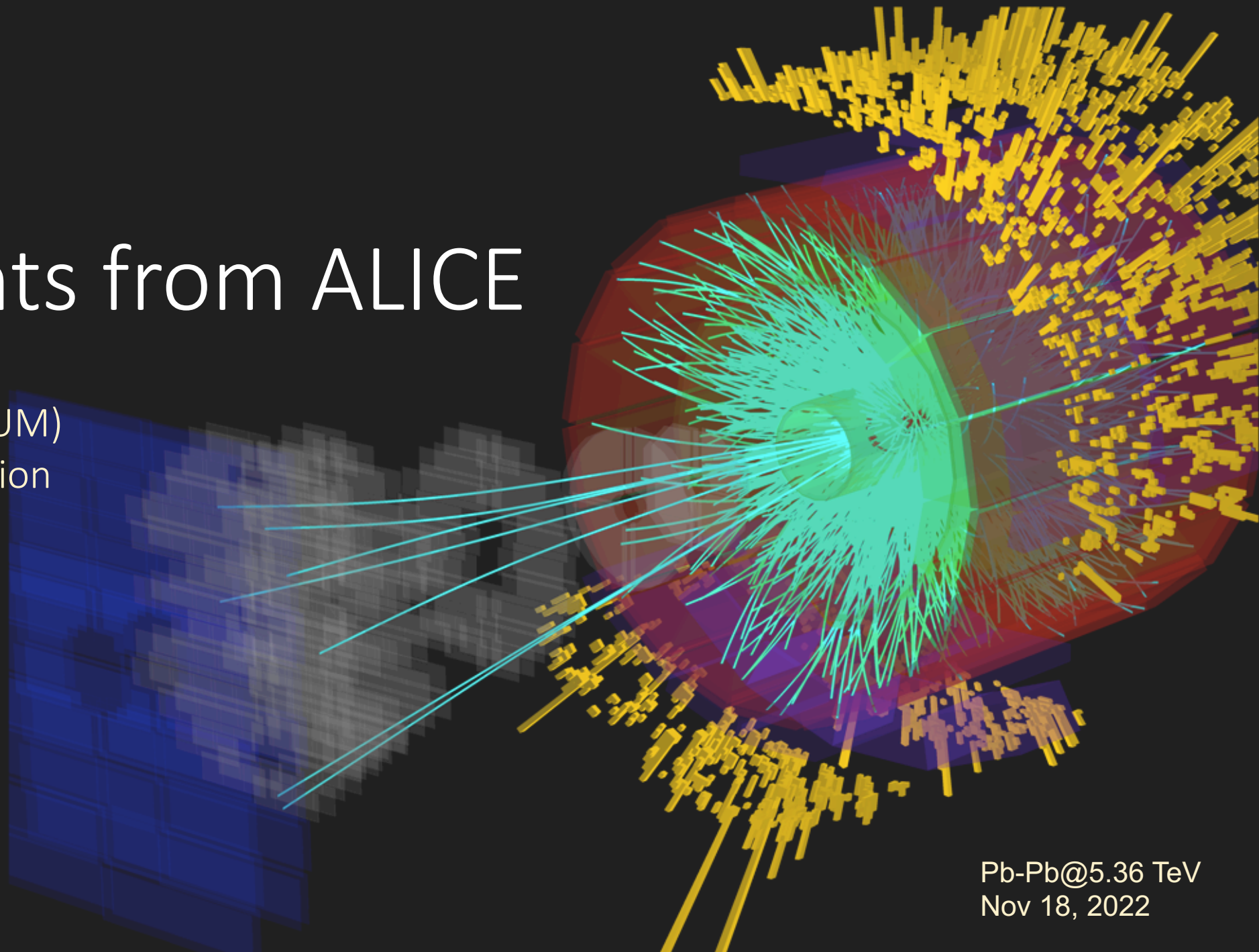
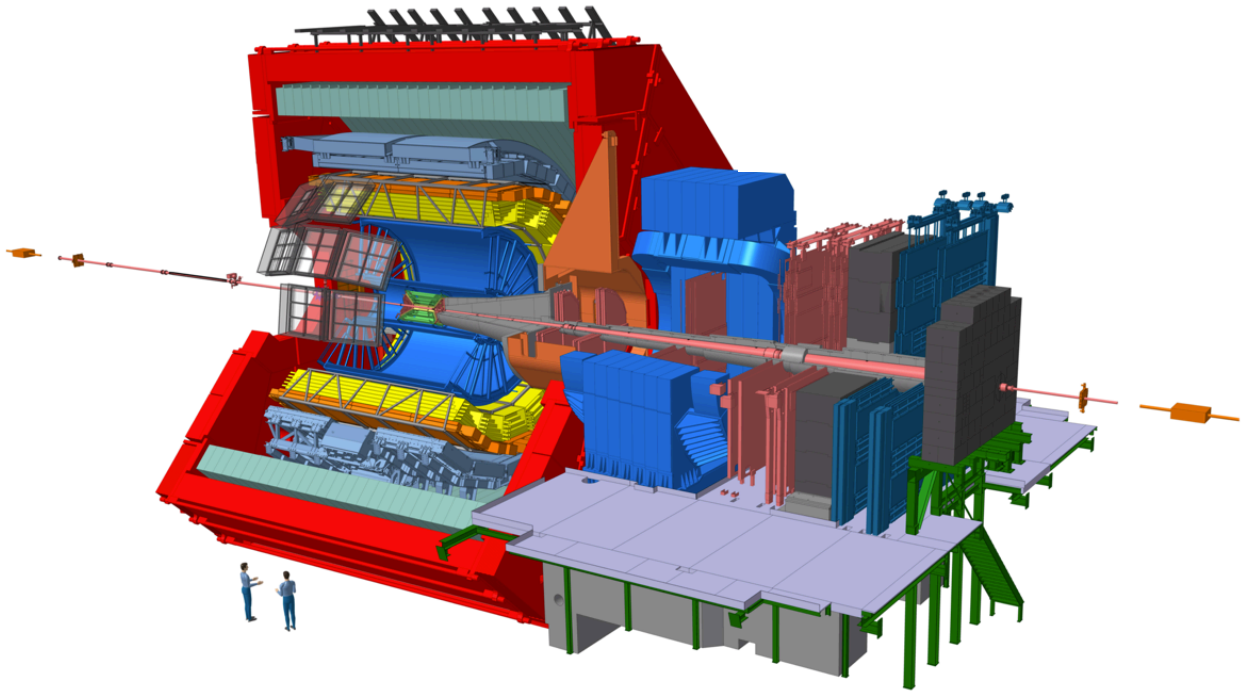
Highlights from ALICE

Igor Altsybeev (TUM)
for the collaboration

28 November
CPOD2022



ALICE detector and datasets in **Run 1&2**

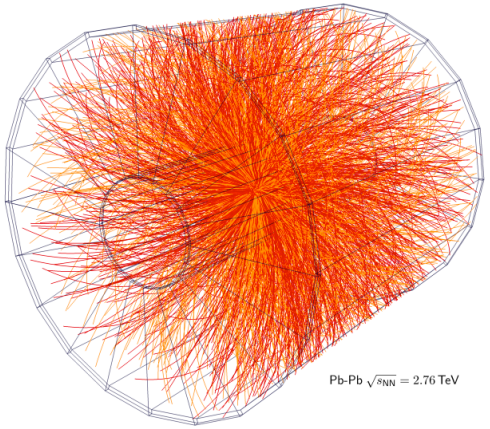


Runs 1&2 (2009-2018):

System	Energy
pp	0.9, 2.76, 7, 8, 13 TeV
p–Pb	5.02, 8 TeV
Pb–Pb	2.76, 5.02 TeV
Xe–Xe	5.44 TeV

Inner Tracking System (ITS)
|η|<0.9, tracking + triggering + particle identification (PID)

Time Projection Chamber (TPC)
|η|<0.8, tracking + PID



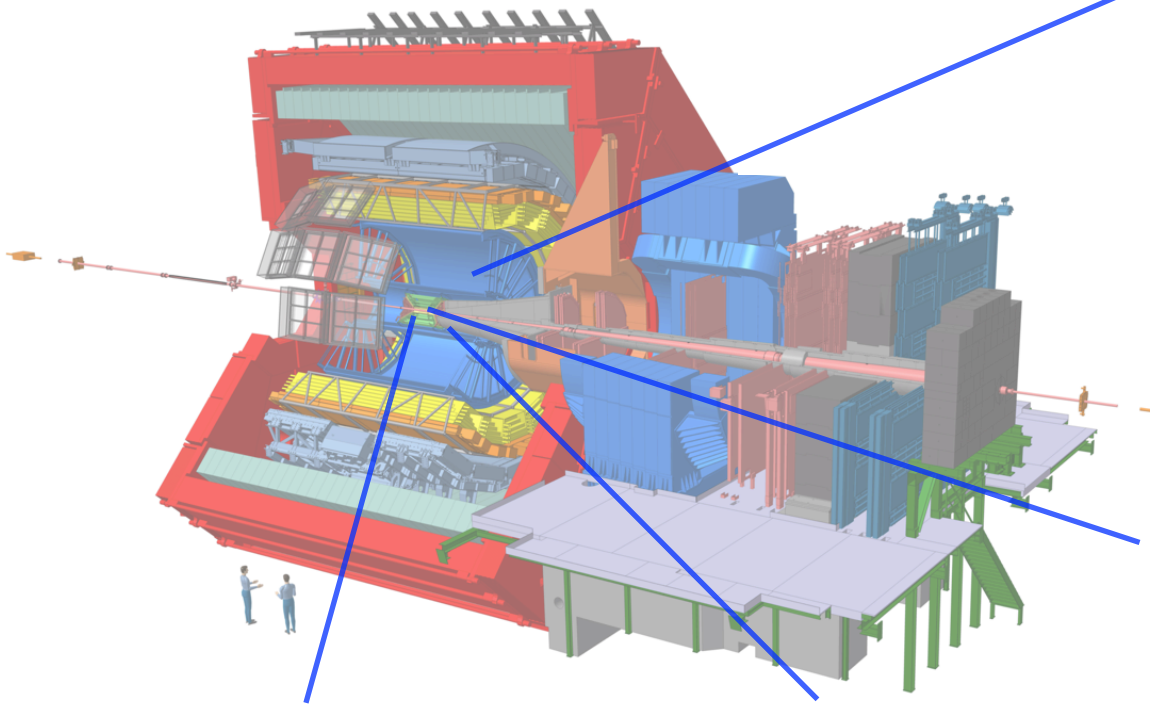
Time Of Flight (TOF)
|η|<0.8, PID

V0 detector
two forward scintillator arrays, triggering + centrality

Zero Degree Calorimeters
centrality + triggering

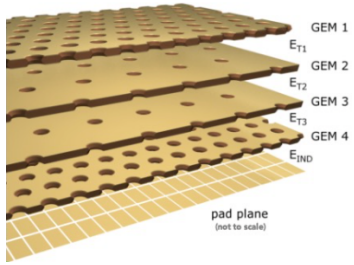
- minimum bias triggers
- rare triggers (muons, EMCAL, PHOS, high mult pp, etc.)

ALICE detector **in Run 3 (2022-2025)**



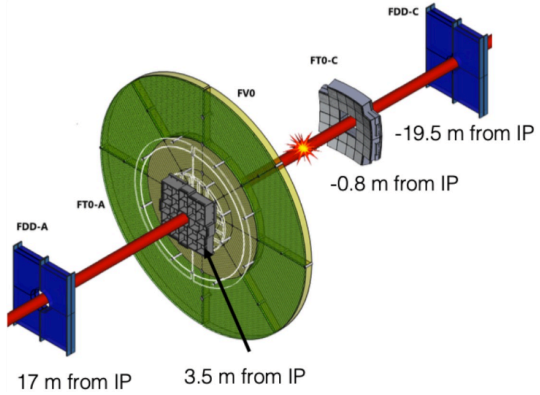
TPC

new readout chambers with
Gas Electron Multipliers (**GEM**s)



New Fast Integration Trigger (FIT)

interaction trigger, online luminometer,
forward multiplicity

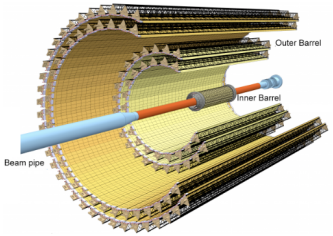


New beampipe

smaller diameter (36.4 mm),
first detection layer at 20 mm

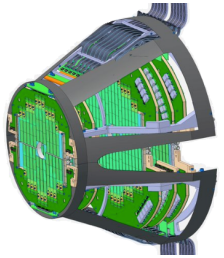
New Inner Tracking System (ITS-2)

7 layers, 10 m^2 silicon tracker
based on MAPS (12 G pixels)



New Muon Forward Tracker (MFT)

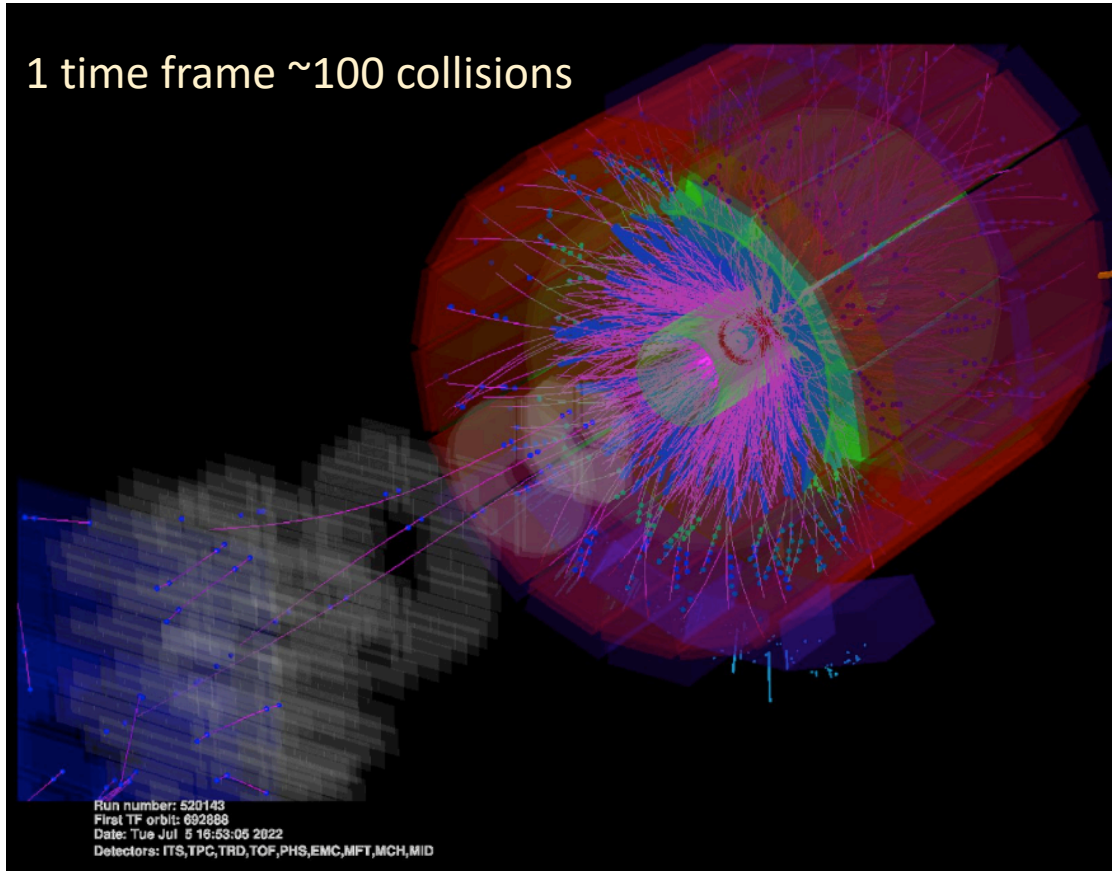
5 planes of MAPS
forward vertexing for muons



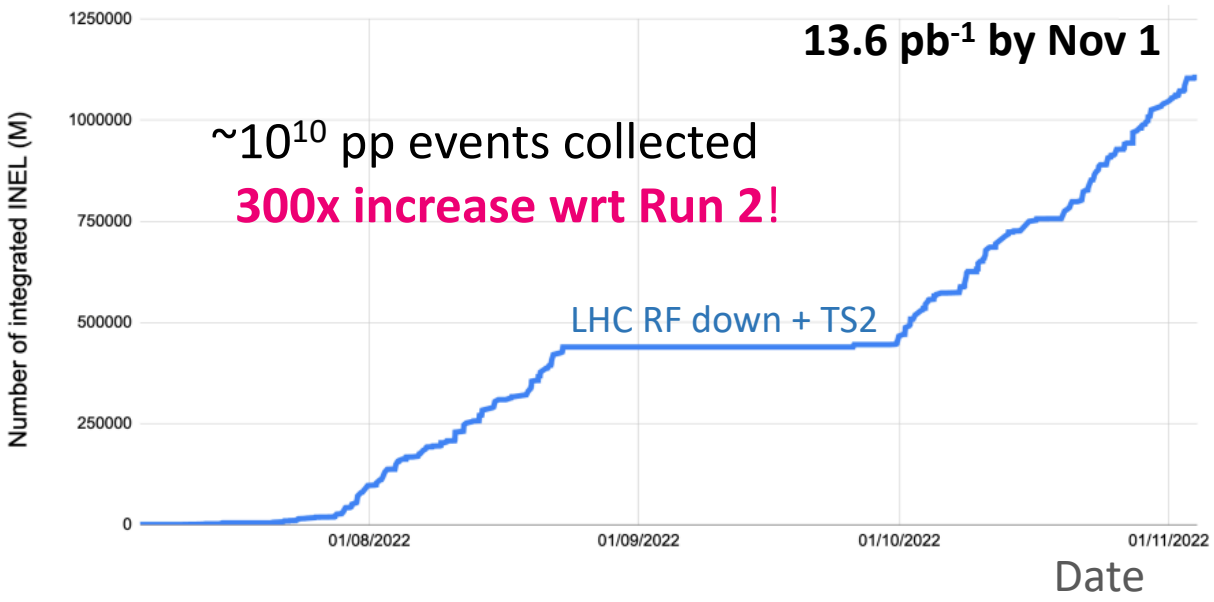
- Better **vertexing** (central and forward)
- **Continuous readout** with **Pb–Pb@50 kHz**
- Statistics up to **x50**

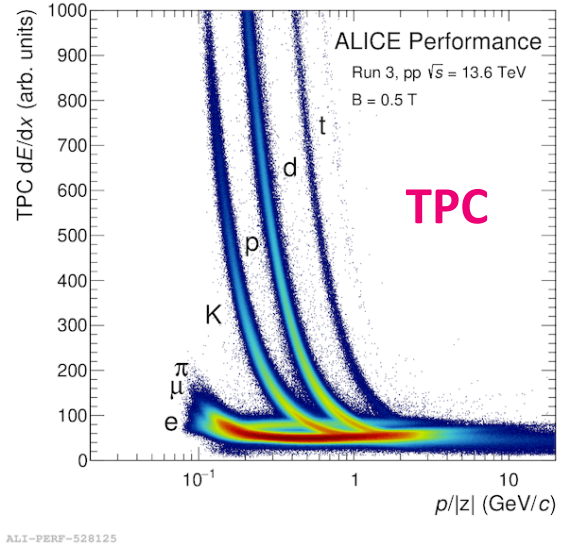
News from ALICE at LHC Run 3

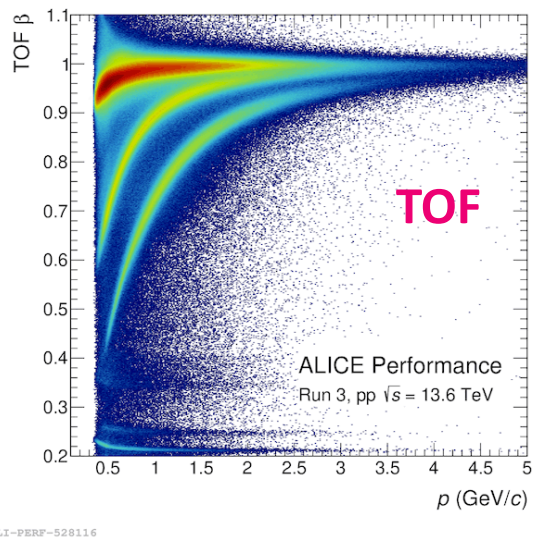
- ***July 2022*** – first pp collisions, operation at 10 kHz **@13.6 TeV**
- Later, ALICE was taking pp physics data at **~500 kHz**
- pp **1-4 MHz** tests (pp@4.5 MHz is equivalent to Pb–Pb@50 kHz)



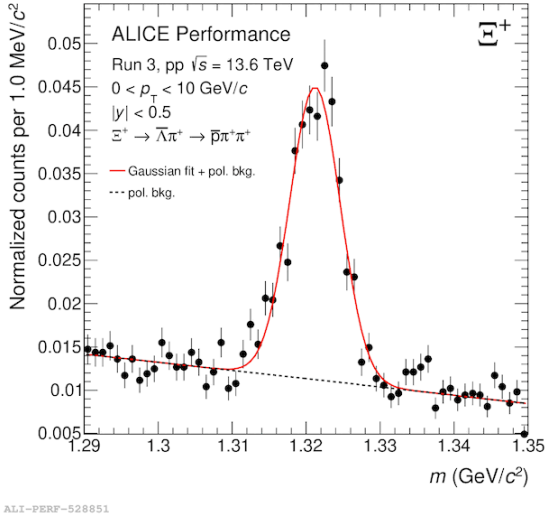
News from ALICE at LHC Run 3







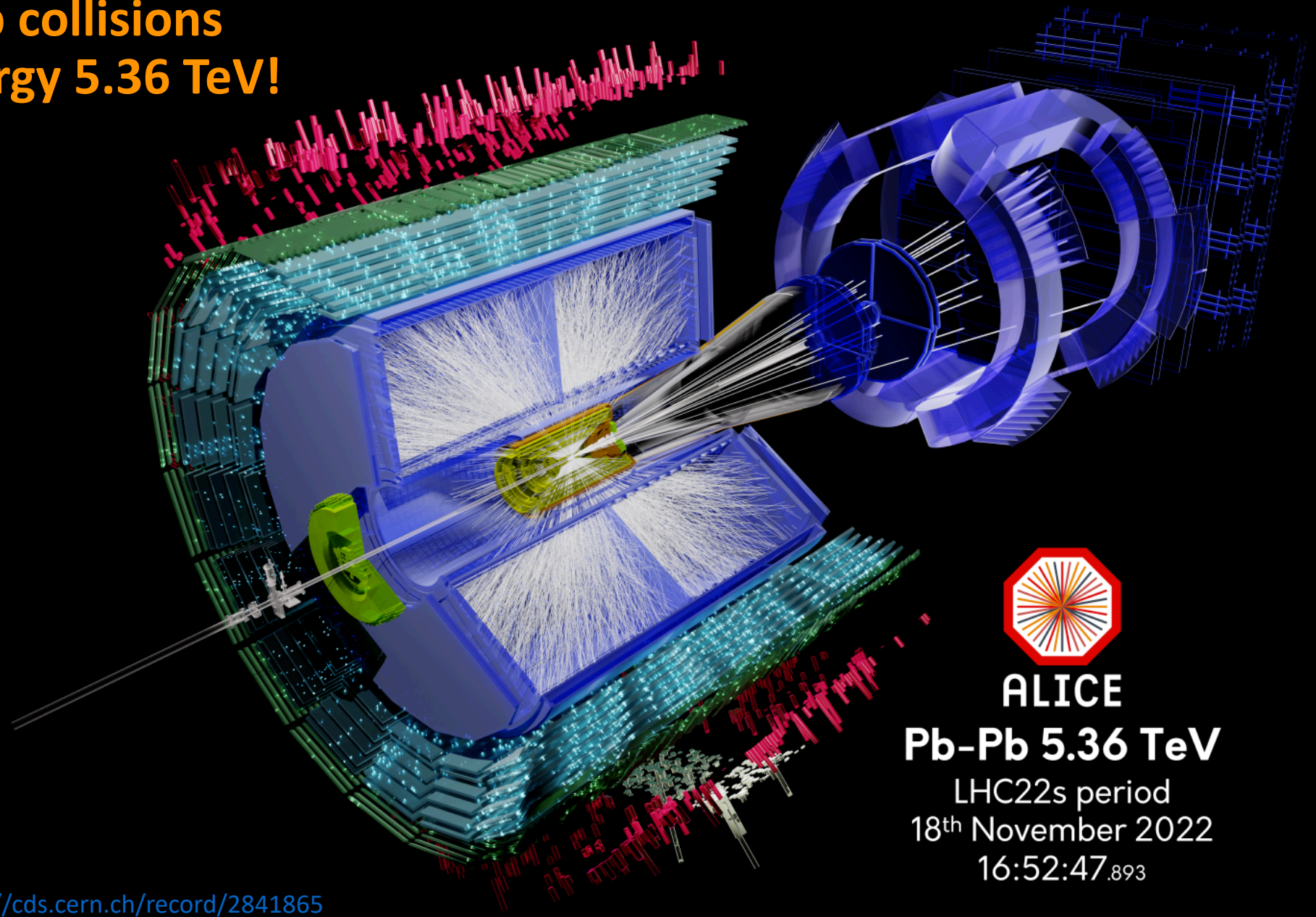
Selection of high-multiplicity and rare events using **software triggers** with a selection factor of **~10^{-3}**



- Due to earlier shutdown of LHC in 2022, planned **Pb–Pb run postponed to 2023**
- *But:* **Pb–Pb test beam** 17-18 November

Nov 18, 2022

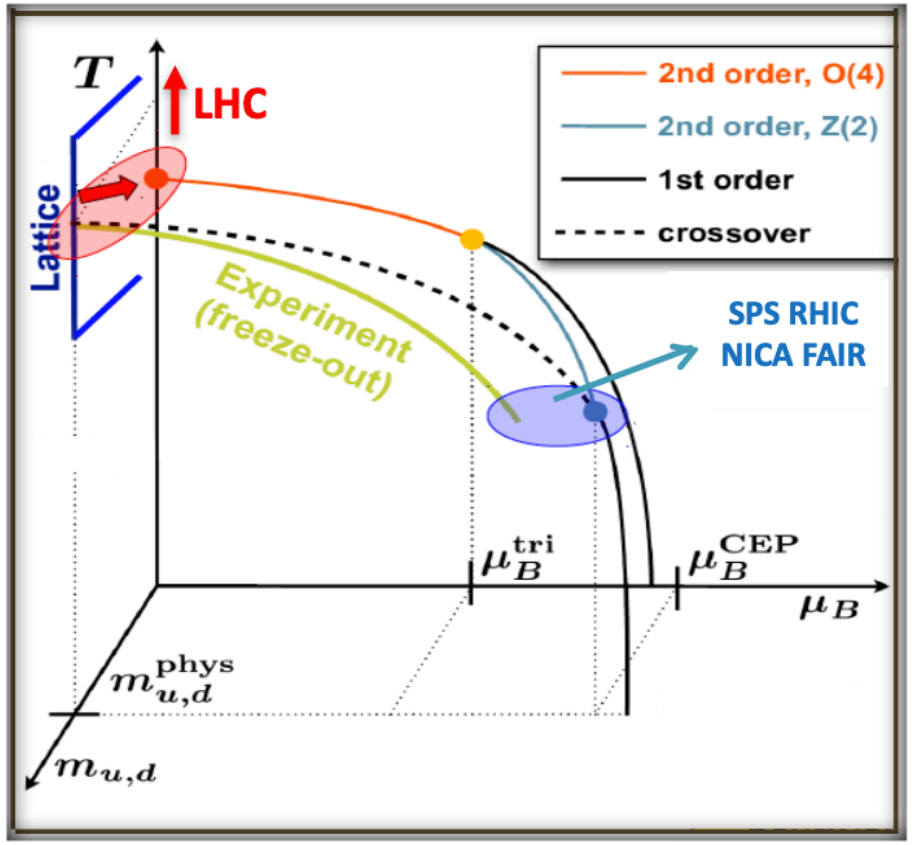
first Pb–Pb collisions at top energy 5.36 TeV!



Event displays: https://cds.cern.ch/record/2841865

Moving on to the results…

F. Karsch, Schleching 2016

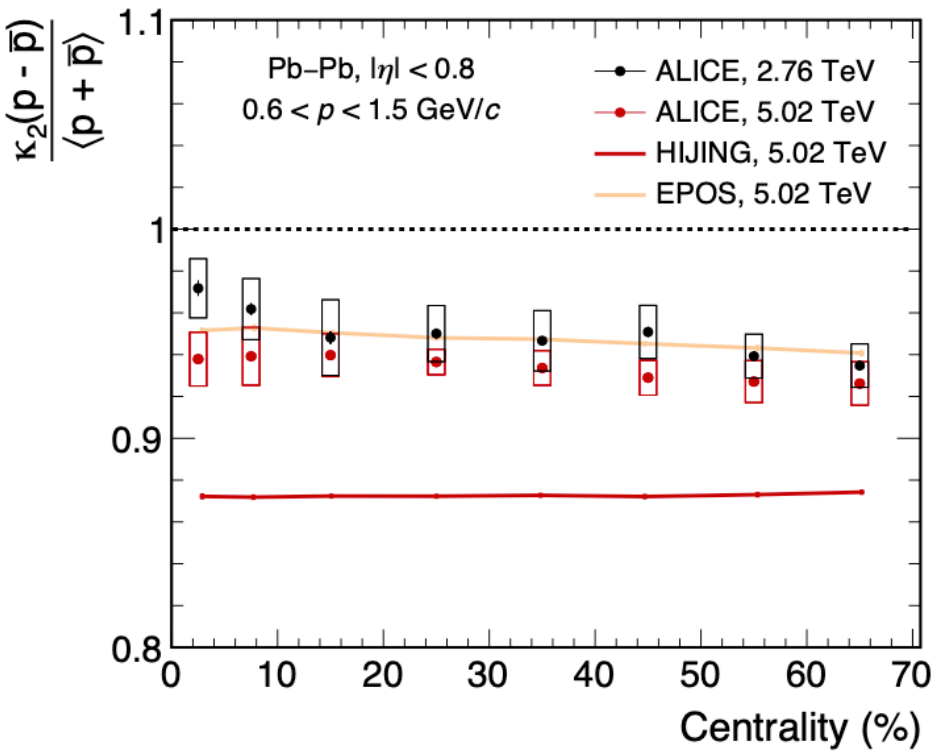


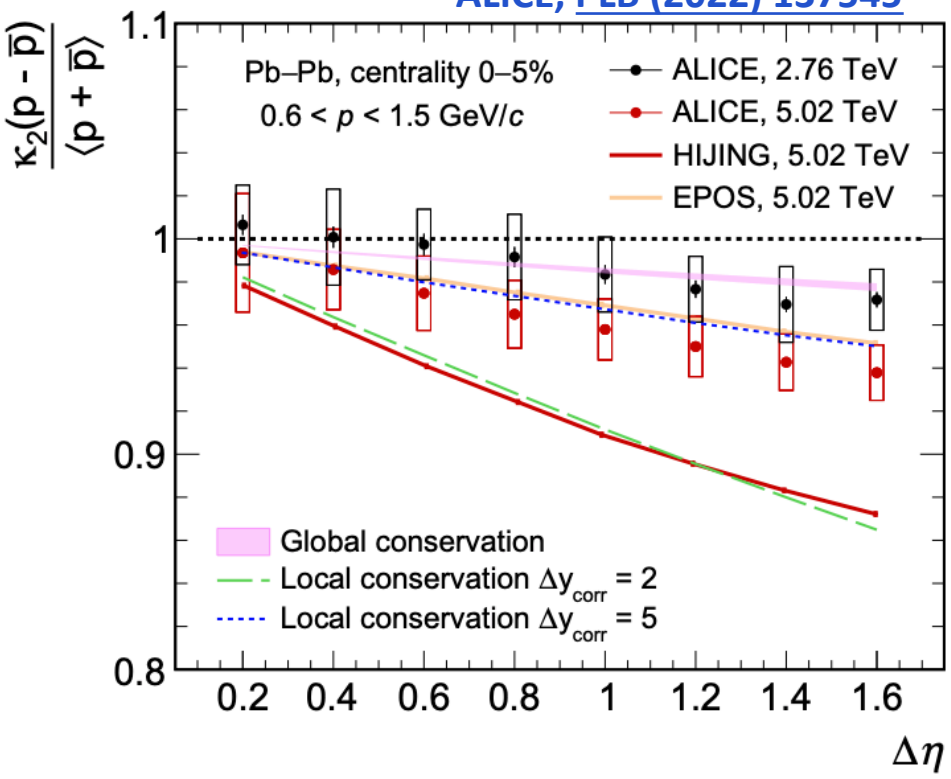
LHC operates at $\mu_B \approx$ **0 MeV**

$T_{pc} \approx T_{fo}$= **156.5 ± 3 MeV**

2nd order cumulants of net-protons

ALICE, PLB (2022) 137545

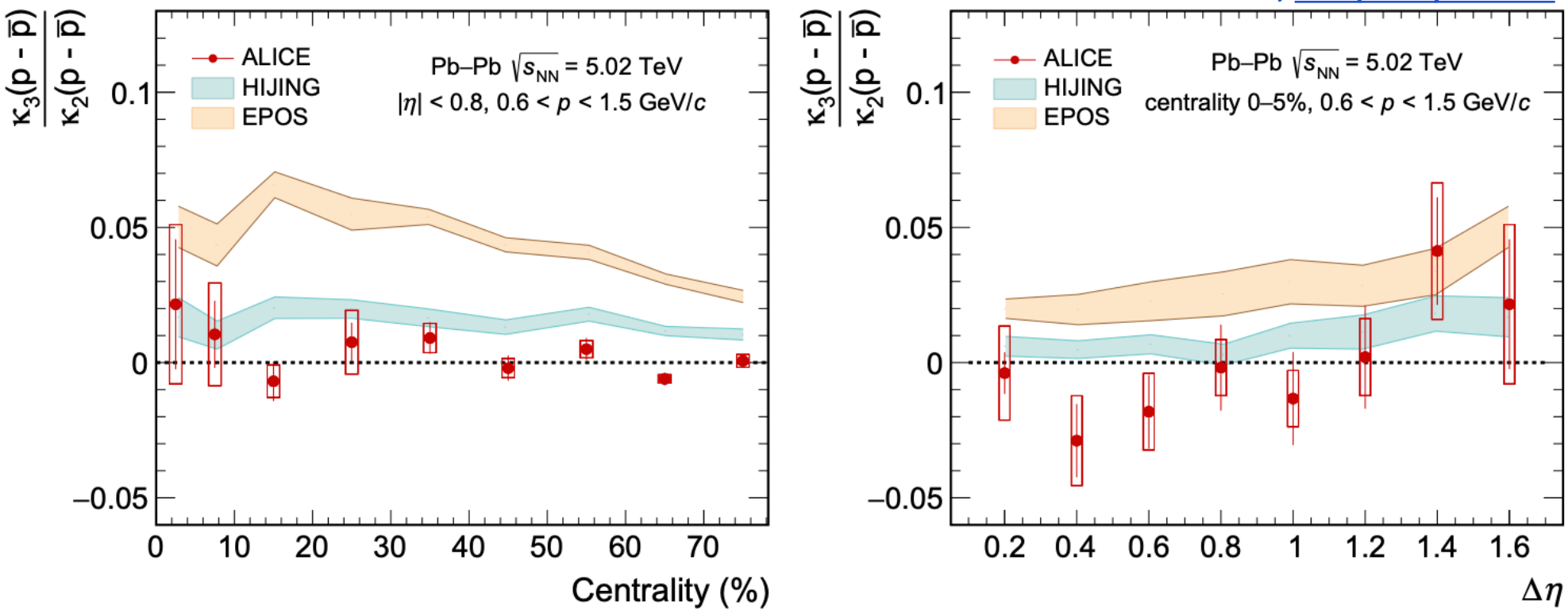




- **baryon number conservation** leads to deviation from the Skellam baseline
- ALICE data suggest **long-range correlations Δy ~ ±2.5** unit or longer → **earlier in time**
- EPOS-LHC agrees with ALICE data but HIJING deviates significantly
  - string fragmentation in HIJING conserves baryon number over Δy ~ ±1 unit

3rd order cumulants of net-protons

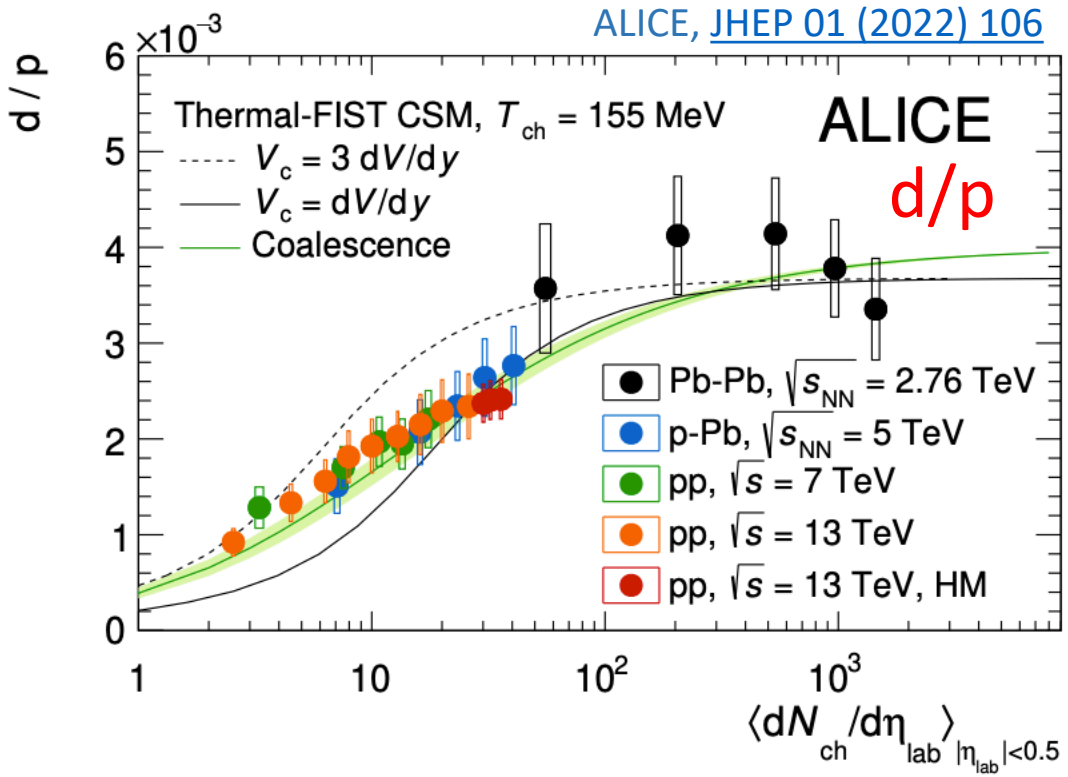
ALICE, PLB (2022) 137545



- Data agree with Skellam baseline "0" since μ_B is very close to 0 at LHC energies
- EPOS-LHC and HIJING deviate from 0 since $p/\bar{p}$ deviates from unity:
  - 1.025 ± 0.004 (EPOS-LHC), 1.008 ± 0.002 (HIJING)

Antideuteron number fluctuations

ALICE, JHEP 01 (2022) 106



*Coalescence **vs** Thermal model:*

Both qualitatively describe deuteron production

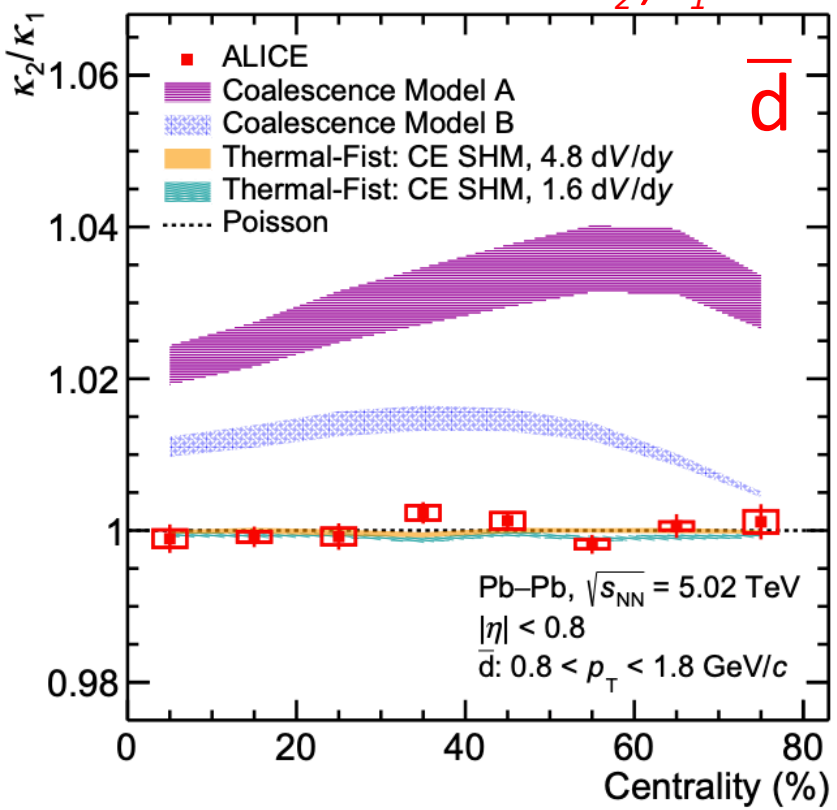
→ **New observables needed to distinguish nuclei synthesis**

Antideuteron number fluctuations

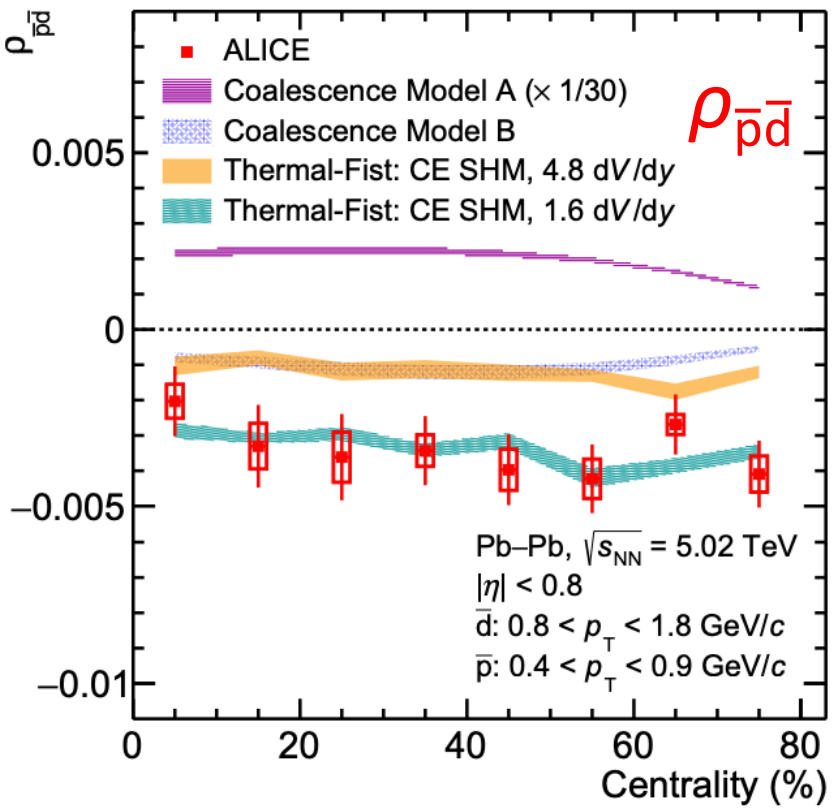
$$\rho_{\bar{p}\bar{d}} = \frac{\langle (n_{\bar{d}} - \langle n_{\bar{d}} \rangle)(n_{\bar{p}} - \langle n_{\bar{p}} \rangle) \rangle}{\sqrt{\kappa_{2\bar{d}} \kappa_{2\bar{p}}}}$$

ALICE

Scaled variance κ_2/κ_1



Pearson correlation coefficient

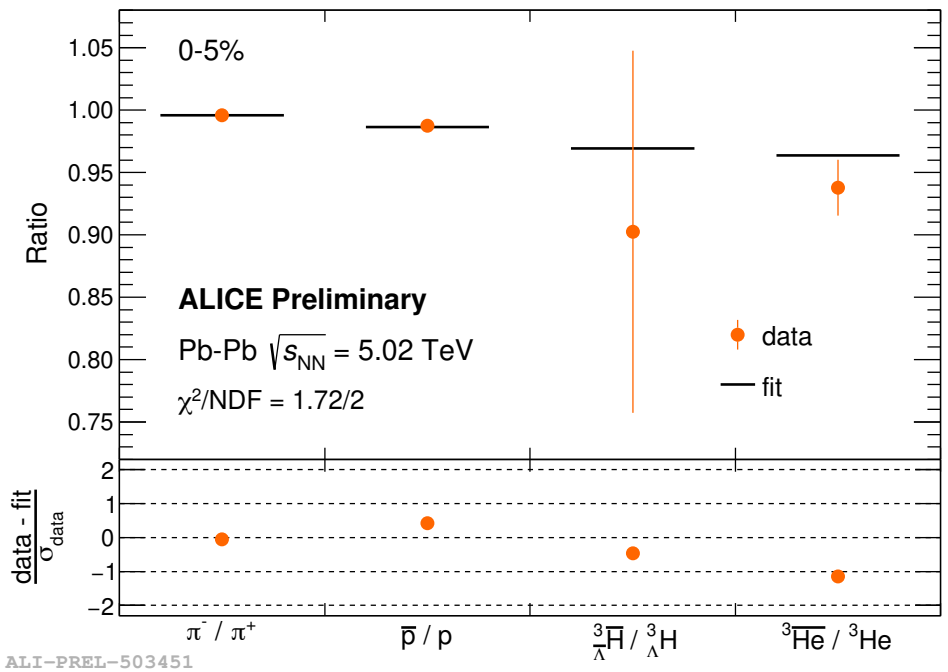


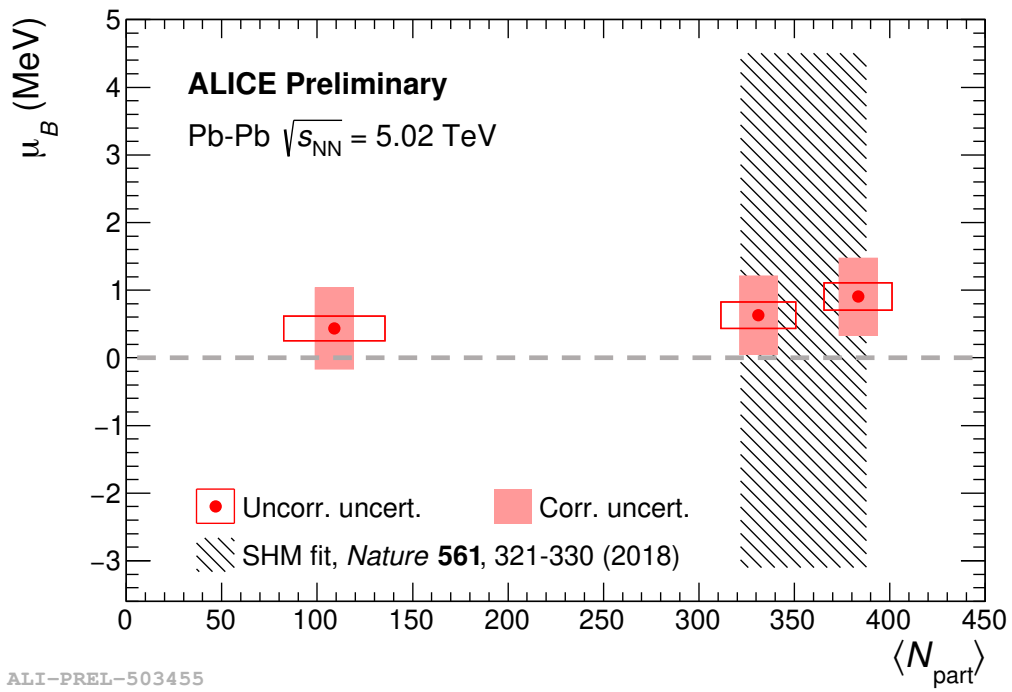
Accepted by PRL
arXiv.2204.10166

- Consistent with Poisson baseline and SHM
- Overpredicted by simple Coalescence model

- **Negative correlation observed**
- Rules out Coalescence with correlated production of nucleons **(A)**
- Qualitatively described by Coalescence with independent nucleons **(B)**
- Explained by **Canonical Ensemble SHM**
  - but smaller correlation volume compared to κ_2/κ_1 of net-protons

Centrality dependence of μ_B in Pb–Pb 5.02 TeV





Using *particle-antiparticle ratios*:

$$\frac{\bar{h}}{h} \propto exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$$

- T = 156.5 ± 1.5 MeV, fixed from SHM studies
- μ_B and μ_{I3} as free fit parameters

A. Andronic et al., Nature 561, (2018) 321

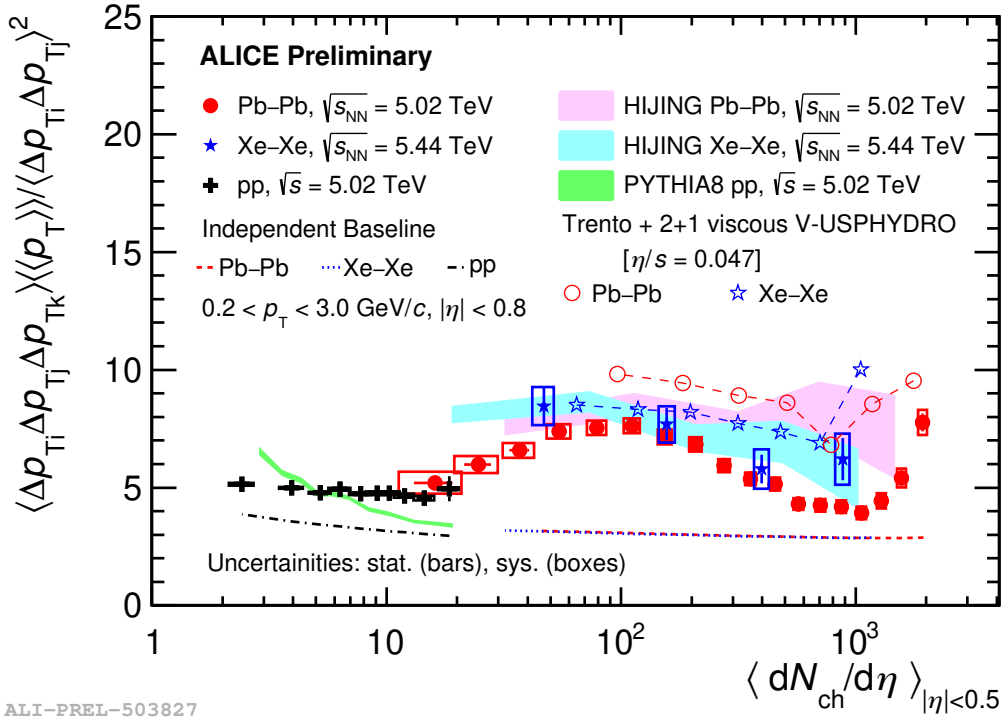
- **Most precise measurement in Pb-Pb at LHC**
  - taking ratios allows to cancel uncertainties
  - 6x improvement in precision with respect to Run 1 estimate
- Small but non-zero $\mu_B \approx 0.7$ MeV at LHC energies

Higher-order mean-p_T fluctuations in pp and Pb–Pb

Intensive skewness ~ independent of $\langle N_{ch} \rangle$

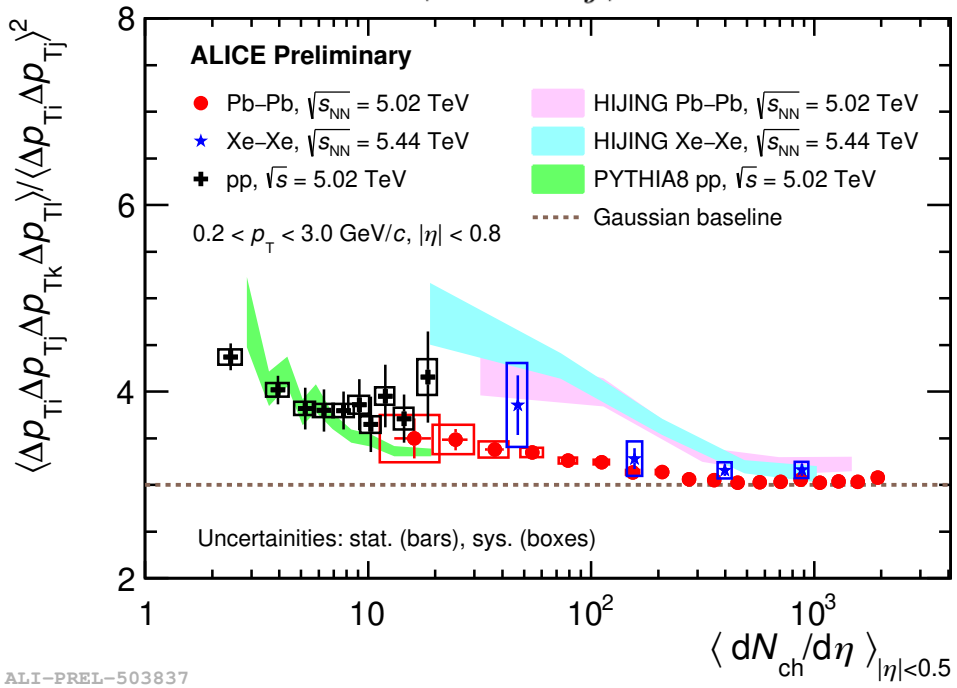
$$\Gamma_{\langle p_T \rangle} = \frac{\langle \Delta p_i \Delta p_j \Delta p_k \rangle \langle \langle p_T \rangle \rangle}{\langle \Delta p_i \Delta p_j \rangle^2}$$

G. Giacalone et al., Phys. Rev. C 103, 024910 (2021)



Kurtosis ~ $1/\langle N_{ch} \rangle$

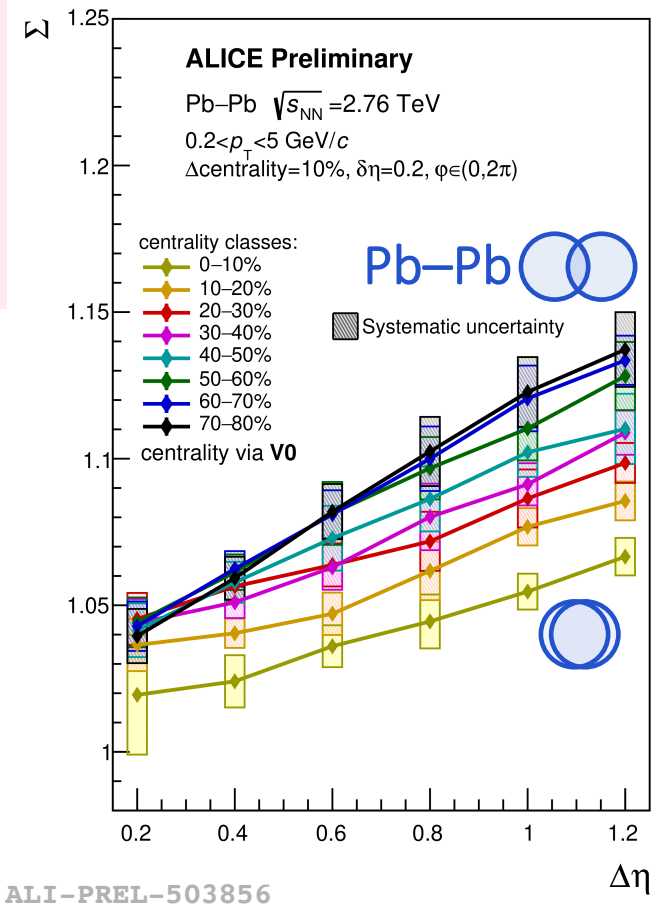
$$\kappa_{\langle p_T \rangle} = \frac{\langle \Delta p_i \Delta p_j \Delta p_k \Delta p_l \rangle}{\langle \Delta p_i \Delta p_j \rangle^2}$$

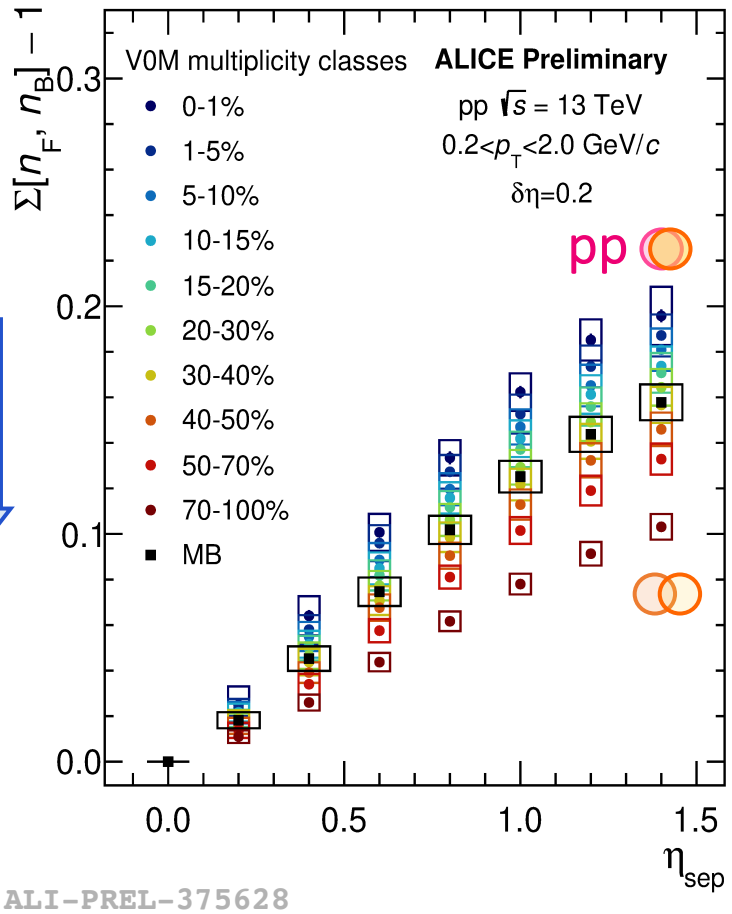


baselines: random sampling the p_T spectrum

- First measurement of skewness and kurtosis of $\langle p_T \rangle$ in pp, Pb-Pb and Xe-Xe collision at LHC energies
- Values remain above the baselines indicating the correlations in the system, however, HIJING and PYTHIA seem to reproduce data

Strongly intensive quantity Σ

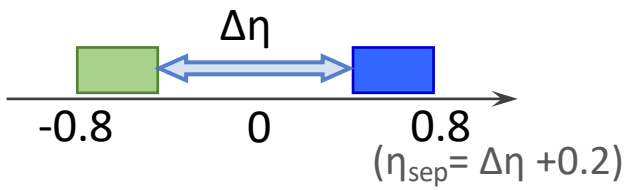




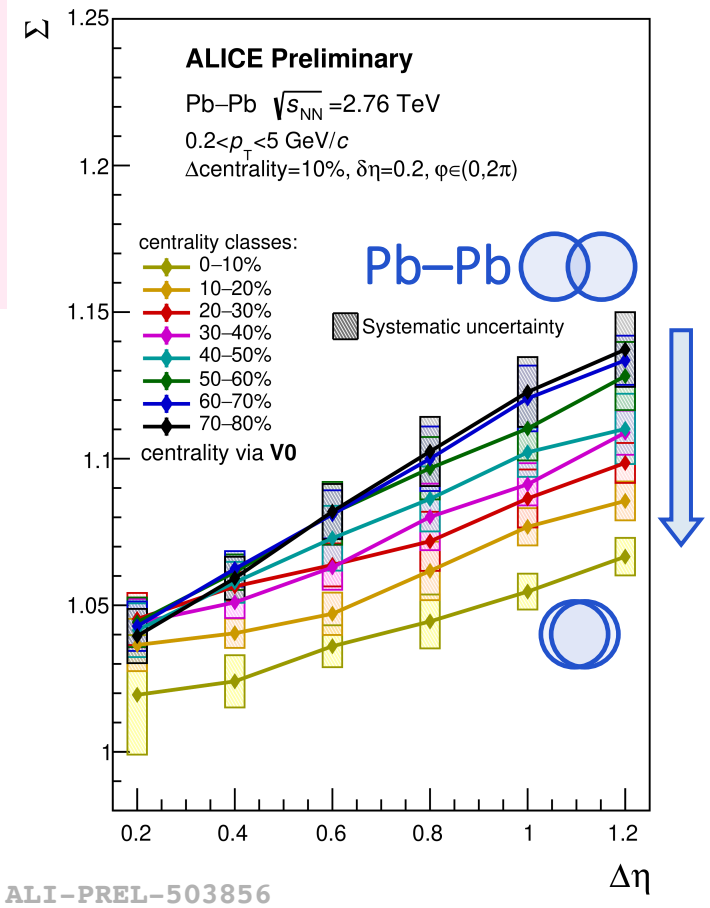
$$\Sigma\left[n_F, n_B\right] = \frac{\langle n_F\rangle\omega[n_B] + \langle n_B\rangle\omega[n_F] - 2\,\mathrm{cov}\left(n_F, n_B\right)}{\langle n_F\rangle + \langle n_B\rangle}$$

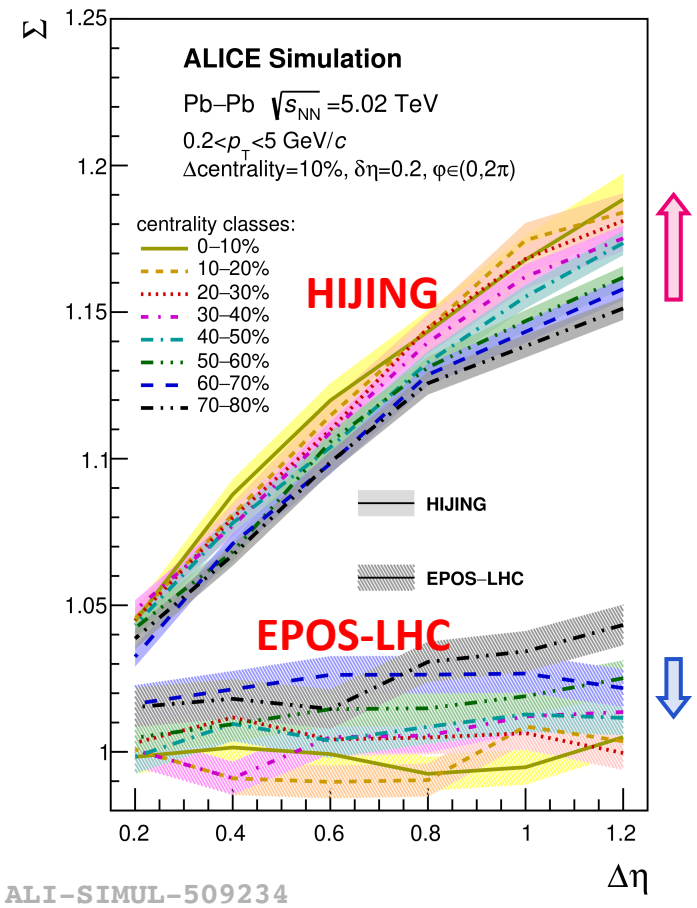
Strongly intensive quantity Σ does not depend on system volume and V.F.

- Σ in **Pb–Pb decreases** with centrality, while Σ in **pp grows** with multiplicity



Strongly intensive quantity Σ

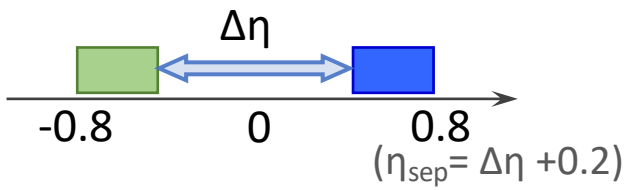




$$\Sigma\left[n_F, n_B\right] = \frac{\langle n_F\rangle\omega[n_B] + \langle n_B\rangle\omega[n_F] - 2\,\mathrm{cov}\left(n_F, n_B\right)}{\langle n_F\rangle + \langle n_B\rangle}$$

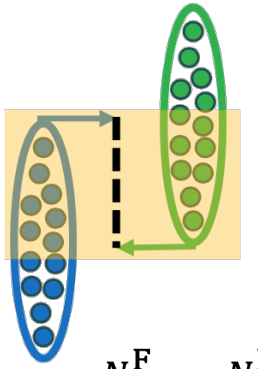
Strongly intensive quantity Σ does not depend on system volume and V.F.

- Σ in **Pb–Pb decreases** with centrality, while Σ in **pp grows** with multiplicity
- The behavior in Pb-Pb is not reproduced by HIJING and EPOS-LHC

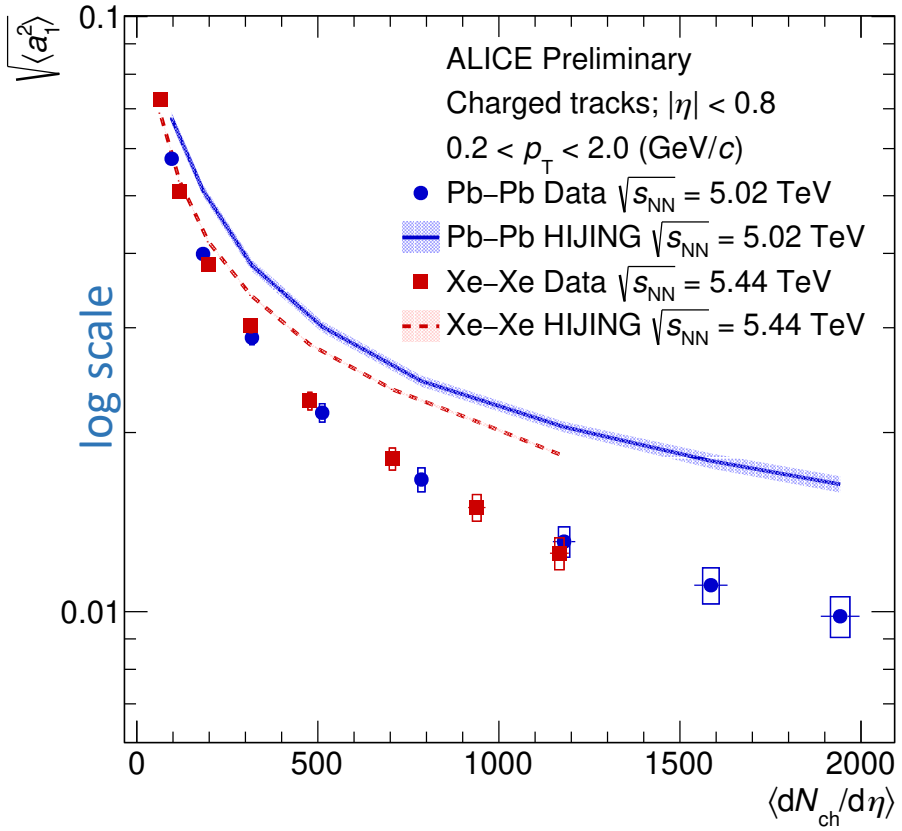


Longitudinal fluctuations in A–A

- probing asymmetric density of the fireball along η



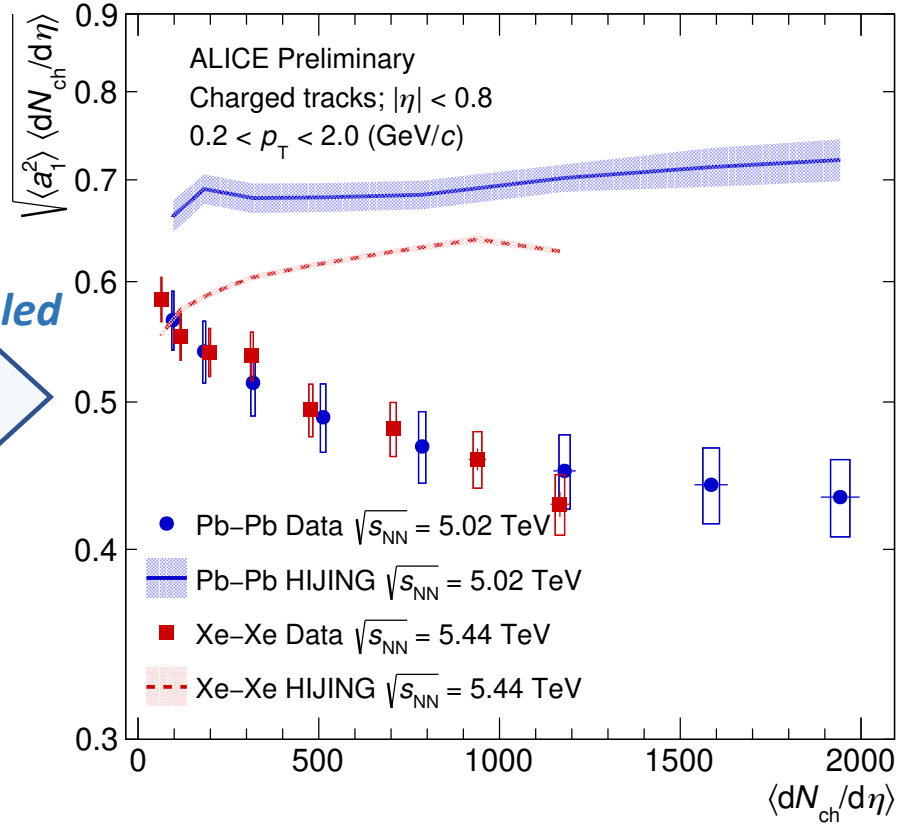
$$A_{\text{part}} = \frac{N^{\text{F}}_{\text{part}} - N^{\text{B}}_{\text{part}}}{N^{\text{F}}_{\text{part}} + N^{\text{B}}_{\text{part}}}$$



Legendre polynomials – coefficients:

$$a_n = \int_{-Y}^{Y} \sqrt{\frac{1}{Y}\left(n + \frac{1}{2}\right)} \left(R(\eta) - 1\right) P_n\left(\frac{\eta}{Y}\right) d\eta$$

rescaled



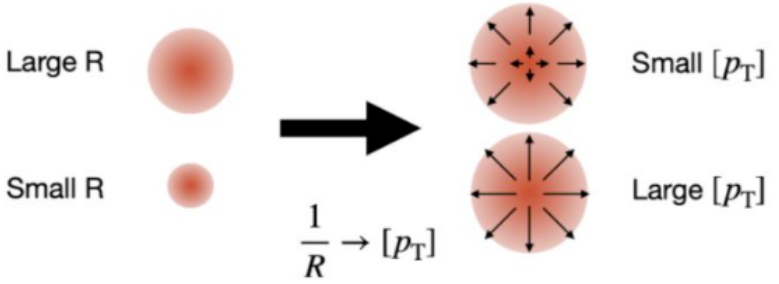
- First measurement of longitudinal coefficient in ALICE, qualitatively comparable to ATLAS
- Universal multiplicity scaling ~ $1/\langle dN_{ch}/d\eta \rangle^{\alpha}$, α~0.5

Accessing the initial state via v_n – mean p_T correlations

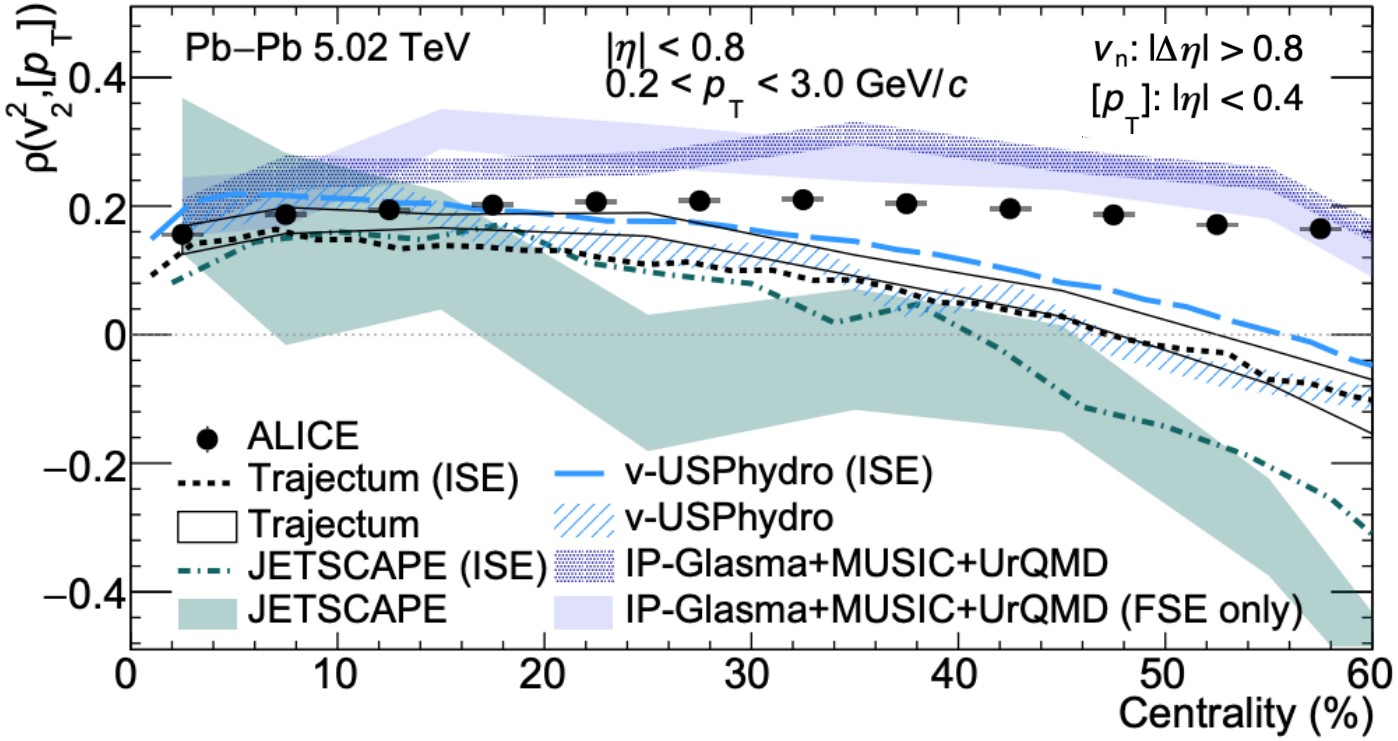
v_n ~ initial shape (eccentricity)
$[p_T]$ ~ initial size

Correlations:

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



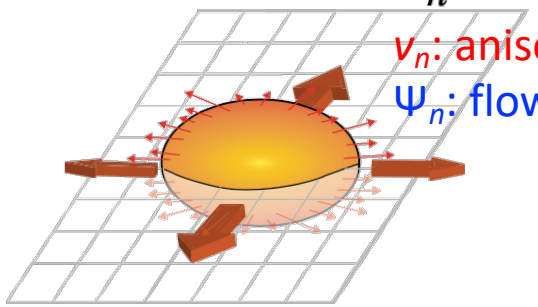
ALICE, Phys. Lett. B 834 (2022) 137393



- Study of the correlation between the **shape of the fireball (v_2)** and its **size ($[p_T]$)**
- New constraints on the **nucleon size**
  - IP-Glasma ~ 0.4 fm; v-USPhydro ~ 0.5 fm; Trajectum ~ 0.7 fm; JETSCAPE (TRENTo) ~ 1.1 fm
  - ALICE data agrees better with width **~ 0.4 fm**, or transverse radius of 0.56 fm

Flow angle and flow magnitude fluctuations in Pb–Pb

$$\vec{V}_n = v_n e^{in\Psi_n}$$



v_n: anisotropic flow

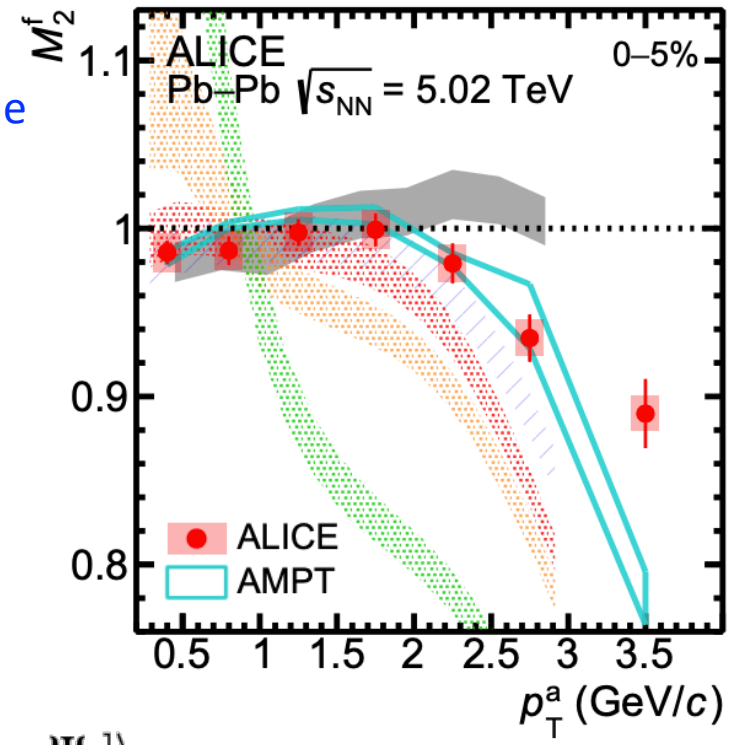
Ψ_n: flow symmetry plane angle

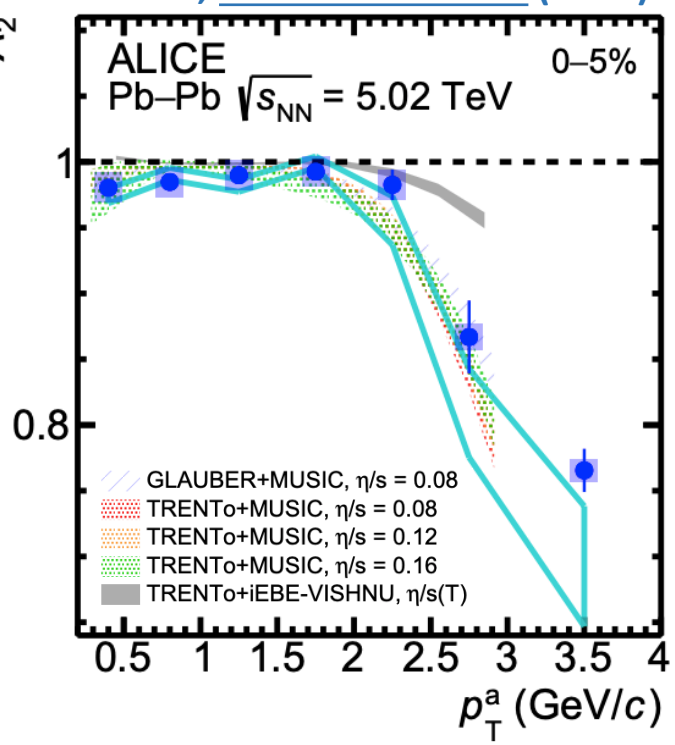
Probe flow magnitude fluctuations M^f_2
and flow angle fluctuations A^f_2
with multi-particle correlations:

$$M_n^{\mathrm{f}} = \frac{\langle v_n^2(p_{\mathrm{T}}^{\mathrm{a}}) v_n^2 \rangle / \langle v_n^2(p_{\mathrm{T}}^{\mathrm{a}}) \rangle \langle v_n^2 \rangle}{\langle v_n^4 \rangle / \langle v_n^2 \rangle^2}$$

$$A_n^{\mathrm{f}} = \frac{\langle\langle \cos n[\varphi_1^{\mathrm{a}} + \varphi_2^{\mathrm{a}} - \varphi_3 - \varphi_4] \rangle\rangle}{\langle\langle \cos n[\varphi_1^{\mathrm{a}} + \varphi_2 - \varphi_3^{\mathrm{a}} - \varphi_4] \rangle\rangle} \simeq \langle \cos 2n [\Psi_n(p_{\mathrm{T}}^{\mathrm{a}}) - \Psi_n] \rangle_{\mathrm{w}}$$

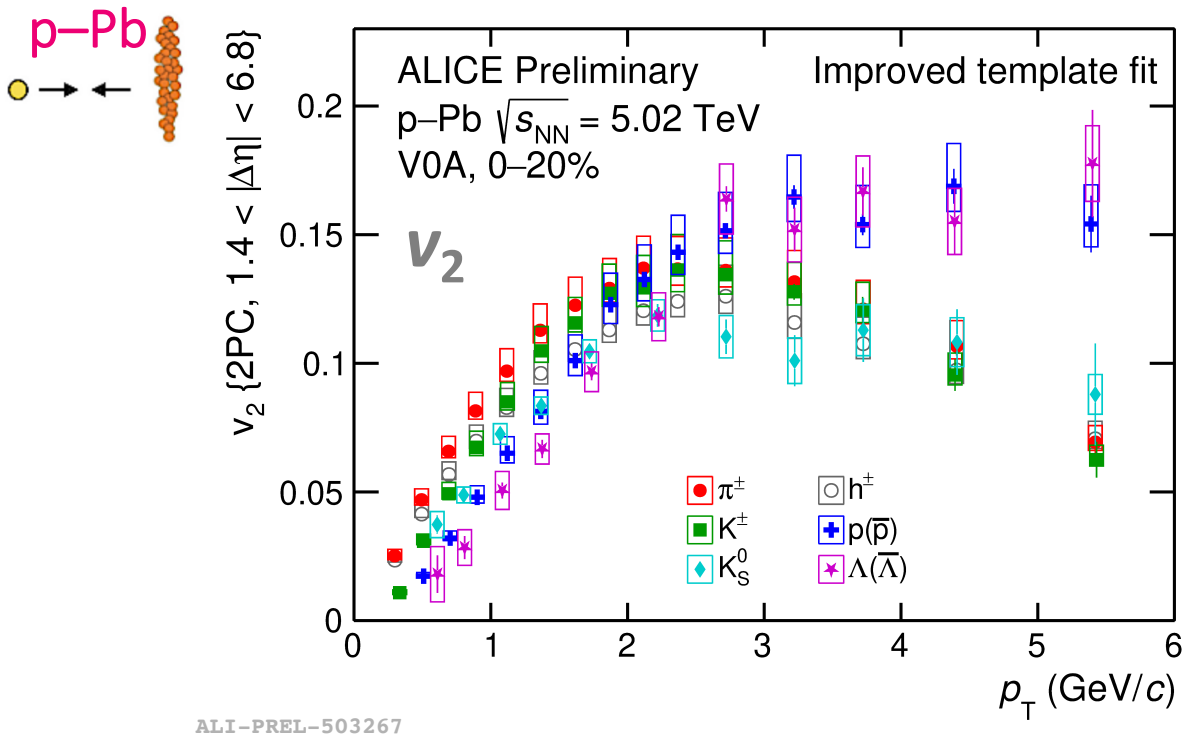
ALICE, arXiv:2206.04574 (2022)

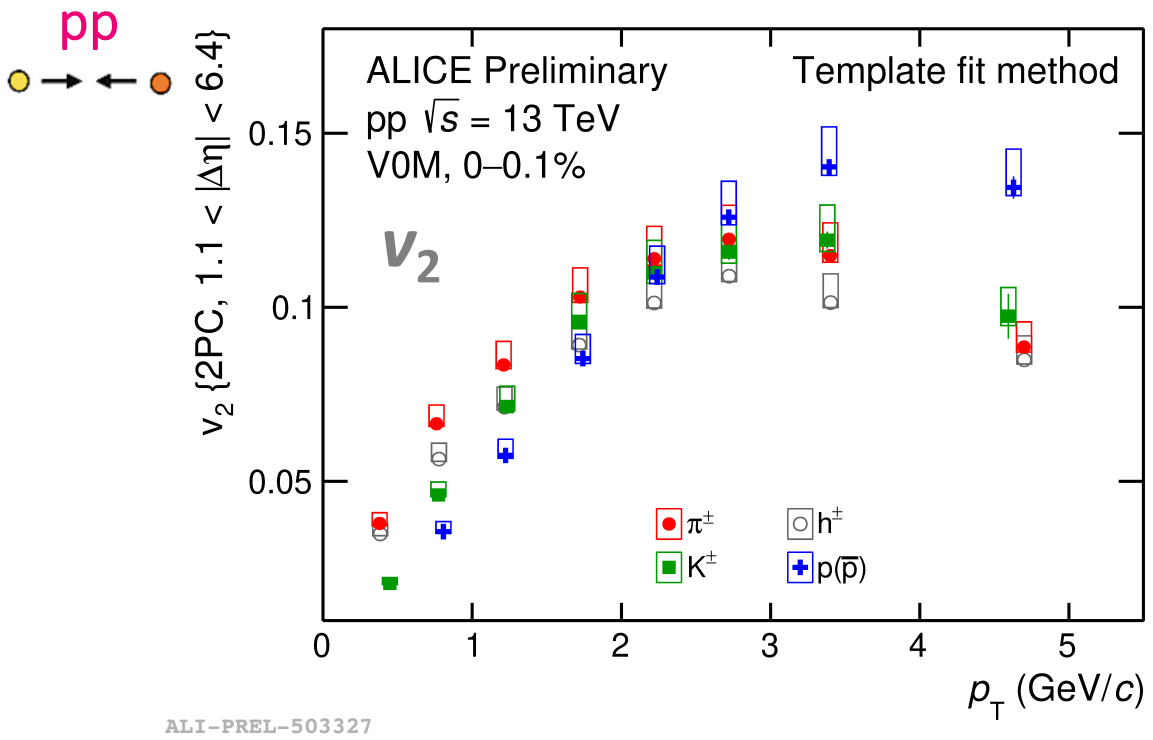




- Large **deviations from unity**, effect most pronounced **at high p_T**
- Comparison with theoretical models: observables are sensitive to **initial state** and the **QGP properties**

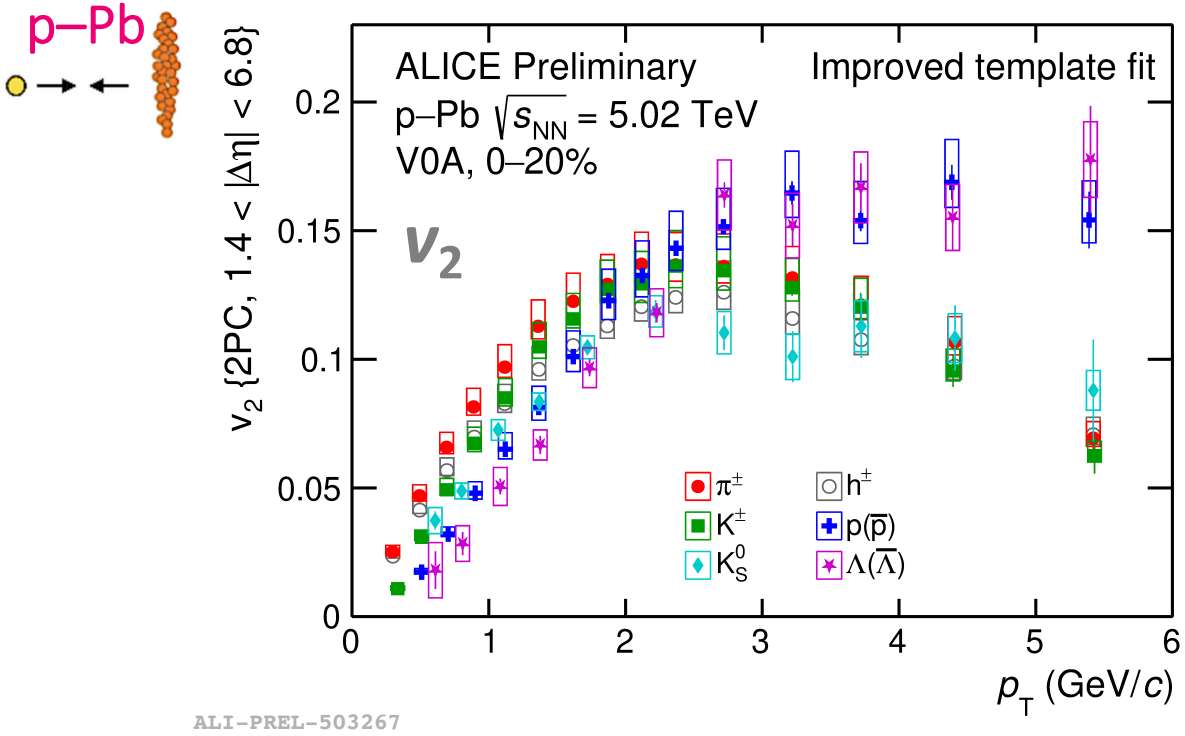
Observation of partonic flow in small collision systems

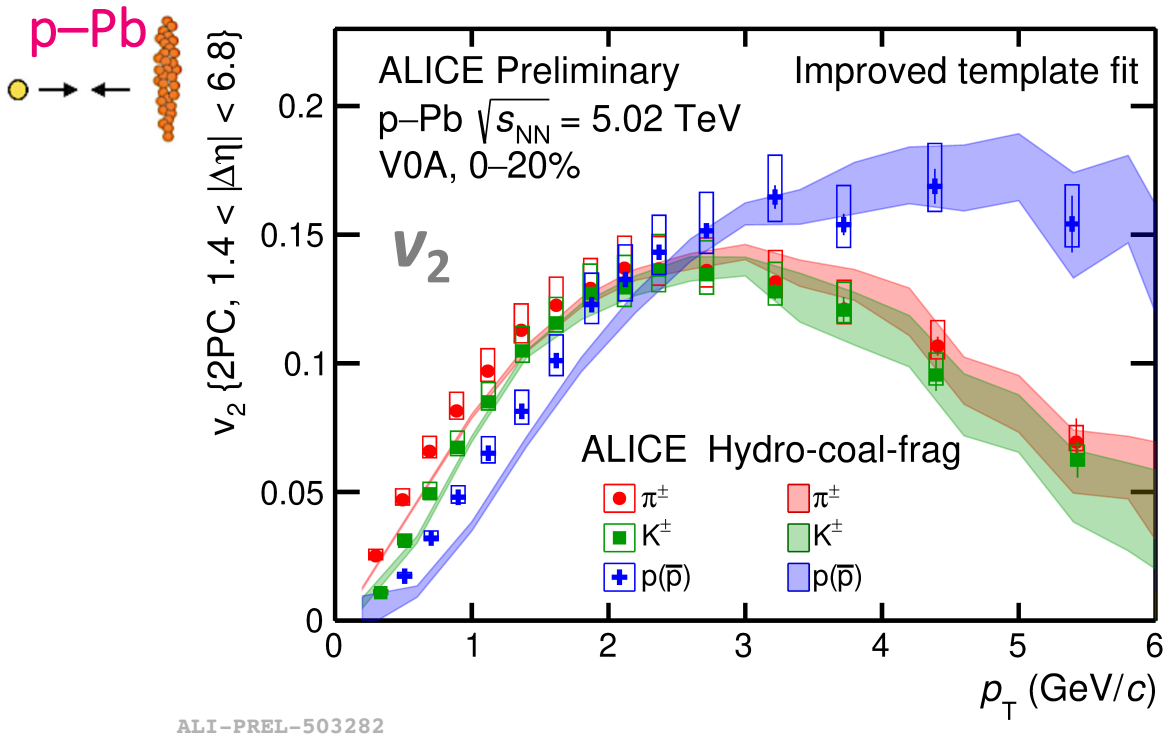




- Mass ordering at low p_T region
- Baryon-meson splitting at intermediate p_T region
- **Also in pp!**

Observation of partonic flow in small collision systems

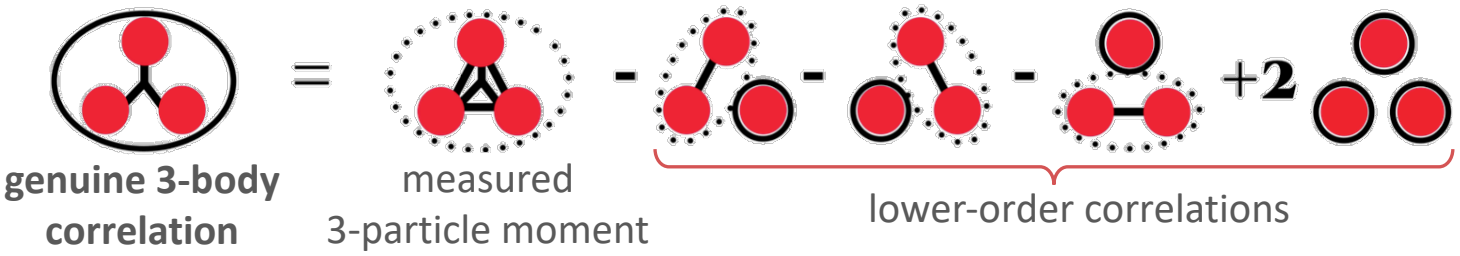




- Mass ordering at low p_T region
- Baryon-meson splitting at intermediate p_T region
- **Also in pp!**

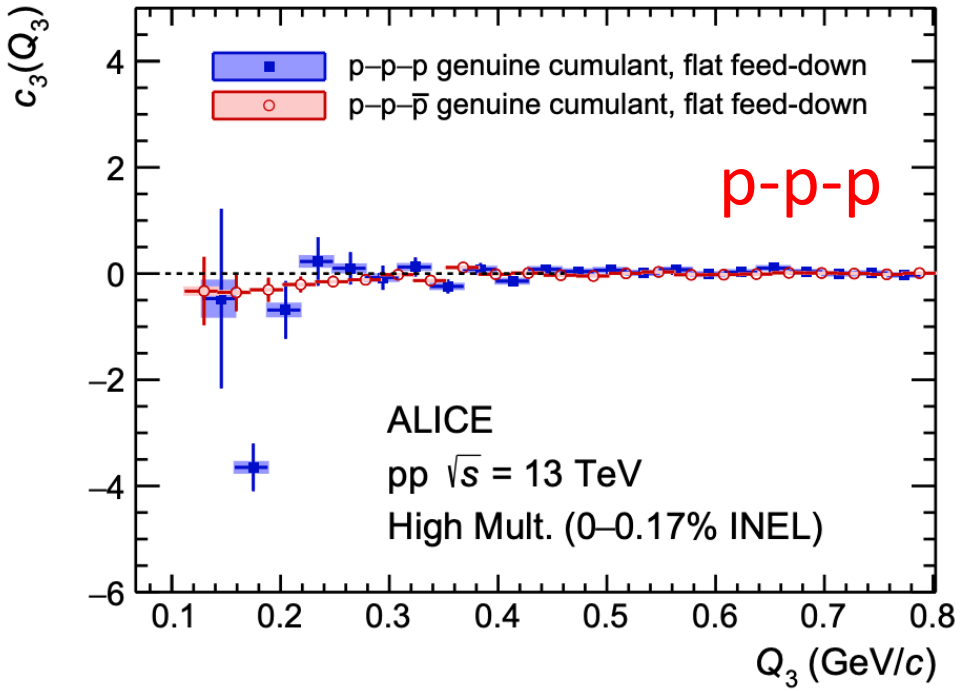
- Model comparison indicates **partonic flow + coalescence** in p–Pb and pp

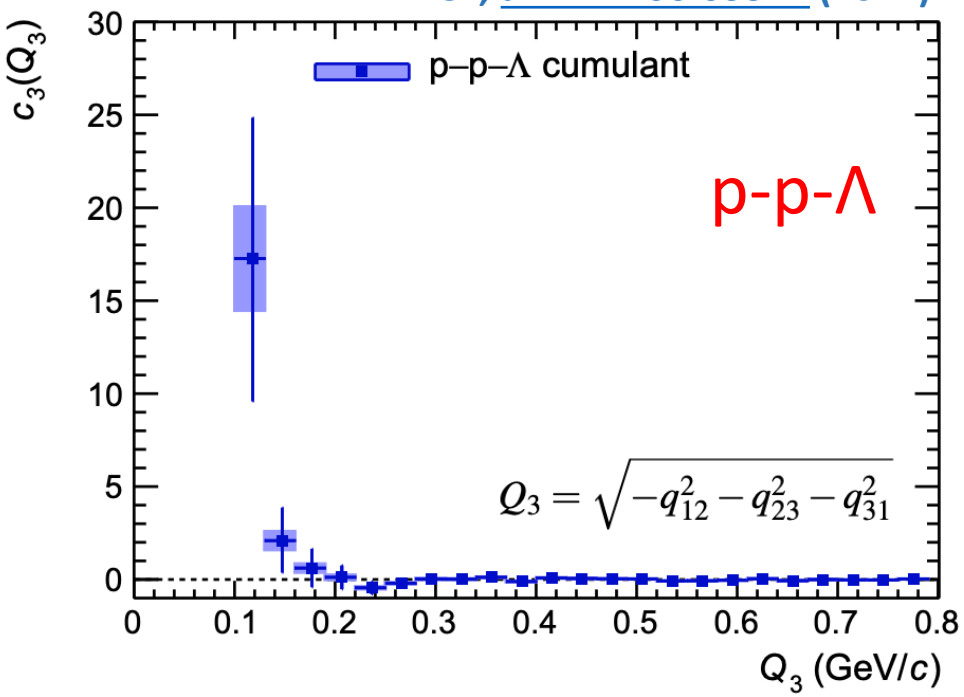
3-body femtoscopic correlations



Accepted by EPJ A

ALICE, arXiv:2206.03344 (2022)





- Measured 3-particle correlation functions deviate from lower-order contributions→ hint to **three-body effects**
- N-N-N and N-N-Λ interactions for the **EoS of neutron stars** *D. Lonardoni et al., PRL 114, 092301 (2015)*

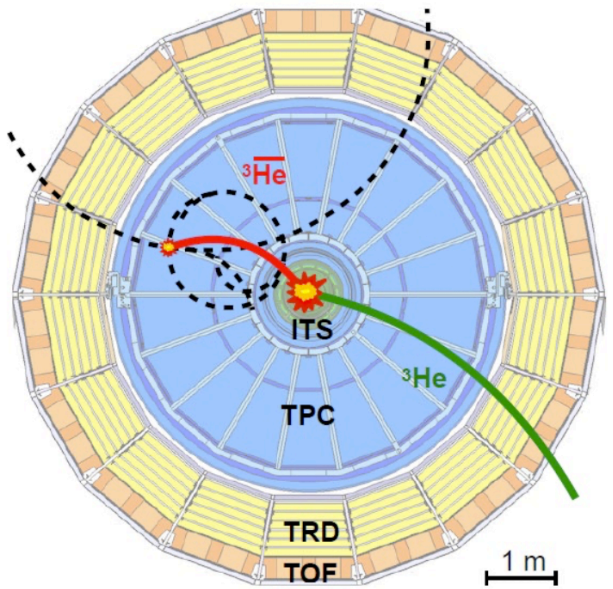
Absorption of $^{3}\overline{\mathrm{He}}$ nuclei in matter

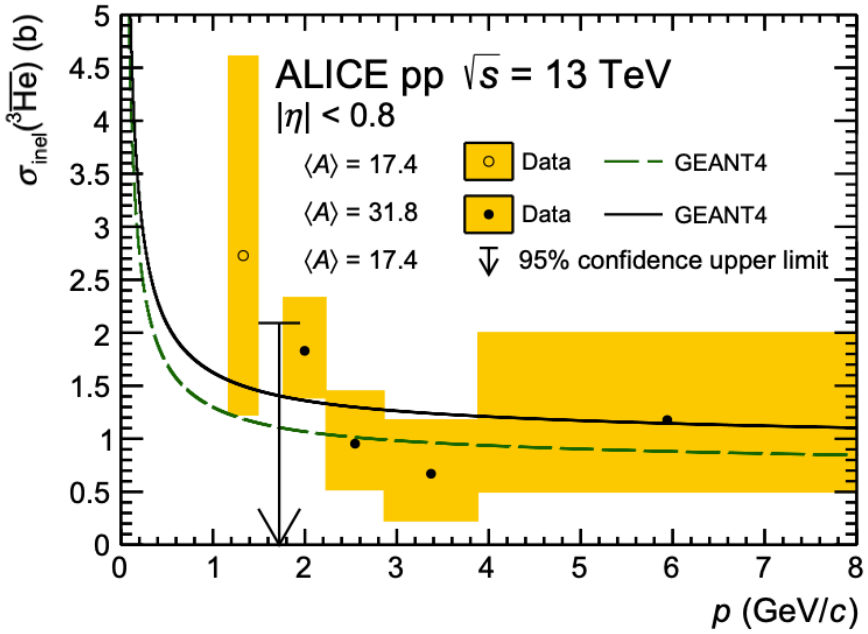
Measurements of antinuclei provide important input for astrophysics and dark-matter studies

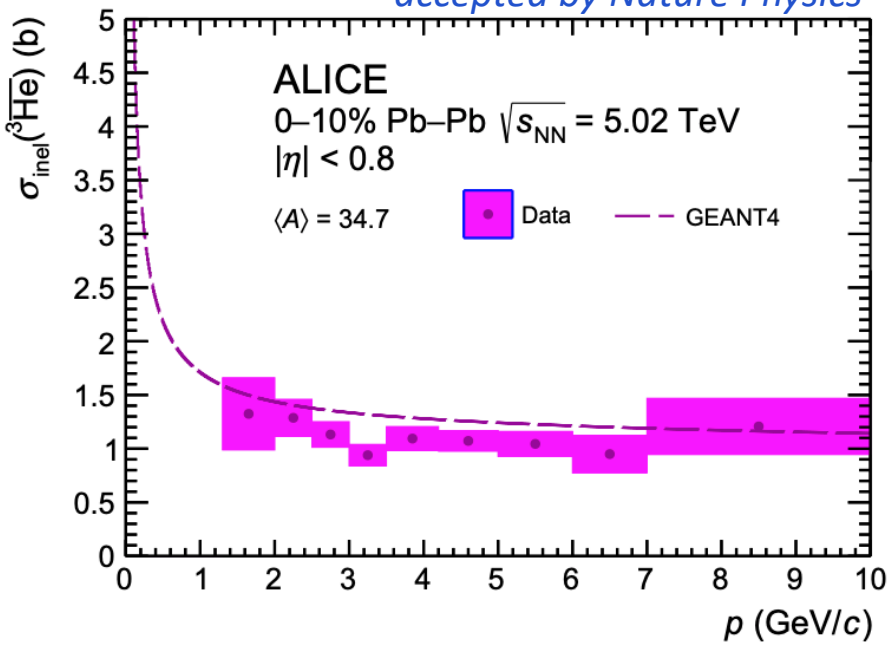
- One of dominant production mechanisms is **DM annihilation** (e.g. $\chi + \chi \rightarrow W^{+}W^{-} \rightarrow {}^{3}\overline{\mathrm{He}} + X$)
- **Disappearance probability** of antinuclei (quantified by σ_{inel}) is crucial for studying the galaxy transparency

- ALICE: antinuclei factory + interaction in detector material → measurement of σ_{inel} for $^{3}\overline{\mathrm{He}}$
- via **baryon/antibaryon ratio** (pp), or **TOF-to-TPC ratio** (Pb–Pb)

ALICE, arXiv.2202.01549
accepted by Nature Physics



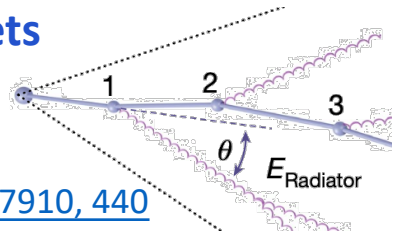




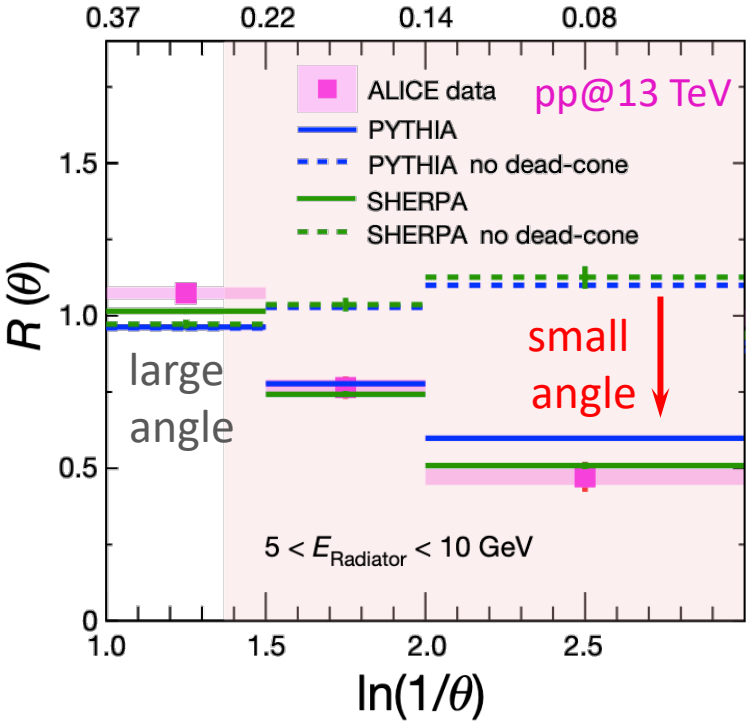
- GEANT4 modeling **consistent within 2σ** with data

More highlights from recent ALICE publications

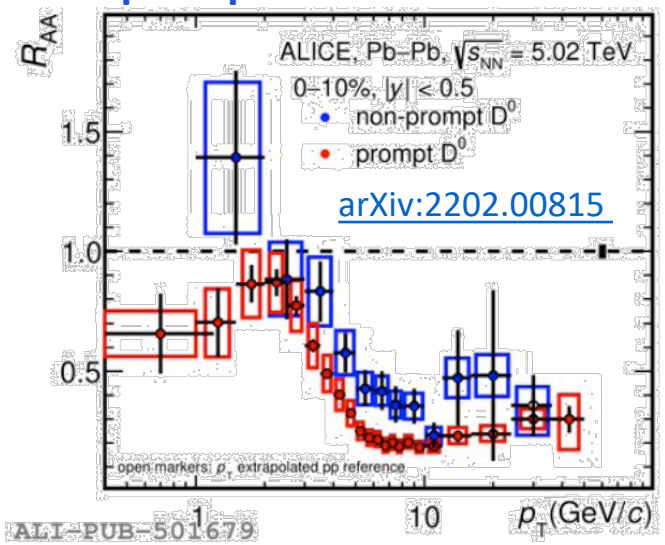
observation of the dead-cone effect with D^0-tagged jets



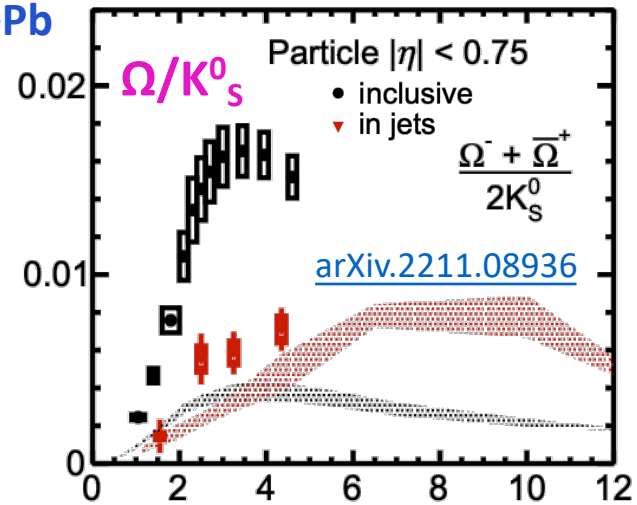
Nature 605 (2022) 7910, 440



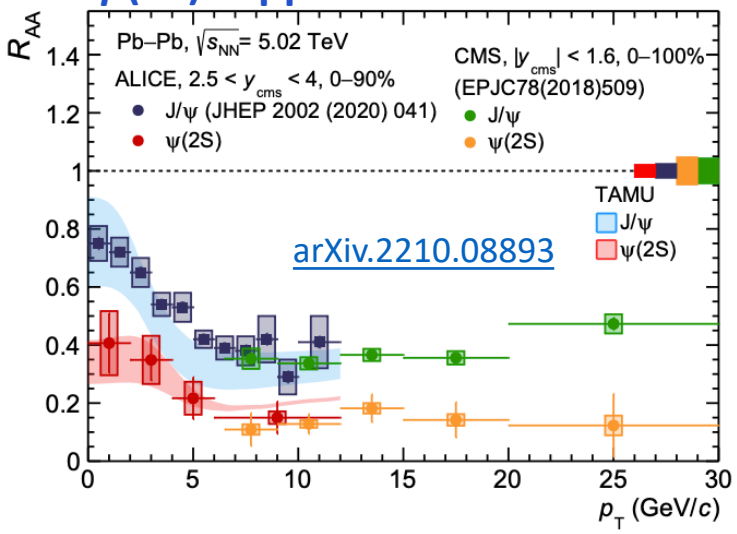
prompt D^0 *vs* b → D^0



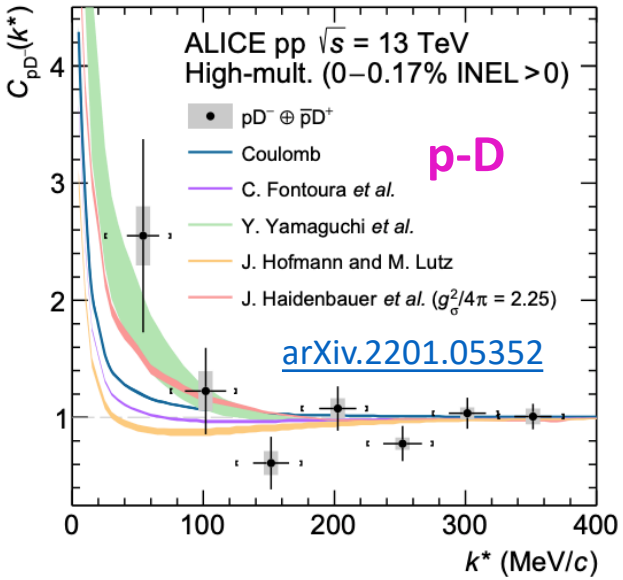
production of K^0_S, Λ, Ξ, Ω in jets and UE in pp & p–Pb



ψ(2S) suppression in Pb-Pb



two-body scattering involving *charm* hadrons



List of recent ALICE publications (since May 2022)

https://twiki.cern.ch/twiki/bin/view/ALICEpublic/ALICEPublicResults

			arXiv	INSPIRE
CF	Two-particle transverse momentum correlations in pp and p-Pb collisions at LHC energies	pp,pPb	2211.08979	2182733
JE	Production of K0S, Λ (Λ^{-}), $\Xi\pm$ and $\Omega\pm$ in jets and in the underlying event in pp and p–Pb collisions	pp,pPb	2211.08936	2182725
JE	Measurement of the angle between jet axes in pp collisions at 5.02 TeV	pp	2211.08928	2182727
	The ALICE experiment -- A journey through QCD	pp,pPb,XeXe,PbPb	2211.04384	2178285
CF	Jet-like correlations with respect to K0S and Λ (Λ^{-}) in pp and Pb-Pb collisions at 5.02 TeV	pp,PbPb	2211.01197	2175449
CF	Search for the Chiral Magnetic Effect with charge-dependent azimuthal correlations in Xe-Xe collisions at 5.44 TeV	XeXe	2210.15383	2172062
DQ	Measurements of azimuthal anisotropies at forward and backward rapidity with muons in high-multiplicity p-Pb at 8.16 TeV	PbPb	2210.08980	2165935
DQ	$\psi(2S)$ suppression in Pb-Pb collisions at the LHC	PbPb	2210.08893	2165947
LF	Measurement of the lifetime and Λ separation energy of $^{3}_{\Lambda}$H	PbPb	2209.07360	2152211
UD	Neutron emission in ultraperipheral Pb-Pb collisions at 5.02 TeV	PbPb	2209.04250	2149540
DQ	Multiplicity dependence of Υ production at forward rapidity in pp collisions at 13 TeV	pp	2209.04241	2149692
	Performance of the ALICE Electromagnetic Calorimeter		2209.04216	2149709
JE	Measurements of groomed-jet substructure of charm jets tagged by D^0 mesons in proton-proton collisions at 13 TeV	pp	2208.04857	2133853
LF	f0(980) production in inelastic pp collisions at 5.02 TeV	pp	2206.06216	2094796
CF	Anisotropic flow and flow fluctuations of identified hadrons in Pb–Pb collisions at 5.02 TeV	PbPb	2206.04587	2093750
CF	Observation of flow angle and flow magnitude fluctuations in Pb-Pb collisions at 5.02 TeV at the LHC	PbPb	2206.04574	2093738
CF	Towards the understanding of the genuine three-body interaction for p–p–p and p–p–Λ	pp	2206.03344	2092560
CF	Closing in on critical net-baryon fluctuations at LHC energies: cumulants up to third order in Pb–Pb collisions	PbPb	2206.03343	2092559
CF	Constraining the K—N coupled channel dynamics using femtoscopic correlations at the LHC	pp,pPb,PbPb	2205.15176	2088954
LF	$\Sigma(1385)\pm$ resonance production in Pb-Pb collisions at 5.02 TeV	PbPb	2205.13998	2088201
HF	First measurement of $\Omega^{0}c$ production in pp collisions at 13 TeV	pp	2205.13993	2088206

List of recent ALICE publications (since May 2022)

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			arXiv	INSPIRE
CF	Two-particle transverse momentum correlations in pp and p-Pb collisions at LHC energies	pp,pPb	2211.08979	2182733
JE	Production of K0S, Λ (Λ¯), Ξ± and Ω± in jets and in the underlying event in pp and p–Pb collisions	pp,pPb	2211.08936	2182725
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CF	Search for the Chiral Magnetic Effect with charge-dependent azimuthal correlations in Xe-Xe collisions at 5.44 TeV	Xe-Xe	2210.15383	2173863
DQ	Measurements of azimuthal anisotropies	PbPb	2210.08980	2165935
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CF	Constraining the K—N coupled channel dynamics using femtoscopic correlations at the LHC	pp,pPb,PbPb	2205.15176	2088954
LF	Σ(1385)± resonance production in Pb-Pb collisions at LHC energies	PbPb	2205.15352	2088964
HF	First measurement of Ω⁰c production in pp collisions at 5.02 TeV	pp	2205.13993	2088206

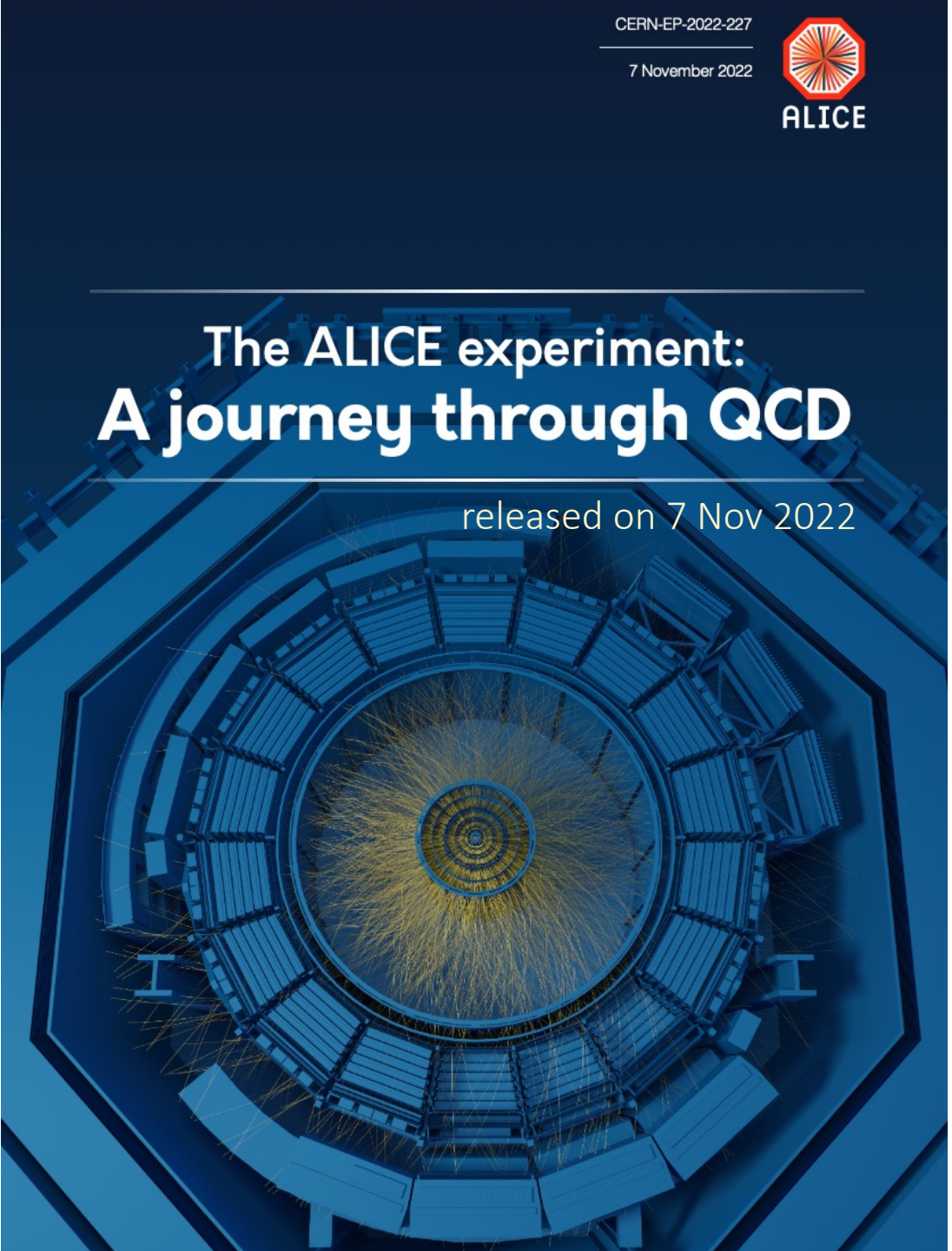
+ papers appeared on arXiv *today*:

1) Measurement of electrons from beauty-hadron decays in pp and Pb-Pb at 5.02 TeV
http://arxiv.org/abs/2211.13985

2) J/ψ production at midrapidity in p-Pb collisions at 8.16 TeV
https://arxiv.org/abs/2211.14153

3) Light (anti)nuclei production in Pb-Pb collisions at 5.02 TeV
http://arxiv.org/abs/2211.14015

4) First measurement of Λ_c^+ production down to p_T = 0 in pp and p-Pb at 5.02 TeV
http://arxiv.org/abs/2211.14032



ALICE review paper: physics results of Run 1+2

CDS, arXiv.2211.04384

***> 400* papers on 2009-2018 data**

Abstract

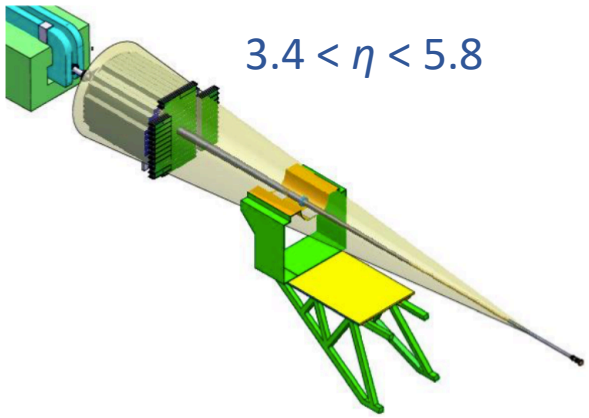
The ALICE experiment was proposed in 1993, to study strongly-interacting matter at extreme energy densities and temperatures. This proposal entailed a comprehensive investigation of nuclear collisions at the LHC. Its physics programme initially focused on the determination of the properties of the quark–gluon plasma (QGP), a deconfined state of quarks and gluons, created in such collisions. The ALICE physics programme has been extended to cover a broader ensemble of observables related to Quantum Chromodynamics (QCD), the theory of strong interactions. The experiment has studied Pb–Pb, Xe–Xe, p–Pb and pp collisions in the multi-TeV centre of mass energy range, during the Run 1–2 data-taking periods at the LHC (2009–2018). The aim of this review is to summarise the key ALICE physics results in this endeavor, and to discuss their implications on the current understanding of the macroscopic and microscopic properties of strongly-interacting matter at the highest temperatures reached in the laboratory. It will review the latest findings on the properties of the QGP created by heavy-ion collisions at LHC energies, and describe the surprising QGP-like effects in pp and p–Pb collisions. Measurements of few-body QCD interactions, and their impact in unraveling the structure of hadrons and hadronic interactions, will be discussed. Finally, prospects for future measurements with the ALICE detector in the context of its planned upgrades will also be briefly described.

ALICE upgrades

Letter-of-Intent: CERN-LHCC-2020-009

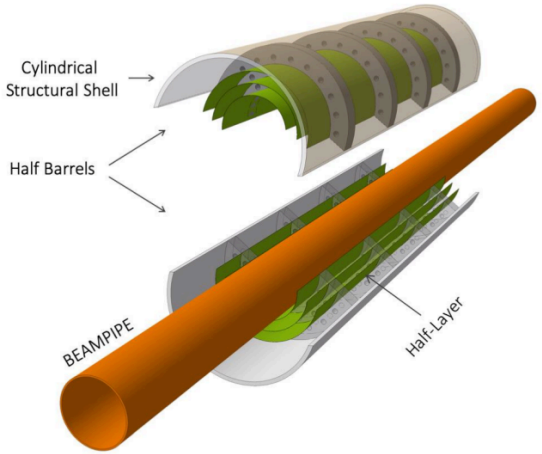
Letter-of-Intent: CERN-LHCC-2019-018

FoCal = ECal+HCal



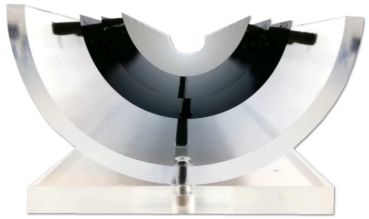
- Goals: direct photon detection to probe gluon density at small x, forward π^0
- Currently: prototype development, beam tests

ITS3

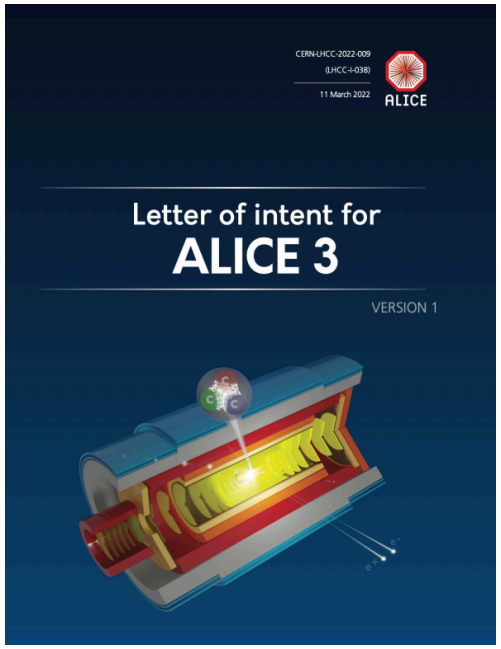


- truly cylindrical inner layers
- closer to the interaction point, reduced material budget

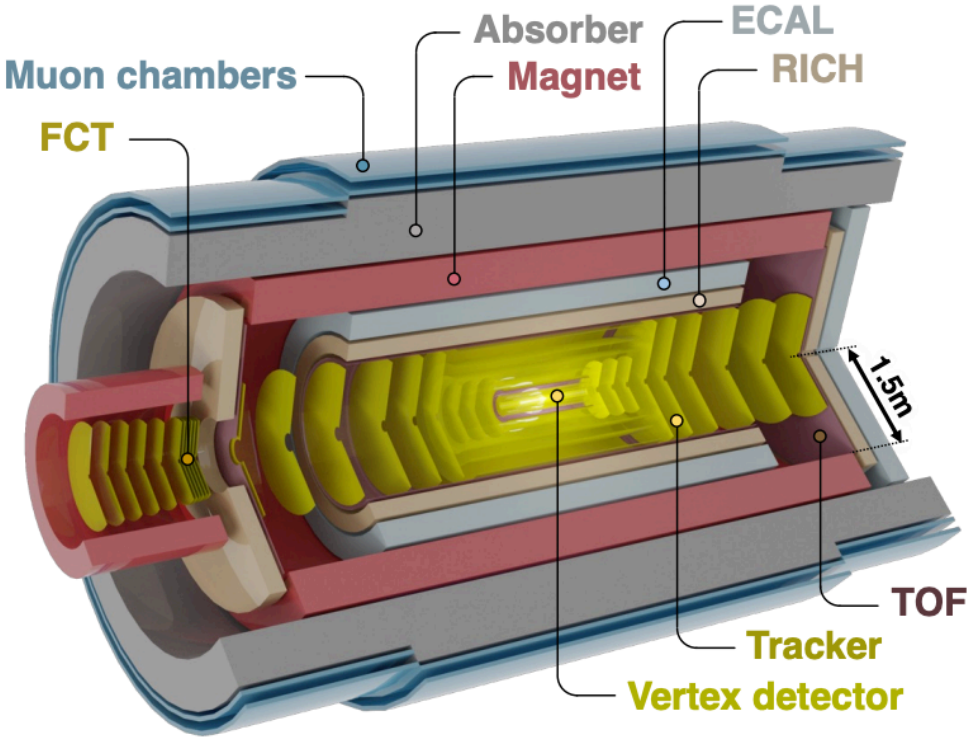
→ **Improved vertexing for heavy flavour probes, thermal dielectrons**



Letter of intent for ALICE 3

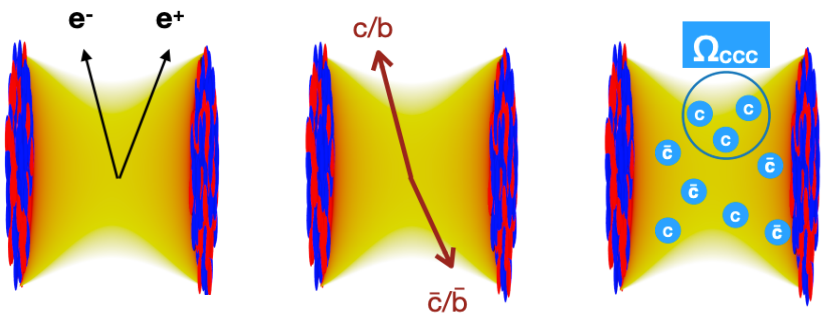


Updated version released Nov 2022 - arxiv.2211.02491



Key objectives:

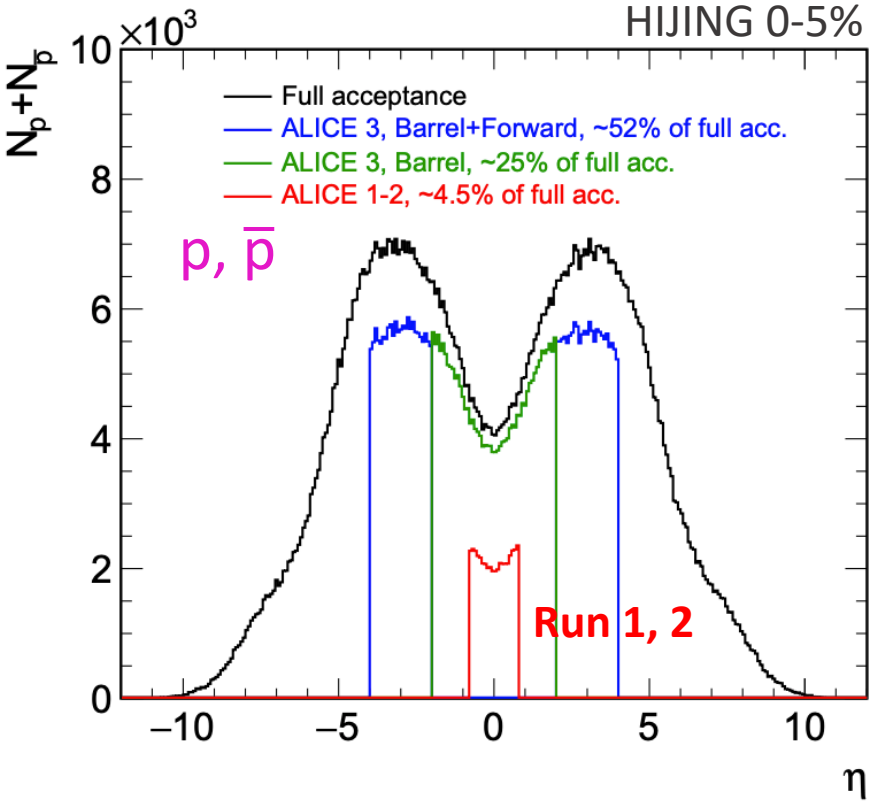
- precision measurements of **dileptons**
- systematic measurements of **(multi-) heavy flavour hadrons**
- hadron long-range correlations

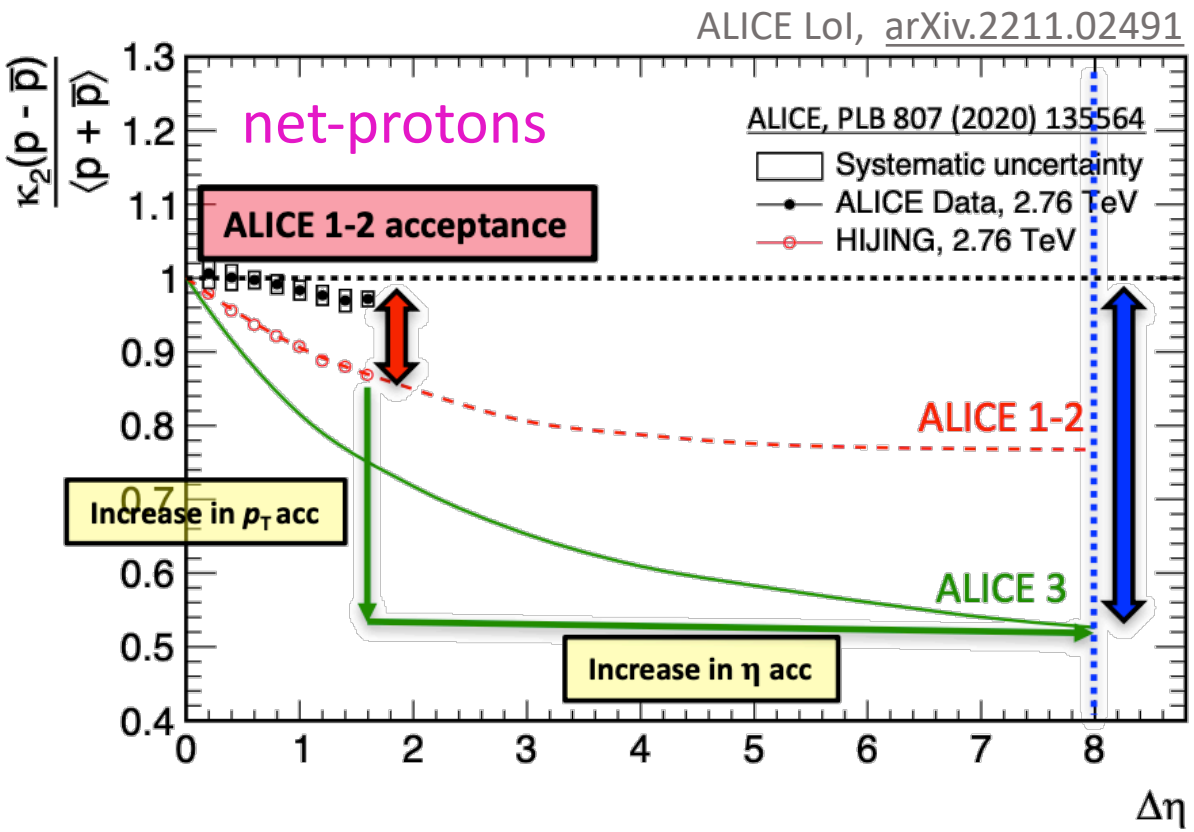


Detector concept:

- compact **low-mass** all-silicon tracker
- excellent **vertex** reconstruction
- wide acceptance $|\eta| < 4$
- PID in $0.3 < p_T < 7$ GeV/c

Conserved charge fluctuations with ALICE 3

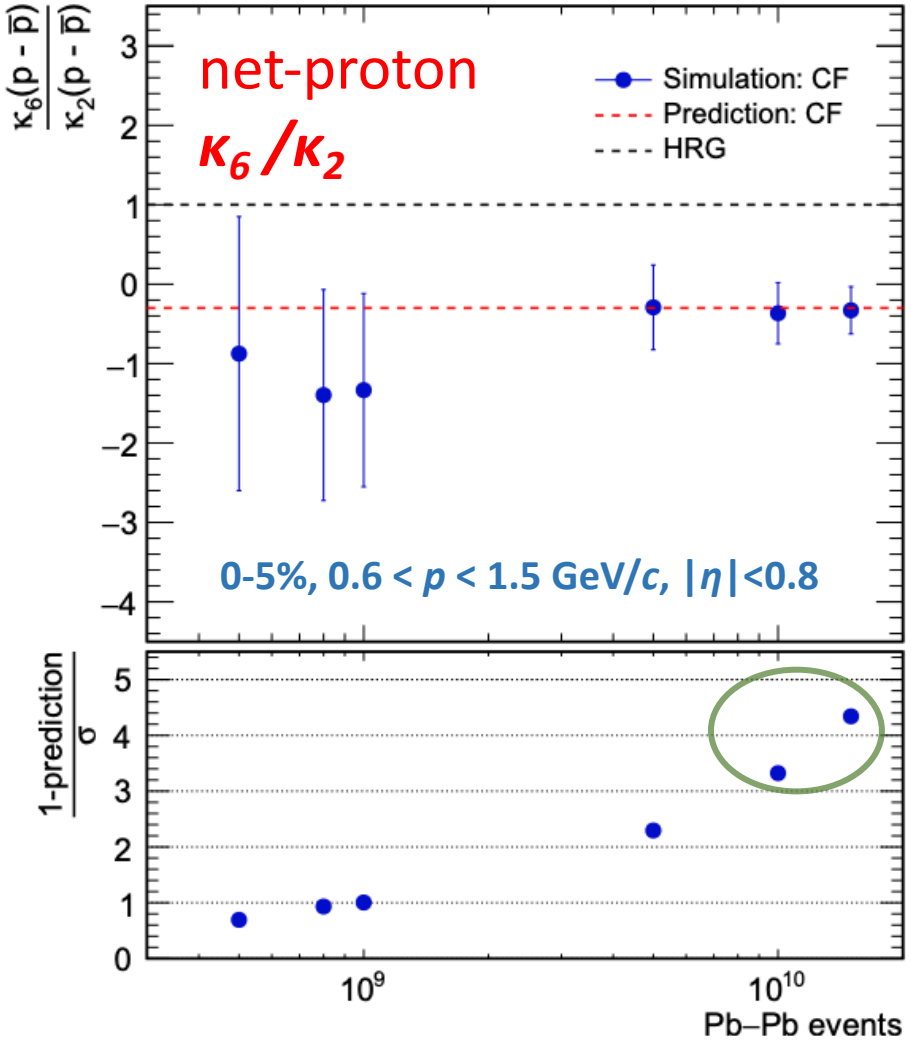




- high PID purity in large kinematic acceptance
- long-range correlations in a very wide acceptance
- constraining effects from baryon number conservation, hydro evolution

Higher-order cumulants

ALICE LoI, arXiv.2211.02491



- Simulation of the Critical Fluctuations (CF) is based on PQM model
  G. A. Almasi, B. Friman, and K. Redlich, Phys. Rev. D96 (2017), 014027

Net-baryon and net-strangeness fluctuations
for $|\eta| \leq 4$ and for 6th order

Summary

- Investigations with new types of observables provide more insights and additional constraints on our models
- A lot of new results from Runs 1+2, many are still to come
- Harvest of physics results from Run 1 and 2 is summarized in the ALICE review paper
- ALICE is successfully taking data in LHC Run 3
- Preparations for the future ALICE upgrades are ongoing, where many observables will benefit from even more statistics and larger ALICE acceptance

Thank you for your attention!