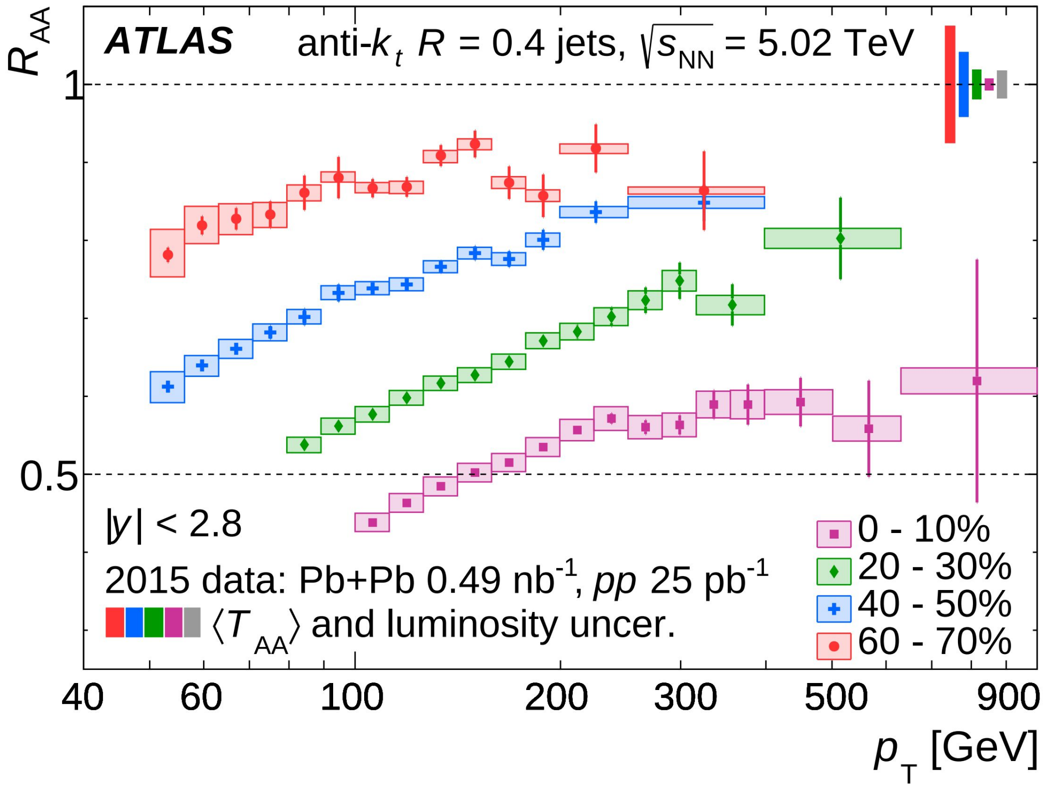
Measurements of the Azimuthal Anisotropy of Jets and High-p_T Charged Particles in Pb+Pb Collisions with the ATLAS Detector

Xiaoning Wang for the ATLAS Collaboration

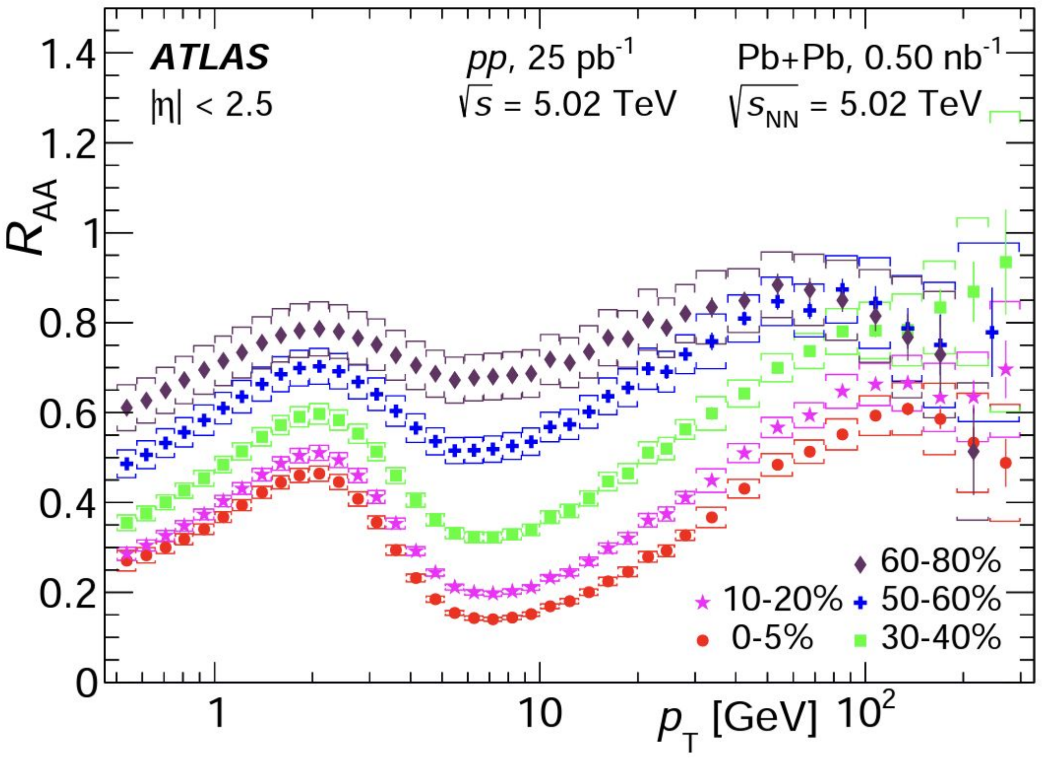
September 23, 2024

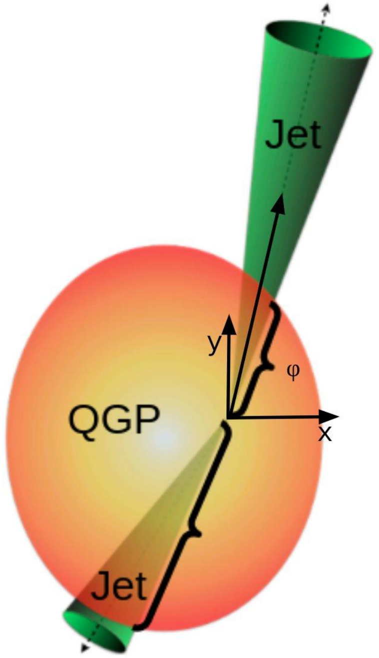
Jet Energy Loss in QGP

Phys.Lett.B 790 (2019) 108-128
DOI: 10.1016/j.physletb.2018.10.076



CERN-EP-2022-221
e-Print: arXiv:2211.15257





- Hard scattered partons lose energy when traversing through QGP
  - Left: jet R_{AA} Right: charged particle R_{AA}
- Energy loss study
  - Probe short-distance parton interaction in QGP

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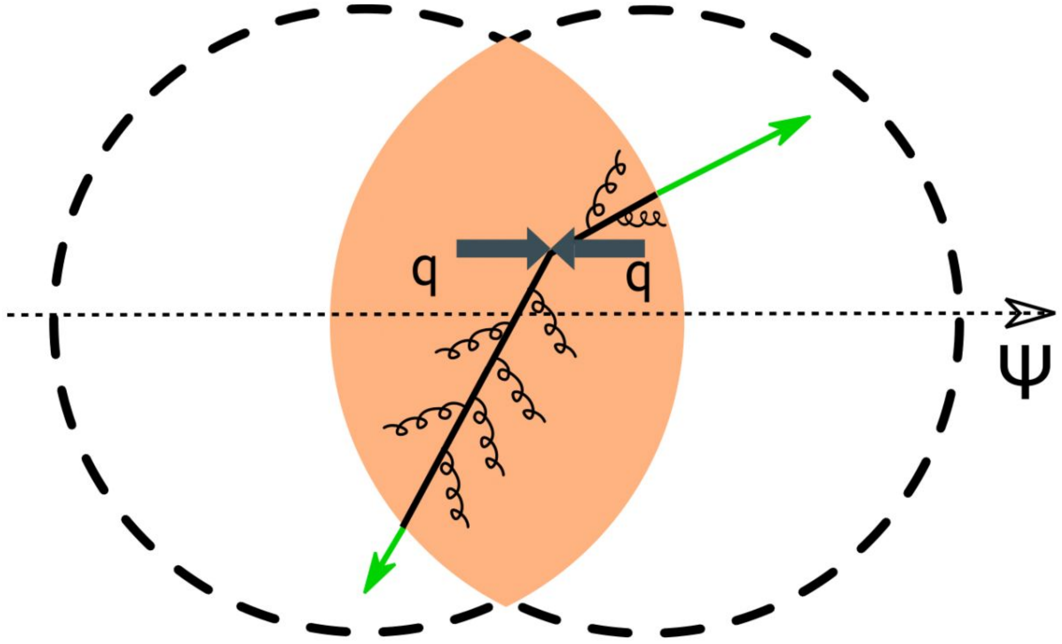
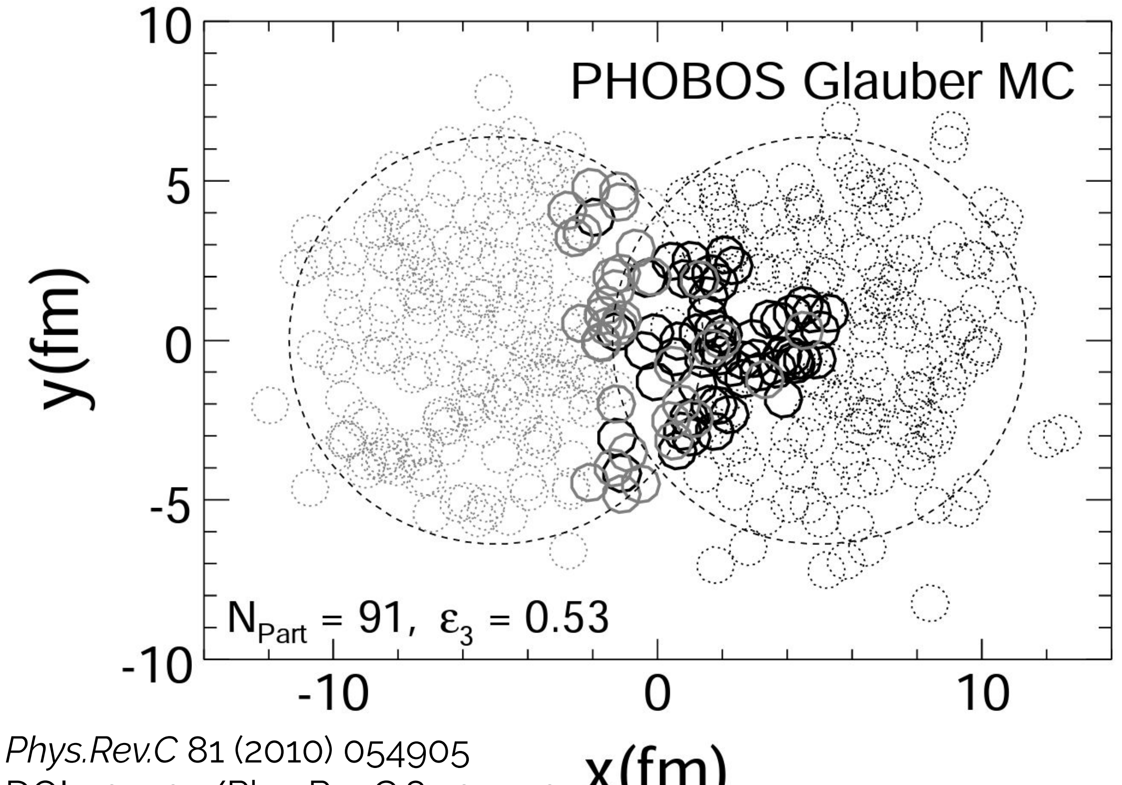
Azimuthal Anisotropies for High-p_T Probes



$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi_i - \Psi_n))$$



Phys.Rev.C 81 (2010) 054905
DOI: 10.1103/PhysRevC.82.039903

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- High-p_T probe v_n are sensitive to **initial state geometry**, **energy loss**, and **jet fragmentation**.
- Initial geometry -> flow harmonics
  - v_2: average geometry
  - Higher-order v_n: event-by-event fluctuation
- Non-flow: contributions from correlations unrelated to initial geometry
  - e.g., short-distance correlations from resonance decay, dijet productions, etc.

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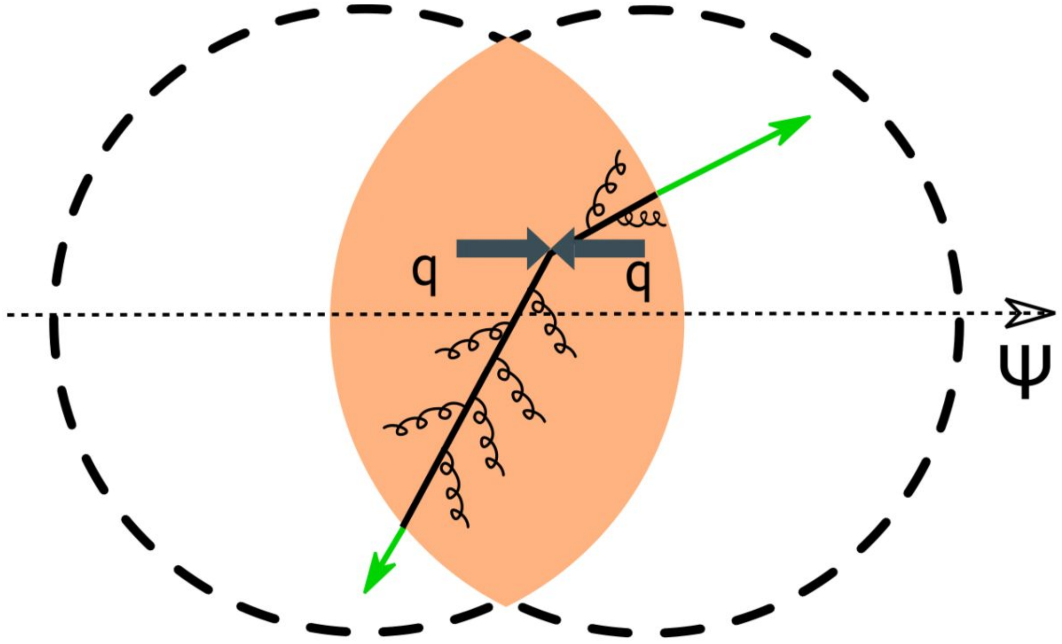

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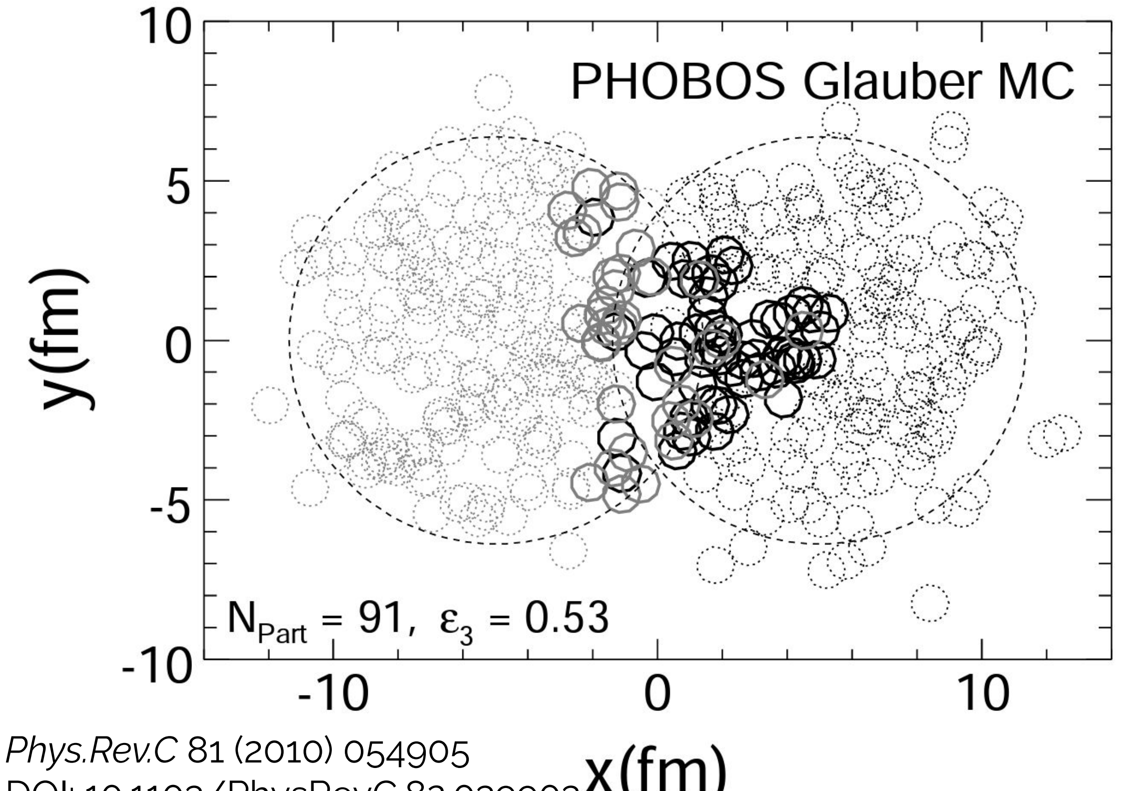

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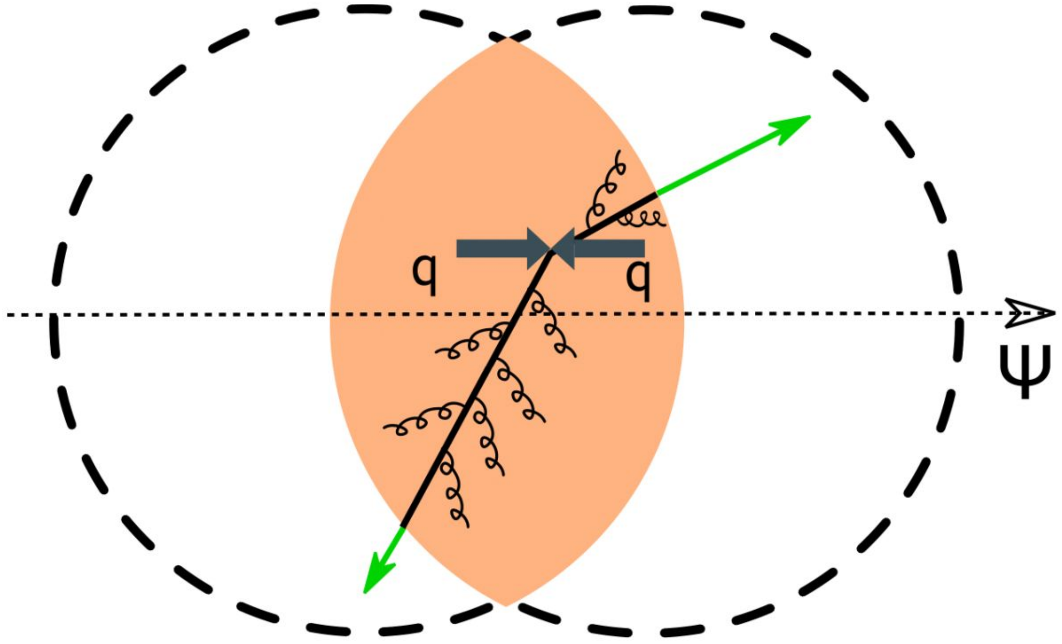

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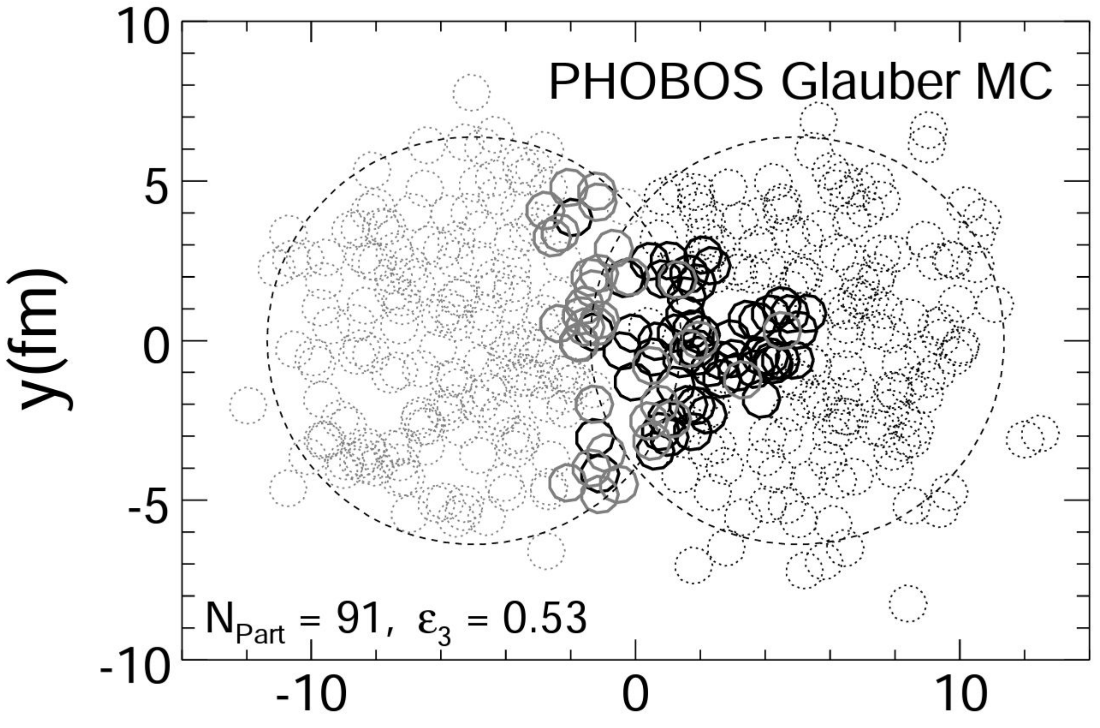

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Probes of Hard Sector Energy Loss

Radius dependent jet quenching measurements from ATLAS
Anne Sickles
Sept 23: 14:00-14:20

- Jet v_n
  - Azimuthal modulation of jet production with respect to the n-th order event plane
  - ATLAS result with Run II data: *Phys.Rev.C* 105 (2022) 6, 064903
    - **Jet w/ barrel calorimeter ($|y| < 1.2$)**
    - **Event plane w/ FCal ($4.0 < |\eta| < 4.9$)**

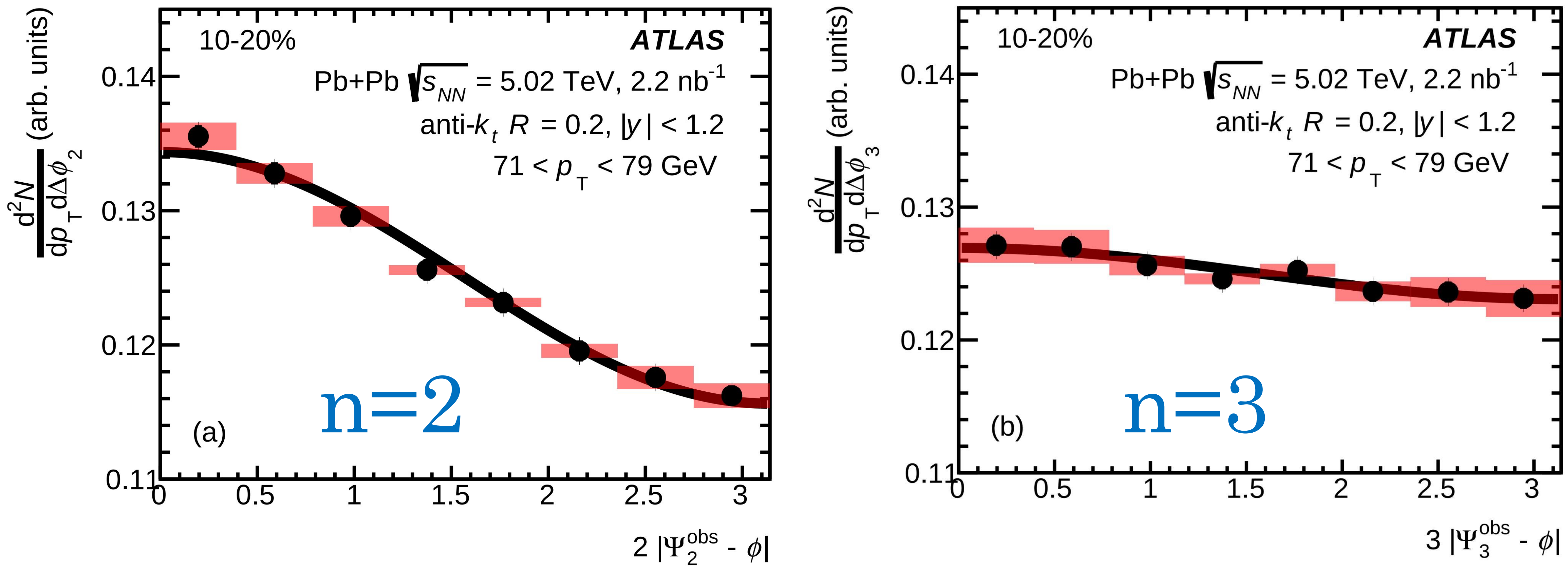
Jet substructure measurements with small and large radius jets
Martin Rybar
Sept 23: 14:20-14:40

Jets: Hard-jet correlation
Riccardo Longo
Sept 26: 11:40-12:05

- High-p_T charged particles v_n
  - High-pT charged particles as proxy of jet, carrying a fraction of jet momentum
  - Preliminary ATLAS result with Run II data: ATLAS-CONF-2023-007
    - **Particle w/ inner detector ($|\eta| < 2.5$)**
    - **Event plane w/ FCal ($3.2 < |\eta| < 4.9$)**

Phys.Rev.C 105 (2022) 6, 064903
e-Print: arXiv: 2111.06606

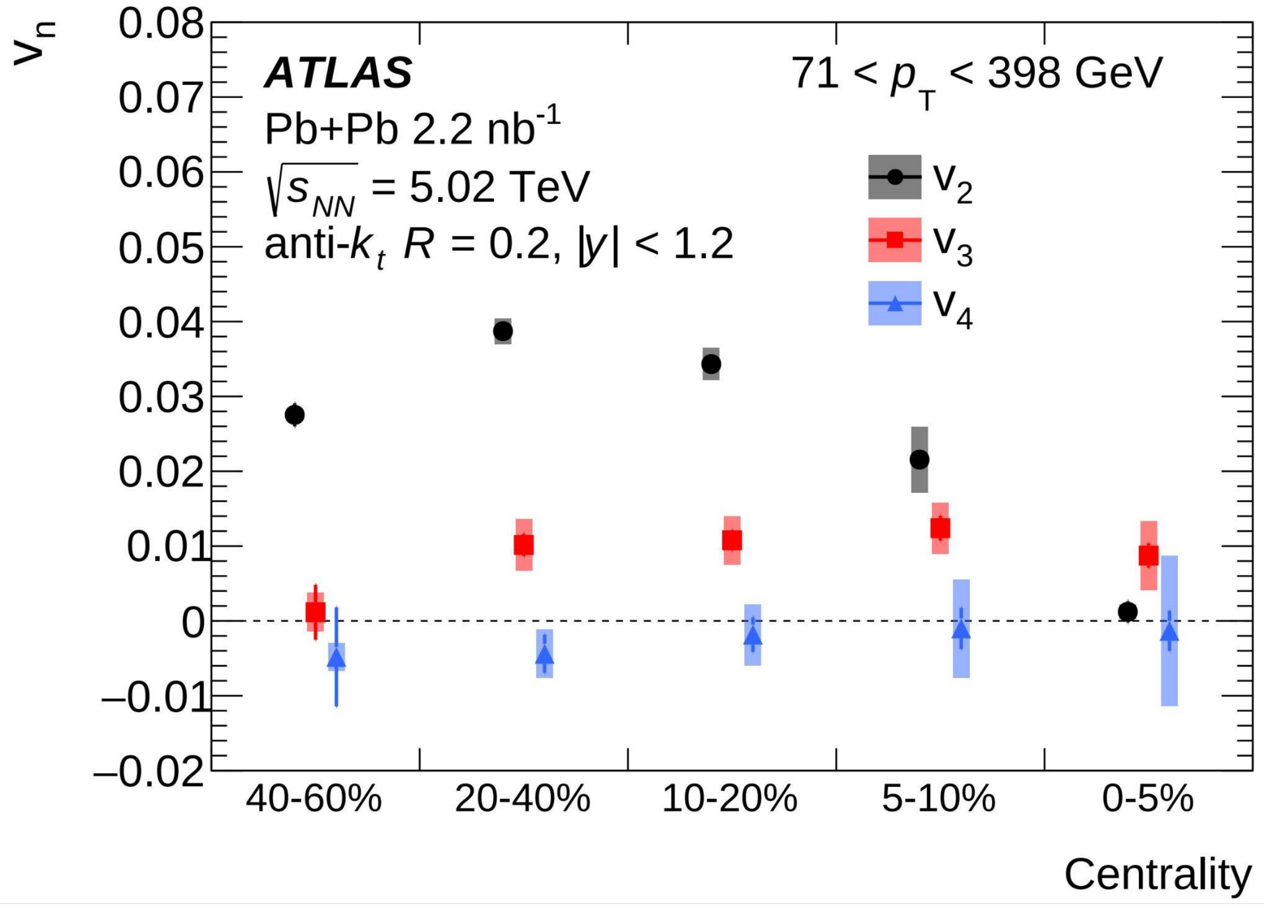
Event Plane Method for Jet v_n



- For each event, measure Ψ_n^{obs} and modulation of jet production in relative azimuthal angle $\Delta\phi$ in bins of jet p_T and event centrality.
- Yields are unfolded in p_T and $\Delta\phi$

Phys.Rev.C 105 (2022) 6, 064903
e-Print: arXiv: 2111.06606

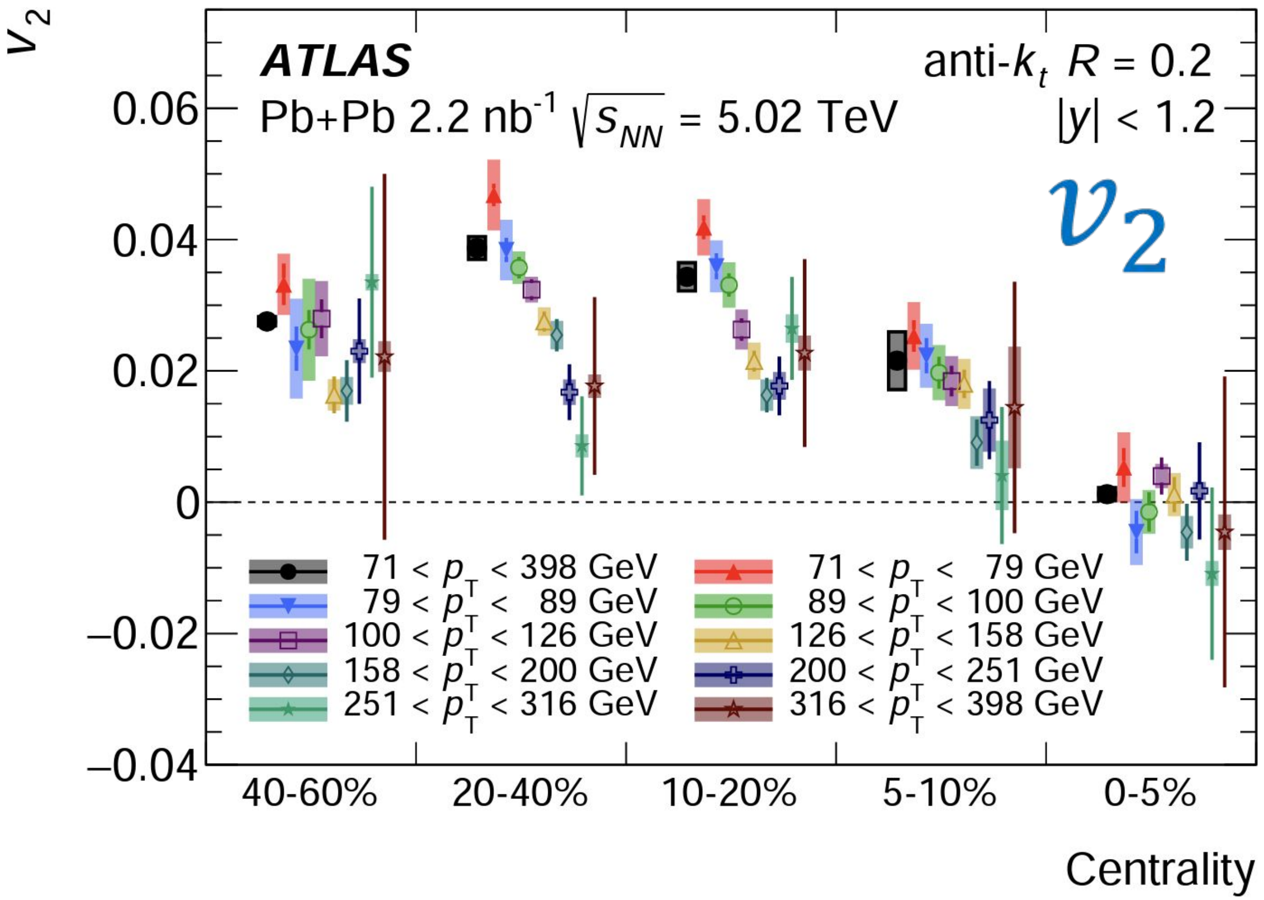
Centrality of Jet v_n

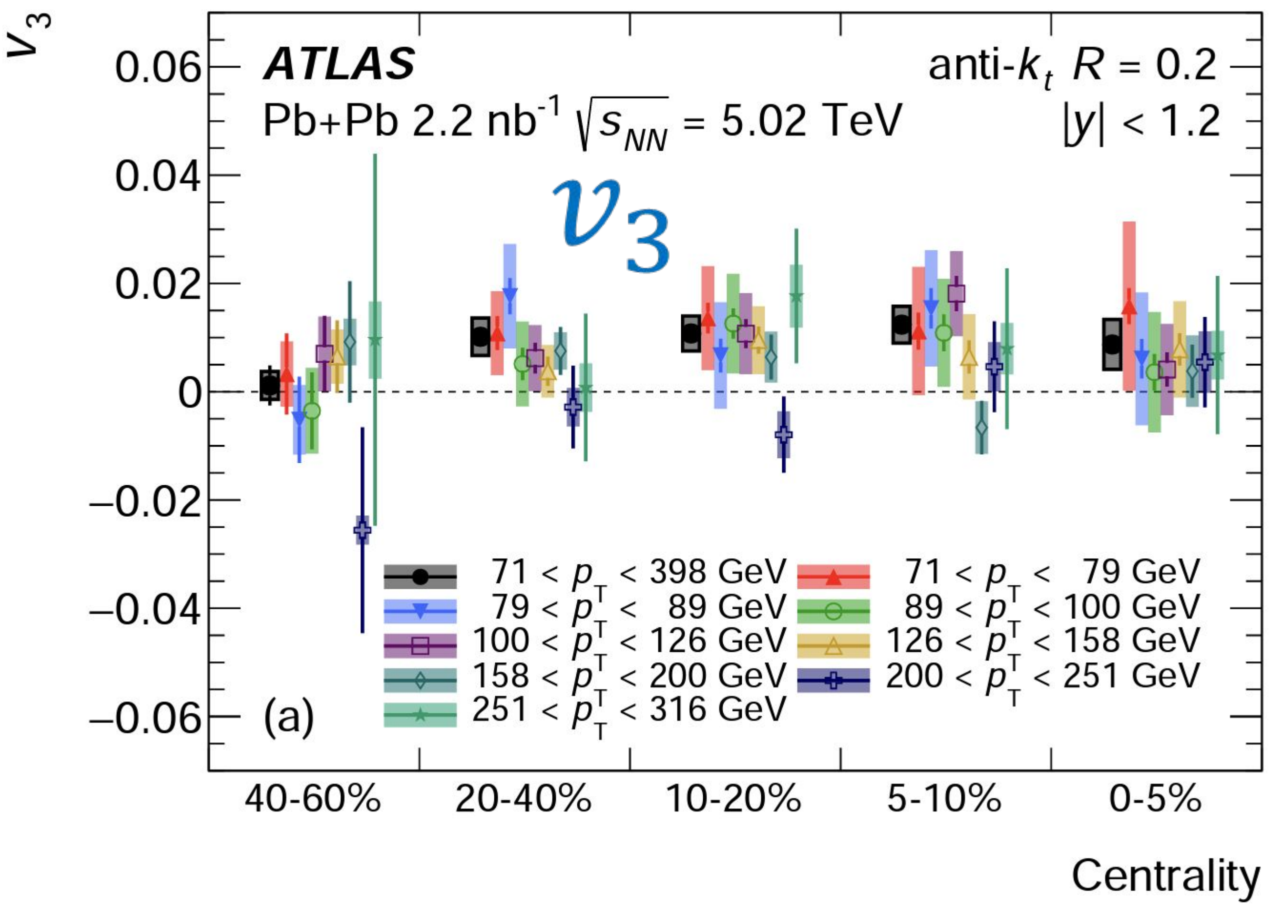


- Non-zero v_2 with **strong centrality dependence** for all except for 0-5%.
- Non-zero v_3 for 0–40% at ~0.01 with **weak centrality dependence**
  - Centrality dependence of v_2 and v_3 similar to inclusive soft hadrons v_n
- No evidence of non-zero v_4

p_T Dependence of Jet v_n

Phys.Rev.C 105 (2022) 6, 064903
e-Print: arXiv: 2111.06606





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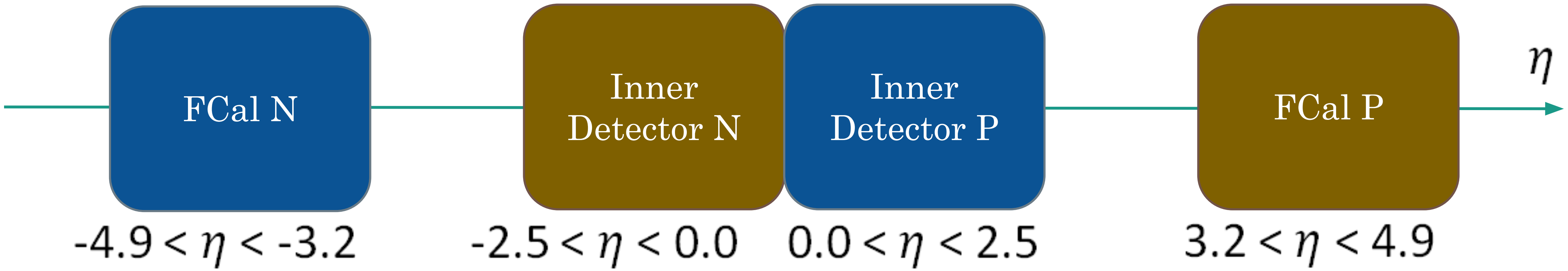
- v_2 decreases with p_T
- v_3 has weak p_T dependence
  - central events: large uncertainties; constant
  - Mid-central events: positive up to ~89 GeV then decreases with p_T

High-p_T Track v_n with Scalar Product (SP) Method

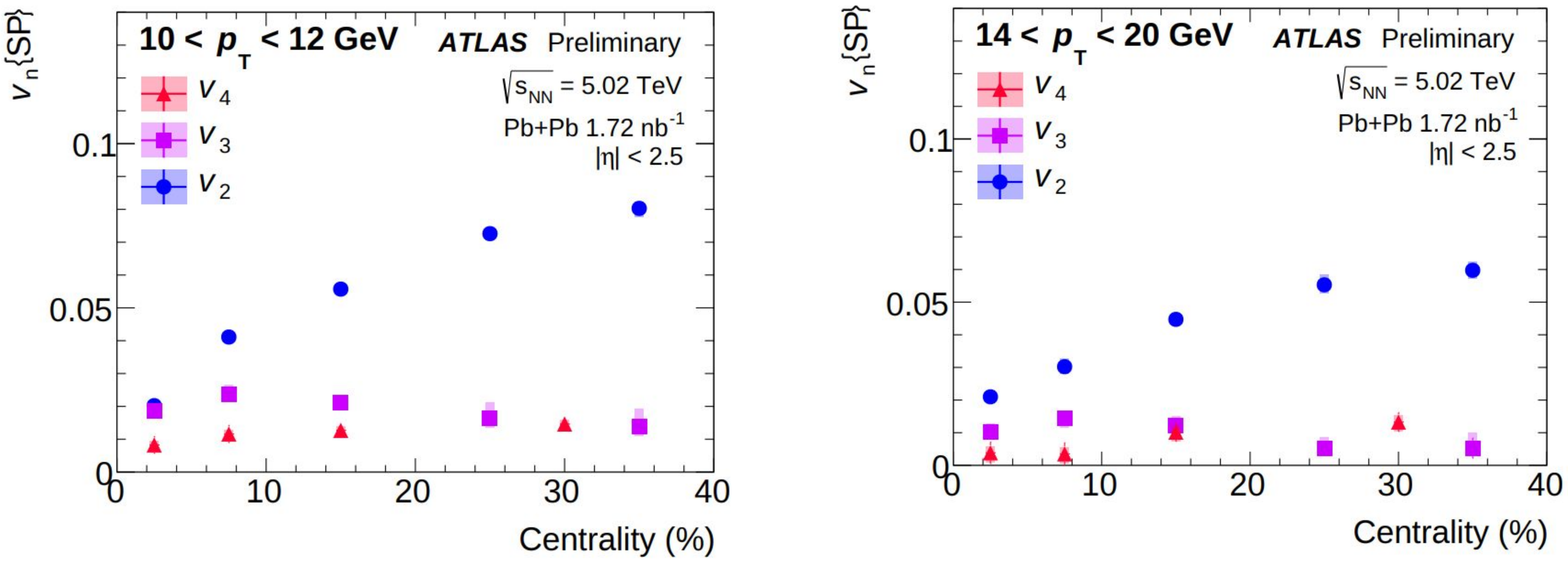


- An event is divided into different regions by pseudo-rapidity
- **Azimuthal angle of tracks** correlated w/ that of **FCal** -> large pseudo-rapidity gap (η > 3.2)
  - suppress non-flow contributions
    - resonance decay, particles of same jet, back-to-back dijet, etc.
- ***This result:***
  - ***full luminosity sampled in high-p_T region w/ ATLAS jet triggers for 2018***
  - ***statistics +; p_T range +***

More about SP Method:

- Explanation of method: *Phys.Rev.C* 87 (2013) 4, 044907, DOI: 10.1103/PhysRevC.87.044907
- ATLAS SP method measurements with 2015 data: *Eur.Phys.J.C* 78 (2018) 12, 997, DOI: 10.1140/epjc/s10052-018-6468-7

Centrality Charged Particle v_n: 10 < p_T < 20 GeV



- Non-zero v_2 with **strong centrality dependence;**
- Non-zero v_3 with weak centrality dependence;
- Similar to soft hadron inclusive v_n;

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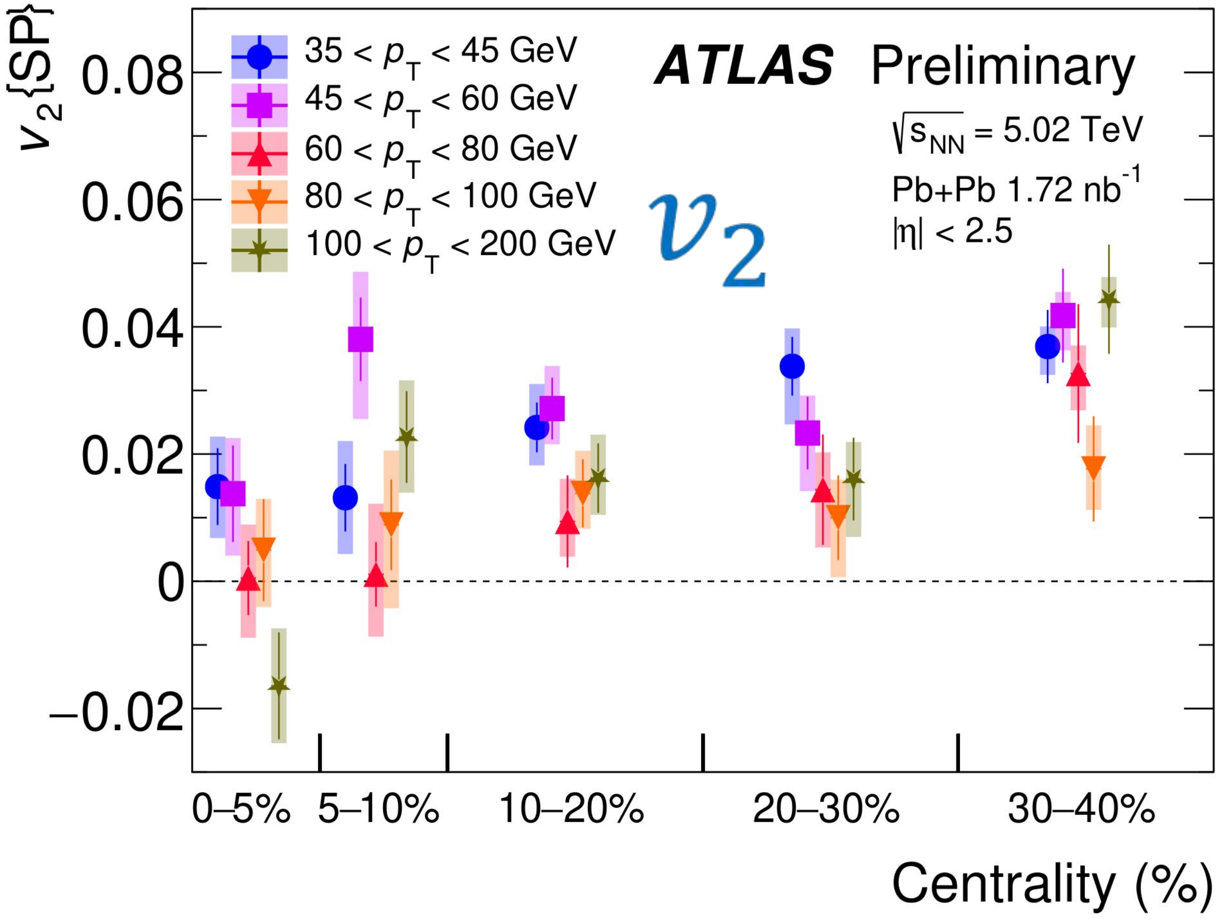
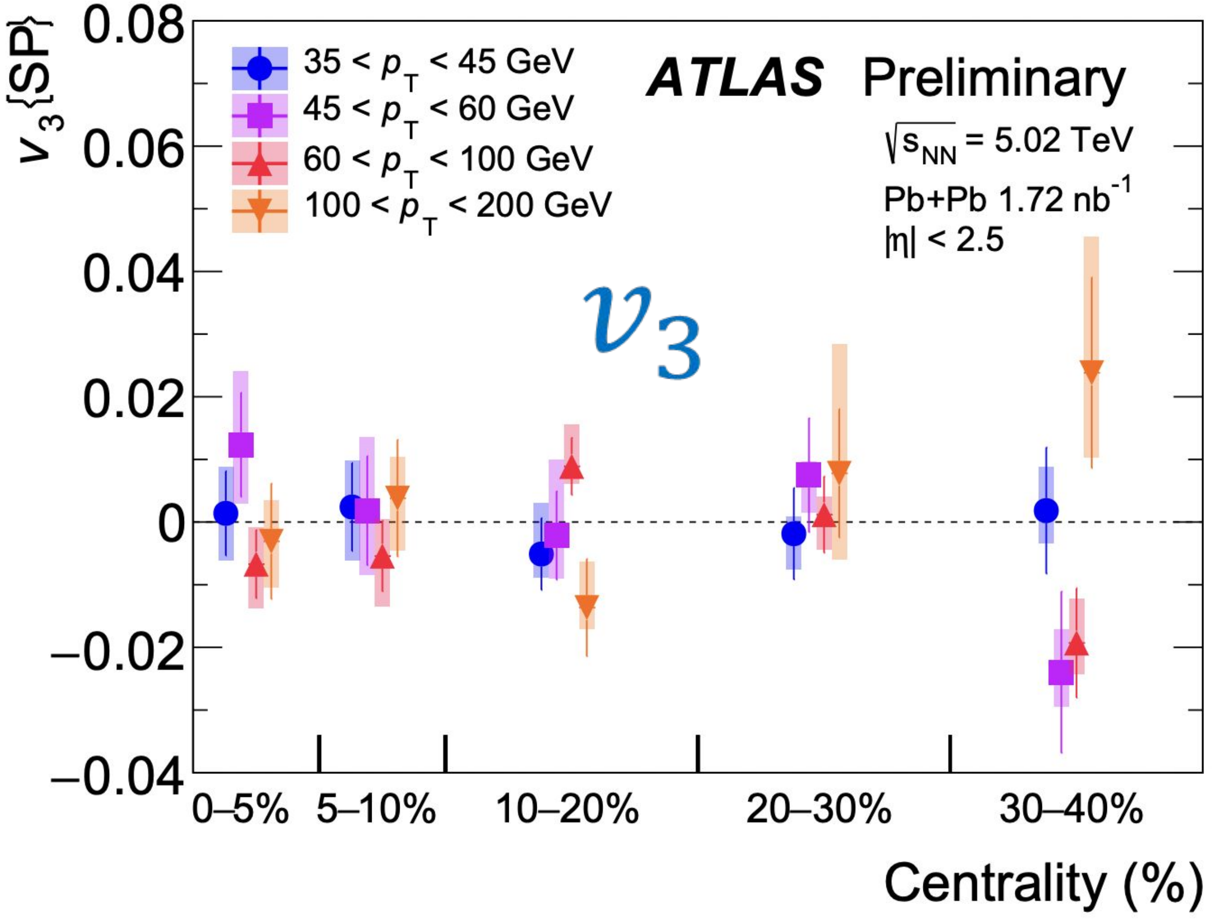
p_T Dependence of Charged Particle v_n: p_T > 35 GeV





- v_2 decreases with p_T
- v_3 for 0–40% for p_T > 35 GeV consistent with 0

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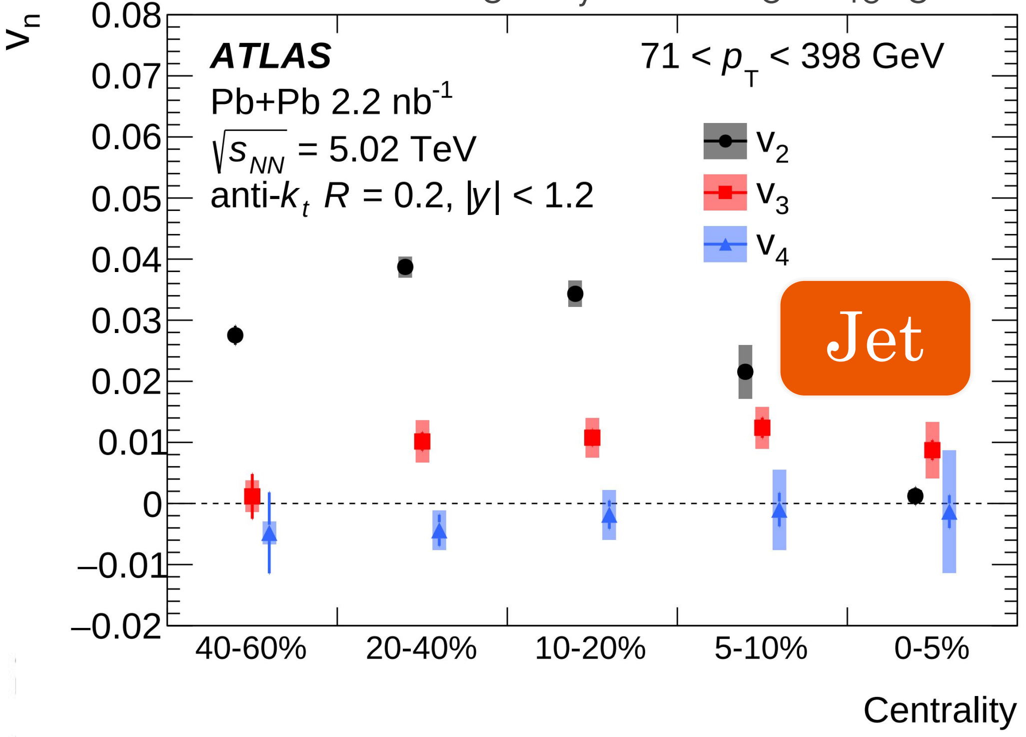
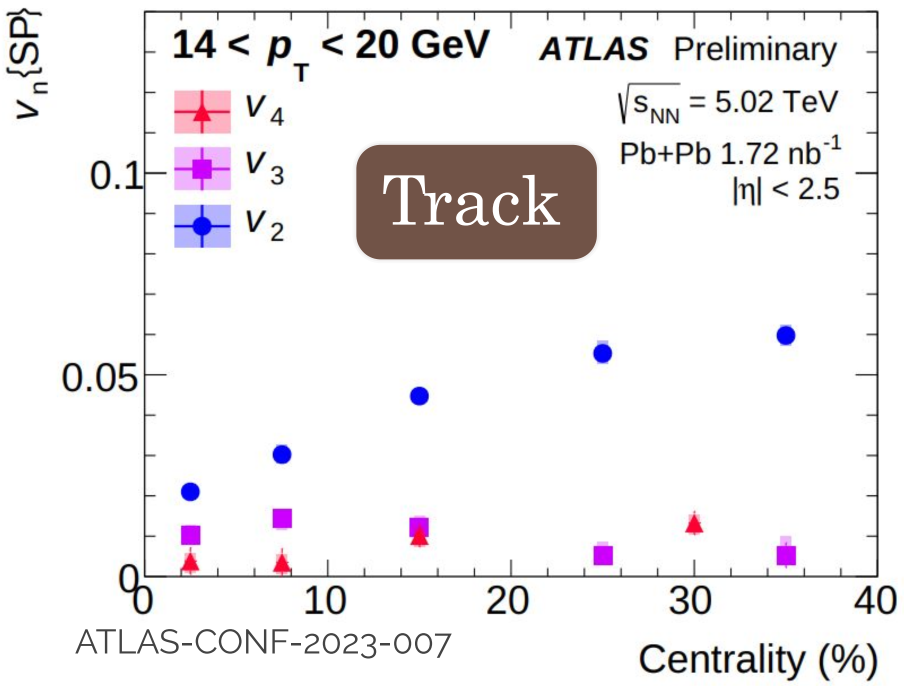
Understanding different probes

Between jets & tracks…

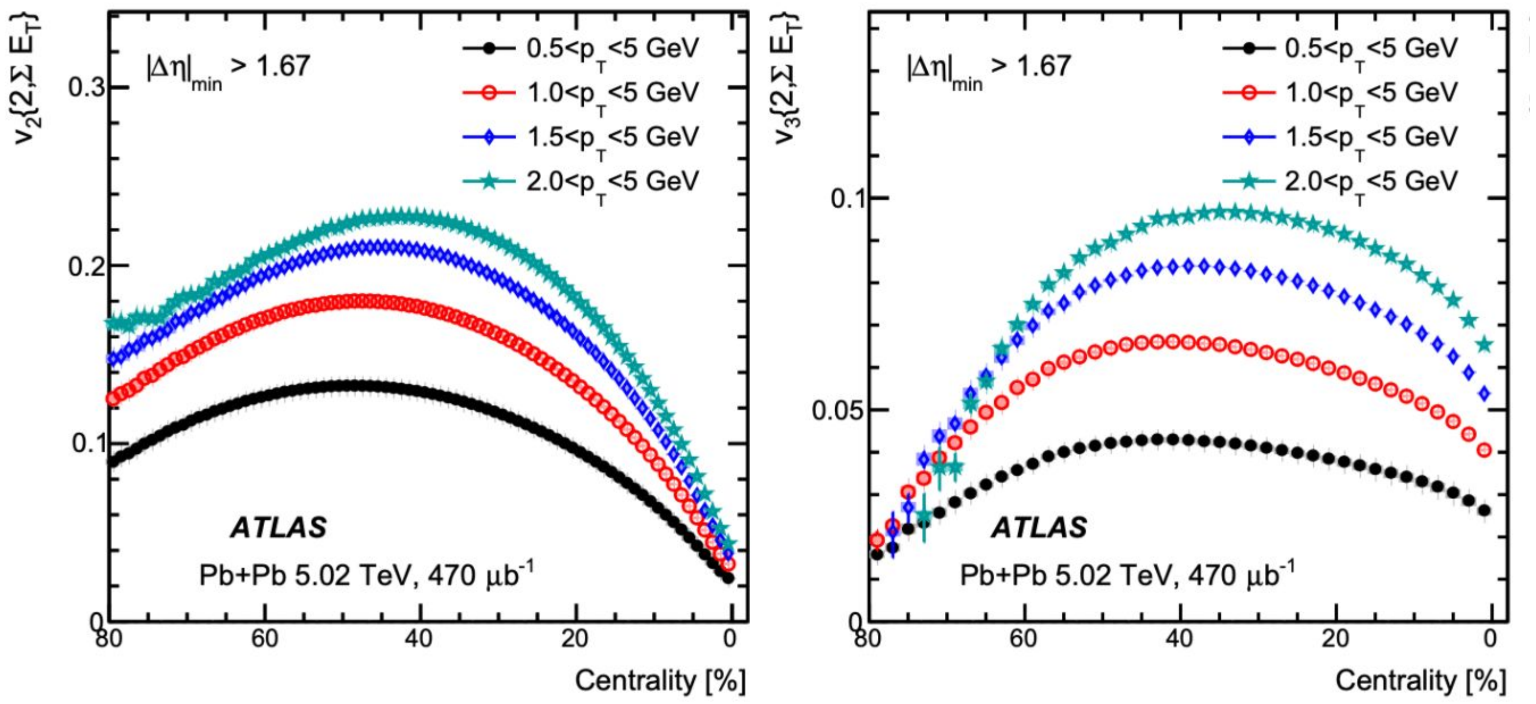
- Similar centrality dependence
    - strong centrality dependence for v_2
    - weak centrality dependence for v_3 in 0-40%
    - similar to those of soft hadron v_n

Phys.Rev.C 105 (2022) 6, 064903
DOI: 10.1103/PhysRevC.105.064903





ATLAS-CONF-2023-007



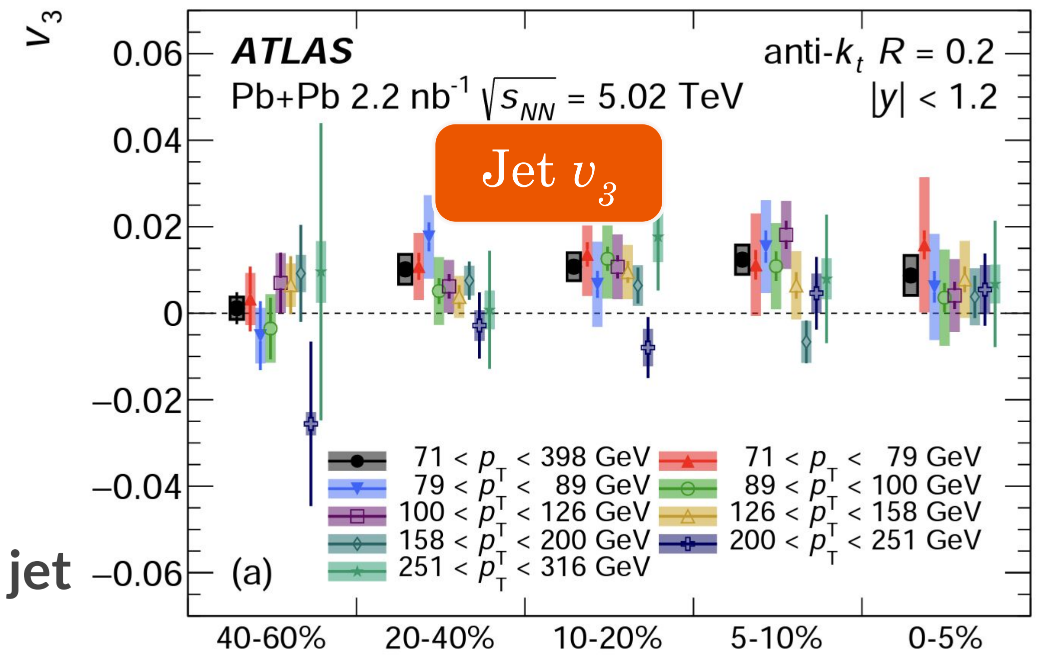
JHEP 01 (2020) 051
DOI: 10.1007/JHEP01(2020)051

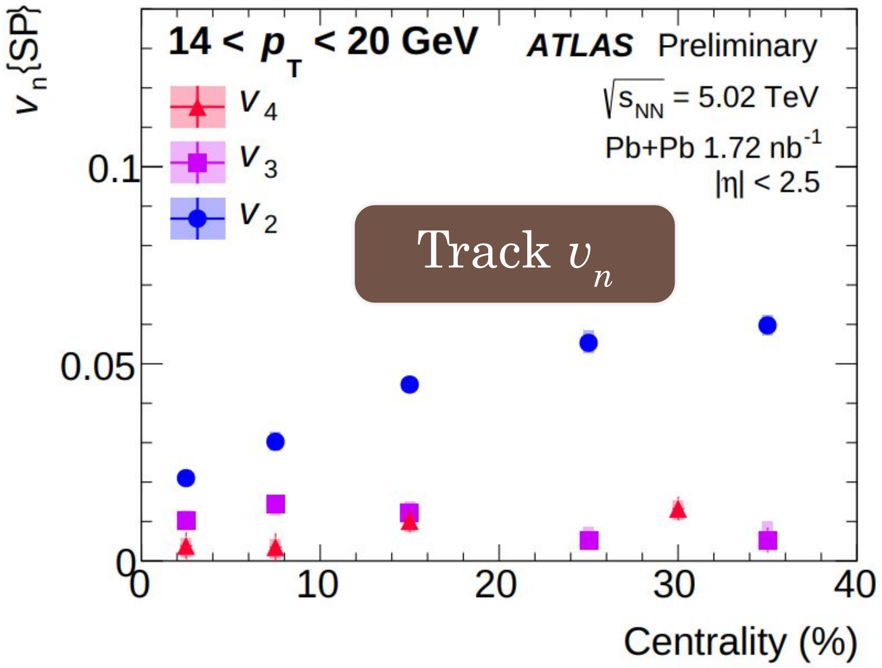
Understanding different probes

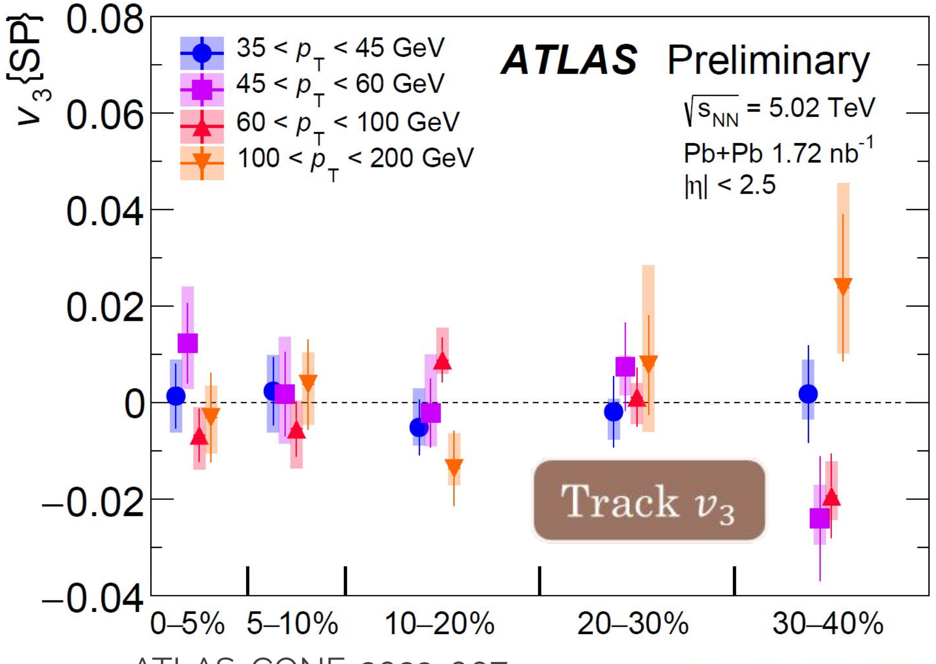
Phys.Rev.C 105 (2022) 6, 064903
DOI: 10.1103/PhysRevC.105.064903

Between jets & tracks...

- **p_T dependence within hard sector**
- In mid-central collisions (10-40%)
    - non-zero jet v_3 up to ~89 GeV
    - non-zero charged particle v_3 up to ~20 GeV
- Difference in the probe:
    - charged-particle sensitive to additional fluctuations in **jet fragmentation**
    - p_T mapping between jets and charged particle can be different between v_2 and v_3







ATLAS-CONF-2023-007

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Understanding different probes

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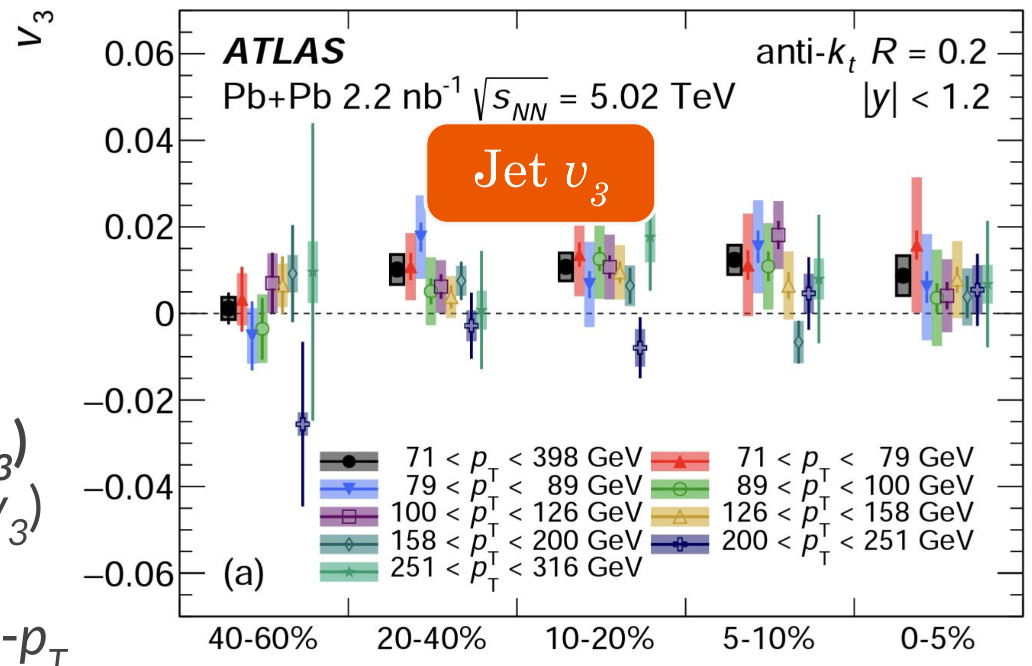
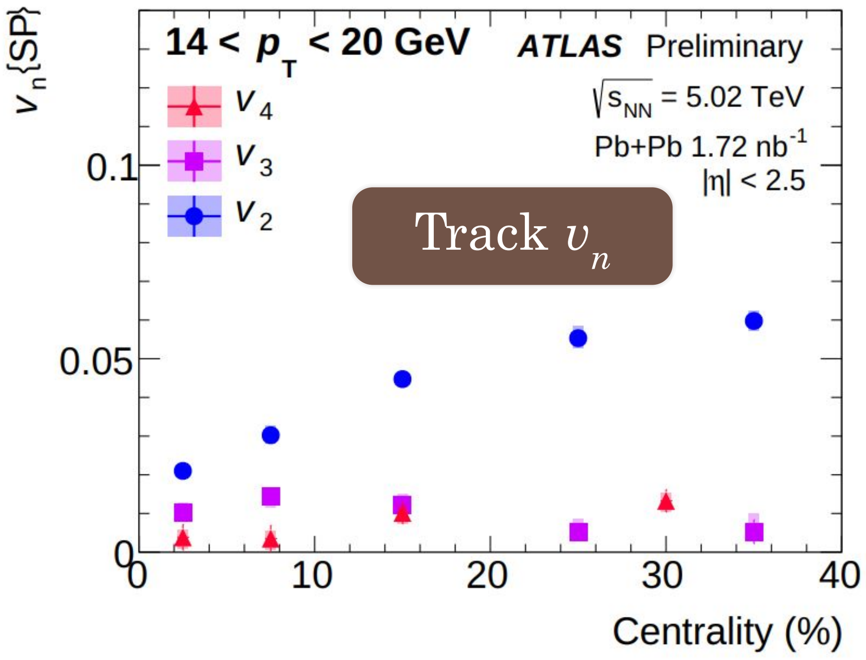
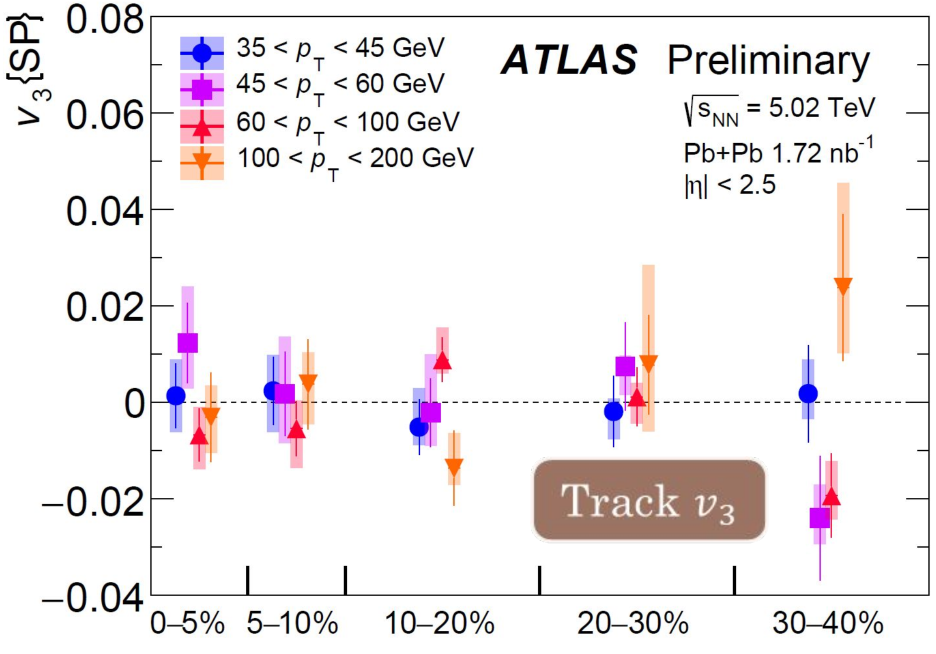
Between jets & tracks...

- ***η* dependence:**
    - Bigger η gap (on average) for charged particles:
        - **suppression of short-range non-flow (-v_3)**
        - **bigger event-plane longitudinal decorrelation (-v_3)**
        - suppression of back-to-back dijet contribution (+v_3)
- Useful tool:
    - η-dependent charged particle v_n measurements in high-p_T







ATLAS-CONF-2023-007

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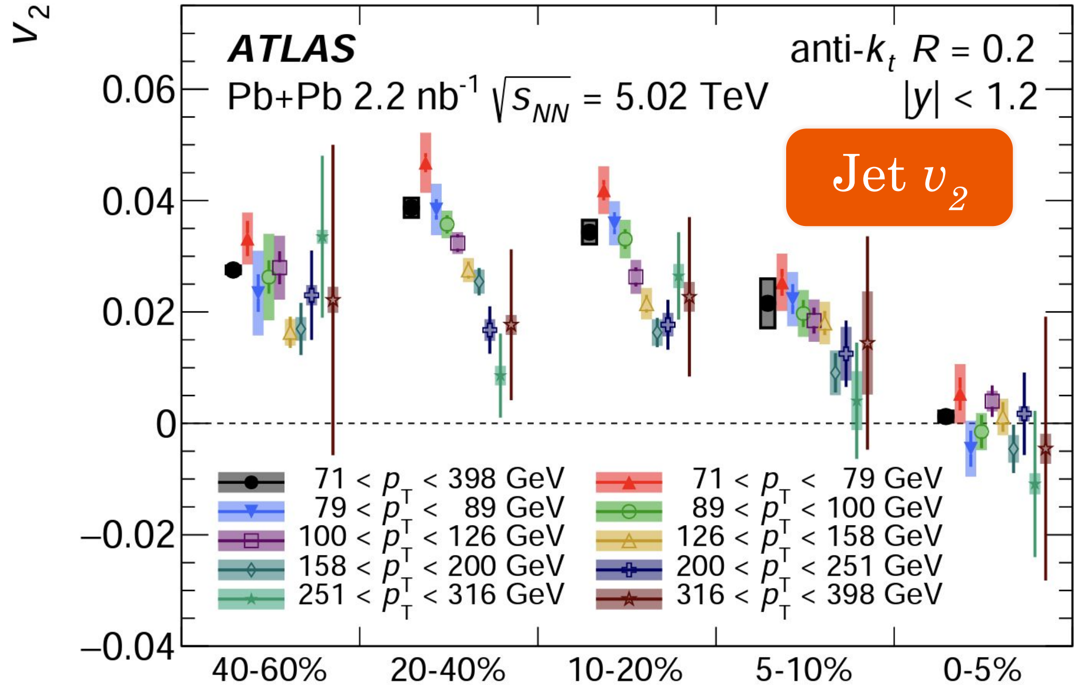
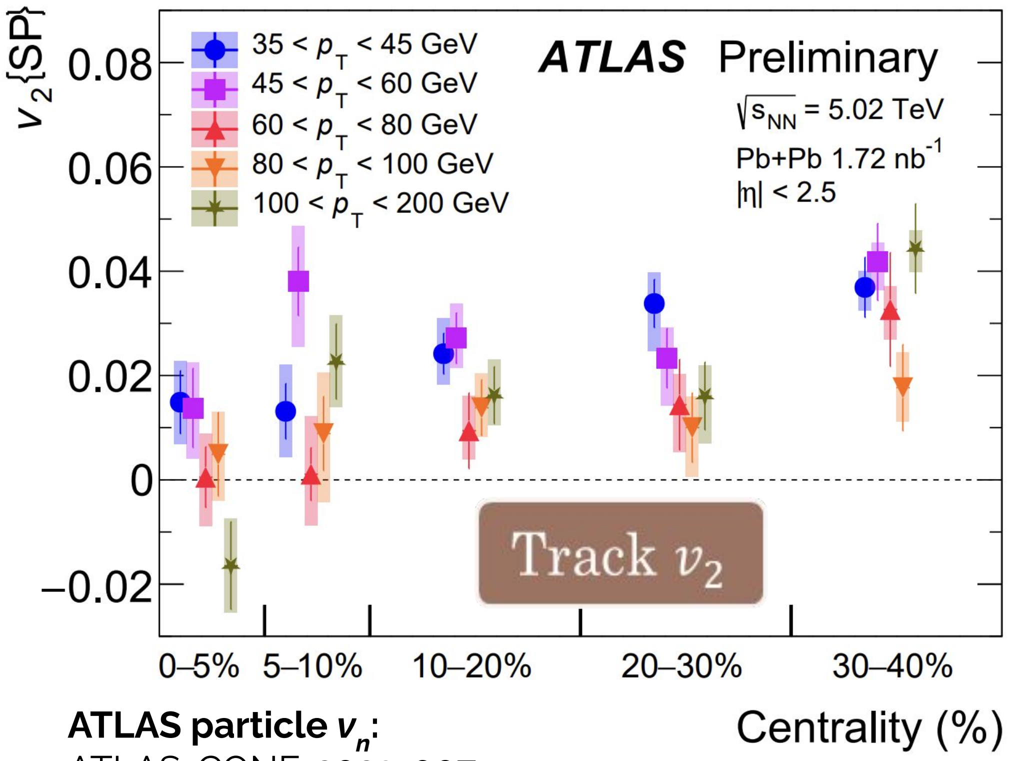
Method Dependence



ATLAS Jet v_n:
Phys.Rev.C 105 (2022) 6, 064903,
e-Print: arXiv: 2111.06606



ATLAS particle v_n:
ATLAS-CONF-2023-007

ATLAS measurements of pT fluctuations and vn-pT correlations
Tomasz Bold
Sept 23: 16:50-17:10
(Last talk)

- v_2{EP} and v_2{SP} have different sensitivity to fluctuations in the underlying v_n distribution
- Useful tool: multi-particle correlation studies

$$v_n\{EP\} \xrightarrow[\text{high res.}]{} \langle v_n \rangle$$

$$v_n\{EP\} \xrightarrow[\text{low res.}]{} \sqrt{\langle v_n^2 \rangle}$$

$$v_n\{SP\} = \sqrt{\langle v_n^2 \rangle}$$

Phys.Rev.C 87 (2013) 4, 044907
e-Print: arXiv: 1209.2323

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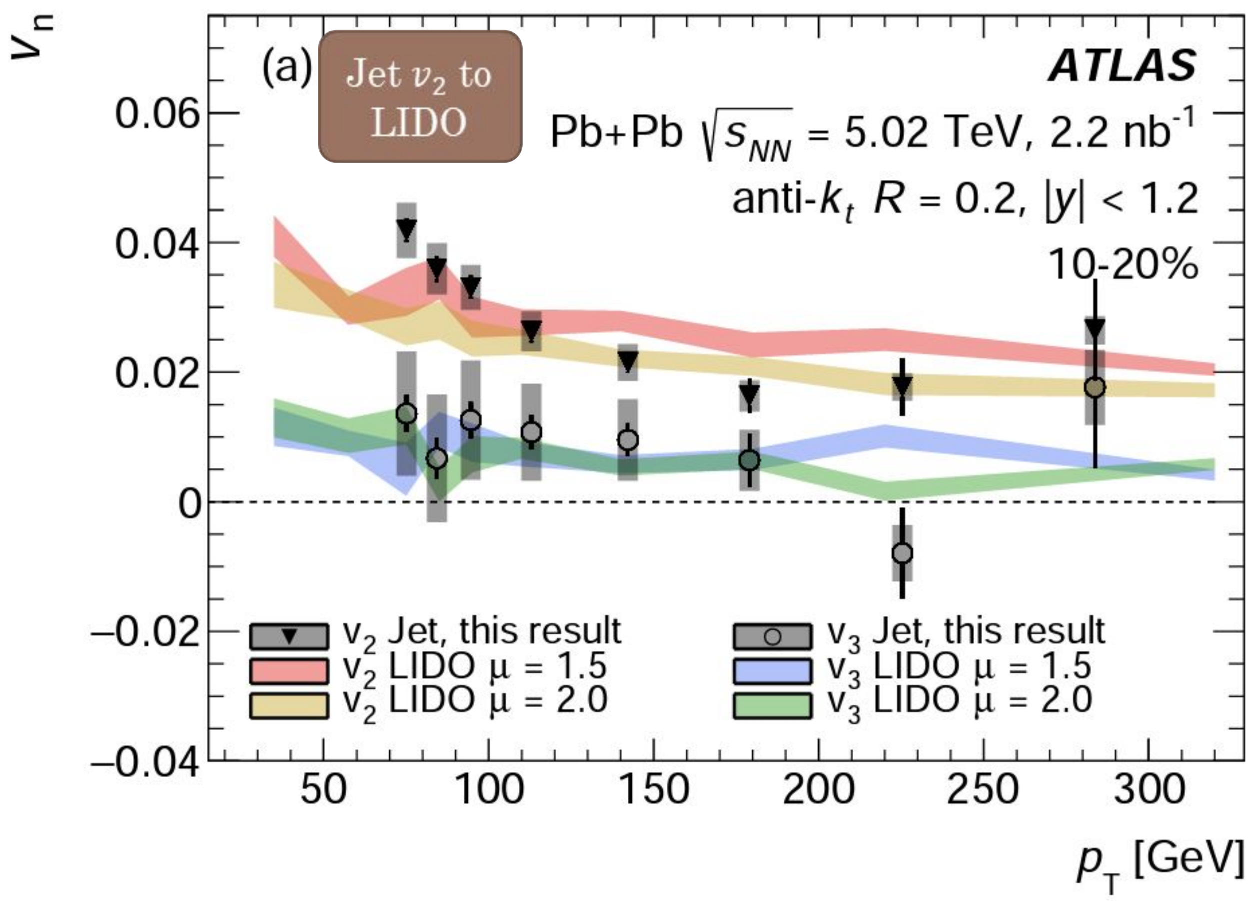
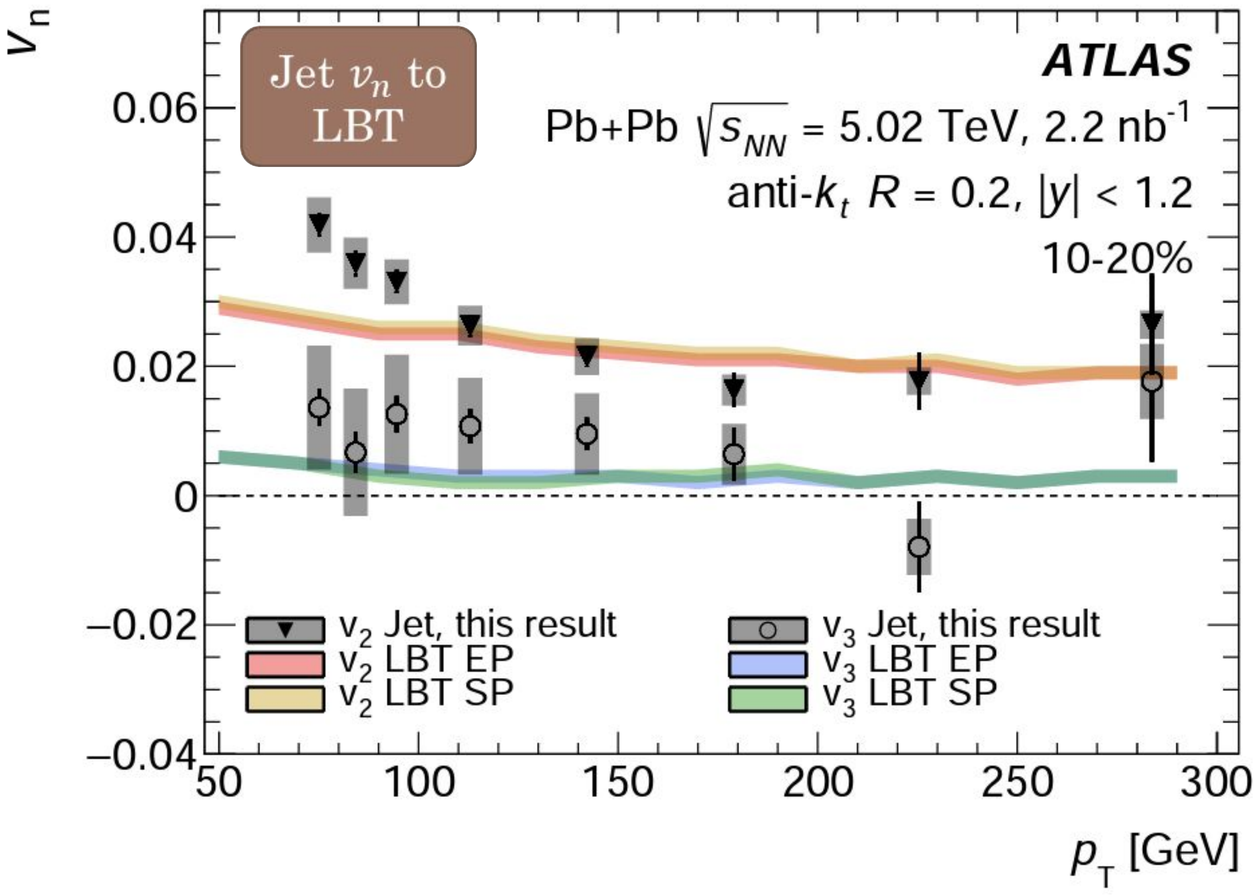
Theoretical Comparisons





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Jet vn this result:
Phys.Rev.C 105 (2022) 6, 064903, arXiv: 2111.06606
LIDO:
JHEP 05 (2021) 041, arXiv: 2010.13680

LBT Models:
Nucl.Phys.A 982 (2019) 635-638, arXiv: 1811.08975
Phys.Rev.C 99 (2019) 5, 054911, arXiv: 1809.02525
Phys.Rev.C 91 (2015) 054908, arXiv: 1503.03313

- Looking forward to theoretical calculations for charged particles!

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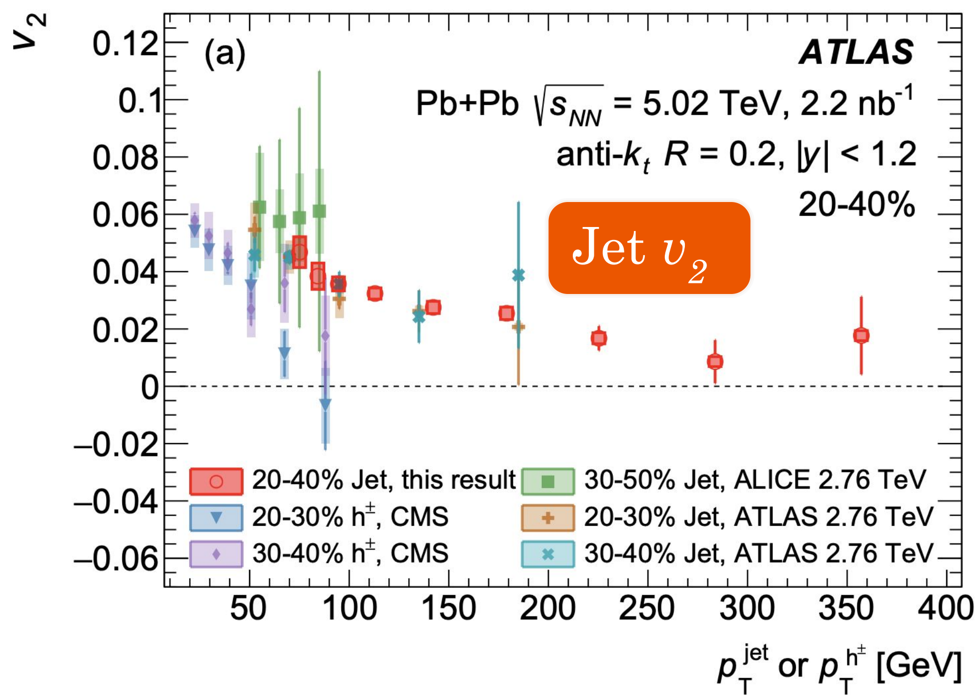
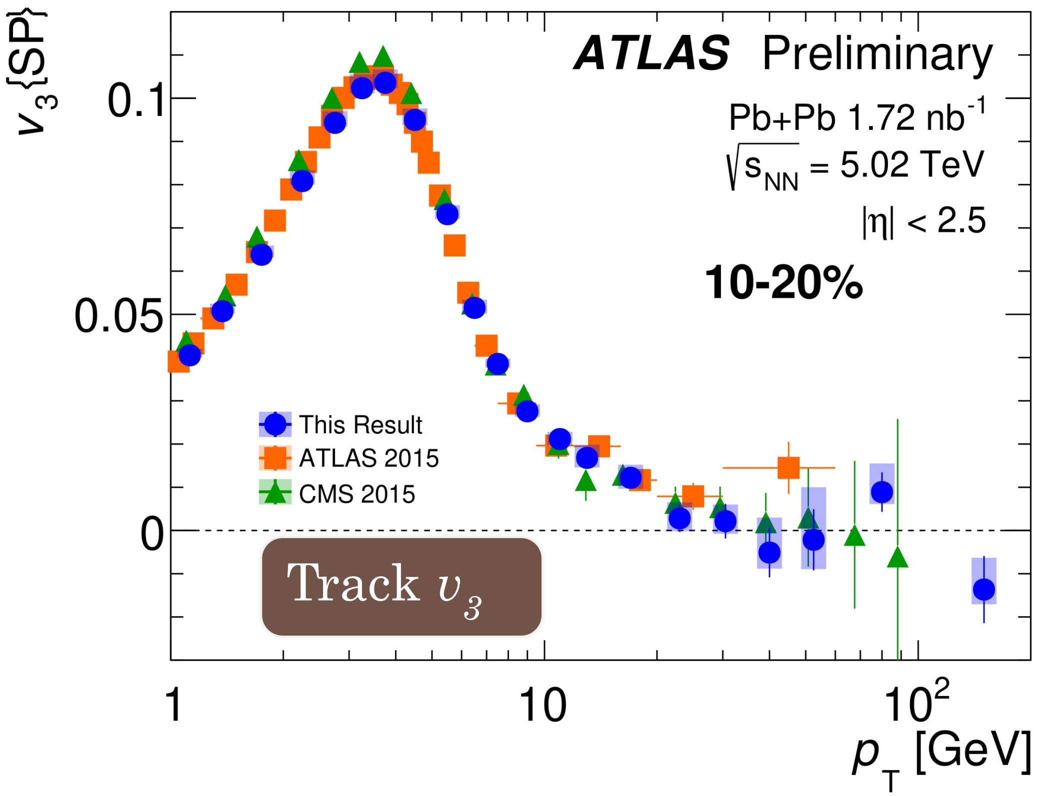
Summary





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- For both jet and charged particle
  - **Similar to soft sector centrality dependence;**
- In mid-centrality
  - **Non-zero jet v_3** up to 100 GeV
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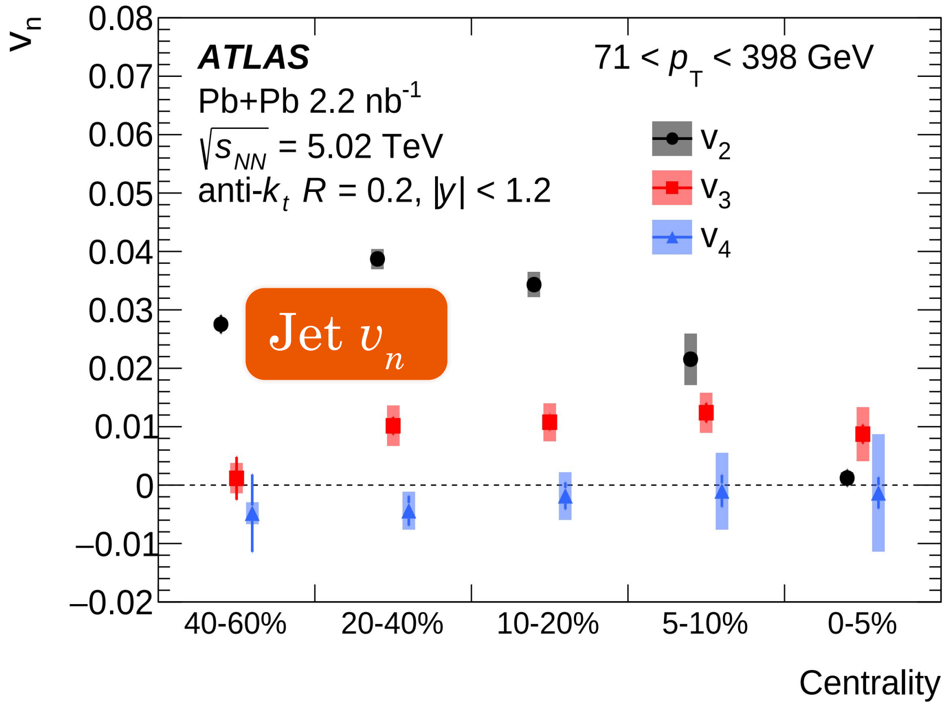
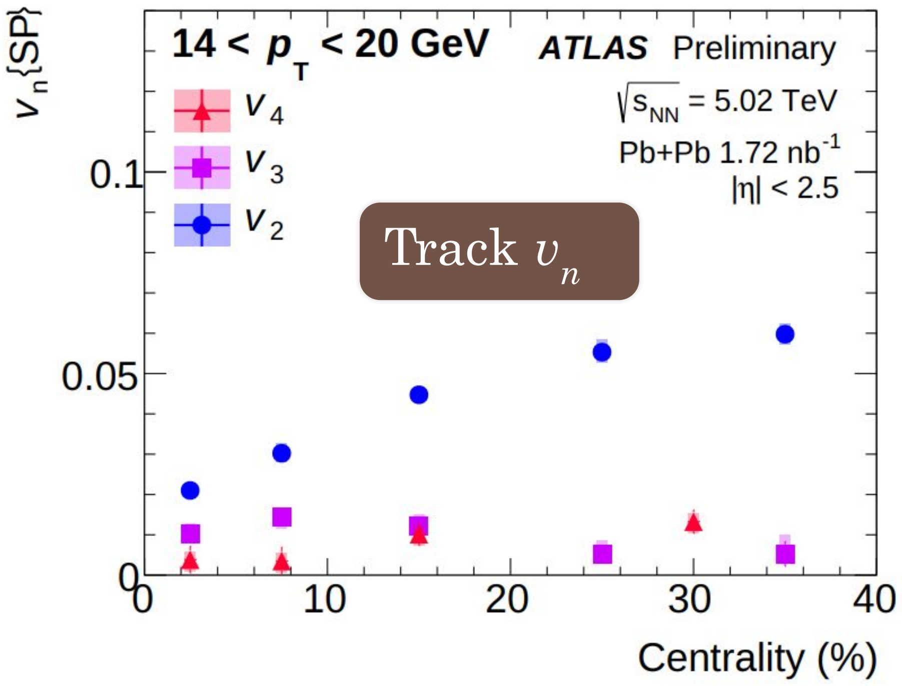
- Multi-particle correlation, eta-dependent study feasible with 2018 Run II data by ATLAS
- ATLAS heavy-ion public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Xiaoning Wang ATLAS Collaboration

Summary





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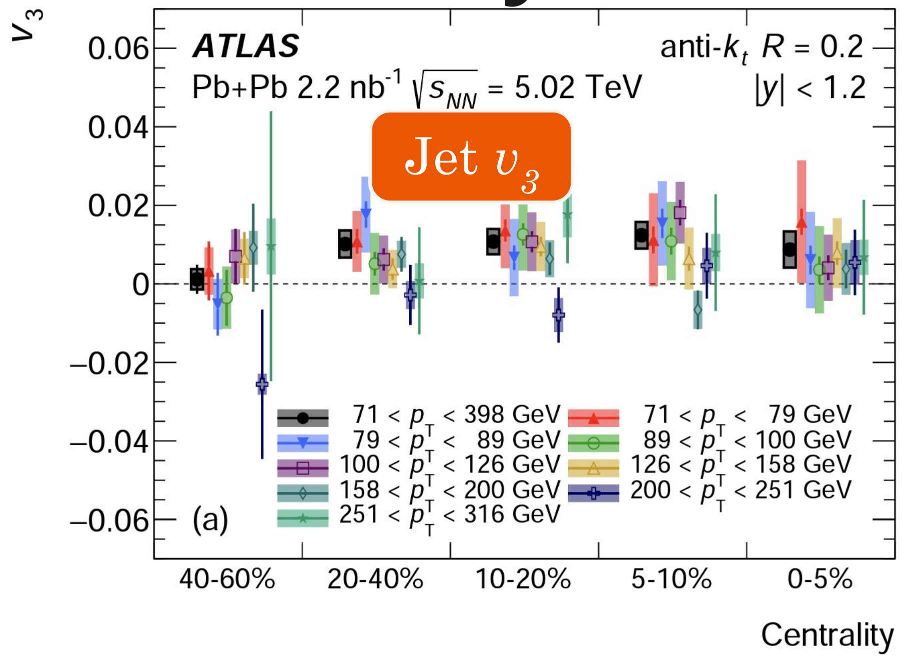

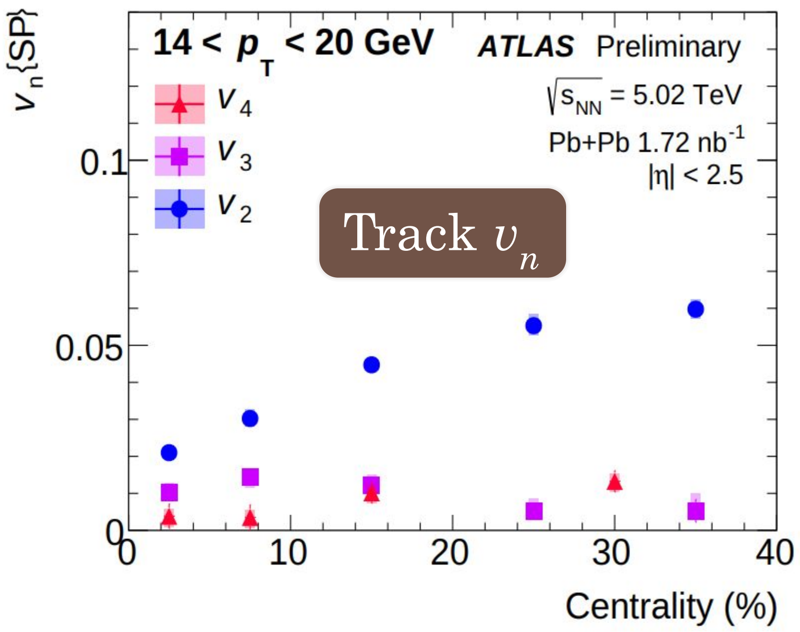

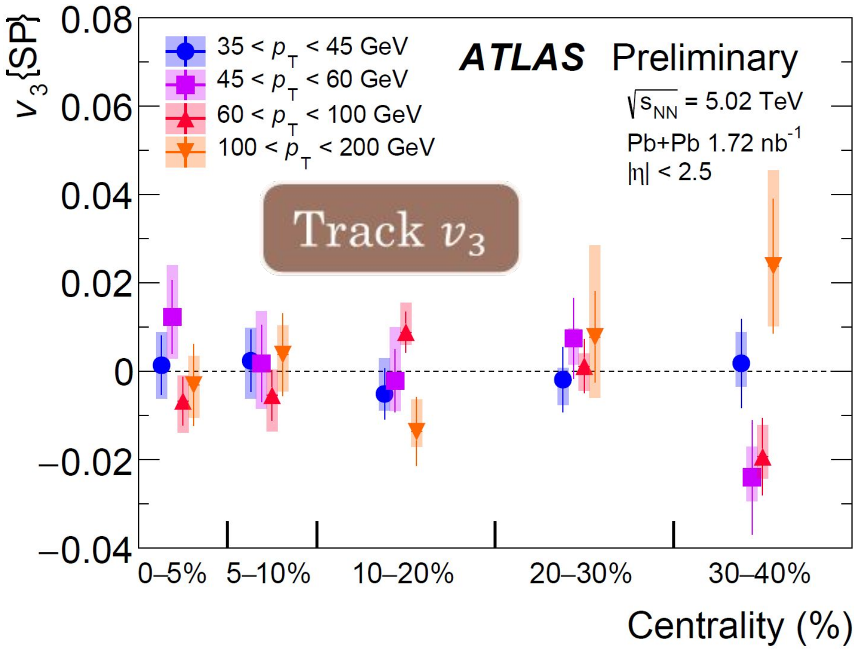

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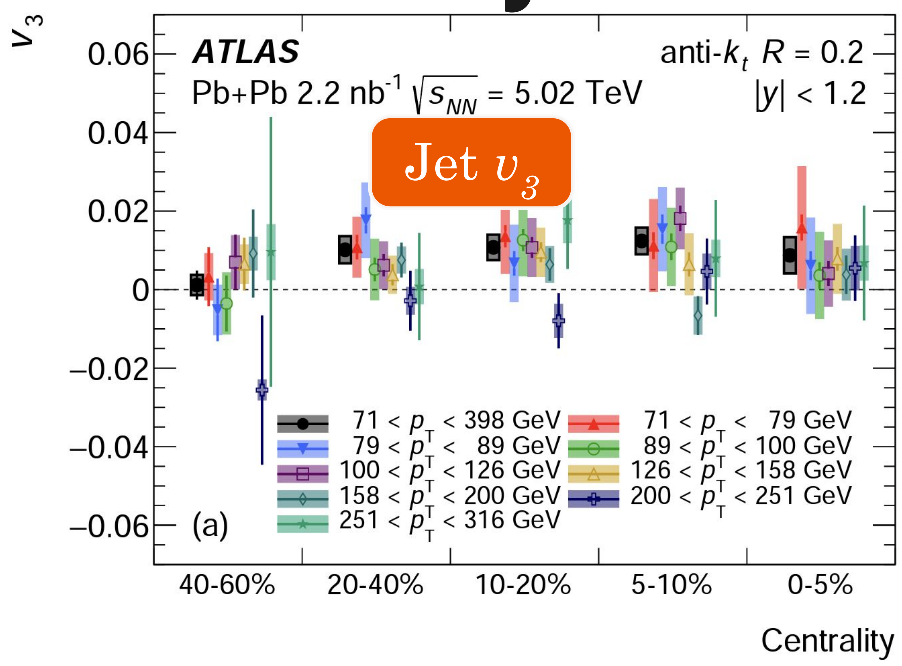

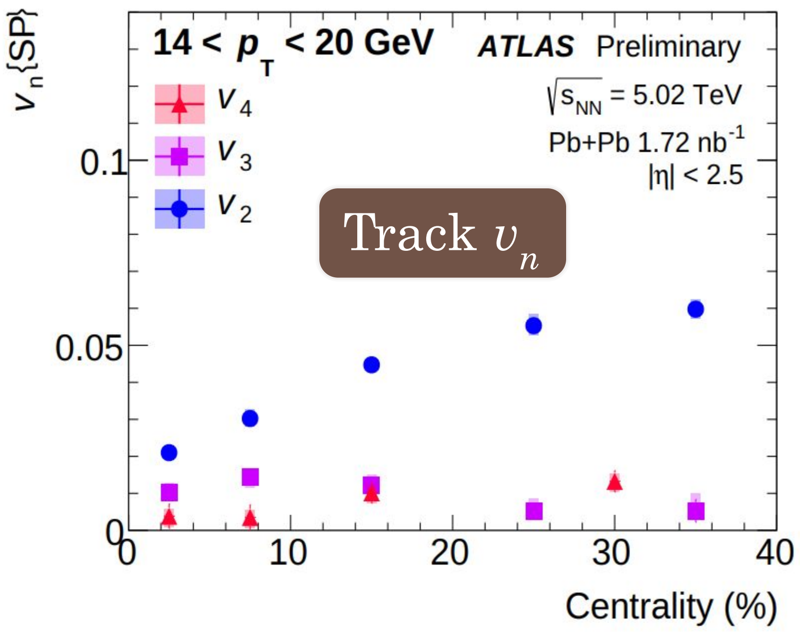

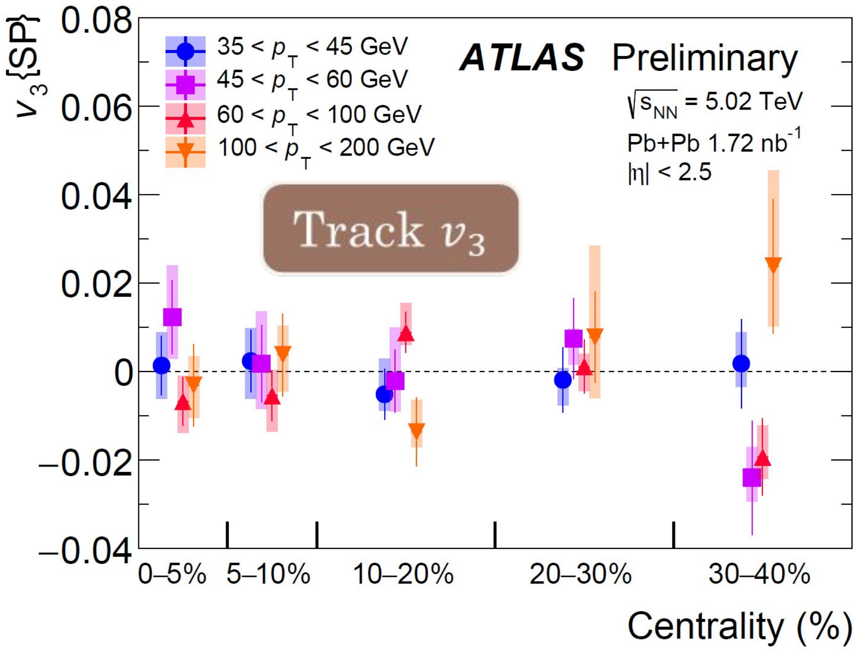

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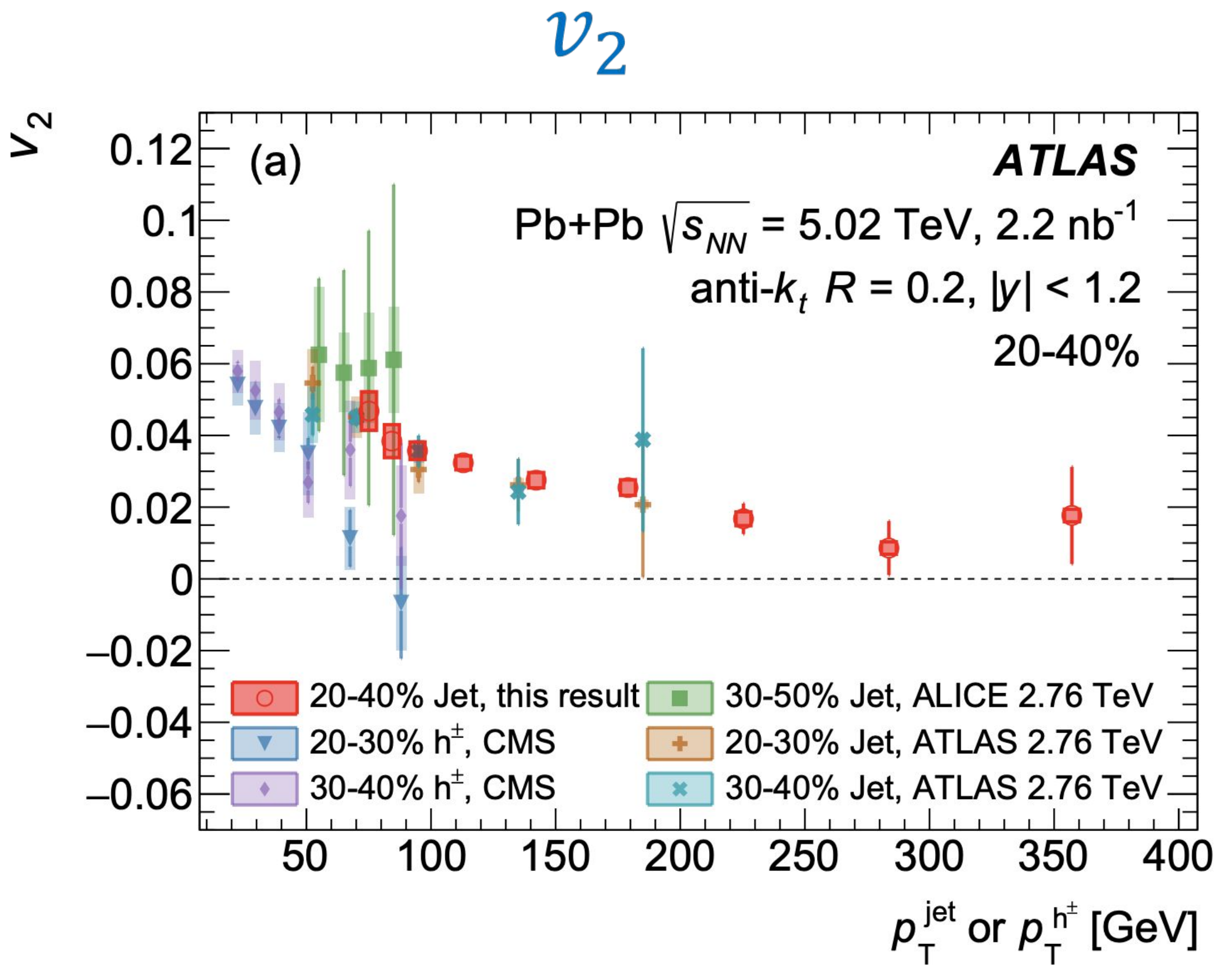
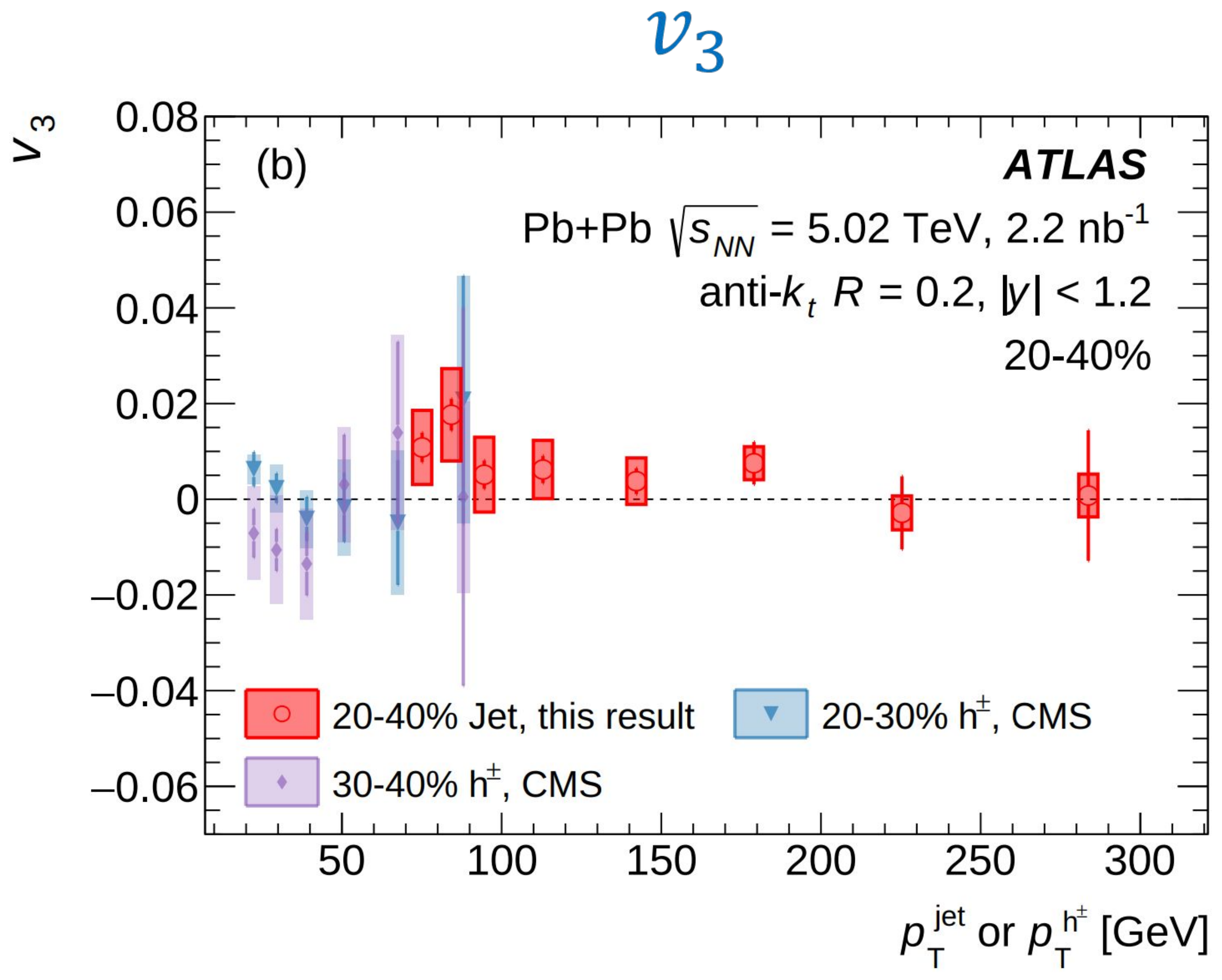
Back-up

Comparison to other v_n measurements





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CMS charged particle:
Phys.Lett.B 776 (2018) 195-216, e-Print: arXiv:1702.00630
ATLAS 2.76 TeV Jet:
Phys.Rev.Lett. 111 (2013) 15, 152301, e-Print: arXiv:1306.6469
ALICE 2.76 TeV Jet:
Phys.Lett.B 753 (2016) 511-525 , e-Print: arXiv:1509.07334

This result:
Phys.Rev.C 105 (2022) 6, 064903
e-Print: arXiv: 2111.06606

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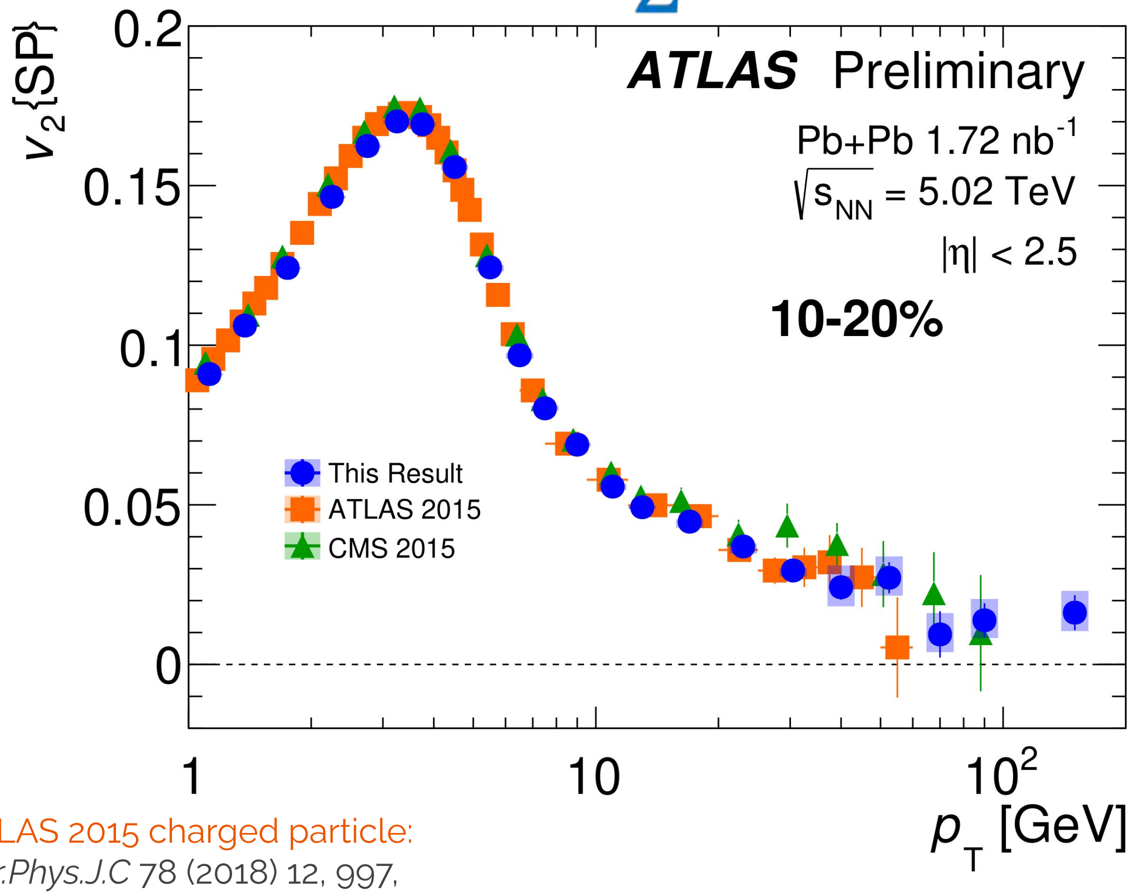
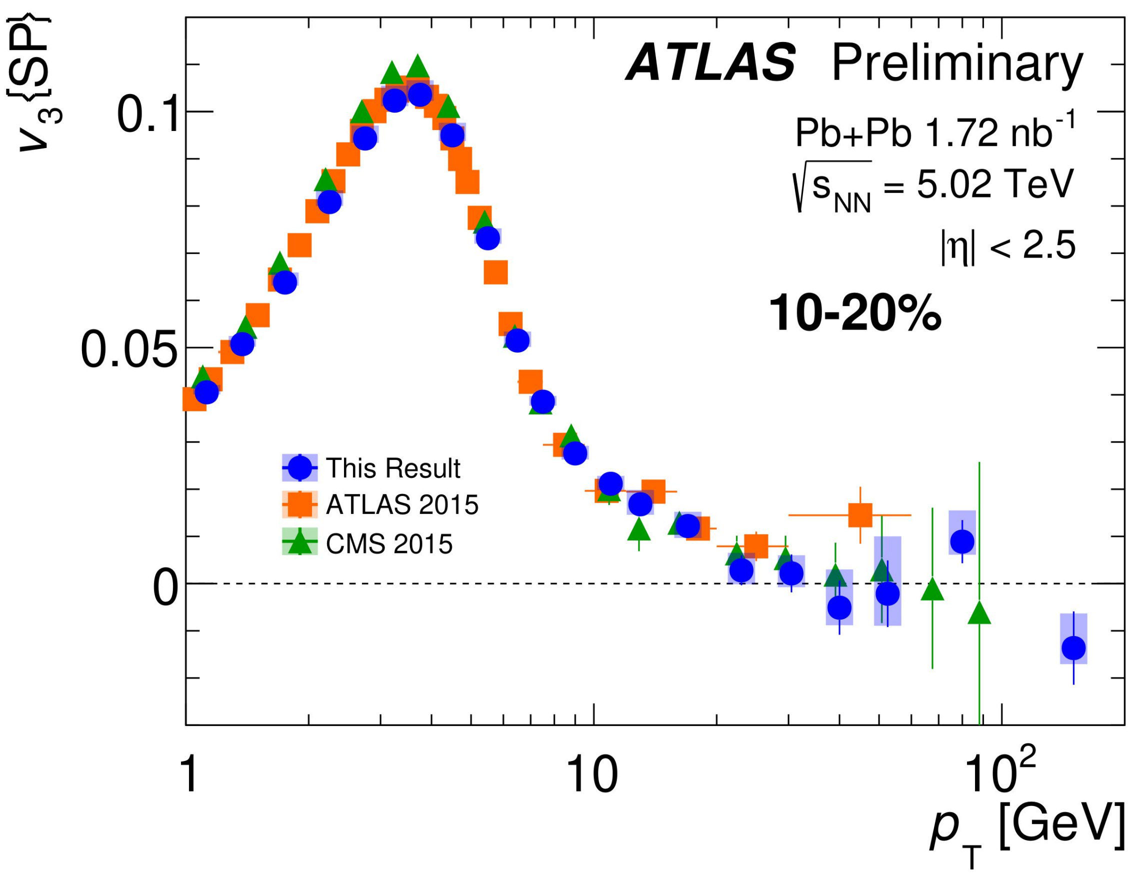
Comparison to other charged particle v_n measurements

This result: ATLAS-CONF-2023-007

v_2



v_3

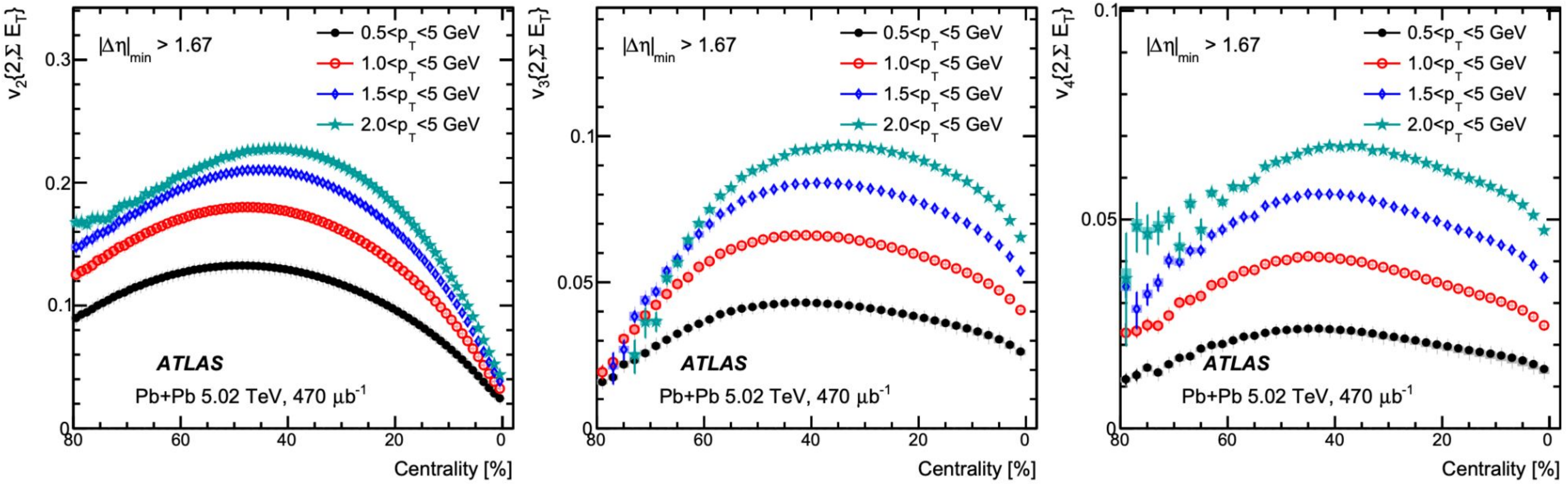


ATLAS 2015 charged particle:
Eur.Phys.J.C 78 (2018) 12, 997,
e-Print: arXiv: 1808.03951
CMS 2015 charged particle:
Phys.Lett.B 776 (2018) 195-216,
e-Print: arXiv:1702.00630

- Consistent with previous measurements
- *Significantly improved statistics and extended measurements to 200 GeV*

Inclusive soft hadron v_n

JHEP 01 (2020) 051
DOI: 10.1007/JHEP01(2020)051



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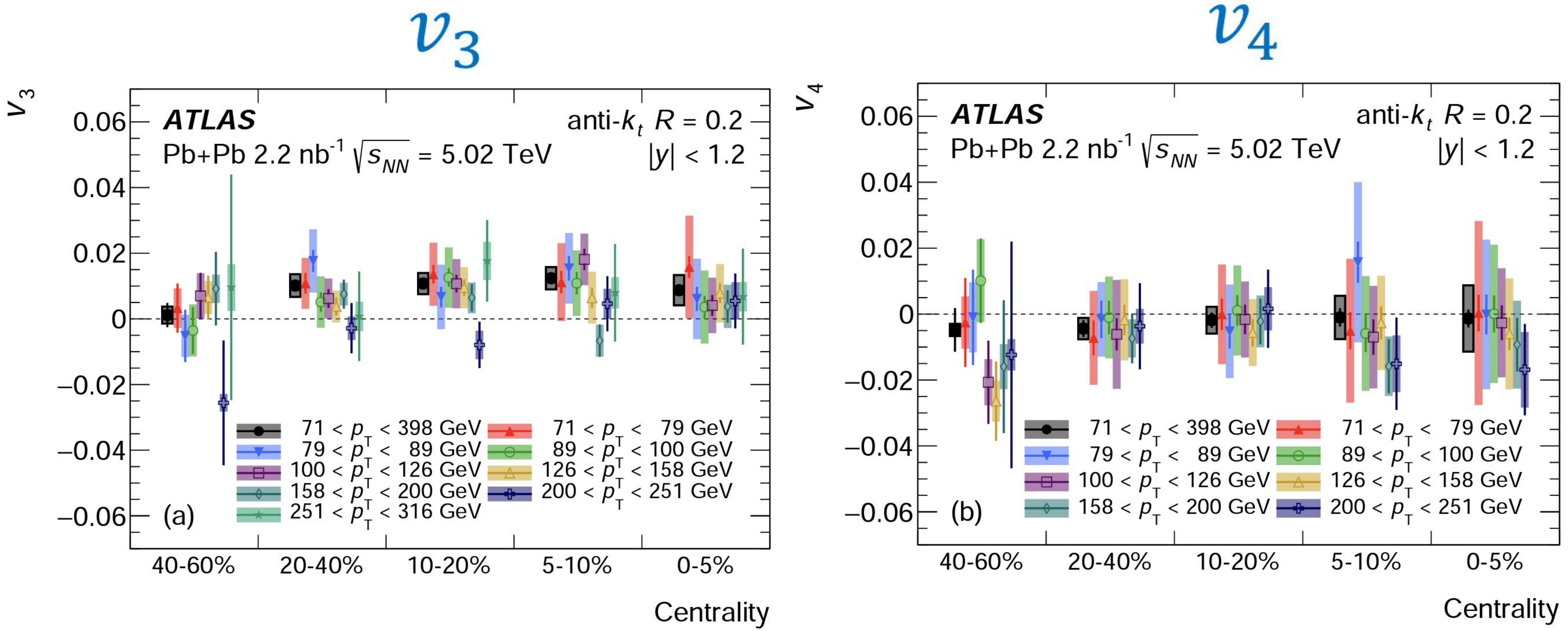
Jet v_3 and v_4 results



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Phys.Rev.C 105 (2022) 6, 064903
e-Print: arXiv: 2111.06606

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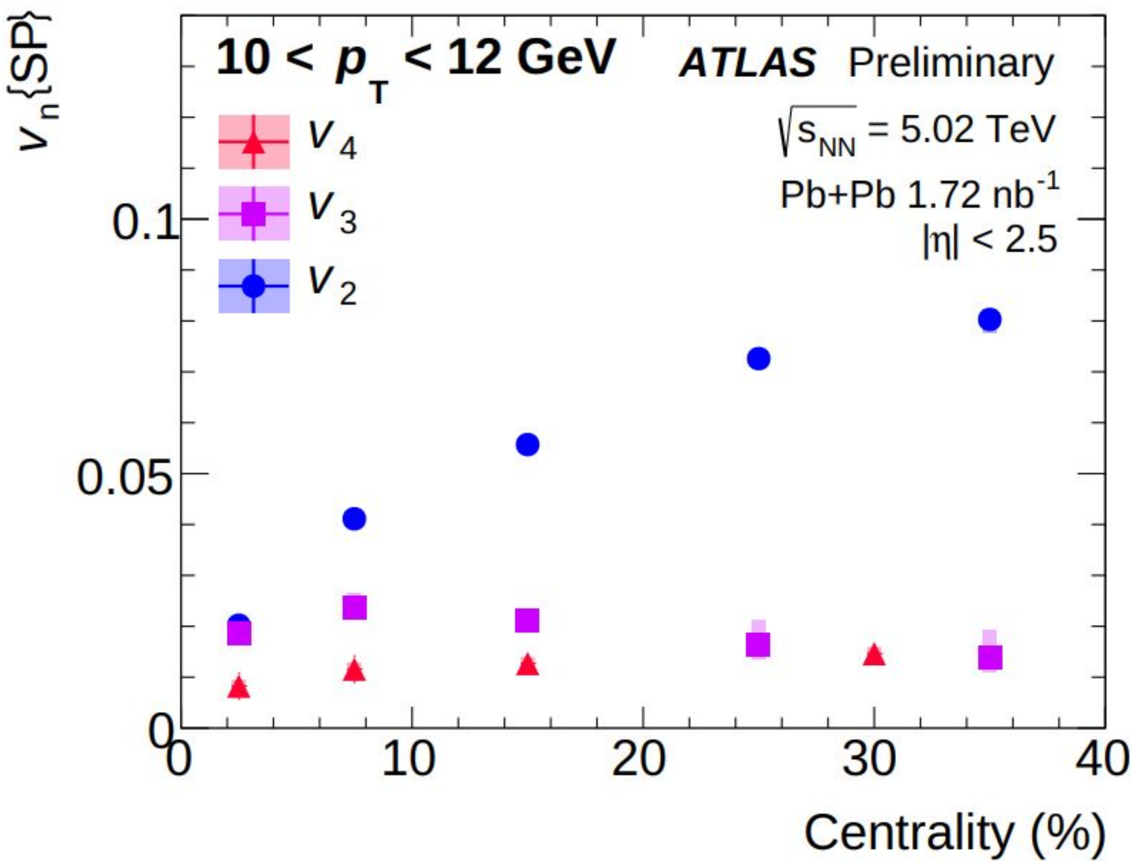
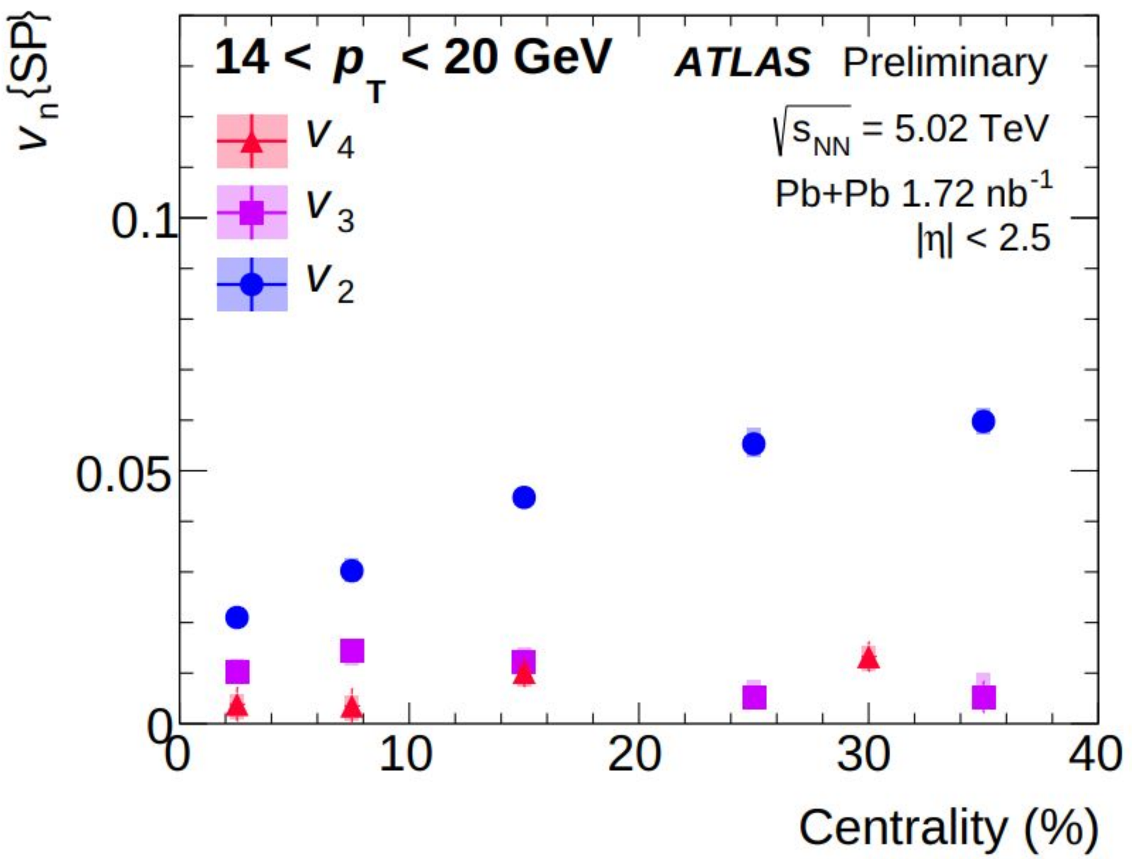
Charged particle v_n for 10-20 GeV





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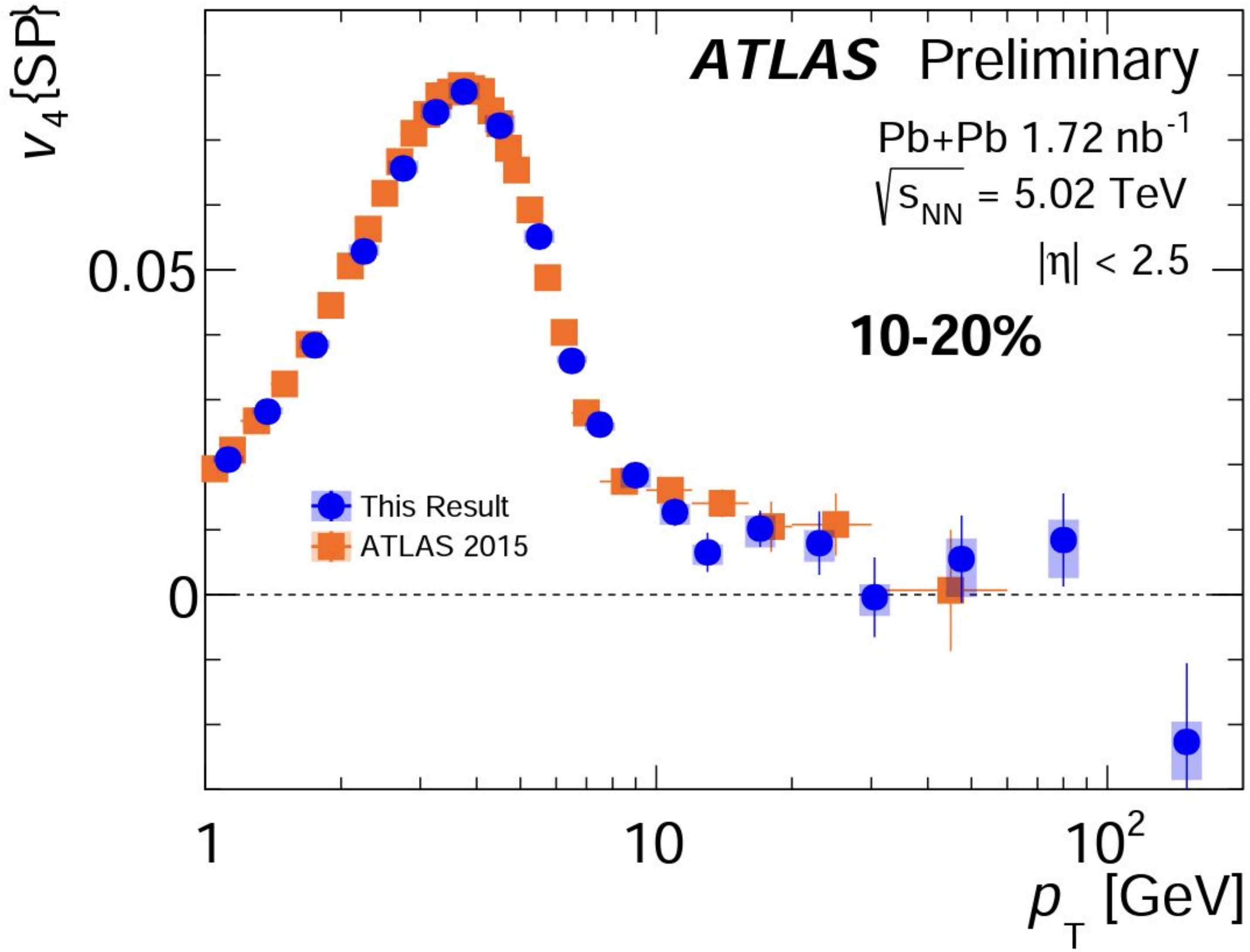
Details of SP Method

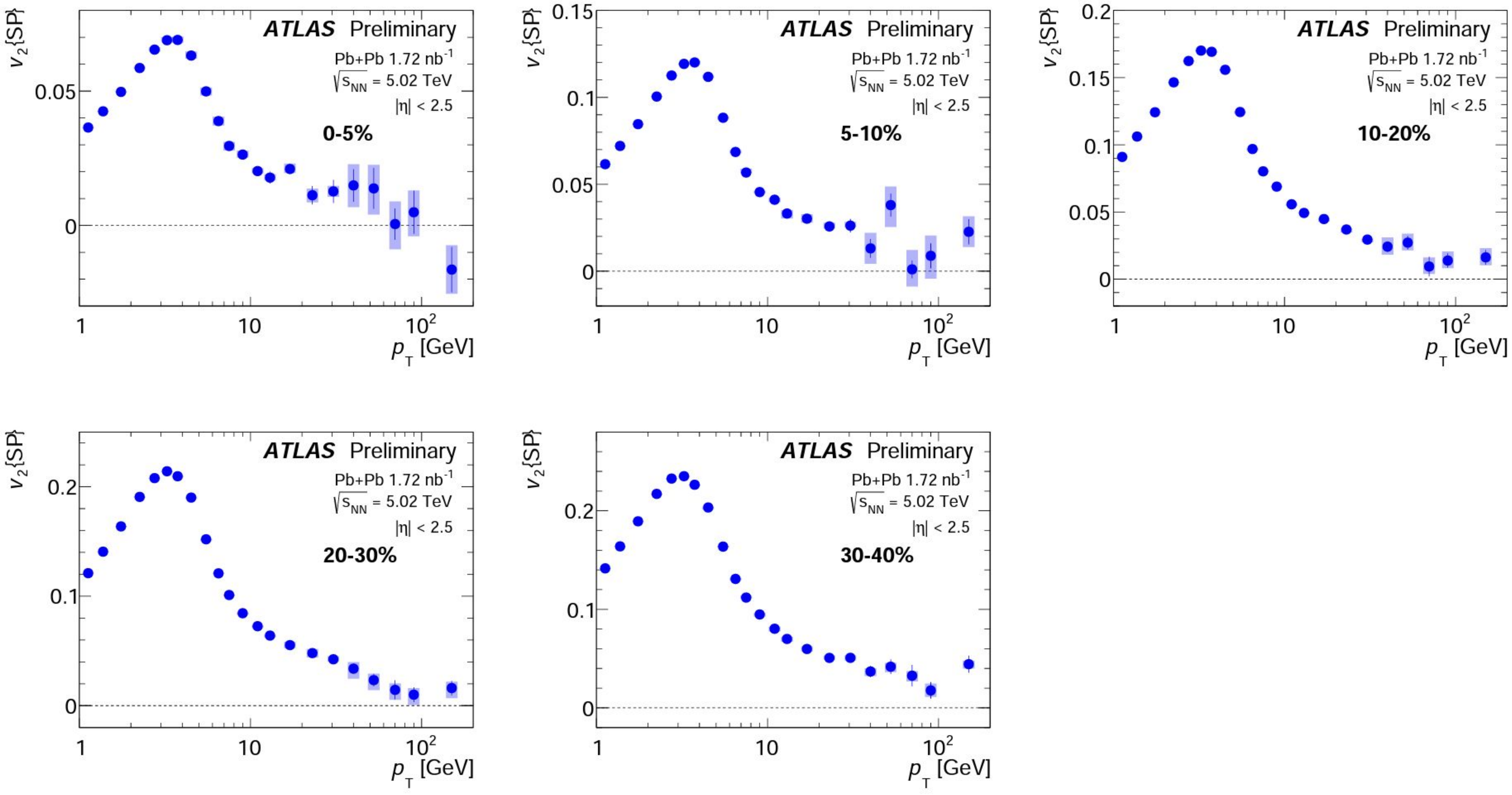
- Flow vectors are computed for each subevent
  - Negative and positive FCal with calorimeter tower energy ($Q^{N|P}$)
  - Negative and positive inner detector with tracks ($q_{n,j}$)
- Final Formula:
  - $v_n\{SP\} = Re \frac{\left\langle q_{n,j}^{*} Q_n^{N|P} \right\rangle}{\sqrt{\langle Q_n^{N*} Q_n^{P} \rangle}}$

Charged particles v_4 compared to ATLAS 2015 measurements

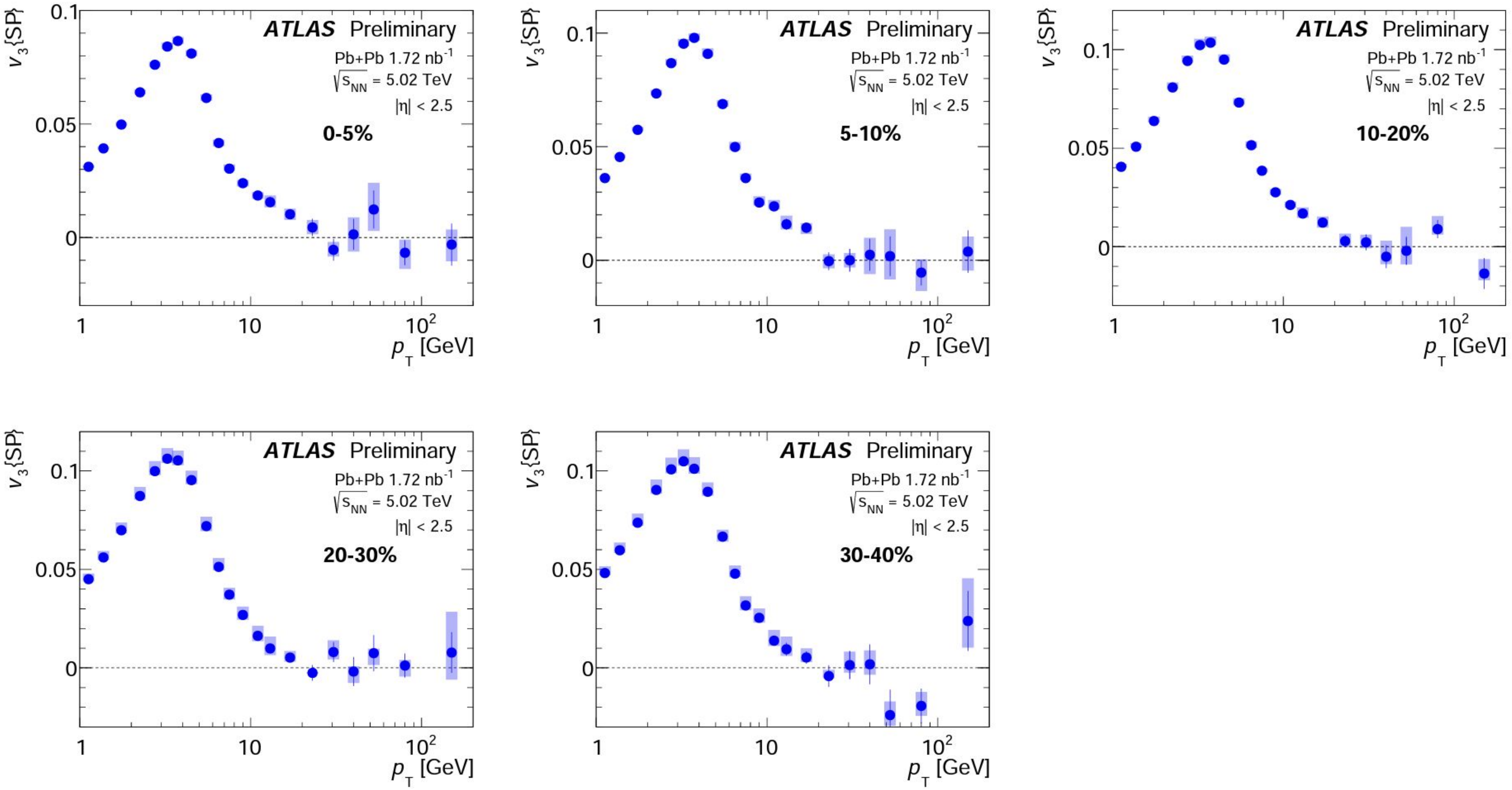


ATLAS-COM-CONF-2023-005

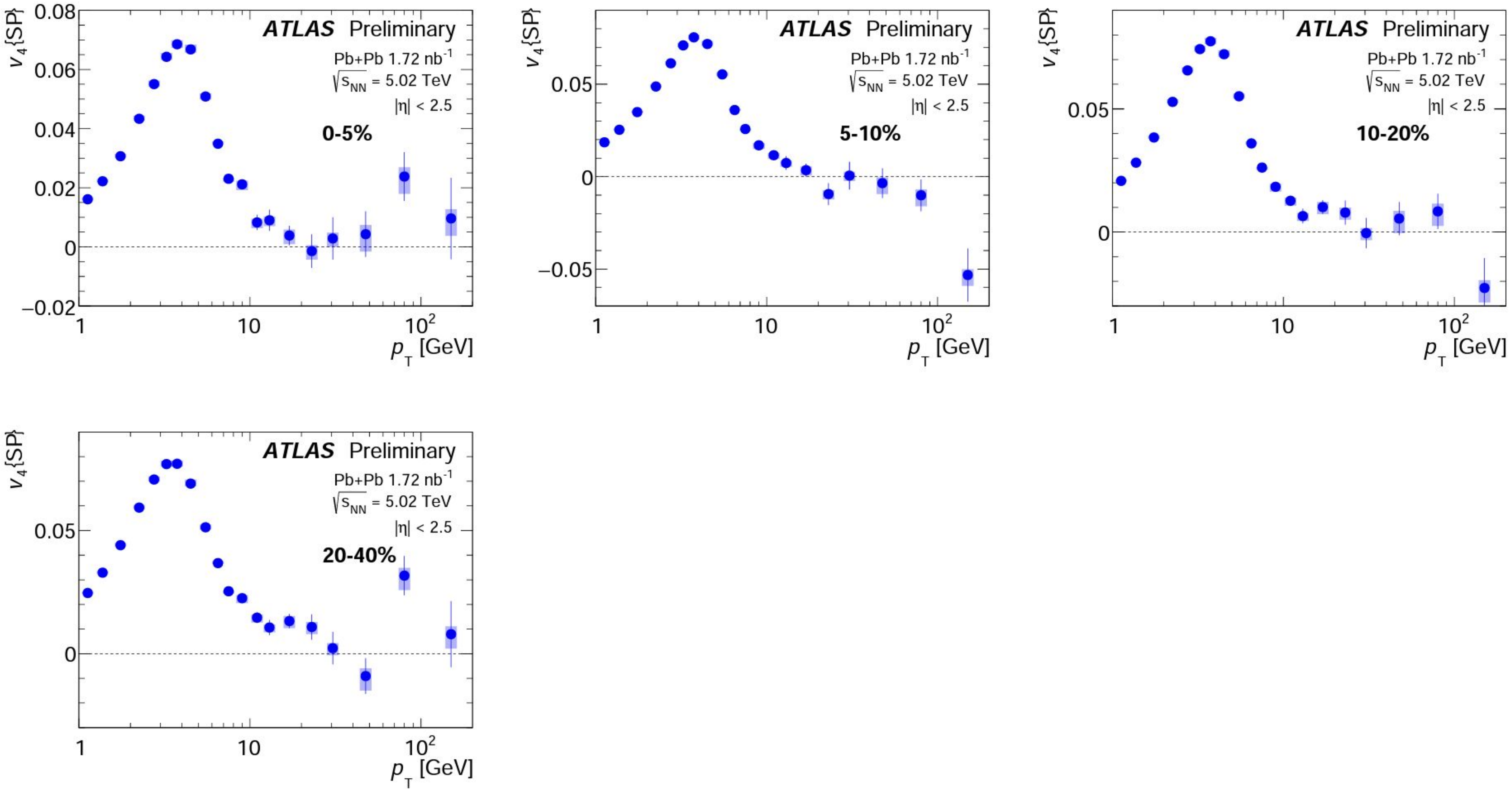
Charged particles v_2 in other centralities



Charged particles v_3 in other centralities



Charged particles v_4 in other centralities



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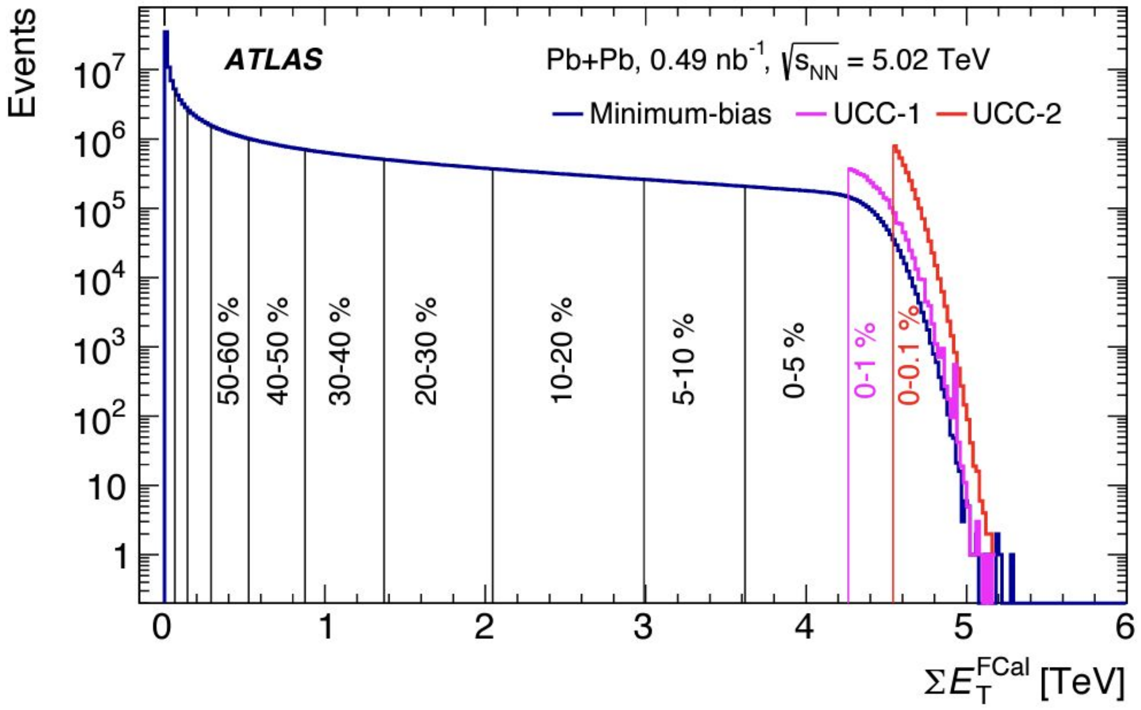
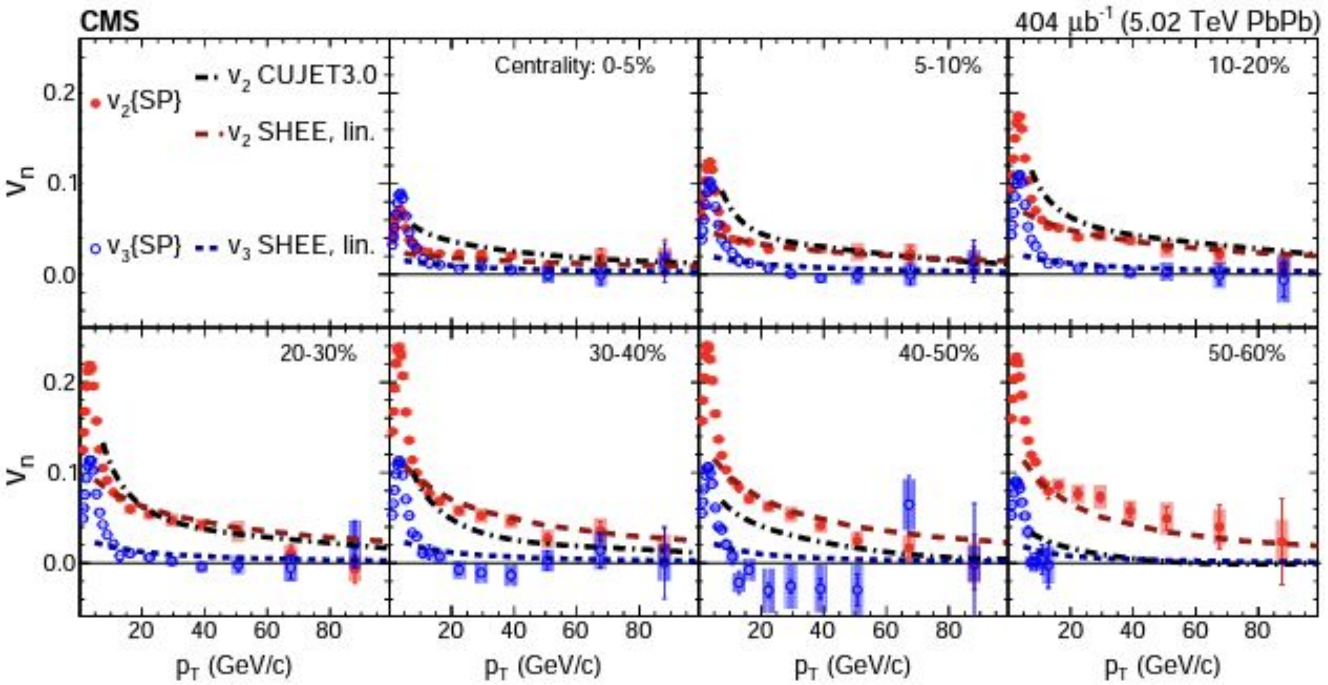
Luminosity Comparisons





ATLAS 2015 charged particle:
Eur.Phys.J.C 78 (2018) 12, 997,
e-Print: arXiv: 1808.03951

CMS 2015 charged particle:
Phys.Lett.B 776 (2018) 195-216,
e-Print: arXiv:1702.00630