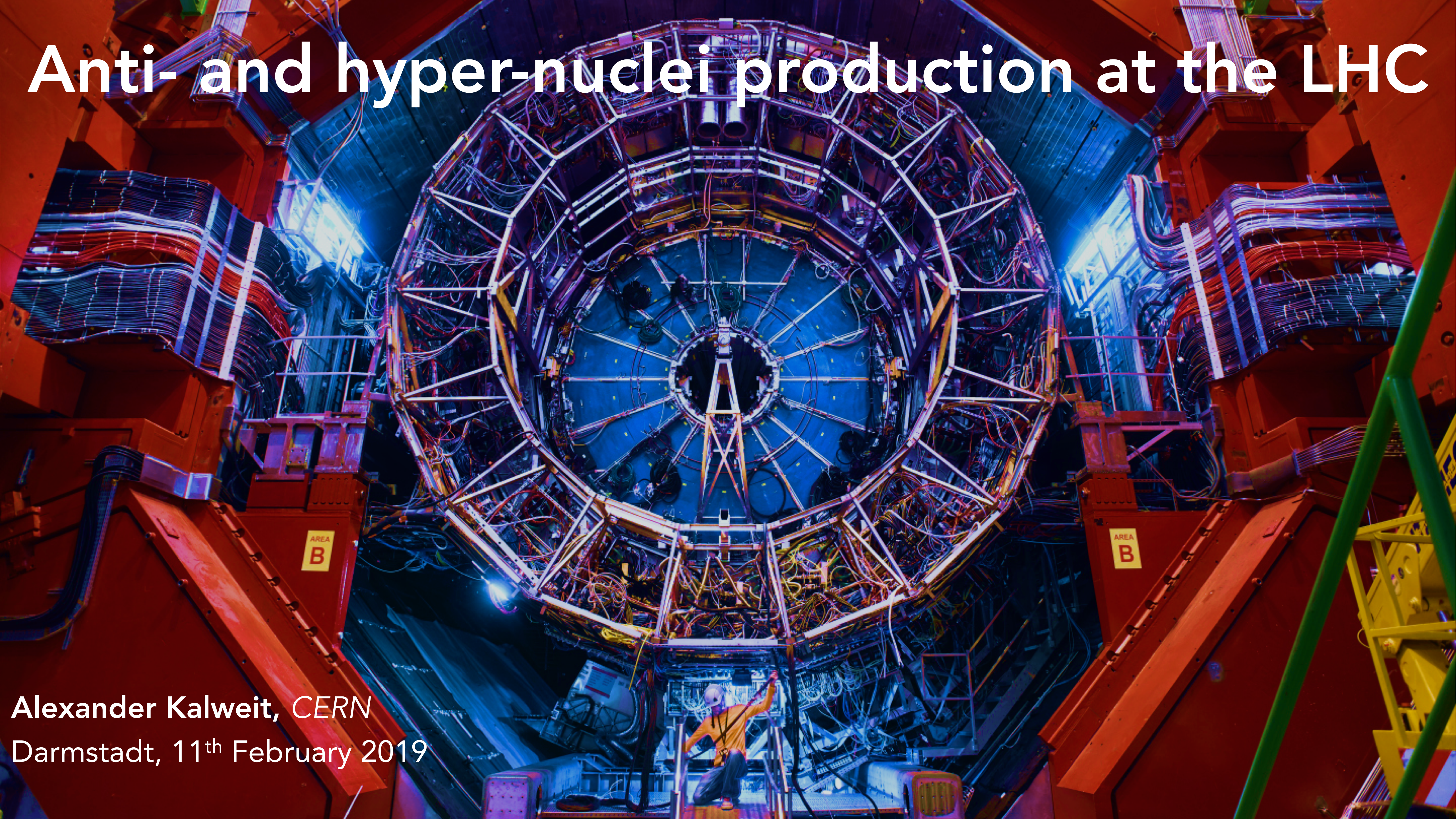


Anti- and hyper-nuclei production at the LHC

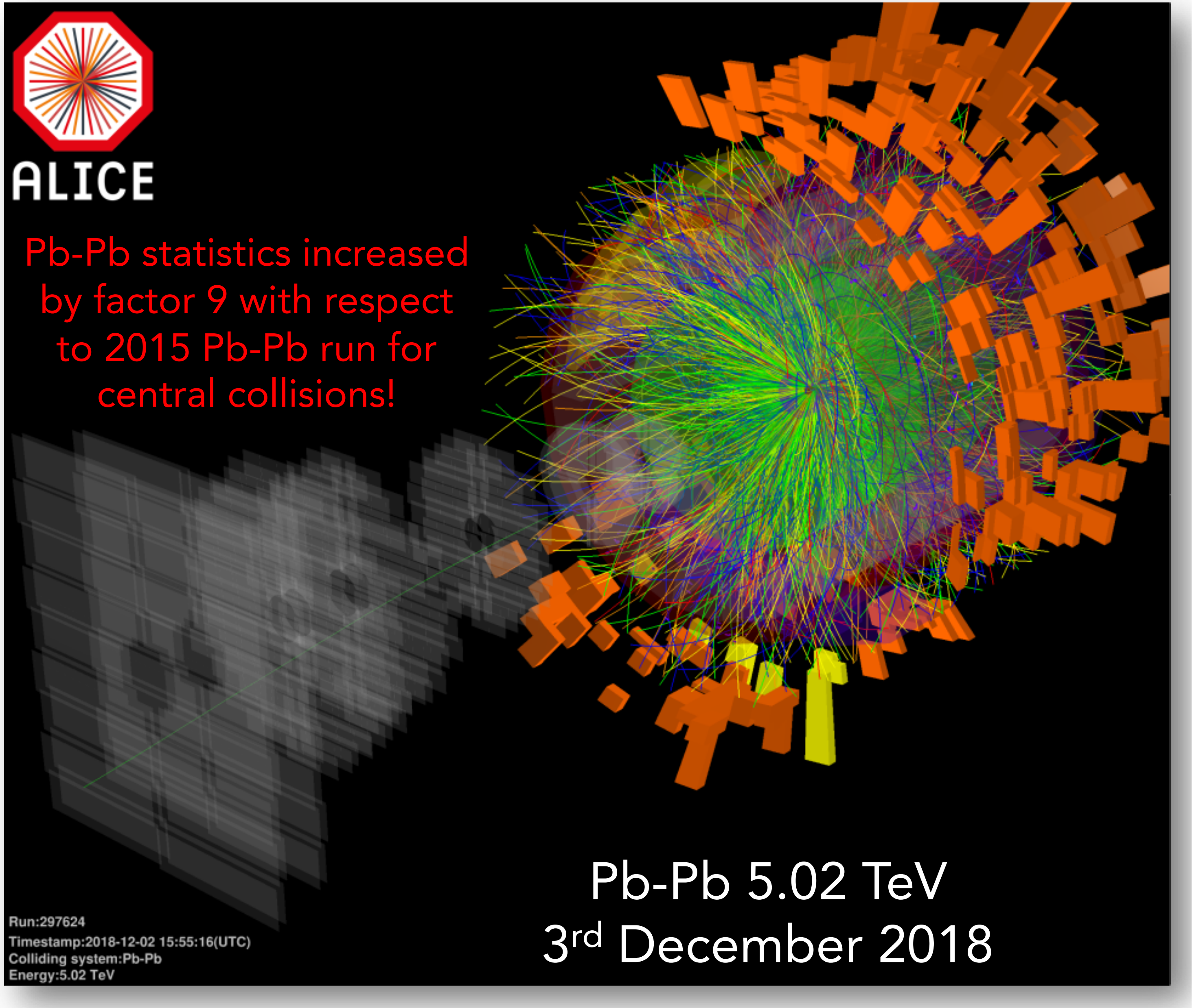
Alexander Kalweit, *CERN*

Darmstadt, 11th February 2019

Introduction

The study of anti- and hyper-nuclei in ALICE developed from a niche topic to **one of the main pillars of the current and future experimental program**.

→ This talk tries to give an overview of the existing and future results. *However, it is only a small selection*!

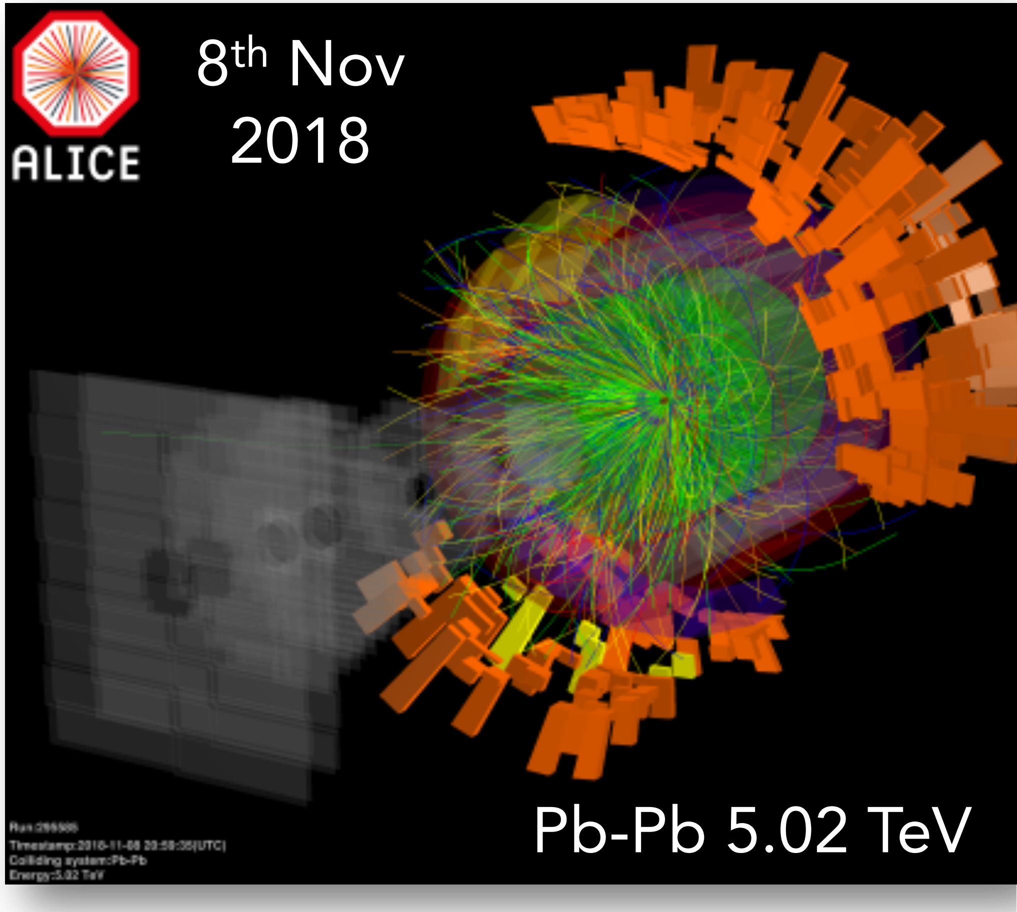


Pb-Pb statistics increased by factor 9 with respect to 2015 Pb-Pb run for central collisions!

Pb-Pb 5.02 TeV
3rd December 2018

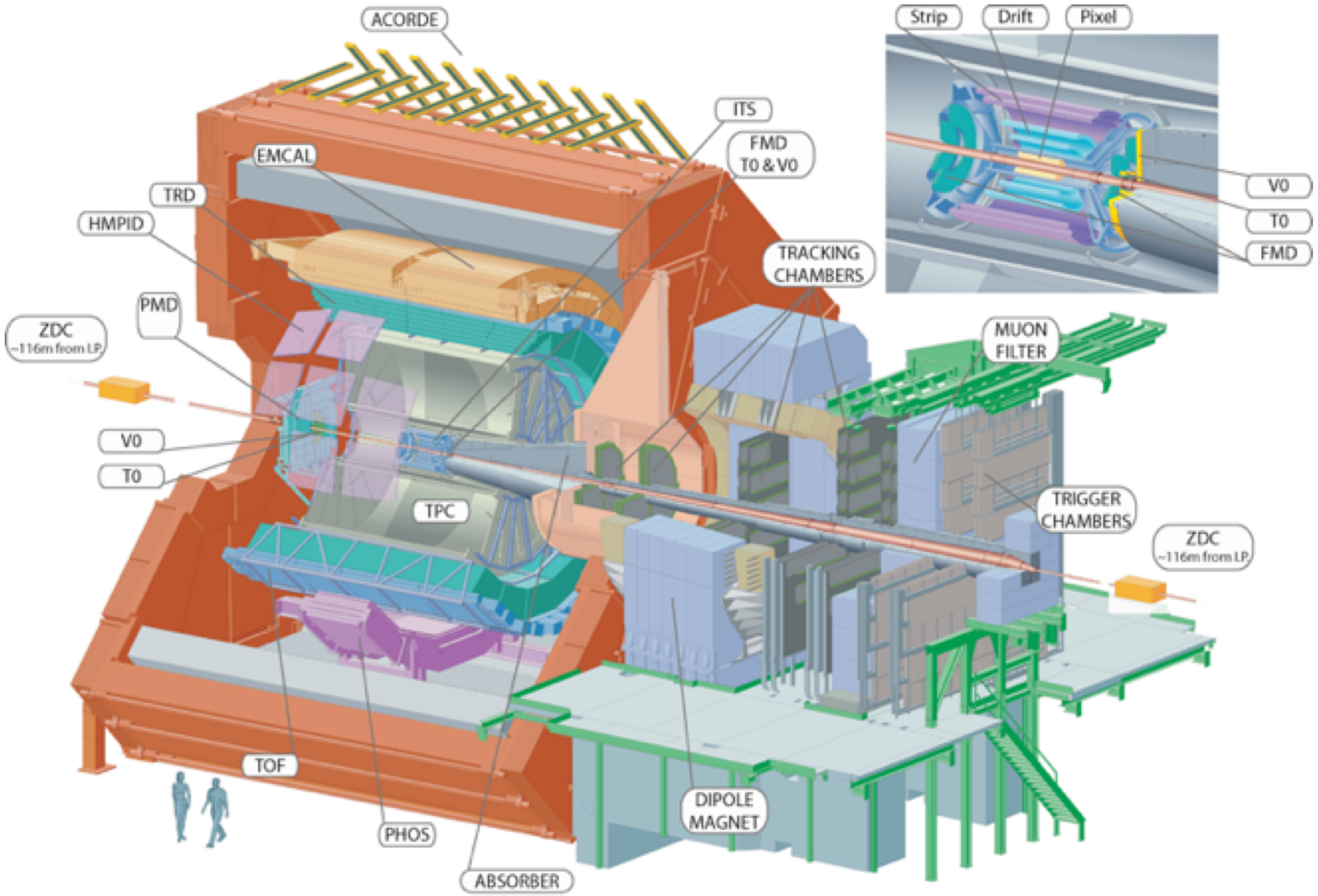
Eight years of data taking

System	**Year(s)**	**$\sqrt{s_{NN}}$ (TeV)**	**L_{int}**
Pb-Pb	2010-2011	2.76	~75 μb^{-1}
	2015	5.02	~250 μb^{-1}
	2018	5.02	~0.9 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013	5.02	~15 nb^{-1}
	2016	5.02, 8.16	~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013	0.9, 2.76, 7, 8	~200 μb^{-1}, ~100 nb^{-1}, ~1.5 pb^{-1}, ~2.5 pb^{-1}
	2015,2017	5.02	~1.3 pb^{-1}
	2015-2017	13	~25 pb^{-1}

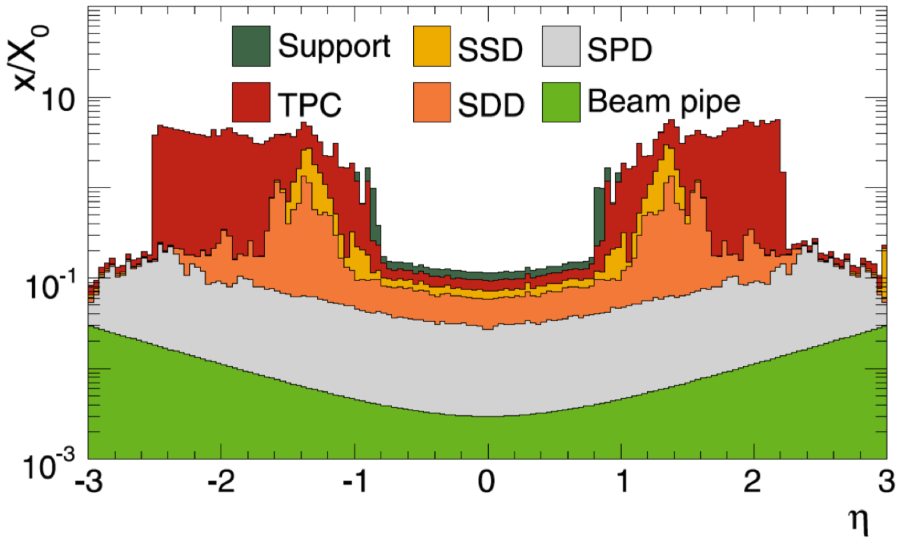


- LHC Run 2 data analysis is in full swing.
- Significant increase in integrated luminosity in pp, p-Pb, and Pb-Pb collisions allows **more and more precise investigation of statistics hungry probes**.

The ALICE Experiment



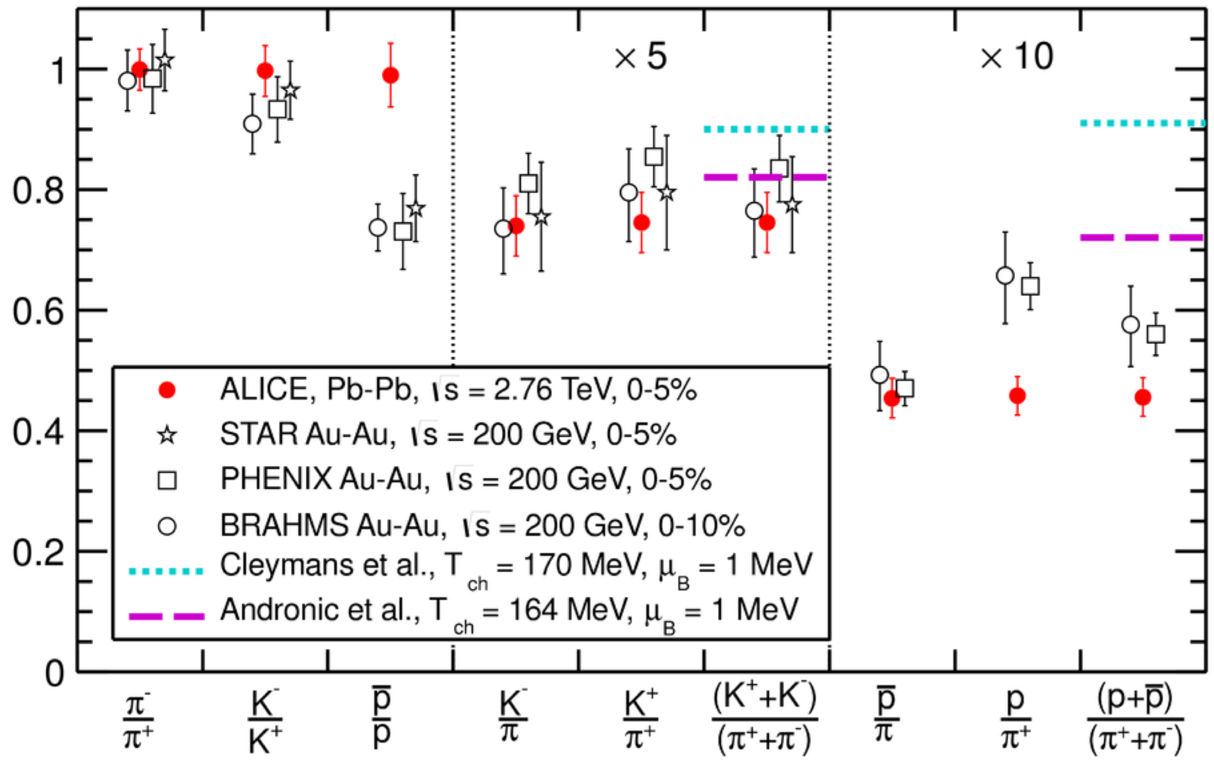
ALICE Central Barrel
B = 0.5 T solenoid, $|\eta| < 0.9$
2π tracking and PID
Lowest material budget in central rapidity region at the LHC



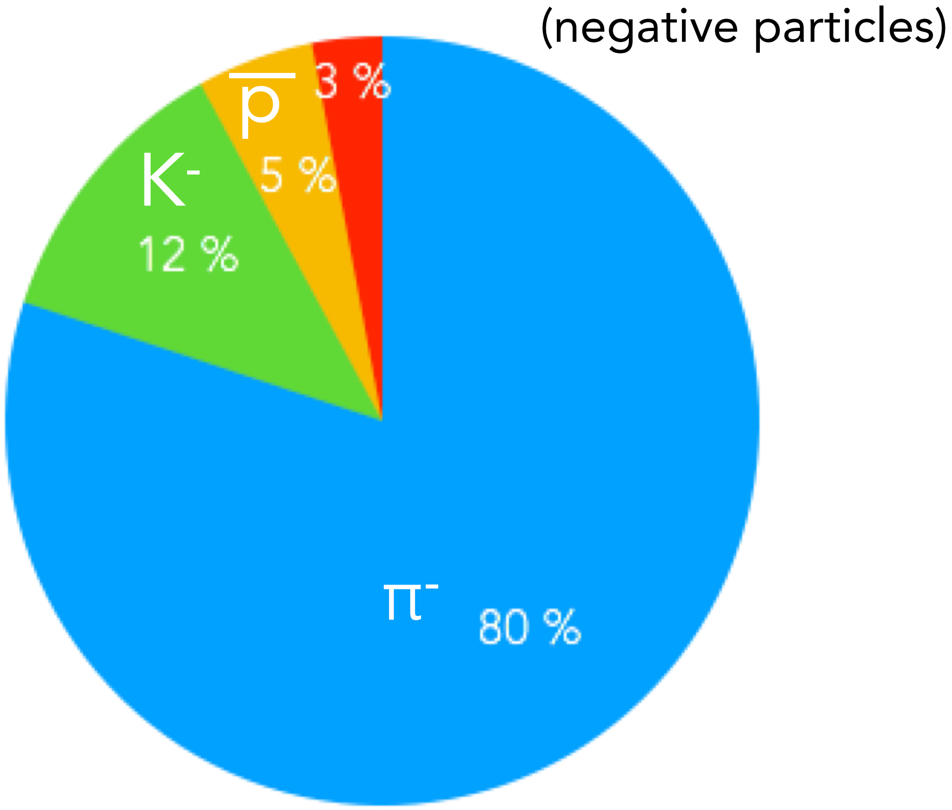
[Eur. Phys. J. C (2009) 62: 237–242]

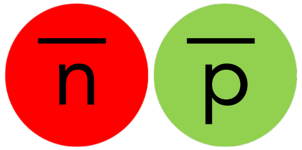
→ Excellent **particle identification** and **continuous tracking** over a wide momentum range (≈ 0.1 GeV/c to ≈ 30 GeV/c) make ALICE an ideal tool for the study of QCD exotica.

Particle production at LHC energies



[Phys. Rev. Lett. 109 (2012) 252301]



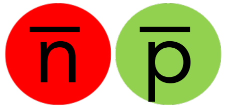


anti-deuteron

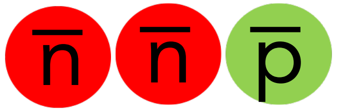
→Only ~5% of all negative particles are anti-protons (the “lightest anti-nucleus”).

→The production of composite anti-particles is **very rare: ~ 0.005% are anti-deuterons.** ➔ Clean PID needed!

Light (anti-)nuclei



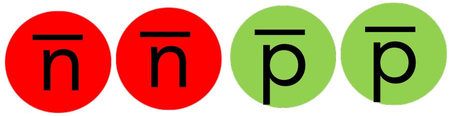
anti-deuteron



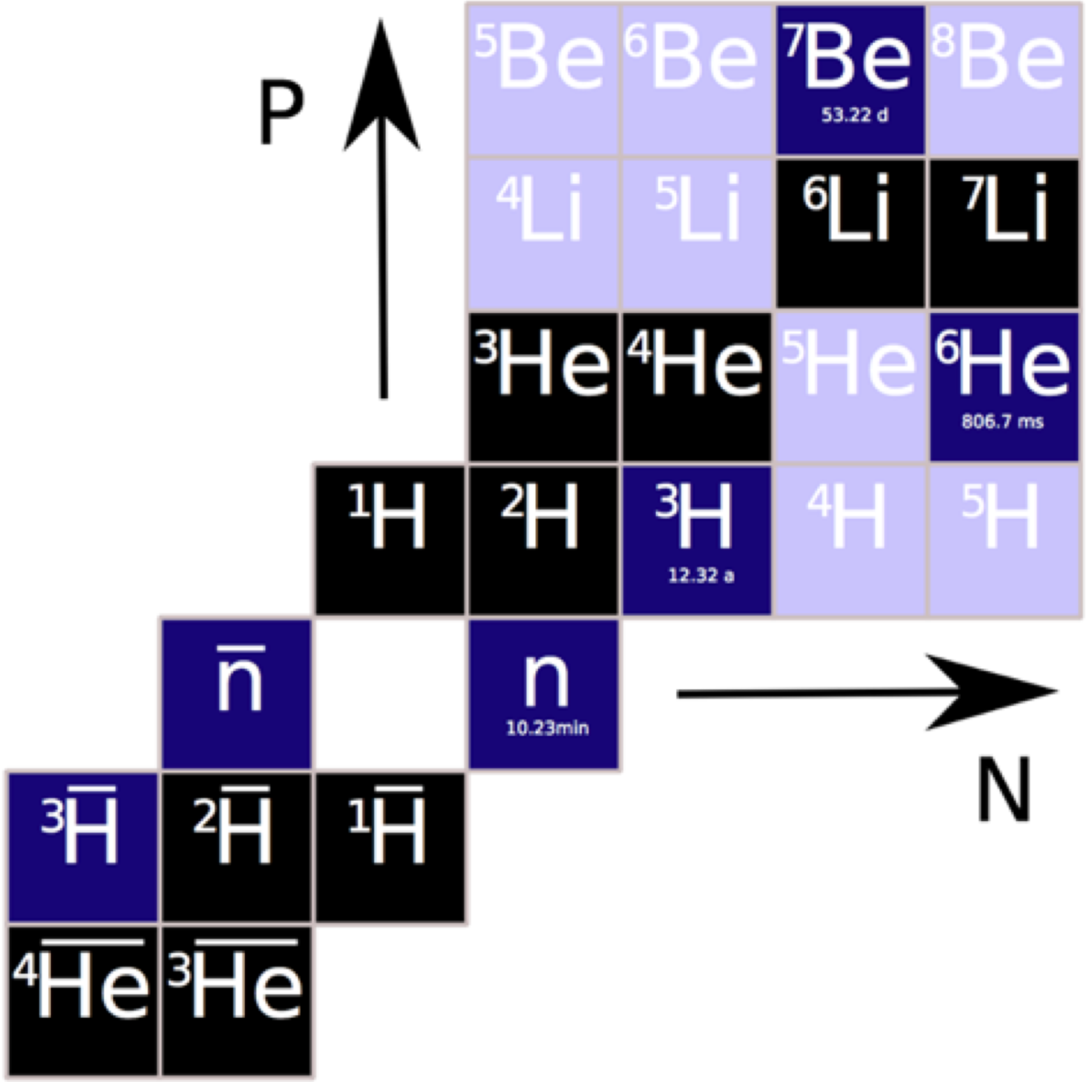
anti-triton

anti-hyper-triton

anti-helium3



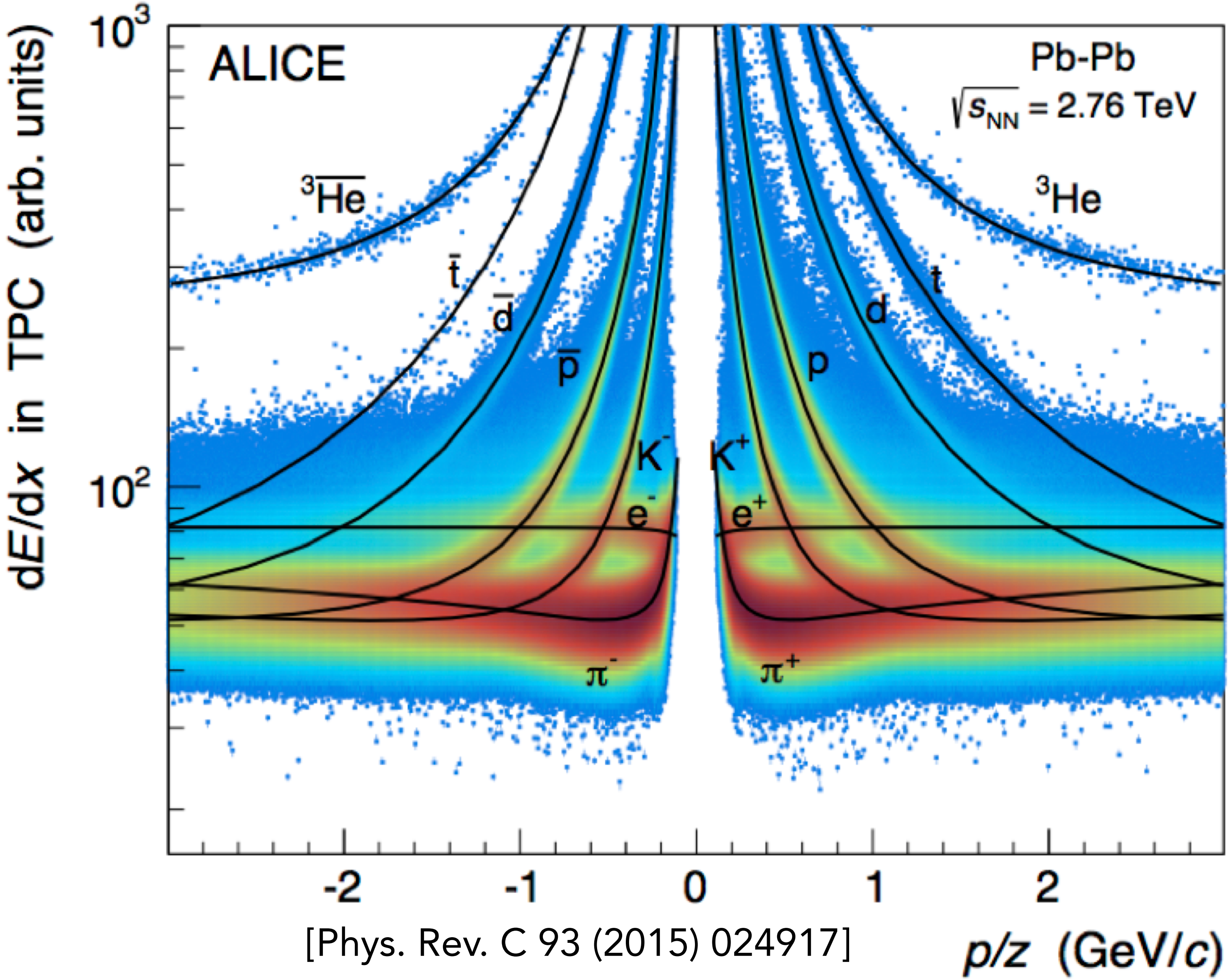
anti-alpha



→ Anti-(hyper)-nuclei up to A=4 are currently in reach at accelerators. The anti-alpha is the heaviest observed so far and was first seen by the STAR experiment in 2011.

1. Experimental aspects

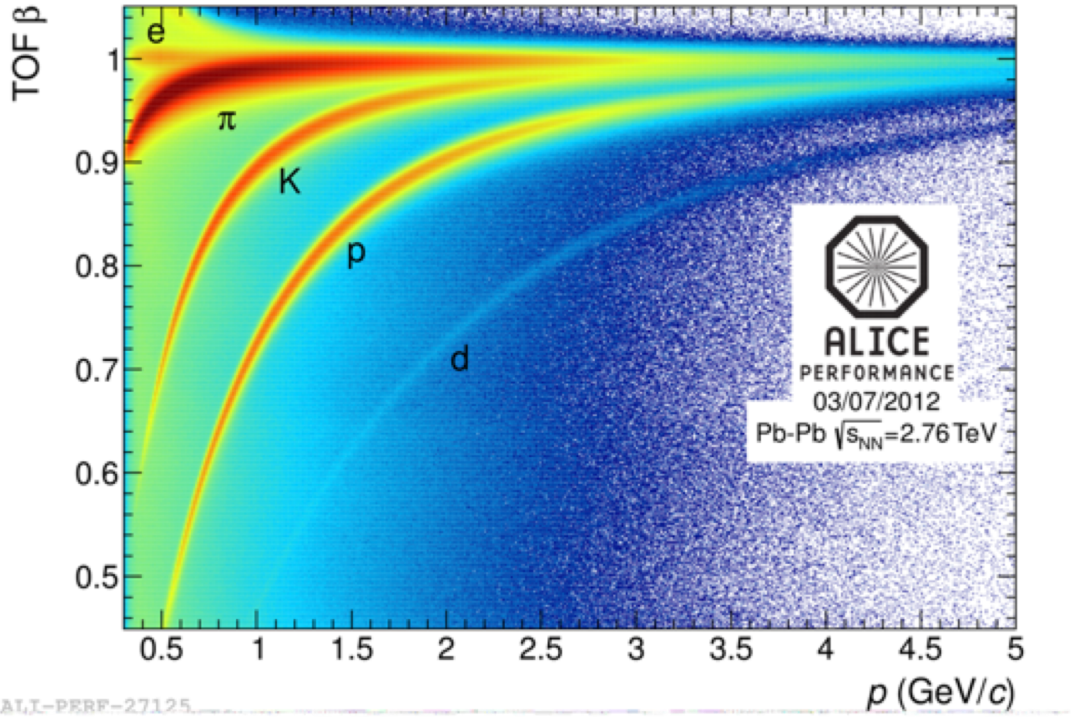
PID via specific energy loss d*E*/dx (*Pb-Pb*)

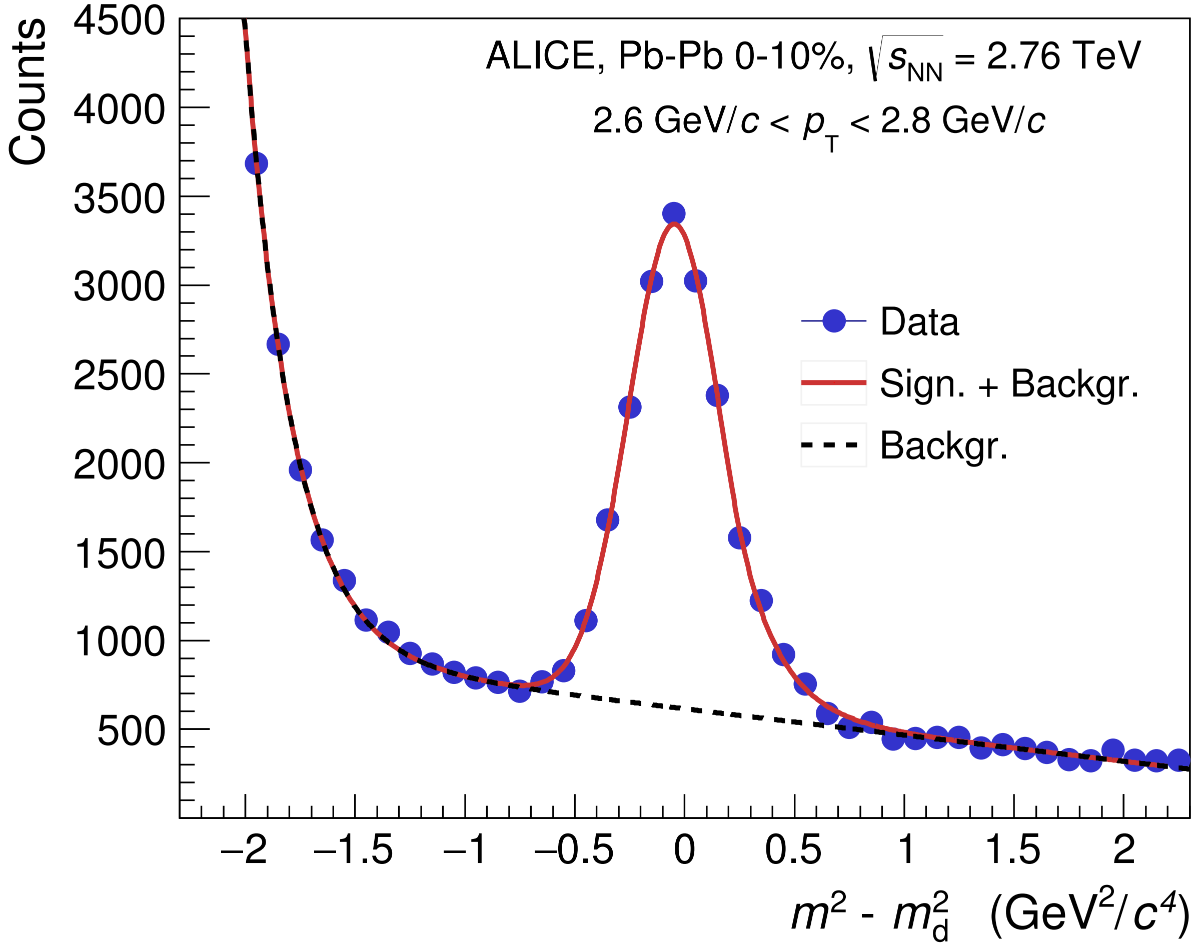


[Phys. Rev. C 93 (2015) 024917]

PID via time-of-flight

[Phys. Rev. C 93 (2015) 024917]



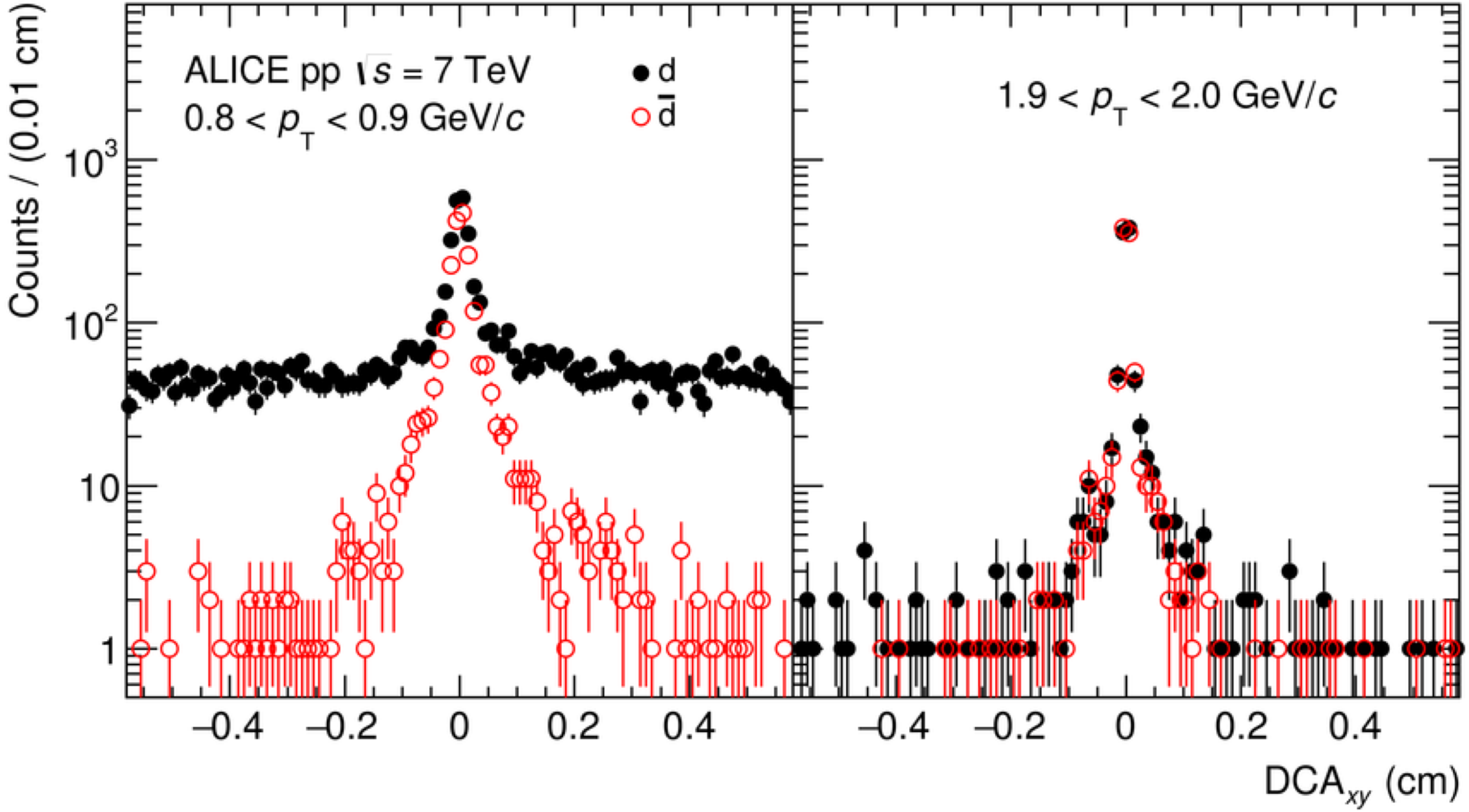


→ Excellent TOF measurement (80 ps time resolution in Pb-Pb collisions) allows identification of light nuclei over a wide momentum range.

Background from mismatched tracks is reduced by a compatibility cut on the TPC d*E*/dx and then subtracted from the signal in each p_T-bin.

Light nuclei from spallation reactions

[Phys. Rev. C 97 (2018) 024615]



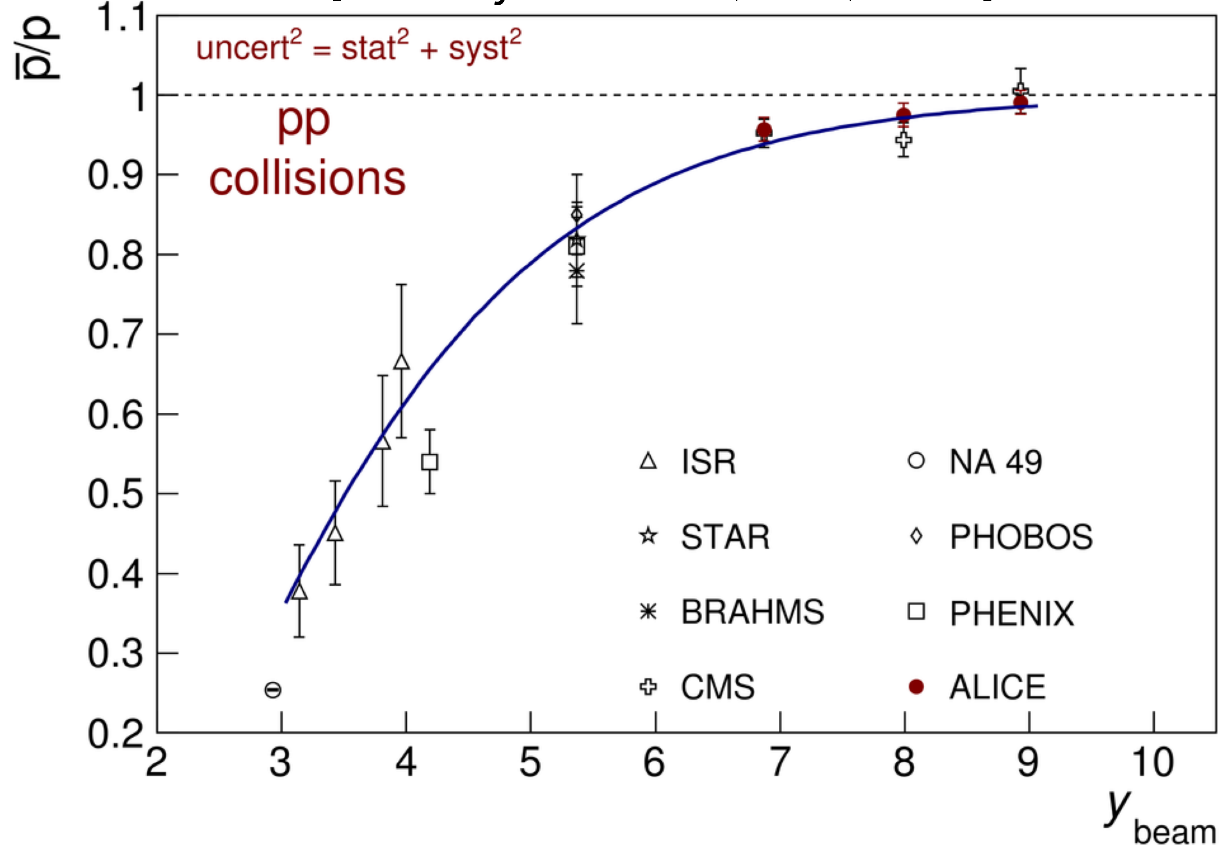
→ About 80% of all deuterons at $p_T = 0.85$ GeV/c are from spallation reactions and not of primary origin.→ This background source is not present in anti-nuclei.

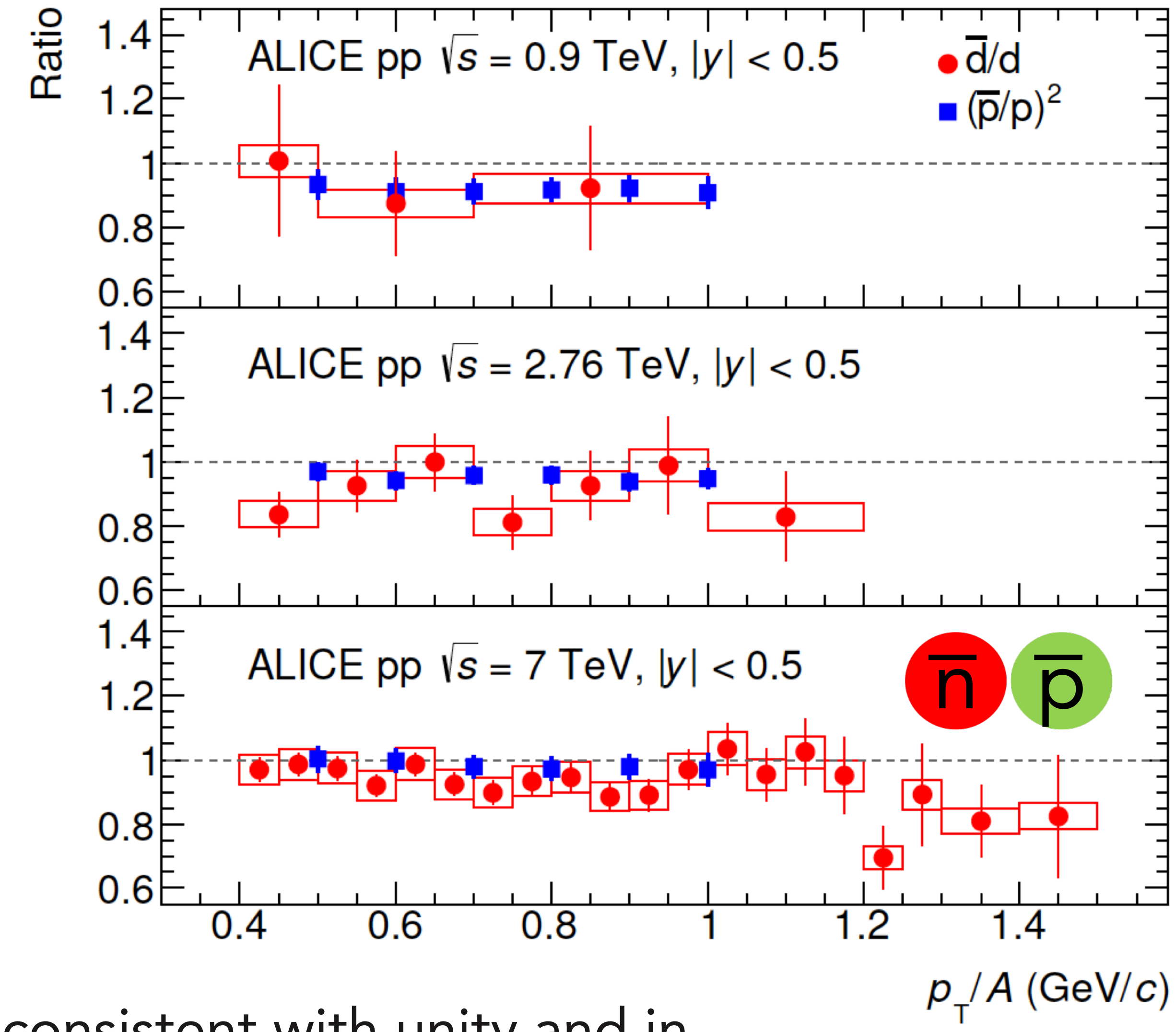
1. Anti-particle to particle ratios

Anti-particle to particle ratios in pp collisions

[Phys. Rev. C 97 (2018) 024615]

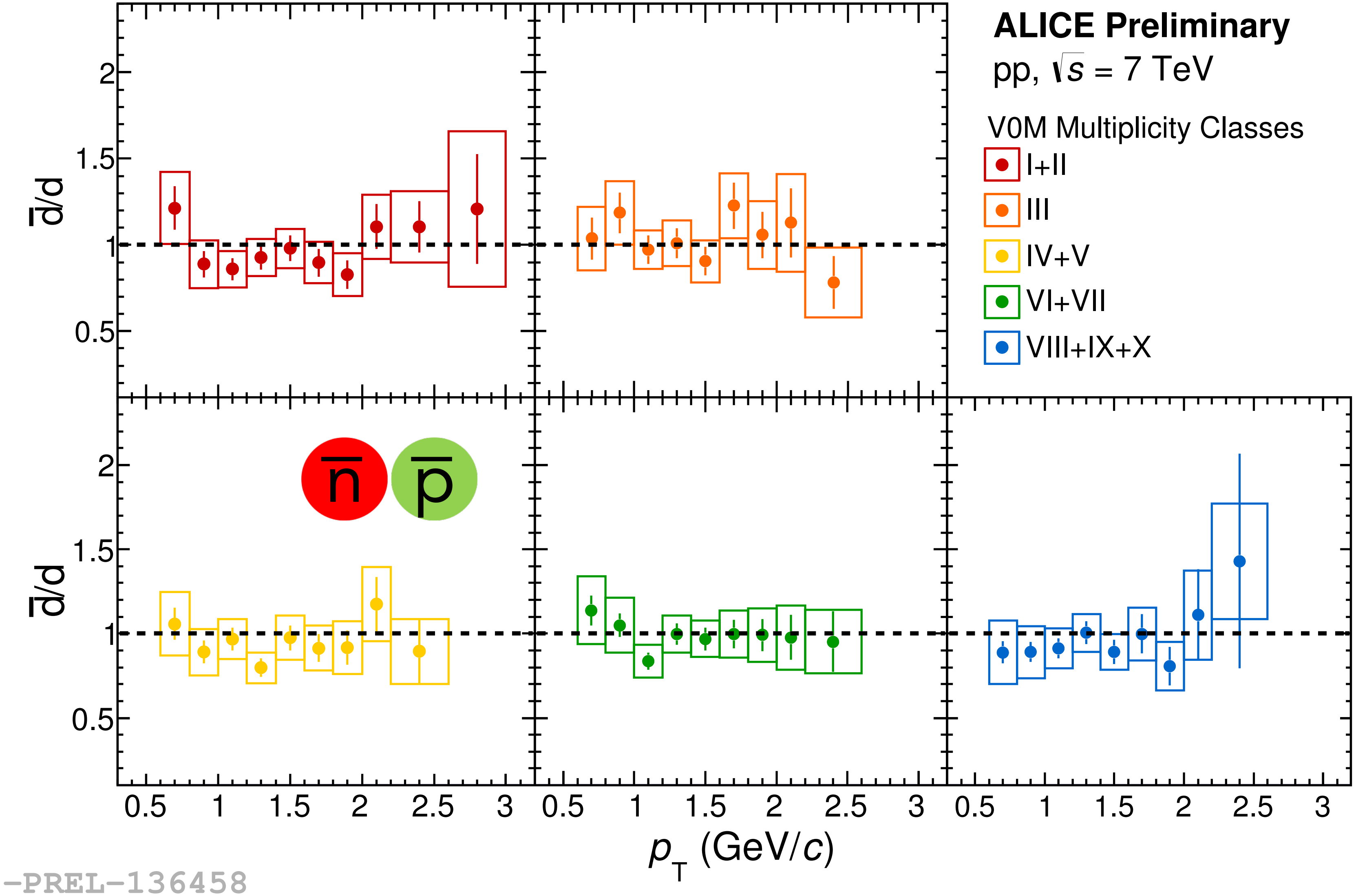
[Eur. Phys. J. C 73 (2013) 2496]





→ Results on anti-particle/particle ratios are consistent with unity and in agreement with basic expectation from thermal and coalescence models.

Anti-particle to particle ratios in pp collisions



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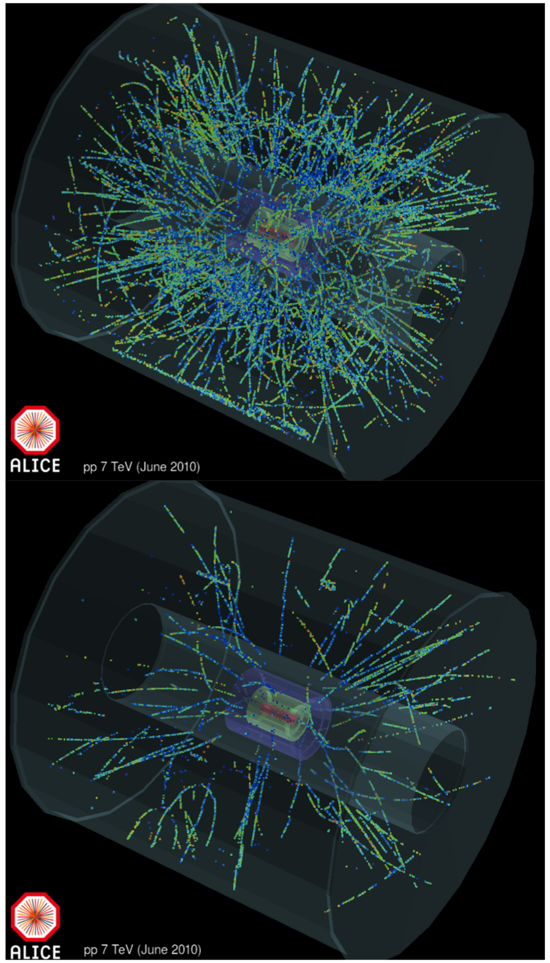
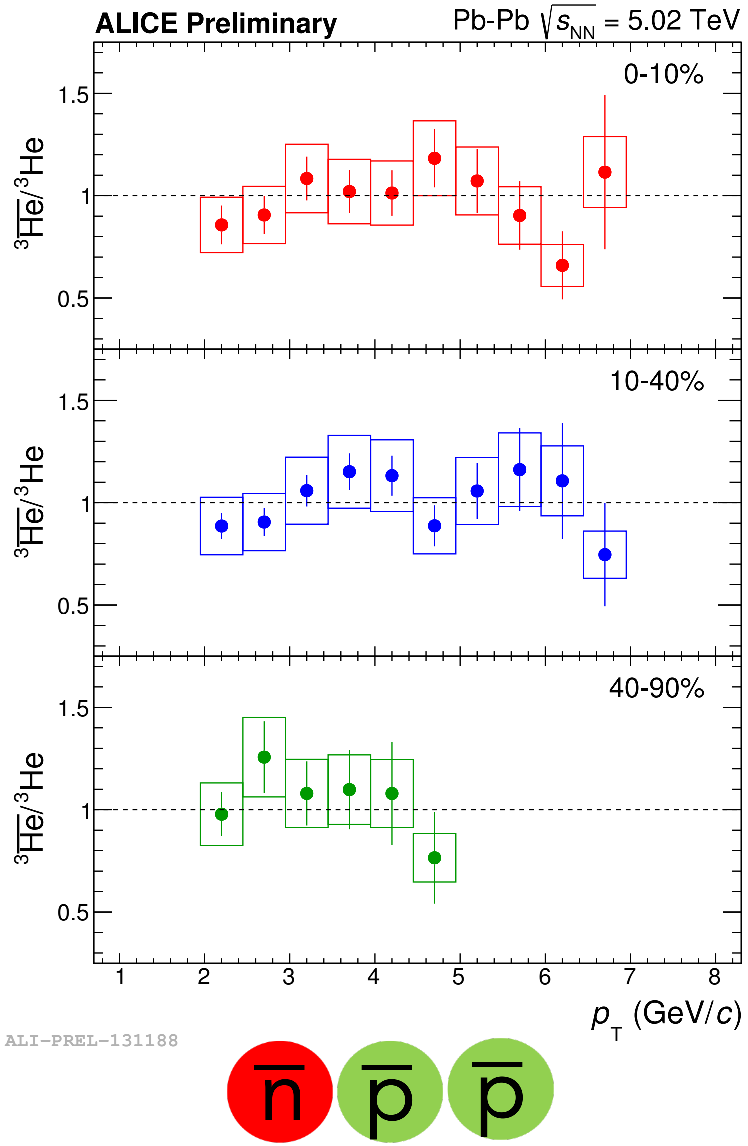
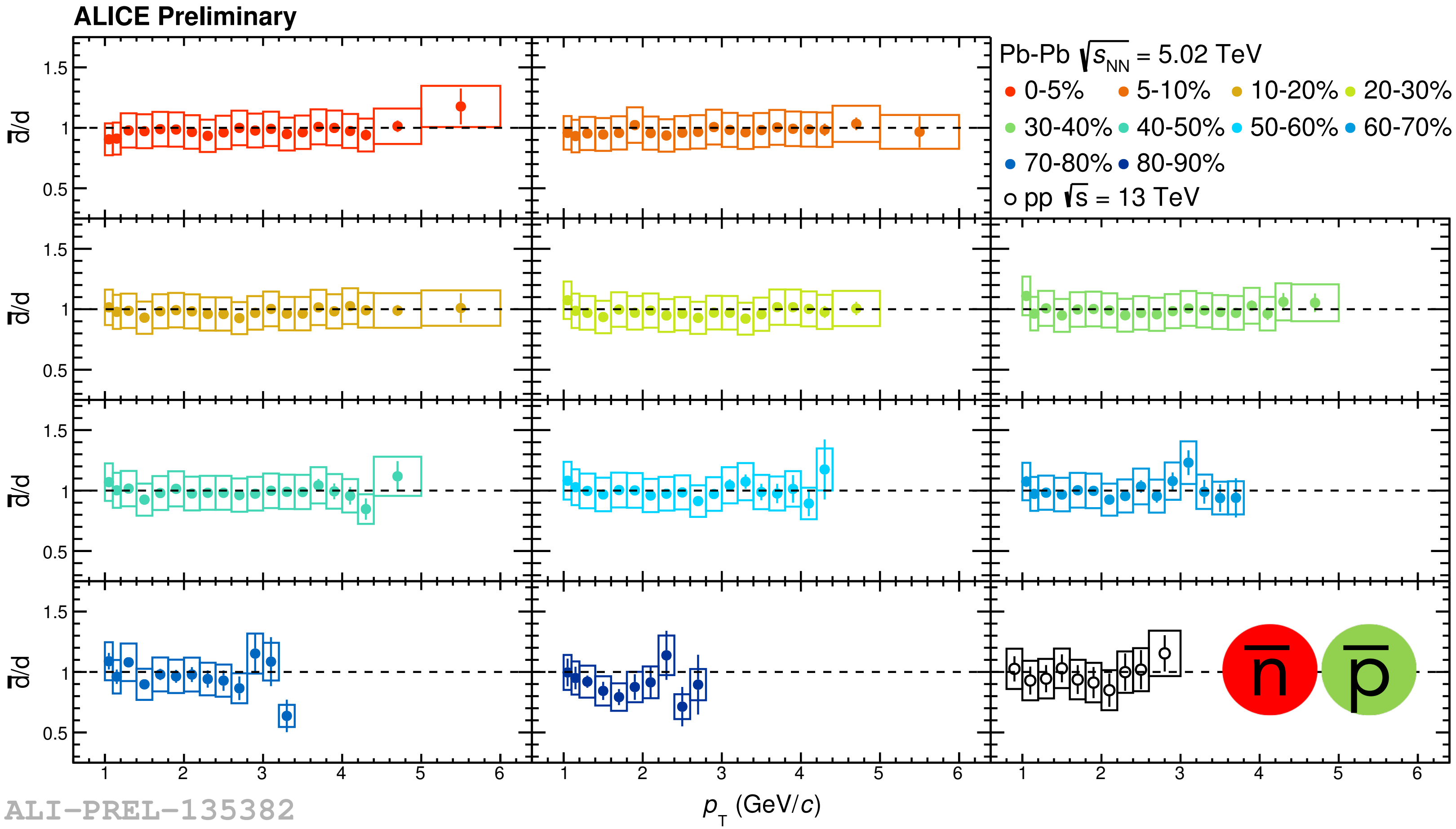


→ No significant dependence of anti-particle to particle ratio with event multiplicity is observed.

Anti-particle to particle ratios in PbPb collisions





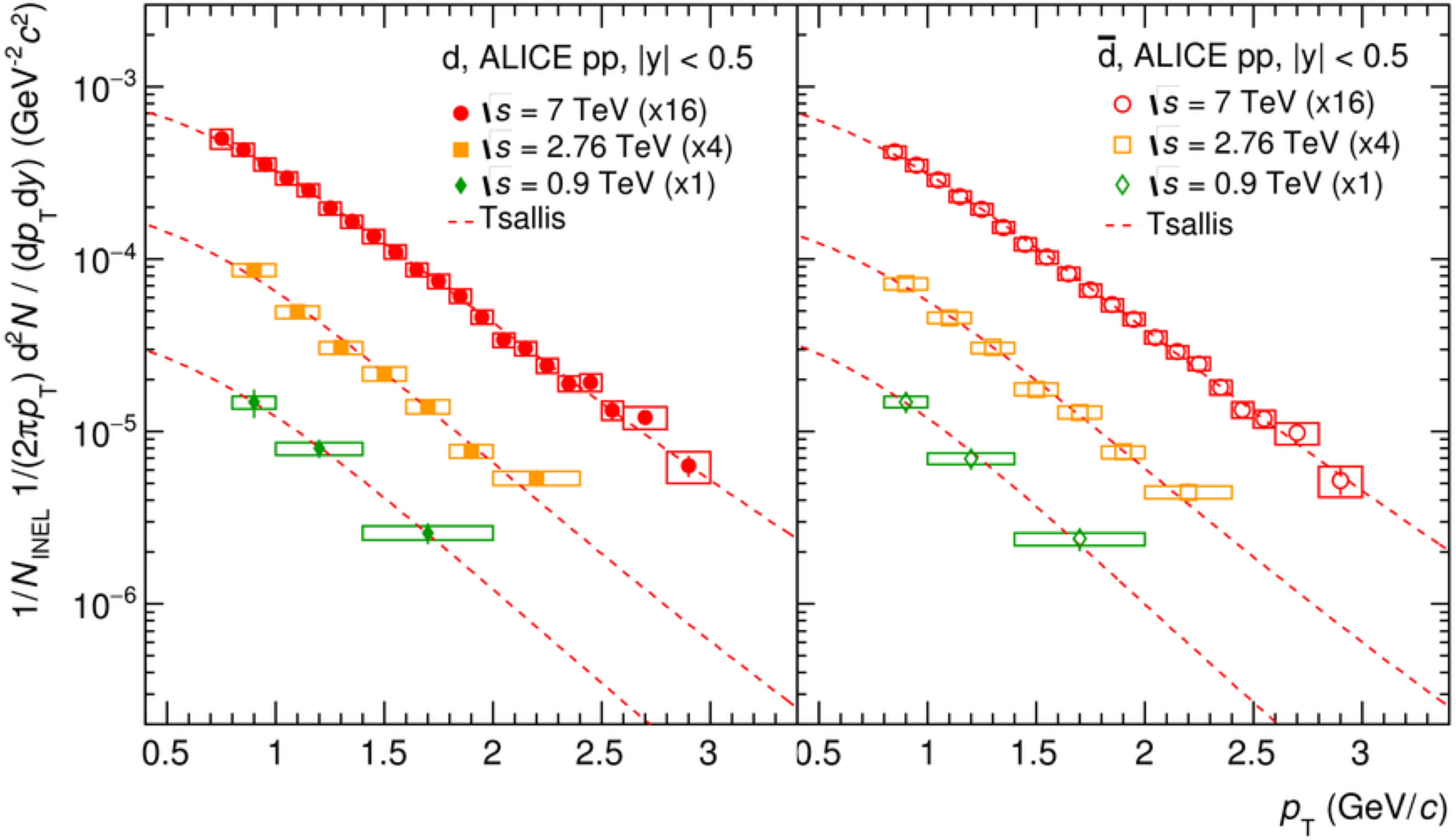
→ Results on anti-particle/particle ratios are consistent with unity and in agreement with basic expectation from thermal and coalescence models.

2. Spectra and p_T-integrated yields

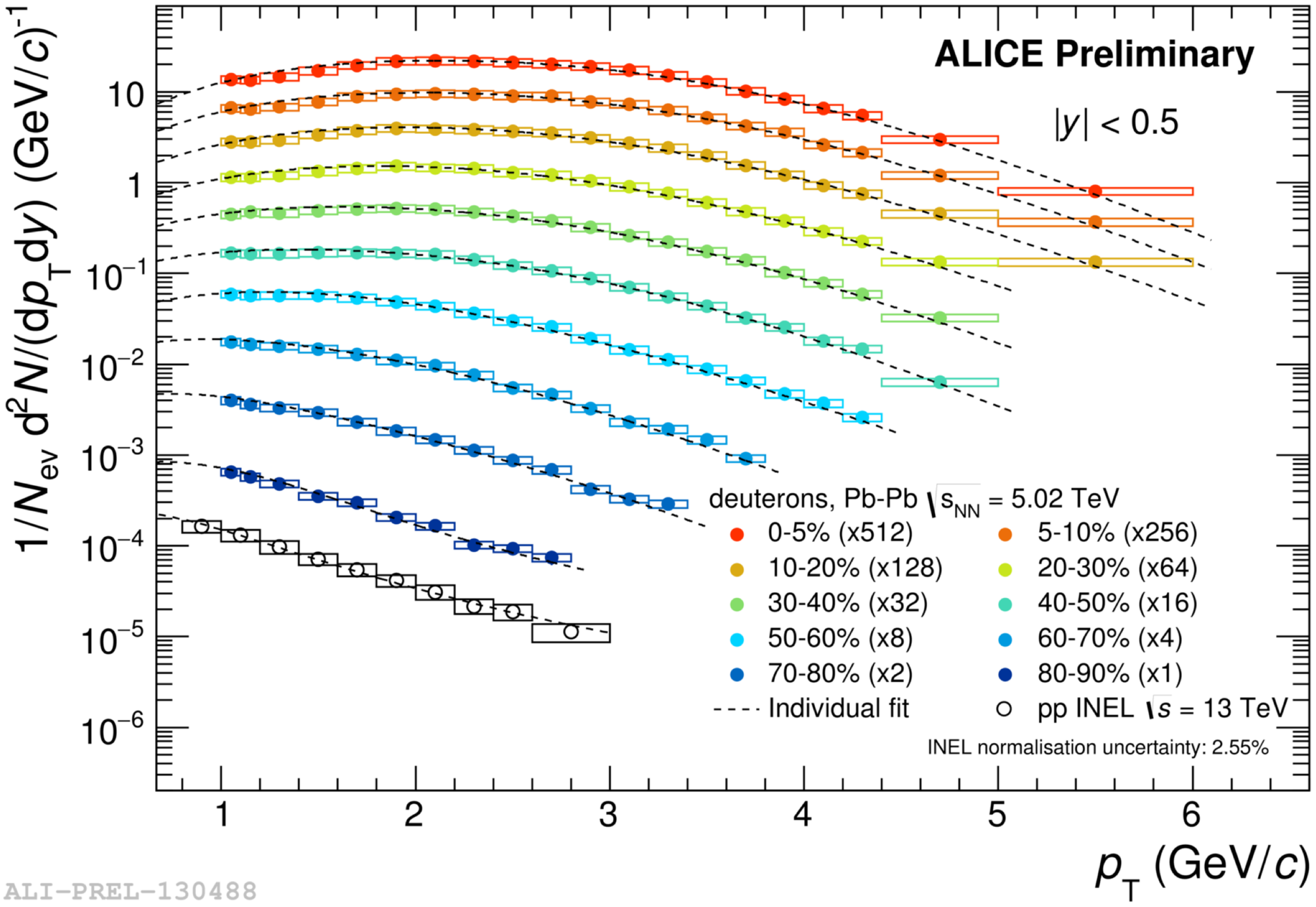
p_T spectra in pp collisions

$\bar{n}$ $\bar{p}$

[Phys. Rev. C 97 (2018) 024615]



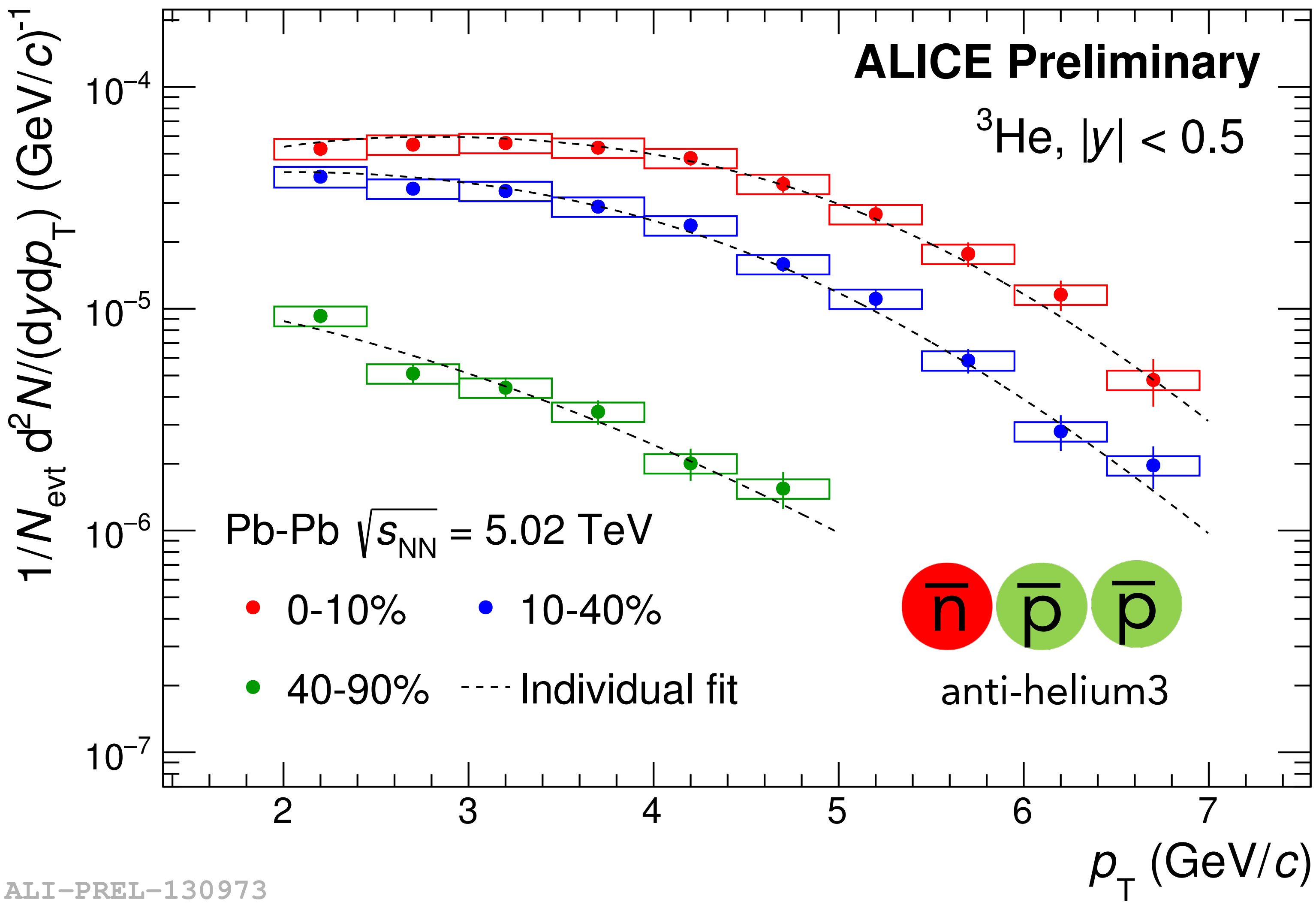
p_T spectra in Pb-Pb collisions (1)



→ Very pronounced hardening of the spectra with increasing centrality observed. Is this a consequence of radial flow?

$\bar{n}$ $\bar{p}$

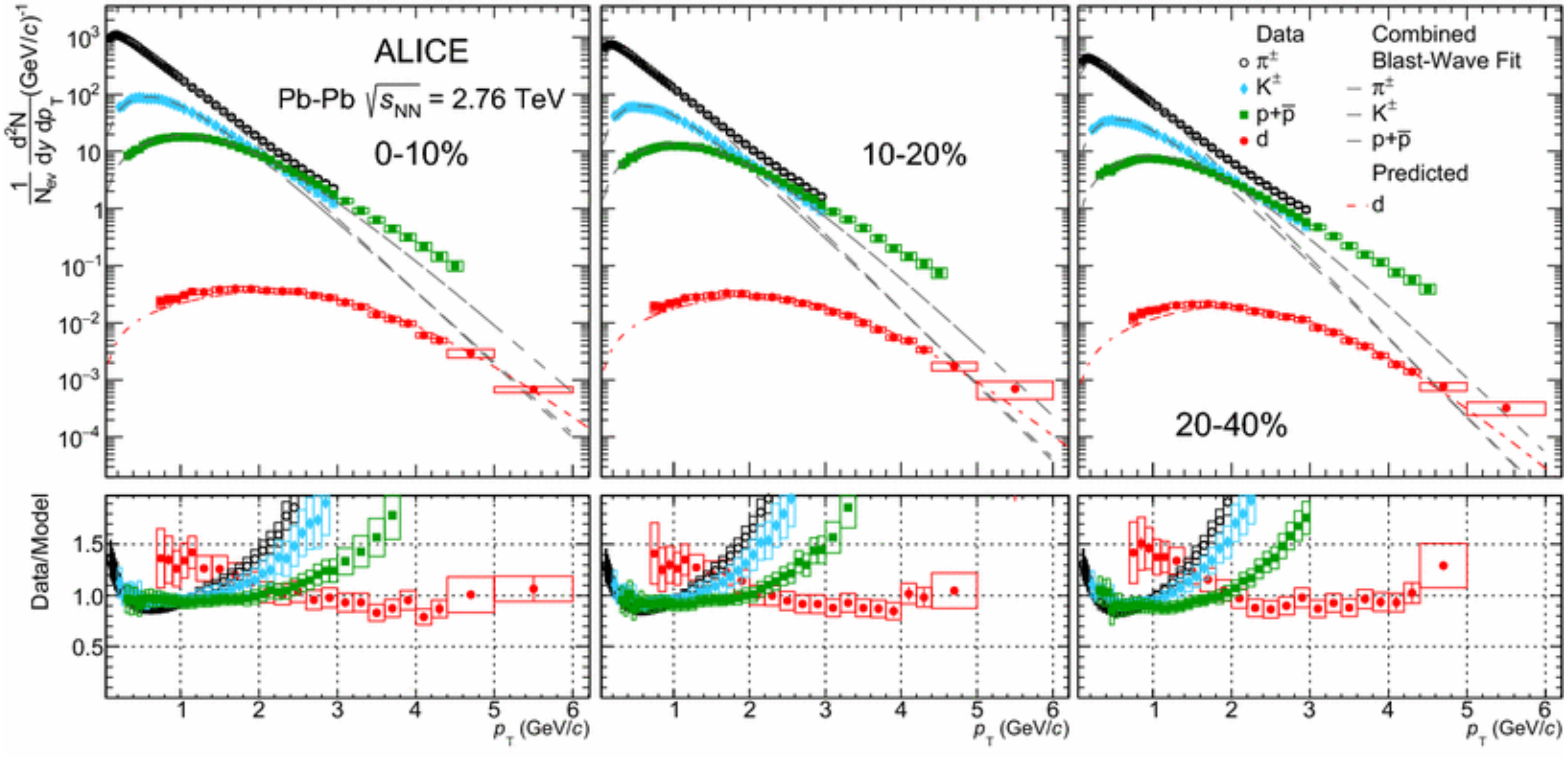
p_T spectra in Pb-Pb collisions (2)



→ Very pronounced hardening of the spectra with increasing centrality observed. Is this a consequence of radial flow?

p_T spectra in Pb-Pb collisions (3)

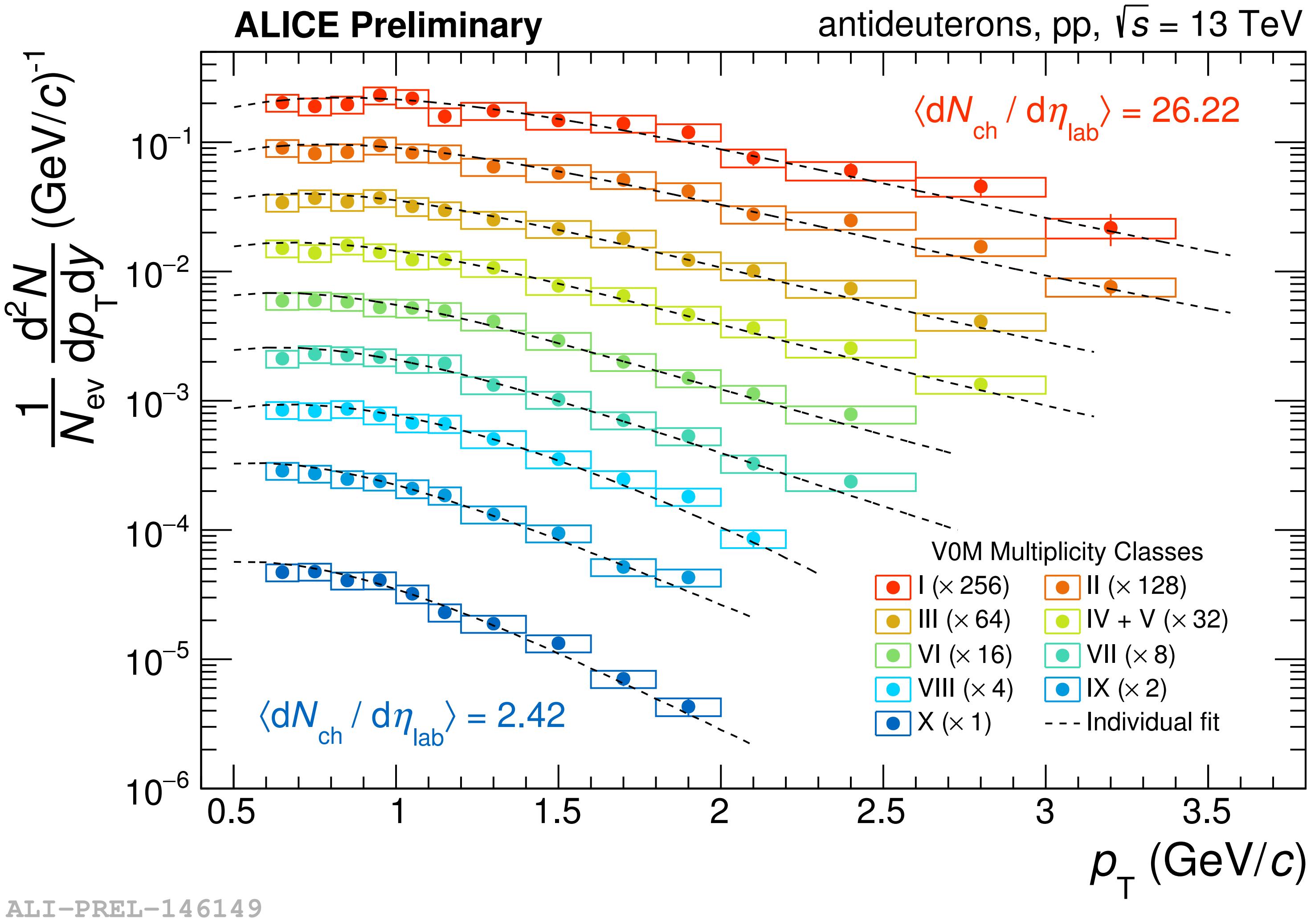
[Eur. Phys. J. C (2017) 77: 658]



$\bar{n}$ $\bar{p}$

→ Spectral shape in Pb-Pb collisions is consistent with a common radial expansion together with all other hadrons (Blast-wave fit)!

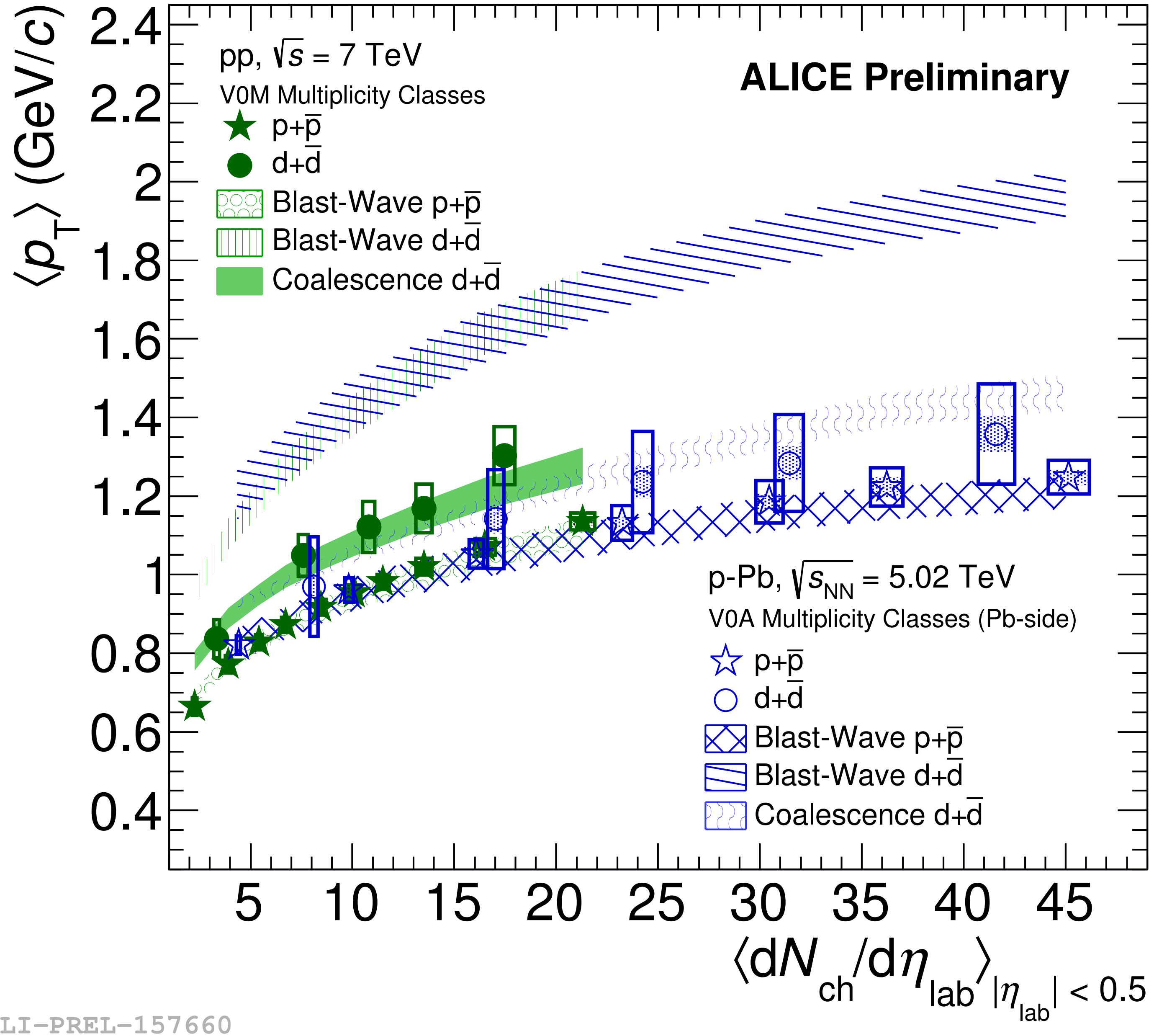
p_T spectra in pp collisions as a function of multiplicity



→ Hardening of the spectra with increasing event multiplicity observed. Is it a result of the hardening of the proton spectra or is it consistent with a collective radial expansion?

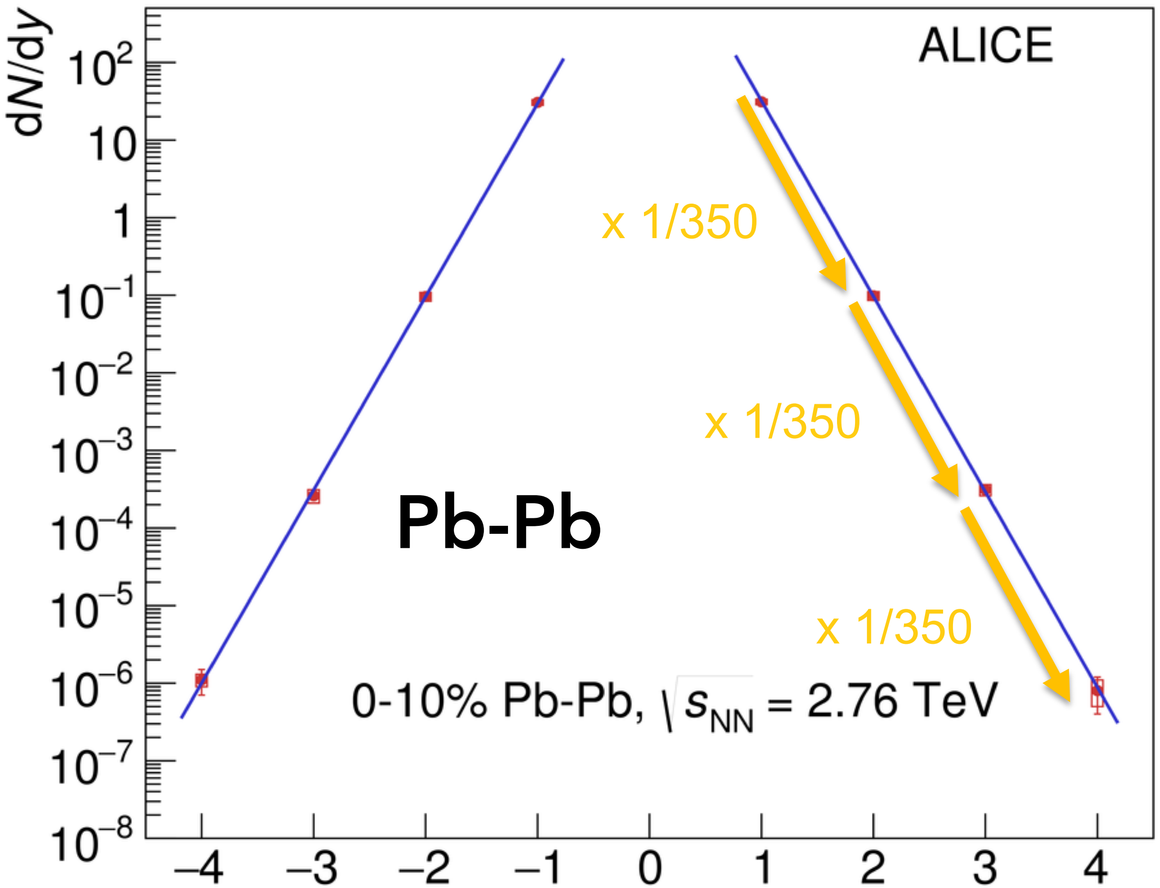
$\bar{n}$ $\bar{p}$

Mean transverse momenta in pp and p-Pb

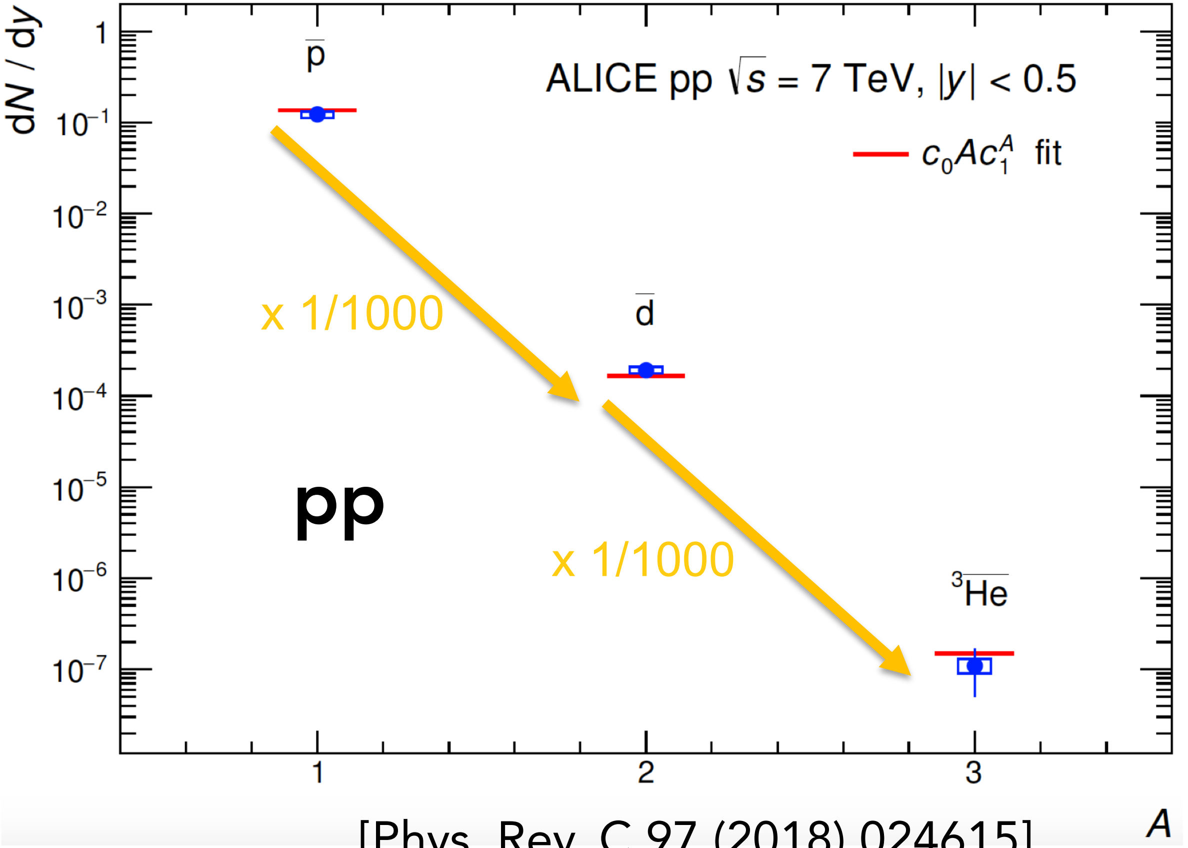


→ In contrast to central Pb-Pb collisions, the spectra in pp and p-Pb collisions, the hardening with increasing multiplicity is not consistent with a common radial expansion together with the other hadrons!

Penalty factor at the LHC



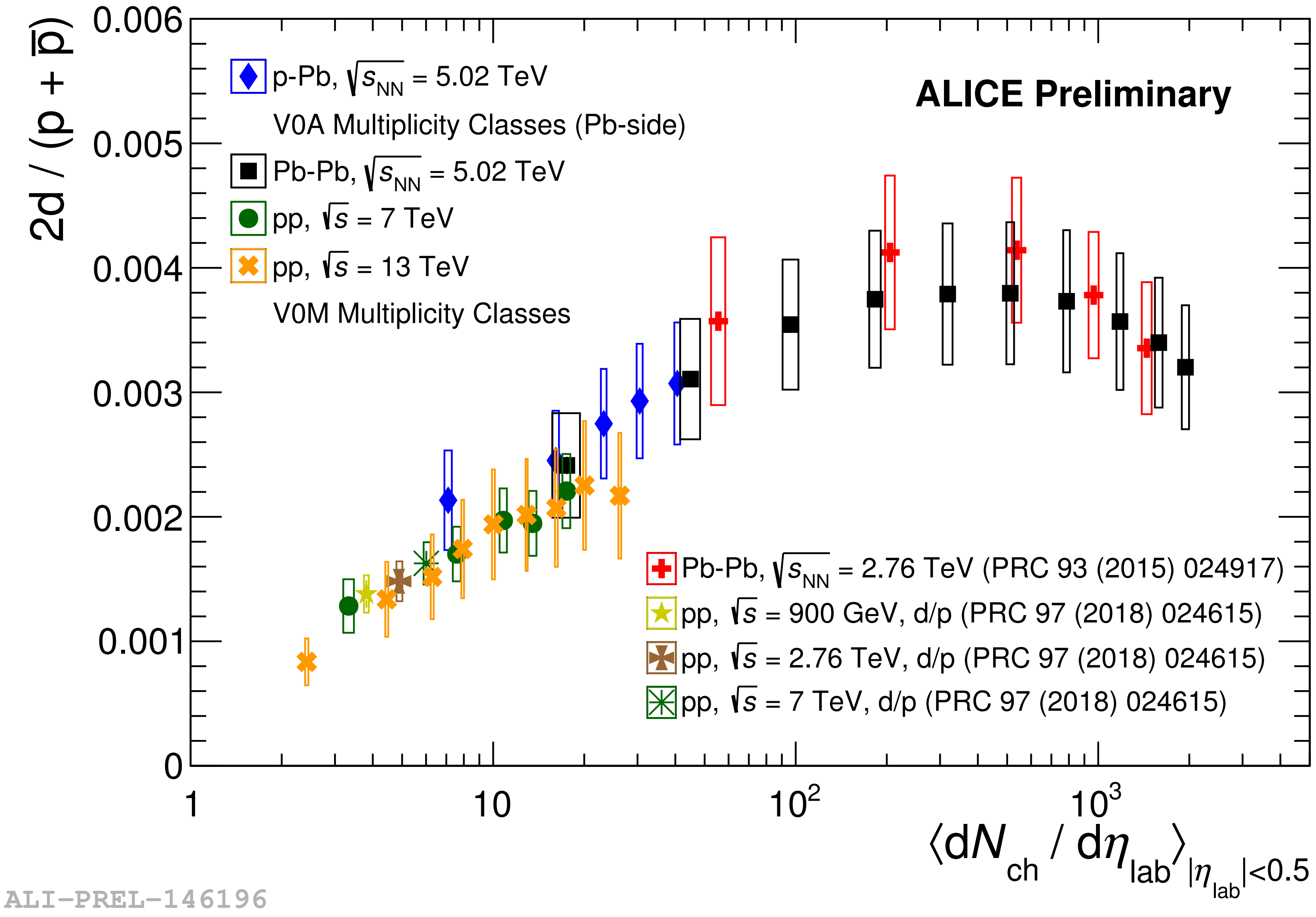
[Nucl. Phys. A 971 (2018) 1-20]



[Phys. Rev. C 97 (2018) 024615]

The production yield of (anti)-nuclei decreases by a factor of about ~350 for each additional nucleon in Pb-Pb (~1000 in pp).

(anti-)deuteron production vs event multiplicity



ALI-PREL-146196

- Increasing and smooth trend for small collision systems and saturation in heavy-ion collisions is observed.

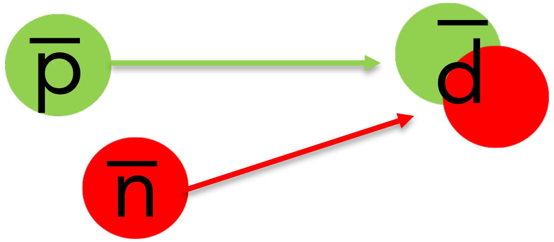
- Different collision systems show similar behavior at similar event multiplicities.

3. Coalescence parameter

Coalescence parameters B_A

- (anti-)nuclei production by coalescence of (anti-)protons and (anti-)neutrons which are close by in momentum and configuration space. Roughly speaking: *"deuteron ∝ proton x neutron => deuteron ∝ proton^2"*

$$\boxed{E_{\mathrm{d}} \frac{\mathrm{d}^3 N_{\mathrm{d}}}{\mathrm{d}p_{\mathrm{d}}^3} = B_2 \left(E_{\mathrm{p}} \frac{\mathrm{d}^3 N_{\mathrm{p}}}{\mathrm{d}p_{\mathrm{p}}^3} \right)^2}$$

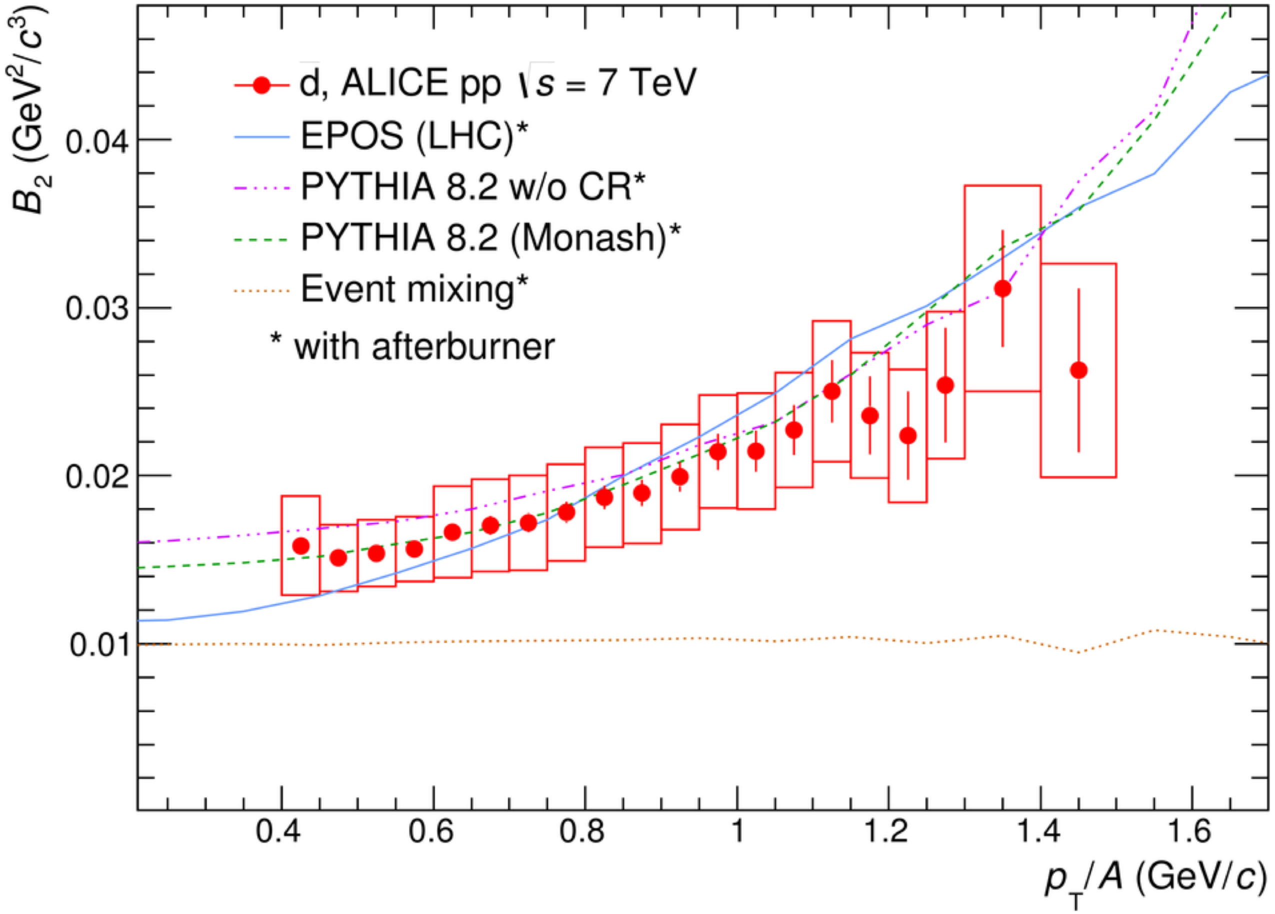


- Spherical approximation: maximum momentum difference (coalescence momentum p_0) is approx. 100 MeV (5.3 MeV kinetic energy of a nucleon in the rest frame of the other).

→ Can be implemented as an *afterburner* to standard event generators.

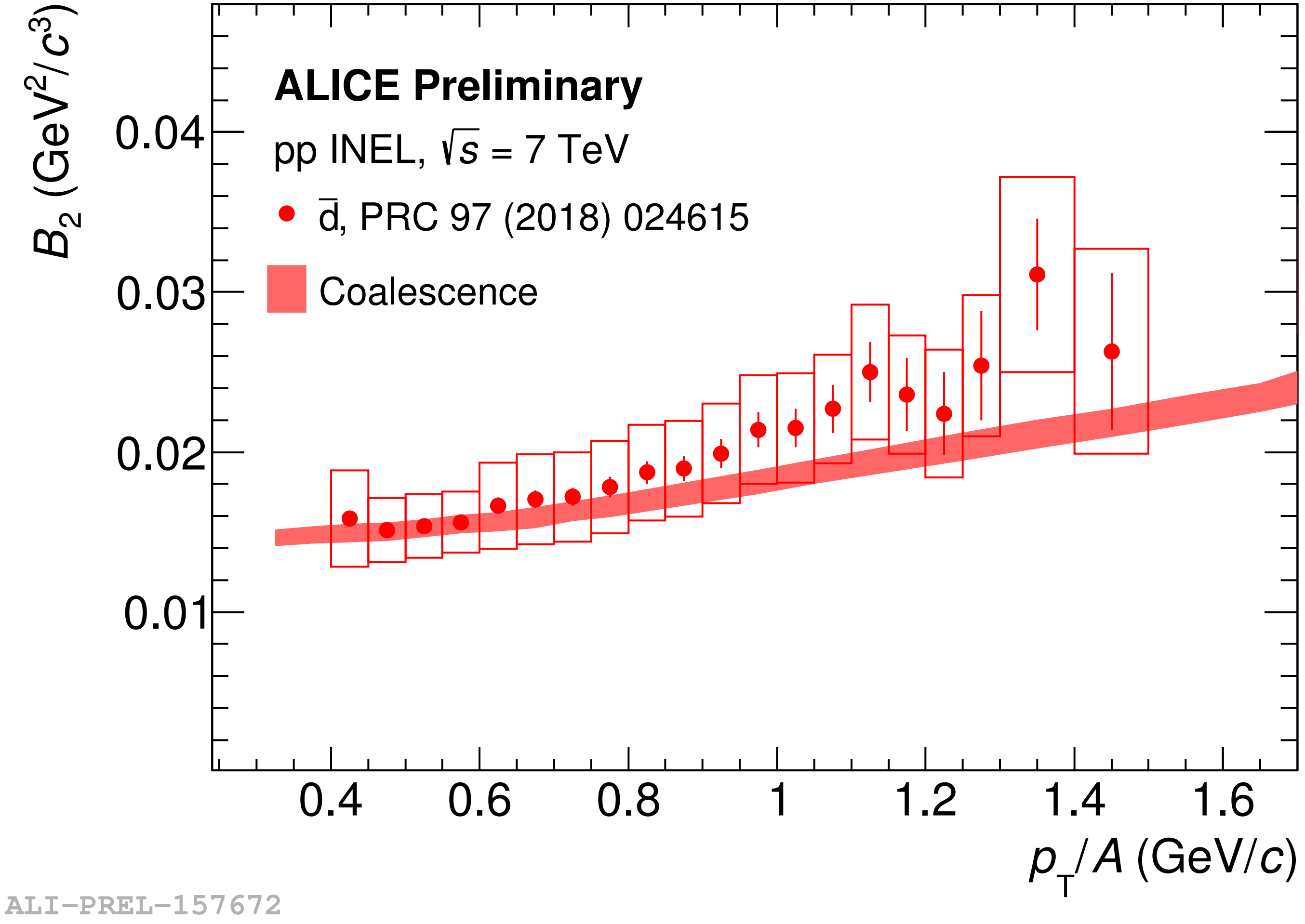
Coalescence parameter B_2

[Phys. Rev. C 97 (2018) 024615]

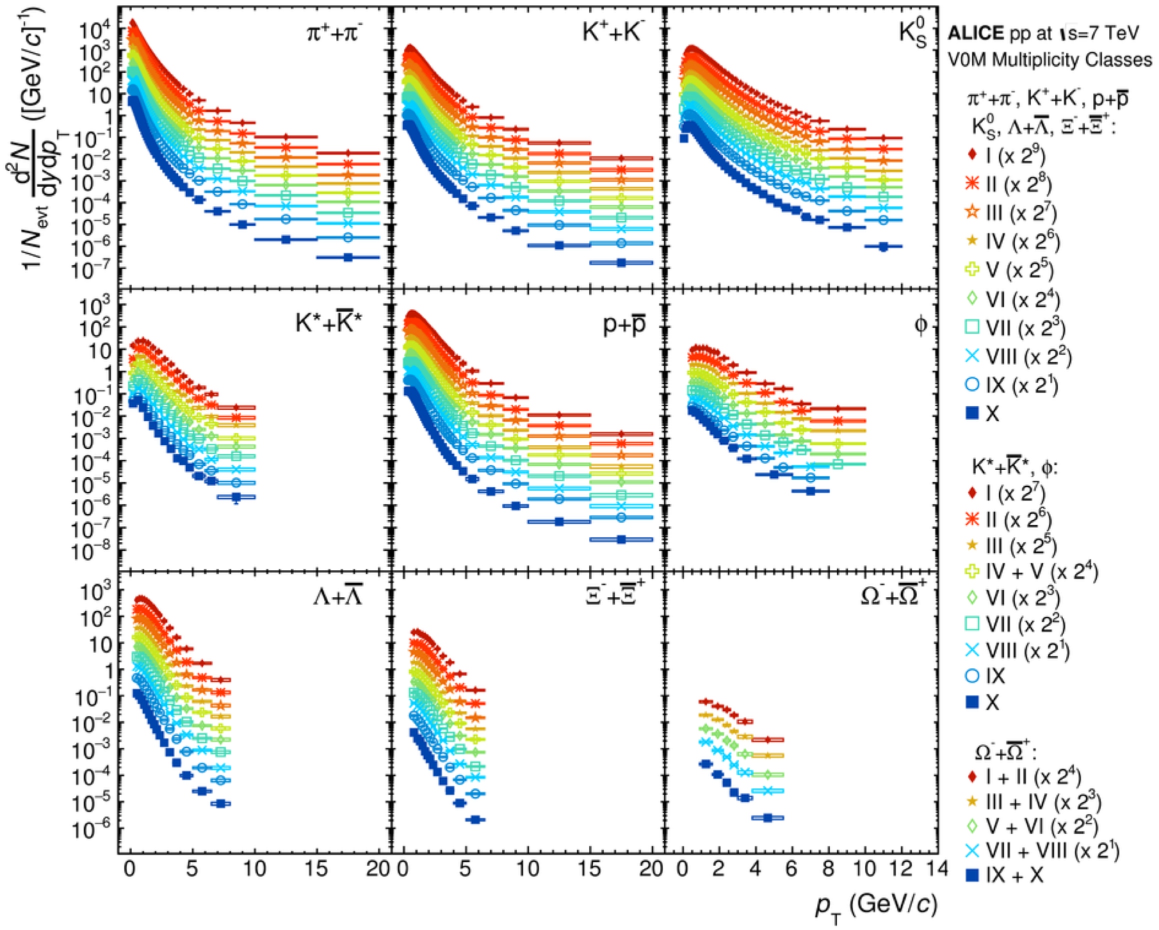


→ Slight p_T-dependence of B_2 can be observed in data which is reproduced by event generators to which an afterburner is added.

p_T-dependence of B_2 in pp

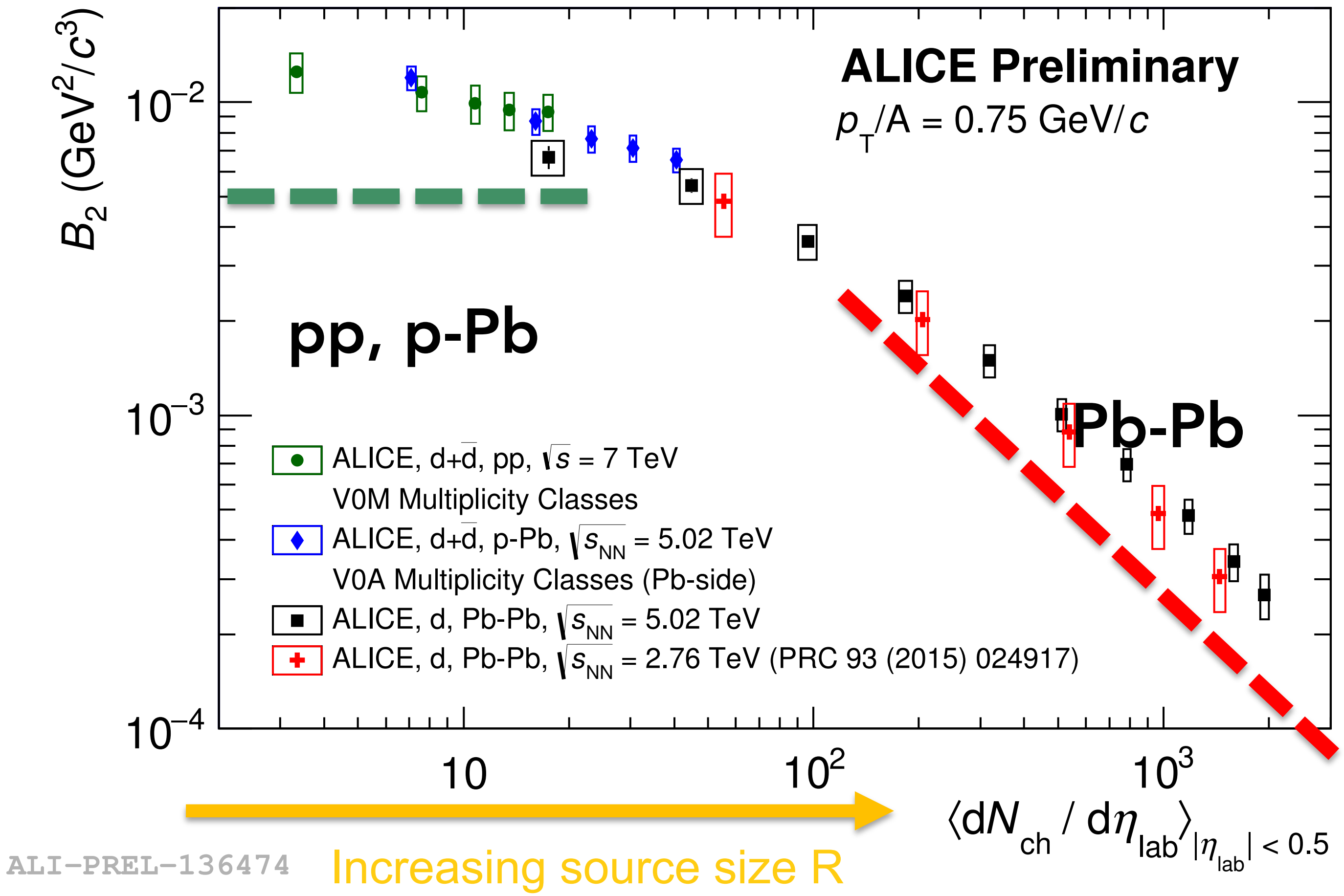


[Phys. Rev. C 99, 024906]



→ Slight p_T-dependence of B_2 can be further explained as a consequence of the hardening of the proton (nucleon) spectrum with multiplicity.

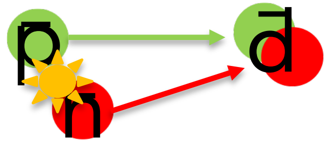
Coalescence models in heavy-ion collisions



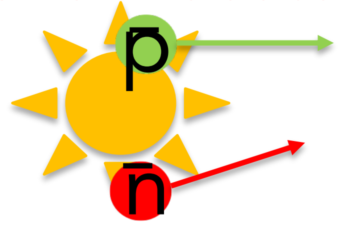
→ Strong dependence of B_2 on collision geometry.

→ Two production regimes observed:

(a.) system size < deuteron size

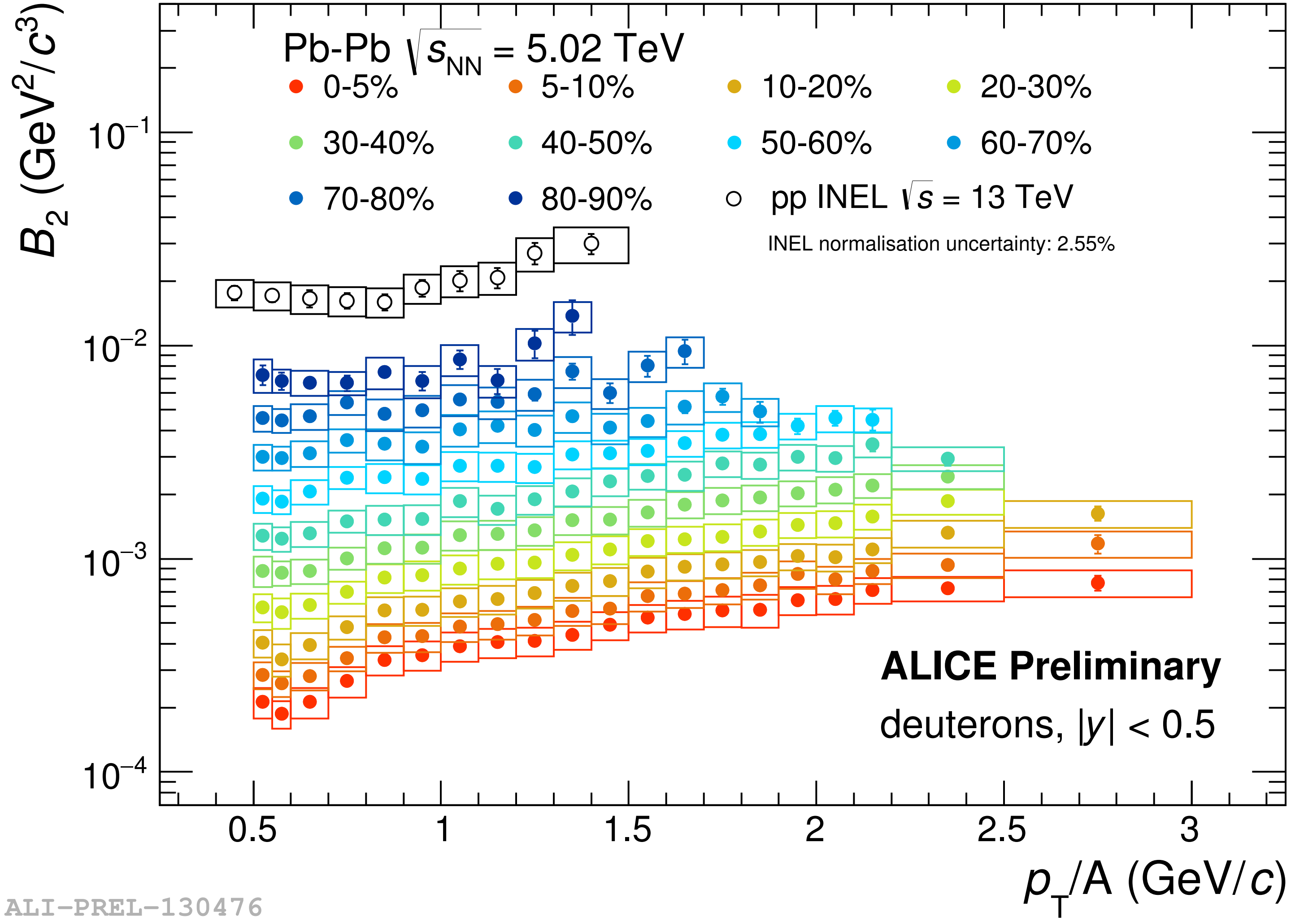


(b.) system size > deuteron size

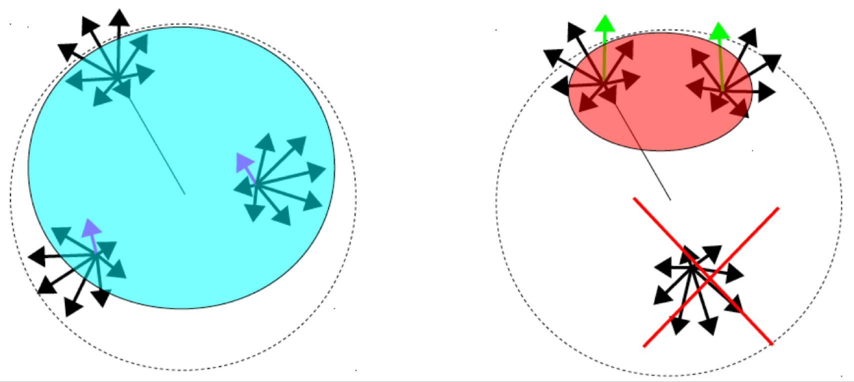


The trend with multiplicity is explained as an increase in the source size R in coalescence models (e.g. *Scheibl,Heinz PRC 59 (1999) 1585*).

p_T dependence of B_2 in Pb-Pb



- A particle emitted from a medium will have a collective velocity β_f and a thermal (random) one β_t
- As observed p_T grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source



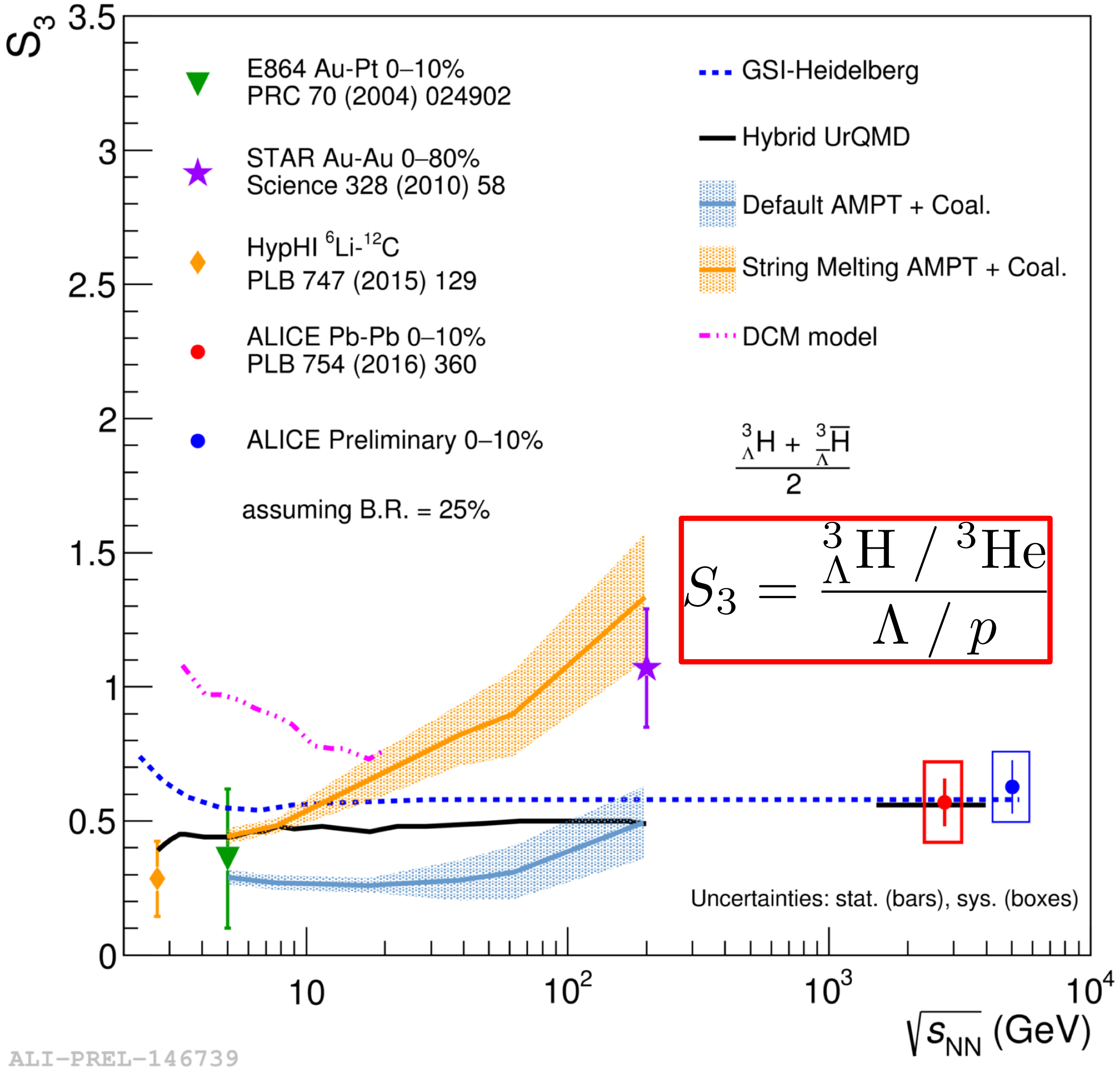
A. Kisiel, Hirschegg 2019

High momenta means => thermal (random) and collective component must align

=> more likely that they come from the same volume element

=> higher coalescence probability

(anti-)hyper-triton in Pb-Pb collisions at 5.02 TeV



$$S_3 = \frac{{}^3_\Lambda\mathrm{H}\ /\ {}^3\mathrm{He}}{\Lambda\ /\ p}$$

$\bar{n}$ $\bar{\Lambda}$ $\bar{p}$ anti-hyper-triton

$\bar{n}$ $\bar{p}$ $\bar{p}$ anti-^{3}He

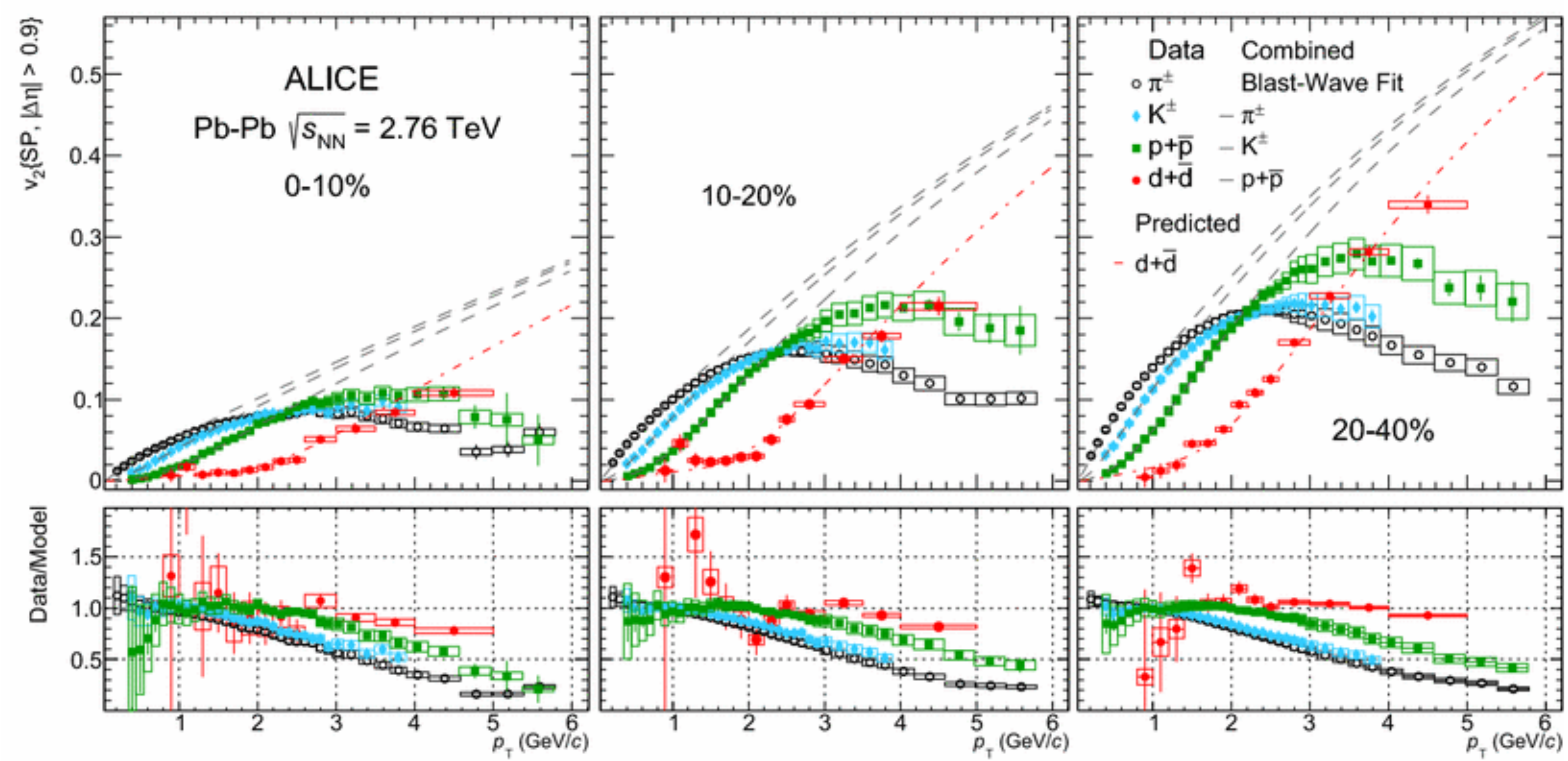
→ Yields of heavy and fragile objects such as (anti-)(hyper-)nuclei in agreement with thermal-statistical model predictions at *chemical* freeze-out.

→ No re-scattering of anti-nuclei in hadronic phase despite large dissociation cross-section.

→ Final-state coalescence after kinetic freeze-out requires more detailed modeling: *naive coalescence* ($S_3 \approx 1$) does not describe data.

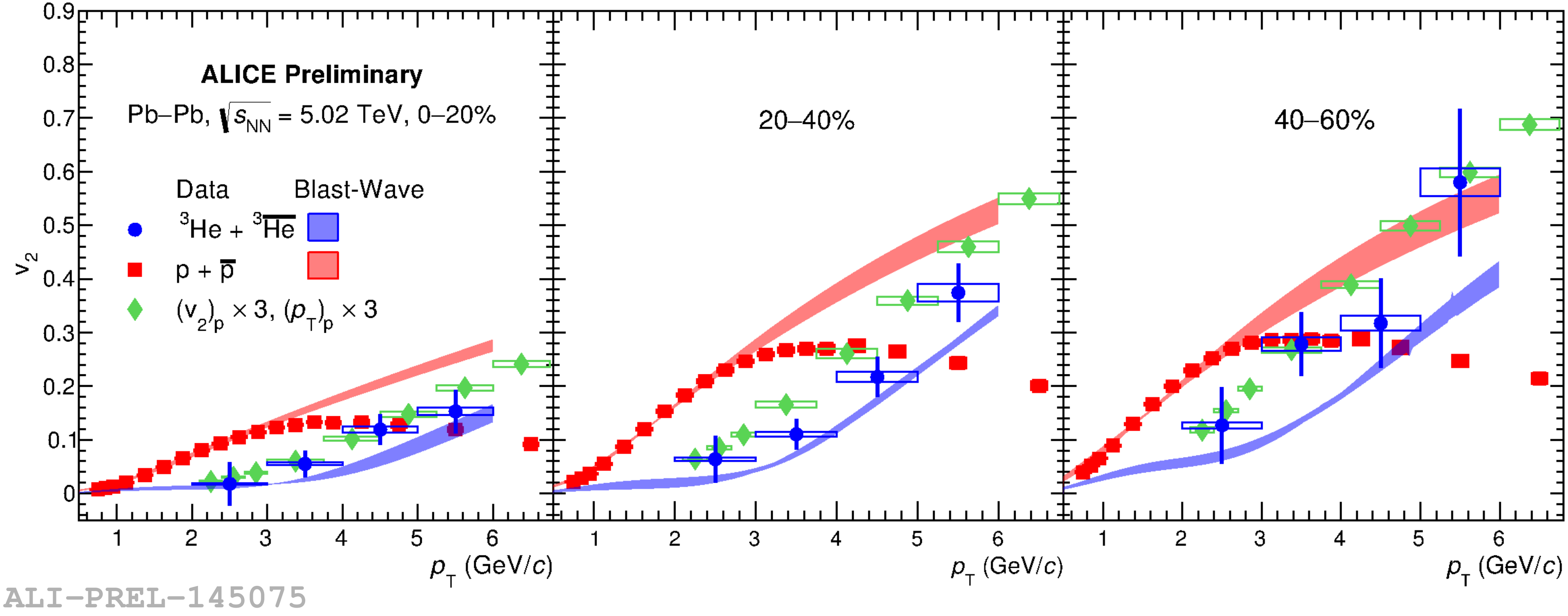
4. Elliptic flow

Elliptic flow of (anti-)deuterons in Pb-Pb collisions



→ Elliptic flow in Pb-Pb collisions is consistent with a common radial expansion together with all other hadrons (Blast-wave fit) and not with simple coalescence!

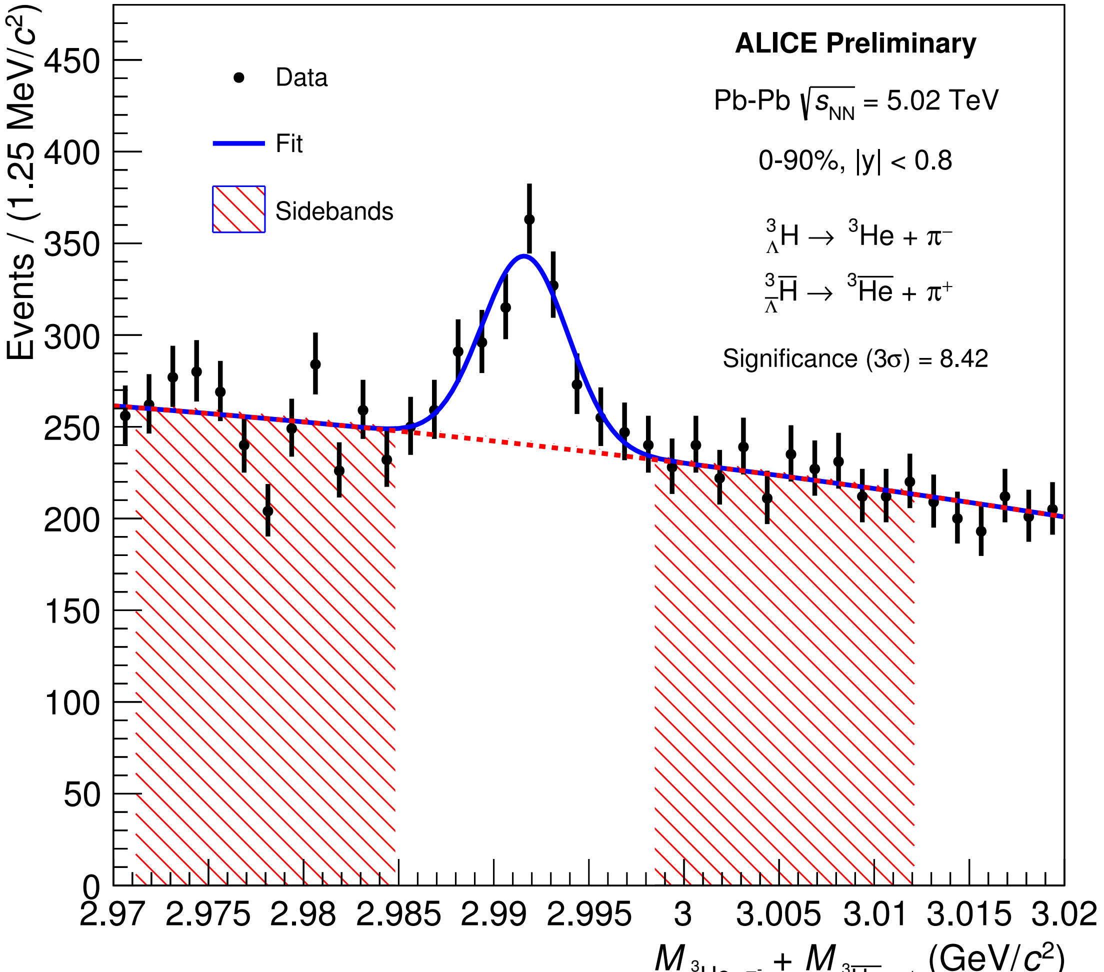
Elliptic flow of (anti-)^{3}He



→ With 2015 Pb-Pb statistics, data consistent with both simple coalescence and blast-wave expectations.

5. Hyper-triton lifetime

Hyper-triton



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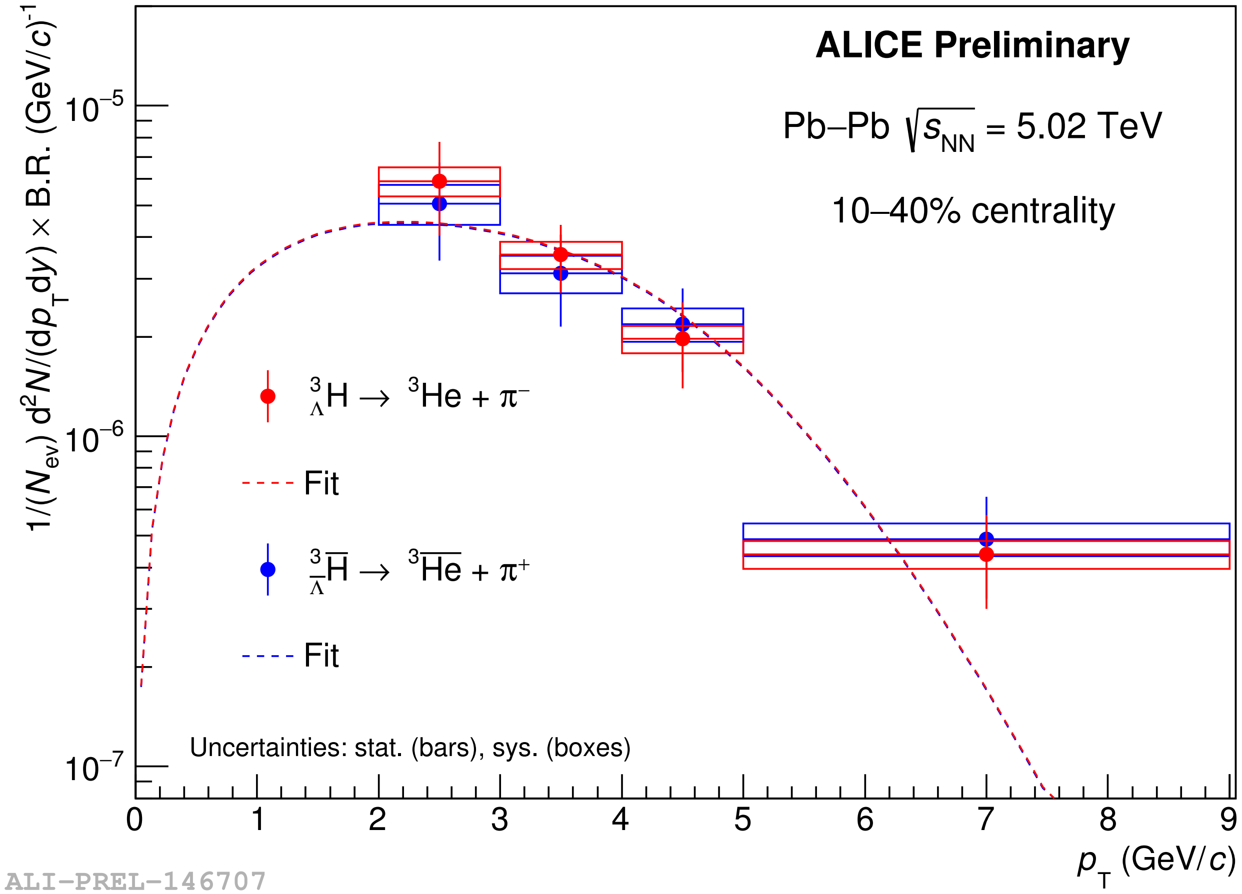
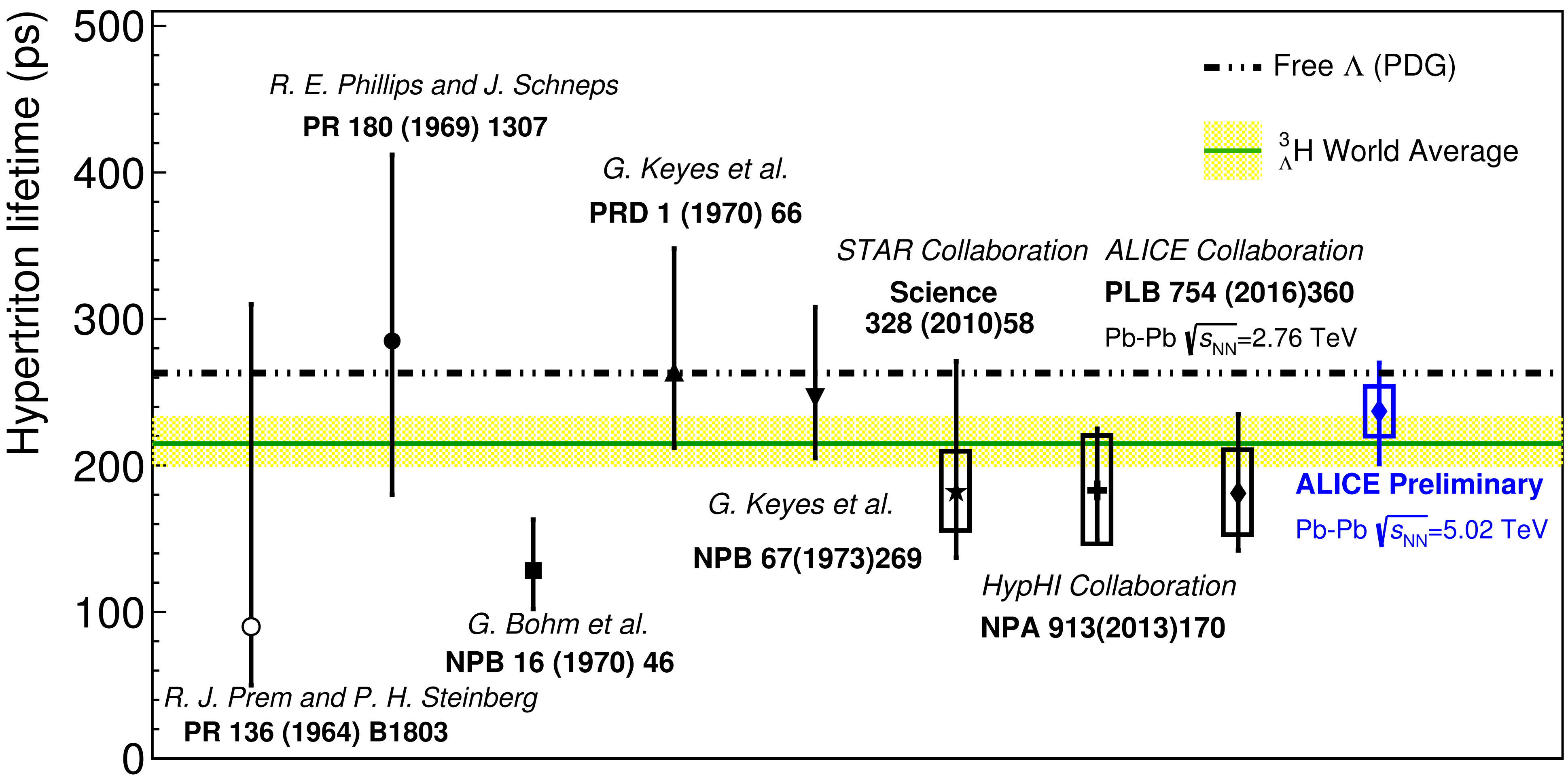


ALI-PREL-146707

Complex decay topology in two and three body decays including a charged mother tracklet.
→ Ideal playground for further optimization with machine learning techniques!

Hyper-triton lifetime



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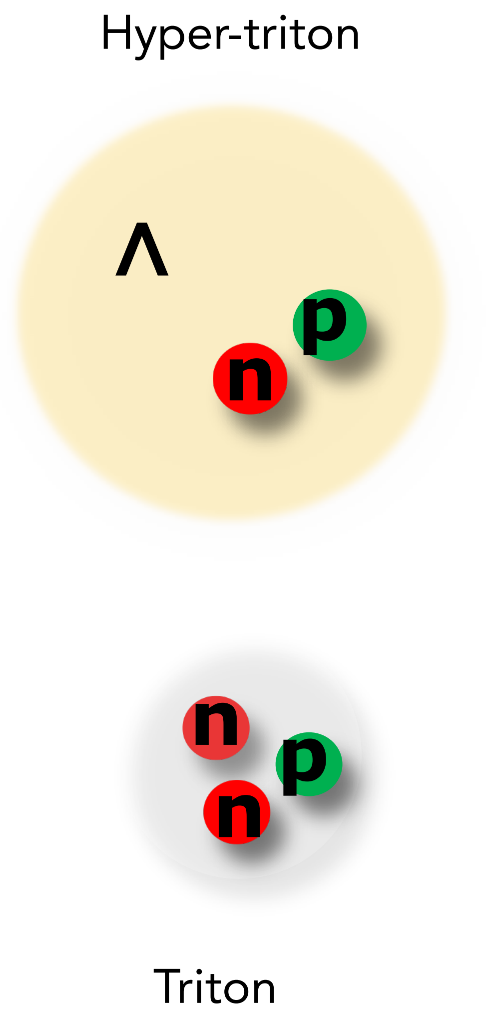
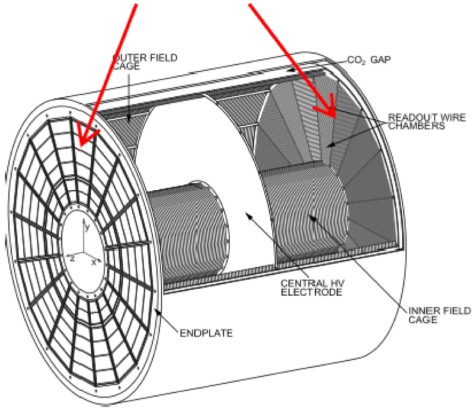
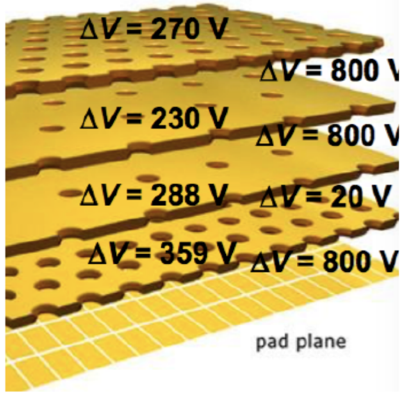


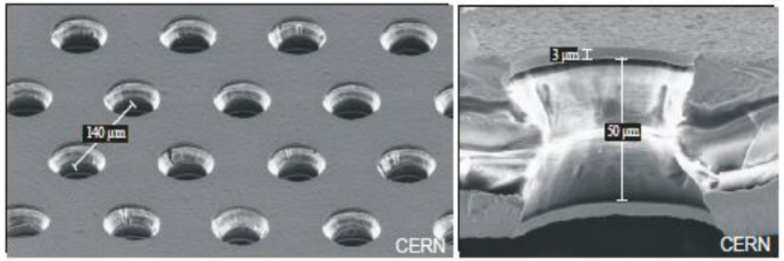
6. Future measurements

TPC with GEM readout for Pb-Pb at 50 kHz

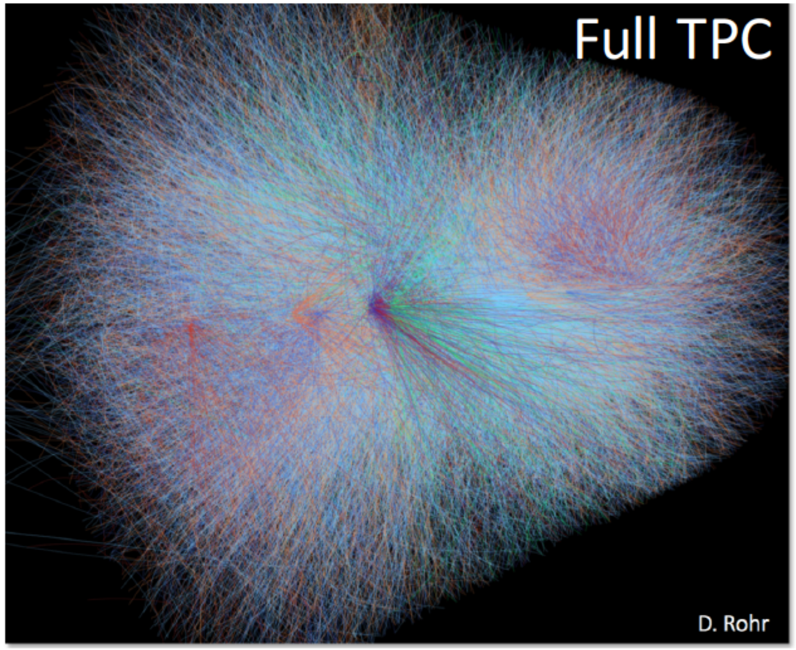
- Current MWPC: readout limited by ion backflow
- New readout chambers (GEM) continuous readout
  - Preserve momentum and dE/dx resolution
- 5 interactions on average during TPC drift time (83μs)
- Calibration and track-to-event assignment in O^2-system

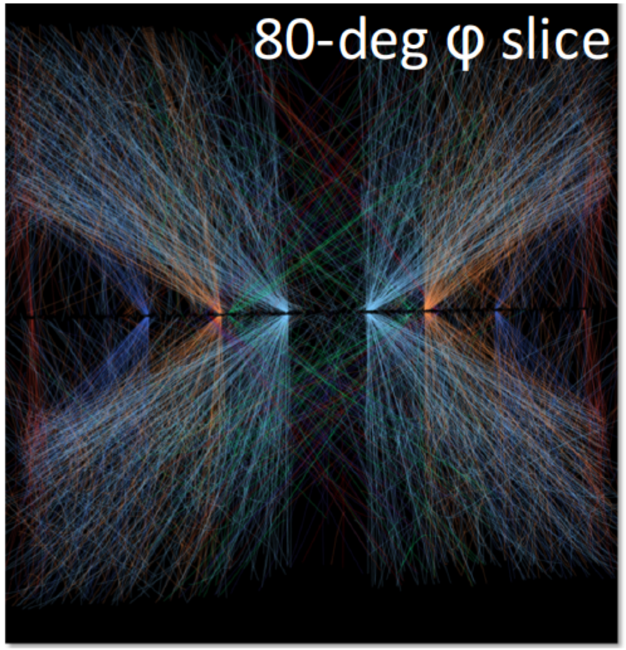

72 readout chambers


Stack of 4-GEM-foils



Electron microscope photograph of a GEM foil


Full TPC

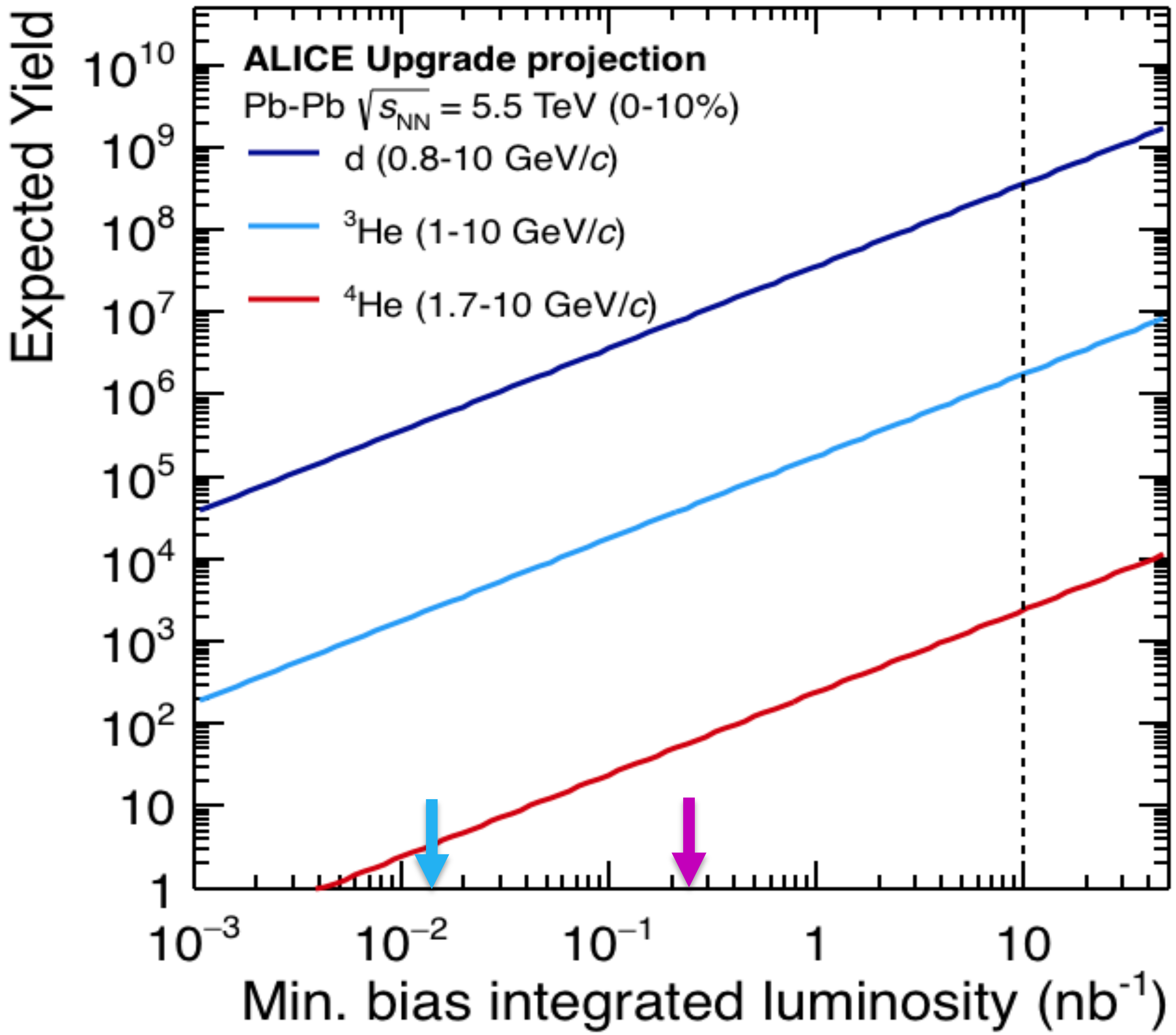

80-deg φ slice

Outlook to LHC Run 3 and 4 (B)

The measurement of the **coalescence parameters** for composite objects with **different sizes** studied as a function of the **multiplicity** can be used to compare the light (anti-)(hyper-)nuclei production scenarios

Physics case for Run3&4:

- → Measure centrality dependence of the hypertriton in Pb-Pb
- → Can we produce at all the hypertriton in pp collisions?
- → Go more differential for A = 3
- → Measure B_4 for ^{4}He, $^4{}_\Lambda$H, $^4{}_\Lambda$He



Outlook to LHC Run 3 and 4 (C)

The measurement of the **coalescence parameters** for composite objects with **different sizes** studied as a function of the **multiplicity** can be used to compare the light (anti-)(hyper-)nuclei production scenarios

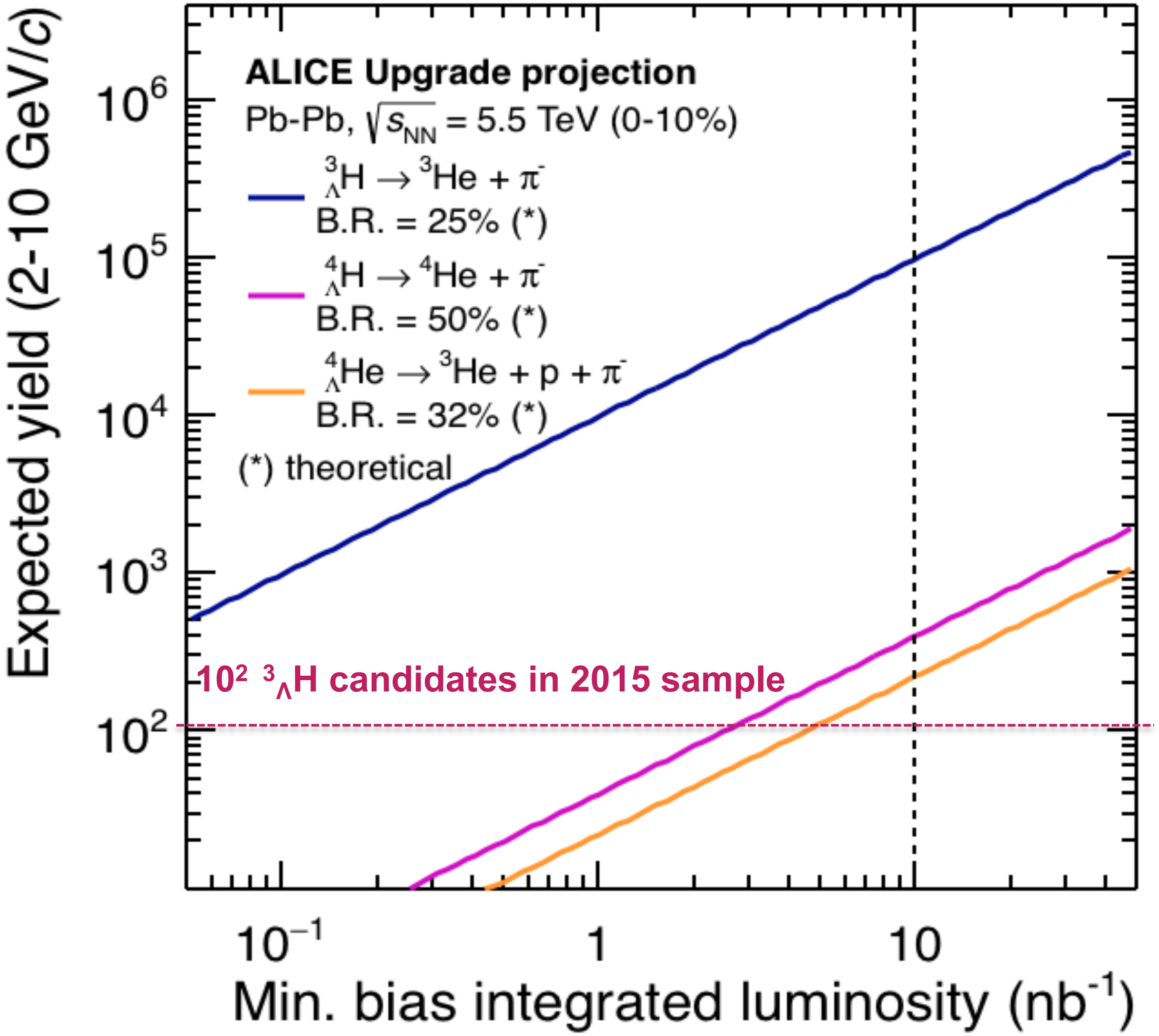
Physics case for Run3&4:

→ Measure centrality dependence of the hypertriton in Pb-Pb

→ Can we produce at all the hypertriton in pp collisions?

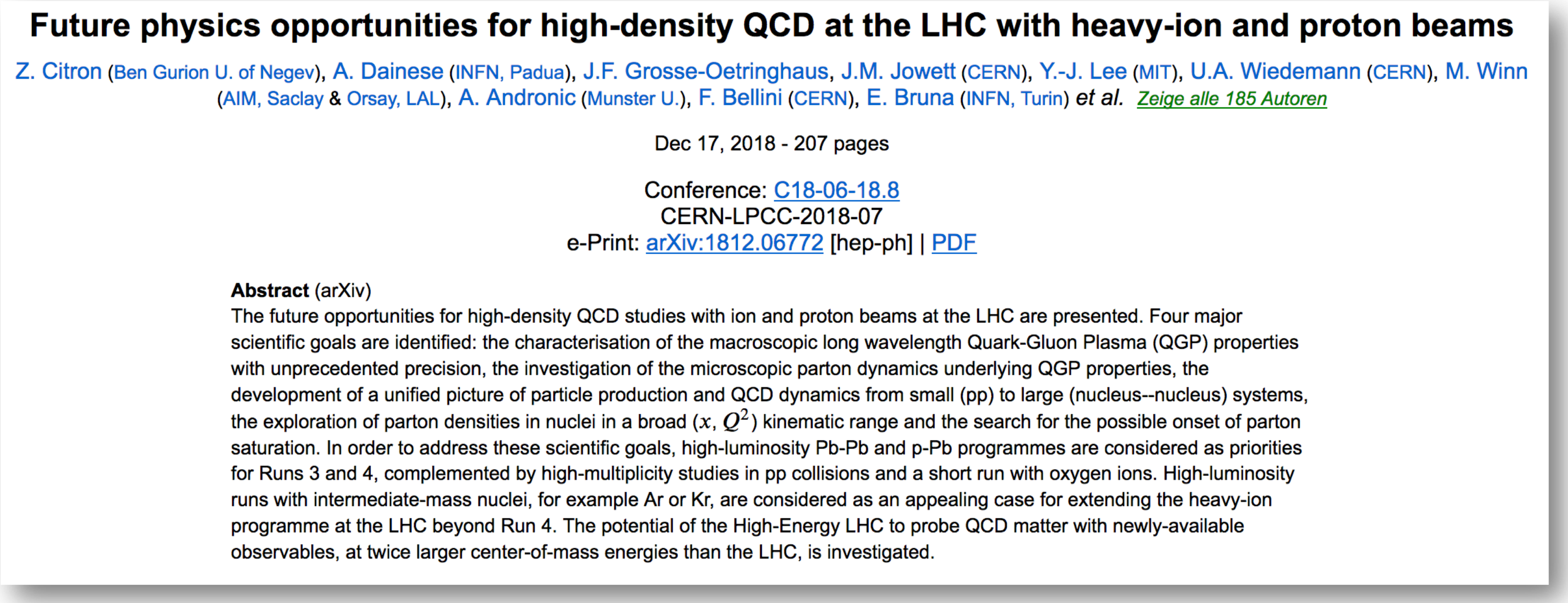
→ Go more differential for A = 3

→ Measure B_4 for ^{4}He, $^4{}_{\Lambda}$H, $^4{}_{\Lambda}$He



Outlook to LHC Run 3 and 4 (4)

→ Check out the entire LHC physics program at LHC Run 3 & 4 which is summarized in the recently released CERN yellow report: arXiv:1812.06772



Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

Z. Citron (Ben Gurion U. of Negev), A. Dainese (INFN, Padua), J.F. Grosse-Oetringhaus, J.M. Jowett (CERN), Y.-J. Lee (MIT), U.A. Wiedemann (CERN), M. Winn (AIM, Saclay & Orsay, LAL), A. Andronic (Munster U.), F. Bellini (CERN), E. Bruna (INFN, Turin) *et al.* *Zeige alle 185 Autoren*

Dec 17, 2018 - 207 pages

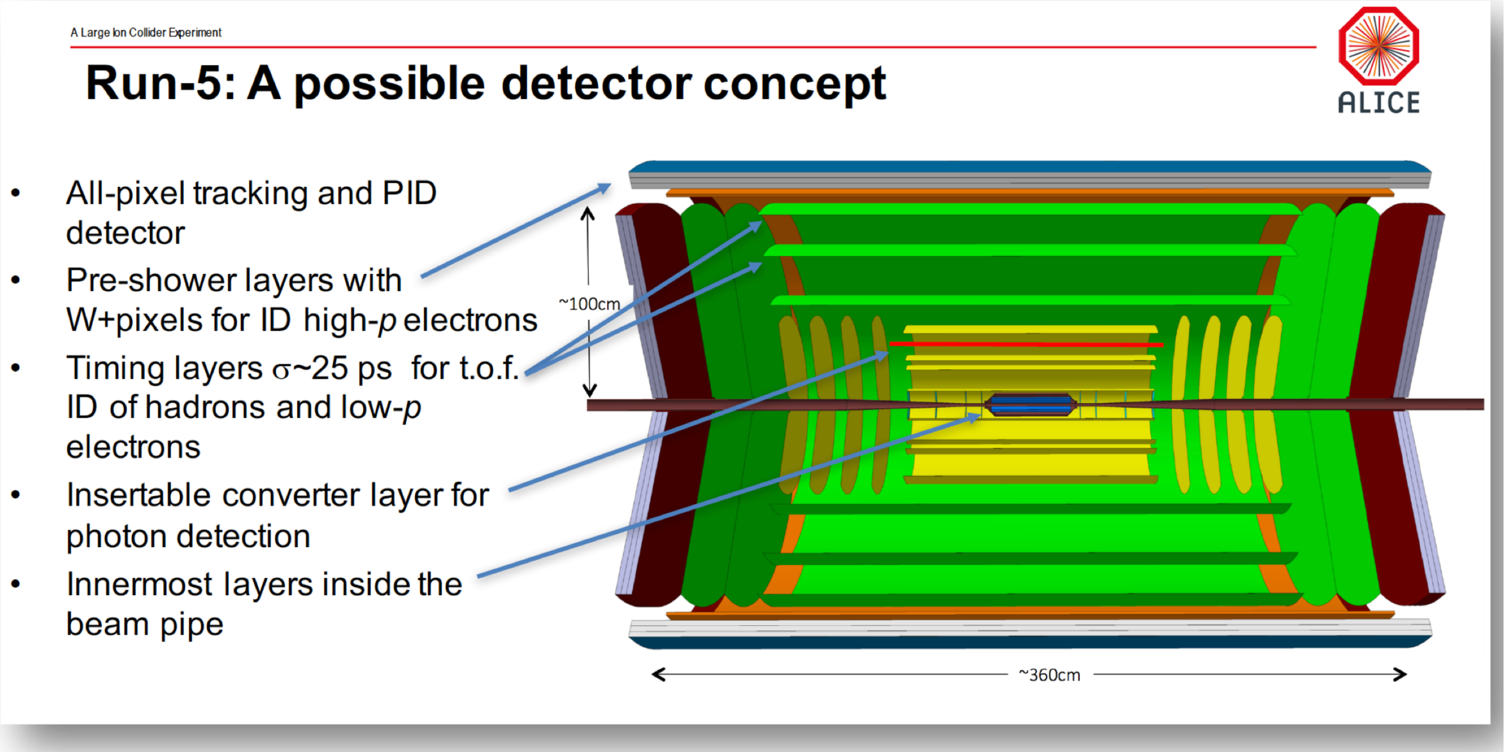
Conference: C18-06-18.8
CERN-LPCC-2018-07
e-Print: arXiv:1812.06772 [hep-ph] | PDF

Abstract (arXiv)
The future opportunities for high-density QCD studies with ion and proton beams at the LHC are presented. Four major scientific goals are identified: the characterisation of the macroscopic long wavelength Quark-Gluon Plasma (QGP) properties with unprecedented precision, the investigation of the microscopic parton dynamics underlying QGP properties, the development of a unified picture of particle production and QCD dynamics from small (pp) to large (nucleus--nucleus) systems, the exploration of parton densities in nuclei in a broad (x, Q^2) kinematic range and the search for the possible onset of parton saturation. In order to address these scientific goals, high-luminosity Pb-Pb and p-Pb programmes are considered as priorities for Runs 3 and 4, complemented by high-multiplicity studies in pp collisions and a short run with oxygen ions. High-luminosity runs with intermediate-mass nuclei, for example Ar or Kr, are considered as an appealing case for extending the heavy-ion programme at the LHC beyond Run 4. The potential of the High-Energy LHC to probe QCD matter with newly-available observables, at twice larger center-of-mass energies than the LHC, is investigated.

Plans for ALICE-II: thin, precise, fast

- ITS 3 (2024 → ultra-light and granular tracker) as testing ground for a completely new detector

- ALICE-II: gain up to two orders of magnitude in statistics by exploiting higher luminosity with lighter ions:
  - Very high rate (10 MHz Ar-Ar)
  - Low material budget
  - Hadron and electron ID (for X)
  - Extended rapidity acceptance (|**η**|<4)
  - Ideal tool to study (besides many other topics): Ω_{cc}, Ω_{ccc}, B_c, XYZ states, anti- and hyper-nuclei



A Large Ion Collider Experiment

Run-5: A possible detector concept

ALICE

- All-pixel tracking and PID detector
- Pre-shower layers with W+pixels for ID high-*p* electrons
- Timing layers σ~25 ps for t.o.f. ID of hadrons and low-*p* electrons
- Insertable converter layer for photon detection
- Innermost layers inside the beam pipe

A. Dainese / L. Musa, Heavy-ion town meeting 2018

Summary and conclusions

- The very rich anti- and hyper-nuclei physics program of ALICE offers unique insights into several physics aspects:
  - Thermal vs coalescence production models
  - Hyperon-nucleon interactions
  - Background for dark matter searches in space (AMS)
  - Determination of unknown hadronic cross sections of anti-nuclei with detector material

- This is just the beginning of an even bigger program:
  - Everything being done for A=2,3 will be done for A=4,5 in LHC Run 3&4&5
  - Anti- and hyper-nuclei will hopefully turn into a solid basis for using pp and heavy-ion collisions at the LHC into the ultimate QCD laboratory to study exotic bound states

Additional slides