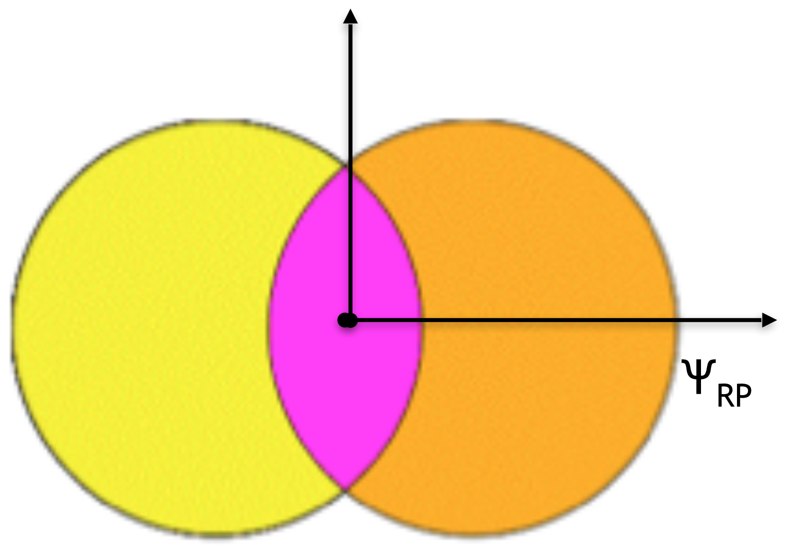
Title:	Collective effects in nuclear collisions
Speaker:	You Zhou (Niels Bohr Institute)
Performer:	Excellent Venezia 2018 Quark Matter presenters
Place:	Palazzo del Cinema
Date:	May 17th, 2018
Producer:	ALICE, ATLAS EXPERIMENT, CMS, HADES, NA61 SHINE, PHENIX, STAR

General flow pictures and methods

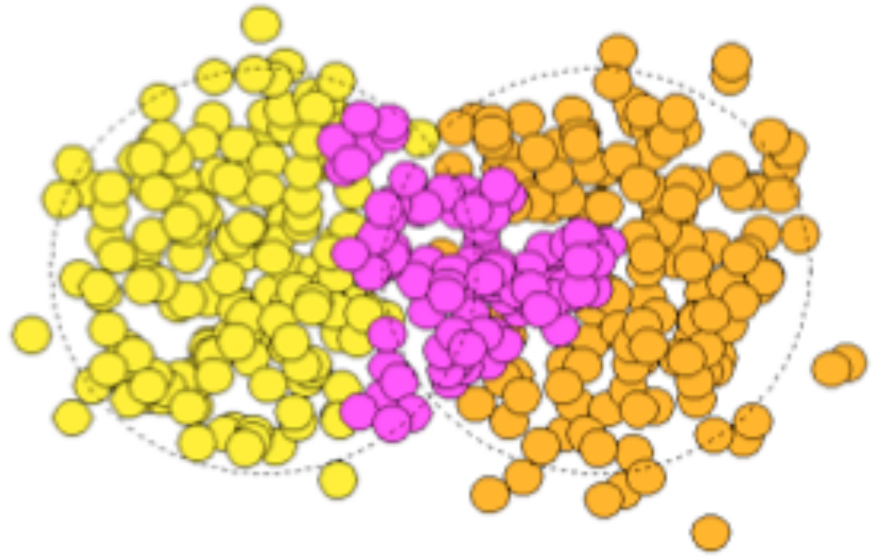
1992



$$v_2\{\Psi_{RP}\} = \langle \cos 2(\phi - \Psi_{RP}) \rangle$$

Ψ_{RP}: Reaction Plane

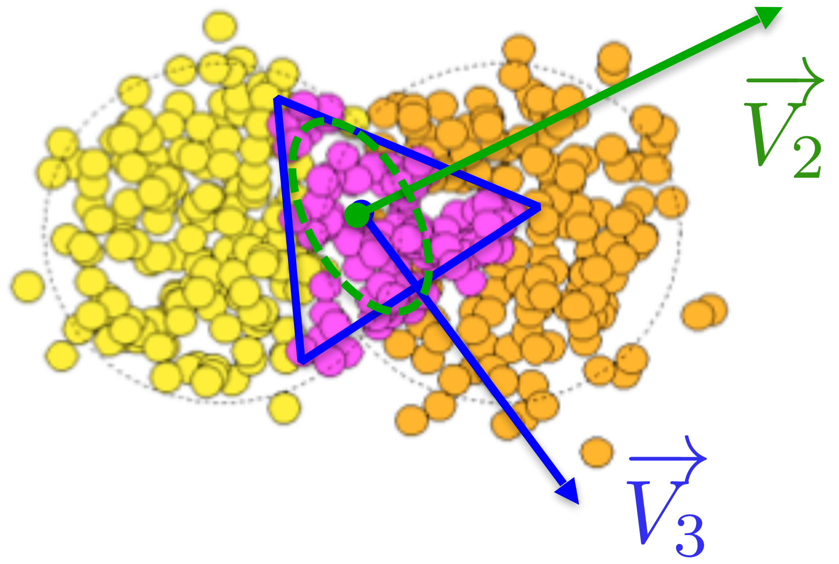
2010



$$v_n = \langle \cos n(\varphi - \Psi_n) \rangle$$

- Flow coefficient v_n
- E-by-E v_n fluctuations

2014



$$\overrightarrow{V_m} = v_m e^{-im\Psi_m}$$

$$\overrightarrow{V_n} = v_n \, e^{-in\Psi_n}$$

- de-correlations of Vn vs p_T & η
- correlations between v_n and v_m ?
- correlations between ψ_n and ψ_m ?

Event-plane (1998)

PHYSICAL REVIEW C VOLUME 58, NUMBER 3 SEPTEMBER 1998

Methods for analyzing anisotropic flow in relativistic nuclear collisions

A. M. Poskanzer[1] and S. A. Voloshin[2,*]

[1]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720*

[2]*Physikalisches Institut der Universität Heidelberg, Heidelberg, Germany*

(Received 20 May 1998)

The strategy and techniques for analyzing anisotropic flow (directed, elliptic, etc.) in relativistic nuclear collisions are presented. The emphasis is on the use of the Fourier expansion of azimuthal distributions. We present formulas relevant for this approach, and in particular, show how the event multiplicity enters into the event plane resolution. We also discuss the role of nonflow correlations and a method for introducing flow into a simulation. [S0556-2813(98)04109-0]

Q-Cumulant (2010)

PHYSICAL REVIEW C **83**, 044913 (2011)

Flow analysis with cumulants: Direct calculations

Ante Bilandzic,[1,2] Raimond Snellings,[2] and Sergei Voloshin[3]

[1]*Nikhef, Science Park 105, NL-1098 XG Amsterdam, The Netherlands*

[2]*Utrecht University, P.O. Box 80000, NL-3508 TA Utrecht, The Netherlands*

[3]*Wayne State University, 666 West Hancock Street, Detroit, Michigan 48201, USA*

(Received 6 October 2010; published 26 April 2011)

Generic framework (2014)

PHYSICAL REVIEW C **89**, 064904 (2014)

Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations

Ante Bilandzic,[1] Christian Holm Christensen,[1] Kristjan Gulbrandsen,[1] Alexander Hansen,[1] and You Zhou[2,3]

[1]*Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark*

[2]*Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*

[3]*Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands*

(Received 20 December 2013; revised manuscript received 6 May 2014; published 9 June 2014)

Studying flow in nuclear collisions

Collective effects in nuclear collisions

v_n

- Charged hadron v_n vs centrality, p_T, η
- $v_n(p_T)$ of $\pi^{\pm}$, $K^{\pm}$, K_S^0, $p(\bar{p})$, Λ, Φ, Ξ, Ω, ^{3}He, D, J/Ψ

V_n correlations

- Differential non-linear flow mode with $\pi^{\pm}$, $K^{\pm}$, $p(\bar{p})$
- Symmetric cumulants in Pb-Pb, Xe-Xe
- $\langle p_T \rangle$ & v_n correlations

V_n fluctuations

- E-By-E v_n distribution and/or $c_n\{m\}$ -> $p(v_n)$
- De-correlations of V_n vs η

New ideas

- Power-spectra
- Deep Learning

Studying flow in nuclear collisions

v_n

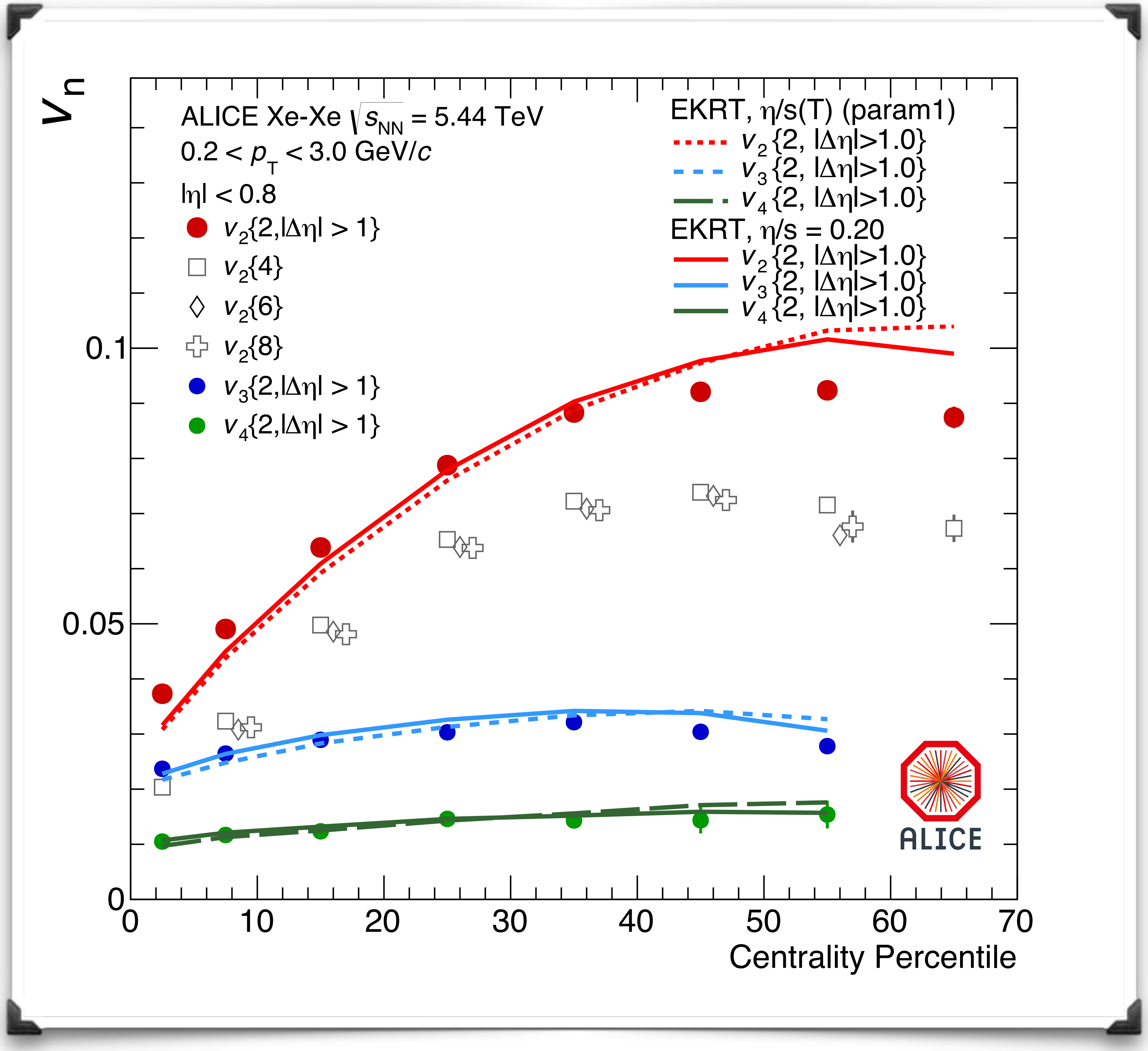
- Charged hadron v_n vs centrality, p_T, η
- $v_n(p_T)$ of $\pi^{\pm}$, $K^{\pm}$, K_S^0, $p(\bar{p})$, Λ, Φ, Ξ, Ω, ^3He, D, J/Ψ

Collective effects in nuclear collisions

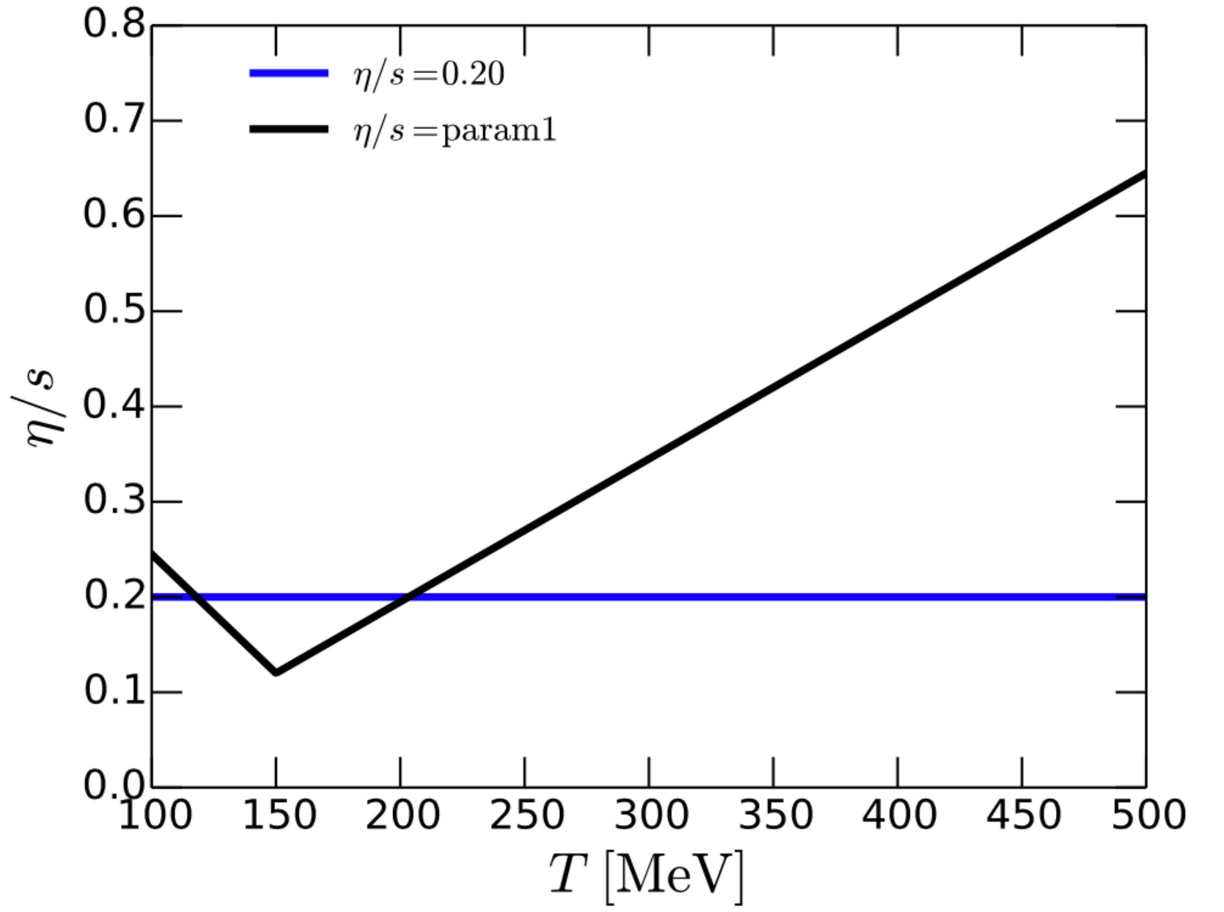
New Systems! Flow in Xe-Xe collisions

ALICE, arXiv:1805.01832

Talk: H. Niemi, May 16th

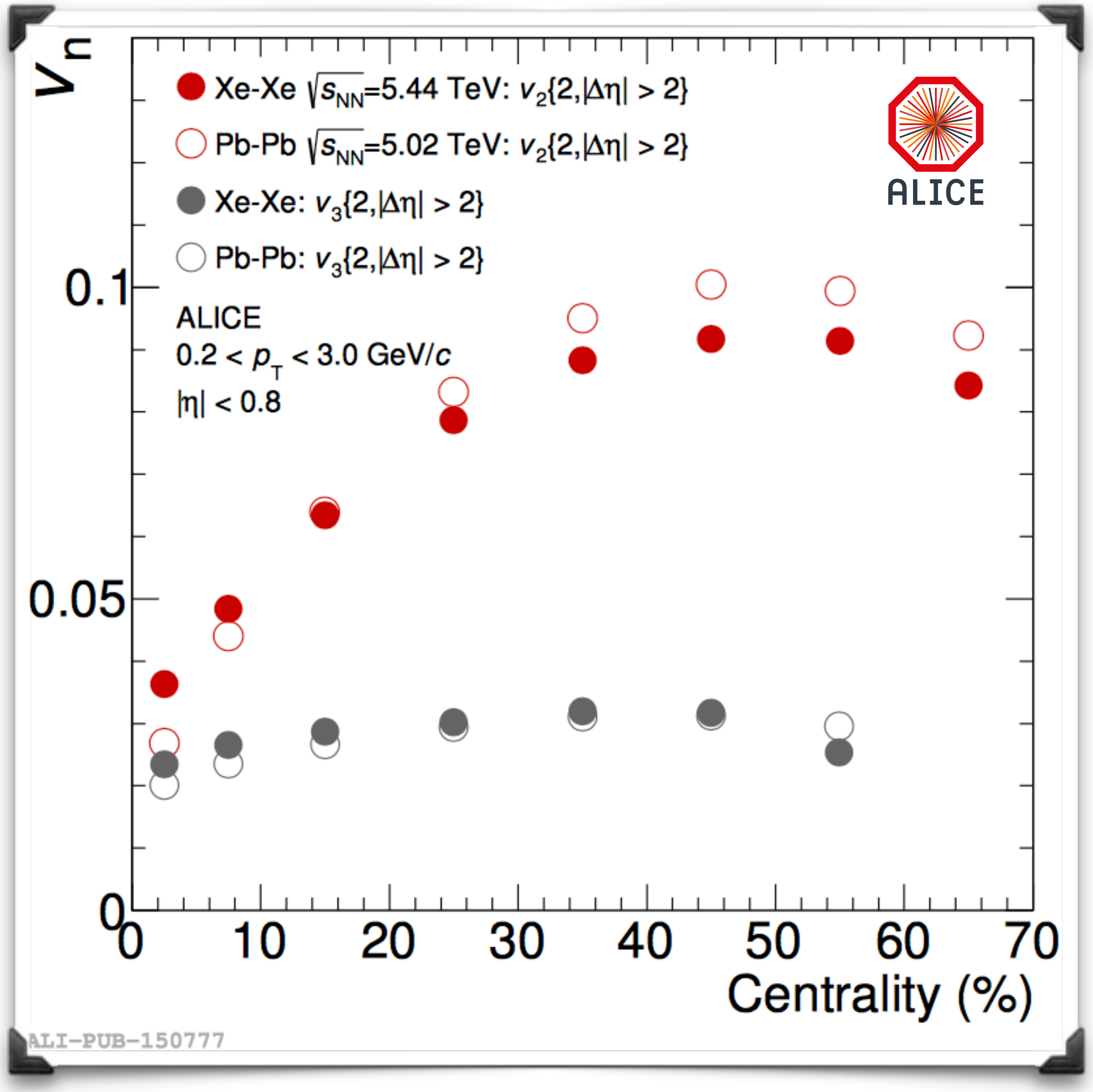


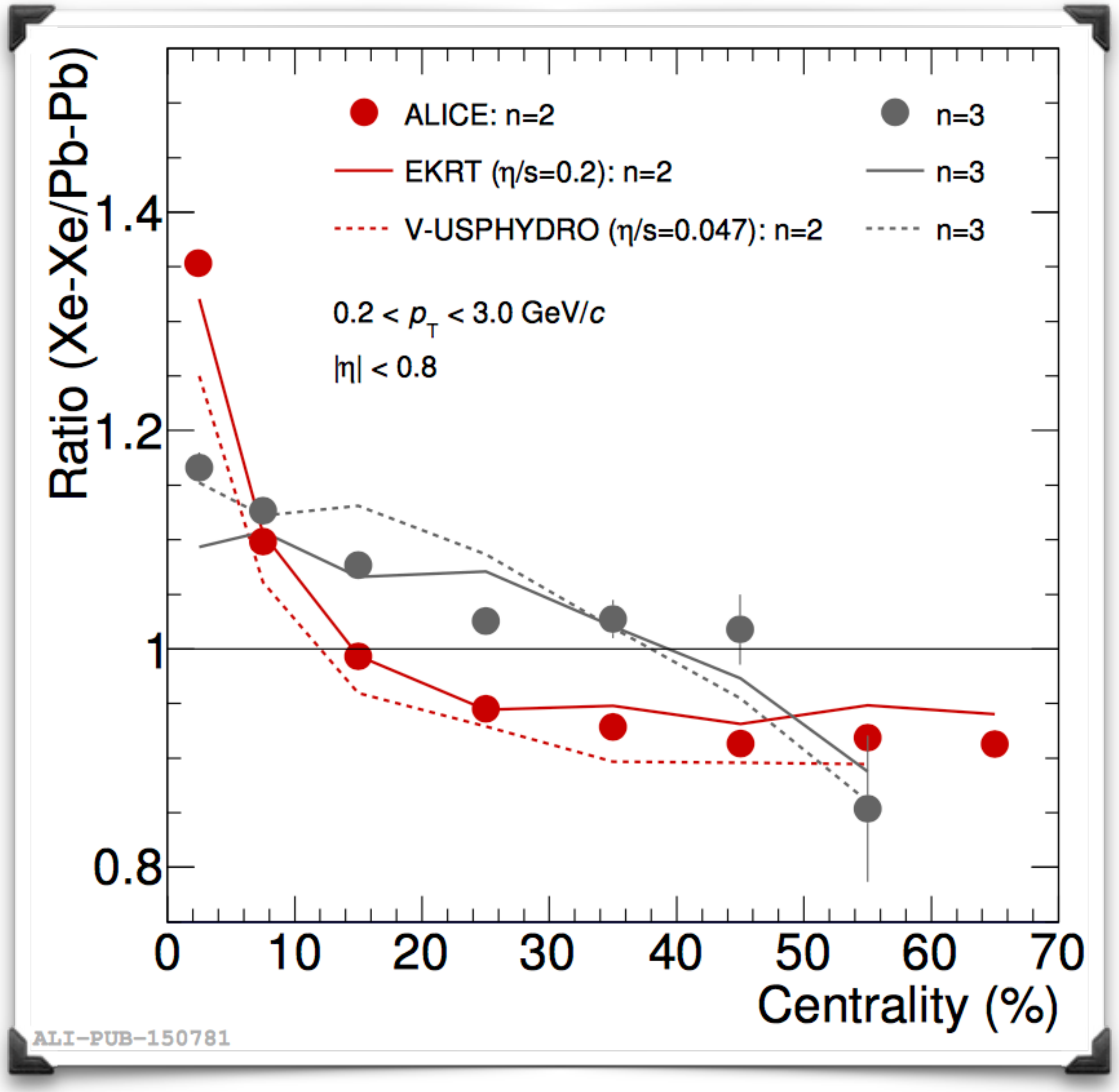
- **First measurement** of v_2, v_3 and v_4 with 2- and multi-particle cumulants in Xe-Xe collisions at 5.44 TeV
  - precious opportunity to examine hydrodynamic model (constrain the initial state models & transport properties)
  - various initial state models have or will be examined
    - EKRT, TRENTo, MC-KLN, MC-Glauber (nucleon, quark) (✔)
    - IP-Glasma, AMPT-IC (?)



K.J. Eskola et al, PRC97, 034911 (2018)

Flow in Xe-Xe and Pb-Pb





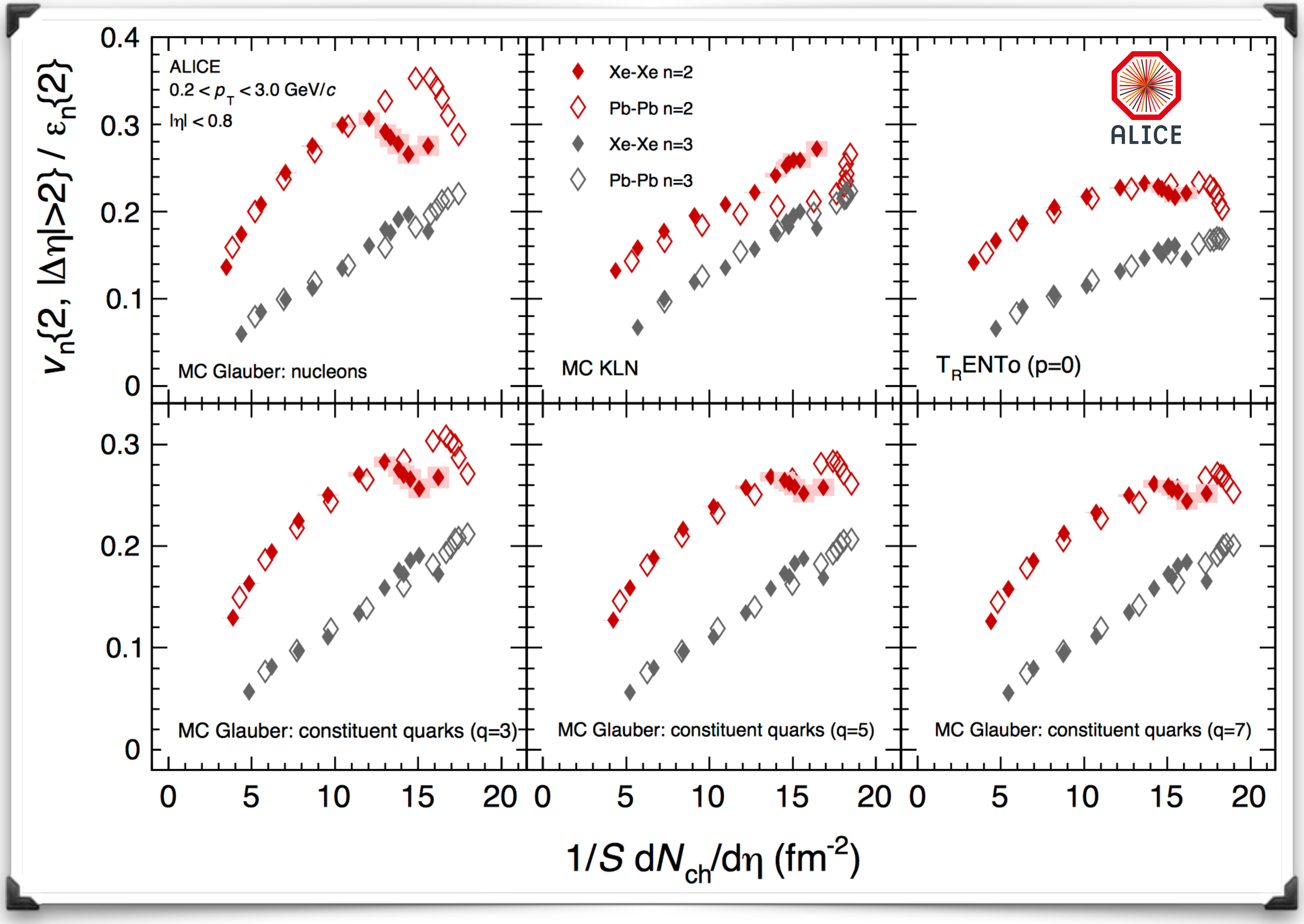
ALICE, arXiv:1805.01832

K.J. Eskola et al, PRC97, 034911 (2018)

G. Giacalone et al., PRC97, 034904 (2018)

- v_2 in Xe-Xe vs Pb-Pb
  - in central collisions, Xe-Xe v_2 is higher up to 35% → Initial geometry fluctuations with consideration of Xeon deformation
  - for non-central collisions, it is smaller in Xe-Xe by 10% → smaller radial flow and/or large viscous effects
- v_3 in Xe-Xe
  - larger in almost all centralities, decreasing from central to peripheral→larger initial geometry fluctuations in Xe-Xe

v_n/ε_n vs transverse energy density

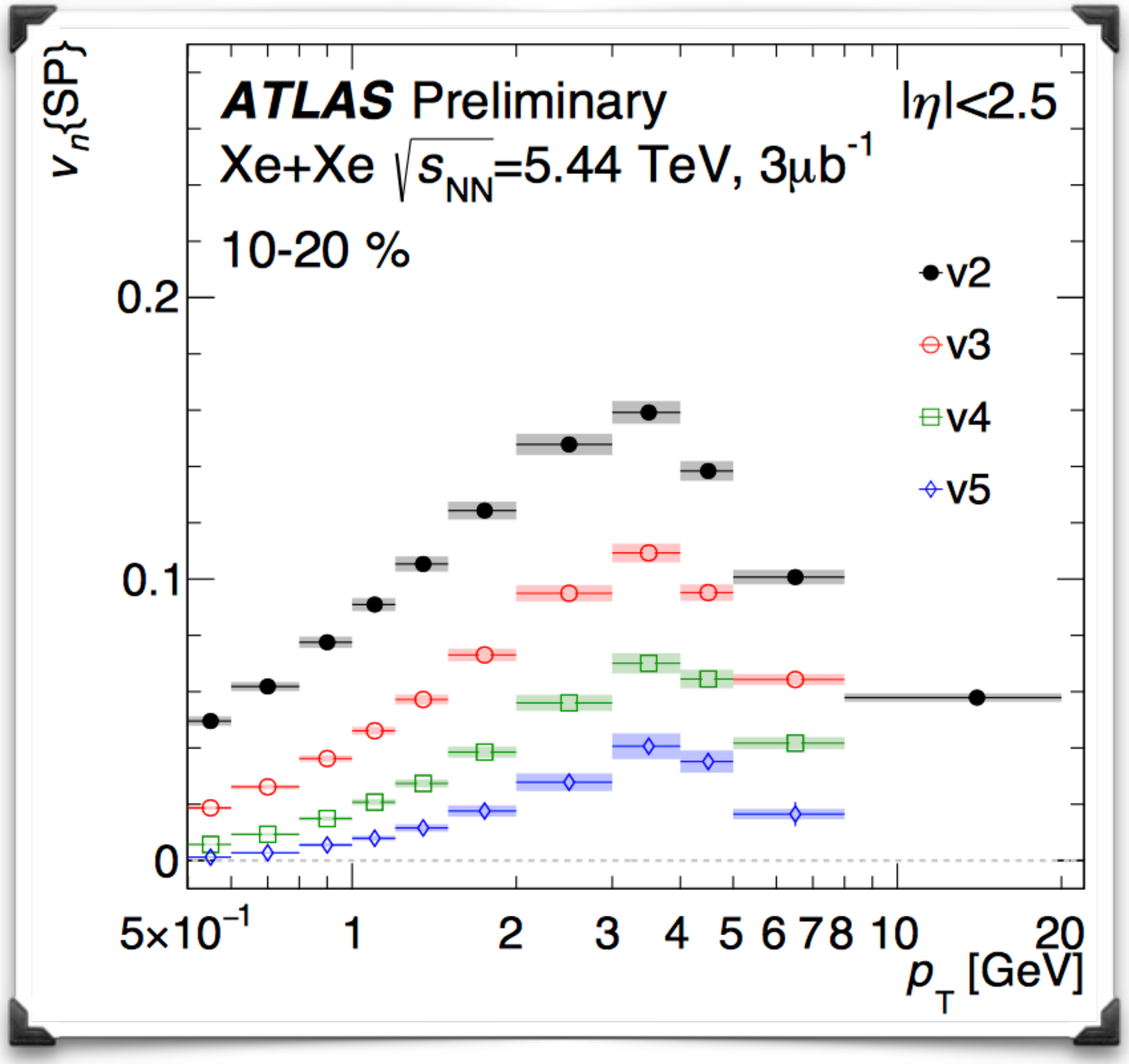


ALICE, arXiv:1805.01832

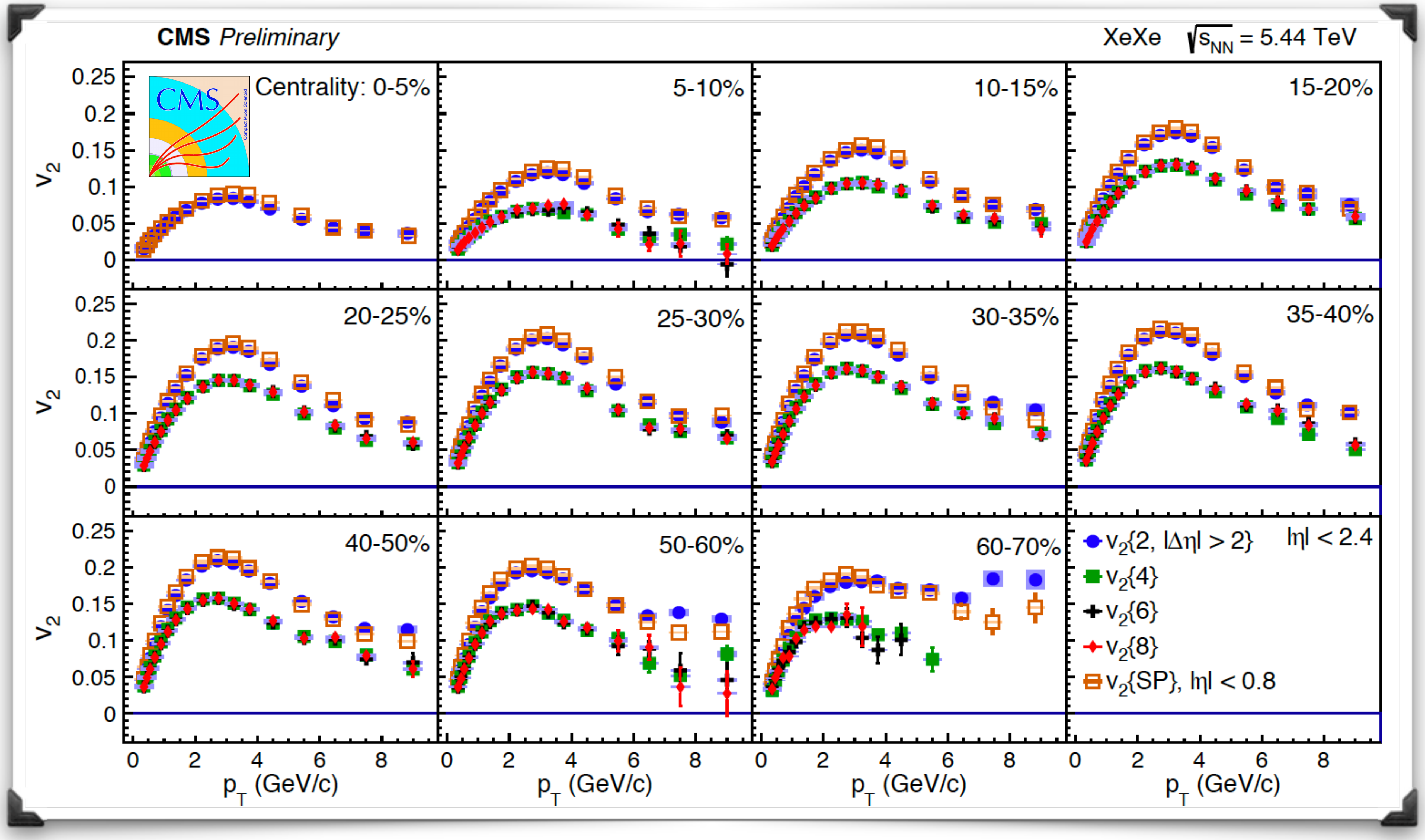
- v_2 and v_3 vs transverse energy density $(1/S)\ dN_{ch}/d\eta$
  - Hydro predicts v_n/ε_n to increase with $(1/S)\ dN_{ch}/d\eta$, same for Pb-Pb and Xe-Xe
  - Central collisions: the increasing trend of v_2/ε_2 is not observed for most IS models, deficiencies in ε_2 calculation?

ATLAS/CMS: Xe-Xe flow

Talk: T. Bold, May 15th

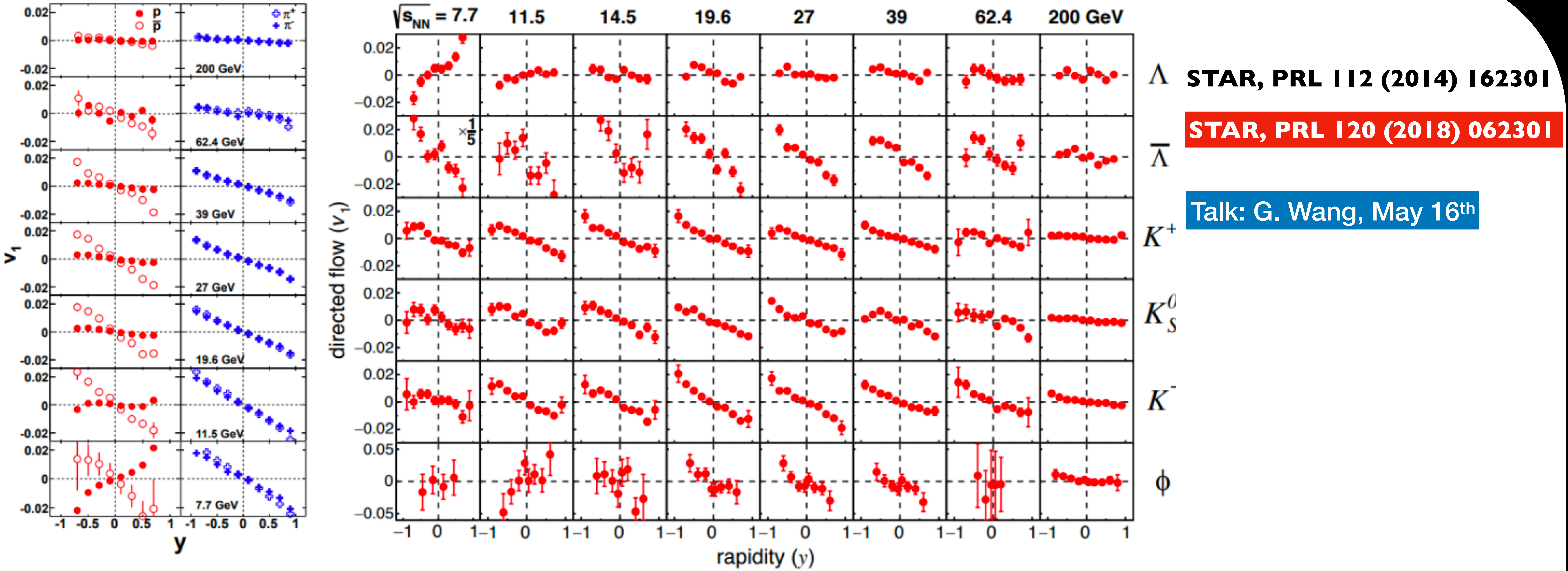


Talk: M. Stojanovic, May 15th



- Precision measurements of 2- and multi-particle cumulants
  - Similar trends of $v_n(p_T)$ are observed among LHC experiments ($v_2 > v_3 > v_4 > v_5$ and $v_2\{2\} > v_2\{4\} = v_2\{6\} = v_2\{8\}$), direct comparisons are certainly needed!
  - Further constraints on theory with "medium collisions systems"
    - e.g. Global Bayesian Analysis with Pb-Pb & Xe-Xe combined fits to extract common transport coefficients

STAR measurements of $v_1(y)$ for 10 species at 8 energies

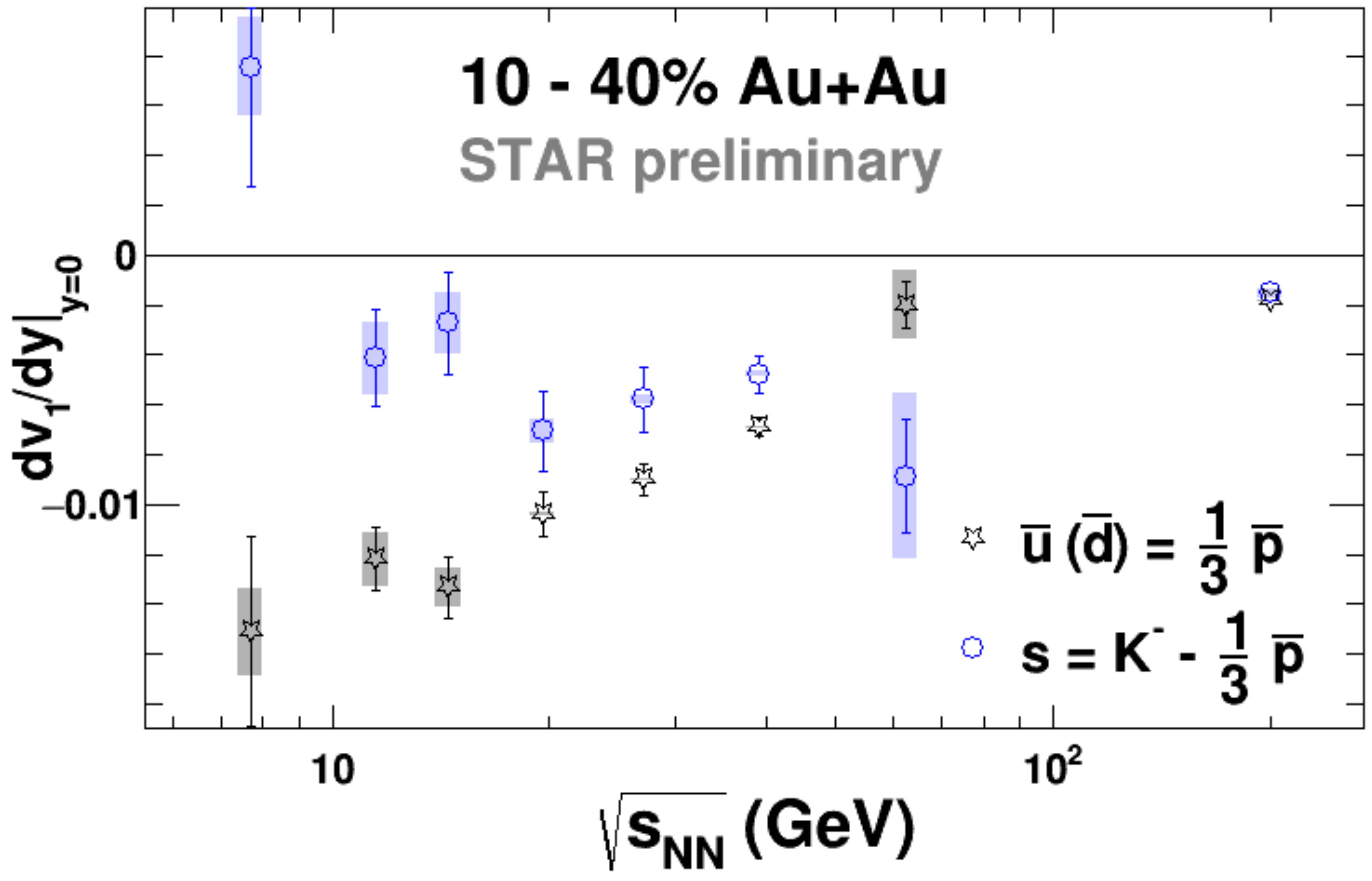


- ❖ Fruitful data from $v_1(y)$ with many particle species at various collisions energies in Au-Au 10-40%
  - ☆ Allows to perform a detailed study of quark v_1

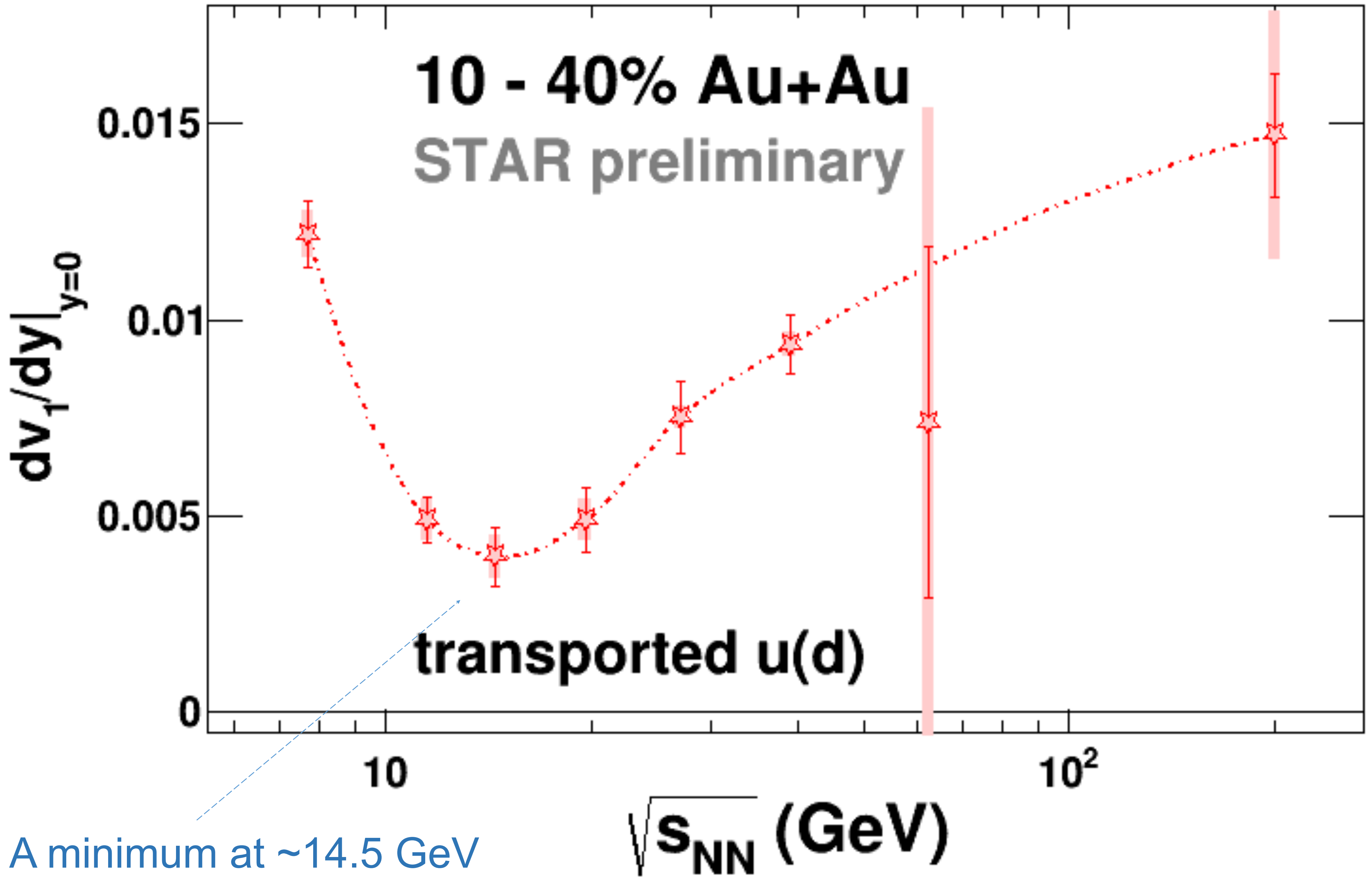
If simple coalescence works

STAR, PRL 120 (2018) 062301 | Talk: G. Wang, May 16th

v_1 of produced quarks



v_1 of transported quarks



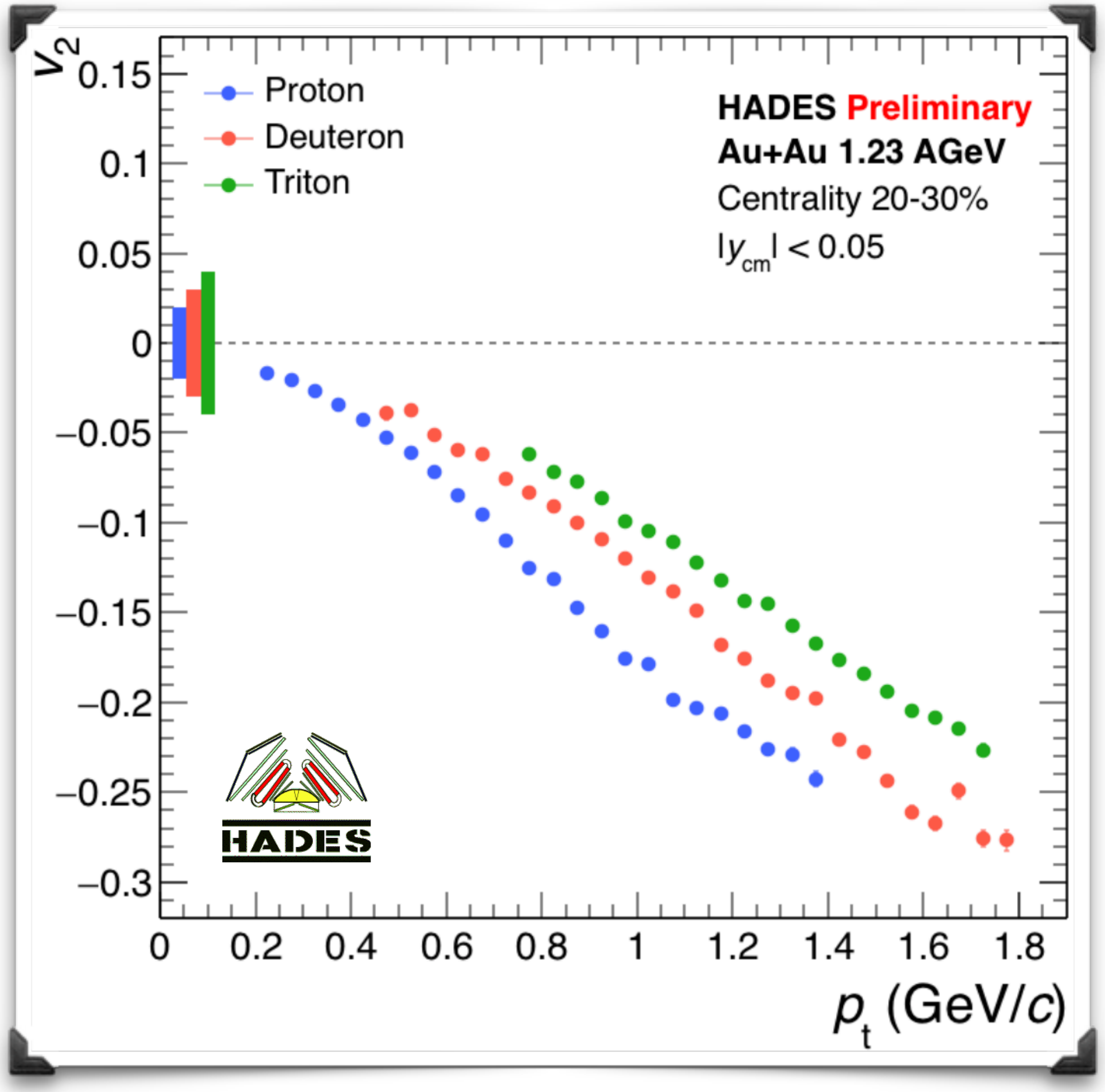
$$(v_1)_{trans.\ u(d)} = [(v_1)_{net\ p} - (3 - N_{trans.\ u+d}) * (v_1)_{\bar{u}(\bar{d})}] / N_{trans.\ u+d}$$

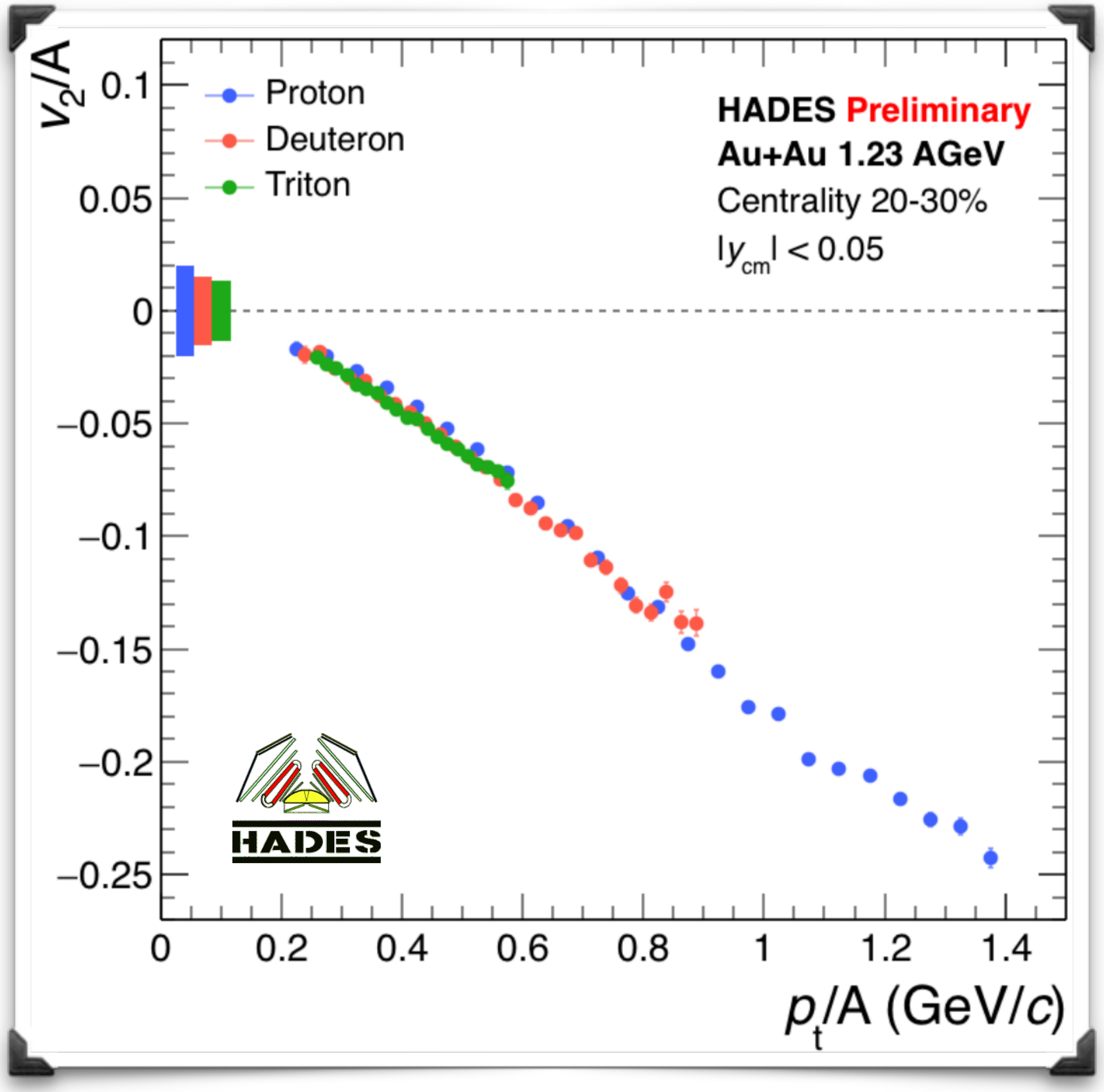
- **ū(đ)** and **s** quarks have similar dv_1/dy at 200 GeV, and deviate at lower energies
- **s** and **$\bar{s}$** quarks are consistent with each other, except at the lowest energy (not shown here see G. Wang's talk).

- v_1 of transported **u(d)** is positive for all beam energies

HADES: v_2 of light nuclei at 1.23 GeV

Talk: B. Kardan, May 16th



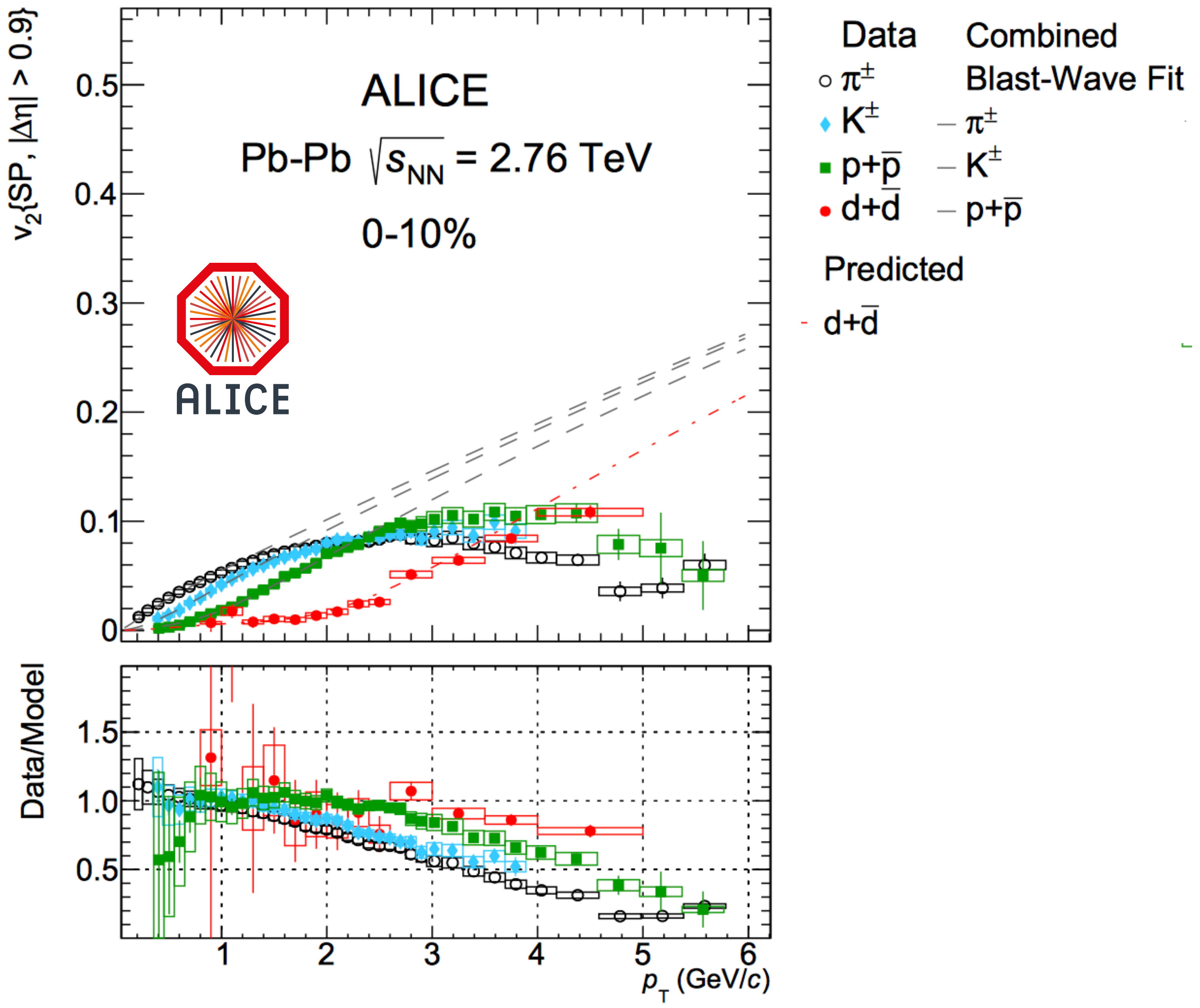


- Comparisons of proton, deuteron and triton v_2 at mid-rapidity
- Scaling of v_2 and p_T with nuclear mass number A
  - A good scaling observed, as expected from nucleon coalescence

ALICE ^{3}He flow

ALICE, EPJC (2017) 77, 658

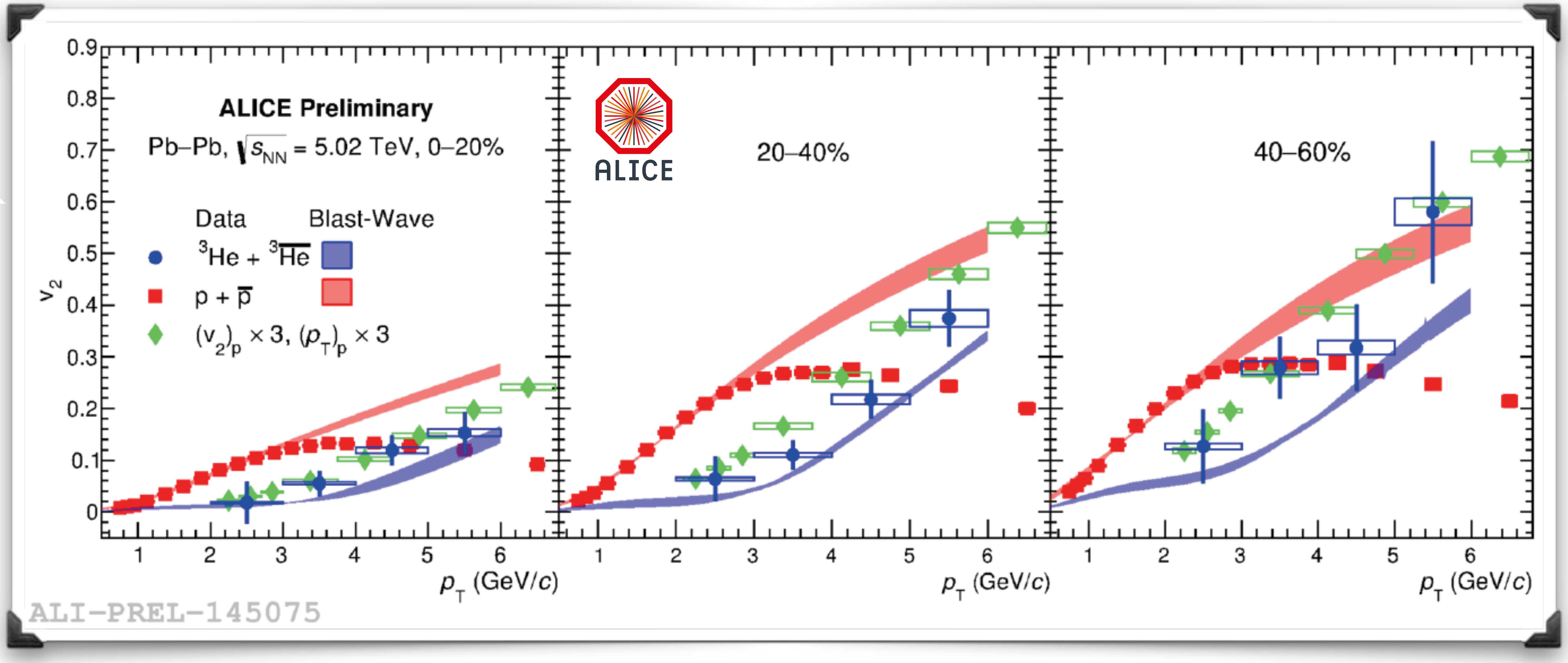
Deuteron v_2 @RUN1



^{3}He v_2@RUN2

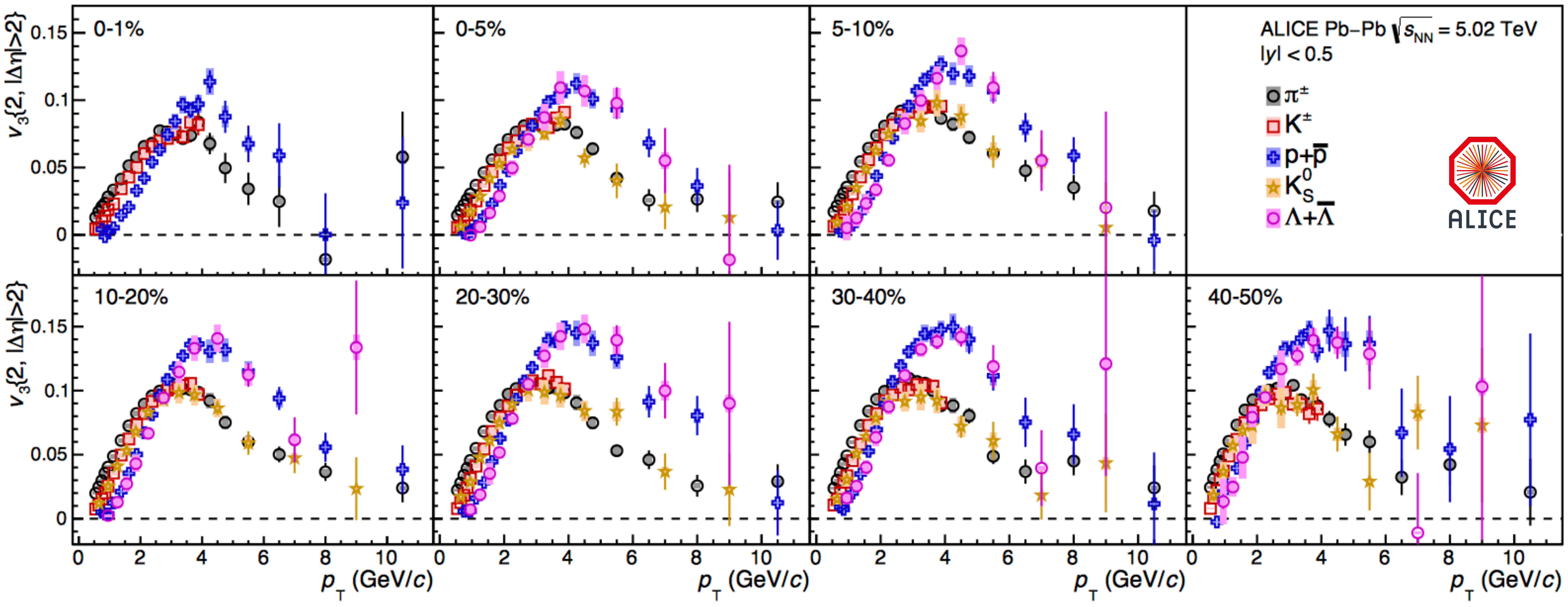
Talk: M. Puccio, May 16th

Poster: A. Calivà



- v_2 measurements of the heaviest baryon so far (^{3}He)!
  - The overall agreement of the Blast-Wave fitted to lighter species prediction for ^{3}He is better in the most central collisions
  - Simple coalescence expectation (using proton v_2) gets closer to the measured ^{3}He v_2 for semi-central collisions
  - Coming Pb-Pb run this year and future data taking at Run3 and Run4 of LHC will help to disentangle this discrepancy!

Higher harmonic flow of identified particles



ALICE, arXiv: 1805.04390

Talk: V. Pacik, May 14th

Talk: N. Mohanmodi, May 15th

Poster: Y. Zhu

***Note**: Results are also available for v_2 and v_4*

- Precision measurements of $v_n(p_T)$ of $\pi^{\pm}$, $K^{\pm}$, K_S^0, $p(\bar{p})$, Λ, Φ, Ξ, Ω, D, J/psi @ RUN2 (not all are shown here)
  - Low p_T: mass ordering -> interplay between radial flow and v_n, reproduced by hydrodynamic calculations
  - Intermediated p_T, baryon-meson v_n grouping, partonic collectivity and coalescence?
  - high p_T: non-zero v_n(pt) for all particle species, better understanding on parton energy loss relies on future data vs theory comparison

Studying flow in nuclear collisions

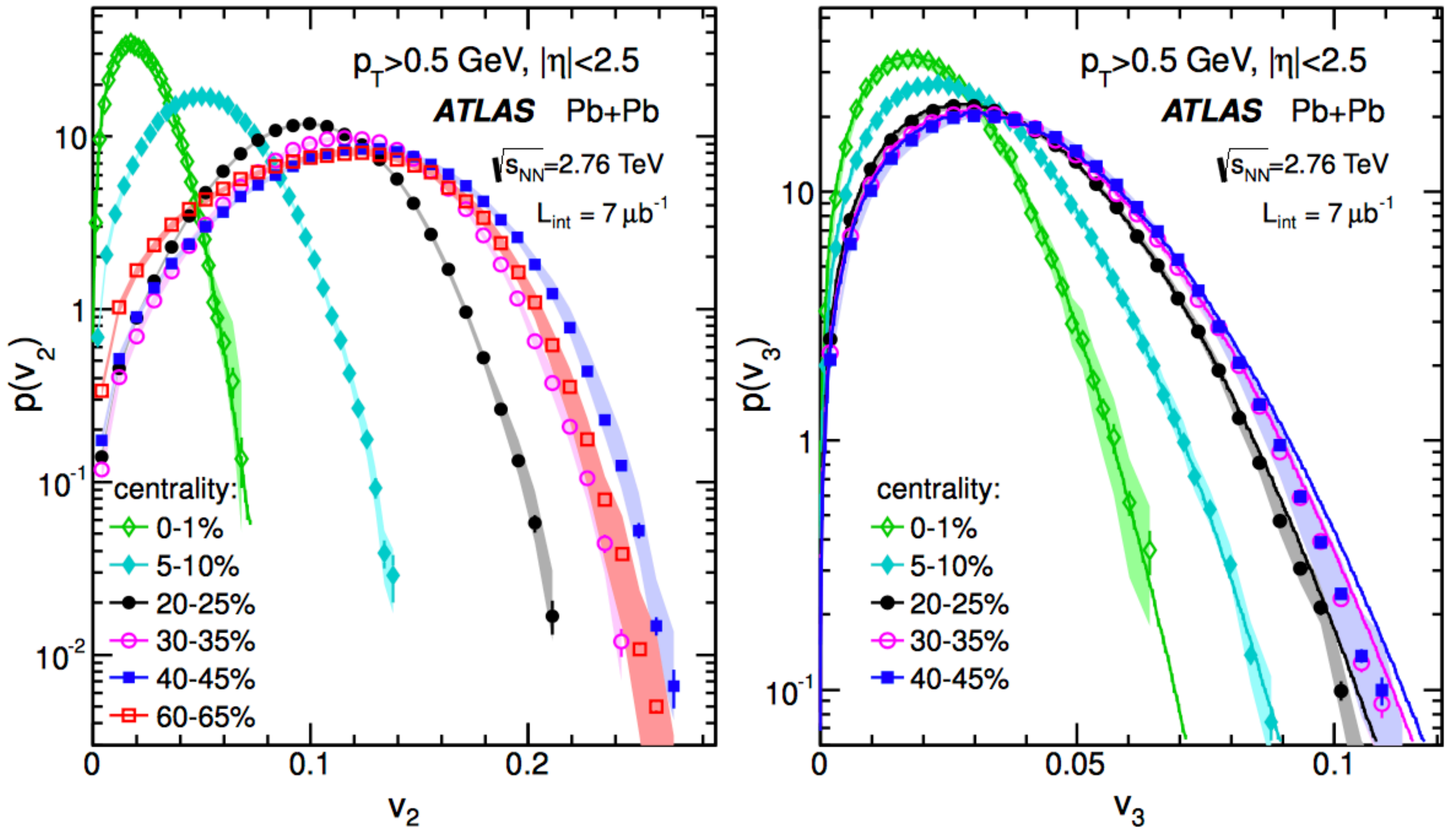
Collective effects in nuclear collisions

V_n fluctuations

- E-By-E v_n distribution and/or $c_n\{m\}$ -> $p(v_n)$
- De-correlations of V_n vs η

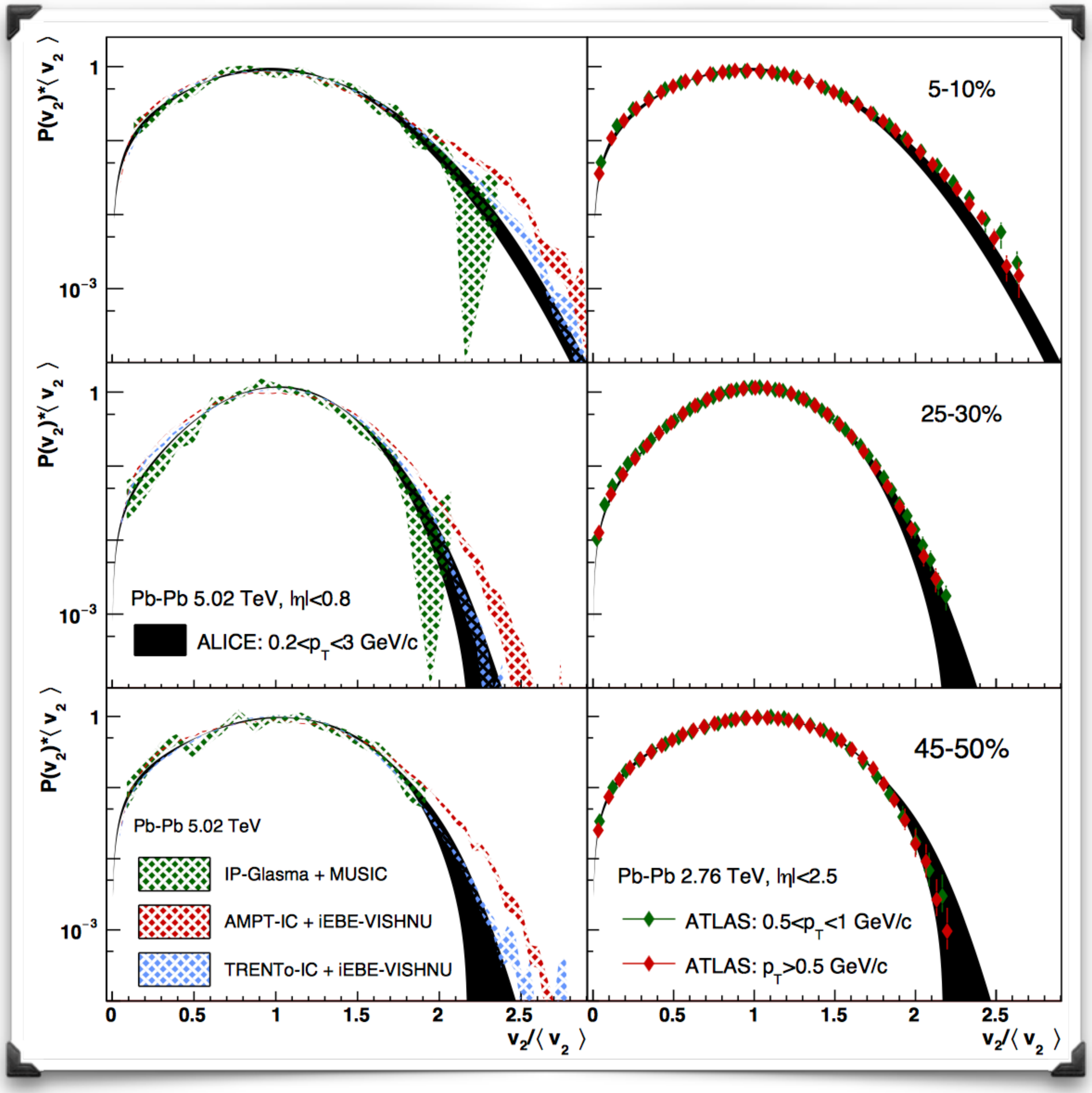
Underlying p.d.f. $P(v_2)$

ATLAS, JHEP11(2013)183



ALICE, arXiv:1804.02944

Talk: J. Margutti, May 15th

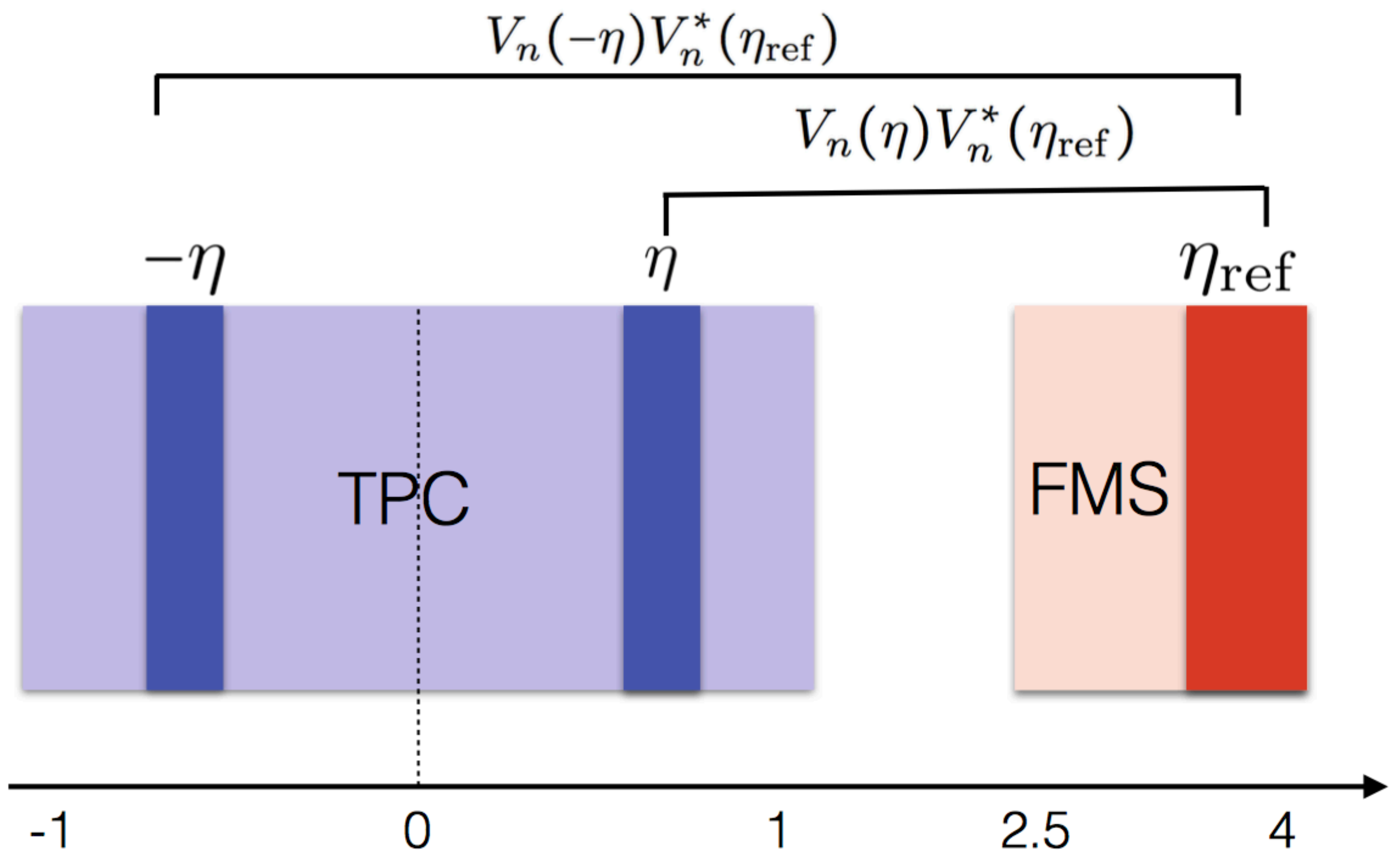


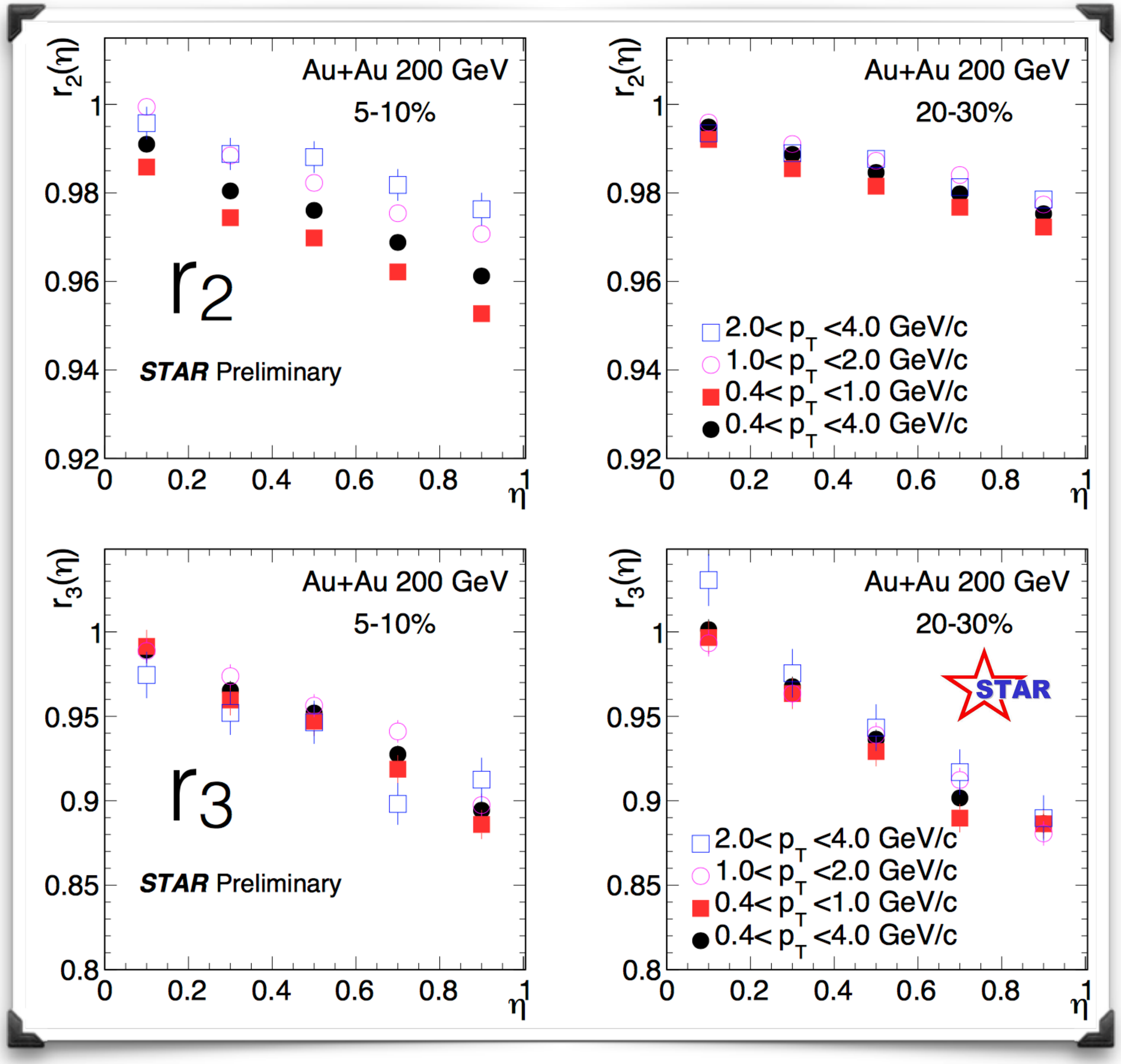
- Run1: ATLAS studied $p(v_n)$ via Bayesian unfolding procedure
- Run2: ALICE extracted $p(v_2)$ via fitting the 2- and multi-particle cumulants via Elliptic-Power function
  - P(v2) rescaled by $\langle v_2 \rangle$ in agreement with ATLAS results -> flow fluctuations has no/weak dependence on energy and kinematic cuts
  - Similar results available from CMS
  - Reproduced by hydro calculations

STAR: Longitudinal decorrelation with r_n

Talk: M. Nie, May 15th

$$r_2(\eta) = \frac{\langle V_2(-\eta) V_2^*(\eta_{\mathrm{ref}})\rangle}{\langle V_2(\eta) V_2^*(\eta_{\mathrm{ref}})\rangle}$$





- $r_2(\eta)$ decreases linearly for the shown centralities, and shows a strong p_T dependence
- $r_3(\eta)$ decreases linearly for the shown centralities but shows weaker p_T dependence
- Similar observations at the LHC energy, where the breakdown of factorization is weaker than RHIC

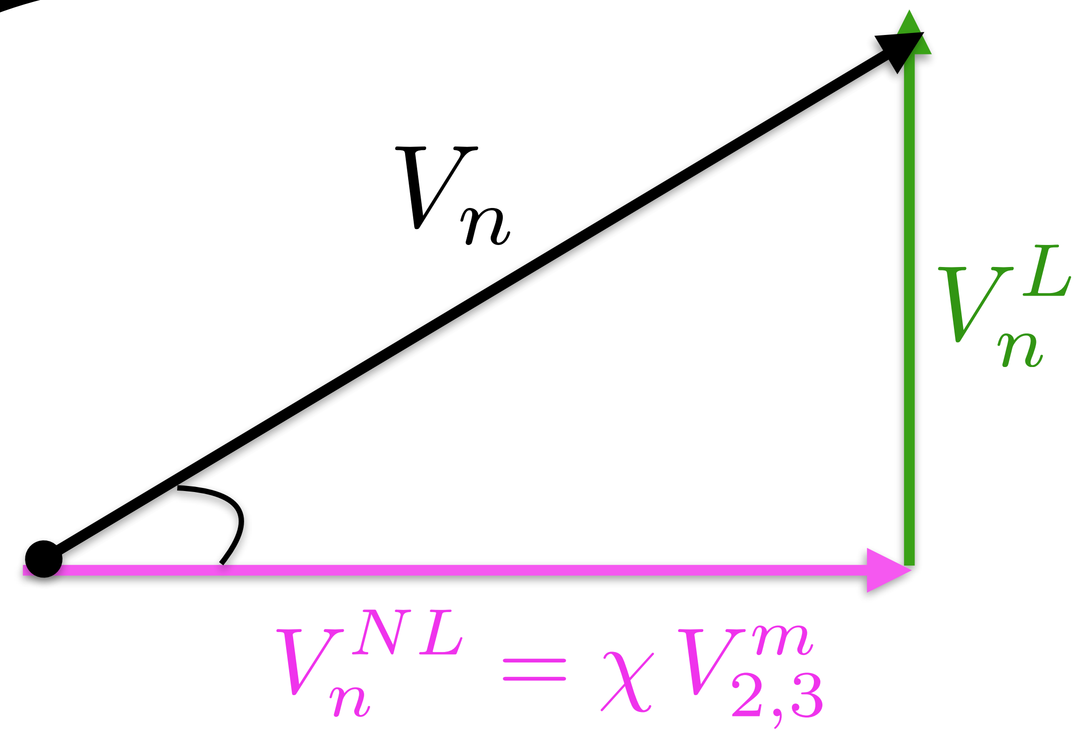
Studying flow in nuclear collisions

V_n correlations

- Differential non-linear flow mode with $\pi^{\pm}$, $K^{\pm}$, $p(\bar{p})$
- Symmetric cumulants in Pb-Pb, Xe-Xe
- $\langle p_T \rangle$ & v_n correlations

Collective effects in nuclear collisions

Non-linear flow mode



$$V_n = V_n^{NL} + V_n^L$$

non-linear response

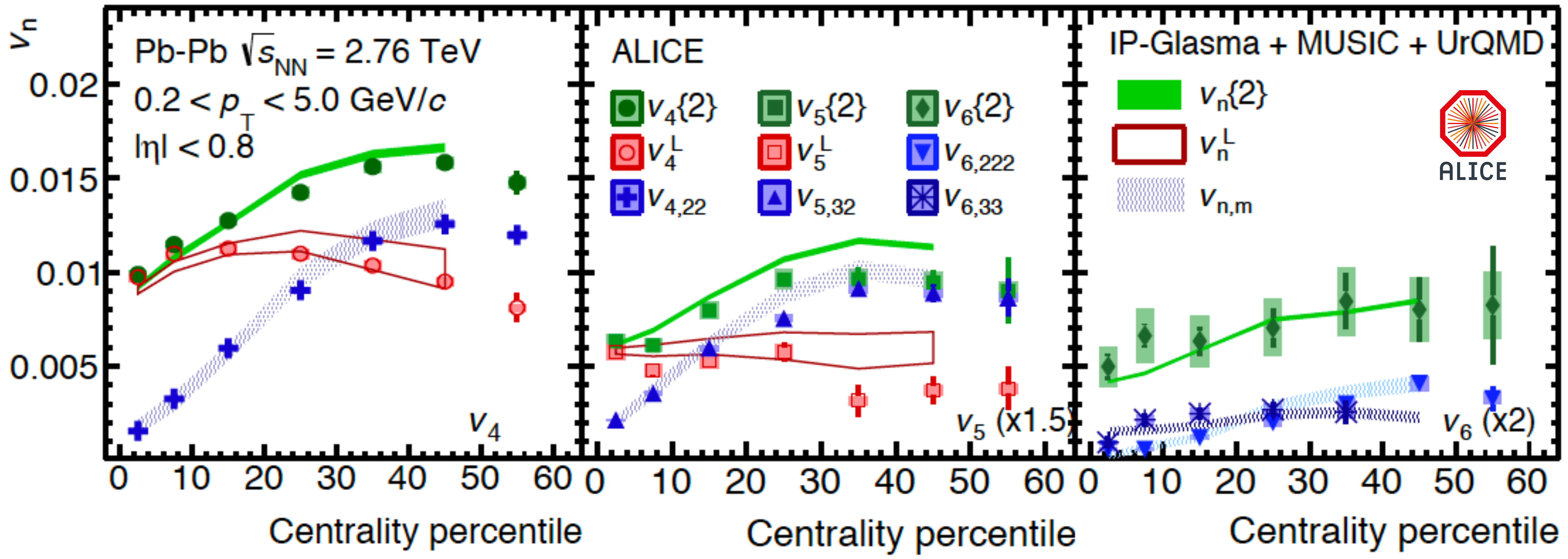
linear response

- Non-linear mode V_n^{NL}
  - ☆ corresponds to lower order initial anisotropy coefficient $\varepsilon_{2,3}$
  - ☆ V_n projection on V_2 or V_3
  - ☆ $v_{n,m}$: magnitude of non-linear response in V_n

- Linear mode V_n^L
  - ☆ naively expected to correspond to ε_n
  - ☆ v_n^L: magnitude of linear response in V_n

❖Higher harmonic flow is modeled as the sum of linear and nonlinear response terms to the initial anisotropy coefficients ε_n

$v_{n,mk}$ @RUN I ALICE, PLB773 (2017) 68



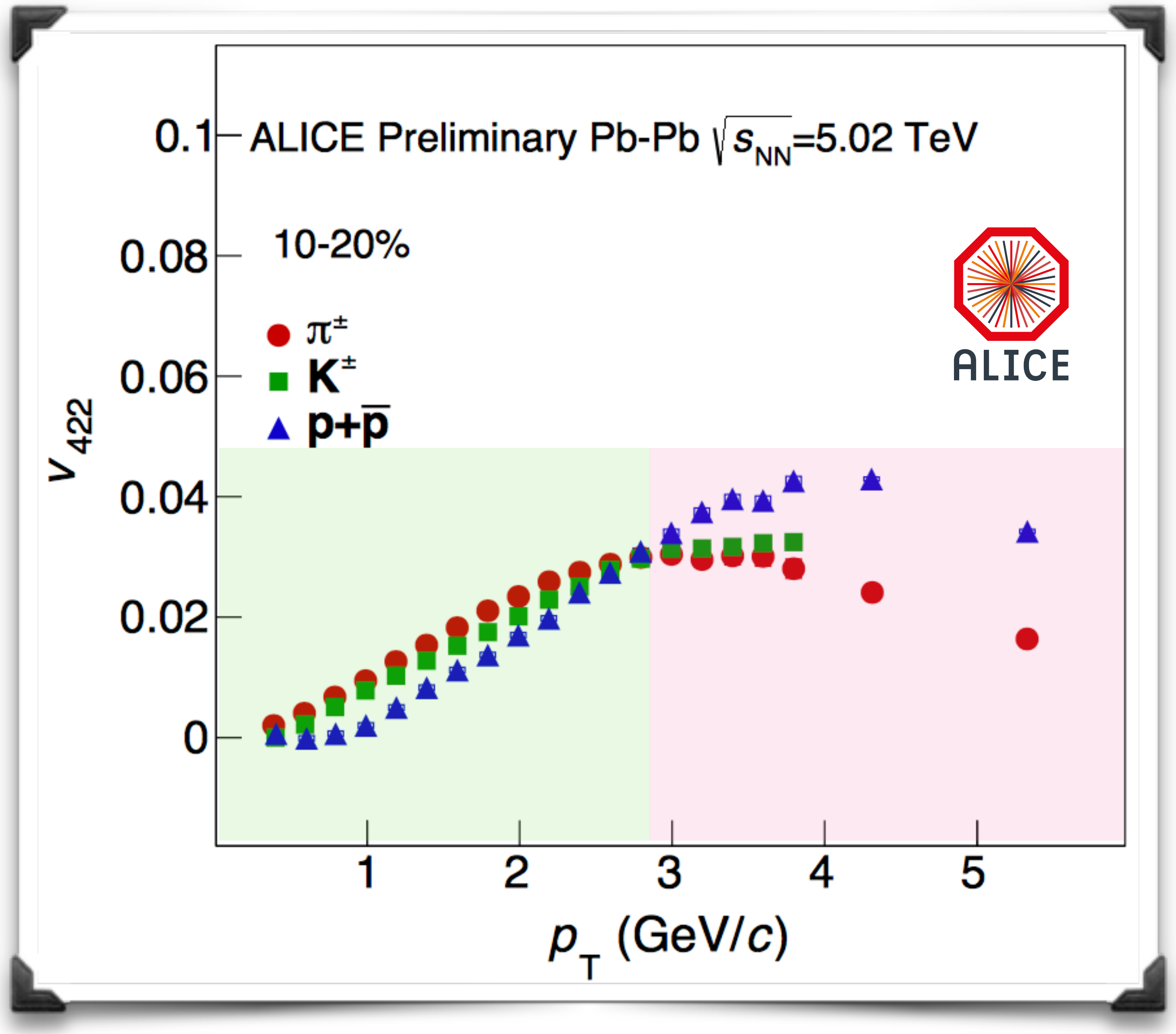
☆ Similar results were presented by CMS @ QM17, and by ATLAS using Event-Shape Engineering

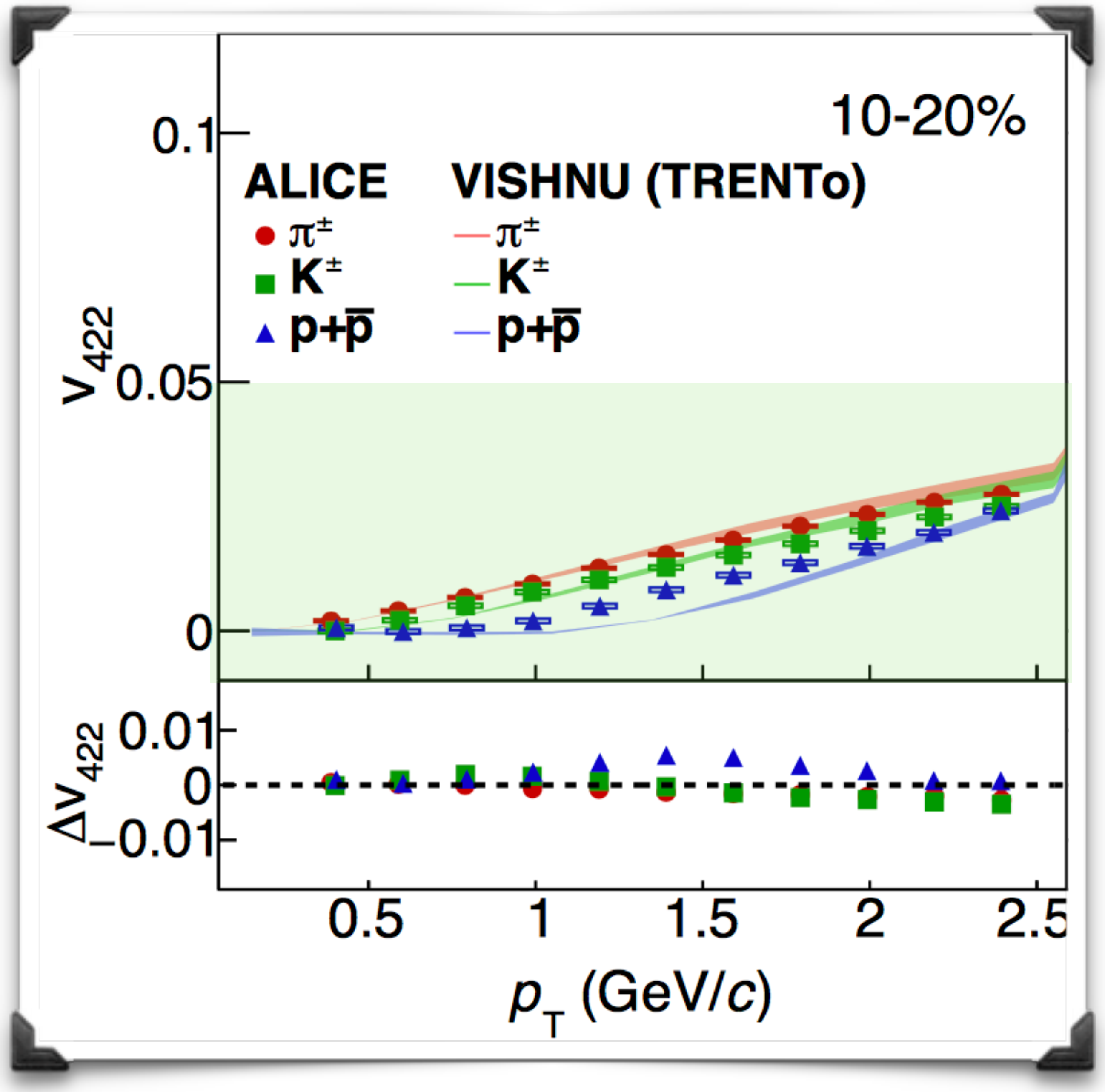
Non-linear flow mode $v_{n,mk}$ with identified particles

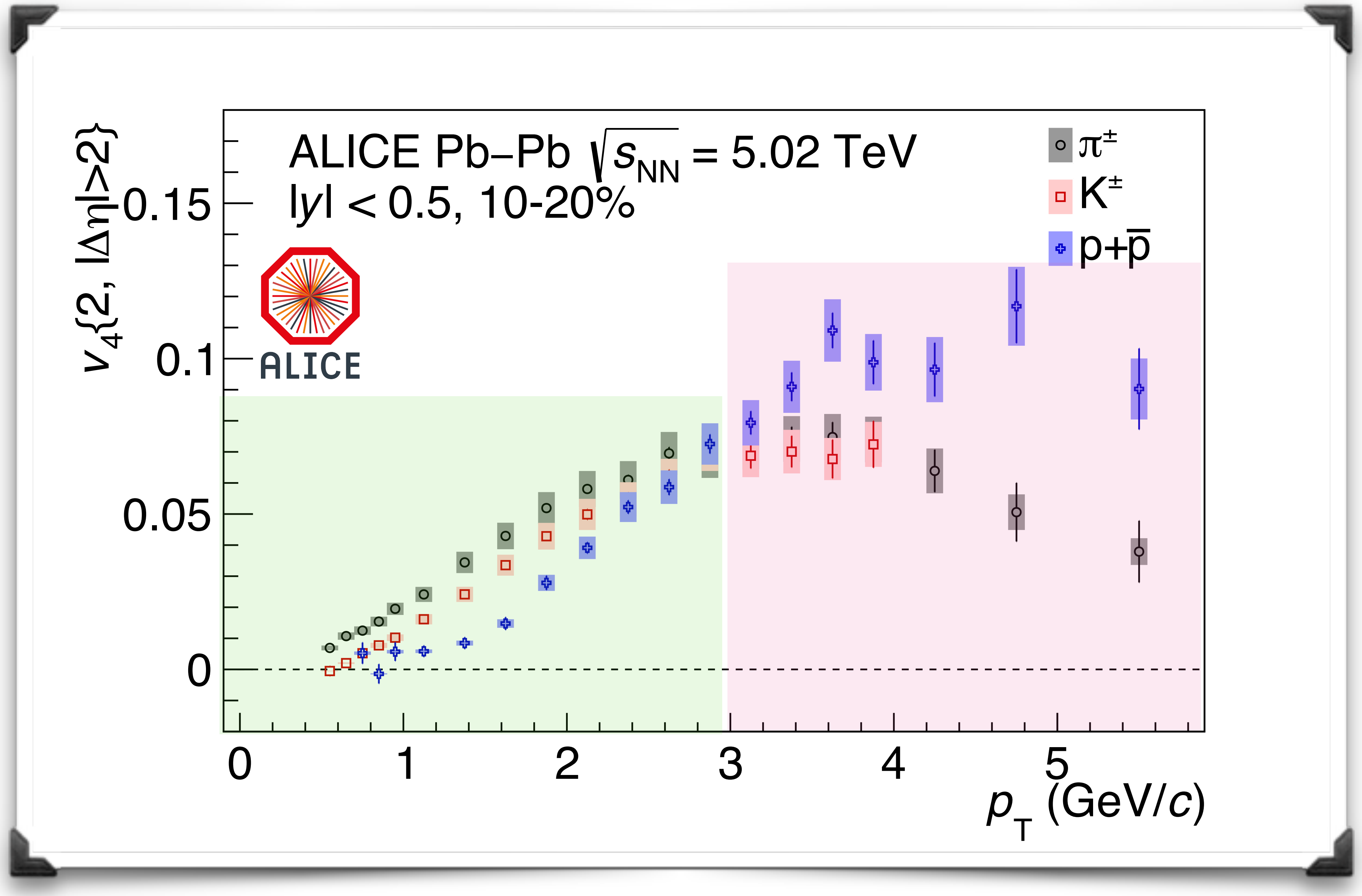
PID $v_{n,mk}(p_T)$ @RUN2

Talk: N. Mohanmodi, May 15th

ALICE, arXiv: 1805.04390







- First measurement of $v_{n,mk}(p_T)$ for identified particles
  - Mass ordering in the low p_T region (p_T <2.5 GeV/c)
  - Particle type grouping in the intermediate p_T region (p_T >2.5 GeV/c)
  - Similar observations as v_n
- Comparisons to hydrodynamic calculations using iEBE-VISHNU
  - Compatible results between data and theory
  - new handle of constraining initial conditions and transport coefficients

Symmetric cumulants in Xe-Xe and Pb-Pb

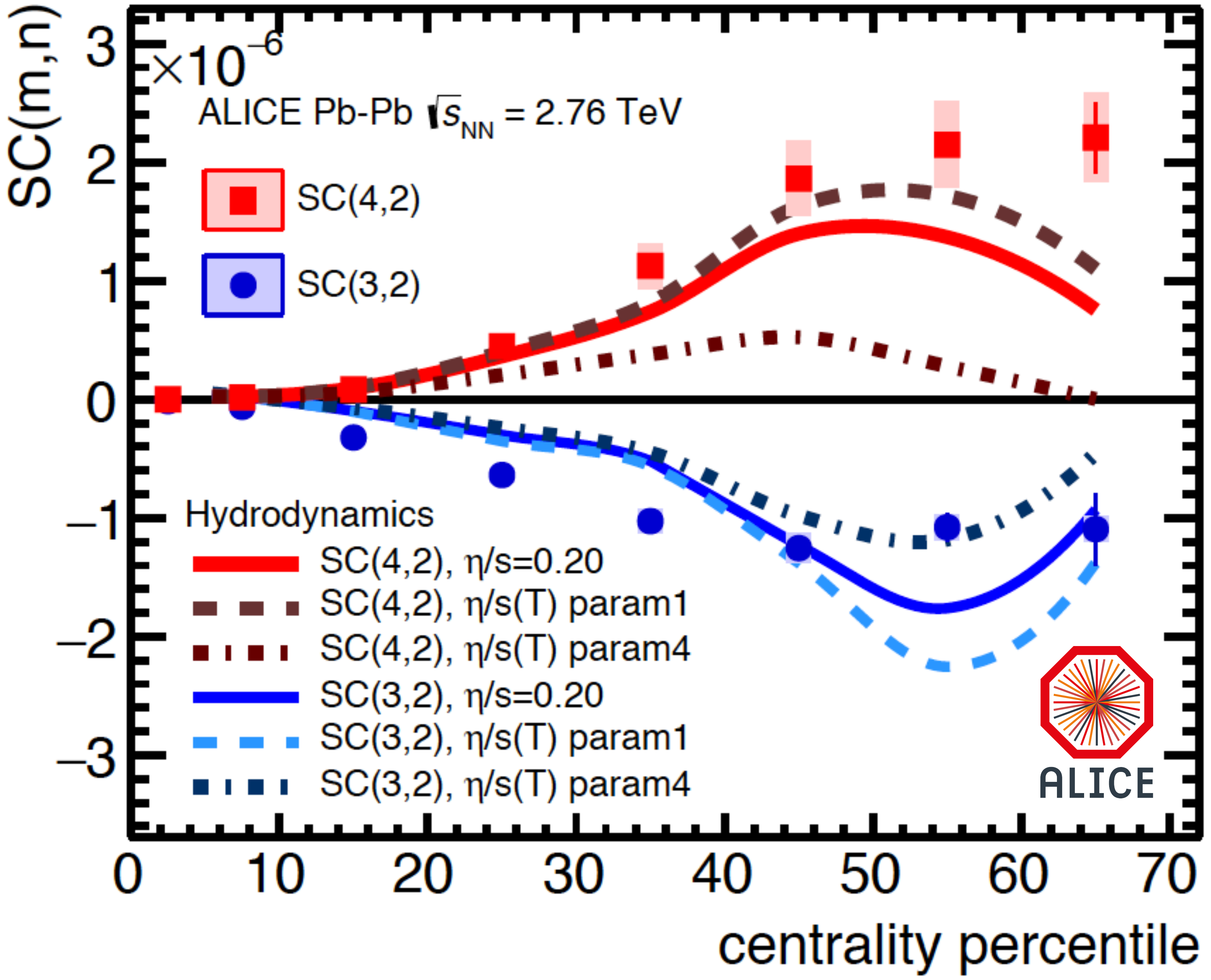
Correlations between v_m and v_n via

Symmetric cumulants:

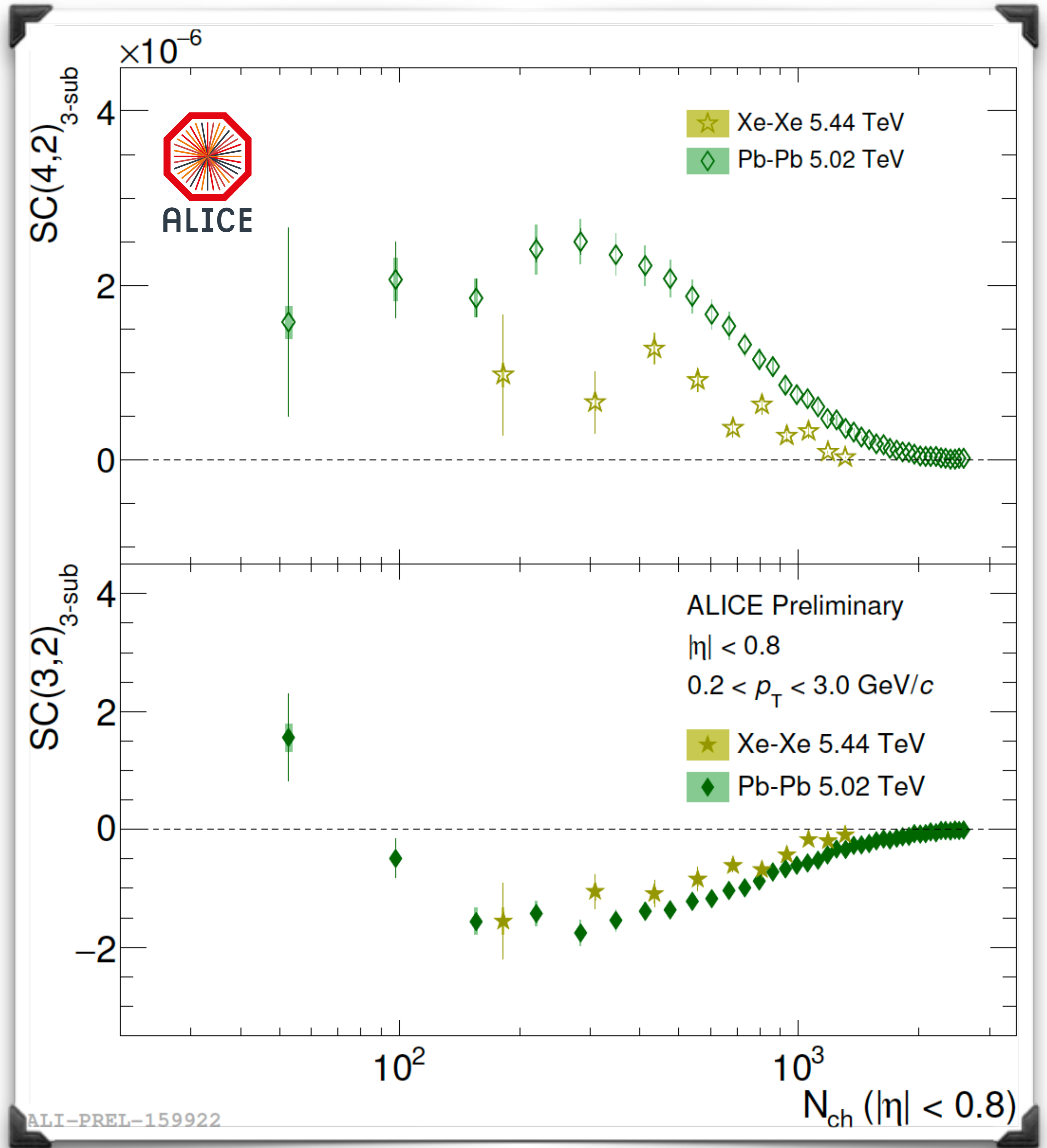
$$SC(m,n) = \langle v_m^2\, v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

A. Bilandzic et al., PRC 89, 064904 (2014)

ALICE, PRL117, 182301 (2016)



Talk: K. Gajdosova, May 15th



- ❖ Weaker (anti-)correlations in Xe-Xe than Pb-Pb at same N_{ch}
- ❖ Unique sensitivity to initial conditions (ε_m and ε_n correlations) and $\eta/s(T)$, constraining future theoretical calculations.

ATLAS: <p_T> & v_n correlations

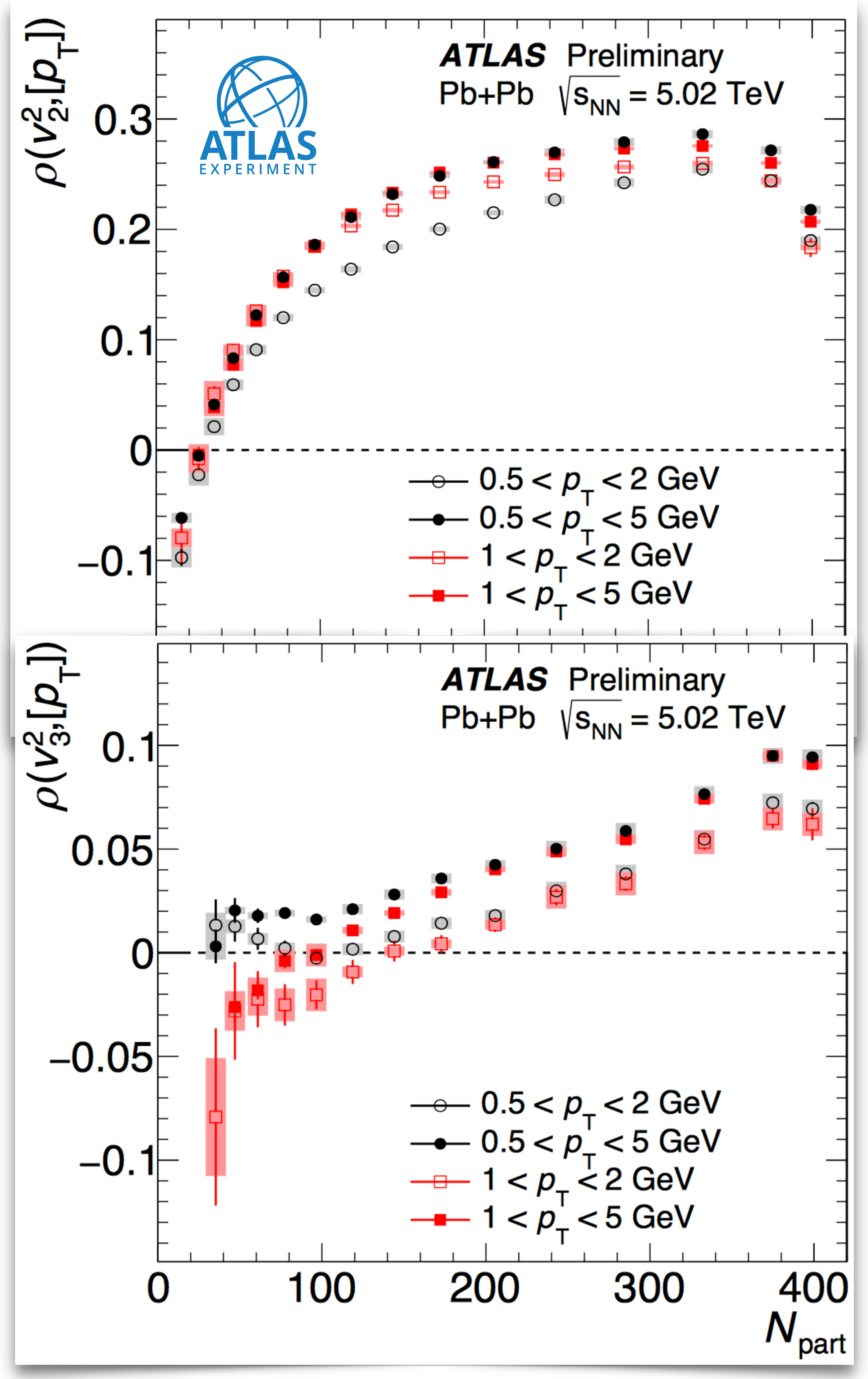
Quantify the correlations between <p_T> and v_n coefficient:

$$\rho(v_n\{2\}^2, [p_\perp]) = \frac{cov(v_n\{2\}^2, [p_\perp])}{\sqrt{Var(v_n^2)_{dyn} C_{p_\perp}}}$$

P. Bozek, PRC 93, 044908 (2016)

- For v_2
  - in peripheral events, negative correlation for v2
  - rise above $N_{part} \simeq 100$, saturation at $\rho \simeq 0.28$
  - difference between various p_T intervals
- For v_3
  - correlation for v_3 weaker compared to v_2
  - positive except for p_T > 1GeV below $N_{part} \simeq 100$
- Will be also interesting to explore further with PID

Talk: T. Bold, May 15th



Studying flow in nuclear collisions

Collective effects in nuclear collisions

New ideas

- Power-spectra
- Machine Learning

New way to study anisotropy: Power spectra

PHYSICAL REVIEW C **86**, 024916 (2012)

Morphology of high-multiplicity events in heavy ion collisions

P. Naselsky, C. H. Christensen, P. R. Christensen, P. H. Damgaard, A. Frejsel, J. J. Gaardhøje, A. Hansen, M. Hansen, and J. Kim
Discovery Center, Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen, Denmark

O. Verkhodanov
Special Astrophysical Observatory, Russian Academy of Sciences, Nizhnij Arkhyz, Russia

U. A. Wiedemann
Physics Department, Theory Unit, CERN, CH-1211 Geneva, 23, Switzerland

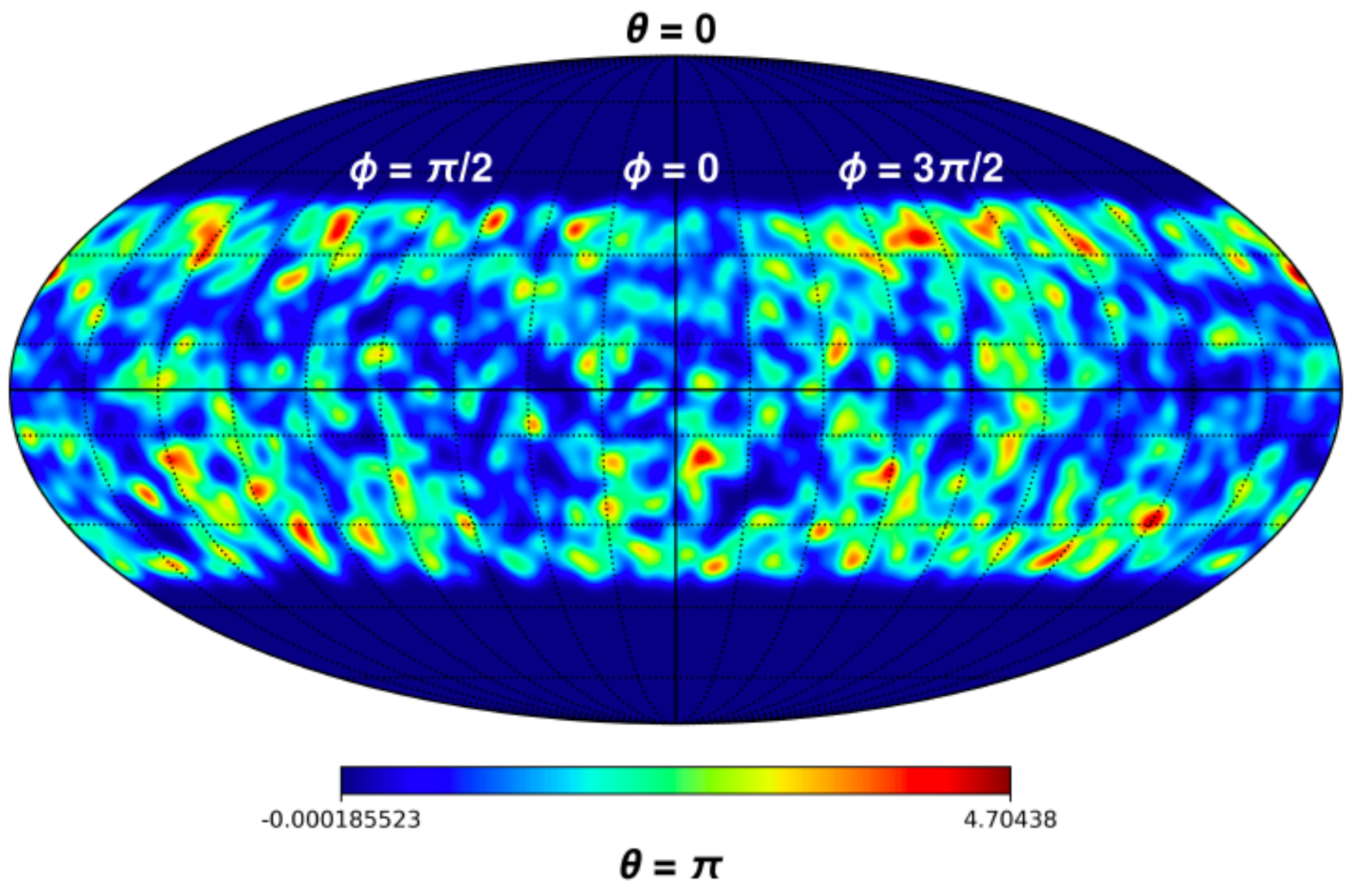
A new study proposes to map the final particle distribution to the surface of a sphere,

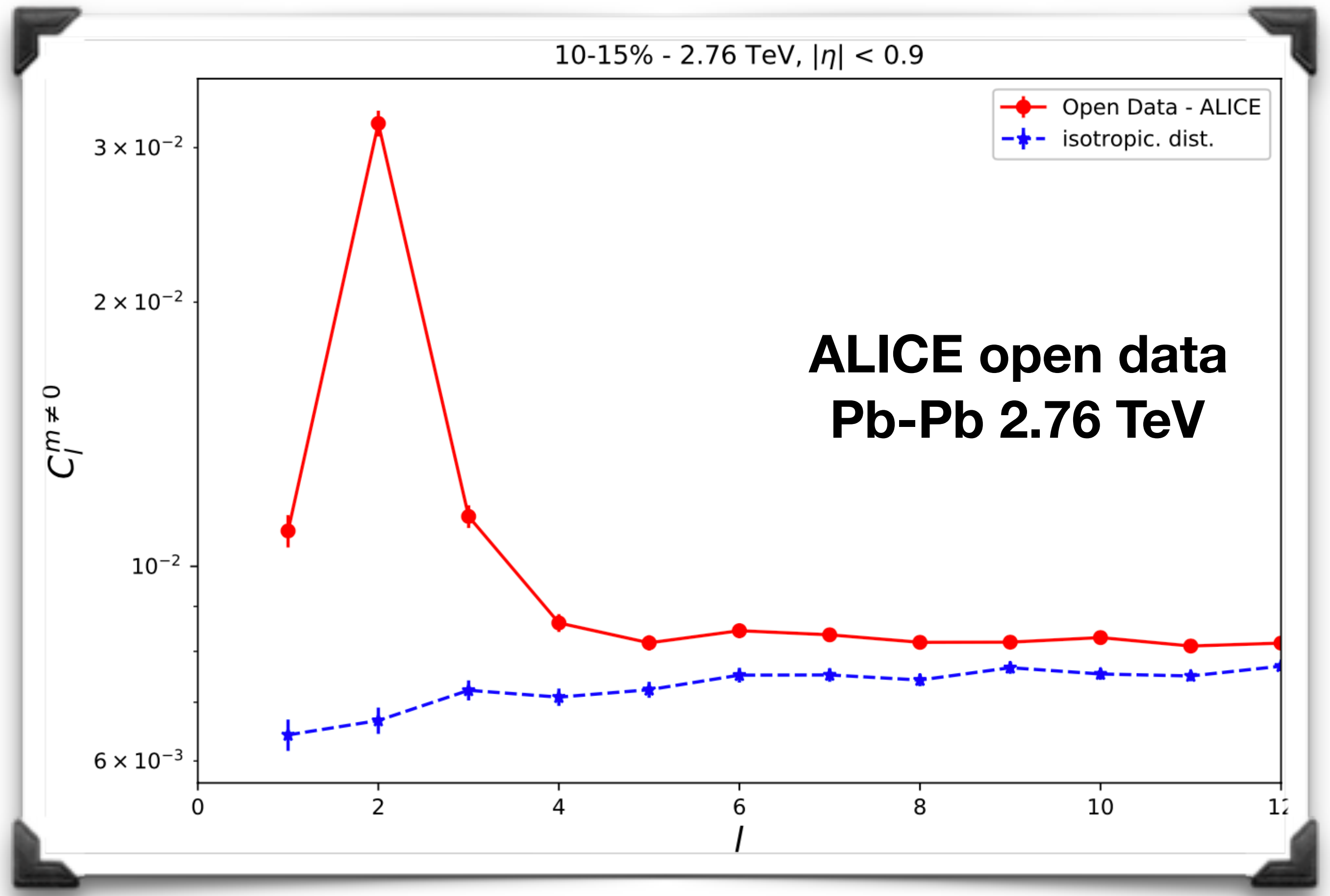
- allows for its expansion in spherical harmonics
- allows the calculation of an angular power spectrum
  - sensitive to anisotropies in both polar and azimuthal (φ) directions
  - probes the properties of the QGP

$$f(\theta,\phi) = \sum_{l=0}^{l_{max}} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi), \quad Y_{lm} = \sqrt{\frac{2l+1}{4\pi}\frac{(l-m)!}{(l+m)!}} P_{lm}(\cos(\theta)) e^{im\phi},$$

$$a_{lm} = \frac{4\pi}{N_{pix}} \sum_{p=0}^{N_{pix}-1} Y^*_{lm}(\theta_p,\phi_p) f(\theta_p,\phi_p), \quad C_l = \frac{1}{2l+1} \sum_{m=-l}^{l_{max}} |a_{lm}|^2.$$

"Sky" mapped by power spectra using ALICE open data

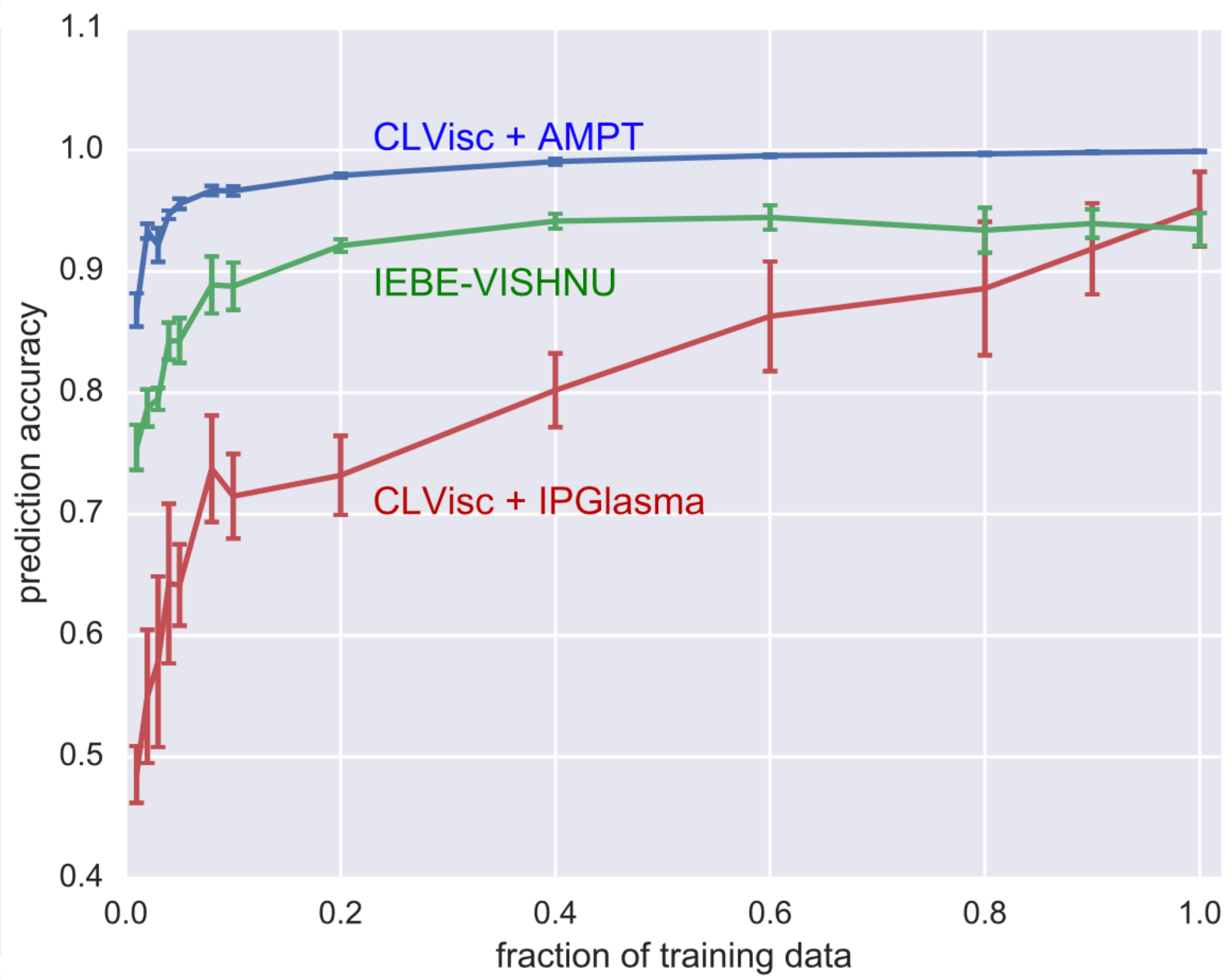




**M. V. Machado
Poster #270**

Deep learning

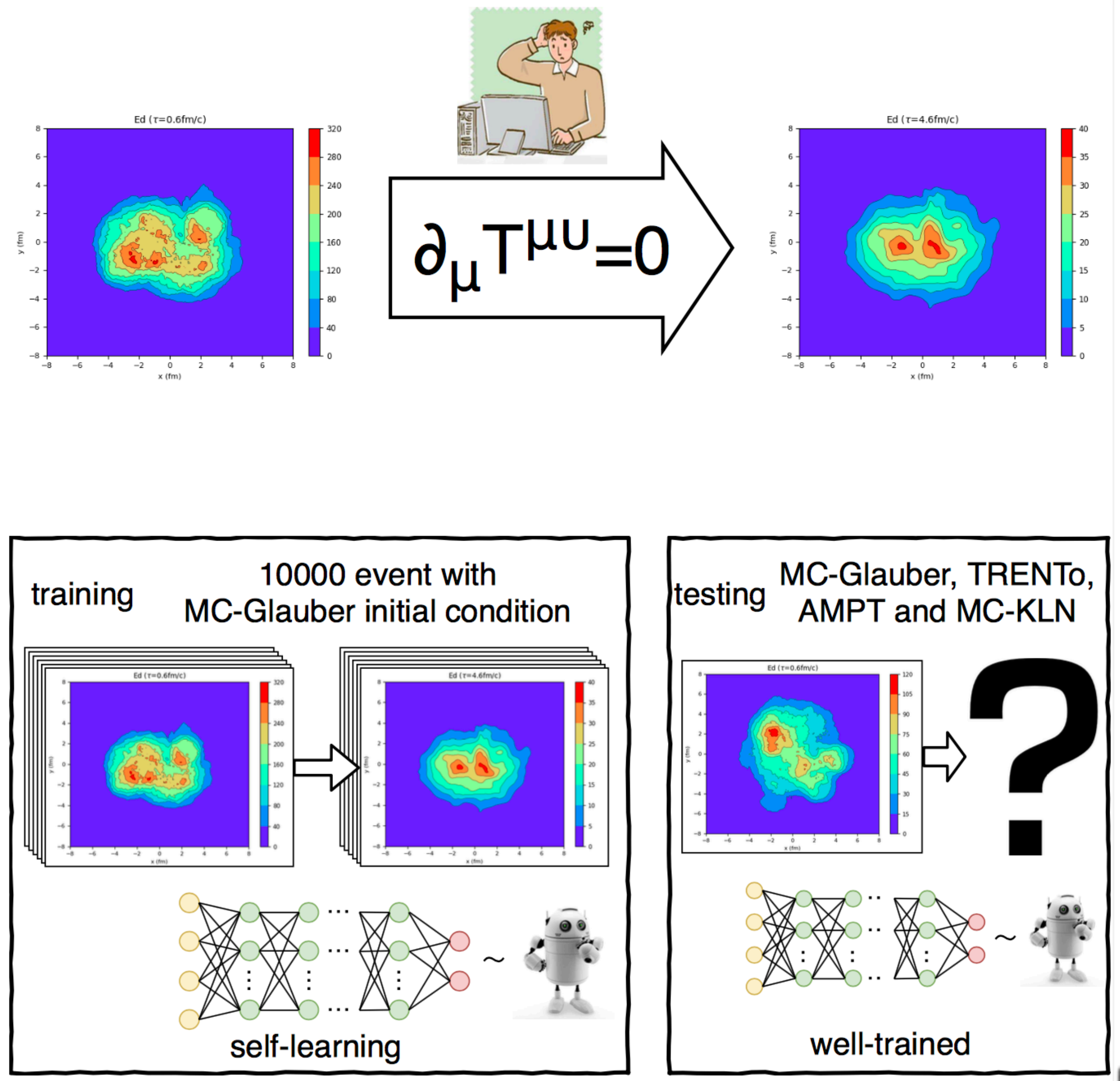
Talk: L-G. Pang, May 16th



- 40000 events from CLVisc+AMPT model have been used for training
- Another 4000 events from CLVisc+AMPT have been used for testing
- 18000 events from another hydrodynamic model IEBE-VISHNU and CLVisc+IPGlasma model have been used for further testing

Talk: H.F. Huang, May 16th

- traditional hydrodynamics
- deep learning

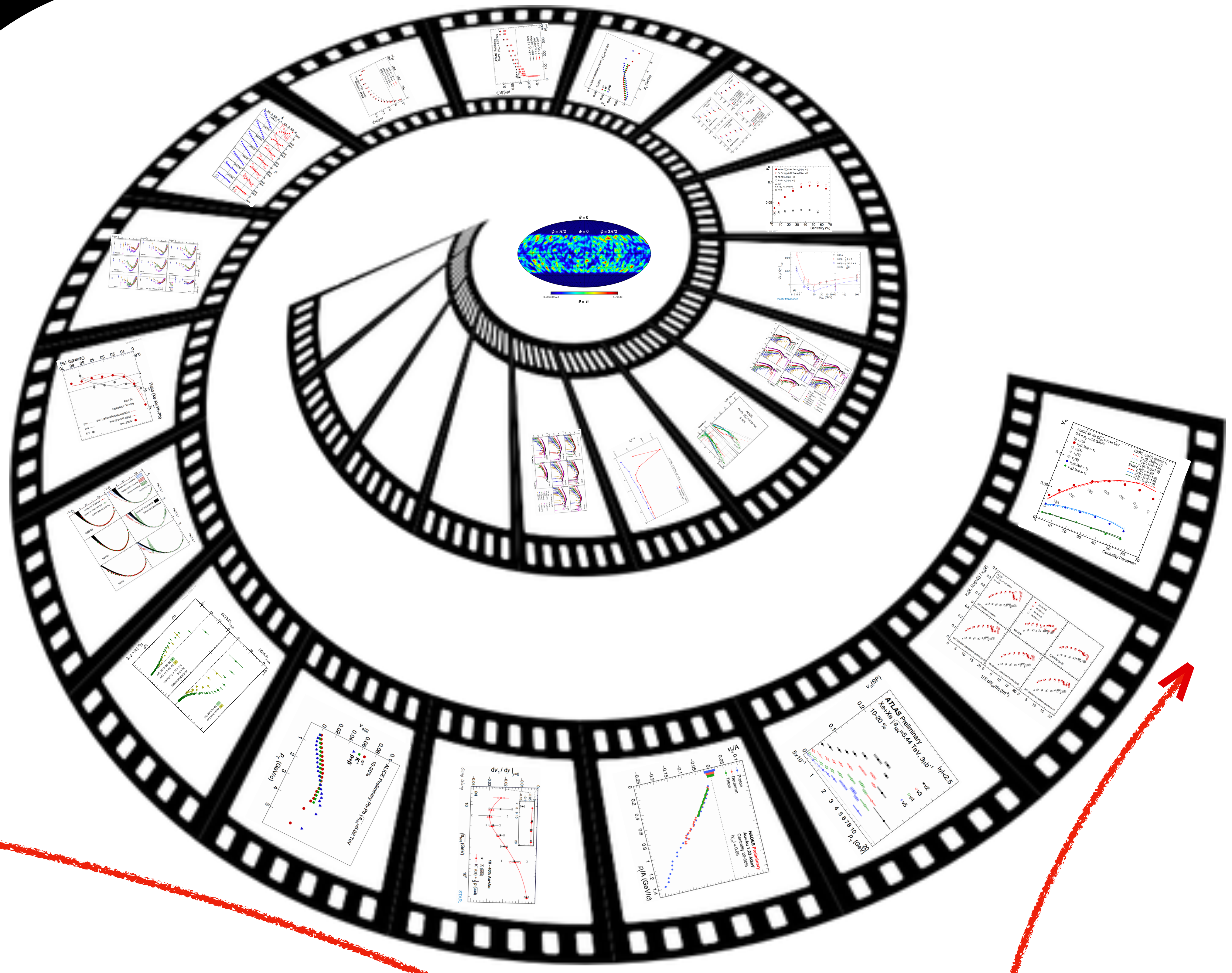


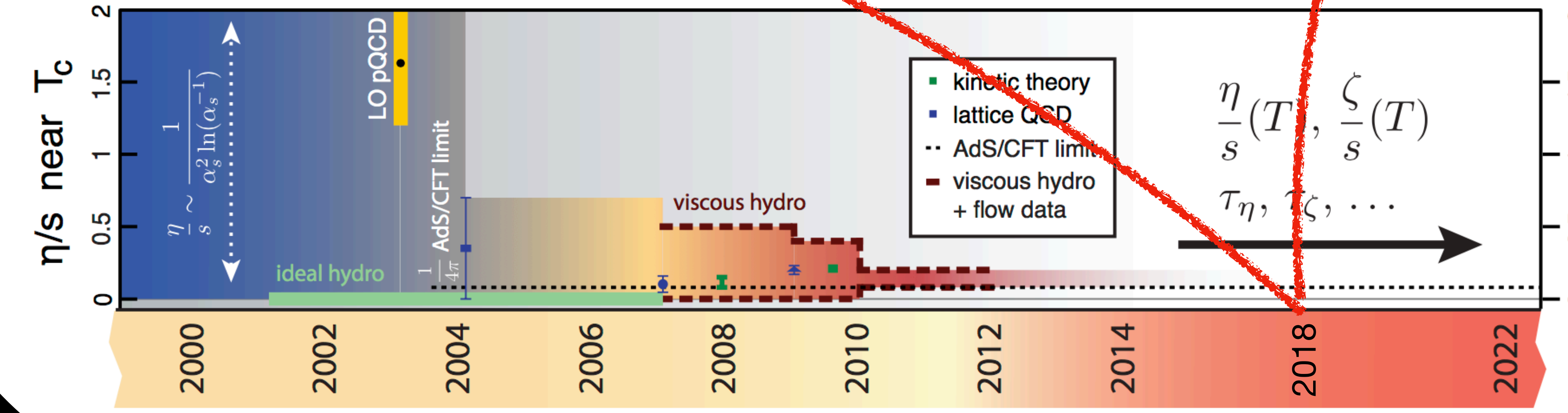
❖ Future possibilities for flow studies in EXP.

Remarkable sets of new results in Quark Matter 2018

UNIVERSITY OF COPENHAGEN

Venezia 2018 Quark Matter





Collective dynamics: I

Measurements of anisotropic flow and flow fluctuations in Xe-Xe and Pb-Pb collisions with ALICE	*Jacopo Margutti*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	09:00 - 09:20
System size dependence of flow observables in hydrodynamic simulations	*Matthew Luzum*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	09:20 - 09:40
Elliptic and higher-order azimuthal anisotropies via multiparticle correlations in pPb and PbPb collisions with the CMS experiment	*Quan Wang*
Phenomenology of the nonlinear coupling of flow harmonics in heavy-ion collisions	*Mr Giuliano Giacalone*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	10:00 - 10:20
Correlation between higher order flow harmonics and their non-linear modes for (un)identified charged hadrons in Pb-Pb collisions measured with ALICE	*Naghmeh Mohammadi*

Collective dynamics: II

Fluid dynamics of out of equilibrium boost invariant plasmas	*Li Yan*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	11:10 - 11:30
Measurement of the azimuthal anisotropy of charged particles in 5.02 TeV Pb+Pb and 5.44 TeV Xe+Xe collisions with ATLAS	*Tomasz Bold*
Kinetic transport is needed to reliably extract shear viscosity from pA and AA data	*Eero Aleksi Kurkela*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	11:50 - 12:10
Measurement of collective flow in XeXe collisions at 5.44 TeV with the CMS experiment	*Milan Stojanovic*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	12:10 - 12:30
SMASH - A new hadronic transport approach	*Hannah Petersen*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	12:30 - 12:50
Measurement of Longitudinal Decorrelation of Anisotropic Flow v_{2} and v_{3} in 54 and 200 GeV Au+Au Collisions at STAR	*Maowu Nie*

Collective dynamics: III

Collective flow and correlations measurements with HADES in Au+Au collisions at 1.23 AGeV	*Mr Behruz Kardan*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	16:50 - 17:10
Elucidating the properties of hot nuclear matter with a comprehensive description of ultra-relativistic heavy-ion collisions	*Dr Bjoern Schenke*
NA61/SHINE measurements of anisotropic flow relative to the spectator plane in Pb-Pb collisions over a wide rapidity range	*Viktor Klochkov*
Collectivity from interference	*Prof. Boris Blok*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	17:50 - 18:10
Latest predictions from the EbyE NLO EKRT model	*Harri Niemi*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	18:10 - 18:30
Light (anti-)nuclei production and elliptic flow in Pb-Pb collisions at the LHC with ALICE	*Maximiliano Puccio*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	18:30 - 18:50

Collective dynamics: IV

(3+1)D hybrid model of heavy-ion collisions at BES energies with dynamical sources	*Lipei Du*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	11:10 - 11:30
Dynamical initialization and hydrodynamic modeling of relativistic heavy-ion collisions	*Dr Chun Shen*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	11:30 - 11:50
Directed Flow of Quarks from the RHIC Beam Energy Scan Measured by STAR	*Gang Wang*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	11:50 - 12:10
Probing the transverse size of initial inhomogeneities with flow observables	*Frederique Grassi*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	12:10 - 12:30
Anisotropic hydrodynamic modeling of heavy-ion collisions at LHC and RHIC	*Mubarak Alqahtani*
Sala Mosaici-1, 3rd Floor, Palazzo del Casinò	12:30 - 12:50
Testing the system size dependence of hydrodynamical expansion and thermal particle production with identified particle measurements in Xe-Xe and Pb-Pb collisions with ALICE	*Francesca Bellini*

Many exciting results reported in the poster session

Theory overview:

Collective effects in nuclear collisions: theory overview	*Jorge Noronha*
Sala Grande, Palazzo del Cinema	11:30 - 12:00

Flow in small systems:

Study of small colliding systems	*Li Yi*
Sala Grande, Palazzo del Cinema	12:00 - 12:30

Thanks for your attentions!

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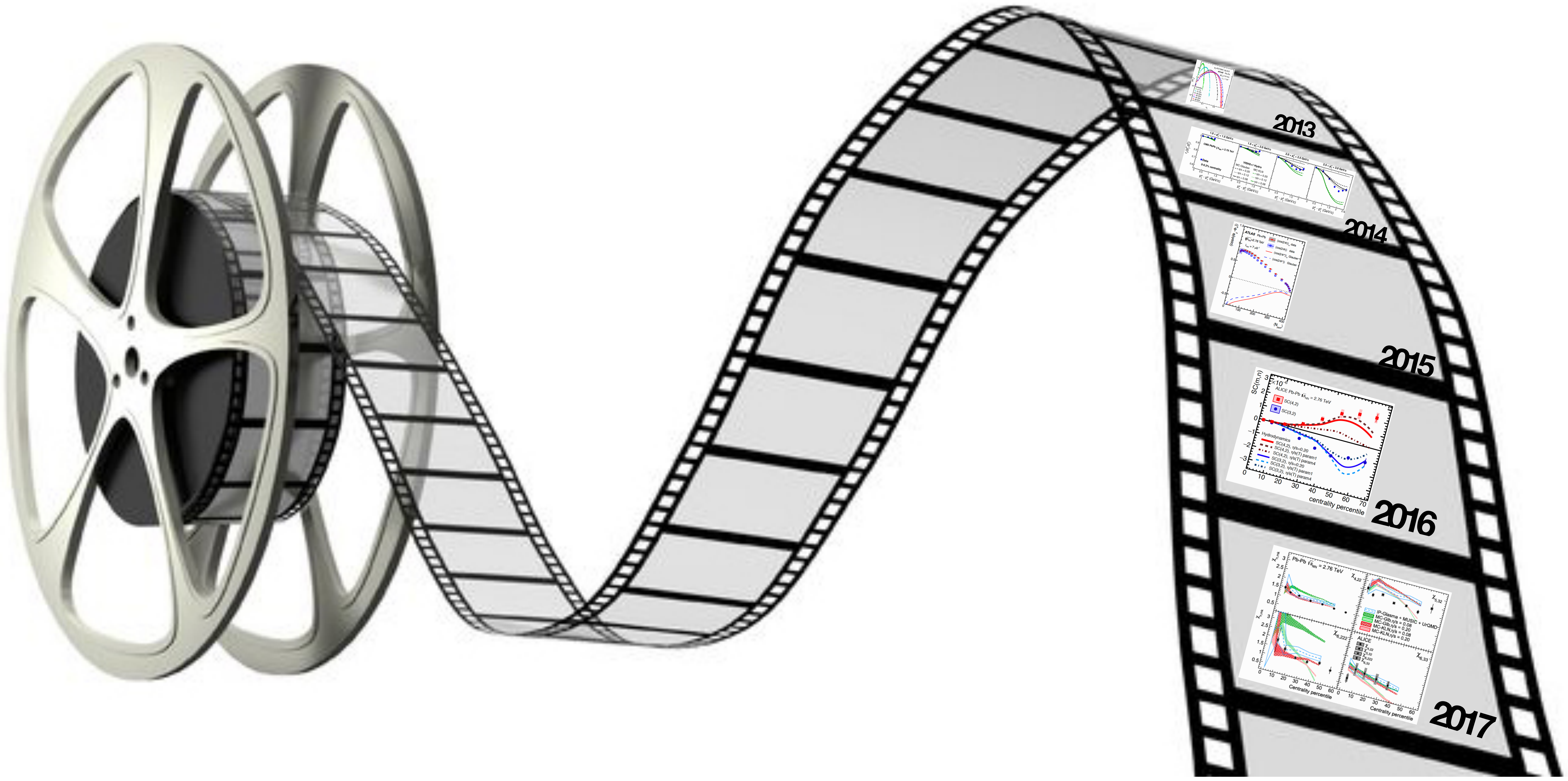
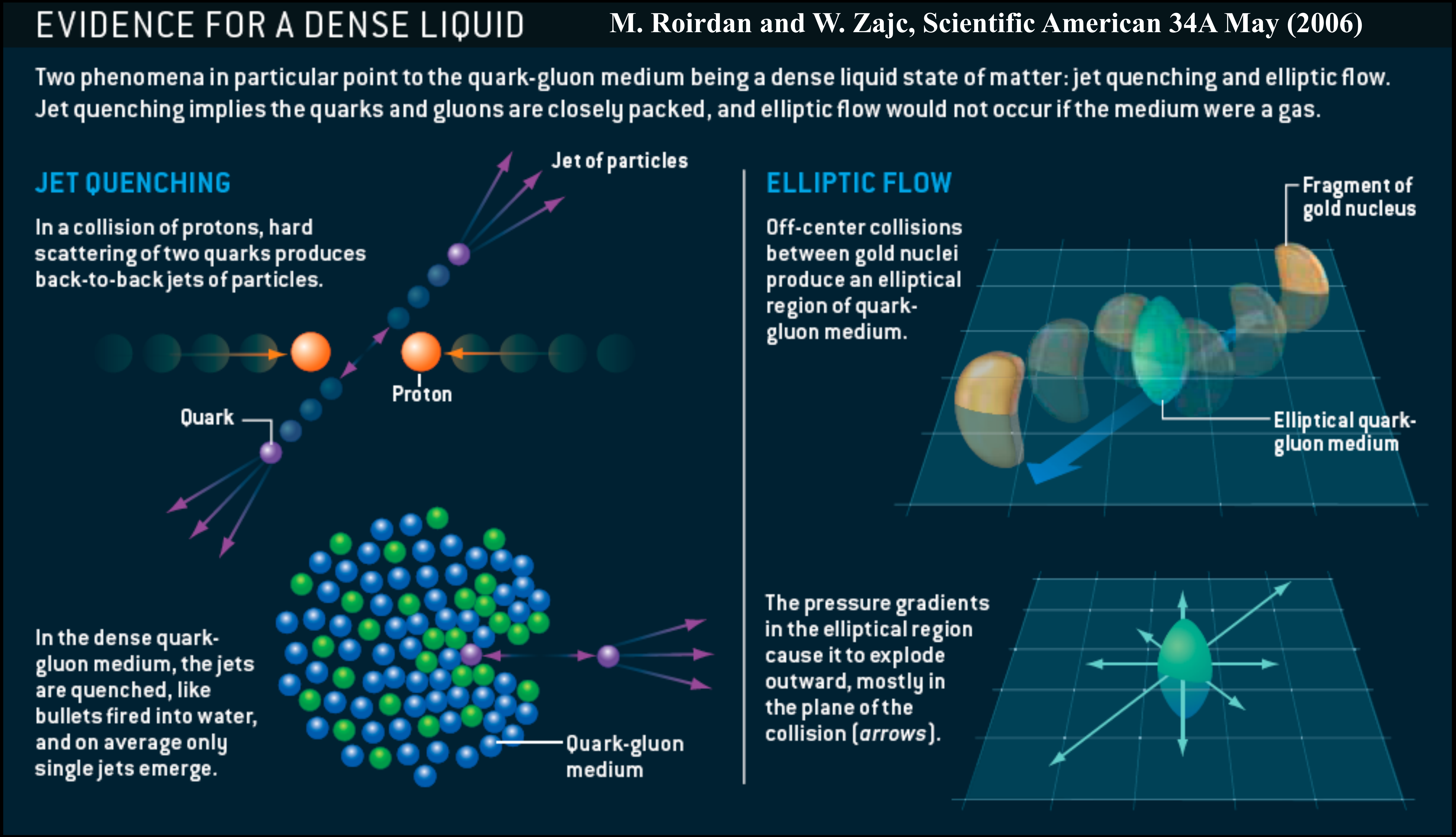

2013
2014
2015
2016
2017

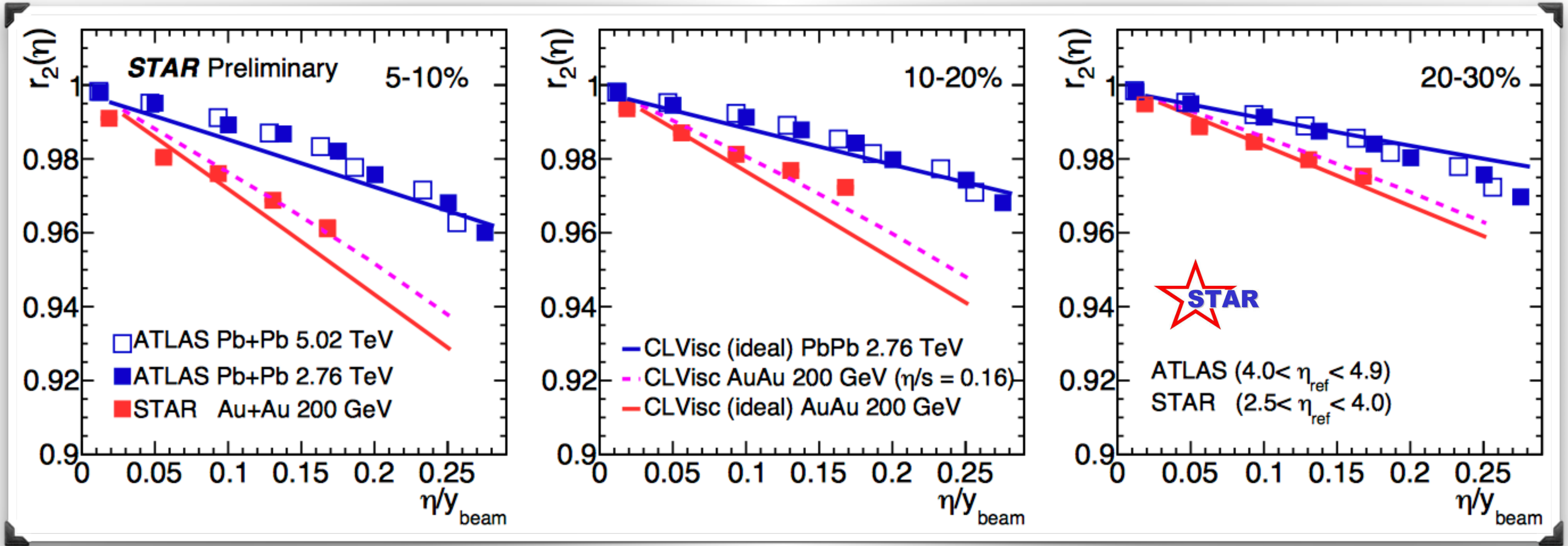
Probes of QGP



M. Roirdan and W. Zajc, Scientific American 34A May (2006)

STAR: Longitudinal decorrelation of V_2 at RHIC and the LHC

Talk: M. Nie, May 15th

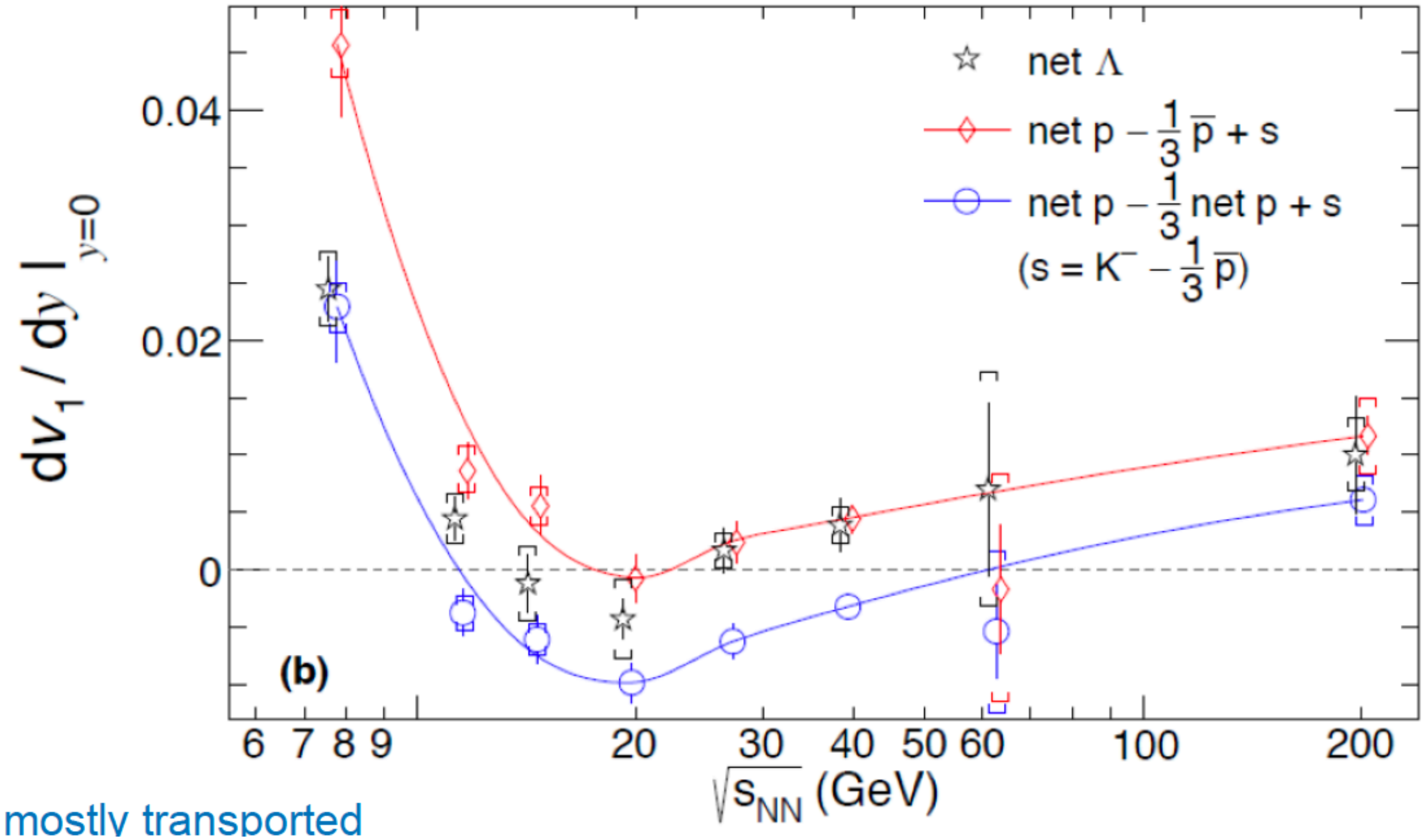


- Significant energy dependence is observed, ~ 2 times stronger de-correlation effect (vs pseudorapidity) than at the LHC energy 2.76 TeV
- Energy dependence remains after y_{beam} normalization, and changes with centrality
  - can't be explained by simple beam rapidity scaling
- Ideal hydro calculation, which roughly describes the LHC data, overestimates the decorrelation effect at RHIC.

Study the coalescence via net-particles v_1

STAR, PRL 120 (2018) 062301

Talk: G. Wang, May 16th



mostly transported

For net particles that contain transported quarks, replace a ***u*** quark in net p with an ***s*** quark to reproduce net-Λ in two scenarios.

- ☆ the ***u*** quark (being replaced) was produced: works at higher energies
- ☆ all the quarks in net p have the same v_1 (mostly transport quarks) works at the lowest energy.