Summary of small system

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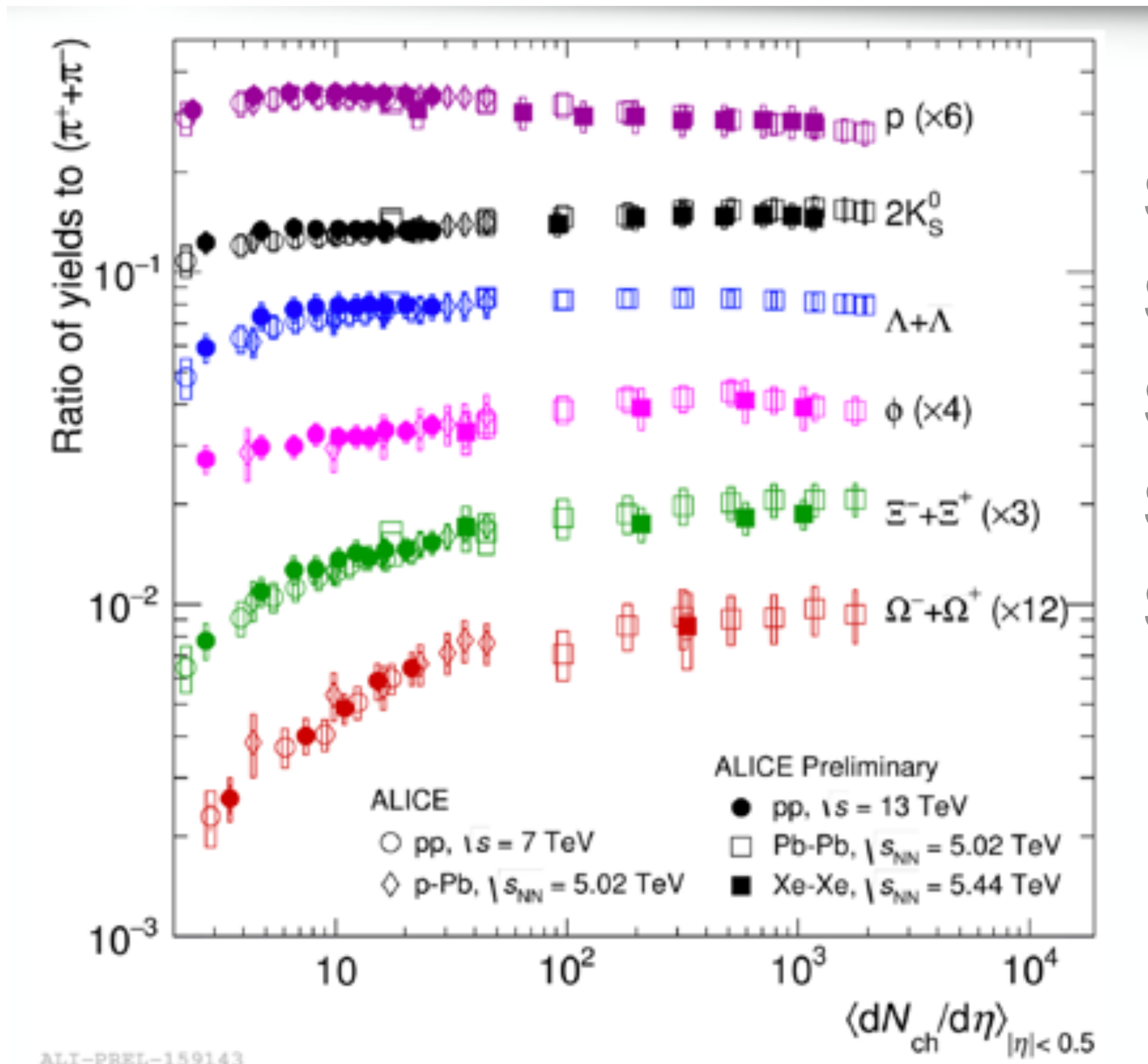
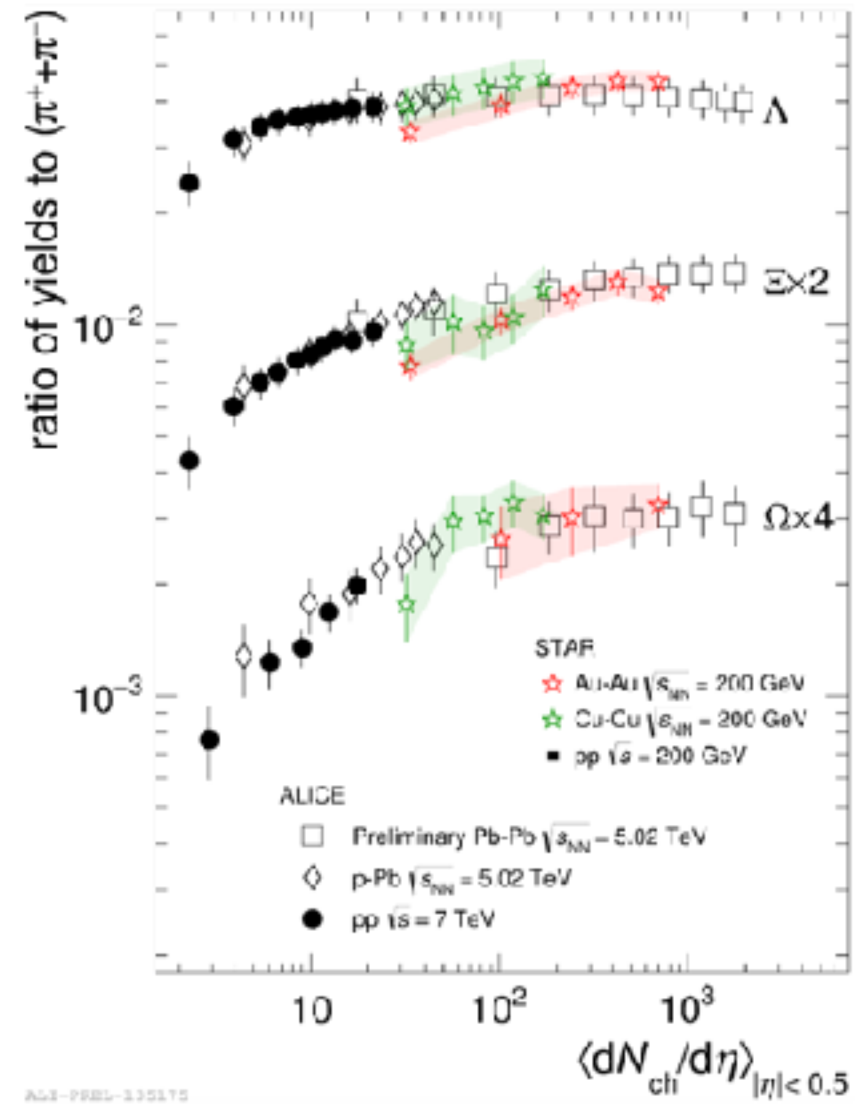
Outline

- Strangeness —> strangeness enhancement?
- Resonances —> dynamics of hadronic medium?
- PID vn —> collectivity?
- vn vs. collision geometry —> initial conditions?
- Multi particle cumulant —> initial or final?
- Symmetric cumulant —> initial or final?
- Ridge in ee collisions —> thermalization/collectivity in ee?

Strangeness production relative to pion



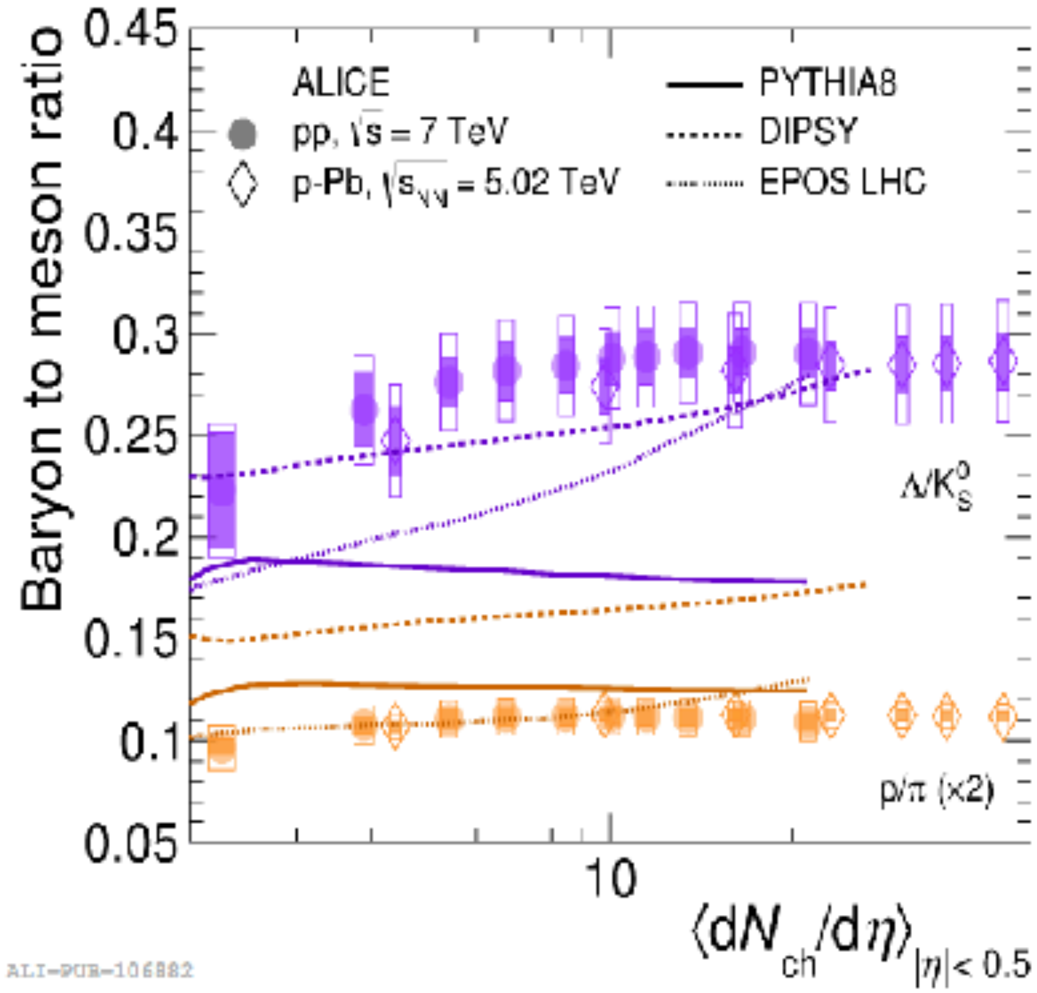
S=1
S=1
S=0
S=1
S=2

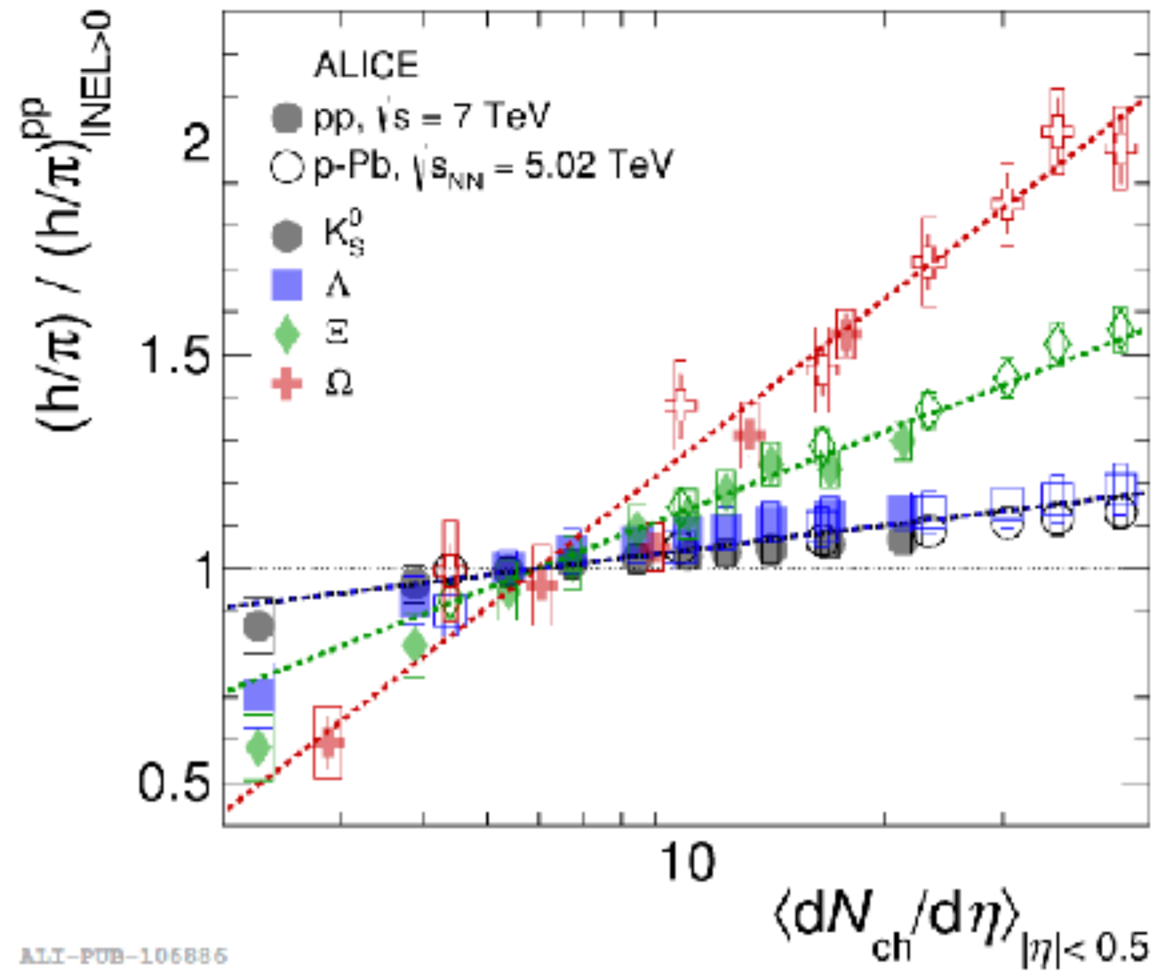


- High precision measurement at the **LHC** in fair agreement with **STAR** results at high multiplicity
- **Only multiplicity plays a role?** neither energy nor system dependence observed
- Measurements in small system at RHIC could help to understand the experimental hints

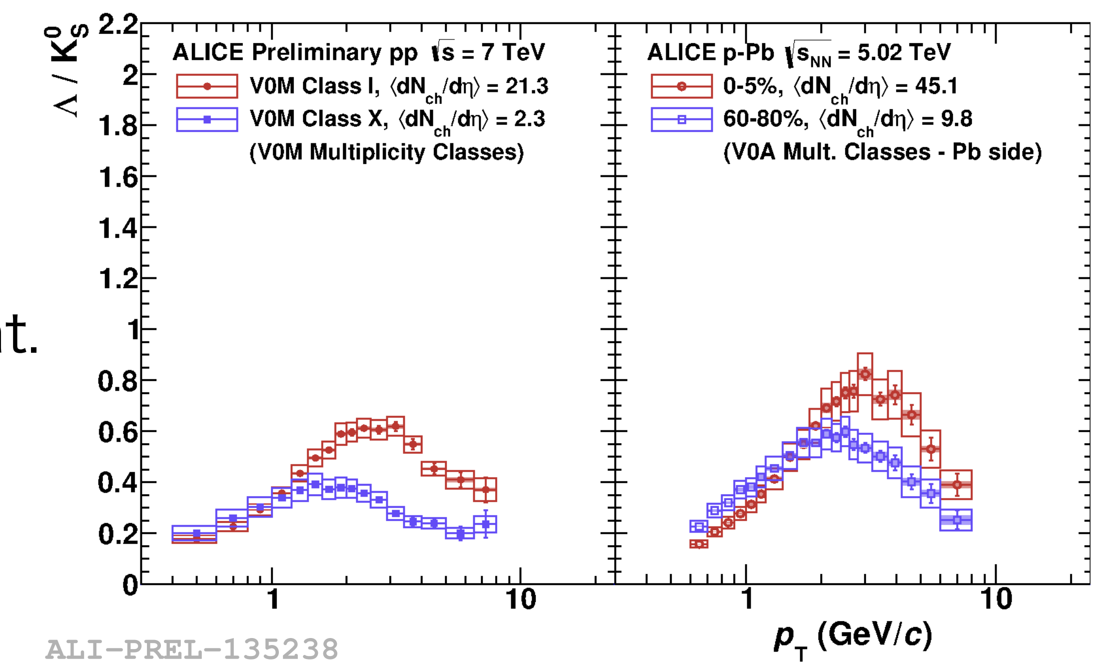
Wrap up of measurements available so far: new results from LHC-Run2 for **pp collisions at 13 TeV** and **Xe-Xe collisions at 5.44 TeV**

Baryon to meson ratio



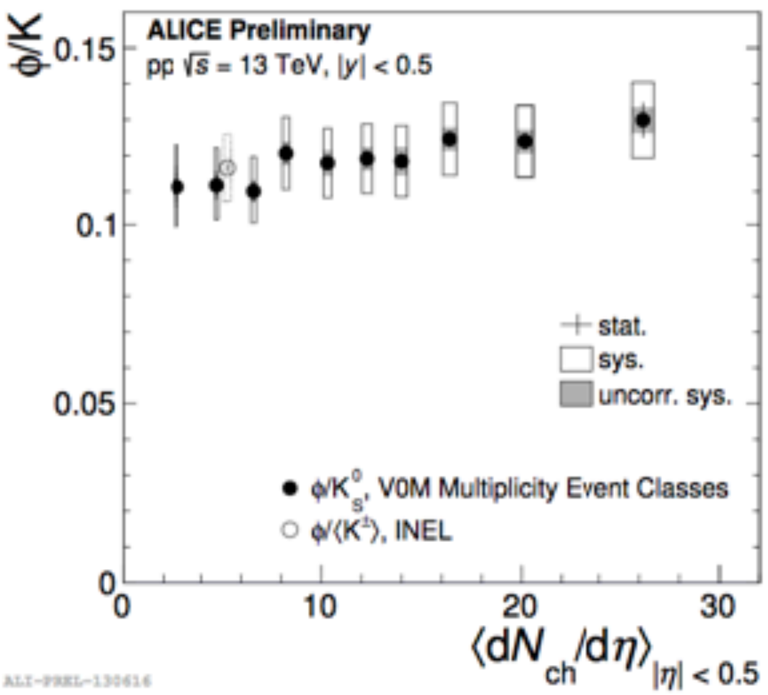


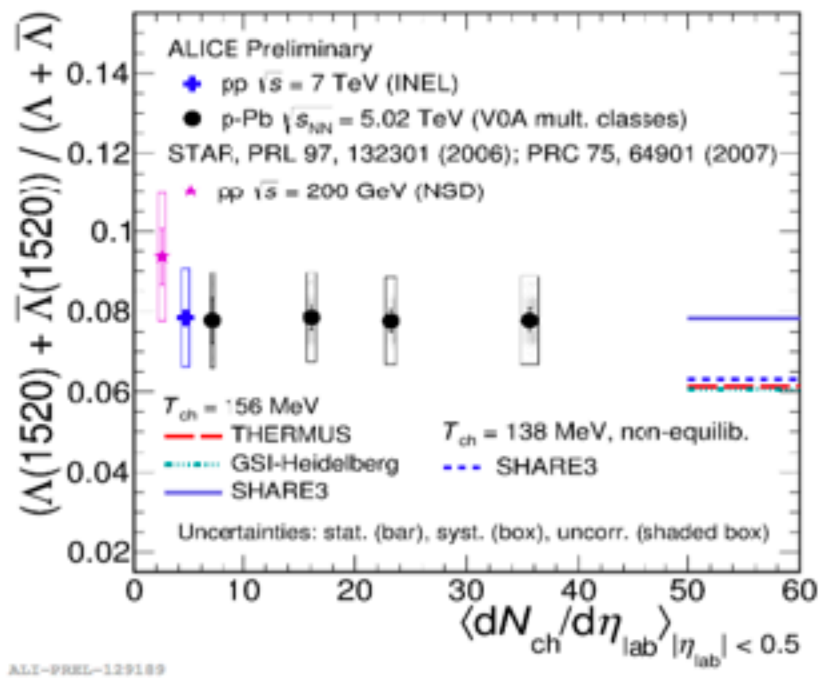
- baryon-to-meson ration with large mass gap has no multiplicity dependence.
- Strangeness enhancement due to strangeness content.
    - ϕ?

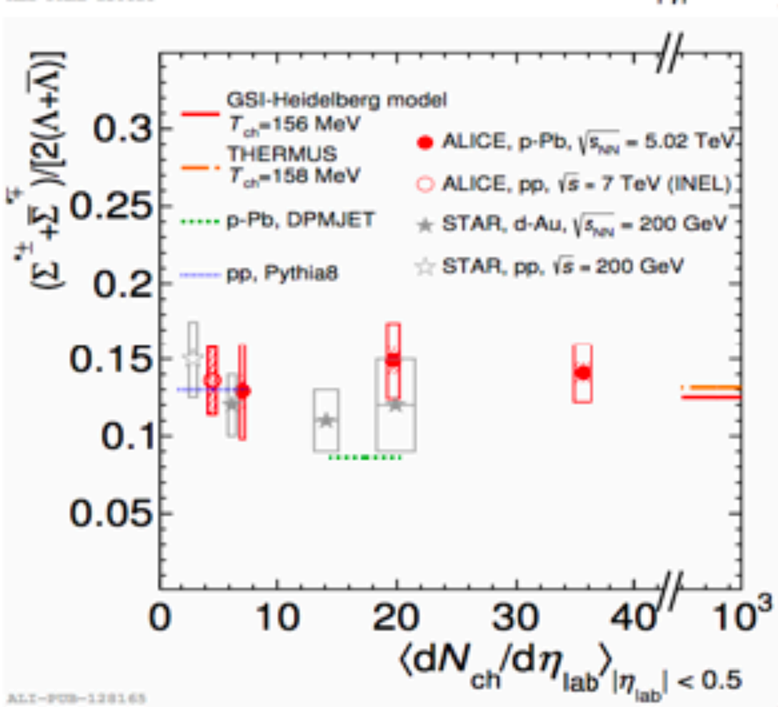


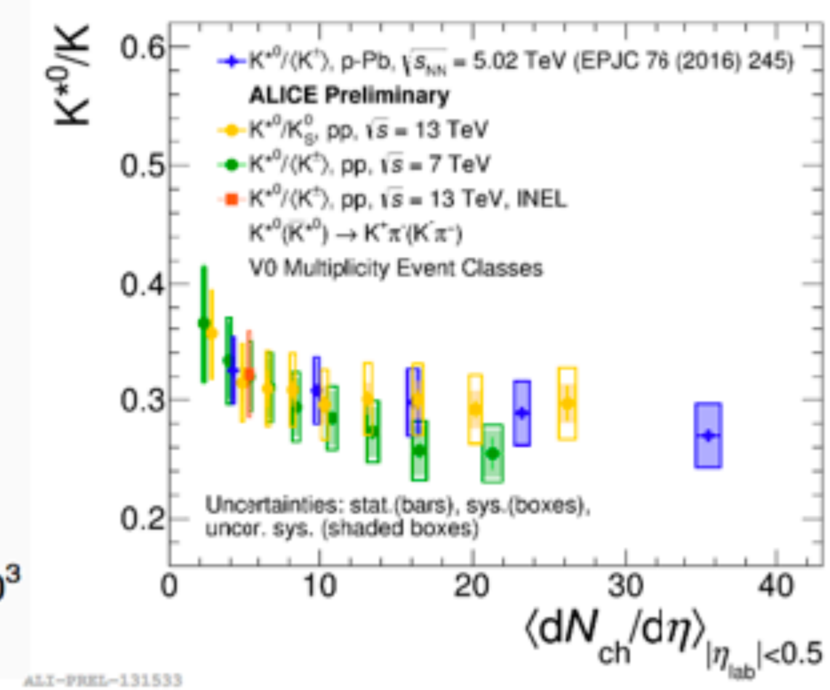
Multiplicity dependence of particle ratio

Resonance	ϕ	Λ*	Σ*±	K*0
Lifetime (fm/c)	46.4	12.6	5.5	4.2









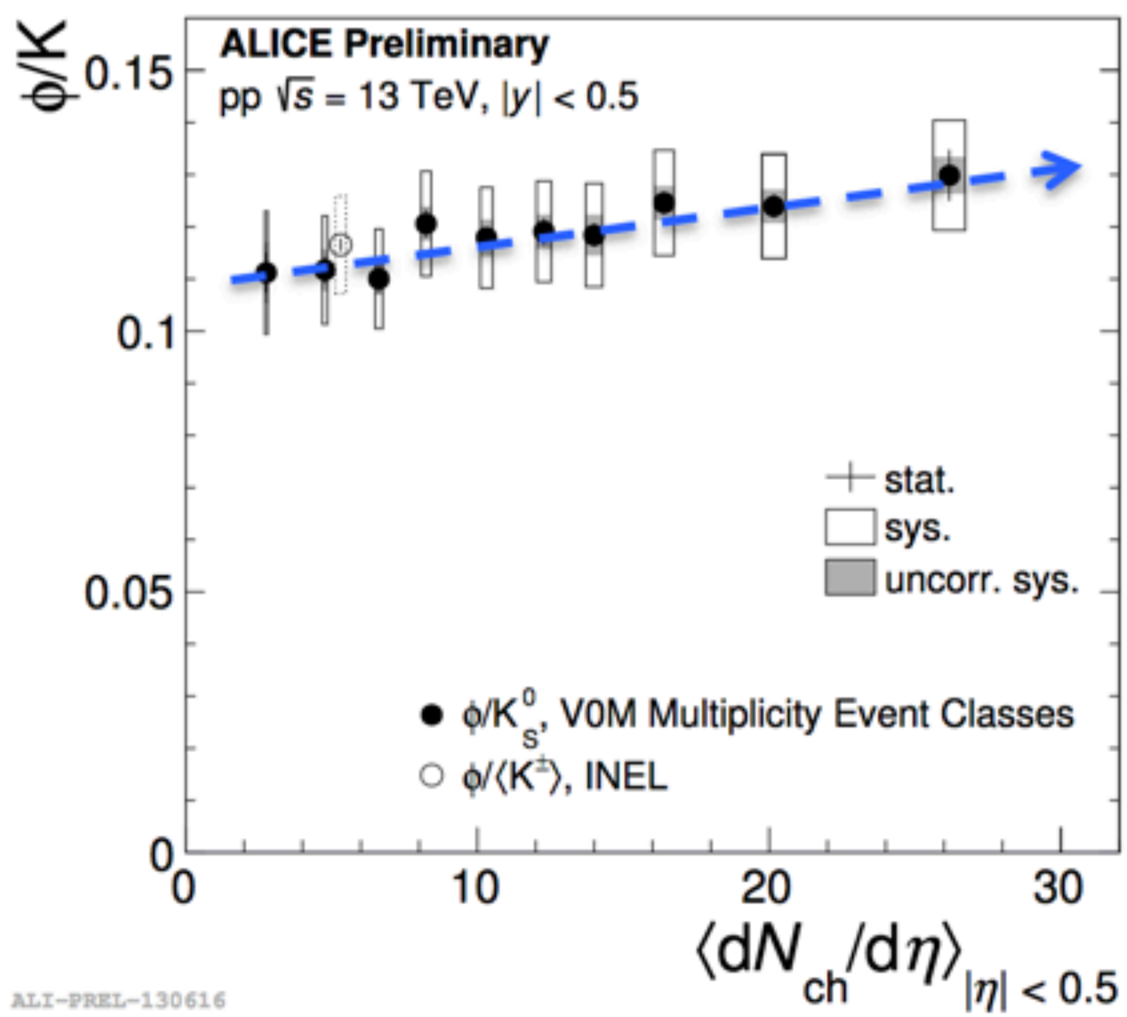
- Results of ϕ/K, Λ*/Λ, Σ*/Λ are flat.

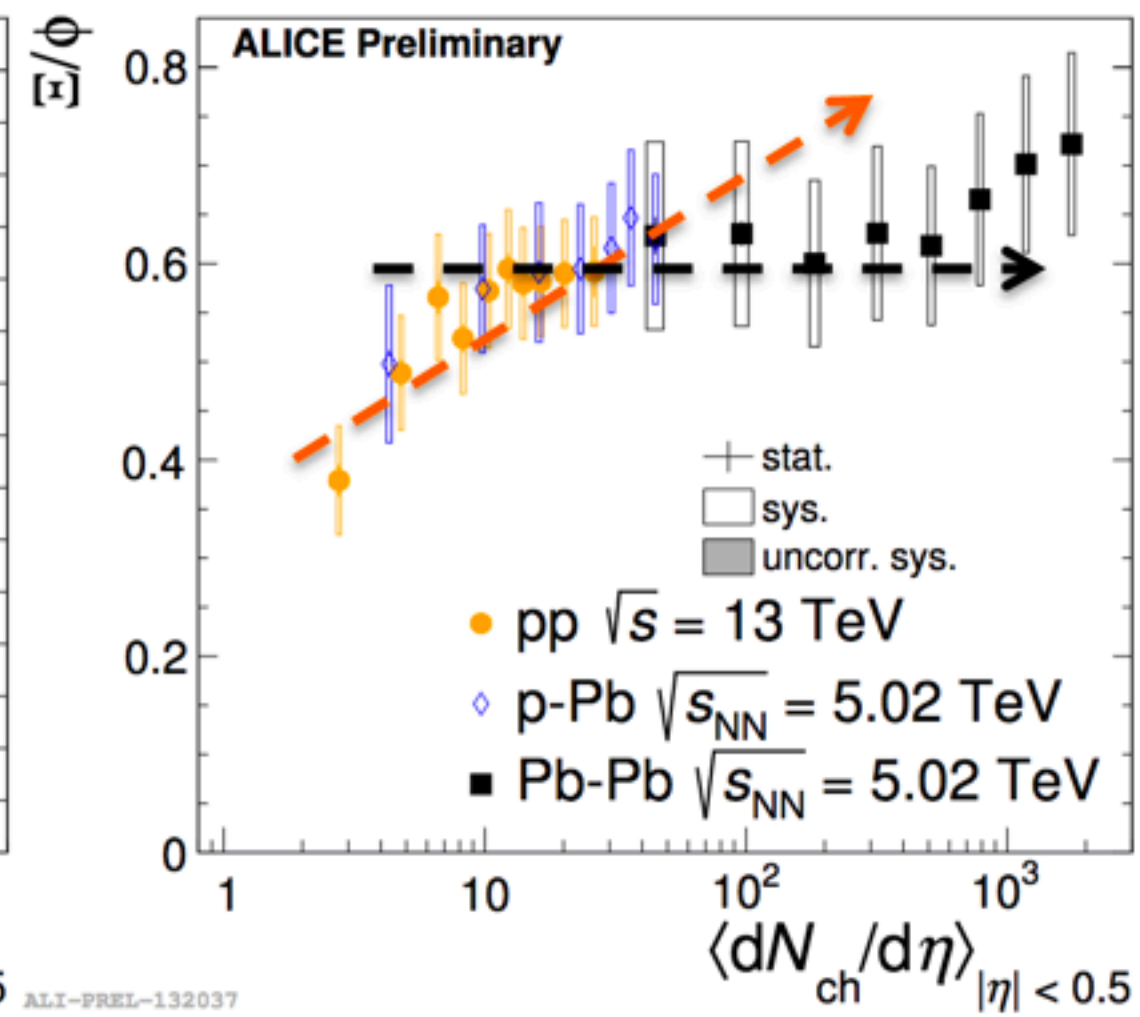
  ▶ No re-scattering or regeneration.

- K^{0*}/K decrease as $dN_{ch}/d\eta$ increase in pp and pPb.

  ▶ Re-scattering?

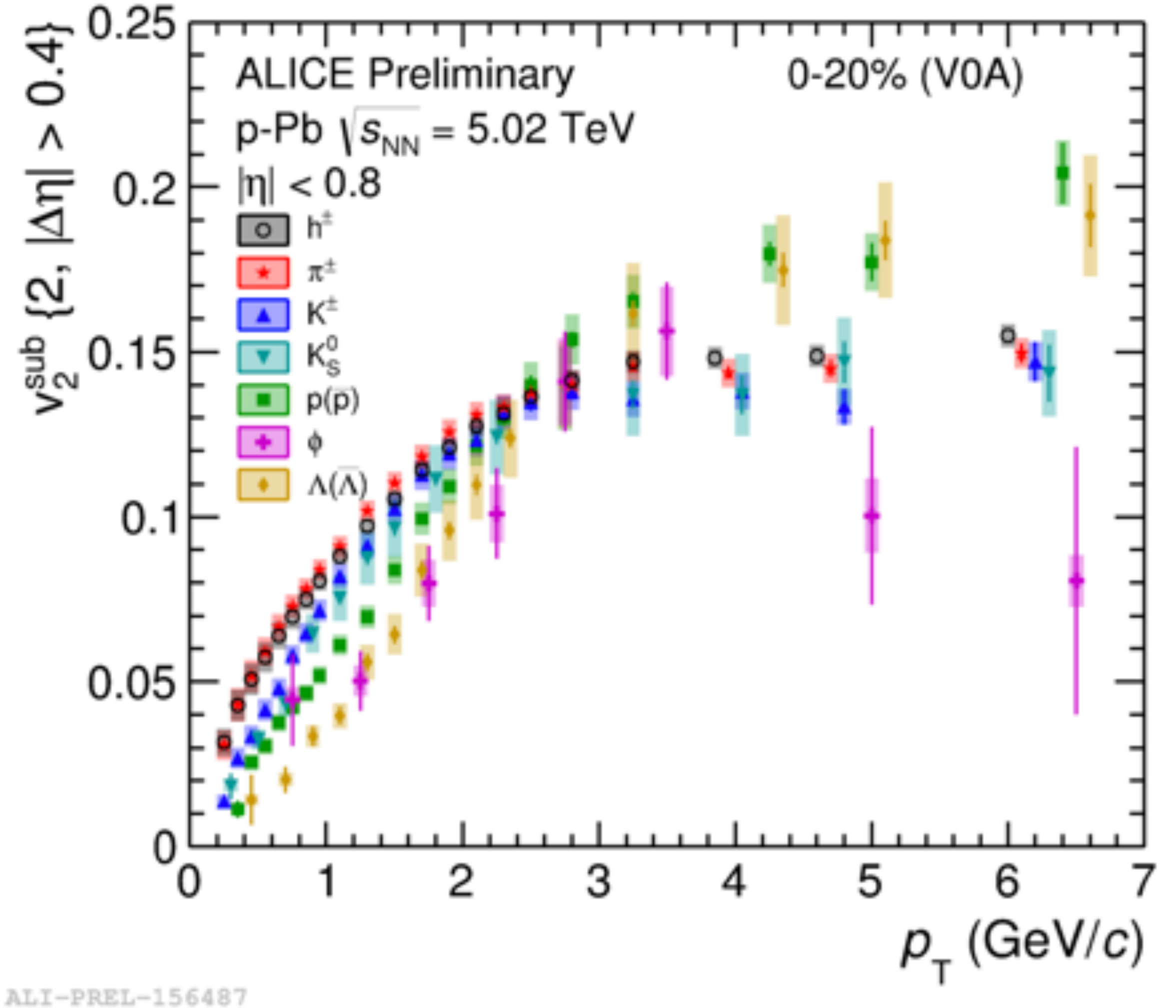
Special role of Φ-meson

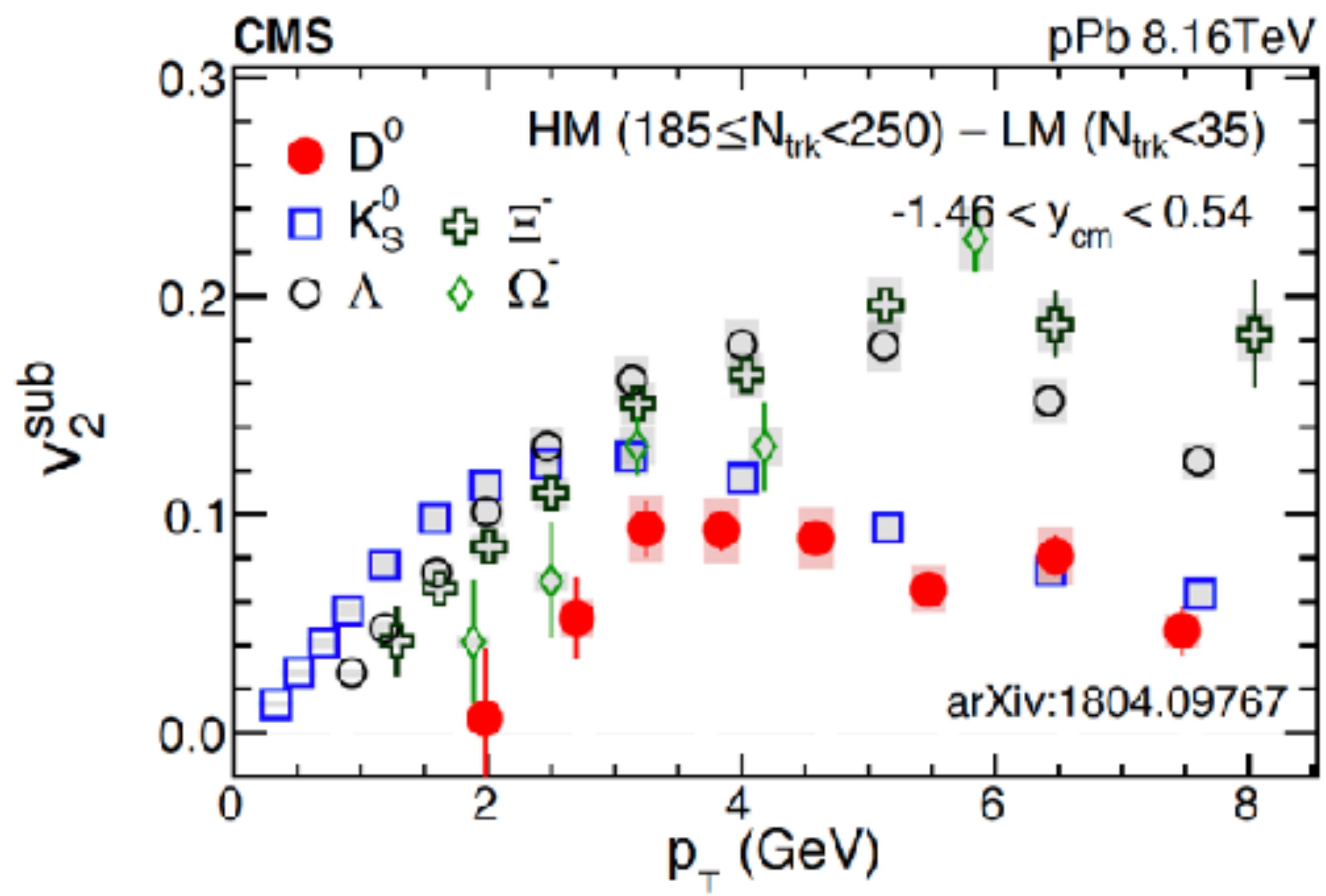




- ϕ/K: Flat or slightly increasing. S＜1?
- Ξ/ϕ:flat S~2 or slightly increasing in pp and pPb. S<2?
  - According to the results, ϕ behaves as 1<S<2?

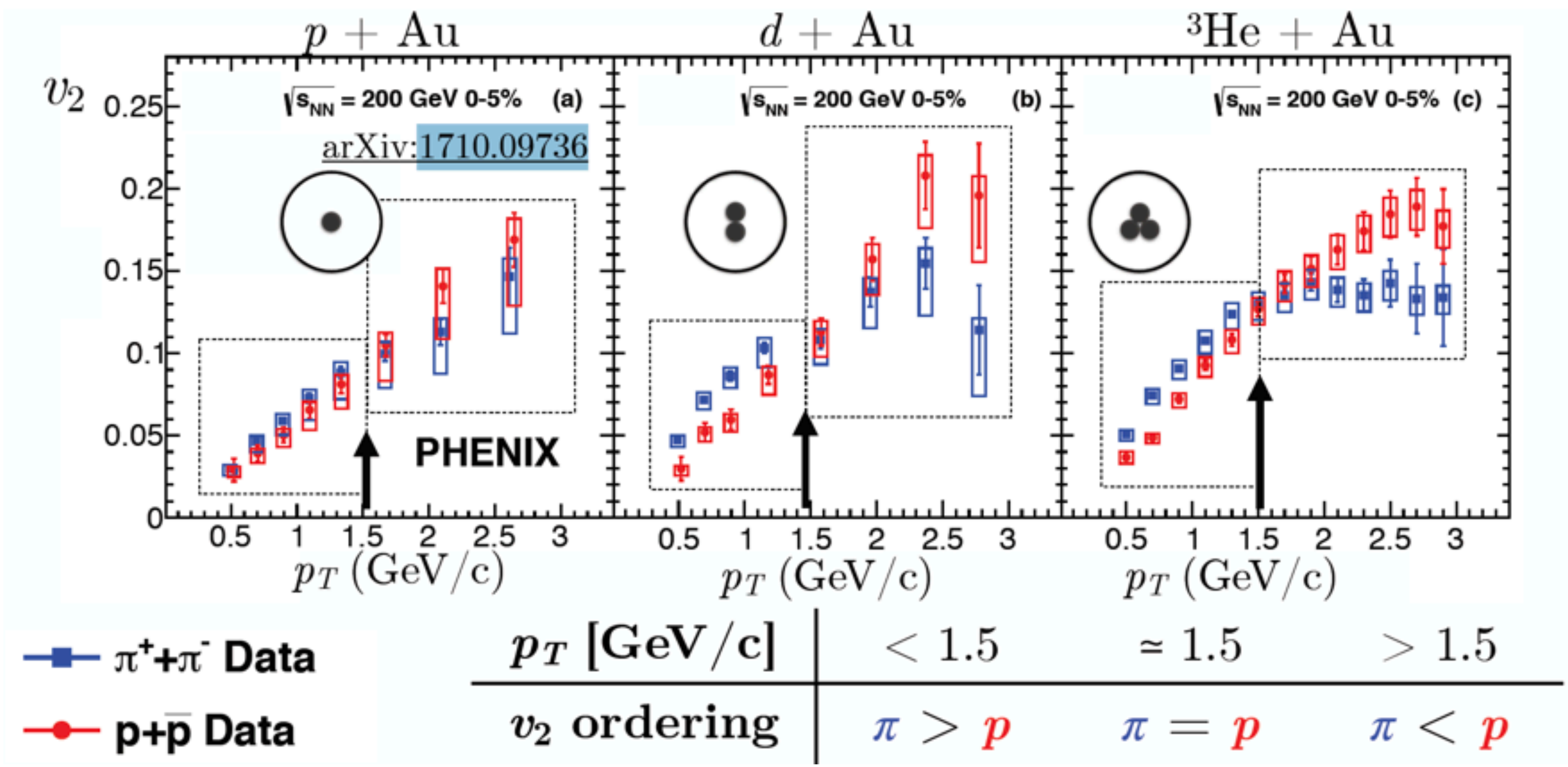
PID v_2 in pPb





- New: v_2 of ϕ, Ξ, Ω, D in pPb.
- Mass ordering at low p_T.
- Baron/meson grouping at intermediate p_T.

PID v_2 in small systems in RHIC

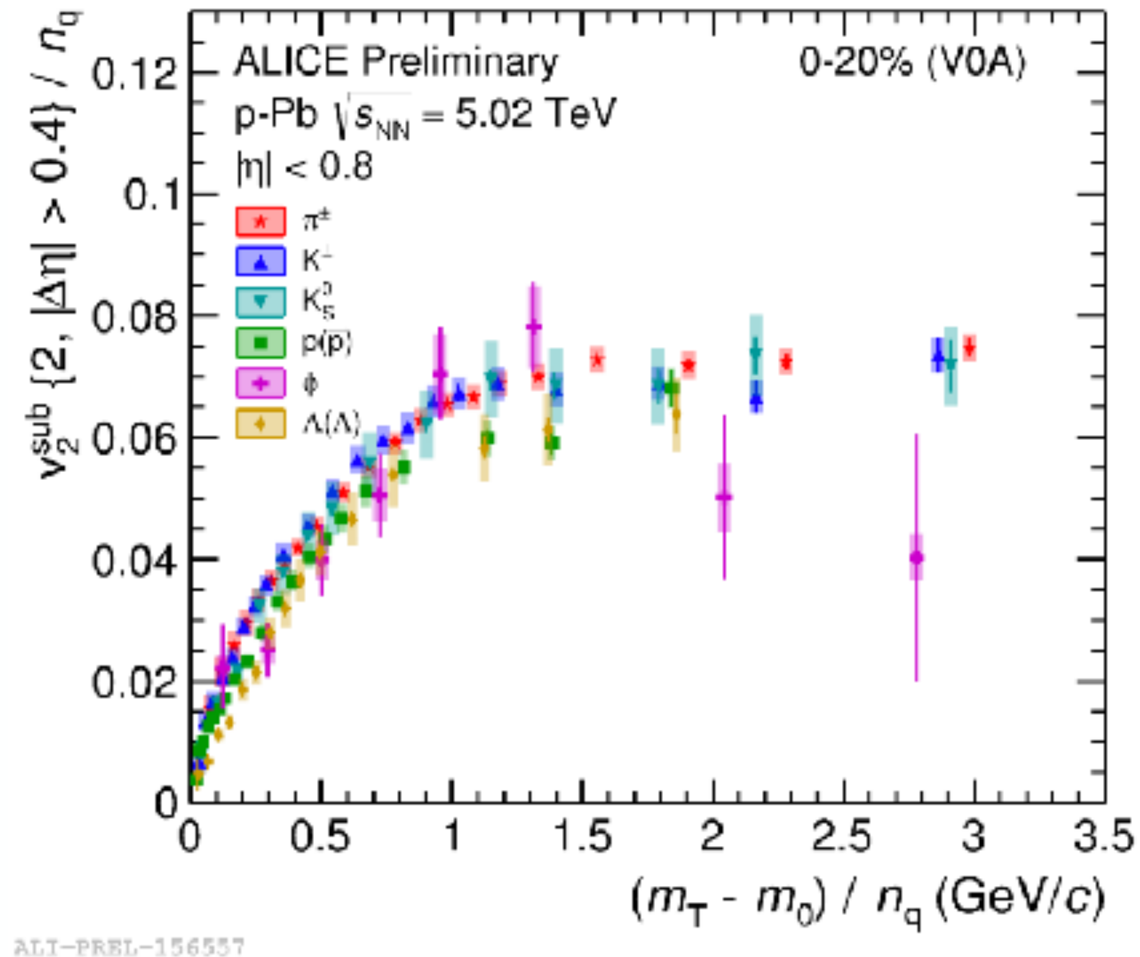


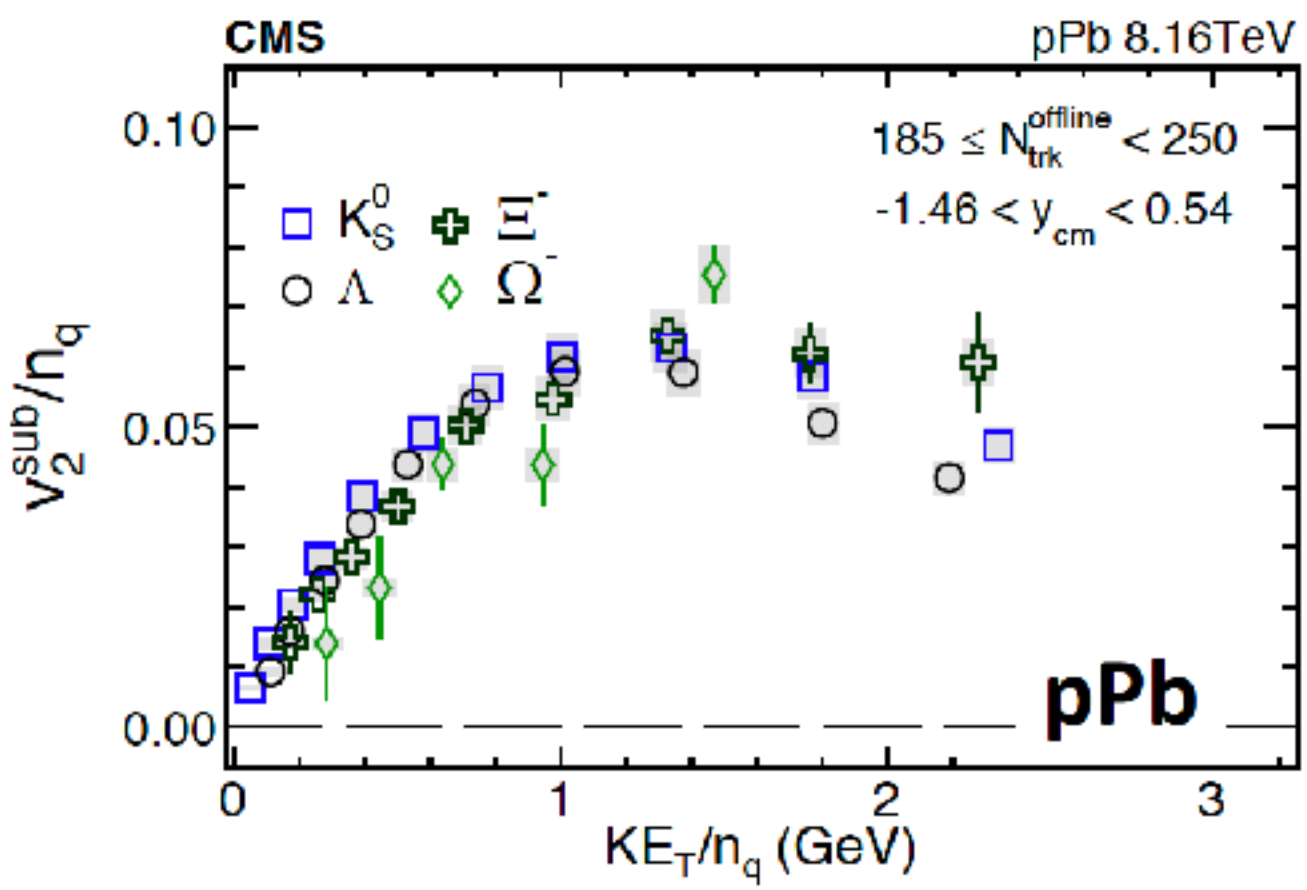
p_T [GeV/c]	< 1.5	$\simeq 1.5$	> 1.5
v_2 ordering	$\pi > p$	$\pi = p$	$\pi < p$

- Mass ordering at low p_T.

Not significant in p-Au

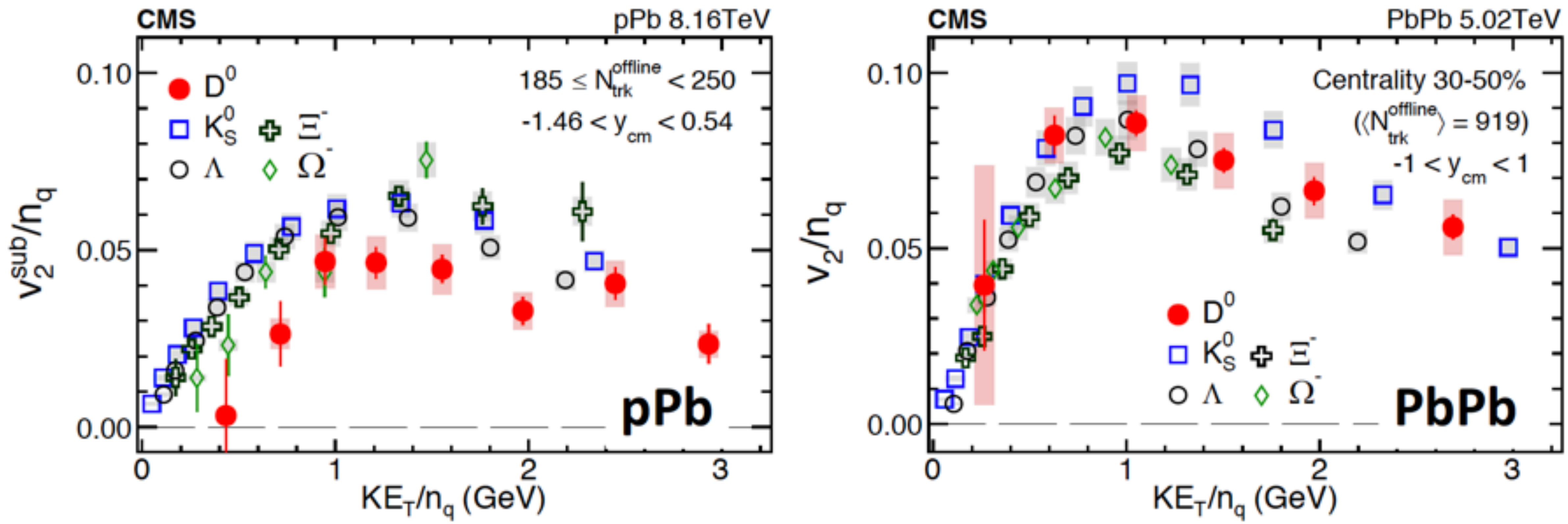
NCQ scaling





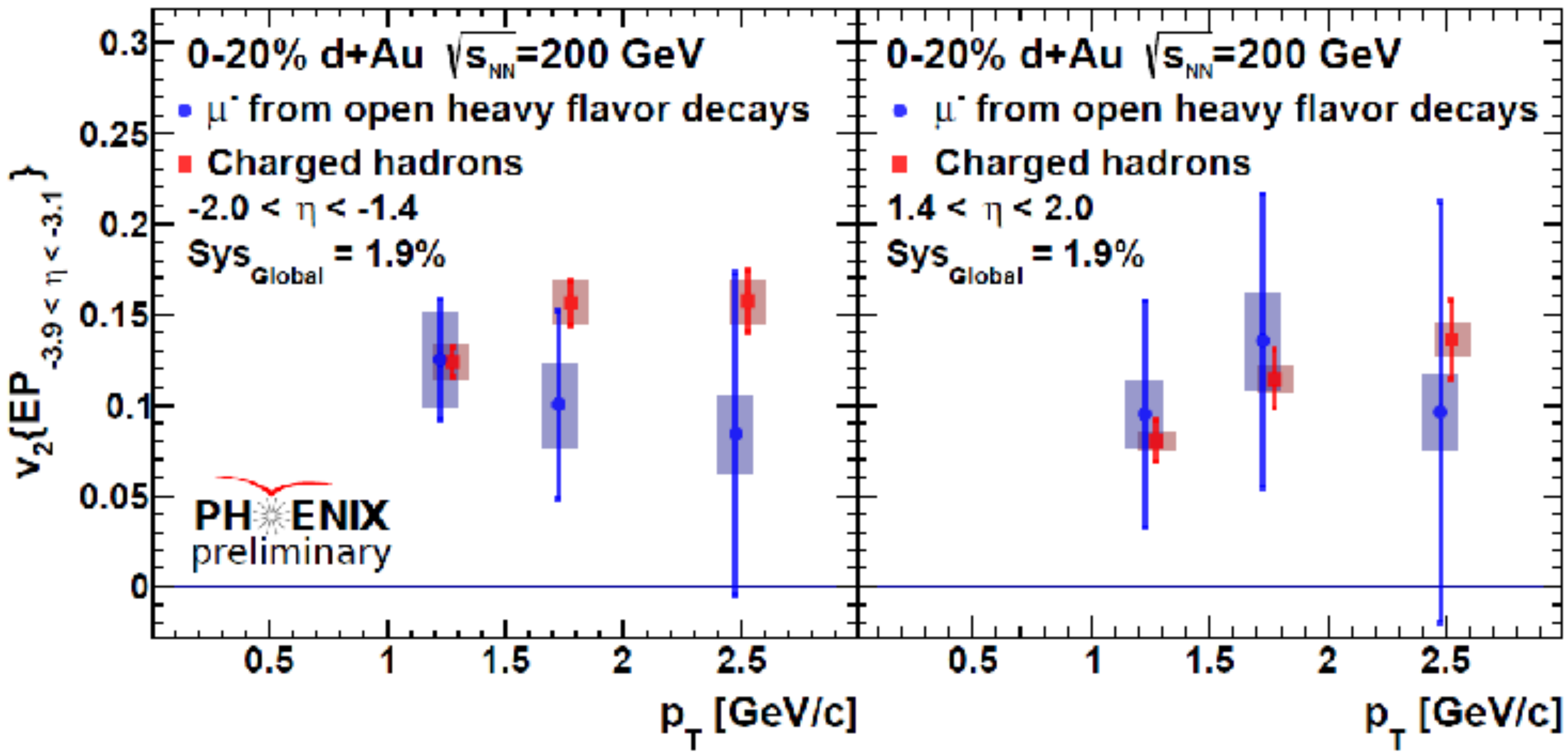
- Light and strange hadrons follows NCQ scaling.

D^0 v_2 in pPb

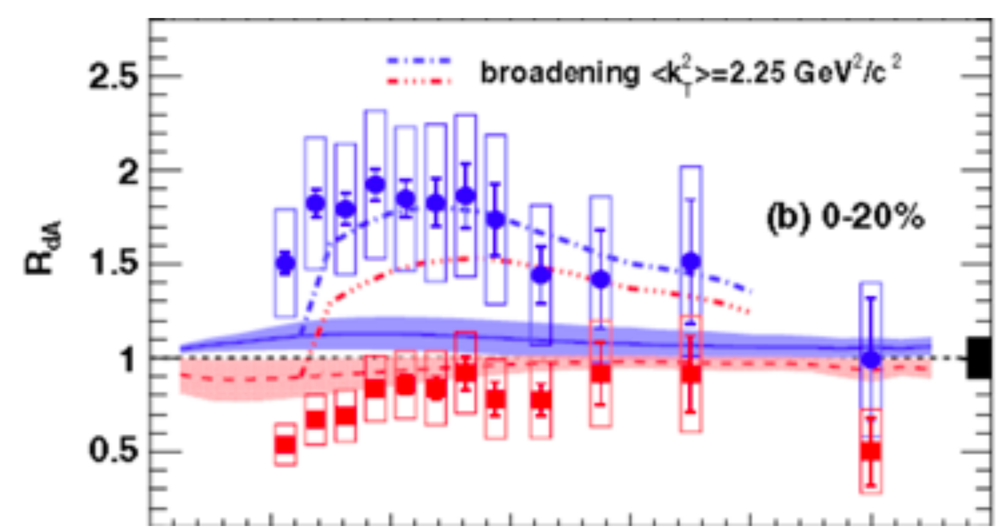


- D^0 v_2 follows NCQ scaling as light hadrons in PbPb.
  - Charm quark may achieve thermalization.
- D^0 v_2 is smaller than light hadrons in pPb.
  - Less flow because system size is small or other?

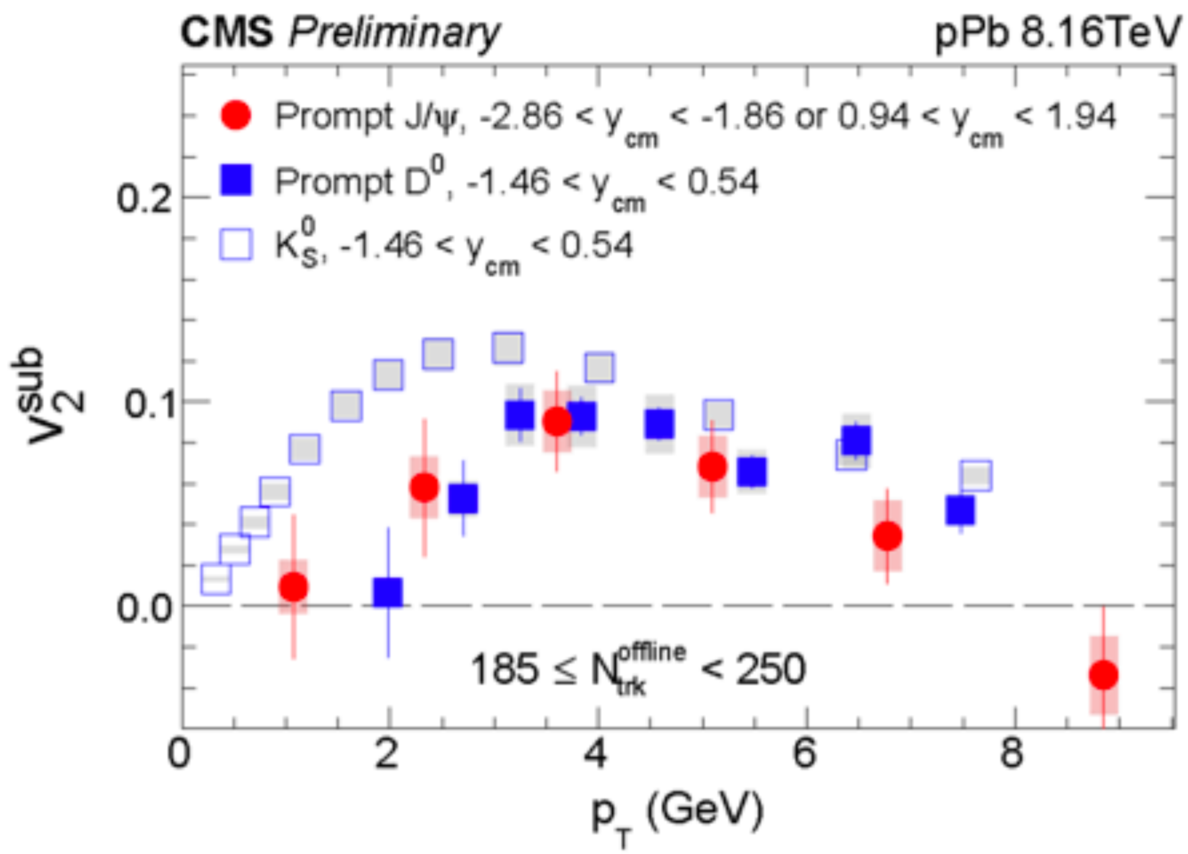
Heavy flavor v_2 in RHIC

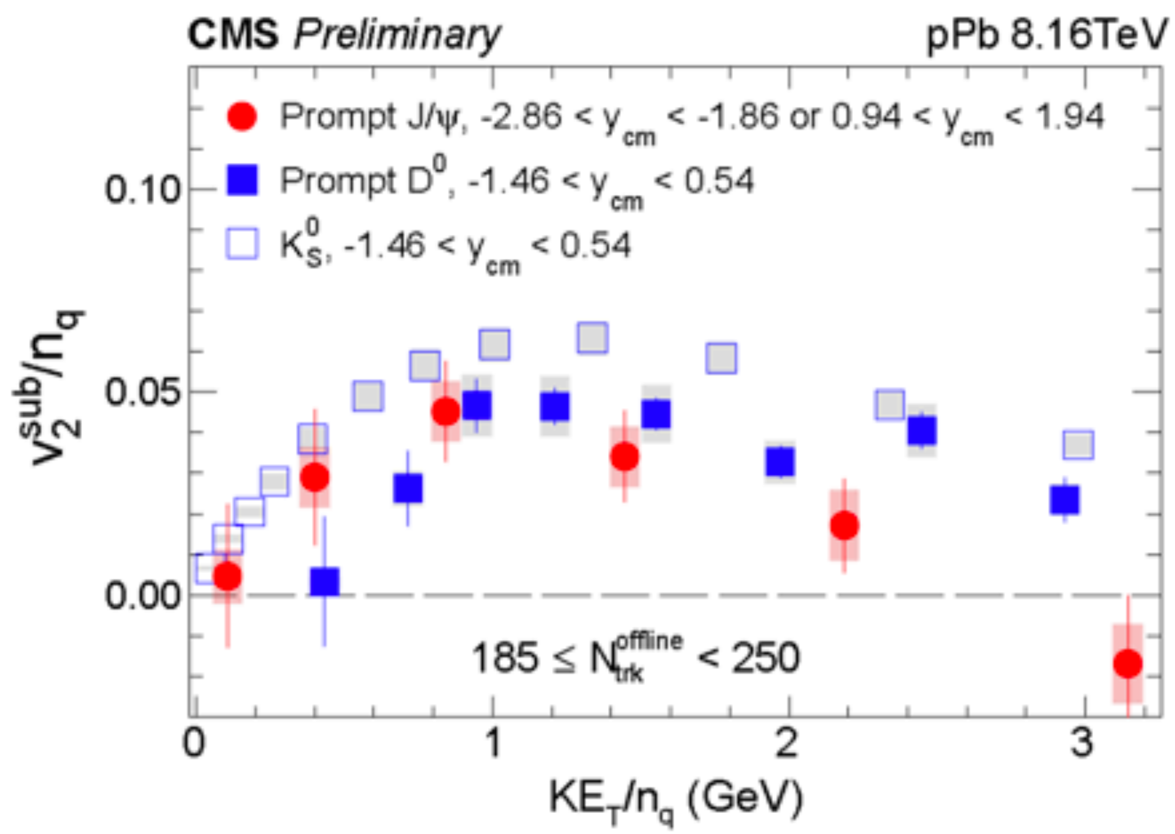


- Significant heavy flavor muon v_2 in dAu.
- RdA: enhancement in Au going, which suppression in d going.
- Similar magnitude to charged hadrons.



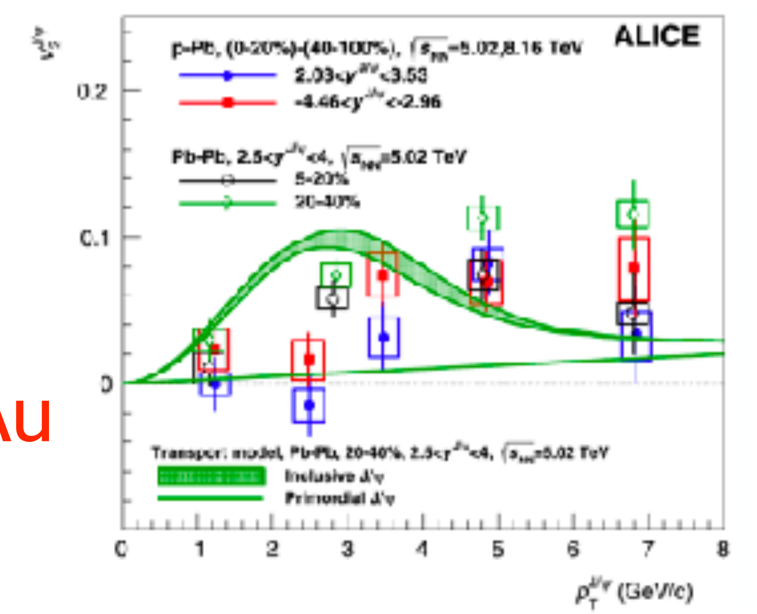
J/Ψ v_2 in pPb

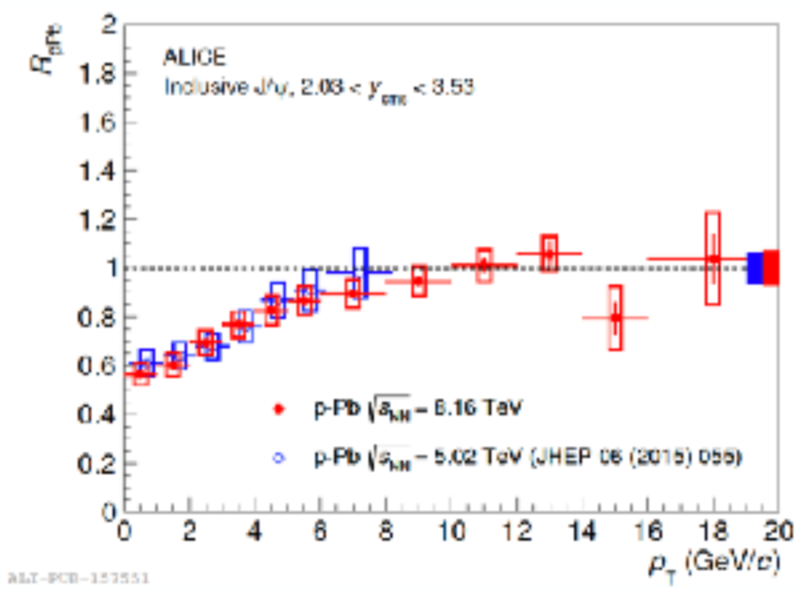




- NCQ scaling v_2(J/Ψ)∼v_2(D0)<K^0_S.
- What is origin?

At RHIC, J/psi v_2 is 0 in Au+Au collisions
How about J/psi v_2 in p/d+Au?





Multi particle cumulant

How do we calculate observables

m-particle correlation — **step 1**

$$\langle\langle 2\rangle\rangle_n = \langle\langle \cos n(\varphi_1 - \varphi_2)\rangle\rangle$$
$$\langle\langle 4\rangle\rangle_n = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$
$$\langle\langle 6\rangle\rangle_n = \langle\langle \cos n(\varphi_1 + \varphi_2 + \varphi_3 - \varphi_4 - \varphi_5 - \varphi_6)\rangle\rangle$$
$$\langle\langle 8\rangle\rangle_n = \langle\langle \cos n(\varphi_1 + \varphi_2 + \varphi_3 + \varphi_4 - \varphi_4 - \varphi_5 - \varphi_6 - \varphi_7 - \varphi_8)\rangle\rangle$$

step 2 — **m-particle cumulant**

$$c_n\{2\} = \langle\langle 2\rangle\rangle_n$$
$$c_n\{4\} = \langle\langle 4\rangle\rangle_n - 2\cdot\langle\langle 2\rangle\rangle_n^2$$
$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\cdot\langle\langle 2\rangle\rangle\cdot\langle\langle 4\rangle\rangle + 12\cdot\langle\langle 2\rangle\rangle^3$$
$$c_n\{8\} = \langle\langle 8\rangle\rangle - 16\cdot\langle\langle 6\rangle\rangle\langle\langle 2\rangle\rangle - 18\cdot\langle\langle 4\rangle\rangle^2 + 144\cdot\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle^2 - 144\cdot\langle\langle 2\rangle\rangle^4$$

flow coefficients — **step 3**

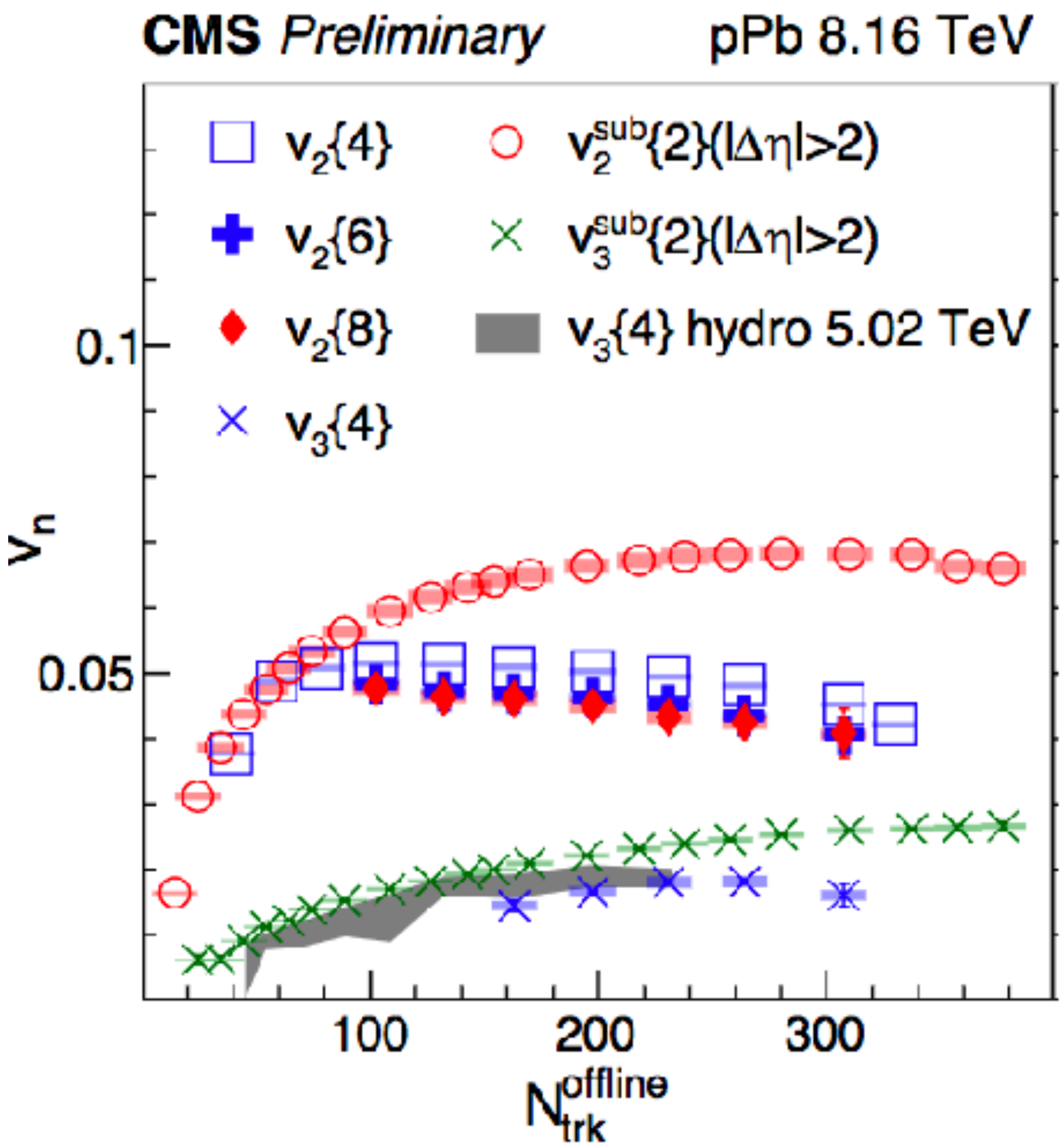
$$v_n\{2\} = \sqrt{c_n\{2\}} \qquad v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}$$
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}} \qquad v_n\{8\} = \sqrt[8]{-\frac{1}{33}c_n\{8\}}$$

$$\left.\begin{aligned} v_n\{2\}^2 &= \langle v_n\rangle^2 + \sigma_n^2 \\ v_n\{4\}^2 &= \langle v_n\rangle^2 - \sigma_n^2 \end{aligned}\right\} \quad v_n\{2\} > v_n\{4\}$$

Gaussian fluctuations ➔

$$v_n\{4\} = v_n\{6\} = v_n\{8\}$$

v_2, v_3 with Multi-Particle cumulant



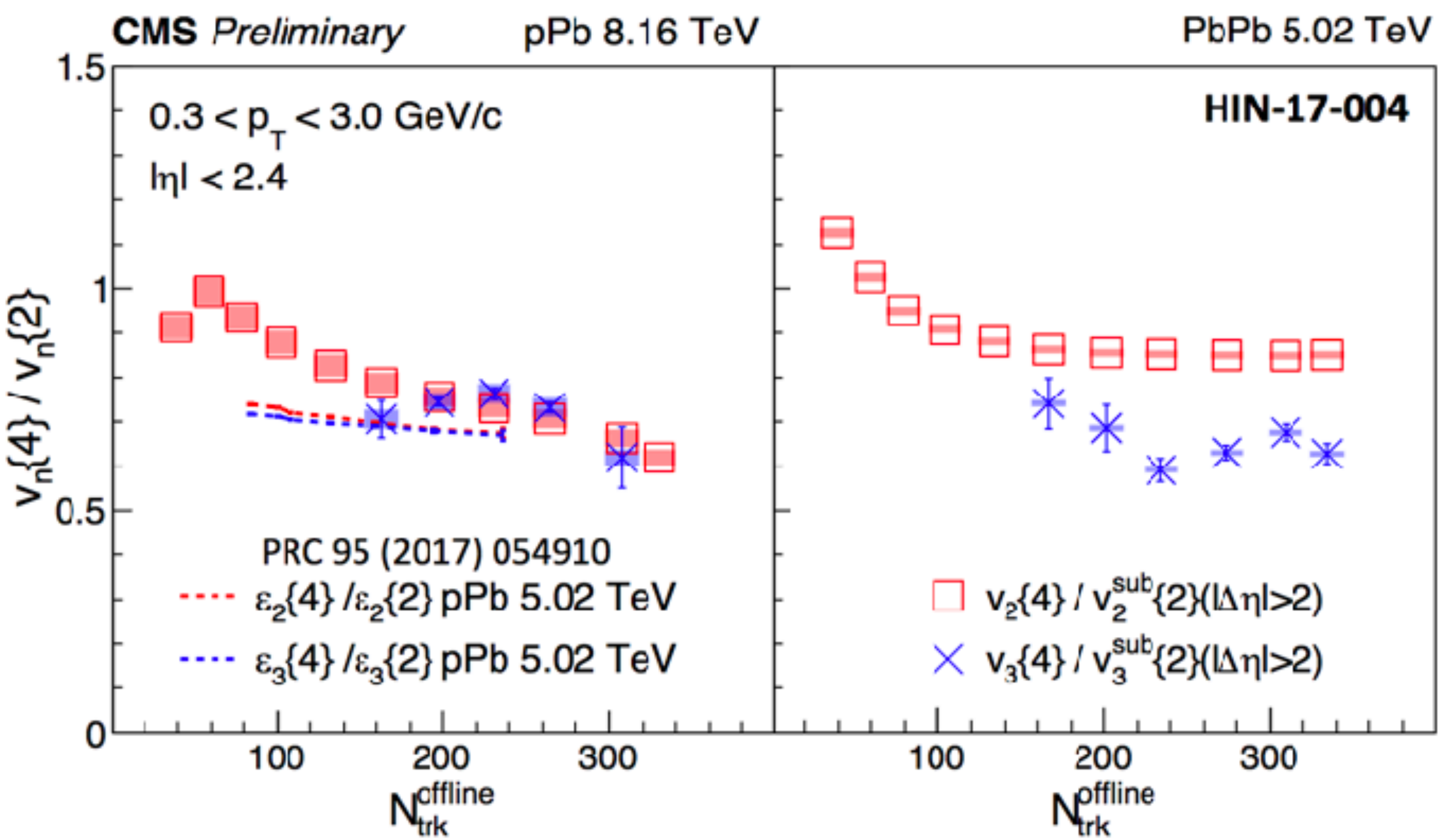
- v2 with multi particle decrease as multiplicity increase in pPb. Different trend to PbPb.

- $v_2\{2\} > v_2\{4\} \gtrsim v_2\{6\} \gtrsim v_2\{8\}$

▶Non-Gaussian fluctuation??

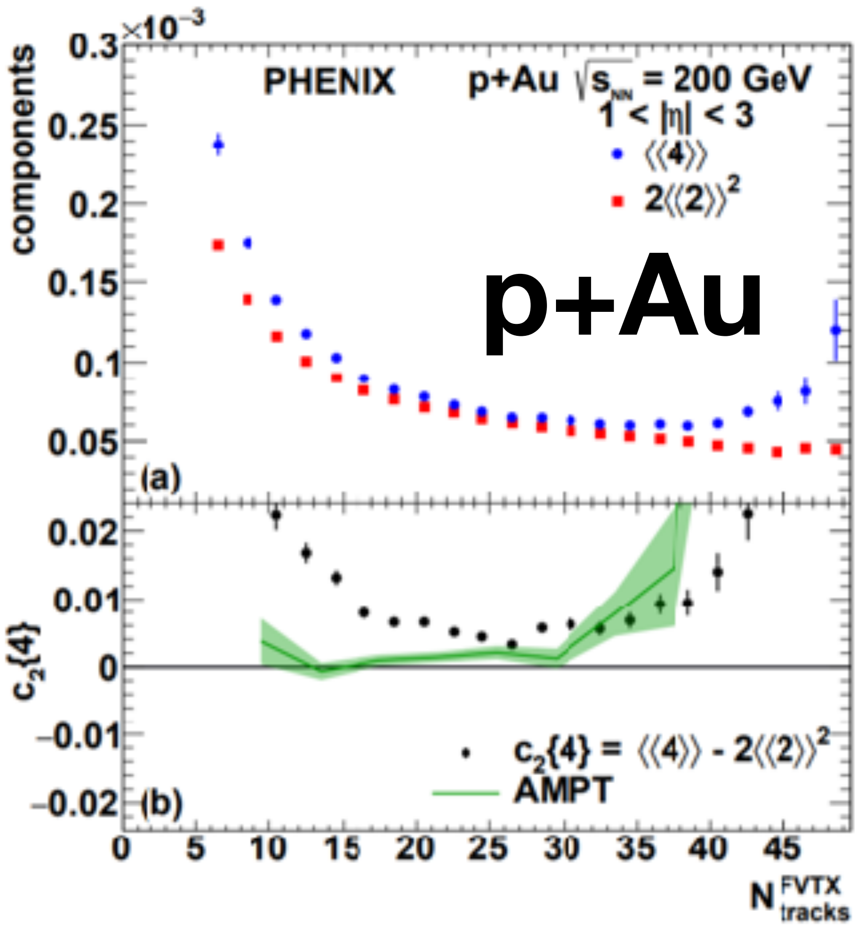
- First measurement of $v_3\{4\}$ in small system
  - Hydro calculation describe data.(arXiv:1405.3976)

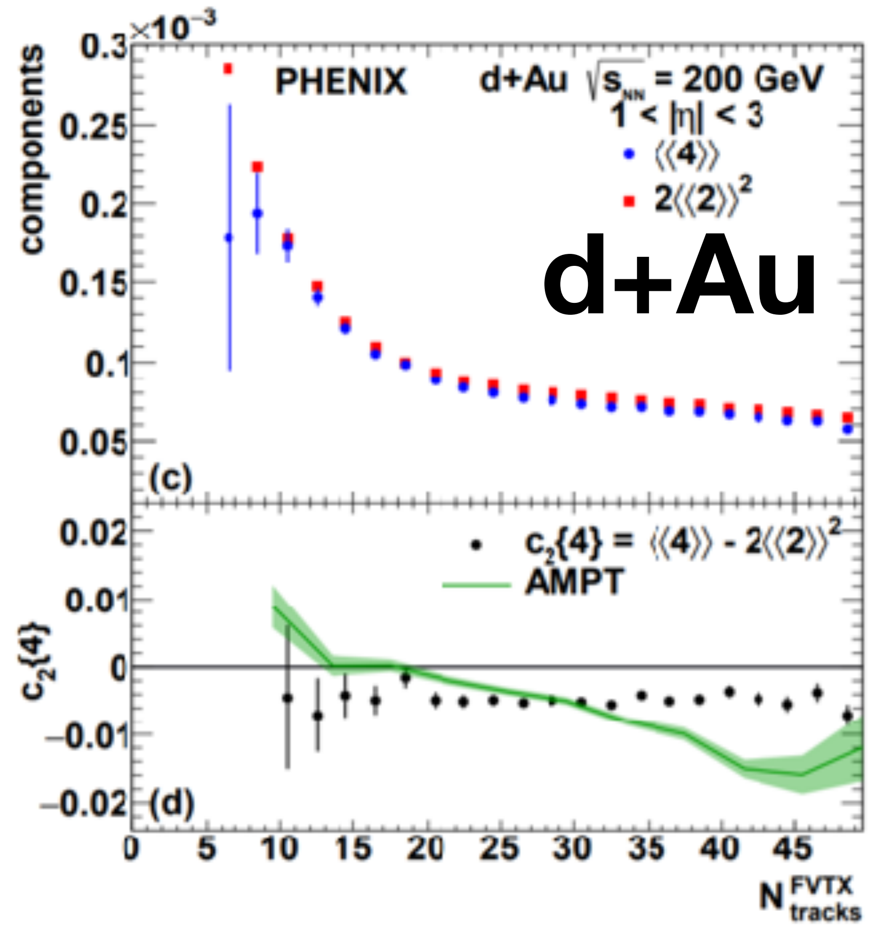
Ratio of $v_n\{4\}$ and $v_n\{2\}$

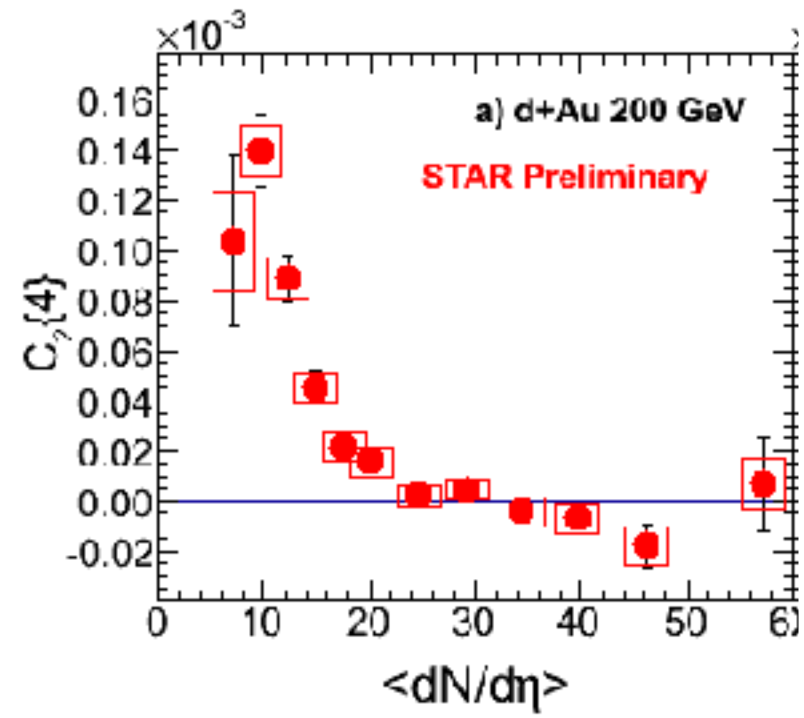


- $v_2\{4\}/v_2\{2\}$ is larger than $v_3\{4\}/v_3\{4\}$ in PbPb
  - Global geometry dominant for v_2
- $v_3\{4\}/v_3\{4\}$ is comparable with $v_2\{4\}/v_2\{2\}$ in pPb
  - initial state fluctuation dominant both for v_2 and v_3
- TRENTo $\varepsilon_n\{4\}/\varepsilon_n\{2\}$ describe pPb data

$C_2\{4\}$ in RHIC

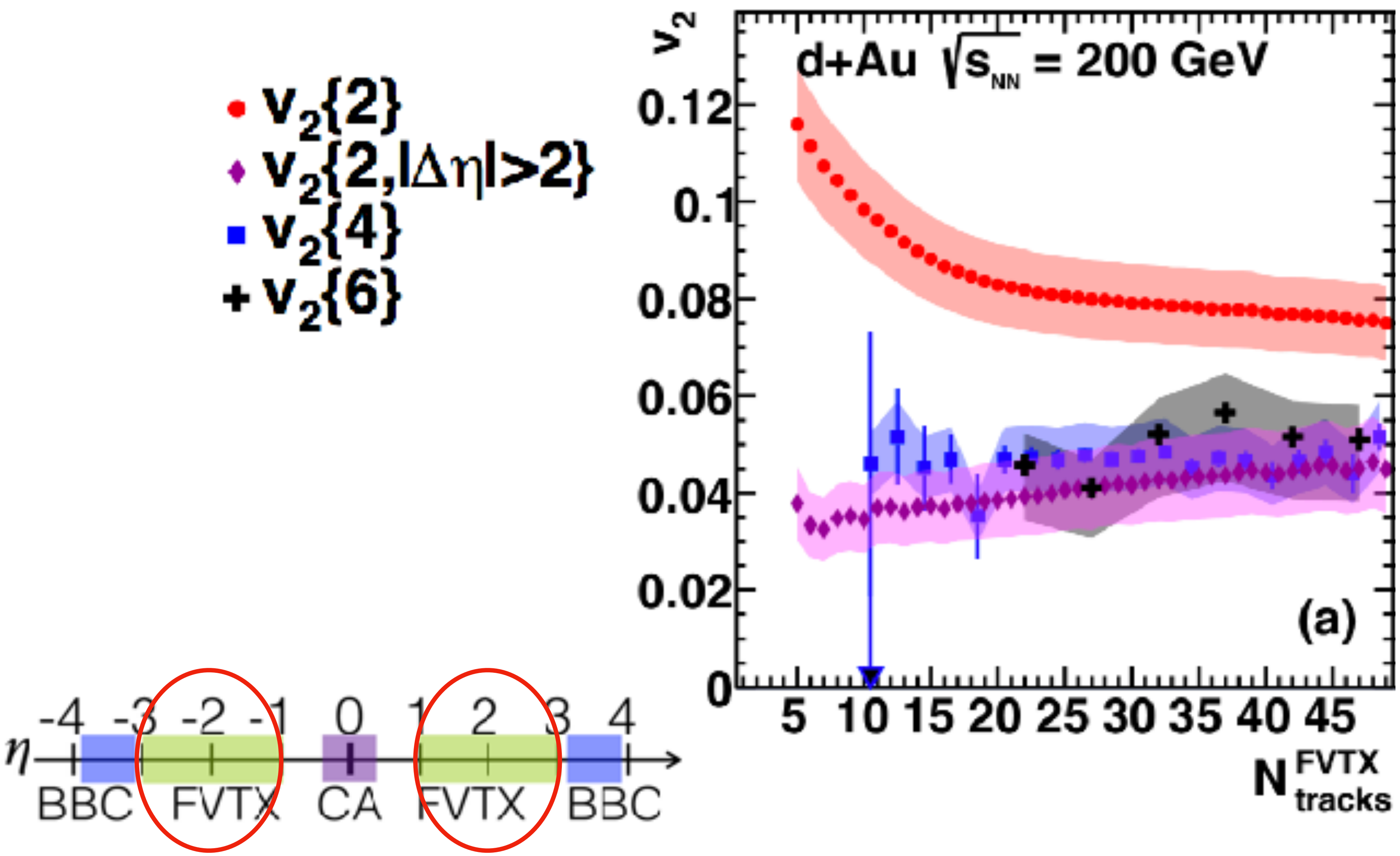






- Positive $c_2\{4\}$ in p+Au, while negative in d+Au.
- If fluctuation σv_2 > mean v_2, $c_2\{4\}$ is positive.
    - non-flow?

Multi-particle correlations in d+Au



Phys. Rev. Lett. 120, 062302 (2018)

- Real $v_2\{4\}$ observed
- $v_2\{4\} \approx v_2\{6\}$, strong indication of collectivity

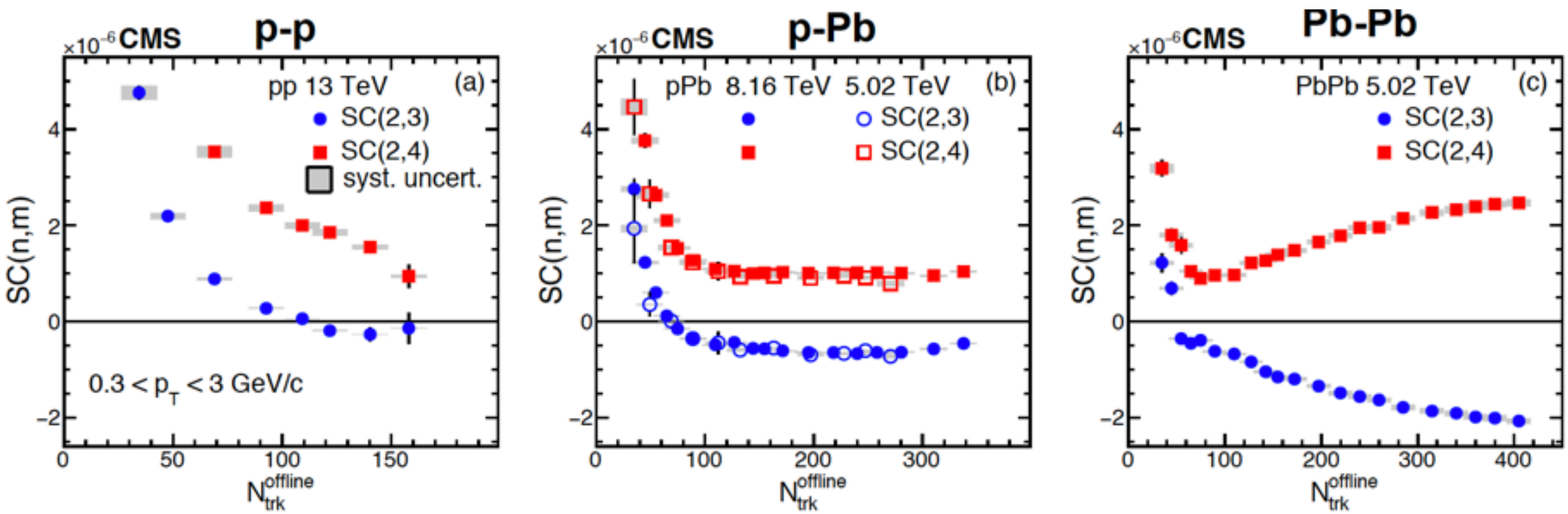
Symmetric cumulant

- Symmmetric cumulant

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

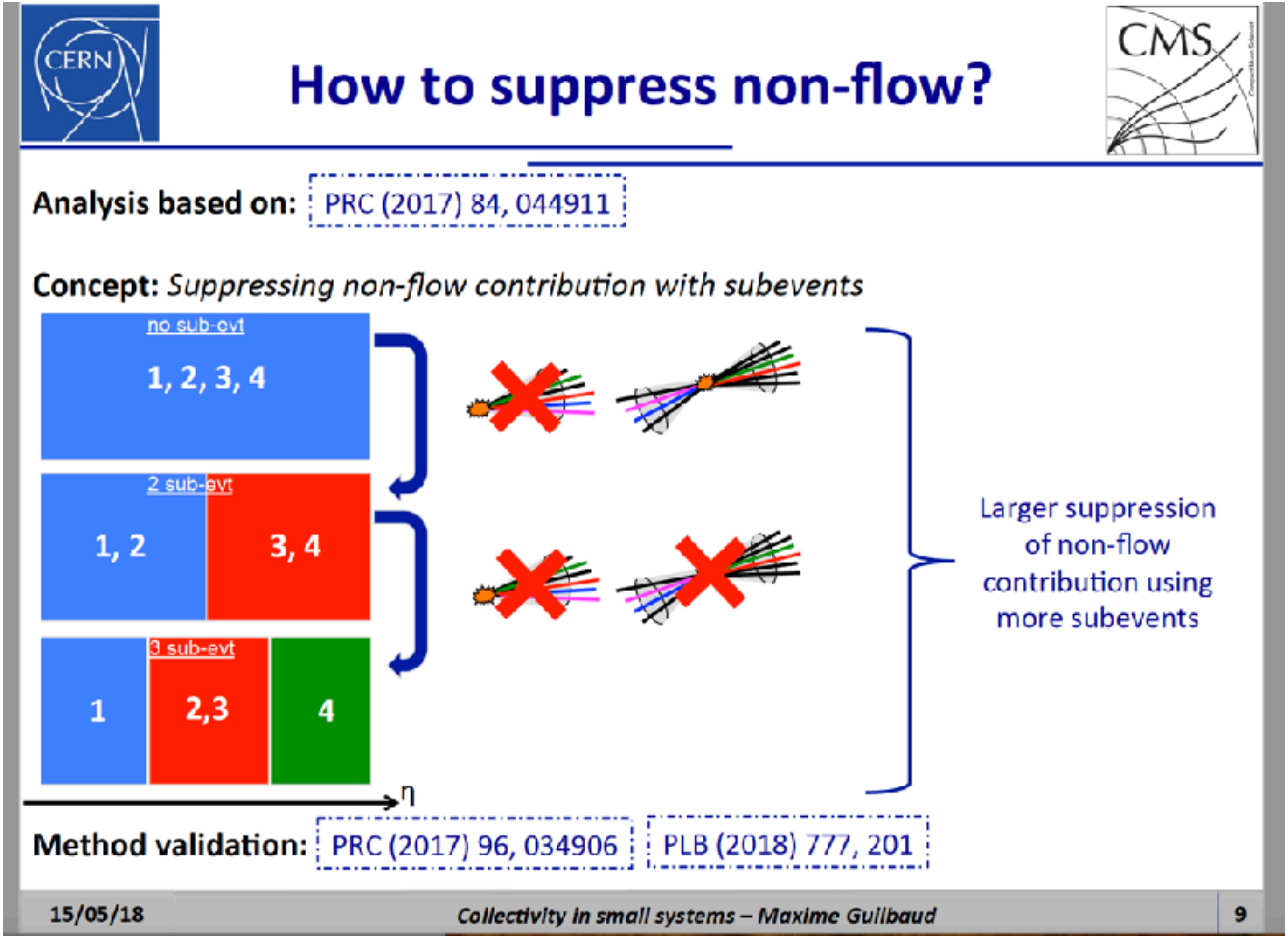
  - Sensitive to IS fluctuation and medium transport coefficient.

PRL (2018)120, 092301

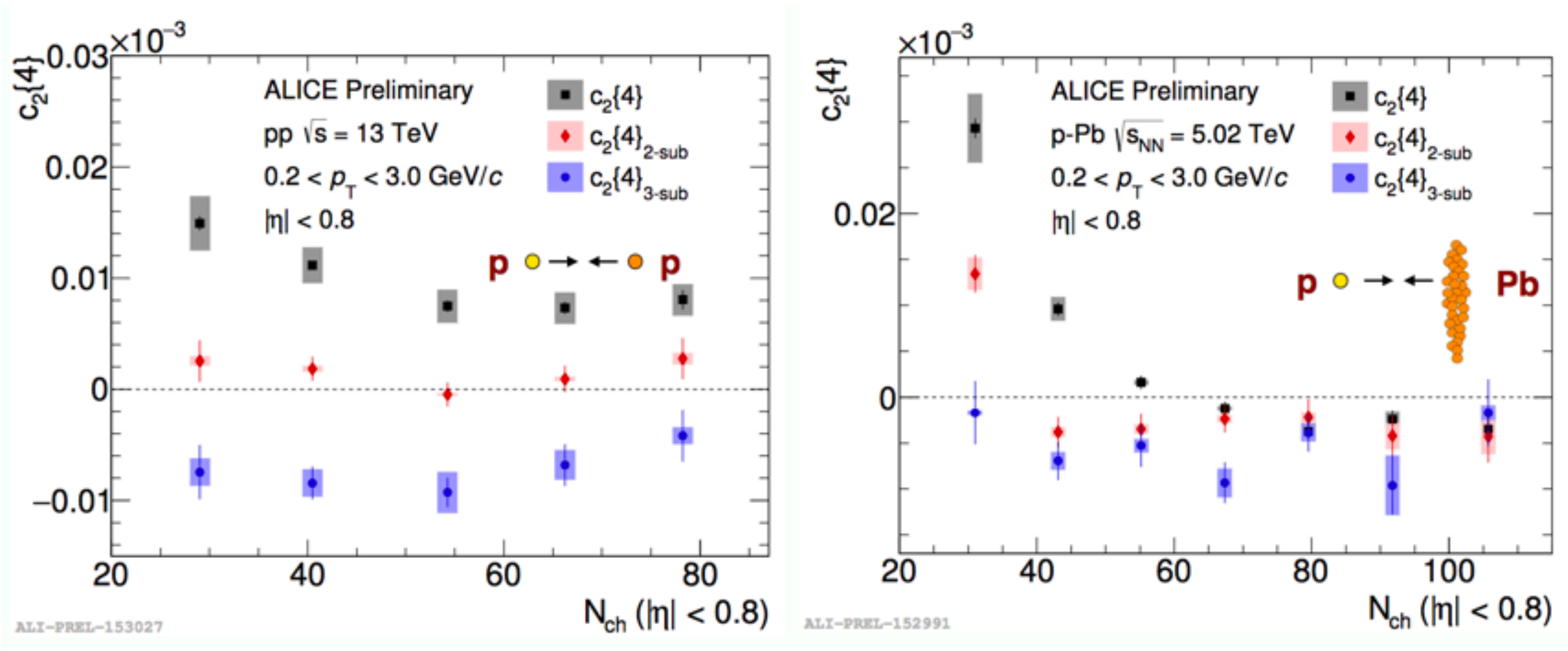


- SC(2,4) is correlated and SC(2,3) is anti-correlated in PbPb
- Non-flow effect is large in pp and pPb.

Sub-event multi-particle cumulant

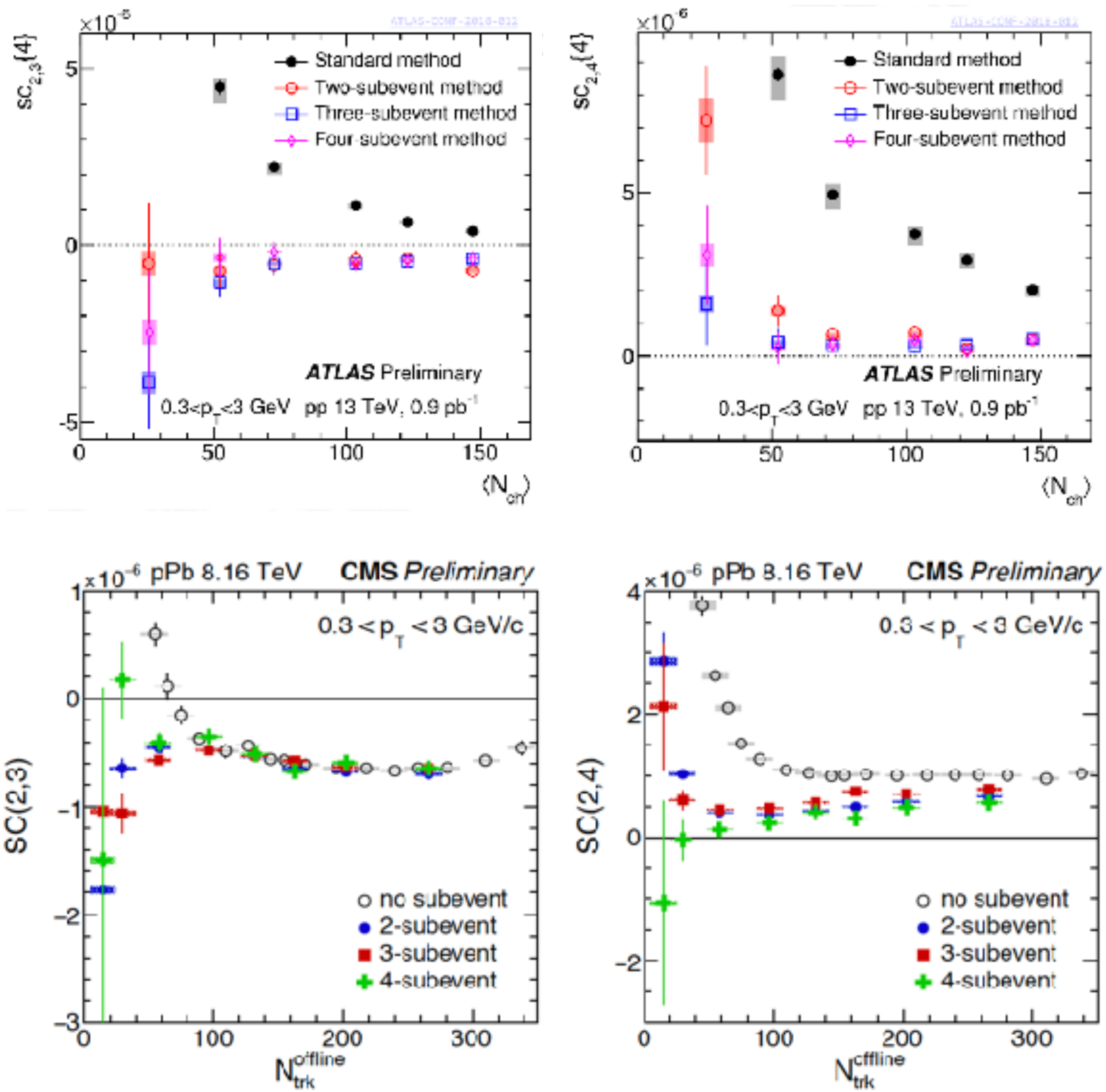


Sub-event Cumulant



- 3sub method largely suppress non-flow in pp and low multiplicity events in pPb.
- Significant negative $c_2\{4\}$ by using 3 sub method in pp.
  - Update from previous QM.

Correlation between harmonics



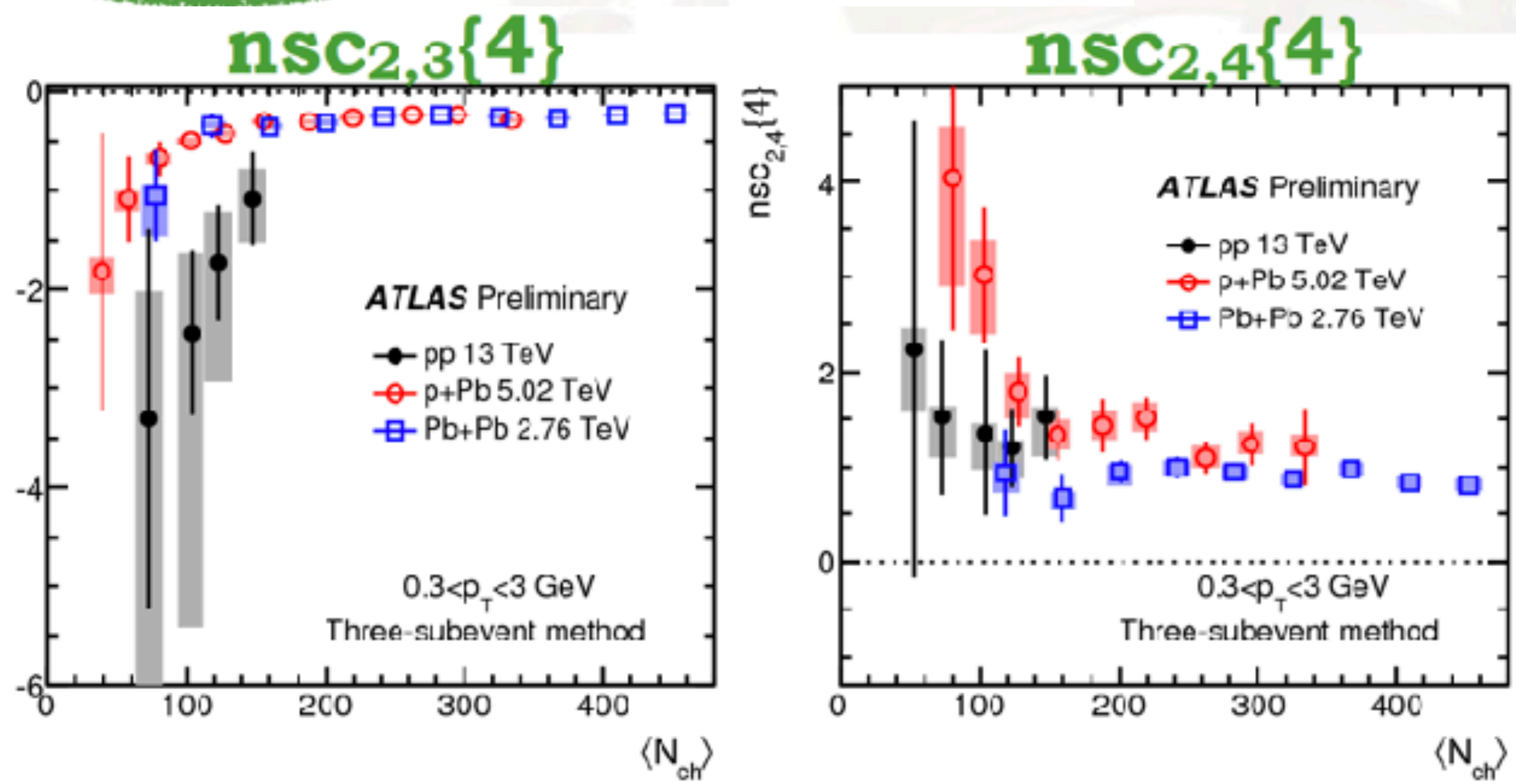
- Non-flow suppressed at low multiplicity by using subevent cumulant in pp and pPb.
- Sub-event results of SC(2,3) and SC(2,4) are comparable in pp.
- SC(2,3) to converge at high multiplicity in pPb.
- SC(2,4) results between standard and subevents are different at high multiplicity in pPb.

Comparison with collision systems

$$nsc_{2,3}\{4\} = \frac{sc_{2,3}\{4\}}{v_2\{2\}^2 v_3\{2\}^2} = \frac{\langle v_2^2 v_3^2\rangle}{\langle v_2^2\rangle\langle v_3^2\rangle} - 1$$

$$nsc_{2,4}\{4\} = \frac{sc_{2,4}\{4\}}{v_2\{2\}^2 v_4\{2\}^2} = \frac{\langle v_2^2 v_4^2\rangle}{\langle v_2^2\rangle\langle v_4^2\rangle} - 1$$

$v_n\{2\}^2$ - obtained from the “improved” **template fit**



- Normalize to compare with different collision systems.
- Strength of the correlations between harmonics similar between all systems except $nsc_{2,3}\{4\}$ in pp.
    - Similar initial state fluctuation

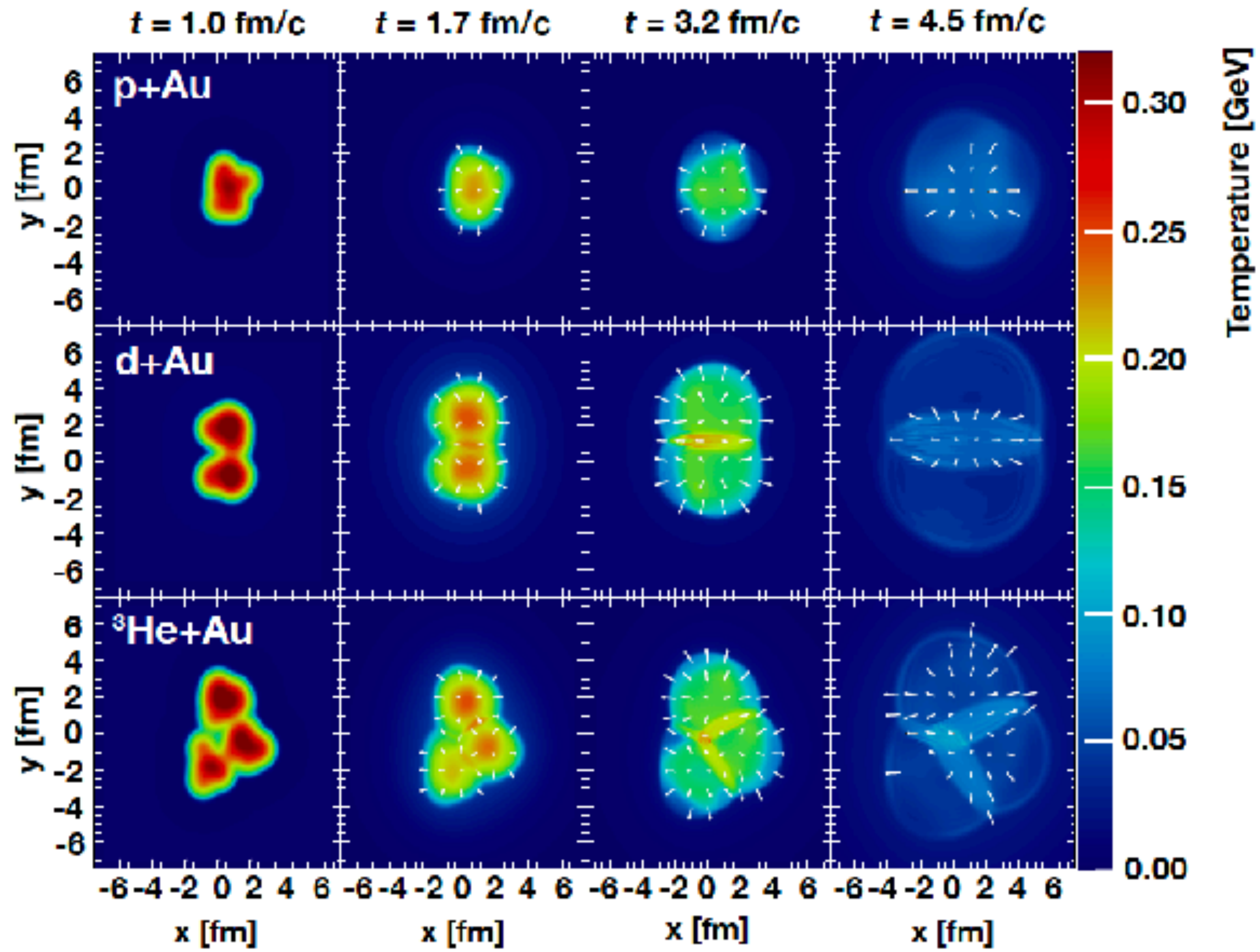
System geometry

Hydrodynamics translates initial geometry into final state

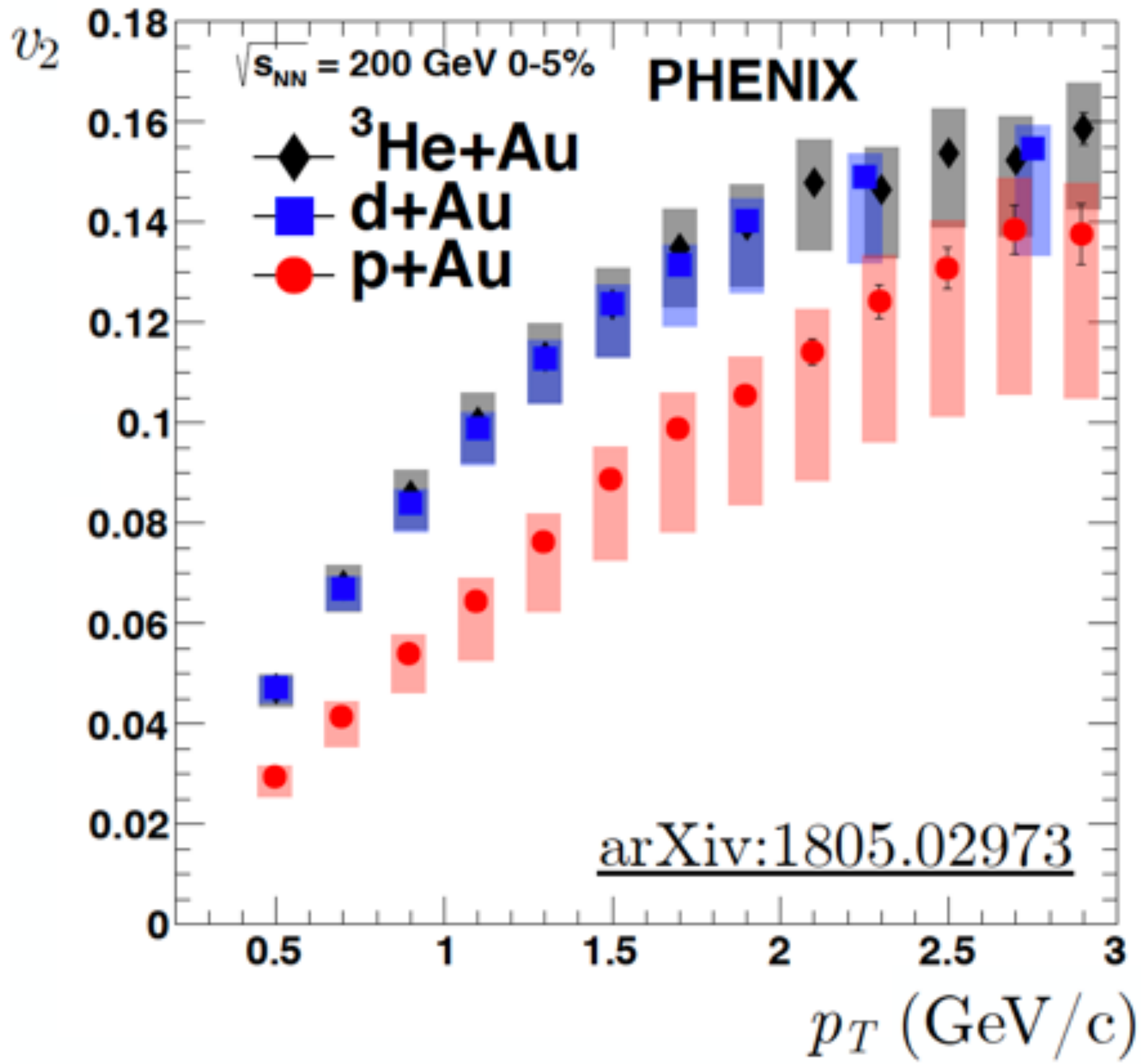
Test hydro hypothesis by varying initial state

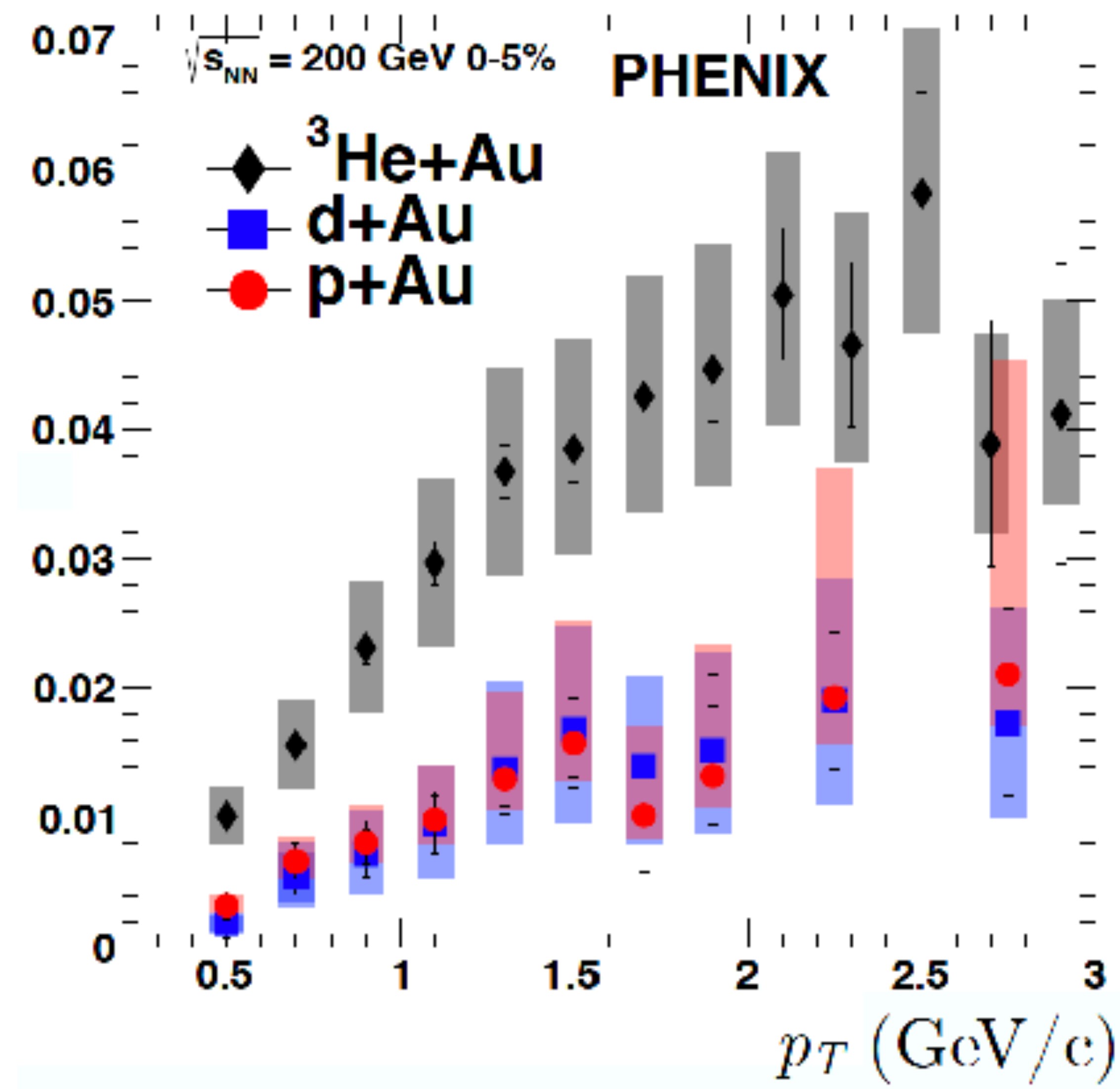
	ε_2	ε_3
p+Au	0.24	0.16
d+Au	0.57	0.17
^{3}He+Au	0.48	0.23

$$\varepsilon_2^{p+Au} < \varepsilon_2^{d+Au} \approx \varepsilon_2^{3He+Au}$$
$$\varepsilon_3^{p+Au} \approx \varepsilon_3^{d+Au} < \varepsilon_3^{3He+Au}$$



v_2 vs initial geometry





$$v_2^{p+\mathrm{Au}} < v_2^{d+\mathrm{Au}} \approx v_2^{^3\mathrm{He+Au}}$$

$$\varepsilon_2^{\mathrm{p+Au}} < \varepsilon_2^{\mathrm{d+Au}} \approx \varepsilon_2^{\mathrm{3He+Au}}$$

$$v_3^{p+\mathrm{Au}} \approx v_3^{d+\mathrm{Au}} < v_3^{^3\mathrm{He+Au}}$$

$$\varepsilon_3^{\mathrm{p+Au}} \approx \varepsilon_3^{\mathrm{d+Au}} < \varepsilon_3^{\mathrm{3He+Au}}$$

Non-Flow subtraction methods

Two Jet Subtraction Methods

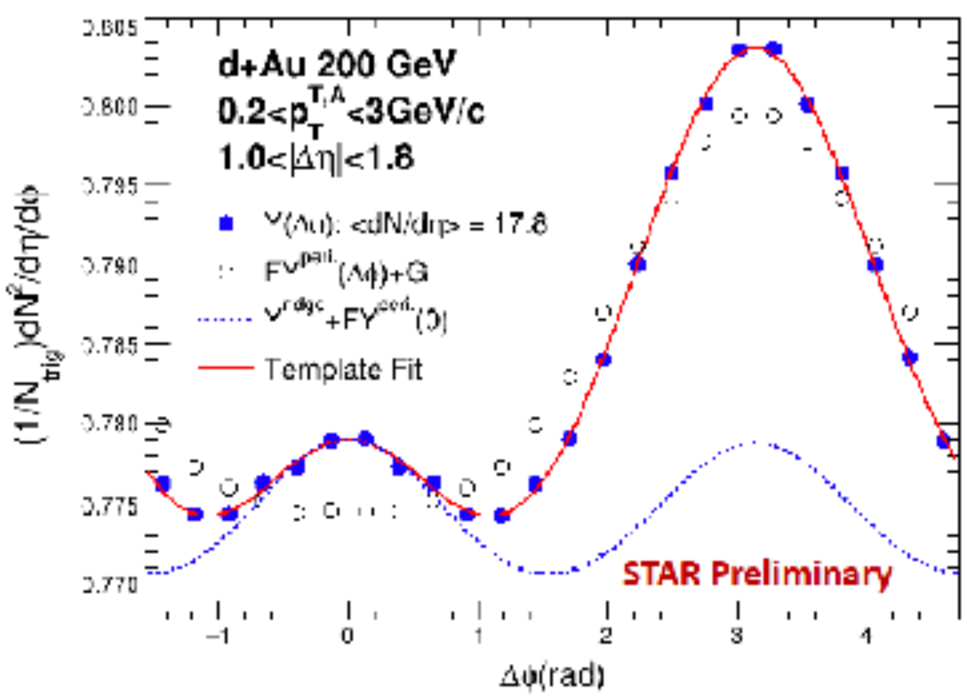
1.Low multiplicity subtraction scaled by short-range (|$\Delta\eta$|<0.5) near-side jet yield

$$V_{n,n}^{HM}(subtracted) = V_{n,n}^{HM} - V_{n,n}^{LM} \times \frac{N_{asso.}^{LM}}{N_{asso.}^{HM}} \times \frac{Y_{jet,near-side}^{HM}}{Y_{jet,near-side}^{LM}}$$

ATLAS:PRC90(2014)044906
CMS:PLB765(2017)193
STAR: PLB743(2015)333

✓ ***Assumption: short-range near-side jet modification = long-range away-side jet modification***

2.Template Fit



✓ **A new developed method to subtract away-side jet contribution by ATLAS:**

$$Y_{templ.}(\Delta\phi) = F \times Y_{LM}(\Delta\phi) + Y_{ridge}(\Delta\phi)$$

where

$$Y_{ridge}(\Delta\phi) = G \times (1 + 2 \times \sum_{n=2}^{4} V_{n,n} \times \cos(n\Delta\phi))$$

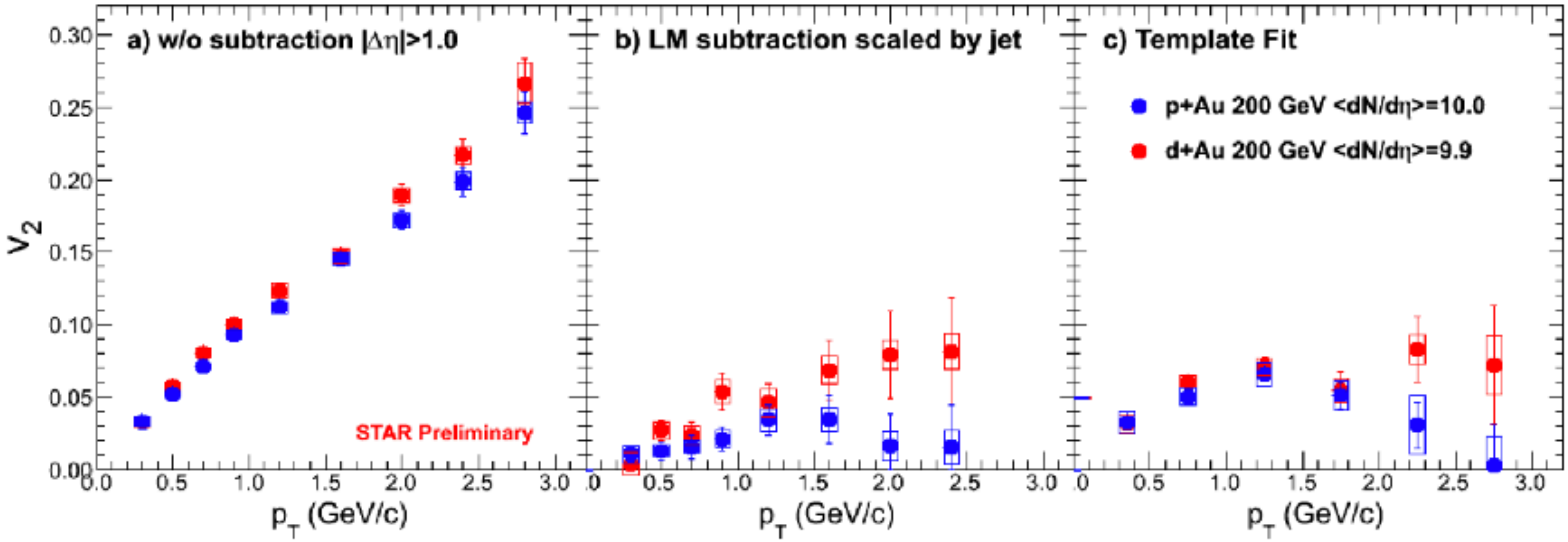
ATLAS:PRL(116)172301

✓ **Assumption: away-side jet shape can be measured in LM events and scaled by fit parameter "F" due to jet modification**

It will cause a bias if assumptions are not correct

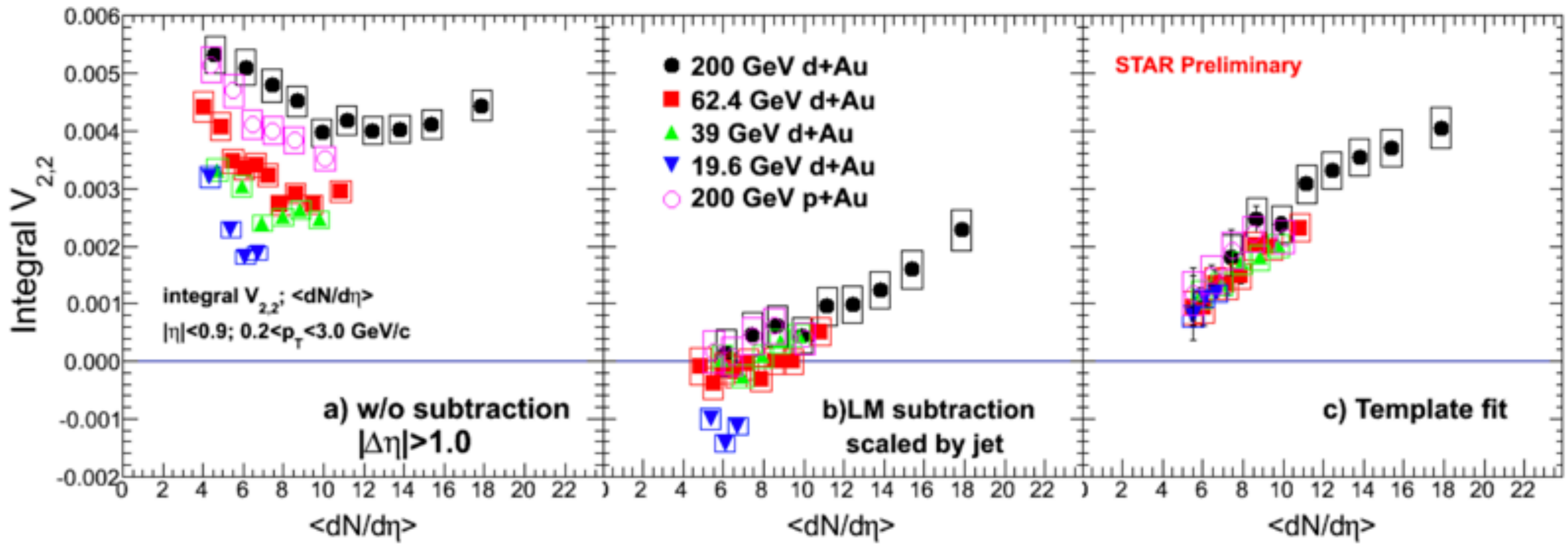
5/14/18 *Shengli Huang*

p/d+Au v_2 with same <dN/dη>



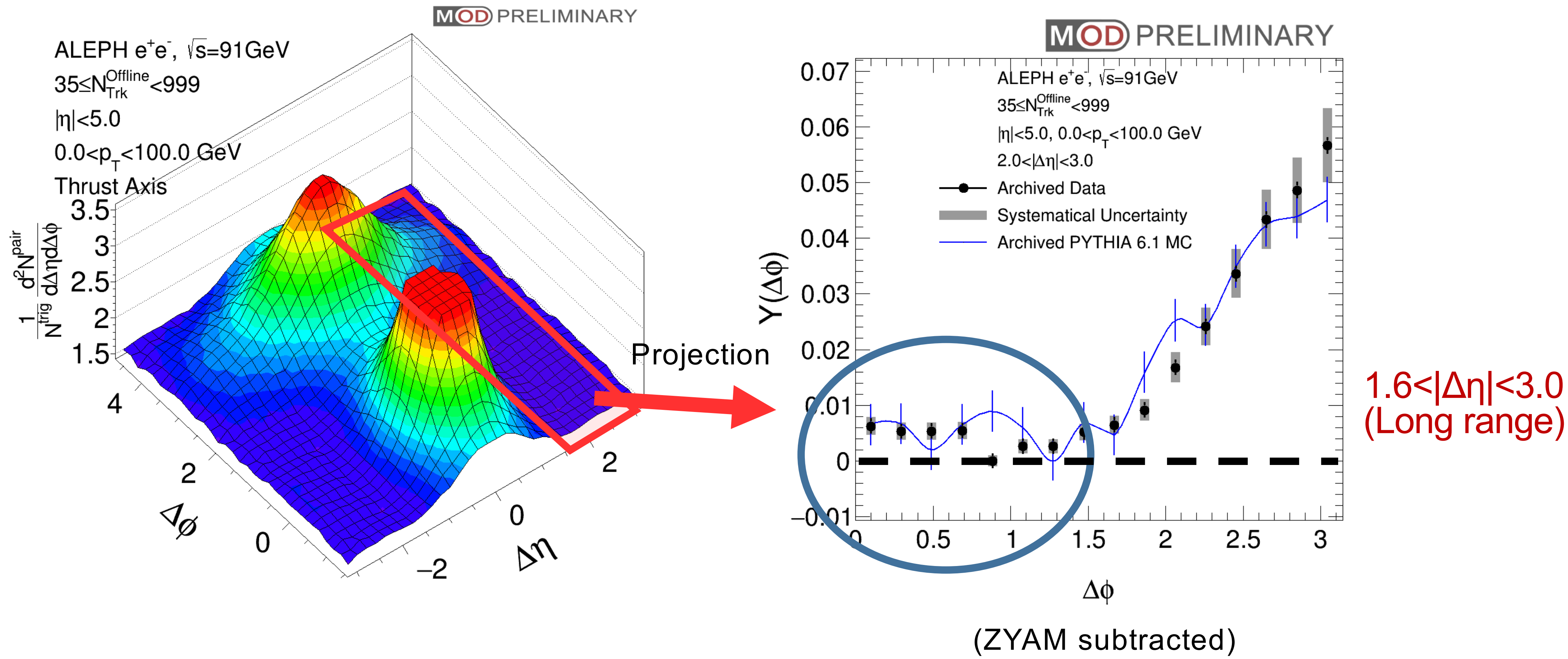
- ❑ By LM subtraction method, v_2 in d+Au is a little bit larger than that of p+Au collisions
- ❑ v_2 between p+Au and d+Au collisions from template fit is similar, while the initial eccentricities are different by a factor of two

Integral $V_{2,2}$ vs. <dN/dη>



- ❑ There is large difference between two methods
- ❑ LM subtraction leads to a negative $V_{2,2}$ at low energy
  - ✓ Different kinematics between near- and away-side jet-like correlations?
- ❑ $V_{2,2}$ from template fit increases as a function of <dN/dη>

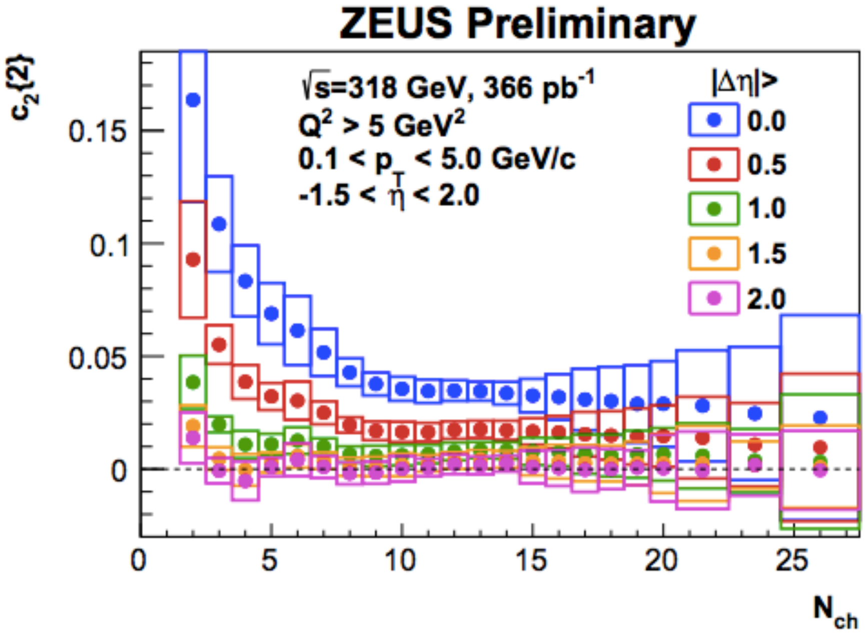
LEP1 Data vs PYTHIA6 N≥35



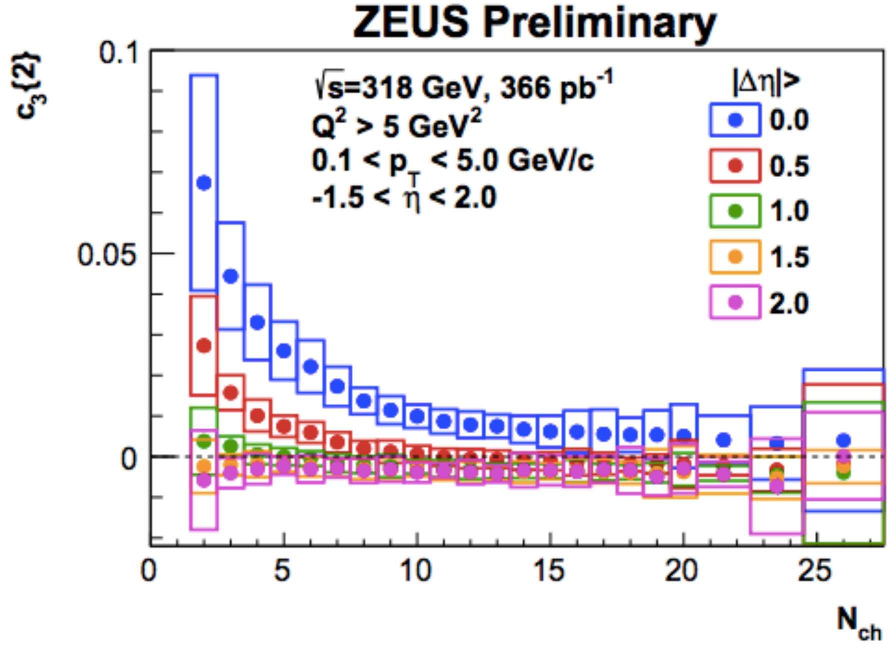
- Hint of near-side peak in data
  - Consistent with PYTHIA6 without final state effects
  - Contribution from multi-jet correlation
- PYTHIA6 reference limited by archive MC statistics

$c_n\{2\}$ in e-p

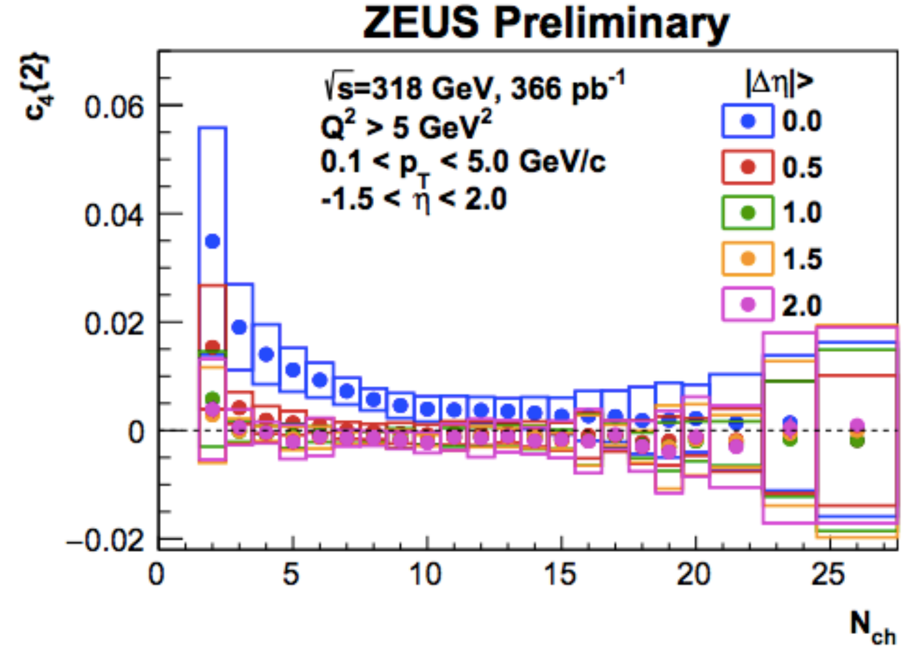
c_2



c_3



c_4



Familiar behaviour: non-flow dominates at small multiplicity and without eta-gap

No flow-like signal seen in high-multiplicity, large eta gap for c_2, c_3, c_4

$c_n\{2\}$ in e-p is consistent with 0 for large Nch with large η gap.

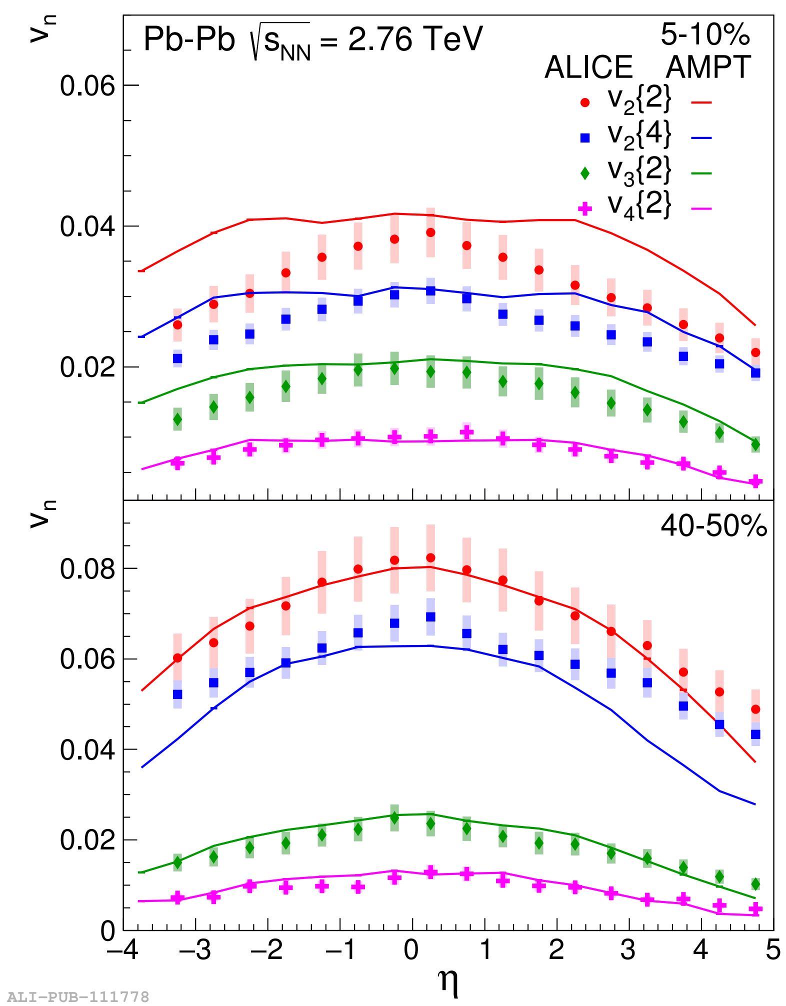
Summary

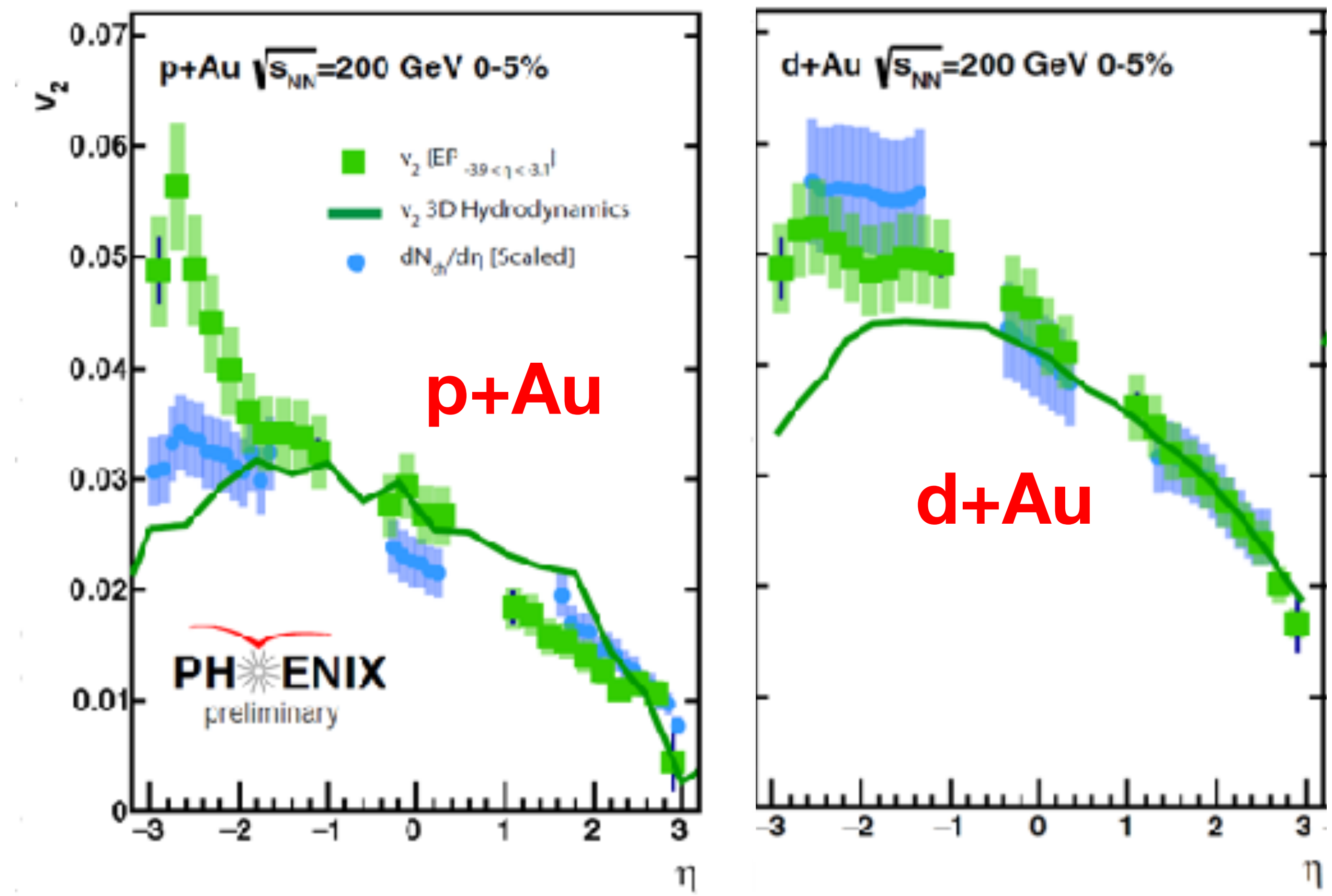
- strangeness —> strangeness enhancement?
  - YES!!
- Resonances —> dynamics of hadronic medium?
  - We saw re-scattering effects from K*.
- PID v_2 —> collectivity?
  - Mass ordering. Charm flow? What is the origin of large J/psi v_2?
- v_n vs. collision geometry —> initial conditions?
  - strong correction with eccentricity
- Multi particle cumulant —> initial or final?
  - $v_2\{4\}/v_2\{2\} = v_3\{4\}/v_3\{2\}$ in p-Pb (not the case for A-A). Importance of initial fluctuation in v_2
  - $c_2\{4\}<0$ with large rapidity gap (sub event cumulant)
  - $c_2\{4\}<0$ in dAu but $c_2\{4\}>0$ in pAu
- Symmetric cumulant —> initial or final?
  - Correlation gets weaker if rapidity gap is required. Same trend in SC(2,4) and SC(2,3) between p-A and A-A. Different in p-p.
- Ridge in ee collisions —> thermalization/collectivity in ee?
  - no ridge in ee collisions. no flow like signal in ee.
  - no

Thank you for your attention!!

backup

$v_2(\eta)$ vs $dN_{ch}/d\eta$ in Geometry Control Scan

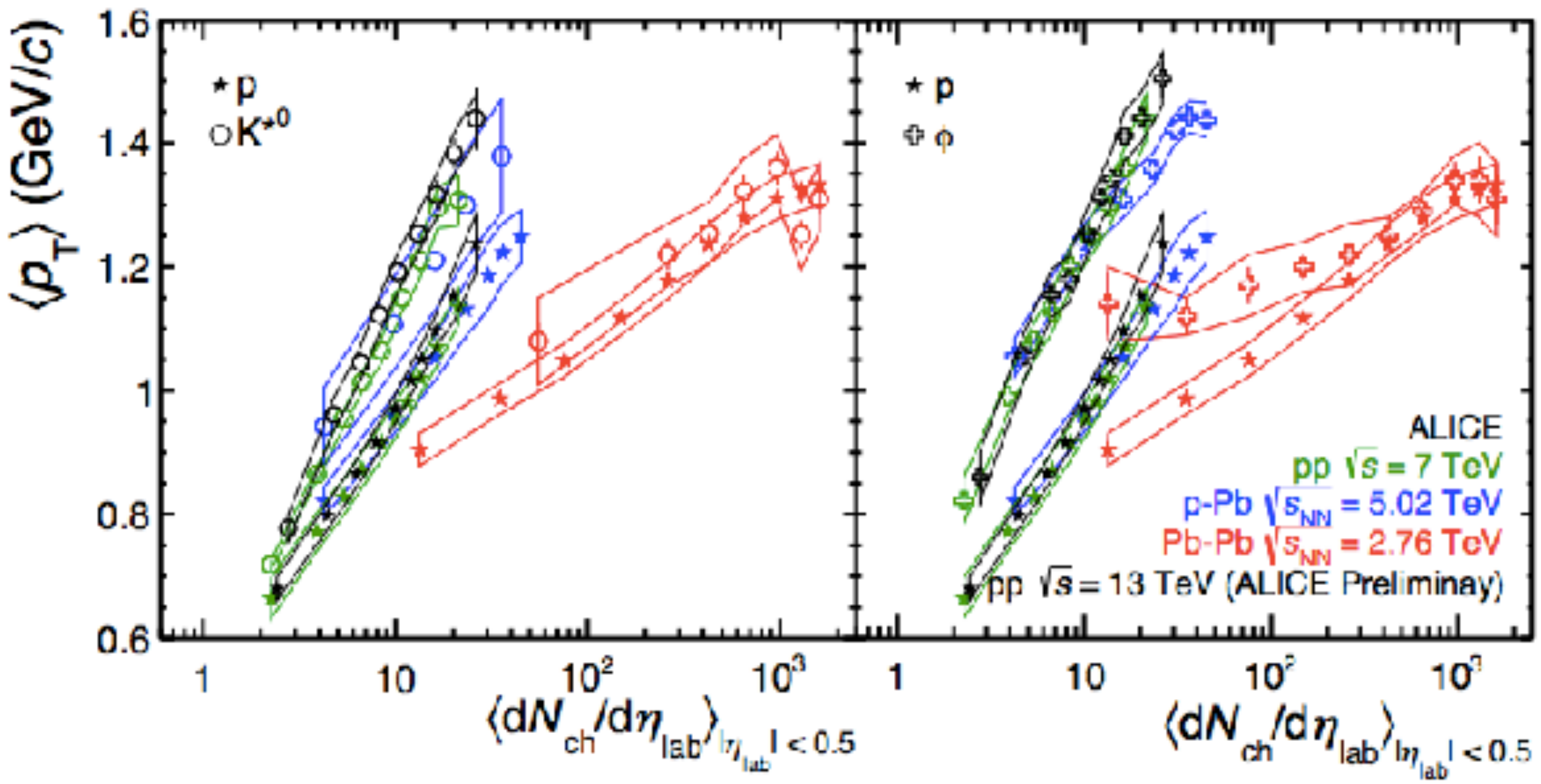


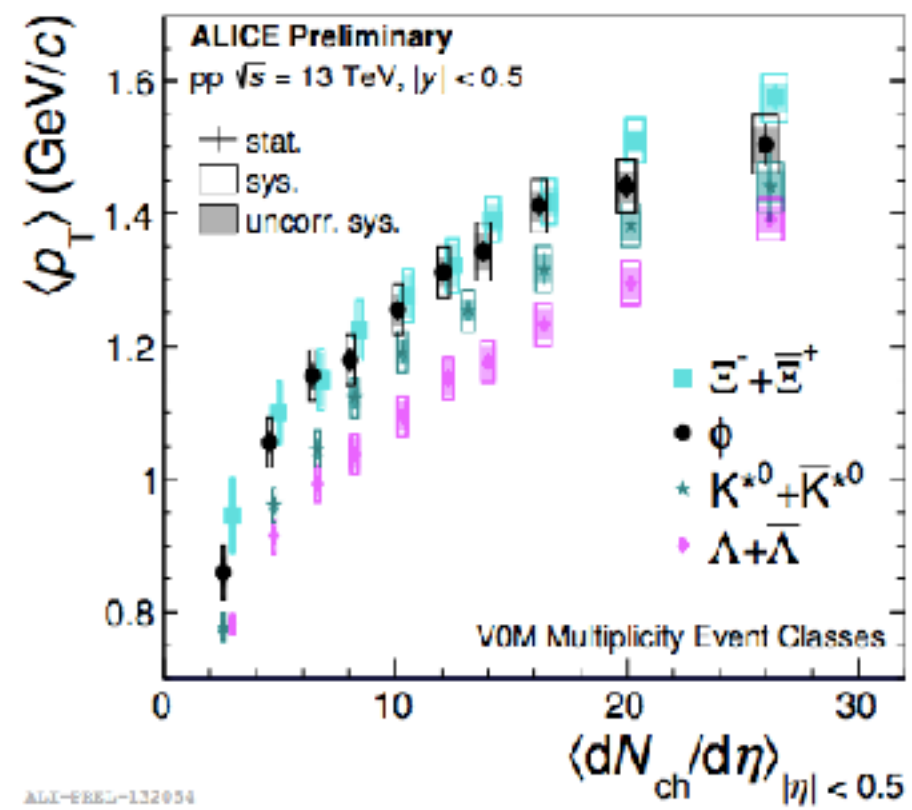


- d+Au scales well, but p+Au does not at backward rapidity
- 3D hydrodynamics quantitatively describes the data in p+Au

The event plane is measured in -3.9 < η < -3.1

mean pT

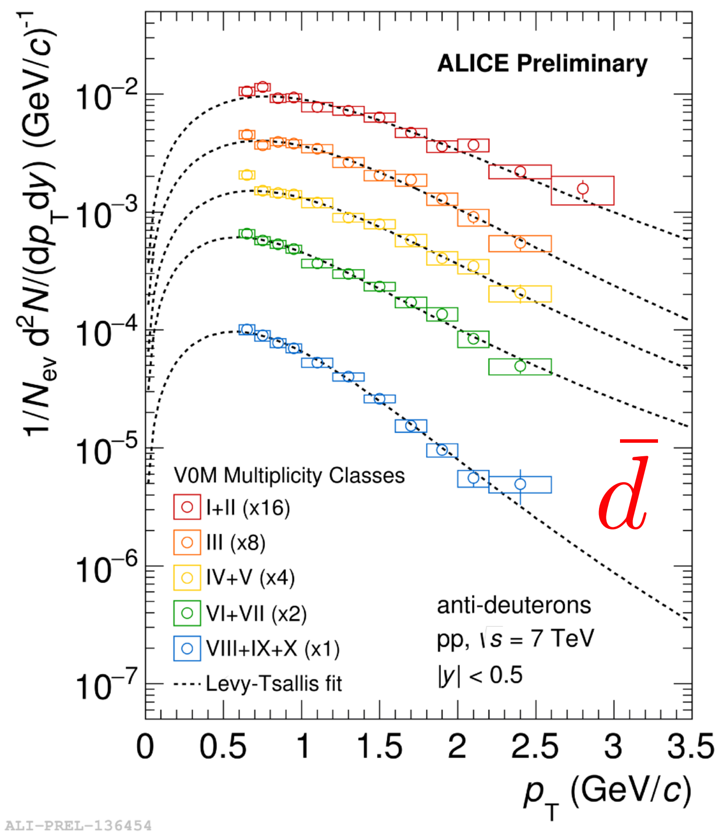


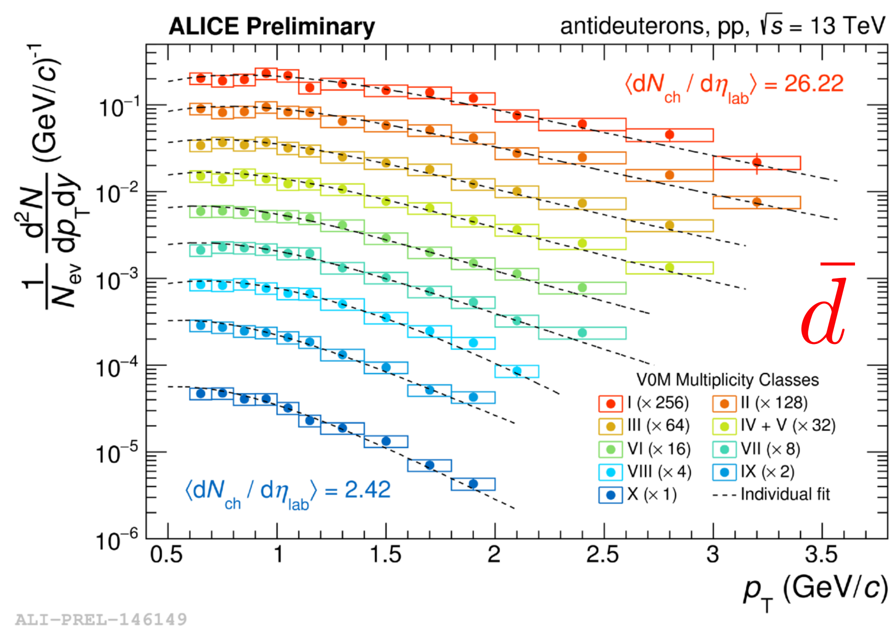


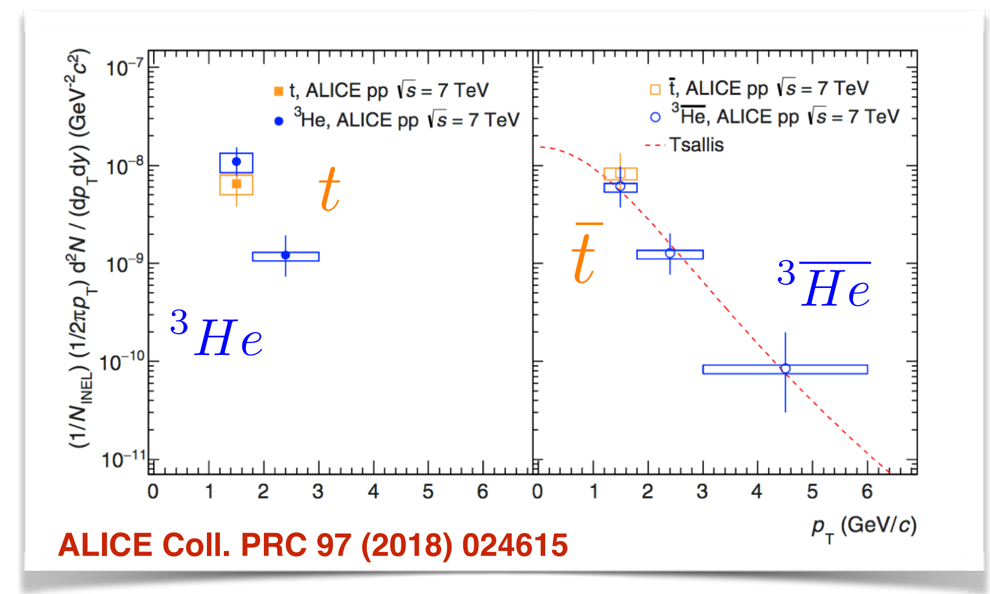
- ✓ Steeper increase in ‹p_T› with multiplicity in smaller systems
- ✓ Mass ordering of ‹p_T› in central Pb-Pb
  - ‹p_T› for K^{*0}, p and φ similar → expected from hydro

    $M(K^{*0})$ = 896 MeV/c^2, M(p) = 938 MeV/c^2, $M(\phi)$ = 1019 MeV/c^2
- ✓ Mass ordering breaks down for smaller collision systems
  - In pp: ‹$p_T(\phi)$› = ‹$p_T(\Xi)$› despite 30% mass difference

heavy nuclei







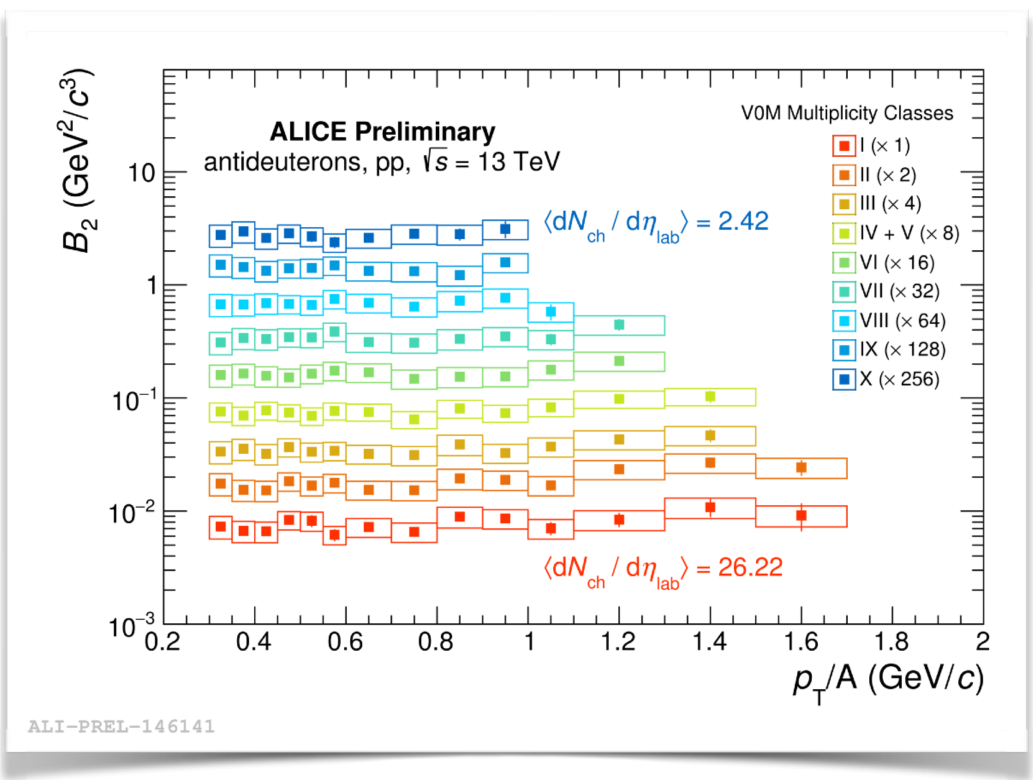
- pp spectrum shows no sign of radial flow (spectra hardening is clearly seen in heavy-ion collisions)
- integrated yields reduced of a factor ~1000 when adding a nucleon
  - ➡ it is ~ 300 and ~ 600 in Pb-Pb and p-Pb collisions, respectively

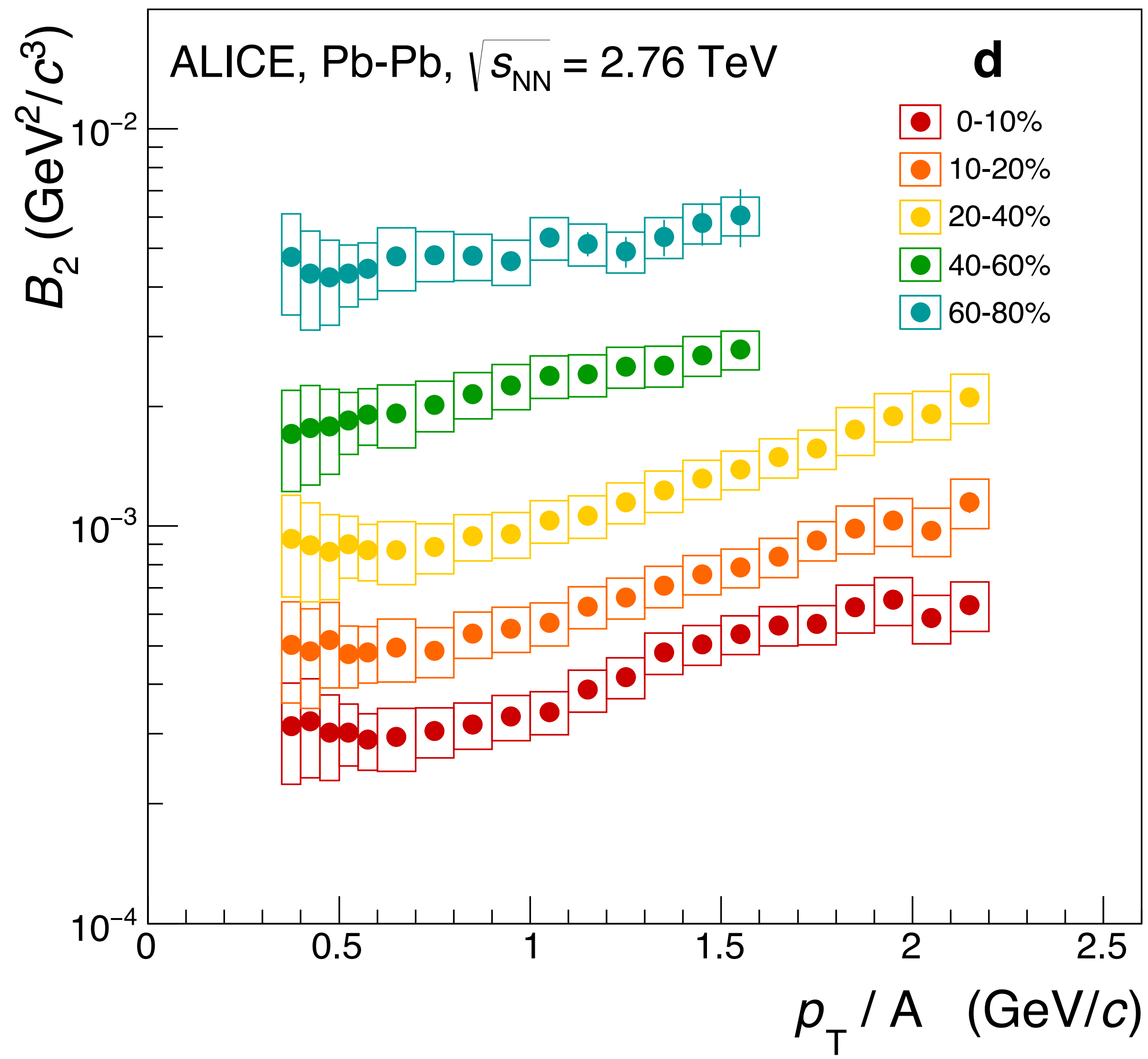
heavy nuclei

The formation probability of composite nuclei can be quantified through the coalescence parameter B_A

$$B_A = \frac{E_A \frac{d^3N_A}{dp_A^3}}{\left(E_p \frac{d^3N_p}{dp_p^3}\right)^A}$$

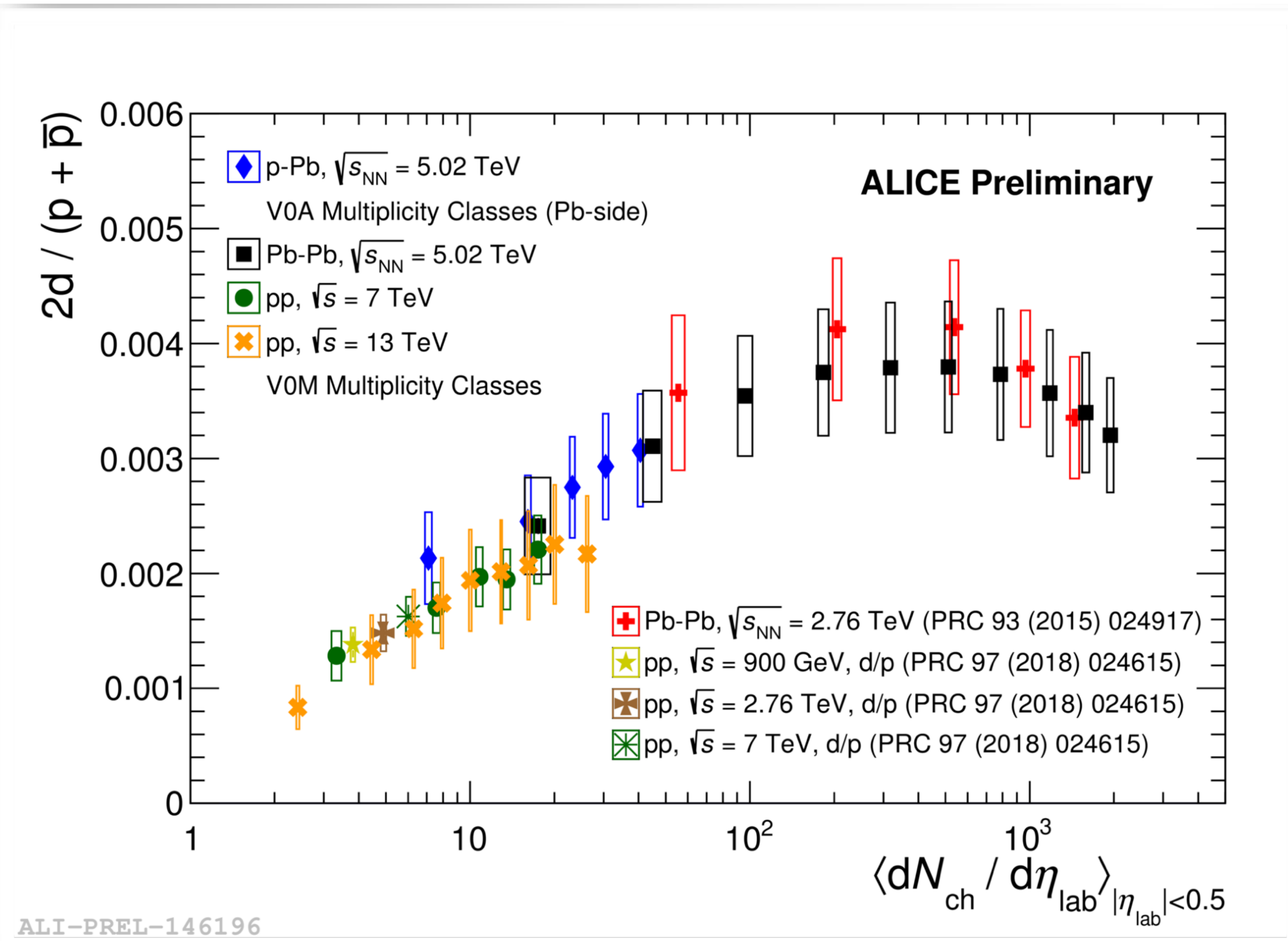
$$B_2 = \frac{3\pi^{3/2}\langle C_d\rangle}{2m_T R_\perp^2(m_T) R_\parallel(m_T)},$$





- No p_T dependence as suggested by simple coalescence models

heavy nuclei



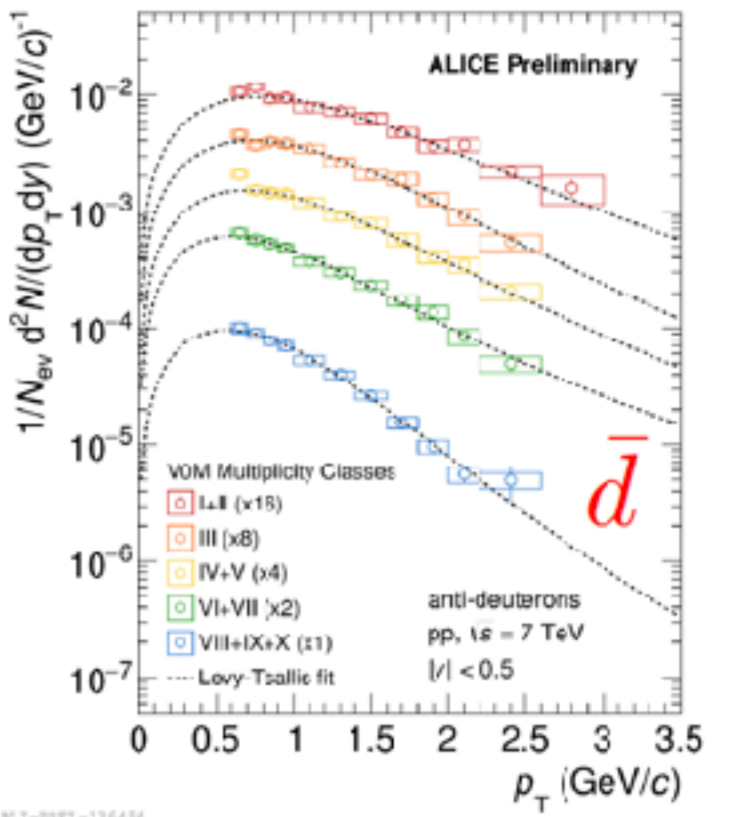
- Latest results in pp at 7 TeV and 13 TeV fit the trend drawn by other energies/colliding systems at the LHC
- matching of pp and p-Pb points at similar multiplicities
- **rising** with multiplicity explained in coalescence models as due to an **increased proton and neutron density**

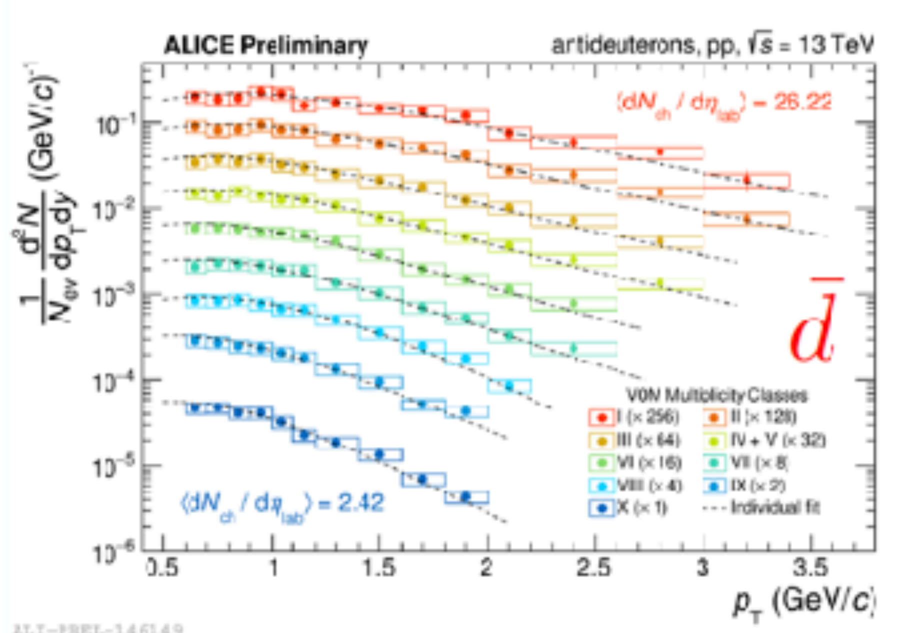
- In pp (and p-Pb) the results point out that the rise in the number of nucleons dominates over the increase in the volume size
- No significant centrality dependence in Pb-Pb collisions in agreement with Thermal-statistical model

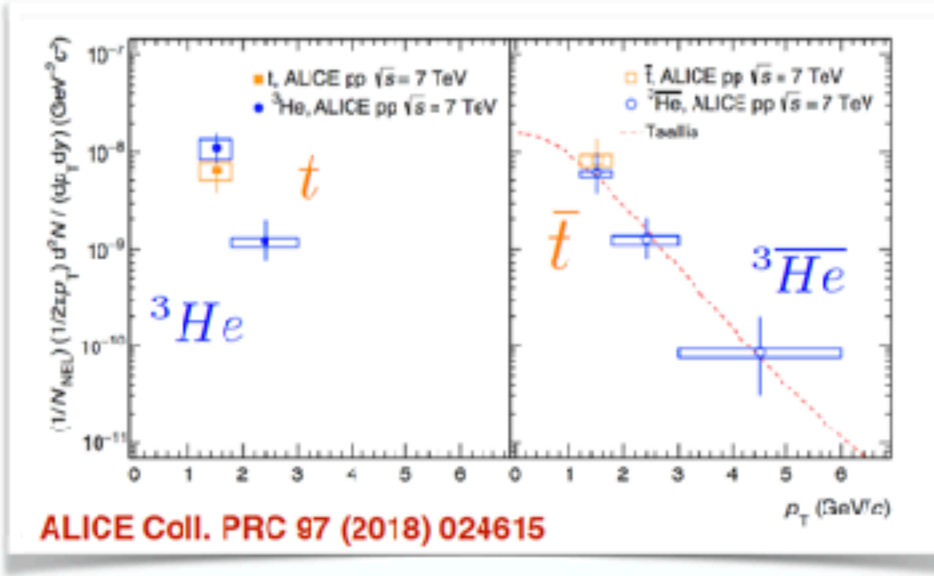
(Anti-)nuclei production in small systems

Latest news

New results from LHC- Run2 at 7 TeV and 13 TeV vs multiplicity and first ever observation of anti-^{3}He in pp collisions from LHC-Run1 data







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- integrated yields reduced of a factor ~1000 when adding a nucleon

➡ it is ~ 300 and ~ 600 in Pb-Pb and p-Pb collisions, respectively

Why study resonances?

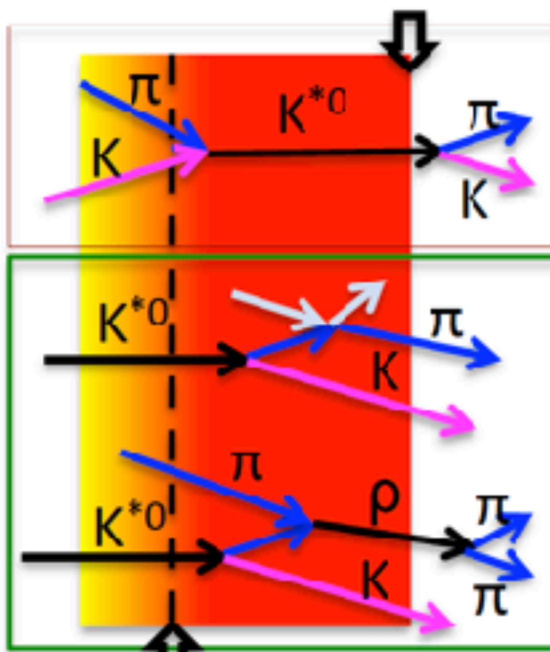
ALICE

✓ Short lifetimes -> can be decayed / regenerated inside the hot and dense matter by final state interactions -> sensitive to the evolution dynamics

Properties of Hadronic Phase

-- Modification of yields and particle ratios as a hint of re-generation/re-scattering effects

Kinetic freeze-out



Regeneration: Pseudo-elastic scattering through resonance state e.g., πK→K*→πK
-> increases yield

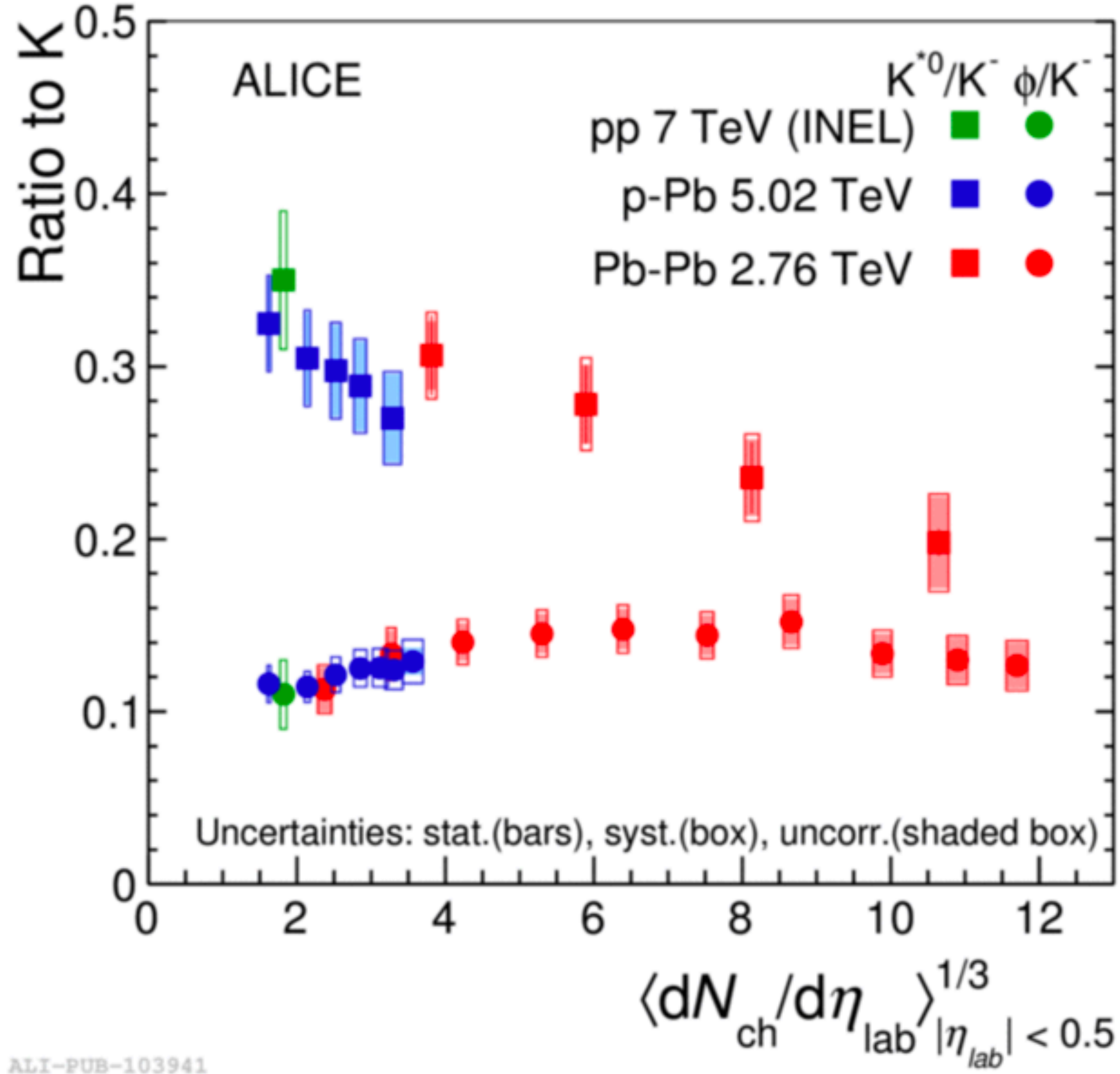
Re-scattering: resonance decay products undergo elastic scattering or pseudo-elastic scattering through a different resonance (e.g. ρ)
-> decreases yield

Chemical freeze-out

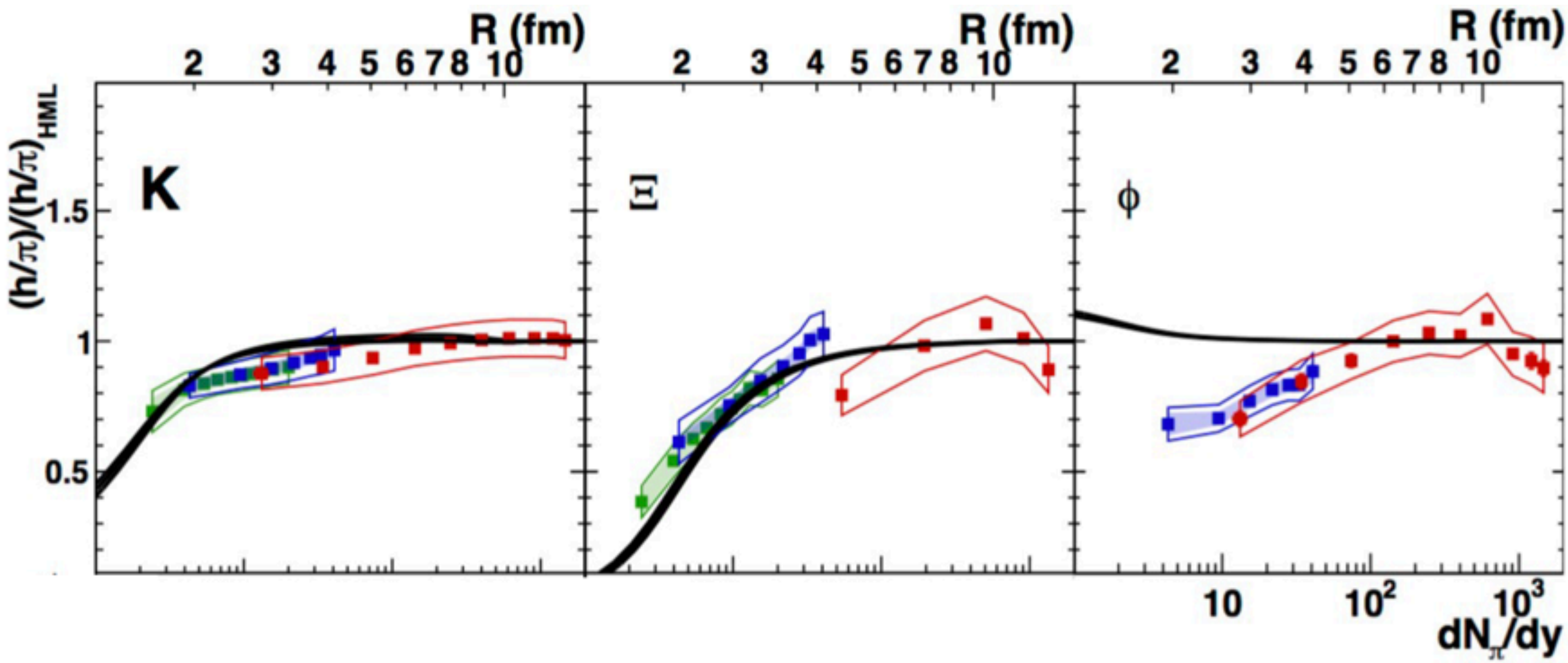
Resonance	τ(fm/c)	Decay	BR (%)
$\rho^0(770)$	1.3	ππ	100
Δ(1232)	1.7	Nπ	99.4
$K^*(892)$	4.2	Kπ	66.6
$\Sigma^{*\pm}(1385)$	5.5	πΛ	87
Λ*(1520)	12.6	pK	22.5
$\Xi^{*0}(1530)$	21.7	Ξπ	66.7
ϕ(1020)	46.4	KK	48.9

- Hadronic phase exists in A-A collisions
- Is there any hadronic phase in high multiplicity pp and p-Pb events?

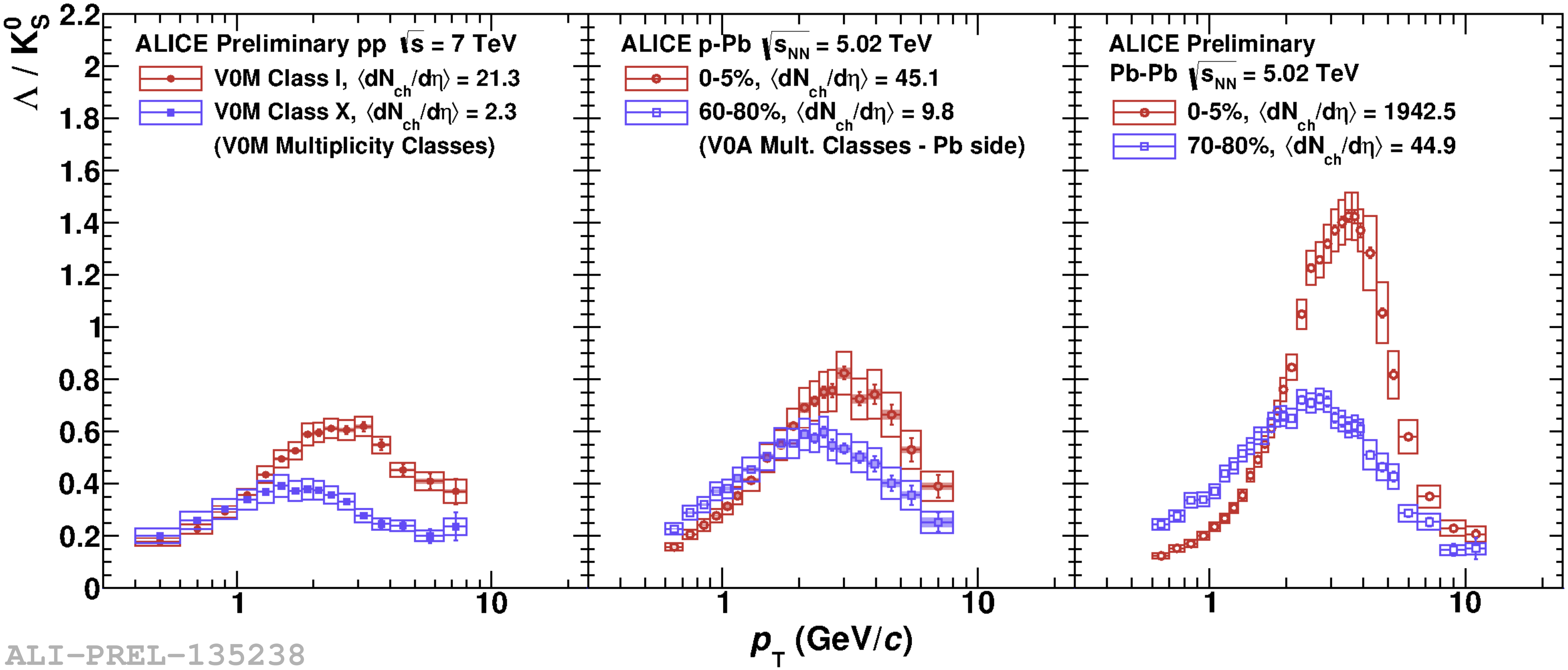
particle ratio as a function of multiplicity



Special role of ϕ

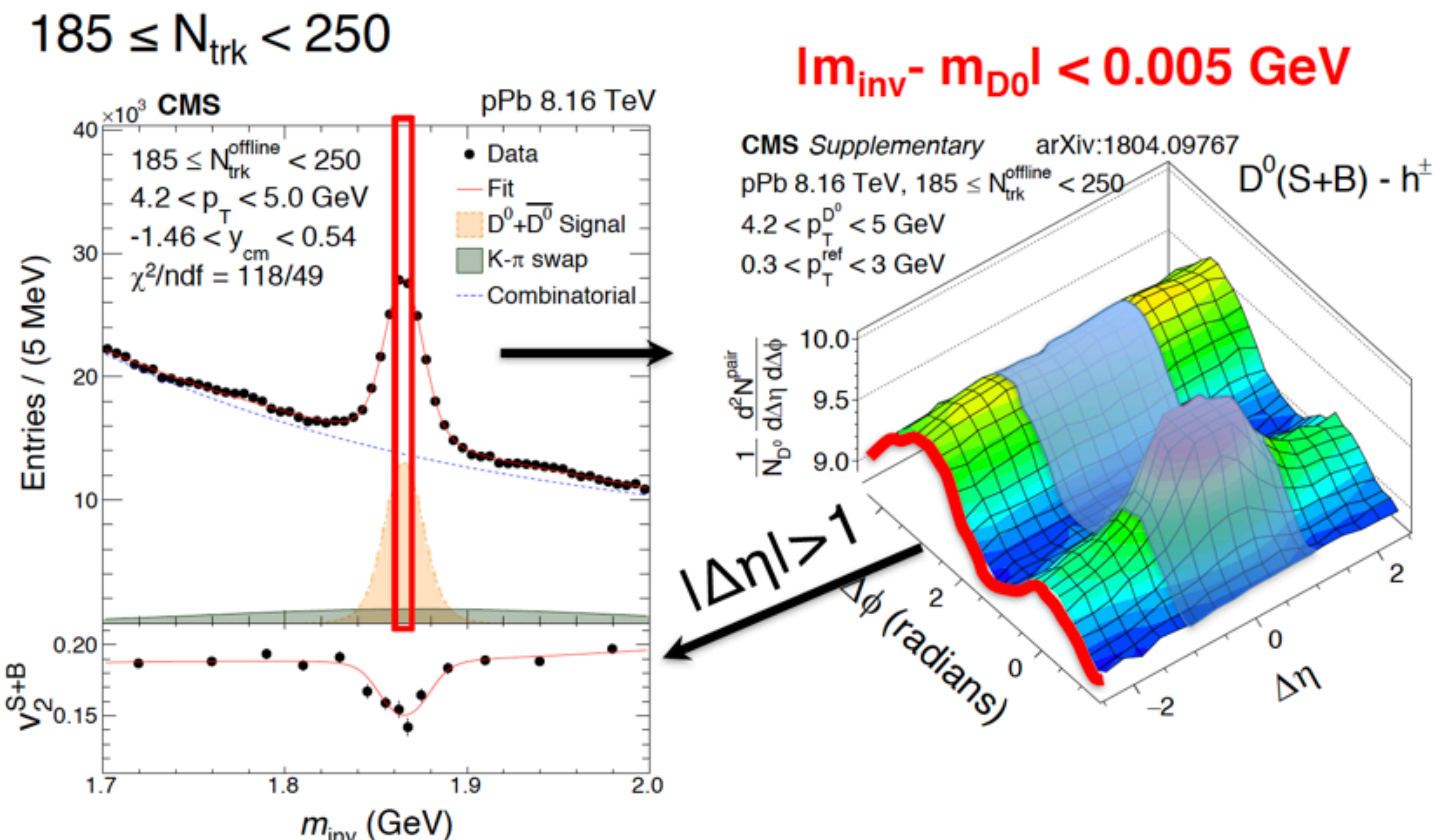


Strangeness enhancement



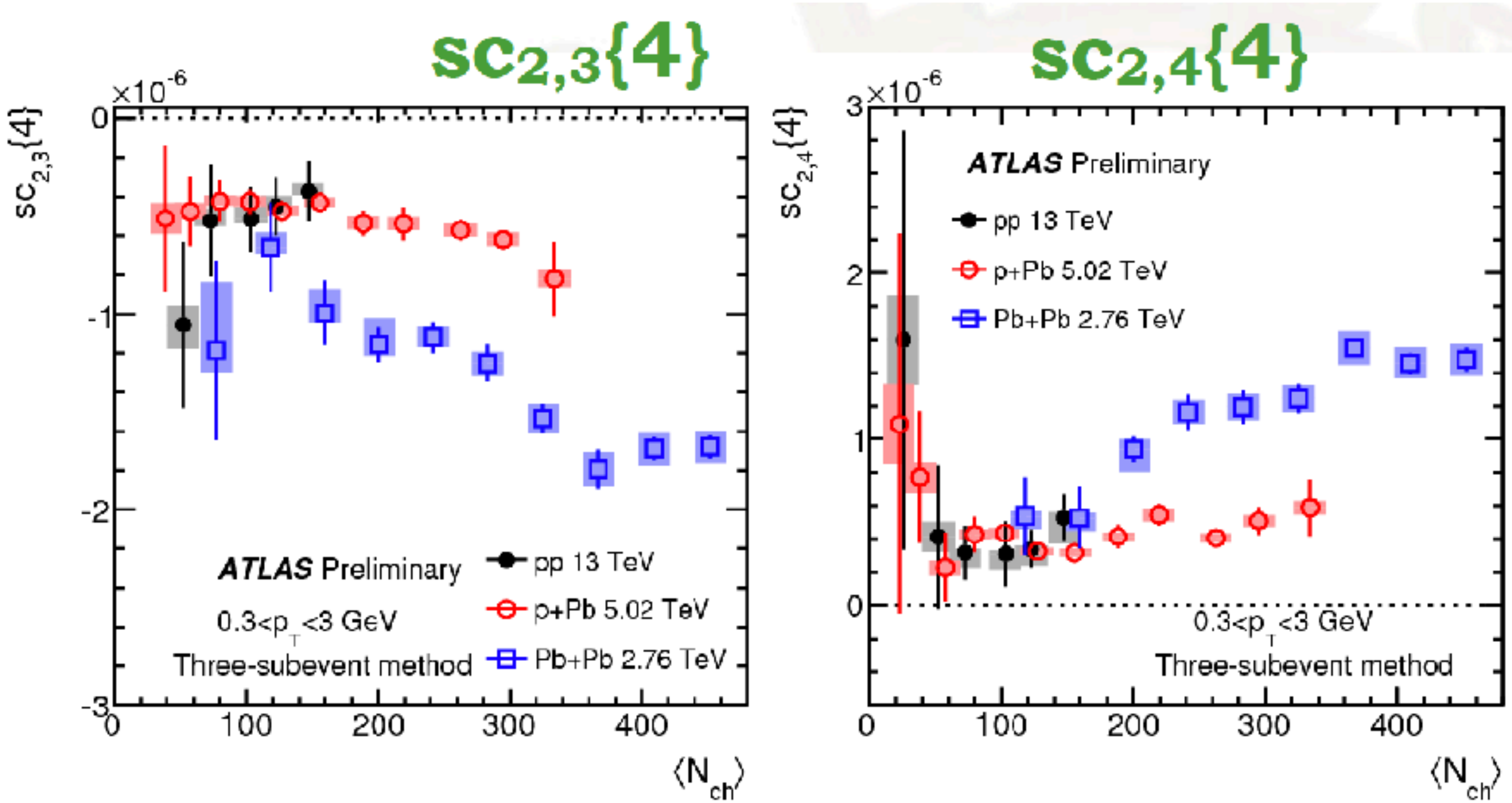
- Strangeness enhanced from pp to PbPb.

D^0 – charged hadron correlations



$$v_n^{Sig+Bkg}(m_{inv}) = \alpha(m_{inv})v_n^{sig} + (1-\alpha(m_{inv}))v_n^{Bkg}$$

Comparison with collision systems



- Symmetric cumulants consistent between all three systems in the <Nch> range covered by p+p collisions.