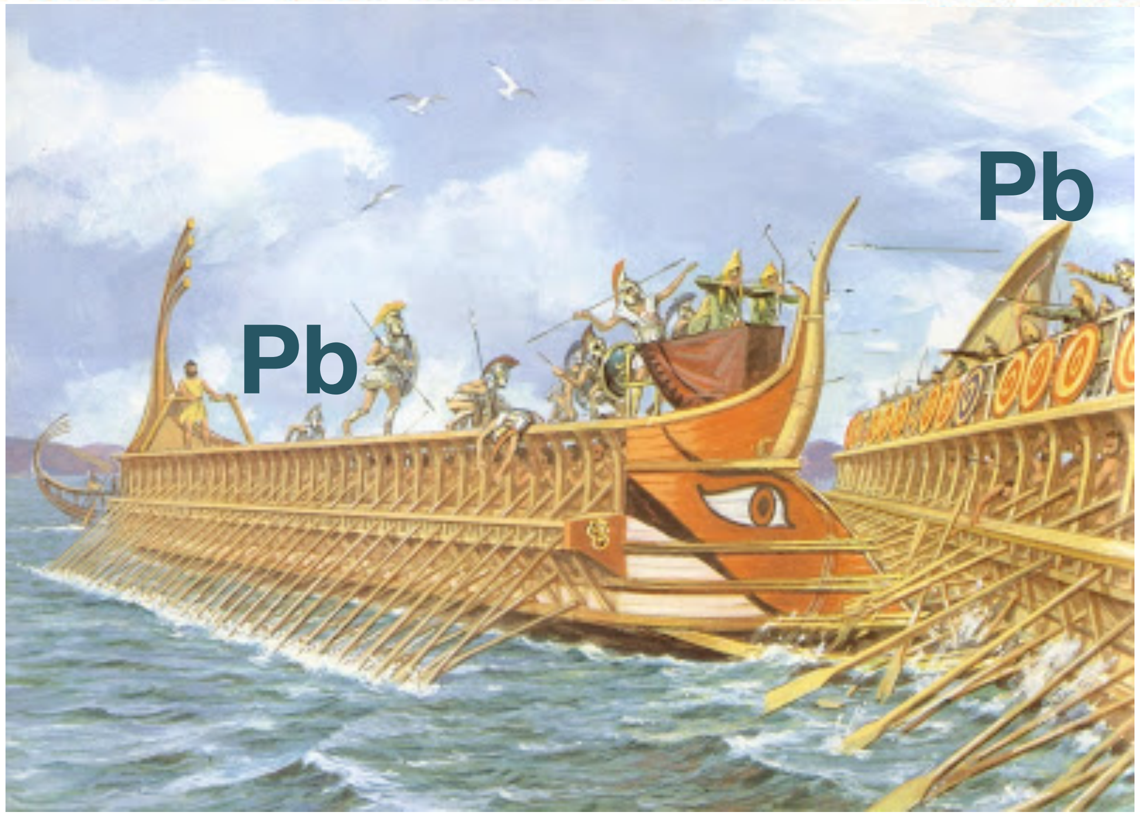
Collective phenomena from high energy proton-proton to heavy-ion collisions at the LHC

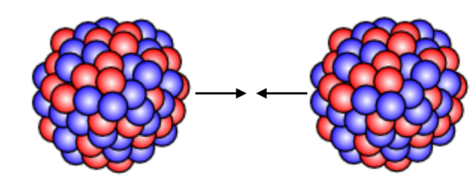
Speaker: Daniele Fasanella
INFN and University of Bologna

on behalf of **CMS**, **ALICE** and **ATLAS** experiments

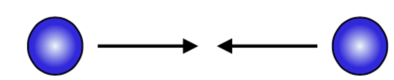


The LHC Heavy Ions Programme

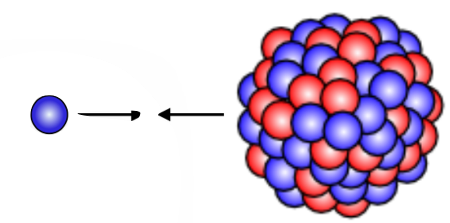
- QCD predicts a **deconfined medium** at high temperature, the Quark-Gluon Plasma ($T_c \simeq 155$ MeV)
- Basic paradigm for LHC HI programme:
  - Collisions **Pb-Pb nuclei** creates the conditions for the phase transition
  - The system gets close to thermal equilibrium and expands collectively
  - Precise measurement of macroscopic properties



  - Collisions in **p-p** used as reference data for the HI measurements



  - Collisions **p-Pb** as control experiment and to evaluate "Cold nuclear matter" effects



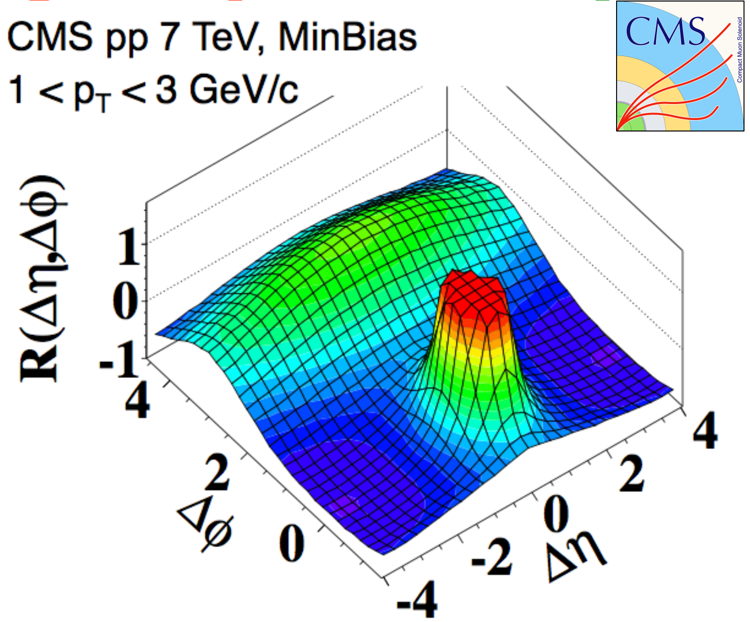
- Extremely successful
  - **Formation of QGP with collective hydrodynamic behaviours confirmed**
  - **High precision results** from CMS, ATLAS and ALICE experiments that describe its proprieties

But….

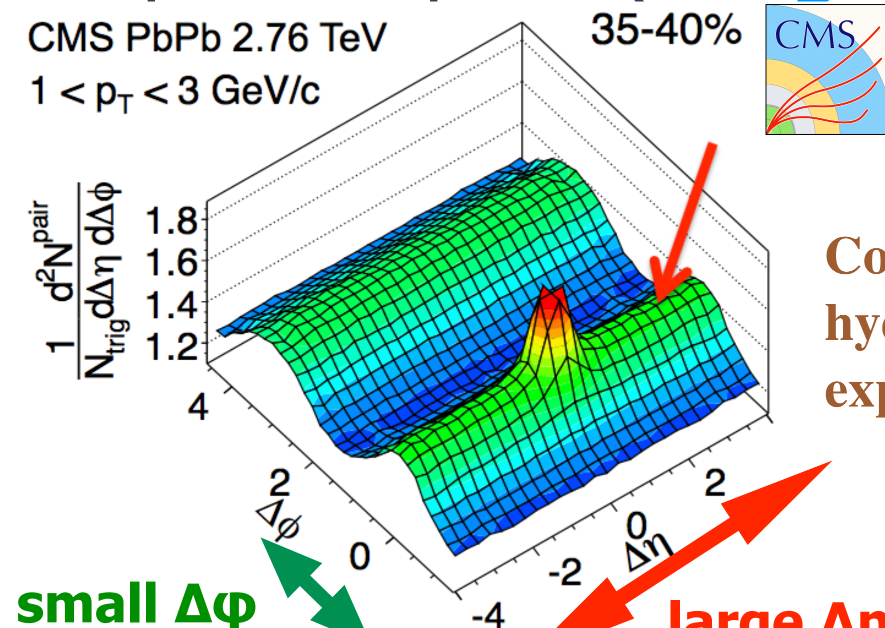
Unexpected phenomena!

- A persuasive piece of evidence for collective behaviour in Pb-Pb collision are **large Δη-small Δφ** correlations for particle pairs ("**ridge**")

JHEP 09 (2010) 091



Eur. Phys. J. C 72 (2012) 2012

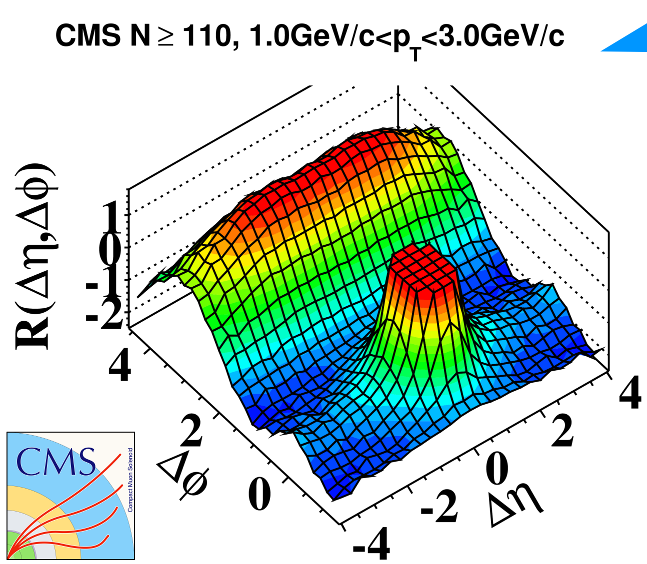


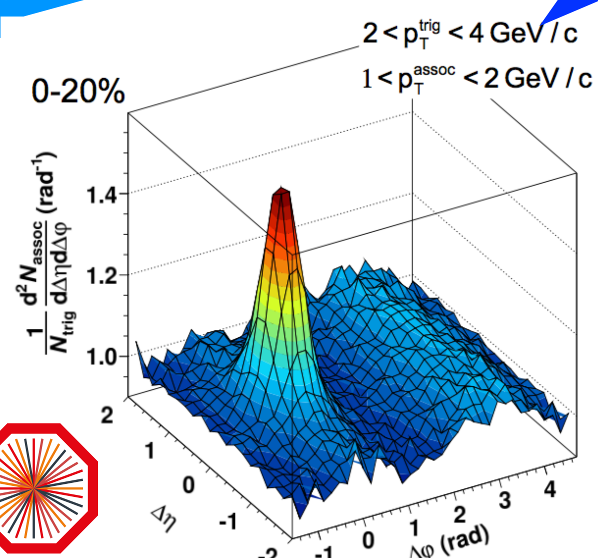
Collective hydrodynamic expansion of QGP

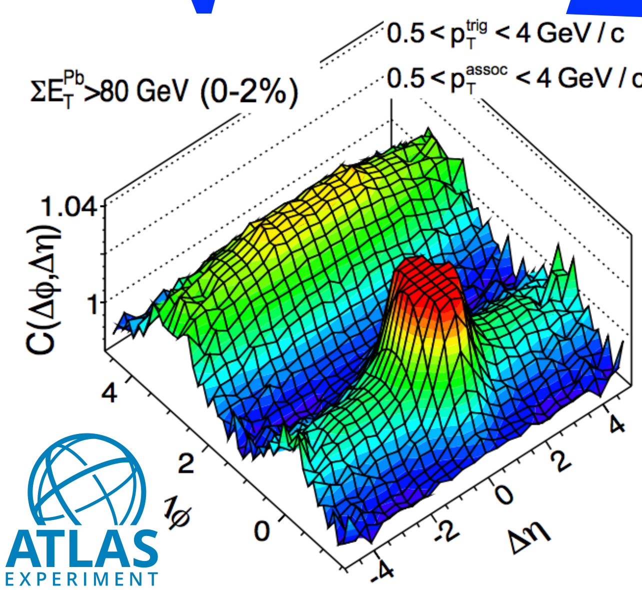
small Δφ

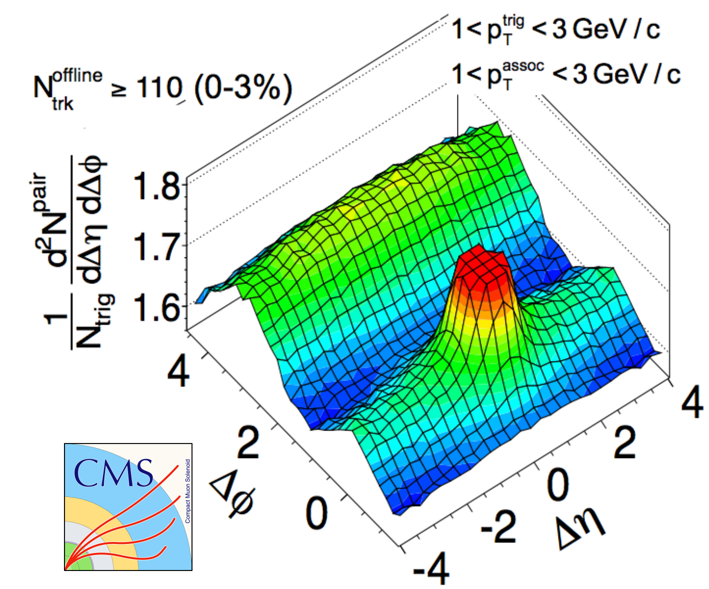
large Δη

- **Same behaviour found in p-p and p-Pb collision at high multiplicity!**









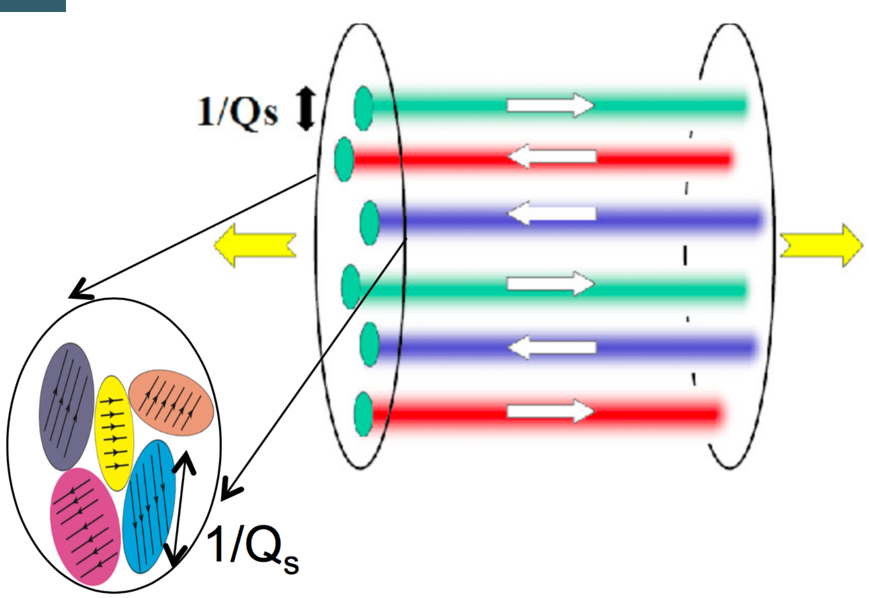
JHEP 09 (2010) 091 | Phys. Lett. B719 | Phys. Rev. Lett. 110, 182302 (2013) | PLB 718 (2013) 795-814

Paradigm shift

- **Phenomena considered hallmarks of heavy-ions seen in smaller systems!**
  - p-p and p-Pb collision are no longer reference, but **actual field of study**
  - important consequence for our understanding of QCD
- **Many open questions:**
  - Can the p-p ridge be attributed to collective flow effects?
  - Can the bulk of the matter created in high-multiplicity collisions be described in terms of hydrodynamics?
  - How can thermalisation happen in such small systems?

CGC **Initial state interactions**

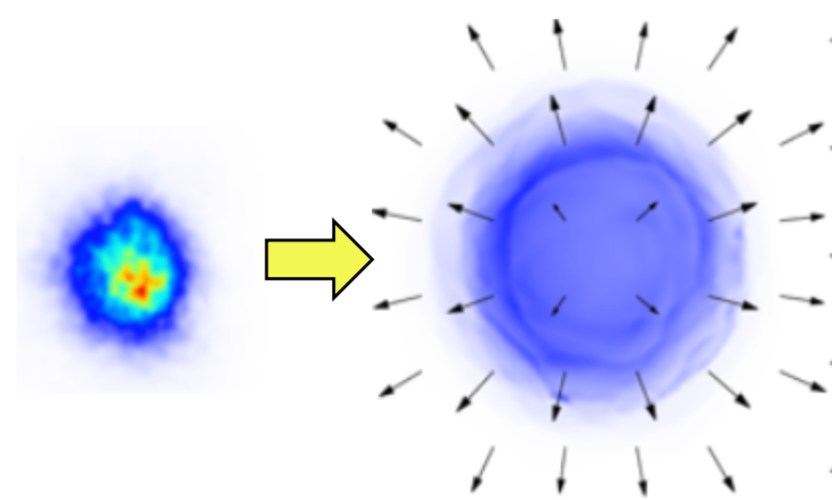
PRD 87 (2013) 094034



- Domain of color fields of size $1/Q_S$, each produce multi-particles correlated across full η.

Hydro **Initial stage fluctuation + final stage interaction**

PRC 88 (2013) 014903



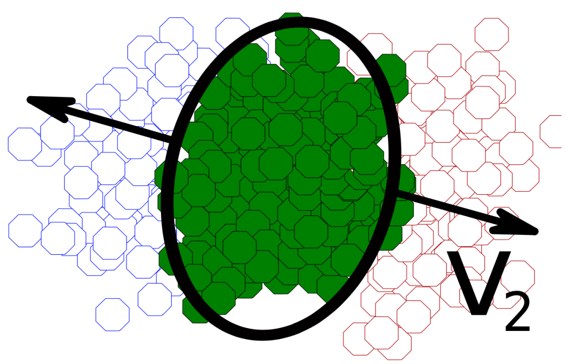
- **Hot spots** (domains) in transverse plane boost-invariant geometry shape
- Expansion and interaction of **hot spots** generate collectivity

Fourier series expansion

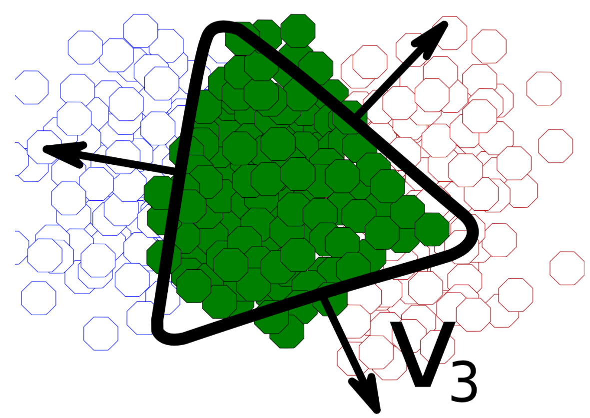
- Expansion in Fourier series projecting the long-range component (|η|>2) on the ΔΦ axis

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi_n))$$

Elliptic flow



Triangular flow



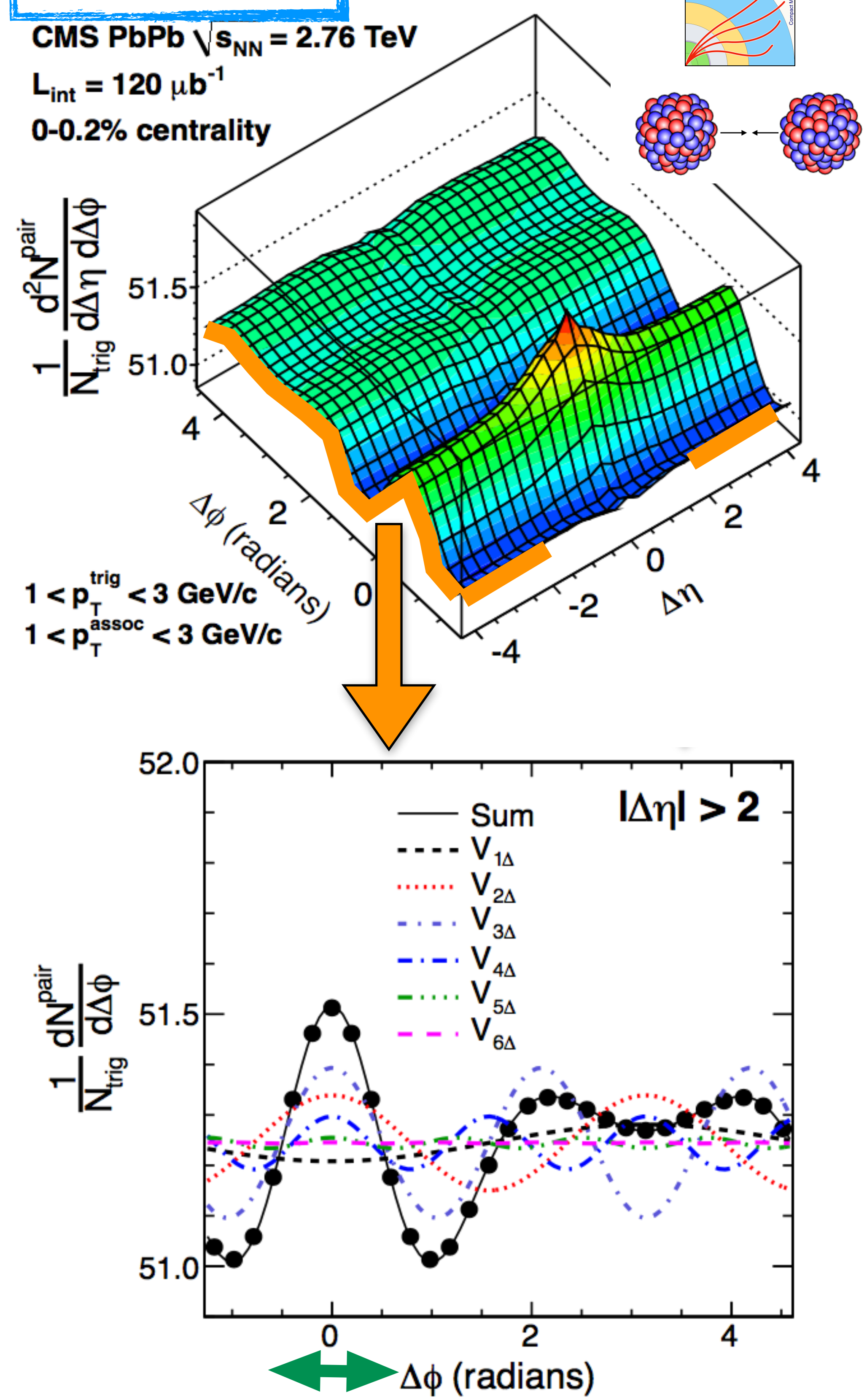
......

$$v_2 = \langle \cos(2(\phi - \psi_2)) \rangle \quad v_3 = \langle \cos(3(\phi - \psi_3)) \rangle \ldots\ldots$$

- Anisotropy harmonic coefficients v_n are sensitive to the full evolution of the collision system

- Sensitive to sub-nucleonic fluctuations of gluon densities (important for precision studies and small systems)

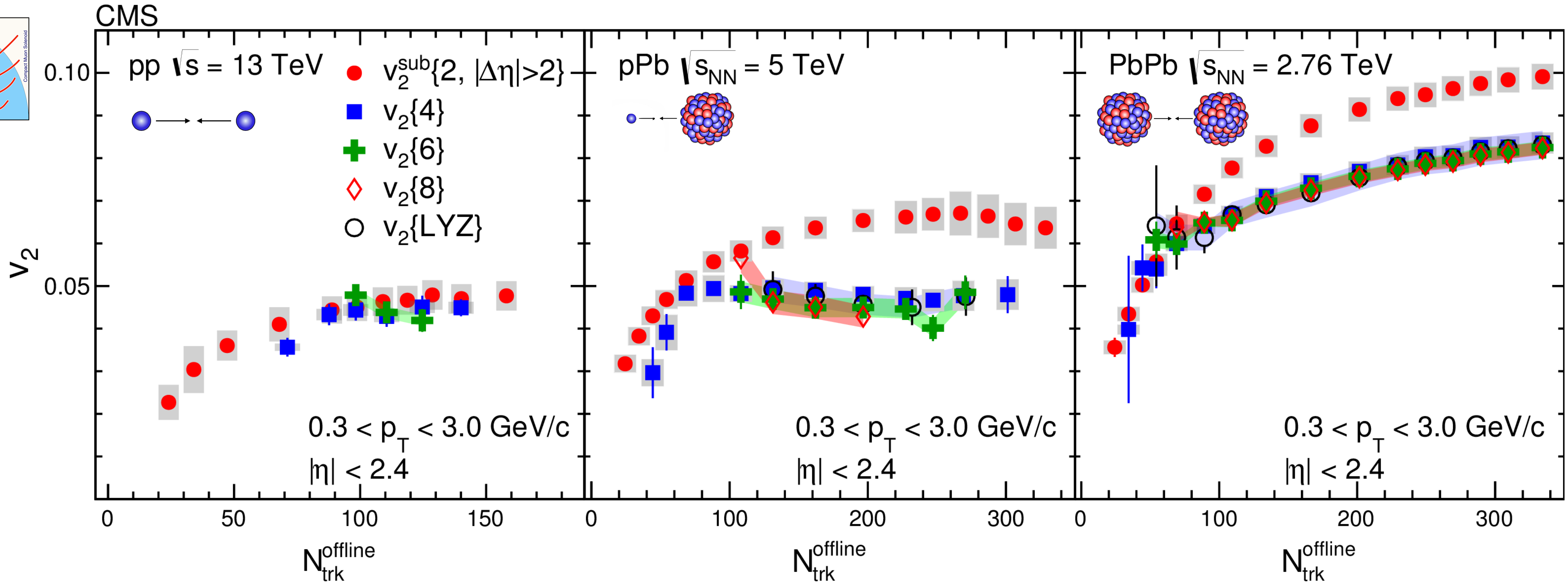
JHEP 02 (2014) 088



enhanced small Δφ

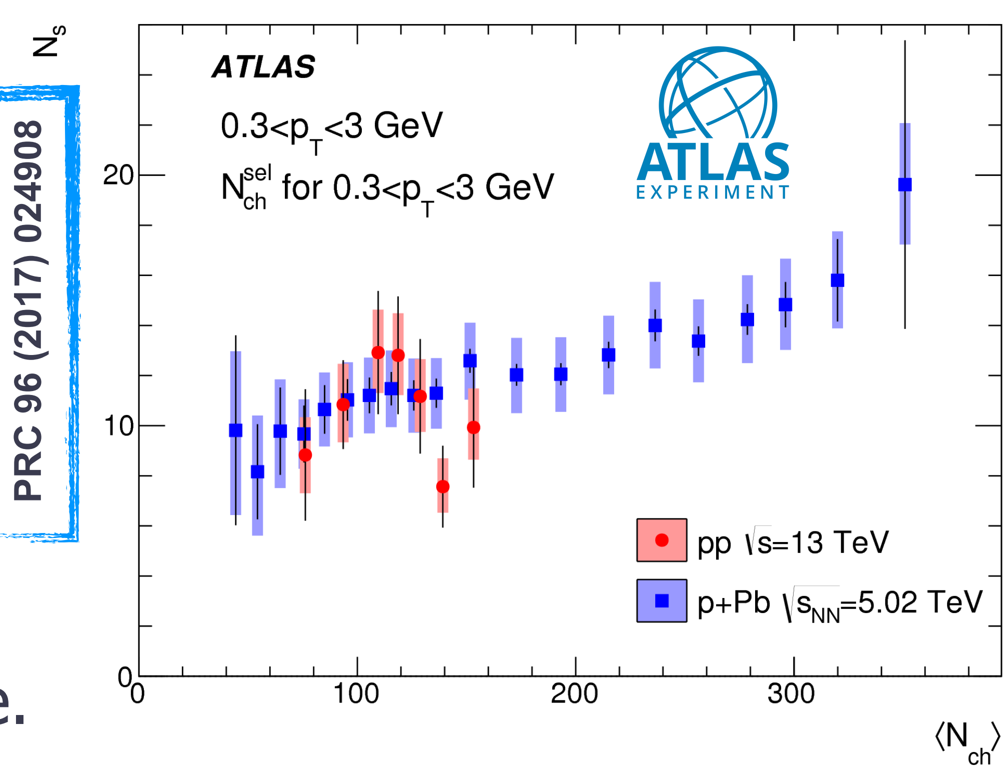
Multi-particle elliptic flow

PLB 765 (2017) 193



- In p-p, like in p-Pb and Pb-Pb, $v_2\{4\} \approx v_2\{6\}$
  - strong evidence for the collective nature of the long-range correlations observed in p-p collisions
- Only in p-p $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$
  - In hydrodynamic models $\frac{v_2\{4\}}{v_2\{2\}} = \left(\frac{4}{3+N_s}\right)^{1/4}$
  - smaller number of initial fluctuating sources that drive the long-range correlations in the final state.

PRC 96 (2017) 024908

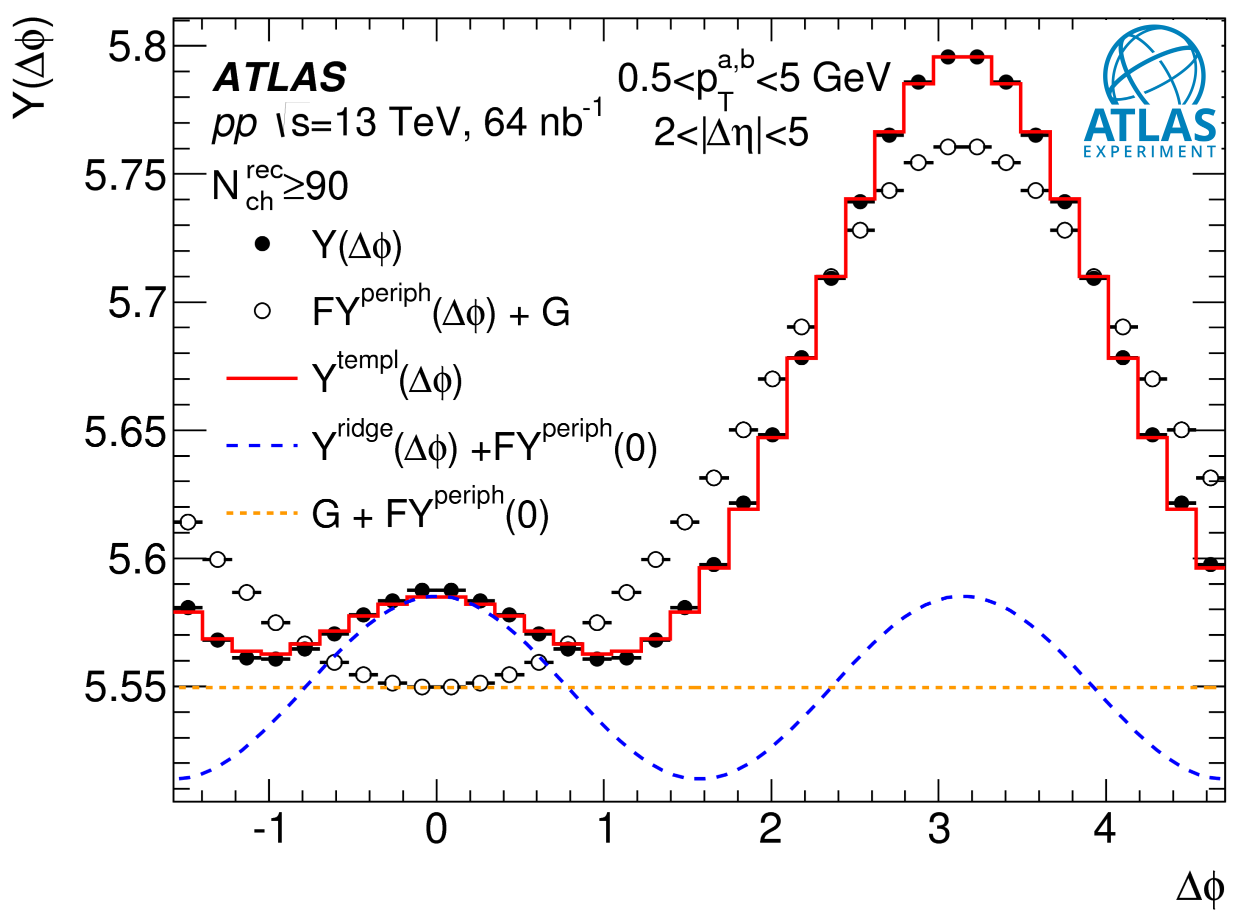


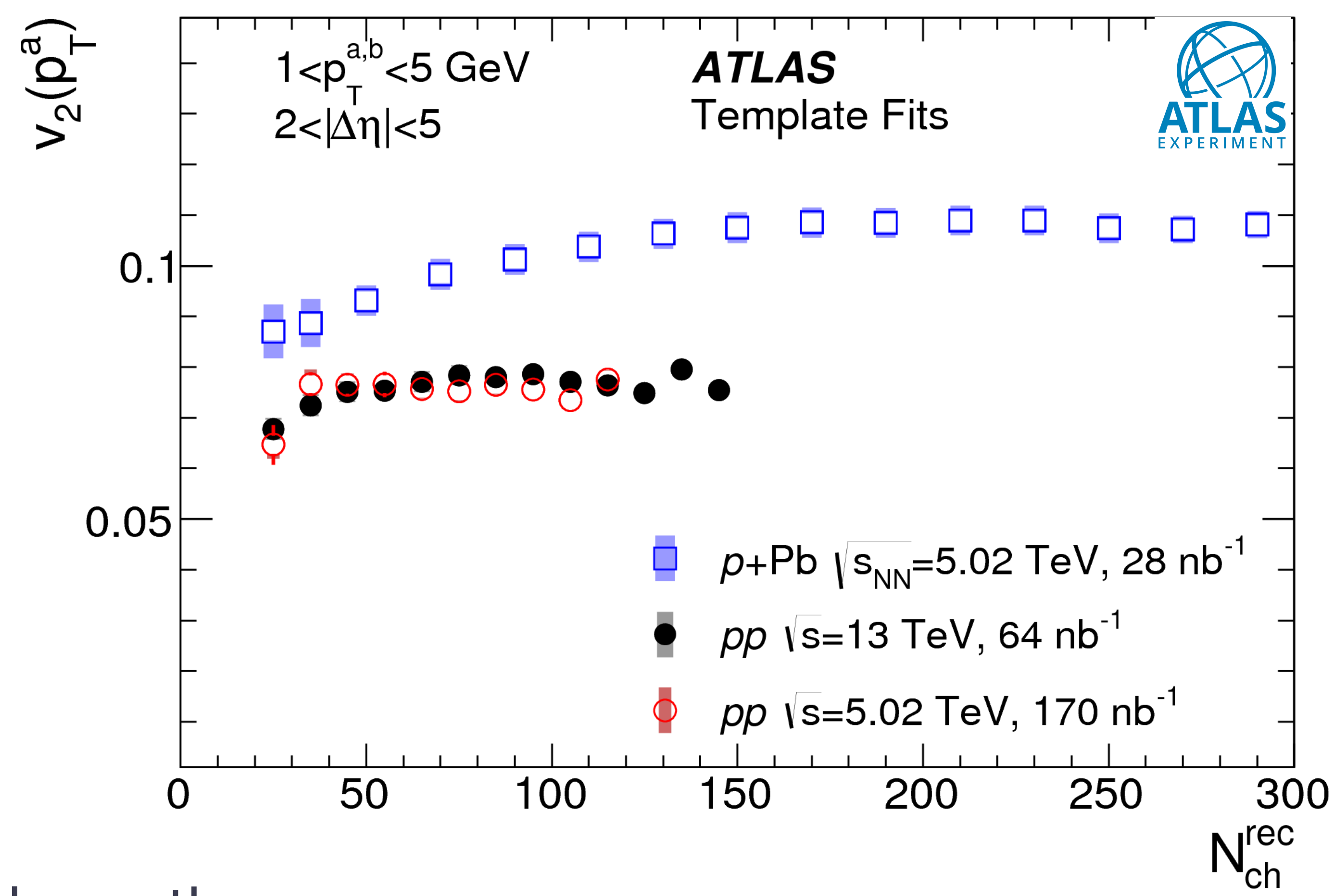
- **Question: Are non-flow effects correctly understood in p-p collisions?**

Template-fits Method

- Developed by Atlas to separate the ridge from other sources of angular correlation, such as di-jets.

$$Y^{\mathrm{templ}}(\Delta\phi) = Y^{\mathrm{ridge}}(\Delta\phi) + F\,Y^{\mathrm{periph}}(\Delta\phi)$$

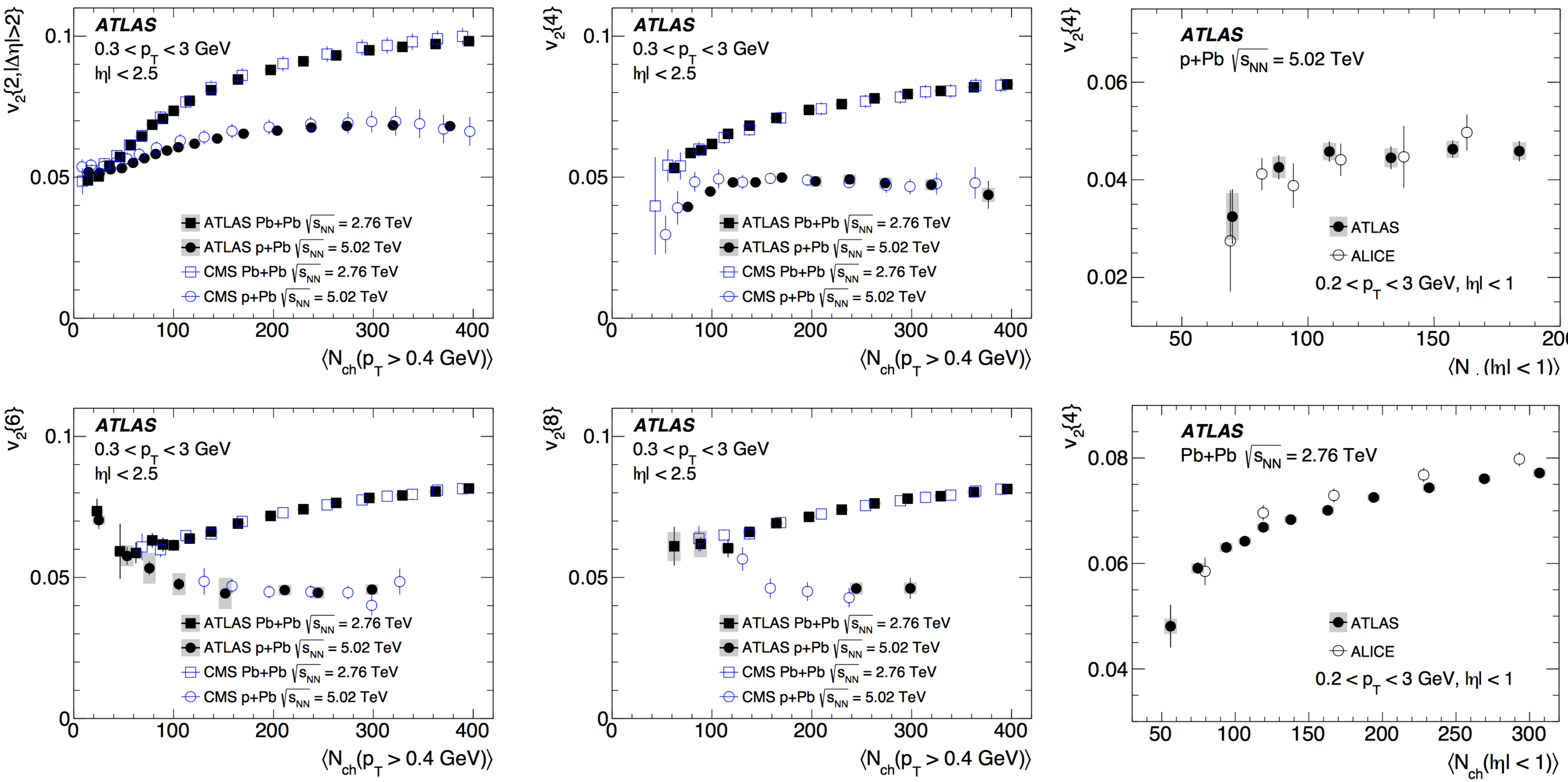




- p-Pb shows a clear N_{ch} dependence and v_2 is larger than p-p
- **v_2 in p-p has only a weak dependence on N_{ch} and no dependence on collision energy**

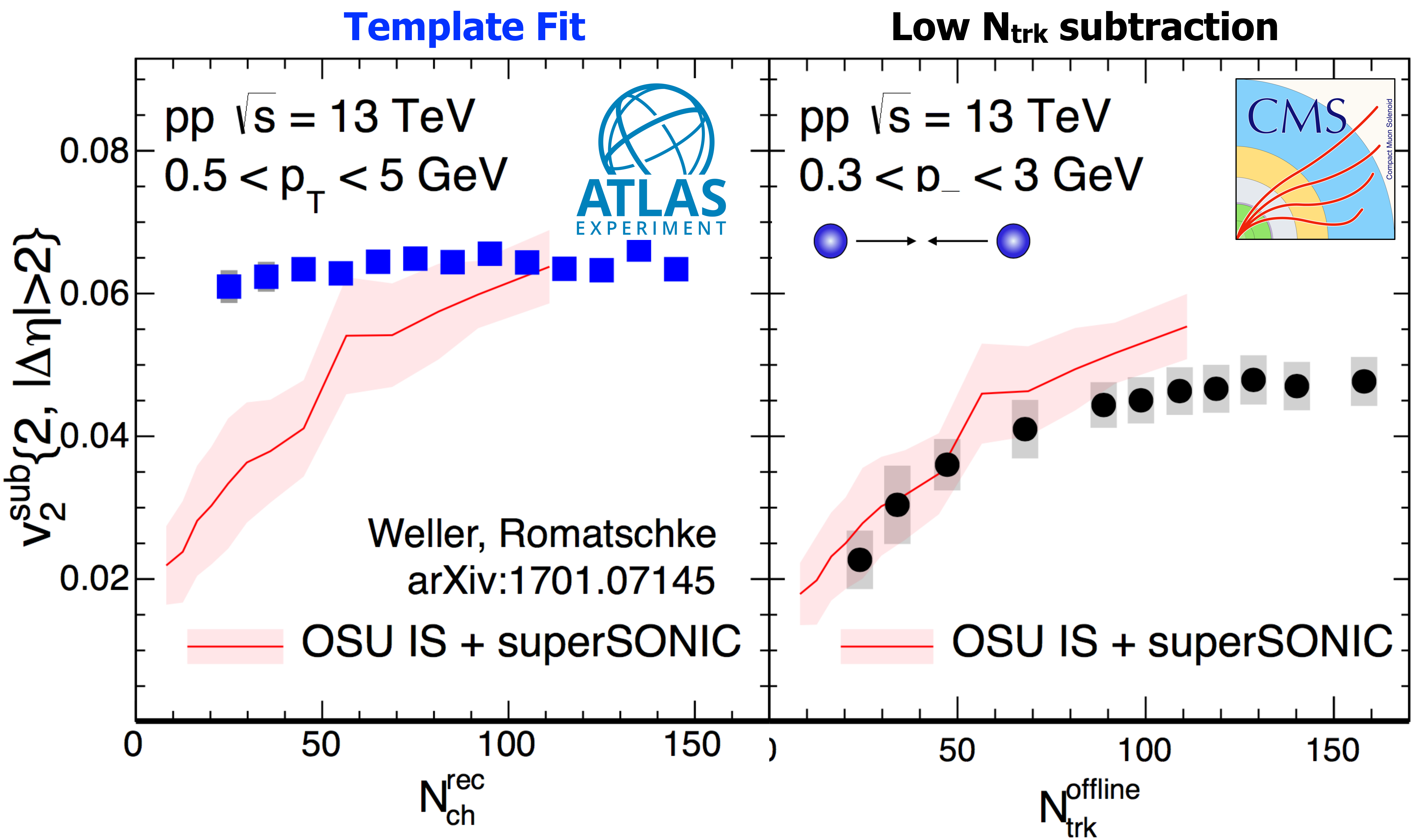
v_2 harmonics in p-Pb and Pb-Pb

Eur. Phys. J. C 77 (2017) 428



- Results for v_2 harmonics obtained with multi-particle cumulants **agree very well between ATLAS and CMS**
- **Similar compatibility of ATLAS and ALICE** for $v_2\{4\}$ in p-Pb collisions.
- For Pb-Pb collisions, the ALICE results on $v_2\{4\}$ are slightly above those measured by ATLAS.

v_2 in p-p: does collectivity turn off at low N_{ch}?

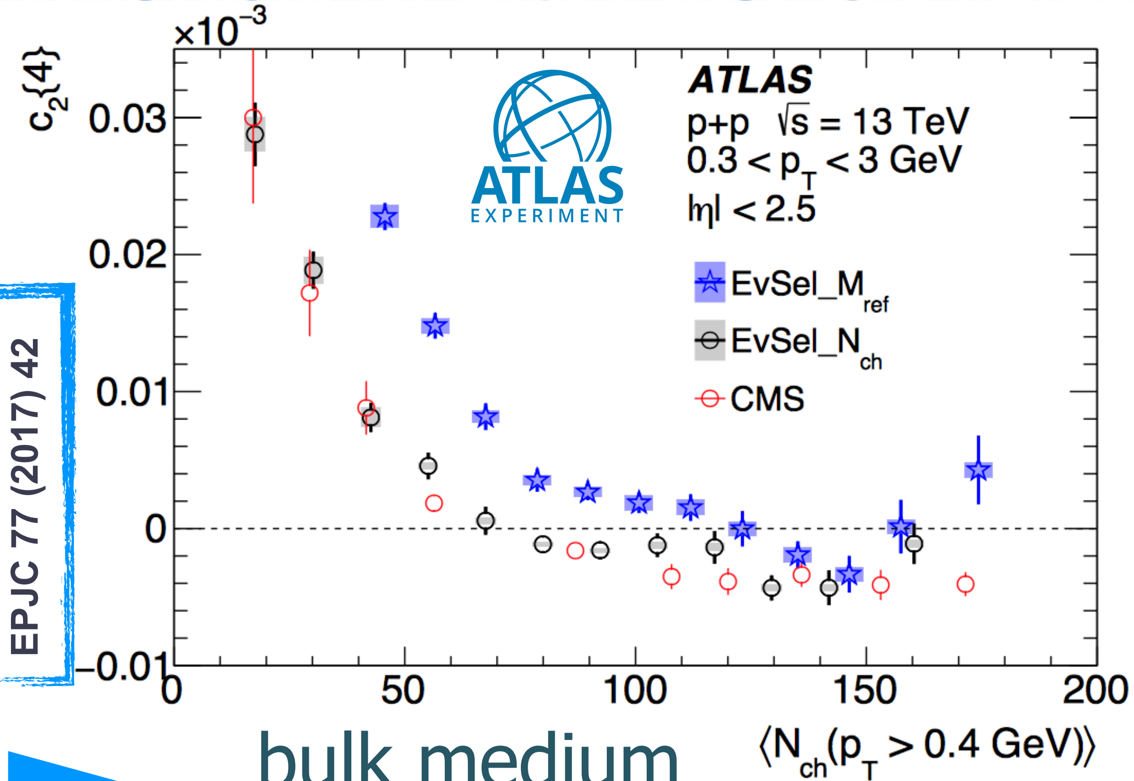


- Different correction methods lead to different shapes between CMS and ATLAS
- **Large differences in the interpretation when comparing to theory**

Flow and non-flow in p-p

- Non-flow particularly important in p-p collisions
  - **non-collective sources from di-jet** dominate the statistical properties of two- or multi-particle correlations
  - strong sensitivity to multiplicity class definition and multiplicity bin-width.

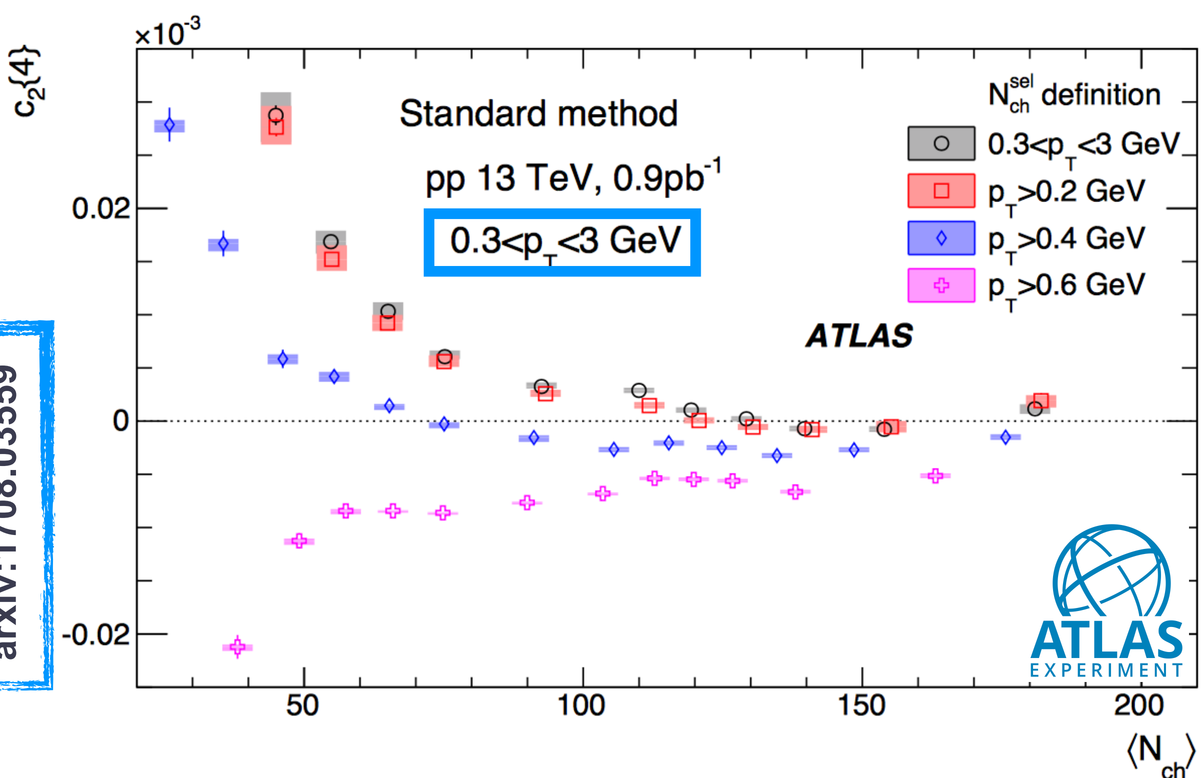
EPJC 77 (2017) 42

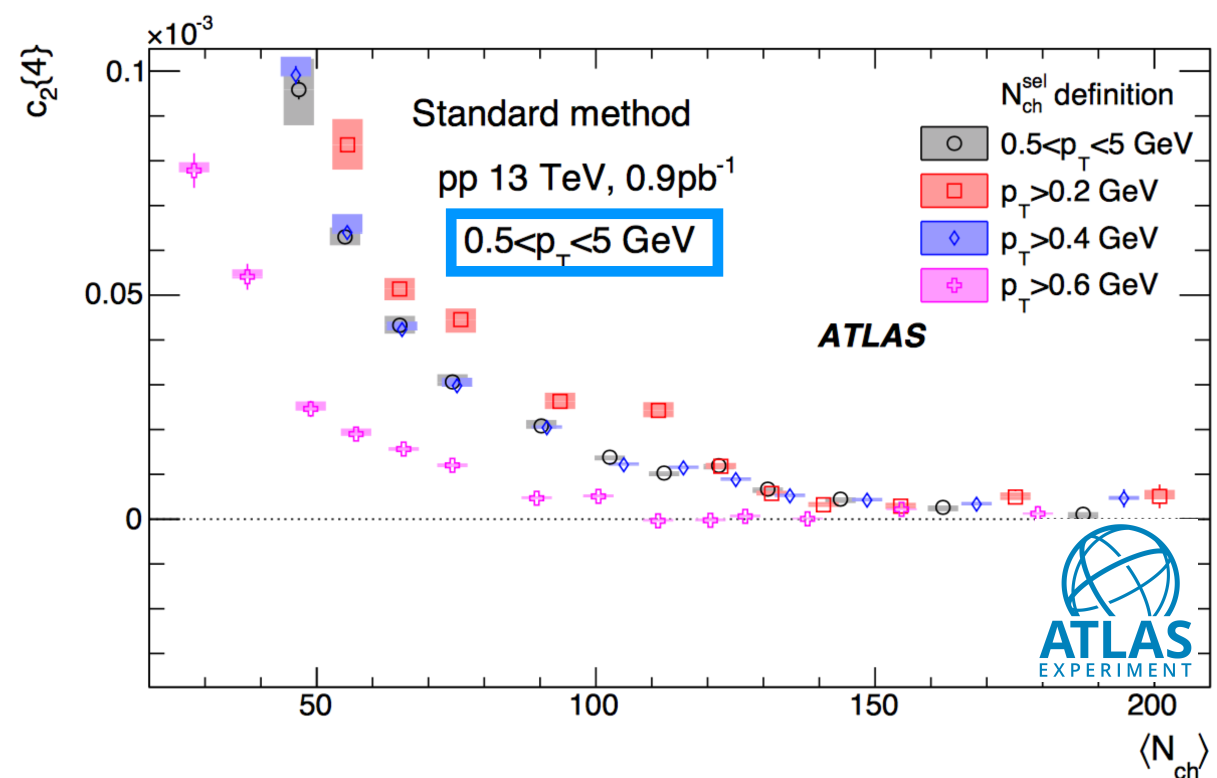


$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$ → not imaginary → bulk medium collective behaviour?

- $c_2\{4\}$ values change dramatically as the event-class definition is varied.

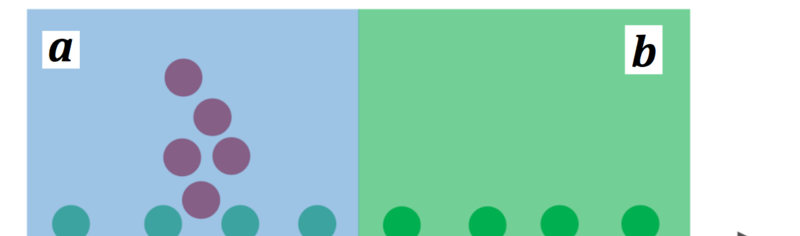
arxiv:1708.03559





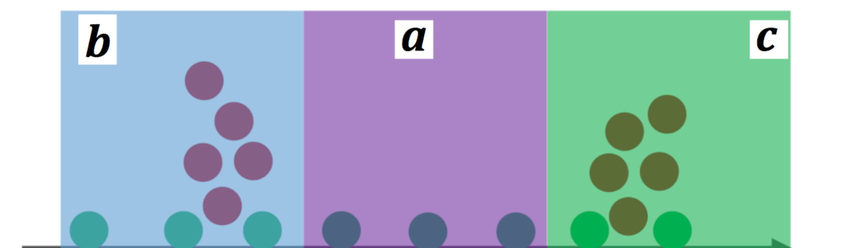
Suppressing non-flow: Subevent cumulants

- Azimuthal correlation (v_2) alone can't distinguish flow and non-flow.
- Improved cumulant method based on particles from different subevents in η ranges
- Pythia studies has shown it's effectiveness in suppressing non-flow arXiv:1701.03830



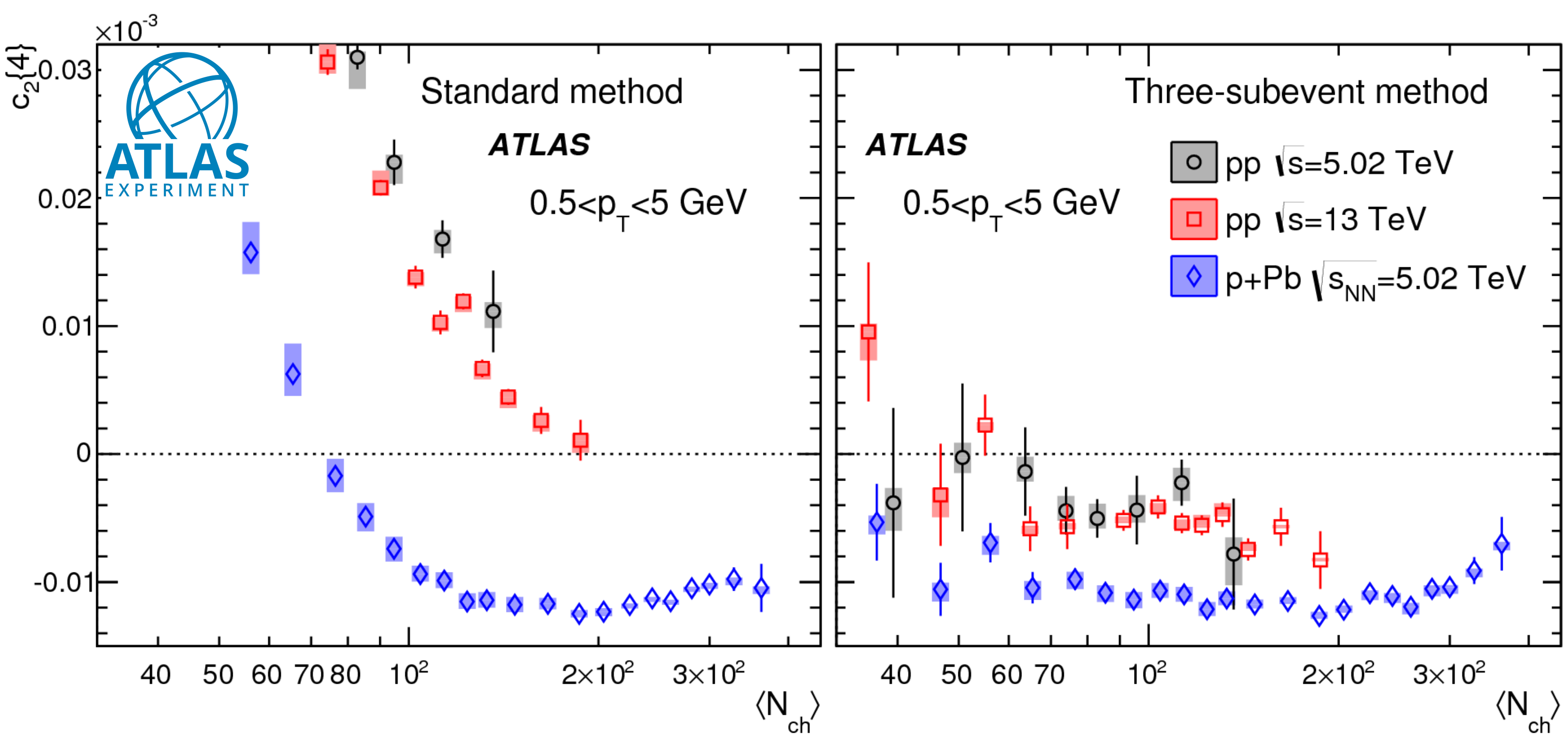
$$\left\langle \cos\left(\phi_1^a + \phi_2^a - \phi_3^b - \phi_4^b\right)\right\rangle$$

2 sub-event
removes intra-jet correlations



$$\left\langle \cos\left(\phi_1^a + \phi_2^a - \phi_3^b - \phi_4^c\right)\right\rangle$$

3 sub-event
removes inter-jet correlations

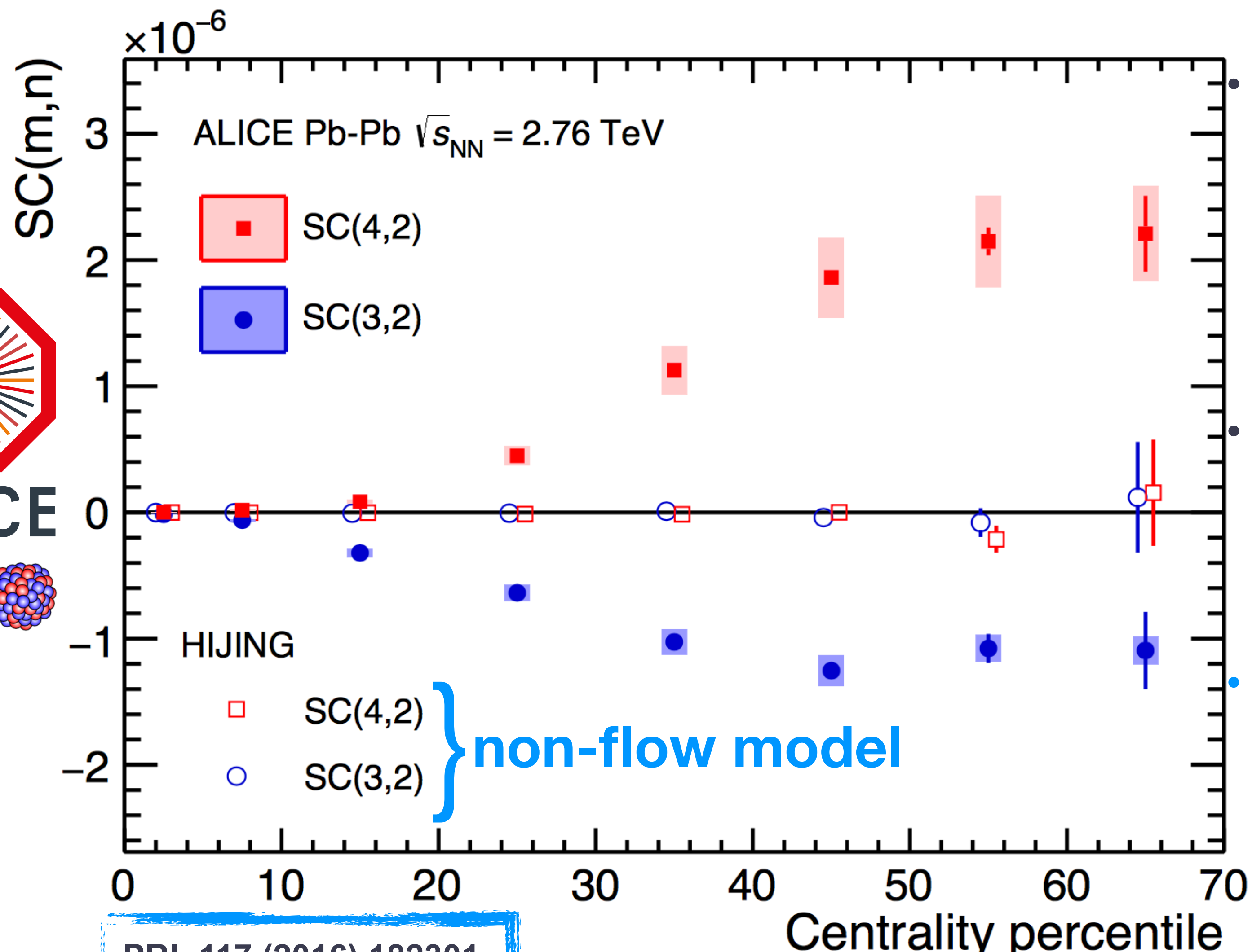


arXiv:1708.03559

- **$c_2\{4\}$ becomes negative in all datasets**
- $c_2\{4\}$ nearly independent of $\langle N_{ch}\rangle$
- **Direct evidence of collective flow in p-p and p-Pb collision**
- Starting at low multiplicity:
  $\langle N_{ch}\rangle \sim 40$

Suppressing non-flow: Symmetric Cumulants

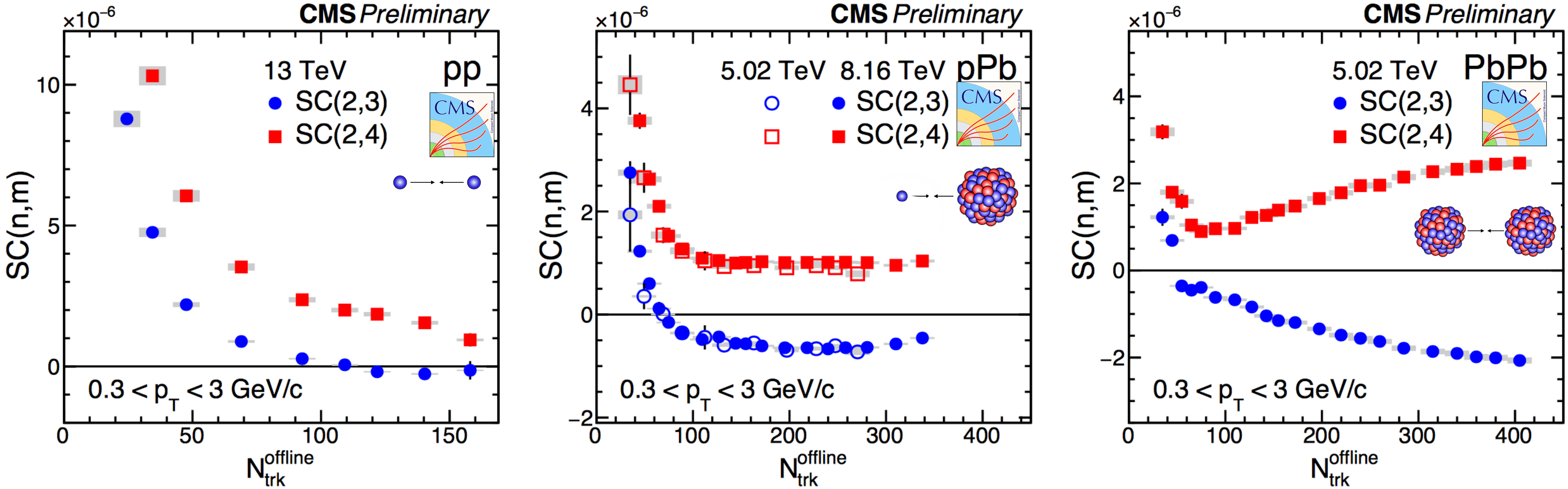
- First used by ALICE in Pb-Pb collisions: $SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$
- Describes the correlation between event-by-event fluctuations of magnitudes of two different harmonics
  - less sensitive to non-flow effects
  - improve treatment of systematics



PRL 117 (2016) 182301

- **SC(4,2) >0**
  - v_2 and v_4 are correlated: $v_2 > \langle v_2 \rangle \Rightarrow v_4 > \langle v_4 \rangle$ in an event
- **SC(3,2) < 0**
  - v_2 and v_3 are anti-correlated
- **Qualitatively similar shape from Hydrodynamical models**

Symmetric Cumulants in small systems

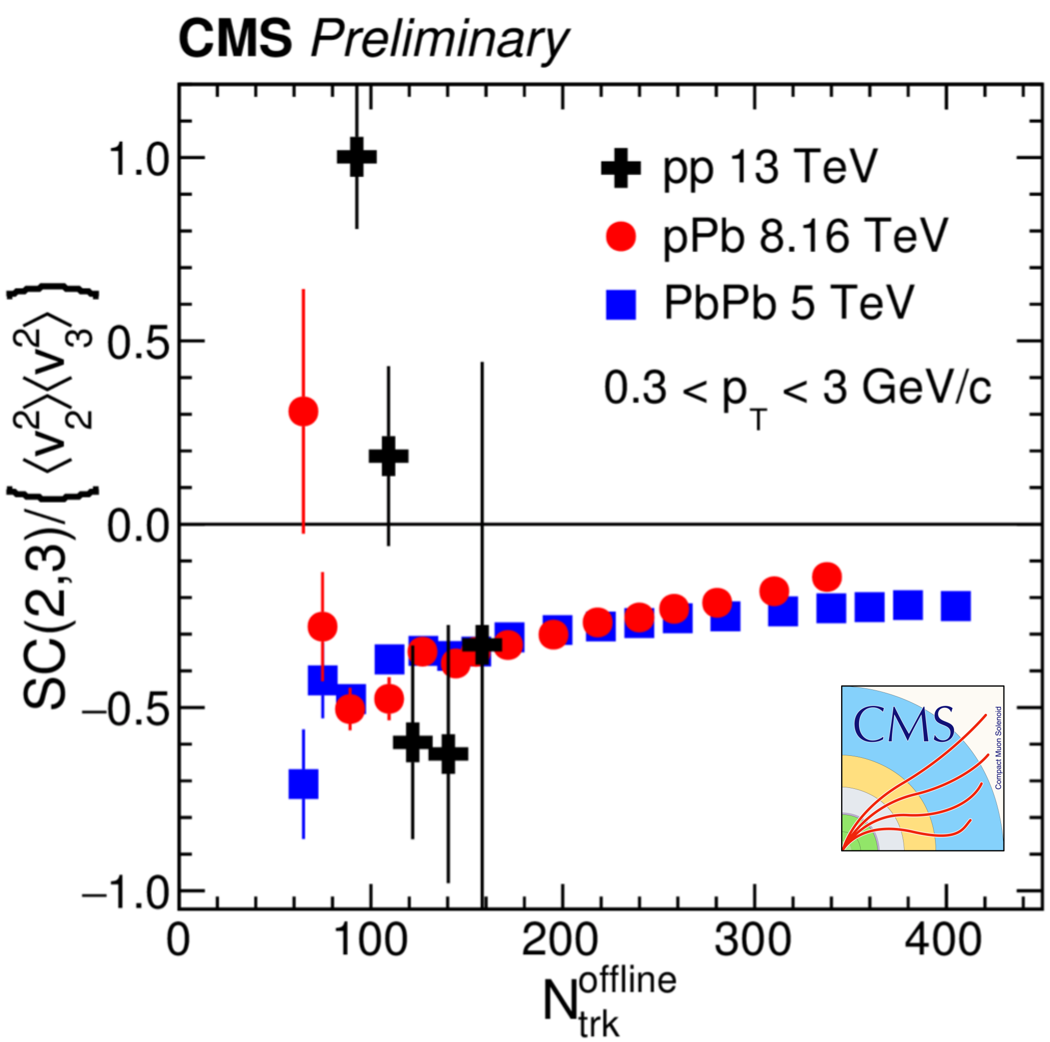


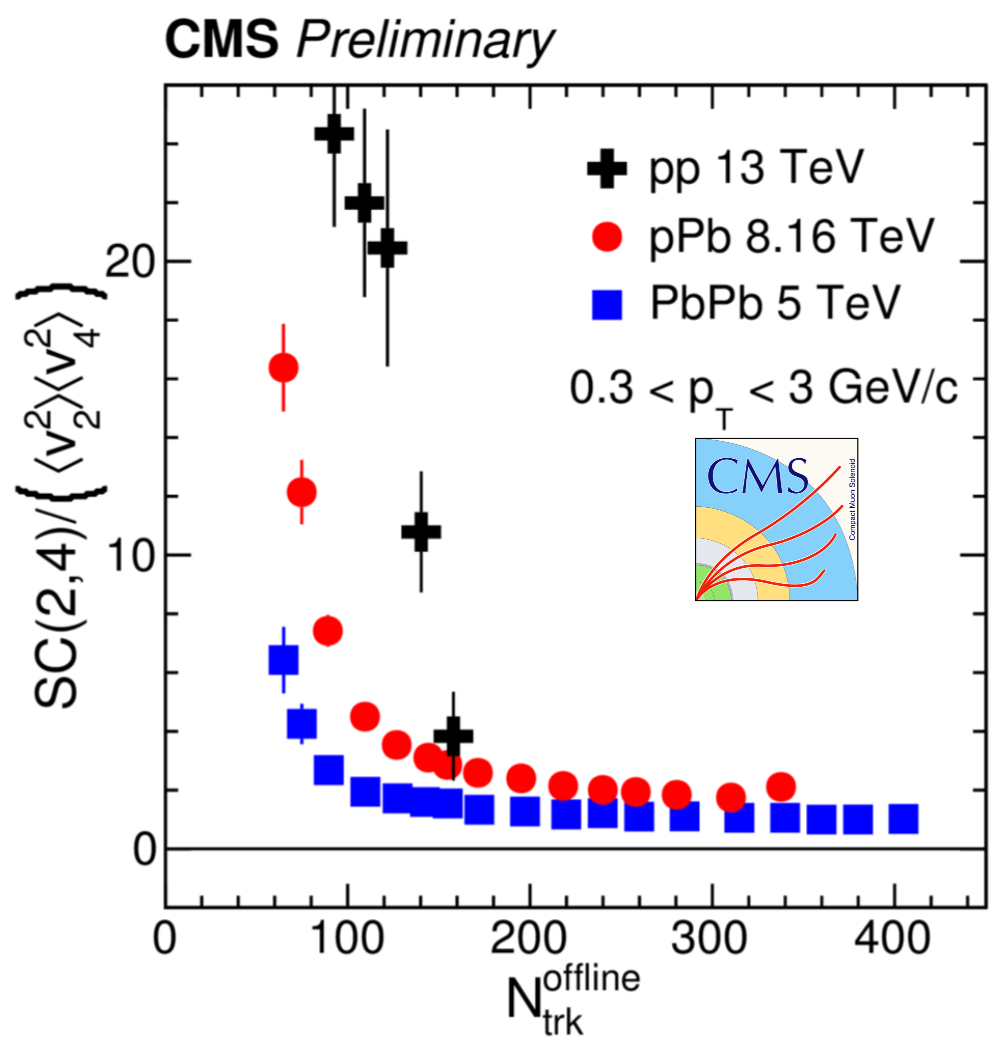
CMS-PAS-HIN-16-022

- **In p-p collisions**
  - both SC(2,3) and SC(2,4) **decrease with N_{ch}**
  - SC(2,3) compatible with remaining positive
- **In p-Pb and Pb-Pb**
  - **From N_{trk} > 60 clear negative values of SC(2,3)**
  - SC(2,4) are positive
  - At low N_{trk} both SC(2,3) and SC(2,4) diverge toward positive values, likely due to short-range correlations.
  - p-Pb values lower than Pb-Pb at high multiplicity
    - **Different magnitude of v_n harmonics?**

Normalised symmetric cumulants

CMS-PAS-HIN-16-022

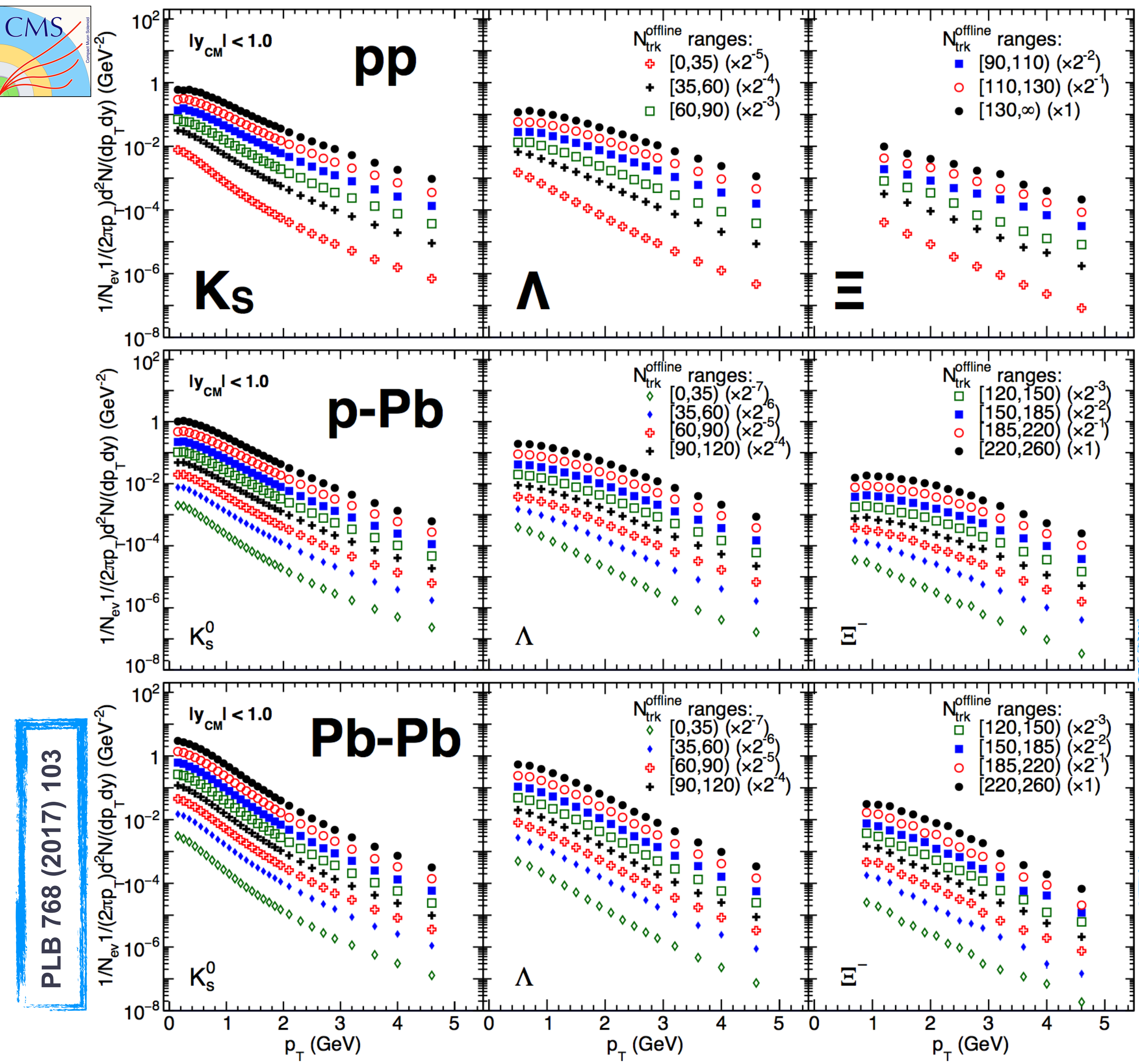




- SC(2,3) is linked to the nature of initial state fluctuations
- **Compatible values at high N_{ch}!**
- Valid also for p-p, with large uncertainties

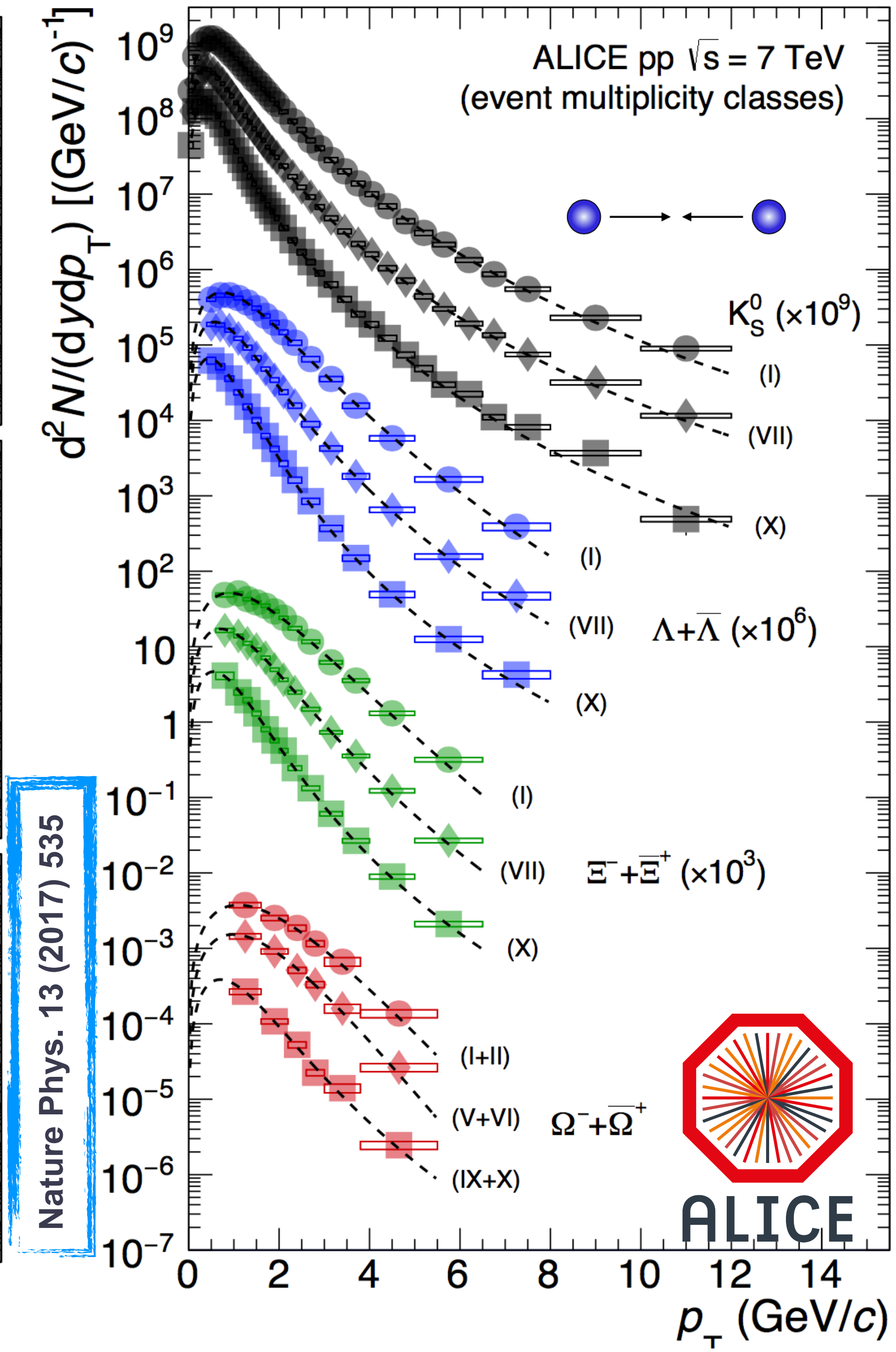
- System size dependence
  - **Larger values for smaller system**
- SC(2,4) sensitive to initial and final states
- Difference between p-Pb and Pb-Pb can come from
  - different contribution of initial state correlations
  - transport properties of the medium

Transverse Momentum Distributions



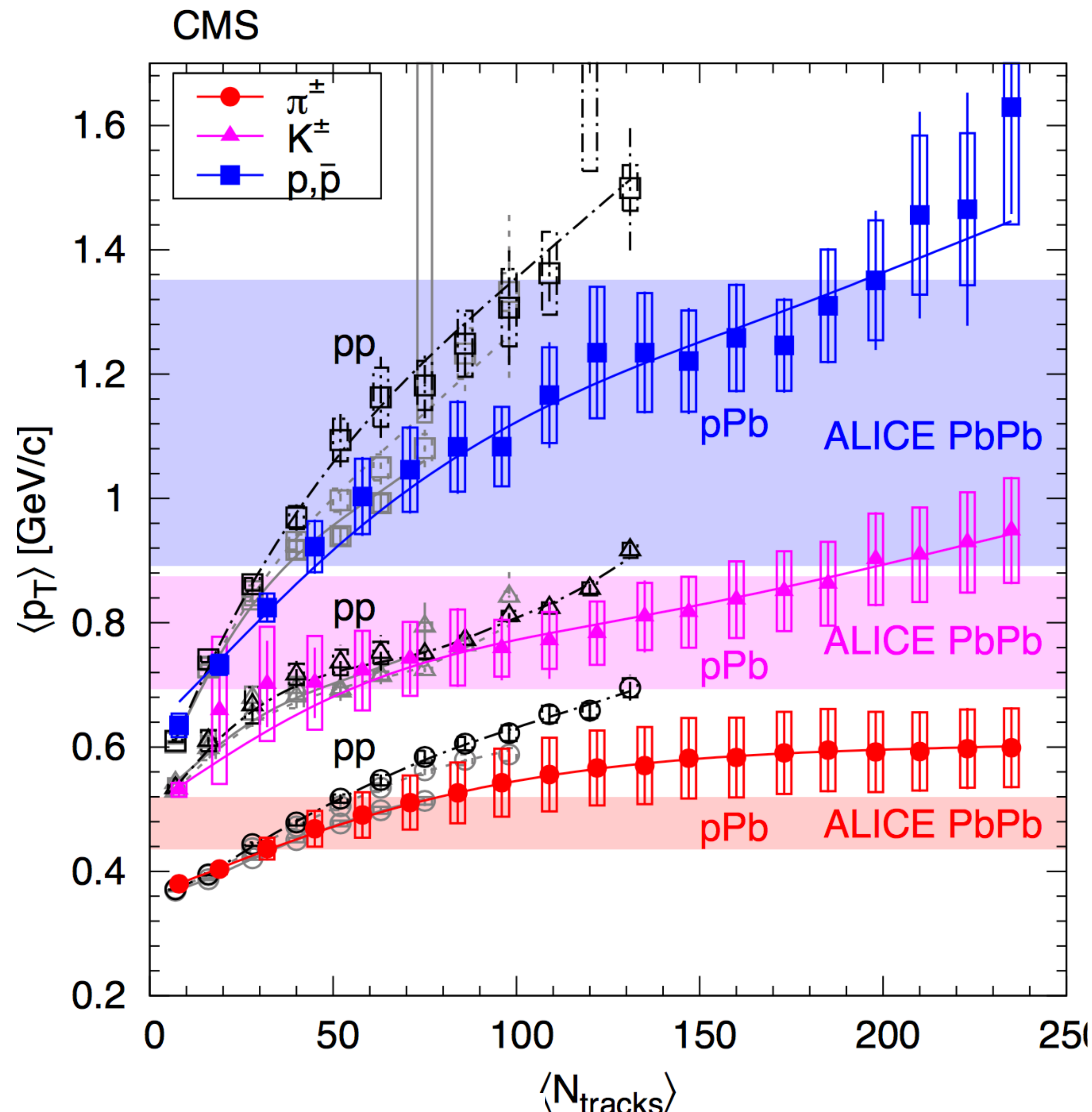
PLB 768 (2017) 103

Nature Phys. 13 (2017) 535



- Wide range of p_T spectra of identified particles in different collisions systems

Mean Transverse Momentum



pp (0.9, 2.76, 7 TeV) EPJC 72 (2012) 2164] arXiv:1706.10194 (hep-ex)

pPb (5.02 TeV) EPJC 74 (2014) 2847]

PbPb (2.76 TeV, periph to central bands)

(Phys Rev C 88 (2013) 044910

- $\langle p_T \rangle$ shows a dependence on N_{ch}
  - **almost independent of √s**
- √s-evolution provides information on the **"saturation scale" (Q_{sat})** of the gluons in the proton
- Connecting Q_{sat} to the impact parameter of the hadronic collision, give a natural dependence of $\langle p_T \rangle$ on the multiplicity
- p-Pb behaves very similarly to p-p for **$N_{ch} \lesssim 40$** (peripheral collisions)
- Highest multiplicity p-Pb and p-p interactions yield higher $\langle p_T \rangle$ than in central Pb-Pb collisions
  - Even the most central Pb-Pb collisions contain a mix of soft and hard
  - In case of p-p or p-Pb specifically the most violent interactions are selected

Blast Wave Fits

- Blast Wave is a hydro-inspired parameterisation

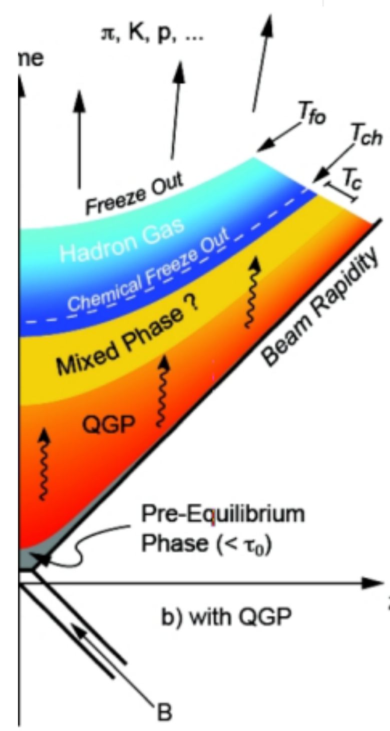
Schnedermann et al., PRC 48 (1993) 2462

$$E\frac{d^3N}{dp^3} \propto \int_0^R m_T\, I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right) r\,dr$$

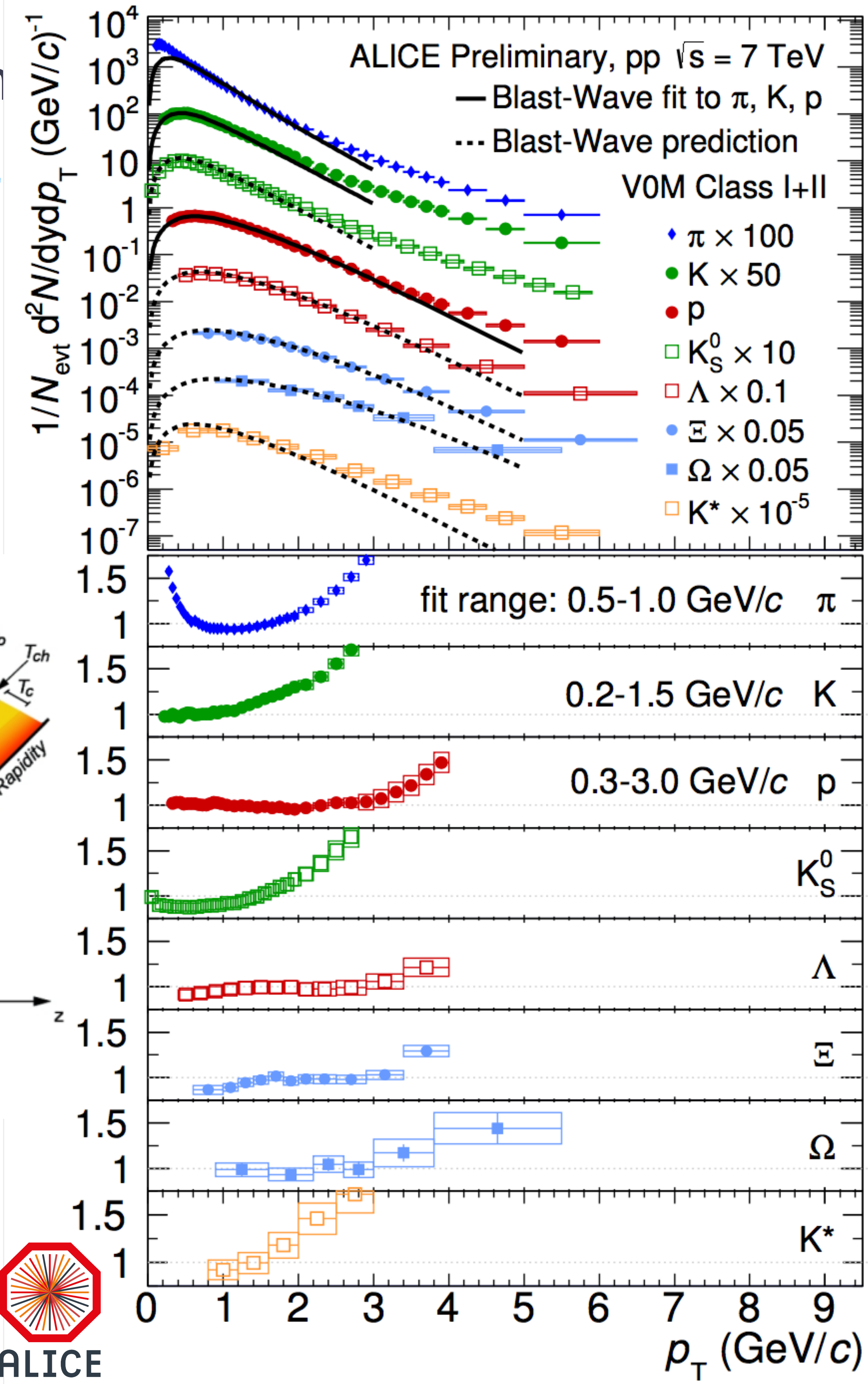
$$m_T = \sqrt{{m_0}^2 + {p_T}^2} \quad \rho = \tanh^{-1}\beta_T \quad \beta_T = \beta_s\left(\frac{r}{R}\right)^n$$

- **Three free freeze-out parameters**

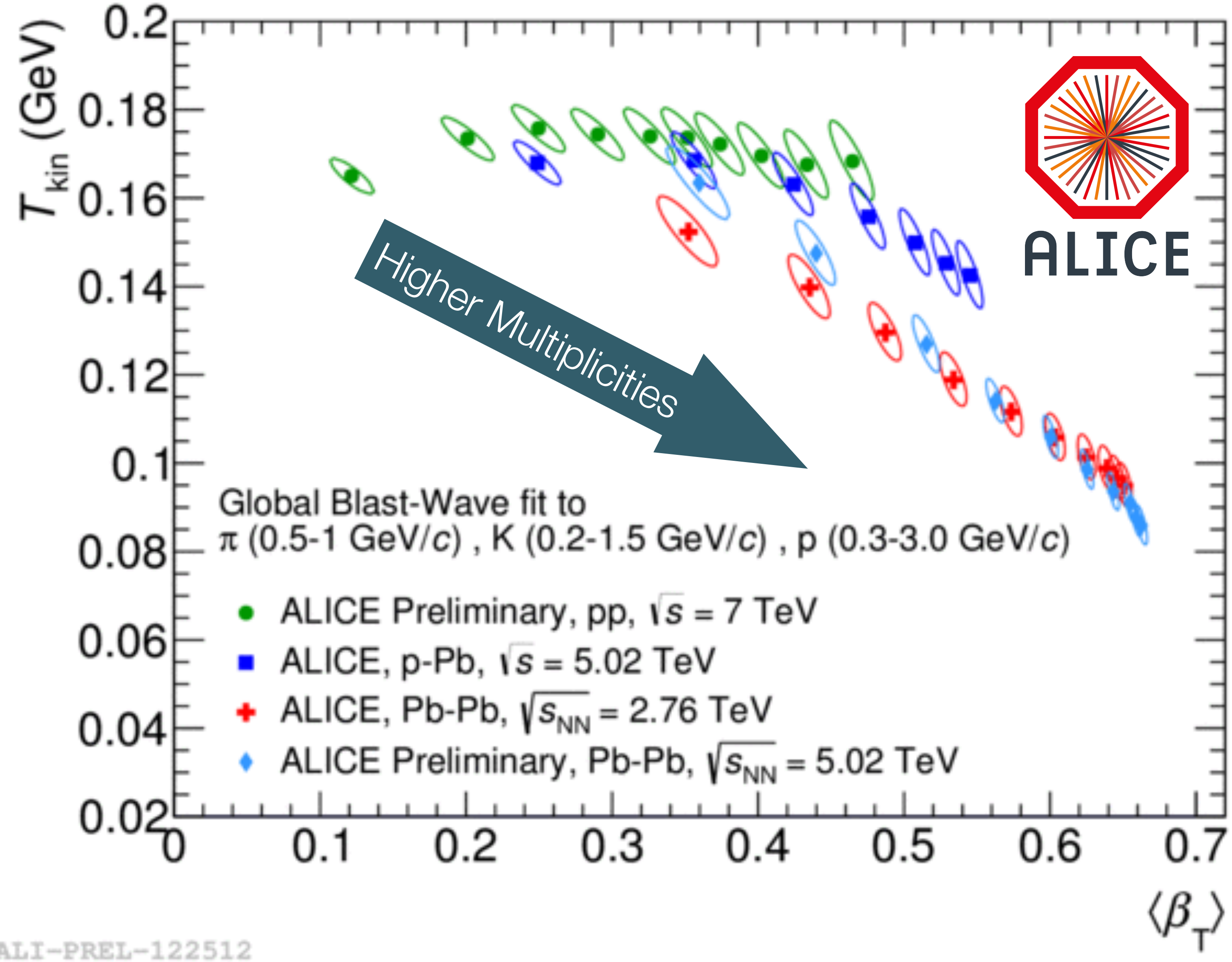
1. Freeze out temperatures T_{kin}
2. average transfer velocity $\langle\beta_T\rangle$
3. exp. of the velocity profile n

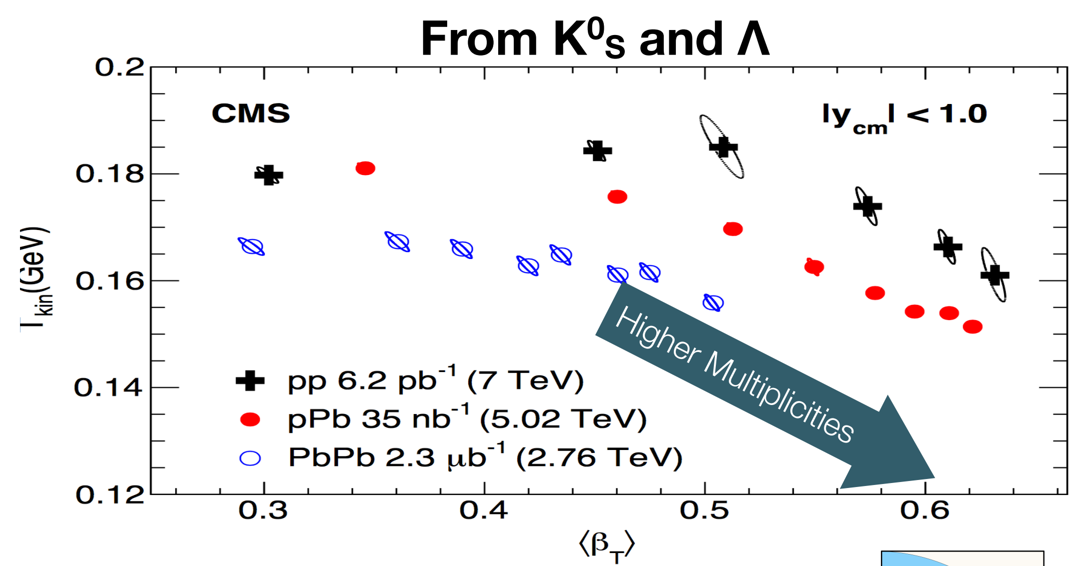


- Fit to π, K, p used to predict Λ, Ξ, Ω shape at low p_T



Blast Wave Parameters



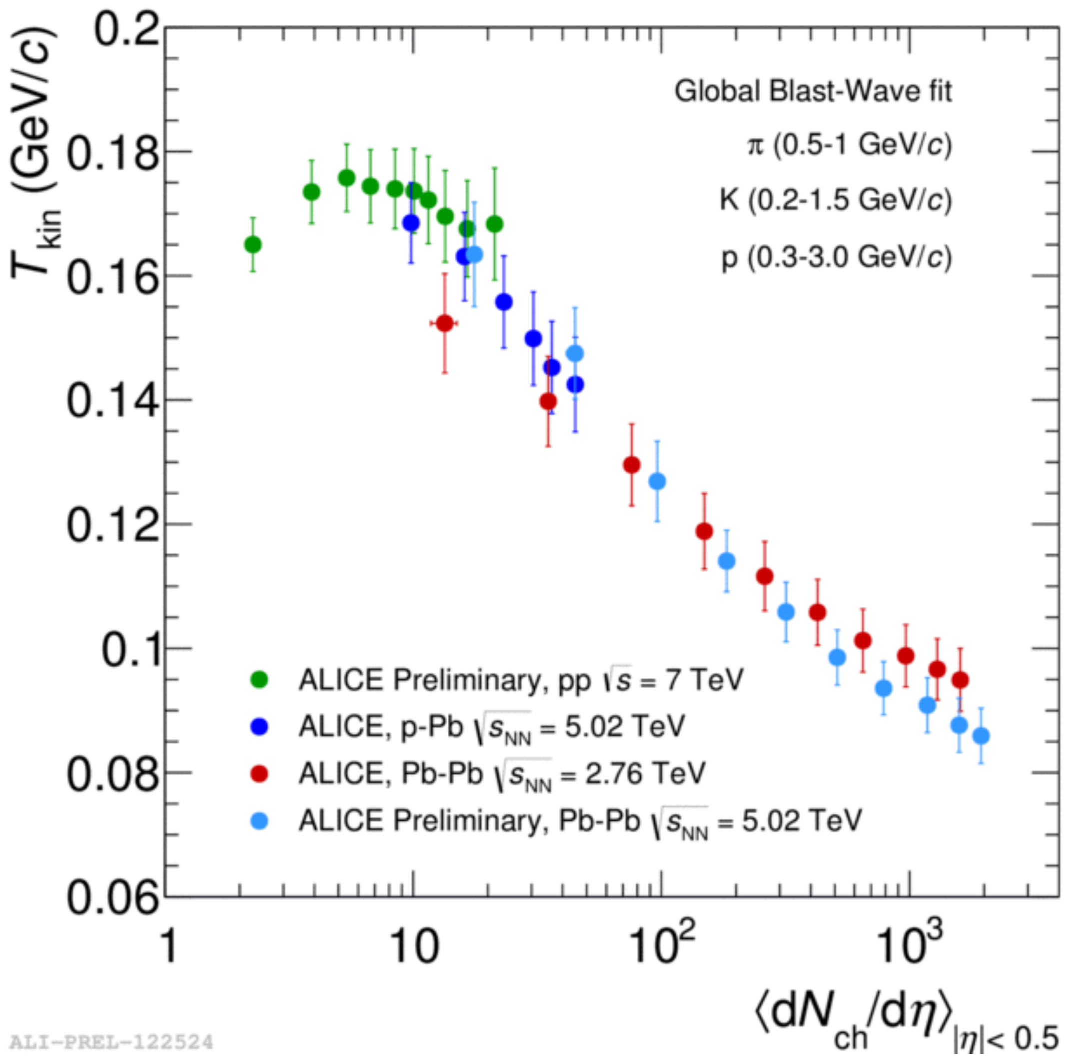


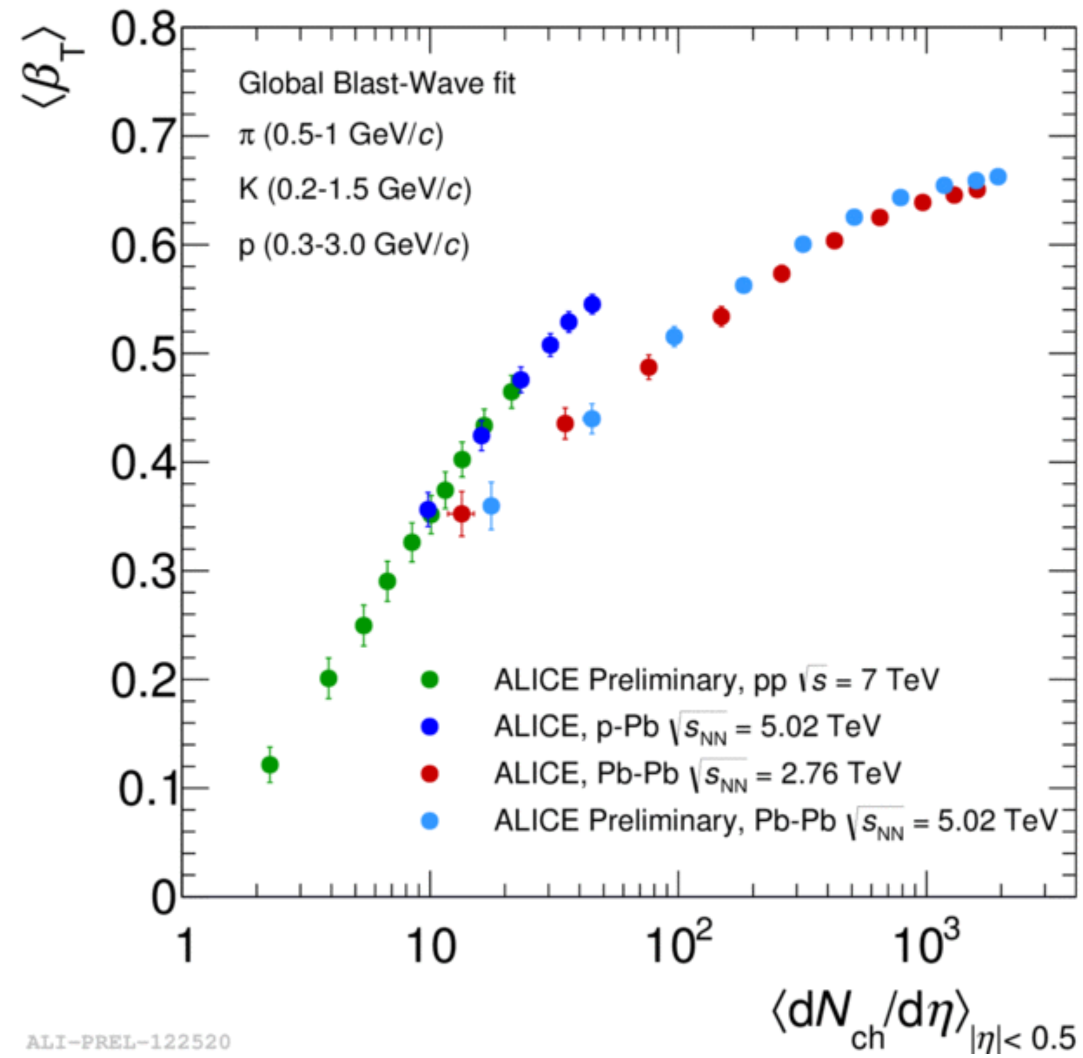
PLB 768 (2017) 103

- Studied by ALICE and CMS for different species
- Parameters depends on the fitting range
- Precise meaning of the T_{kin} and $\langle\beta_T\rangle$ parameters is model dependent: **Not to be interpreted literally!**

Blast Wave Parameters vs N_{ch}

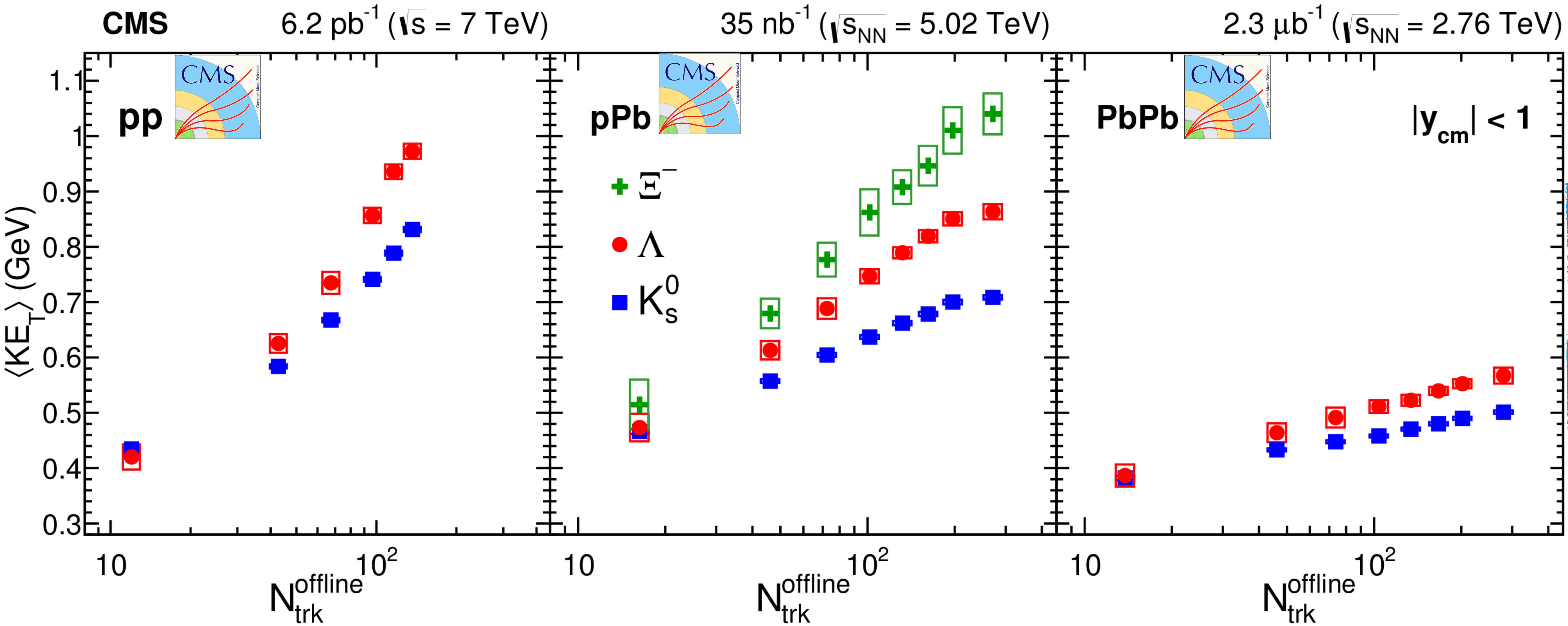
ALICE





- Comparing the parameters of different systems at similar dN_{ch}/η
  - **T_{kin}** values are similar
  - **$\langle \beta_T \rangle$** larger for small systems:
    - **larger radial flow in small system as consequence of stronger gradients**

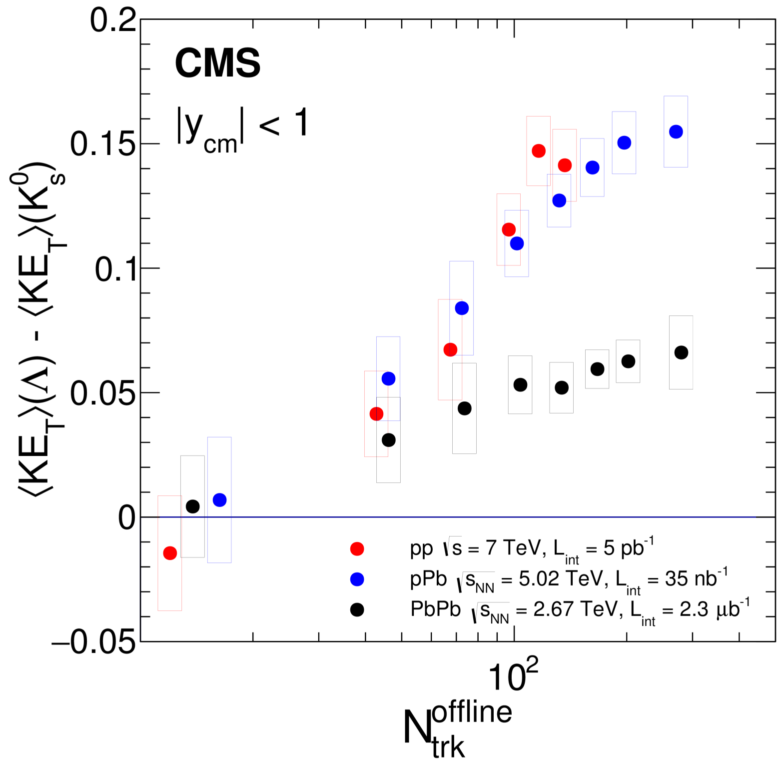
Average transverse kinetic energy



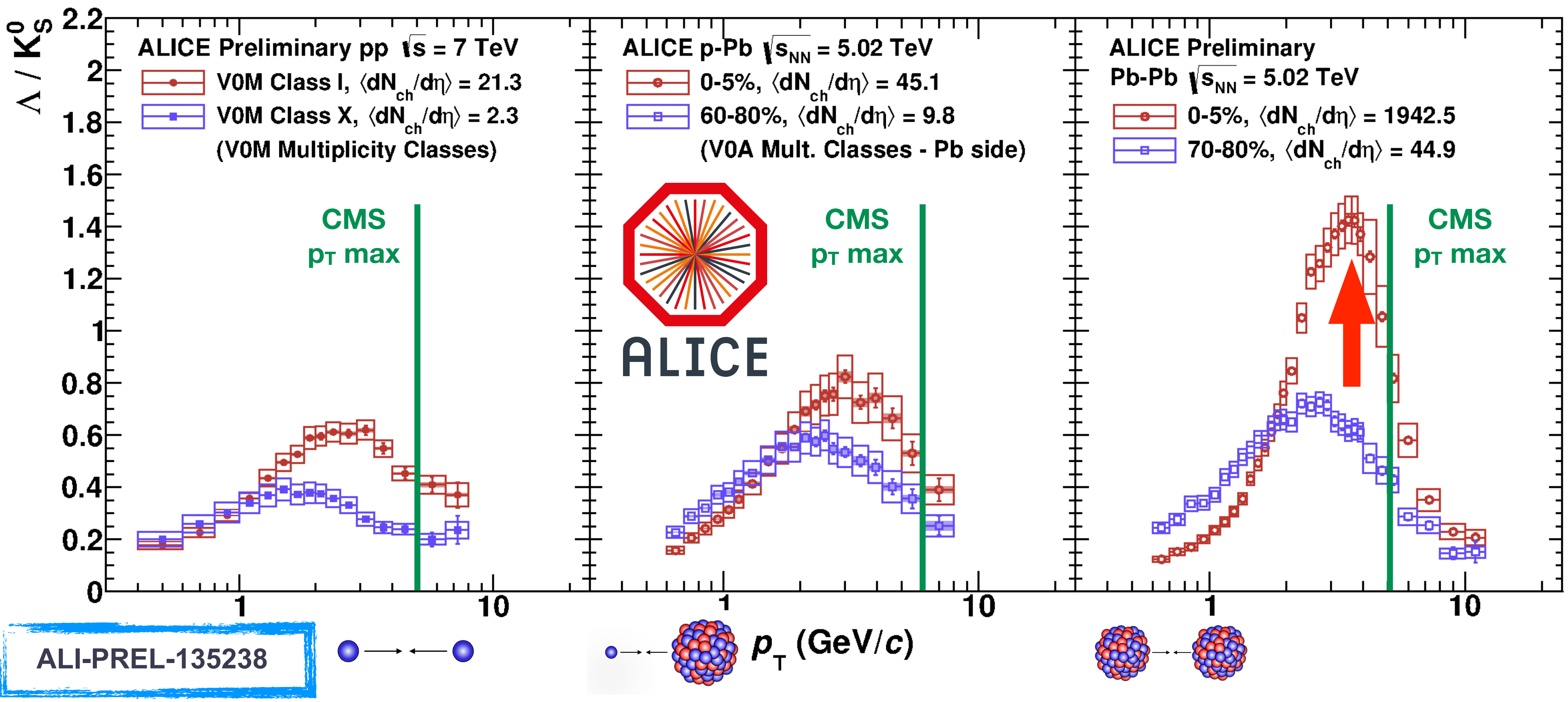
PLB 768 (2017) 103

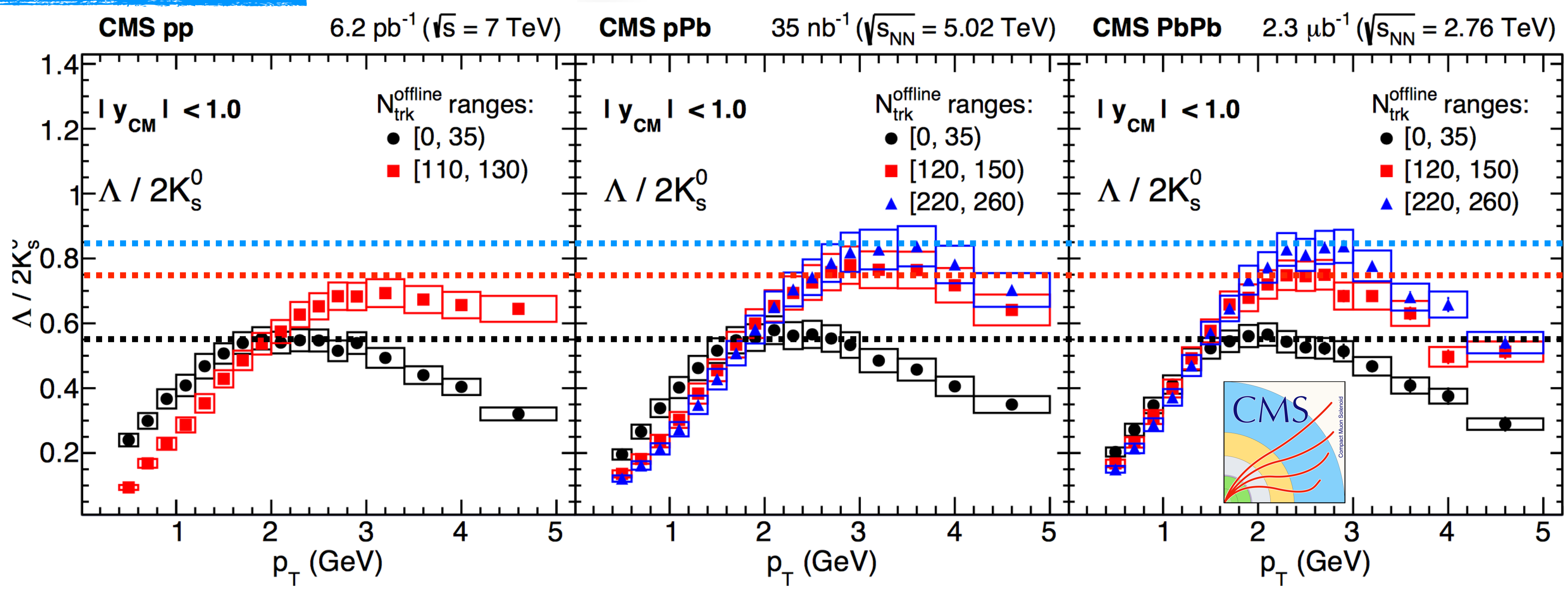
$$KE_T = m_T - m_0 = \sqrt{p_T{}^2 - m_0^2} - m_0$$

- **Similar values at low multiplicity!**
- Increase is faster for heavier particles
  - value at a given N_{ch} proportional to particle mass
  - In Pb-Pb collision explained with the onset on radial flow
  - Higher absolute values in p-p and p-Pb



Baryon Enhancement





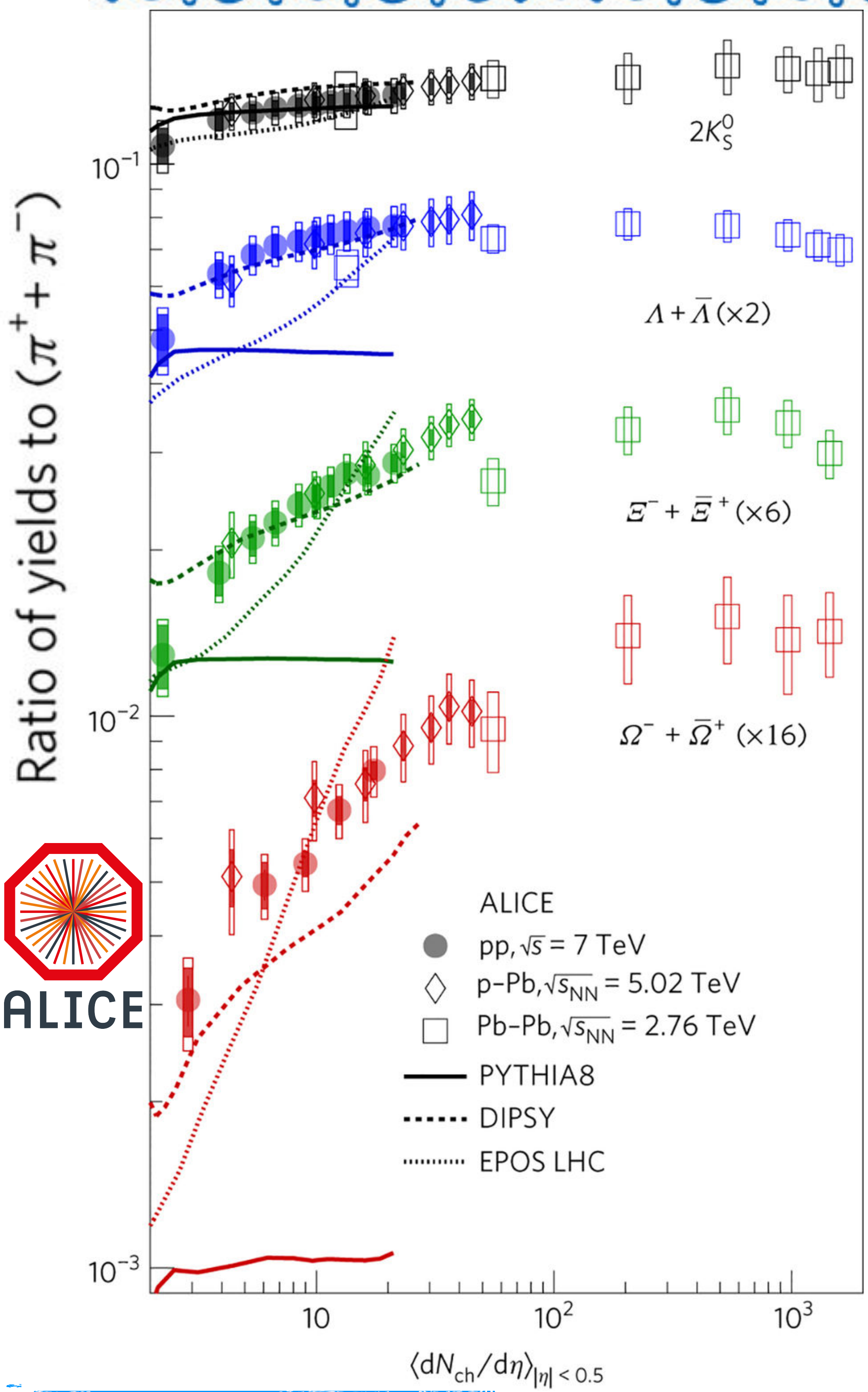
Three regions:

- **low-p_T**: depletion
- **mid-p_T**: enhancement: boosts of heavier particles from radial flow?
- **high-p_T**: unchanged, no effect of N_{ch} on hard fragmentation

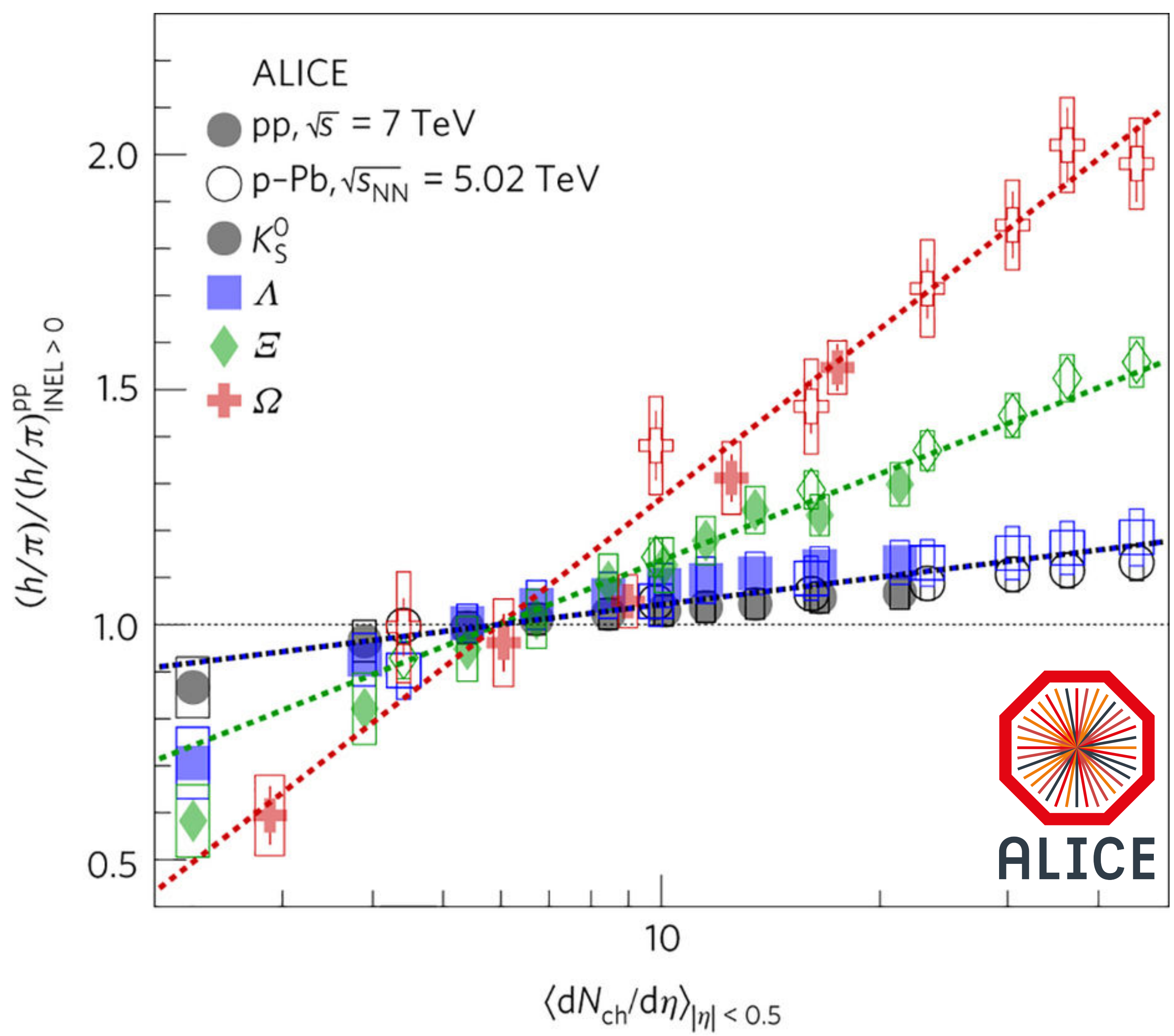
- **p_T maximum** has **similar value** for all collision processes in the same multiplicity range.

PLB 768 (2017) 103

Strangeness Enhancement

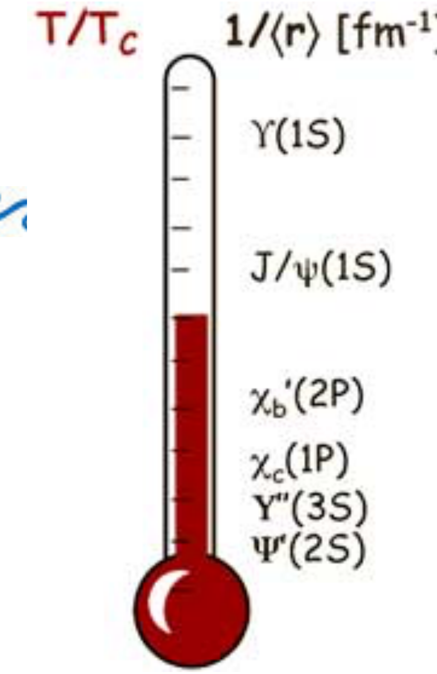


- One of the first proposed signs for QGP
- **Enhancement is driven by the strangeness, not by the mass of the particle**



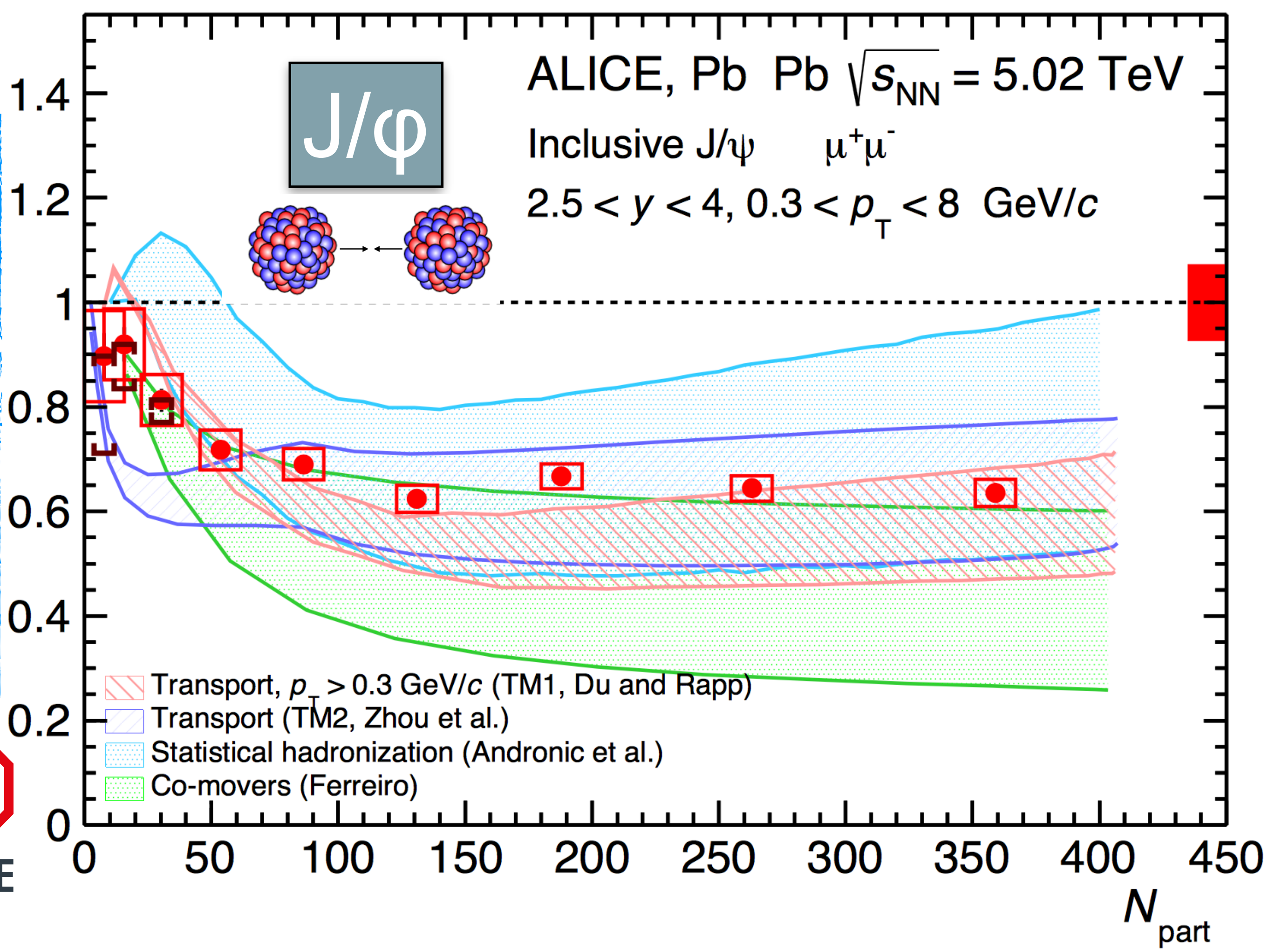
Nature Phys. 13 (2017) 535-539

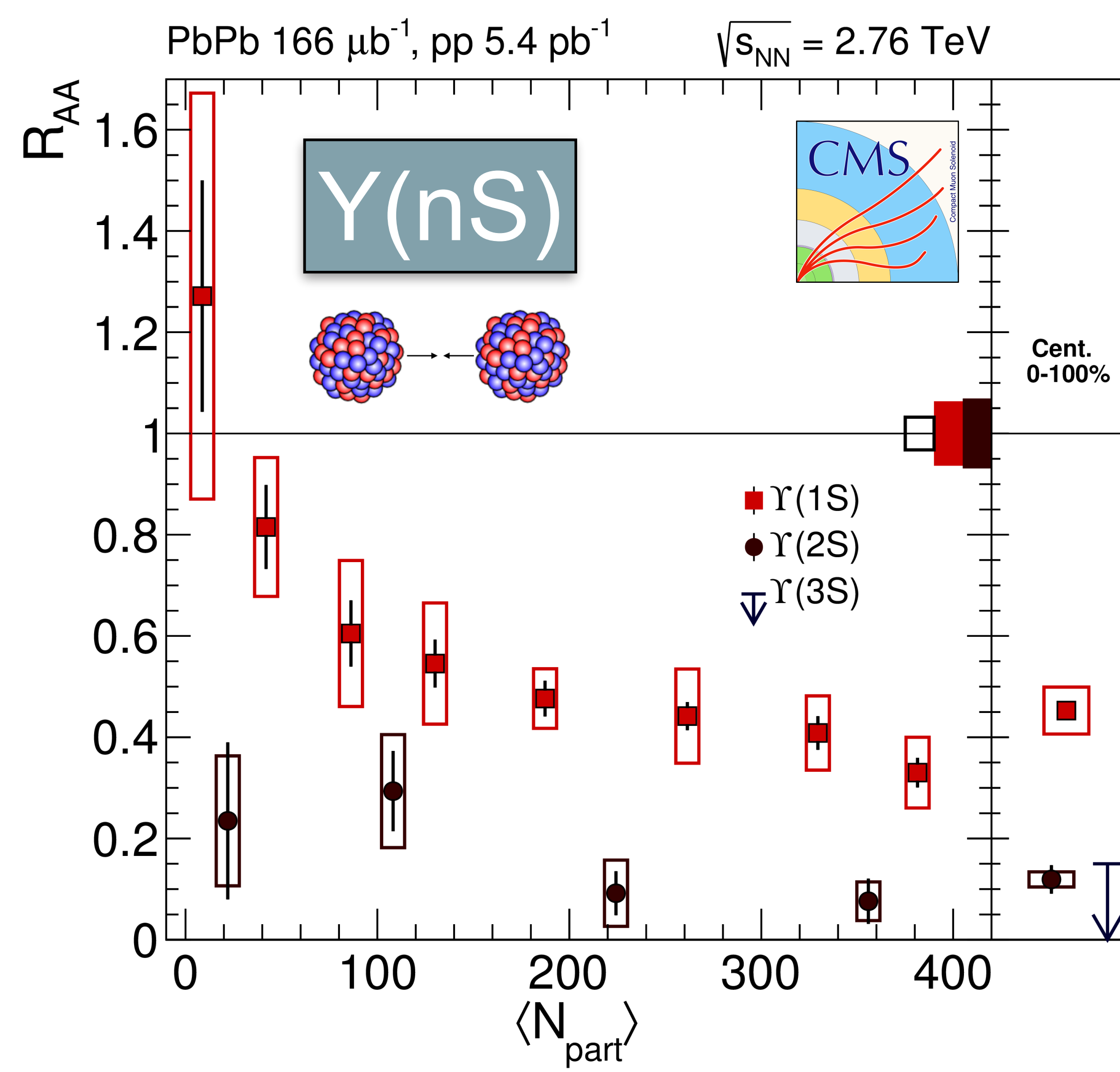
Quarkonia Production



- Quarkonia production important in understanding QGP formation
  - **color screening from a deconfined medium**
  - suppression linked to the bounding energy

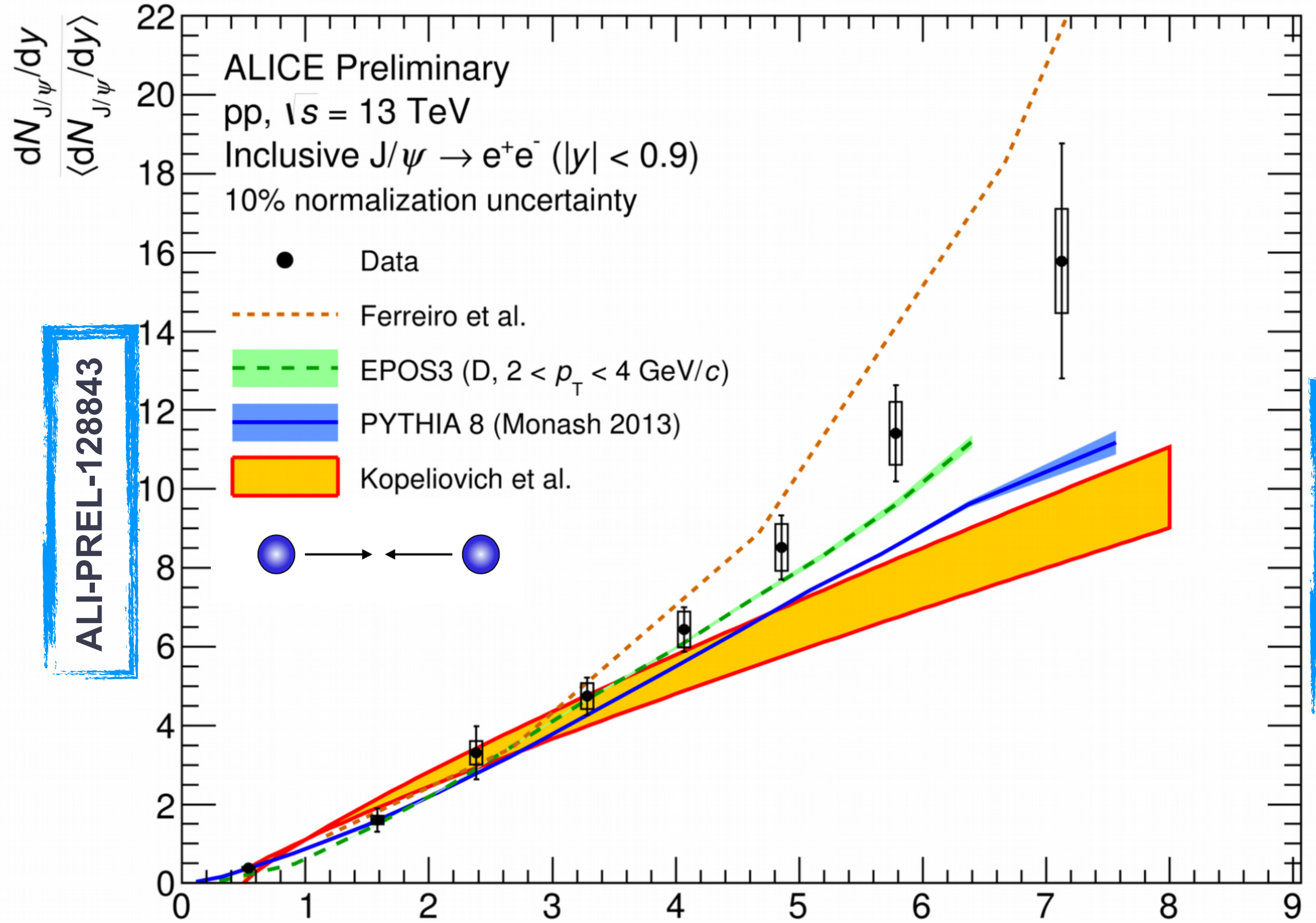
Phys. Lett. B 766 (2017) 212-224



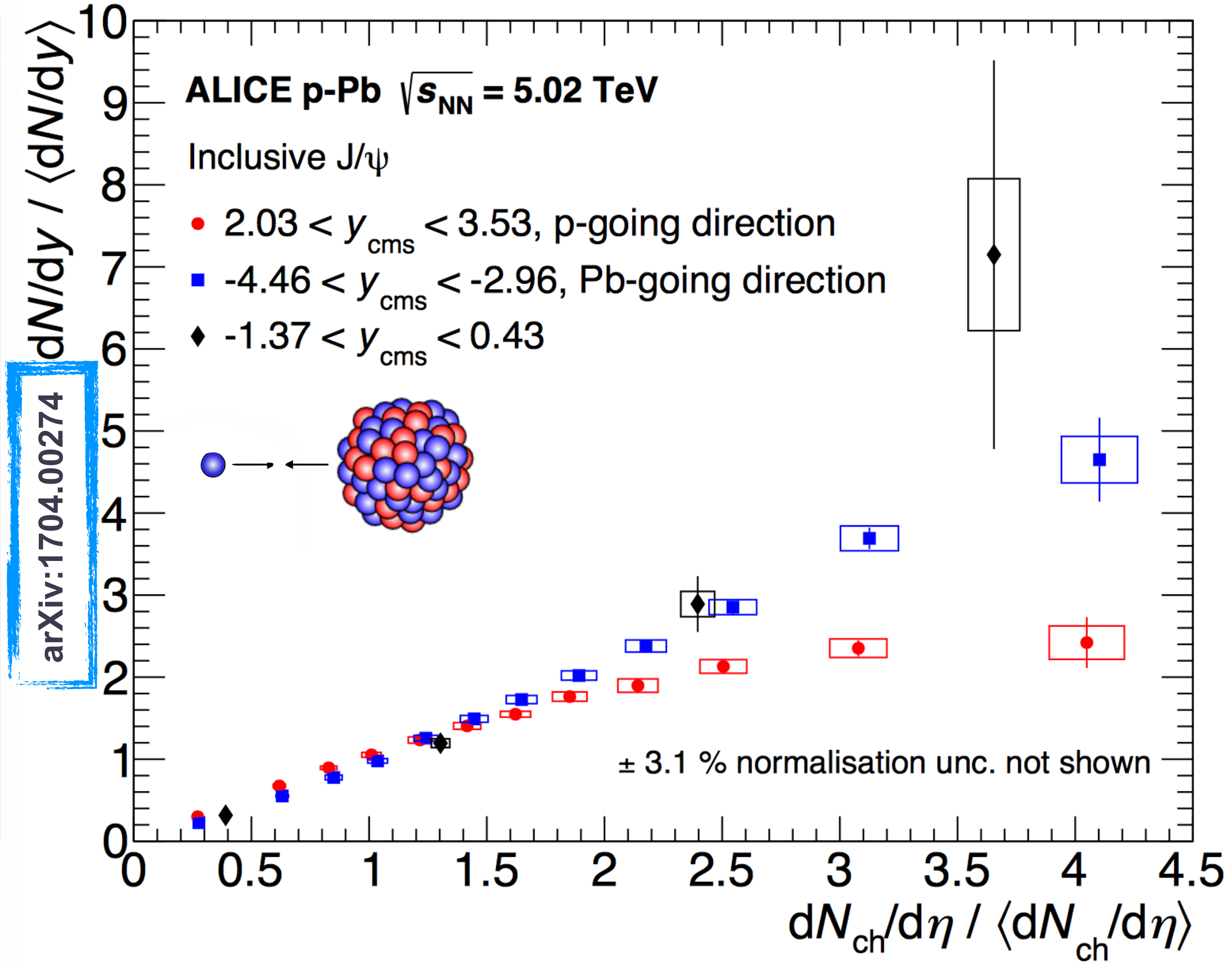


- Compatible with a **combination of suppression** (high p_T) and **regeneration** (low p_T) in the QGP
- **Suppression of excited states** over the ground state.

Charmonium in Small Systems



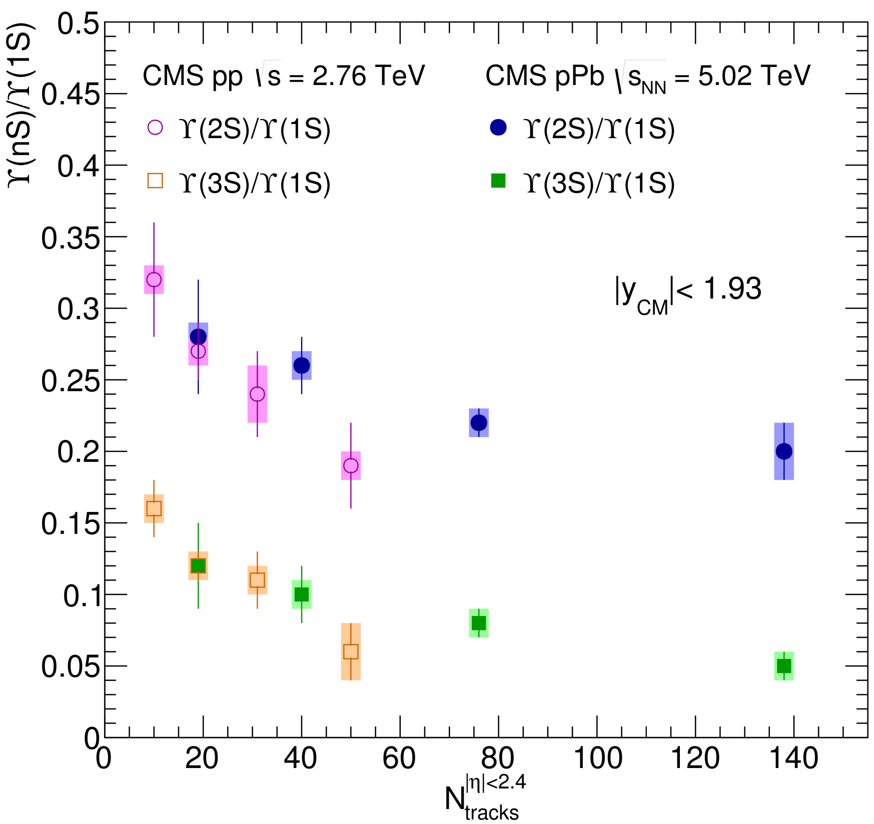
Ferreiro, Pajares, PRC86 (2012) 034903
EPOS3, Werner et al., Phys.Rept.350 (2001) 93
PYTHIA8, Sjostrand et al., Comput.Phys.Commun.178(2008)852
Kopeliovich et al., PRD88 (2013) 116002

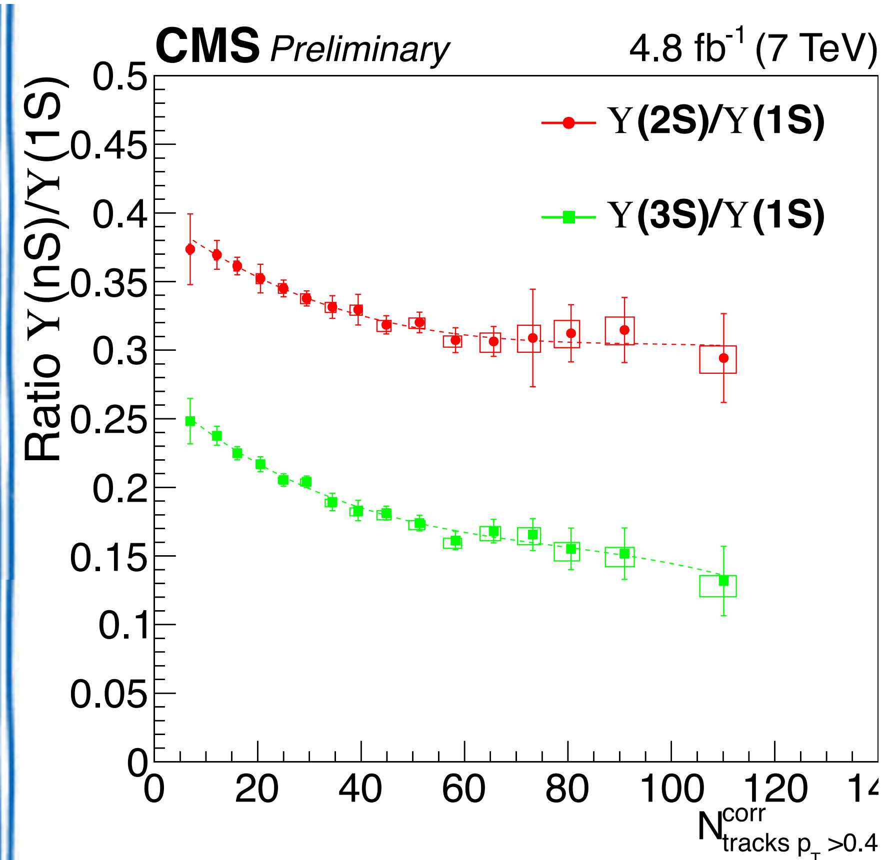


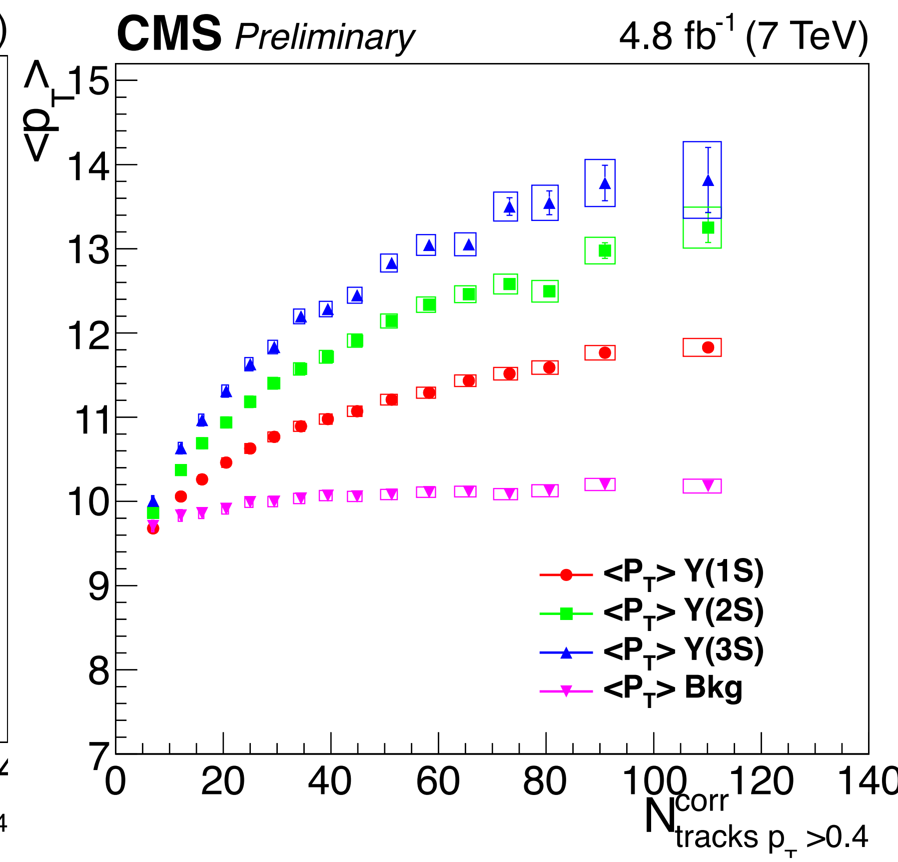
- **Clear increase of relative J/ψ yields with a slope larger than 1**
- Trend described by different theoretical models
- Indication that the slope grows with the J/ψ p_T

- Behaviour in rapidity regions similar up to 1.5-2 ×<N_{ch}>
- At Higher multiplicities:
  - **grows continues like in p-p for mid and backward y_{cms}**
  - **at forward rapidities signs of saturations (enhanced suppression)**

Bottomonium in Small Systems







J. High Energy Phys. 04 (2014) 103

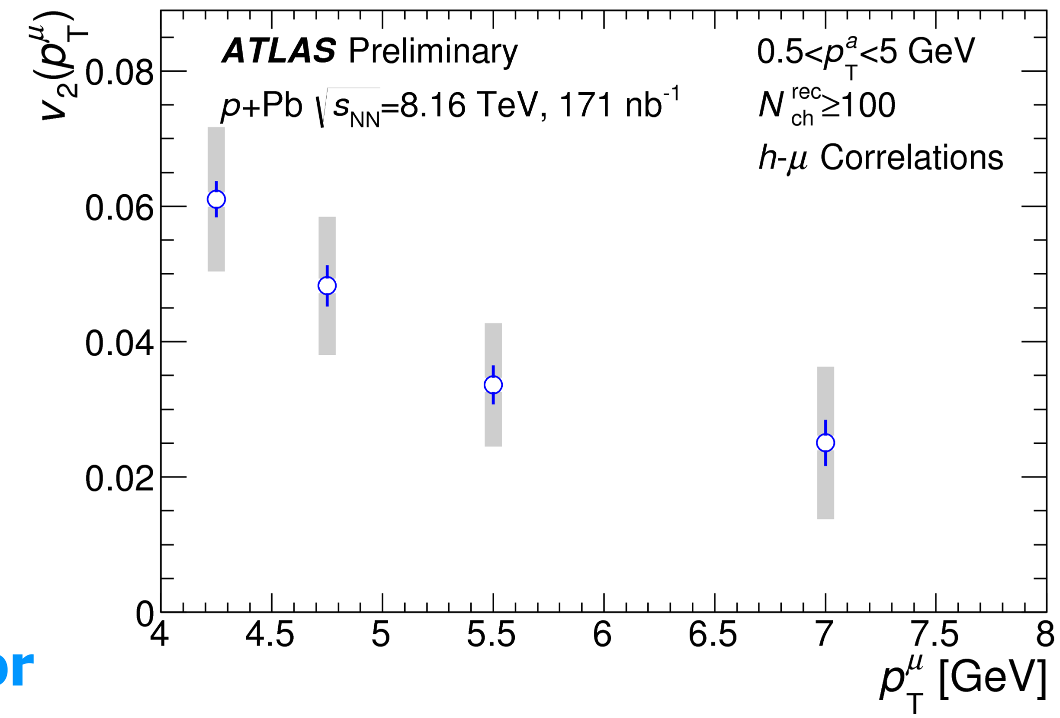
- Υ(nS)/Υ(1S) decrease with N_{ch}
- Similar effect both in **p-Pb** and in the control **p-p** sample

CMS-PAS-BPH-14-009

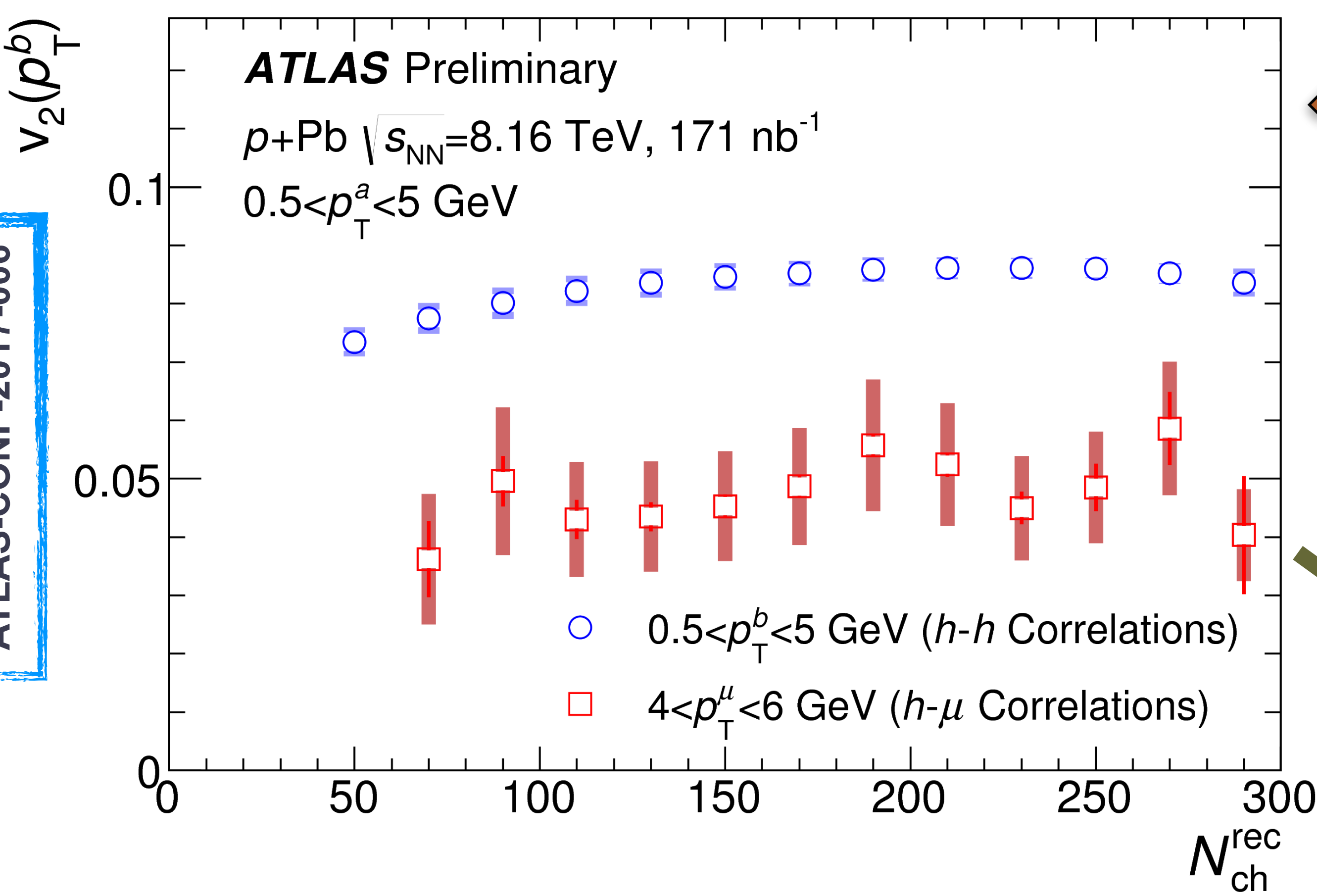
- Additional study with a larger 7 TeV p-p sample
- **Decrease confirmed, effect starting from low N_{ch}**
- mass dependent increase of $<p_T>$ vs N_{ch}

Muon Correlations in Pb-p

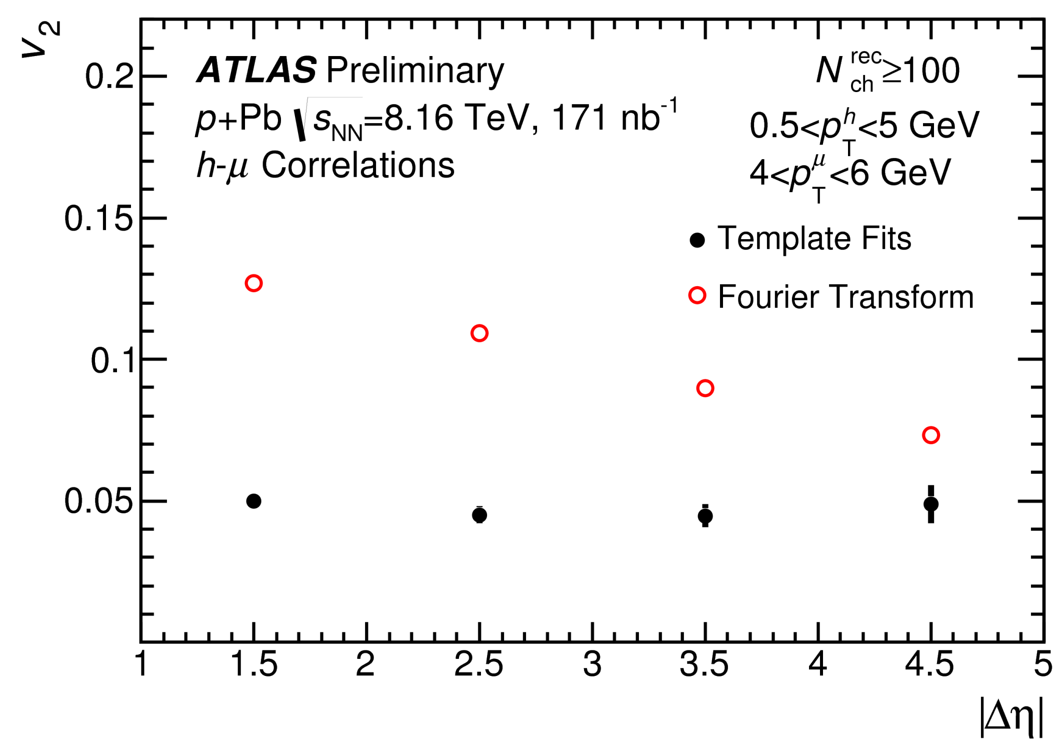
- If QGP is produced in p-Pb collisions, then **partial thermalization of heavy-flavor is expected**
- Muons with $4<p_T<8$ GeV come primarily from heavy-flavor decays
  - understanding of the long-range correlations involving heavy-flavor quarks
- Significant v_2 values are observed
  - no N_{ch} dependence in the studied range
  - **presence of azimuthal anisotropy for heavy-flavor particles produced in p+Pb**



- Muon-v2 values decrease with increasing p_T.



ATLAS-CONF-2017-006

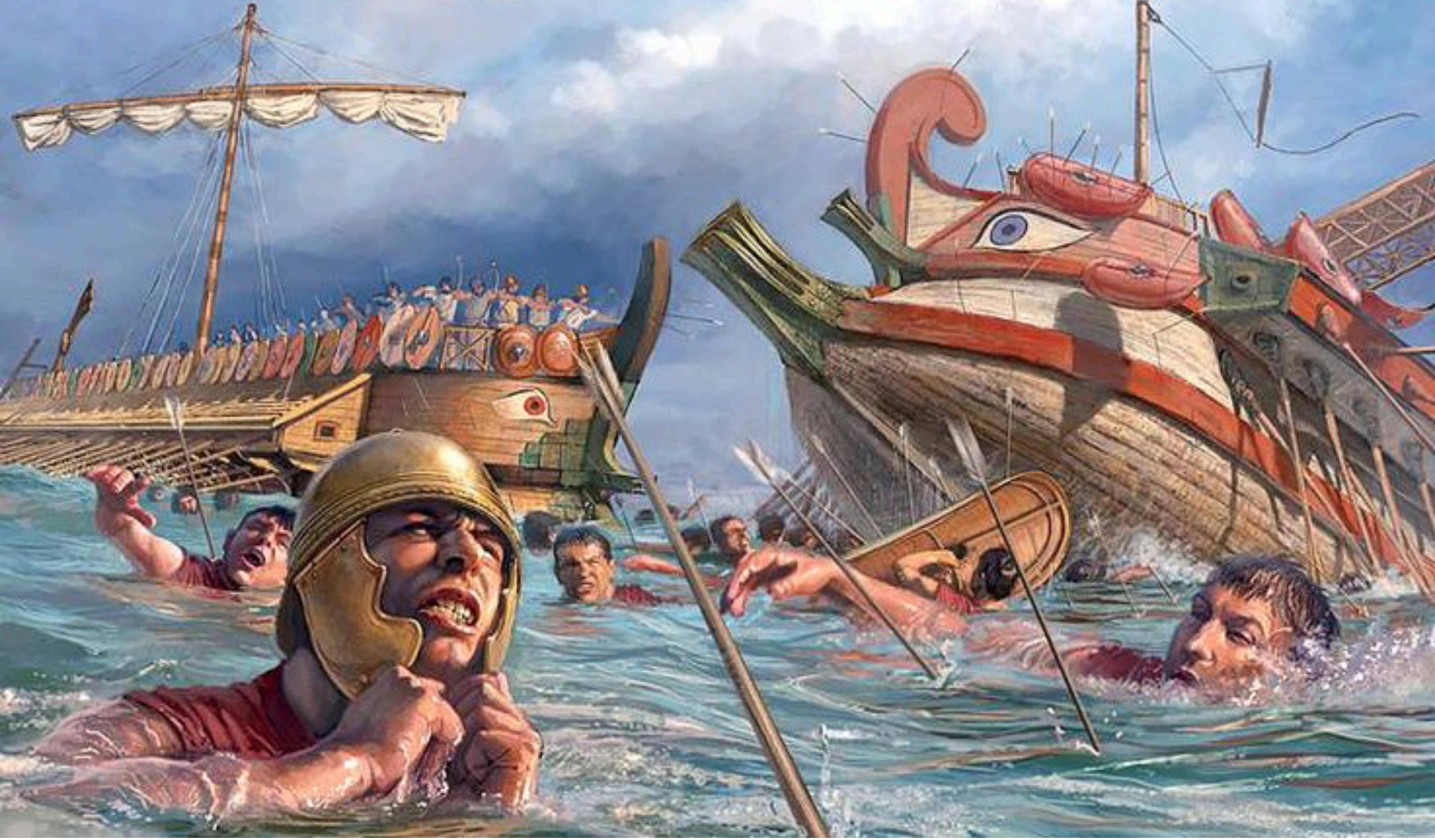


- Weak dependence on Δη→long-range correlations
- Strong bias from dijets removed in the template fits.

Summary

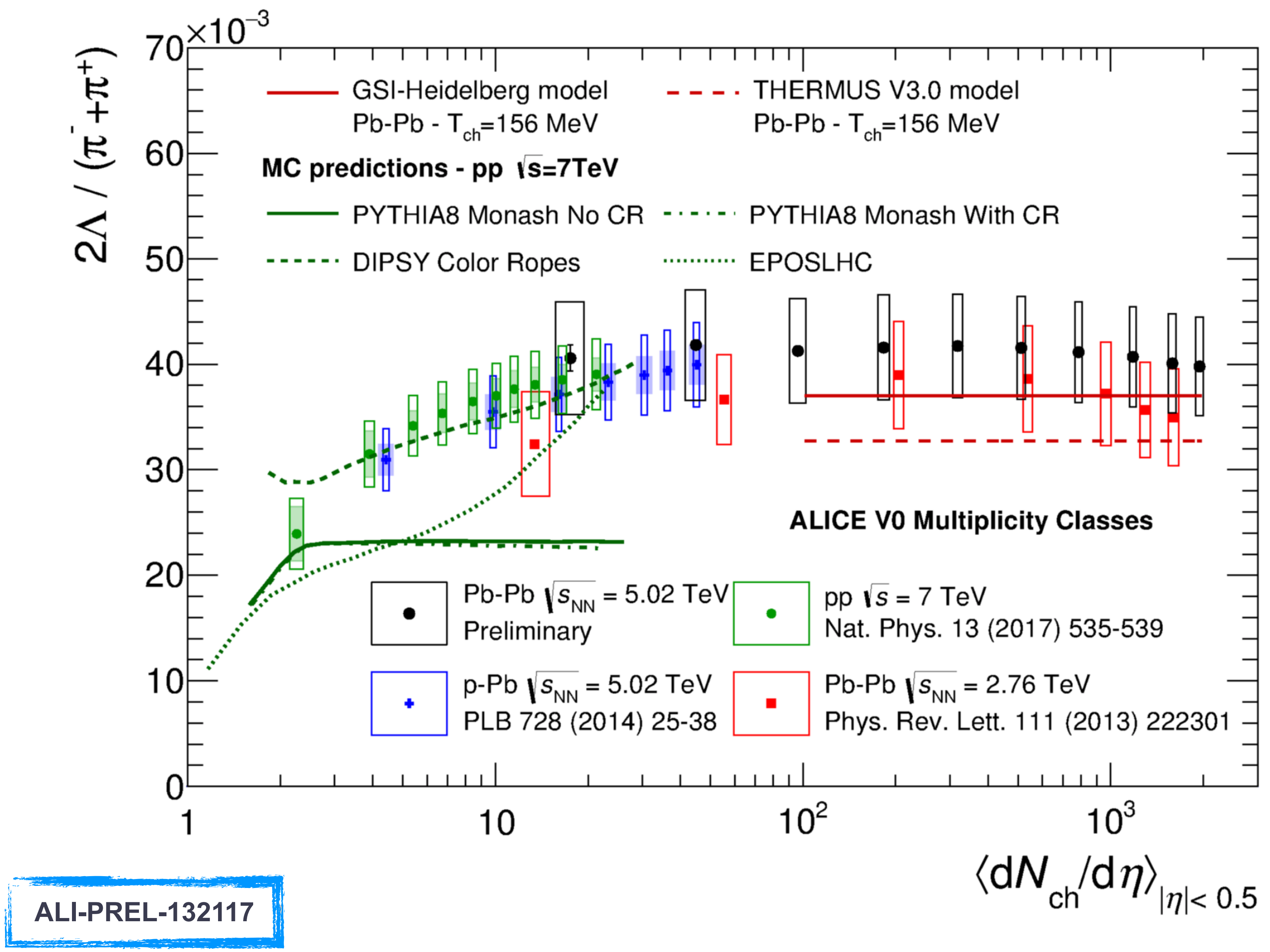
- Long way since the discovery of the “ridge” in p-p collisions
- **Signs of collective phenomena appear in all collision systems**
- **Common underlying physics mechanism?**
  - Particle production strongly correlated with N_{ch} rather than with the center-of-mass energy ⇒ constrained by the amount of initial parton energy available in any given collision
- To distinguish QGC or Hydro models from flow studies **crucial to clarify whether collectivity turns off al low N_{ch}**
  - main challenge is to clear up non-flow effects

- **Additional ingredients from Pb-Pb to Pb-p and p-p:**
  - **p_T distributions** ⇨ Blast wave description, mass scaling
  - **Baryon enhancement** at mid p_T in small systems
  - **Strangeness enhancement** in small systems vs. N_{ch}
    - production evolves smoothly from low-N_{ch} p-p to high-N_{ch} p-Pb
  - **Quarkonia production in small systems**
    - suppression in small system difficult to explain with QGC models



Backup

Hadrochemistry: Λ

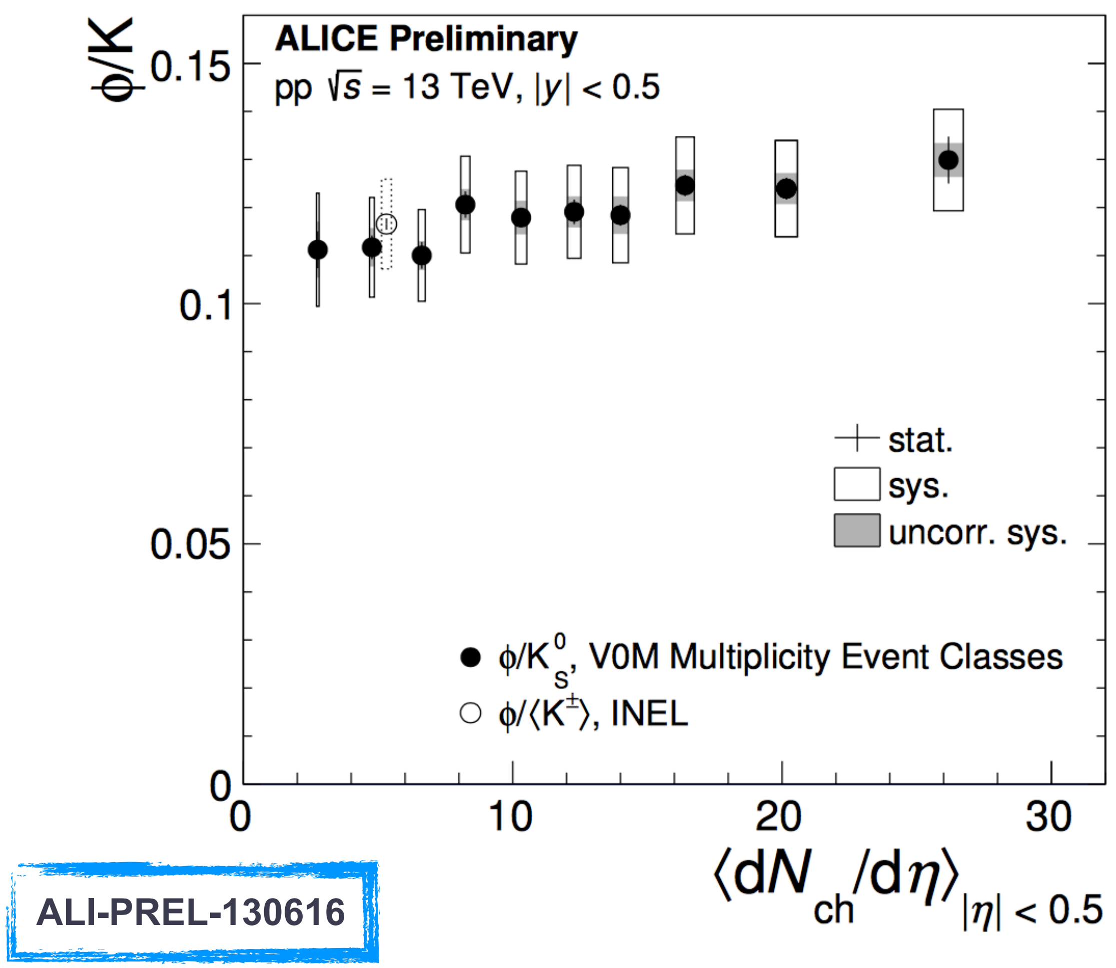


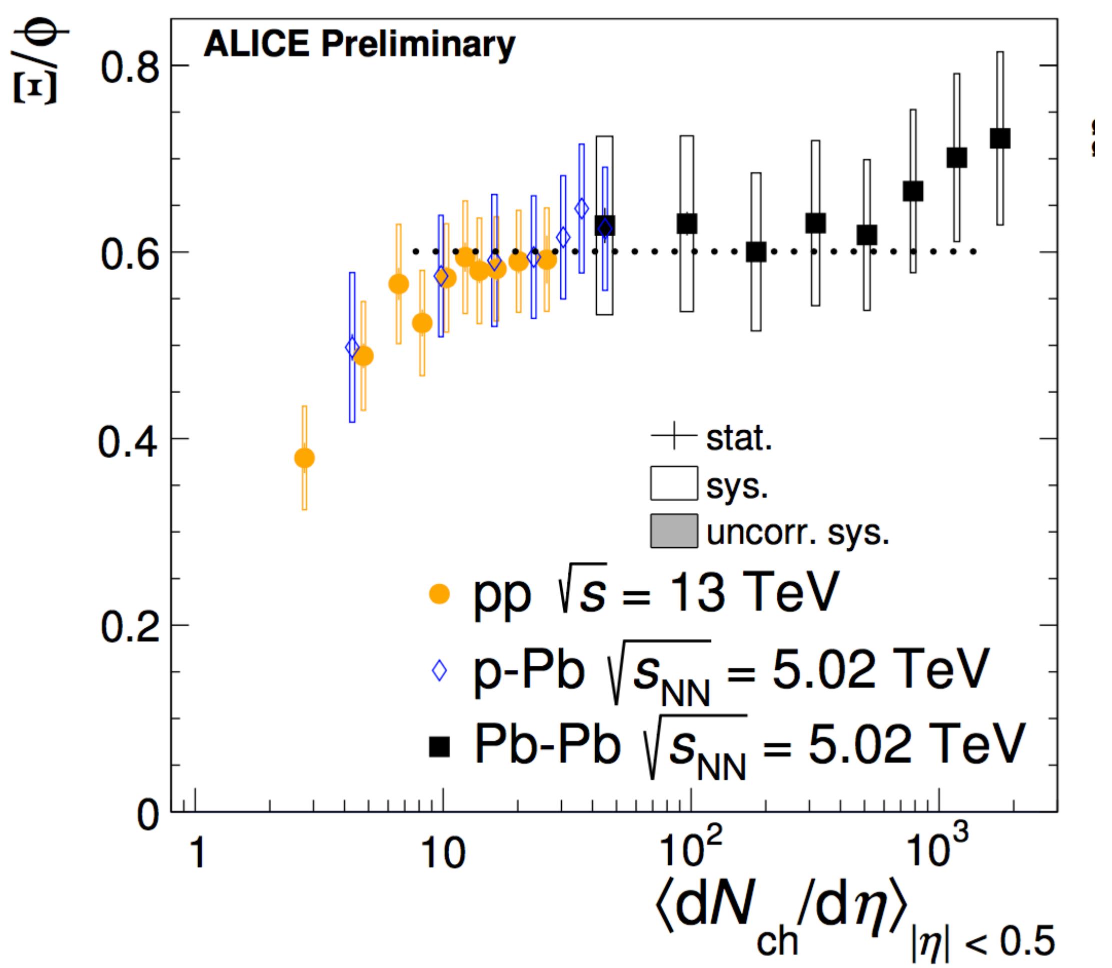
ALICE

- Ratio of p_T-integrated yield to pions show compatibility among different measurements
  - **Smooth transition among different systems**
  - **No evident energy dependence!**

The Φ meson

- The observed enhancement for strange particles goes with strangeness content rather than with mass or baryon number of the hadron.
- It reaches Heavy Ions values, described by a grand canonical statistical mode for an hadron gas in thermal and chemical equilibrium

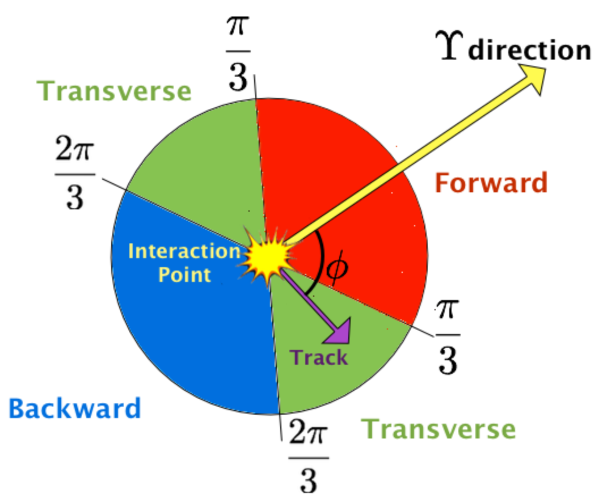


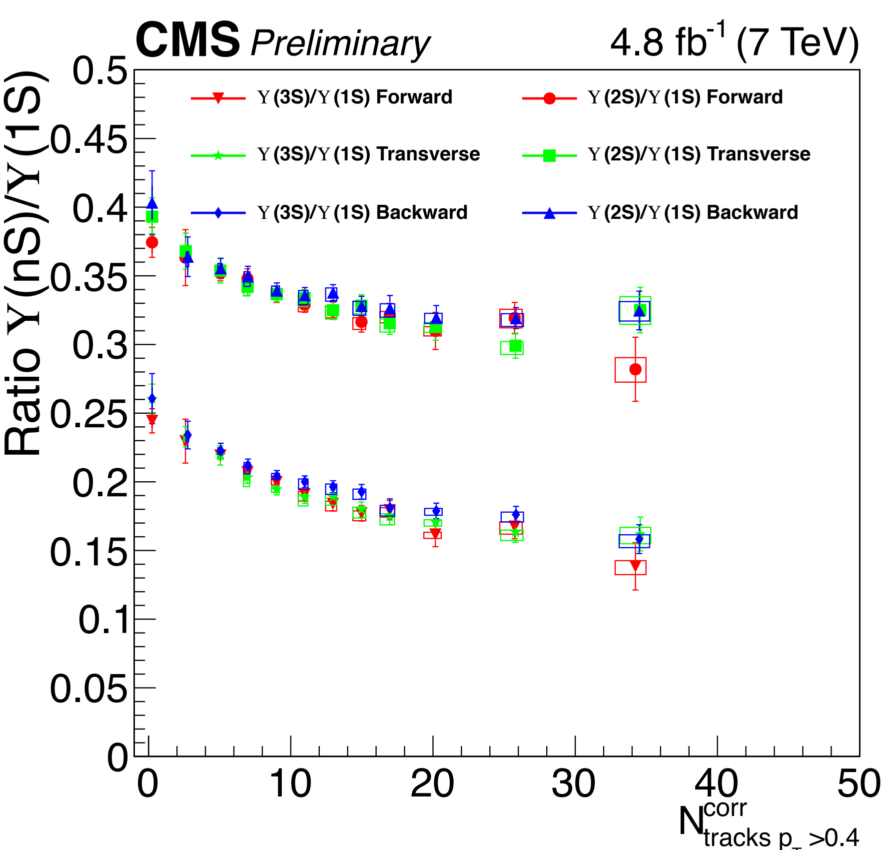


- Φ meson shows enhancement with increasing $dN_{ch}/d\eta$
  - does not behave as a hadron with zero strangeness quantum number
- Ξ/Φ show a light increase with $dN_{ch}/d\eta > 10$
- Φ/K is almost flat
  - the Φ meson behaves ~ as a particle made of two strange quarks

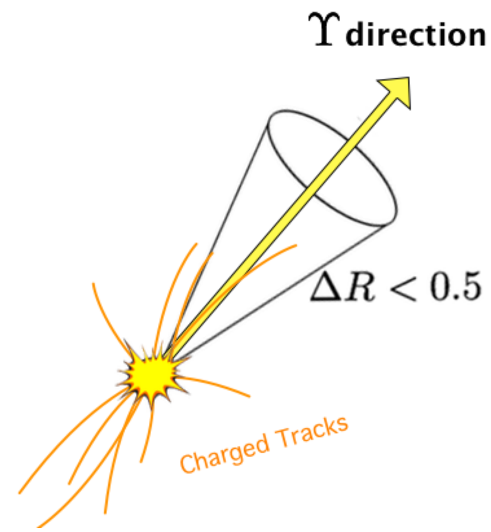
Υ(nS) ratio and Underlying event

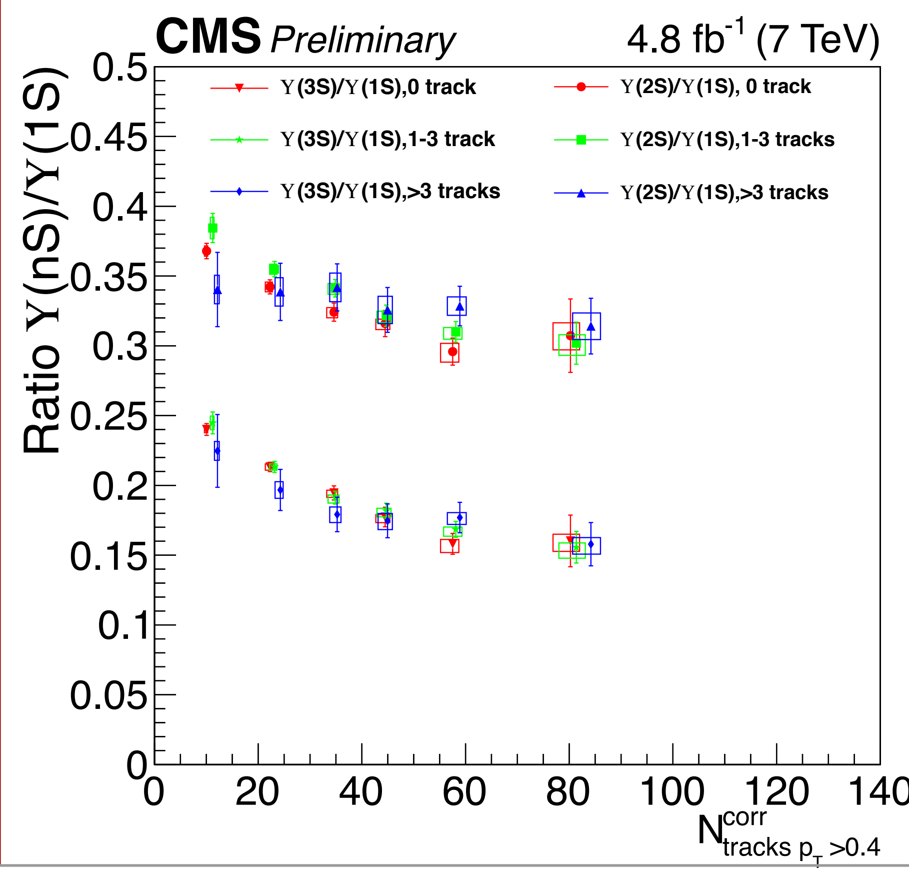
- Υ(nS) ratios vs charged particle in different region w.r.t. the Υ(nS)





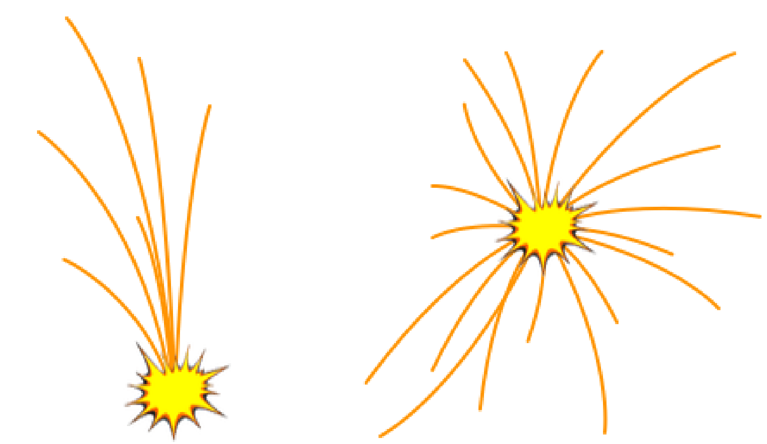
- Υ(nS) ratios for different number of tracks along Υ(nS) direction

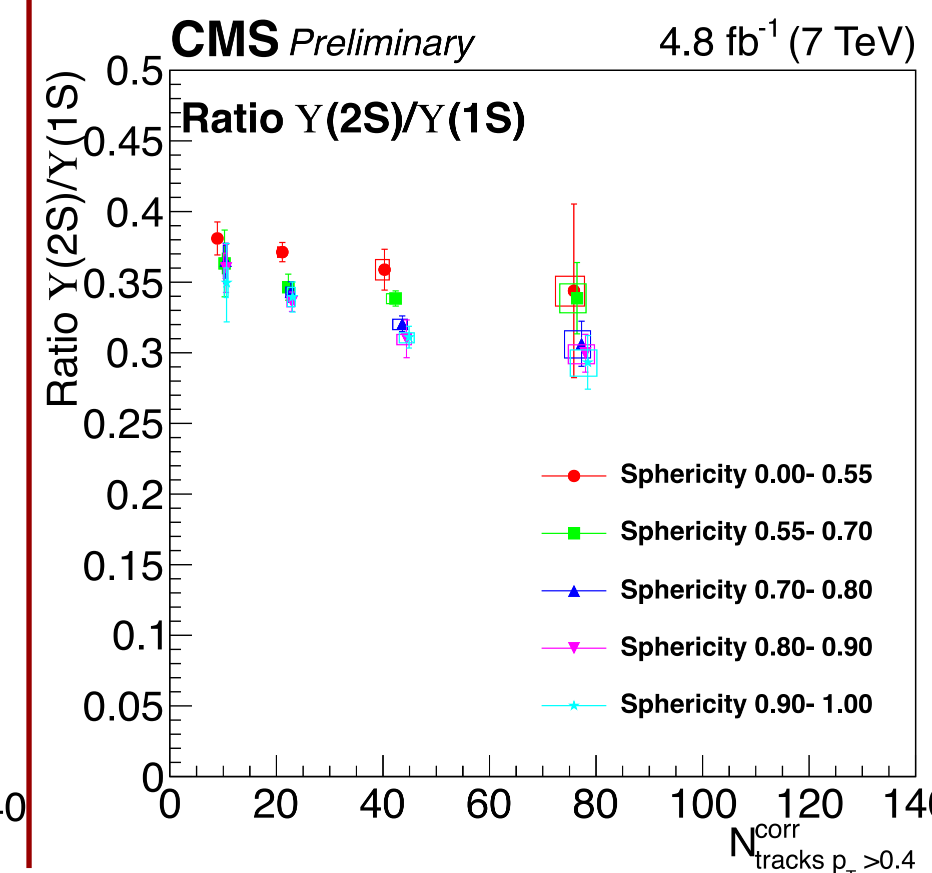




- Υ(nS) ratios for different underlying event sphericity

Sphericity→0 **Sphericity→1**

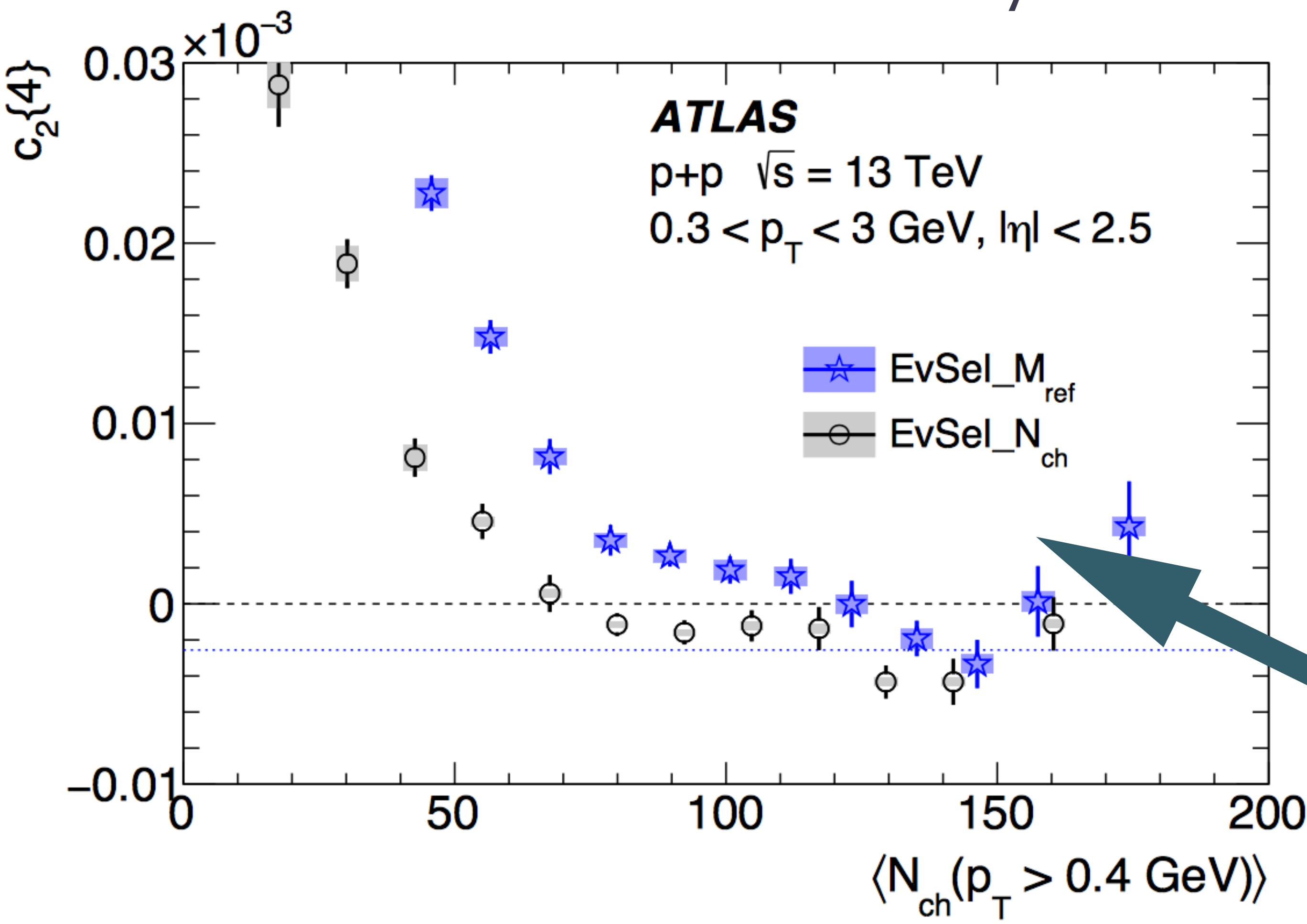


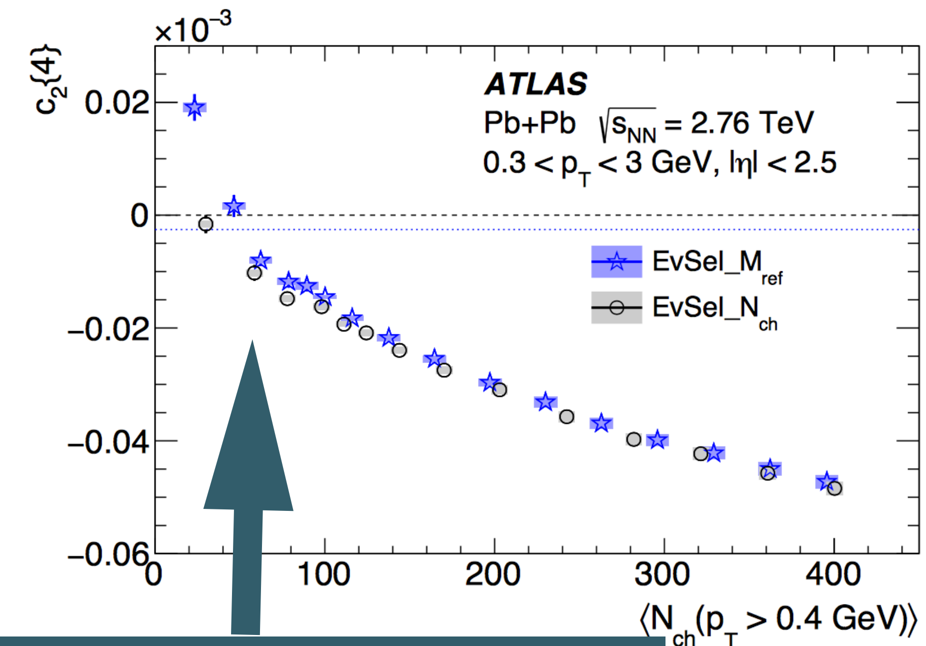


No correlations found with the observed decrease

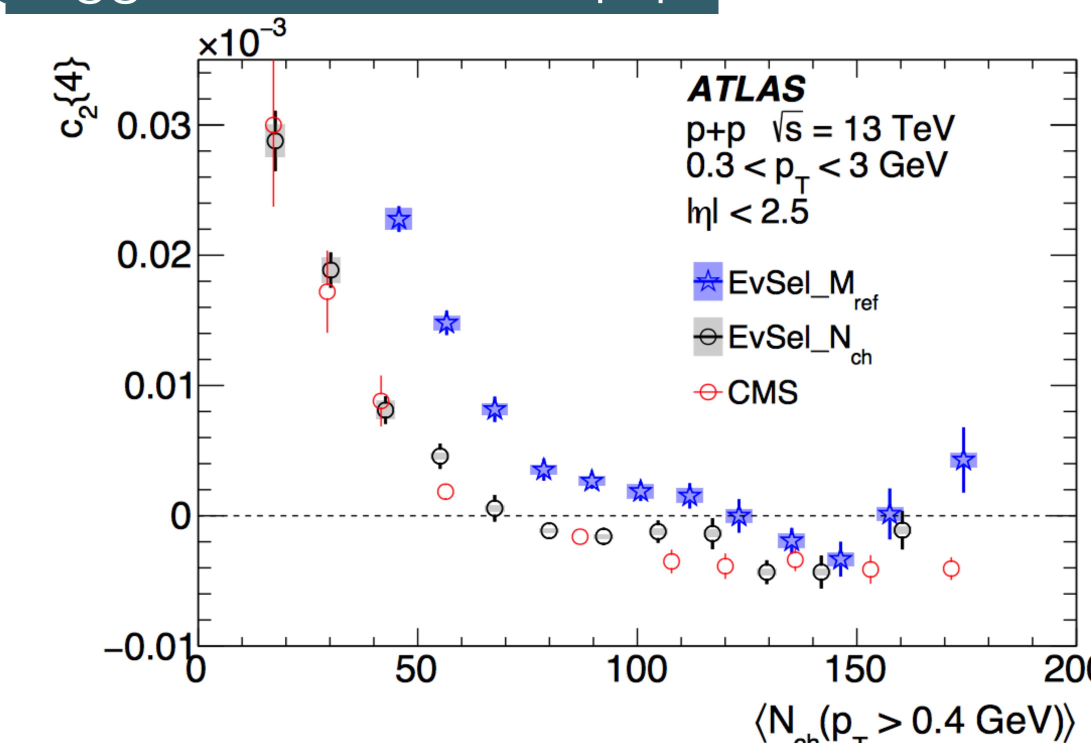
Particle cumulants CMS-ATLAS

- The ATLAS M_{ref} selection has
  - different sensitivity to event-by-event multiplicity fluctuations
  - biased in a different manner by contributions from non-flow correlations



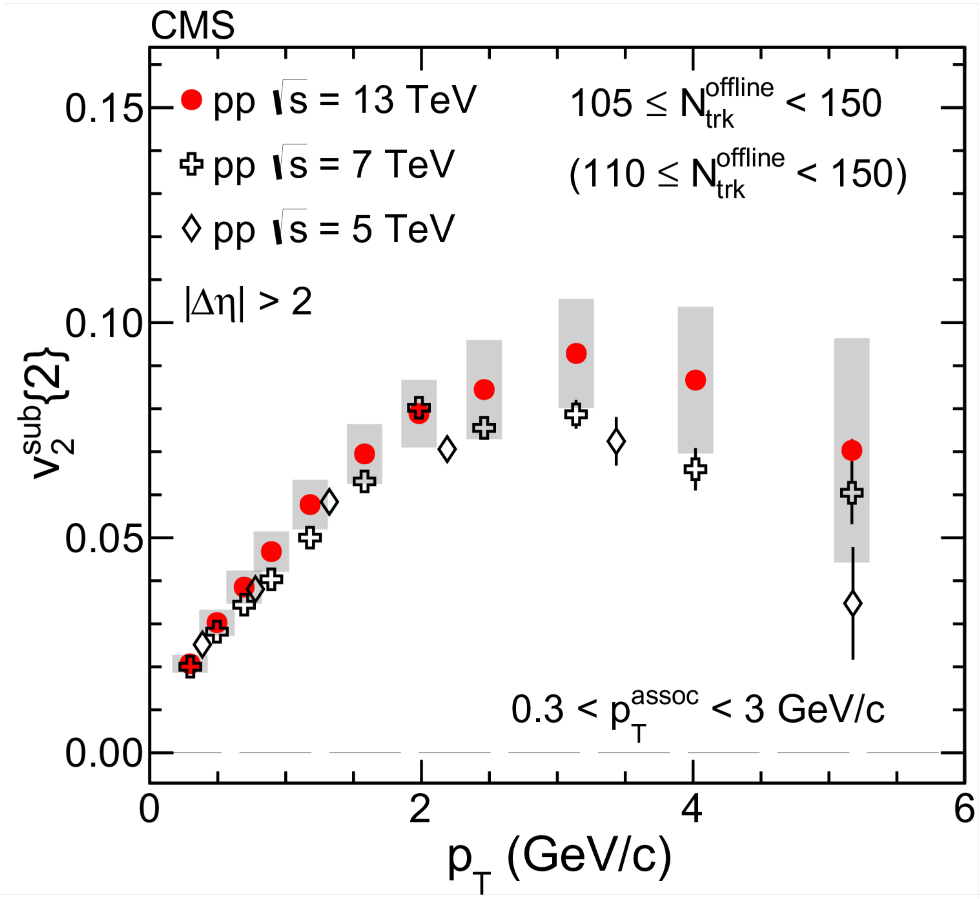


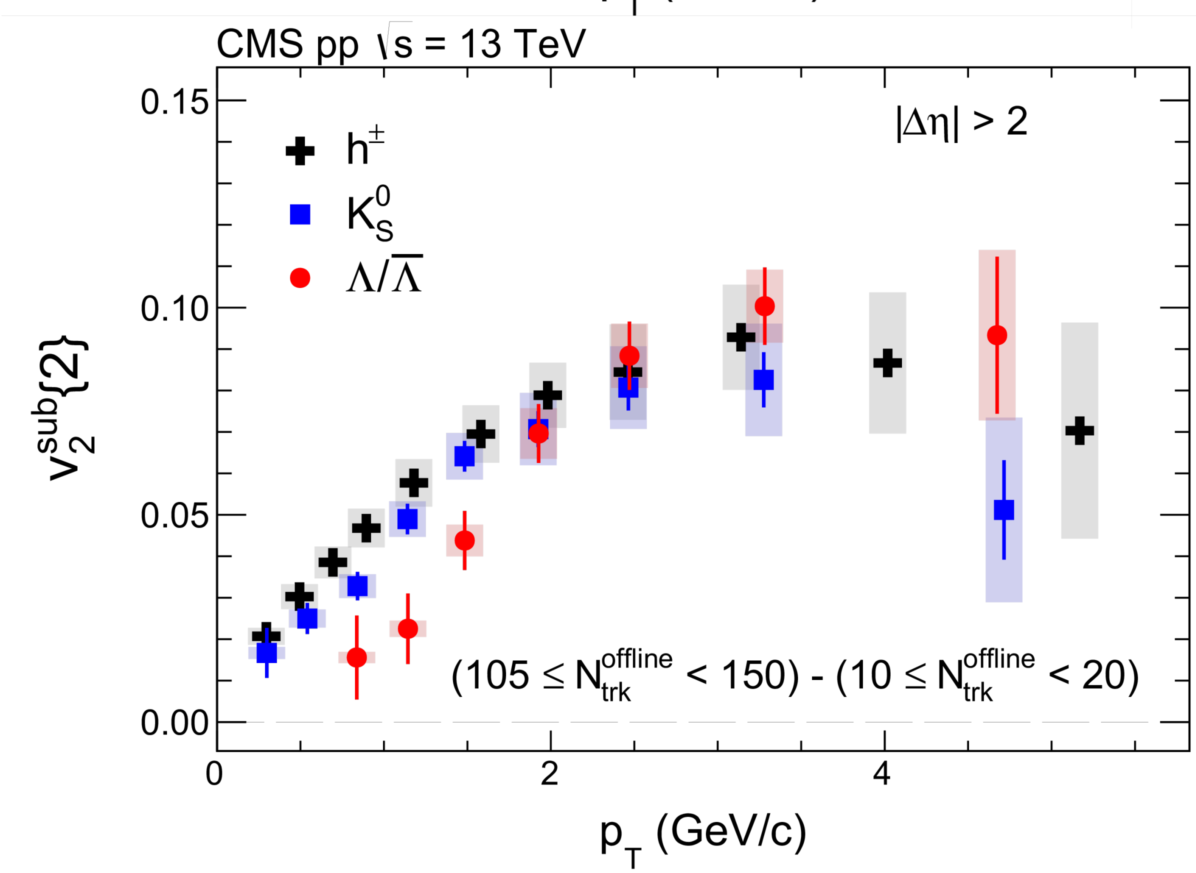
Bigger differences in p-p!



- This seems the source of the c2{4} discrepancy between ATLAS and CMS in p-p at 13 TeV

Elliptic Flow vs p_T





- **No or very weak dependence on the collision energy.**
- In higher-multiplicity region, **v_2 of K^0_S is found to be larger than that of Λ.**
  - similar to what observed for identified particles produced in p-Pb and A-A collisions at RHIC and the LHC.
- Mass ordering tends to reverse at **higher p_T values**