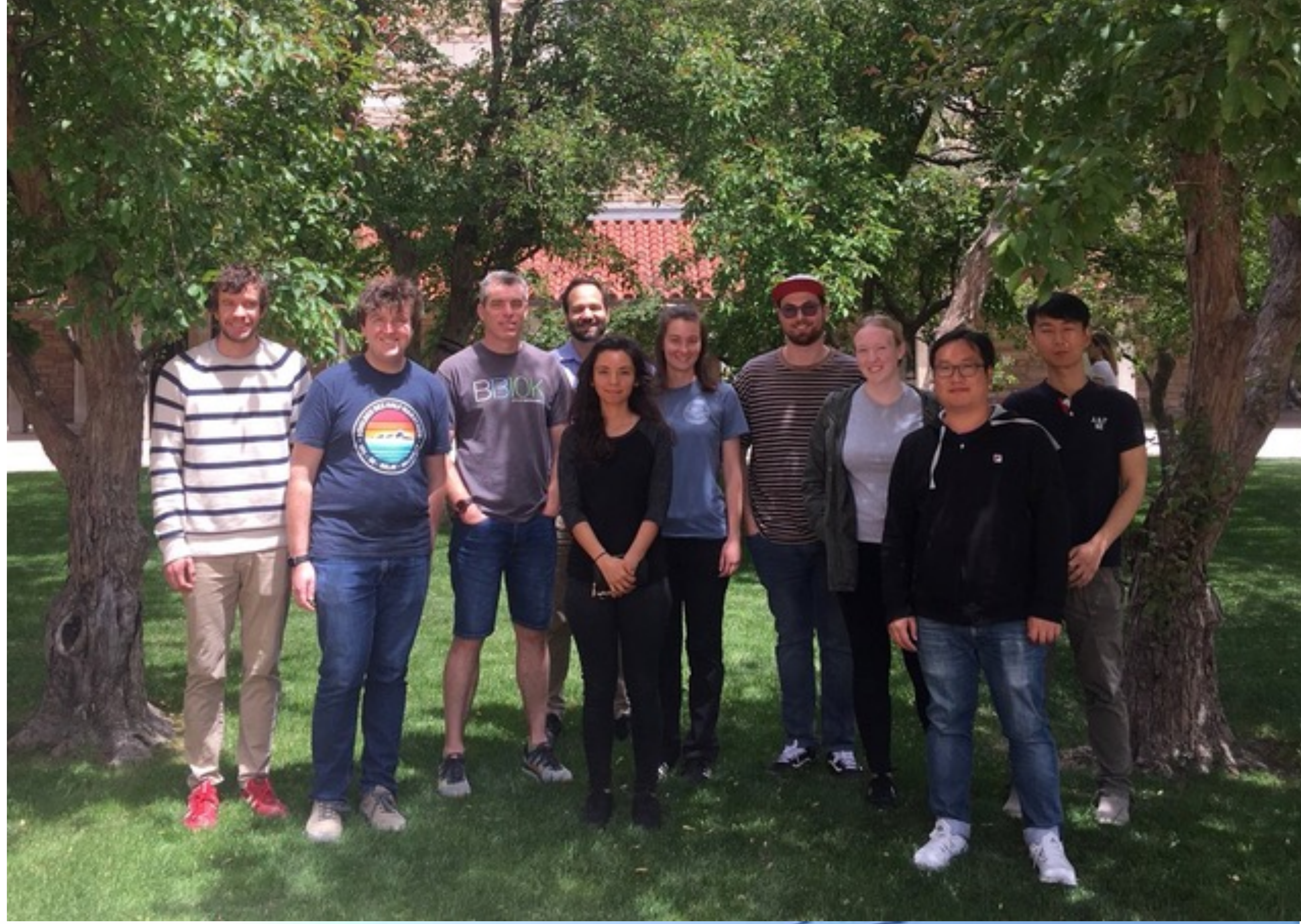
What can stop the flow?

Azimuthal anisotropies at large mass, high p_T, and in extremely small systems with ATLAS

Dennis V. Perepelitsa
University of Colorado Boulder

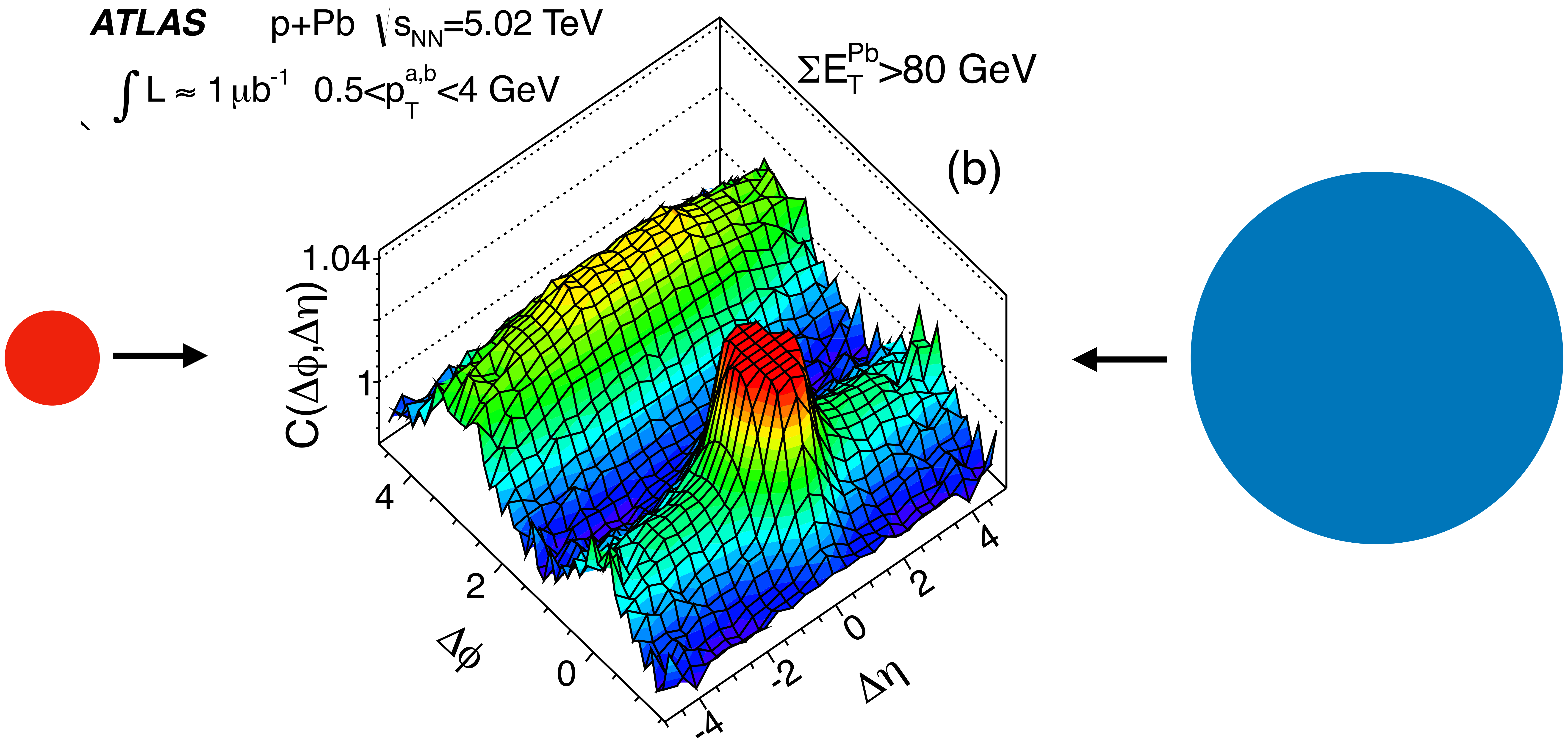
Nuclear Physics Seminar
Brookhaven National Laboratory
8 September 2020



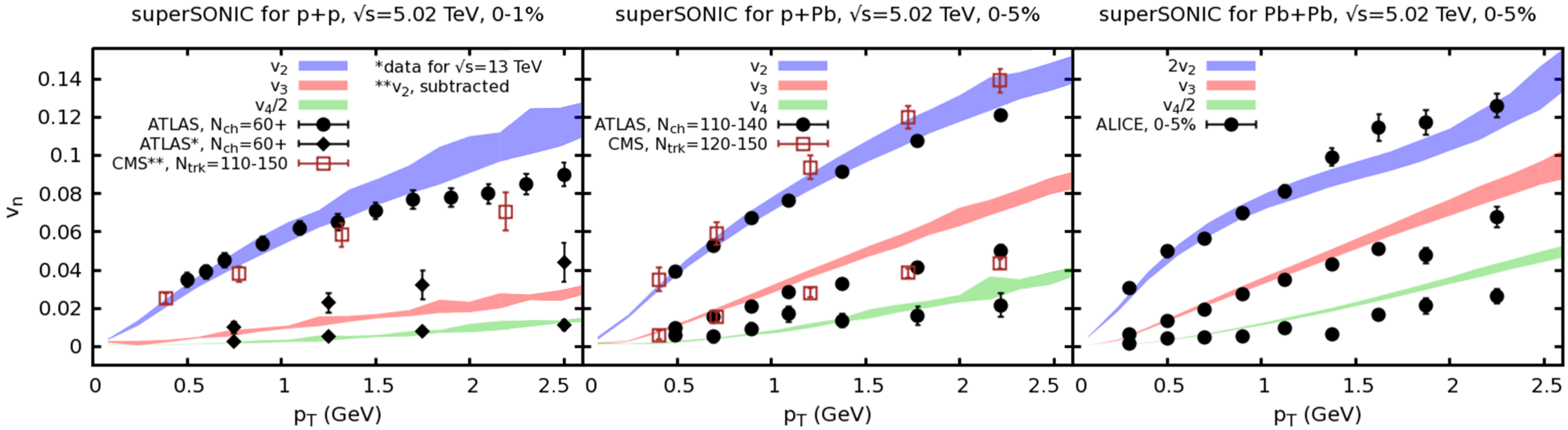
socially distanced panorama version

What is the nature of the QCD system formed in *pp* or *p*+A collisions?

ATLAS, PRL 110 (2013) 182302



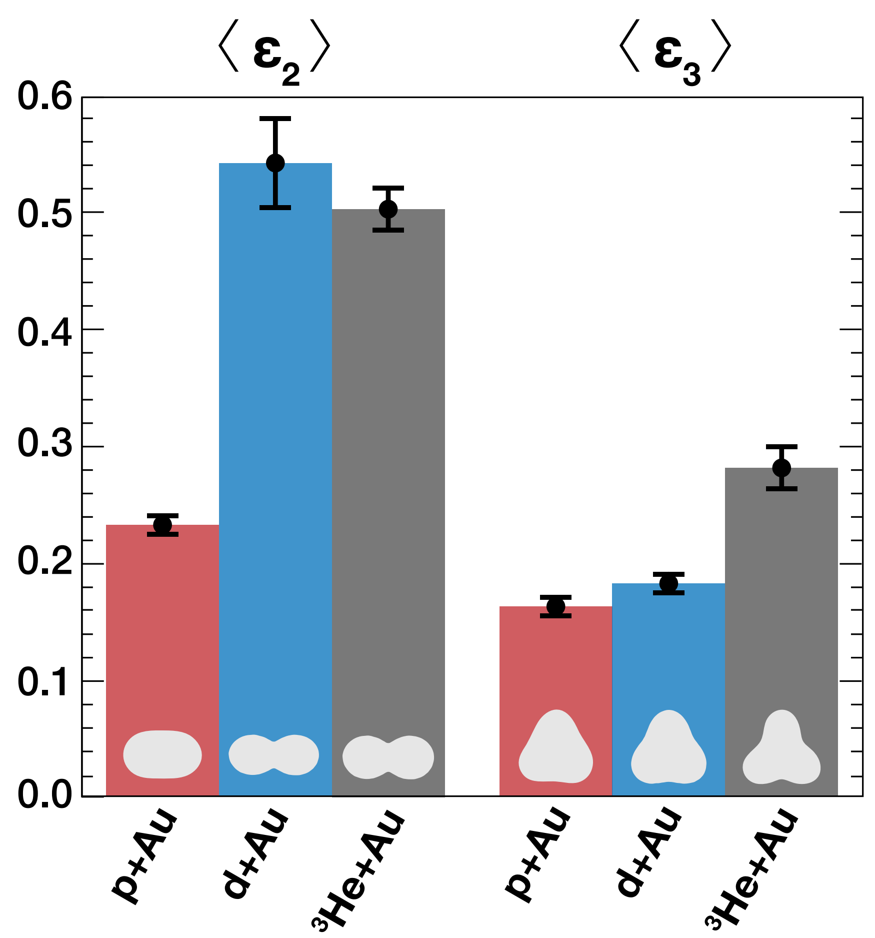
Collective behavior in small systems

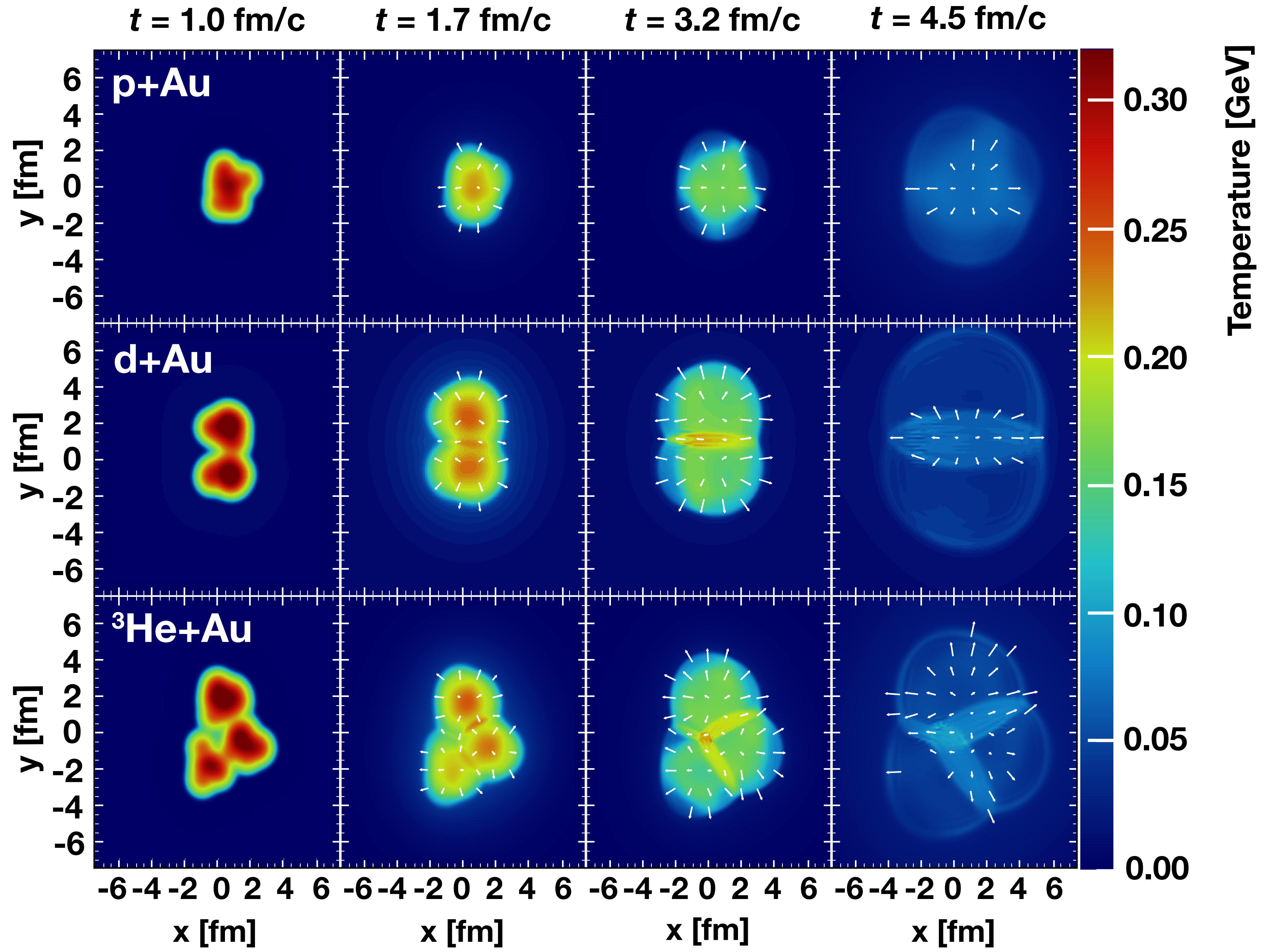


Broadly successful description of v_n in *p*+A and even high-multiplicity *pp* systems within AA-like hydrodynamic framework!

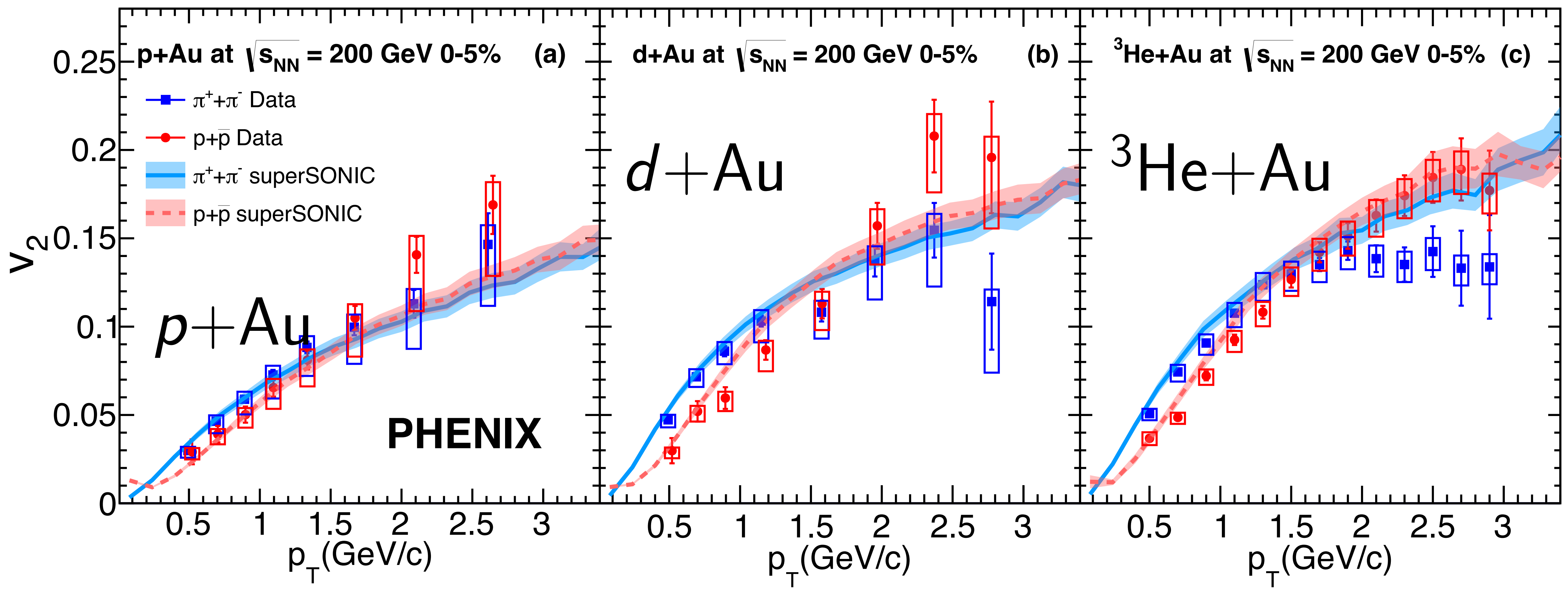
Corroborative evidence for hydrodynamic paradigm

- Projectile scan at RHIC - v_2 & v_3 respond to changes in ϵ_2 and ϵ_3 and thus originate from final-state interactions





- Mass-ordering as expected from common fluid velocity



- Other evidence (multi-particle correlations, etc.)

Goal: push measurements of collectivity in small systems into new regimes

- Many possible signatures of collective behavior - focus here on azimuthal anisotropies
- Delineate the boundaries of where we observe collective effects - can we get azimuthal anisotropies to “turn off” in some regime?
- What do our observations imply about the underlying physics mechanisms?

Kurt Hill
(Ph.D. 2020)

1. Behavior of high-p_T particles in p+Pb collisions

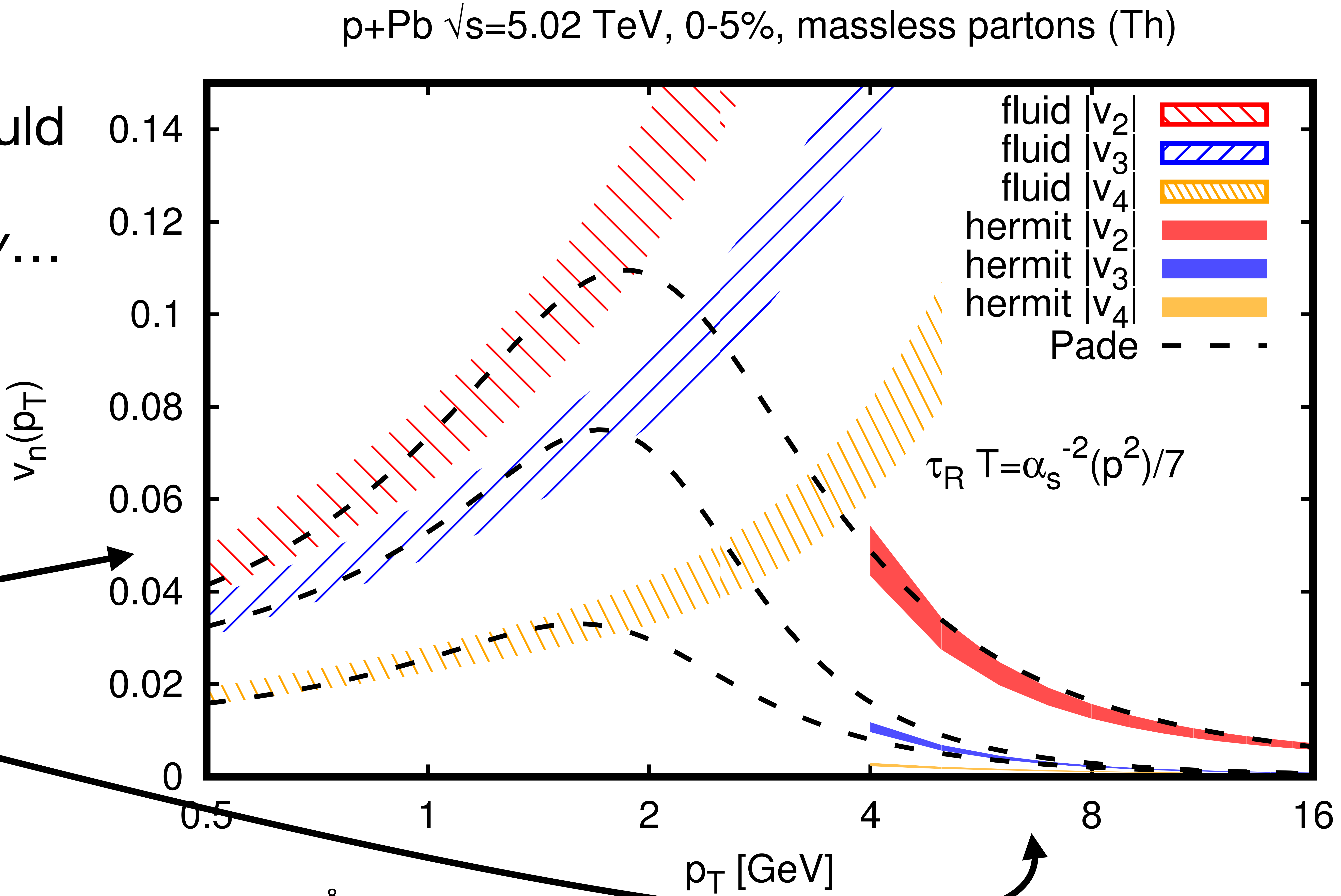
ATLAS, Eur. Phys. J C80 (2020) 73

What to expect in the hard sector?

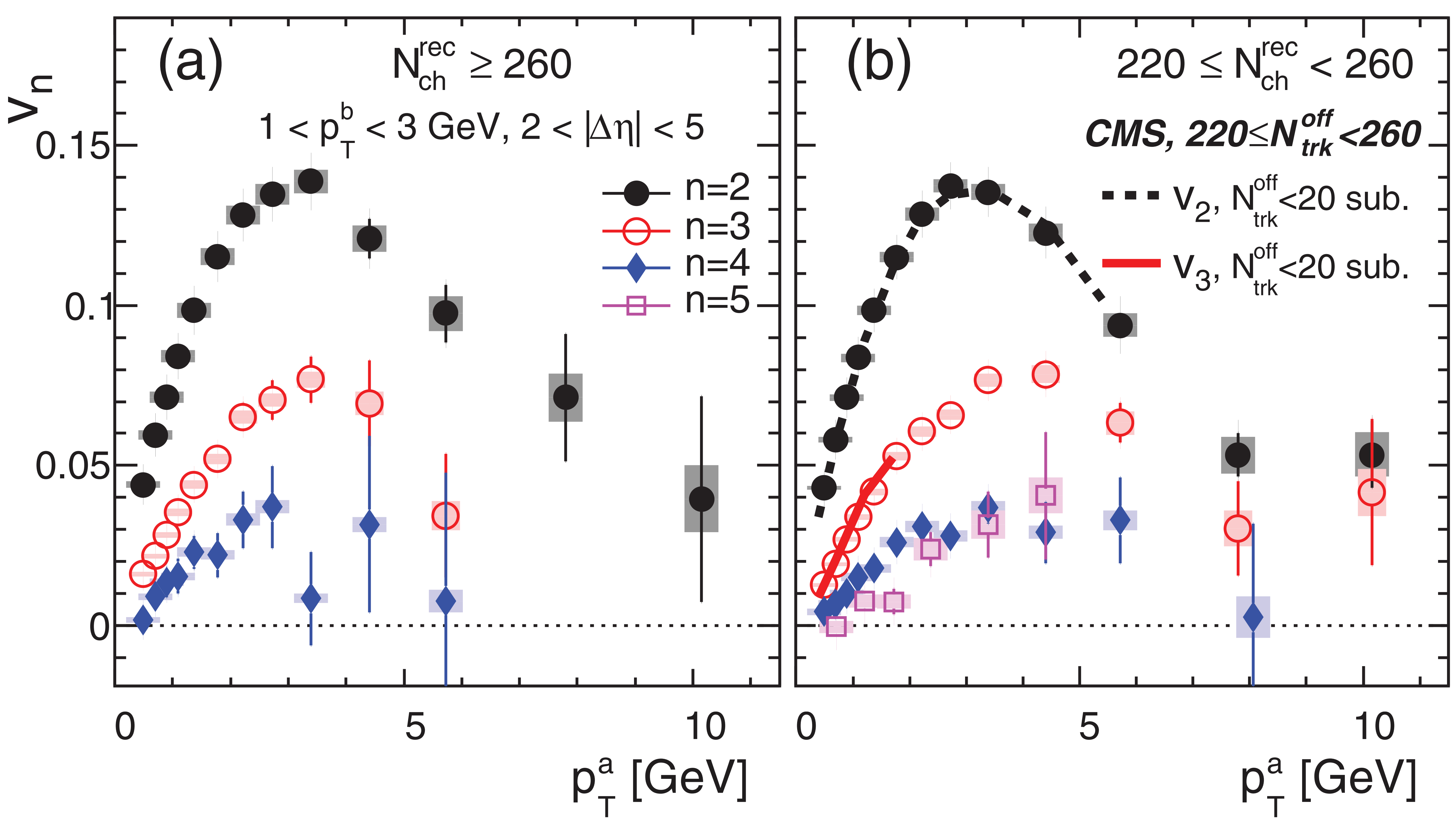
Romatschke, EPJC 78 (2018) 636

Final-state interactions should result in flow & jet modification *simultaneously*…

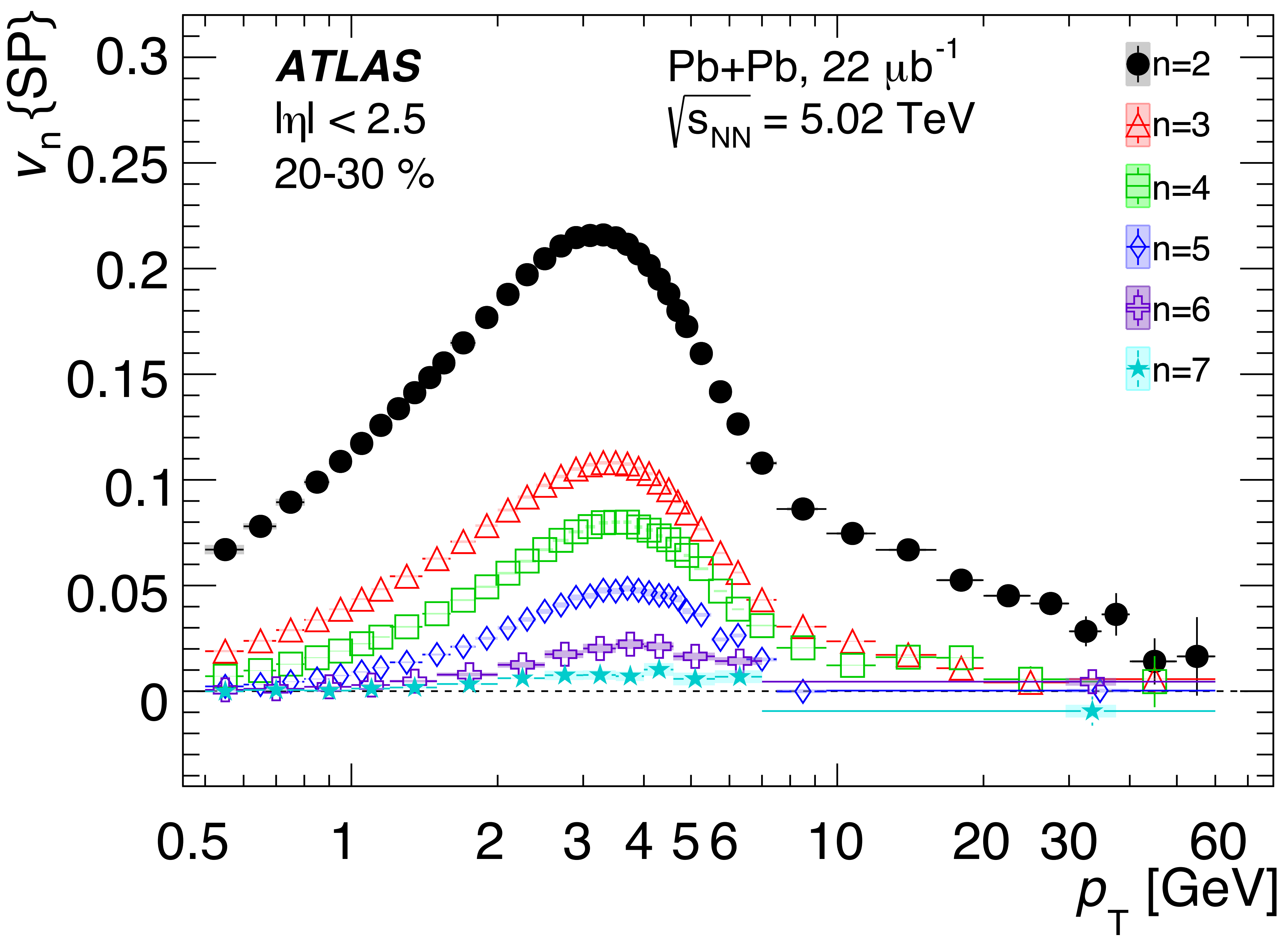
Same QGP fluid in *p*+A, but calculate v_n under <u>many-scatterings</u> and <u>few-scatterings</u> expansions



High-p_T v_2 in early LHC p+Pb data



In 2013 p+Pb data, large v_2
@ p_T ~ 10 GeV in 0-1% p+Pb…



In AA systems, high-p_T (> 5-10 GeV) v_2 understood as energy loss (diff. energy loss in vs. out of plane)

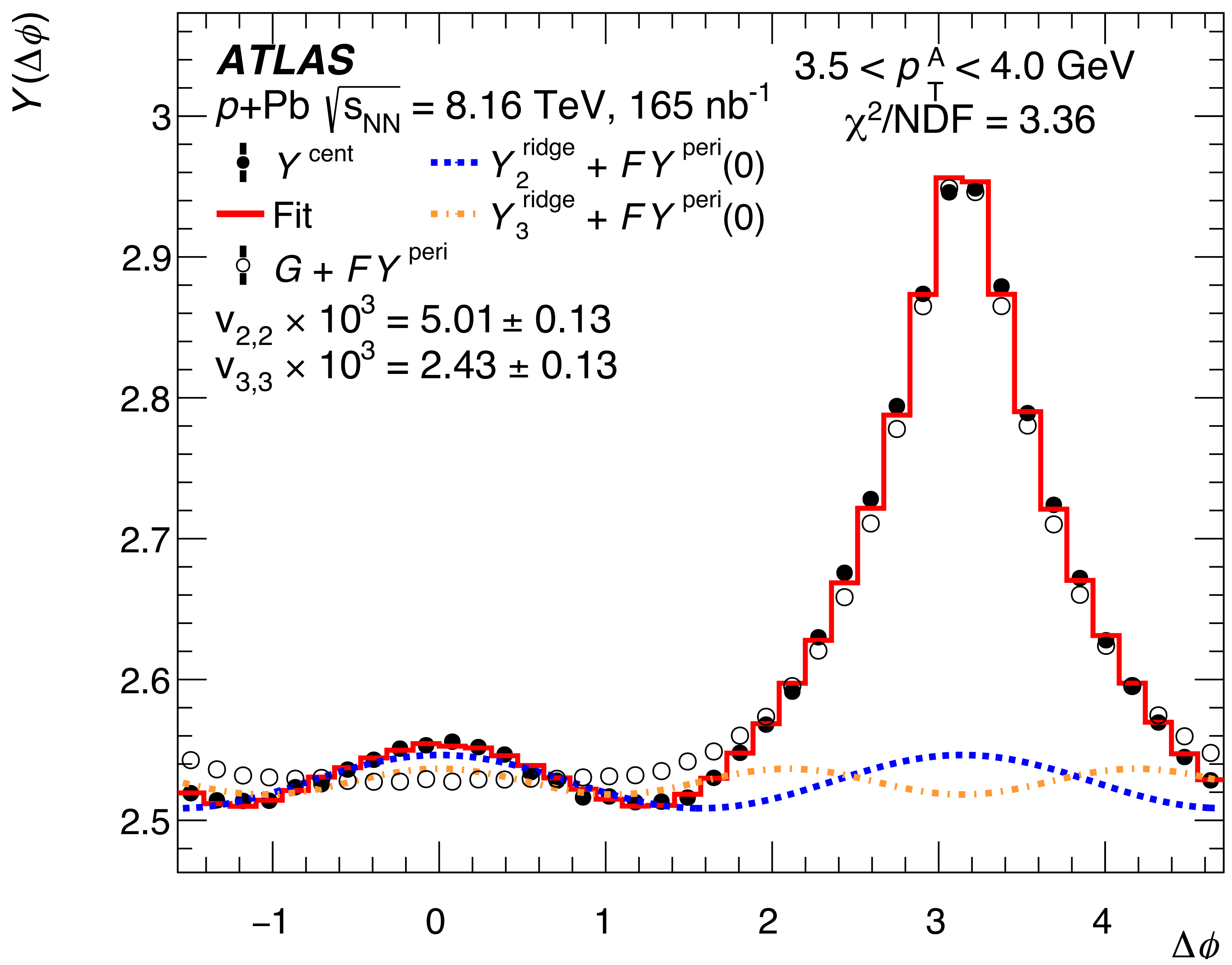
Using 2016 p+Pb data, push much farther in centrality and p_T!

Two-particle correlations for high-p_T particles

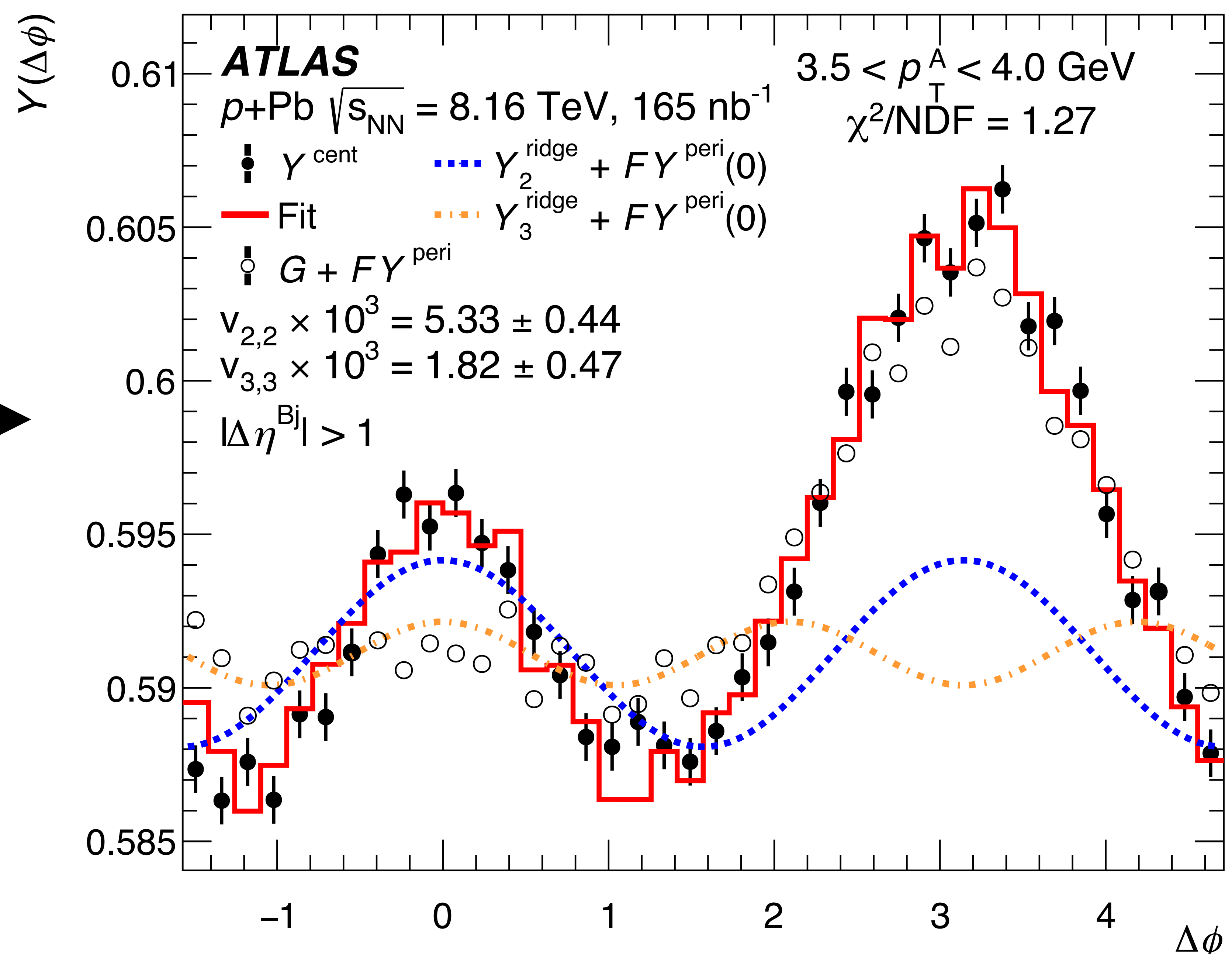
Two-particle Δϕ correlation analysis with $|\Delta\eta| > 2$, with "template fit" to subtract low-multiplicity-like non-flow component

Use jet-triggered events for a large high-p_T particle yield (far above what would be obtained in minimum-bias collisions)

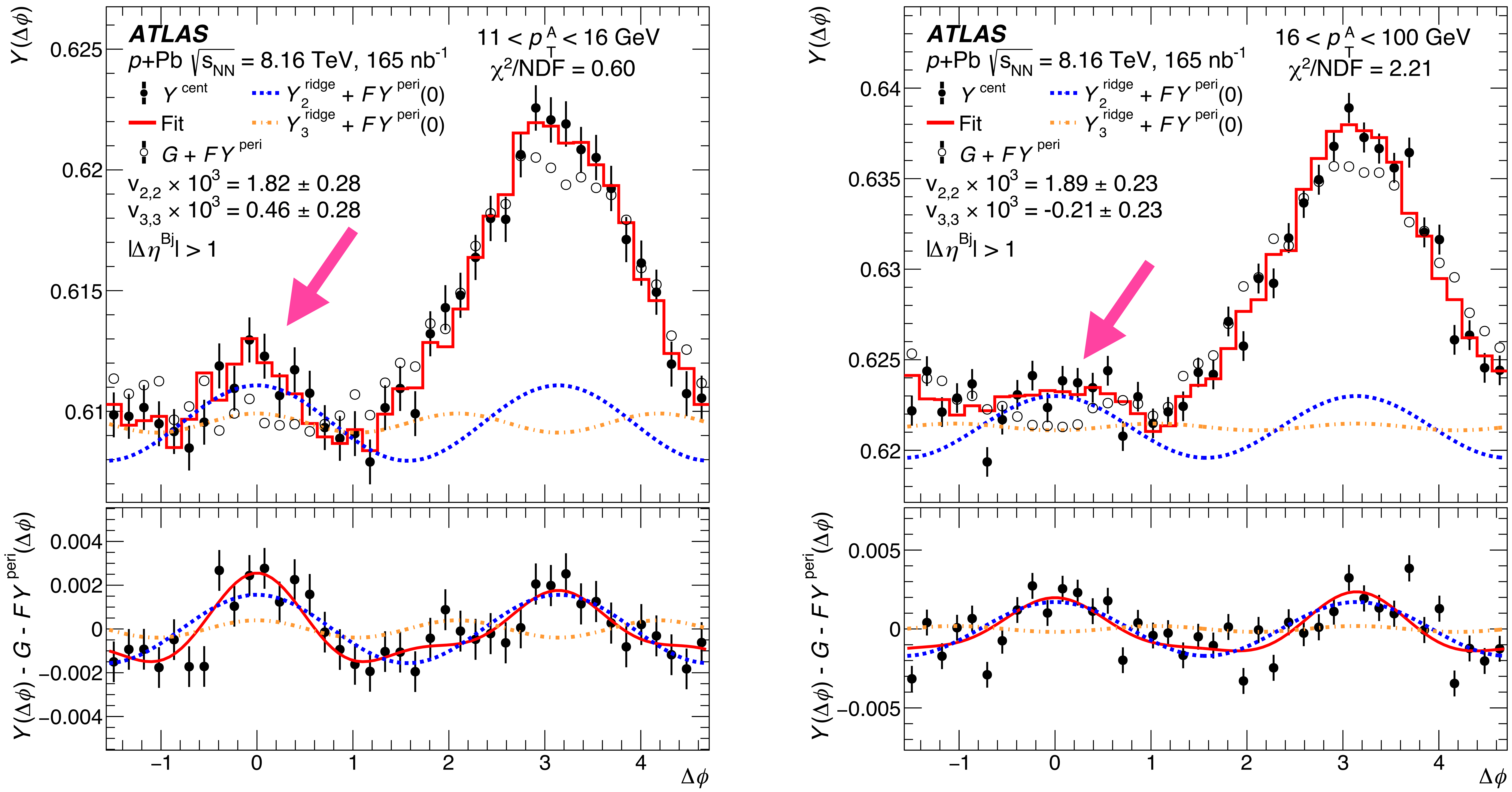
Further reduce non-flow by requiring associated particles to be separated from any jets in the event…



Require $|\Delta\eta^{B,jet}| > 1$



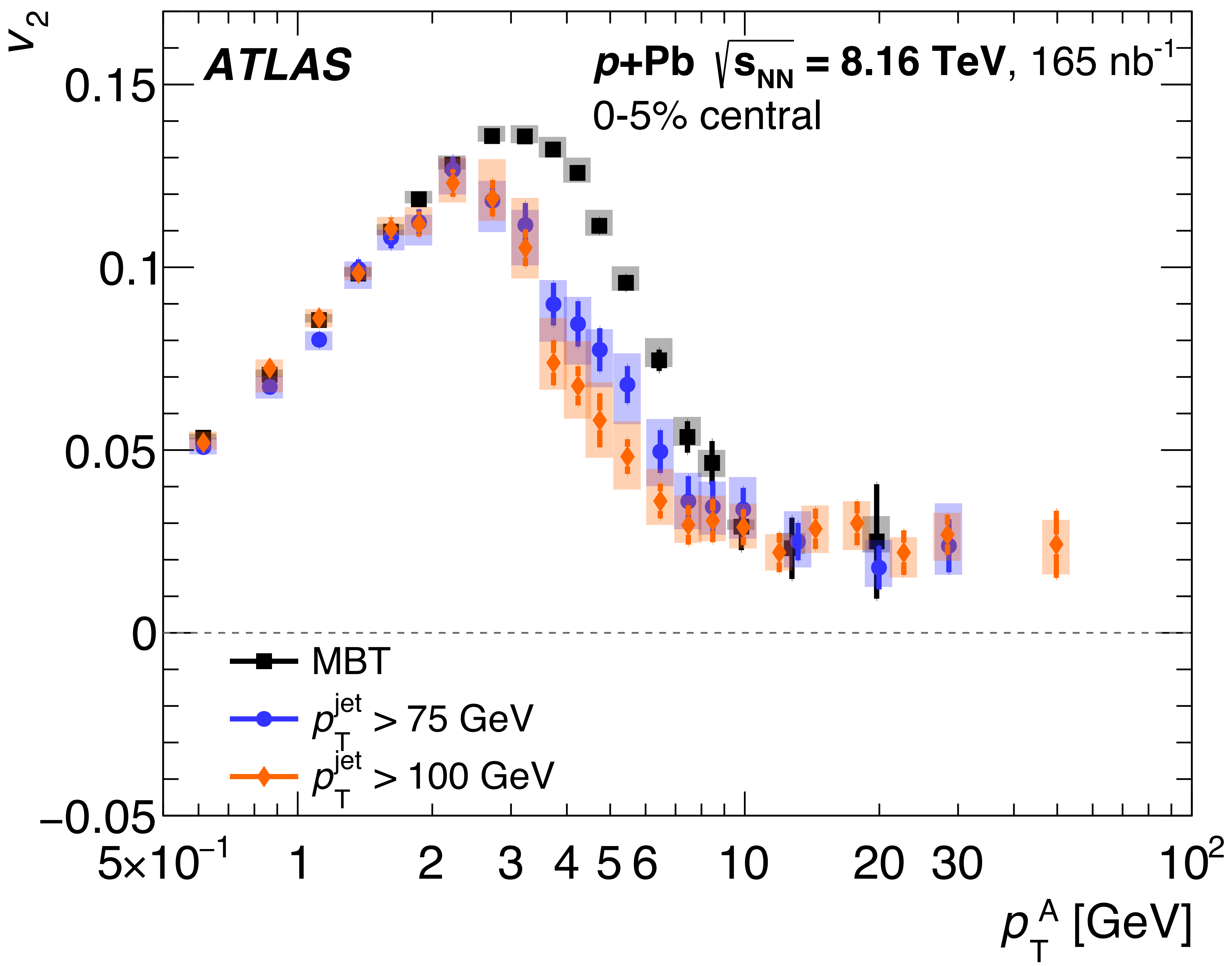
Two-particle correlations for high-p_T particles

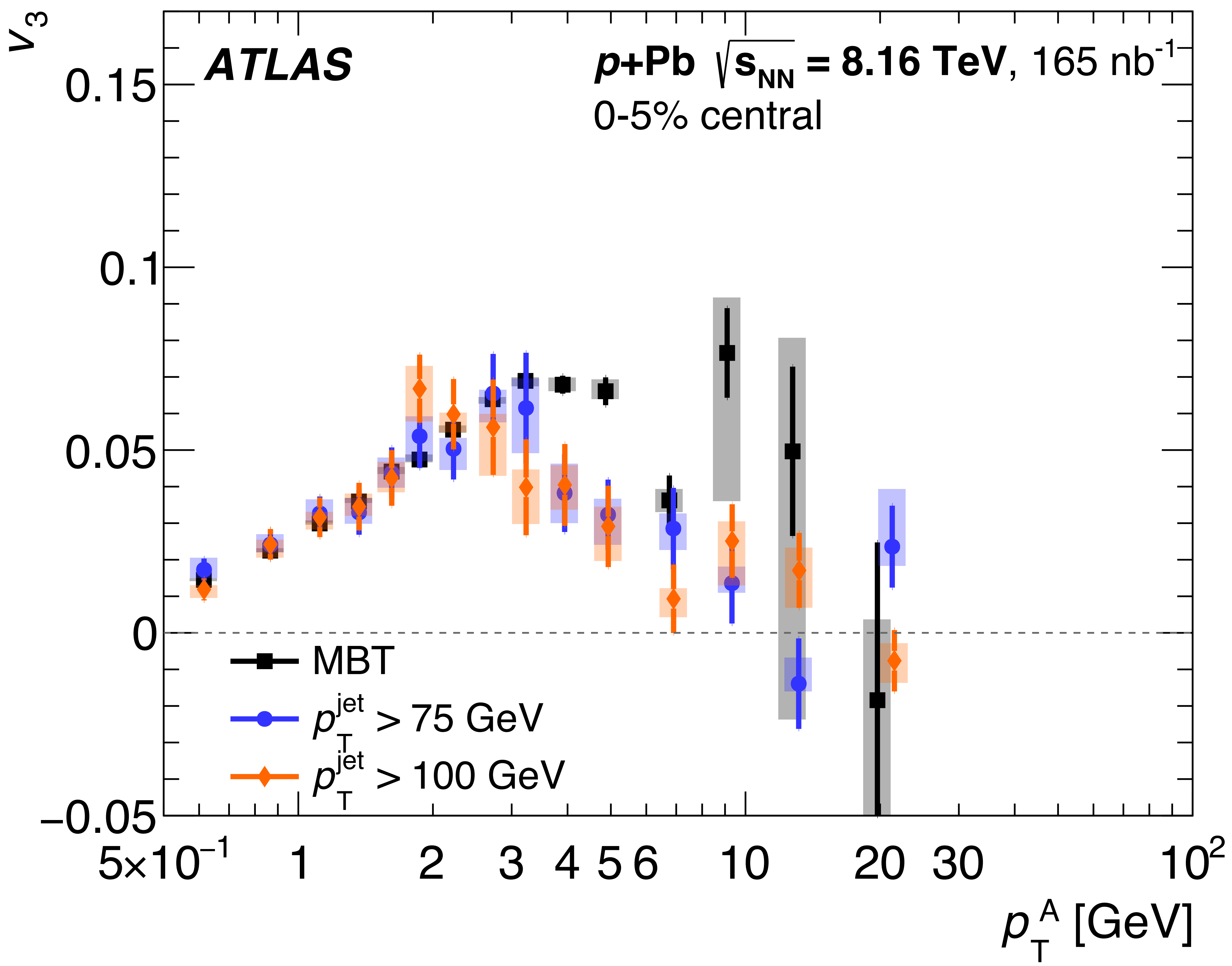


bottom panels show modulation after non-flow subtraction

Two high-p_T selections shown here - visible near-side enhancement!

v_2 and v_3 results



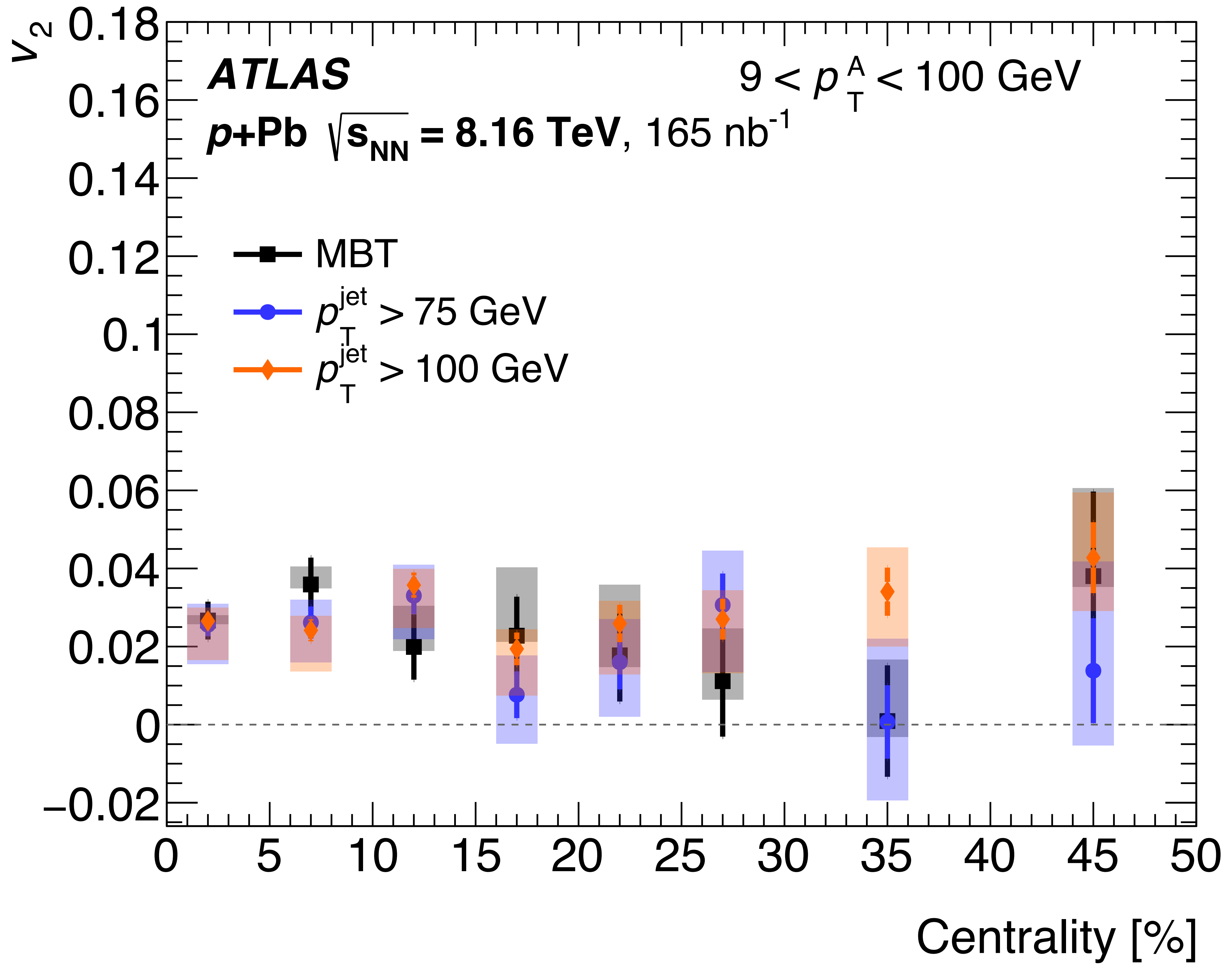


In >100 GeV jet events, v_2 ~ 2-3% at p_T^{ch} = 50 GeV!

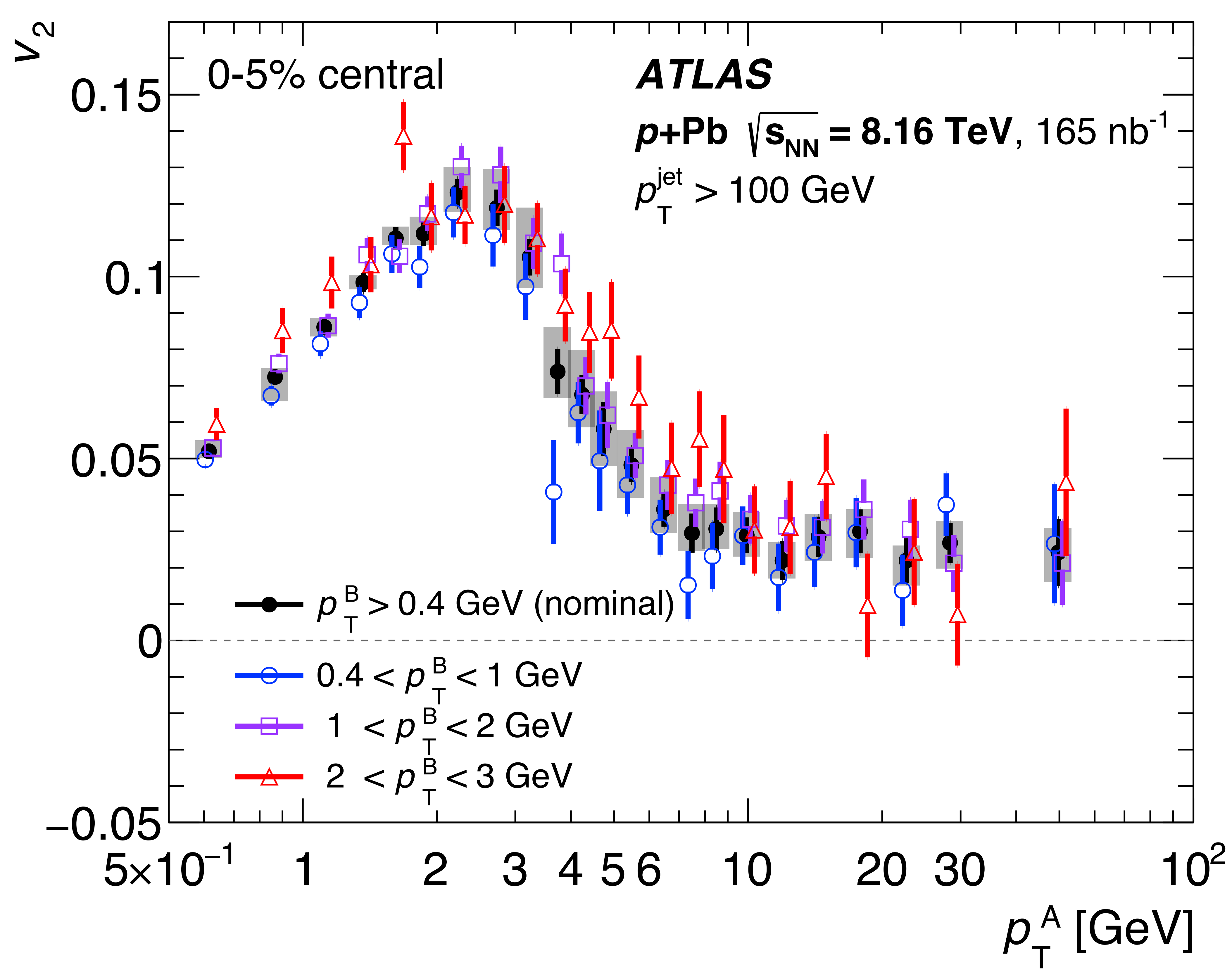
More difficult to measure v_3, but it's ~1-2% for p_T^{ch} = 10 GeV

Notice different p_T dependence in **minimum-bias triggered** vs. **jet-triggered events**…

Robustness of signal

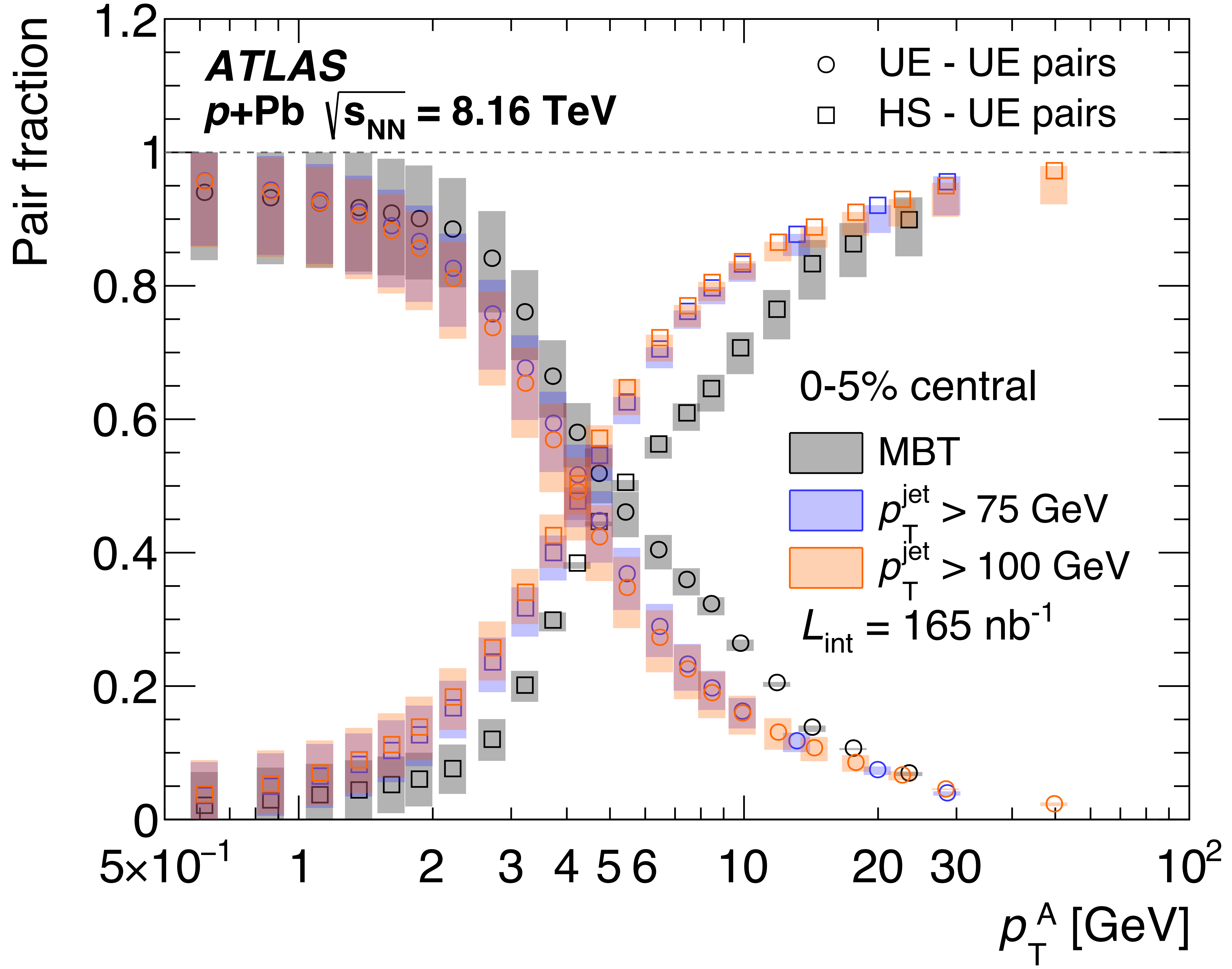


Evidence for non-zero v_2 at high-p_T in a significant fraction of p+Pb events (not just top 1%!)

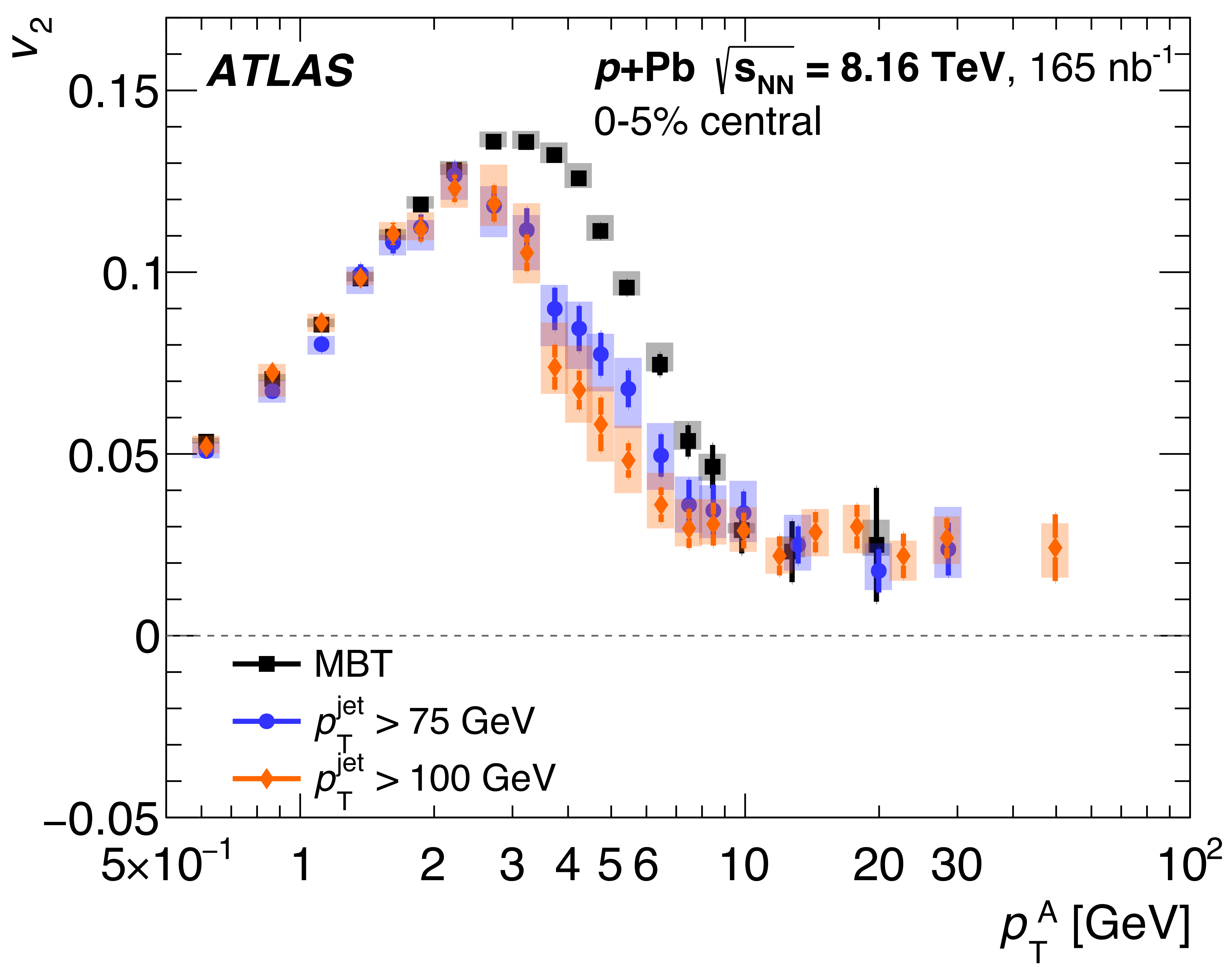


Results pass "factorization test" - interpret as a single-particle v_2

Process-dependence to azimuthal anisotropy?



Decompose particles into ones produced by “soft” processes (azimuthally ~independent) and “hard” processes (aligned with jets)

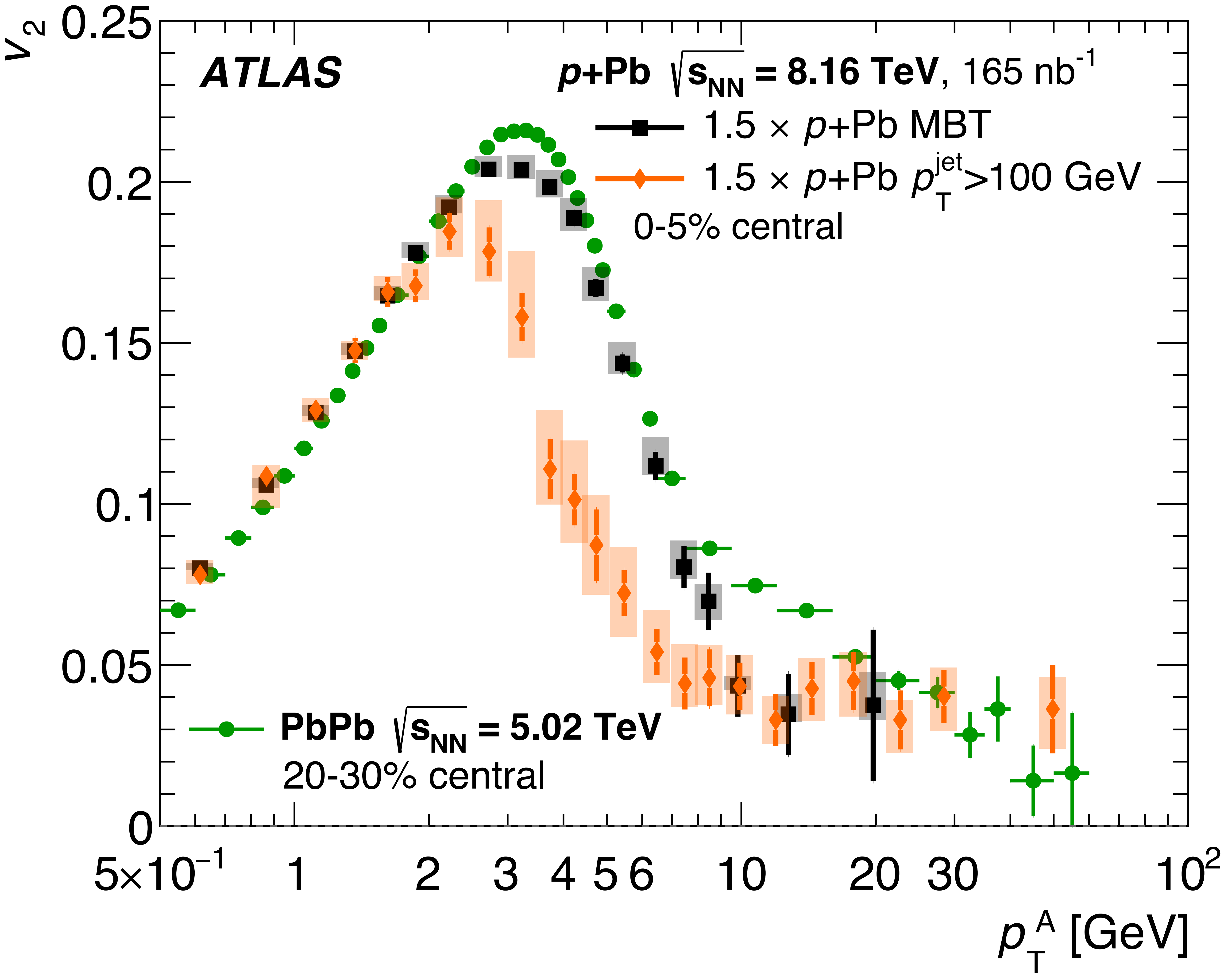


In 3-9 GeV region, particles in jet events are more likely to come from “hard” processes (compared to 3-9 GeV particles in MB events) — lower v_2

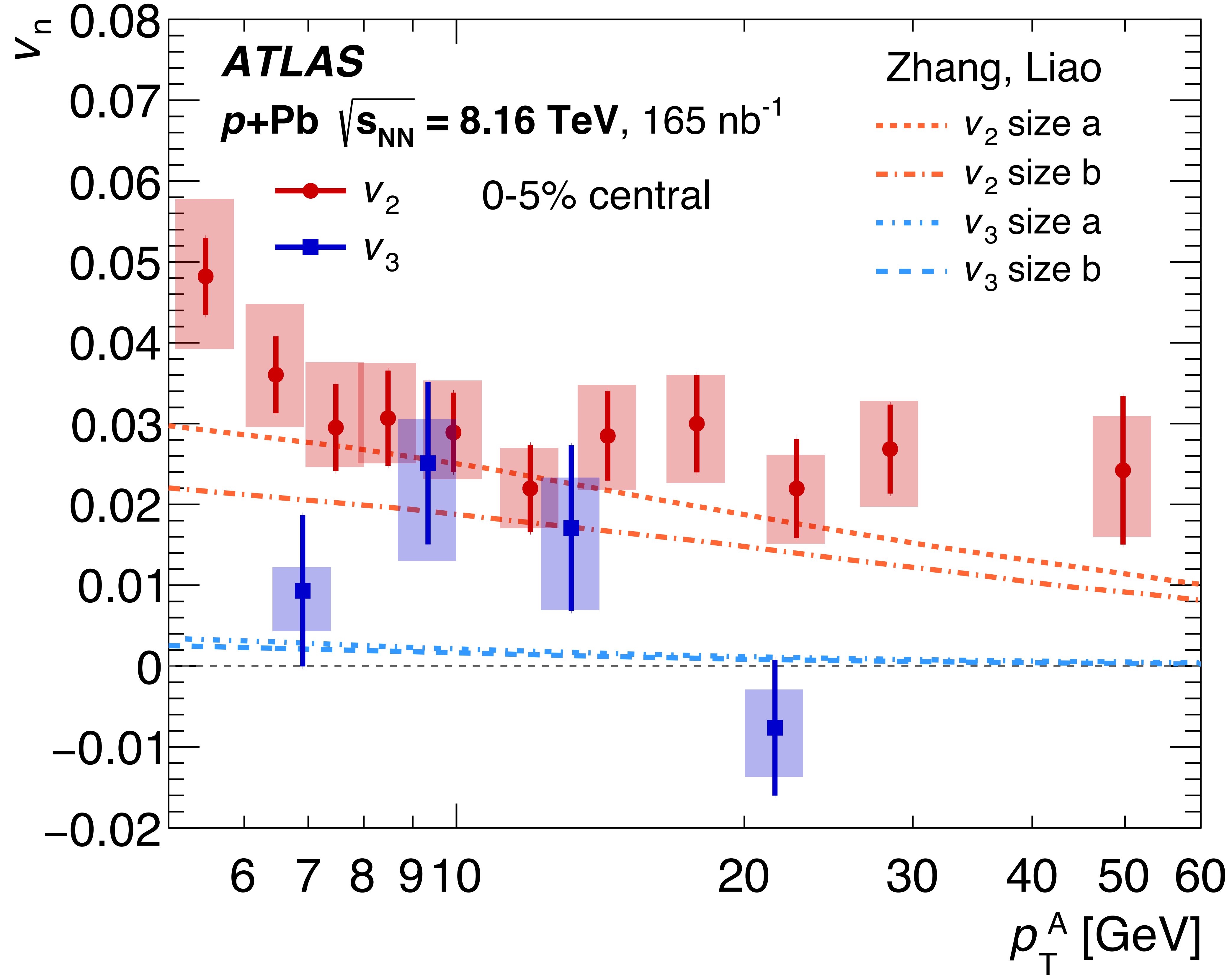
Comparison to Pb+Pb

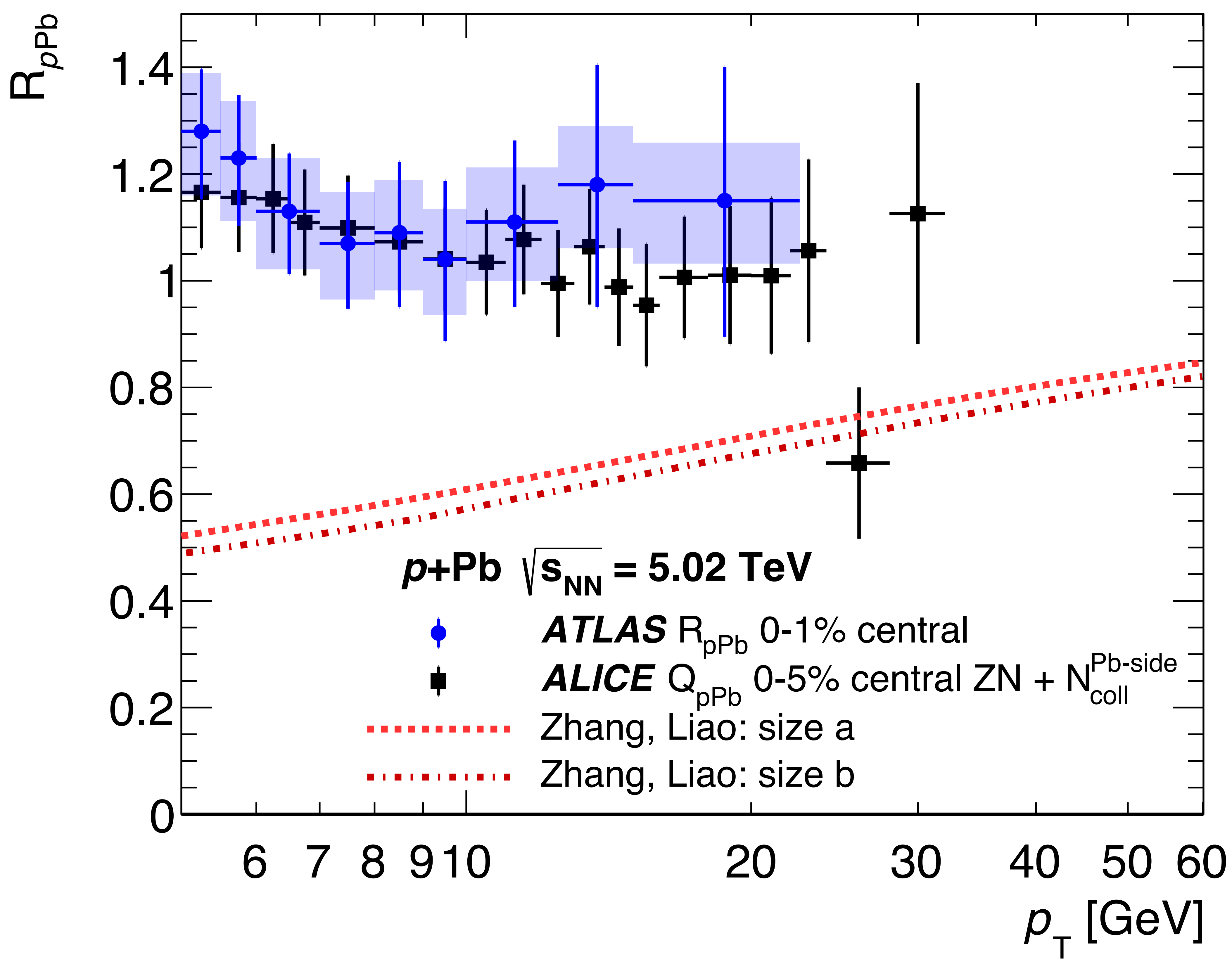
Compare v_2 in **MB** and **jet-triggered** p+Pb events to that in **Pb+Pb** events w/ same ε_2 (with ad-hoc scaling factor)

Remarkably similar p_T-dependence - in Pb+Pb, the high-p_T behavior arises from jet quenching…



Interpretation in energy-loss models



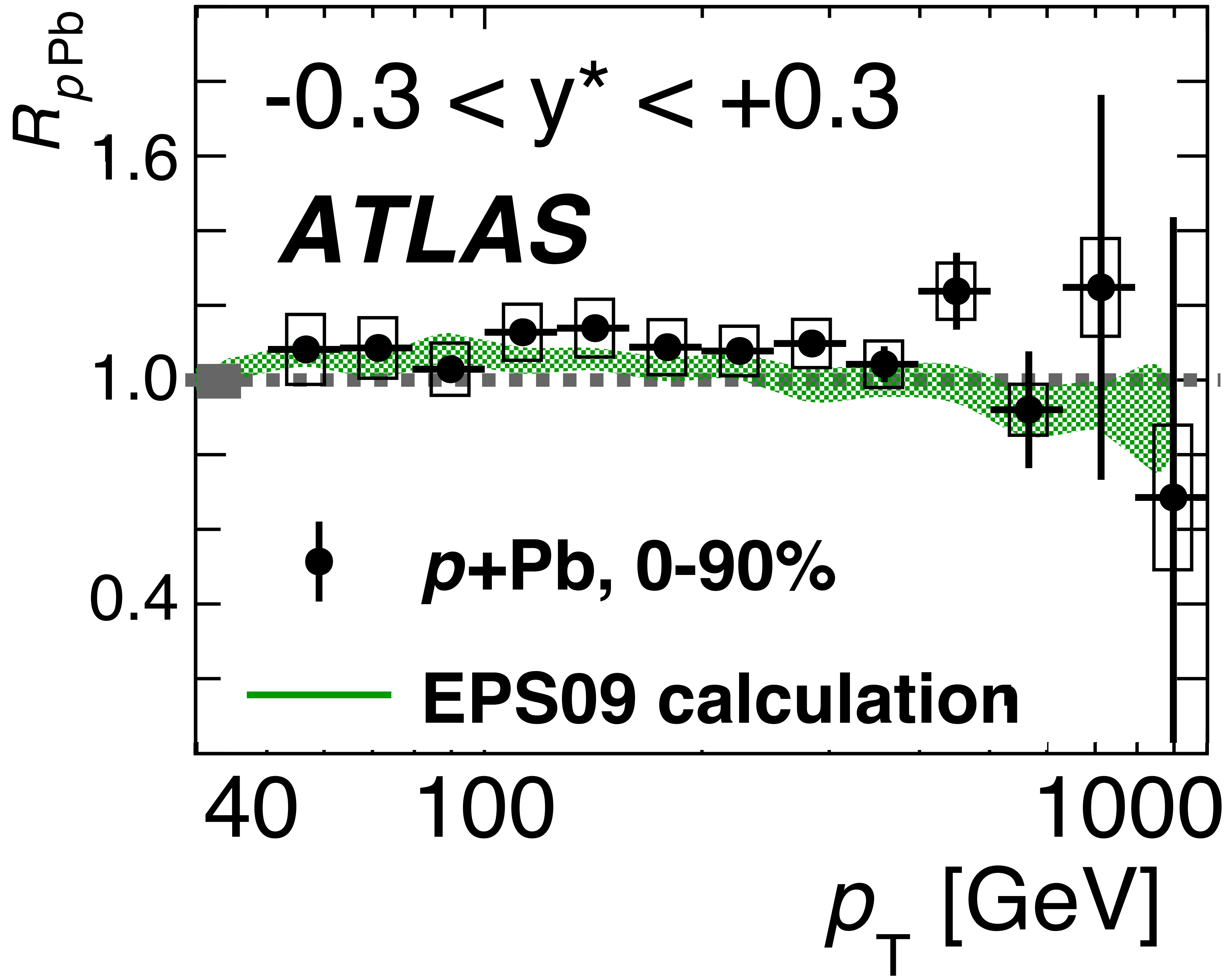


Magnitude of v_2 and v_3 agrees with calculation by Zhang & Liao…

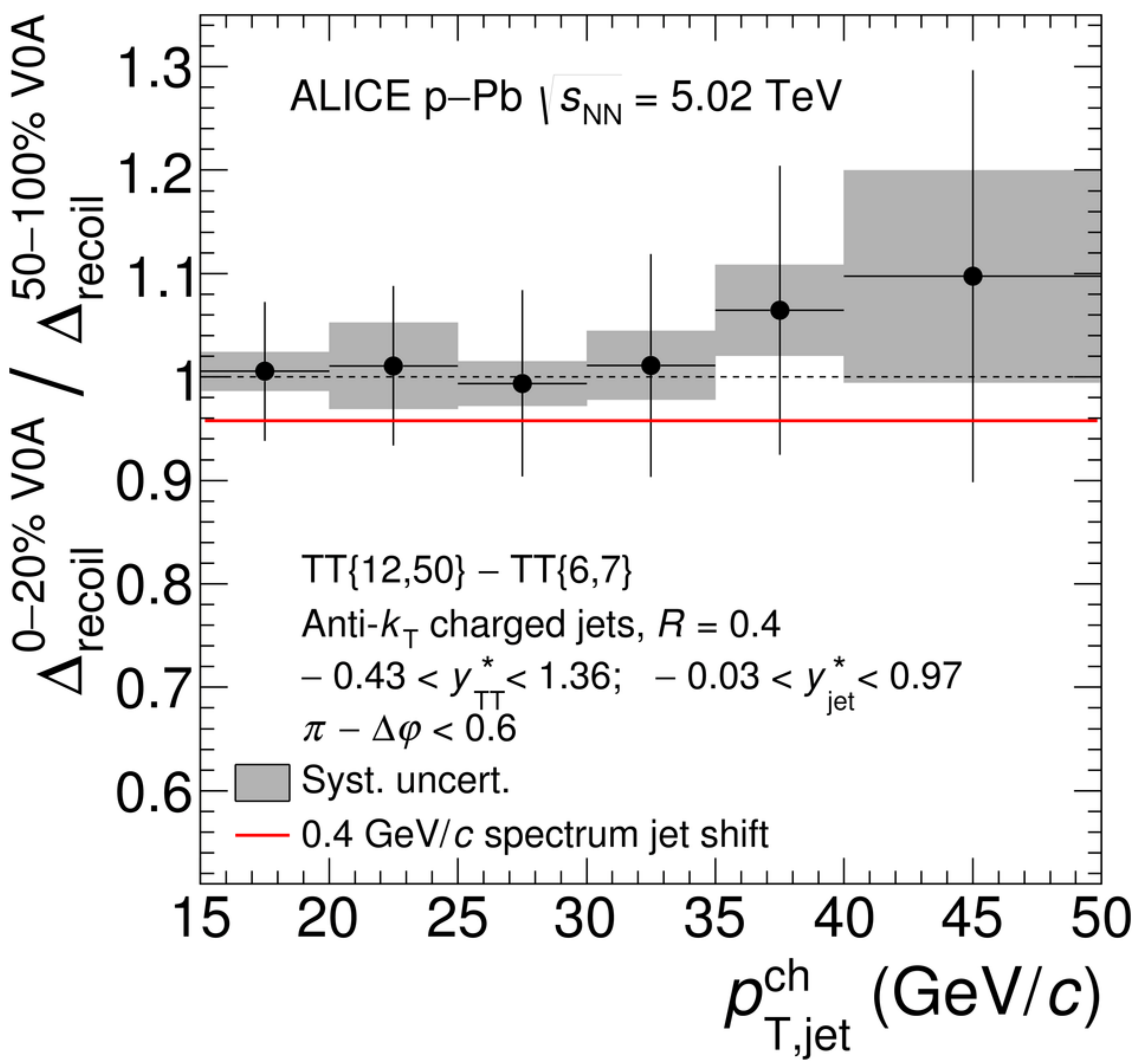
… but measurements of R_{pA} rule out the predicted suppression

What could jet quenching in *p*+A look like?

ATLAS, PLB 748 (2015) 392



ALICE, PLB 783 (2018) 95



Traditional approaches based on centrality-integrated R_{pA} (left) or intra-event correlations (right) have placed limits on “out of cone” energy loss

For small *E*-loss, biggest effect could be in softening of (in cone) fragmentation…

What could jet quenching in p+A look like?

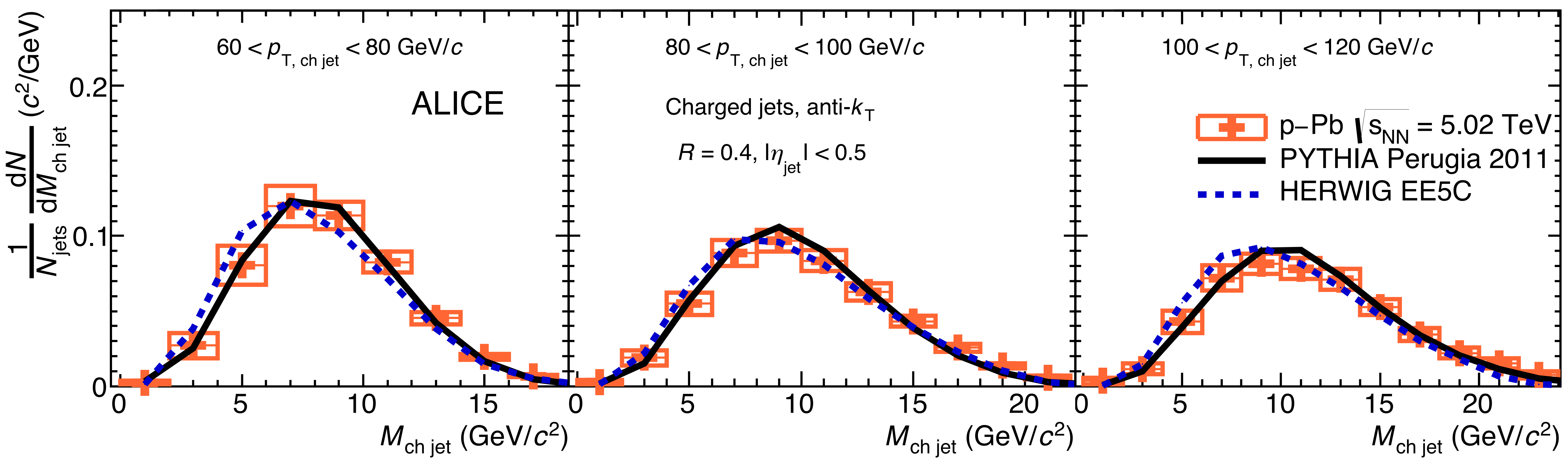
Some limits from centrality-integrated jet mass (top)

and fragmentation functions (bottom)

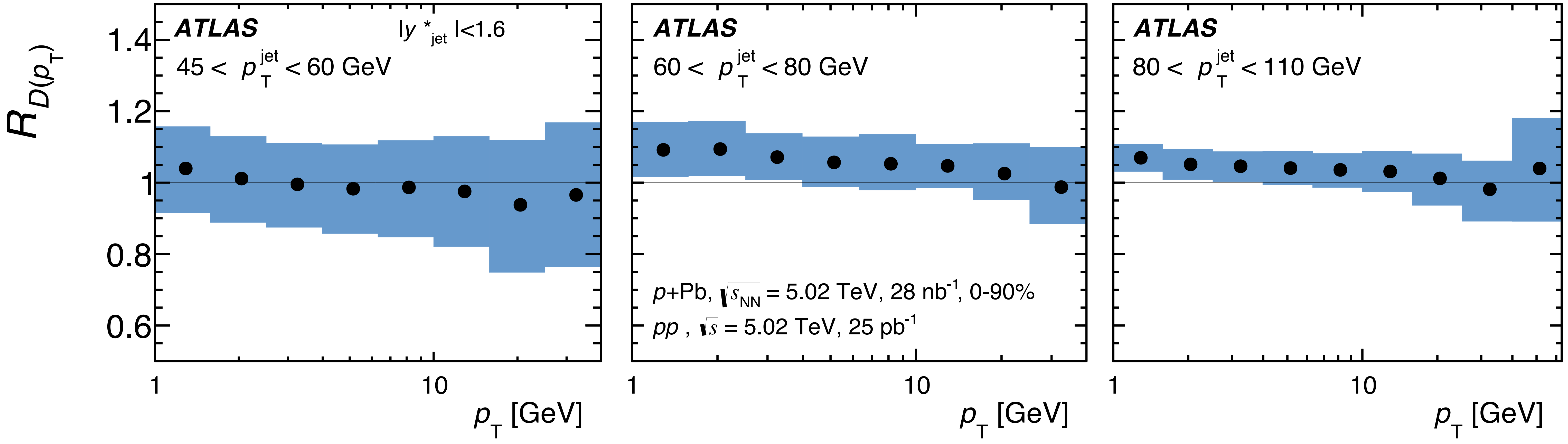
but need more systematic control and statistics (for central event selection)

Theory guidance for jet modification in p+Pb?

ALICE, PLB 776 (2018) 249



ATLAS, NPA 978 (2018) 65



Sanghoon Lim
Qipeng Hu

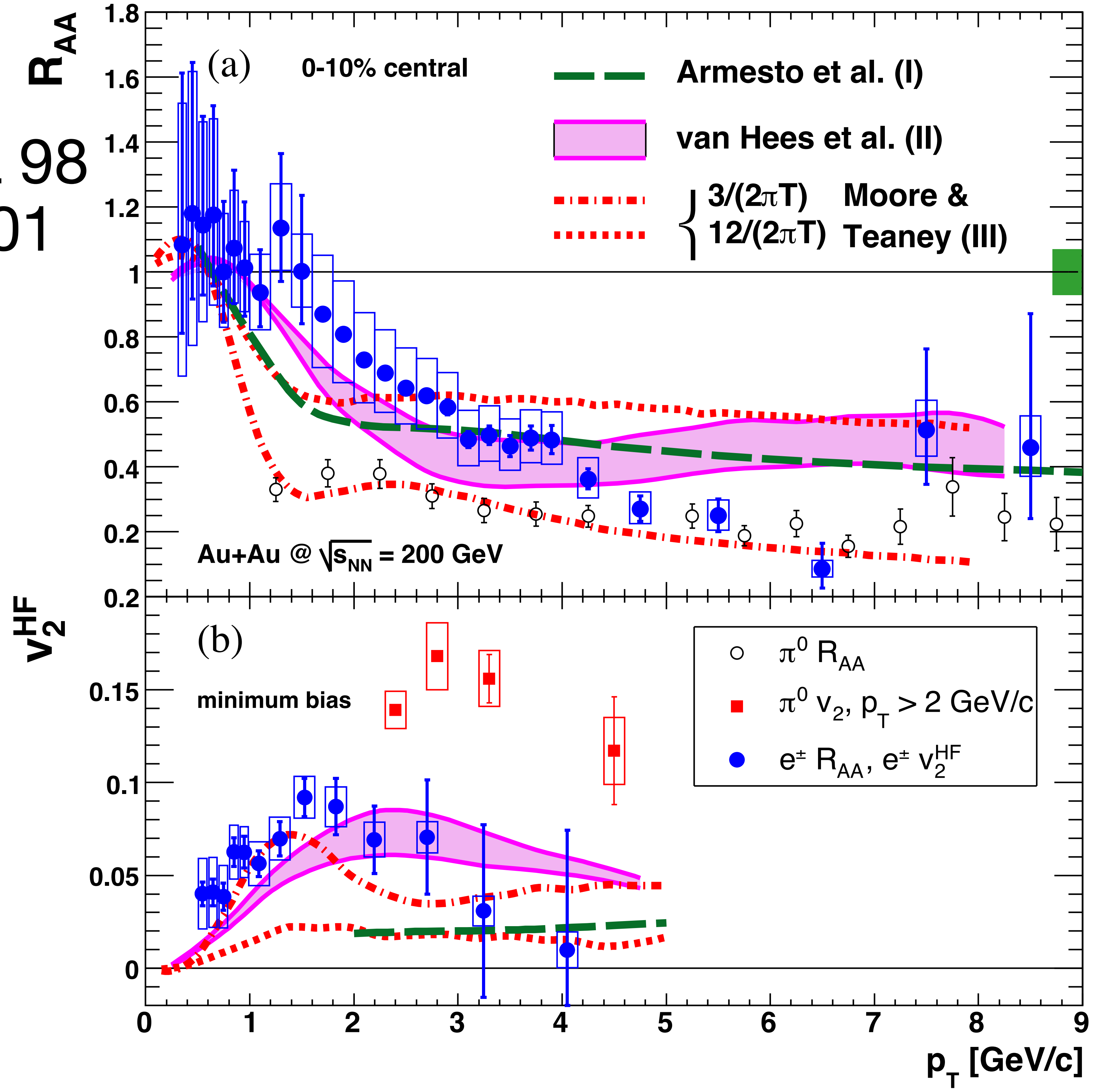
2. Charm and bottom quarks in *pp* collisions

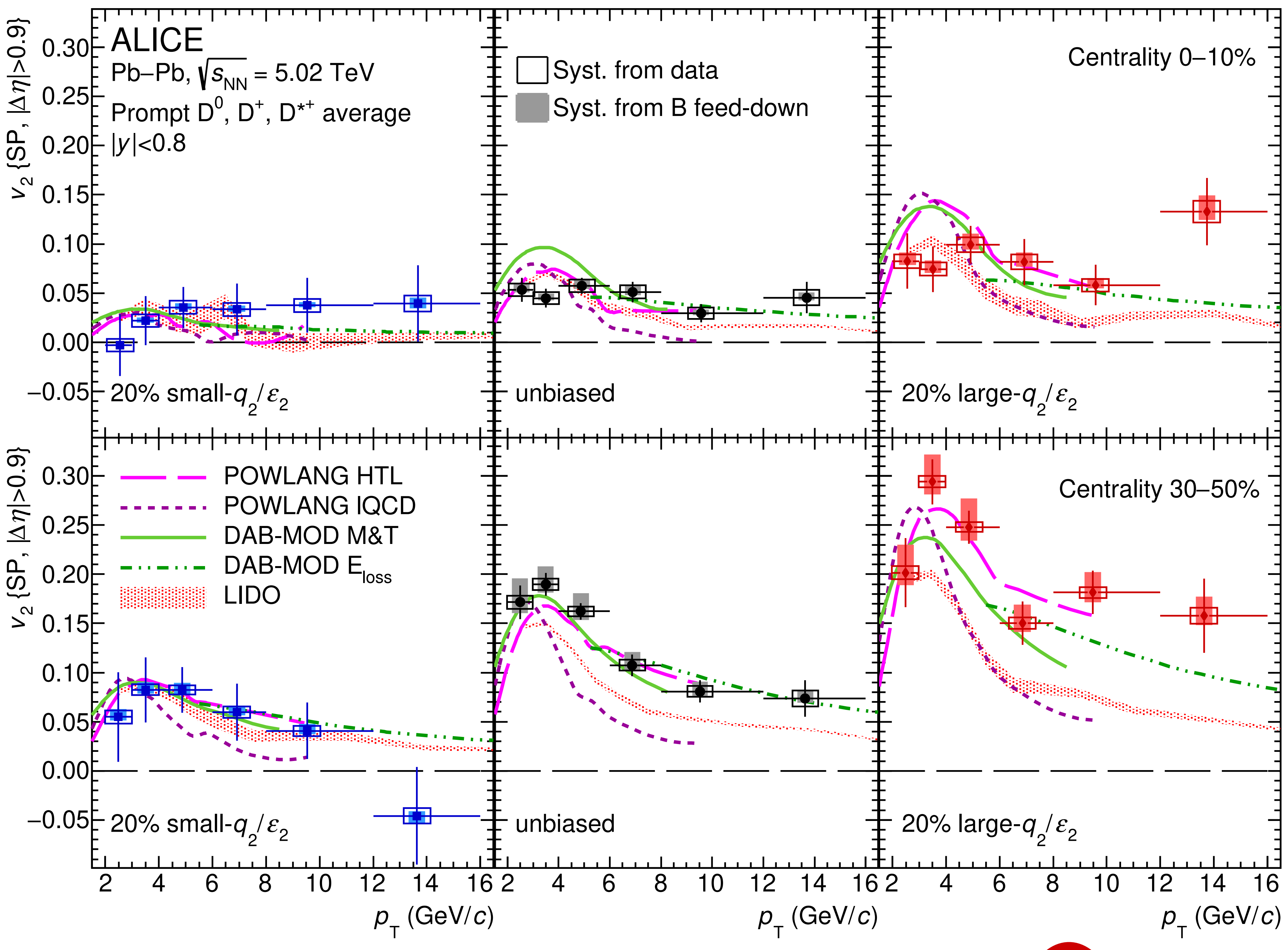
ATLAS, Phys. Rev. Lett. 124 (2020) 082301

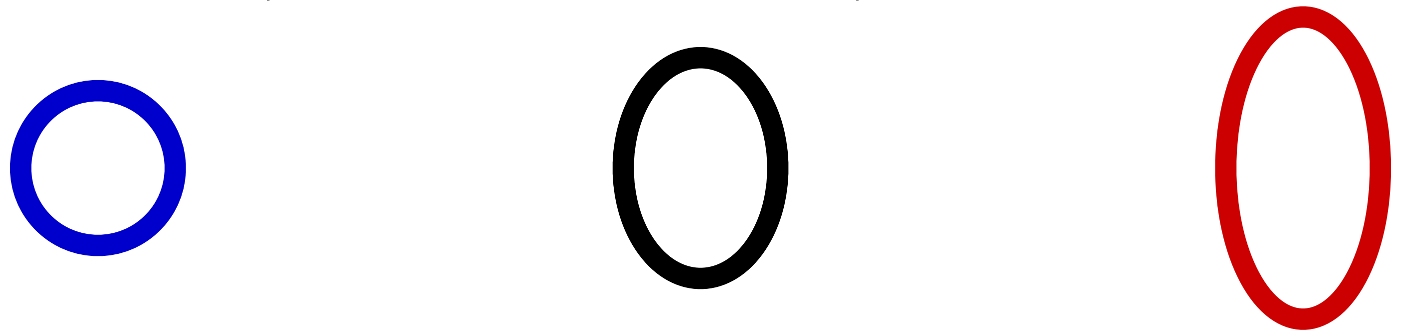
Heavy flavor modification in Au+Au

ALICE, nucl-ex/2005.11131

PHENIX, PRL 98 (2008) 172301







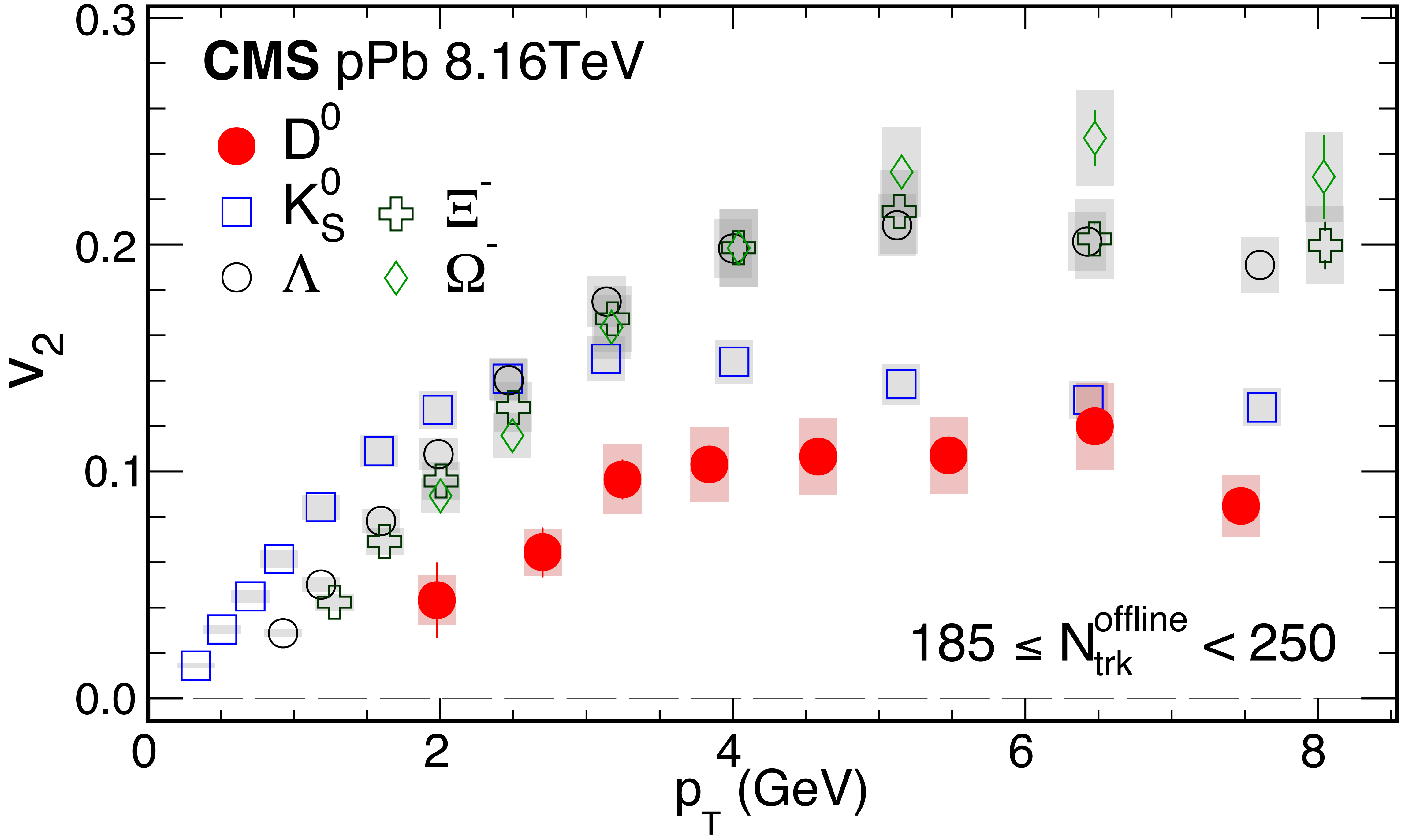
Substantial *E*-loss and flow of HF electrons at RHIC — one motivation for $\eta/s = 1/4\pi$ bound!

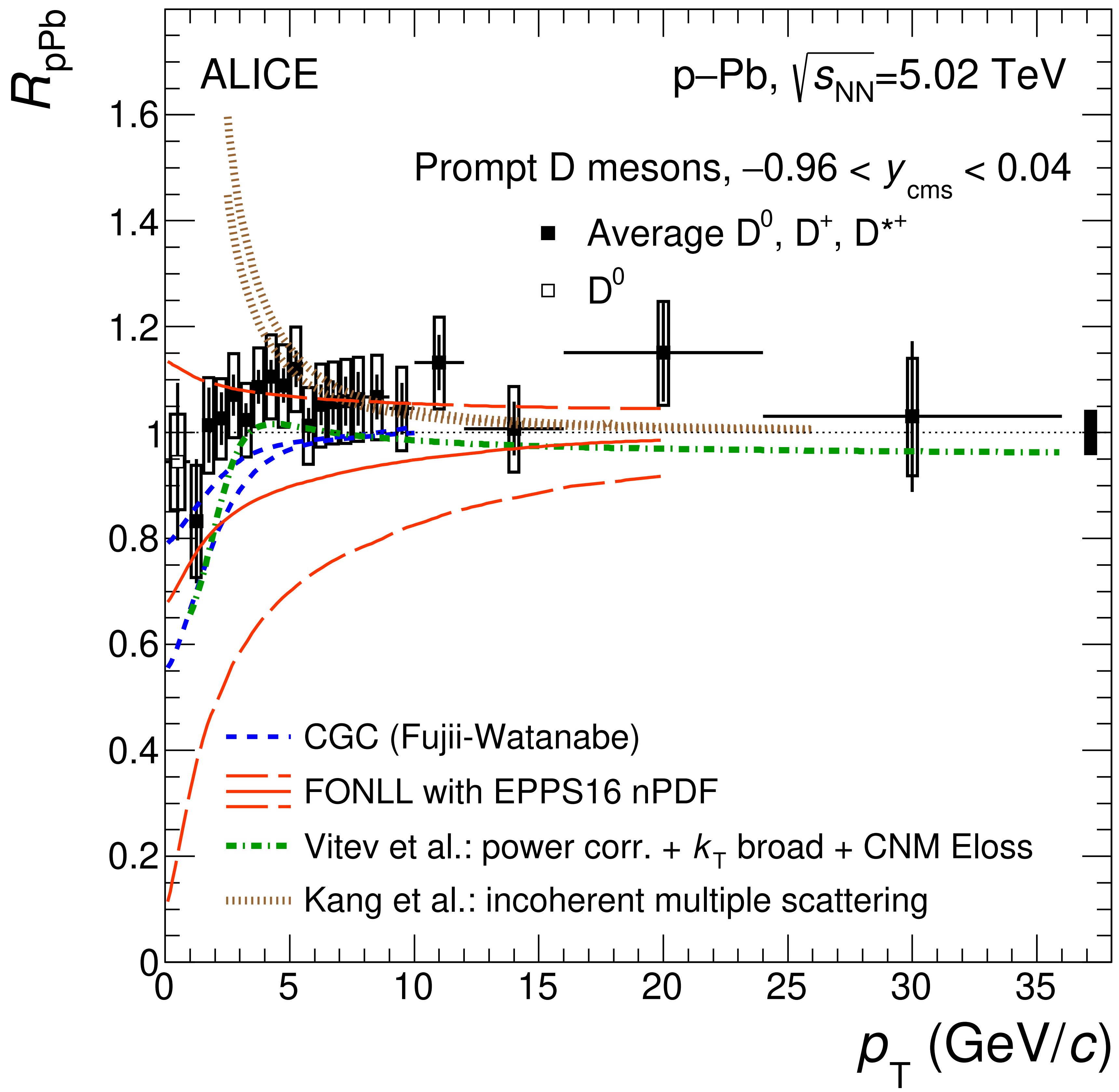
Thermalized charm “feels the shape” of the QGP region at the LHC

Heavy flavor modification(?) in *p*+A

ALICE, JHEP 12 (2019) 092

CMS, PRL 121 (2018) 082301



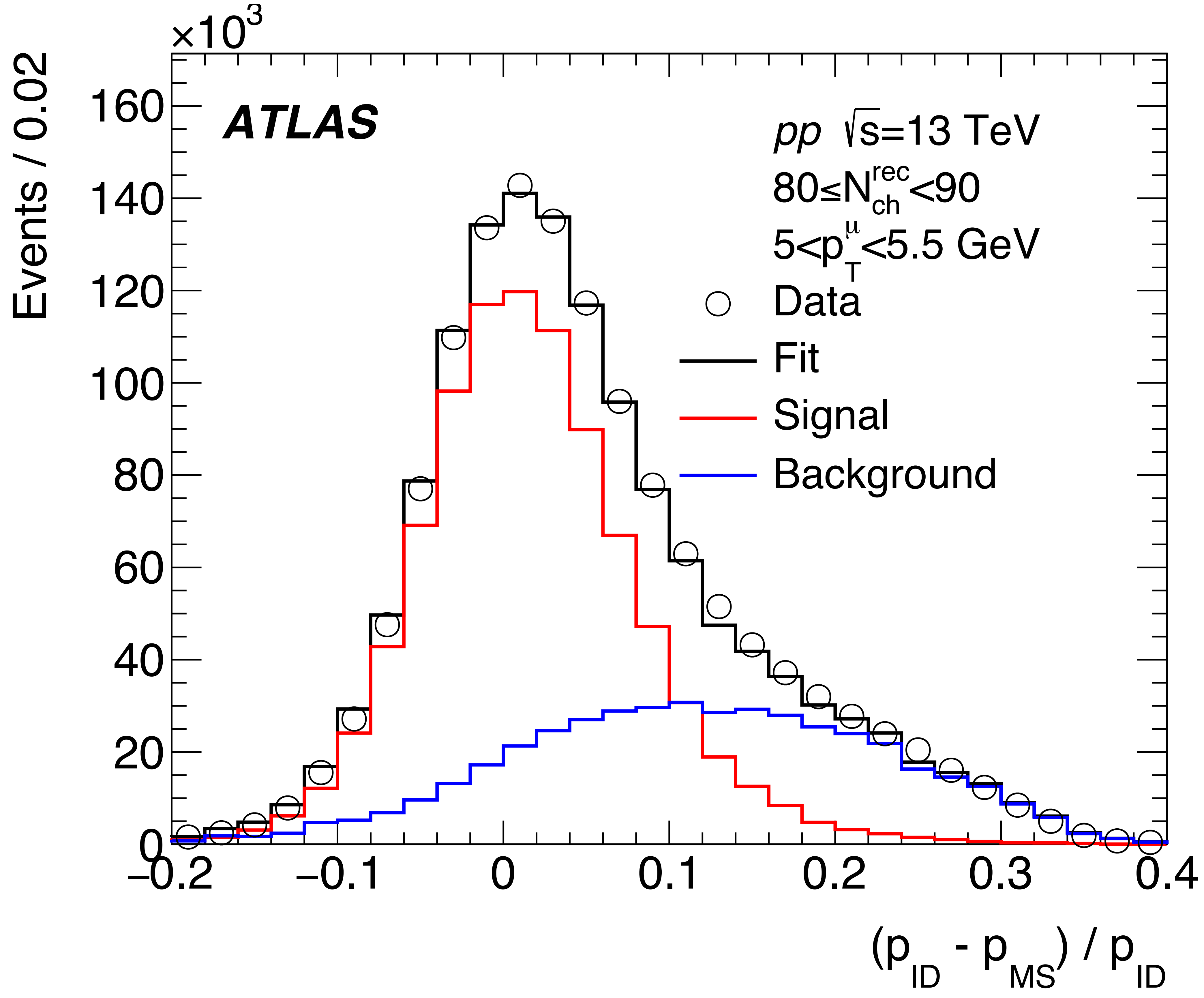


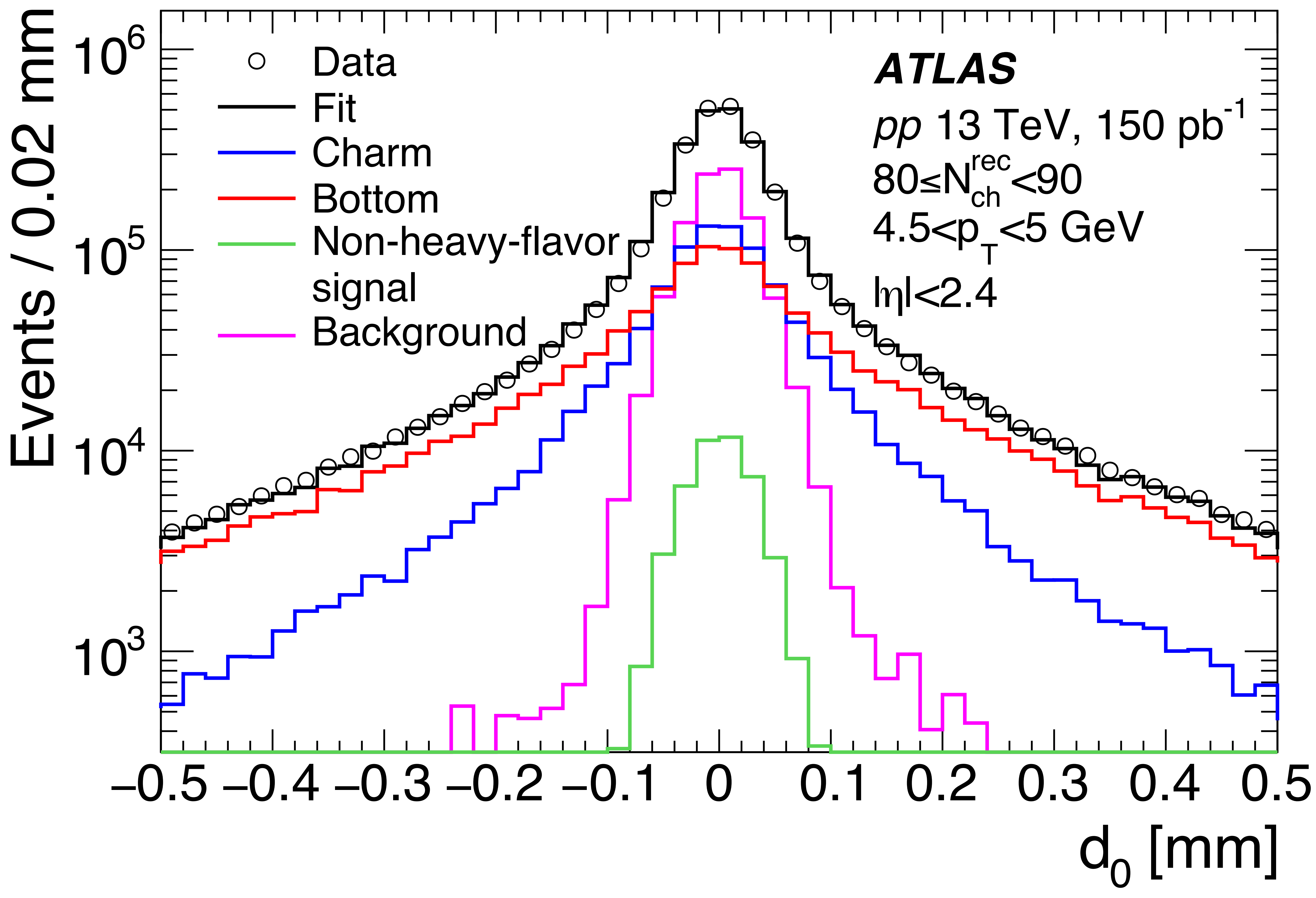
Similar v_2 magnitude for **charm hadrons** in (very high multiplicity) *p*+Pb

Good constraints on R_{pPb} for charm hadrons in minimum-bias collisions

What about charm and bottom in *pp* collisions?

Selecting heavy flavor muons in *pp*

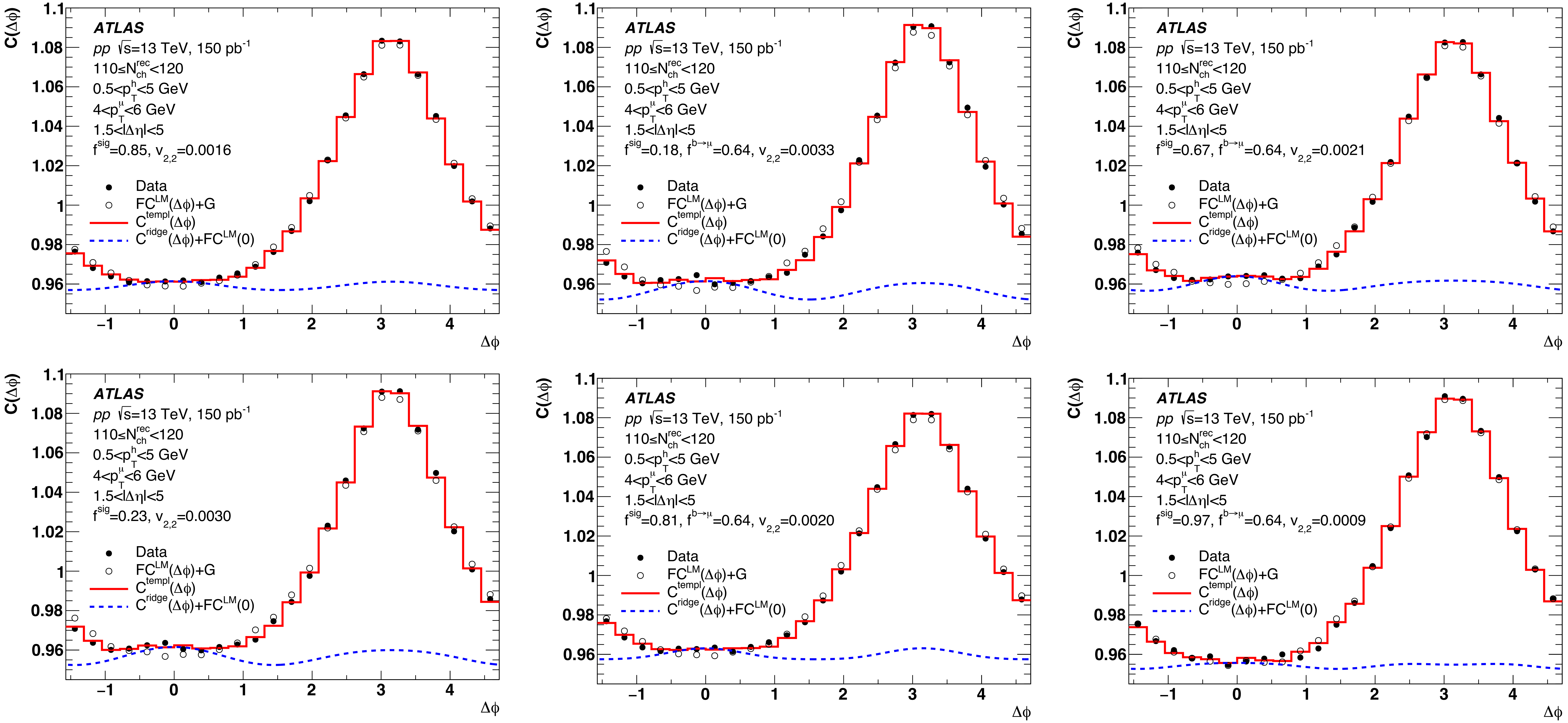




Heavy flavor decay muons separated from **in-flight decays, punch-throughs, etc.** via inner tracker - muon spectrometer *p* match

Decay muons from **charm** and **bottom** hadrons separated via transverse impact parameter

Two-particle correlation analysis



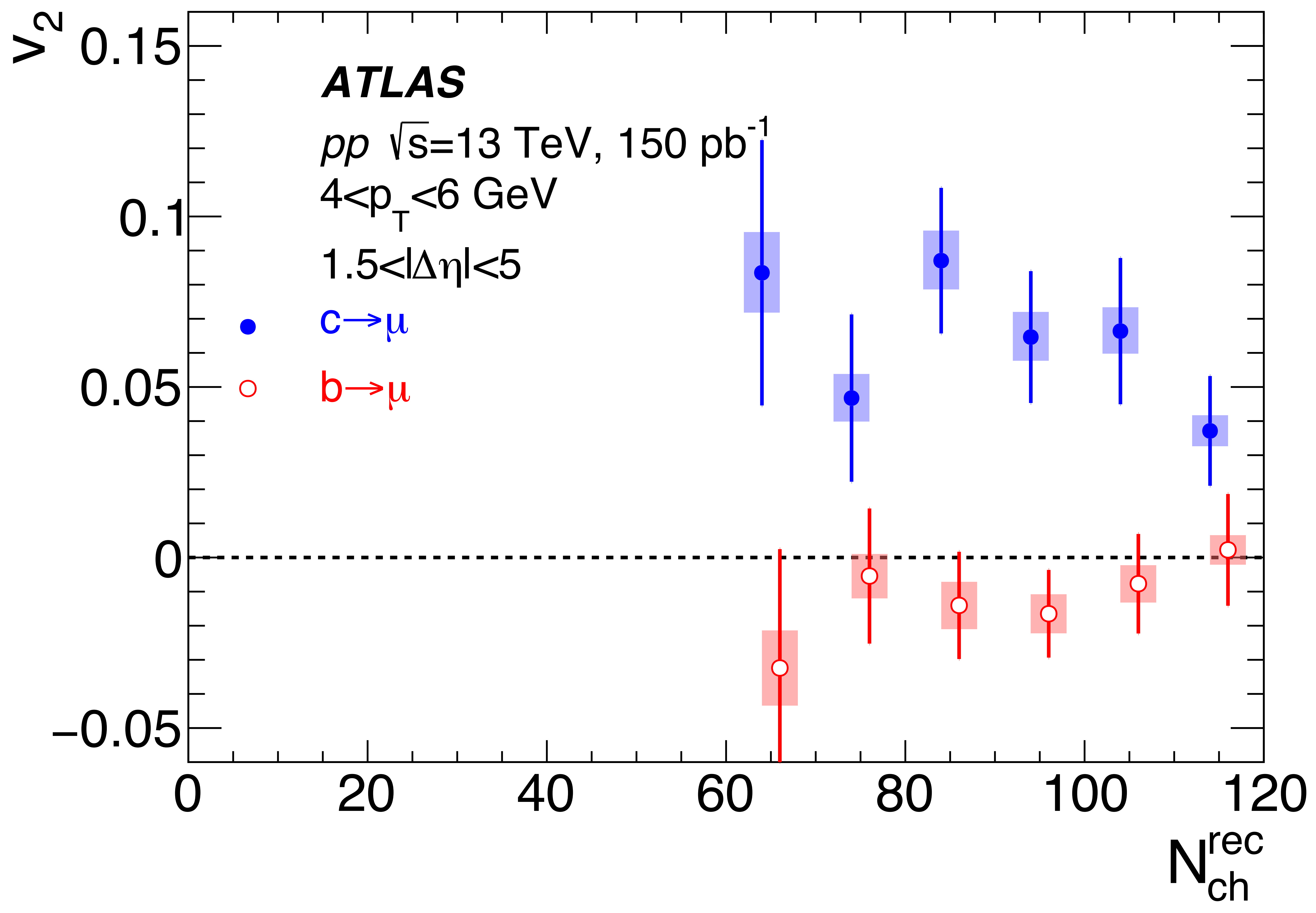
Rapidity-separated two-particle Δϕ correlations with template fit to remove non-flow

Performed in selections with different (genuine muon, background) and (charm, bottom) fractions, extrapolated to v_2 for pure charm and pure bottom

Charm and bottom v_2 in *pp* collisions

Large v_2 values for muons from **c-hadrons** in high-multiplicity *pp* collisions (~0-7% *pp*)!

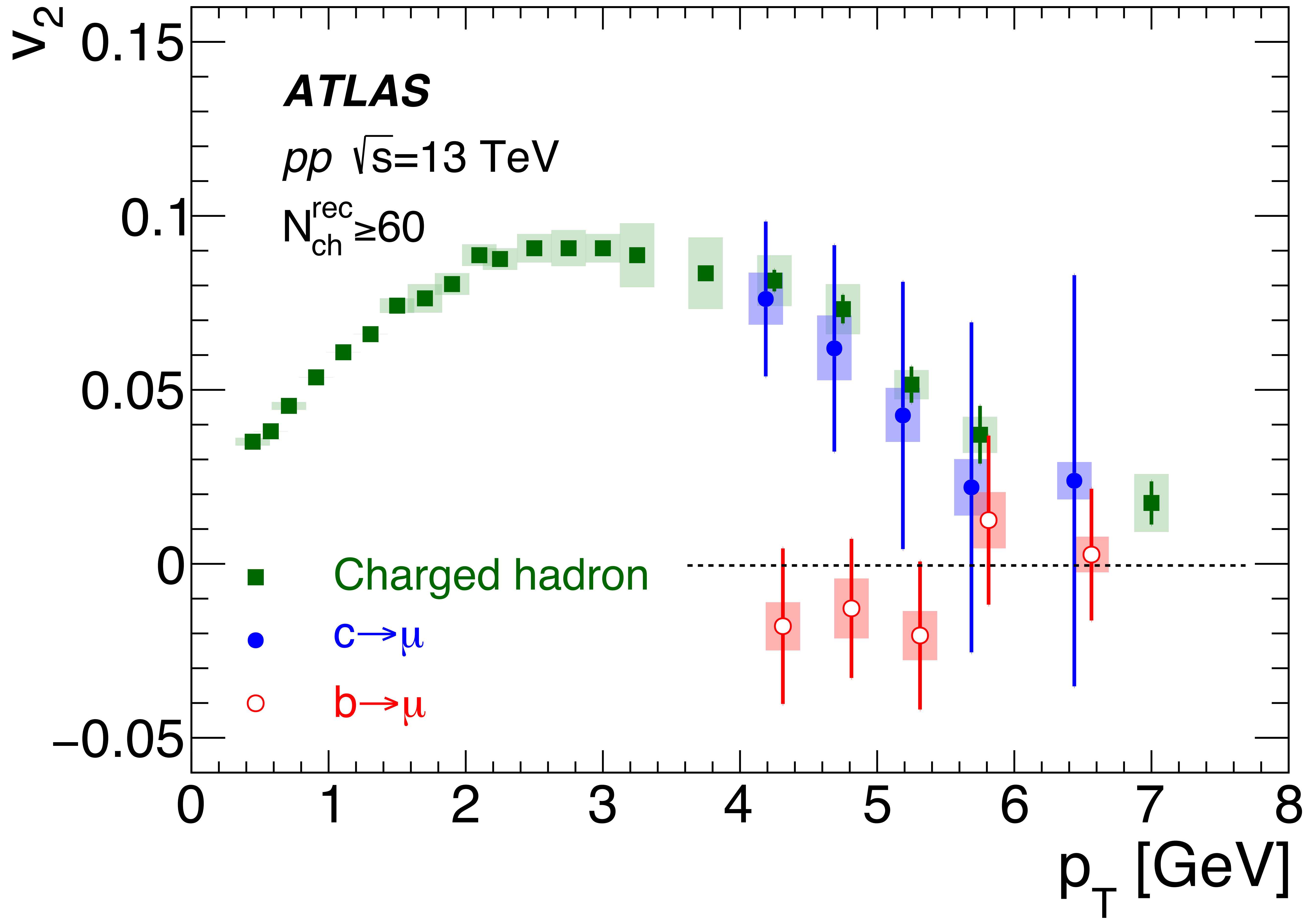
on the other hand, v_2 ~ 0 for ***b*-hadrons**



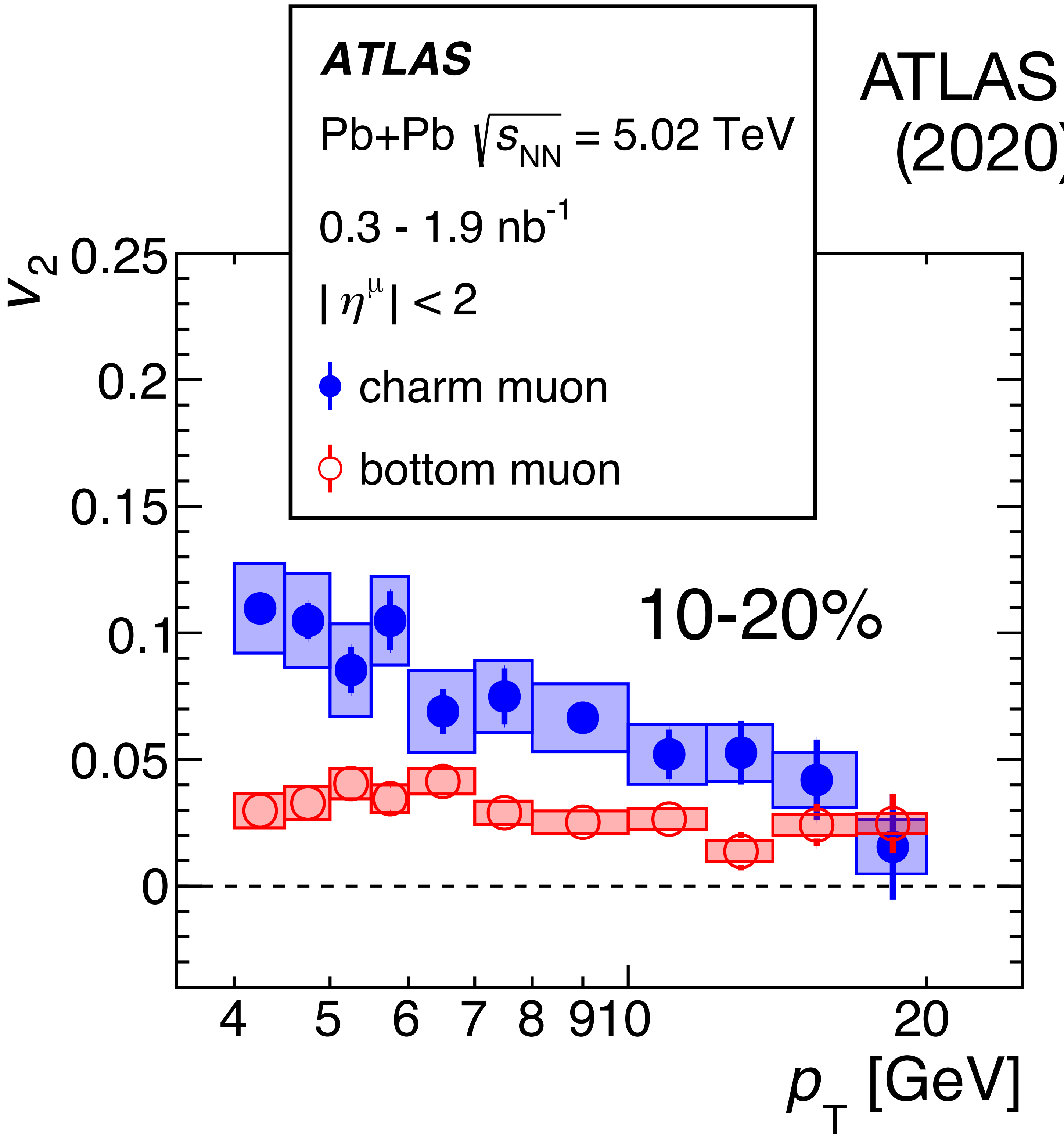
Charm and bottom v_2 in *pp* collisions

p_T-dependence of **charm v_2** matches **light hadrons** (but remember decay kinematics!)

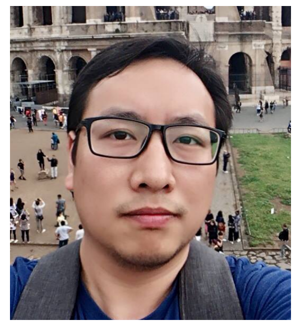
Possible to have **bottom v_2** at lower p_T, where physics mechanisms change?
($p_T^{\mu} > 4$ GeV similar to $p_T^{b\text{-hadron}} \gtrsim 6$ GeV)

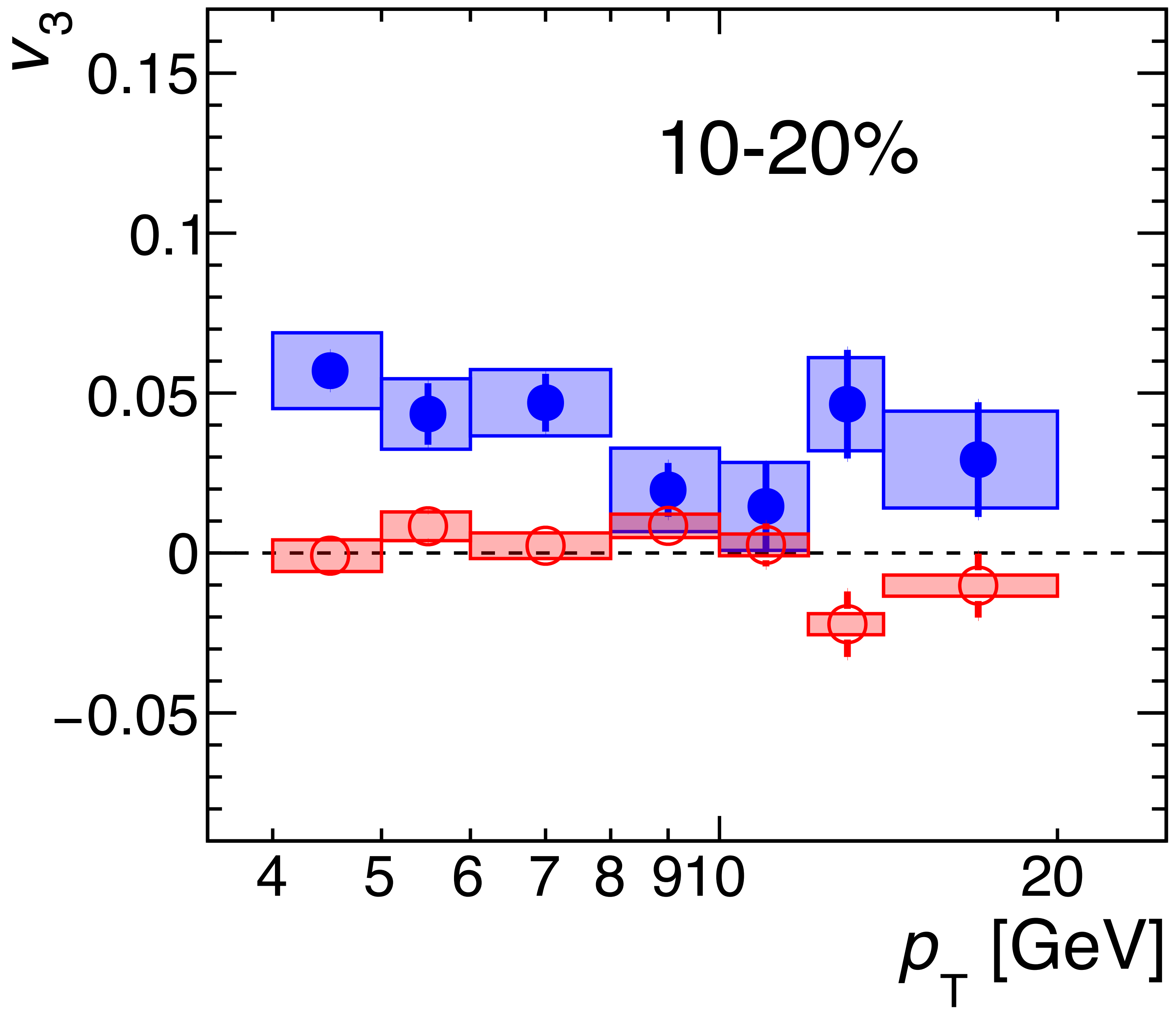


Importance of b-quarks in Pb+Pb

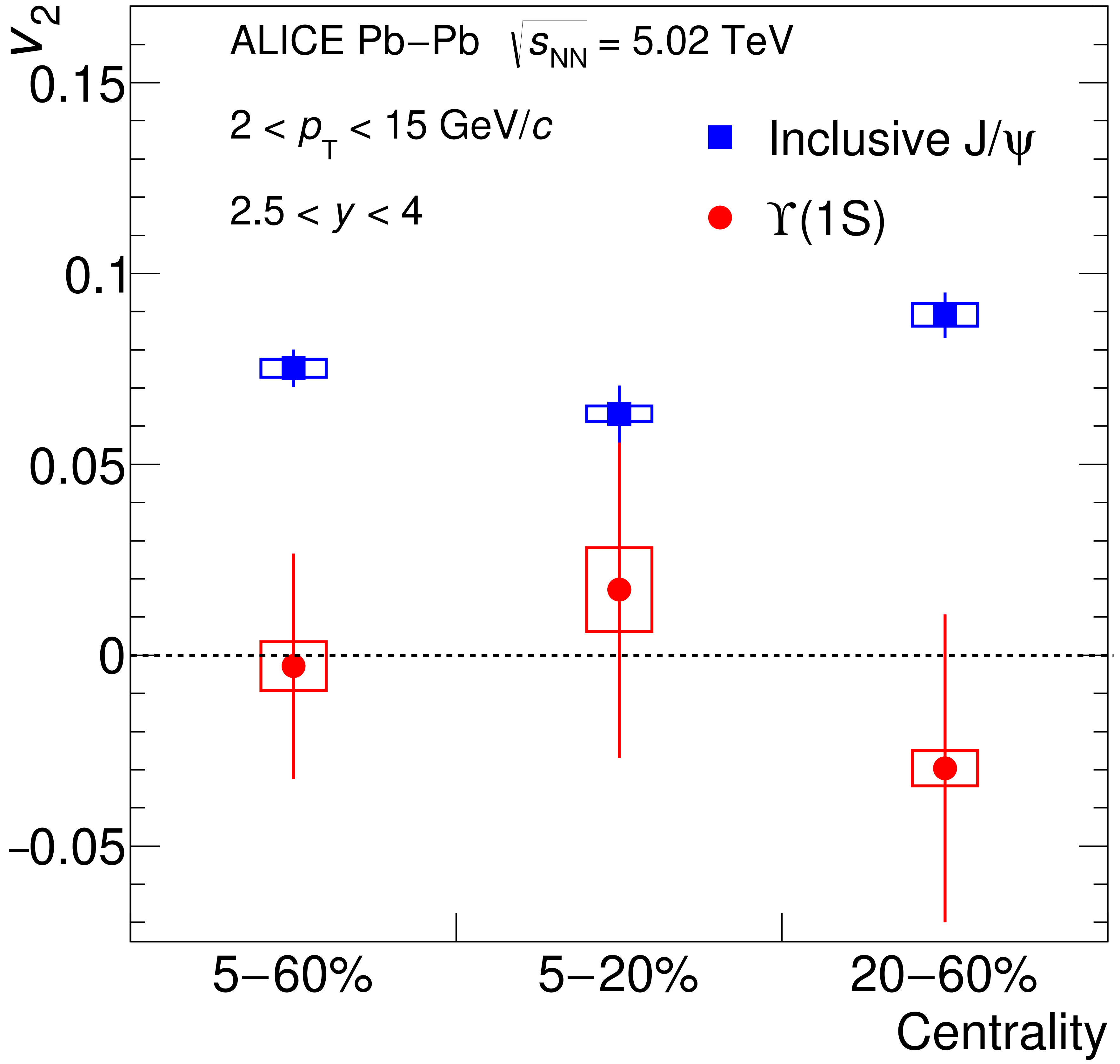


ATLAS, PLB 807 (2020) 135595





ALICE, PRL 123 (2019) 192301



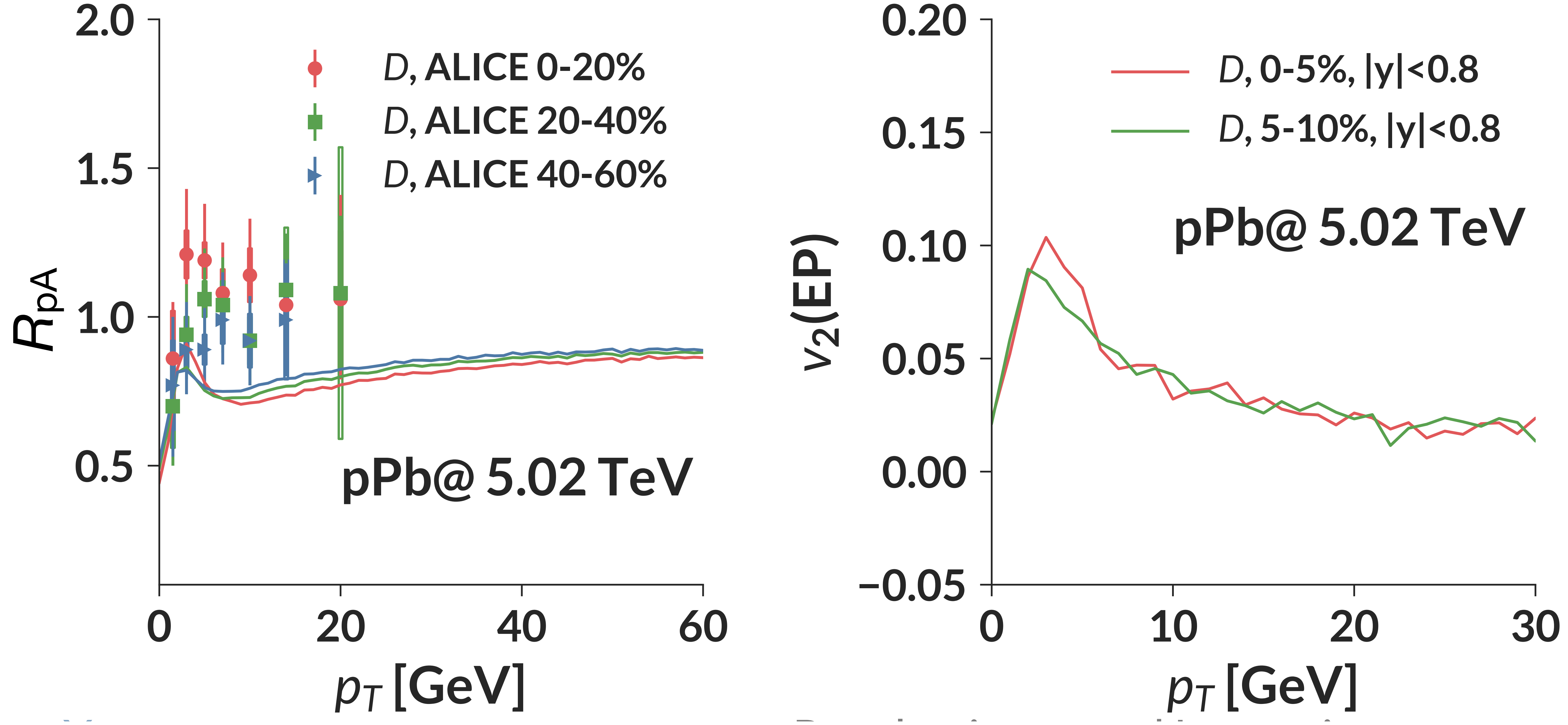
Mass effect also important in Pb+Pb: v_2 for muons from **c-hadron** vs. ***b*-hadron**

Sizable v_3 for muons from **c-hadrons** in Pb+Pb, but ~0 for ***b*-hadrons**!

v_2 for Upsilons in **Pb+Pb** also compatible with zero…

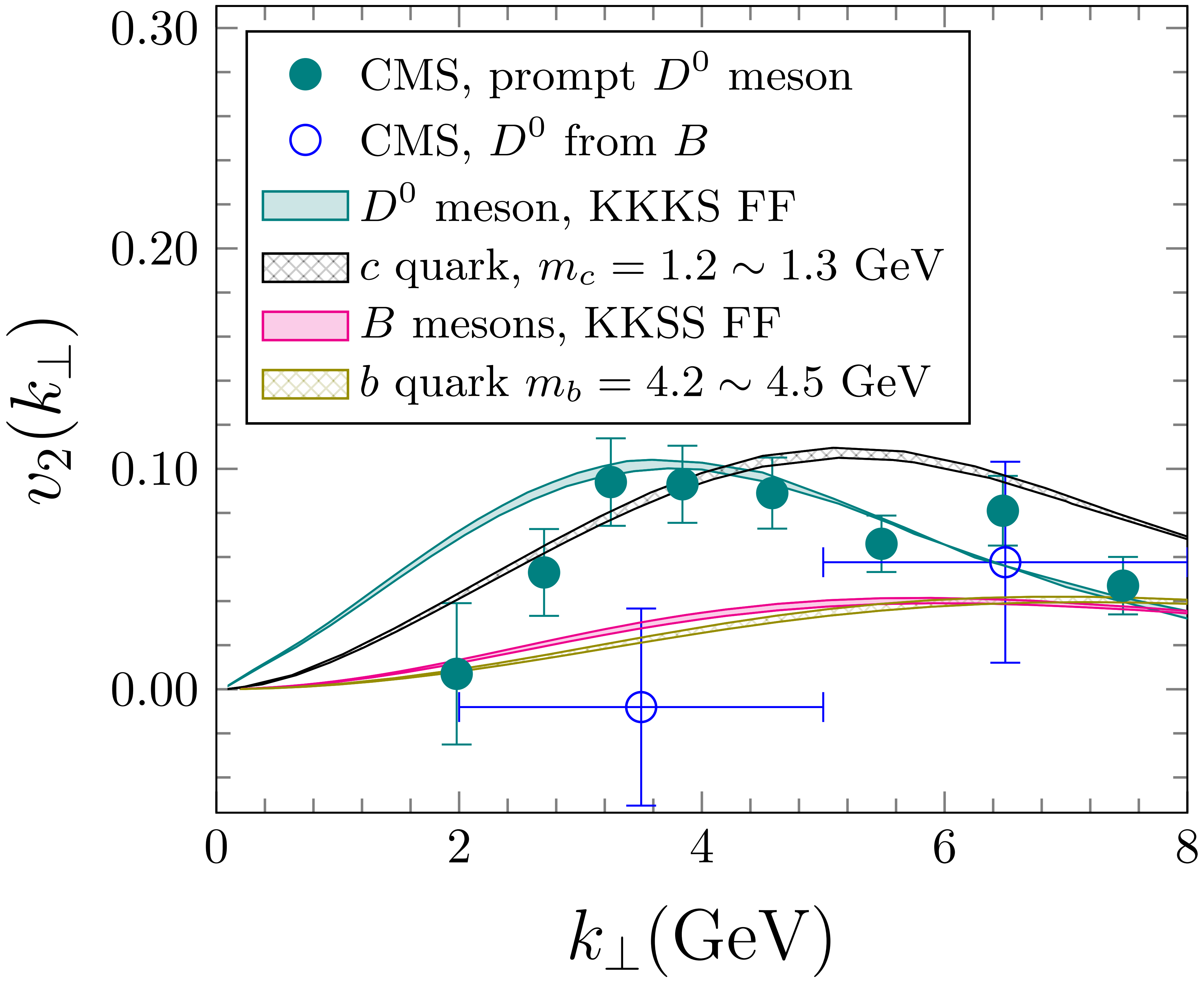
Interpretation (for *p*+A)

Xu, Ke, Bass, RHIC-AGS AUM 2018



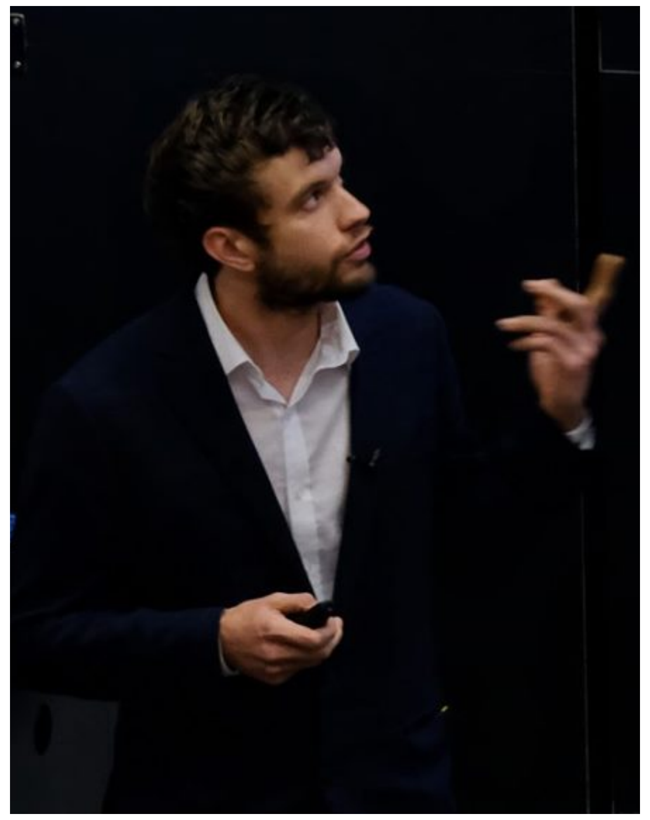
Langevin approach with parameters from Bayesian analysis of Pb+Pb data - difficult to reconcile observed R_{pA}

Zhang et al., PRD 102, 034010 (2020)



CGC calculation w/ interesting other predictions

What do these look like in *pp* (smaller system, no $A^{1/3}$ saturation enhancement)?



Blair Seidlitz

3. Searching for collective phenomena in photo-nuclear collisions

Preliminary result ATLAS-CONF-2019-022

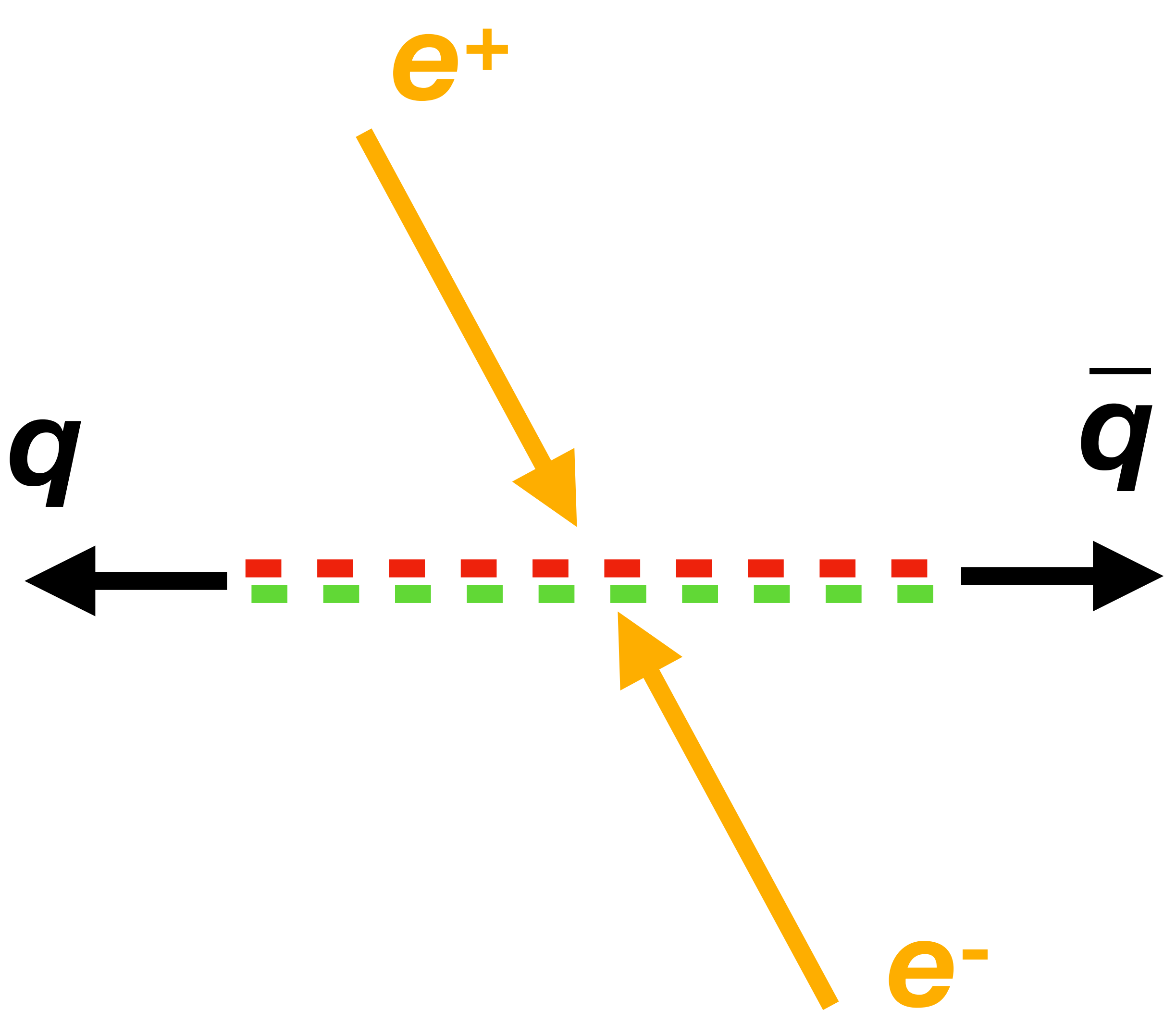
Limiting conditions for collectivity?

- In a final-state interaction picture, non-zero v_n values arise from an *intrinsic transverse geometry*, not "just" a large multiplicity

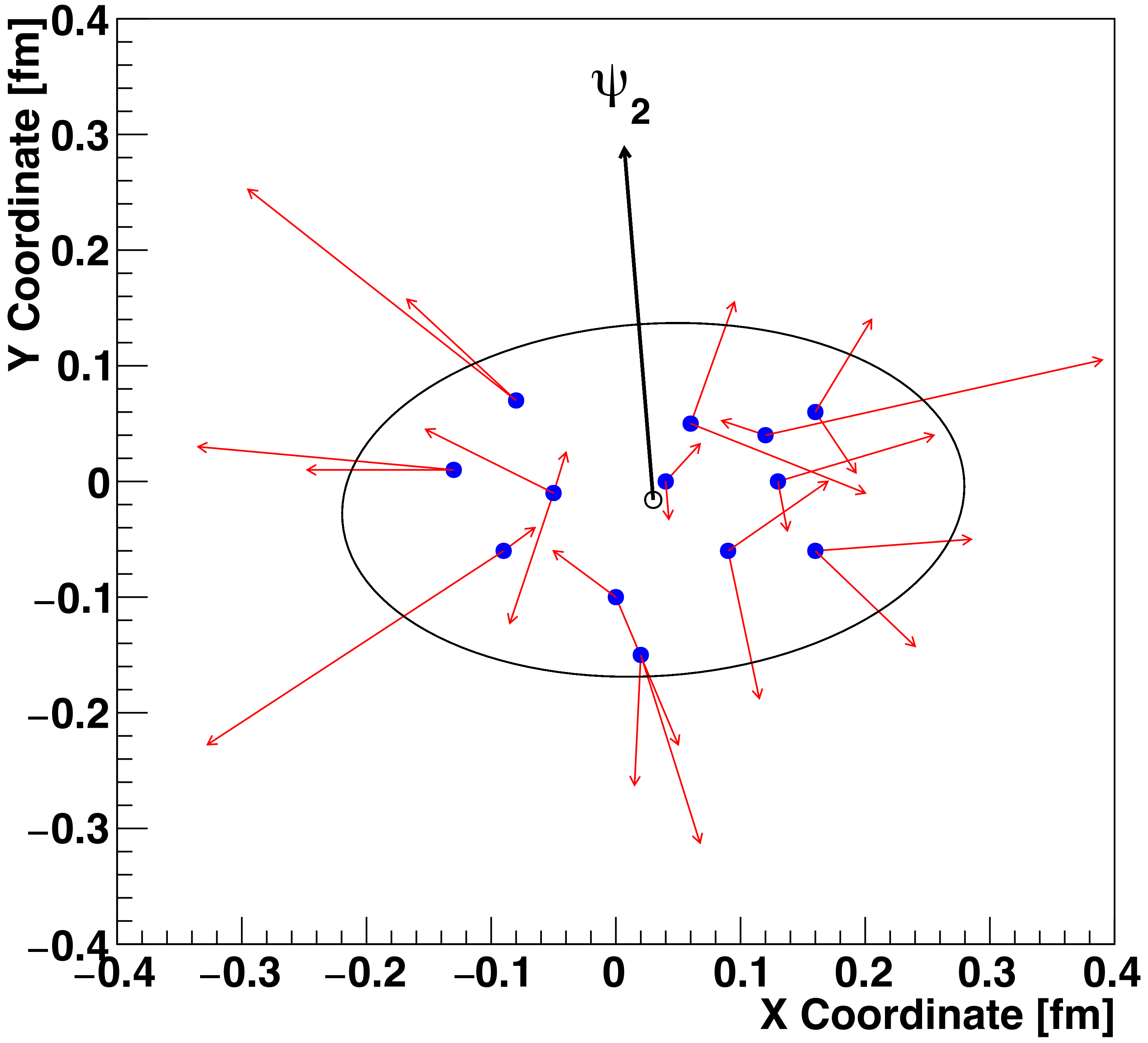
  ➡ without a "long-range" geometry - one persisting across large rapidity range - particle rescattering cannot generate a v_2 (or v_3, v_4…)

AMPT model of e^+e^- $(\rightarrow Z) \rightarrow q\bar{q}$

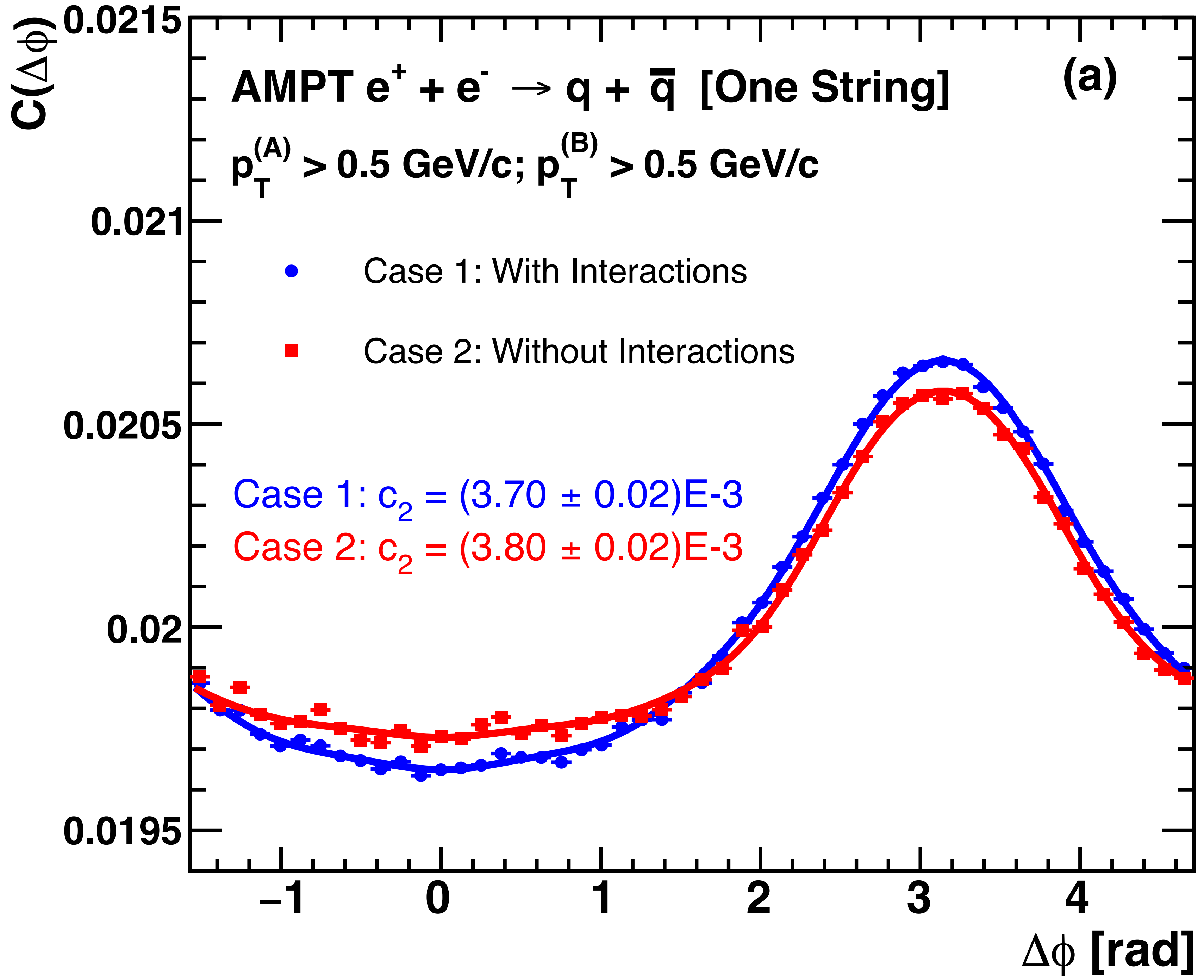
Nagle, Belmont, Hill, Orjuela Koop, Perepelitsa, Yin (CU) + Lin (ECU)
PRC 97 (2018) 024909



Model as a single string stretched between two receding quarks with $E = m_Z/2$



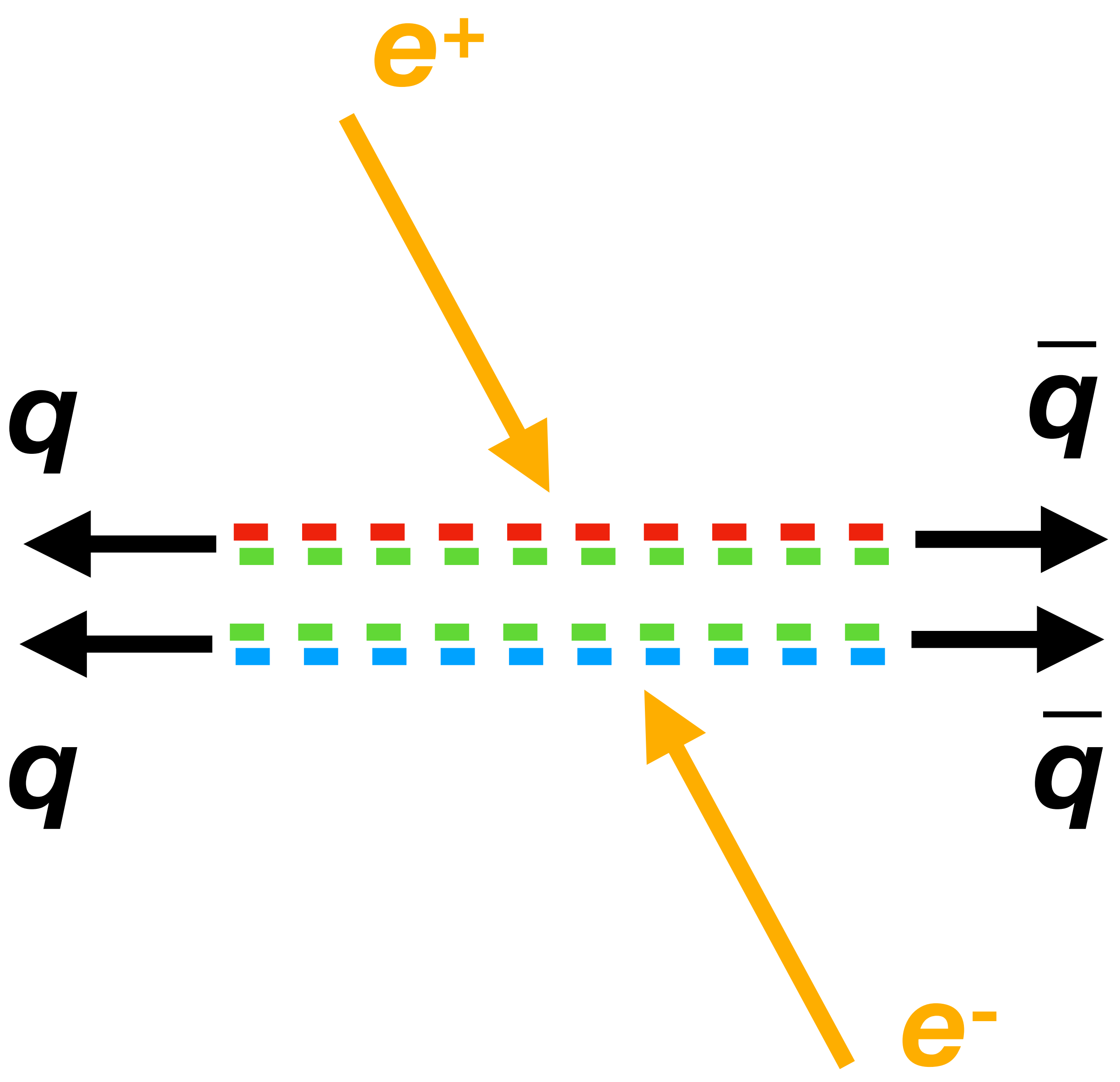
Snapshot of partons with momentum vectors in transverse plane



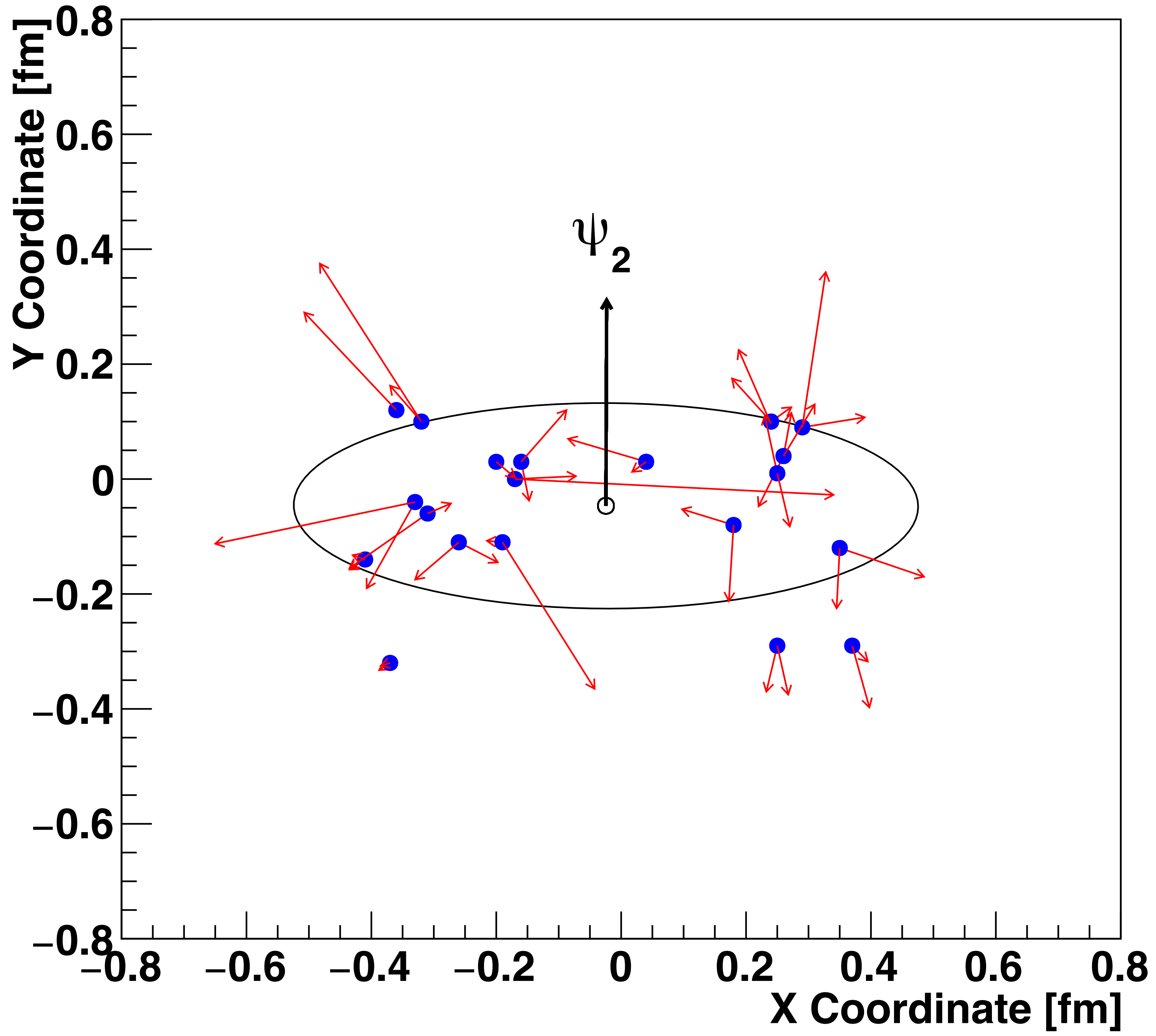
Parton rescatterings in the final state are happening - but no "preferred" final direction - no long-range ridge!

AMPT two-string example

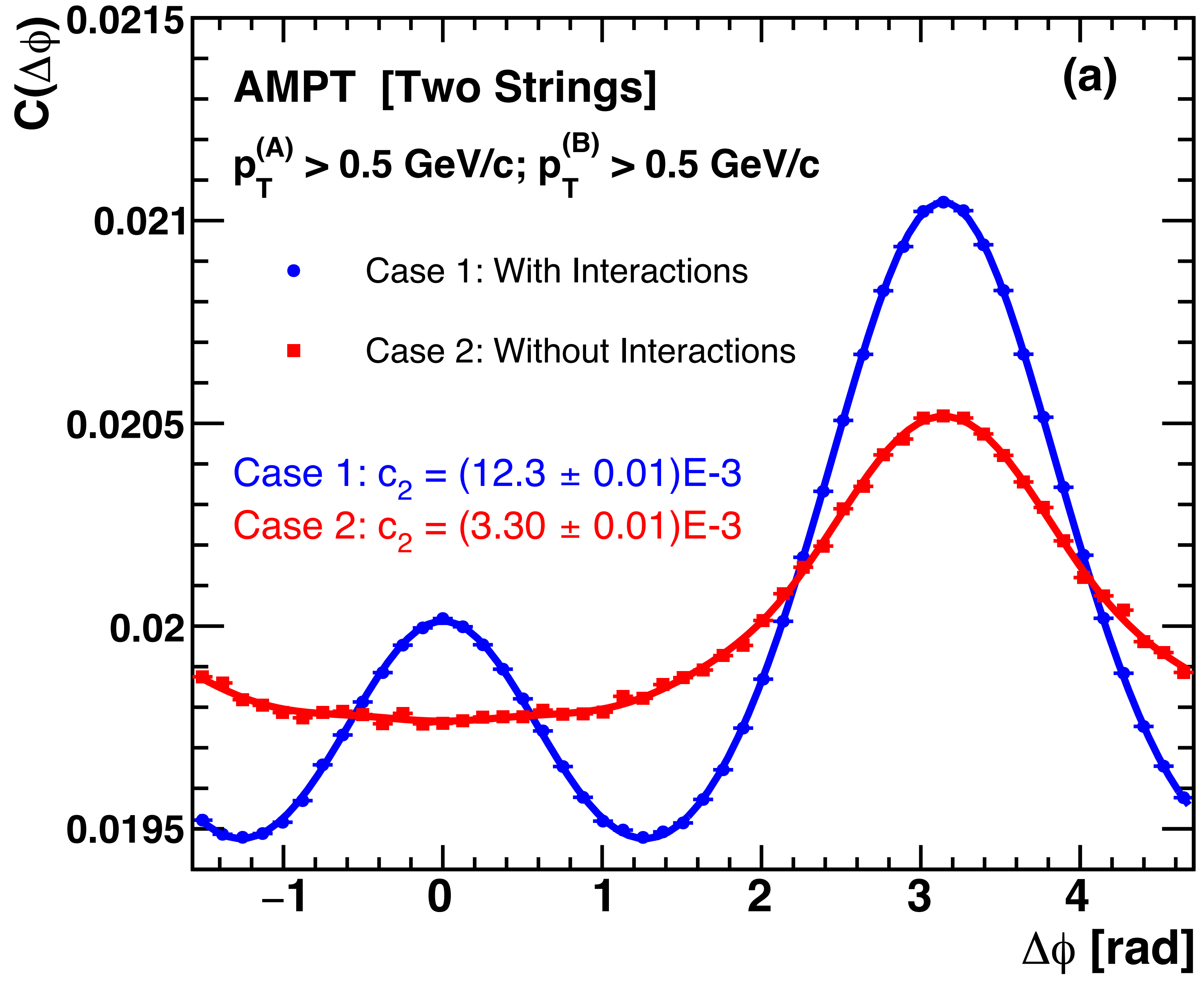
Nagle, Belmont, Hill, Orjuela Koop,
Perepelitsa, Yin (CU) + Lin (ECU)
PRC 97 (2018) 024909



Consider ficitious case with two parallel strings



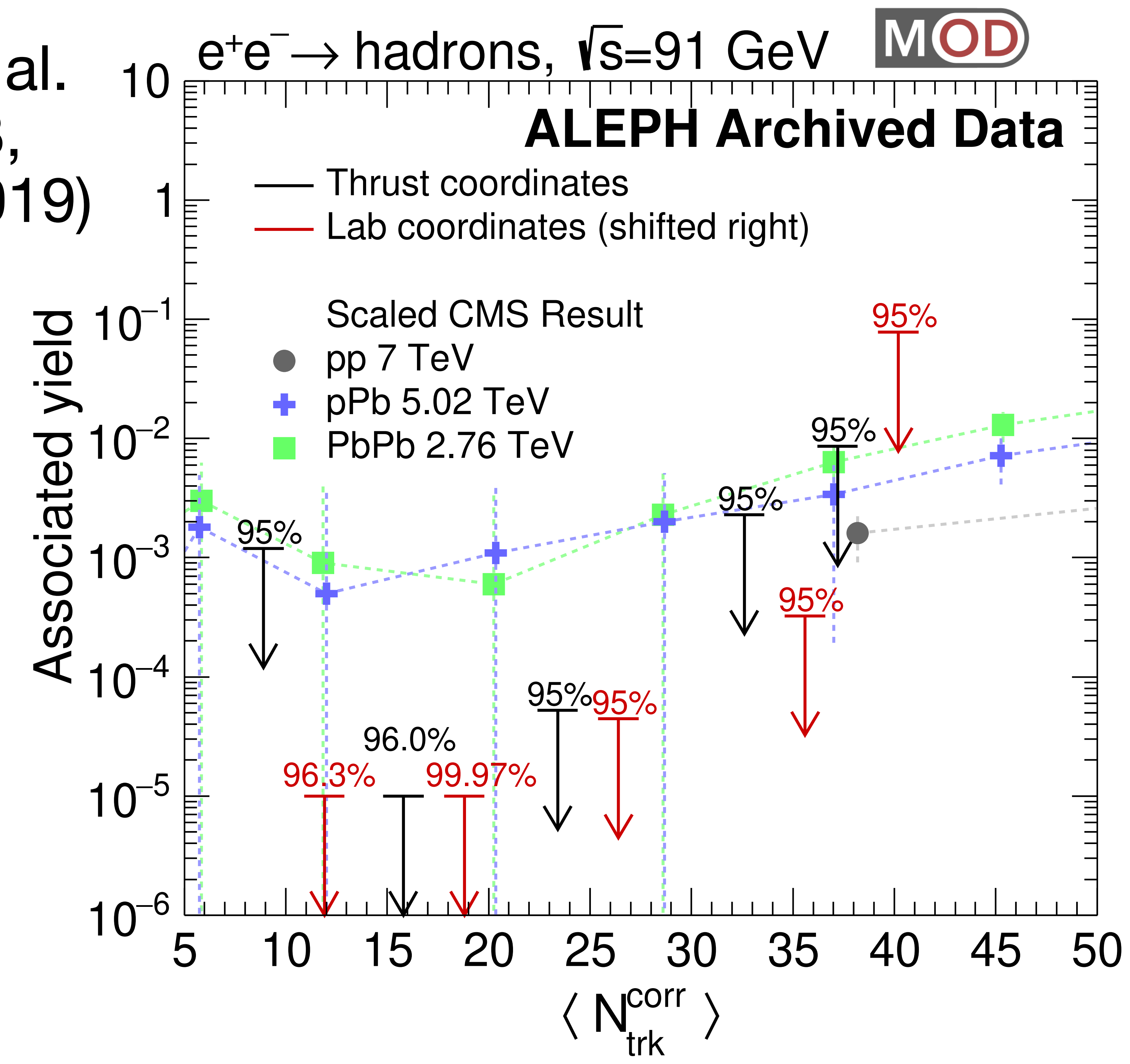
Same total energy, same total multiplicity — but now there is a long-range geometry



Parton rescatterings now generate a long-range azimuthal correlation

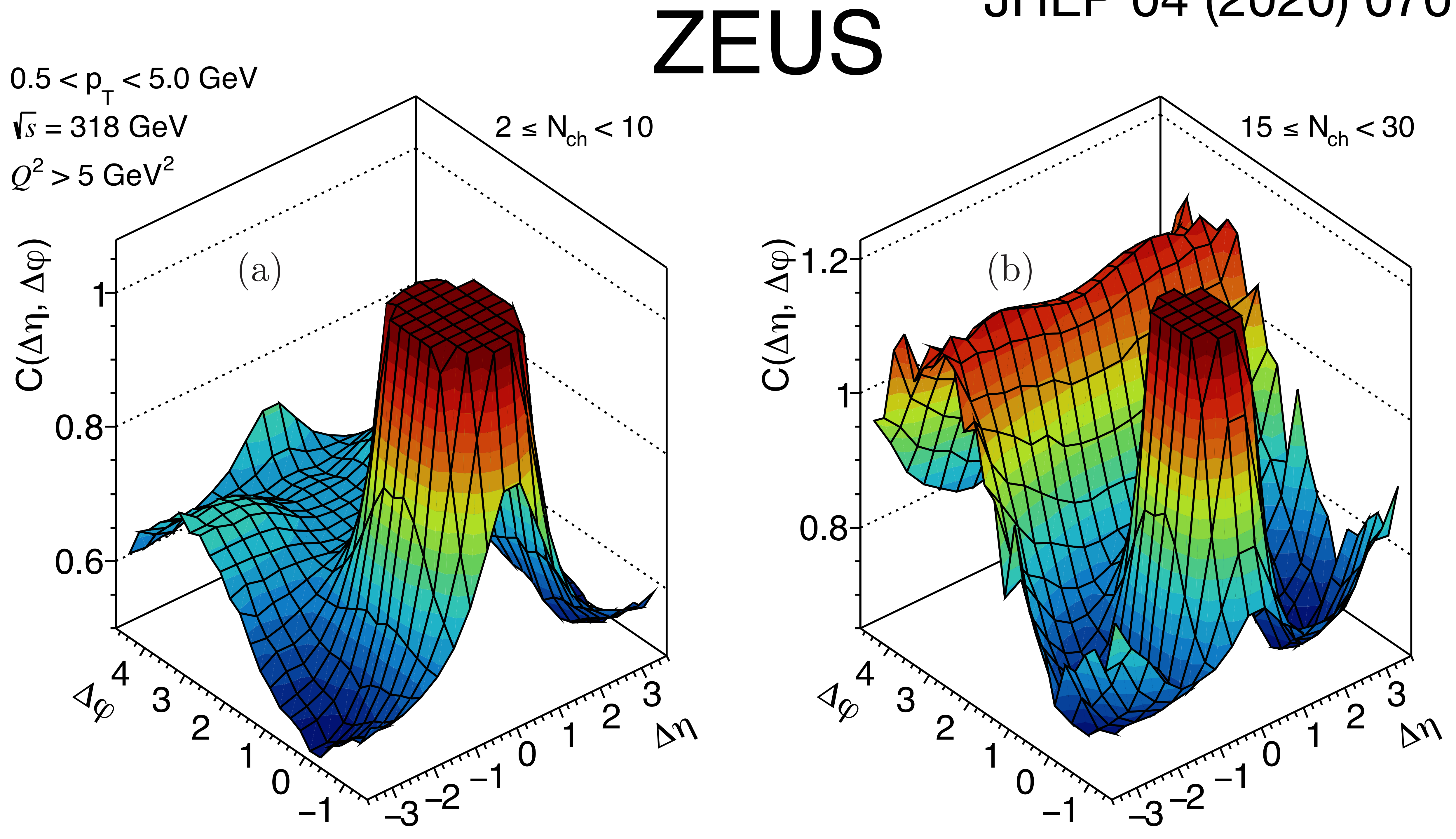
Studies in archived data

Badea, et al. PRL 123, 212002 (2019)



Strong limits on possible magnitude of v_2 - as expected in FSI picture w/ no long-range geometry!

Abt et al. (ZEUS), JHEP 04 (2020) 070

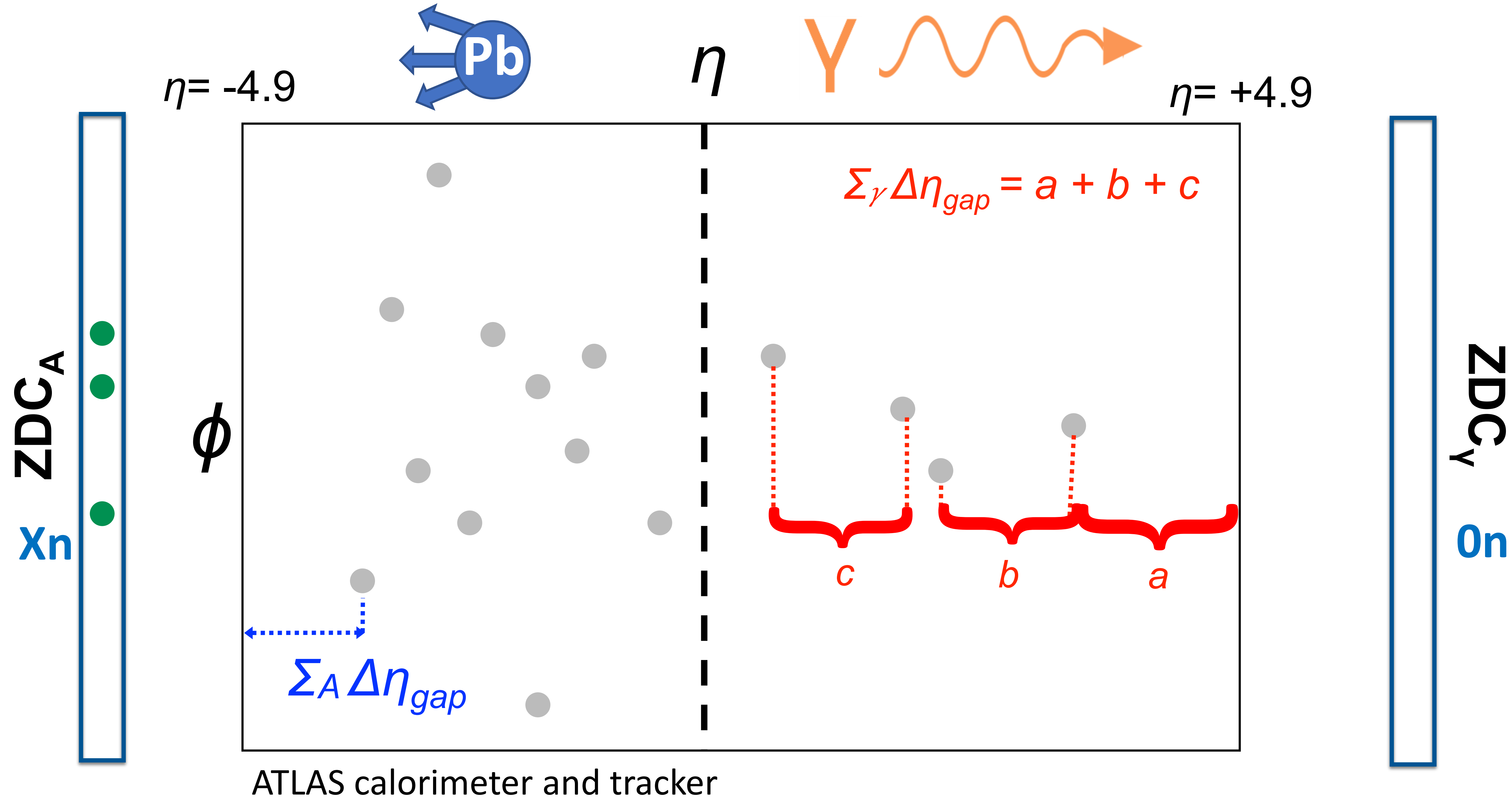


DIS *ep* collisions - structures dominated by multijet production, not compatible with collective effects…

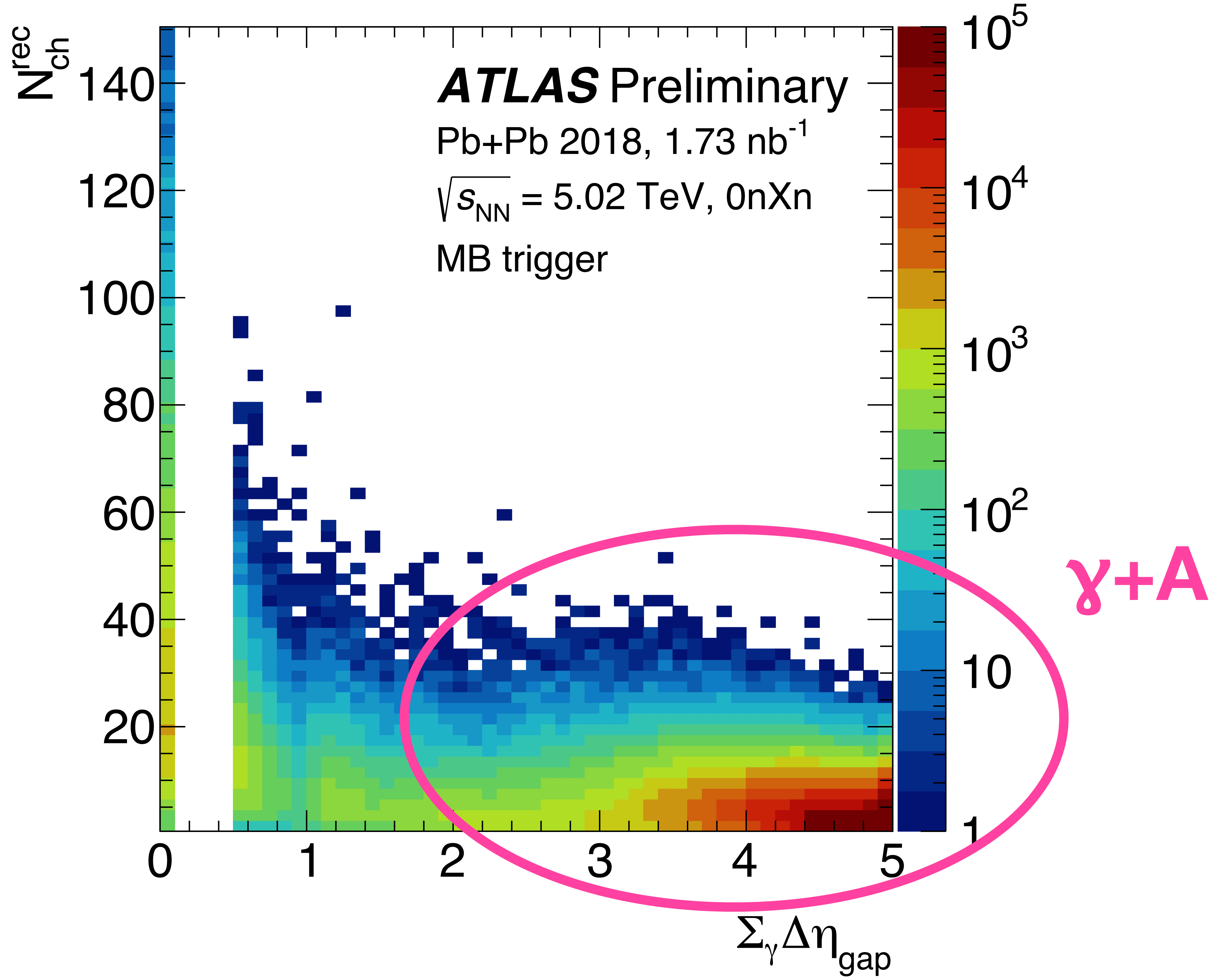
What about a system “between” *pp*/*p*A and *ee*/*ep*?

- Photo-nuclear (ɣ+A) interactions: quasireal photon from one nuclear interacts with the other (which may generally break up)
- Identifiable by characteristically asymmetric topology
- “Clean” environment - photoproduction limit of DIS on nuclei (like at EIC!)

Photo-nuclear event selection



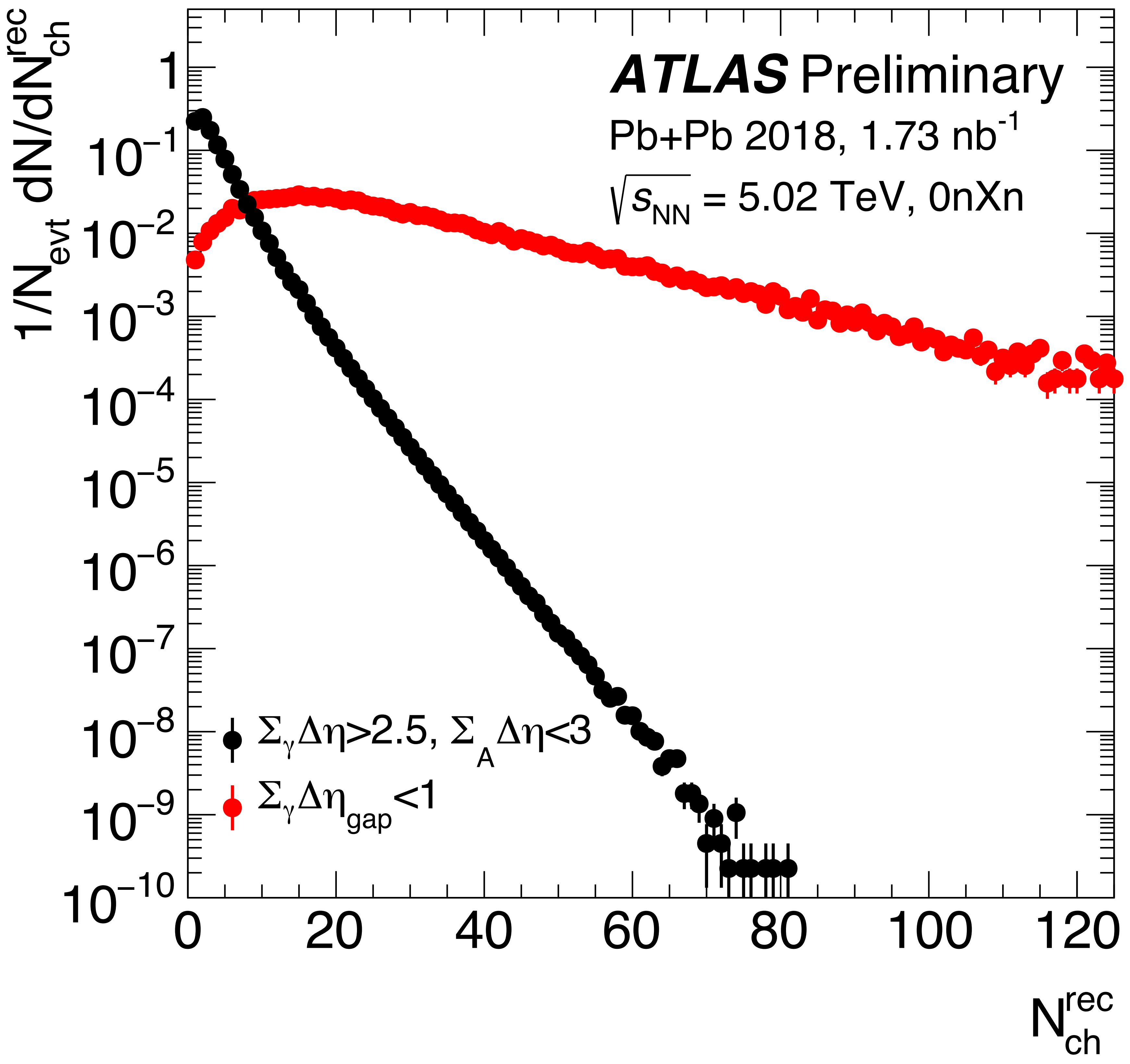
Event Selection: $\Sigma_A \Delta\eta_{gap} < 3$ $\Sigma_\gamma \Delta\eta_{gap} > 2.5$



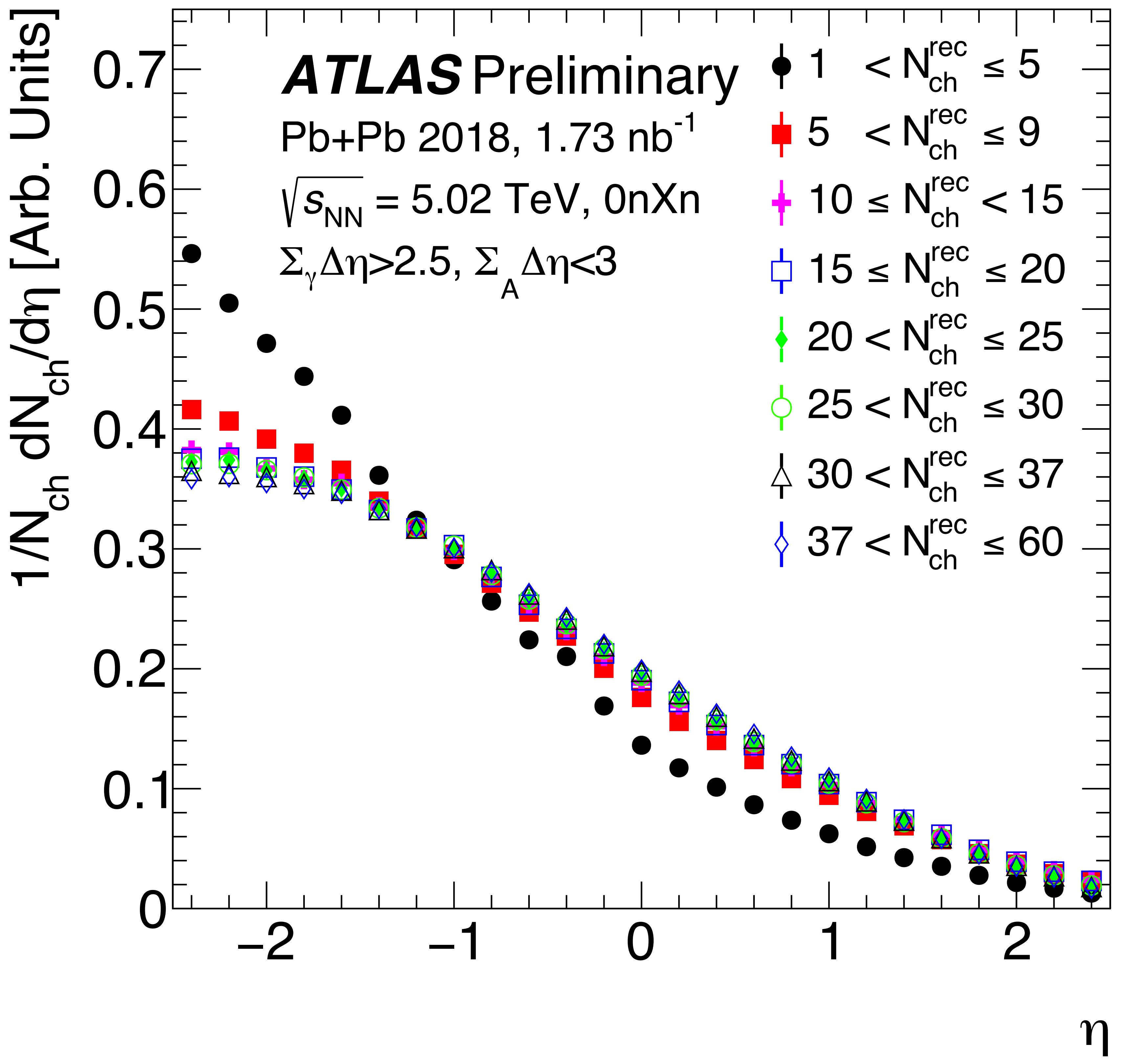
Identify events via large "sum of gaps" in calorimeter+tracker plus ZDC veto on one side

Select events with large photon-side sum-of-gaps

Photo-nuclear event properties

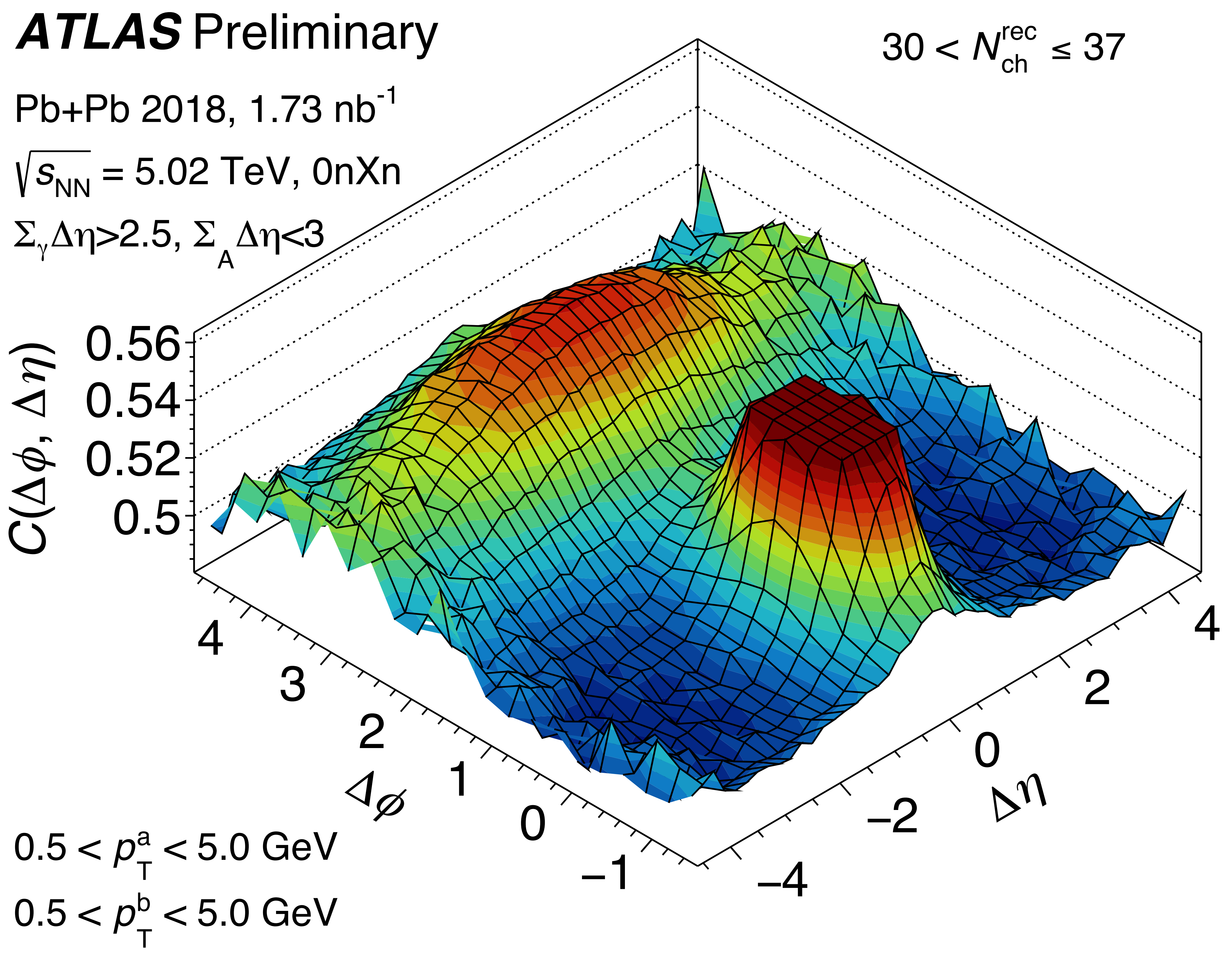


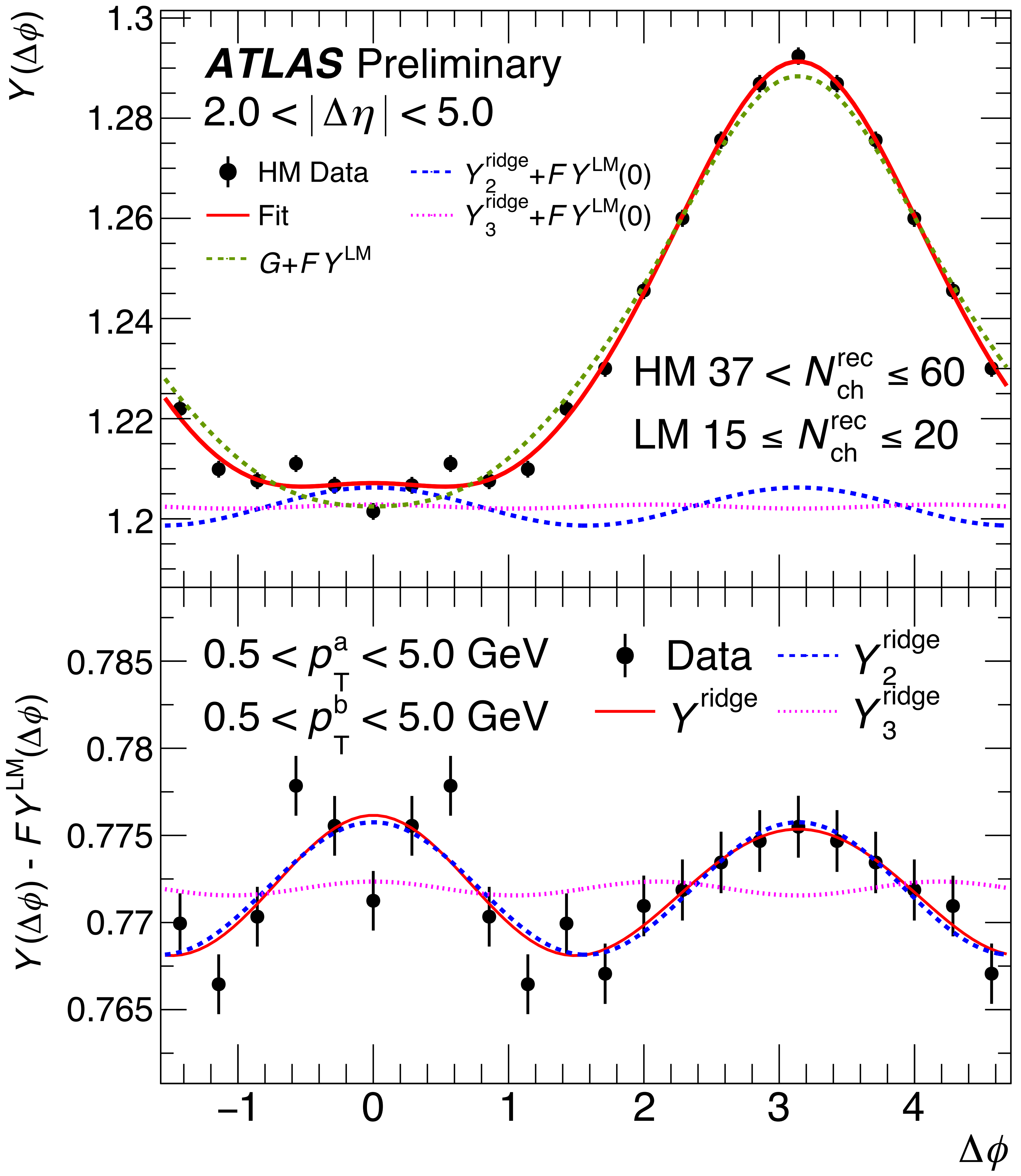
Steeply falling multiplicity distribution for **γ+A** events - specialized trigger used to collect large statistics!



Asymmetric $dN/d\eta$ as in p+A collisions

Two-particle correlations

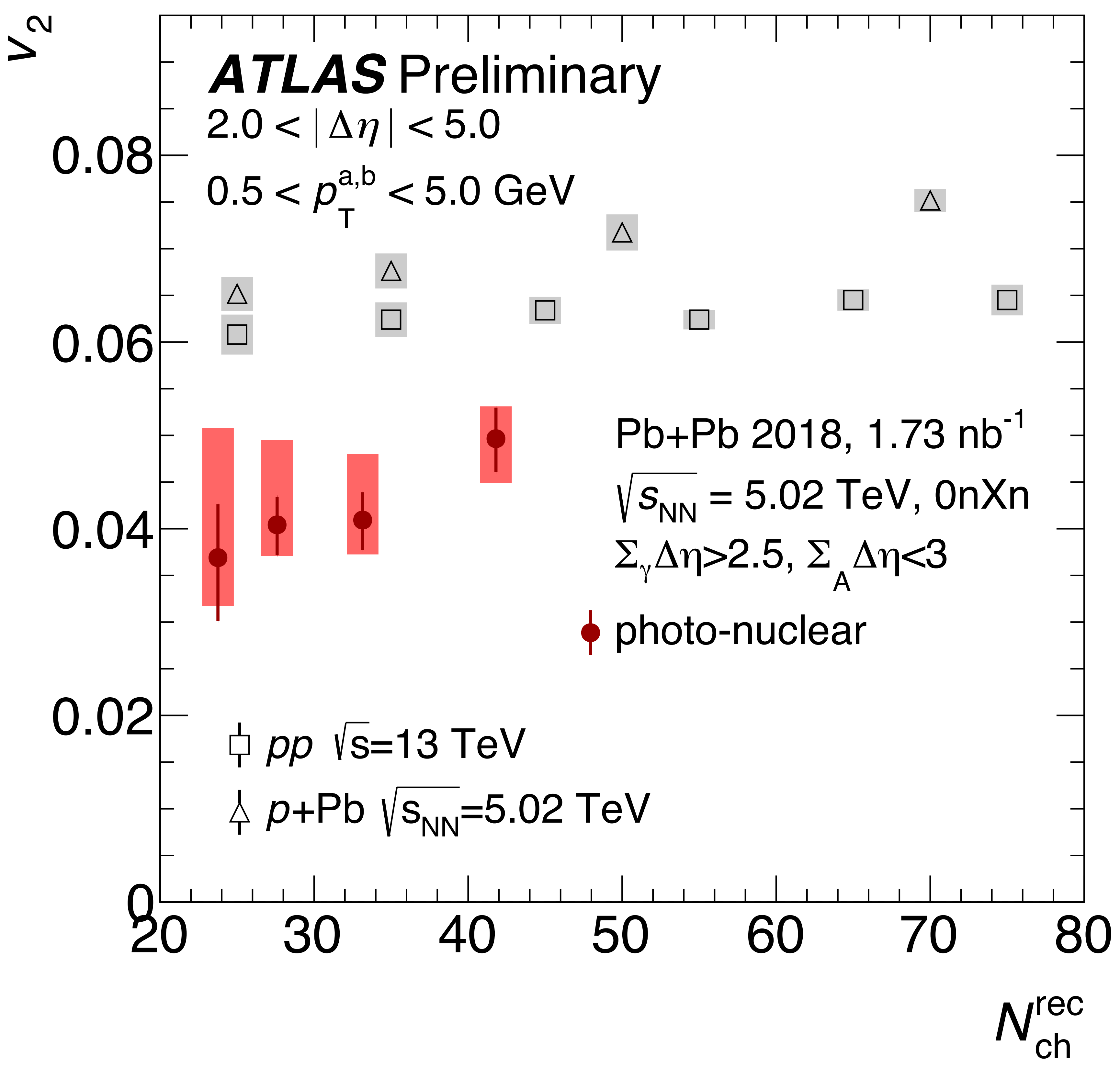




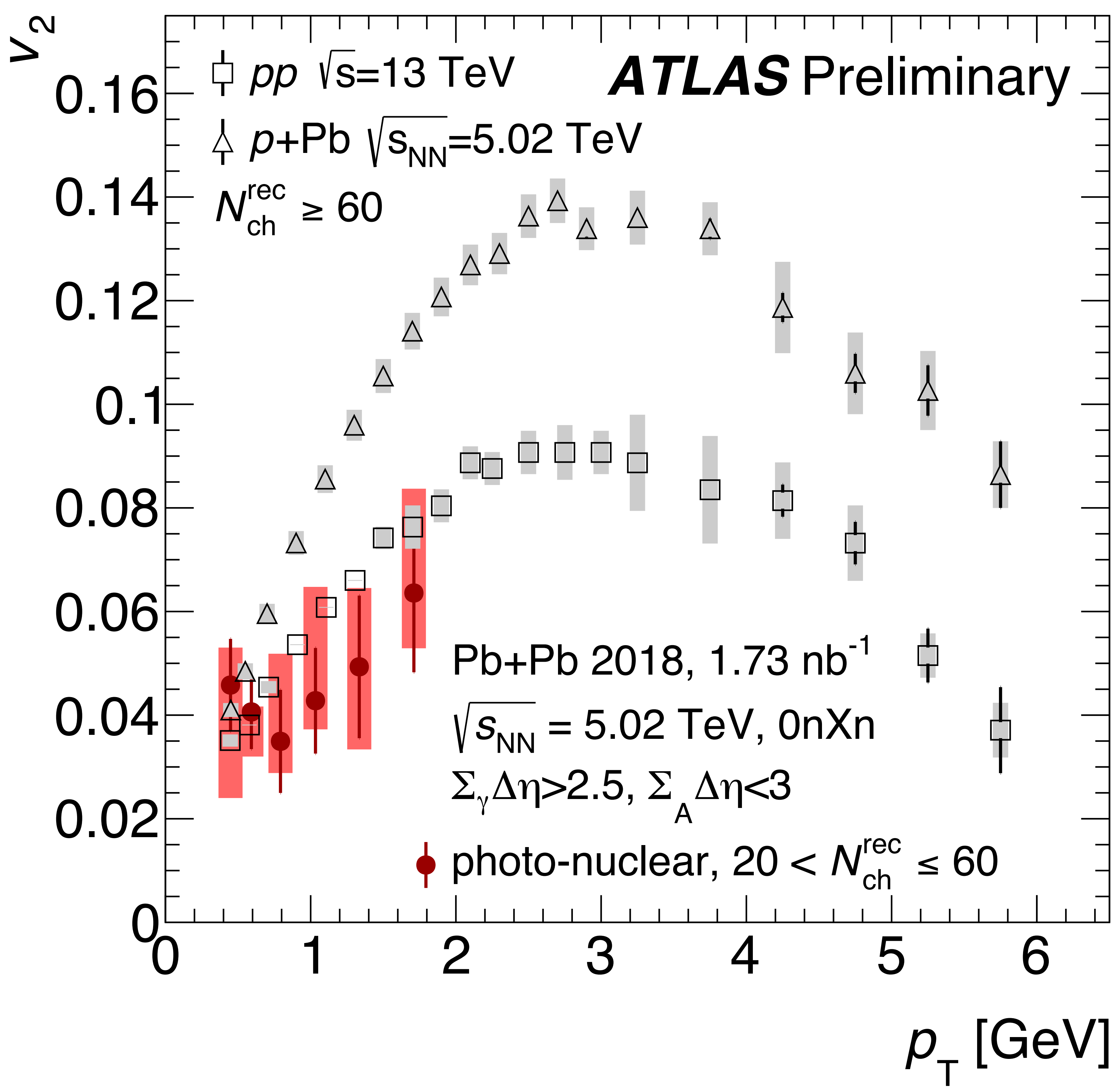
Similar structures in 2-D correlation function as in hadronic collisions!

Near-side enhancement in HM events - v_{22} signal extracted via template fit (non-flow subtraction)

v_2 in photo-nuclear events

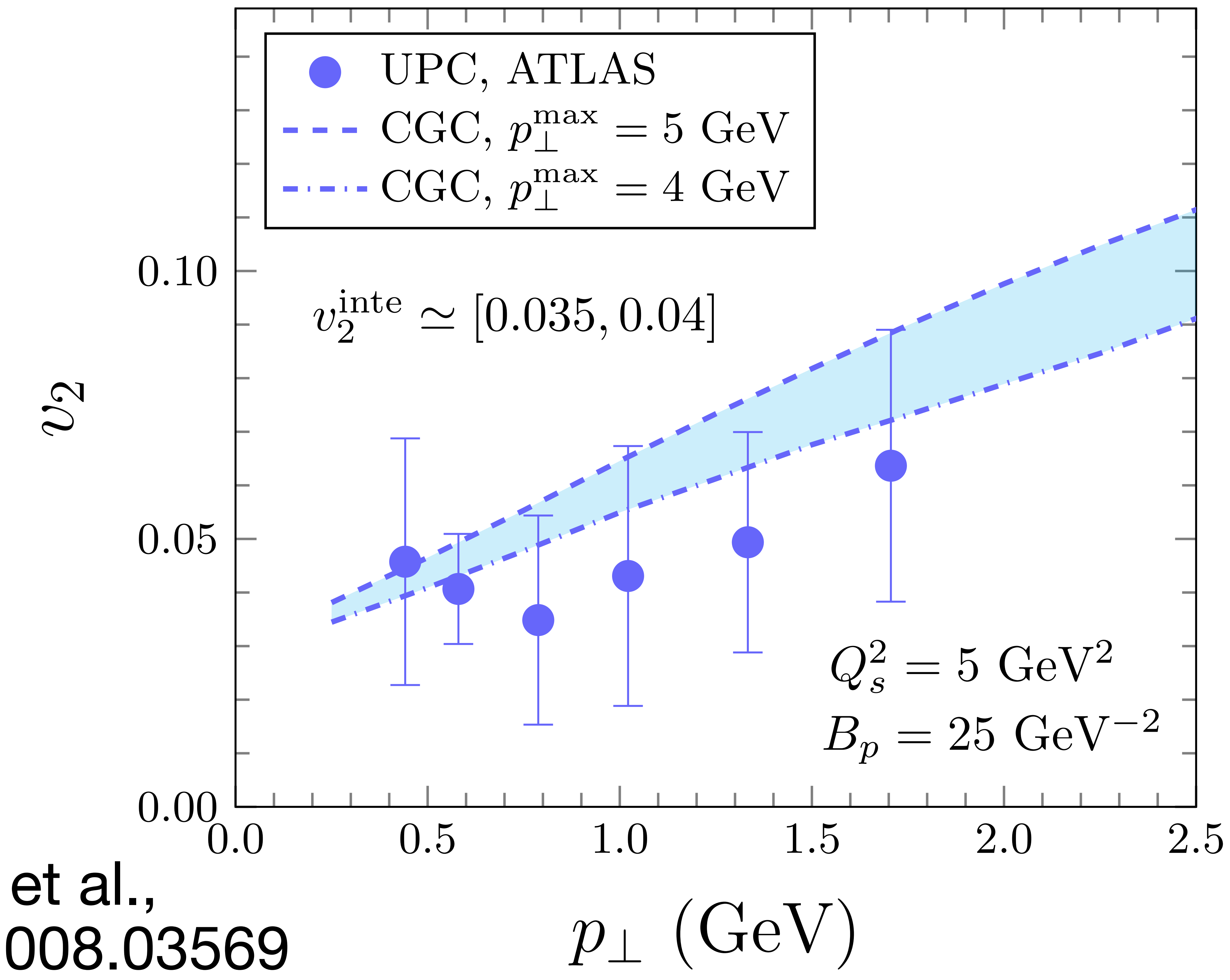


p_T-integrated v_2 ~ 4%, weaker than that for *pp* and *p*+Pb - multiplicity ~independent

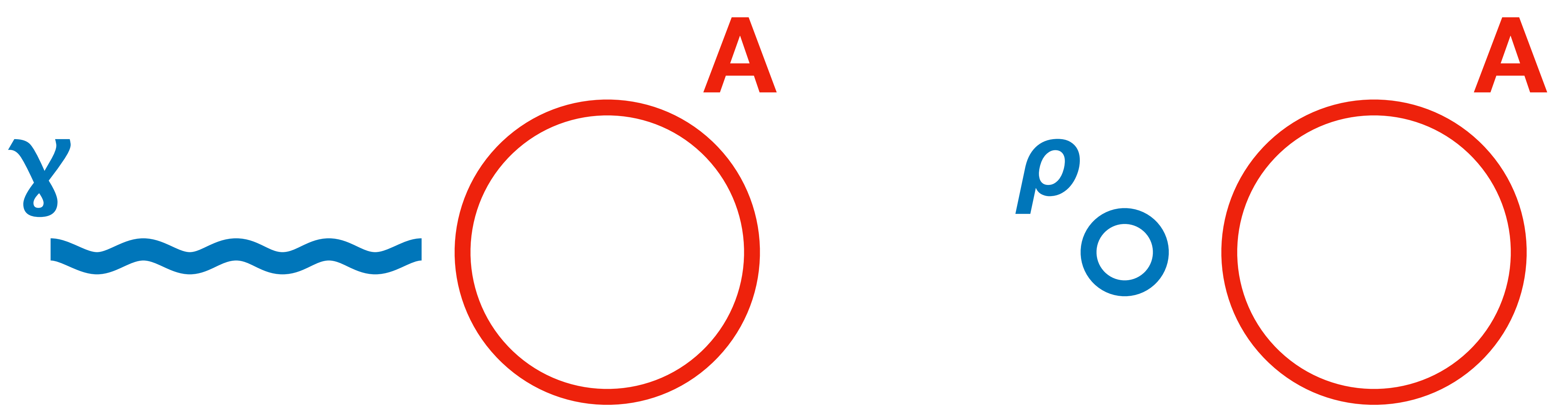


Similar p_T dependence from 0.5-2 GeV, but larger uncertainties

Initial or final state?



Shu et al., hep-ph/2008.03569



Vector Meson Dominance picture - these interactions proceed as, e.g. ρ+A collisions

Can initialize hydro with ρ+A geometry - but non-trivial complications from E_ρ-b correlation, rapidity boost, etc.

CGC based calculation - use γ+A as benchmark for signal in EIC!

Any takers?

What can stop the flow?

- Azimuthal anisotropy signatures:
  - ➡ persist for p_T ~ 50 particles in a wide range of *p*+Pb events! If this arises from final-state interactions, where is the accompanying jet modification?
  - ➡ show a clear mass effect for heavy flavor quarks in *pp* collisions - can we use future charm and bottom studies to separate physics mechanisms?
  - ➡ are in photo-nuclear events! Is this a testbed for collectivity at the EIC, or is there a final-state interaction picture with an underlying geometry?

ATLAS, Eur. Phys. J C80 (2020) 73

ATLAS, Phys. Rev. Lett. 124 (2020) 082301

Preliminary result ATLAS-CONF-2019-022

Thank you!