Physics of identified spectra and nuclei, net-charge fluctuations

Workshop on the physics of HL-LHC, and perspectives at HE-LHC

F. Bellini (CERN), on behalf of ALICE

01.11.2017

Outline

- Introduction
- Nuclei and hypernuclei
  - Projections for nuclei and exotica
  - Measurements in pp
- Net-charge fluctuations
  - Statistics requirements for net-proton
  - LHCb potential
- Conclusions and next steps

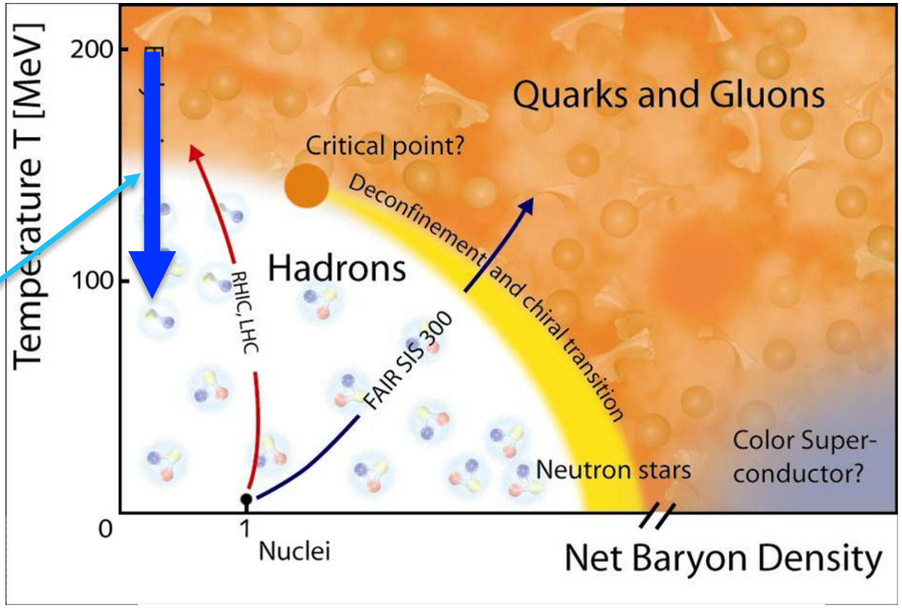
Only partly (nuclei) covered in
ALICE Upgrade LoI: *CERN-LHCC-2012-012*
ALICE ITS Upgrade TDR: *CERN-LHCC-2013-024*

QCD phase transition

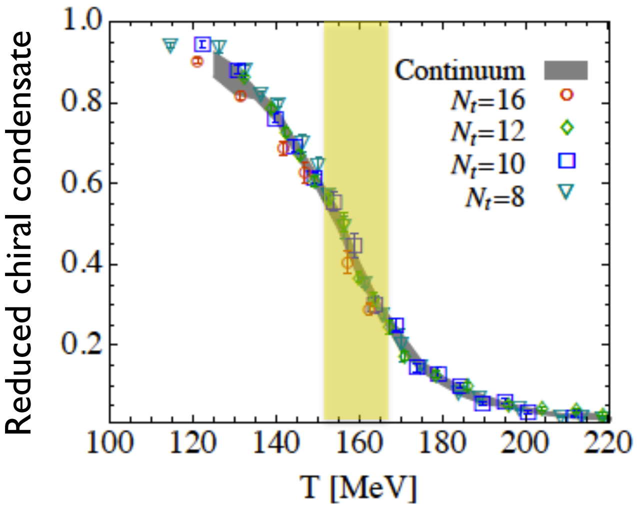
Phase transition: nuclear matter → QGP
Chiral transition, crossover at $\mu_B \sim 0$
[Y. Aoki, Nature 443 (2006) 675]

Phase transition: QGP → hadron gas
T_c **= (154 ± 9) MeV** from Lattice-QCD
[HotQCD Coll., PRD 90 (2014) 094503]

Chemical freeze-out → hadrochemistry fixed
T_{ch} **= 156 ± 2 MeV** from fit to ALICE data
[ALICE Coll., arXiv:1710.07531]



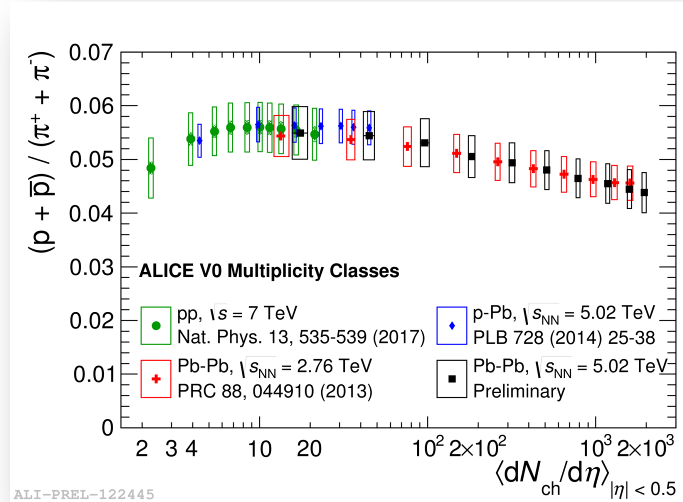
Identified (light flavour) particles:
→ Probes for thermal properties of the medium, particle formation mechanisms and collectivity
→ Search for evidence of partial chiral symmetry restoration at the phase boundary

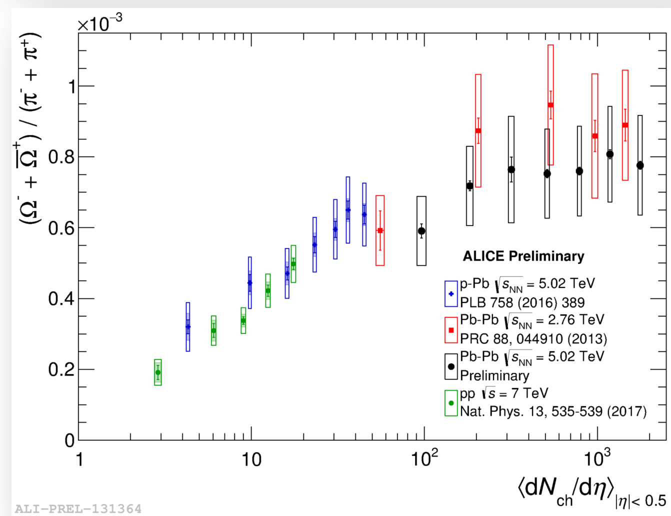


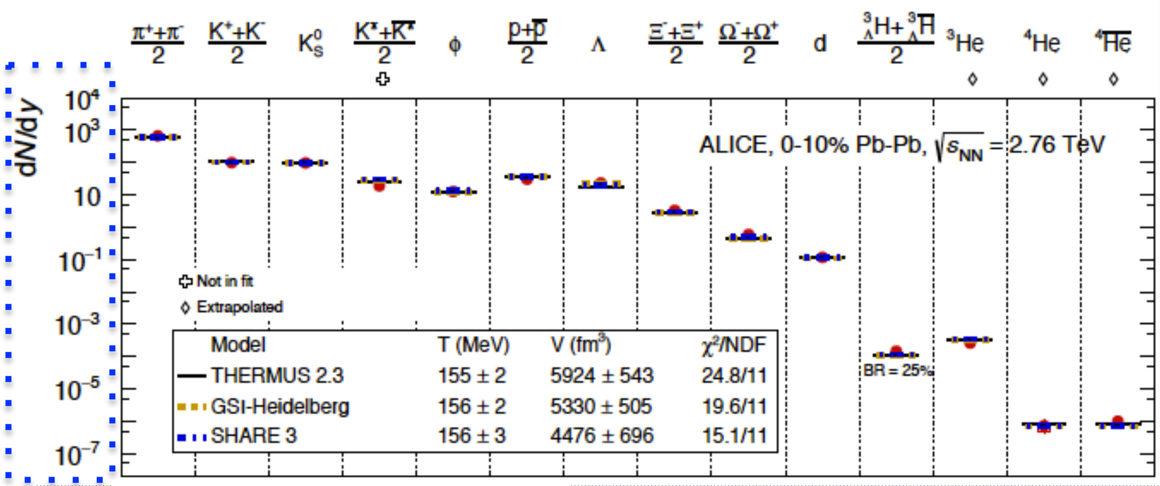
Wuppertal-Budapest Coll., arXiv:1109.5032v1

Identified particles at the LHC Run 1+2

- A comprehensive set of measurements in Pb-Pb, span over 9 orders of magnitude in yield
- Systematic study of system size dependence of particle production including pp, p-Pb
- Strangeness production
- Insights on collective dynamics and hadrochemistry
  - local thermodynamical equilibrium → chemical equilibrium







ALICE Coll., arXiv:1710.07531

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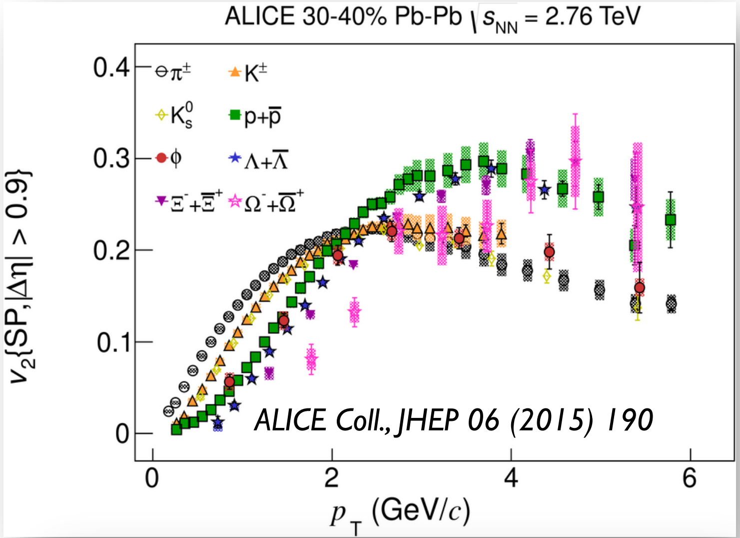
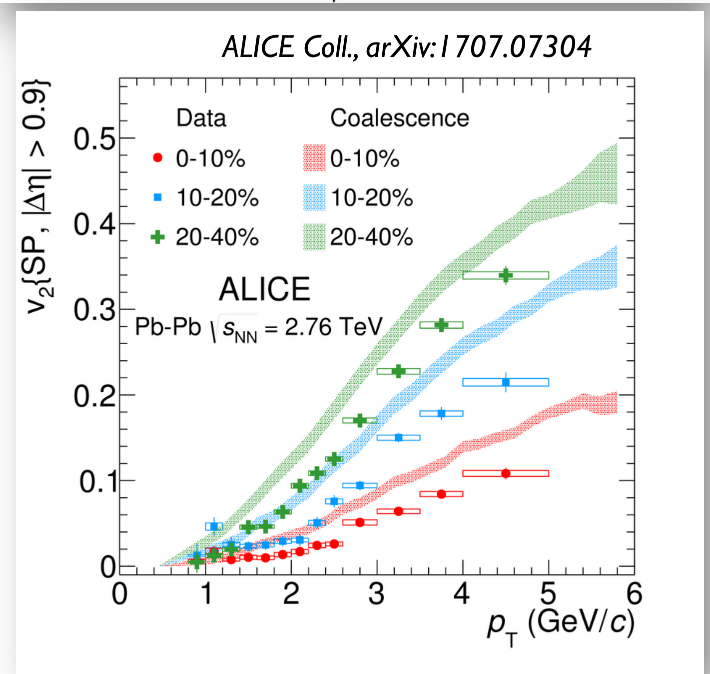
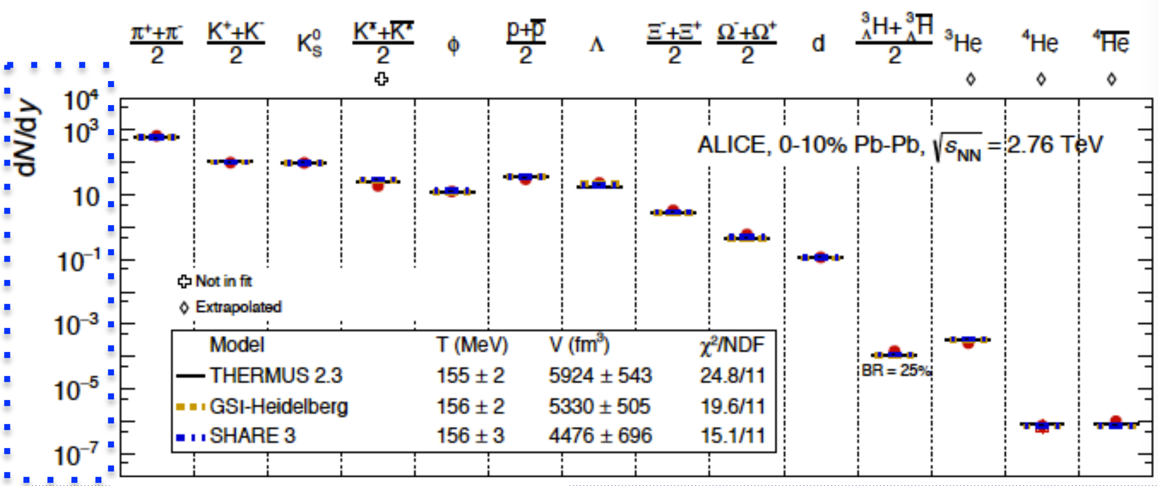
  - local thermodynamical equilibrium → chemical equilibrium
- Constraint on QGP parameters with spectra, v_2 and higher flow harmonics [e.g. S. Bass et al., arXiv: 1704.07671]
- Production of nuclei and survival in the fireball







ALICE Coll., arXiv:1710.07531

Physics with light flavour in Run 3+4

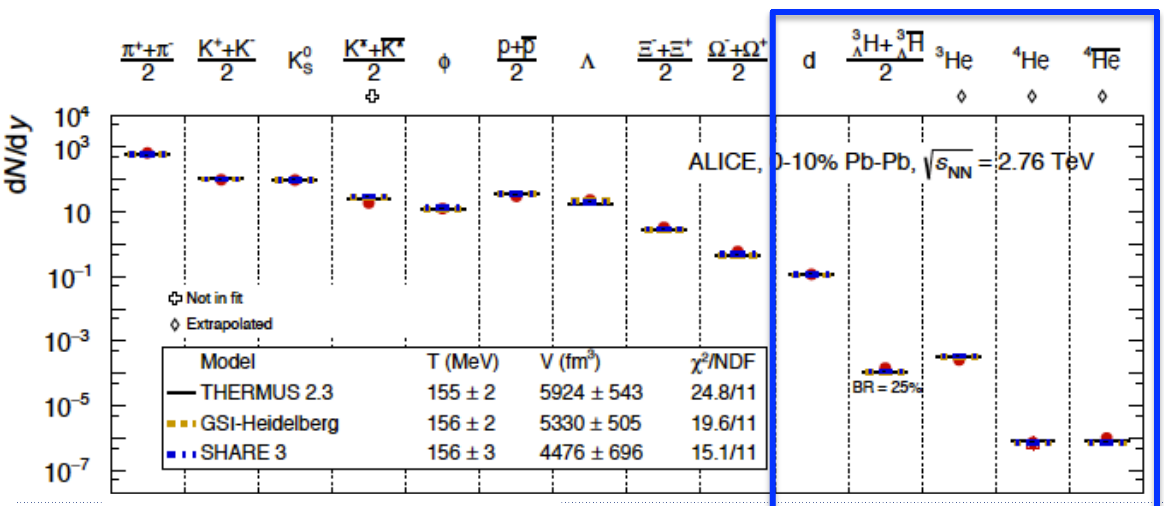
Focus on statistics-hungry measurements and searches with L = 10 nb^{-1} min bias Pb-Pb **(100x Run1+2)**

Today focus on

- **(anti)(hyper)nuclei and (strange) exotica sector**
- **net-charges, net-proton fluctuations**

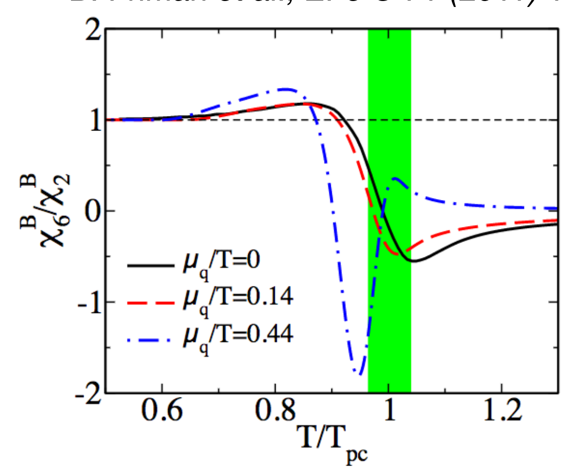
Depend on complementarity of several detectors and PID techniques

- **ALICE** PID performance already well exploited in Run1+2
- **LHCb** potential with upgraded detector → see dedicated slide
- **ATLAS / CMS** → to be assessed



ALICE Coll., arXiv:1710.07531

B. Friman et al., EPJ C 71 (2011) 1694



(ANTI-)NUCLEI AND (ANTI-)HYPERNUCLEI

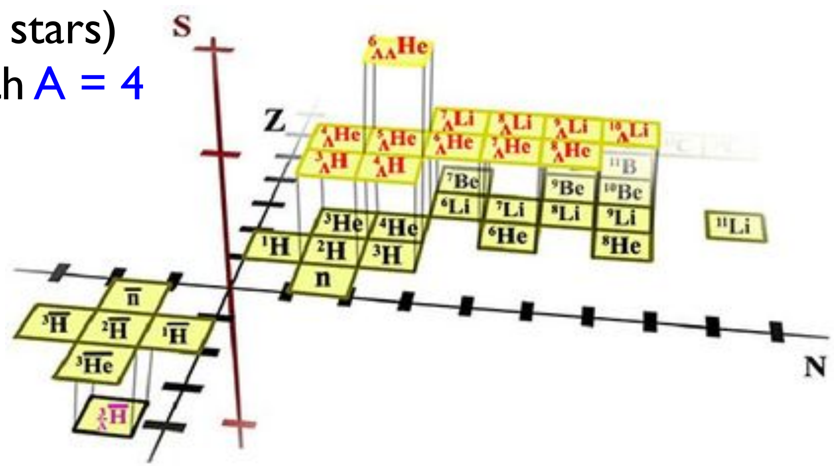
Physics case for (anti-)(hyper-)nuclei

- **Test** coalescence, thermal production
  - Good sensitivity to theoretical models parameters
  - freeze-out temperature
  - equilibrium vs. non equilibrium of strangeness, for hyper-nuclei

- **Precision** measurements of signals rarely produced in Run 1+2
  - ${}^{3}_{\Lambda}H$ lifetime and spectrum
  - v_2 of ${}^{3}He$ and ${}^{3}_{\Lambda}H$: mass scaling vs. p scaling
  - survival of loosely bound states in the collective expansion

- **Search** for rarely produced anti- and hyper-matter
  - Insights on the strength of the hyperon-nucleon interaction, relevant for nuclear physics and nuclear astrophysics (neutron stars)
  - First observation for anti-hyper-nuclei with A = 4

- **Constrain** productions models with measurements in pp collisions
  → application in estimates of astrophysical background for dark matter searches



Production models

2 main models give predictions consistent in order of magnitude but based on different parameters

Thermal production at chemical freeze-out/phase boundary

- Key parameters are mass and chemical freeze-out temperature: **dN/dy ~ exp ($-m/T_{ch}$)**
- Model provides yields but no p_T spectra (no dynamics)

Coalescence of nucleons at kinetic freeze-out

- Key parameters are nuclear wave functions, size of the (hyper)nucleus
- Production probability quantified by **coalescence parameter B_A**
  - related to coalescence volume in momentum space p_0
- "Simple" coalescence model limited – source size to be included in modeling
- Model provides spectra

$$E_i \frac{d^3N_i}{dp_i^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^A \quad B_A = \left(\frac{4\pi}{3} p_0^3 \right)^{A-1} \frac{M}{m^A}$$

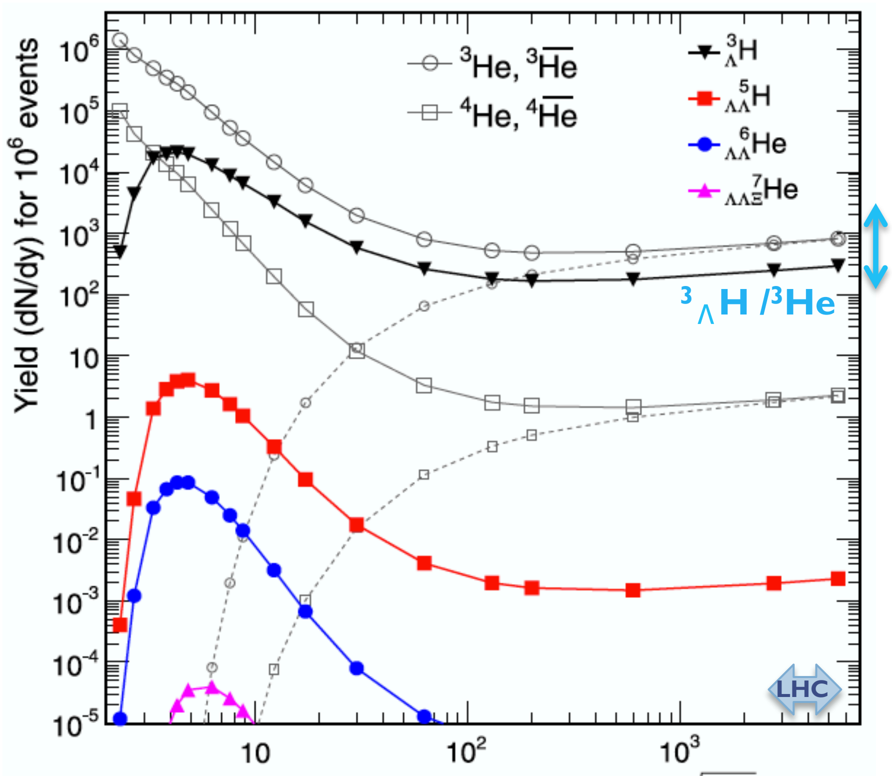
Exemplary case: compare ^{3}He and $^3_\Lambda$H

- Very similar mass but different binding energy and different size

Production models

THERMAL

$dN/dy \sim \exp(-m/T_{ch})$



A. Andronic et al., PLB 697, 203 (2011)

COALESCENCE

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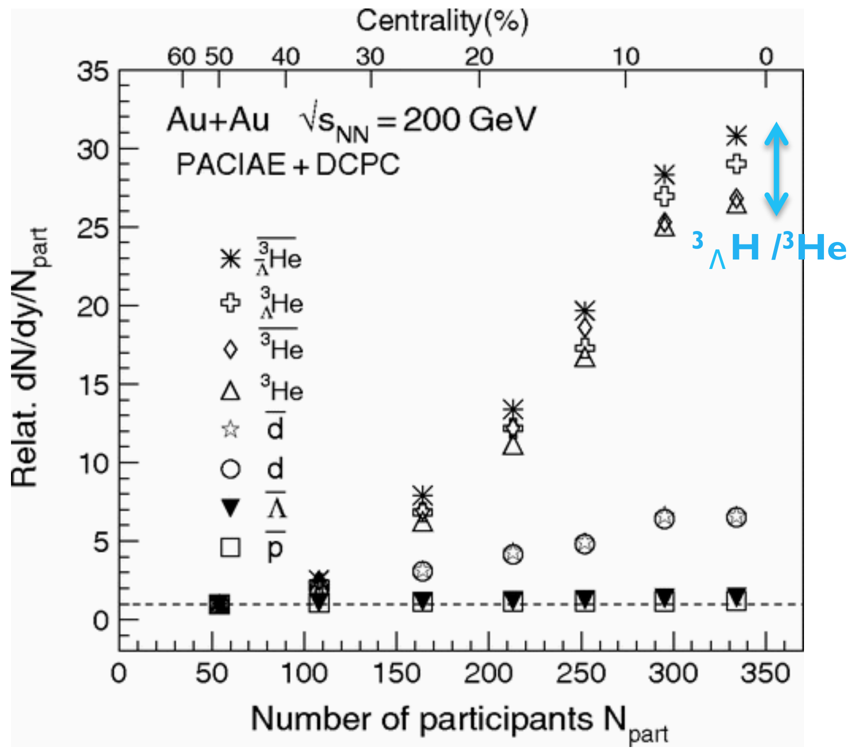


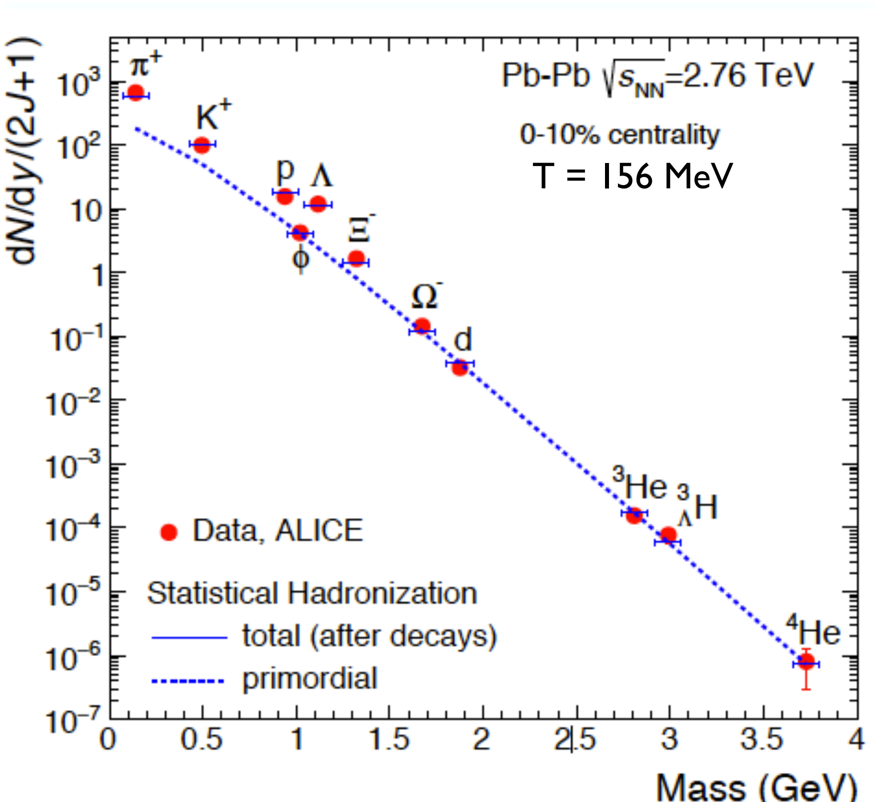
G. Chen et al., PRC 88, (2013) 034908

Yields/participant normalised to 40-60% centrality

Production models

THERMAL

d*N*/dy ~ exp (-*m*/*T*$_{ch}$)



A. Andronic et al., arXiv:1710.09425

COALESCENCE

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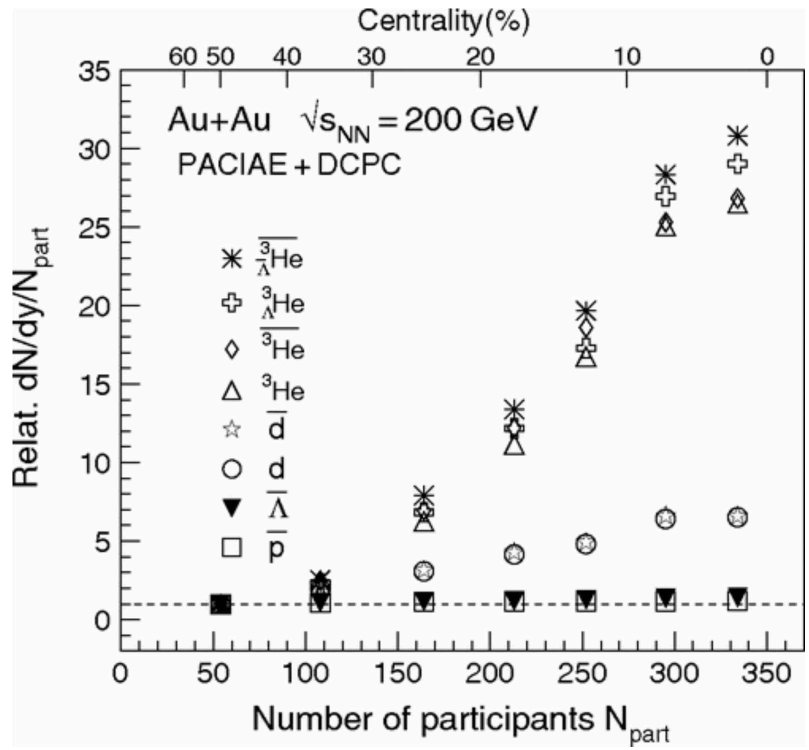

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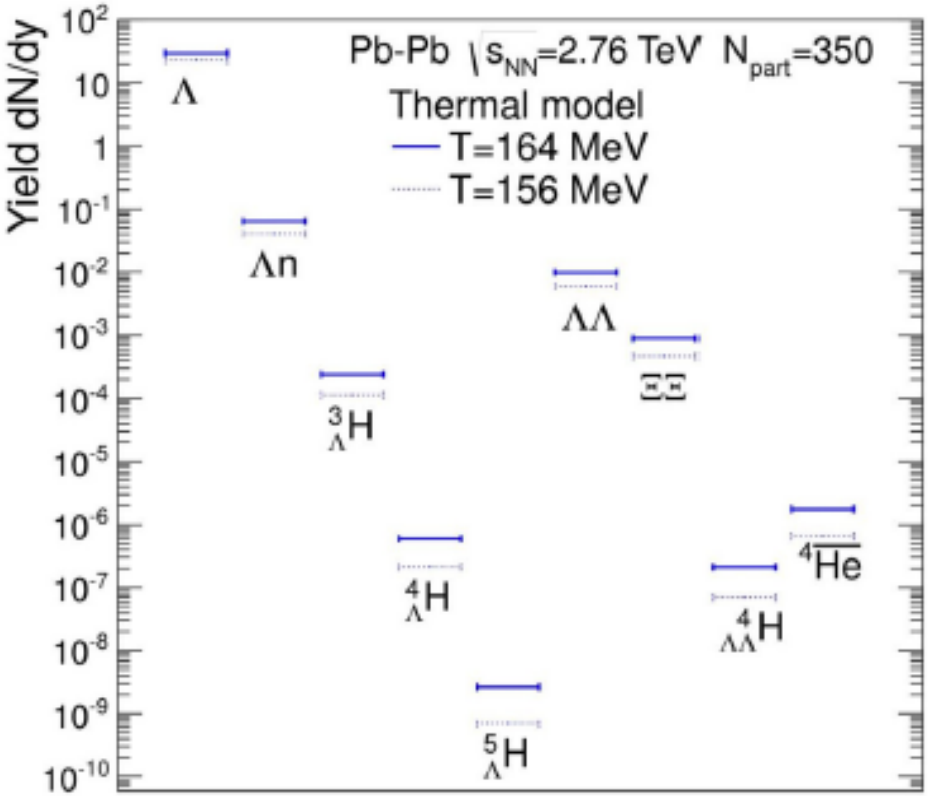

A. Andronic, priv. communication

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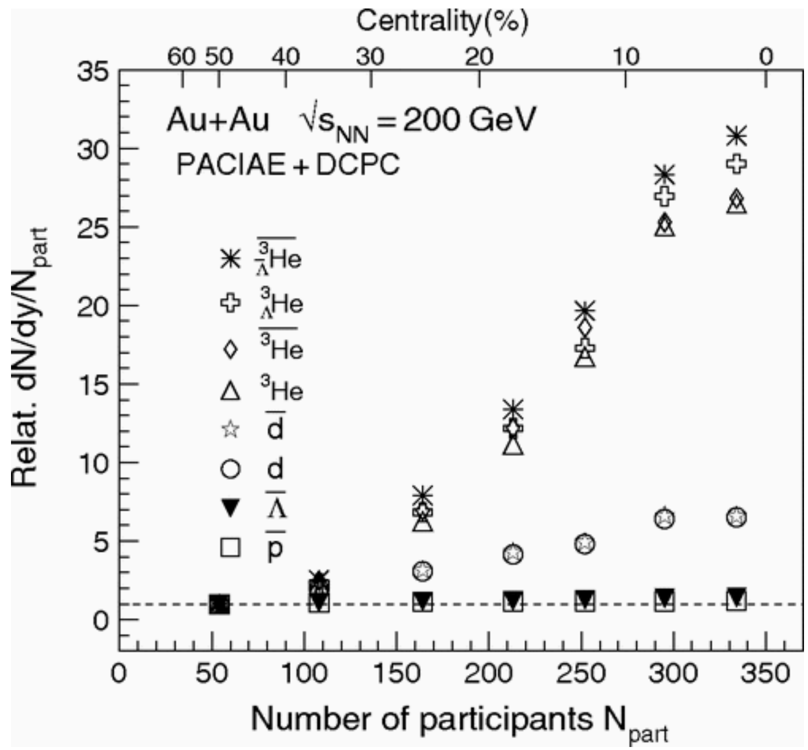

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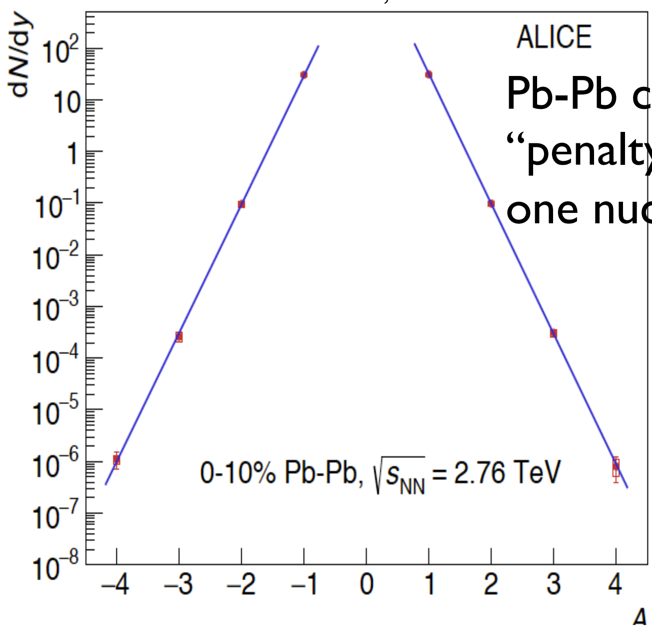
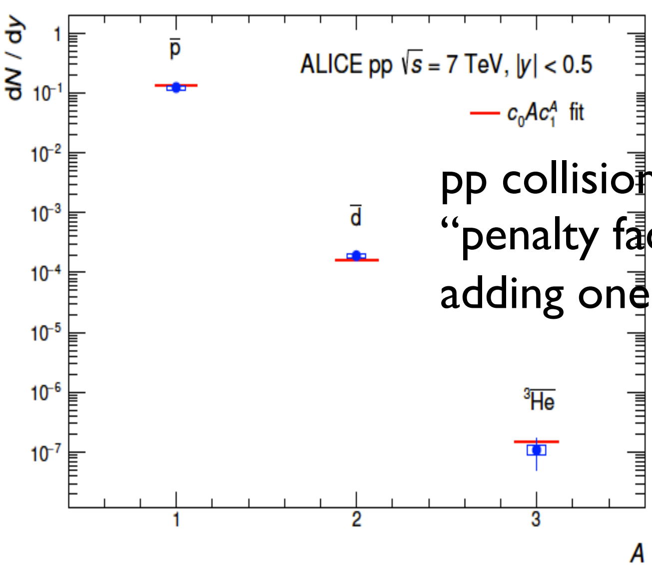
Production at the LHC – Run I+II

ALICE Coll., arXiv:1710.07531

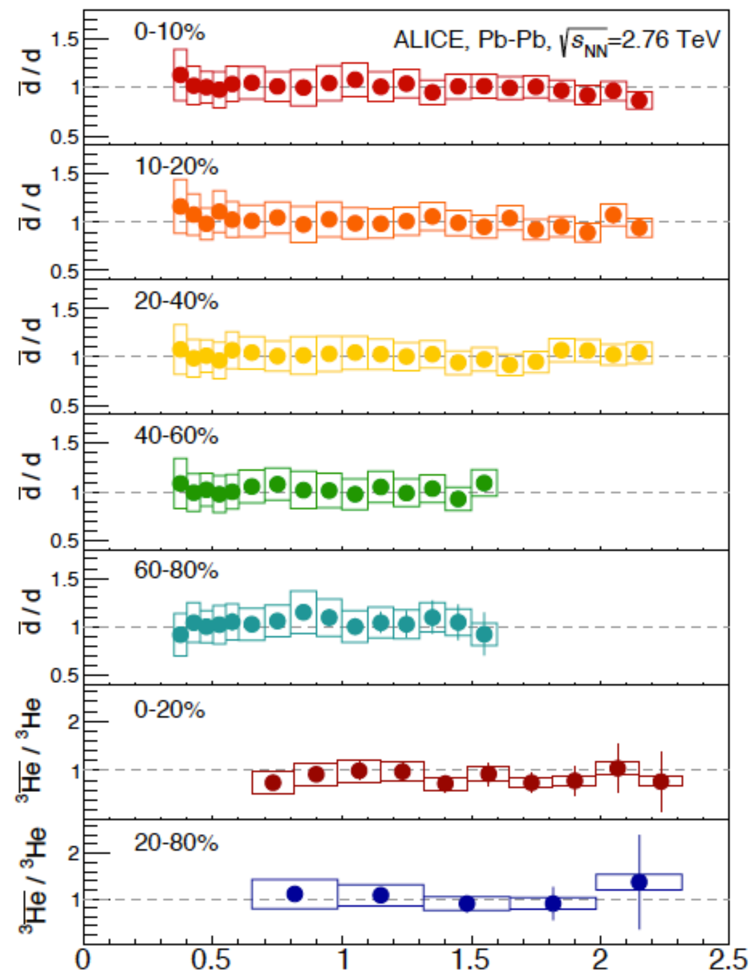


Pb-Pb collisions:
“penalty factor” for adding one nucleon ~ 350



pp collisions:
“penalty factor” for adding one nucleon ~ 10^3

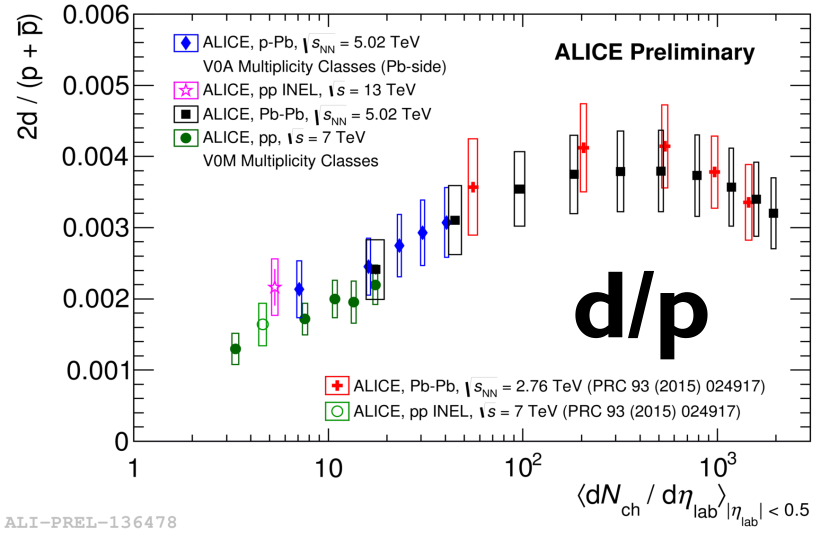
Anti-matter / matter ~ 1



ALICE Coll. PRC 93, 024917 (2016)

Production at the LHC – Run I+II

- consistency of particle ratios and yields with thermal model expectations
- no significant $\sqrt{s}$ dependence at $\mu_B = 0$



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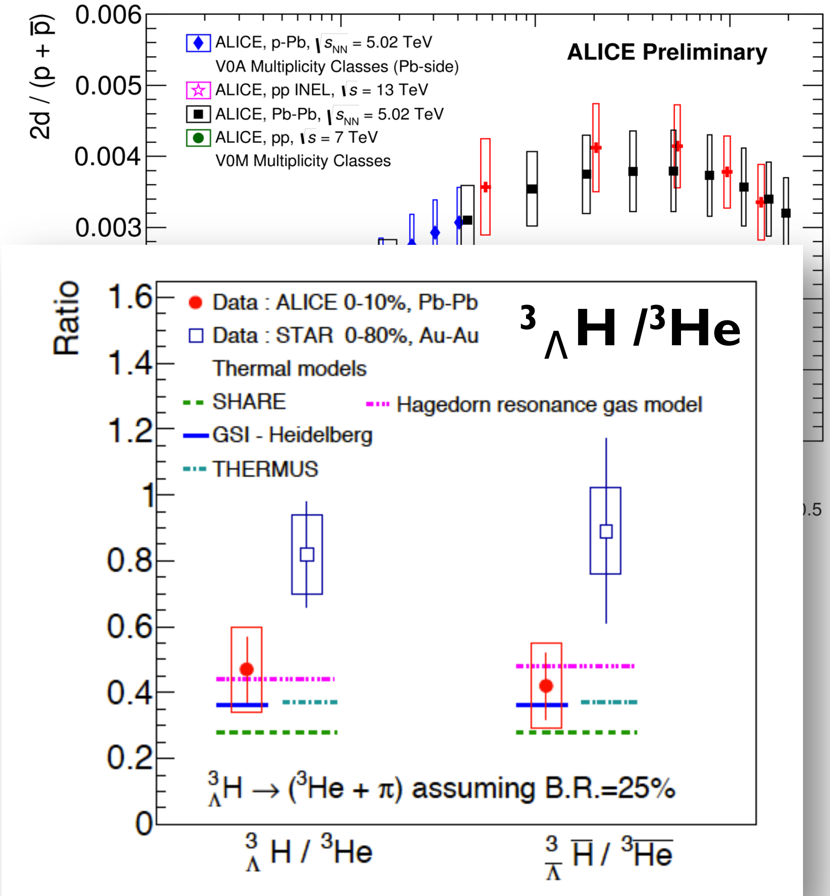

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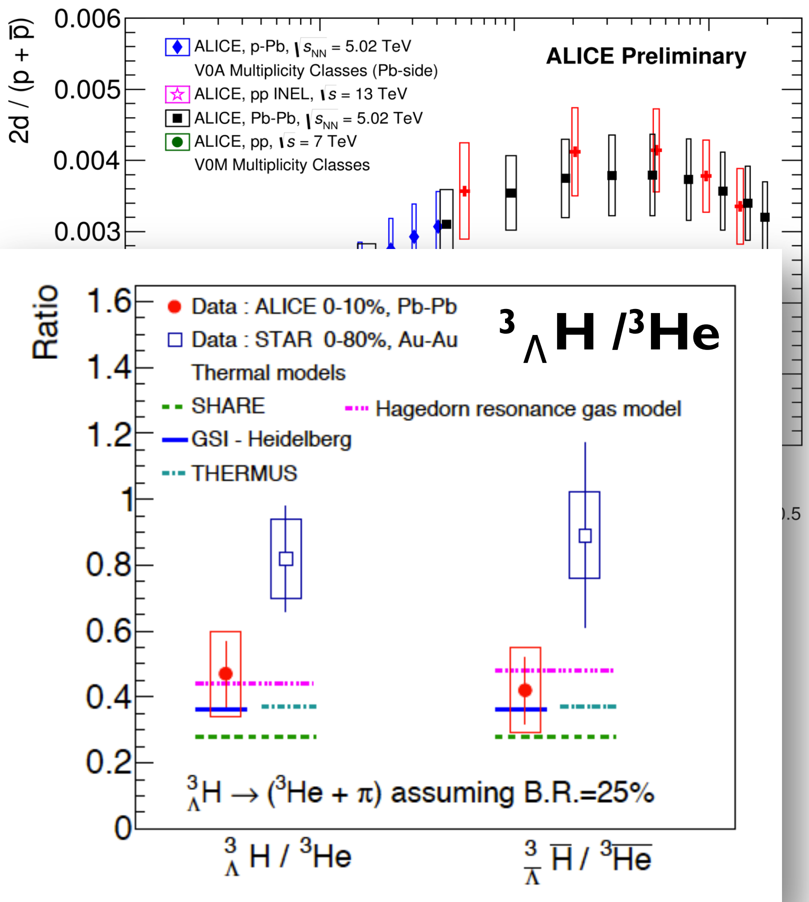
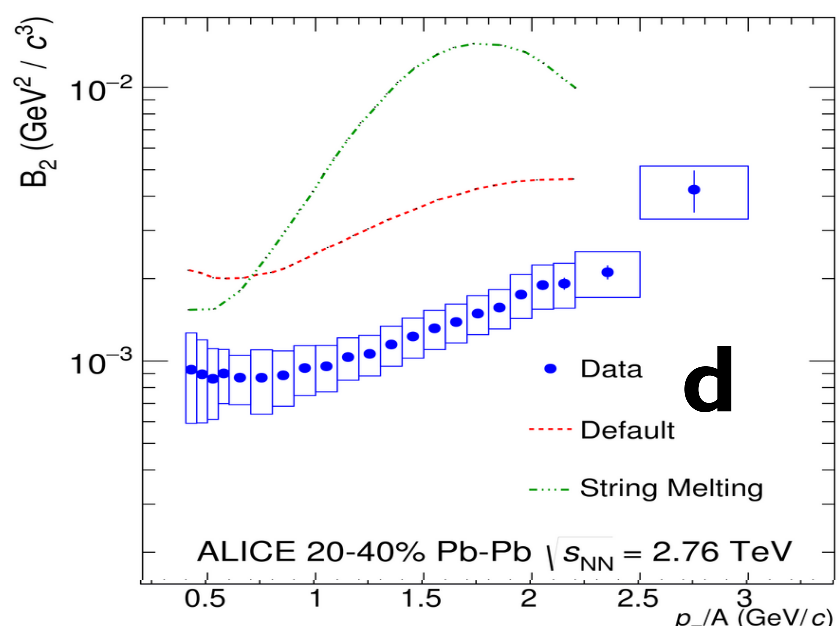
- Simple coalescence fails in reproducing the deuteron B_2 and v_2



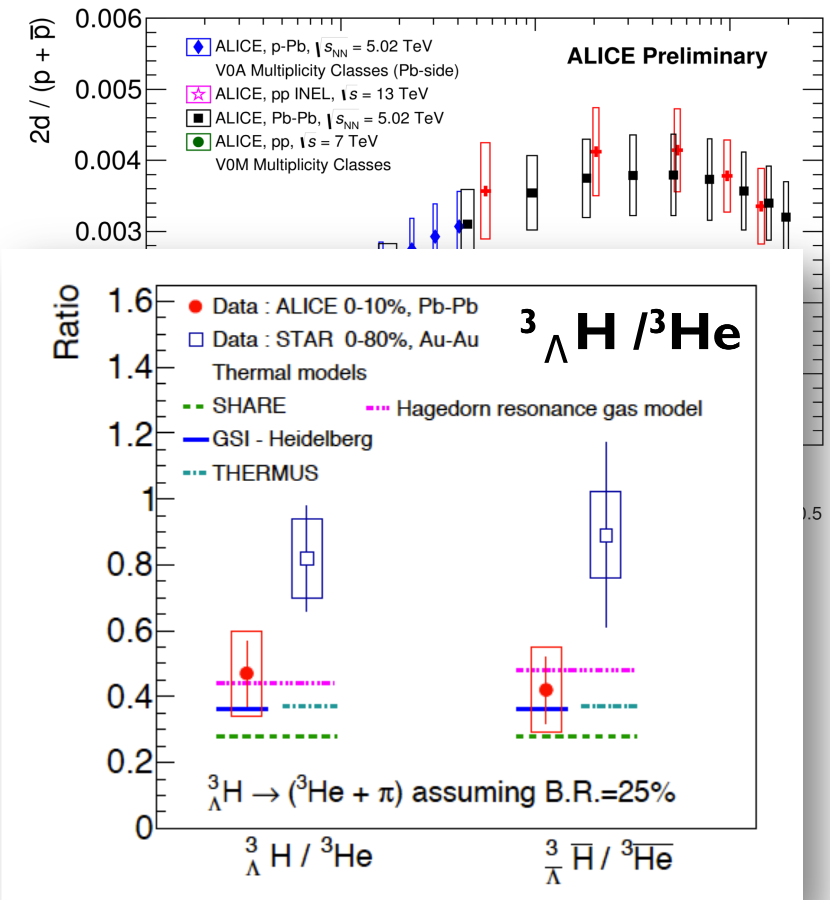


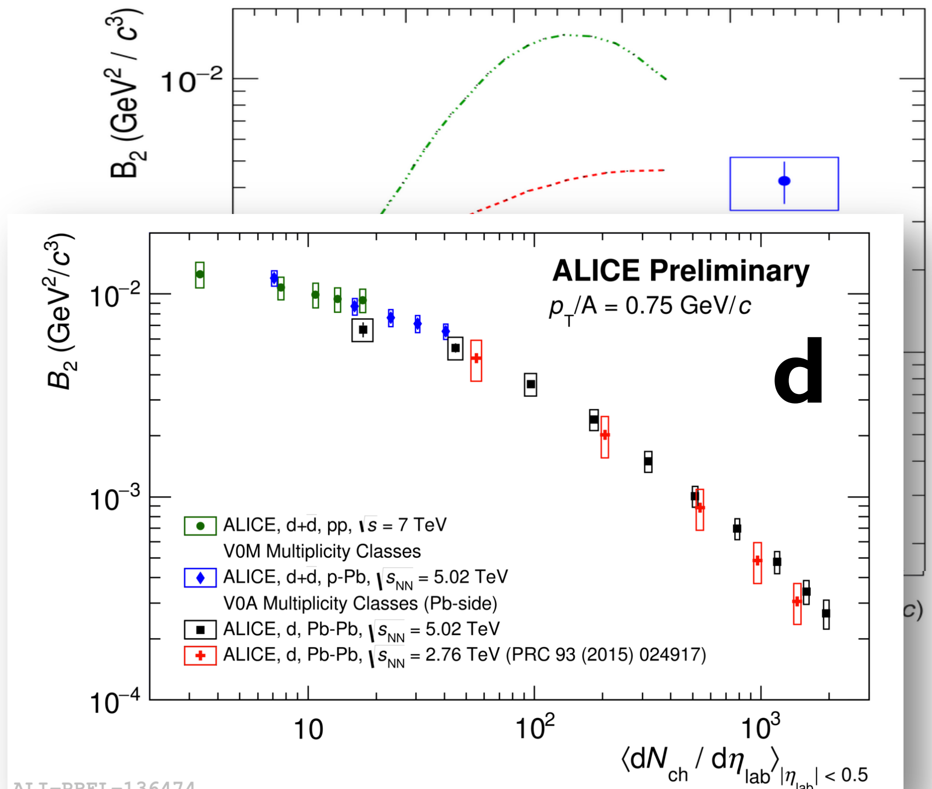
ALICE Coll., arXiv:1707.07304

Production at the LHC – Run I+II

- consistency of particle ratios and yields with thermal model expectations
- no significant $\sqrt{s}$ dependence at $\mu_B = 0$

- Simple coalescence fails in reproducing the deuteron B_2 and v_2
- B_2 decrease with centrality in Pb-Pb is explained as an increase in the source volume (not in simple coalescence)





Nuclei yield reach in Run 3+4

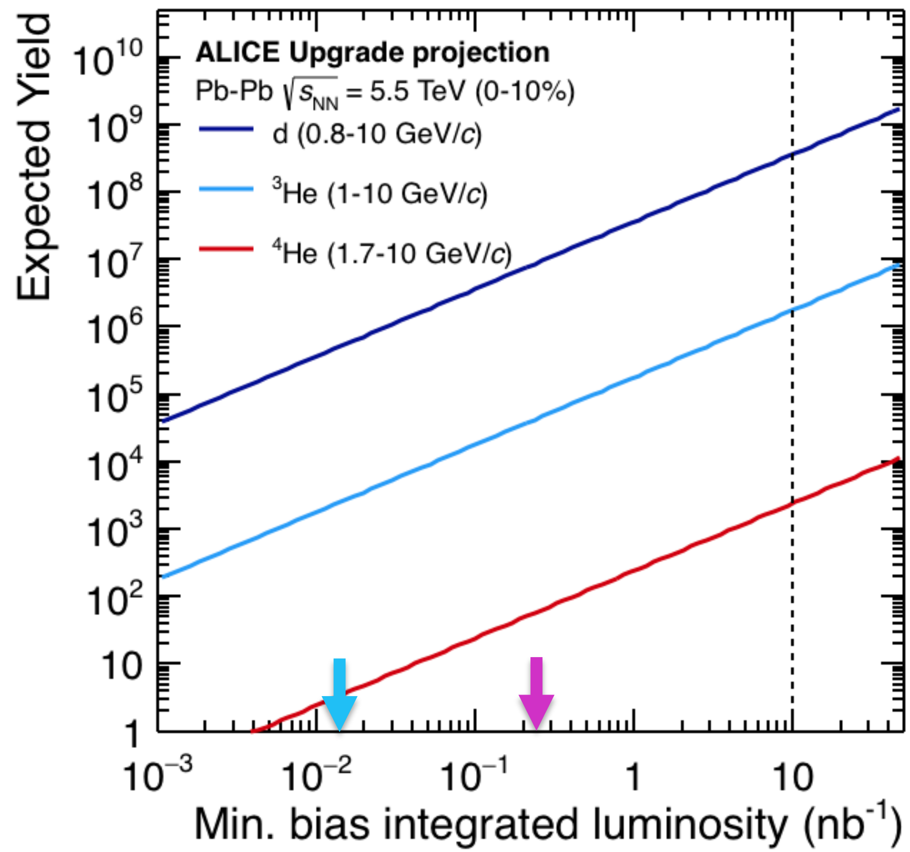
Accessible candidates assuming:

- Thermal production (validated by Run1+2 results) at T_{ch} **= 156 MeV**
- Run 2 efficiencies in | η |< 0.9 (TPC+TOF)

With upgraded detector

→ ALICE-GEM TPC tracking performance similar to MWPC TPC (distortion calibration to restore momentum resolution)

→ impact of upgraded ITS detector geometry and material to be assessed



For ref. 2015 min bias sample ~ 13/μb
2018 min bias sample ~ 250/μb

→ as many d as p in Run 1+2

→ as many anti-nuclei as nuclei

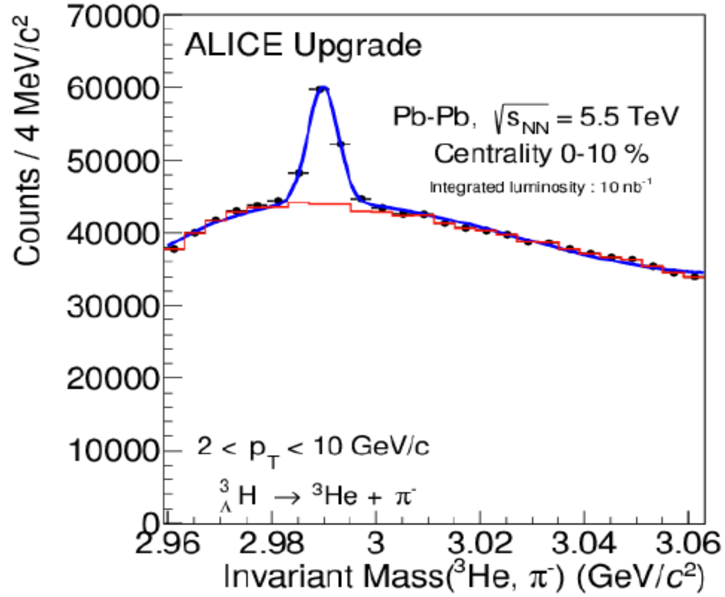
→ **What is now measured for A = 2 and A = 3 will be accessible for A = 4**

Hyper-nuclei yield reach in Run 3+4

- High statistics sample of min bias Pb-Pb
- Improved tracking resolution from the ALICE ITS upgrade
- **$^{3}_{\Lambda}H$ reconstruction** feasible in 2-body and 3-body decay with charged products
  - Lower background but also lower B.R. for 2-body

- B.R. not well known [1,2]
- precise evaluation of absorption cross section of $^{3}_{\Lambda}H$ and ^{3}He is needed

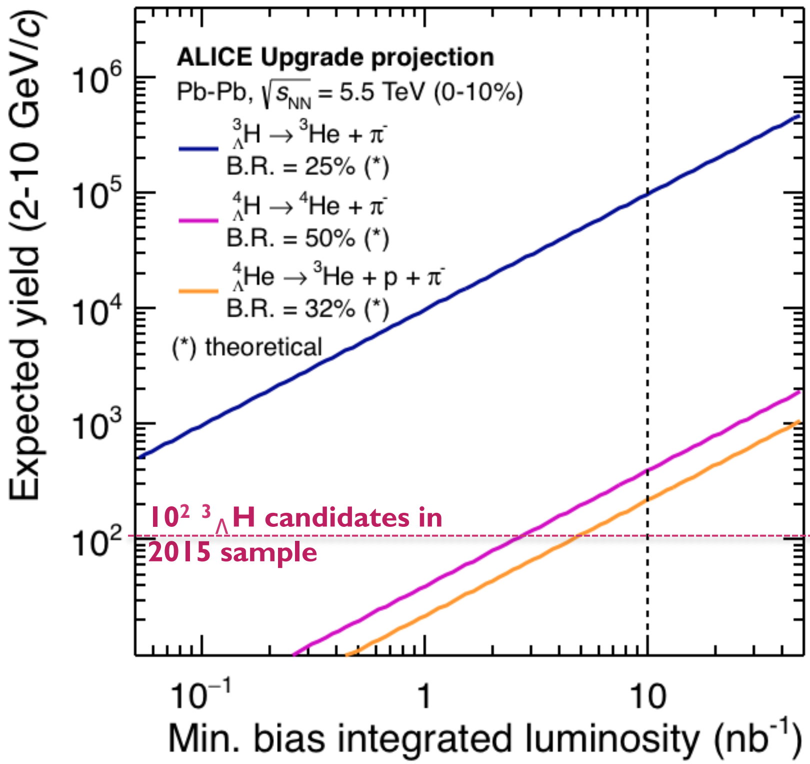
ALICE ITS upgrade TDR, : *CERN-LHCC-2013-024*

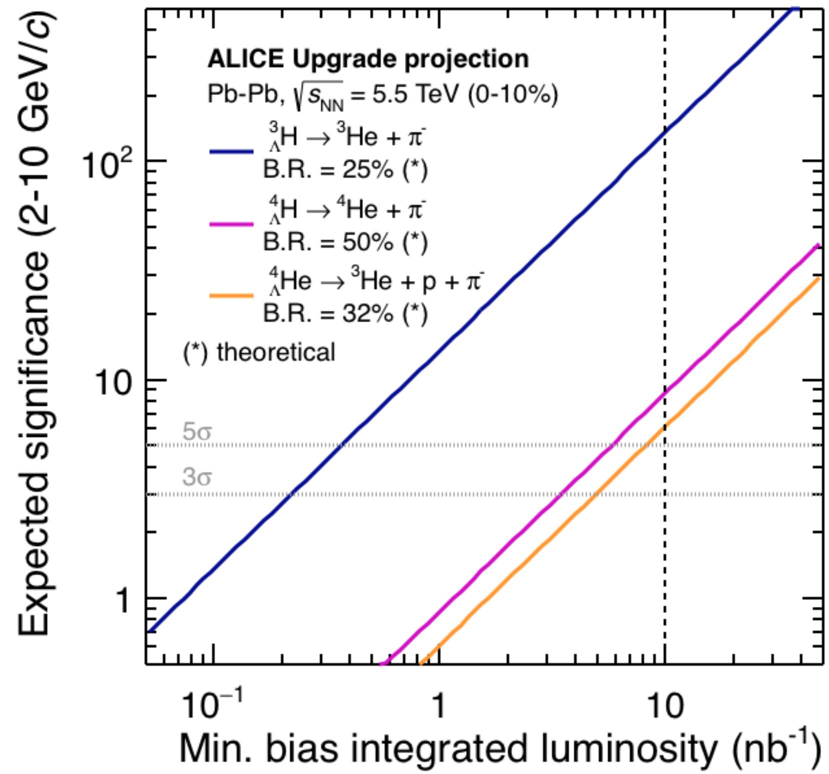


	Mass (GeV/c²)	Decay channel (B.R.)	dN/dy (SHM)
$^{3}_{\Lambda}H$	2.991	**$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$ (25% [1])** $^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$ (41% [1])	1×10^{-4}
$^{4}_{\Lambda}H$	3.931	$^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$ (50% [1])	2×10^{-7}
$^{4}_{\Lambda}He$	3.929	$^{4}_{\Lambda}He \rightarrow {}^{3}He + p + \pi^{-}$ (32% [2])	2×10^{-7}

[1] H. Kamada et al., PRC 57, 1595 (1998), [2] H. Outa et al., NPA 639 (1998) 251-260

Hypernuclei with 10/nb





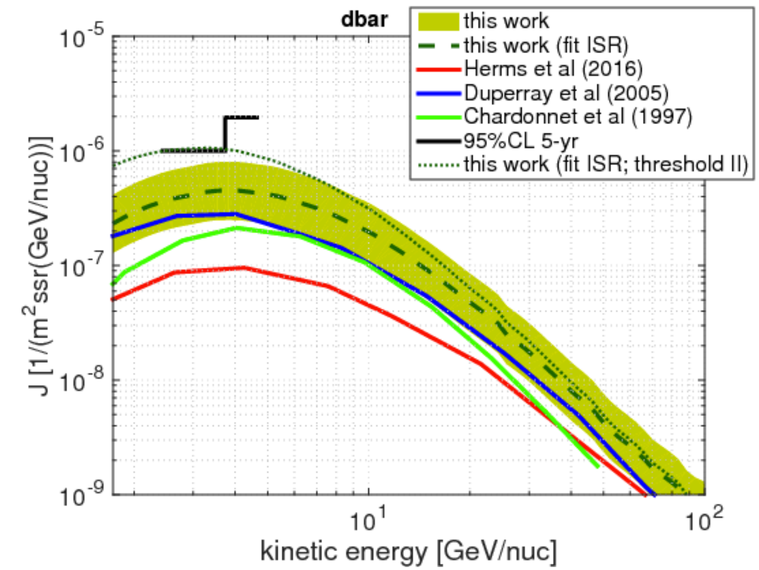
- Updated estimates wrt *CERN-LHCC*-2013-024, include efficiency of Run 2 analysis and upgraded ITS

- With the expected 10/nb **anti-$^4{}_\Lambda$H, anti-$^4{}_\Lambda$He "discovery" in reach**

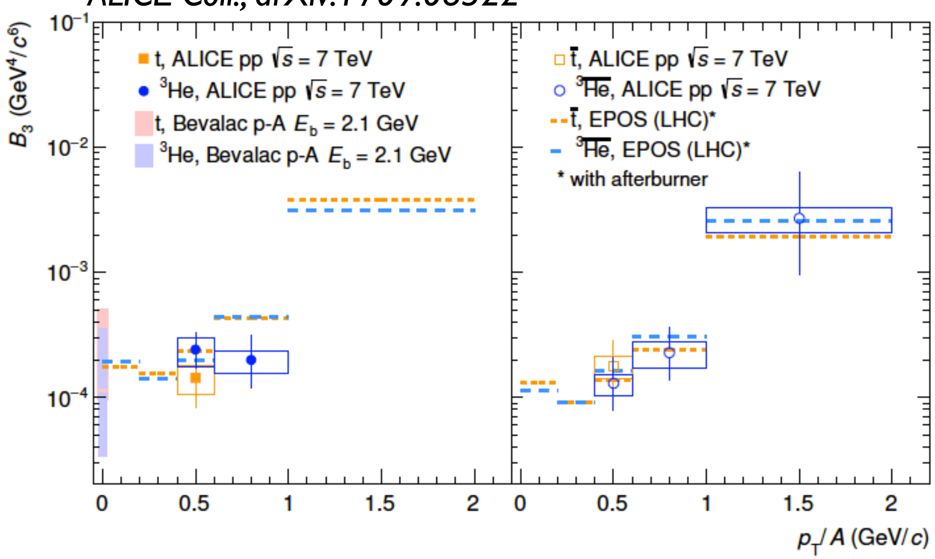
Nuclei in pp collisions

Searches for **dark matter WIMP** candidate decaying in d-bar and anti-^{3}He require **estimate of expected secondary astrophysical background** (secondary anti-nuclei produced in cosmic ray spallation)

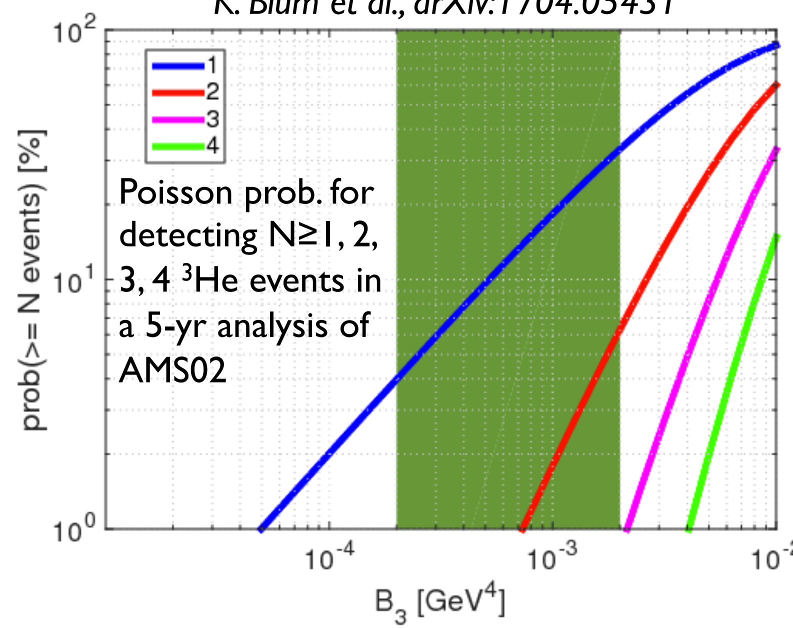
→ Precise measurement **of coalescence parameters** at the LHC can provide constraints for models



ALICE Coll., arXiv:1709.08522



K. Blum et al., arXiv:1704.05431



NET-CHARGE, NET-BARYON FLUCTUATIONS

Physics case for conserved net-charges

Deconfinement transition in the vicinity of the chiral limit ($m_{u,d}$~0) boundary

- Higher moments of baryon number related to chiral transition
- Measurements of event-by-event fluctuations in particle production
- Direct correspondence with the thermodynamic susceptibilities (χ) that can be extracted *ab initio* by L-QCD

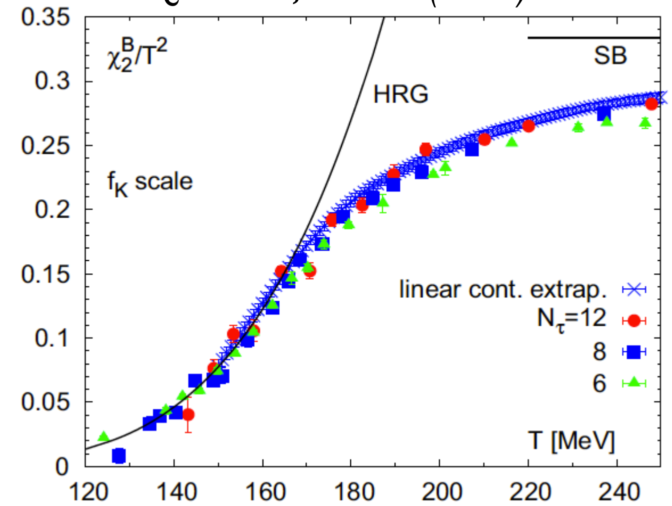
$$\hat{P} \equiv \frac{P}{T^4} = \frac{\ln Z}{VT^3} \qquad \hat{\chi}_N \equiv \frac{\chi_N}{T^2} = \frac{\partial^2 \hat{P}}{\partial(\mu_B / T)^2}$$

$$\hat{\chi}_N = \frac{\chi_N}{T^2} = \frac{1}{VT^3}\sum_{n=1}^{|q|} n^2(\langle N_n\rangle + \langle N_{-n}\rangle)$$

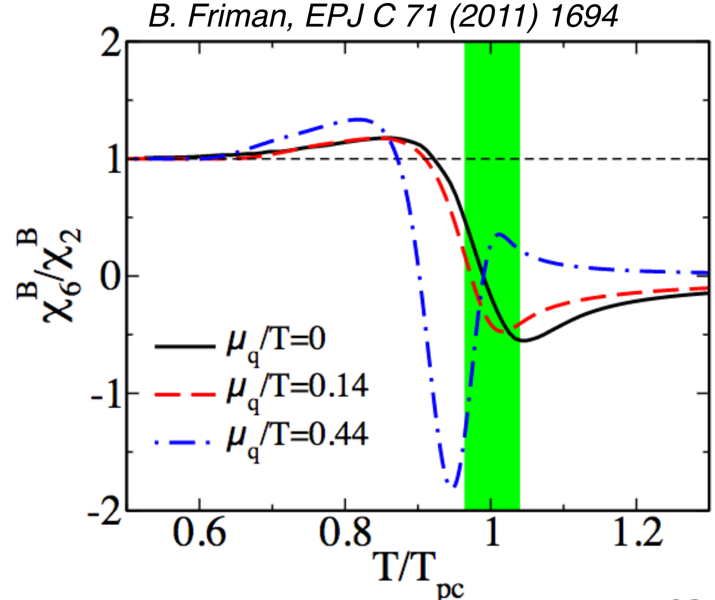
N = B, Q, S
n = 1, 2, 3

- Net-baryon ~ net-proton
  [P. Braun-Munzinger at al., PLB 747 (2015) 292]
- Net-strangeness

HotQCD Coll., PRD 85 (2012) 054503

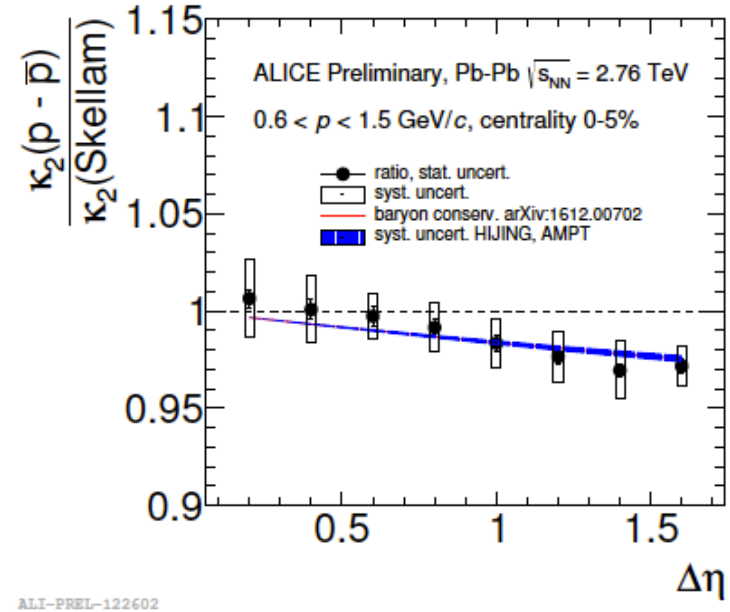


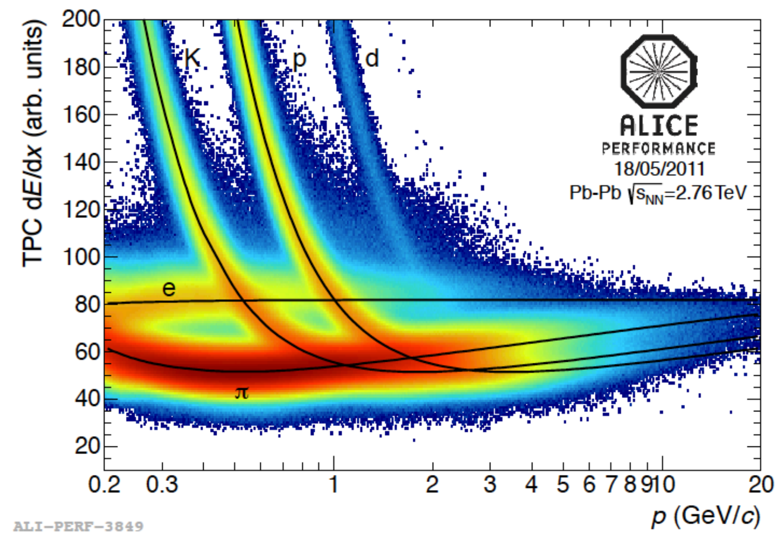
B. Friman, EPJ C 71 (2011) 1694



High order cumulants of net-proton

- Measure higher order cumulants of particle distributions
- Ratio of susceptibilities
  - Correct to cancel volume fluctuations
    [Nucl. Phys. A 960 (2017) 114–130]
- Measurements sensitive to detector acceptance → global baryon number conservation
- Baryon transport at forward rapidity
- Detector performance:
  - Low p_T proton PID
  - Discrimination of secondaries





Net-proton: statistics requirements

First projection with toy MC

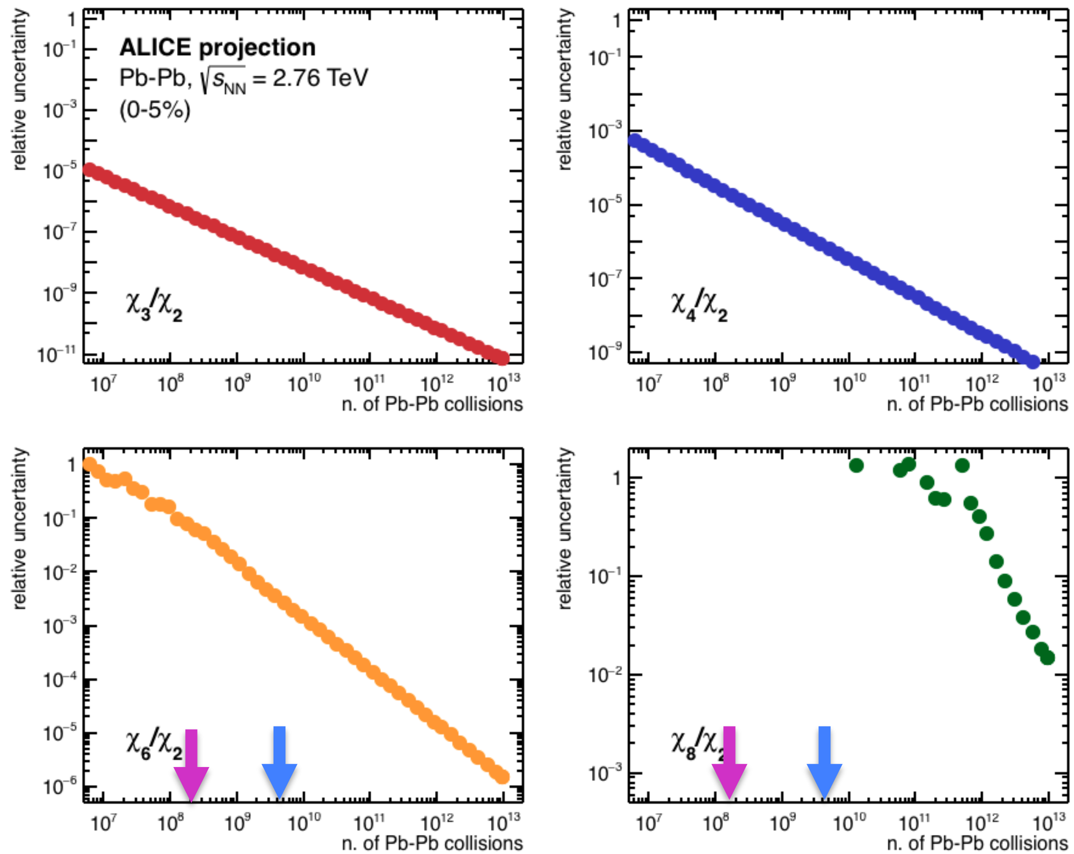
- p, p-bar yield measured in Pb-Pb 2.76 TeV (0-5%)
- $\mu_B \sim 0$ → p-bar/p = 1
- Current ALICE detector, $\Delta\eta$ = 1.6
- TPC PID in $0.4 < p_T < 0.8$ GeV/c
- Same efficiency for p, p-bar

To be estimated:

→ Projections at 5.5 TeV with upgraded detector acceptance [ongoing]

→ Performance with B = 0.2 T in upgraded detector

→ Projections for net strangeness



2018 central sample, **Run 3+4** central sample

LHCb PID capabilities

- Hadron PID in two RICH → Primary particle PID exploited successfully in fixed target mod
  Δy = 1.5 down to p_T(p) = 0.5 GeV/c

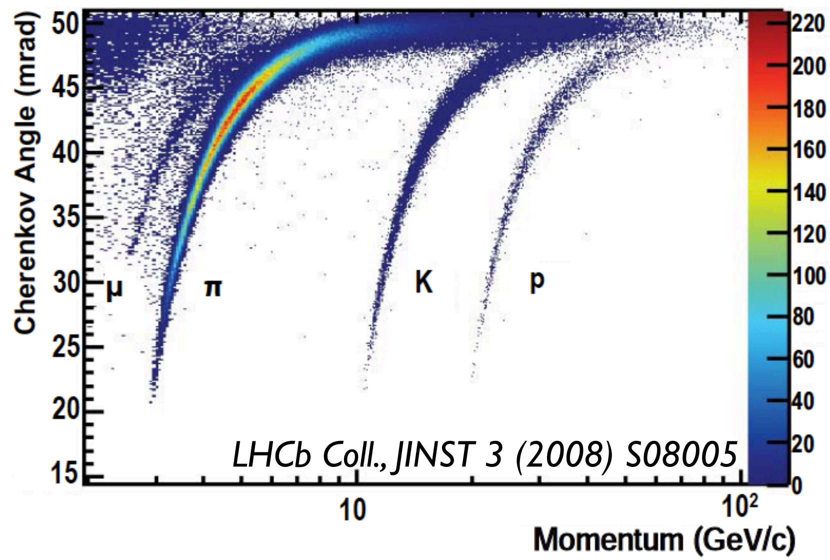
→ Potential for net-charge fluctuations

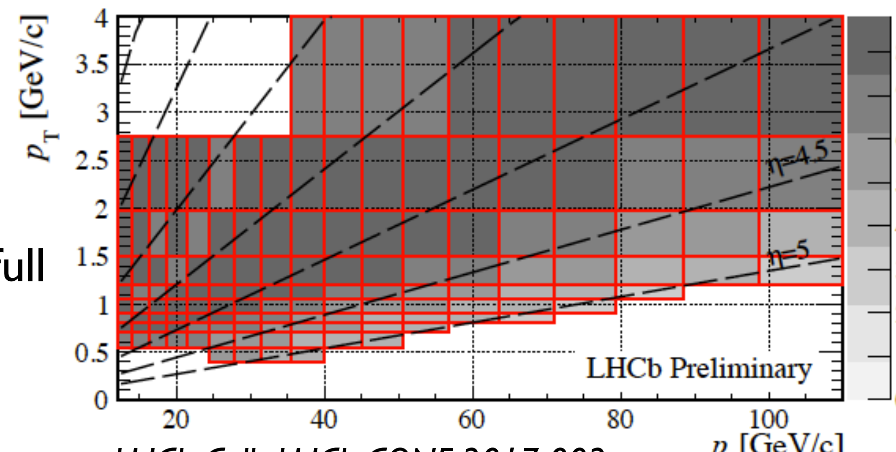
- Forward acceptance as complementary for longitudinal dynamics and baryon transport

- Increased tracker granularity in Run 3+4

→ Need precise estimates from full Run3+4 detector simulation for measurement capabilities

- Addition of TOF (TORCH) in LS3 under discussion, would enhance capabilities over full η acceptance down to low p_T





LHCb Coll., LHCb-CONF-2017-002
Proton ID via RICH veto on π,K for p > 10 GeV/c

LHCb PID capabilities

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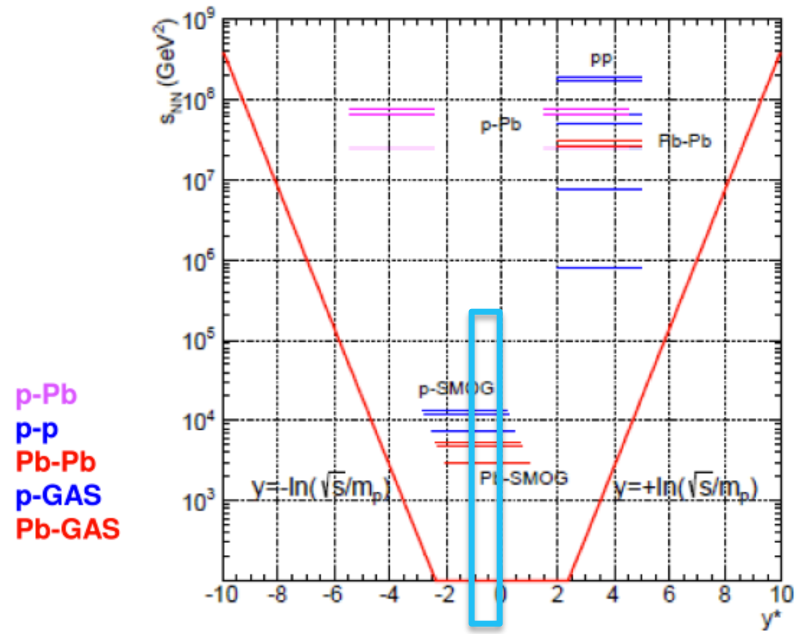
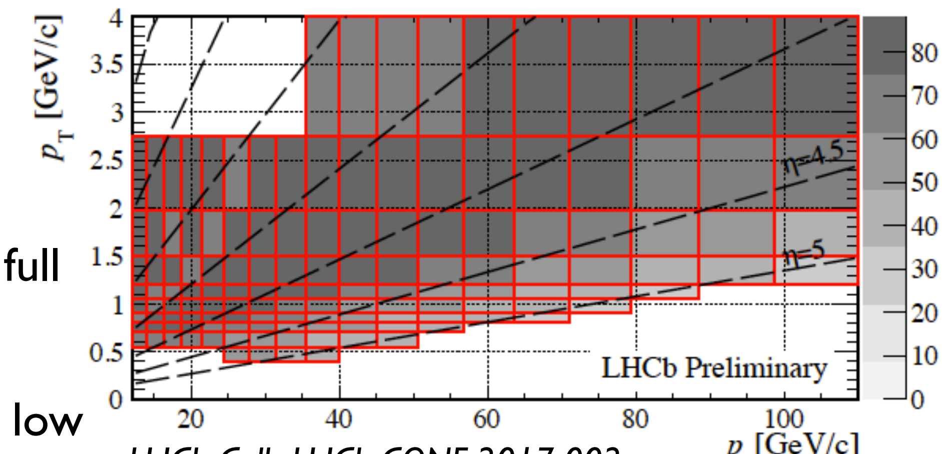
→ Fixed target mode (midrapidity coverage at low p_T) and collider mode (baryon transport)





LHCb Coll., LHCb-CONF-2017-002
Proton ID via RICH veto on π,K for p > 10 GeV/c

Summary and next steps

Nuclei and hypernuclei sector

- precision test of thermal model with feeddown-free signals and strangeness
- test/input for coalescence models
- A = 2 → A = 4
- Potential for discovery for A = 4 anti-hyper-nuclei
- Astrophysical / DM searches application in pp collisions

To do list:

- update estimates for nuclei efficiencies with upgraded ALICE-ITS

- evaluation of nuclei absorption in upgraded detector material

→ *need dedicated simulation*

– Assessment of potentialities in pp

→ *need input from theory/astroph.*

Conserved net-charges

- Access evidence for chiral transition via measurements of susceptibilities
- Direct link to Lattice-QCD
- Information about baryon transport

Further ideas to explore in (LF) identified particle sector?

What's needed:

- Extend toy MC statistics for Run 3+4 acceptance scenario
- Performance study with B = 0.2 T

→ *need dedicated simulation*

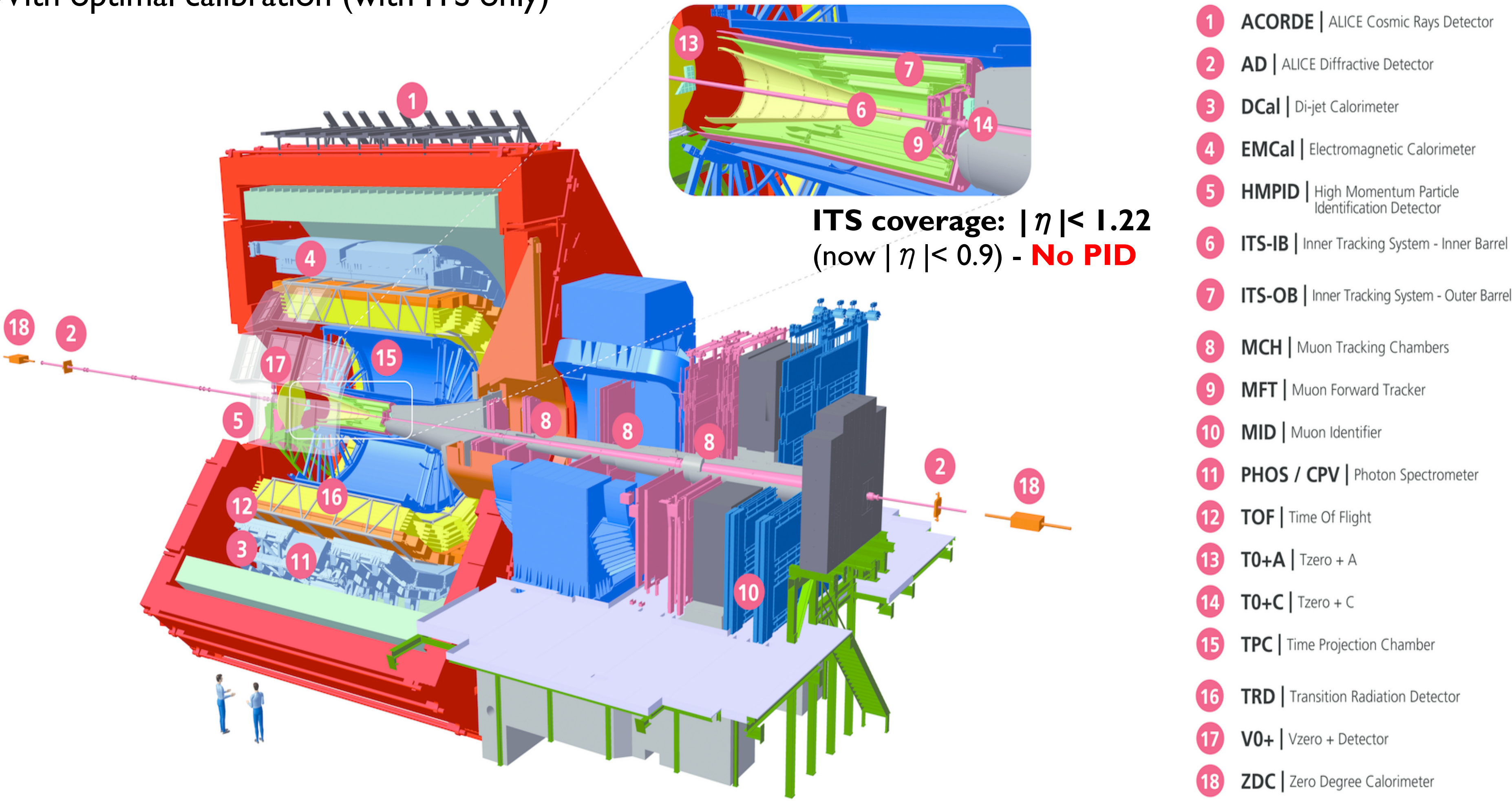
- Projections for net-strangeness?
- Assessment from other experiments

BACKUP

ALICE upgraded detector

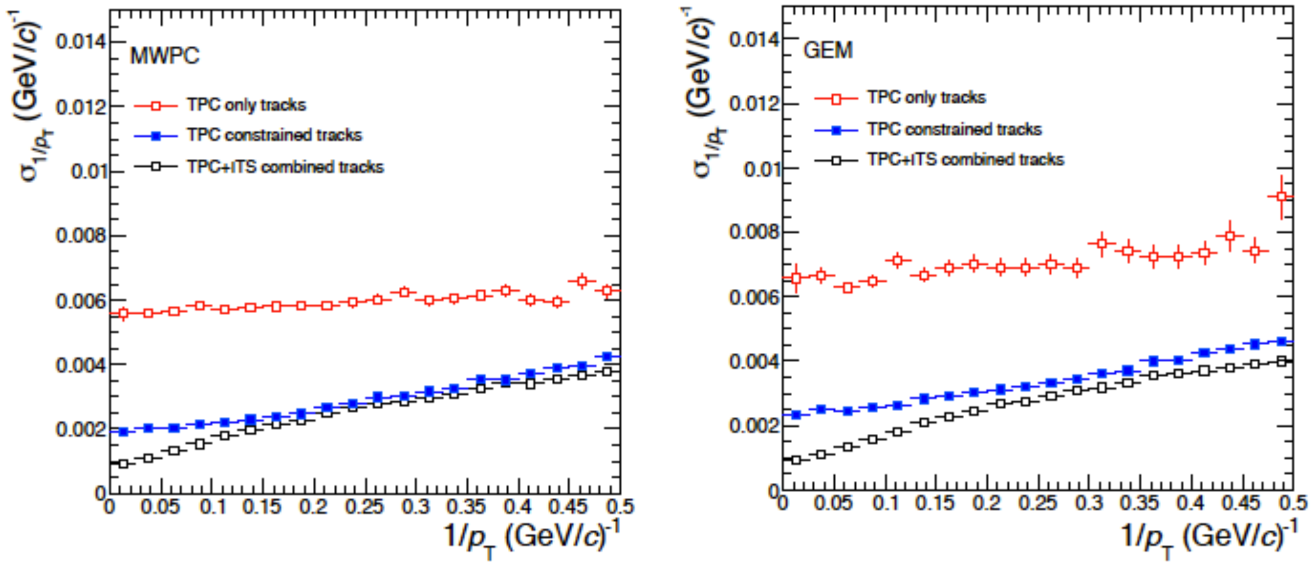
TPC coverage: | η | < 0.8 (1.4)
With optimal calibration (with ITS only)

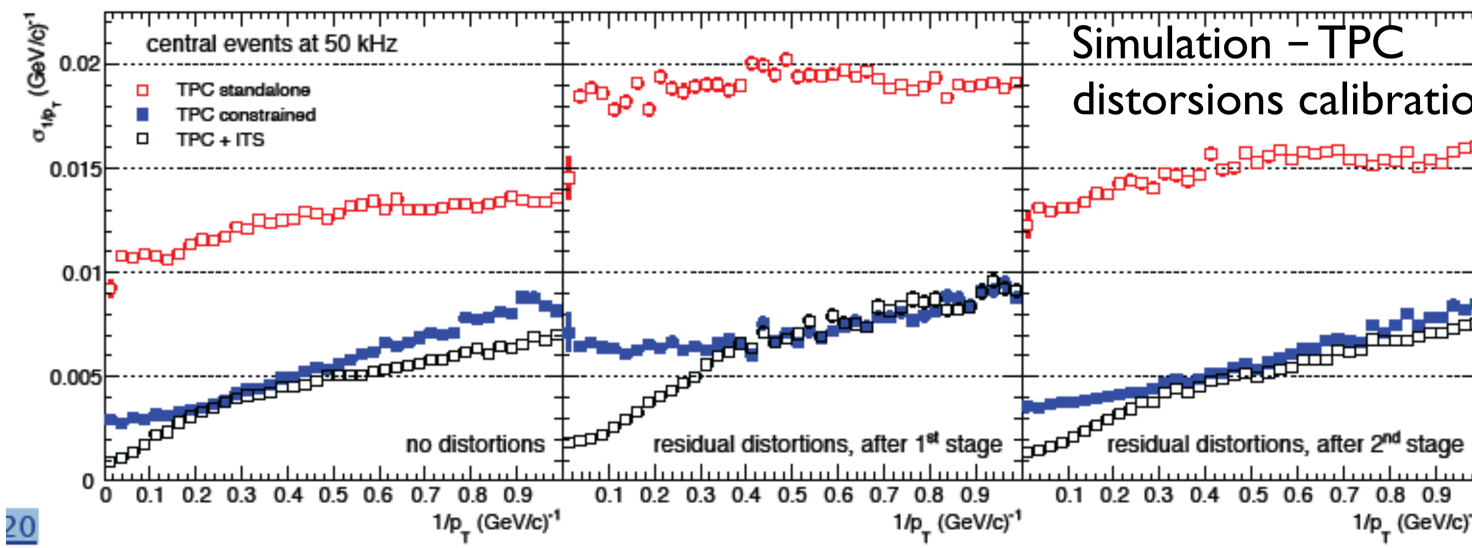
ITS coverage: | η |< 1.22
(now | η |< 0.9) - **No PID**



ALICE upgrade - Tracking performance

ALICE TPC Upgrade TDR > CERN-LHCC-2013-020

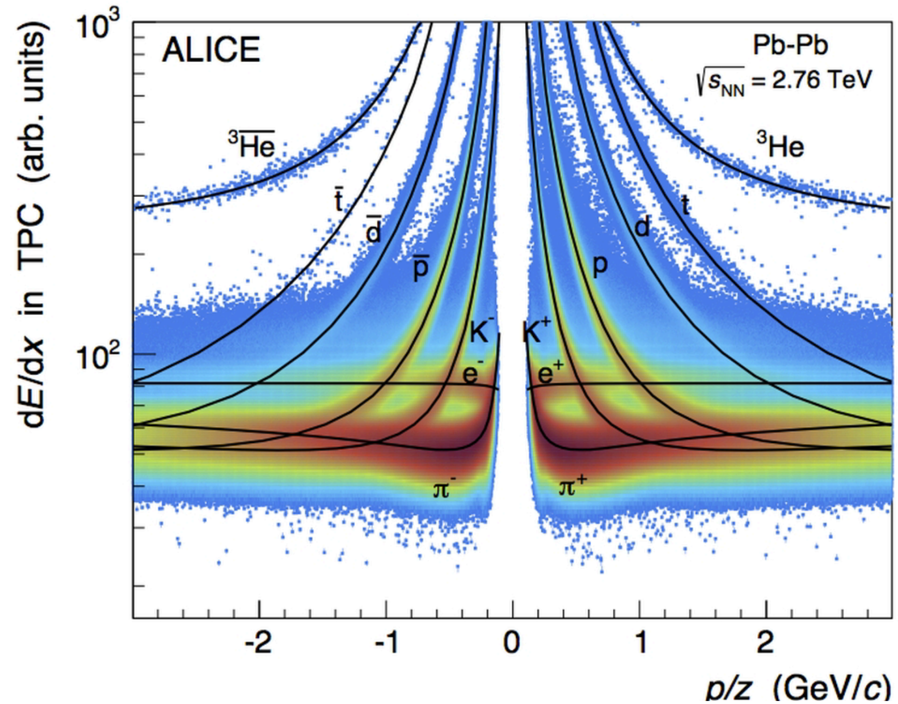


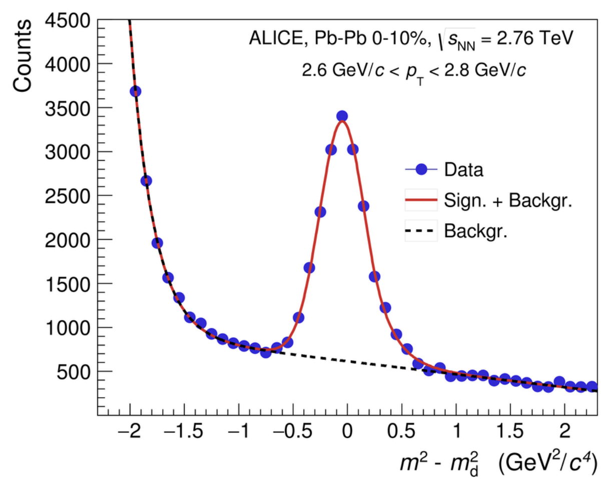


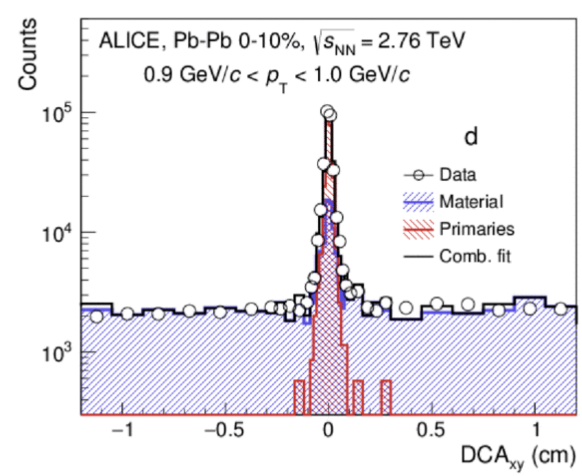
Simulation – TPC distorsions calibration

(anti)nuclei – Experimental aspects

- Identification at low momenta with dE/dx in the ALICE TPC
- Identification at high momenta via time-of-flight in TOF
- Knock-out from detector material is a significant problem at low p_T (only for nuclei not for anti-nuclei)
- Dominating systematics: knowledge of the material budget and hadronic absorption cross section for anti-nuclei







ALI-PUB-107762

Production at the LHC – Run II

RUN II (2015 sample)
Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV