Recent results on light flavor and correlation from ALICE

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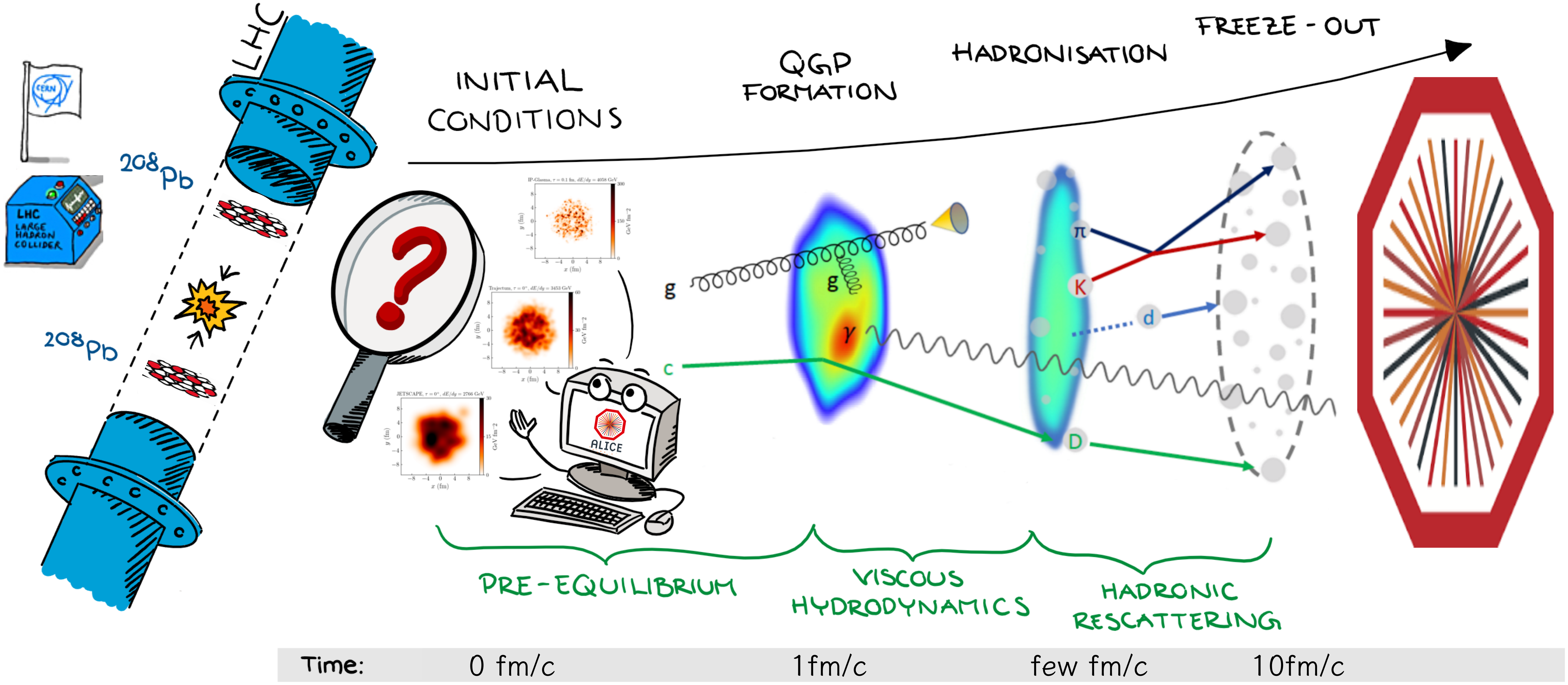
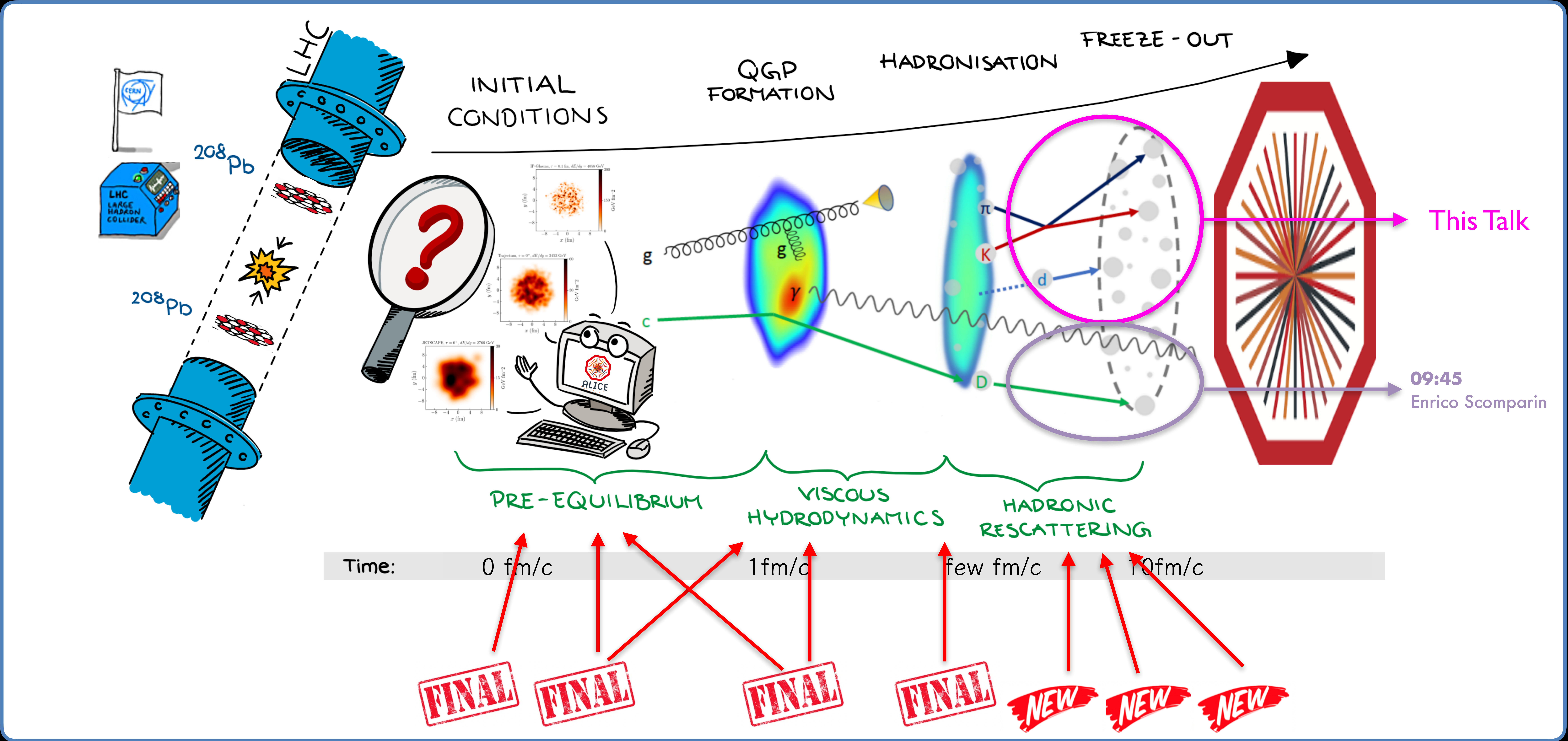
ALICE

THE VELUX FOUNDATIONS
VILLUM FONDEN ✕ VELUX FONDEN

Study of heavy-on physics with ALICE



Study of heavy-on physics with ALICE



Accessing the initial conditions via v_n-$[p_T]$ correlations

- ❖ Anisotropic flow v_n -> initial shape (eccentricity)
- ❖ $[p_T]$ -> initial size
- ❖ Final state: correlation between v_n and $[p_T]$

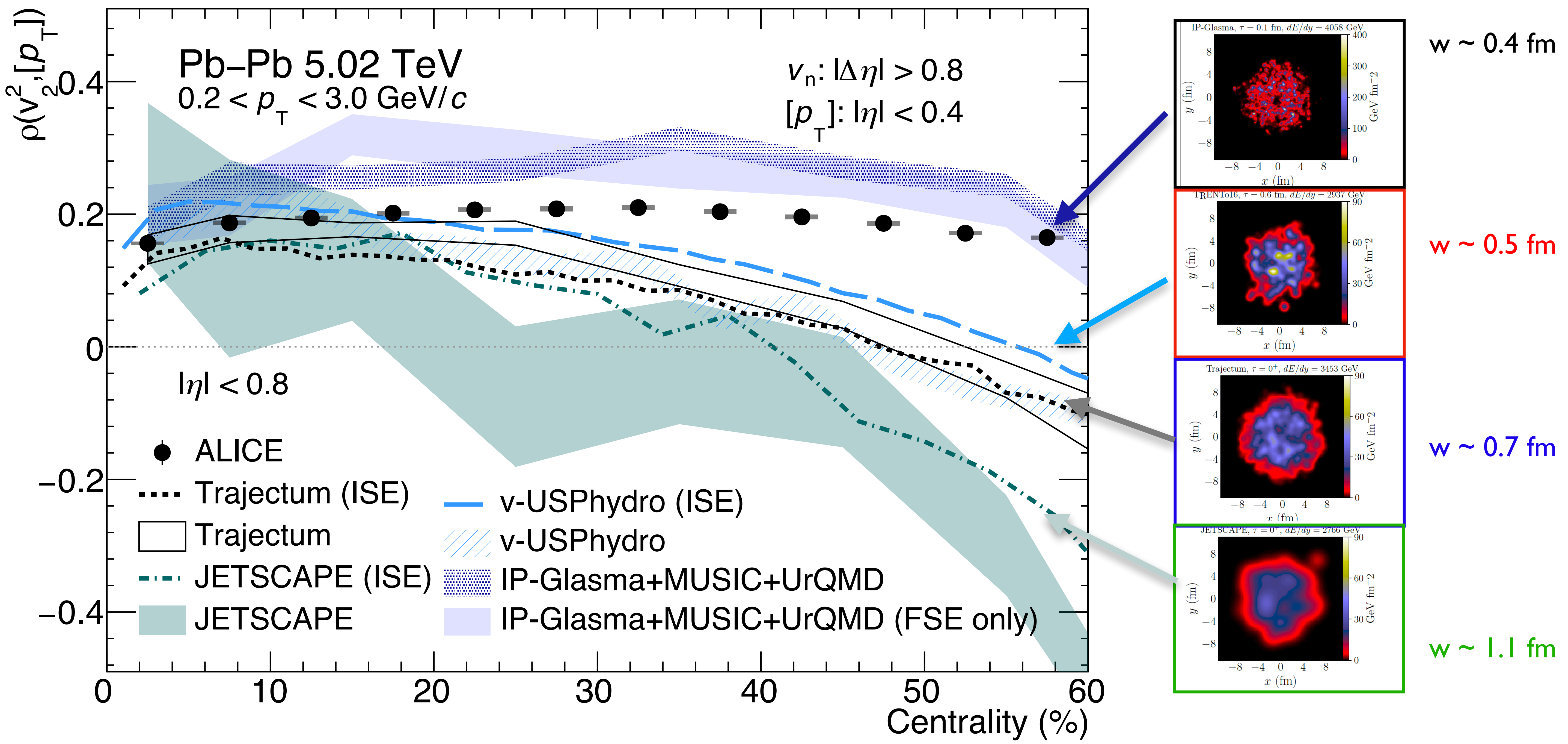
$$\rho(v_n^2, [p_T]) = \frac{cov(v_n^2, [p_T])}{\sqrt{var(v_n^2)}\sqrt{var([p_T])}}$$

P. Bozek etc, PRC96 (2017) 014904

-> $\rho(v_n^2, [p_T]) = \rho(\varepsilon_n^2, [E_0])$

final-state model calculation — *Initial-state* model estimation

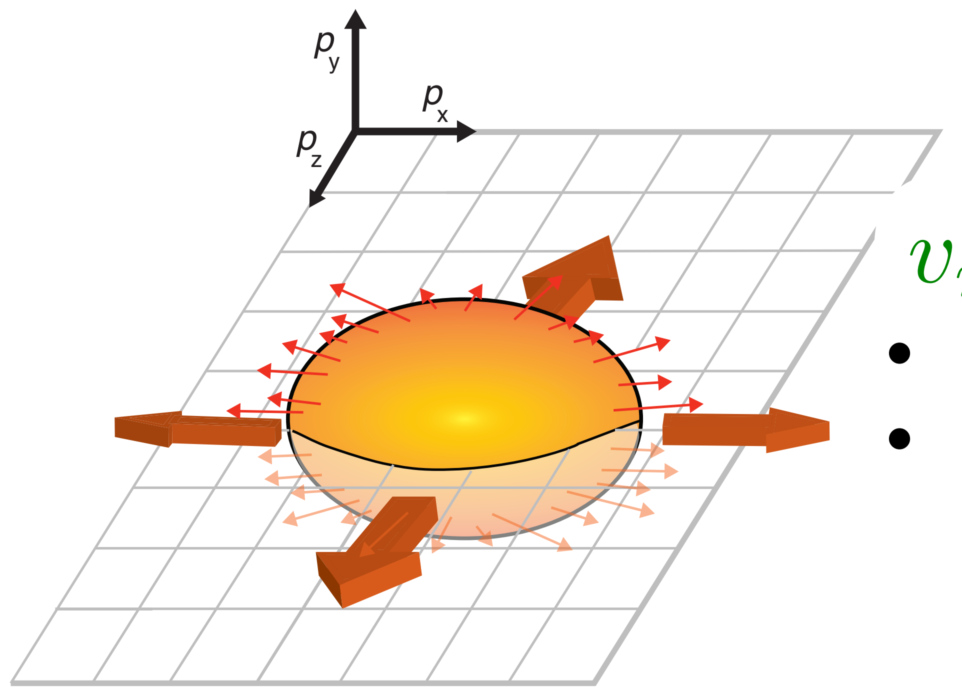
ALICE, arXiv:2111.06106



- ❖ TRENTo-IC based calculations all show strong centrality dependence, negative values for centrality >40%
  - v-USPhydro, Trajectum, JETSCAPE
- ❖ Sensitive to the nucleon width parameter (size of nucleon)
  - IP-Glasma ~ 0.4 fm; v-USPhydro ~ 0.5 fm; Trajectum~0.7 fm; JETSCAPE (TRENTo) ~ 1.1 fm
  - New constraints on the ***nucleon size.*** ALICE data agrees better with w~0.4 fm, or transverse radius of 0.56 fm.

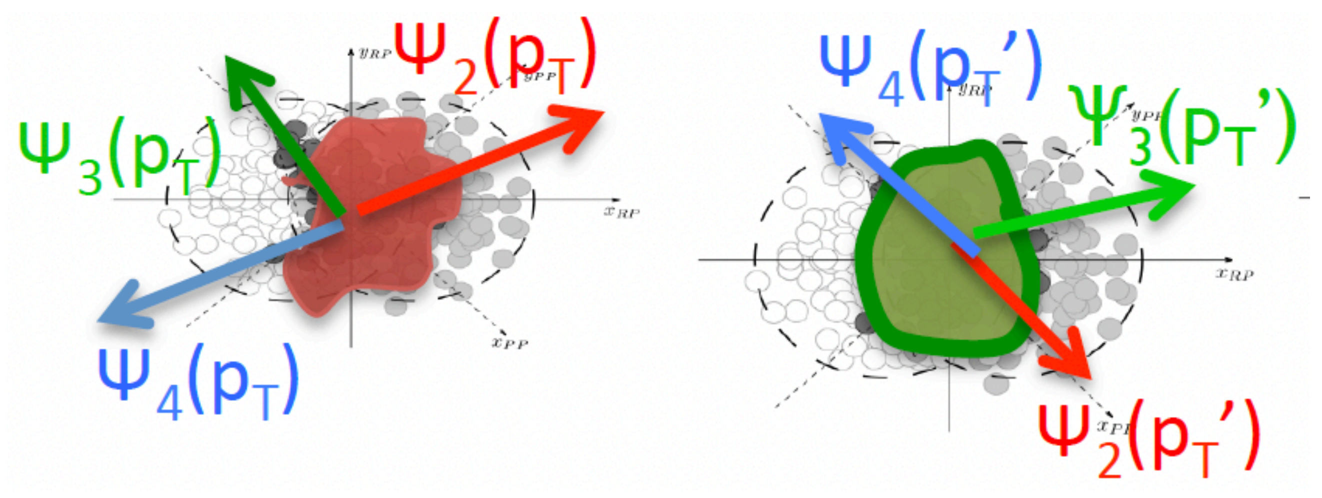
FINAL

Flow magnitude fluctuations and flow angle fluctuations

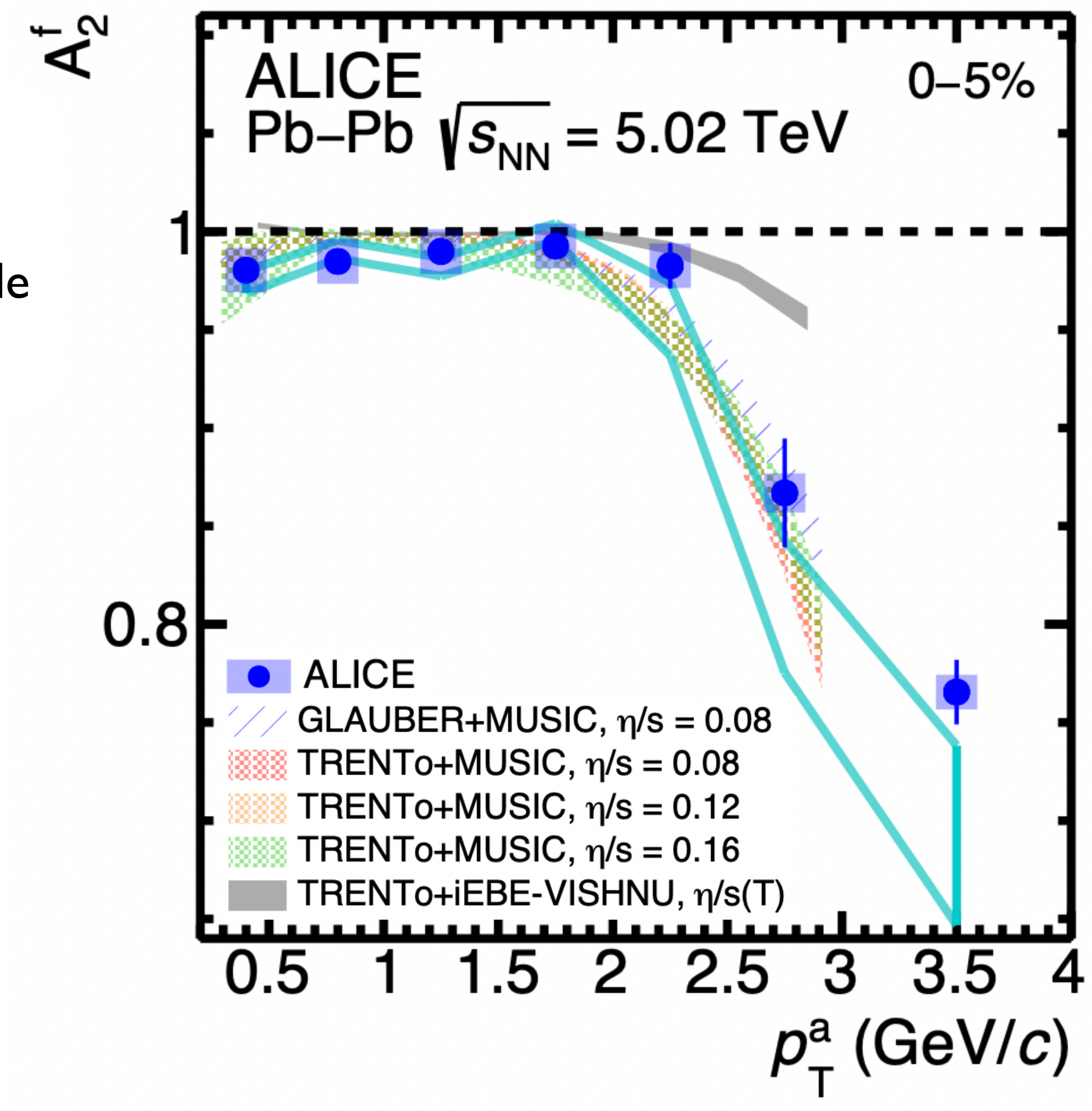


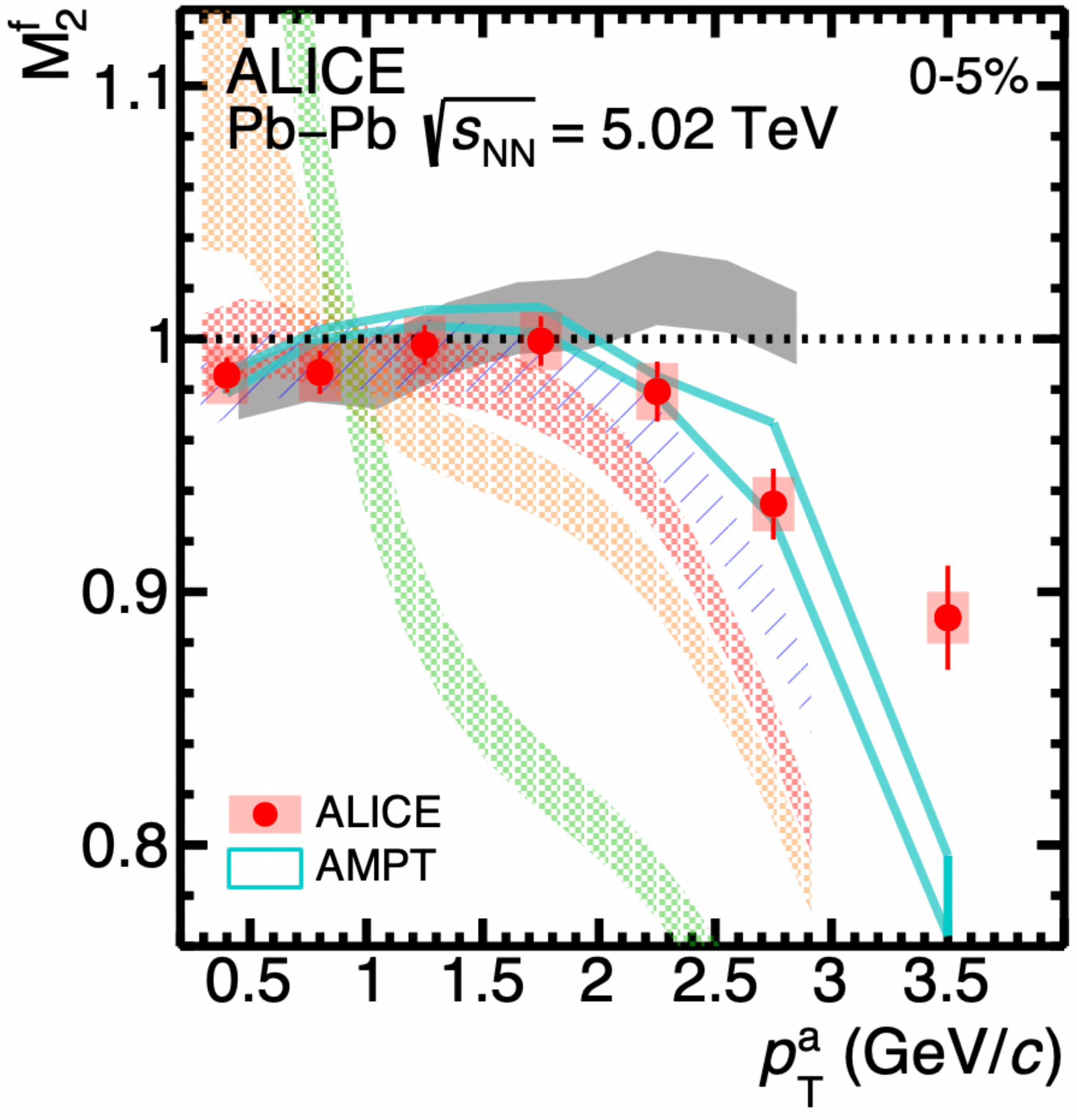
$v_n = \langle \cos n(\varphi - \Psi_n) \rangle$

- v_n : Anisotropic flow
- Ψ_n : Flow symmetry plane angle



Probe flow angle fluctuations A_2^f and flow magnitude fluctuations M_2^f with multi-particle correlations





ALICE, arXiv: 2206.04574

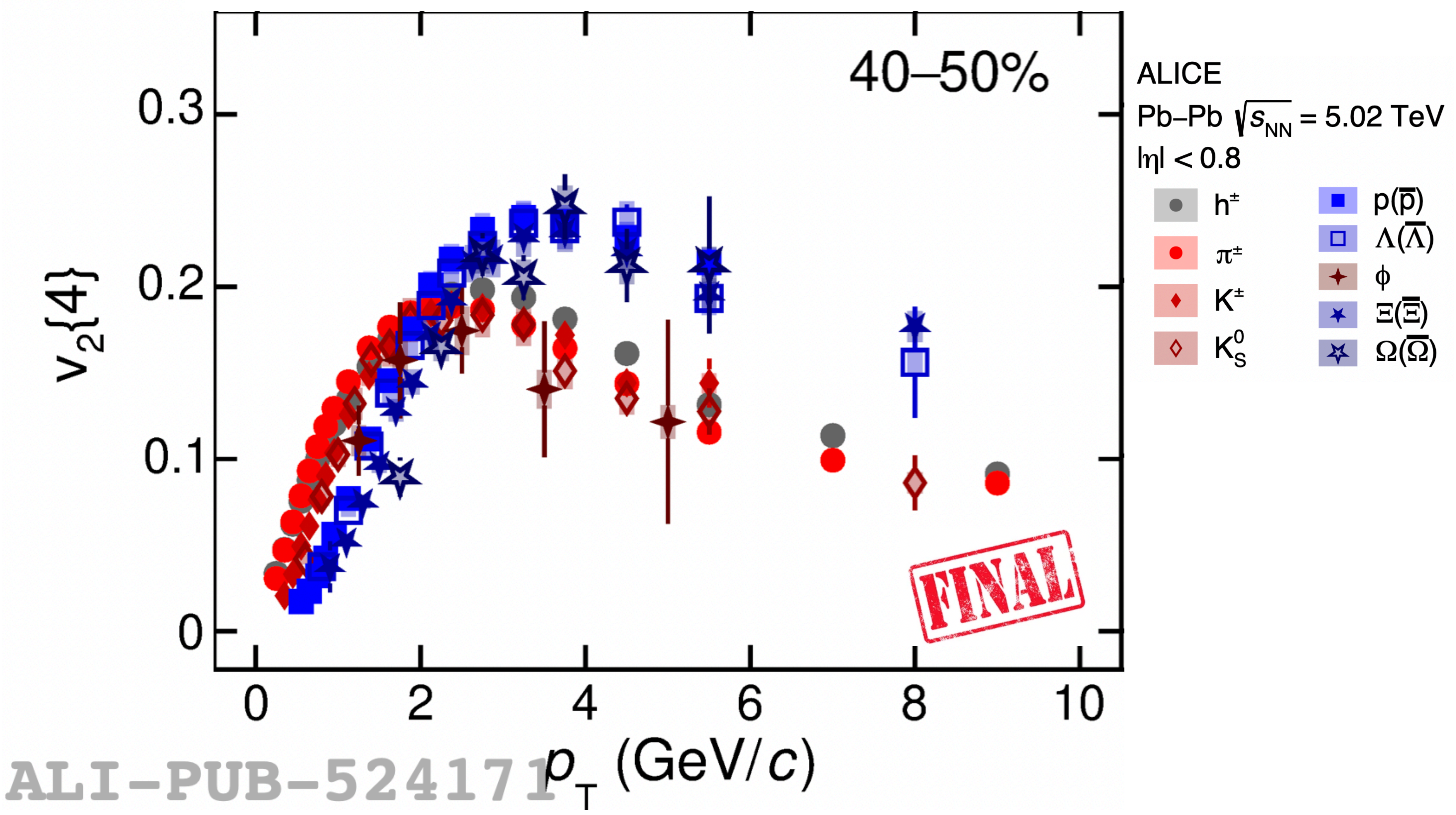
iEBE-VISHNU: W. Zhao etc, EPJC77 (2017) 645
MUSIC: P. Bozek etc, PRC105 (2022) 034904

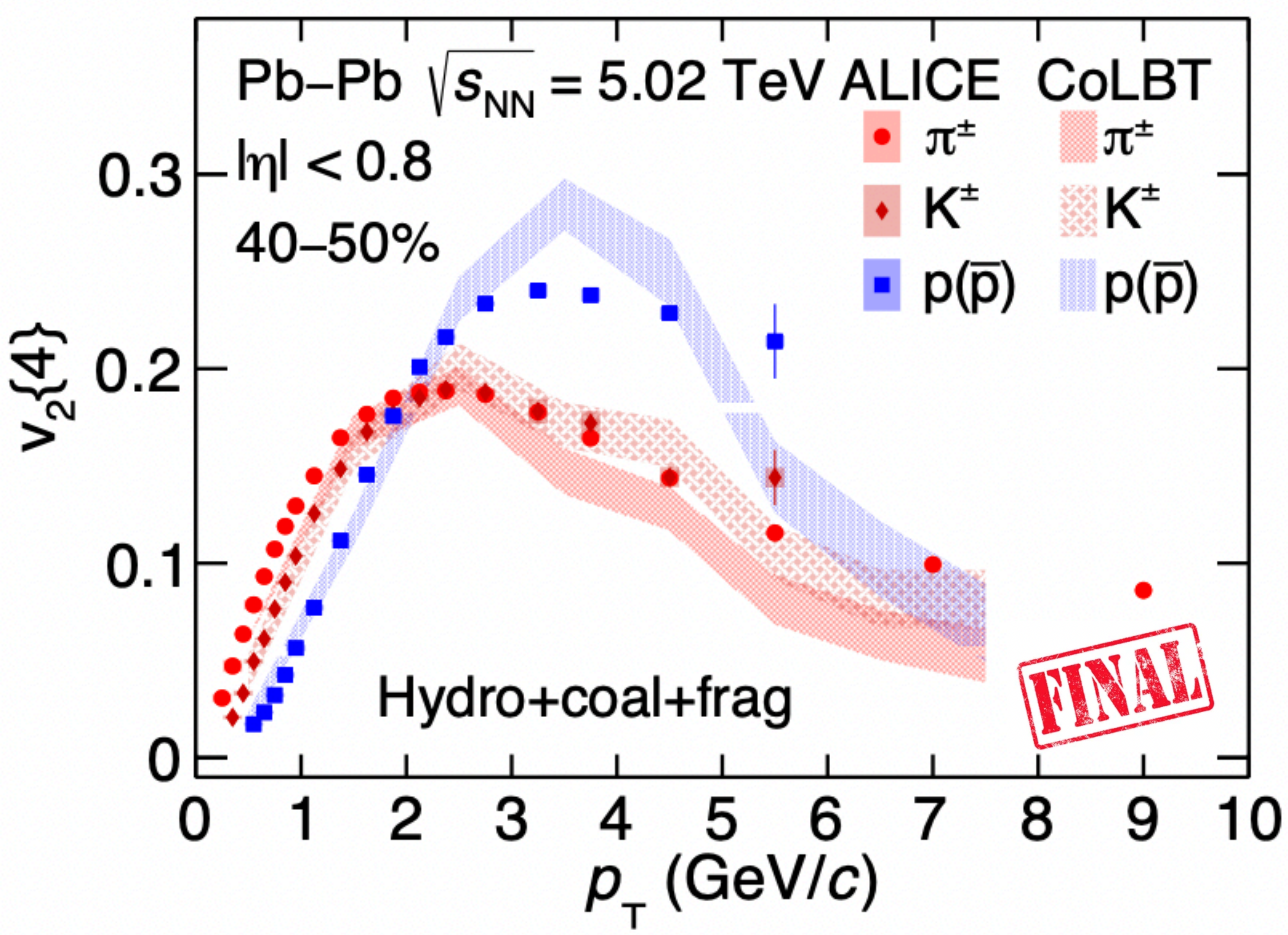
- Large deviations from unity of both A_2^f and M_2^f → **First observation of flow angle and flow magnitude fluctuations!**
- Comparison with theoretical models suggest observables are sensitive to **initial state** and the **QGP properties.**

FINAL

$v_2\{4\}$ for identified hadrons in Pb-Pb collisions

ALICE





❖ The first measurements of v_2 of 4-particle cumulants, $v_2\{4\}$, for $\pi^\pm$, $K^\pm$, K^0_S, $p(\bar{p})$, $\Lambda(\bar{\Lambda})$, φ, $\Xi(\bar{\Xi})$, $\Omega(\bar{\Omega})$

- Insensitive to non-flow contaminations, less bias in data/model comparisons
- Quantitatively described by CoLBT model with hydro+coal+frag

ALICE, arXiv: 2206.04587
CoLBT: PRL128 (2022) 022302

Flow fluctuations with identified hadrons

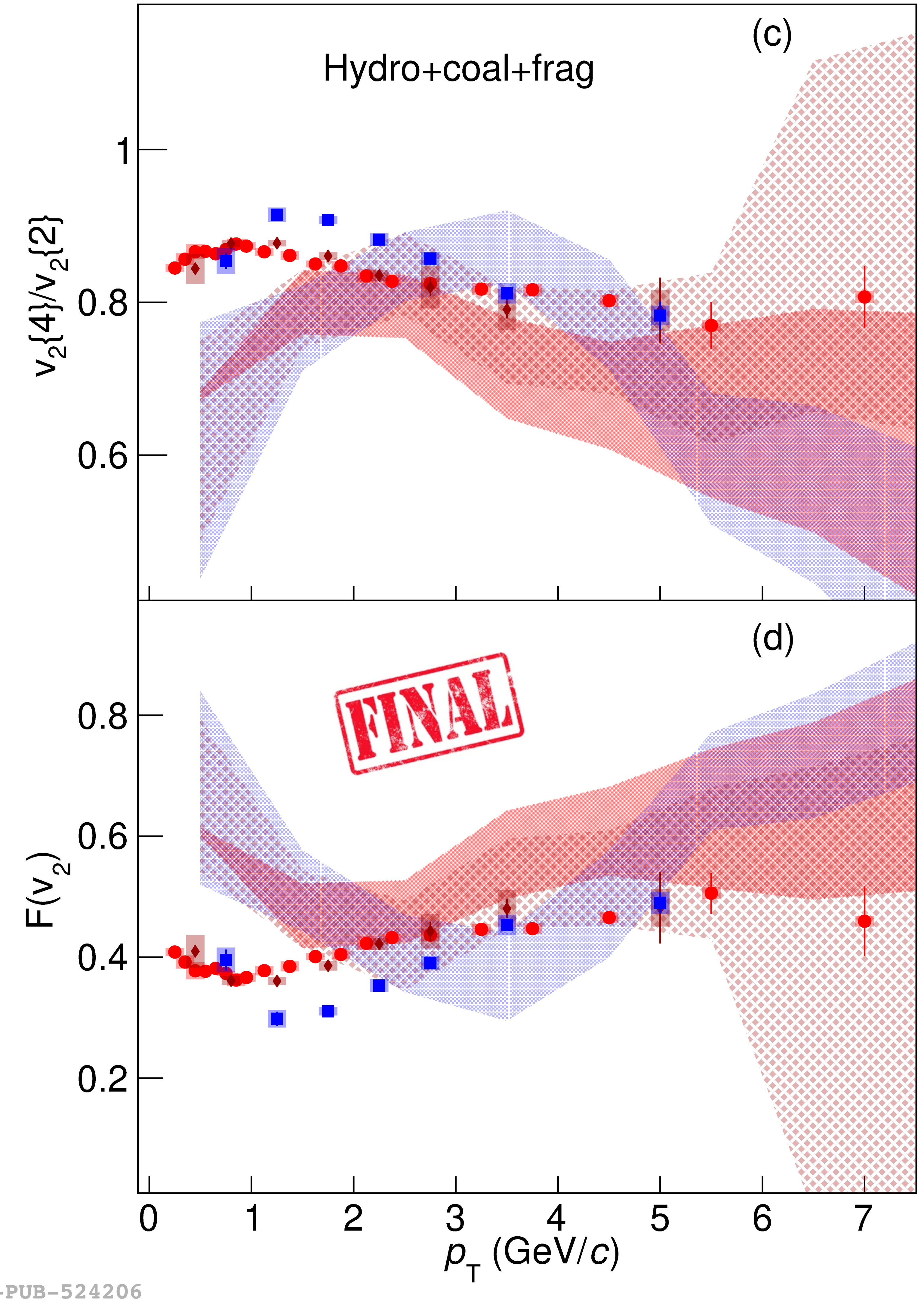
ALICE, arXiv: 2206.04587 CoLBT: PRL128 (2022) 022302

- Flow fluctuations with $v_n\{2\}$ and $v_n\{4\}$

$$v_n^2\{2\} = \langle v_n \rangle^2 + \sigma_{v_n}^2,$$
$$v_n^2\{4\} \approx \langle v_n \rangle^2 - \sigma_{v_n}^2,$$

$$v_n\{4\}/v_n\{2\}$$

$$F(v_n) = \sqrt{\frac{v_n^2\{2\} - v_n^2\{4\}}{v_n^2\{2\} + v_n^2\{4\}}}$$



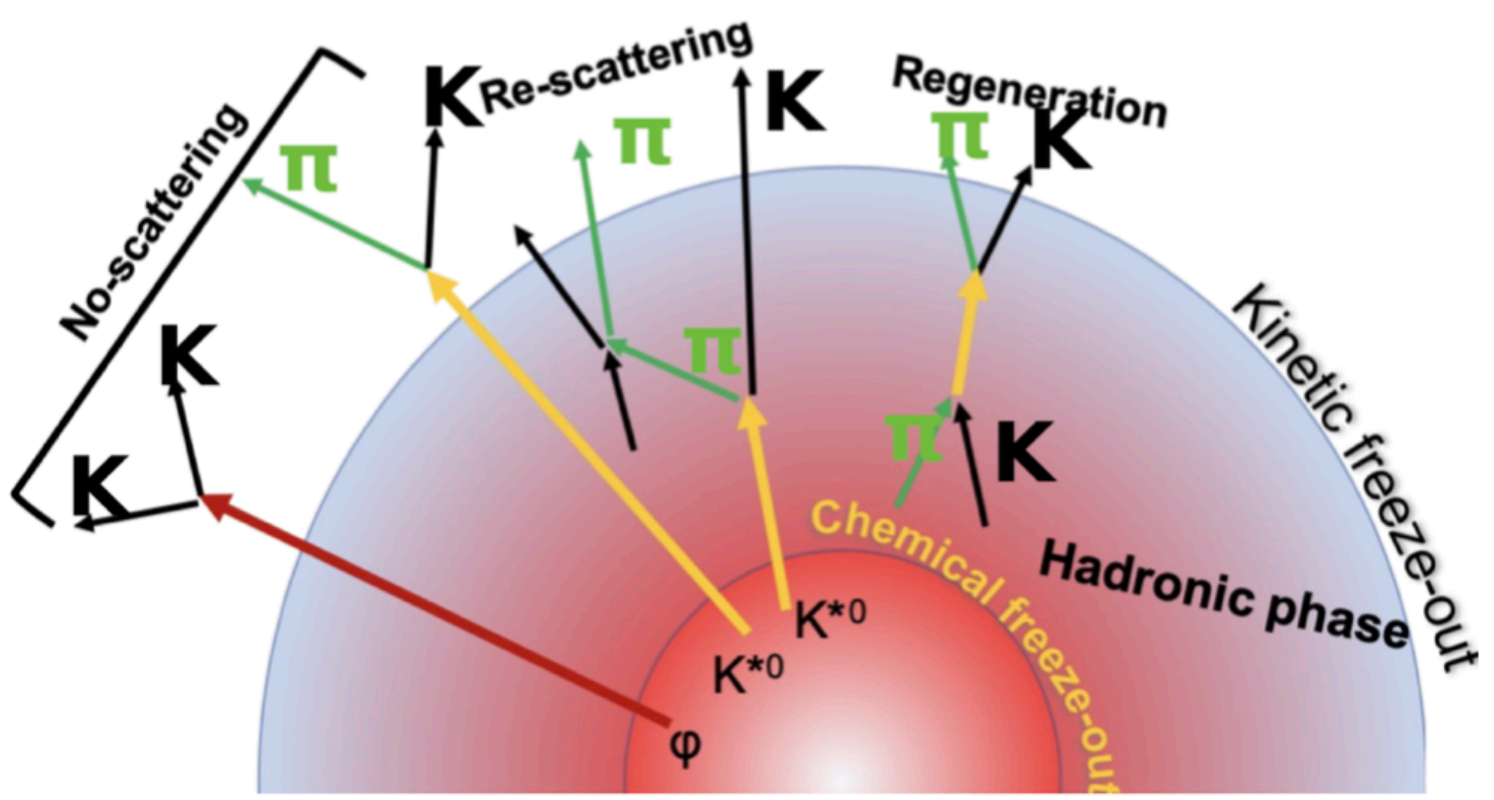
- Characteristic p_T and particle species dependence of $v_2\{4\}/v_2\{2\}$ and $F(v_2)$
  - Contributions not only from initial eccentricity fluctuations (p_T independent) but also system dynamic evolutions

Characterize the properties of hadronic phase with resonances

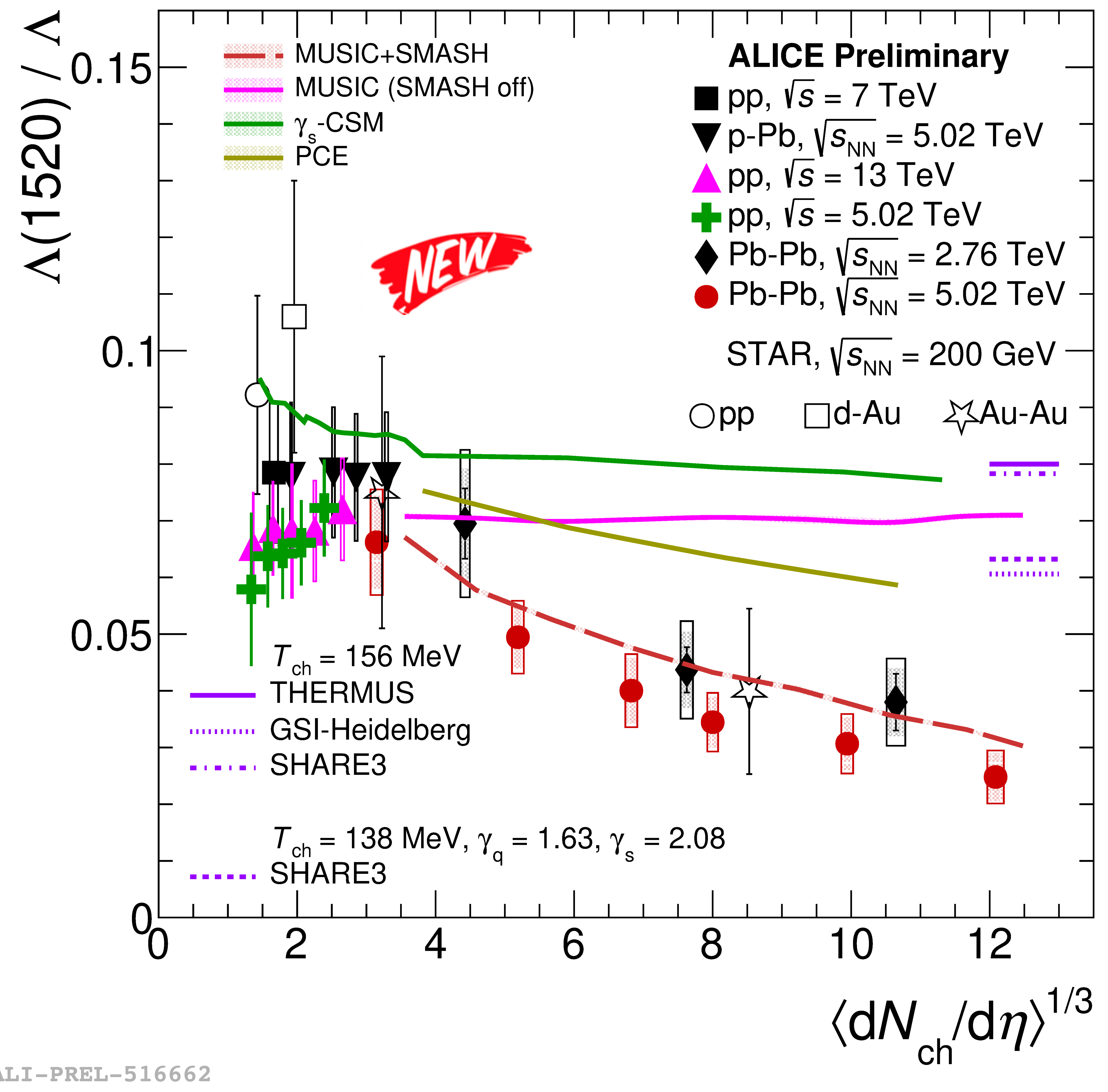
ALICE

Lifetime (fm/c):

$\rho^0(1.3) < K^{*\pm}\ (4.0) < K^{*0}\ (4.16) < \Sigma^{*\pm}\ (5.0\text{-}5.5) <$ **Λ^* (12.6)** $< \Xi^{*0}\ (21.7) < \phi(46.3)$



❖ Precision measurement of Λ(1520) yields
- Suppression in central Pb-Pb collisions w.r.t. peripheral established
- Centrality dependence reproduced by hydro (MUSIC) with the hadronic afterburner (SMASH)
- no suppression in high multiplicity pp and p-Pb



14 Jun 2022, 09:40, Dukhishyam Mallick @ Resonances and Hyper-nuclei

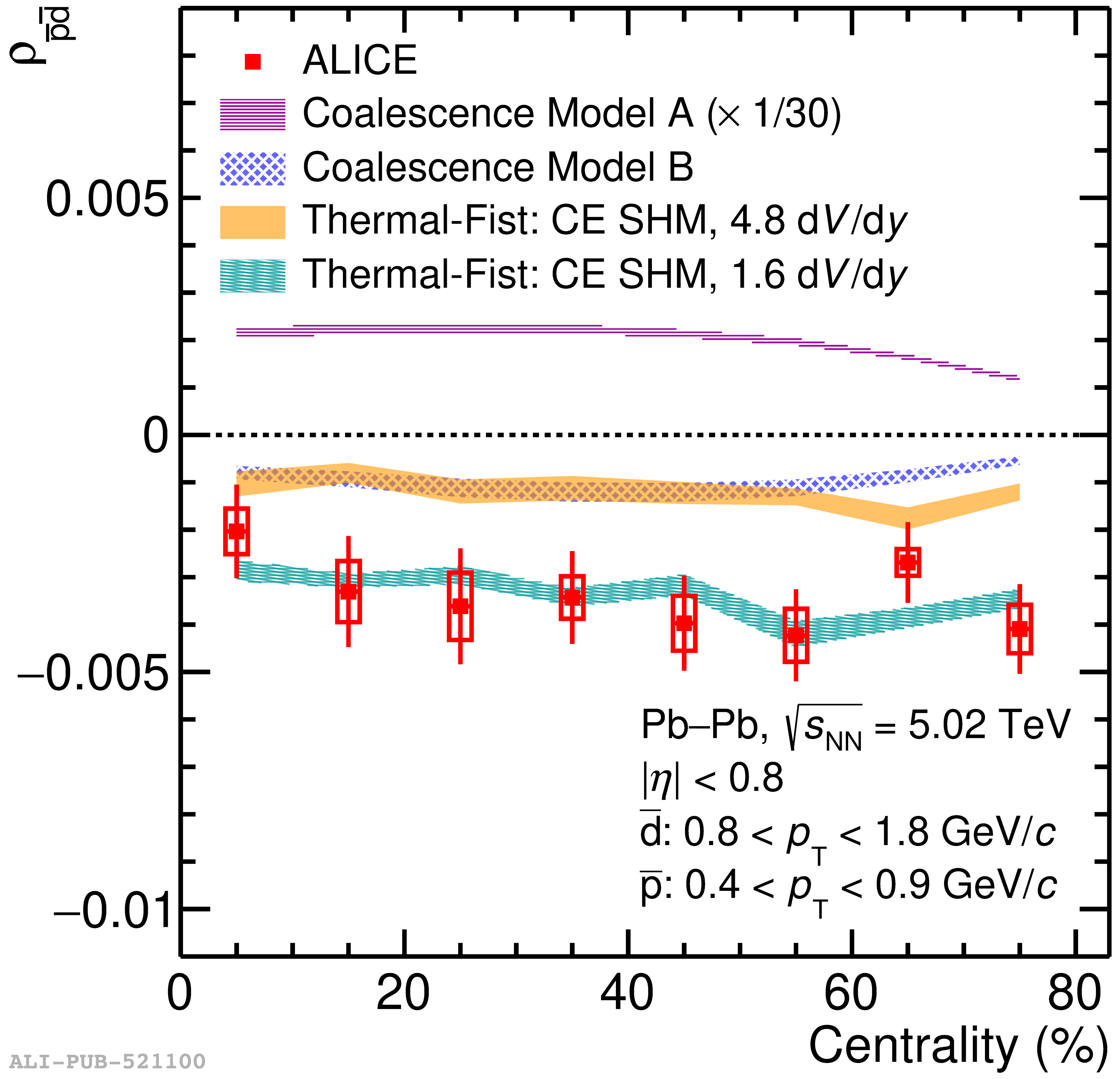
Antiproton-antideuteron Pearson correlation

❖ Antiproton-antideuteron Pearson correlation

$$\rho_{ab} = \langle (n_a - \langle n_a \rangle)(n_b - \langle n_b \rangle) \rangle / \sqrt{\kappa_{2a}\kappa_{2b}}$$

- Negative correlation between antiproton and antideuteron is observed in data
- Predicted by Canonical Ensemble thermal model with correlation volume V_c = 1.6 dV/dy,
  - smaller than for cumulant measurements of protons
- Coalescence model B (independent proton and neutron production) qualitatively but not quantitatively describe the data
- Coalescence model A (full correlation among protons and neutrons) can be ruled out

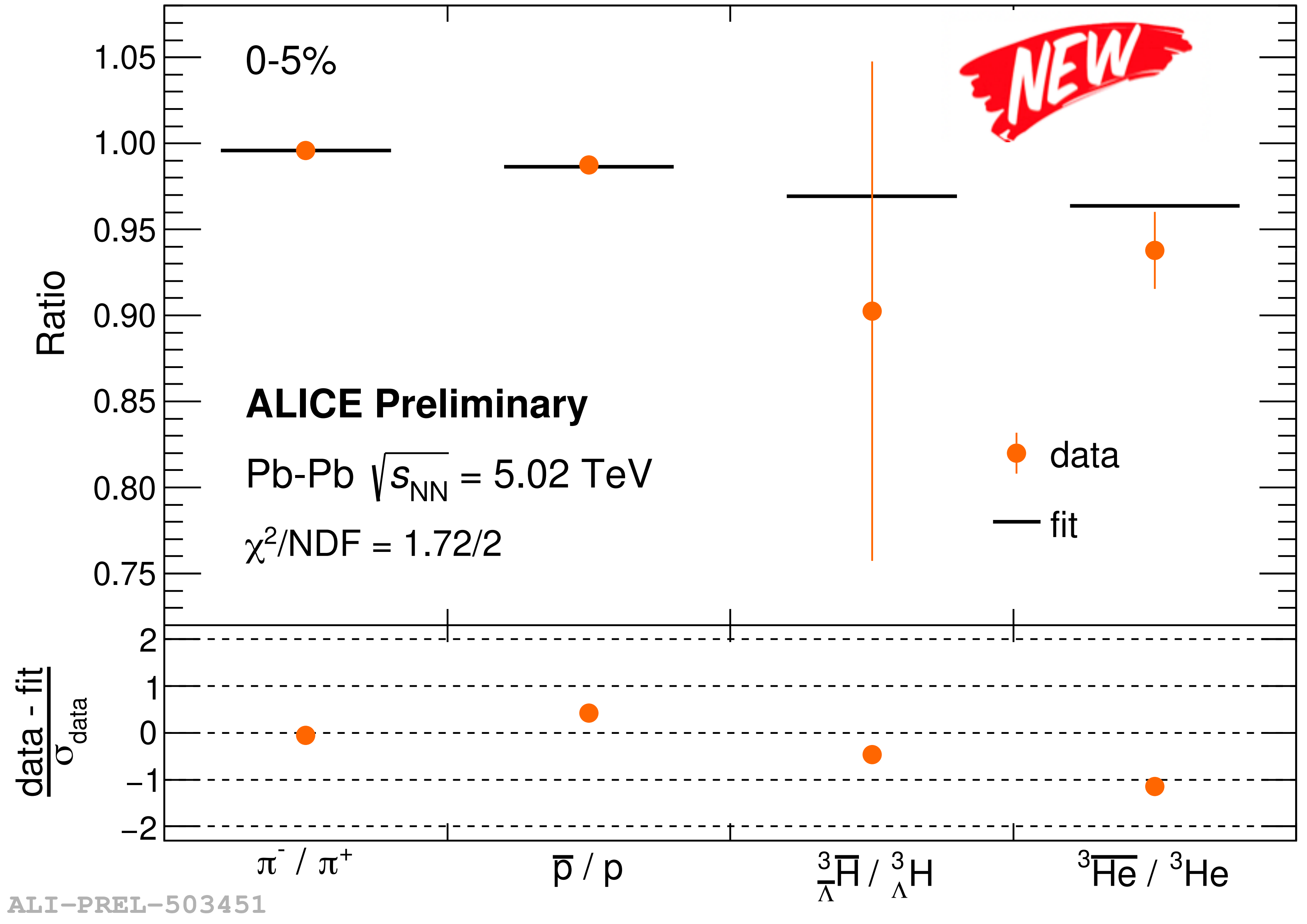
ALICE, arXiv:2204.10166

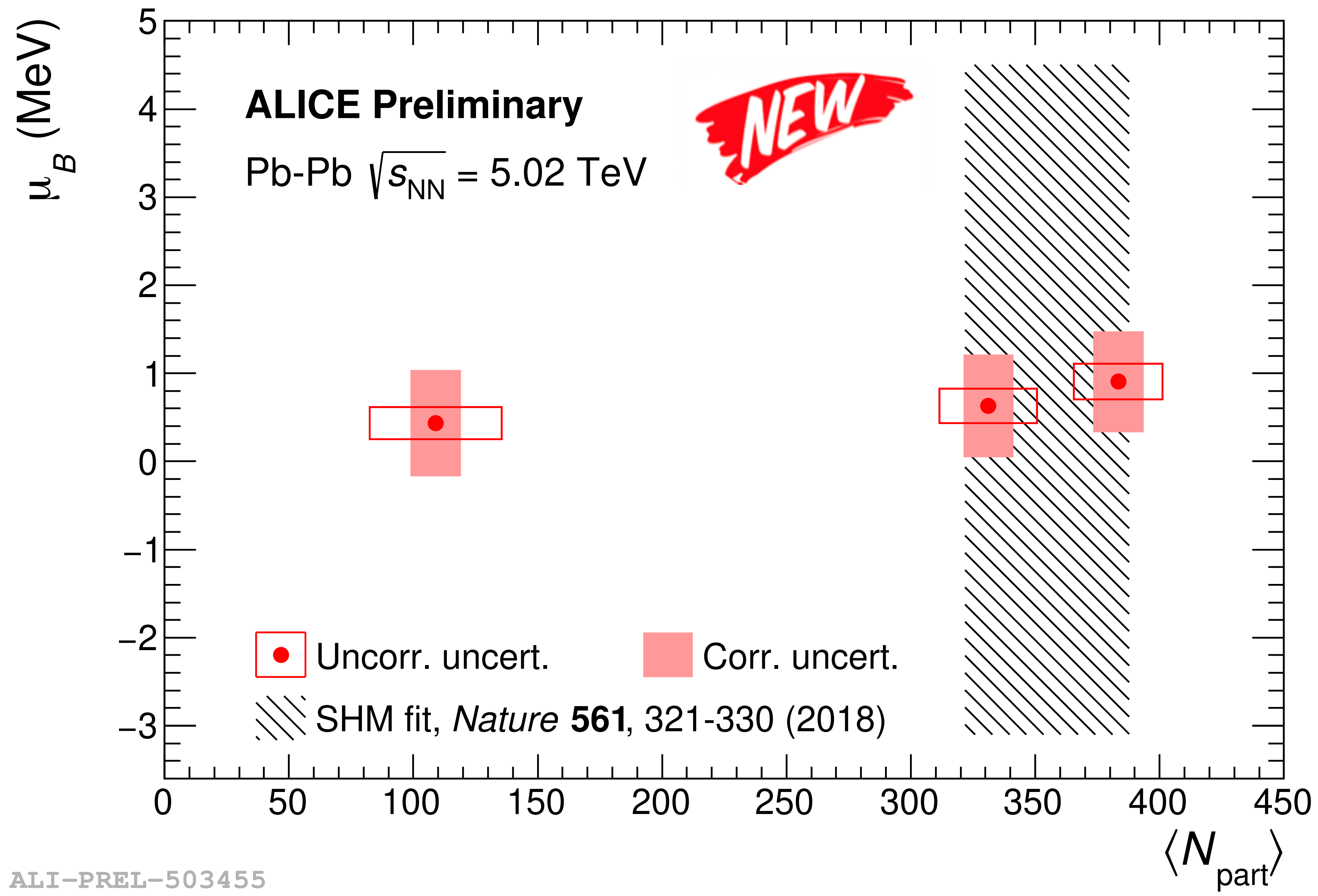


14 Jun 2022, 10:50, Mario Ciacco @ Light-flavor and Strangeness

Precision μ_B measurements via $\bar{B}/B$ ratio

ALICE





- Fitting the ratio with SHM equation
  - $\bar{h}/h \propto \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$
  - Extract μ_B and μ_{I3} from the fits

	π^+	p	^{3}He	$^3_\Lambda$H
B+S/3	0	1	3	8/9
I_3	1	1/2	1/2	0

14 Jun 2022, 10:50, Mario Ciacco
@ Light-flavor and Strangeness

- Consistent with previous studies but with ***O(10) improvements*** in precision
  - Most precise measurements of μ_B at the TeV scale!
- A decreasing trend from central to peripheral collision, because of baryon stopping, is not observed.

Net proton number fluctuations

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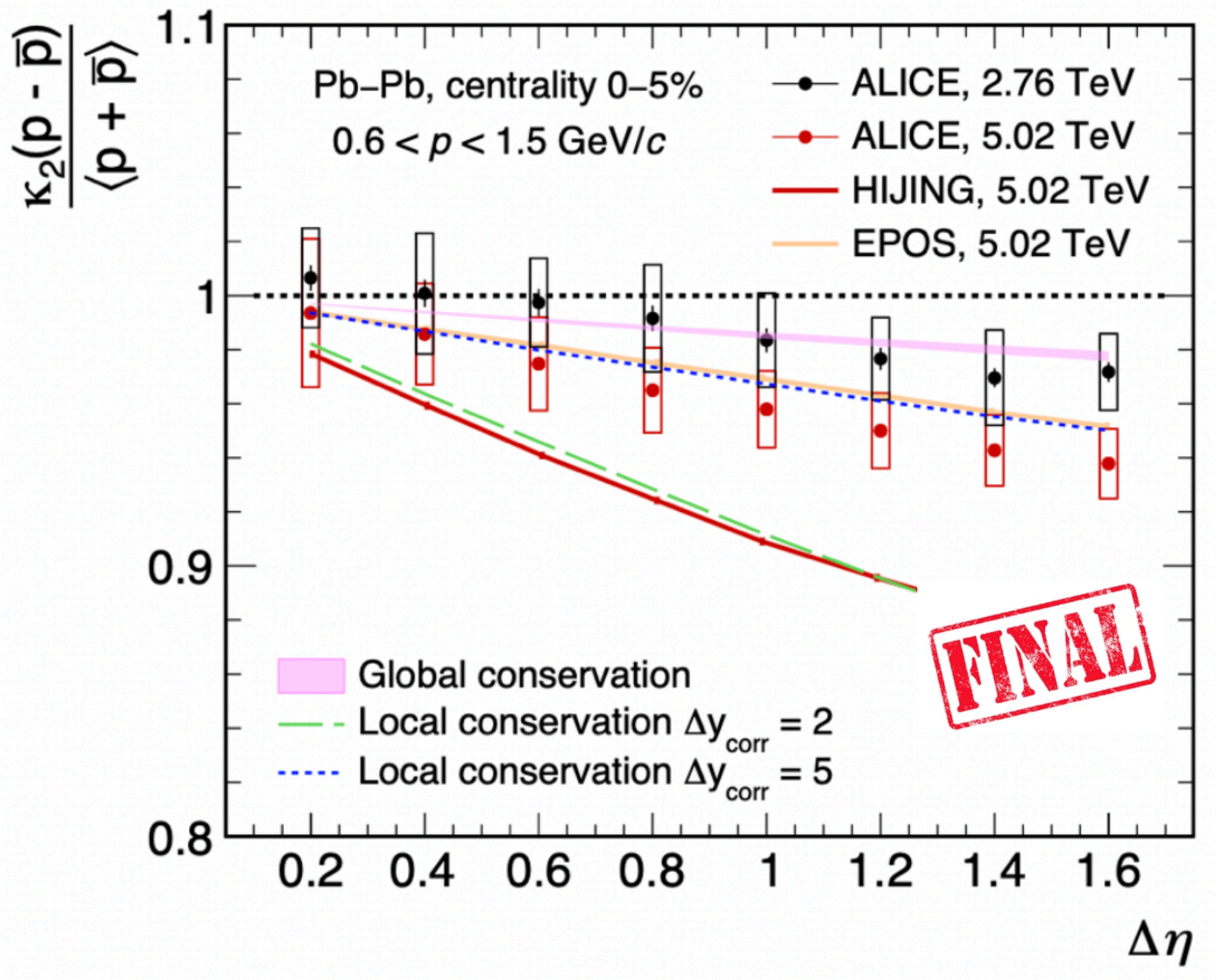
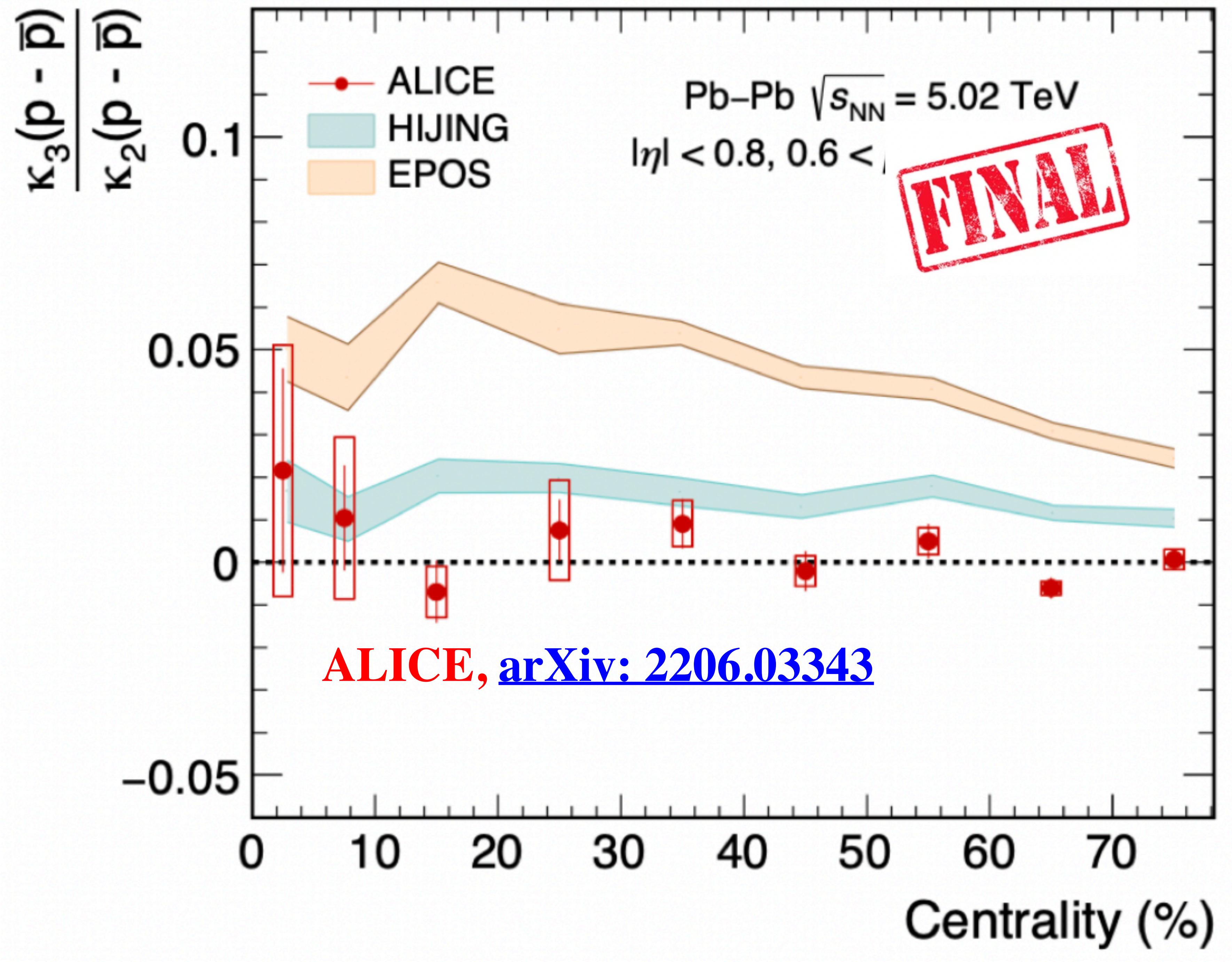
15 Jun 2022, 11:30, Mesut Arslandok @ Bulk matter phenomena, QCD phase diagram, and Critical point

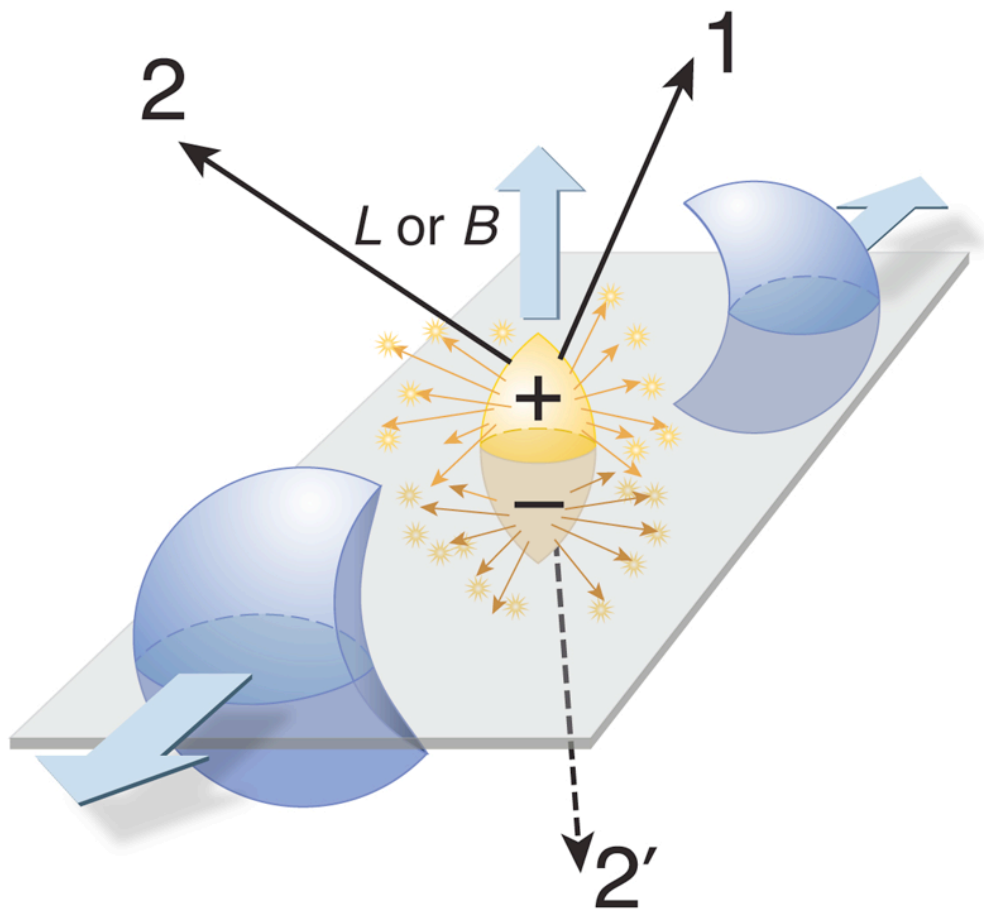
- Up to 3rd order net proton cumulants agree with LQCD expectations

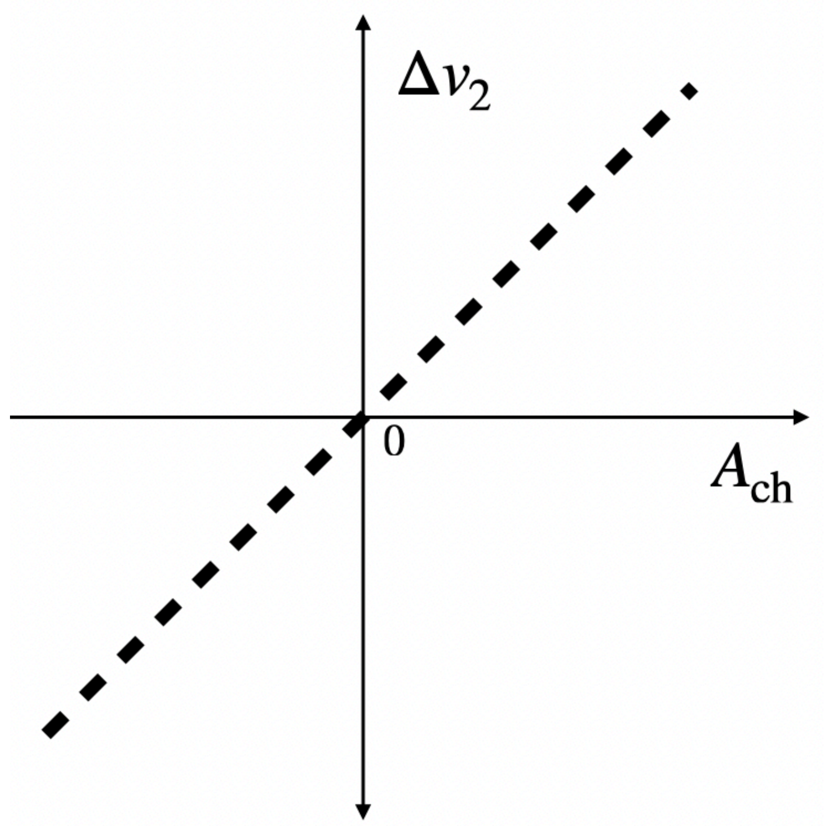




- 2nd order: Long-range correlations ($\Delta\eta$) originating from early phase of the collision
- 3rd order: Agrees with Skellam baseline "0"
- μ_B is very close to 0 at the LHC energies

Searches for Chiral Magnetic Wave (CMW)



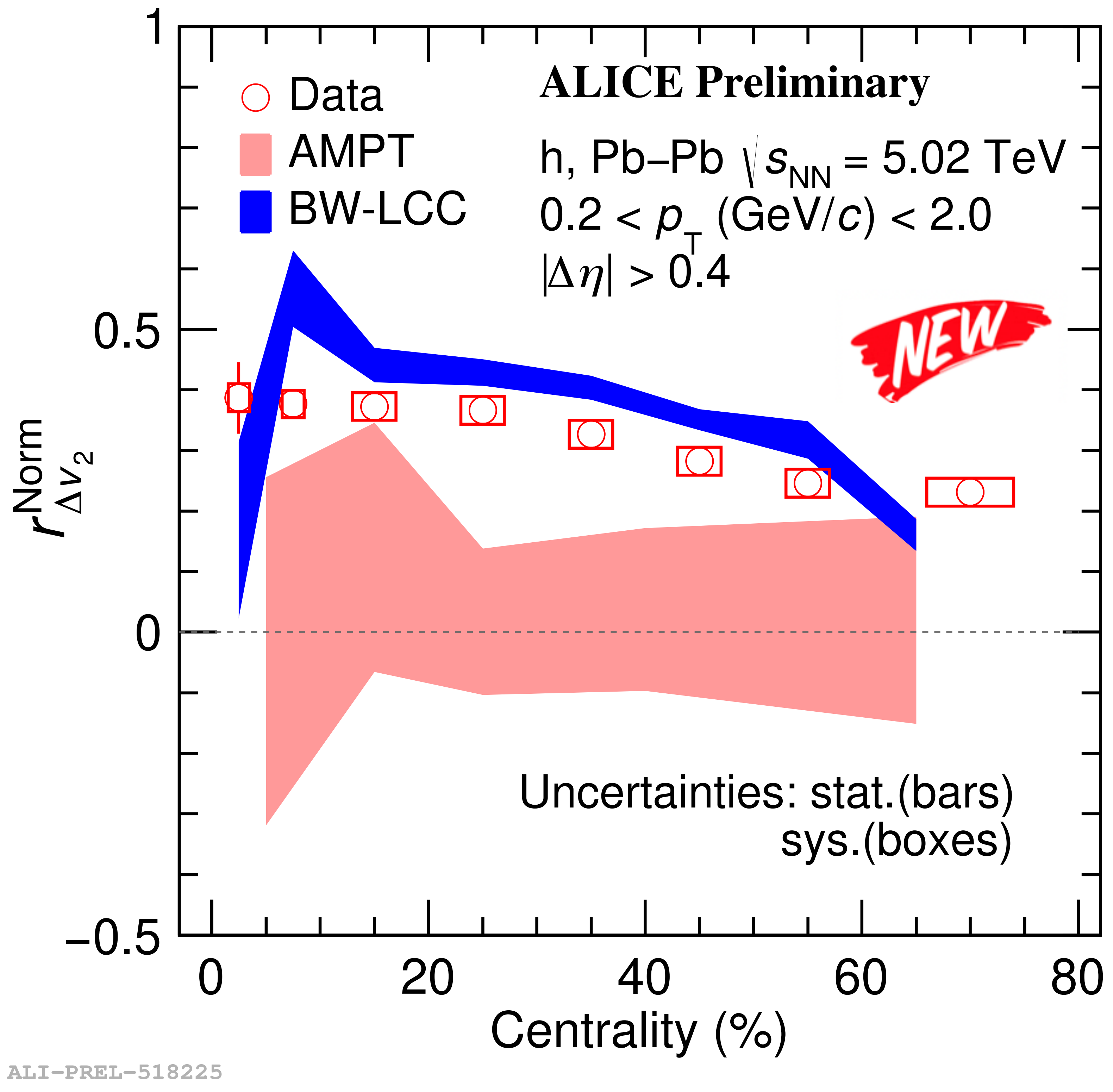


$$\Delta v_2 = v_2^- - v_2^+ = rA_{ch} \qquad \langle v_2 \rangle = \frac{v_2^{h^+} + v_2^{h^-}}{2}$$

$$A_{ch} = \frac{N^+ - N^-}{N^+ + N^-}$$

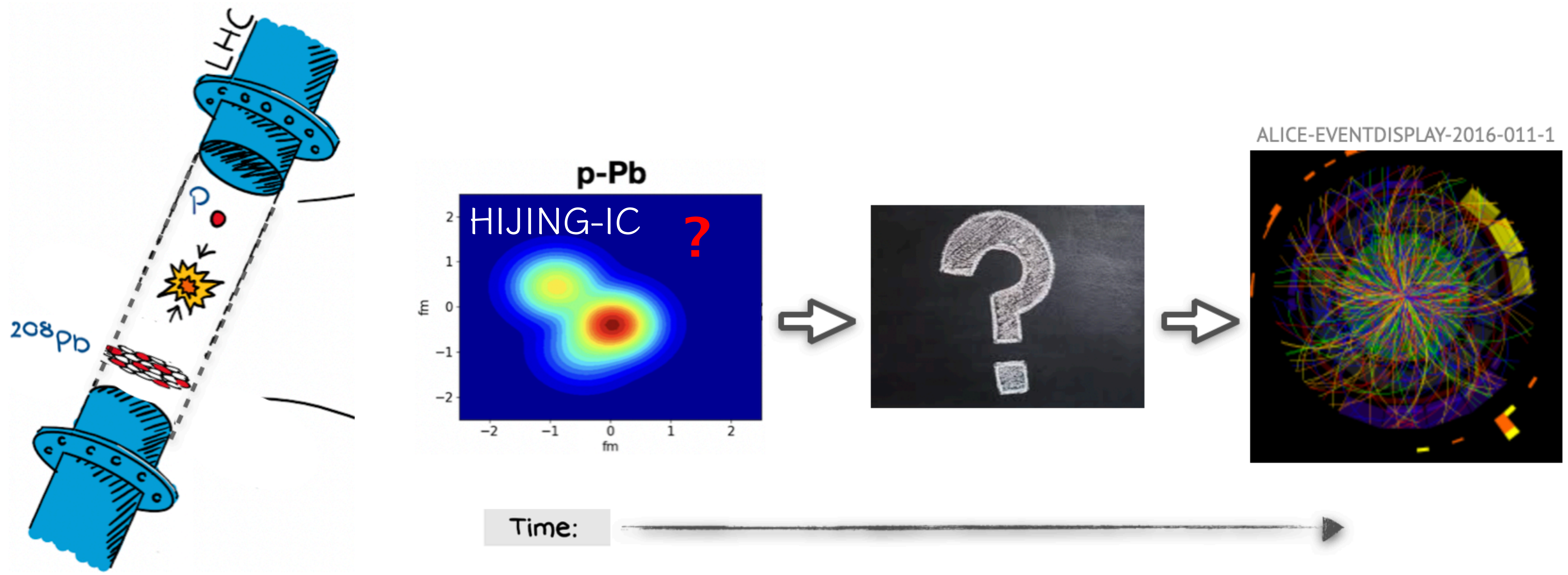
CMW observable: Normalized slope, $r_{\Delta v_2}^{Norm.} = \dfrac{d(\frac{\Delta v_2}{\langle v_2 \rangle})}{dA_{ch}}$

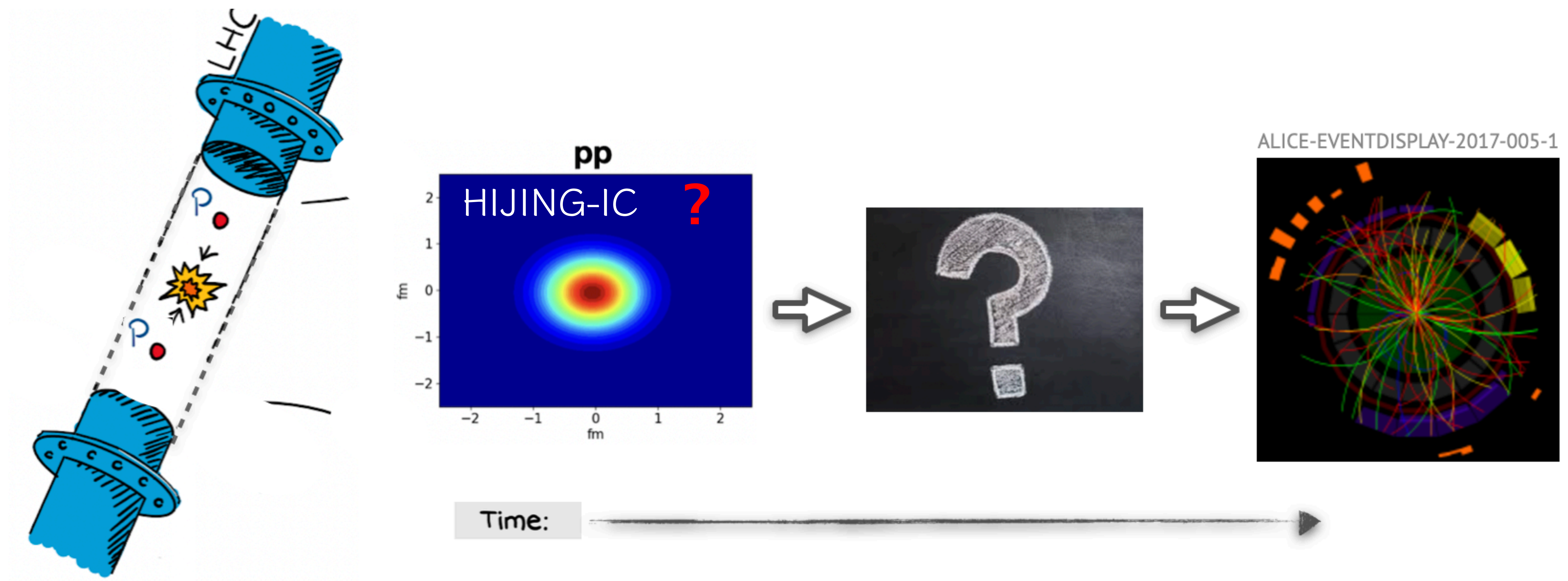
14 Jun 2022, 16:30, Wenya Wu @ Bulk matter phenomena, QCD phase diagram, and Critical point



- AMPT model (***no*** *CMW signal,* ***no*** *LCC background)*
  → slope is zero
- BW-LCC model (***no*** *CMW signal,* ***with*** *LCC background)*
  - ***observed effect approximately compatible with background***

p-Pb and pp collisions: smaller but not simpler





- *Similarities* between pp, p-Pb, Xe-Xe and Pb-Pb observed
  - ***Strangeness enhancement***
  - ***Sizeable anisotropic flow***

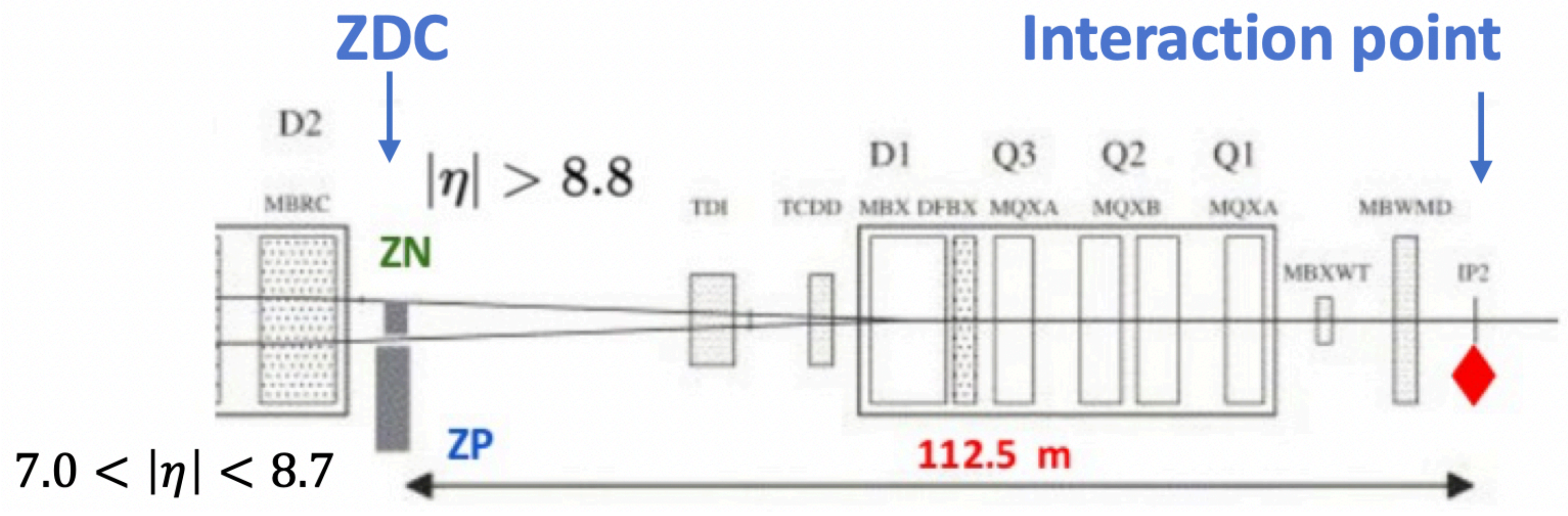
Initial stage effects on strangeness enhancement

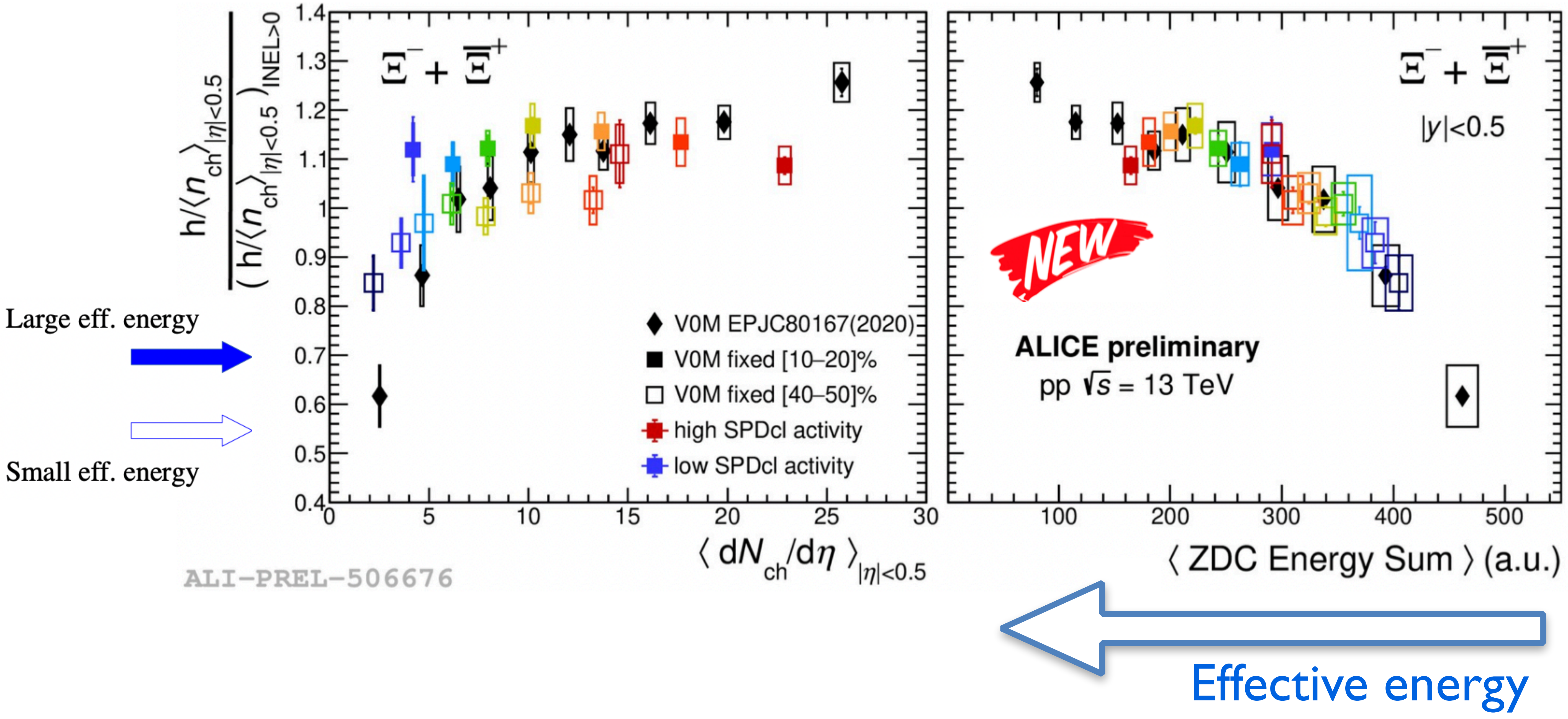
ALICE

- Strangeness enhancement:
  - correlated only with ***final state*** charged multiplicities?
  - ***initial stage*** of the collision play a role?

- Study initial stages effects via ***effective energy***, the energy effectively available for particle production, in the initial stages

$$\mathrm{E_{eff}} \simeq \sqrt{\mathrm{s}} - \langle \mathrm{ZDC\ energy\ sum} \rangle$$



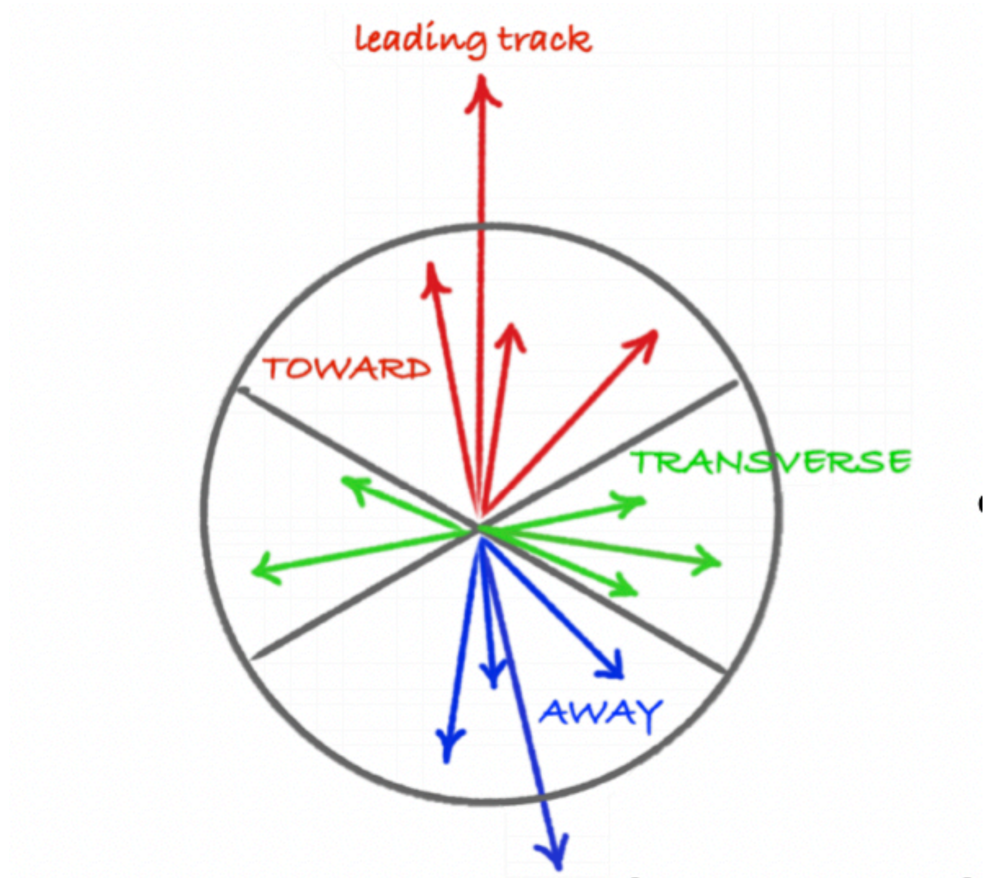


- Strangeness enhancement visible, at approximate fixed multiplicity, when increasing effective energy
- Effective energy (from the initial stages of the collisions) plays an important role in the strangeness enhancement

14 Jun 2022, 11:10, Romain Schotter @ Light-flavor and Strangeness

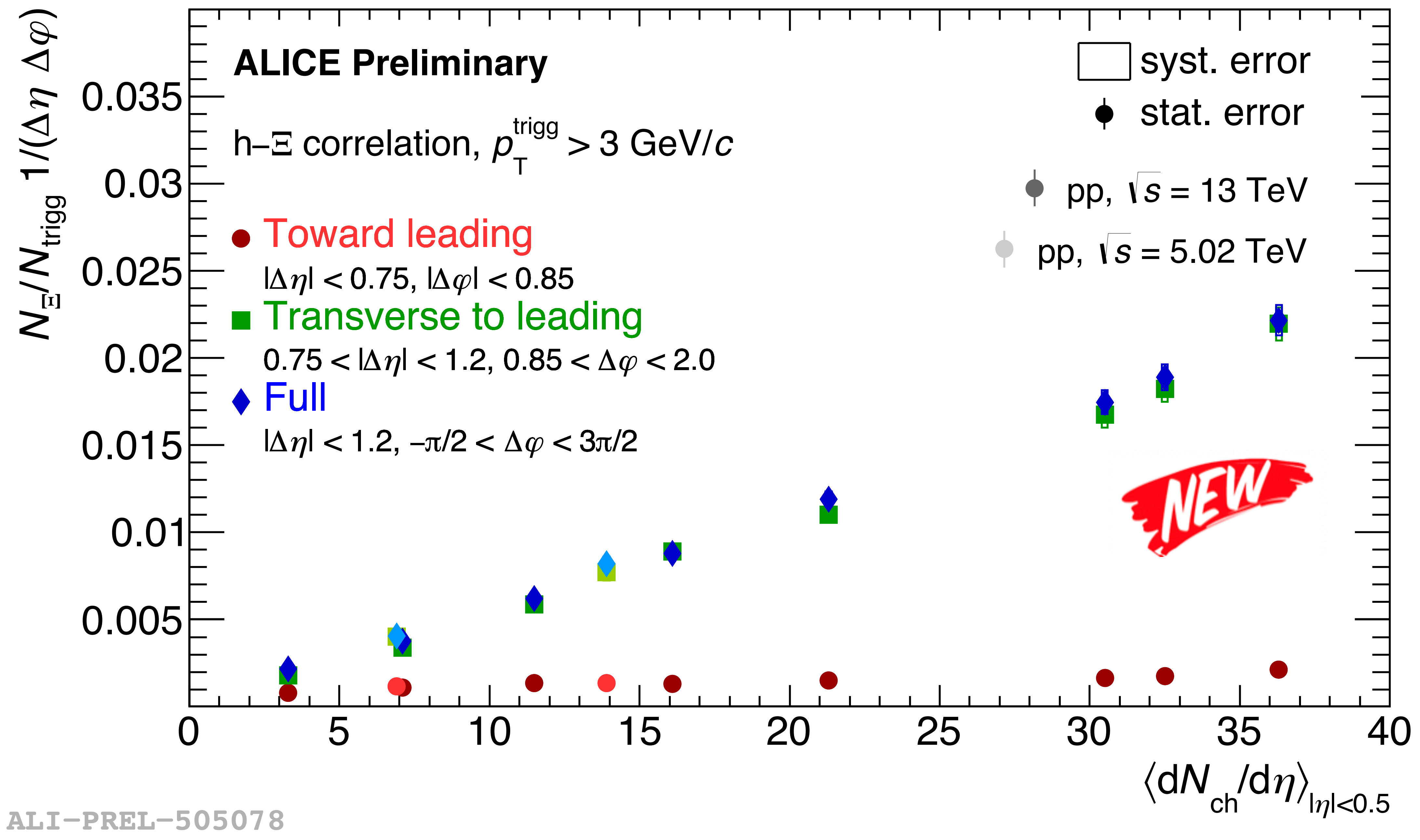
multi-differential investigation of strangeness production

- Study strangeness production via angular correlation between trigger (leading tracks) and associate particles (strange hadrons)



Toward region (Jet + UE)

Transverse region (UE)



- Both Full and Transverse to leading particle yields increase with $dN_{ch}/d\eta$
- Toward leading particle yield shows an almost flat dependence with multiplicity
- No collision energy dependence

→ Strange hadrons in pp collisions are dominantly produced in the transverse region (to the leading particles)

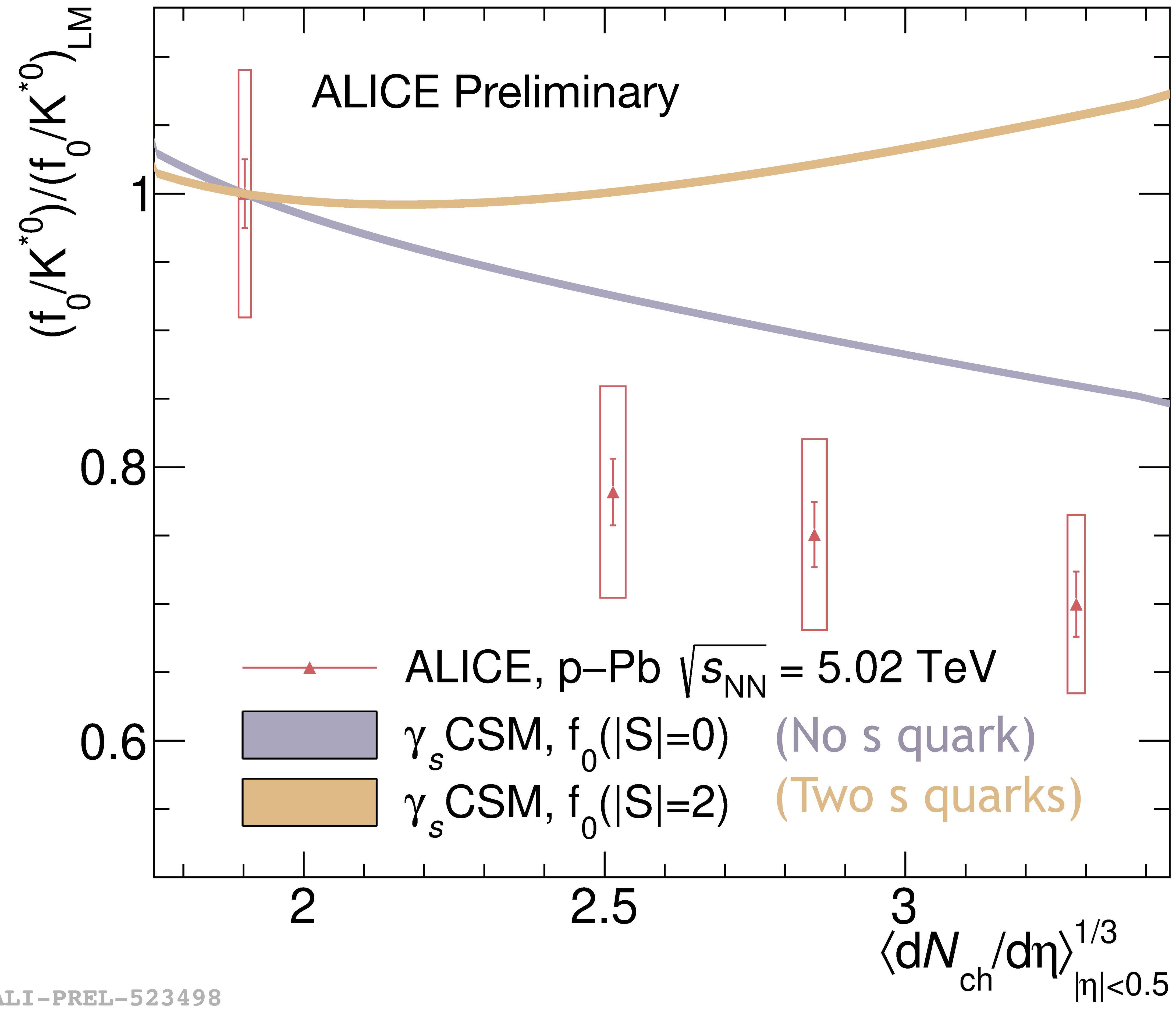
14 Jun 2022, 11:10, Romain Schotter @ Light-flavor and Strangeness

f_0(980) production

- The quark content and structure of scalar meson f_0(980) are still controversial, with potential candidates:
  - Two-quark state: PRD 67, 094011 (2003)
  - Tetraquark state ($q\bar{q}s\bar{s}$): PRD 103, 014010 (2021)
  - $K\bar{K}$ molecule state: PRD 101, 094034 (2020)

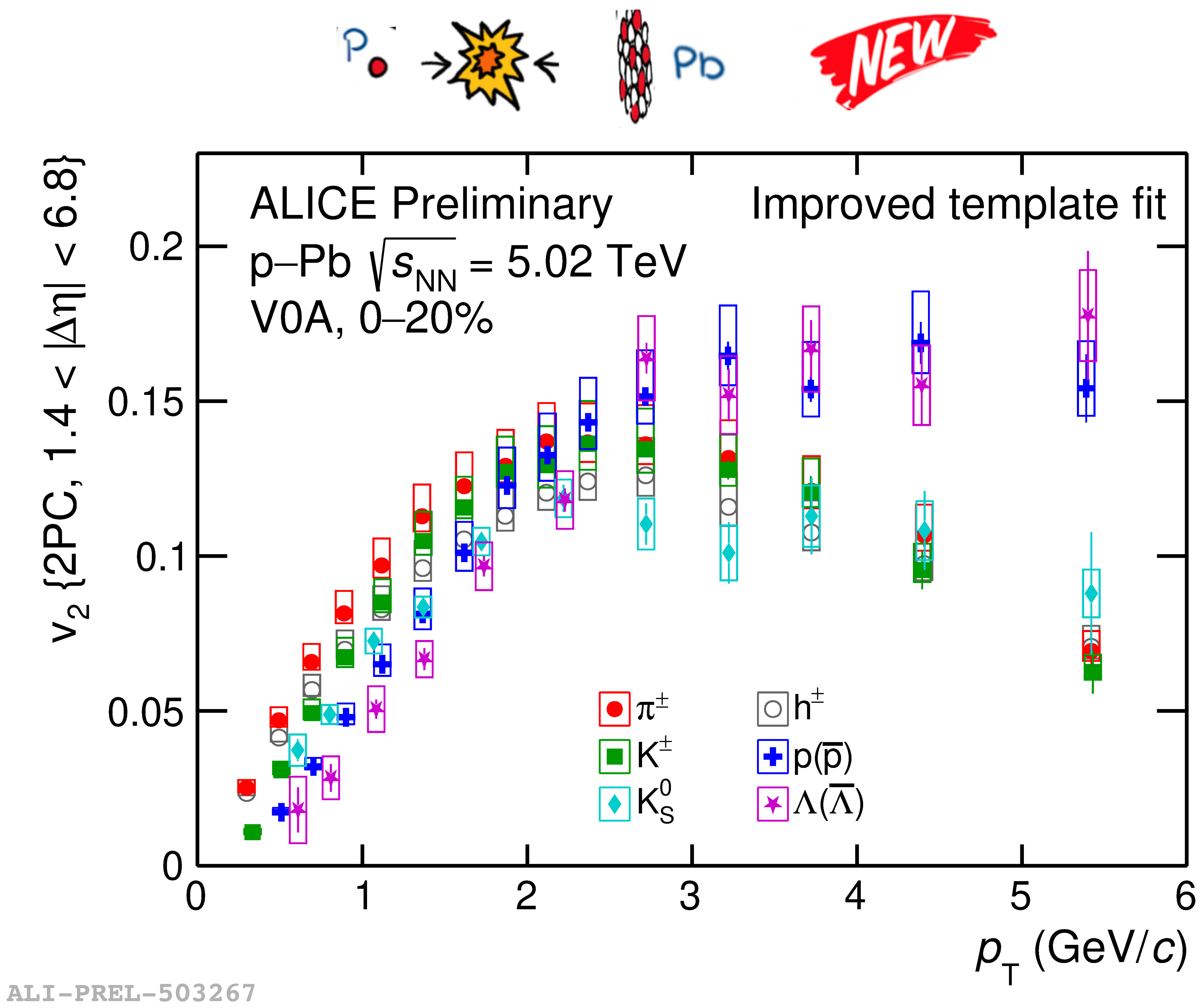
	ρ^0	K^*	$f_0(980)$	ϕ
Mass (MeV/c^2)	775	892	990	1020
J^P	1^-	1^-	0^+	1^-
Contents	$\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}$	$d\bar{s}$	???	$s\bar{s}$
lifetime (fm/c)	1.3	4.2	$\sim$ 2–20 fm/c	46.2

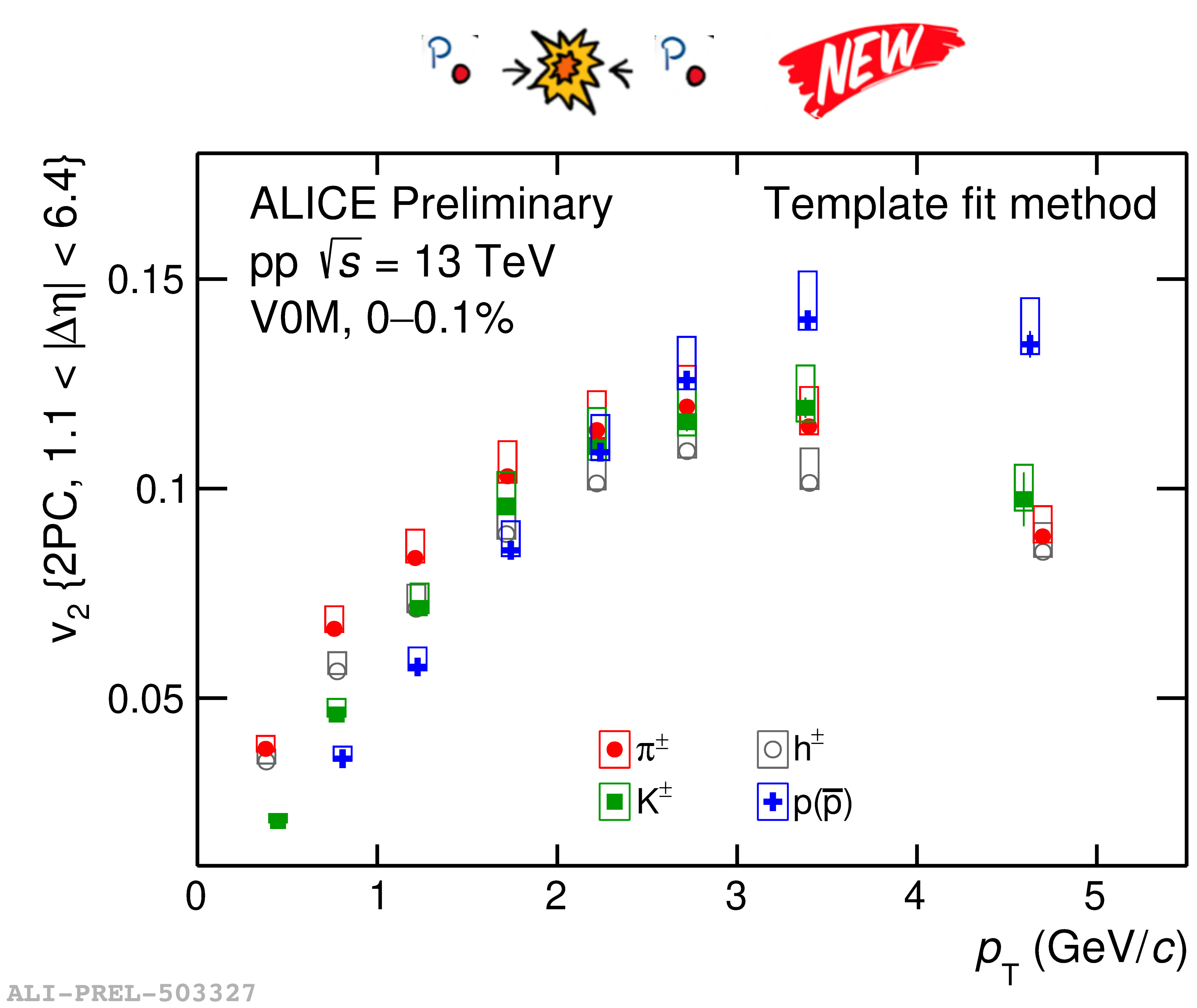
- Canonical statistical model (CSM) with multiplicity dependent $\gamma_s \leq 1$ is used to predict (f_0/K^{*0}) ratio for strangeness content hypotheses
  - a flat $dN_{ch}/d\eta$ dependence for **|S|=2**
  - a decreasing trend with **|S|=0**, agrees qualitatively with data



14 Jun 2022, 10:50, Junlee Kim @ Resonances and Hyper-nuclei

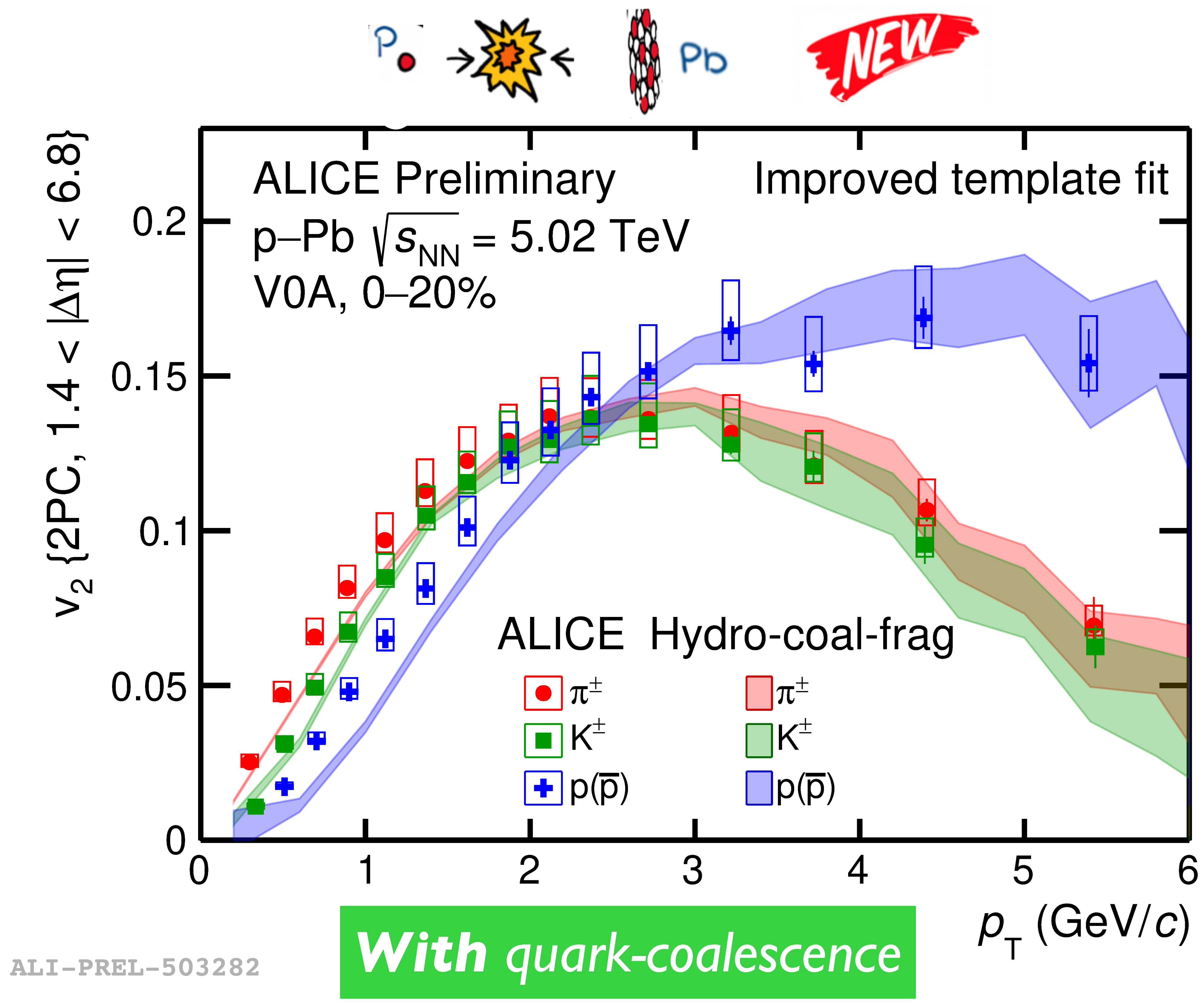
v_2 of identified hadrons in p-Pb and pp, similar as Pb-Pb

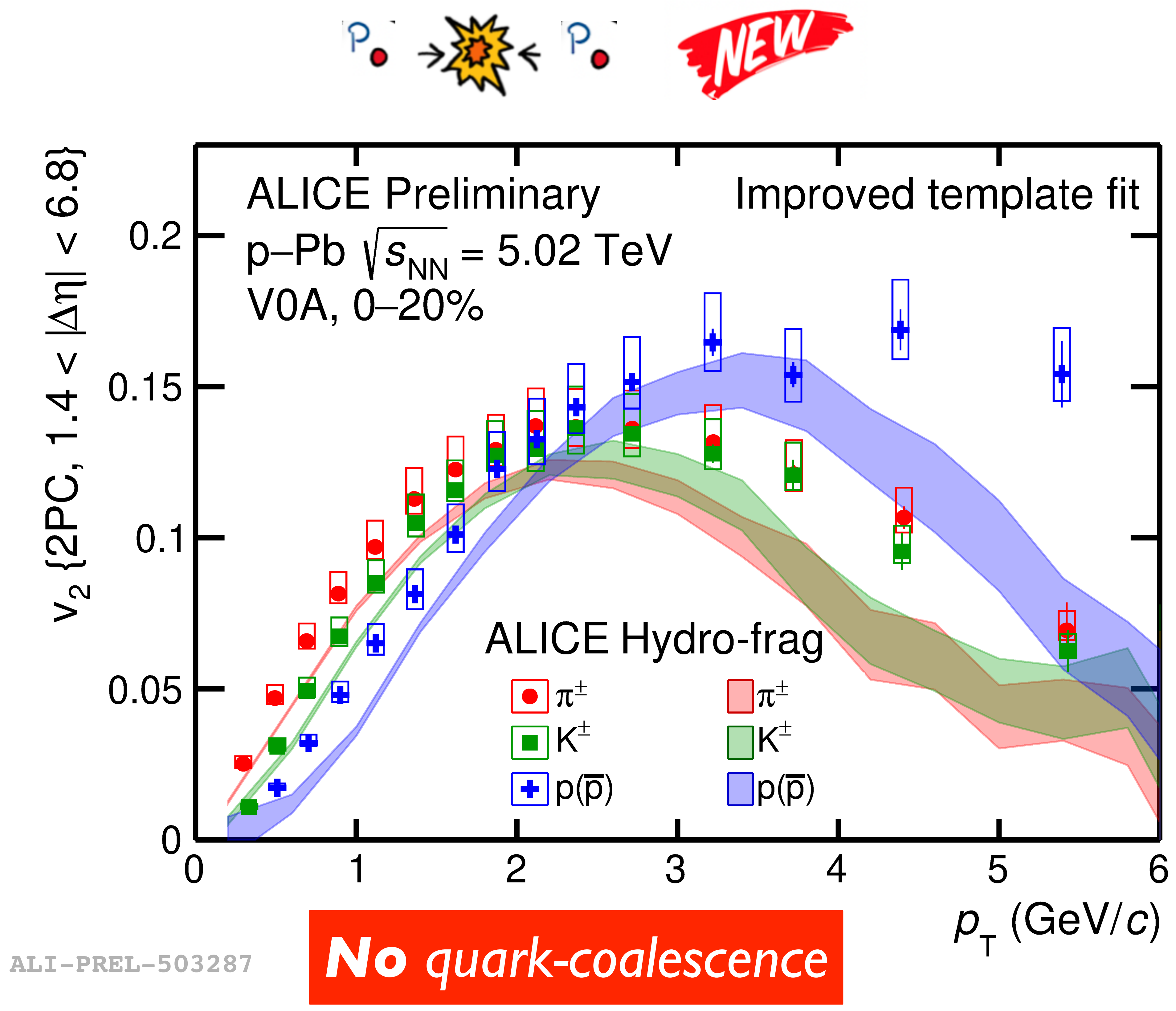




- Flow of identified particles, using long-range di-hadron correlations, in p-Pb and pp collisions
  - ***Mass ordering*** in low p_T region (described by hydrodynamics)
  - ***Baryon-meson v_2 splitting*** at intermediate p_T region by > 3σ
  - Characteristic flow behaviours in Pb-Pb collisions, have been observed in p-Pb and pp collisions

Partonic flow in small systems



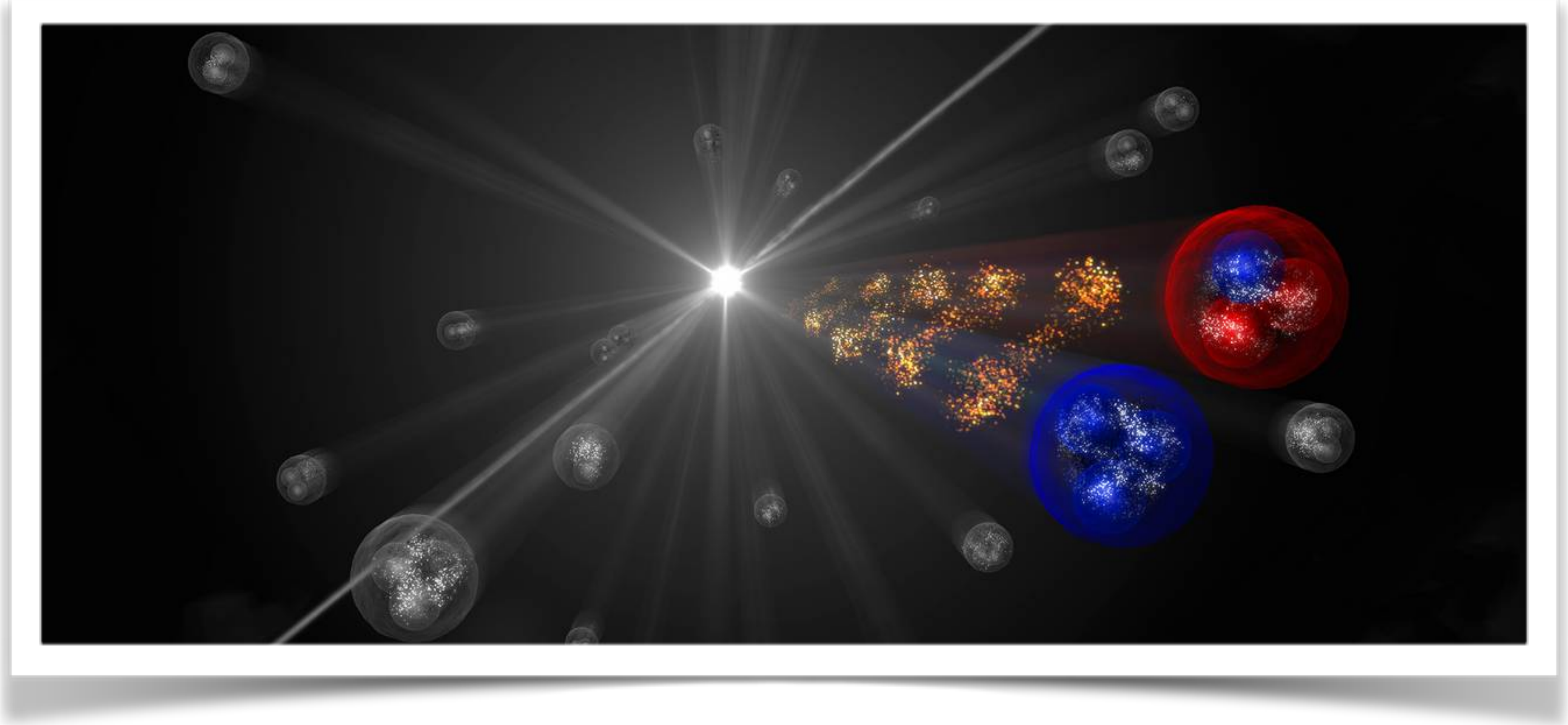


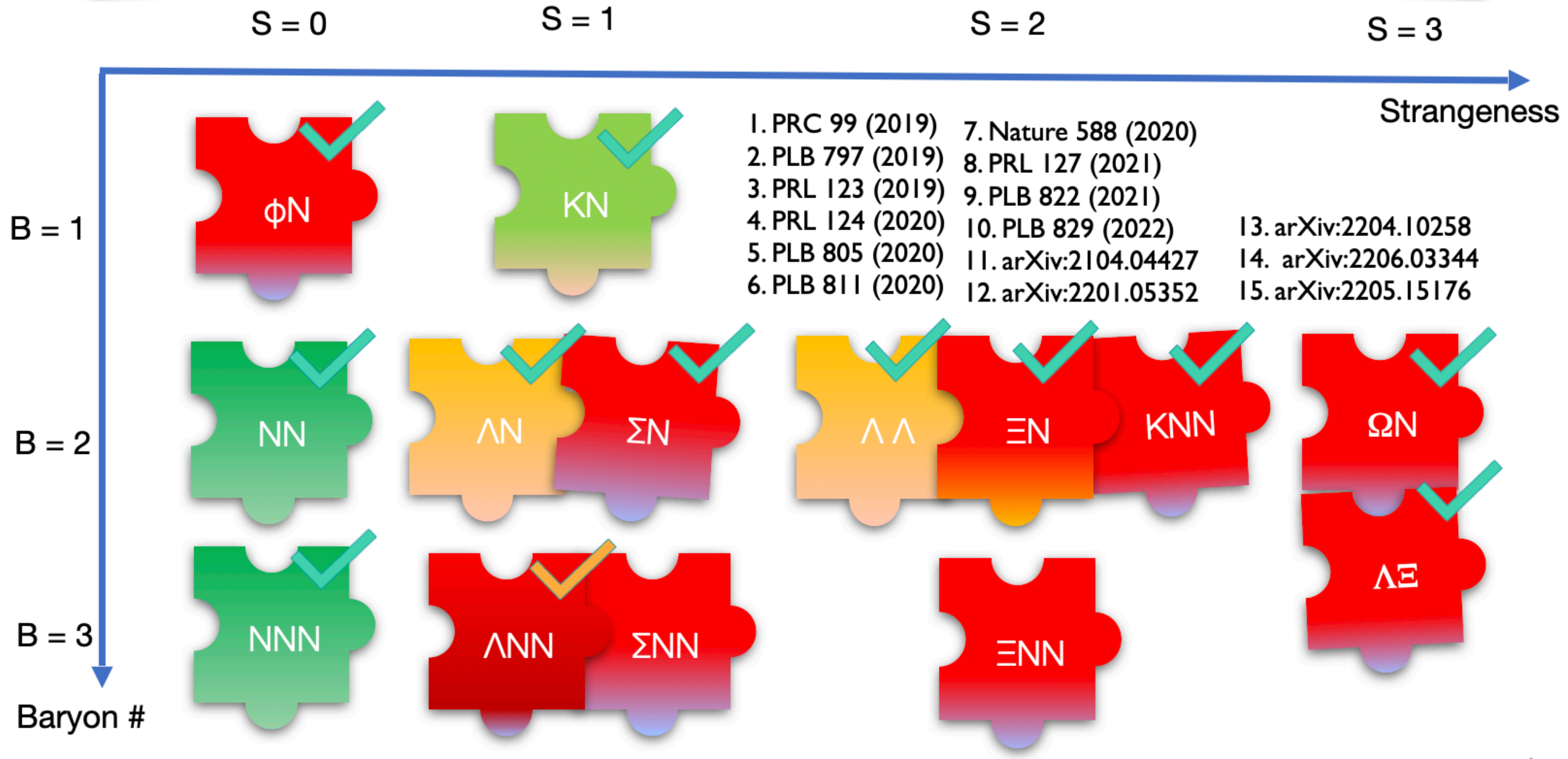
Model: W. Zhao etc, PRL125 (2020) 7, 072301

- CoLBT model with hydro+coal+frag reproduces the new ALICE measurements
- Model without quark coalescence cannot qualitatively describe trends seen in data
- **Indication** of partonic flow in small systems

Hadron-hadron interactions

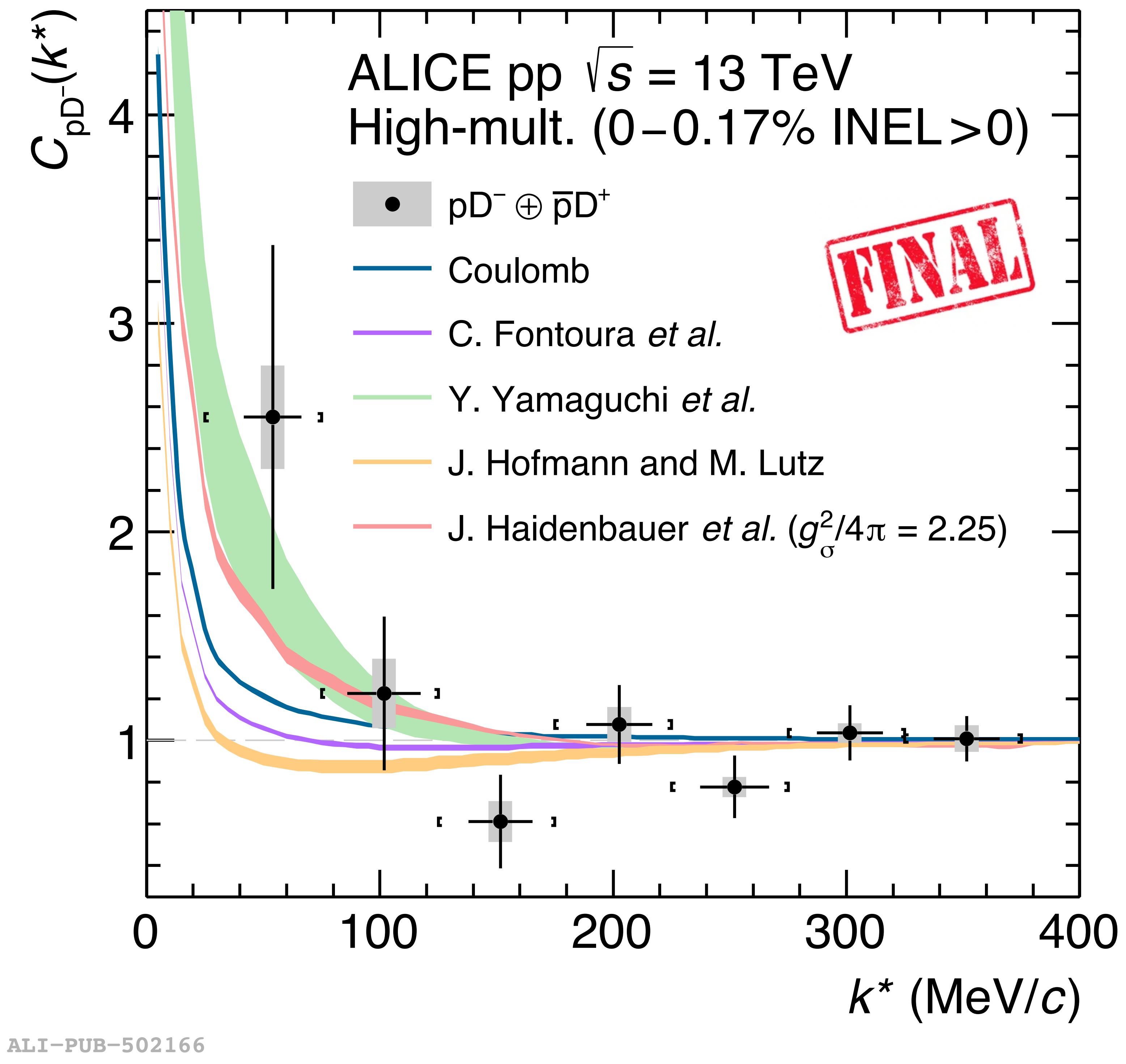
ALICE is pioneering the study of strong interactions using femtoscopic correlations





14 Jun 2022, 15:30, Emma Chizzali@ Heavy-flavor and Quarkonia

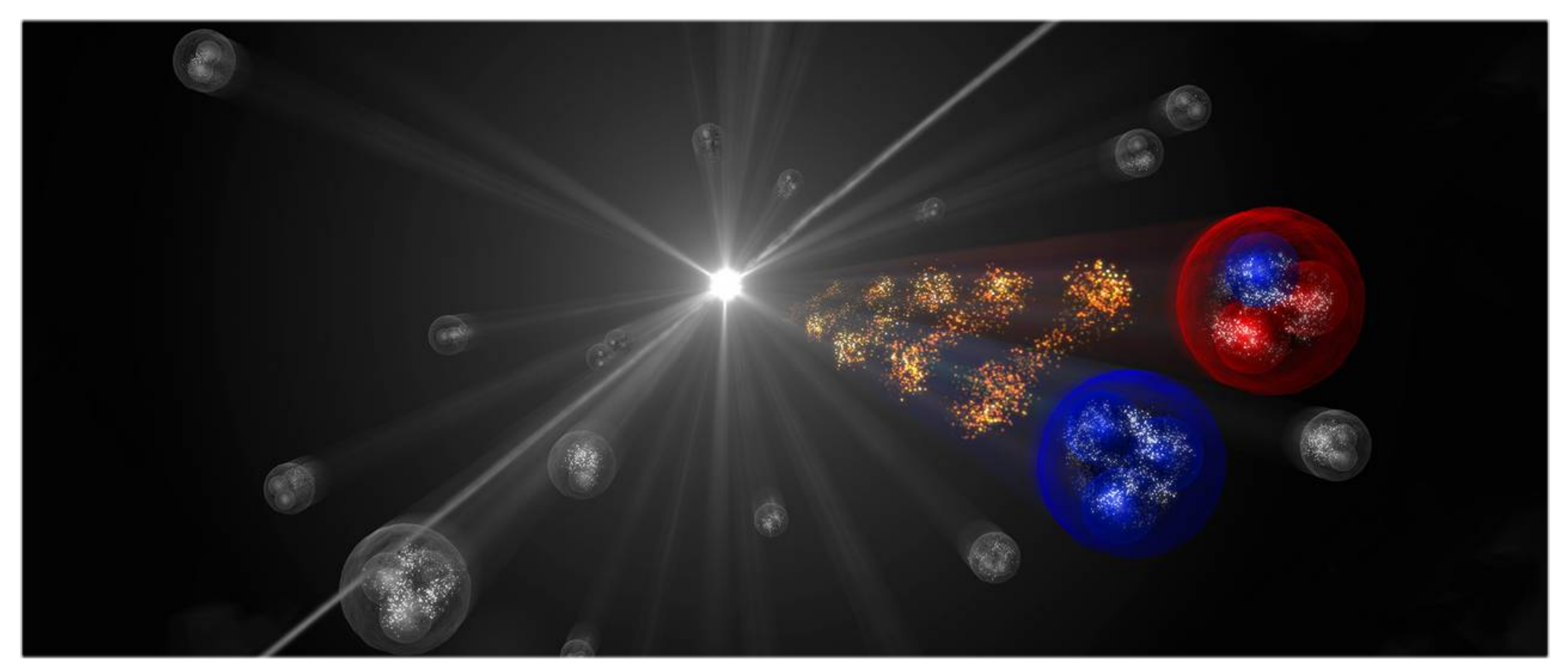
ALICE: arXiv: 2201.05352

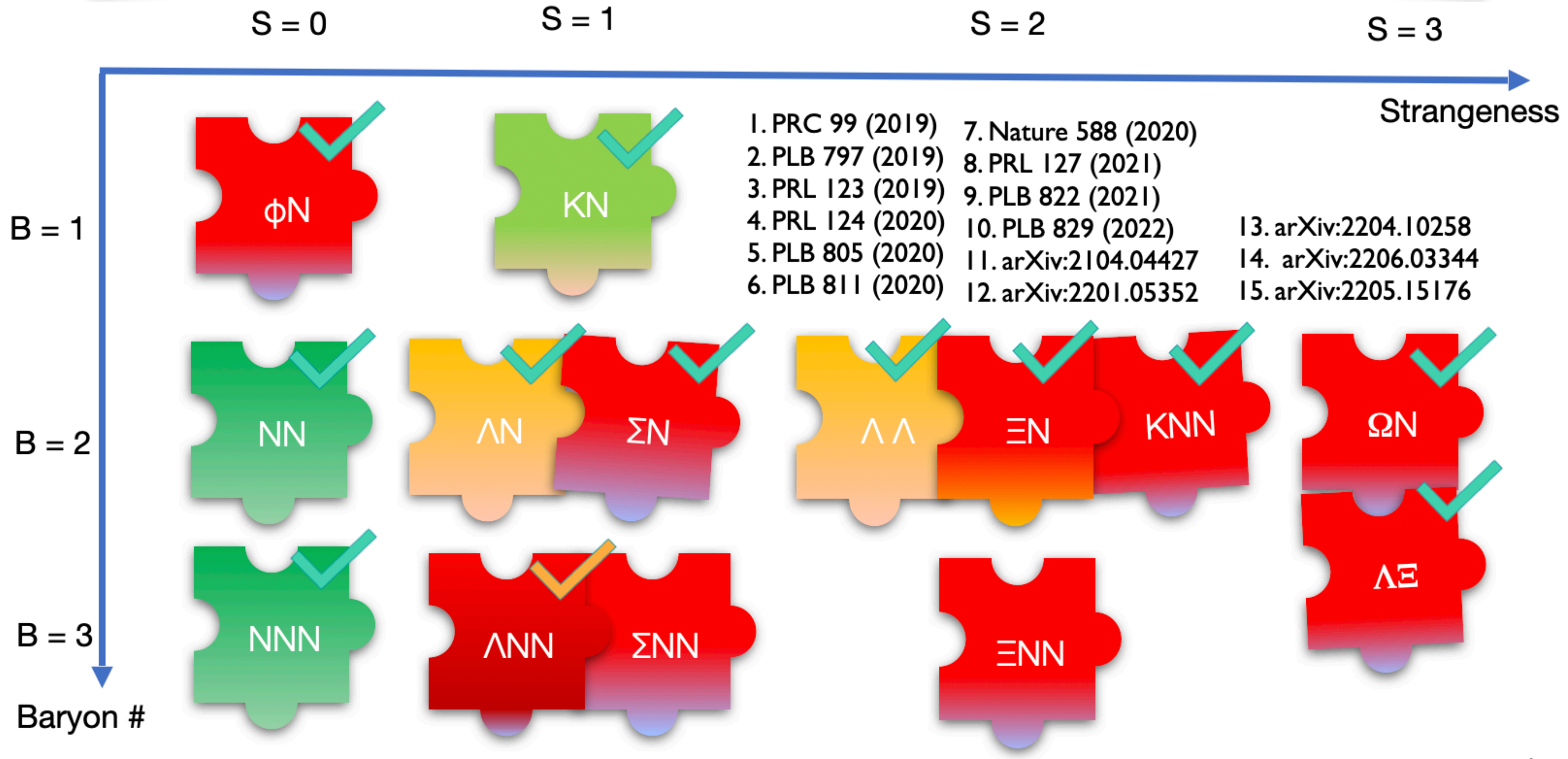


- ❖ First studies of residual strong interaction between charm and light flavour hadrons p($\bar{p}$)
  - ALICE results are compatible with Coulomb interaction and with shallow attractive strong interaction

Hadron-hadron interactions

ALICE is pioneering the study of strong interactions using femtoscopic correlations





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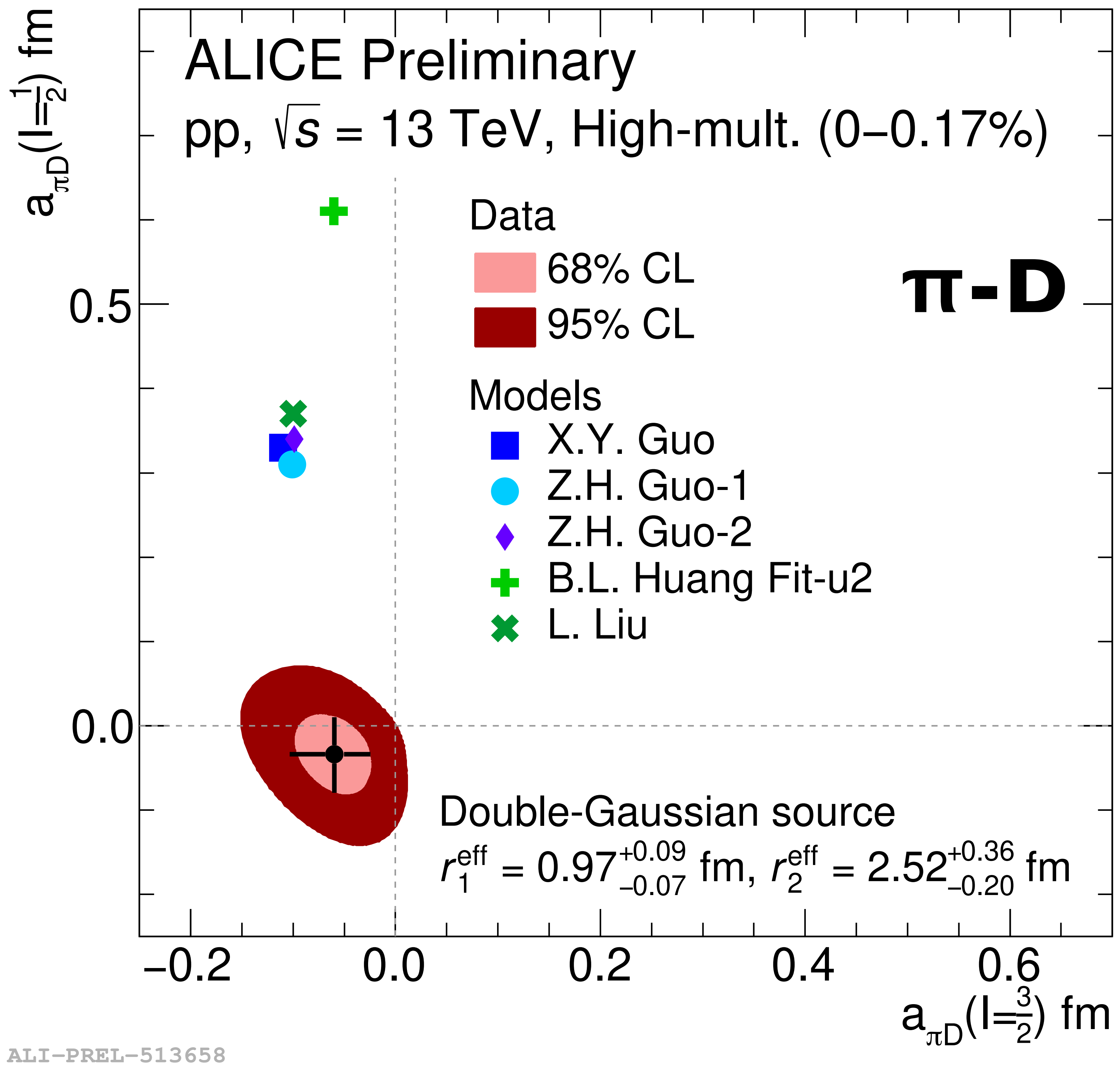
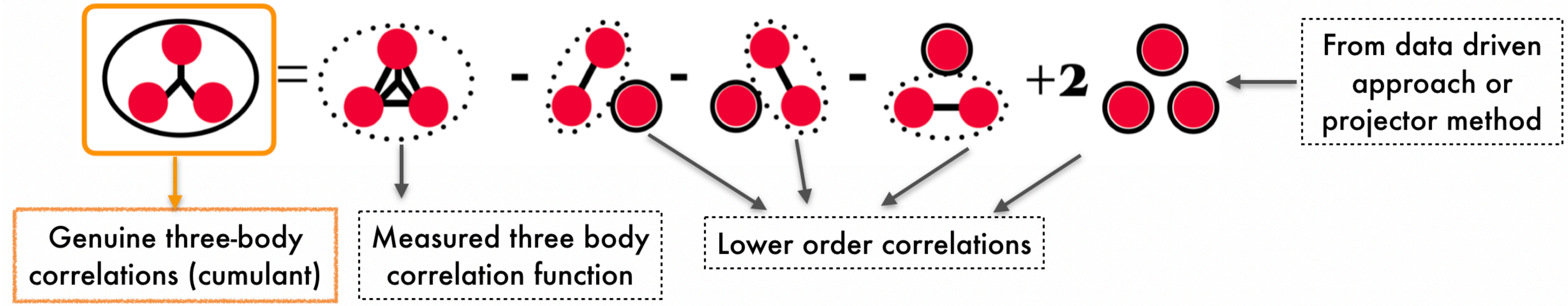
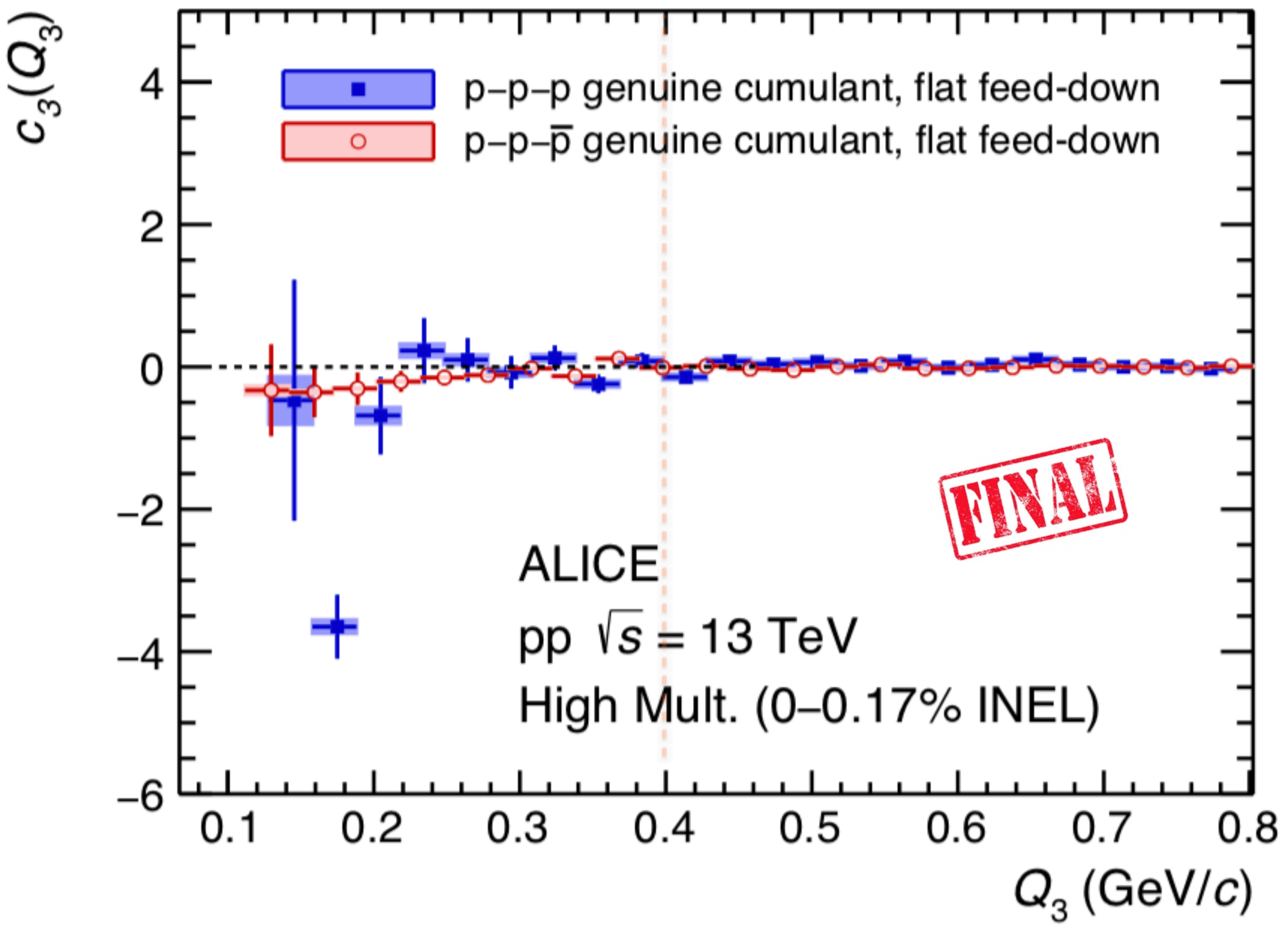


❖ First studies of residual strong interaction between charm and light flavour hadrons $\pi^{\pm}$, $K^{\pm}$

- Scattering parameters extracted are lower than LQCD expectations

Three-body interactions





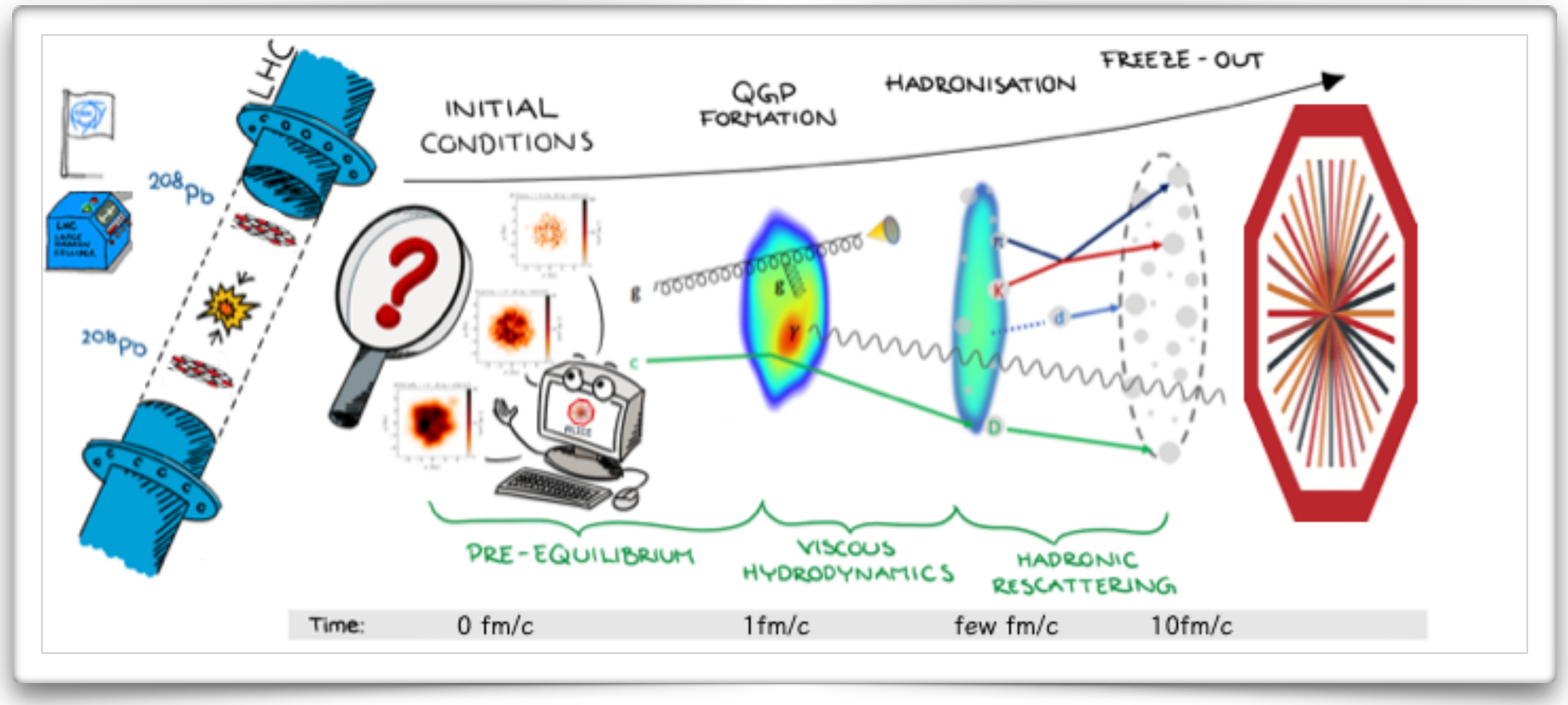
- p-p-p: n_σ = 6.7 for Q_3 < 0.4 GeV/c

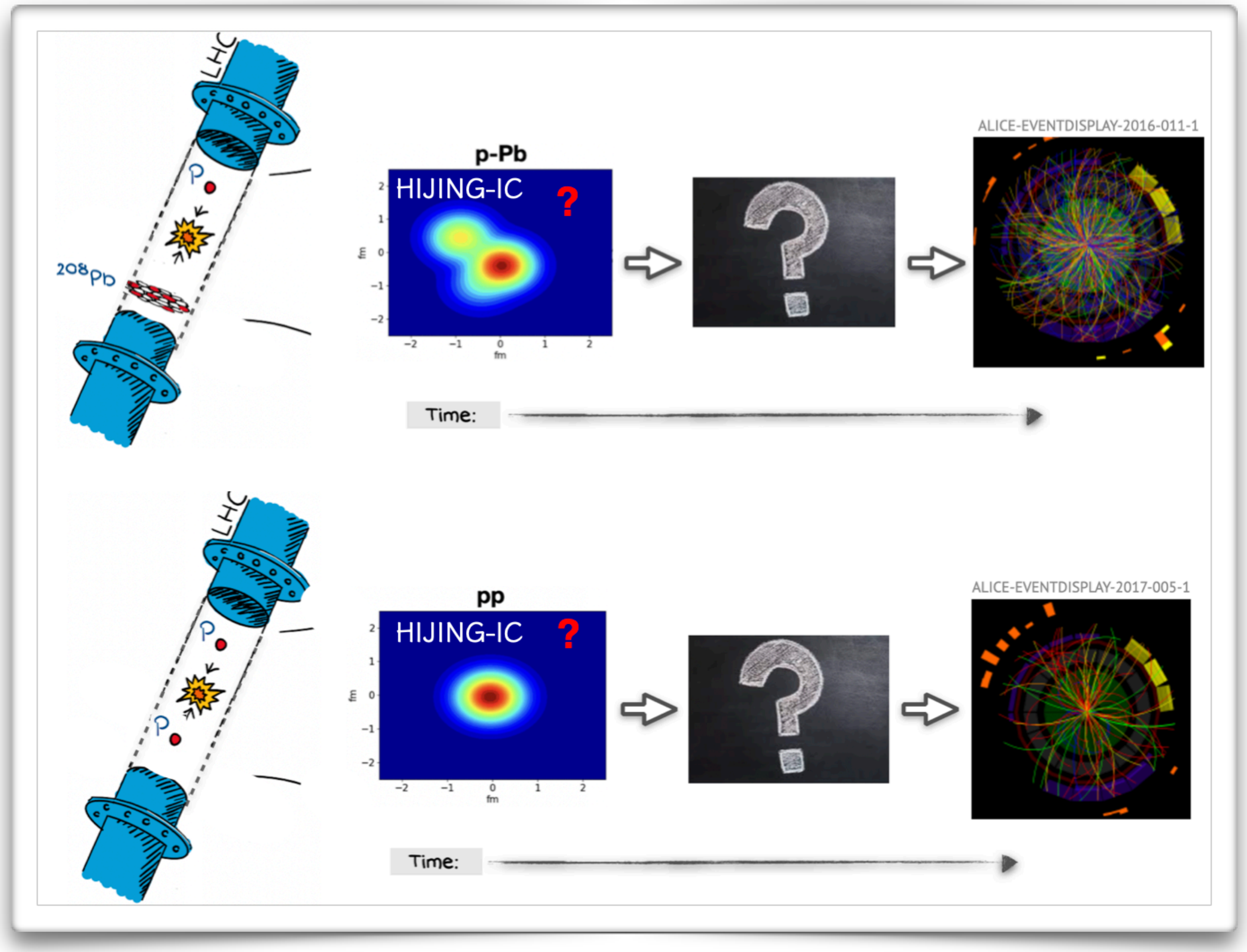
  -> presence of a genuine three-body effect in p-p-p!

  -> coming Run 3 data taking will largely improve the precision

15 Jun 2022, 09:20, Bhawani Singh @ Other topics

Summary





❖ ***Heavy-ion collisions***:

ALICE measurements of Light flavor particle productions and correlations significantly improve our overall knowledge of different phases

❖ ***Small systems***:

ALICE measurements shed new light into the understanding of emergence of hot and dense QCD matter in small systems

List of relevant ALICE talks

ALICE

14 June, 09:20, “Measurement of the production of (anti)(hyper)nuclei with ALICE”, Chiara Pinto @ PA-RES
14 June, 09:40, “Exploring the hadronic phase of relativistic heavy-ion collisions with resonances in ALICE”, Dukhishyam Mallick @ PA-RES
14 June, 10:50, “Understanding the nature of $f_0(980)$ with ALICE at the LHC”, Junlee Kim @ PA-RES
14 June, 11:10, “Rescattering effects on resonances production in small systems with ALICE at the LHC”, Antonina Rosano @ PA-RES

14 June, 10:00, “Light-flavor hadron production in small collision systems with ALICE”, Adrian Fereydon Nassirpour @ PA-LF
14 June, 10:50, “(Anti)nucleosynthesis in heavy-ion collisions and (anti)nuclei as "baryonmeter" of the collision”, Mario Ciacco @ PA-LF
14 June, 11:10, “A multi-differential investigation of strangeness production in pp collisions with ALICE”, Romain Schotter @ PA-LF
14 June, 15:00, “Constraining the KN coupled channel dynamics using femtoscopic correlations with ALICE at the LHC”, Maximilian Korwieser @ PA-LF

15 June, 09:20, “Extending the ALICE strong-interaction studies to nuclei: measurement of proton-deuteron, K±-deuteron, and Λ-deuteron correlations in pp collisions at $\sqrt{s}$ = 13 TeV”, Bhawani Singh @ PA-OTH
15 June, 10:00, “The dark side of ALICE: from antinuclei interactions to dark matter searches in space”, Pavel Larionov @ PA-OTH

14 June, 11:30, “Particle production as a function of underlying event-activity and very forward energy with ALICE”, Feng Fan @ PA-BLK
14 June, 16:30, “Search for the Chiral Magnetic Wave in Pb−Pb collisions with the ALICE detector”, Wenya Wu @ PA-BLK
14 June, 11:30, “Net-conserved charge fluctuations in ALICE and long-term perspectives”, Mesut Arslandok @ PA-BLK
14 June, 11:50, “Measurements of charge, strangeness, and baryon number balance functions in pp and Pb-Pb collisions in ALICE”, Sumit Basu @ PA-BLK

14 June, 15:30, “ALICE determines the scattering parameters of D mesons with light-flavor hadrons”, Emma Chizzali @ PA-HF

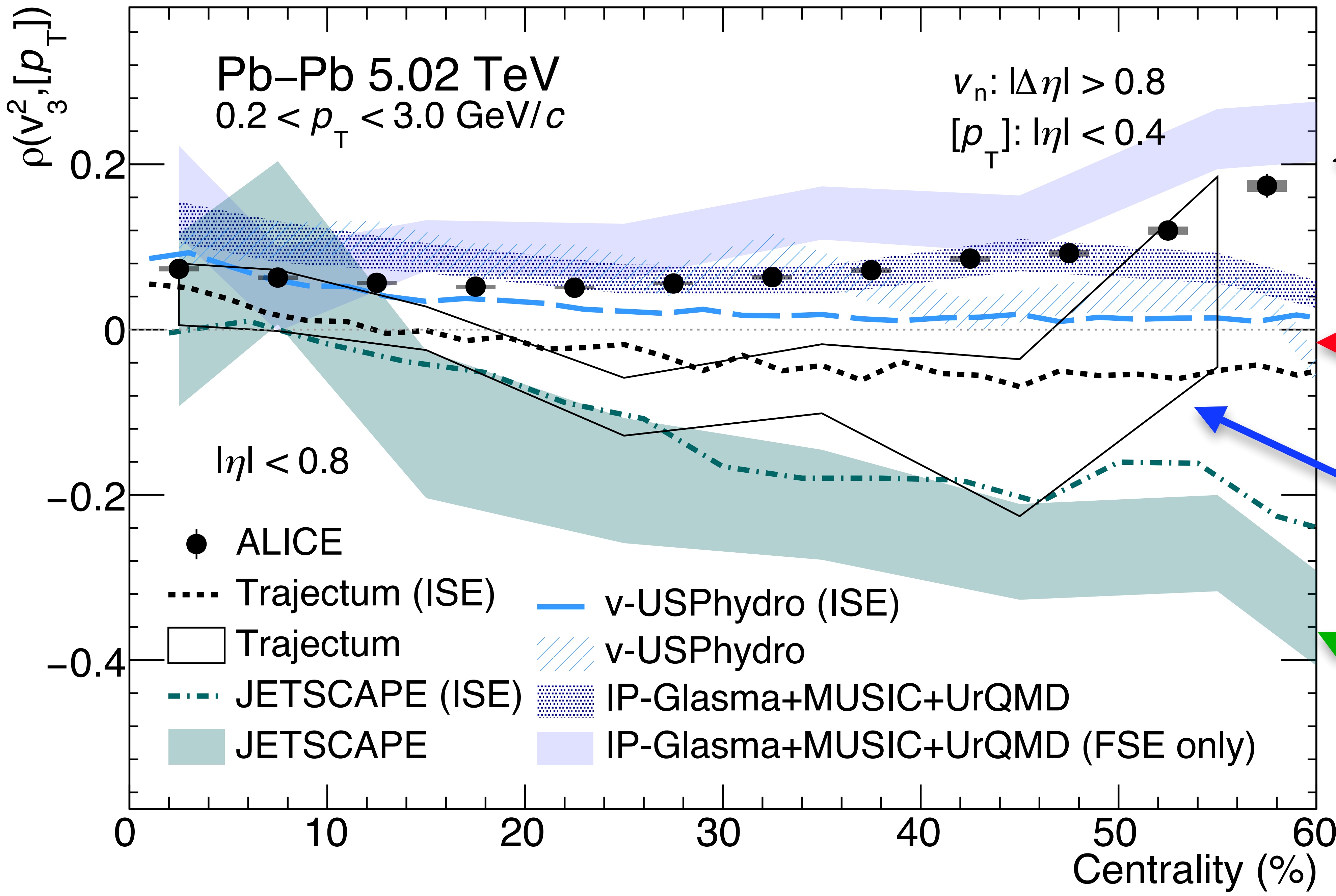
Recent ALICE publications on the topic

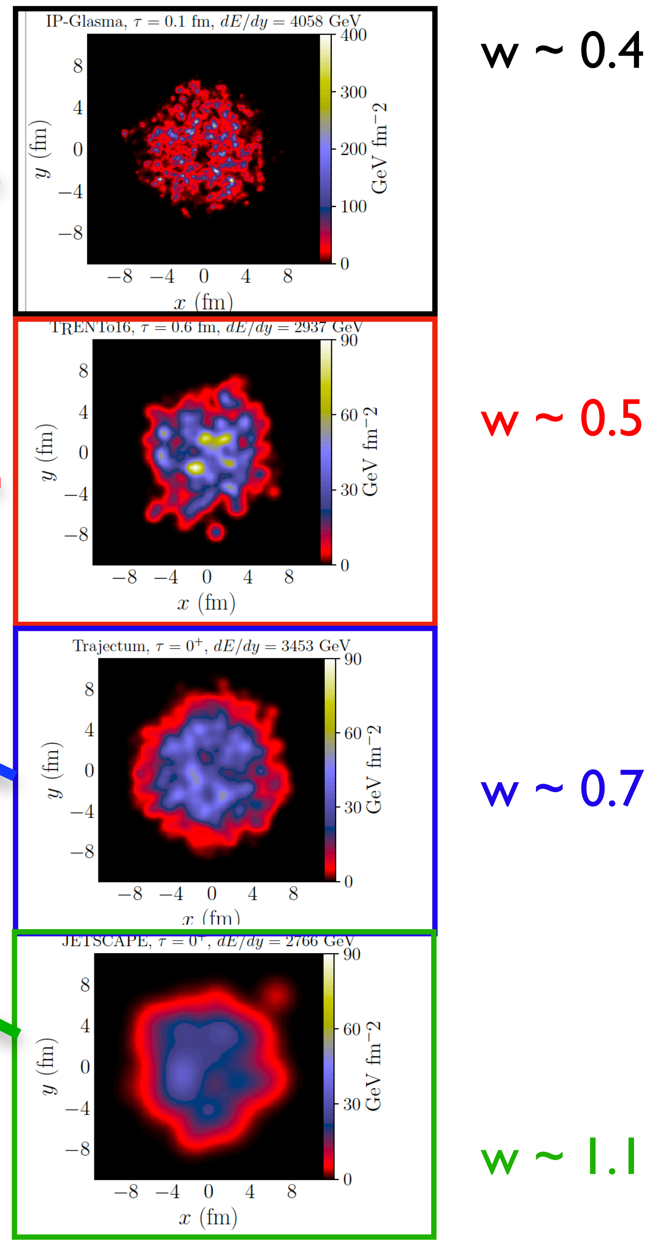
- ALICE Collaboration, "*$\Sigma(1385)^{\pm}$ resonance production in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*", arXiv: 2205.13998
- ALICE Collaboration, "*Constraining the $\bar{K}N$ coupled channel dynamics using femtoscopic correlations at the LHC*", arXiv: 2205.15176
- ALICE Collaboration, "Closing in on critical net-baryon fluctuations at LHC energies: cumulants up to third order in Pb-Pb collisions", arXiv: 2206.03343
- ALICE Collaboration, "Towards the measurement of the genuine three-body interaction for ppp and ppΛ", arXiv: 2206.03344
- ALICE Collaboration, "Observation of flow angle and flow magnitude fluctuations in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV at the LHC", arXiv: 2206.04574
- ALICE Collaboration, "Anisotropic flow and flow fluctuations of identified hadrons in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV", arXiv: 2206.04587


Bonus!

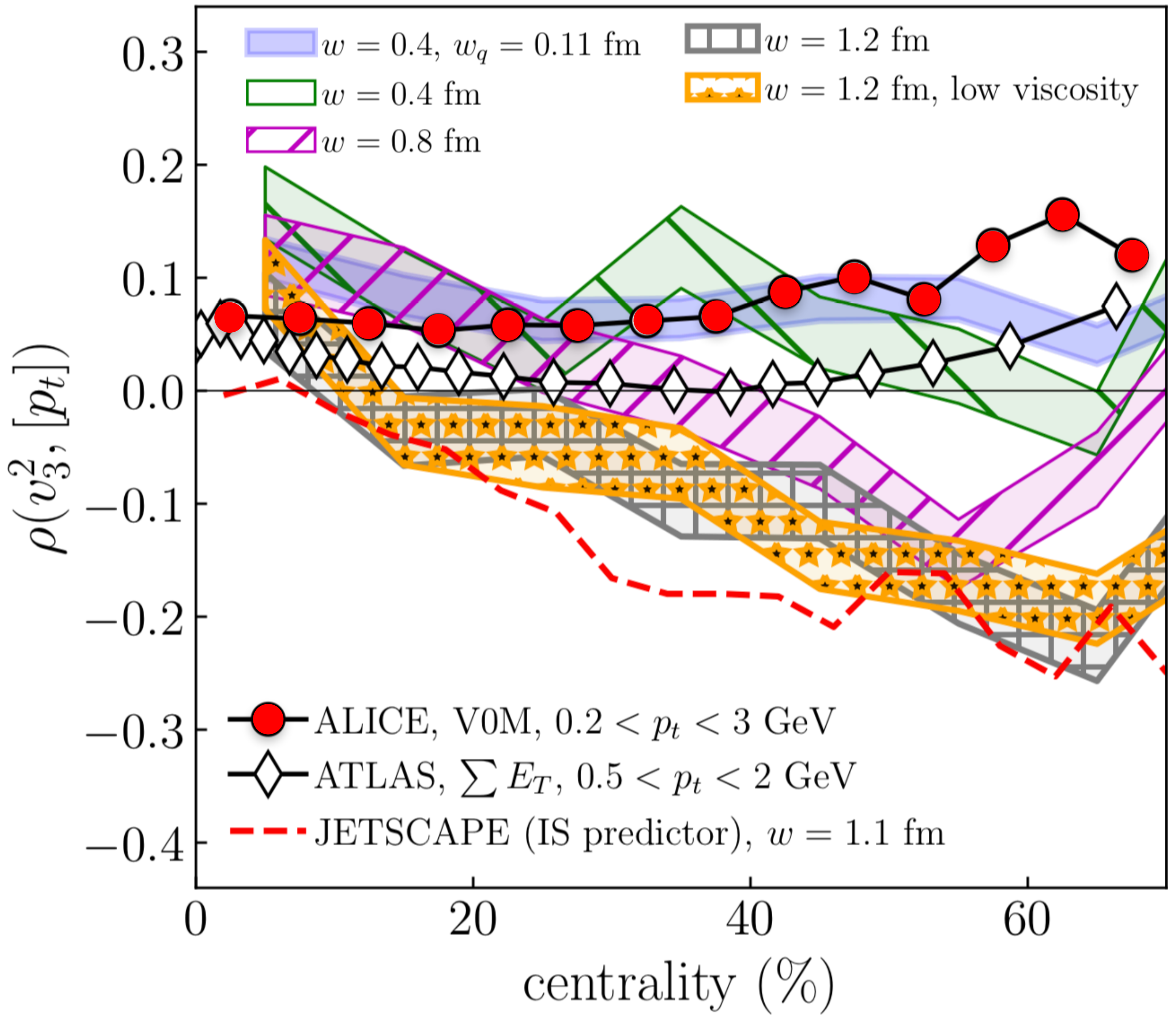
Constraining the Nucleon Size

ALICE, arXiv:2111.06106





G. Giacalone etc., PRL128 042301 (2022)



- ❖ v_3 —$[p_T]$ correlation with ρ_3:
  - positive value, has a modest centrality dependence for the presented centralities,
  - better described by IP-Glasma, TRENTo predicts negative ρ_3 , getting worse for Trajectum and JETSCAPE calculations
- ❖ Sensitive to the nucleon width parameter (size of nucleon)
  - IP-Glasma ~ 0.4; v-USPhydro ~ 0.5; Trajectum~0.7; JETSCAPE (TRENTo) ~ 1.1
  - New constraints on the ***nucleon size.*** ALICE data agrees better with w~0.4 fm, or transverse radius of 0.56 fm.

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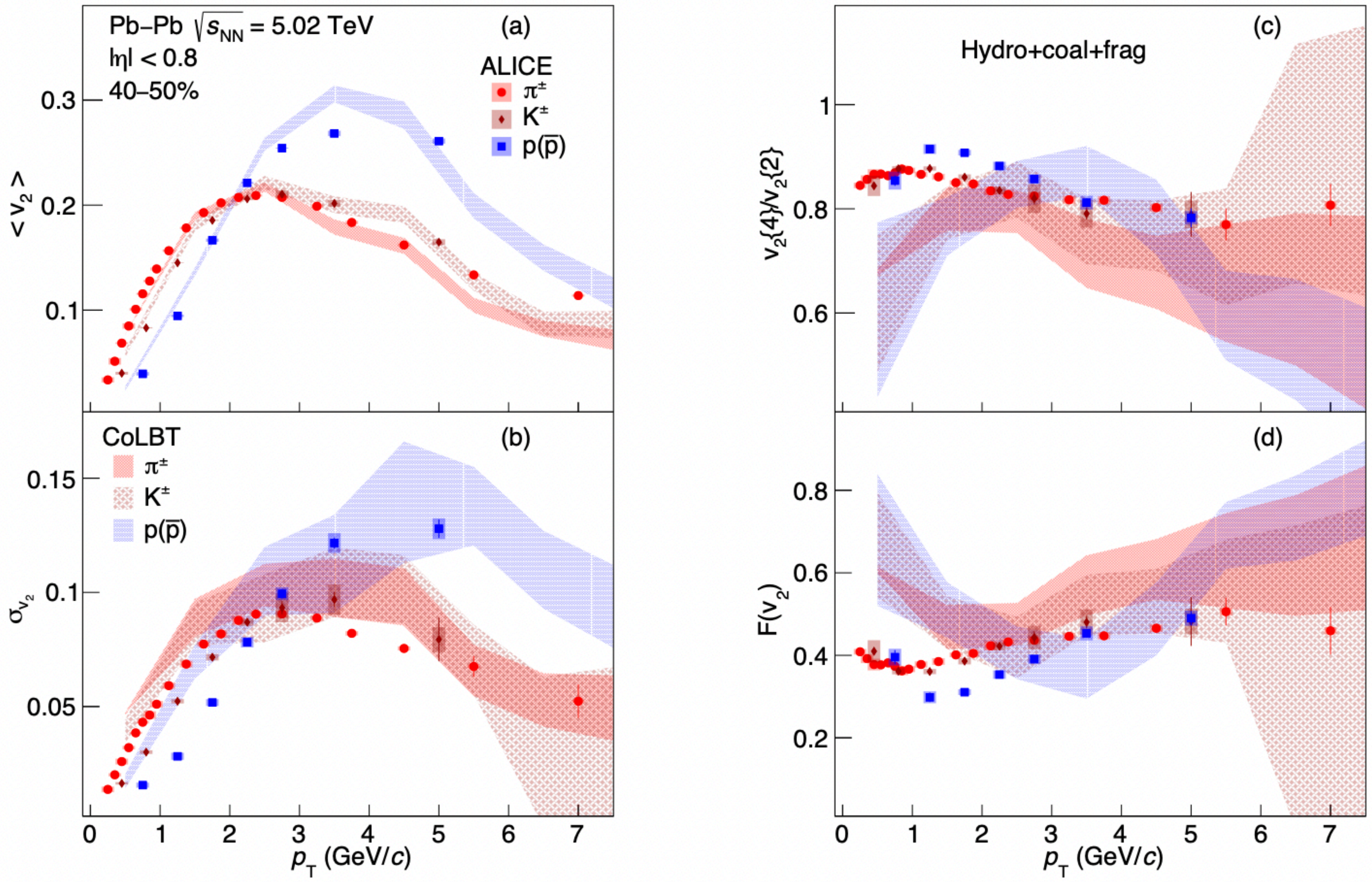
Flow fluctuations with identified hadrons

❖ Using the combination of $v_2\{2\}$ and $v_2\{4\}$, one can obtain both mean v_2 (from flow symmetry plane) and flow fluctuation σ_{v2}

$$v_n^2\{2\} = \langle v_n \rangle^2 + \sigma_{v_n}^2,$$
$$v_n^2\{4\} \approx \langle v_n \rangle^2 - \sigma_{v_n}^2,$$

⇓

$$\langle v_n \rangle \approx \sqrt{\frac{v_n^2\{2\} + v_n^2\{4\}}{2}}$$
$$\sigma_{v_n} \approx \sqrt{\frac{v_n^2\{2\} - v_n^2\{4\}}{2}}.$$
$$F(v_n) = \frac{\sigma_{v_n}}{\langle v_n \rangle}$$



ALICE, arXiv: 2206.04587

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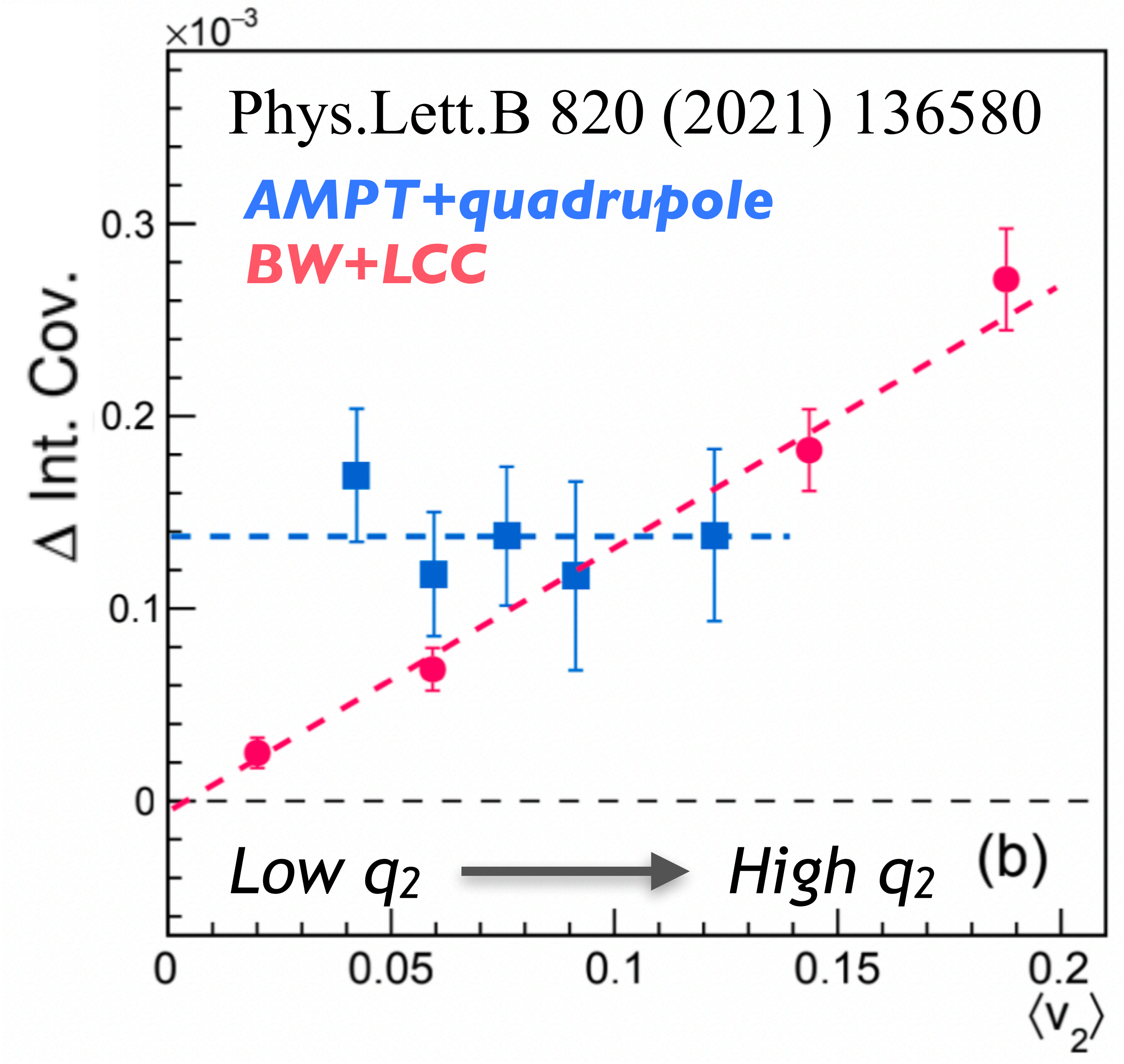
❖ Characteristic p_T and particle species dependence of $v_2\{4\}/v_2\{2\}$ and $F(v_2)$

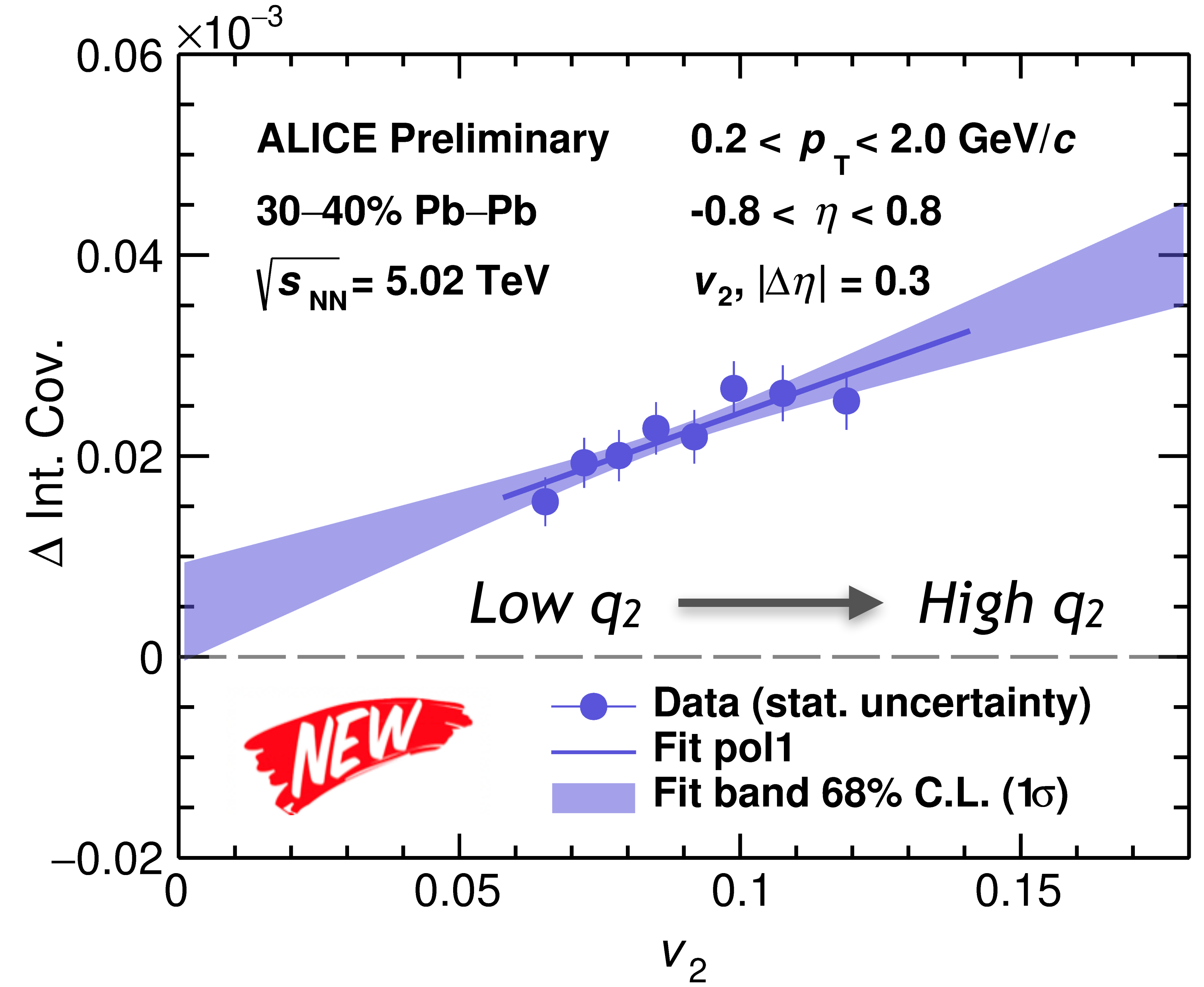
- Contributions not only from initial eccentricity fluctuations (p_T independent) but also system dynamic evolutions

Constrain CMW with event-shape engineering

ALICE

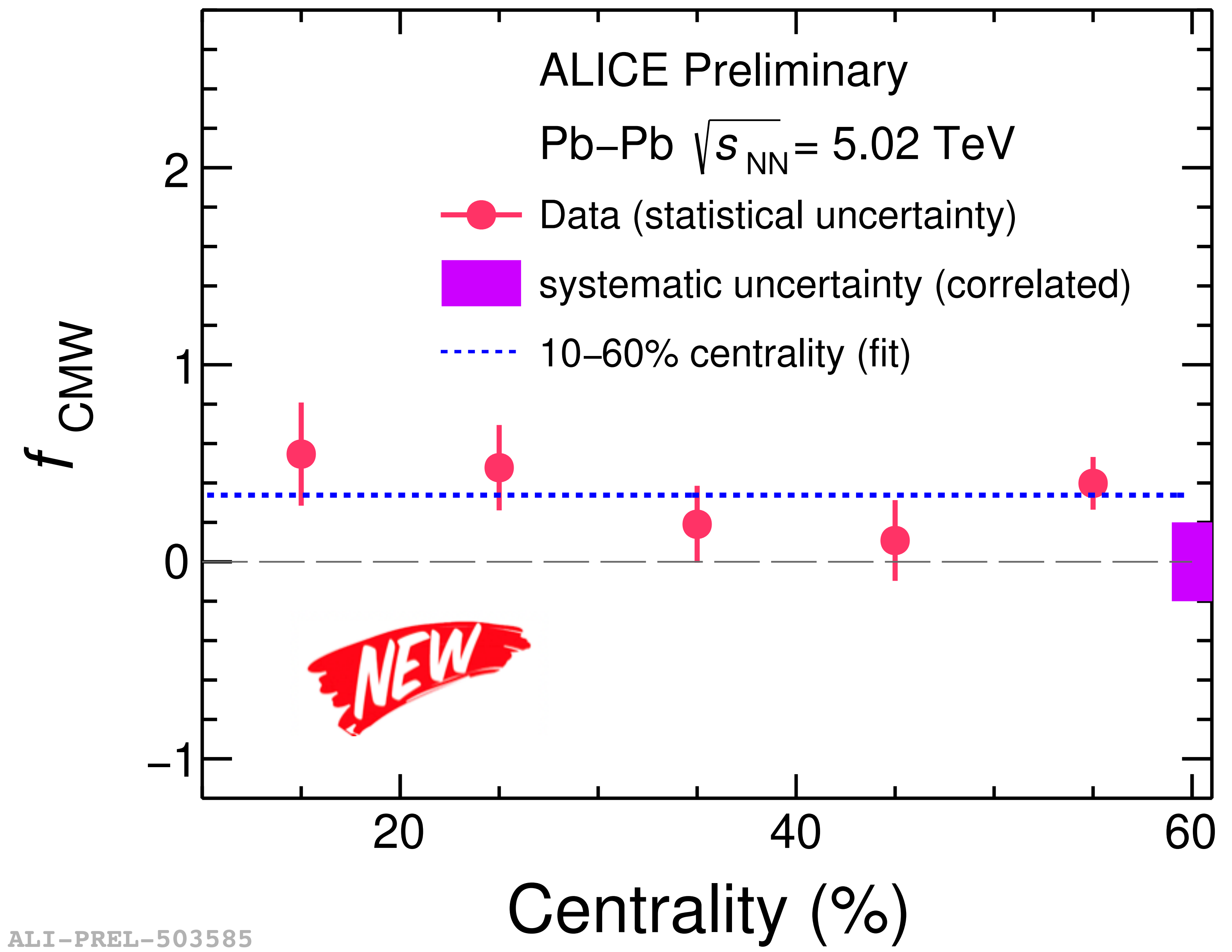
$$\Delta \text{Int.Cov.} \equiv (\langle v_2^{\pm} A_{ch} \rangle - \langle A_{ch} \rangle \langle v_2^{\pm} \rangle)_{neg-pos}$$





ALI-PREL-503580

CMW fraction: $f_{CMW} \equiv \frac{b}{a \times \overline{\langle v_2 \rangle} + b}$



ALI-PREL-503585

Model studies with Event-shape engineering (ESE)

- AMPT+quadrupole (with CMW signal)

  -> ΔInt. Cov. vs v_2 : **finite** intercept

- BW+LCC (no signal, w/ background)

  -> ΔInt. Cov. vs v_2: **zero** intercept

- ΔInt. Cov. vs v_2 with ESE in ALICE
- Linear fit: $F(v2) = a \times v_2 + b$

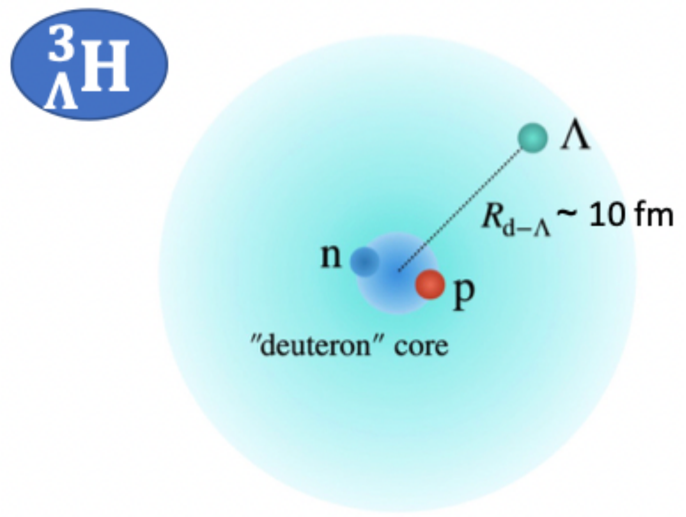
- For 10-60% centrality,

f_{CMW}: 0.338±0.084(stat.)±0.198(syst.)

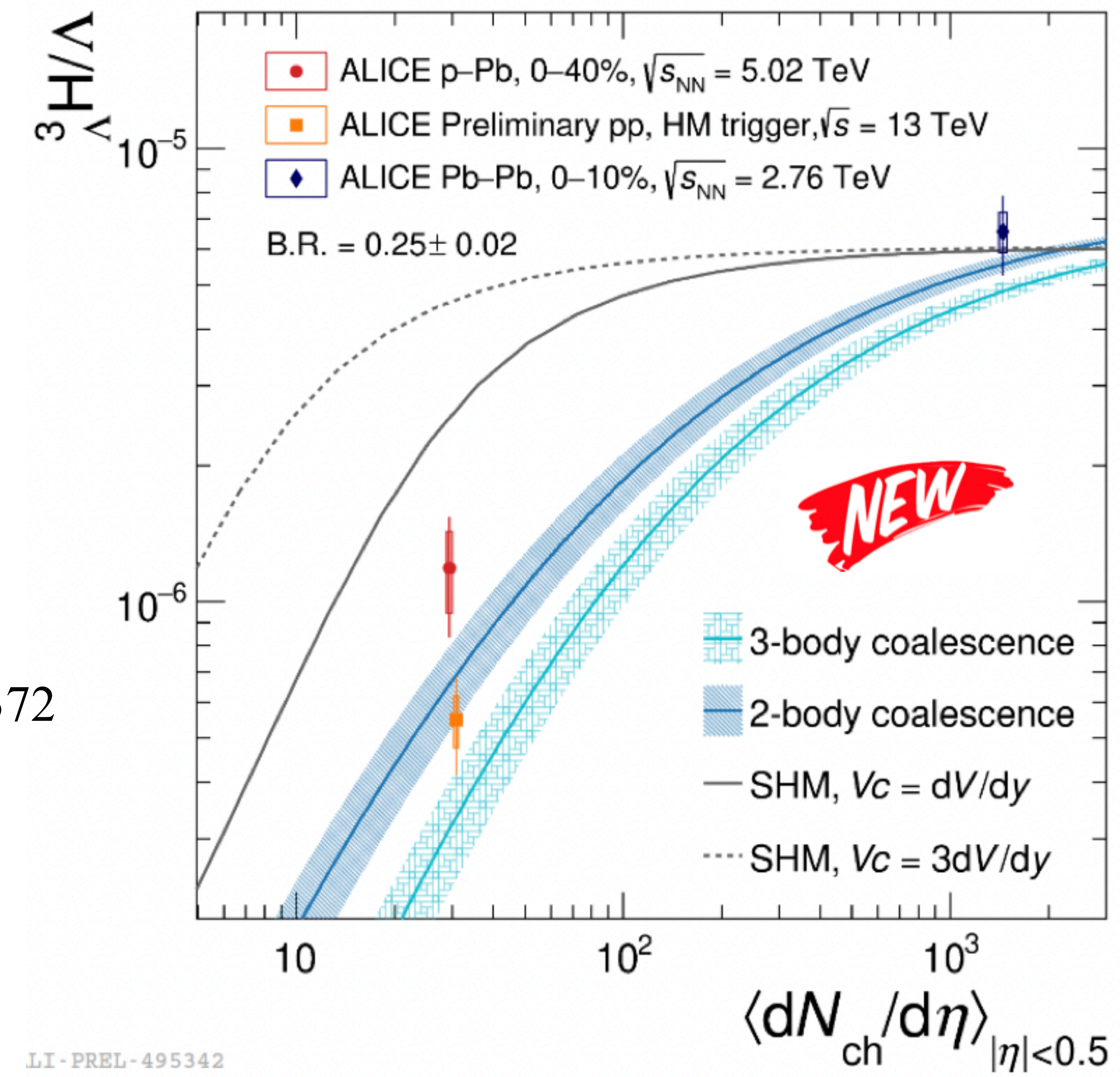
14 Jun 2022, 16:30, Wenya Wu @ Bulk matter phenomena, QCD phase diagram, and Critical point

production of (anti)(hyper)nuclei in ALICE

- Production mechanism usually described with two classes of phenomenological models:
  - statistical hadronization model (SHM)
  - coalescence model
- (anti)(hyper)nuclei production in small collision systems are particularly interesting:
  - system created in the collision has a size smaller or equal to that of the nucleus under study
  - allows for the study of coalescence since nucleons are created close to each other
  - model predictions are quite different, ideal to constrain the production mechanism



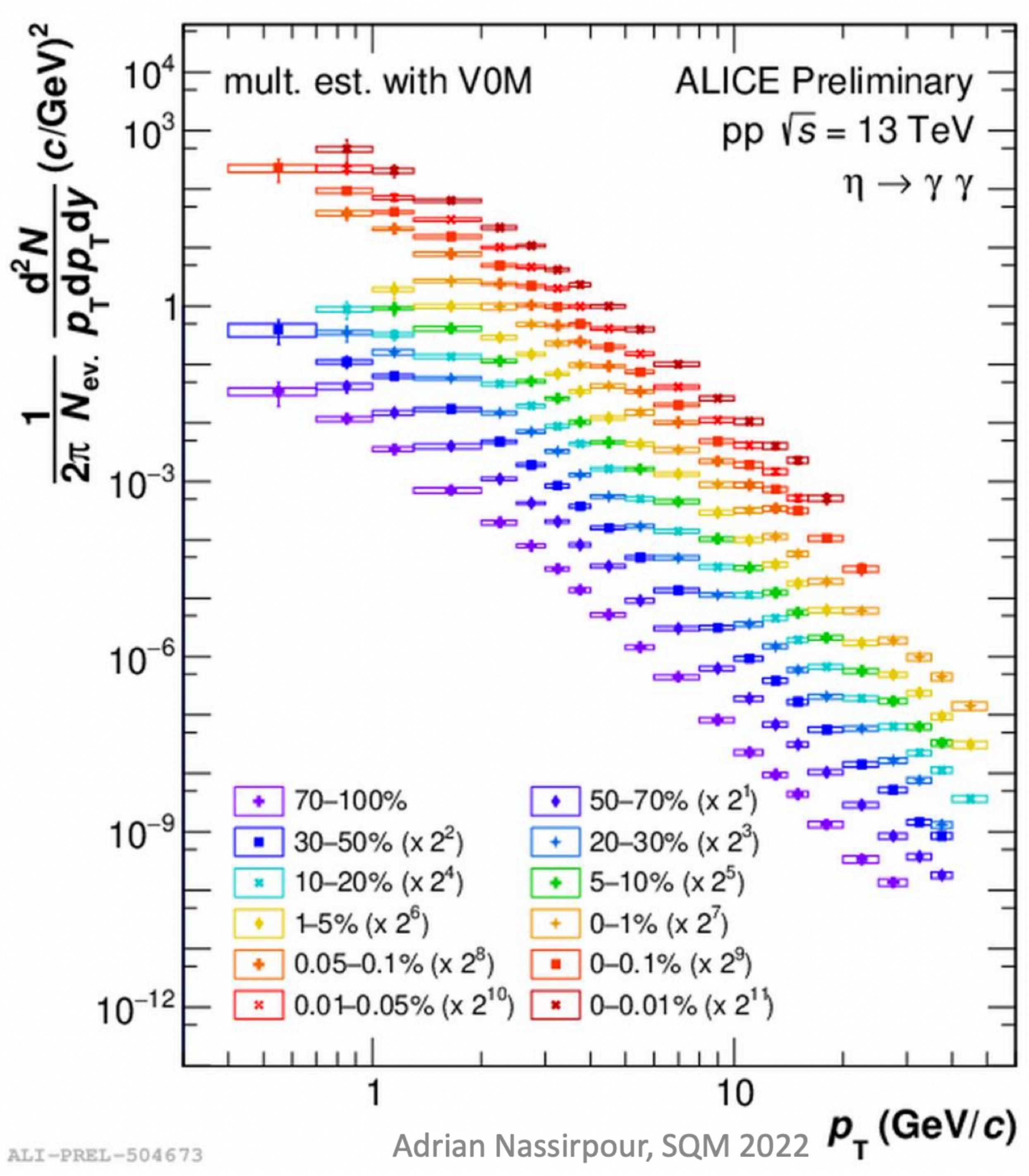
p—Pb: arXiv:2107.10627
Pb—Pb: PLB 754 (2016) 360-372

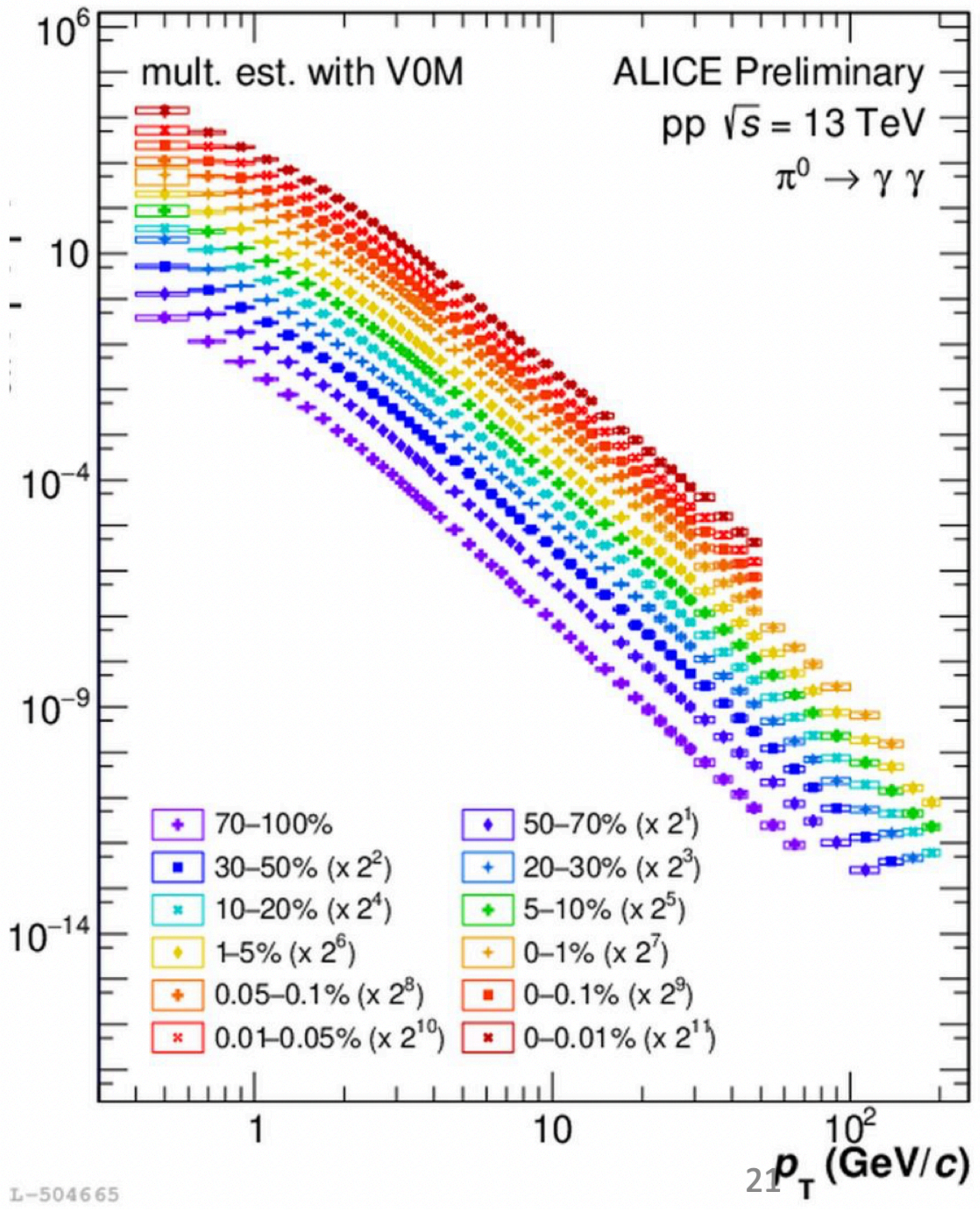


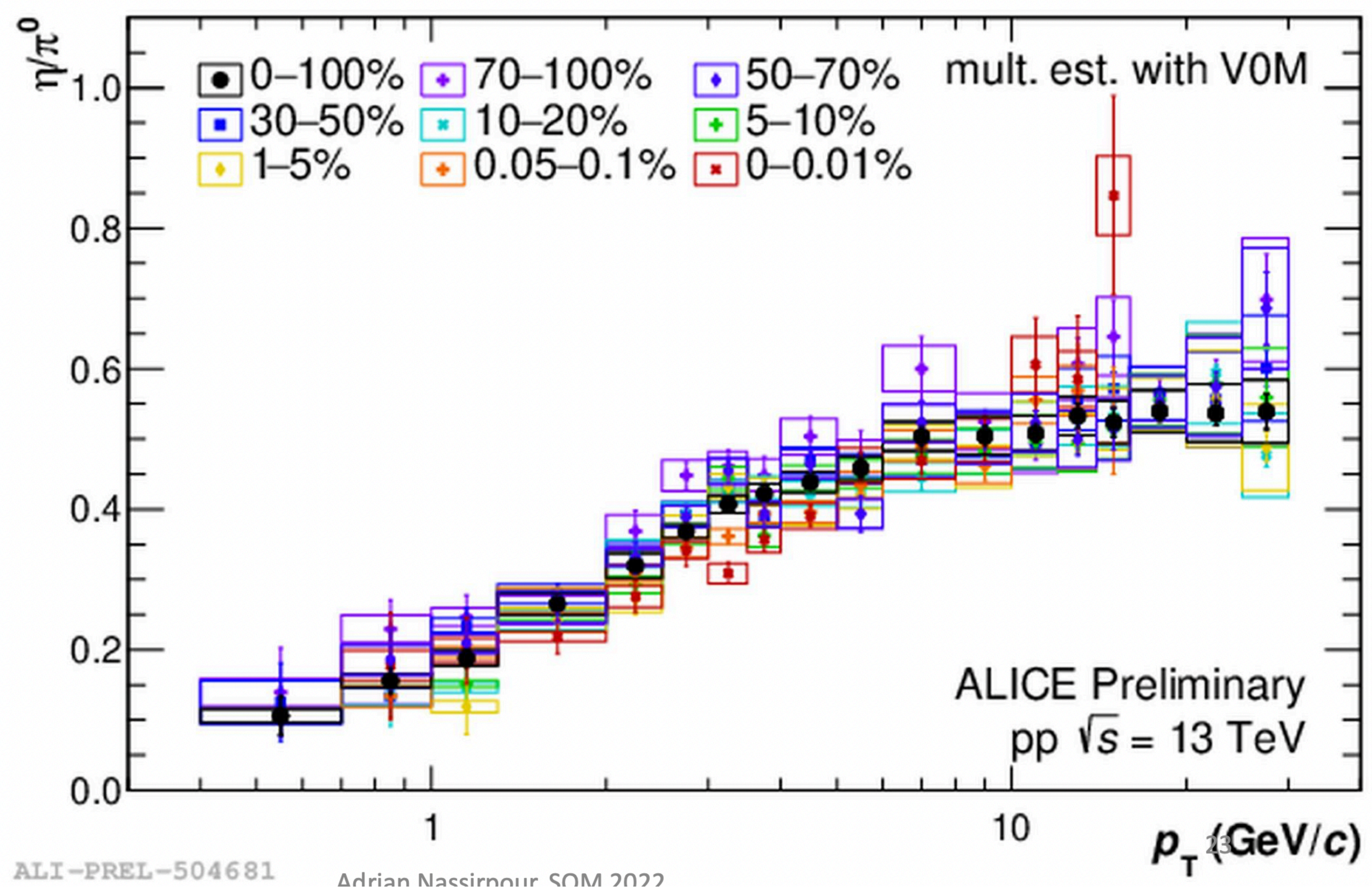
- Measurements in pp and p-Pb collisions:
  - larger separation between production models than Pb-Pb
  - Good agreement with 2-body coalescence
  - tension with SHM at low charged-particle multiplicity region
  - calculation with V_C = 3dV/dy is excluded by more than 6σ

14 Jun 2022, 09:20, Chiara Pinto
@ Resonances and Hyper-nuclei

Neutral Meson Production







Antideuteron number fluctuations

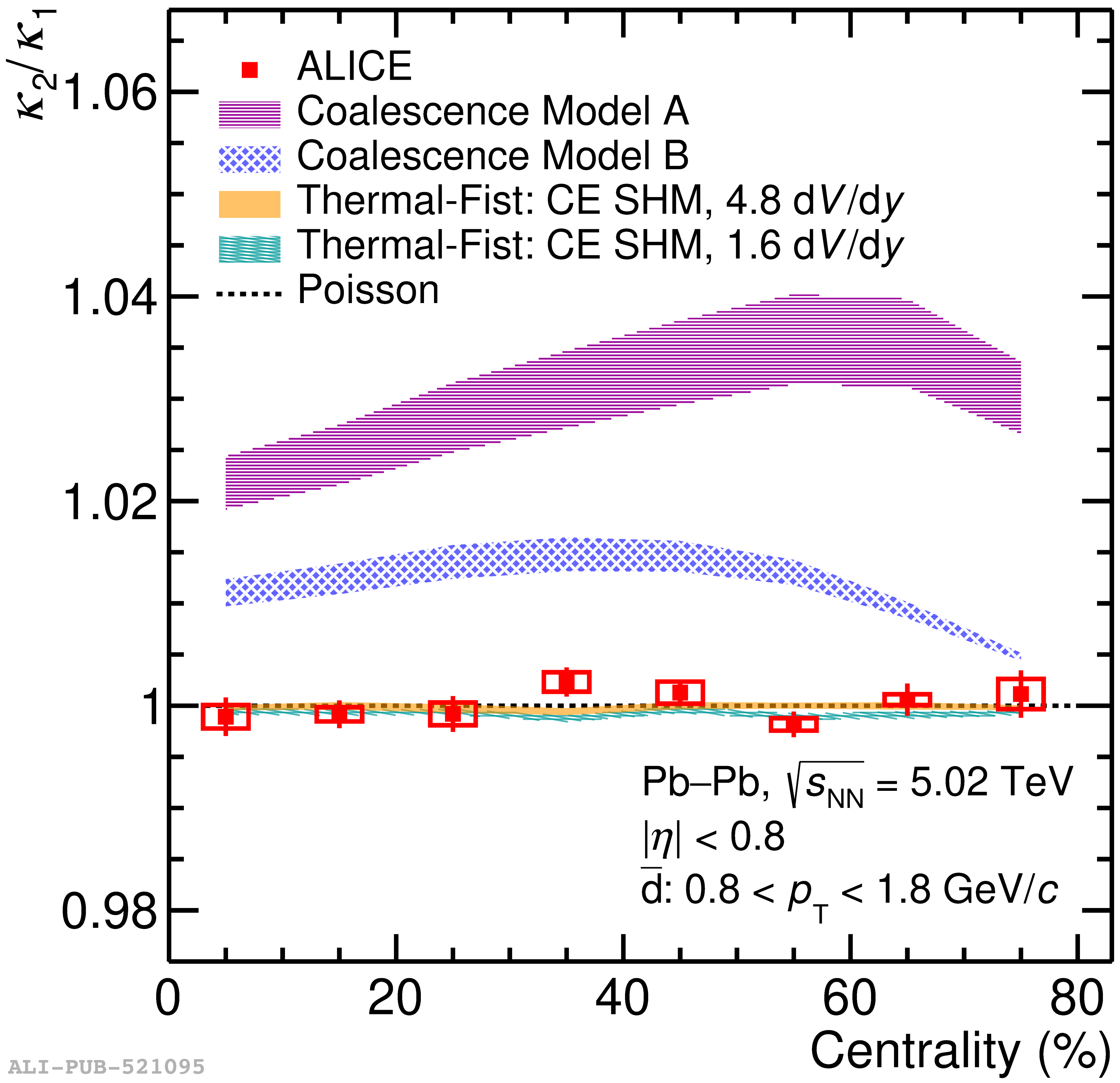
- Cumulants

$$\kappa_1 = \langle n \rangle$$
$$\kappa_m = \langle (n - \langle n \rangle)^m \rangle, \; m = 2, 3$$

  - Poisson -> $\kappa_1 = \kappa_2 = \kappa_3$, $\kappa_2/\kappa_1 = 1$

- κ_2/κ_1 cumulant ratio consistent with unity
  - described by Grand Canonical SHM (Poisson)
  - In general coalescence model (A and B) overestimate the data
  - limited sensitivity to baryon number conservation of Canonical Ensemble

ALICE, arXiv:2204.10166



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14 Jun 2022, 10:50, Mario Ciacco
@ Light-flavor and Strangeness