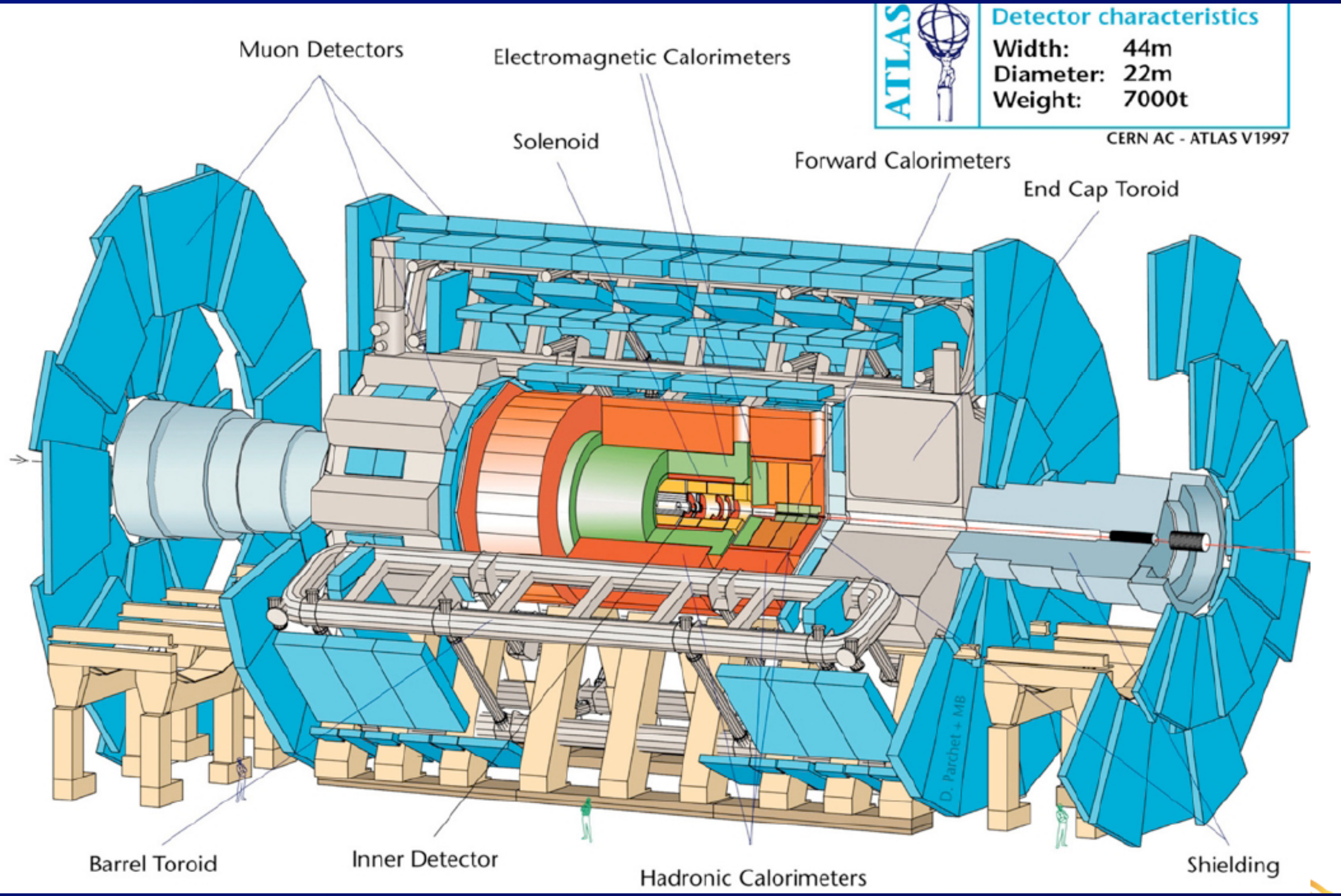
Thoughts on light ion collisions in ATLAS

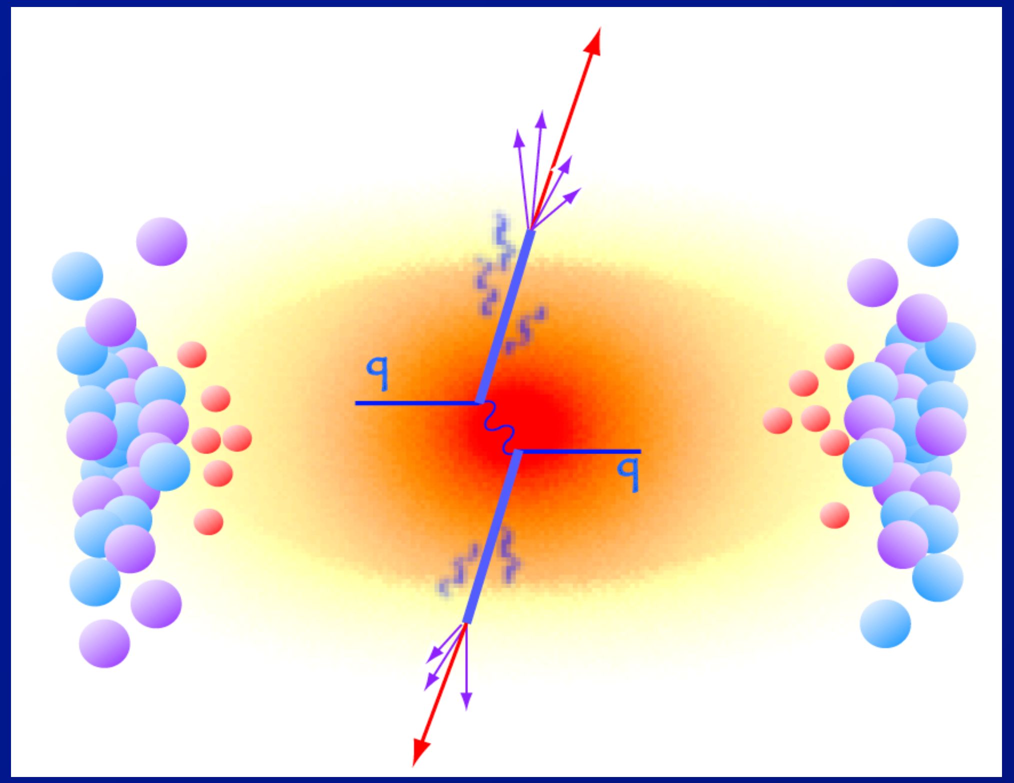
Prof. Brian Cole, Columbia University

November 13, 2024

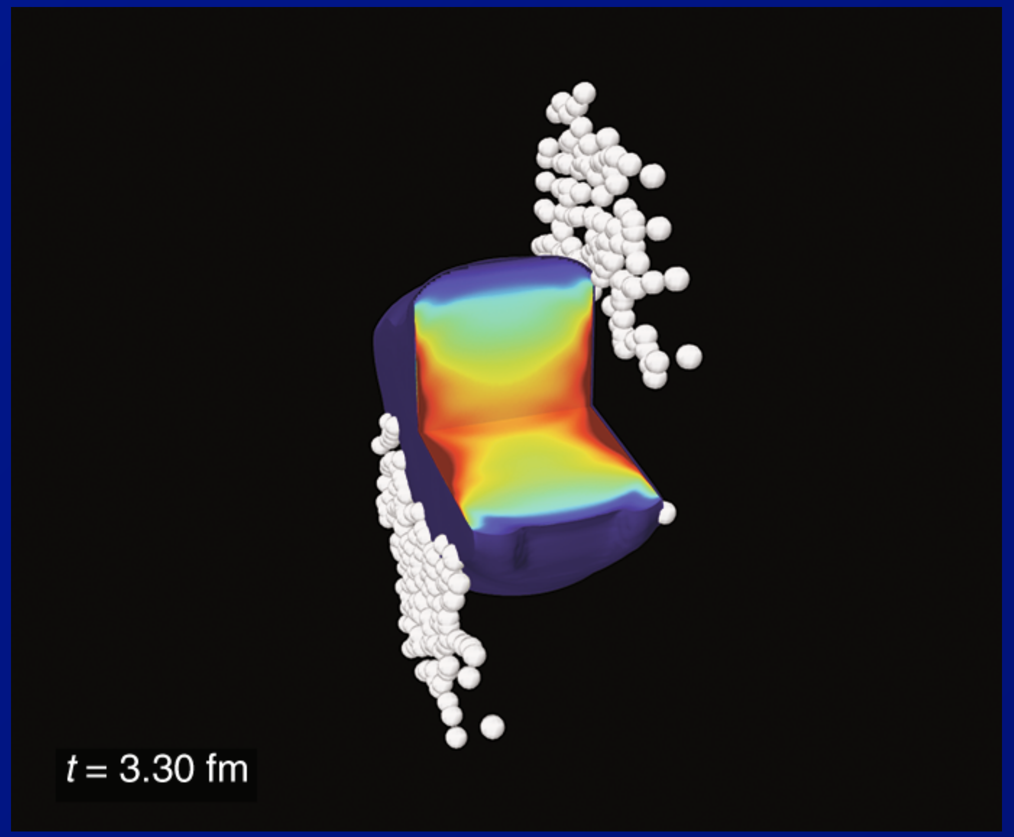


Light ion: Physics motivations

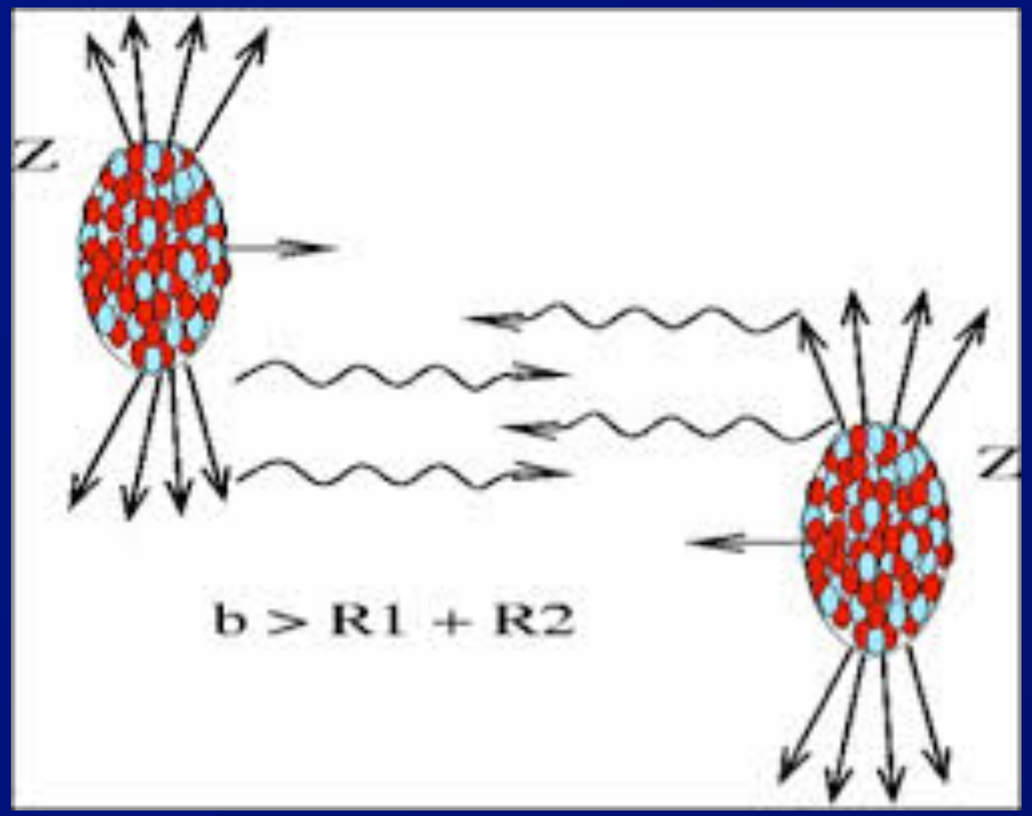
Hard scattering, jet quenching



Anisotropic Flow, Radial flow, dn/dη



Ultra-peripheral collisions



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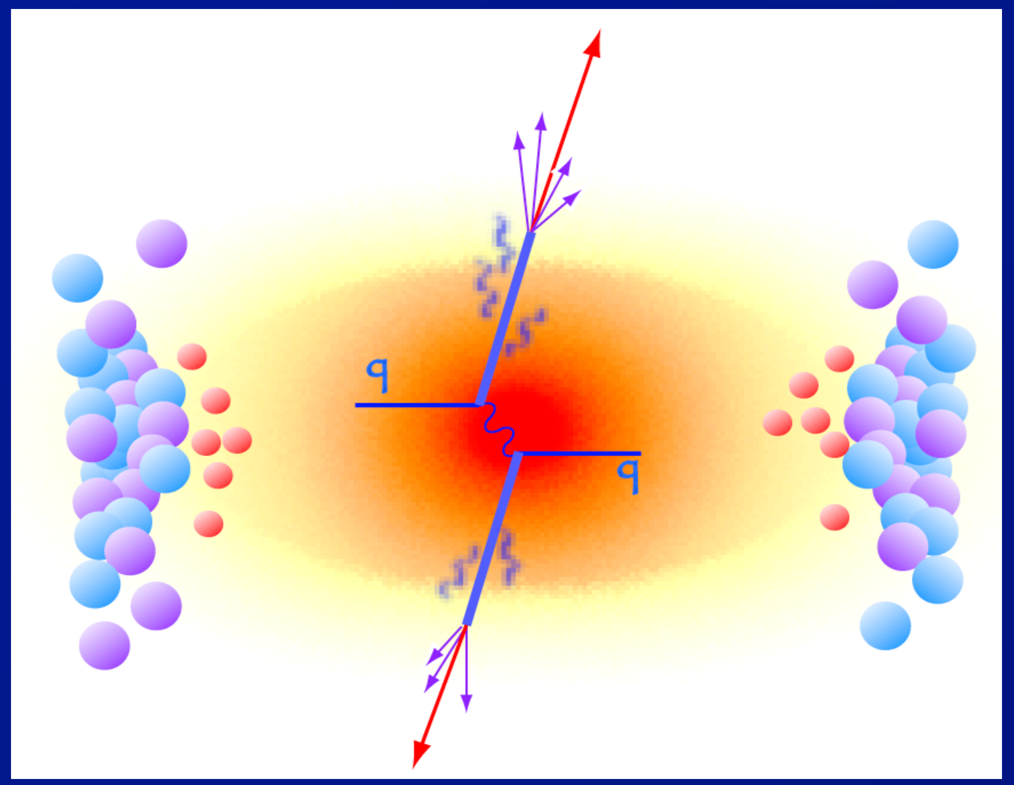

Transverse size dependence of QGP phenomena

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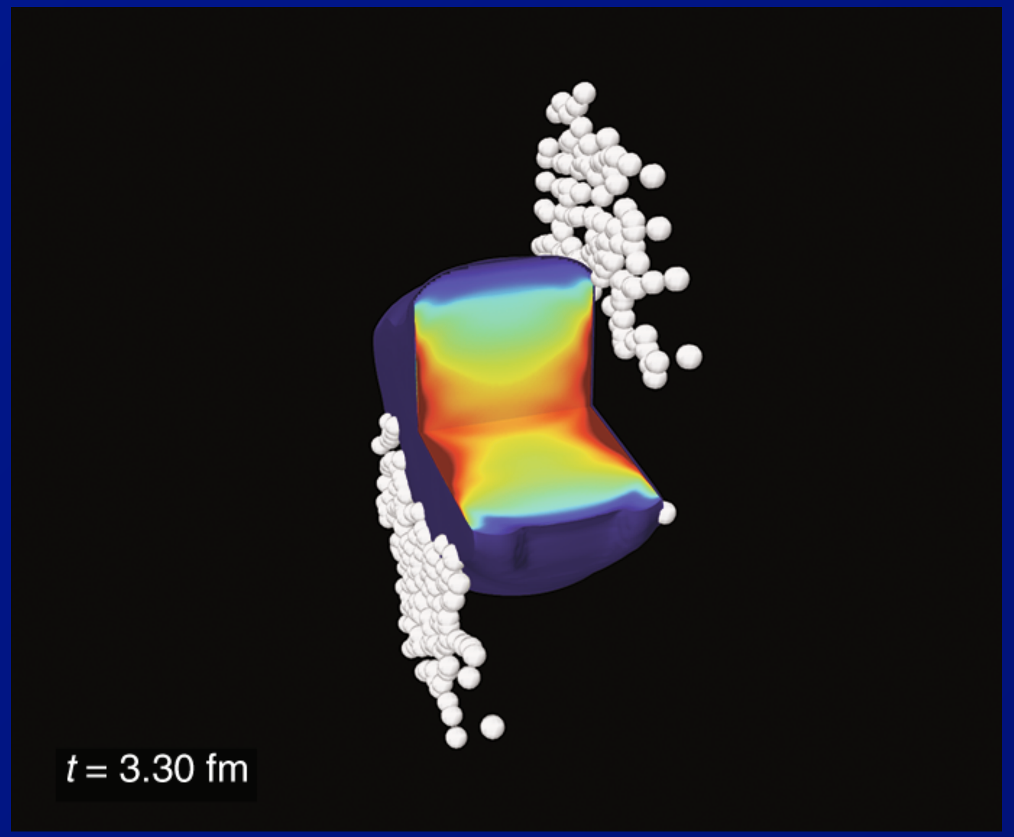

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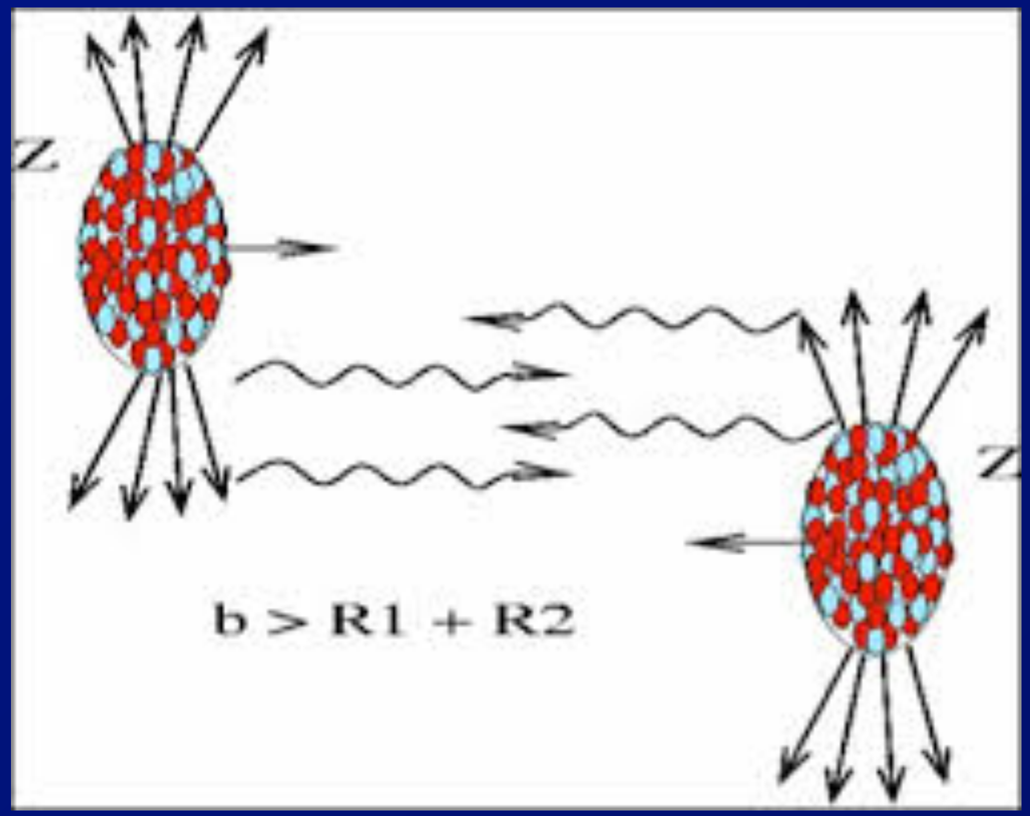

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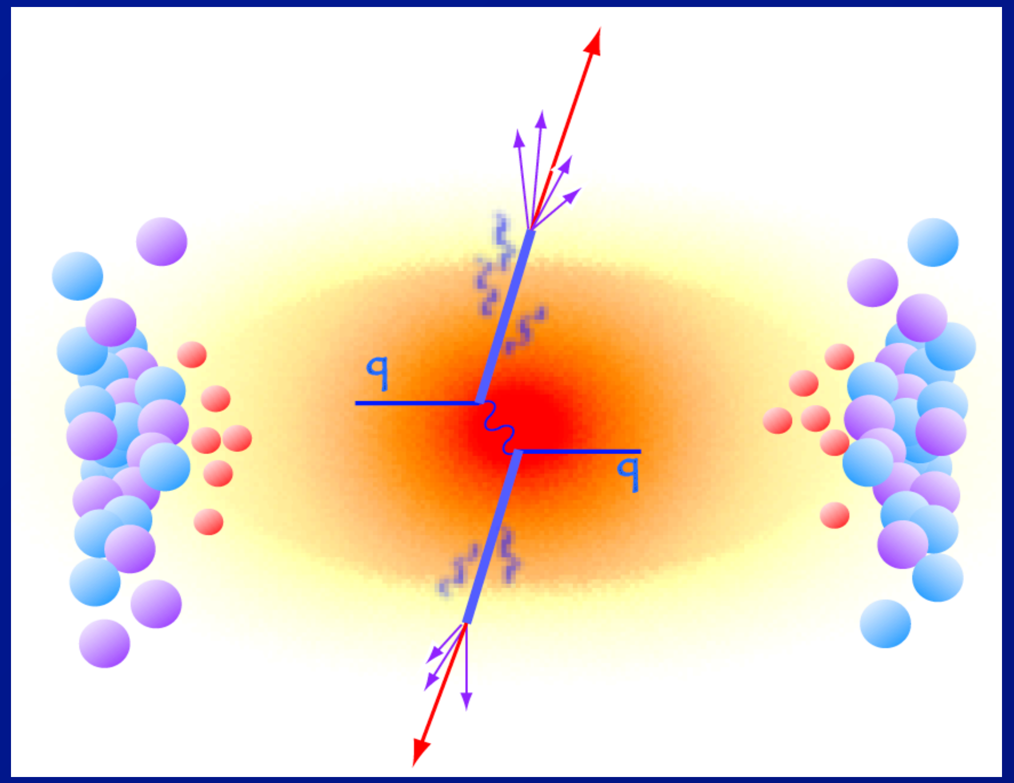

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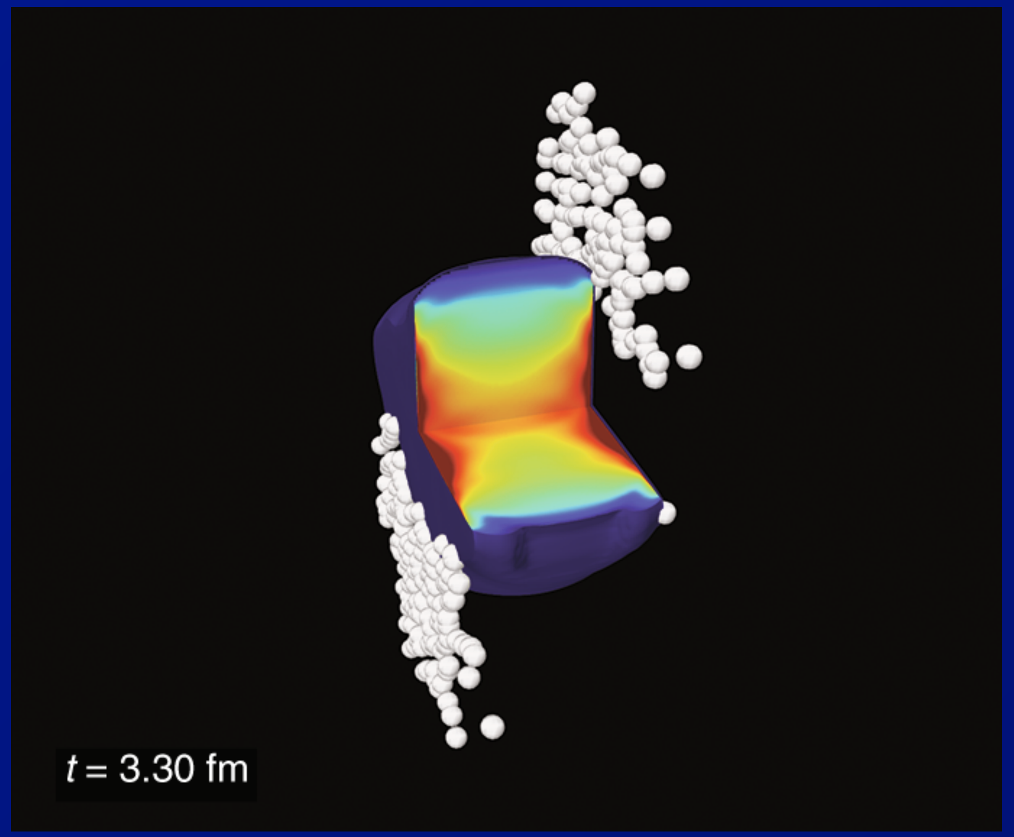

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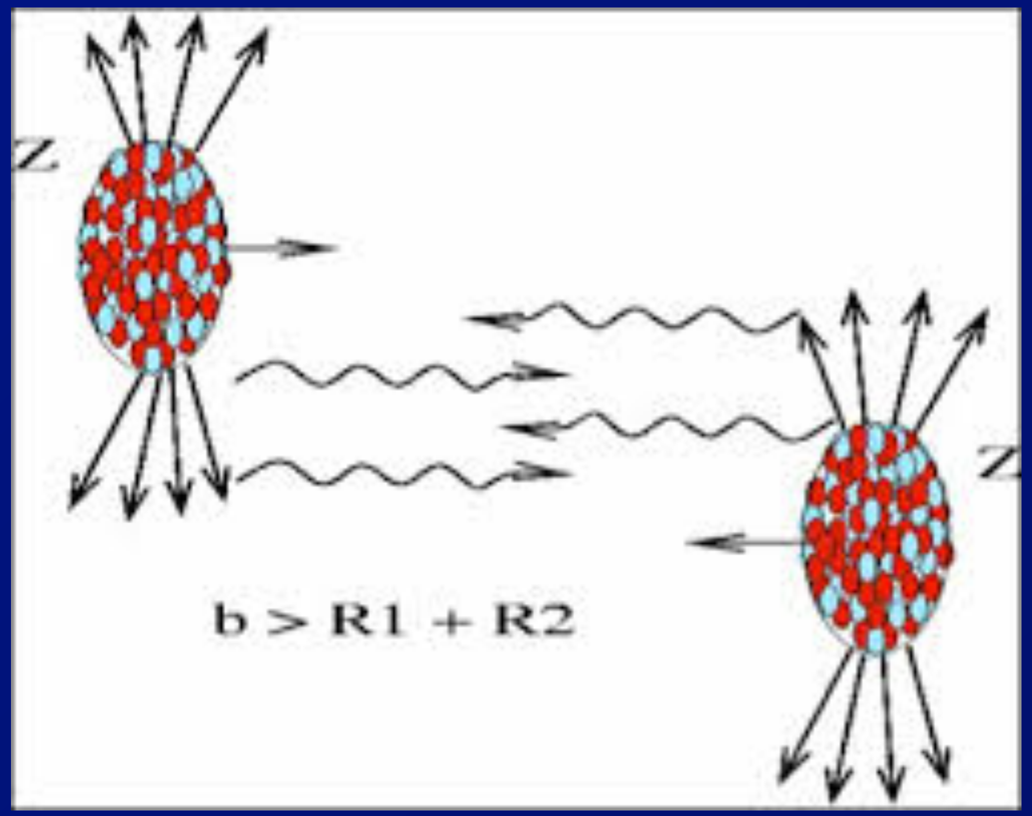

Initial-state
fluctuations
and thermalization

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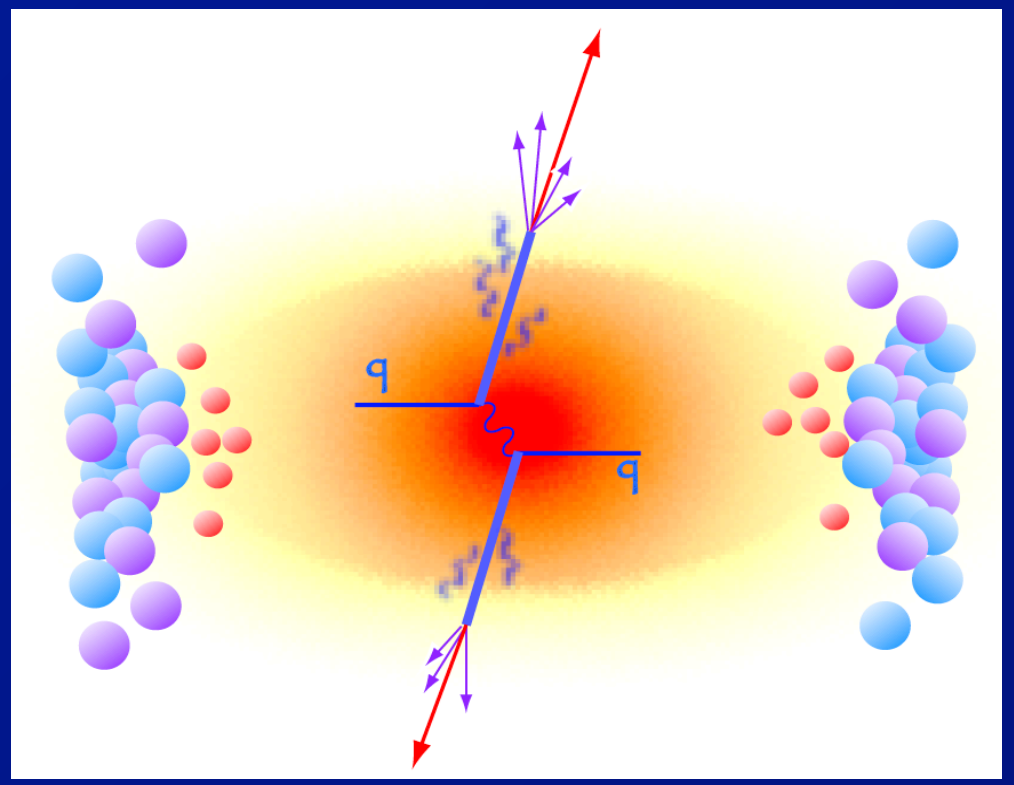

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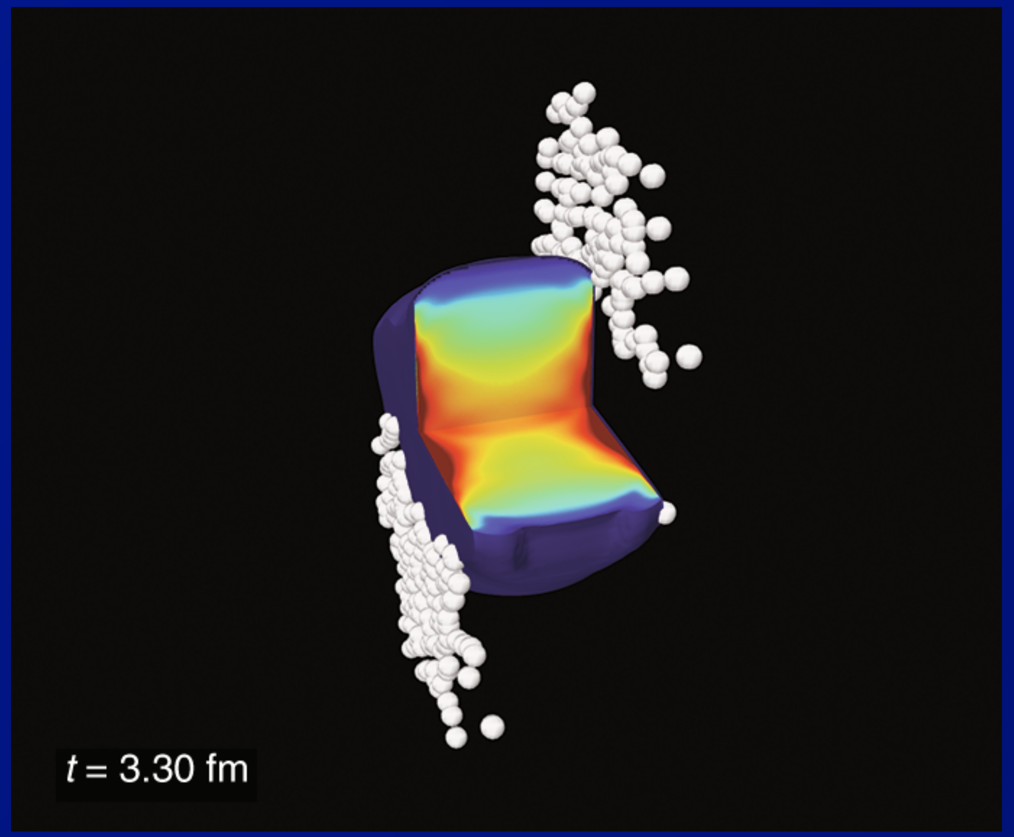

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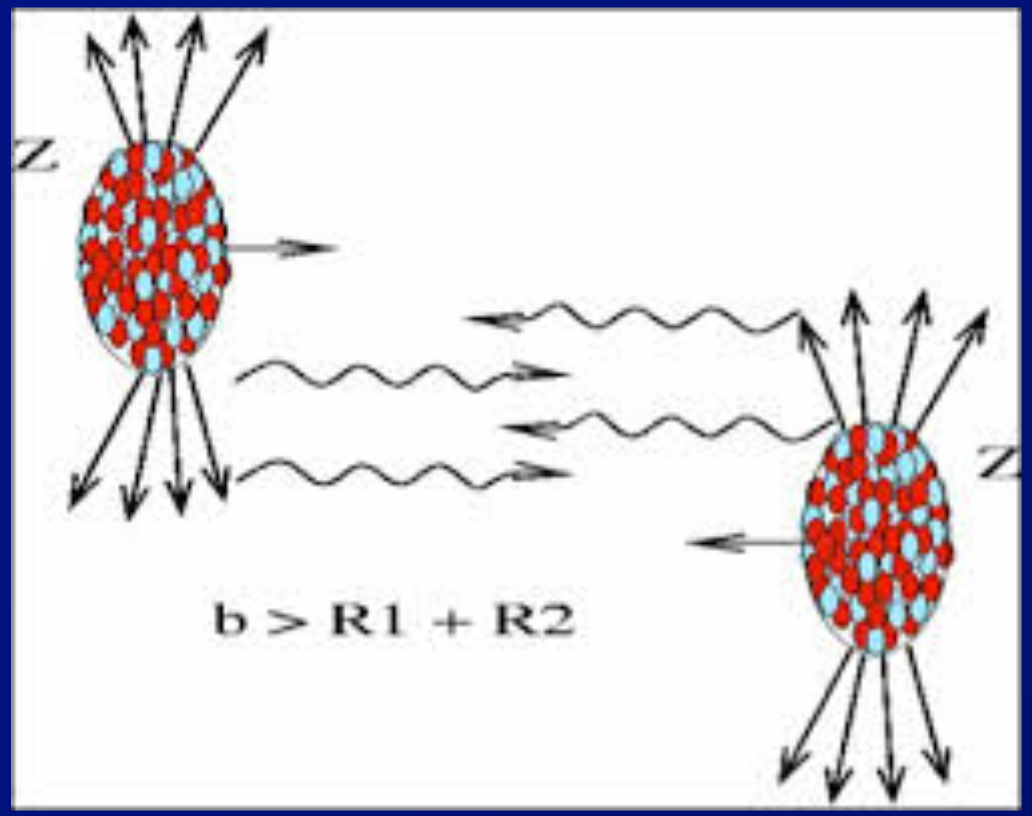

High-energy probes
of nuclear structure

Light ion: Physics motivations

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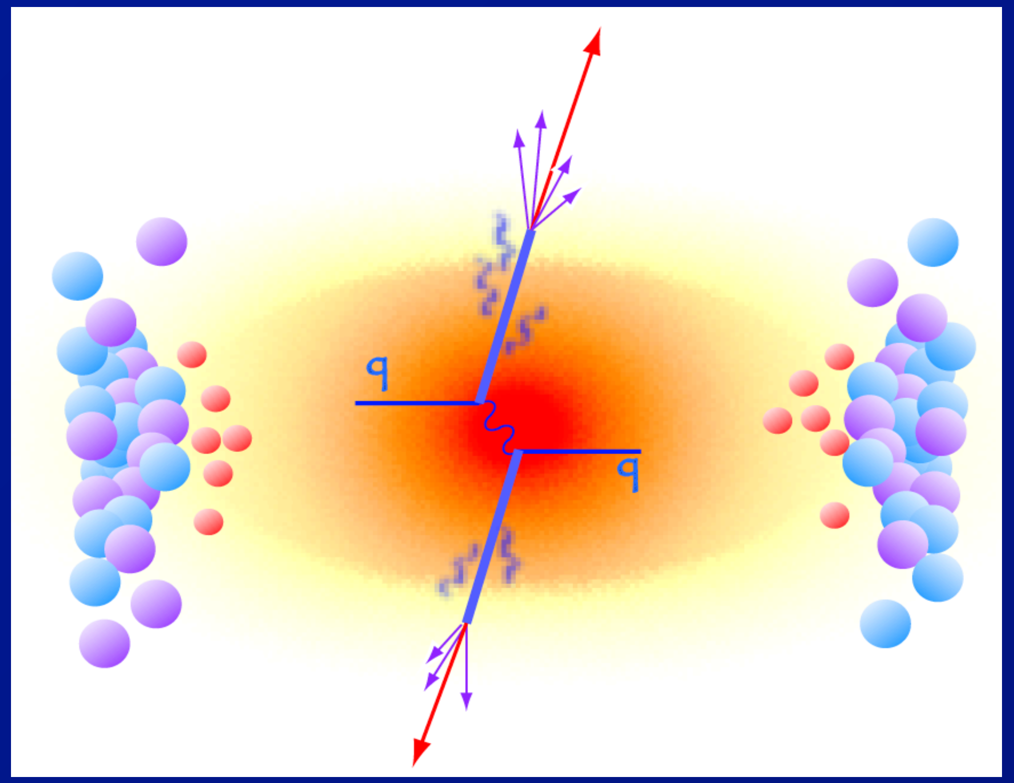

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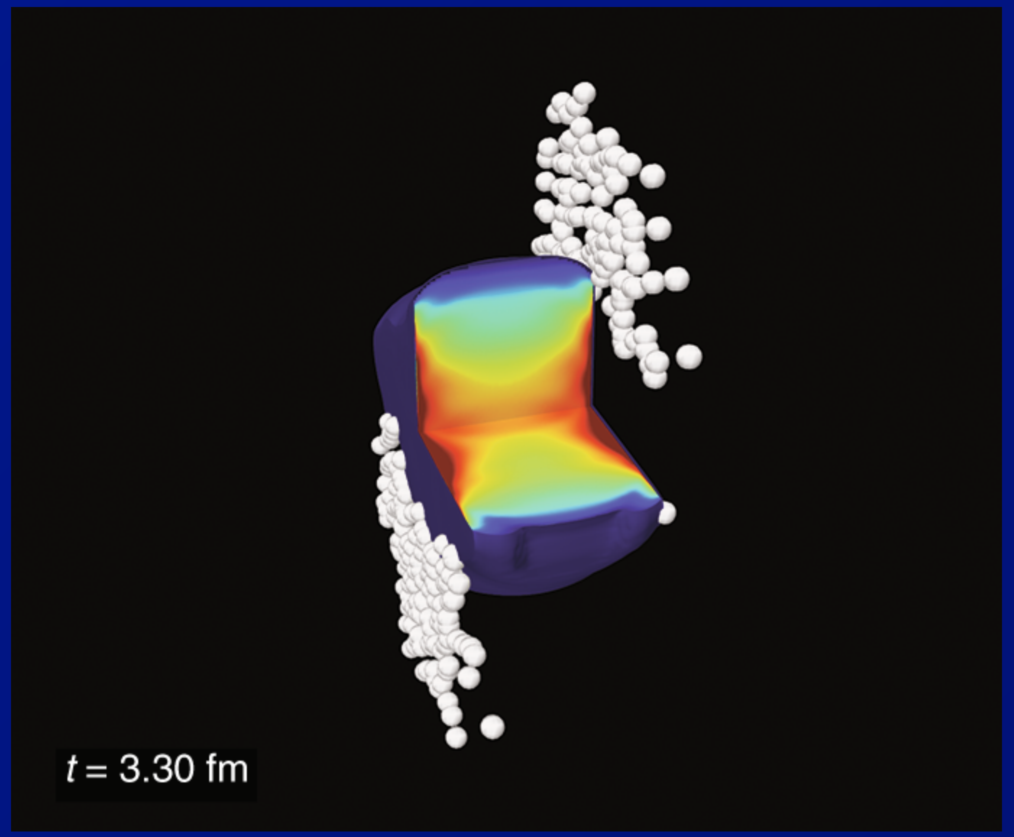

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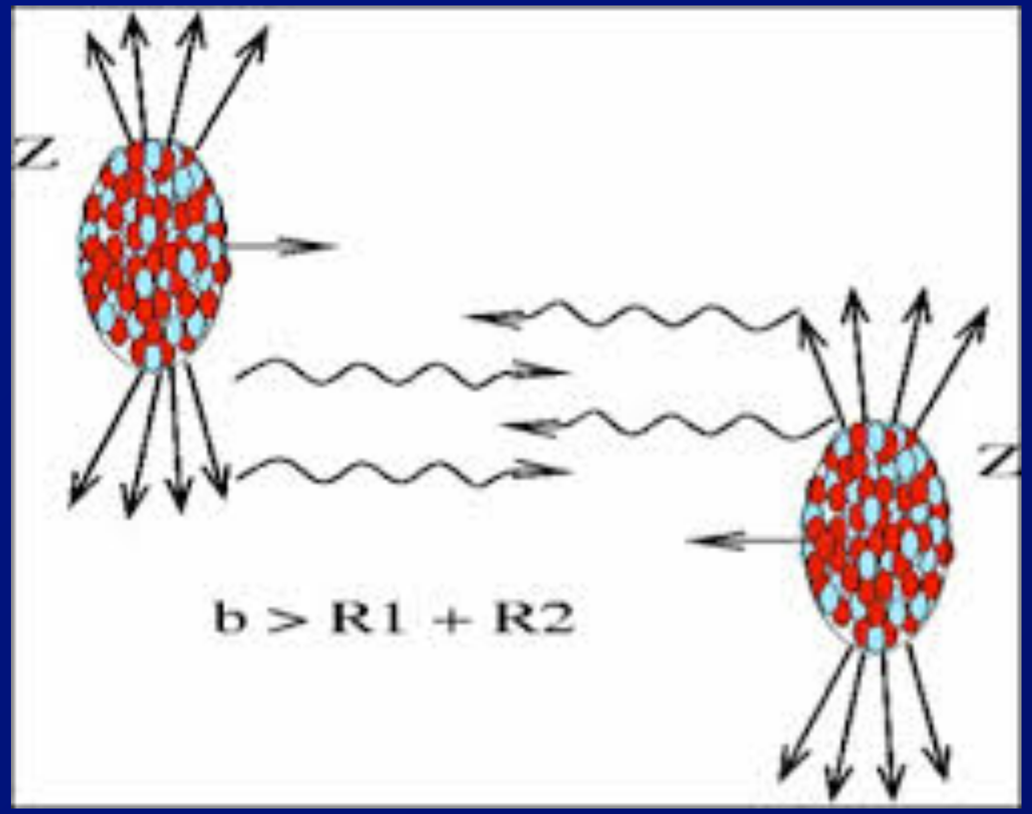

Transverse size
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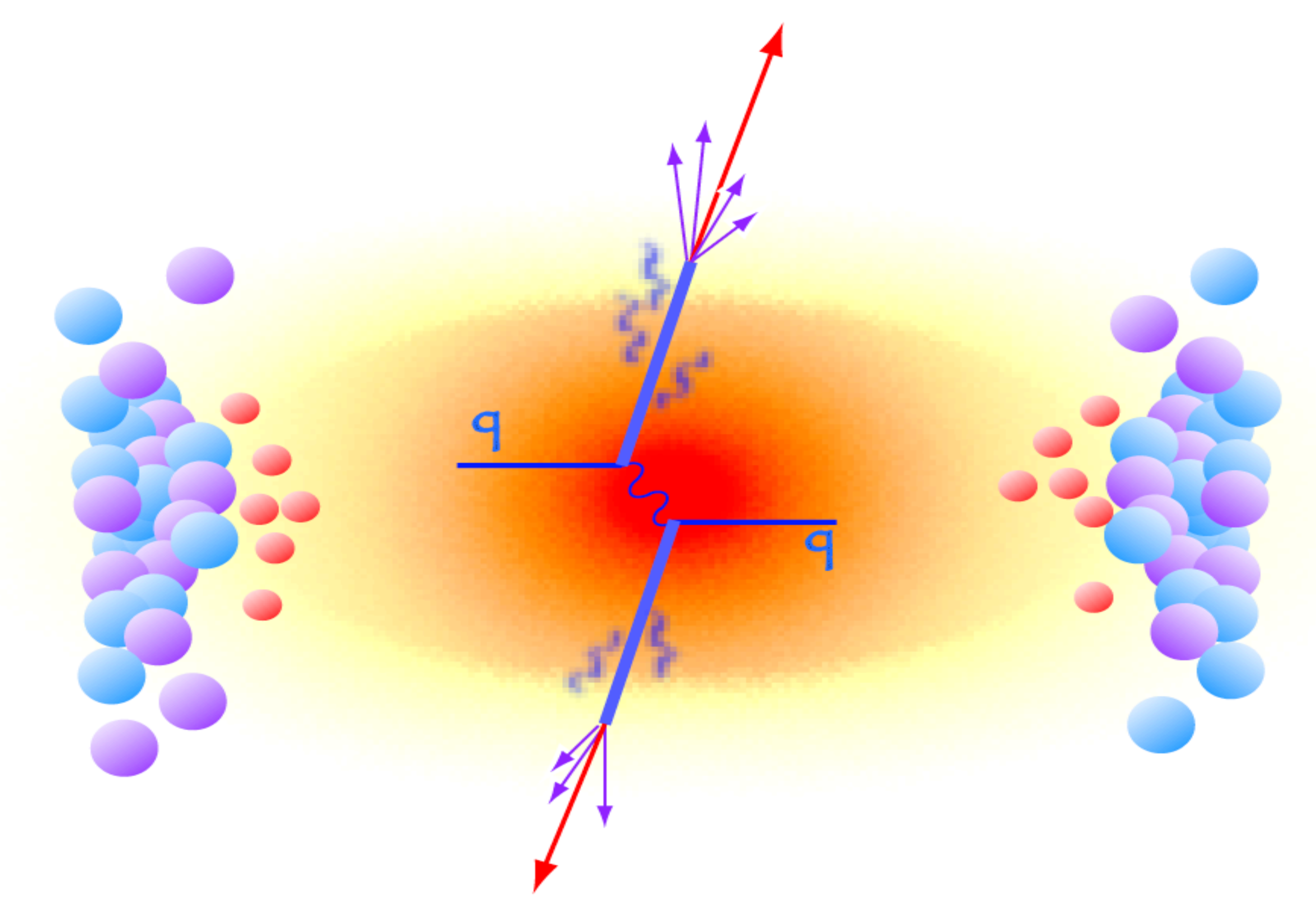
Jet quenching in light ion collisions

Jet suppression

- Goal: probe quenching l dependence with “simple” (central) geometry



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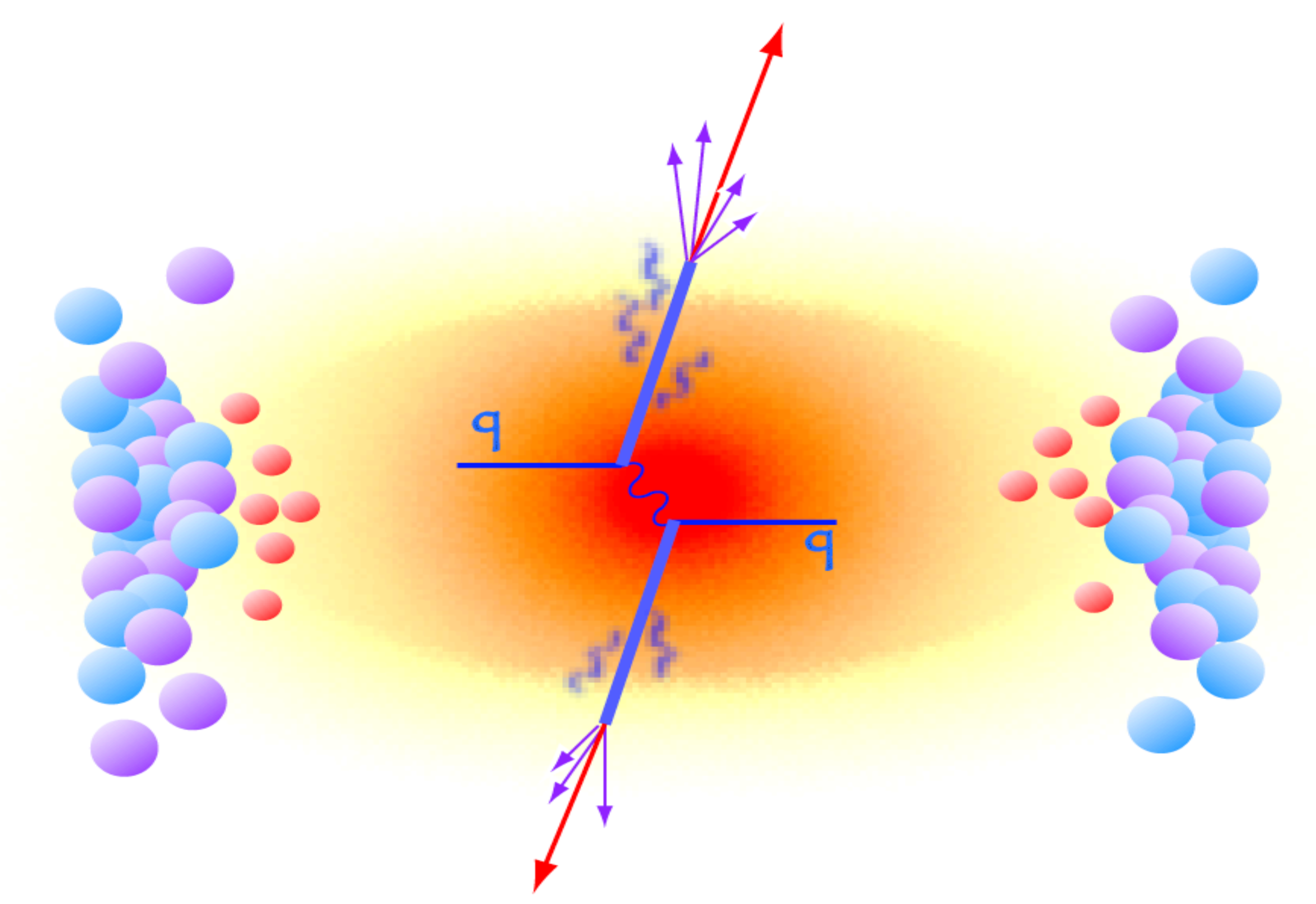
⇒Is this all we want to do?



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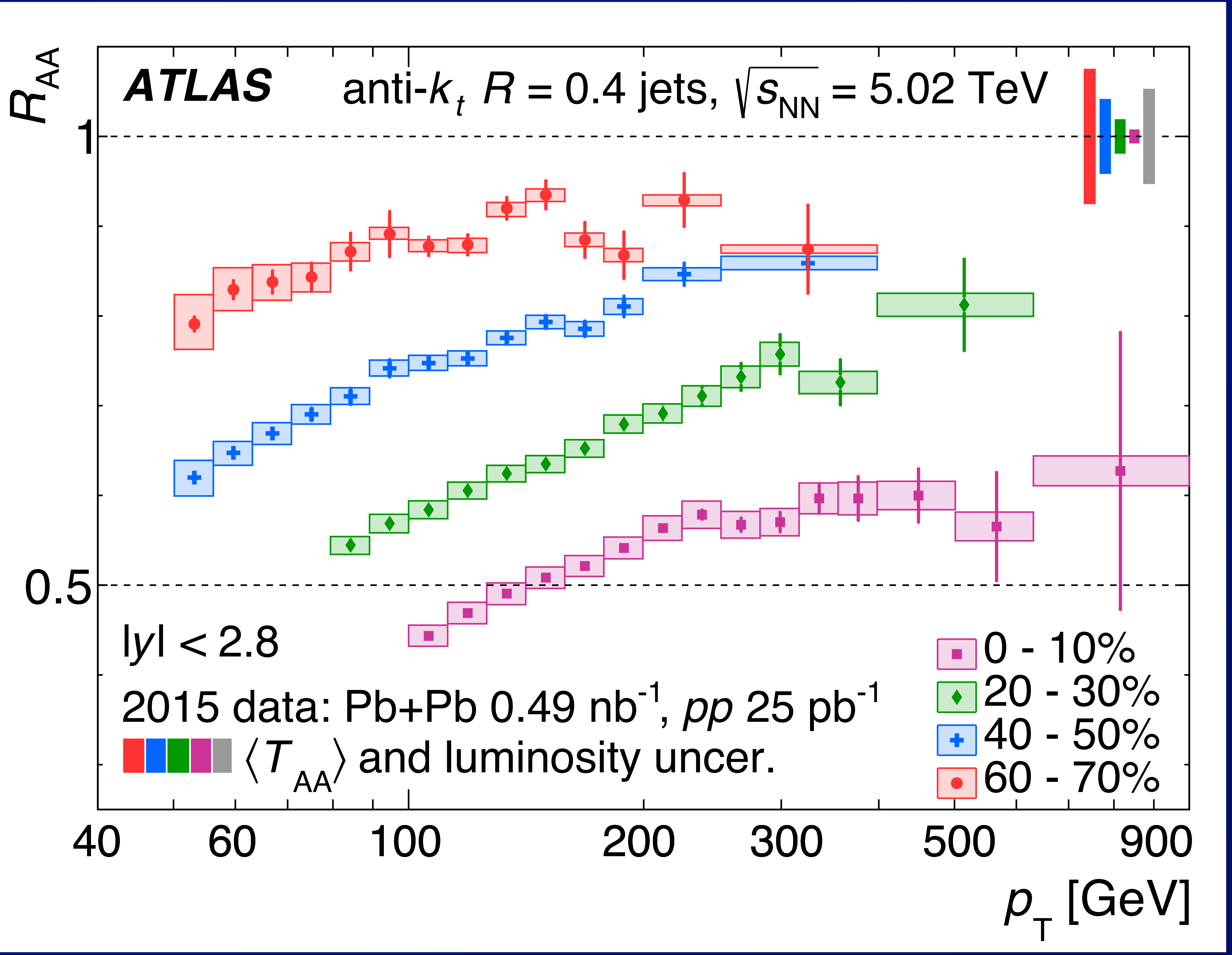

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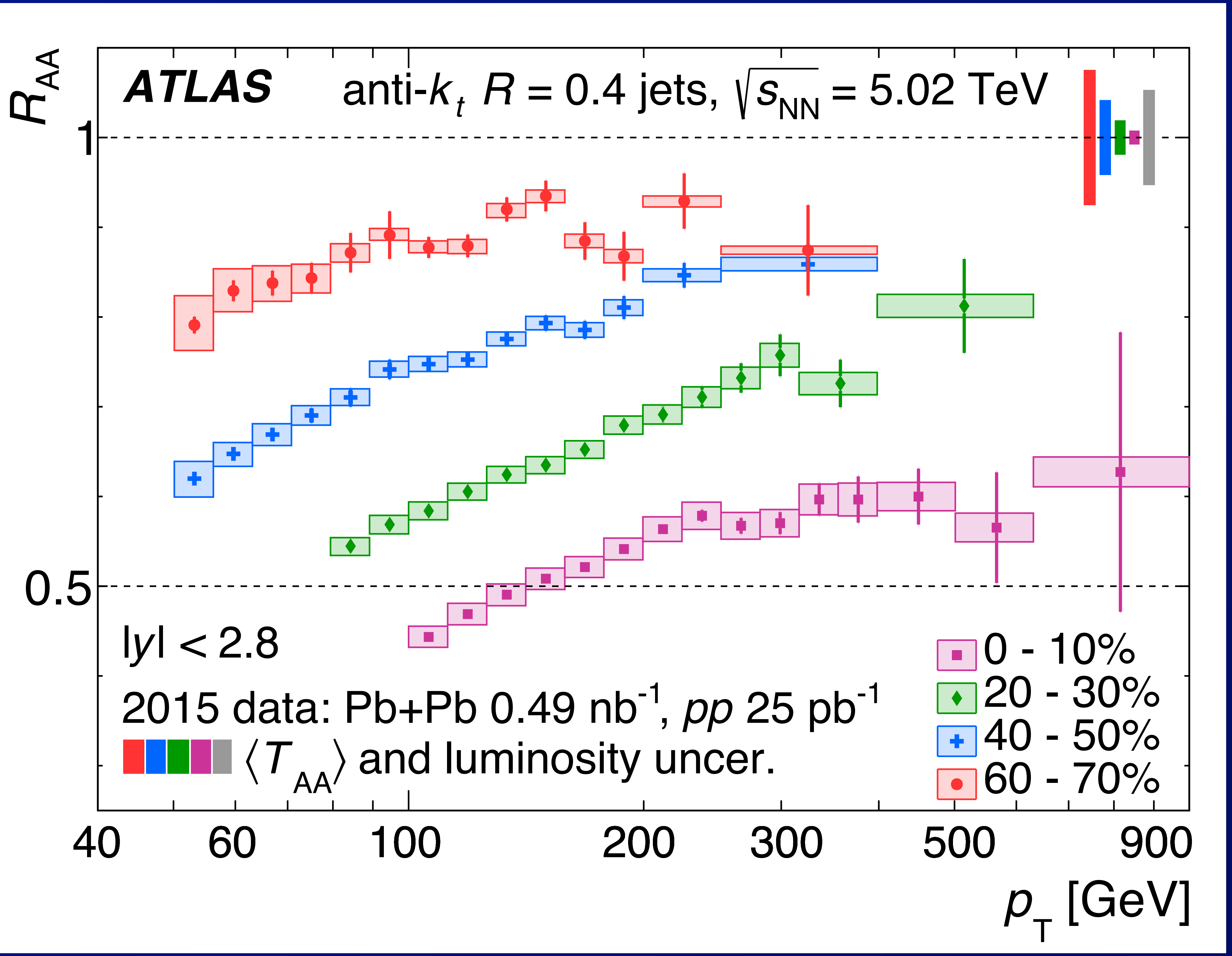

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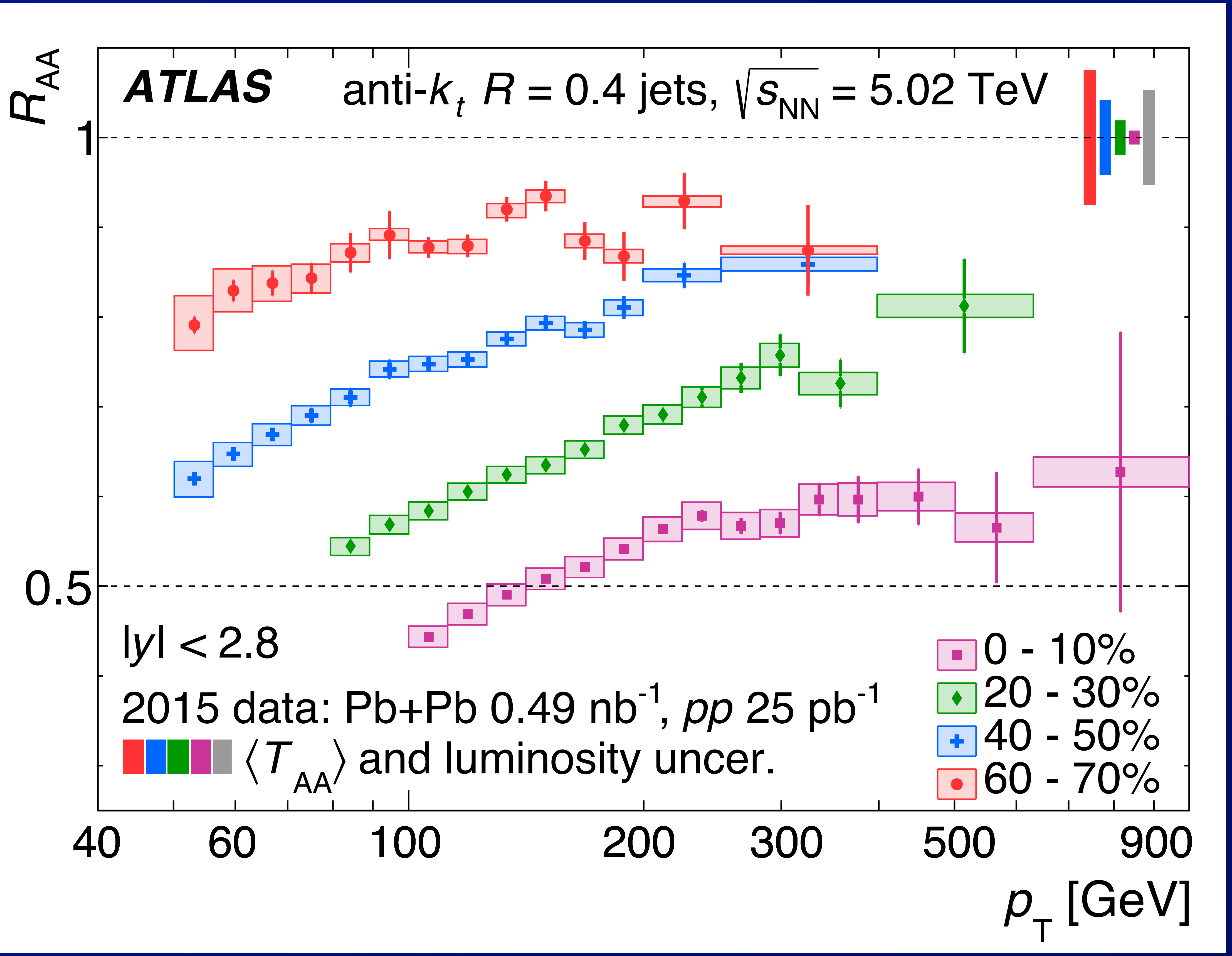

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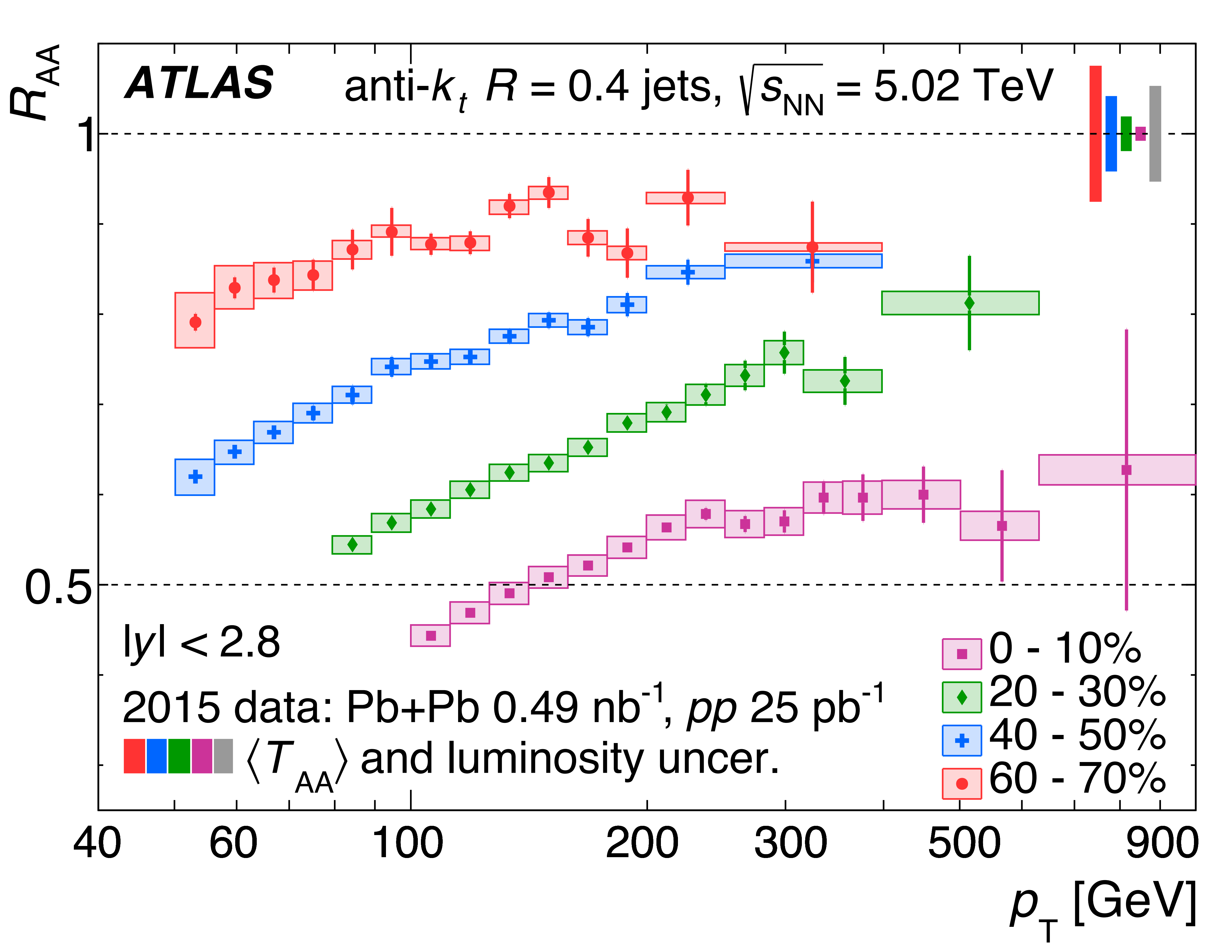

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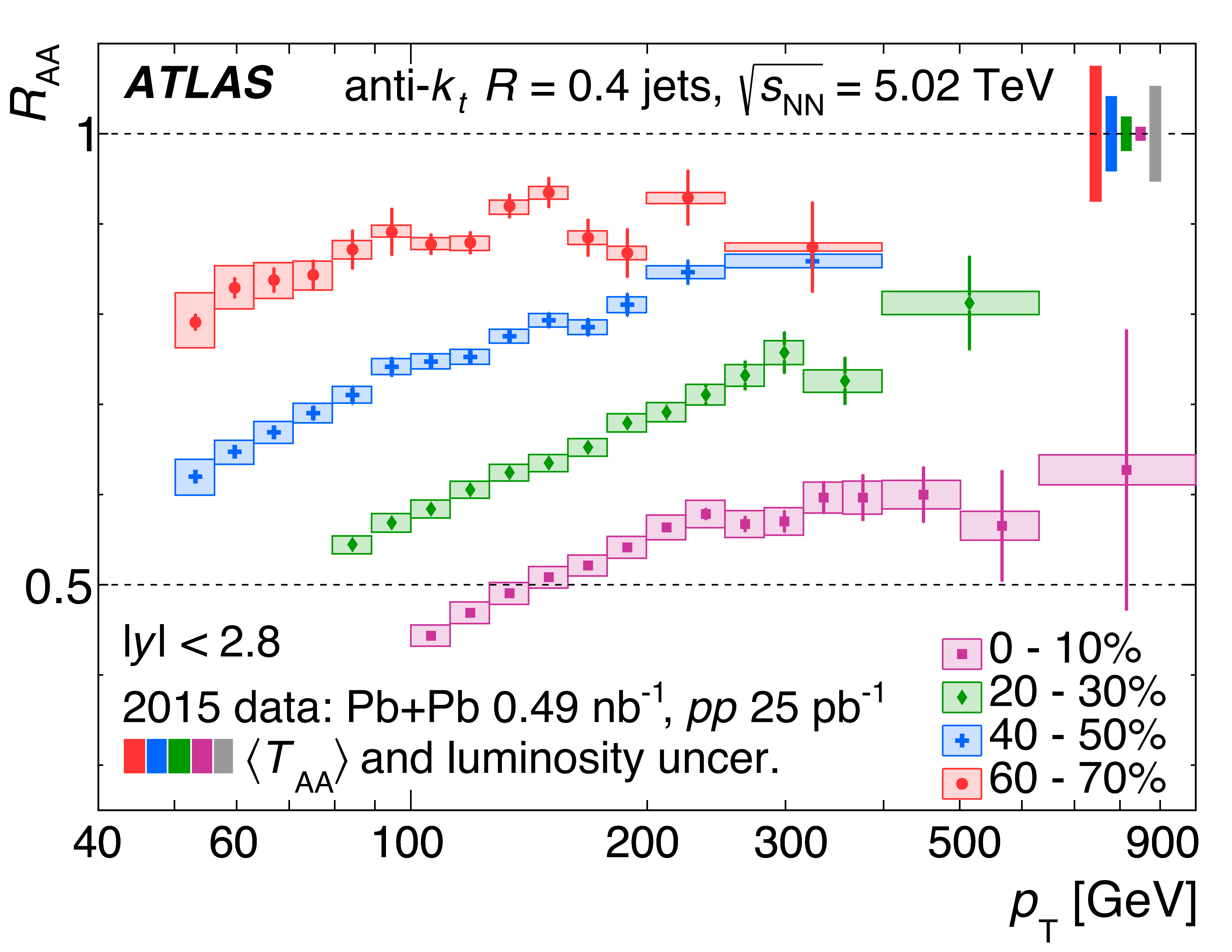
  - Nuclear pdf effects comparable to quenching effects (e.g. O+O)
- What to do?



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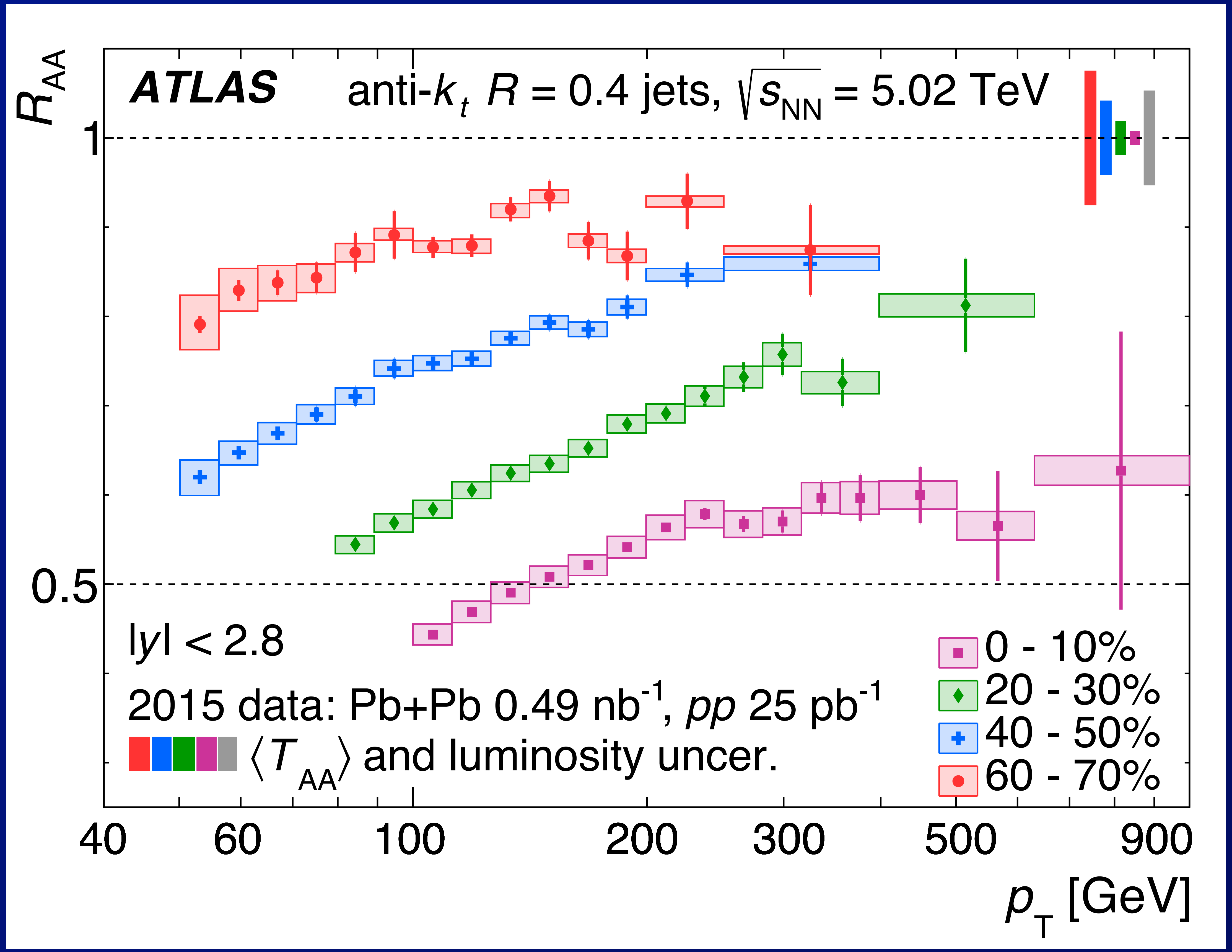


- What to do?

– Use measurements not sensitive to absolute yields

– Use measurement with enhanced sensitivity to quenching

⇒Do both at the same time?

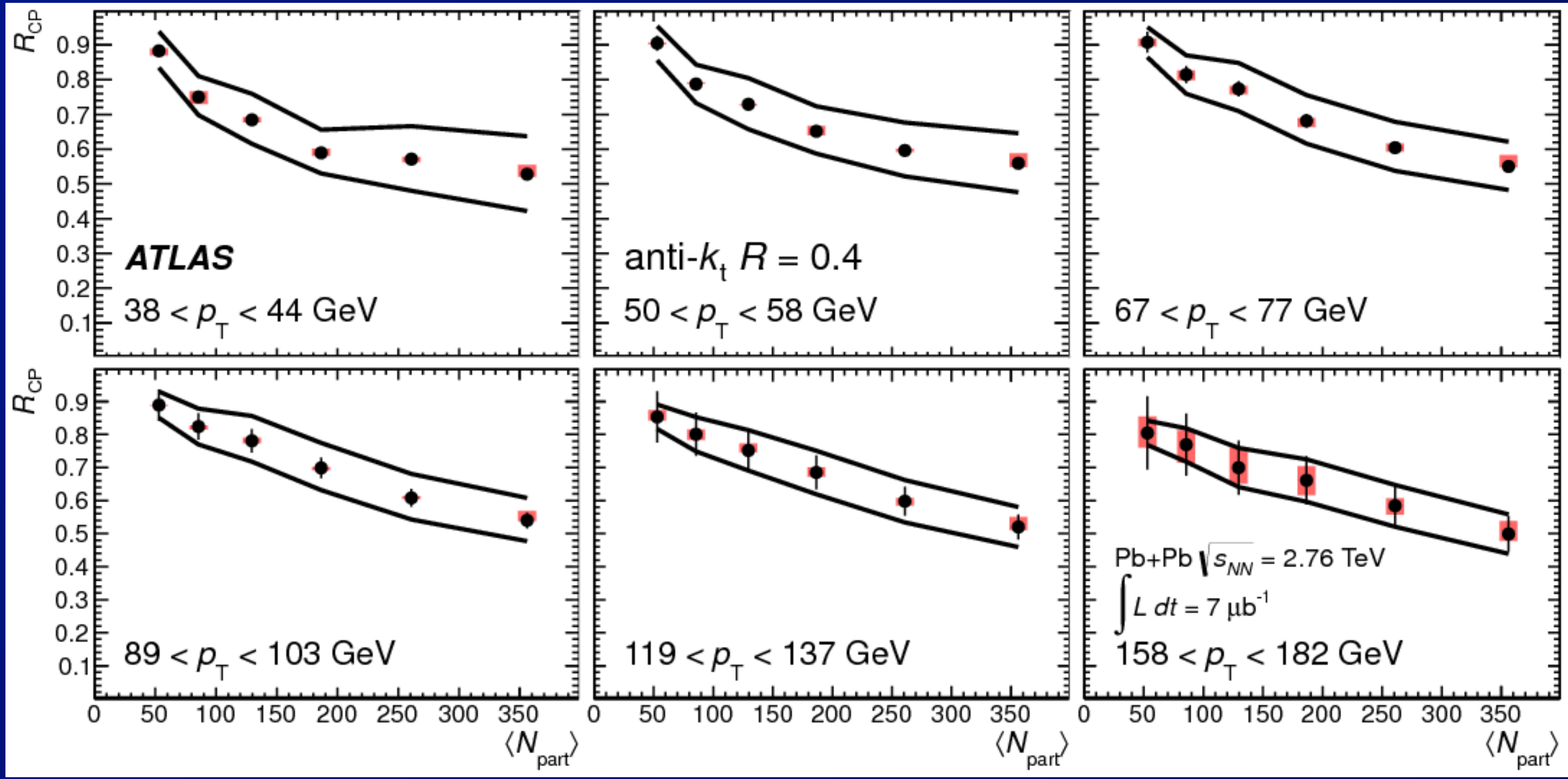
Jet R_{cp}

- Rcp is generally considered inferior to R_{AA}
  - But in the unfortunate situation that pp comparison unavailable
  - Or that nuclear pdf modifications ~ size of quenching effects

  ⇒ A possible solution
- ∃ a proof of principle (first jet suppression measurement)
  - Key issue is the yield of "peripheral" jets

  ⇒In O+O, T_{AA} for 50-70% is ~ 1/10 of that for 0-10%

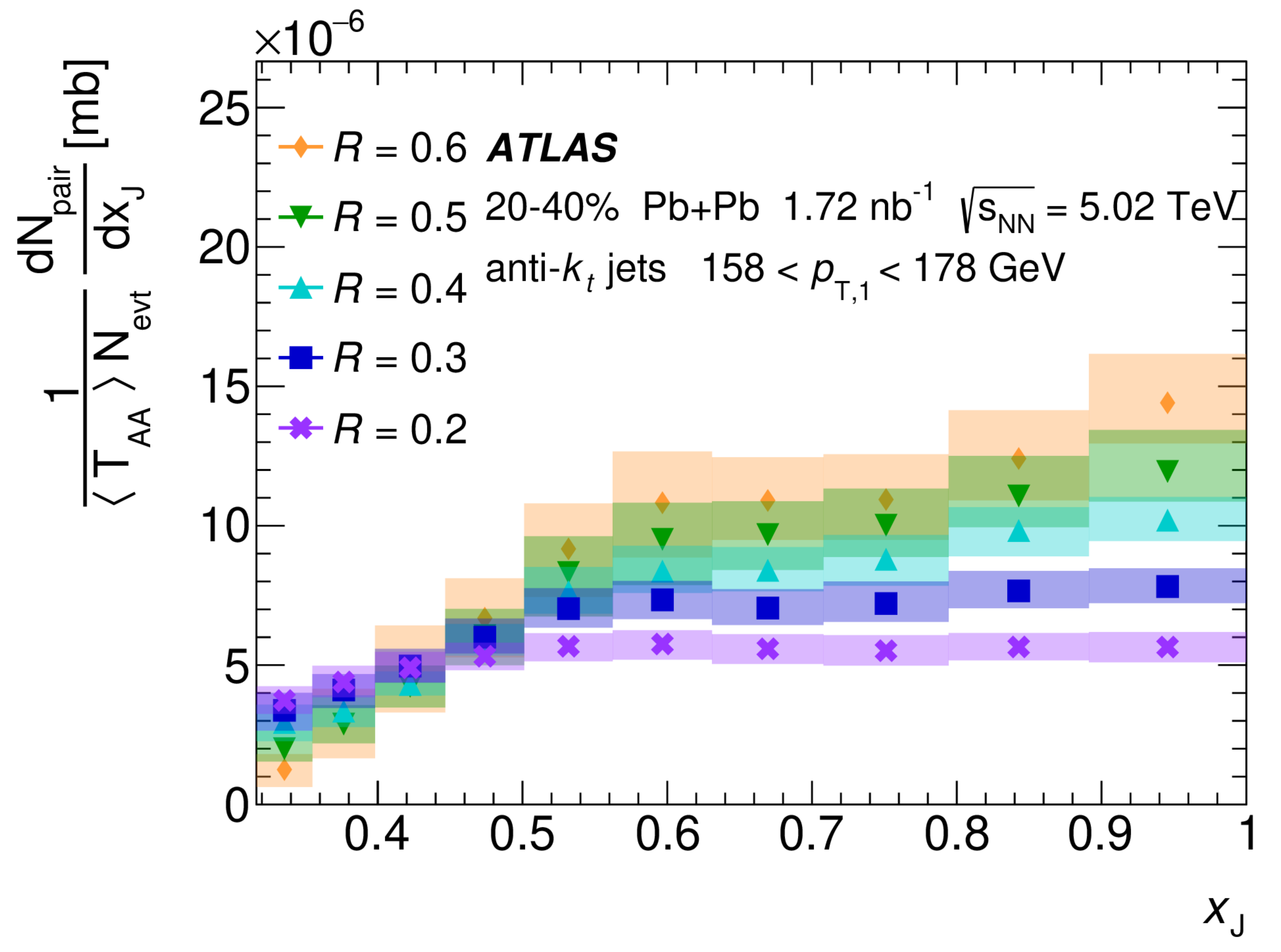
  ⇒Not as bad as in Pb+Pb



Dijet asymmetry

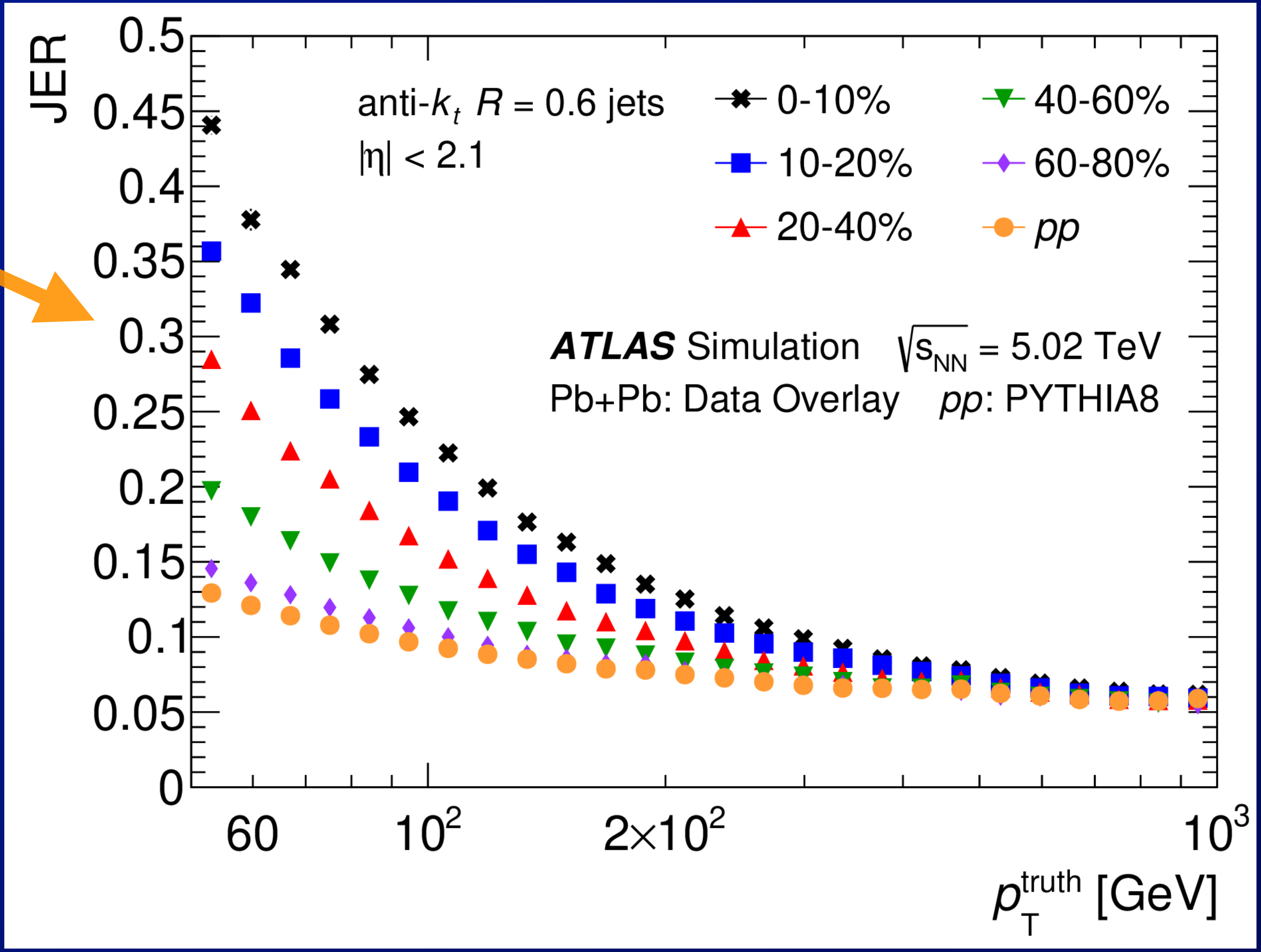
- ATLAS has "made a science out of" dijet asymmetry measurements
  - See larger quenching impacts for smaller radii, lower jet p_T
  - Not sensitive to absolute rates

$\Rightarrow$ But statistics! (Next slide)



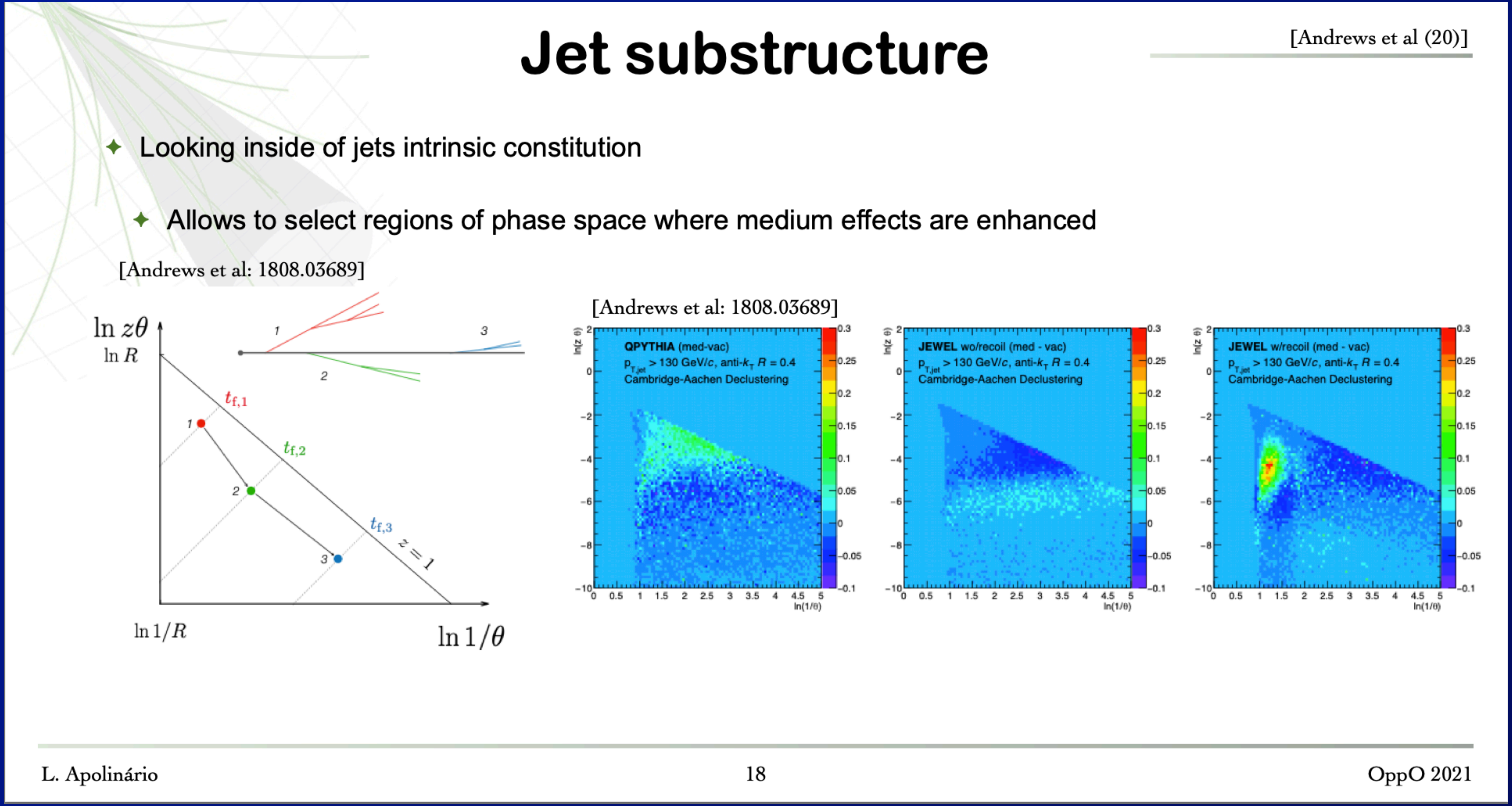
Jet energy resolution, p_T range

- For light ion collisions
  - smaller UE event fluctuations
  - ⇒substantially better jet energy resolution
  - ⇒We can measure much lower in jet p_T
- With lower pT
  - ⇒better sensitivity to reduced quenching
  - ⇒significantly increased yield
    - » But smaller radii less attractive due to larger jets



Jet substructure

From 2021 O+O workshop



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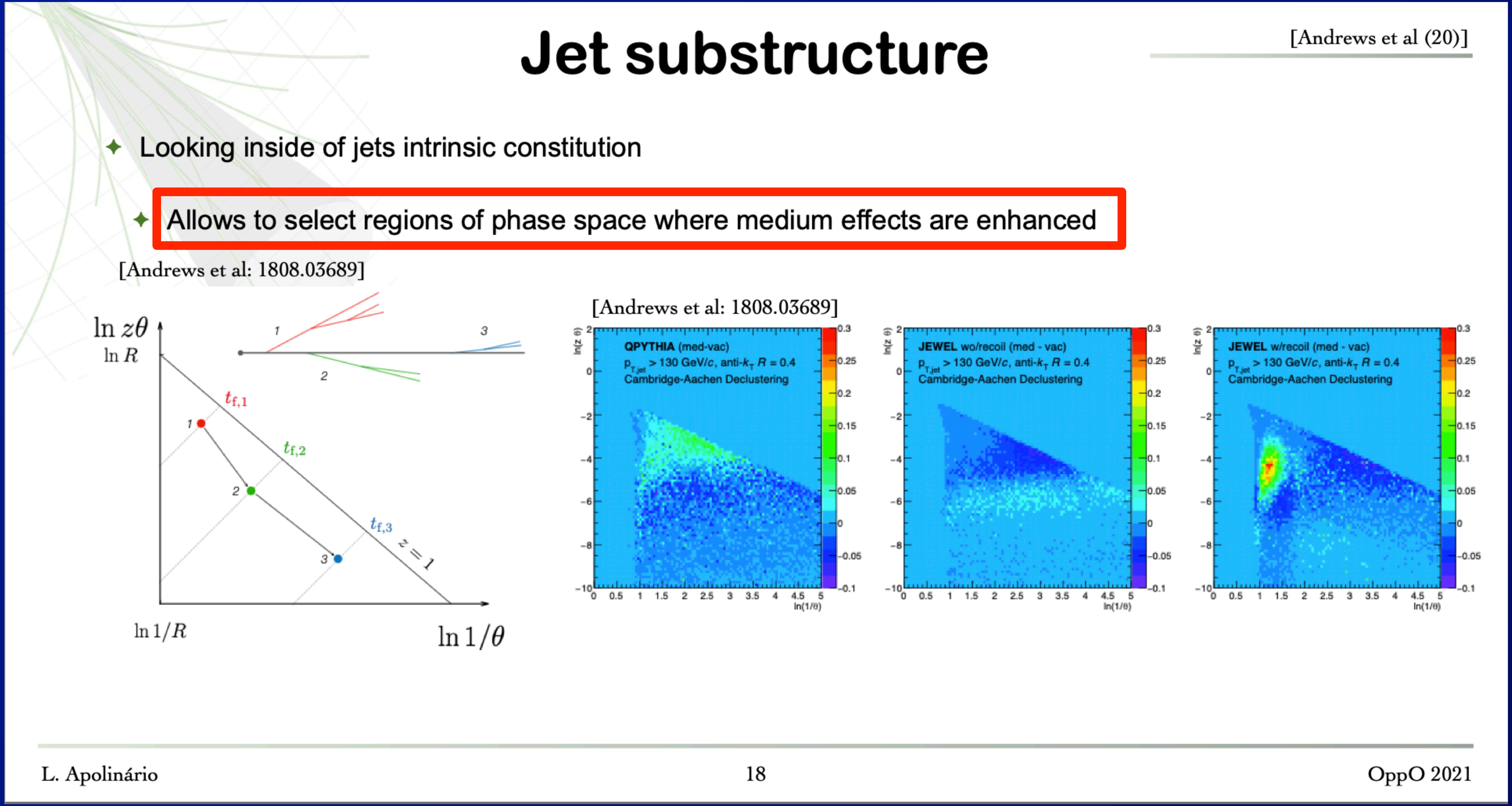
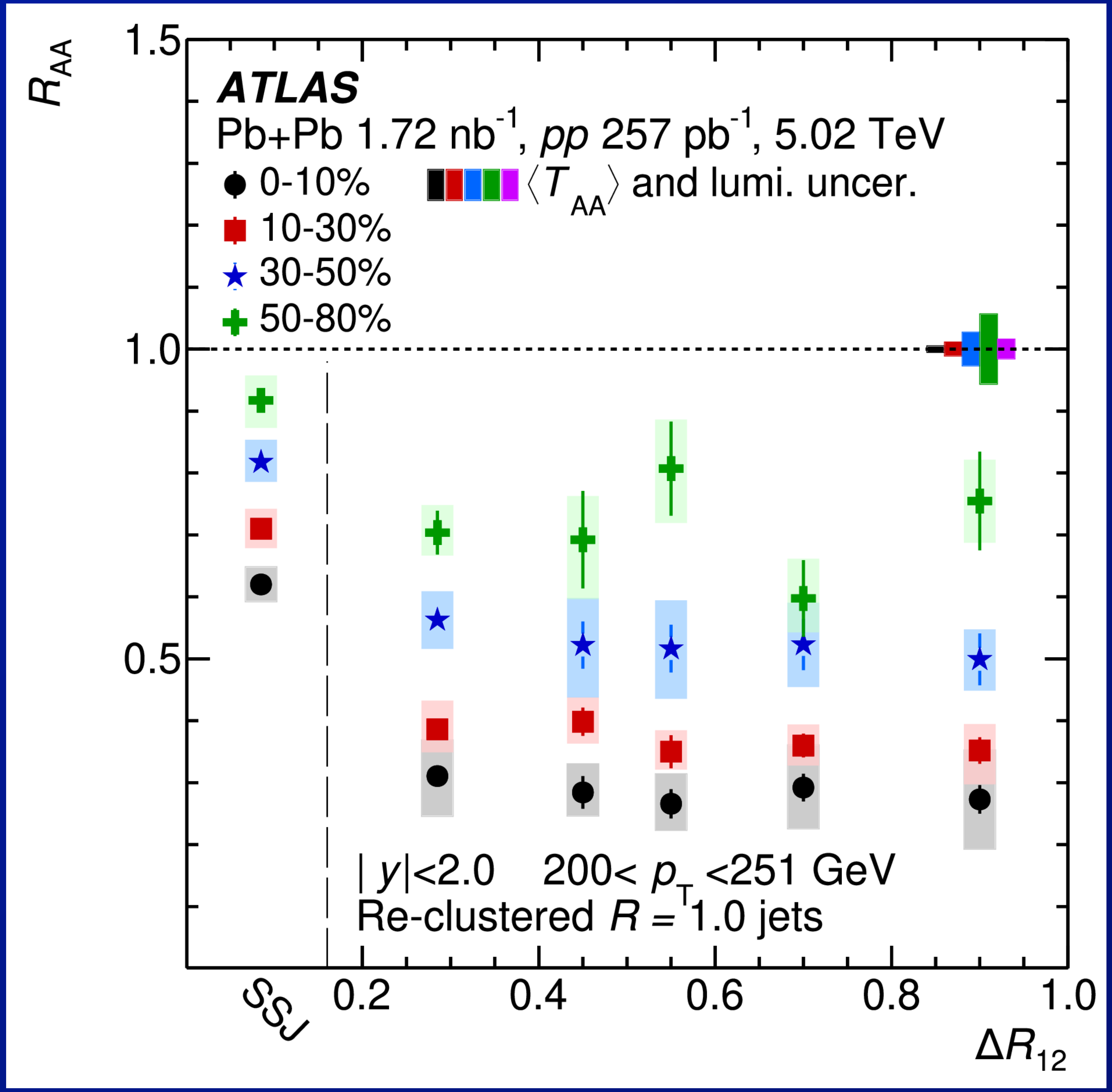


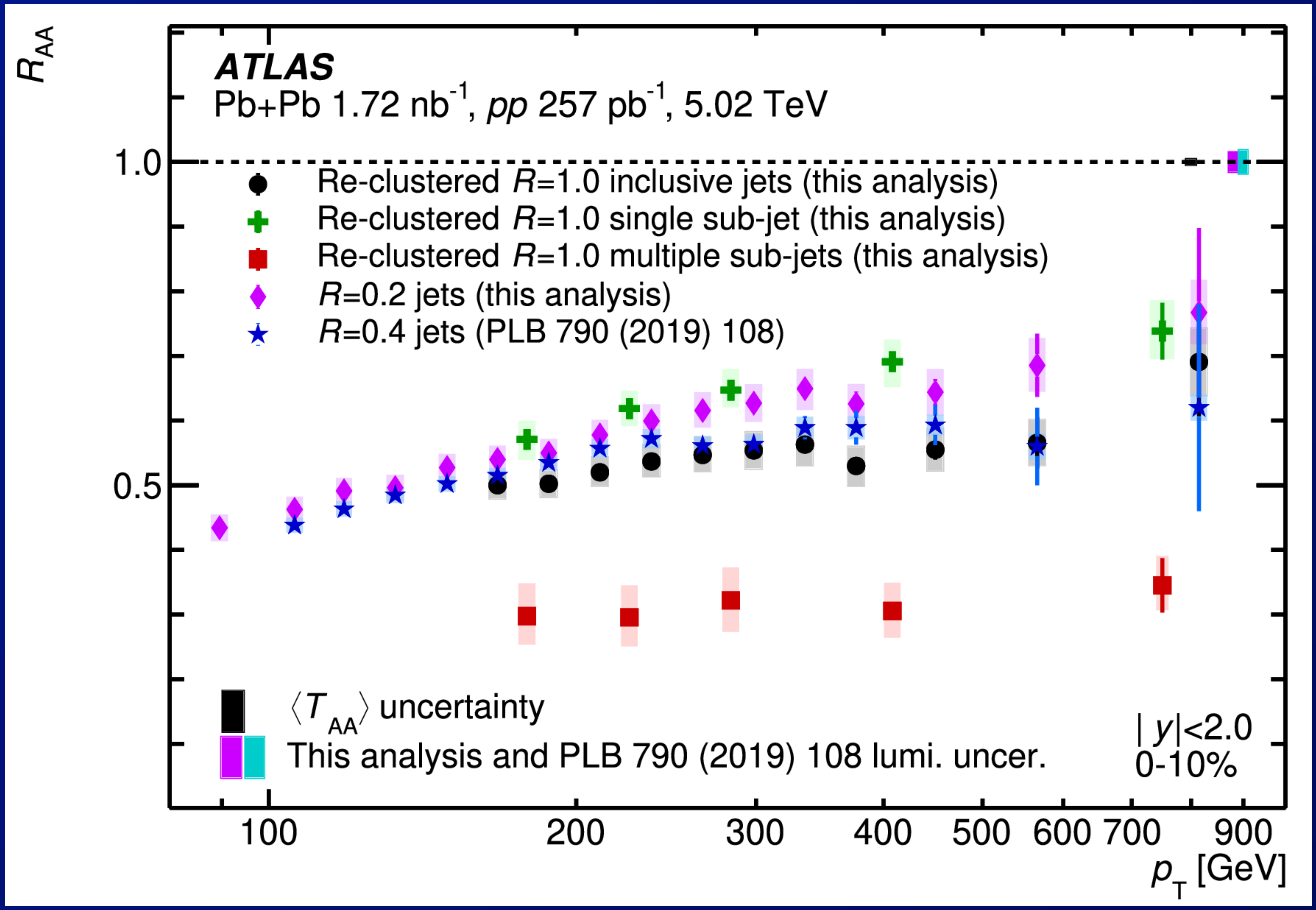
⇒This has been experimentally realized

Large-R jet sub-structure

- ATLAS has observed substantial increase in quenching of jets with $\Delta R > 0.2$ splittings compared to inclusive / those without

⇒ Nuclear pdf modifications should show no ΔR dependence (Q^2 ?)

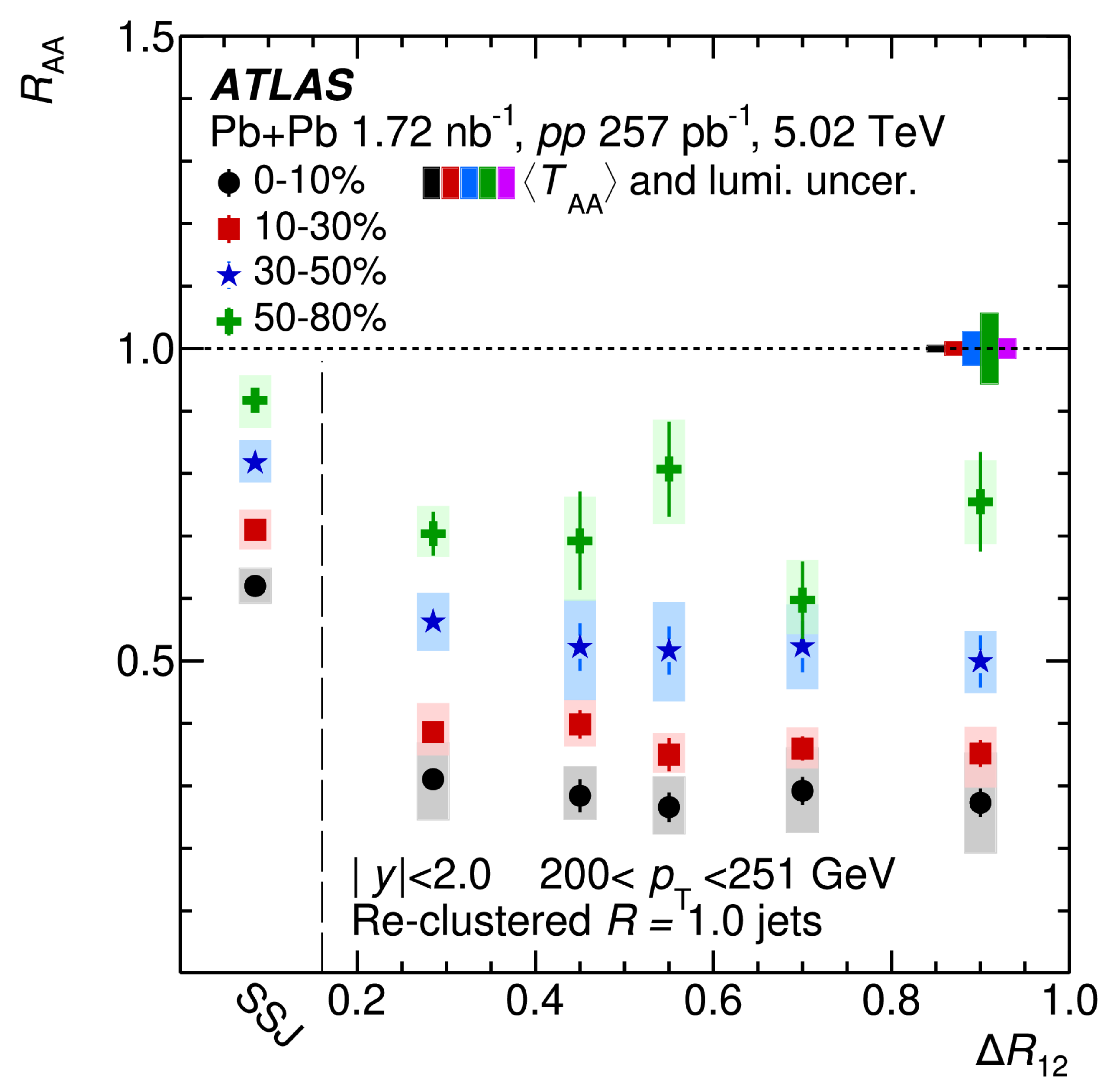


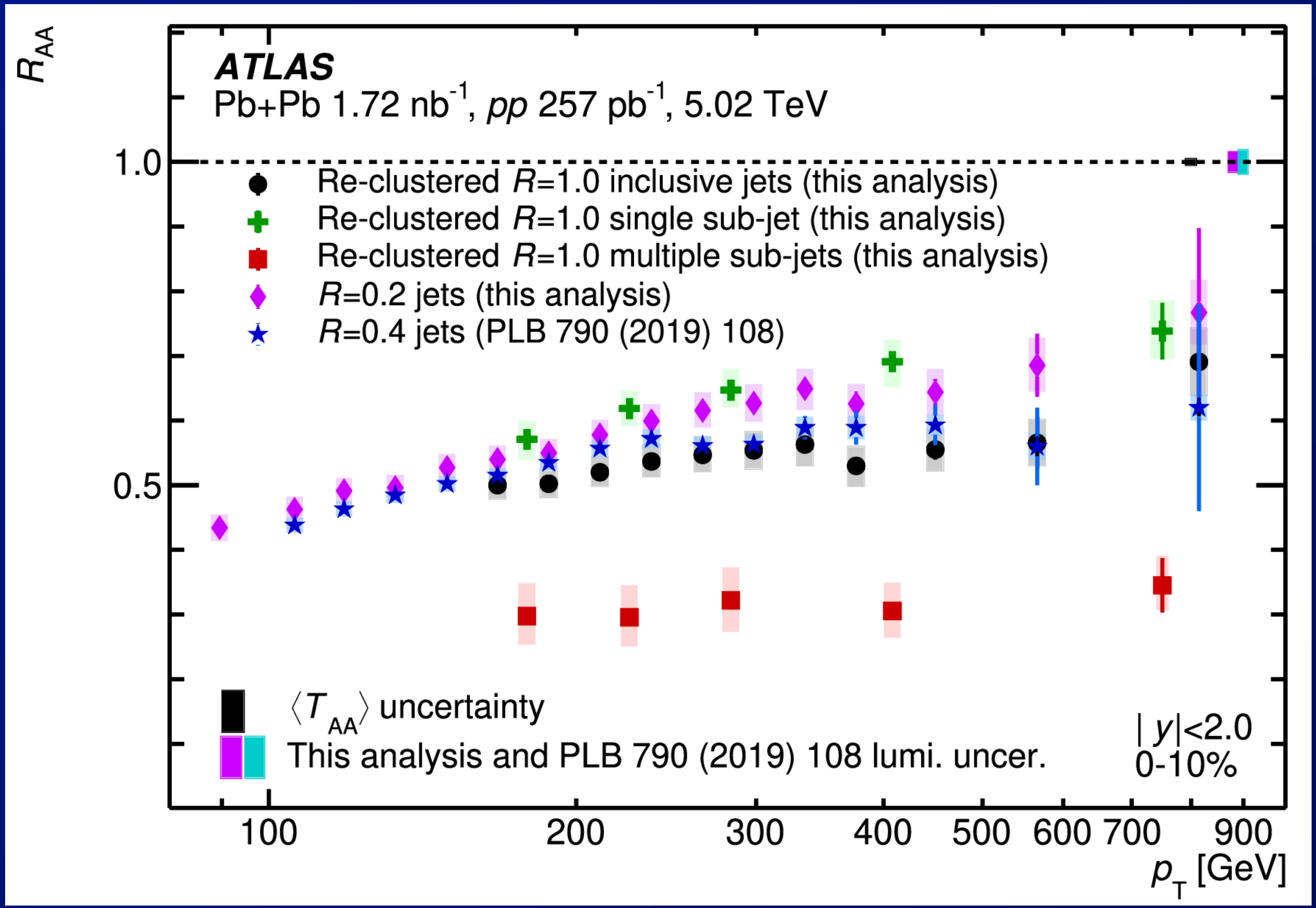


Large-R jet sub-structure

- In Pb+Pb, used k_T reclustering of $R = 0.2$ jets to suppress UE
  - In light ion collisions, less underlying event

⇒Maybe directly reconstruct $R = 1$ jets





Jet "modifications" in light ion collisions

- Probe quenching l dependence with "simple" (central) geometry

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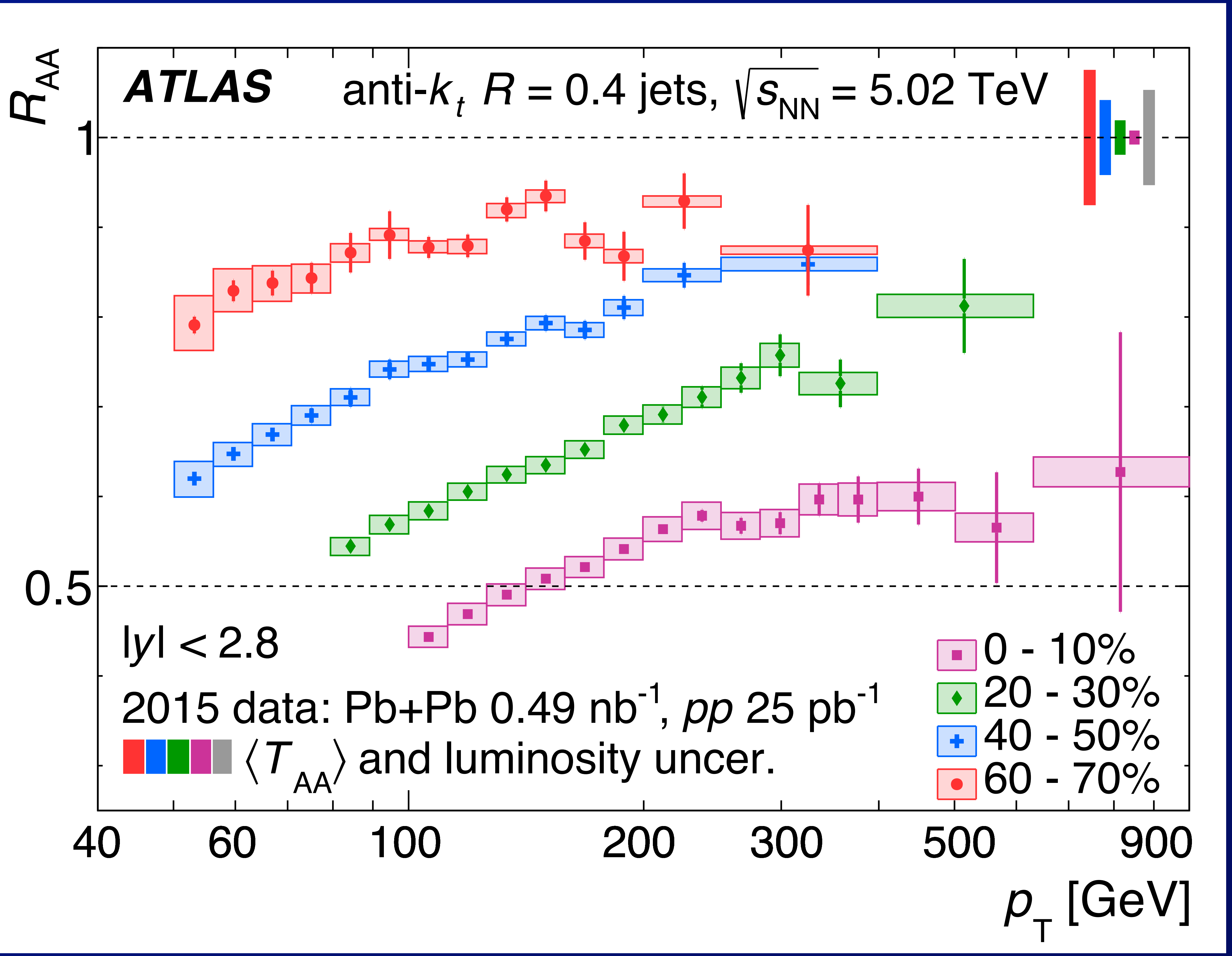
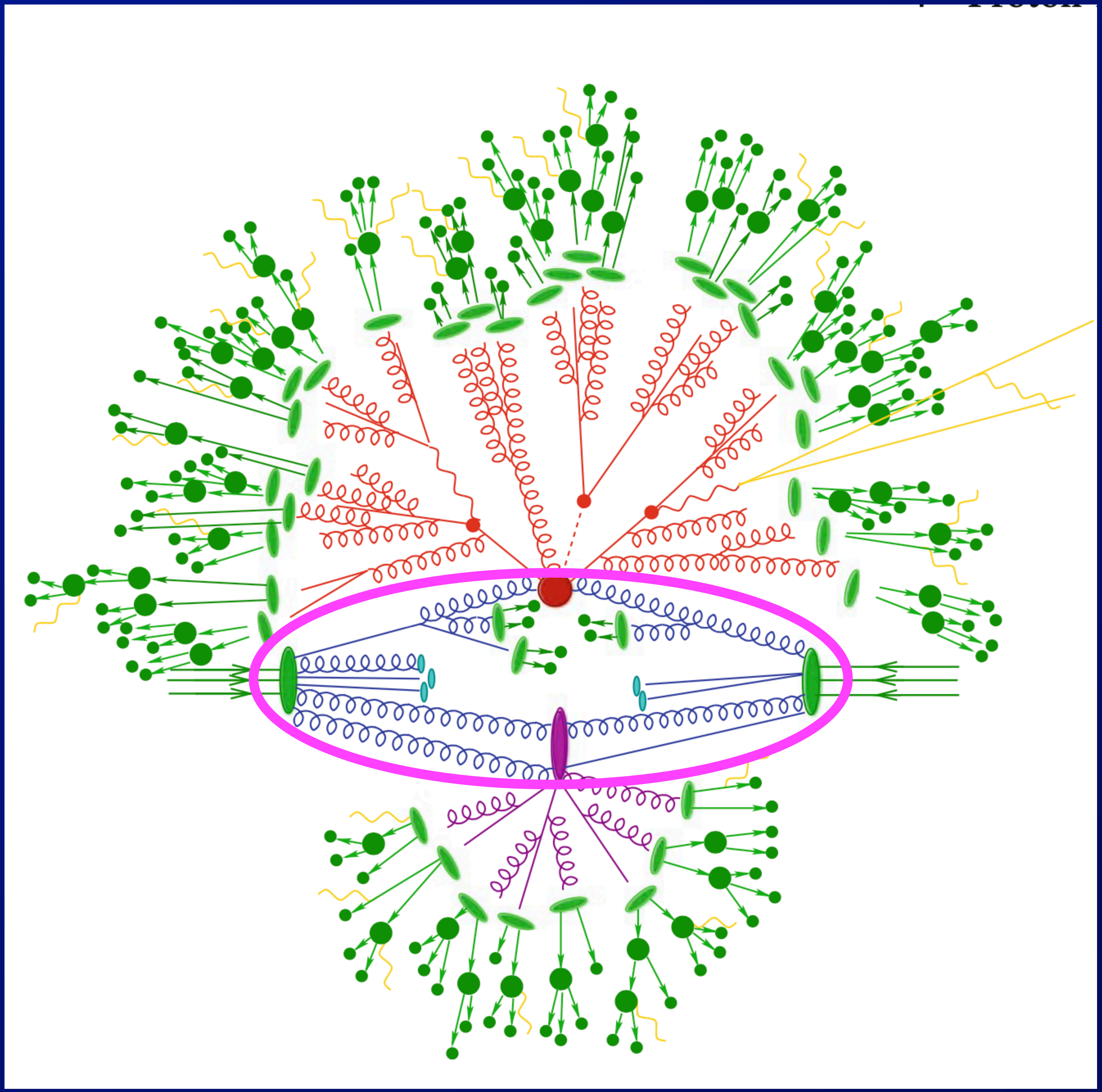


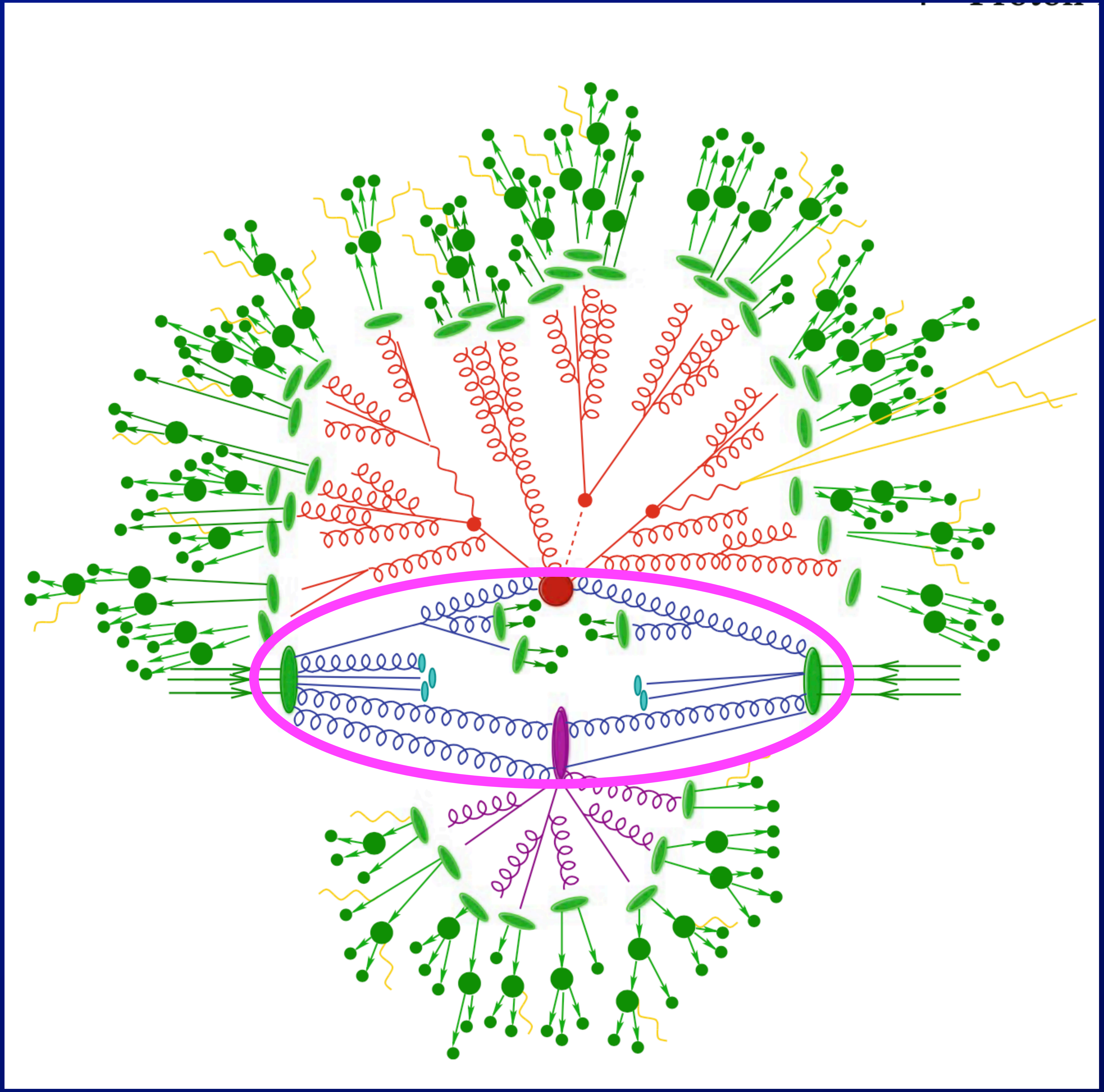
Coupling between ridge and hard-processes in pp

- I am interested in the following question:
  - ⇒ To what extent does the soft(?) underlying event decouple from hard scattering processes?



Coupling between ridge and hard-processes in pp

- I/we are interested in the following question:
  - ⇒To what extent does the soft(?) underlying event decouple from hard scattering processes?
- Test by studying correlations between jet fragments, UE



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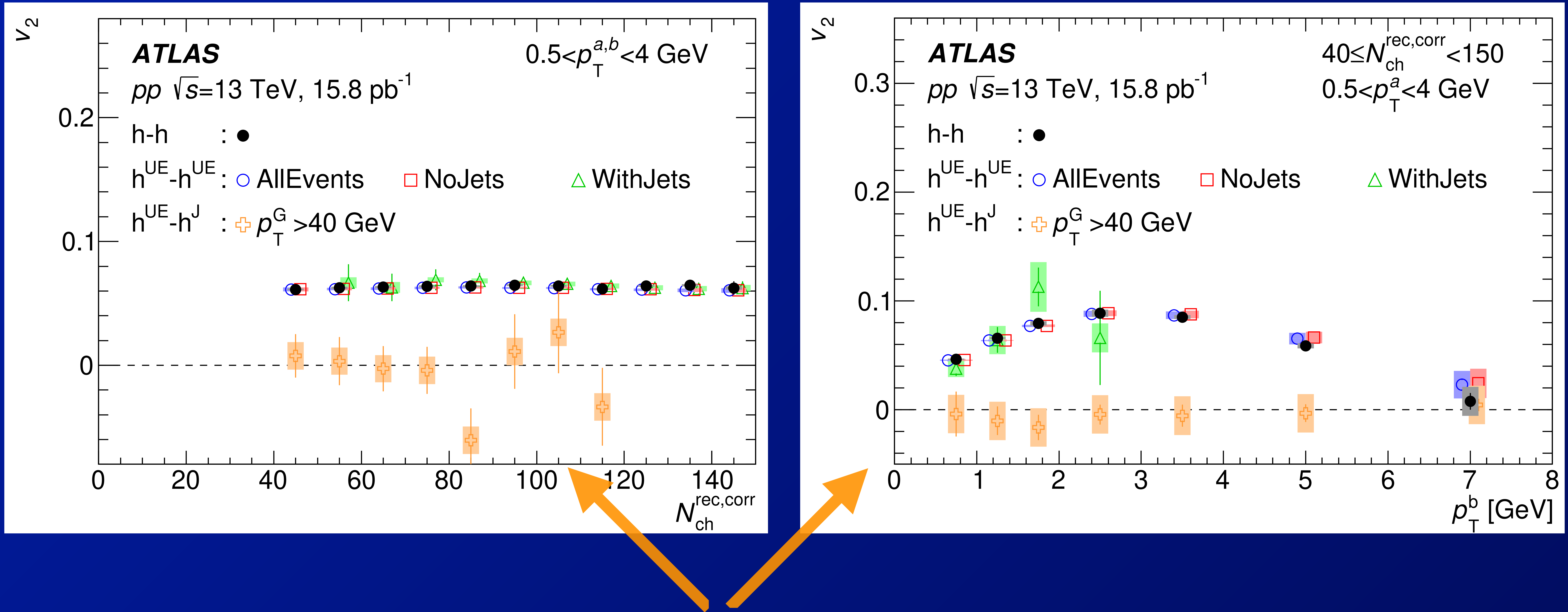

- In pp collisions, we see no coupling between jet fragments and the UE

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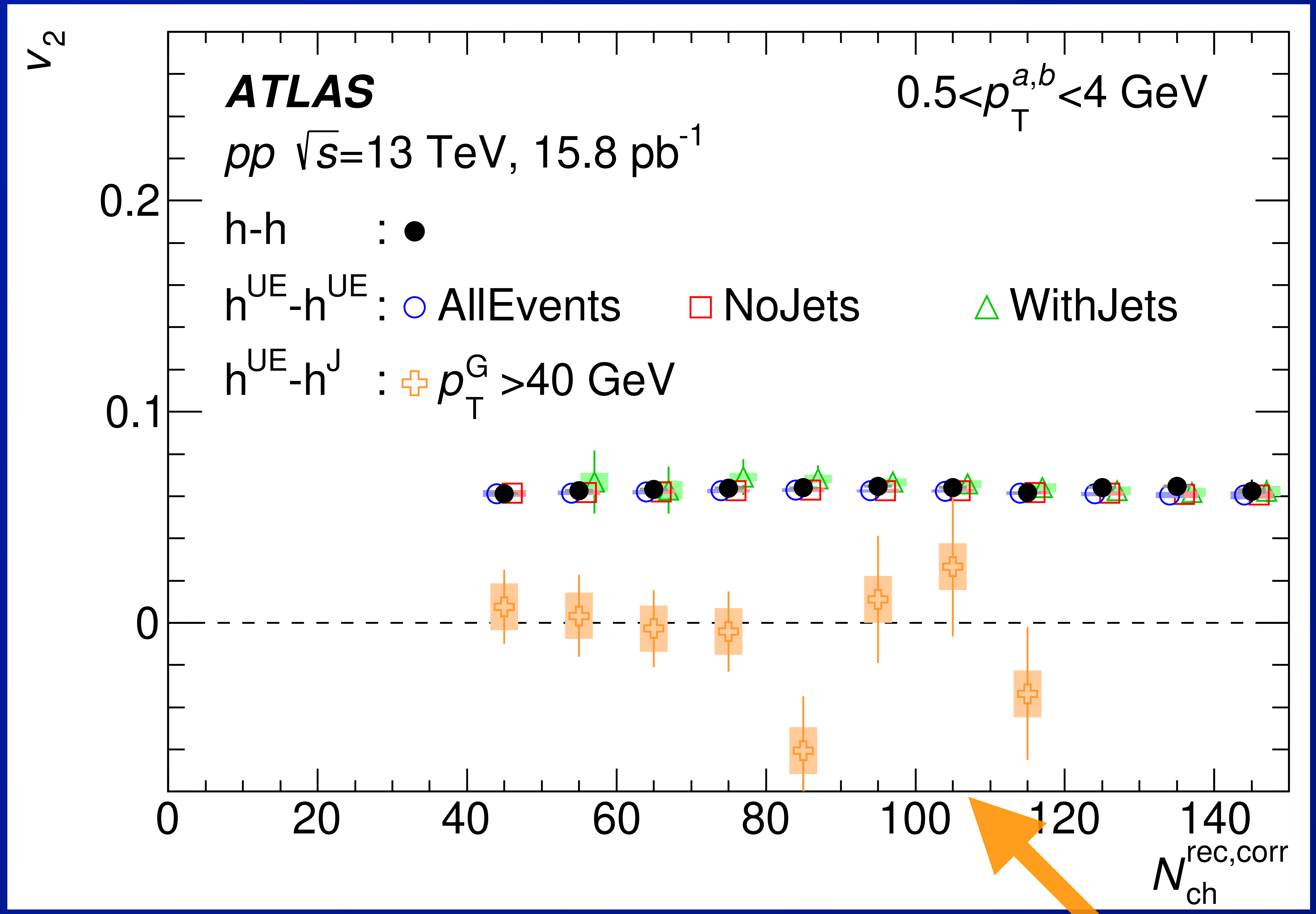
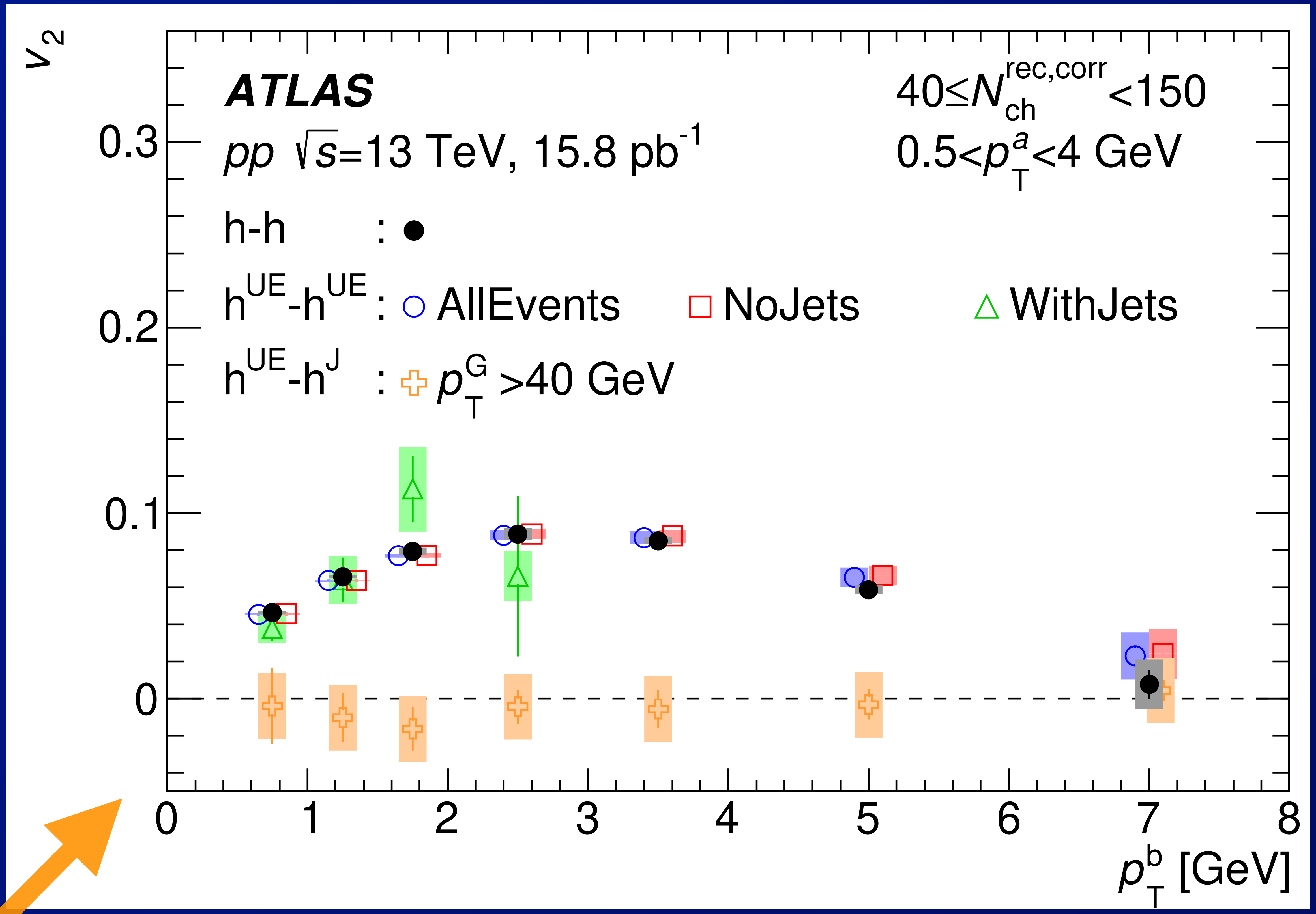


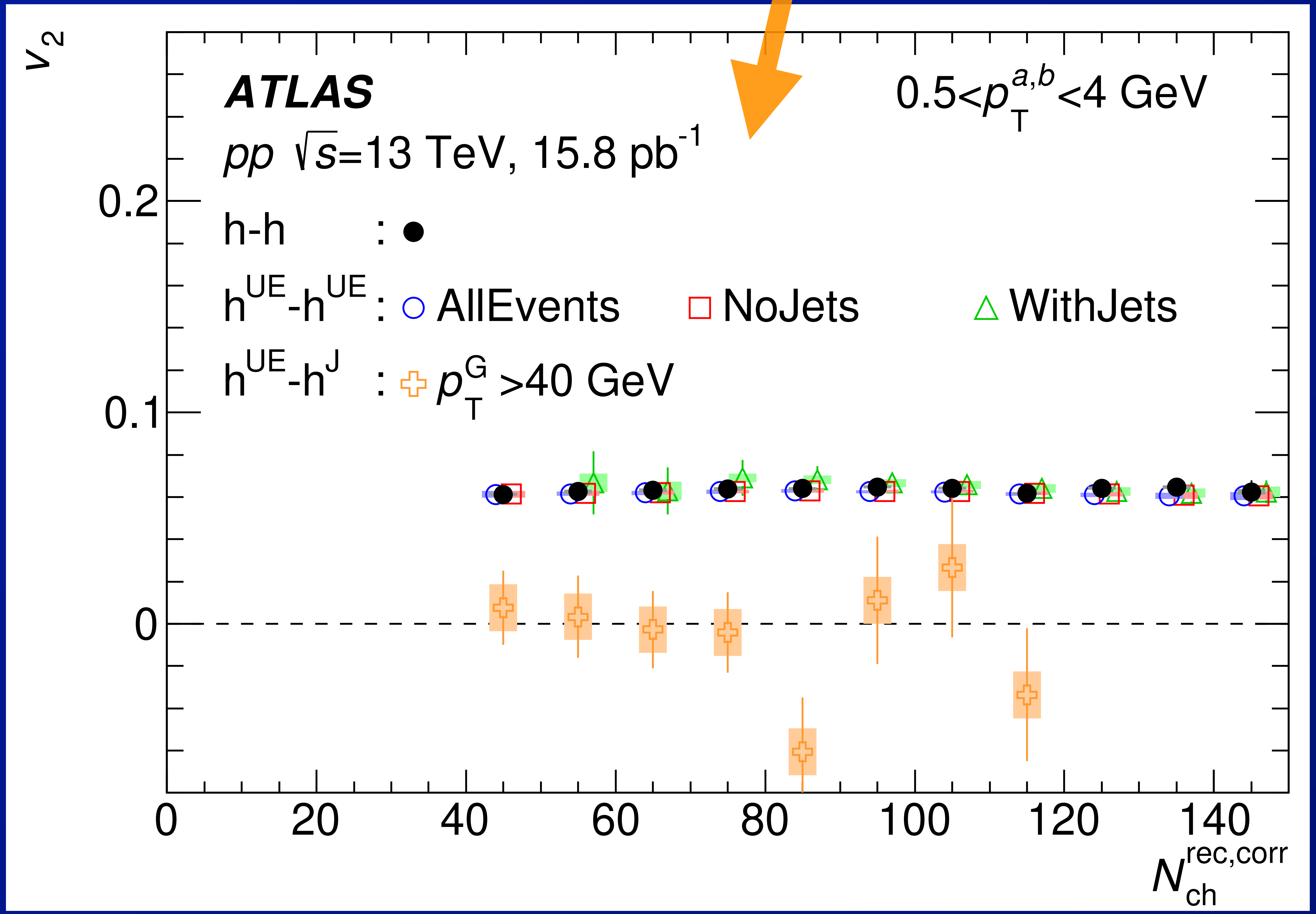


- In pp collisions, we see no coupling between jet fragments and the UE
- In p+Pb collisions, we do see such coupling (not shown)

⇒ I think that we will ultimately see the this is an initial-state effect

Coupling between ridge and hard-processes in pp

- How do we go from this



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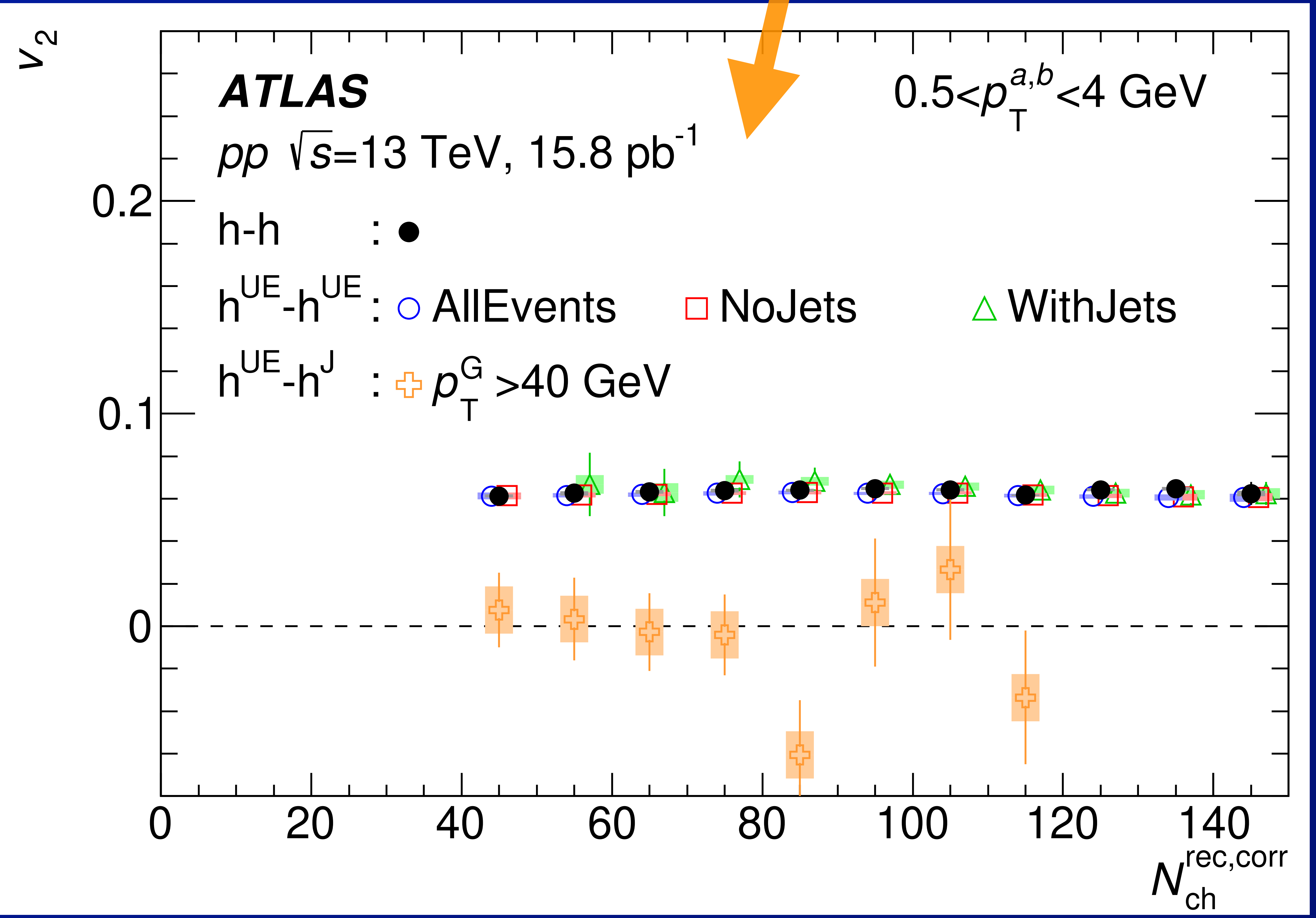
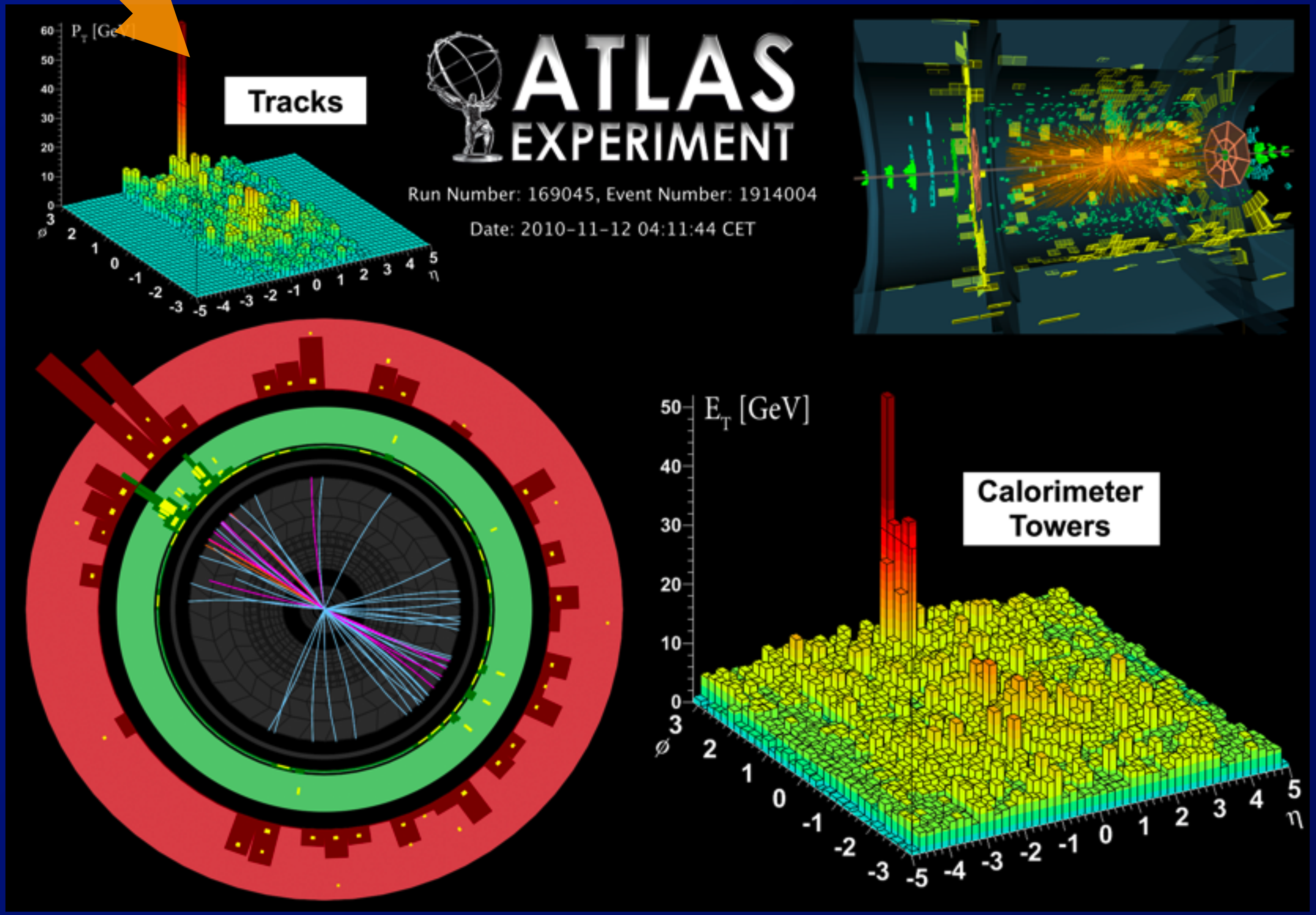
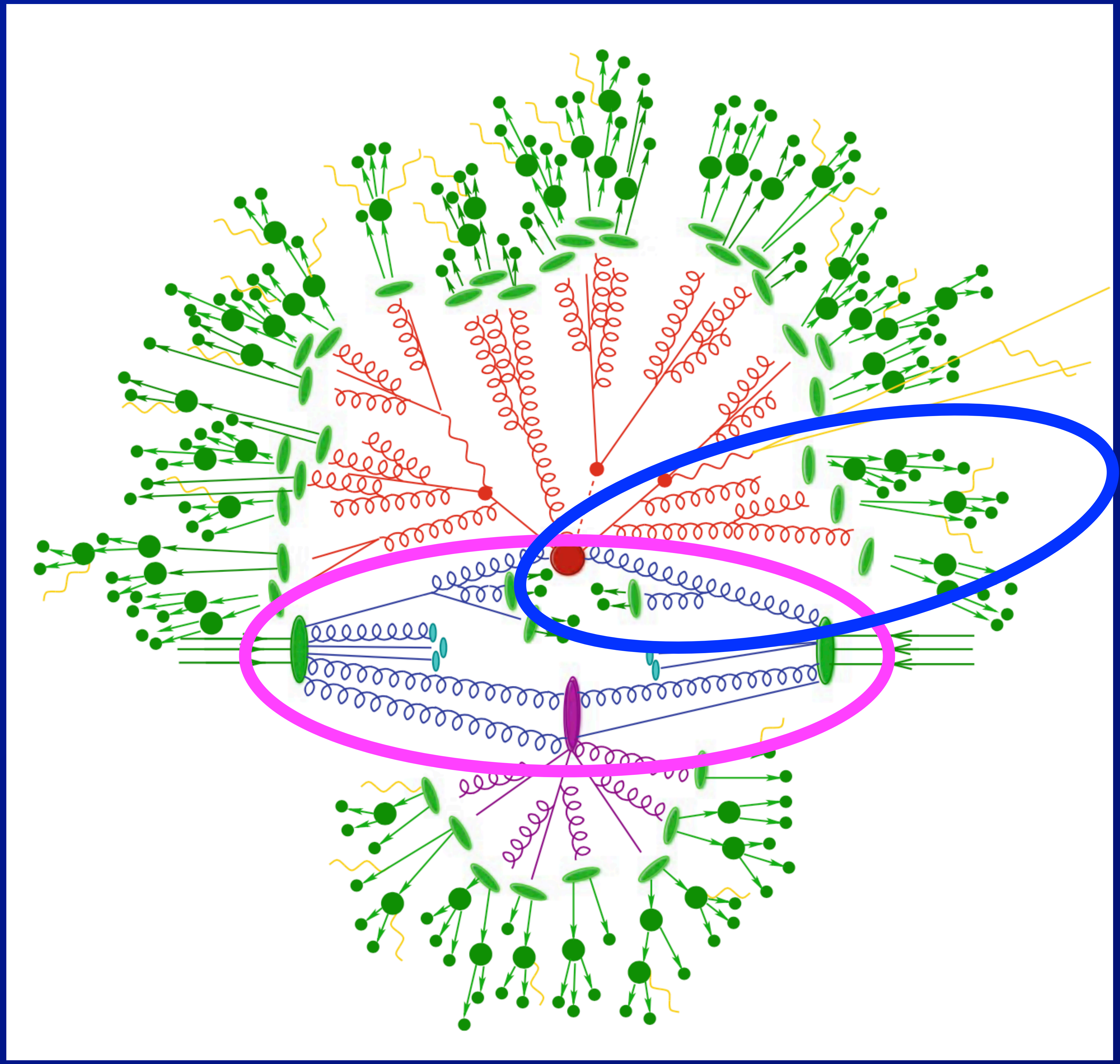


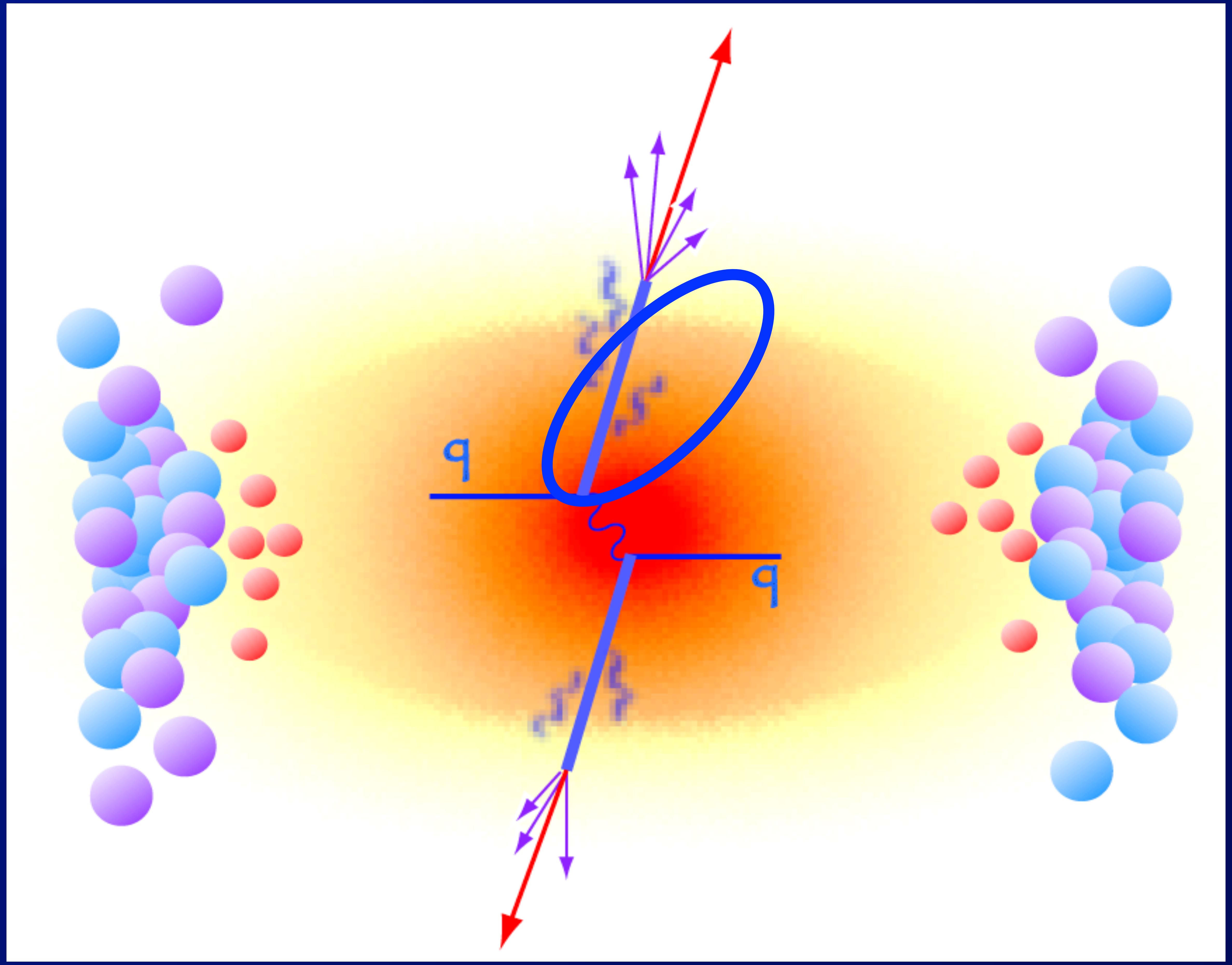


Coupling between ridge and hard-processes in pp

- Is there an R, A where we can see large angle (earliest radiated) fragments couple to the collective dynamics of the UE? i.e. flow

⇒Before the quenching effects start distorting the UE (wakes, …)

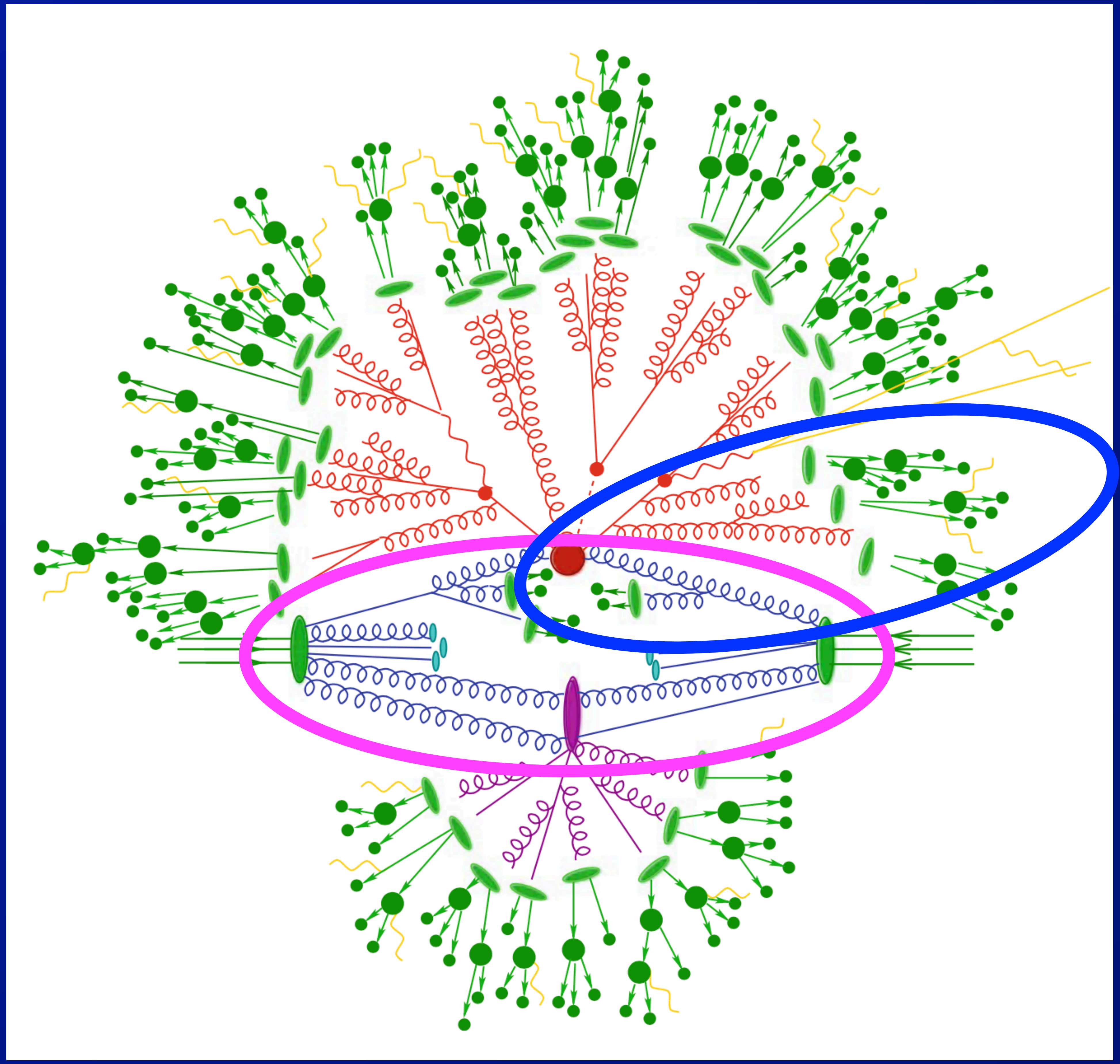


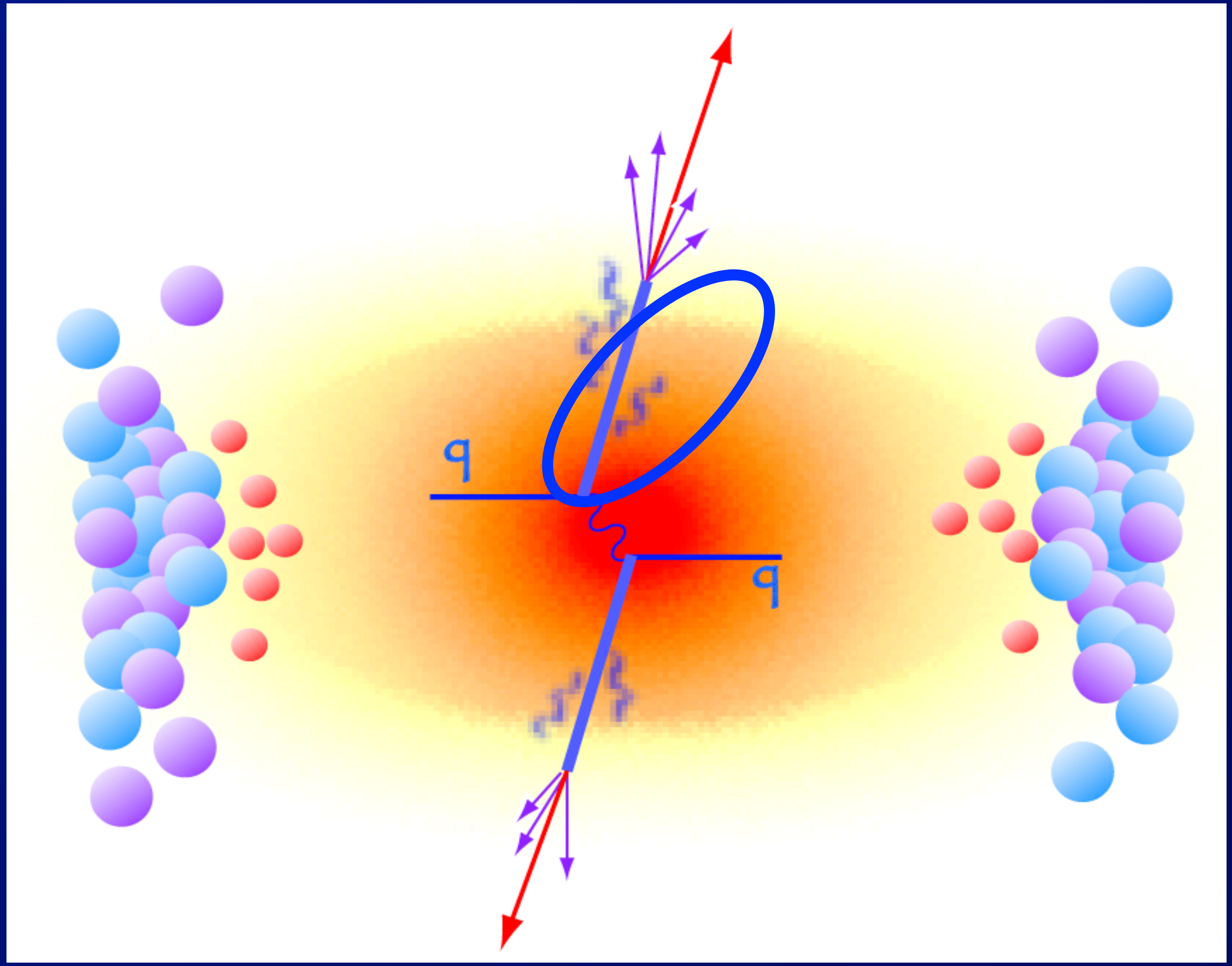


Coupling between ridge and hard-processes in pp

- Can we observe the onset of quenching?

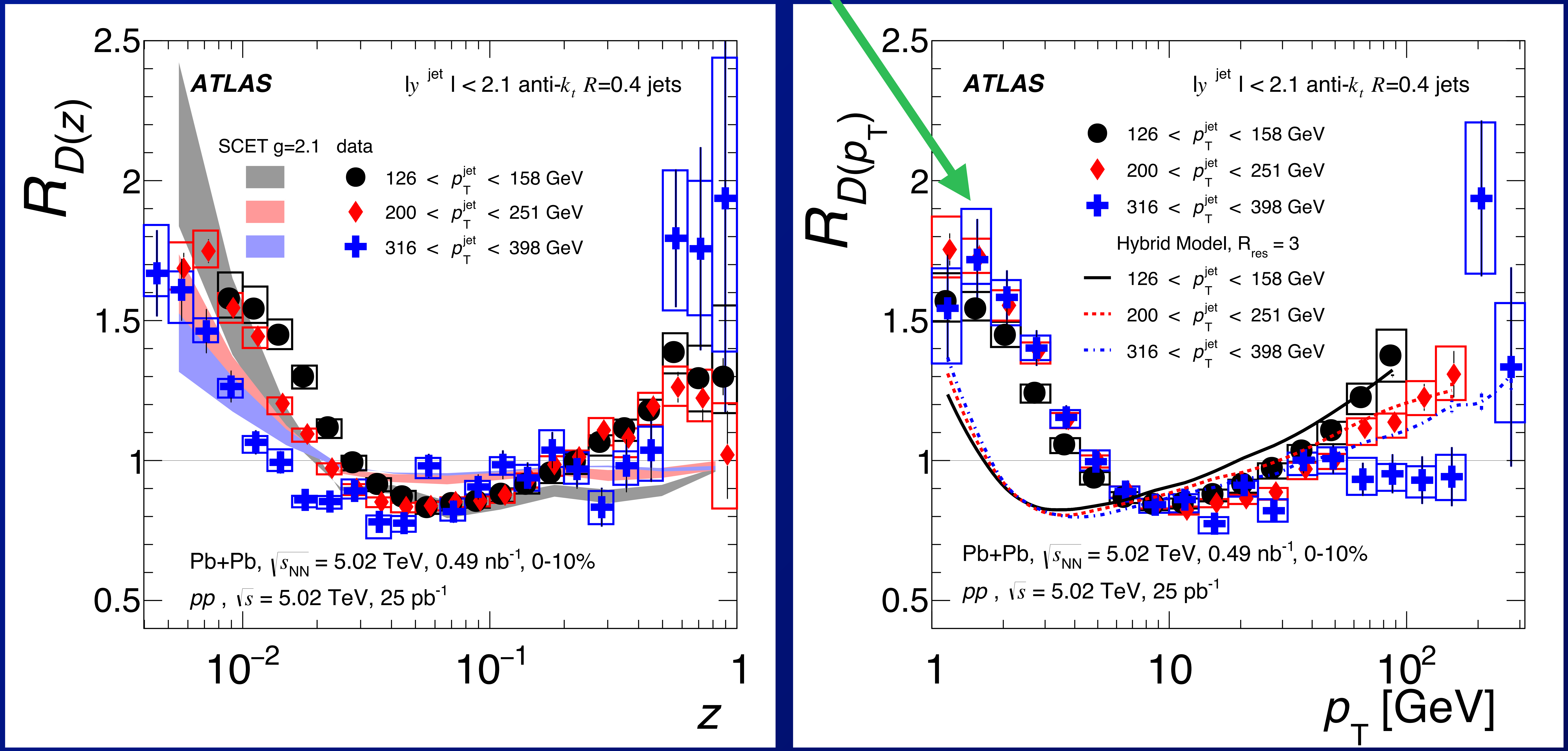
⇒ See first (with increasing R) in soft(er)/large-angle modes?





Fragmentation functions

- In Pb+Pb, see modifications at large z, mostly due to q/g quenching
  - Substantial increase in low-p_T modes



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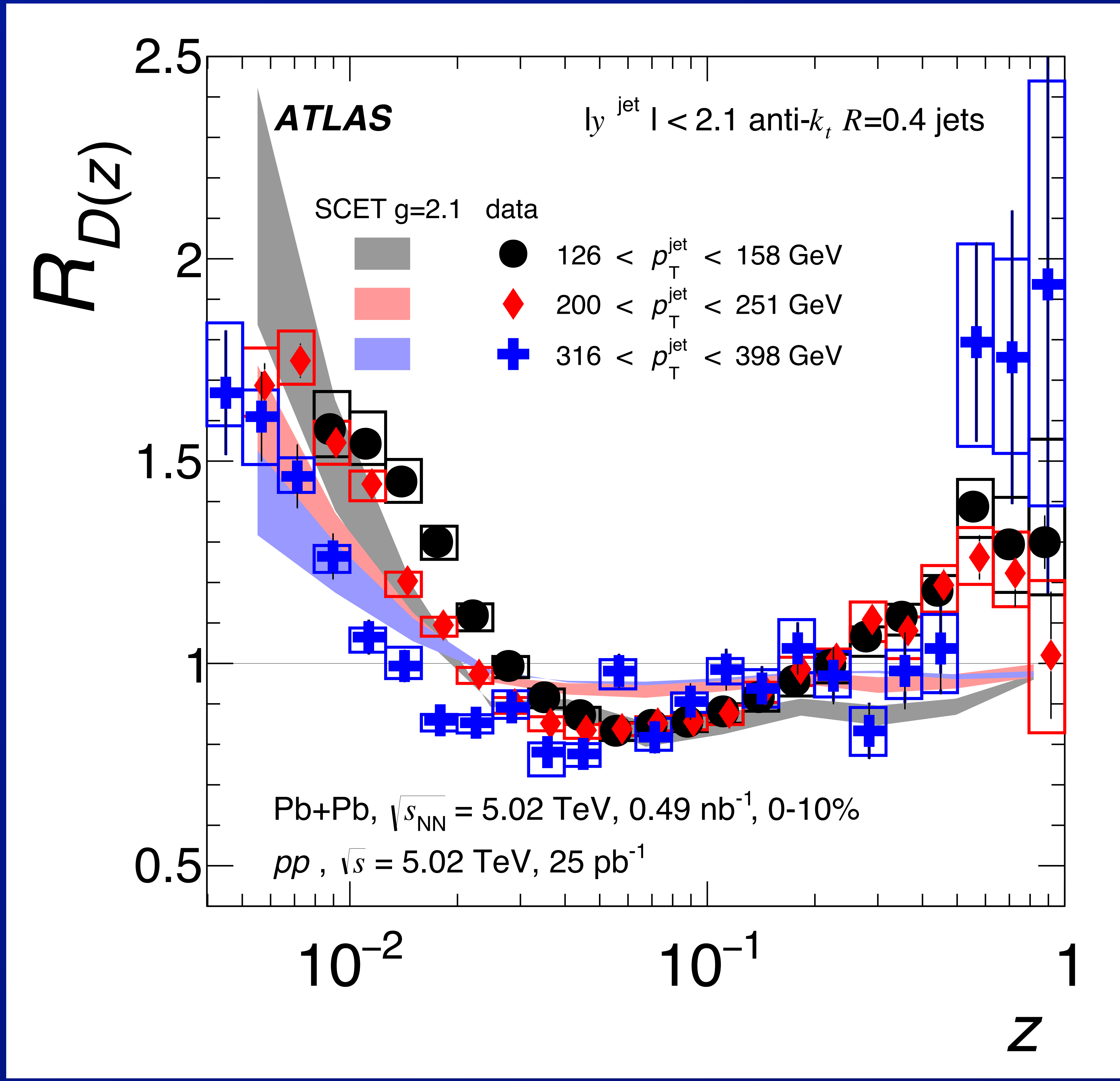
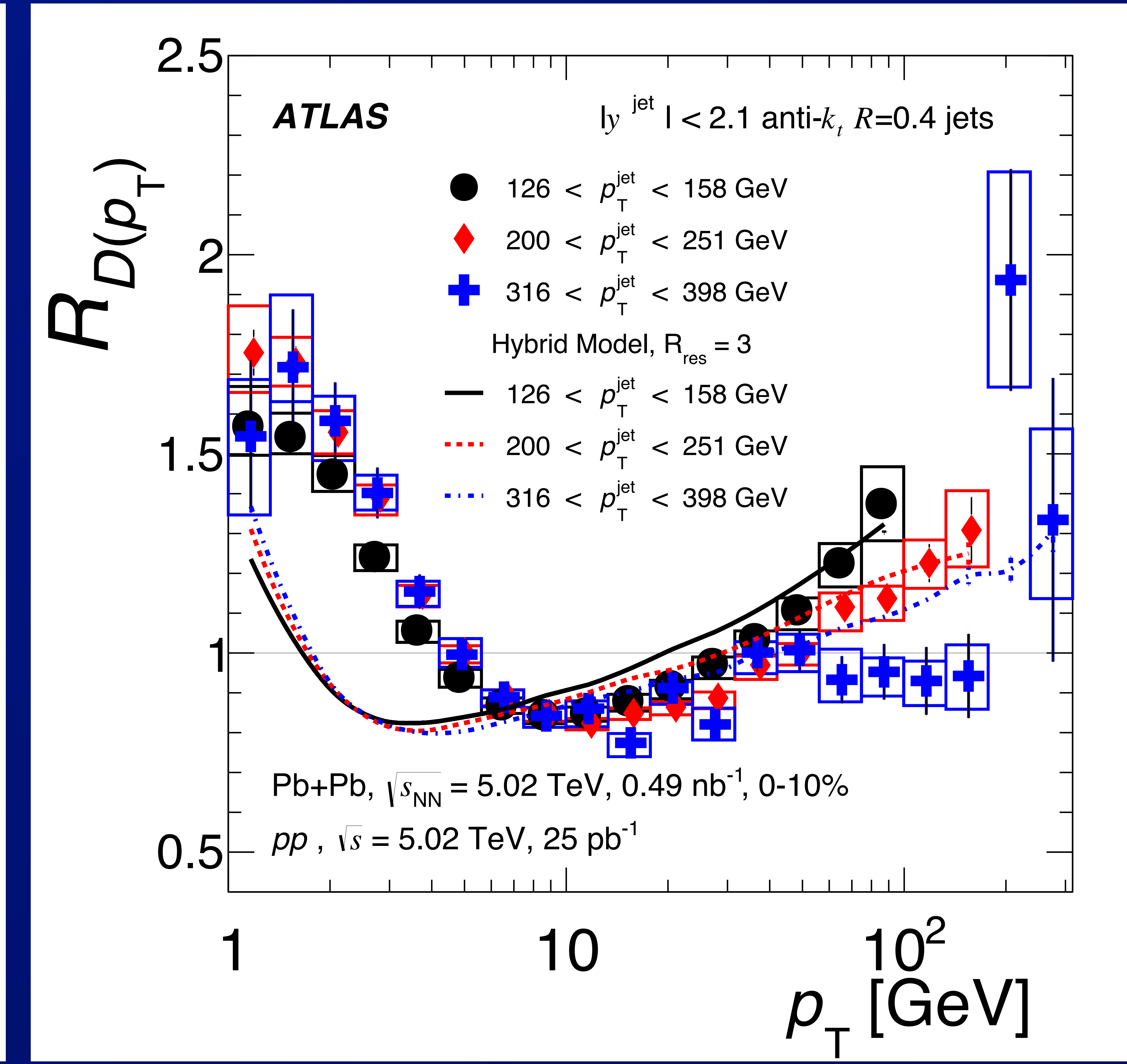
⇒ Probably complicated mix of PS modifications and medium response





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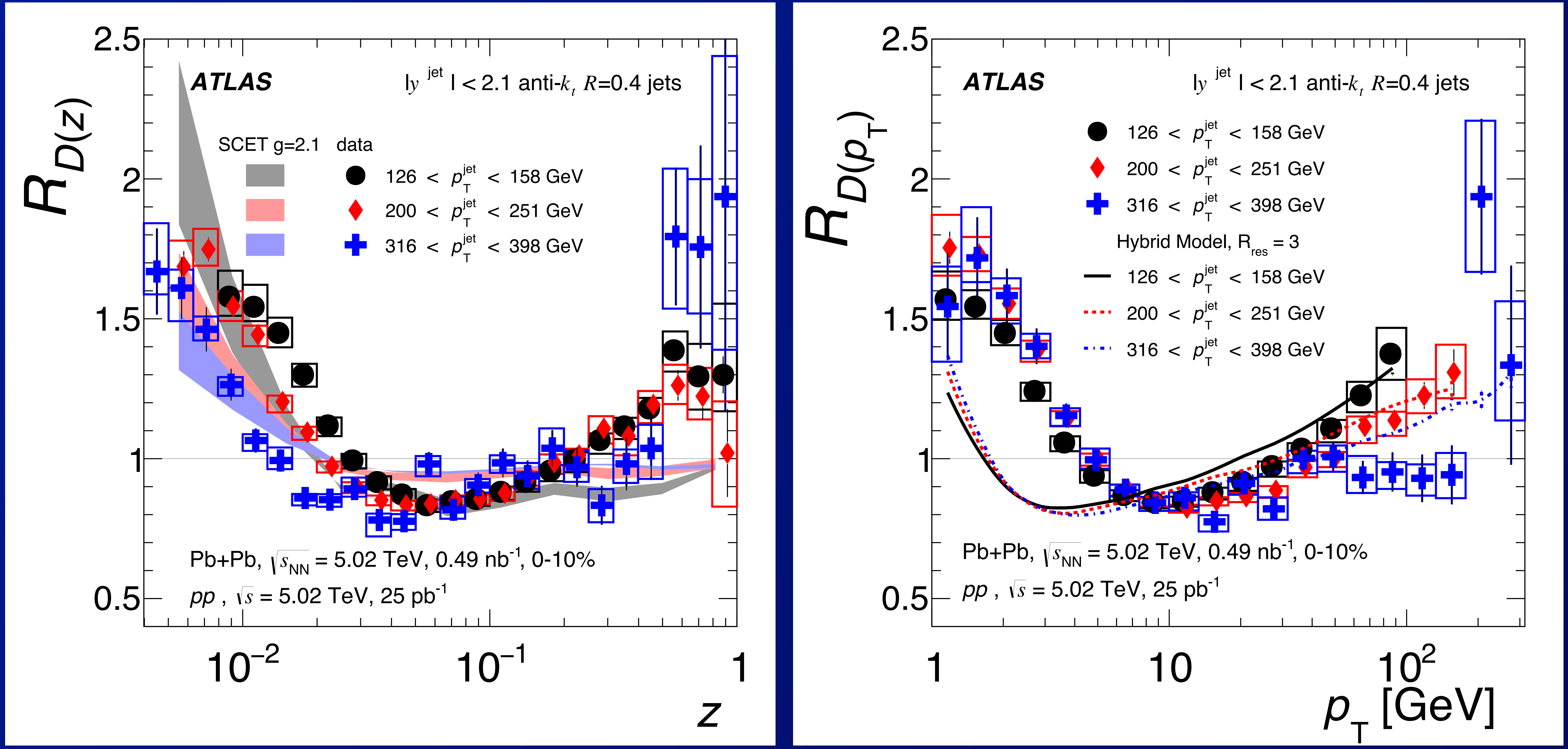
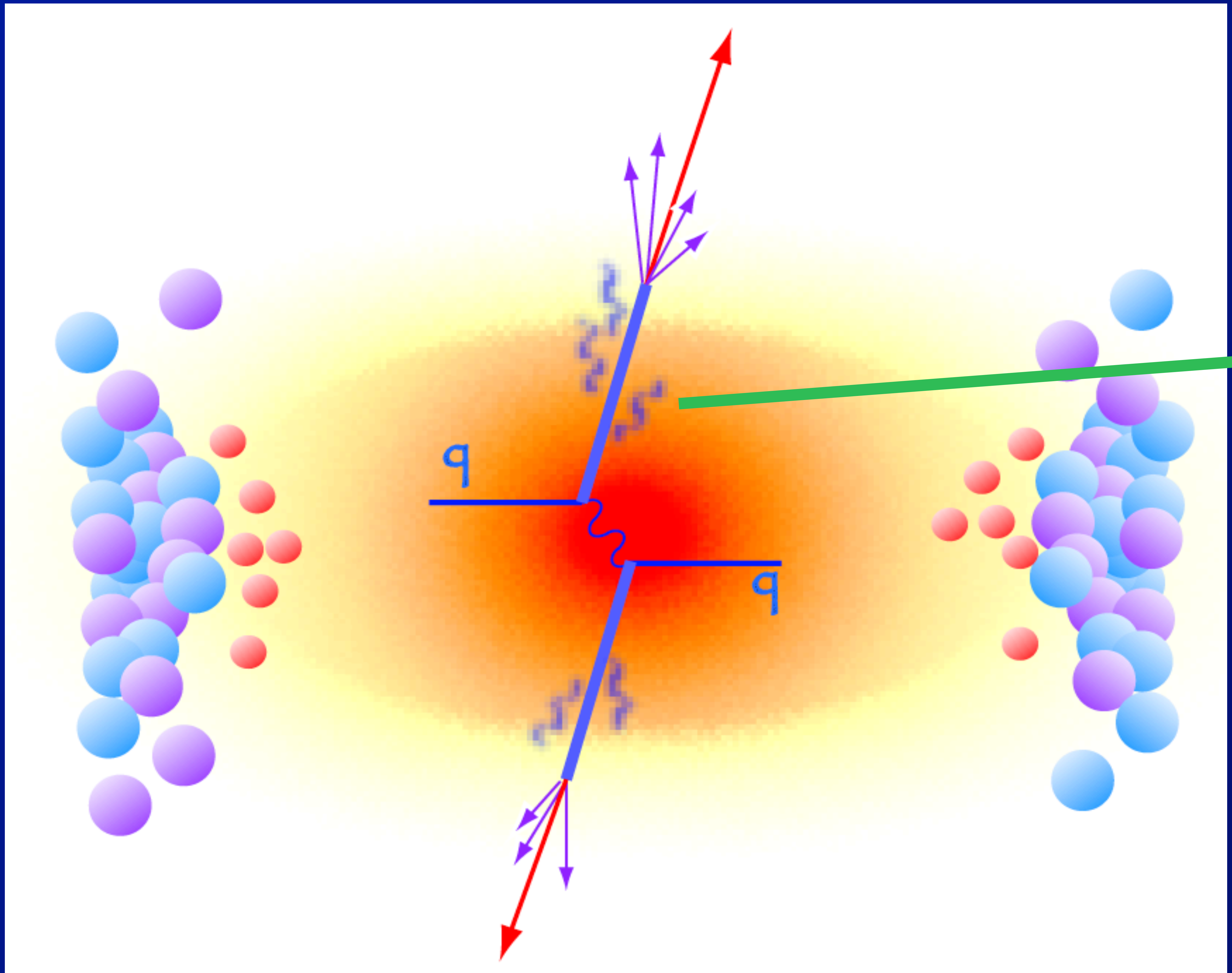
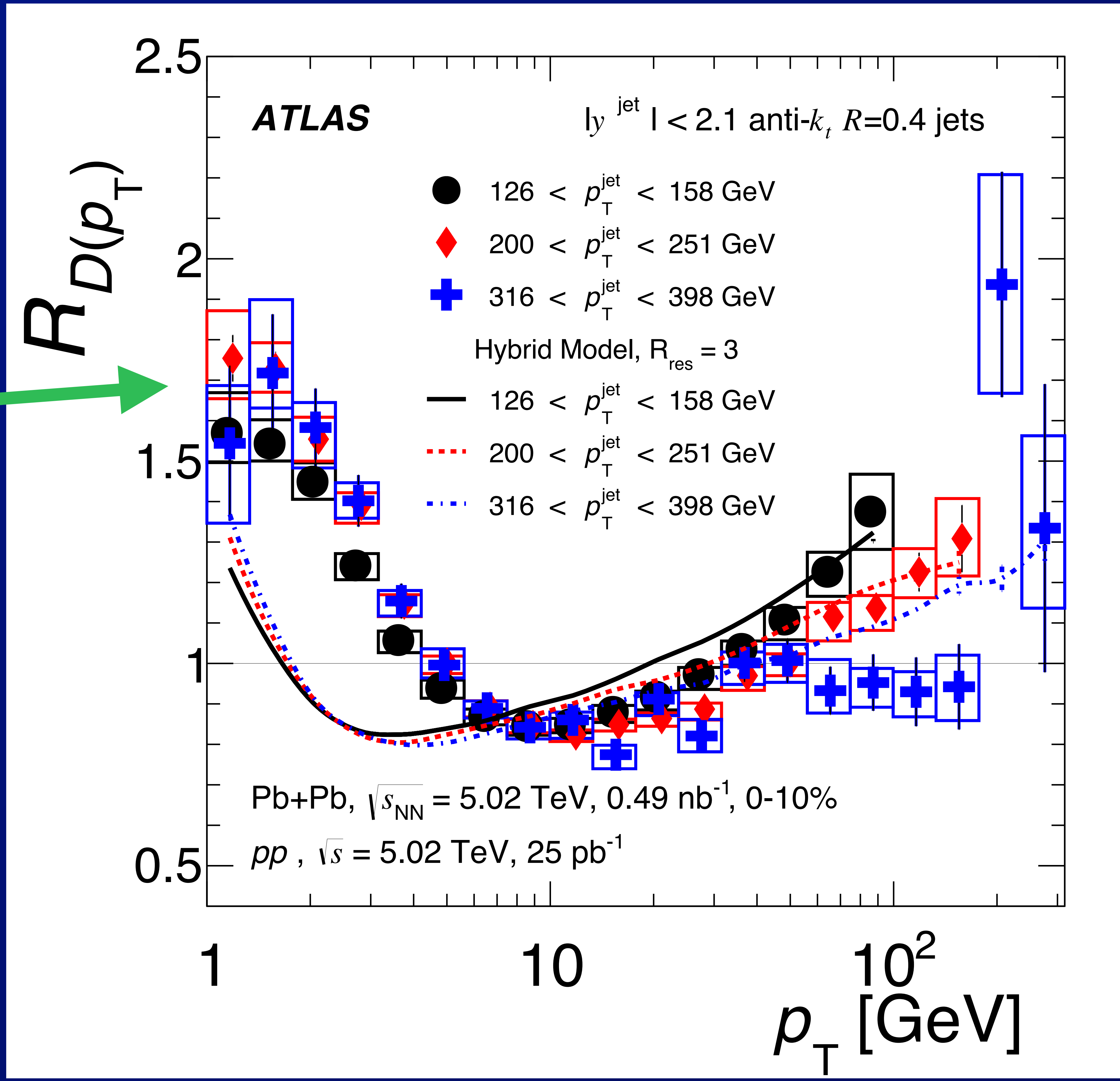
⇒p_T range and experimental systematics limited by large UE



Fragmentation functions

- **In light ion collisions:**
  - Smaller UE → small systematic uncertainties, go to lower p_T
  - ⇒ Also going to lower jet p_T, plenty of statistics(?), but how large effect?

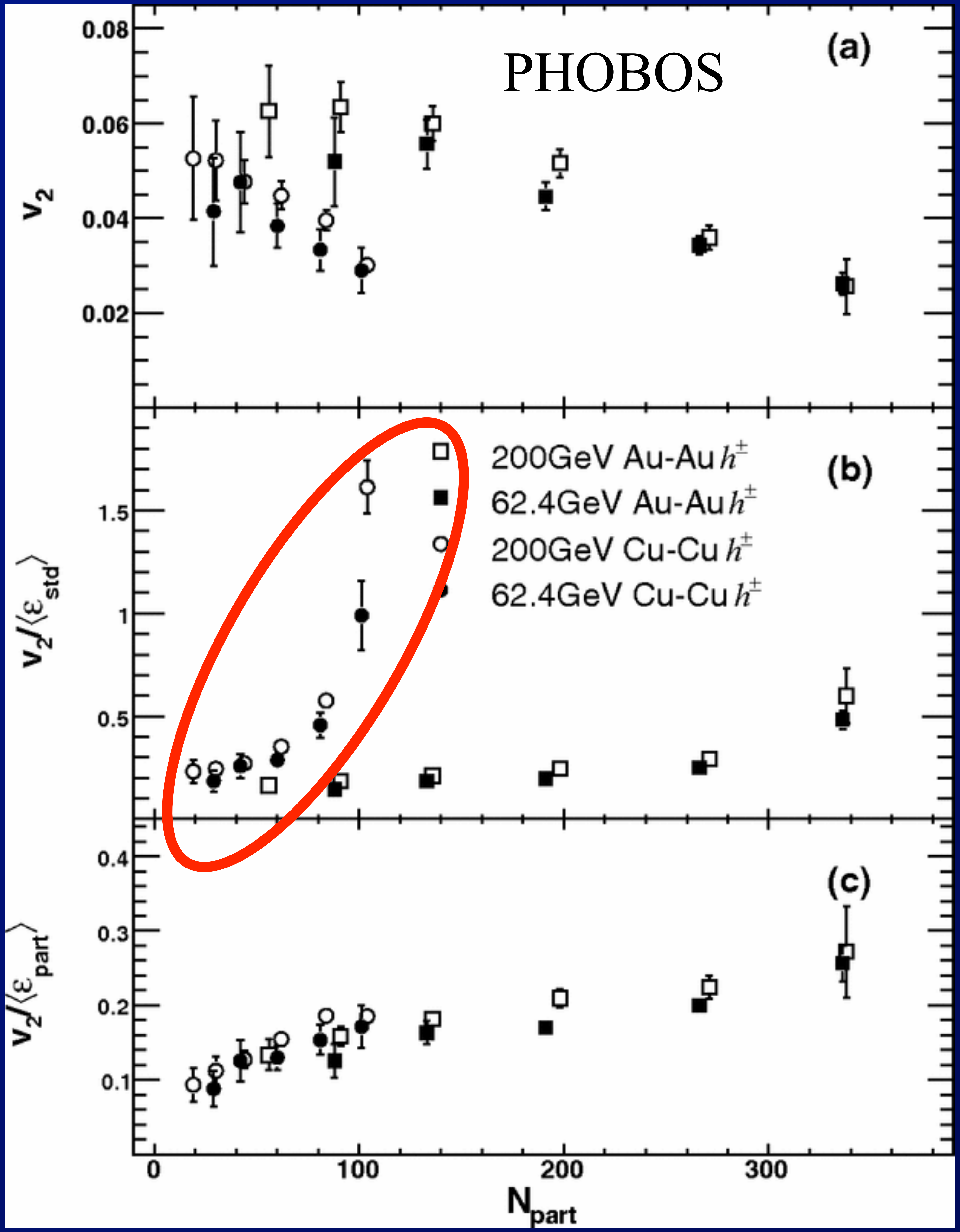




Collectivity and thermalization

Some history …

- It's worth remembering the impact of the 1st small system flow measurement @ RHIC
  - ⇒ Unexpectedly large v_2 in central Cu+Cu
- Led to paradigm shift in the field
  - ⇒Role of nucleon structure in determining the initial-state eccentricities
    - » It only took us another 5 years to realize that the resulting fluctuations could produce odd harmonics …
- Could O+O collisions produce similar breakthrough?
  - – See clearly the role of sub-nucleonic DOF?



Light ion systems: IS fluctuations

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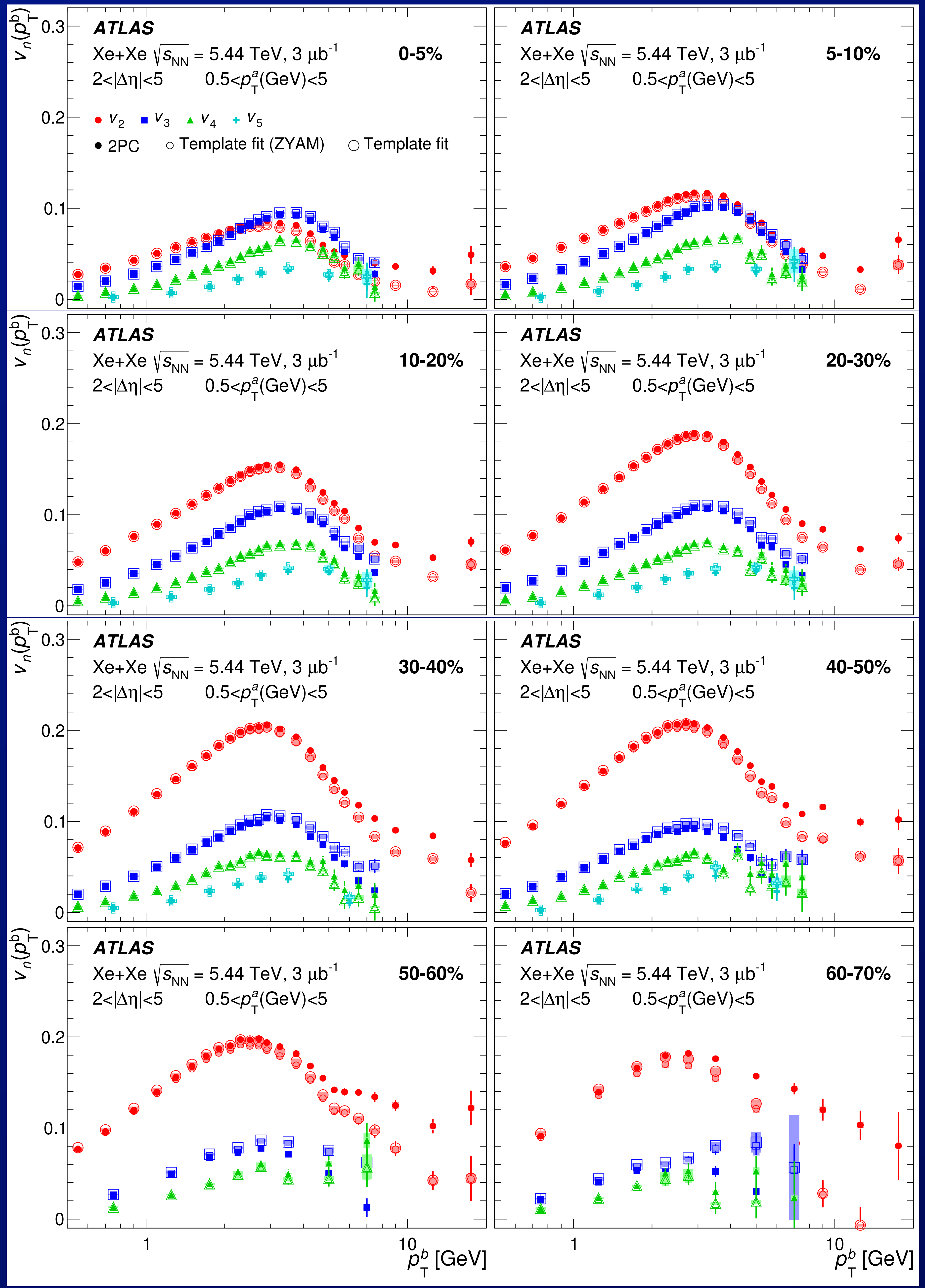
  - Momentum anisotropies (v_n)
- Non-flow effects become more important in smaller systems
  - ⇒ Already play a role in Xe+Xe collisions at higher p_T



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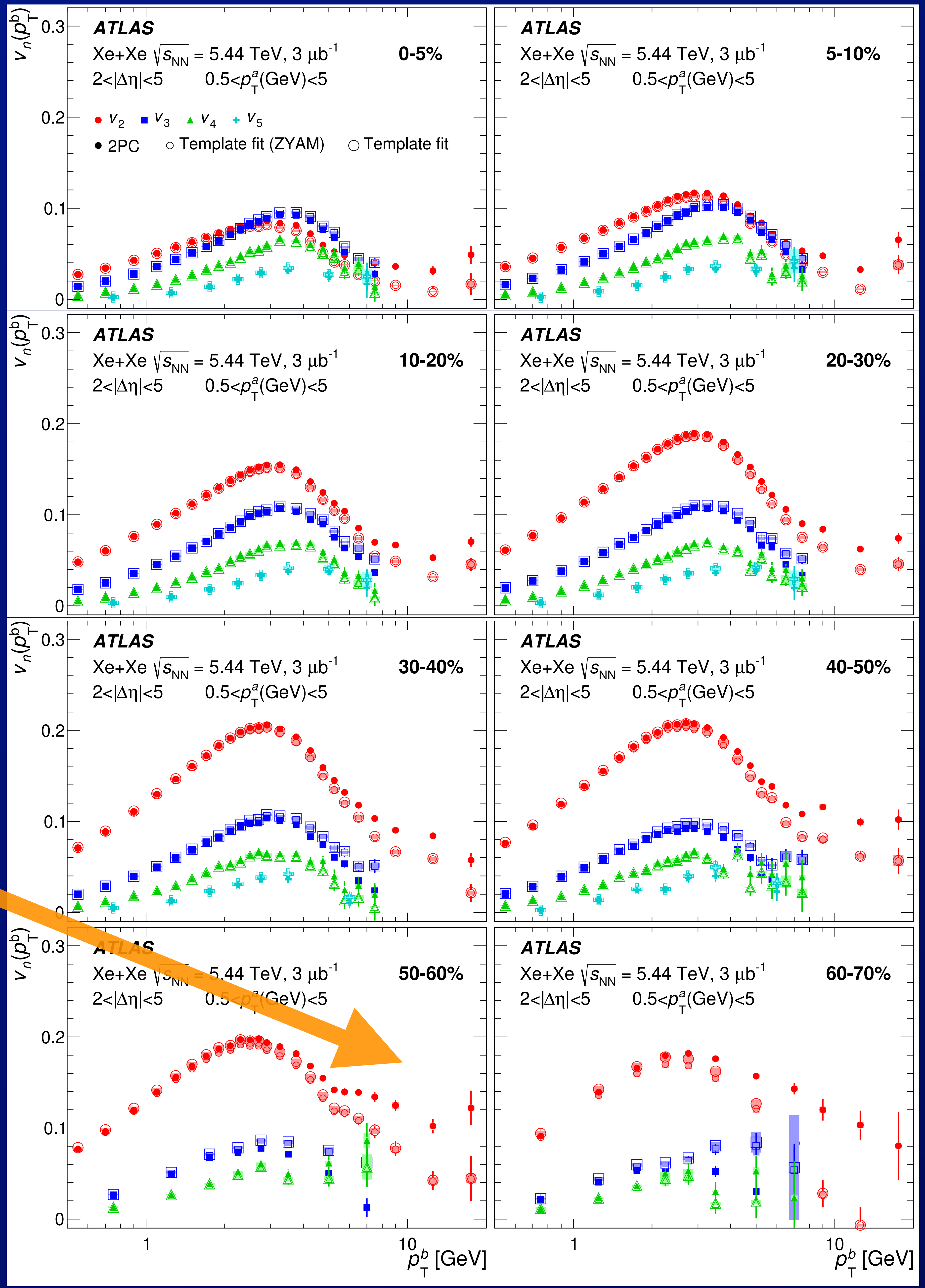

Light ion systems: IS fluctuations

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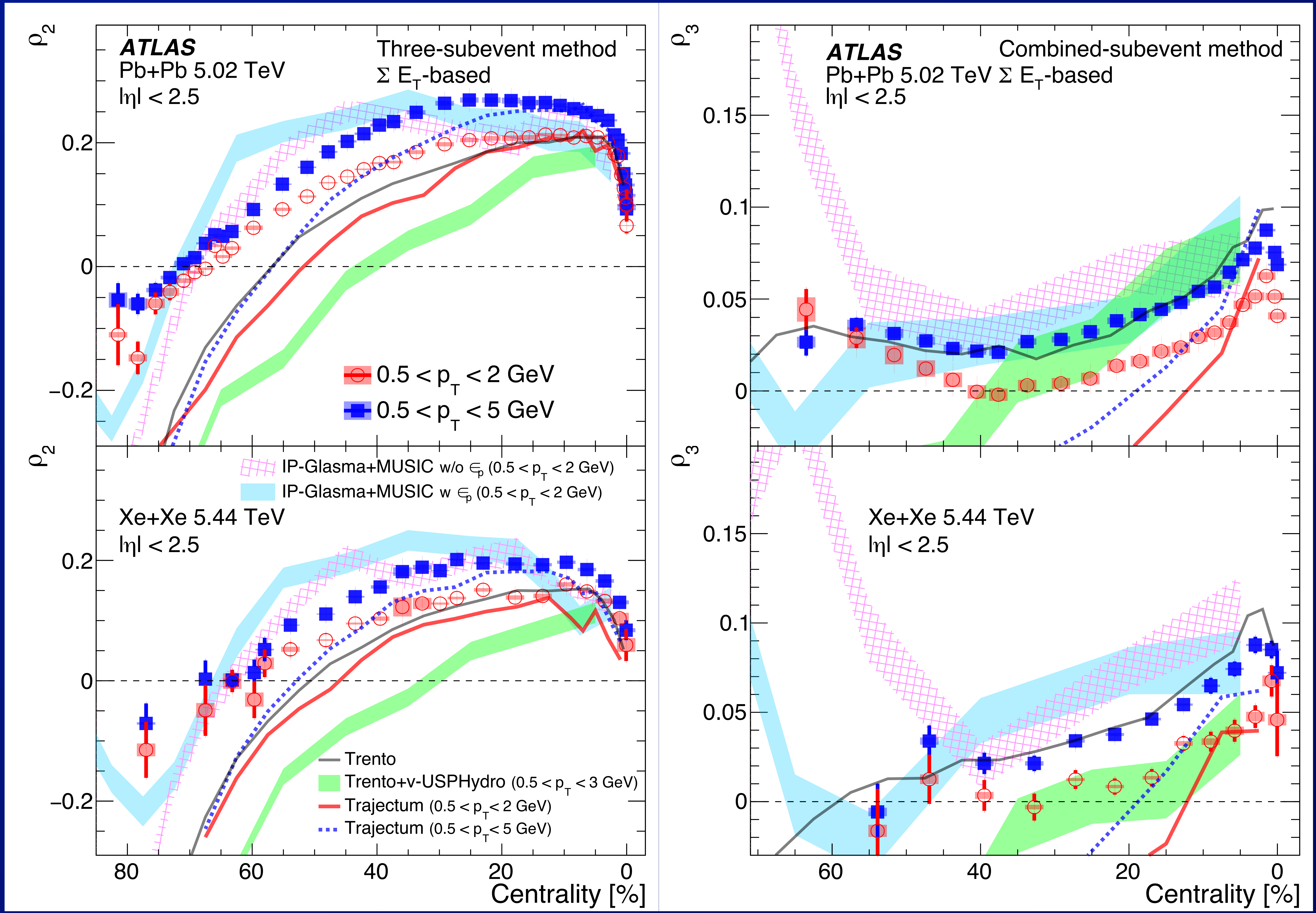
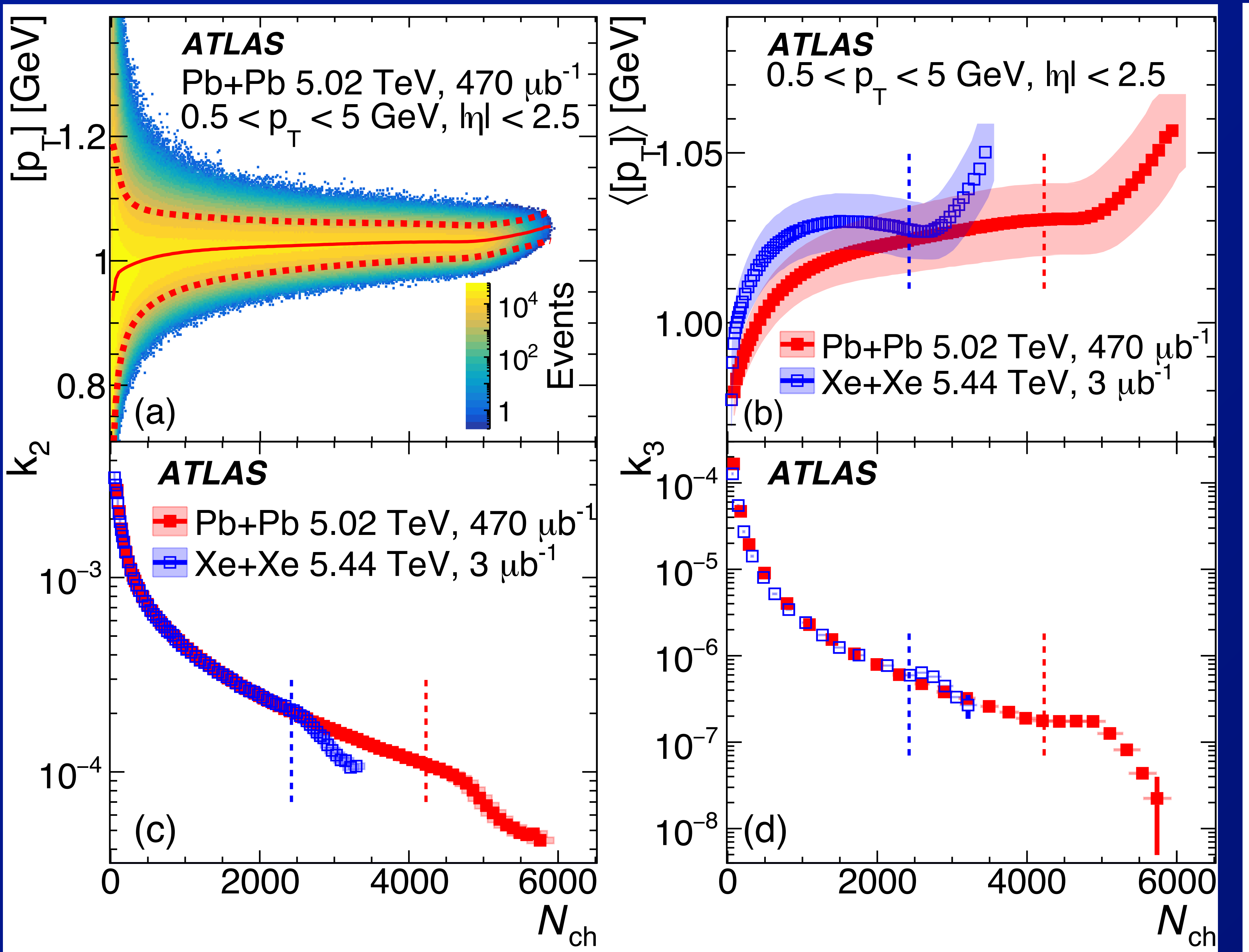
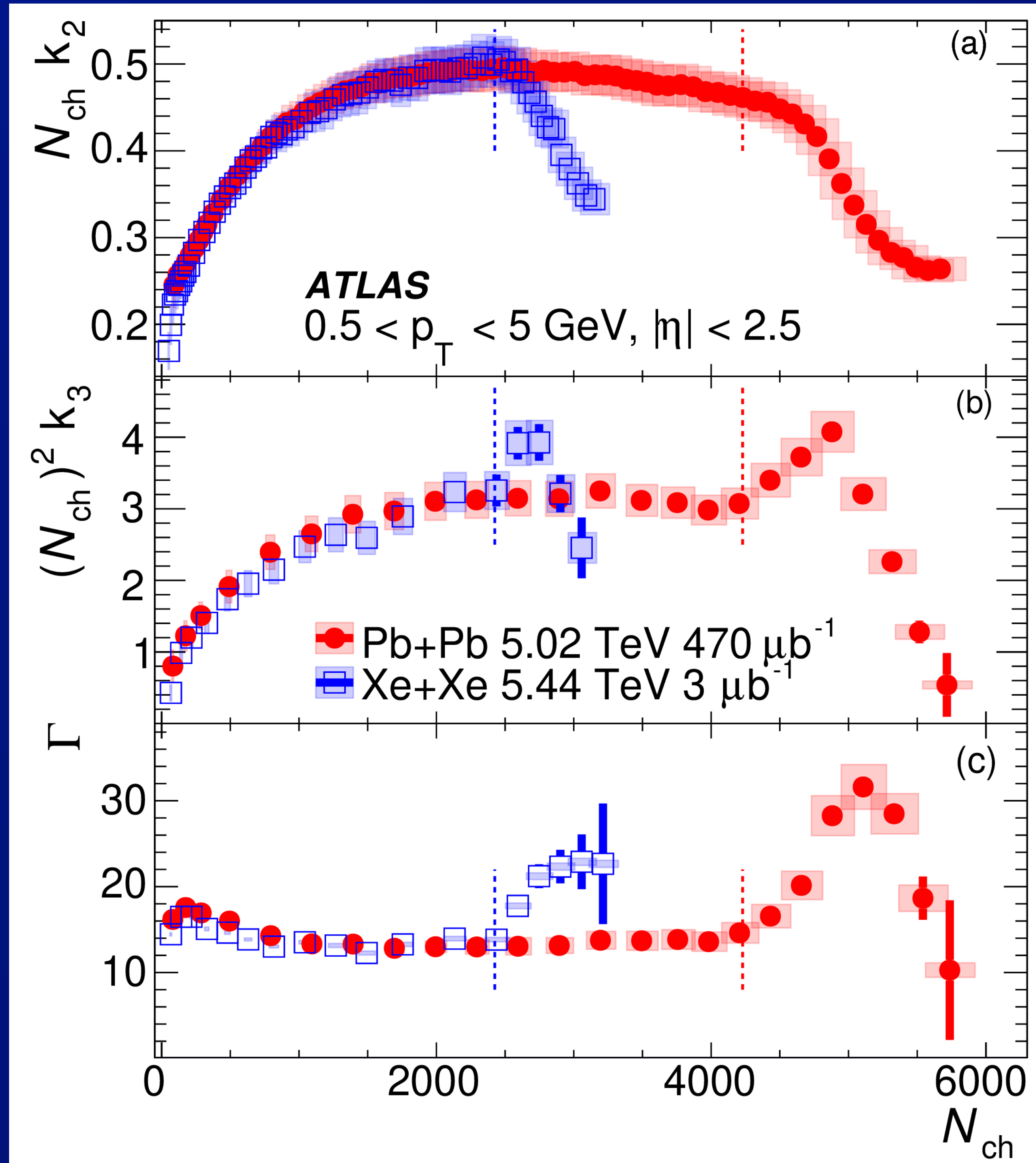
  - v_n - p_T correlations

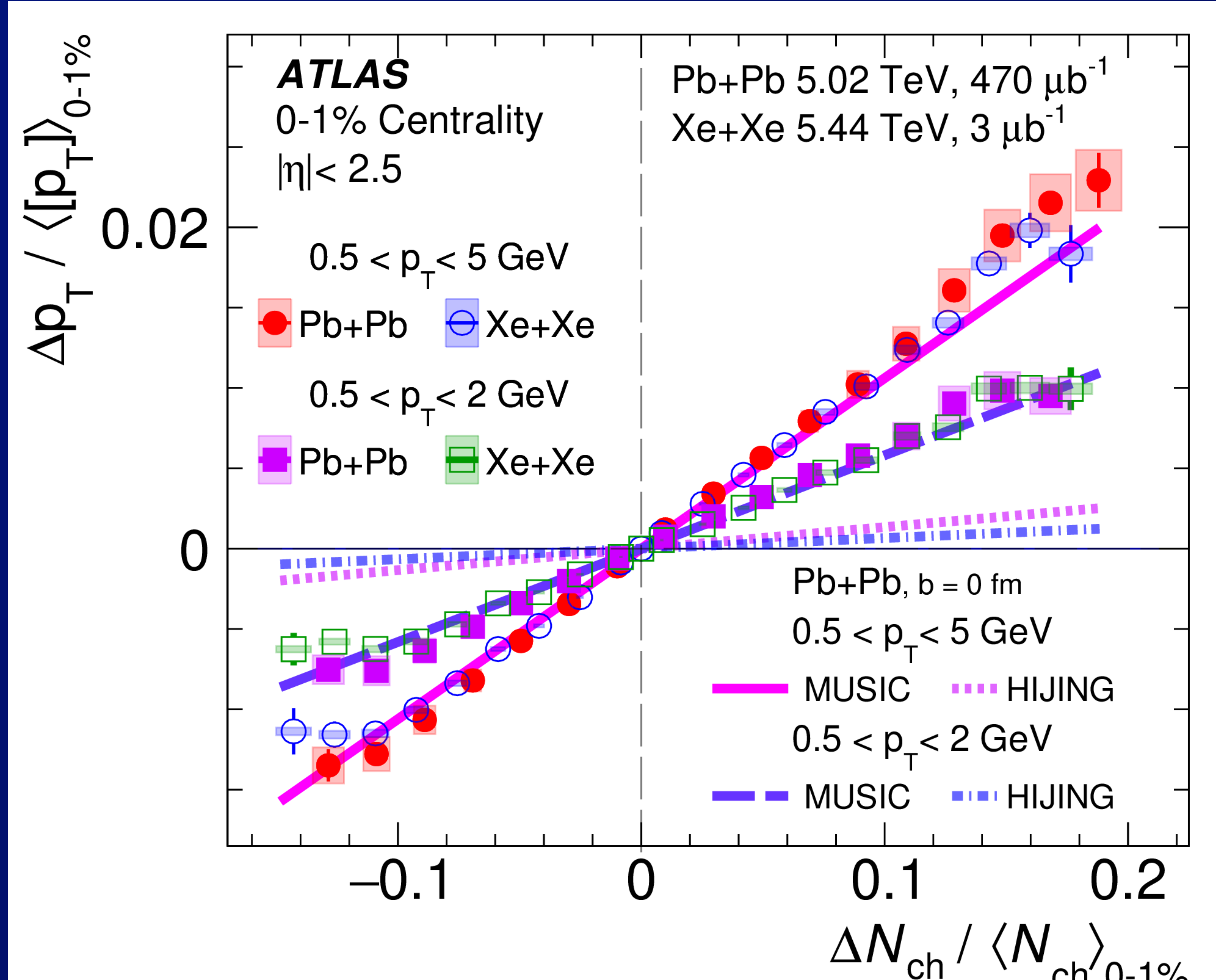


Light ion systems: IS fluctuations

- We know how to study experimentally:
  - [p_T] - multiplicity correlations
    - ⇒ Is the thermalization inefficient/slow in O+O collisions?
    - ⇒ Do hot spots complicate the hydrodynamic response?
    - ⇒ Or make it more interesting?
      - » Will we have enough O+O and/or [x]+[x] statistics to answer?







Light ion systems: IS fluctuations

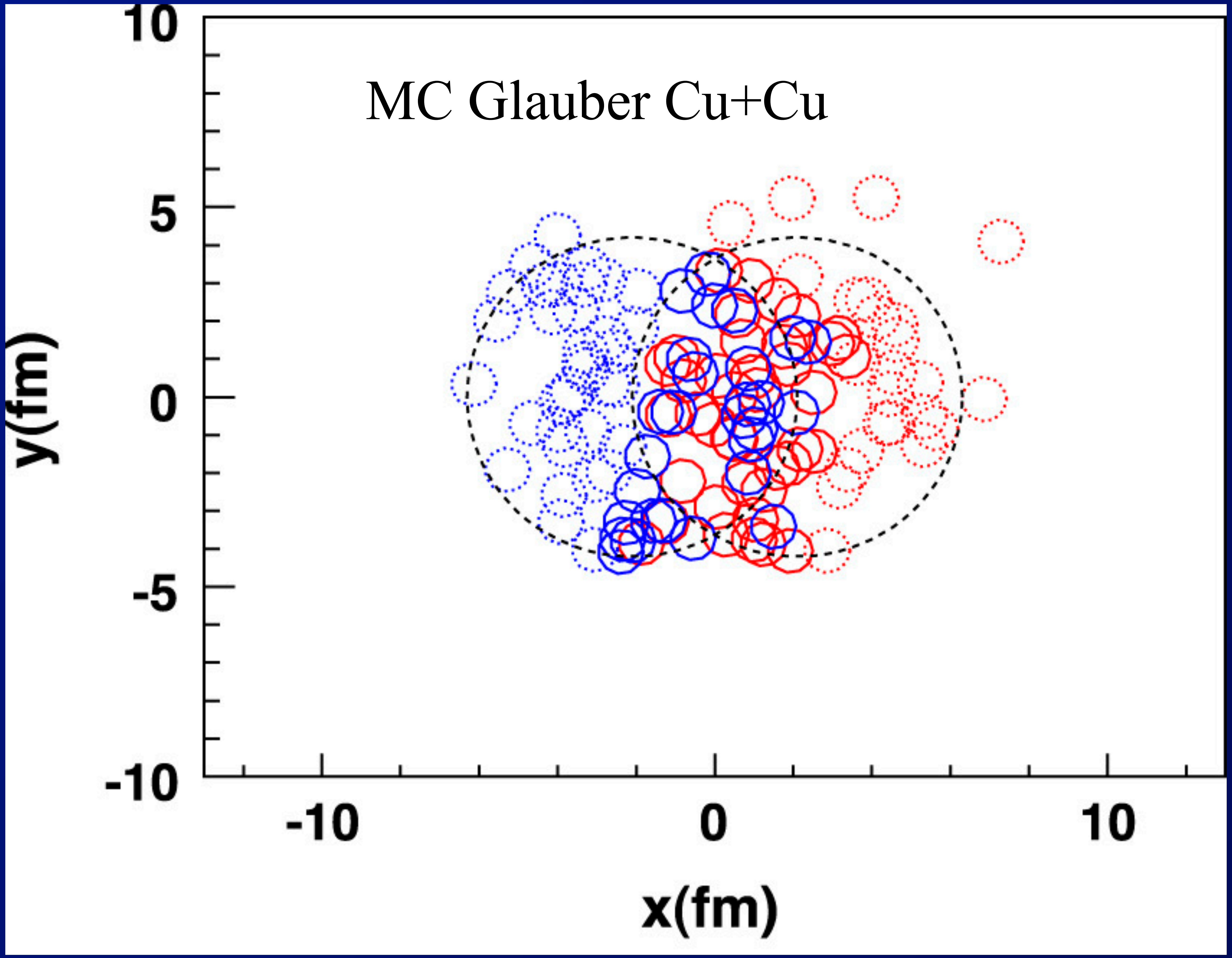
- New ideas to study experimentally:

$\Rightarrow$ History of the field suggests these are highly likely …

Light ion systems: IS fluctuations

- **Separating participant from sub-nucleonic fluctuations?**
  - In light ion collisions will have strong participant fluctuations
  - How to distinguish from other sources of IS variations (hot spots)

  ⇒ If only we had detectors that could tell us # participants …



Ultra-peripheral collisions

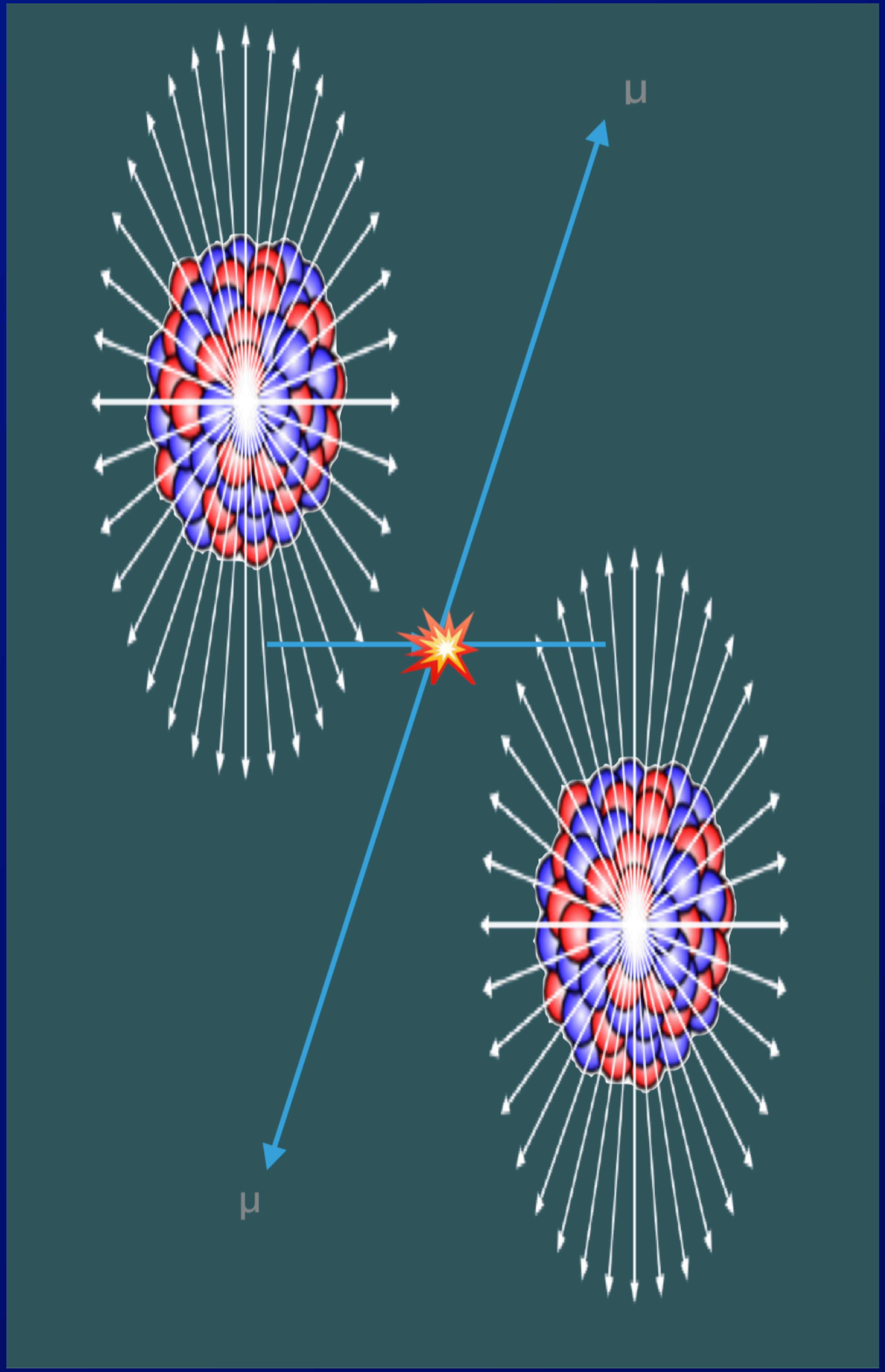
UPC and light ion collisions

- Photon fluxes scale as z^2
- Then, approximately:
  - $\sigma_{\gamma A} \propto z^2 A$ — in O+O, factor 10^3 < than Pb+Pb
  - $\sigma_{\gamma\gamma} \propto z^4$ — in O+O, factor of 10^4 < than Pb+Pb

  ⇒ Why even discuss?

- UPC processes provide unique probe of "nuclear structure"
  - Both strong and electromagnetic probes

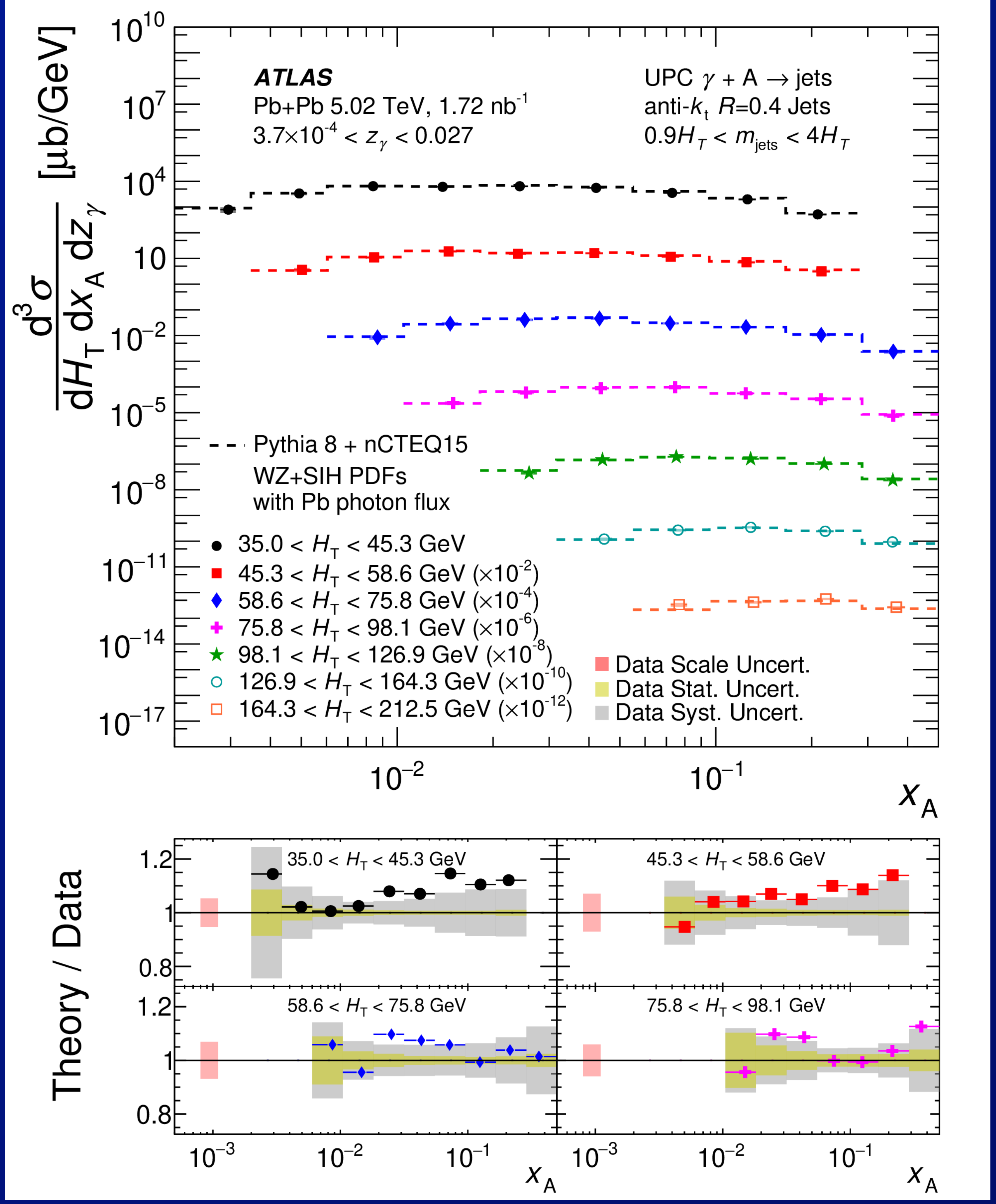
  ⇒ At hard, intermediate, and soft scales

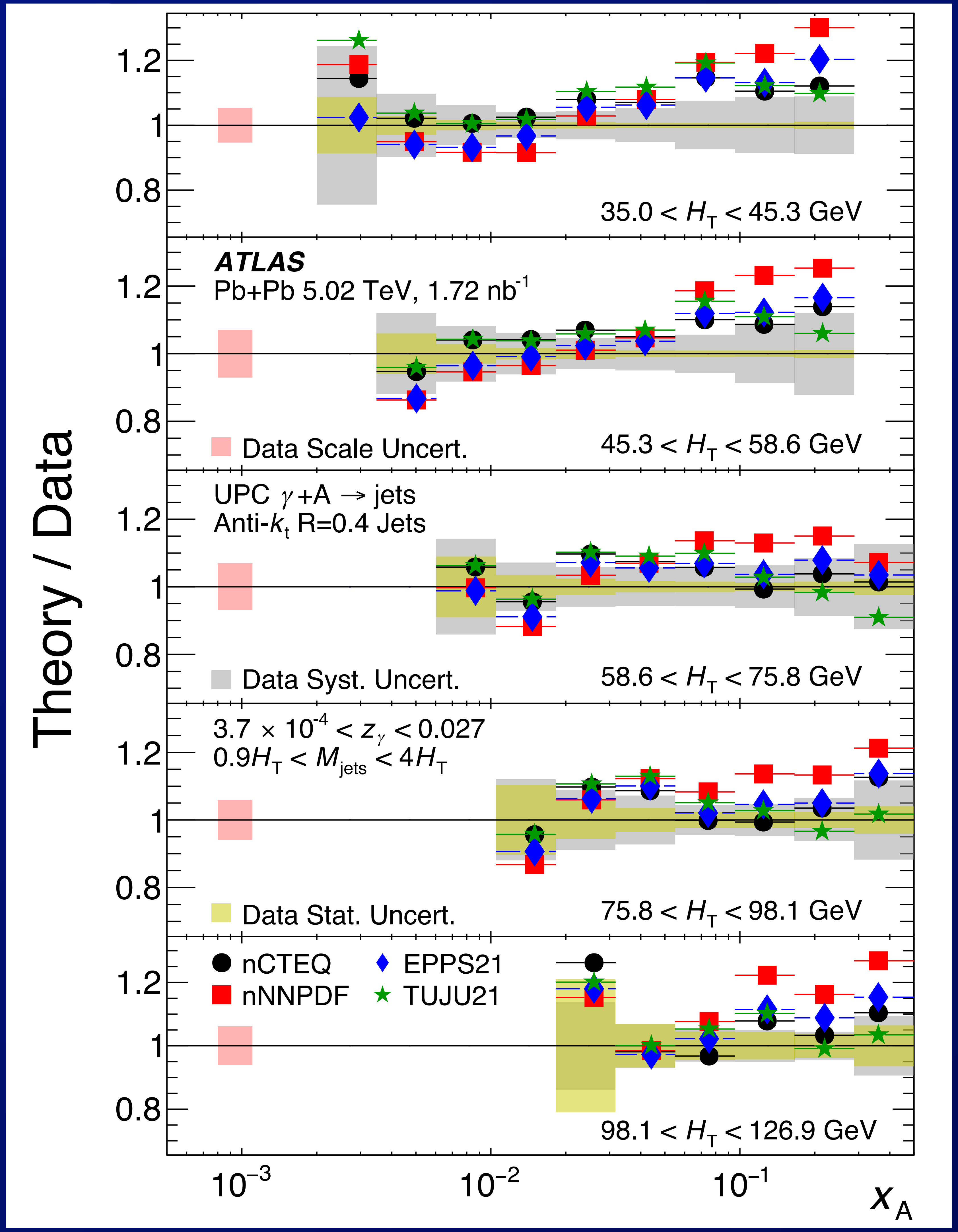


UPC and light ion collisions, hard scales

- Direct probe of nuclear PDFs with $\gamma + A \rightarrow$ jets
  - Realized in Pb+Pb with recent paper

  ⇒ Just the beginning
- We need better data for lighter nuclei
  - Ideally with multiple measurements covering different kinematics





UPC and light ion collisions, hard scales

- Direct probe of nuclear PDFs with $\gamma + A \rightarrow$ jets
  - Realized in Pb+Pb with recent paper

  $\Rightarrow$ Just the beginning
- We need better data for lighter nuclei

  $\Rightarrow$ Additional motivation …

PHYSICAL REVIEW LETTERS **133,** 152502 (2024)

Modification of Quark-Gluon Distributions in Nuclei by Correlated Nucleon Pairs

A. W. Denniston,[1,*] T. Ježo,[2,†] A. Kusina,[3] N. Derakhshanian,[3] P. Duwentäster,[2,4,5] O. Hen,[1] C. Keppel,[6] M. Klasen,[2,7] K. Kovařík,[2] J. G. Morfín,[8] K. F. Muzakka,[2,9] F. I. Olness,[10] E. Piasetzky,[11] P. Risse,[2] R. Ruiz,[3] I. Schienbein,[12] and J. Y. Yu.[12]

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[9]*Institut für Energie- und Klimaforschung, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
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(Received 15 January 2024; revised 19 April 2024; accepted 7 August 2024; published 11 October 2024)

We extend the QCD Parton Model analysis using a factorized nuclear structure model incorporating individual nucleons and pairs of correlated nucleons. Our analysis of high-energy data from lepton deep-inelastic scattering, Drell-Yan, and *W* and *Z* boson production simultaneously extracts the universal effective distribution of quarks and gluons inside correlated nucleon pairs, and their nucleus-specific fractions. Such successful extraction of these universal distributions marks a significant advance in our understanding of nuclear structure properties connecting nucleon- and parton-level quantities.

DOI: 10.1103/PhysRevLett.133.152502

UPC and light ion collisions, hard scale

- **Direct probe of nuclear PDFs with $\gamma + A \to$ jets**
  - We will not be able to do this in O+O sadly
  - ⇒ But the lack of data on smaller nuclei may affect O+O physics impact
- **In a future A>16 light ion program**
  - ⇒ Should ensure that we have enough luminosity for such a measurement

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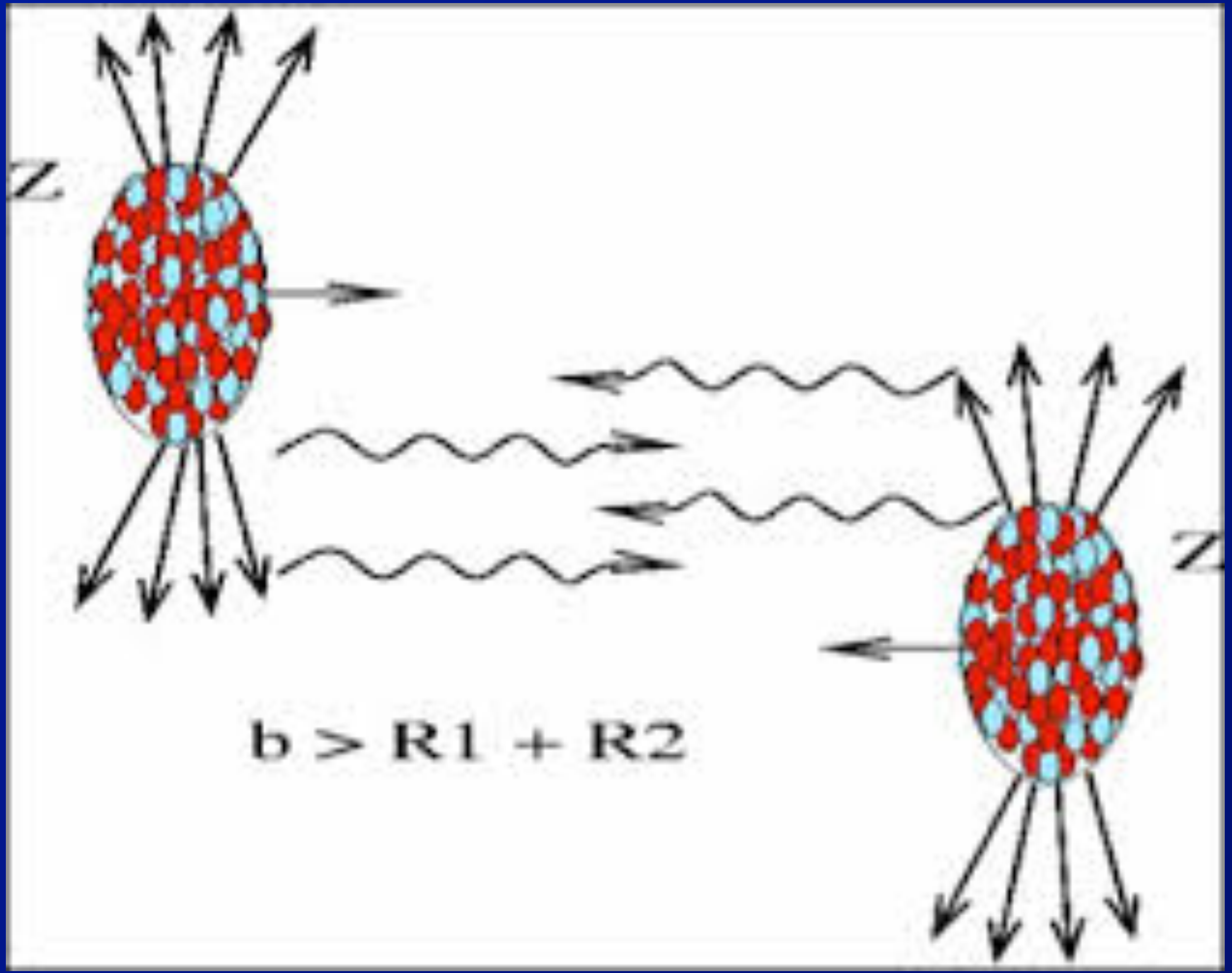
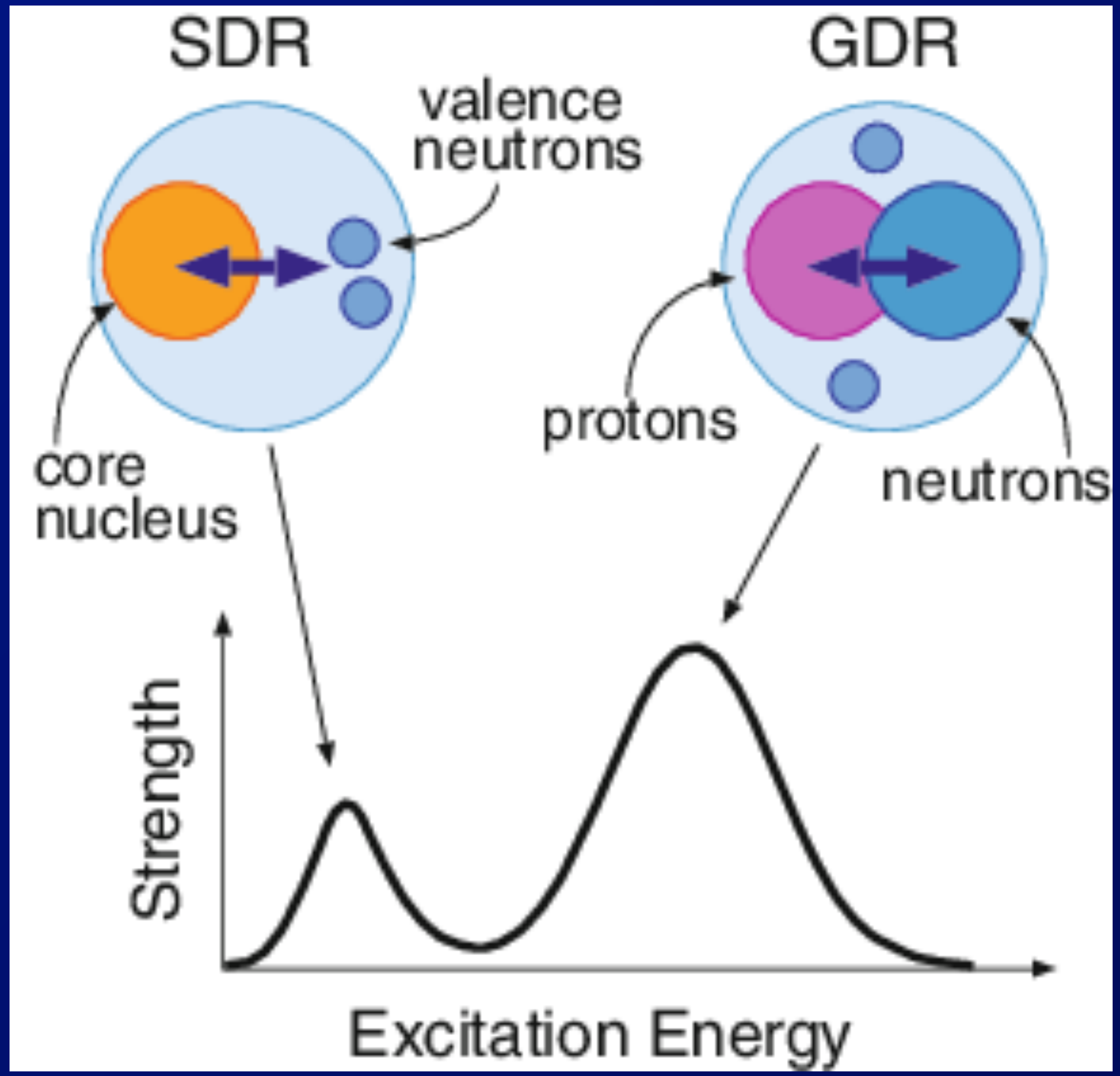
UPC and light ion collisions, very soft scales

- **Nuclear breakup in UPC processes dominated by GDR**
  - Collective (separate) oscillation of protons and neutrons
  - Old result in nuclear physics:

⇒GDR accounts for nearly 100% of the electric dipole EM SR

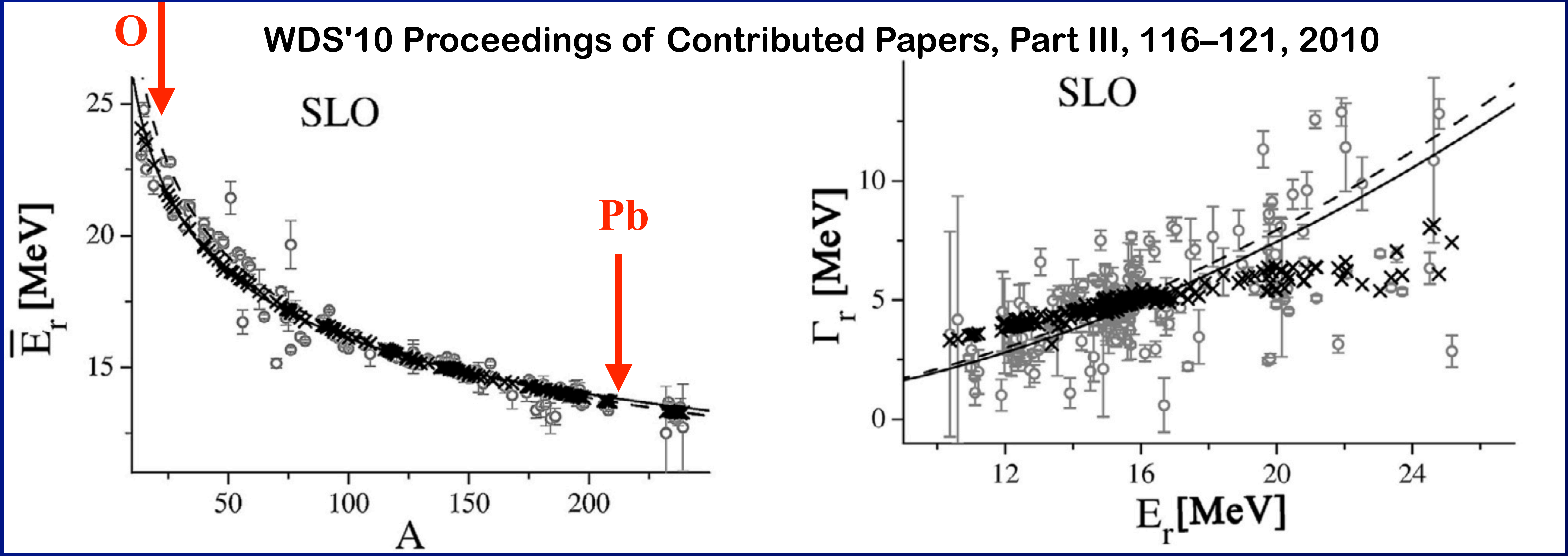




UPC and light ion collisions, very soft scales

- GDR excitation energy and width varies significantly with A
  - Use measurements of EM dissociation in O+O, other light ion collisions to test our ability to predict nuclear breakup processes

  ⇒ Especially their impact parameter dependence (esp. interesting in O+O?)
- Should be an easy measurement in any A+A with ZDCs

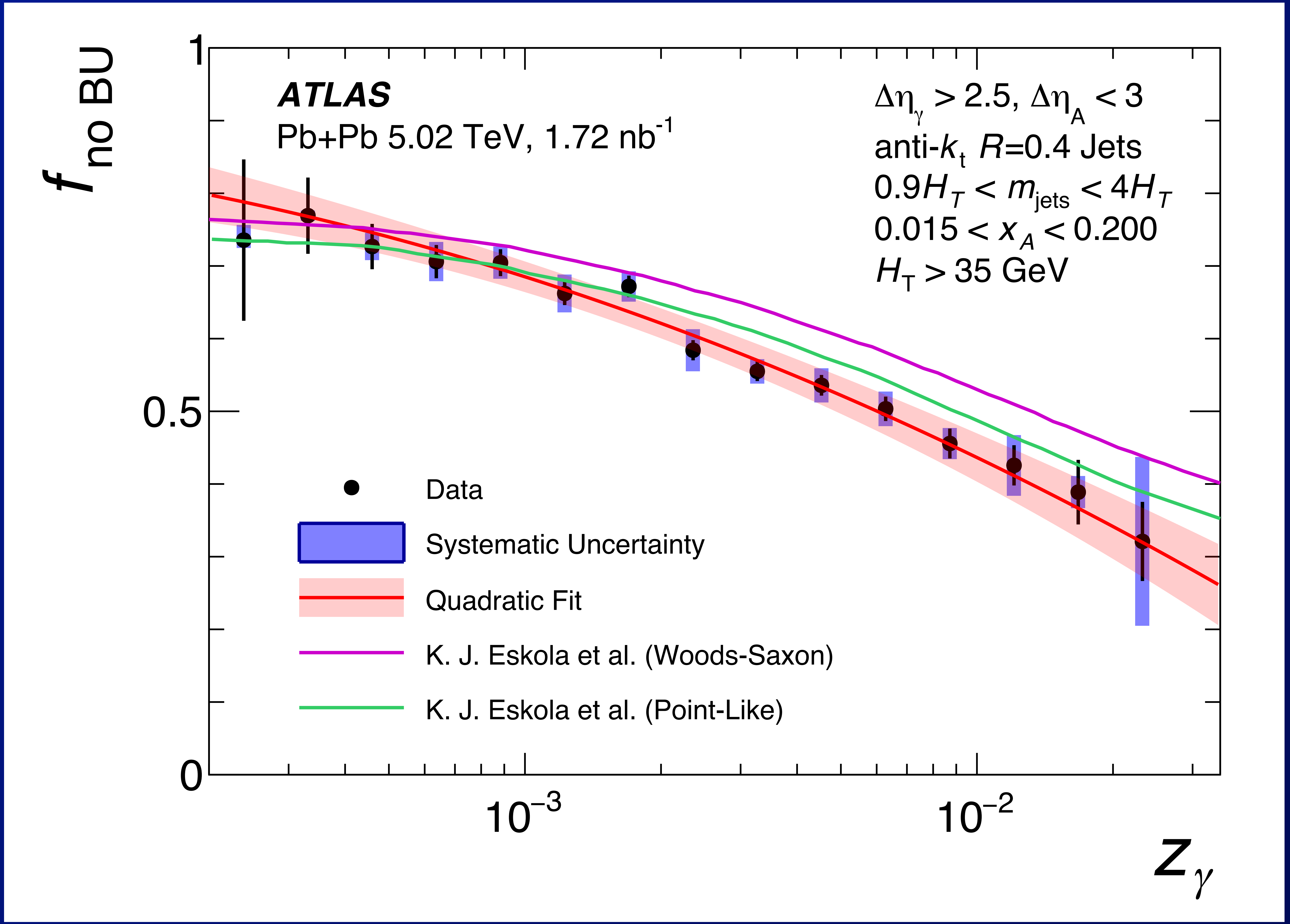


Light ion collisions, EM dissociation

- Testing our understanding of EM dissociation processes important for many different UPC measurements:

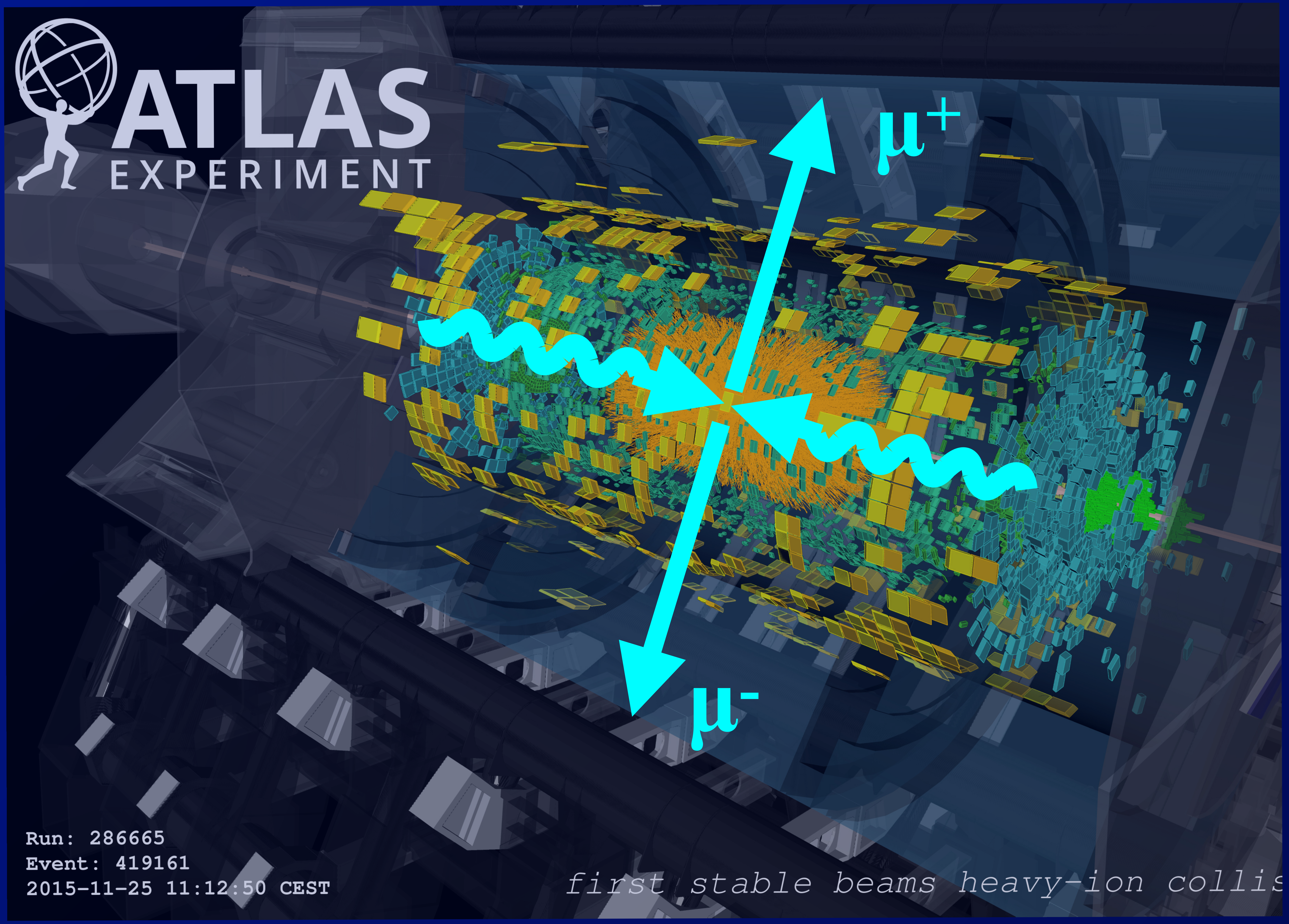
  ⇒e.g. UPC dijets

From UPC dijet paper, https://arxiv.org/abs/2409.11060



UPC and light ion collisions, ~ soft scales

- Measurements of $\gamma + \gamma \rightarrow l^+l^-$ in hadronic A+A collisions probe EM structure of parent nuclei:



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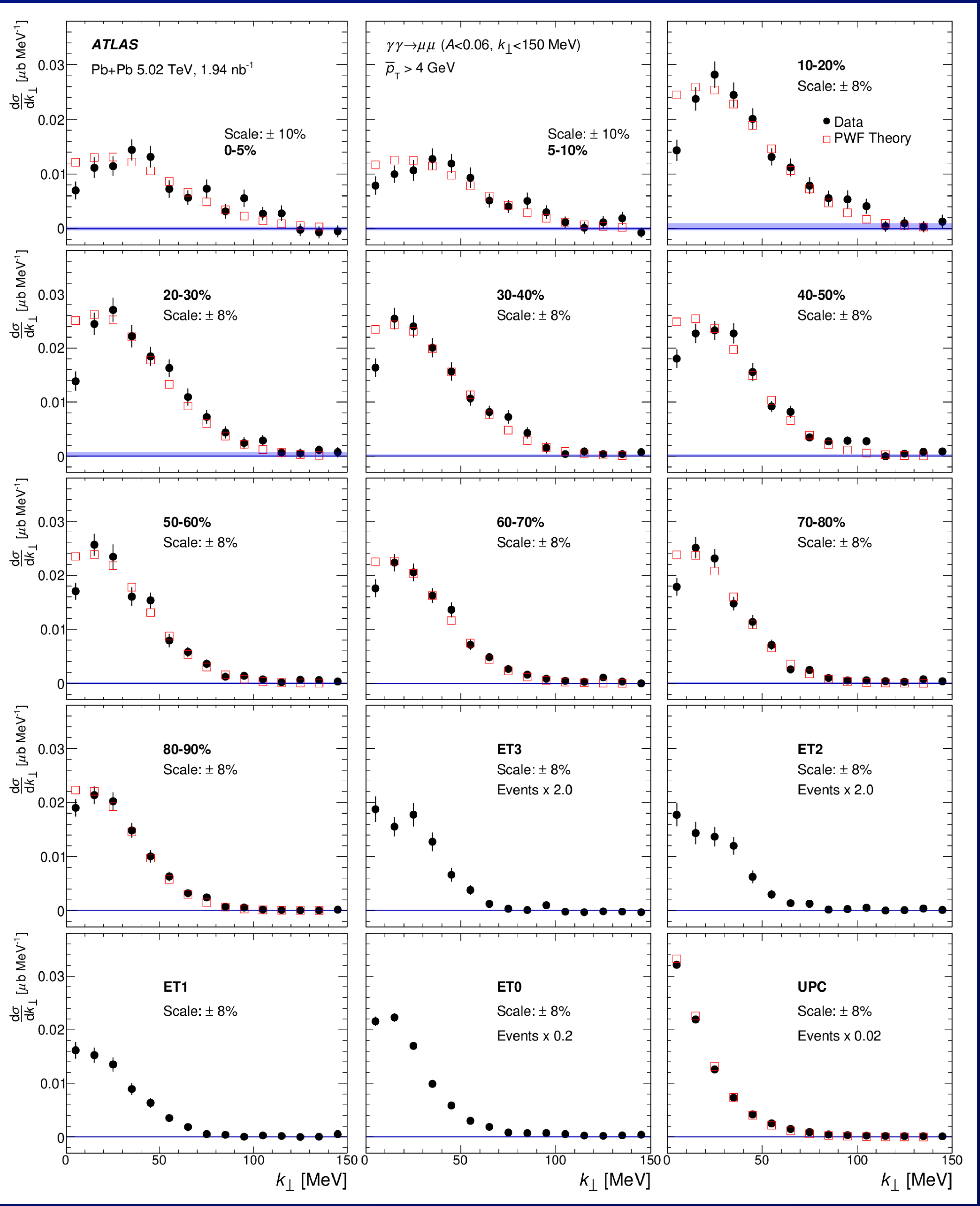
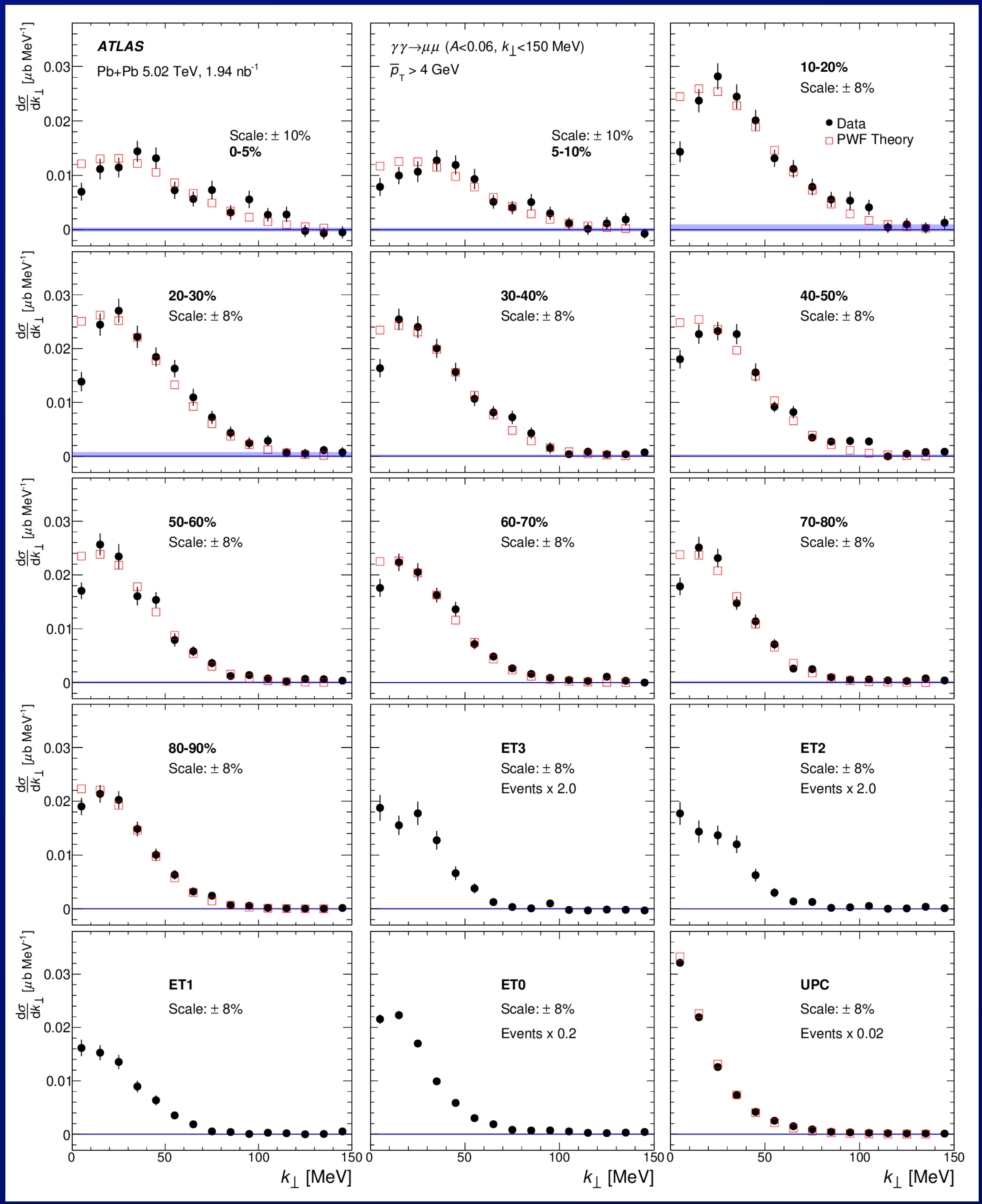


UPC and light ion collisions, ~ soft scales

- Measurements of $\gamma + \gamma \rightarrow l^+ l^-$ in hadronic A+A collisions probe EM structure of parent nuclei:
  - Broadening and distortion of the acoplanarity or (better) k_T distribution vs centrality

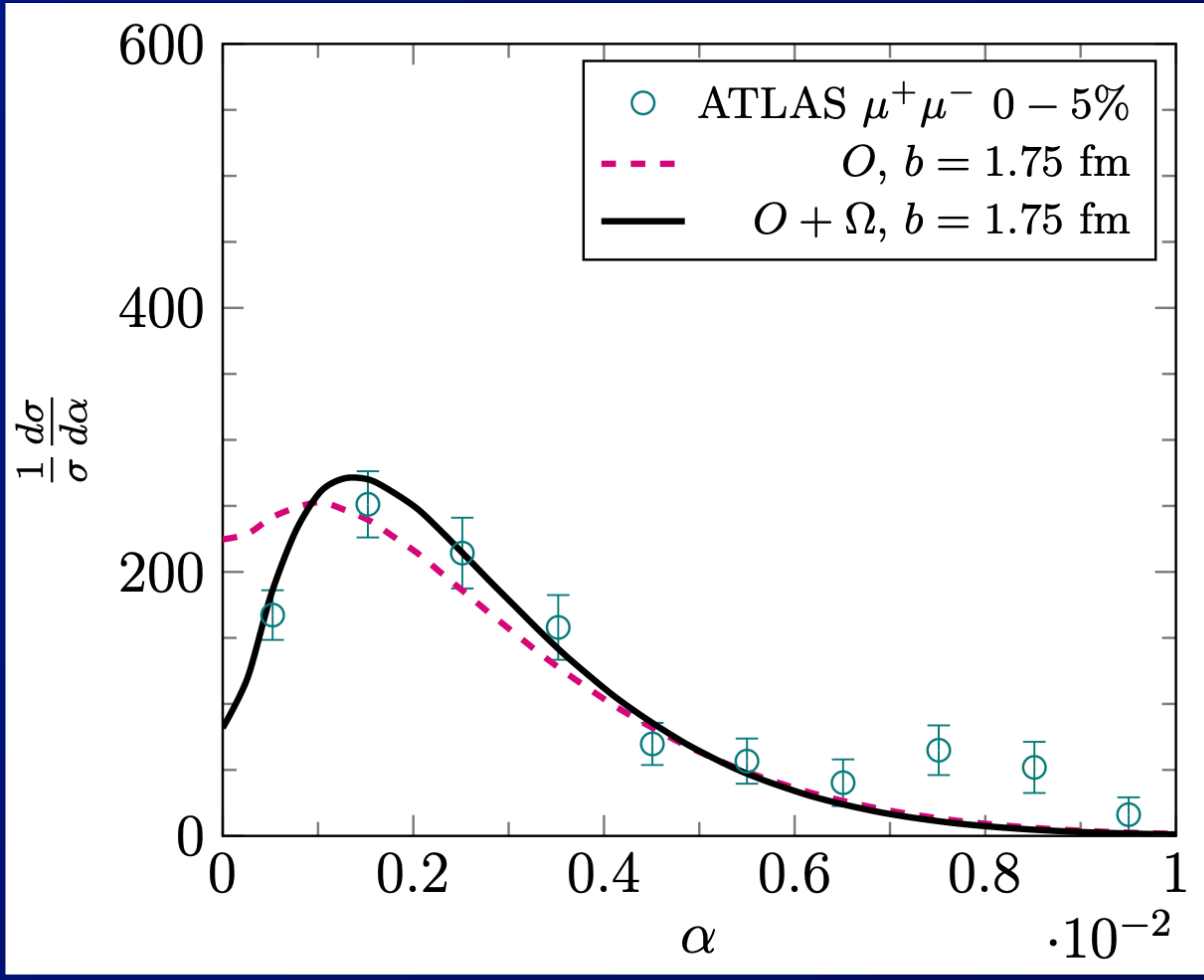


UPC and light ion collisions, ~ soft scales

- Measurements of UPC $\gamma + \gamma \to l^+l^-$ probe EM structure of the parent nuclei:
  - Broadening and distortion of the acoplanarity or (better) kT distribution vs centrality
  - Described well in calculations using photon Wigner distribution

⇒Sensitive to the nuclear $\rho_q(r)$!

Shi, Chen, Wei, Xiao, https://arxiv.org/abs/2406.07634



UPC and light ion collisions, ~ soft scales

- Measurements of UPC $\gamma + \gamma \rightarrow l^+l^-$ probe EM structure of the parent nuclei:

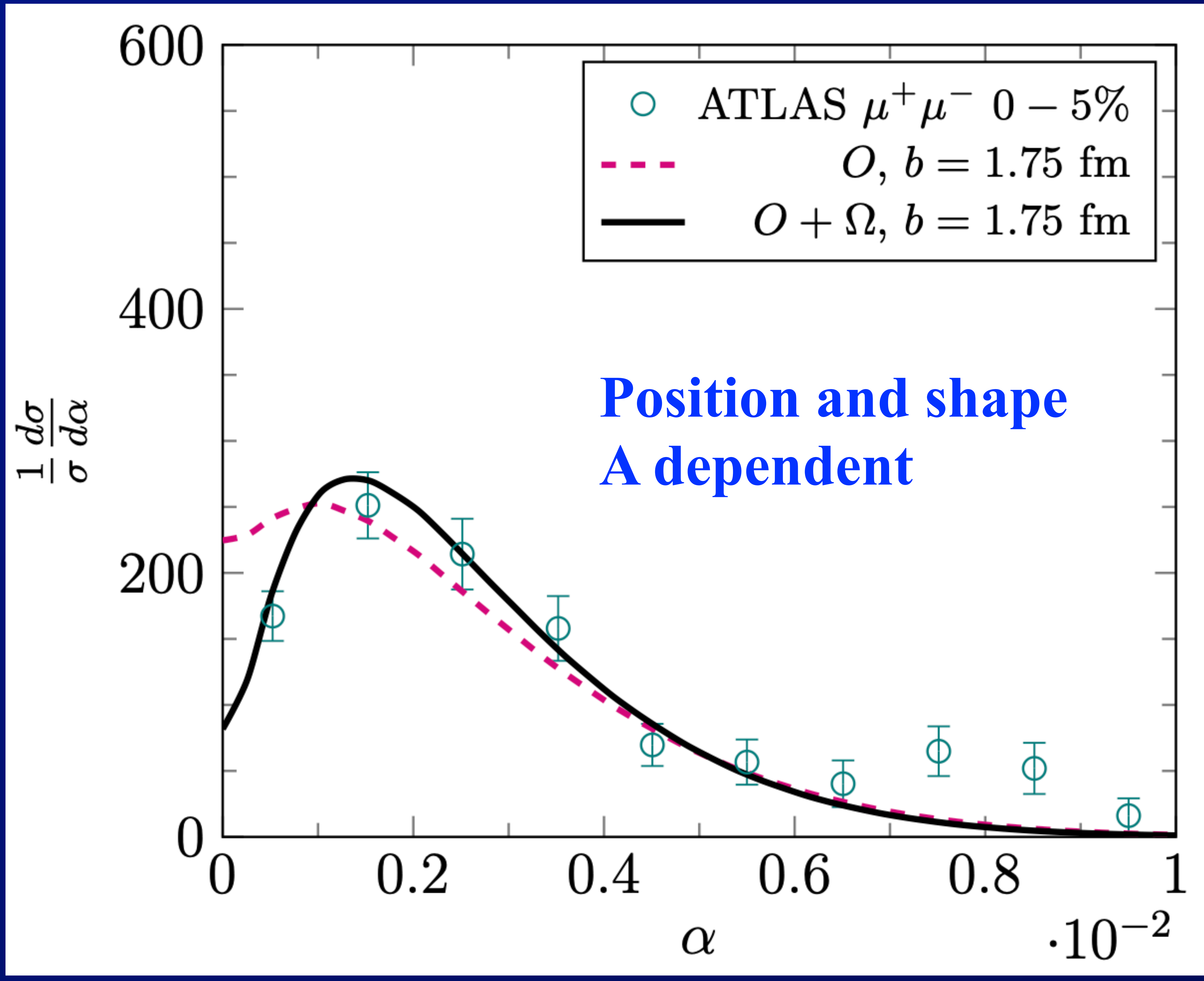
⇒Sensitive to the nuclear shape!

Shi, Chen, Wei, Xiao, https://arxiv.org/abs/2406.07634

- Measurement in A+A other than Pb would provide a valuable test of how photon Wigner distribution depends on nuclear shape, size
  - Feasibility depends on $\mathscr{L} Z^4$
  - Less HF background with light(er) ionsthan in Pb+Pb collisions

⇒ Unlikely in 0.5 nb^{-1} O+O

⇒In larger Z, higher lumi, plausible, but would need quantitative study



UPC and light ion collisions, ~ soft scales

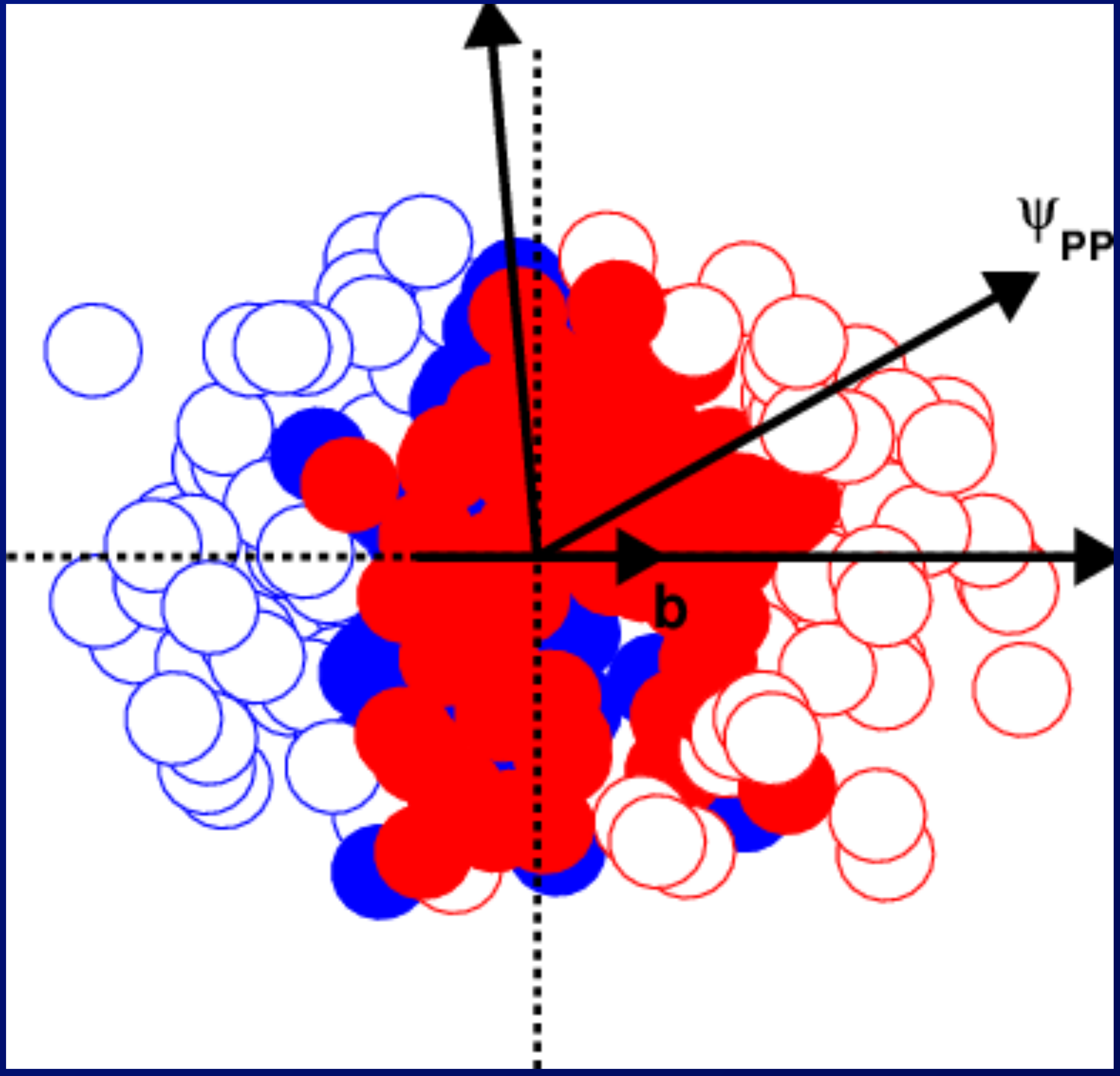
- Measurements of UPC $\gamma + \gamma \to l^+ l^-$ probe EM structure of the parent nuclei:

⇒Sensitive to the nuclear shape!

- Aspirational (crazy?)
  - EM probe of initial states selected (e.g.) with large v_n's, large $[p_T]$, …
  - Especially measuring wrt ψ_n's

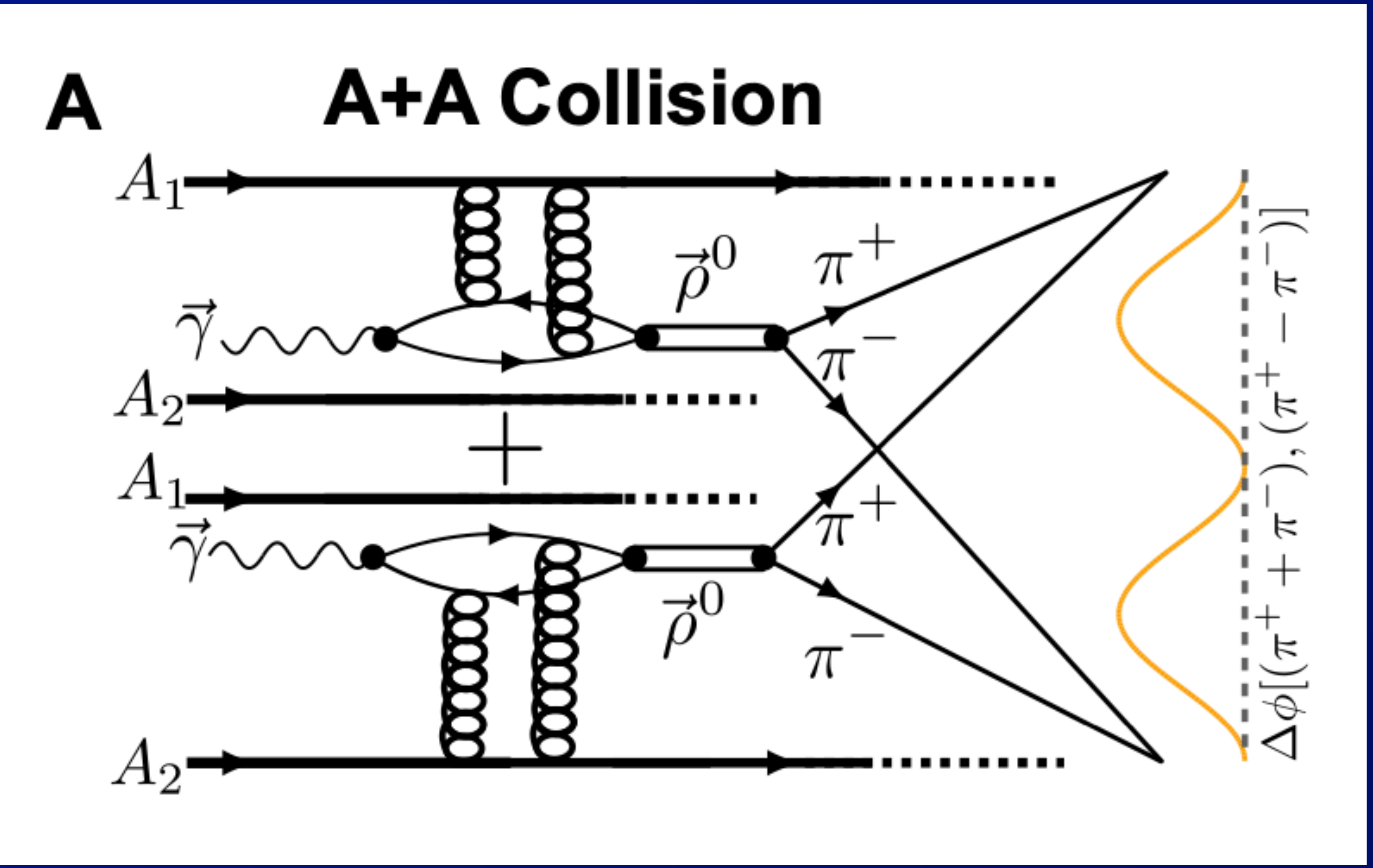
  ⇒Can we "see" distortions (eccentricities) of $\rho_q(r)$ in the initial state?
  - Need lighter ions with little spectator Q
- Need large $\mathscr{L}\, Z^4$ (Run 5?)

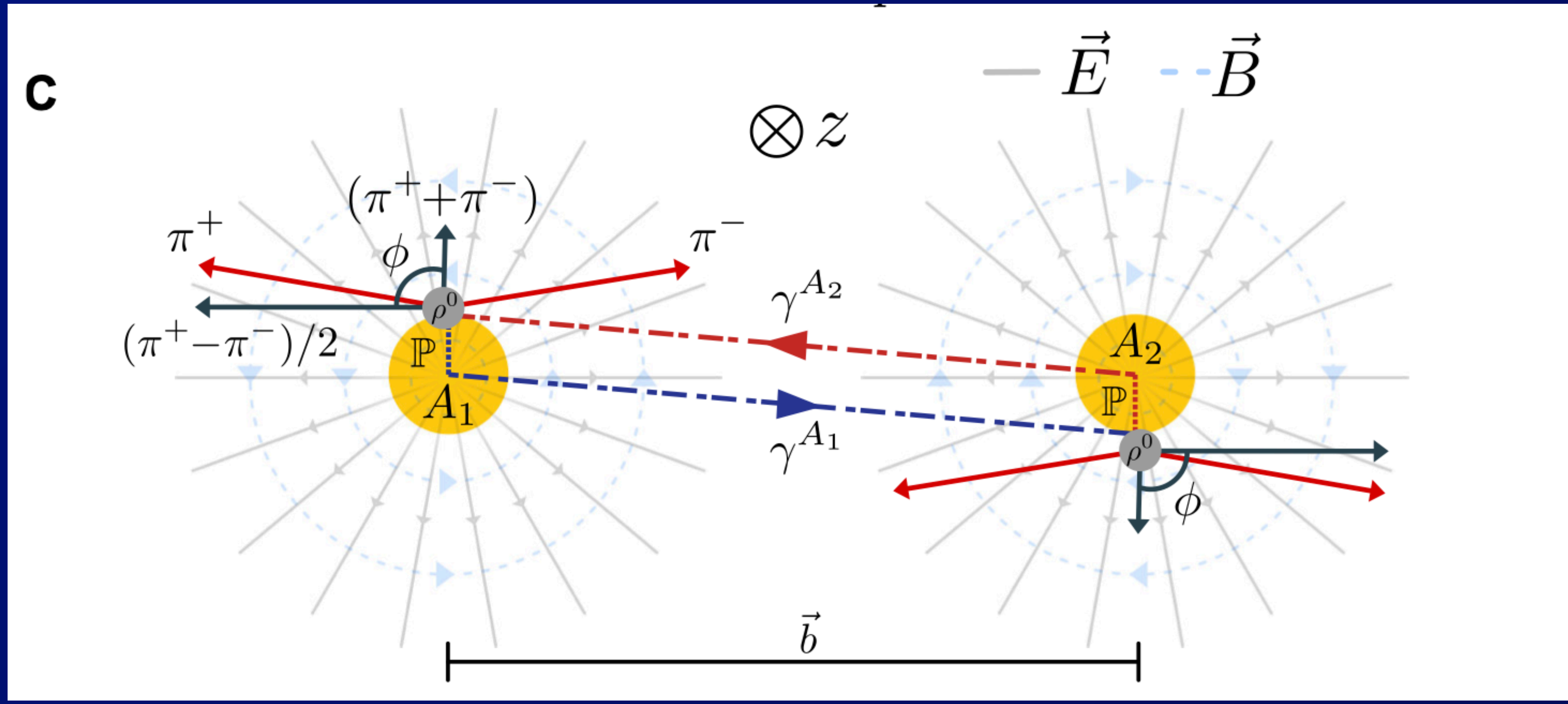
⇒Would be interesting to know if this is even possible …



UPC and light ion collisions, intermediate scales

- Coherent vector meson (ρ) production in light ion collisions
  - ⇒Can we use coherent pomeron to "image" nuclear structure?
- Interesting measurement by STAR
  - Use ρ polarization ,~same as γ polarization to determine $\vec{b}$ direction
  - Make use of quantum interference





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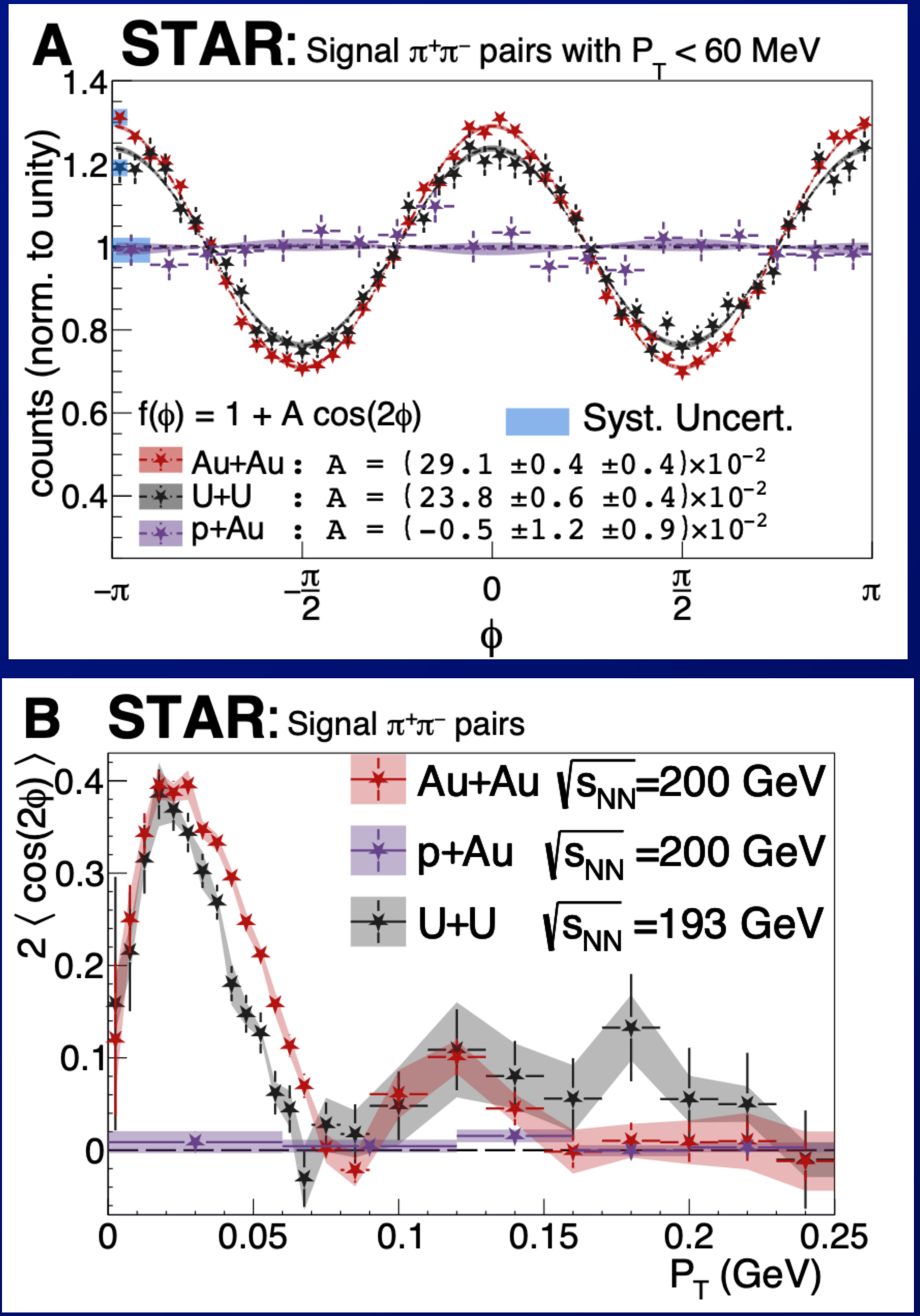


UPC and light ion collisions, intermediate scales

- **Why light ions?**

  ⇒Much more likely to have sensitivity to details of nuclear structure

  ⇒Even nuclear deformation (aspirational)?

- **Plausible in (e.g.) O+O?**

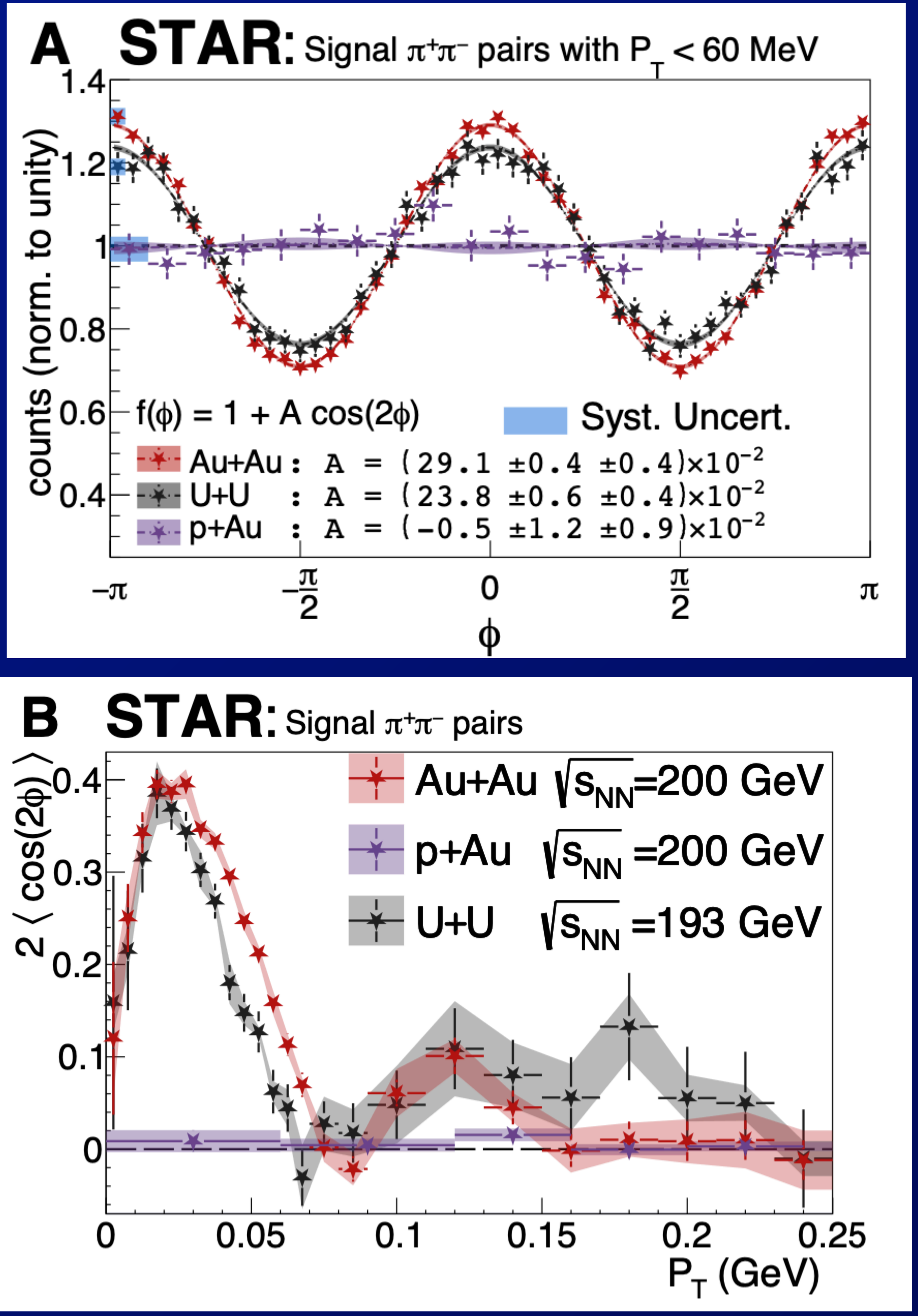
  – Back-of-the-envelope estimate ($Z^2 A^{4/3}$ scaling from Pb+Pb), $d\sigma/dy \approx 1$ mb

  ⇒ For 0.5 nb^{-1}, dN/dy ~ 6×10^5

- **Crucially:**

  – in (initial) O+O, no Level-1 triggering needed

  ⇒ATLAS should be able to select exclusive ρ final states using high-level trigger with good efficiency



Summary

Very rich program using light ions:

- QGP physics on smaller length scales
  - Path length dependence of jet quenching

  ⇒ More generally, coupling between hard processes and underlying event
  - Hydrodynamic response
- QGP response to enhanced initial-state fluctuations
  - Effects on hydrodynamicization / thermalization
- High-energy probes of nuclear structure
  - Effects of nuclear shape on collectivity
  - EM probes

  ⇒ Probe of nuclear E1/GDR structure using dissociative processes

  ⇒ EM probes of nuclear structure using $\gamma + \gamma \rightarrow l^{+}l^{-}$
  - Pomeron probes

Experimental Practicalities

- ATLAS makes extensive use of ZDCs and Forward calorimeters in heavy ion measurements for centrality, UPC triggering, …
  - Hadronic pileup is an issue for these measurements
  - One of scenarios originally proposed for O+O has $\mu \sim 0.6$

  ⇒ ~30% probability to have second hadronic interaction

  ⇒ Depending on ability to separate, could negatively affect some physics
- Bunch spacing (mostly an issue for p+Pb?)
  - In ATLAS ZDCs, signals confined to 1 bunch crossing to few %
  - But, large dynamic range in the # neutrons, especially with pileup

  ⇒ 25 ns bunch spacing would be a problem

  ⇒ Large # neutrons in one BC masks small # neutrons in following BC
- Luminosity (mainly for UPC)
  - Luminosity calibration for 4 experiments needs $\gtrsim 1$ day

Programmatic considerations

- ATLAS heavy ion program has been anxious for light ion collisions
  - ⇒ Made a proposal to do Ar+Ar in Run 1 (2016?)
  - ⇒ I would like to see a non-pilot light ion program @ LHC in my lifetime
- Physics case is compelling, especially w/ multi-week program
  - – But we shoot ourselves in the foot if we don't have pp comparison data
  - ⇒ Sadly, the 2016 p+Pb program fell well short of its full potential
- There are alternatives to measuring R_{AA}
  - ⇒ But they should be considered last resort
- From physics perspective:
  - ⇒ It would be truly unfortunate (i.e. unmitigated disaster) to have O+O, p+O, p+Pb, Pb+Pb, X+X data-sets all at different energies
  - ⇒ Necessary to balance physics and operational considerations