



ALICE Results in Small Systems and Light Ions

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for the ALICE collaboration

Initial Stages 2025, Taipei

“And early on, still with proton beams, we tripped over another **surprise** – the first, and arguably still the most unexpected, **LHC discovery**. A feeble, but distinct, very long-range correlation between particles, **never before seen** in any elementary collisions [...]” (*Jurgen Schukraft, [Recollections](#), 18.10.24*)

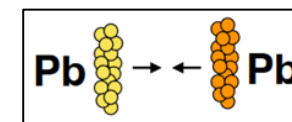
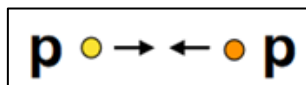
“We have immediately set-up an independent analysis (control group) and organized a full set of tests and cross-checks to kill the effect. [...] If we are here today it is because **we didn't succeed to kill it.**”
(Guido Tonelli, [LHC seminar](#), 21.10.10)

“This is a subtle effect in a complex environment – careful work is needed to **establish physical origin**”
(Gunther Roland, [LHC seminar](#), 21.10.10)

Paradigm 15 Years Ago

Small and large systems governed by totally different physics

Single-process limit
Vacuum



Thermal limit
Dense system

which is directly reflected in experimental programs at that time

1.1.3 ALICE experimental programme

In general, to establish experimentally the collective properties of the hot and dense matter created in nucleus–nucleus collisions, both systematics-dominated and luminosity-dominated questions have to be answered at LHC. Thus, ALICE aims firstly at accumulating sufficient integrated luminosity in Pb–Pb collisions at $\sqrt{s} = 5.5$ TeV per nucleon pair, to measure rare processes such as jet transverse-energy spectra up to $E_T \sim 200$ GeV and the pattern of medium induced modifications of bottomium bound states. However, the interpretation of these experimental data relies considerably on a systematic comparison with the same observables measured in proton–proton and proton–nucleus collisions as well as in collisions of lighter ions. In this way, the phenomena truly indicative of the hot equilibrating matter can be separated from other contributions.

ALICE physics performance report, *J.Phys.G* 30 (2004) 1517-1763



Yet, there was interest by a few people
in high-multiplicity pp collisions leading to

Discoveries

... and then came the surprise

Life and Physics
Science

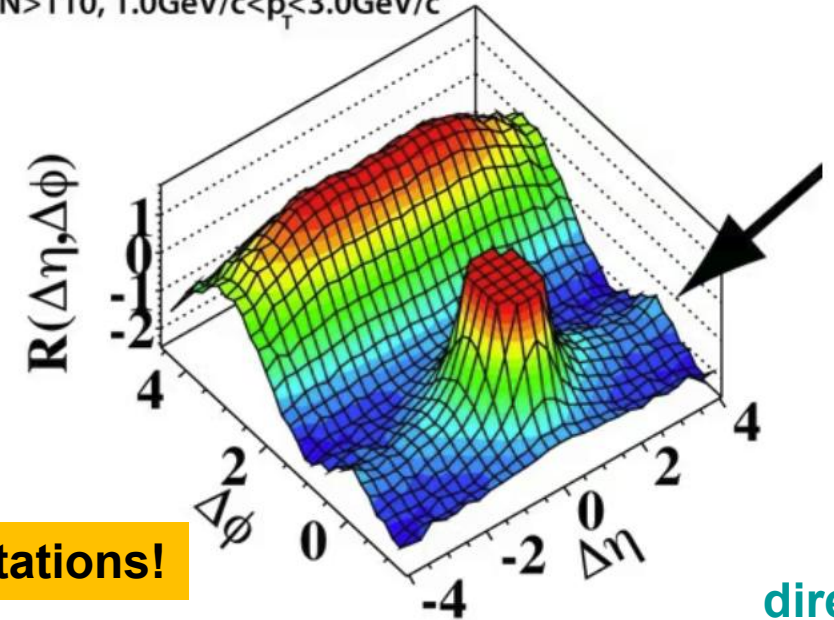
This article is more than 14 years old

A surprise from the LHC already!

The CMS experiment at the Large Hadron Collider (LHC) announced a surprise yesterday which may dramatically change our ideas about quarks, gluons and protons

There was a special Cern seminar yesterday evening on some **new results** from the CMS experiment, one of the detectors at the Large Hadron Collider. The result is summarised in this colourful landscape.

$N > 110, 1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



22.09.2010



Jon Butterworth

Wed 22 Sep 2010 12.05 CEST

The CMS experiment at the Large Hadron Collider (LHC) announced a surprise yesterday which may dramatically change our ideas about quarks, gluons and protons

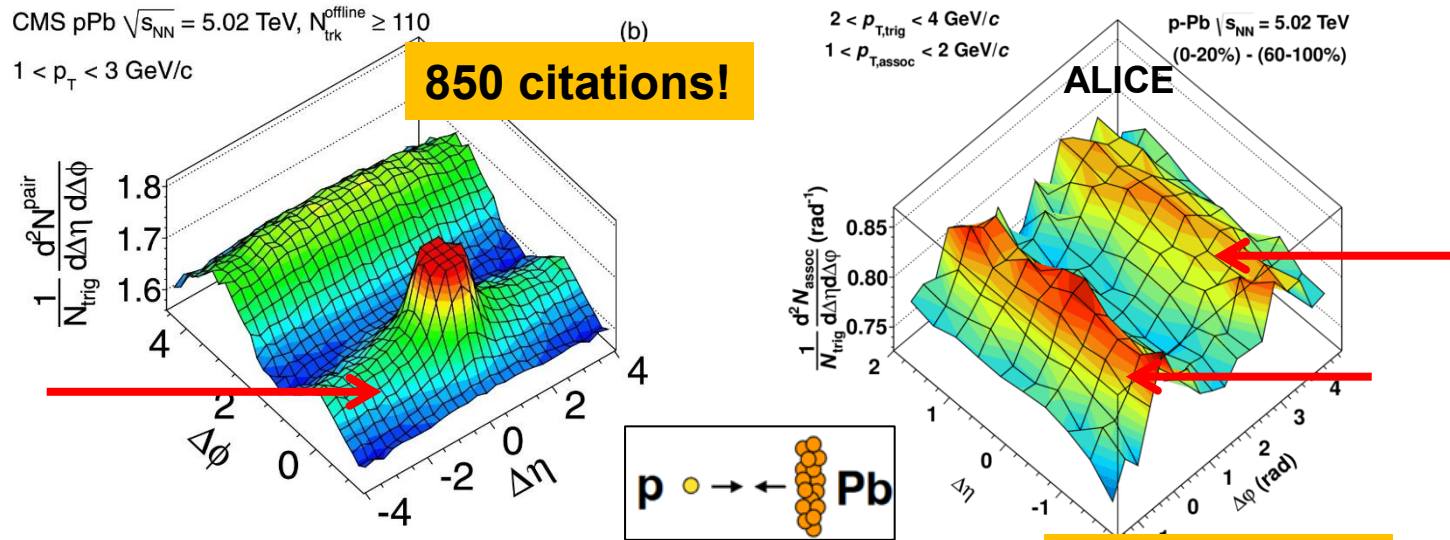


1250 citations!

[direct link](#)

First Discovery: Ridge and Ridges

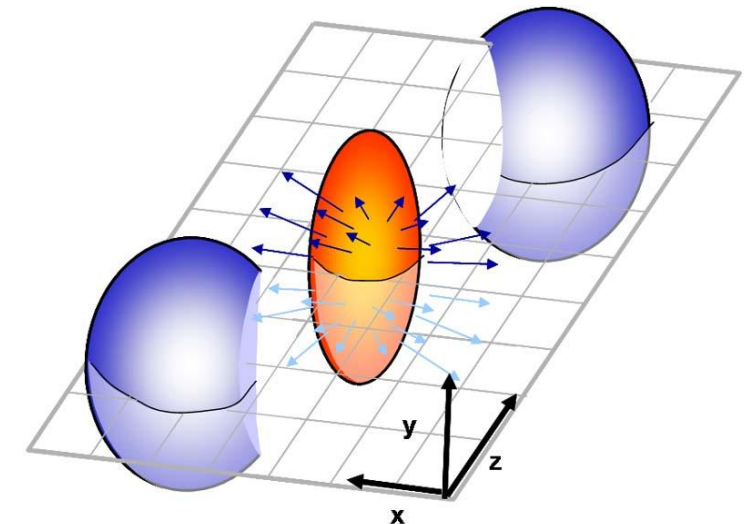
- Same feature observed in p-Pb collisions
- Second ridge discovered
(with subtraction procedure, see later)



ALICE, PLB719 (2013) 29
 and ATLAS, PRL110(2013)18,182302
 and CMS, PLB718(2013)795
 and LHCb, PLB762 (2016) 473

Unexpected in pp and p-Pb collisions

Well known from A-A collisions

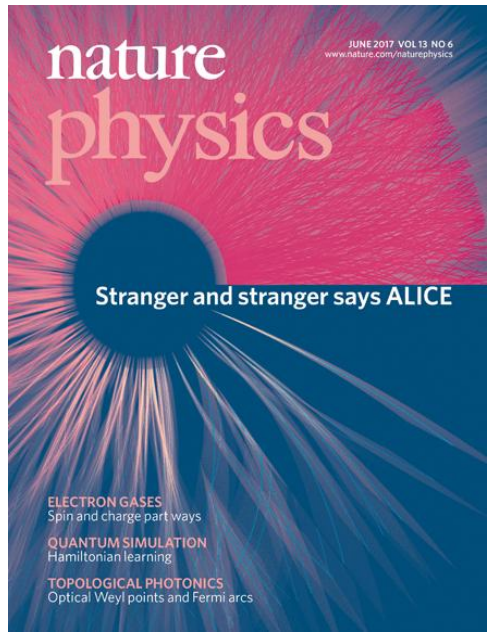


Ridges are a direct consequence in
 hydrodynamic expansion description
 (called flow in heavy-ion collisions)



Second discovery: Strangeness Enhancement

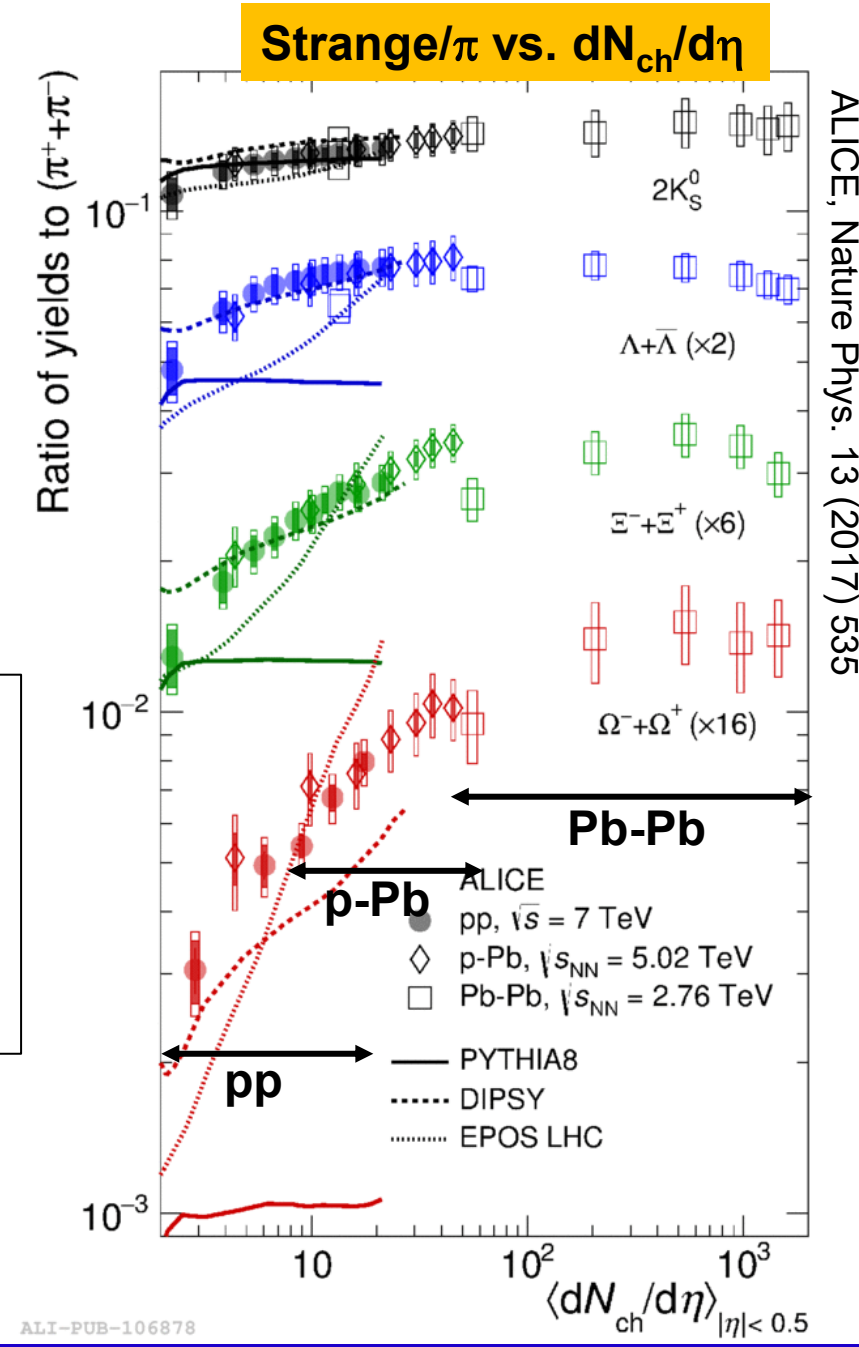
- Strange baryon production (K, Λ , Ξ , Ω) increases **faster than multiplicity**
- Smooth across collision system from pp to Pb-Pb



Historically, consequence of **energetically cheaper** production of $s\bar{s}$ in Quark-Gluon Plasma (compared to $K\bar{K}$ in vacuum)

s
 \bar{s}
vs.
K
 \bar{K}

Cannito – Wed 11:50





Second discovery: Strangeness Enhancement

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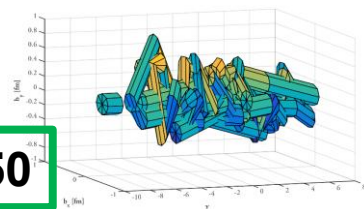
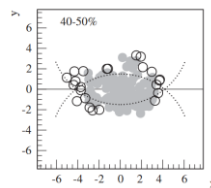
✗ Independent fragmentation (mainly)

Torbjorn Sjostrand (arXiv:1808.03117): “we lack some **fundamental** insight on baryon production”

✓ EPOS
(core-corona)

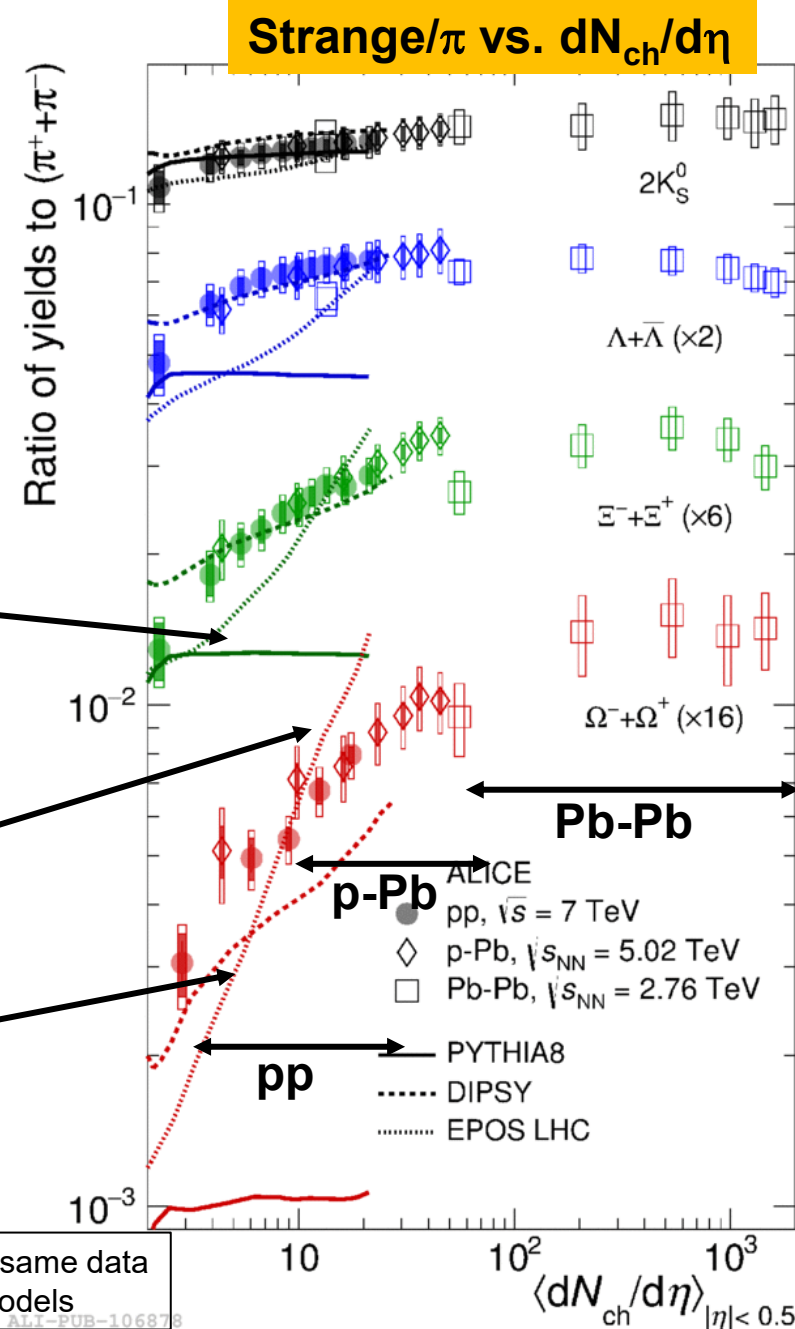
✓ Colour rope mechanism
(DIPSY)

Cannito – Wed 11:50

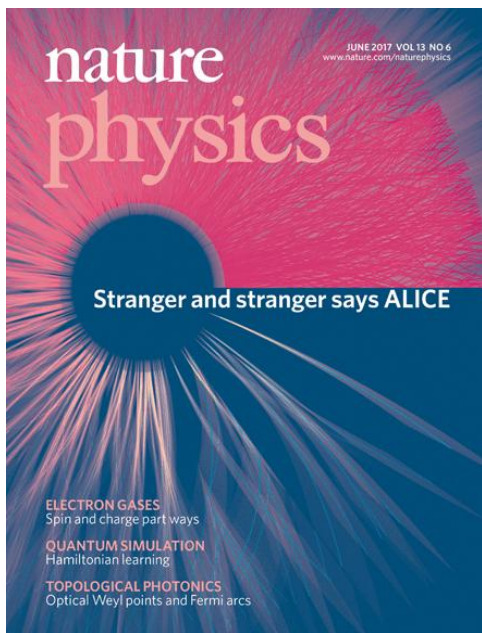


Christian Bierlich

see [backup](#) for same data with updated models



ALICE, Nature Phys. 13 (2017) 535





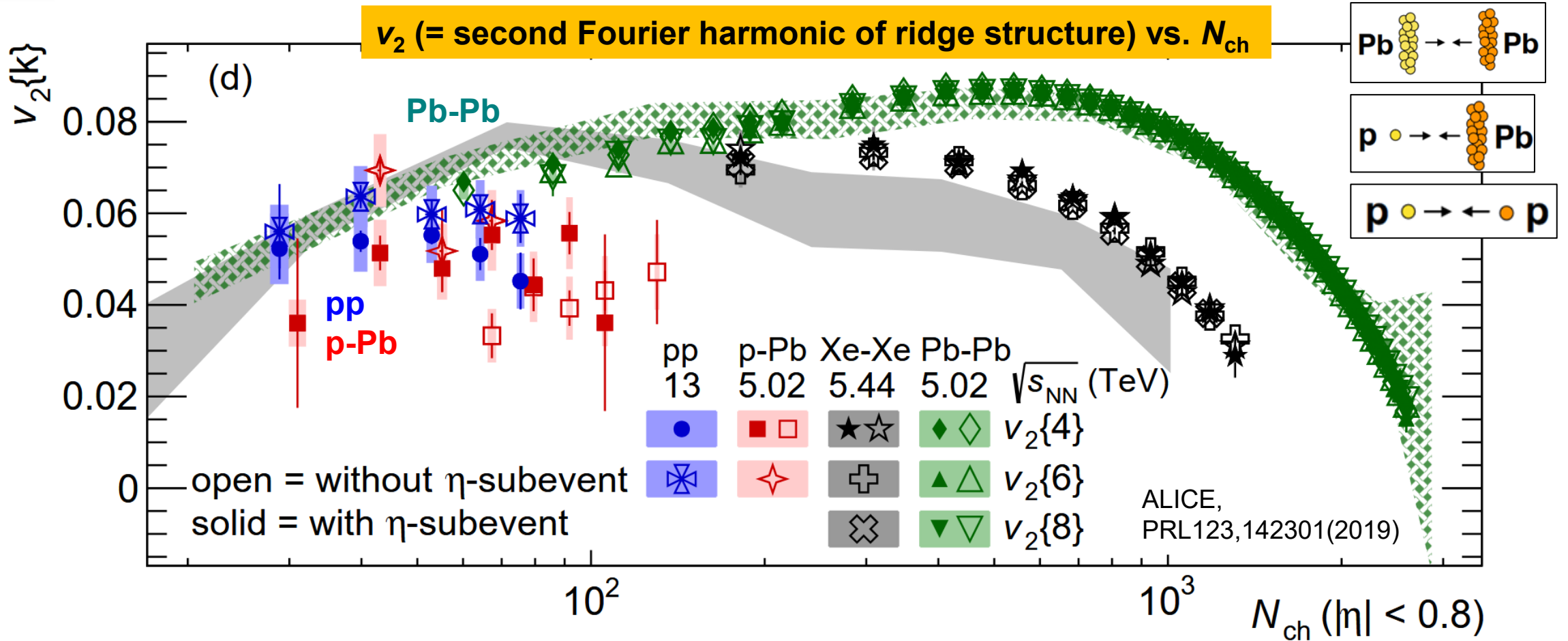
Detailed characterization...



ALICE

Higher-Orders Collectivity

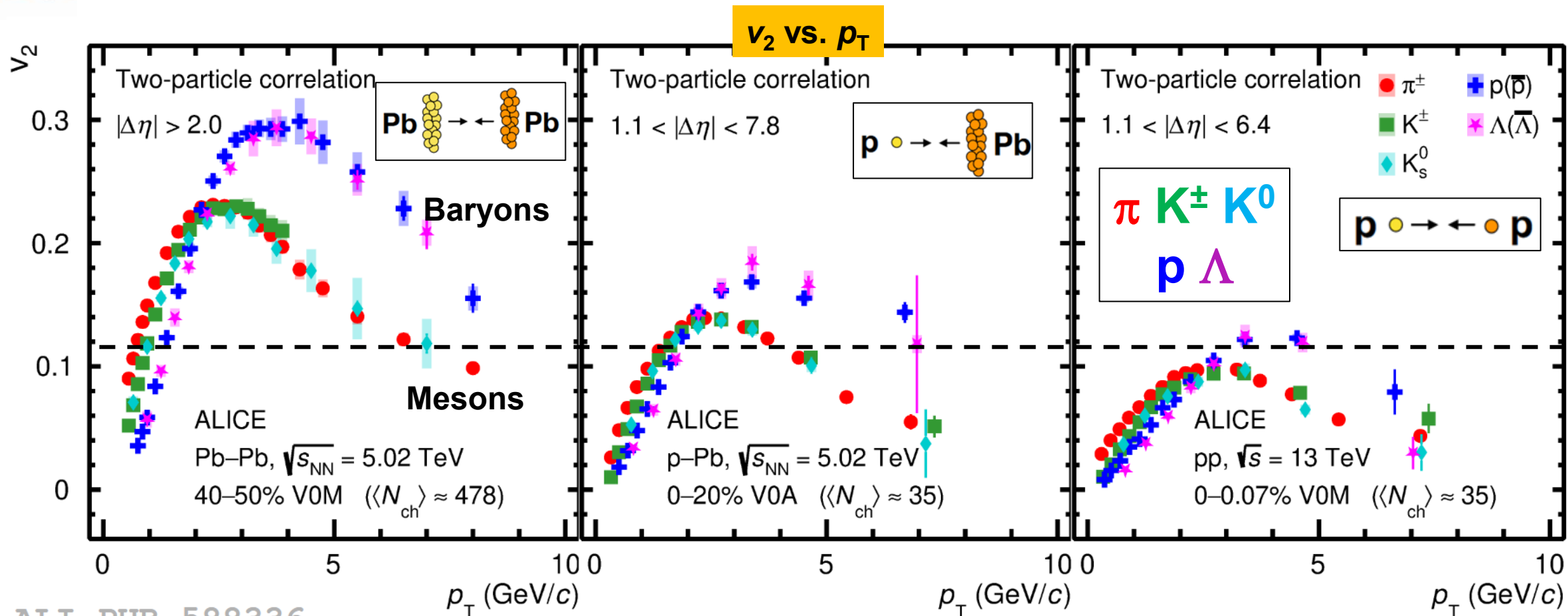
How many particles contribute to the phenomena?



**Ridge component characterized with multi-particle correlations: pp ~ p-Pb < Pb-Pb
 → At least 6 particles involved above $N_{ch} \approx 30$**

(see also [CMS](#), PLB 765 (2017) 193)

Identified-Particle Collectivity



Similar trends in all systems

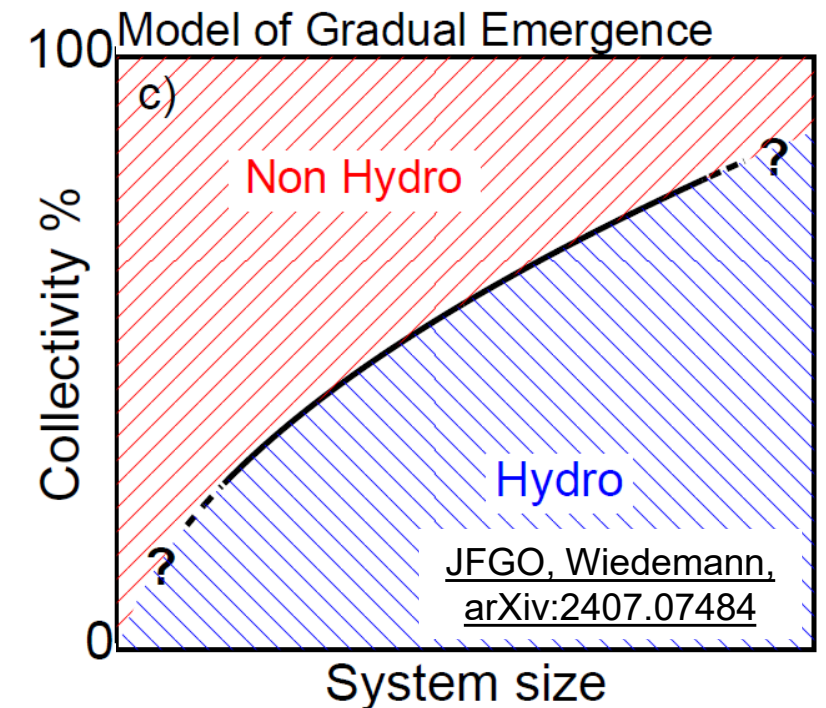
Baryon and meson grouping observed in all systems \rightarrow partonic degrees of freedom?

Different magnitudes (factor 2-3): $pp < p\text{-Pb} < \text{Pb-Pb}$

ALICE,
arXiv:2411.09323

Open Questions...

- Most collective phenomena observed in large systems can be identified in small systems like pp and p-Pb
 - Most studies at high multiplicity. What about the low-multiplicity limit?
- If collective phenomena are due to parton-parton interactions, then there are parton-parton interactions...
 - So where is the energy loss?
- Both hydrodynamic and non-fluid dynamic d.o.f. relevant at most (all?) sizes
 - Experimental handle (species) to dial the relative contribution → tool to study QGP d.o.f.
 - Done with LHC light ion run





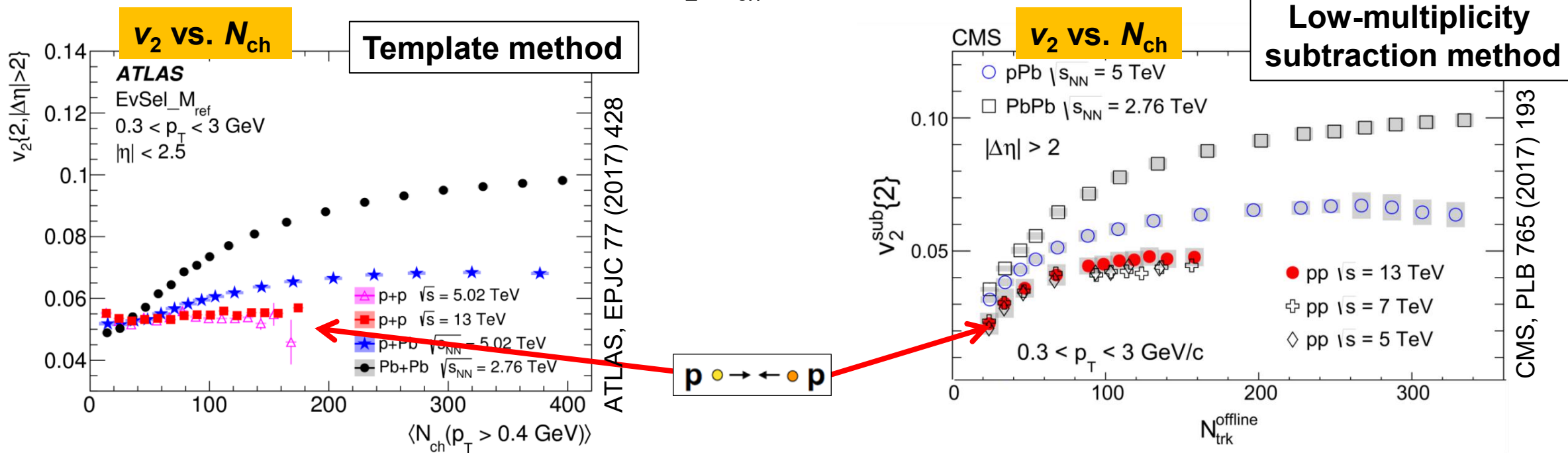
New Results from ALICE

pp and p-Pb

Low Multiplicity

Does the phenomena switch off?

- Low-multiplicity correlations dominated by mini-jets and resonances
 - Ridge “too small to stick out” (~negligible in high-multiplicity pp or p-Pb)
 - Extracting v_2 coefficient requires subtraction procedure
 - Accuracy of procedures depends on $v_2(N_{ch})$. See [backup](#)

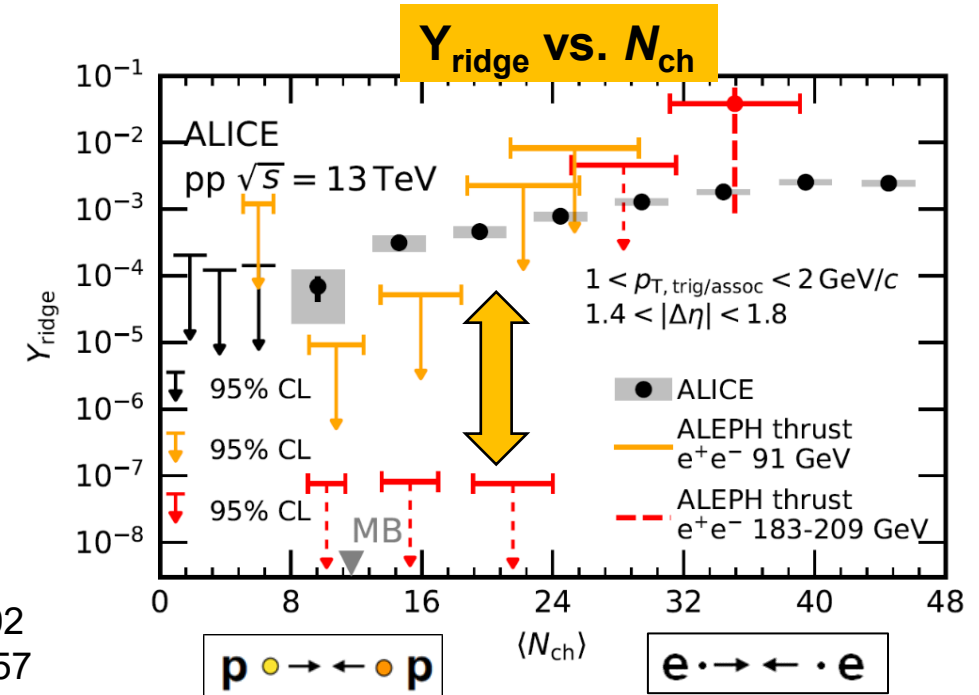
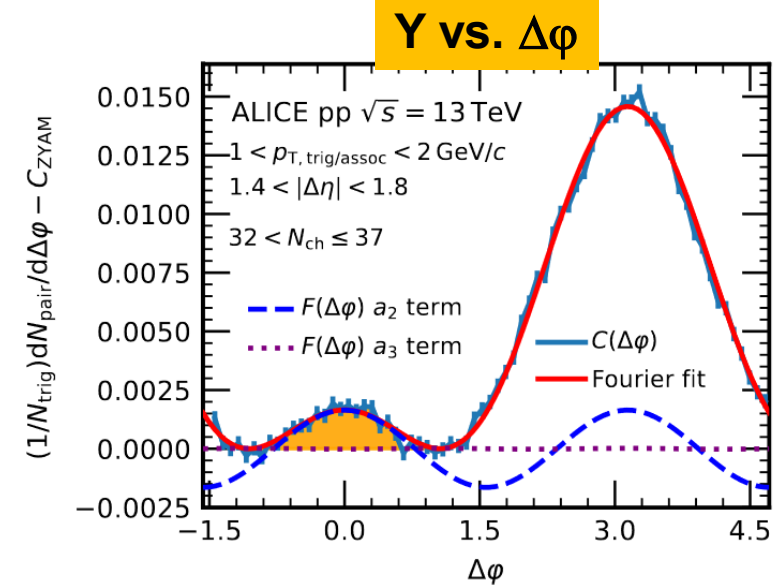


Experimental result procedure dependent – in particular at low multiplicity

Low Multiplicity pp vs. e^+e^-

- Low-multiplicity pp collisions studied on near side
 - Near-side ridge found for N_{ch} as low as minimum bias
- e^+e^- (ALEPH) data re-analyzed
 - Thrust axis analysis on archived data
 - No ridge observed (minor hint at high multiplicity, see [backup](#))
- 5σ difference between pp and e^+e^- at the same multiplicity
 - Comparison as a function of multiplicity challenging (see [backup](#))

ALICE, PRL132(2024)17,172302
Chen et al, PLB856(2024)138957

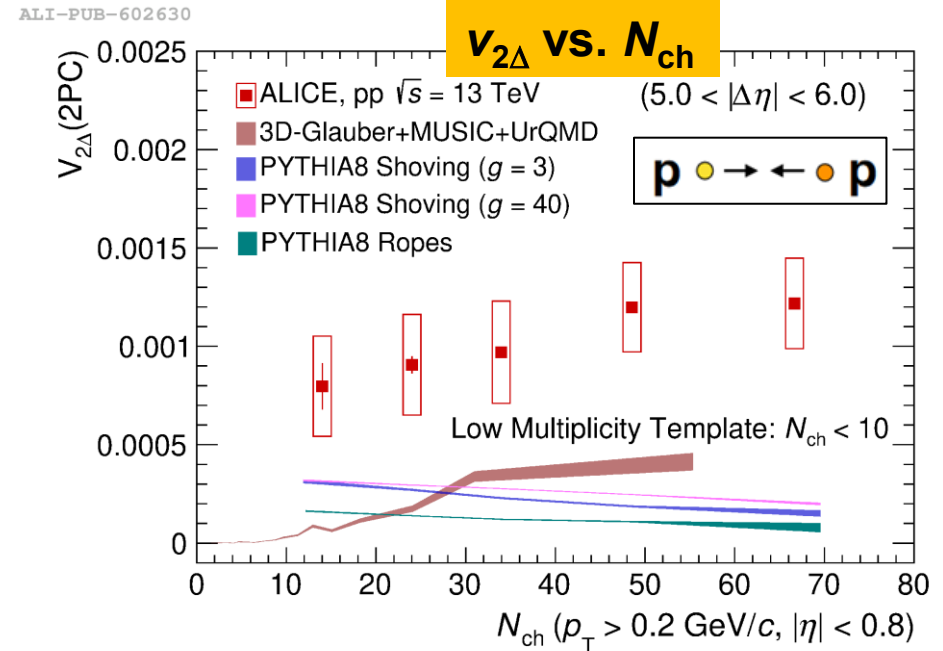
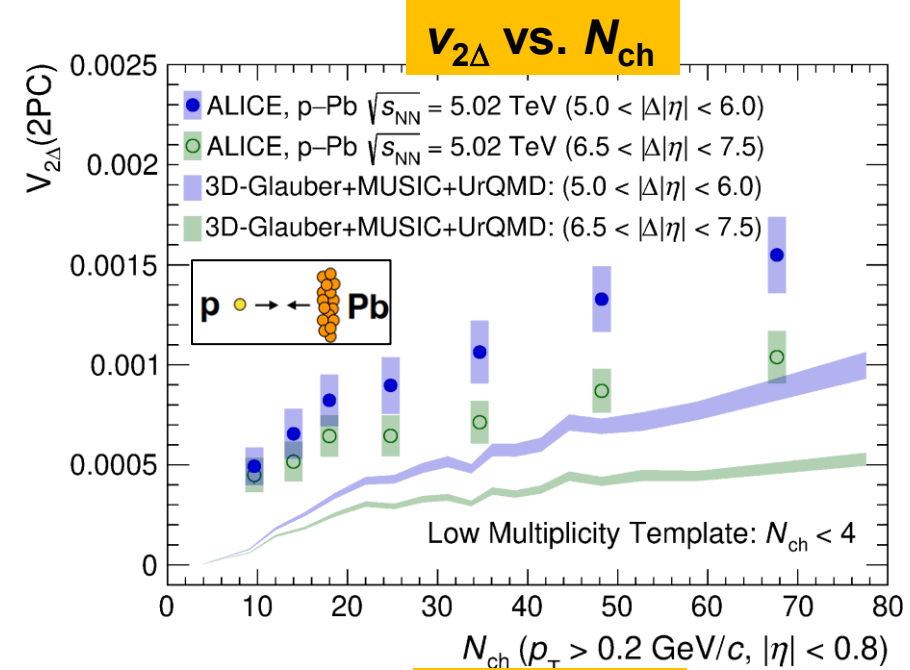




Very-Long-Range Correlations

- Forward detectors in pp and p-Pb collisions
 - FMD: $1.7 < \eta < 5.1$ and $-3.1 < \eta < -1.7$
 - Separation of up to 7.5 units in $\Delta\eta$
- Finite v_2 even at low multiplicity
- Hydrodynamic simulations underestimate observed v_2 by factor 2 (in pp and p-Pb)
- PYTHIA with string shoving does not reproduce magnitude and trend (in pp)

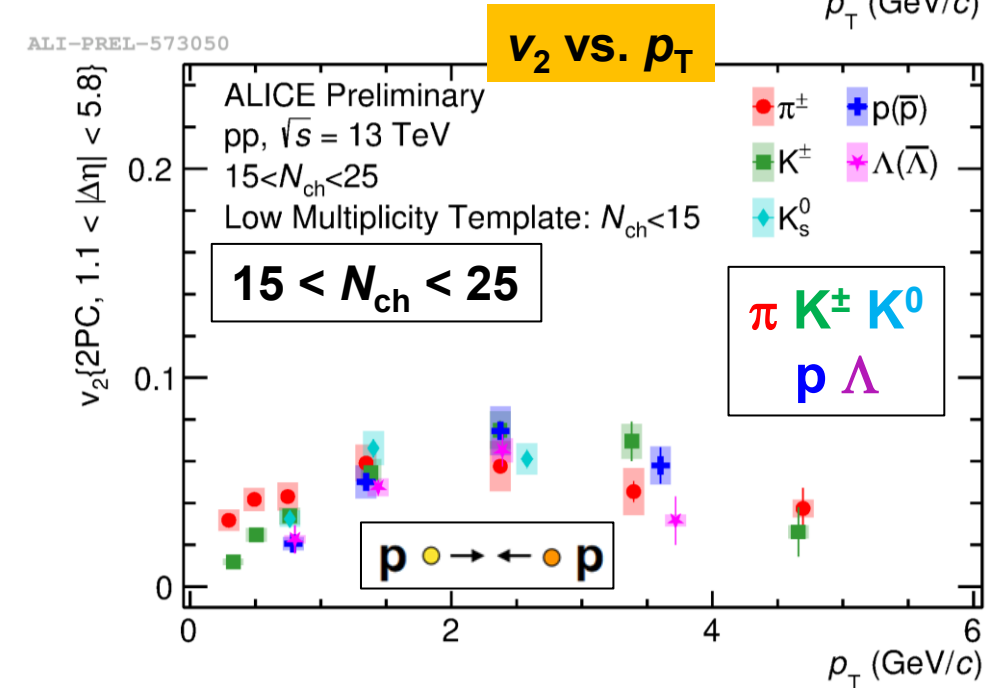
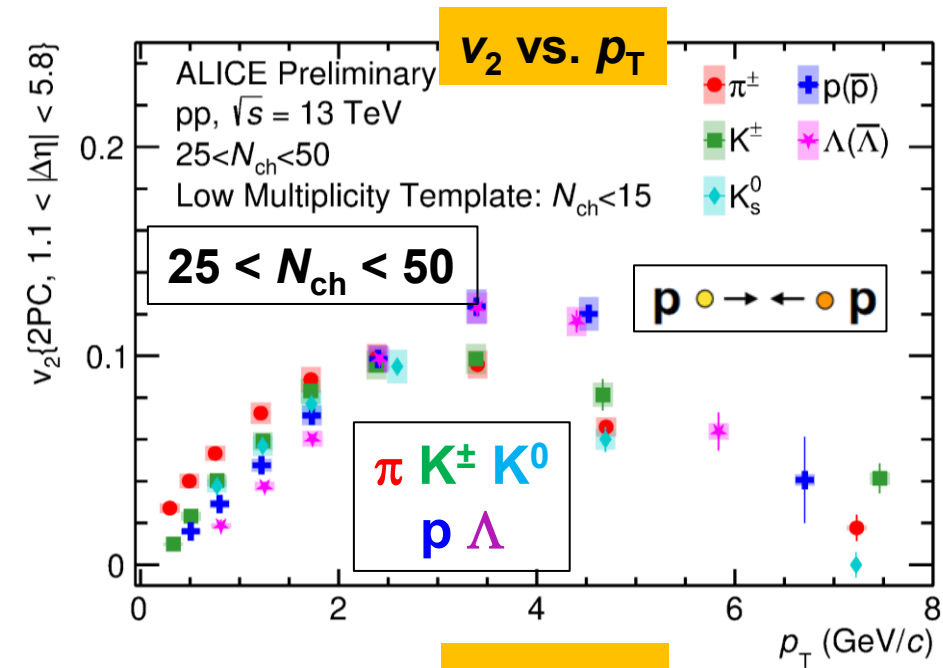
ALICE, arXiv:2504.02359



ALI-PUB-602625

Identified v_2 at low N_{ch}

- Identified-flow measurements have been extended into low-multiplicity region
 - Non-flow subtraction with template method
- pp
 - High and intermediate N_{ch} : baryon-meson grouping and mass splitting
 - $N_{ch} < 25$: splitting less apparent, uncertainties increase
- p-Pb: similar findings (plots see [backup](#))



ALI-PREL-573045



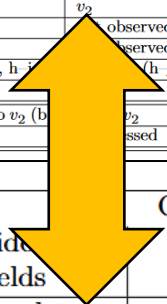
Very Small Systems...

- Smaller system like pp and p-Pb are very well characterized at high N_{ch}
 - Only few studies at low N_{ch} but activity ramping up
- Reanalysis of archived ee and ep has happened, essentially no further statistical power
- Ultraperipheral collisions (γ -Pb and γ -p) very interesting for future studies of collective phenomena

Table 1. Summary of observables or effects in high multiplicity p-Pb, a-A and pp collisions. References to key measurements are given. (high N)

Observable or effect	High N_{ch} studies	Refs.
Near-side ridge yields	yes	yes
Azimuthal anisotropy	$v_1 - v_9$	$v_2 - v_4$
Weak γ dependence	yes	yes
Characteristic mass dependence	$v_2 - v_5$	v_2, v_3
Higher-order cumulants (mainly $v_2\{n\}, n \geq 4$)	"4 \approx 6 \approx 8 \approx LYZ" + higher harmonics	"4 \approx 6 \approx 8 \approx LYZ" + higher harmonics
Symmetric cumulants (SC)	up to (5, 3)	only (4, 2), (3, 2)
Non-linear flow modes	up to v_7	not measured
Factorization breaking	$n = 2, 4, \{2\}, \{4\}$	$n = 2, 3, \{2\}$
Event-by-event v_n distributions	$v_2 - v_4$	not measured
Flow- p_T correlation	up to v_4	v_2
Directed flow (from spectators)	yes	no
Charge-dependent correlations	yes	yes
Low p_T spectra ("radial flow")	yes	yes
Intermediate p_T ("recombination")	yes	yes
Particle ratios	GC level	GC level
Statistical model	$\gamma_s^{GC} = 1$	$\gamma_s^{GC} \approx 1$
HBT radii ($R(k_T), R(\sqrt{N})$)	$R_{out}/R_{side} \approx 1$	$R_{out}/R_{side} \lesssim 1$
Direct photons at low p_T	yes	not measured
v_n in events with Z, jets	not measured	up to v_3
Jet constituent v_n	v_2	v_2 in jet frame
Jet quenching through R_{AA}	yes	not observed
... through dijet asymmetry	yes	not observed
... through correlations	yes (Z-jet, γ -jet, h-jet)	not measured
... through high p_T v_n and jet- v_n	yes	not measured
Heavy flavour anisotropy	up to v_3 (c), up to v_2 (b)	up to v_2
Quarkonia production	suppressed	not measured

High N_{ch} studies



System	Near-side ridge yields	Azimuthal anisotropy (v_n)	Higher-order cumulants
γ -Pb (in Pb-Pb UPC)	observed (template)	up to v_3 (template)	not studied
γ -p (in p-Pb UPC)	not observed	up to $v_3 \approx$ MC (template)	not studied
γ -P (in ep)	not studied	up to $v_2 \approx$ MC	$n = 4 \approx$ MC wrong sign
ep (DIS)	not studied	up to $v_2 \approx$ MC	not studied
pp (low N)	observed	up to v_2 (template)	not studied
ee	limits + hint at 1.02σ	up to $v_2 \approx$ MC	not studied

Low N_{ch} + other collision systems

JFGO, Wiedemann, [arXiv:2407.07484](https://arxiv.org/abs/2407.07484),
World Scientific Annual Review of Particle Physics

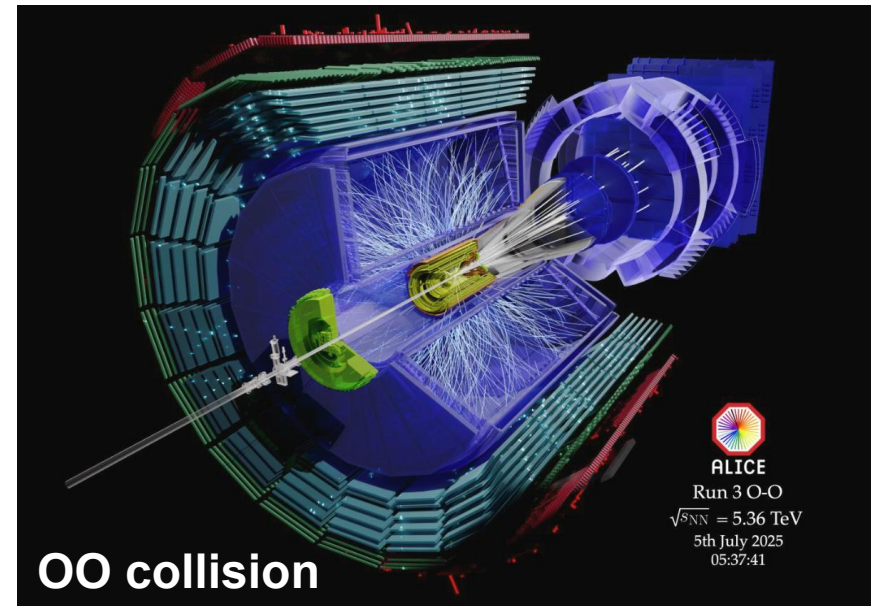
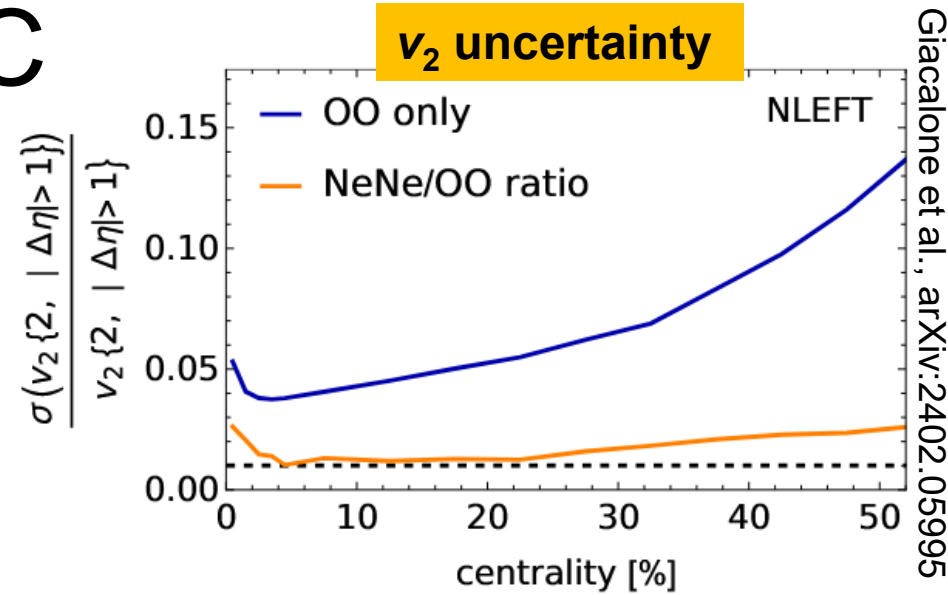
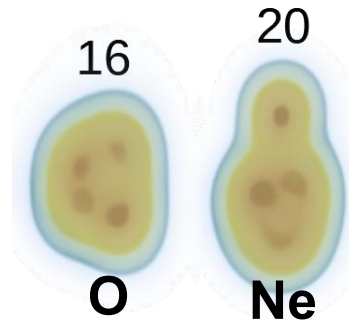


New systems...

OO and Ne-Ne

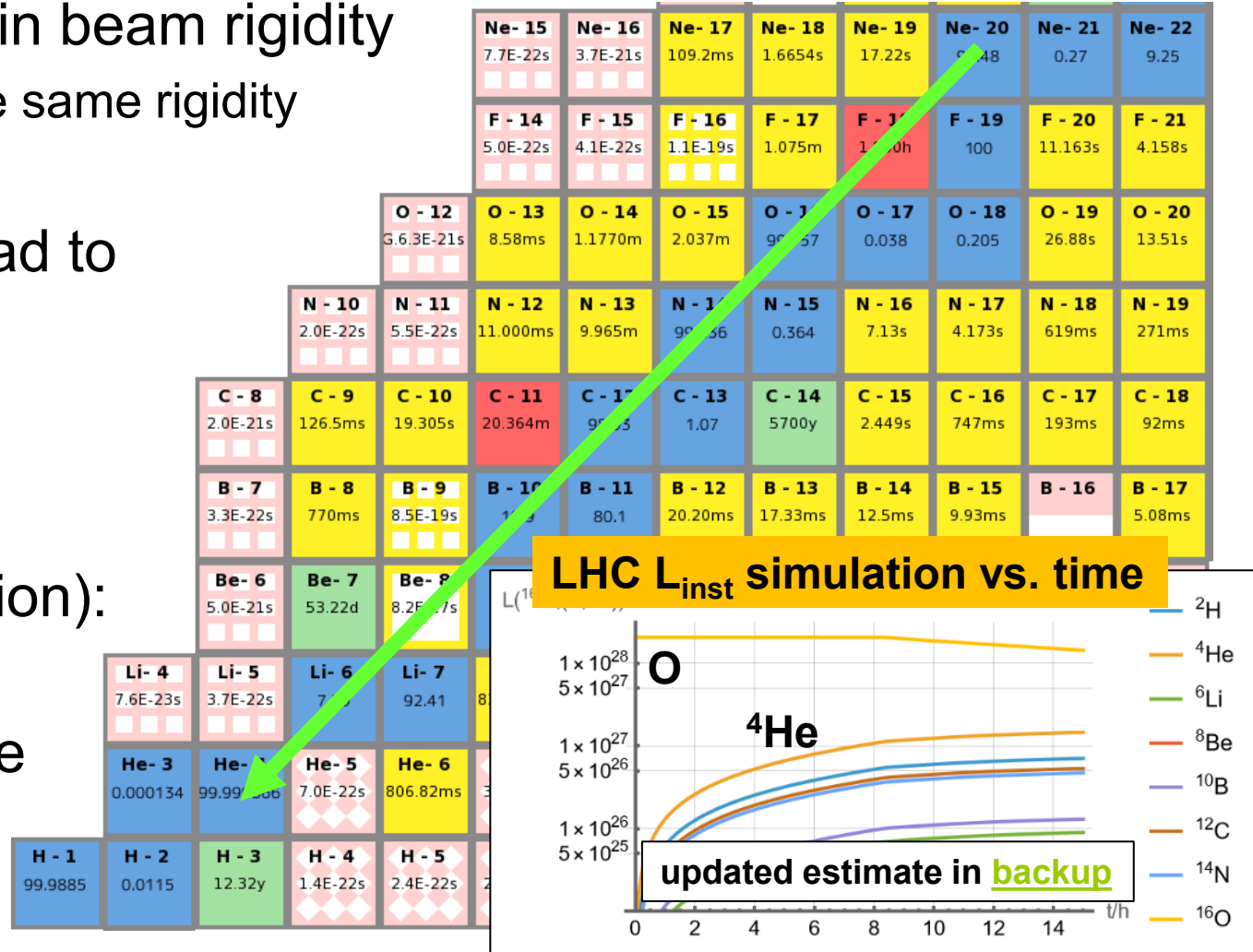
Oxygen and Neon run at LHC

- Special run week in July for cosmic-ray and heavy-ion community
- Modelling uncertainties cancel in light-ion ratios
- LHC and ALICE performed with excellence
 - pO: recorded 7.27 nb^{-1} | $3 \cdot 10^9$ events (93% eff.)
 - OO: recorded 5.01 nb^{-1} | $6 \cdot 10^9$ events (97% eff.)
 - Ne-Ne: recorded 0.84 nb^{-1} | 10^9 events (99.8% eff.!)
- Interesting new background in these beams
 - Transmutation



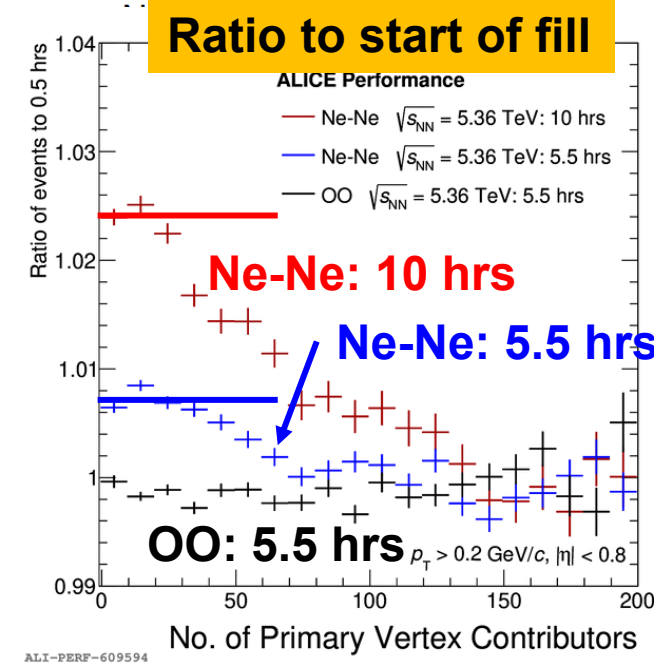
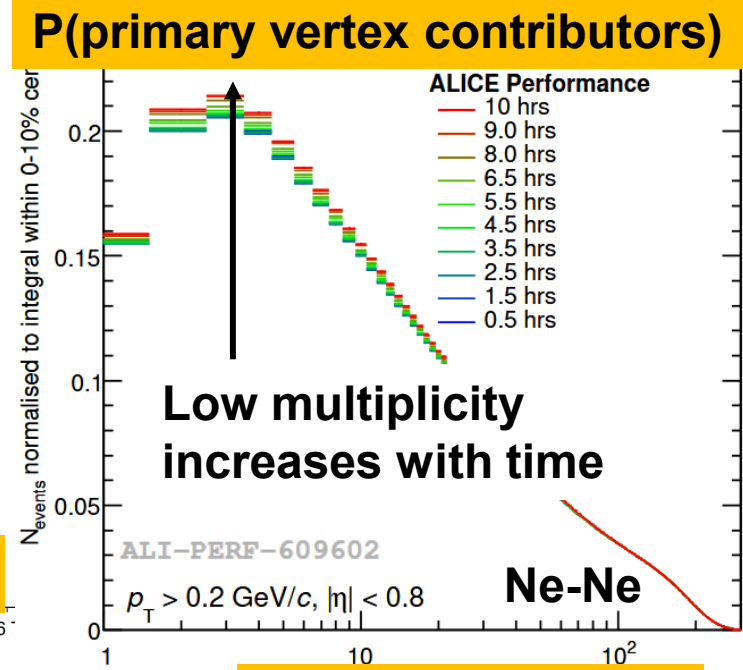
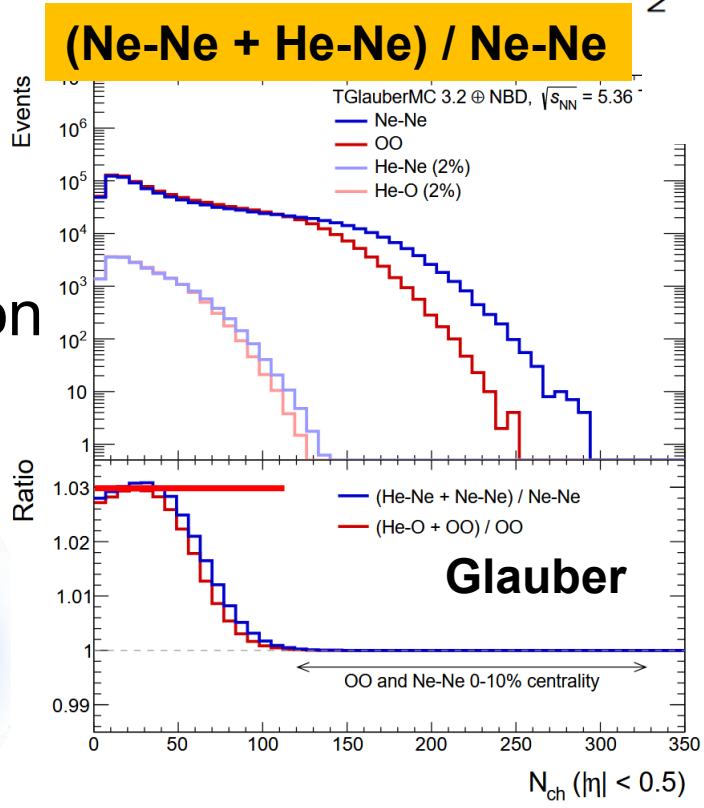
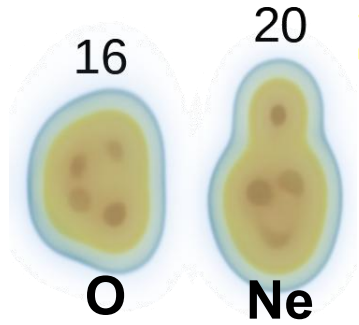
Transmutation (theory)

- Accelerator configured for a certain beam rigidity
 - Ions with the same A/Z ratio have the same rigidity
 - ^{16}O and ^{20}Ne are on $A = 2Z$
- Hadronic and e.m. interactions lead to ^{16}O , ^{14}N , ^{12}C , ^{10}B , ^8Be , ^6Li , ^4He , d (all except Be stable)
 - What happens in the beam, stays in the beam...
- Main contamination (from simulation): He-O and O-He collisions
- Experimental assessment of these contaminations crucial



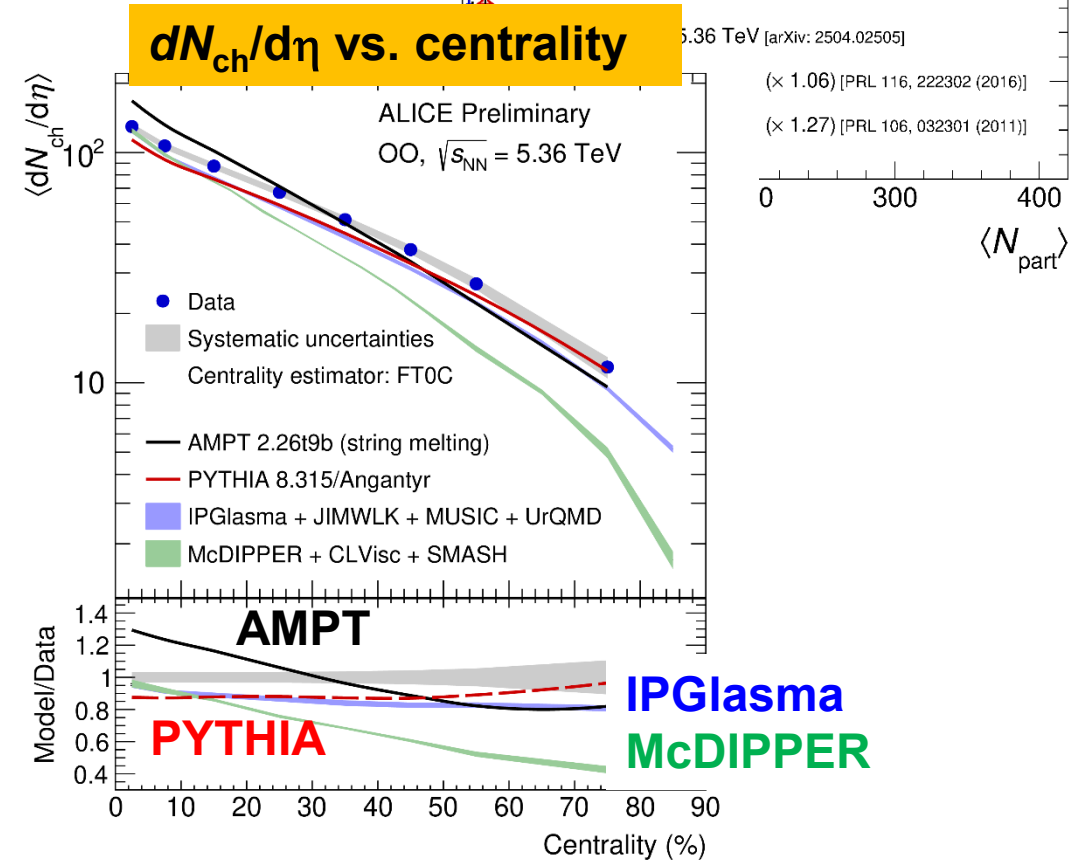
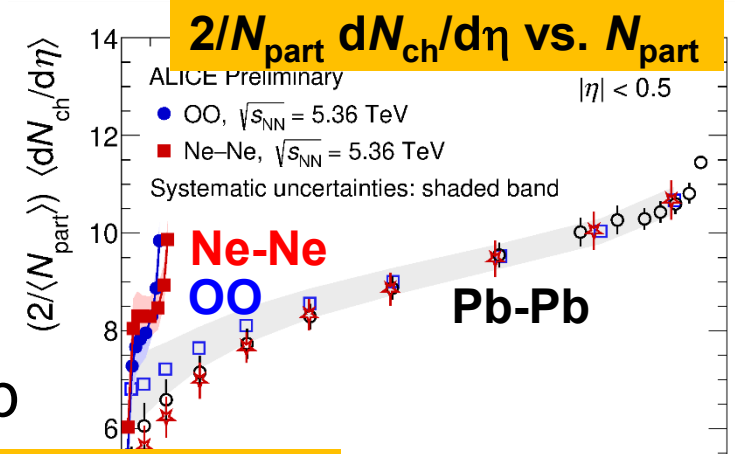
Transmutation (experiment)

- Experimental assessment through time dependence of multiplicity distributions and observables
 - Good benchmark: time dependence of primary-vertex contributors (tracks in a reco. vertex)
 - He-O collisions have lower multiplicity than O-O
- Comparison with Glauber
 - O: no or very little contamination
 - Ne: 2% He after 10 hours
- ZDC studies ongoing



$dN_{ch}/d\eta$ in OO and Ne-Ne

- Midrapidity measurement as function of (fwd) centrality
- N_{ch}/N_{part} vs. N_{part} very different trend compared to Pb-Pb
- N_{ch} vs. centrality vs. models (OO)
 - IP-Glasma + MUSIC + UrQMD: good in central, then 10% too low
 - McDIPPER + CLVisc + SMASH: good in central, then 60% too low
 - PYTHIA 8 Angantyr: 10% too low
 - AMPT (with string melting): too high in central, then too low

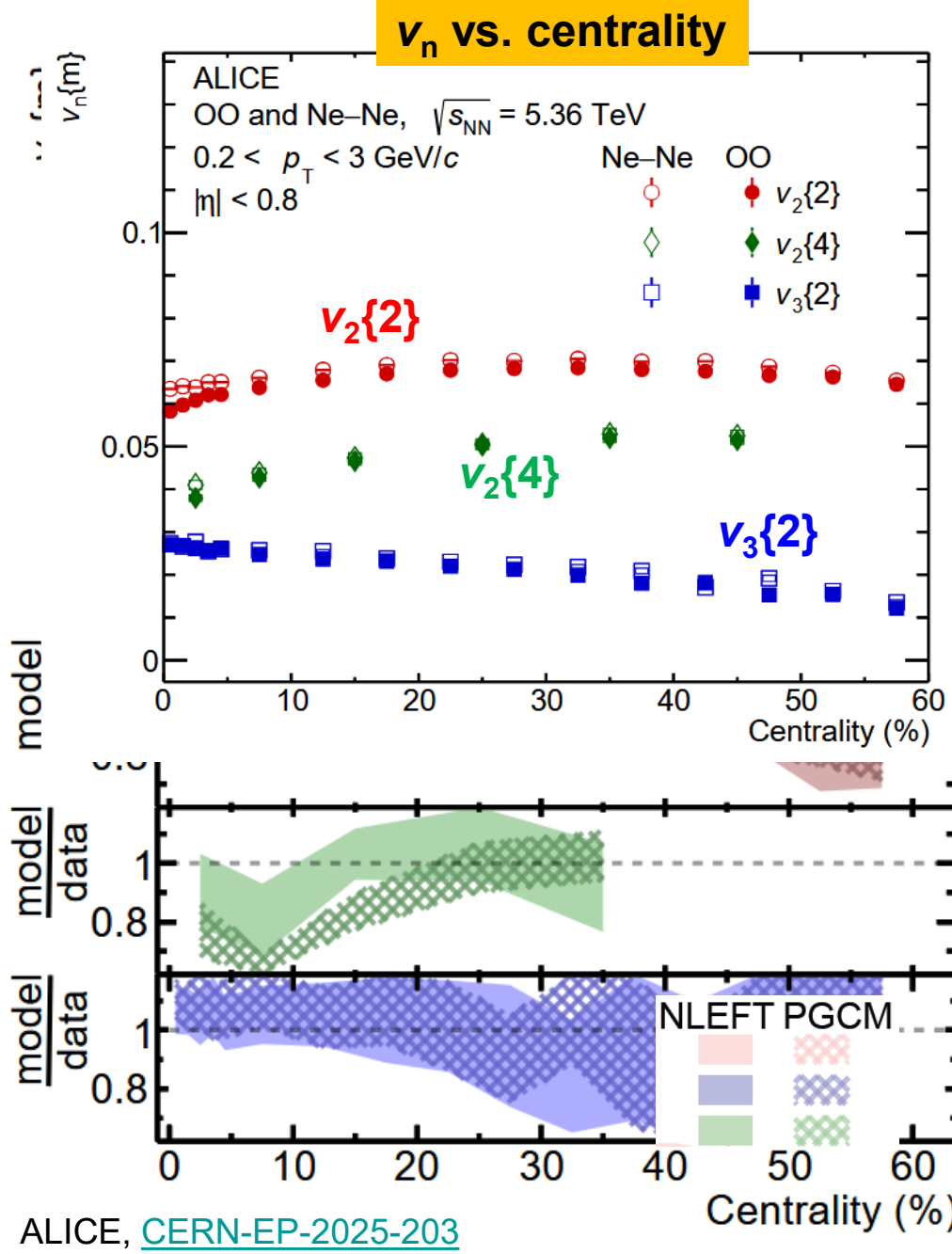


Urioni – Tue 14:00

v_n in OO and Ne-Ne

- $v_2\{2\}$ and $v_2\{4\}$, $v_3\{2\}$ as fct of (fwd) centrality
 - Sizable v_2 and v_3 with weak centrality dependence
 - v_3 has different centrality dependence than ε_3 underlining importance of hydro evolution
→ hydrodynamic phase in OO and Ne-Ne
- Reproduced by Trajectum up to 50% centrality within few %
 - With two different initial state models
 - $v_2\{4\}$ better reproduced by NLEFT

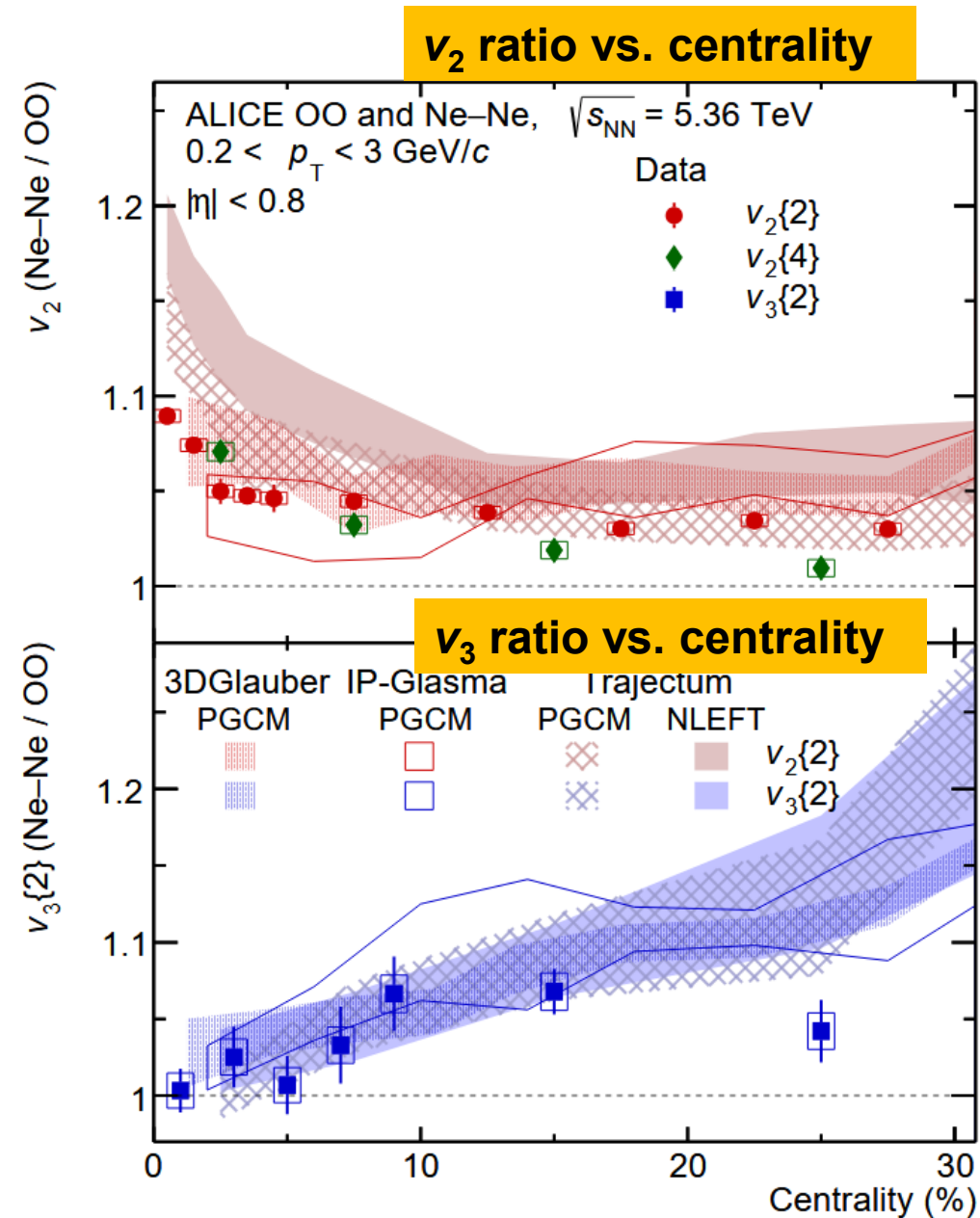
- **NLEFT: EFT + Lattice QCD. Probes clustering and collective phenomena in the ground state of nuclei.**
- **PGCM: ab-initio fw, suited to capture strong static correlations associated with shape deformation and fluctuations, N3LO chiral EFT Hamiltonian**





v_n in OO and Ne-Ne

- Ratios between OO and Ne-Ne reduces uncertainties (< 0.01 exp. for v_2)
 - v_2 peaks for central: stronger quadropole deformation of Ne compared to tetrahedral O
 - v_3 increases with centrality: tetrahedral O leads to larger v_3
- IP-Glasma captures ratios well
- Trajectum overestimates ratio in 0-10%
- PGCM favored
 - Differences between IP-Glasma and Trajectum initial conditions related to subnucleon width \rightarrow results support a smaller width than found by Bayesian analysis using data from large systems



ALICE, [CERN-EP-2025-203](#)

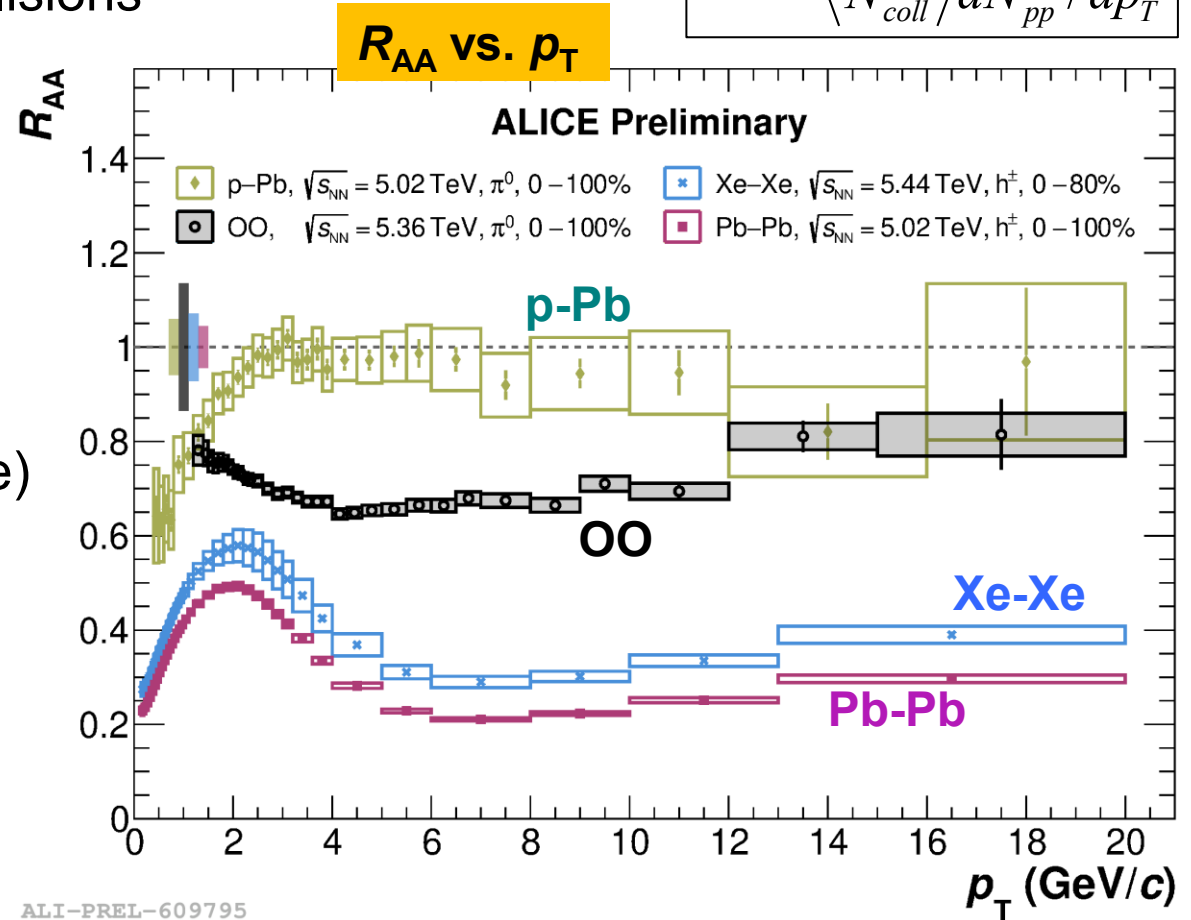
$\pi^0 R_{AA}$ in OO

- Strong energy loss in Pb-Pb; nothing found in p-Pb
 - Production of particle with respect to pp collisions

$$R_{AA} = \frac{dN_{AA} / dp_T}{\langle N_{coll} \rangle dN_{pp} / dp_T}$$

- Measured using EMCAL
 - In “0-100%” centrality
 - $R_{AA} \sim 0.65$ at 4 GeV/c (4.0σ from unity)
 - Dominant uncertainty from vdM scan (normalization) in pp reference (will improve)

- Compared to inclusive R_{AA} , values between p-Pb and Pb-Pb



Strangmann – Thu 11:30

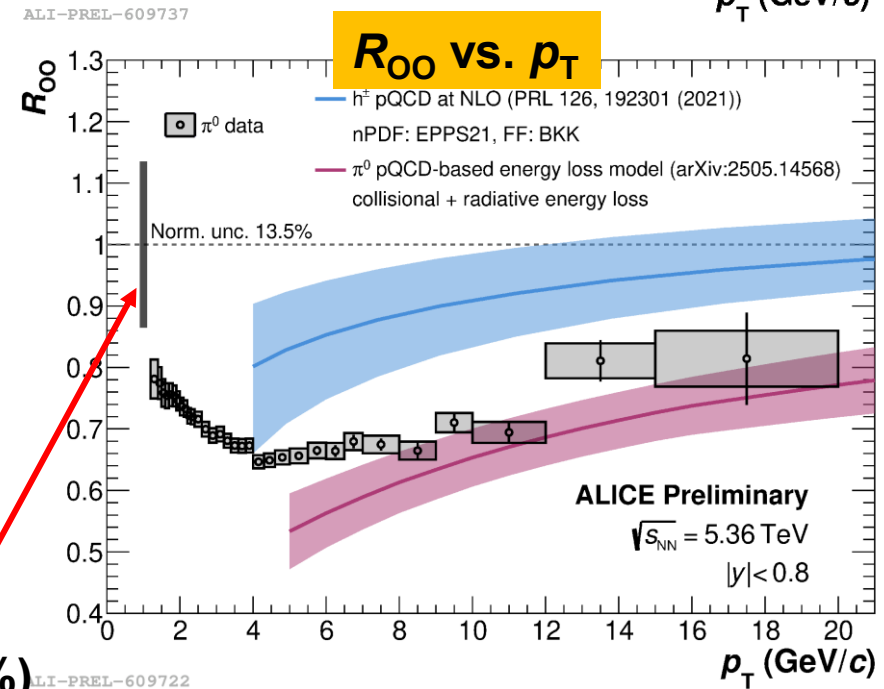
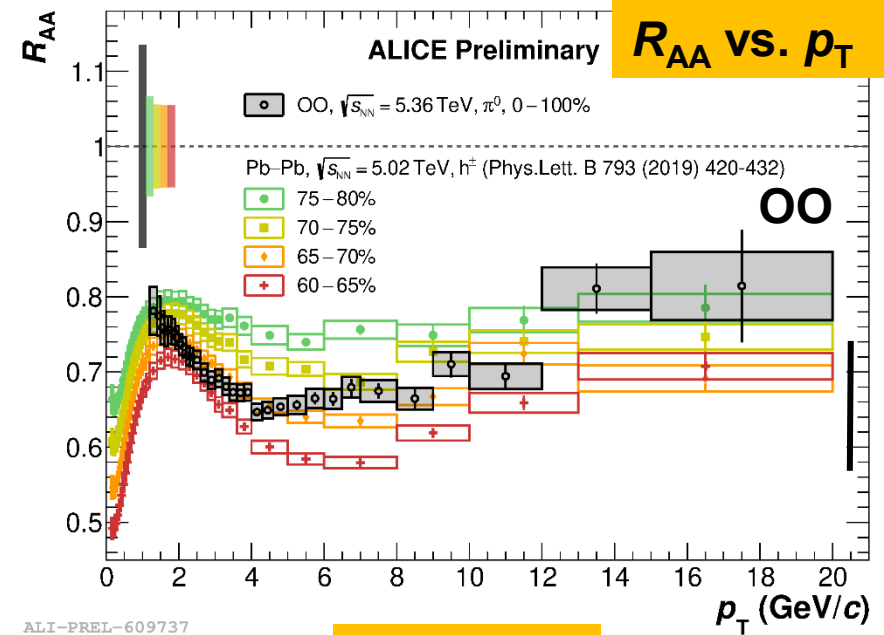
ALI-PREL-609795

$\pi^0 R_{AA}$ in OO

- Comparison to differential Pb-Pb R_{AA}
 - Most similar to 65-70%

- Do we see energy loss?
 - $R_{AA} \sim 0.65$ at 4 GeV/c (4.0σ from unity)
 - Comparing to CNM pQCD without energy loss: 2.4σ
 - Compatible with energy loss calculation (Faraday, Horowitz, 2505.14568)
 - Normalization uncertainty will reduce

Energy loss answer at the horizon...

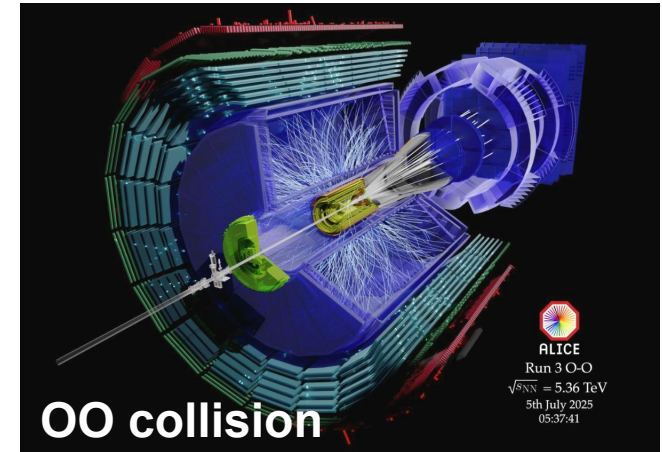


will go down
(expectation: 5%)

Strangmann – Thu 11:30

Summary

- Small system observations challenged **two paradigms** at once
 - Smallest system in which heavy-ion “standard model” remains valid?
 - Can the standard tools for pp physics remain standard?
- Vibrant field emerged involving experiment and theory
- Presented results show that phenomena extend...
 - ...to low multiplicity (beyond e^+e^-)
 - ...to very long range ($\Delta\eta > 7.5$)
 - ...to identified particles at intermediate multiplicity
- Successful Oxygen and Neon run at LHC
 - $dN_{\text{ch}}/d\eta$: high-precision characterization
 - v_2 : hydrodynamics describes results, hydrodynamic phase needed
 - Hint of energy loss signal seen in OO collisions in $\pi^0 R_{\text{AA}}$



Thank you very much for your attention



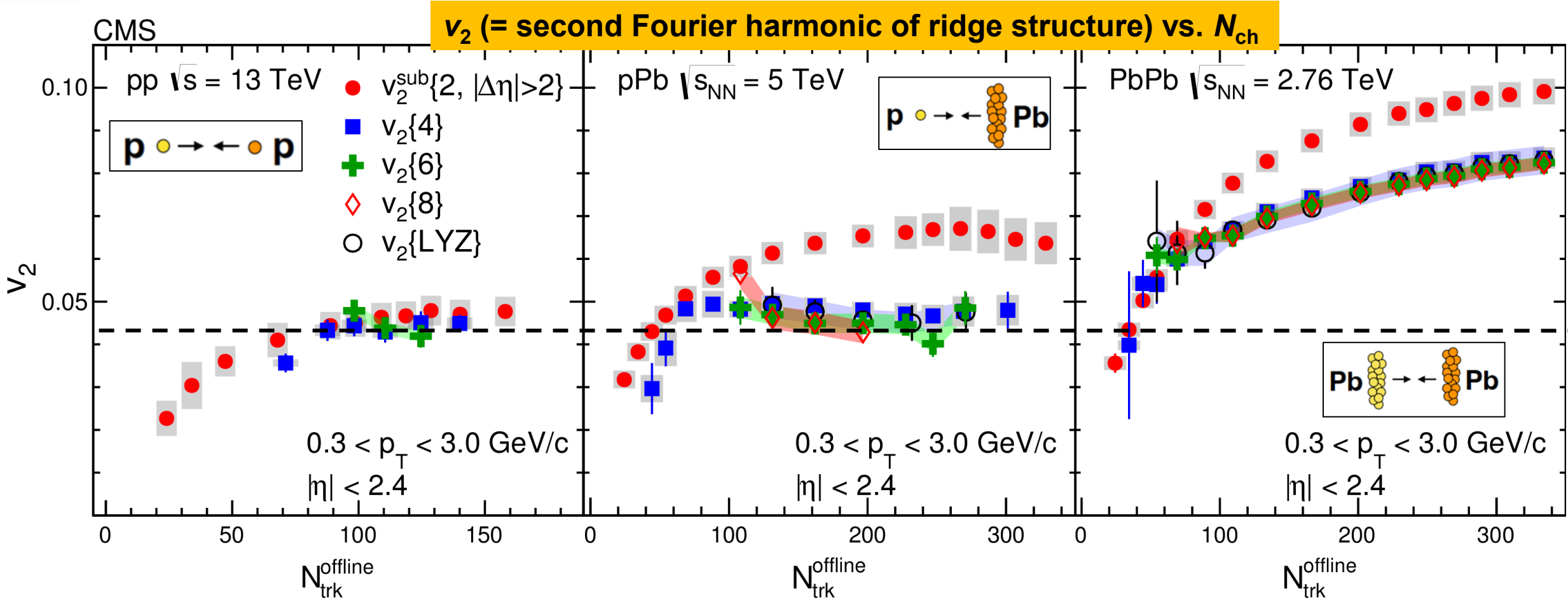
Backup



ALICE

Higher-Orders Collectivity

How many particles contribute to the phenomena?



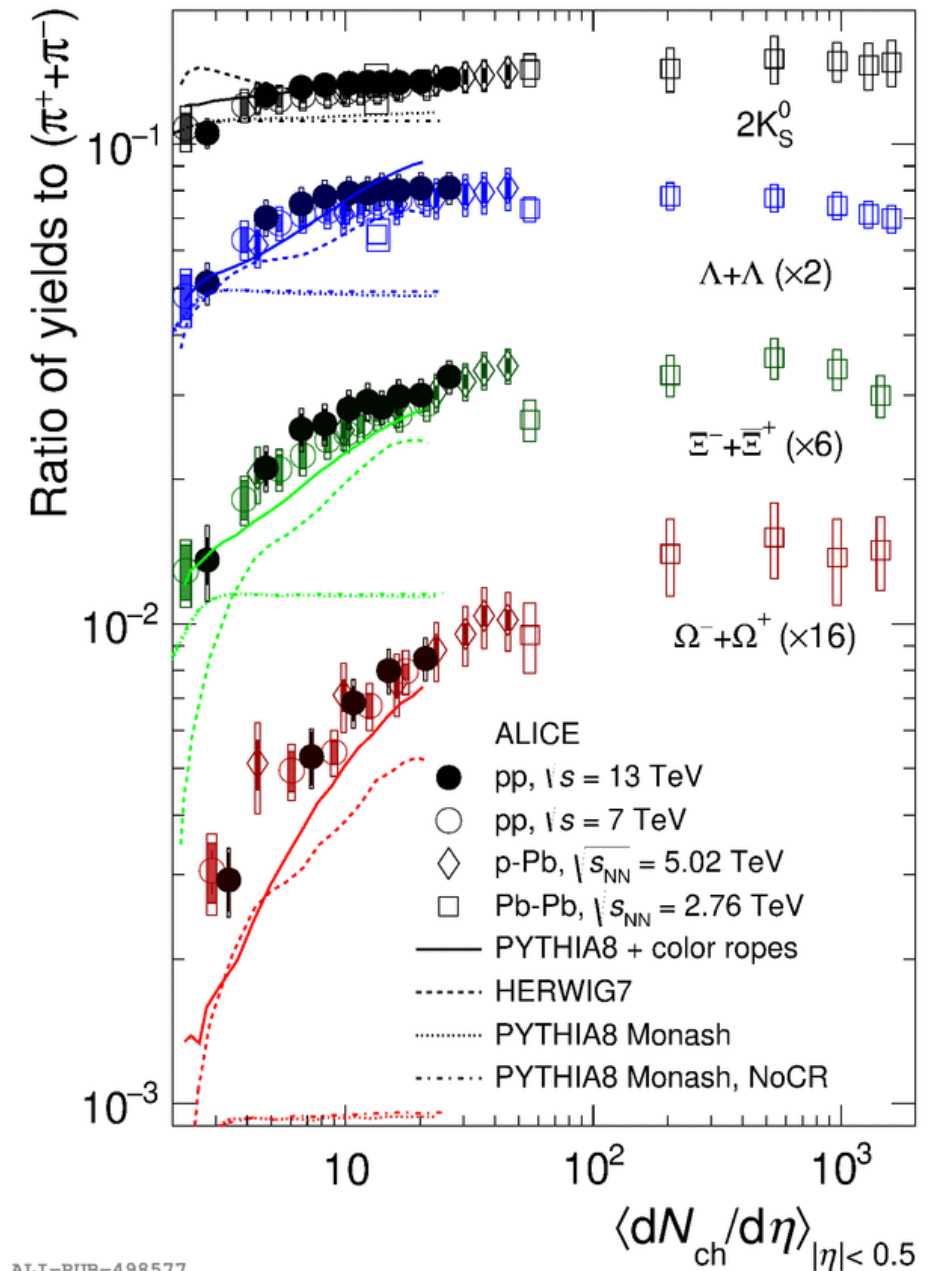
**Ridge component characterized with multi-particle correlations: pp ~ p-Pb < Pb-Pb
 → At least 6 particles involved above $N_{ch} \approx 90$**

CMS,
 PLB 765 (2017) 193



Strangeness

- Strangeness enhancement with updated models



ALI-PUB-498577

Subtraction Procedures

- Extracting v_2 coefficient requires **subtraction procedure** $\Delta Y(\Delta\varphi) = Y_N - a Y_M$
- Accuracy of procedures depends on $v_2(N_{ch})$. Let's assume: $v_{n,M}^2 = \alpha_N v_{n,N}^2$
- Low-multiplicity subtraction

$$\Delta Y(\Delta\varphi) = G' + N \sum_n 2v_n^2 \cos(n\Delta\varphi)$$

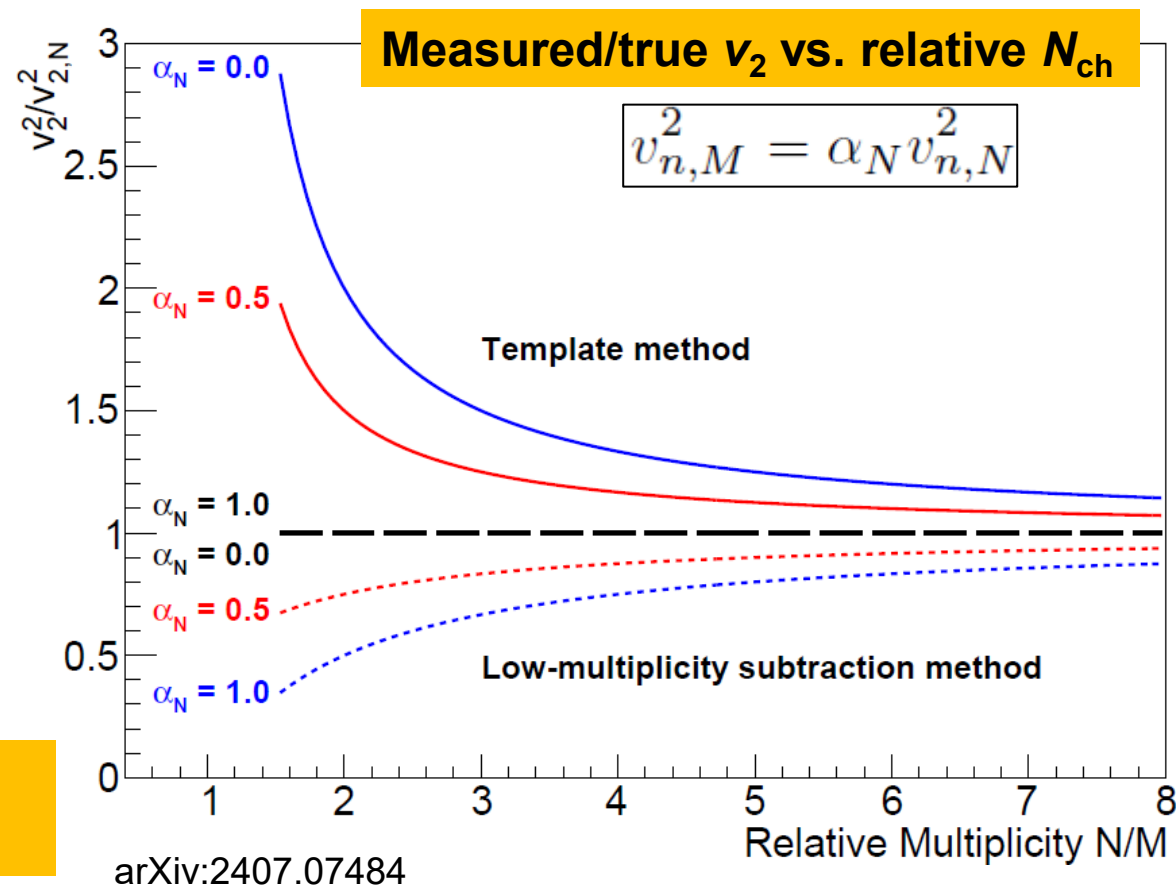
– Exact for $v_2 \rightarrow 0$ for $M \rightarrow 0$ ($\alpha_N = 0$)

- Template fit method

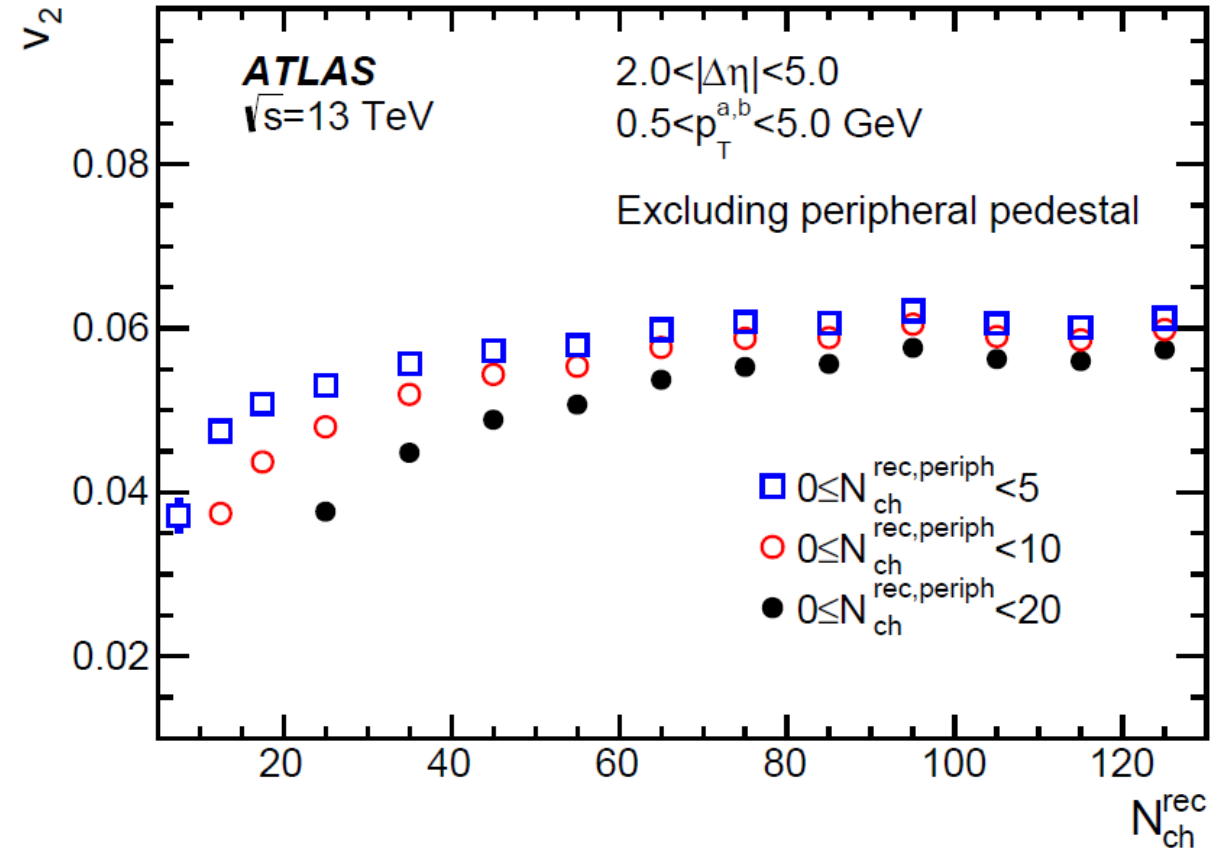
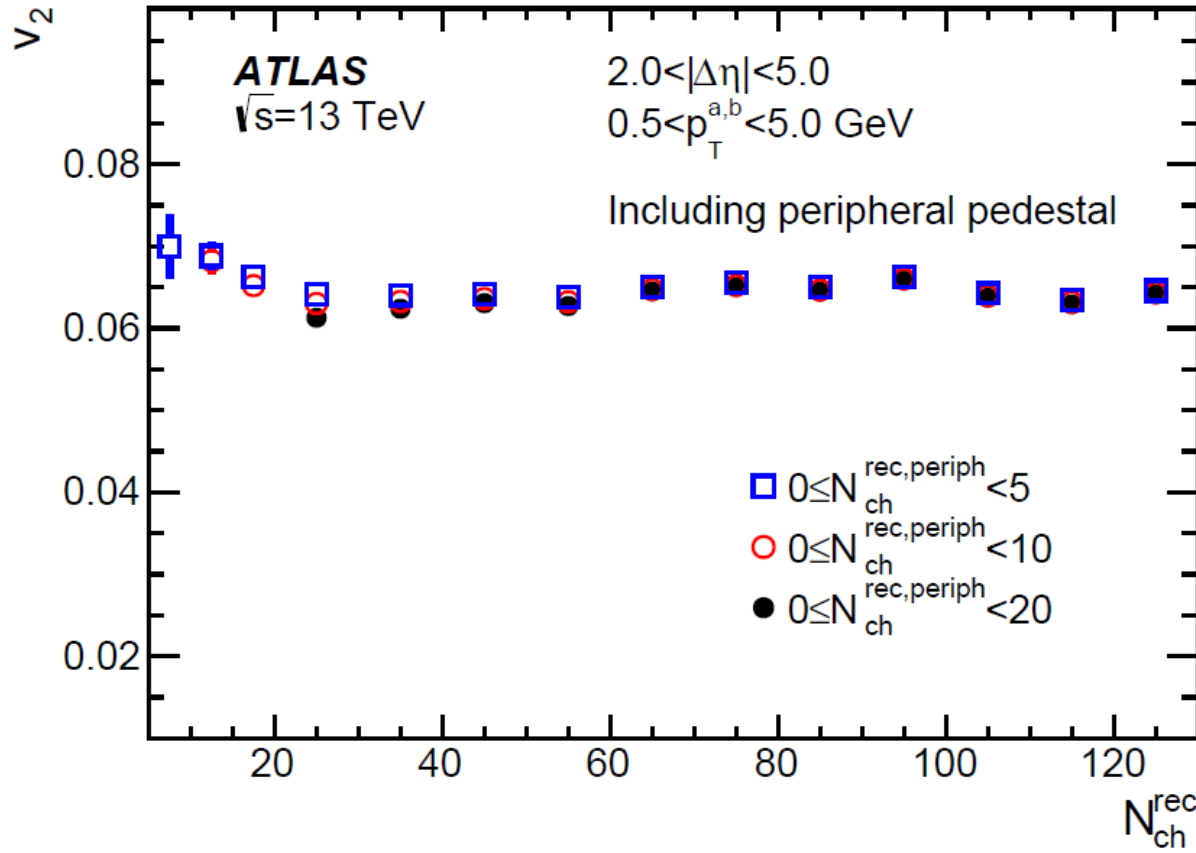
$$\Delta Y(\Delta\varphi) = G \left(1 + \sum_n 2v_n^2 \cos(n\Delta\varphi) \right)$$

– Exact for v_2 independent of M for small M ($\alpha_N = 1$)

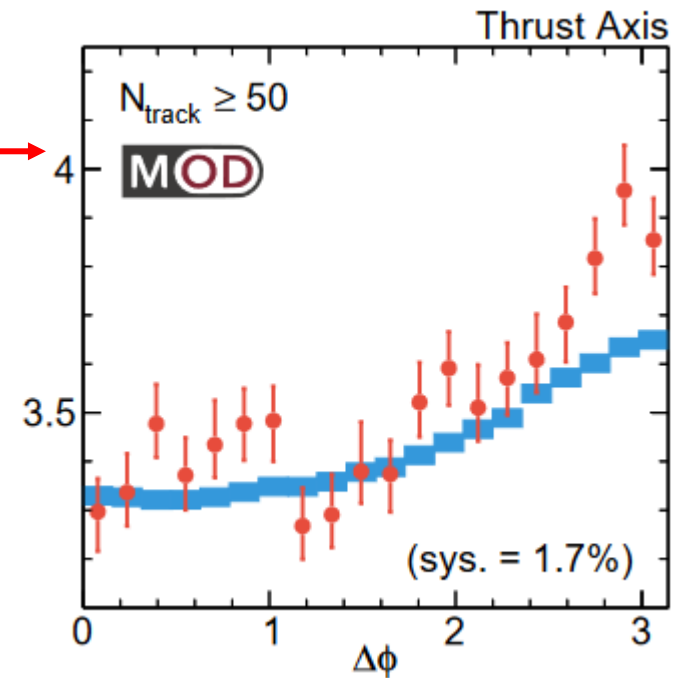
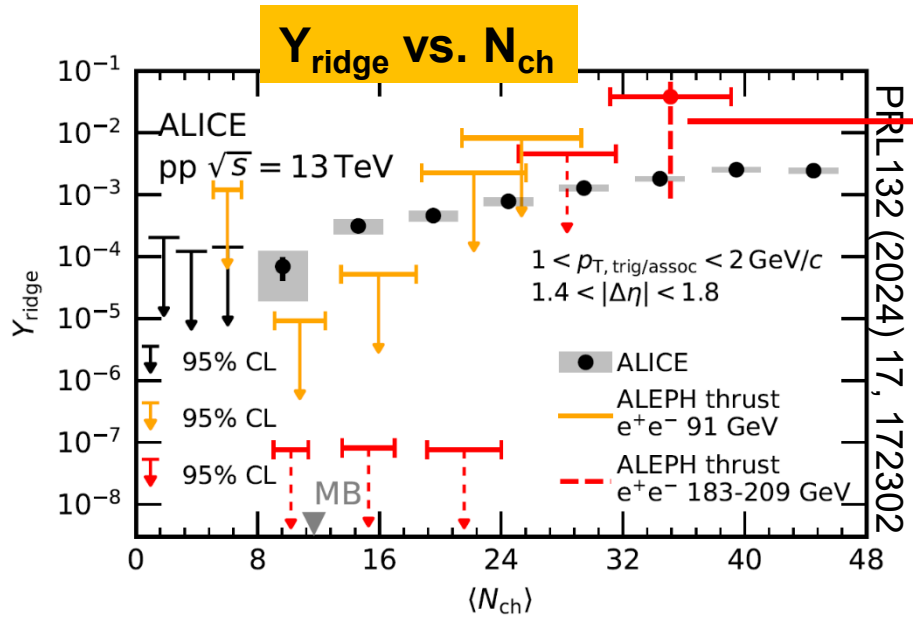
**Experimental result procedure dependent –
in particular at low multiplicity**



Subtraction Procedures (2)



e^+e^- Highest Bin

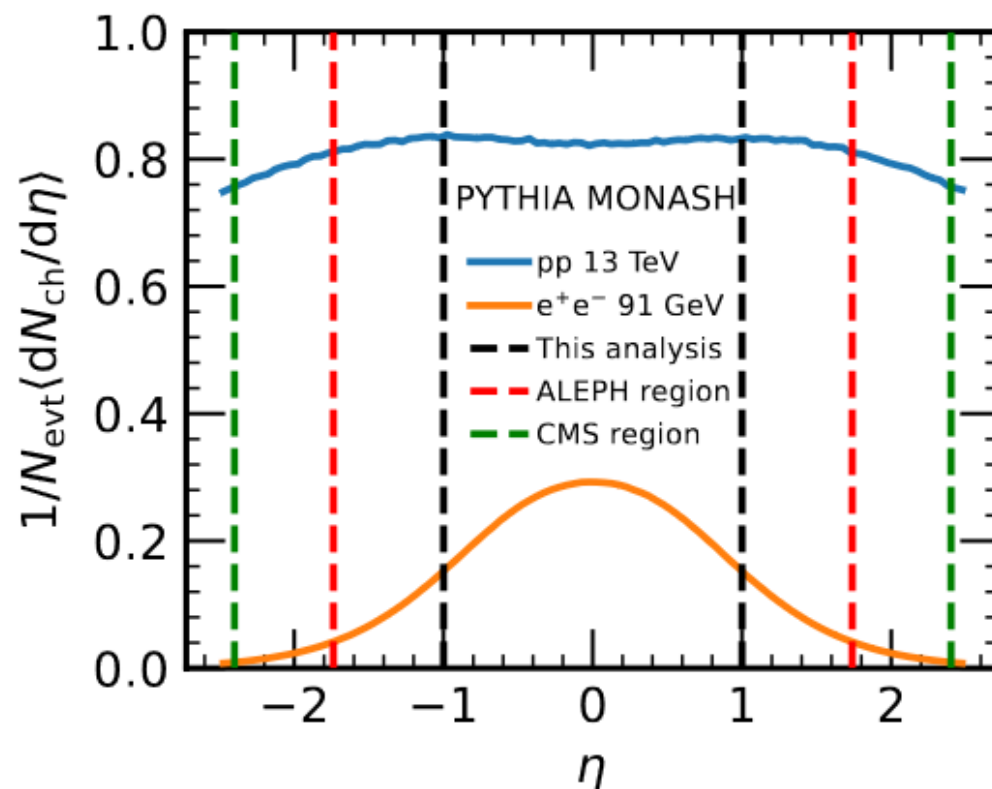


arXiv:2312.05084

1.02σ

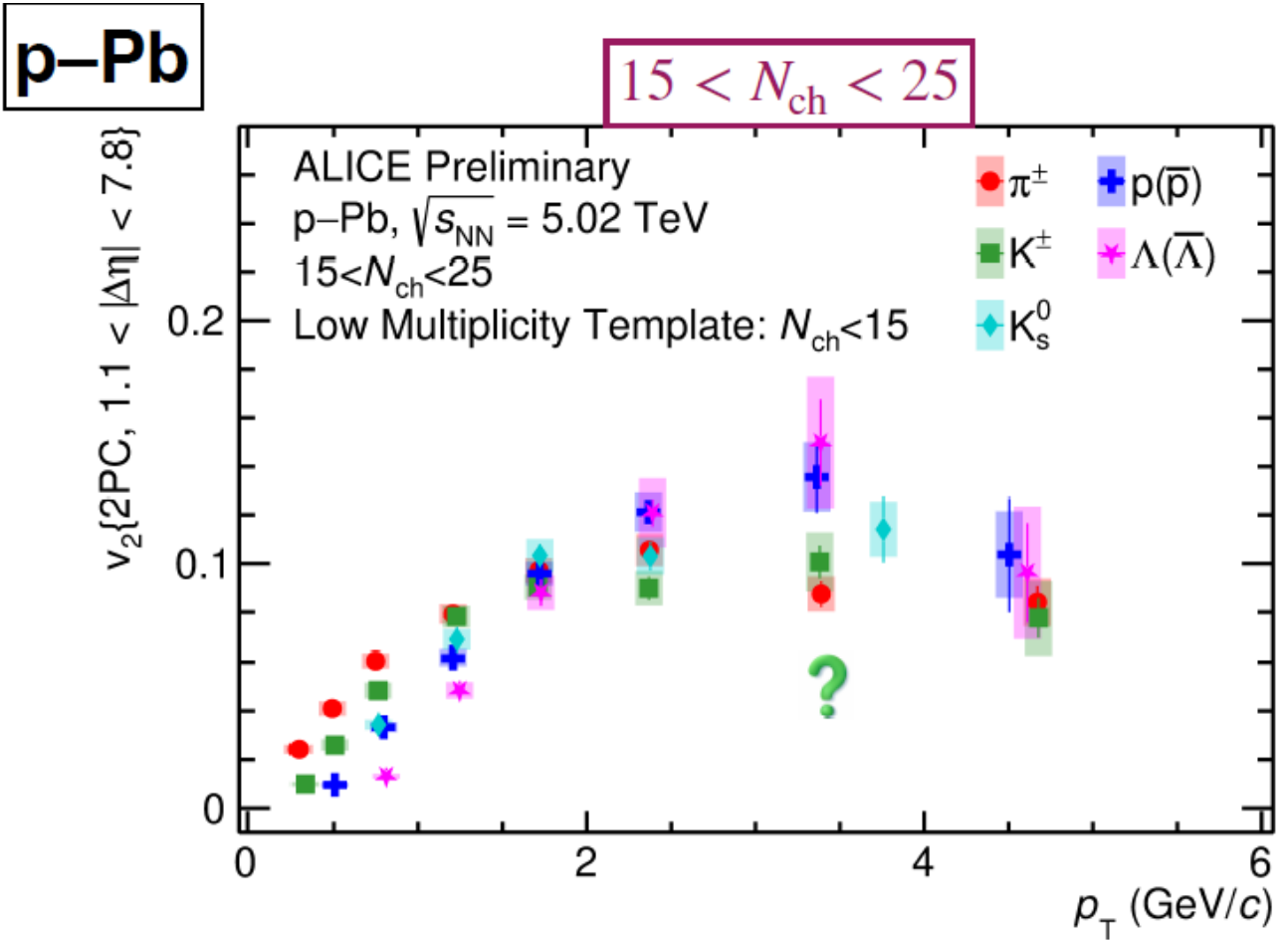
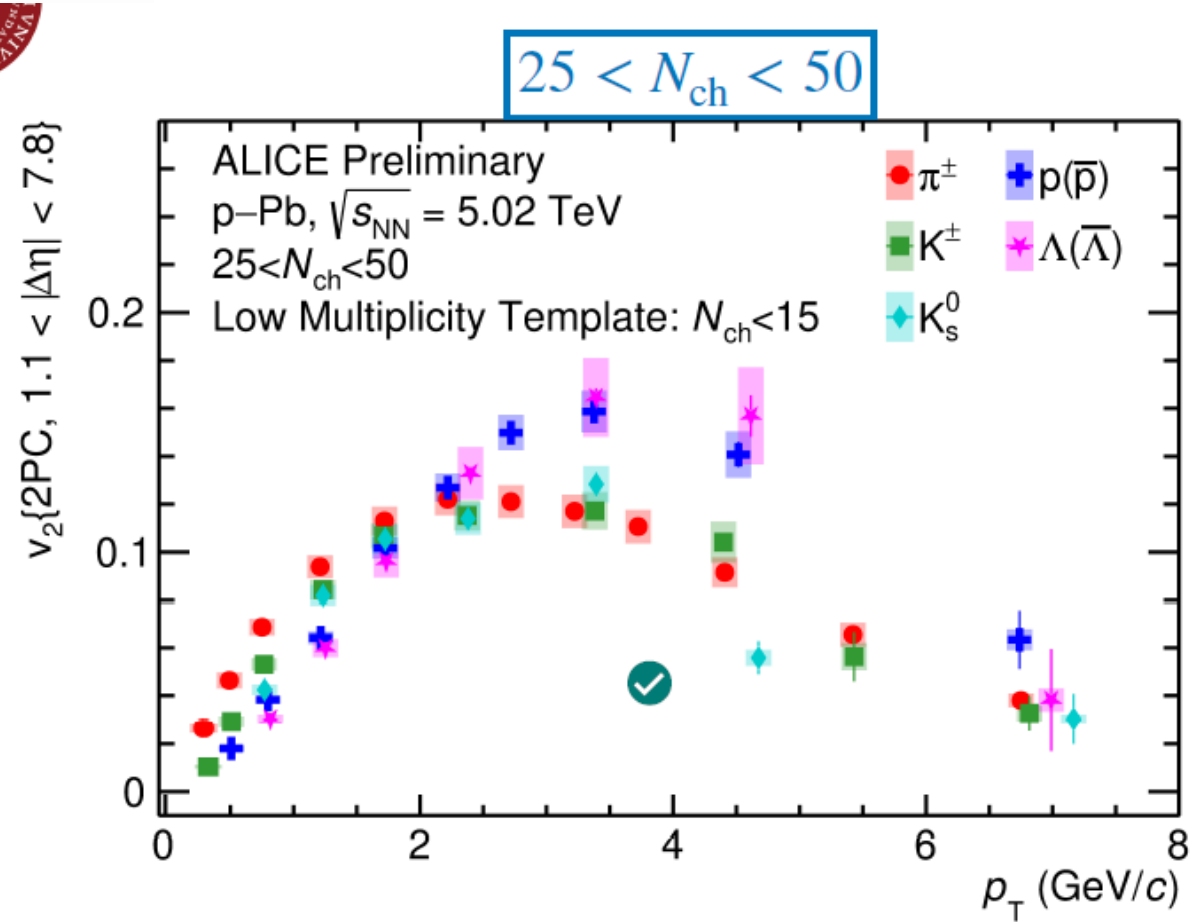
- Estimate the limits of uncertainty on the conversion of the multiplicity
- Target: multiplicity defined by accepted particles within $|\eta| < 1.0$, $p_T > 0.2 \text{ GeV}/c$
- Multiplicity conversion between different systems and experiments is done using PYTHIA
 - 1 Simulate pp at $\sqrt{s} = 13 \text{ TeV}$ in both experimental acceptances. Multiplicity ratio to obtain α_A
 - 2 Simulate e^+e^- at $\sqrt{s} = 91 \text{ GeV}$ in both experimental acceptances. Multiplicity ratio to obtain α_B

Experiment	$ \eta_{\max} $	$p_{T,\min}$	\sqrt{s}
ALICE pp	1.0	0.2	13 TeV
ALEPH e^+e^-	1.738	0.2	91 GeV



Method	Experiment	Corr. factor $\alpha_{A/B}$
PYTHIA	ALEPH pp 13 TeV	0.57 (A)
	ALEPH e^+e^- 91 GeV	0.78 (B)
Flat $dN/d\eta$	ALEPH	0.63

Identified v_n at low N_{ch} (p-Pb)



ALI-PREL-573060

Updated LHC Transmutation Estimate for OO

