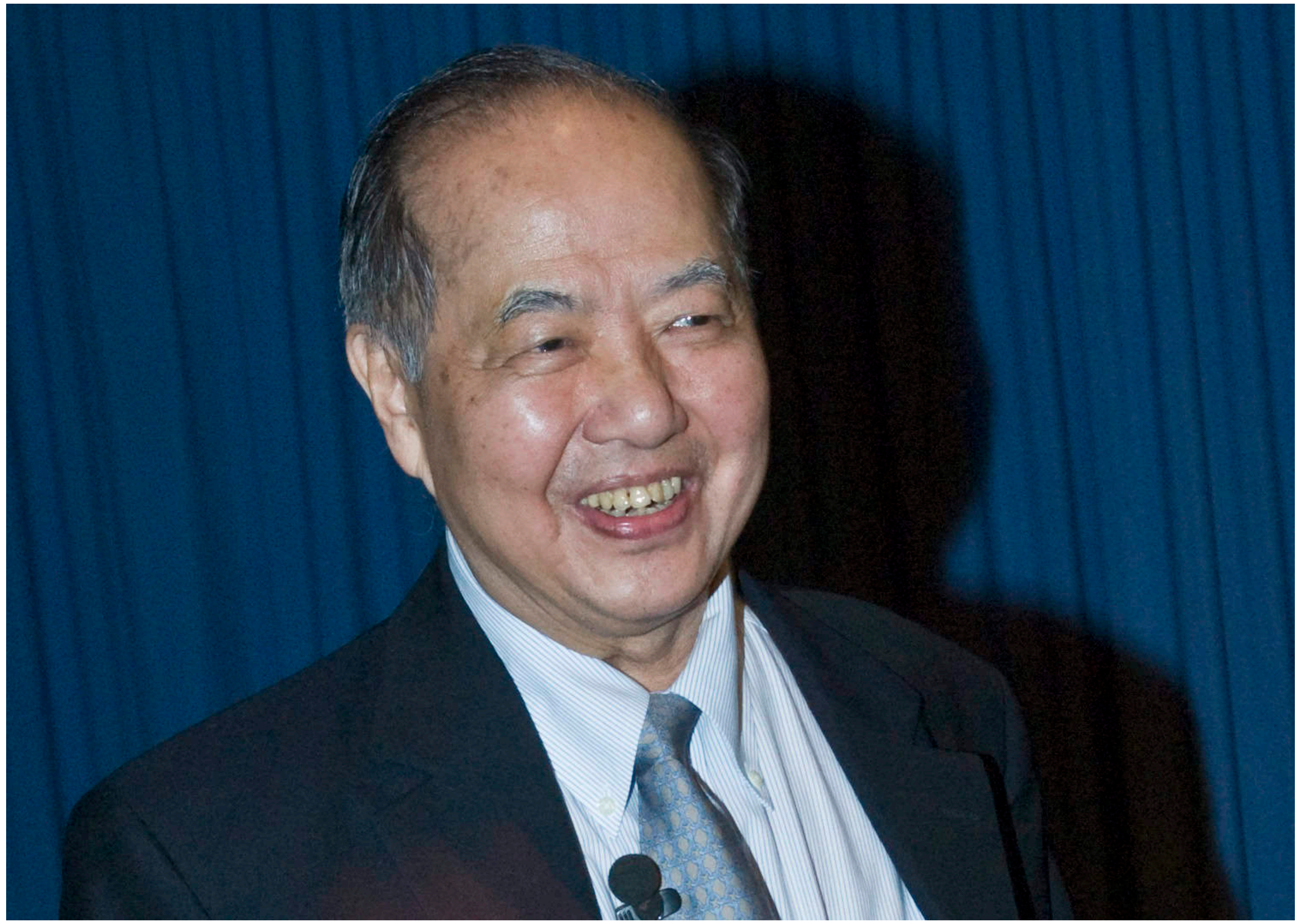
Recent experimental results on QGP formation and properties at the LHC

Heavy Ion Collisions

24-11-1926 — 4-8-2024



"It would be intriguing to explore new phenomena by distributing high energy or high nuclear matter over a relatively large volume."

"In this way one could temporarily restore broken symmetries of the physical vacuum and possibly create abnormal states of nuclear matter."

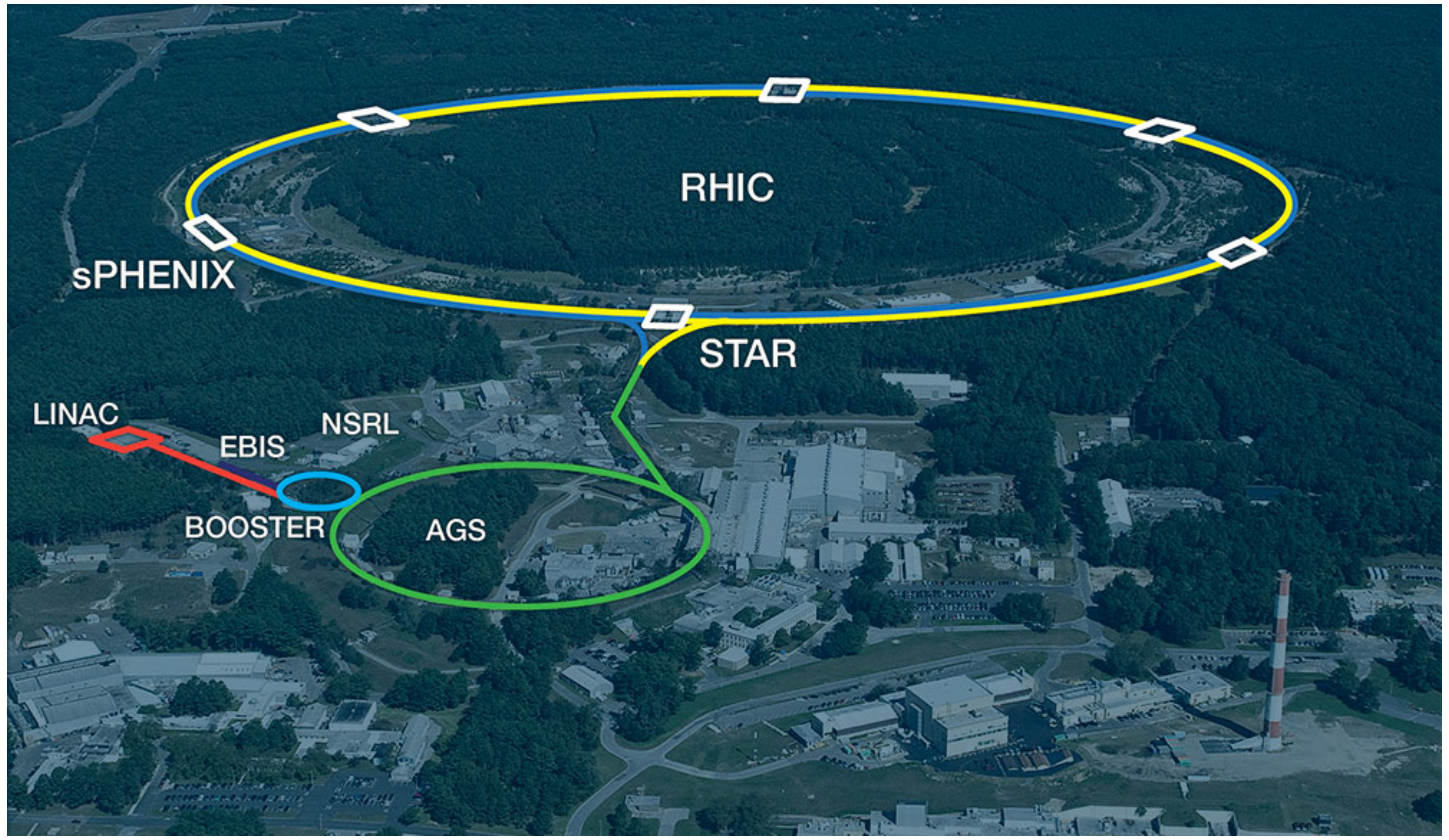
T.D. Lee, Bear Mountain, NY, 1974.

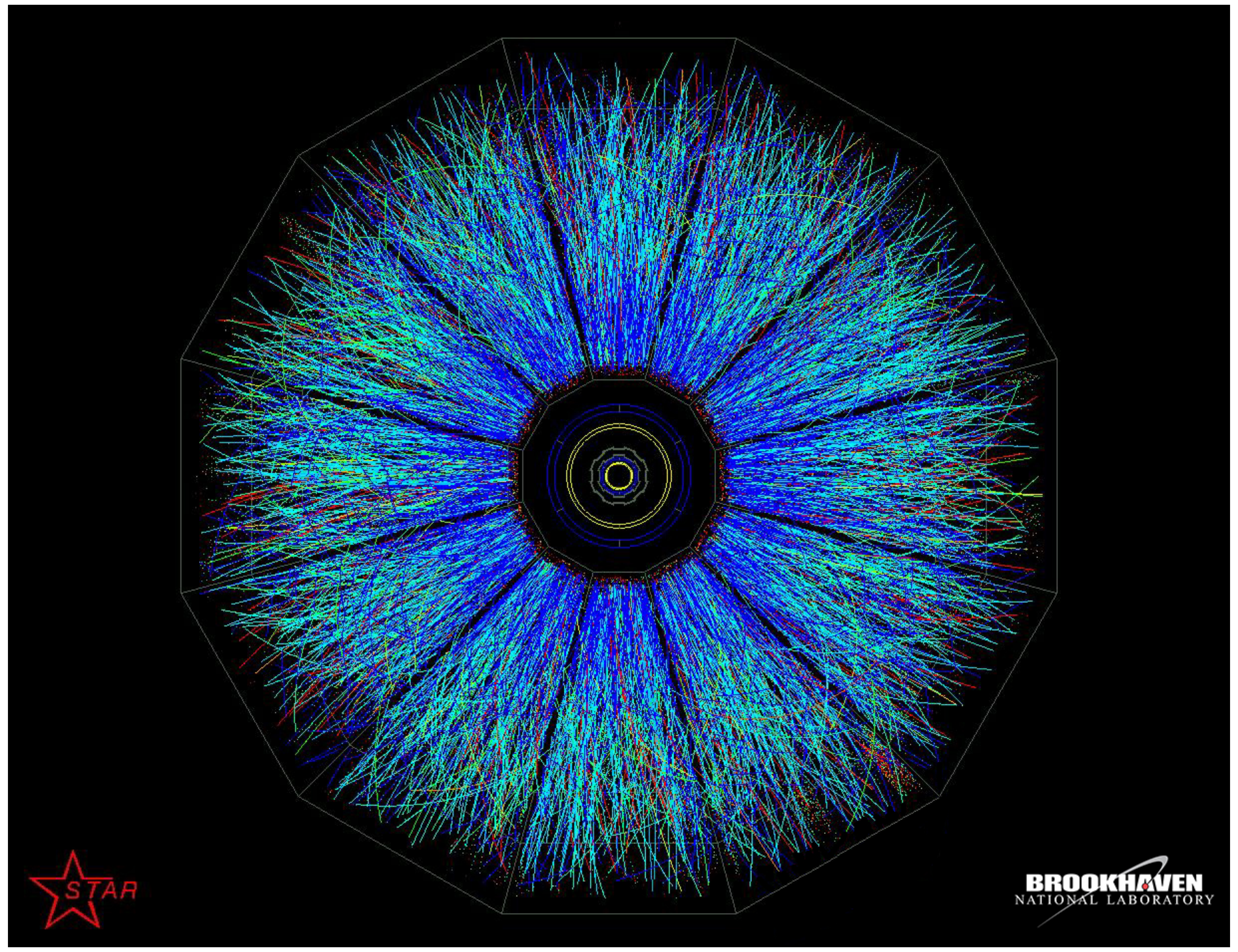
22-6-1934 — 6-8-2024

"Nevertheless, such speculations reminds us that the possibility of totally unexpected phenomena may be the most compelling reason to consider relativistic nucleus-nucleus collisions. It is regrettable that It is so hard to estimate the odds for this to happen."

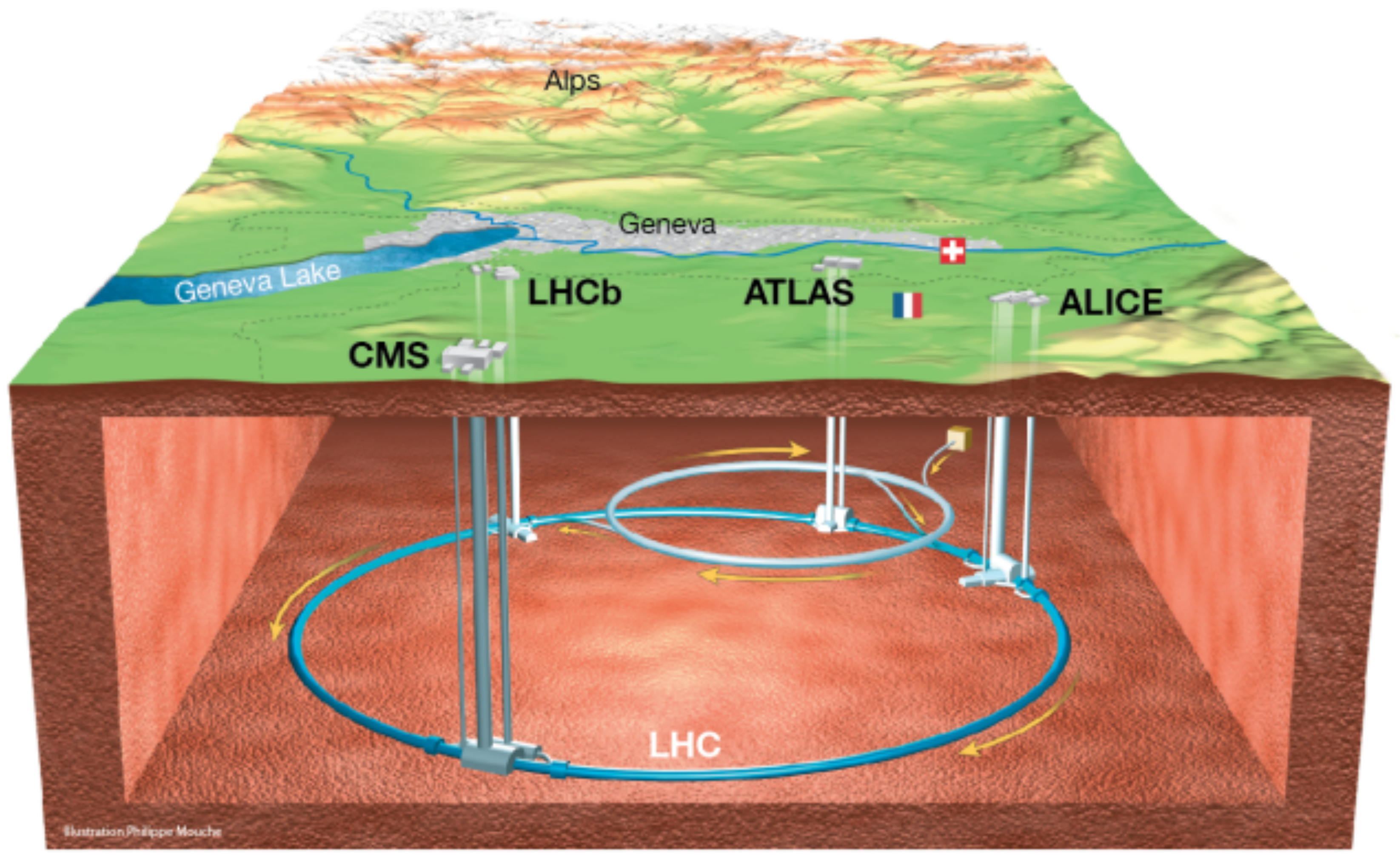
J.D. Bjorken, FNAL, PRD 27 (1983) 140.

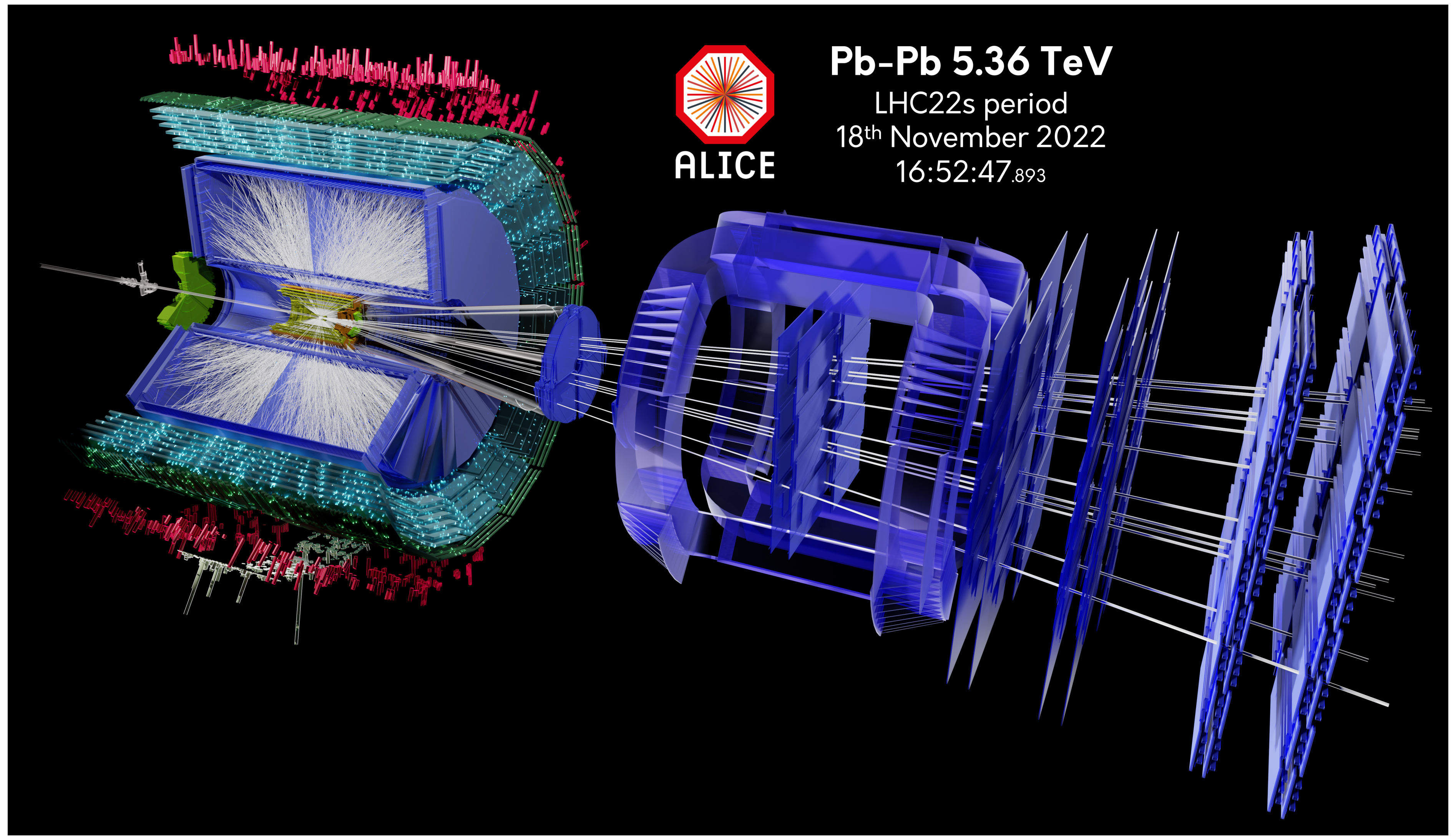
RHIC and the LHC

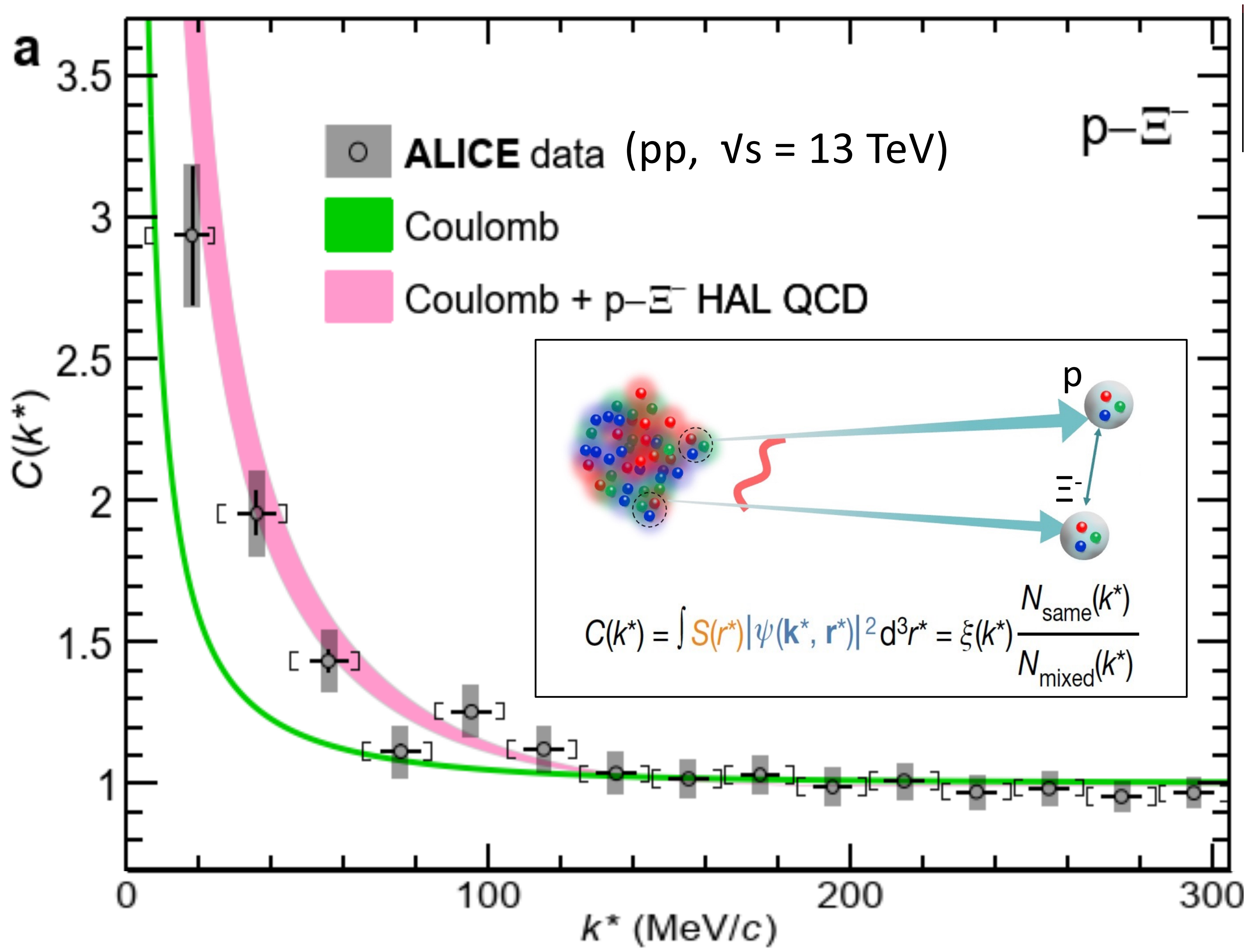




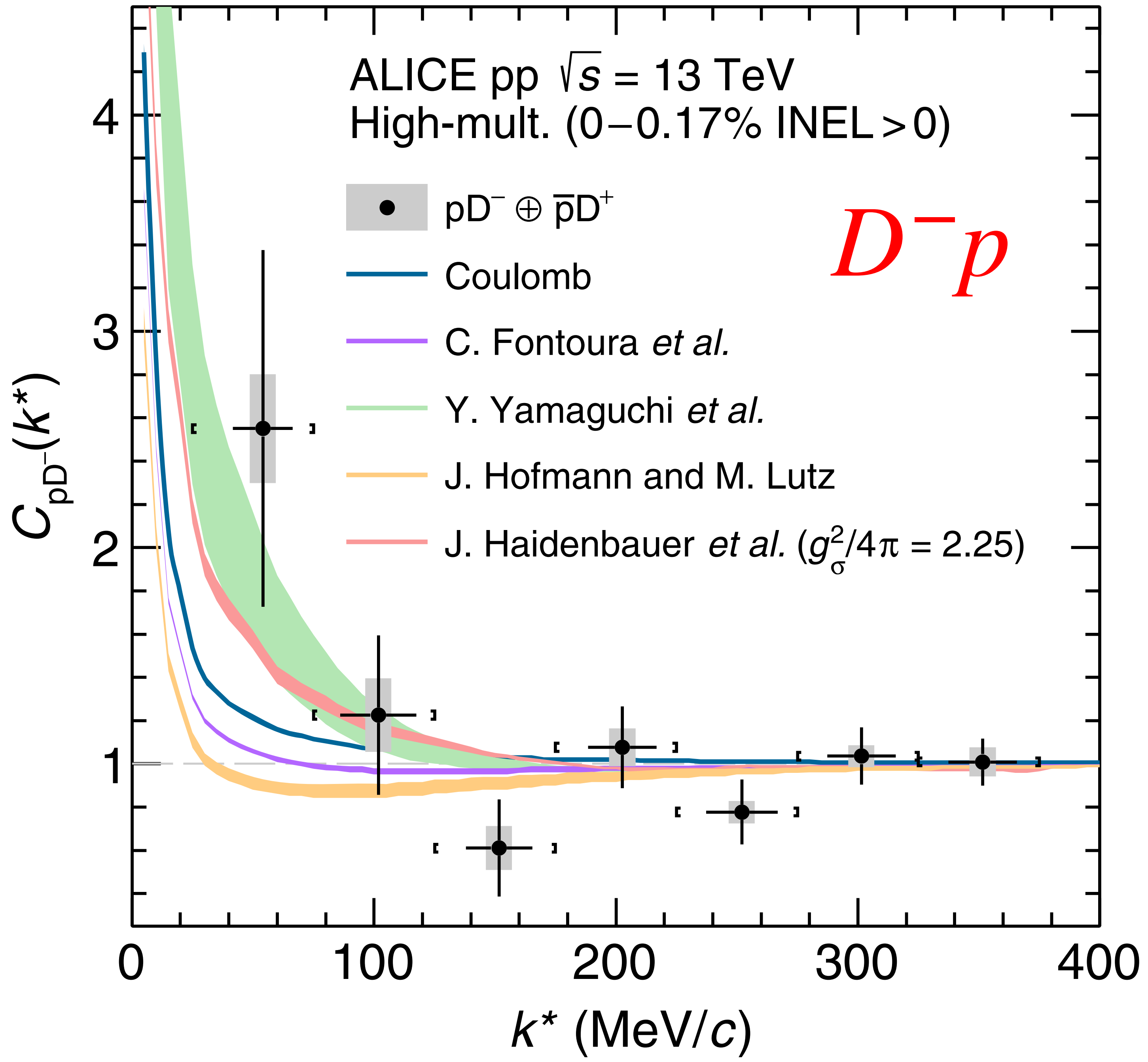
The dream of T.D. Lee and J.D Bjorken came true!



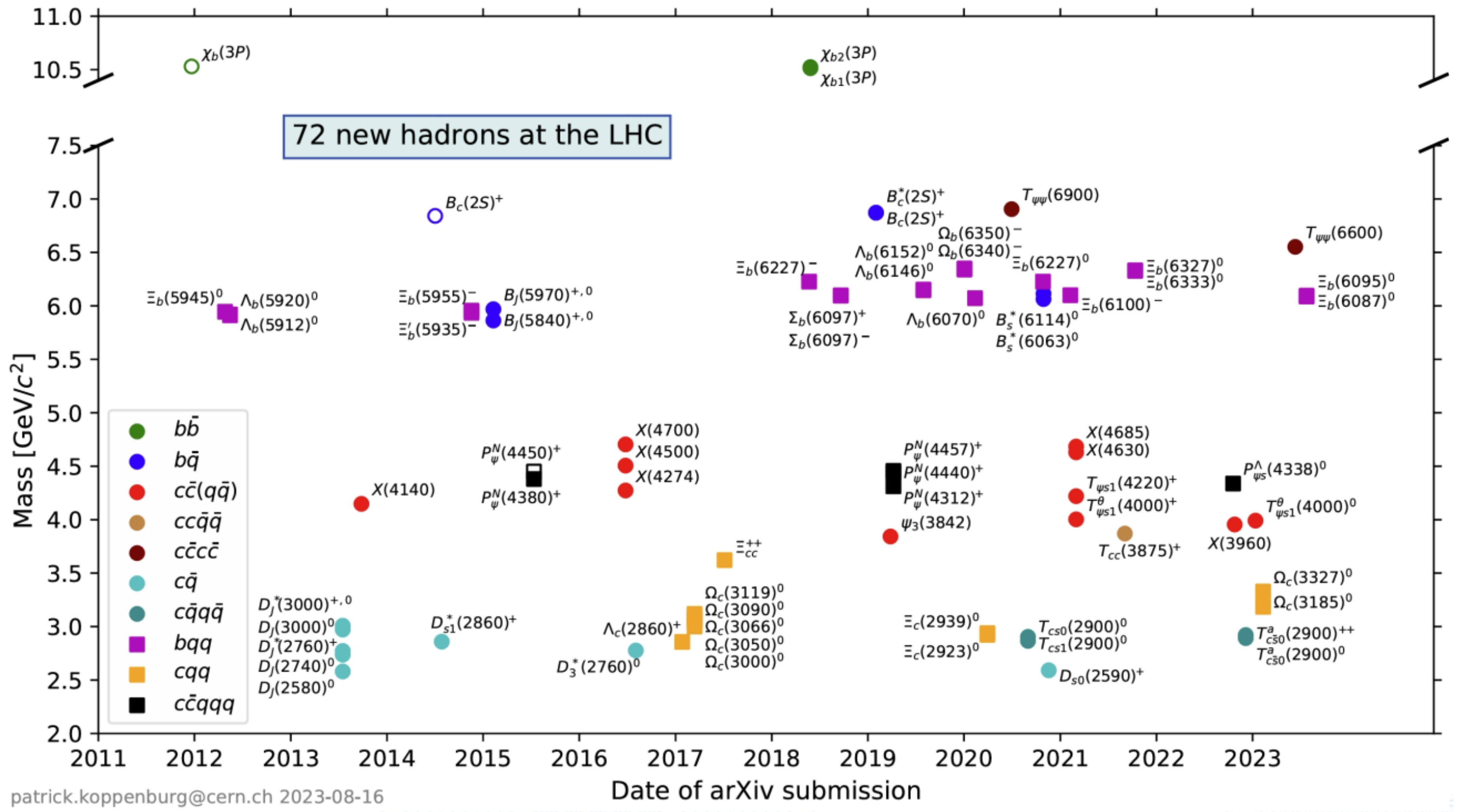


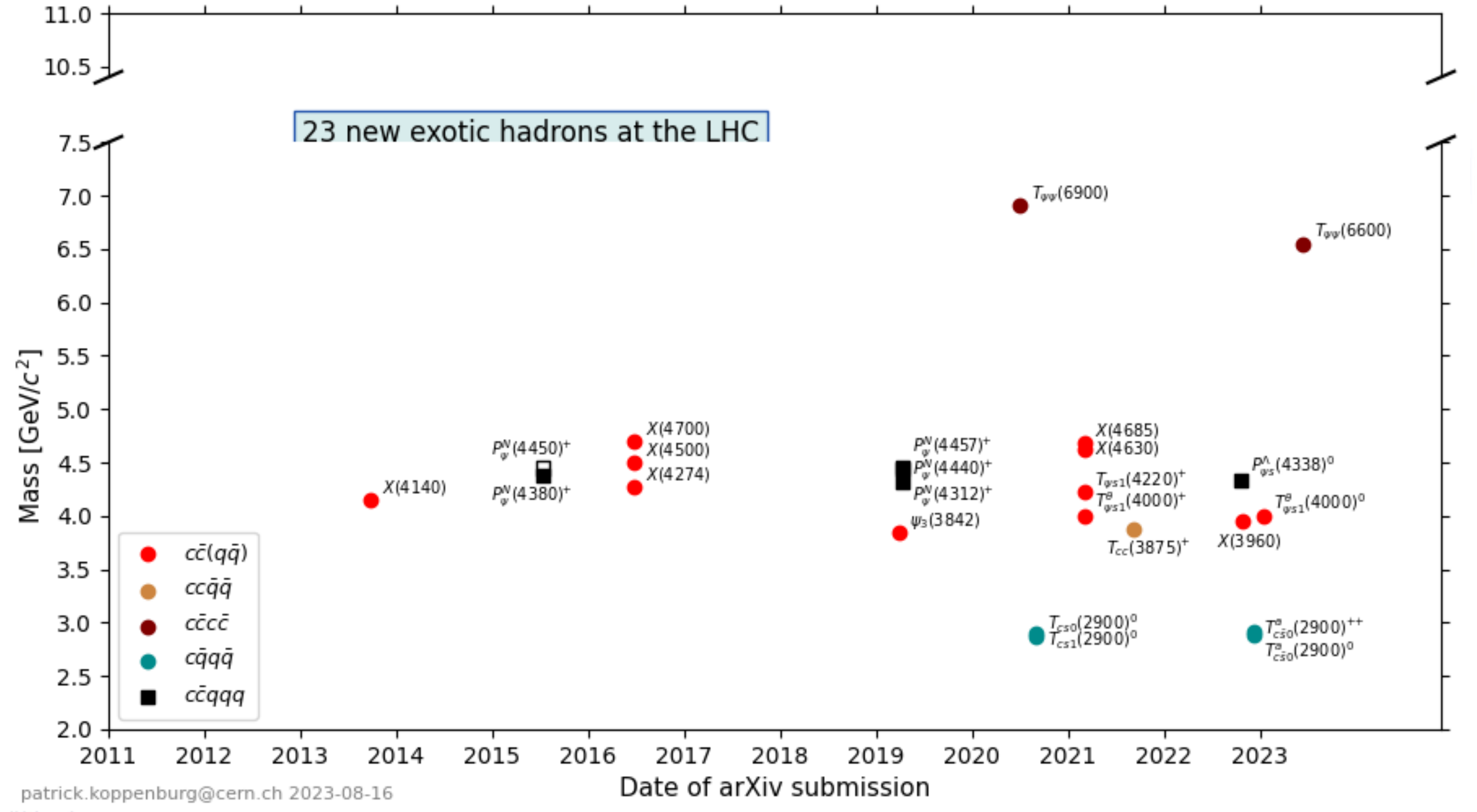


See talk Tetsuo Hatsuda



See talk Tetsuo Hyodo

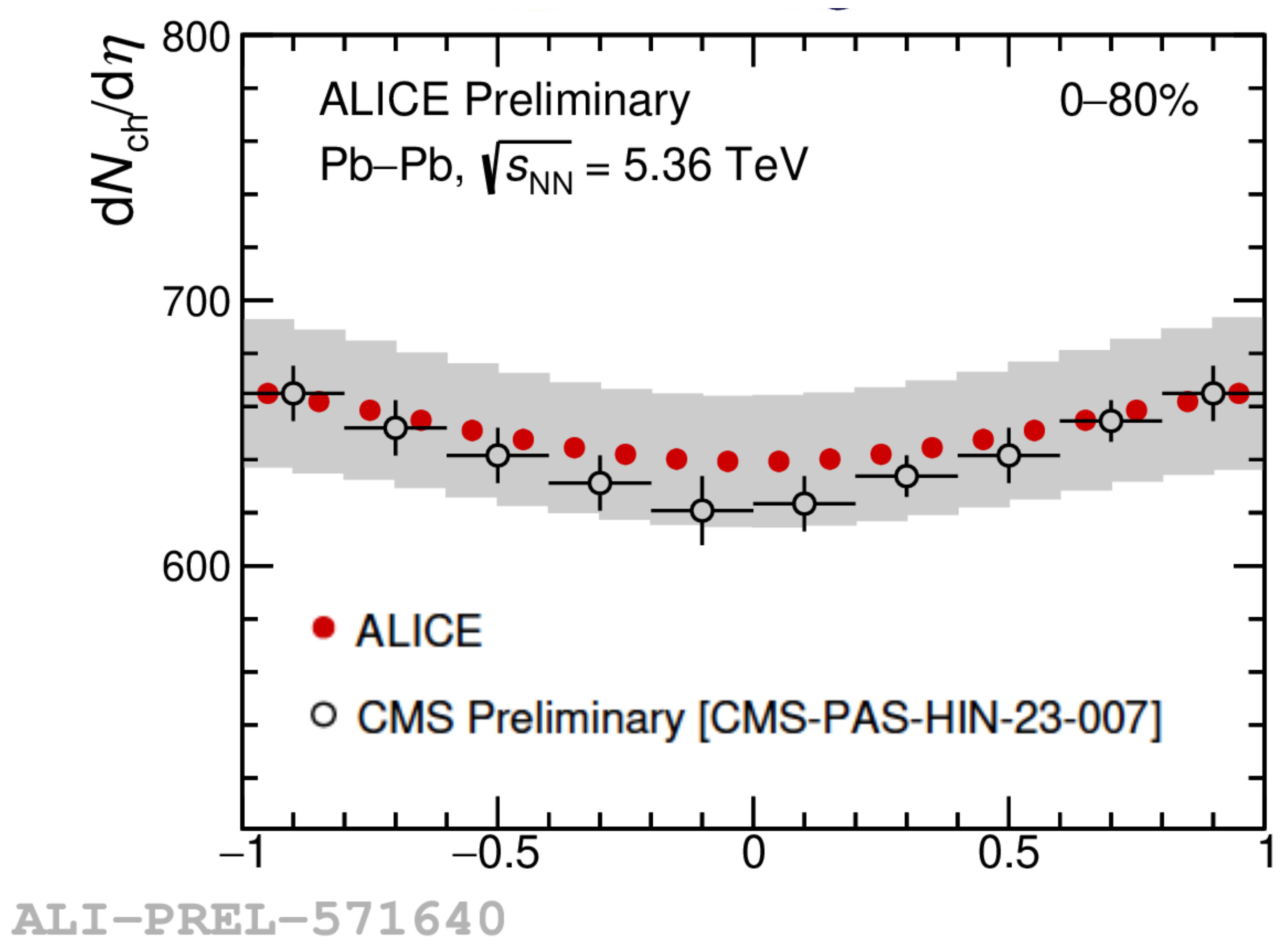


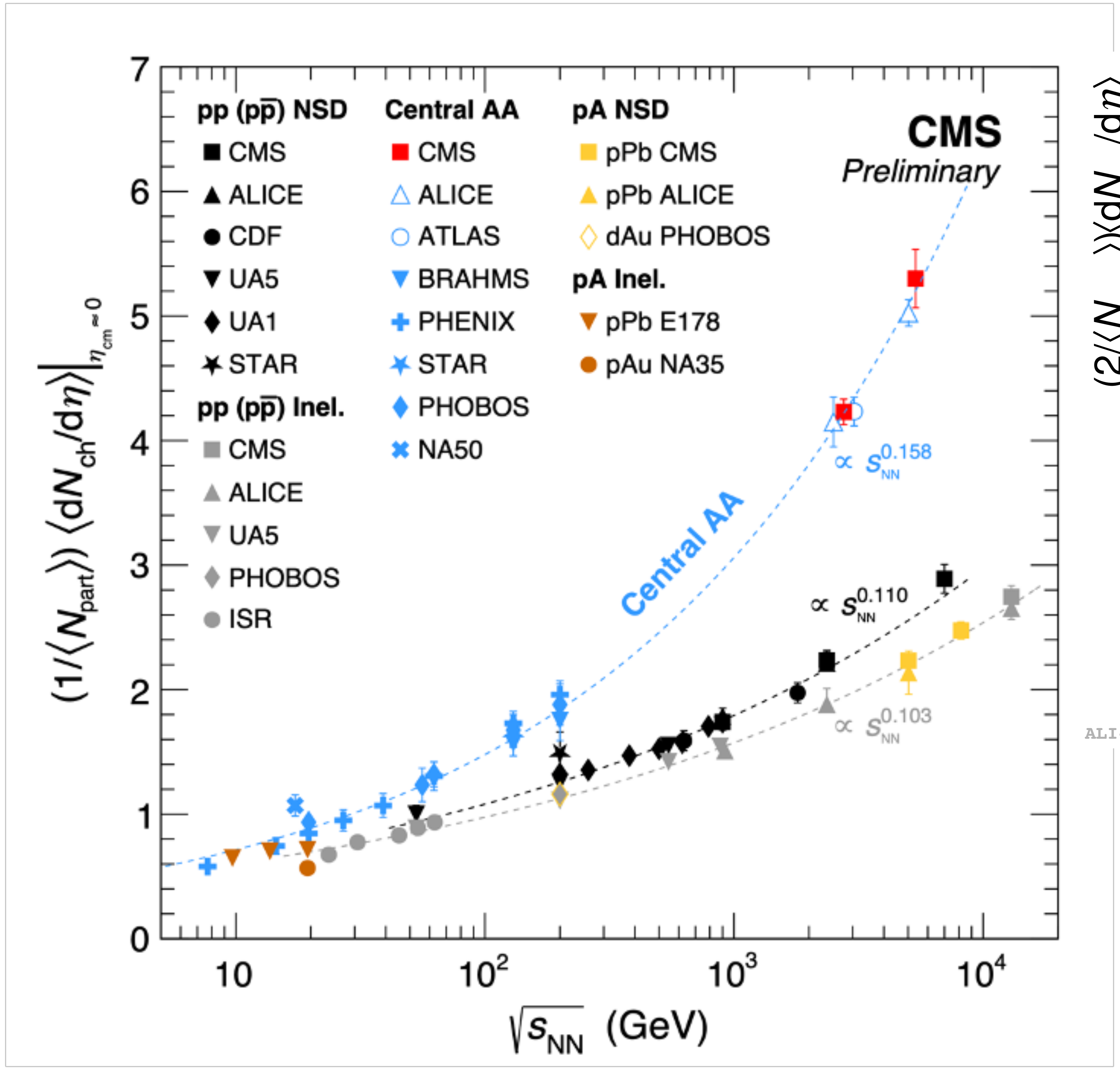


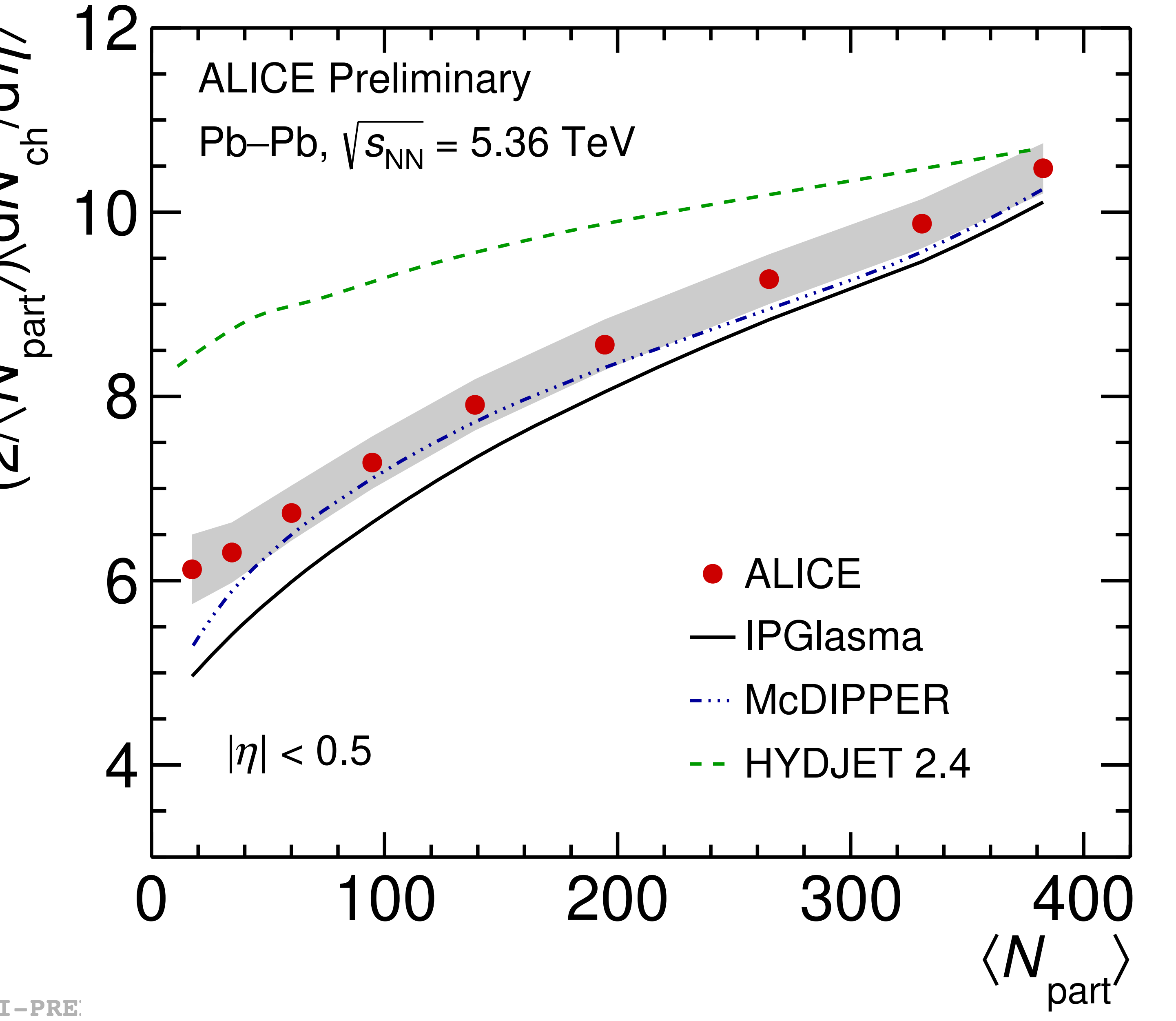
See talk Chengping Shen

The LHC is a beautiful machine for hadron physics!

Particle Production in pp, pA and AA

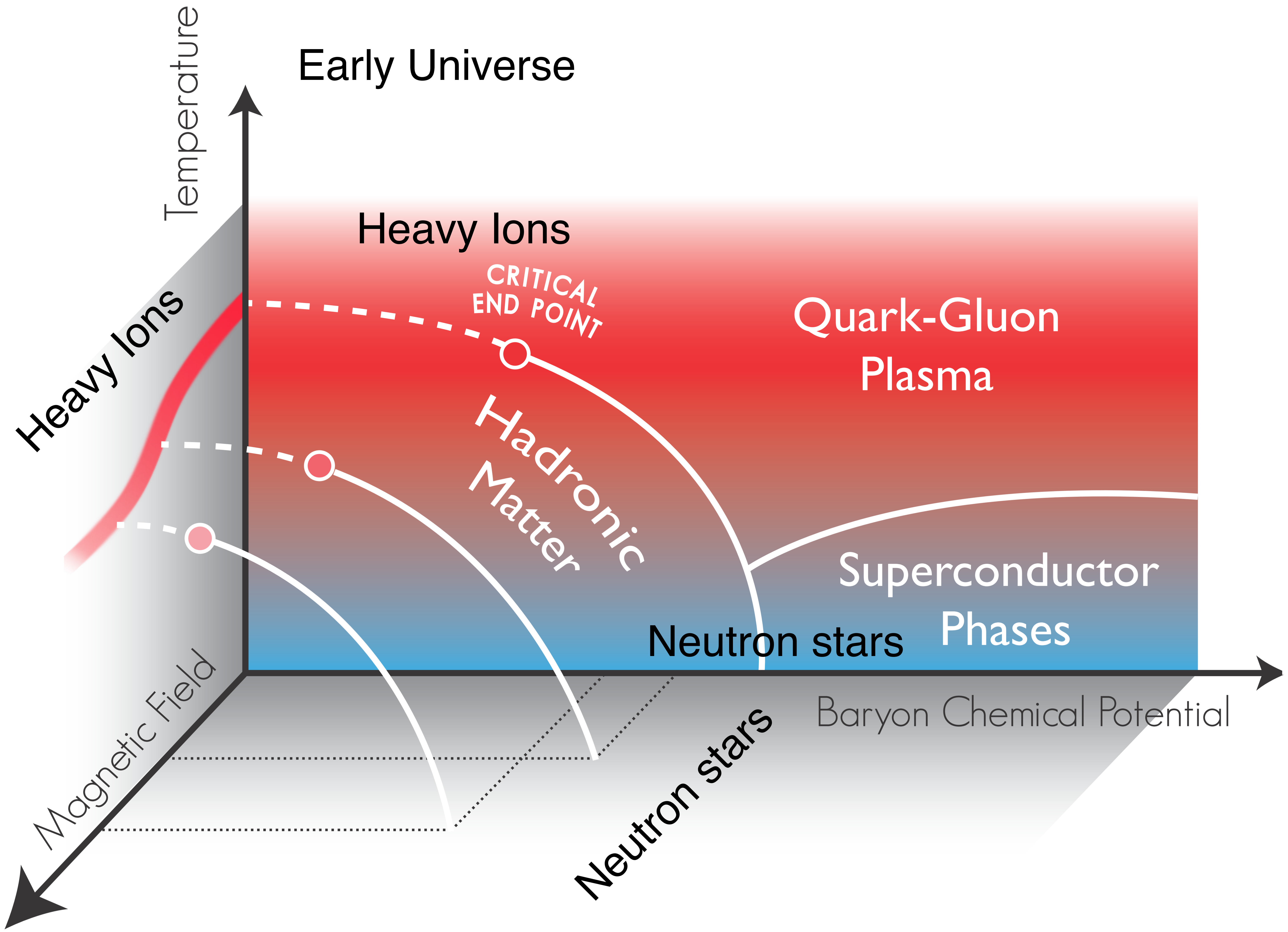


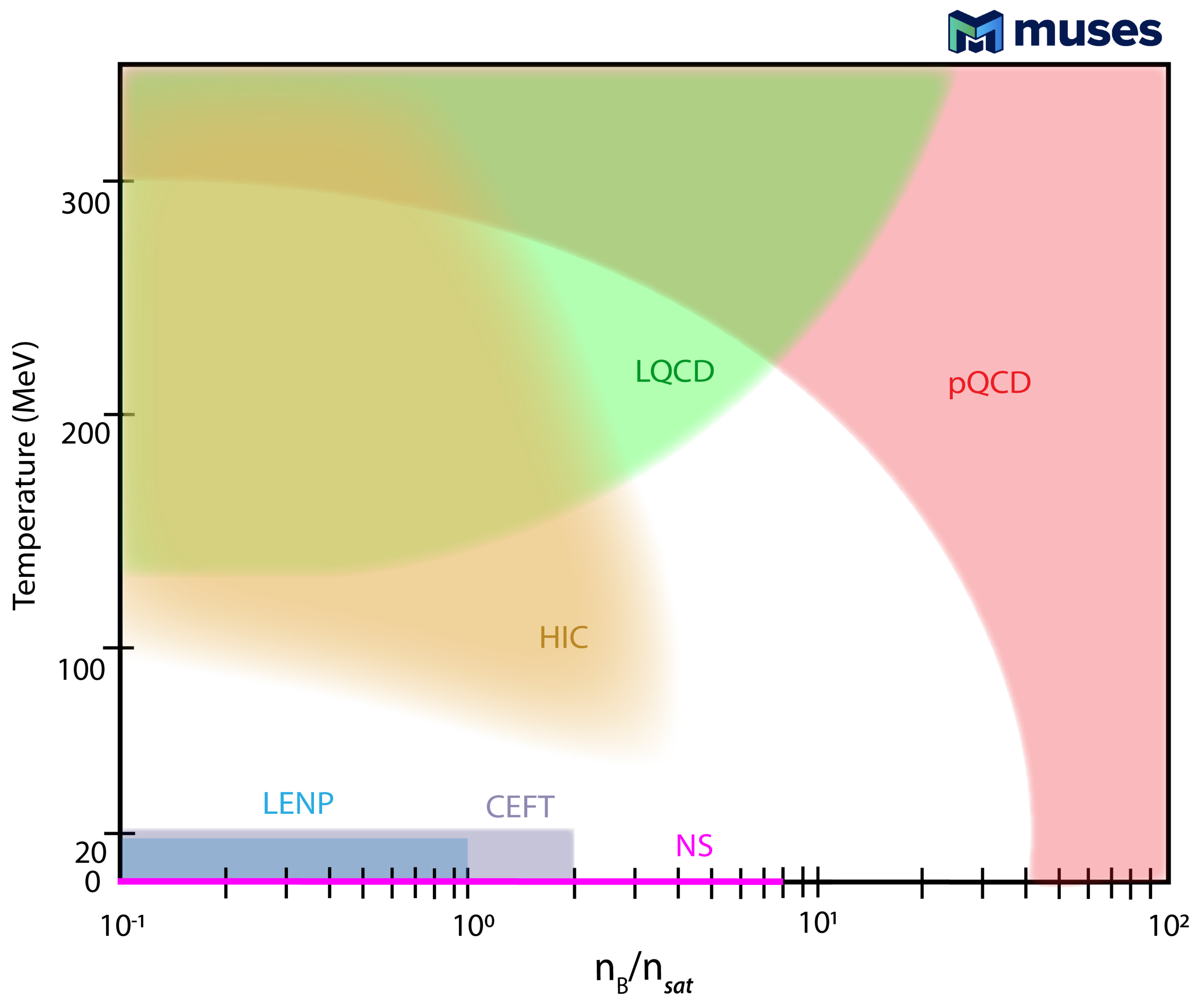




Multiplicity dependence follows power laws from lower energies and grows faster in AA collisions, magnitude and rapidity dependence (even in pp) not fully described by MC calculations

Heavy Ion Collisions

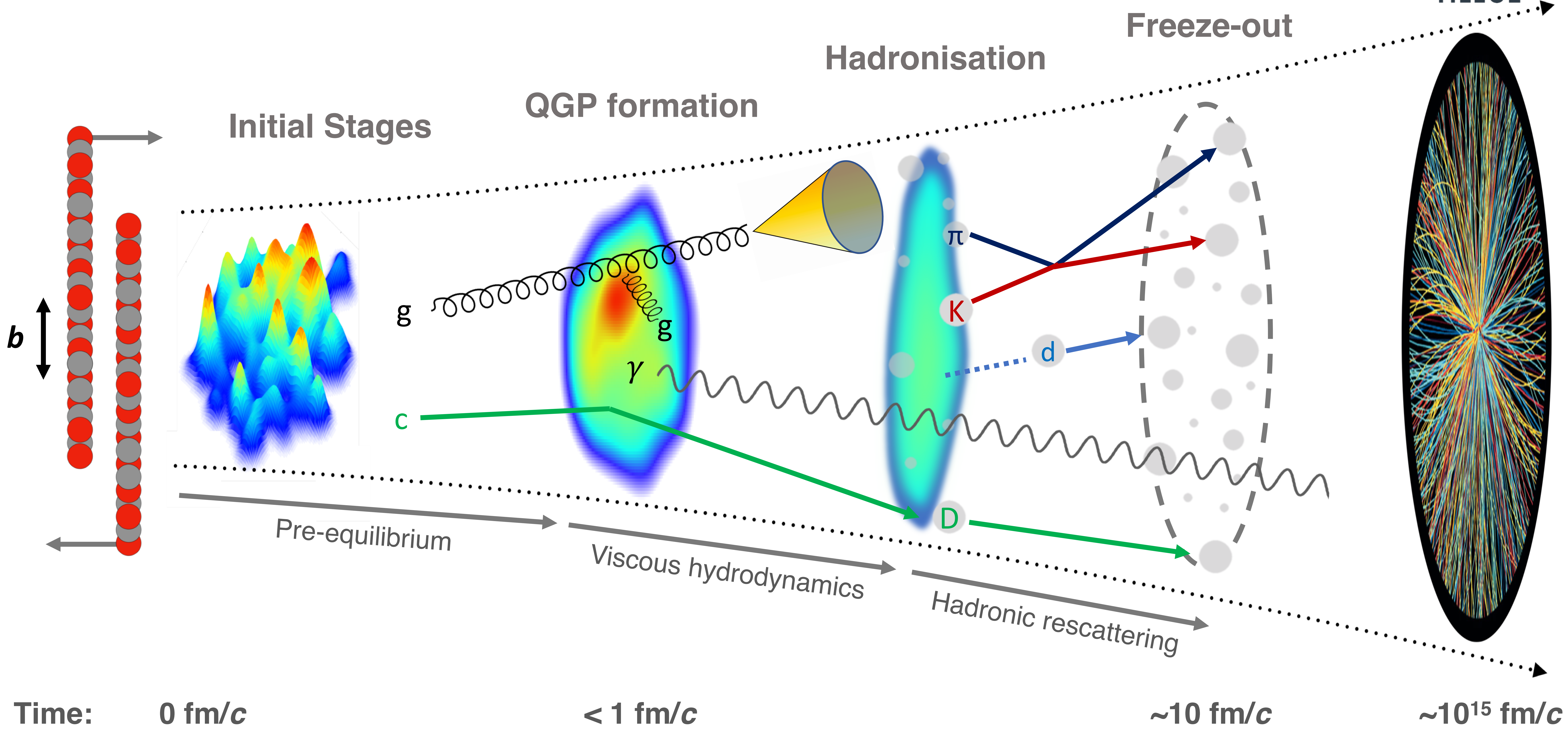




Veronica Dexheimer

Heavy Ion Collisions

See talk of Akihito Monnai



Heavy-Ion Collisions (pre-RHIC)

The model of heavy-ion collisions

The standard model of particle physics

pre-RHIC heavy-ions were modelled by a stitch work of models, one model for each observable

Heavy-Ion Collisions (now)

The standard model of heavy-ion collisions ***The standard model of particle physics***

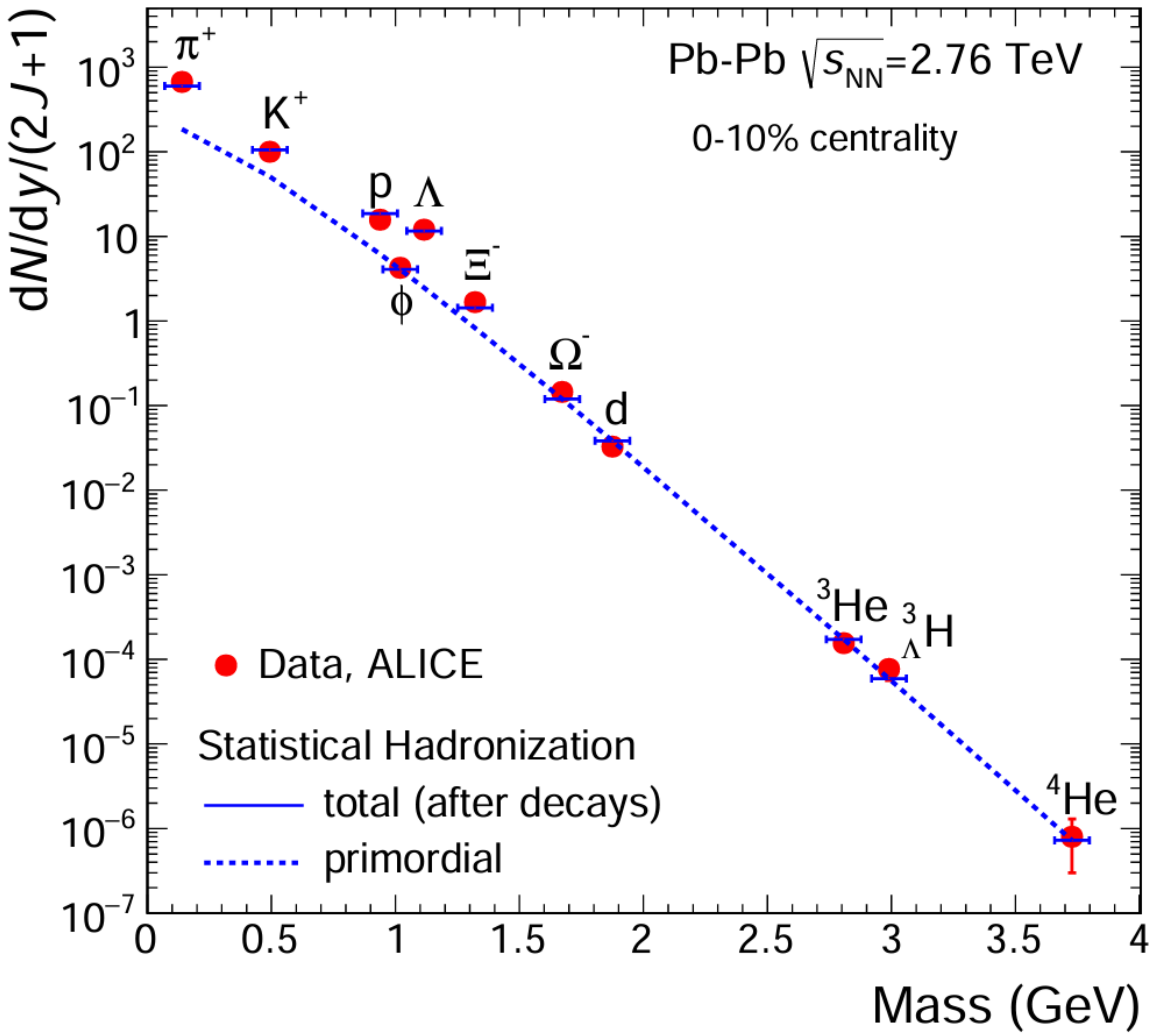
I would like to convince you that due to huge theoretical progress and the experimental measurements at RHIC and the LHC we now have, at least for the soft sector, one standard description

Particle Yields

$$N \propto (2J+1)e^{-m/T}$$

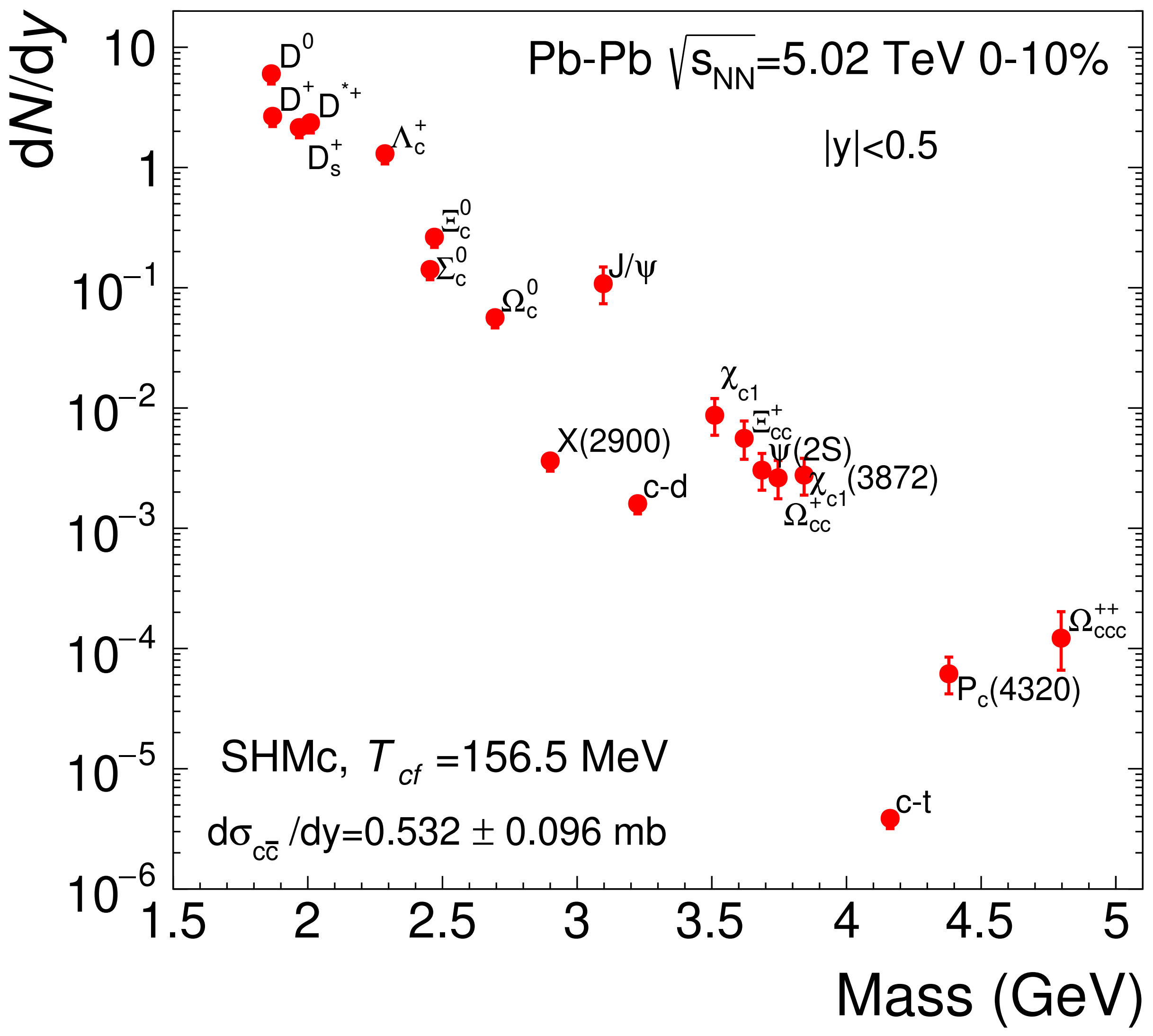
With $T = 156 \pm 2$ MeV, plus resonance feeddown and final state rescattering

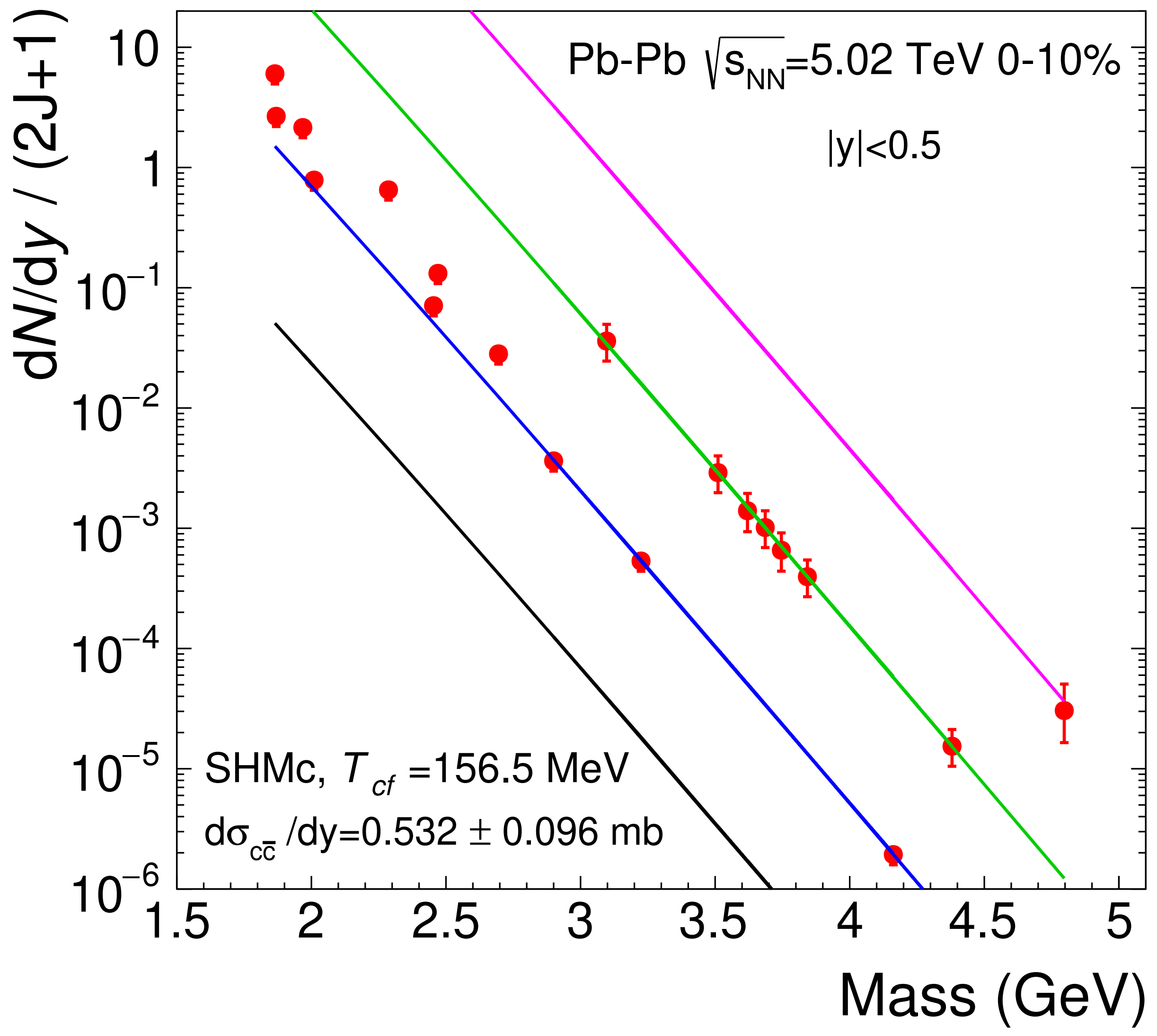
Yield vs mass



Andronic A., et al. Nature 561, 321-330

A. Andronic et al., JHEP07 (2021) 035





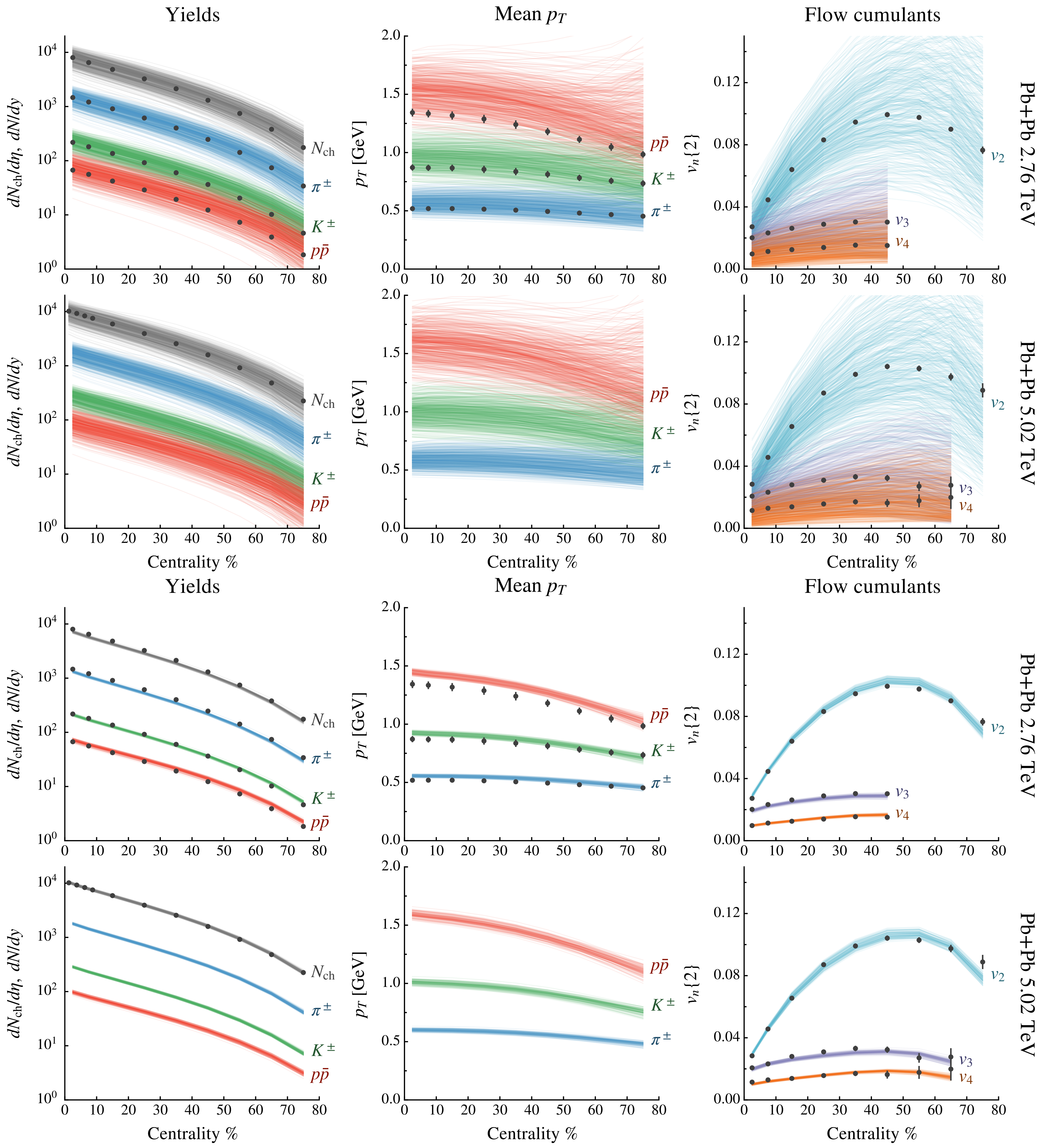
See talks D. Roerich and M. Kweon

Particle abundances, to high precision, are described by thermal models

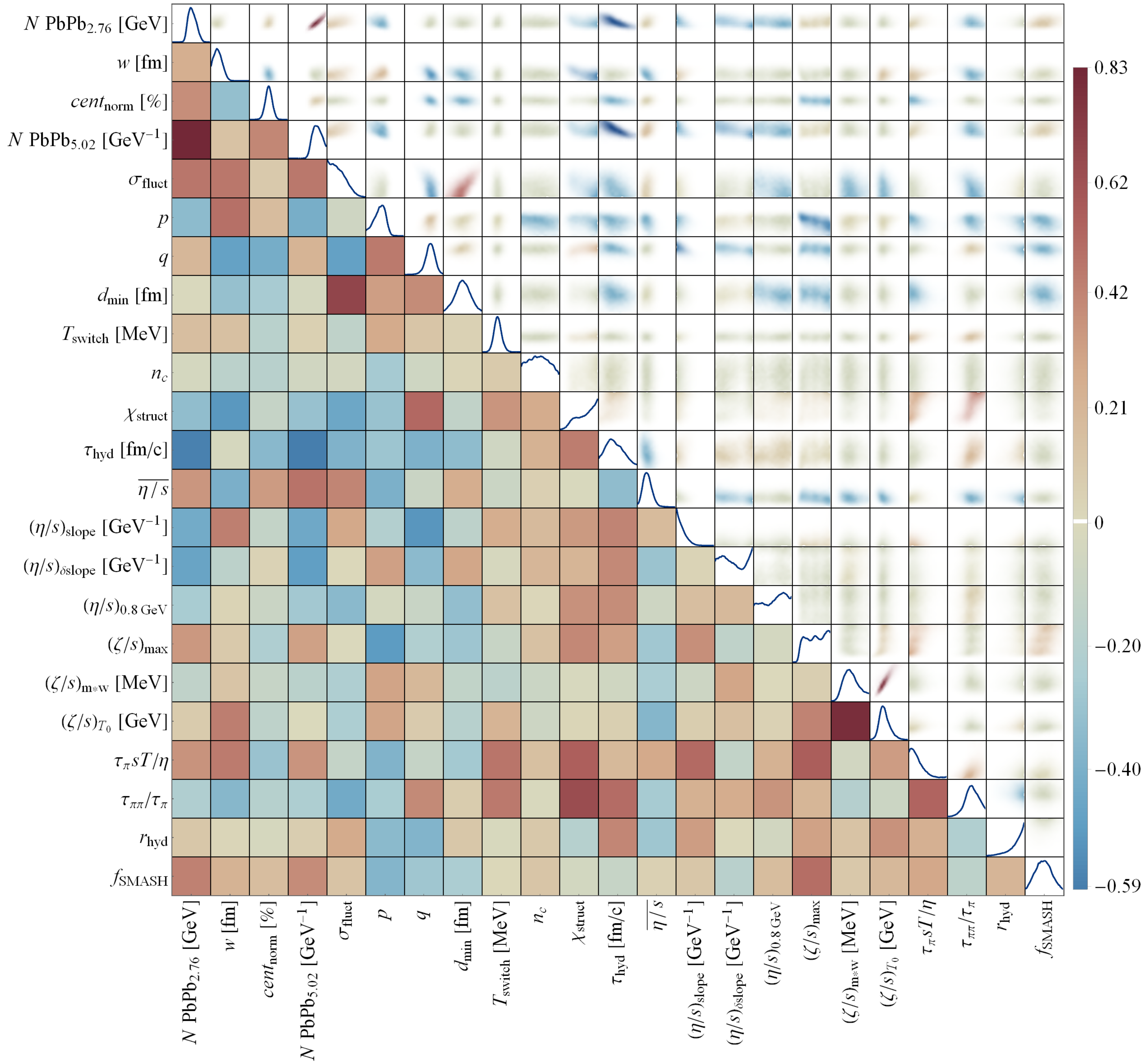
We would like to test them in the future also for the multi-charm particles in detail

Global Bayesian Analysis

S. Bass, J. Bernhard, J. Scott Moreland, arXiv:1704.07671, arXiv:1808.02106

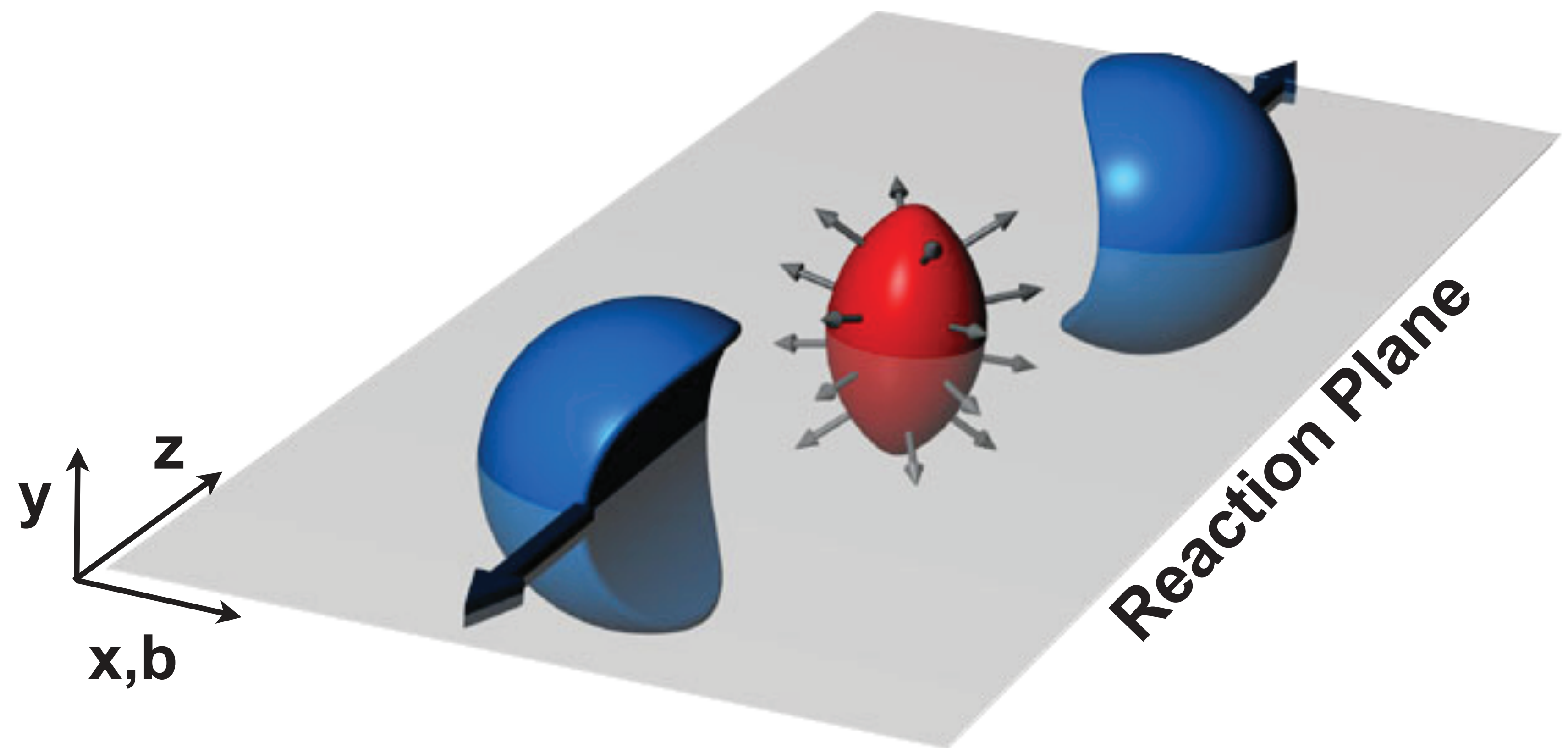


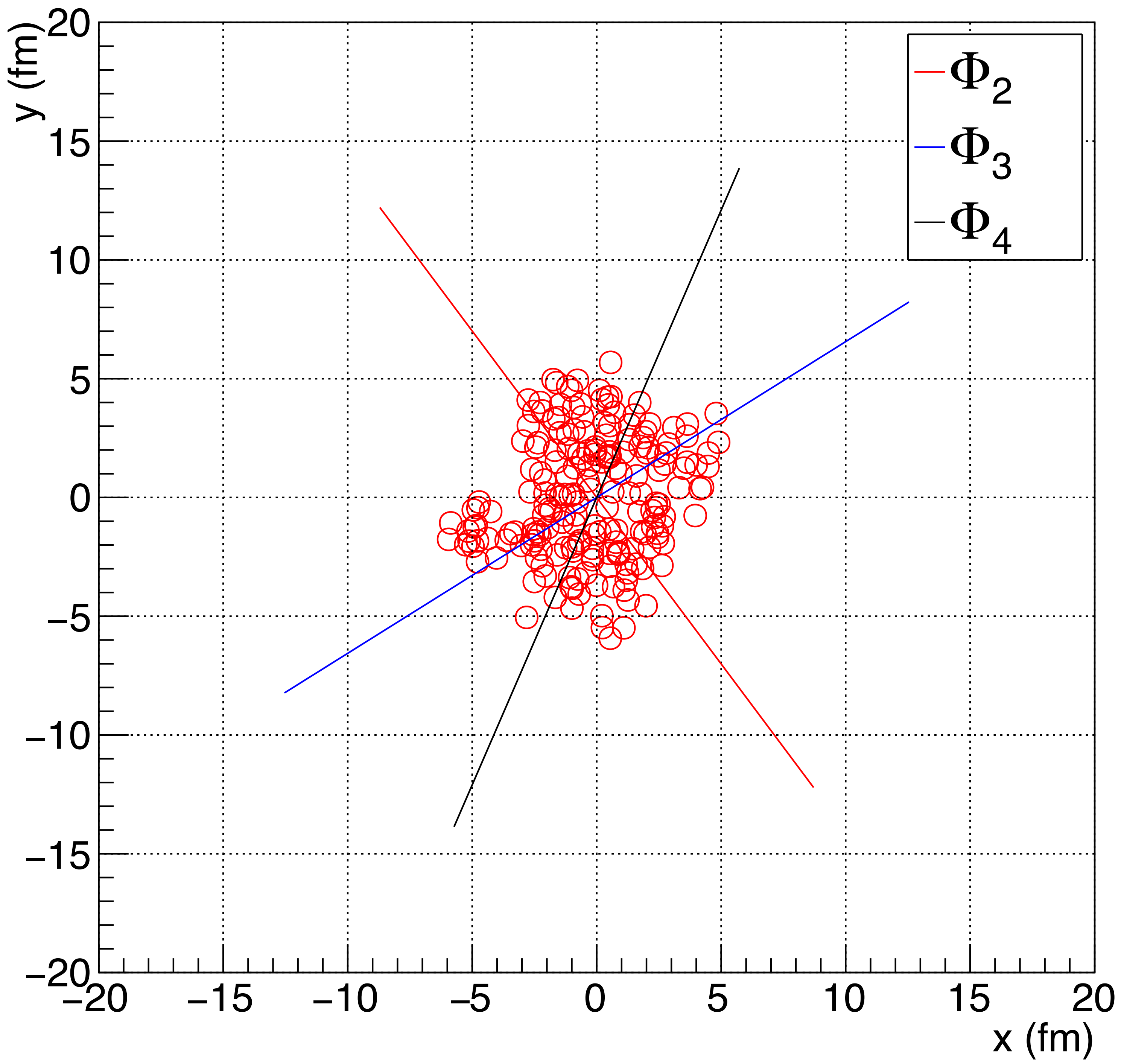
G.Nijs and W. van der Schee. arXiv:2304.0619v1



How can these sets of observables constrain so many model parameters?

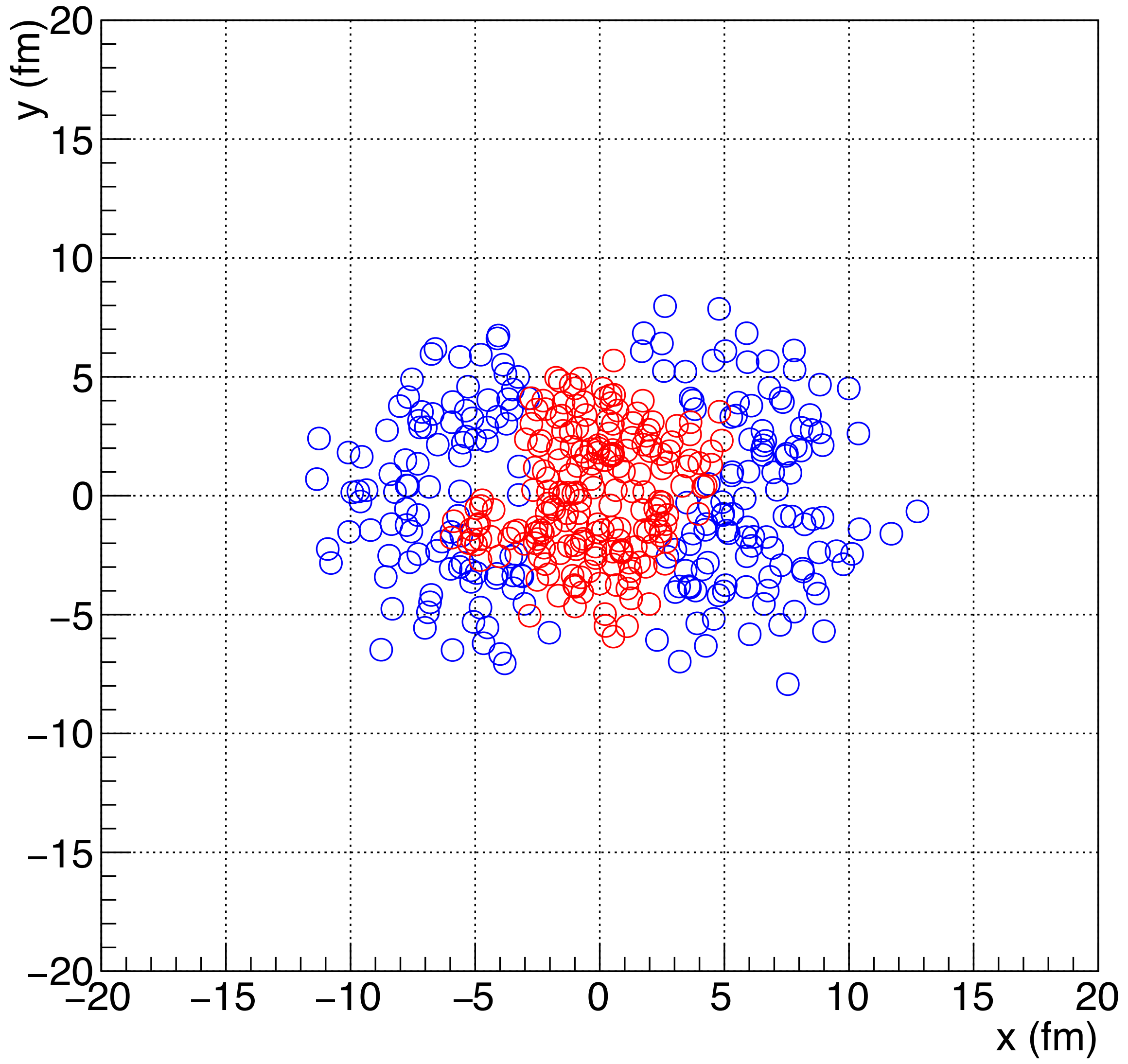
Planes



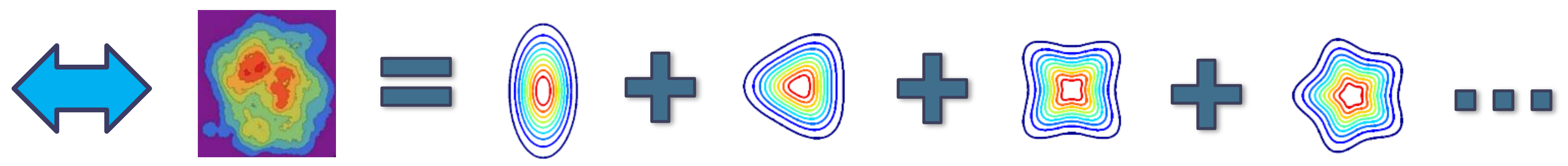


$$\varepsilon_1, \varepsilon_2, \varepsilon_3, \cdots \longrightarrow v_1, v_2, v_3, \cdots$$

$$\Phi_1, \Phi_2, \Phi_3, \cdots \longrightarrow \Psi_1, \Psi_2, \Psi_3, \cdots$$



$$f(\varphi) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right]$$



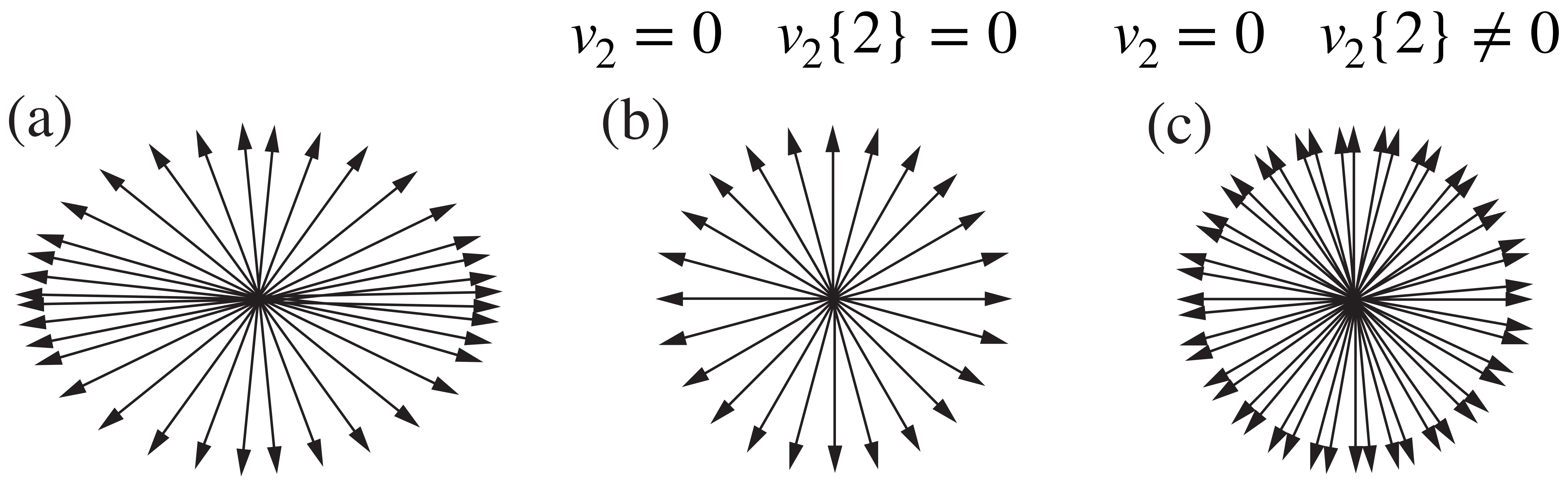
Proportionality v_n to initial geometry ε_n and correlation between v_n's very sensitive to the initial stage and the properties of the QGP

See talk A. Bilandzic

v_n Observables Via Correlations

$$v_n(p_t, y) = \langle \cos[n(\varphi - \Psi_n)] \rangle$$

$$\langle\langle e^{i2(\varphi_1-\varphi_2)}\rangle\rangle = \langle\langle e^{i2(\varphi_1-\Psi_{RP}-(\varphi_2-\Psi_{RP}))}\rangle\rangle$$
$$= \langle\langle e^{i2(\varphi_1-\Psi_{RP})}\rangle\langle e^{-i2(\varphi_2-\Psi_{RP})}\rangle + \delta_2\rangle,$$
$$= \langle v_2^2 + \delta_2\rangle,$$



$$c_2\{2\} \equiv \left\langle\left\langle e^{i2(\varphi_1-\varphi_2)}\right\rangle\right\rangle = \left\langle v_2^2 + \delta_2\right\rangle.$$

$$c_2\{4\} \equiv \left\langle\left\langle e^{i2(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\right\rangle\right\rangle - 2\left\langle\left\langle e^{i2(\varphi_1-\varphi_2)}\right\rangle\right\rangle^2,$$
$$= \left\langle v_2^4 + \delta_4 + 4v_2^2\delta_2 + 2\delta_2^2\right\rangle - 2\left\langle v_2^2 + \delta_2\right\rangle^2,$$
$$= \left\langle -v_2^4 + \delta_4\right\rangle.$$

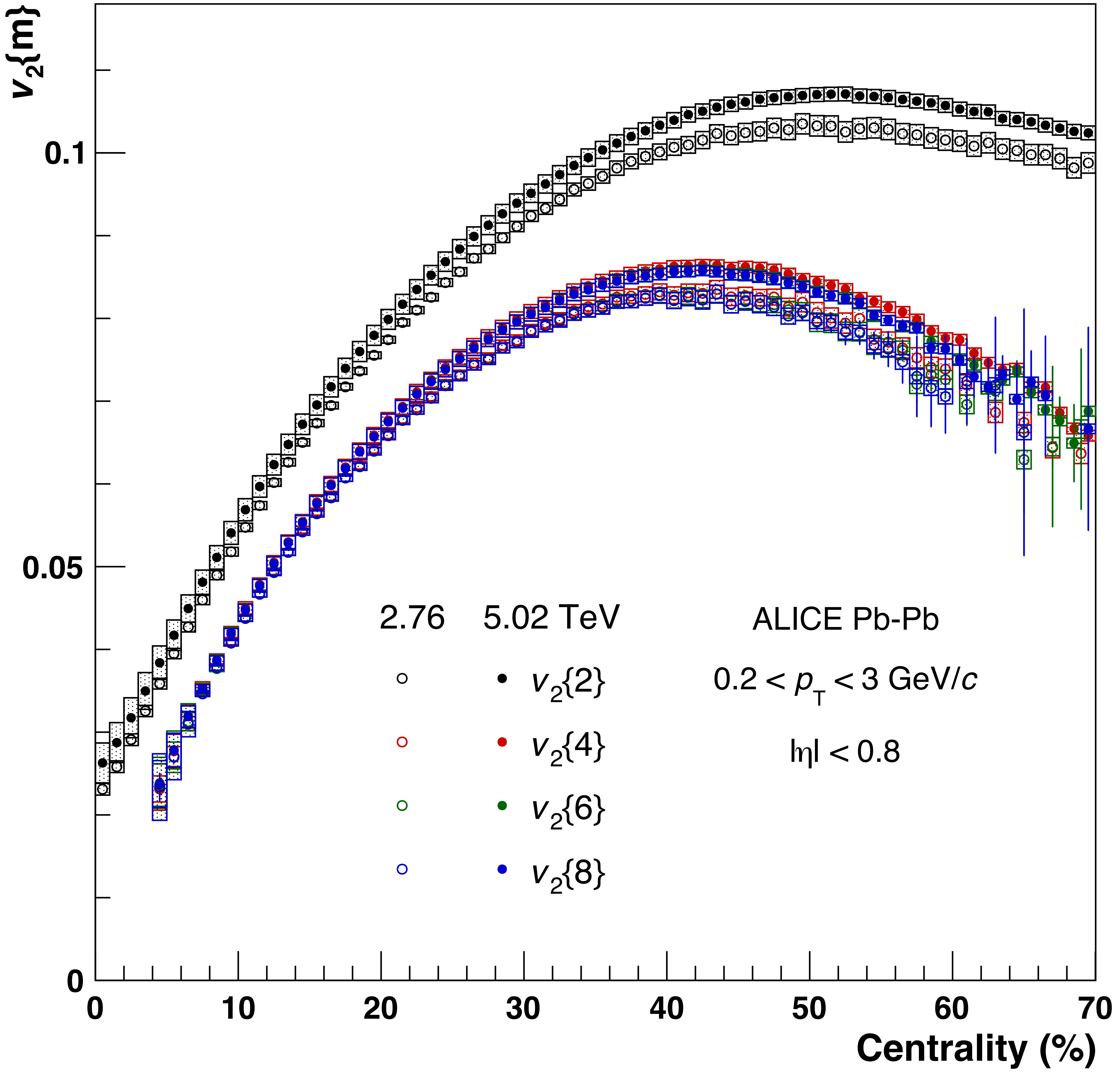
Non flow $\quad \delta_2 \propto 1/N_C \quad \delta_4 \propto 1/N_C^3$

Fluctuations $\quad \langle v_2^2\rangle = \langle v_2\rangle^2 + \sigma^2$

if $\sigma \ll \langle v \rangle$ then

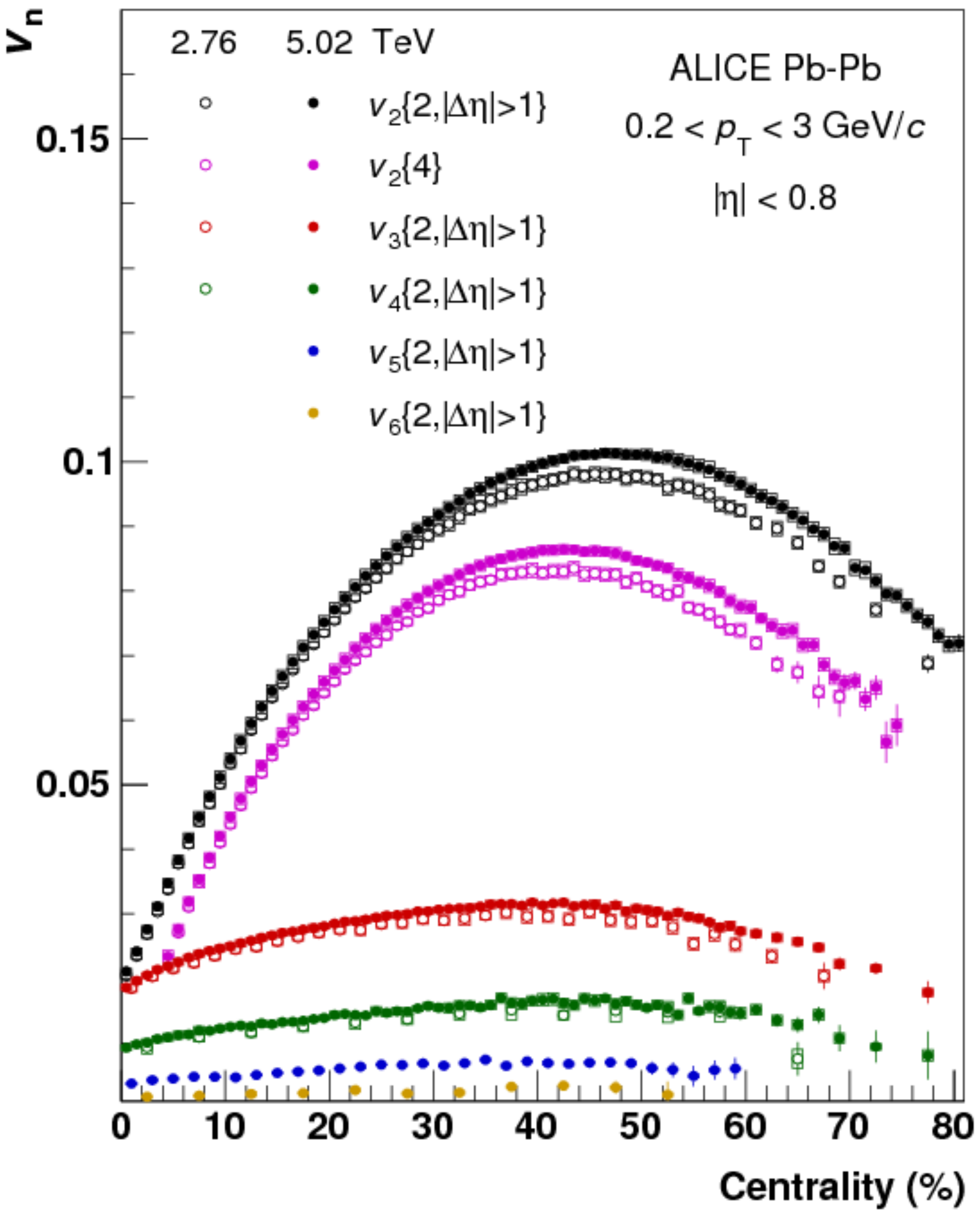
$$v_2\{2\} = \langle v_2\rangle + \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle},$$
$$v_2\{4\} = \langle v_2\rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle},$$
$$v_2\{6\} = \langle v_2\rangle - \frac{1}{2}\frac{\sigma^2}{\langle v_2\rangle}.$$

Anisotropic Flow



The different measurements of v_2 are sensitive to the moments of the v_2 distribution, if $v_2\{4\}=v_2\{6\}=v_2\{8\}$ the distribution is a Bessel-Gaussian p.d.f.

ALICE, JHEP 1807 (2018) 103

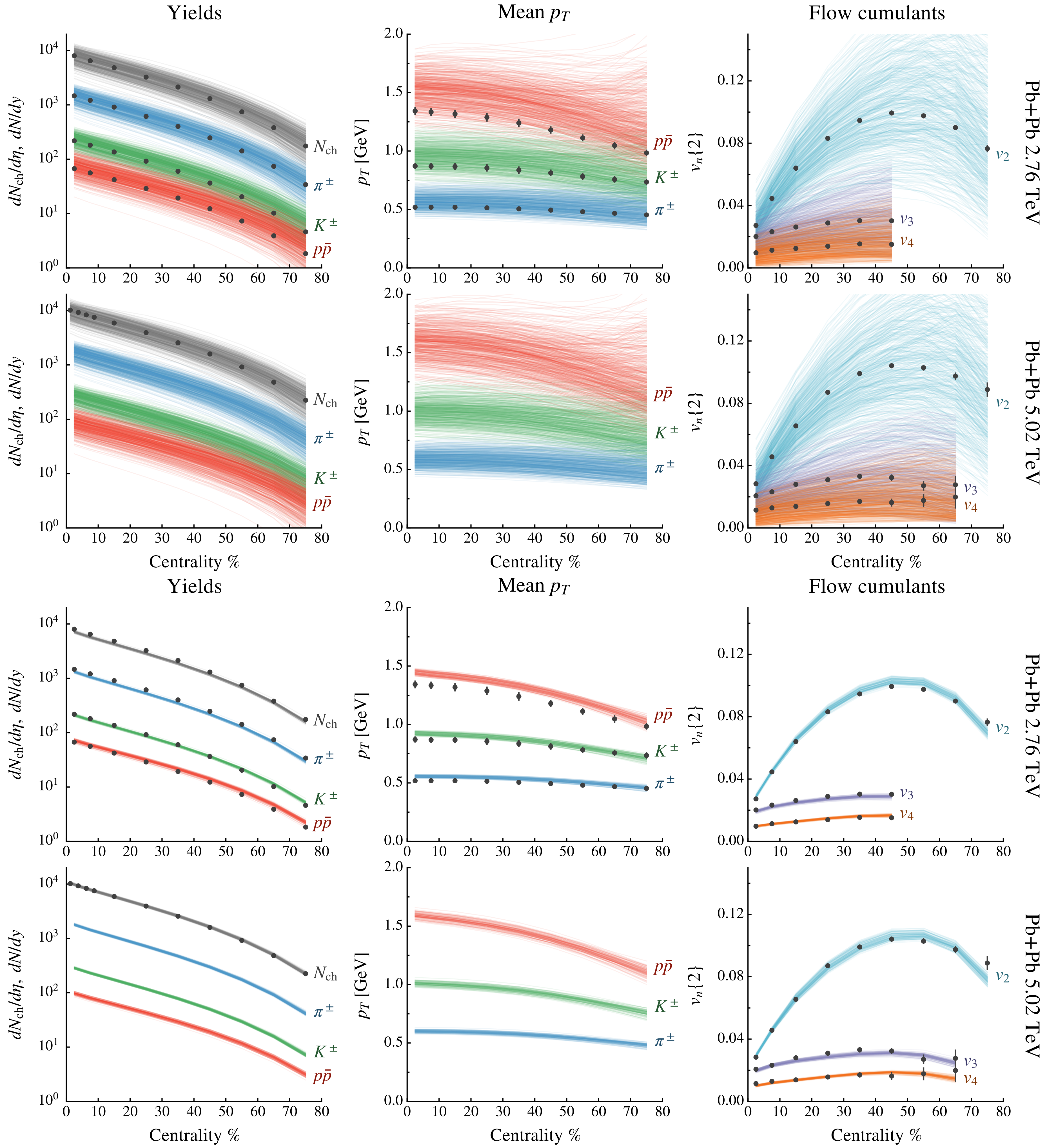


Anisotropic Flow

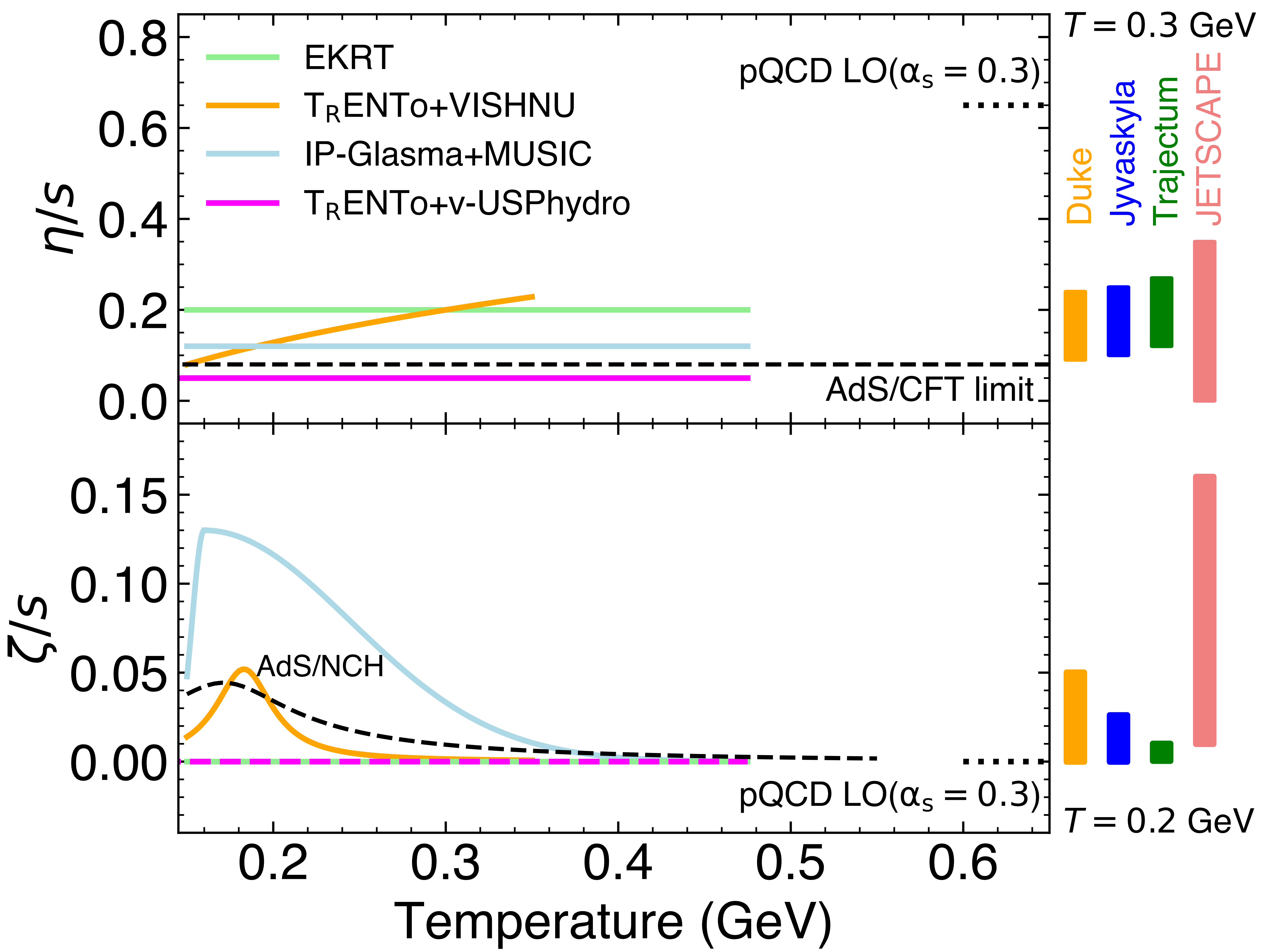
- ✓The v_2's show a typical mass dependence at low-p_T which is expected from a boosted thermal system
- ✓At intermediate p_T they show a number of quark scaling expected from recombination
- ✓Also the charm sector exhibits these v_2's for open charm and for J/Ψ, the Υ does not show v_2 within uncertainties
- ✓Difference between v_2 of the prompt and non-prompt D's show evidence for coalescence

Global Bayesian Analysis

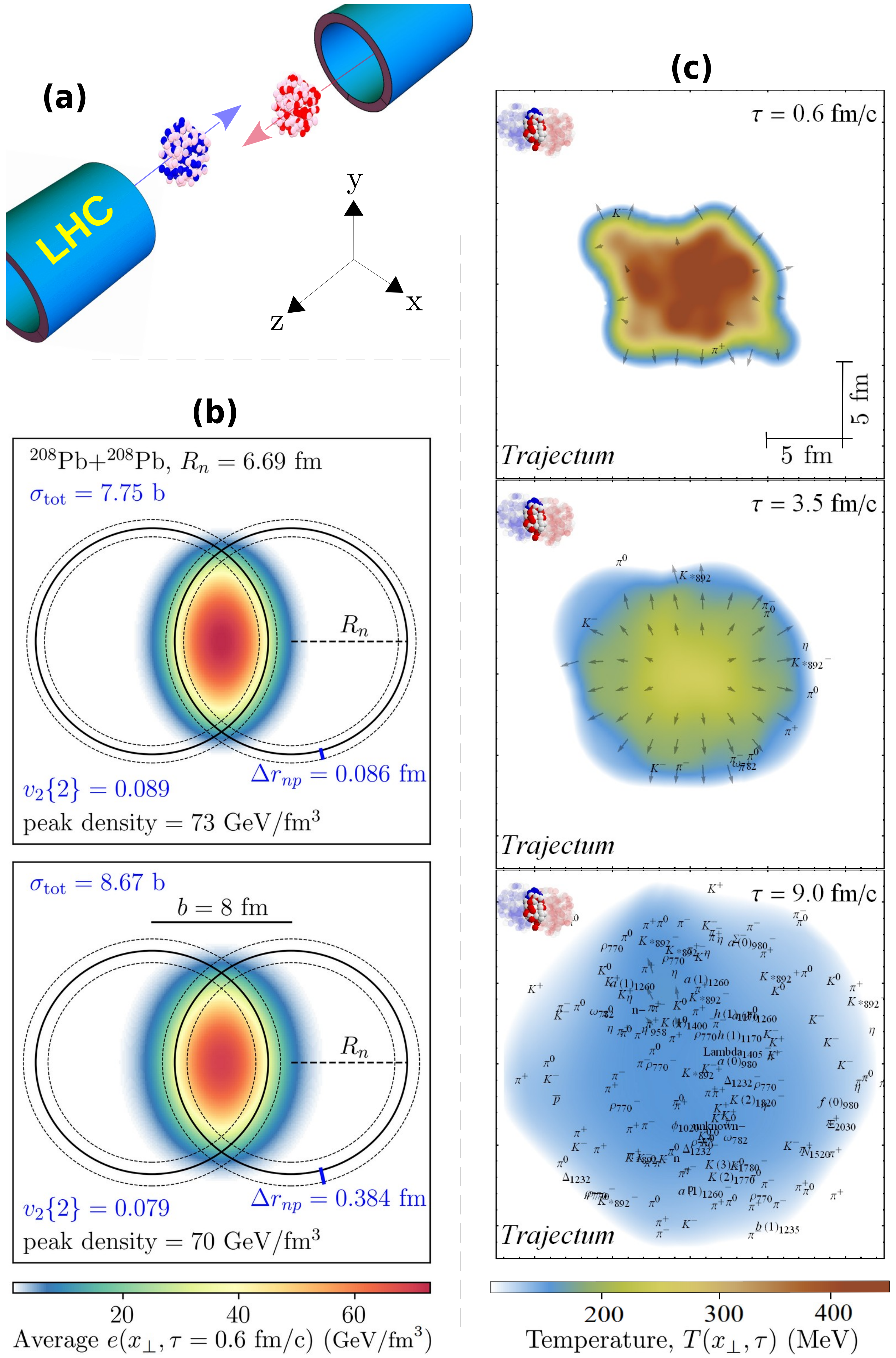
S. Bass, J. Bernhard, J. Scott Moreland,
arXiv:1704.07671, arXiv:1808.02106

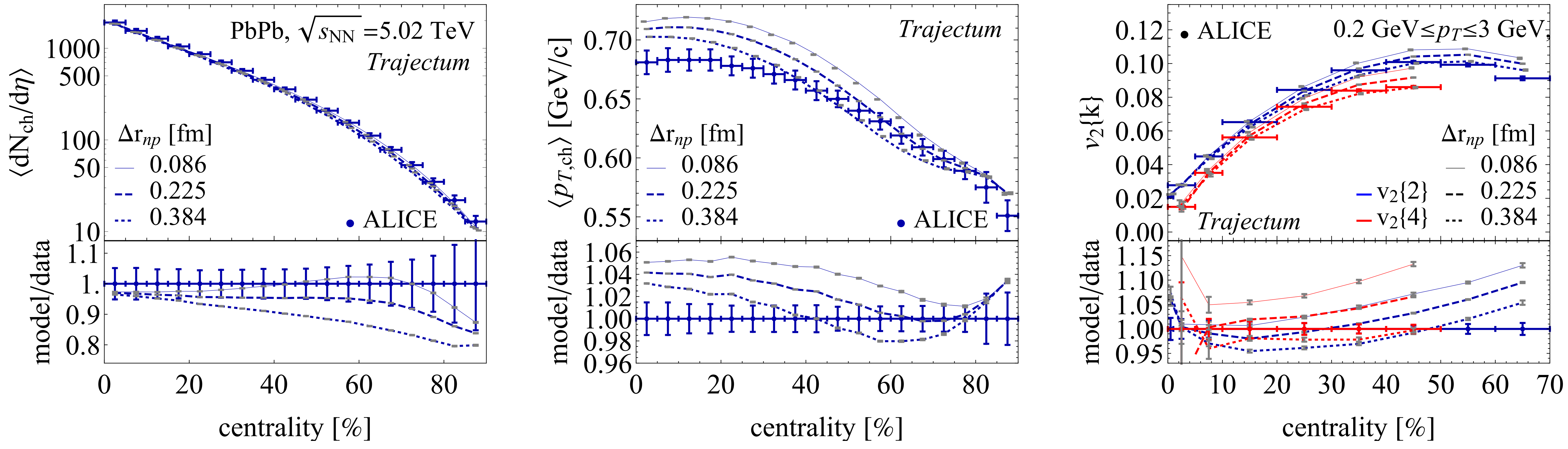


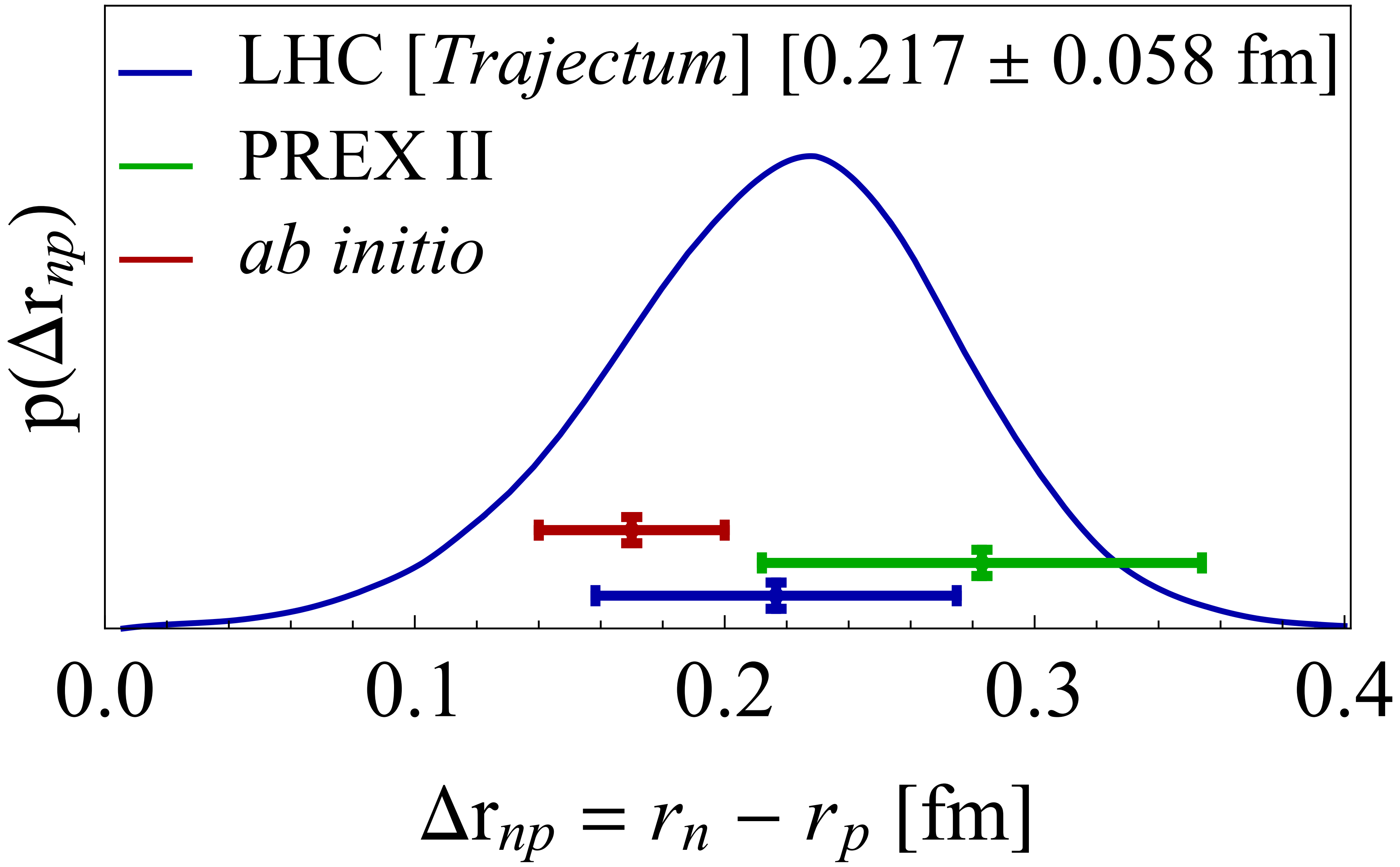
ALICE Collaboration:arXiv:2211.04384

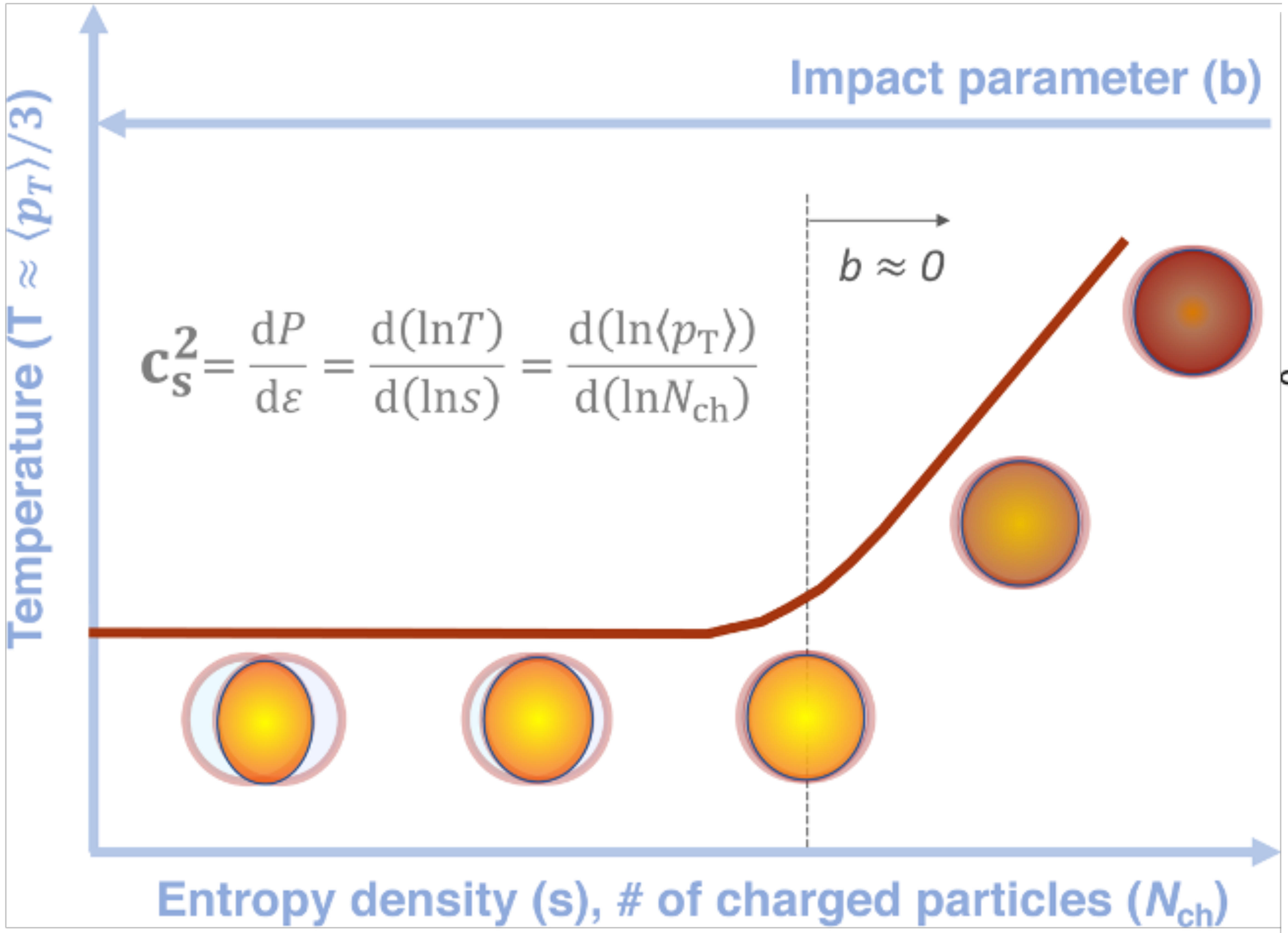


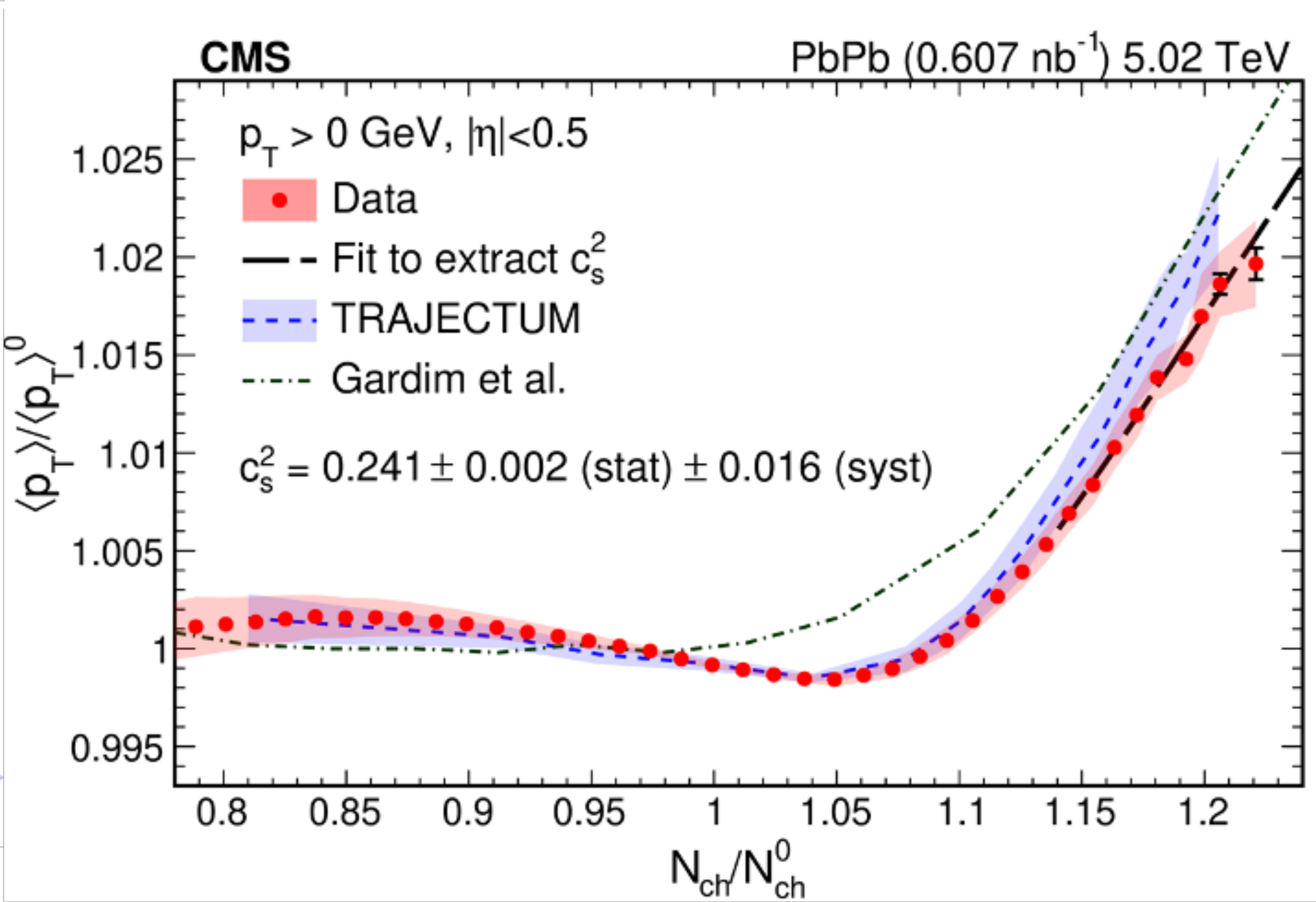
Neutron Skin







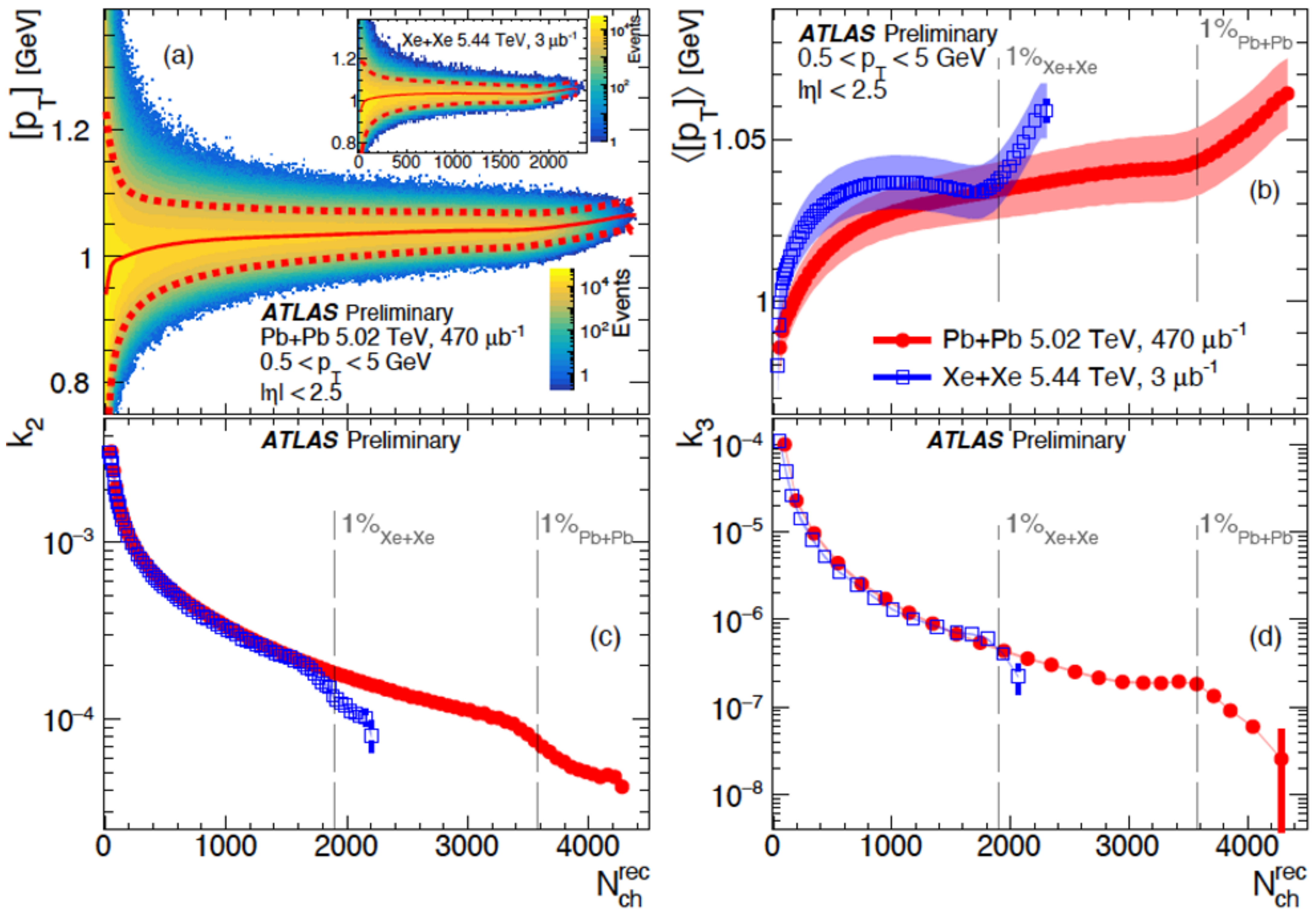


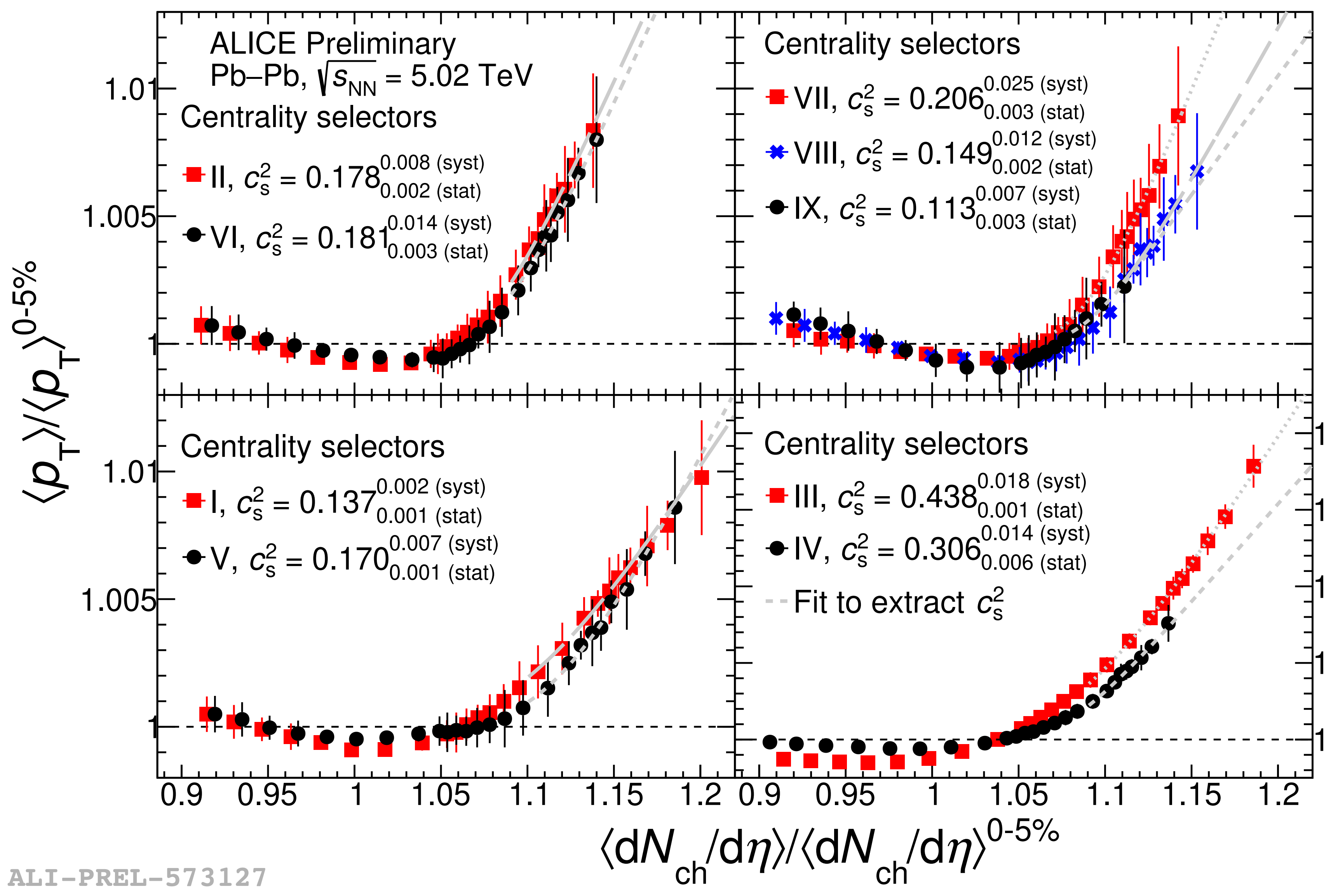


Idea is that in ultra-central events the entropy increases at fixed volume, which allows one to measure the speed of sound
CMS measurement in very good agreements with model predictions

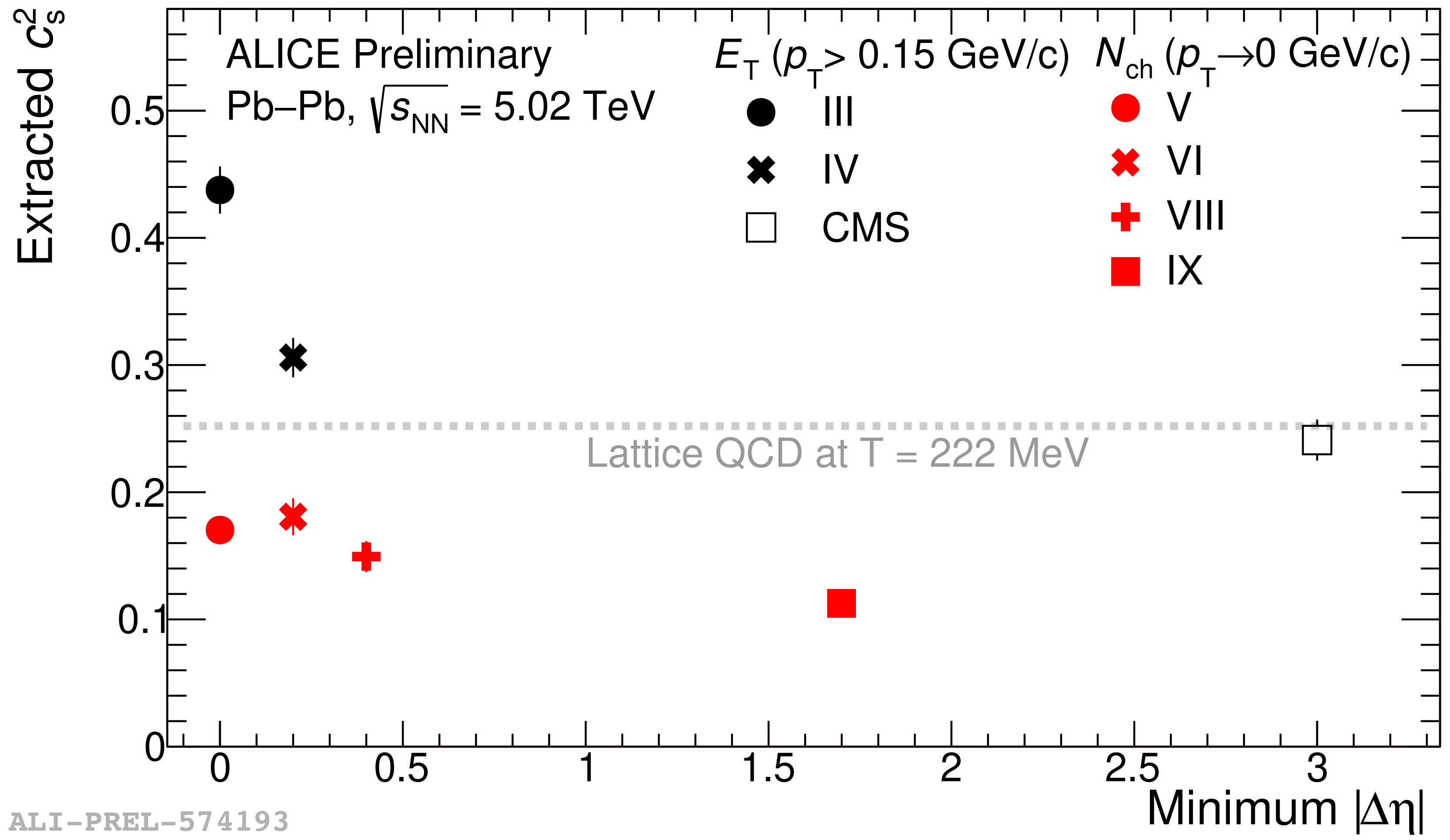
F. Gardim et al., PLB 809, 135749

CMS, arXiv: 2401.06896



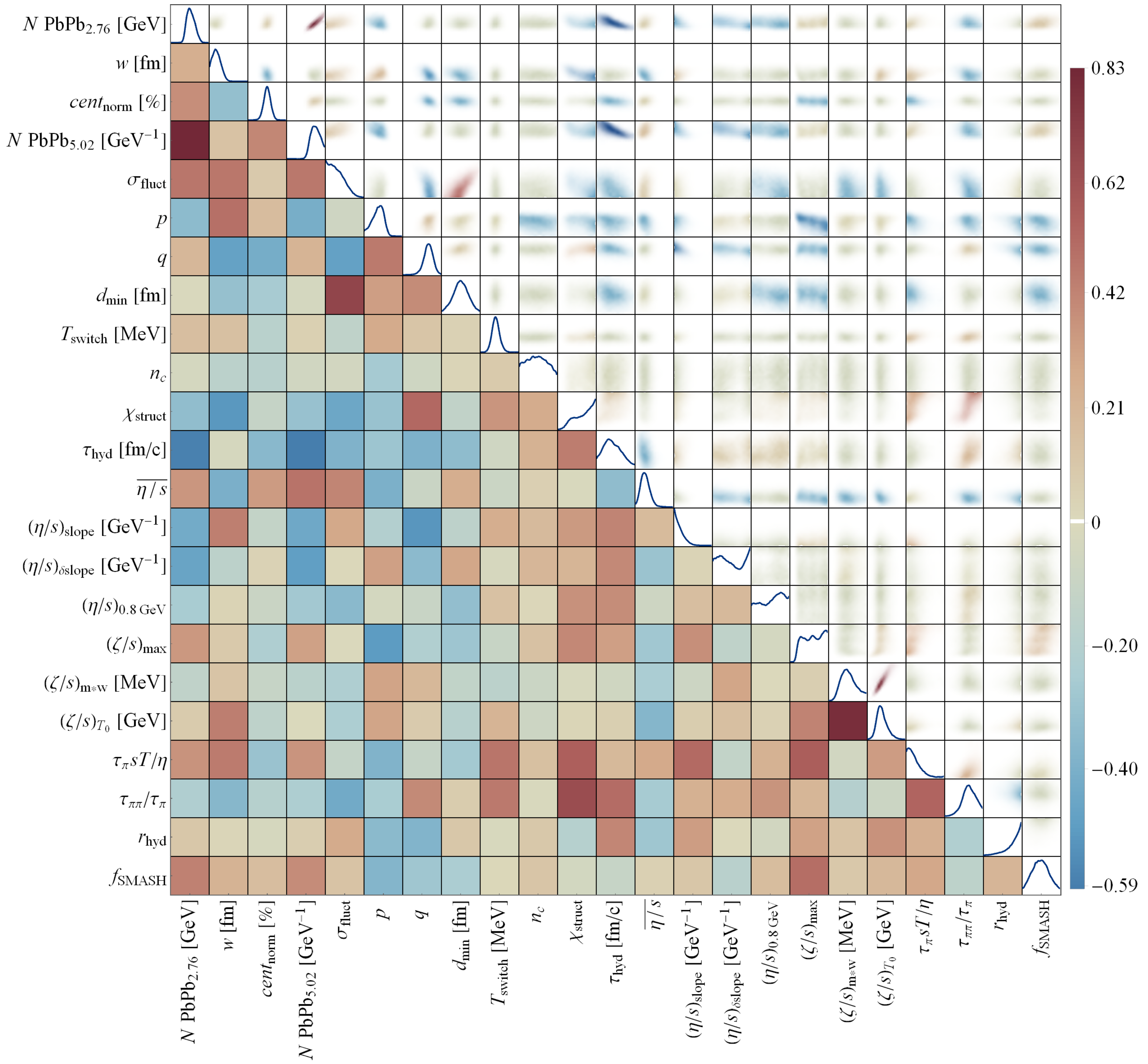


ATLAS and ALICE observe similar behaviour
However different centrality estimates give different values of the speed of sound



G. Nijs and W. Van der Schee, PLB 853 138636

Heavy-Ion Collisions (now)



The standard model of heavy-ion collisions

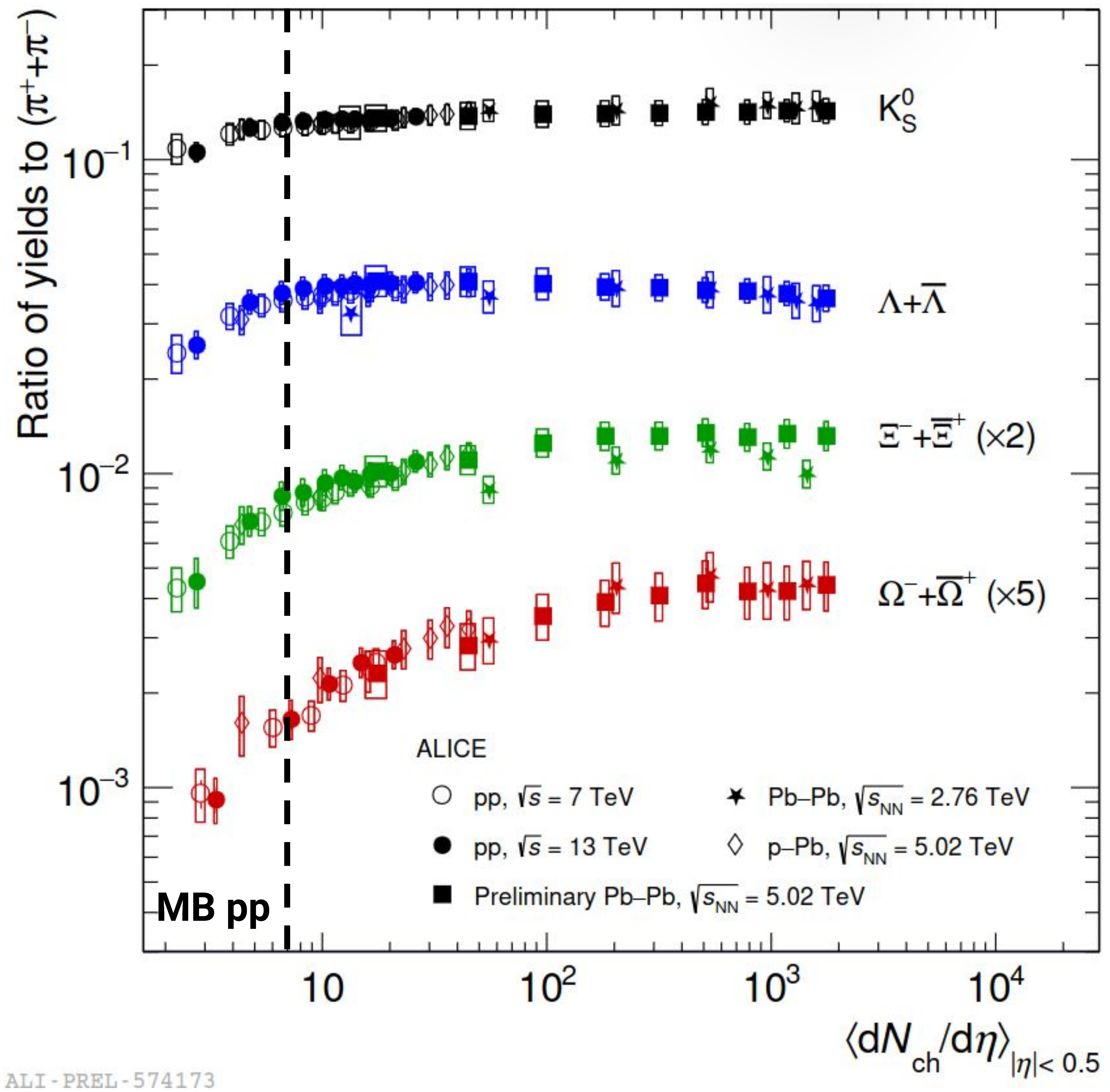
In AA we create a system which can be described very well by hydrodynamics and we can start to extract the properties of the QGP with uncertainties (EoS, transport parameters).

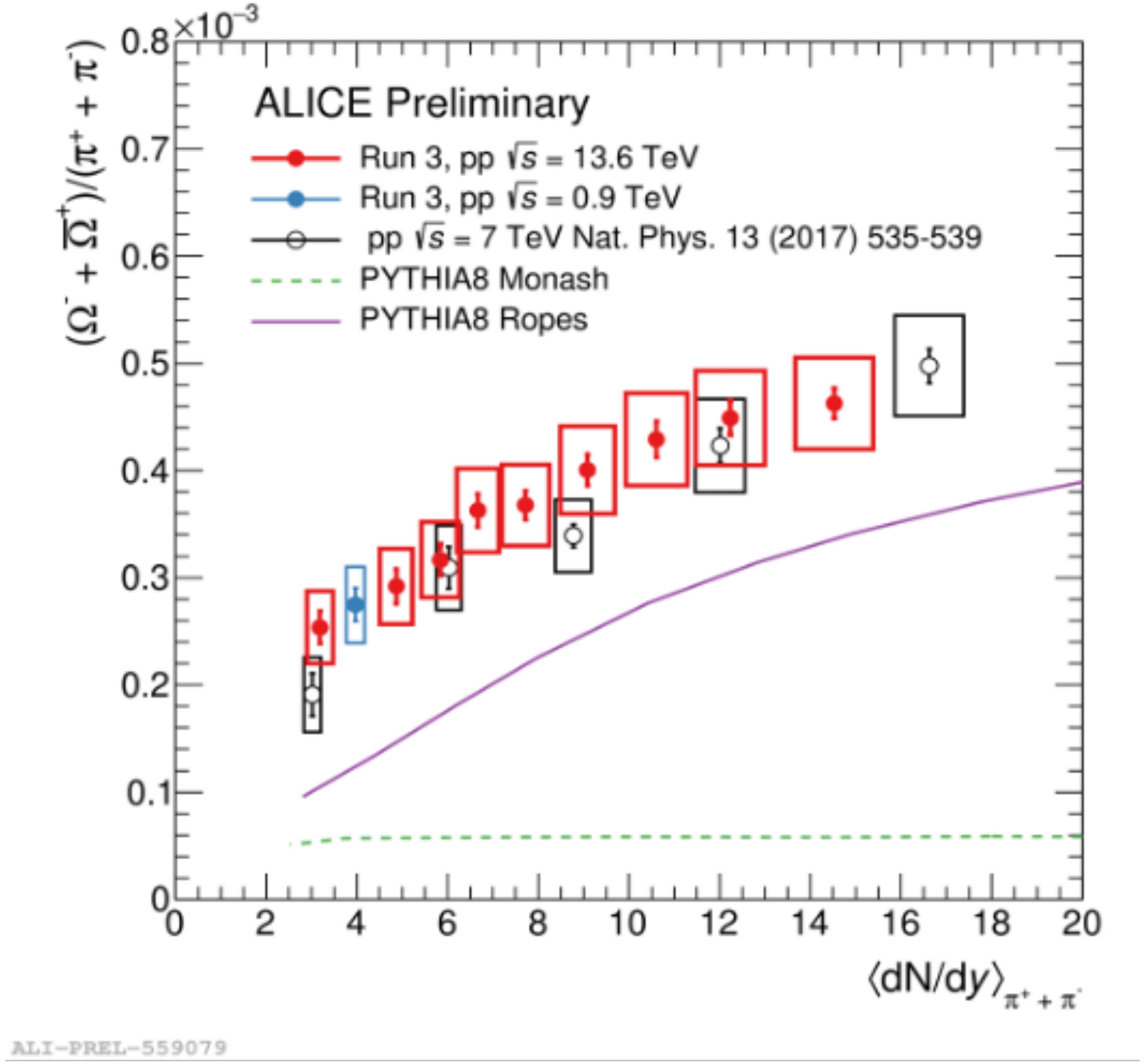
Can we understand the underlying microscopic properties which lead to this hydrodynamic behaviour?

To understand the microscopic properties of the system we can move away from the large system where thermalisation and hydrodynamics dominate and look at smaller systems such as pA and even pp

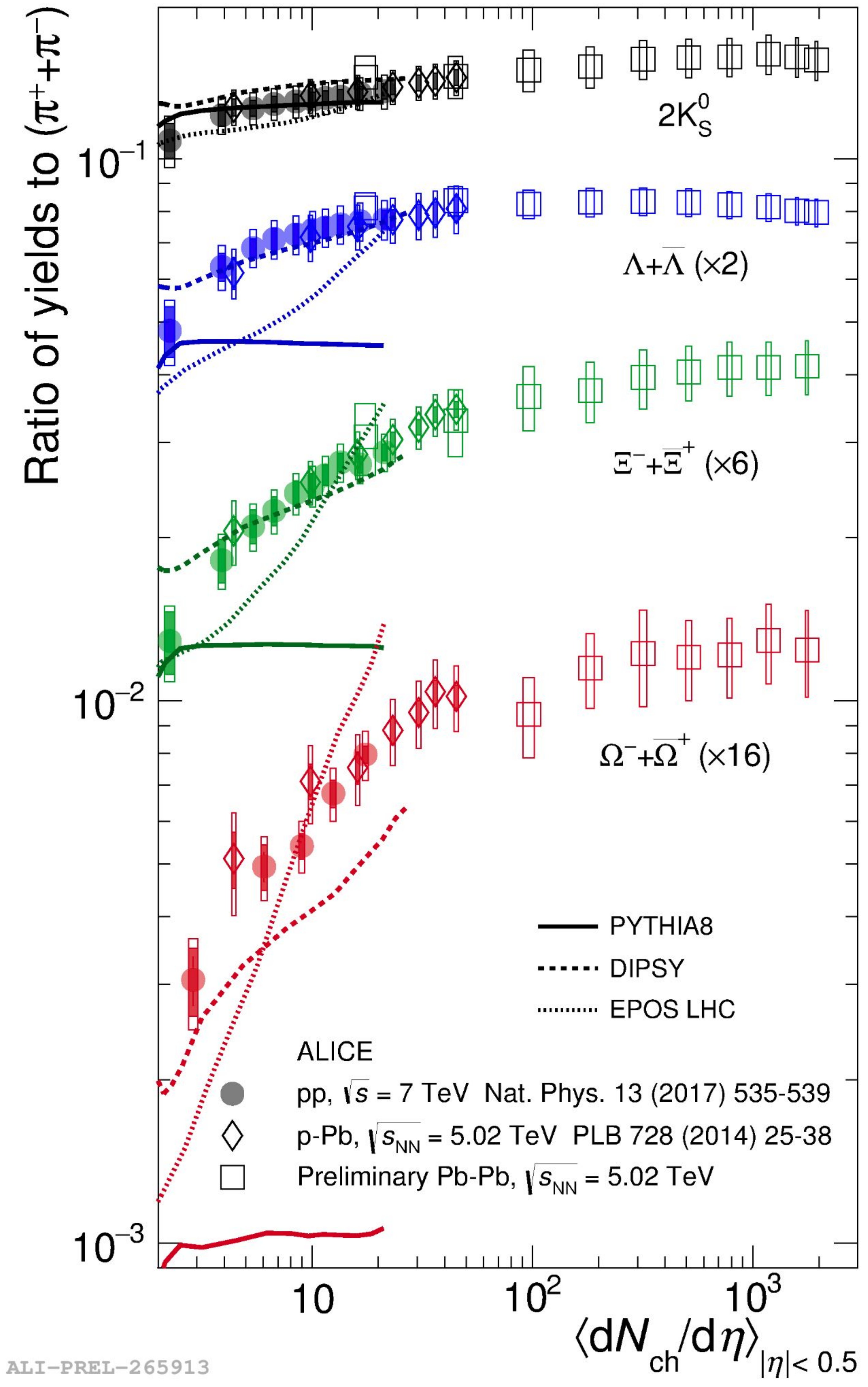
In the remainder of the talk I will show results as function of system size on strangeness production, the v_2 for different particle species, and even the $\Upsilon(nS)$ production in pA

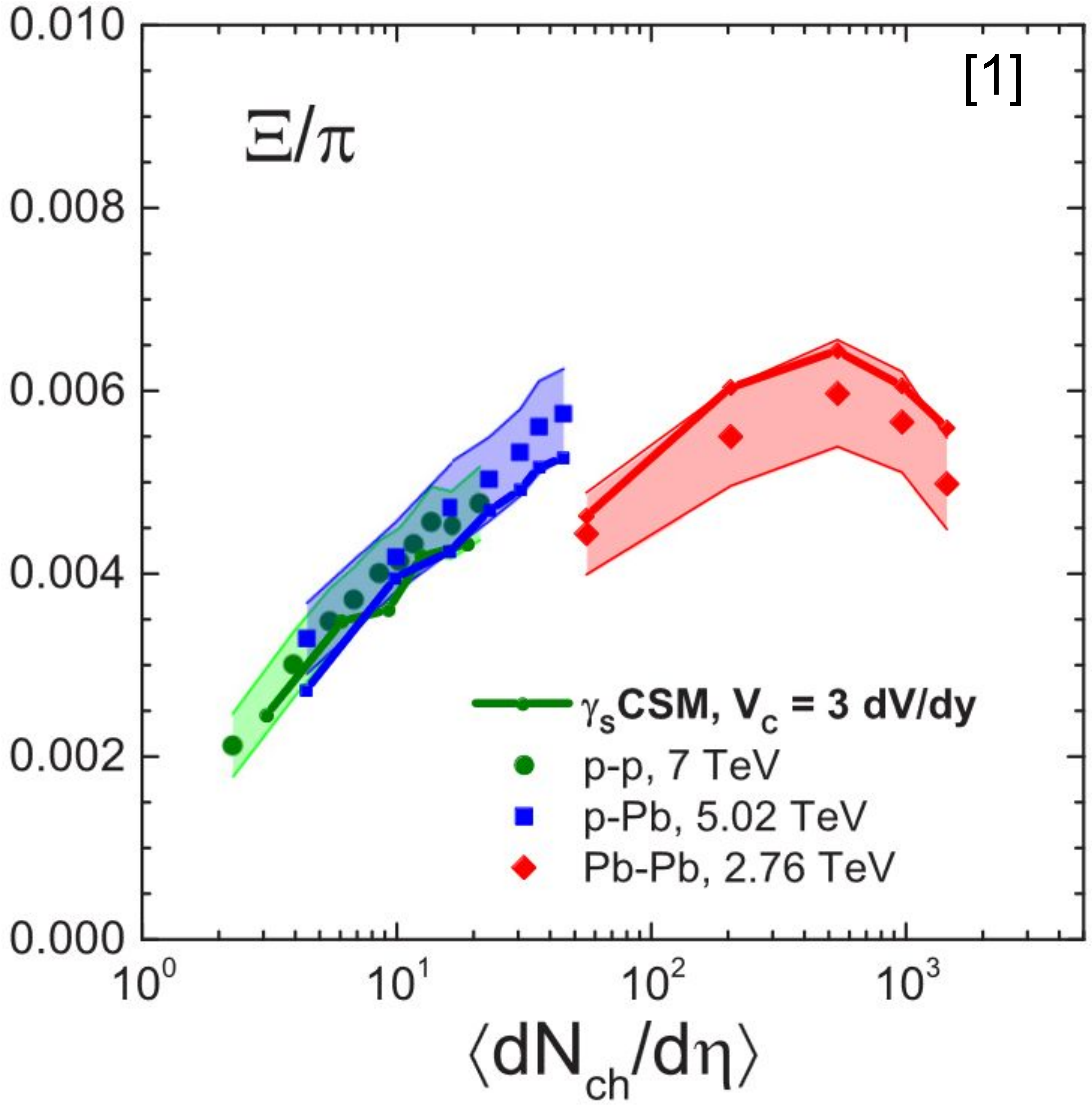
Strangeness Enhancement





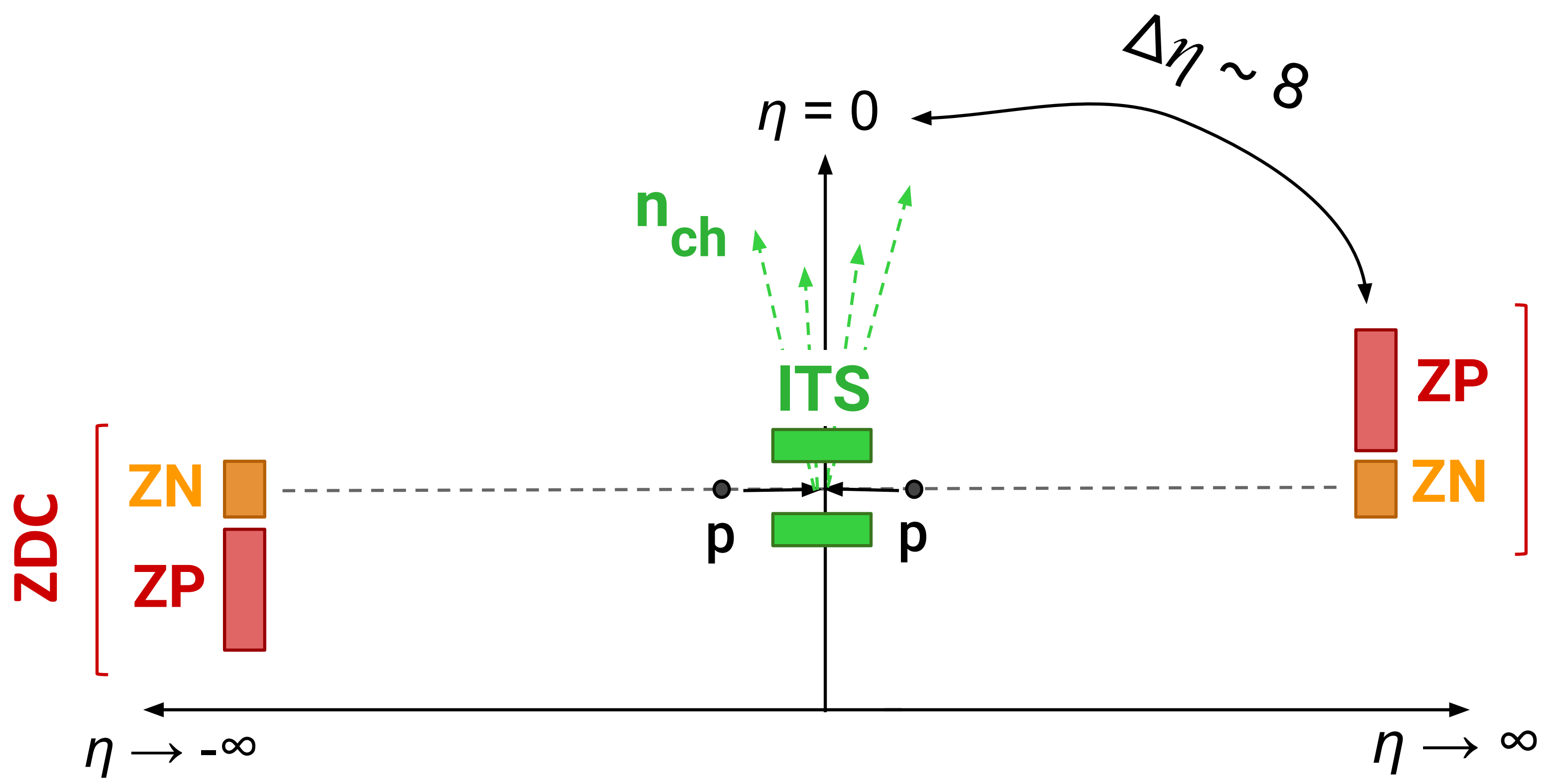
Strangeness increases with multiplicity, hierarchy with strangeness content
ALICE provided more differential results in run3 which show that pQCD inspired models need extra mechanisms for strangeness production





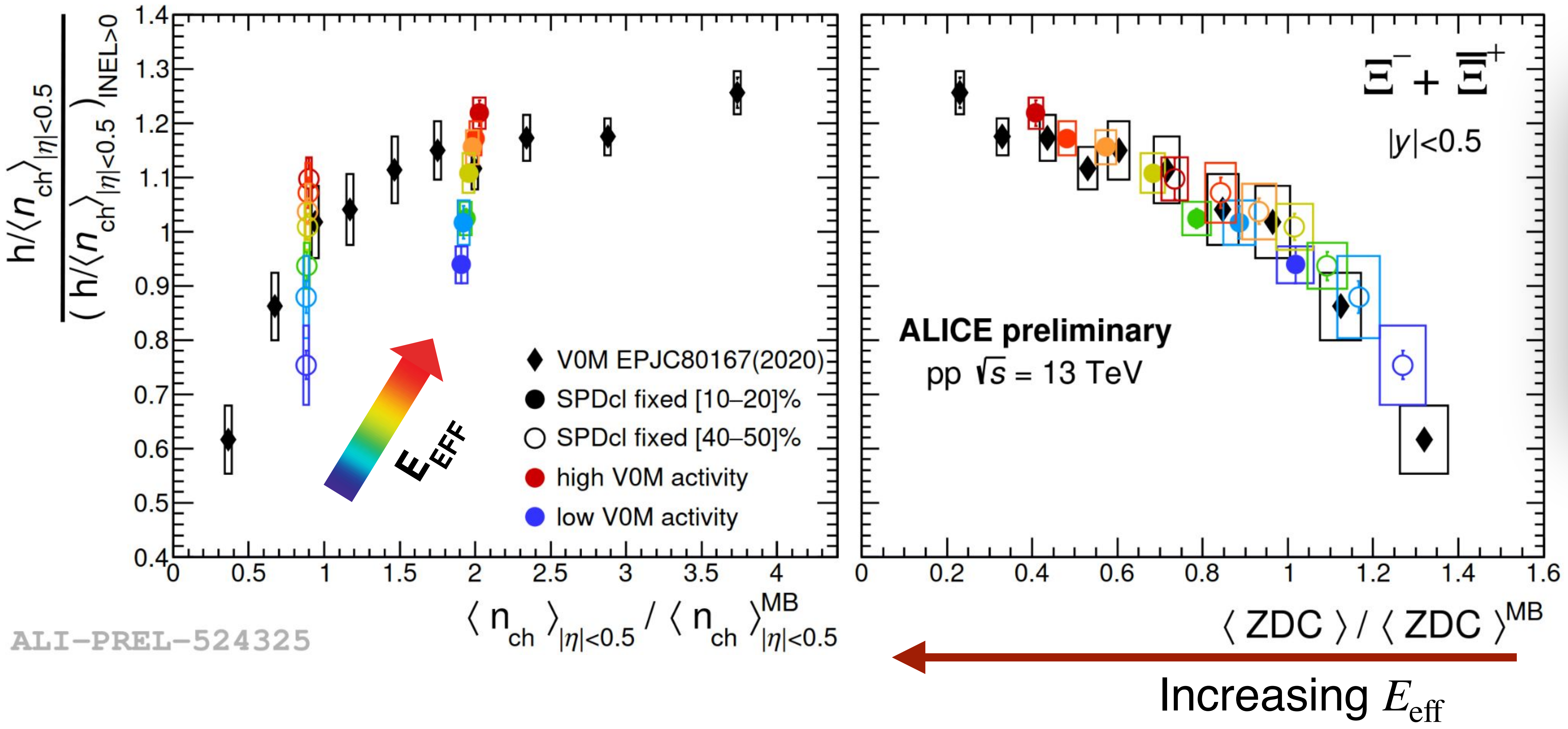
Also more phenomenological models do not describe the strangeness production. Thermal models do very well but different in pp, pA and AA

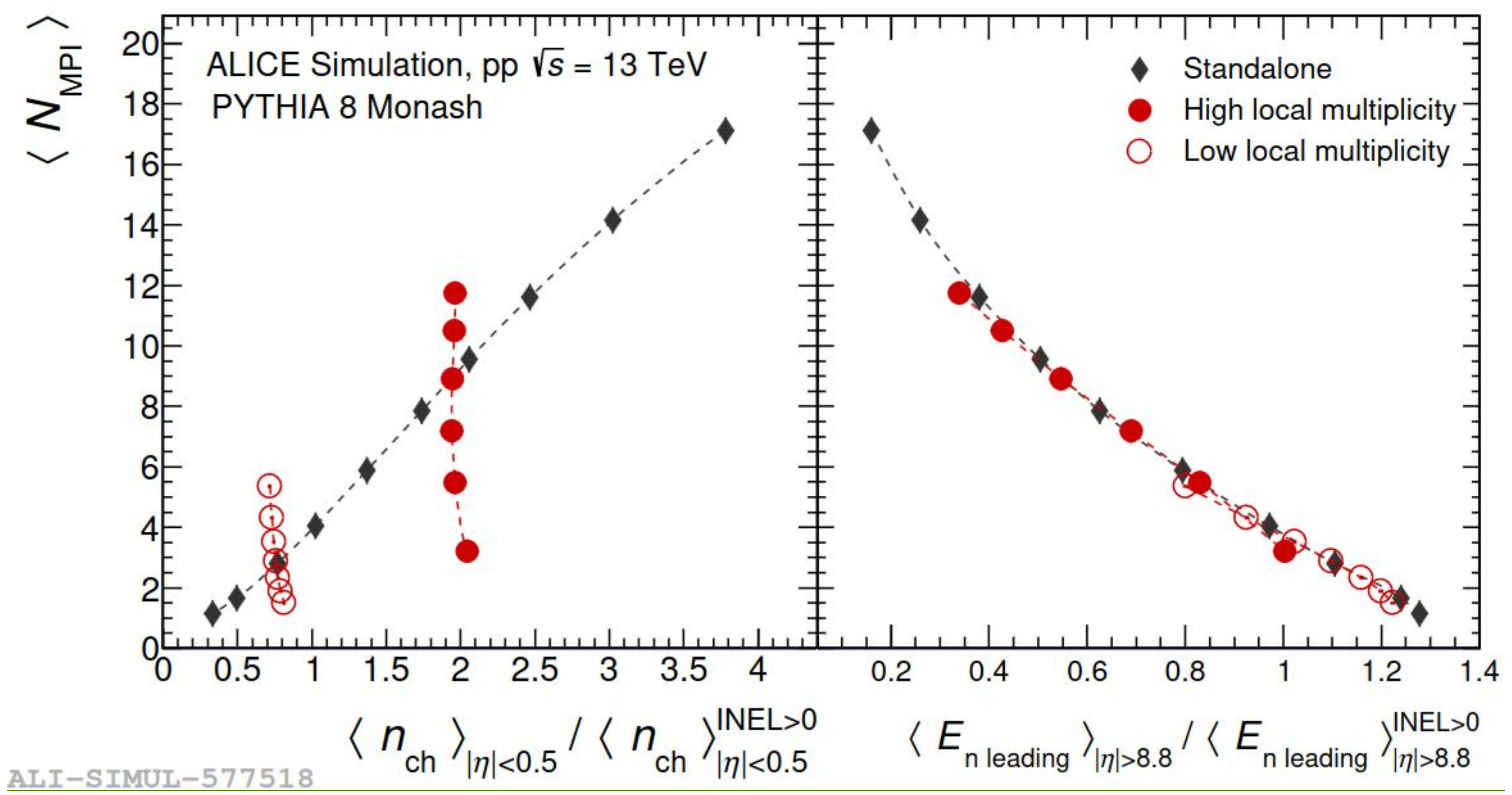
Is charged particle multiplicity a good variable to characterise the system produced in pp and pA collisions?



$$E_{\text{eff}} = \sqrt{s} - E_{\text{leading}} \approx \sqrt{s} - E_{\text{ZDC}}$$

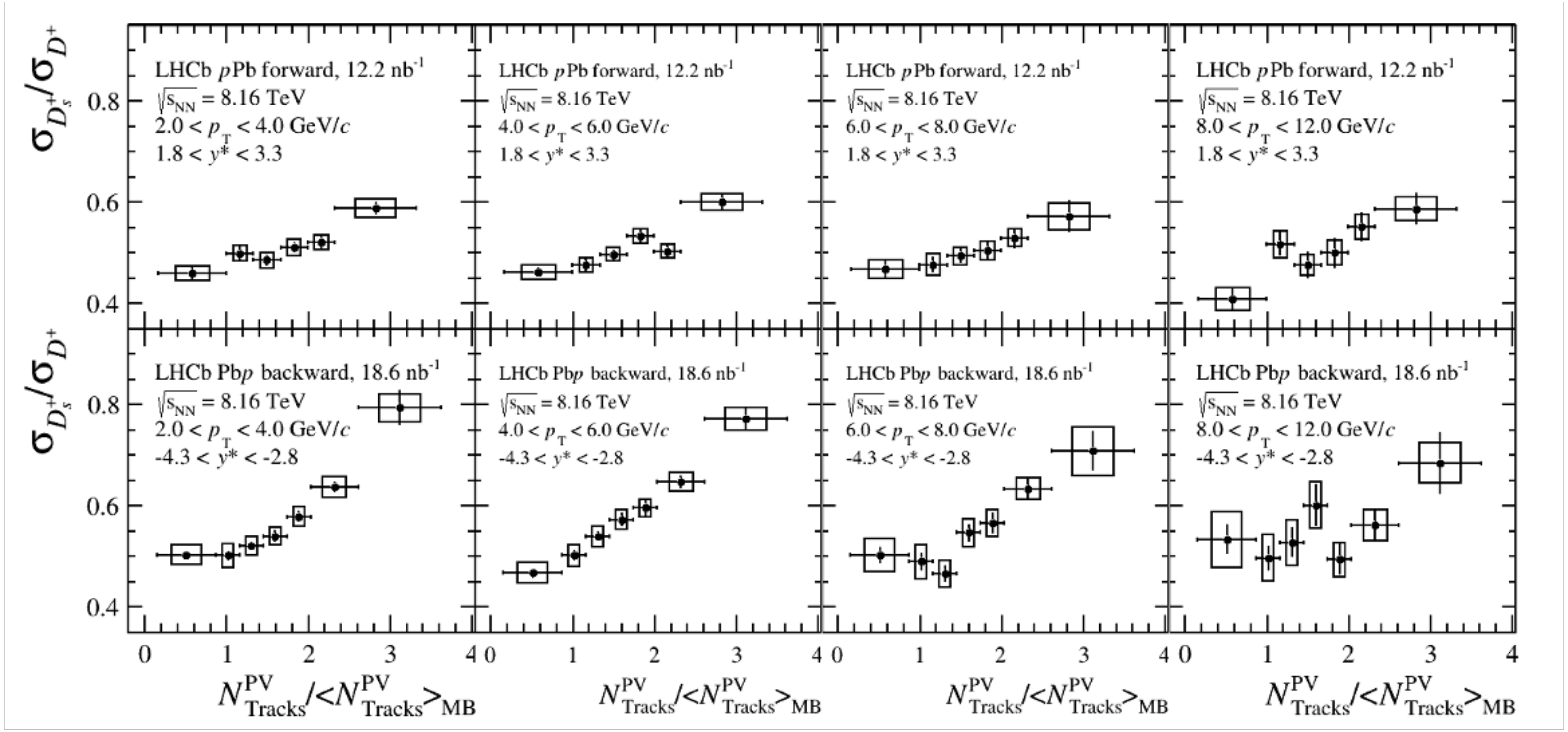
See talk F. Ercolessi





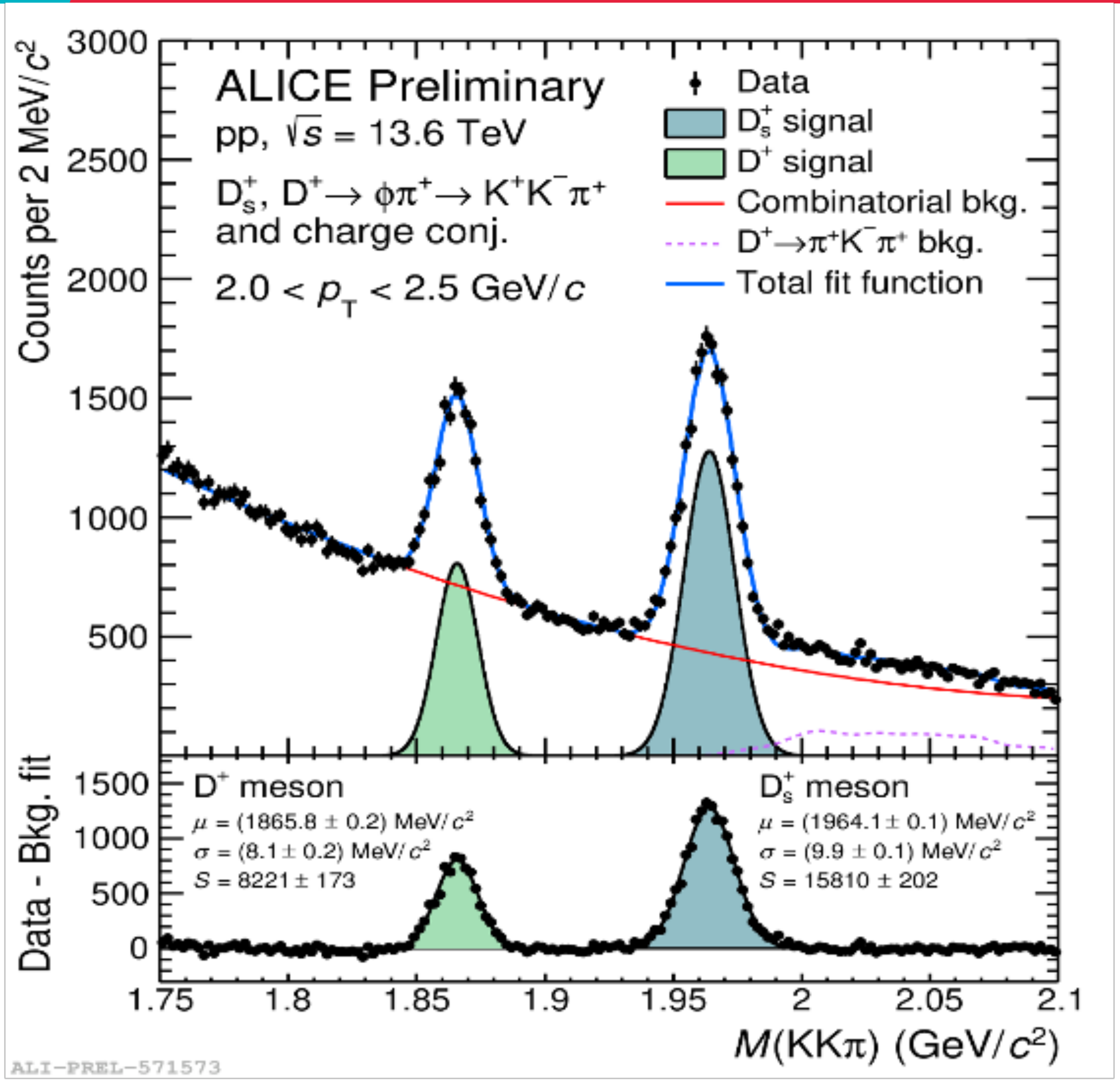
When using the effective energy E_{eff} to characterise the collision one sees that for fixed multiplicity one gets different strangeness production as function of E_{eff} and strangeness production scales with E_{eff} similar to number of MPI in Pythia 8 Monash

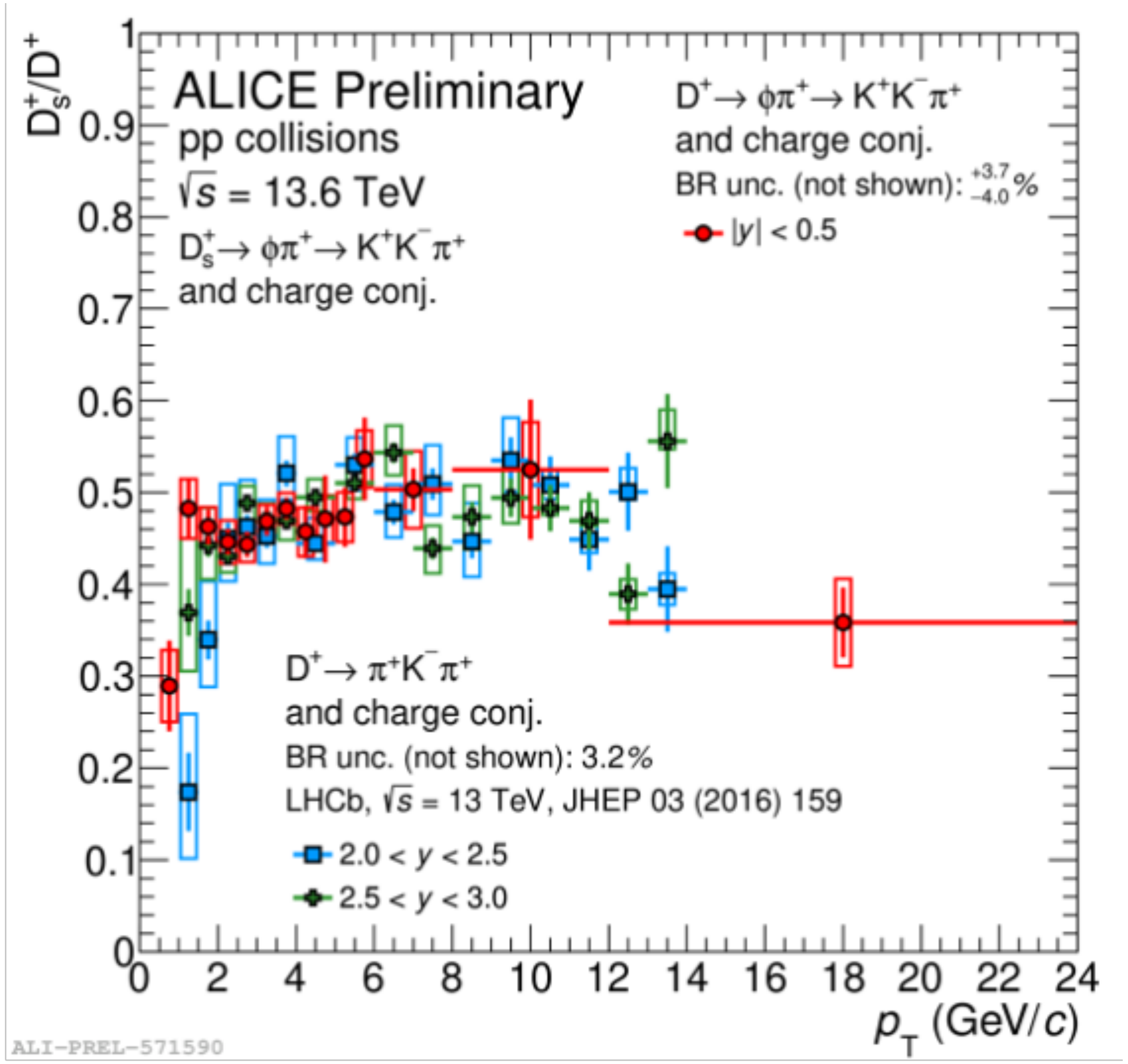
Strangeness Enhancement and Charm



Compare production of D mesons with and without strangeness, ratio increases as function of multiplicity and in backward rapidity. Shows strangeness enhancement in the charm sector and indicates coalescence for charm meson production

Strangeness Enhancement and Charm

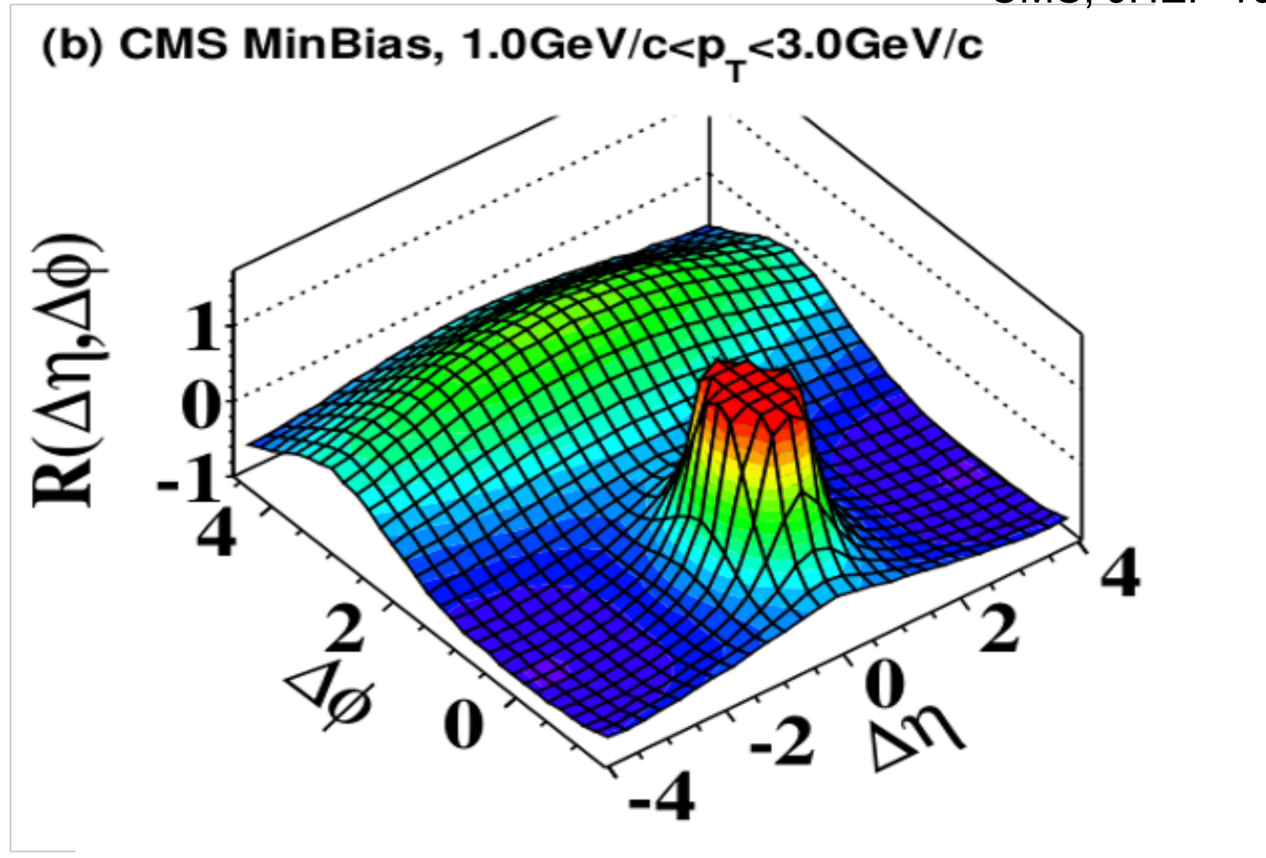


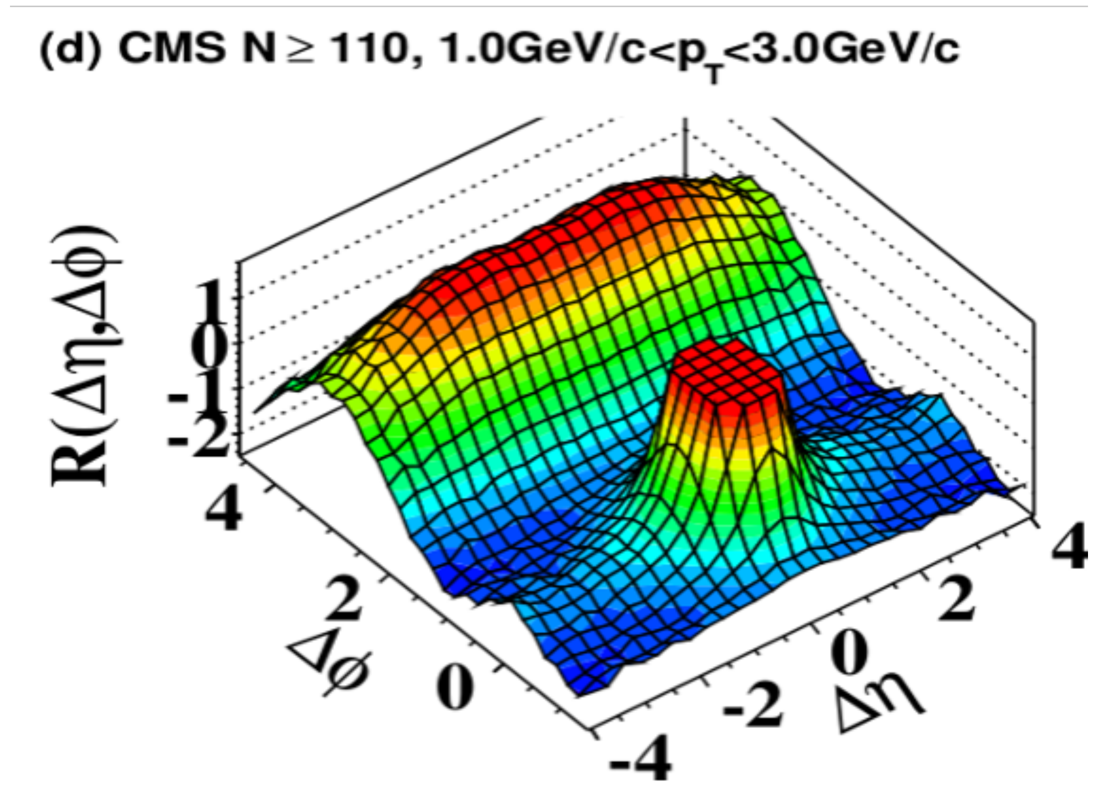


Compare production of D mesons with and without strangeness in ALICE, results in good agreement with LHCb

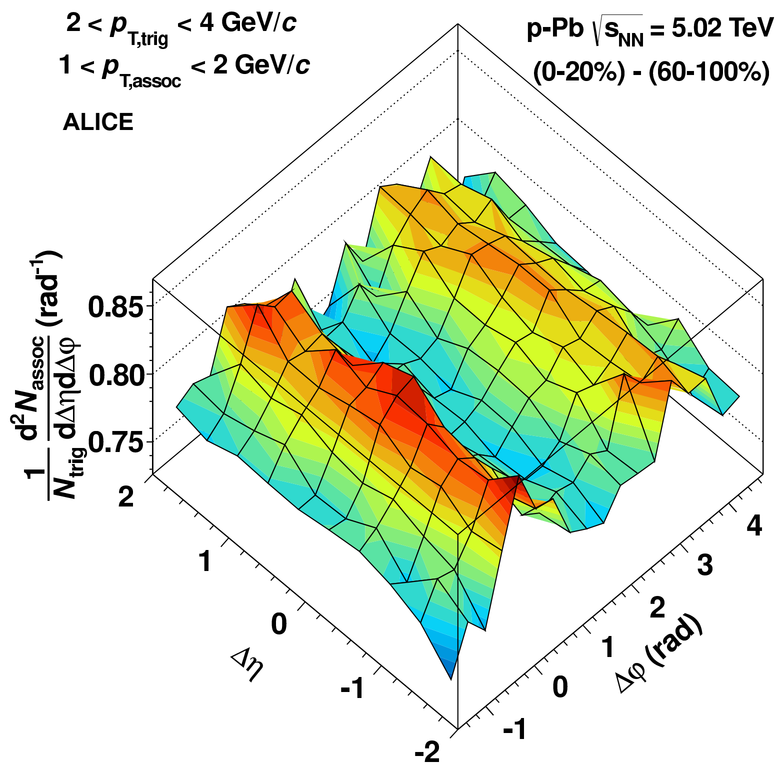
p-p and pA collisions (correlations)

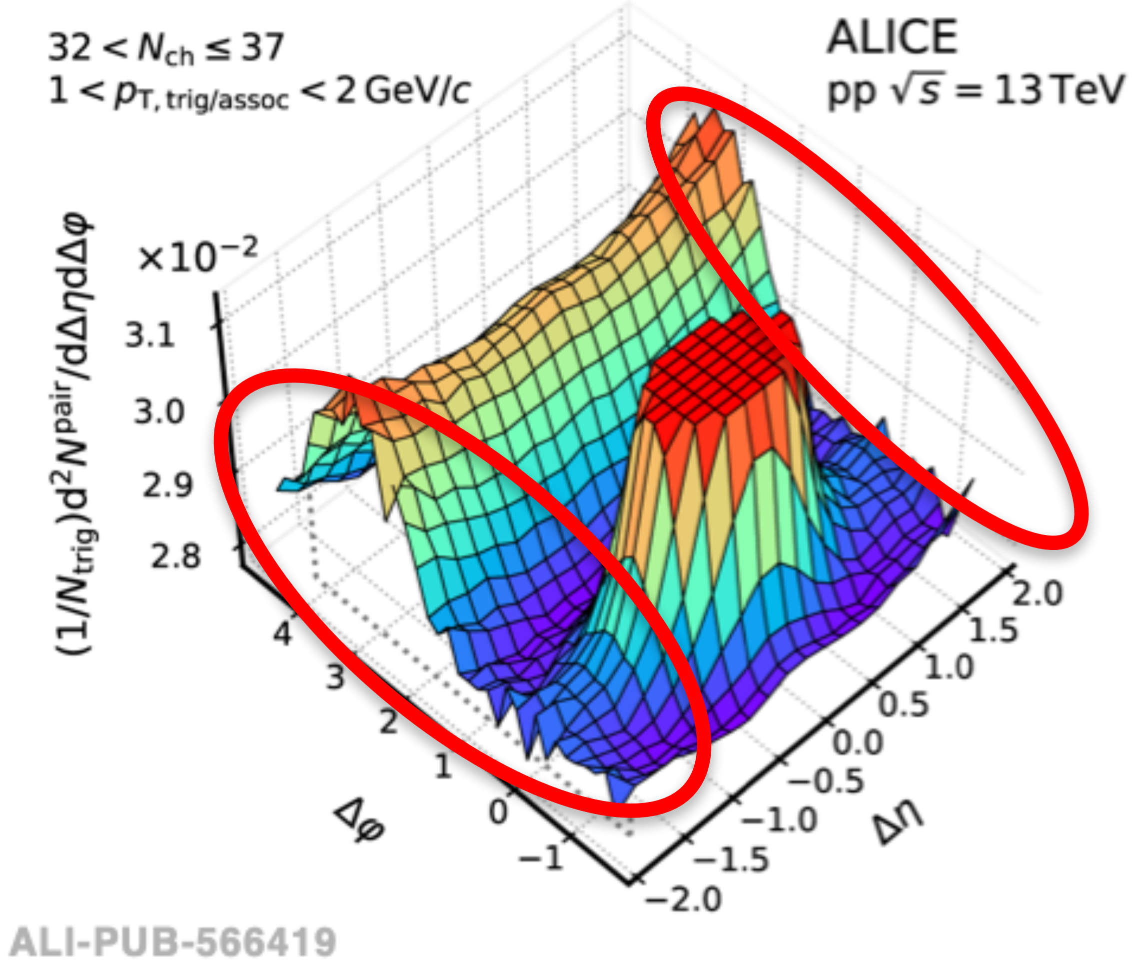
CMS, JHEP 1009 (2010) 091

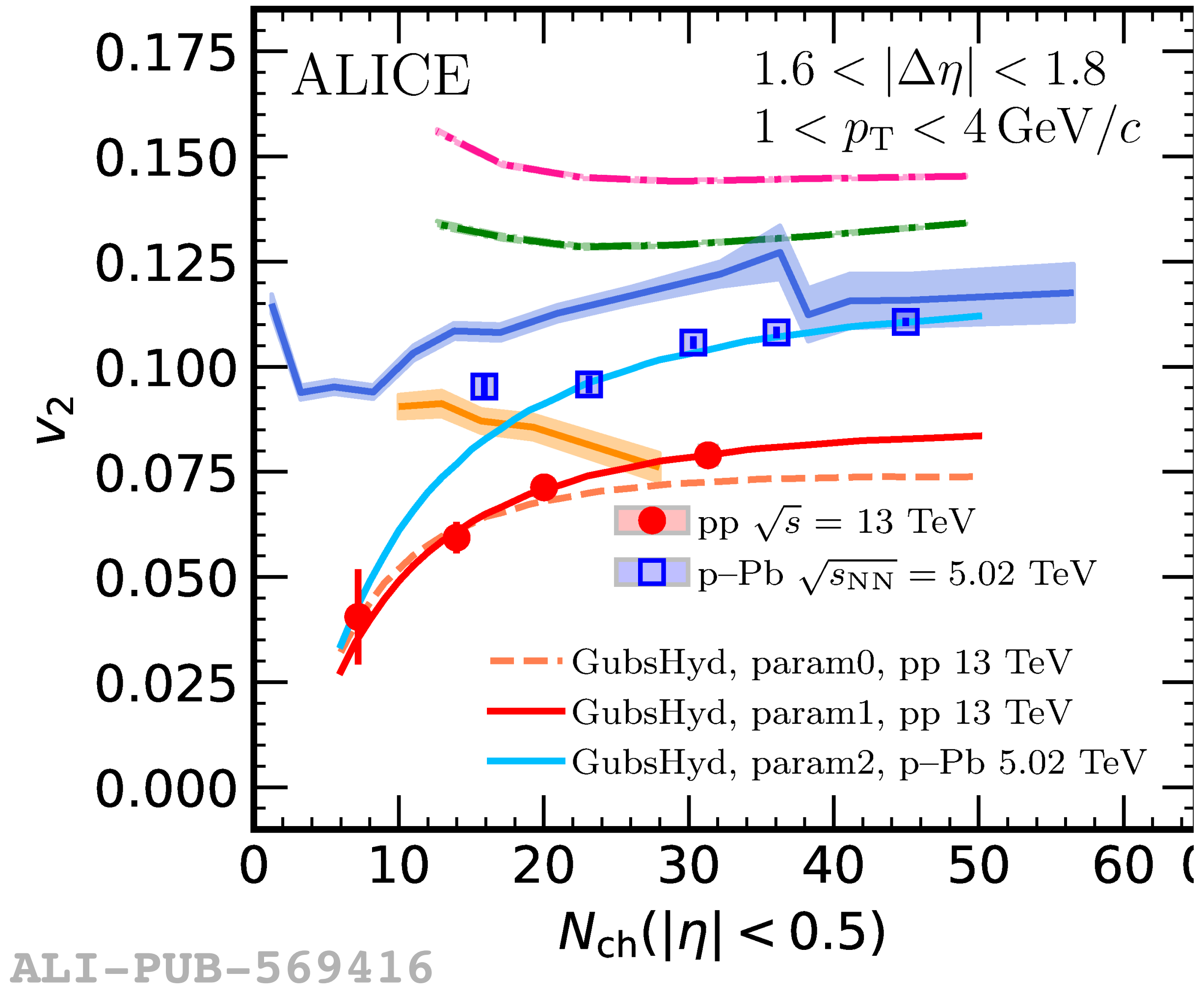


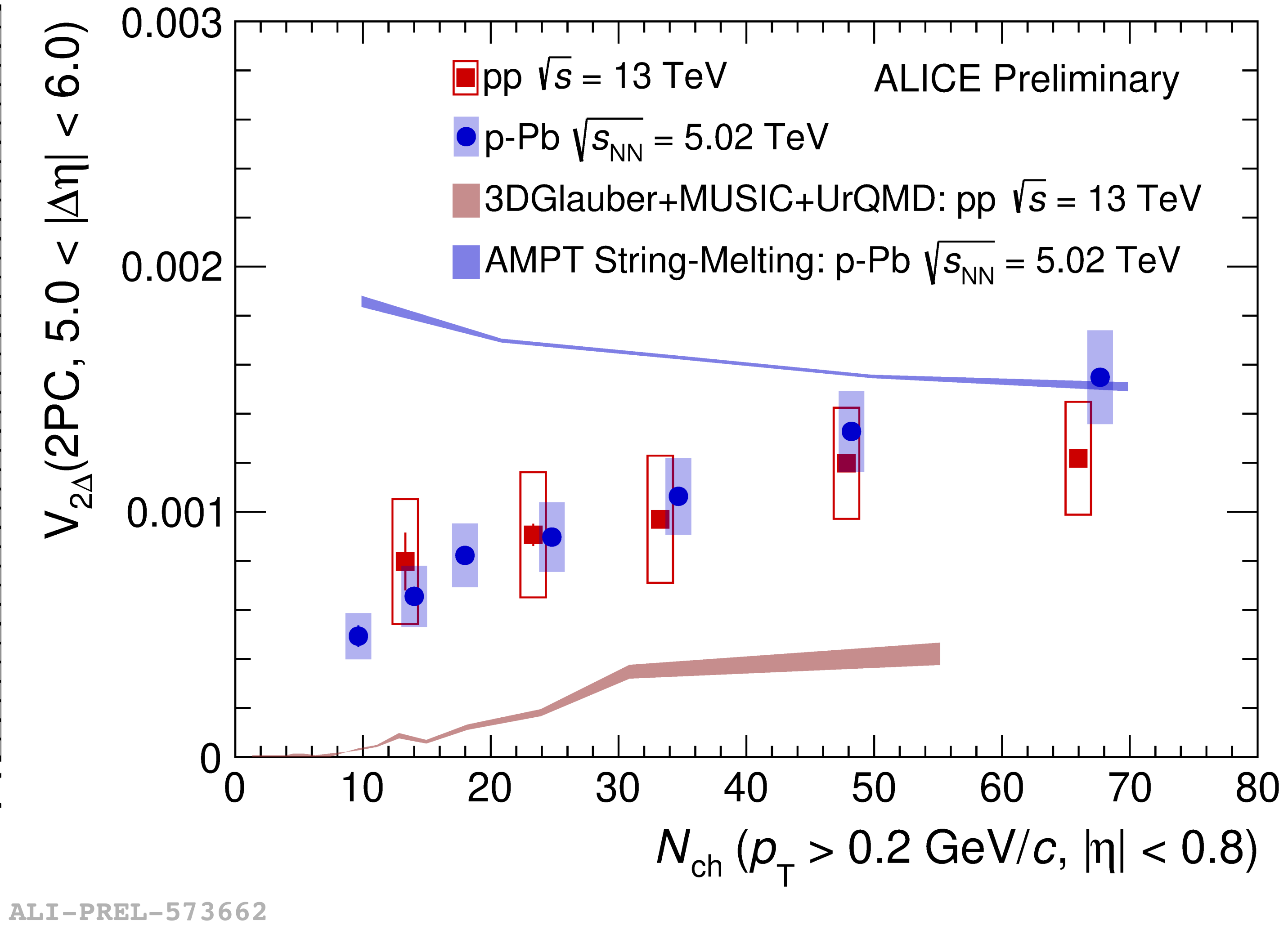


ALICE pA





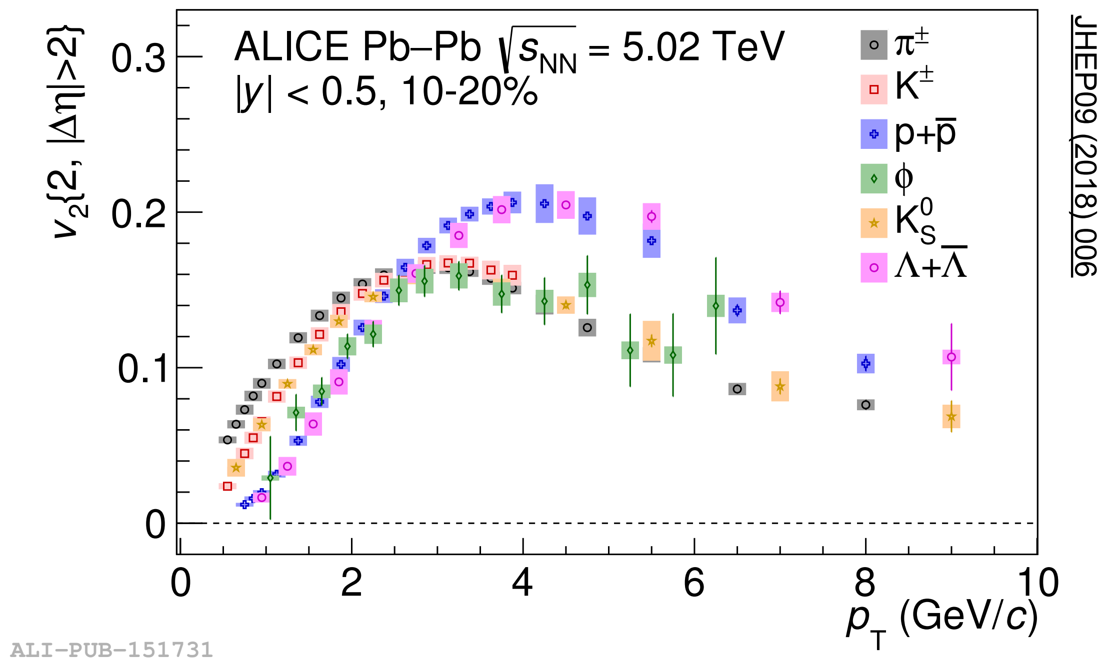




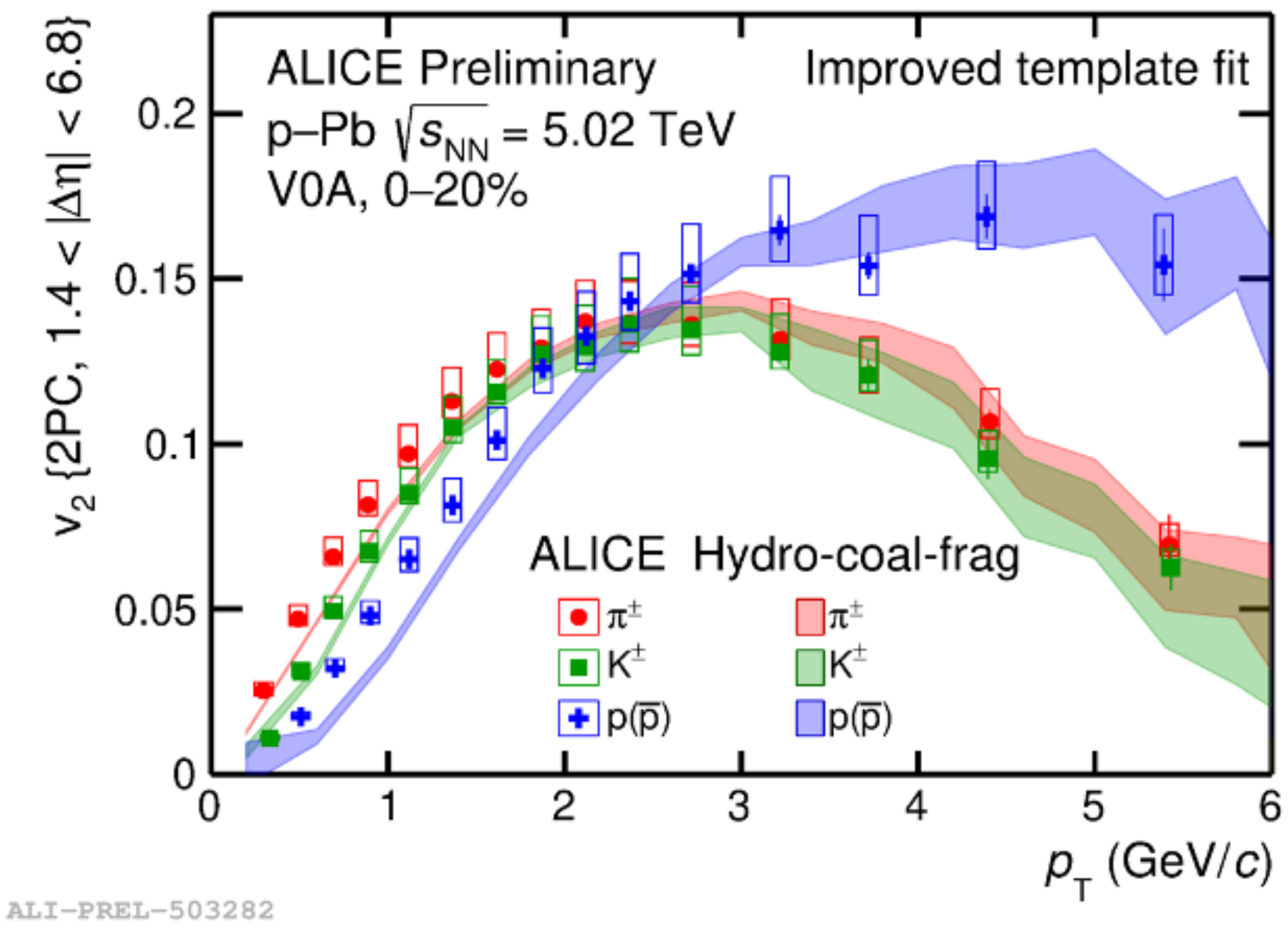
Near side ridge observed in pp and pA already at small multiplicities which shows correlation over large rapidity range > 5 units. Characterised with v_n coefficients (who's magnitude depend on rapidity gap)

pA and pp collisions (light flavour)

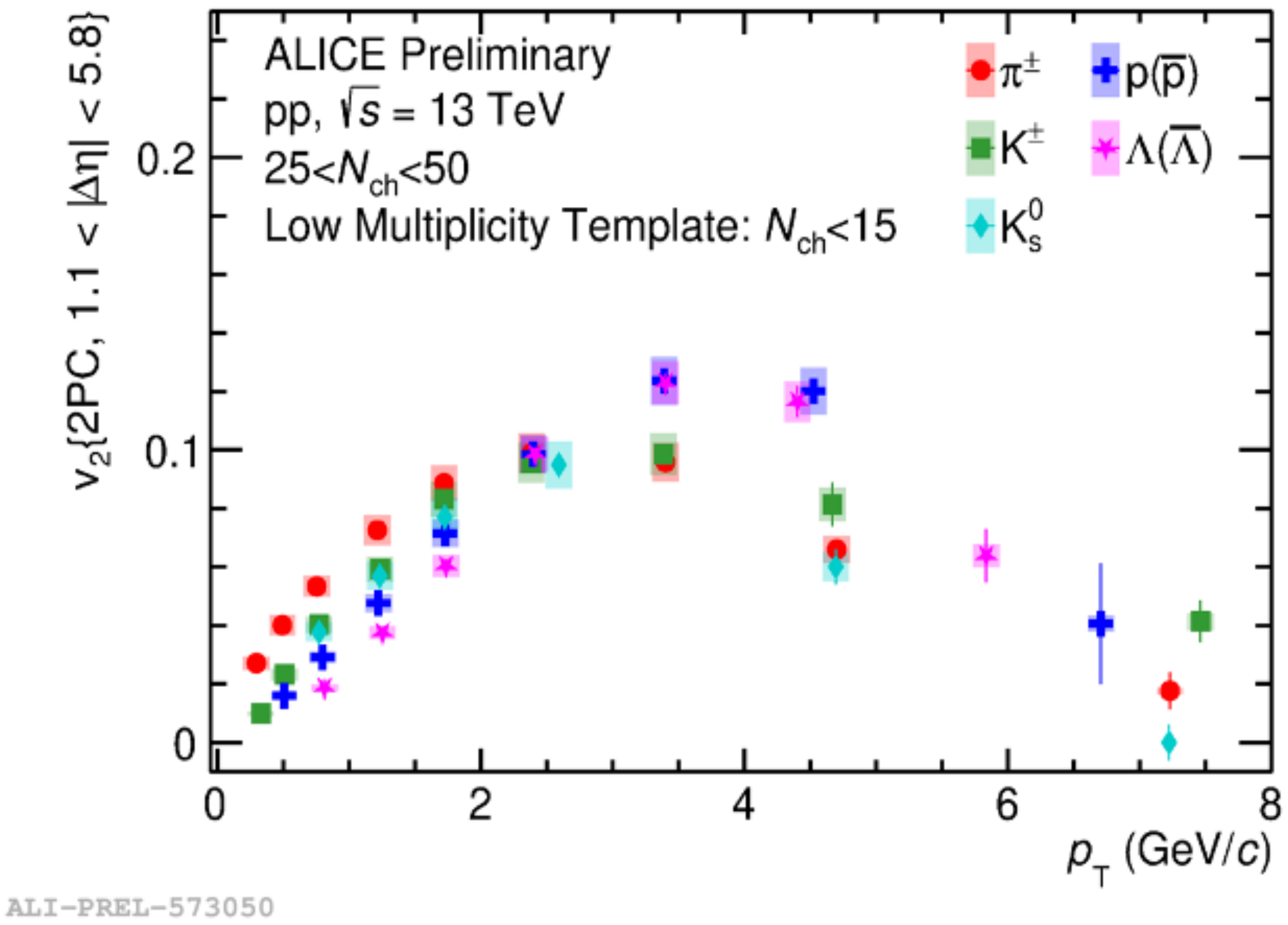
AA



pA

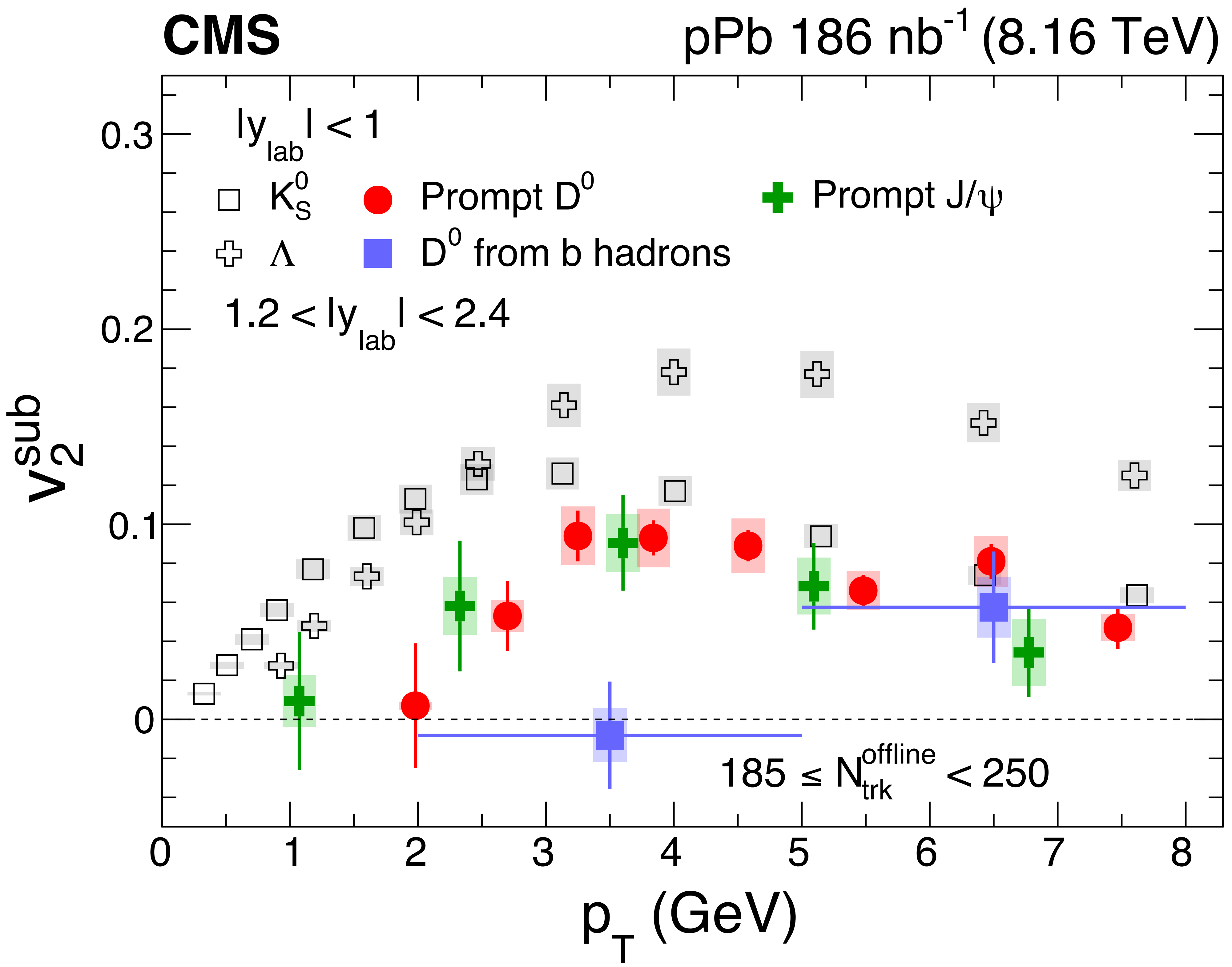


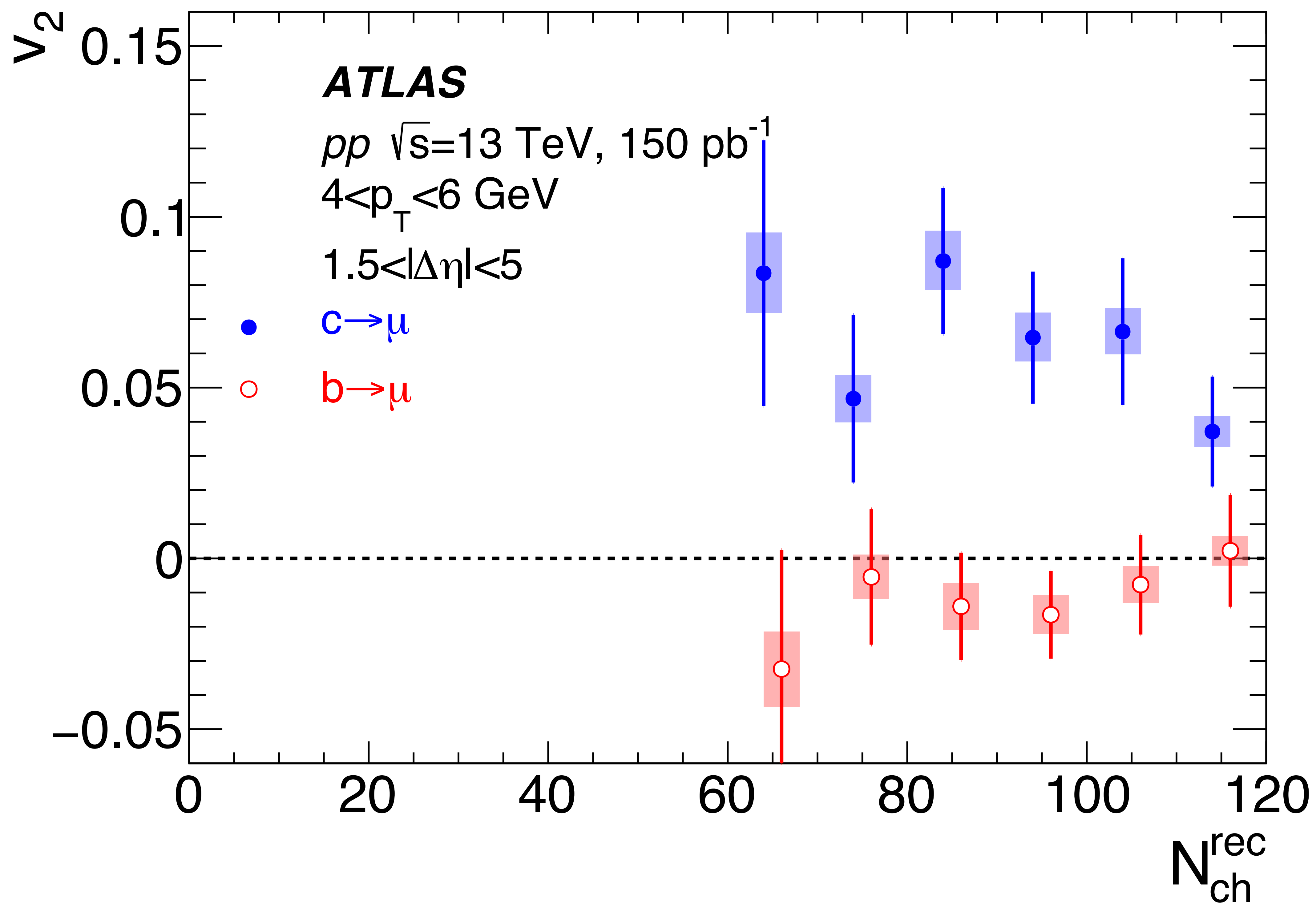
pp



✓The v_2's in pA and pp show a typical mass dependence at low-p_T which is expected from a boosted thermal system
✓At intermediate p_T they show a number of quark scaling expected from recombination

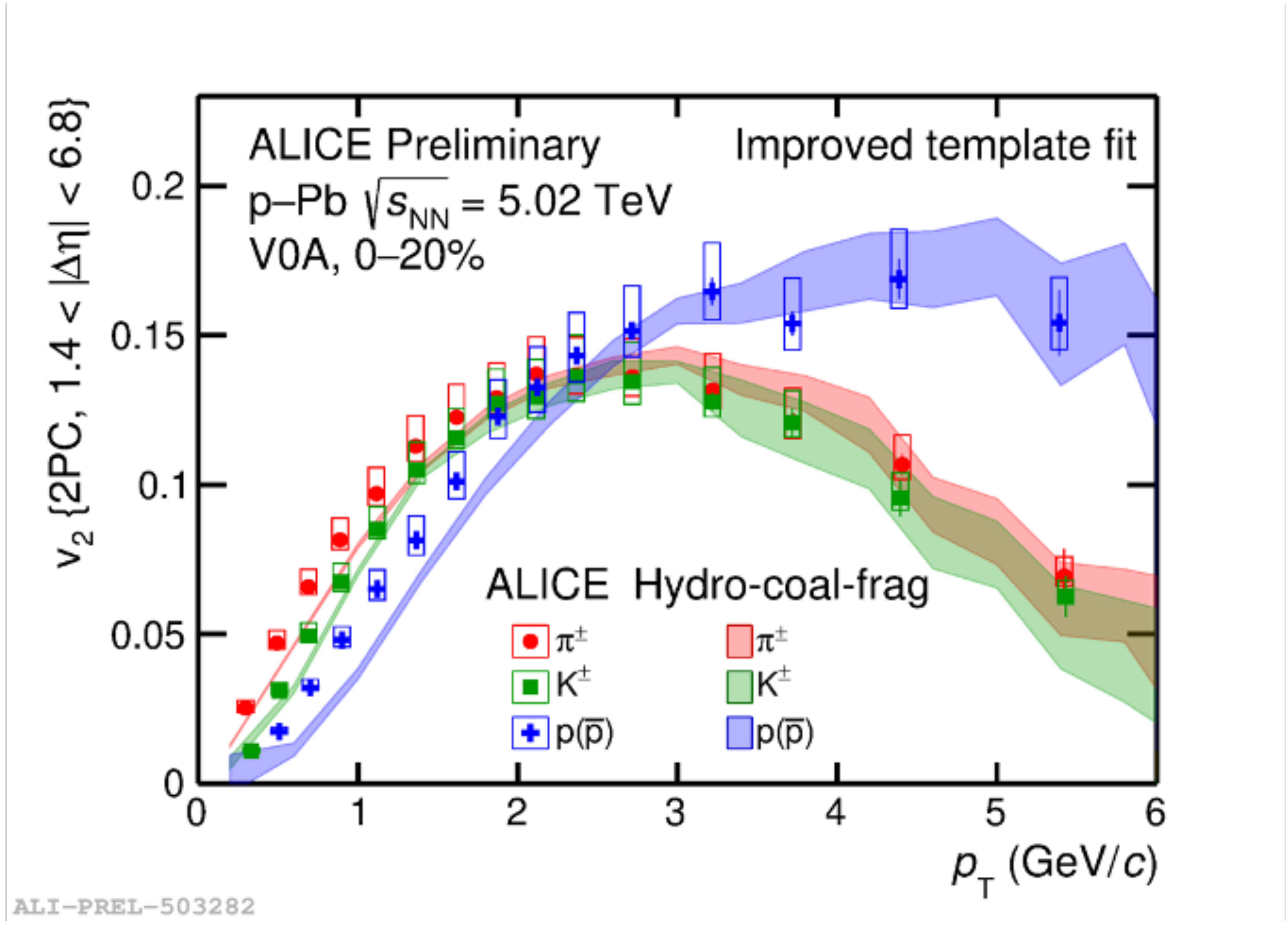
pA and pp collisions (heavy flavour)

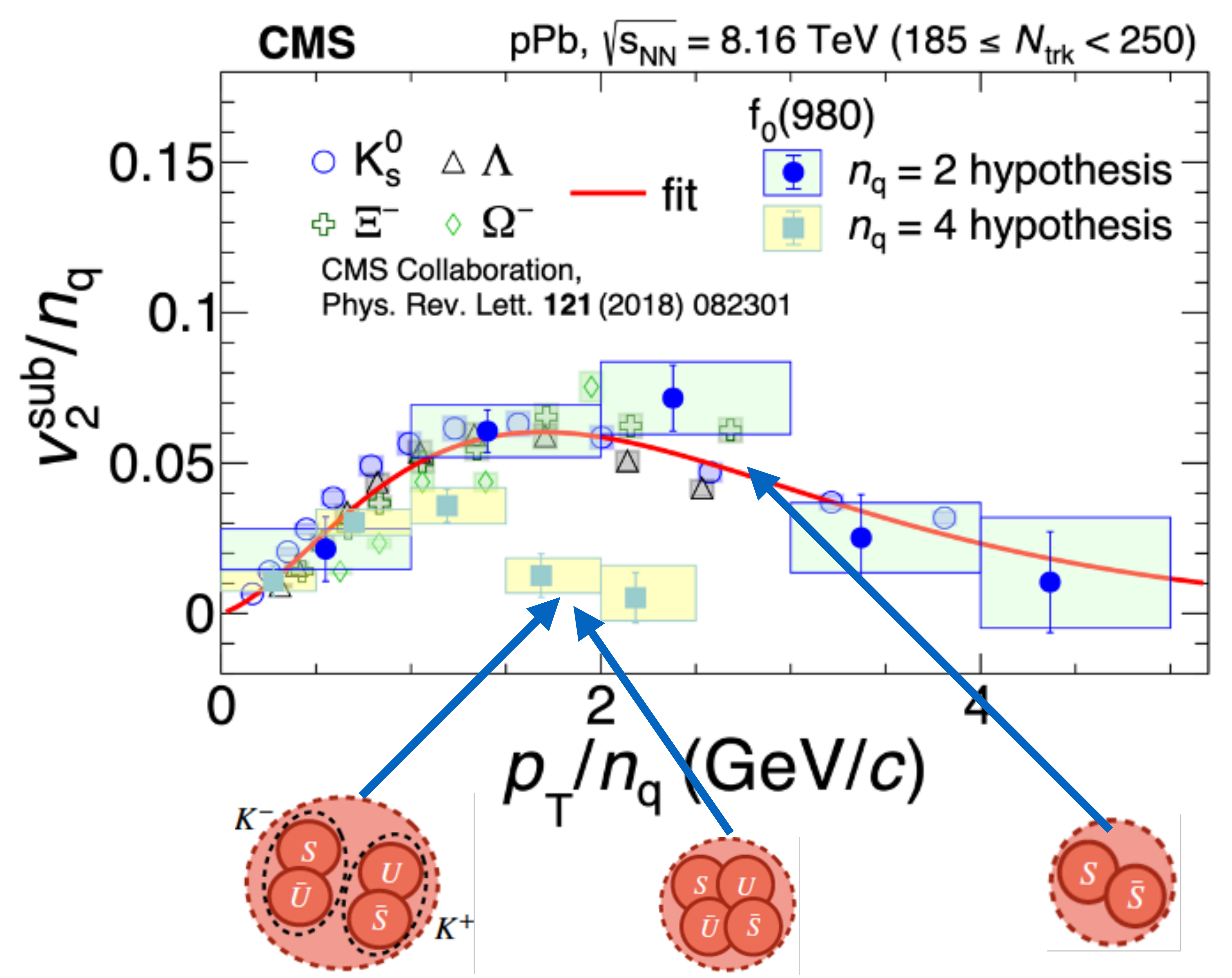




- ✓The v_2's in pA and pp show a typical mass dependence at low-p_T which is expected from a boosted thermal system
- ✓At intermediate p_T they show a number of quark scaling expected from recombination
- ✓Also the charm sector exhibits these v_2's for open charm and for J/Ψ, the D^0 from b-hadrons does not show v_2 within uncertainties

pA collisions (f_0 (980))





We can use this scaling behaviour to also say something about the nature of the f_0 of which the structure is unknown (di-quark, tetra-quark, KK molecule). Use v_2/n_q scaling to extract number of quarks.

n_q = 4 is excluded at $\geq 3.1\sigma$ and n_q = 2 is favoured.

p-A collisions

Ramona Vogt

M. Strickland, S. Thapa, R. Vogt arXiv:2401.16704v1

Summary

What has been observed for the QGP at the LHC?

✓In AA we create a system which can be described very well by hydrodynamics and we started to extract the properties of the QGP with uncertainties (EoS, transport parameters)

✓In pp and pA we observe the onset of the collective behaviour

- ✓We observe spectra in pp and pA which show similar behaviour as in AA (m_T scaling and recombination)
- ✓We observe long range correlations (v_2) in pp and pA which show mass dependence and follow similar behaviour as in AA (for heavy quarks so far pA)
- ✓J/Ψ and Υ are suppressed in pA which can be understood from nPDF but $\Upsilon(nS)$ does show sequential suppression in pA
- ✓We do not observe jet quenching in pp and pA collisions (even not for back to back jets)

✓I hope I showed you that collisions of pp, pA and AA produce not completely different environments but that collective medium effects builds up gradually with system size and this gives us an unique opportunity to understand the underlying microscopic dynamics and provide a uniform description

The standard model of heavy-ion collisions

The standard model of particle physics

Heavy-Ion Collisions (future)

My big dream: combine the standard model of heavy-ion collisions and particle physics

The standard model of particle physics

Thanks