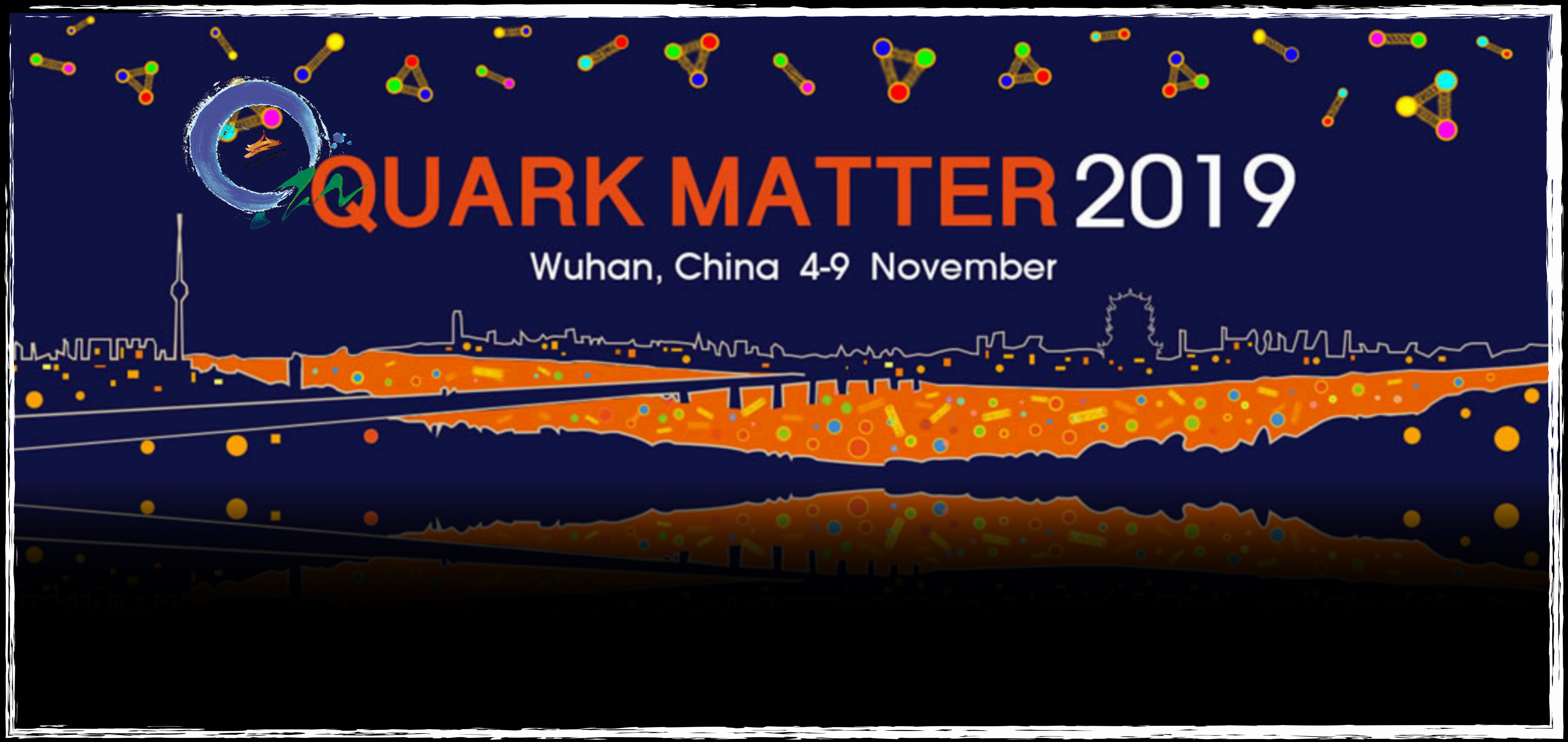
One fluid may not rule them all

— "the negative sign issue"



You Zhou

Niels Bohr Institute

Based on:

- **W. Zhao**, YZ, H. Xu, W. Deng and **H. Song**, Phys. Lett. B 780, 495
- **W. Zhao**, YZ, K. Murase and **H. Song**, in preparation

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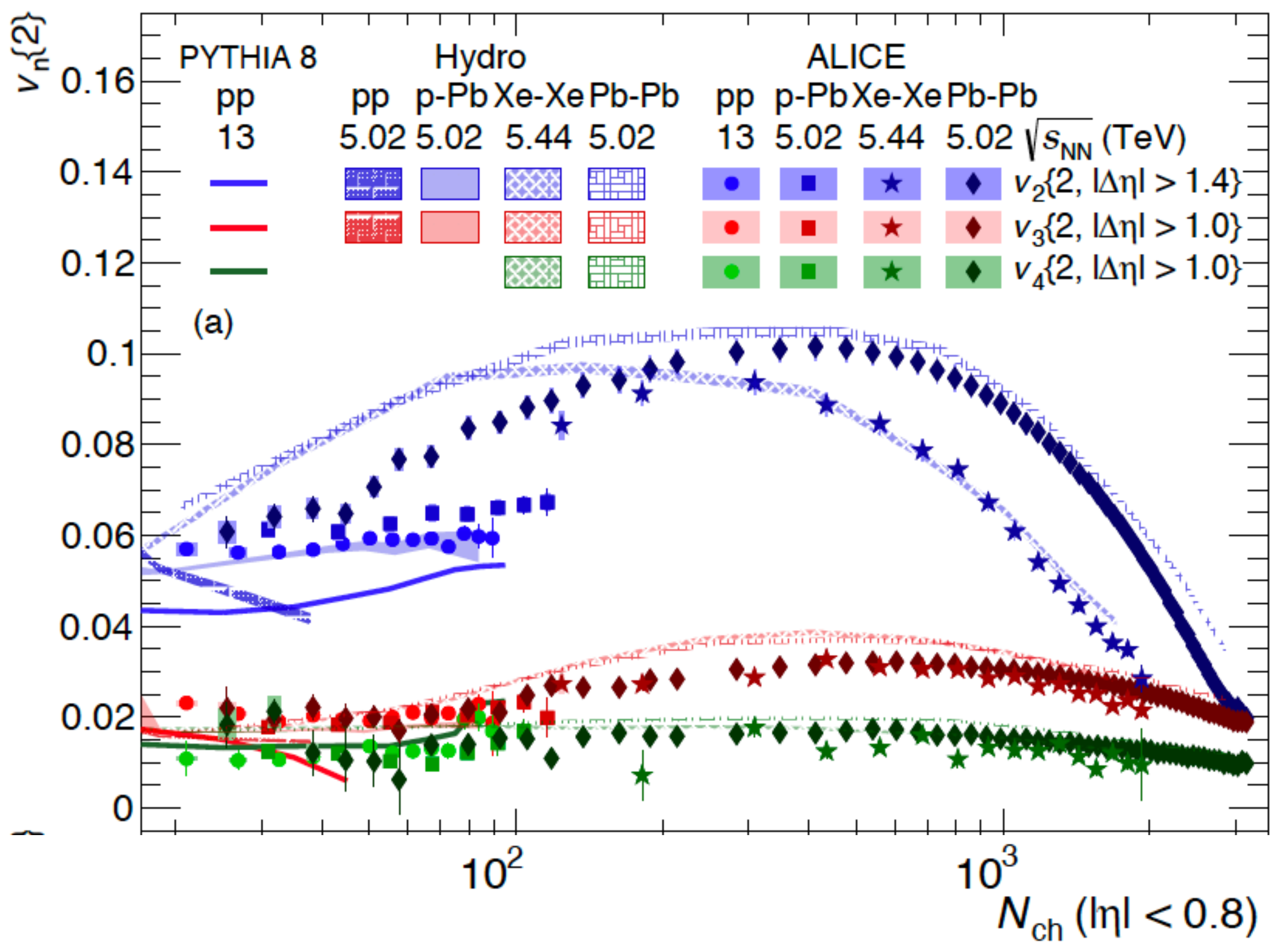
Danish National Research Foundation

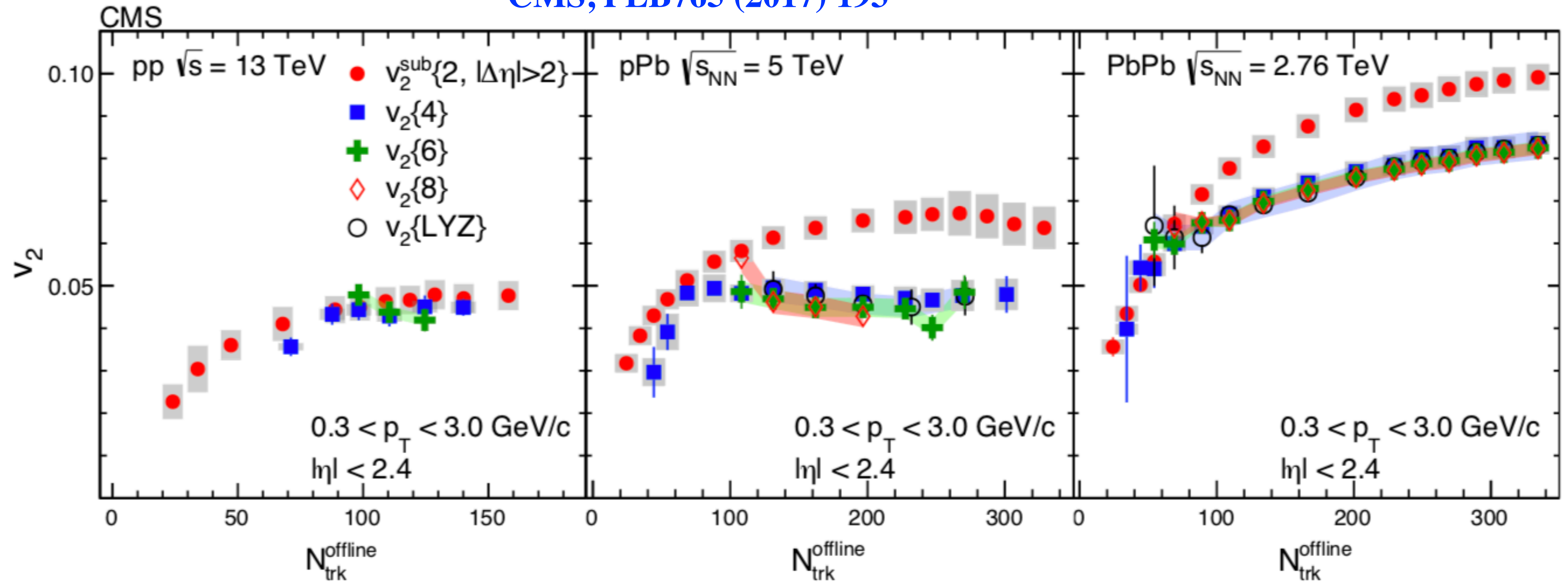
VILLUM FONDEN

Flow in small systems

ALICE, PRL123, 142301 (2019)



CMS, PLB765 (2017) 193



❖ 2-particle correlations in p-Pb and pp collisions

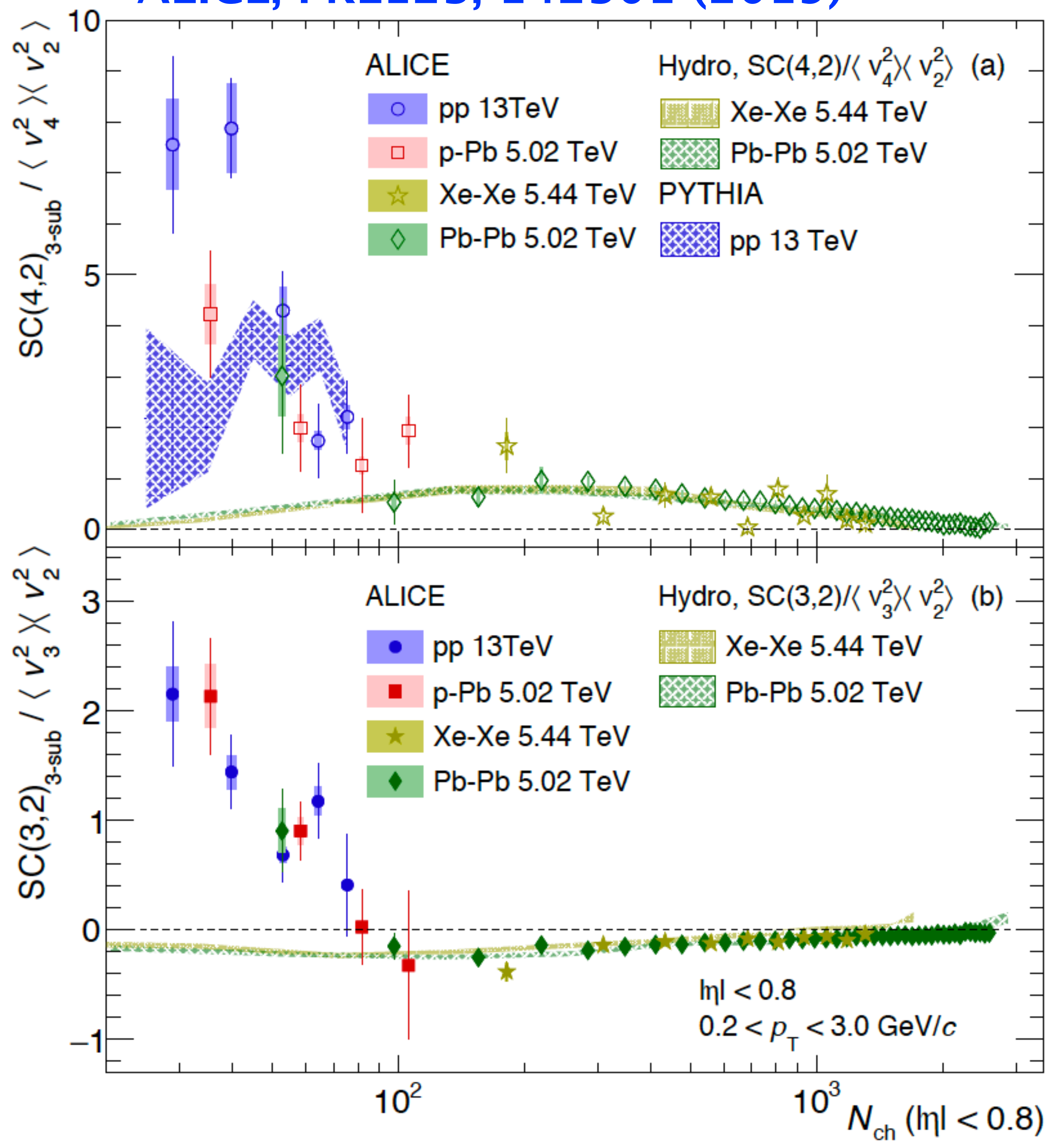
- comparable with Pb-Pb at low N_{ch}, weak multiplicity dependence
- ordering $v_2 > v_3 > v_4$

❖ Multi-particle cumulants

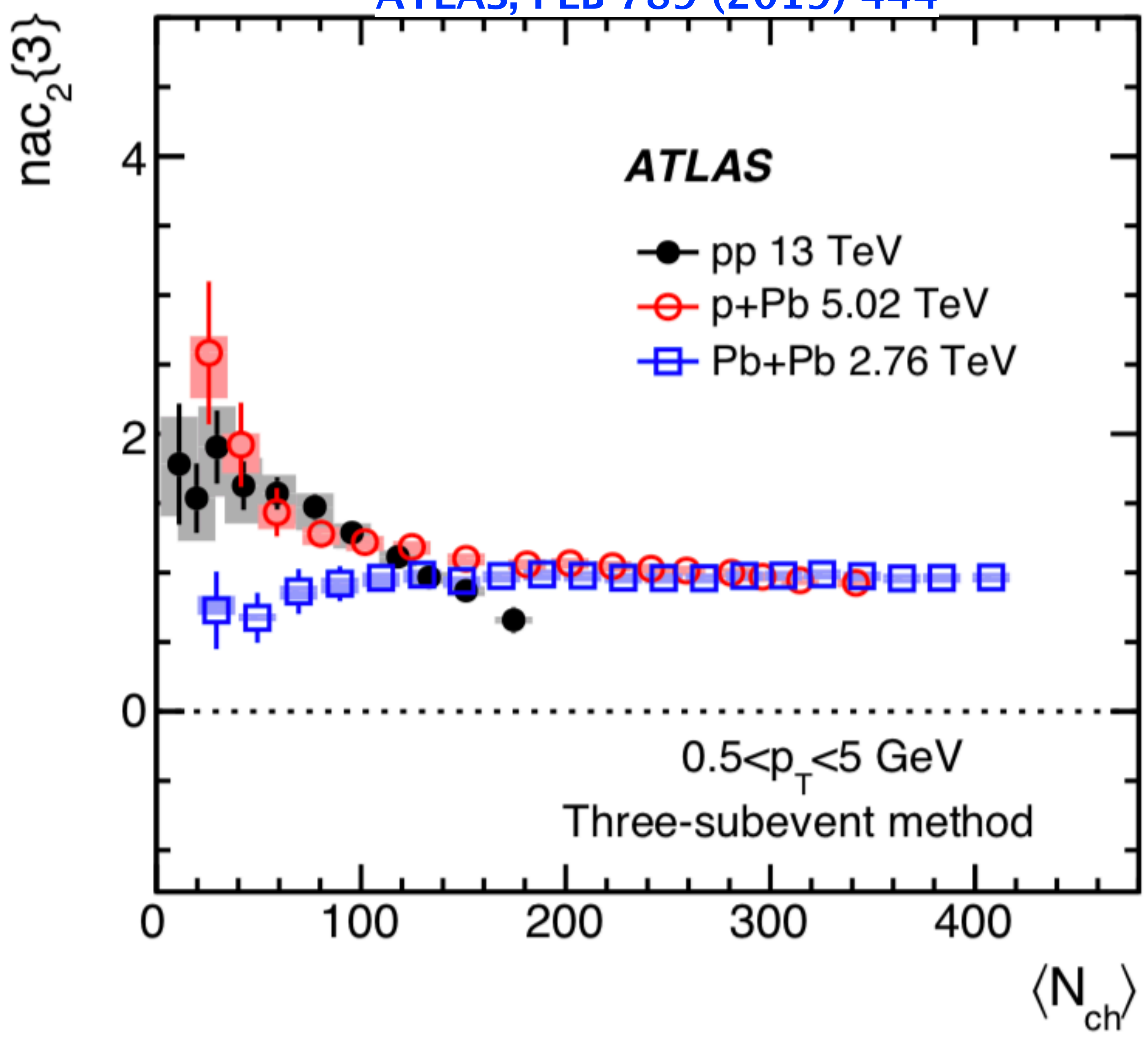
- $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- Long-range multi-particle correlations in all systems -> ***anisotropic flow!***

Flow vector correlations in small systems

ALICE, PRL123, 142301 (2019)



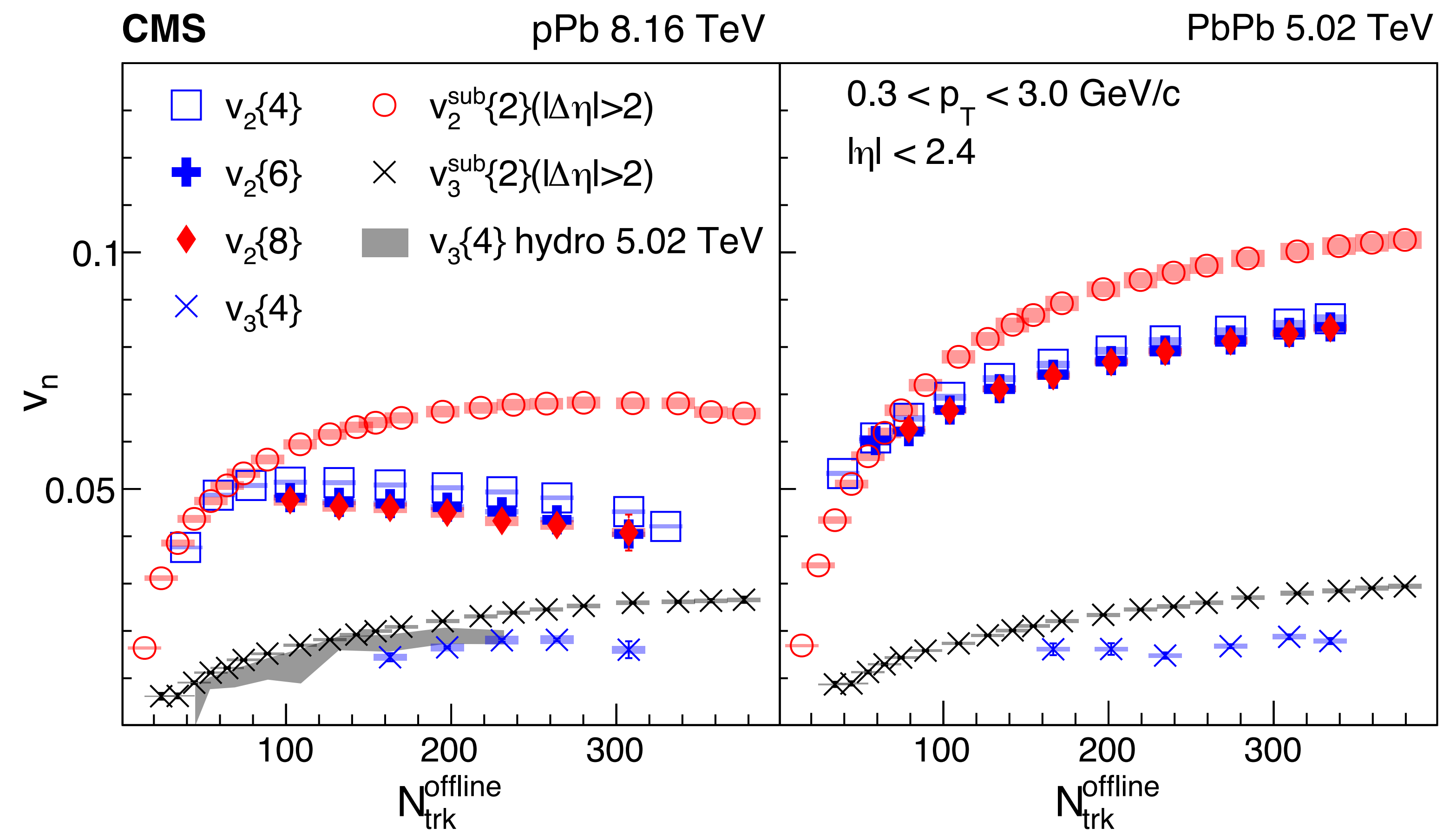
ATLAS, PLB 789 (2019) 444

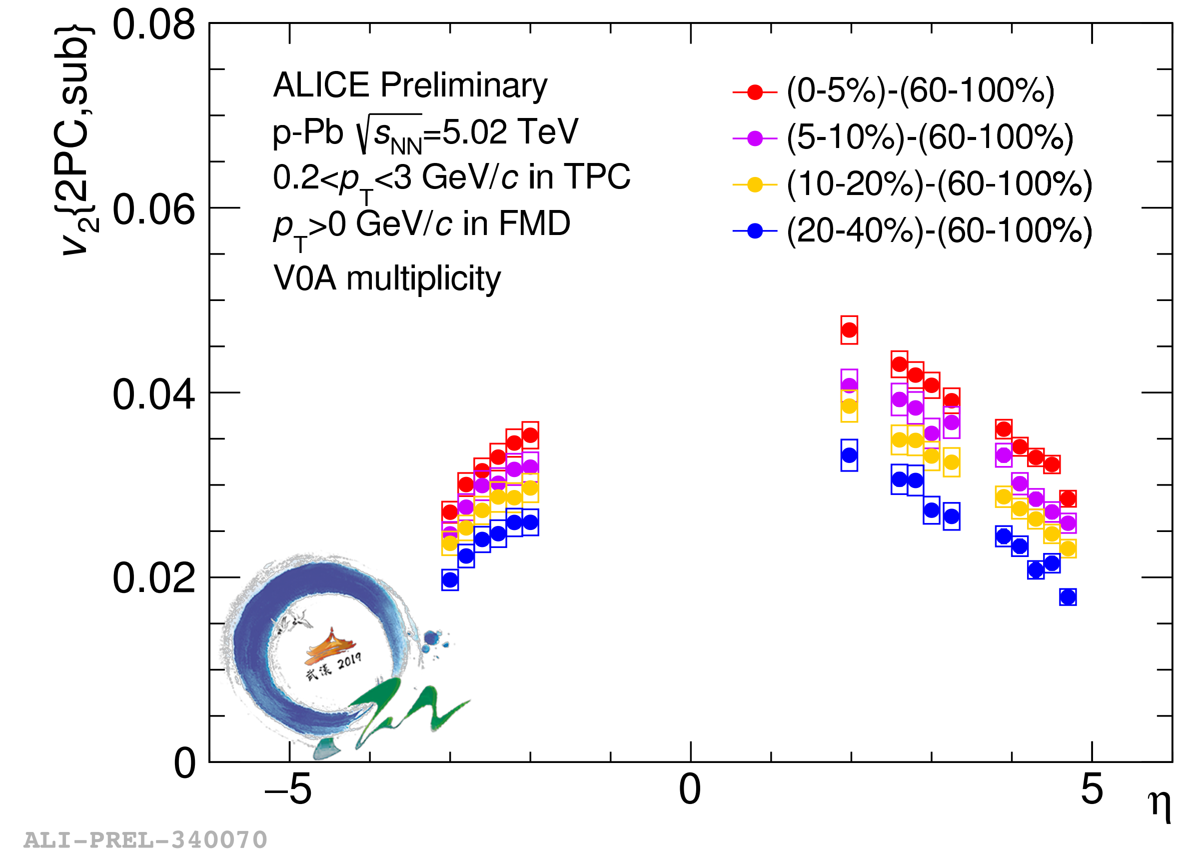


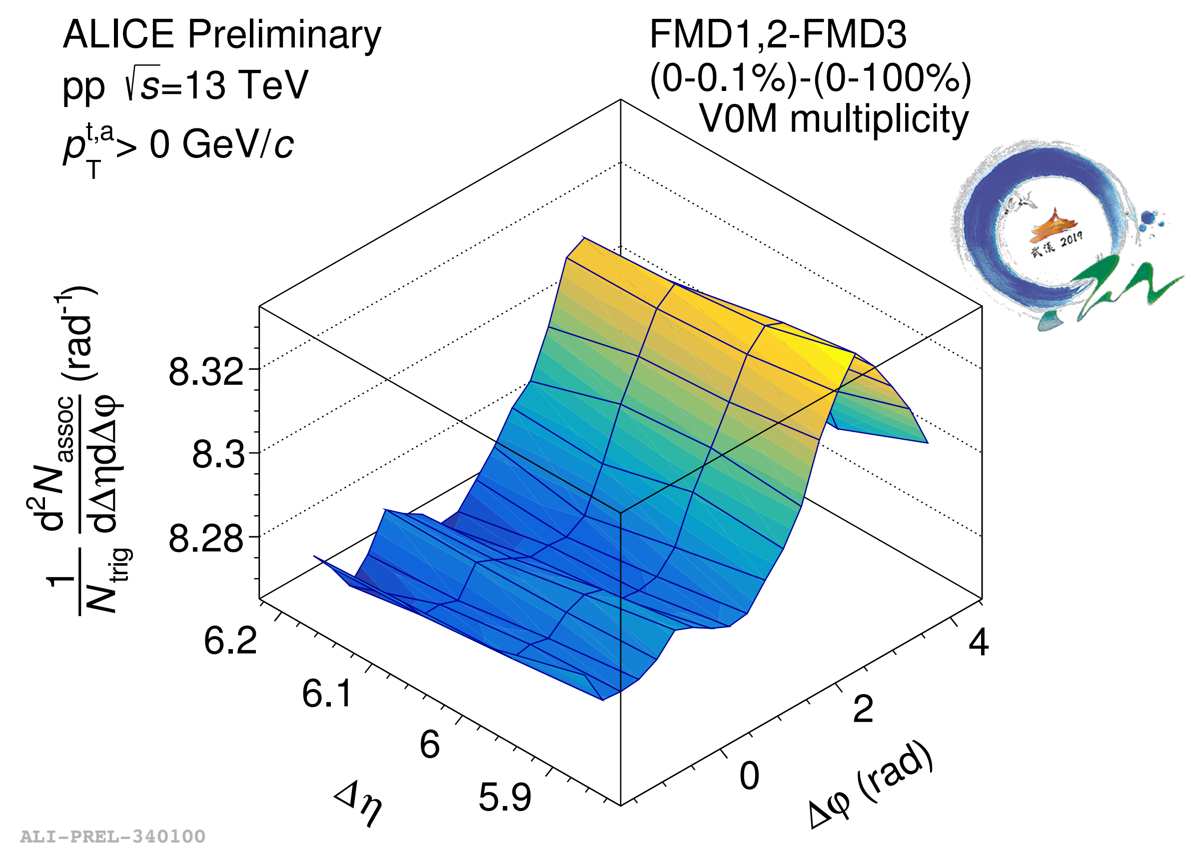
❖ Similar correlations between different order flow vectors observed

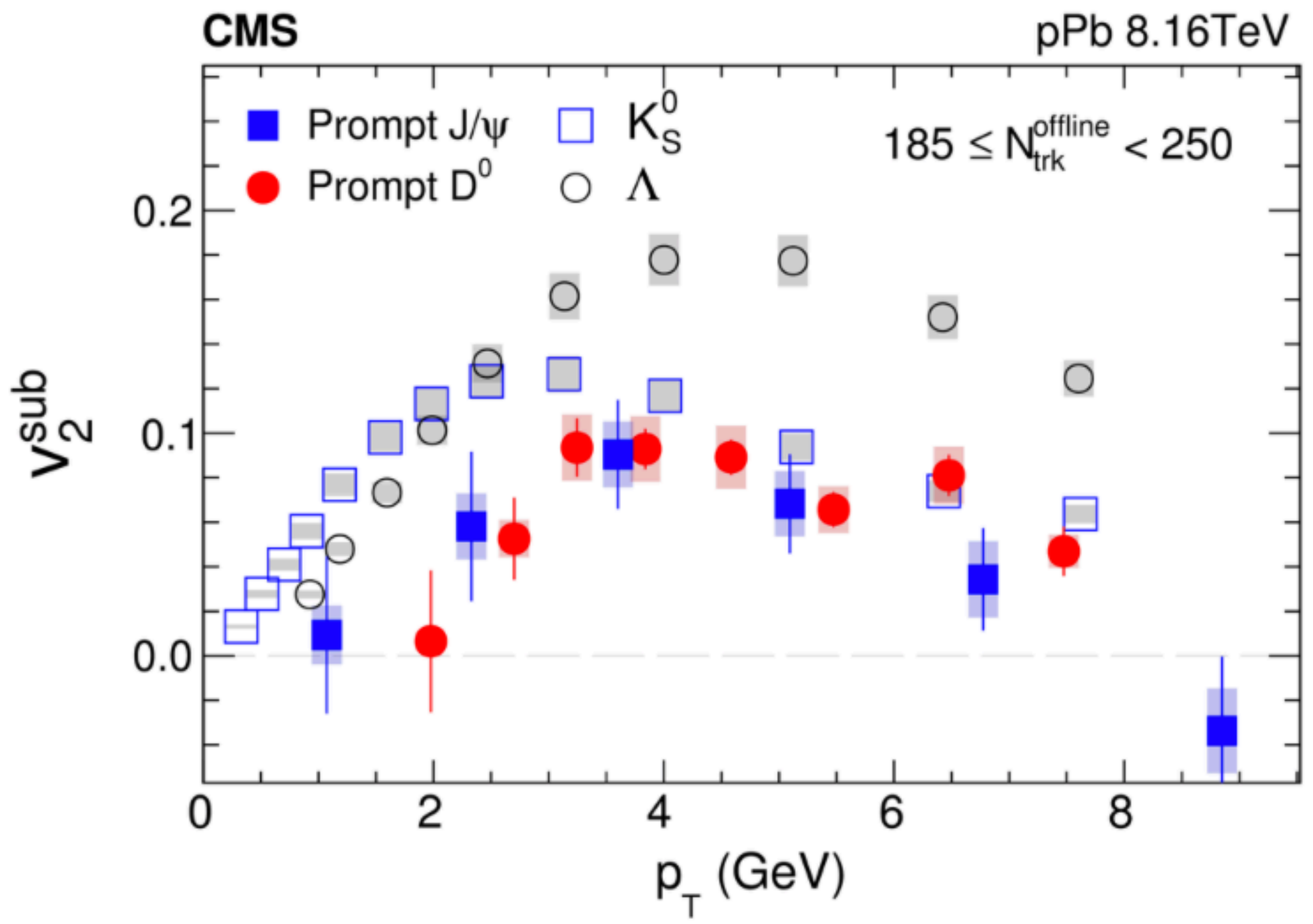
- Correlations between flow harmonics, via symmetric cumulants
- Correlations between flow symmetry planes, via asymmetric cumulants

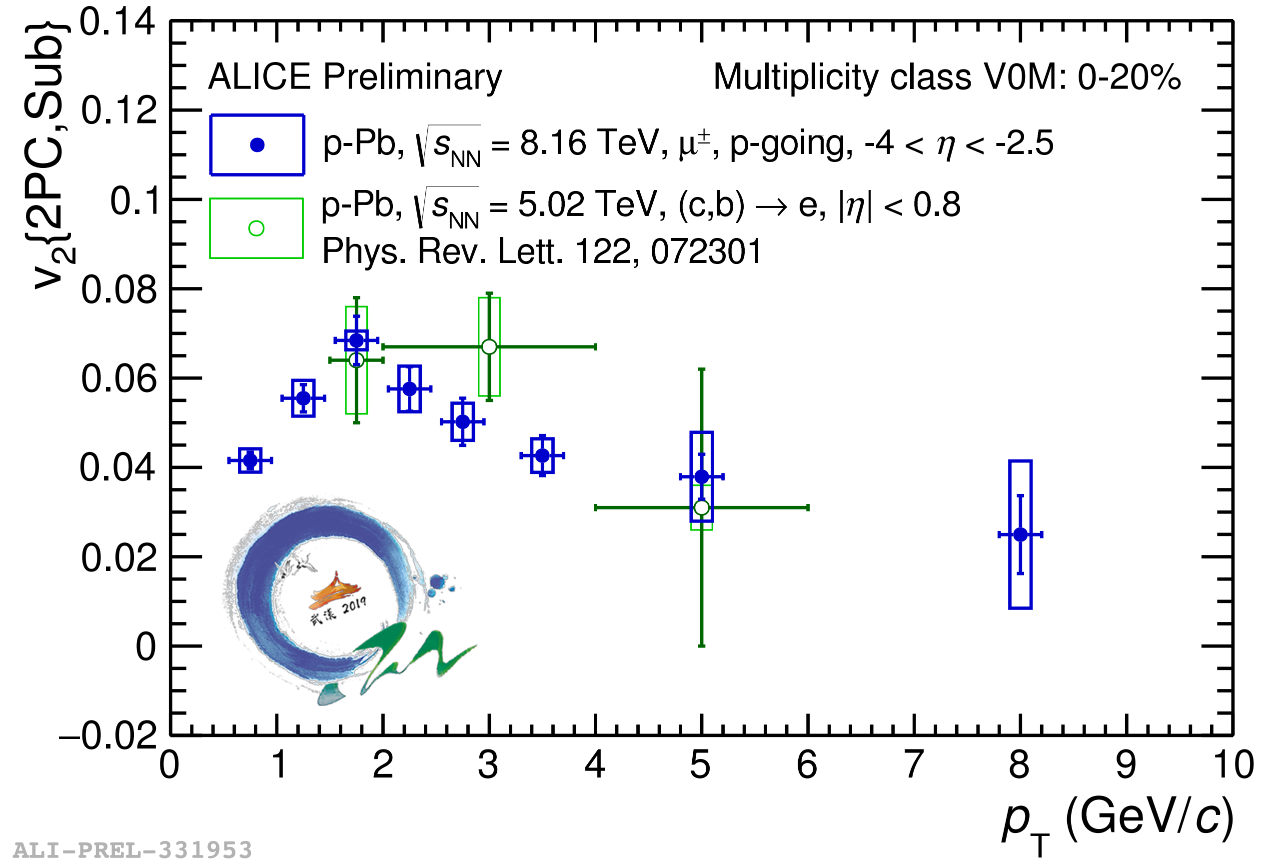
Everything flows, everywhere flows (?)

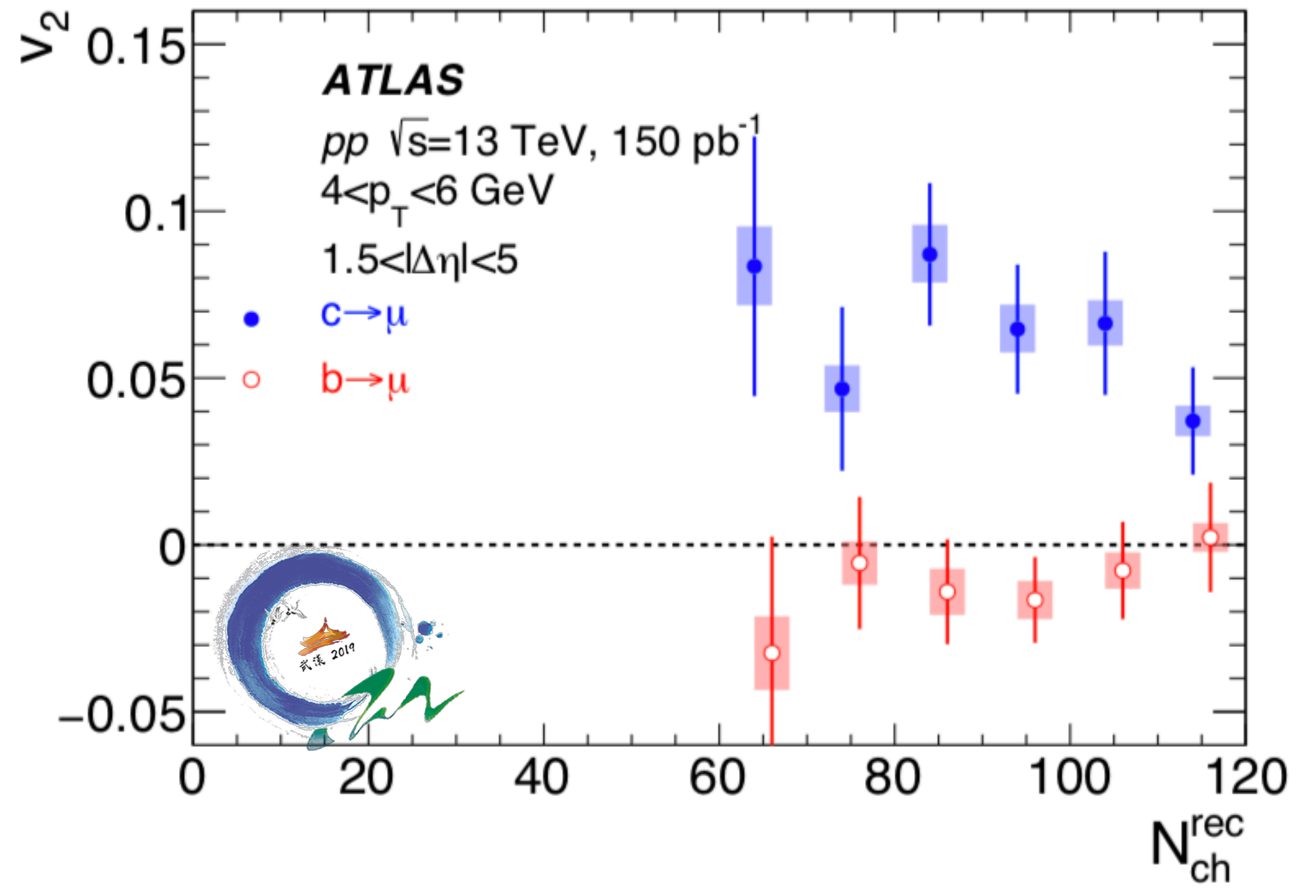












- And many more in this QM, excellent reviews, see J. Nagle Mon.14:30, K.K.Gajdosova Thur. 9:30

Summary Table

C. Loizides NPA956 (2016) 200

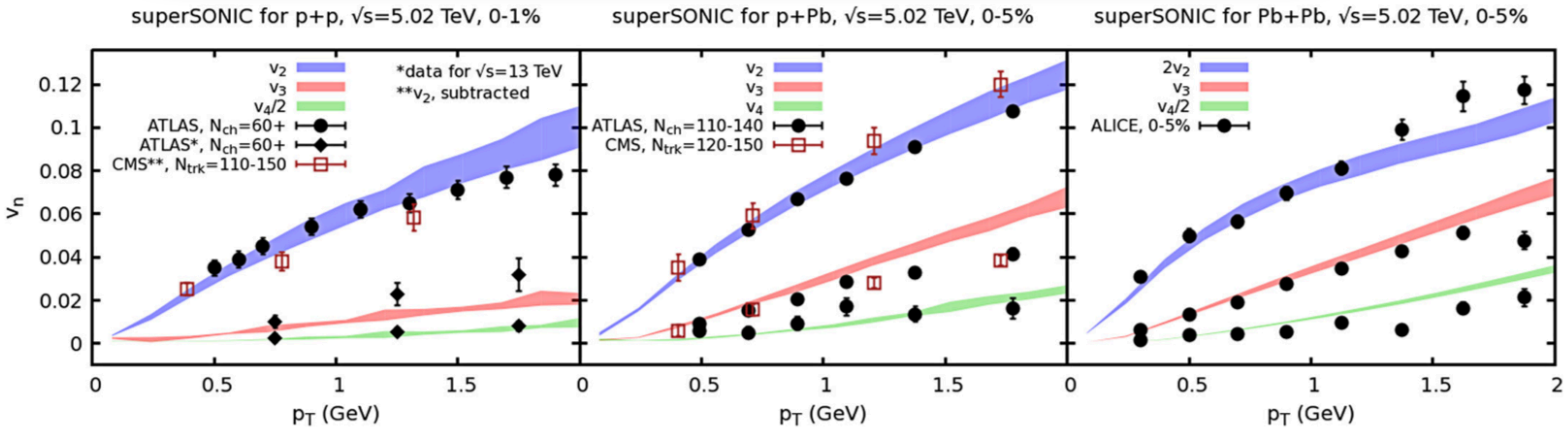
CERN Yellow Report: CERN-LPCC-2018-07

Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)
Low p_T spectra ("radial flow")	yes	yes	yes
Intermediate p_T ("recombination")	yes	yes	yes
Particle ratios Statistical model	GC level $\gamma_s^{GC} = 1$, 10–30%	GC level except Ω $\gamma_s^{GC} \approx 1$, 20–40%	GC level except Ω MB: $\gamma_s^{C} < 1$, 20–40%
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$
Azimuthal anisotropy (v_n) (from two particle correlations)	v_1–v_7	v_1–v_5	v_2–v_4
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2
Directed flow (from spectators)	yes	no	no
Charge-dependent correlations	yes	yes	yes
Higher-order cumulants (mainly $v_2\{n\}, n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$"
Symmetric cumulants	up to SC(5, 3)	only SC(4, 2), SC(3, 2)	only SC(4, 2), SC(3, 2)
Non-linear flow modes	up to v_6	not measured	not measured
Weak η dependence	yes	yes	not measured
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured
Event-by-event v_n distributions	$n = 2$–4	not measured	not measured
Direct photons at low p_T	yes	not measured	not observed
Jet quenching through dijet asymmetry	yes	not observed	not observed
Jet quenching through R_{AA}	yes	not observed	not observed
Jet quenching through correlations	yes (Z–jet, γ–jet, h–jet)	not observed (h–jet)	not measured
Heavy flavor anisotropy	yes	yes	not measured
Quarkonia production	suppressed†	suppressed	not measured

" One fluid to rule them all "

One fluid to rule them all: Viscous hydrodynamic description of event-by-event central p+p, p+Pb and Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV

Ryan D. Weller [a], Paul Romatschke [a,b,*]   Physics Letters B 774 (2017) 351–356



❖ superSONIC describes v_2 and v_3 data in pp, p-Pb and Pb-Pb using a single choice for the fluid parameter

- Suggests ***common hydrodynamic origin*** including **pp** collisions

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Headlines in newspapers

A Tiny Droplet of the Early Universe?

Tiny droplets of early universe matter created

Proton-Size Droplets of Primordial Soup May Be the Tiniest in the Universe

Researchers Create The Tiniest Droplets Of Early Universe Matter Yet

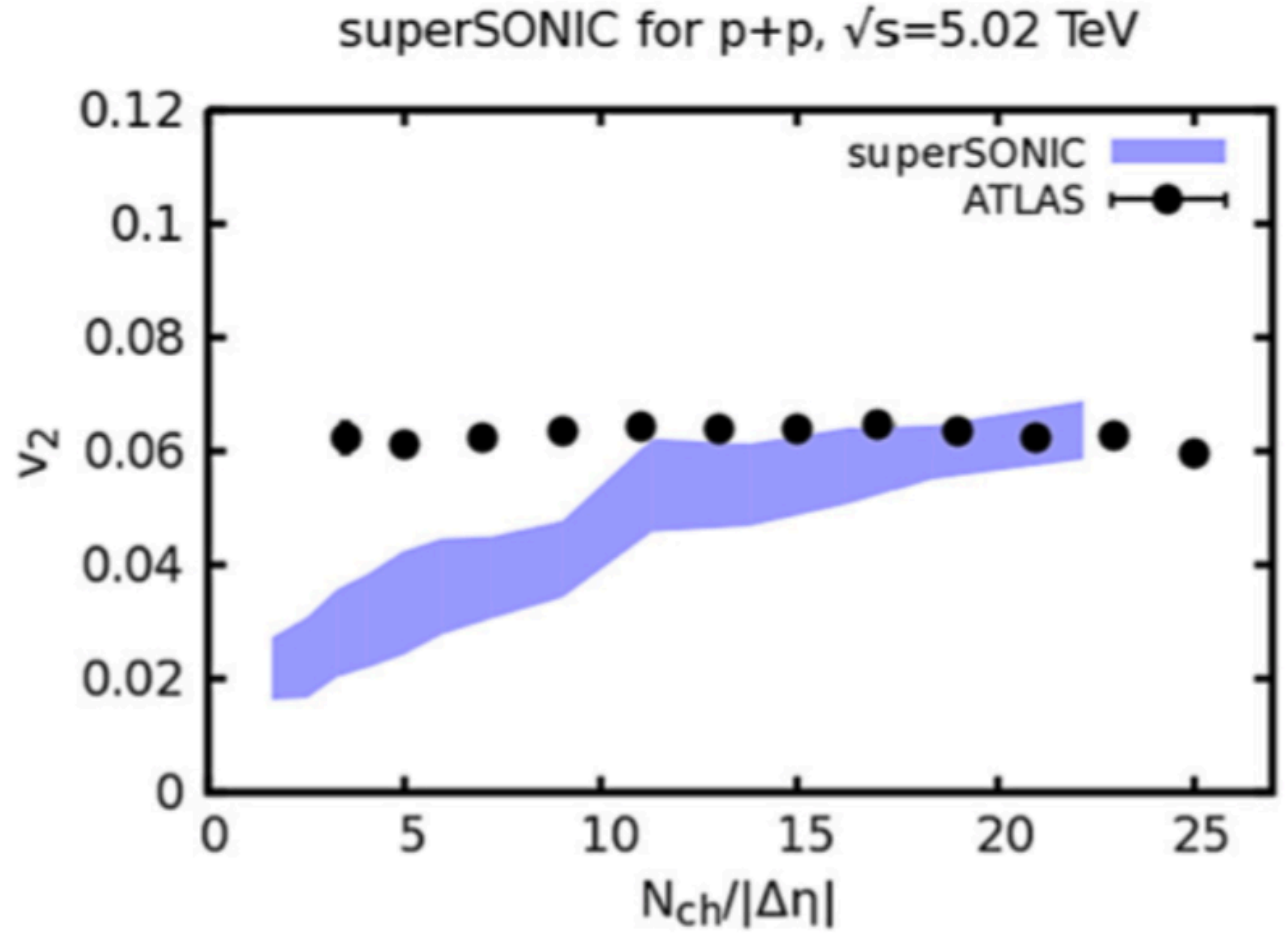
Q: Tiniest size of the hydrodynamic fluid?

Task: Search for hydrodynamic flow in pp

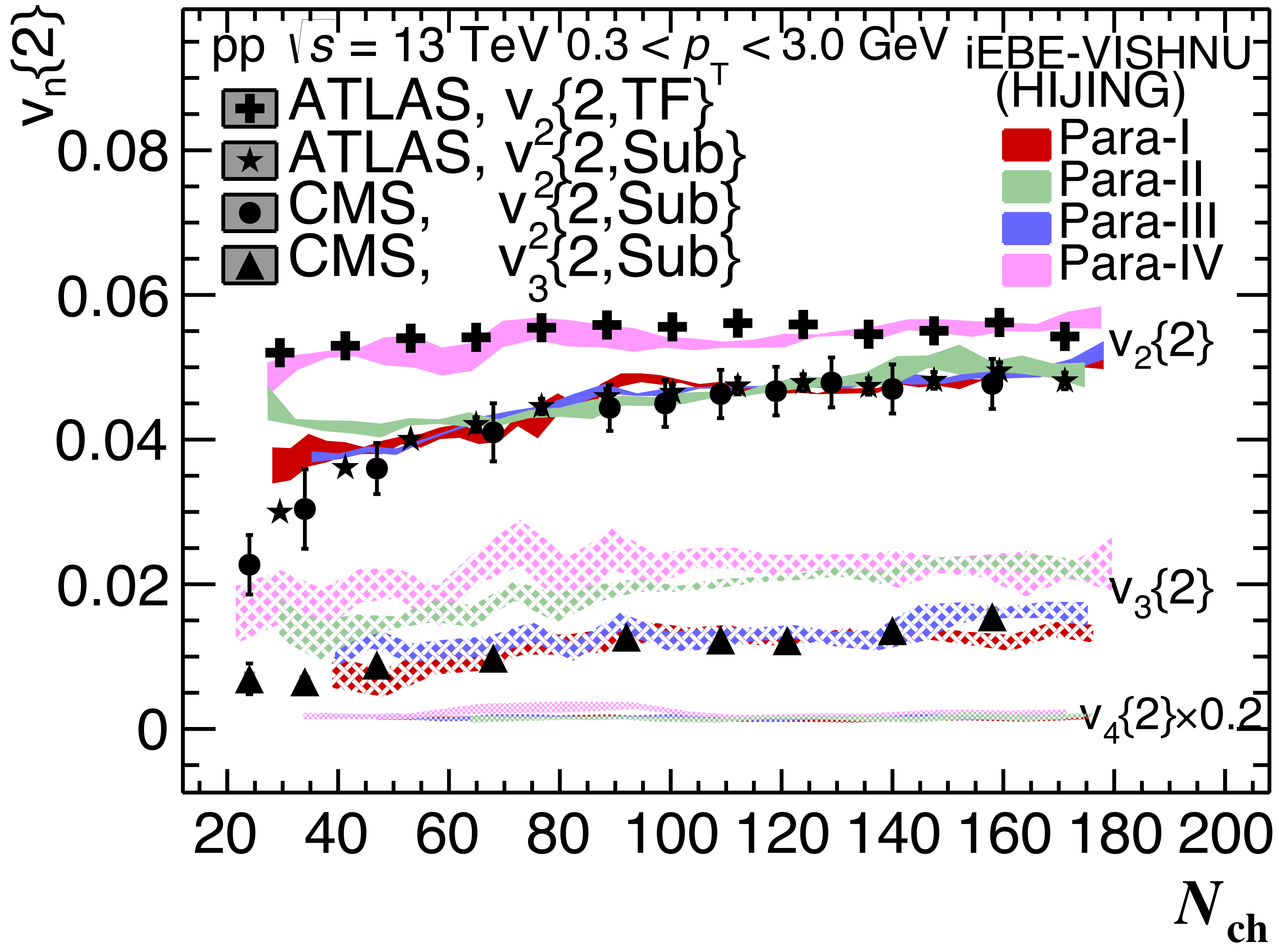
Tool: iEBE-VISHNU

Preparations for hydro calculations

R. Weller, P. Romatschke, PLB 774 (2017) 351



W. Zhao, YZ, H. Xu, W. Deng, H. Song, PLB 780 (2018) 495

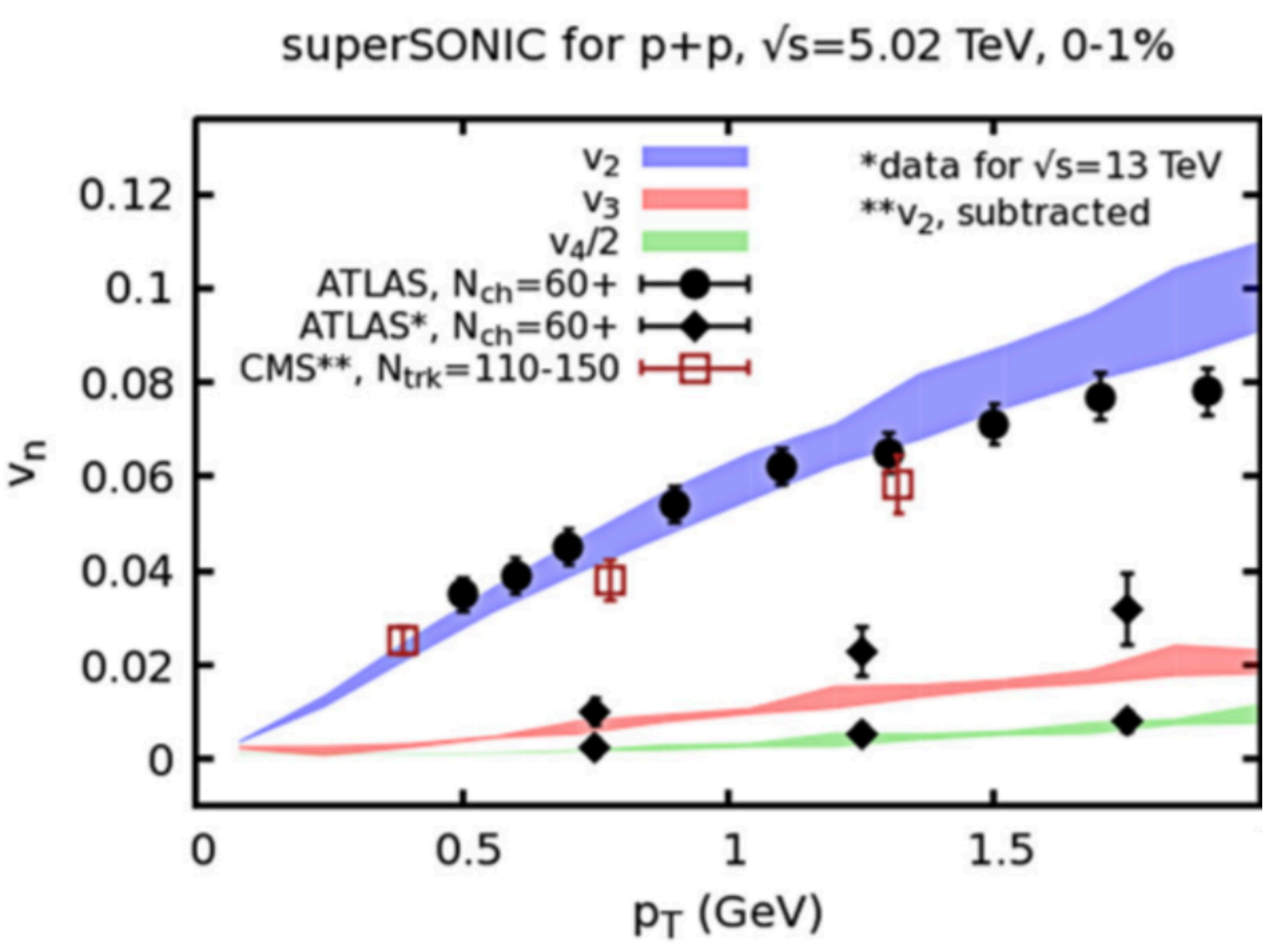


❖ Tune parameters in hydrodynamic framework

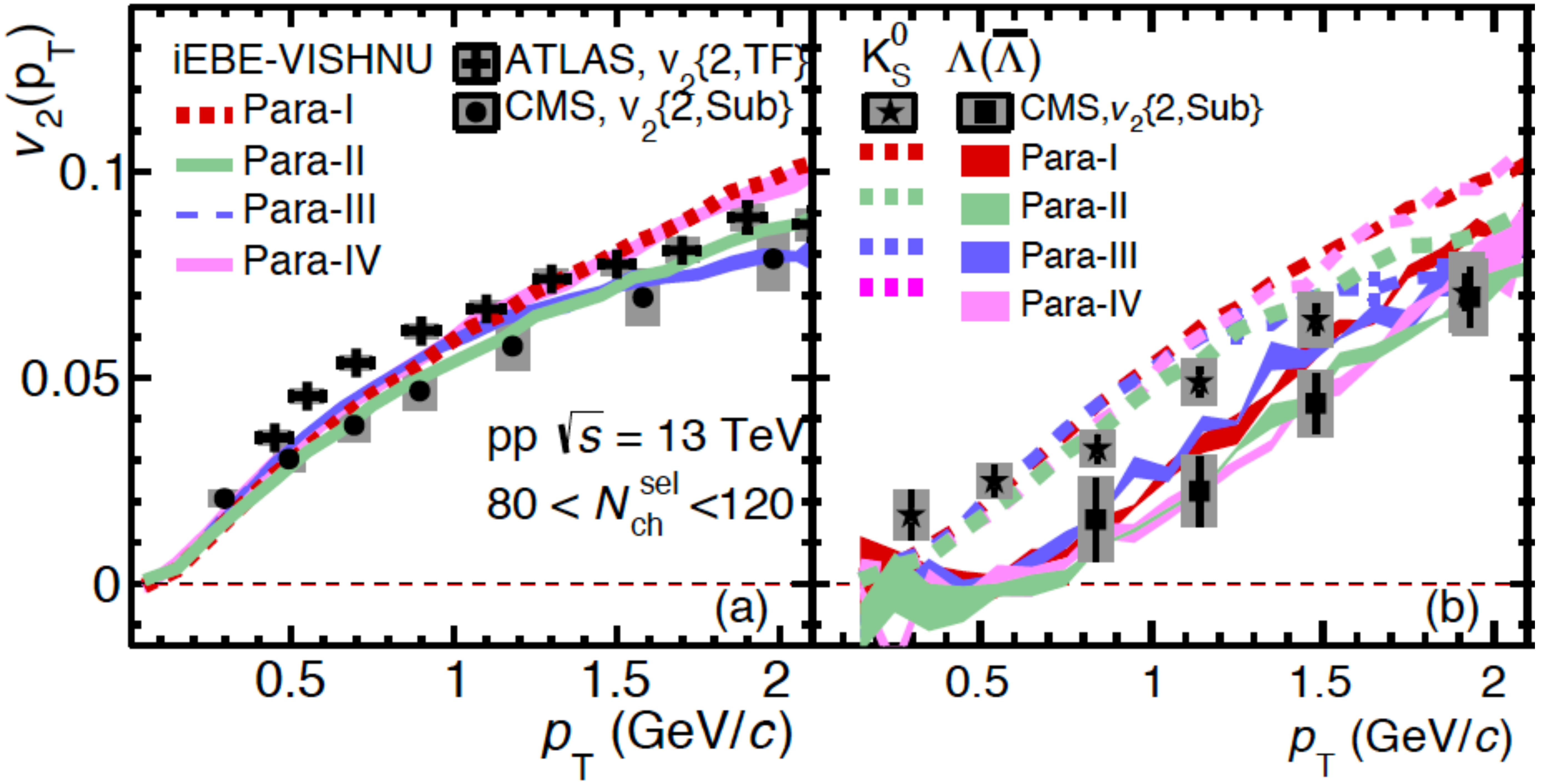
- fit particle spectra and integrated v_n
- good agreements between data and iEBE-VISHNU with HIJING-IC
- not worse than superSONIC calculations

Validation of hydro framework

R. Weller, P. Romatschke, PLB 774 (2017) 351



W. Zhao, YZ, H. Xu, W. Deng, H. Song, PLB 780 (2018) 495

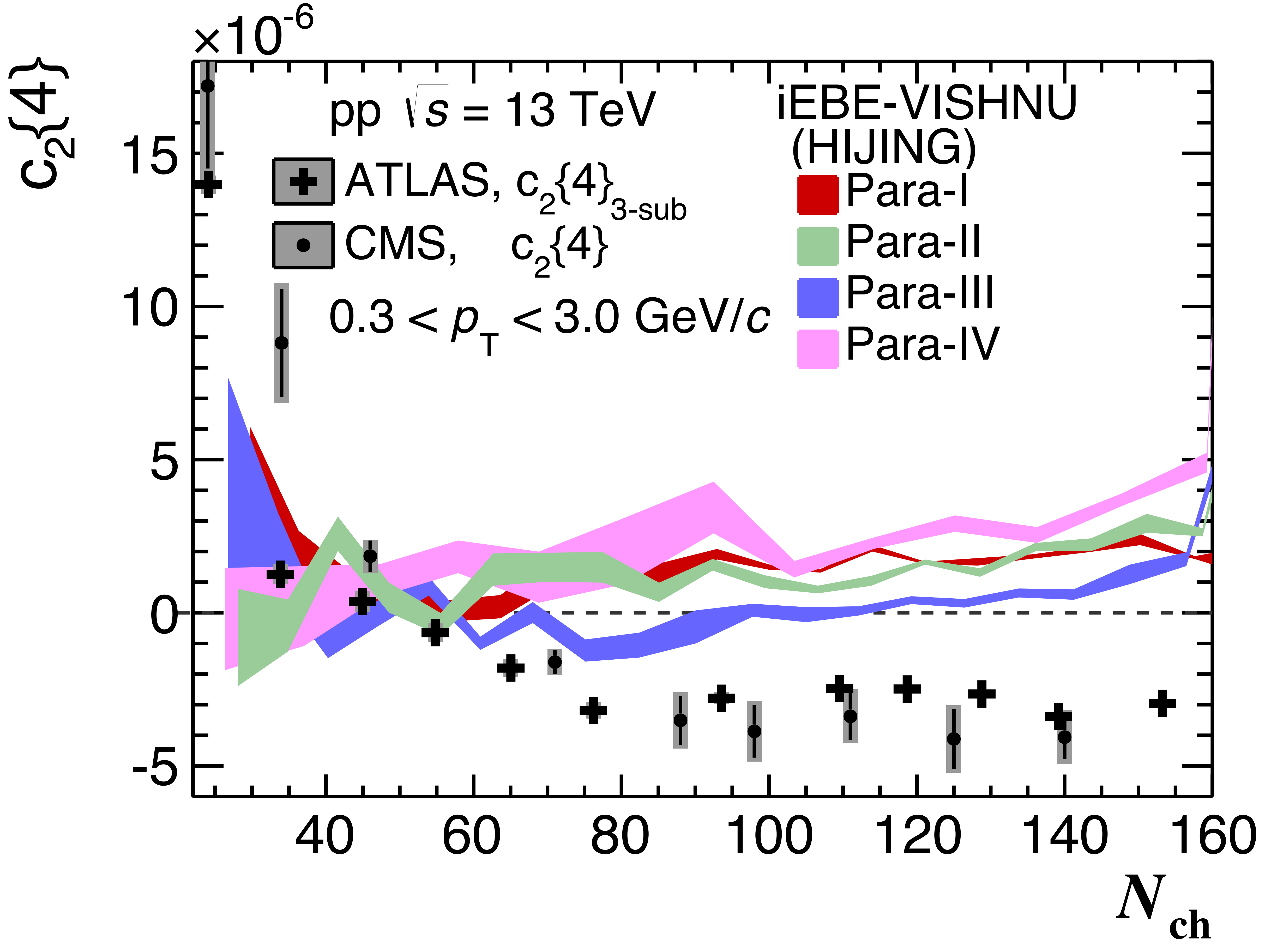


❖ Examinations of tuned hydrodynamic framework

- Describe quantitatively p_T differential v_2 of both charged and identified particles -> so far so good

Negative $c_2\{4\}$

W. Zhao, YZ, H. Xu, W. Deng, H. Song, PLB 780 (2018) 495



$c_2\{4\} = -v_2^4$

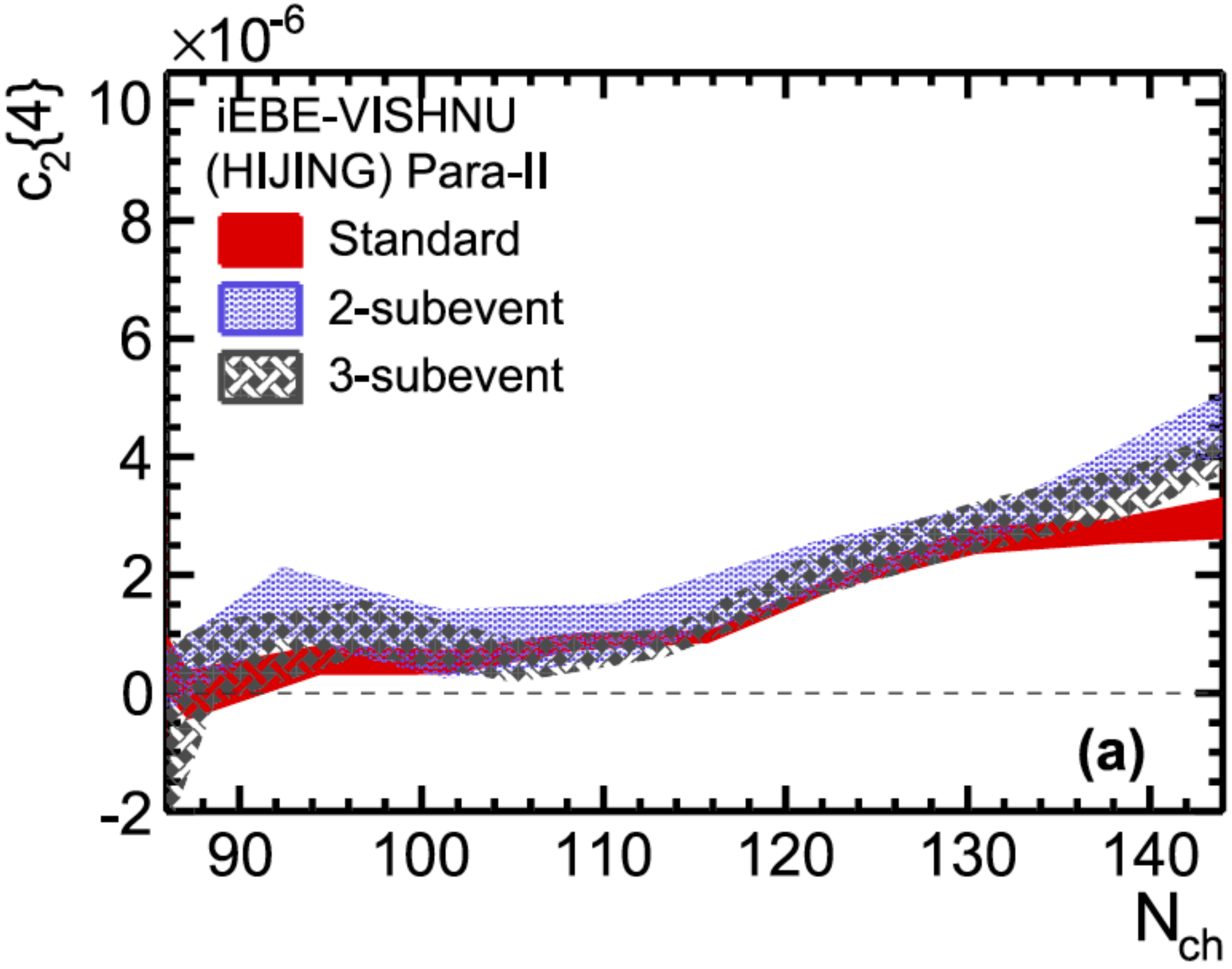
❖ **Multi-particle cumulant**:

- opposite sign of $c_2\{4\}$!

- ***Positive $c_2\{4\}$ does not necessarily suggest non-flow***
- ***Negative $c_2\{4\}$ does not necessarily imply hydrodynamic flow***

No trivial bias

W. Zhao, YZ, H. Xu, W. Deng, H. Song, PLB 780 (2018) 495



❖ Not non-flow (resonance decays)

- $c_2\{4\} = c_2\{4\}_{2sub} = c_2\{4\}_{3sub}$

❖ Not multiplicity fluctuations

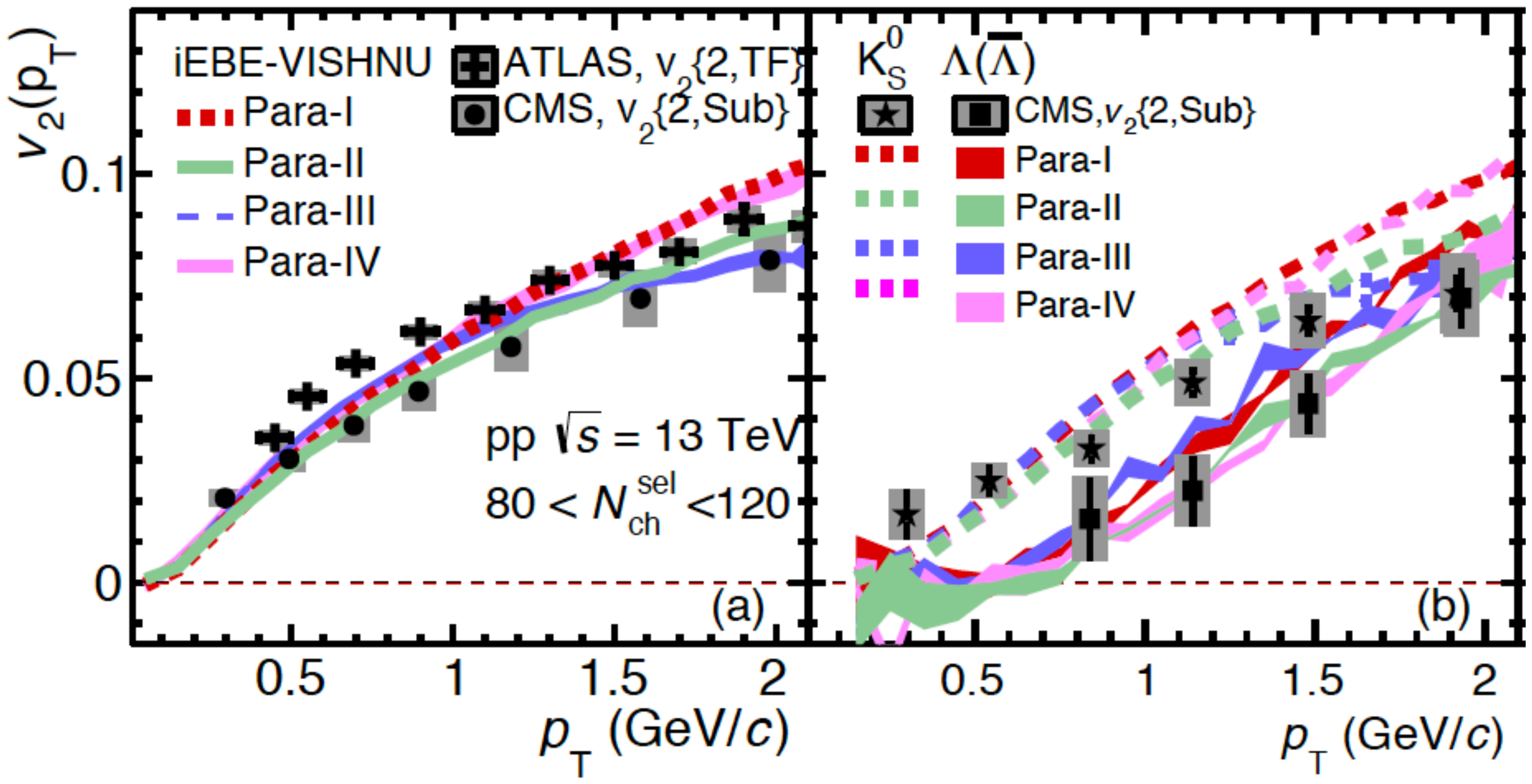
- Using unit N_{ch} bin and then rebin into wider bin, same as experiments

❖ Not statistical stability

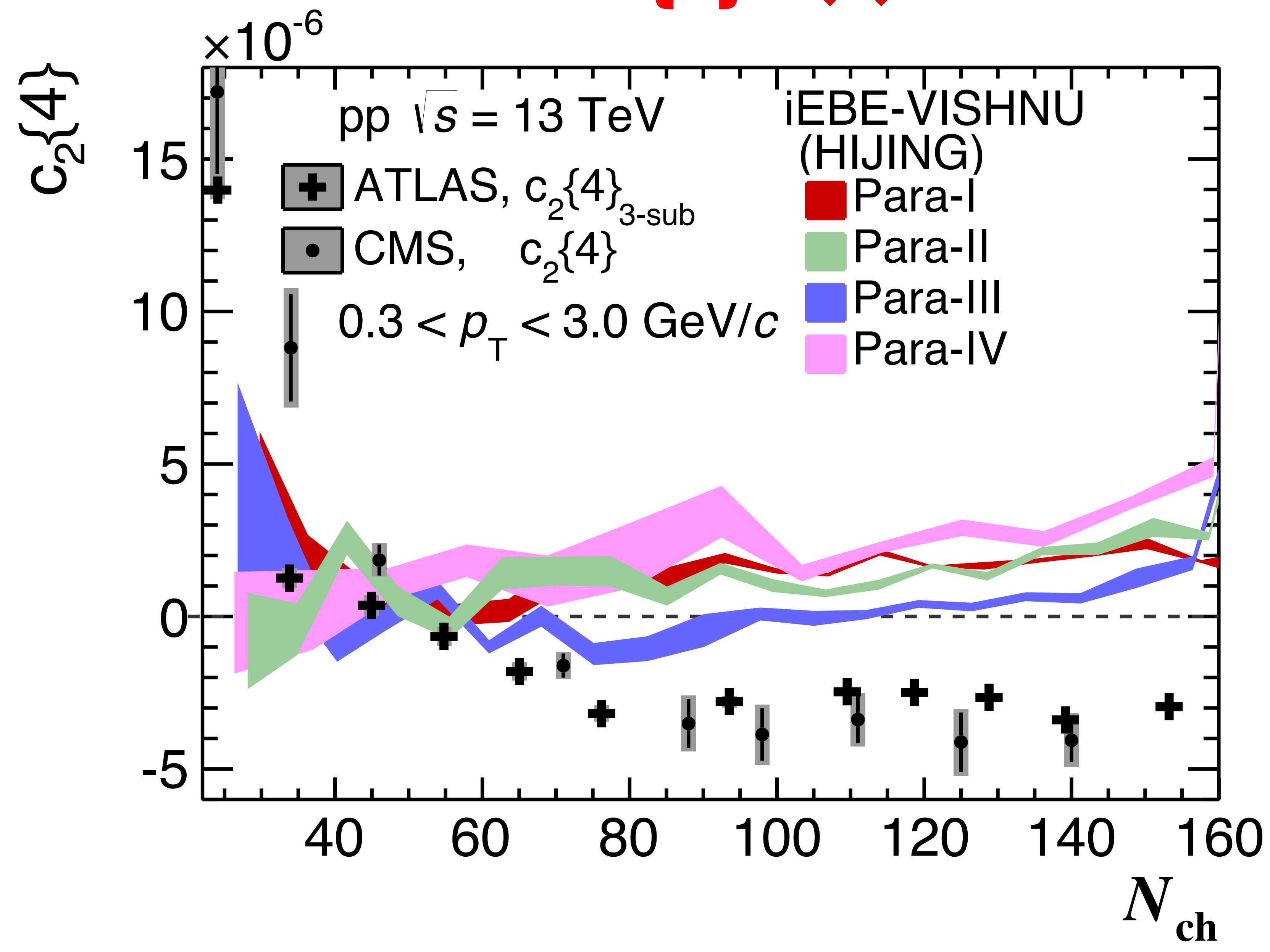
- Huge hydro data sample has been produced

Combine $v_2\{2\}$ and $v_2\{4\}$

$v_2\{2\}$ ✅



$v_2\{4\}$ ❌

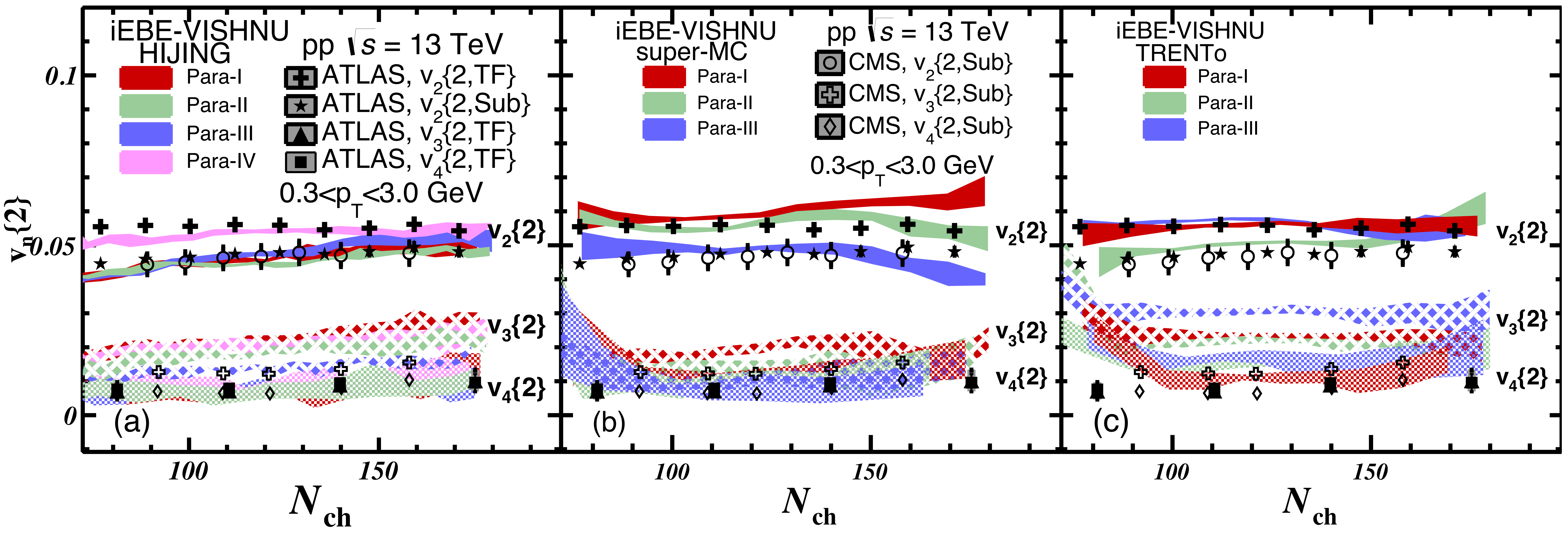


- $v_2\{2\}$: flow + flow fluctuations ✅
- $v_2\{4\}$: flow − flow fluctuations ❌

❖ iEBE-VISHNU (HIJING-IC) works for $v_2\{2\}$ but not $v_2\{4\}$

- This hydro calculation does not describe neither flow nor flow fluctuations in pp

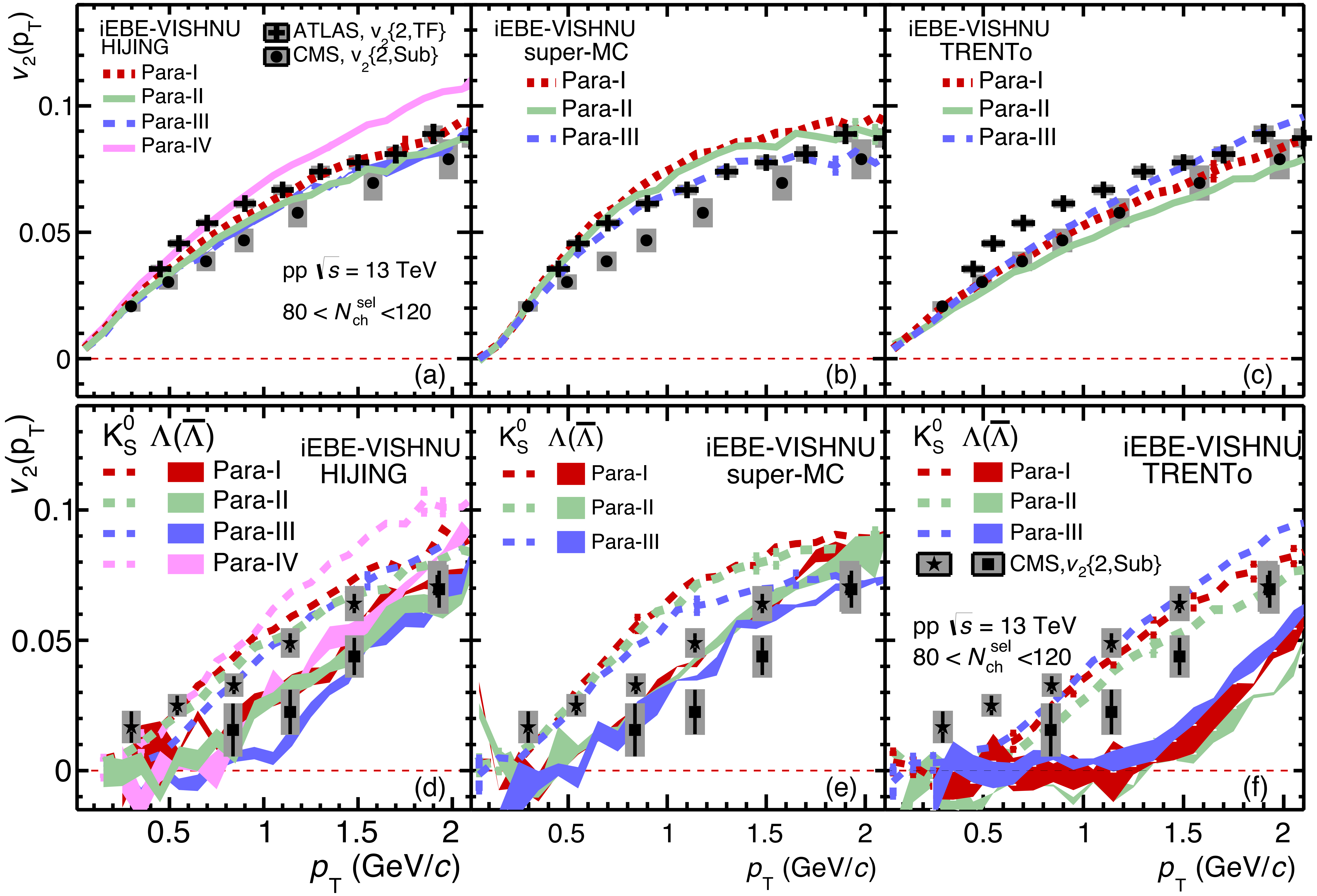
Preparations with 3 initial conditions



❖ Testing two other different initial conditions

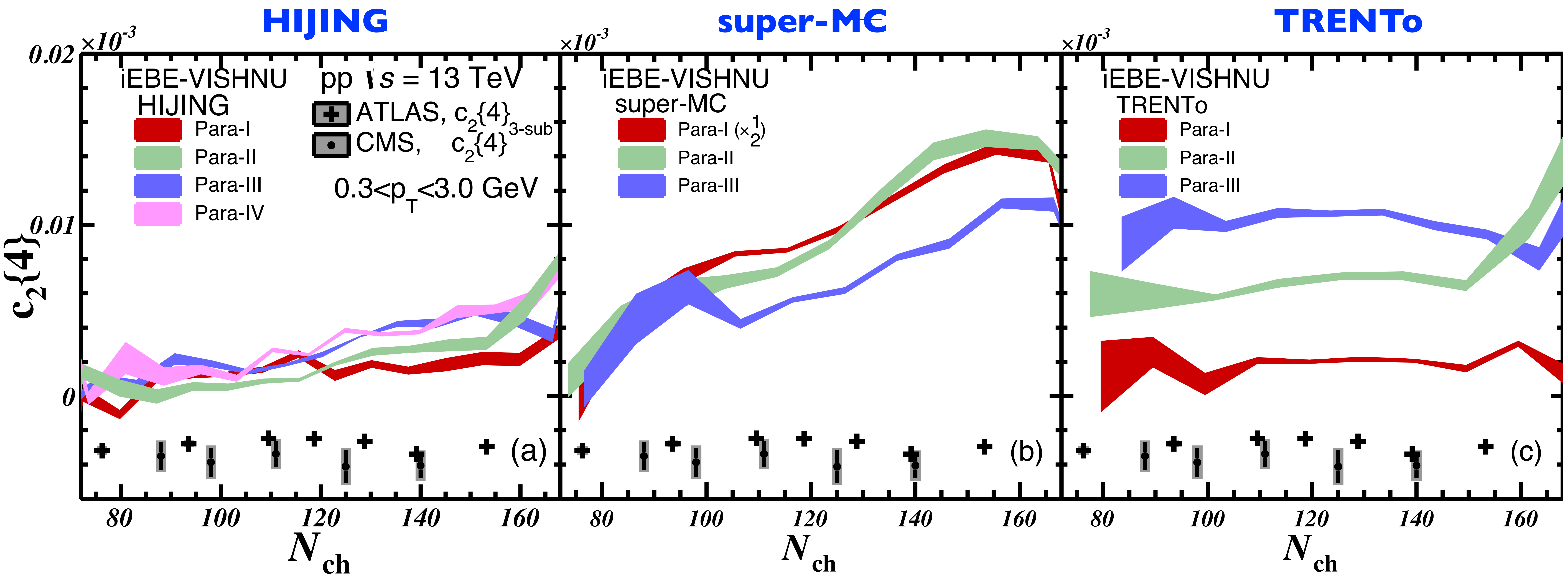
- Hydrodynamic calculations could fit the data with selected set of parameters (HIJING and super-MC work better than TRENTo)

$v_2(p_T)$ with three IC



❖ Describe qualitatively p_T differential v_2 of both charged and strange particles

All hydro give positive $c_2\{4\}$

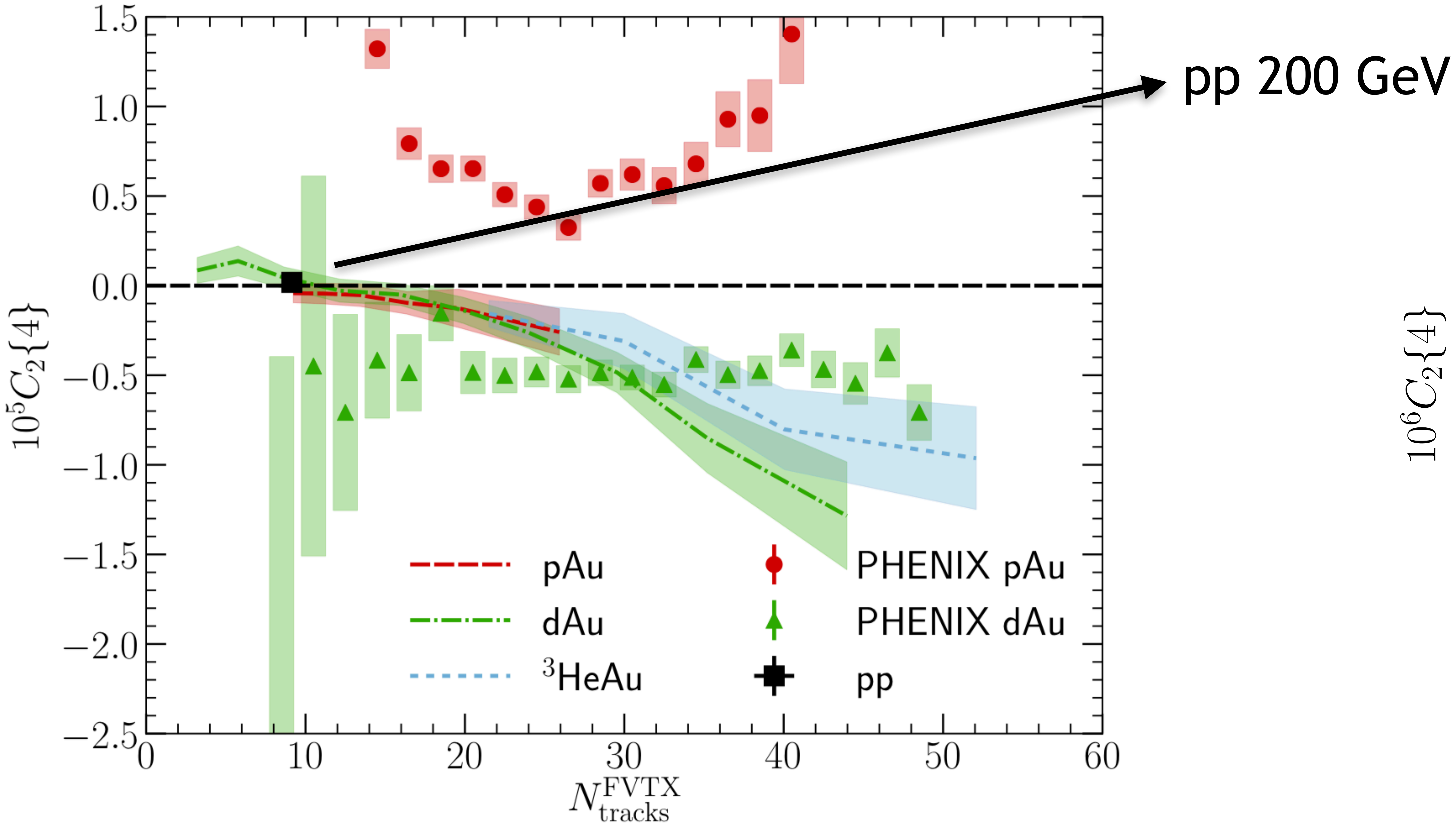


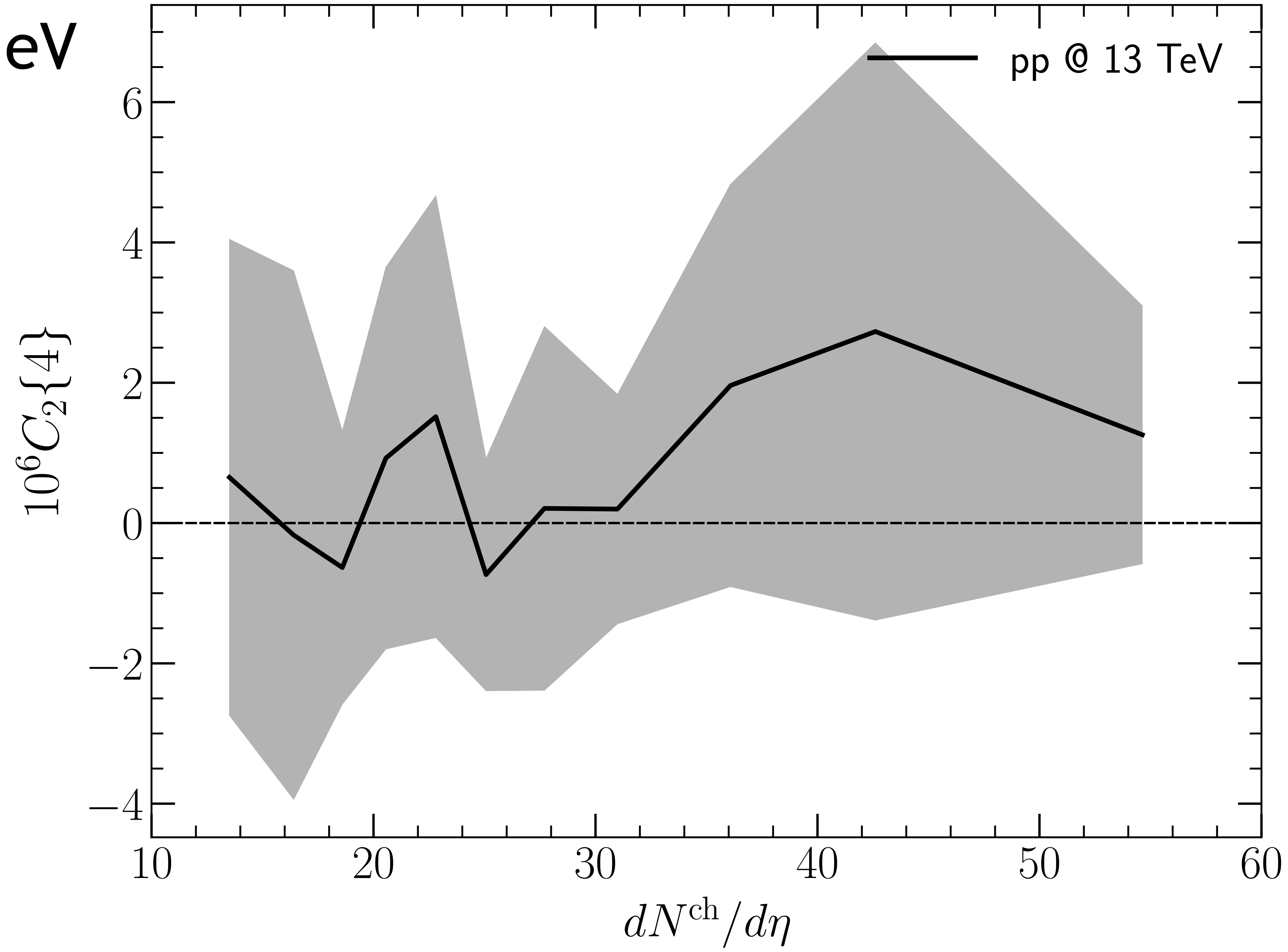
❖ Hydrodynamic calculations using super-MC and TRENTo initial conditions gives even larger positive $c_2\{4\}$, and far away from data

Not only for iEBE-VISHNU

B. Schenke, C. Shen, and P. Tribedy, arXiv:1908.06212

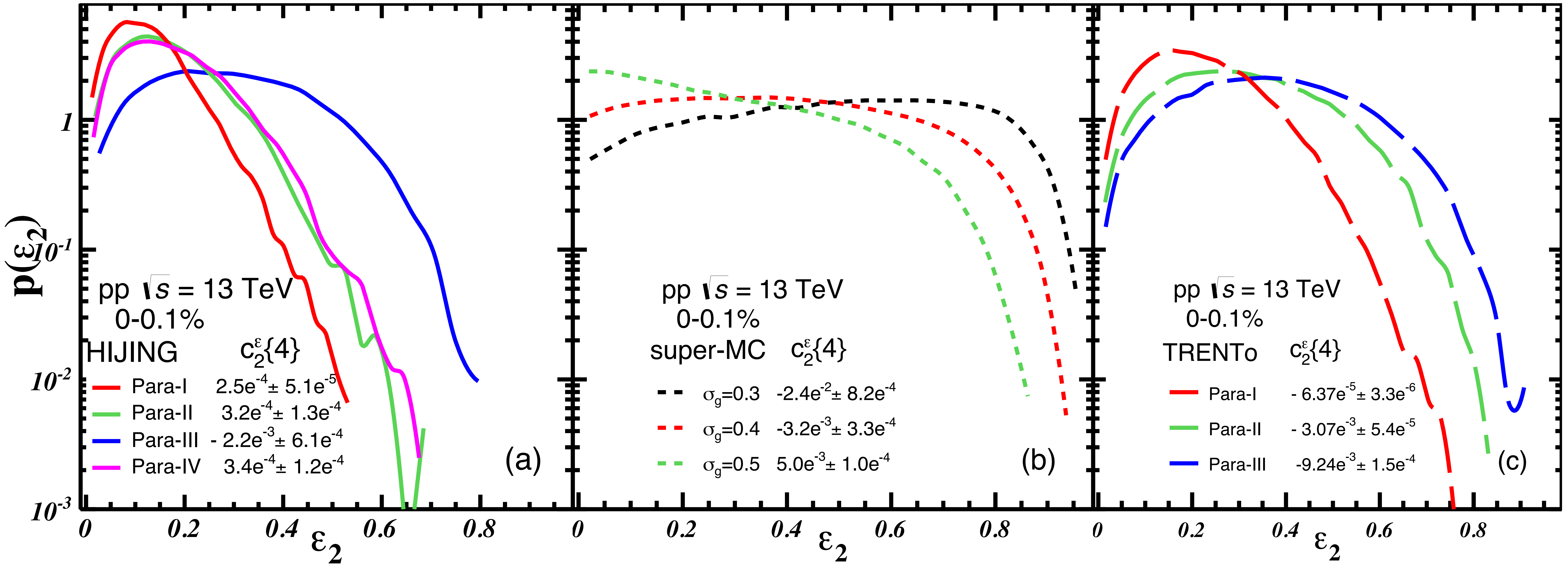
Details, see: B. Schenke, Wed. 14.00
C. Shen, Thu.9.00





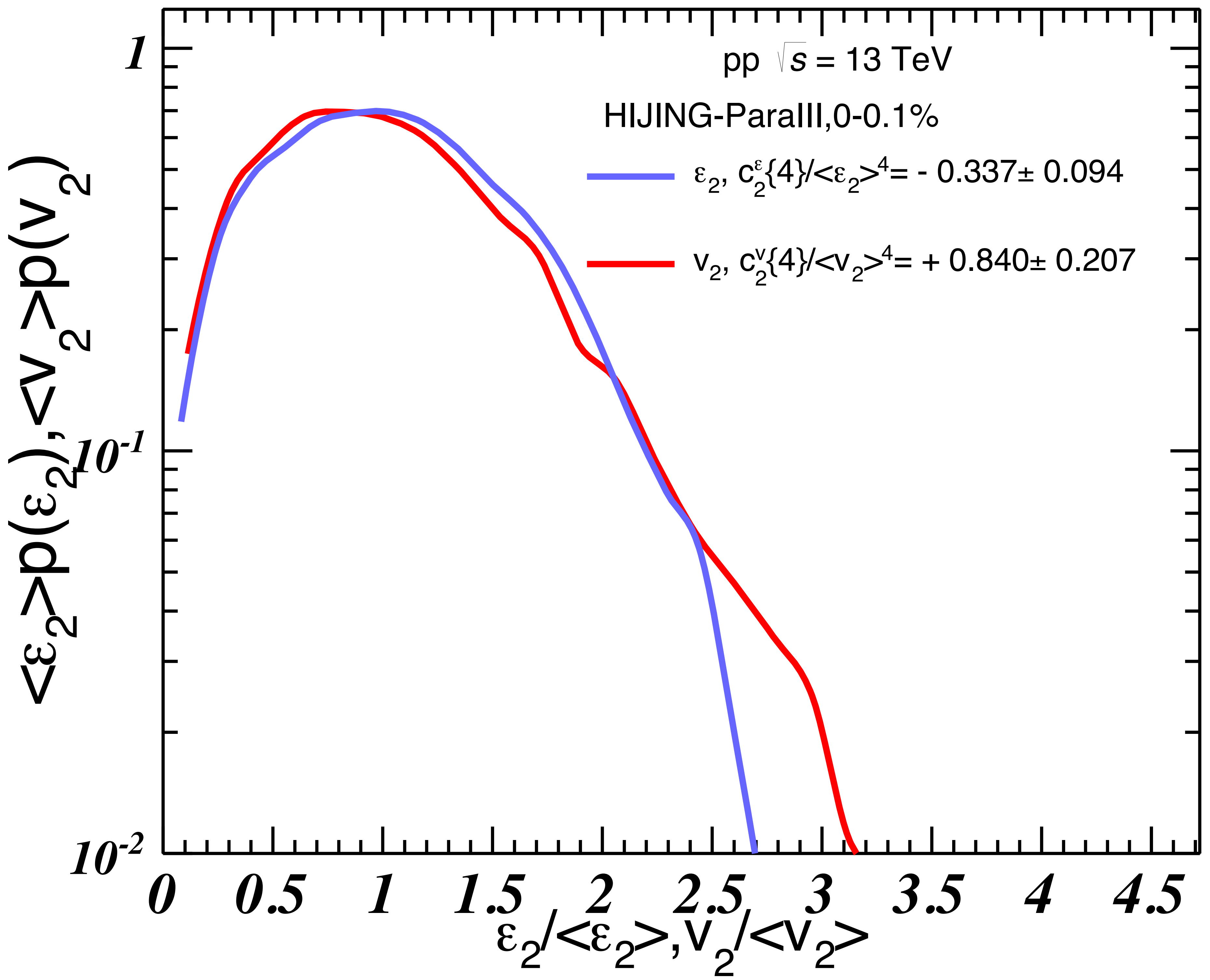
❖ Not only for iEBE-VISHNU but maybe a current difficulty

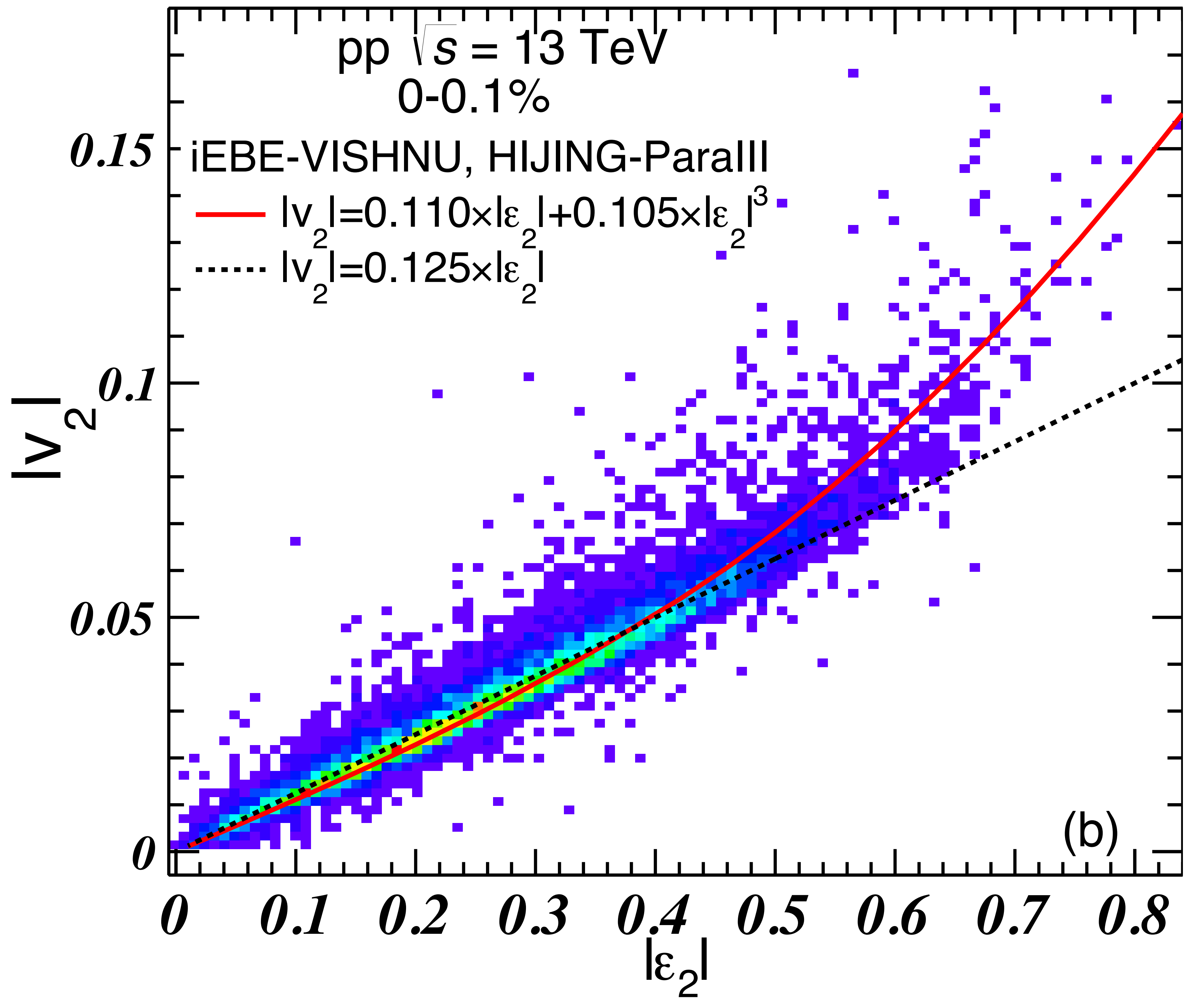
Initial eccentricity distributions



- ❖ Positive $-\varepsilon_2\{4\}^4$ results in positive $c_2\{4\}$
  - Expected if $v_2 \propto \varepsilon_2$
- ❖ Negative $-\varepsilon_2\{4\}^4$ also leads to positive $c_2\{4\}$
  - Unexpected if $v_2 \propto \varepsilon_2$
  - Corresponds to wider $p(\varepsilon_2)$ distribution (larger ε_2 fluctuations, larger $<\varepsilon_2>$)

Non-linear hydrodynamic response

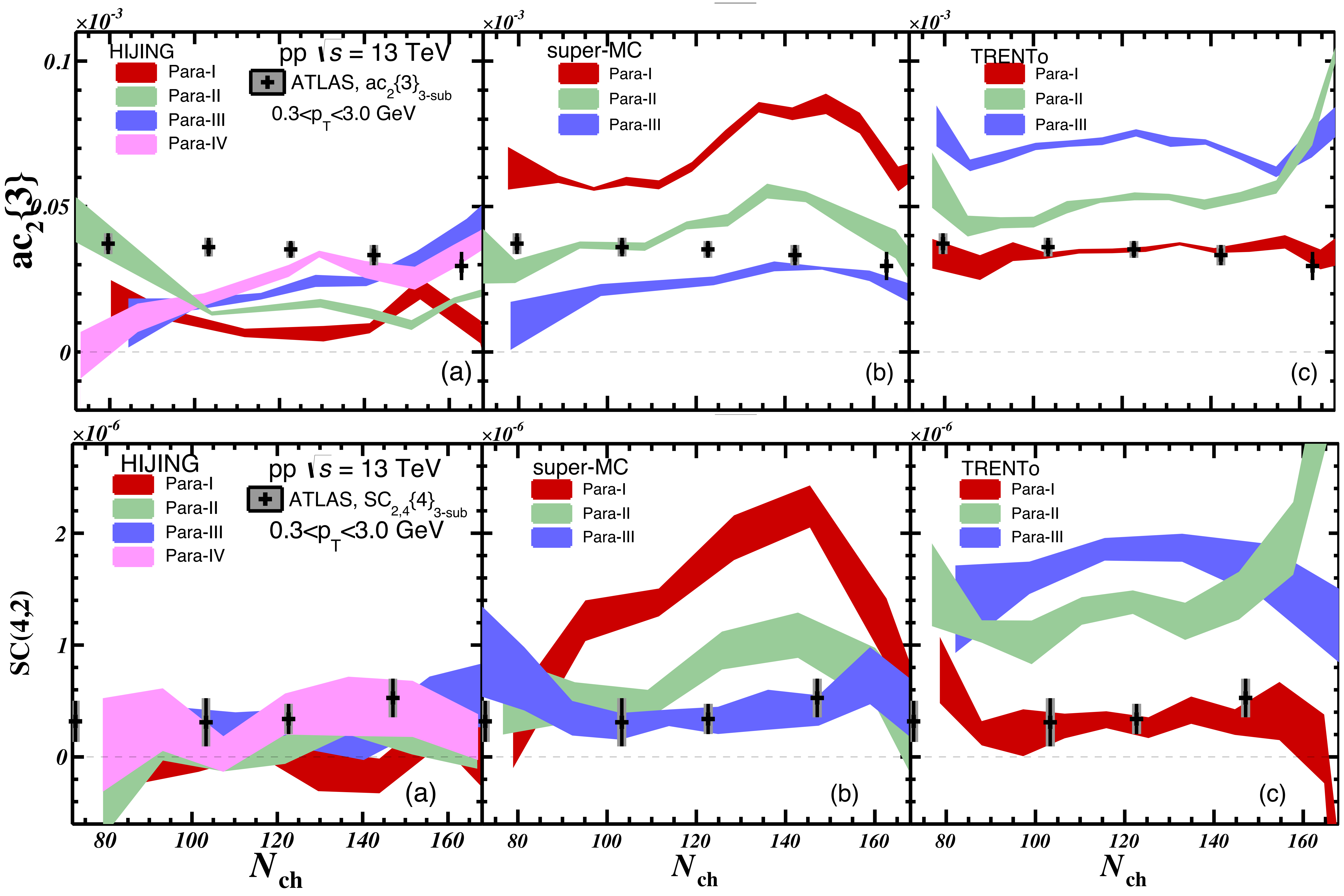




- Hydro modifies the $p(v_2)$ distributions, especially the larger ε_2 region
- For the same ε_2 region, a significant non-linear (cubic) hydrodynamic response of v_2 to ε_2

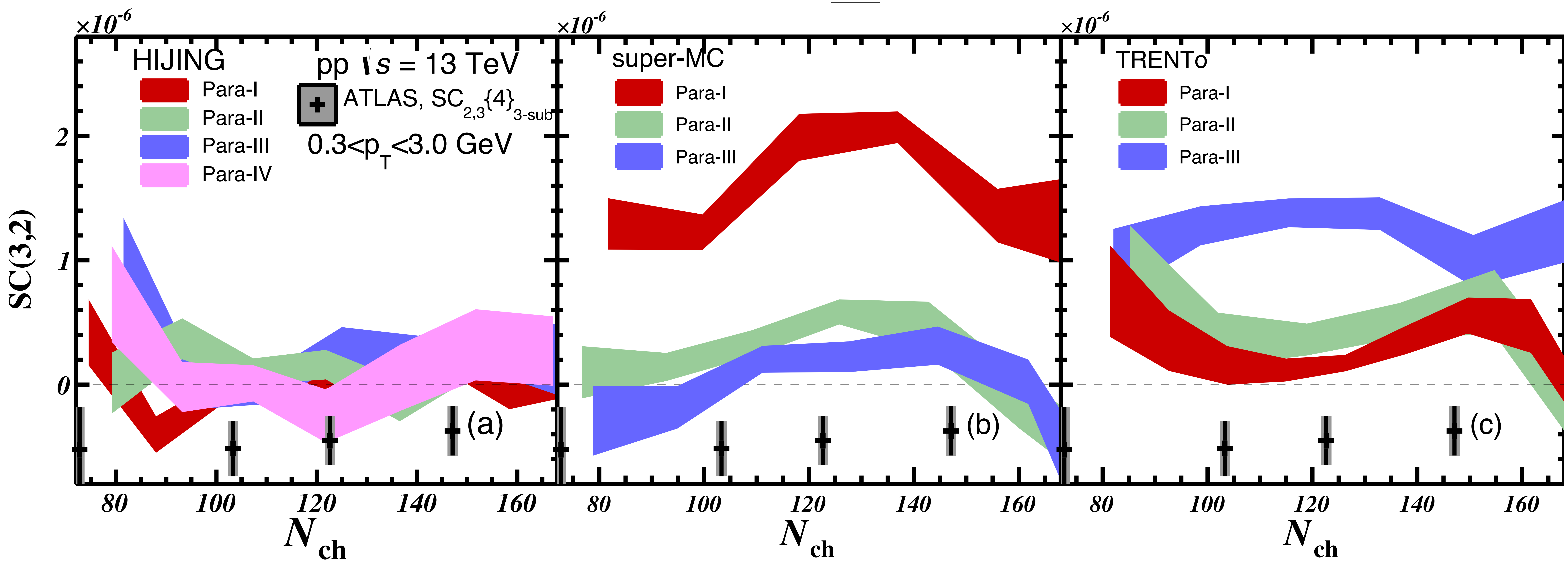
non-linear response ⇒ additional fluctuations ⇒ positive $c_2\{4\}$

Flow vector correlations



❖ Hydrodynamic calculations could qualitatively describe the asymmetric cumulants ac{3}, and symmetric cumulants SC(4,2)

Flow harmonic correlations



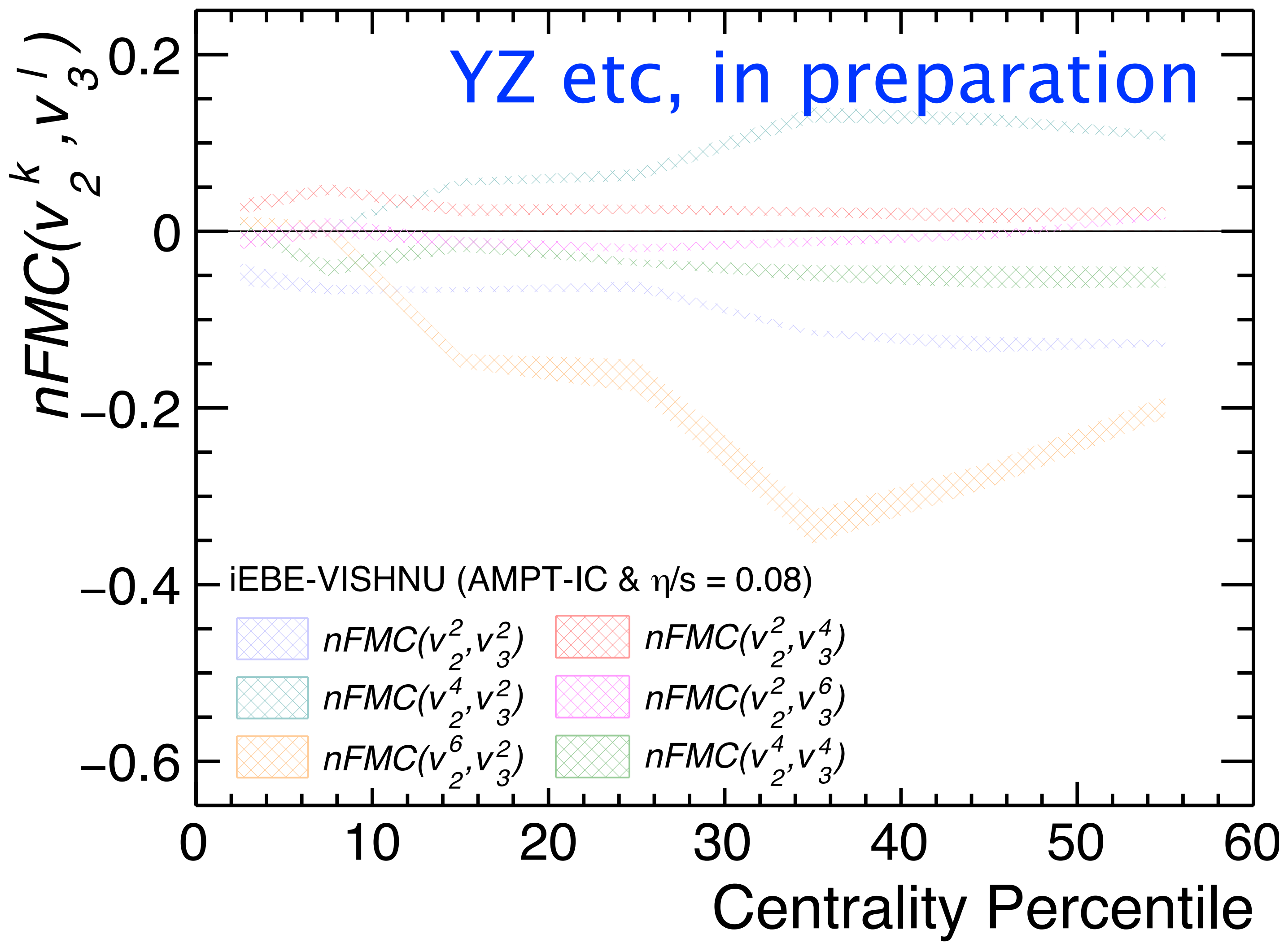
- ❖ Negative SC(3,2) observed in data, while all hydrodynamic calculations give positive SC(3,2)!
- ❖ It seems that hydrodynamic calculations have the difficulty to generate multi-particle (single/mixed harmonic) cumulants correctly

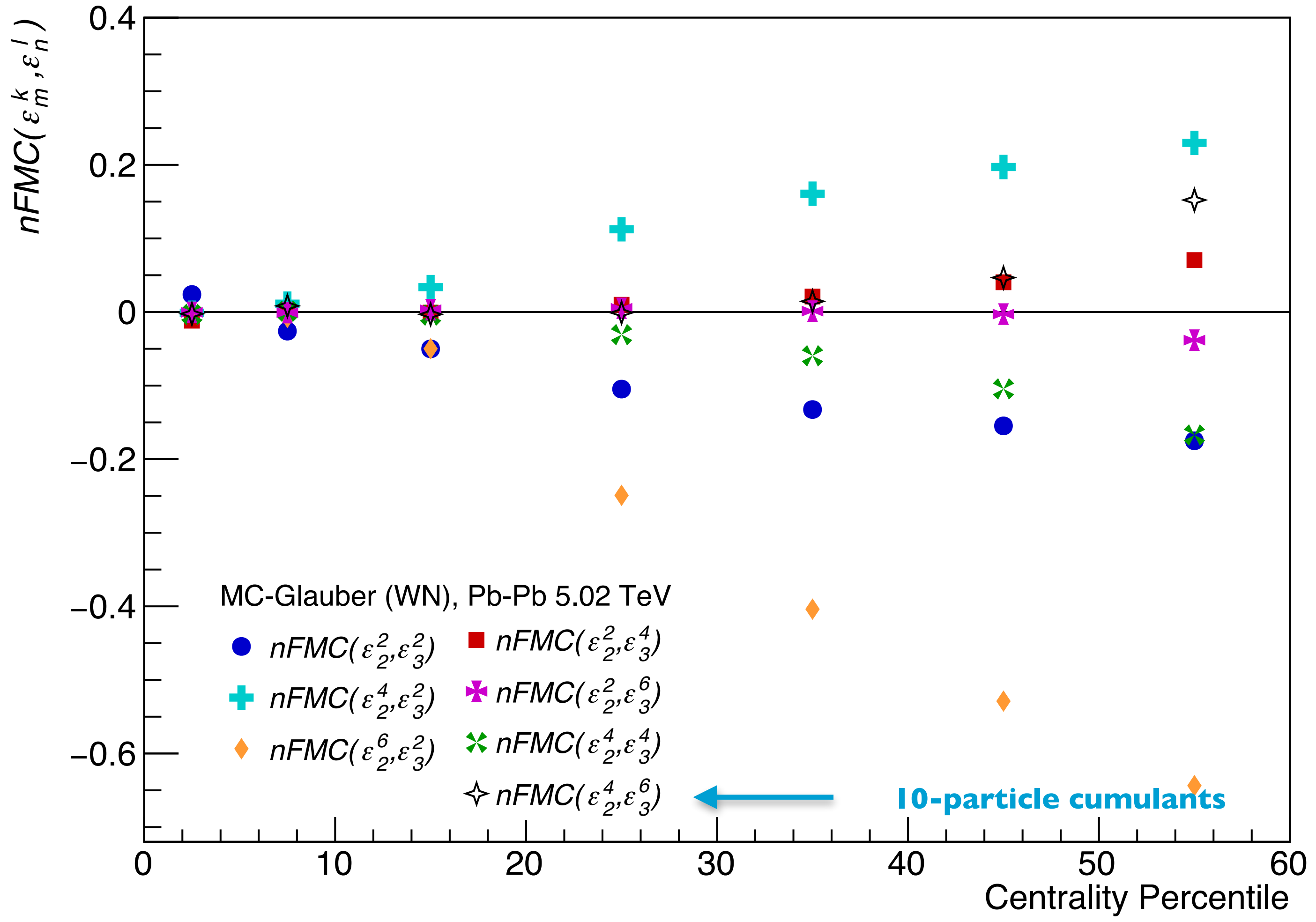
What next (EXP)

❖ EXP

- ❖ Recheck statistical stability: what is the limit of 3-sub-event of 4-particle cumulants in large N_{ch}
- ❖ Other sensitive observables on flow and flow correlations
  - Multi-particle mixed harmonic correlations (shows -, +, -, + signs of 4-, 6-, 8- and 10-particle cumulants in hydro)
  - How about small systems?

FMC(v_2^k, v_3^l) probes correlations between <v_2^k> and <v_3^l>





What next (TH)

- ❖ Other initial conditions?
  - Using global bayesian analysis to constrain the parameters in IC?
  - dipole formulation of BFKL evolution (arXiv:1907.12871)
- ❖ Improvements in hydro framework?
  - With other 2+1D hydro framework
  - 3+1D hydro?
- ❖ None of the above works?
  - Other mechanisms, AMPT-escape, Kinematic, string shoving etc.
  - One fluid might not (yet) rule pp collision?

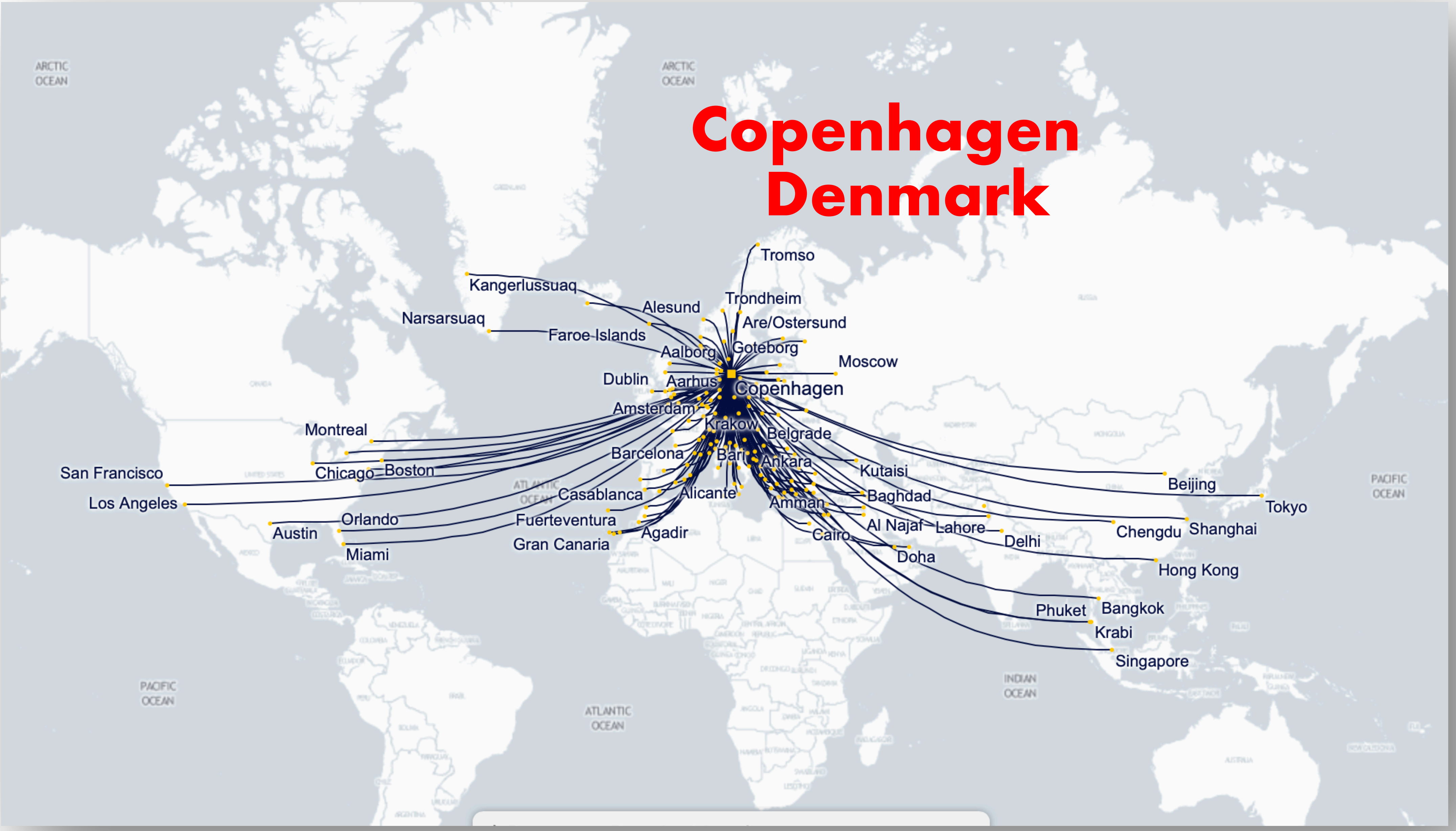
Conclusions

❖ Probe hydrodynamic flow in pp collisions using iEBE-VISHNU

- works well for all 2- and 3-particle correlations,
- can not reproduce negative signs of $c_2\{4\}$ and NSC(3,2)

❖ Further testings on new IC as well as hydro developments must be performed, to confirm if ***the fluid*** may rule pp collisions

The " research investment "

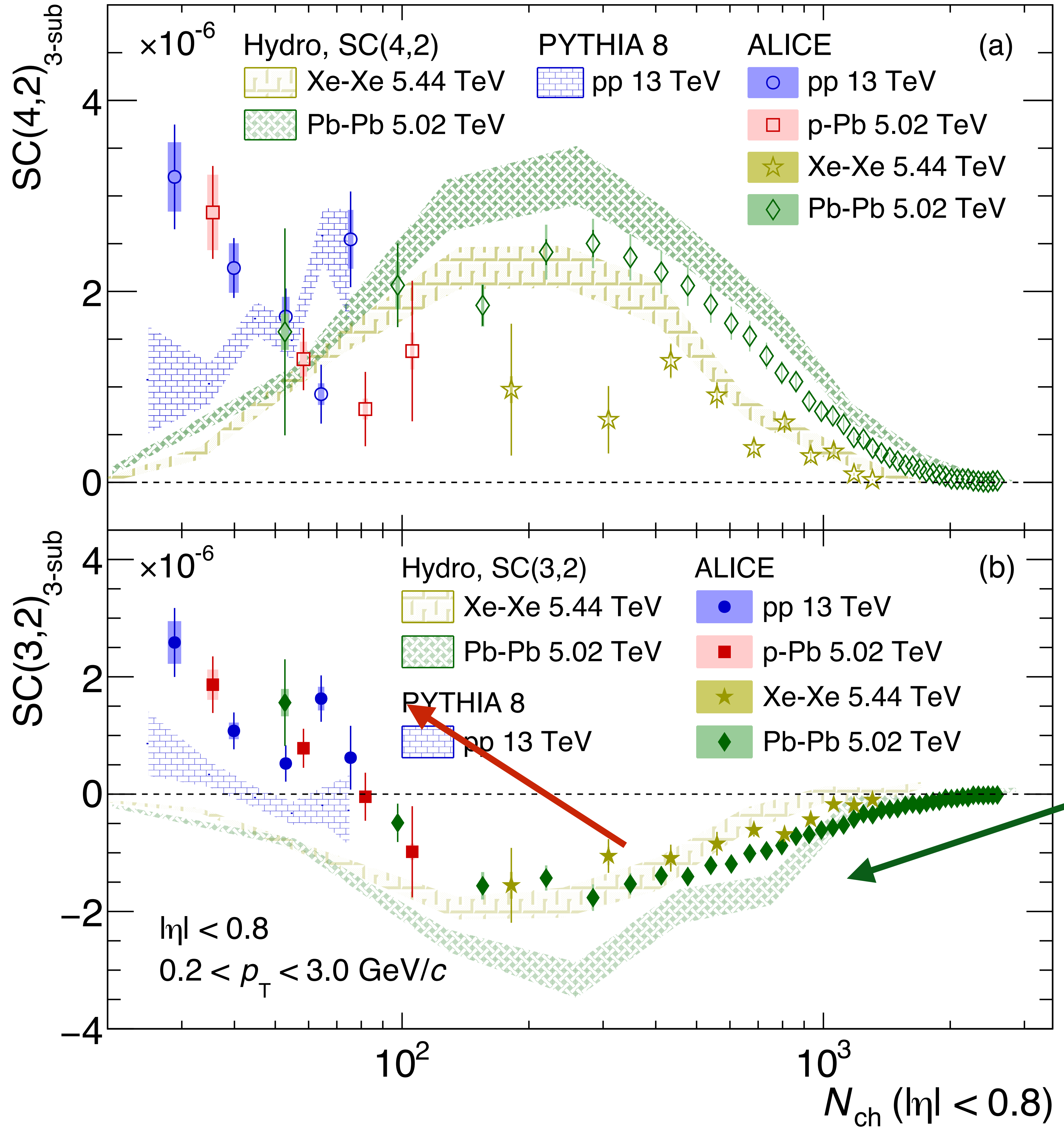


- The negative signs have been headache for a while …

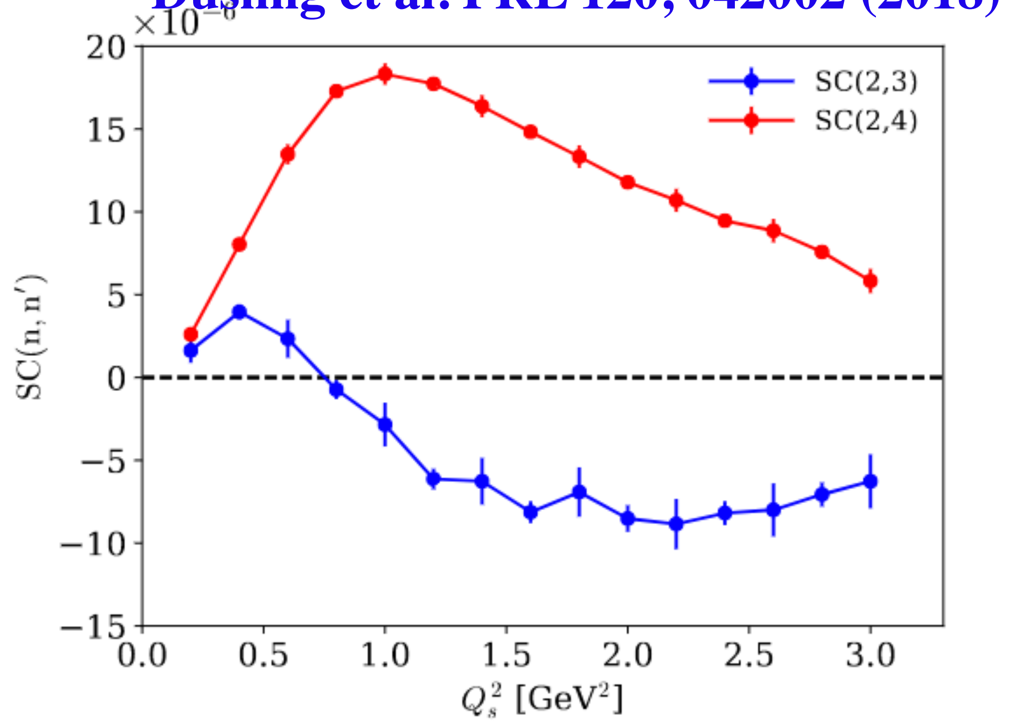
- Whoever helps to solve the puzzle first, she/he is invited to give a seminar at NBI in Copenhagen

Backup

Symmetric Cumulants in small systems



Dusling et al. PRL 120, 042002 (2018)



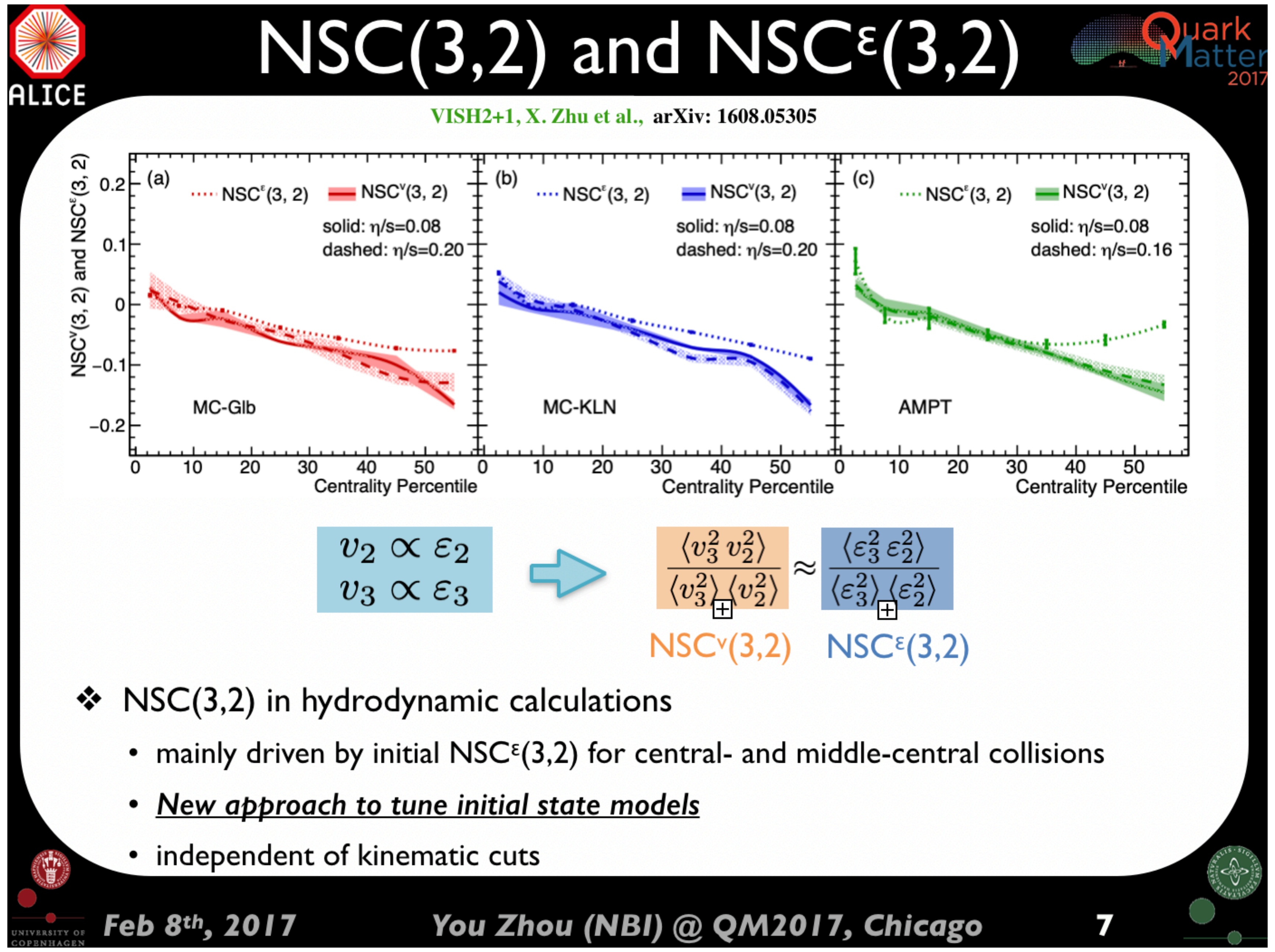
❖ Symmetric cumulants

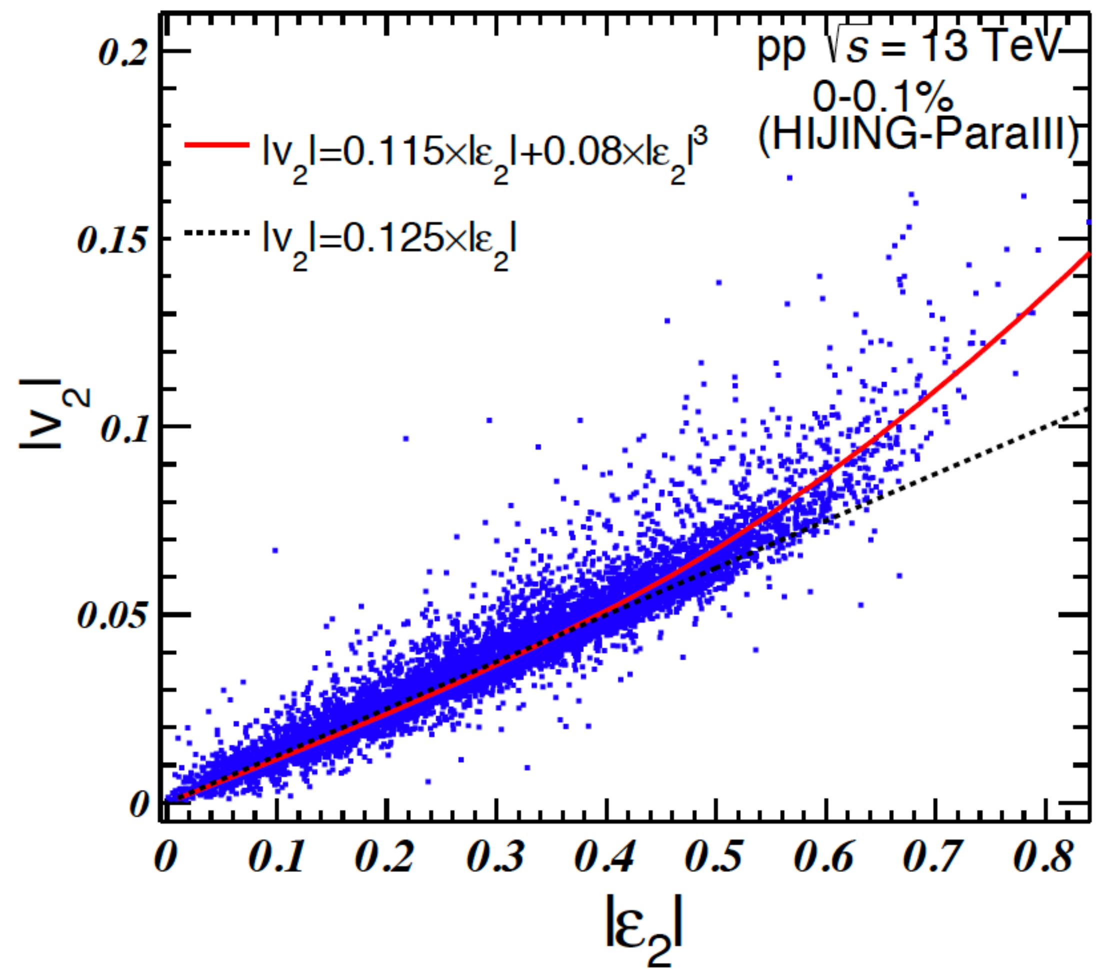
- **Correlation** between v_2^2 and v_4^2 in all systems
- **Anti-correlation** between v_2^2 and v_3^2 at high multiplicities, a **transition** to positive correlation followed by both small and large systems
- Not described by non-flow only models, but qualitatively predicted by model with initial stage correlations

❖ What's next:

- SC(m^i,n^j), SC(m,n,k)
- challenges: **statistics**

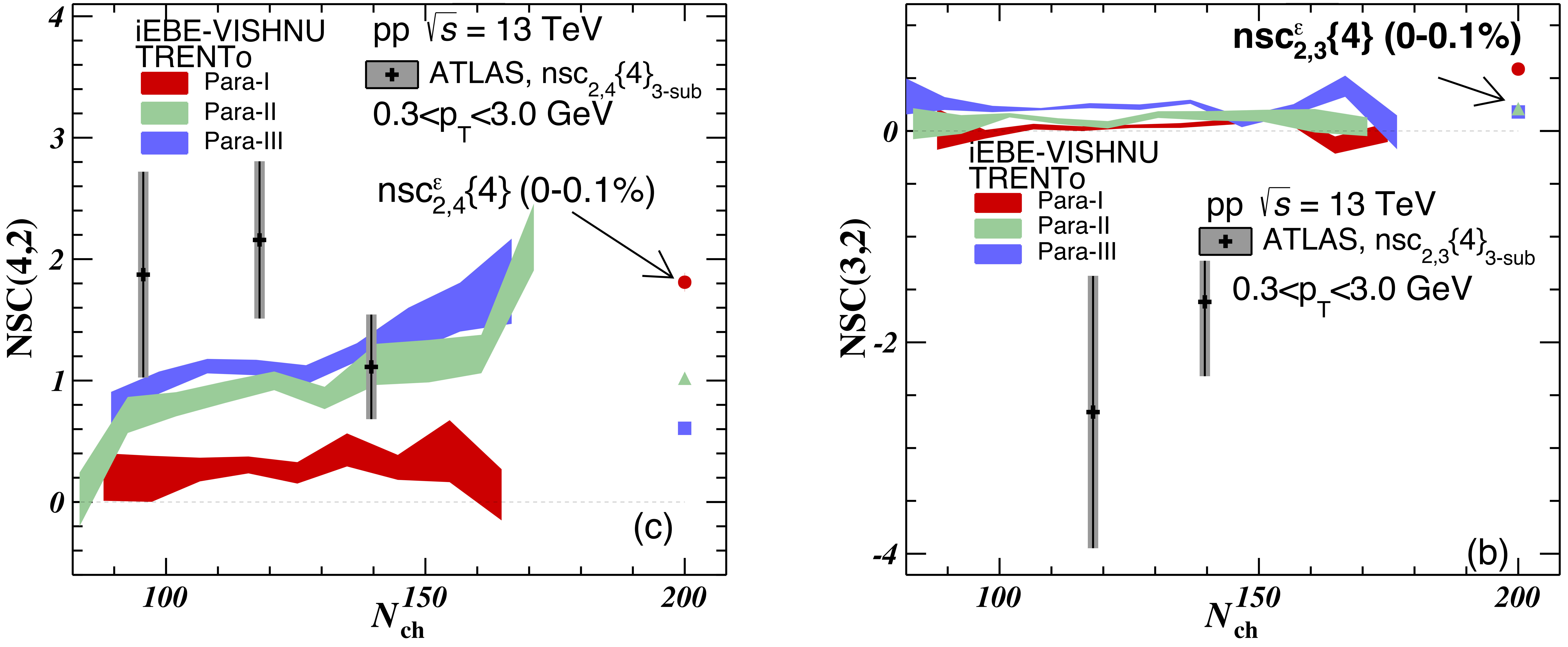
Normalized Symmetric Cumulants



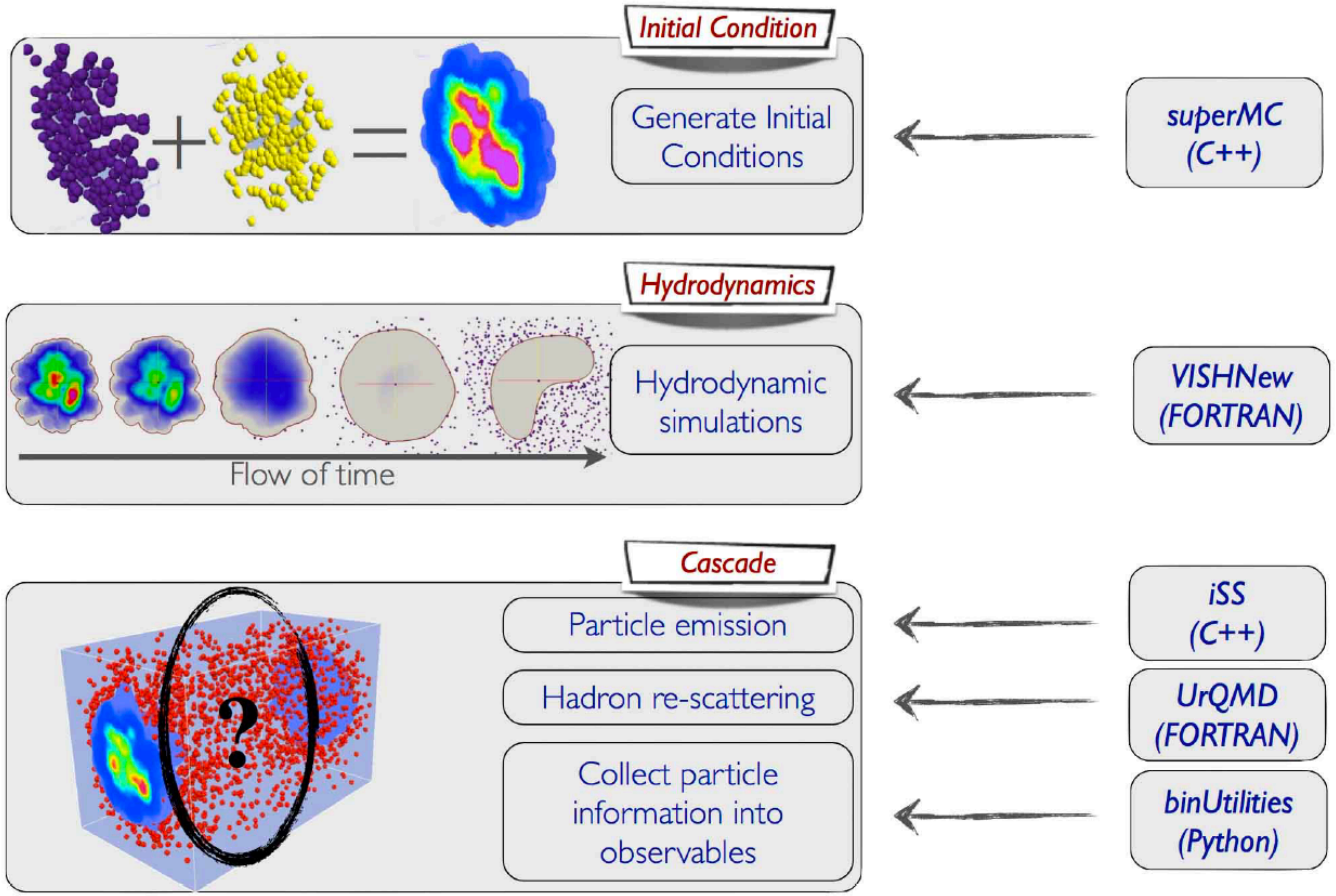


Similar discussions on additional fluctuations in PHENIX PRL paper with AMPT

- ❖ Linear response of v_n to ε_n in heavy ion -> $NSC^v(3,2) = NSC^\varepsilon(3,2)$
  - Use $NSC^v(3,2)$ to constrain initial state model
- ❖ v_n might not be linearly correlated with ε_n in small systems (e.g. pp)
  - it generates additional fluctuations which changes sign of $c_2\{4\}$
  - one should not compare initial $NSC^\varepsilon(3,2)$ in model calculations to $NSC^v(3,2)$ data
  - It also make less sense to compare $v_2\{6\}\{8\}/v_2\{4\}$ and $\varepsilon_2\{6\}\{8\}/\varepsilon_2\{4\}$ in SS.


iEBE-VISHNU
TRENTo
Para-I
Para-II
Para-III
pp $\sqrt{s}$ = 13 TeV
ATLAS, $nsc_{2,4}\{4\}_{3\text{-sub}}$
$0.3<p_T<3.0$ GeV
$nsc^{\varepsilon}_{2,4}\{4\}$ (0-0.1%)
NSC(4,2)
N_{ch}
(c)
$nsc^{\varepsilon}_{2,3}\{4\}$ (0-0.1%)
iEBE-VISHNU
TRENTo
Para-I
Para-II
Para-III
pp $\sqrt{s}$ = 13 TeV
ATLAS, $nsc_{2,3}\{4\}_{3\text{-sub}}$
$0.3<p_T<3.0$ GeV
NSC(3,2)
N_{ch}
(b)

❖ iEBE-VISHNU



C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass and U. Heinz. Comput. Phys. Commun. **199**, 61 (2016)

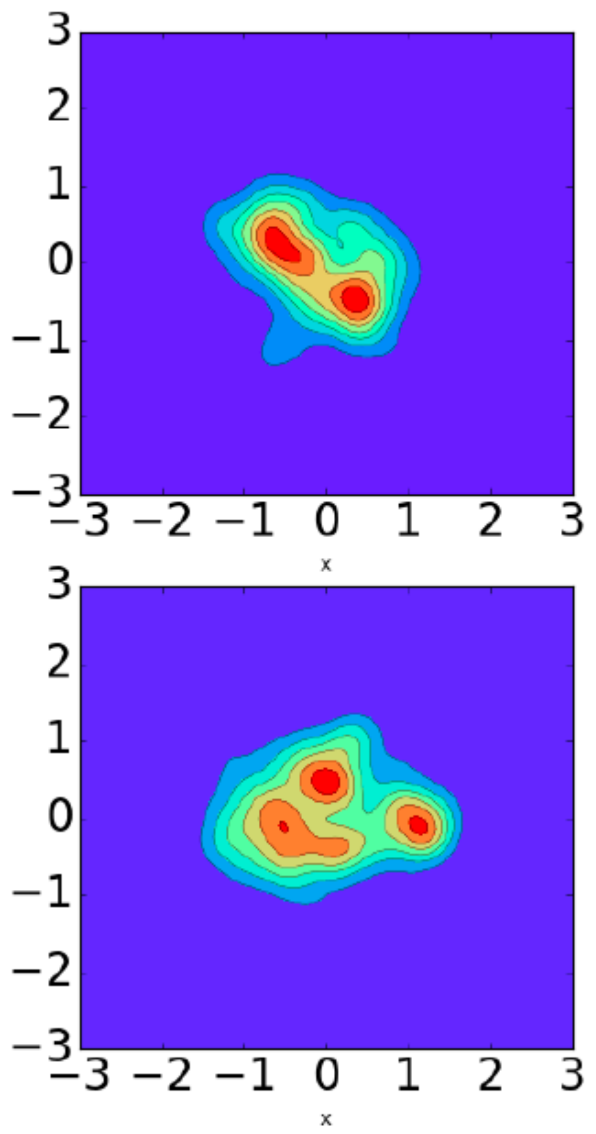
HIJING IC

In HIJING initial model, the produced jets pairs and excited nucleus are treated as independent strings, and these strings break into partons and quickly form hot spots for succeeding hydrodynamics. The center positions of strings (x_c, y_c) are sampled by Saxon-Woods distribution, and positions of partons within the strings are sampled by, $\exp\left(-\frac{(x-x_c)^2+(y-y_c)^2}{2\sigma_R^2}\right)$

	σ_R	σ_0	τ_0	η/s	$T_{\rm sw}$(MeV)	K
Para-I	1.0	0.4	0.1	0.07	147	1.26
Para-II	0.8	0.4	0.2	0.08	148	1.25
Para-III	0.4	0.2	0.6	0.20	148	1.13
Para-IV	0.6	0.4	0.4	0.05	147	1.28

HIJING constructs energy density by energy decompositions of individual partons via a Gaussian smearing:

$$\epsilon = K \sum_i \frac{E_i^*}{2\pi\sigma^2\tau_0\Delta\eta_s} \exp\left(-\frac{(x-x_i)^2+(y-y_i)^2}{2\sigma^2}\right),$$



super-MC & TRENTo

In super-MC the entropy density is:

$$s(\mathbf{r}) = \frac{\kappa_s}{\tau_0} \sum_{k=1}^{3} \gamma_k^{(i)} \frac{e^{-(\mathbf{r}-\mathbf{r}_k^{(i)})^2/(2\sigma_g^2)}}{2\pi\sigma_g^2}, \quad (5)$$

where γ_k is sampled from Γ distribution, $\mathbf{r}_k^{(i)}$ is quark's positions, σ_g is width of gluons.

	σ_R	σ_0	τ_0	η/s	$T_{\rm sw}$(MeV)
Para-I	1.0	0.4	0.1	0.07	147
Para-II	0.8	0.4	0.2	0.08	148
Para-III	0.4	0.2	0.6	0.20	148
Para-IV	0.6	0.4	0.4	0.05	147

In TRENTo the initial entropy density is:

$$s = s_0 \left(\frac{\tilde{T}_A^p + \tilde{T}_B^p}{2} \right)^{1/p}, \quad (6)$$

where $\tilde{T}(x,y) \equiv \int dz \, \frac{1}{n_c} \sum_{i=1}^{n_c} \gamma_i \, \rho_c \, (\mathbf{x} - \mathbf{x_i} \pm \mathbf{b}/2)$, n_c is the number of the independent constituents and $\rho_c(\mathbf{x}) = \frac{1}{(2\pi v^2)^{3/2}} \exp\left(-\frac{\mathbf{x}^2}{2v^2}\right)$,

	p	v	k	n_c	τ_0	η/s	$T_{\rm sw}$(MeV)
Para-I	0.5	0.3	1.5	4	0.2	0.08	149
Para-II	0.0	0.2	0.81	6	0.6	0.28	149
Para-III	0.5	0.2	1.0	4	0.8	0.28	149