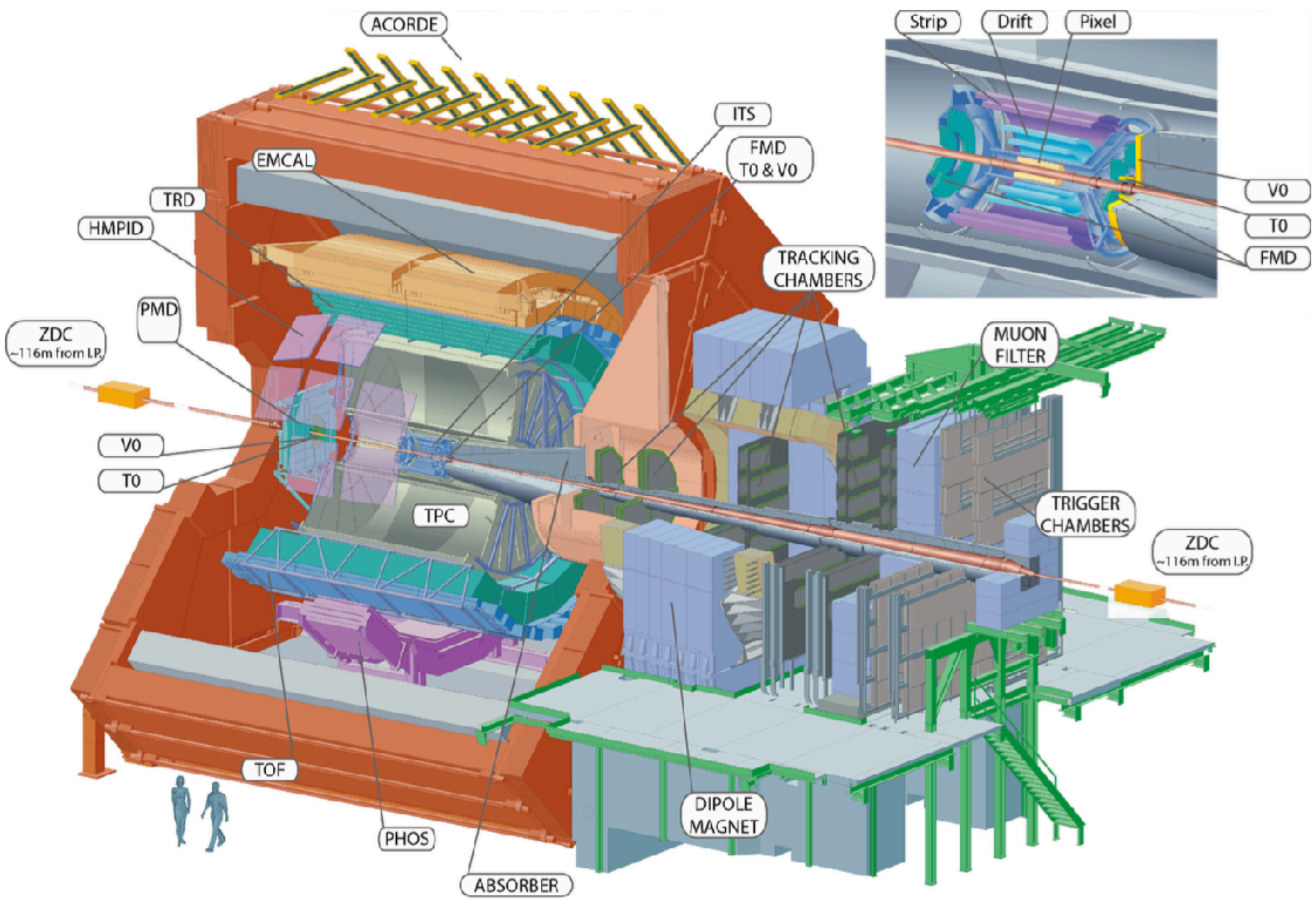
Flow, femtoscopy and correlations in pp, p-Pb and Pb-Pb collisions at ALICE

Hans Beck (University of Heidelberg)
for the ALICE Collaboration

QCD challenges in pp, pA and AA collisions at high energies
ECT* Trento, February 2017

ALICE



Inner Tracking System:
Trigger, vertexing, tracking

Time Projection Chamber:
Tracking, vertexing, particle ID (dE/dx)

Time of Flight:
Particle ID, tracking

V0:
Trigger, centrality, flow vector

FMD:
Flow vector

- Great performance of detectors, see e.g. Int. J. Mod. Phys. A 29 (2014) 1430044

Datasets

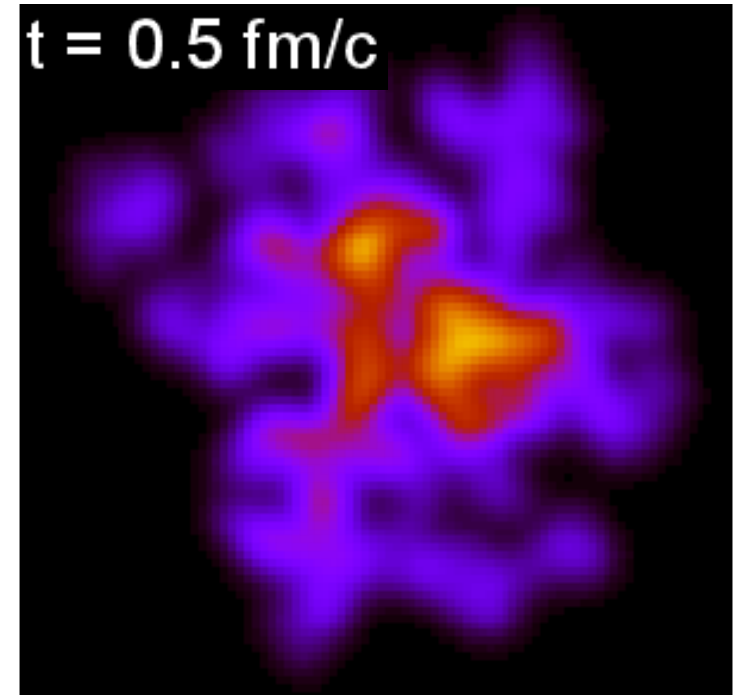
Used in discussed analyses:

- pp
  - 7 TeV: 250M MB (2010)
  - 13 TeV: 60M MB, 85M HM V0+SPD (2015)
- p-Pb
  - 5 TeV: 100M MB + 1M HM (2013)
- Pb-Pb
  - 2.76 TeV: 13M MB (2010), 40M MB + CENT (2011)
  - 5 TeV: 60M MB (2015)

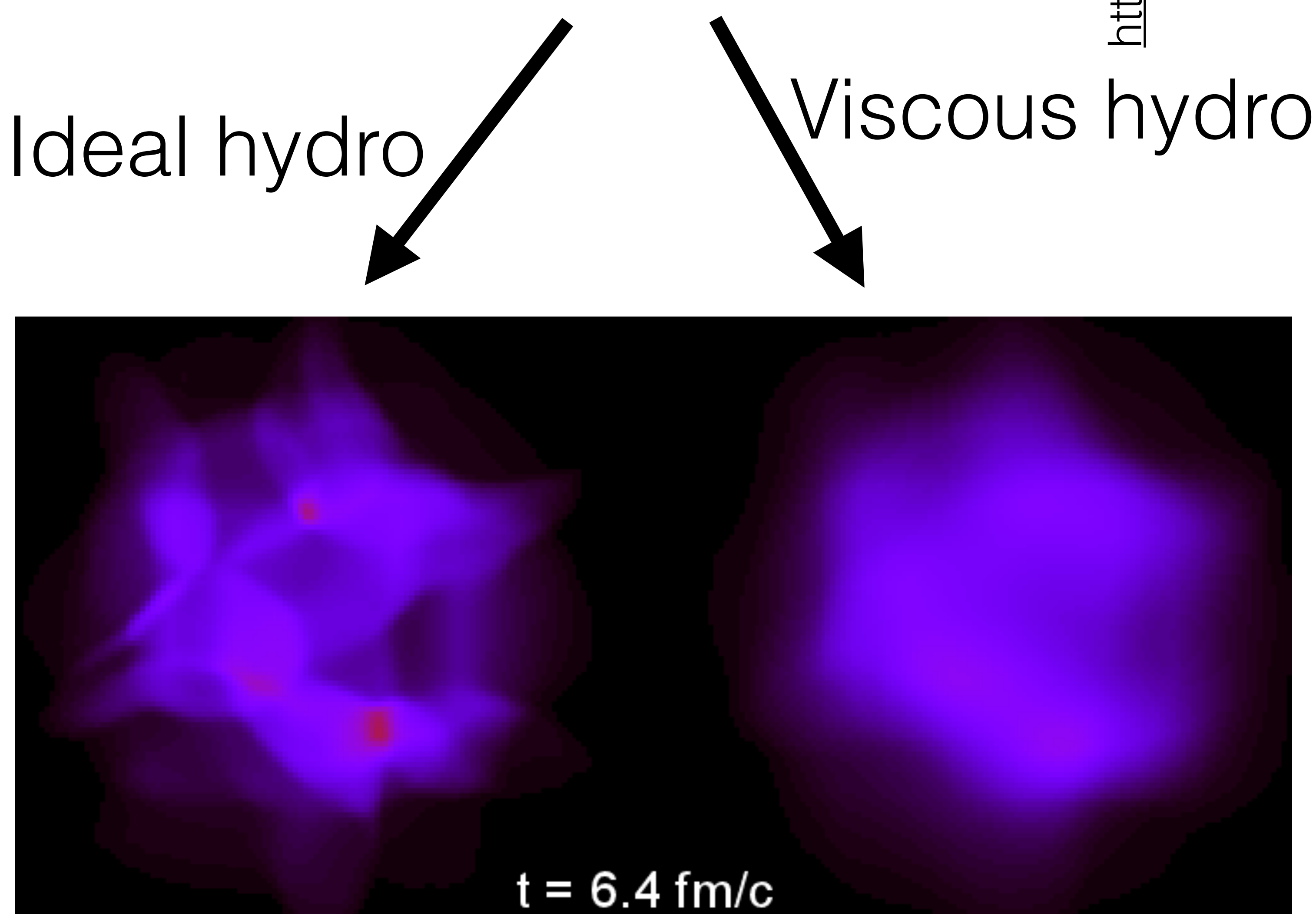
Flow

- Learn about QGP medium properties, in particular *η/s* and its *T* dependence

- Look at azimuthal momentum anisotropies generated via strong initial pressure gradients



B. Schenke, arXiv:1109.6289, https://quark.phy.bnl.gov/~bschenke/



Flow Techniques

- Scalar product: $v_2\{\mathrm{SP}\} = \frac{\langle \vec{Q}_2 \cdot \vec{u}_{2,i}(\eta, p_\mathrm{T}) \rangle}{2\sqrt{\langle \vec{Q}_2^\mathrm{A} \cdot \vec{Q}_2^\mathrm{B} \rangle}}$ $\quad \vec{Q}_2 = \left(\sum_{j=1}^{N} \cos 2\varphi_j, \sum_{j=1}^{N} \sin 2\varphi_j \right)$
  - Select *Q* in different *η* region, e.g., V0C detector: -3.7 < *η* < -1.7

- Cumulants: $\langle\langle 2 \rangle\rangle \equiv \langle\langle e^{in(\phi_1 - \phi_2)} \rangle\rangle \quad \langle\langle 4 \rangle\rangle \equiv \langle\langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle\rangle$

A. Bilandzic et al., PRC83 (2011) 044913

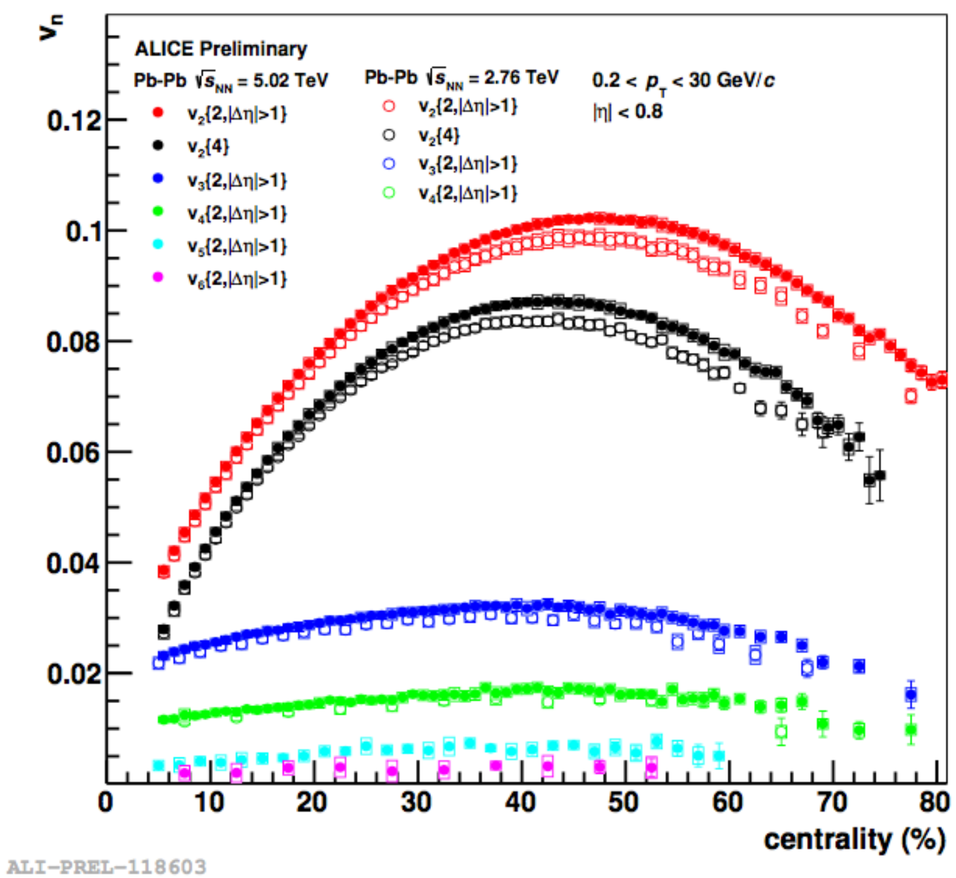
$$c_n\{2\} = \langle\langle 2 \rangle\rangle \qquad c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$$

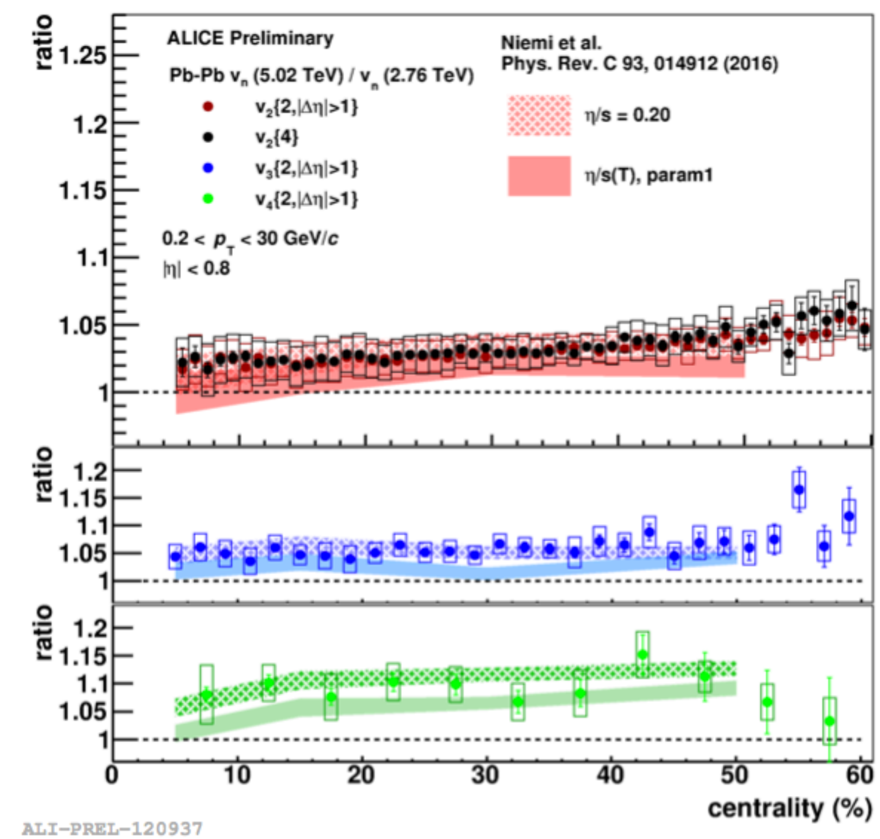
$$v_n\{2\} = \sqrt{c_n\{2\}} \qquad v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

- Non flow & fluctuations: $v_2\{2\}^2 - v_2\{4\}^2 = \delta_2 + 2\sigma_{v_2}^2$

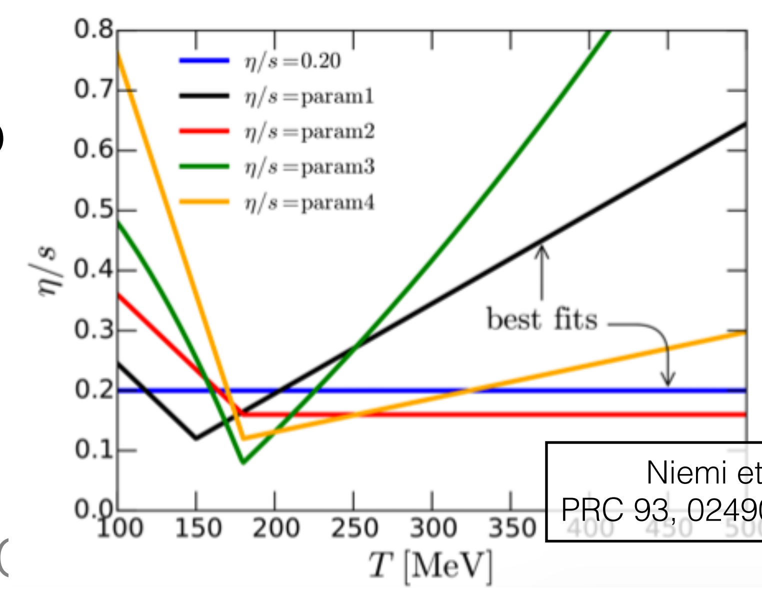
Unidentified, integrated v_n

- v_n up to n = 6 for p_T up to 30 GeV/c
- Higher harmonics determine η/s indirectly by constraining initial state
- Energy dependence in Pb-Pb collisions: 2.76 & 5.02 TeV



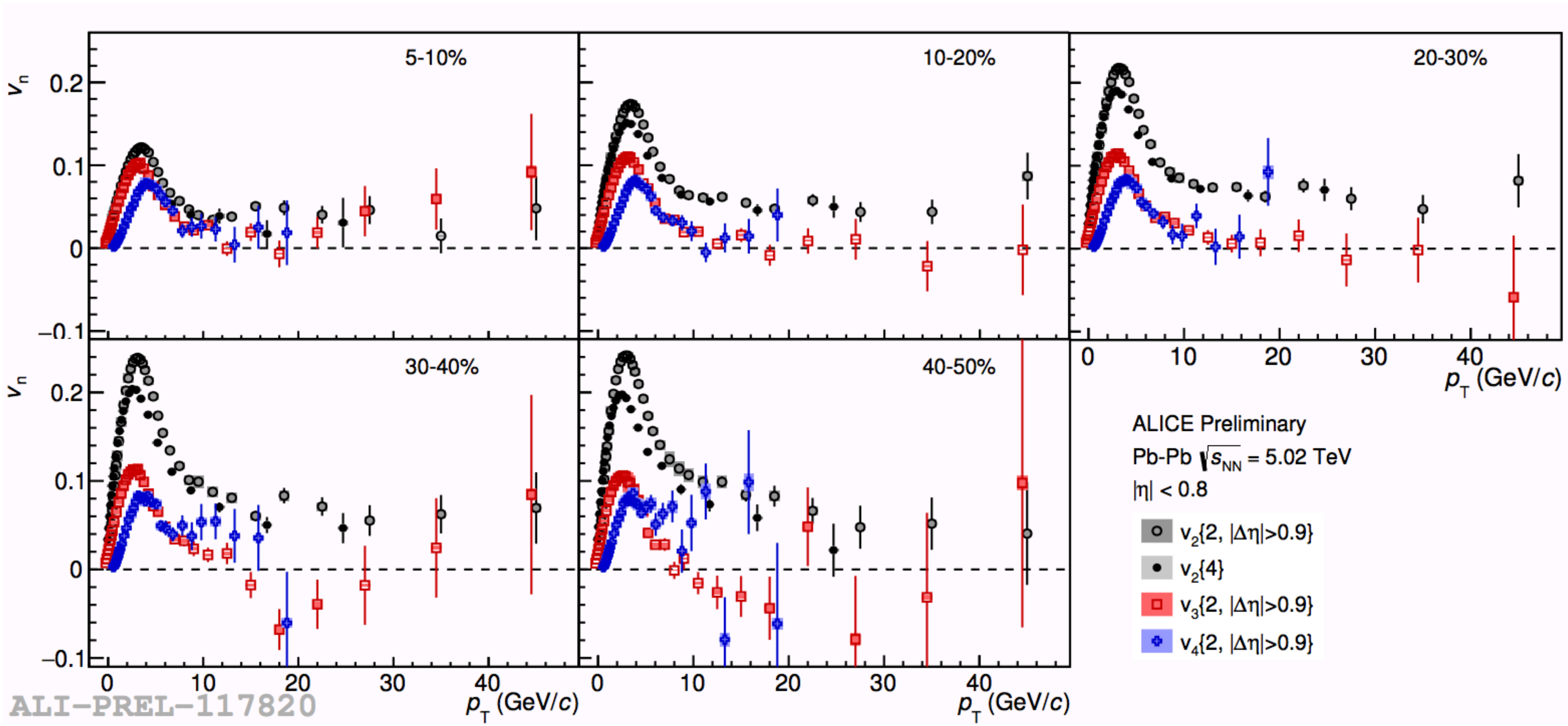


- Theoretical uncertainties partially cancel in $\sqrt{s_{NN}}$ ratio
- Parametrizations tuned to $v_n\{2\}$ at 2.76 TeV
- Const. η/s = 0.2 or param1 preferred
  - Also from RHIC data



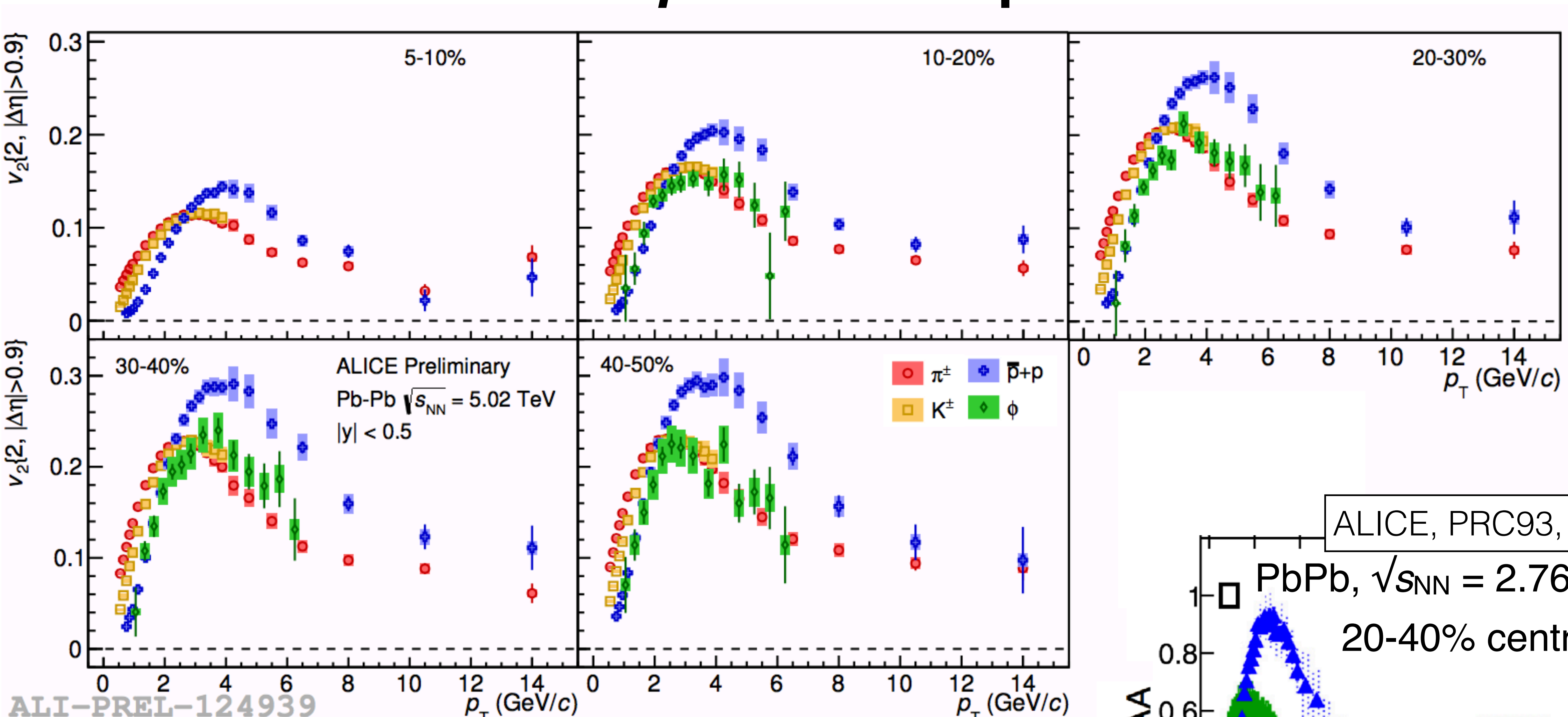
Niemi et al, PRC 93, 024907 (2016)

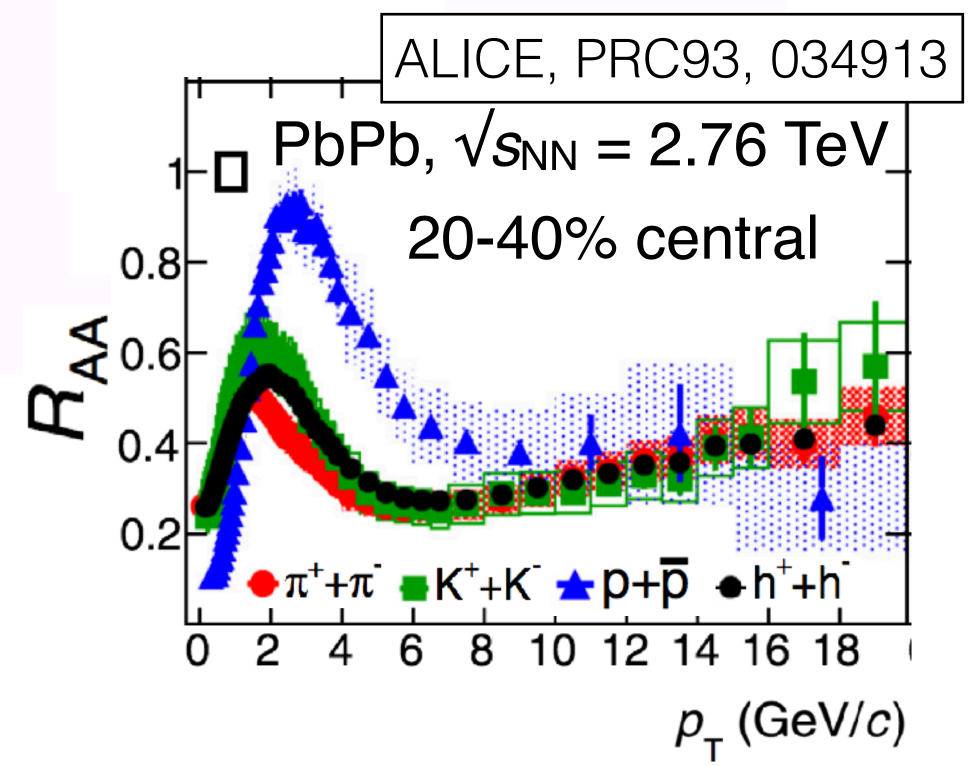
Unidentified, p_T-dependent v_n



- $v_2\{2\}$ vs $v_2\{4\}$: non-flow (resonances, jets), v_2 fluctuations
- Low $p_T \lesssim 7$ GeV/c: hydrodynamics
- High $p_T \gtrsim 7$ GeV/c: parton energy loss
    - Non-zero measurement of higher harmonics driven by IS fluctuations?

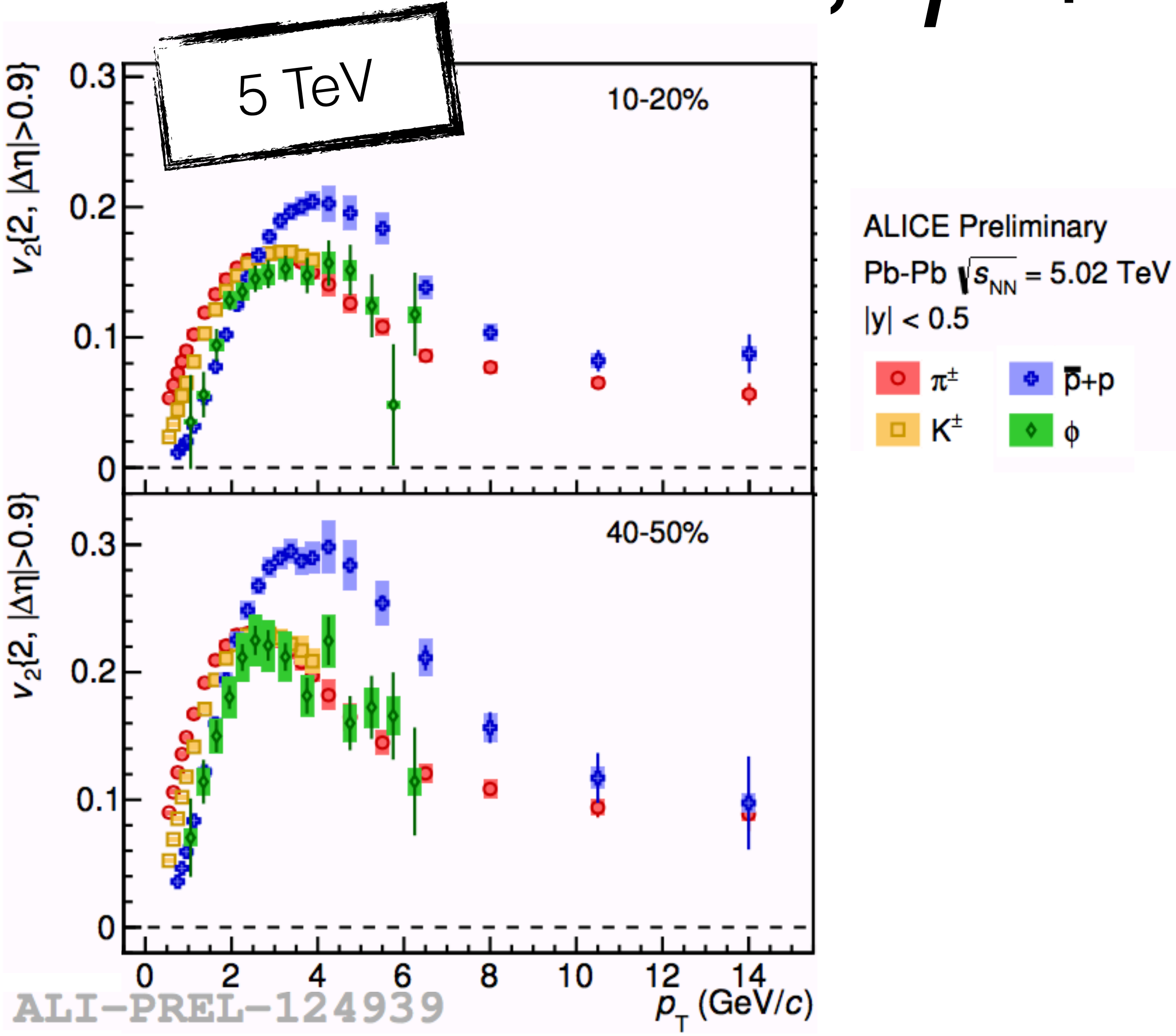
Identified, p_T-dependent v_2

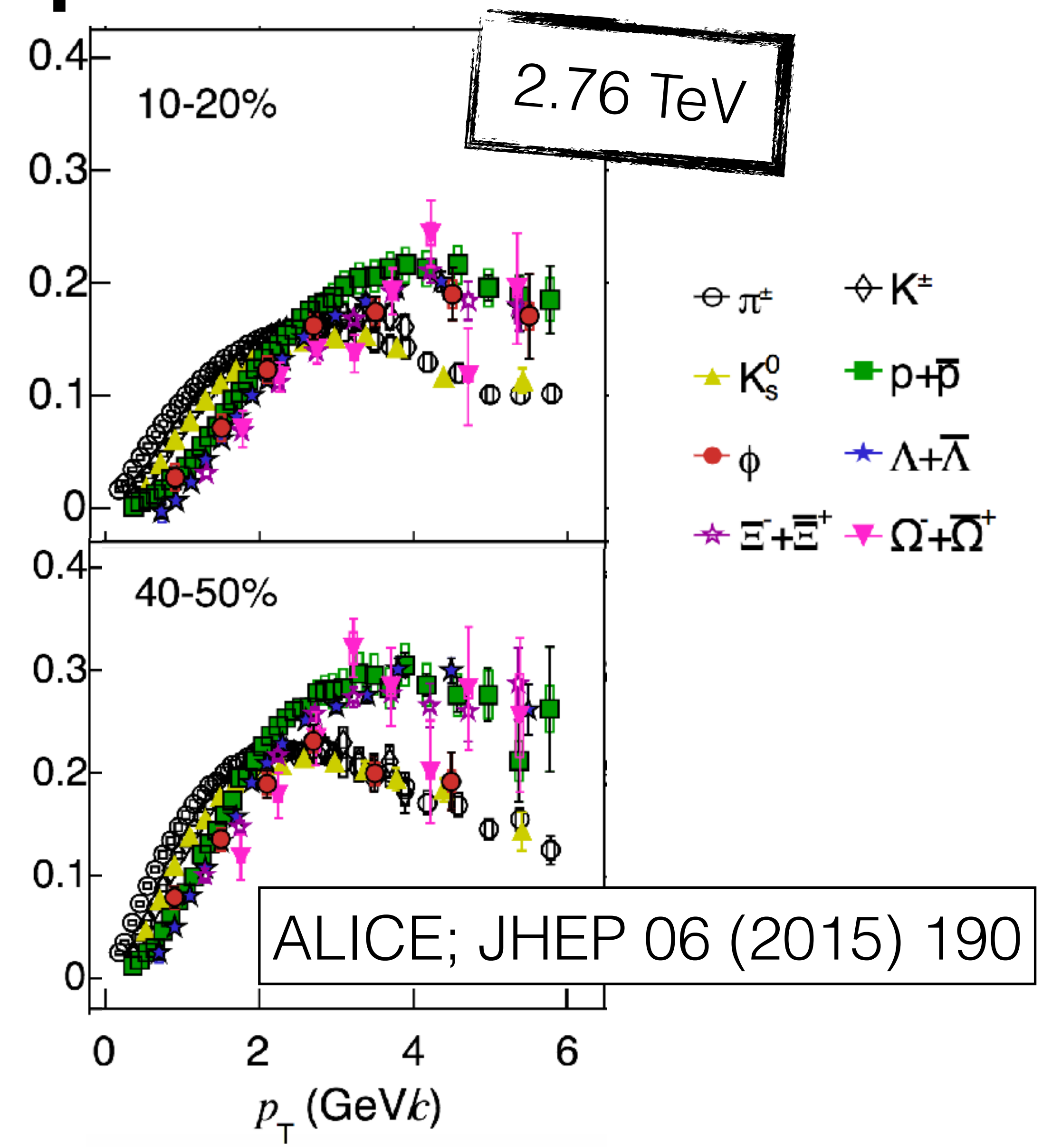




- Mass ordering below 2 GeV/*c*
  - *m*(ϕ) ≈ *m*(p); v_2(ϕ) ≈ v_2(p)
- Baryon / meson grouping for 2 ≲ p_T ≲ 8 GeV/*c*
- Species independent flow for high p_T > 10 GeV/*c*

Identified, p_T-dependent v_2





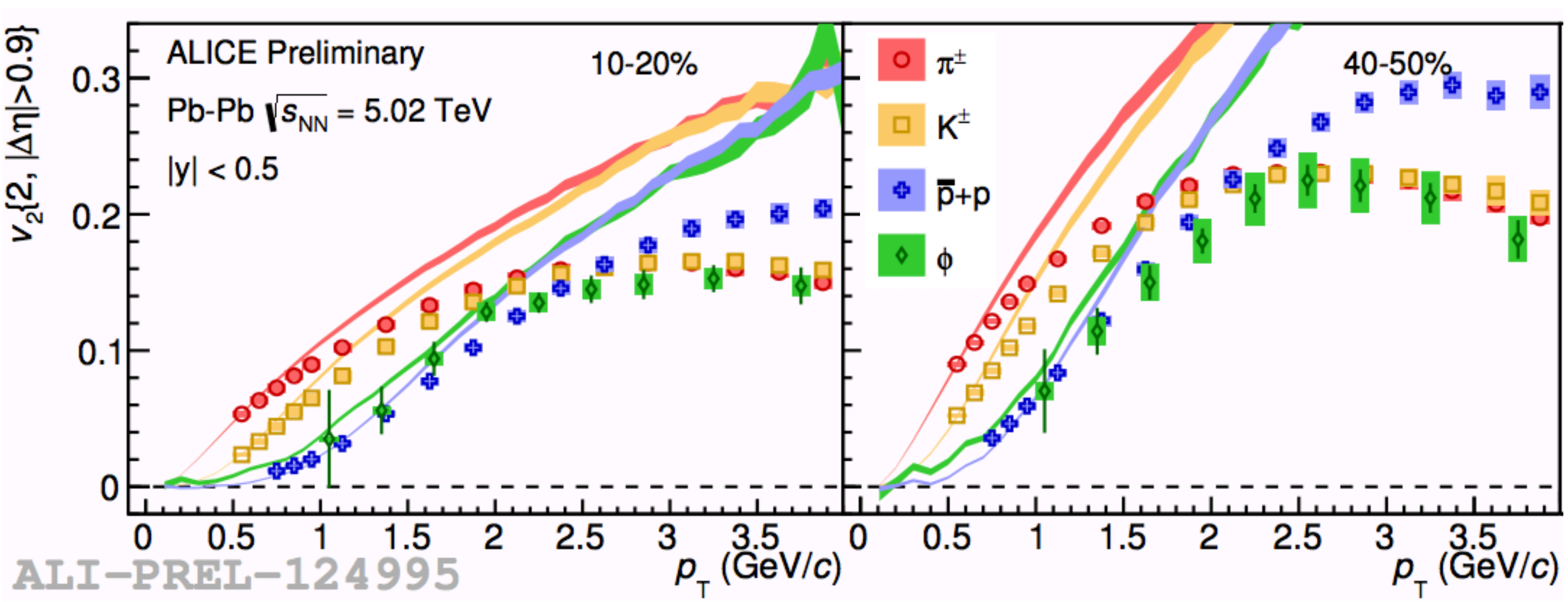
- Higher stats 5 TeV Run II data set:
  - Extended kinematic reach
  - Better precision
  - Clearer meson grouping
  - $\sqrt{s_{NN}}$ dependence

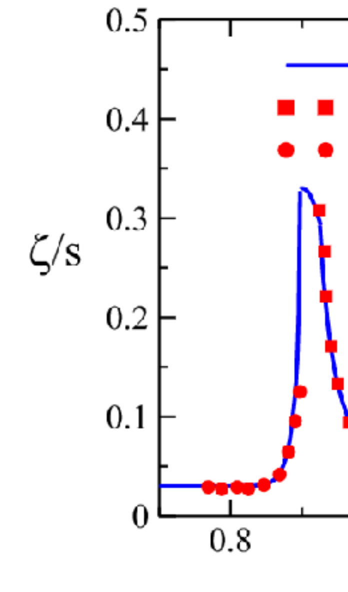
Identified, p_T-dependent v_2

- Model: IP Glasma + MUSIC + UrQMD

McDonald et al, arXiv:1609.02958

- Hydro at τ_0 = 0.4 fm/c
- Transport at T = 145 MeV
- η/s = 0.095
- bulk

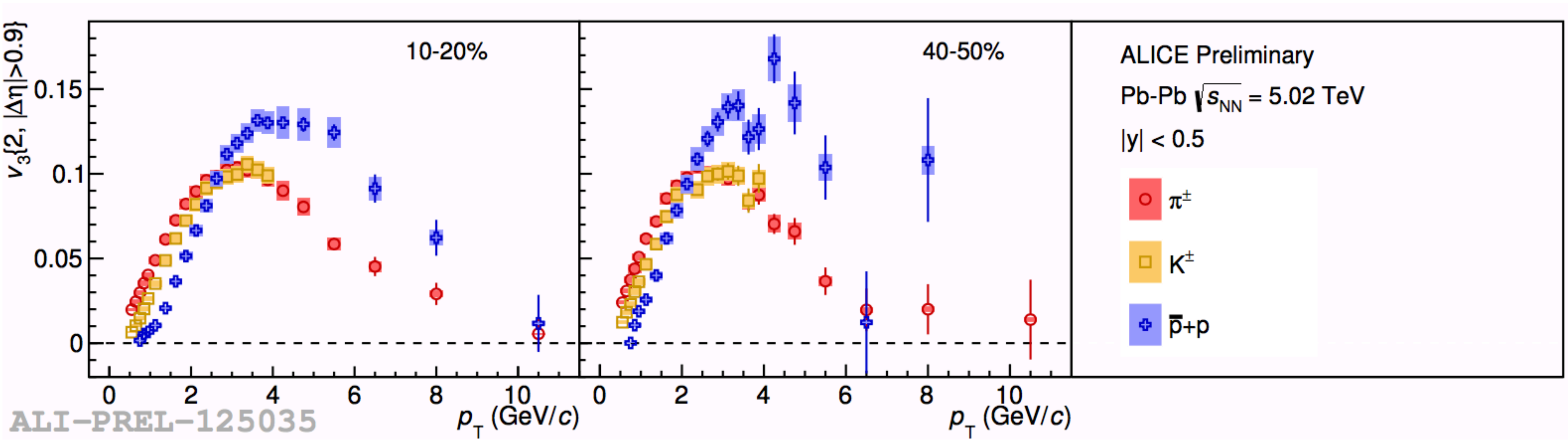




S. Ryu et al; PRL115 (2015), 132301

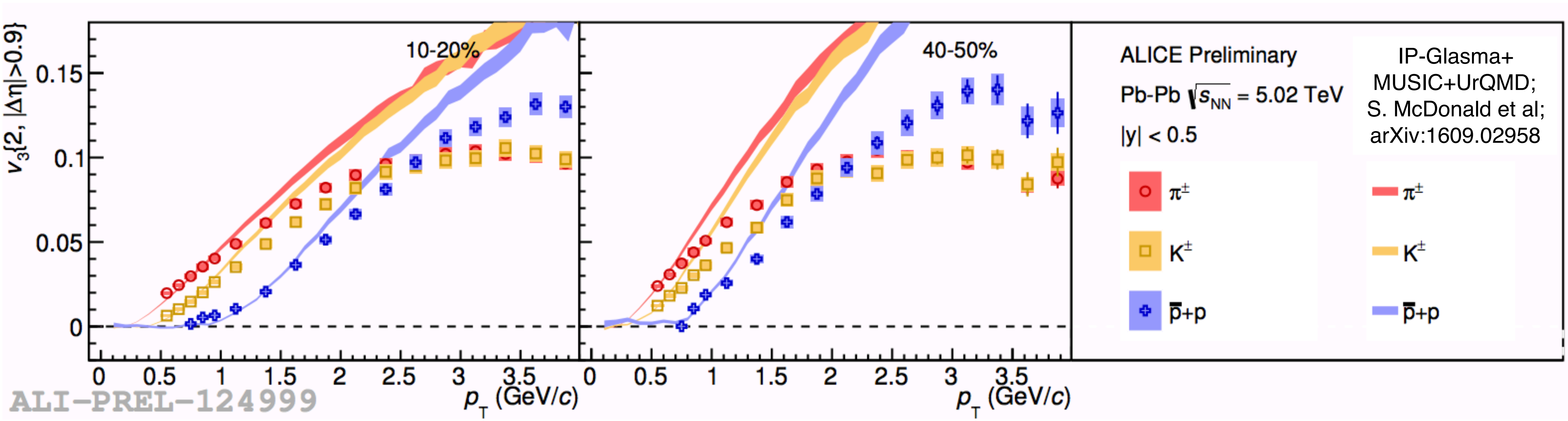
- Model constrained by previous ALICE flow data
  - Identified 2.76 TeV: JHEP 06 (2015) 190
  - Unidentified 5 TeV: PRL116 (2016) 132302
- Good agreement for p_T < 1 GeV/c in central collisions
- Over-prediction of flow for mid-central events

Identified, p_T-dependent higher harmonics: v_3



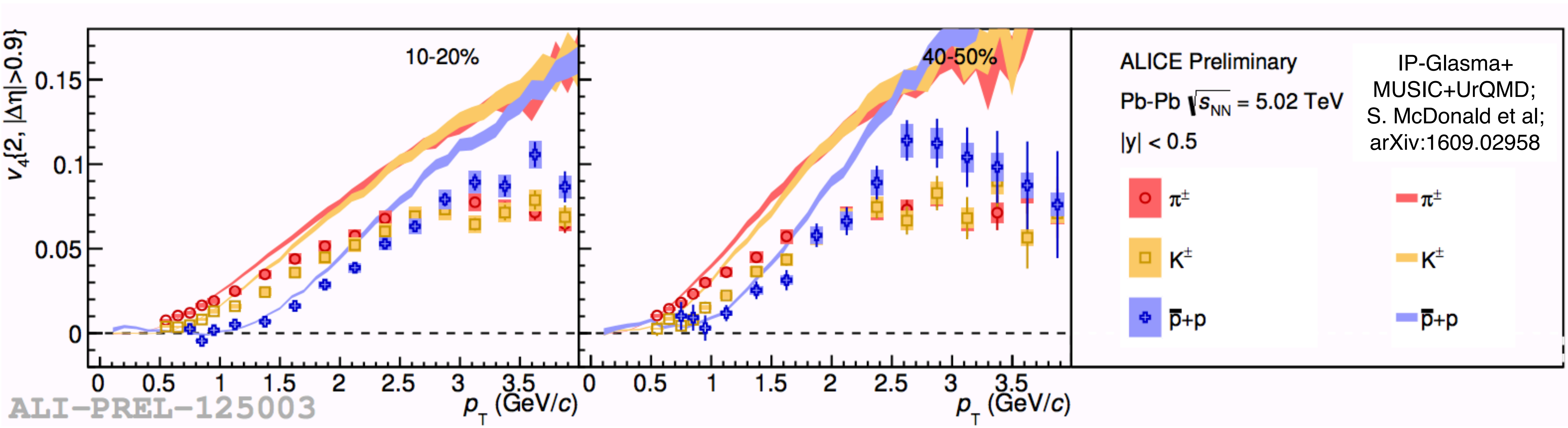
- Significant v_3 out to 8 GeV/c
  - Species dependence remains over full p_T range
- Similar behavior as v_2:
  - Mass ordering at low p_T
  - Crossing at $p_T \approx 2.5$ GeV/c

Identified, p_T-dependent higher harmonics: v_3



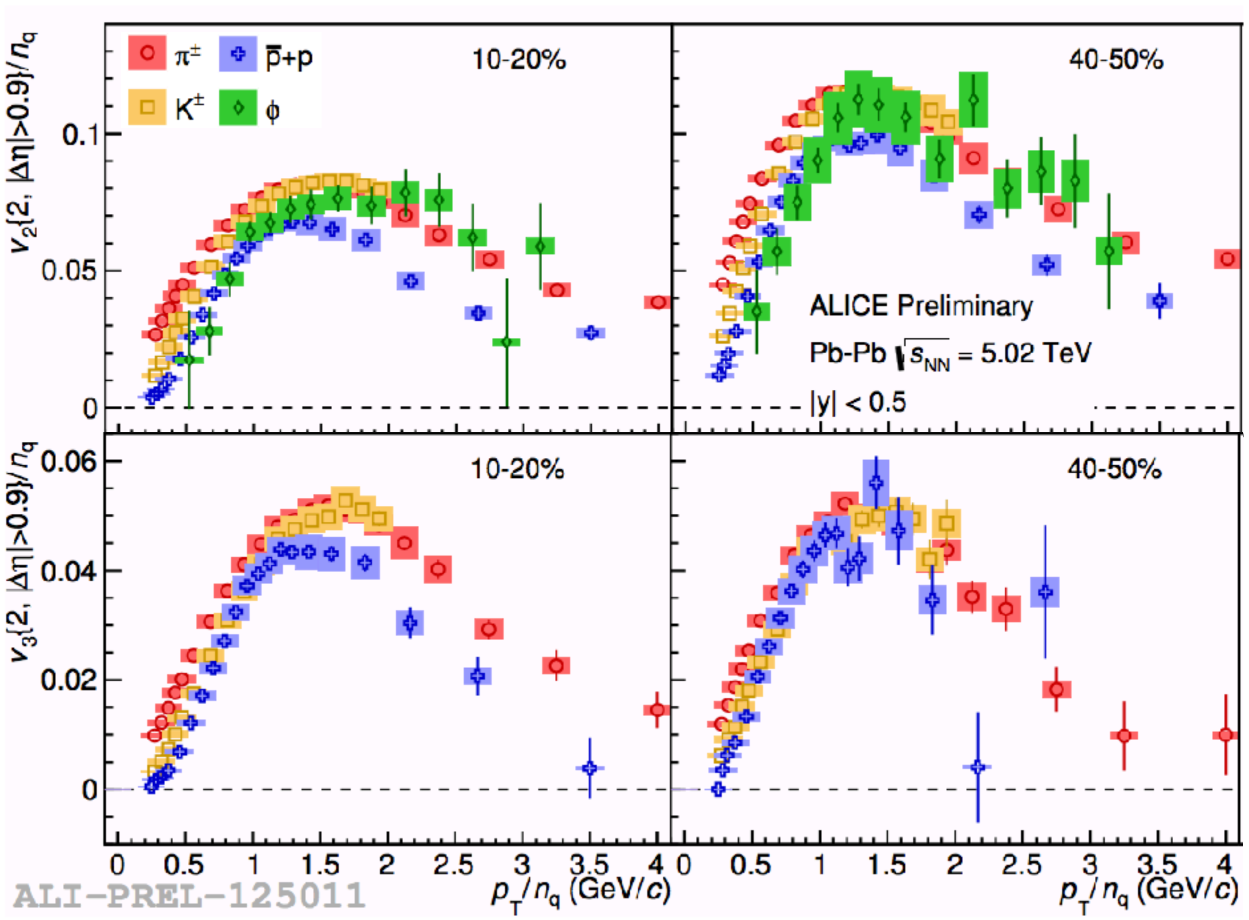
- Similar observation as for v_2
  - Good agreement for p_T < 1 GeV/c in central collisions
  - Over-prediction of flow for mid-central events

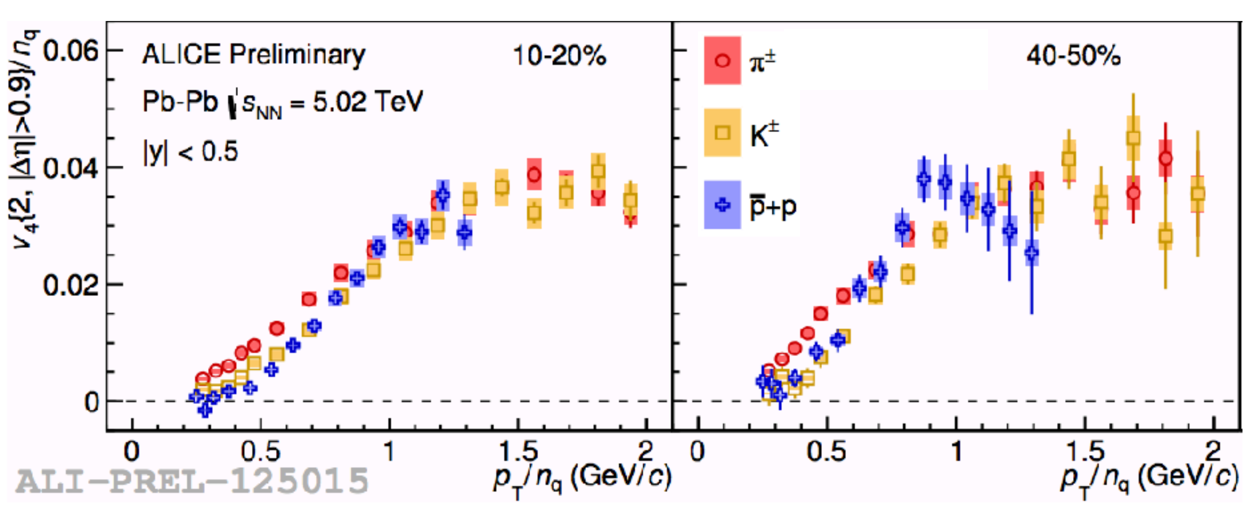
Identified, p_T-dependent higher harmonics: v_4



- Similar observation as for v_2 & v_3
  - Good agreement for p_T < 1 GeV/c in central collisions
  - Over-prediction of flow for mid-central events

NCQ Scaling?



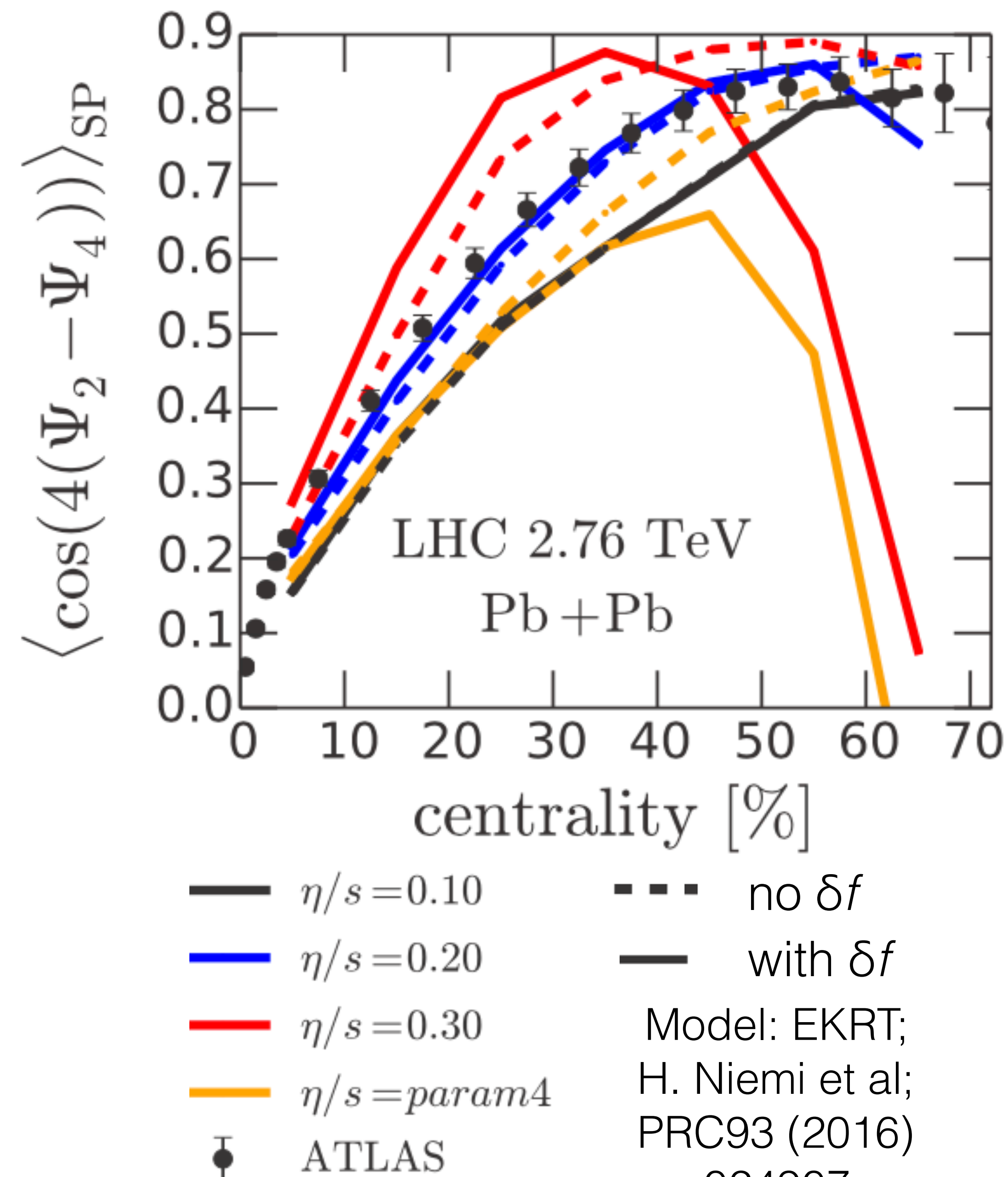


- NCQ scaling expected in coalescence picture
- Scaling only approximate

Flow Correlations

Flow Correlations: Sensitivity

- v_n are reduced by
  - Viscous correction δf to Boltzmann distribution
  - Viscosity during evolution
- Flow correlations are
  - Reduced by δf
  - **Enhanced** by viscosity in the evolution

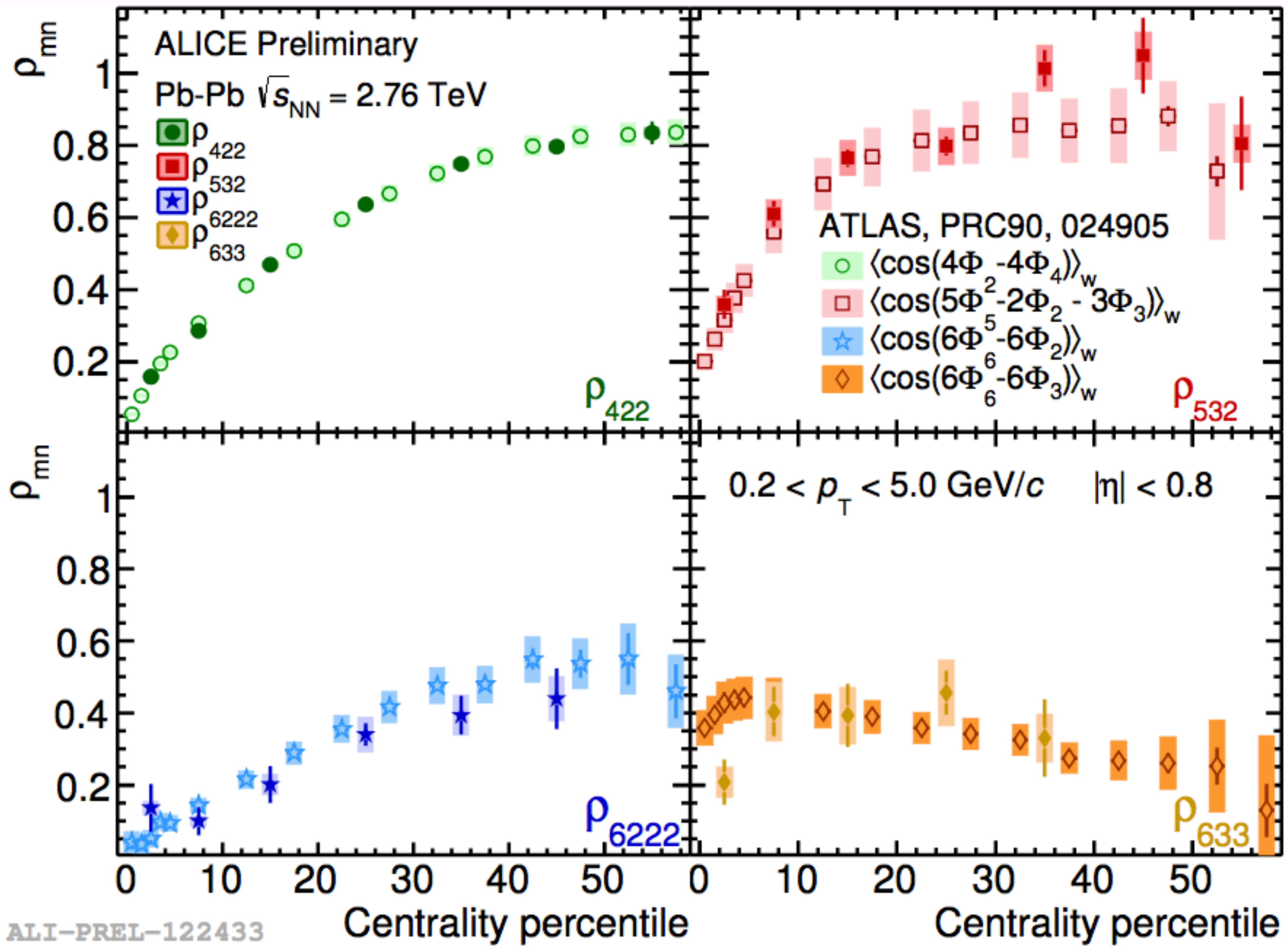


Model: EKRT; H. Niemi et al; PRC93 (2016) 024907

- Small effect of δf in central and mid-central

➡ Particularly sensitive to viscosity during evolution

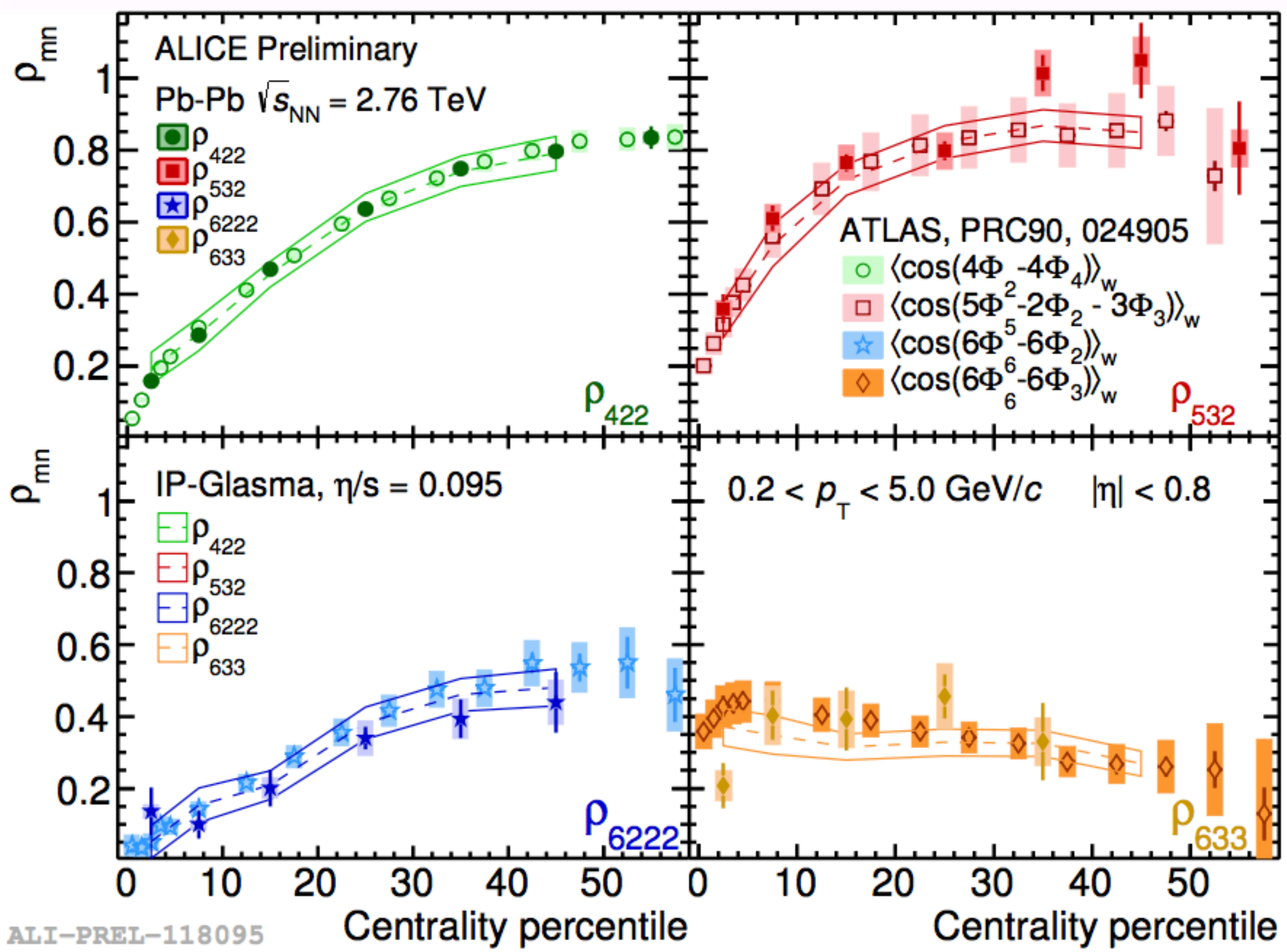
Symmetry Plane Correlations



$$\rho_{422} \approx \langle \cos(4\Psi_4 - 4\Psi_2) \rangle$$
$$\rho_{532} \approx \langle \cos(5\Psi_5 - 3\Psi_3 - 2\Psi_2) \rangle$$
$$\rho_{6222} \approx \langle \cos(6\Psi_6 - 6\Psi_2) \rangle$$
$$\rho_{633} \approx \langle \cos(6\Psi_6 - 6\Psi_3) \rangle$$

- ALICE and ATLAS data agree (non-trivially due to different η coverage)

Symmetry Plane Correlations



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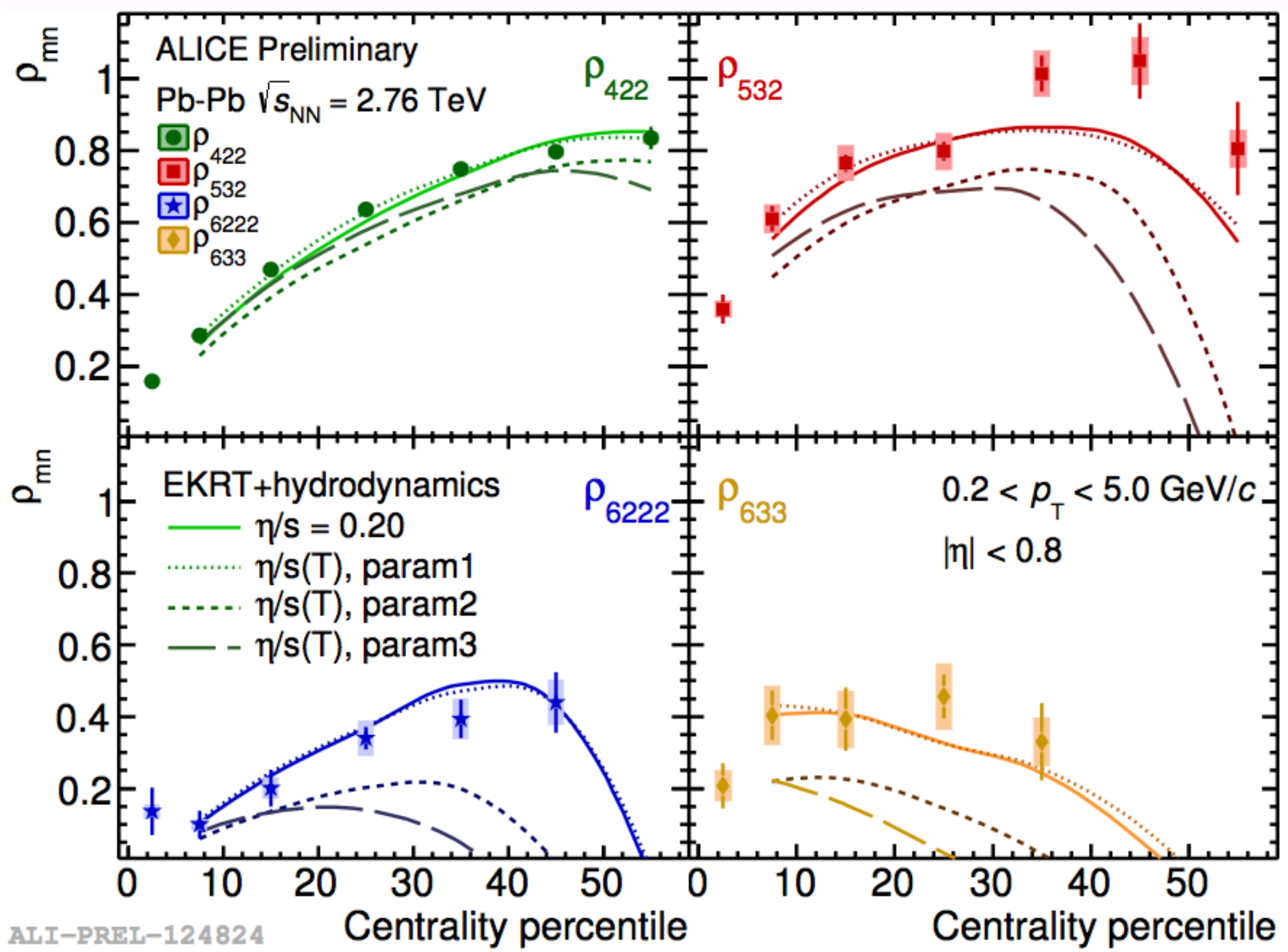
IP Glasma;
S. McDonald et al.;
arXiv:1609.0295

- ALICE and ATLAS data agree (non-trivially due to different η coverage)
- Data described by IP Glasma

Symmetry Plane Correlations



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IP Glasma,
S. McDonald et al.,
arXiv:1609.0295

EKRT,
H. Niemi et al.,
PRC93, 024907 (2016)

- ALICE and ATLAS data agree (non-trivially due to different *η* coverage)
- Data described by IP Glasma & EKRT
- Sensitivity to *η/s(T)* evident

Flow Correlations: Beyond Flow Angles

- Look not only at angles but also at magnitude

- Symmetric Cumulants:

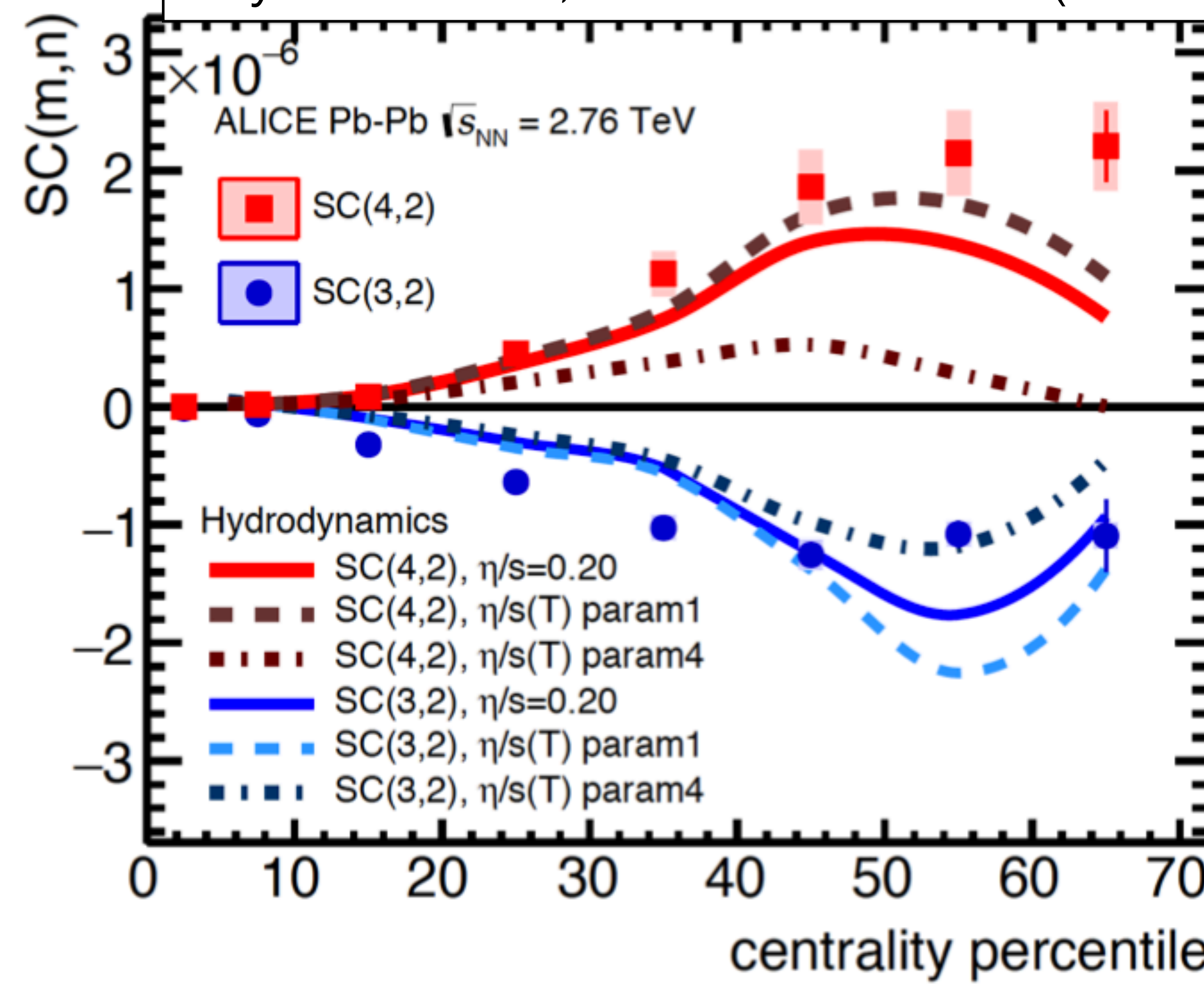
$$\mathrm{SC}(m,n) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

Bilandzic et al, PRC 89, 064904 (2014)

- Normalized SC:

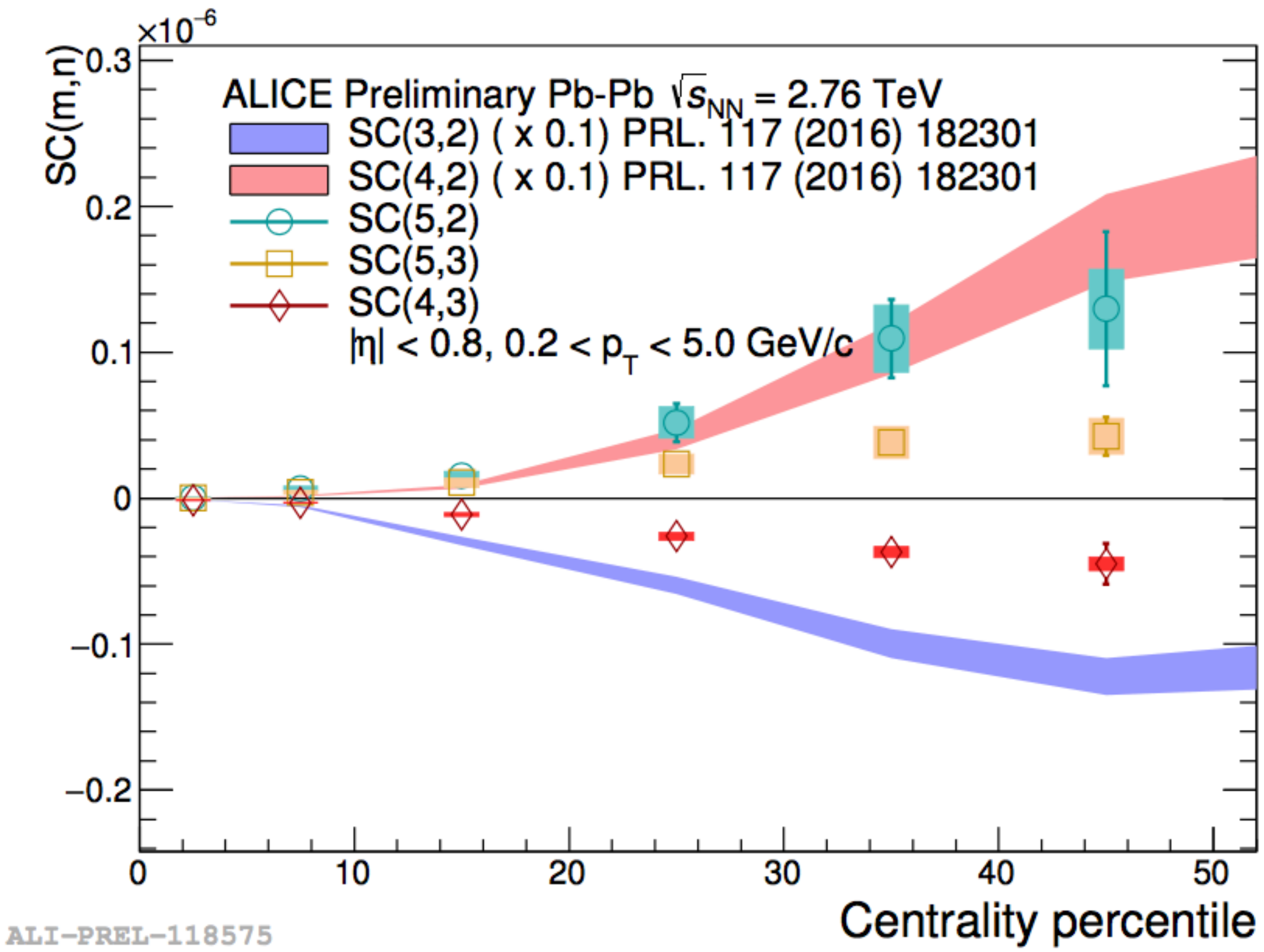
$$\mathrm{NSC}(m,n) = \frac{\mathrm{SC}(m,n)}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$$

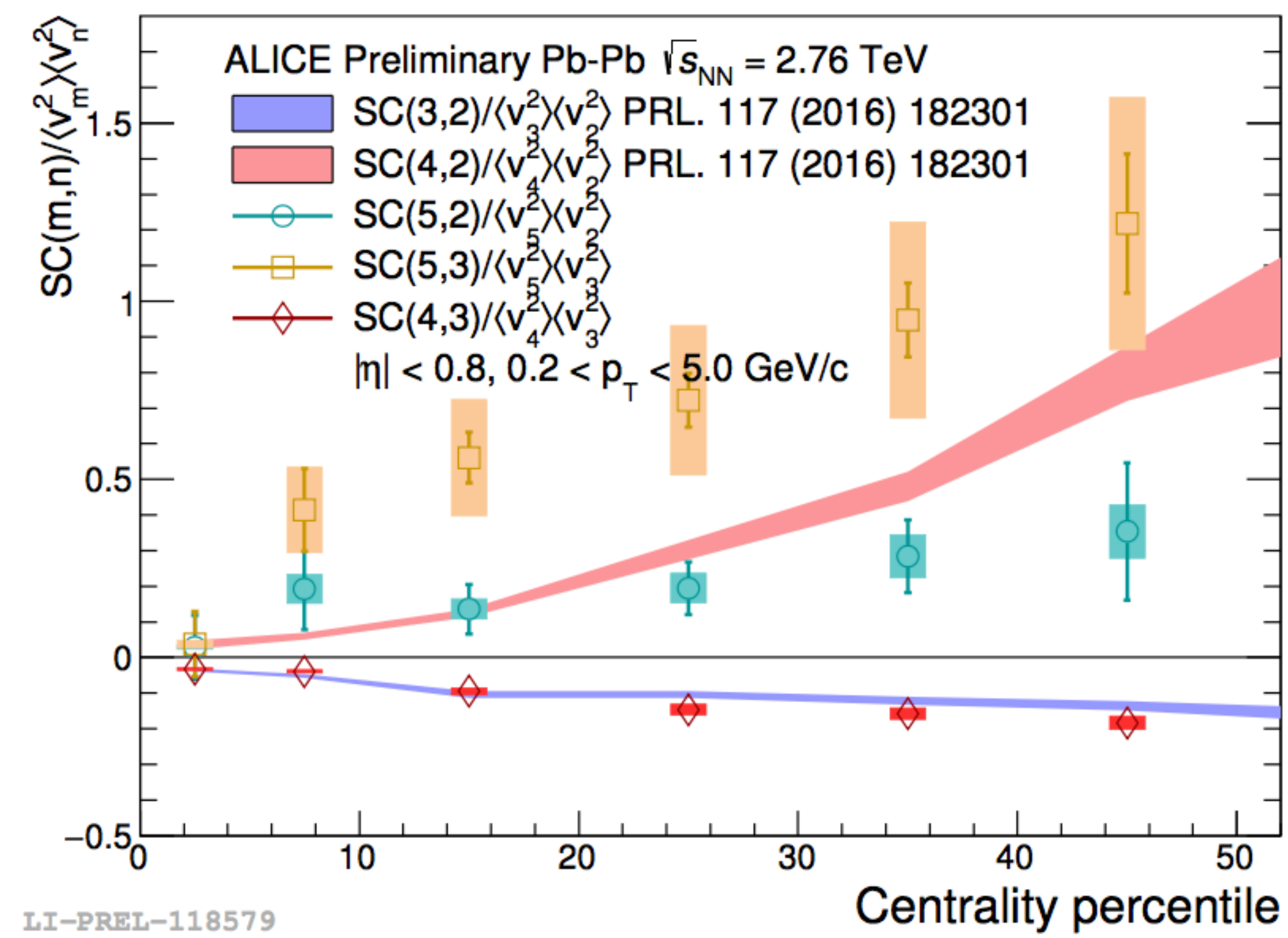
Data: ALICE; PRL 117, 182301 (2016)
Hydro: EKRT; PRC 93 024907 (2016)



- Investigate higher order correlations!

Higher Order SC & NSC

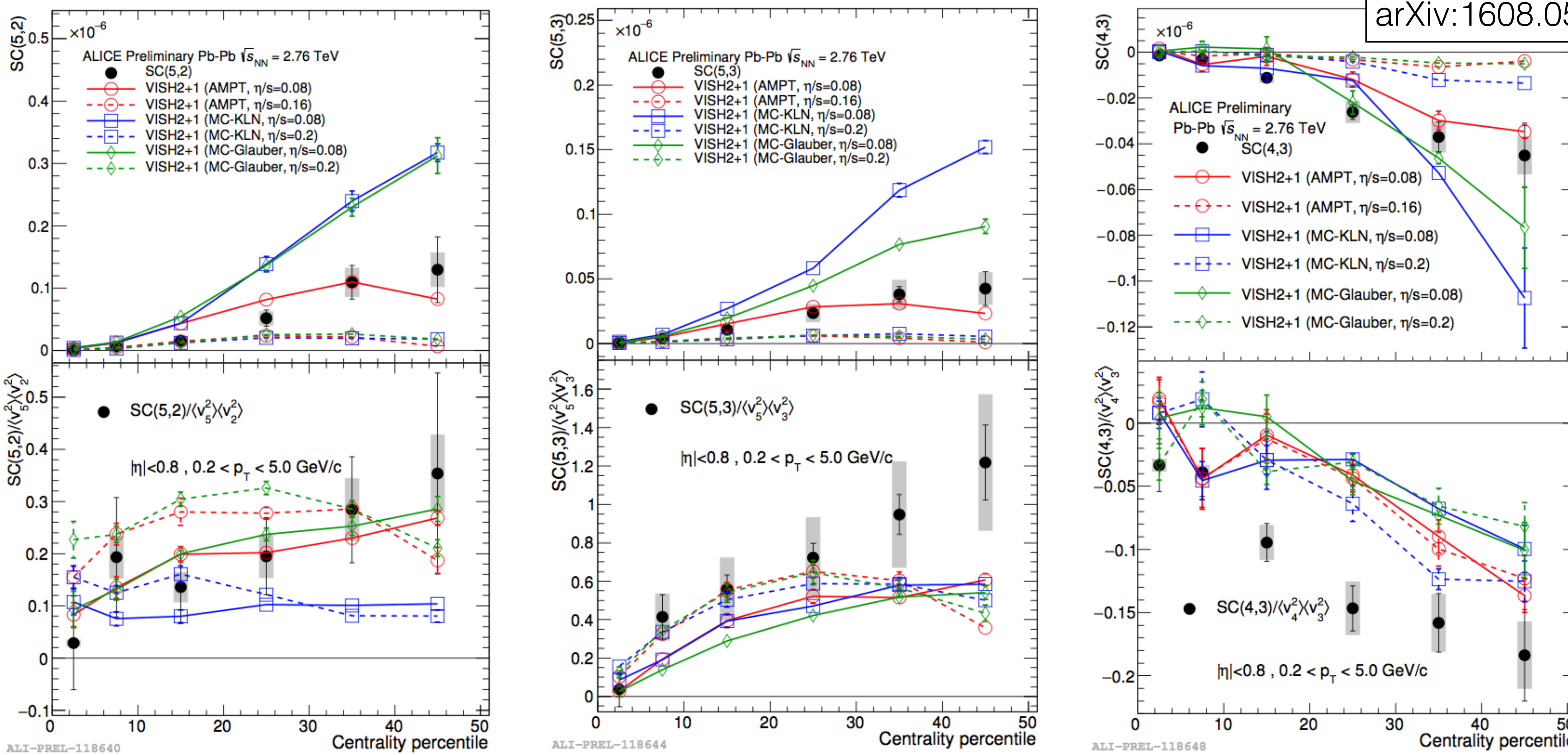




- Positive correlation for (v_5, v_2) and (v_5, v_3), anticorrelation for (v_4, v_3), largest NSC for (v_5, v_3)

Higher Order SC & NSC Model Comparison

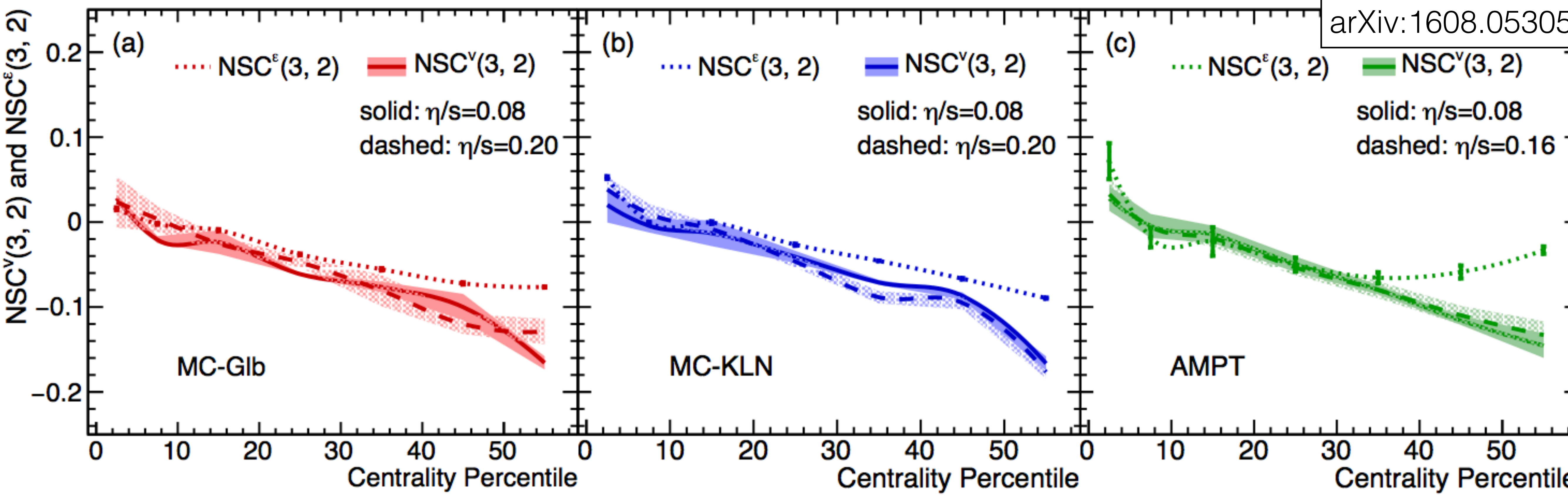
Visc. 2+1 hydro; Zhu et al; arXiv:1608.05305



- Model can not describe complete data
  - More elaborate *T* dependence of *η/s* needed?
- Sensitivity to initial state apparent → investigate further!

NSC: Initial State Sensitivity

Visc. 2+1 hydro;
Zhu et al;
arXiv:1608.05305

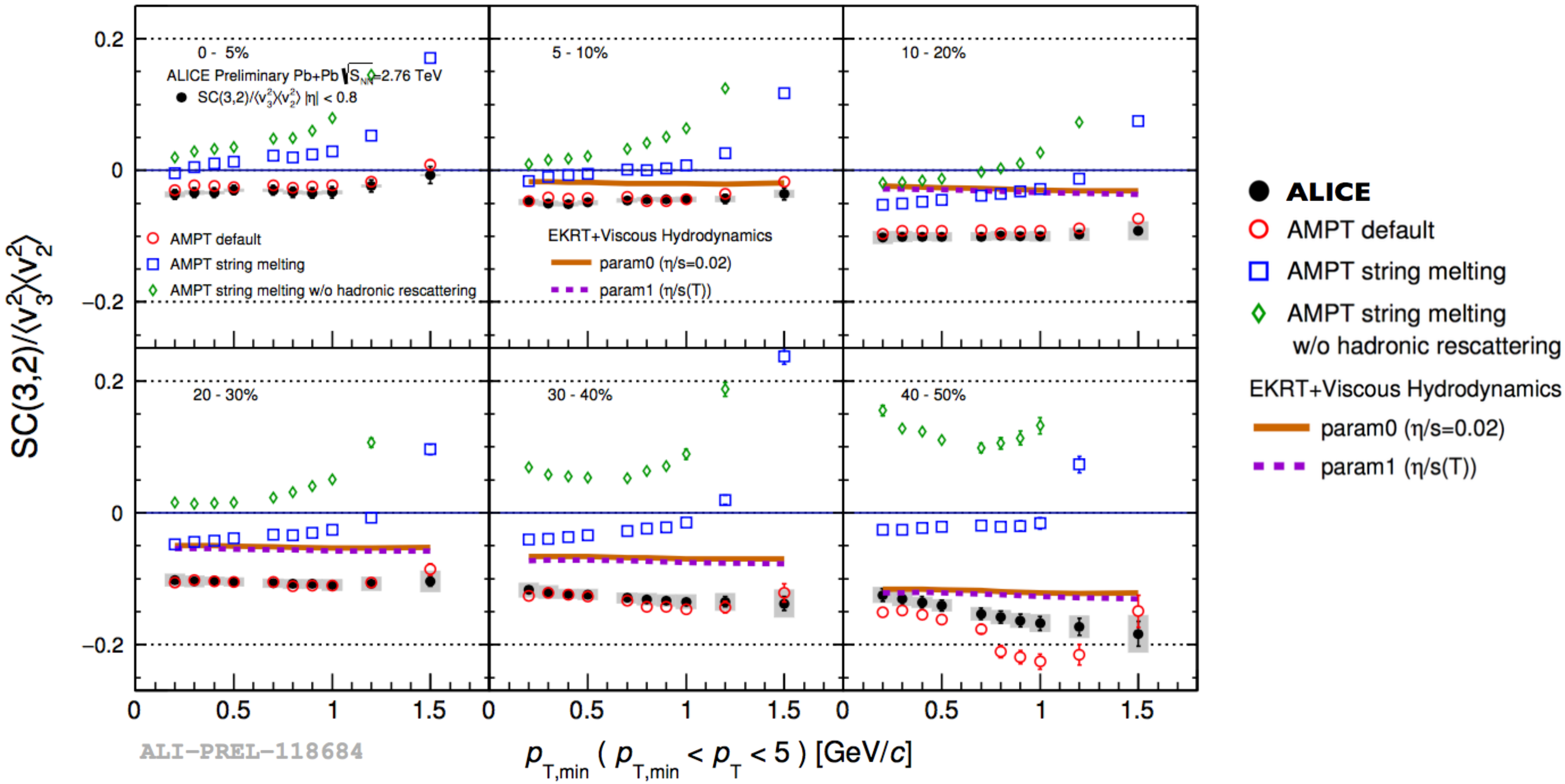


- In the model, (v_3, v_2) correlation driven by initial state

$$\frac{\langle v_3^2 v_2^2 \rangle}{\langle v_3^2 \rangle \langle v_2^2 \rangle} = \mathrm{NSC}^v(3,2) \approx \mathrm{NSC}^\epsilon(3,2) = \frac{\langle \epsilon_3^2 \epsilon_2^2 \rangle}{\langle \epsilon_3^2 \rangle \langle \epsilon_2^2 \rangle}$$

- New constraints on initial state correlations?

NSC: Initial State Sensitivity



- NSC(3,2) generally independent of min. p_T cut in data
  - Slight decrease with min. p_T for centrality > 30%
  - p_T dependent trend reproduced by hydro & AMPT
- Magnitude reproduced only by AMPT (which does not describe v_n)

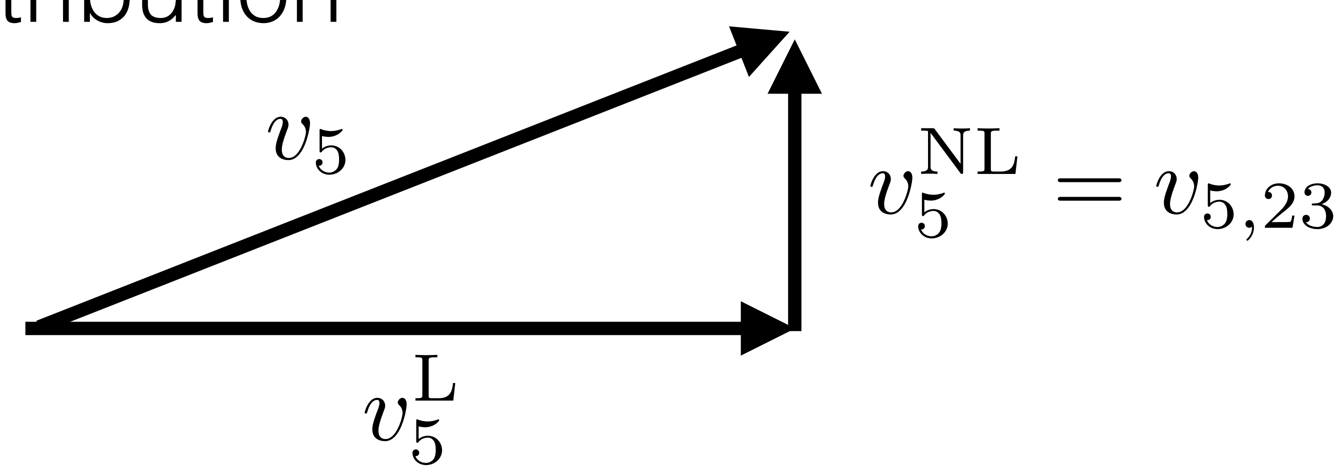
➡ Further input to initial state dynamics

Non-Linear Hydro Response

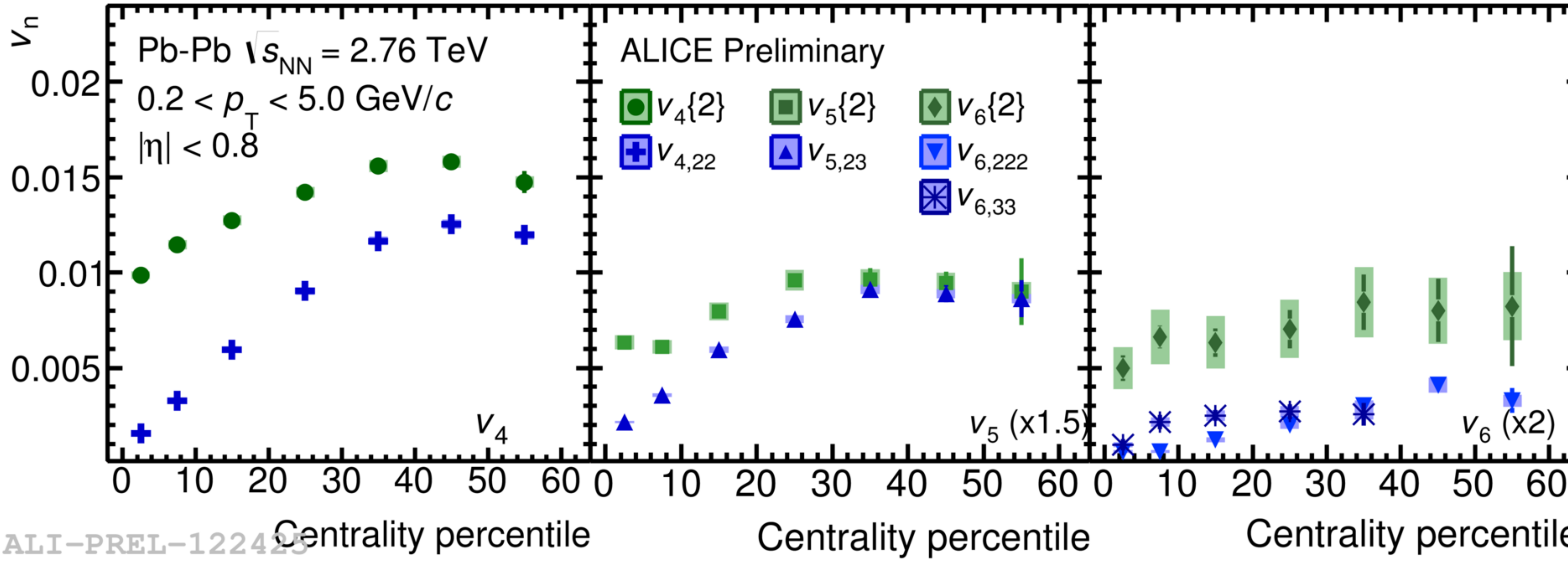
- Observed correlation between (v_5, v_2) and (v_5, v_3)
- How much of v_5 is feed-up, how much is native v_5?
- $v_{5,23}$ is v_5 with respect to 2nd and 3rd symmetry plane

$$v_{5,23} = v_5\{\Psi_{23}\} = \frac{Re\langle V_5 V_2^* V_3^* \rangle}{\sqrt{\langle |V_2|^2 |V_3|^2 \rangle}}$$

- Decompose higher harmonics in linear v_n^{L} and non-linear v_n^{NL} contribution

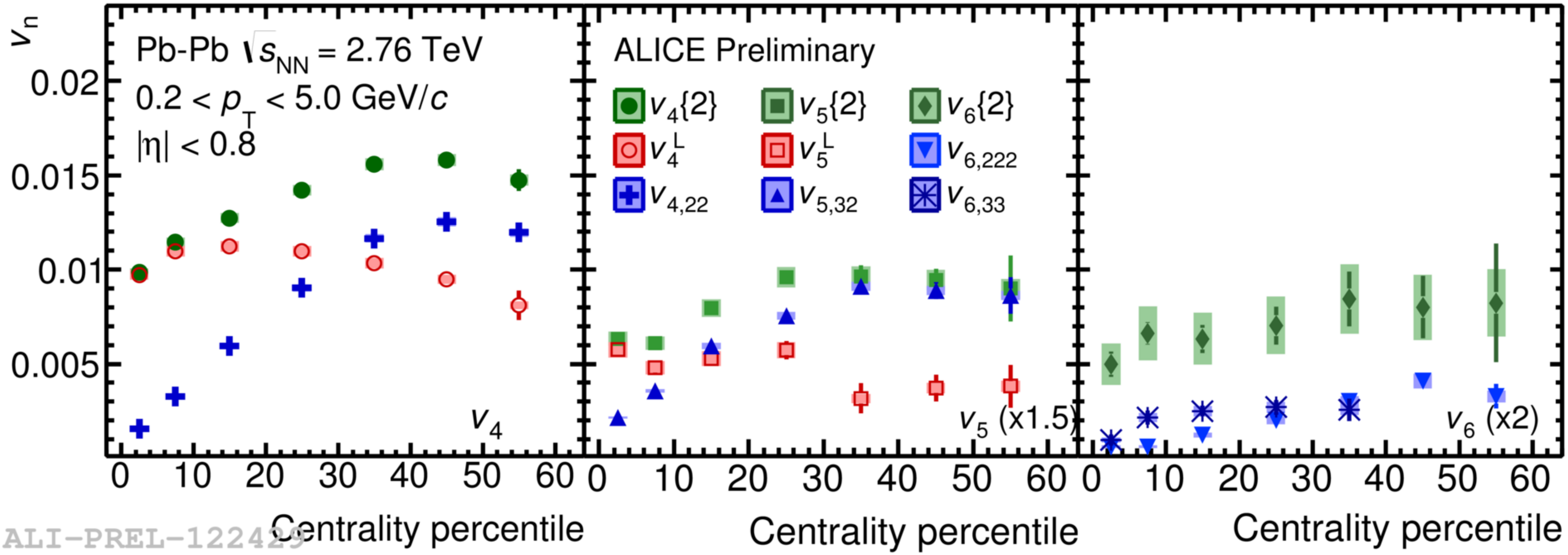


Response Decomposition



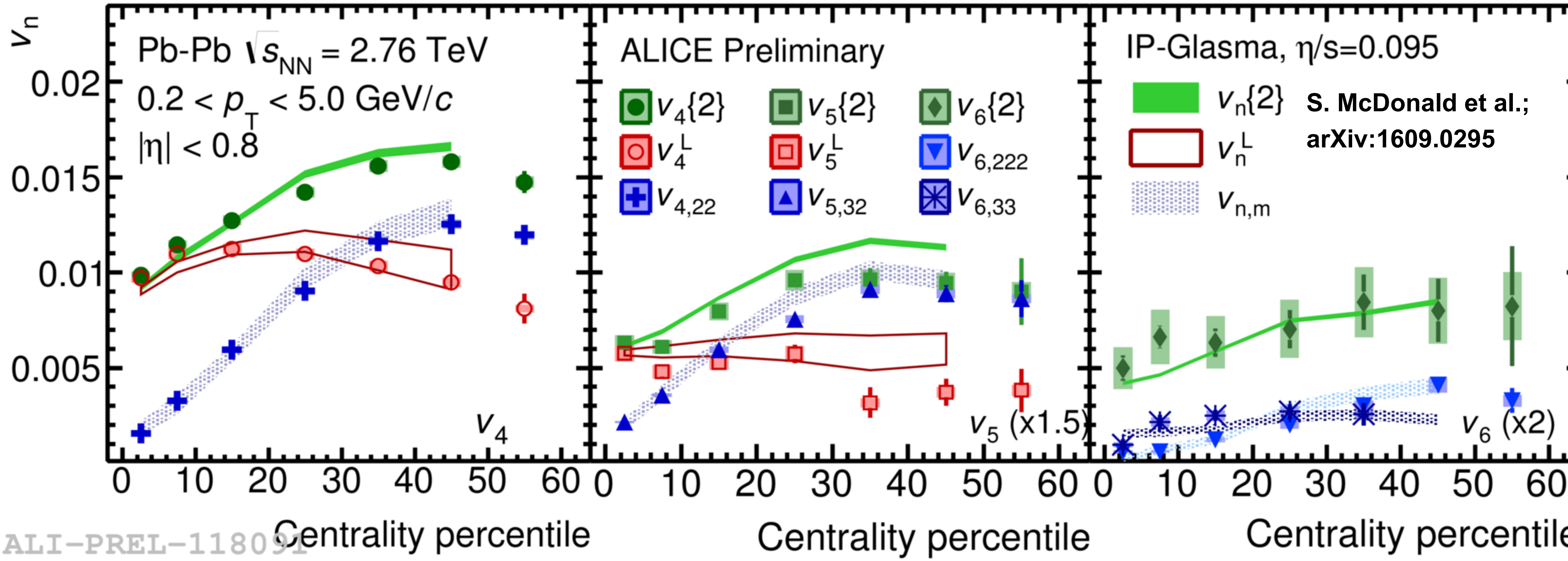
- Non-linear contribution dominant for peripheral events

Response Decomposition



- Non-linear contribution dominant for peripheral events
- Linear $v_5^{\rm L}$ only weakly dependent on centrality

Response Decomposition



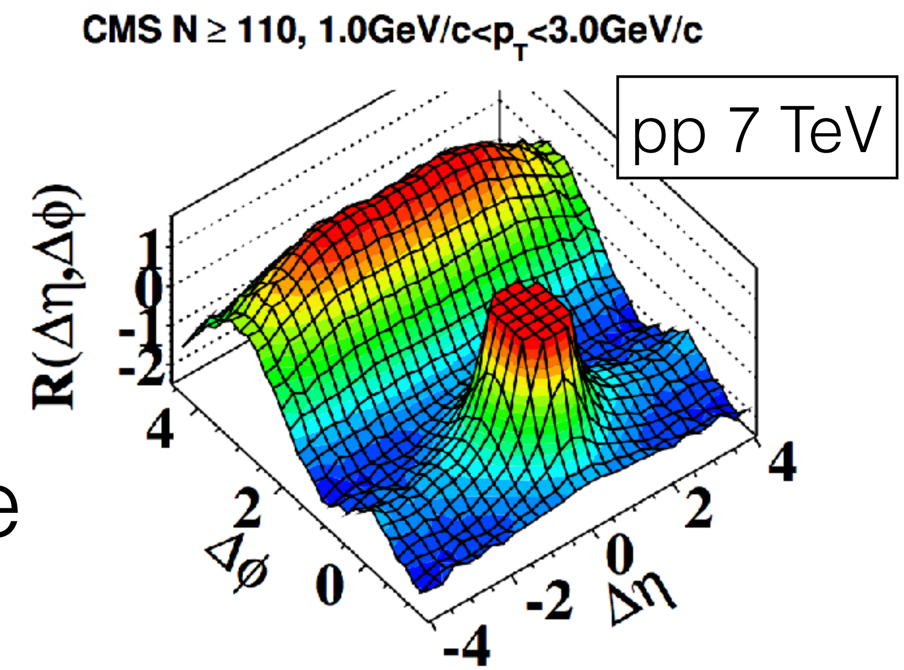
- Non-linear contribution dominant for peripheral events
- Linear v_5^L only weakly dependent on centrality
- Quantitatively reproduced by IP-Glasma

Collectivity in small systems

Di-Hadron Ridges

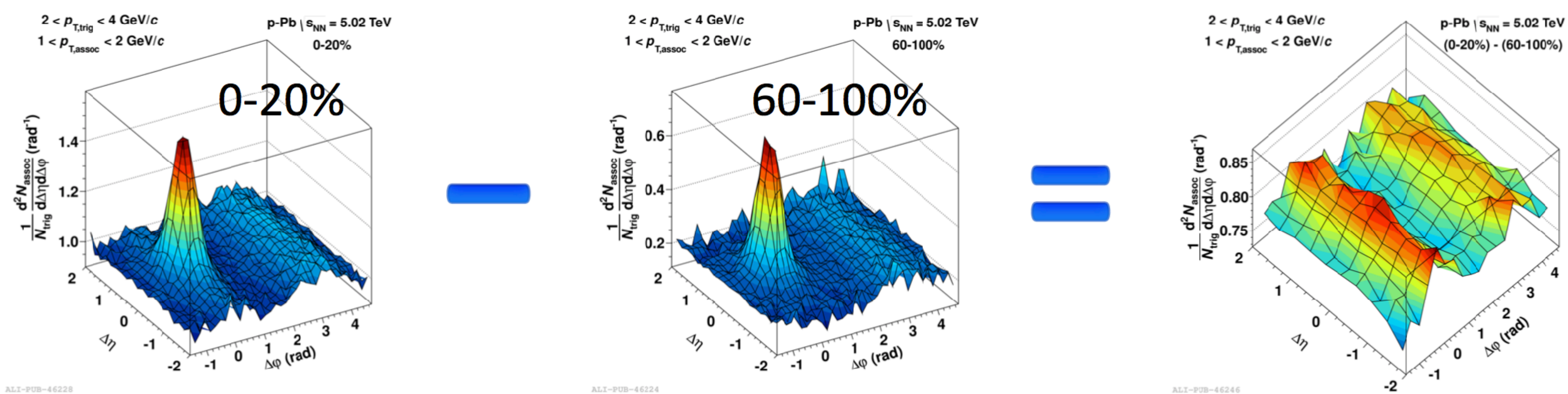
- CMS saw the ridge

JHEP09 (2010) 091;
PLB 718 (2013) 795



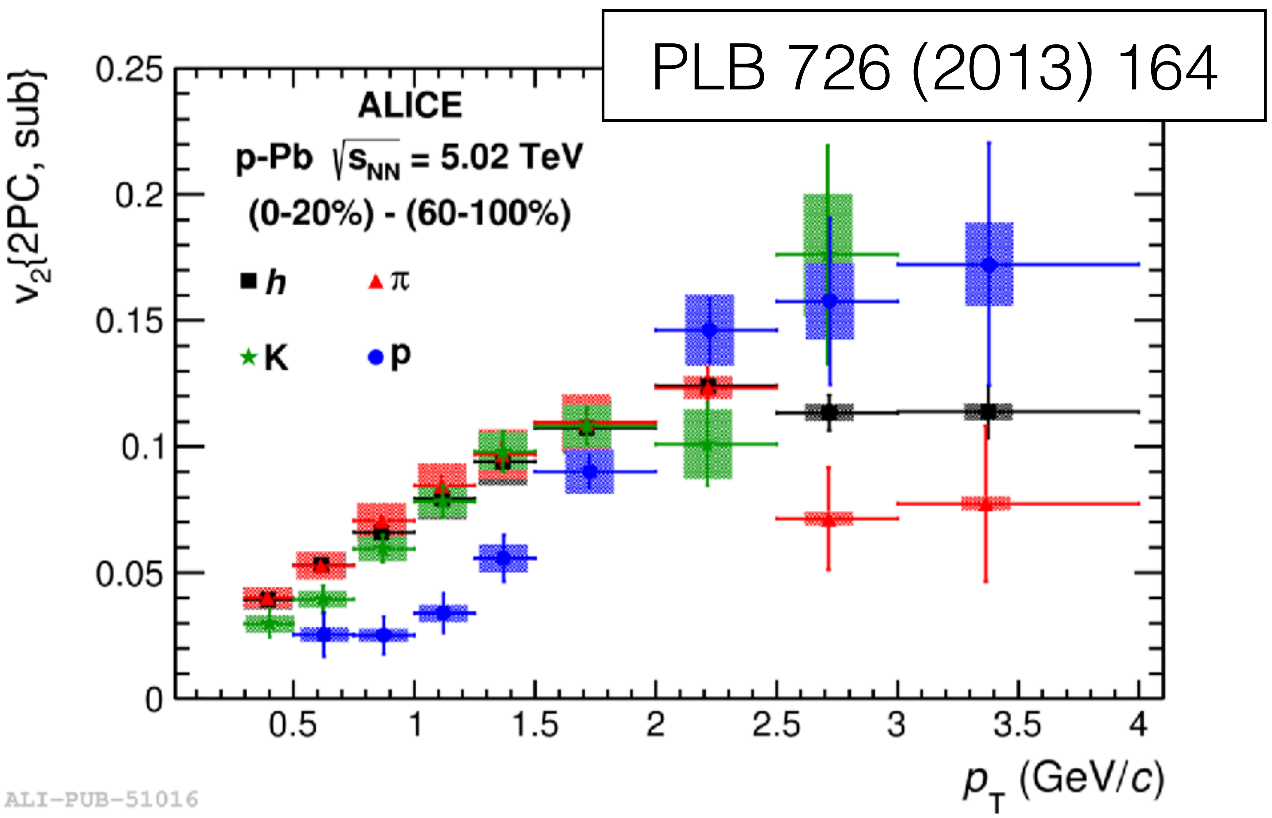
- ALICE saw the double ridge

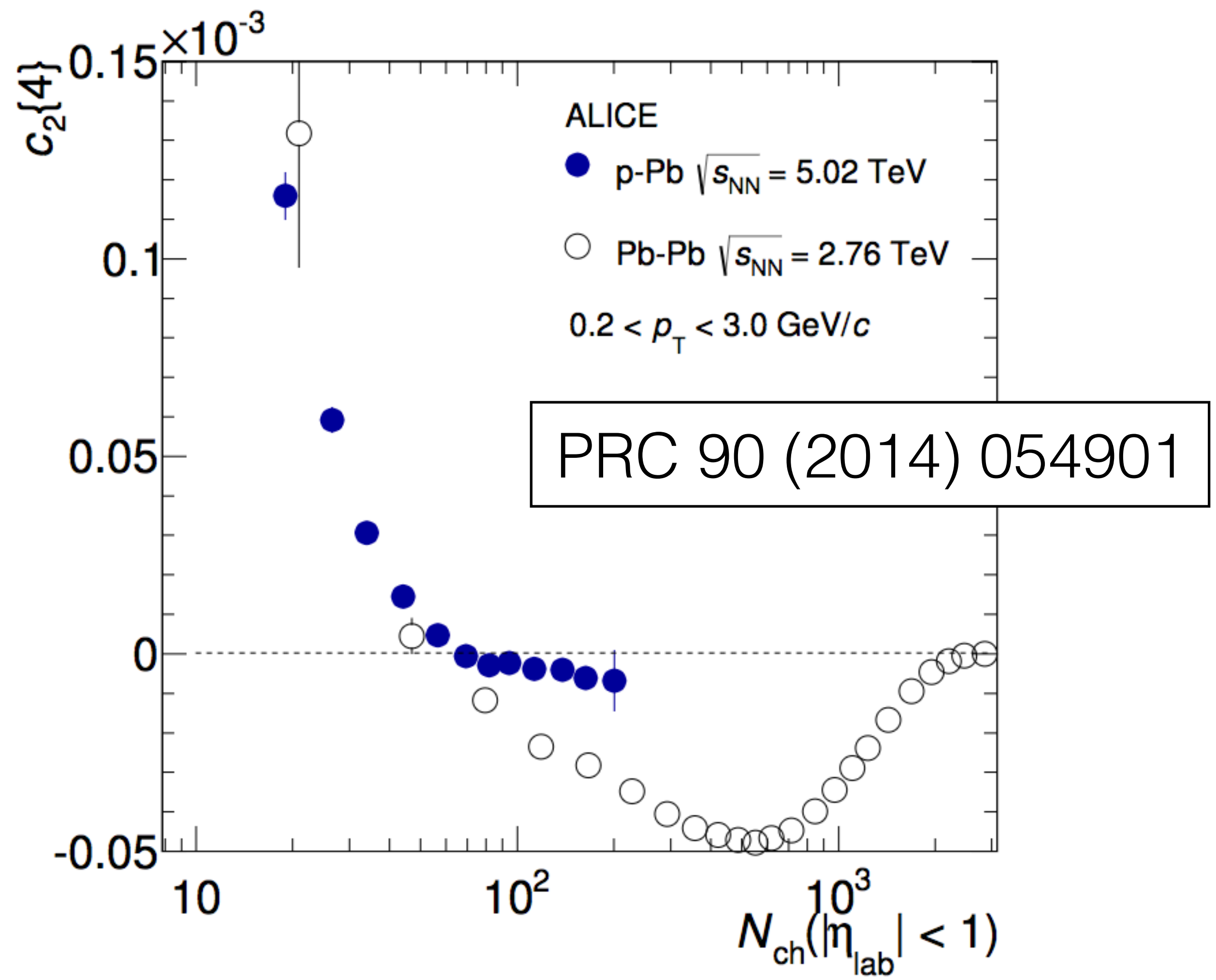
PLB 719 (2013) 29



Is It Flow?

- ALICE measurements in p-Pb reveal signals reminiscent of flow in large Pb-Pb system





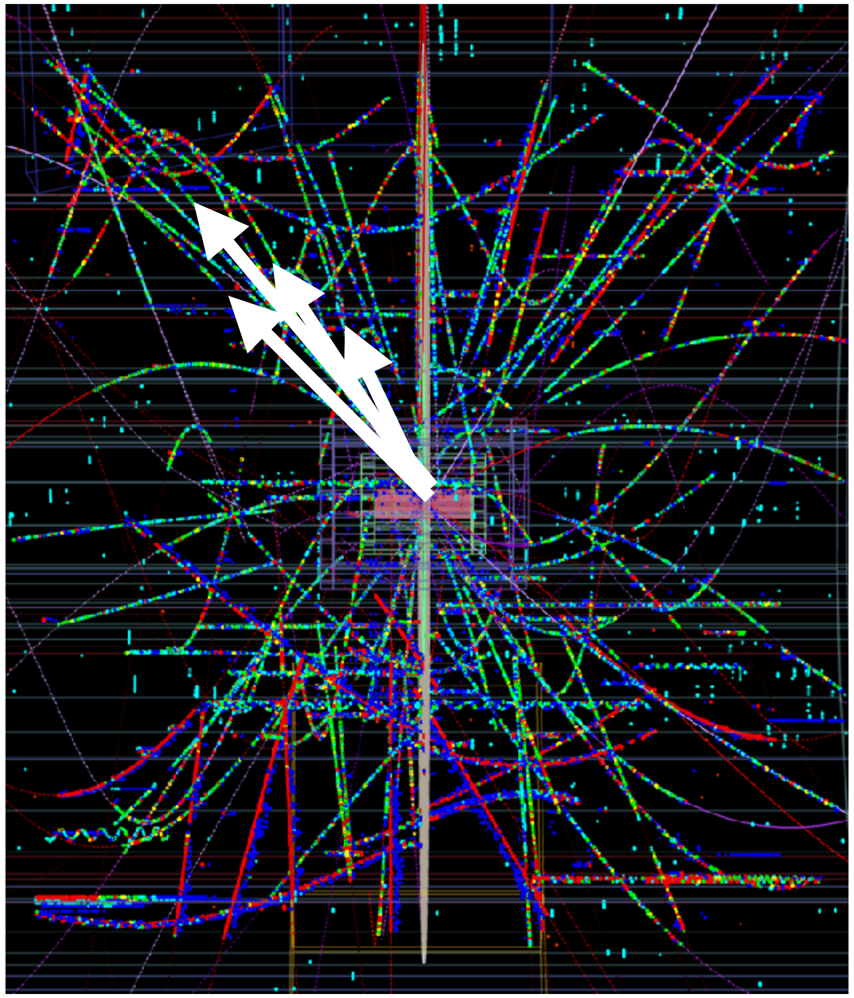
✓ PID dependence

- Global correlation?

➡ Need to examine non flow!

Non Flow Suppression

- 4 particles in a p-Pb collision can originate from one jet



https://cds.cern.ch/record/1477949

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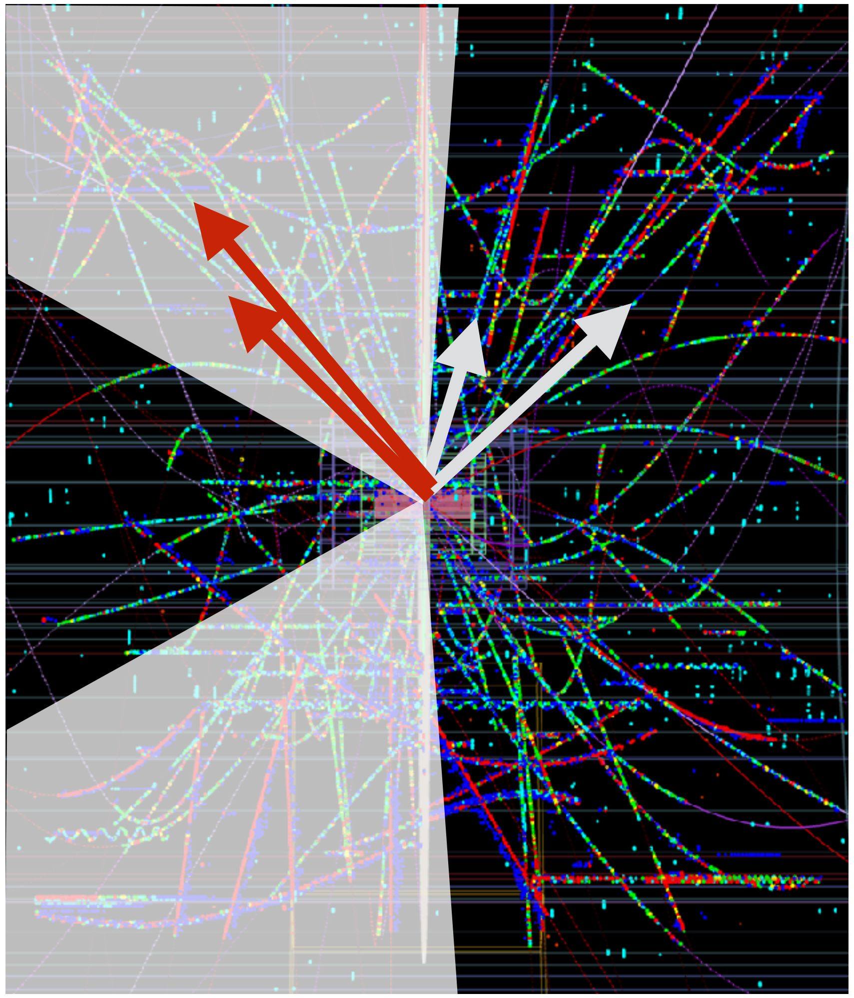
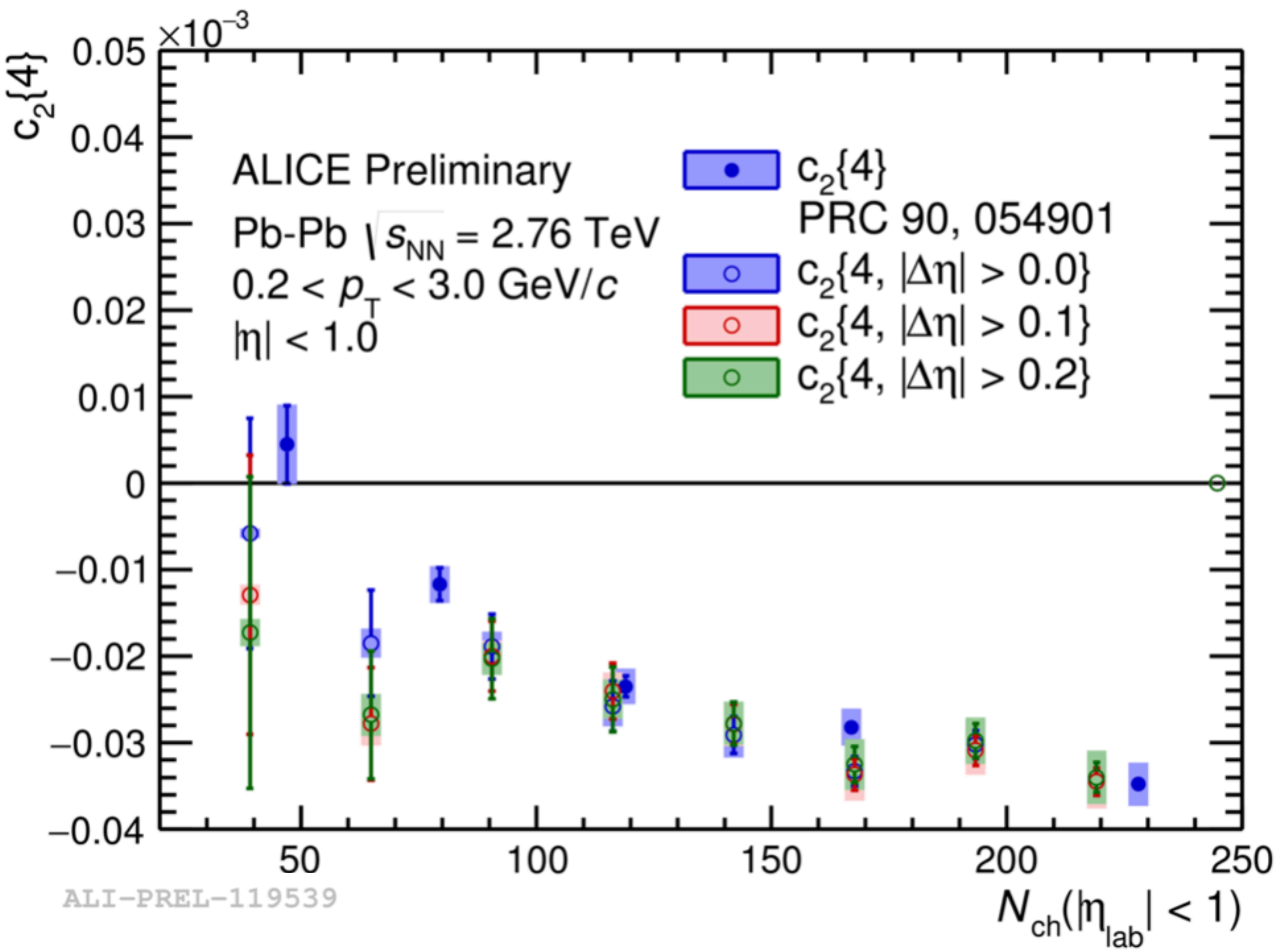


- Require η gap between track doublets
- Two-particle correlation explicitly removed in cumulant

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$$

Non Flow Suppressed Cumulants

- Remember $v_n\{4\} = \sqrt[4]{-c_n\{4\}}$
- Use Pb-Pb as paradigm for flow



- $c_2\{4\}$ crossing $N_{ch} \approx 70$
- Mild non flow removed for low multiplicities

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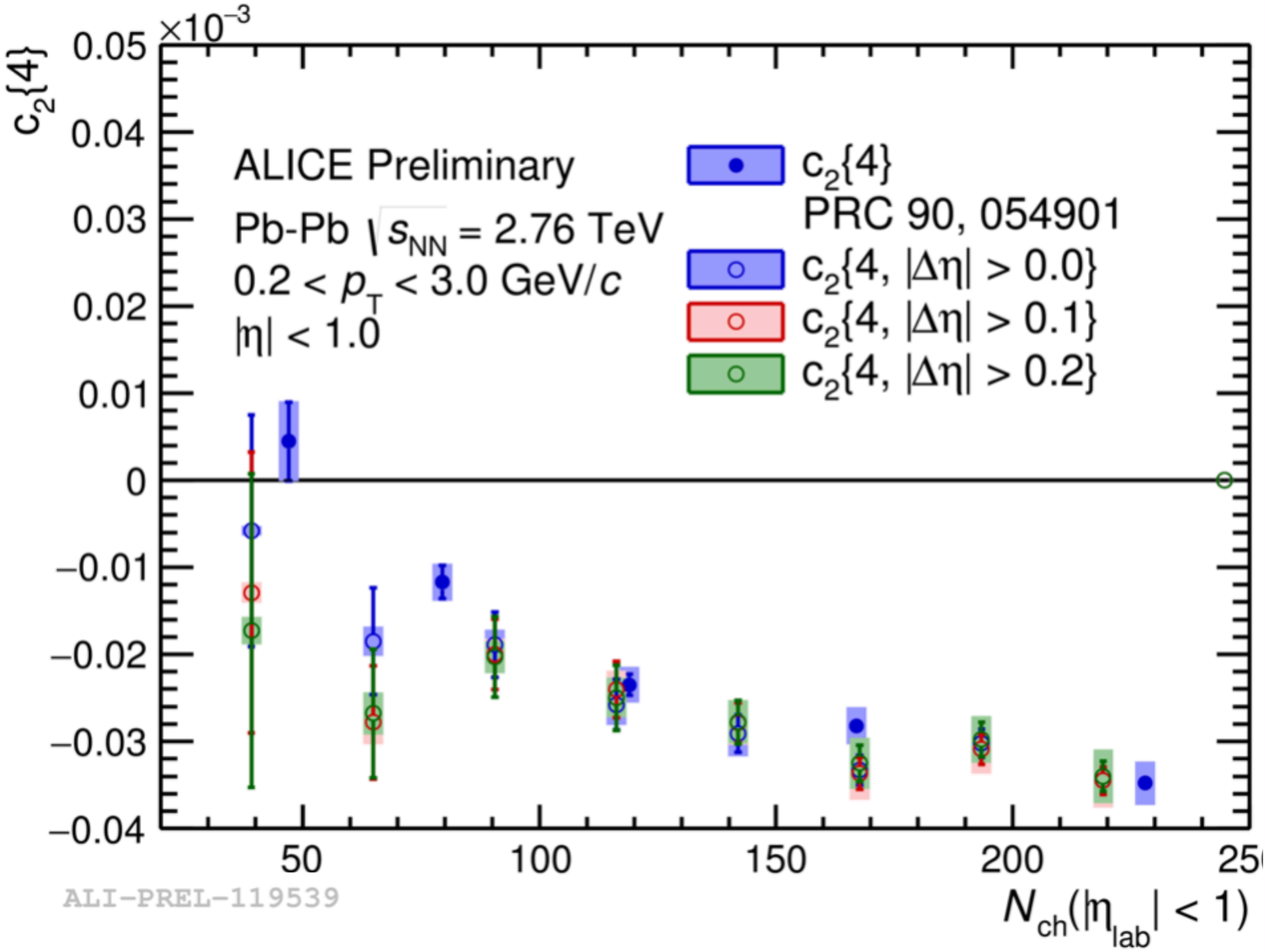
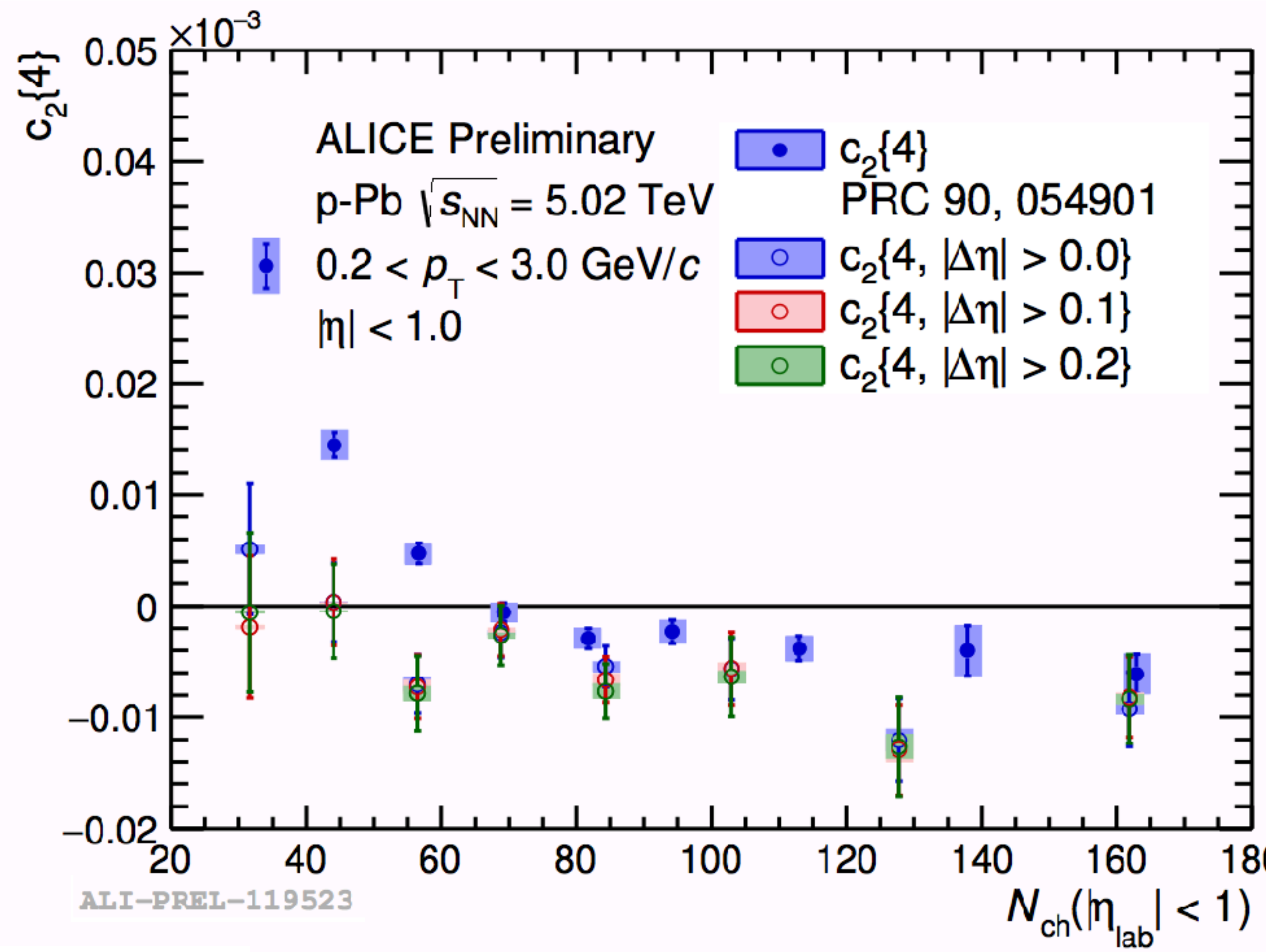
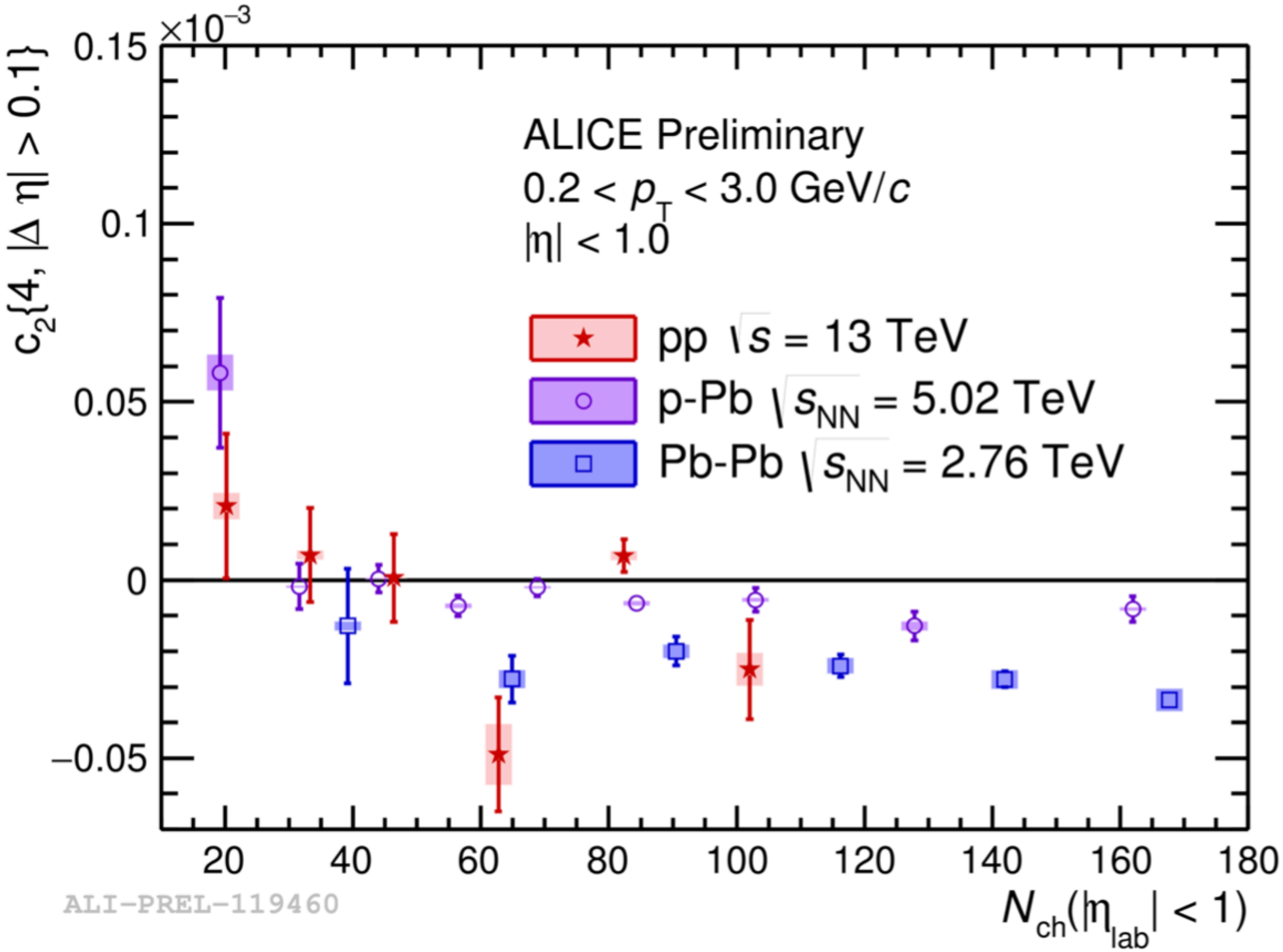




- $c_2\{4\}$ crossing $N_{ch} \approx 70$
- Mild non flow removed for low multiplicities

- $c_2\{4\}$ crossing $N_{ch} \approx 70$
- η gap suppresses non flow throughout

$c_2\{4,|\Delta\eta|\}$ System Comparison

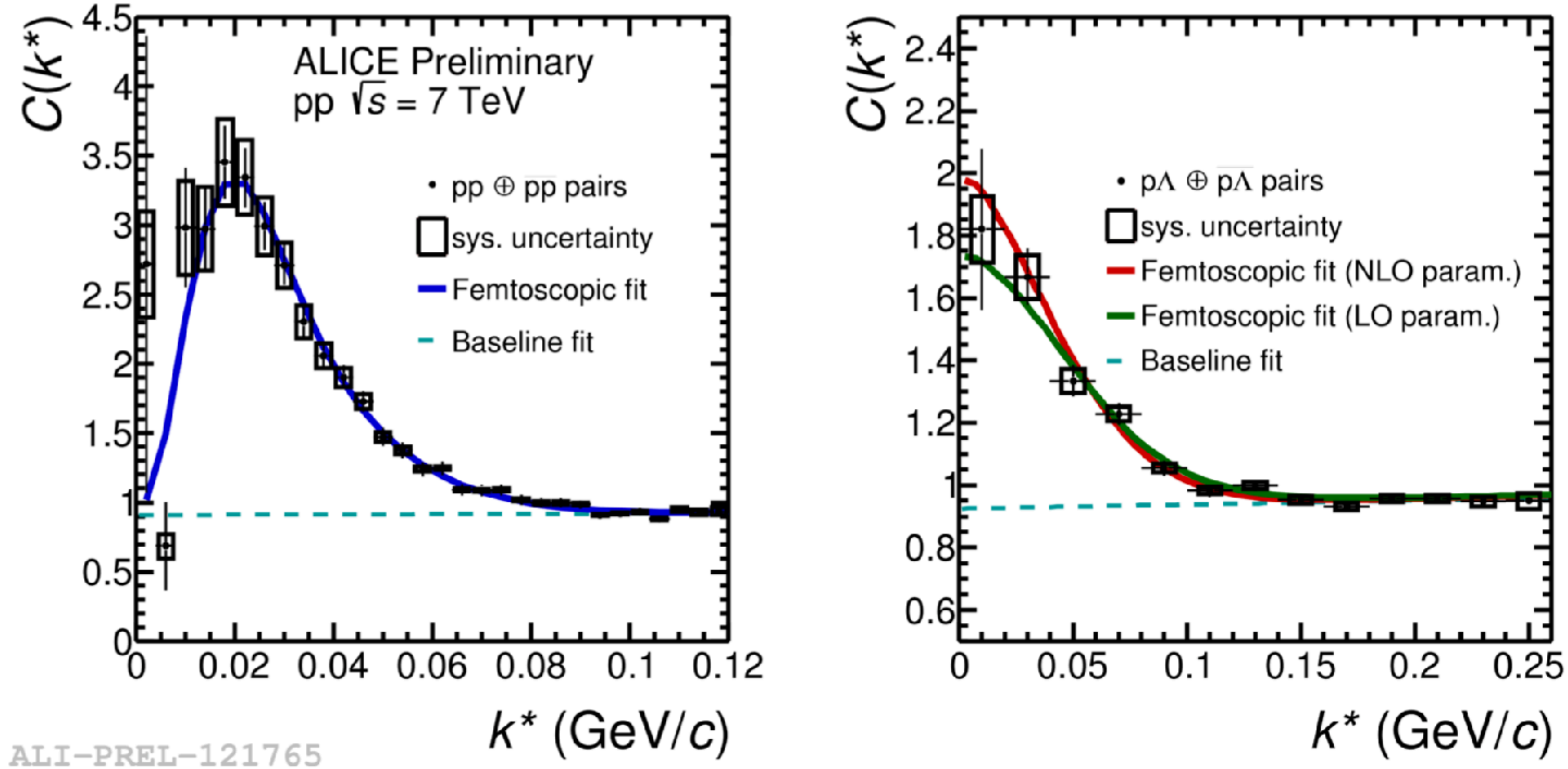


- No definite sign of $c_2\{4,|\Delta\eta|\}$ in pp collisions
- Negative $c_2\{4,|\Delta\eta|\}$ for $N_{ch} > 40$ in Pb-Pb and p-Pb

Femtoscopy

Strange Baryons.. ..in pp

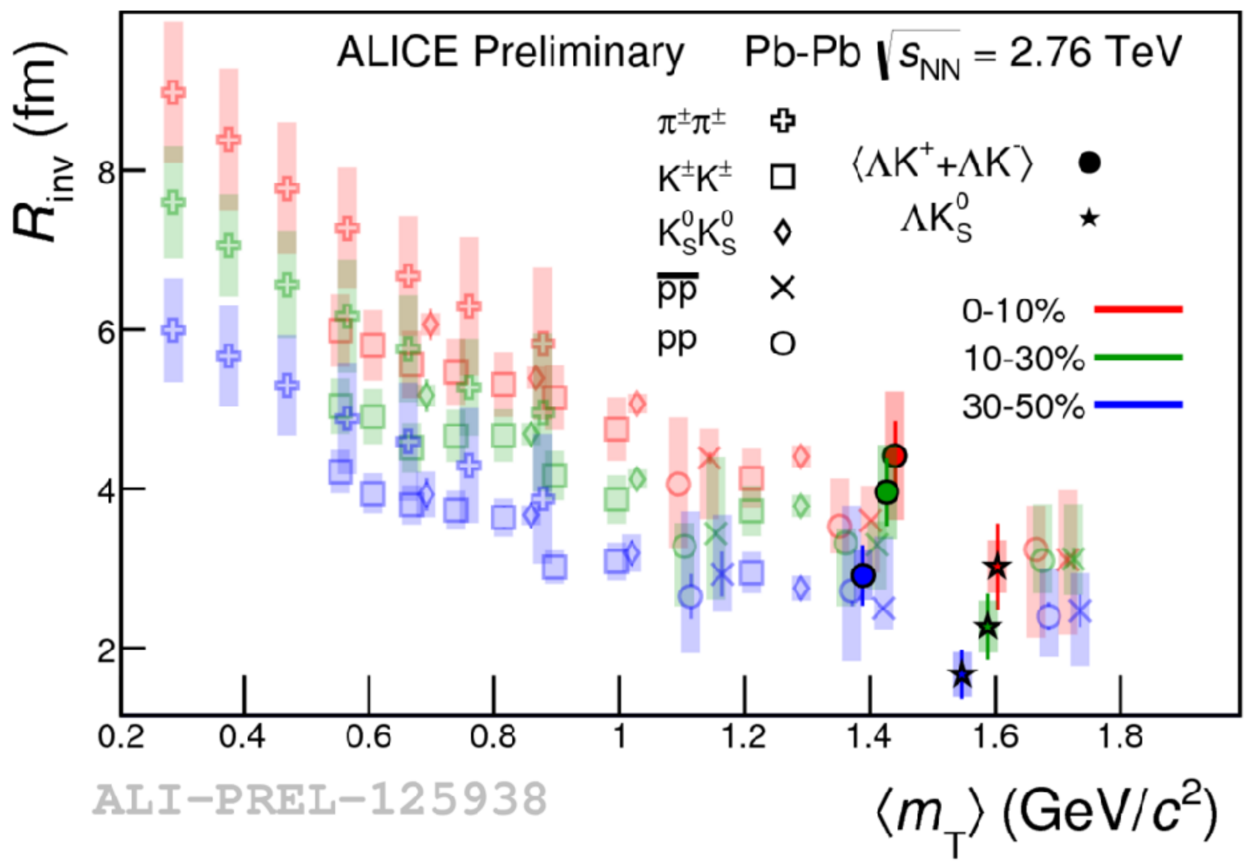
- Simultaneous fit of pp and pΛ correlations
- Aim: determine strong potentials

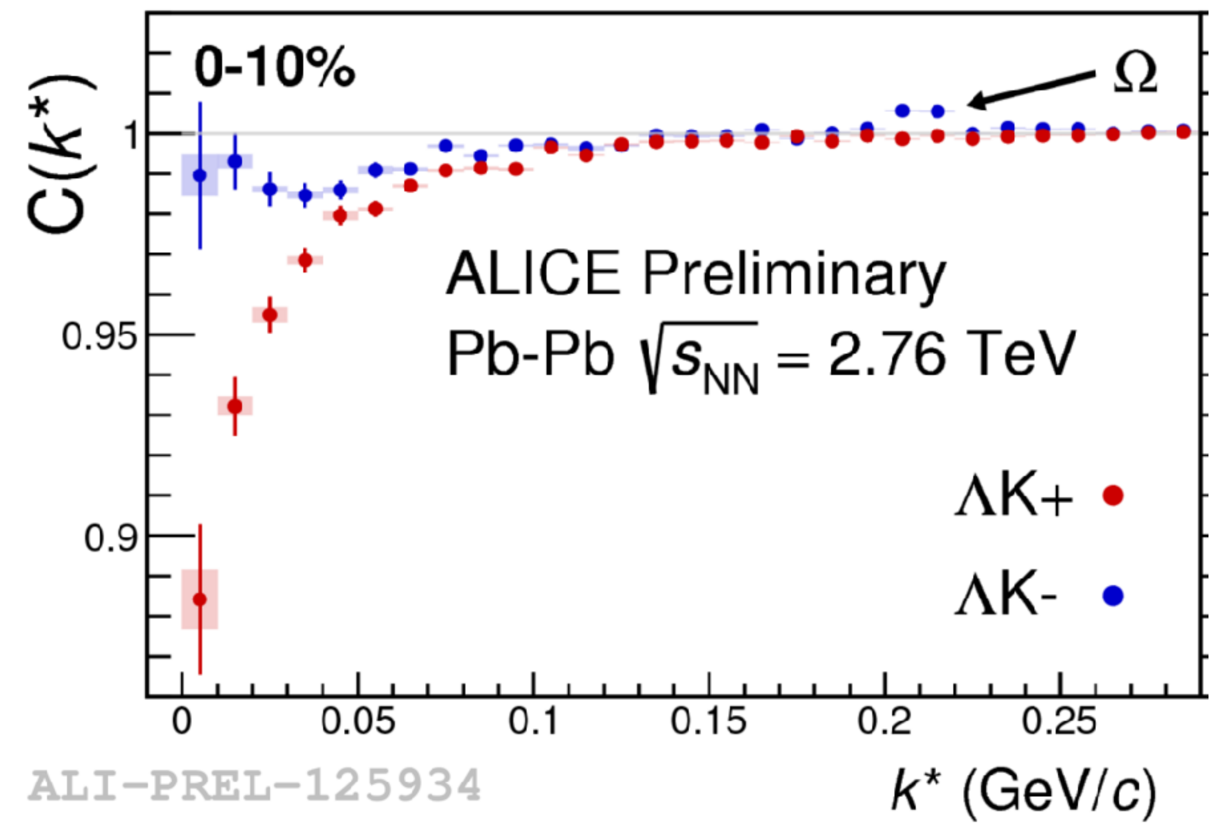


- Sensitivity to pΛ strong interaction
- Playground for lesser known systems pΞ, …

Strange Baryons.. ..in Pb-Pb

- Pairs of ΛK⁻, ΛK⁺, ΛK⁰, and charge conjugates

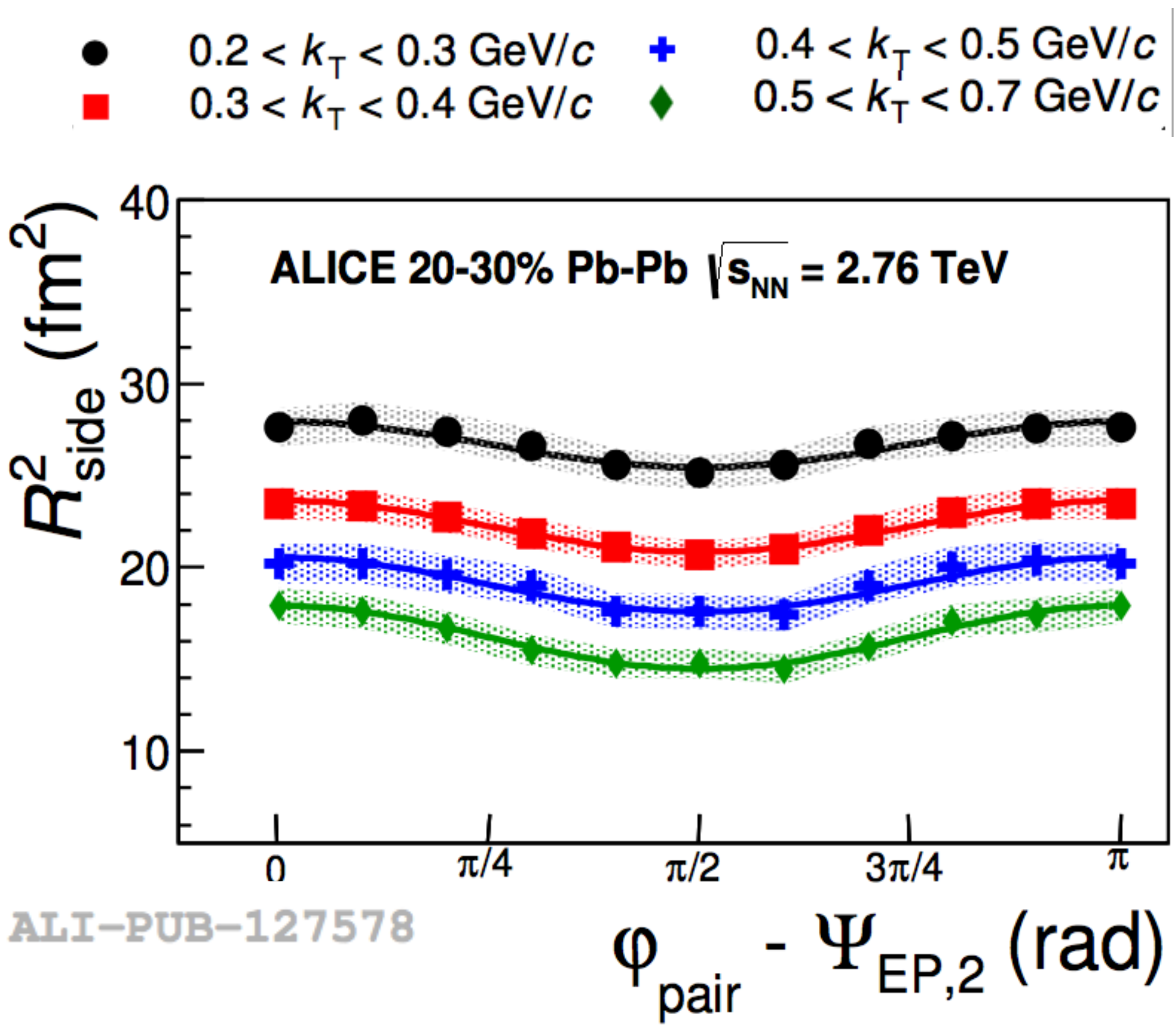


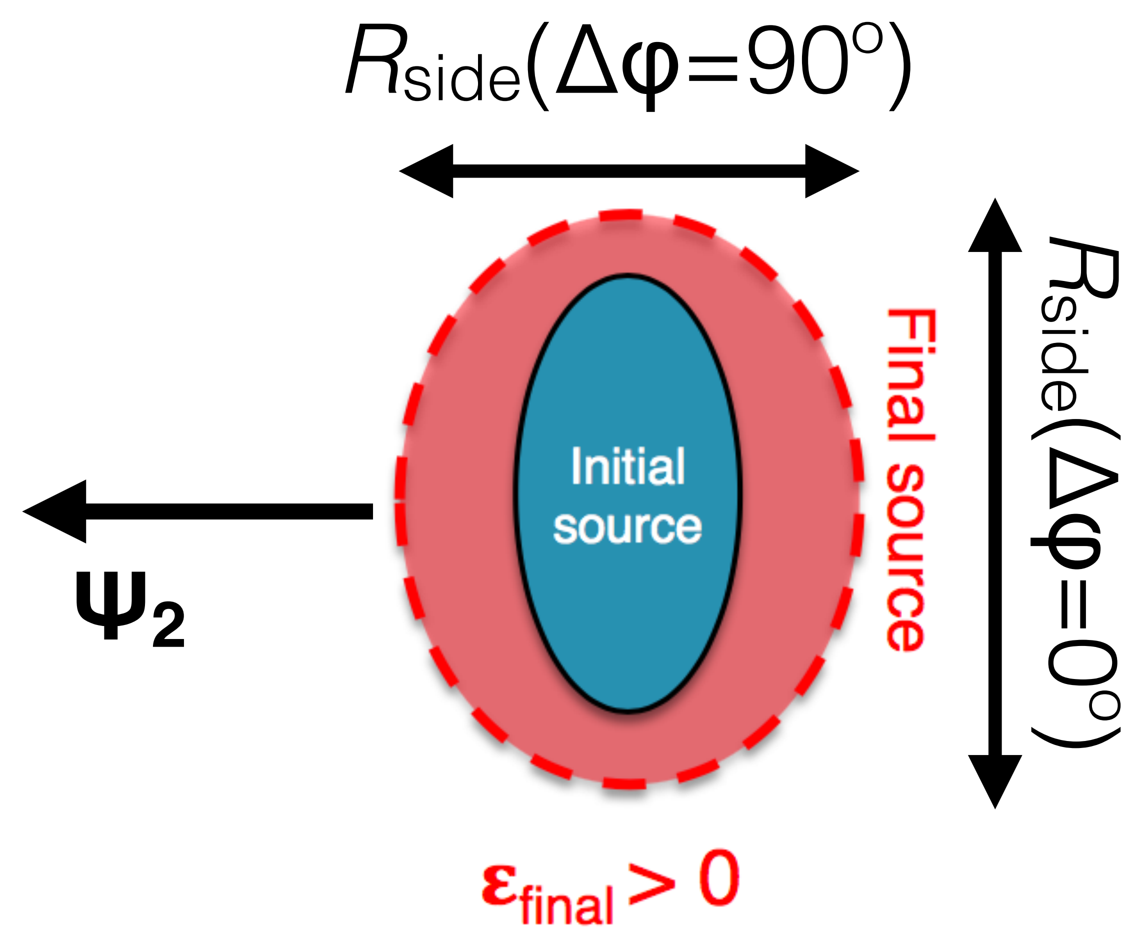


- Understanding of strong inelastic interactions
  ΛK^+ is $S = 0$, ΛK^- is $S = -2$

- Extraction of strong potentials:
  ΛK^+: $\Re f_0 = -0.69 \pm 0.27$, $\Im f_0 = 0.39 \pm 0.18$, $d_0 = 0.64 \pm 1.70$; …

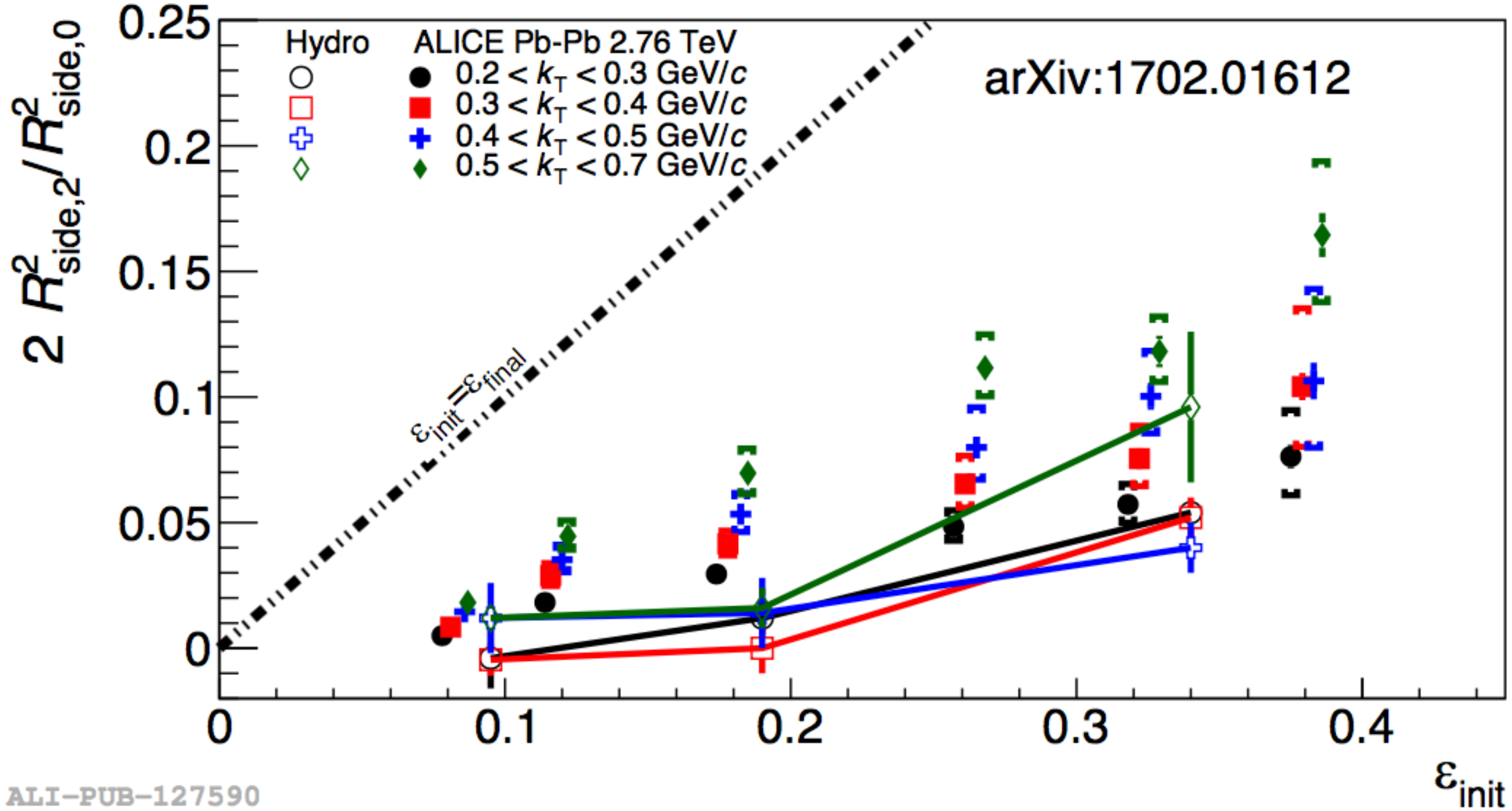
Azimuthal HBT: 2nd Order

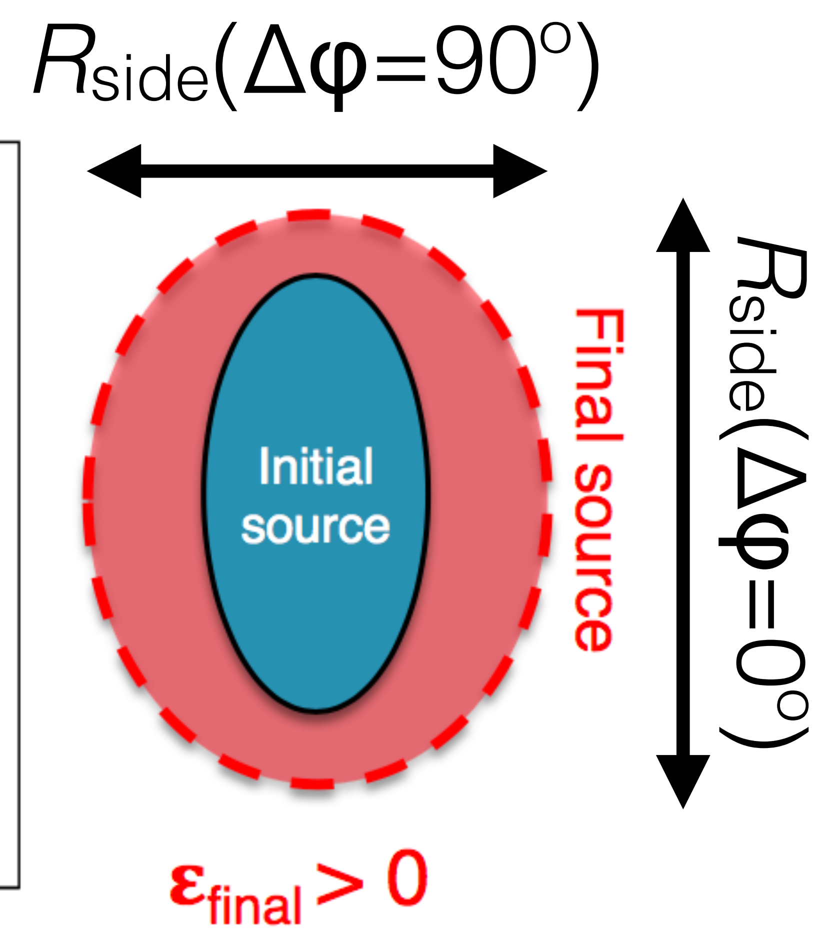




Azimuthal HBT: 2nd Order

- Source shape depends on lifetime and source dynamics

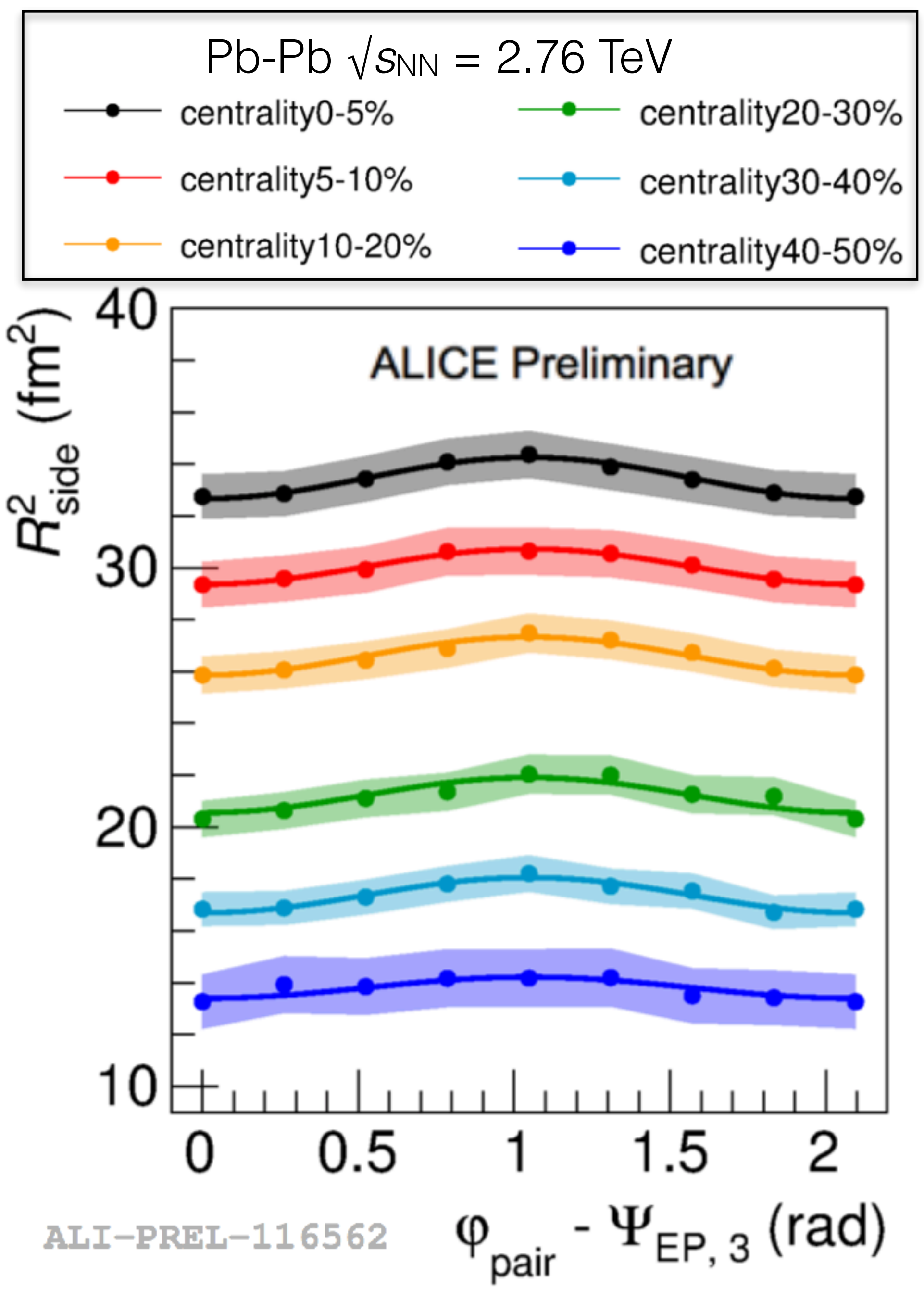


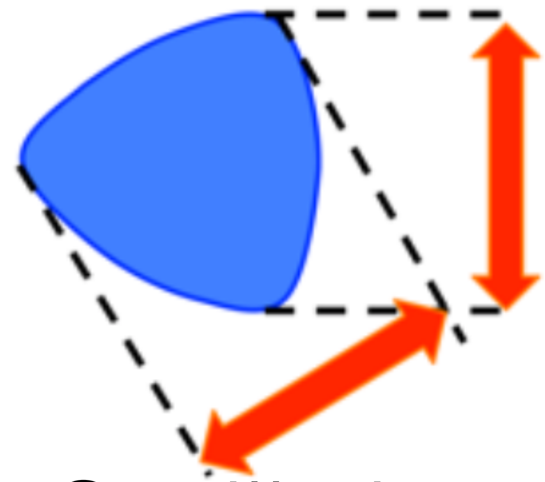


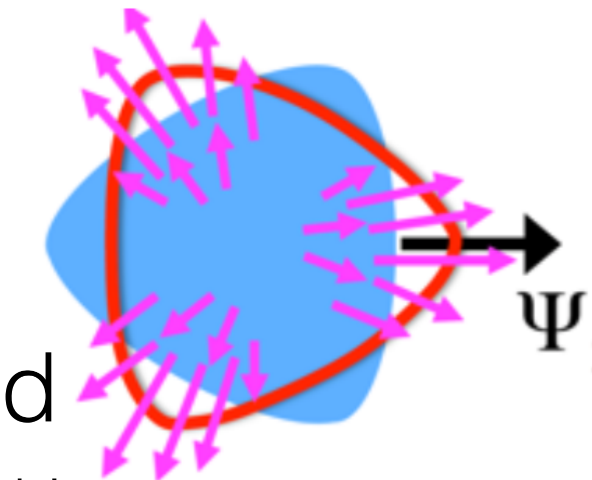
- Smaller eccentricity than at RHIC
- Still positive eccentricity
- Underestimated by hydro simulation

Azimuthal HBT: 3rd Order

- Without expansion no radii oscillations







- Oscillations introduced dynamically

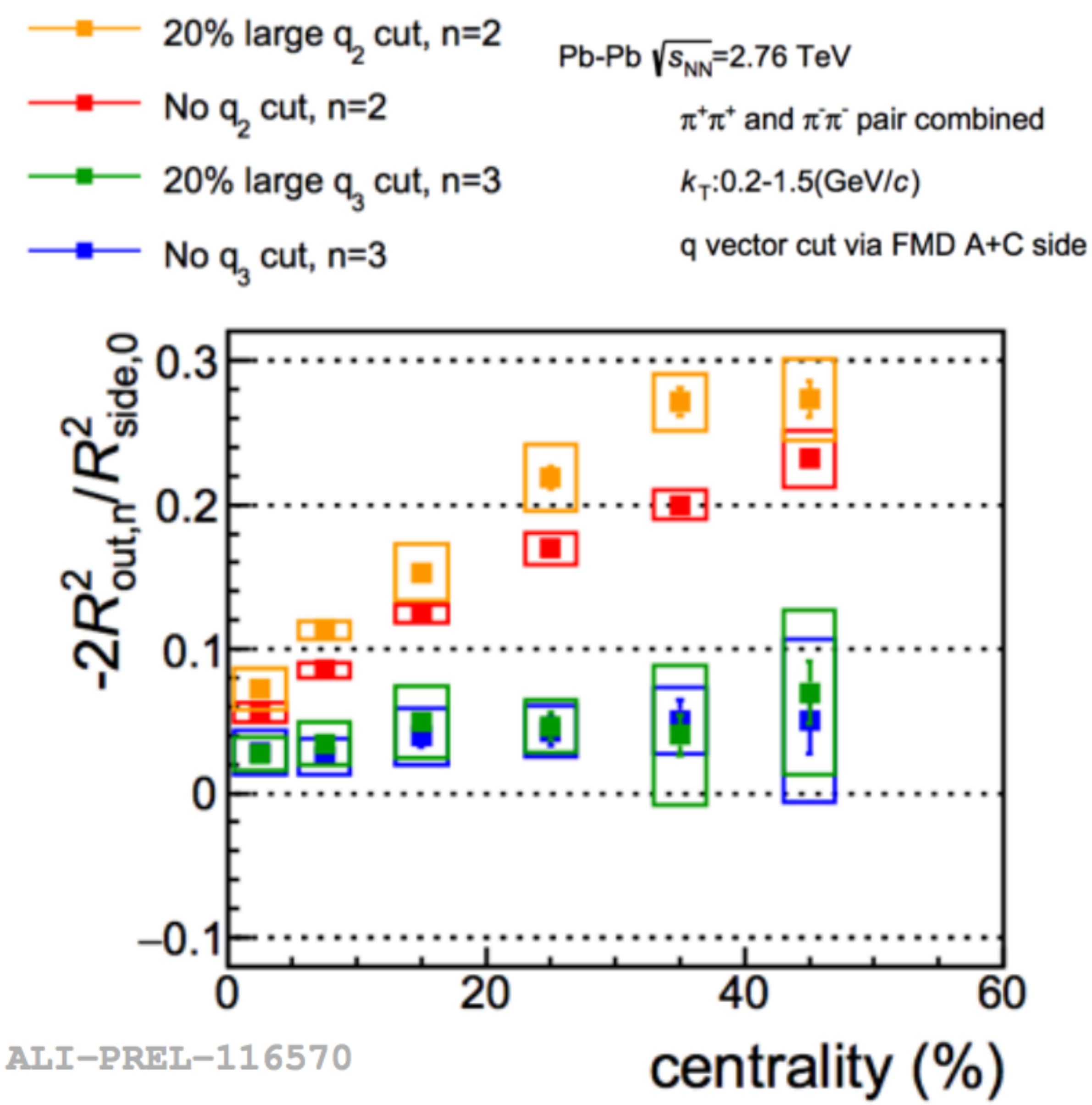
S.Voloshin, arXiv:1106.5830

  - only particles with similar velocity interact

- In phase oscillations observed
  - Confirms spatial origin of v_3
  - Qualitative agreement with hydro calculation

Azimuthal HBT: ESE

- Event shape engineering (ESE) by selection of 20% largest 2nd and 3rd order flow vectors



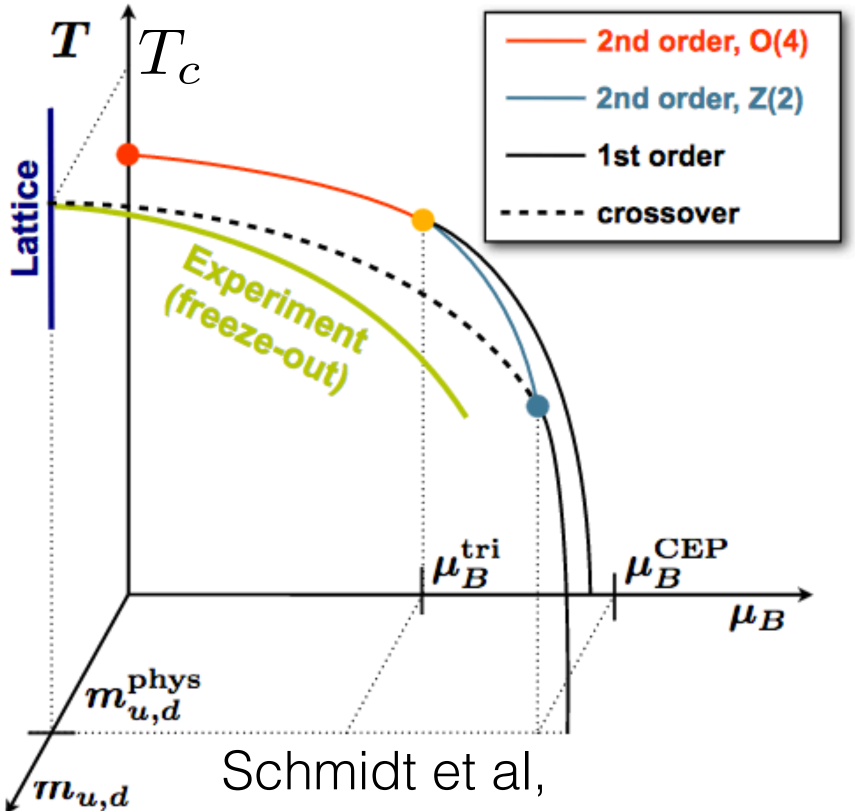
- Biased samples show
  25% larger v_2
  15% larger v_3

- More elliptical source for 2nd order ESE events: +20% R_{out} oscillation

- Minor effect on triangularity

Correlations

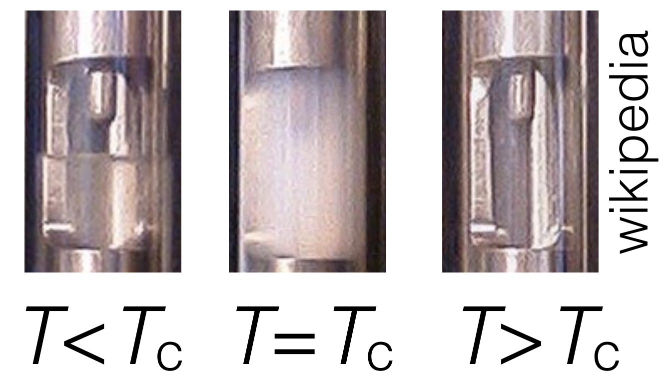
Net Baryon Fluctuations



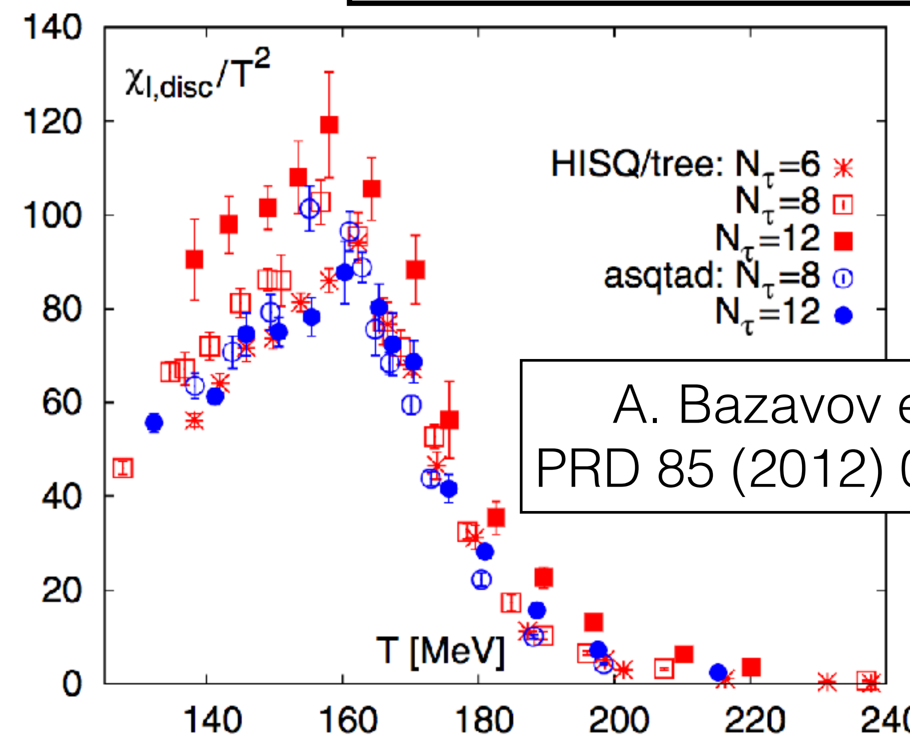
Schmidt et al, arXiv:1212.4278

- Match lattice transition temperature to experimental freeze-out

- Critical fluctuations as signal of phase transition



- Chiral susceptibility measures chiral transition; diverges at pseudocritical temperature T_c



A. Bazavov et al
PRD 85 (2012) 054503

Net Baryon Fluctuations

- Lattice: susceptibilities as derivative of partition fct.

$$\left(VT^3\right)\cdot \chi_{ijk}^{BQS}(T) = \left(\partial^{i+j+k} \ln Z(T,\mu_B,\mu_Q,\mu_S)\right) \Big/ \left(\partial\hat{\mu}_B^i \partial\hat{\mu}_Q^j \partial\hat{\mu}_S^k\right)$$

arXiv:1212.4278

- Thermal, grand canonical system in **fixed volume V**

$$\hat{\chi}_2^B = \frac{\left\langle \Delta N_B^2 \right\rangle - \left\langle \Delta N_B \right\rangle^2}{VT^3} = \frac{\kappa_2\left(\Delta N_B\right)}{VT^3} \quad \rightarrow \quad \frac{\hat{\chi}_4^B}{\hat{\chi}_2^B} = \frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)}$$

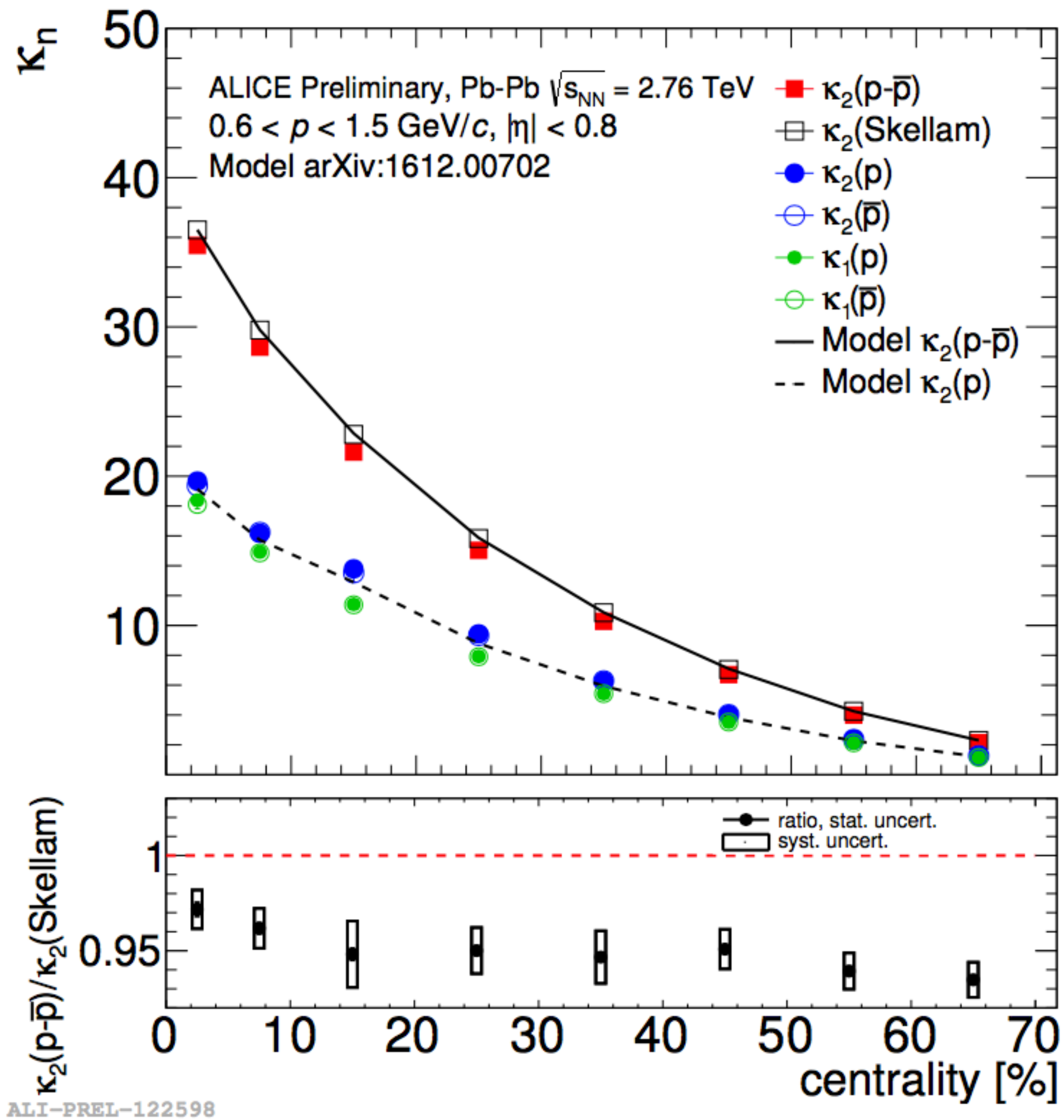
- In experiments, volume fluctuates

$$\hat{\chi}_n^B \neq \frac{\kappa_n\left(\Delta N_B\right)}{VT^3}$$

Braun Munzinger et al,
arXiv: 1612.00702

- Solution: model participant fluctuations

Modeling Volume Fluc.



- Input to model:
  $\kappa_1(p)$, $\kappa_1(\bar{p})$
  centrality procedure

Braun Munzinger et al, arXiv: 1612.00702

- Output:

$$\kappa_2(N_B - N_{\overline{B}}) = \langle N_w \rangle \kappa_2(n_B - n_{\overline{B}}) + \langle n_B - n_{\overline{B}} \rangle^2 \kappa_2(N_w)$$

zero

$$\kappa_2(N_B) = \langle N_w \rangle \kappa_2(n_B) + \langle n_B \rangle^2 \kappa_2(N_w)$$

LHC: net-particles not affected by N_w fluctuations

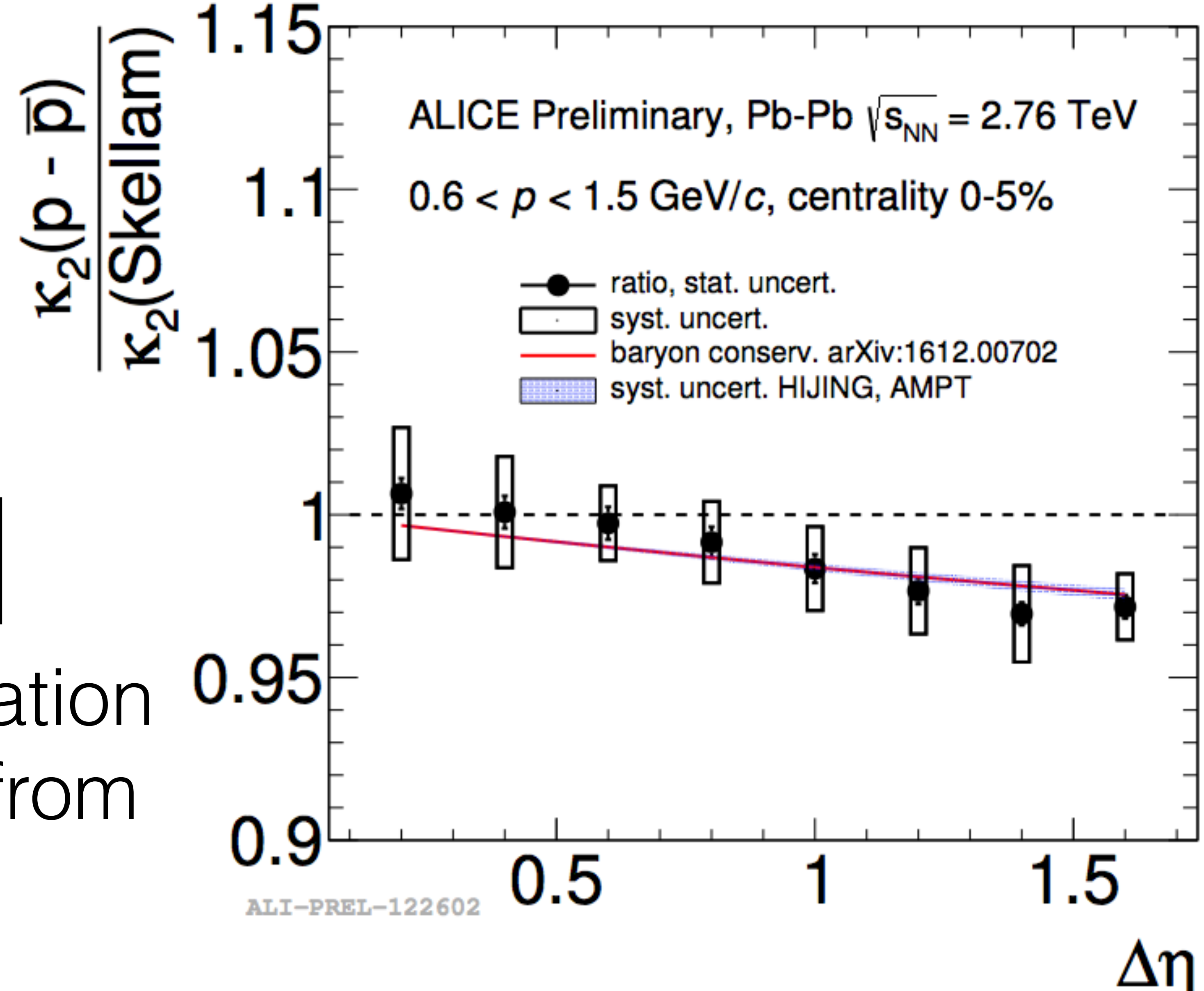
Global Baryon Conservation

- Contribution like:

$$\frac{\kappa_2(p-\bar{p})}{\kappa_2(Skellam)} = 1-\alpha$$

$$\alpha = \frac{\langle p \rangle^{measured}}{\langle B \rangle^{4\pi}}$$

Braun Munzinger et al, arXiv: 1612.00702



- Global baryon conservation accounts for deviation from Skellam baseline
  - Effects under control, higher moments on their way

Summary: Femtoscopy / Correlations

- Femto analyses with strange baryons determine strong potentials
- Azimuthal HBT determines source dynamics and shows how triangularity evolves
- First measurement of 2^{nd} moment net-protons at LHC, volume fluctuations & baryon conservation important, higher moments will match experiment & lattice

Summary: Flow/Collectivity

- $\sqrt{s_{NN}}$ dependence of v_n measurements probes temperature dependence of η/s
- Mass ordering of identified particle v_n for p_T < 2 GeV/*c;* Meson / baryon grouping for p_T > 2.5 GeV/*c*
- Smart correlation coefficients particularly sensitive to initial state and temperature dependence of η/s

➡ New data puts stringent constraints on initial state & $\eta/s(T)$

! New cumulant measure suppresses non flow and exhibits clear sign of collectivity in p-Pb

Backup

Flow: Event Plane Bias

PRC87, 044907 (2013)

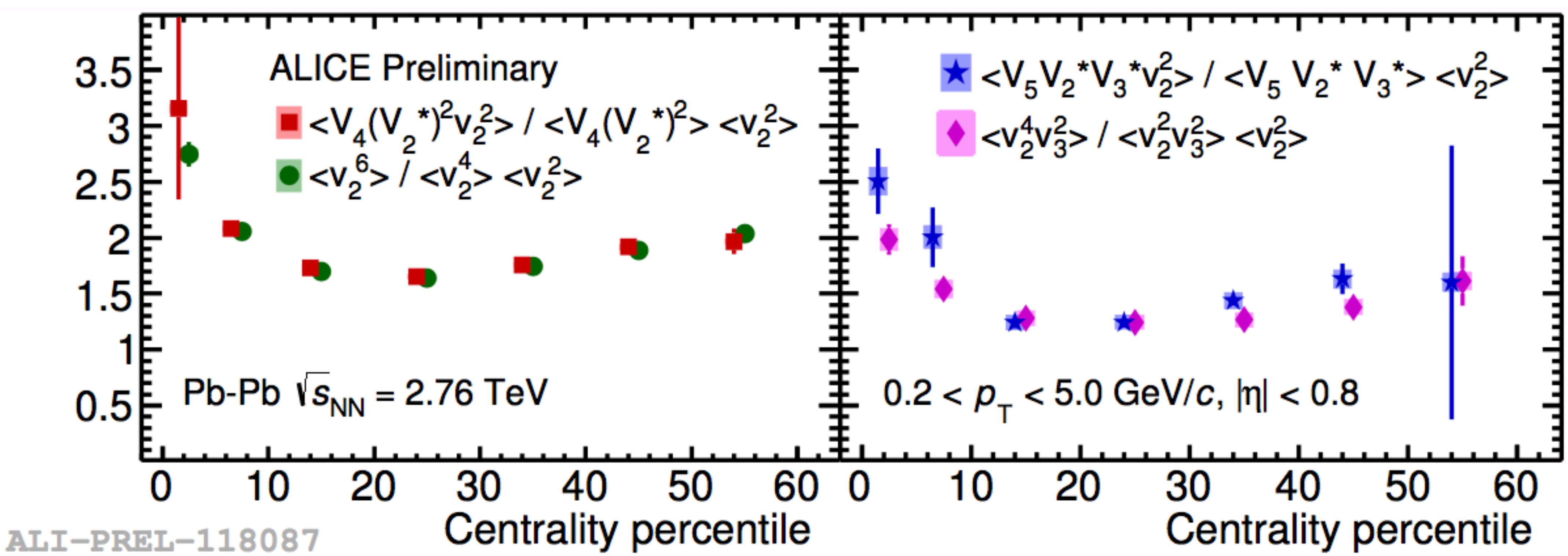
- Event plane measures sth between $\langle v_n \rangle$ and $\sqrt{\langle v_n^2 \rangle}$ depending on resolution of detector
  - Few percent on v_2
  - 10% on v_3 and higher harmonics
  - Factor 2 for correlations between v_n

Uncorrelated linear and non-linear response

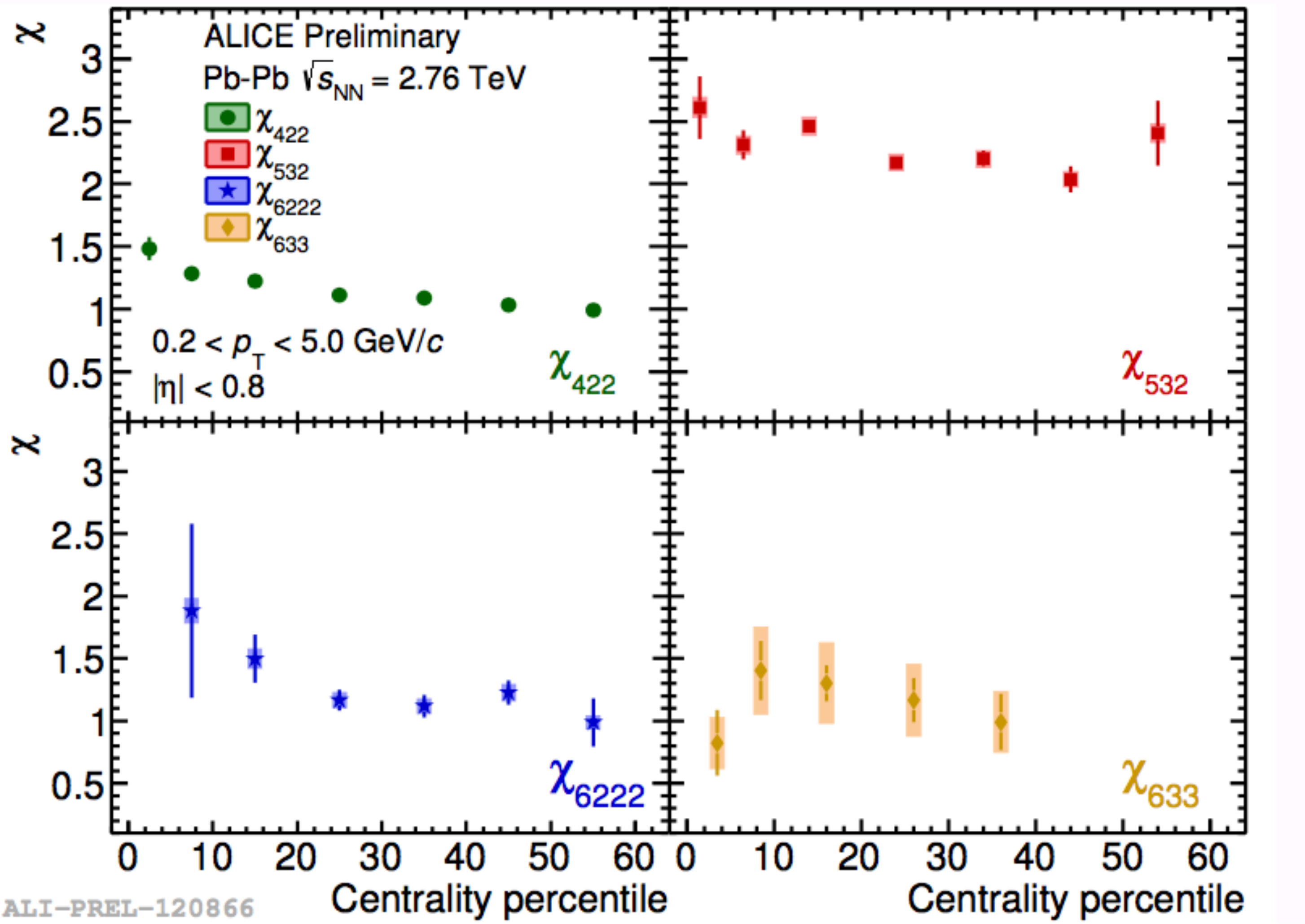
- If linear and non-linear are uncorrelated, the following holds:

L. Yan et al, PLB744 (2015) 82

$$\frac{\langle V_4 (V_2^*)^2 v_2^2 \rangle}{\langle V_4 (V_2^*)^2 \rangle \langle v_2^2 \rangle} = \frac{\langle v_2^6 \rangle}{\langle v_2^4 \rangle \langle v_2^2 \rangle} \qquad \frac{\langle V_5 V_2^* V_3^* v_2^2 \rangle}{\langle V_5 V_2^* V_3^* \rangle \langle v_2^2 \rangle} = \frac{\langle v_2^4 v_3^2 \rangle}{\langle v_2^2 v_3^2 \rangle \langle v_2^2 \rangle}$$



Non-Linear Response Coefficient



$$V_4 = V_4^L + \chi_{422}\, v_2^2$$
$$V_5 = V_5^L + \chi_{532}\, v_2\, v_3$$
$$V_6 = V_6^L + \chi_{624}\, V_2\, V_4^L + \chi_{633}\, V_3^2 + \chi_{6222}\, V_2^3$$

$$\chi_{422} = \frac{v_{4,22}}{\sqrt{\langle v_2^4 \rangle}} \qquad \chi_{6222} = \frac{v_{6,222}}{\sqrt{\langle v_2^6 \rangle}}$$

$$\chi_{523} = \frac{v_{5,32}}{\sqrt{\langle v_2^2\, v_3^2 \rangle}} \qquad \chi_{633} = \frac{v_{6,33}}{\sqrt{\langle v_3^4 \rangle}}$$

- Constant, as naively expected