Recent [ATLAS] results on collectivity in small-systems

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(Columbia University)

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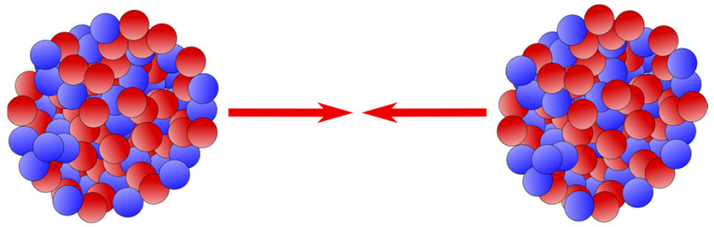
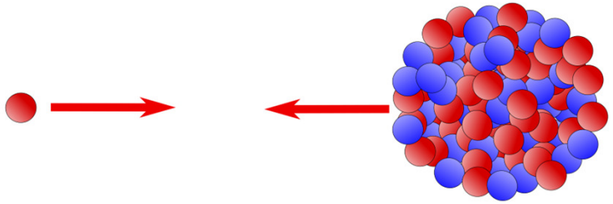
QGP in small systems?



ion-ion

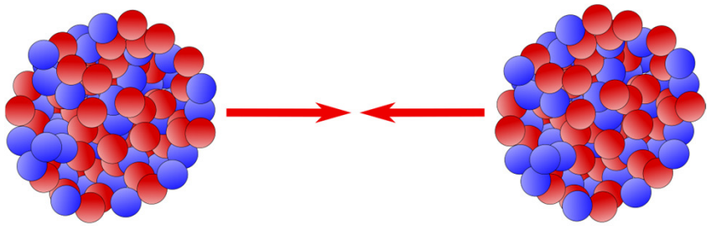
QGP ✓



proton-ion

QGP ?

QGP in small systems?



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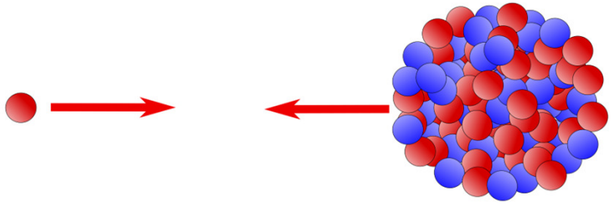

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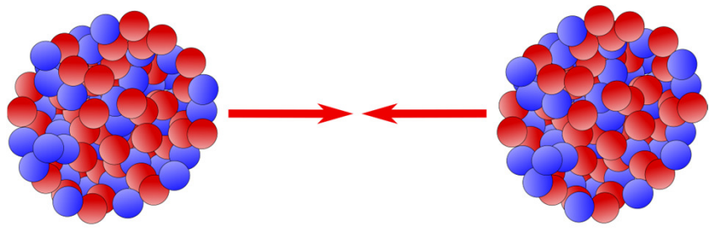

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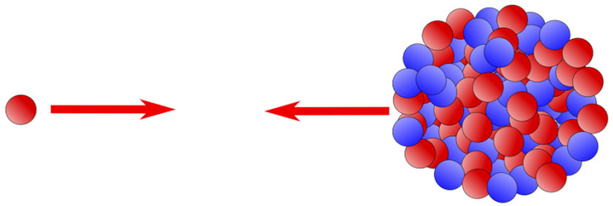
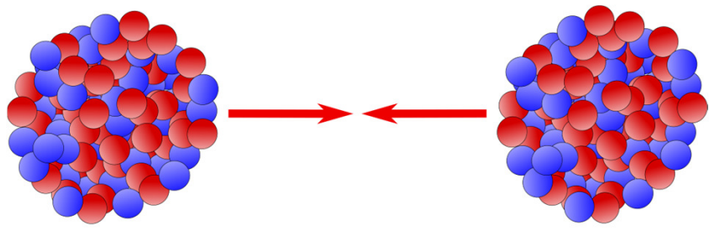


proton-ion QGP ✓

proton-proton QGP ?

QGP in small systems?



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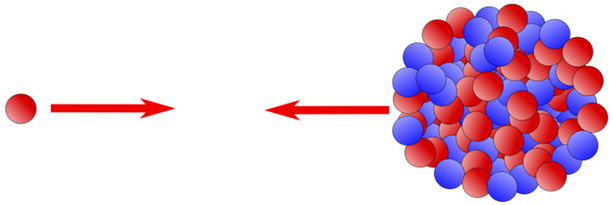
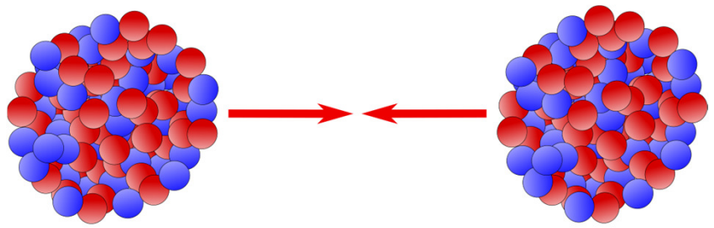


proton-ion QGP ✓

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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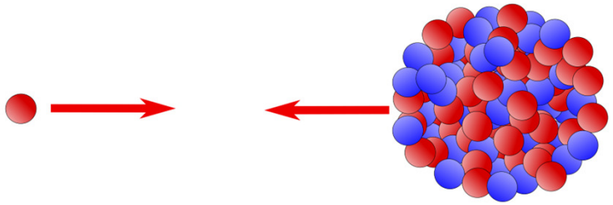

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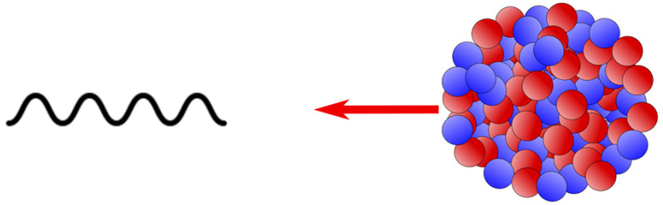
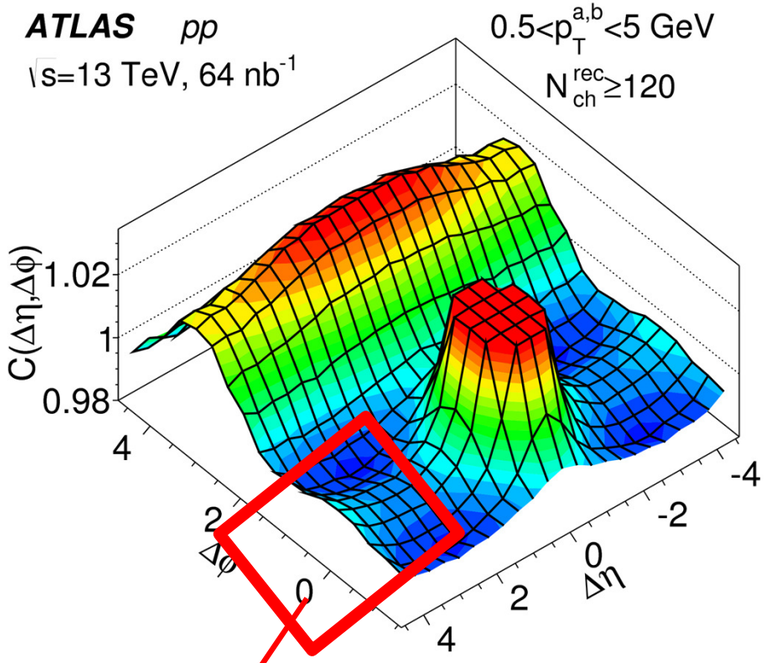


photon-ion

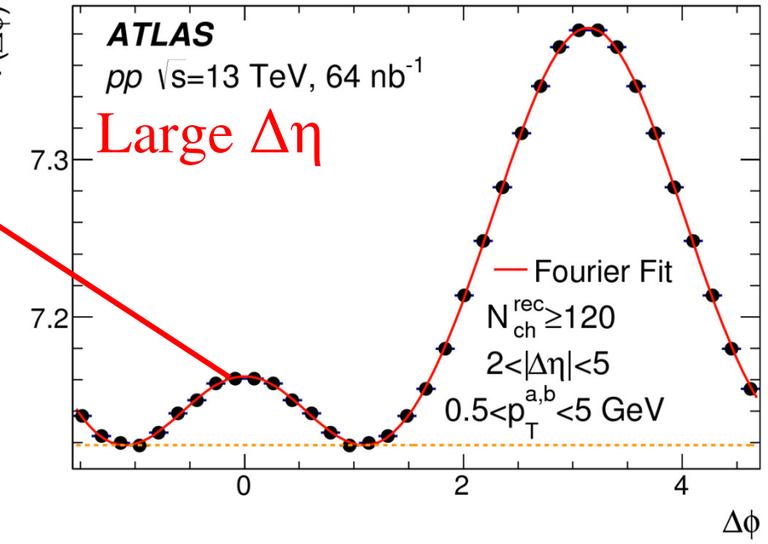
photon-proton

What about even smaller systems?

The ridge in *pp* collisions

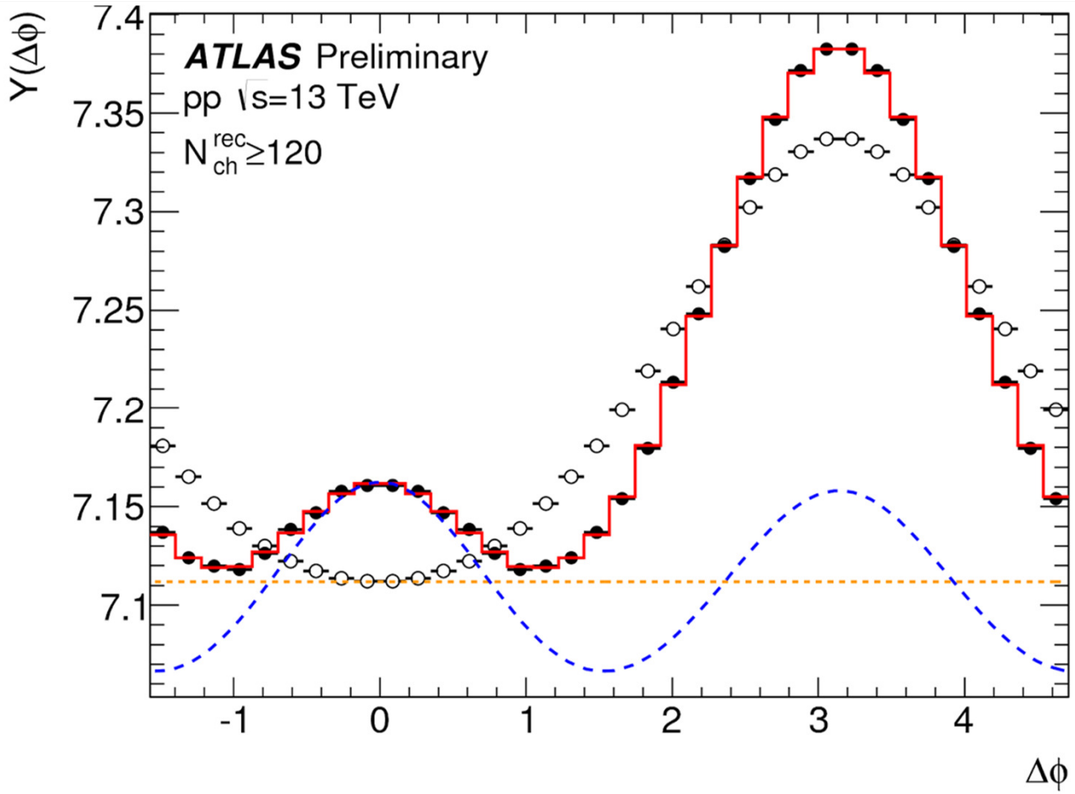


pp ridge



- 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.

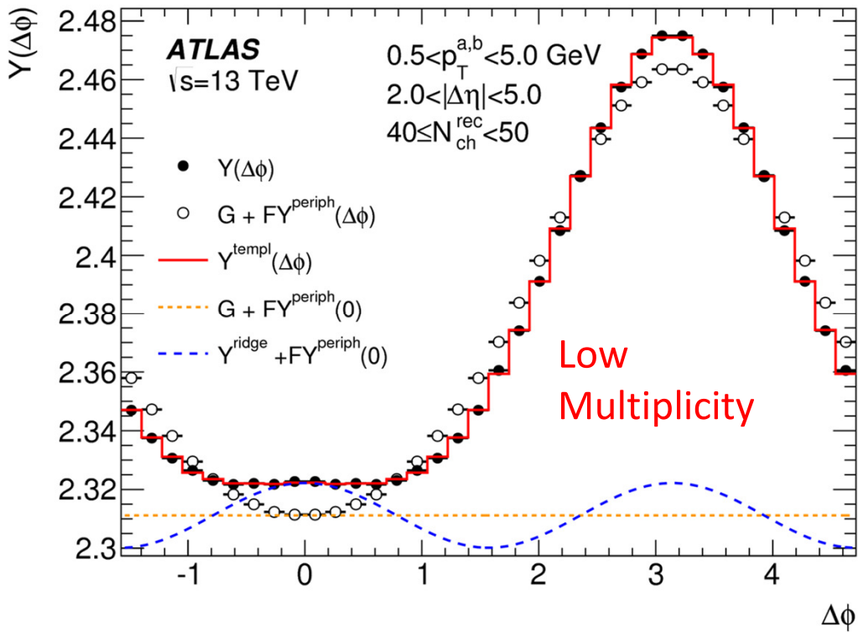
Analysis technique: Template Fitting Procedure

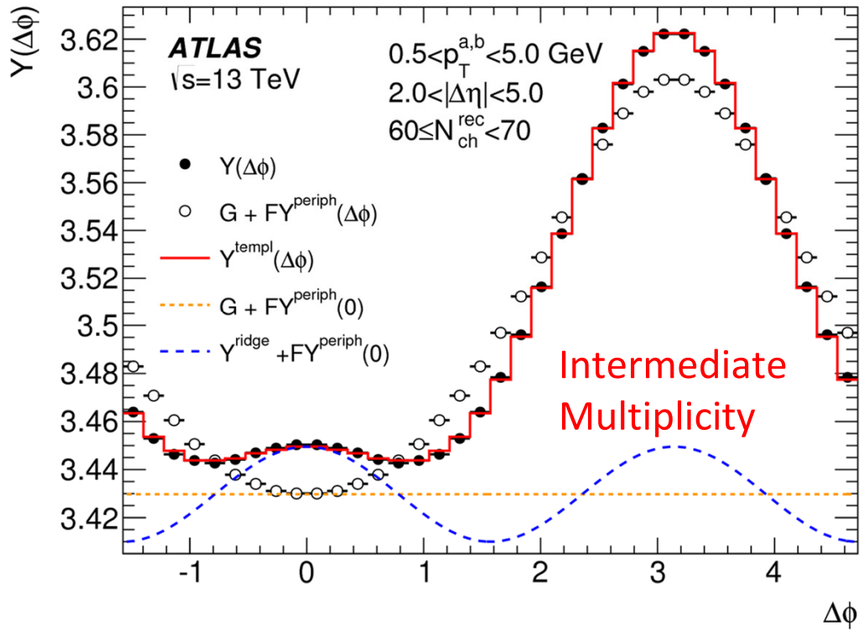


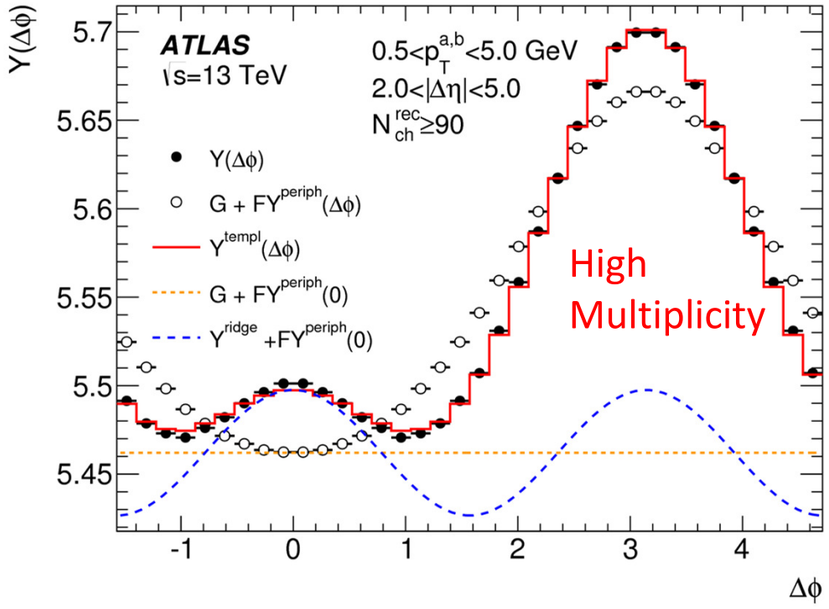
$$Y^{\text{templ}}(\Delta\phi) = F\,Y^{\text{periph}}(\Delta\phi) + Y^{\text{ridge}}(\Delta\phi),$$
$$Y^{\text{ridge}}(\Delta\phi) = G\,(1 + 2v_{2,2}\cos(2\Delta\phi)),$$

- A template fitting procedure used to extract long-range correlation
- Fit the yield in high multiplicity events with Template of two components:
  - Y^{periph}: Yield in peripheral events (N_{ch}<20)
  - Y^{ridge} : Pedestal*(1 +2* $v_{2,2}$cos(2Δϕ)) signal
- Yields much larger than what ZYAM gives
  - Compare modulation of blue line with height of ZYAM peak

Template Fitting : Multiplicity dependence





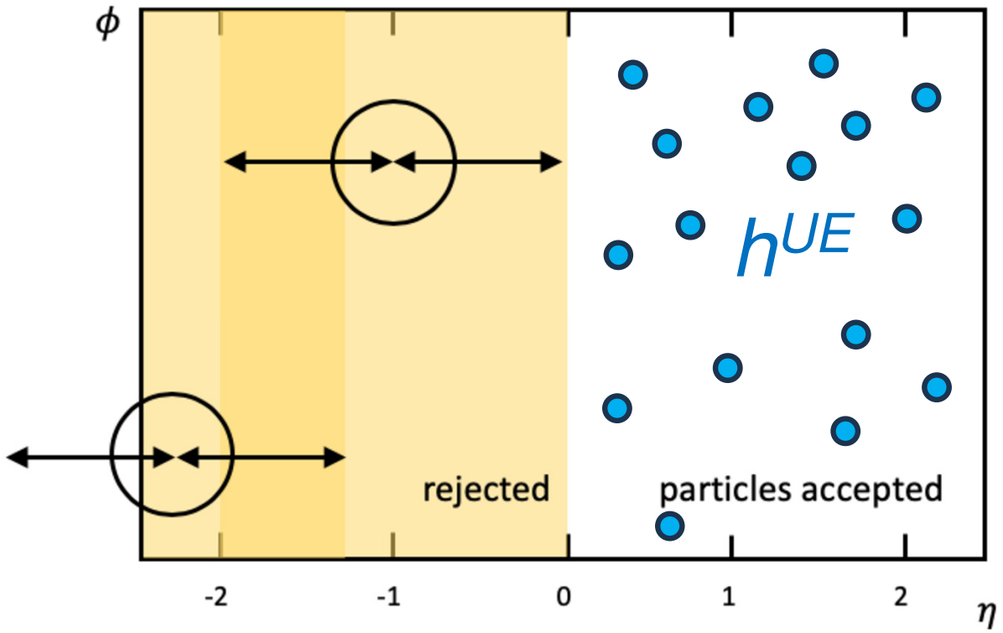


Considerable long-range correlation even in low & intermediate multiplicity events.
(ZYAM procedure would give zero yields)

Broadening of away-side and emergence of peak on near-side well described.

Define multiple correlation classes

- h : inclusive hadrons (tracks) in the event
- h^{UE} : tracks from the underlying event (UE):
  - require that the track is separated by at least one unit in $|\eta|$ from all jets with $p_{\mathrm{T}}^{\mathrm{G}}$ >15 GeV



ATLAS: PRL 131 (2023) 162301

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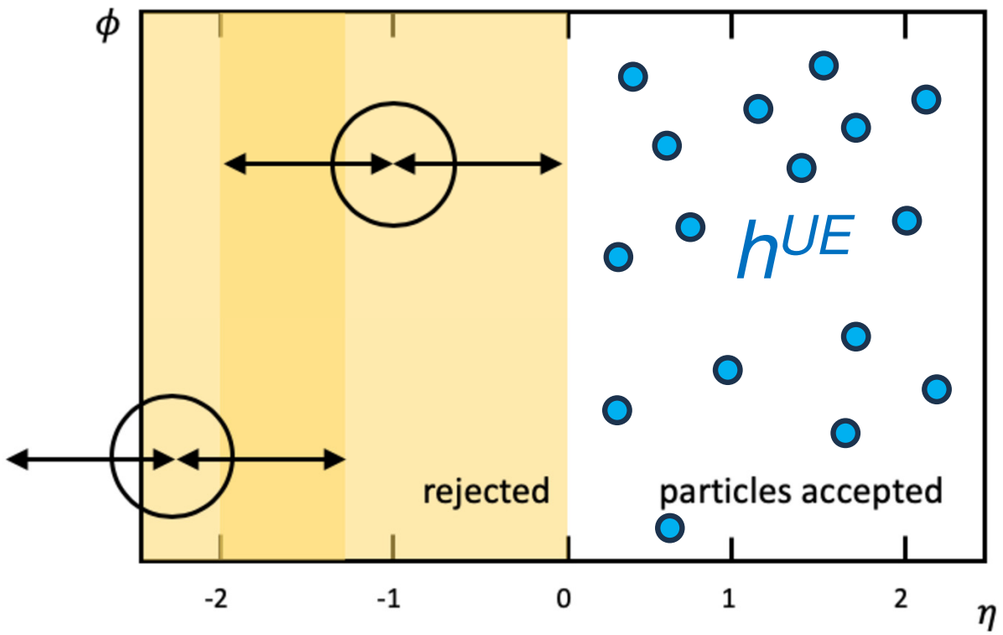

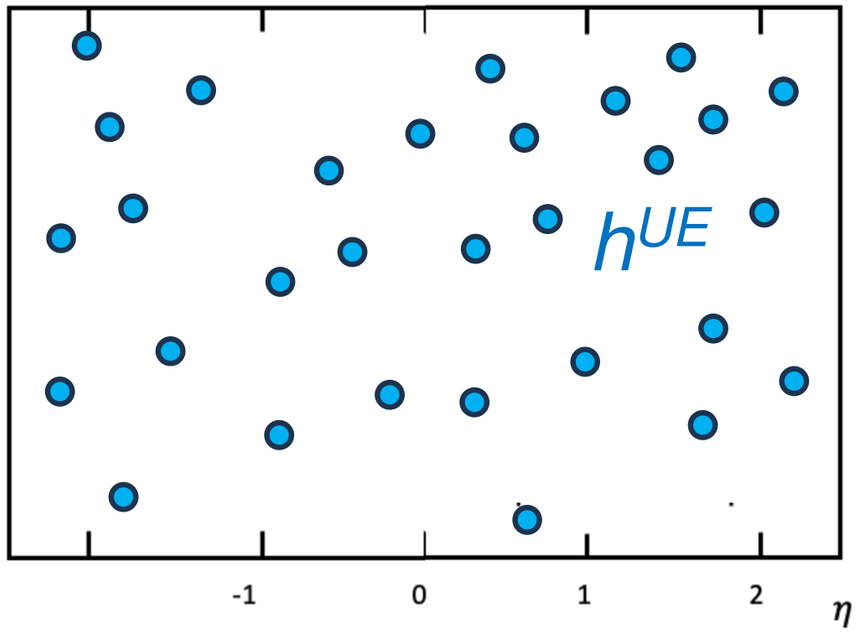

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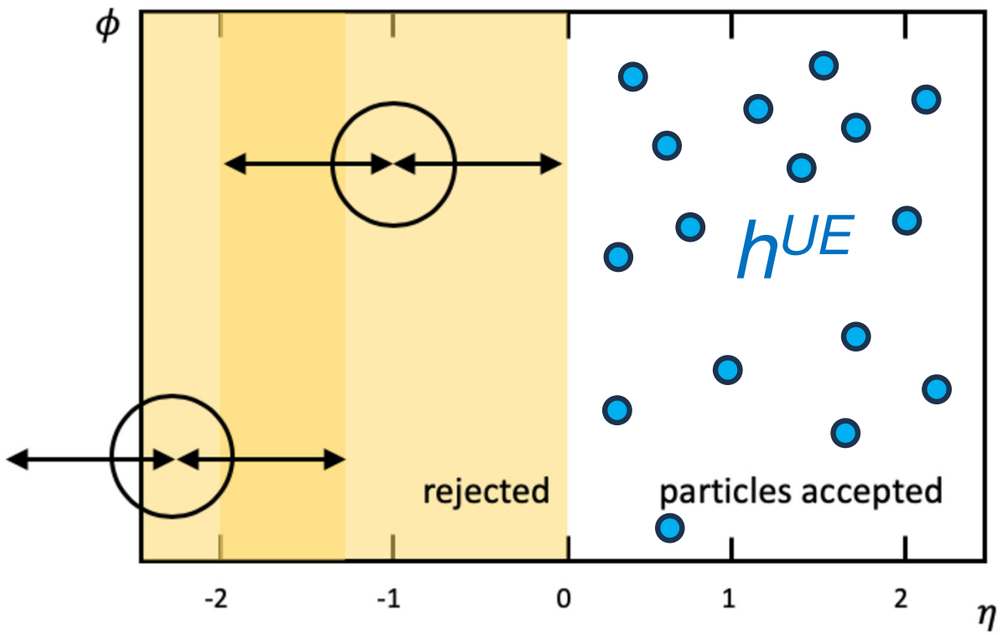
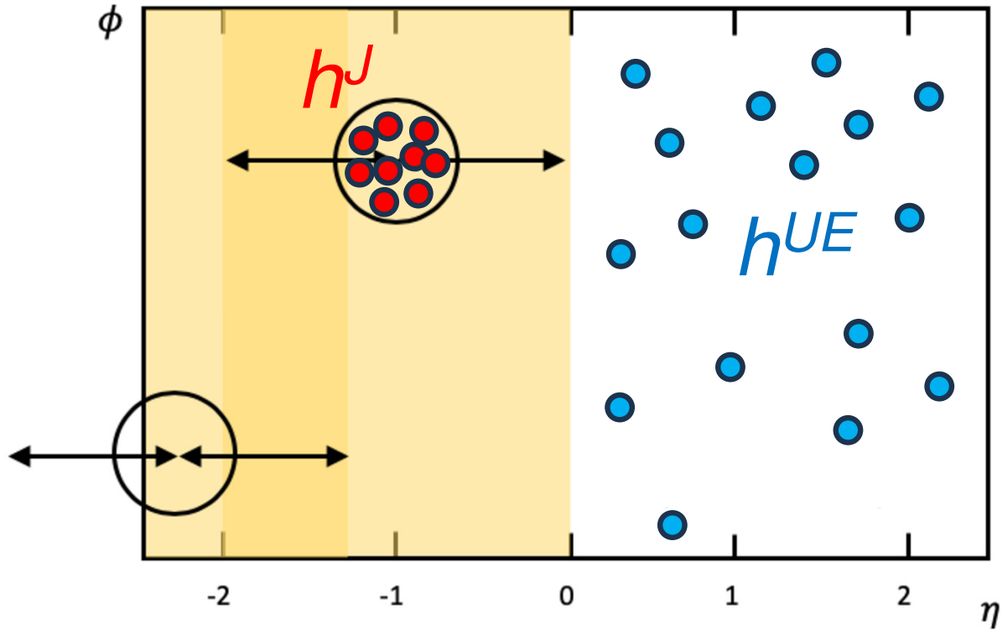
  - require that the track is separated by at least one unit in $|\eta|$ from all jets with p_T^G >15 GeV
- h^J : track associated with a jet
  - require that the track is within a 0.4 cone of a p_T^G >40 GeV Jet





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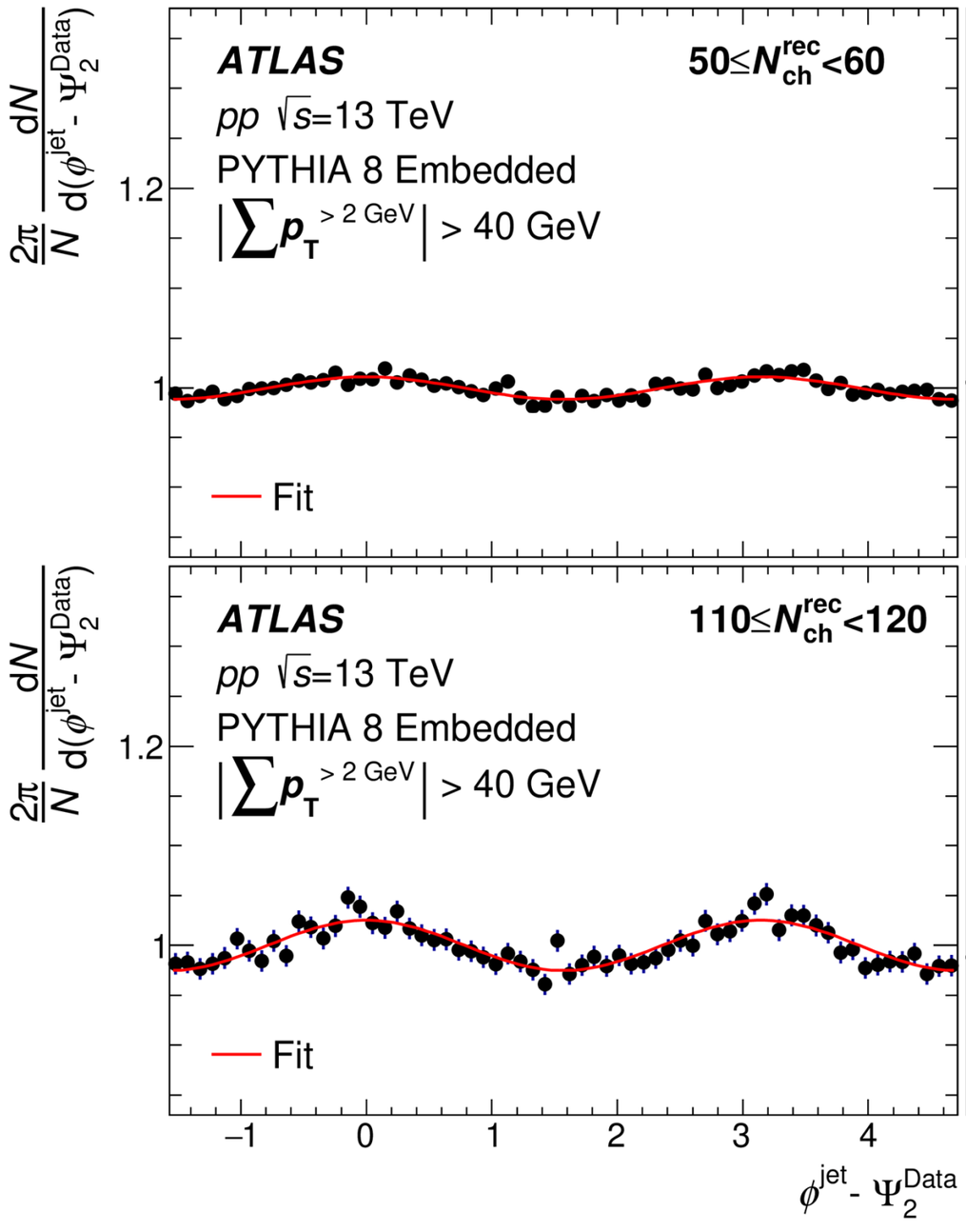
Grooming the Jets

Jet yields are found to be correlated with event-plane angles.

Effect known from heavy-ion measurements, here observed in *pp* collisions.

Naturally leads to bias in jet-selected correlations.



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Grooming the Jets

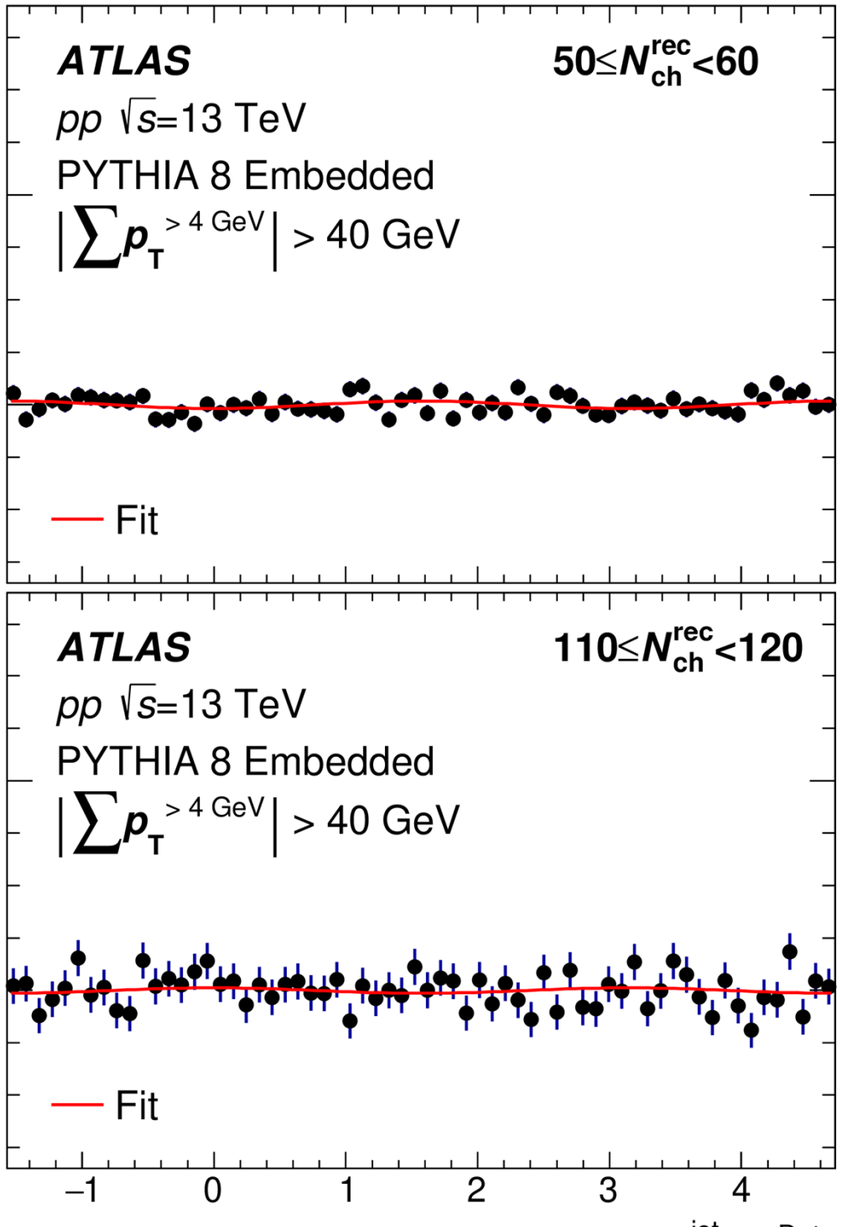
Jet yields are found to be correlated with event-plane angles.

Effect known from heavy-ion measurements, here observed in *pp* collisions.

Naturally leads to bias in jet-selected correlations.

We define a groomed jet- p_T to account for this effect.

$$p_{\mathrm{T}}^{\mathrm{G}} = \left| \sum_{\text{constituents}} \boldsymbol{p}_{\mathrm{T}}^{> 4\ \mathrm{GeV}} \right|$$



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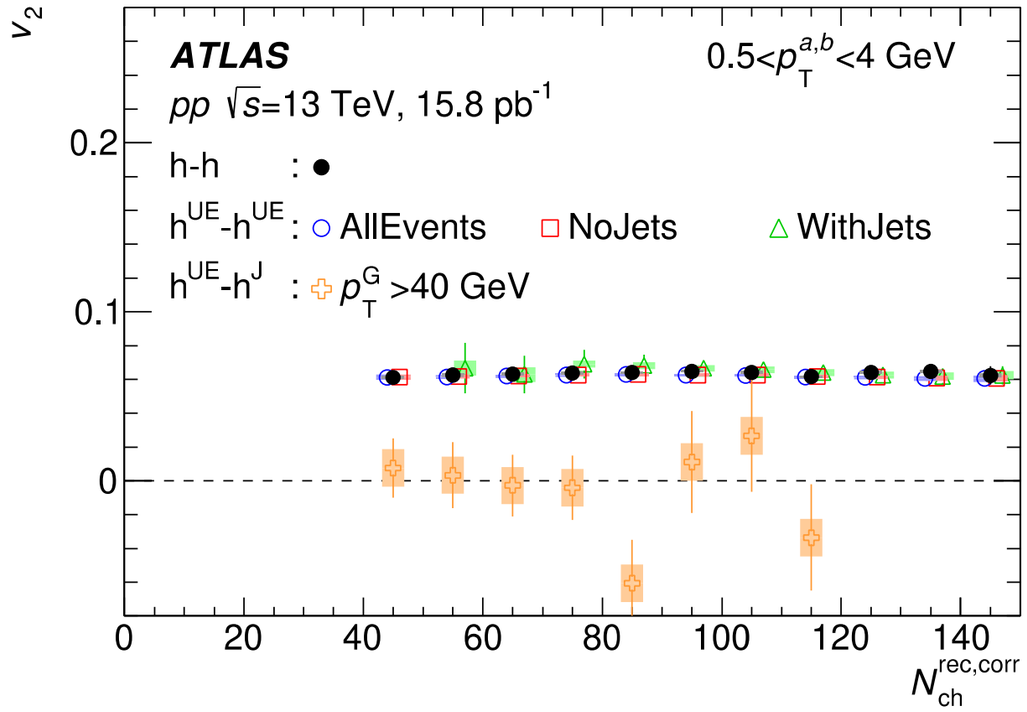
v_2 : comparison between cases



- 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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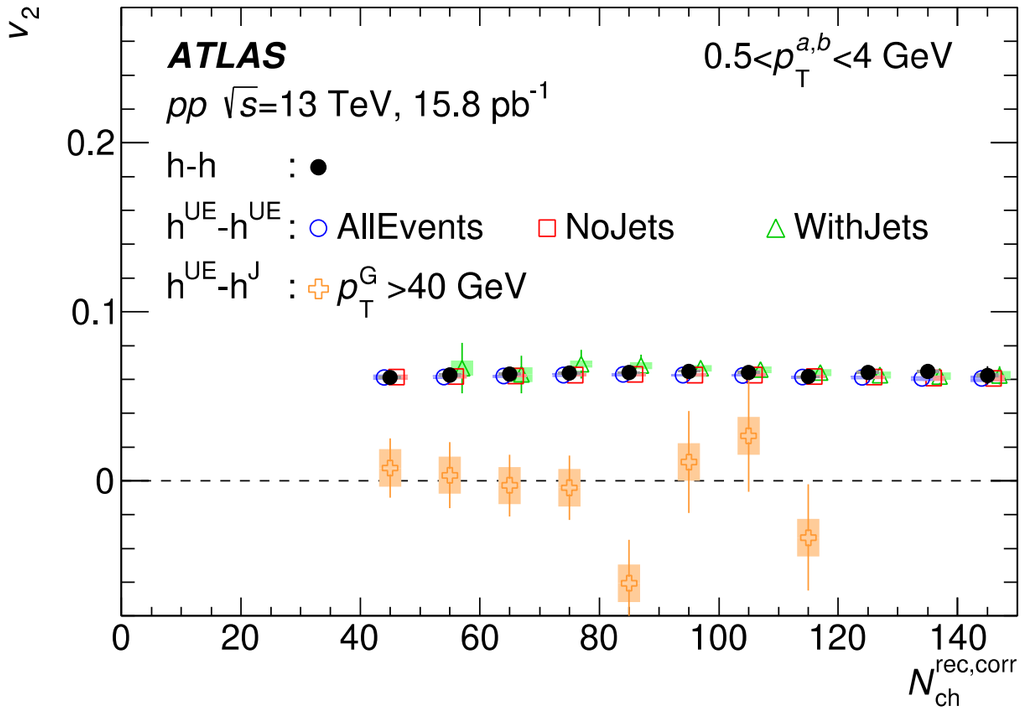

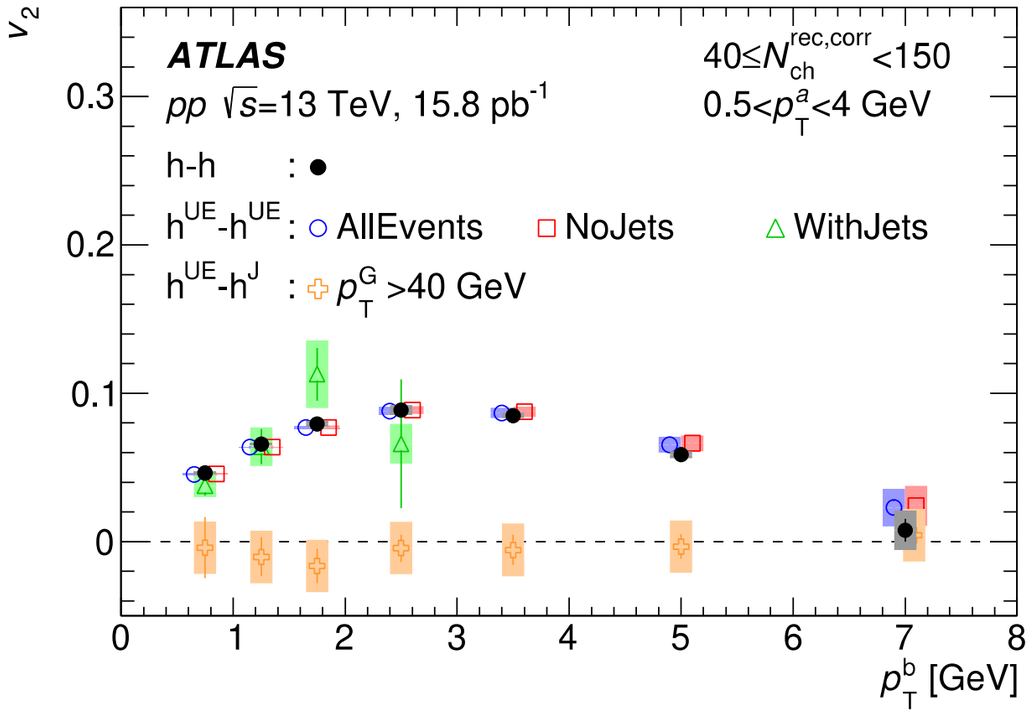

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  - Presence/absence of Jets in events does not impact the v_2
- h^{UE}-h^{J} v_2 consistent with zero within uncertainties
  - Ridge is not related to jets!
  - Behavior is true as function of p_T as well.

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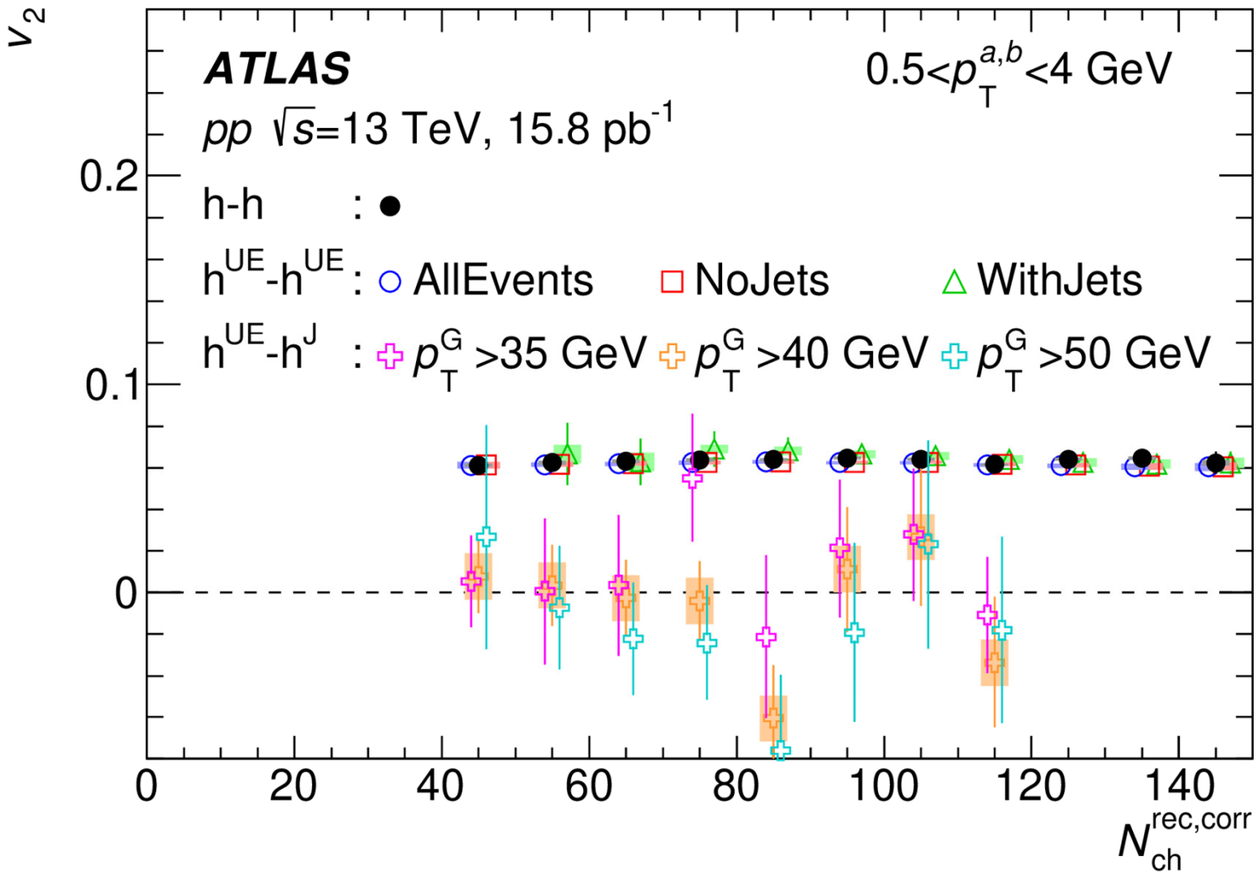
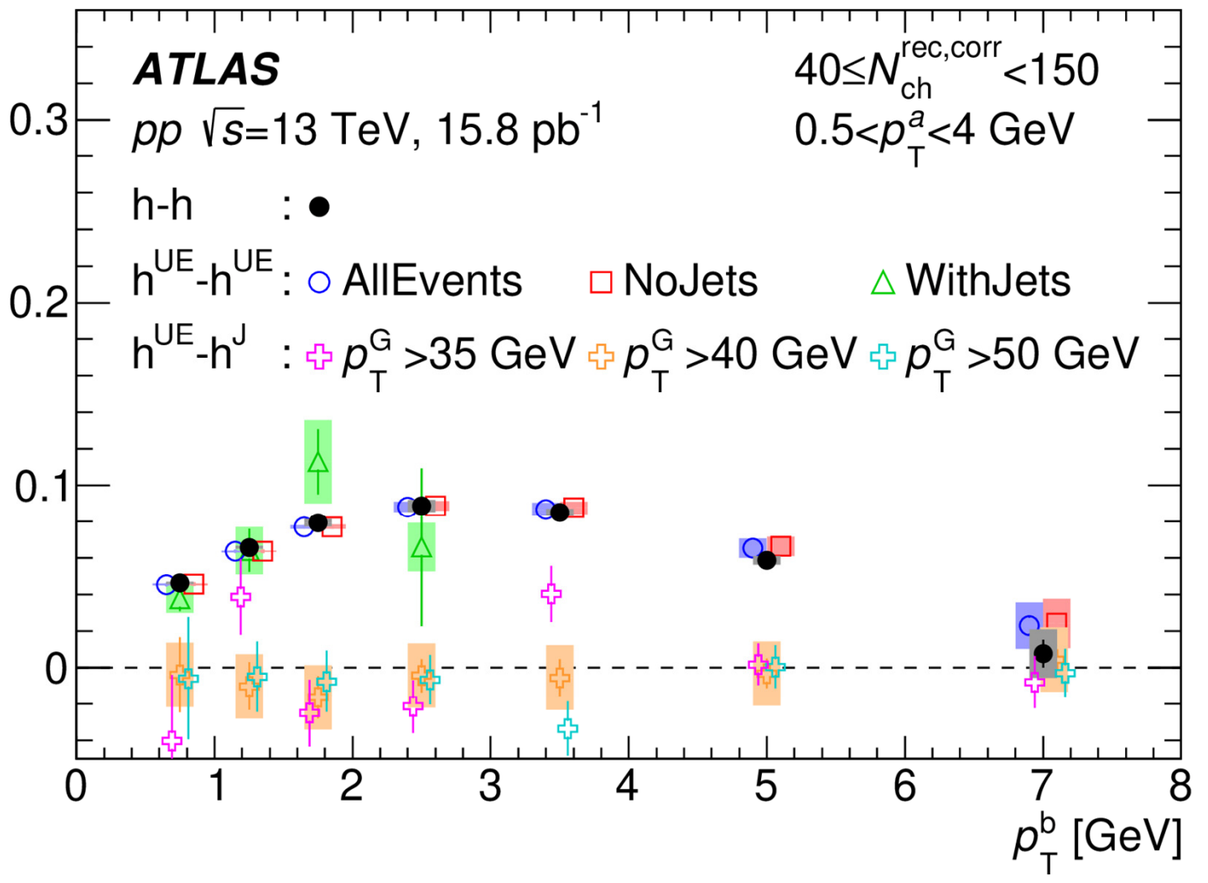
v_2 : Dependence on jet selection





Results not sensitive to p_T threshold of Jets used in measurement

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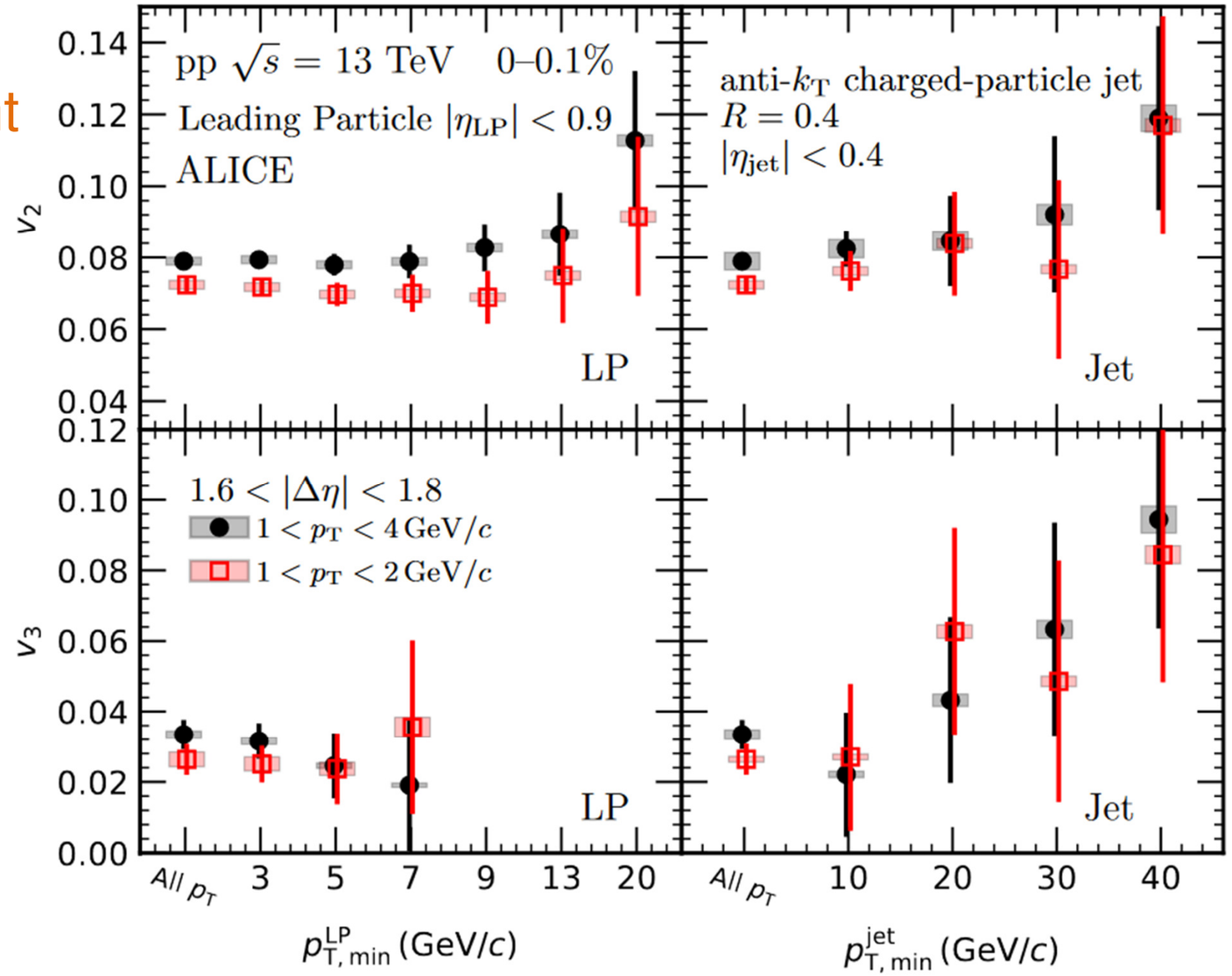
Similar measurements from ALICE

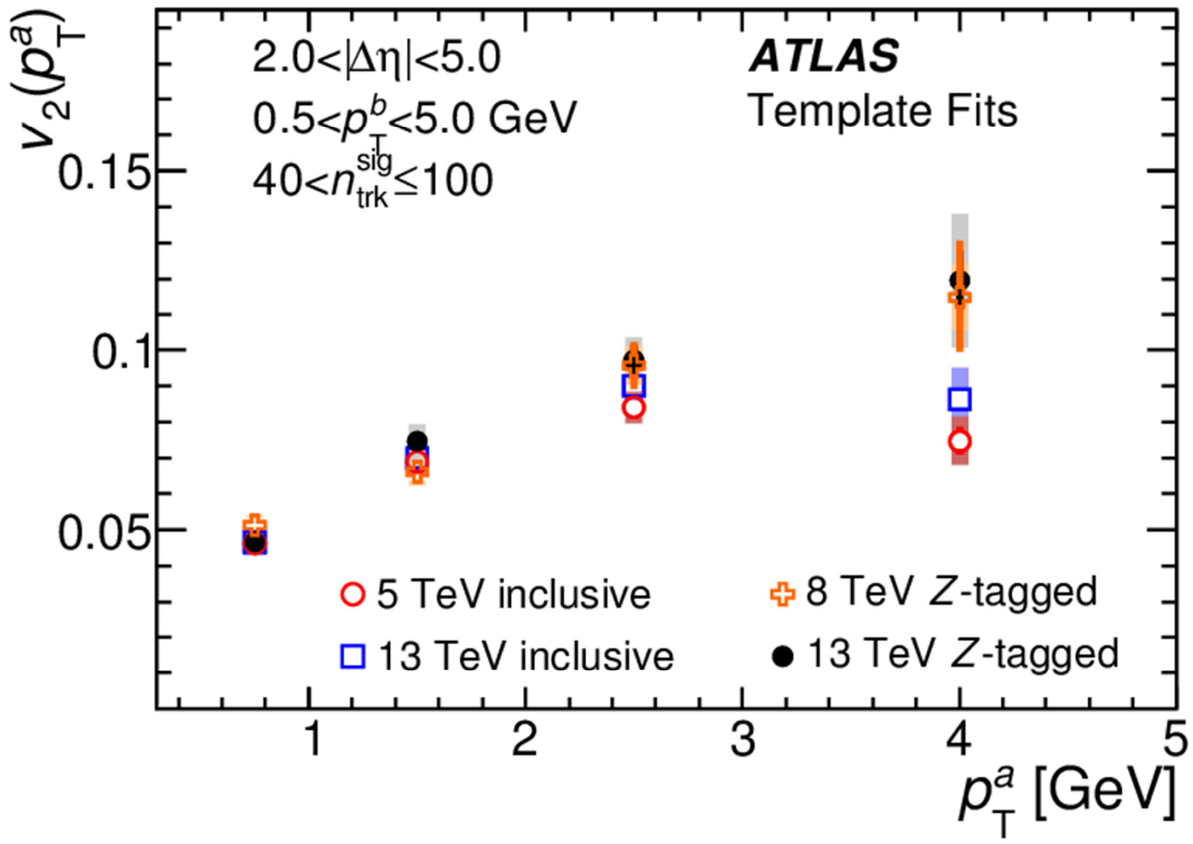
- Measure the v_2,v_3 in *pp* collisions
  - p_T of leading particle (LP) in event
  - p_T of jet in event in event
  - LP/Jet picked at mid-rapidity
- Top panels: v_2, bottom panels: v_3
- Left panel: vs leading particle p_T
- Right panel: vs leading-jet p_T

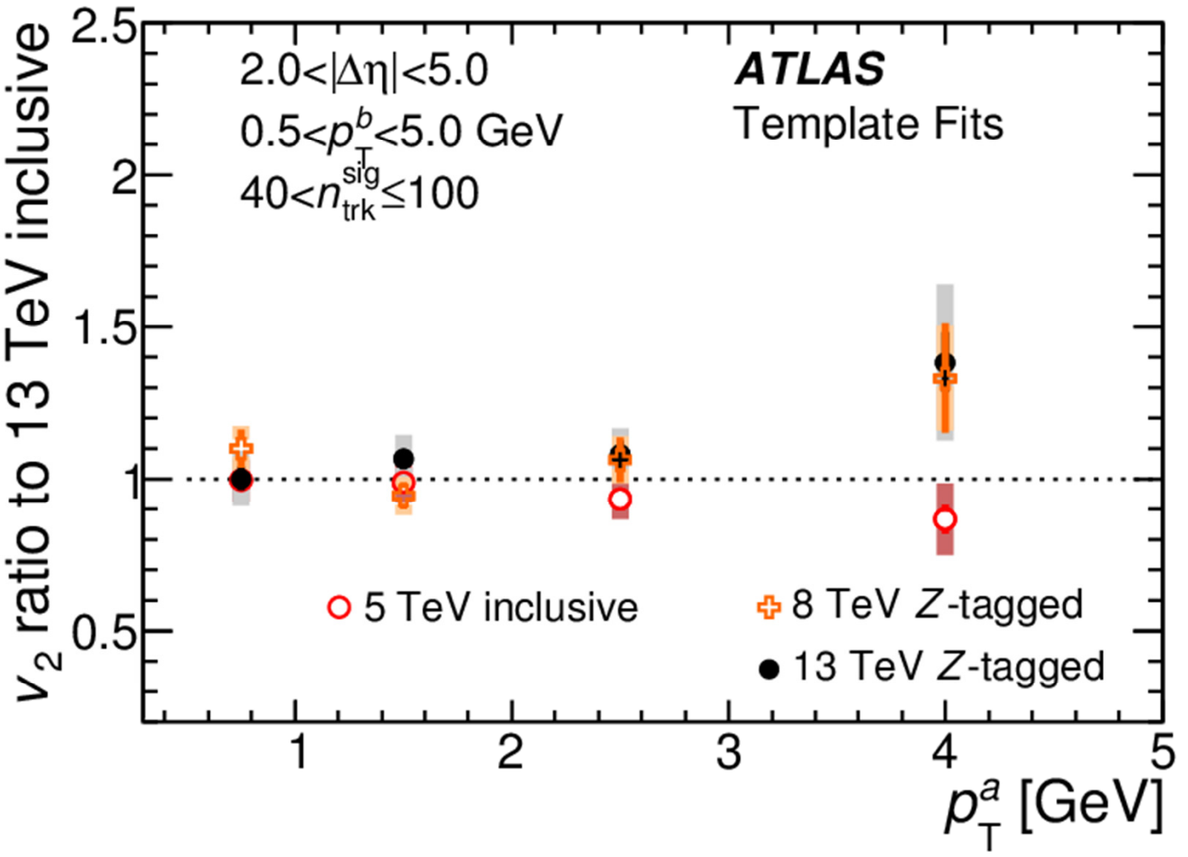
Same conclusions as ATLAS
(within uncertainties)



ALICE: arXiv:2308.16591

v_2 in Z-boson tagged *pp* events: constrain impact-parameter

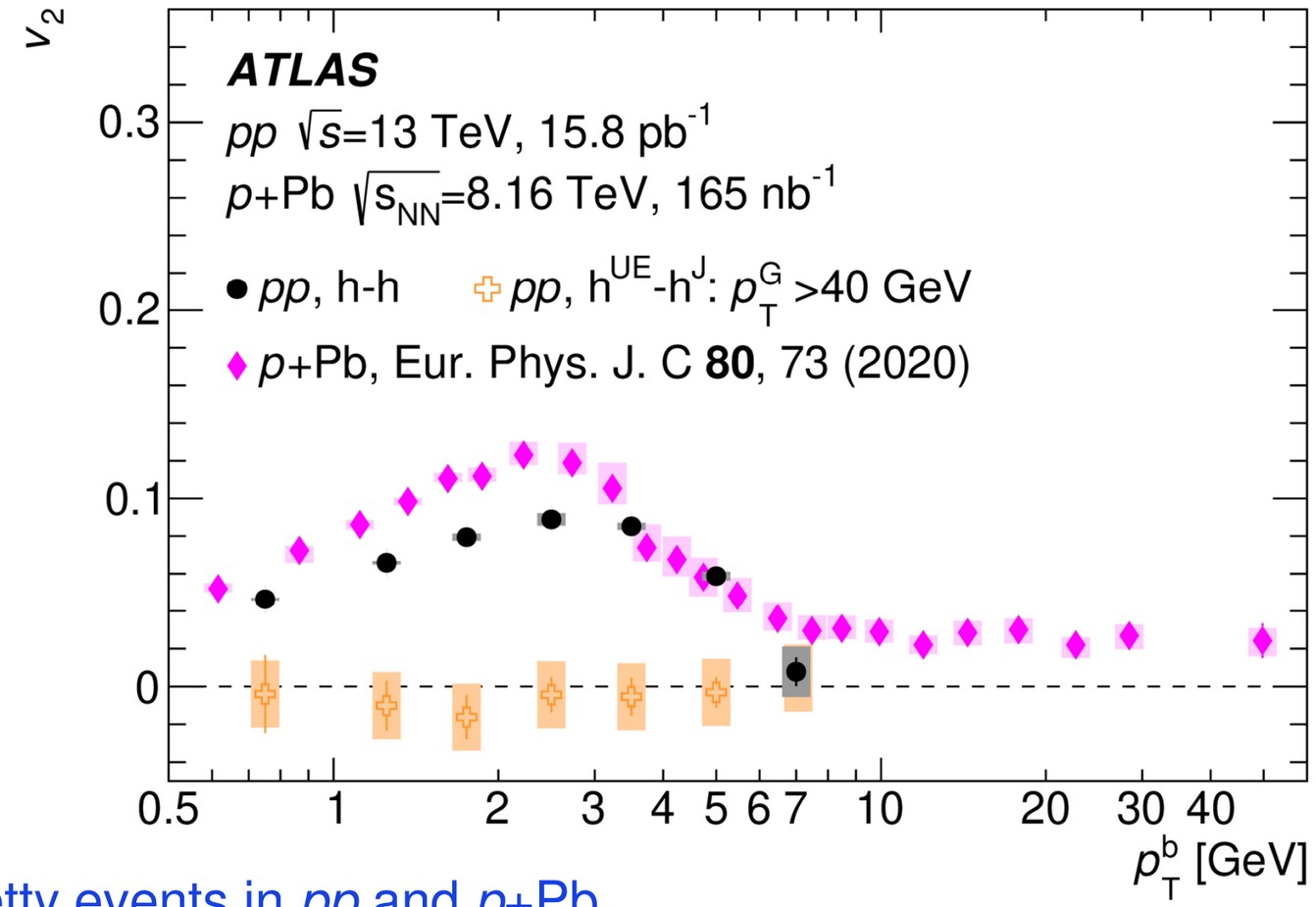




- Can constrain smaller impact parameter indirectly: by requiring the presence of a hard scattering, for example presence of a Z-boson.
- Use high-luminosity *pp* data at 8 and 13 TeV
- The *pp*-v_2 in *Z*-boson tagged events consistent with inclusive measurements.

ATLAS Collaboration
EPJC 80 (2020) 64

v_2 in Jetty events: *pp* vs *p*+Pb



- Compare the v_2 in Jetty events in *pp* and *p*+Pb
  - About 2% high-p_T v_2 observed in *p*+Pb
  - Consistent with 0 in *pp*
- Note that measurement techniques are different!

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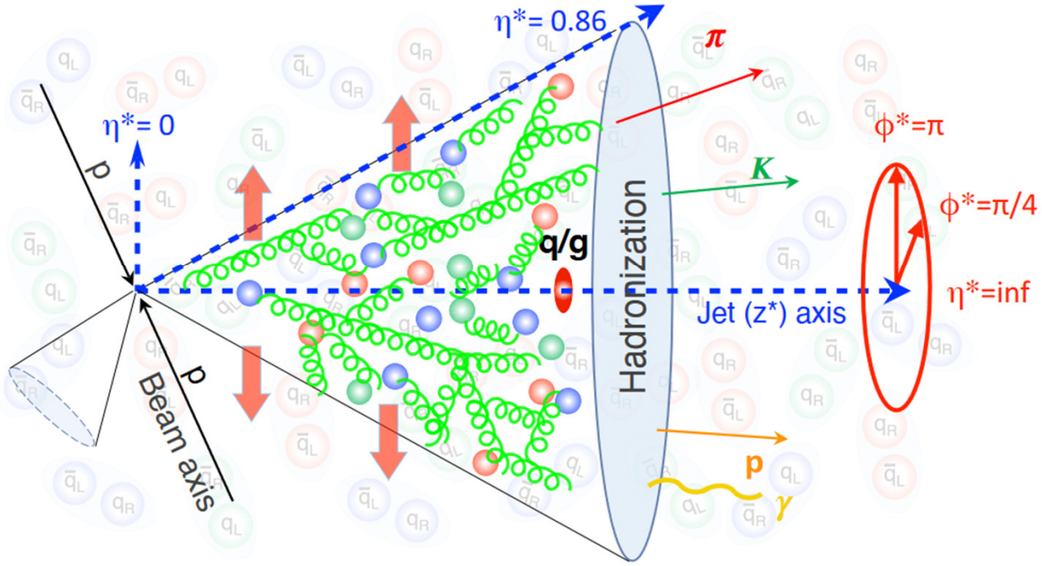
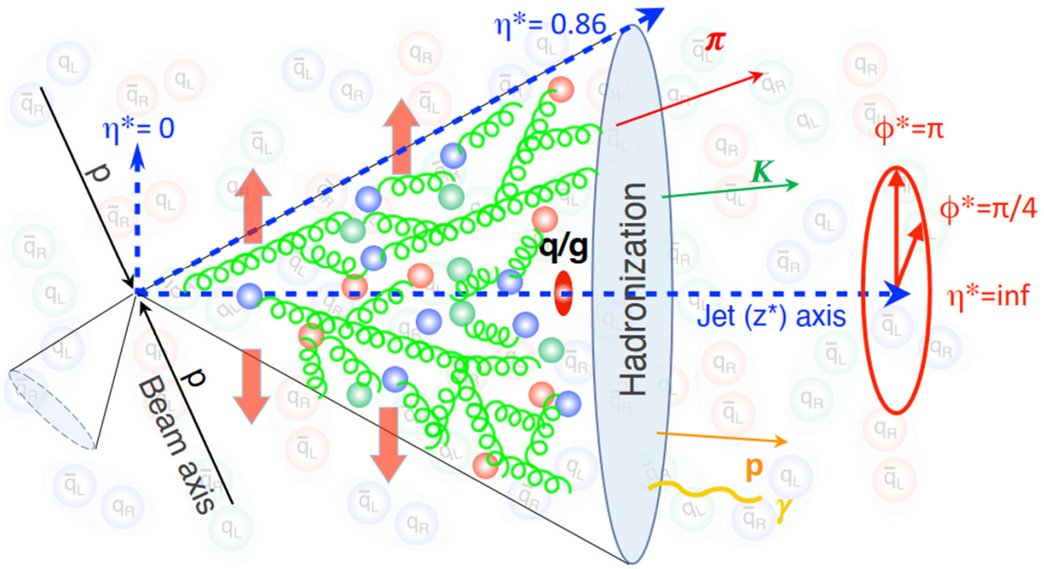
Intra-jet Collectivity

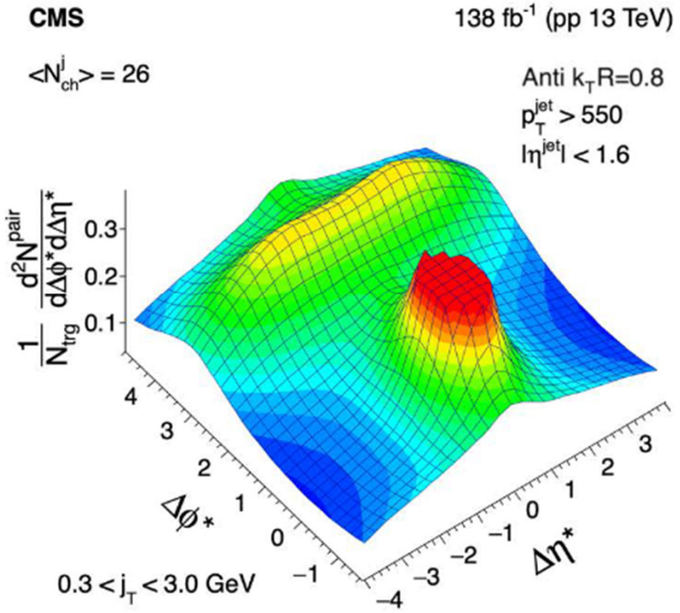


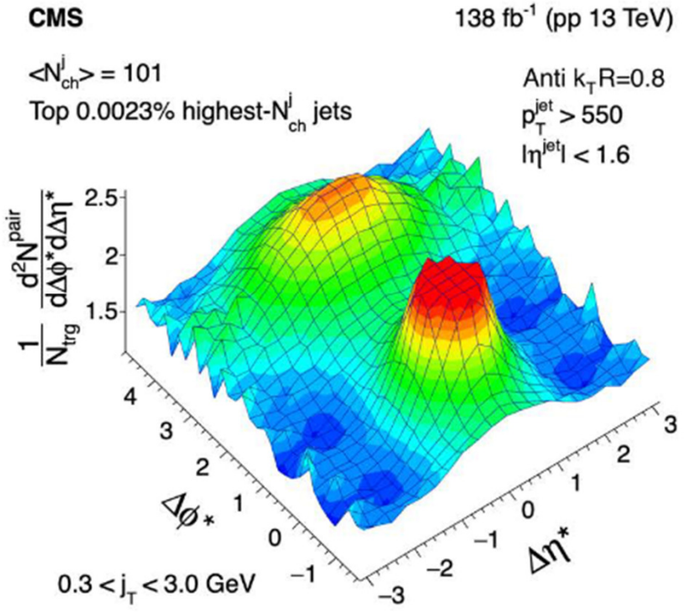
- CMS measurements to explore if there is “collective” behavior within constituents of high-multiplicity-jet.
  - Align coordinate system with jet-axis (η^*)
  - Measure two-particle correlations in ($\Delta\eta^*$, $\Delta\phi^*$) between constituents

CMS: arXiv:2312.17103

Intra-jet Collectivity







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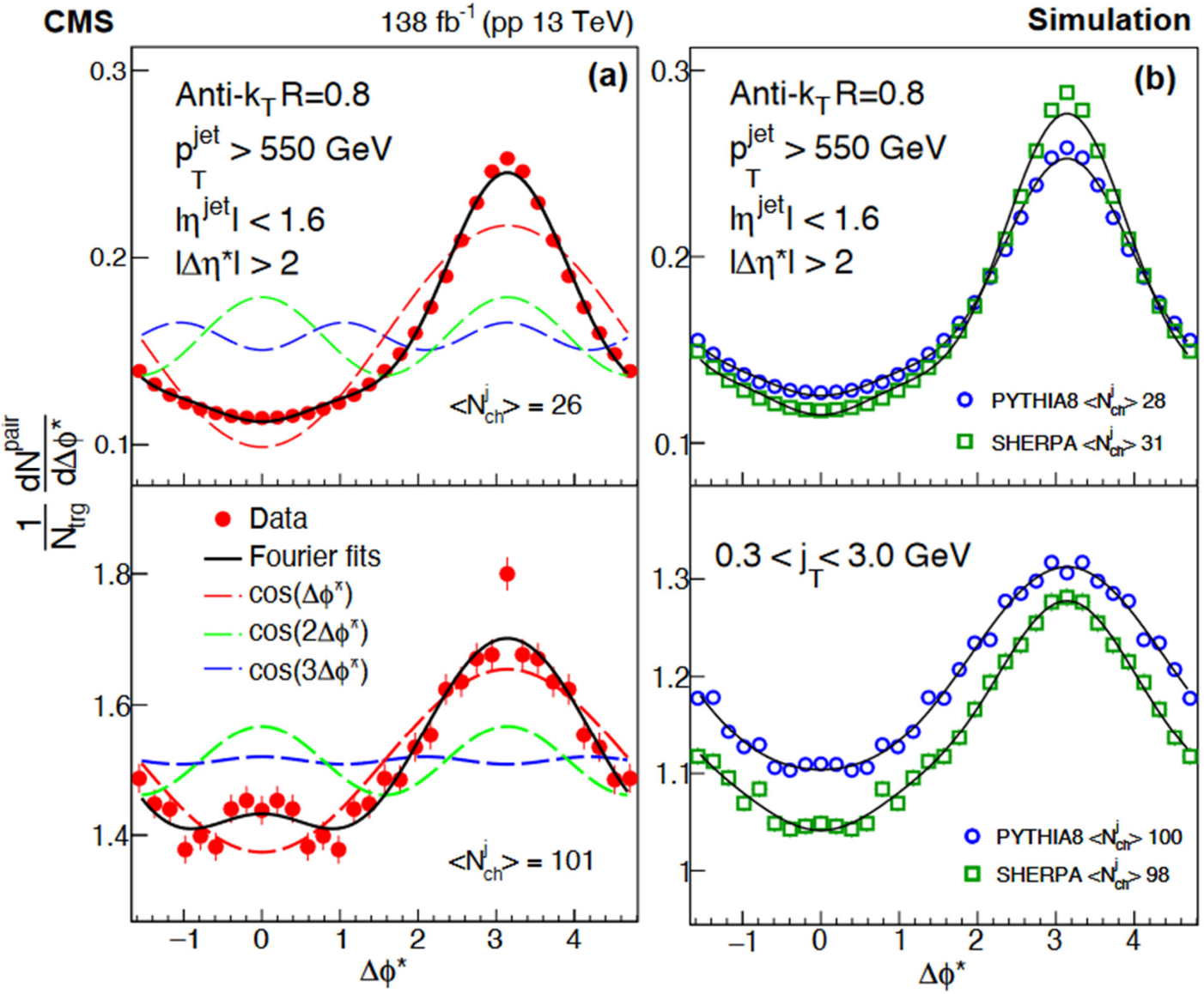
  - Align coordinate system with jet-axis (η^*)
  - Measure two-particle correlations in ($\Delta\eta^*$, $\Delta\phi^*$) between constituents
- Shown here are 2PCs for low-multiplicity and high-multiplicity jets

CMS: arXiv:2312.17103

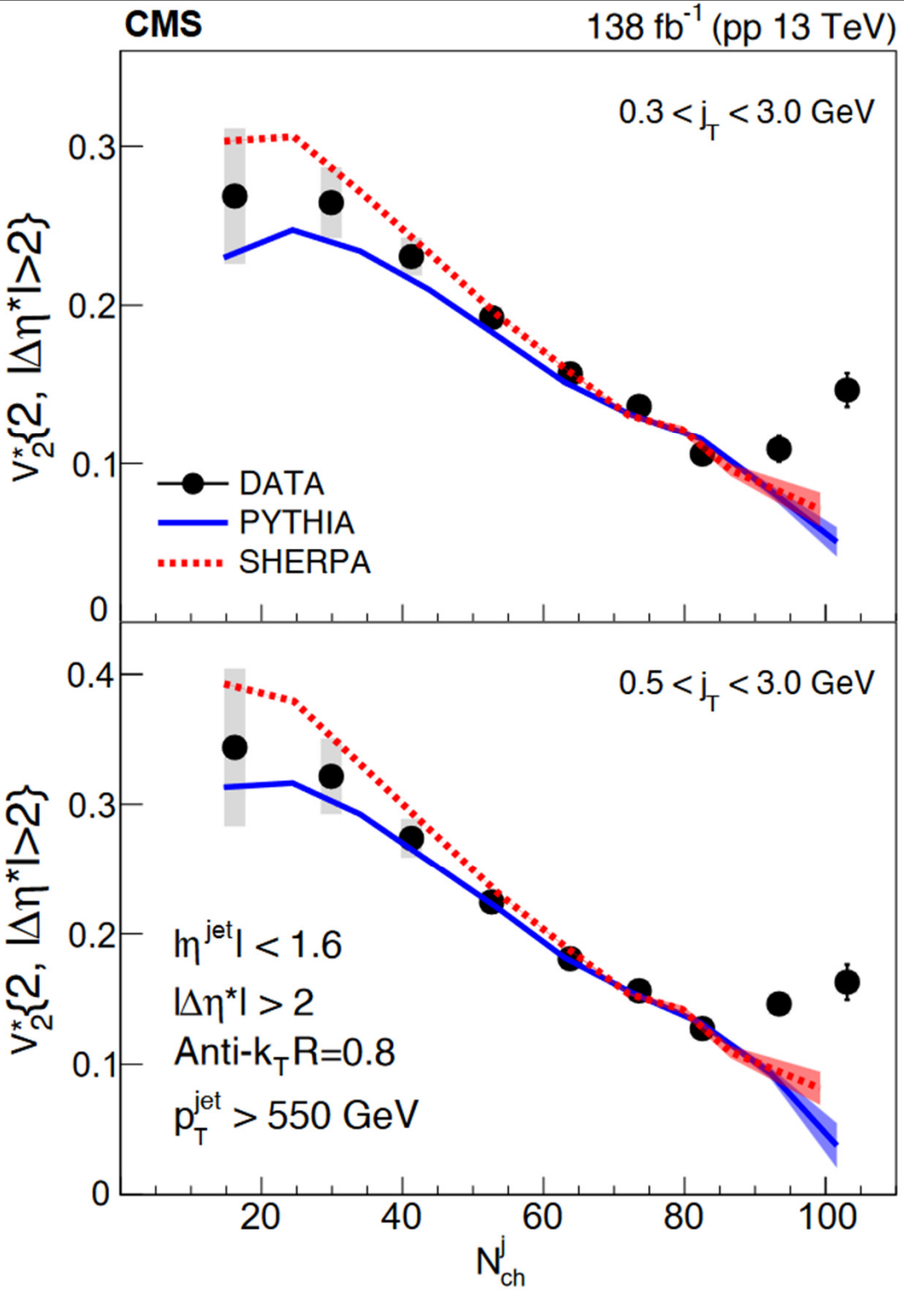
Intra-jet Collectivity



- 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

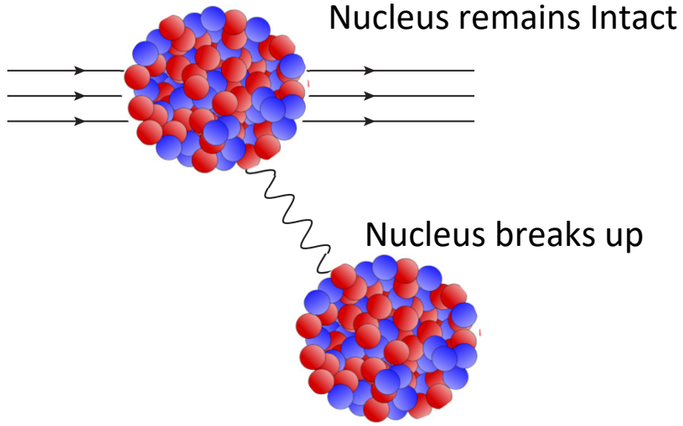


- The v_2 values vs jet multiplicity in Data and MC
- MC & Data v_2 decreases with multiplicity
  - Consistent for jet multiplicity<80
- For multiplicity>80: v_2 in data increase,
  - Inconsistent with MC
- Indicating of some collective behavior?
  - Need more guidance from theory

CMS: arXiv:2312.17103

Photon-ion and photon-proton collisions

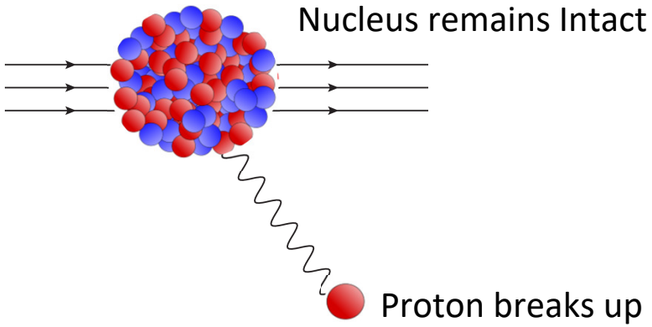
Ultra Peripheral Pb+Pb



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

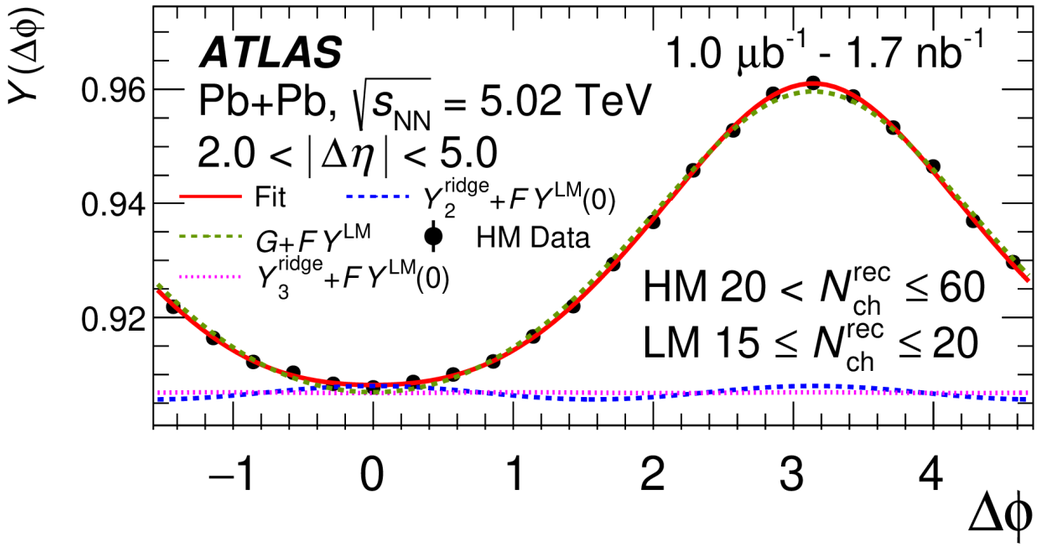
Ultra Peripheral Pb+*p*



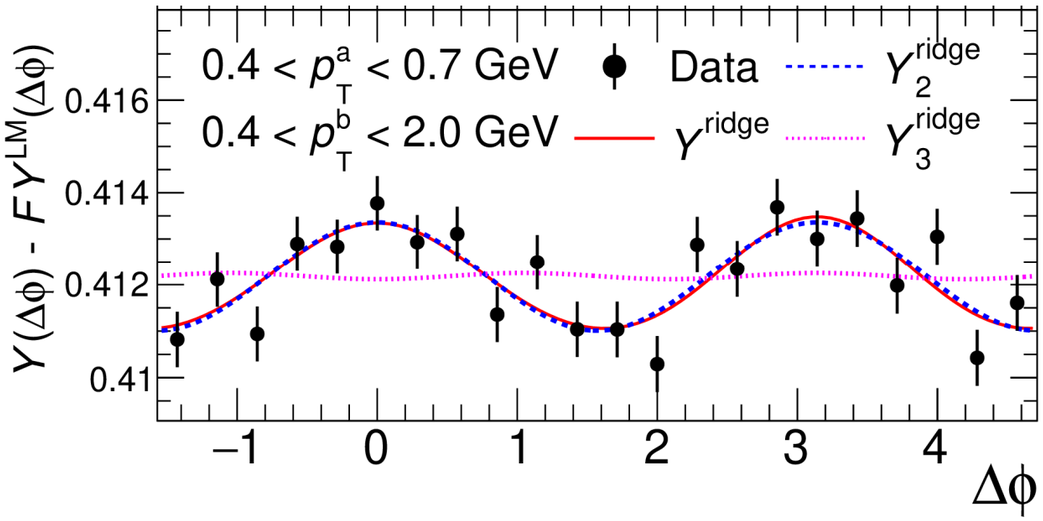
Similar process in UPC Pb+*p* : γ+*p* collisions

Collectivity in γ+Pb collisions

Raw correlation



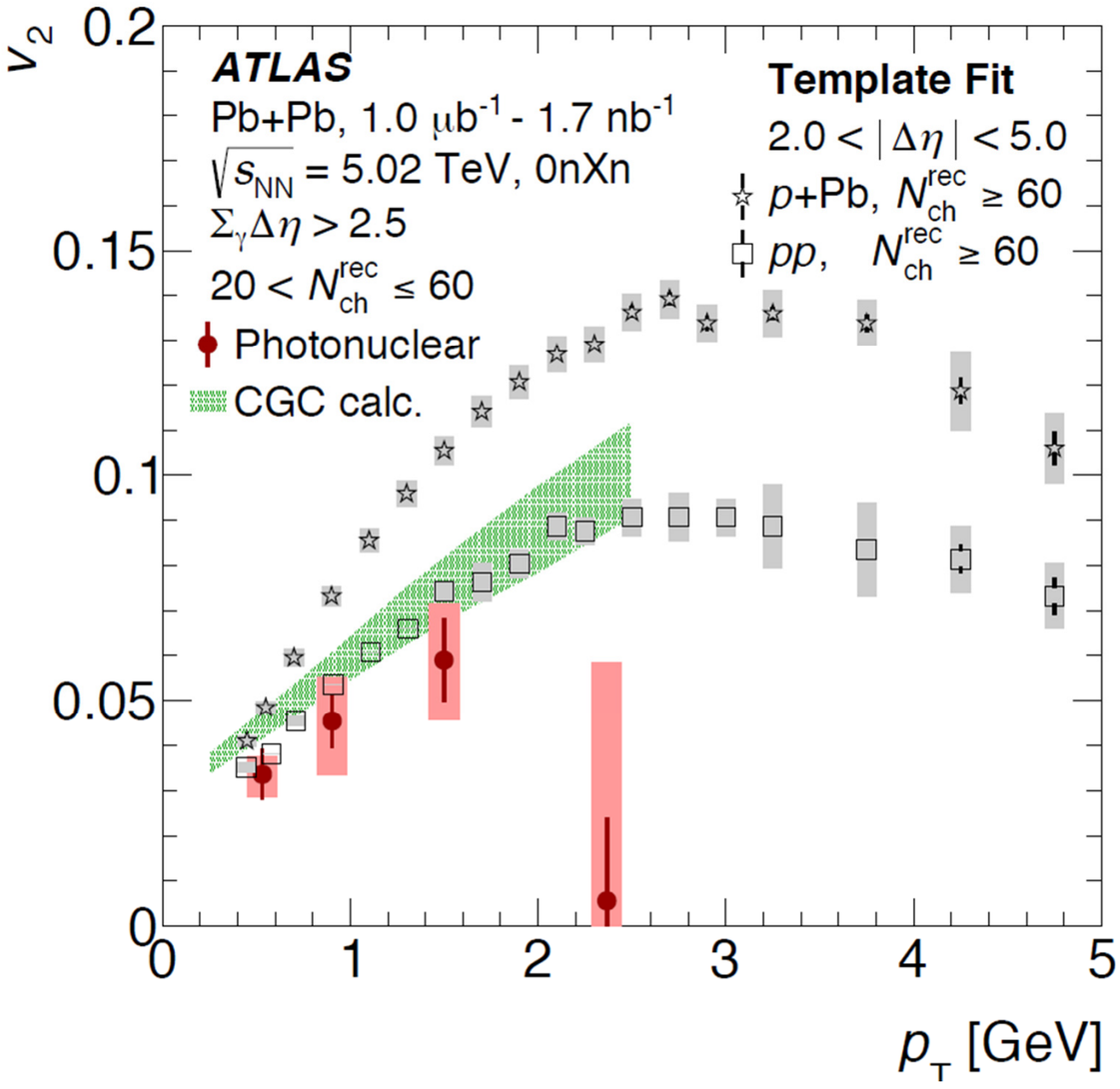
After non-flow subtraction



- The v_2 in γ +Pb are extracted using the Template-fit method.
- 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

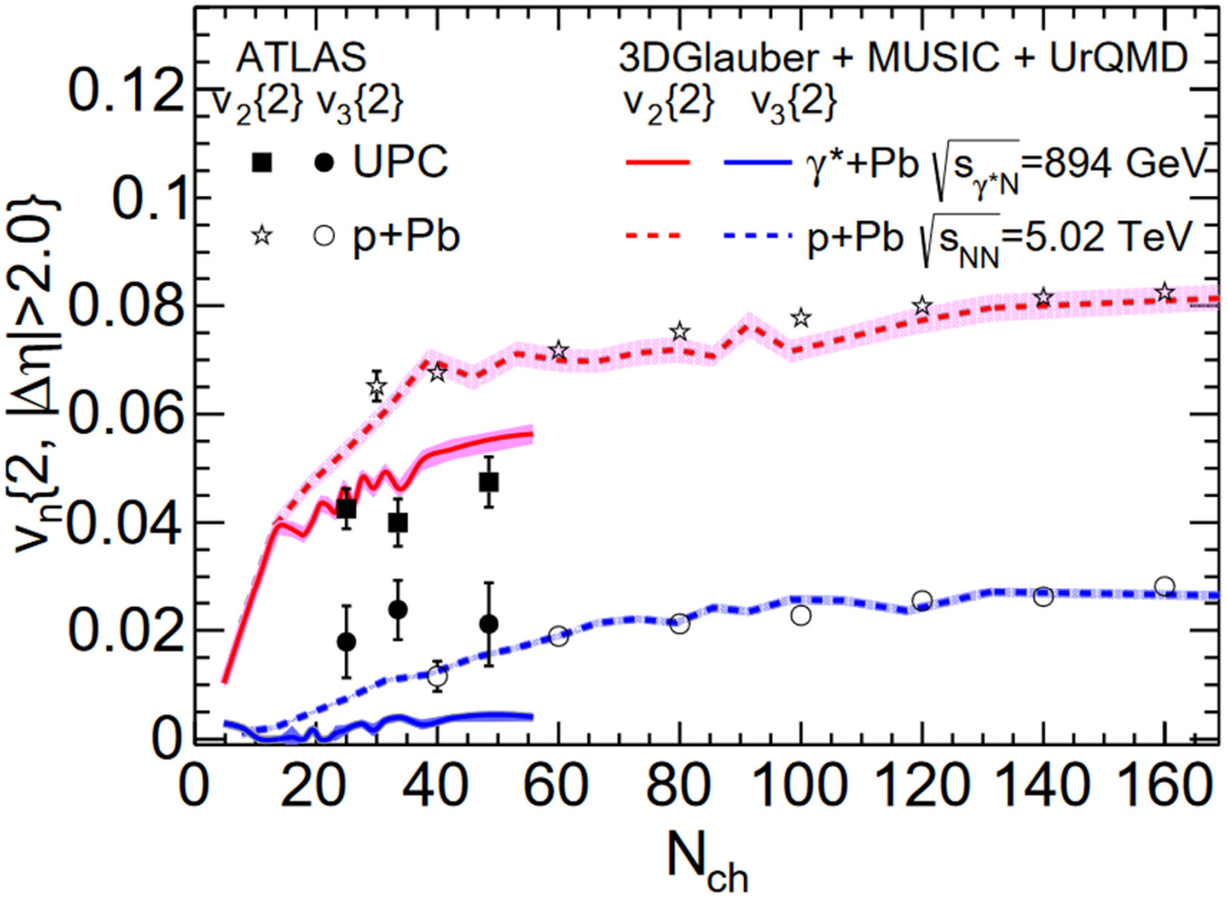
Collectivity in γ+Pb collisions



- 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 and v_3 in p+Pb
  - v_2 in γ+Pb

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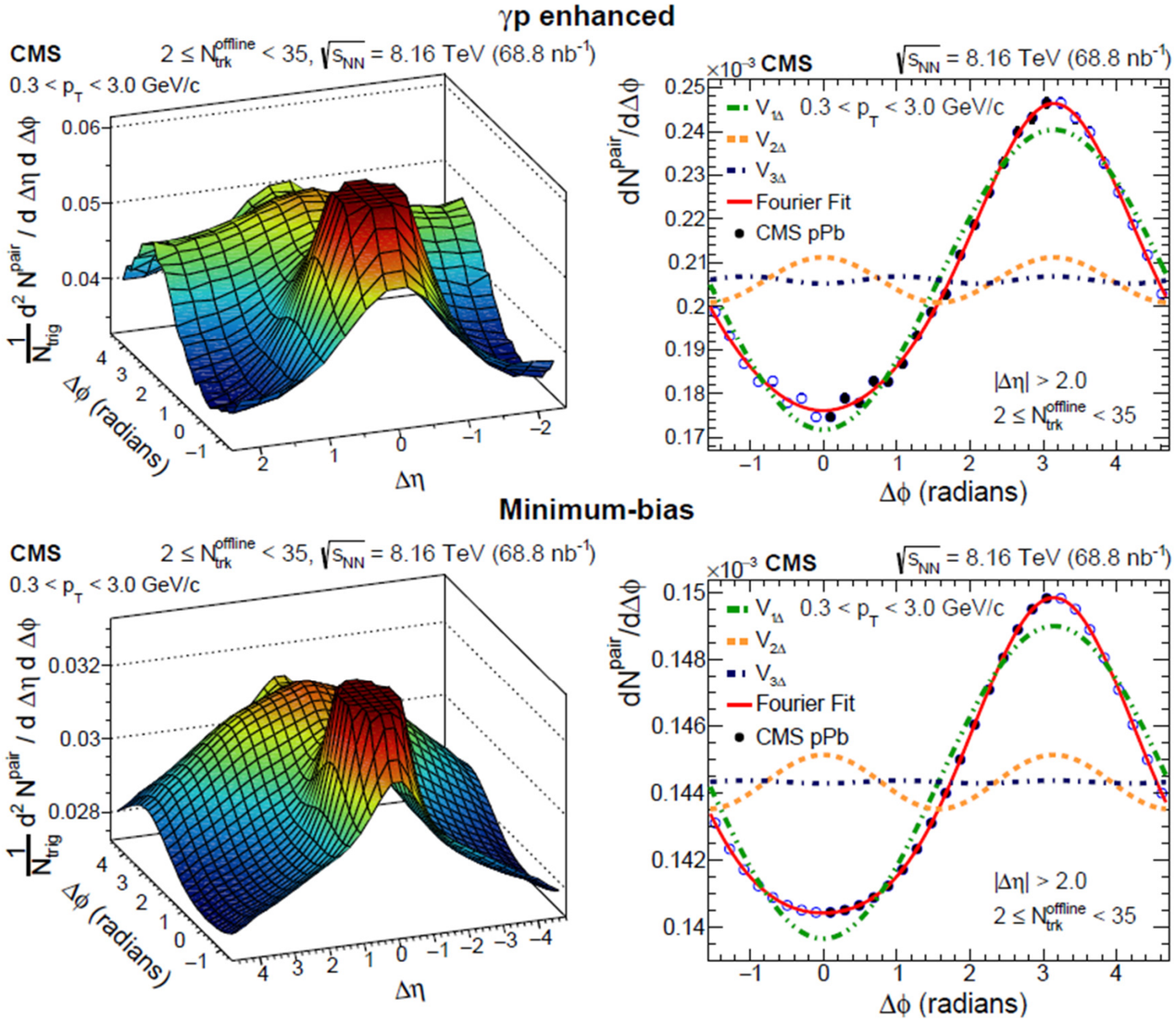
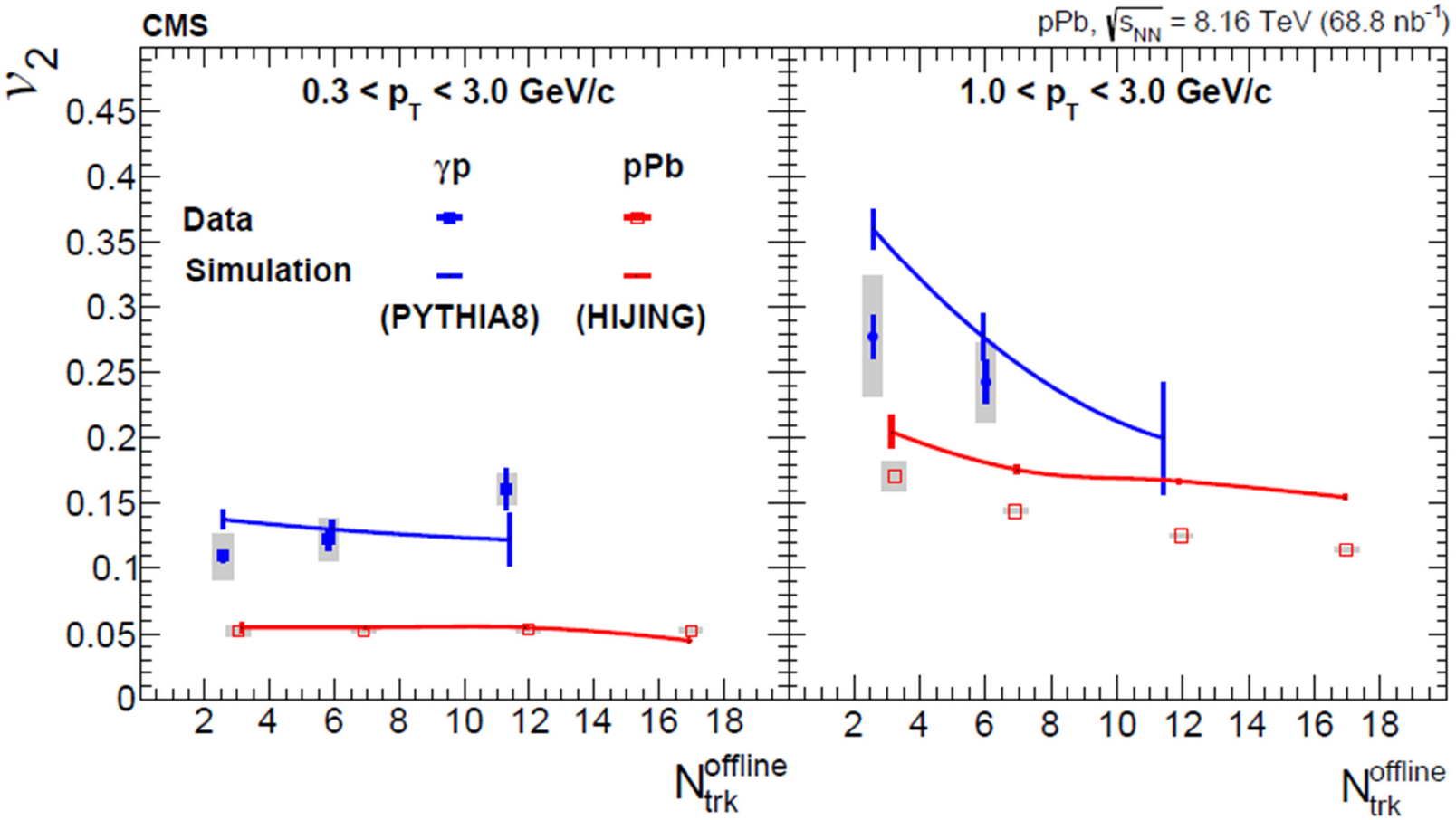
First look at γ+p collisions by CMS



- 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



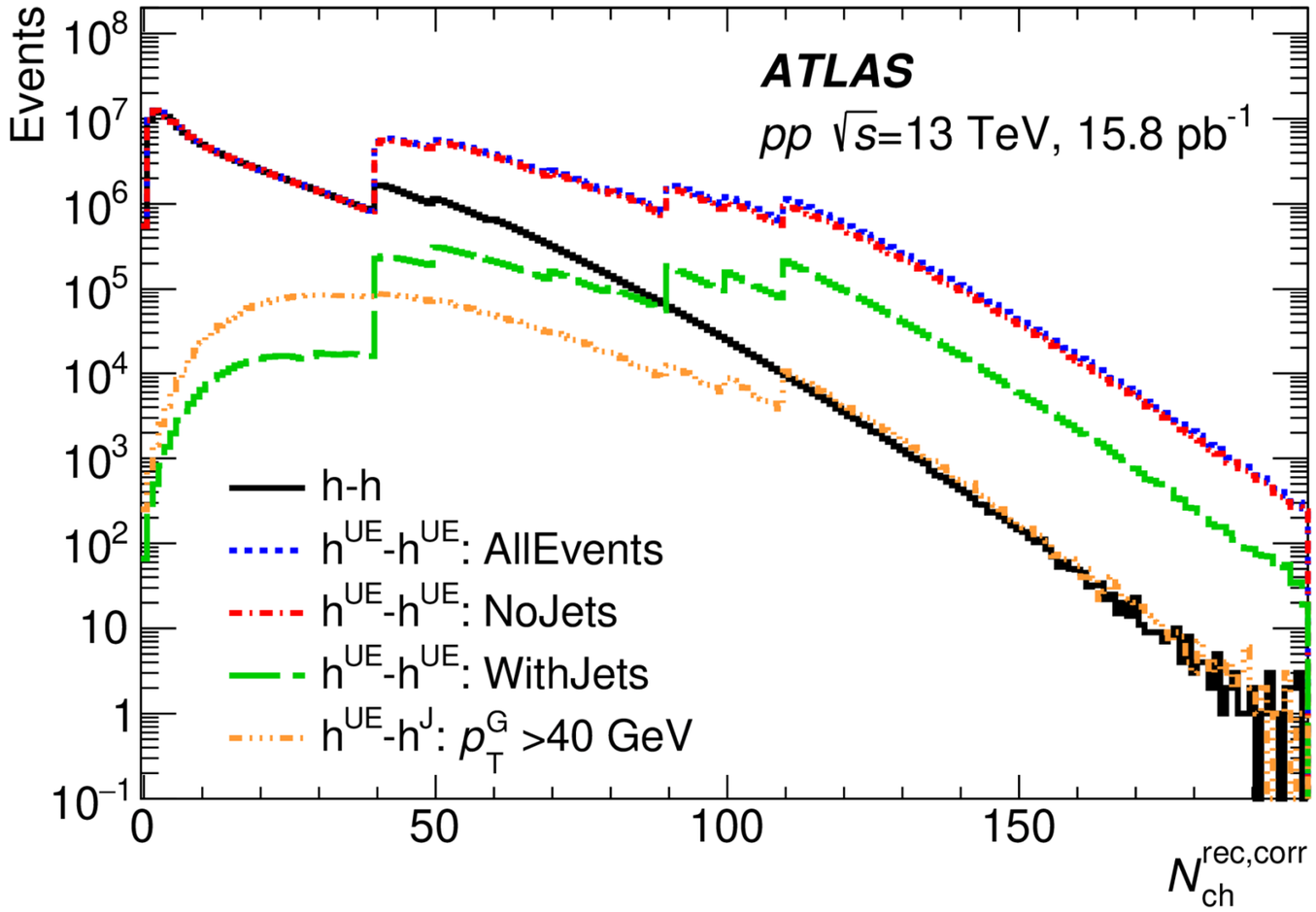
CMS: Phys. Lett. B 844 (2023) 137905

- 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

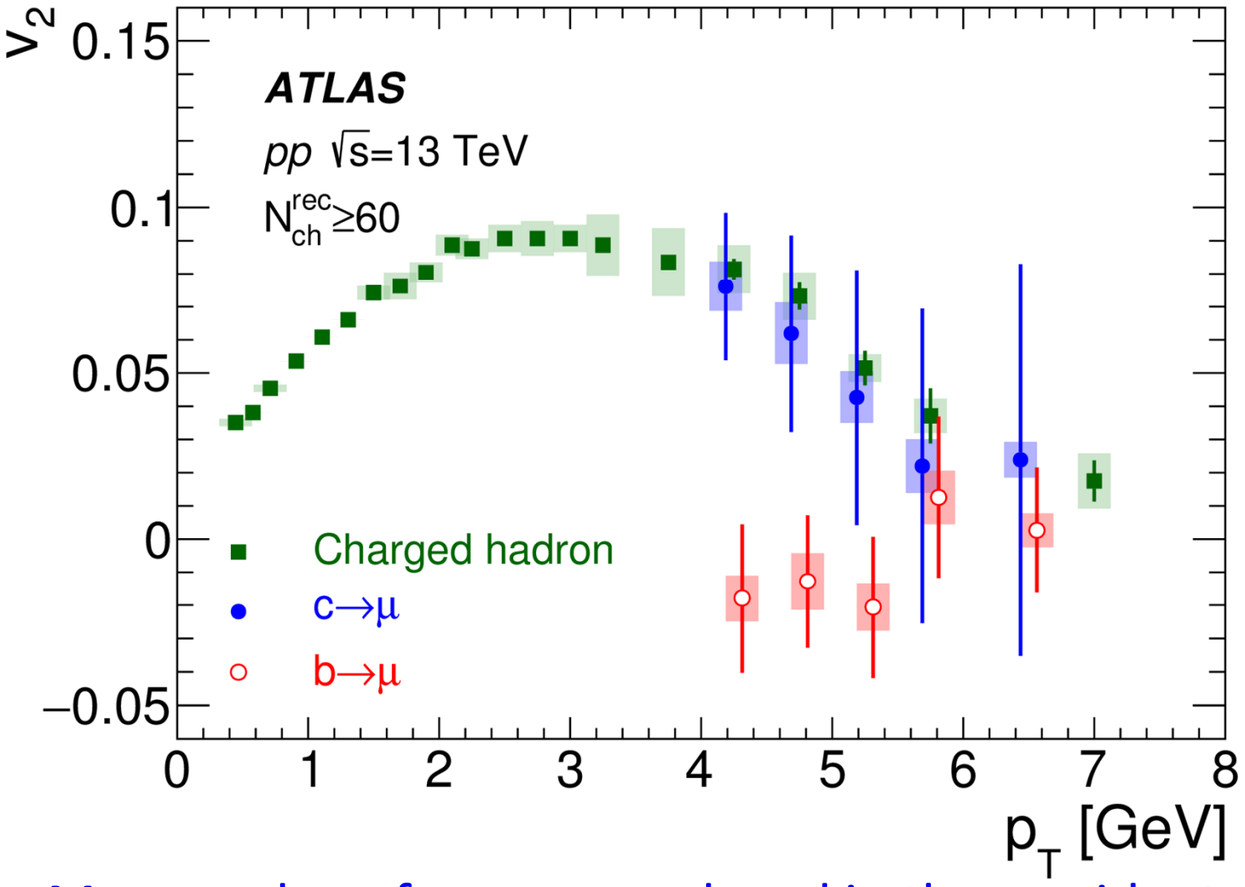
- Multiple recent measurements from ATLAS (CMS,ALICE) investigate collectivity in small collision systems.
- ATLAS : ridge in *pp* collisions with/without jets, “jet-constituent”-UE correlations
  - low-p_T v_2 not affected by presence/absence of jets.
  - Jet-fragments do not exhibit correlations with UE particles.
  - Hard-scattering & UE-collectivity are uncorrelated!
  - No observed dependence of v_2 on collision Q^2 (*Z*-tagged measurements).
- CMS : Measured correlations within jet-fragments
  - Correlation in low multiplicity jets consistent with MC generators.
  - Constituents in highest multiplicity jets show hints of collectivity.
- 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.
- CMS & ATLAS : 2PC measurements in γ+*p* and γ+Pb events.
  - Smallest collision systems at the LHC.

Event multiplicity distributions



ATLAS: PRL 131 (2023) 162301

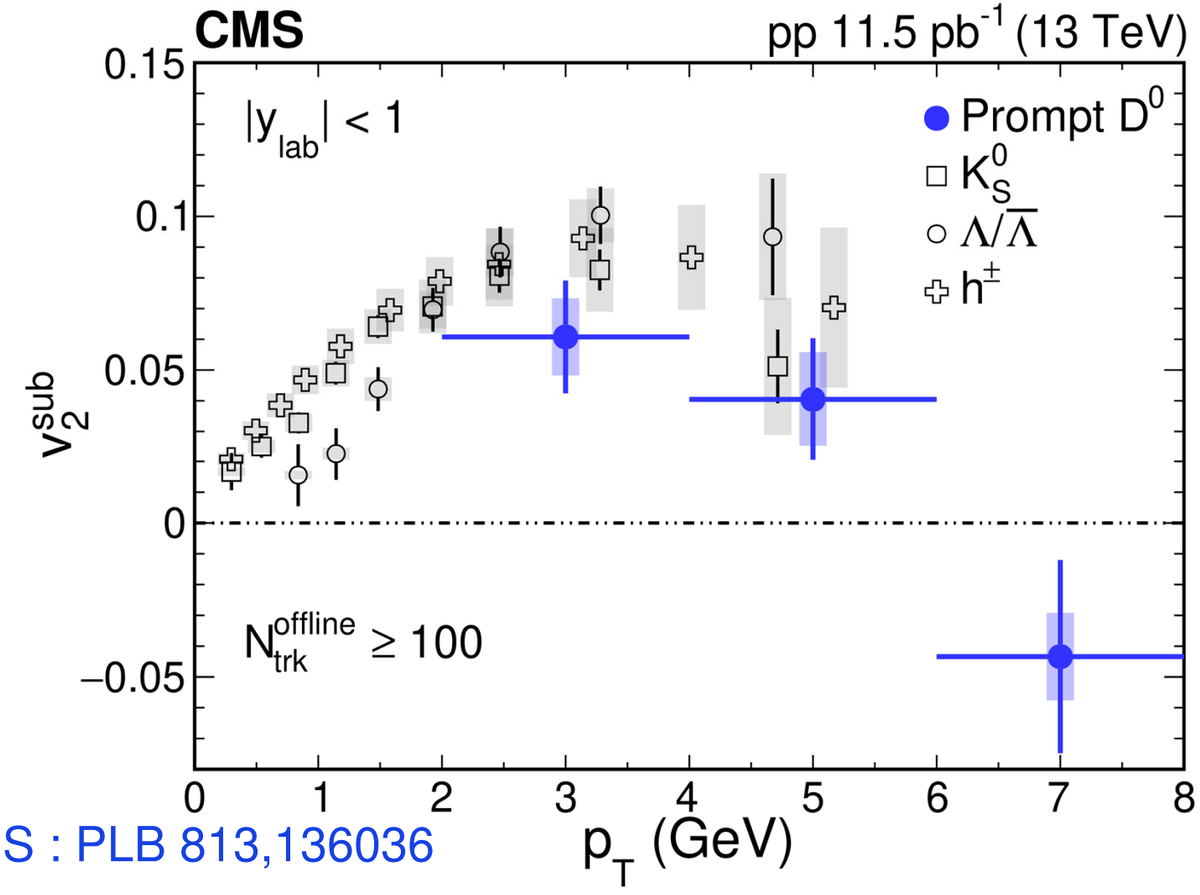
Extra-1: HF collectivity in *pp* collisions



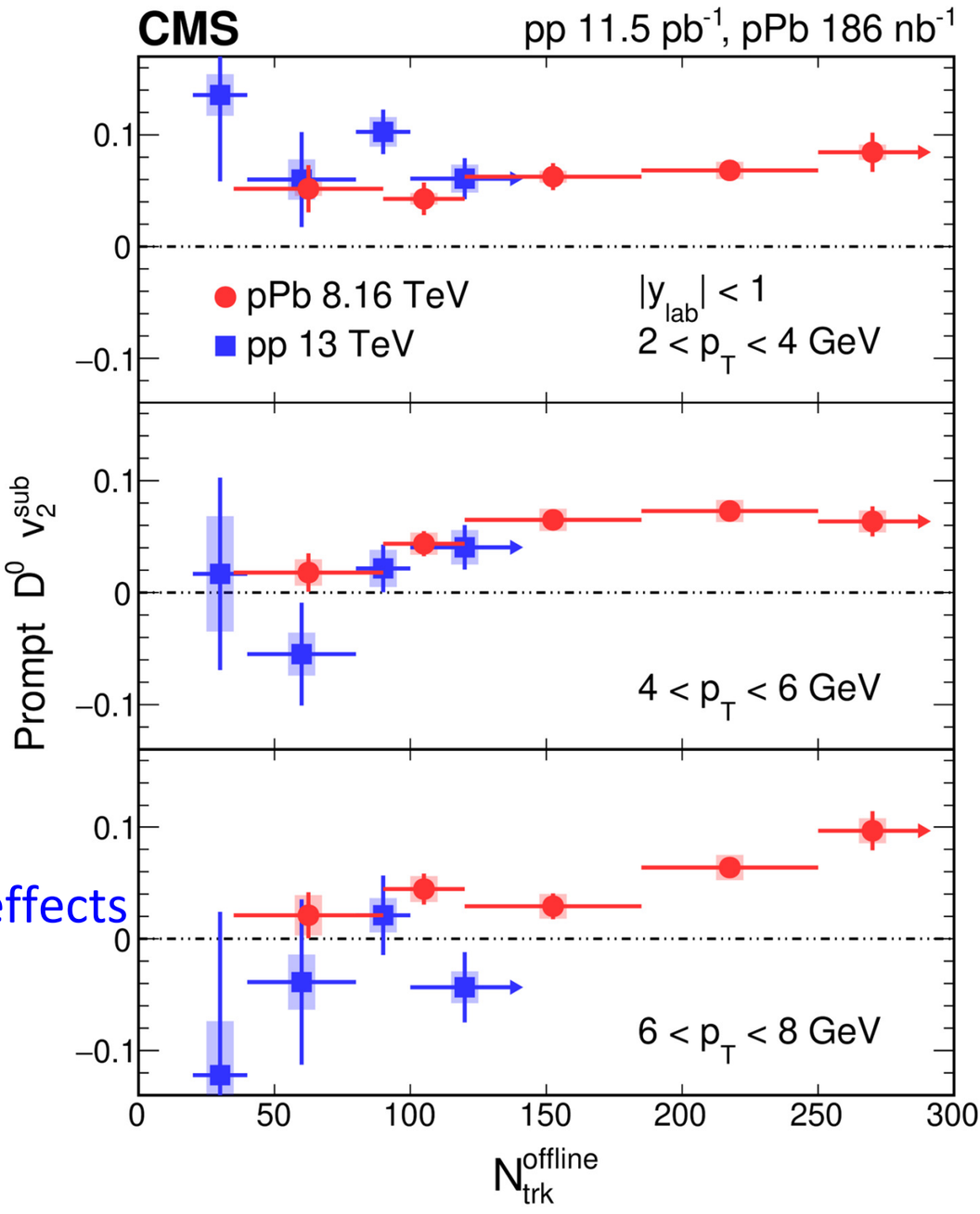
ATLAS : PRL-124, 082301

- 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