What can stop the flow?

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

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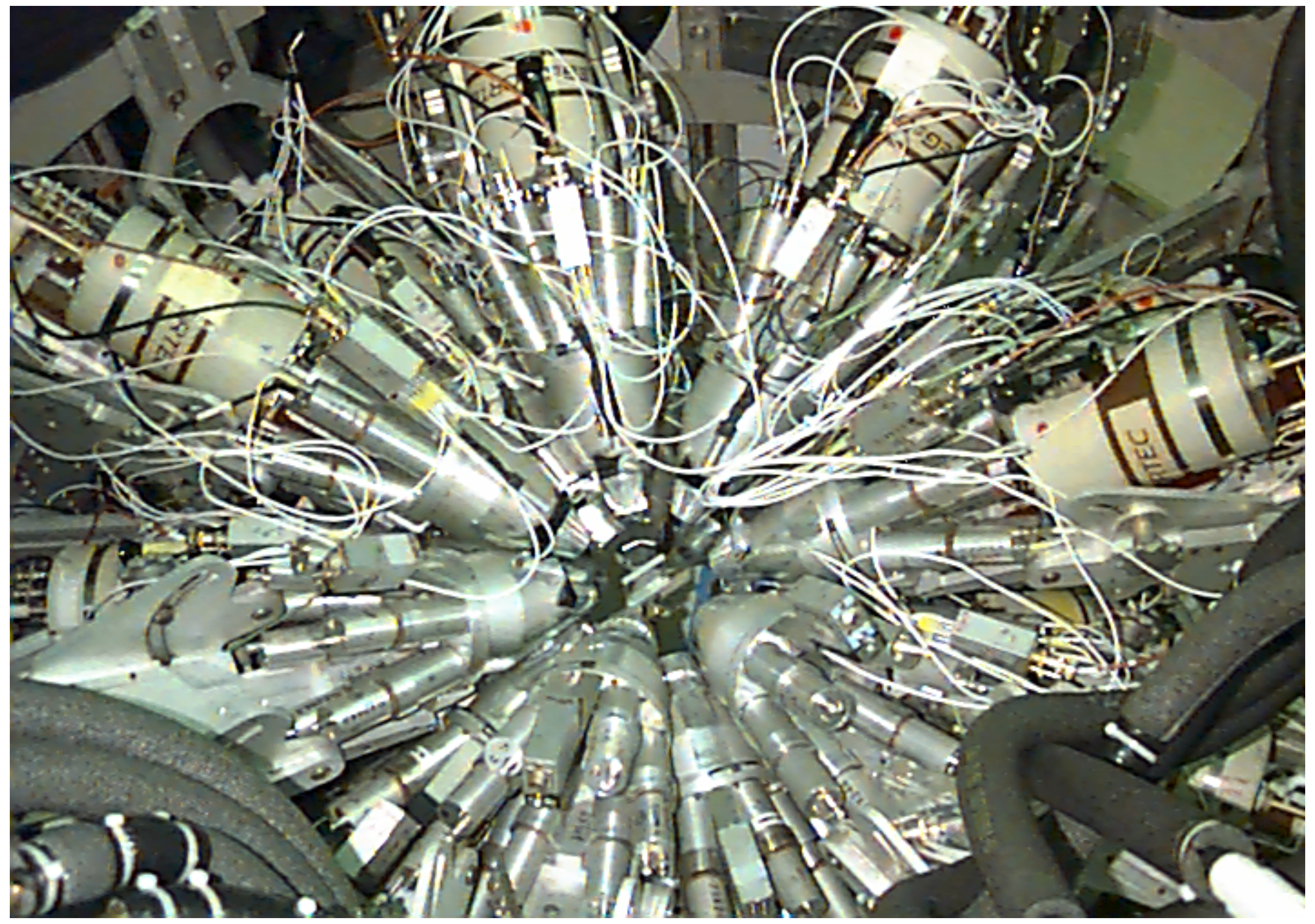
P-3 Seminar
Los Alamos
National Laboratory
4 August 2021

“Back” to Los Alamos!

I was a summer undergraduate student in 2007 with the Weak Interactions Team in P-23!



GEANIE array

LANSCE linac

PHYSICAL REVIEW C **79**, 054604 (2009)

Neutron inelastic scattering and reactions in natural Pb as a background in neutrinoless double-β-decay experiments

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(Received 6 October 2008; published 8 May 2009)

Inelastic neutron scattering and reactions on Pb isotopes can result in γ rays near the signature end-point energy in a number of $\beta\beta$ isotopes. In particular, there are γ-ray transitions in ^{206,207,208}Pb that might produce energy deposits at the ^{76}Ge $Q_{\beta\beta}$ in Ge detectors used for $0\nu\beta\beta$ searches. The levels that produce these γ rays can be excited by $(n, n'\gamma)$ or $(n, xn\gamma)$ reactions, but the cross sections are small and previously unmeasured. This work uses the pulsed neutron beam at the Los Alamos Neutron Science Center to directly measure reactions of interest to $\beta\beta$-decay experiments. The cross section on $^{\mathrm{nat}}$Pb to produce the 2041-keV γ ray from ^{206}Pb is measured to be 3.6 ± 0.7 (stat.) $\pm$ 0.3 (syst.) mb at $\approx$9.6 MeV. The cross section on $^{\mathrm{nat}}$Pb to produce the 3061,3062-keV γ rays from ^{207}Pb and ^{208}Pb is measured to be 3.9 ± 0.8 (stat.) $\pm$ 0.4 (syst.) mb at the same energy. We report cross sections or place upper limits on the cross sections for exciting some other levels in Pb that have transition energies corresponding to $Q_{\beta\beta}$ in other $\beta\beta$ isotopes.

DOI: 10.1103/PhysRevC.79.054604 PACS number(s): 23.40.−s, 25.40.Fq

PHYSICAL REVIEW C **87**, 064607 (2013)

Neutron inelastic scattering in natural Cu as a background in neutrinoless double-β decay experiments

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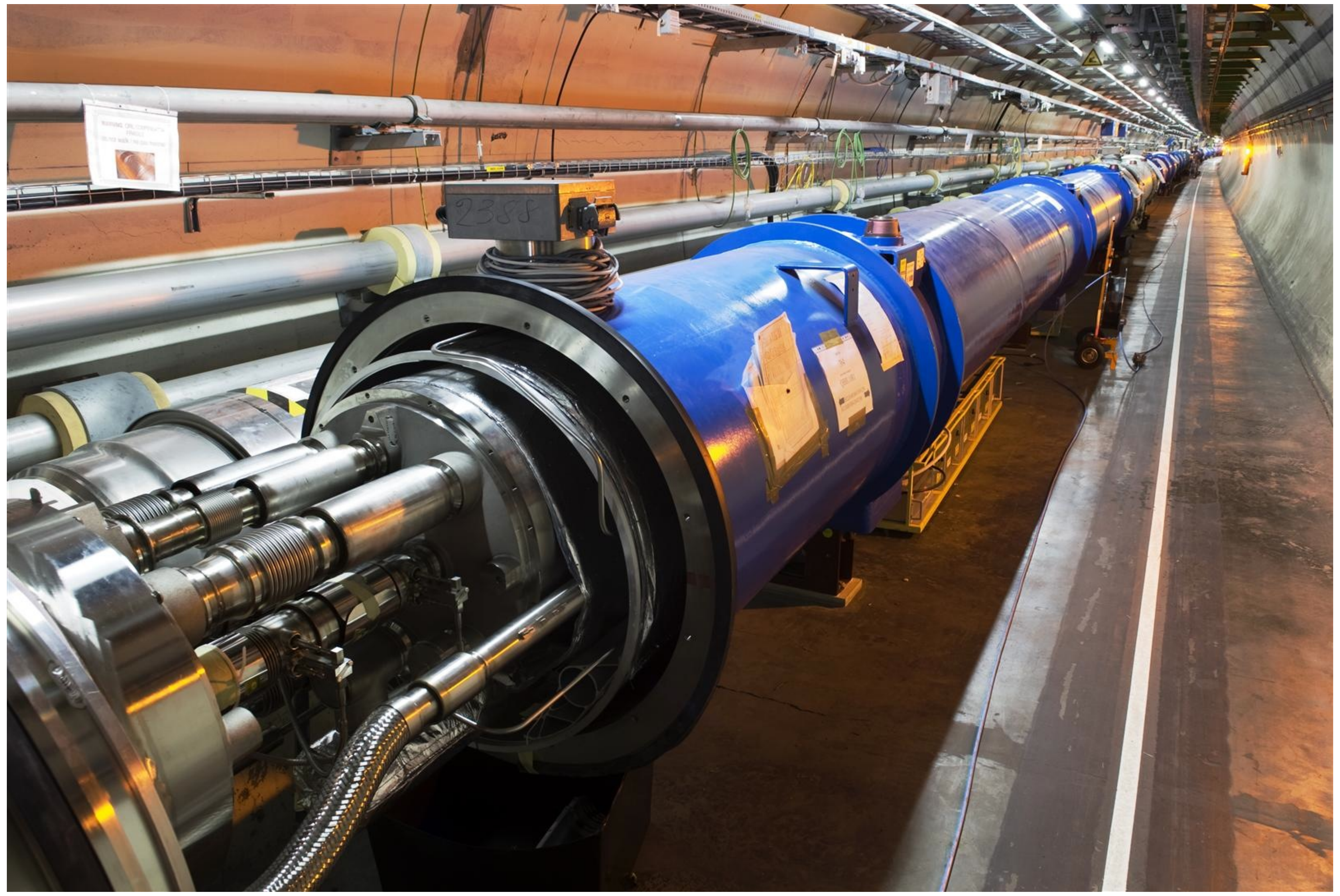
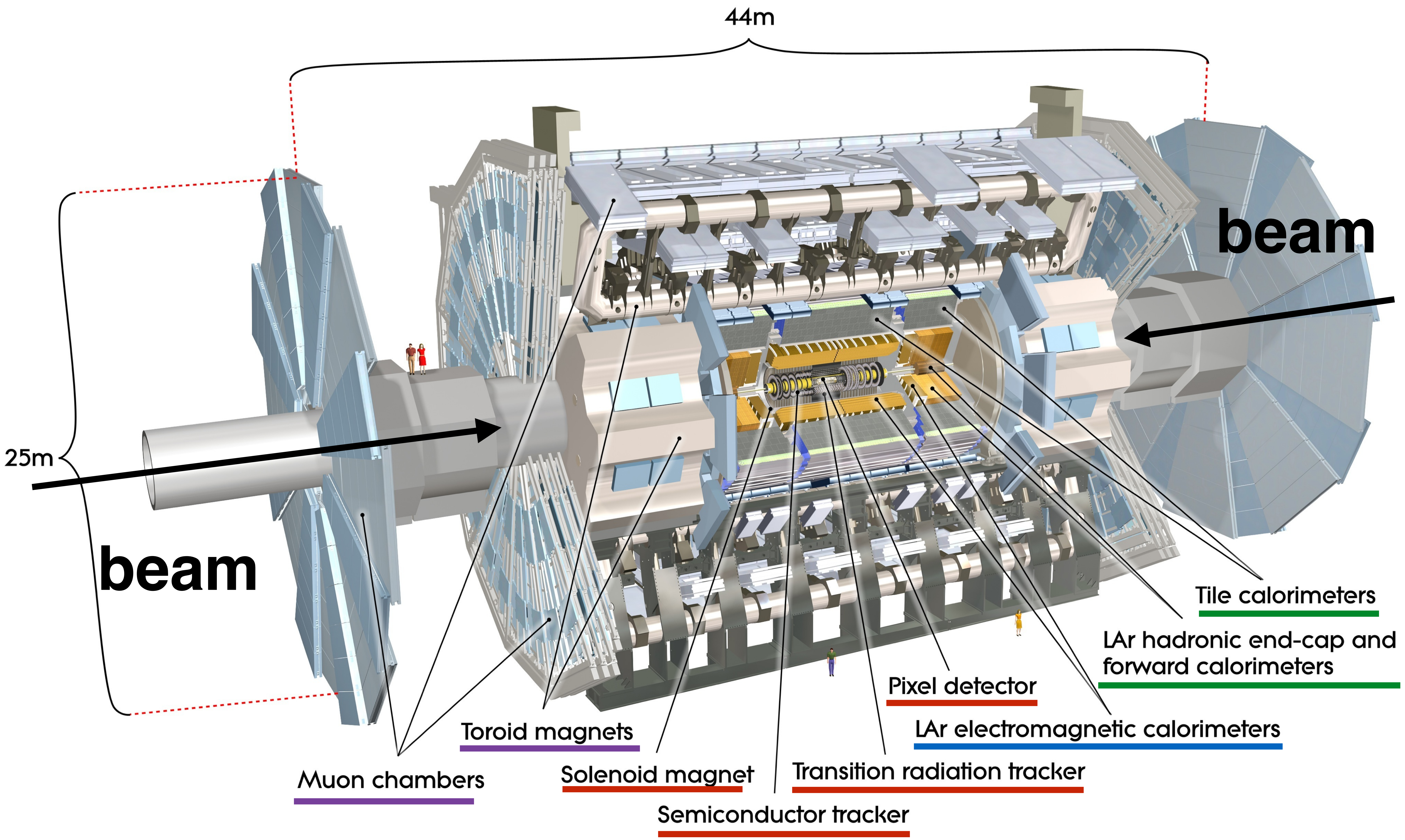
(Received 22 October 2012; published 13 June 2013)


COFFEE

ATLAS Experiment @ LHC

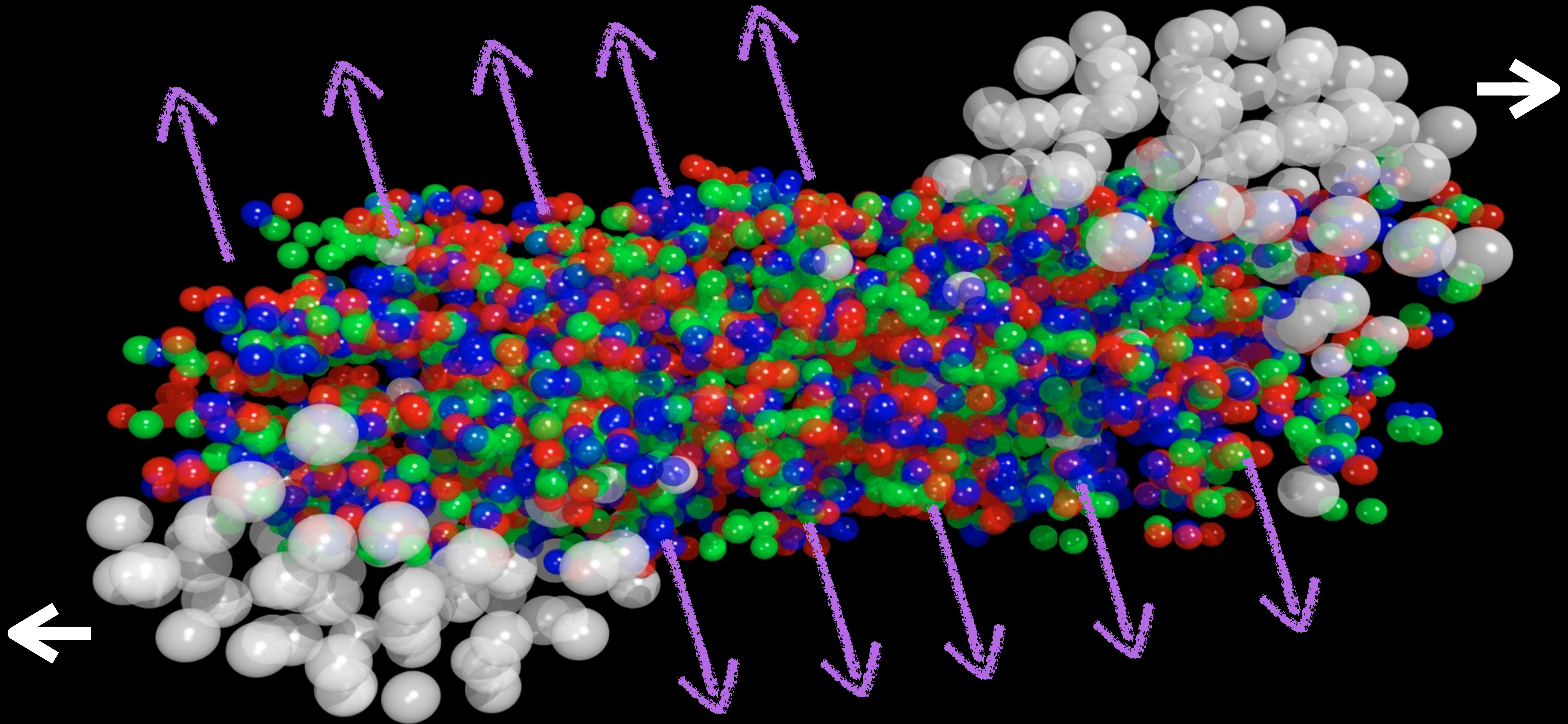


Inside the Large Hadron Collider tunnel

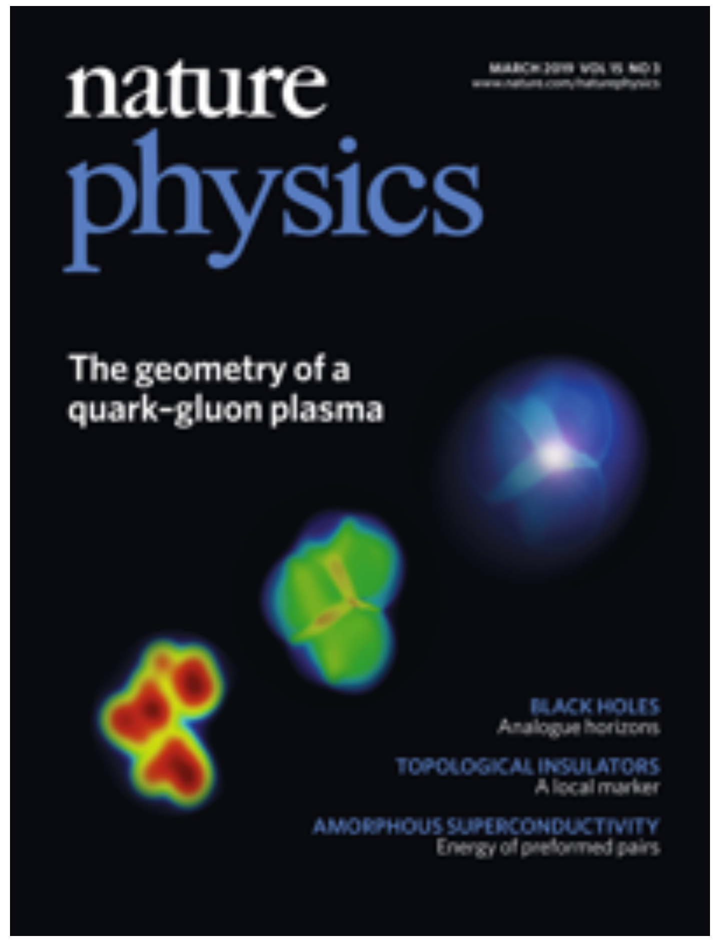


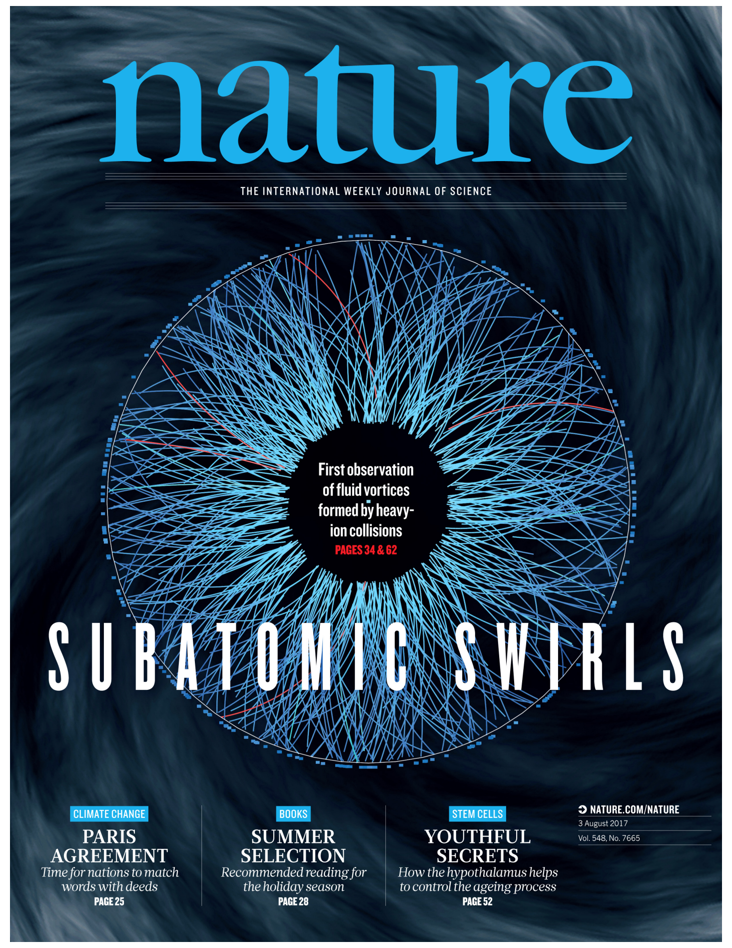
Specialized detectors for measuring:
charged hadrons, **photons**, **neutral hadrons**, **muons**

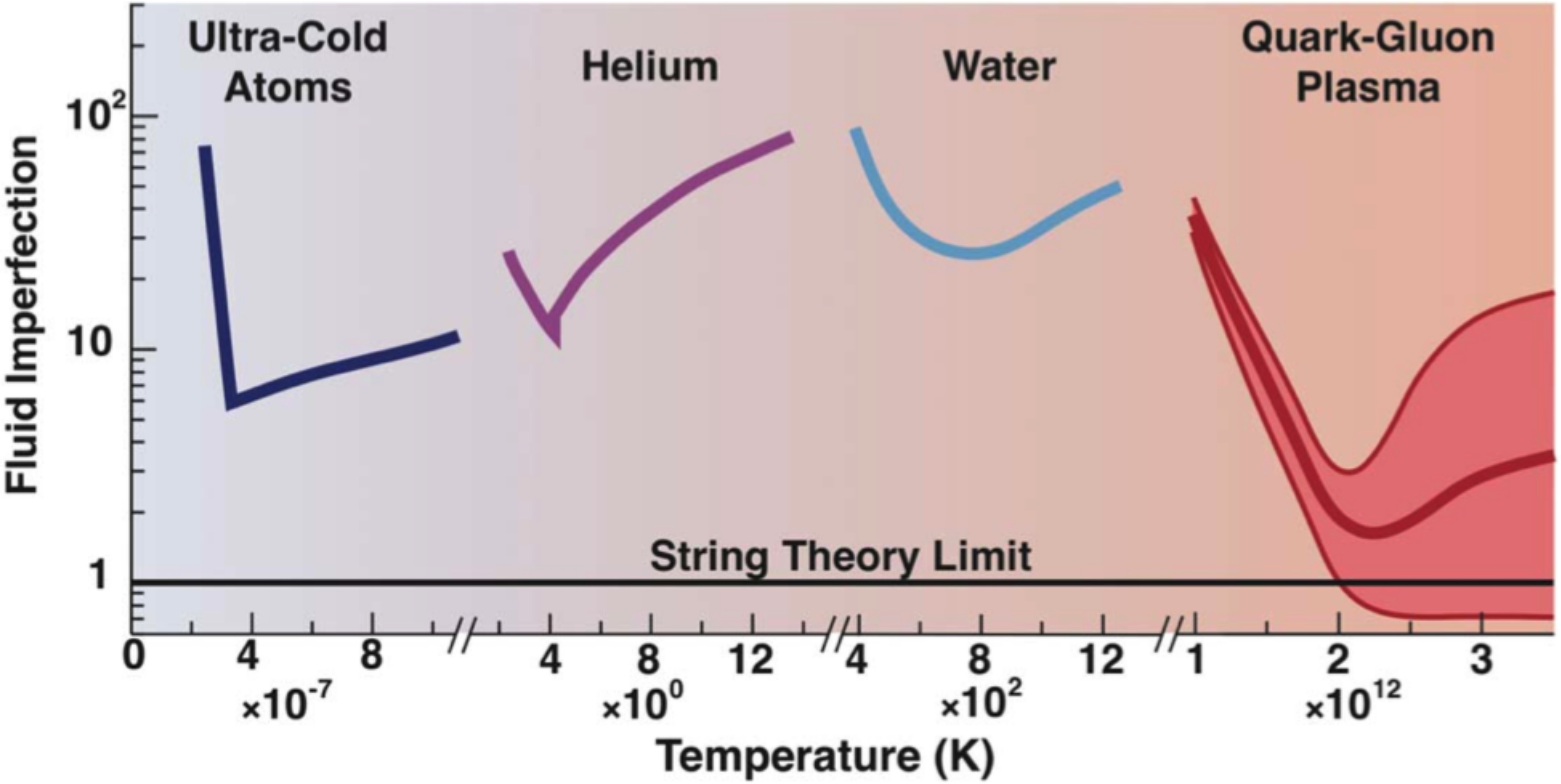
nucleus-nucleus (AA) collisions
99.99999% the speed of light



*trillion-degree-Kelvin **quark-gluon plasma** fireball expands toward detectors*





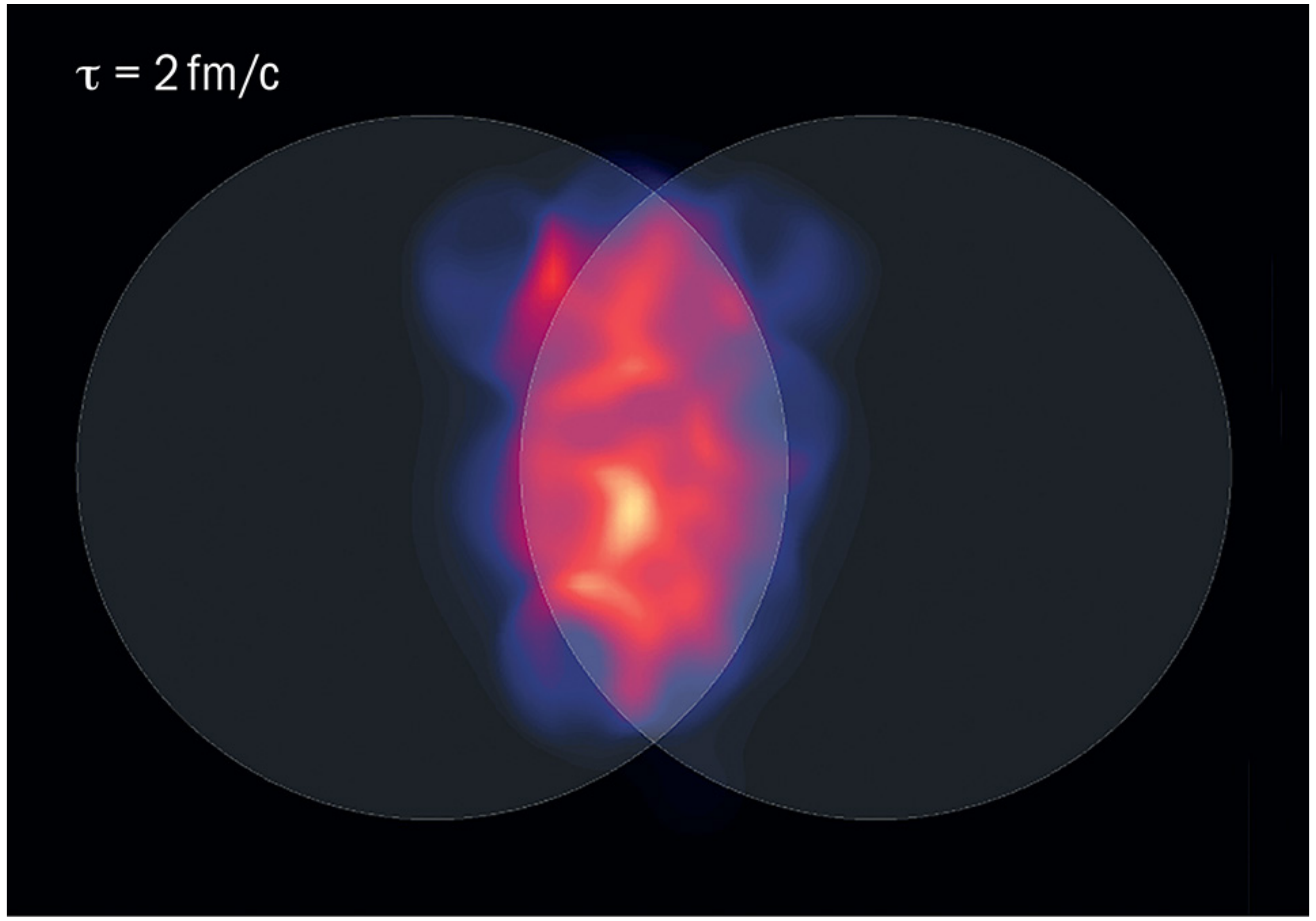


Big surprise: the QGP is so strongly coupled, it behaves as an almost **perfect fluid**

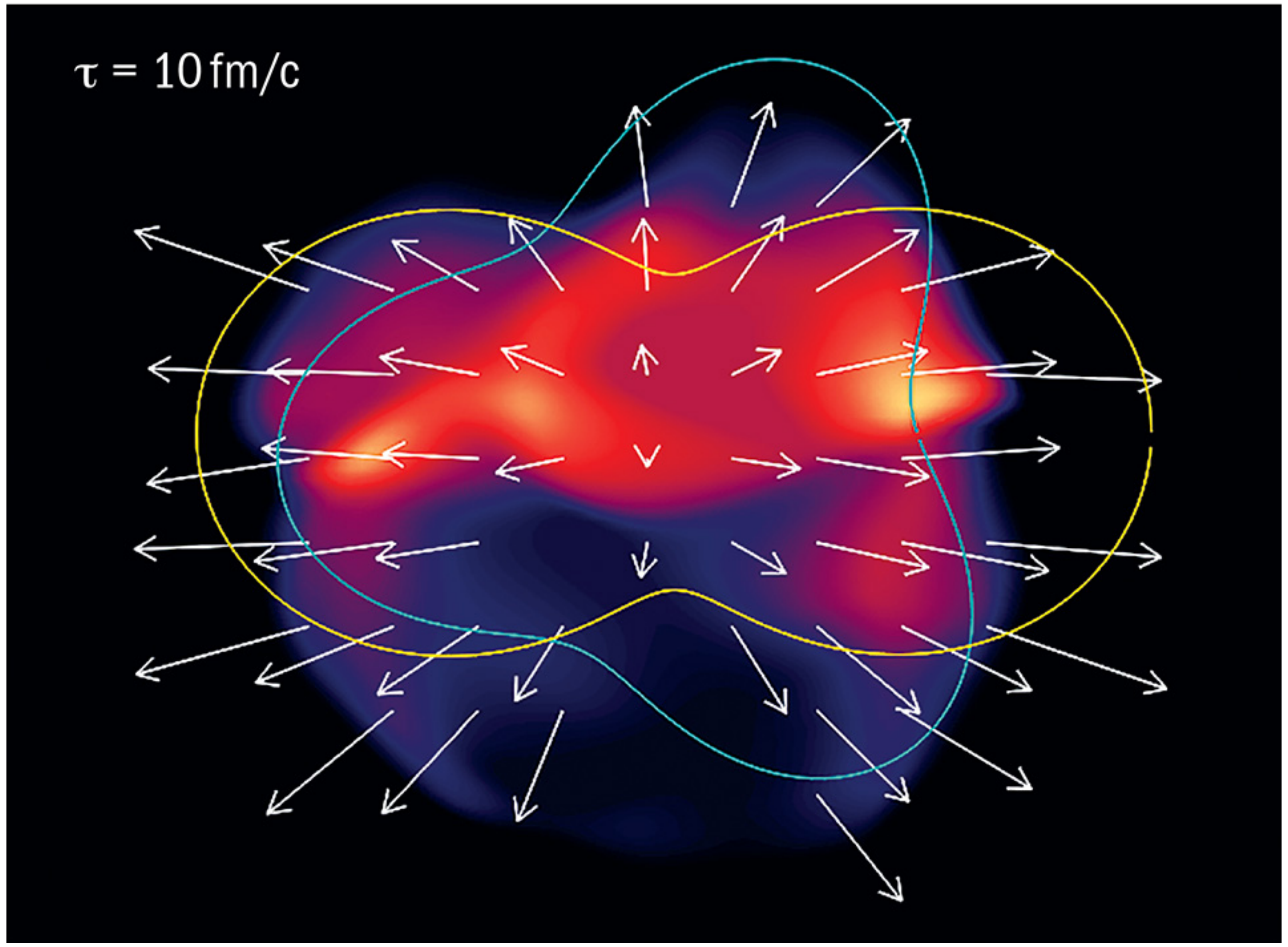
➡ expansion governed by *relativistic hydrodynamics*

➡ *lowest specific viscosity* (η/s) of any known material

Fluid motion in the QGP (1/3)

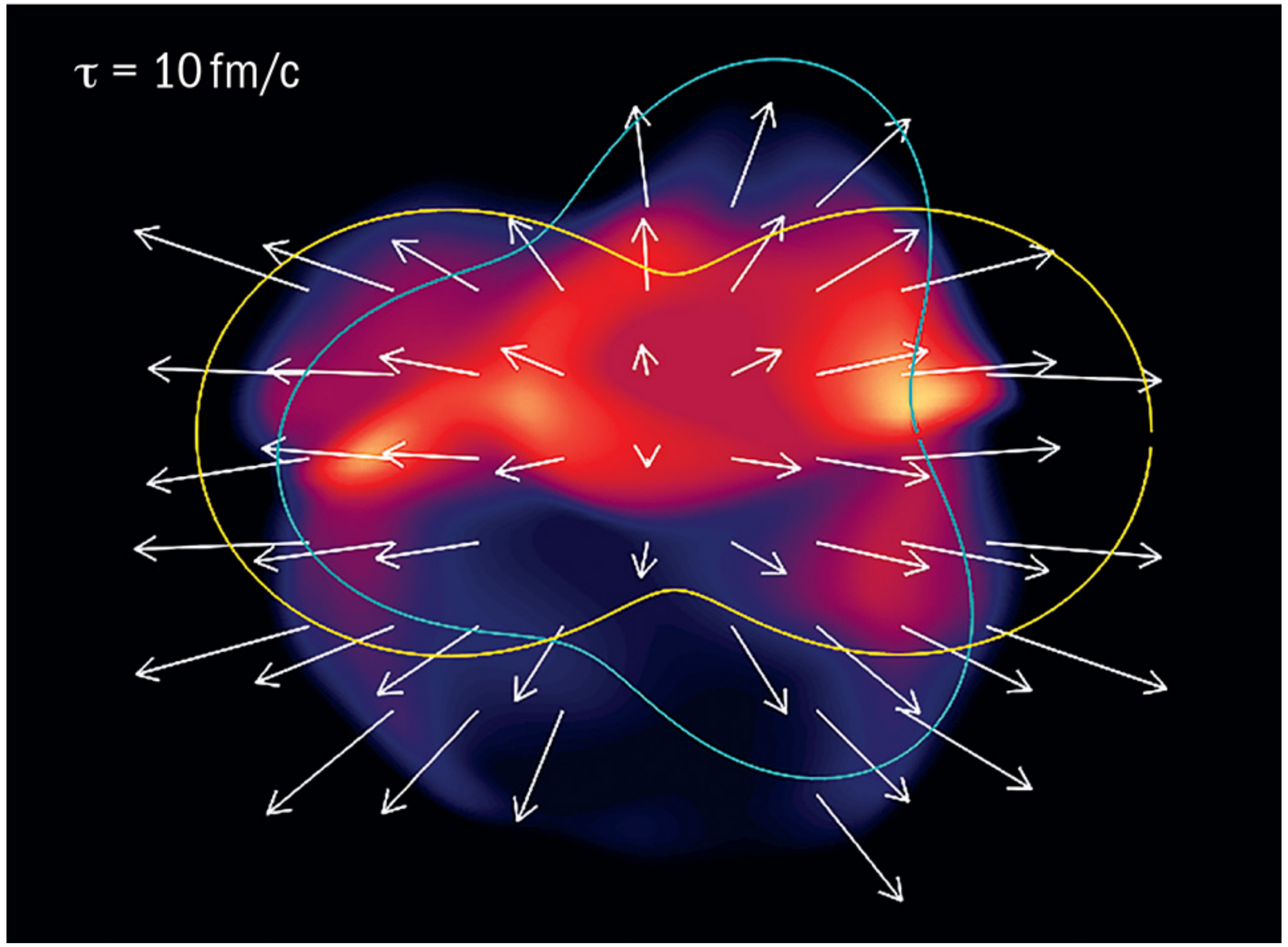


"Almond-shaped" Quark Gluon Plasma region…

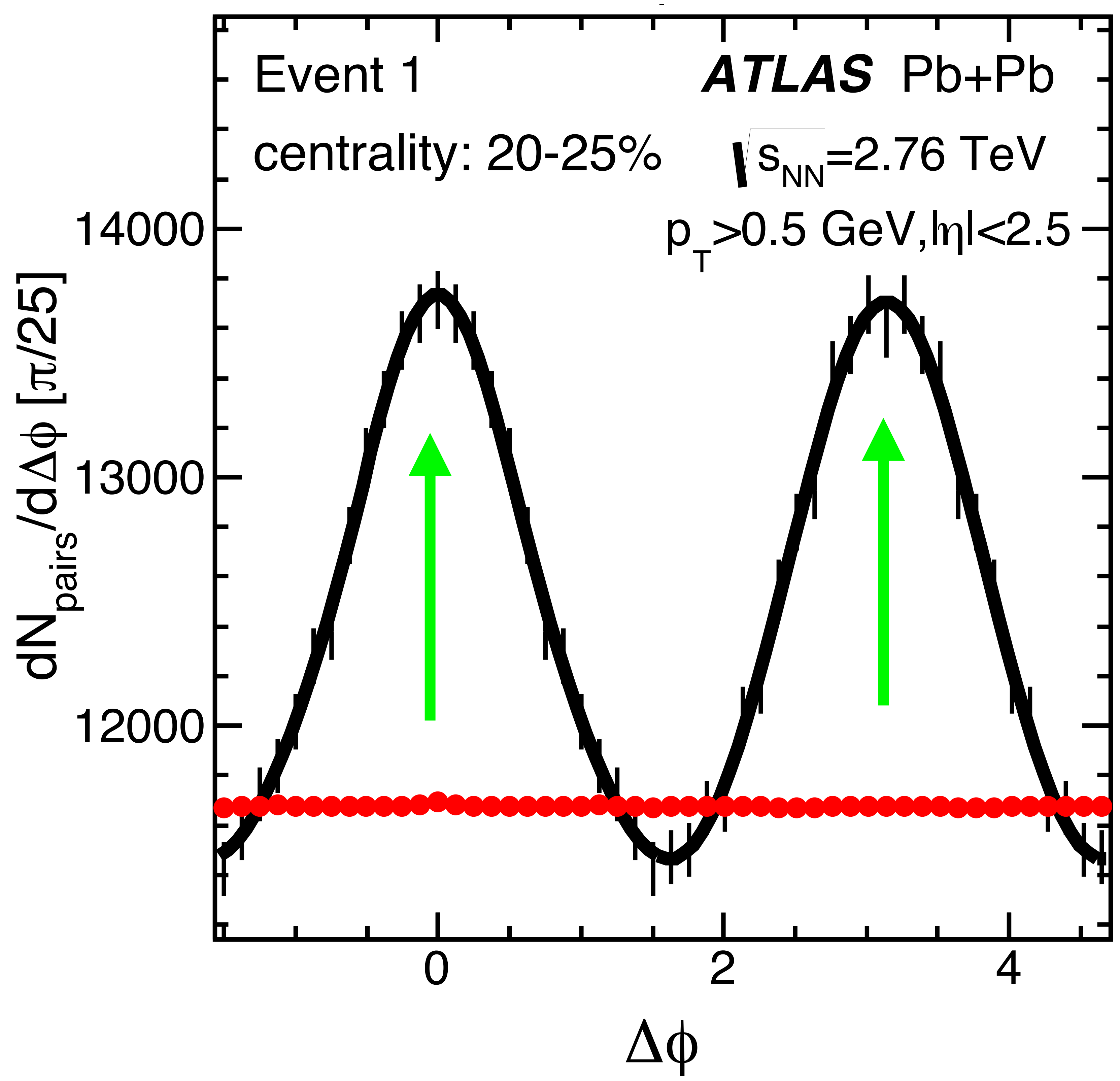


… particles are pushed out along directions of larger pressure gradients

Fluid motion in the QGP (2/3)

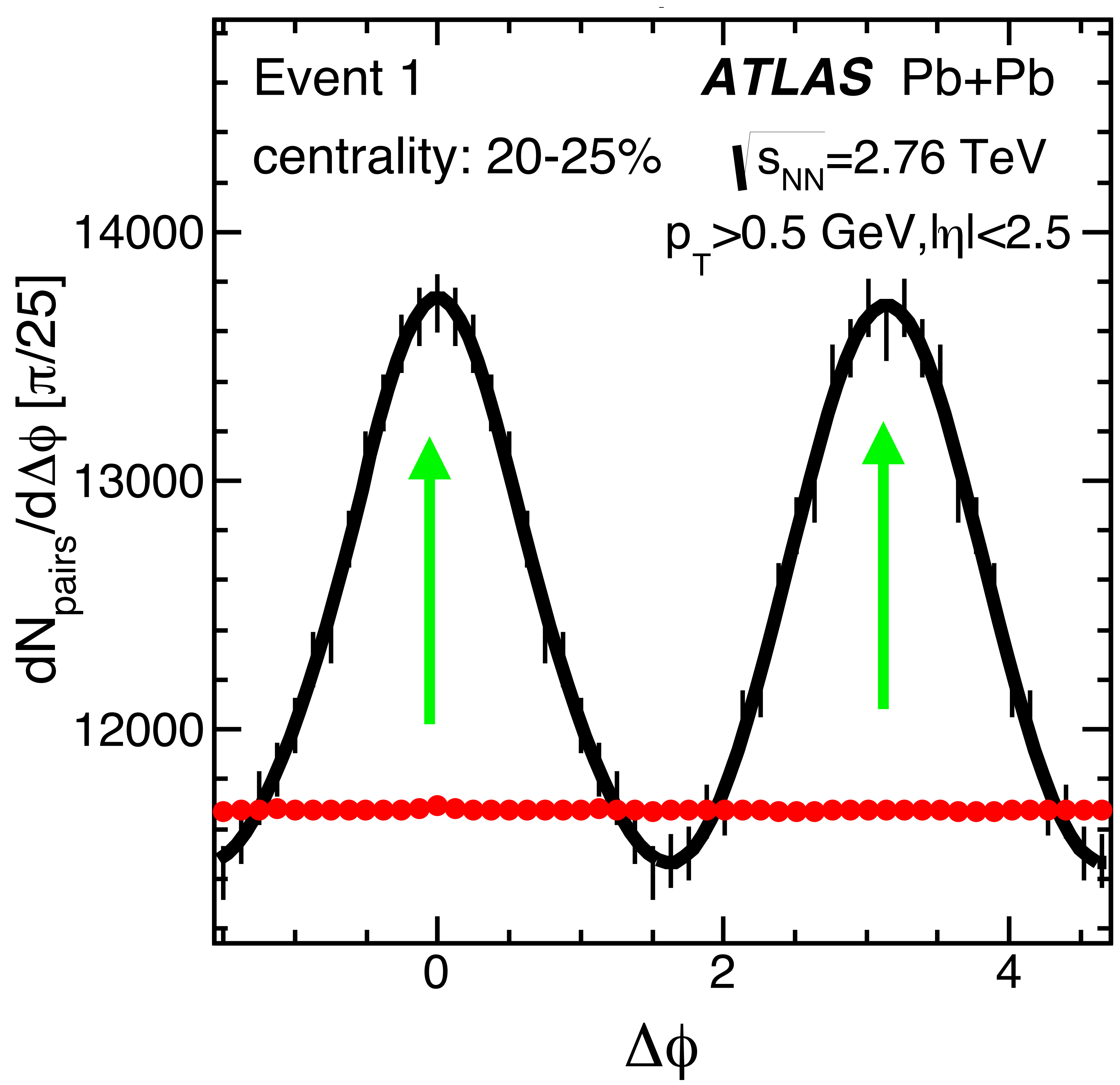


Particles are pushed out along directions of larger pressure gradients…

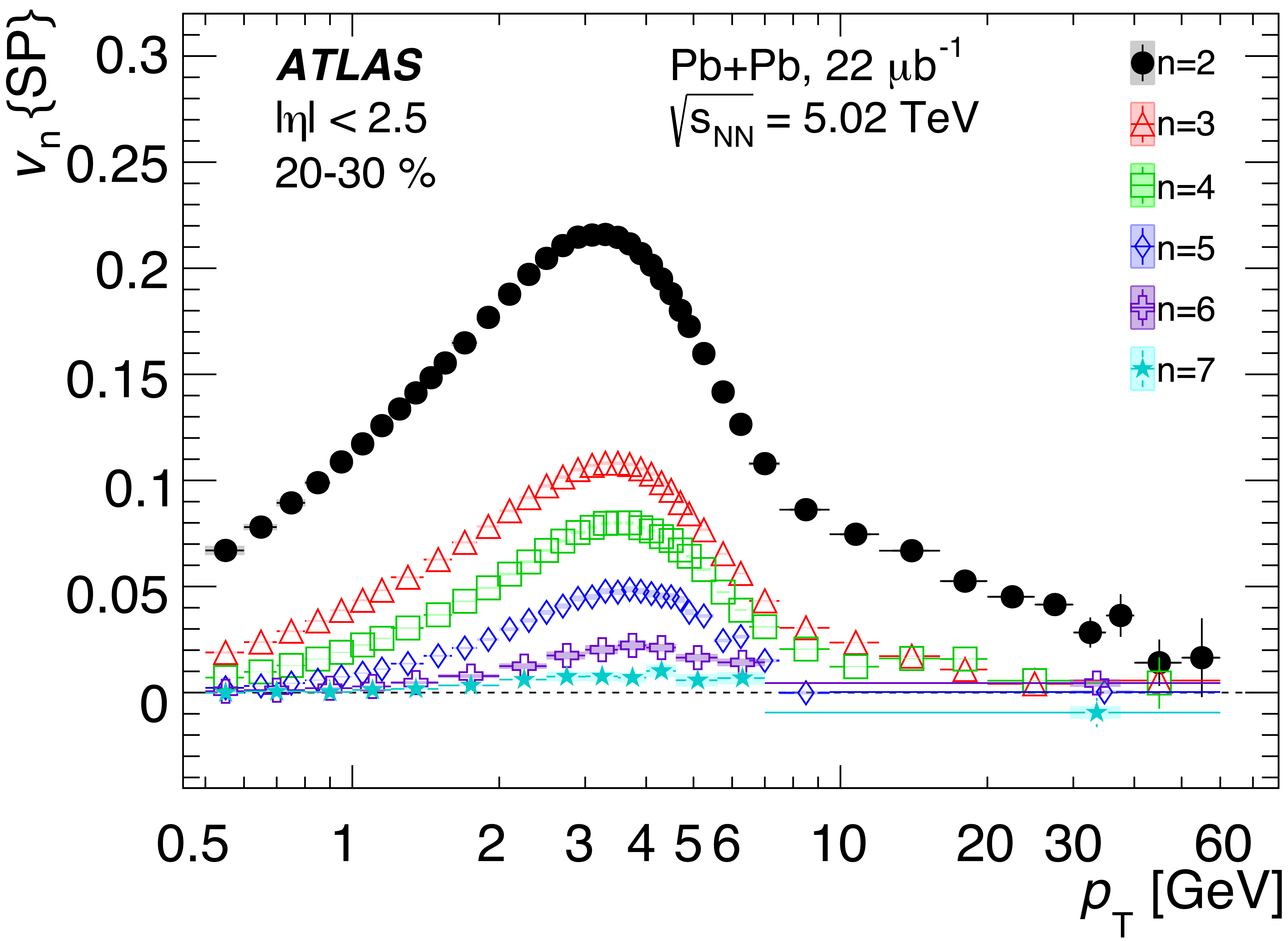


… measuring particle pairs as a function of Δϕ results in peaks at 0 and π!

Fluid motion in the QGP (3/3)



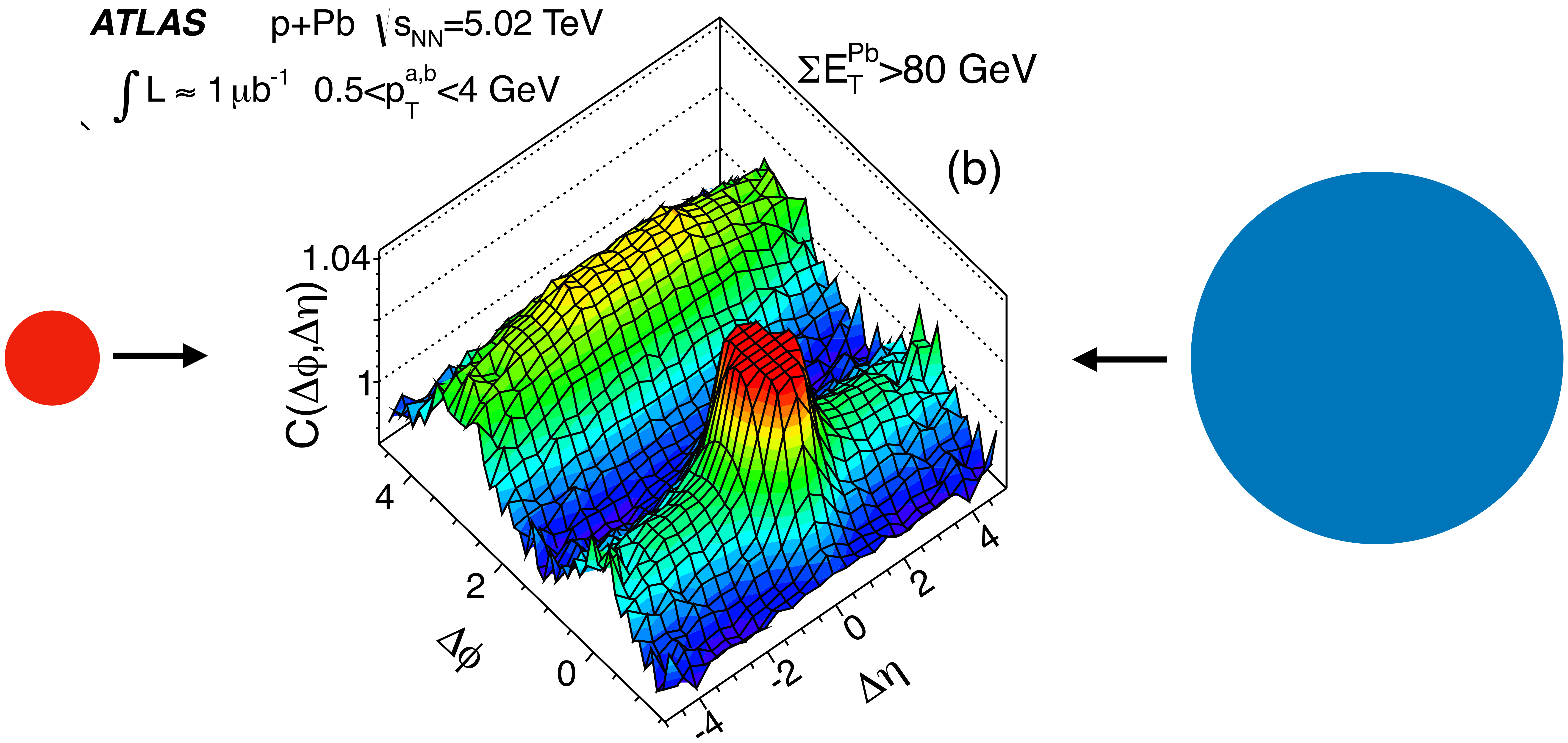
Measuring particle pairs as a function of Δϕ results in peaks at 0 and π…



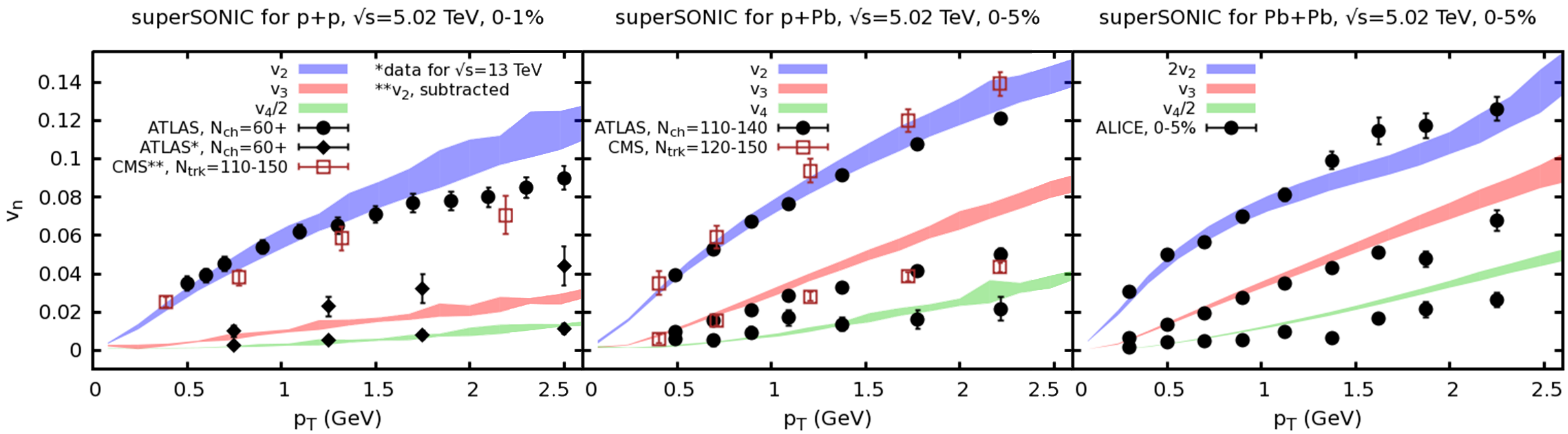
Characterize the strength of the anisotropy with Fourier coefficients "v_n" (for n=2, etc.)

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

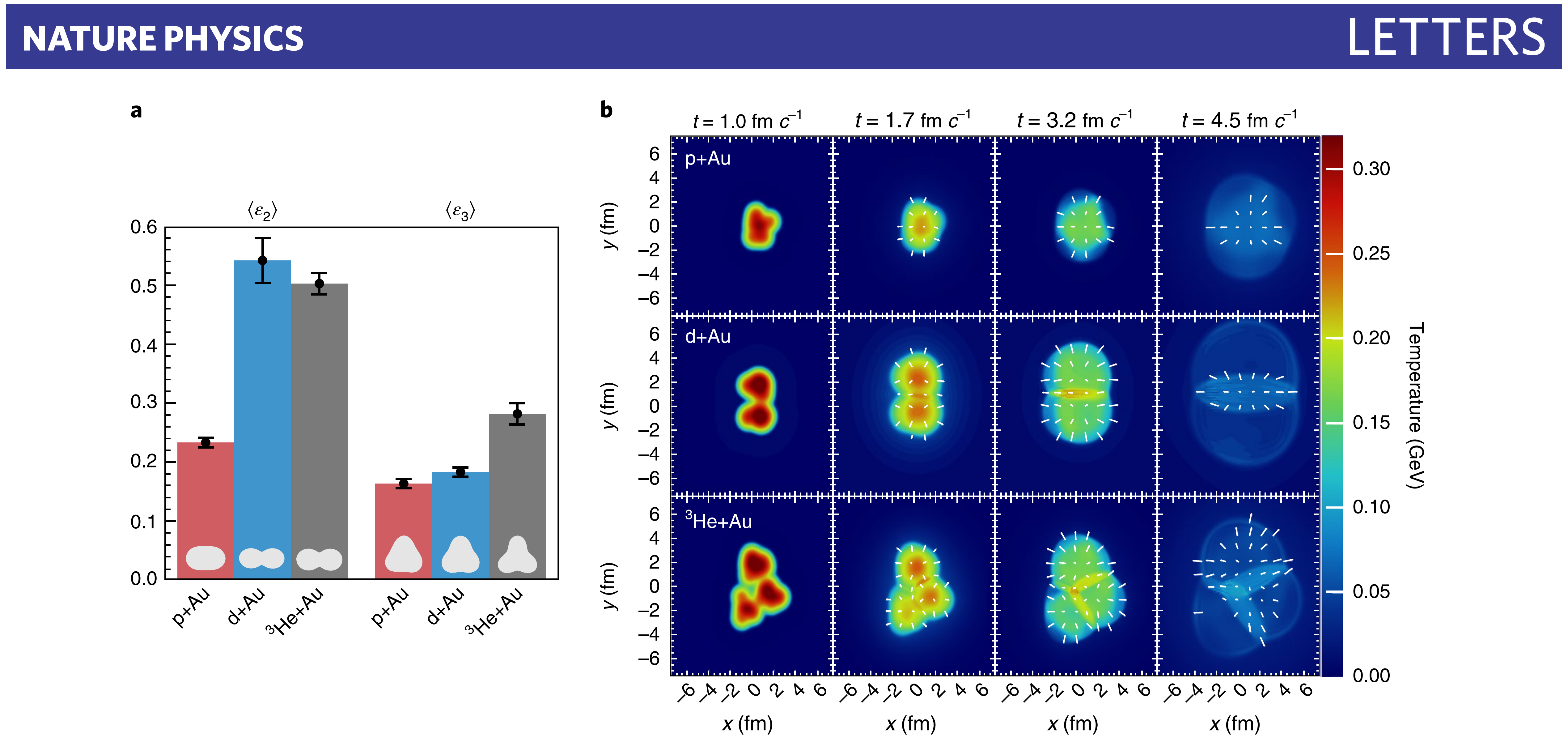


Similar v_n values observed in *p*+A and even high-multiplicity *pp*!

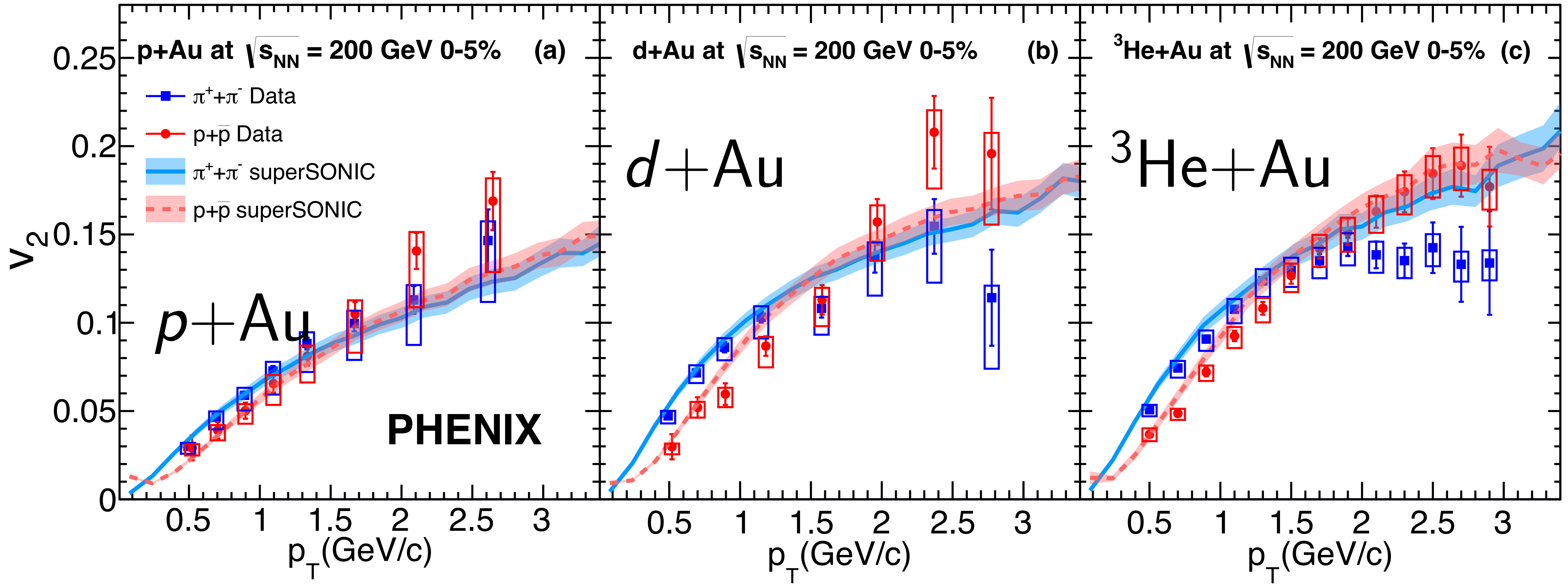
Broadly successful description of phenomena in all systems within AA-like hydrodynamic framework!

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

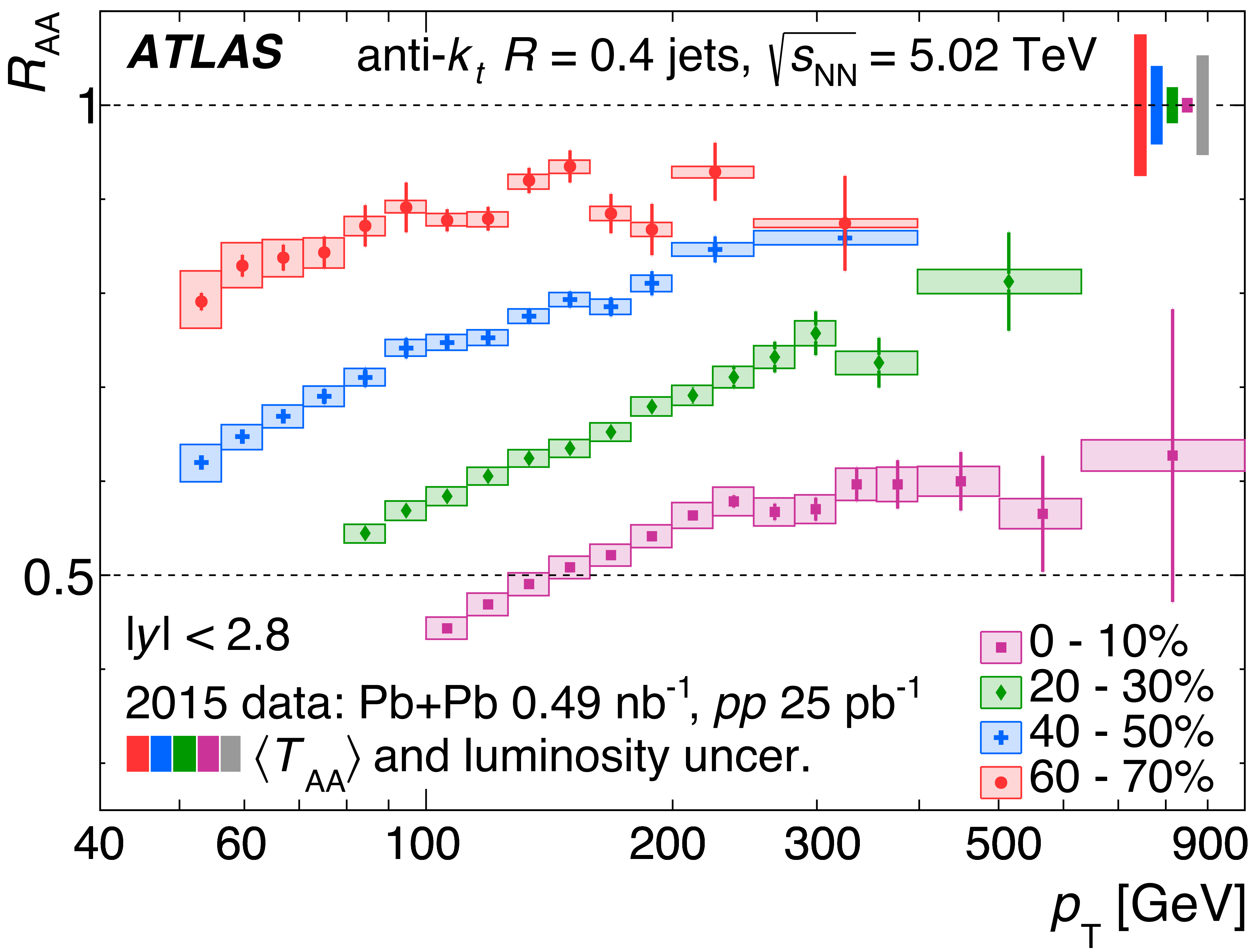


- Mass-ordering as expected from common fluid velocity

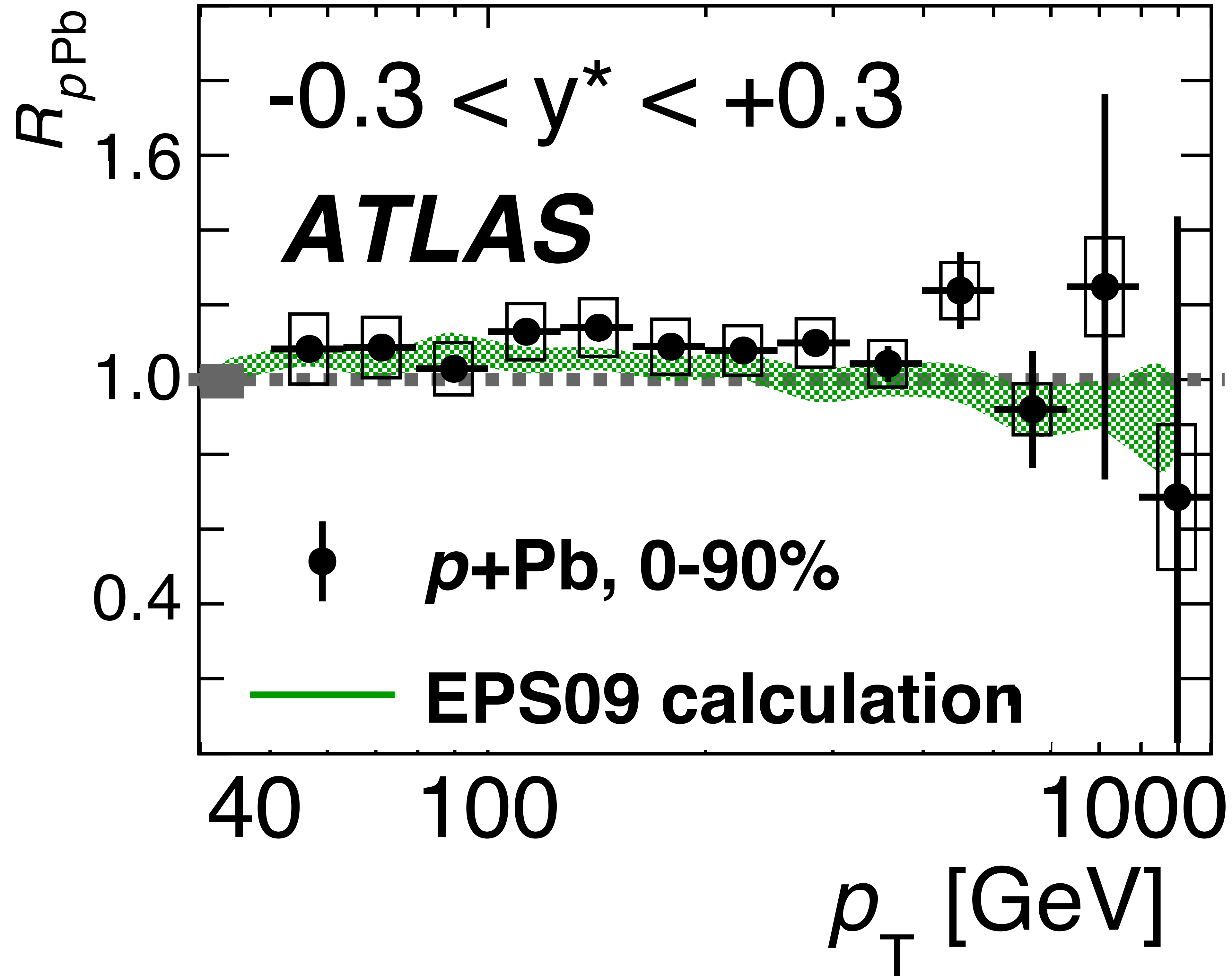


- Other evidence (multi-particle correlations, etc.)

Are small collision systems creating “mini”-QGPs?



ATLAS, PLB 748 (2015) 392



Partons lose energy as they move through the QGP → significant decrease in the rate of emerging of high-p_T jets and hadrons

… no (obvious) “jet quenching” in the small collision systems

Goal: push measurements of collective "flow" in small systems to the limits

- Flow for very high-p_T hadrons, for high-mass quarks, and in "exotic" small systems — challenge the hydro paradigm!
- 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?

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

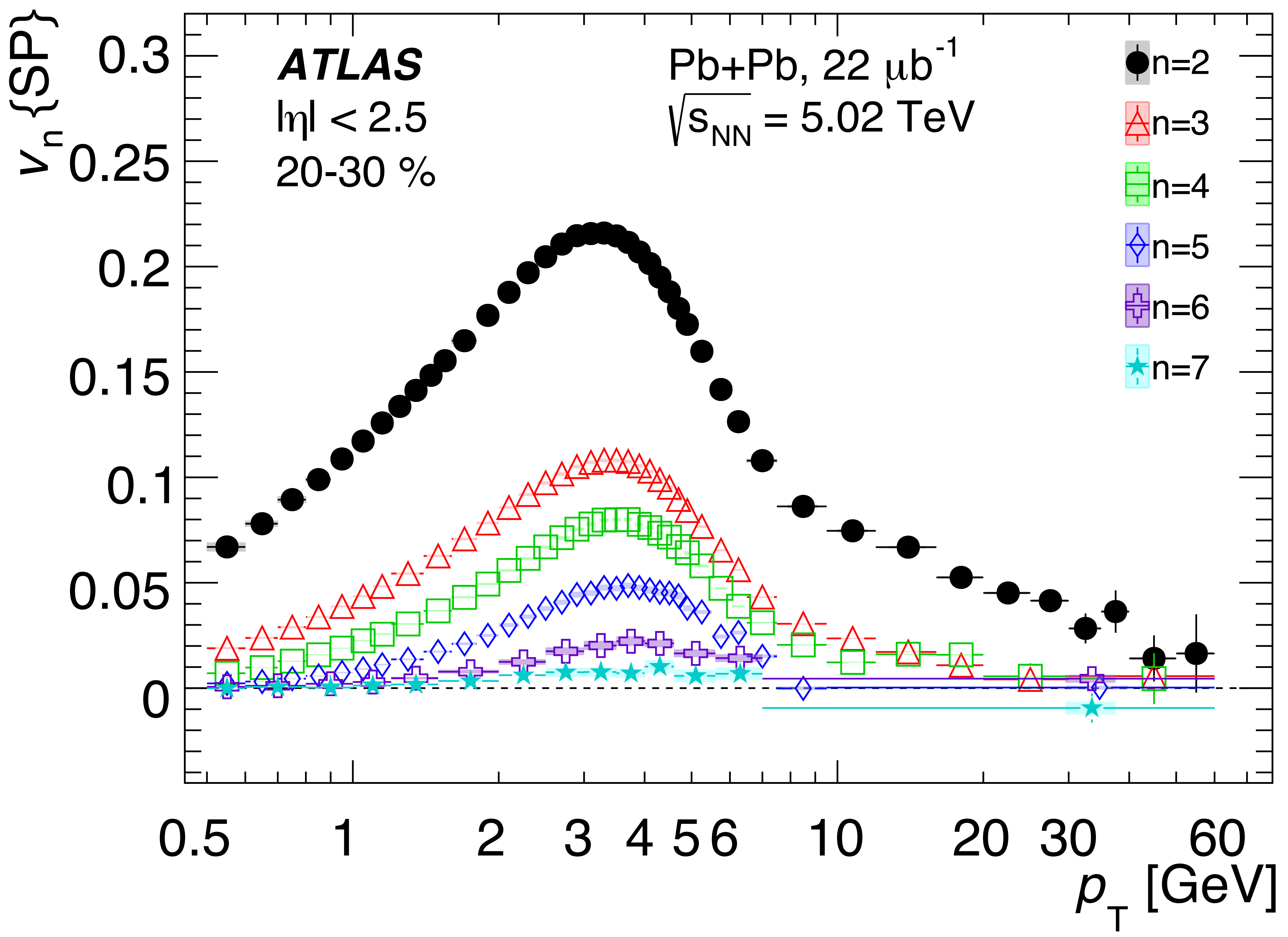
ATLAS, Eur. Phys. J C80 (2020) 73

Kurt Hill
(Ph.D. 2020)

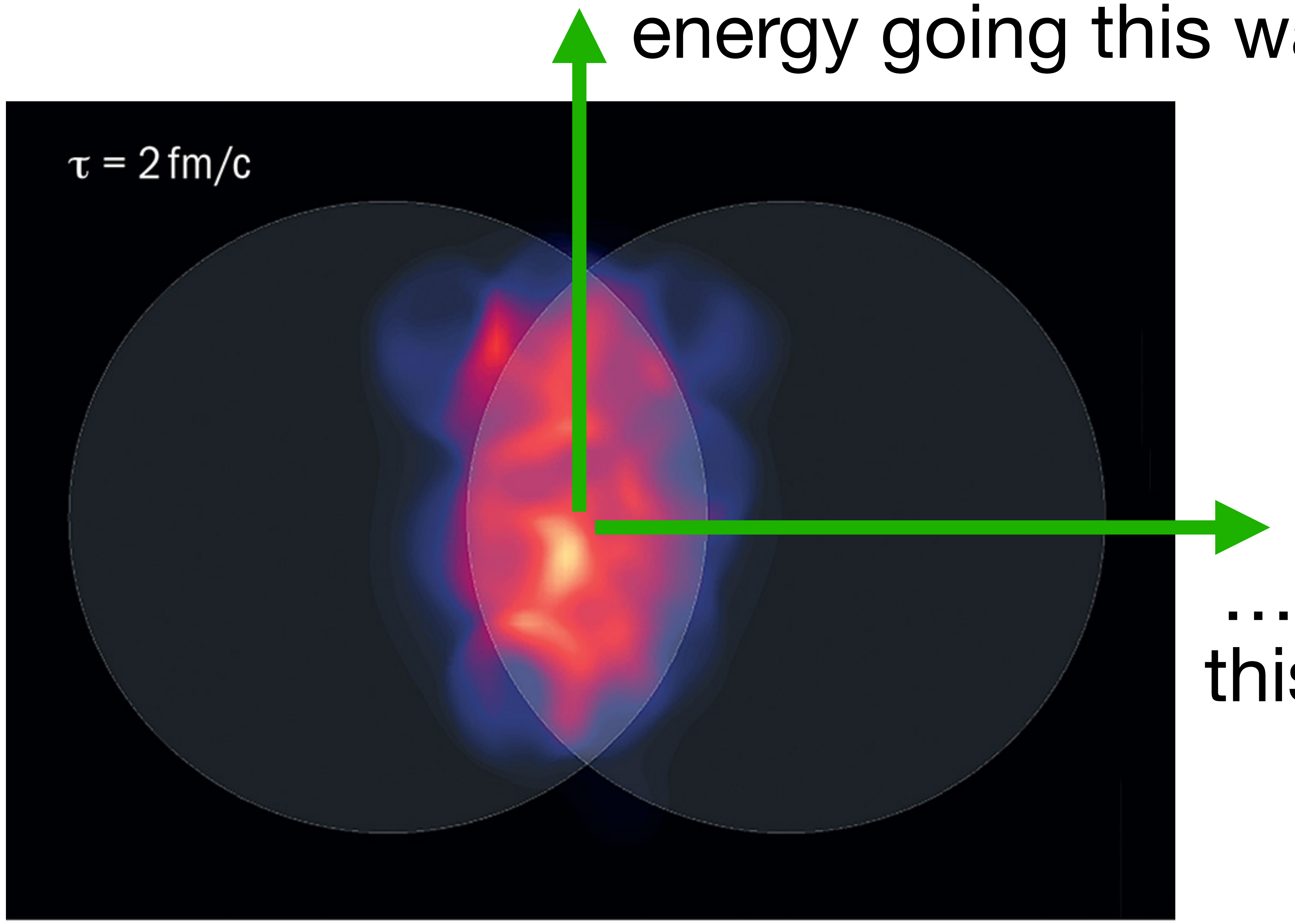
ATLAS EXPERIMENT

Thesis
Award 2021

High-p_T particles in AA collisions…



Partons lose more energy going this way…



… than this way

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

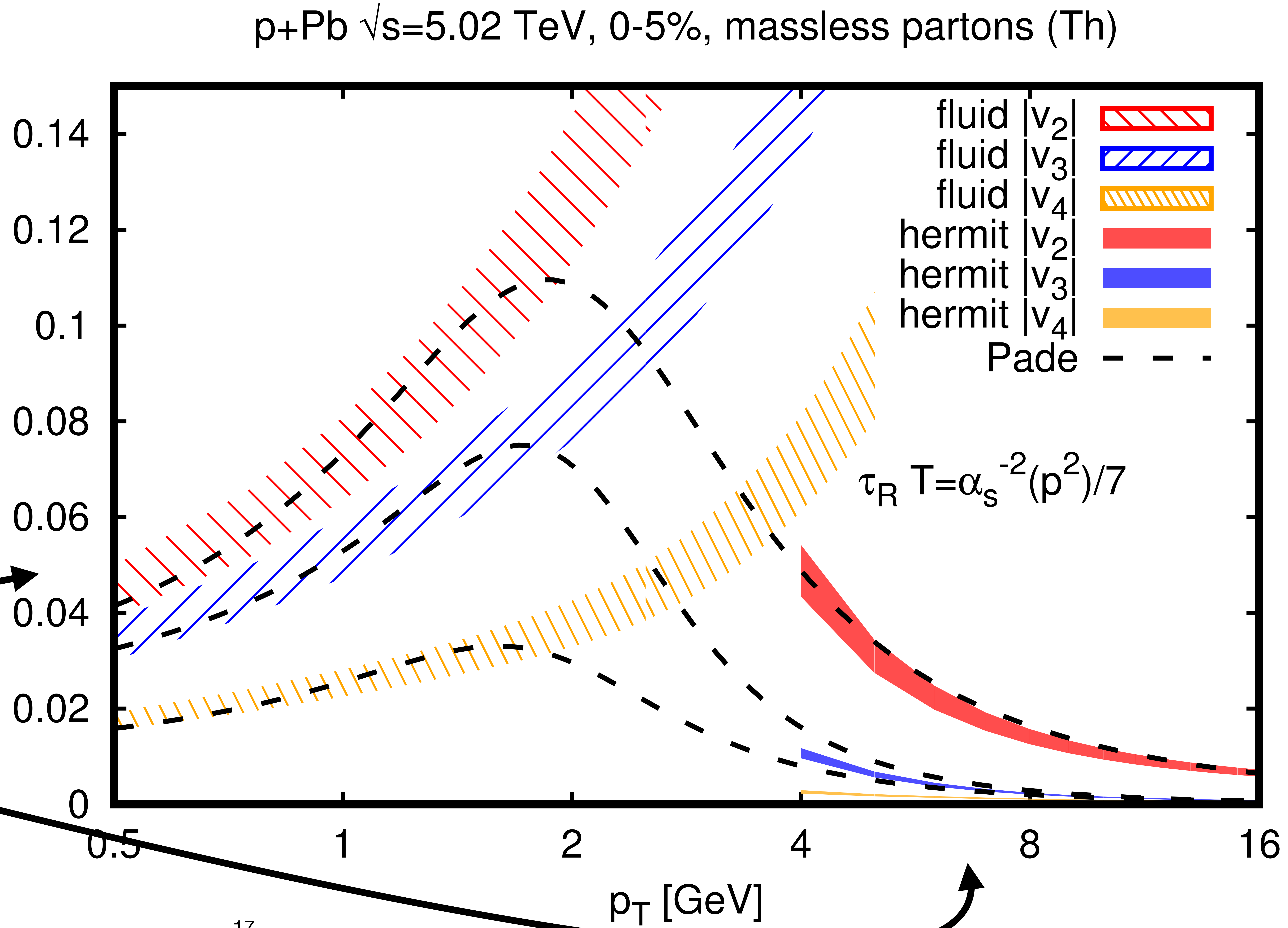
i.e. also arises from AA collision geometry, but for different physical reason

What to expect in the hard sector?

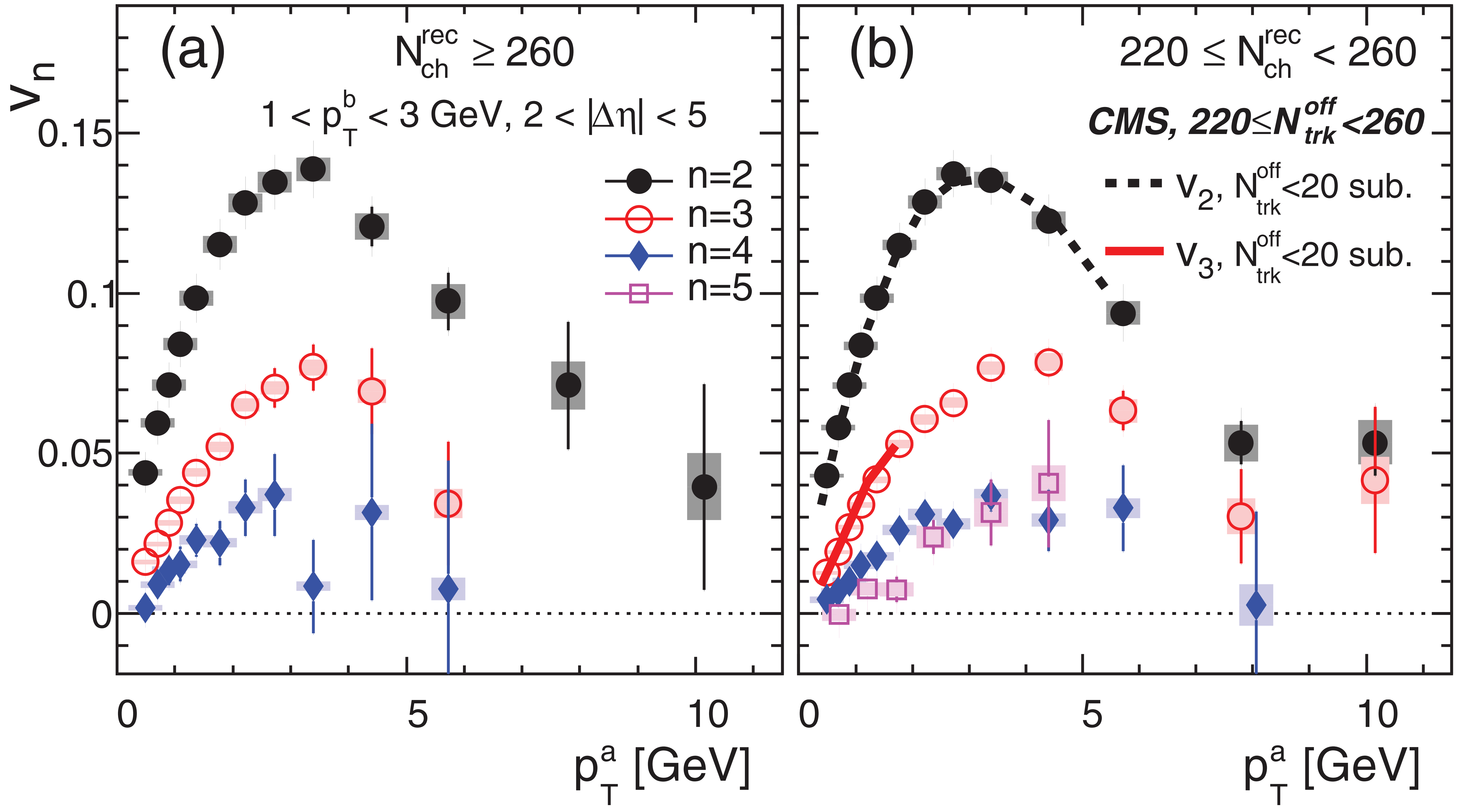
Romatschke, EPJC 78 (2018) 636

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…

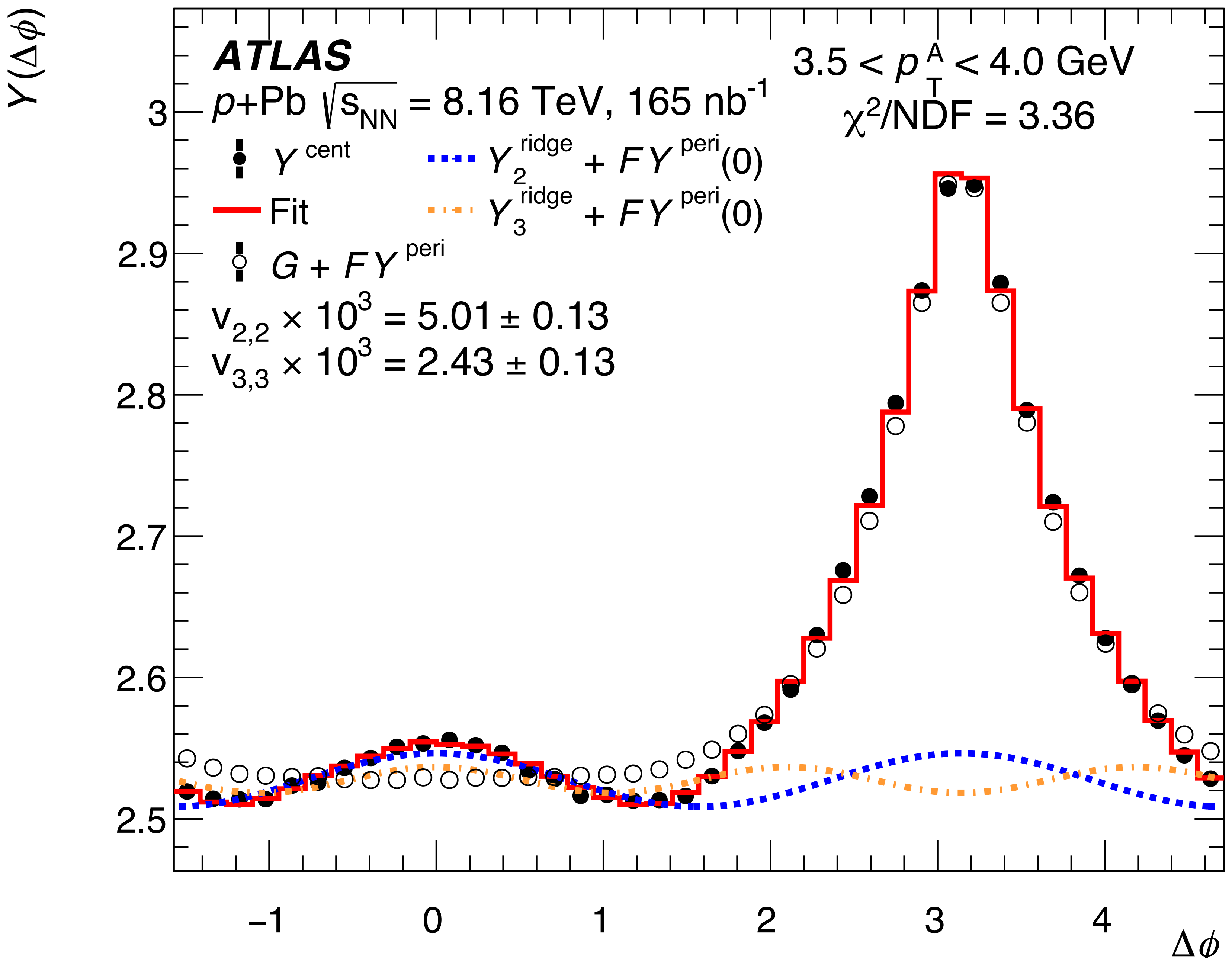
Using 2016 p+Pb data, push much farther in centrality and p_T!

Two-particle correlations for high-p_T particles

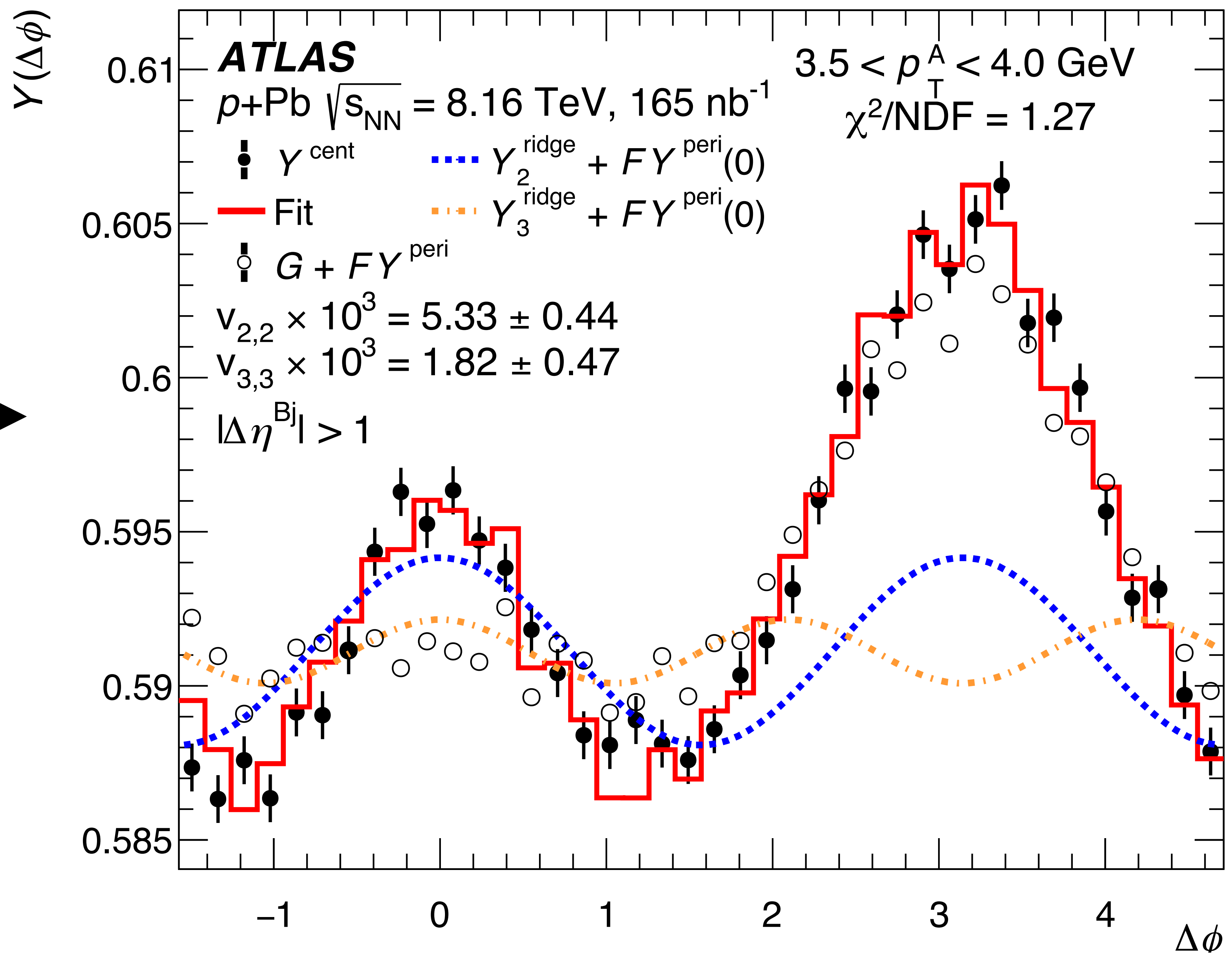
Traditional two-particle Δϕ correlation analysis results in huge away-side peak from non-flow effects! (even with $|\Delta\eta| > 2$)

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

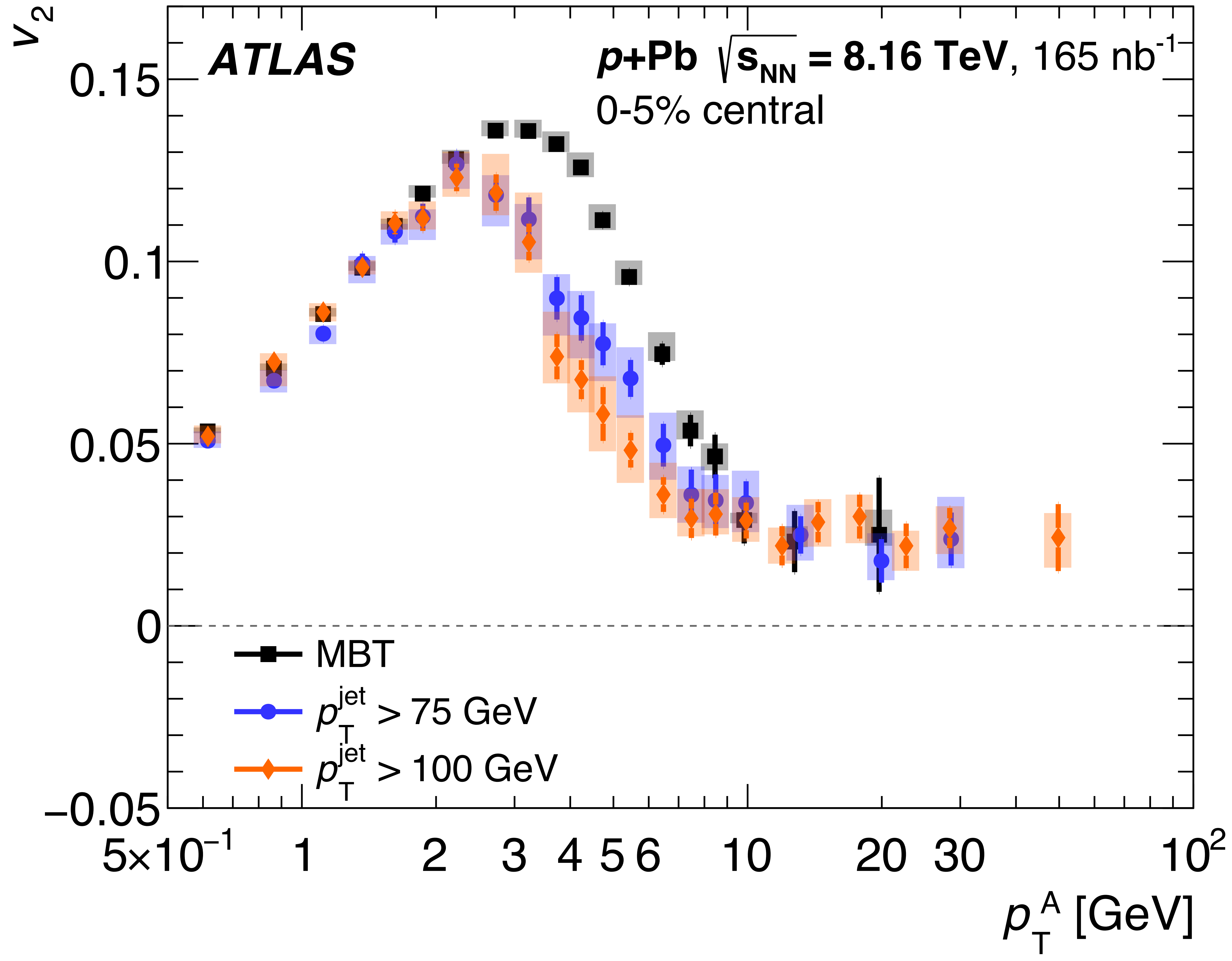
Use "template fit" to subtract low-multiplicity-like non-flow component

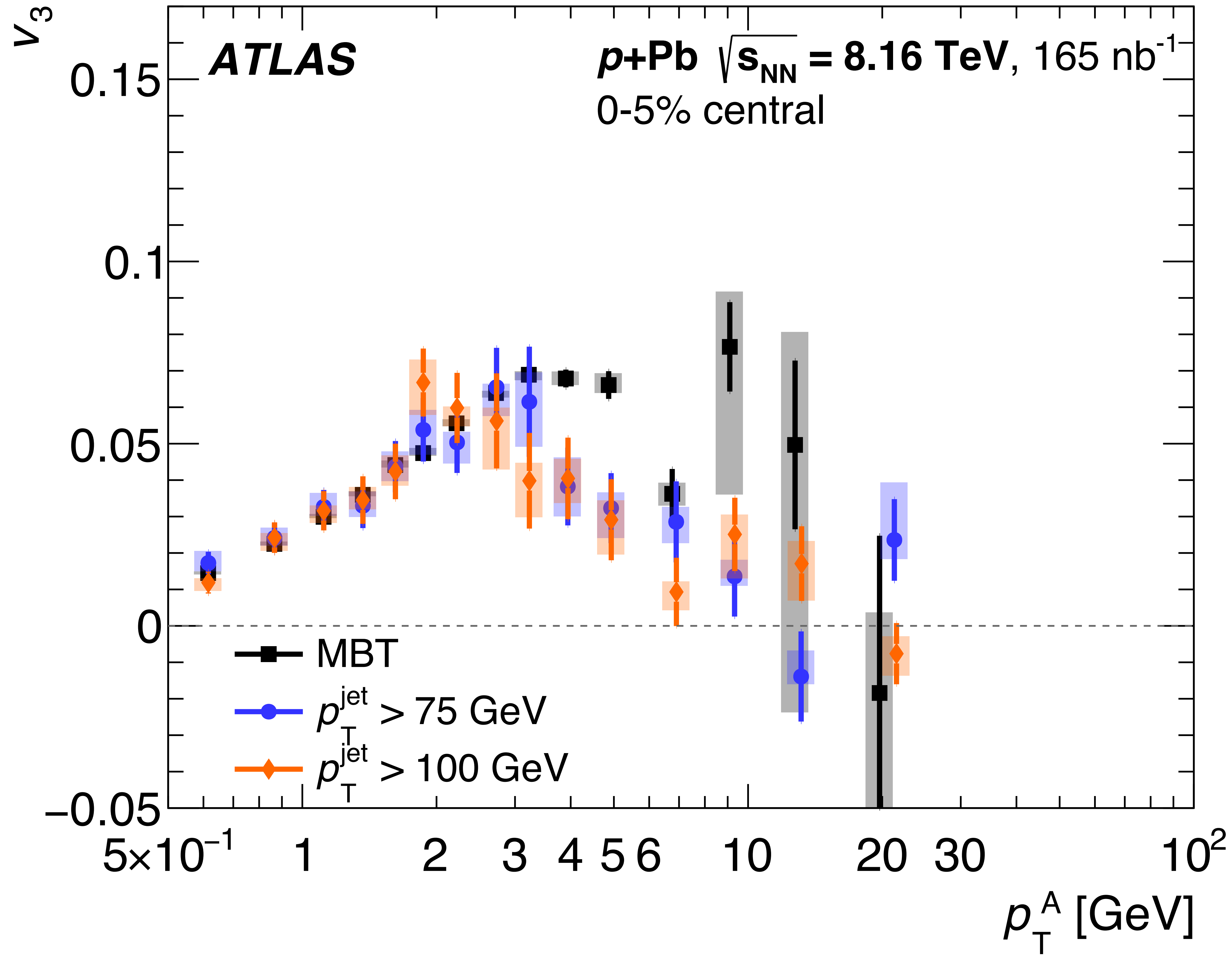


Require $|\Delta\eta^{B,jet}| > 1$



v_2 and v_3 results





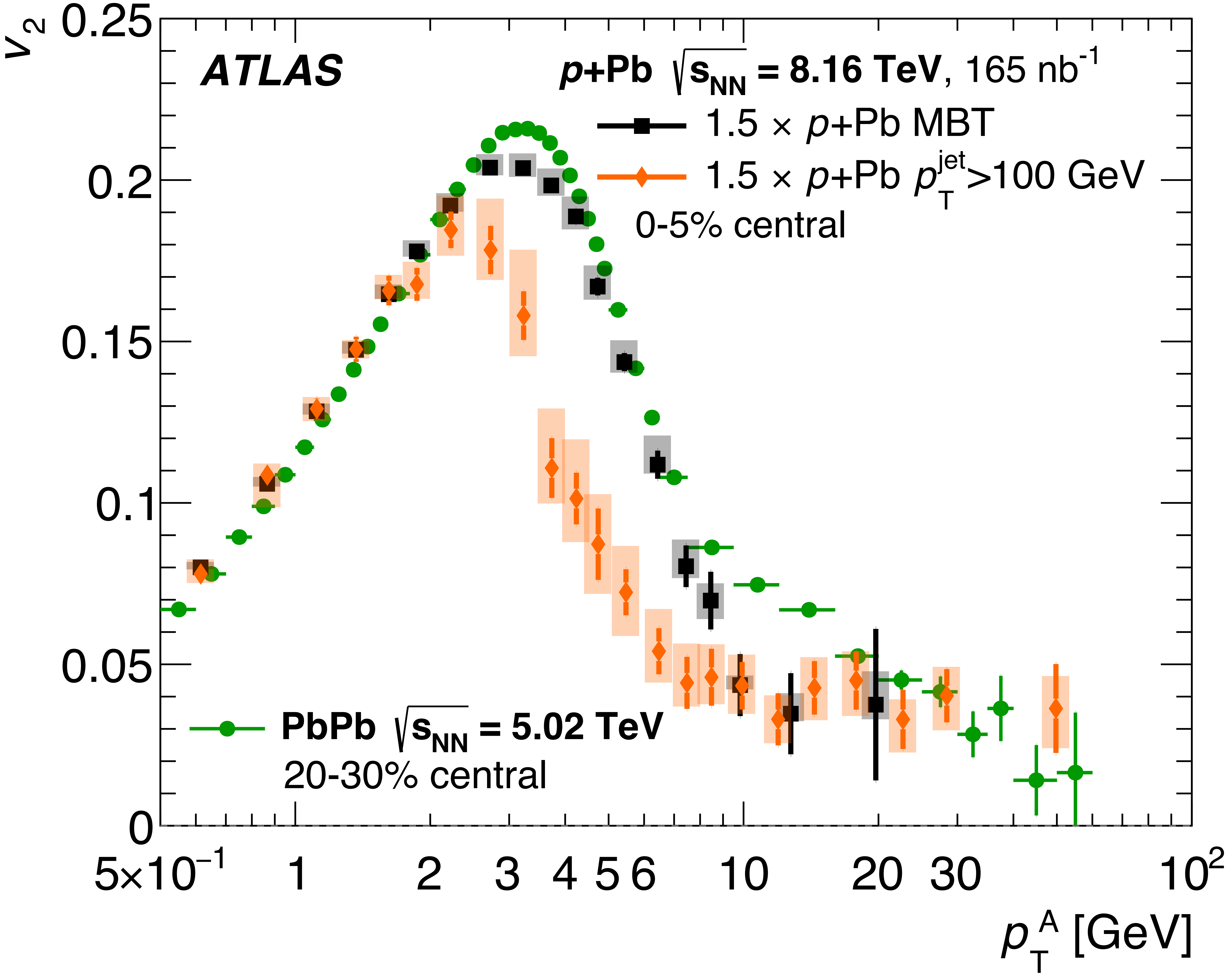
In >100 GeV jet events, v_2 ~ 2-3% at p_T^{ch} = 50 GeV!

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

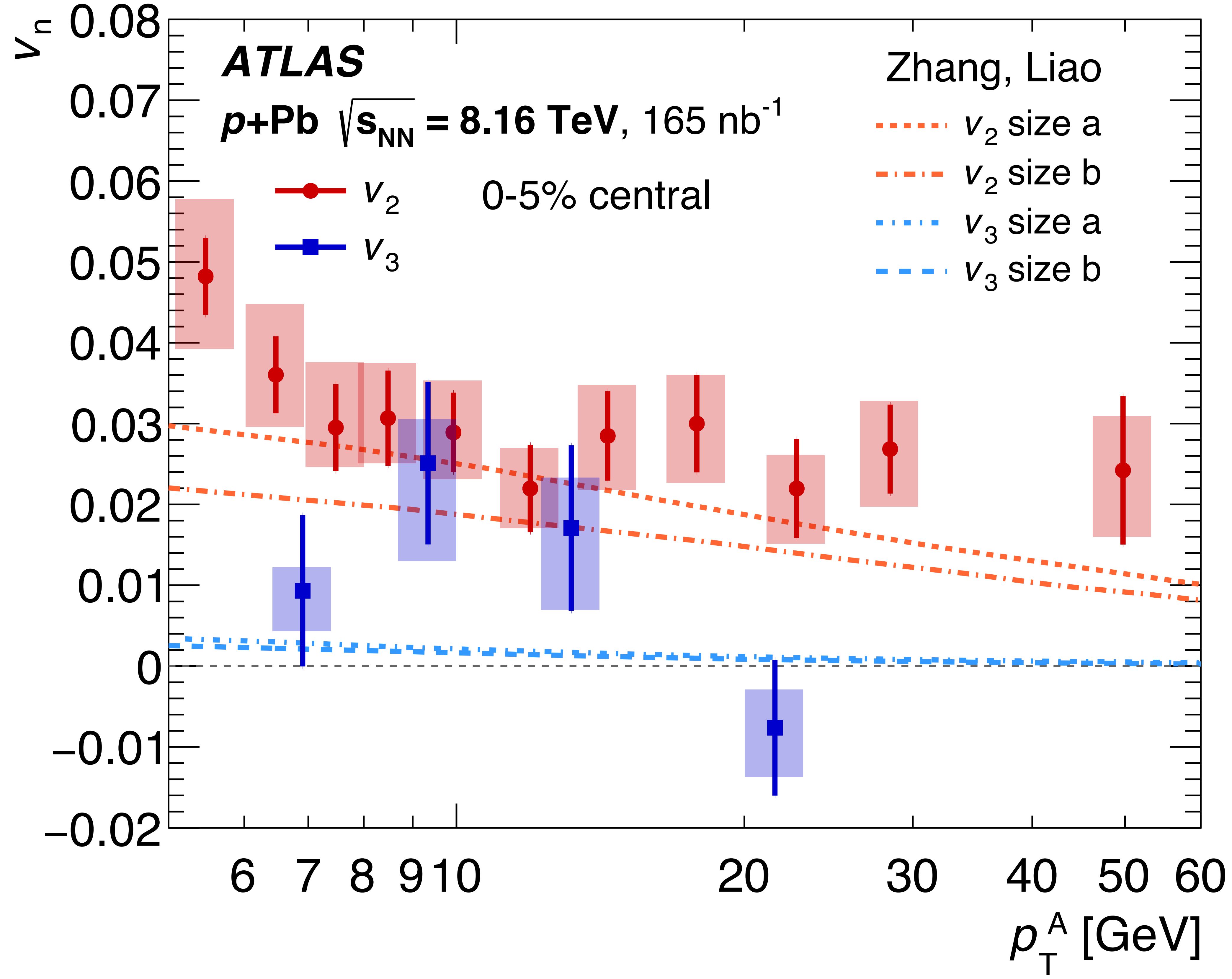
Comparison to Pb+Pb

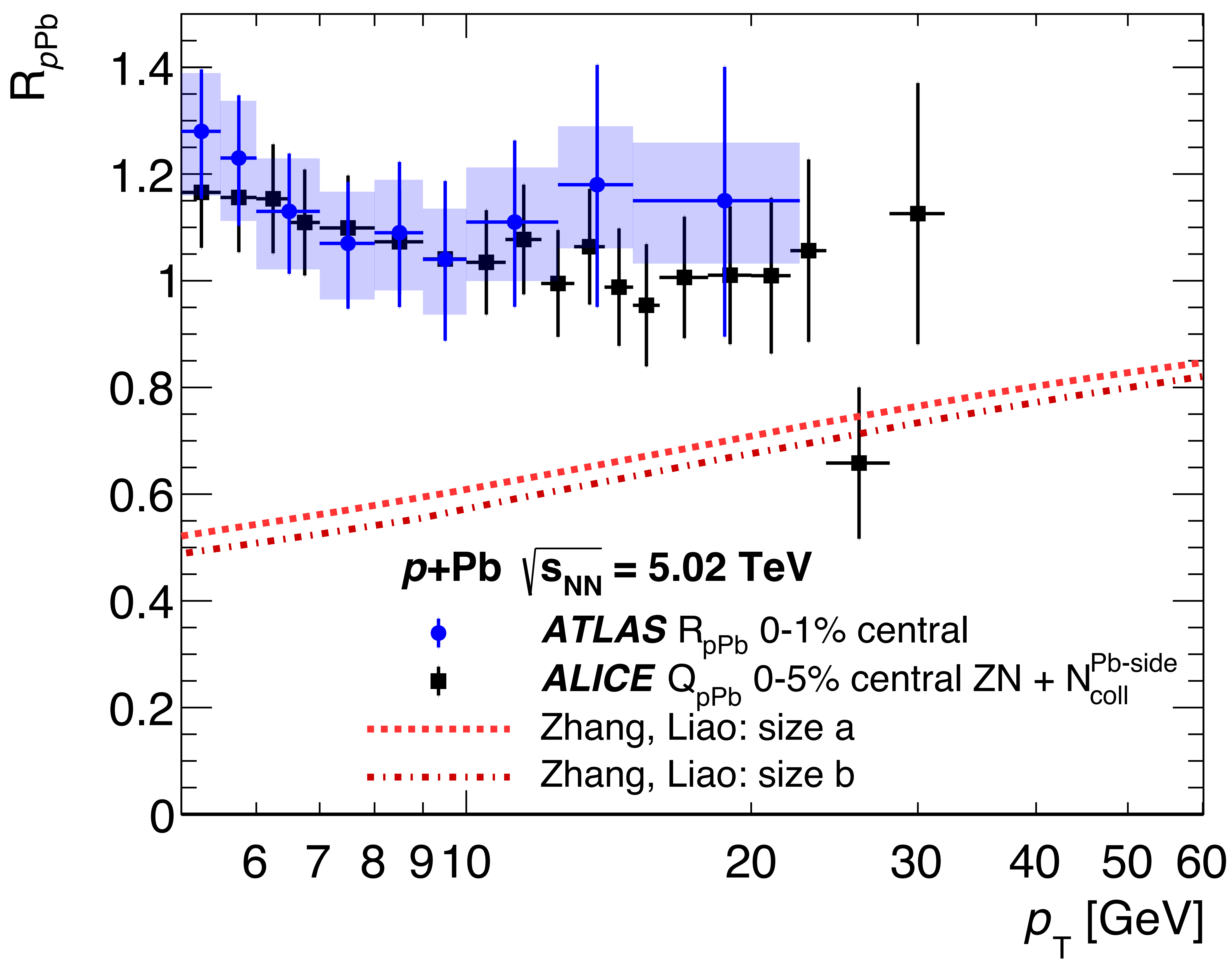
Compare v_2 in **MB** and **jet-triggered** p+Pb events to that in **Pb+Pb** events w/ same ε_2 (with ad-hoc scaling factor)

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



Interpretation in energy-loss models



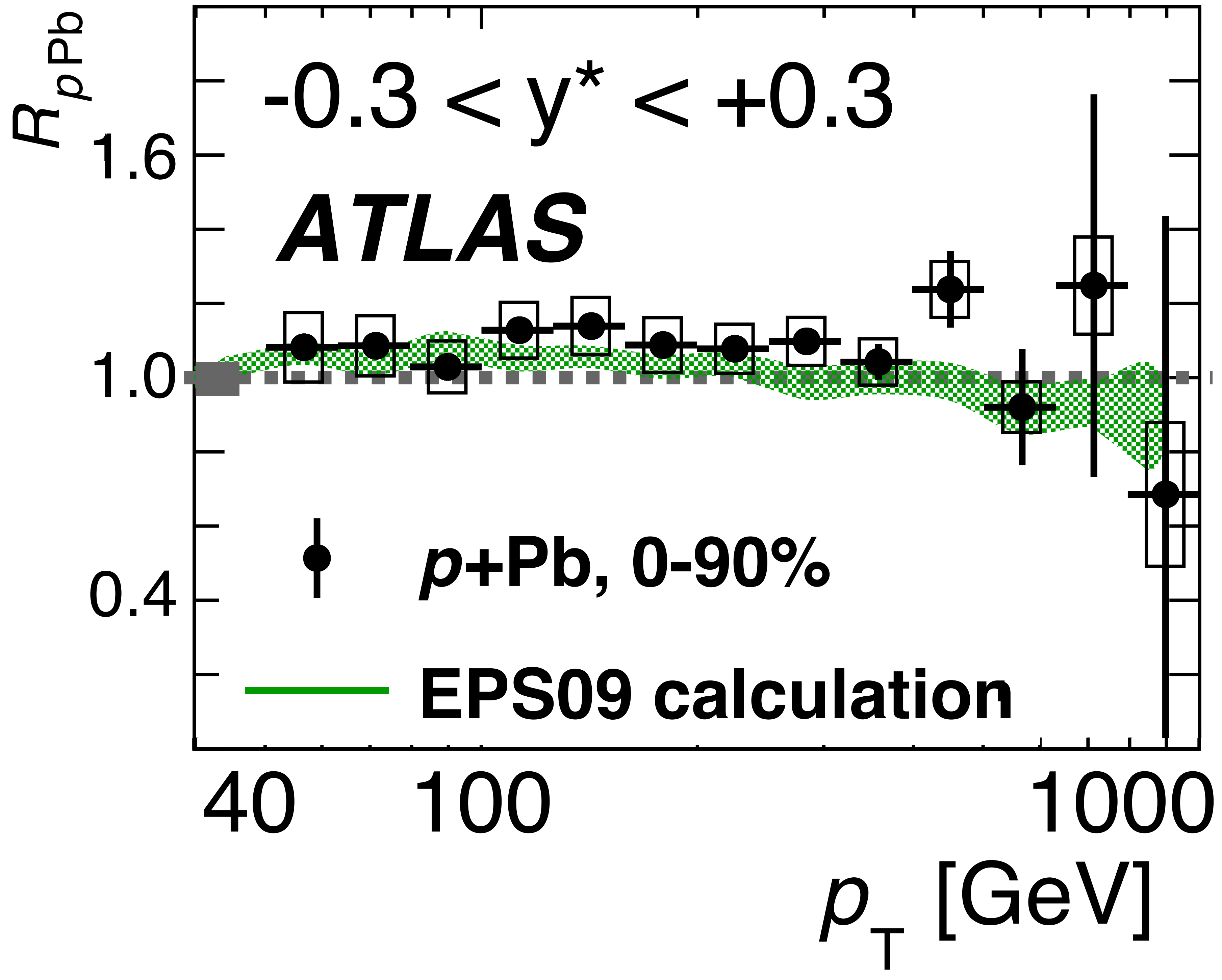


Magnitude of v_2 and v_3 agrees with calculation by Zhang & Liao…

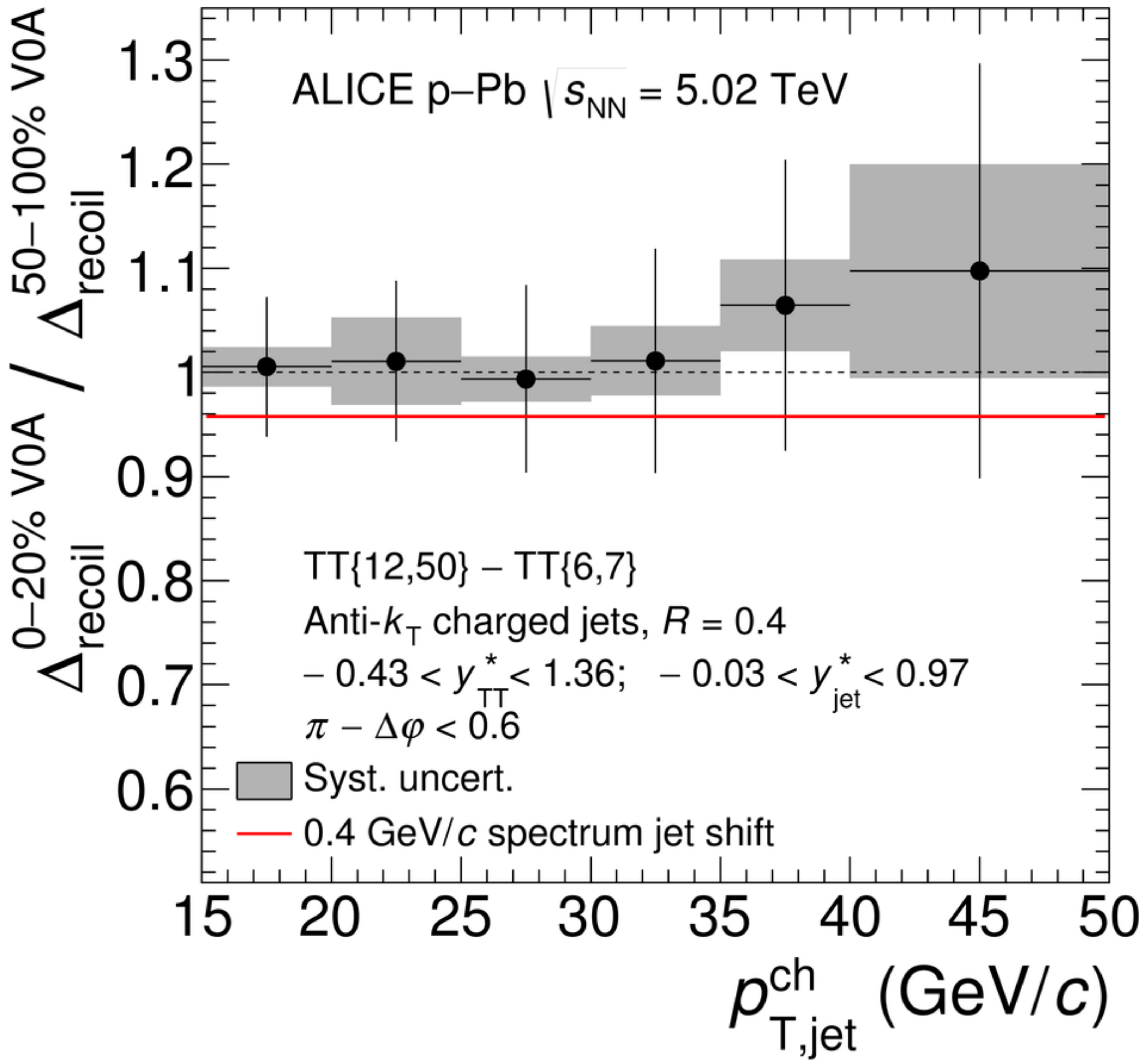
… but measurements of R_{pA} rule out the predicted suppression

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?

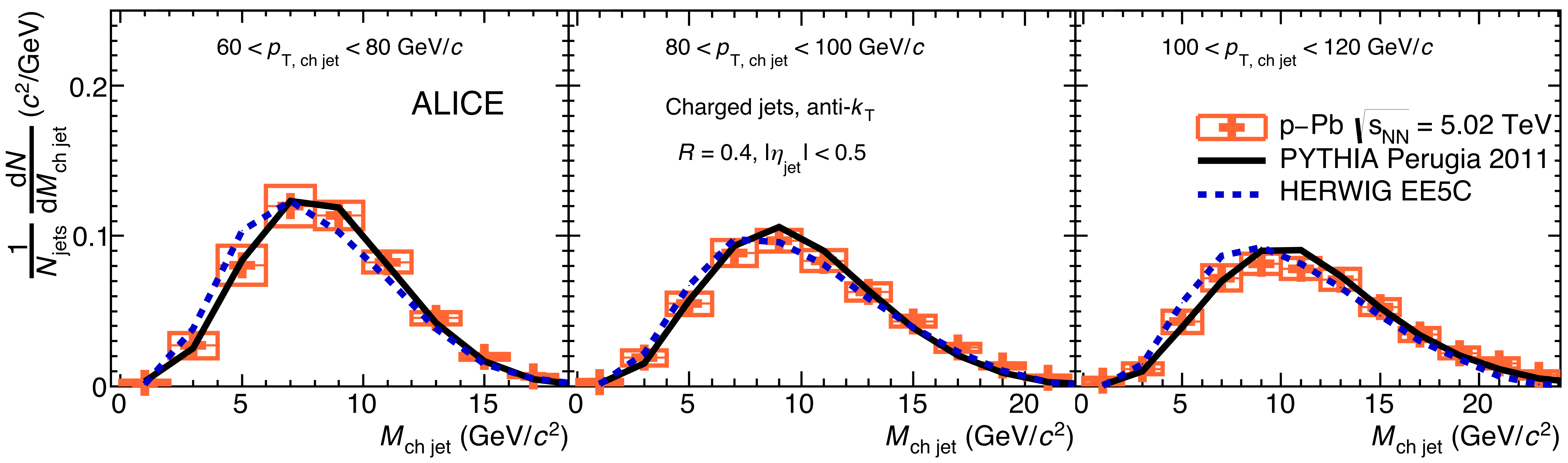
Some limits from centrality-integrated jet mass (top)

and fragmentation functions (bottom)

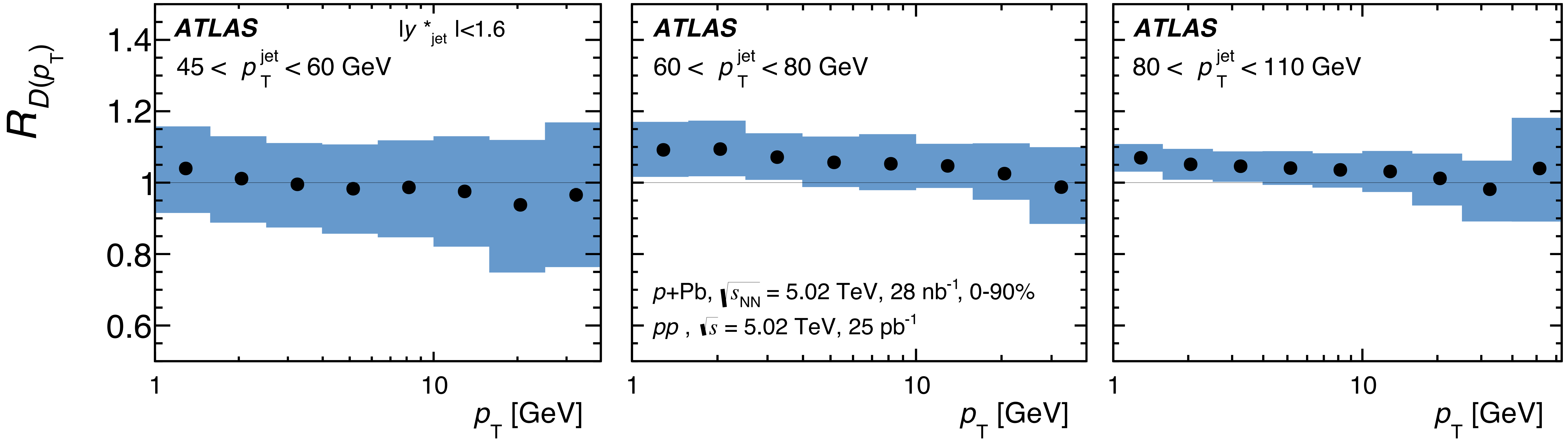
TODO: high-statistics 2016 p+Pb data, ZDC for unbiased centrality selection…

Theory guidance for jet modification in p+Pb?

ALICE, PLB 776 (2018) 249



ATLAS, NPA 978 (2018) 65



2. Charm and bottom quarks in *pp* collisions

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

Sanghoon Lim

→ Prof @

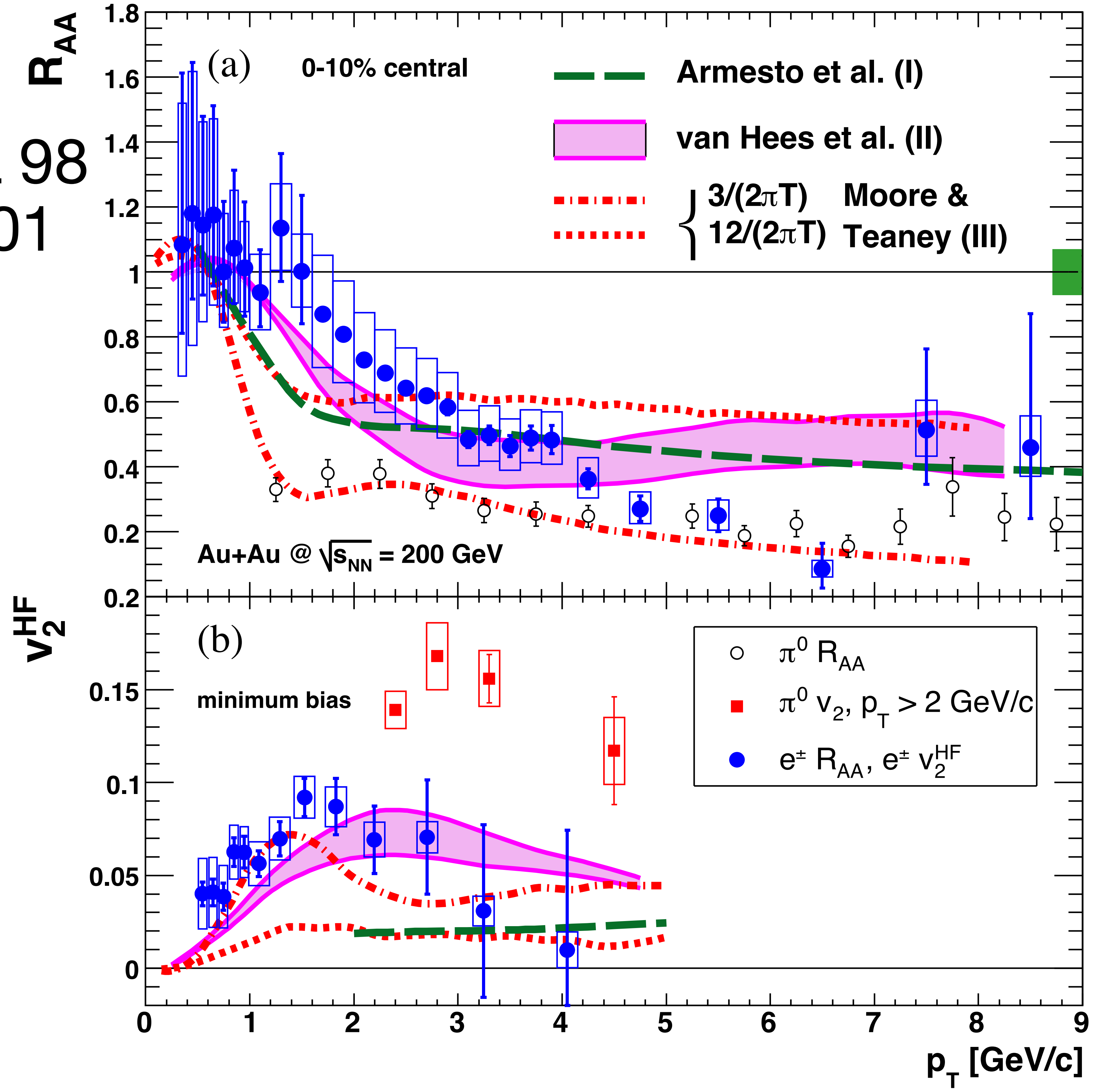
Qipeng Hu

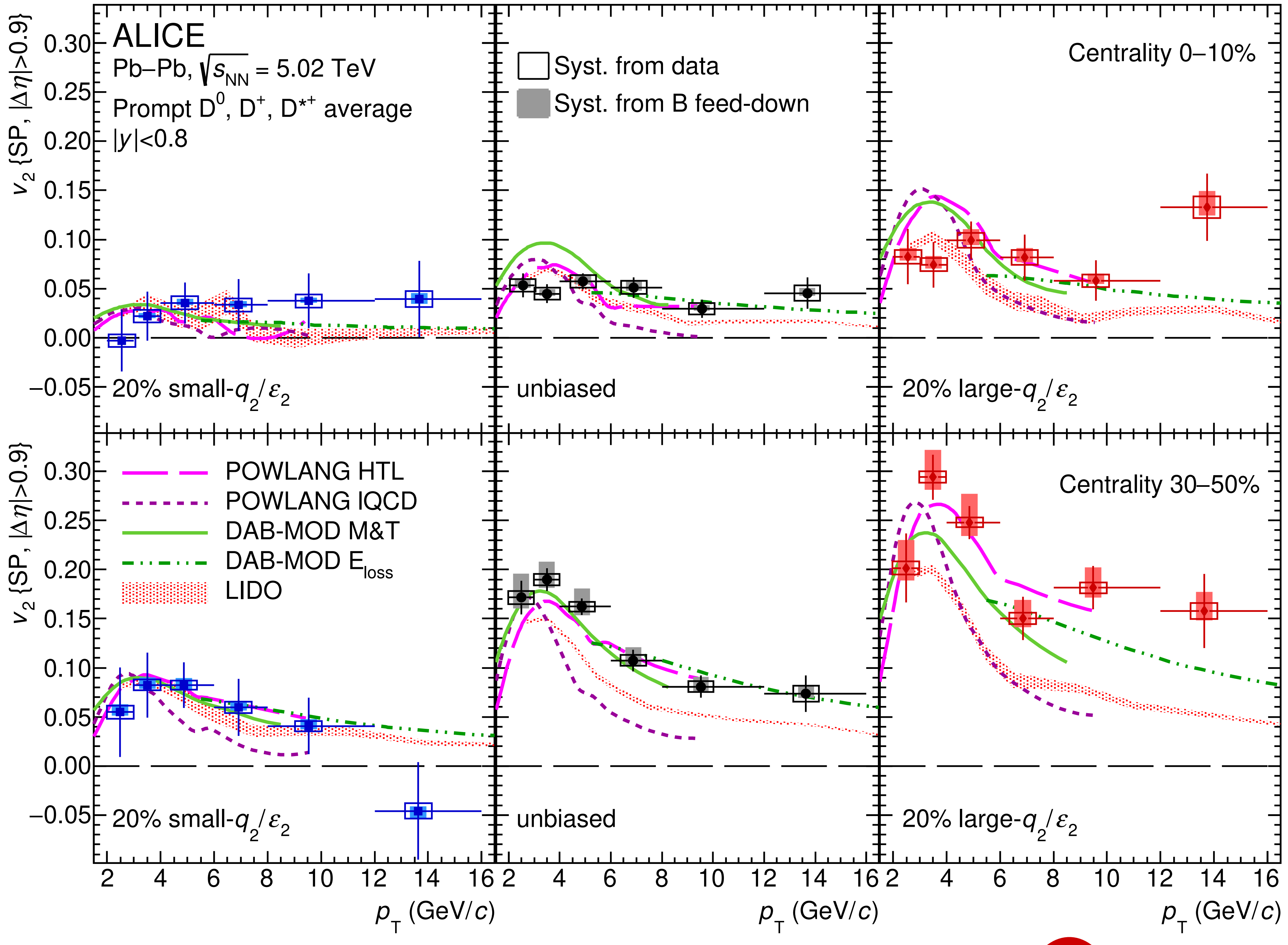
→ Lawrence Livermore National Laboratory

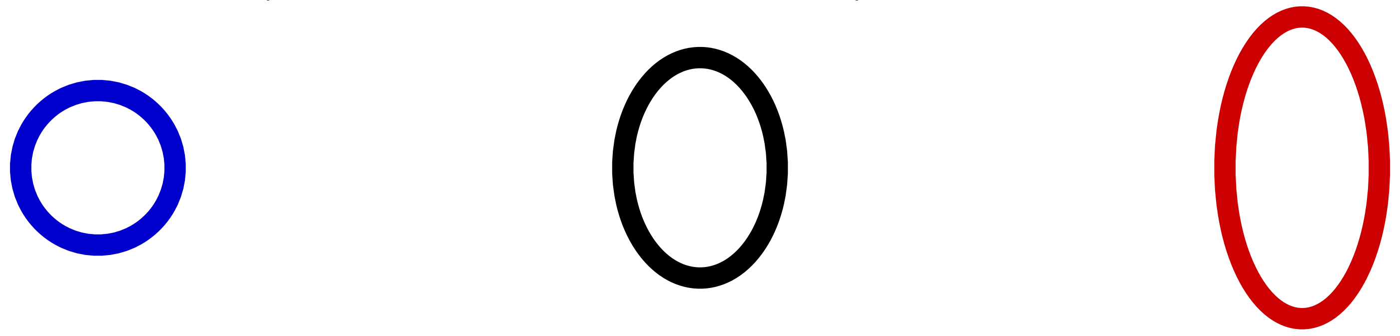
Heavy flavor modification in Au+Au

ALICE, nucl-ex/ 2005.11131

PHENIX, PRL 98 (2008) 172301





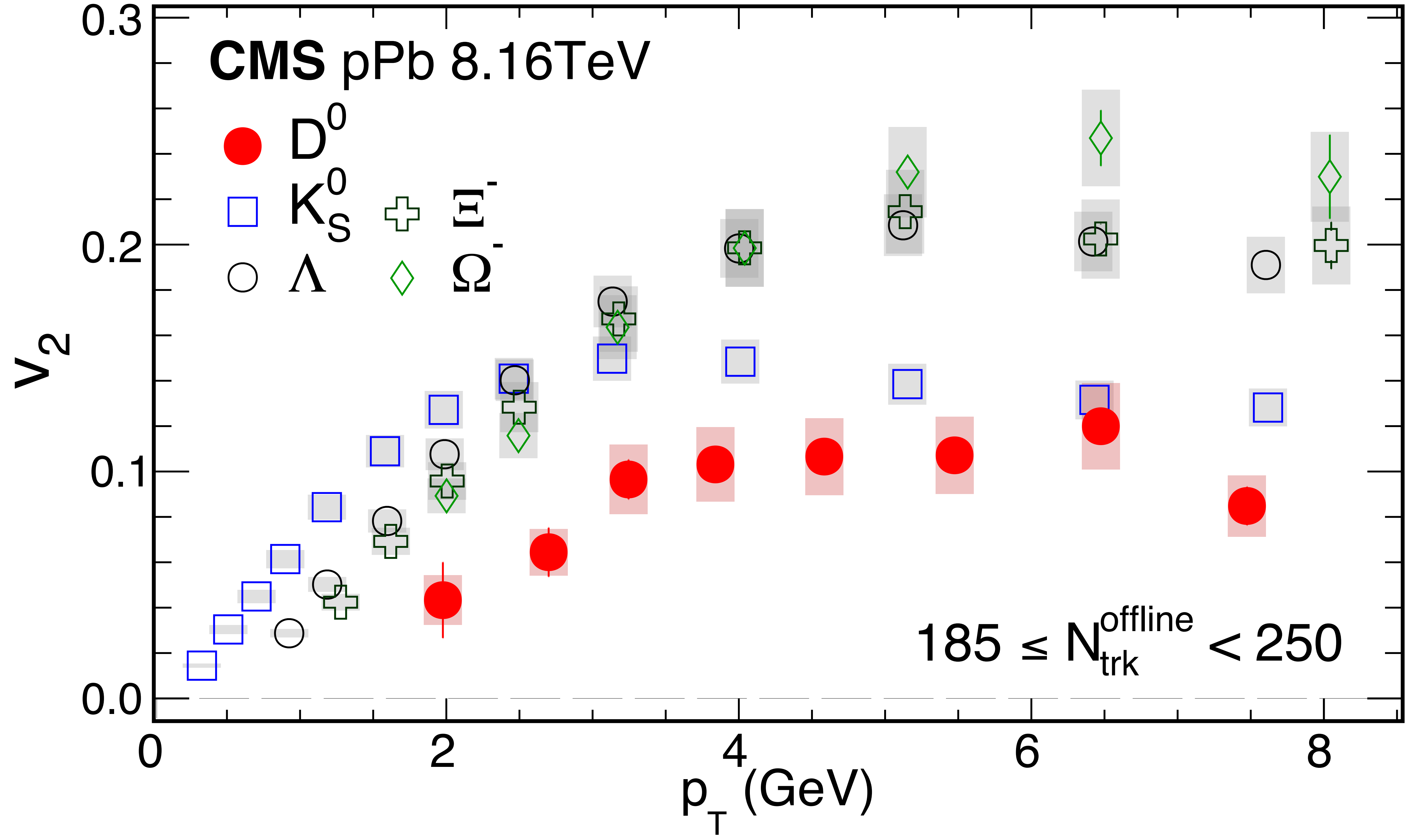


Substantial *E*-loss and flow of HF electrons at RHIC — one motivation for $\eta/s = 1/4\pi$ bound!

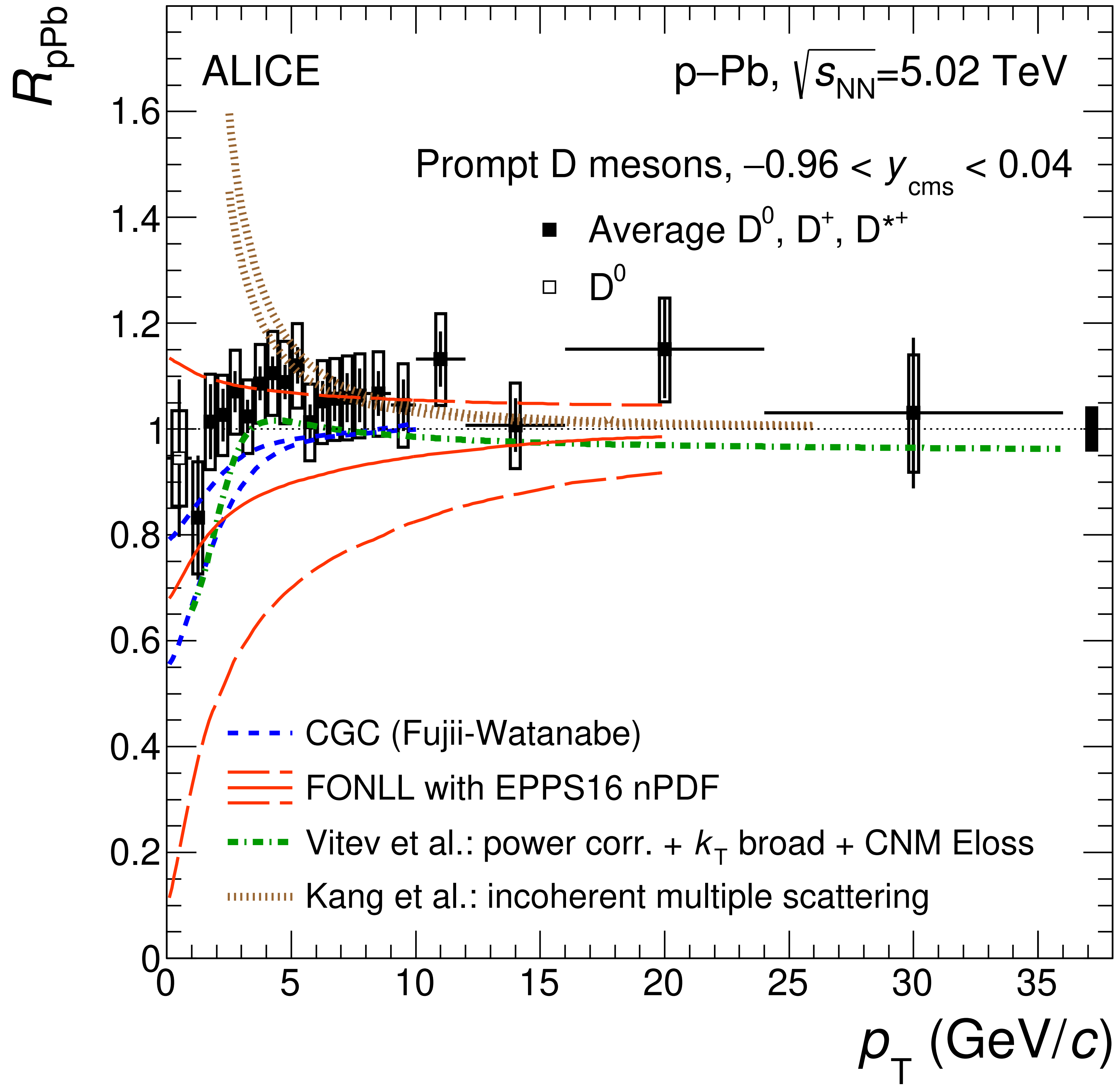
Thermalized charm "feels the shape" of the QGP region at the LHC

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

CMS, PRL 121 (2018) 082301



ALICE, JHEP 12 (2019) 092

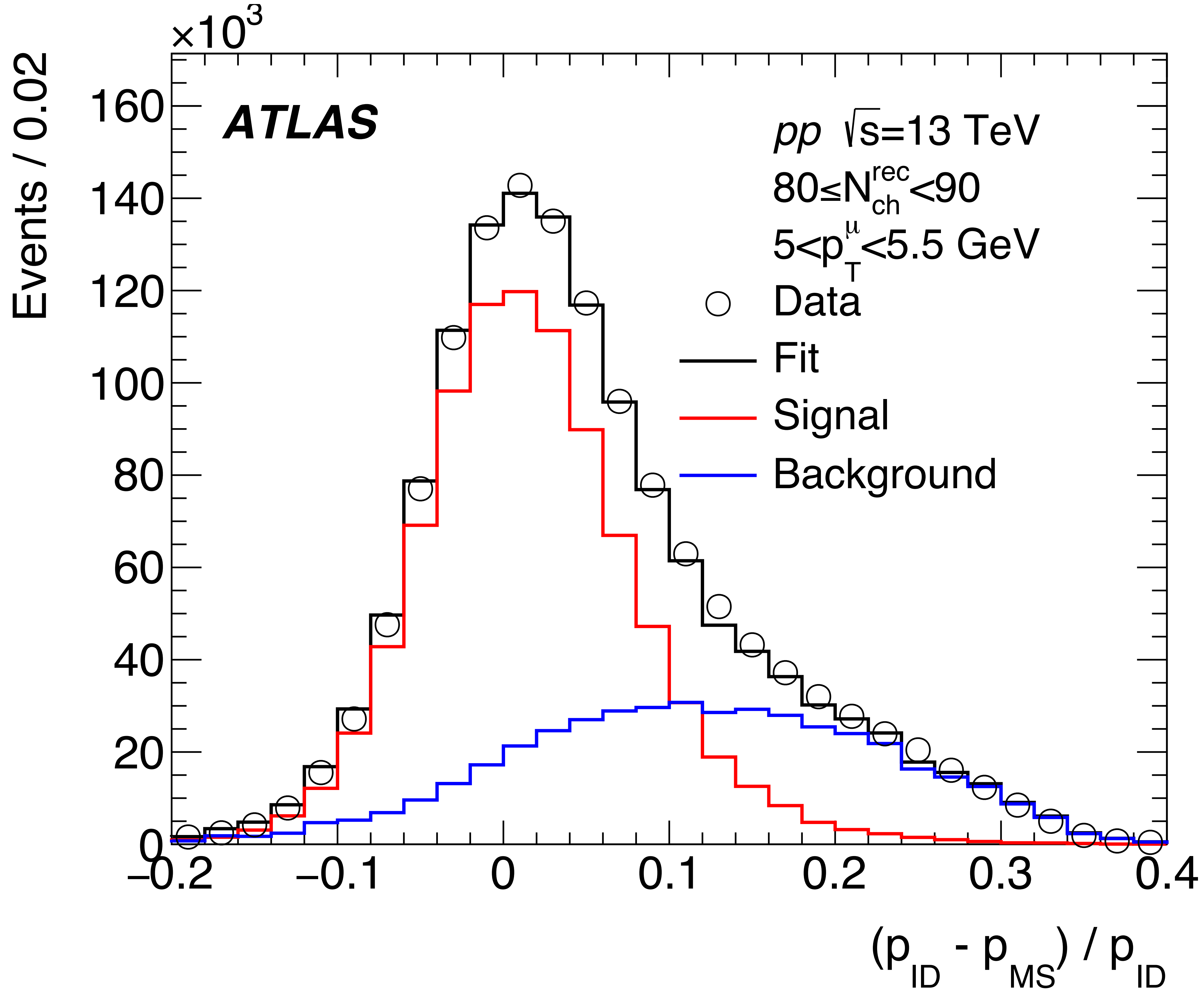


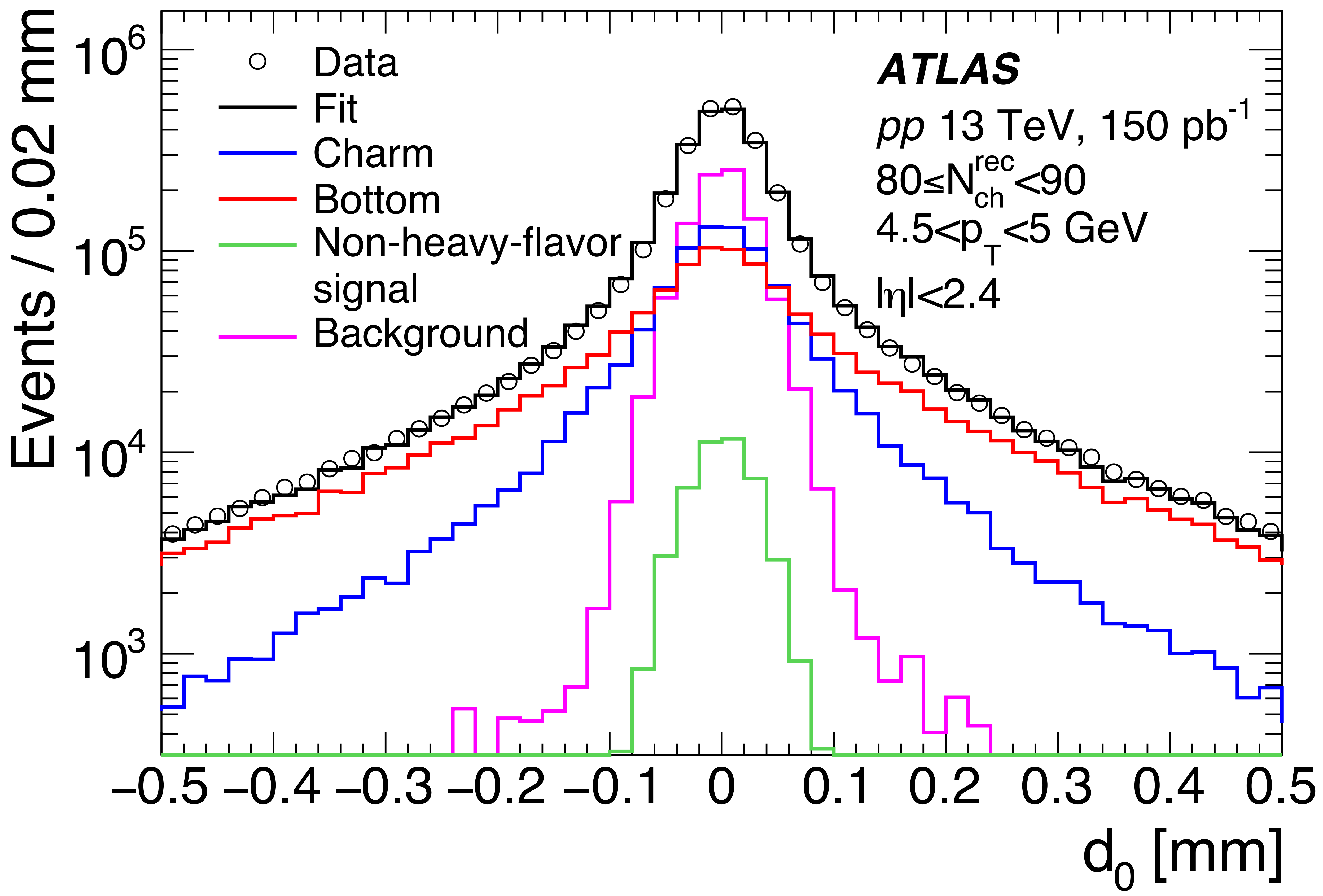
Similar v_2 magnitude for **charm hadrons** in (very high multiplicity) *p*+Pb

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*

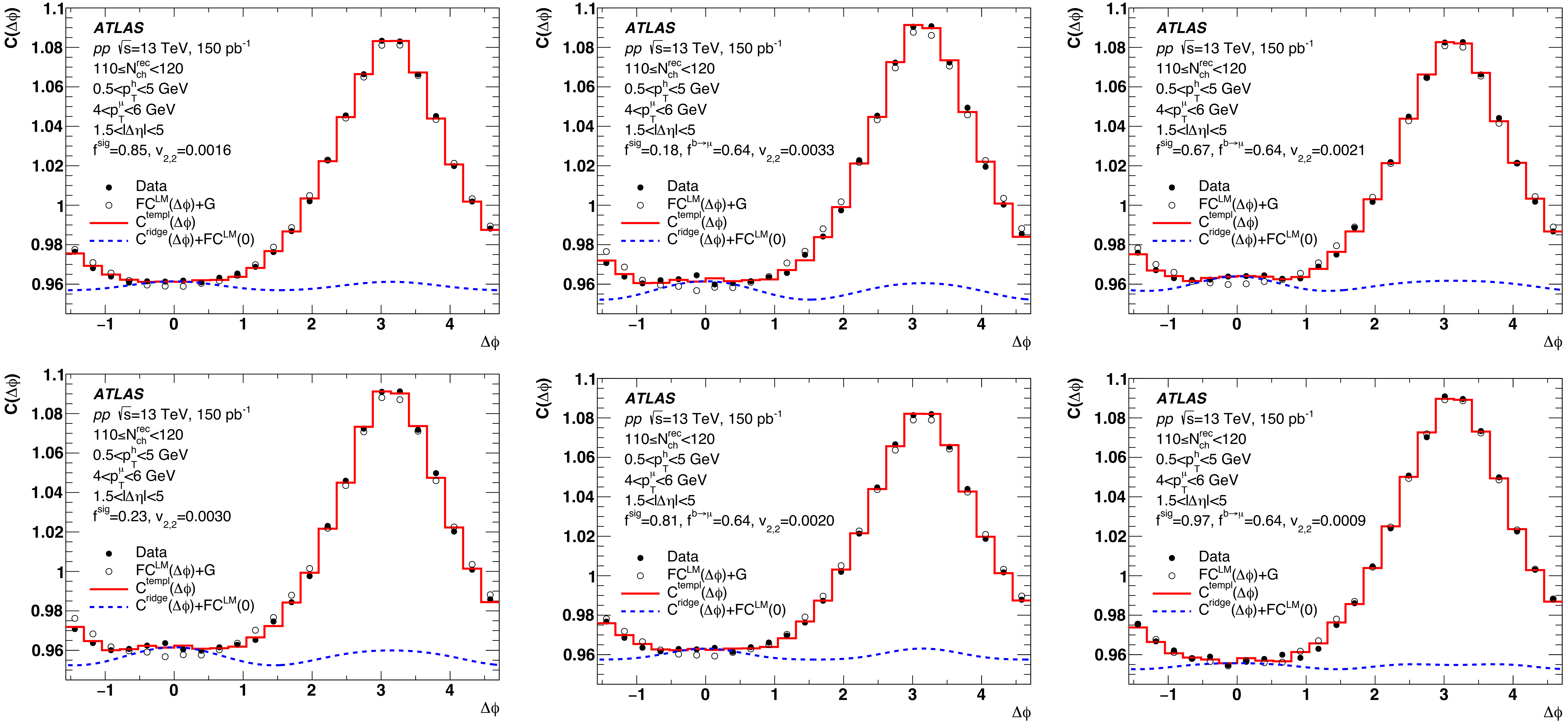




Heavy flavor decay muons separated from **in-flight decays, punch-throughs, etc.** via inner tracker - muon spectrometer *p* match

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

Two-particle correlation analysis



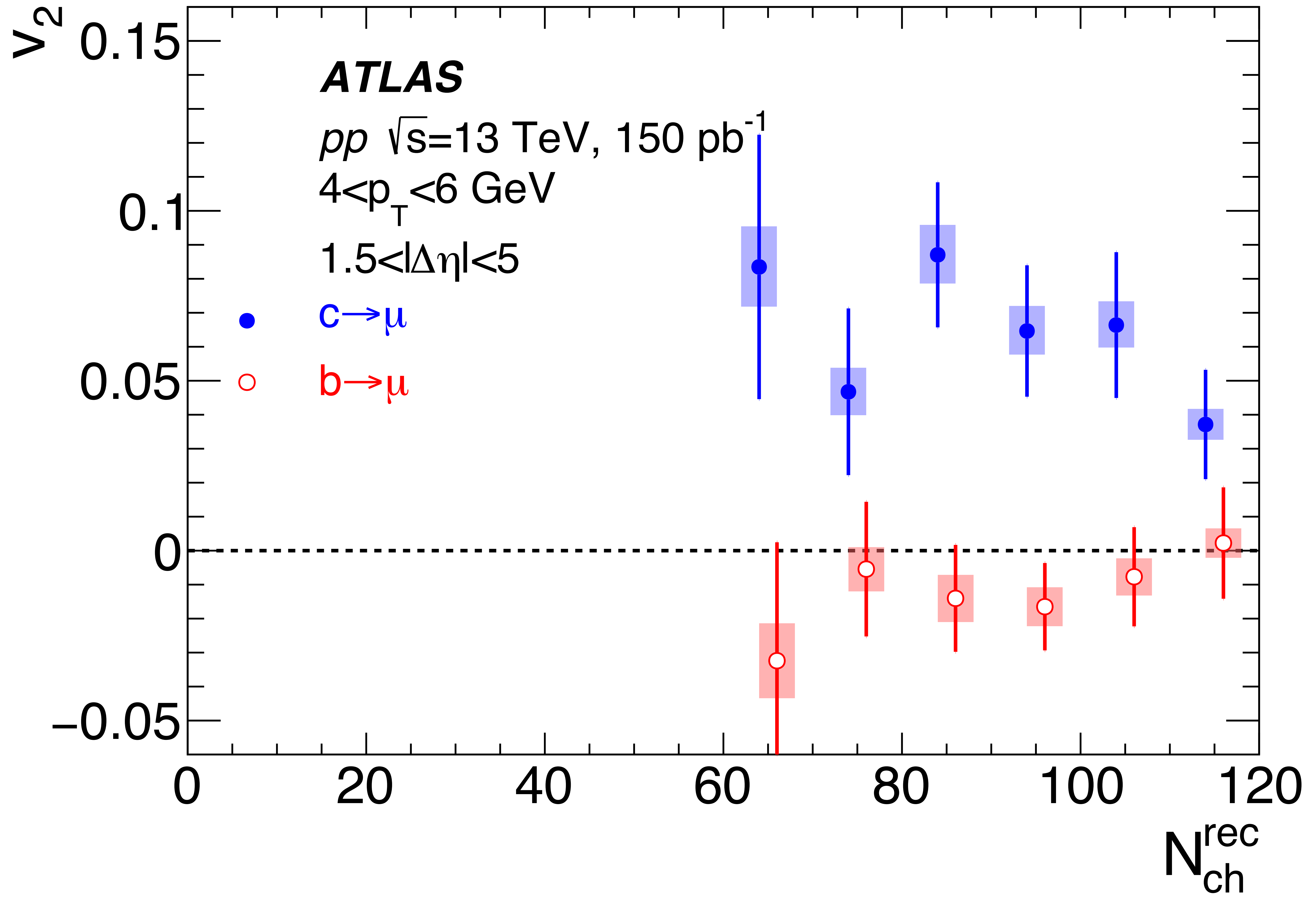
Rapidity-separated two-particle Δϕ correlations with template fit to remove non-flow

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*)!

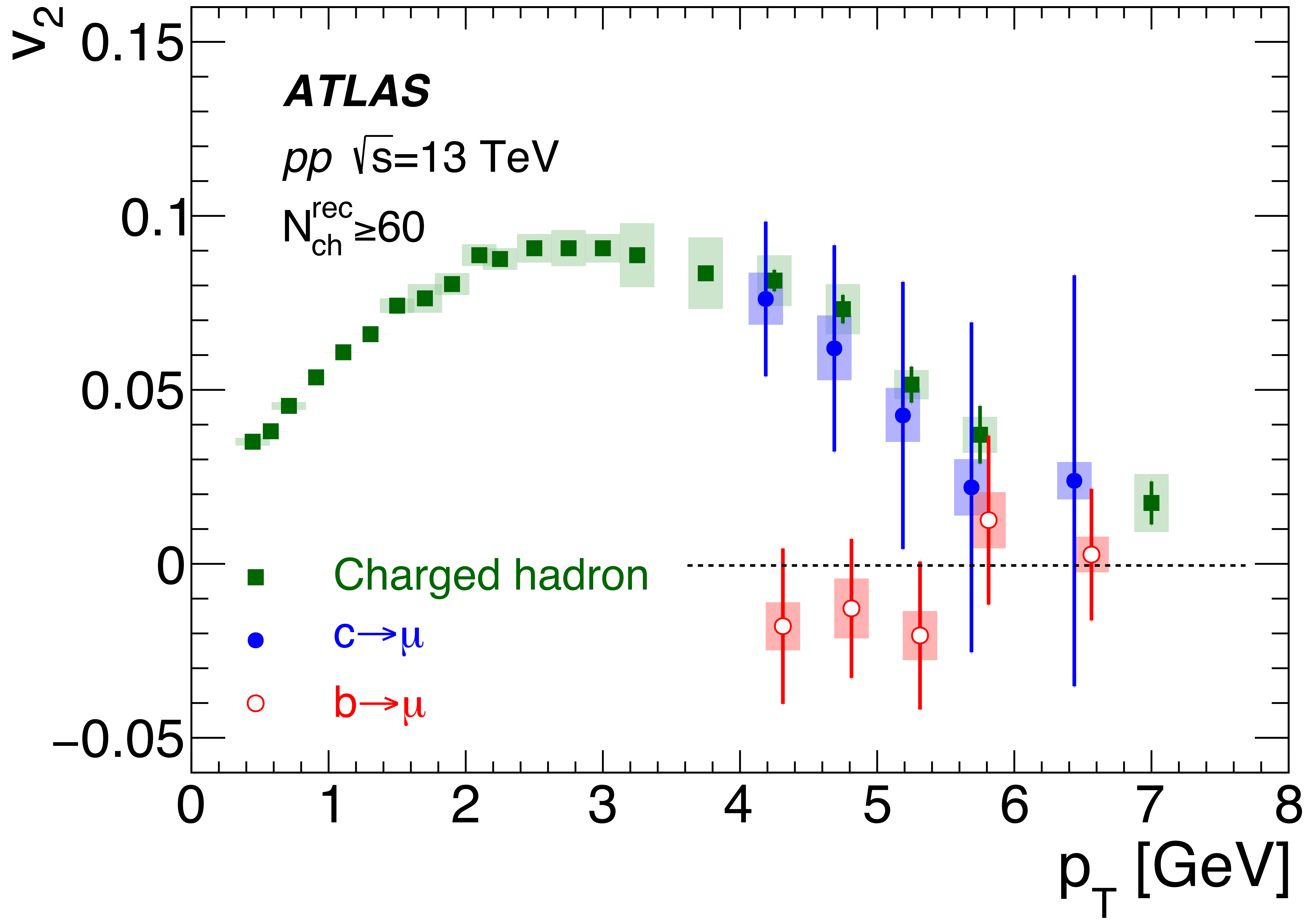
on the other hand, $v_2 \sim 0$ for ***b*-hadrons**



Charm and bottom v_2 in *pp* collisions

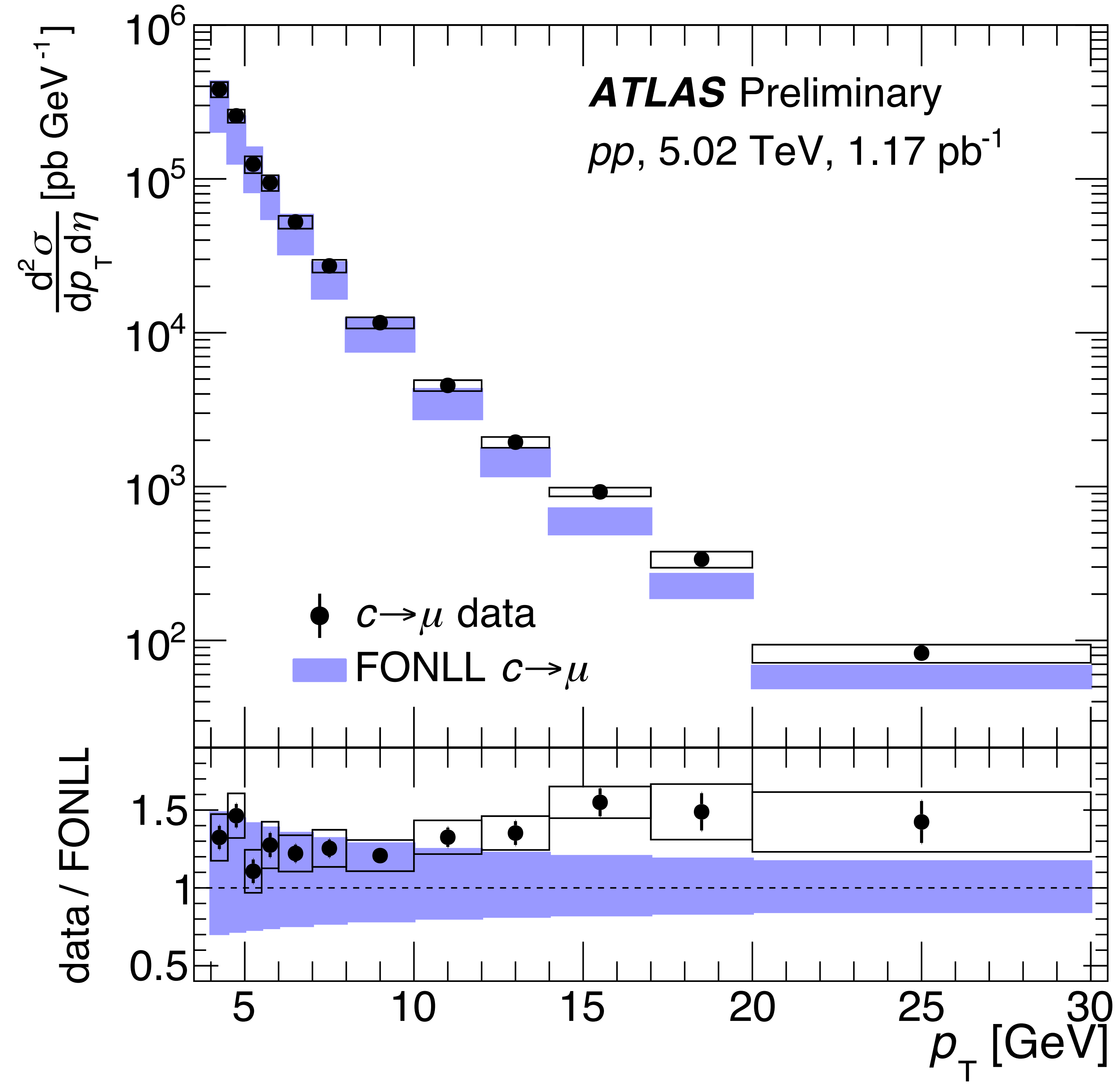
p_T-dependence of **charm v_2** matches **light hadrons** (but remember decay kinematics!)

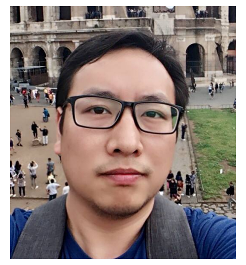
Possible to have **bottom v_2** at lower p_T, where physics mechanisms change?
(p_T^{μ} > 4 GeV similar to $p_T^{\text{b-hadron}} \gtrsim$ 6 GeV)



Interpretation

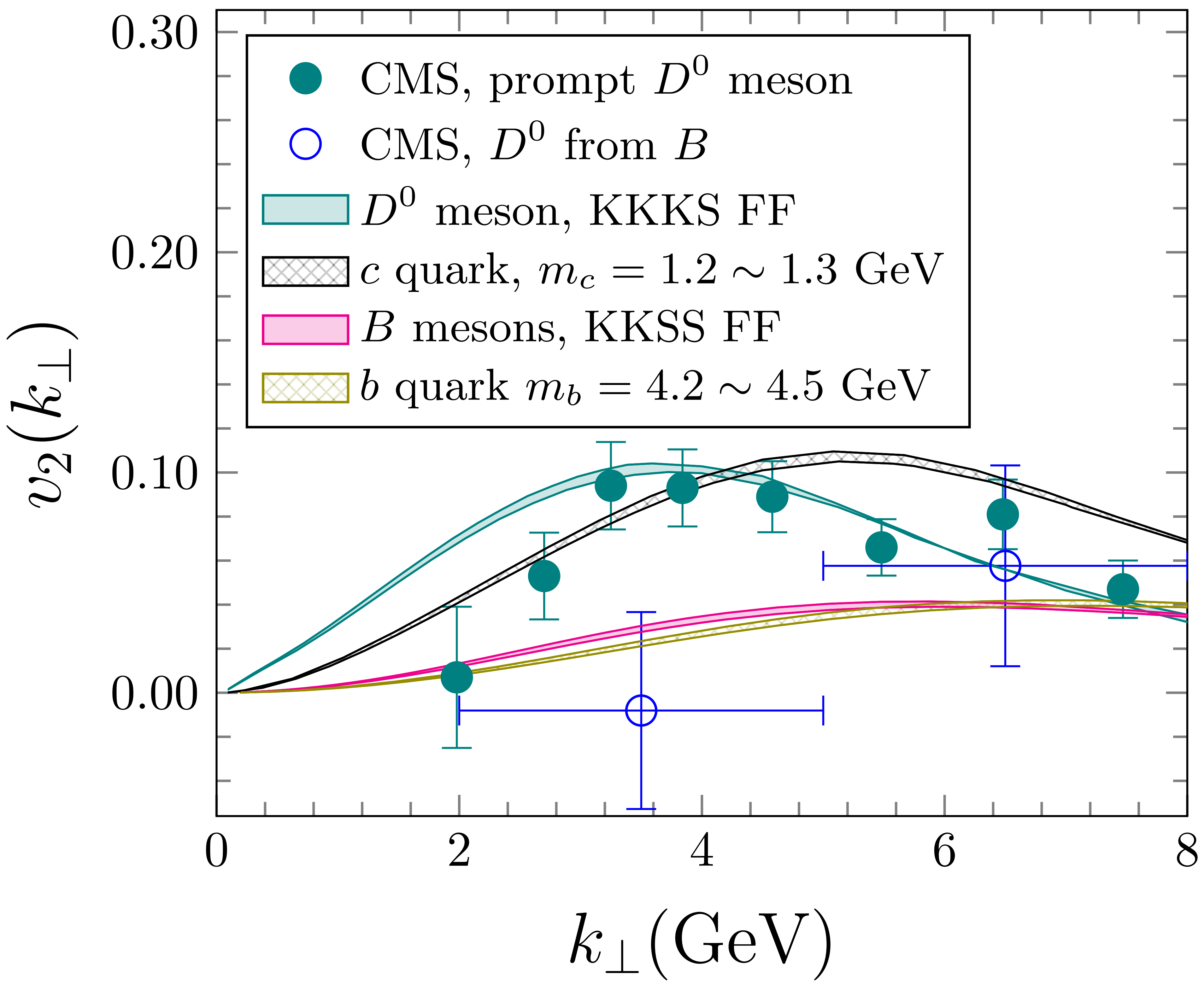
ATLAS-CONF-2021-020





The p_T spectrum for charm compares well to FONLL in this region… little room for modification of p_T distribution!

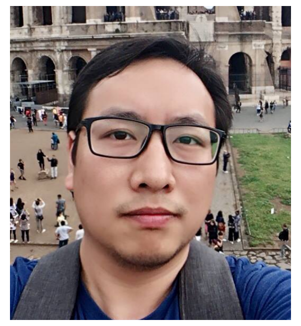
Zhang et al., PRD 102, 034010 (2020)

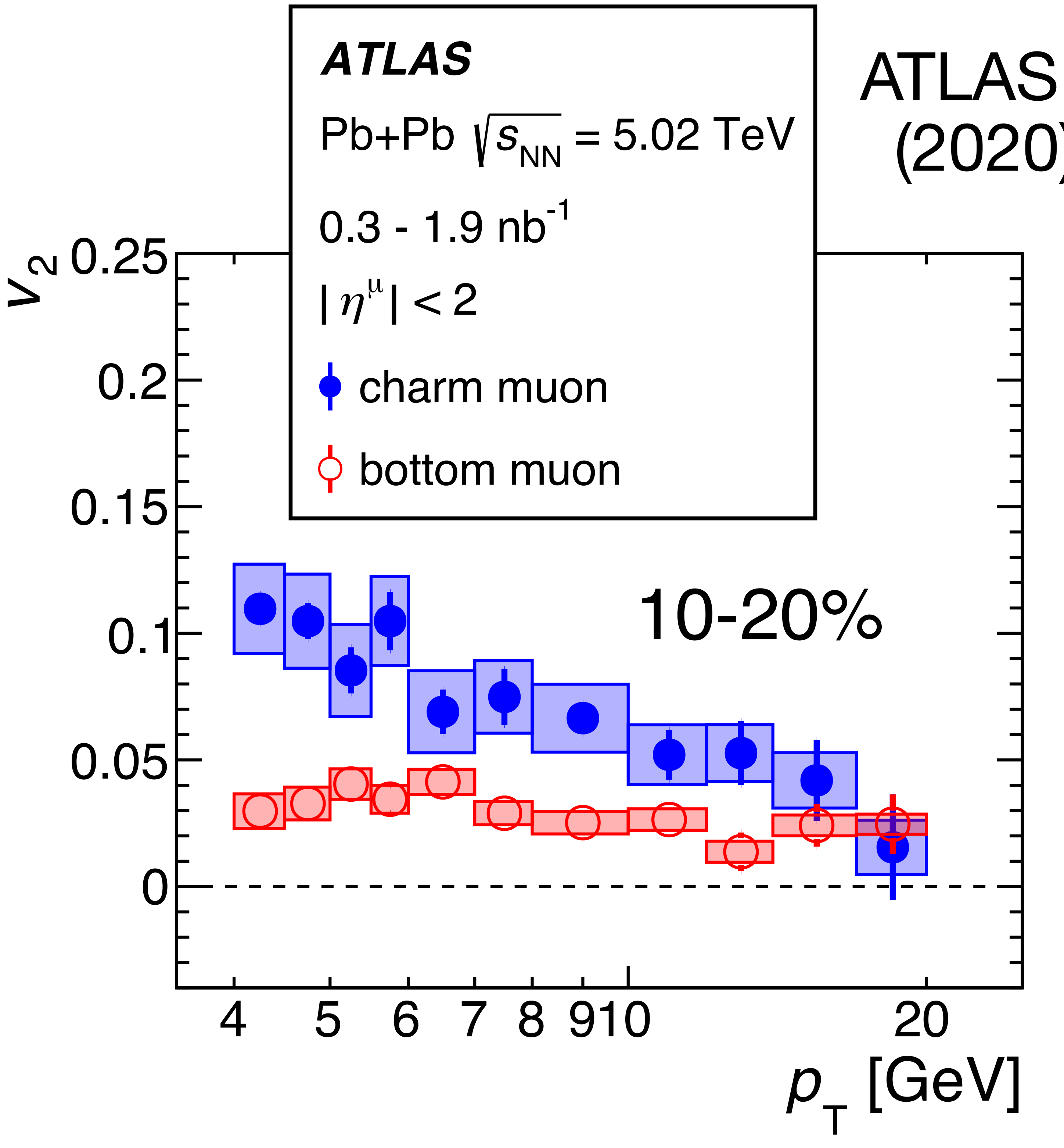


CGC can describe charm flow in p+A - what about in pp (no $A^{1/3}$ saturation enhancement)?

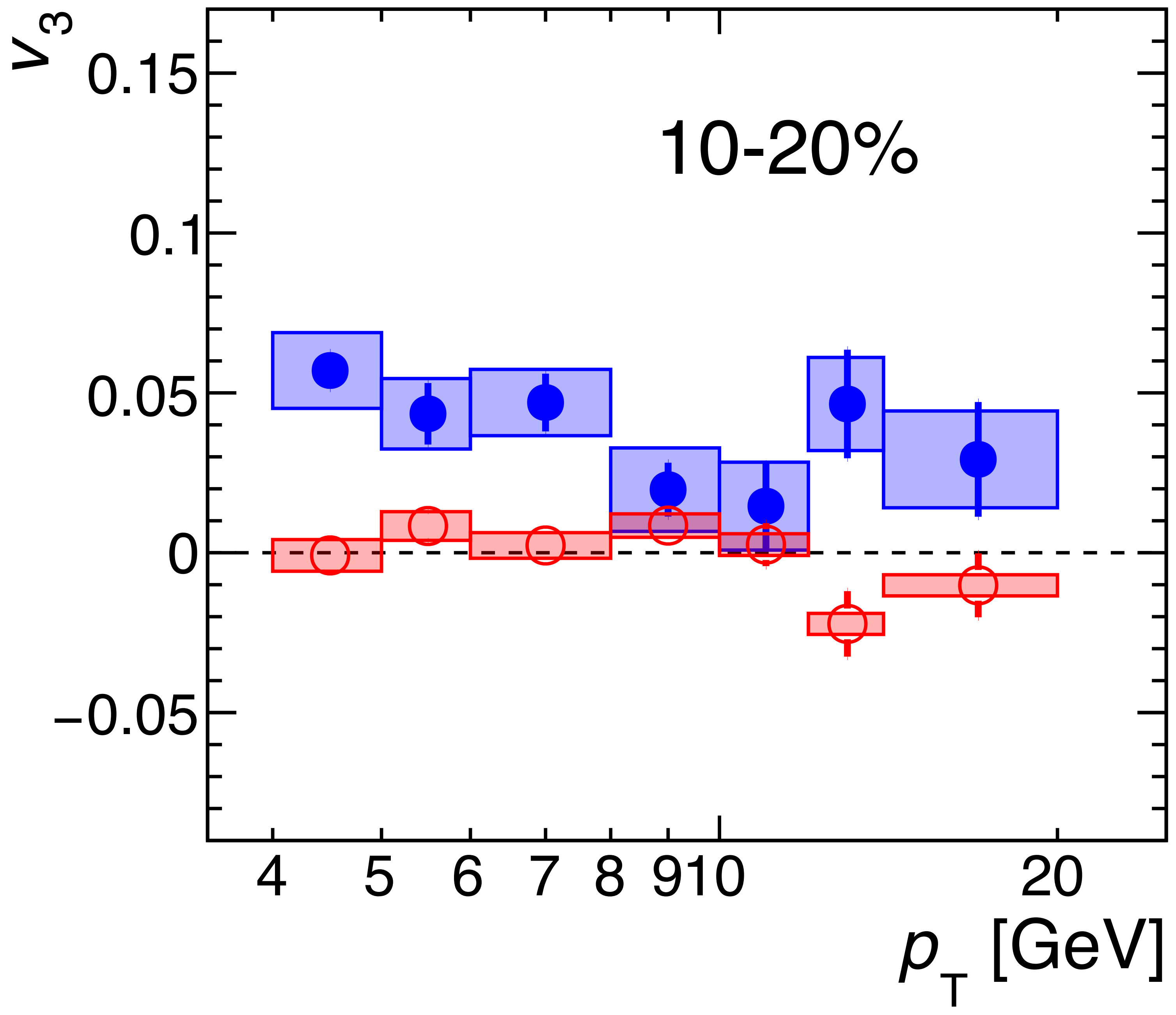
Importance of *b*-quarks in Pb+Pb

ATLAS, PLB 807 (2020) 135595



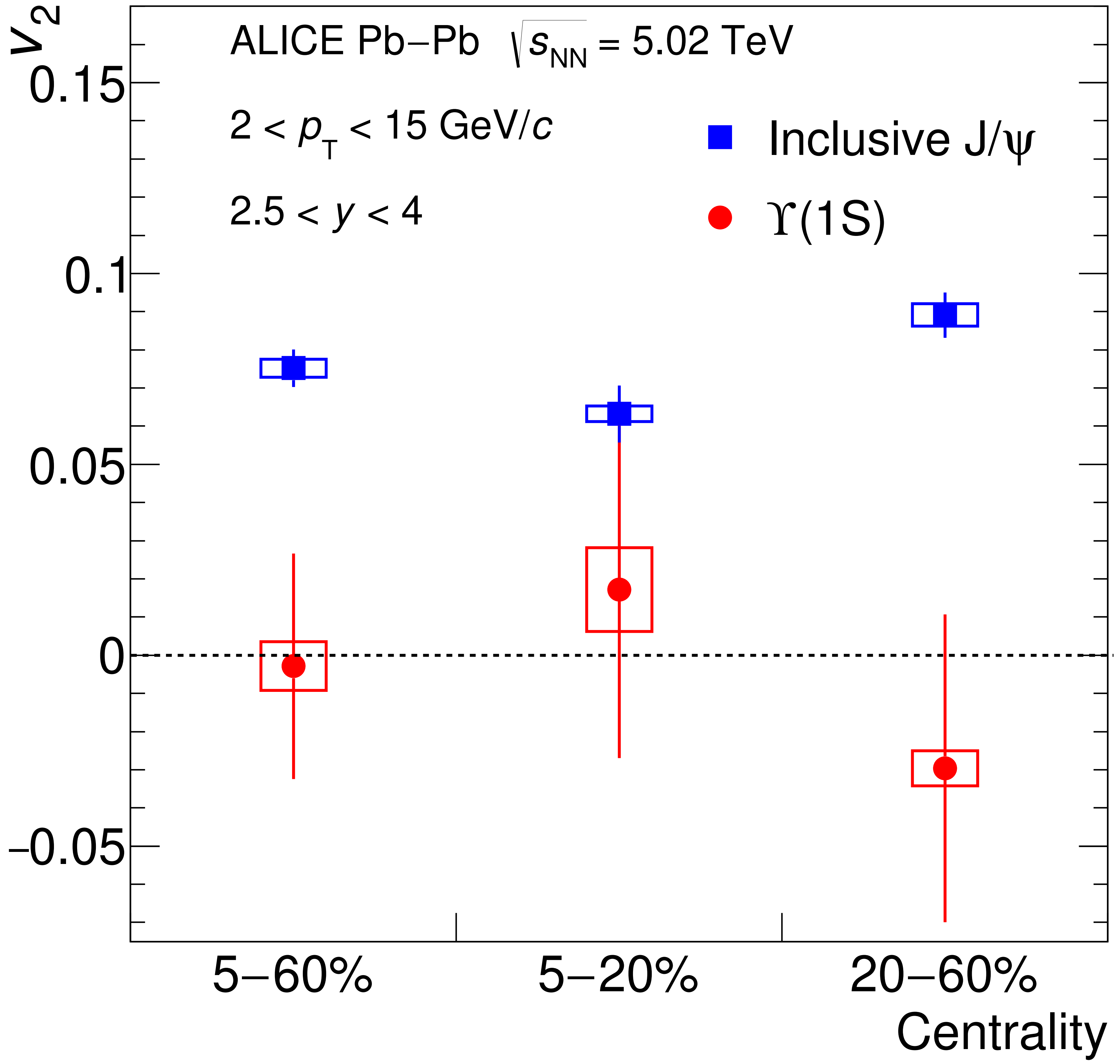


Mass effect also important in Pb+Pb: v_2 for muons from ***c*-hadron** vs. ***b*-hadron**



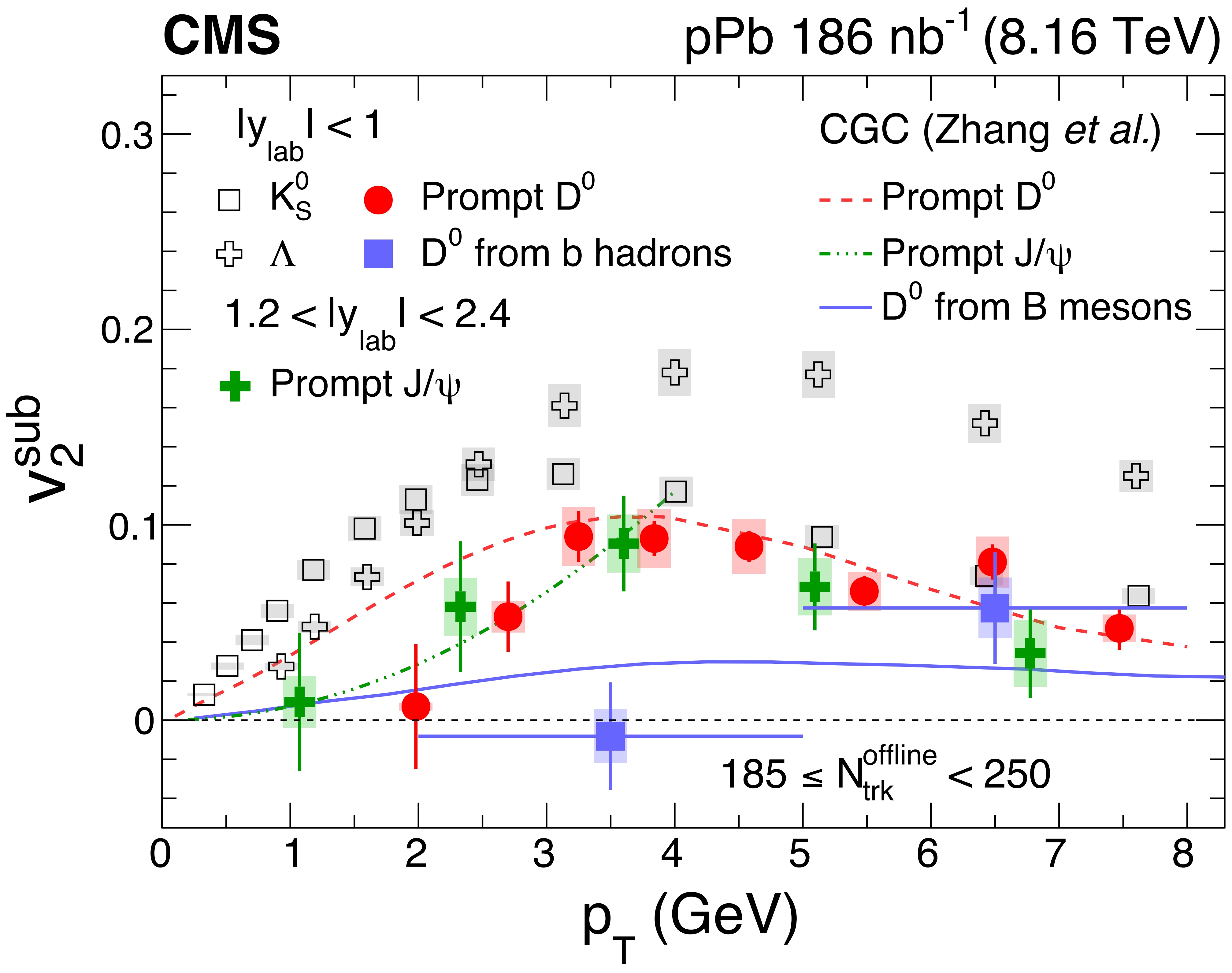
Sizable v_3 for muons from ***c*-hadrons** in Pb+Pb, but ~0 for ***b*-hadrons**!

ALICE, PRL 123 (2019) 192301



v_2 for **J/Ψ** but not for **Upsilons** in Pb+Pb…

When do *b*-quarks *start* flowing?

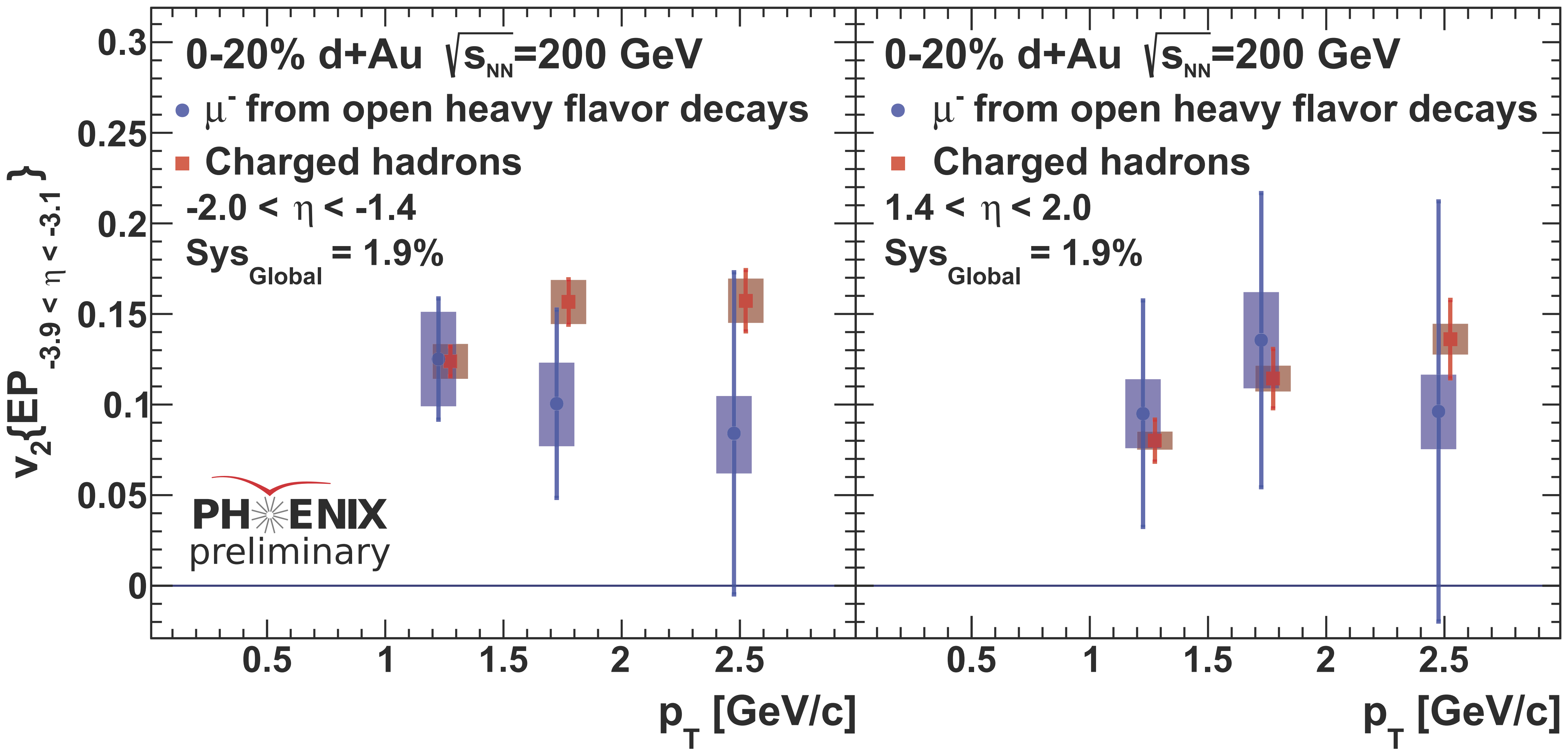


CMS, PLB 813 (2021) 136036

Mixed evidence for ***b*-quark flow in *p*+Pb**
(using D^0's from *B* mesons)

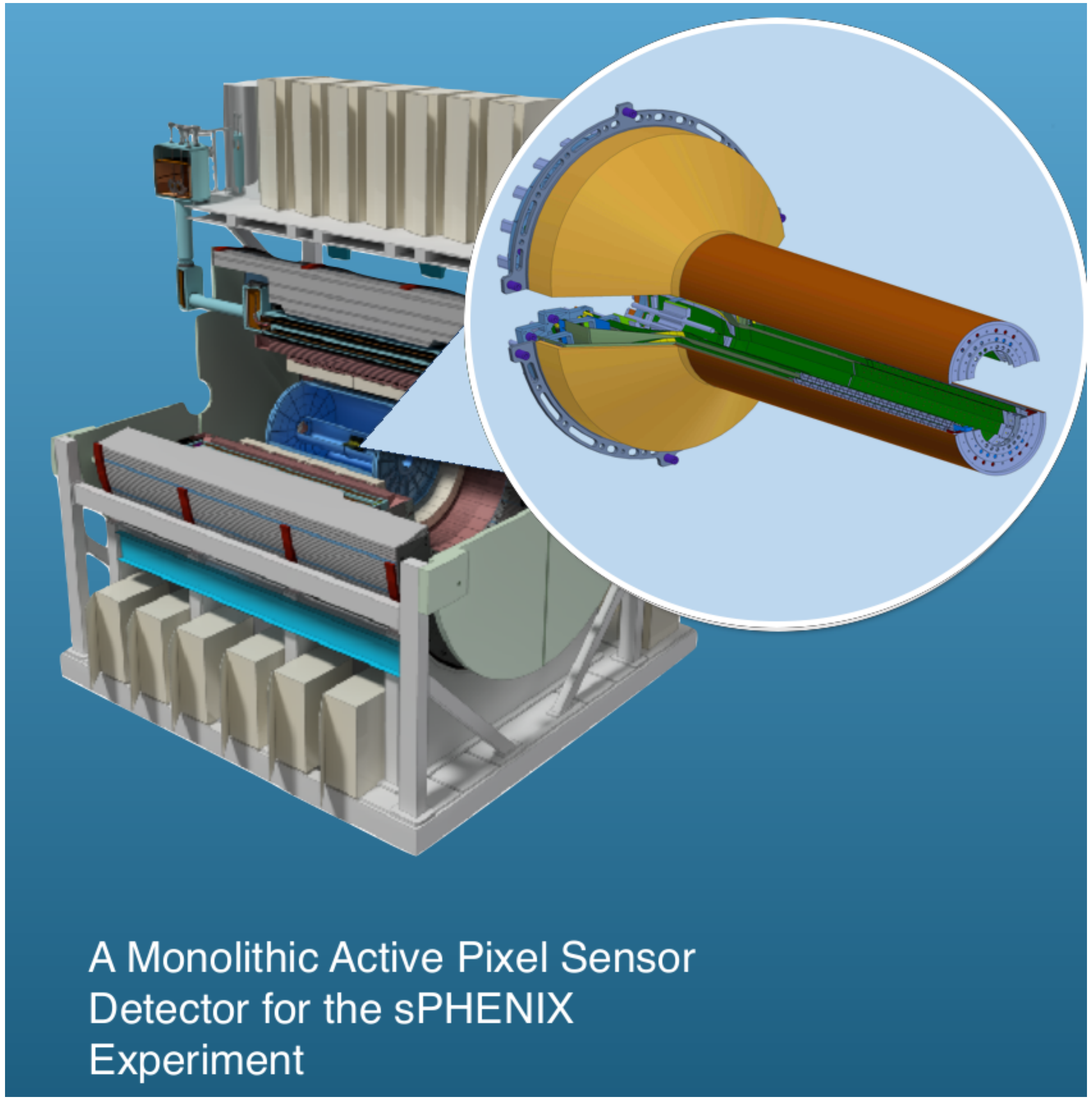
TODO: can we make a definitive measurement here?

HF flow in small systems at RHIC!

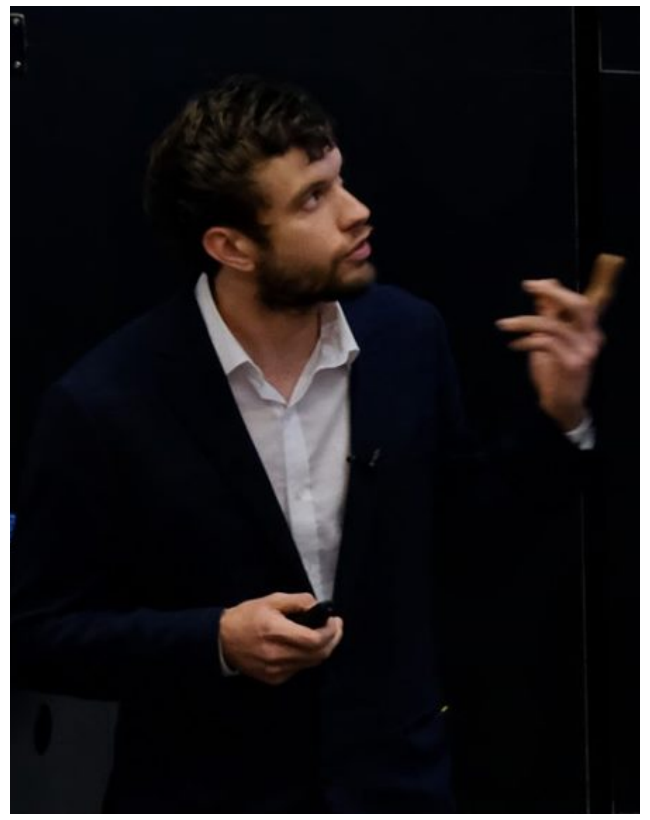


Significant hint of heavy flavor (mostly charm) flow in *d*+Au collisions at RHIC…

Excellent opportunity to do this physics with the MVTX in sPHENIX in the next few years!

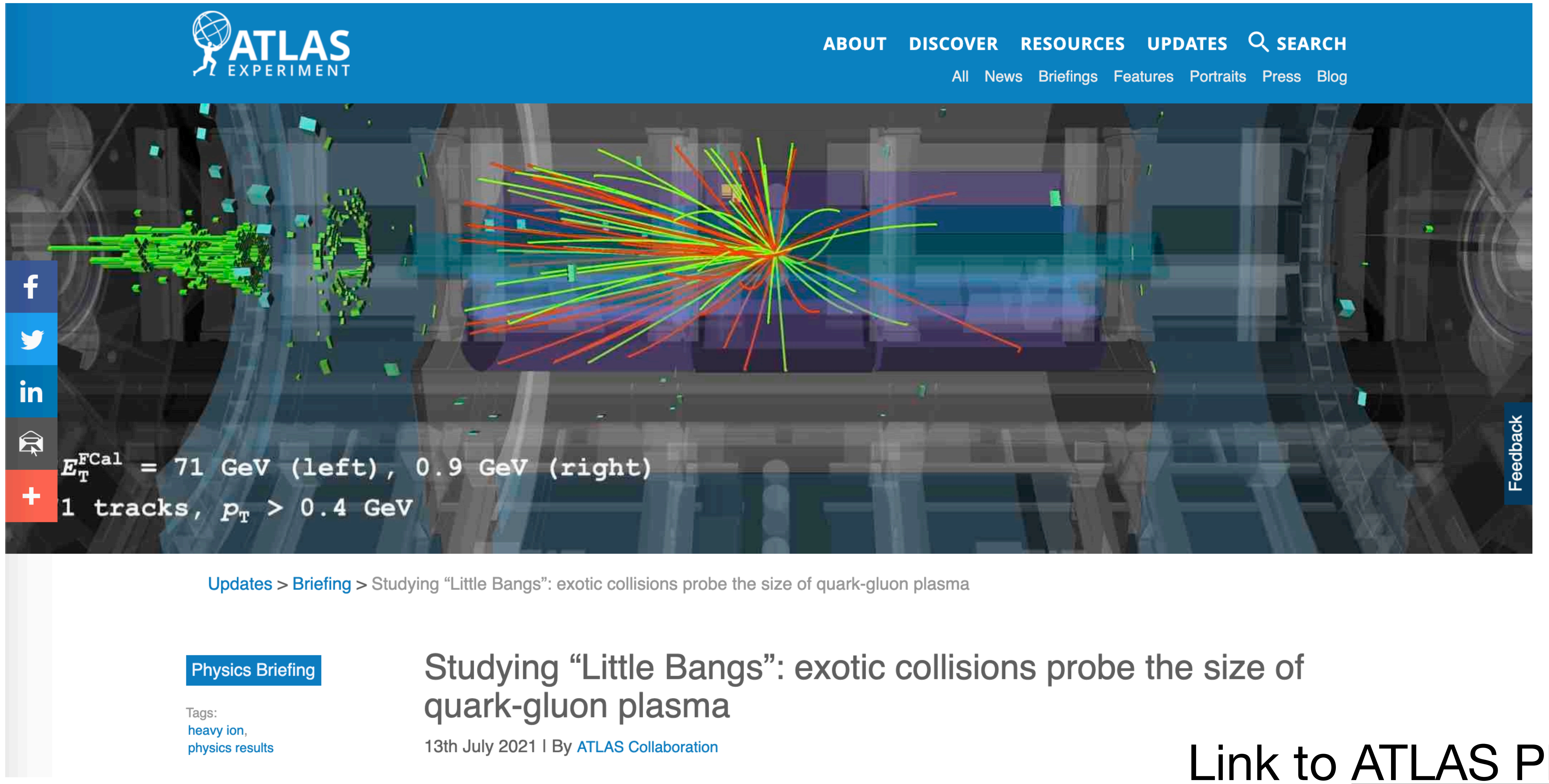


3. Searching for collective phenomena in photo-nuclear collisions



Blair Seidlitz
(Est. Ph.D. 2021!)

ATLAS, Phys. Rev. C104 (2021) 014903



Link to ATLAS Physics Briefing

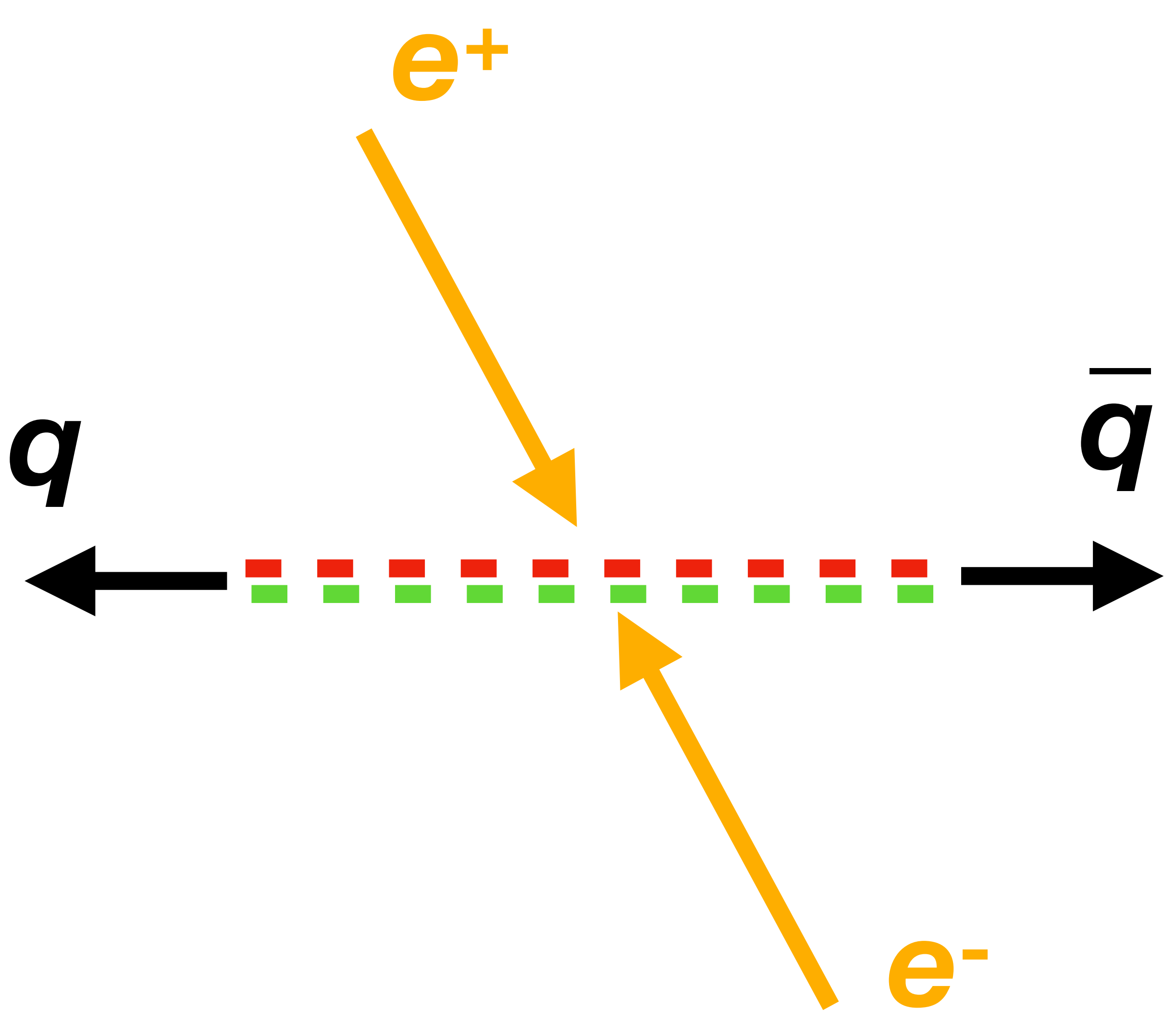
Limiting conditions for collectivity?

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

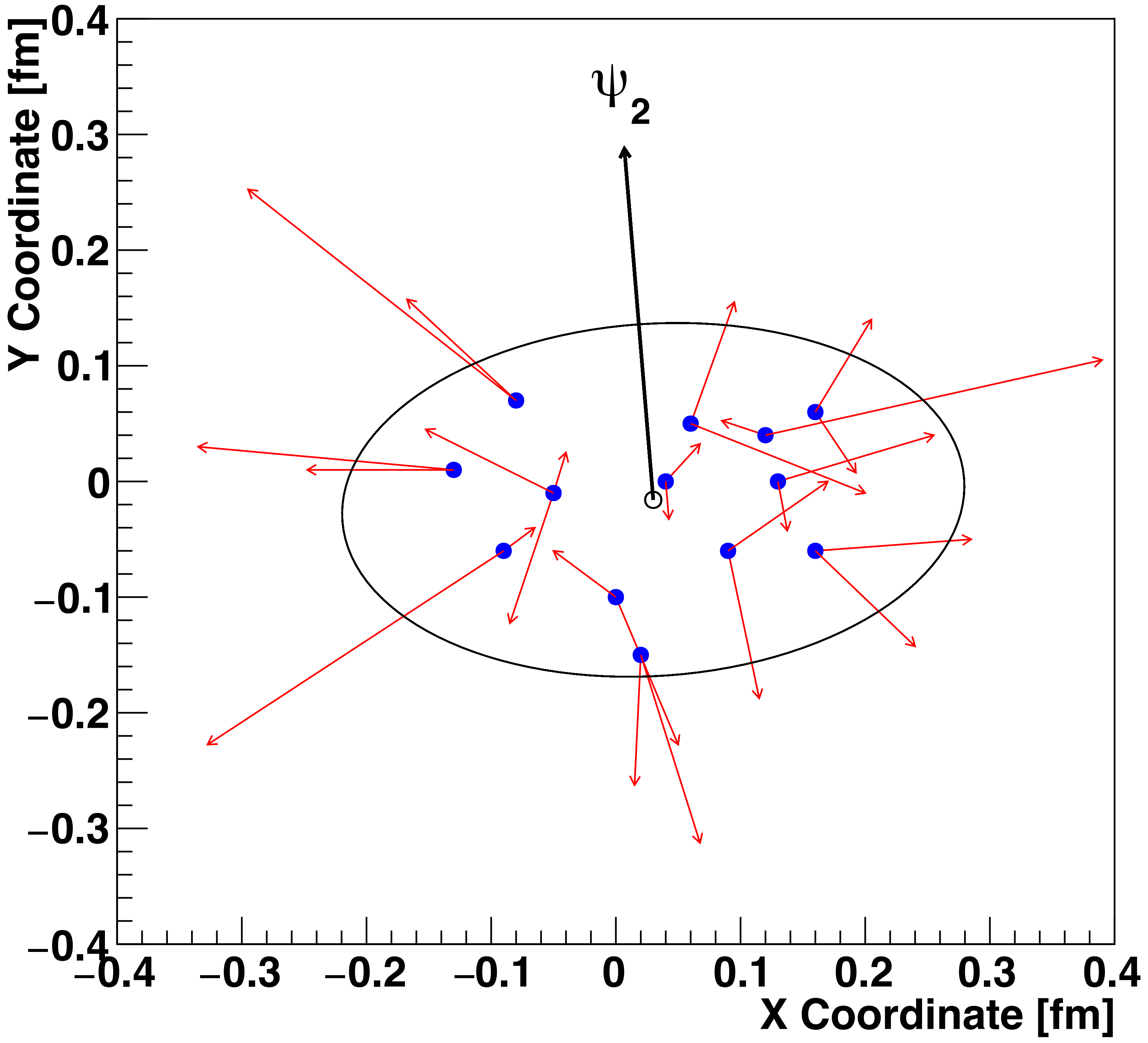
  ➡ without a “long-range” geometry - one persisting across large rapidity range - particle rescattering cannot generate a v_2 (or v_3, v_4…)

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

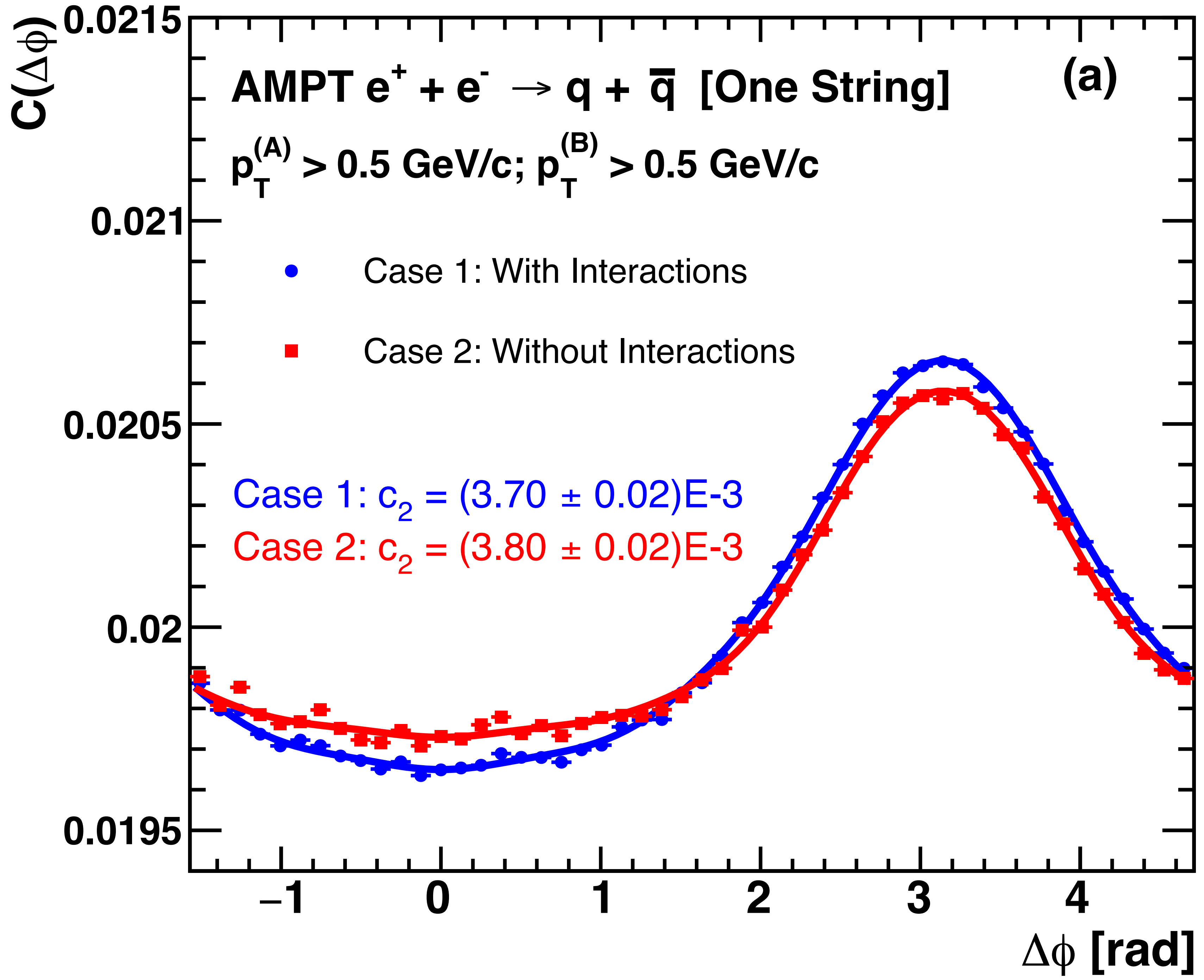
Nagle, Belmont, Hill, Orjuela Koop, Perepelitsa, Yin (CU) + Lin (ECU)
PRC 97 (2018) 024909



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



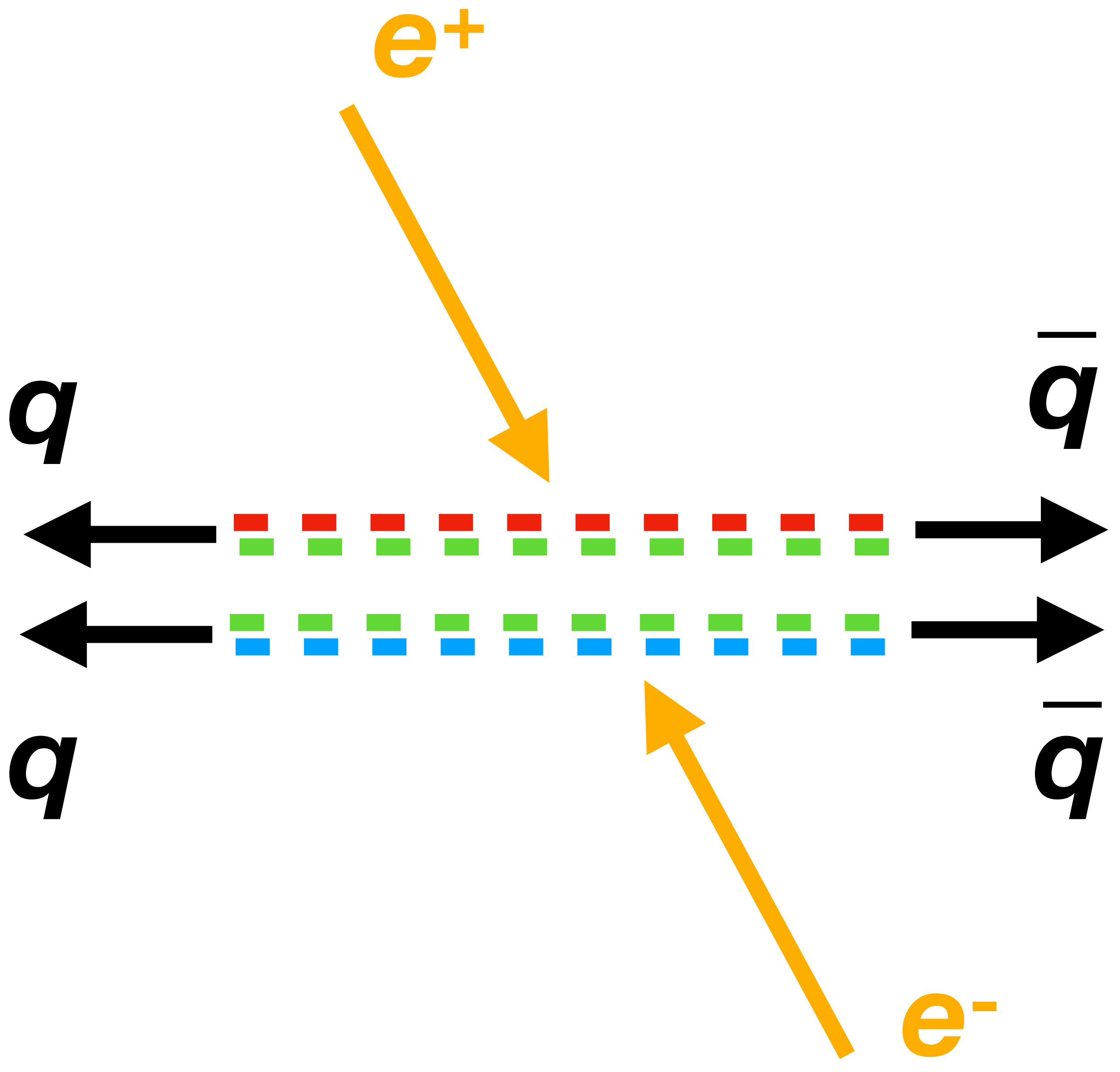
Snapshot of partons with momentum vectors in transverse plane

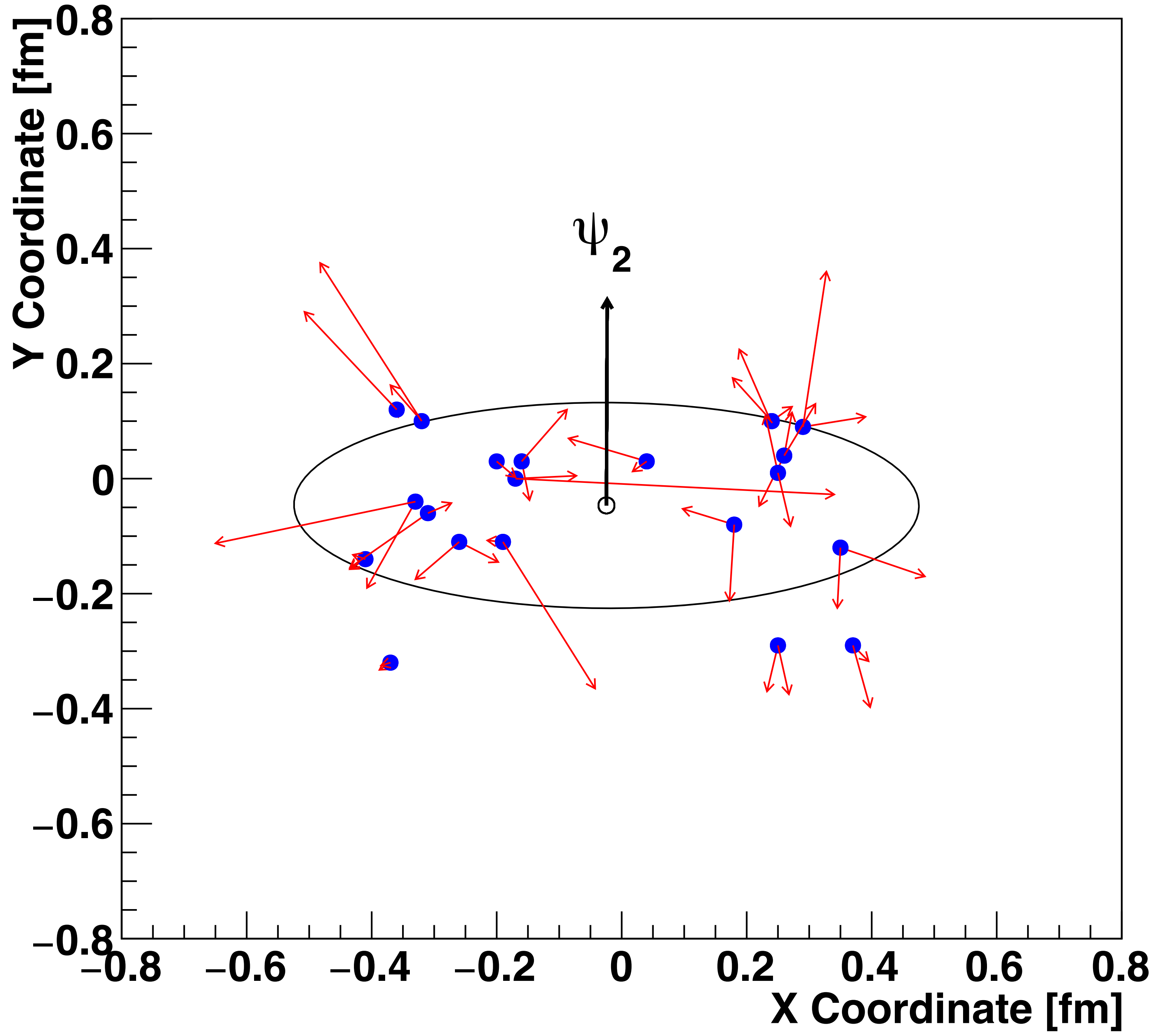


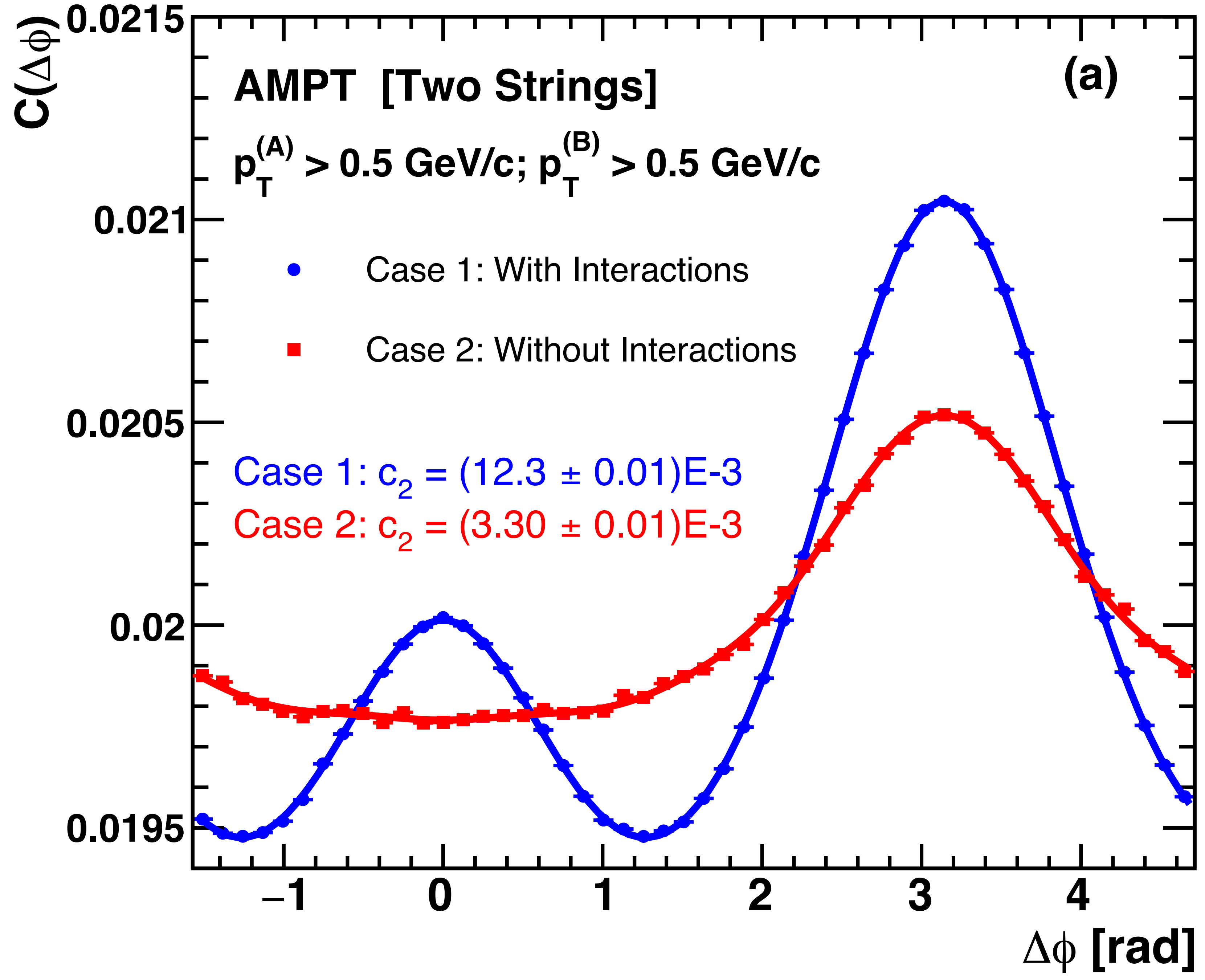
Parton rescatterings in the final state are happening - but no “preferred” final direction - no long-range ridge!

AMPT two-string example

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







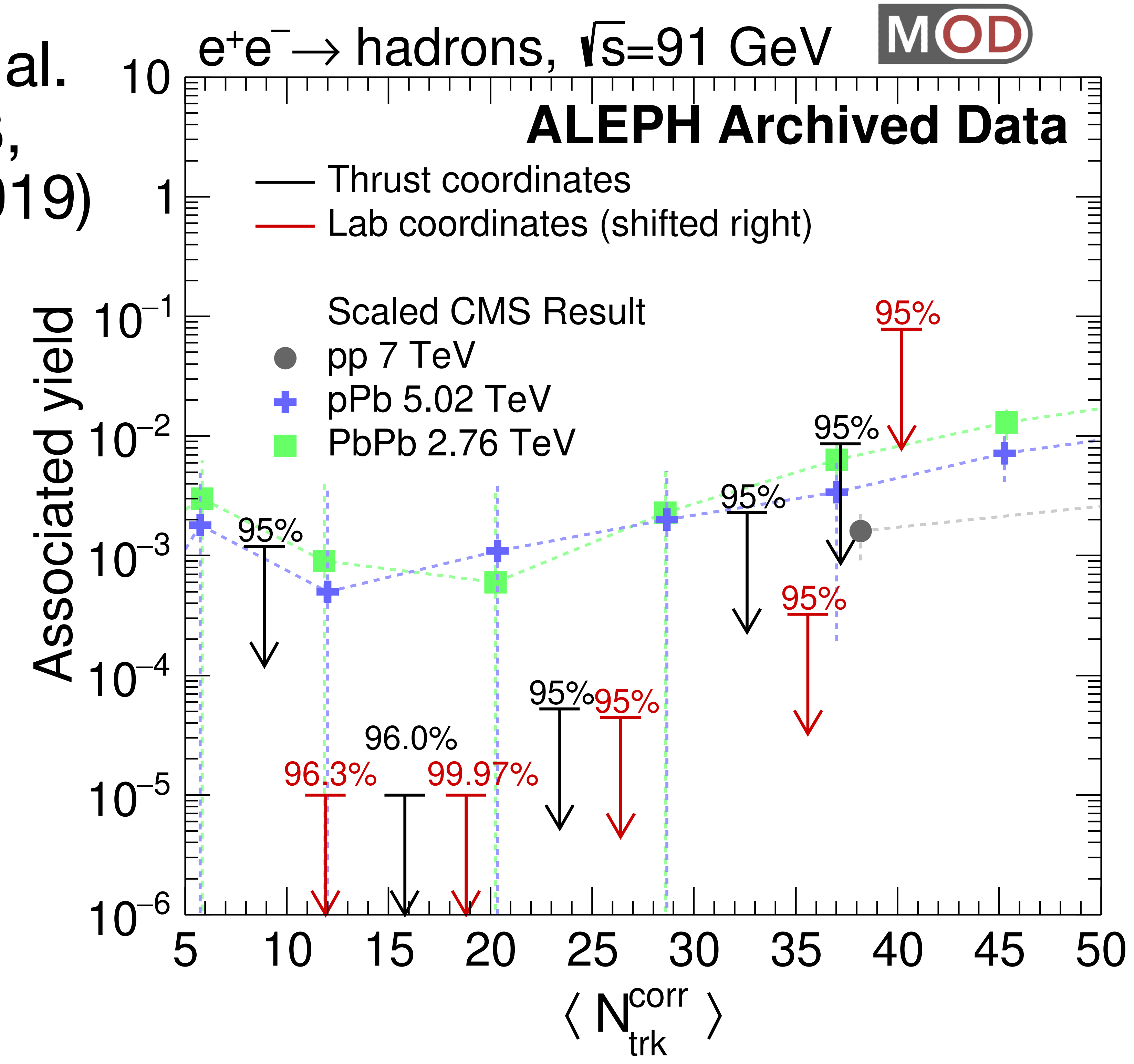
Consider ficitious case with two parallel strings

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

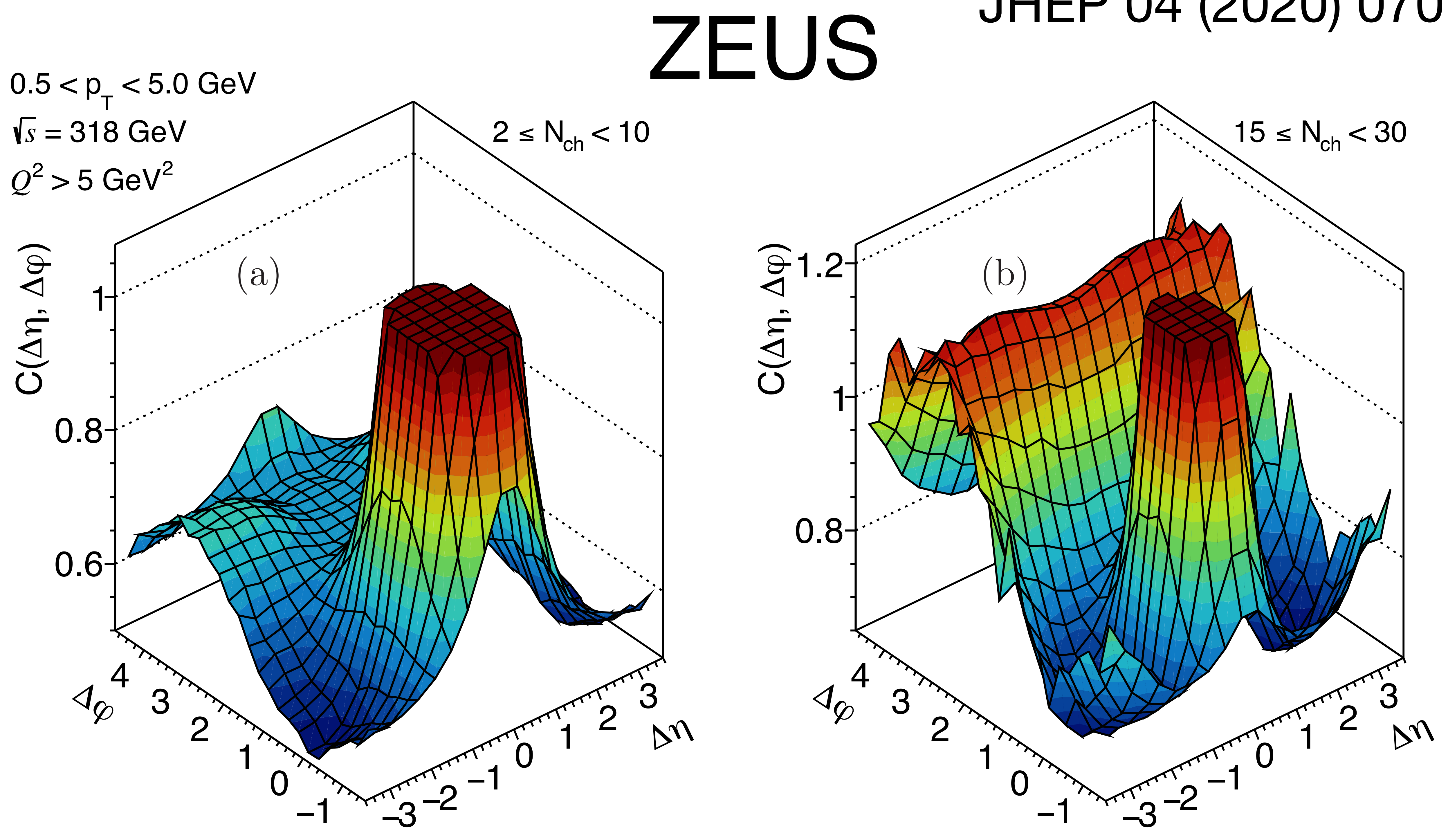
Parton rescatterings now generate a long-range azimuthal correlation

Studies in archived data

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



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



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

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

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

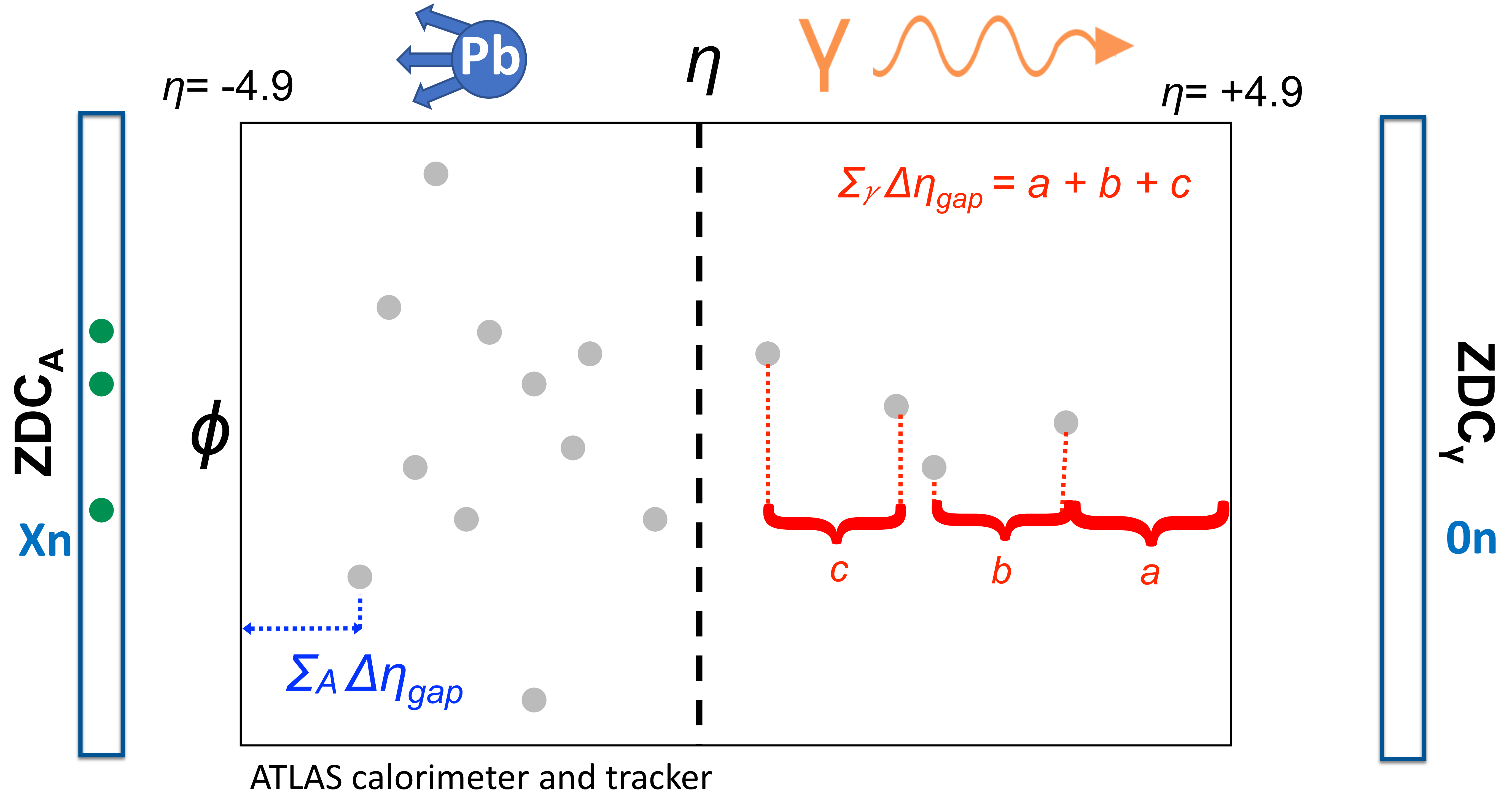
Photo-nuclear (γ+A) interactions

Quasireal photon from one nucleus interacts with the other

➡ Identifiable by characteristically asymmetric topology

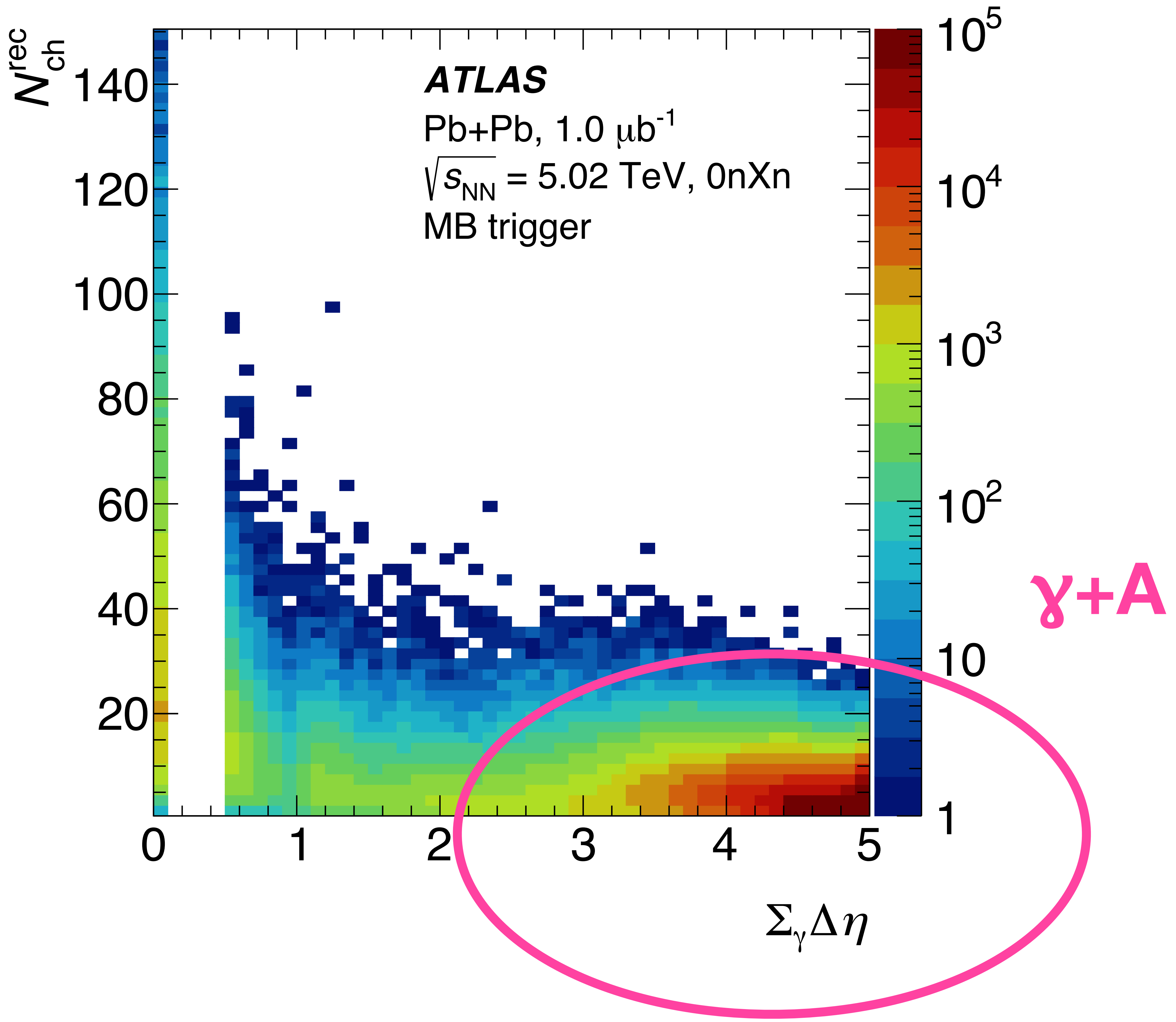
➡ “Clean” environment - photoproduction limit of DIS on nuclei (like at EIC!)

Photo-nuclear event selection



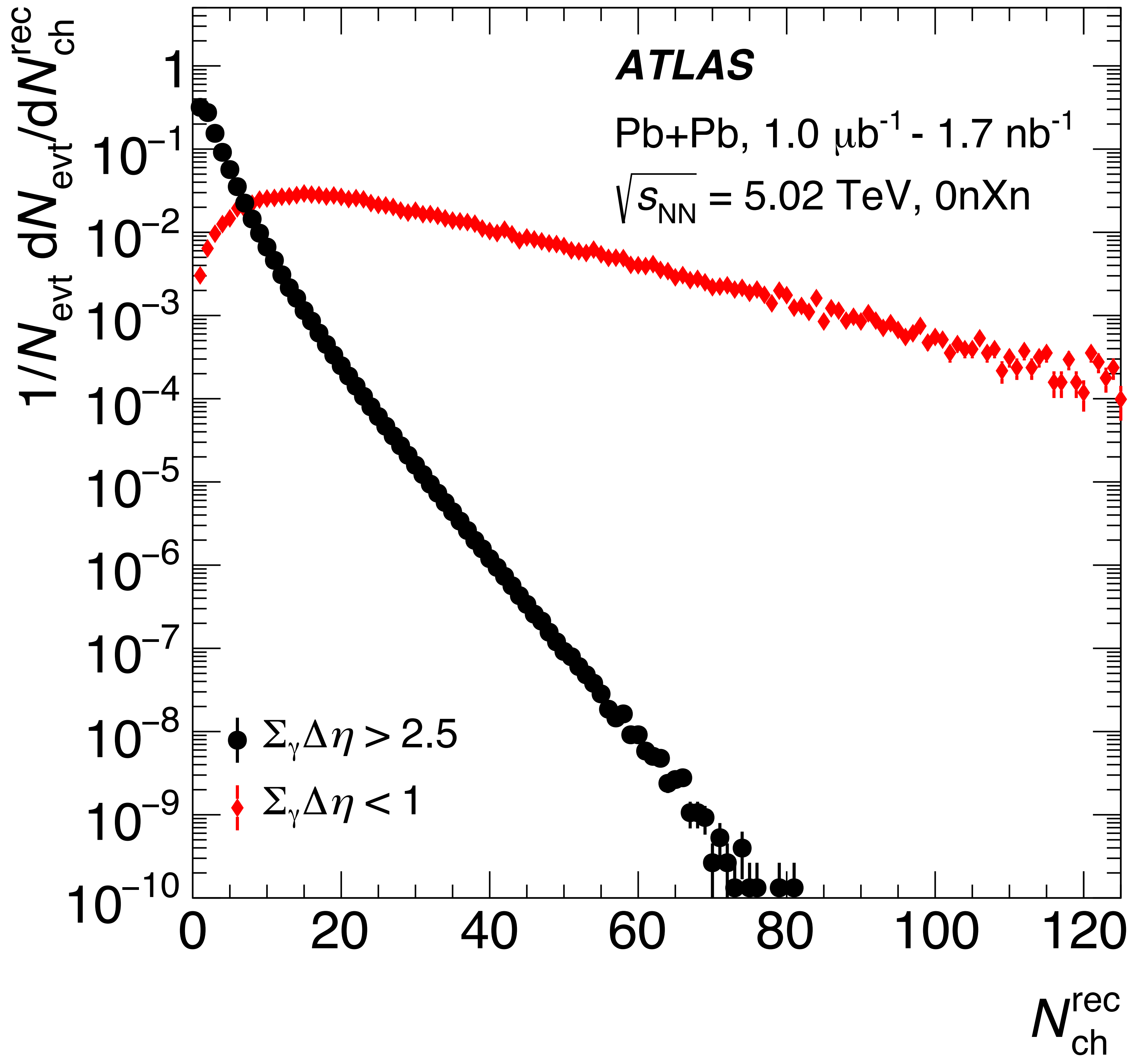
Event Selection: $\Sigma_A \Delta\eta_{gap} < 3$ $\Sigma_\gamma \Delta\eta_{gap} > 2.5$

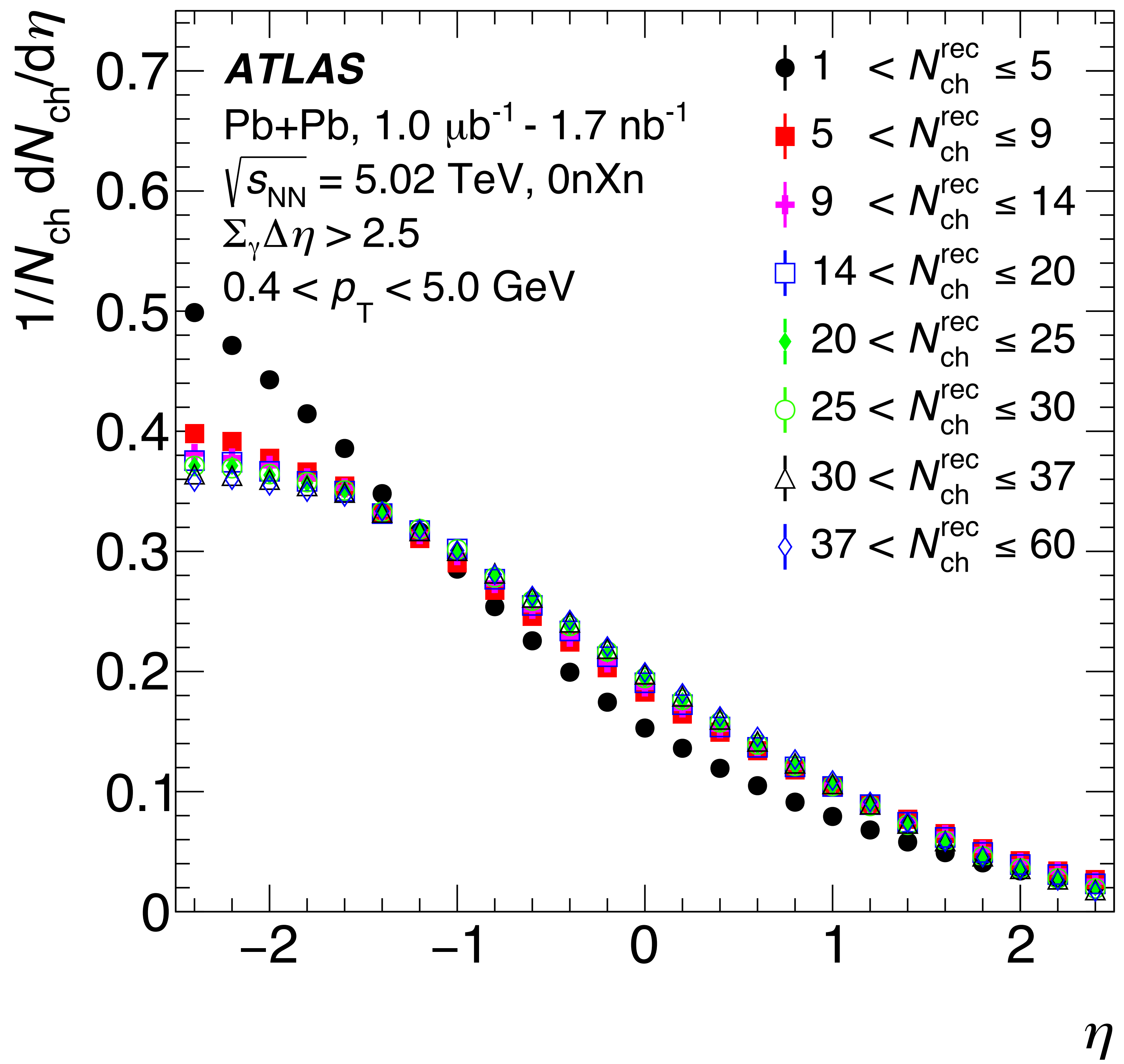
Identify events via large "sum of gaps" in calorimeter+tracker plus ZDC veto on one side



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

Photo-nuclear event properties

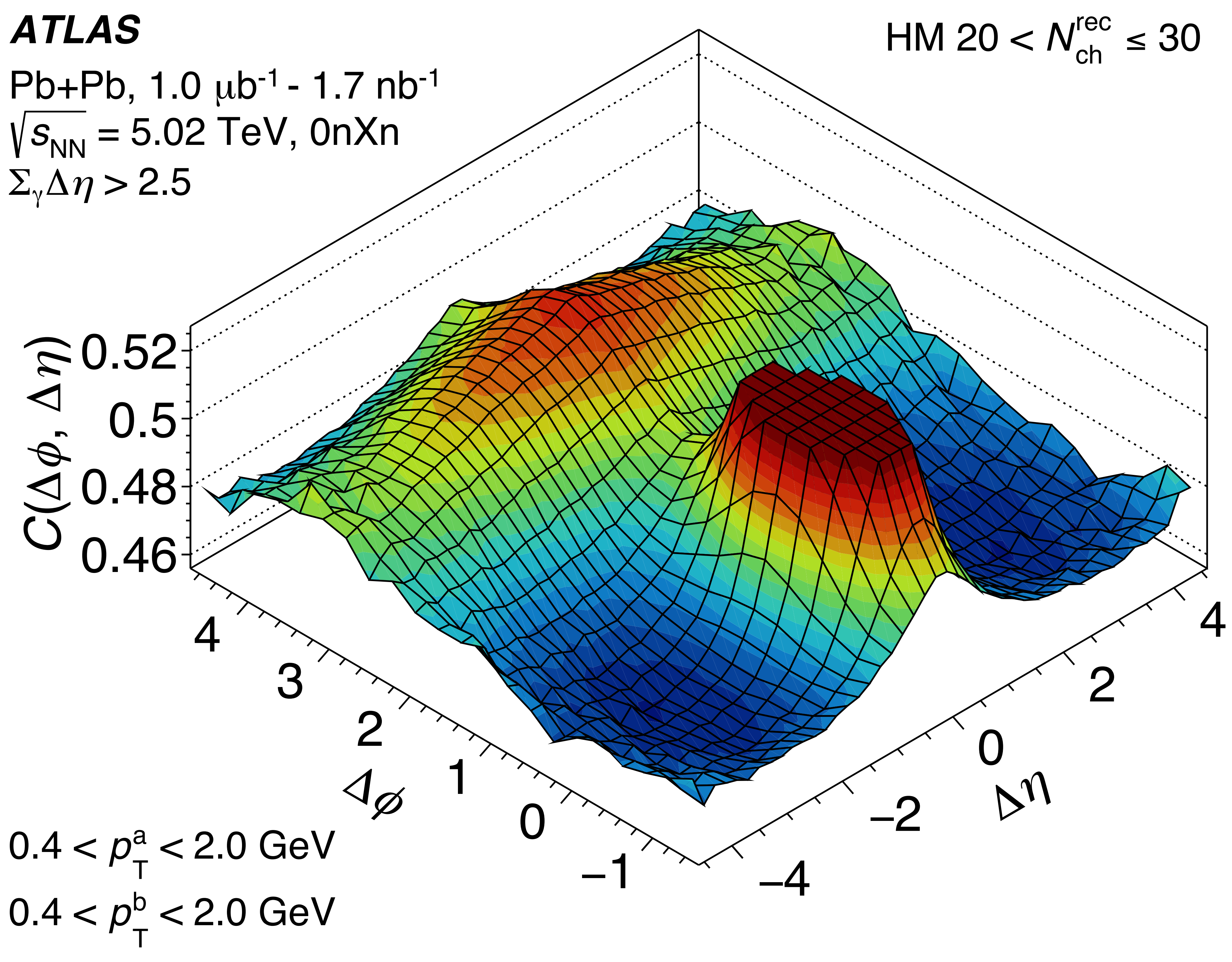


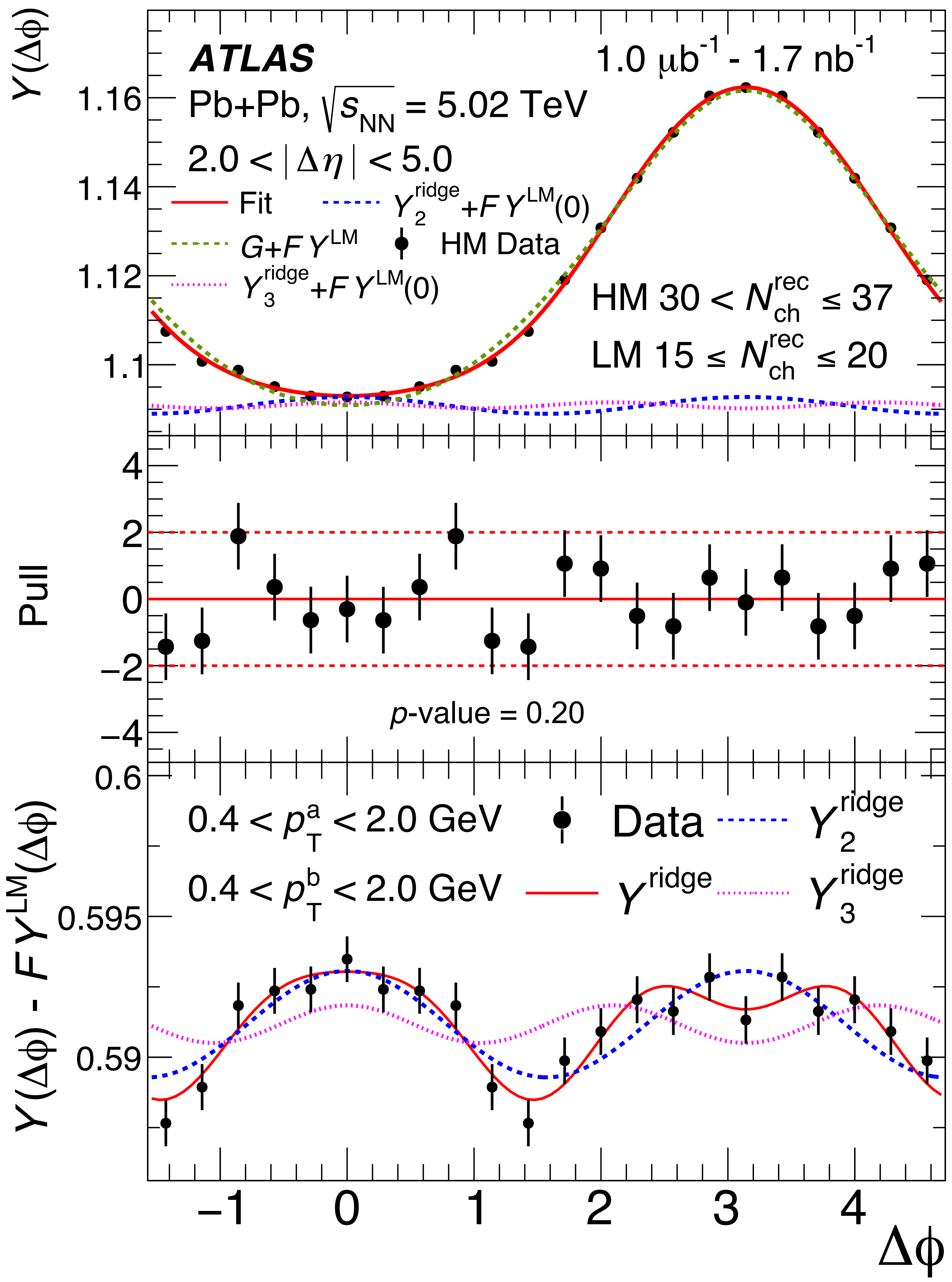


Steeply falling multiplicity distribution for **γ+A** events - specialized trigger used to collect large statistics!

Asymmetric *d*N/*d*η as in *p*+A collisions

Two-particle correlations

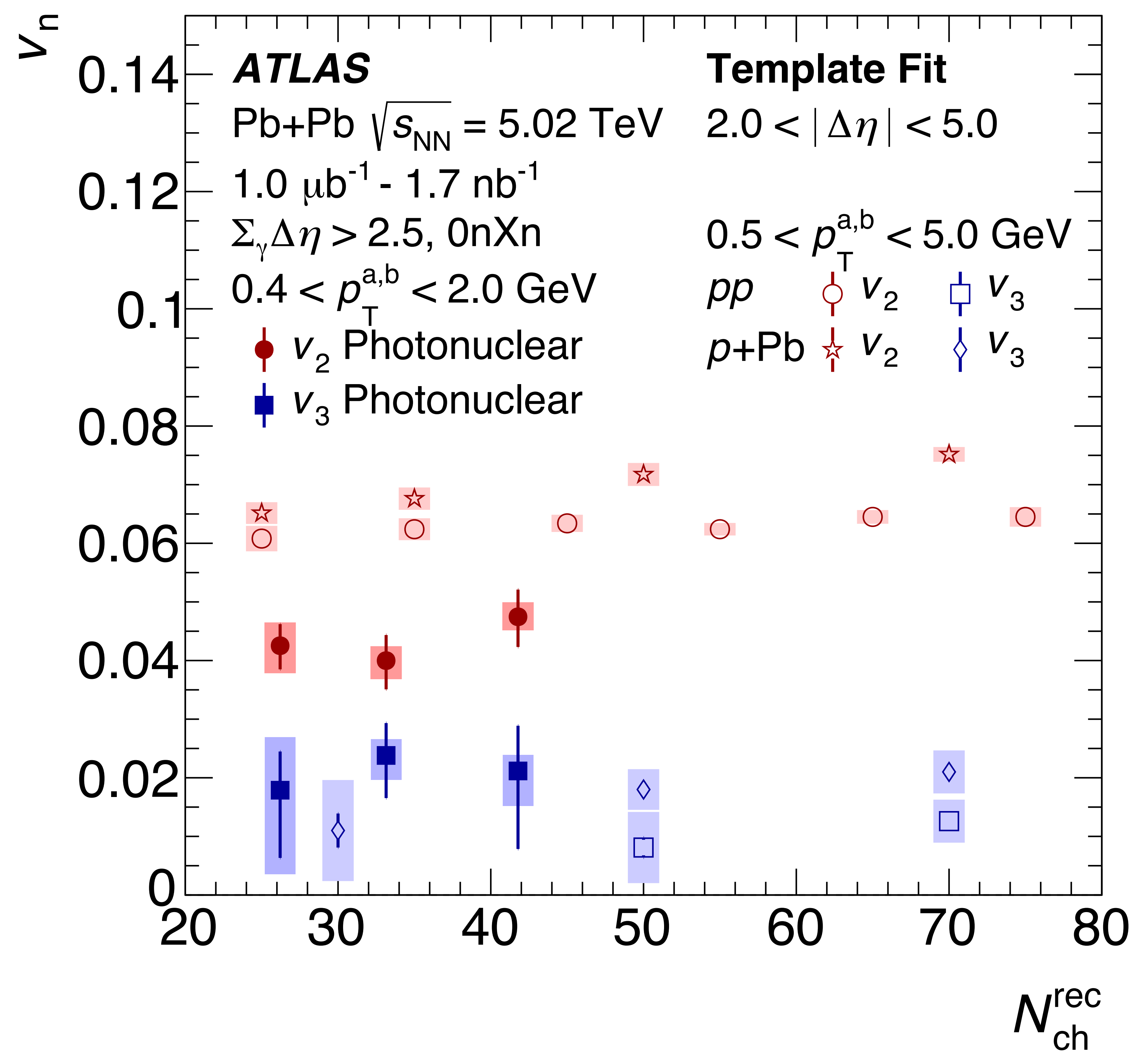




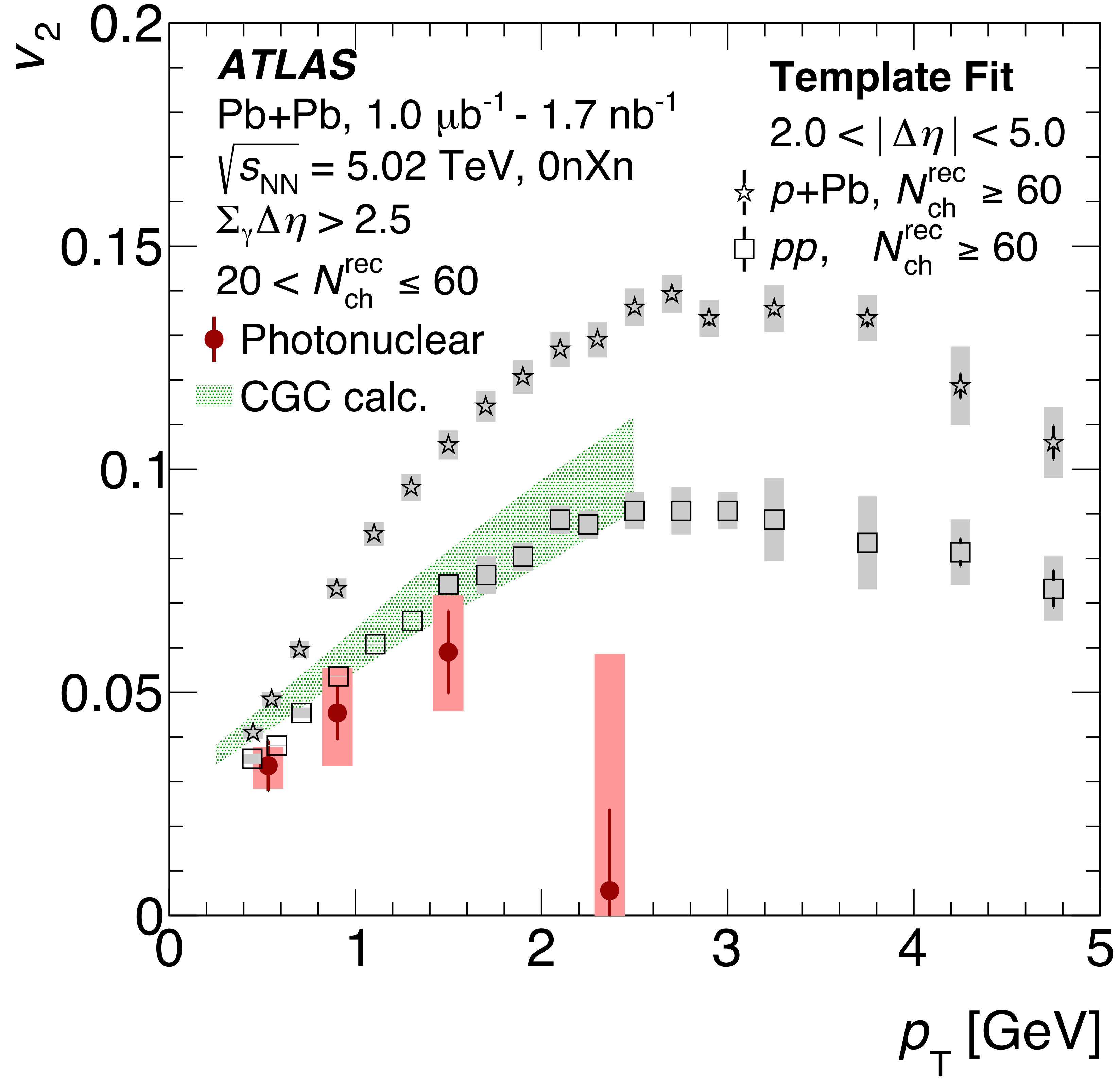
Similar structures in 2-D correlation function as in hadronic collisions!

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

v_2 in photo-nuclear events



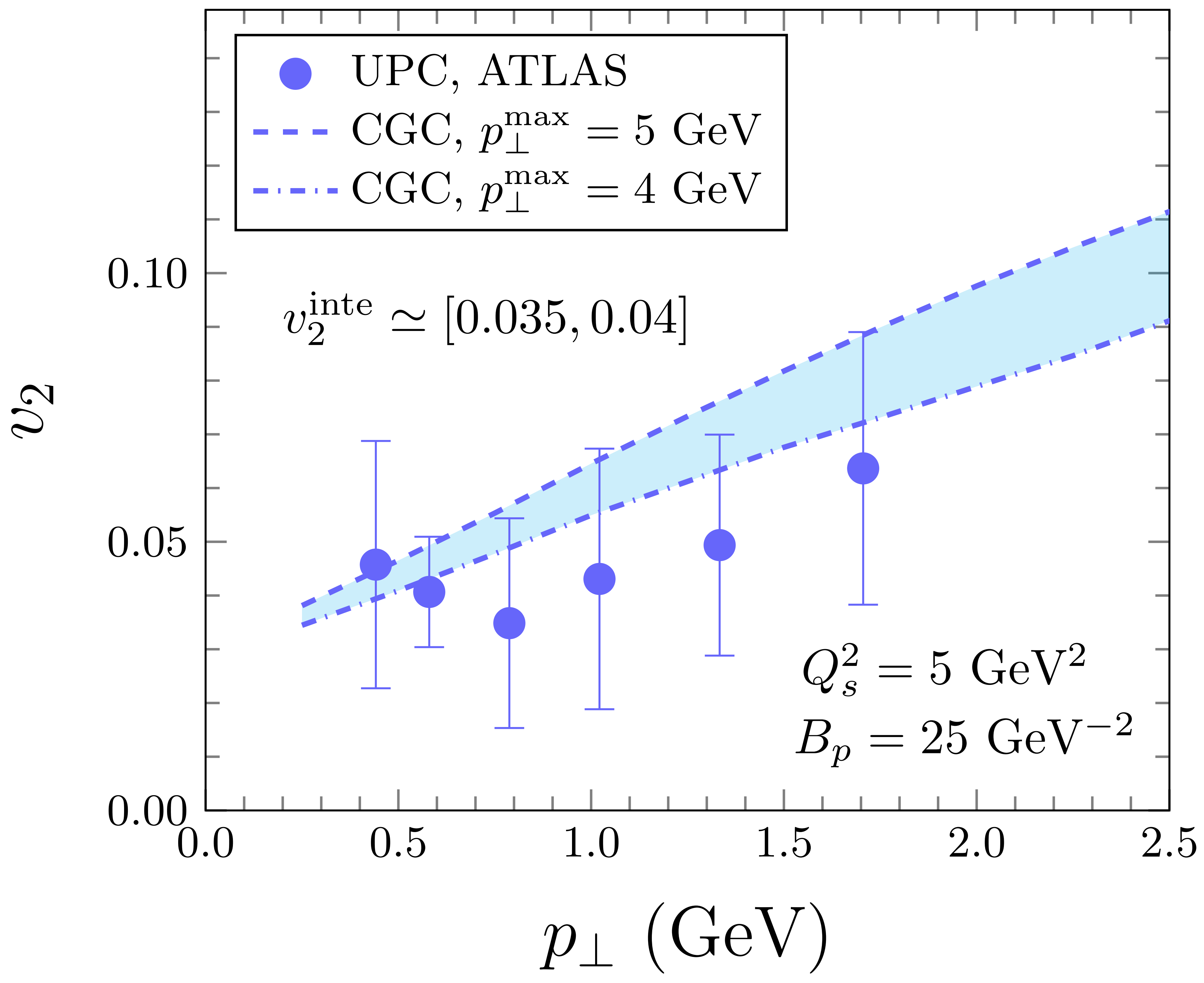
p_T-integrated v_2 ~ 4%, weaker than that for *pp* and *p*+Pb - multiplicity ~independent



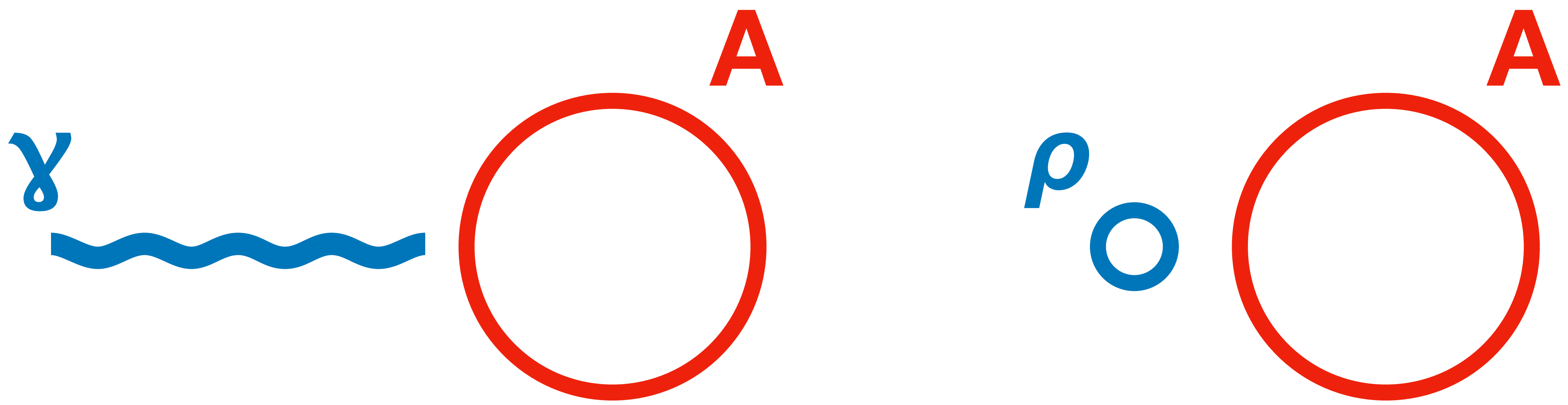
Similar p_T dependence from 0.5-2 GeV, but larger uncertainties

Initial or final state?

Shu et al., Phys. Rev. D 103, 054017 (2021)



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



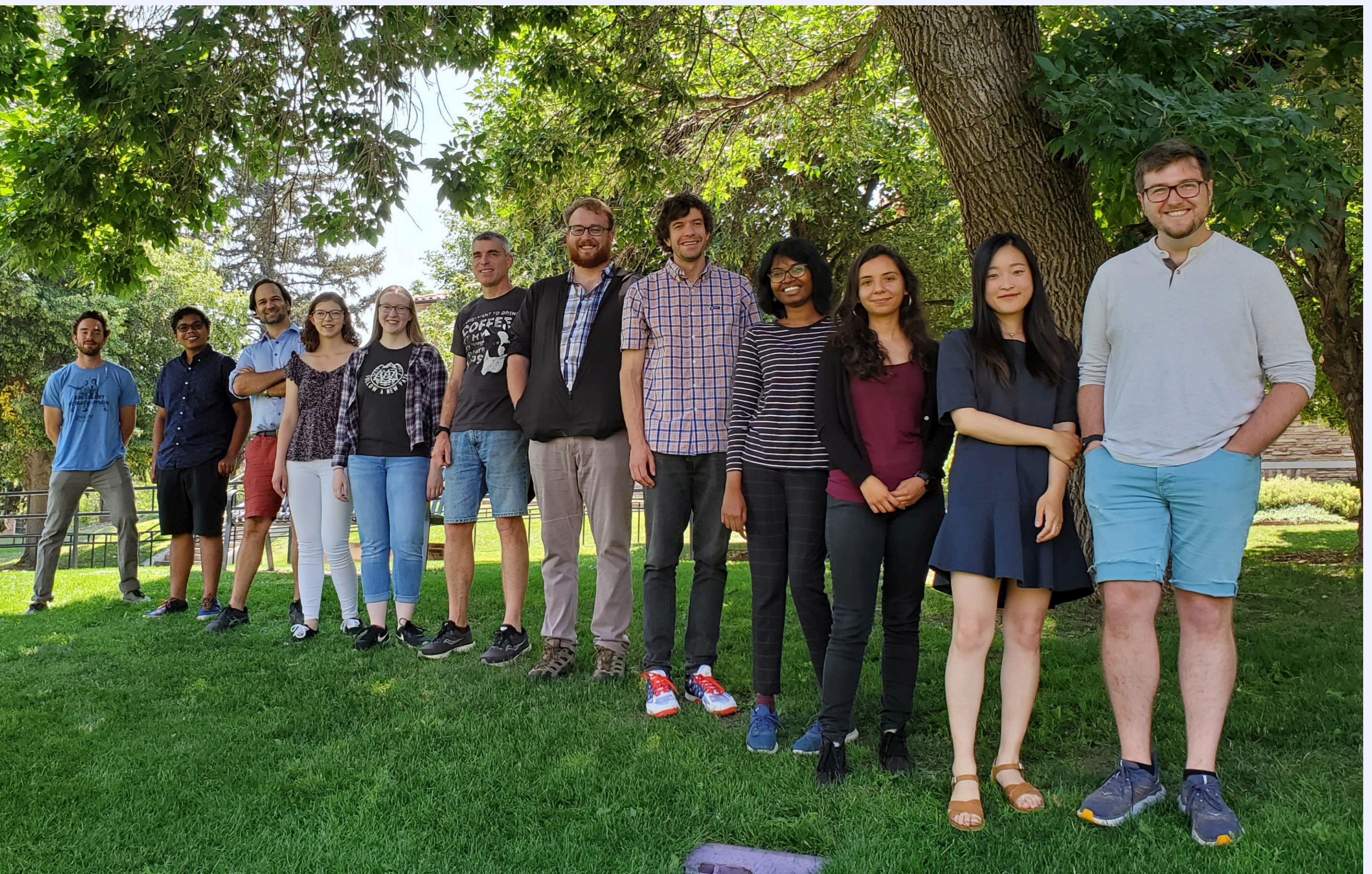
Vector Meson Dominance paradigm - these interactions proceed as, e.g. *ρ*+A collisions

For theorists — can we initialize hydro with *ρ*+A geometry (complications from E_ρ-*b* correlation, rapidity boost, etc.)?

TODO: check chemistry of high-multiplicity ɣ+A events (strangeness enhancement, baryon anomaly)

What can stop the flow?

- Azimuthal anisotropy signatures:
    - ➡ persist for p_T ~ 50 GeV 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 present 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

ATLAS, Phys. Rev. C104 (2021) 014903

Thank you!