IS2021

Review of Flow, Non-flow and Decorrelation Observables

Qipeng Hu (Lawrence Livermore National Laboratory)

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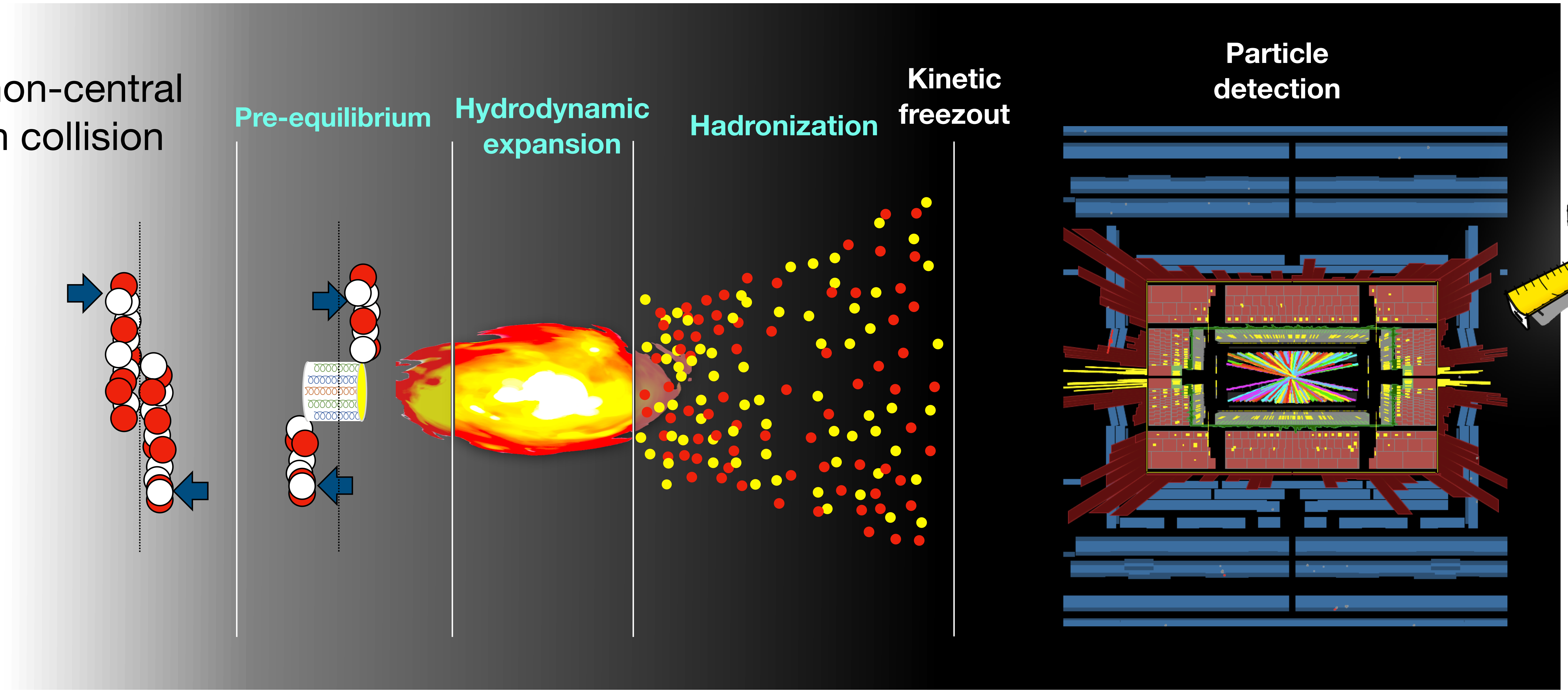
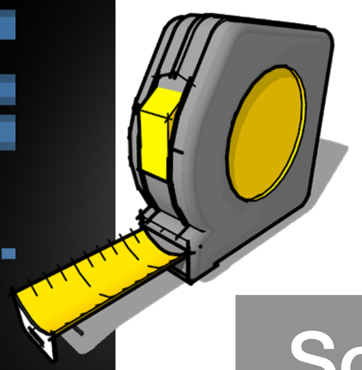
Initial Stages 2021, Online

Lawrence Livermore National Laboratory

Flow in heavy ion collisions

A typical non-central heavy-ion collision





Measurements

Soft particle spectra

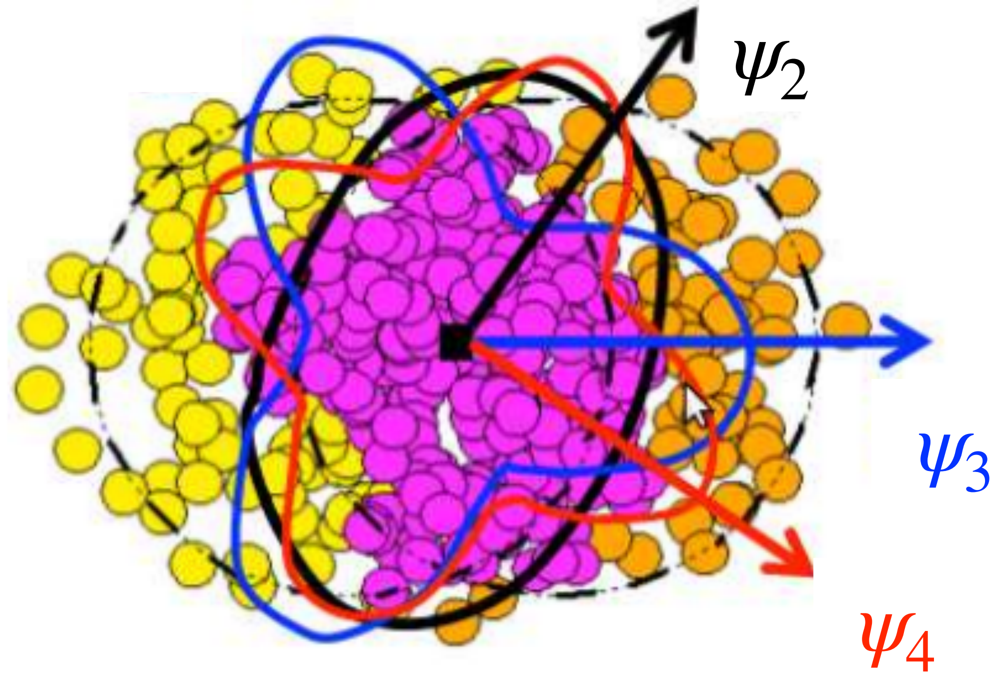
Azimuthal anisotropy

Interpretation

Hydrodynamic radial flow

Fluctuation

Hydrodynamic radial flow anisotropy



Event geometric orientation

Flow: Final state anisotropy, interpreted as **hydrodynamic flow**, correlated to the entire event orientation

Non-flow: anything else, locally anisotropy caused by multi-particle correlation

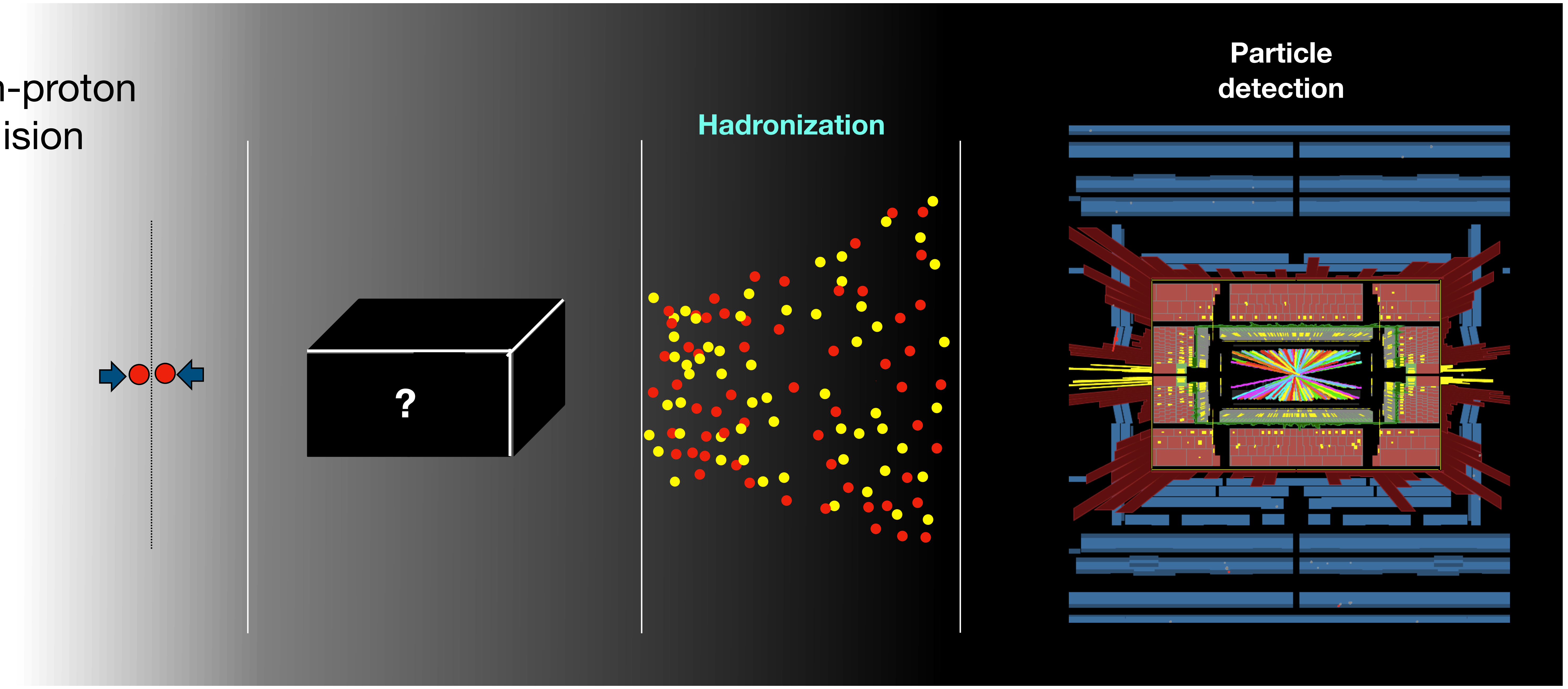
Main focus of this talk:

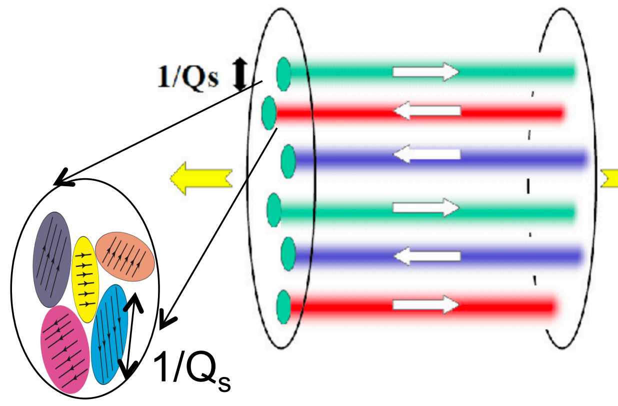
Hydrodynamic response to **initial state:** spatial and/or momentum anisotropy

Flow in small system

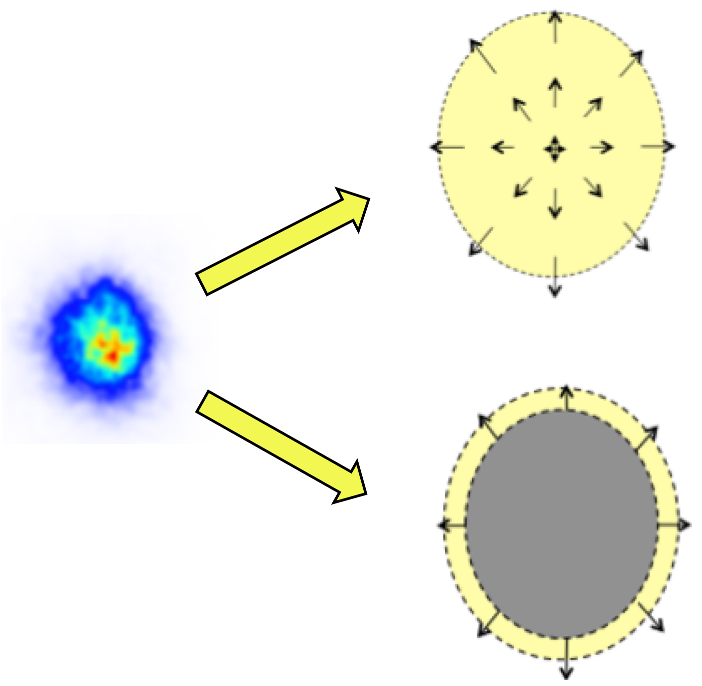
CMS, Phys. Lett. B 765 (2017) 193

Proton-proton collision





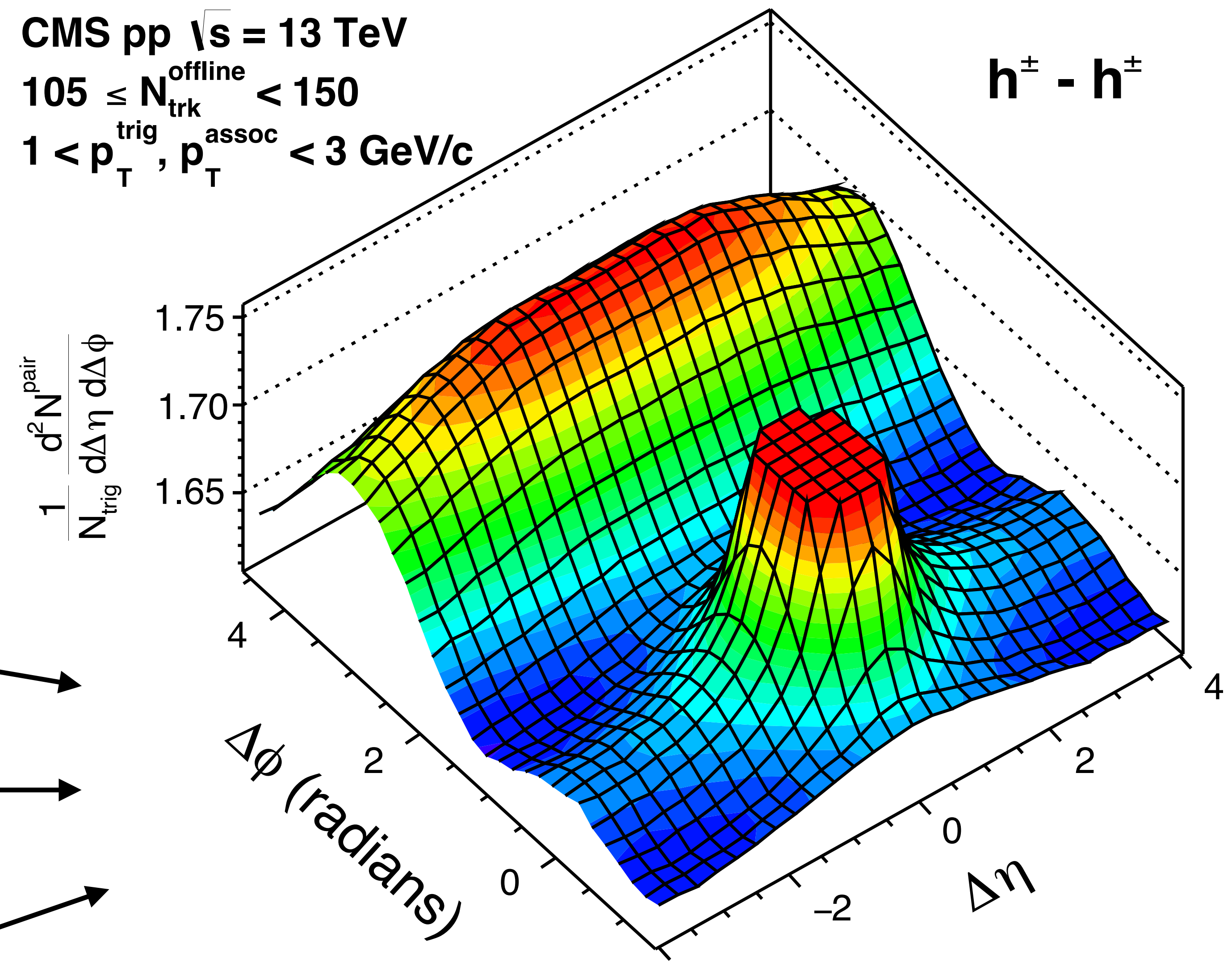
Momentum correlation



Hydro

Parton escape

Azimuthal anisotropy



"Flow" = measured anisotropy - **non-flow**

But hydrodynamic flow is not the only Interpretation

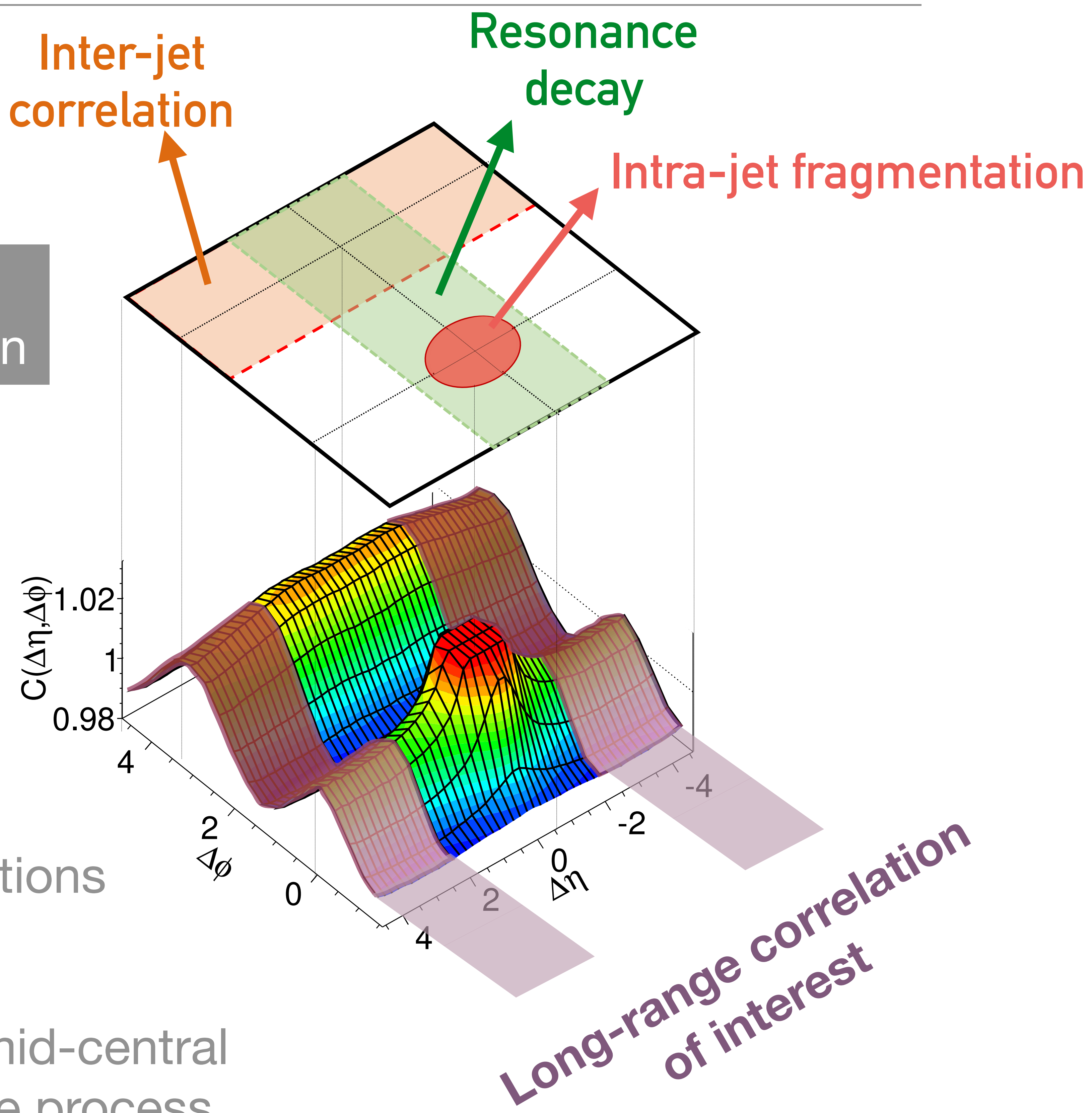
Observables — flow magnitude

Flow magnitude quantifies Fourier coefficient v_n of azimuthal (φ) anisotropy

$$P(\varphi) \propto 1 + 2\sum_n v_n \cos\left(n(\varphi - \Psi_n)\right) = \sum_{-\infty}^{\infty} V_n e^{-in\varphi}$$

v_n is determined from correlations:

Non-flow sources in two-particle correlation

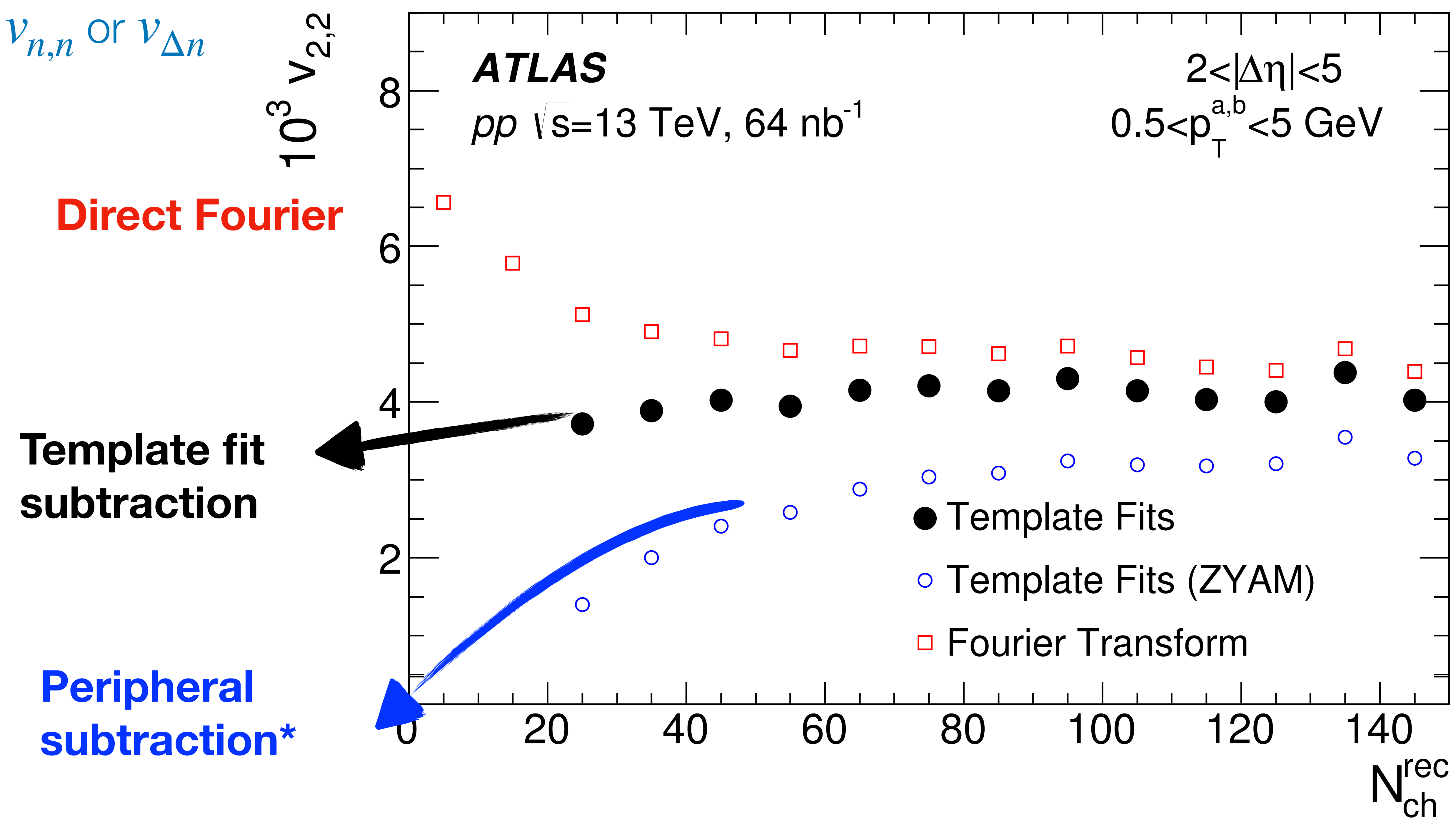


Correlation method	Non-flow Removal	Limitations	Applications
Event plane/ Scalar product	η gap (particle, EP) in definition	Jet bias in low multiplicity	Central/mid-central A+A, rare process
Two-particle correlation	η gap + non-flow subtraction	Subtraction sensitive to jet correlation	Small to large with meaningful results
Multi-particle cumulant	Sub-event method (w/ η gap)	Multi. jet residual; statistics	Extreme events (low multiplicity and or high p_T)

Non-flow subtraction in 2PC

ATALS, Phys. Rev. C 96 (2017) 024908

Two-particle $v_{n,n}$ or $v_{\Delta n}$



Flow-like anisotropy in small system is not necessarily a high multiplicity phenomenon

- Peripheral subtraction: $v_{n,n}(N_{\rm ch}=0) \sim 0$
- Template fit subtraction: $v_{n,n}(N_{\rm ch}=0)$ is allowed to be non-zero

Both methods use low multiplicity event to model non-flow at high multiplicity

Non-flow contribution becomes significant at low multiplicity and high p_T

* Template fit with ZYAM yields identical results as peripheral subtraction

Factorization and decorrelation

Model, S. McDonald at el., Phys. Rev. C 95 (2017) 064913
CMS, Phys. Rev. C 92 (2015) 034911

Correlation of hydrodynamic flow factorizes in an ideal world, for two-particle correlation:

$$v_{n,n}(a,b) = v_n(a) \cdot v_n(b)$$

Determination of $v_n(p_\mathrm{T}^a, \eta^a)$ is independent of choices of particle b

Breaking of factorization is called **decorrelation**

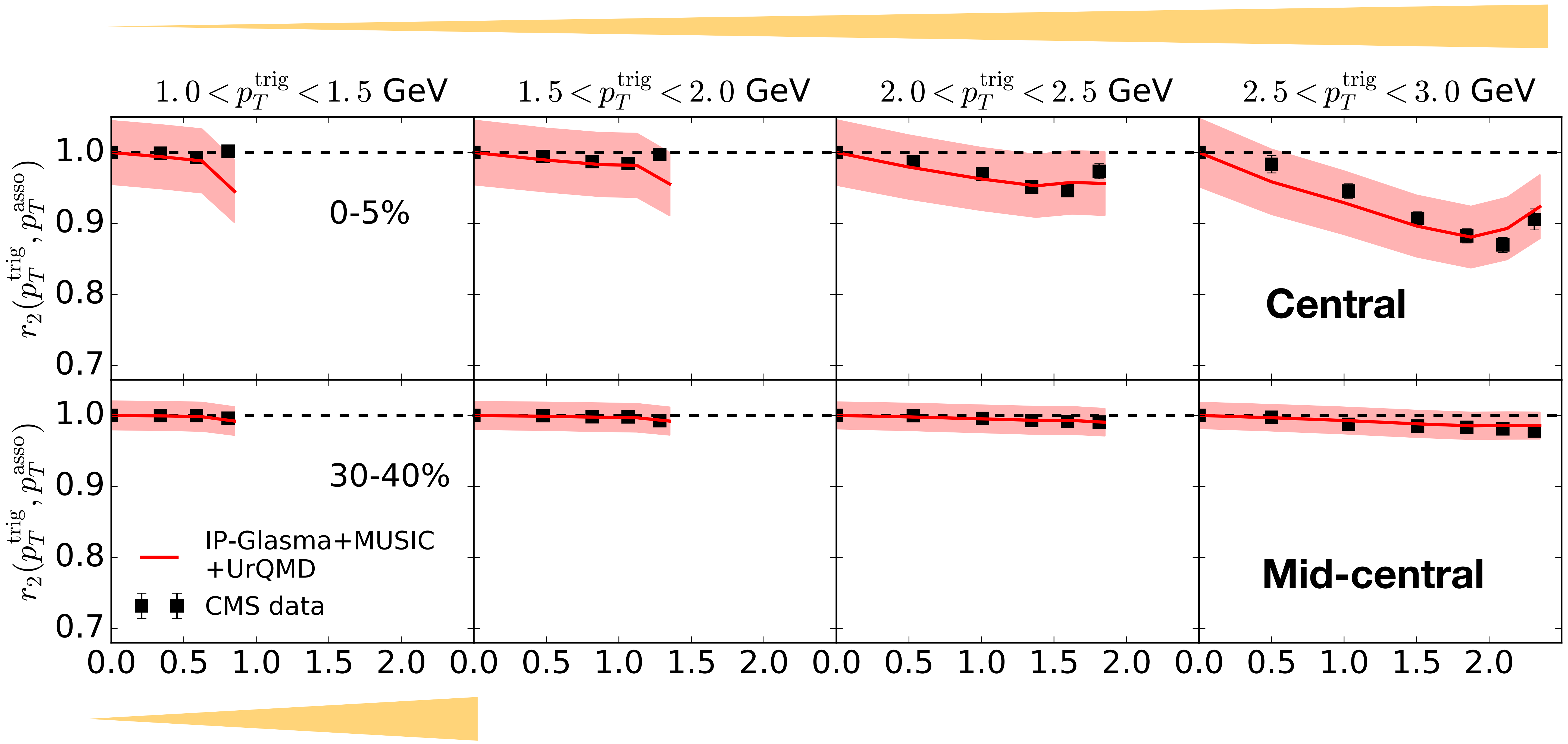
Decorrelation in p_T:

- Non-flow, pronounced in peripheral/low multiplicity
- Fluctuation of energy density, $\Psi_n(p_\mathrm{T}^a) \neq \Psi_n(p_\mathrm{T}^b)$, pronounced in central, described by hydro

$$r_n(p_\mathrm{T}^a - p_\mathrm{T}^b) = \frac{v_{n,n}(p_\mathrm{T}^a, p_\mathrm{T}^b)}{v_n(p_\mathrm{T}^a) \cdot v_n(p_\mathrm{T}^b)}$$

Quantify relative decorrelation with $\Delta p_\mathrm{T} = p_\mathrm{T}^a - p_\mathrm{T}^b$

p_T^a



$p_\mathrm{T}^a - p_\mathrm{T}^b$

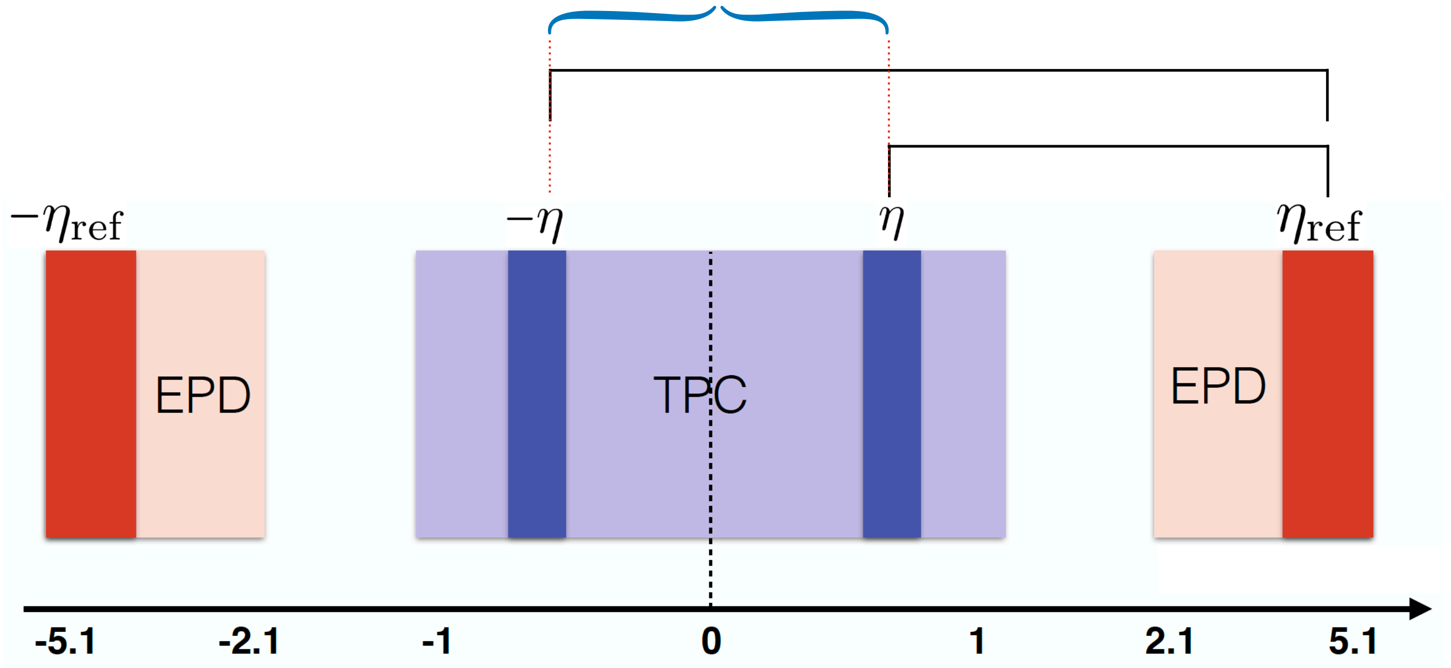
Longitudinal flow decorrelation

STAR, QM2019

Hydro, L. Pang at el. Phys. Rev. C 97 (2018) 064918

$$r_n(\eta) = \frac{v_{n,n}(-\eta, \eta^{\text{ref}})}{v_{n,n}(+\eta, \eta^{\text{ref}})}$$

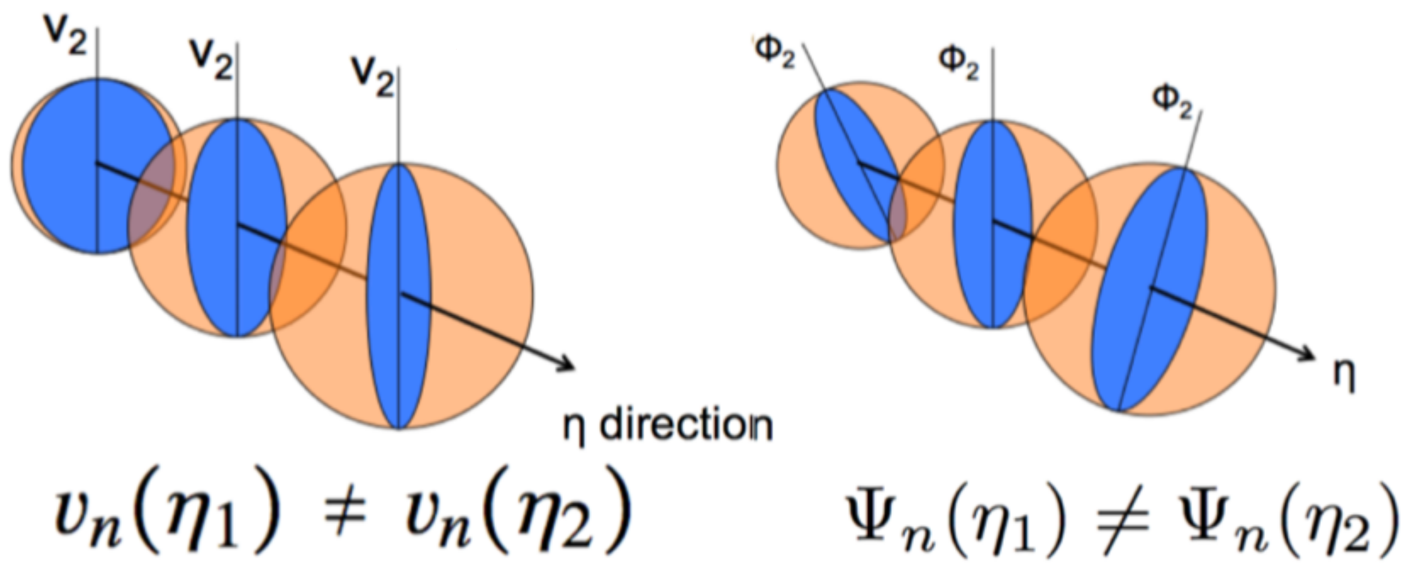
Quantify relative decorrelation with $\Delta\eta = 2\eta$



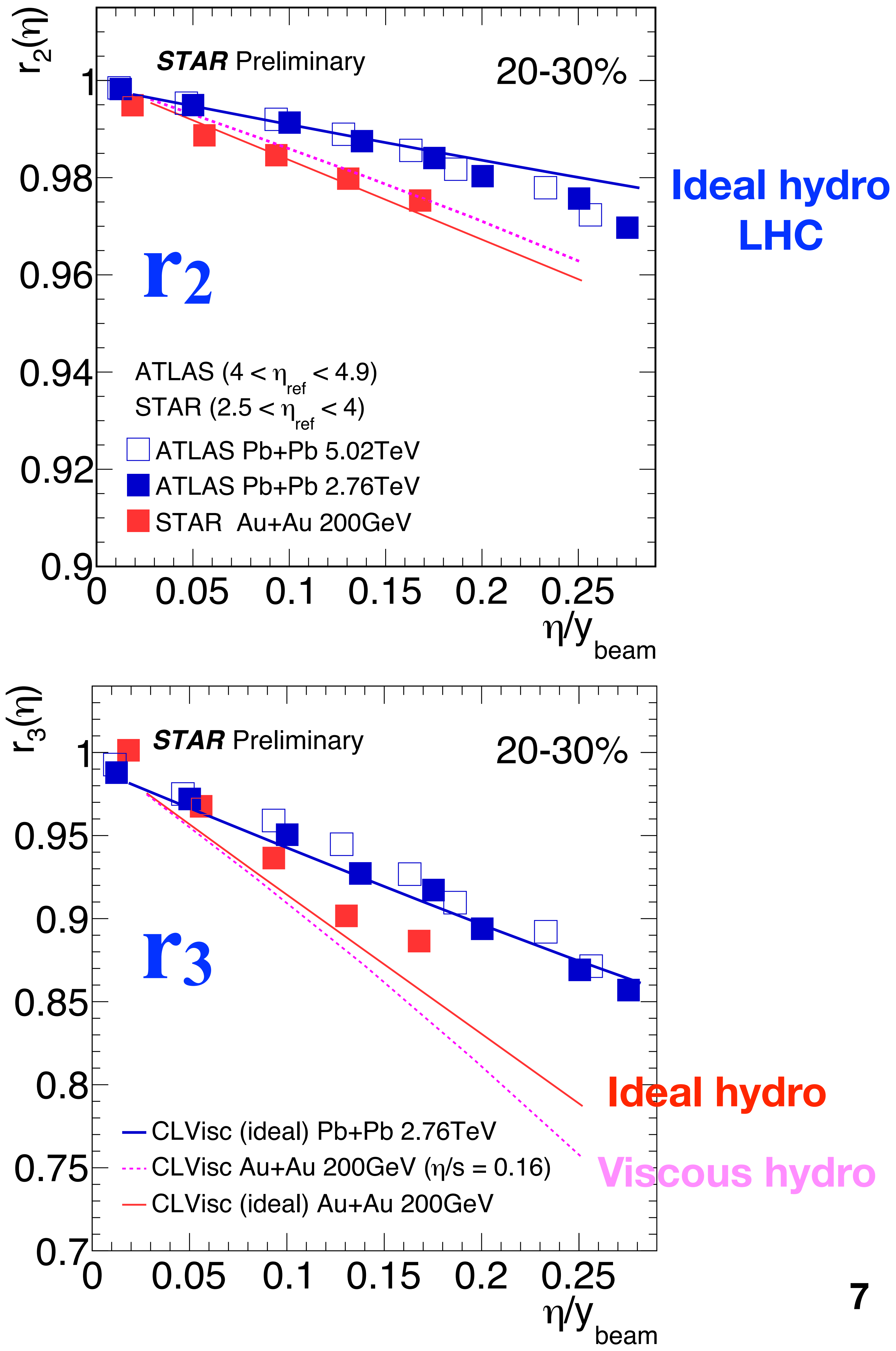
Decorrelation in η:

- Non-flow
- Longitudinal initial state fluctuation, longitudinal hydro evolution, described by hydro

J. Jia et al., arXiv:1701.02183

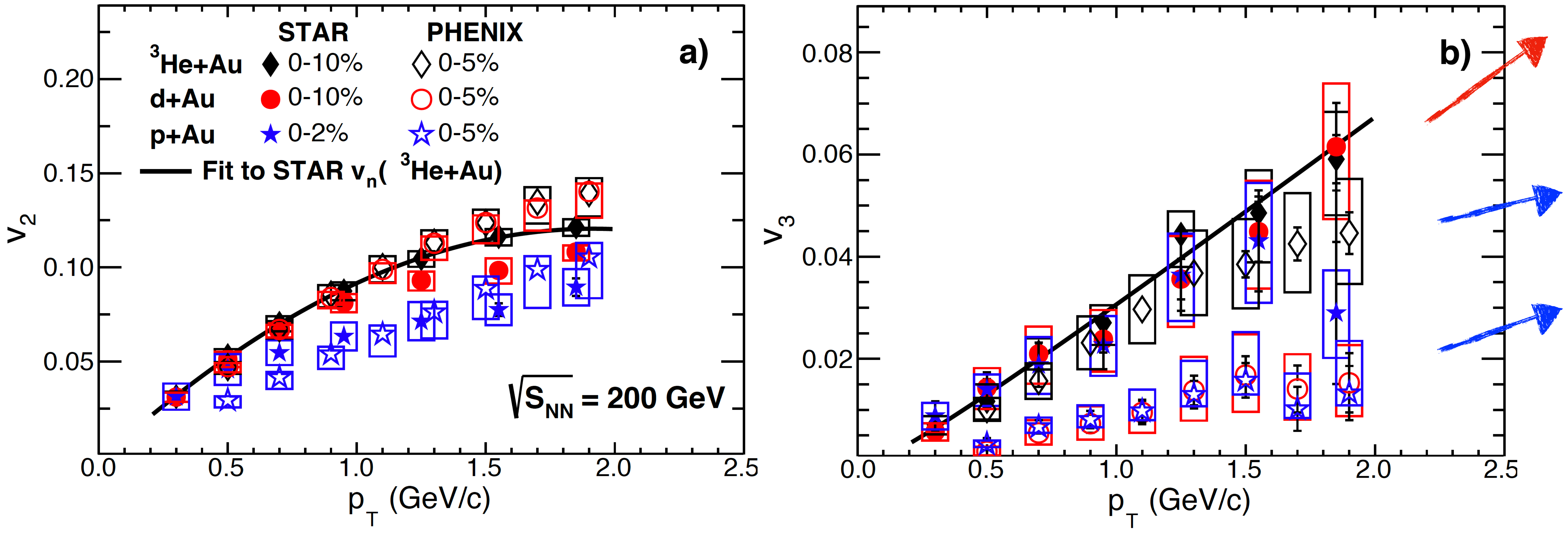


- Longitudinal decorrelation observed at LHC and RHIC, larger decorrelation effect for higher order
- Hydro gives reasonable description of decorrelation in Au+Au and Pb+Pb, insensitive to viscous effect



Non-flow and decorrelation

PHENIX Nature Phys. 15 (2019) 214-220
STAR, QM2019

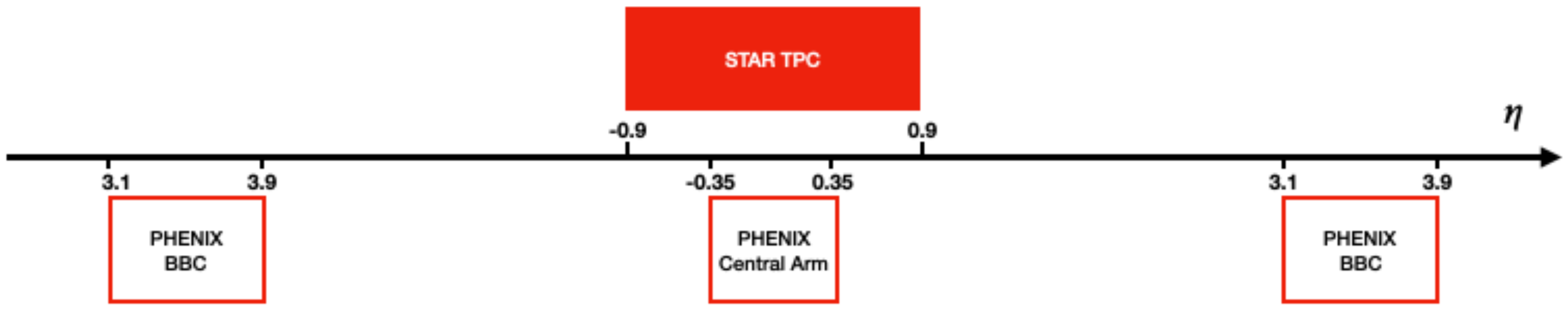


STAR
p+Au, d+Au, ^{3}He+Au

PHENIX
^{3}He+Au

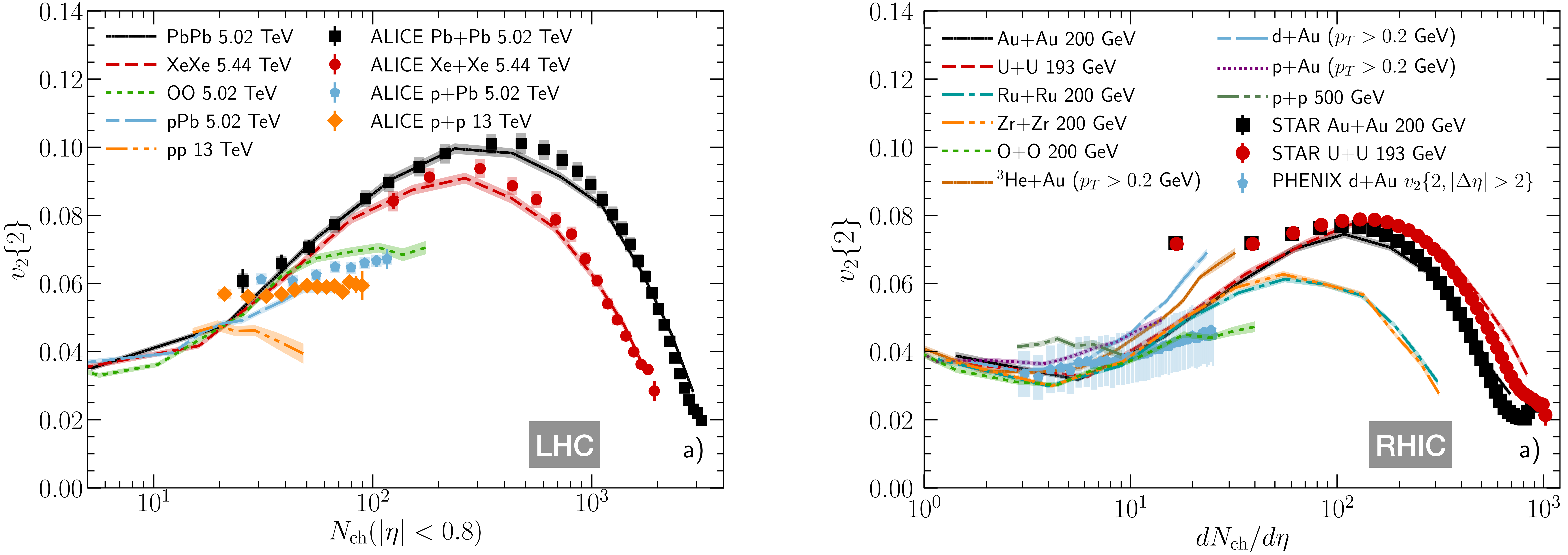
PHENIX
p+Au, d+Au

- Good agreement in v_2; while discrepancy in v_3
- On-going task force understanding v_3. Check longitudinal dynamics etc.
- Impacts of non-flow and decorrelation should be evaluated in flow measurements



Test the limit of model

B. Schenke et al., Phys. Rev. C 102 (2020) 044905
ALICE, Phys. Rev. Lett. 123, 142301 (2019)



- LHC (ALICE) and RHIC v_2 results vs. hybrid framework IP-Glasma+MUSIC+UrQMD
- Model cannot describe low multiplicity data results where non-flow subtraction is sensitive to its assumption

Mixed harmonic correlation

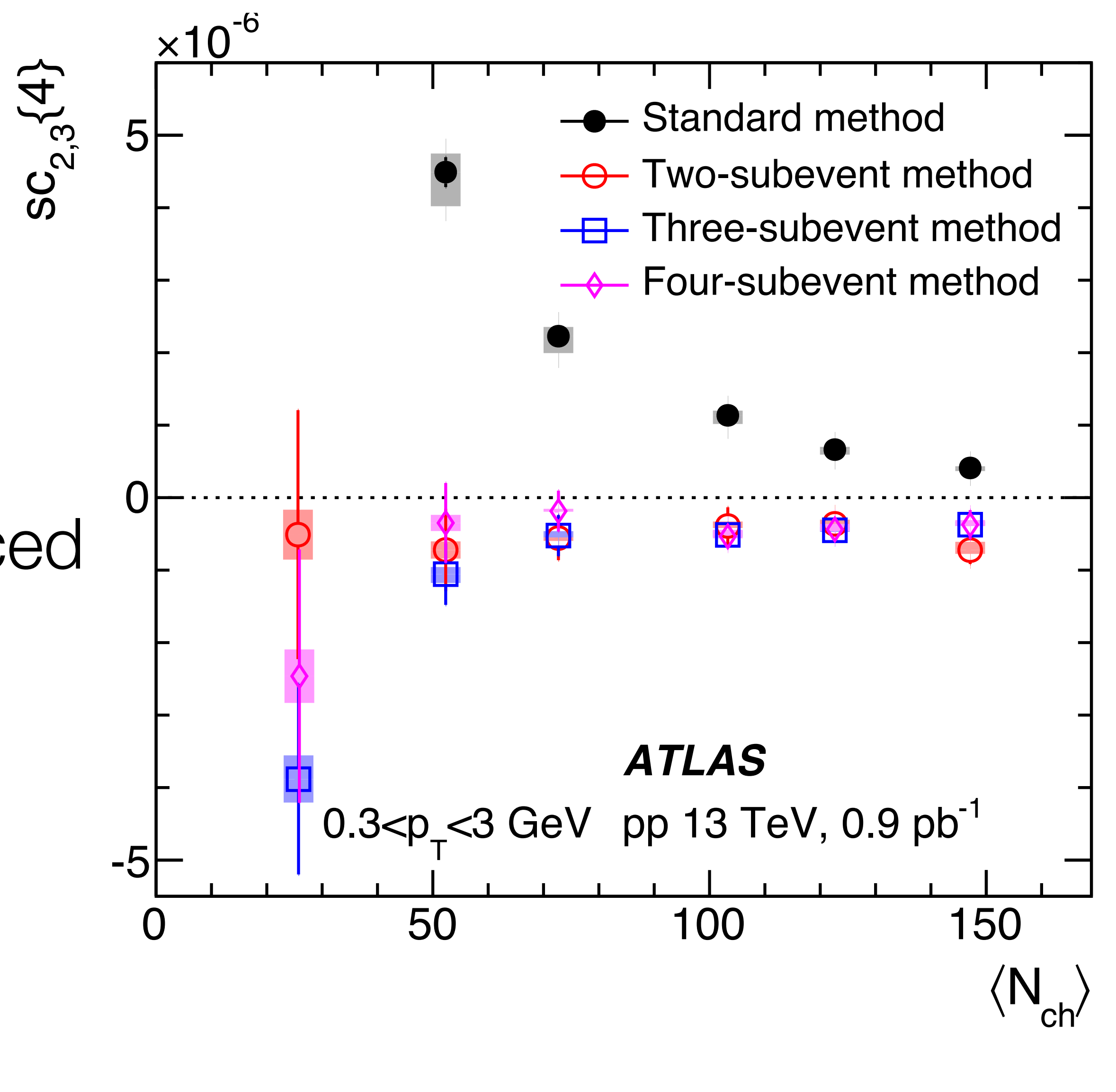
ATLAS Phys. Lett. B. 789 (2019) 444
ALICE Phys. Rev. Lett. 123, 142301 (2019)
Hybrid model, H. Mäntysaari et al., Phys. Lett. B772 (2017) 681

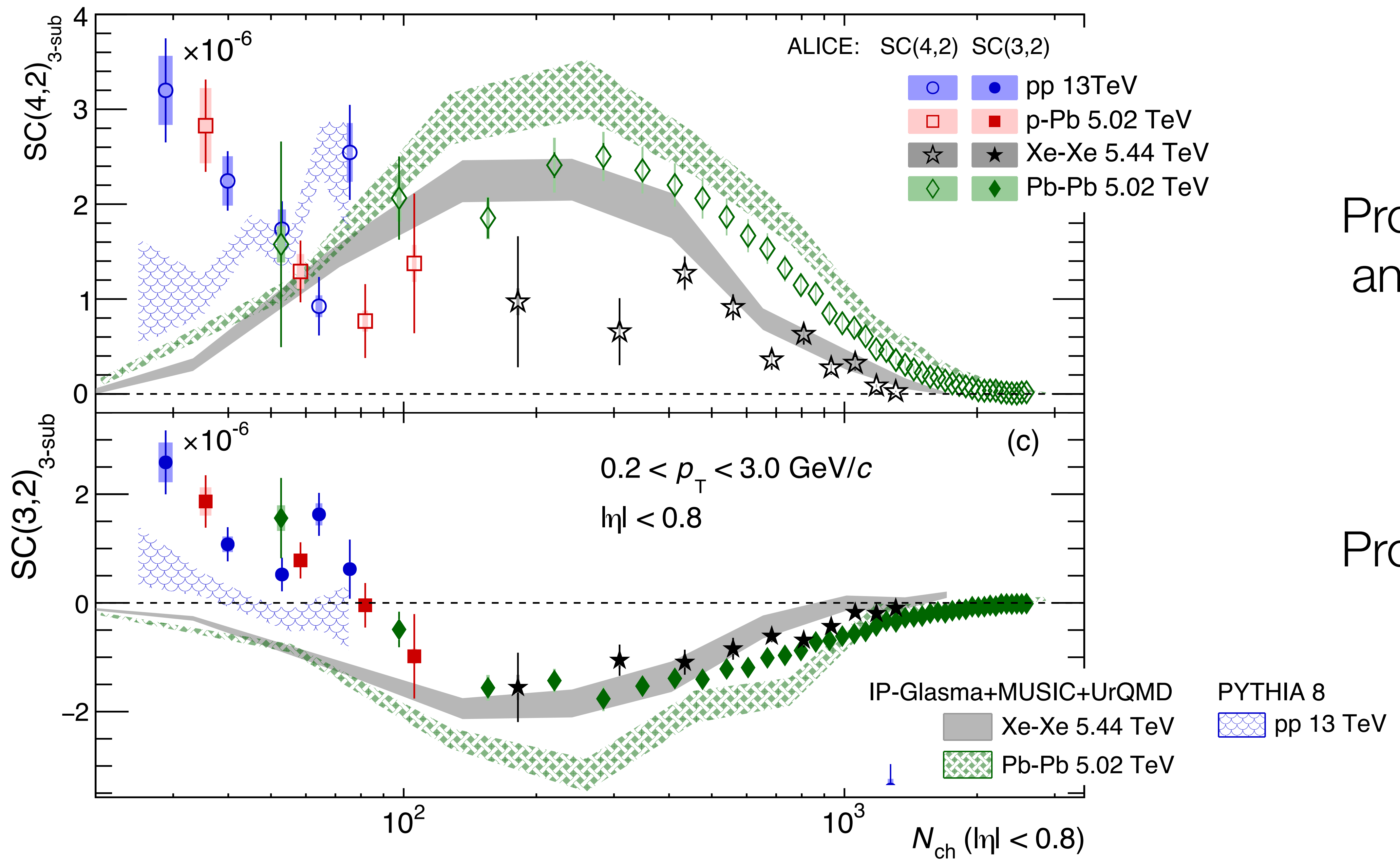
Correlation of flow magnitude

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

pp data

Non-flow reduced by sub-events, residual at low multiplicity





SC(4,2)
Probing initial condition and medium evolution

SC(3,2)
Probing initial condition

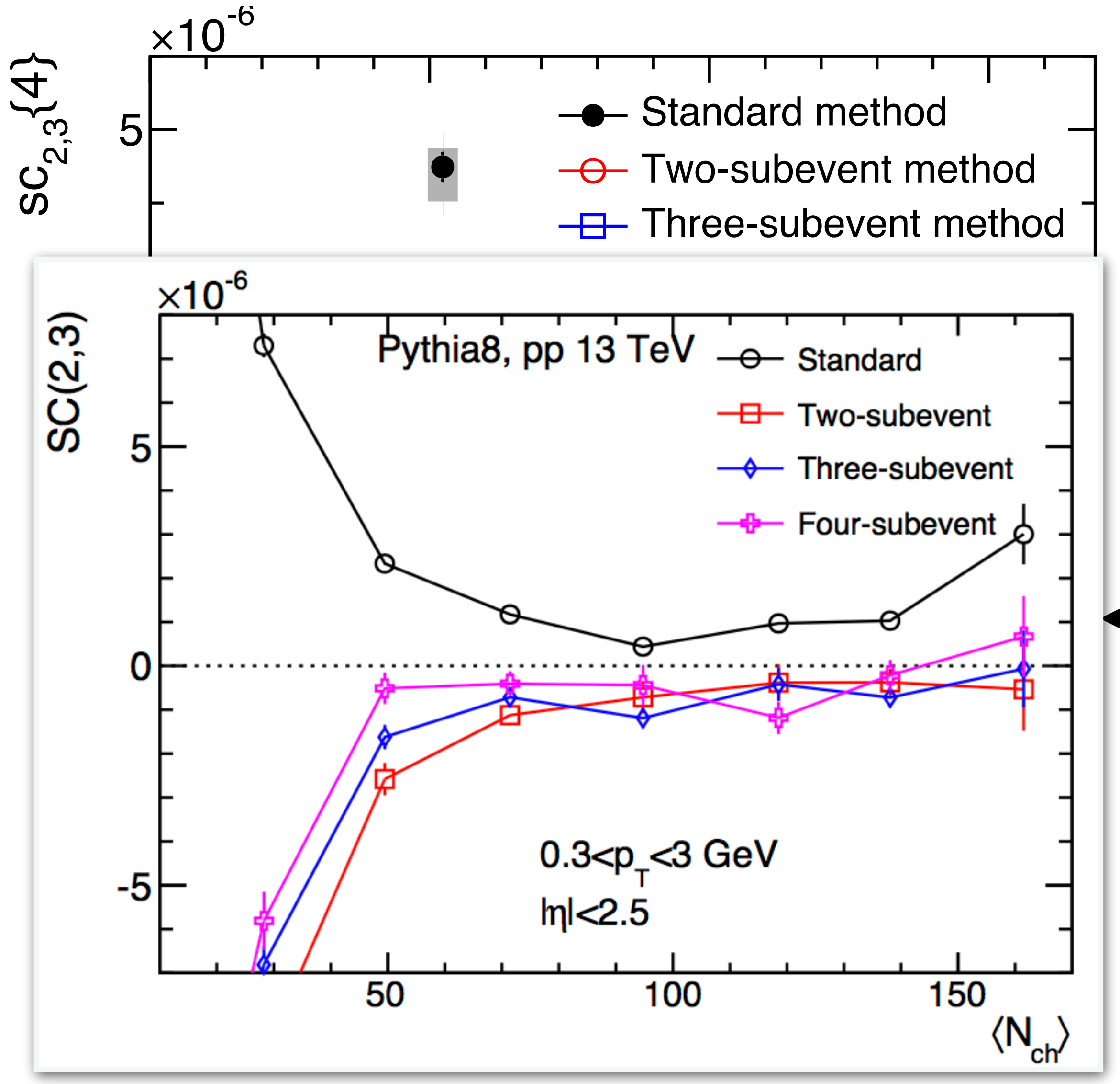
- SC(4,2) stays positive, due to nonlinear effect, sensitive to initial condition and evolution
- SC(3,2) negative at high multiplicity, anti-correlation between ε_2 and ε_3
- SC(3,2) positive at low multiplicity *pp* (ALICE)

Mixed harmonic correlation

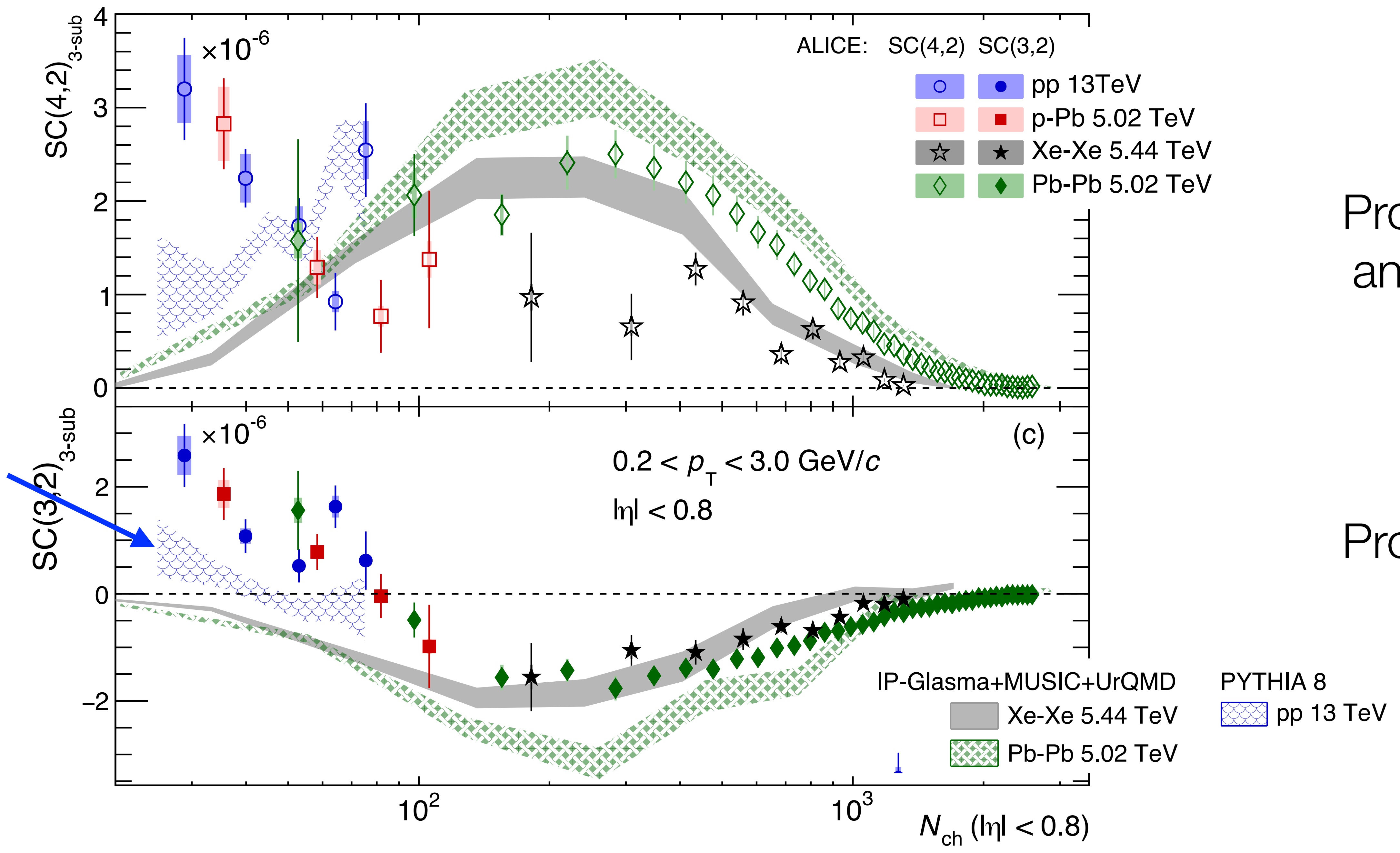
ATLAS Phys. Lett. B. 789 (2019) 444
ALICE Phys. Rev. Lett. 123, 142301 (2019)
Hybrid model, H. Mäntysaari et al., Phys. Lett. B772 (2017) 681

Correlation of flow magnitude

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



Pythia



SC(4,2)
Probing initial condition and medium evolution

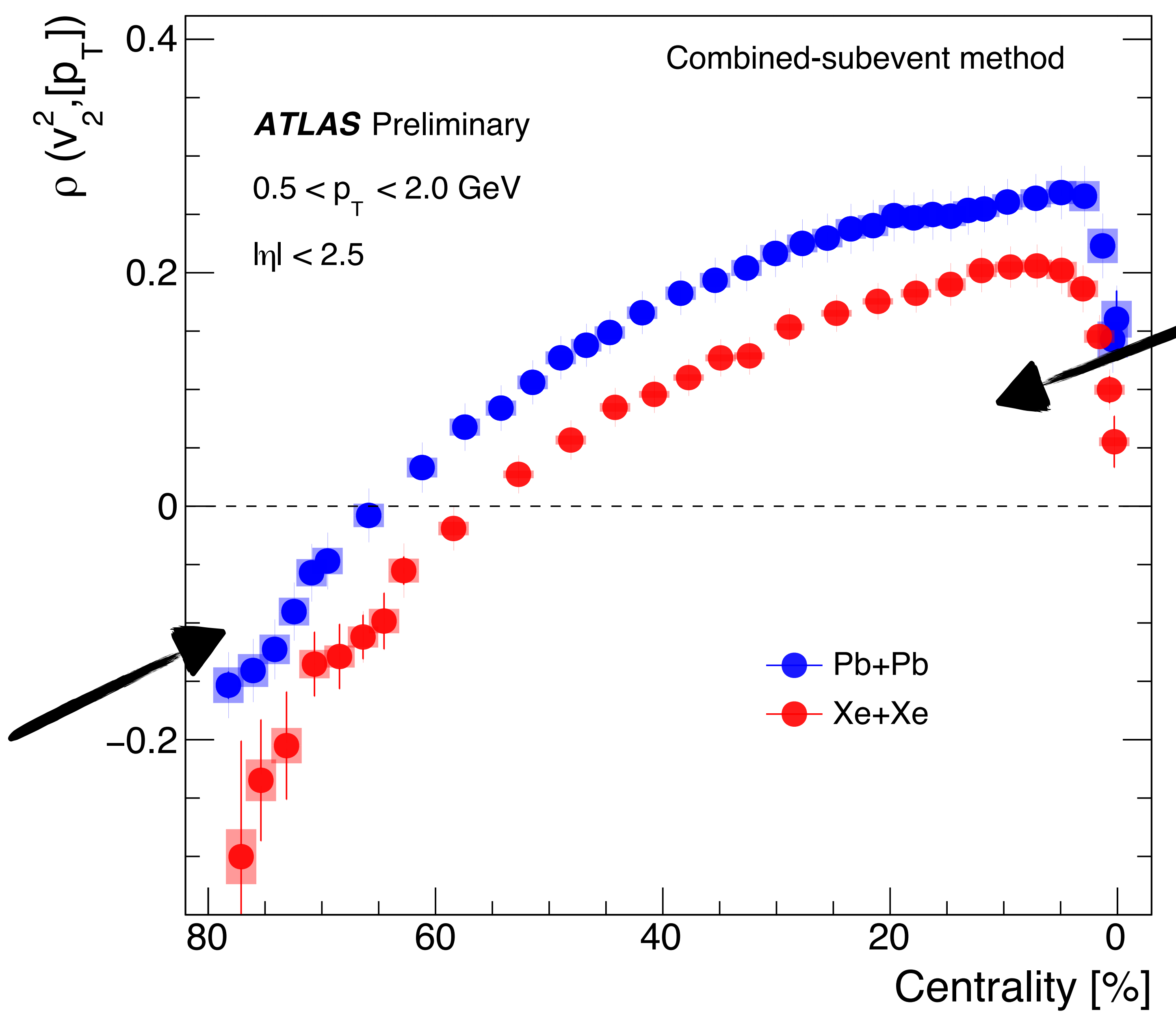
SC(3,2)
Probing initial condition

- $SC(4,2)$ stays positive, due to nonlinear effect, sensitive to initial condition and evolution
- $SC(3,2)$ negative at high multiplicity, anti-correlation between ε_2 and ε_3
- $SC(3,2)$ positive at low multiplicity *pp* (ALICE), ATLAS-ALICE difference: different event selection and non-flow

v_n-p_T correlation in large system

Piotr Bożek, Phys. Rev. C 93 (2016) 044908
ATALS: ATLAS-CONF-2021-001

$$\rho(v_n^2, \langle p_\mathrm{T}\rangle) = \frac{\langle v_n^2 \langle p_\mathrm{T}\rangle\rangle - \langle v_n^2\rangle\langle\langle p_\mathrm{T}\rangle\rangle}{\sigma(v_n^2)\sigma(\langle p_\mathrm{T}\rangle)}$$



Smaller hotter fireball:
- Larger $\langle p_T \rangle$
- Larger hydro response

Smaller hotter fireball:
- Larger $\langle p_T \rangle$
- Smaller ε_2

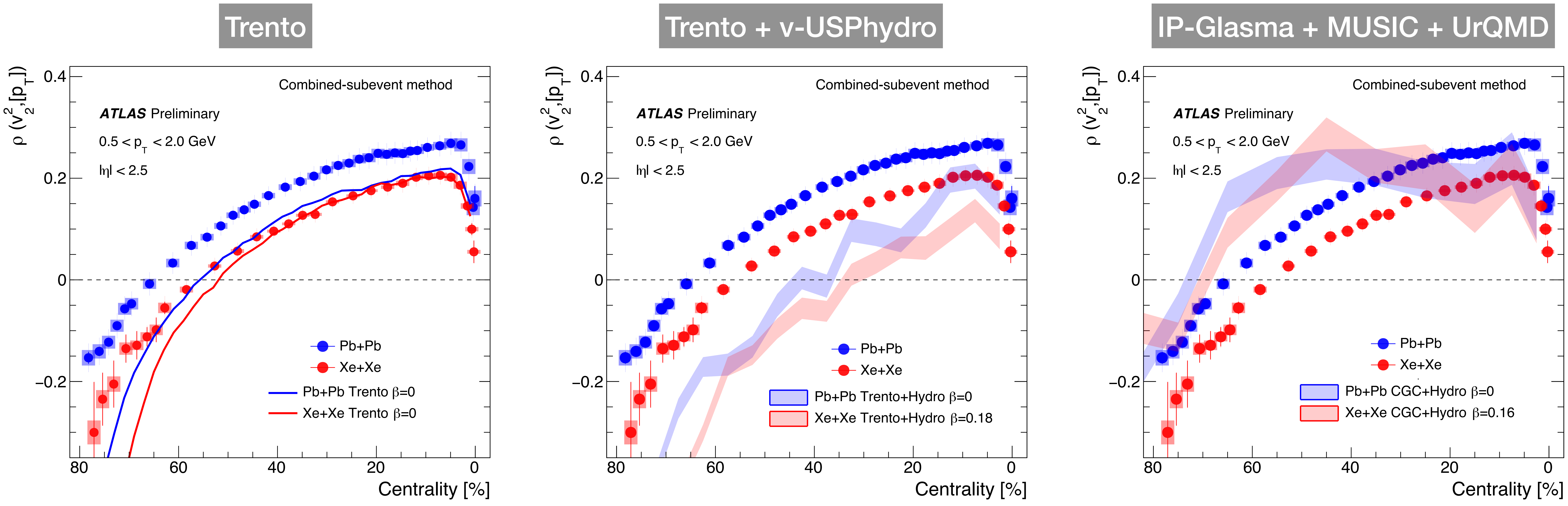
- Central: positive correlation driven by hydro response, sensitive to nuclear deformation
- Peripheral: negative correlation driven by initial geometry eccentricity

v_n-p_T correlation in large system

ATLAS: ATLAS-CONF-2021-001

Trento: G. Giacalone et al. Phys. Rev. C 102 (2020) 024901

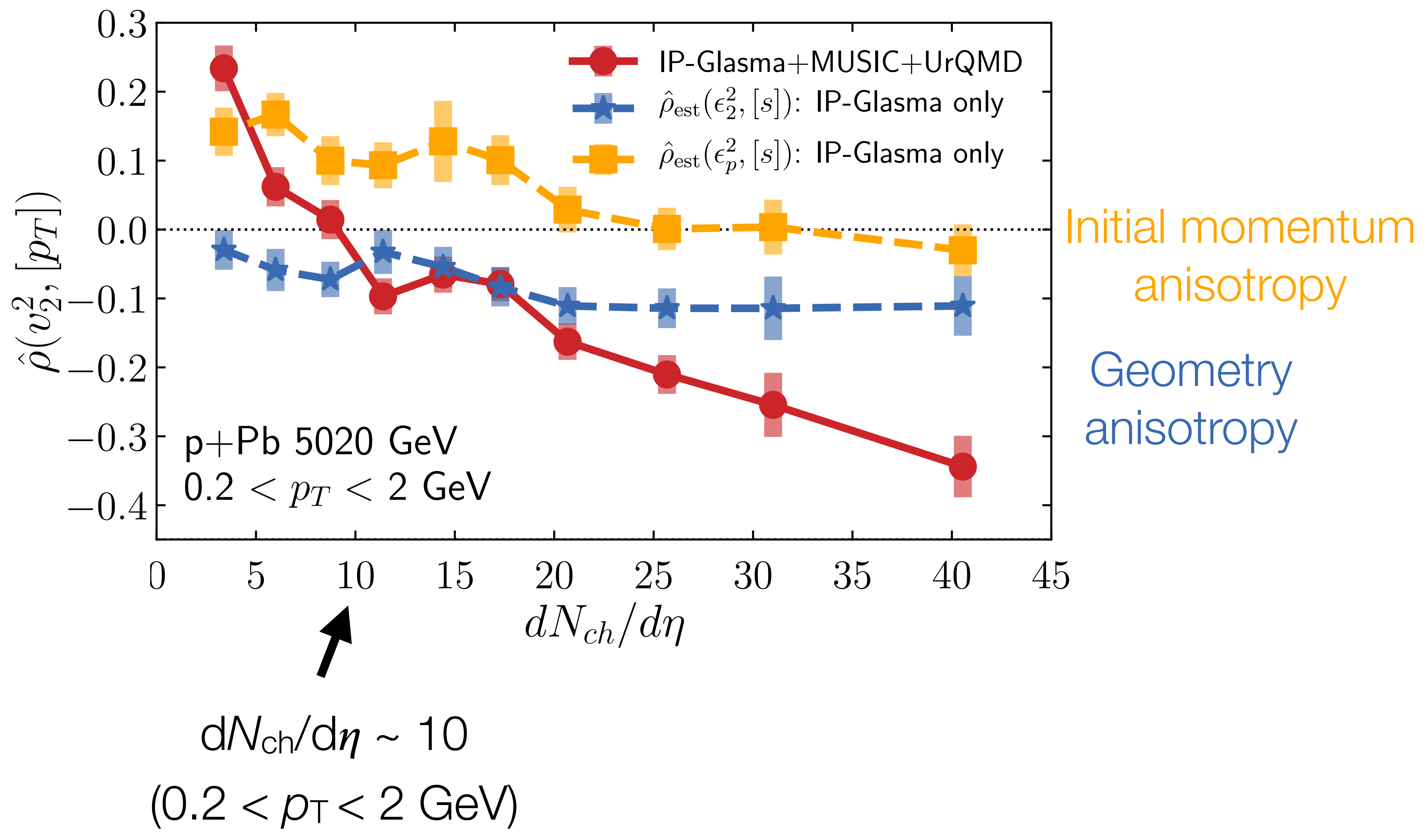
IP-Glasma+MUSIC+UrQMD: B. Schenke et al. Phys. Rev. C 102 (2020) 034905

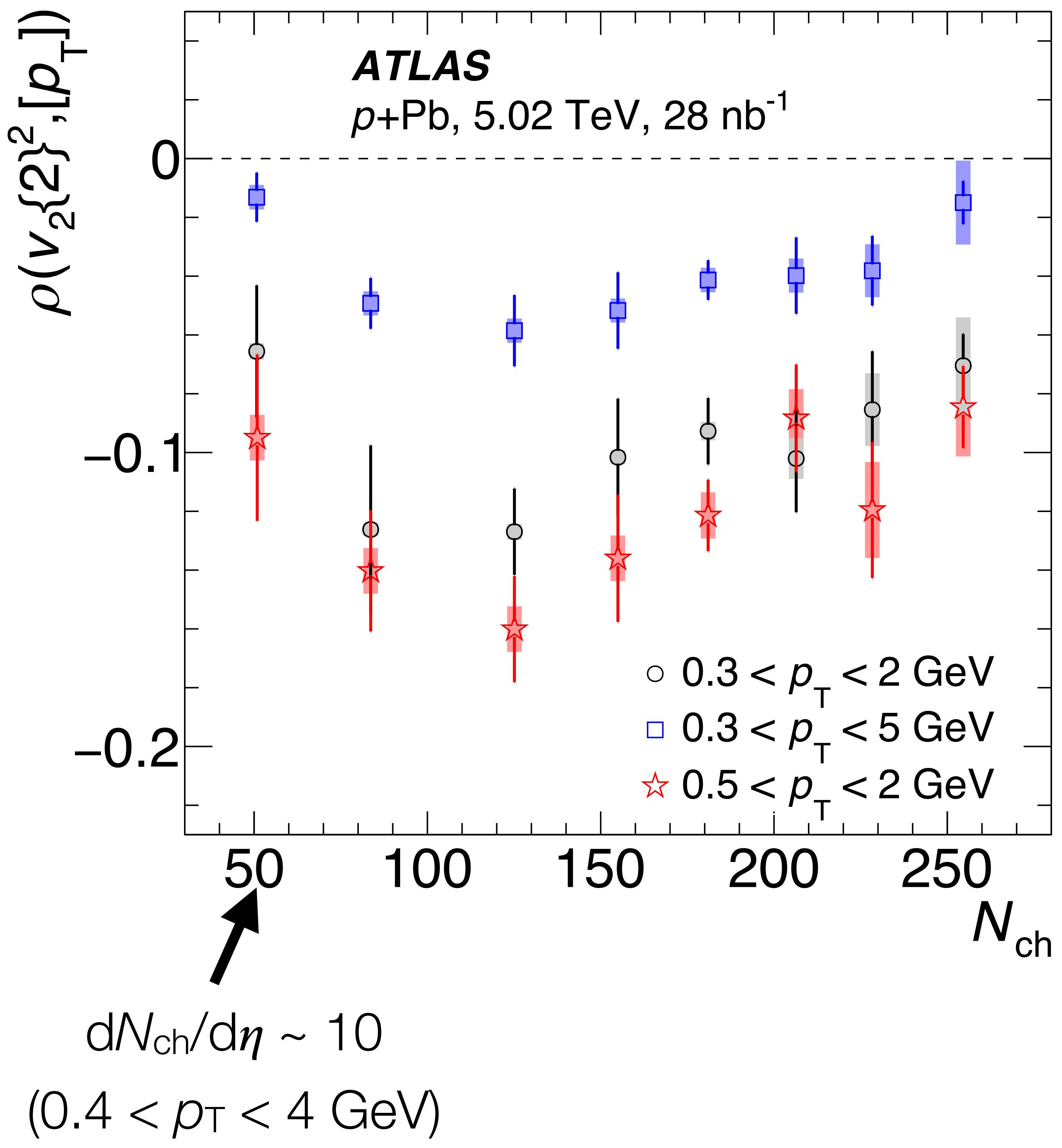


- Trento initial-state predictor give right ordering and centrality dependence, not the magnitude
- Trento+v-USPhydro has the right ordering but underestimates the magnitude
- IP-Glasma+MUSIC+UrQMD overestimates magnitude in peripheral, no clearing ordering

v_n-p_T correlation in small system

G. Giacalone et al. Phys. Rev. Lett. 125 (2020) 192301
ATLAS Eur. Phys. J. C 79 (2019) 985





v_n-p_T correlation in p+A with different origins:

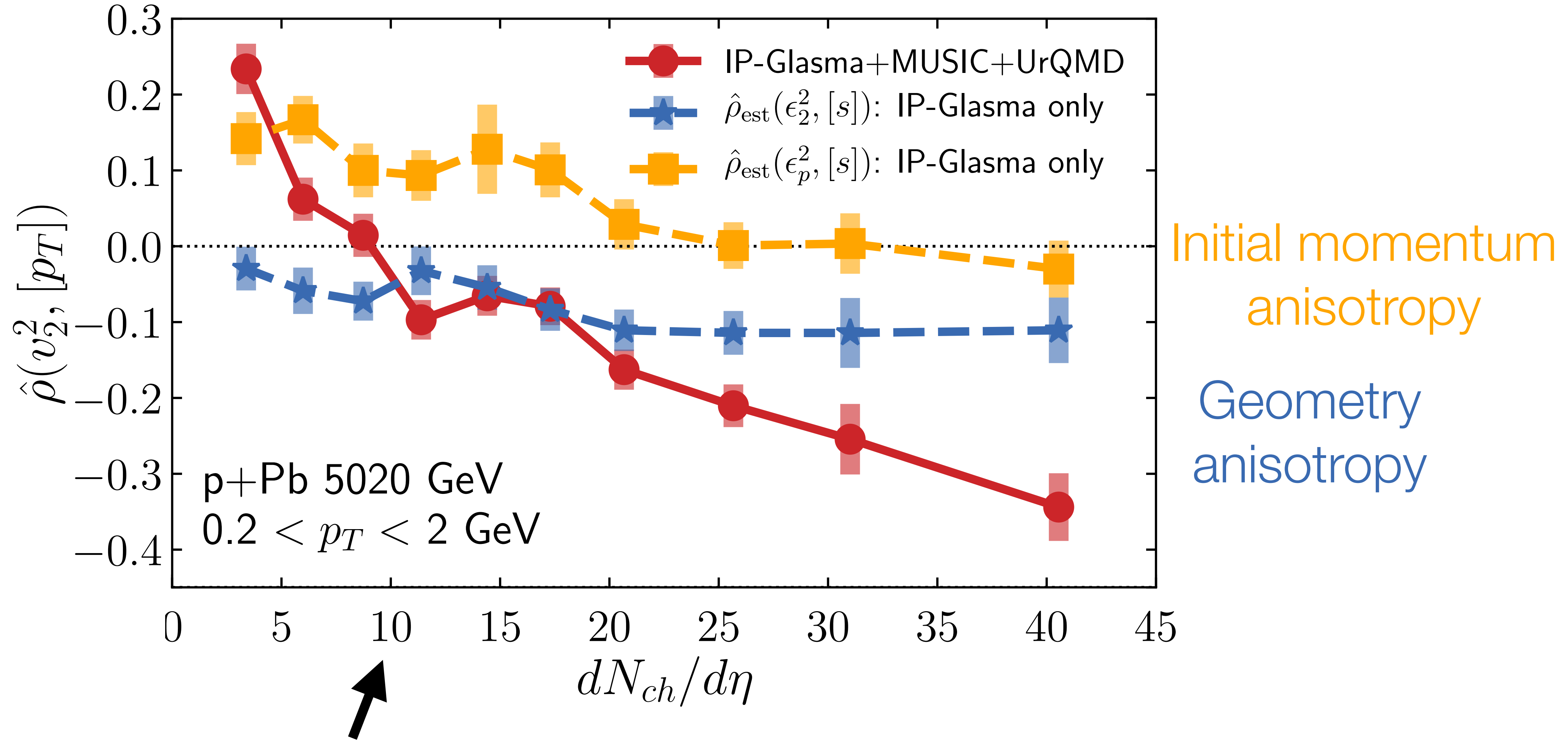
- IS geometry anisotropy: negative as in peripheral Pb+Pb
- IS momentum anisotropy: positive, smaller size → larger $\langle p_T \rangle$ → less color domain

Sign change due to initial momentum anisotropies is predicted for p+A at low multiplicity

Challenge in measurements: statistics for subevent cumulants, non-flow

v_n-p_T correlation in small system

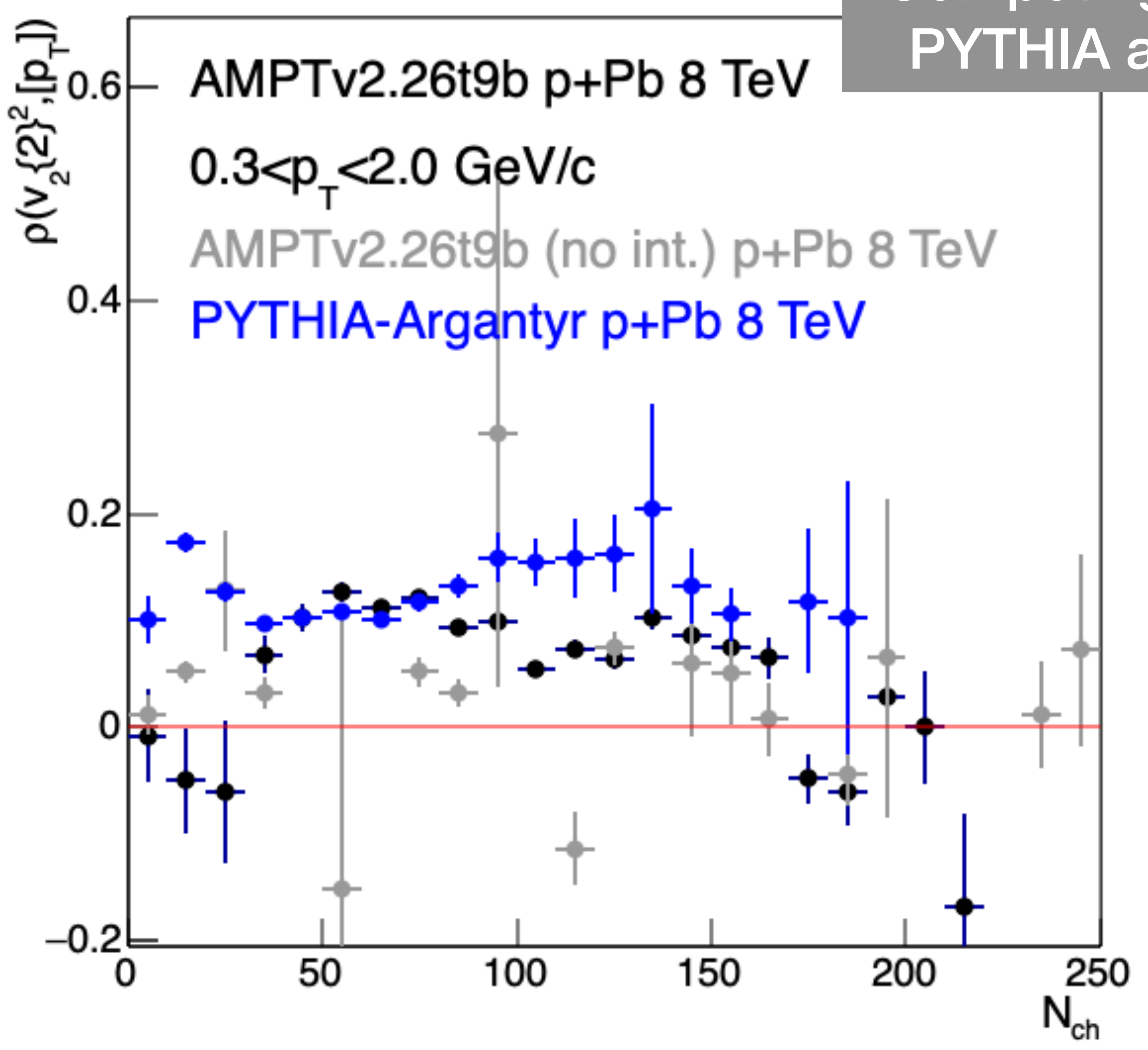
G. Giacalone et al. Phys. Rev. Lett. 125 (2020) 192301



$dN_{ch}/d\eta$ ~ 10

($0.2 < p_T < 2$ GeV)

S. Lim, J. Nagle



Competing effects in PYTHIA and AMPT

v_n-p_T correlation in p+A with different origins:

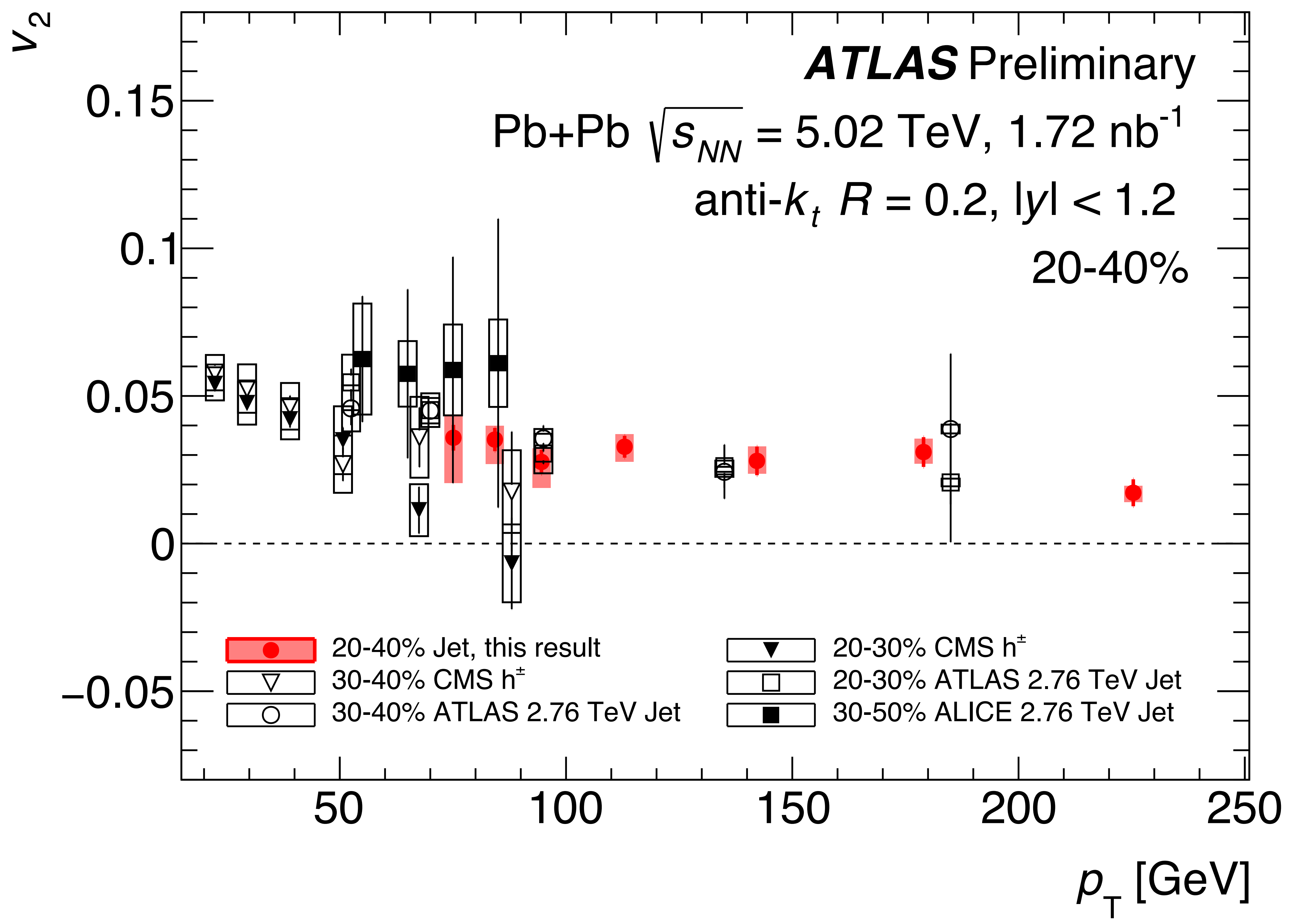
- IS geometry anisotropy: negative as in peripheral Pb+Pb
- IS momentum anisotropy: positive, smaller size → larger $\langle p_T \rangle$ → less color domain

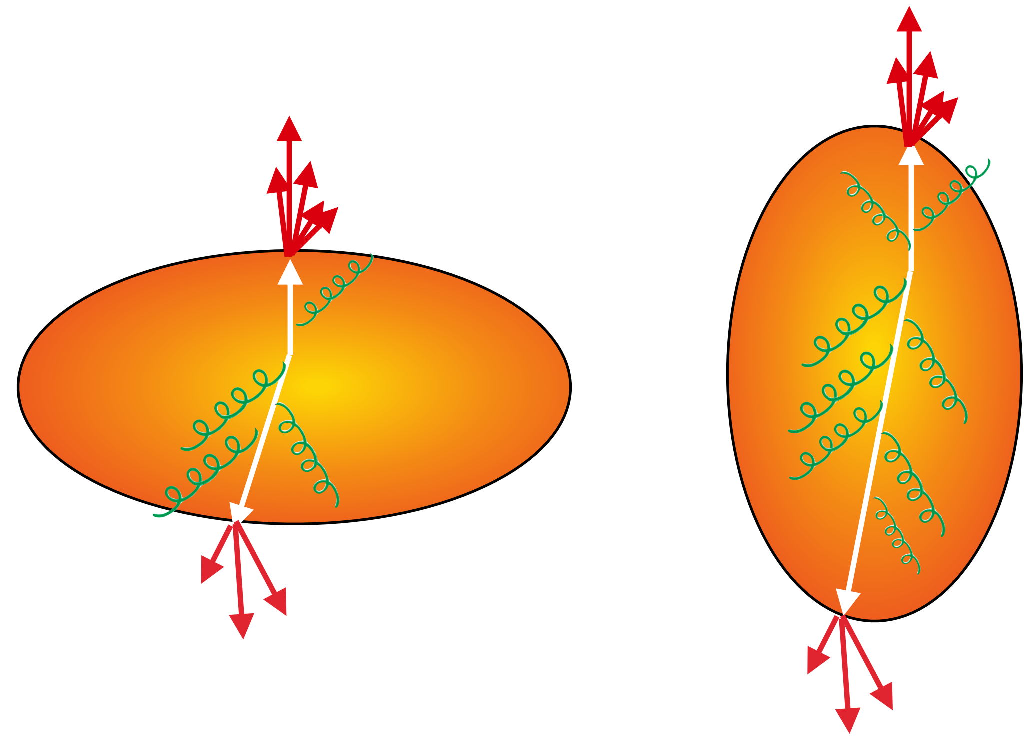
Sign change due to initial momentum anisotropies is predicted for p+A at low multiplicity

Challenge in measurements: statistics for subevent cumulants, non-flow

Hard-soft correlation

ATLAS: Phys. Rev. Lett. 111 (2013) 152301, ATLAS-CONF-2020-019
CMS: Phys. Lett. B 776 (2017) 195
ALICE: Phys. Lett. B 753 (2016) 511



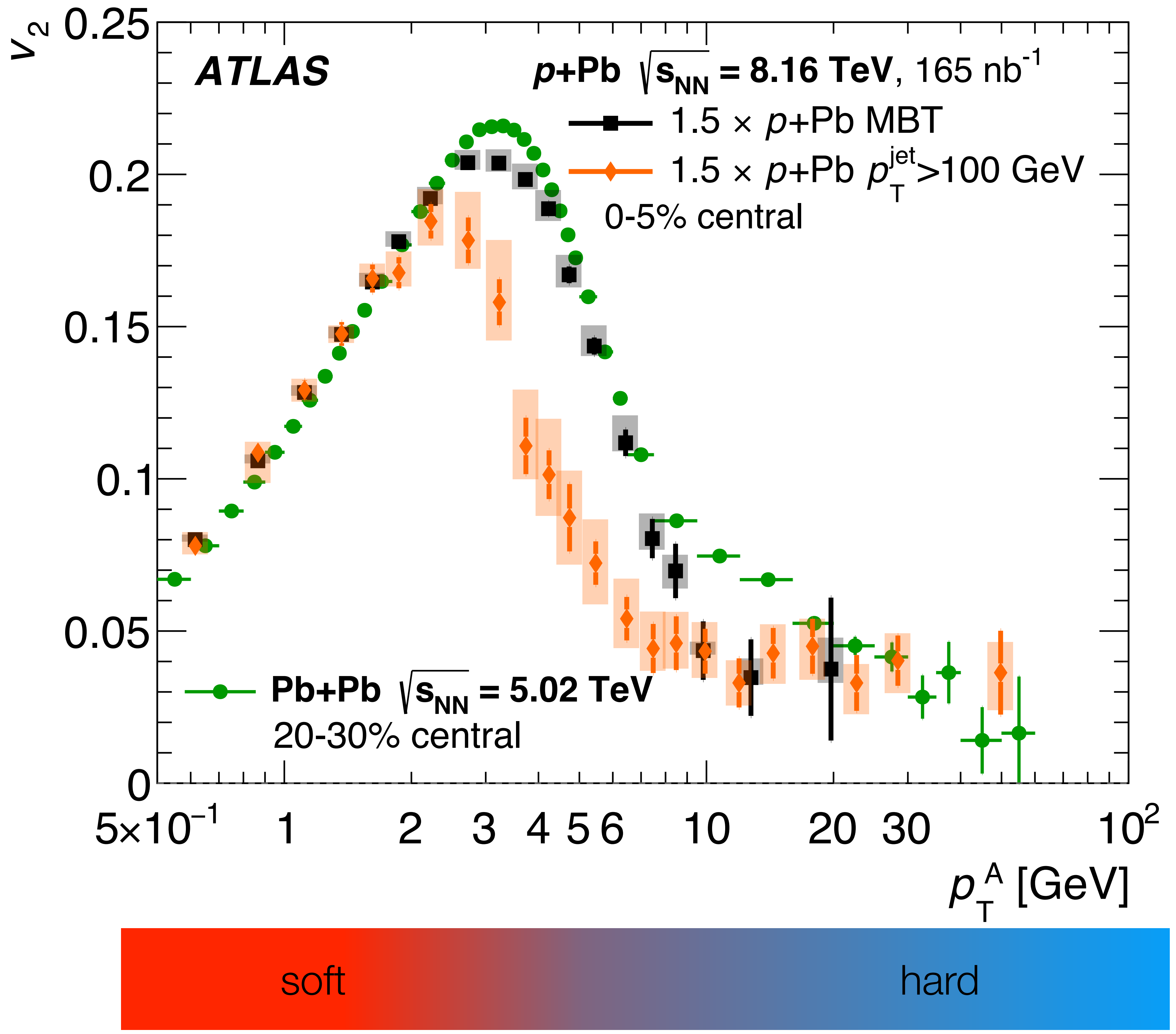


Jet quenching with different path lengths

- Intra hard process is considered as non-flow, but differential hard-QGP(soft) interaction results in anisotropy correlated with event orientation
- Anisotropy extracted from hard-soft correlation is referred as “flow” of the hard process. **Different** from the narrowly hydrodynamic flow for soft sector
- High p_T v_2 measured using jet or charged hadron up to 200 GeV in mid-central Pb+Pb collisions, p_T independent v_2 ~ 0.03

High p_T v_2 in p+Pb

ATLAS, Eur. Phys. J. C 80 (2020) 73

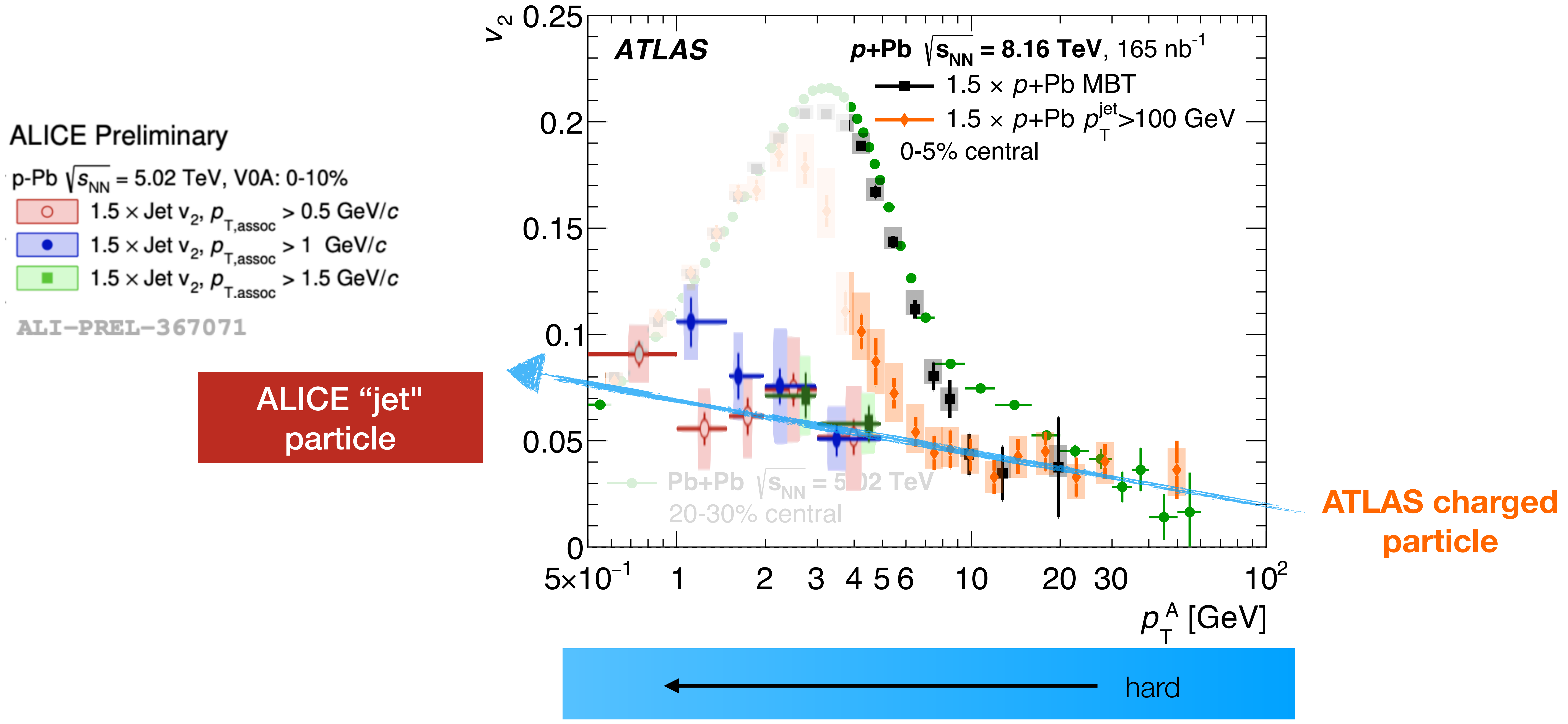


p+Pb results scaled by 1.5 to compare shape

- Two particle correlation using template fit non-flow subtraction
- Default subtraction does not work at high p_T. Additional suppression of jet-jet correlation by eliminating particle pairs both from identified jets
- Factorization breaking at high p_T 10~20%

"Hard" particle p_T v_2 in p+Pb

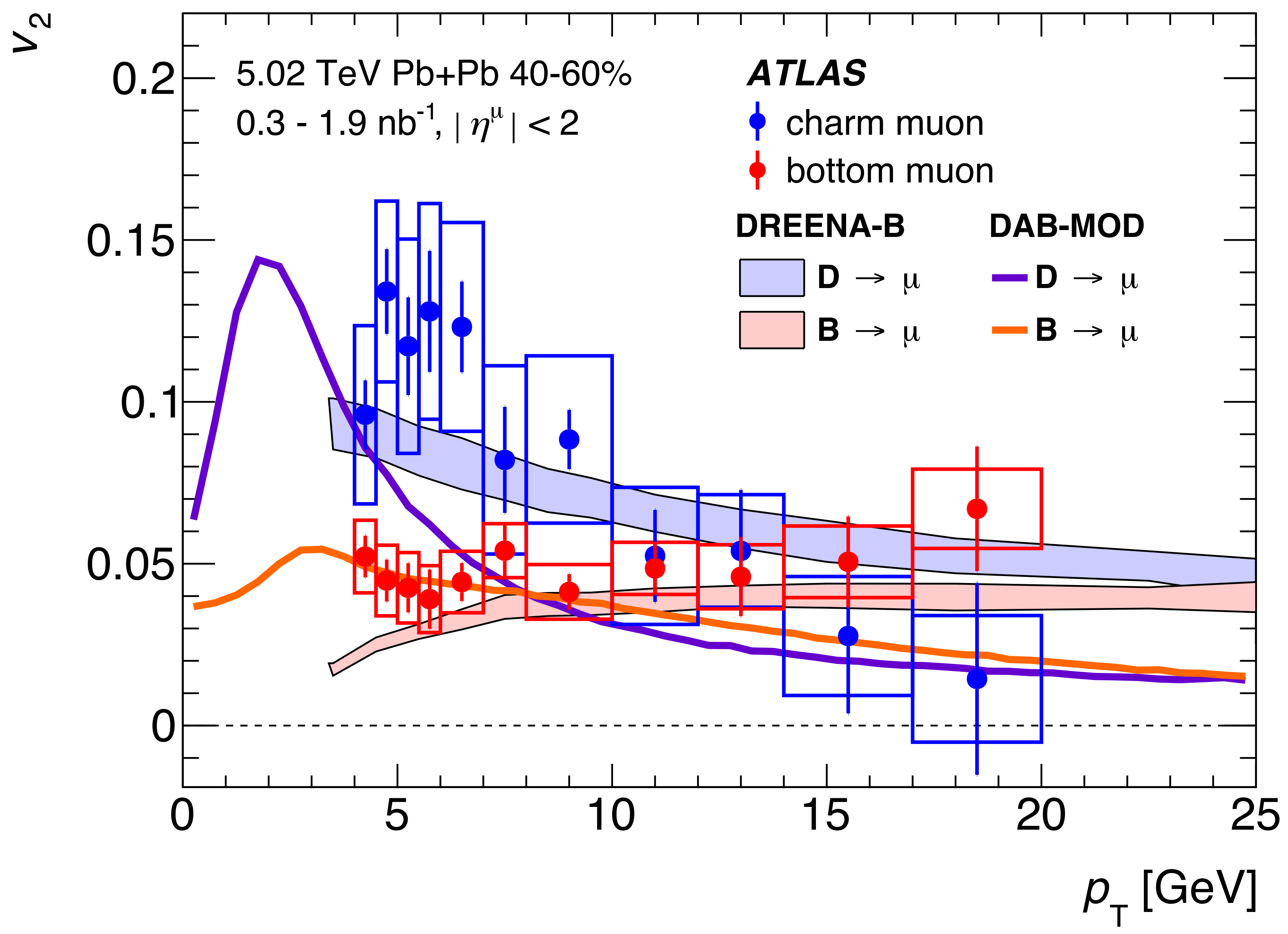
ATLAS, Eur. Phys. J. C 80 (2020) 73
ALICE, S. Tang, IS2021 poster



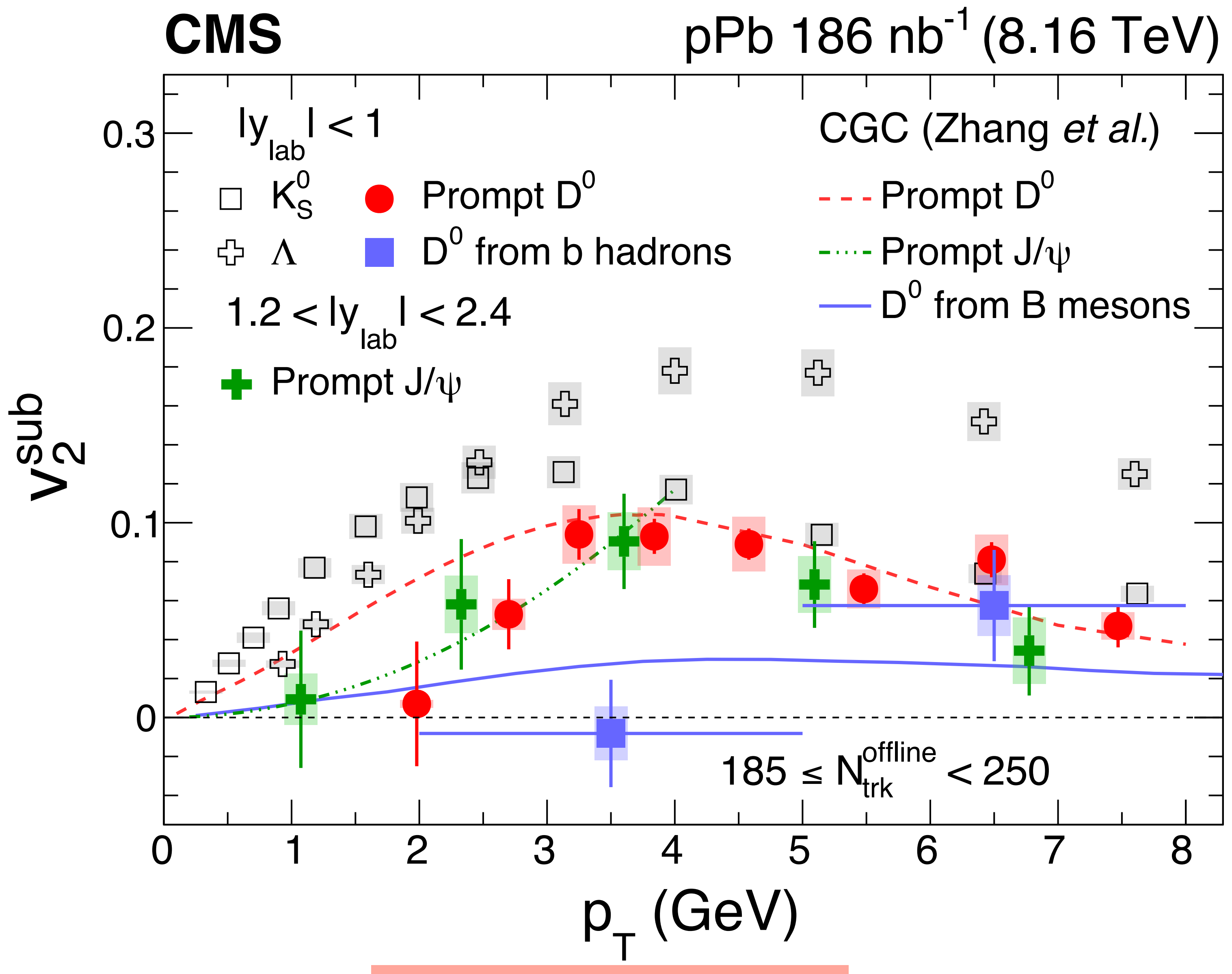
- ALICE measurement of statistically extract jet particle v_2 down to low p_T
- Significant non-zero v_2 in a wide p_T range, while no strong modification of p_T spectra

ATLAS Phys. Lett. B 807 (2020) 135595
DREENA-B, D. Zigic et al., Phys. Lett. B 791 (2019) 236
CMS prompt D, Phys. Rev. Lett. 121 (2018) 082301
CMS non-prompt D, arXiv:2009.07065
CGC J/psi, C. Zhang et al., Phys. Rev. Lett. 122 (2019) 172302
CGC D, C. Zhang et al., Phys. Rev. D 102 (2020) 034010
ATLAS, Phys. Rev. Lett. 124 (2020) 082301

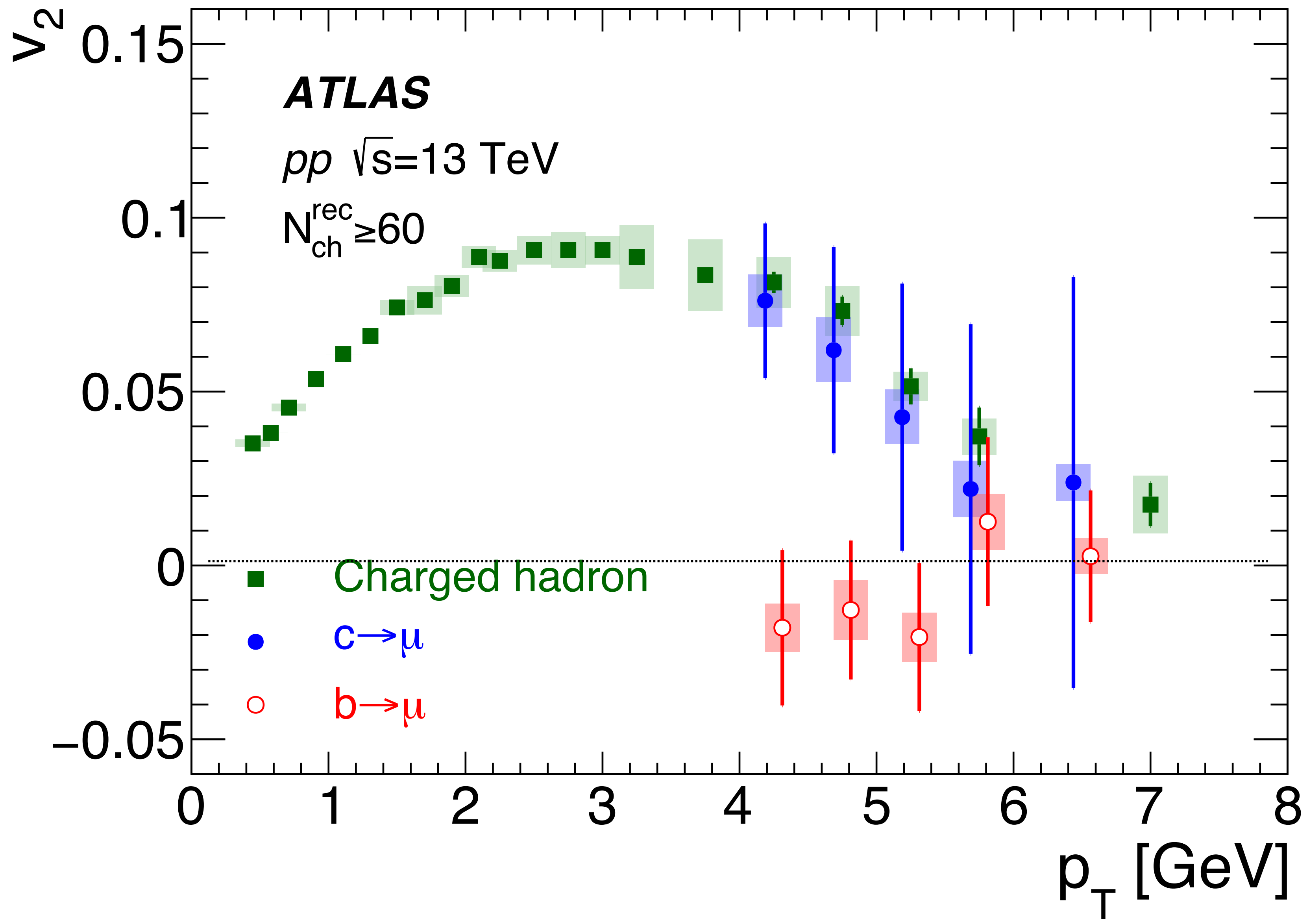
Open heavy flavor flow



Pb+Pb
~ energy loss in hydro



***p*+Pb**
~ color domain



pp

- ***v_2 (Light) ~ v_2 (D) > v_2 (B)*** for all systems at intermediate p_T (4~10 GeV)
- No strong modification to p_T spectra in *p*+Pb (R_{pPb} ~ 1) and *pp* (~ pQCD)
- Pb+Pb ~differential energy loss in QGP, while *p*+Pb ~ CGC color domain

Same hydro not directly applicable for small system, need consistent picture for soft & hard as this is hard-soft correlation

Summary

Sorry if I was not able to cover your results here

- Non-flow and decorrelation could bias flow interpretation, should be evaluated in measurements (non-flow) and included in model (decorrelation). Non-flow subtraction could be biased by its assumptions
- Observables sensitive to initial state effects, flow in small system, SC(2,3), v_n-p_T correlation ect., are also sensitive to non-flow effects
- Hard-soft correlation: need systematic description of light and hard “flow” in small system