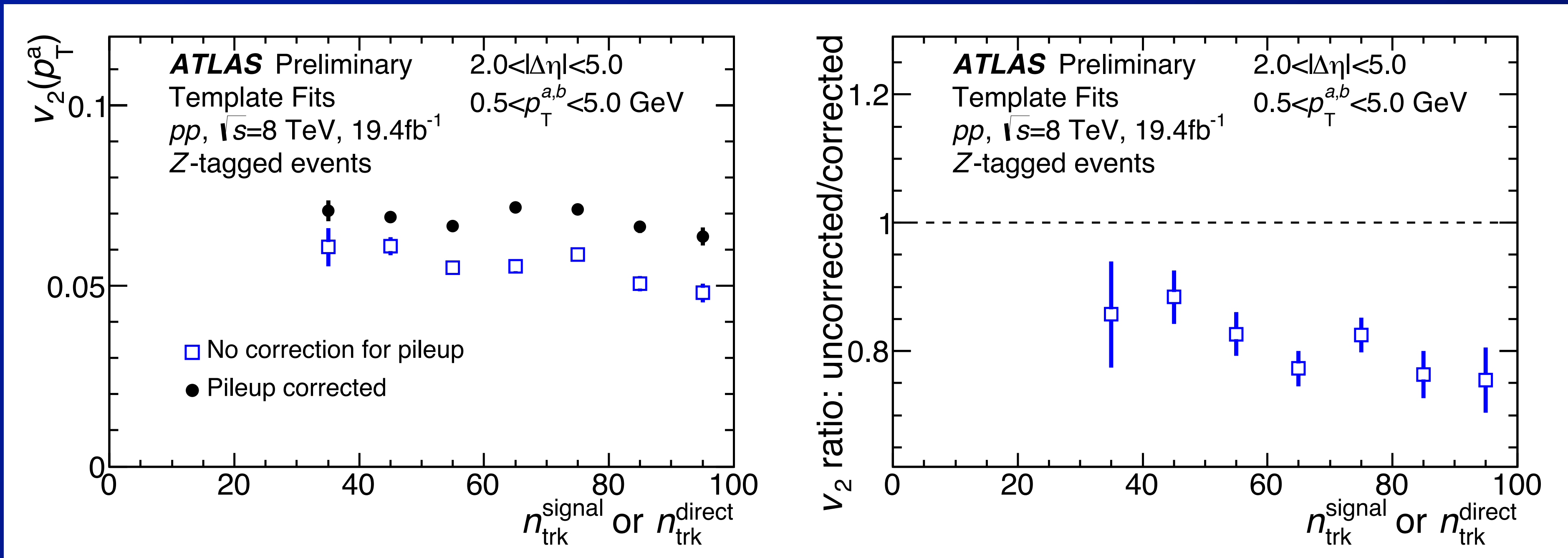


- Apply template fit method using $20 < N_{trk} < 30$ (after correction) as peripheral reference
  - only v_2 term included in the ridge contribution

  ⇒ as in inclusive pp collisions @ 5 and 13 TeV, the two-particle correlation function well described by scaled peripheral + cos(2φ) term

Two-particle correlation analysis

- Comparison of v_2 obtained from template analysis before and after pileup correction



– Corrected: versus corrected multiplicity

– Uncorrected: versus direct multiplicity

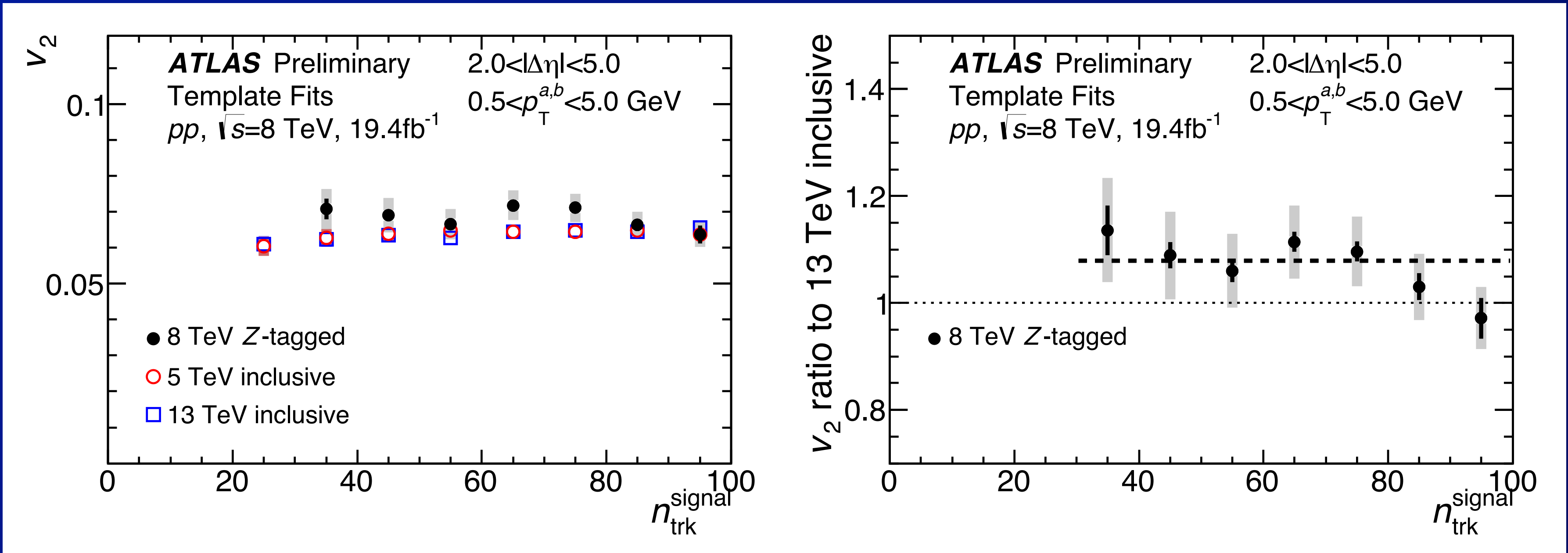
⇒ essentially no multiplicity dependence to either

⇒ subtraction reduces v_2 by 20%

Two-particle correlation results

- **Main physics result:**
  - v_2 versus corrected N_{trk} compared to previous minimum-bias pp results @ 5 and 13 TeV

⇒reminder: no √s dependence observed



⇒ Z-tagged p_T-integrated v_2 8±6% higher than in minimum-bias pp collisions

⇒No multiplicity dependence seen

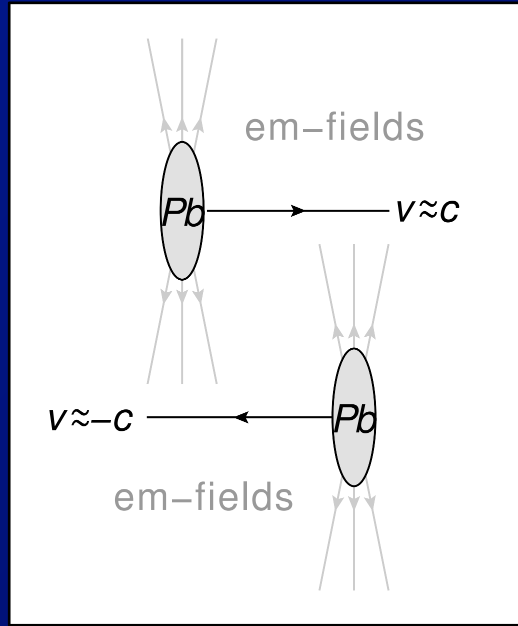
Ultra-peripheral Pb+Pb collisions

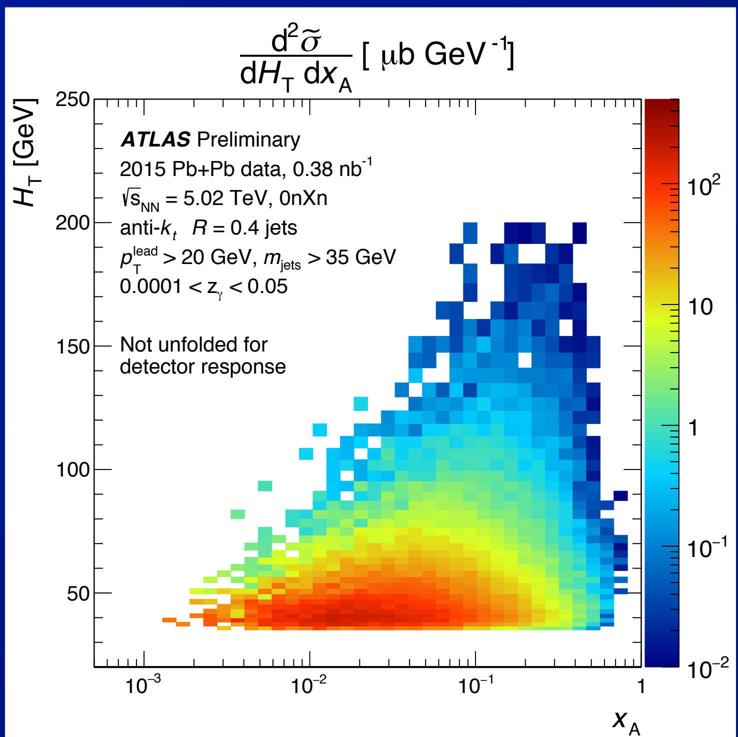
- Ultra-relativistic nuclei are sources of very strong coherent EM fields
  - Equivalently, sources of photons w/ high flux extending to >~ 50 GeV

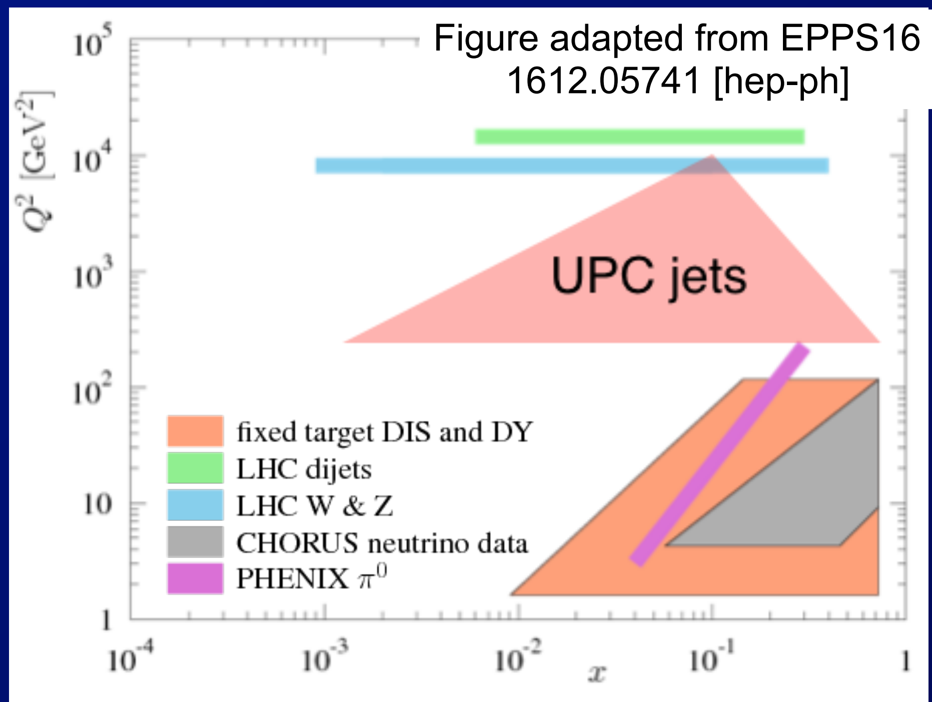
⇒ Use to probe "initial state" of Pb+Pb collisions using γ+A collisions

⇒ e.g. γ+A→di-/multi-jets

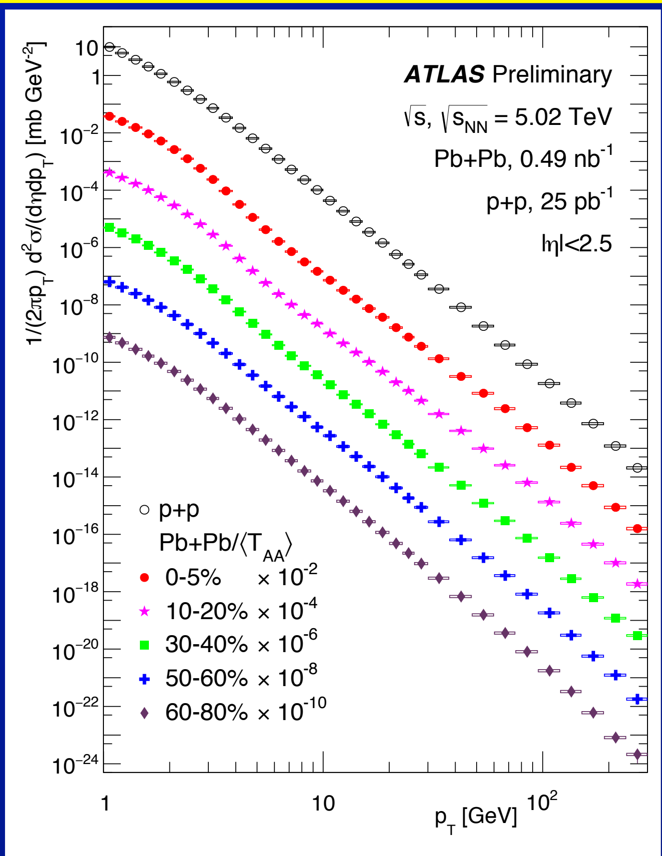
» probe nuclear PDFs

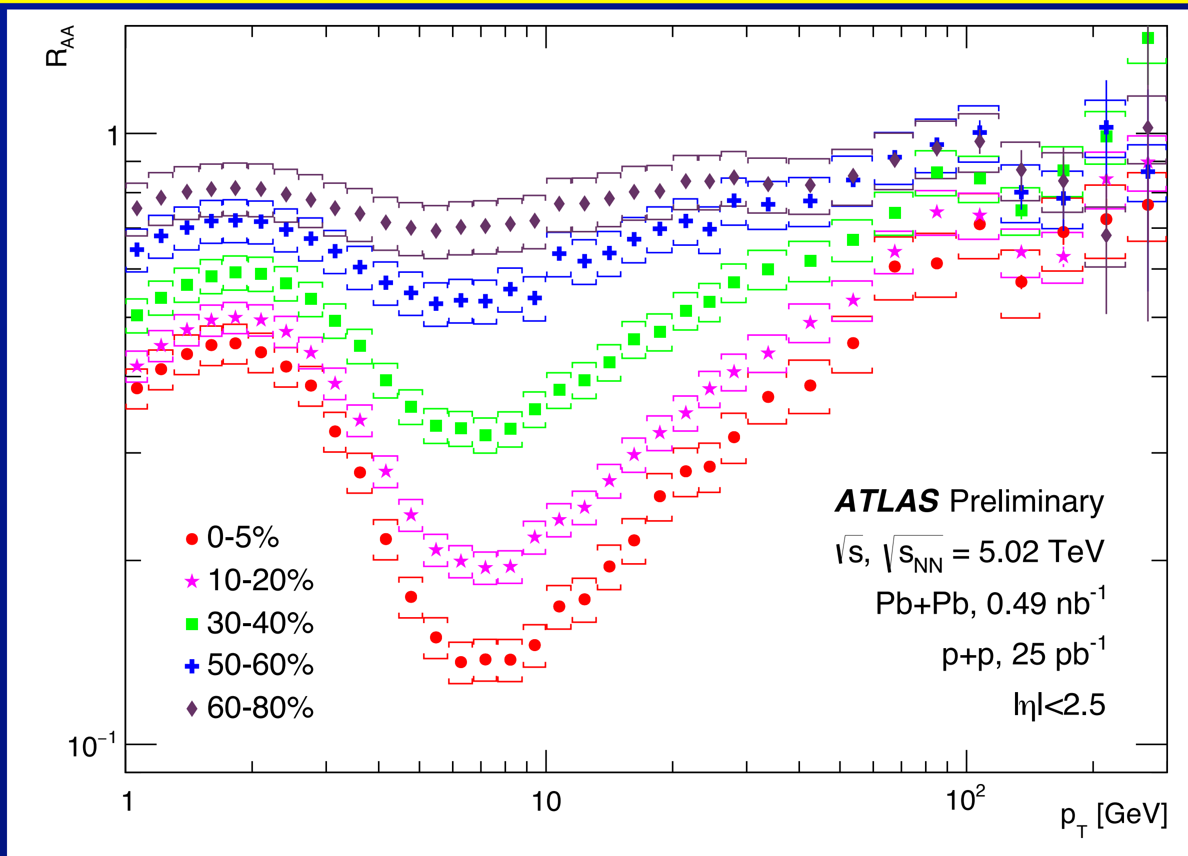






Charged hadron suppression, Pb+Pb



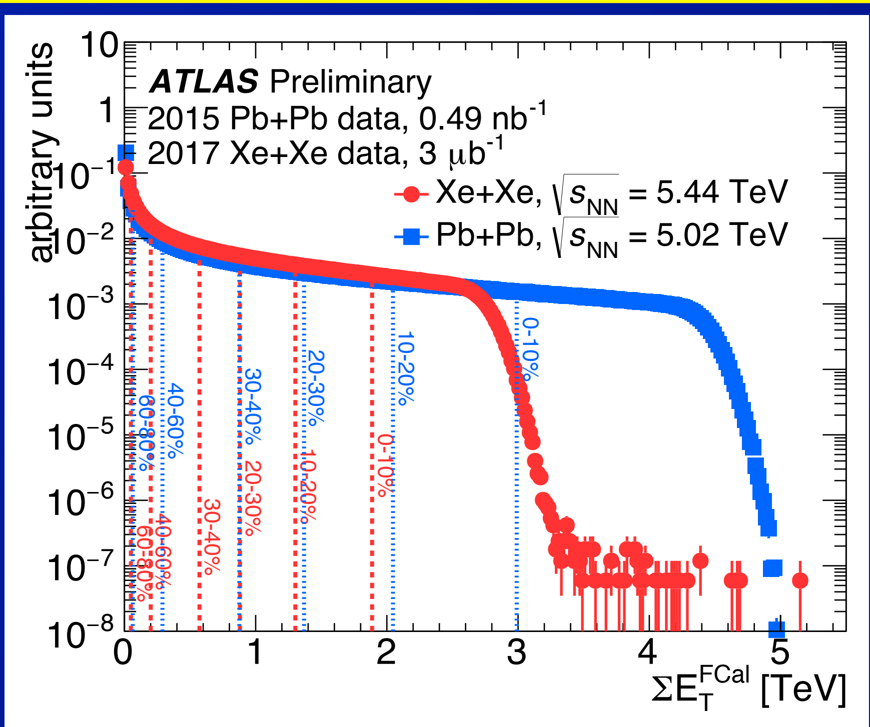


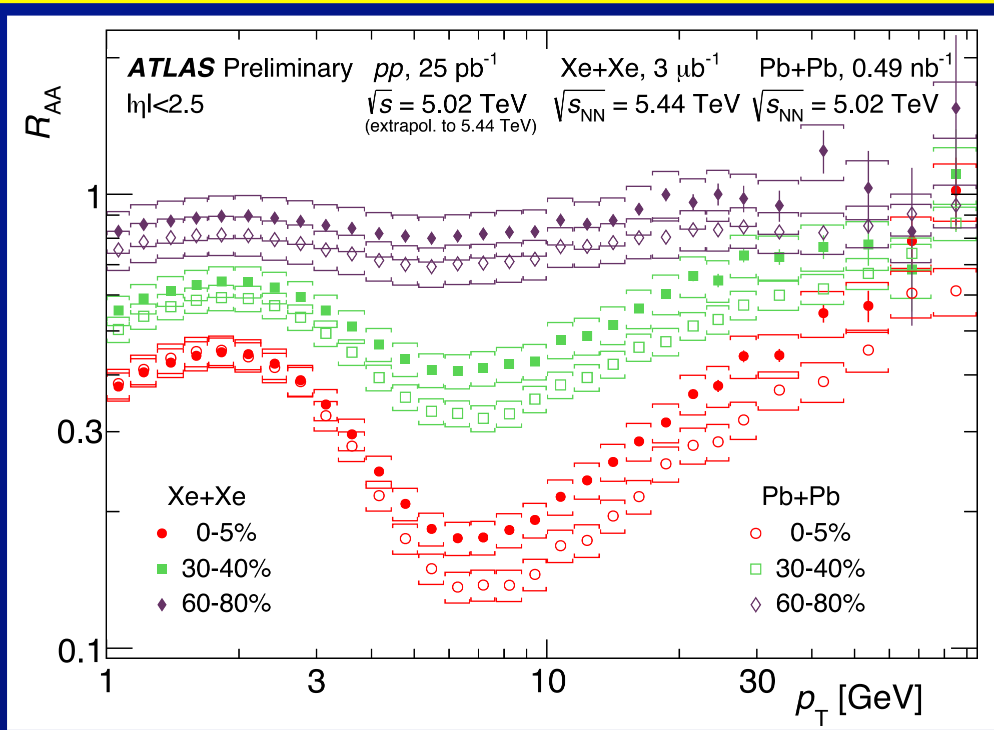
- Energy loss of hard-scattered quarks & gluons reduces the yield of high-p_T hadrons
  - Measure in Pb+Pb and pp, divide accounting for geometry → R_{AA}

⇒observe complicated p_T dependence

» collective flow @ low p_T, jet quenching @ high p_T

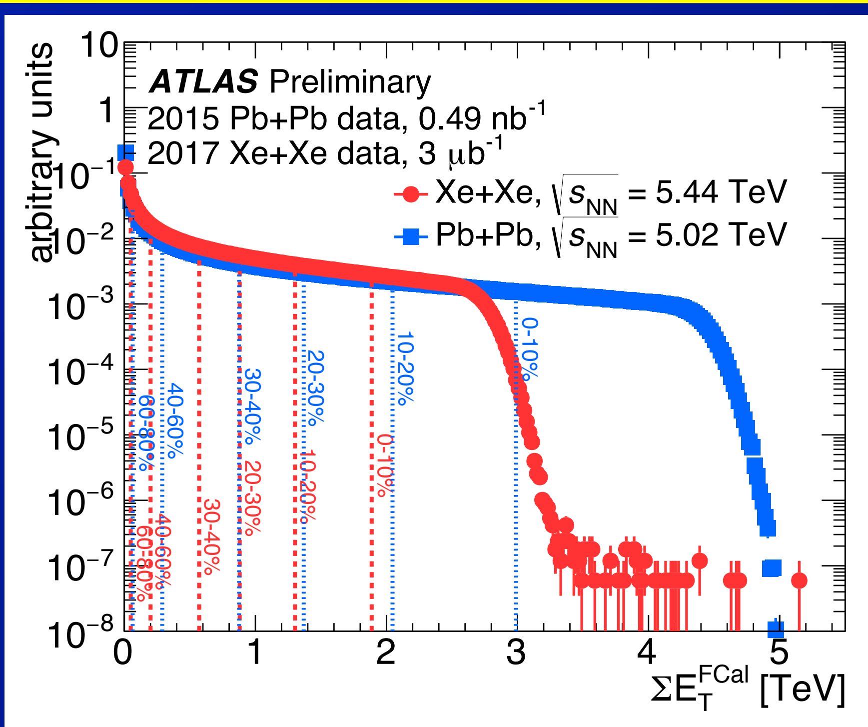
Charged hadron suppression, Pb+Pb & Xe+Xe

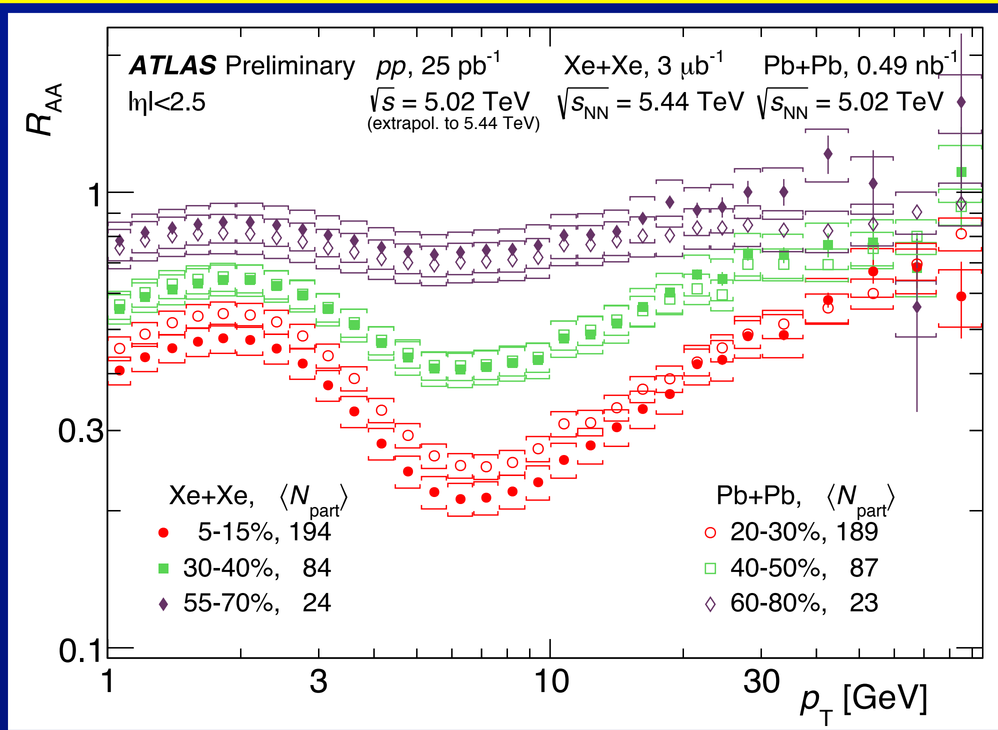




- Xe+Xe collisions produce smaller (transversely) QGP
  - and produce fewer particles (less $\sum E_T$)
- If Pb+Pb, Xe+Xe are matched at the same centrality:
  - ⇒ observe more suppression in Pb+Pb than in Xe+Xe
    - » not surprising

Charged hadron suppression, Pb+Pb & Xe+Xe

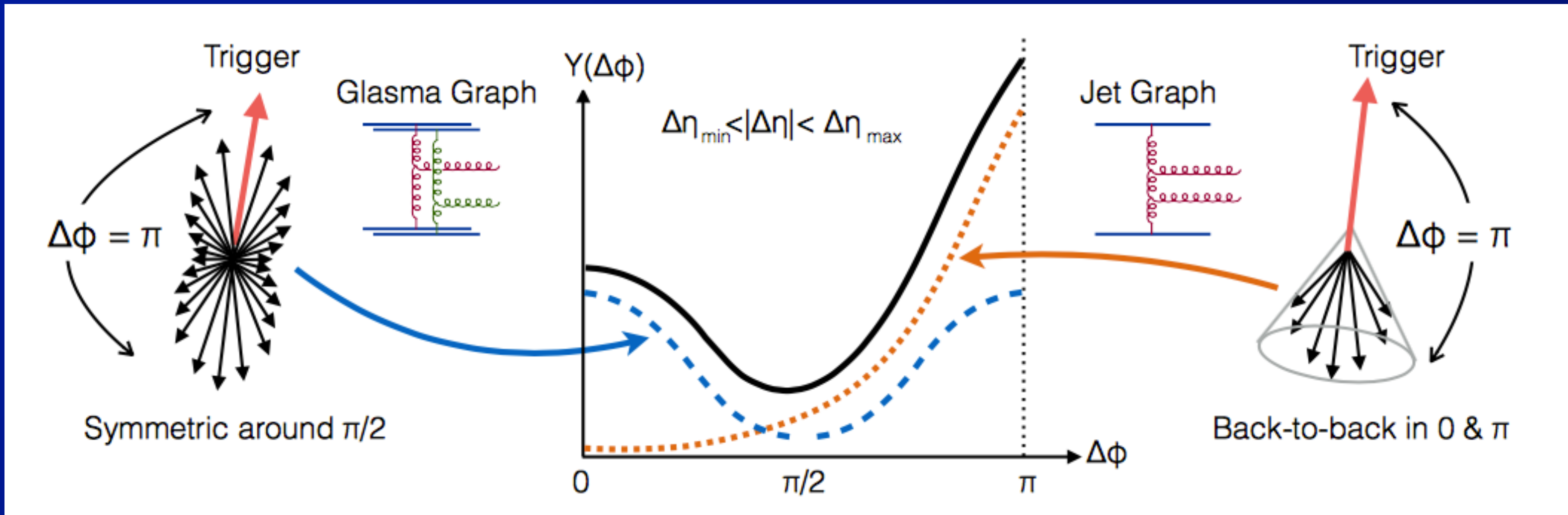




- Xe+Xe collisions produce smaller (transversely) QGP
  - and produce fewer particles (less $\sum E_T$)
- If Pb+Pb, Xe+Xe are matched at the same N_{part} (~$\sum E_T$):
  - ⇒ observe more suppression in Xe+Xe in central collisions
    - » likely due to isotropic (Xe+Xe) vs anisotropic (Pb+Pb) geometry
    - » needs theoretical analysis/confirmation

pp ridge: soft or (semi)hard?

- **But, what about alternatives:**
  - glasma, CGC/BEC, MPI+string interactions, …



- **More generally, can ask the question:**
  - Is there any "coupling" between ridge phenomenon and hard or semi-hard processes

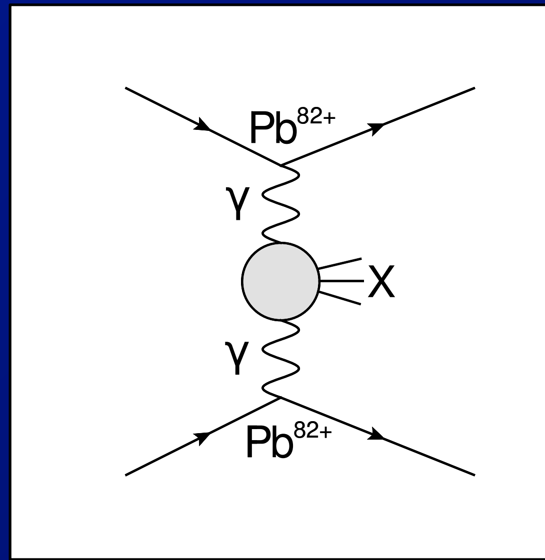
  ⇒ Study using pp events with Z production

  ⇒ Large-Q^2 process, but without back-to-back jets
  - Even if ridge reflects collectivity, does requiring a hard process change the geometry of the initial state?

Ultra-peripheral Pb+Pb collisions

- Ultra-relativistic nuclei are sources of very strong EM fields
  - Equivalently, sources of photons w/ high flux extending to >~ 50 GeV

  ⇒ Can also probe *fundamental* physics in γ+γ collisions



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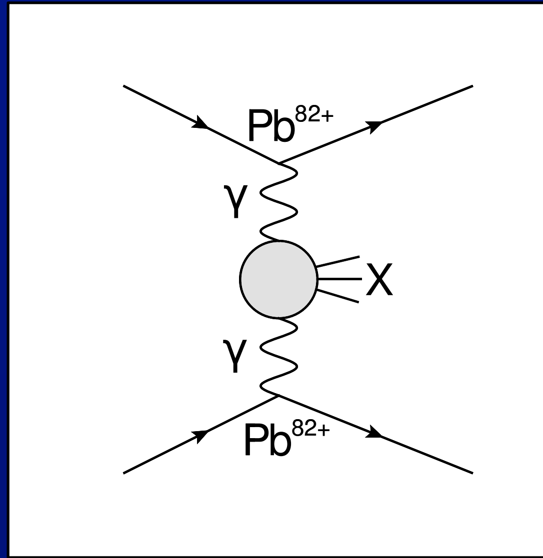
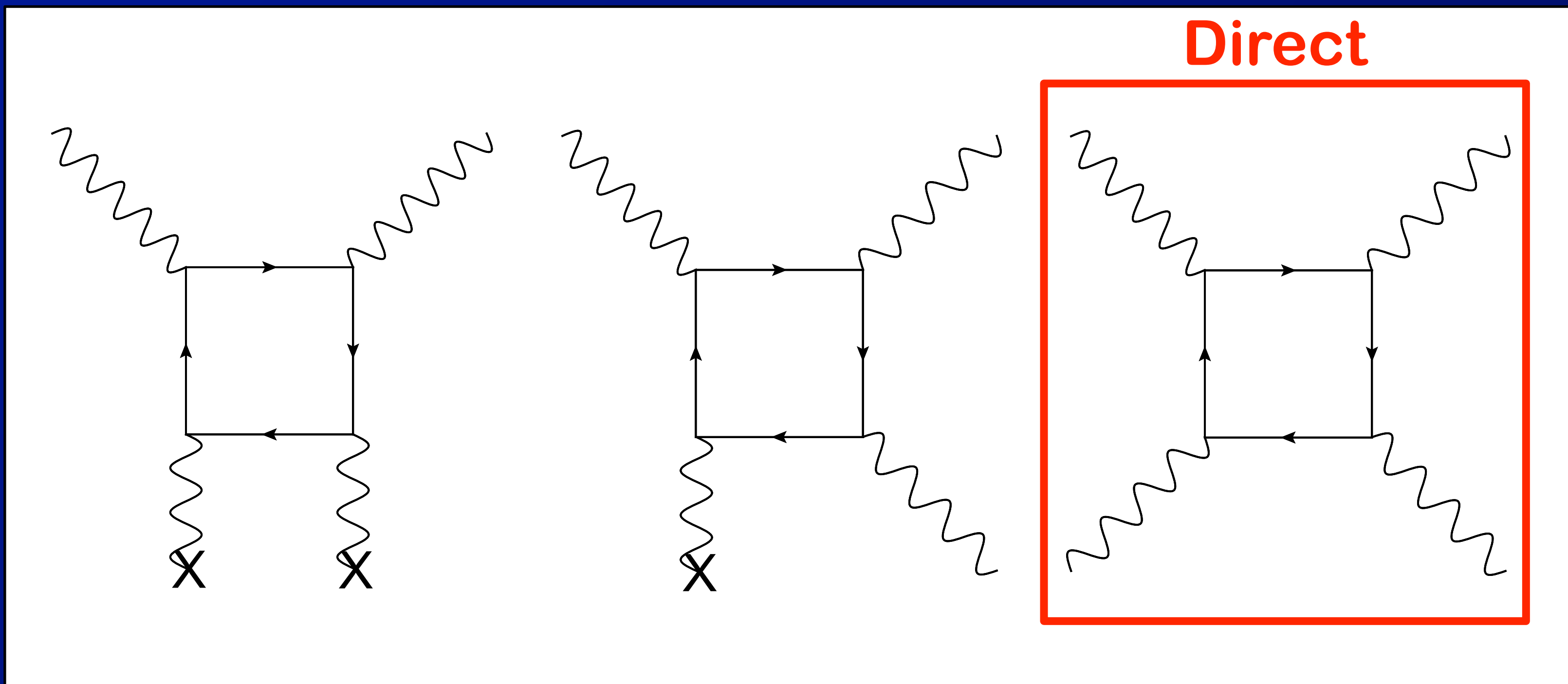
  - ⇒ e.g. γ+γ → γ+γ, AKA light-by-light





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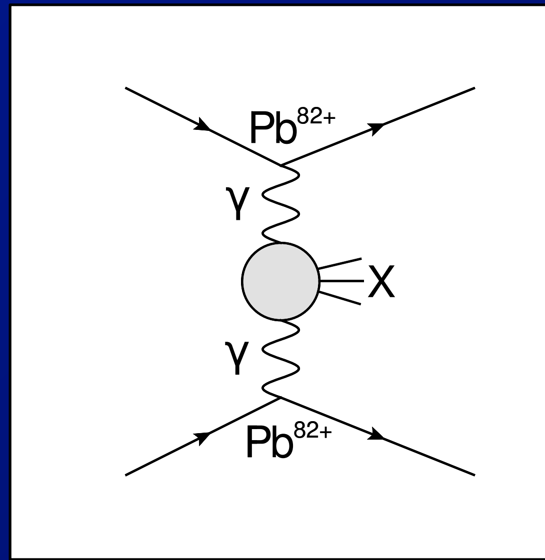
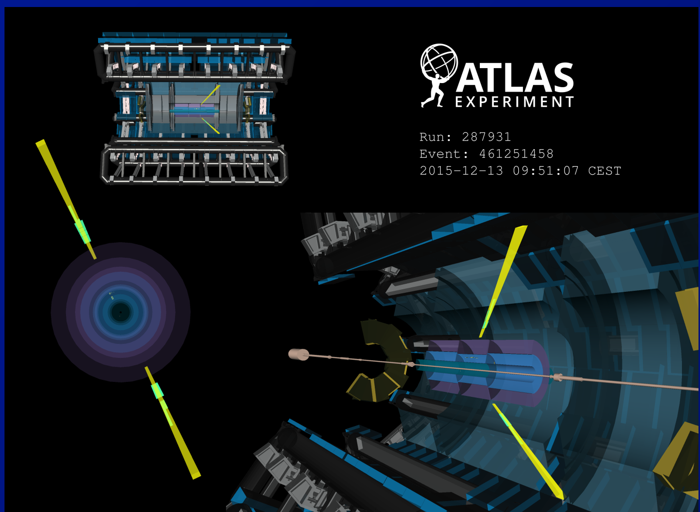
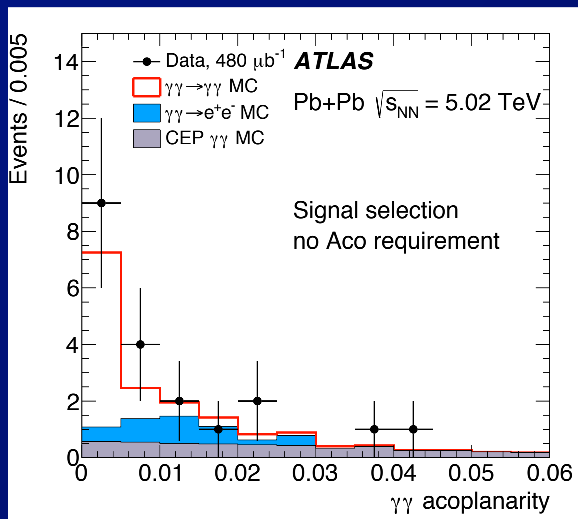
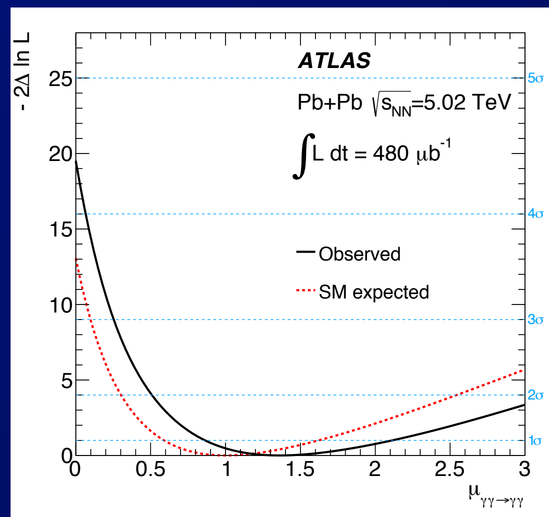


- **ATLAS performed first measurement of direct L-by-L**
  - ⇒ Nature Physics 13 (2017) 852:





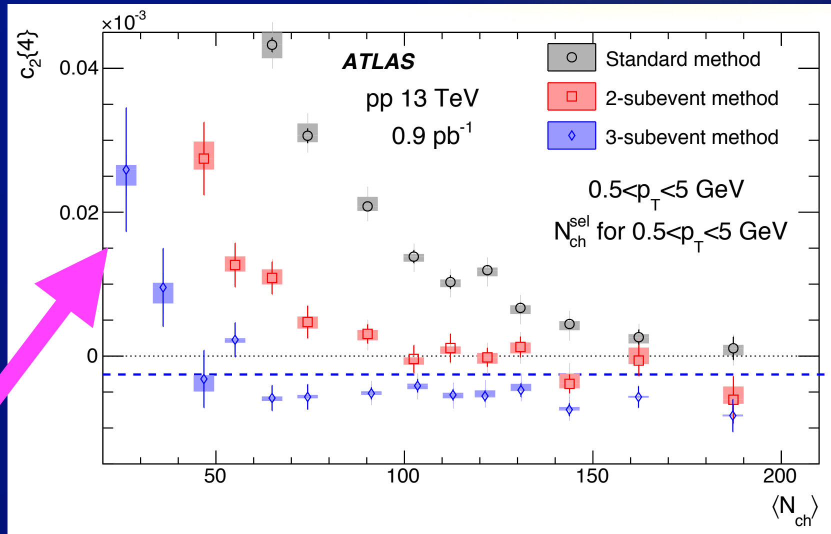


Multi-particle correlations: pp, p+Pb

- >2 particle correlations (e.g. 4) important for showing global azimuthal correlations in pp, p+Pb
  - but problems with “non-flow” (hard) contamination

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

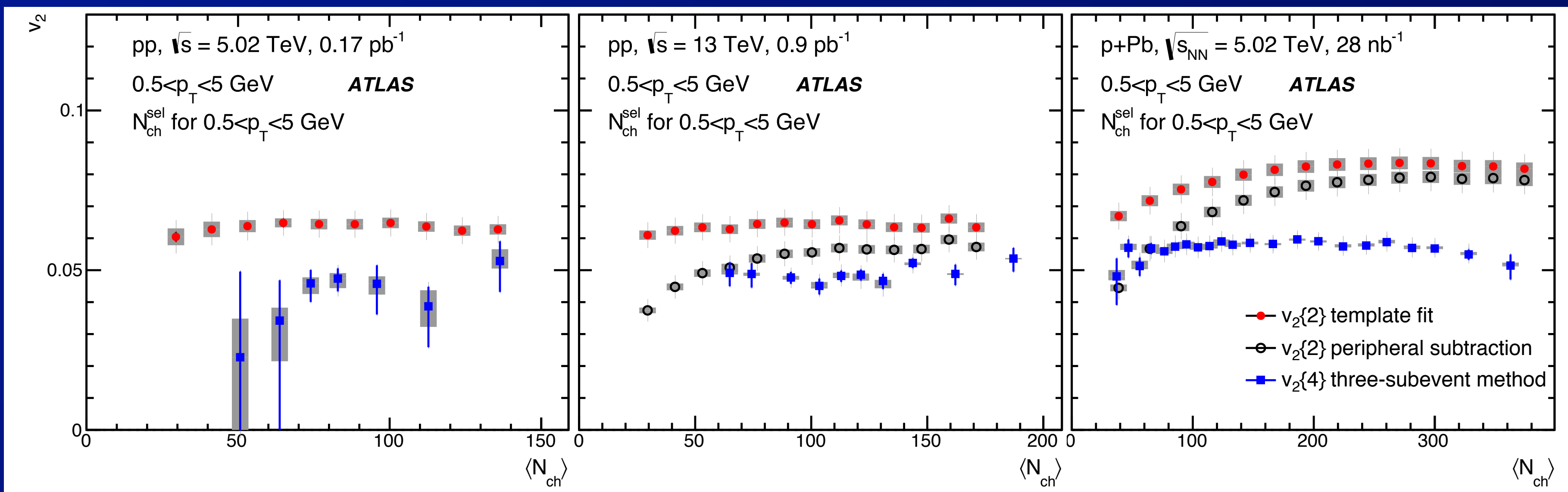
  ⇒ positive $c_2\{4\}$



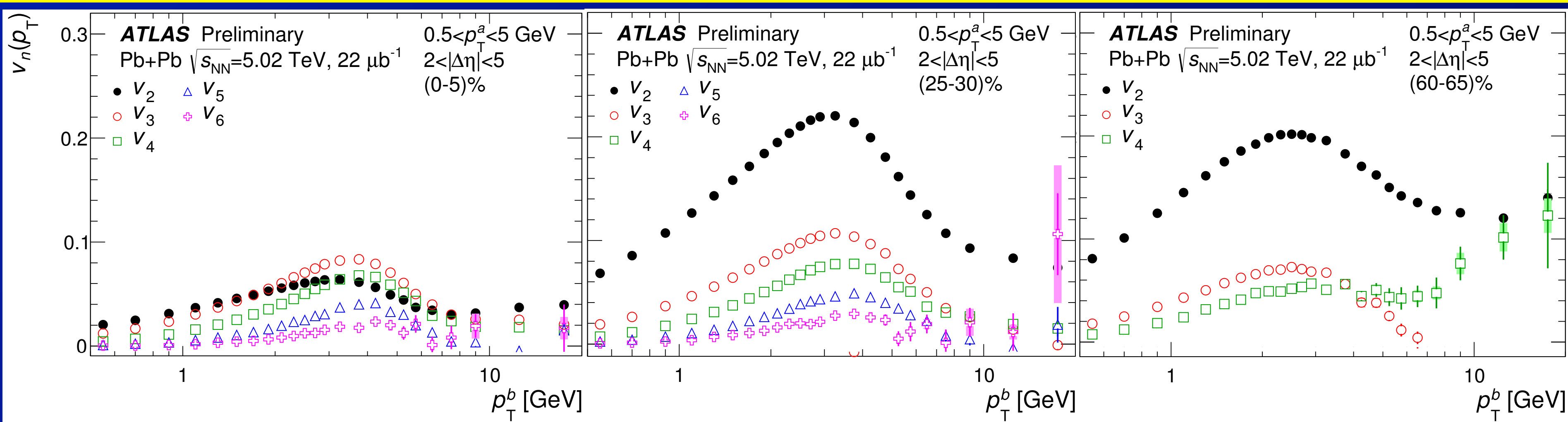
- Recent progress using sub-event cumulants
  - *a al* J. Jia ()

  ⇒ N_{ch} - independent $c_2\{4\}$ and v_2

  » modulo residual non-flow (N_{ch} < 50)

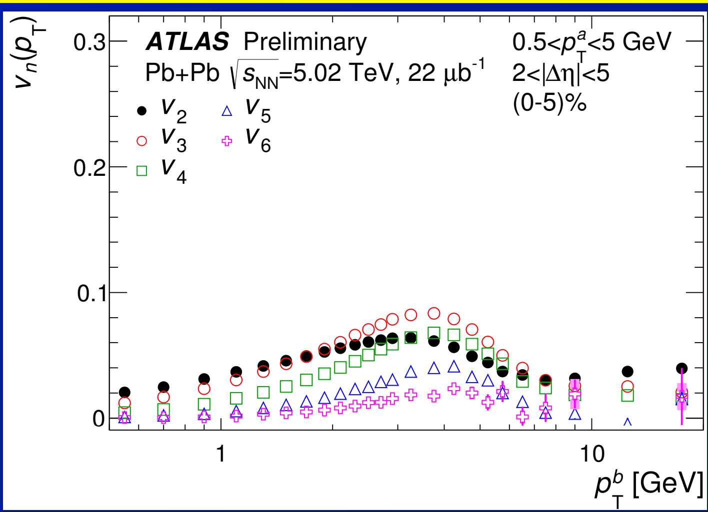


Pb+Pb v_n measurements



- p_T dependence of v_2 - v_6 for same three centralities
- Centrality evolution:

Pb+Pb v_n measurements



- p_T dependence of v_2 - v_6 for same three centralities
- Centrality evolution:
  - 0-5% (central): dominated by initial state fluctuations
    - ⇒ v_2 comparable to other v_ns

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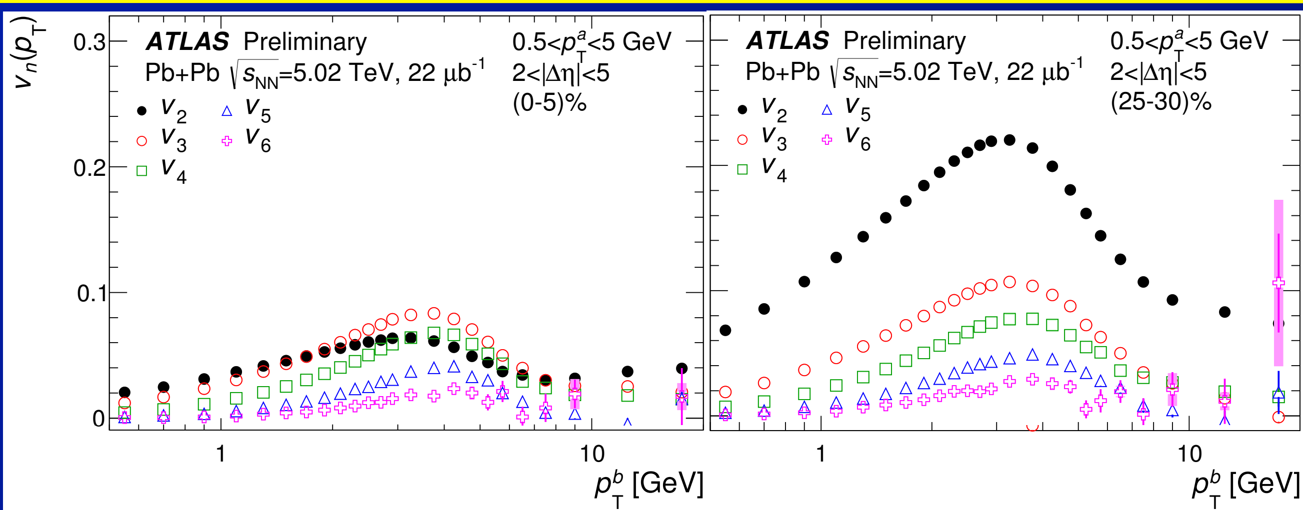

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    ⇒ v_2 larger than other v_ns

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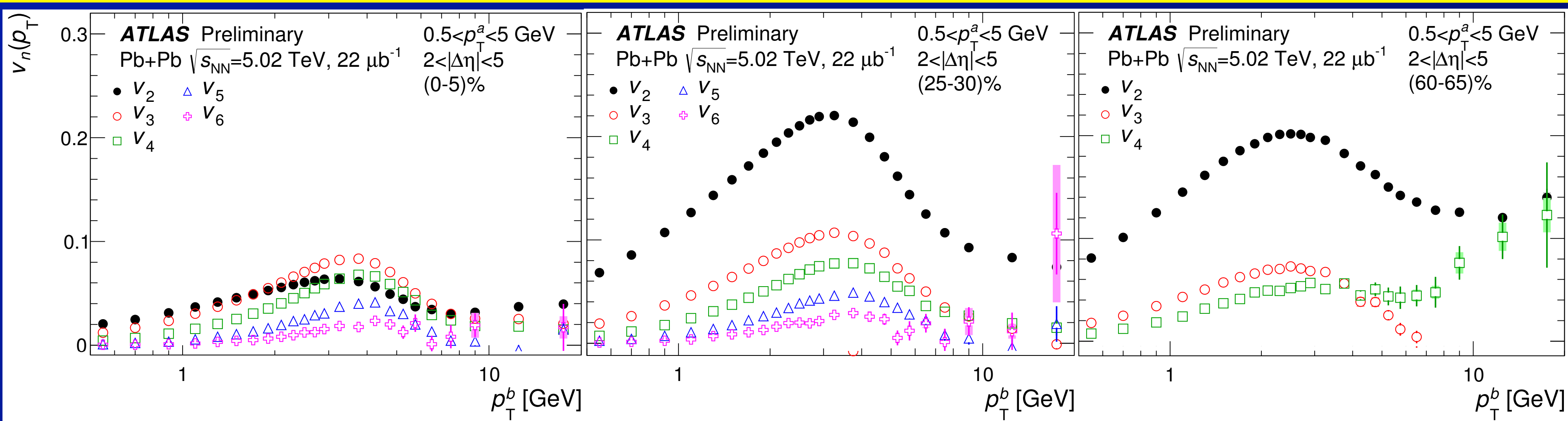

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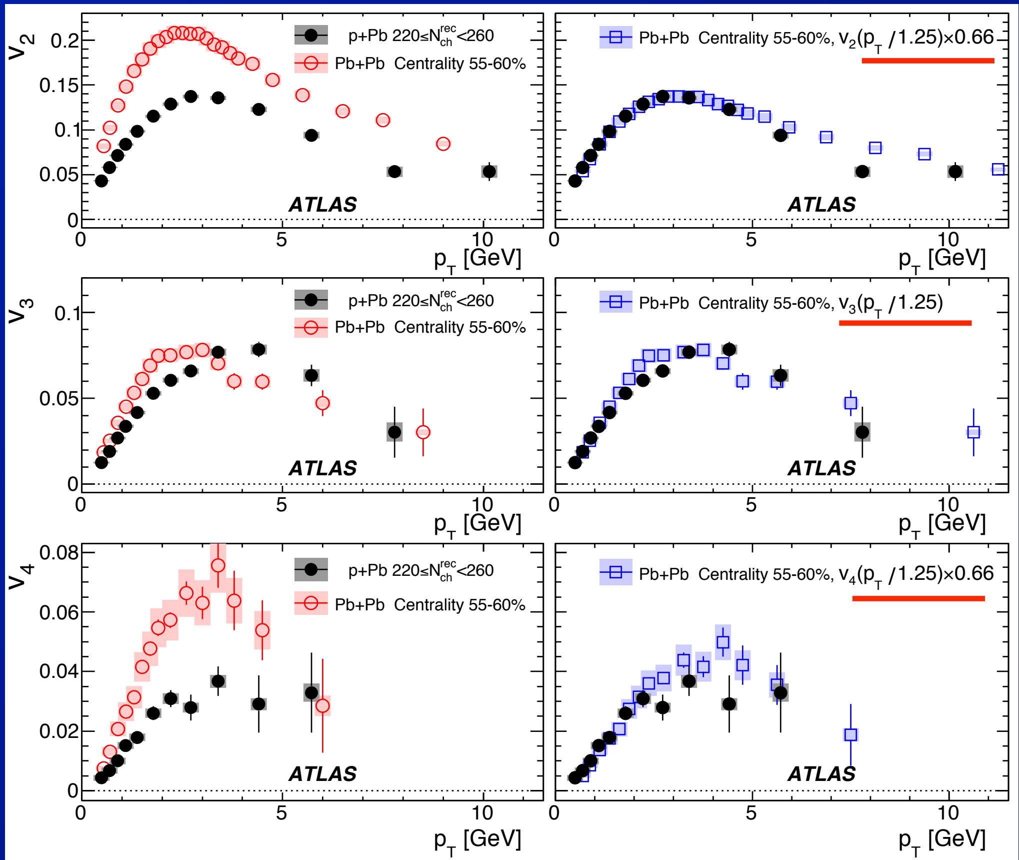
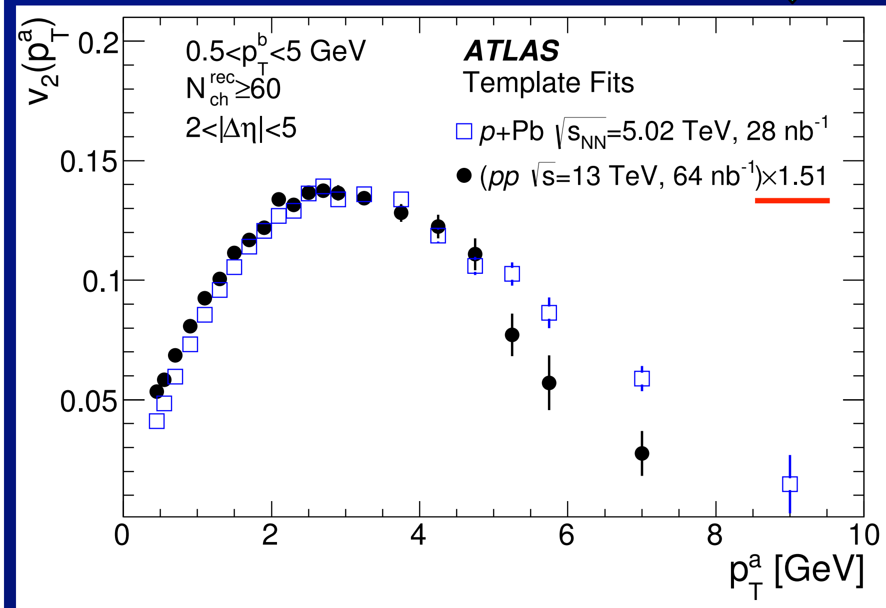
  - 25-30% (mid-central): dominated by geometry
    ⇒ v_2 larger than other v_ns
  - 60-65% (peripheral): viscous effects and “non-flow”
    ⇒ smaller v_ns @ low p_T, “problems” at high p_T

v_2 p_T dependence



p+Pb & Pb+Pb

pp & p+Pb



- When re-scaled to match maximum v_2
  - and mean p_T (for p+Pb ↔ Pb+Pb)

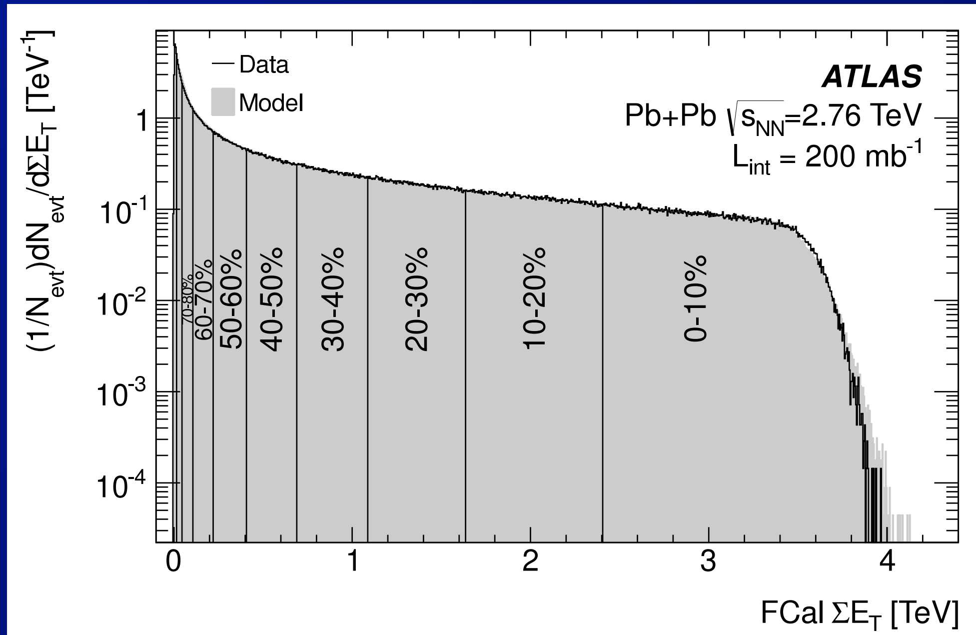
  ⇒ p_T dependence of v_n's ~ same for Pb+Pb, p+Pb, pp
- Except for pp with p_T > 5 GeV

  ⇒ where away-side peak broadens in increase N_{ch}

"Centrality" in Pb+Pb collisions

- **Procedure:**
  - Characterize A+A collision using an "extensive" quantity
  - ⇒ Multiplicity, E_T, ...

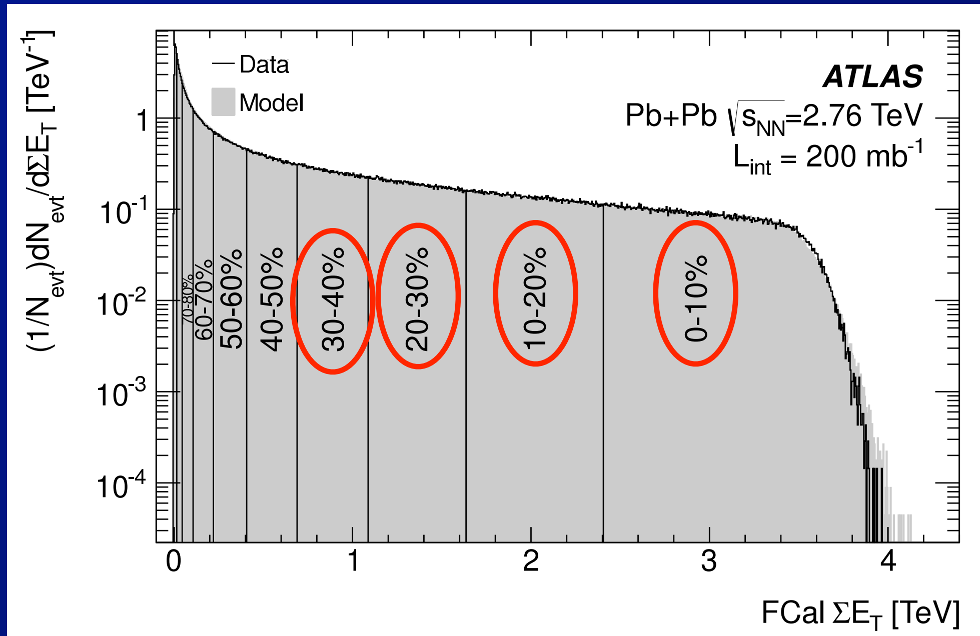
ATLAS Pb+Pb ΣE_T^{FCal}



“Centrality” in Pb+Pb collisions

- **Procedure:**
  - Characterize A+A collision using an “extensive” quantity
    - ⇒ Multiplicity, E_T, ...
  - Divide distribution into percentiles.

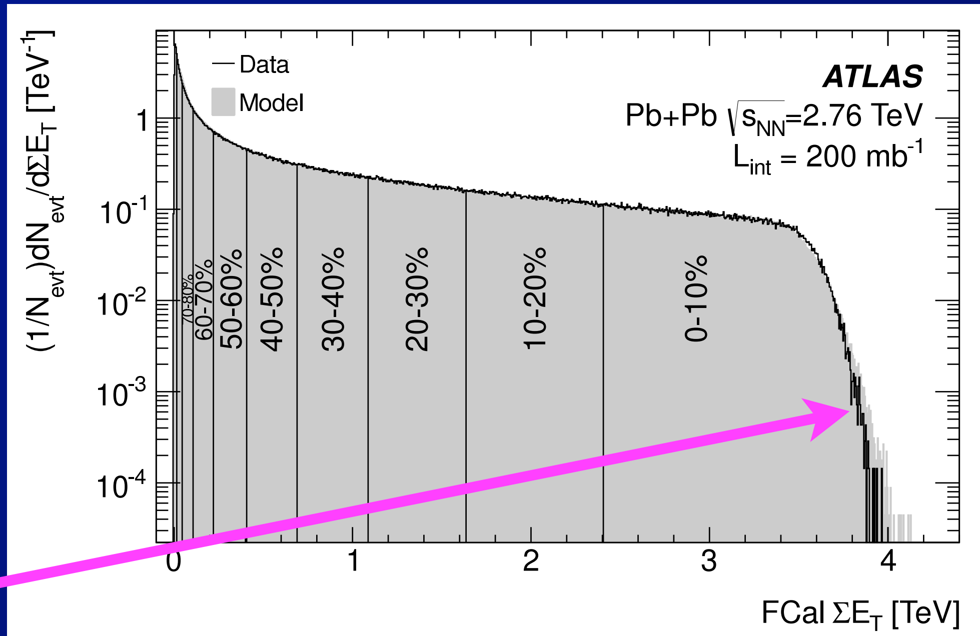
ATLAS Pb+Pb ΣE_T^{FCal}

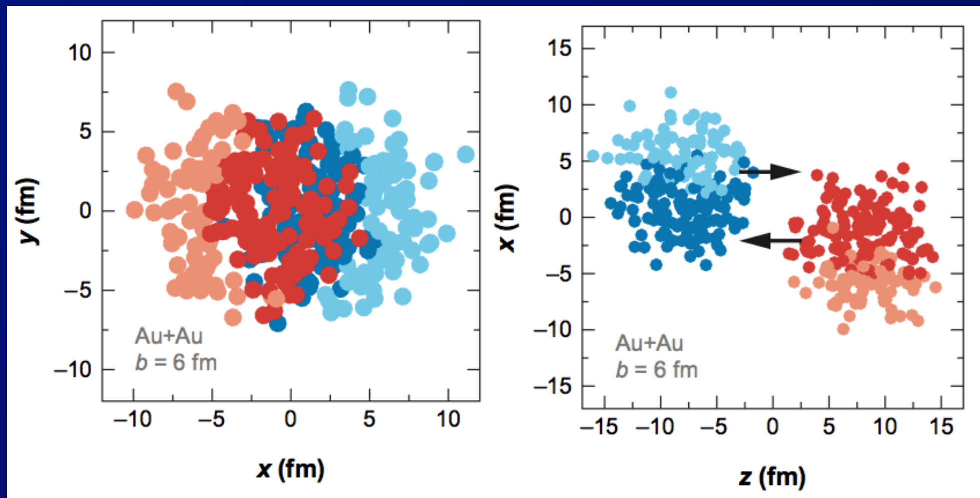


"Centrality" in Pb+Pb collisions

- **Procedure:**
  - Characterize A+A collision using an "extensive" quantity
  - ⇒ Multiplicity, E_T, …
  - Divide distribution into percentiles.
  - Perform Glauber model convolution of p-p to "fit" Pb+Pb distribution

ATLAS Pb+Pb ΣE_T^{FCal}

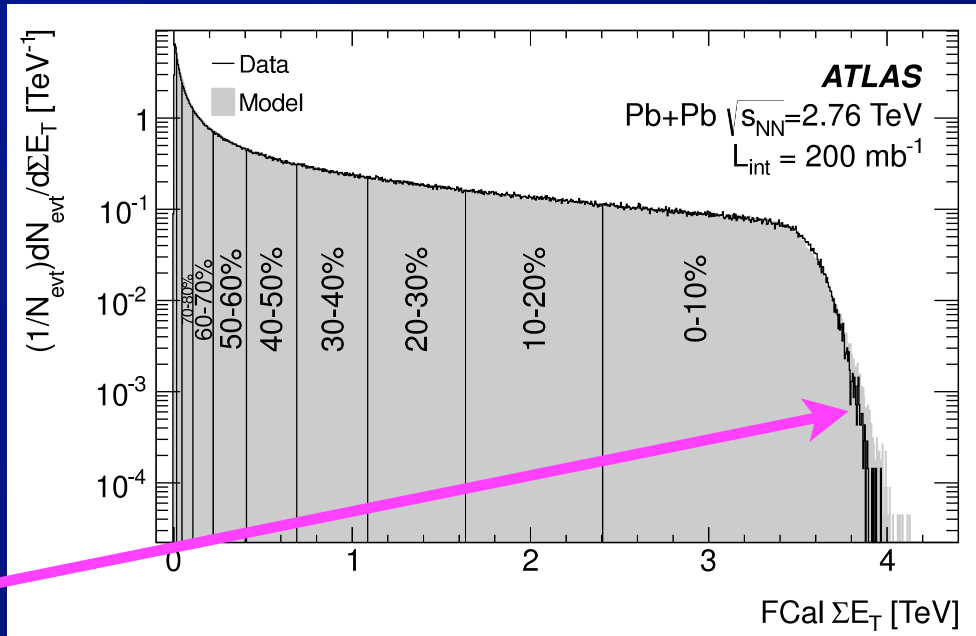


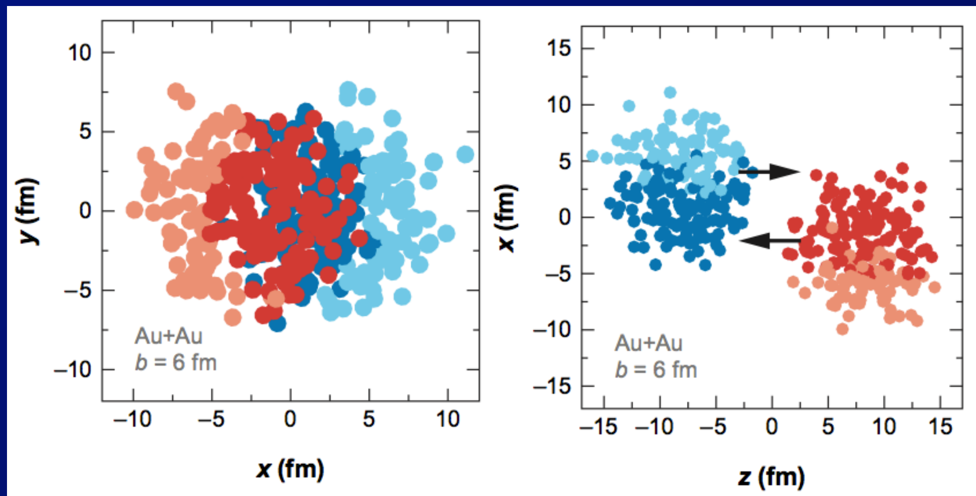


“Centrality” in Pb+Pb collisions

- **Procedure:**
  - Characterize A+A collision using an “extensive” quantity
    - ⇒ Multiplicity, E_T, …
  - Divide distribution into percentiles.
  - Perform Glauber model convolution of p-p to “fit” Pb+Pb distribution
  - Extract
    - ⇒ # of colliding nucleons or “participants” (N_{part})
    - ⇒ # of collisions (N_{coll})
    - ⇒ T_{AA} (nucleon luminosity)

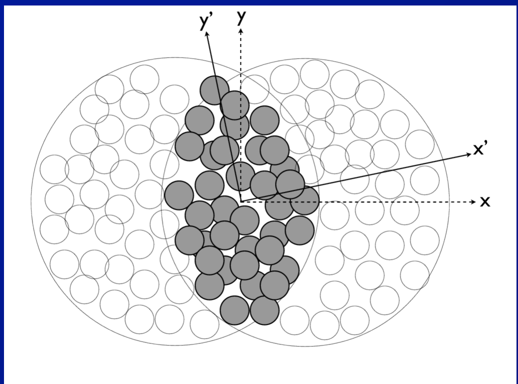
ATLAS Pb+Pb ΣE_T^{FCal}

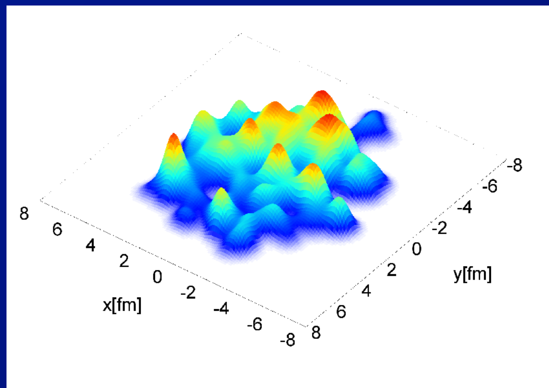


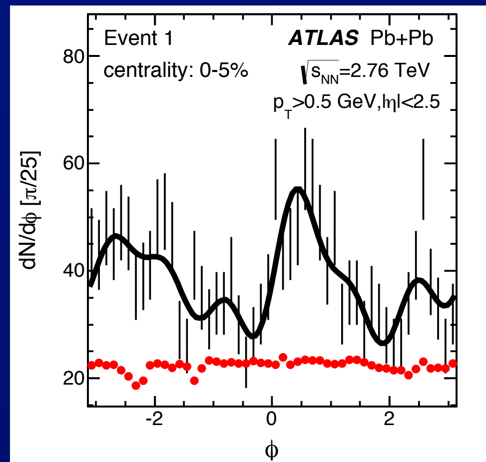


Collective dynamics: overview

- **Initial-state (transverse) anisotropies of QGP**
  - due to geometry + initial-state fluctuations
- **Get imprinted on azimuthal angle (φ) distributions of produced particles**
  - by hydrodynamic evolution of the QGP







- **Characterize by relative Fourier coefficients, v_n, and phase angles, ψ_n:**

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