

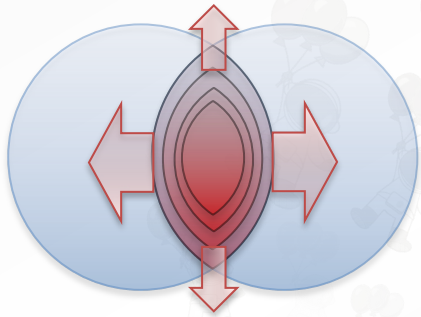
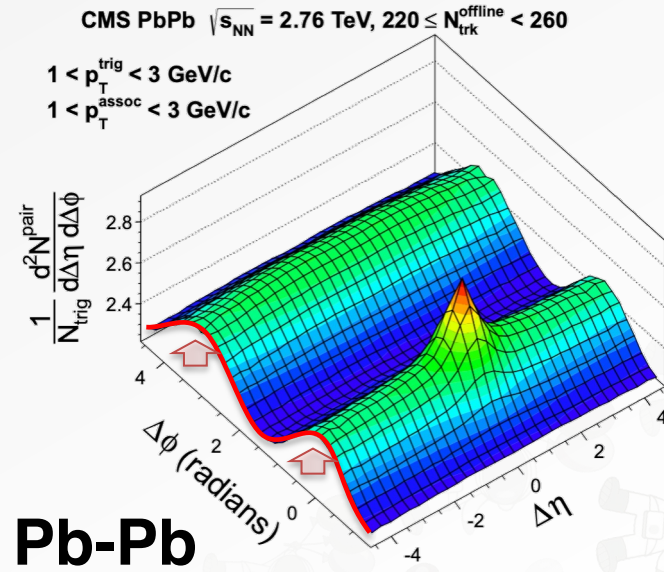
Collective dynamics: experimental overview

Quark Matter 2023 – 7th September 2023

David Dobrigkeit Chinellato

Elliptic flow across systems

Phys. Lett. B 724 (2013) 213

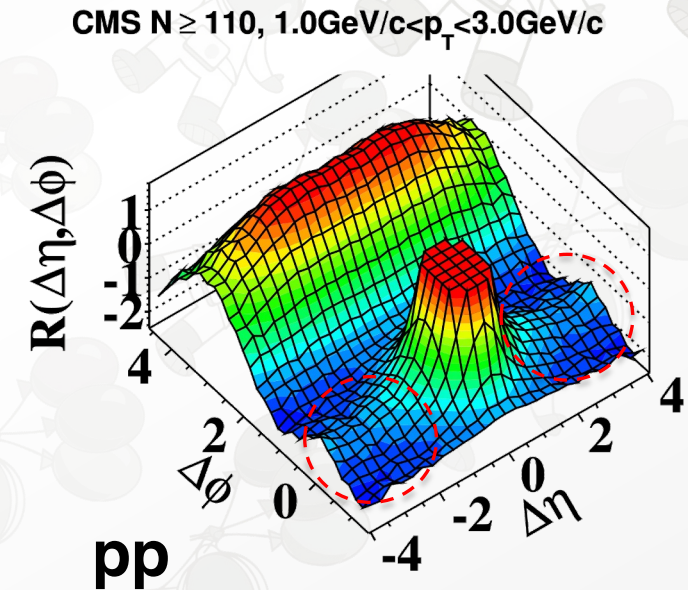
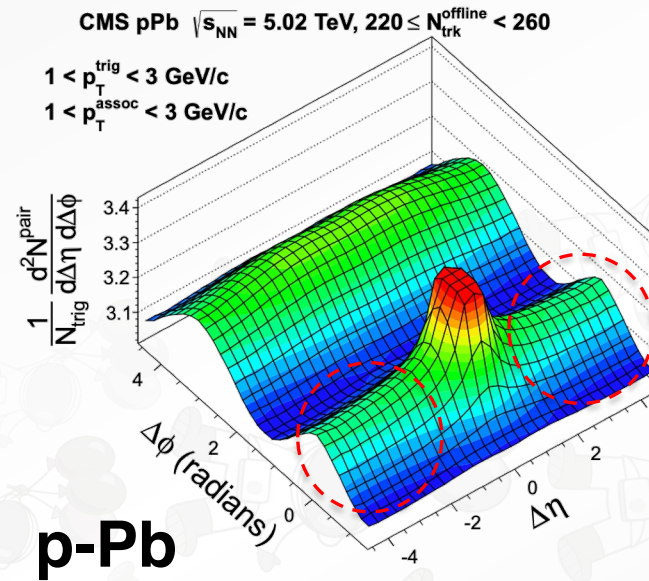
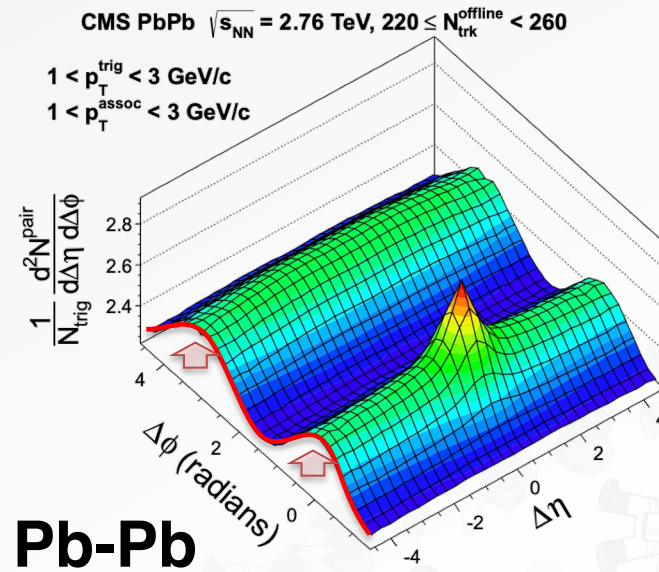


Collective expansion

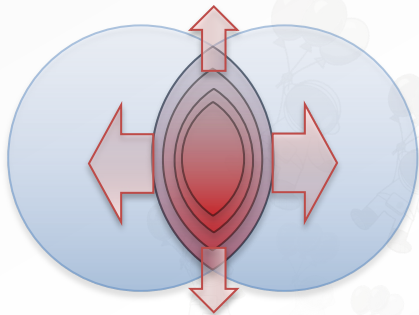
- In Pb-Pb collisions, particles are emitted with a modulation in azimuth due to **collective expansion of an elliptic initial condition**

Elliptic flow across systems

Phys. Lett. B 724 (2013) 213



JHEP 1009:091,2010



Collective expansion

- In Pb-Pb collisions, particles are emitted with a modulation in azimuth due to **collective expansion of an elliptic initial condition**
- Also observed in p-Pb and pp
 - Initial condition not necessarily elliptic
 - **Experimental:** under which conditions does this **not** happen?
 - **Pheno/theory:** collective expansion also at play? Or some other (common?) phenomenon?

Beyond 'leading order': Higher order flow and fluctuations

- Fluctuations in the initial condition (IC) give rise to higher order flow harmonics
 - higher order flow harmonics encode info about IC
 - Hydro modeling significantly more constrained
- Correlations of flow amplitudes of different orders: at the core of various new tools being utilized today
- Fundamental to understand if origin of collectivity is similar in various collision systems

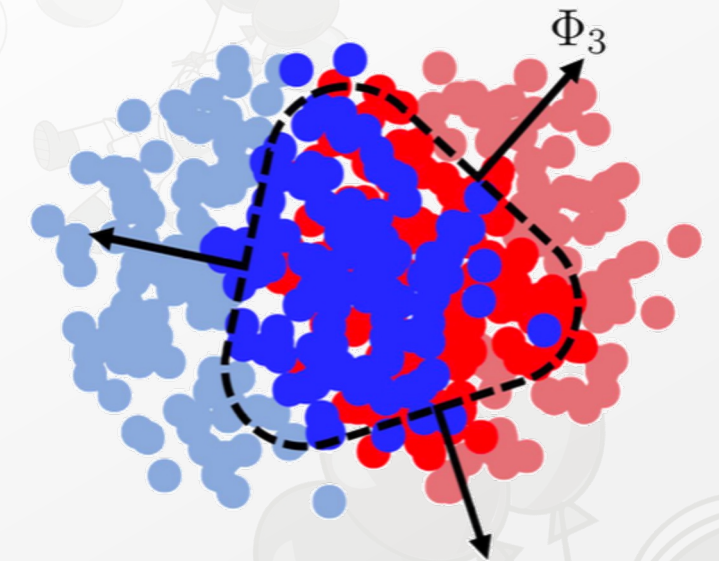
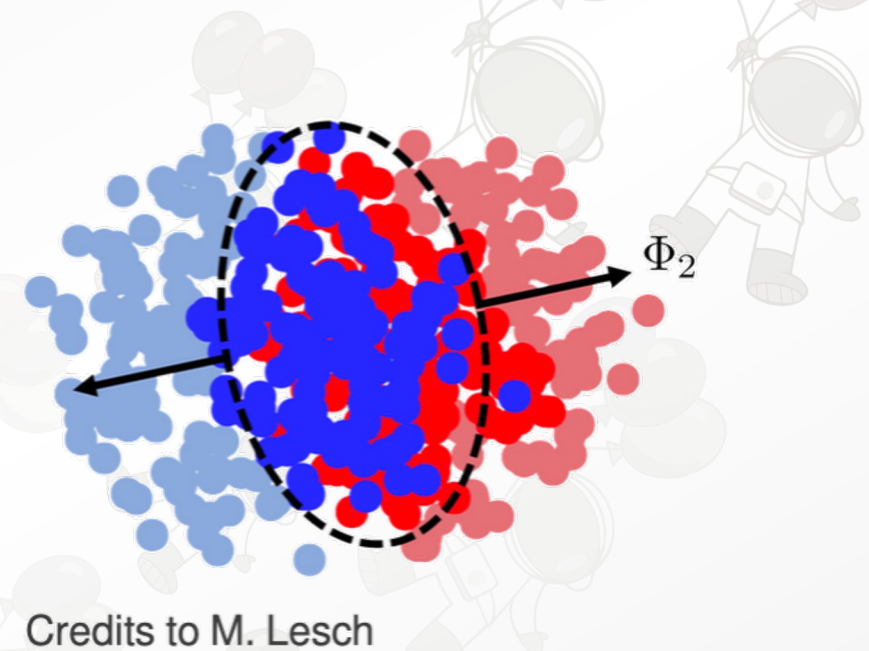
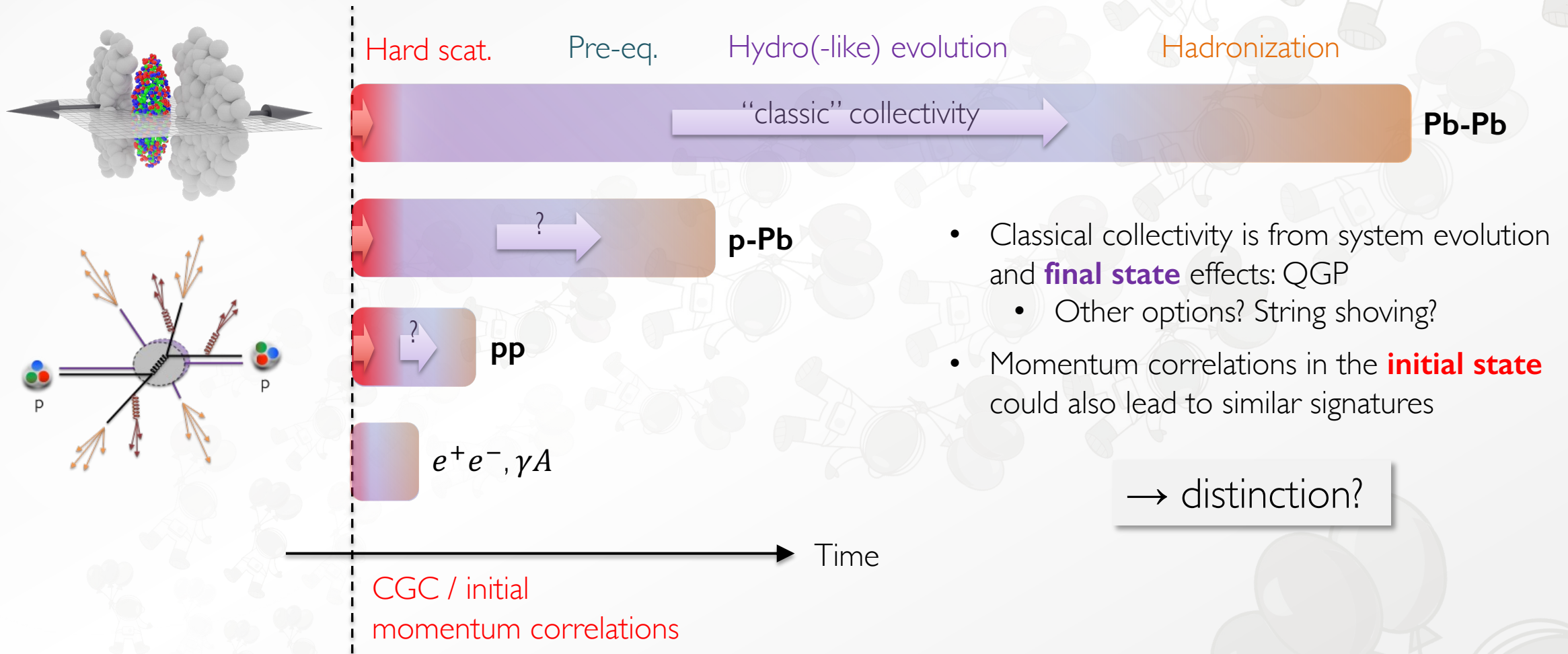
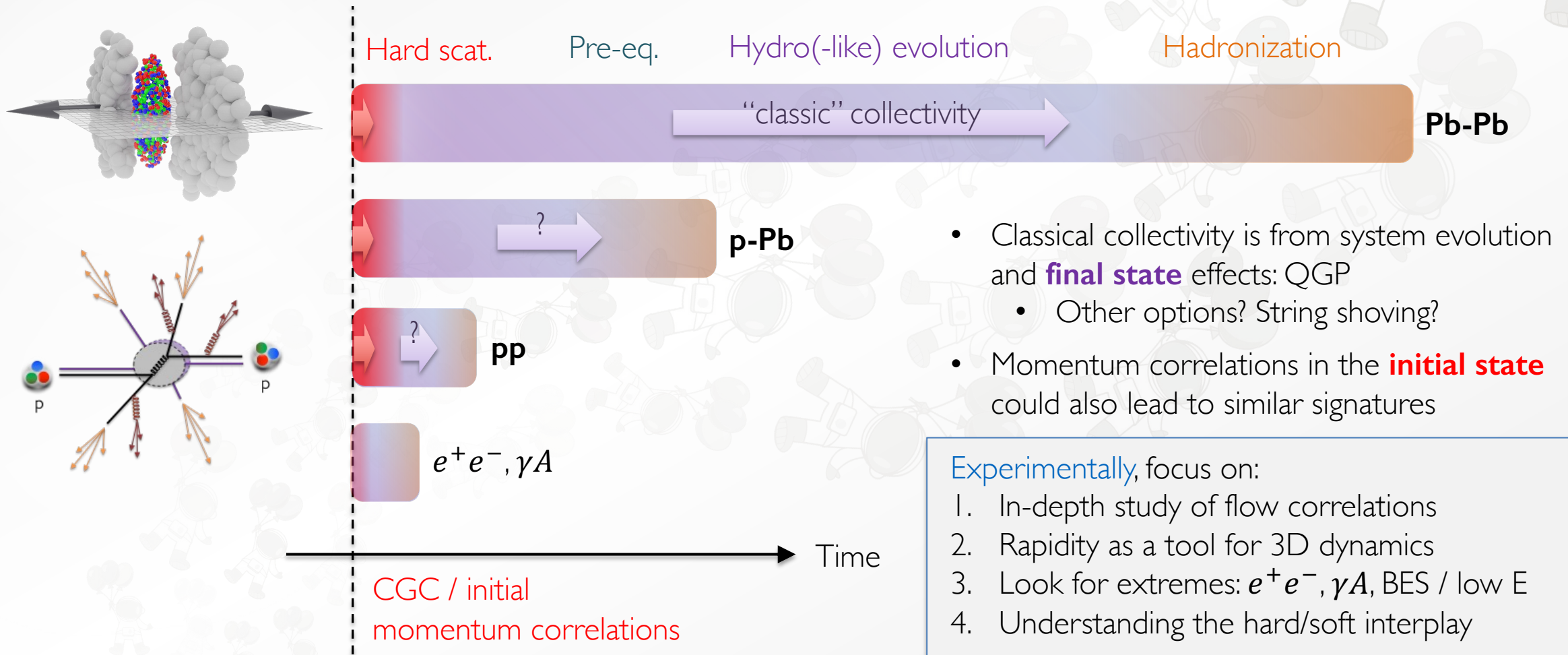


Figure from Cindy Mordasini's talk

Origins of collectivity and role of system evolution



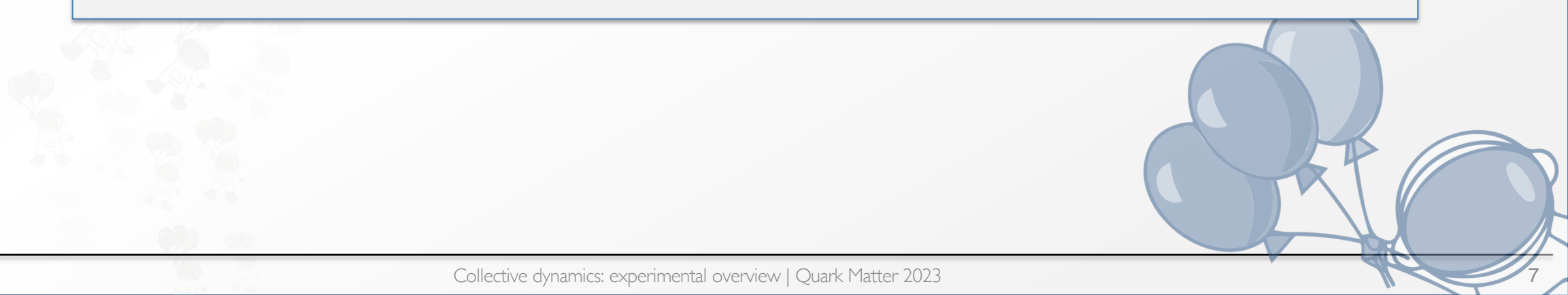
Origins of collectivity and role of system evolution





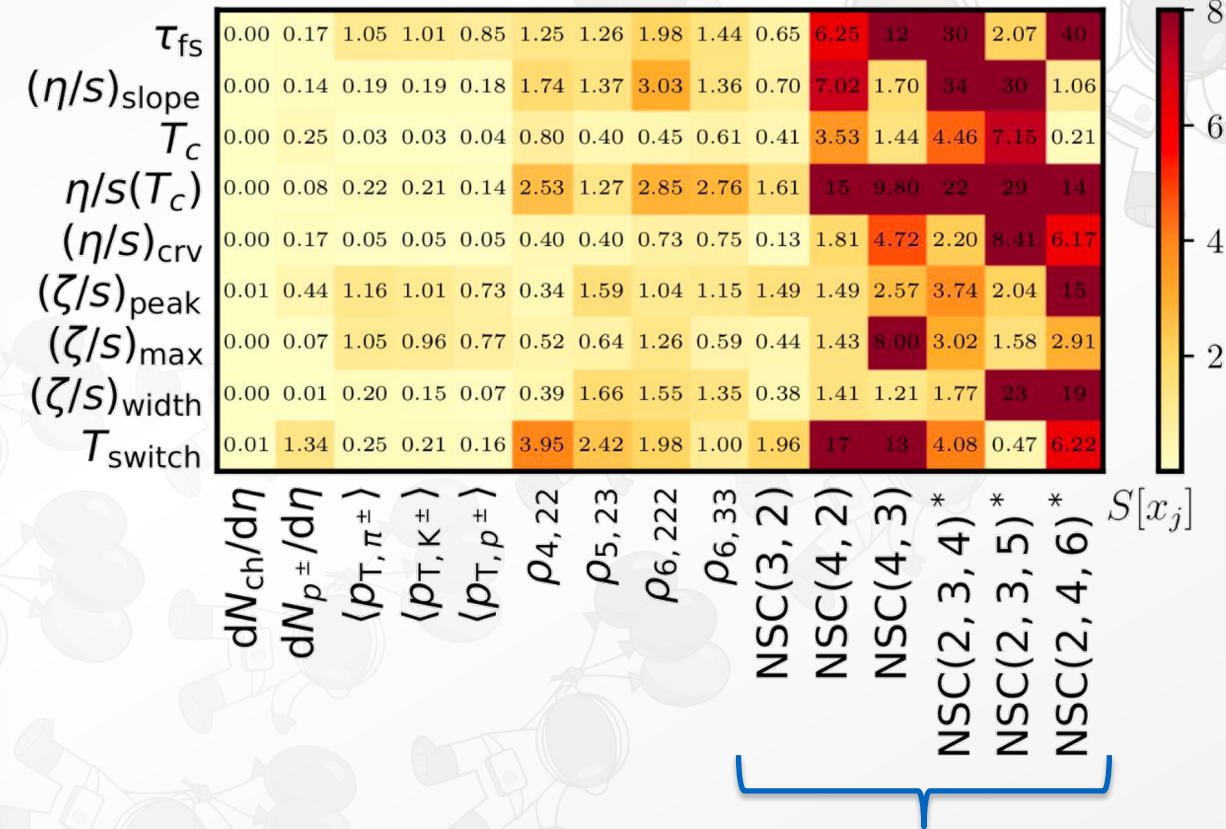
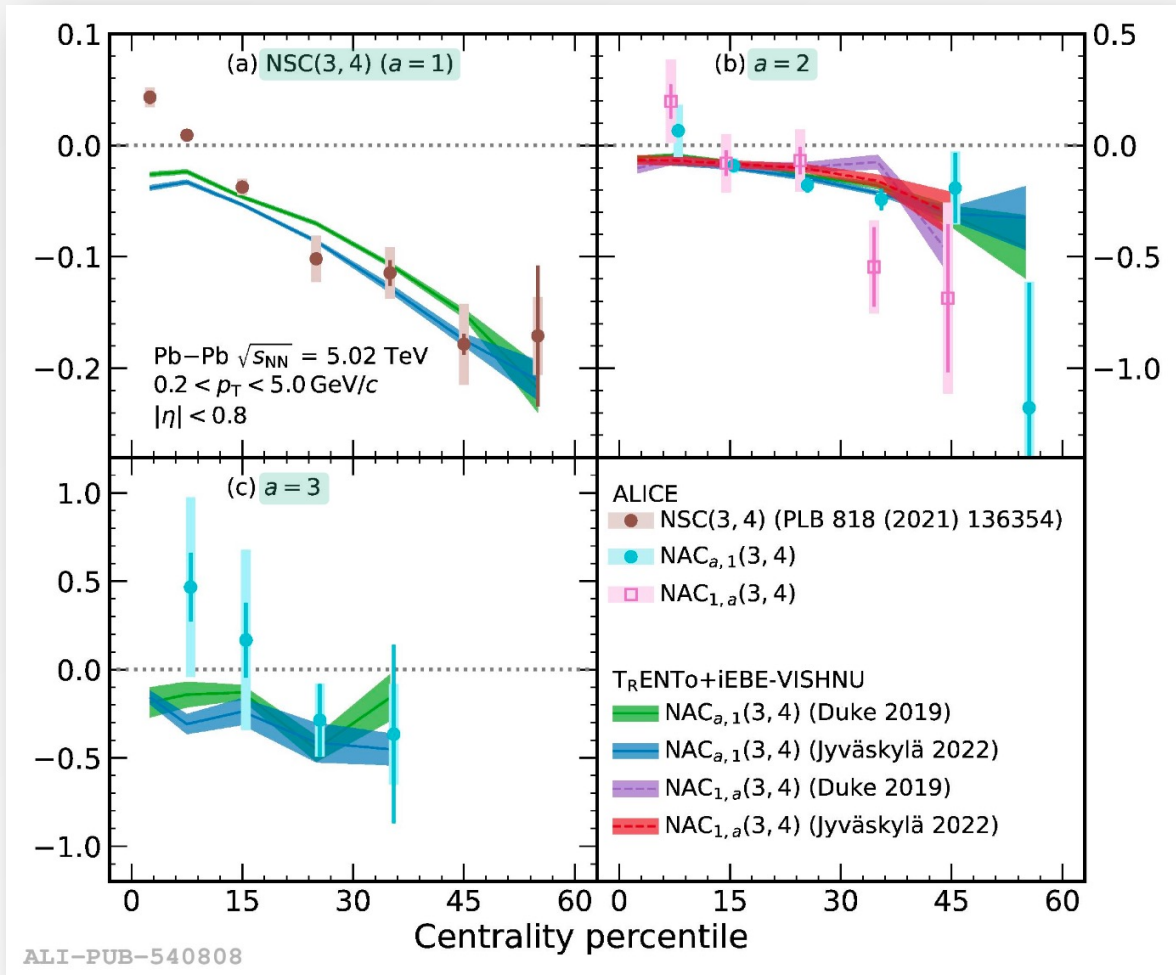
Experimentally, focus on:

1. In-depth study of flow correlations

- Role of initial condition vs dynamics
2. Rapidity as a tool for 3D dynamics
 3. Look for extremes: e^+e^- , γA , BES / low E
 4. Understanding the hard/soft interplay
- 

Flow correlations in Pb-Pb

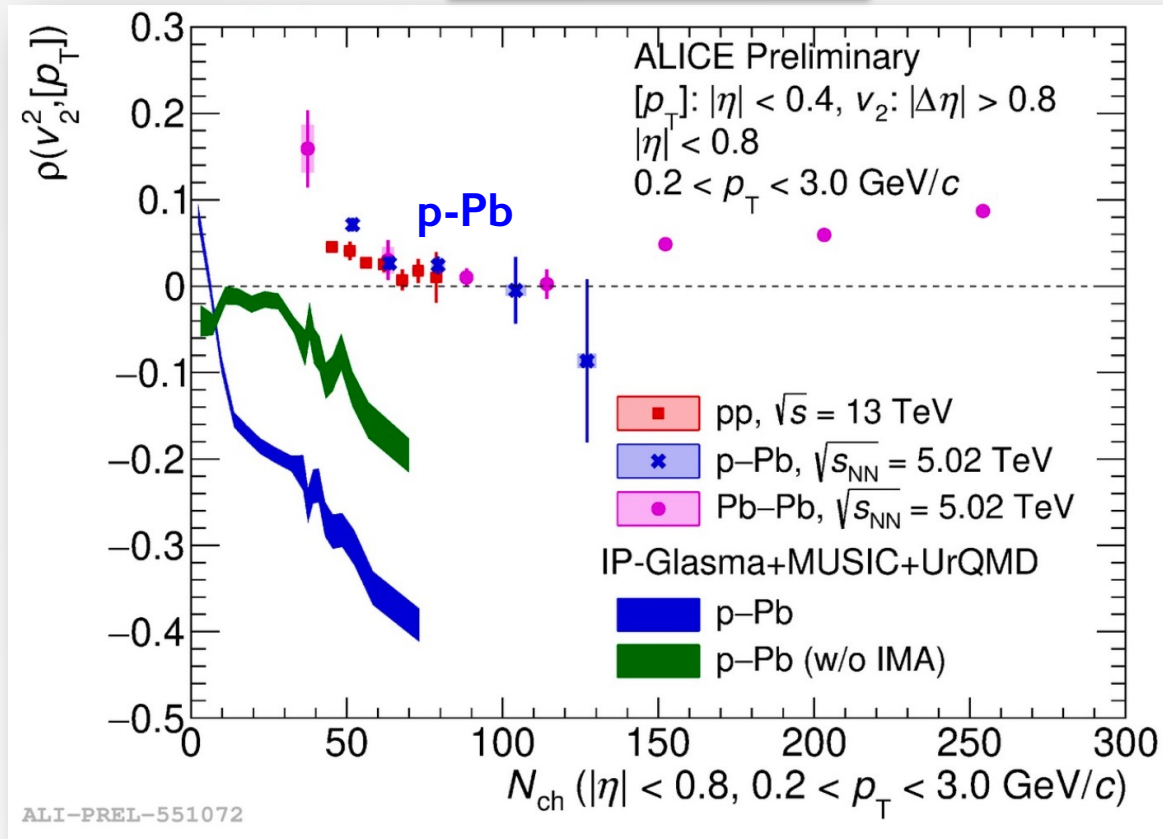
✓ Flow correlations → see [Cindy Mordasini's talk](#)



- Normalized symmetric cumulants: encode information about how flow components are correlated to one another → **strong constraint to hydro**
- Deviations with respect to state-of-the-art models** observed in central events

Correlation between v_2 and $\langle p_T \rangle$

✓ Flow correlations

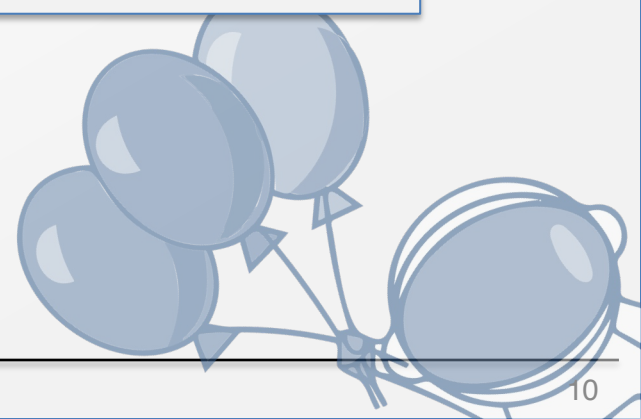


→ see [Mingrui Zhao's talk](#)

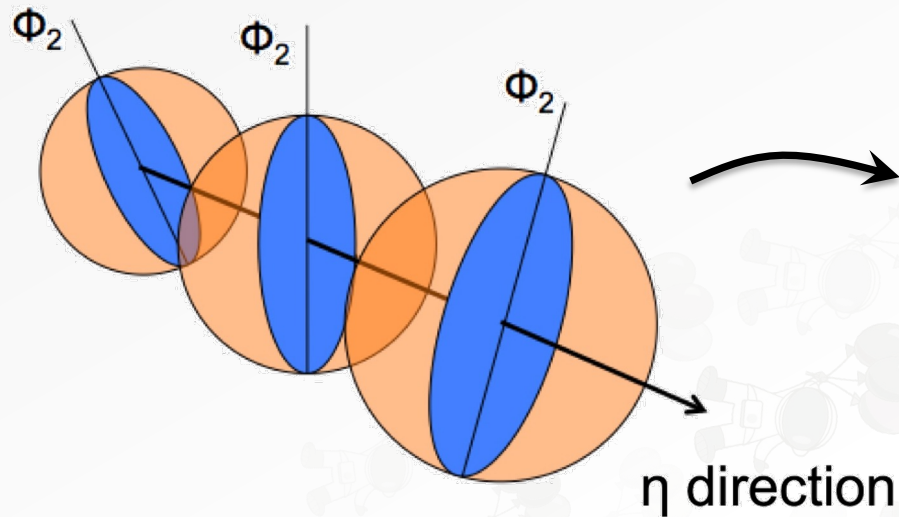
- Why use the correlation between v_2 and $\langle p_T \rangle$?
 - Disentangle **role of geometric response** and **IC**
 - Shape and elliptic flow: v_2 ;
 - size/expansion/radial flow: $\langle p_T \rangle$
- Tested against state-of-the-art model:
 - IP-Glasma + MUSIC + UrQMD**
 - With and without **Initial Momentum Anisotropy**
- Simple **geometric picture does not explain results**
- Predictions far from measurement at low multiplicity
 - Radial vs elliptic flow mismatch?**
→ breakdown of hydro picture?



Experimentally, focus on:

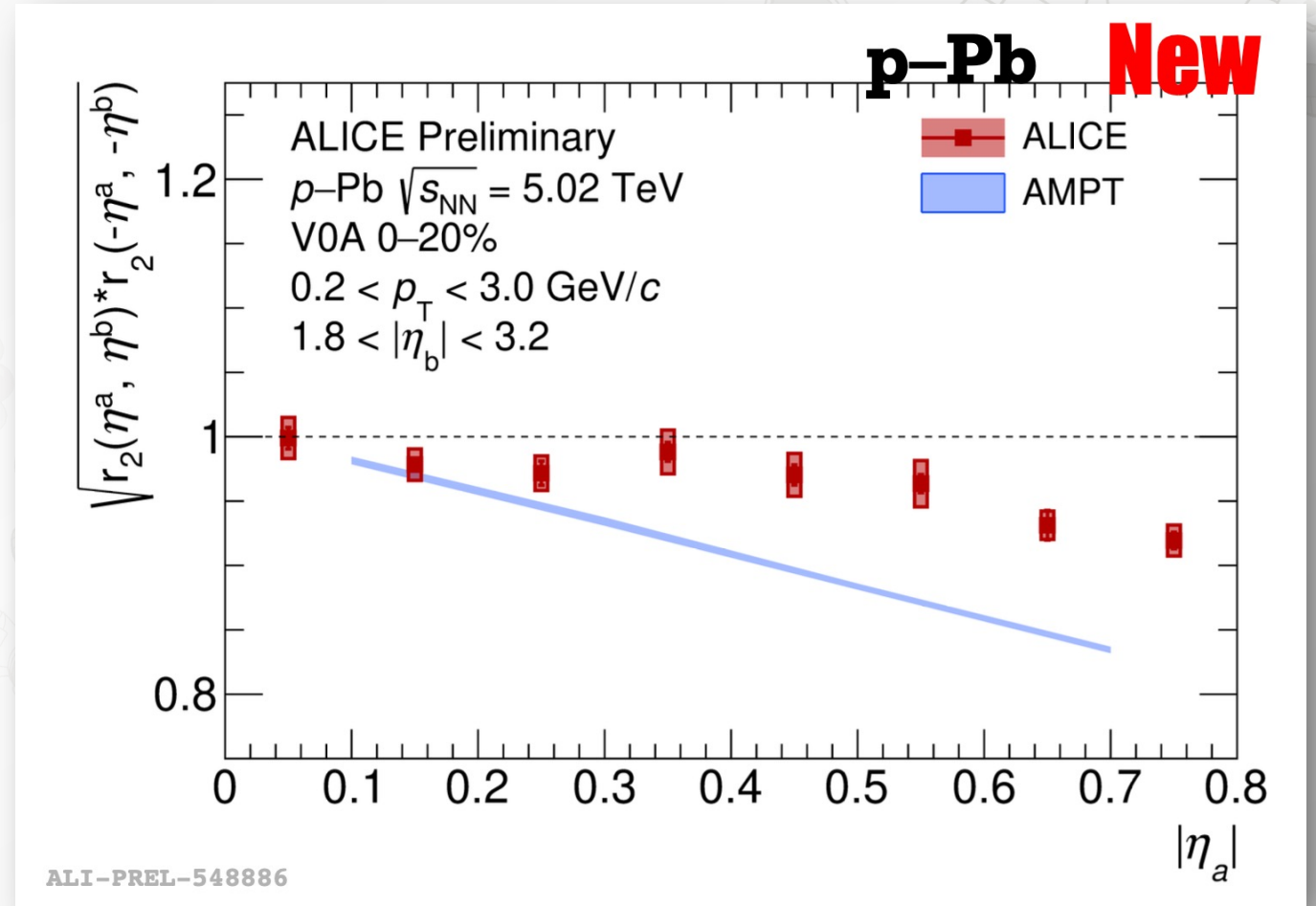
1. In-depth study of flow correlations
 - 2. Rapidity as a tool for 3D dynamics**
 - Correlate longitudinal direction? Geometry / causality / time
 3. Look for extremes: e^+e^- , γA , BES / low E
 4. Understanding the hard/soft interplay
- 

Flow decorrelation vs pseudorapidity: p-Pb



→ see [Mingrui Zhao's talk](#)

- ✓ Flow correlations
- ✓ 3D dynamics

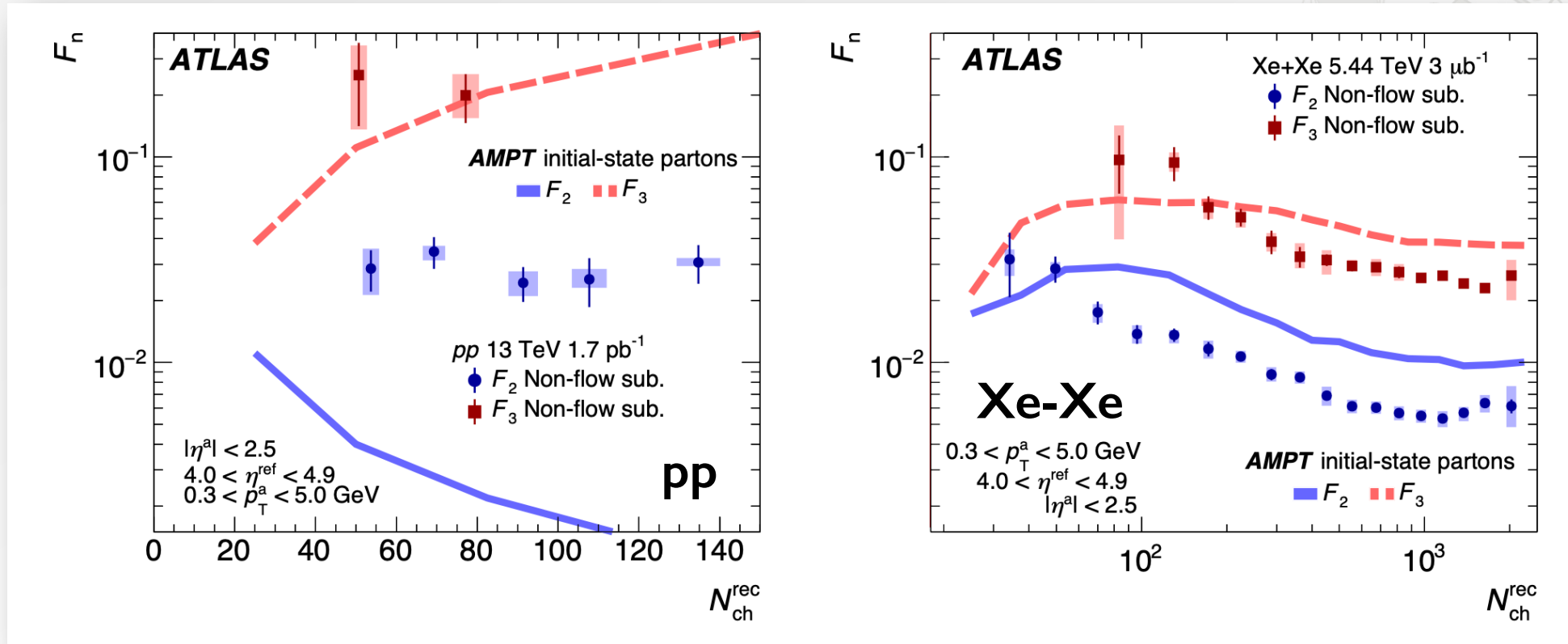


- Correlate v_2 and pseudorapidity
- Longitudinal correlations → not well reproduced by AMPT

- ✓ Flow correlations
- ✓ 3D dynamics

Flow decorrelation vs pseudorapidity: pp vs AA

<https://arxiv.org/abs/2308.16745>



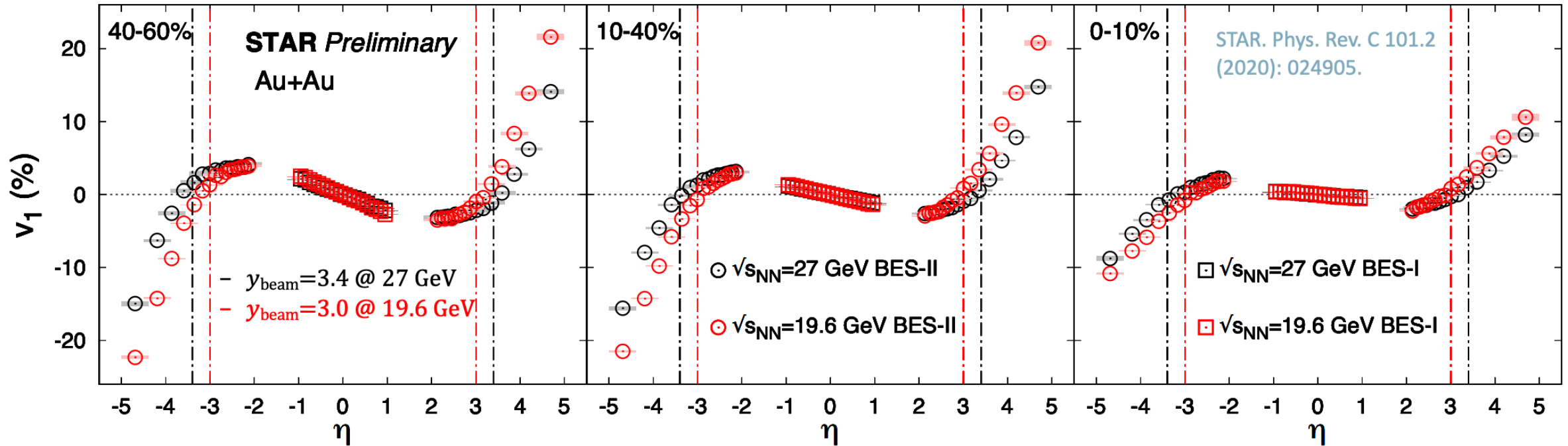
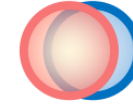
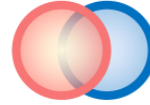
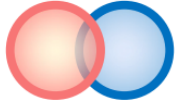
- F_n : quantifies (non-flow-subtracted) n -th flow coefficient decorrelation versus rapidity
- Large decorrelation factors that are N_{ch} -independent (pp) and decrease (Xe-Xe)
- Not reproduced well by AMPT, except perhaps qualitatively in AA
 - sub-nucleonic structure and fluctuations in longitudinal energy deposition in pp are needed

→ see [talk by Blair Daniel Seidlitz](#)



Longitudinal dynamics from directed flow

✓ 3D dynamics

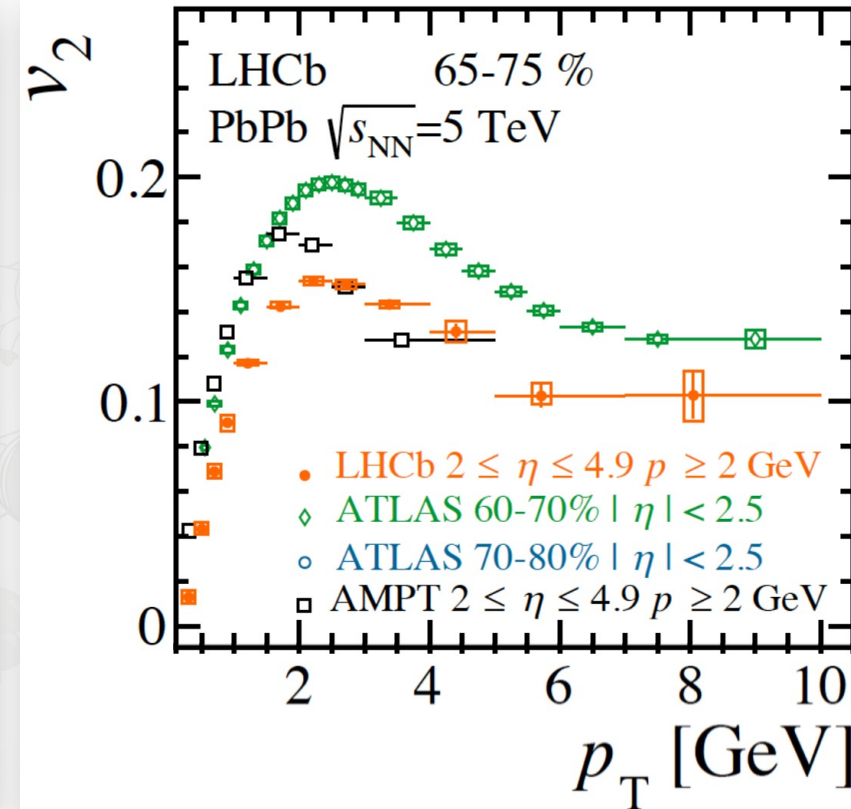
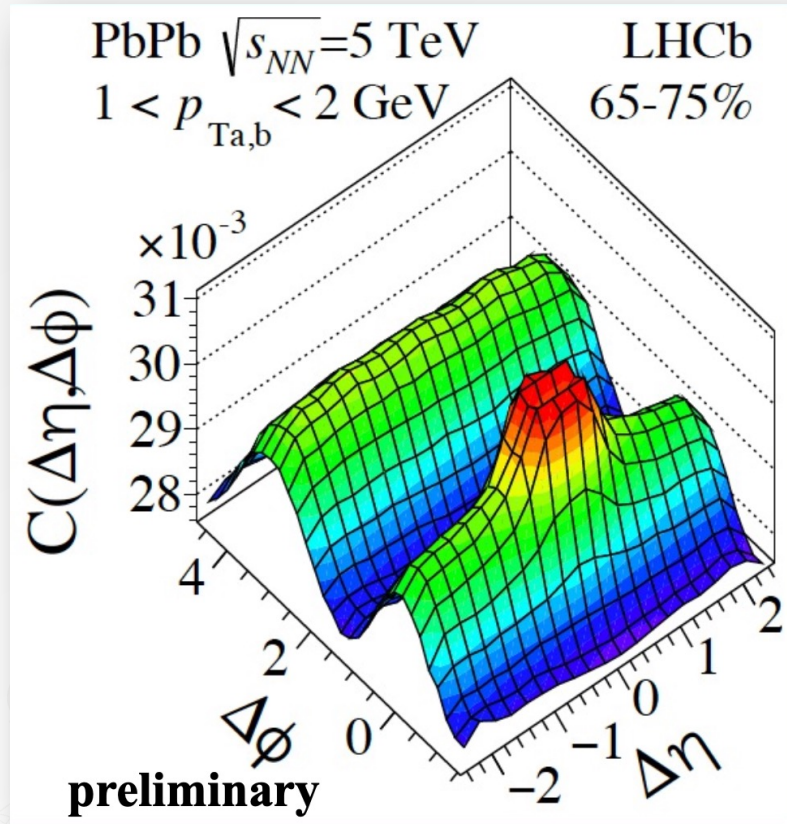


- Directed flow measured over large pseudorapidity range by STAR in BES
- Fundamental input for hydro modeling
 - BES: also potentially relevant for [switch in dynamics](#) (more later!)

→ see [talk by Xiaoyu Liu](#)

- ✓ Flow correlations
- ✓ 3D dynamics

LHCb: measuring (very) forward flow in Pb-Pb

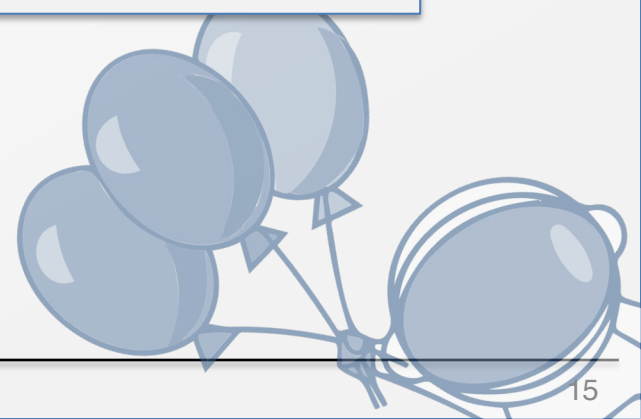


- Elliptic flow coefficient measured by LHCb: first [very forward acceptance results](#) in Pb-Pb
- [Further constraint](#) to full three-dimensional hydrodynamical modeling

→ See talk by [Cheuk Ping Wong](#)



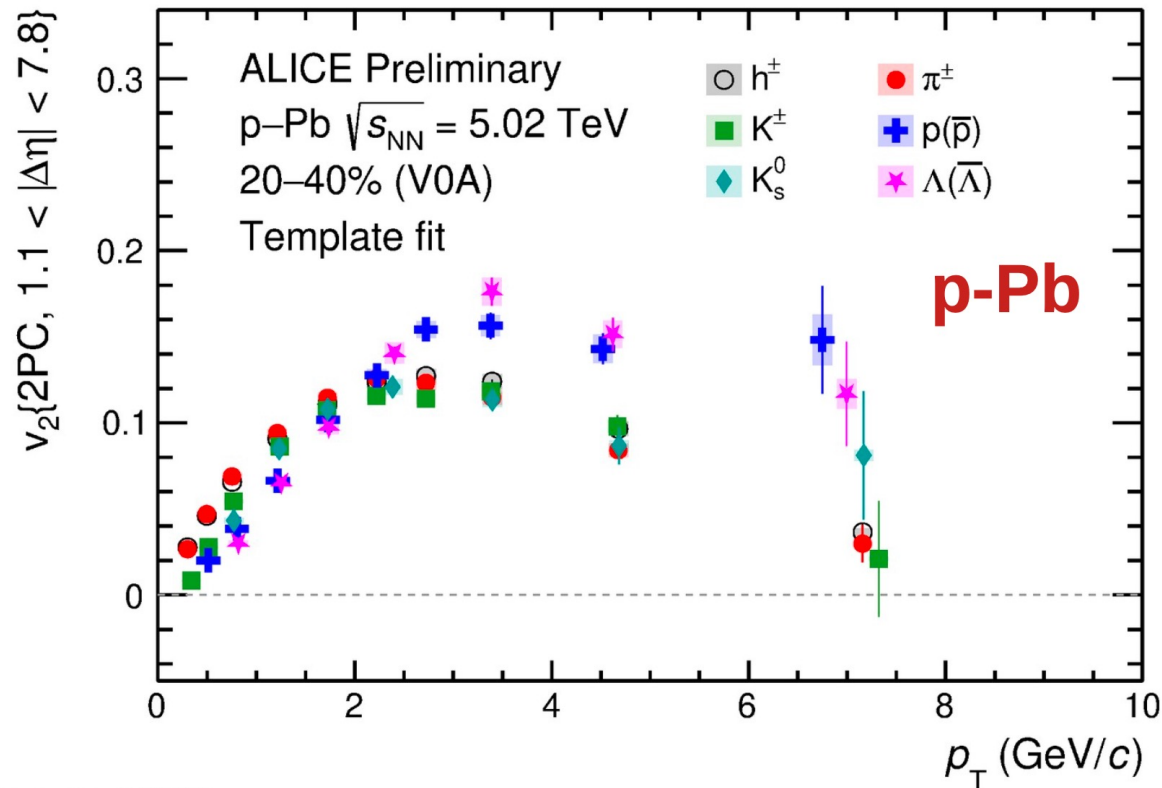
Experimentally, focus on:

1. In-depth study of flow correlations
 2. Rapidity as a tool for 3D dynamics
 - 3. Look for extremes: e^+e^- , γA , BES / low E**
 - Search for a 'breaking point' and for limits of validity
 4. Understanding the hard/soft interplay
- 

ALICE: mass ordering in p-Pb

✓ Specific processes/extremes

→ See [Mingrui Zhao's talk](#)

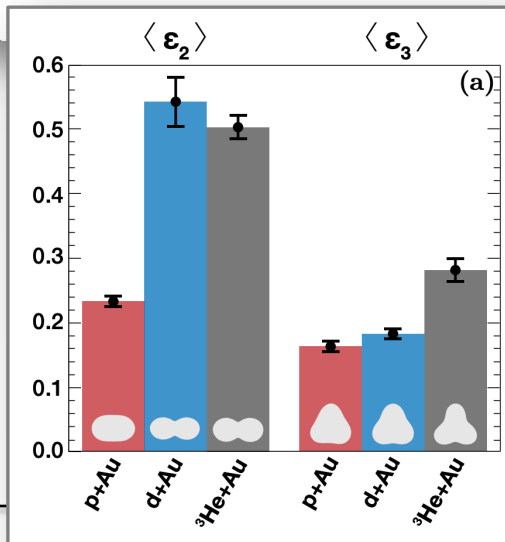
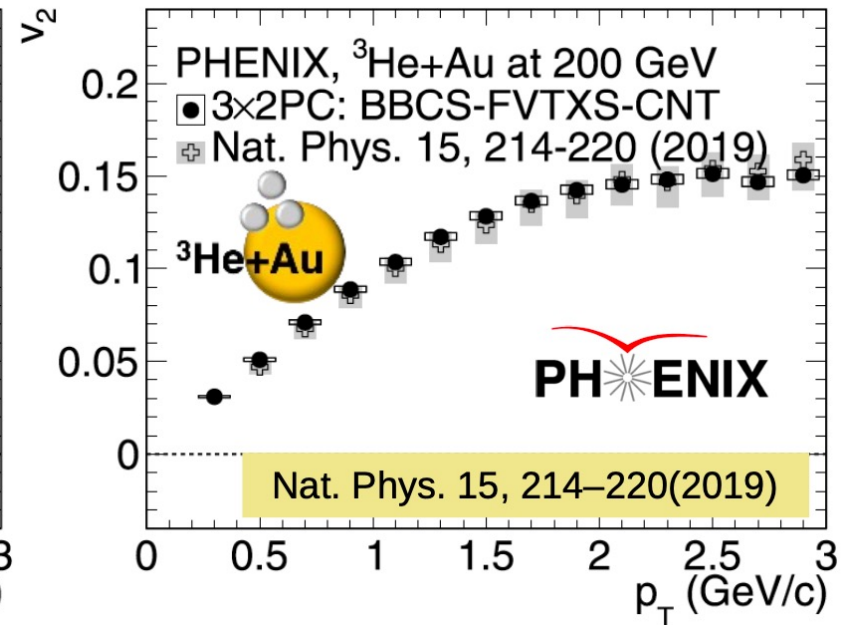
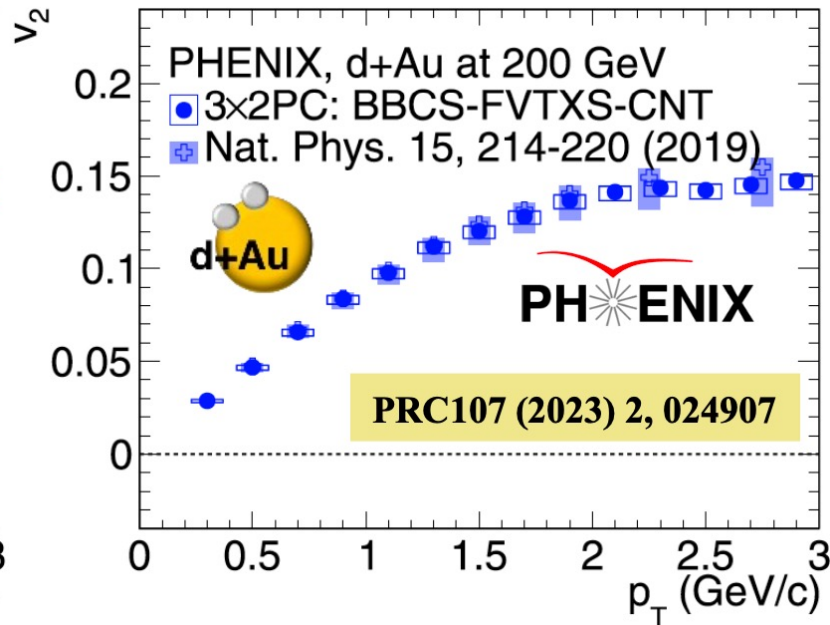
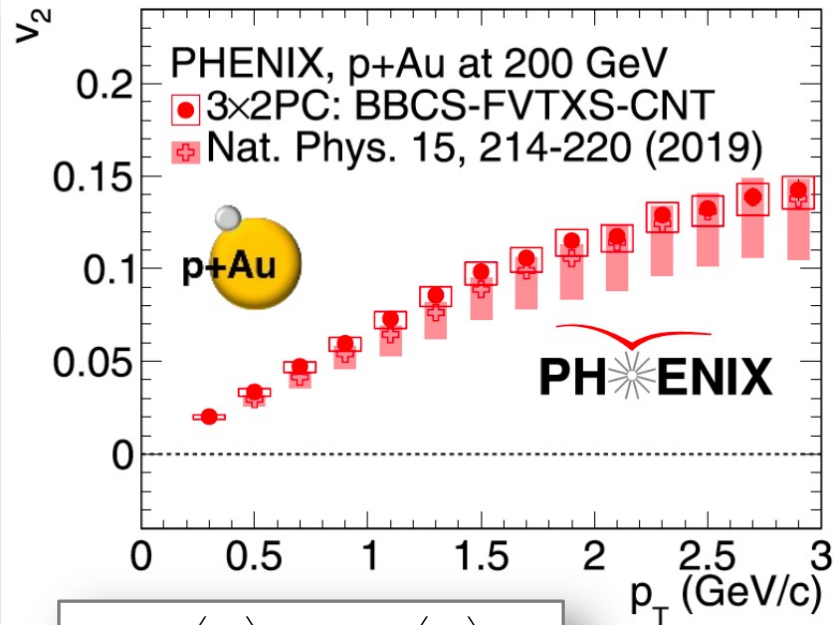


ALI-PREL-543472

- Mass ordering observed at low transverse momentum
 - Now measured with 2pc correlations
 - Non-flow under better control
 - Consistent with hydro-like behaviour
- Baryon/meson grouping at intermediate p_T
 - Matches observations from other systems
- Begs the question:
 - how far can we push the usual patterns?
 - Small systems at RHIC energies?

v_2 in small collision systems at RHIC top energies

✓ Specific processes/extremes

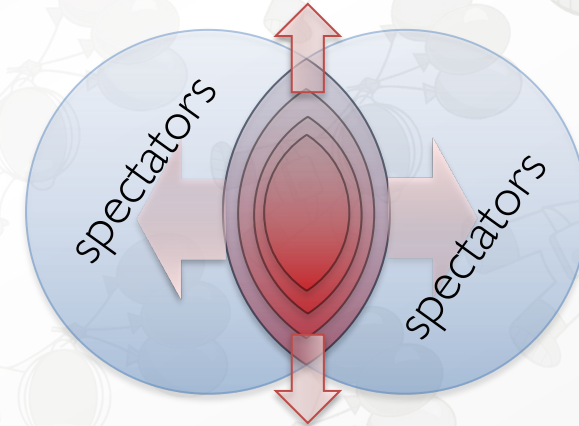
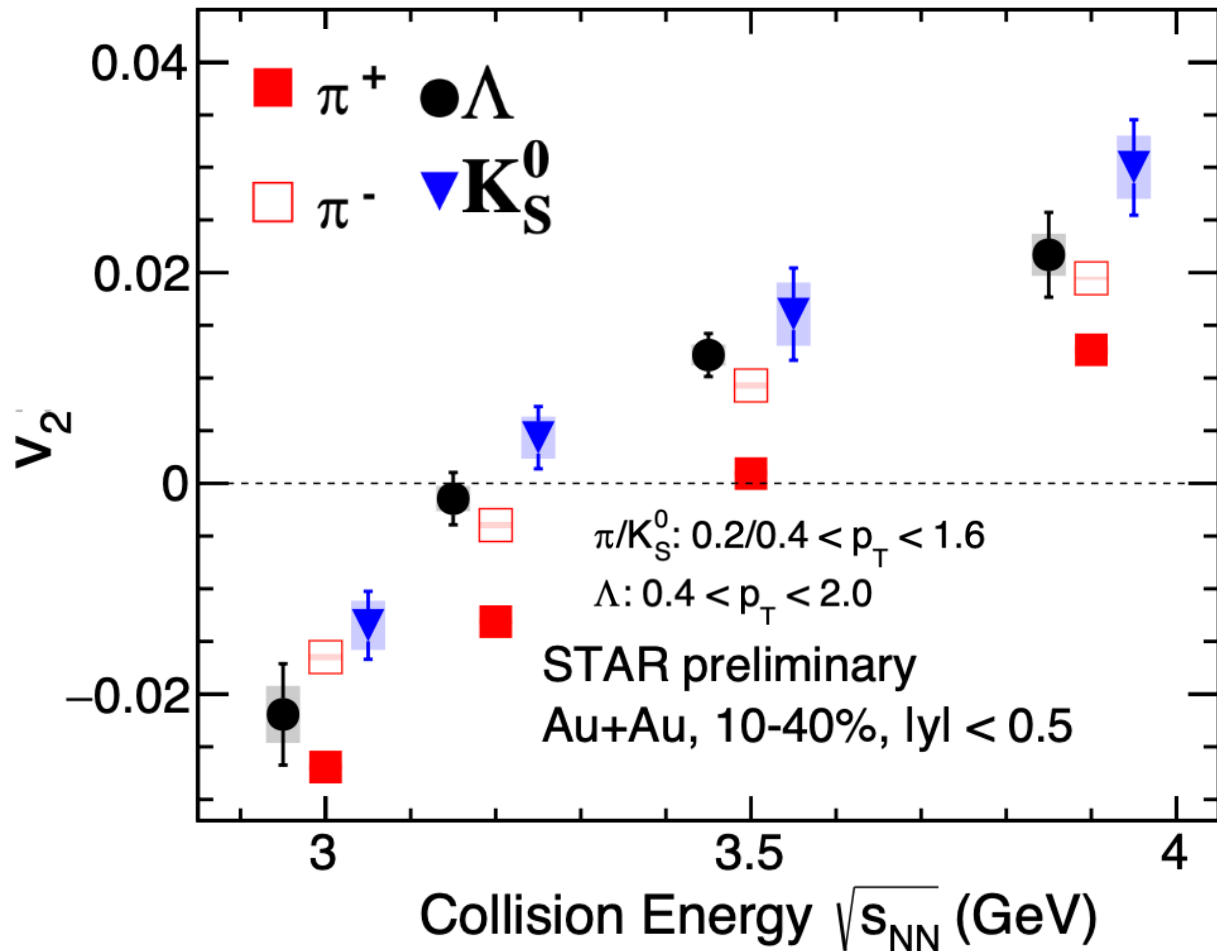


- Results from Nat. Phys. 15, 214-220 (2019) confirmed with two-particle correlations
- Consistent with hydrodynamics expectations and “small droplet of QGP”
 - ...especially if taken together with v_3 results → role of IC confirmed
 - N.B.: rapidity dependence important when comparing to STAR
- → see [Björn Schenke's talk](#)

Identified particle v_2 vs collision energy

✓ Specific processes/extremes

→ See [Zuowen Liu's talk](#)

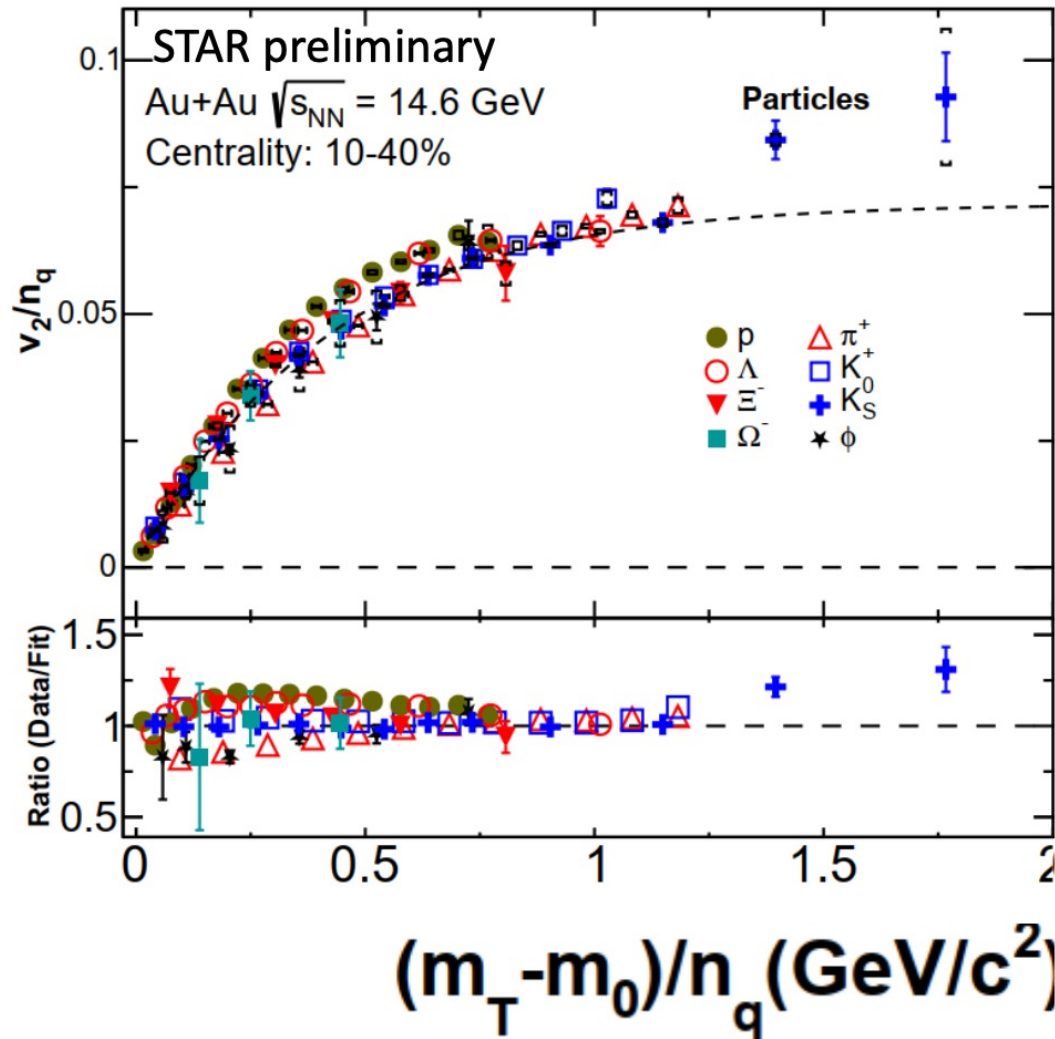


- Regime change also observed around 3.2 GeV
- Switchover between [out-of-plane](#) and [in-plane flow](#)
 - Spectators affect particles emitted from interaction
- Larger energies:
 - regime of progressively more intense [in-plane flow from collective expansion / geometry](#)

v_2 NCQ scaling: search for breakdowns

✓ Specific processes/extremes

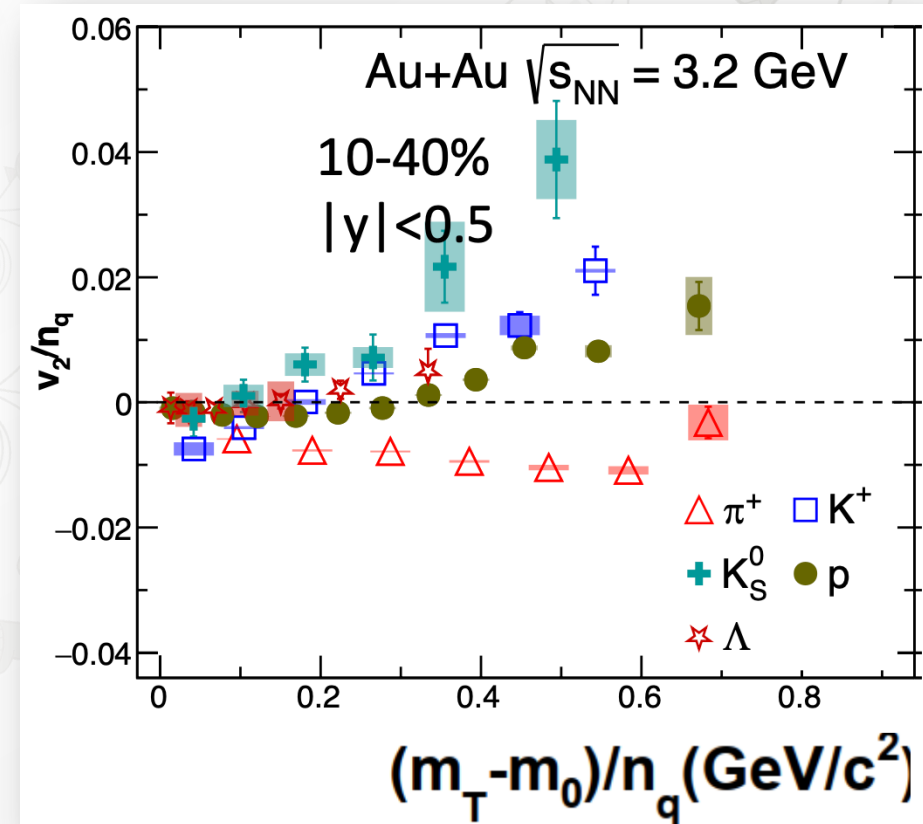
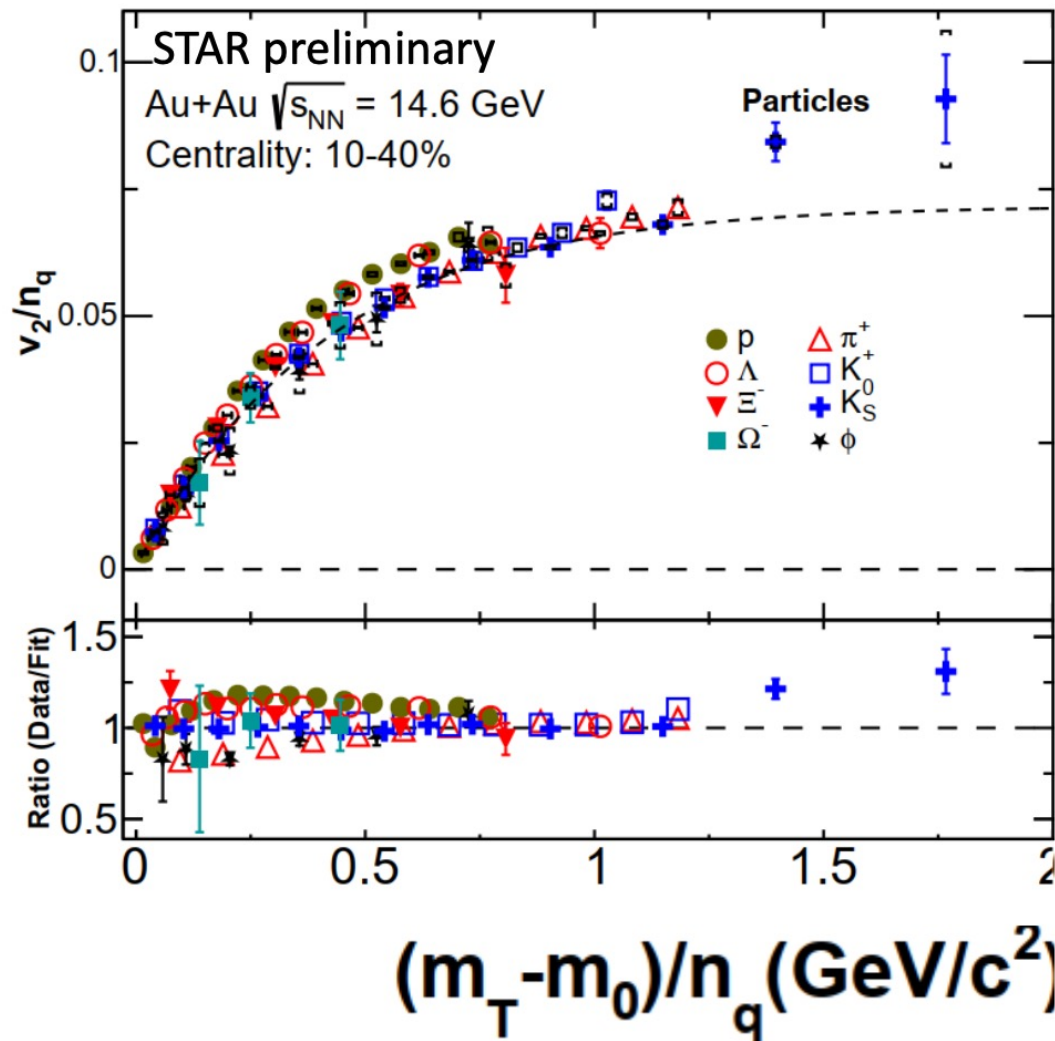
→ See [Zuowen Liu's talk](#)



- STAR BES observation: NCQ scaling of v_2
 - ...is followed in Au+Au at 14.6 GeV

v_2 NCQ scaling: search for breakdowns

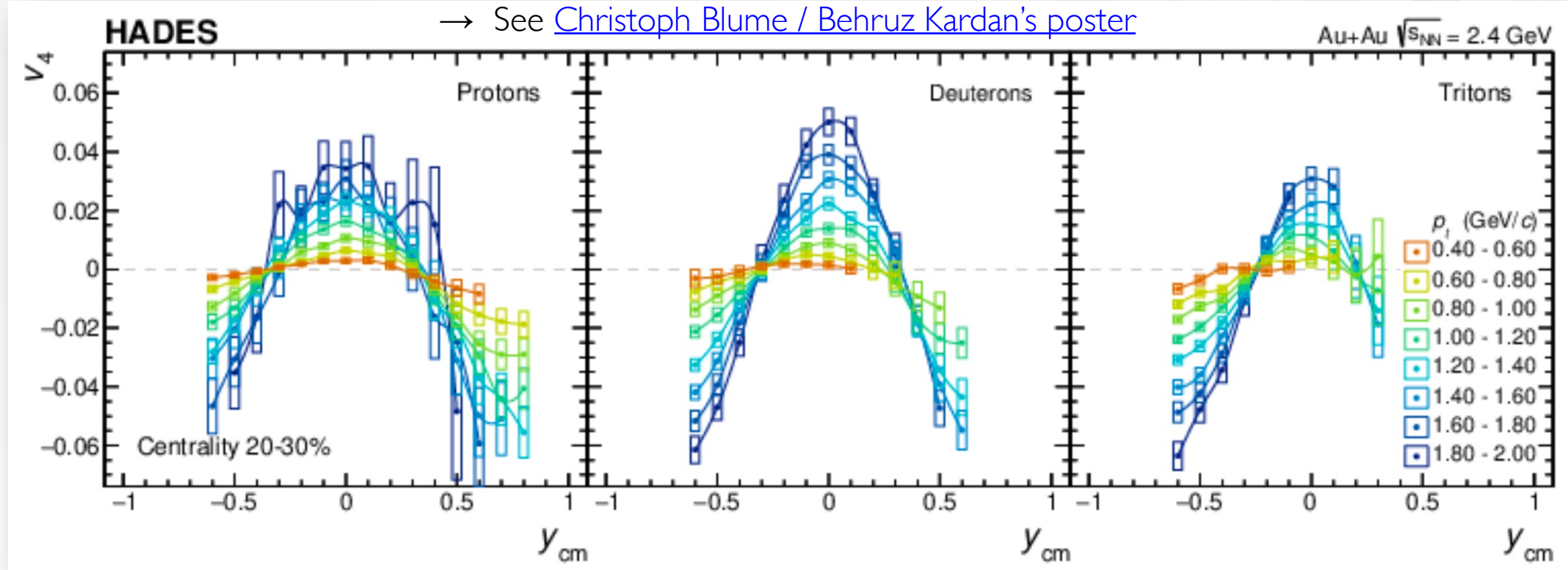
✓ Specific processes/extremes



- STAR BES observation: NCQ scaling of v_2
 - ...is followed in Au+Au at 14.6 GeV
 - ...but breaks down at 3.2 GeV: hadronic vs partonic regime

HADES: observation of low-energy collectivity

- ✓ Specific processes/extremes
- ✓ 3D dynamics



- STAR BES information on collectivity [complementary to HADES measurements](#)
- [High precision measurements from HADES](#) constrain proton / deuteron / triton v_2
 - Access also rapidity dimension → serves as [further constraint to theory](#)

Observation of non-zero flow in photo-nuclear events

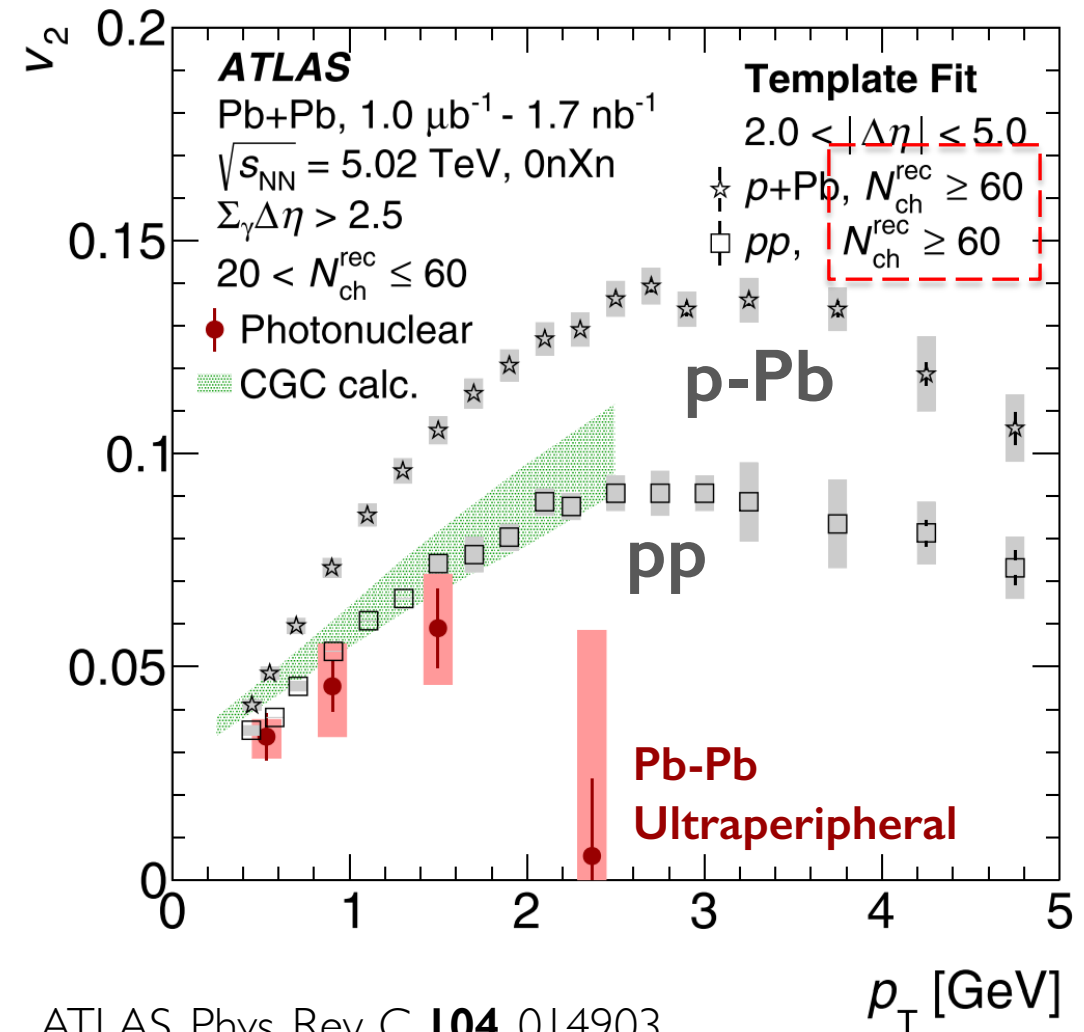
→ see talk by [Sruthy Das](#)

✓ Specific processes

- Ultra-peripheral collisions: photonuclear processes
 - High-multiplicity events selected for analysis
 - Non-zero v_2 ,
...but lower than hadron-hadron collisions!
- Similar to result by CMS [2] in γp interactions (in p-Pb)
- Can be explained using CGC predictions [1]
- Caveat: v_2 coefficients vulnerable to (residual) non-flow
- Begs the question: can we characterize these collisions?
 - What about other QGP signatures?

[1] Phys. Rev. D **103**, 054017

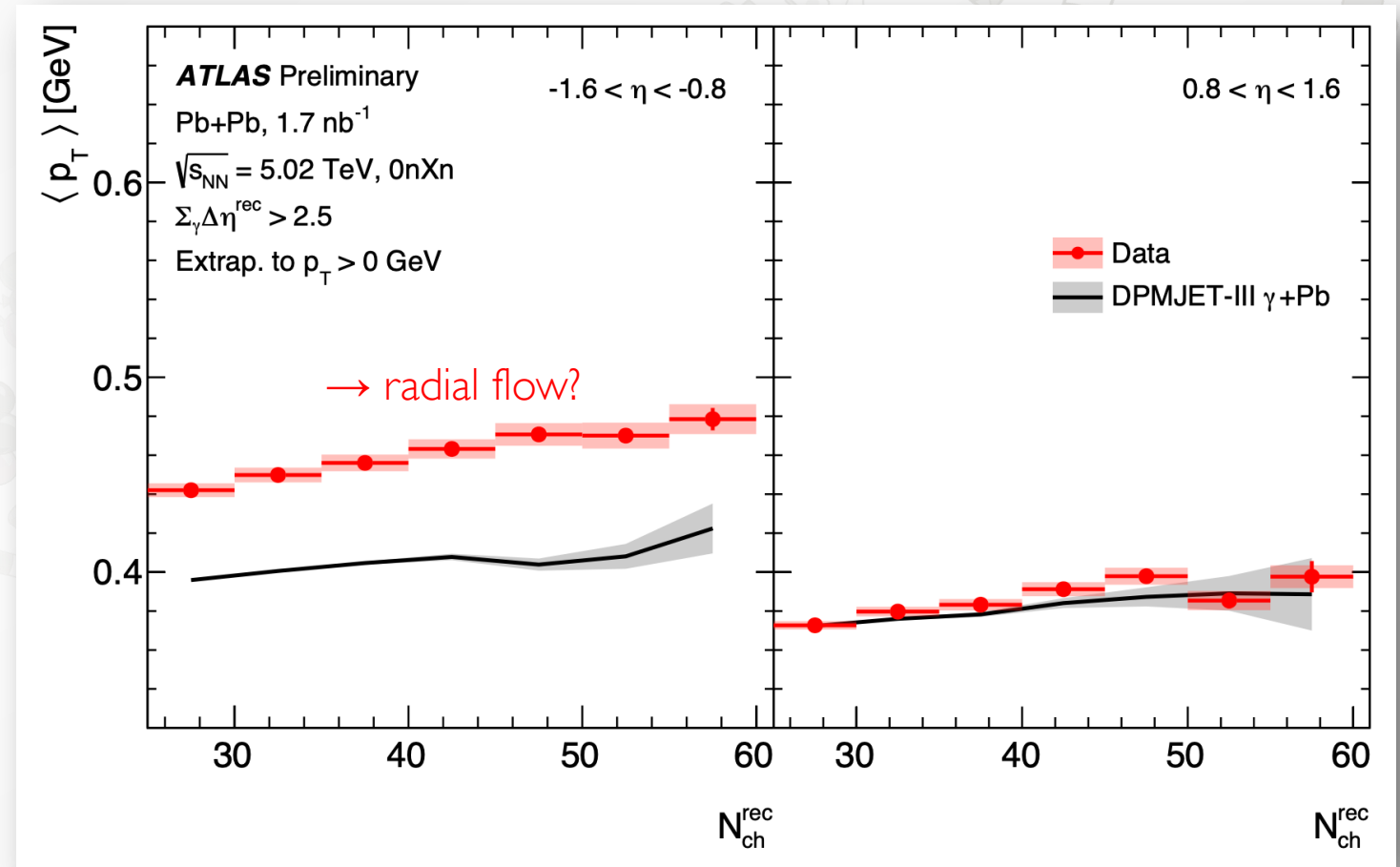
[2] <https://arxiv.org/abs/2204.13486>



Search for QGP signatures in photo-nuclear events

✓ Specific processes/extremes

- Indications of **radial flow in UPC collisions**
 - In backward pseudorapidity region
 - Excess not described well by AMPT



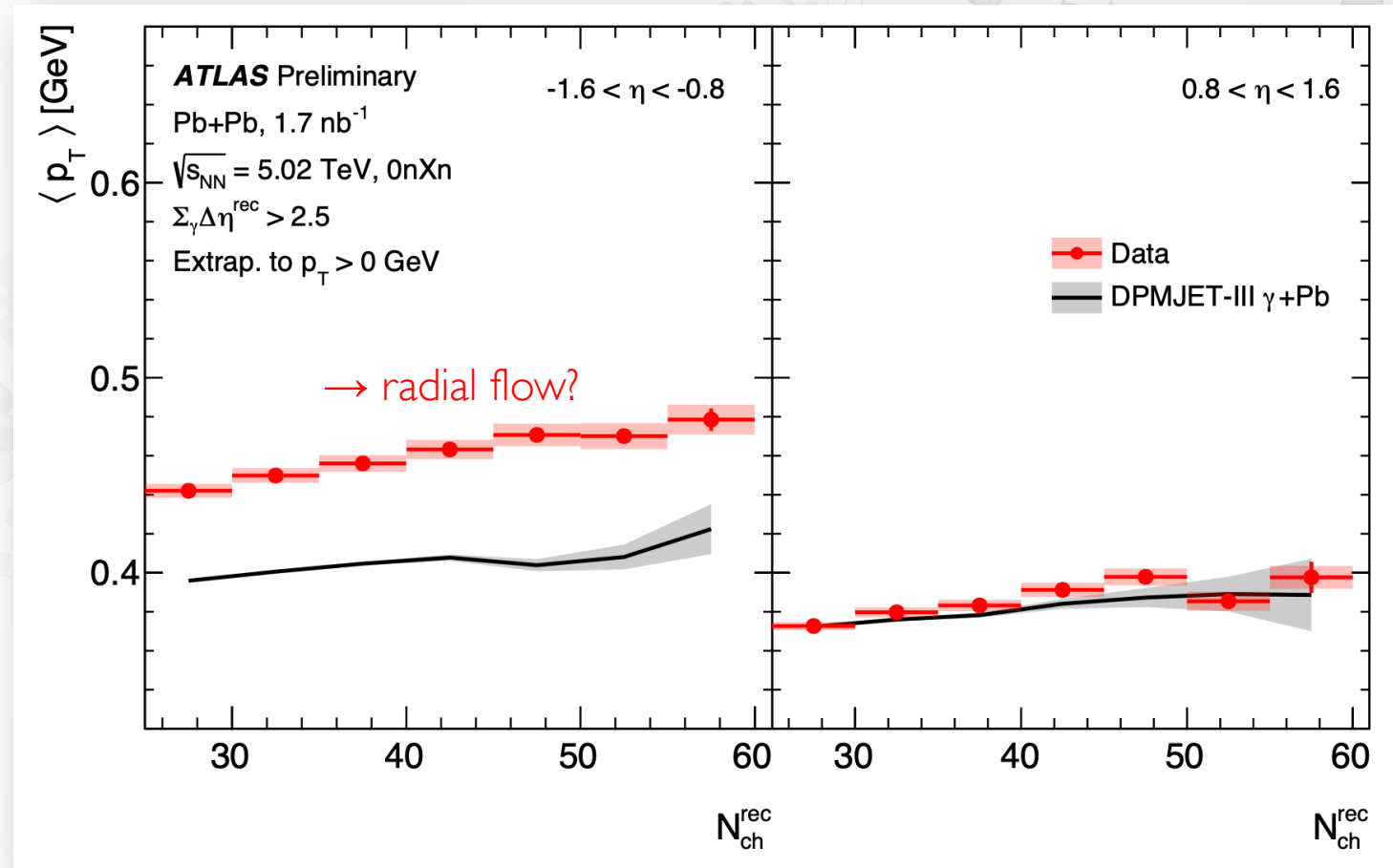
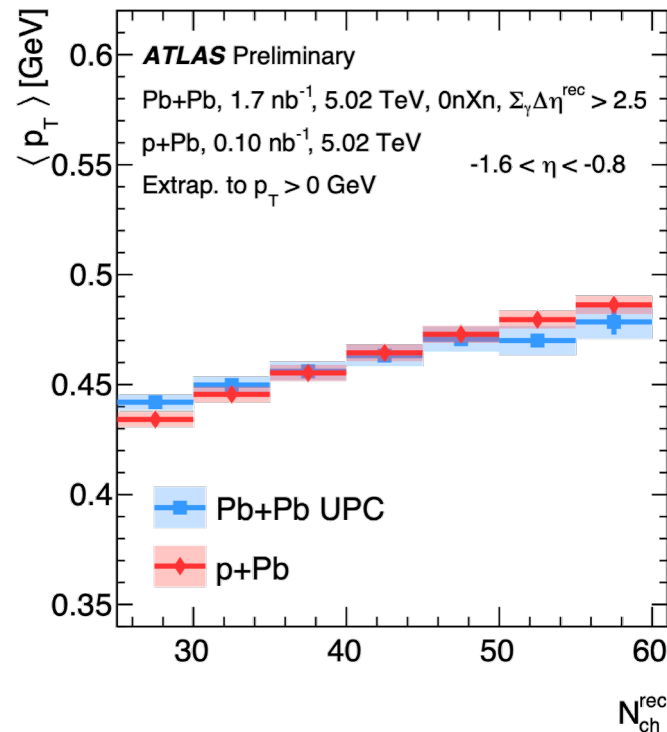
→ see talk by [Sruthy Das](#)



Search for QGP signatures in photo-nuclear events

✓ Specific processes/extremes

- Indications of **radial flow in UPC collisions**
 - In backward pseudorapidity region
 - Excess not described well by AMPT
- Backward η $\langle p_T \rangle$ matches p-Pb at the same multiplicities



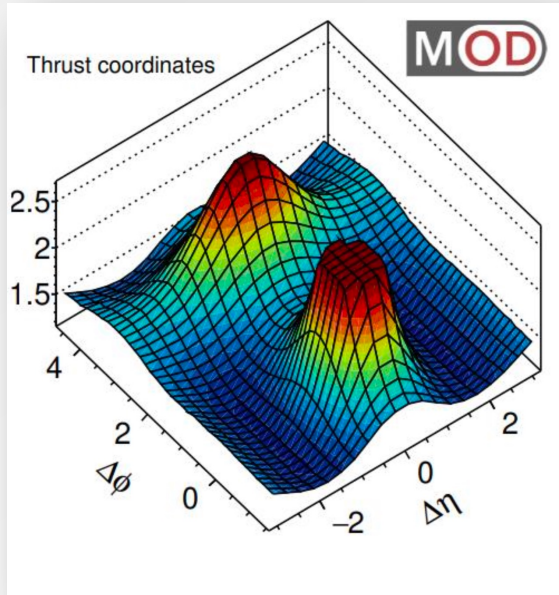
→ see talk by [Sruthy Das](#)



What about e^+e^- collisions?

✓ Specific processes/extremes

- Minimum-bias e^+e^- collisions: exhibit no near-side ridge
- However: e^+e^- provides access to various processes

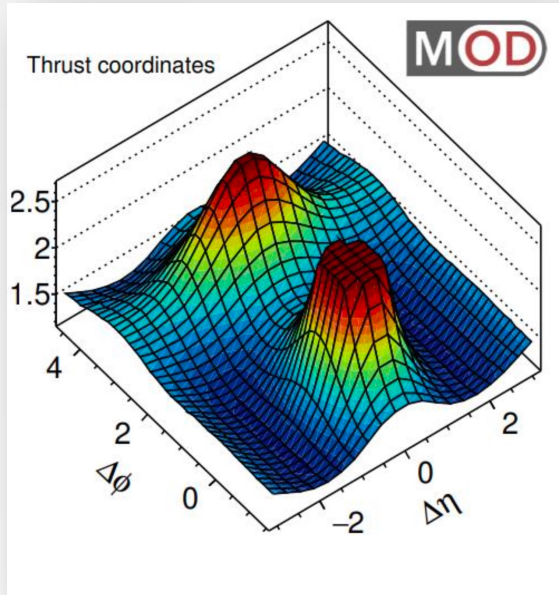


Phys. Rev. Lett. 123, 212002 (2019)

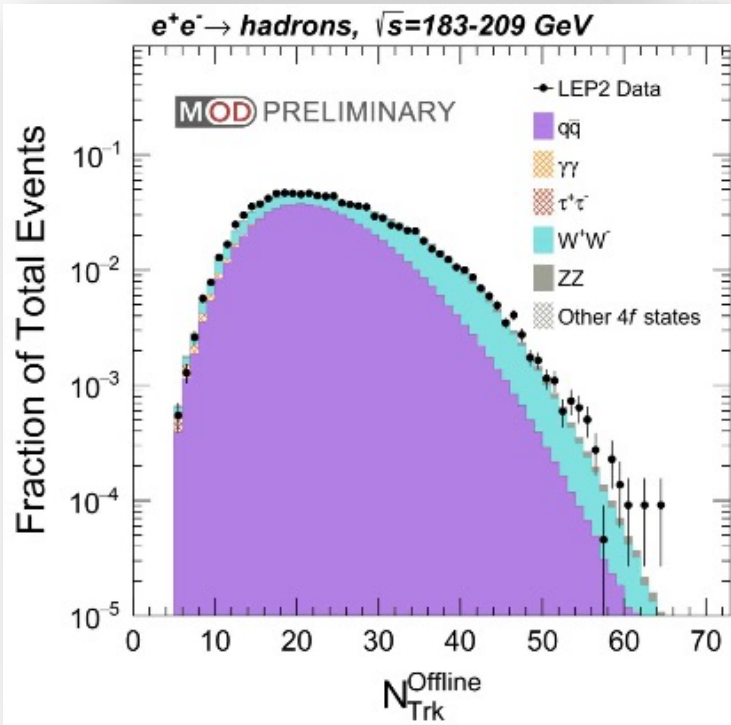
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✓ Specific processes/extremes

- Minimum-bias e^+e^- collisions: exhibit no near-side ridge
- However: e^+e^- provides access to various processes
 - High-multiplicity e^+e^- enriched with $e^+e^- \rightarrow W^+W^-$: a two-string system



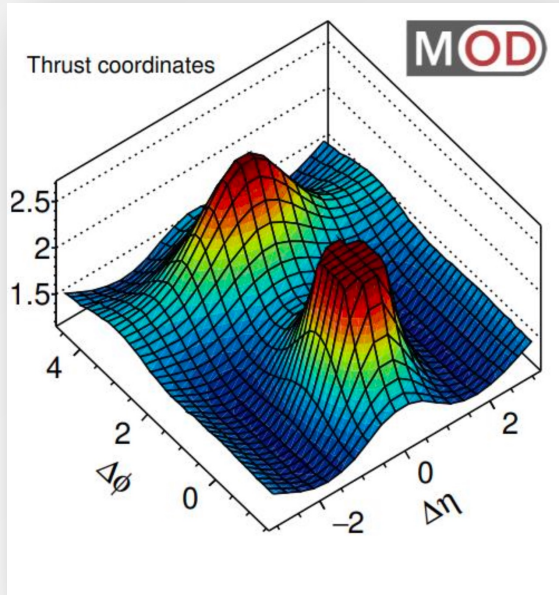
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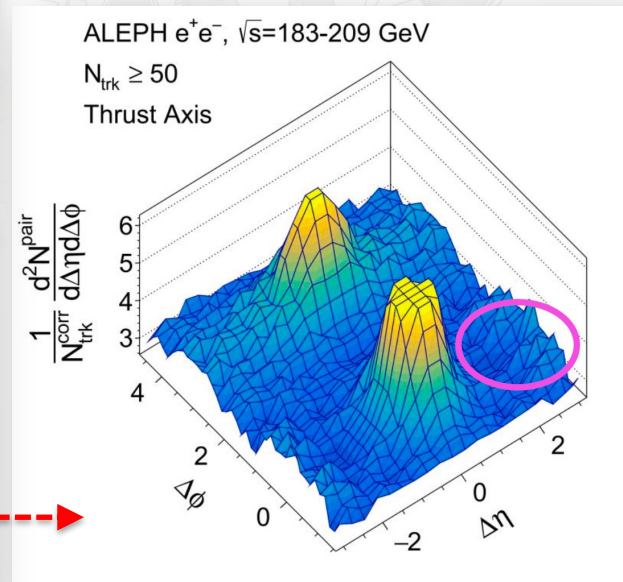
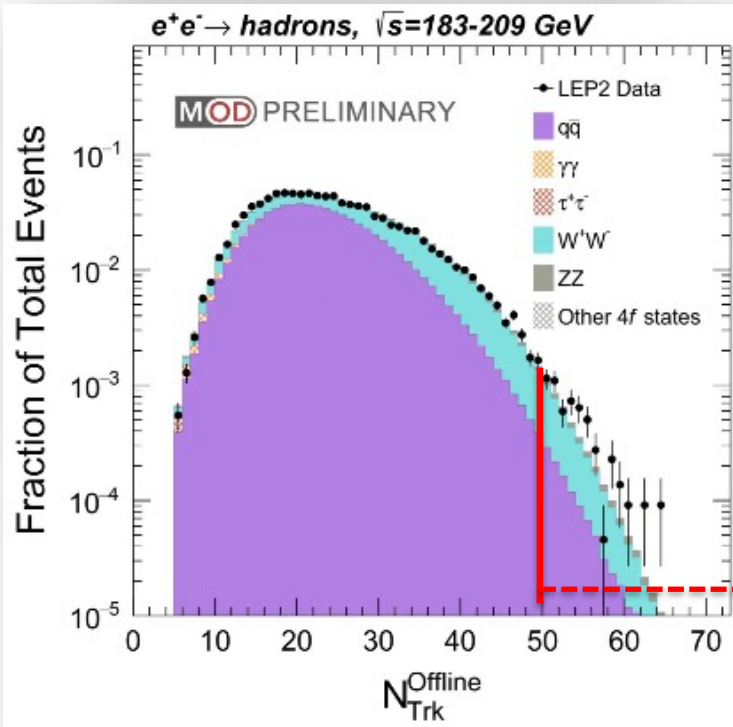
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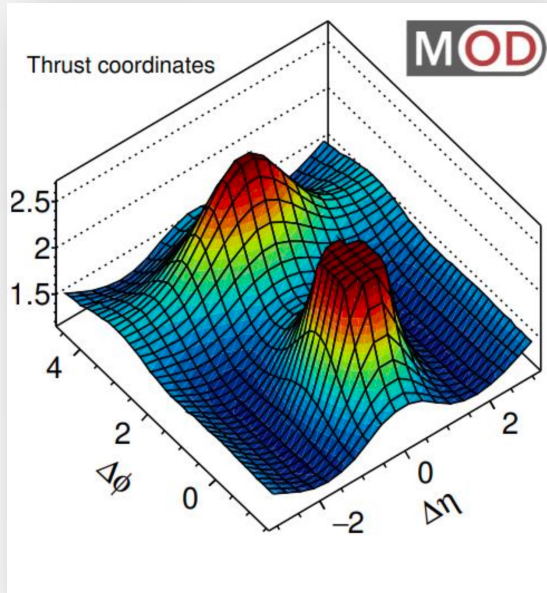
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What about e^+e^- collisions?

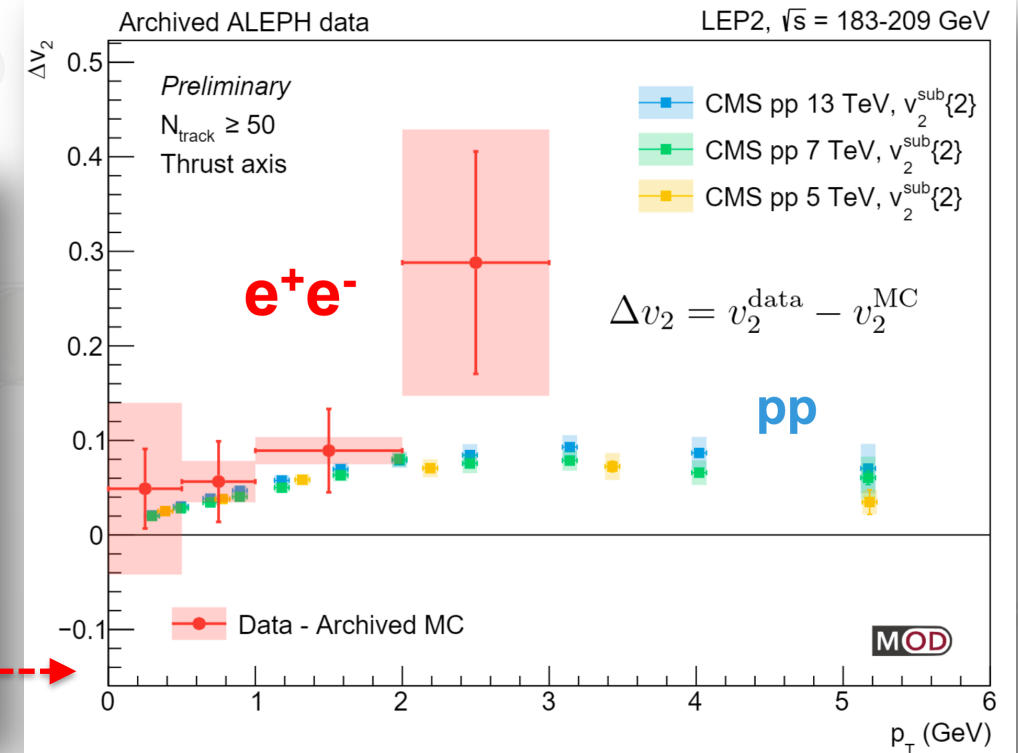
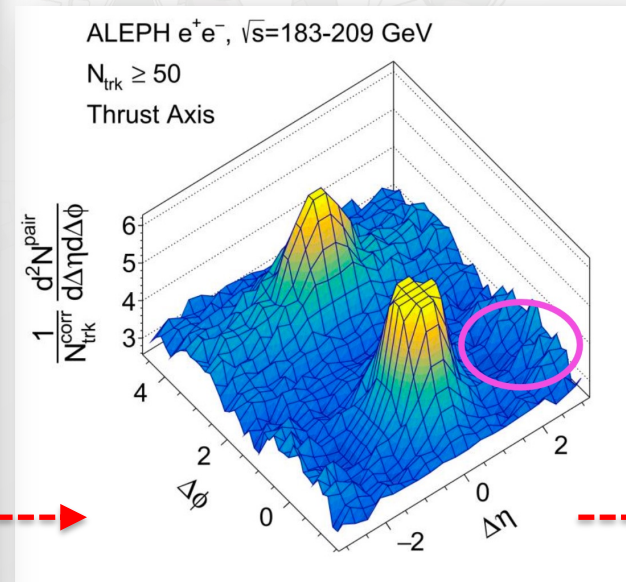
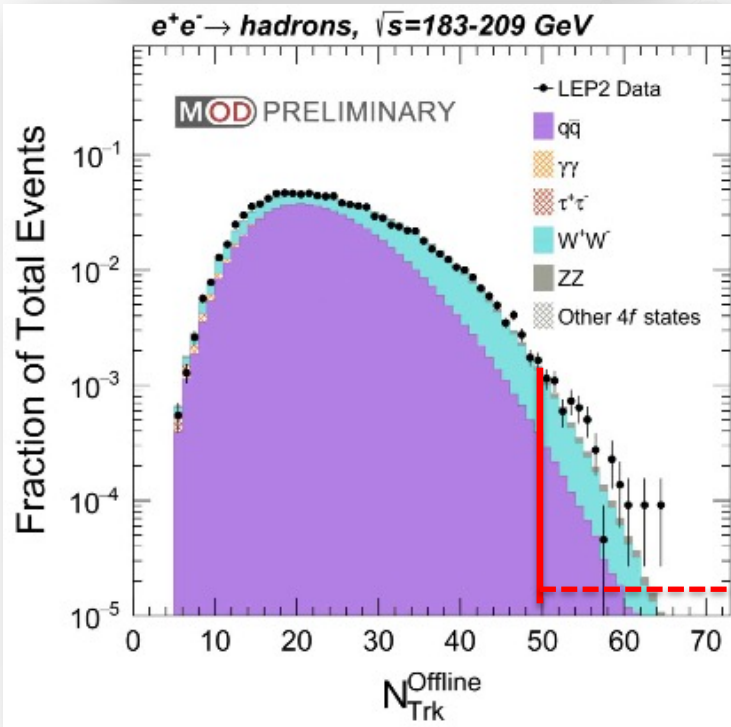
✓ Specific processes/extremes

- Minimum-bias e^+e^- collisions: exhibit **no near-side ridge**
- However: e^+e^- provides access to various processes
 - High-multiplicity e^+e^- enriched with $e^+e^- \rightarrow W^+W^-$: a two-string system
 - Results at high multiplicity similar to pp collisions!



Phys. Rev. Lett. 123, 212002 (2019)

→ see [Yu-Chen \(Janice\) Chen's poster](#)



• $\Delta v_2 = v_2^{\text{Data}} - v_2^{\text{MC}}$



Experimentally, focus on:

1. In-depth study of flow correlations
2. Rapidity as a tool for 3D dynamics
3. Look for extremes: e^+e^- , γA , BES / low E

4. Understanding the hard/soft interplay

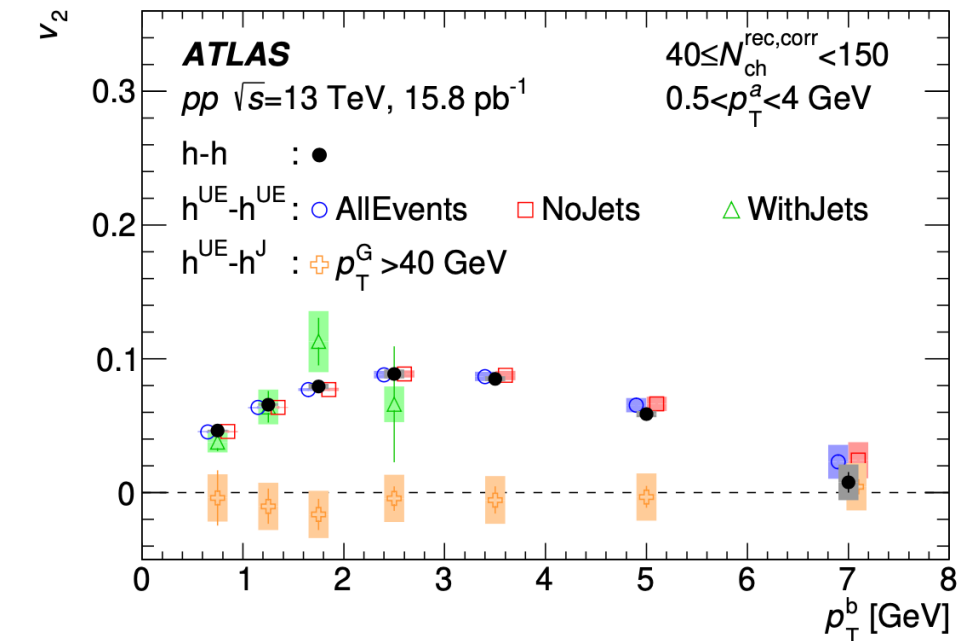
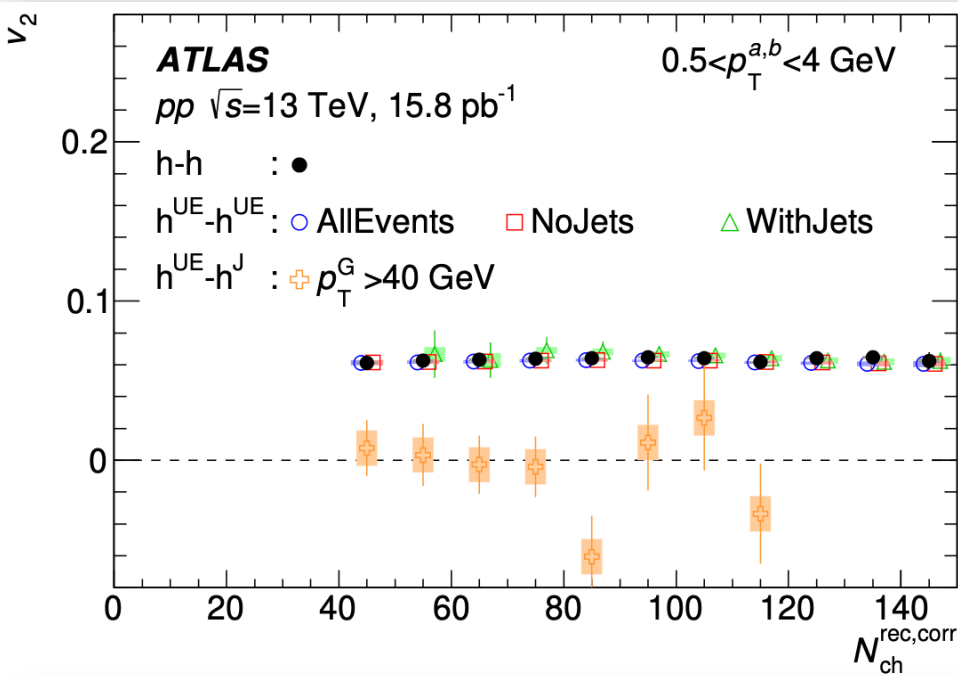
- Understand how phenomena such as jets and others connect to flow
- 

Correlation between elliptic flow and jets in pp collisions

- ✓ Flow correlations
- ✓ Hard/soft interplay

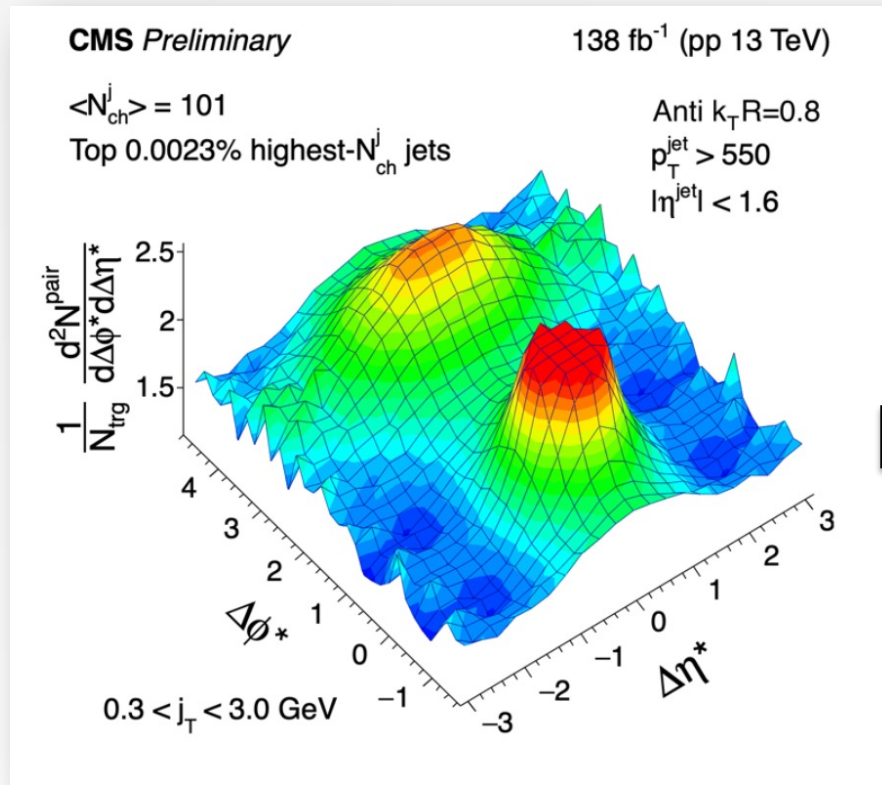
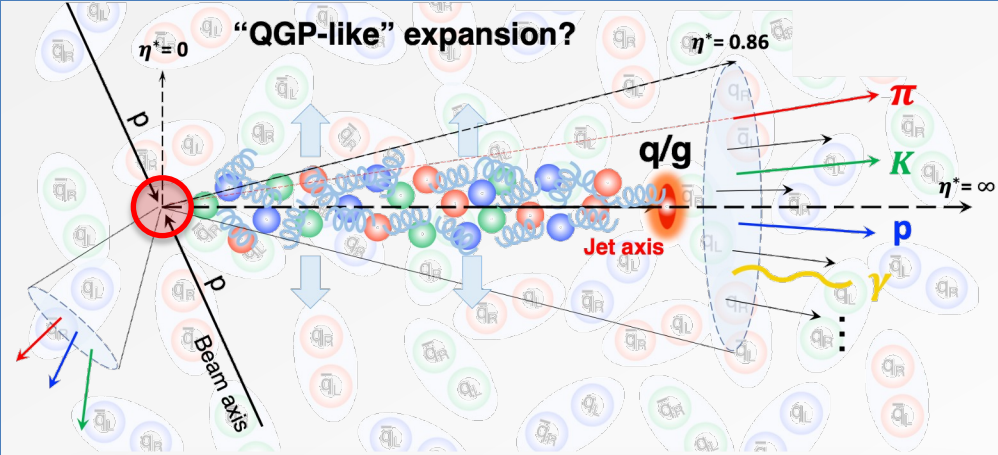
- Basic question: is there any **relationship between jets and the presence of collective effects** (v_2) in pp?
- ATLAS measurement indicates:
 - No **significant change in the v_2 of the underlying event** with the absence / presence of a jet
 - Consistently, **hadron-jet correlation indicates negligible v_2**
- **Independence** is interesting but **could potentially depend on phase space** (jet momentum)
 - Consideration: **soft / hard correlations?**
 - Appears elsewhere in pheno discussions, etc

→ see [talk by Soumya Mohapatra](#)

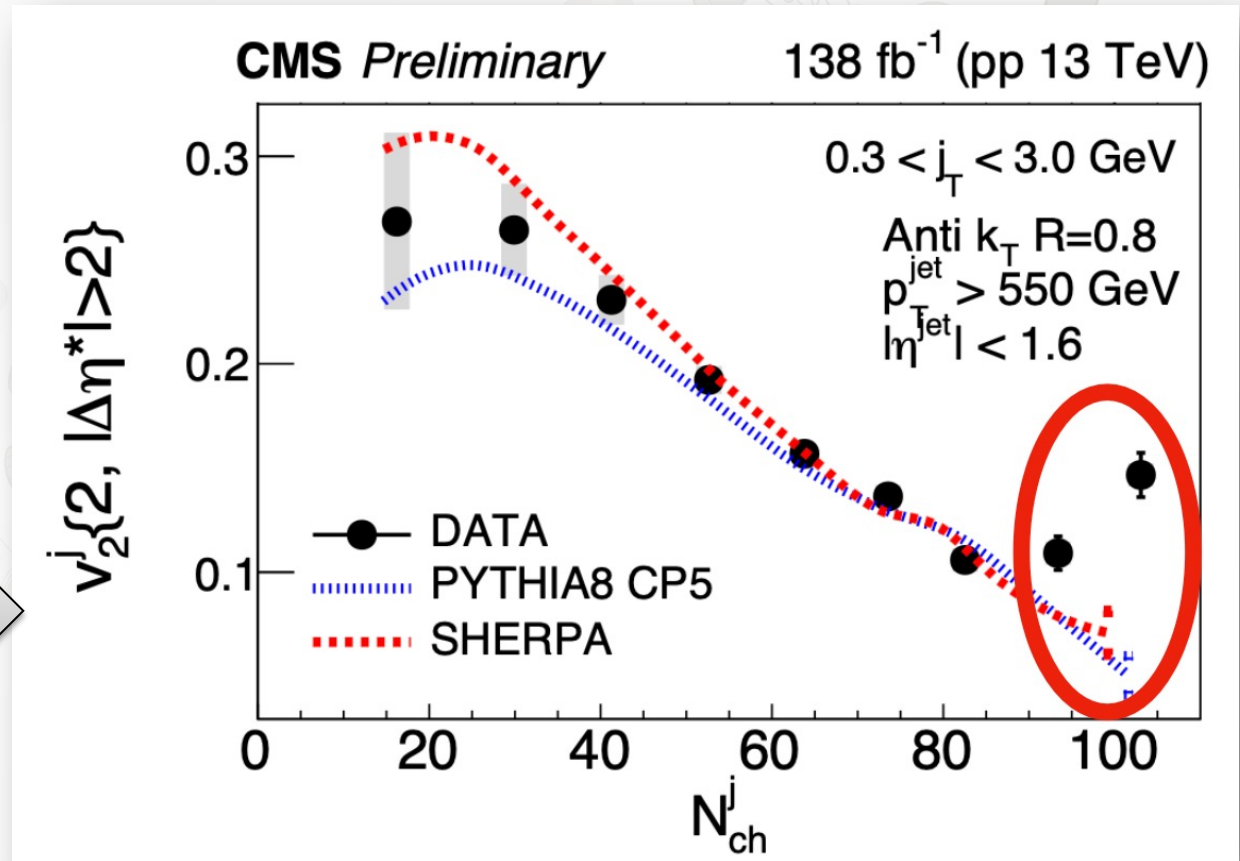


Flow in individual jets?

→ See [talk by Parker Gardner](#)



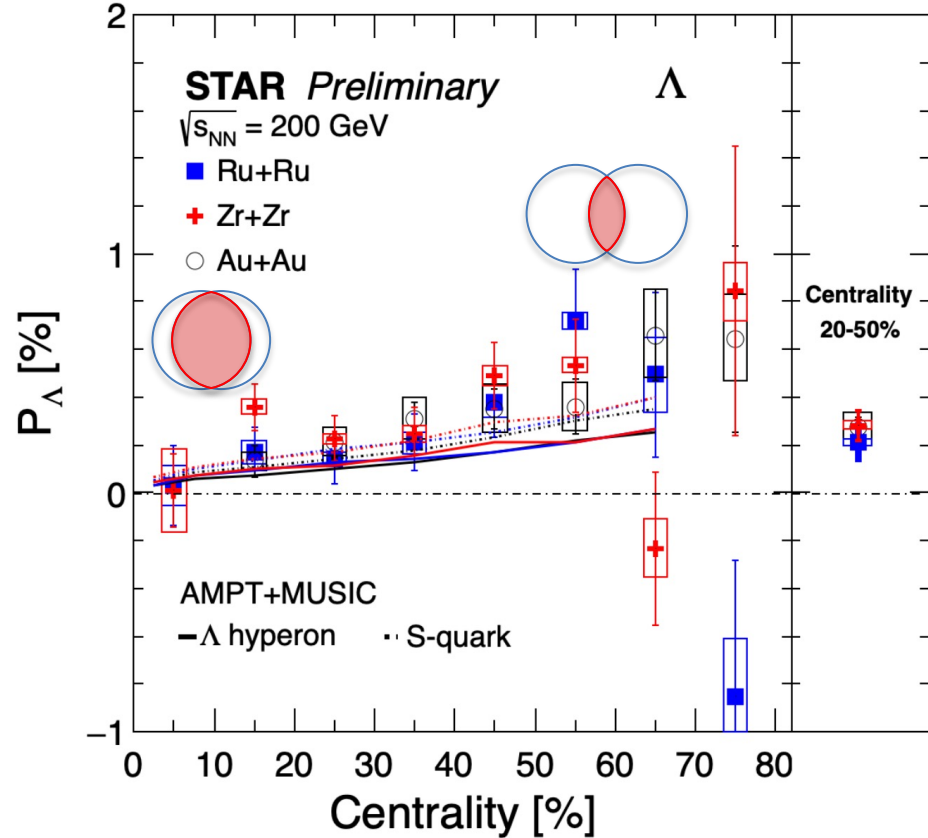
$v_2^j\{2, |\Delta\eta^*| > 2\}$



- Elliptic flow with respect to jet axis anomalously high for high N_{ch}^j
- Possibly a sign of collectivity in jets?

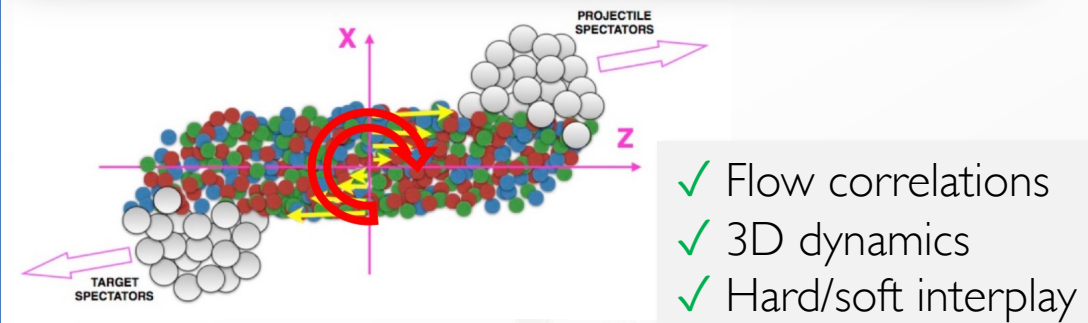
- ✓ Flow correlations
- ✓ Hard/soft interplay

Hyperon polarization and collectivity

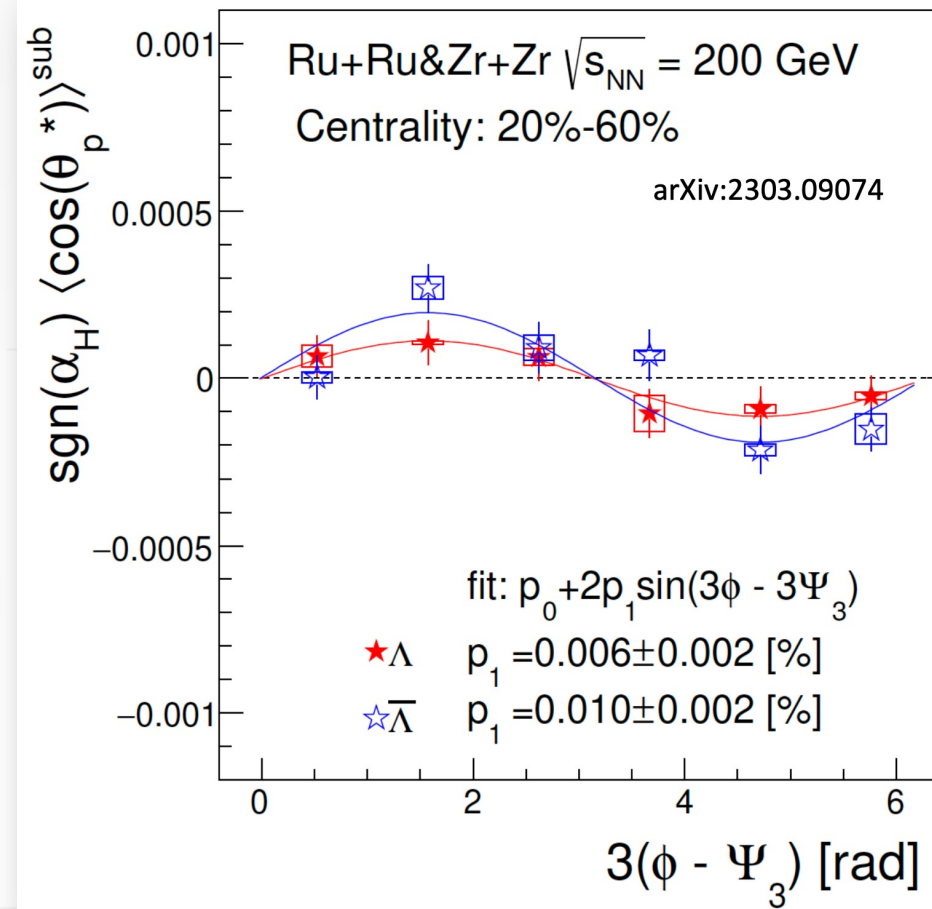
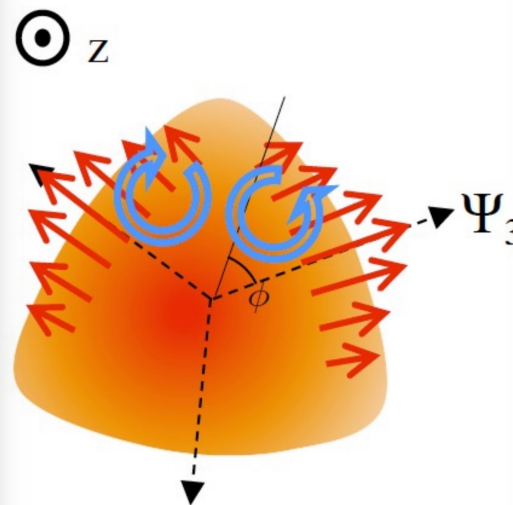
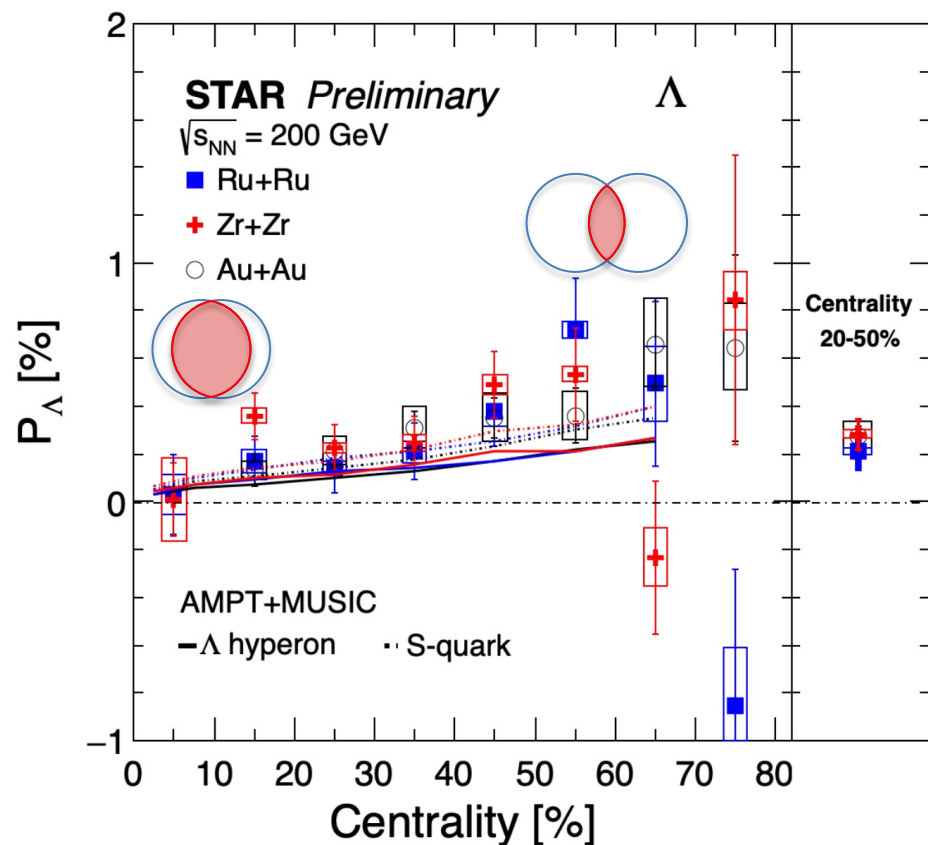


→ see [talk by Xingrui Gou](#)

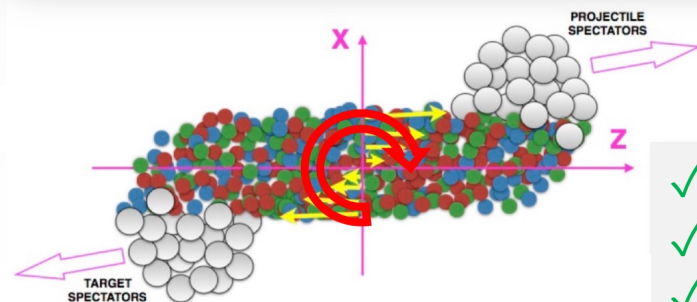
- Hydrodynamic flow impinges polarization to hyperons



Hyperon polarization and collectivity



→ see [talk by Xingrui Gou](#)



- ✓ Flow correlations
- ✓ 3D dynamics
- ✓ Hard/soft interplay

- Hydrodynamic flow impinges polarization to hyperons
- Now: [first observation of polarization wrt third-order event plane](#)
- Other directions of polarization studies being explored: hard/soft interplay and jet quenching (see [Willian Serenone's talk](#))

Summary

- The classical collectivity picture is being expanded experimentally
 - Generically, our descriptions work! But... a few puzzles remain:
 - **Flow correlations** → disentangle different dynamic origins of flow (IC, etc)
 - Still something to be understood to unify radial and elliptic flow
 - **Rapidity and 3D dynamics** → characterise and confront with 3D hydro / other theory
 - Rapidity dependence of correlations still presents a challenge
 - **Specific regimes / processes** → stress-testing / breaking the usual picture: small systems, etc
 - Hadronic and photonuclear collisions of sufficient energy follow usual patterns; BES results present new frontier
 - **Soft / hard interplay** → less compartmentalization, consistent theory required
 - Exciting new directions: relationship between jets and soft physics, small systems puzzle, new ideas
 - Disclaimer: this was just a selection!
 - More news incoming! BES, LHC Run 3+, and beyond
- New measurements present new theoretical challenges! → see next talk

Thank you!

Backup