Recent experimental results on collectivity in small-systems

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(Columbia University)

On behalf of the ATLAS and CMS Collaborations

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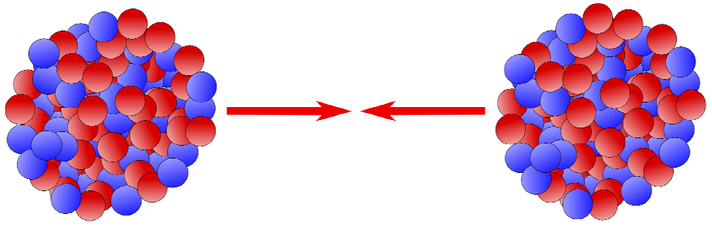
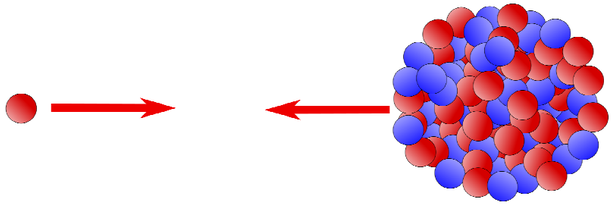
DOE-FG02-86ER-40281

QGP in small systems?



ion-ion

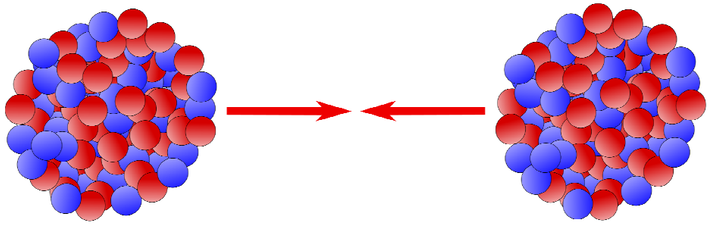
QGP ✓



proton-ion

QGP ?

QGP in small systems?



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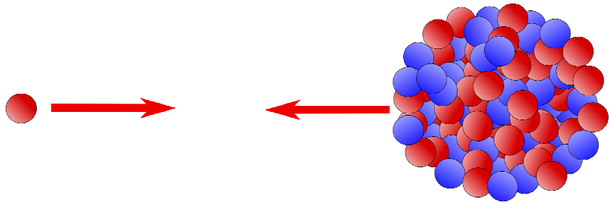

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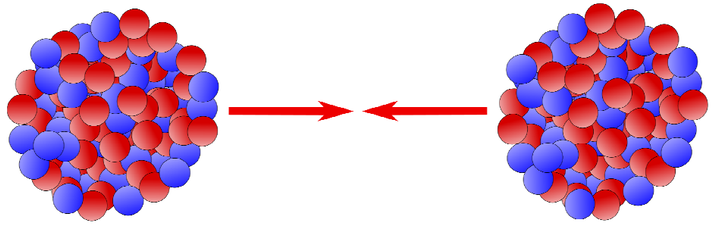

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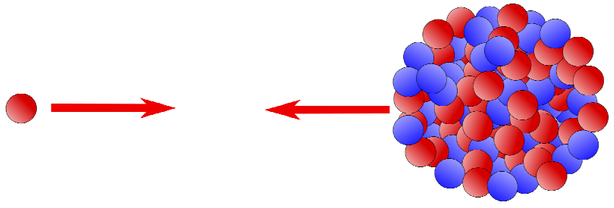

proton-ion QGP ✓

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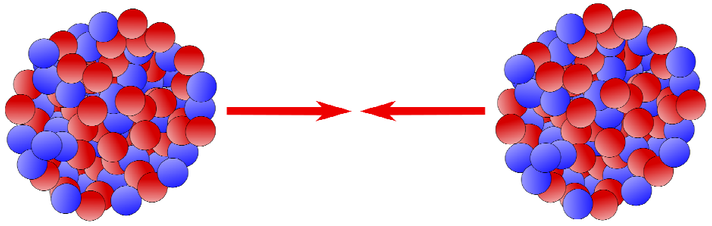

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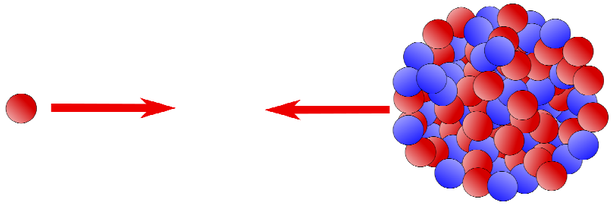
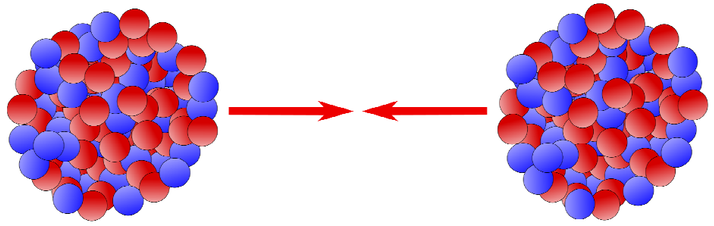


proton-ion QGP ✓

proton-proton QGP 

Many new measurements performed in last few years some of which will be discussed today.

QGP in small systems?



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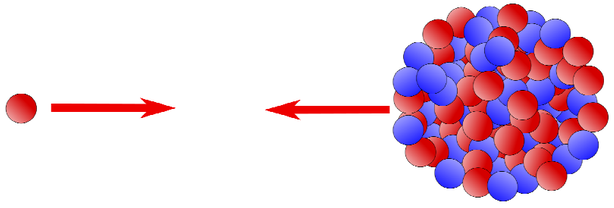

proton-ion QGP ✓

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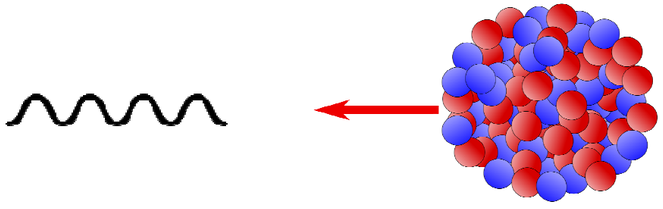
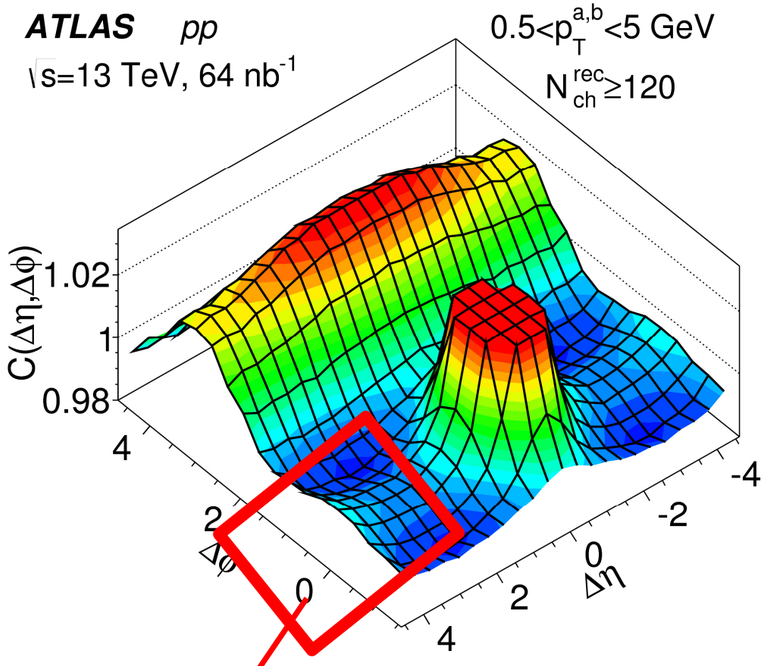


photon-ion

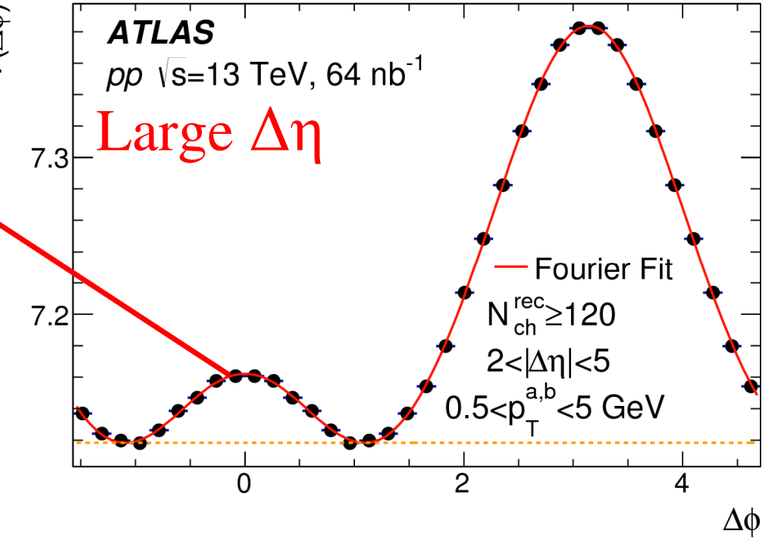
photon-proton

What about even smaller systems?

The ridge in *pp* collisions



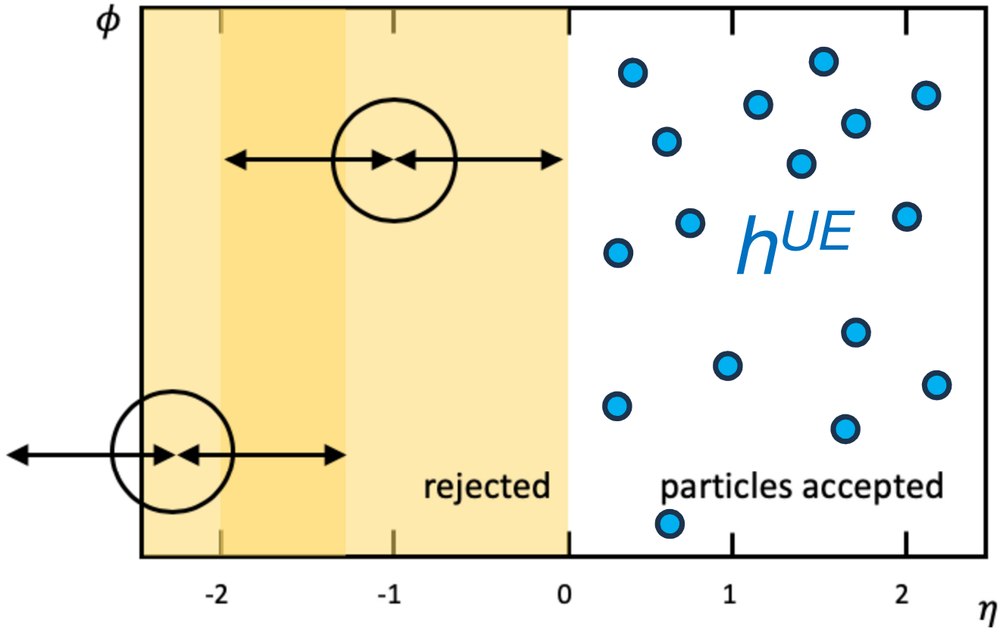
pp ridge



- First indication of "collective behavior" in *pp* collisions was the observation of the ridge in two-particle correlation measurements.
- Try to further our understanding of the origin of the *pp* ridge.
  - Does it arise from collective (hydro) behavior?
  - Or is it driven by semi-hard processes? Perhaps related to gluon saturation.
- If latter, then actively selecting/rejecting events with semi-hard processes (low-p_T jets) should enhance/weaken the ridge.

Define multiple correlation classes

- h : inclusive hadrons (tracks) in the event
- h^{UE} : tracks from the underlying event (UE):
  - require that the track is at least one unit in |η| from all jets with p_T >15 GeV



ATLAS: PRL 131 (2023) 162301

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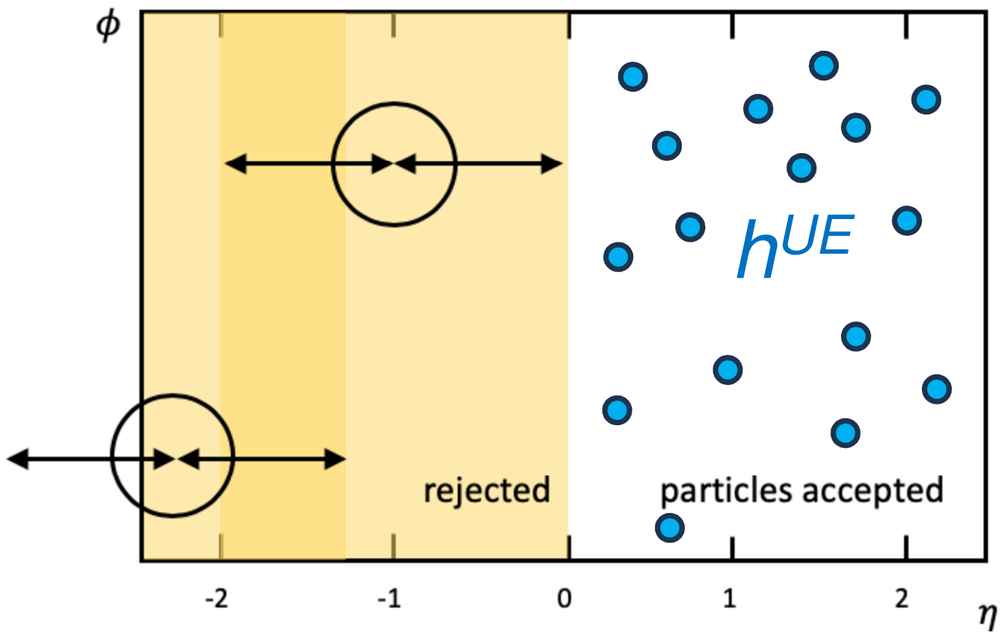

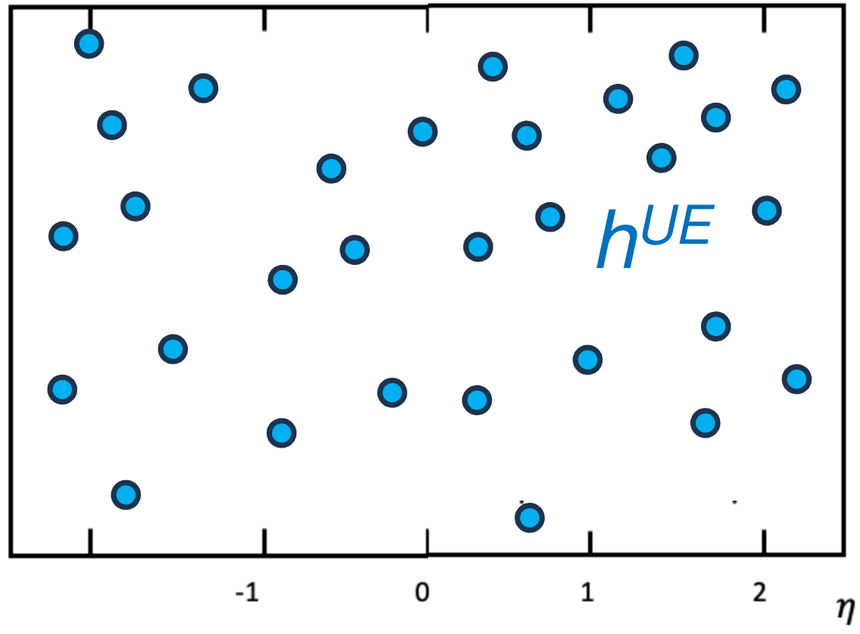

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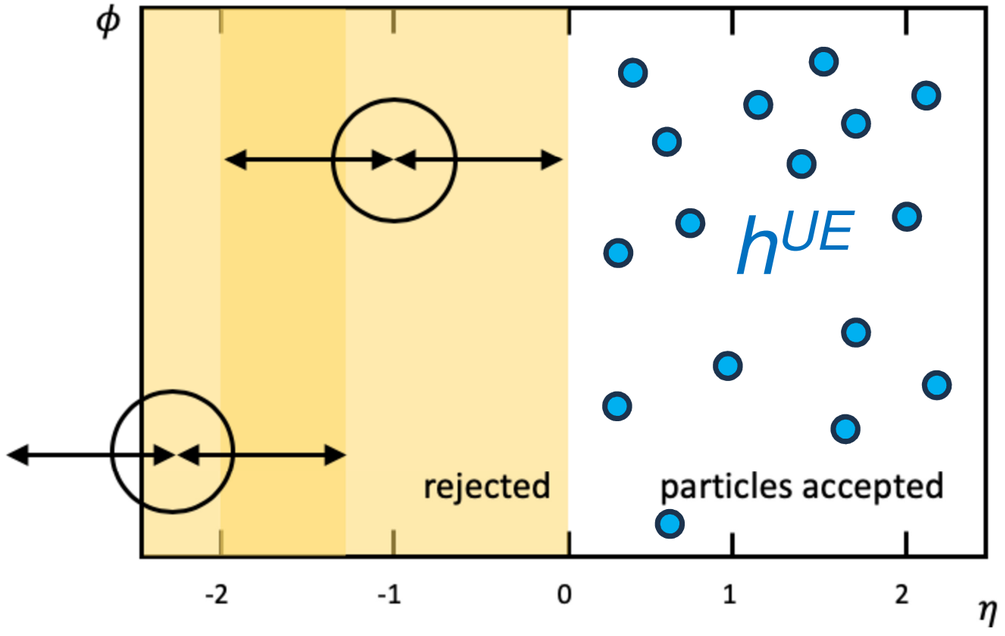
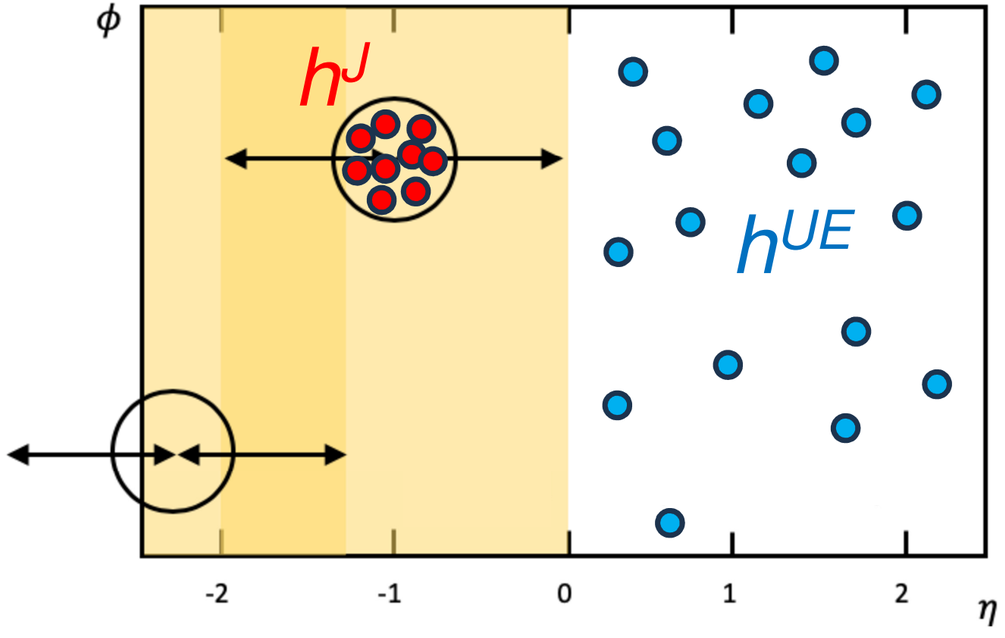
- h^{J} : track associated with a jet
  - require that the track is within a 0.4 cone of a p_T >40 GeV Jet





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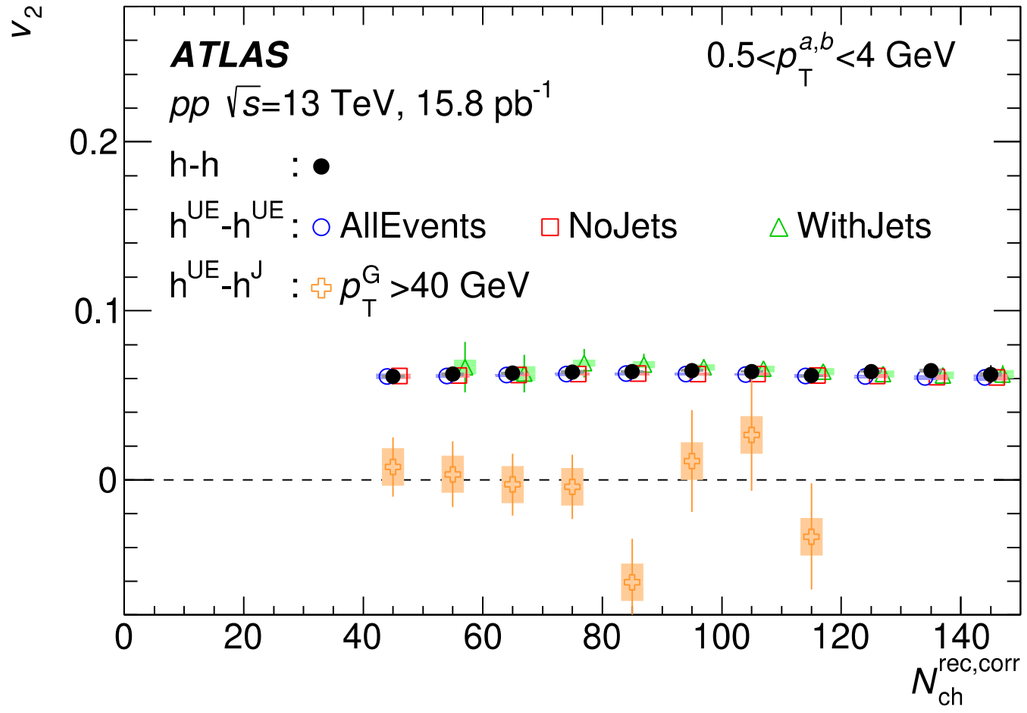
v_2 : comparison between cases



- The v_2 values are observed to vary weakly with multiplicity,
  - v_2 values for the h^{UE}-h^{UE} correlations: *NoJets*, *WithJets* and *All Events* are identical
  - Removing particles associated with jet has negligible impact on v_2
  - Presence/absence of Jets in events does not impact the v_2
- h^{UE}-h^{J} v_2 consistent with zero within uncertainties
  - Ridge is not related to jets!

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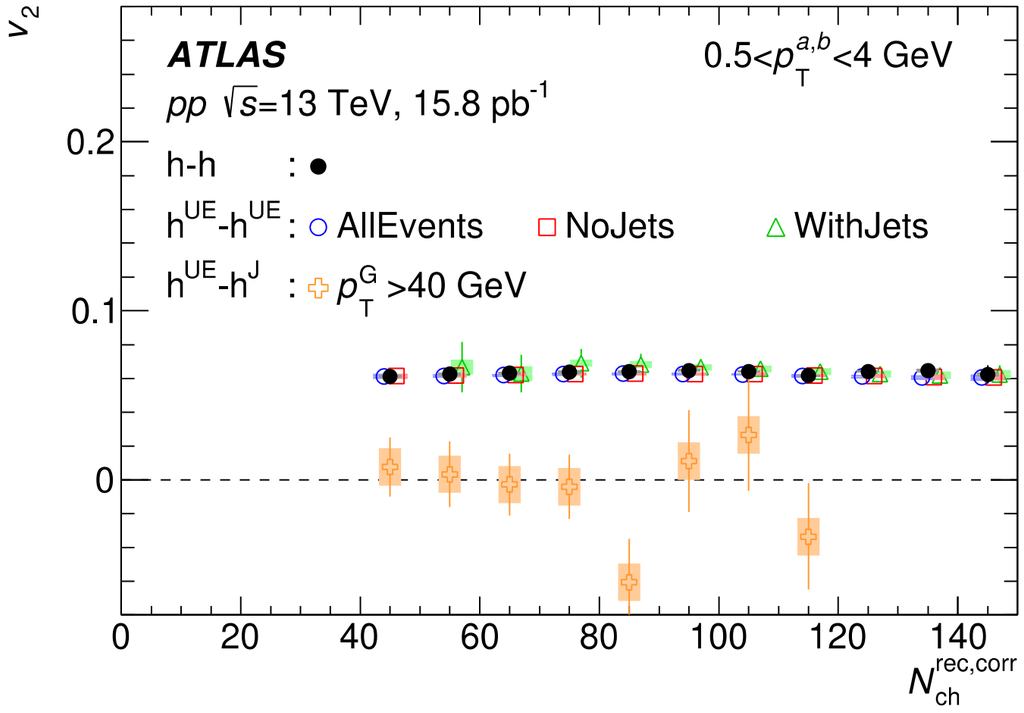
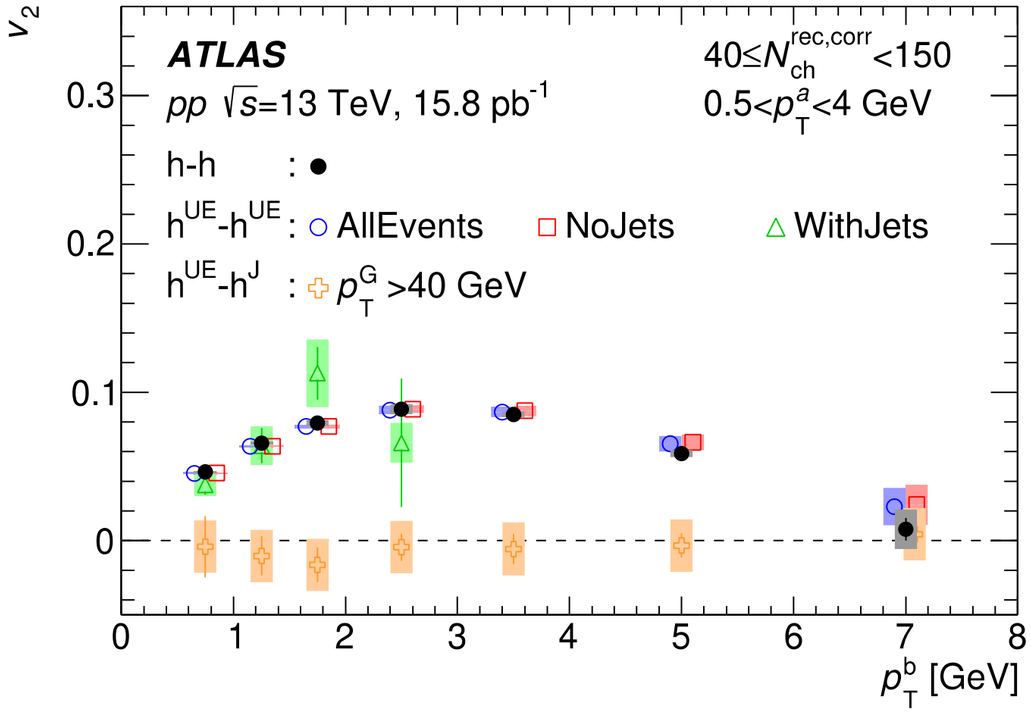
v_2 : comparison between cases





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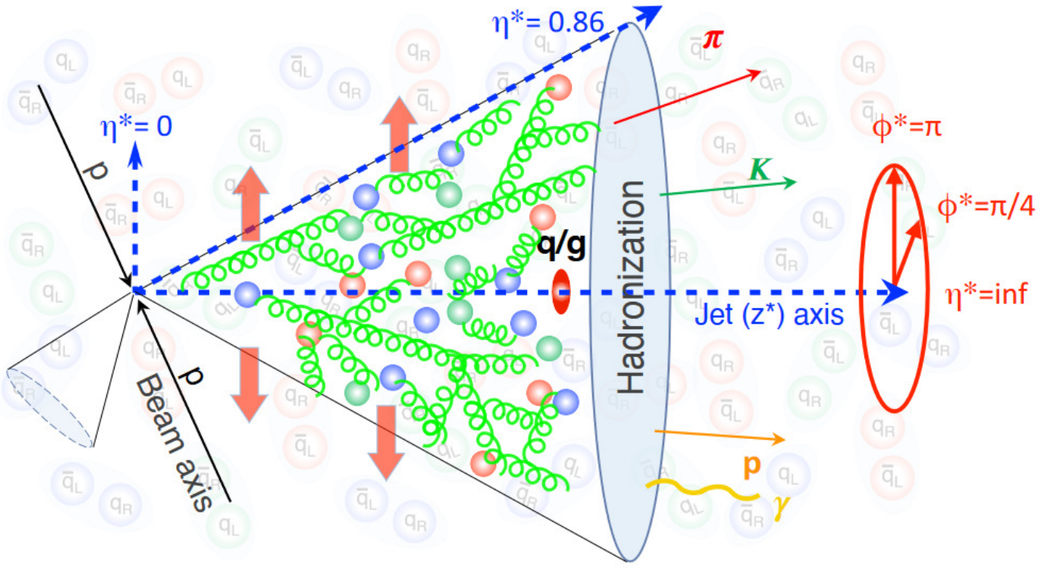
  - Presence/absence of Jets in events does not impact the v_2
- h^{UE}-h^{J} v_2 consistent with zero within uncertainties
  - Ridge is not related to jets!
  - Behavior is true as function of pT as well.

ATLAS: PRL 131 (2023) 162301

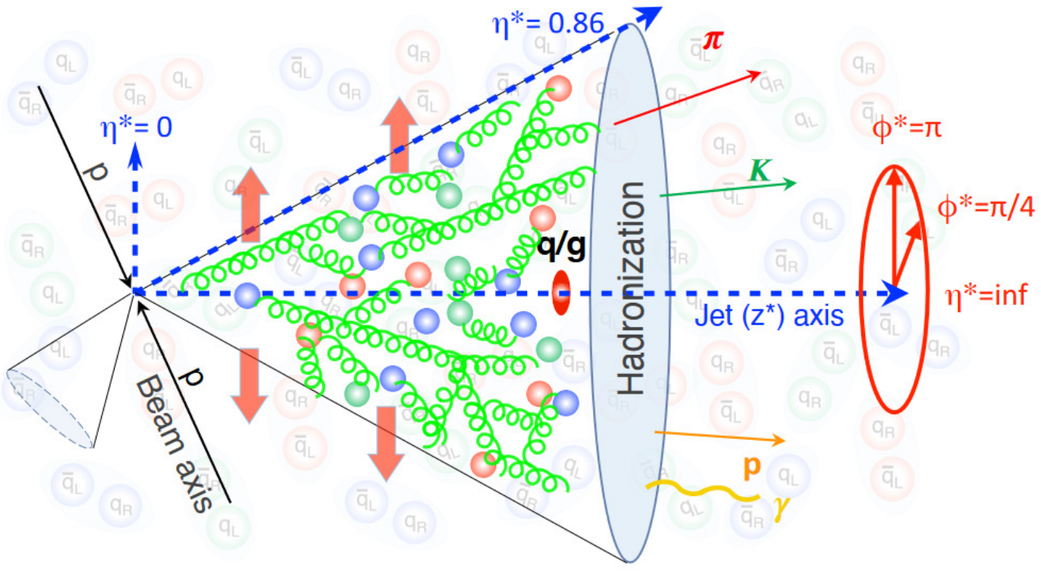
Intra-jet Collectivity

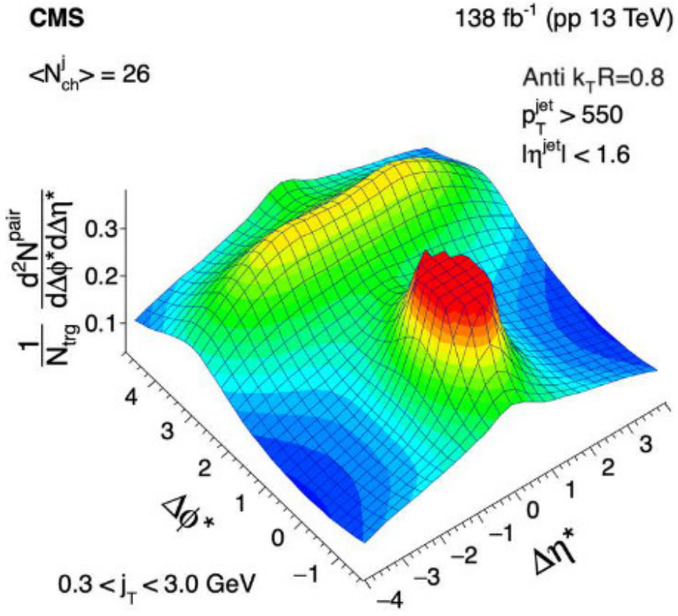


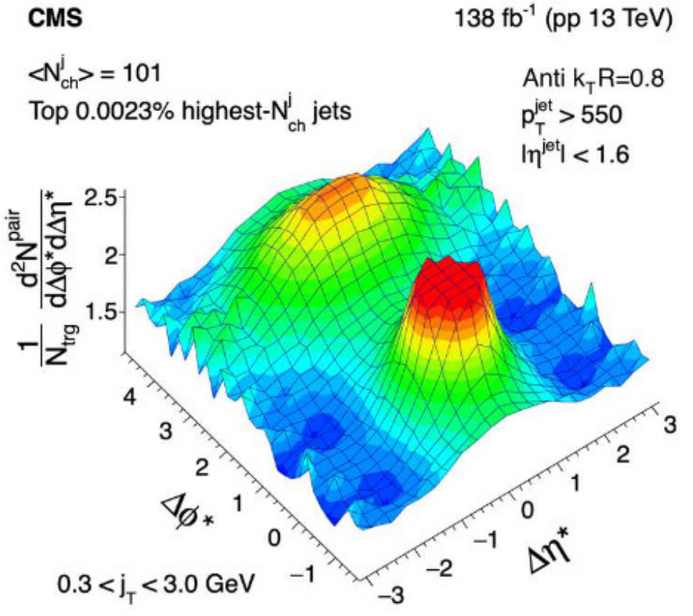
- CMS measurements to explore if there is “collective” behavior within constituents of high-multiplicity-jet.
  - Align coordinate system with jet-axis ()
  - Measure two-particle correlations in ($\Delta\eta^*$, $\Delta\phi^*$) between constituents

CMS: arXiv:2312.17103

Intra-jet Collectivity



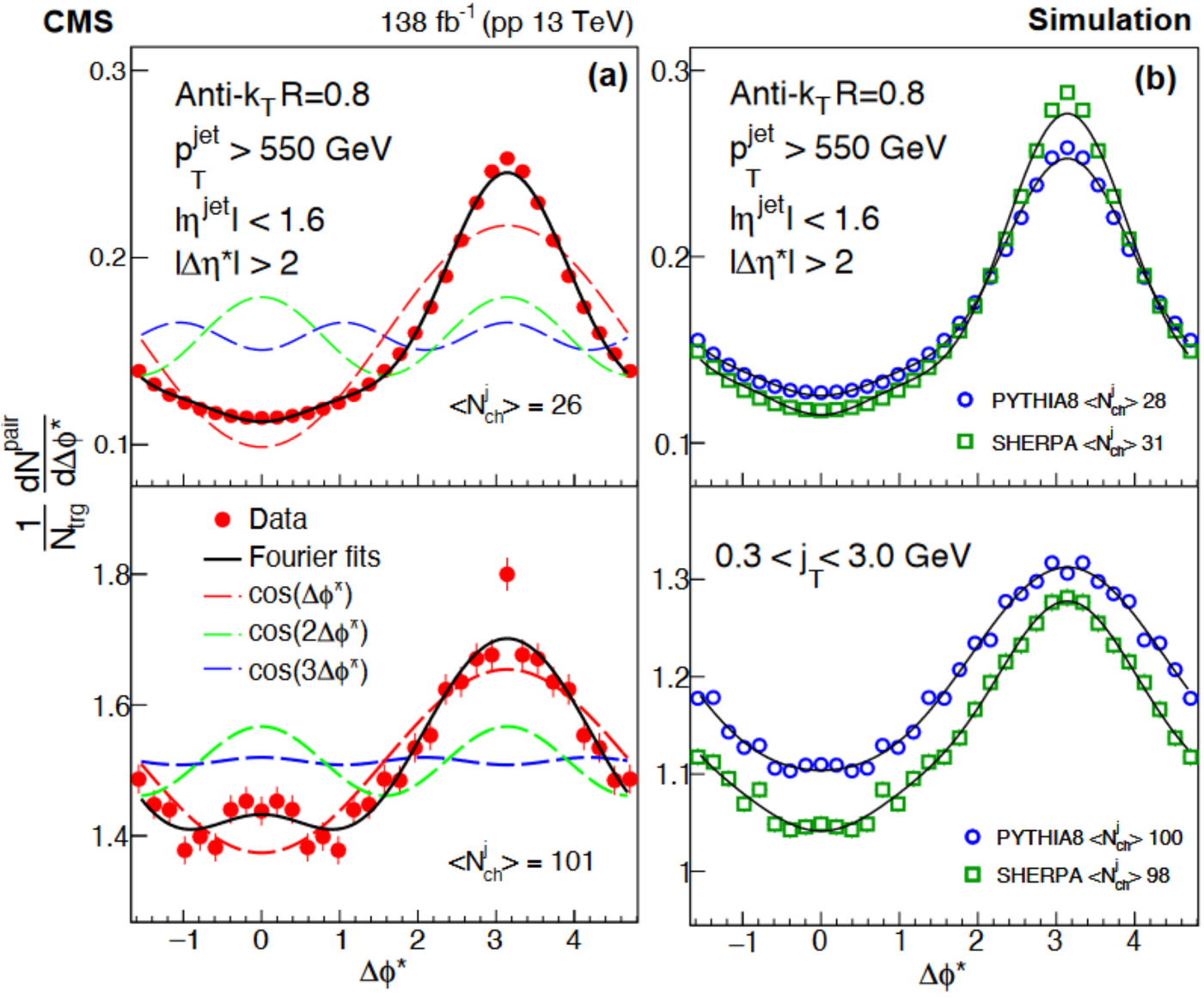




- CMS measurements to explore if there is “collective” behavior within constituents of high-multiplicity-jet.
  - Align coordinate system with jet-axis (η^*, $\Delta\phi^*$ →)
  - Measure two-particle correlations in ($\Delta\eta^*$, $\Delta\phi^*$) between constituents
- Shown here are 2PCs for low-multiplicity and high-multiplicity jets

CMS: arXiv:2312.17103

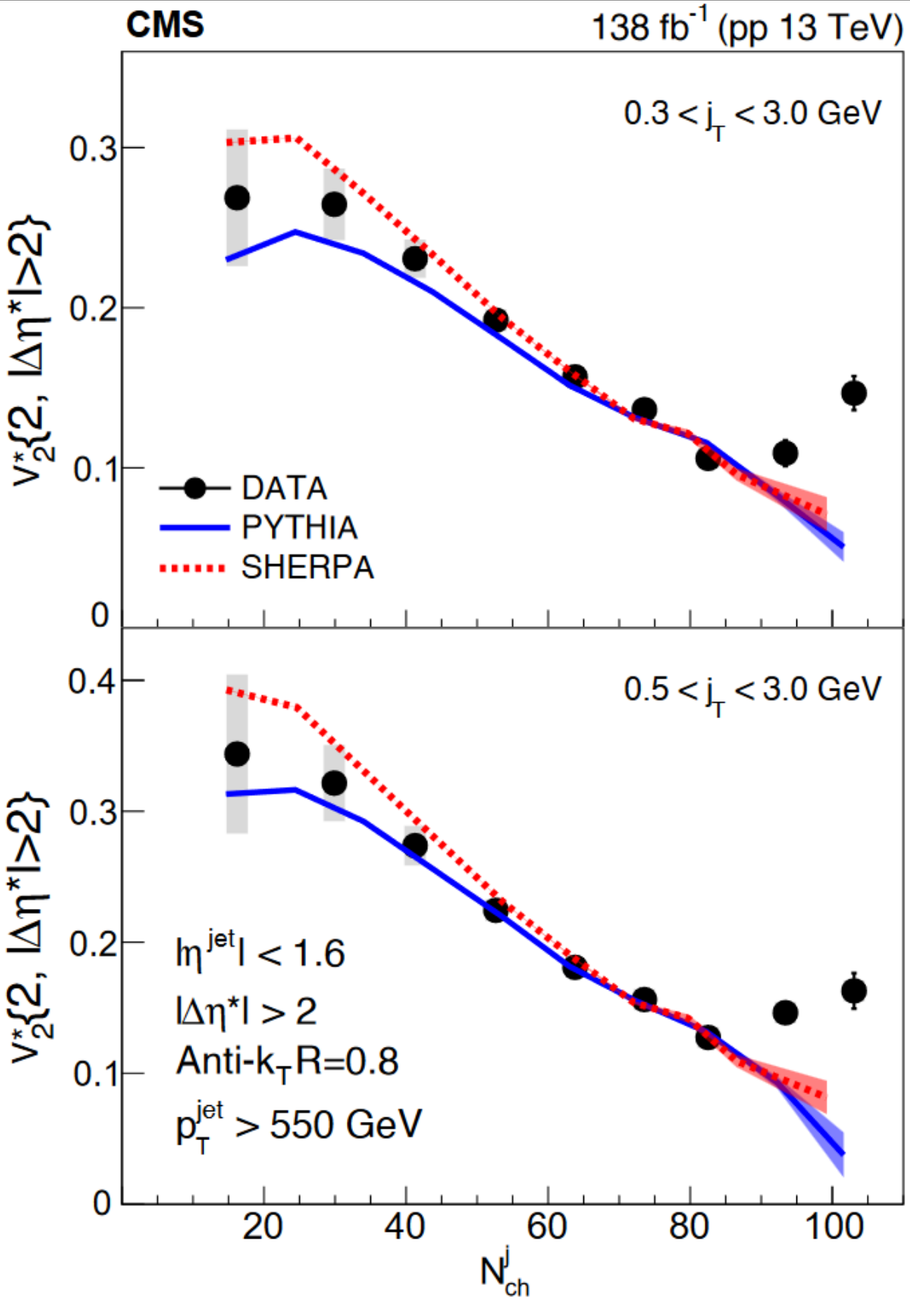
Intra-jet Collectivity



- 1D correlation functions with Fourier components (Data and MC)
- See small near-side peak for high multiplicity jets the data
- Such a peak is absent in the MC (Pythia/Sherpa)

CMS: arXiv:2312.17103

Intra-jet Collectivity

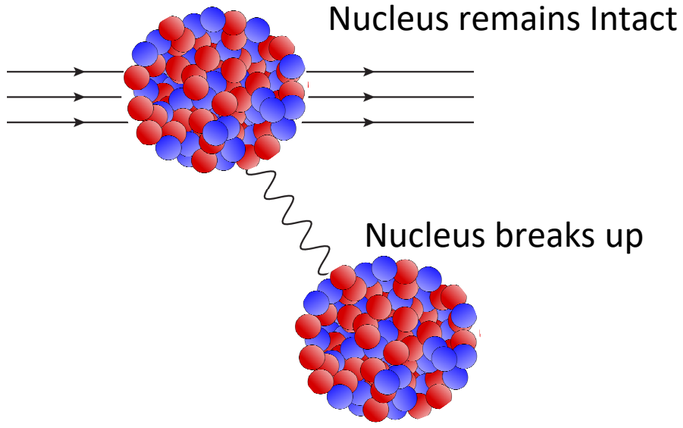


- The v_2 values vs jet multiplicity in Data and MC
- MC & Data v_2 decreases with multiplicity
  - Consistent for jet multiplicity<80
- For multiplicity>80: v_2 in data increase,
  - Inconsistent with MC
- Indicating of some collective behavior?
  - Need more guidance from theory

CMS: arXiv:2312.17103

Photon-ion and photon-proton collisions

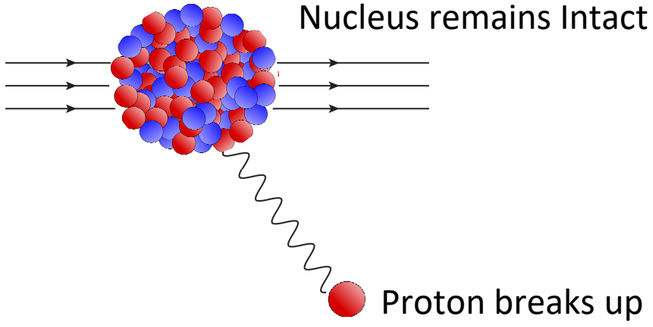
Ultra Peripheral Pb+Pb



EM fields of Lorentz contracted nuclei can be treated as flux of quasi-real photons.

In UPC Pb+Pb collisions, Photons coherently emitted from one Pb nuclei can interact with another: γ+Pb collisions

Ultra Peripheral Pb+*p*

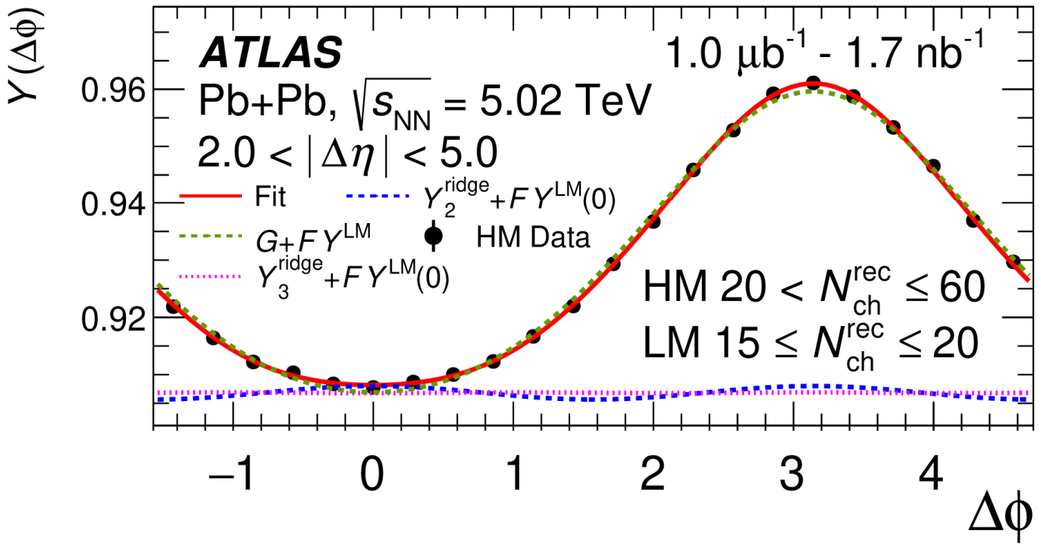


Similar process in UPC Pb+*p* : γ+*p* collisions

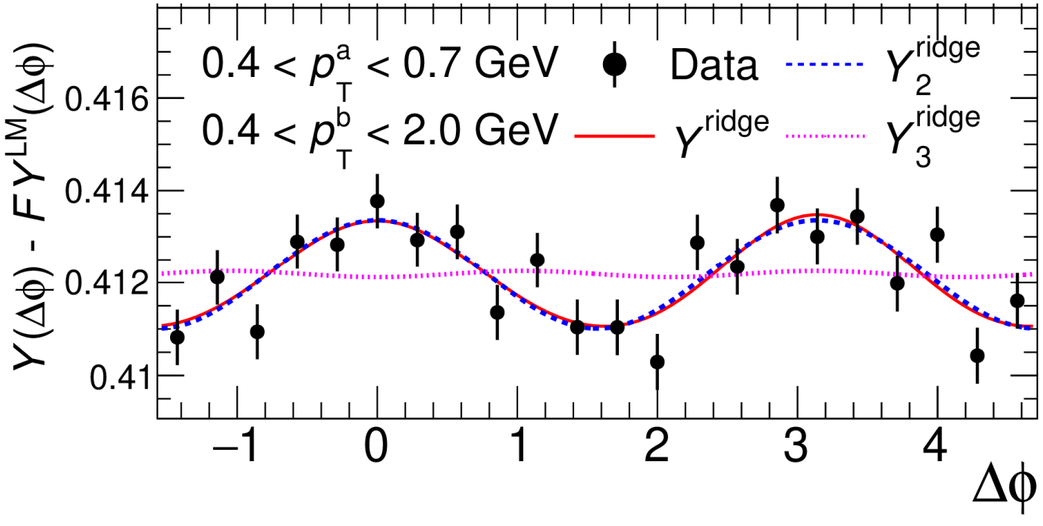
Also see talk by Joakim Nystrand yesterday

Collectivity in γ+Pb collisions

Raw correlation



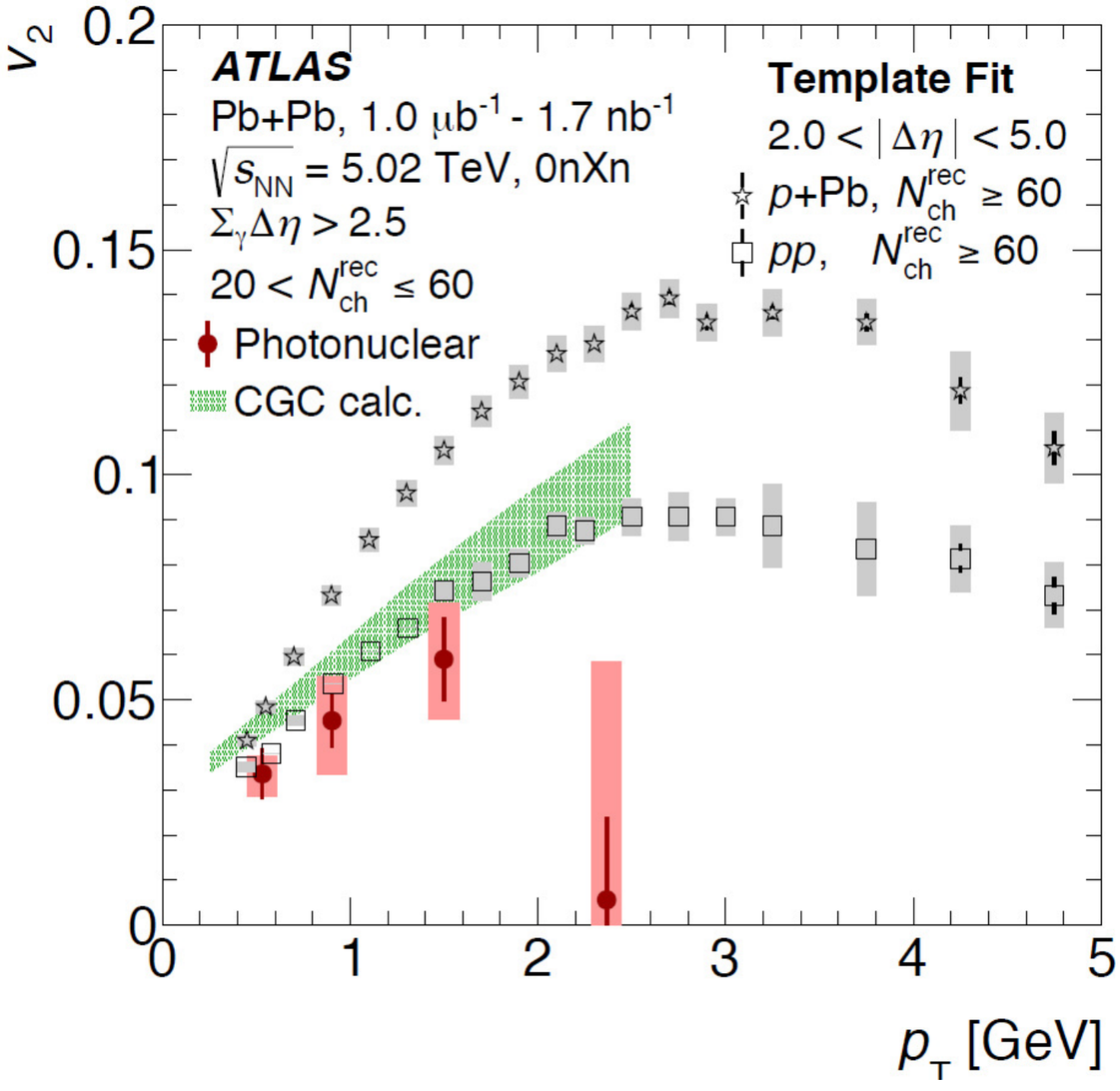
After non-flow subtraction



- The v_2 in γ +Pb are extracted using a non-flow subtraction procedure.
- Correlation in low multiplicity (LM) events subtracted from correlation measured in higher multiplicity (HM) events.
- Subsequently Fourier harmonics v_n, extracted from the “Non-flow” corrected correlation.

ATLAS: Phys. Rev. C. 104 104903

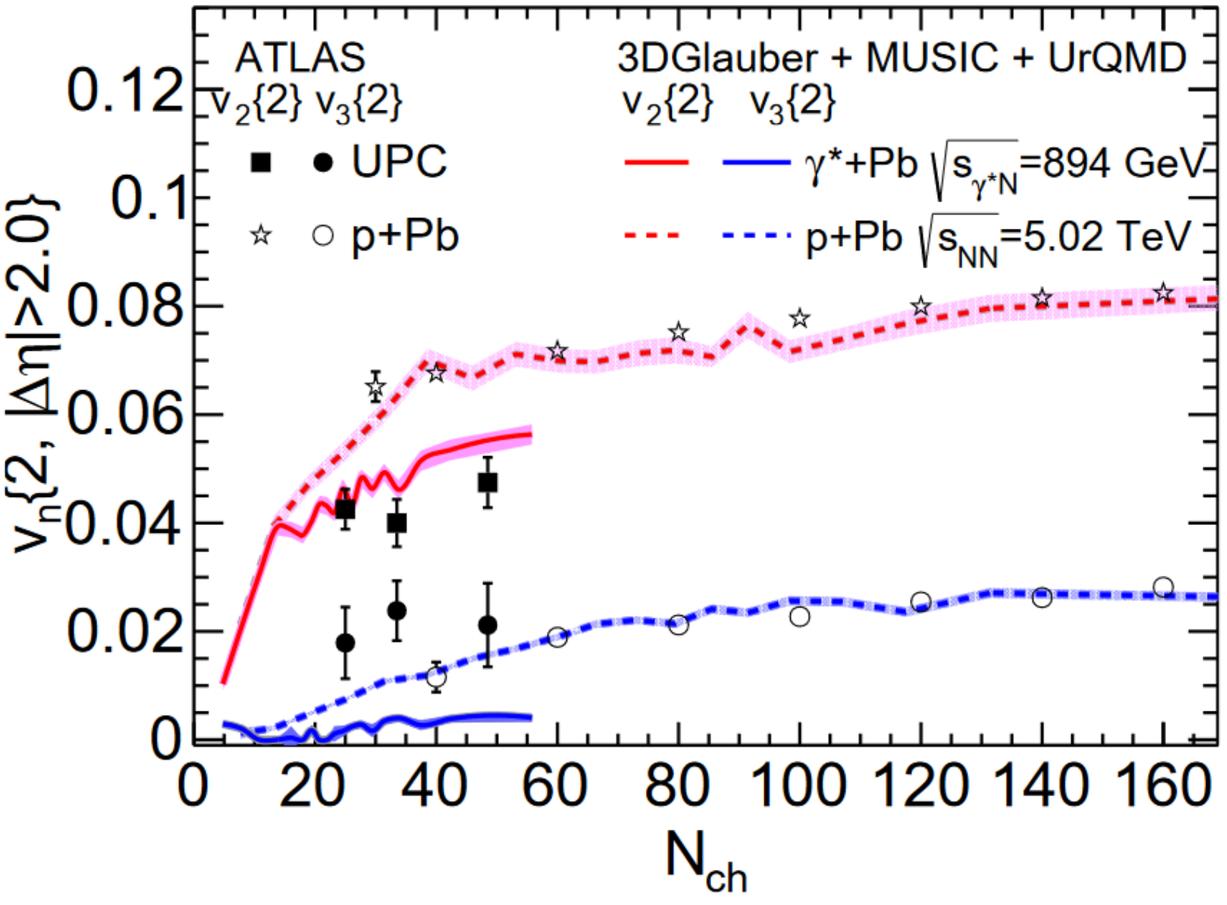
Collectivity in γ+Pb collisions



- p_T-differential v_2 comparable with pp over the 0.4-2 GeV p_T range.
- Can be reproduced by tuning CGC calculations (initial-state effects only).
  - *Shu et al., PRD 103, 054017*
  - Considerable leeway available in tuning.

ATLAS: Phys. Rev. C. 104 104903

Collectivity in γ+Pb collisions

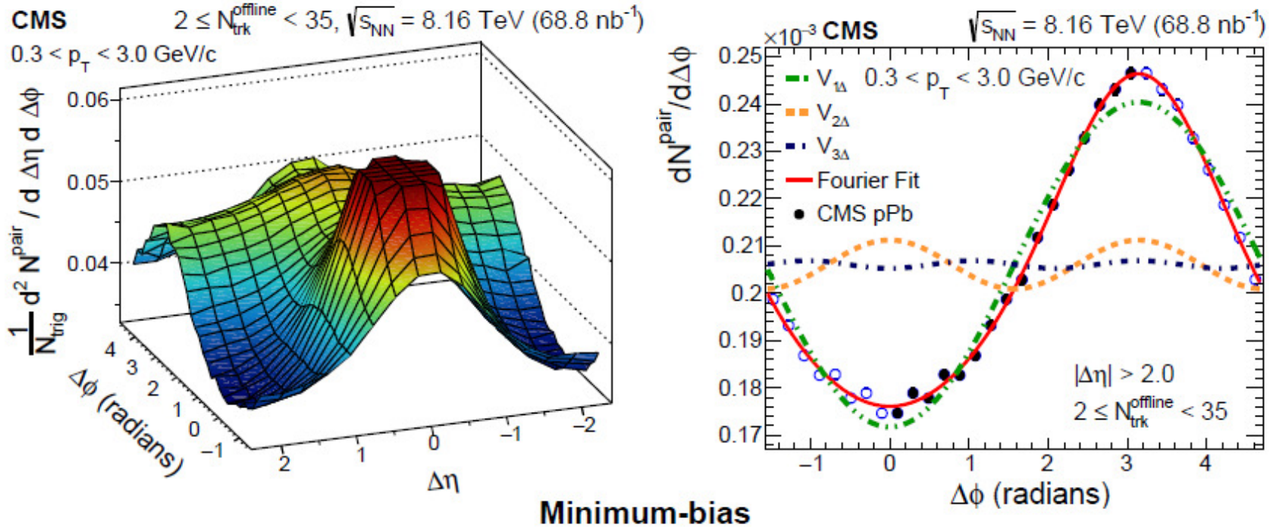


- Comparison of v_2, v_3 of multiplicity dependence to 3+1D hydro calculations
  - Zhao, Shen, Schenke, PRL 129, 252302
  - Treating the γ as meson
- Good agreement for v_2.

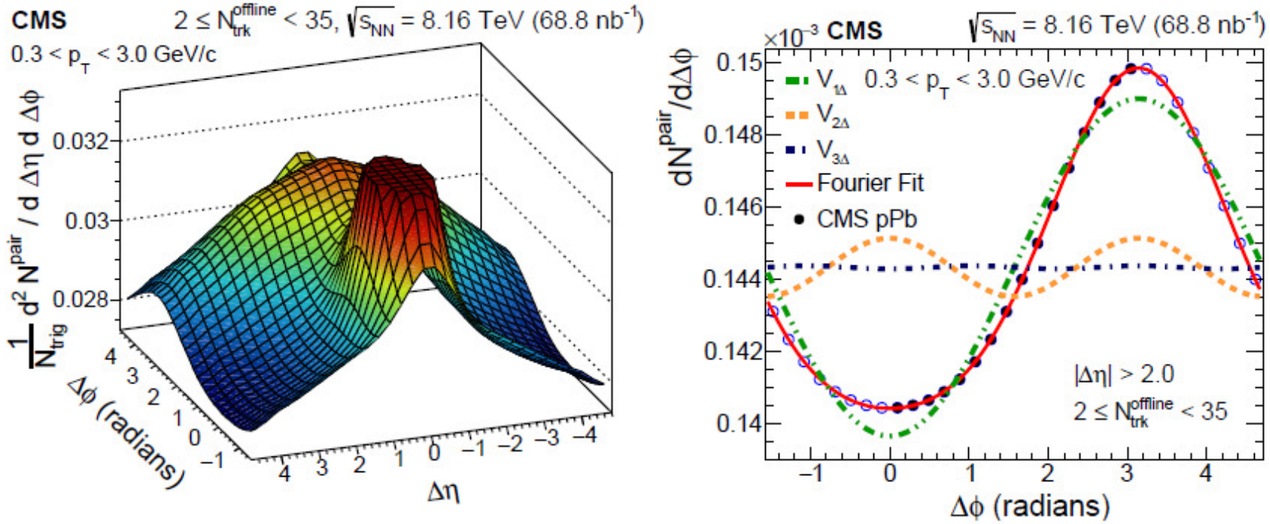
ATLAS: Phys. Rev. C. 104 104903

First look at *γ+p* collisions

γp enhanced



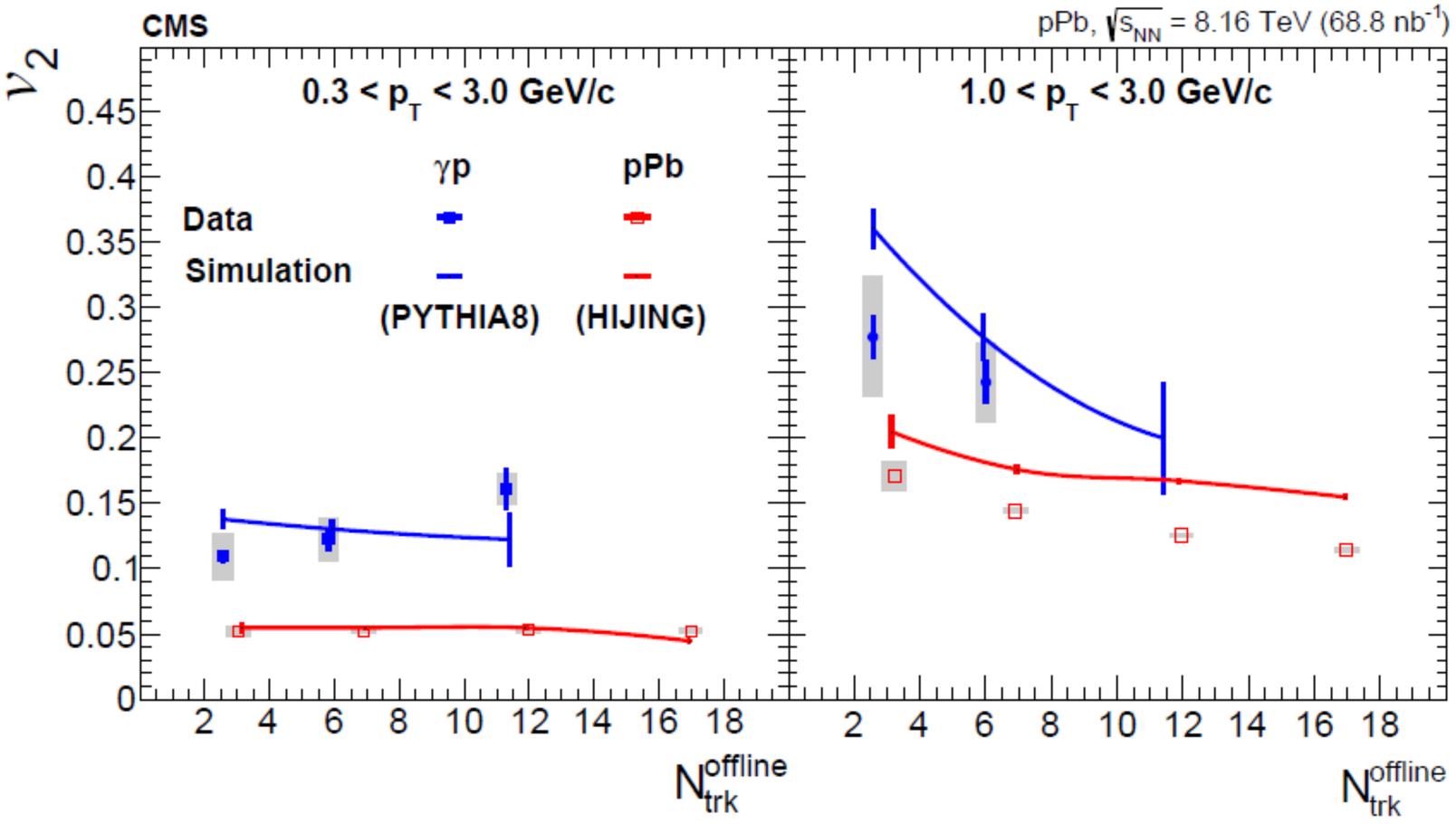
Minimum-bias



- Select enriched sample of *γ+p* events in UPC p+Pb collisions.
- Require no neutron on Pb-going size ZDC, as well as a large region with no detector activity on Pb going side.
- Plots show 2D and 1D 2PCs in *γ+p* events and min-bias *p*+Pb events.
- Stronger away-side correlation observed in *γ+p* events compared to min-bias *p*+Pb.

CMS: Phys. Lett. B 844 (2023) 137905

First look at *γ+p* collisions



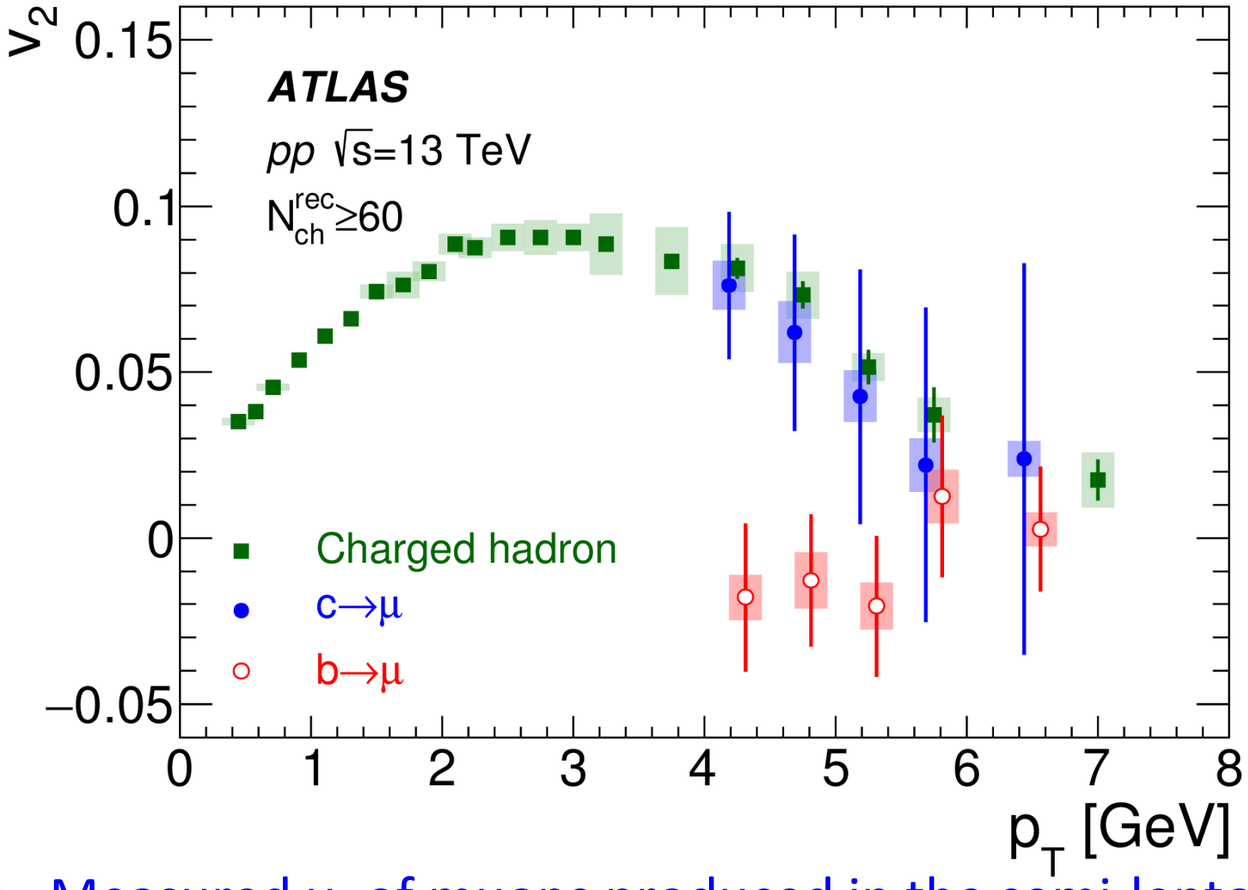
CMS: Phys. Lett. B 844 (2023) 137905

- Larger v_2 observed in *γ+p* events compared to min-bias events
  - Need to be careful as no “non-flow” subtraction is performed
  - i.e. jet-like correlations dominate the measurement.
- Measurements can extend search for collectivity to *γ+p* events

Summary

- Multiple recent measurements from ATLAS and CMS investigate collectivity in small collision systems.
- ATLAS : ridge in *pp* collisions with/without jets, “jet-constituent”-UE correlations
  - low-p_T v_2 not affected by presence/absence of jets. (See also ALICE: arXiv:2308.16591)
  - Jet-fragments do not exhibit correlations with UE particles.
  - Hard-scattering & UE-collectivity are uncorrelated!
- CMS : Measured correlations within jet-fragments
  - Correlation in low multiplicity jets consistent with MC generators.
  - Constituents in highest multiplicity jets show hints of collectivity.
- CMS & ATLAS : 2PC measurements in *γ+p* and *γ*+Pb events.
  - Smallest collision systems at the LHC.
- Not covered in this talk: ATLAS and CMS : also measured HF v_2 in *pp* events.
  - *charm* v_2 consistent with inclusive hadrons, *bottom* v_2 consistent with zero.

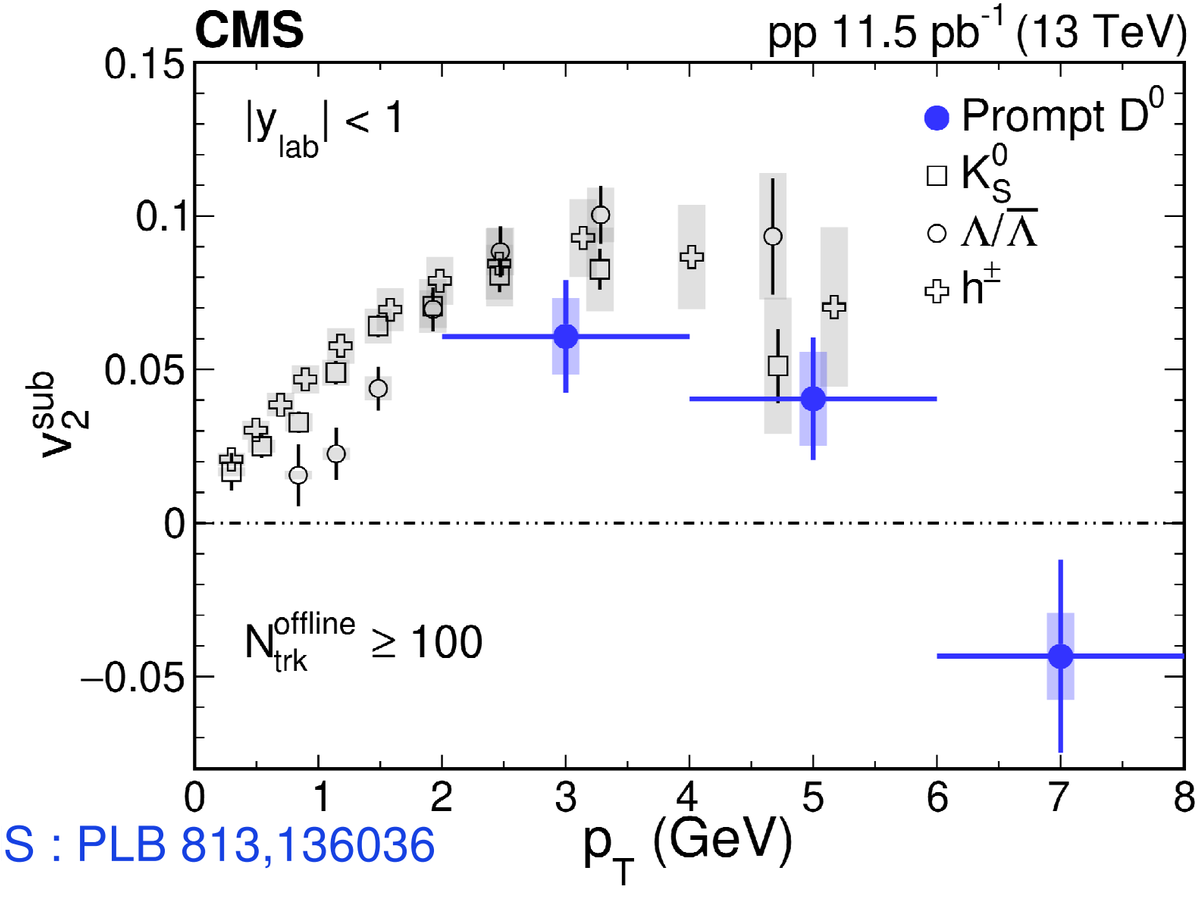
Extra-1: HF collectivity in *pp* collisions



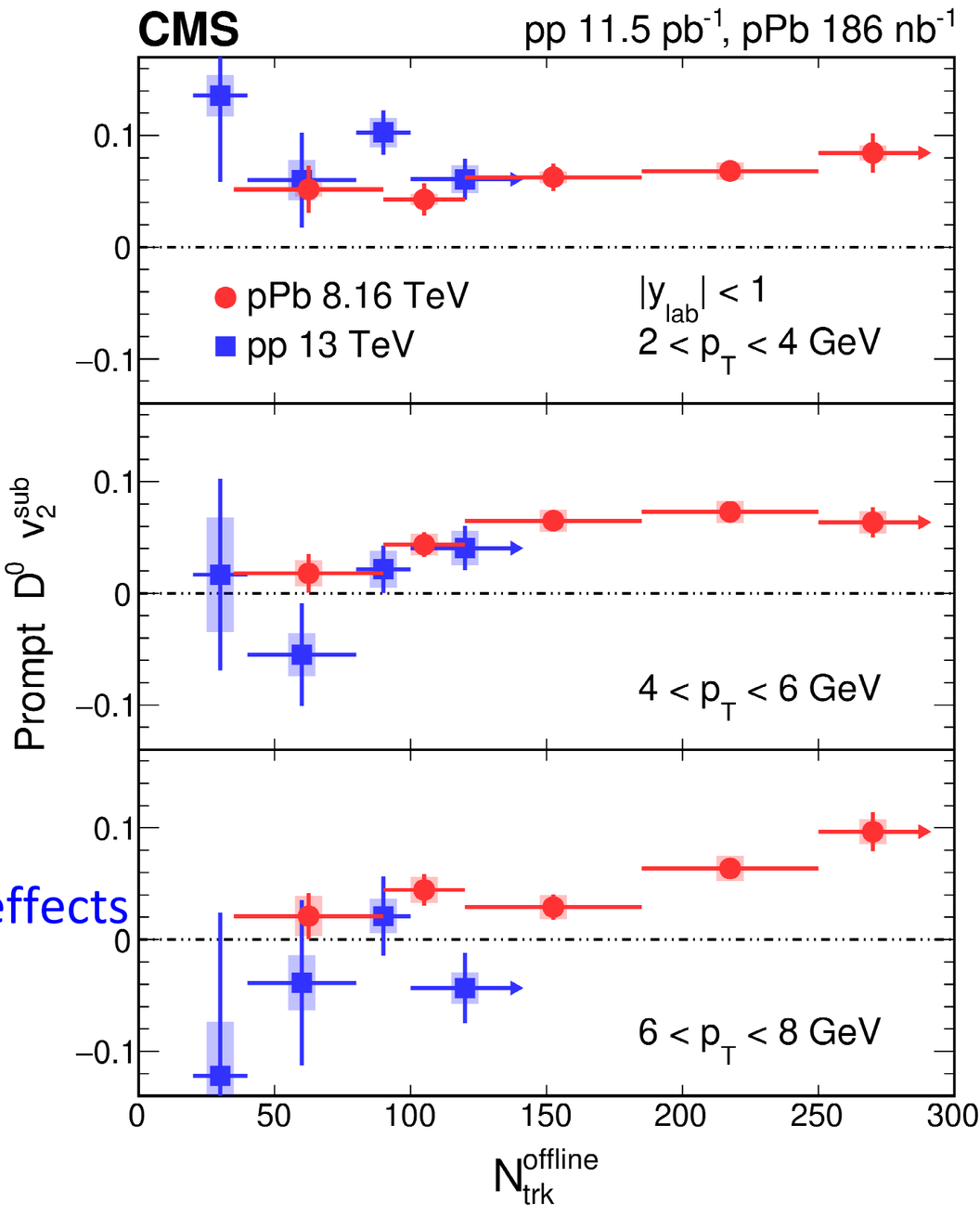
ATLAS : PRL-124, 082301

- Measured v_2 of muons produced in the semi-leptonic decays of *b* and *c* hadrons.
- Significant anisotropy observed for muons from charm decay: consistent with inclusive hadrons.
- v_2 for muons from *b* decays consistent with zero.
- These HF anisotropy measurements can lead to further understanding of origin of the *pp* ridge.

Extra-2: HF collectivity in *pp* collisions

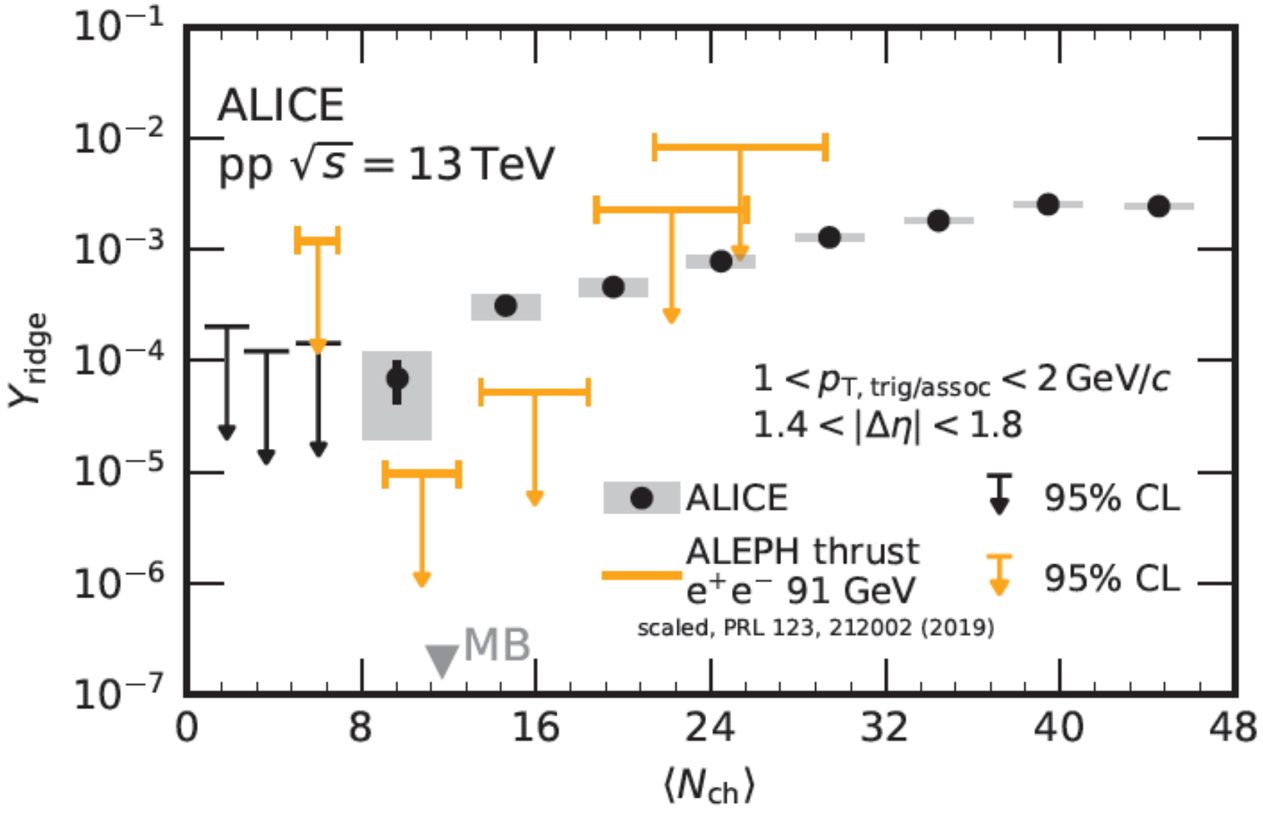


CMS : PLB 813,136036



- HF collectivity can potentially separate initial vs final-state effects
- v_2 of prompt D^0 mesons in *pp* collisions.
- Significant anisotropy observed : Comparable to inclusive hadrons.
- Comparable to v_2 in *p*+Pb collisions at similar multiplicity

Extra-3: Long-range correlations in e^+e^- vs pp collisions

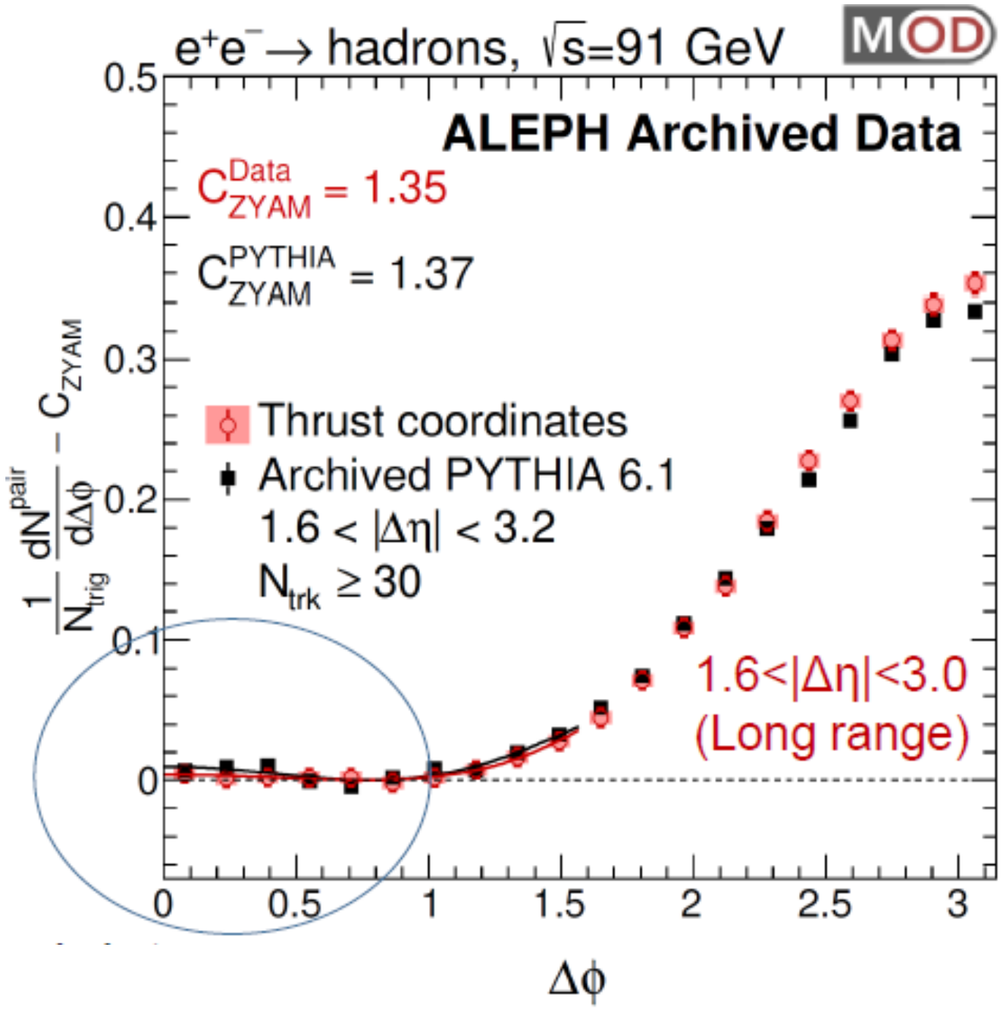


ALICE: arXiv 2311.14357

ALEPH, A.Badea & collaborators
PRL 123,212002

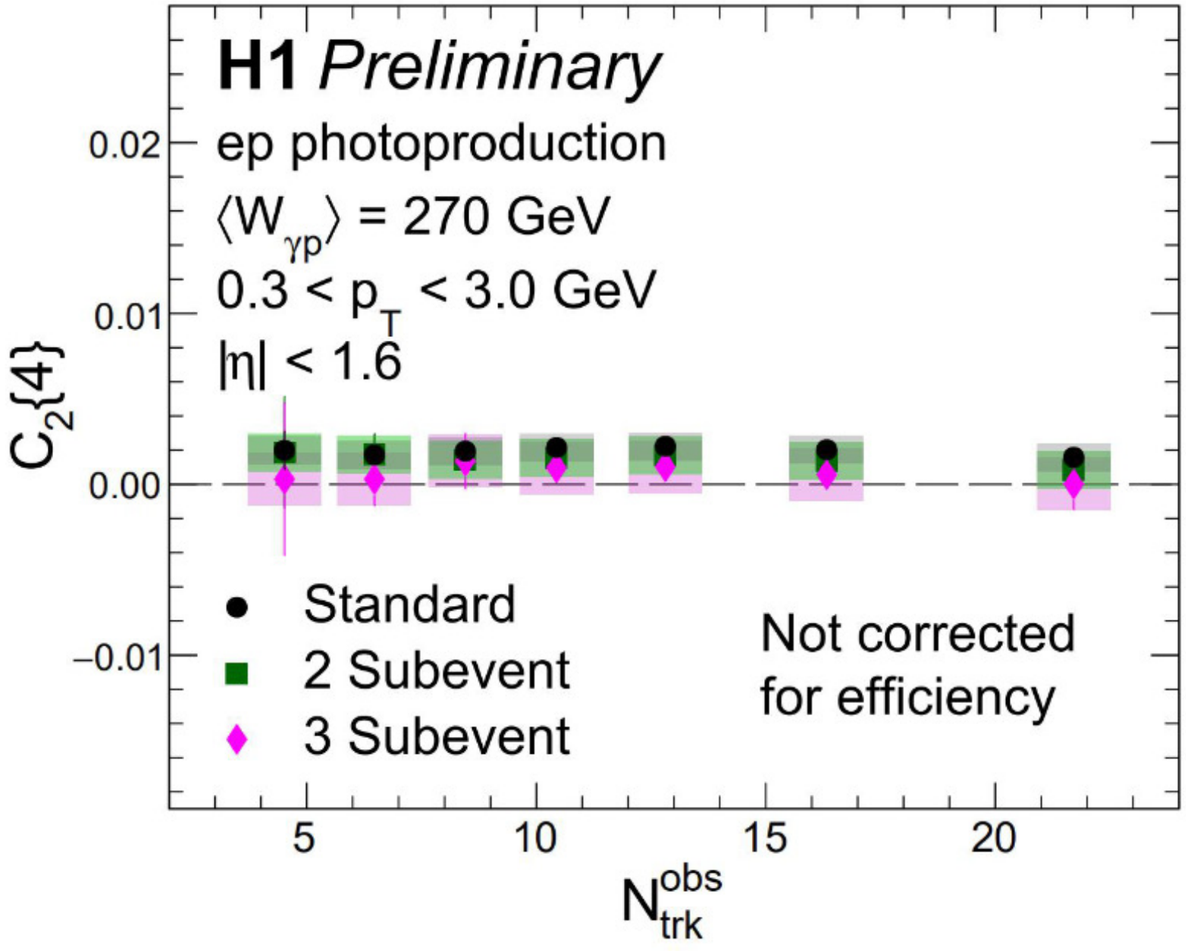
- Comparison of ridge-yield in e^+e^- (ALEPH) vs similar multiplicity pp collisions (ALICE).
- pp Yields significantly larger over 8-18 multiplicity range

Extra-4: Long-range correlations in e^+e^- collisions



- Data from ALEPH (91 TeV)
  - Similar measurements shown by BELLE
- Correlations well reproduced by PYTHIA6
- No indications of ridge in high-multiplicity events.
- Possibilities
  - Not high-enough energy density (P. Castorina et al, arXiv:2011.06966)
  - Not expected in a single color-string (J. Nagle et al, PRC 97, 024909 (2018))

Extra-5: And in *ep* collisions



- *ep* measurements at HERA
- Measured using 4-particle cumulants
  - Consistent with no collectivity