A Large Ion Collider Experiment

ALICE

Hadron Physics with ALICE at the LHC

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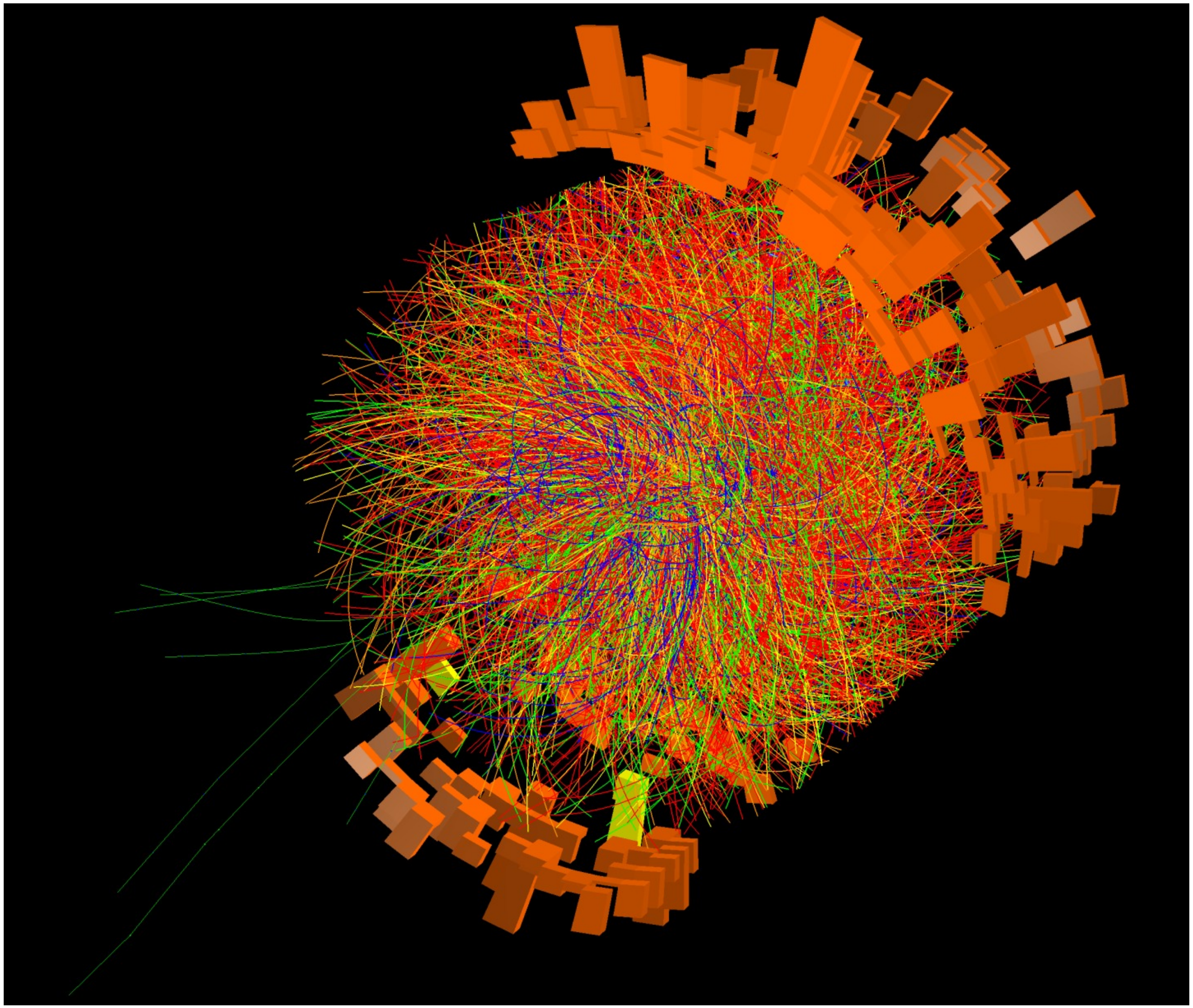
ALICE Physics Programme

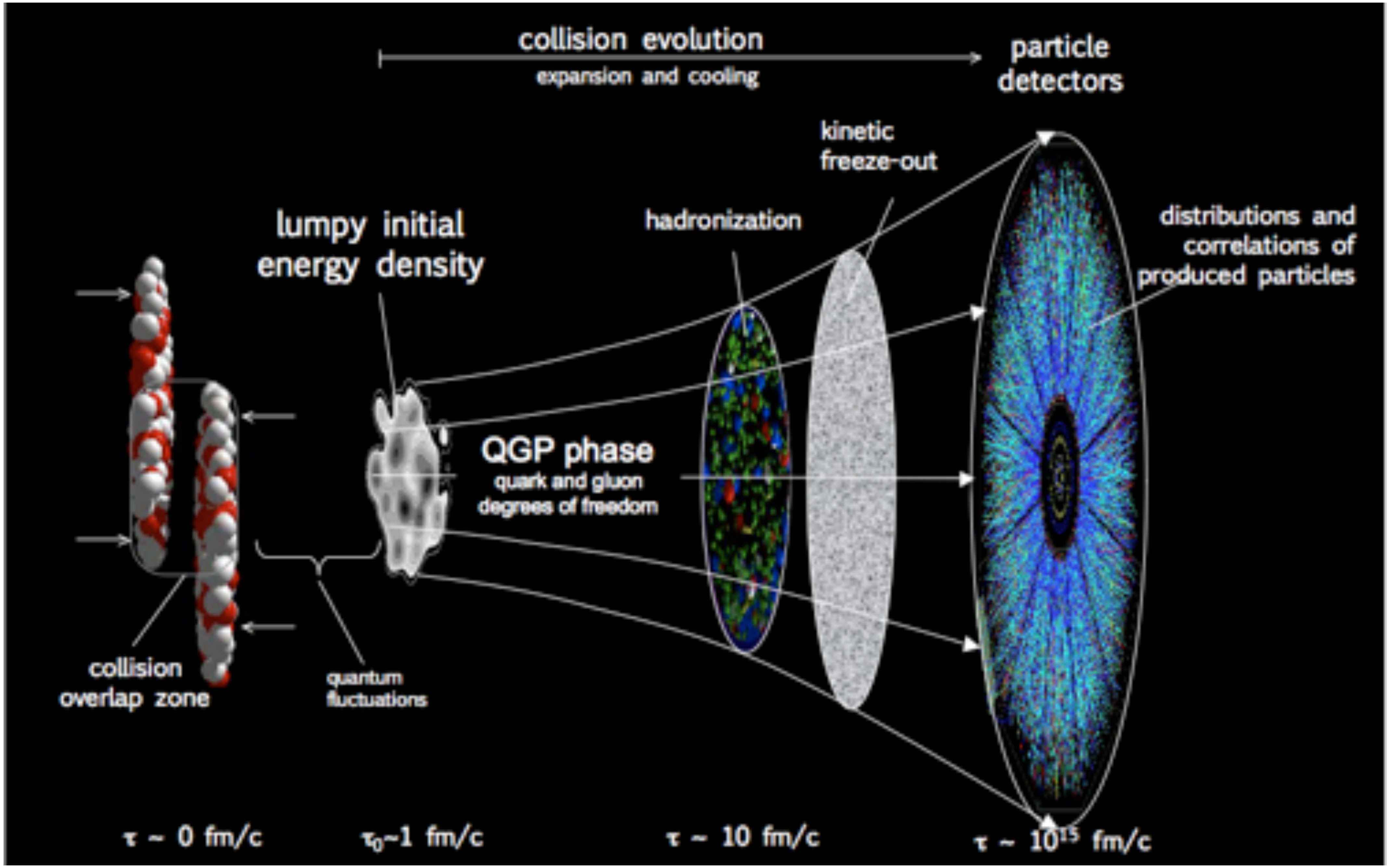
- Characterize the quark gluon plasma, a deconfined state of matter at high temperatures
- Formed in heavy-ion collisions at the LHC
  - Temperature of the order 10^{12} K or ~1 GeV
- (Almost) all observations rely on the detection of final state hadrons
  - i.e. pions, kaons, protons, hyperons …

A Pb-Pb collision

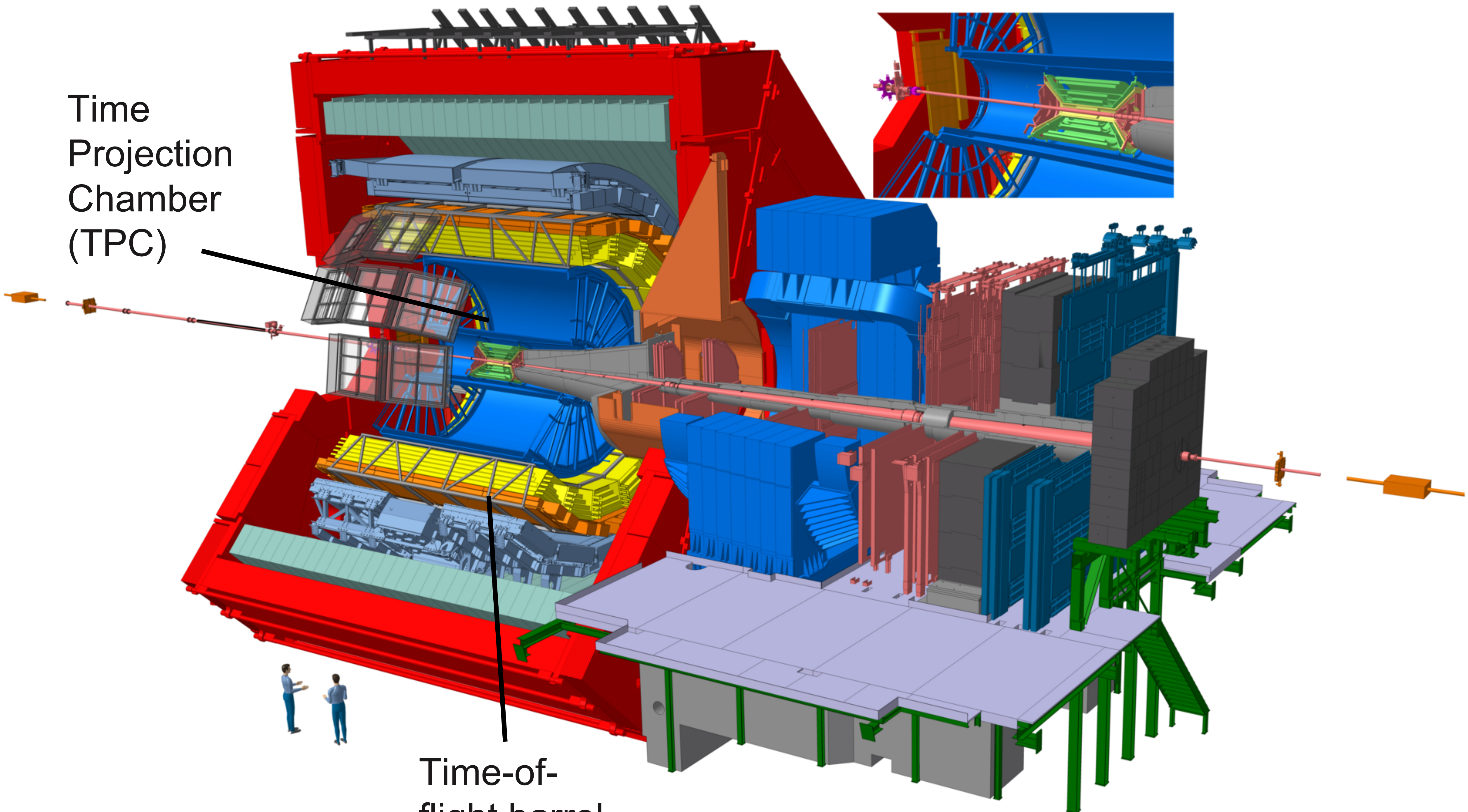


Over 2000 particles can leave tracks in the detector

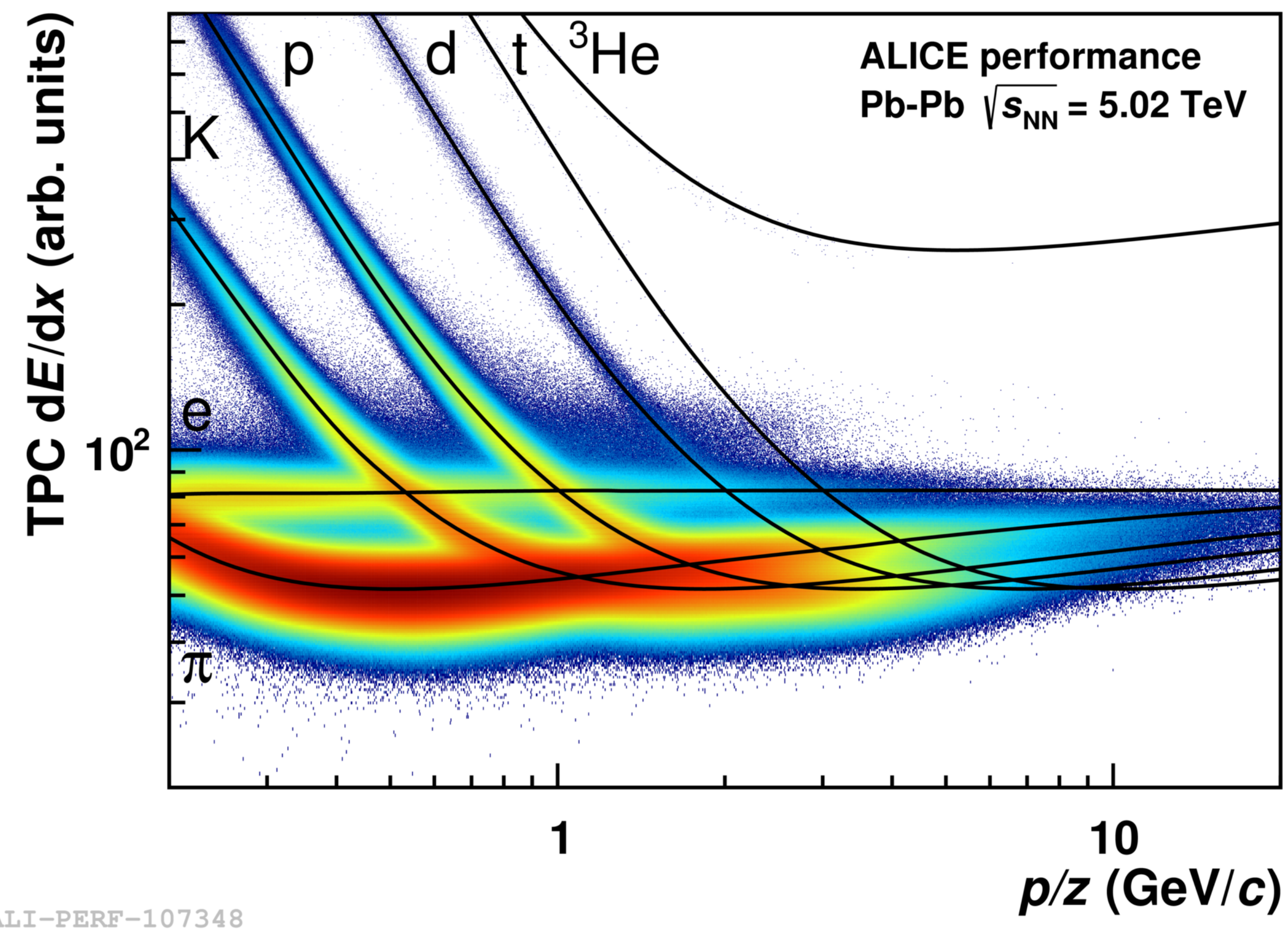
Schematic of the collision evolution

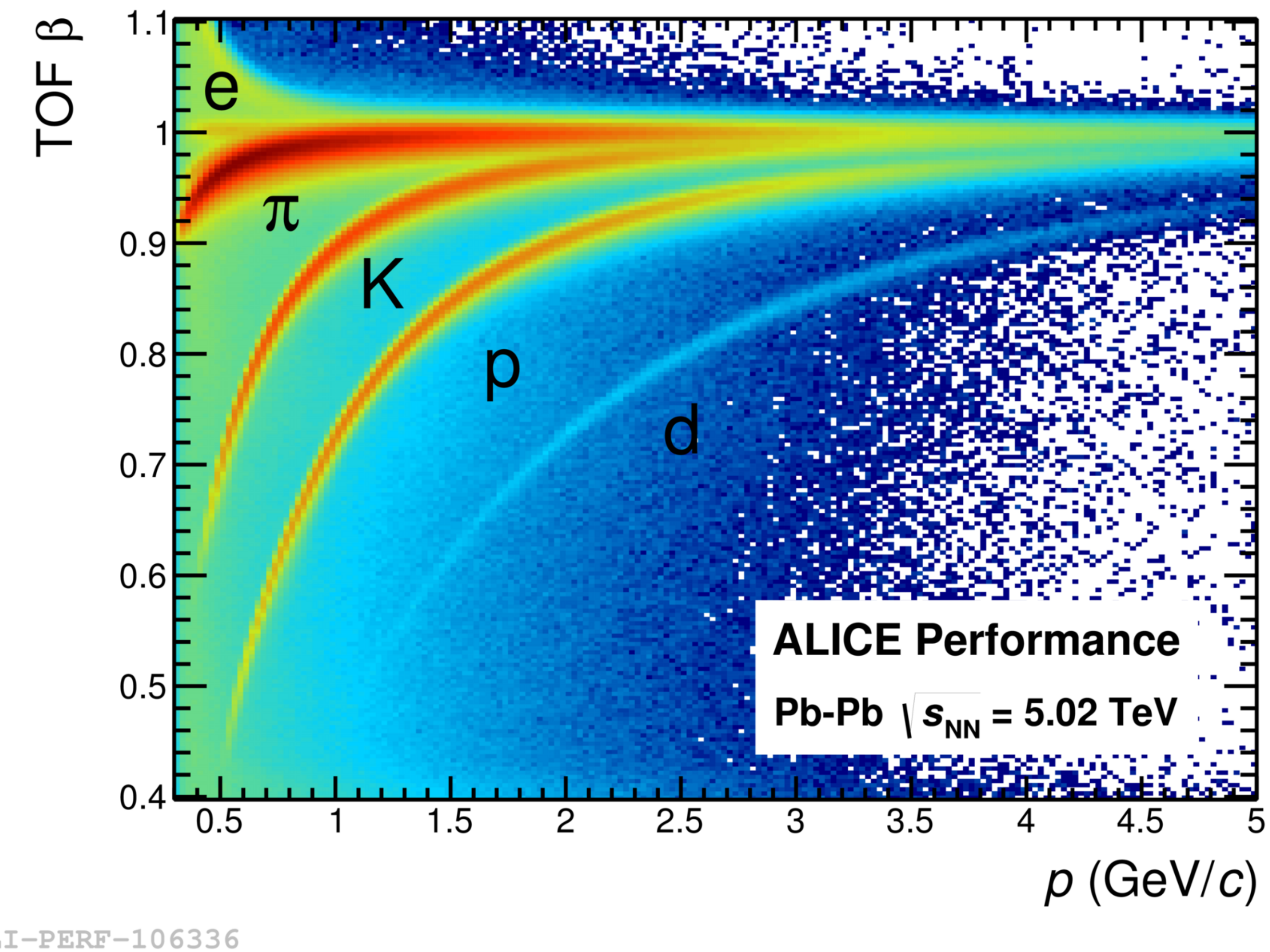


ALICE Detector



ALICE Particle Identification





- In TPC gas, energy loss vs momentum
- Time of flight vs momentum

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Hadron Physics

- How and where can ALICE contribute to hadron physics?
- Final hadronic yields described by a statistical model with minimal parameters
  - includes also light nuclei

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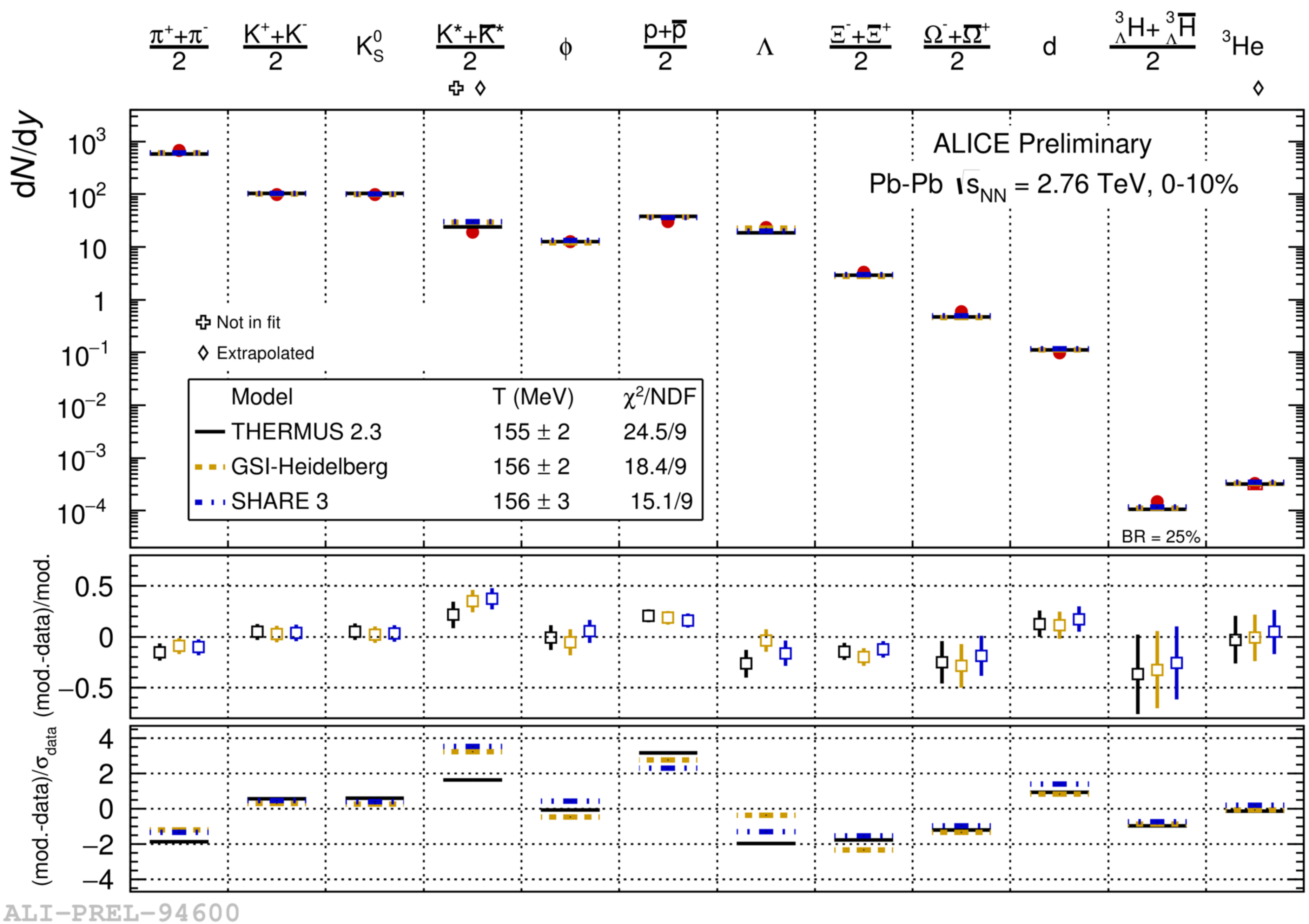
Thermal model



- Model(s) describe hadron yields over several orders of magnitude
- T ≅ 156 MeV
- Deviations typically less than 2**σ** and/or 20%

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Hadron Physics

- How and where can ALICE contribute to hadron physics?
- Final hadronic yields described by a statistical model with minimal parameters
  - includes also light nuclei
- ‘Factory’ for antimatter and hypernuclei
- Hadron phase with many hadronic interactions

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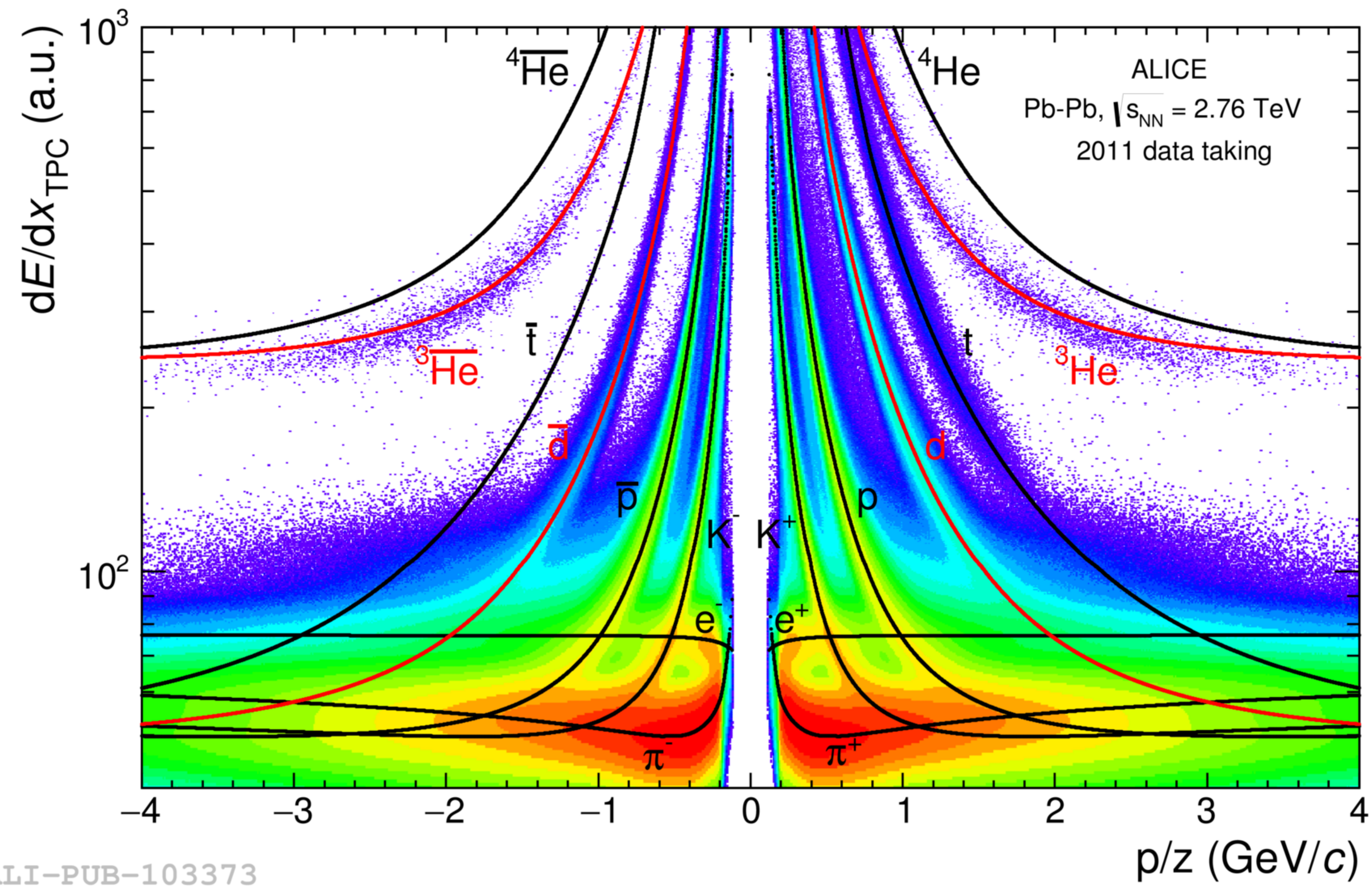
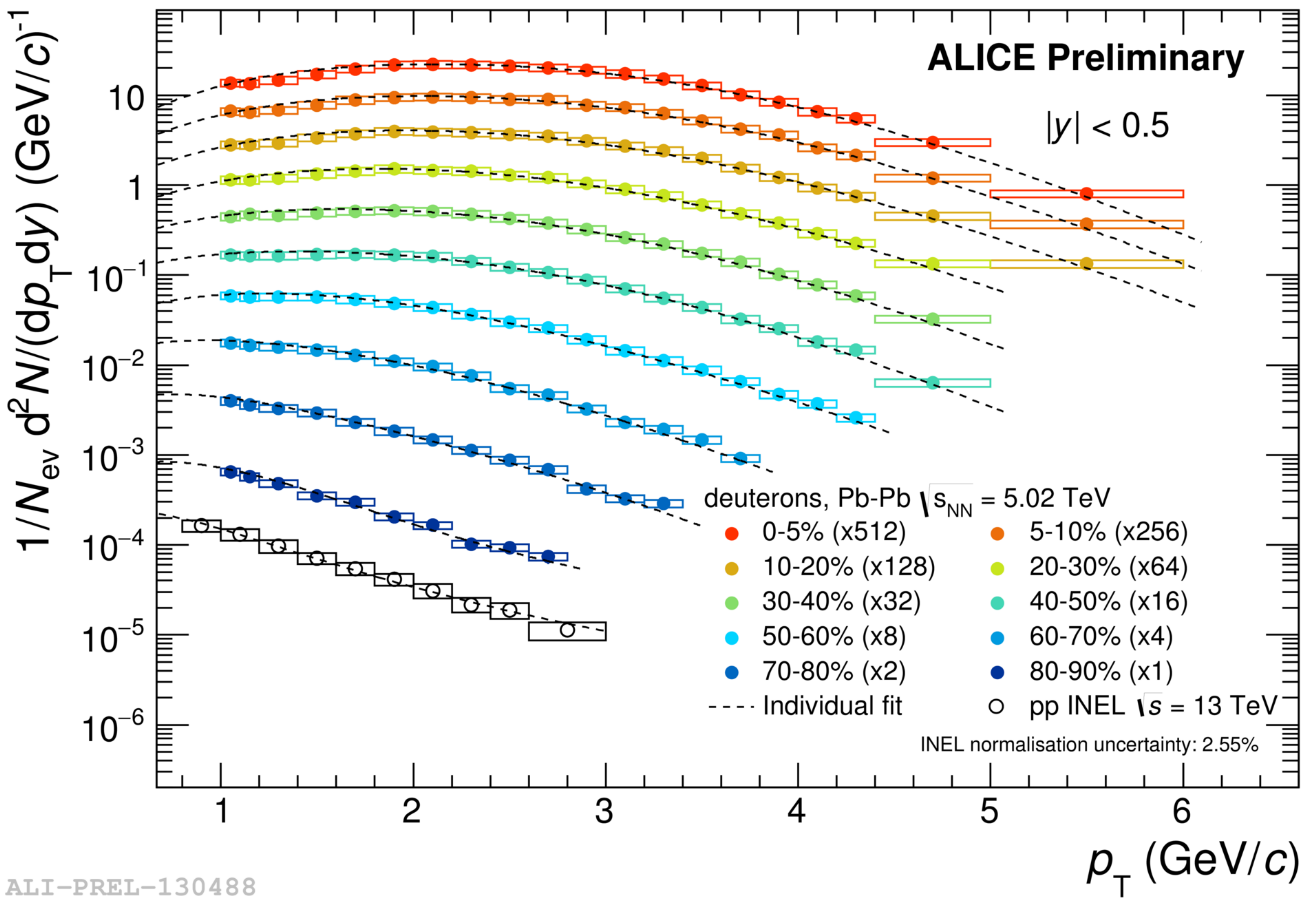
LHC Heavy-ion collisions as an anti-matter and exotic hadron factory

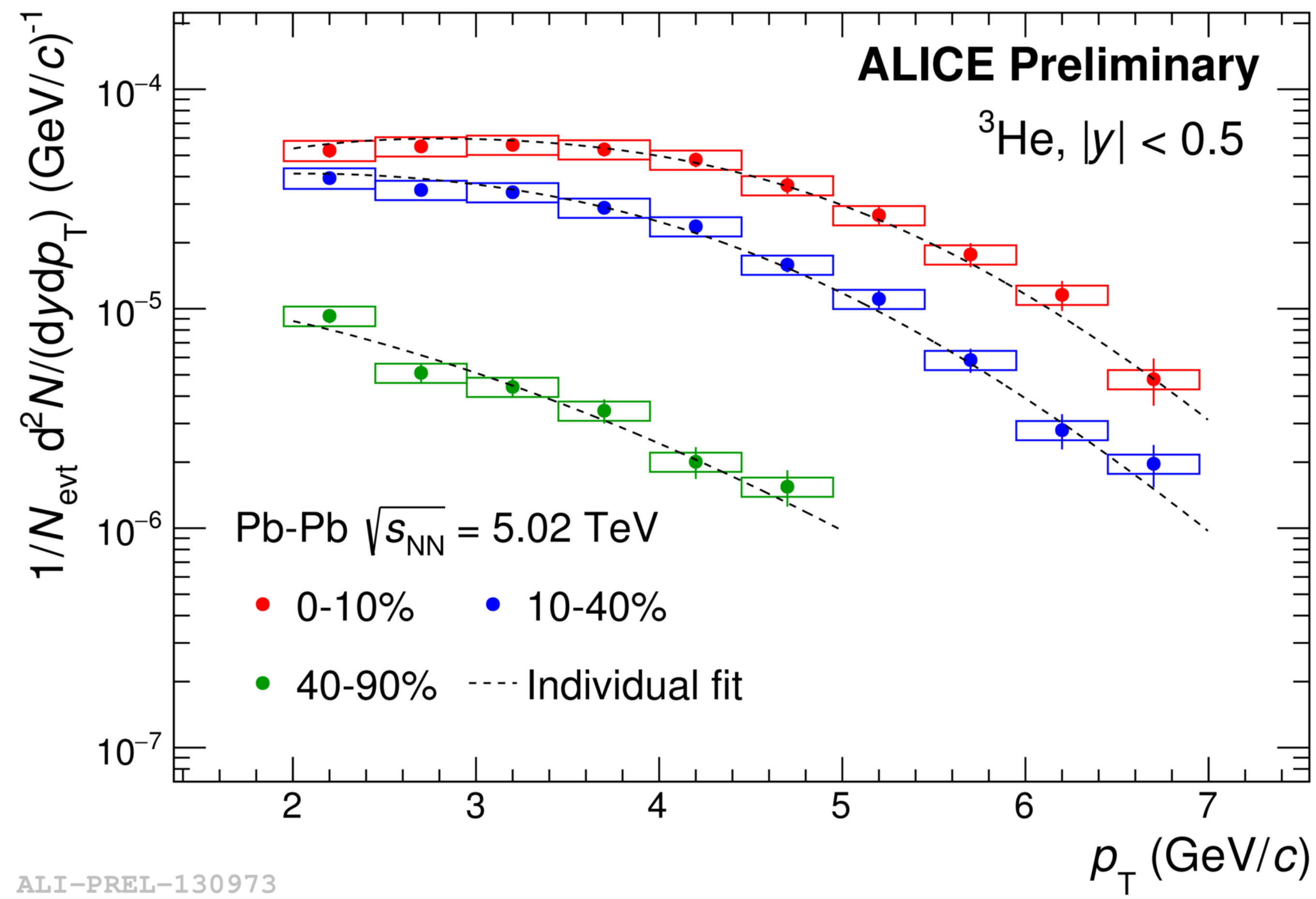
Nuclei and anti-nuclei detection



Nuclei production – momentum dependence

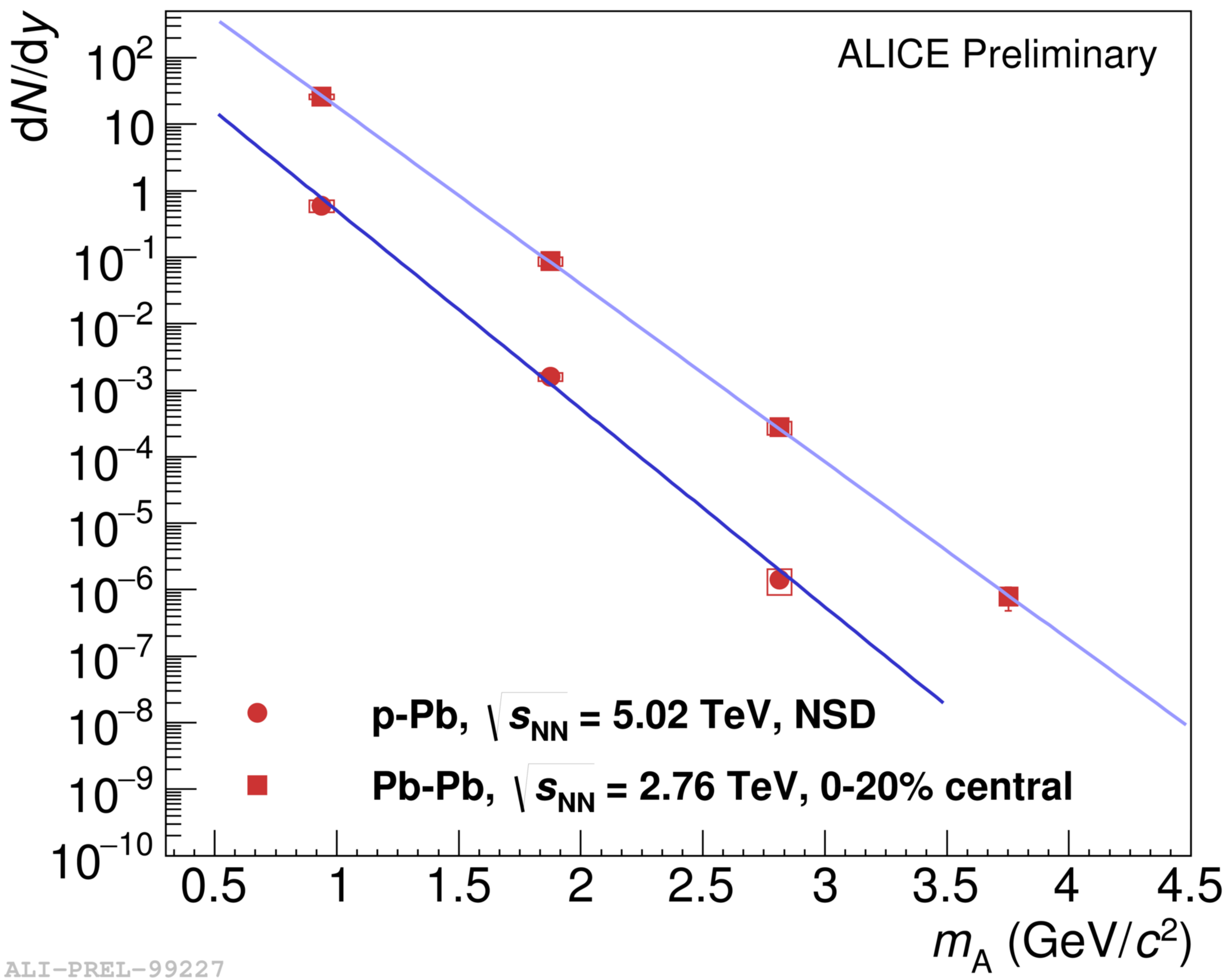
ALI-PREL-130973





- Both d and ^{3}He transverse momentum spectra measured for different centrality (system size)
- Shows that they participate in collective dynamics

Nuclei production – mass dependence



- Production follow an exponential decrease
  - Predicted by simple thermal model
- In Pb-Pb collisions 'penalty factor' for adding one baryon is ~300
  - In p-Pb ~600

Mass Difference between light nuclei and anti-nuclei

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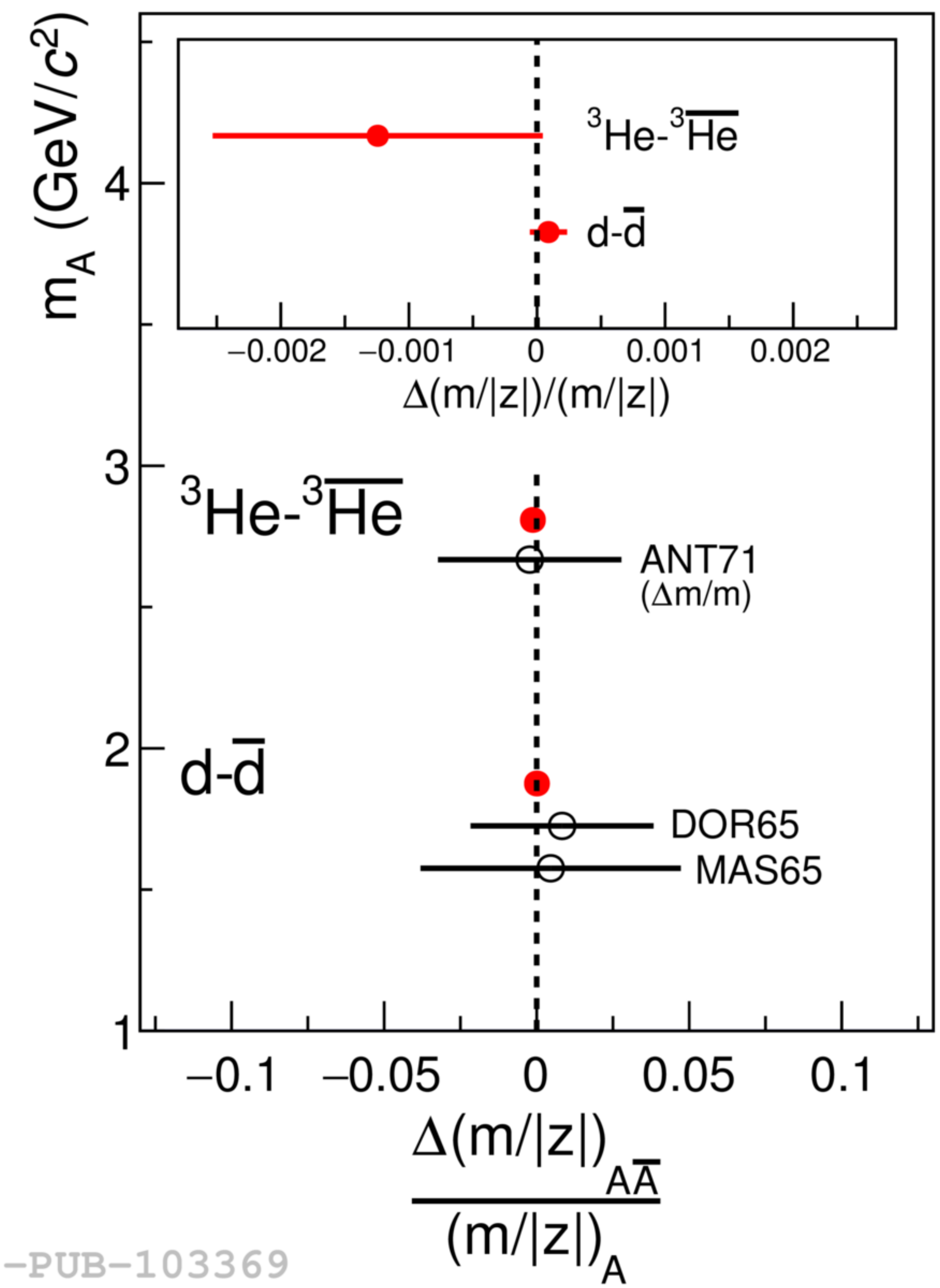

[-PUB-103369

$$\frac{\Delta\mu}{\mu} = [-1.2 \pm 0.9\,(\text{stat.}) \pm 1.0\,(\text{syst.})] \times 10^{-3} \quad {}^3\text{He-}\,{}^3\overline{\text{He}}$$

$$\frac{\Delta\mu}{\mu} = [0.9 \pm 0.5\,(\text{stat.}) \pm 1.4\,(\text{syst.})] \times 10^{-4} \quad \text{d-}\bar{\text{d}}$$

- Highest precision direct measurements of mass differences in the nuclei sector
- One to two orders of magnitude improvement over the results from 40+ years ago

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Nature Phys. 11 (2015) 811

Mass Difference between light nuclei and anti-nuclei

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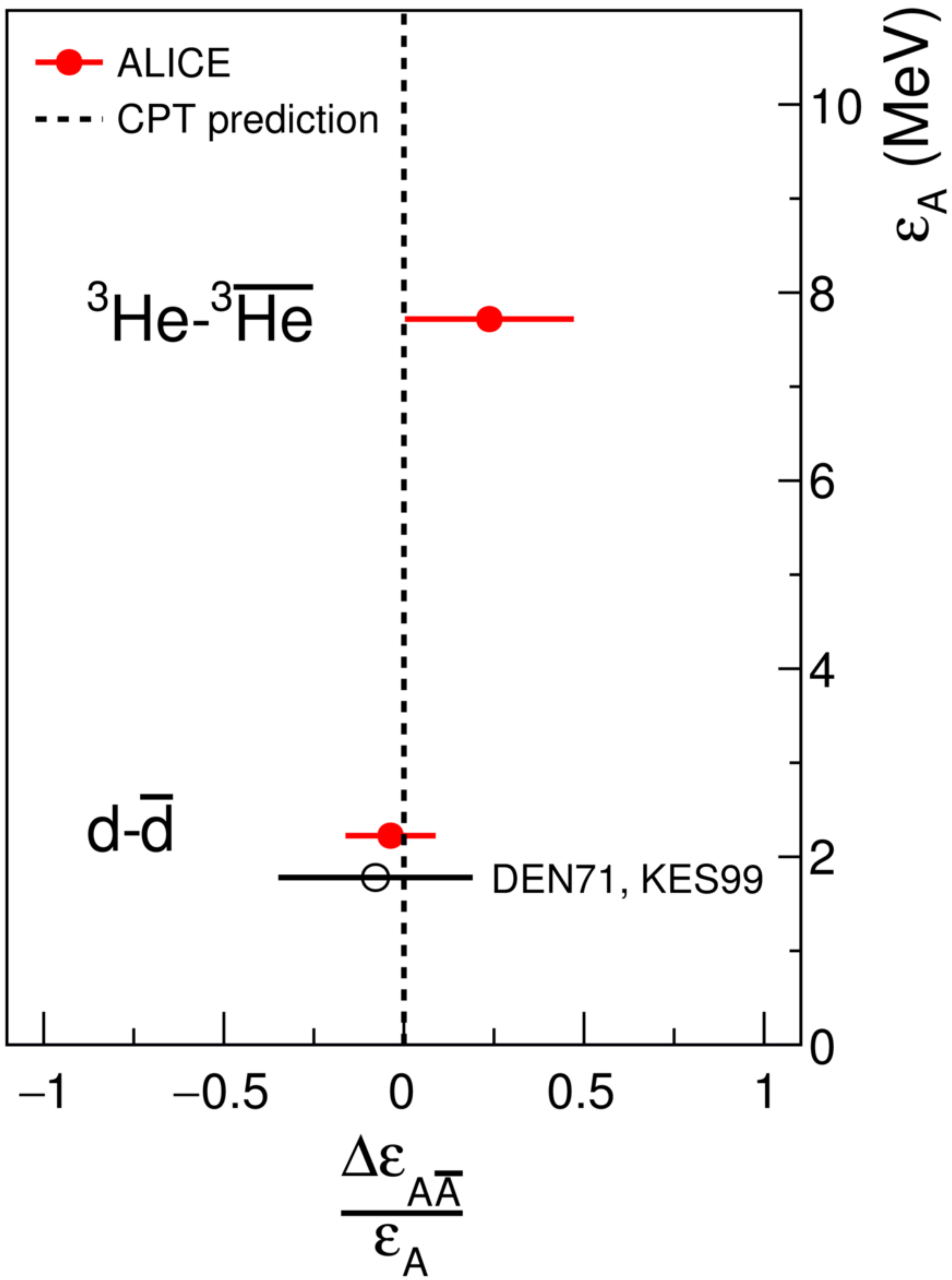


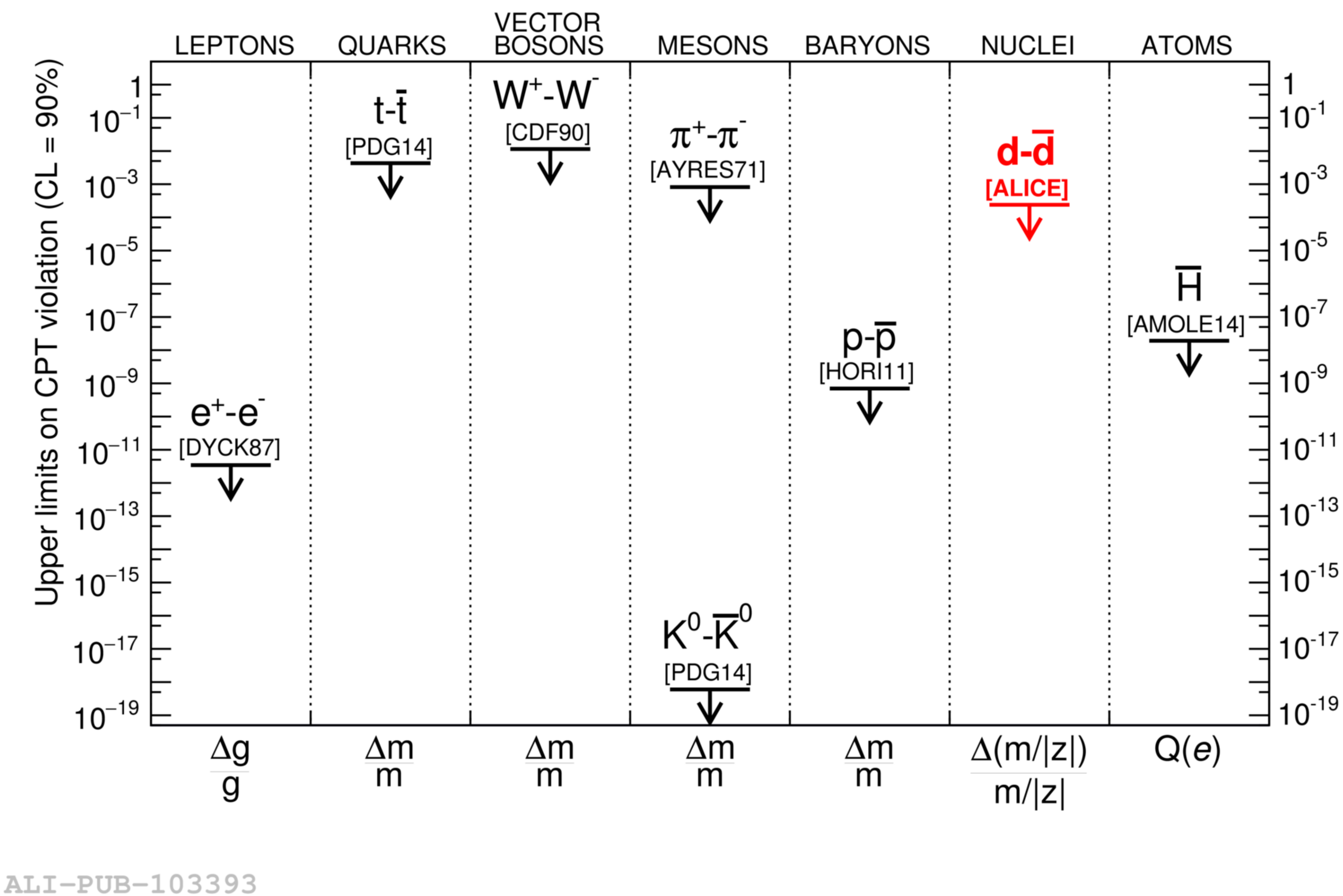
$$\Delta\varepsilon_{\mathrm{A\bar{A}}} = Z\Delta m_{\mathrm{p\bar{p}}} + (A-Z)\Delta m_{\mathrm{n\bar{n}}} - \Delta m_{\mathrm{A\bar{A}}}$$

$$\frac{\Delta\varepsilon}{\varepsilon} = -0.04 \pm 0.05\,(\text{stat.}) \pm 0.12\,(\text{syst.}) \qquad \text{d-}\bar{\text{d}}$$

$$\frac{\Delta\varepsilon}{\varepsilon} = 0.24 \pm 0.16\,(\text{stat.}) \pm 0.18\,(\text{syst.}) \qquad {}^3\text{He-}\,{}^3\overline{\text{He}}$$

- Constraint improved by factor 2 for deuteron case
- First Δε determination for ^{3}He

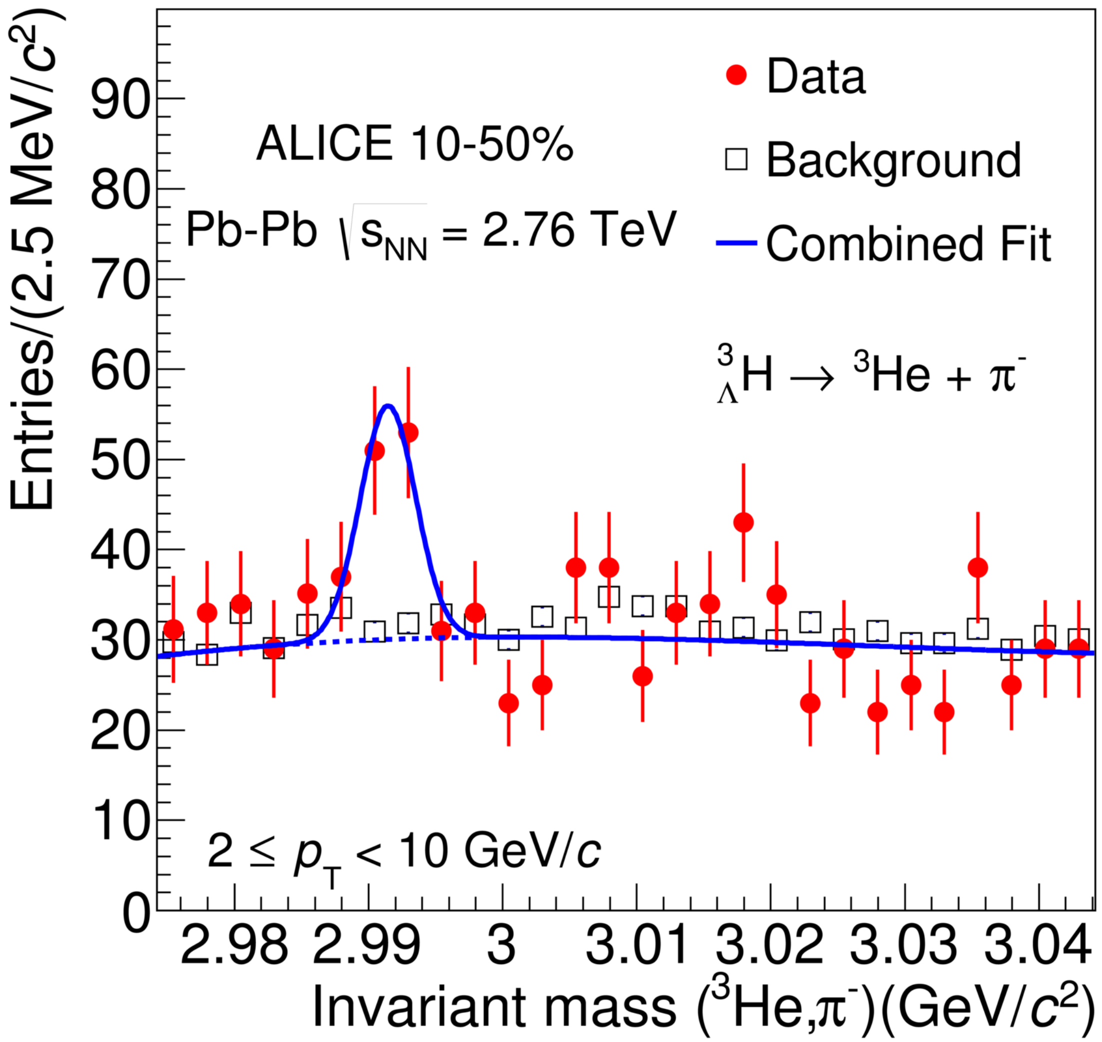
CPT Experimental Tests



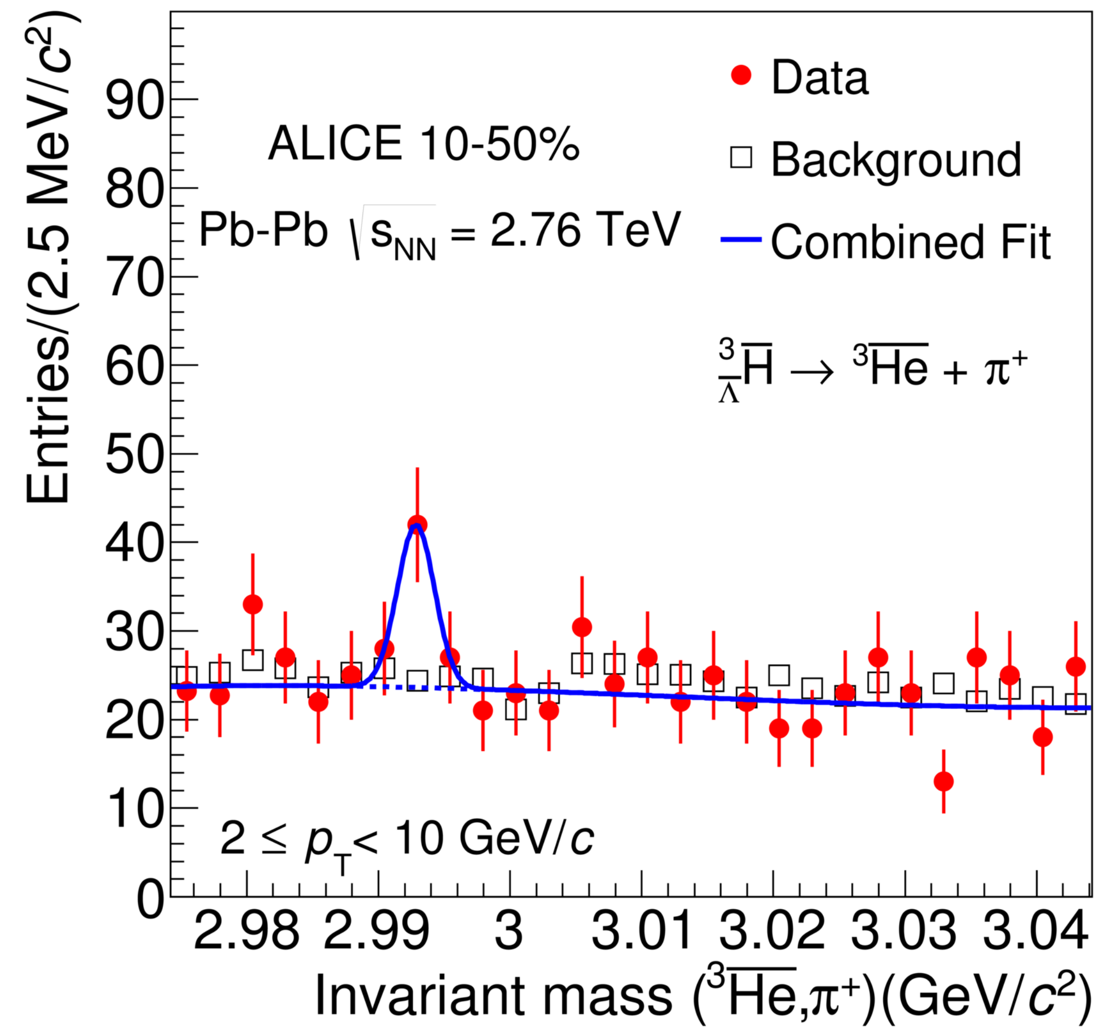
- Comparison of experimental limits for different possible CPT violating sectors
  - Additional tests since 2015 include anti-hydrogen charge and 1s-2s transition

ALICE-PUBLIC-2015-002

Hypertriton $^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$



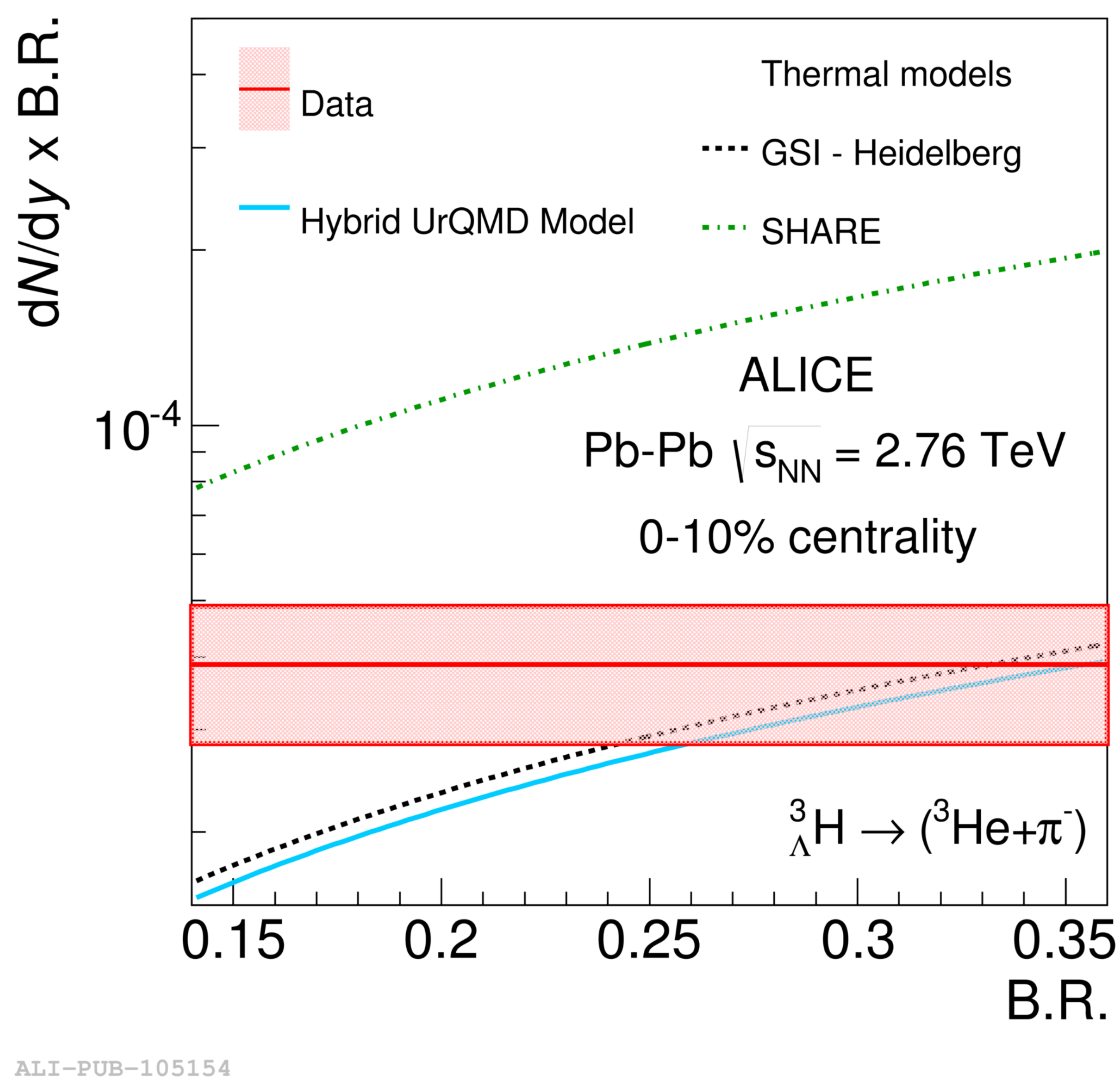
ALI-PUB-105130



ALI-PUB-105134

- Lightest hypernucleus: pnΛ
- Reconstruct weak decay with displaced vertex
- Small binding energy, Λ separation energy
  - 130±50 keV

Hypertriton model comparison

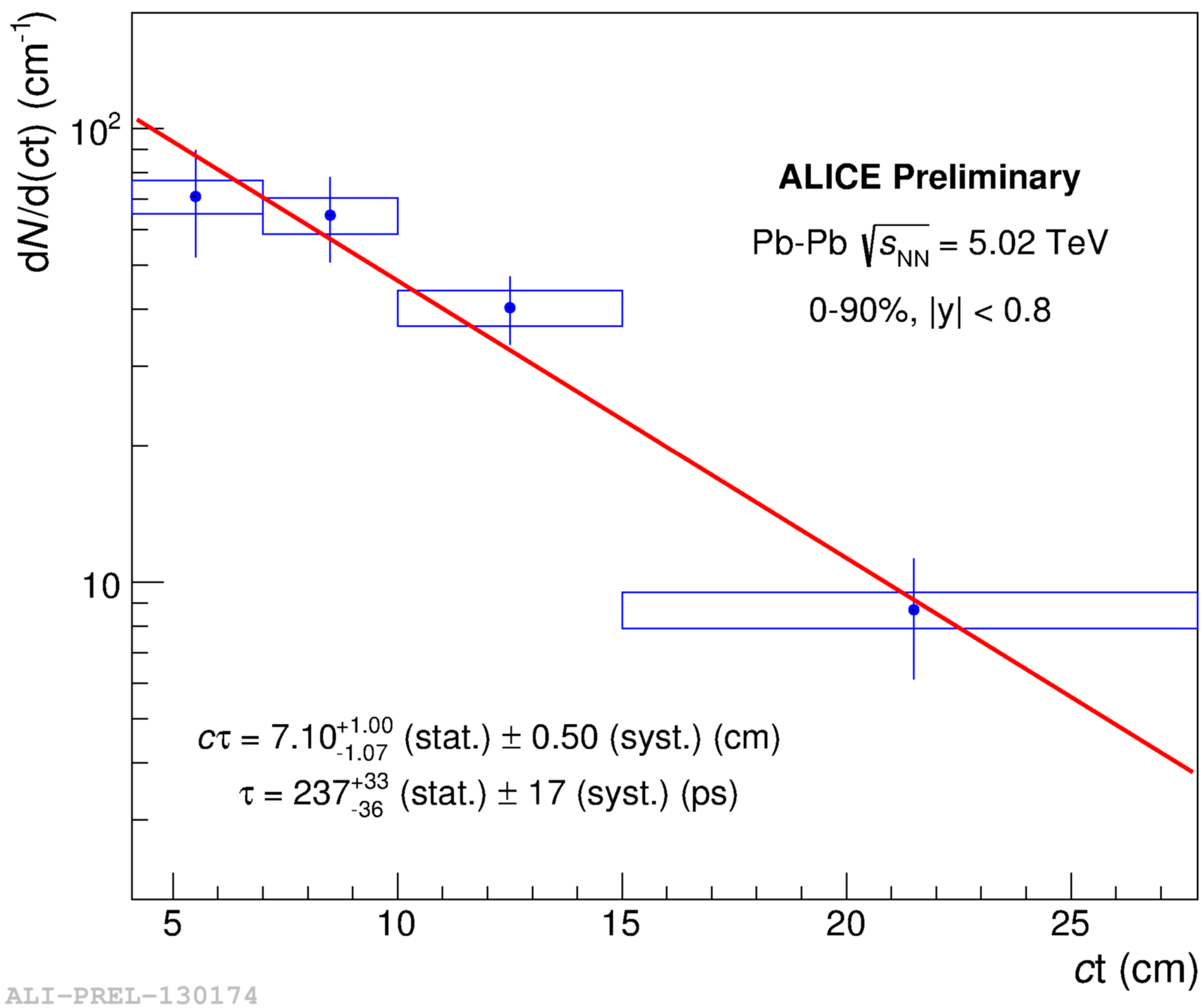


- Branching ratio (B.R.) not so well determined
- Shows yield × B.R. vs B.R. around preferred value of 25%
- Equilibrium model with T=156 MeV gives consistent description

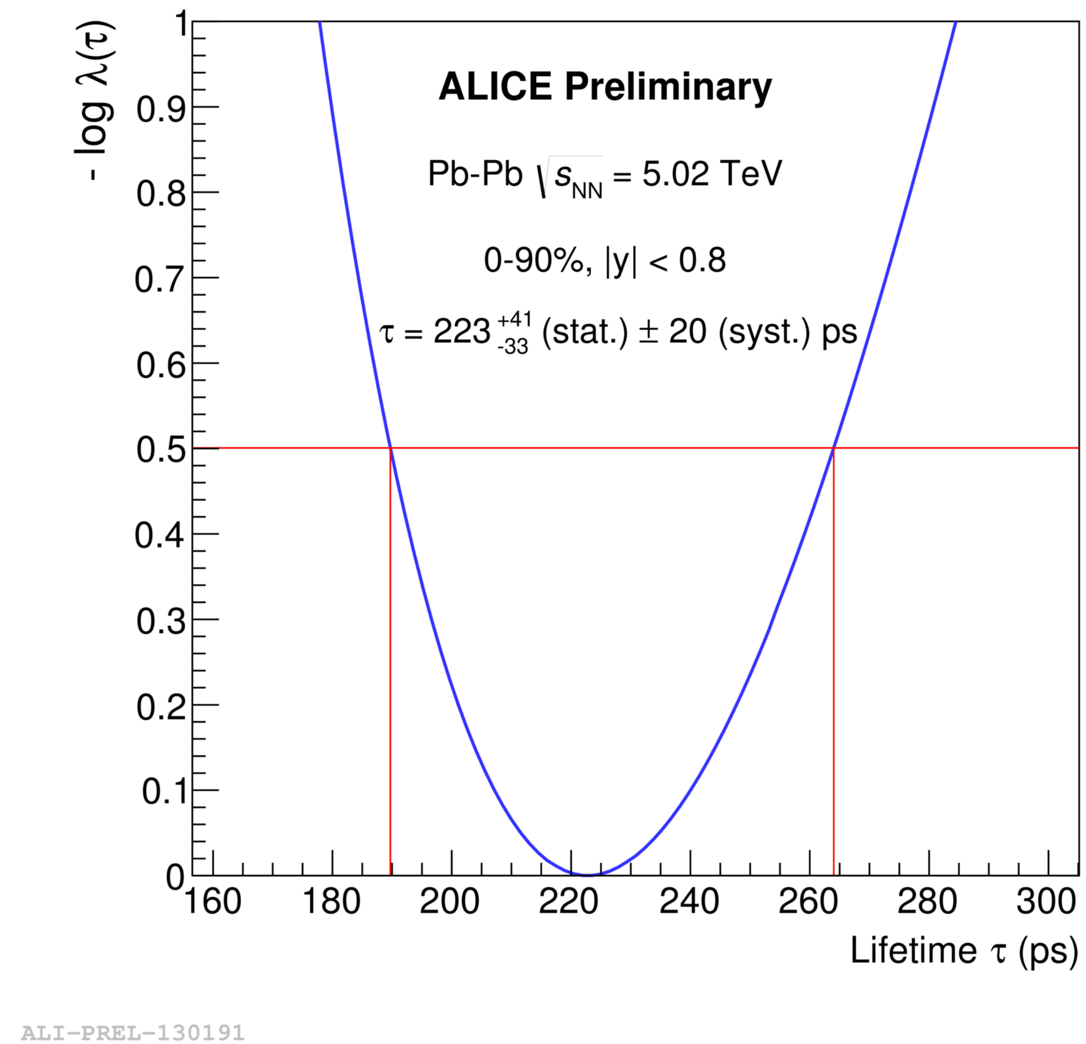
Phys. Lett. B 754 (2016) 360–372

Hypertriton lifetime

[ALI-PREL-130174]



[ALI-PREL-130191]



- New 2015 Pb-Pb data
- Two methods for estimation

- Most accurate lifetime determination to date

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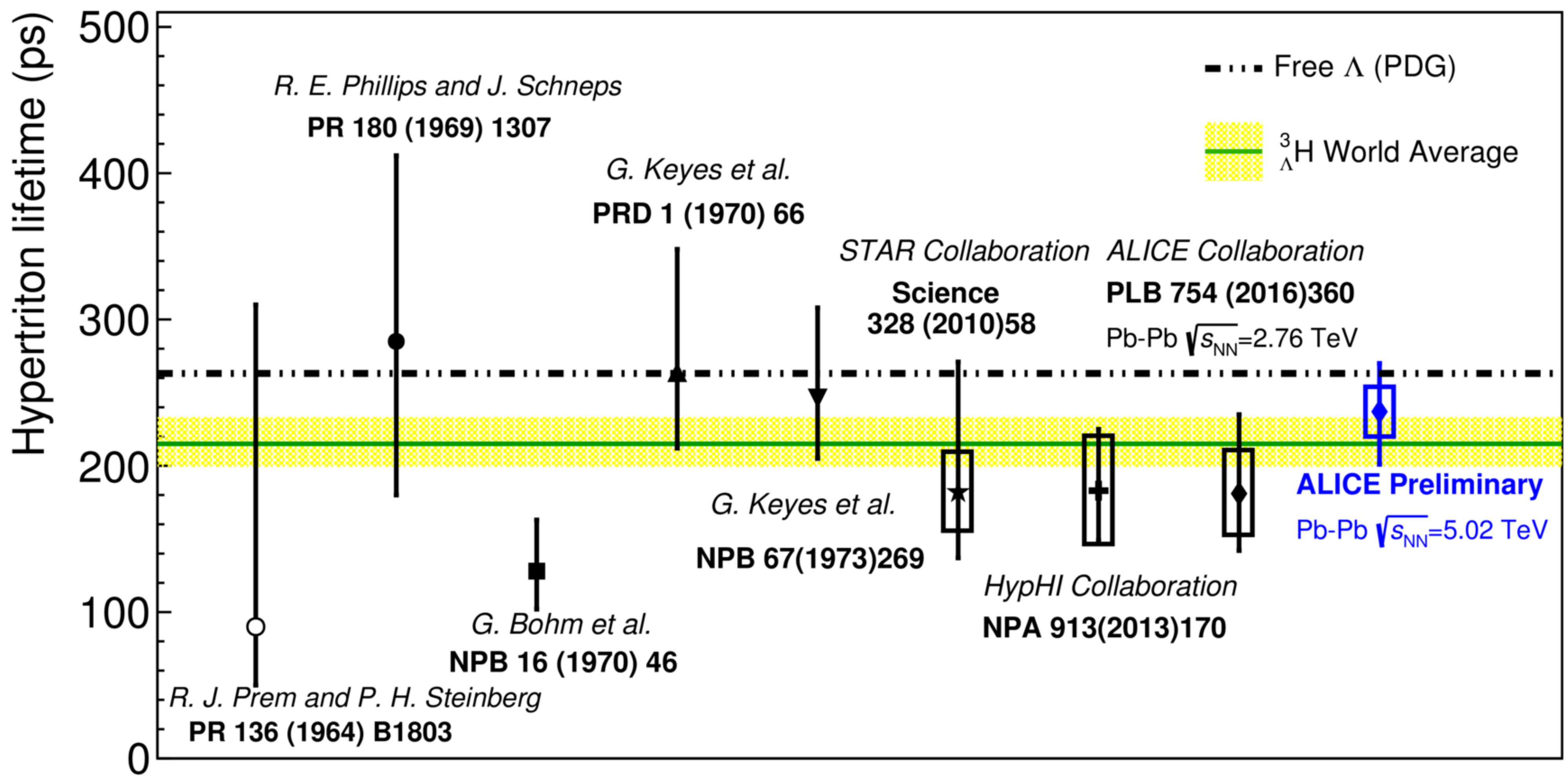
Hypertriton lifetime

ALI-PREL-130195



ALI-PREL-130195

- World average unexpectedly below the free Λ lifetime
- Further improvements on precision are possible in future

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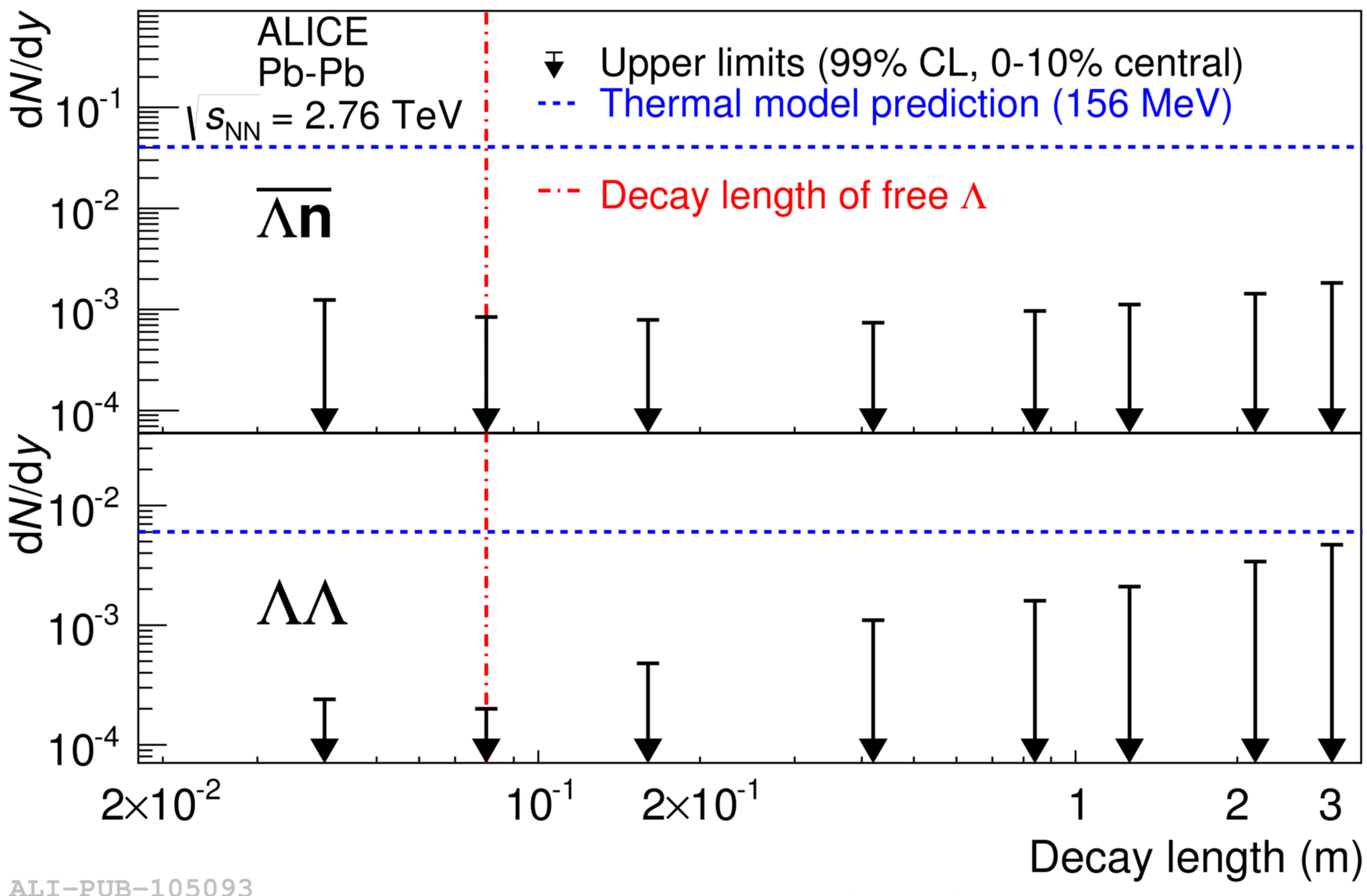
Strange di-baryon searches

$$(\overline{\Lambda n})_b \rightarrow \bar{d} + \pi^+$$



- Weak decay searches
  - H-dibaryon with ΛΛ bound state
  - Λn bound state (as antiparticle)

Phys. Lett. B 752 (2016) 267–277

$$(\Lambda\Lambda)_b \rightarrow \Lambda + p + \pi^-$$

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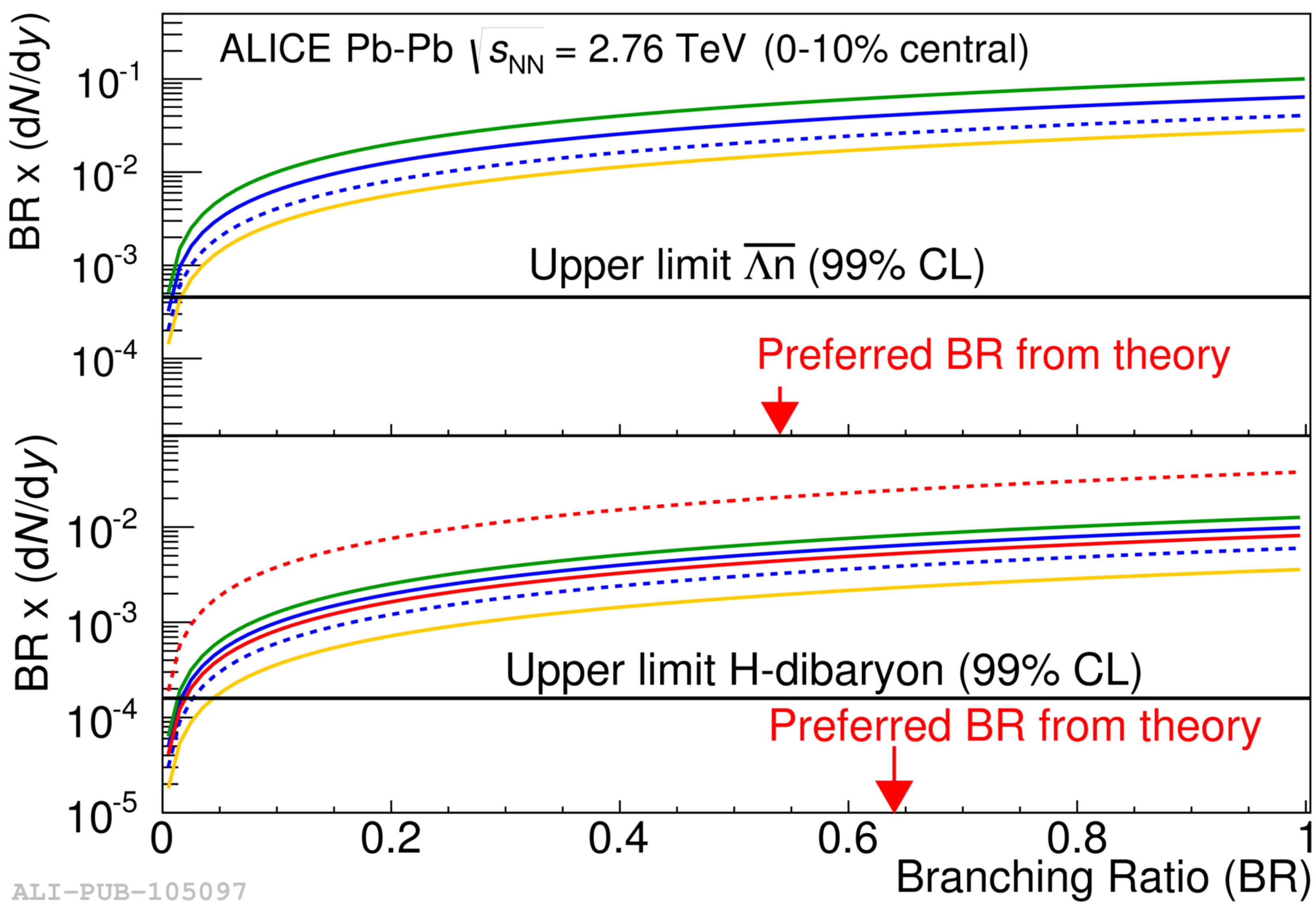
Strange di-baryon searches



- Comparison of limit to predicted yields × B.R. from thermal model
- Only **very** small B.R. values are not ruled out
- *Or* production is not thermal

[Phys. Lett. B 752 (2016) 267–277](#)

The hadronic phase

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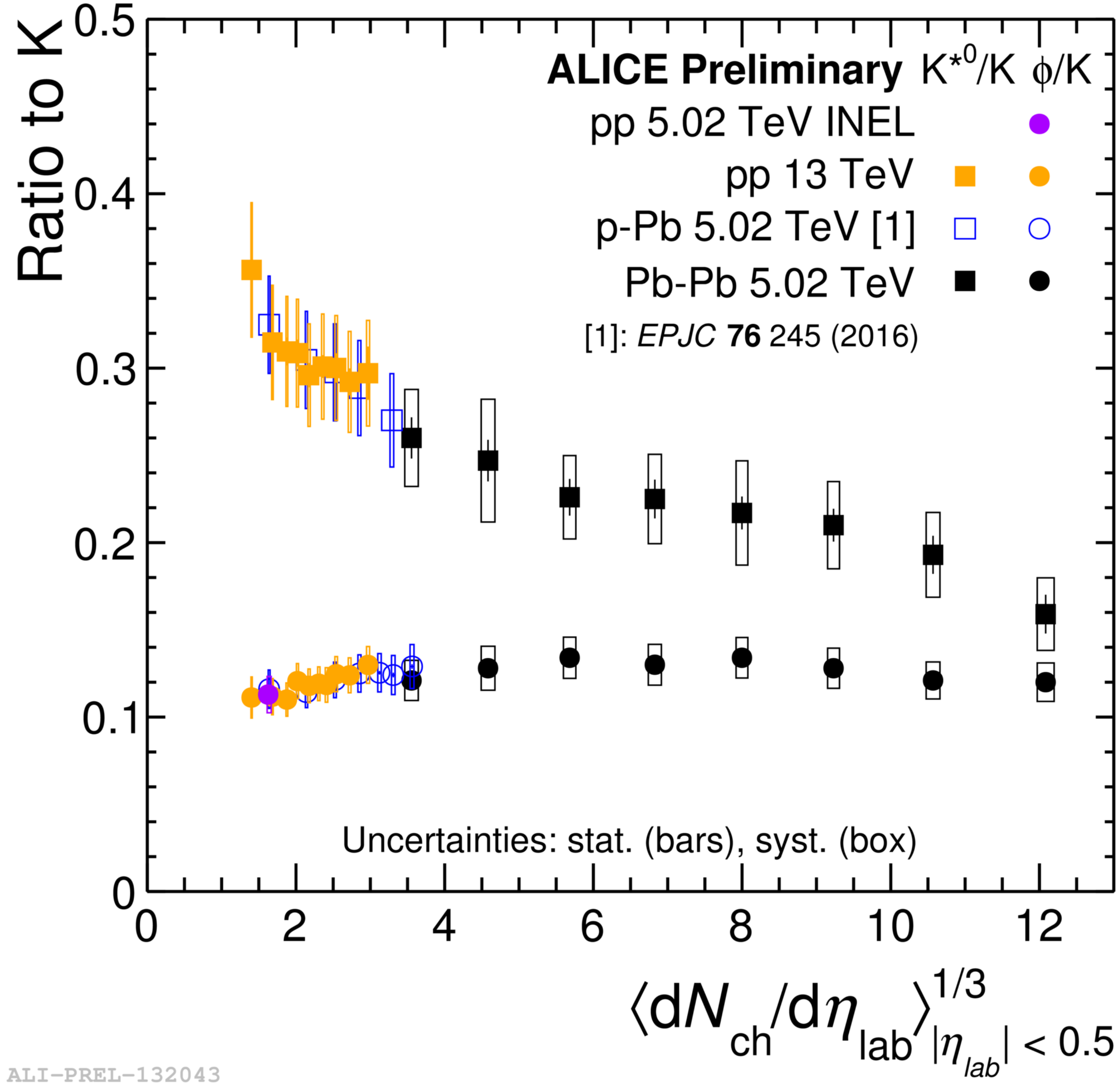
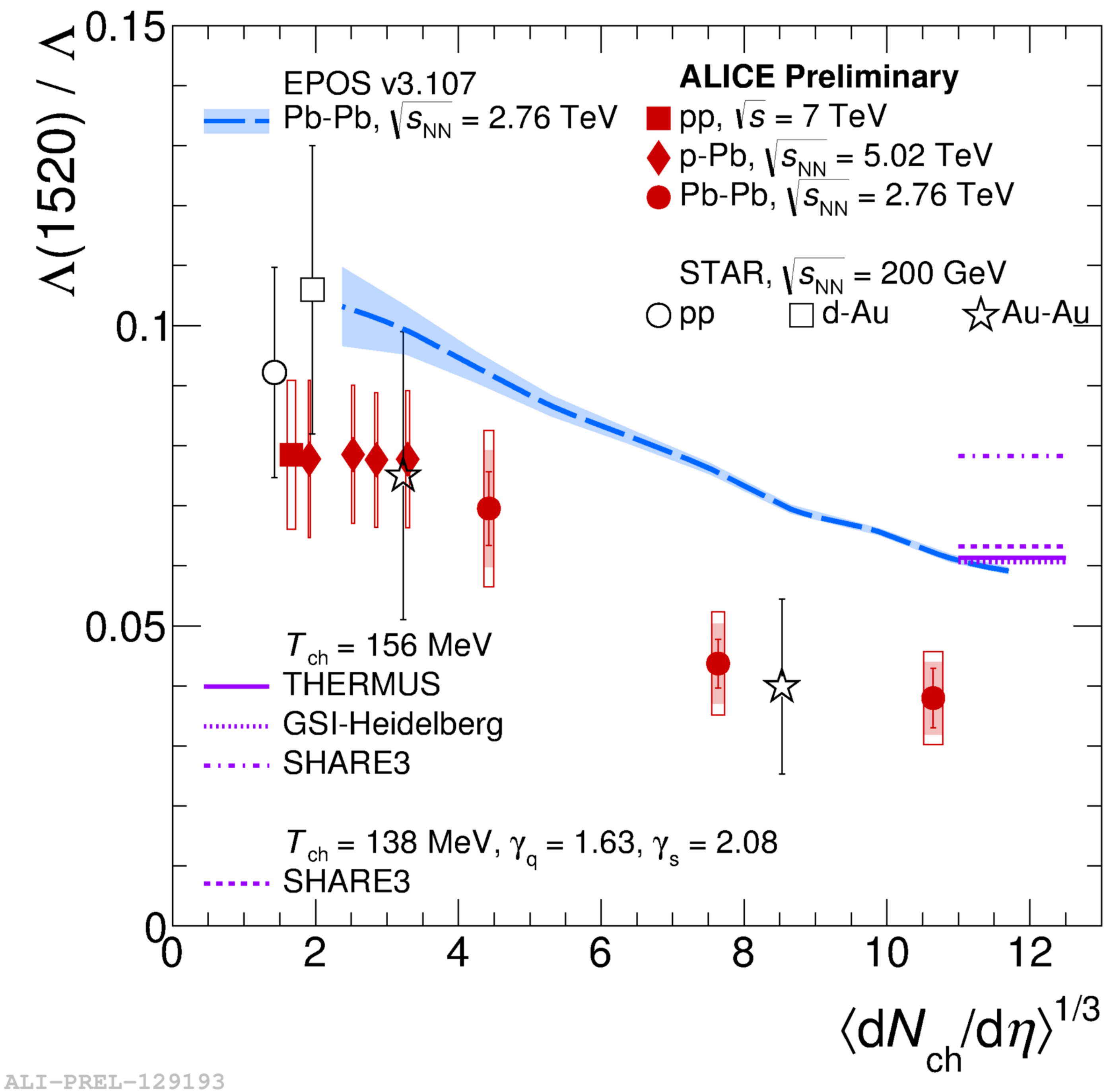
Evidence for hadronic phase



ALI-PREL-132043

- Factor 2 reduction in K*(892)/K ratio from pp to central Pb-Pb collisions
- Evidence for scattering of π and K decay products

Evidence for hadronic phase



- Factor 2 reduction in $\Lambda^*(1520)/\Lambda$ ratio from pp to central Pb-Pb collisions
- Evidence for scattering of p and K decay products

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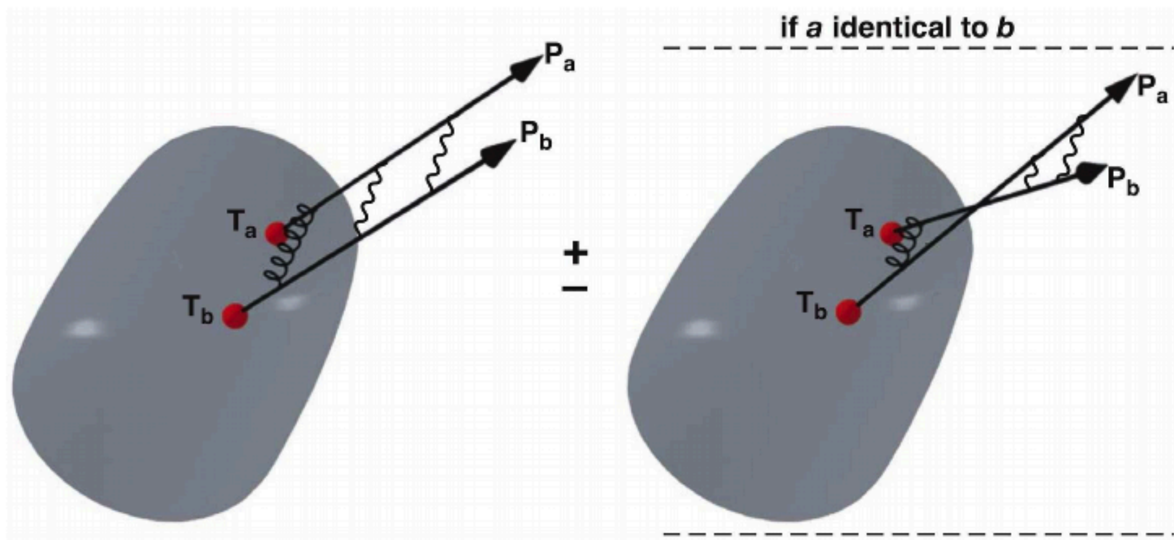
Hadron-hadron correlations - concept

M.Lisa *et al*, Annu. Rev. Nucl. Part. Sci. 55 (2005), 357

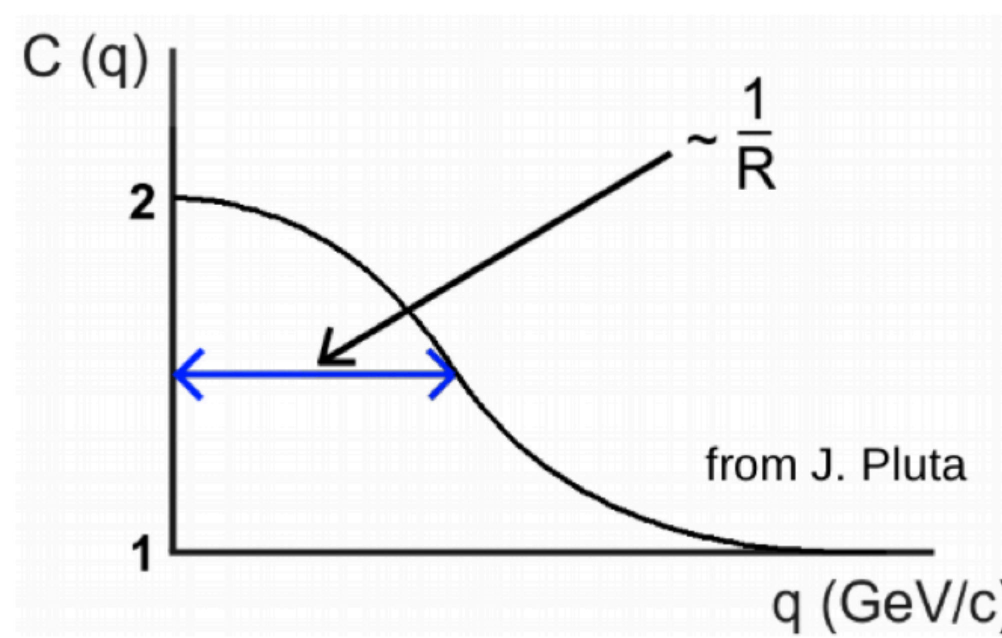


$$q = p_a - p_b, \quad q = 2 \cdot k^*$$

$$r = T_a - T_b$$

$$C(q) = 1 + \lambda \cos(q.r)$$

- Correlation function C(q)
- R is the "HBT radius"
- Correlation function inversely proportional to R



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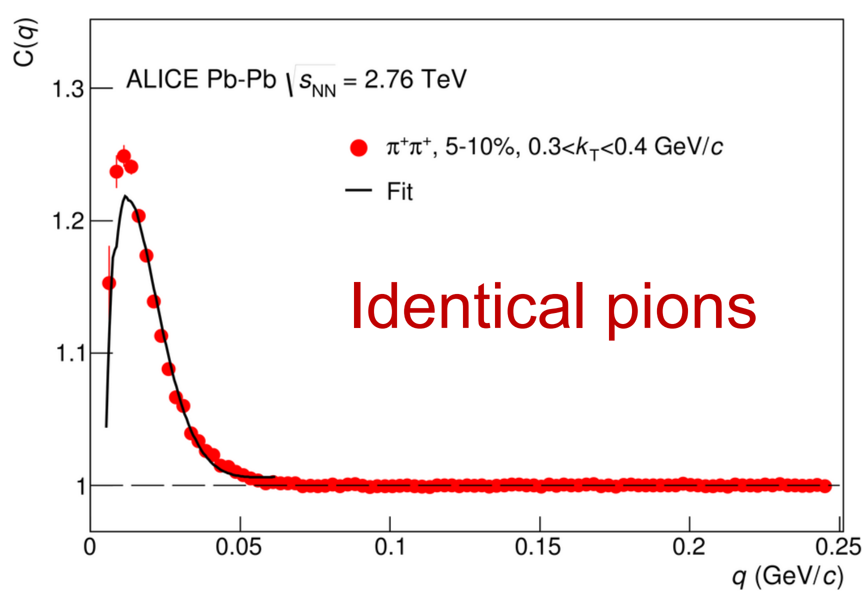
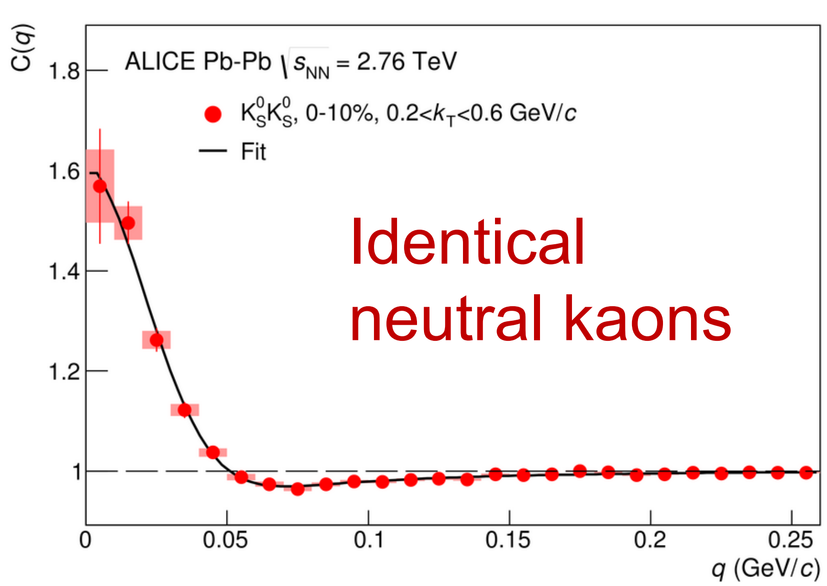
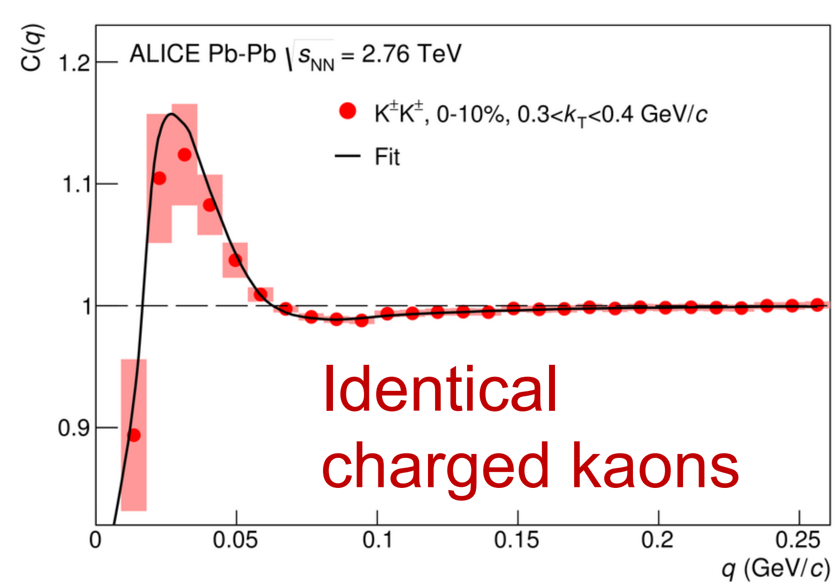
Hadron-hadron correlations - examples



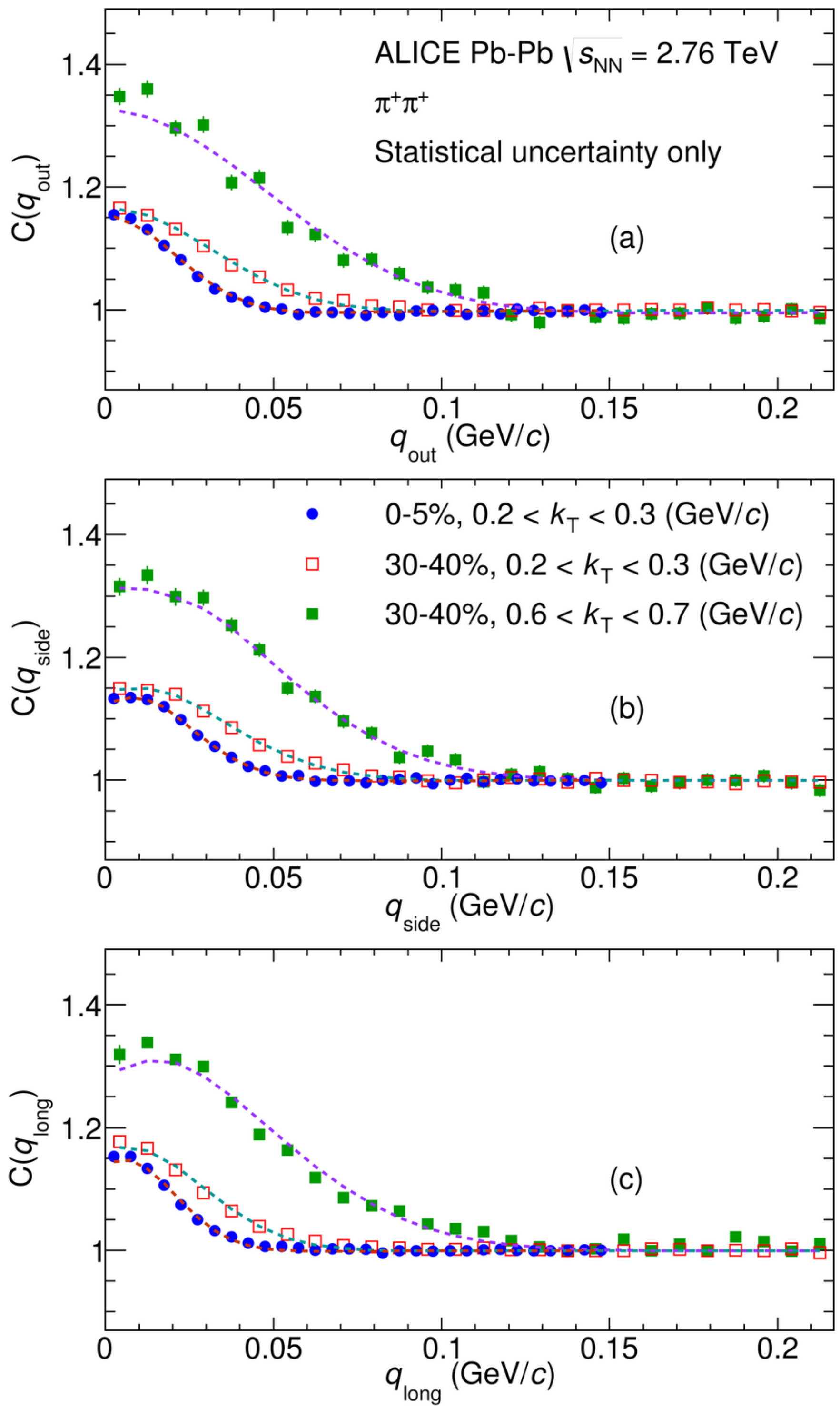
- Experimentally
  C(q) = A(q)/B(q)
  where A is formed by pairs from same event and B background pairs from mixed events





PRC 92 (2015) 054908

Hadron-hadron correlations - examples



- Experimentally **C(q) = A(q)/B(q)** where A is formed by pairs from same event and B background pairs from mixed events

- Figure shows 3-d decomposition of q and R
- Demonstrates dependence of width on centrality (system size)
- It is possible to measure volume and lifetime of system

PRC 93 (2016) 024905

Extracting interaction parameters

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$$C(q) = \int S(r) |\Psi(q,r)|^2 d^4 r$$

Measured correlation

Emission function
(size and shape)

Pair wave function
(includes cross section)

- Following derivation, assuming final state interaction (FSI), by Lednicky & Lyuboshitz
  - Sov. J. Nucl. Phys. 35, 770 (1982)
- 3 parameters characterize C(q)
  - radius R
  - Scattering length f_0
  - Effective radius d_0

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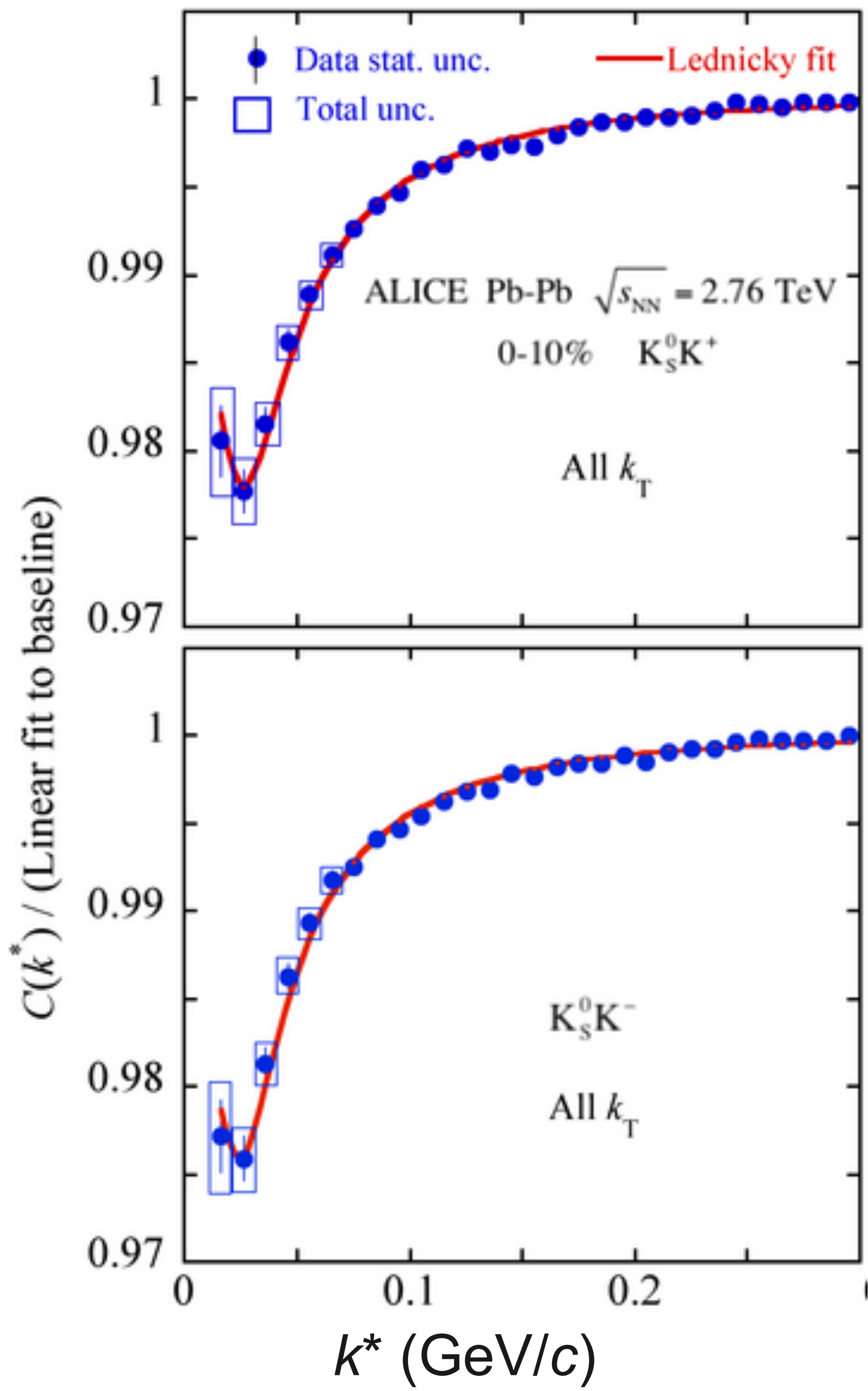
Non-identical kaon correlations

- Correlations sources
  - Quantum statistics - $K^0_S K^0_S$ and $K^{\pm}K^{\pm}$
  - Coulomb FSI - $K^{\pm}K^{\pm}$
  - Strong FSI - $K^0_S K^0_S$ via $f_0(980)$ and $a_0(980)$ resonances

- What about $K^0_S K^{\pm}$ pairs?
  - Only strong FSI and **only** a_0 has isospin=1
  - Possibility to study a_0
  - Fits to data using a_0 FSI parameterization



arXiv:1705.04929

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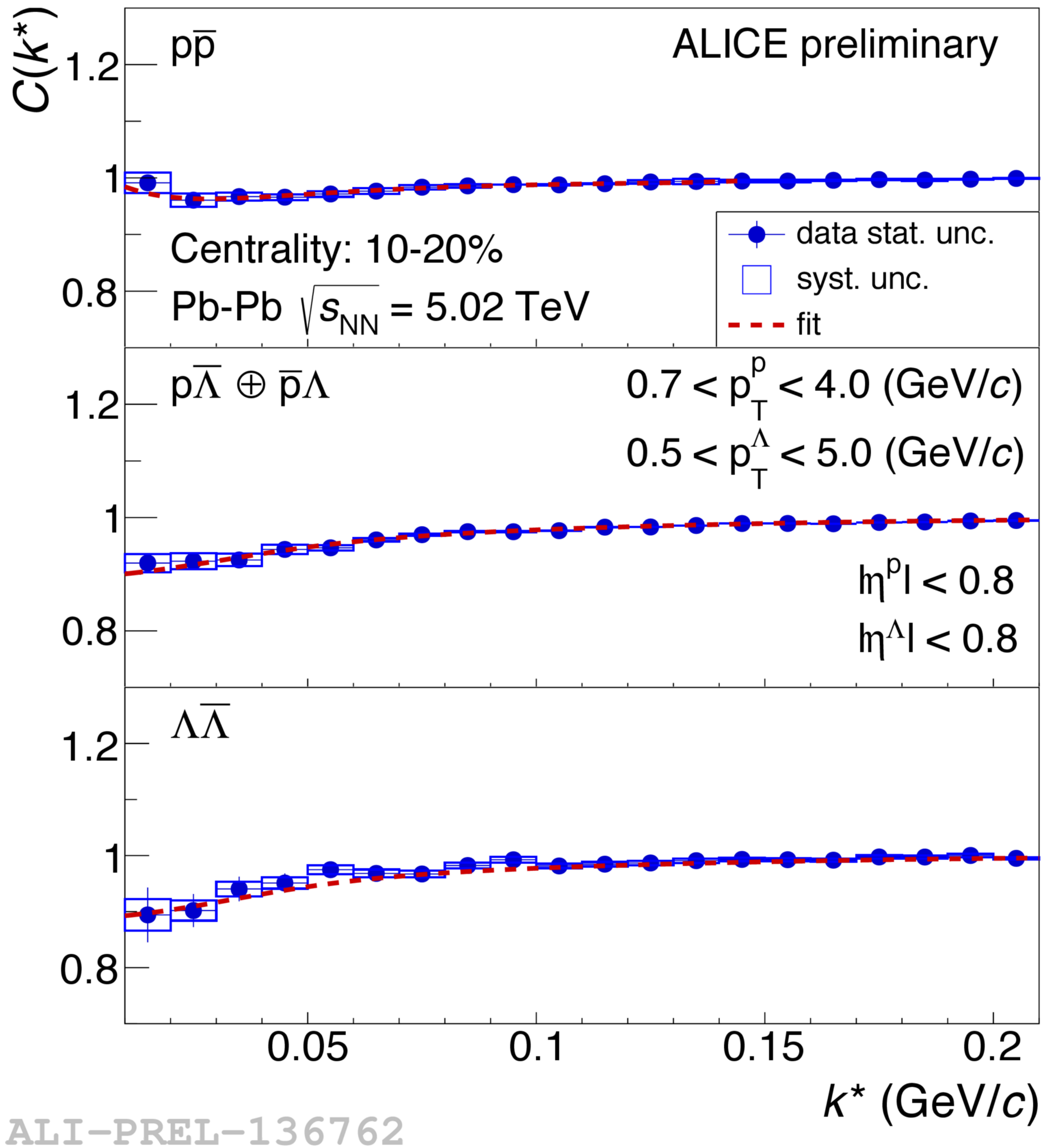
Baryon-(anti)baryon correlations



ALI_PREL-136762

- Multiplicity of p, Λ and their anti-particles permit correlation studies
- Three correlations functions formed as b—anti-b are combined
- This is an example for one centrality interval at one centre-of-mass energy

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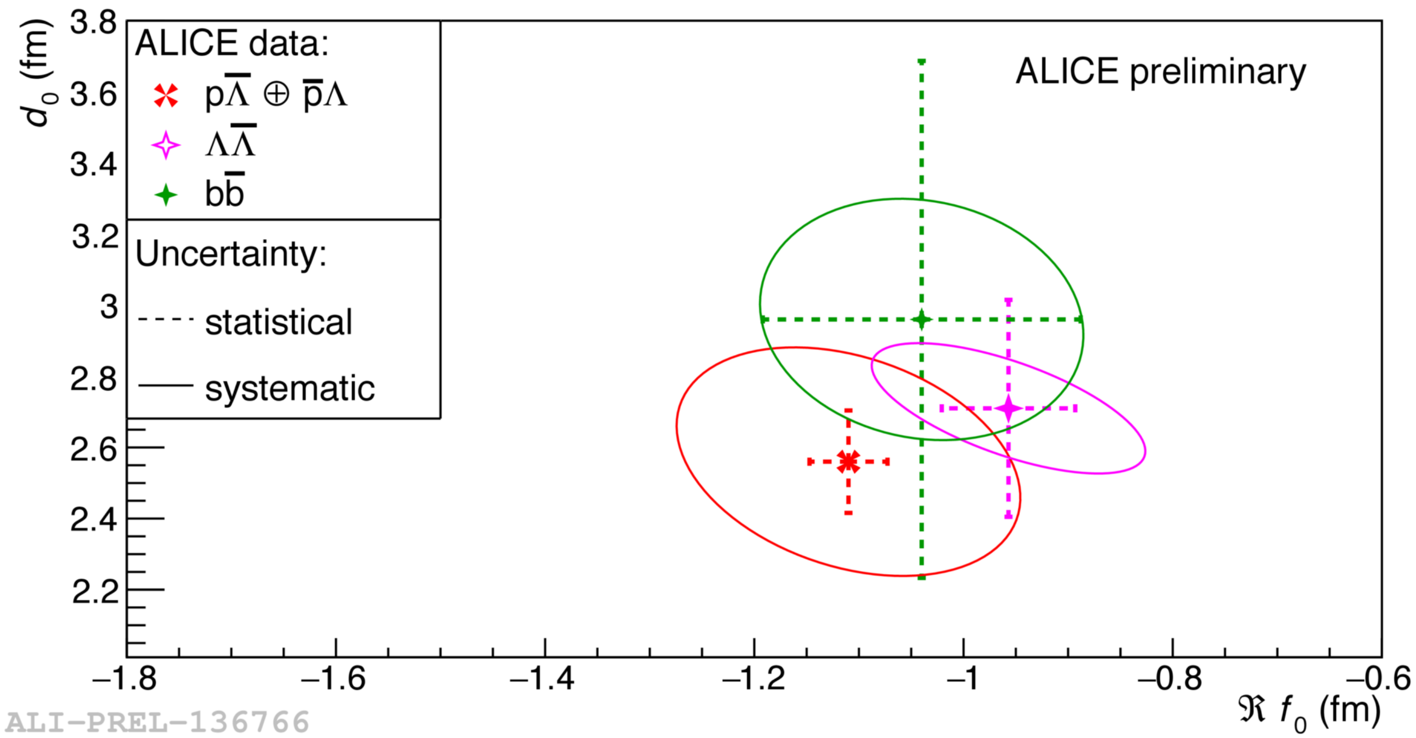
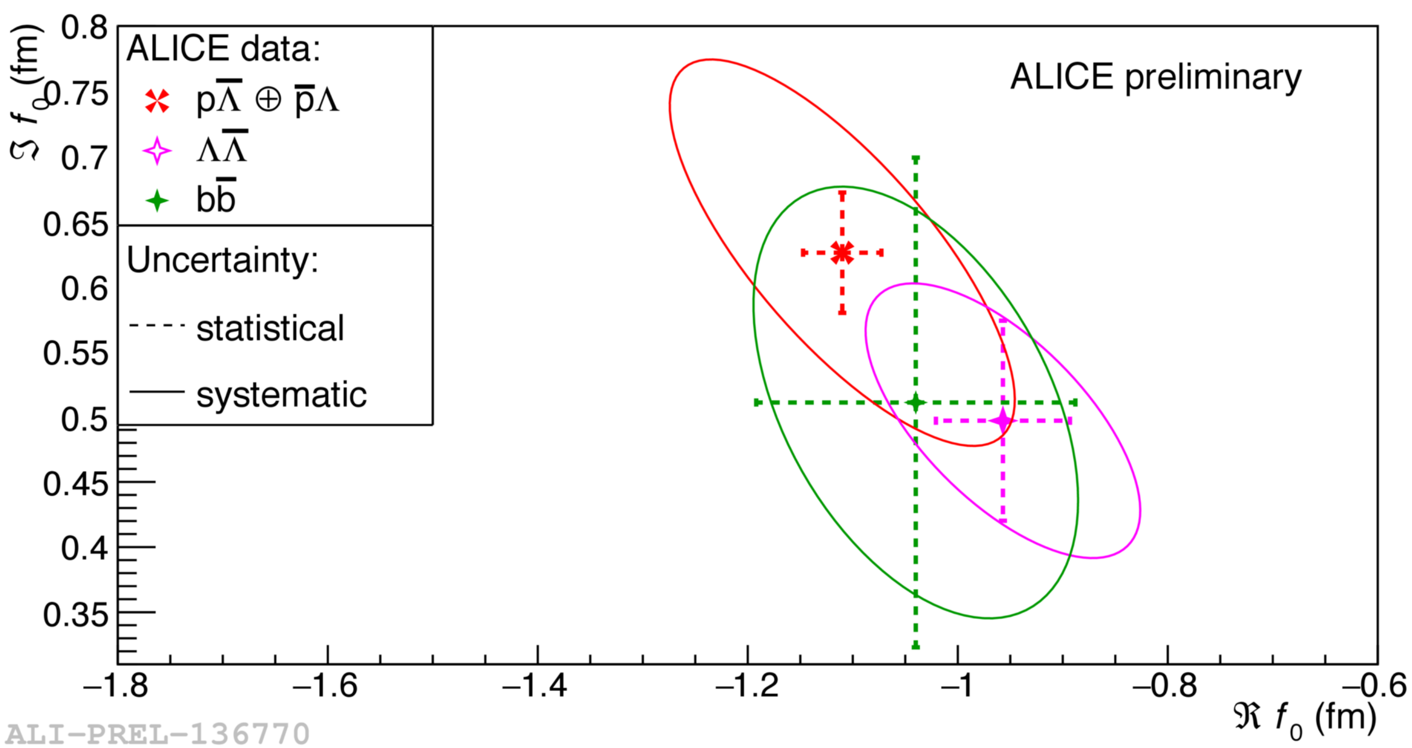
Baryon correlations - extracted parameters

ALI-PREL-136766



ALI-PREL-136770



- Interaction parameters extracted from simultaneous fits to correlation functions in different centralities and energies
  - R will vary but interaction parameters have to be common
- Results favour **slightly repulsive** interaction between baryons and antibaryons

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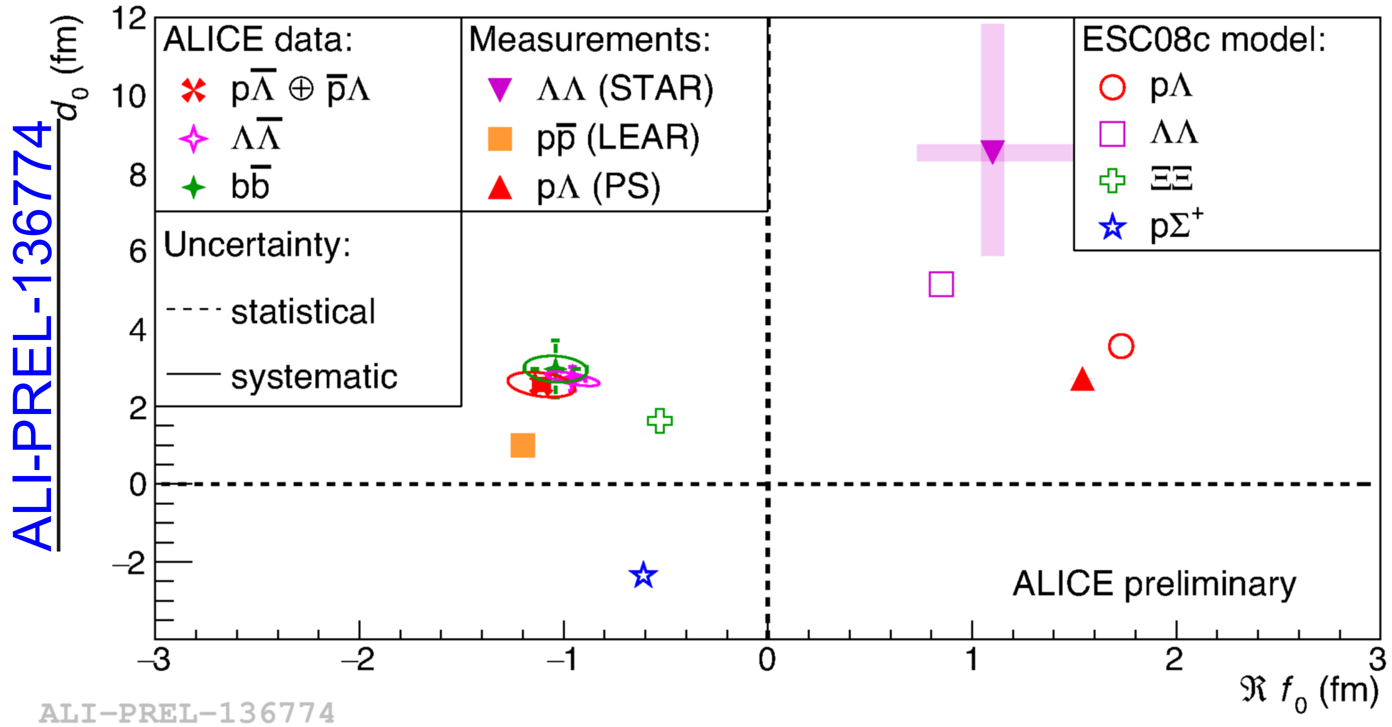
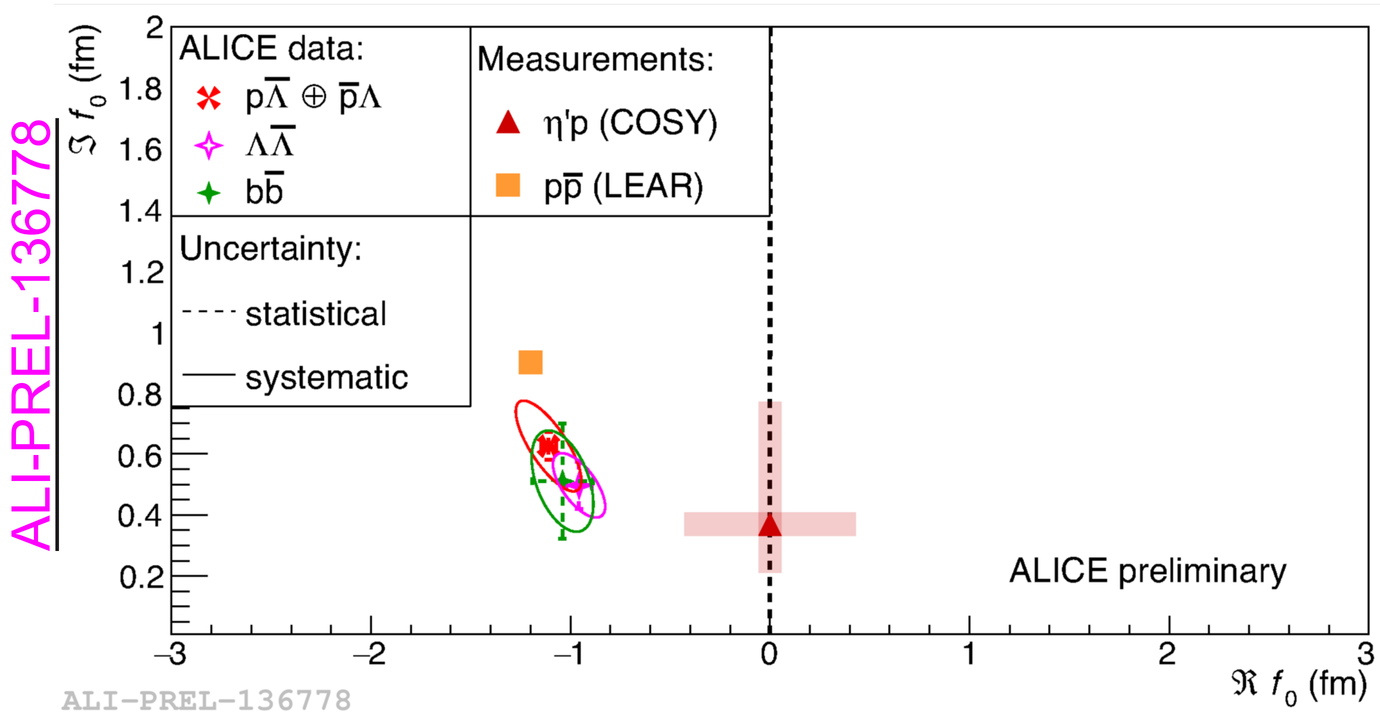
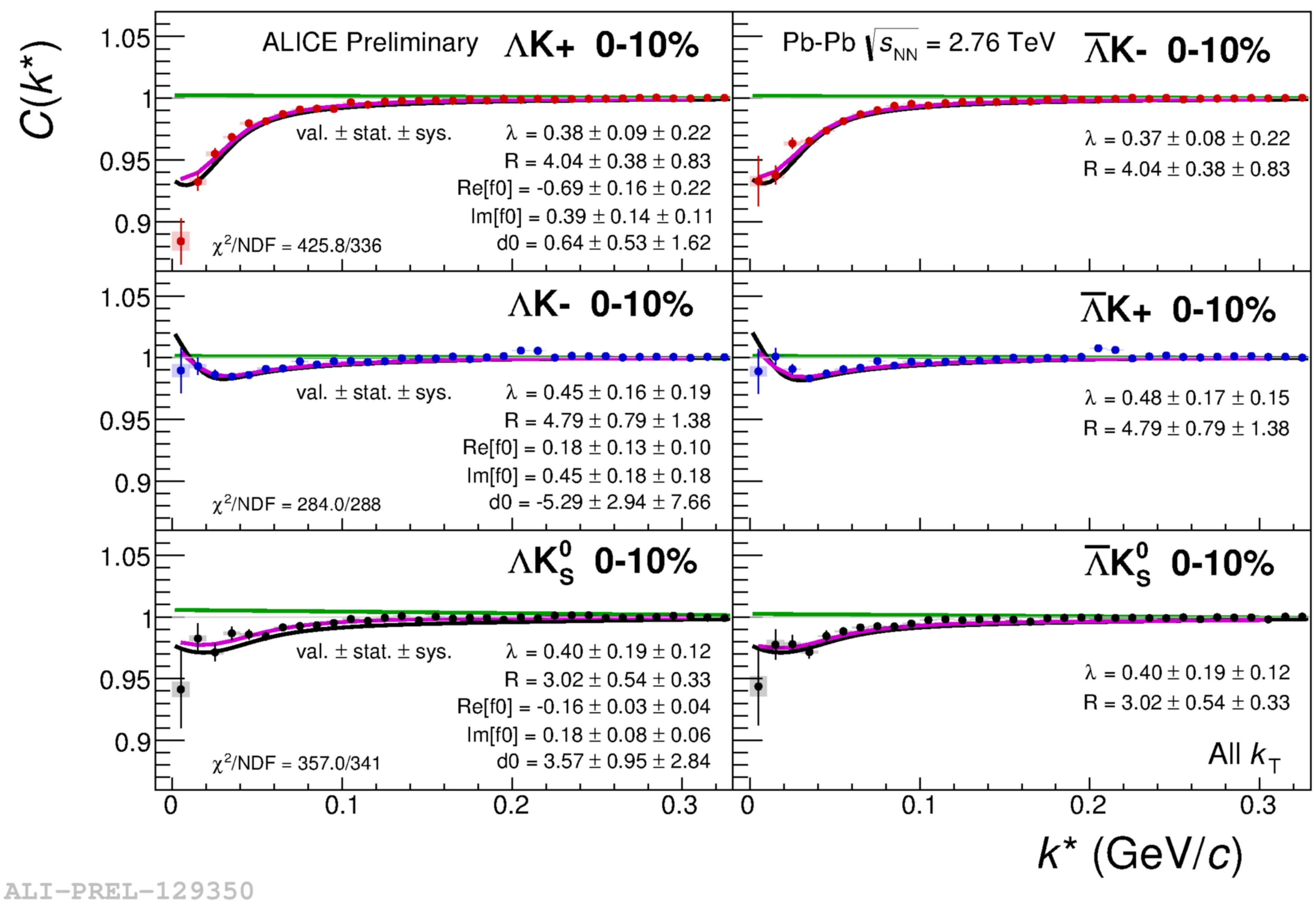
Baryon correlations - extracted parameters





- d_0 vs Re(f_0)
  - Comparison to other experimental results and to model
- Im(f_0) vs Re(f_0)
  - Comparison to experiment

Baryon-meson correlation (example)



- Can learn about Λ-K interactions too
- All combinations of Λ, anti- Λ and K^+, K^-, K^0_S available

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Outlook and conclusion

- ALICE has demonstrated ability to use high-energy collisions to make some unique measurements in
  - Properties of exotic hadrons
  - Constraining matter–anti-matter differences
  - Measuring hadron-hadron interaction properties
- Many of these became feasible, or were much improved, during LHC Run 2 (2015-present)
- Expect further progress in Run 3 (2020-) when ALICE will be upgraded to record up to 100 times more data!

Stay tuned and thank you