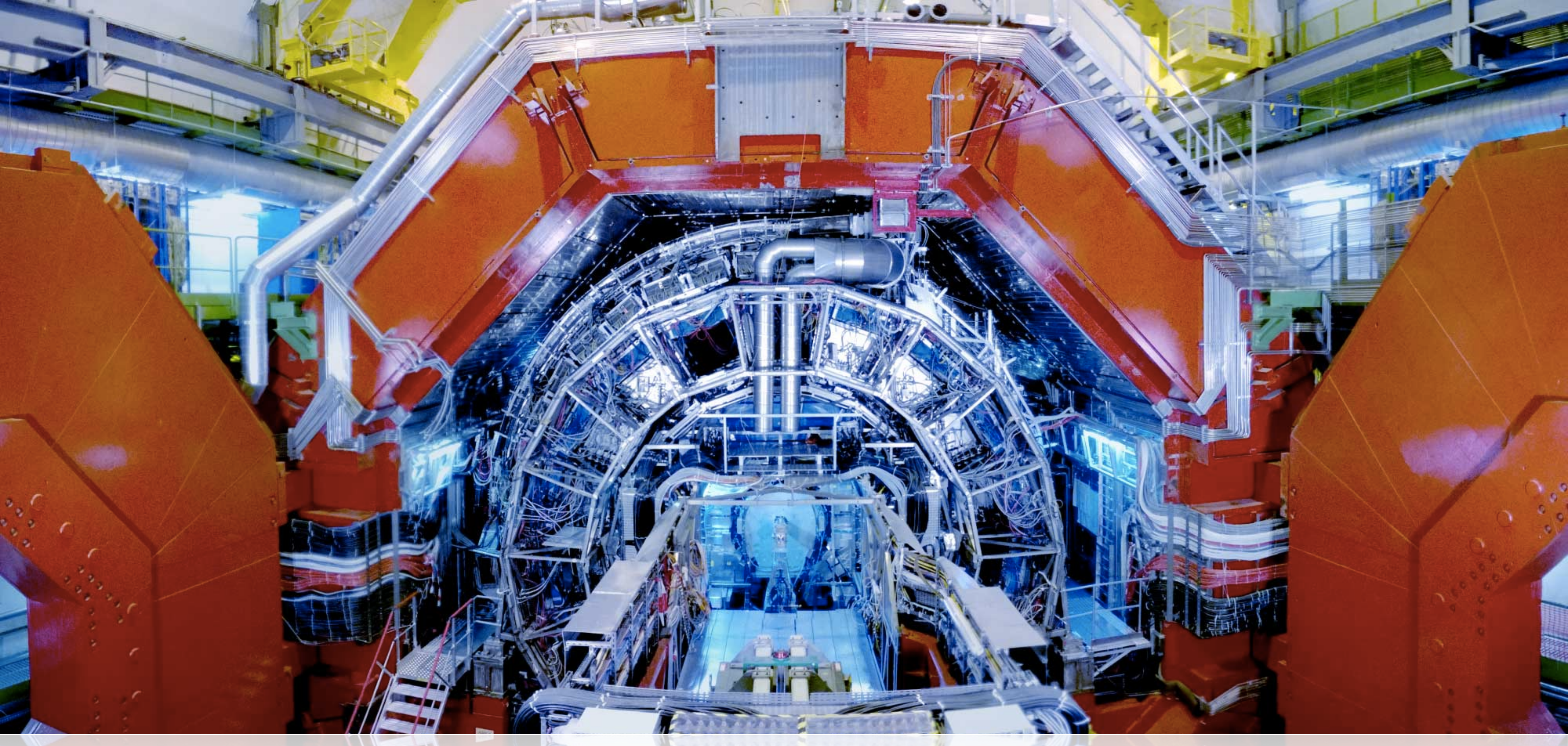


Studio della produzione di materia (iper-)nucleare a LHC con l'esperimento ALICE

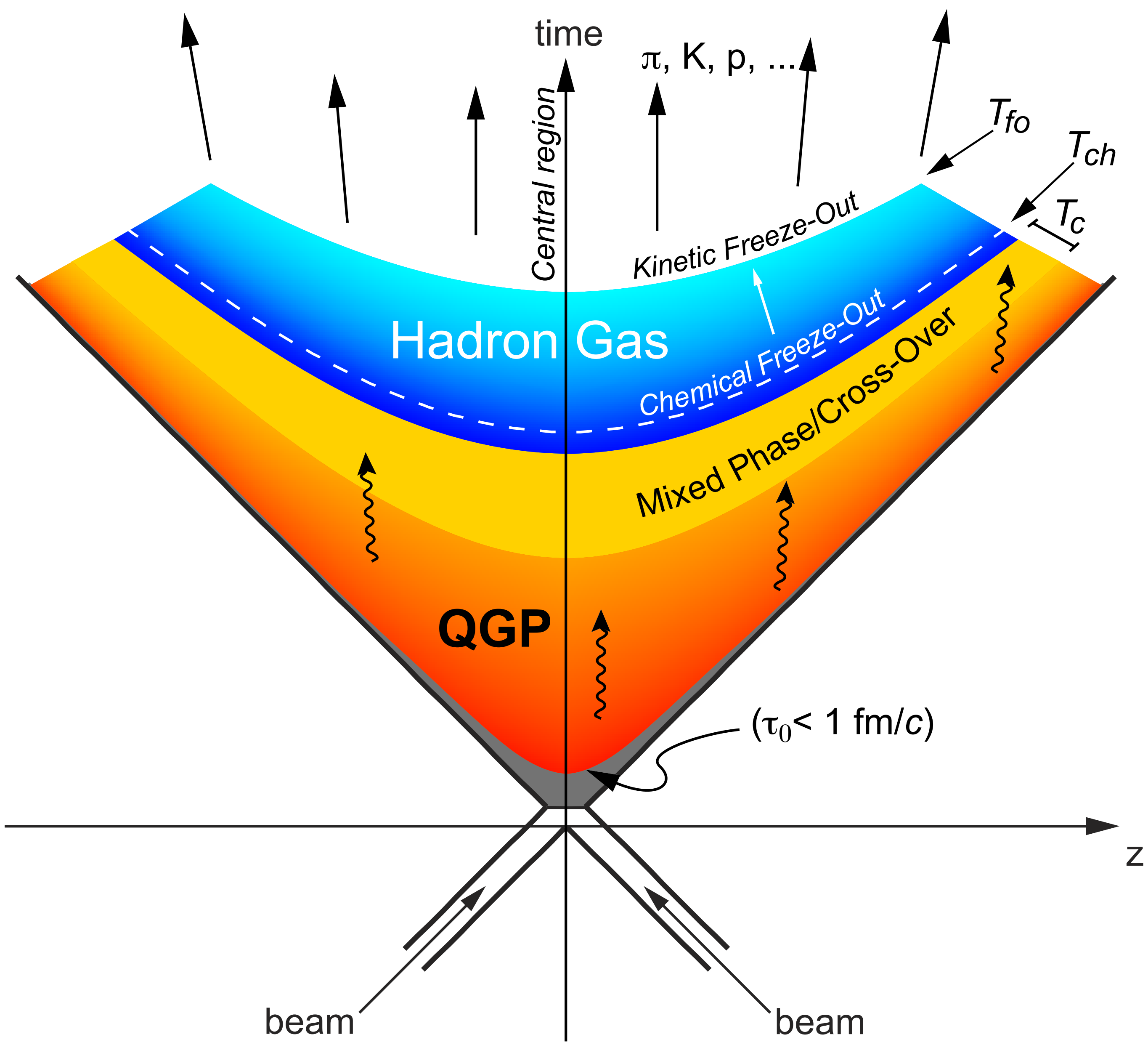
Maximiliano Puccio
Università & INFN Torino

Terzo Incontro Nazionale di Fisica Nucleare - LNF - 14 Novembre 2016

Why studying nuclei in Heavy Ion Collisions?

In high energy Heavy Ions collisions

- a dense and hot partonic phase is created and undergoes a rapid expansion
- hydrodynamical models are used to describe this rapid expansion
- as a result of this evolution it is possible to observe collective phenomena



SOFT PROBES

- Low p_T (p_T < 2 GeV/c) light flavoured particles coming from the interaction region
- Their constituents are produced in the late stages of the collisions
- They are useful to study the freeze-out conditions

Light nuclei and hyper-nuclei are soft probes and as they are loosely bound composite objects it is interesting to study their production in HI collisions.

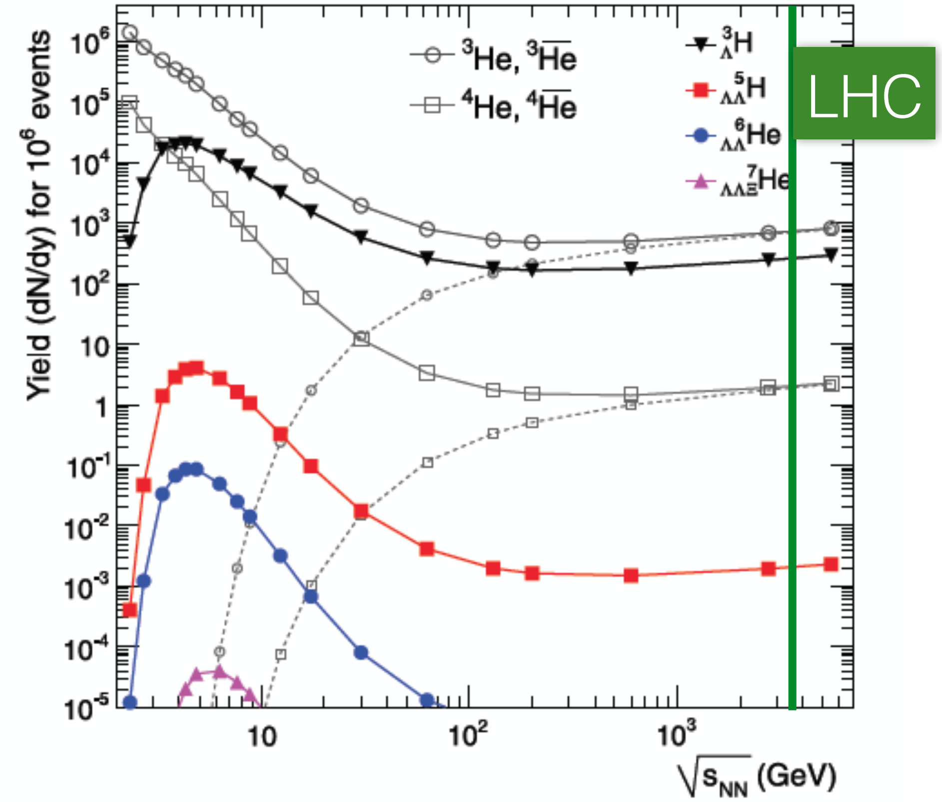
(Hyper-)Nuclei production models

(Hyper-)Nuclei production models

THERMAL MODELS

- Hadrons emitted from the interaction region in statistical equilibrium when the fireball reaches limiting temperature
- Abundances fixed at chemical freeze-out
- Freeze-out temperature T_{chem} is a key parameter
- Abundance of a species $\propto \exp(-m/T_{chem})$:
  - ➡ For nuclei (large *m*) strong dependence on T_{chem}

A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stoecker
Phys. Lett. B607, 203 (2011), 1010.2995

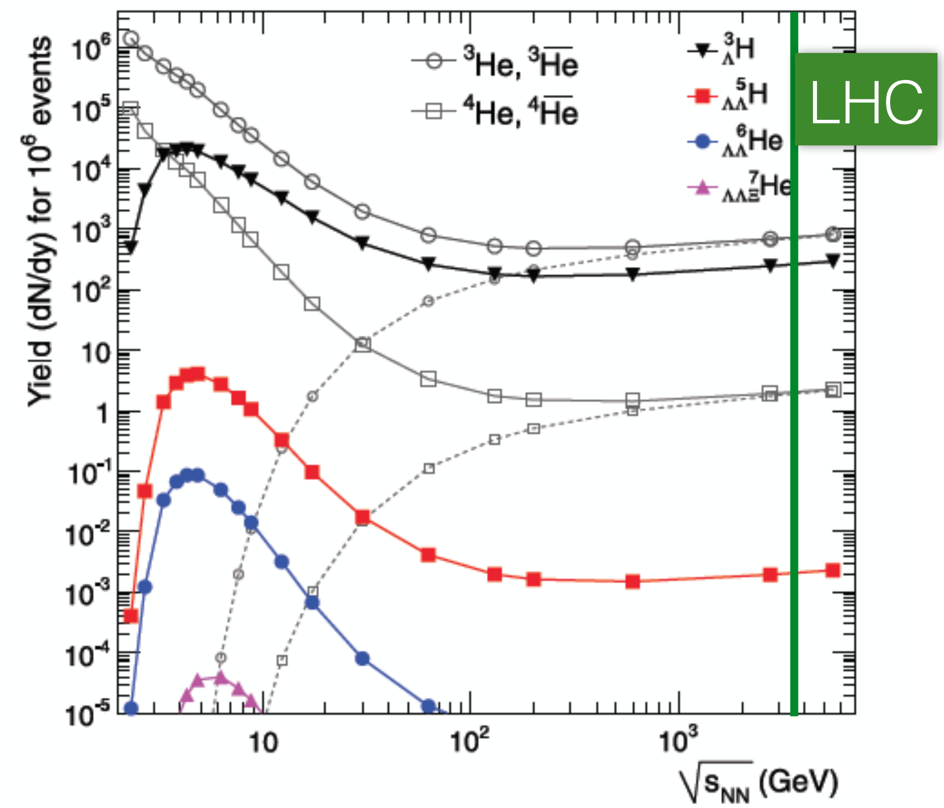


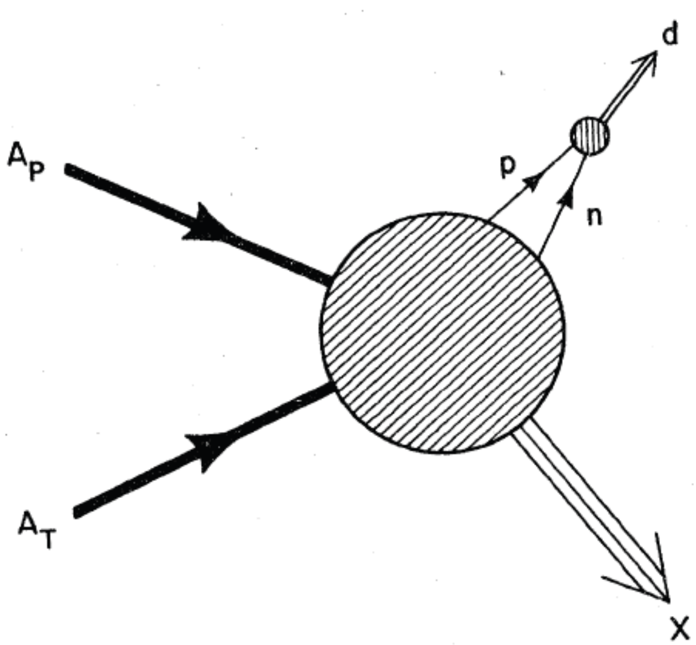
(Hyper-)Nuclei production models

THERMAL MODELS

- Hadrons emitted from the interaction region in statistical equilibrium when the fireball reaches limiting temperature
- Abundances fixed at chemical freeze-out
- Freeze-out temperature T_{chem} is a key parameter
- Abundance of a species $\propto \exp(-m/T_{chem})$:
  - ➡ For nuclei (large m) strong dependence on T_{chem}

A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stoecker
Phys. Lett. B607, 203 (2011), 1010.2995



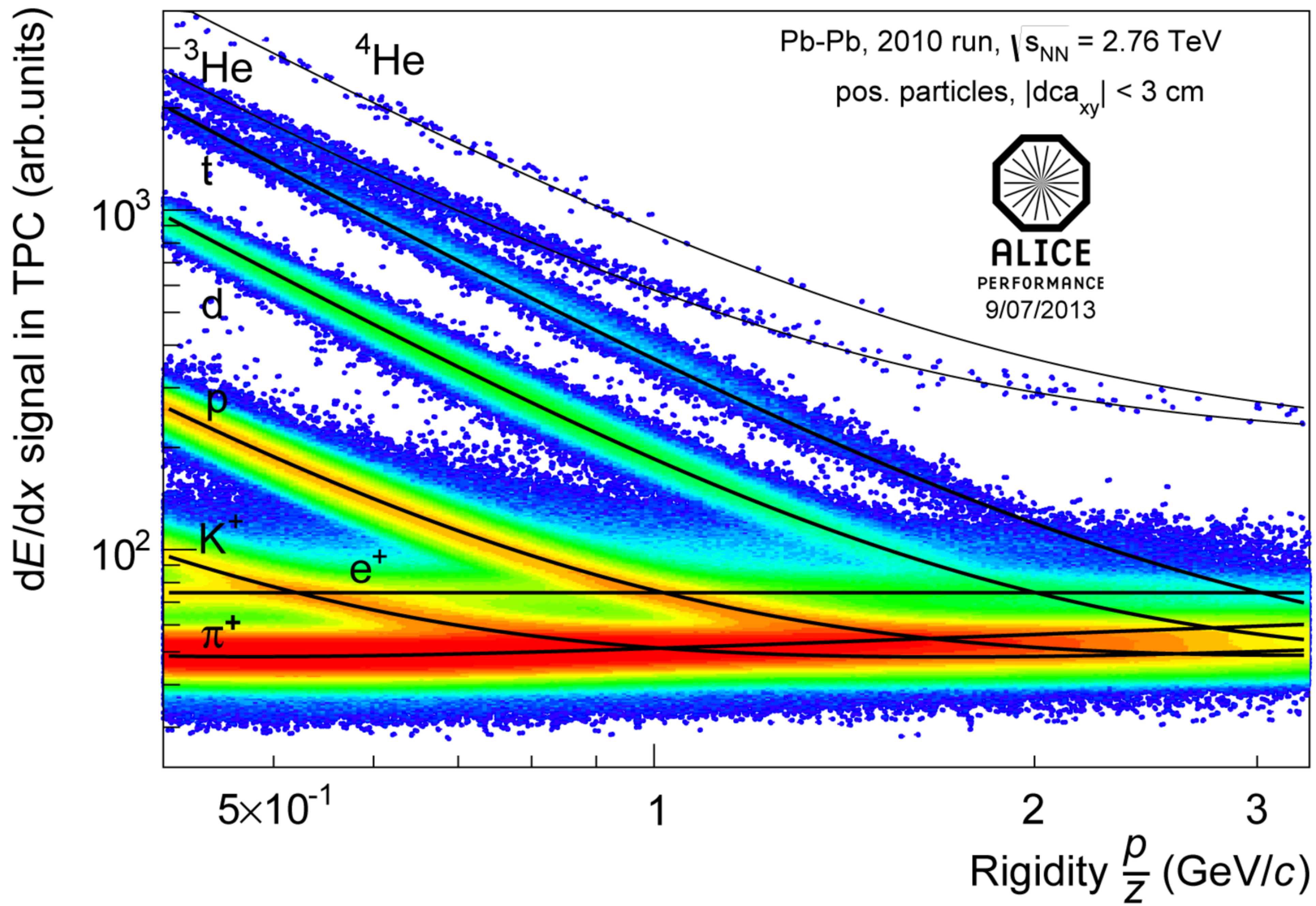


COALESCENCE

- If (anti-)baryons are close in phase space after the kinetic freeze-out they can form a (anti-)nucleus
- (Anti-)nuclei produced at the chemical freeze-out might break and re-form during the time span between the chemical freeze-out and the kinetic freeze-out.

J. I. Kapusta, Phys.Rev. C21, 1301 (1980)

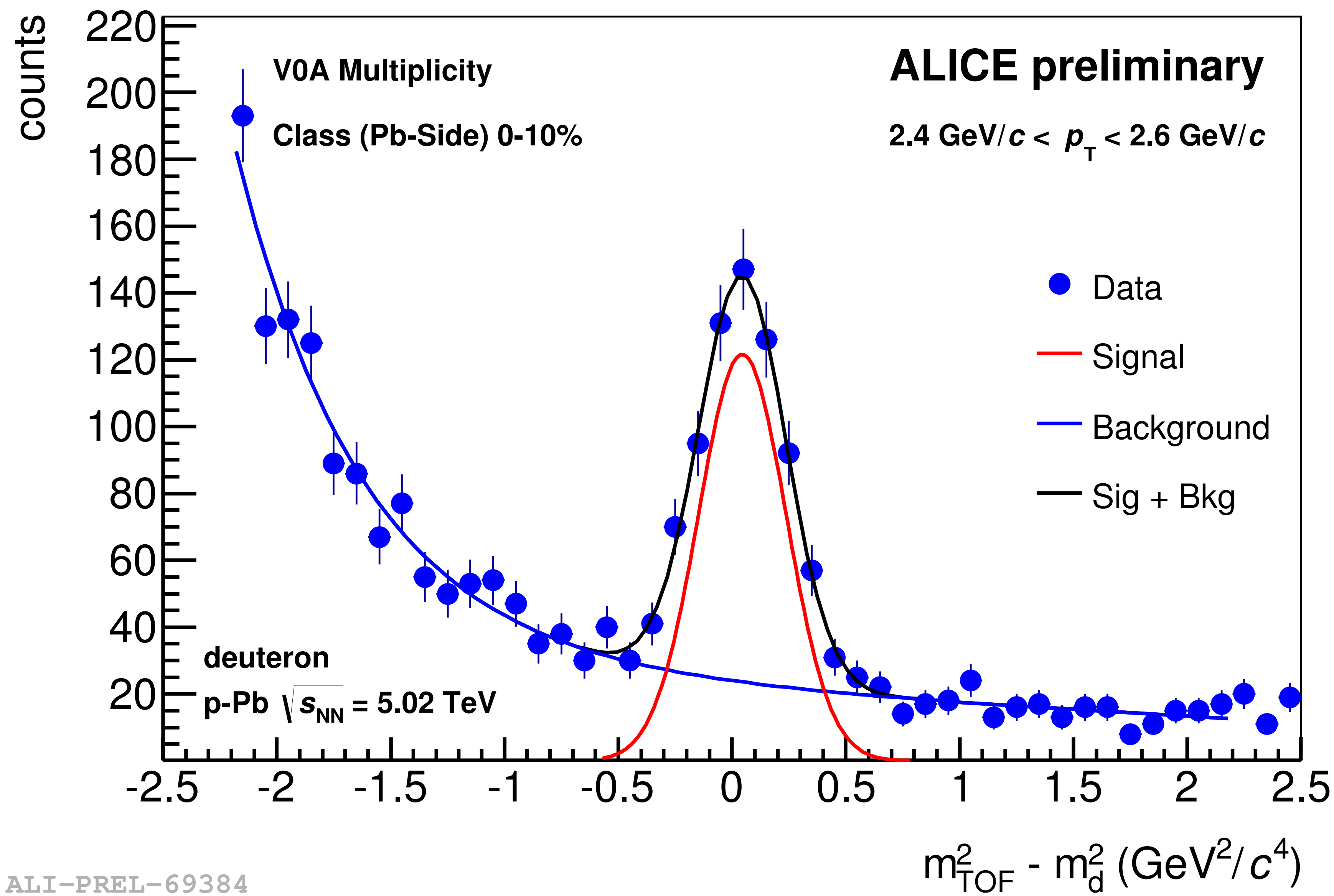
Detecting nuclei: TPC specific energy loss



Specific energy loss in the **T**ime **P**rojection **C**hamber volume provides an excellent PID for light nuclei.

➡ $\sigma_{dE/dx}$~7% (in Pb-Pb collisions)

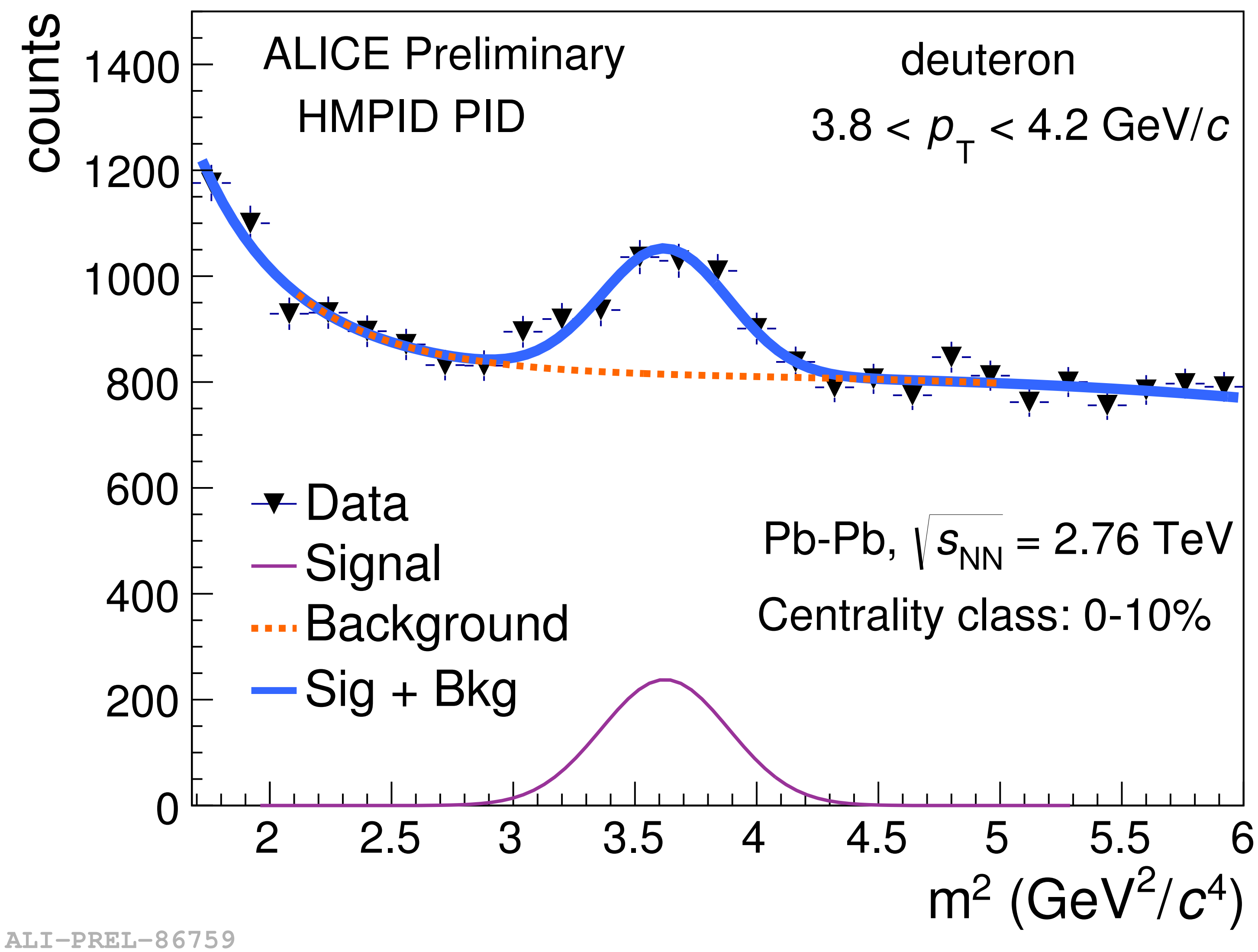
Detecting nuclei: Time of flight



Tracking information + time of flight measured by the **T**ime **O**f **F**light detector → *m* of the particle

➡ $\sigma_{time\text{-}of\text{-}flight}$~ 80 ps (in Pb-Pb)

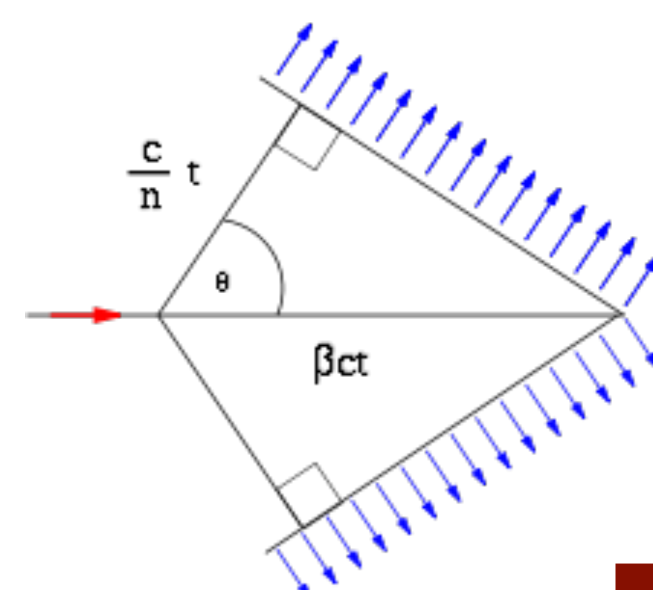
Detecting nuclei: Cherenkov light



$$m_{\mathrm{HMPID}} = \frac{p}{\beta\gamma} \quad \text{where} \quad \beta = \frac{1}{n \cdot cos\theta_c}$$

Tracking information + **H**igh **M**omentum **P**article **ID**entification detector (Cherenkov light detector) signal

→ *m* of the particle



Detecting hyper-nuclei

Hyper-triton is the lightest hyper-nucleus. ALICE collaboration measured its production in the charged 2 body decay channel.

Mass = 2.991 GeV/c^2
Lifetime ~ 215 ps

Signal Extraction:

- Identify ^{3}He and π
- Evaluate (^{3}He,π) invariant mass
- Apply topological cuts in order to:
  - identify secondary decay vertex
  - reduce combinatorial background

DECAY MODES

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

$${}^3_\Lambda\mathrm{H} \rightarrow {}^3\,\mathrm{H} + \pi^0$$

$${}^3_\Lambda\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^-$$

$${}^3_\Lambda\mathrm{H} \rightarrow \mathrm{d} + \mathrm{n} + \pi^0$$

+ anti-hypertriton

Detecting hyper-nuclei

Hyper-triton is the lightest hyper-nucleus. ALICE collaboration measured its production in the charged 2 body decay channel.

Mass = 2.991 GeV/c^2
Lifetime ~ 215 ps

Signal Extraction:

- Identify ^{3}He and π
- Evaluate (^{3}He,π) invariant mass
- Apply topological cuts in order to:
  - identify secondary decay vertex
  - reduce combinatorial background

DECAY MODES

published → $^3_\Lambda\mathrm{H} \rightarrow {}^3\,\mathrm{He} + \pi^-$

$^3_\Lambda\mathrm{H} \rightarrow {}^3\,\mathrm{H} + \pi^0$

$^3_\Lambda\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^-$

$^3_\Lambda\mathrm{H} \rightarrow \mathrm{d} + \mathrm{n} + \pi^0$

+ anti-hypertriton

Detecting hyper-nuclei

Hyper-triton is the lightest hyper-nucleus. ALICE collaboration measured its production in the charged 2 body decay channel.

Mass = 2.991 GeV/c^2
Lifetime ~ 215 ps

Signal Extraction:

- Identify ^{3}He and π
- Evaluate (^{3}He,π) invariant mass
- Apply topological cuts in order to:
  - identify secondary decay vertex
  - reduce combinatorial background

DECAY MODES

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

$^3_\Lambda\mathrm{H} \rightarrow ^3\mathrm{H} + \pi^0$

ongoing → $^3_\Lambda\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^-$

$^3_\Lambda\mathrm{H} \rightarrow \mathrm{d} + \mathrm{n} + \pi^0$

+ anti-hypertriton

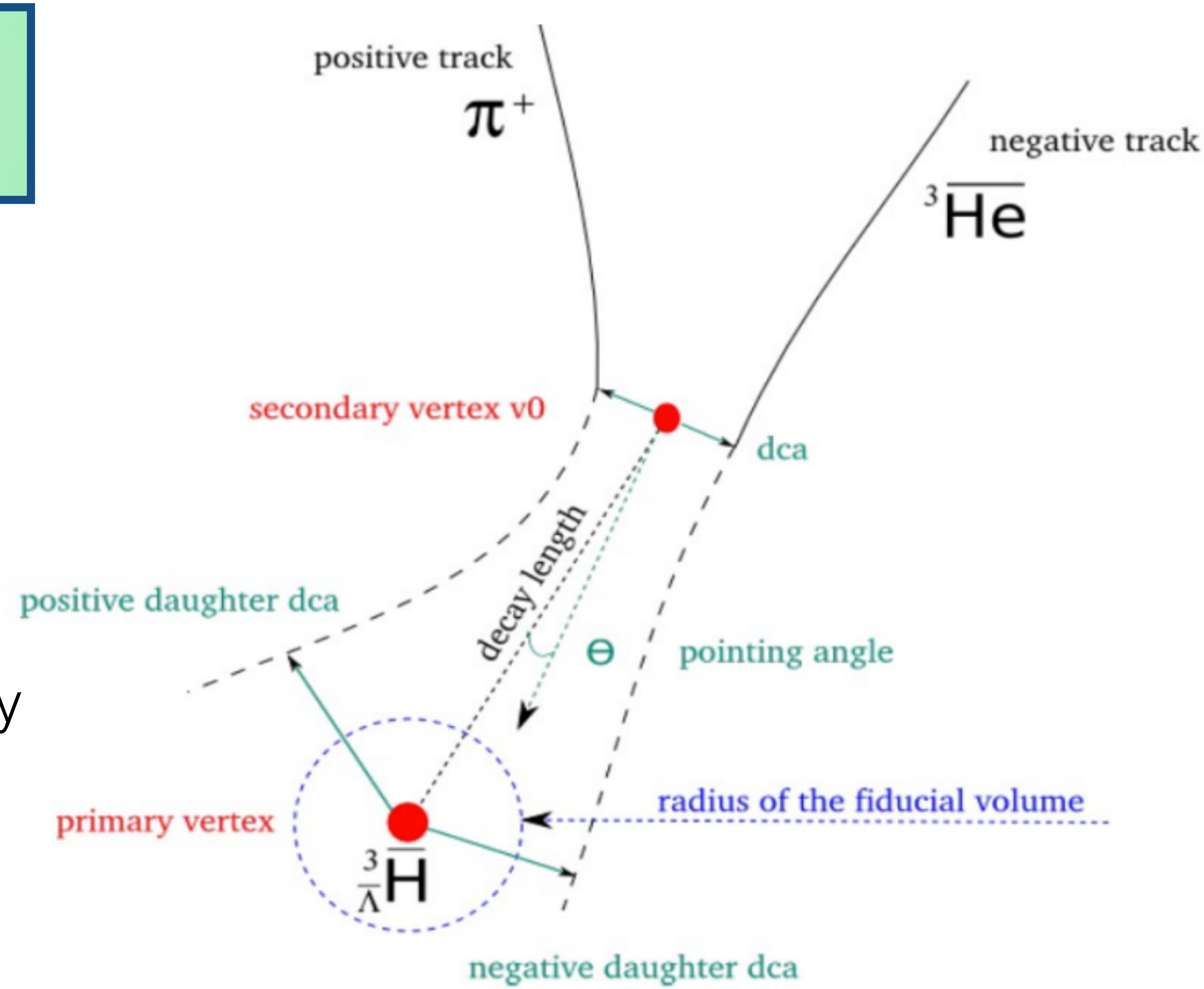
Detecting hyper-nuclei

Hyper-triton is the lightest hyper-nucleus. ALICE collaboration measured its production in the charged 2 body decay channel.

Mass = 2.991 GeV/c^2
Lifetime ~ 215 ps

Signal Extraction:

- Identify ^{3}He and π
- Evaluate (^{3}He,π) invariant mass
- Apply topological cuts in order to:
  - identify secondary decay vertex
  - reduce combinatorial background



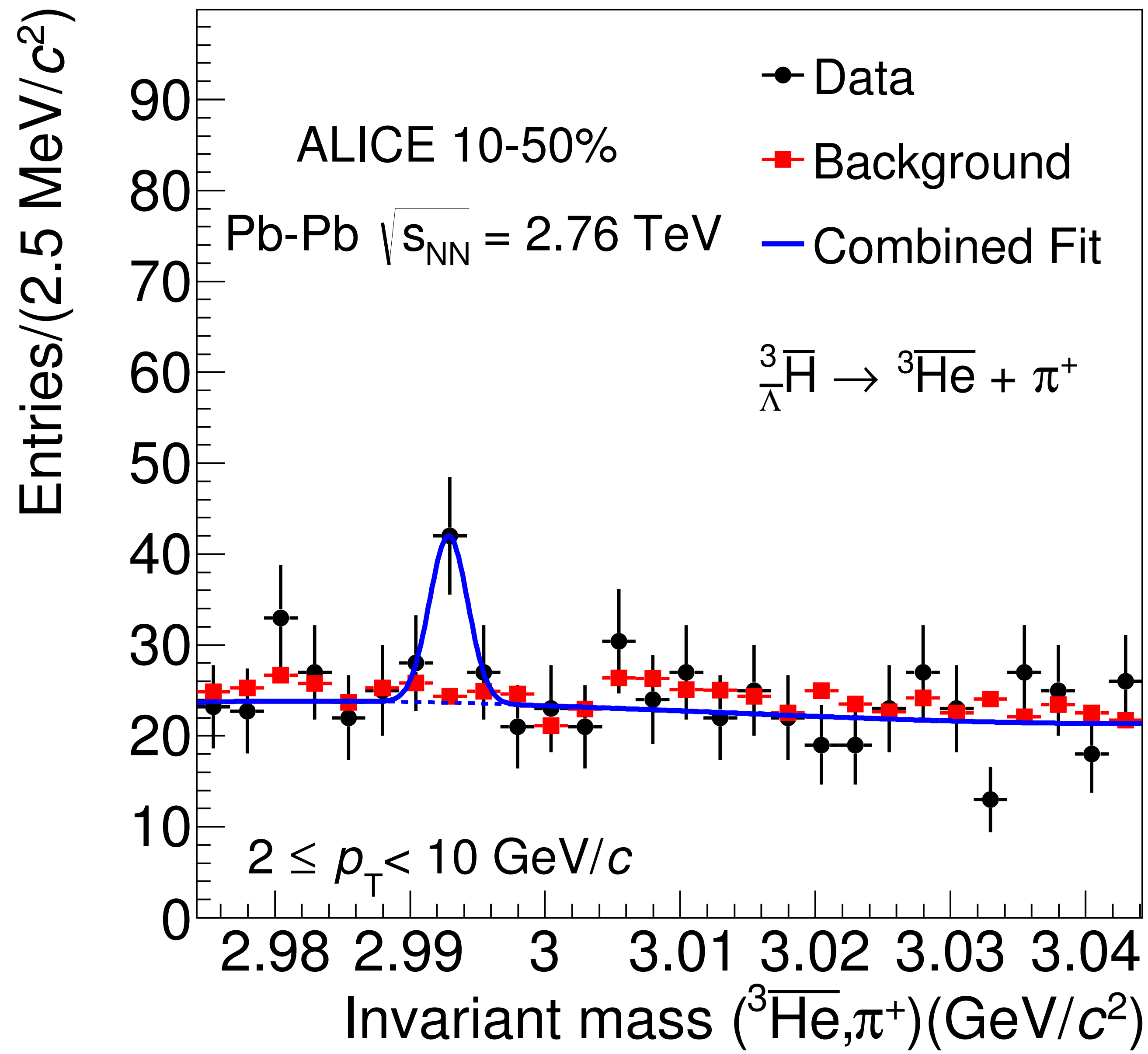
Detecting hyper-nuclei

Hyper-triton is the lightest hyper-nucleus. ALICE collaboration measured its production in the charged 2 body decay channel.

Mass = 2.991 GeV/c^2
Lifetime ~ 215 ps

Signal Extraction:

- Identify ^{3}He and π
- Evaluate (^{3}He,π) invariant mass
- Apply topological cuts in order to:
  - identify secondary decay vertex
  - reduce combinatorial background



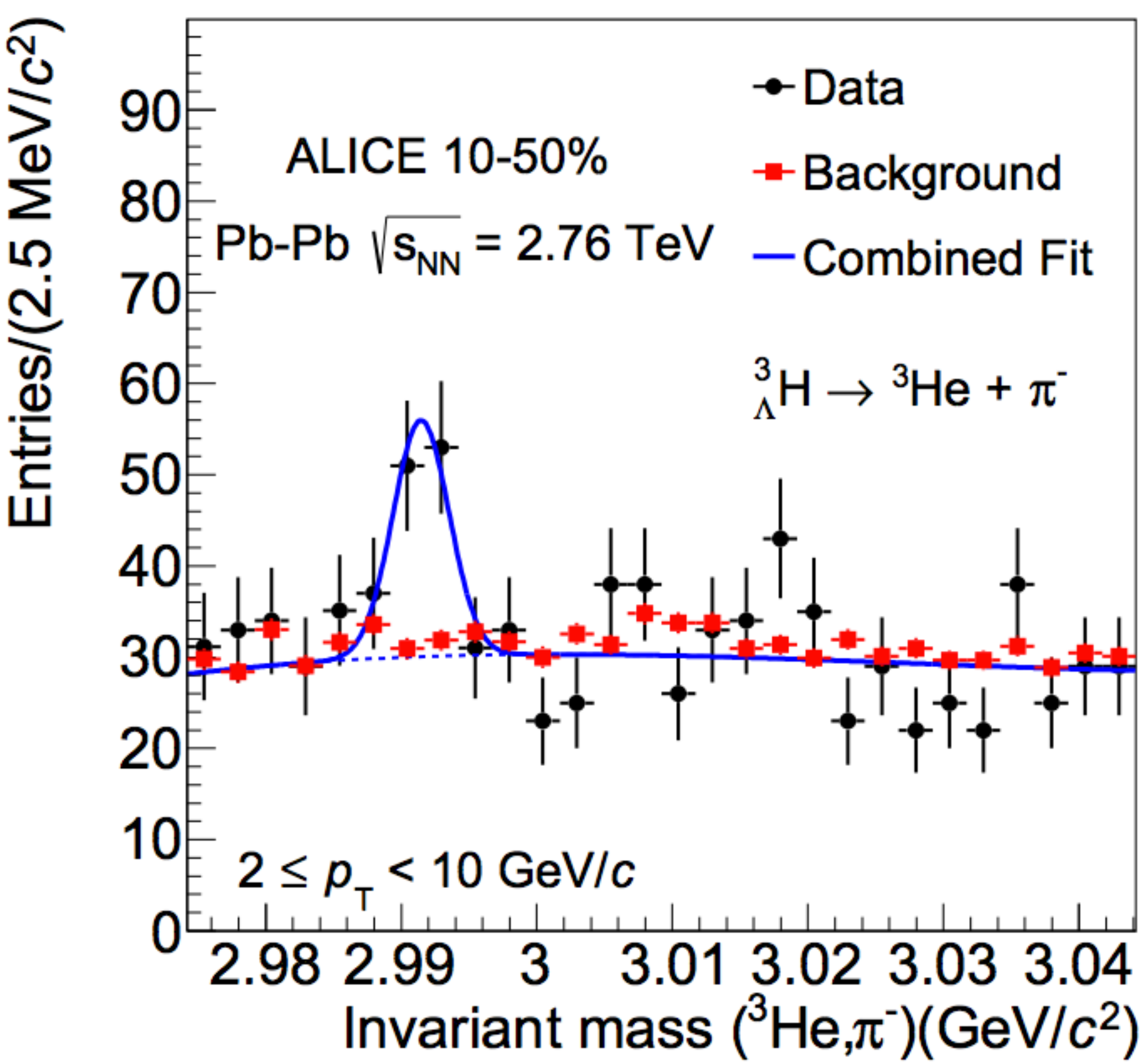
Detecting hyper-nuclei

Hyper-triton is the lightest hyper-nucleus. ALICE collaboration measured its production in the charged 2 body decay channel.

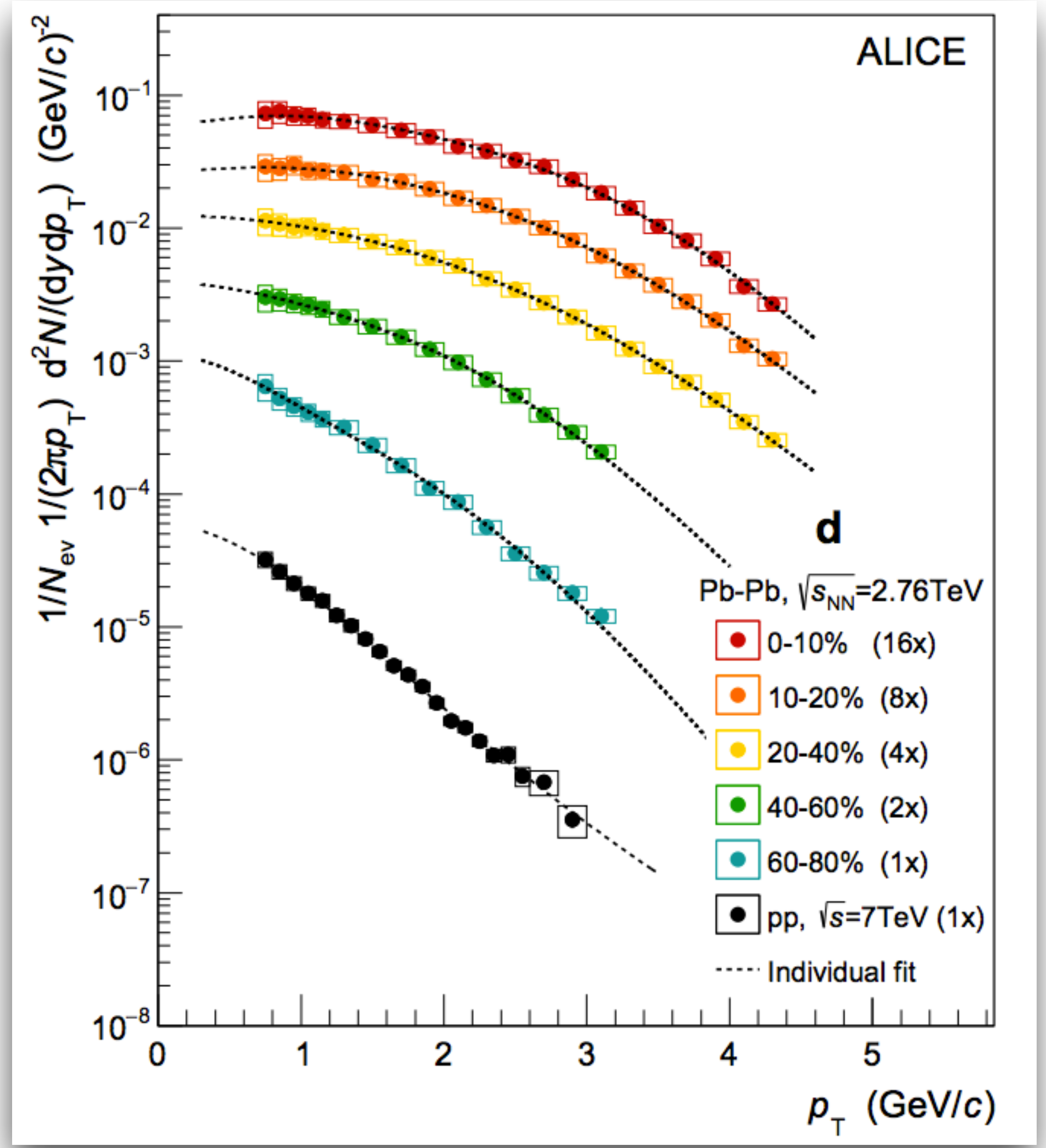
Mass = 2.991 GeV/c^2
Lifetime ~ 215 ps

Signal Extraction:

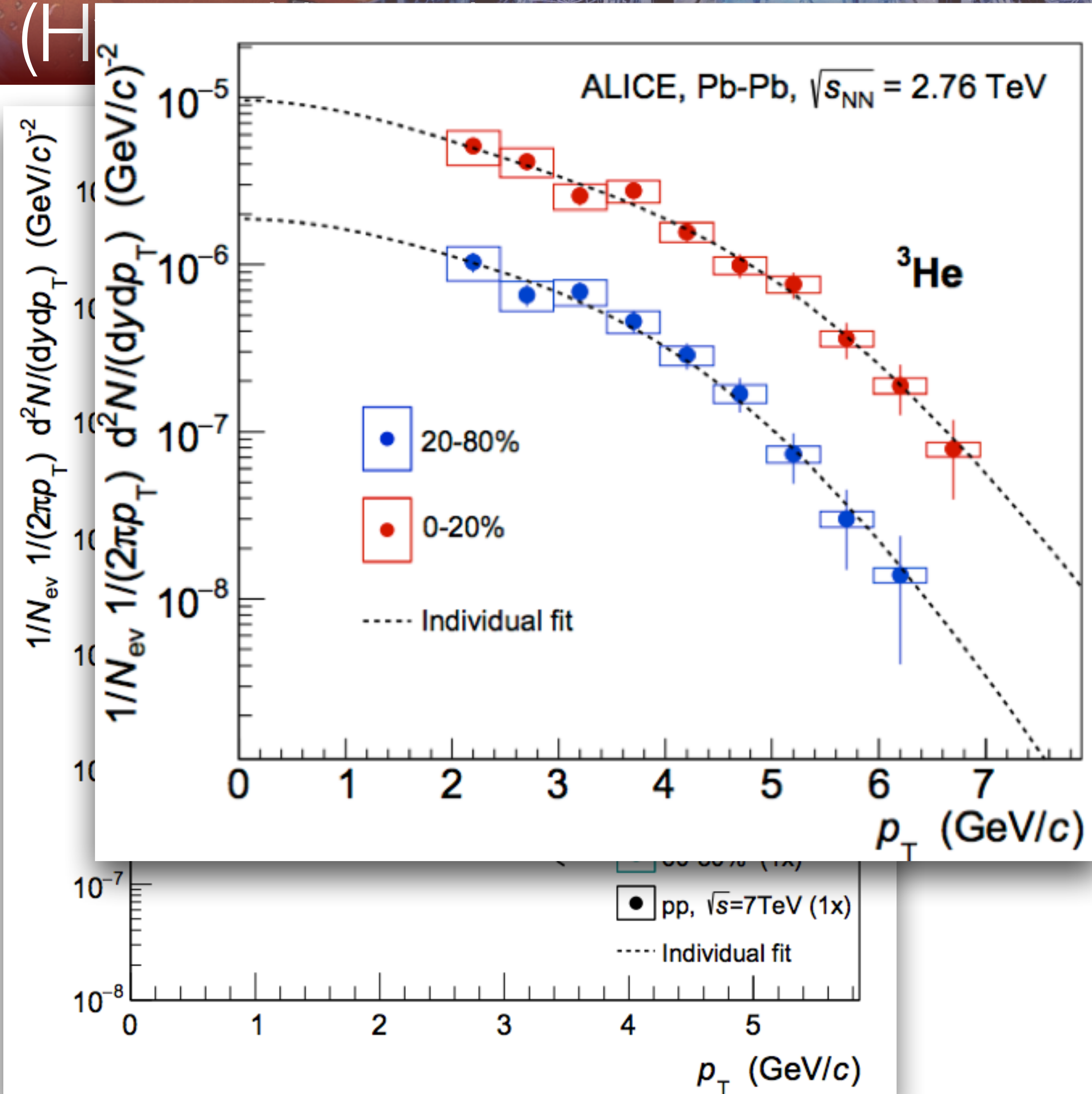
- Identify ^{3}He and π
- Evaluate (^{3}He,π) invariant mass
- Apply topological cuts in order to:
  - identify secondary decay vertex
  - reduce combinatorial background



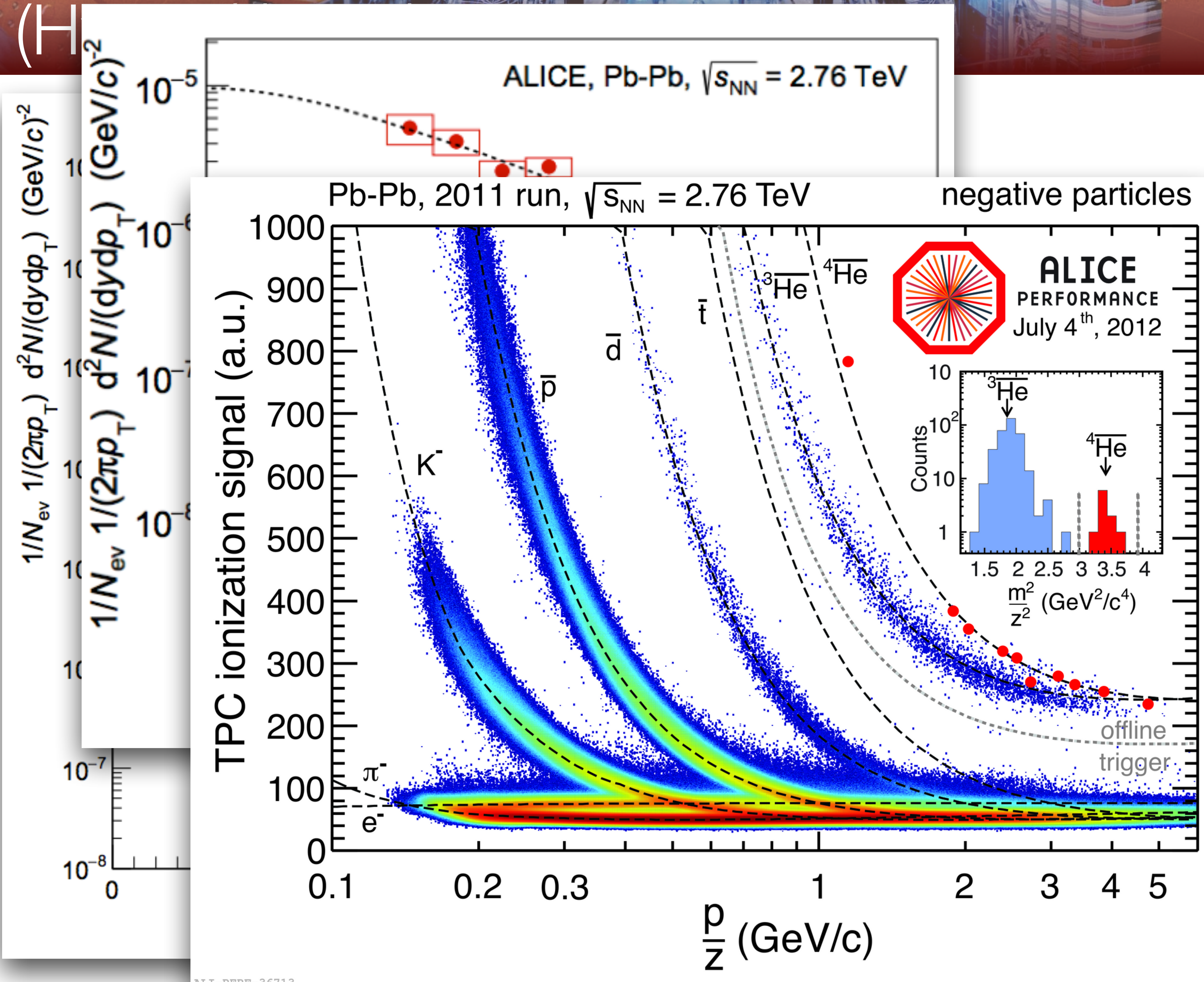
(Hyper-)(Anti-)nuclei production



(H

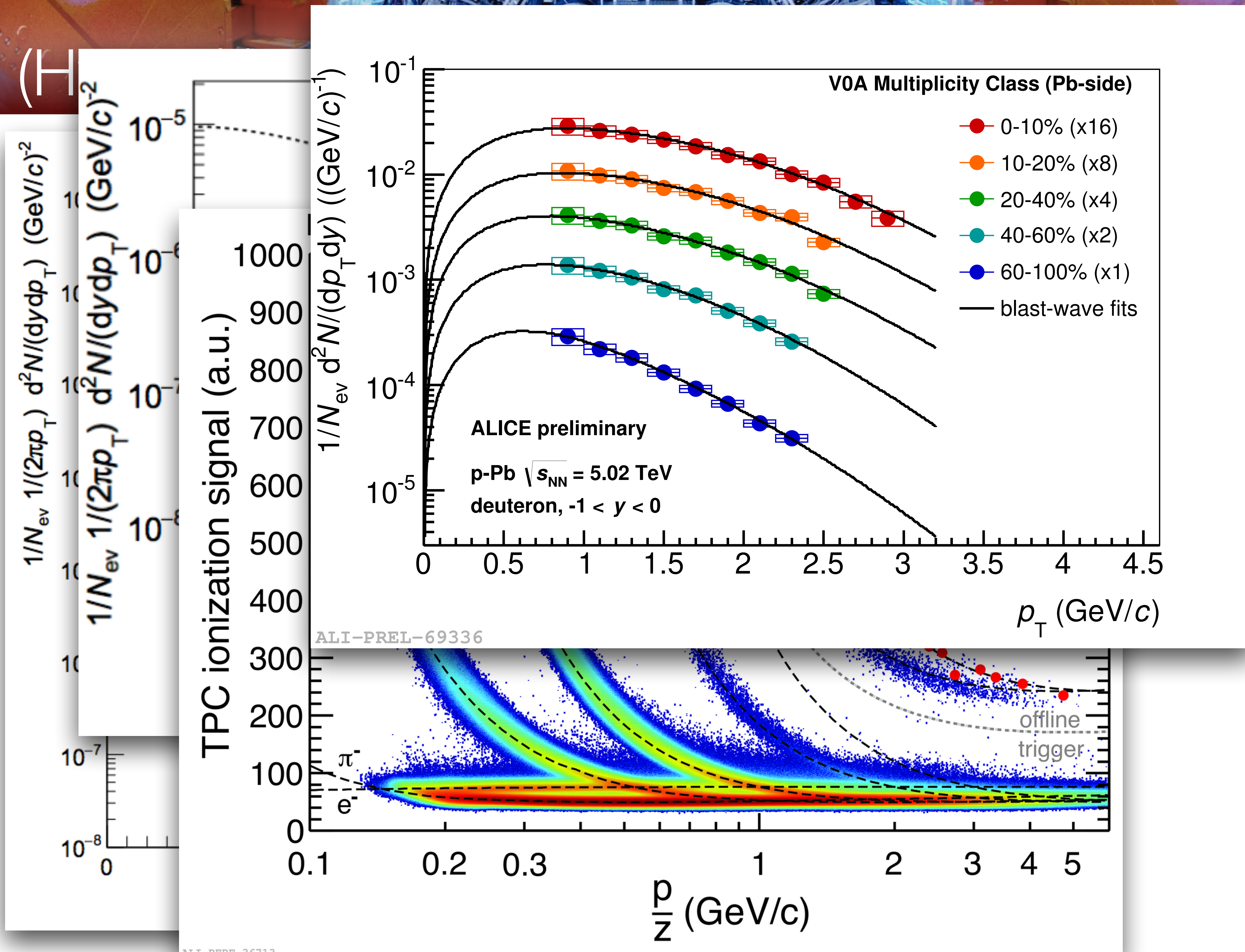

ALICE, Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
^{3}He
20-80%
0-20%
Individual fit
$1/N_{ev}\ 1/(2\pi p_T)\ d^2N/(dydp_T)\ (GeV/c)^{-2}$
p_T (GeV/c)
pp, $\sqrt{s}$=7TeV (1x)
Individual fit
p_T (GeV/c)

(H

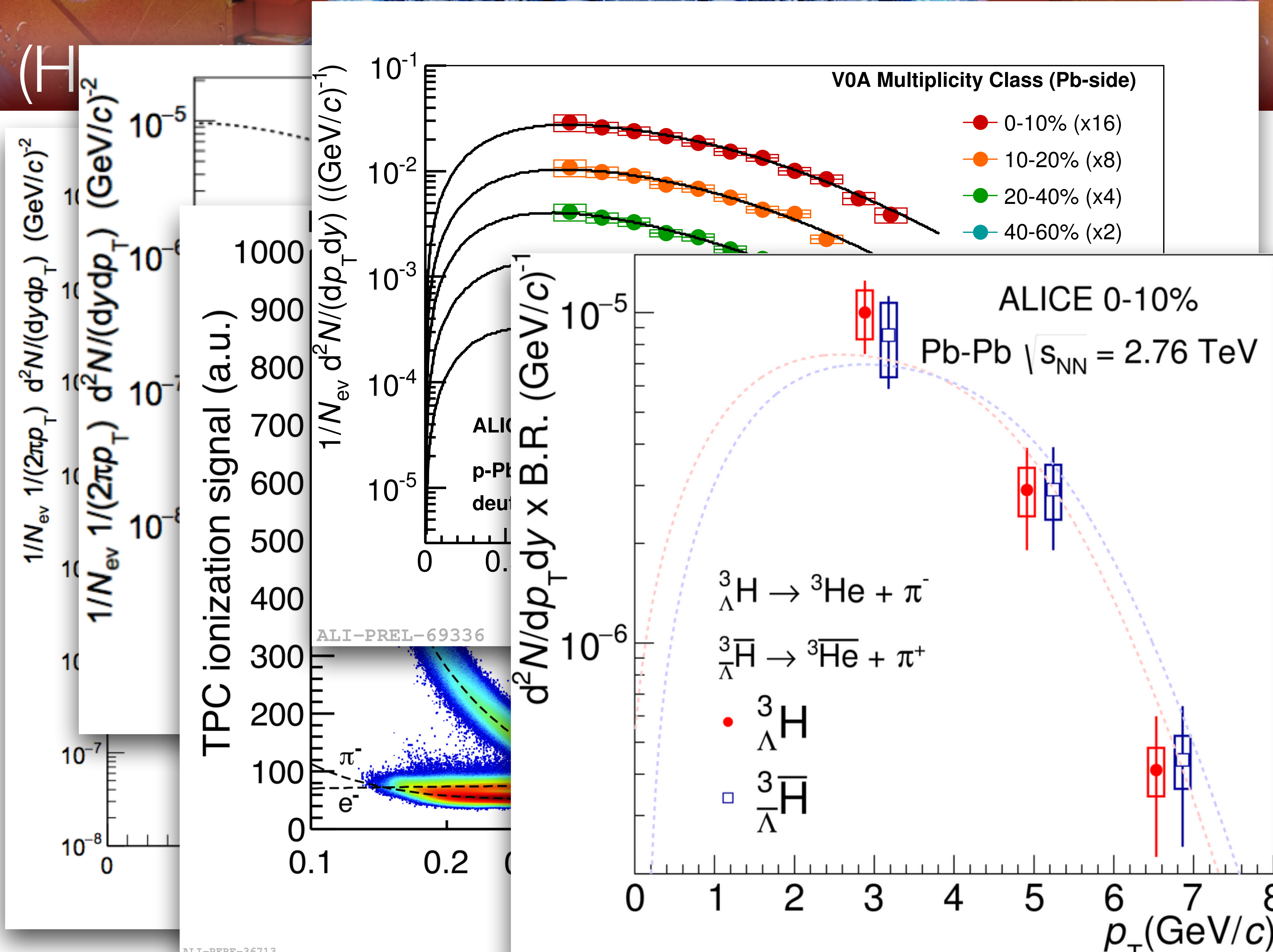


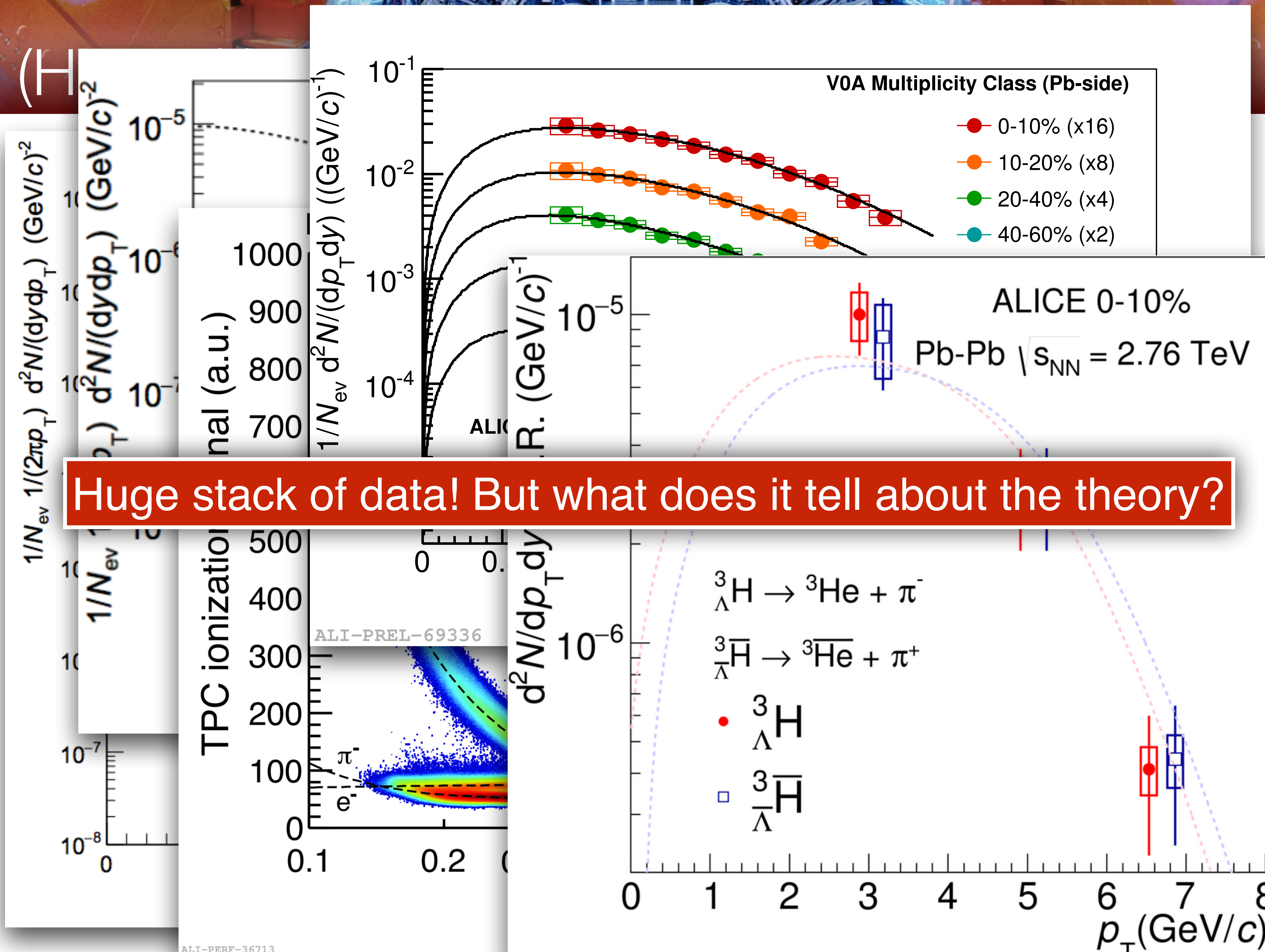
ALICE, Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
$1/N_{ev}$ $1/(2\pi p_T)$ $d^2N/(dydp_T)$ $(GeV/c)^{-2}$
Pb-Pb, 2011 run, $\sqrt{s_{NN}}$ = 2.76 TeV
negative particles
TPC ionization signal (a.u.)
$\frac{p}{z}$ (GeV/c)
K⁻
$\bar{p}$
$\bar{d}$
$\bar{t}$
$^3\overline{He}$
$^4\overline{He}$
π⁻
e⁻
offline
trigger
ALICE
PERFORMANCE
July 4th, 2012
Counts
$\frac{m^2}{z^2}$ (GeV^2/c^4)
ALI-PERF-36713

(H


V0A Multiplicity Class (Pb-side)
0-10% (x16)
10-20% (x8)
20-40% (x4)
40-60% (x2)
60-100% (x1)
blast-wave fits
ALICE preliminary
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
deuteron, -1 < y < 0
$1/N_{ev}\ d^2N/(dp_T dy)$ ((GeV/c)$^{-1}$)
p_T (GeV/c)
ALI-PREL-69336
TPC ionization signal (a.u.)
π^-
e^-
offline
trigger
p/z (GeV/c)
ALI-PERF-36713
$1/N_{ev}\ 1/(2\pi p_T)\ d^2N/(dydp_T)$ (GeV/c)$^{-2}$

(H

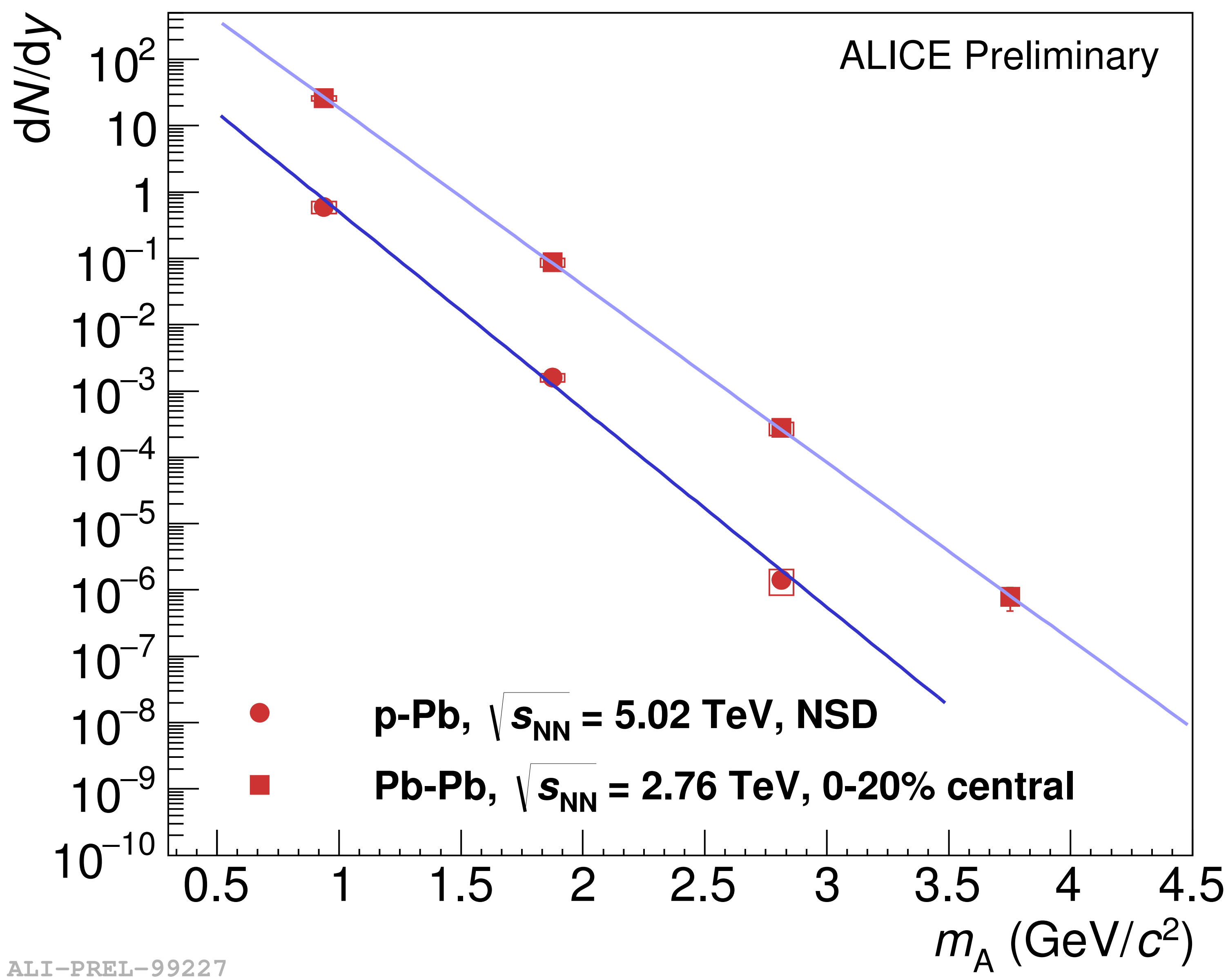

V0A Multiplicity Class (Pb-side)
0-10% (x16)
10-20% (x8)
20-40% (x4)
40-60% (x2)
ALIC
p-Pb
deut
ALI-PREL-69336
TPC ionization signal (a.u.)
π-
e-
ALI-PERF-36713
ALICE 0-10%
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$
$^{3}_{\bar{\Lambda}}\bar{H} \rightarrow {}^{3}\overline{He} + \pi^{+}$
$^{3}_{\Lambda}H$
$^{3}_{\bar{\Lambda}}\bar{H}$
$d^2N/dp_T dy$ x B.R. $(GeV/c)^{-1}$
p_T (GeV/c)



Huge stack of data! But what does it tell about the theory?

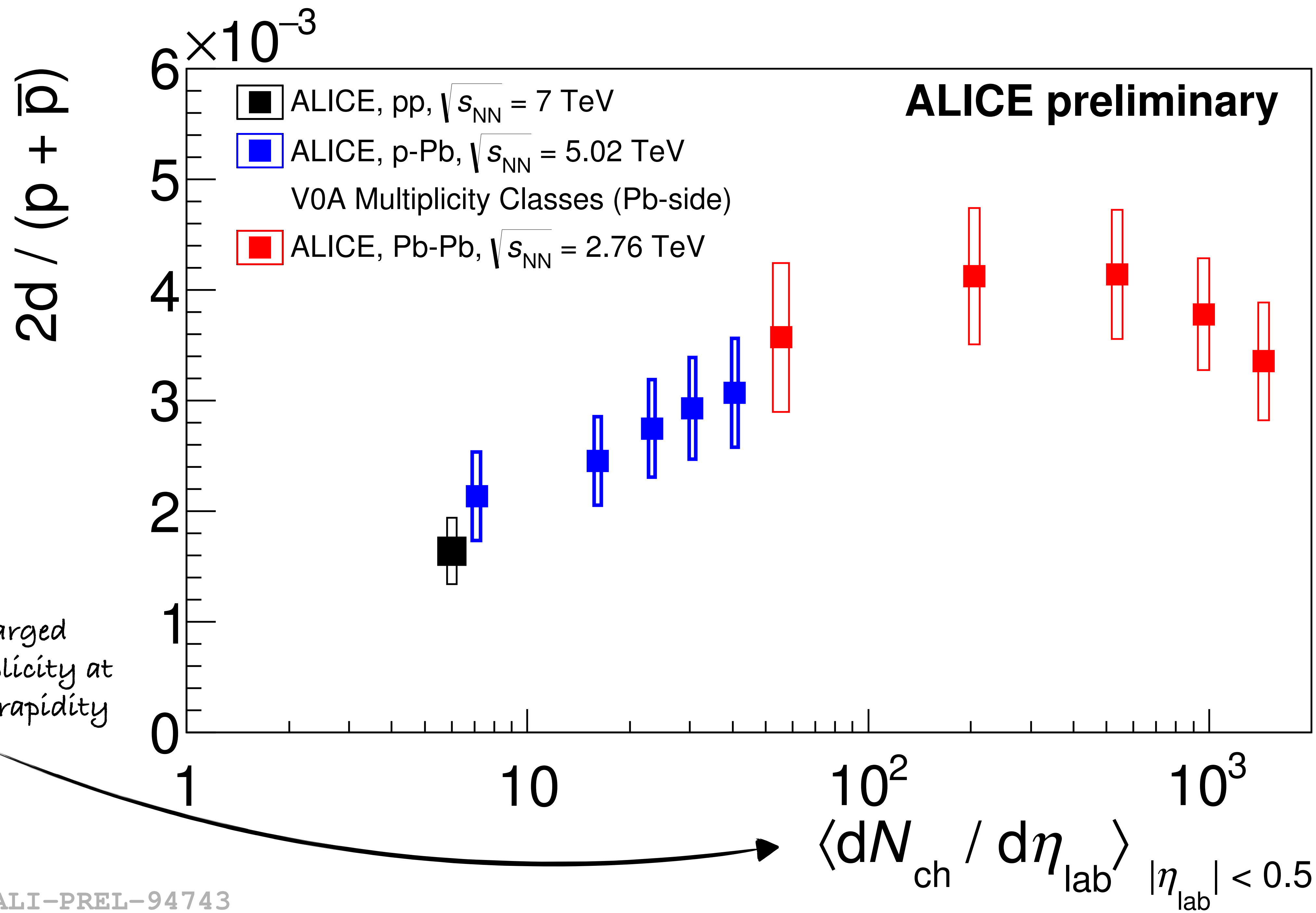
Mass scaling in nuclei production

Nuclei production yields follow an exponential decrease with mass as predicted by the thermal model



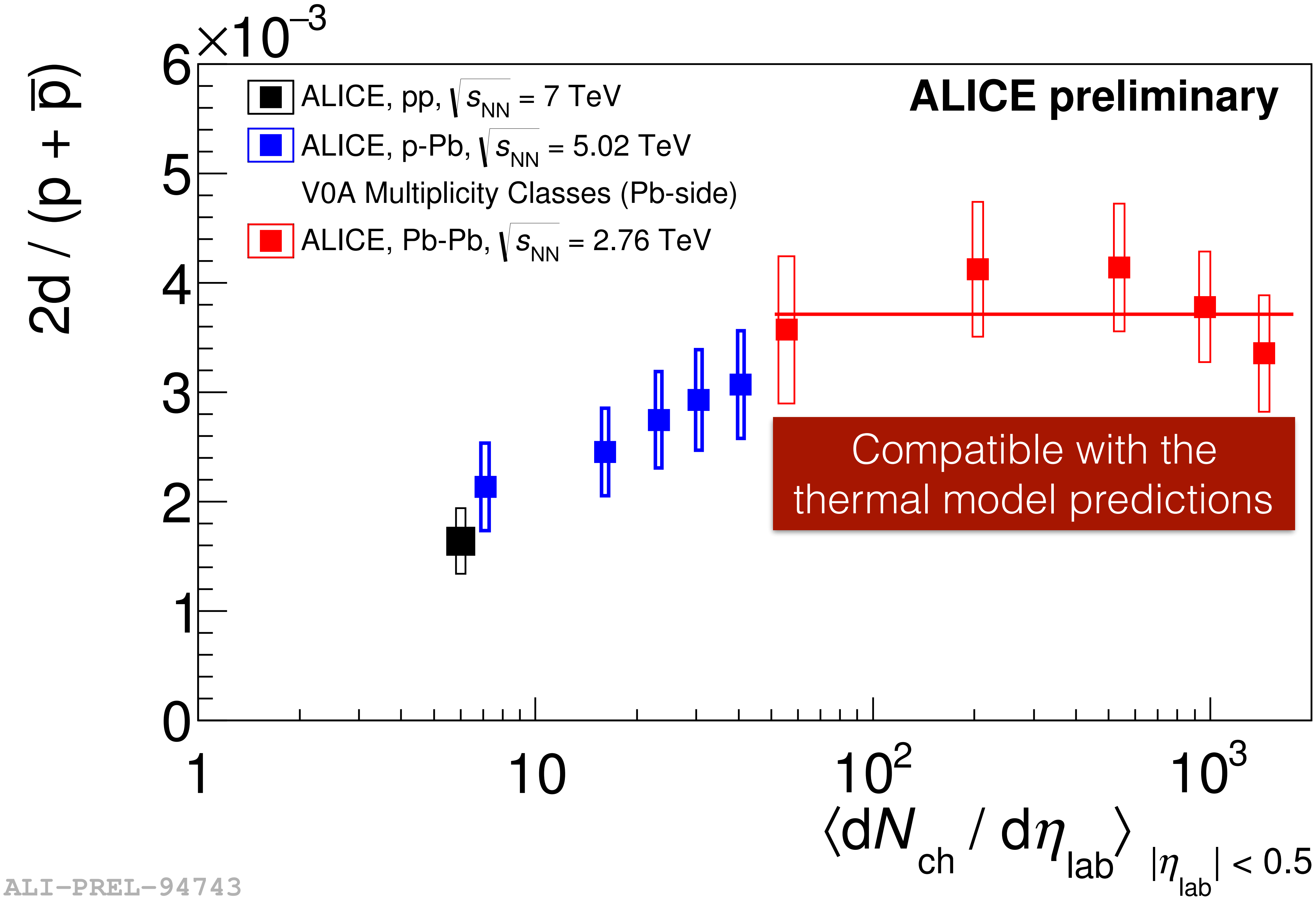
The penalty factor for adding one baryon is in Pb-Pb ~300 and for p-Pb ~600

Deuteron over proton ratio

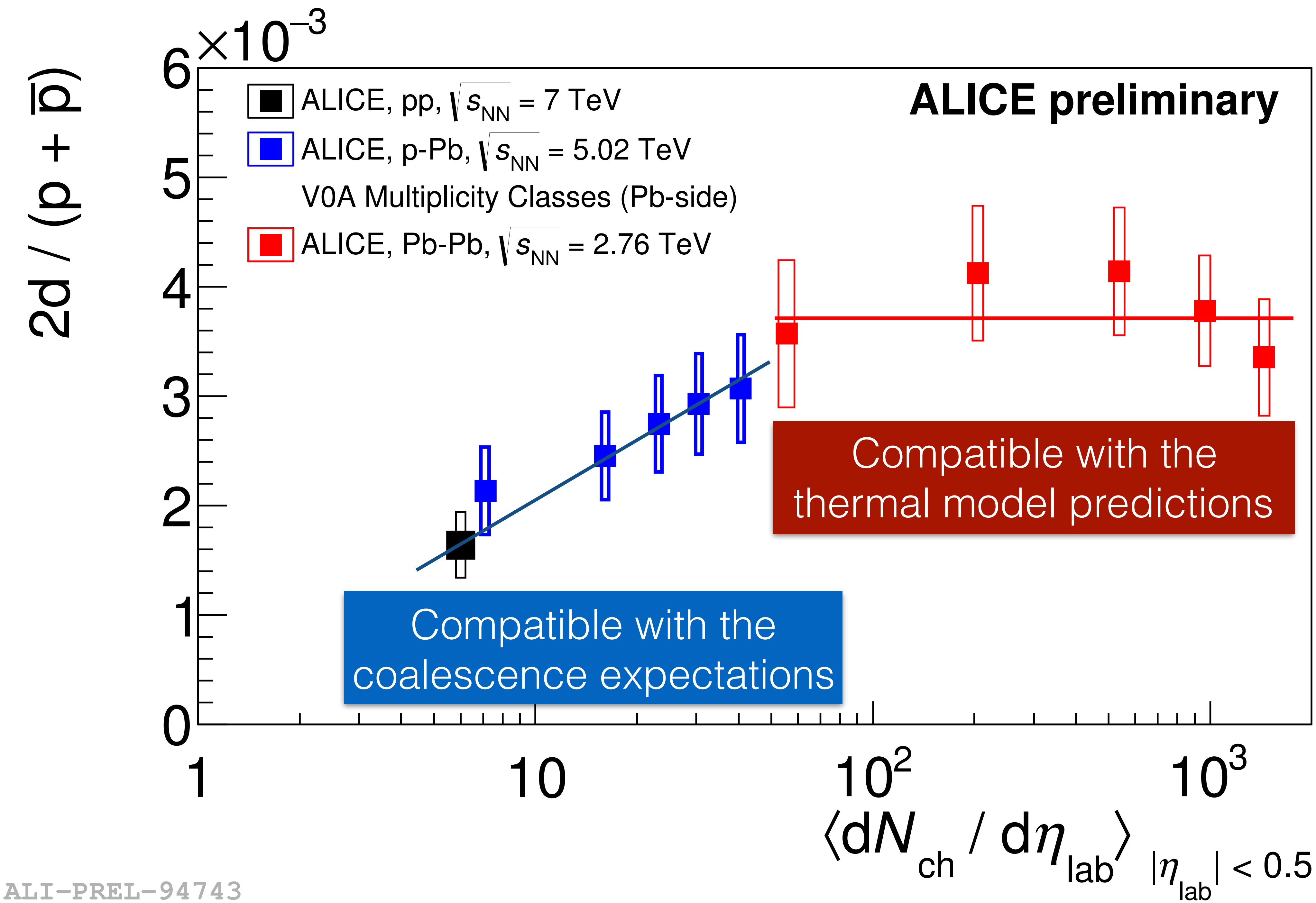


Average charged particle multiplicity at central pseudorapidity

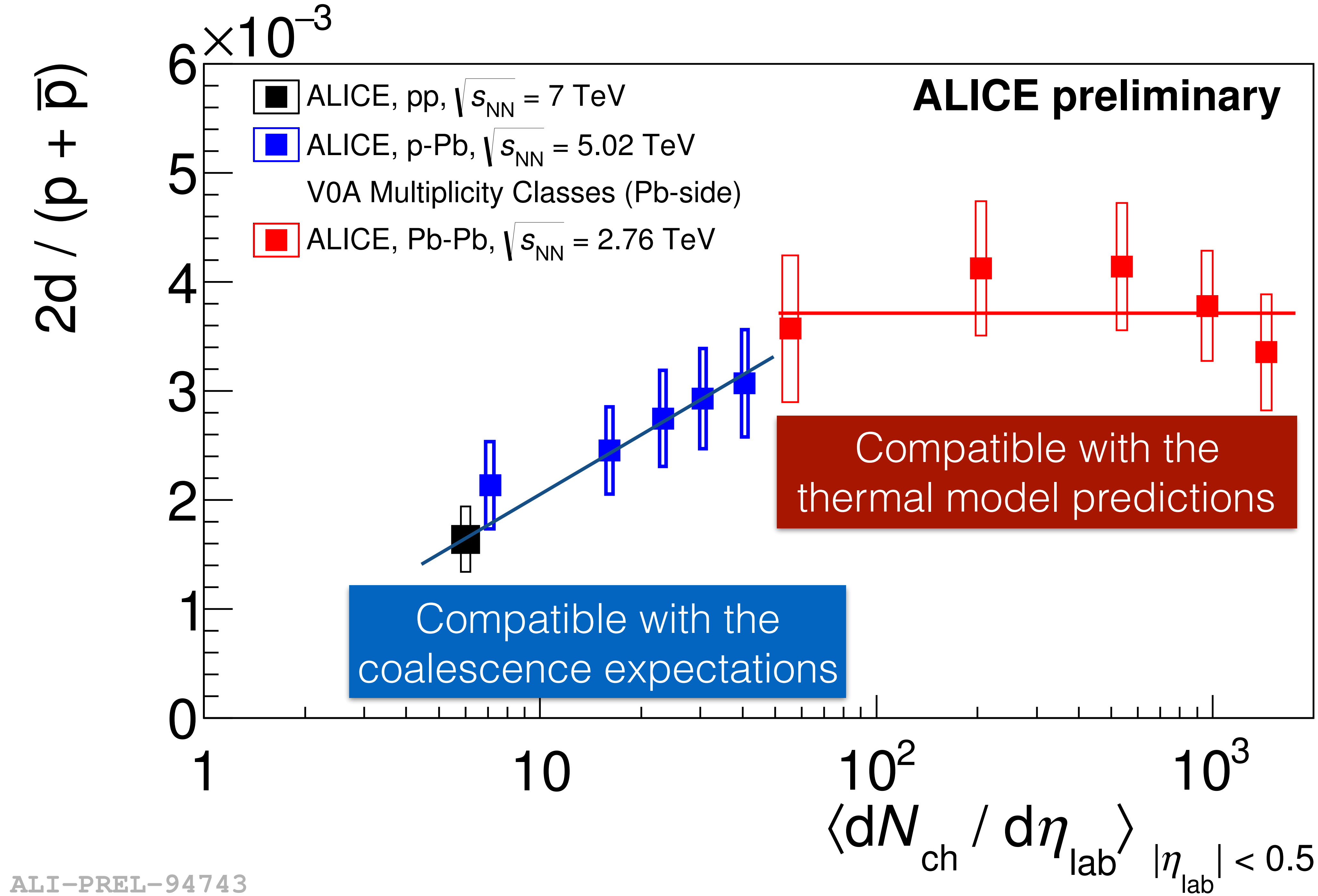
Deuteron over proton ratio



Deuteron over proton ratio



Deuteron over proton ratio

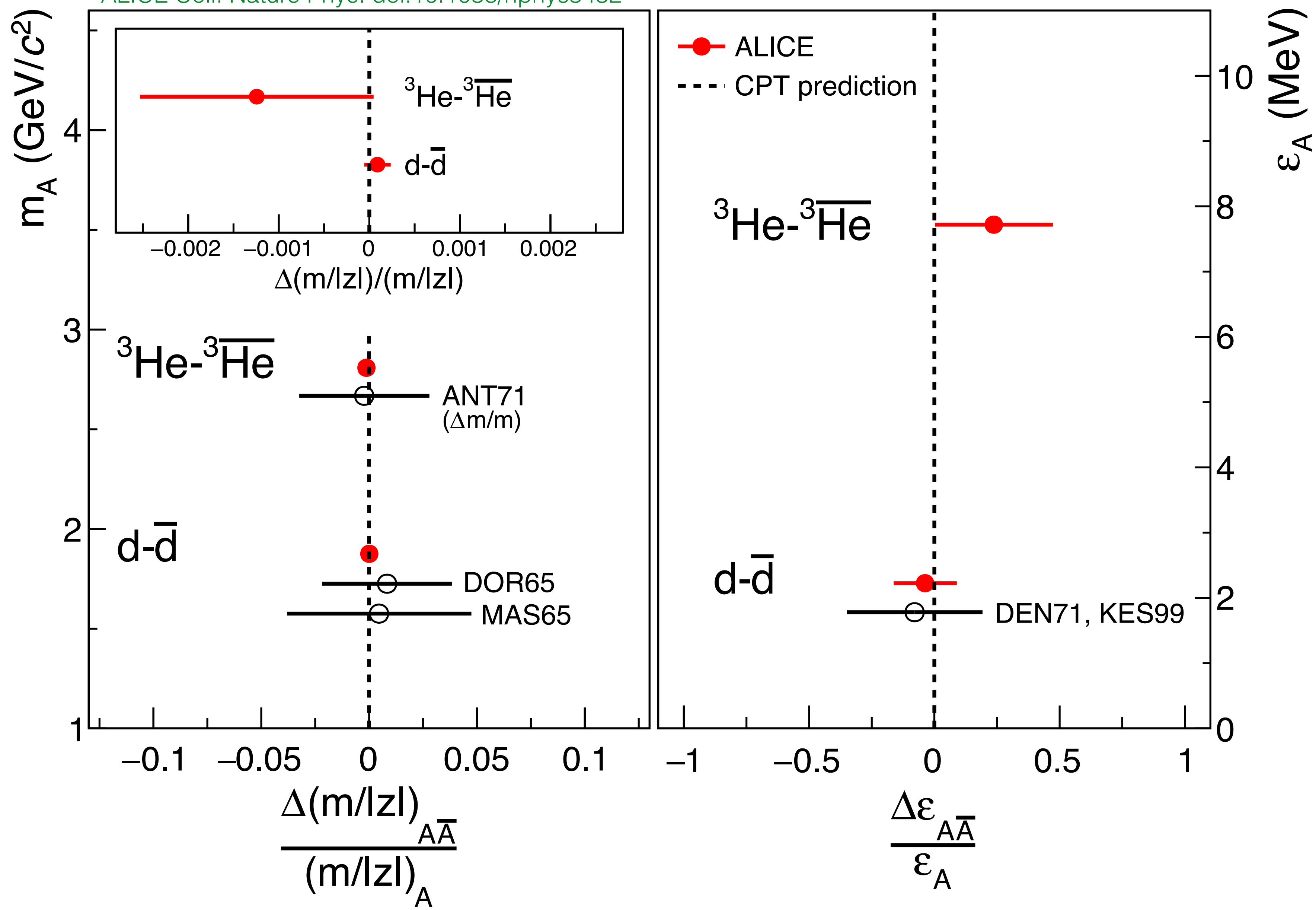


Simple coalescence seems to work in the small systems while thermal models describe better the data in Pb-Pb

CPT tests in the nuclei sector!

CPT invariance: no mass difference between nuclei and anti-nuclei

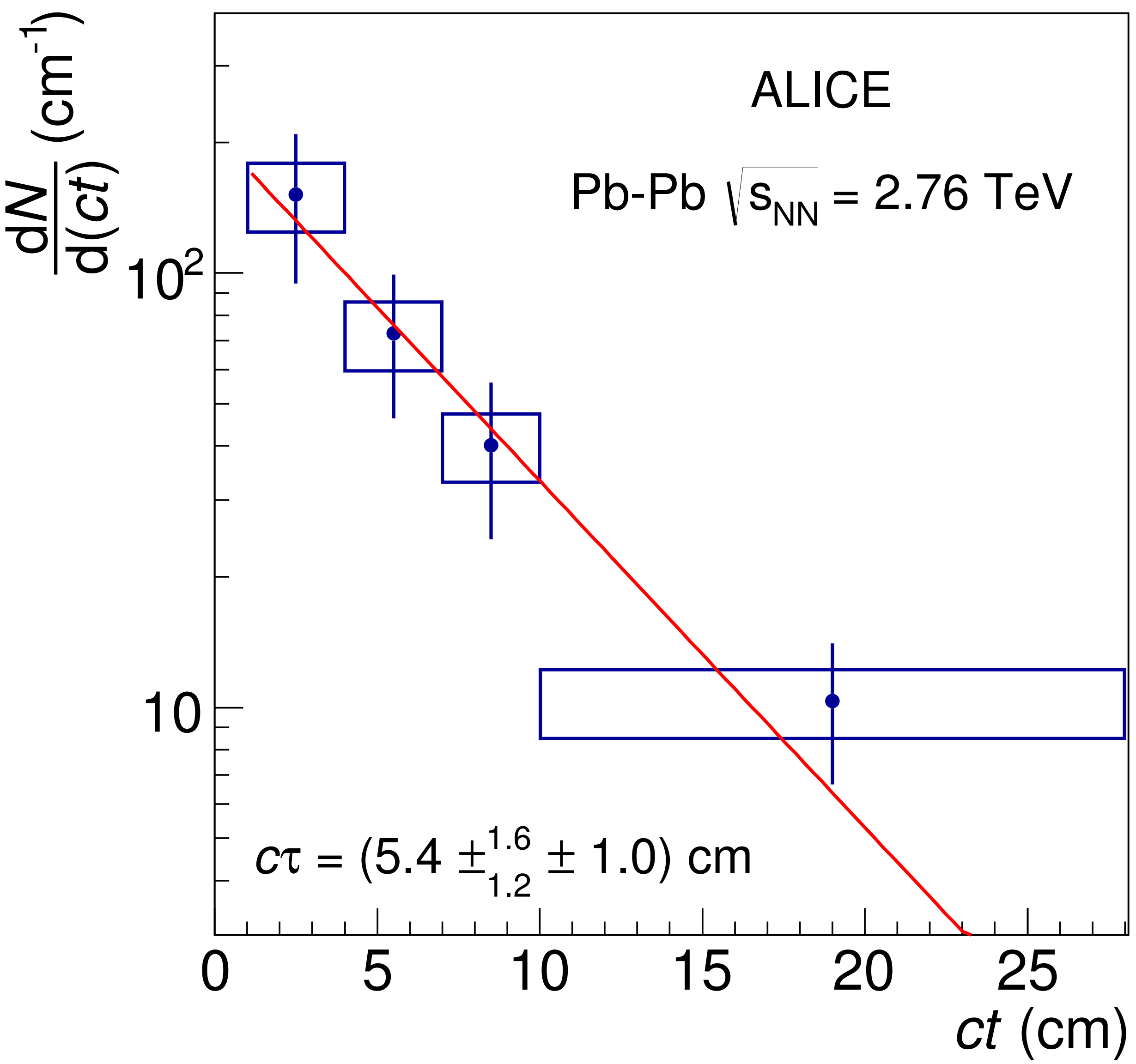
ALICE Coll. Nature Phys. doi:10.1038/nphys3432



This test shows that the **mass of nuclei and anti-nuclei are compatible** within the uncertainties. The binding energies are compatible in nuclei and anti-nuclei as well.

ANT71: Nucl. Phys. B31 (1971) 235
DOR65: PRL 14 (1965) 1003
MAS65: Nuovo Cim. 39 (1965) 10

Open puzzle: hyper-triton lifetime



From the exponential fit to the differential yield in different *ct* bins it is possible to extract the lifetime of the hyper-triton

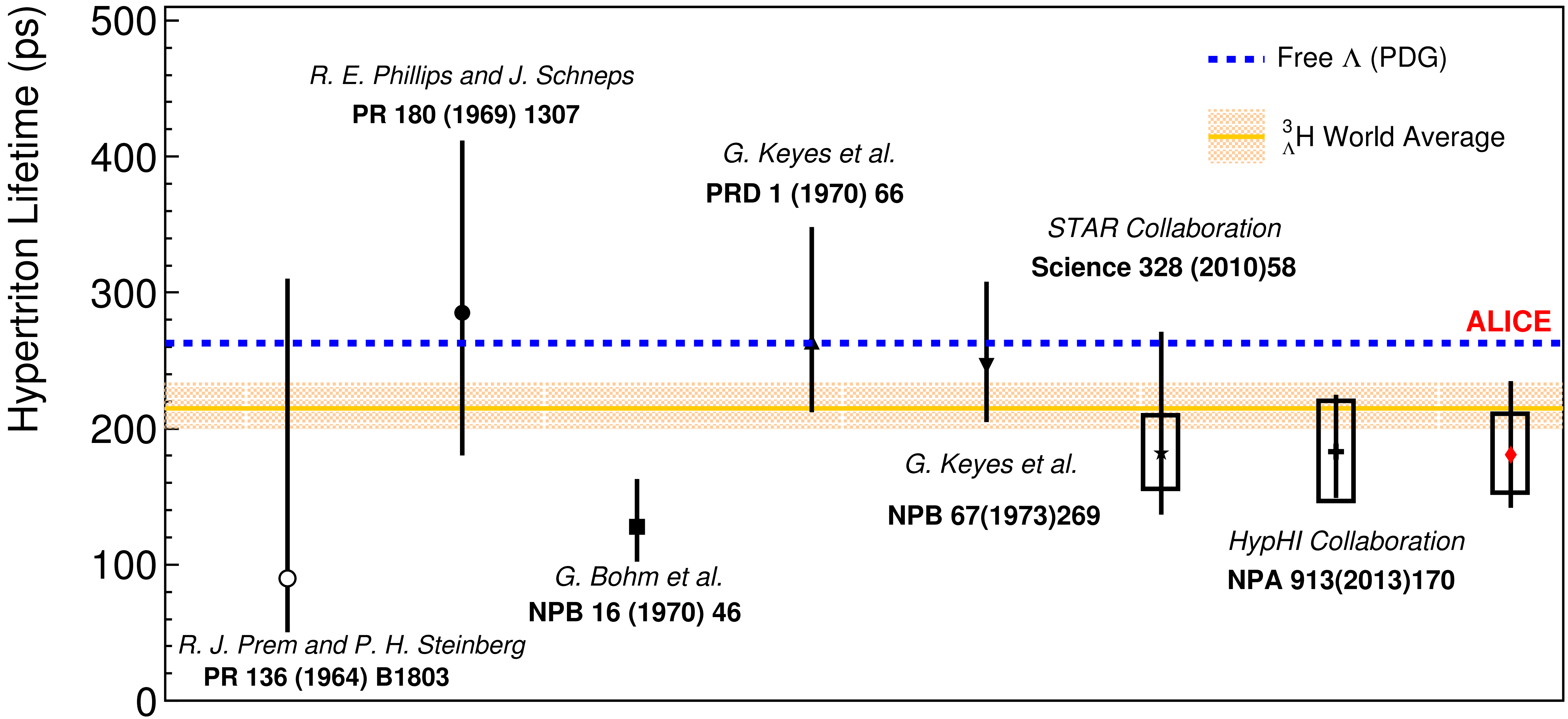
ALICE

$$\tau(181^{+54}_{-39}(\mathrm{stat.}) \pm 33(\mathrm{syst})) \; \mathrm{ps}$$

World average

$$\tau = 215^{+18}_{-16} \; \mathrm{ps}$$

Open puzzle: hyper-triton lifetime



From the exponential fit to the differential yield in different *ct* bins it is possible to extract the lifetime of the hyper-triton

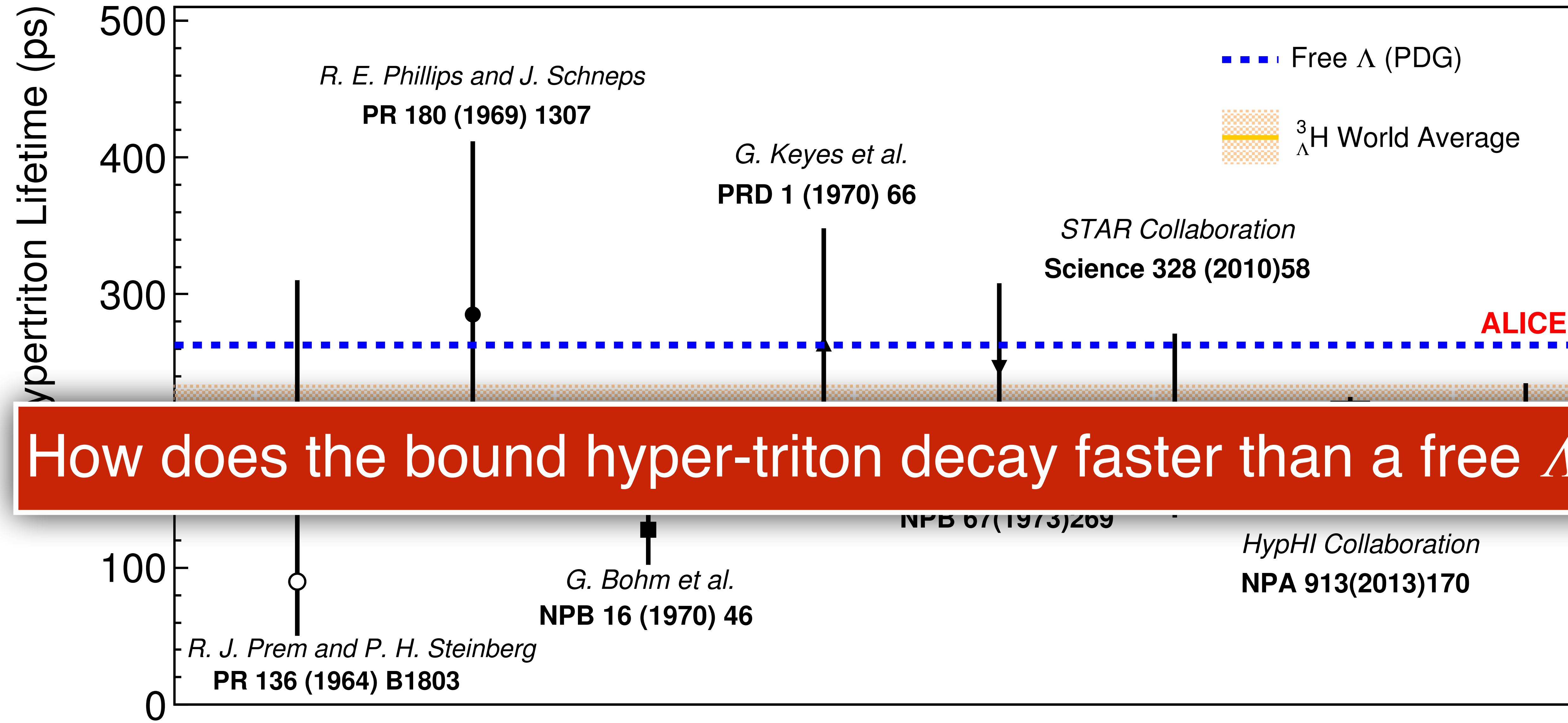
ALICE

$$\tau(181^{+54}_{-39}(\mathrm{stat.}) \pm 33(\mathrm{syst})) \ \mathrm{ps}$$

World average

$$\tau = 215^{+18}_{-16} \ \mathrm{ps}$$

Open puzzle: hyper-triton lifetime



How does the bound hyper-triton decay faster than a free Λ?

From the exponential fit to the differential yield in different *ct* bins it is possible to extract the lifetime of the hyper-triton

ALICE

$$\tau(181^{+54}_{-39}(\text{stat.}) \pm 33(\text{syst}))\ \text{ps}$$

World average

$$\tau = 215^{+18}_{-16}\ \text{ps}$$

Conclusions

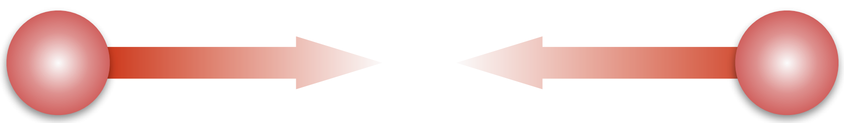
The study of (hyper-)(anti-)nuclei at the LHC allows one to investigate:

- Coalescence model and thermal models as production mechanisms
- CPT invariance
- Hadronic phase of the QGP
  - How can loosely bound objects survive such conditions?
- Outstanding puzzle of the hyper triton lifetime

Data and results from Run2 of the LHC will help to answer the open questions.


Backup slides

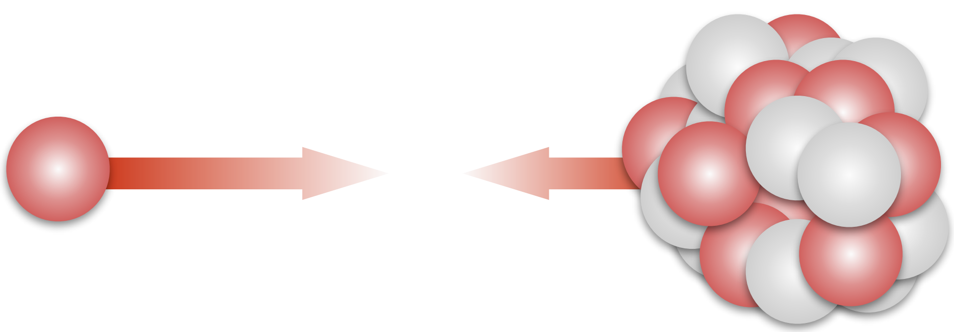
Collision systems at the LHC



pp

$\sqrt{s}$
0.9 TeV
2.76 TeV
5.02 TeV
7 TeV
8 TeV
13 TeV

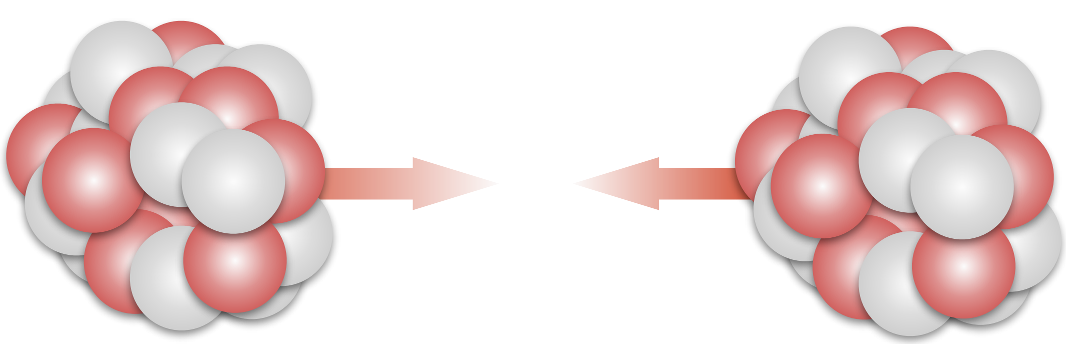
Reference for measurement in other systems



p-Pb
Pb-p

$\sqrt{s_{NN}}$
5.02 TeV
5.02 TeV

Study of nuclear matter effects



Pb-Pb

$\sqrt{s_{NN}}$
2.76 TeV
5.02 TeV

Study of hot and dense QCD matter

Three collision systems: unique opportunity to further study hadronisation and the strong interaction at extreme regimes of energy density and temperature

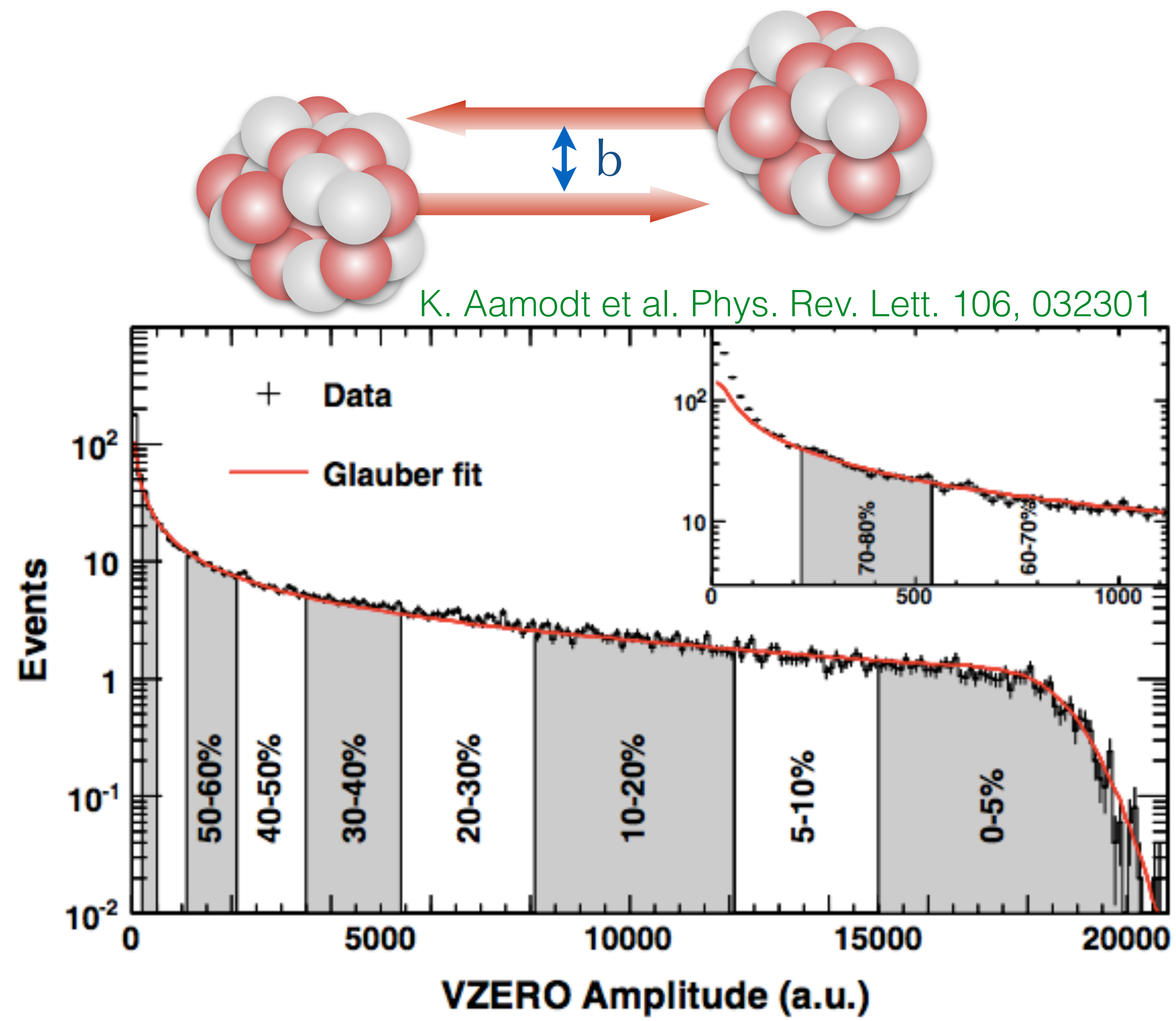
Centrality of a collision

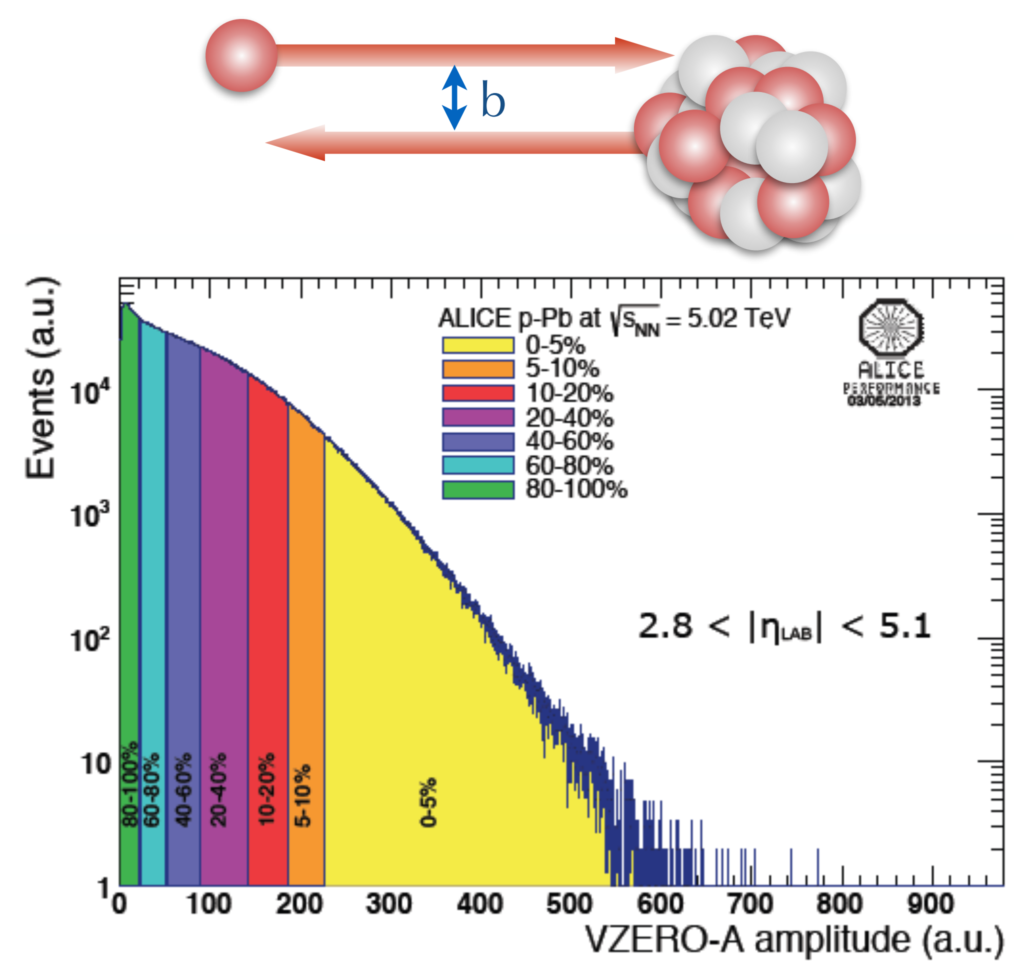
The centrality of a collision is defined by the impact parameter *b*:

Most central collision ⇔ Smallest b

Experimentally it is possible to correlate the charged particle multiplicity to *b* by fitting data with the function shape predicted by the Glauber model.

The correlation between charged particle mult. and impact parameter in p-Pb is broader.





V-ZERO is a scintillator hodoscope used for centrality estimation and for the trigger.

Coalescence parameter

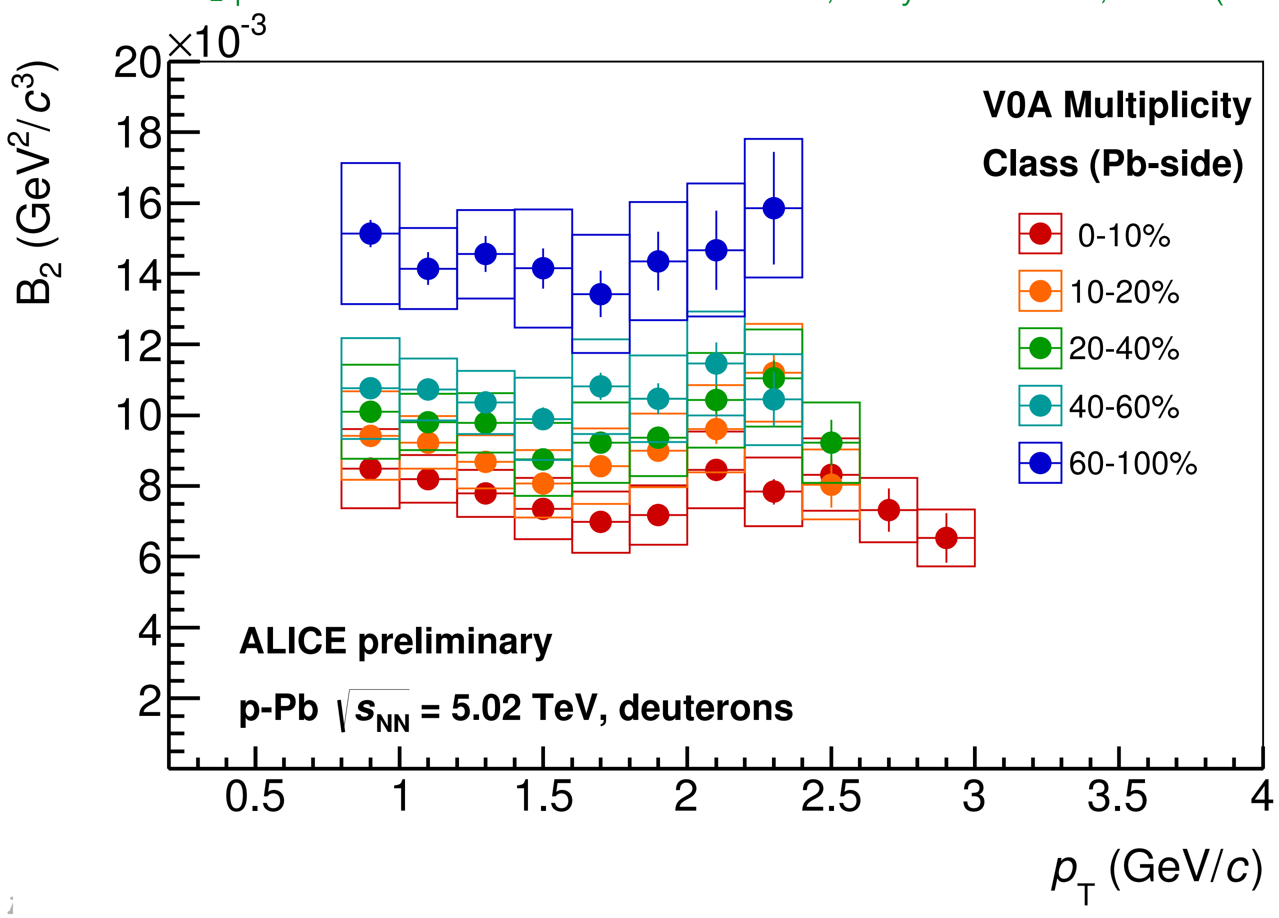
The coalescence parameter, defined as:

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

is predicted to be p_{T} independent by the simplest formulation of coalescence model.

This is observed in p-Pb collisions.

B_2 parameter: R. Scheibl and U. Heinz, Phys.Rev. C59, 1585 (1999)



Coalescence parameter

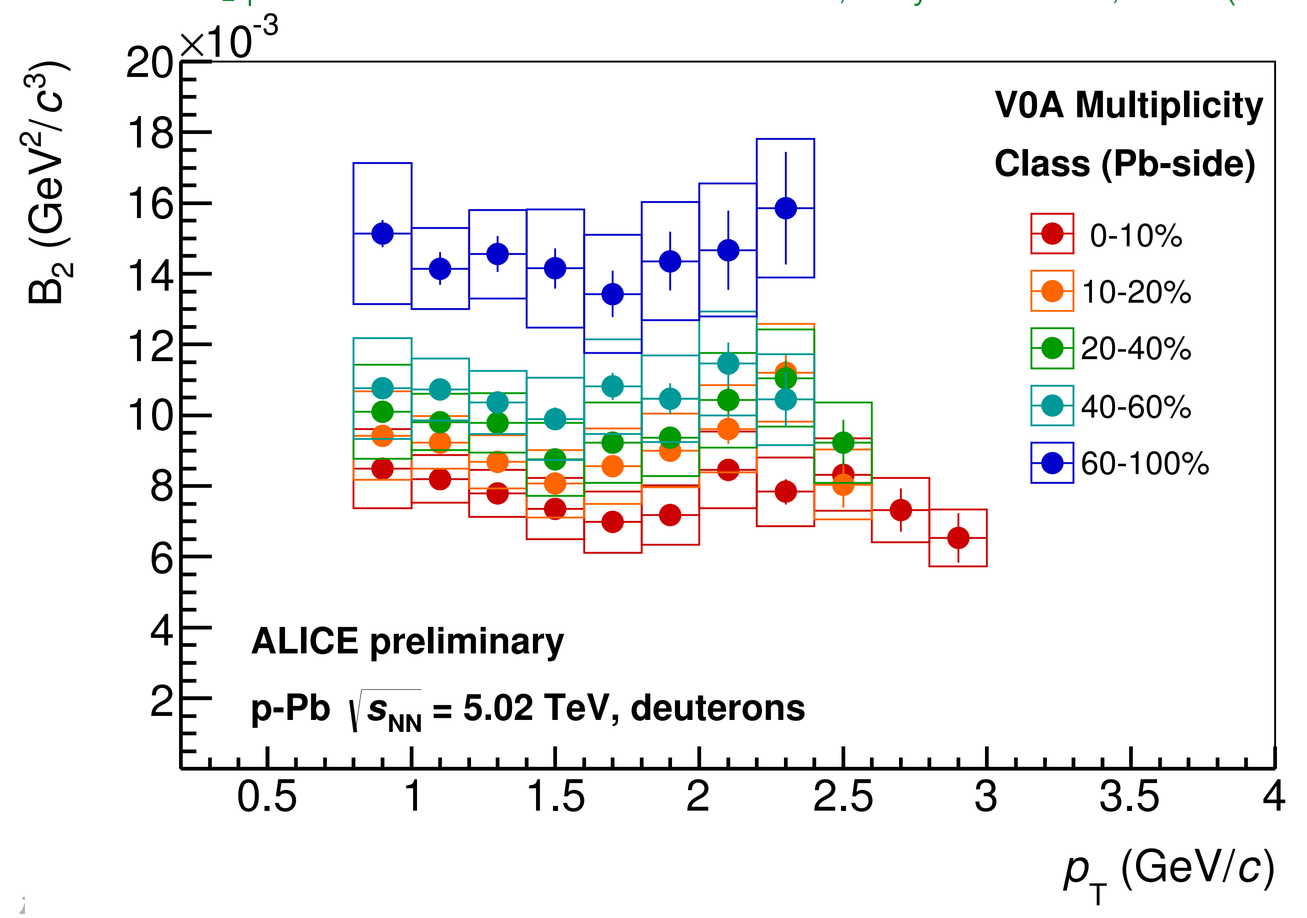
The coalescence parameter, defined as:

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

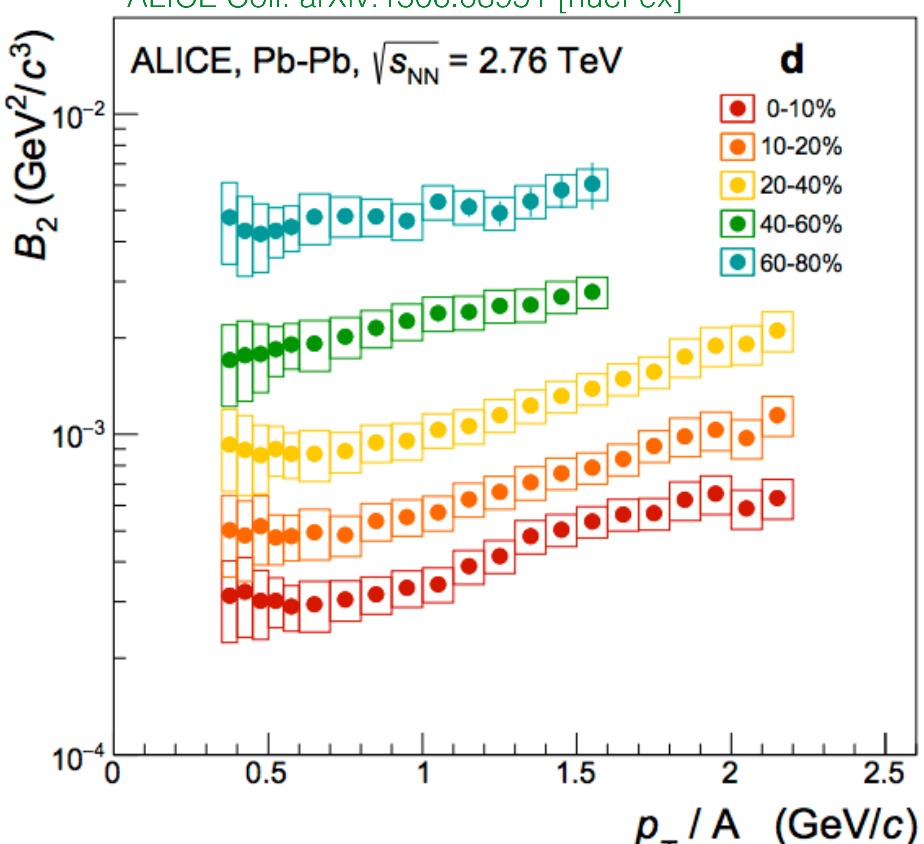
is predicted to be $p_{\rm T}$ independent by the simplest formulation of coalescence model.

This is observed in p-Pb collisions.

B_2 parameter: R. Scheibl and U. Heinz, Phys.Rev. C59, 1585 (1999)



ALICE Coll. arXiv:1506.08951 [nucl-ex]



The coalescence parameter gets smaller as the events are more central. This is due to the increasing size of the emitting source.

The B_2 depends on $p_{\rm T}$ in central events, which could be explained by looking at the Hanbury Brown and Twiss (HBT) radii dependence of the B_2.

Coalescence and HBT radii

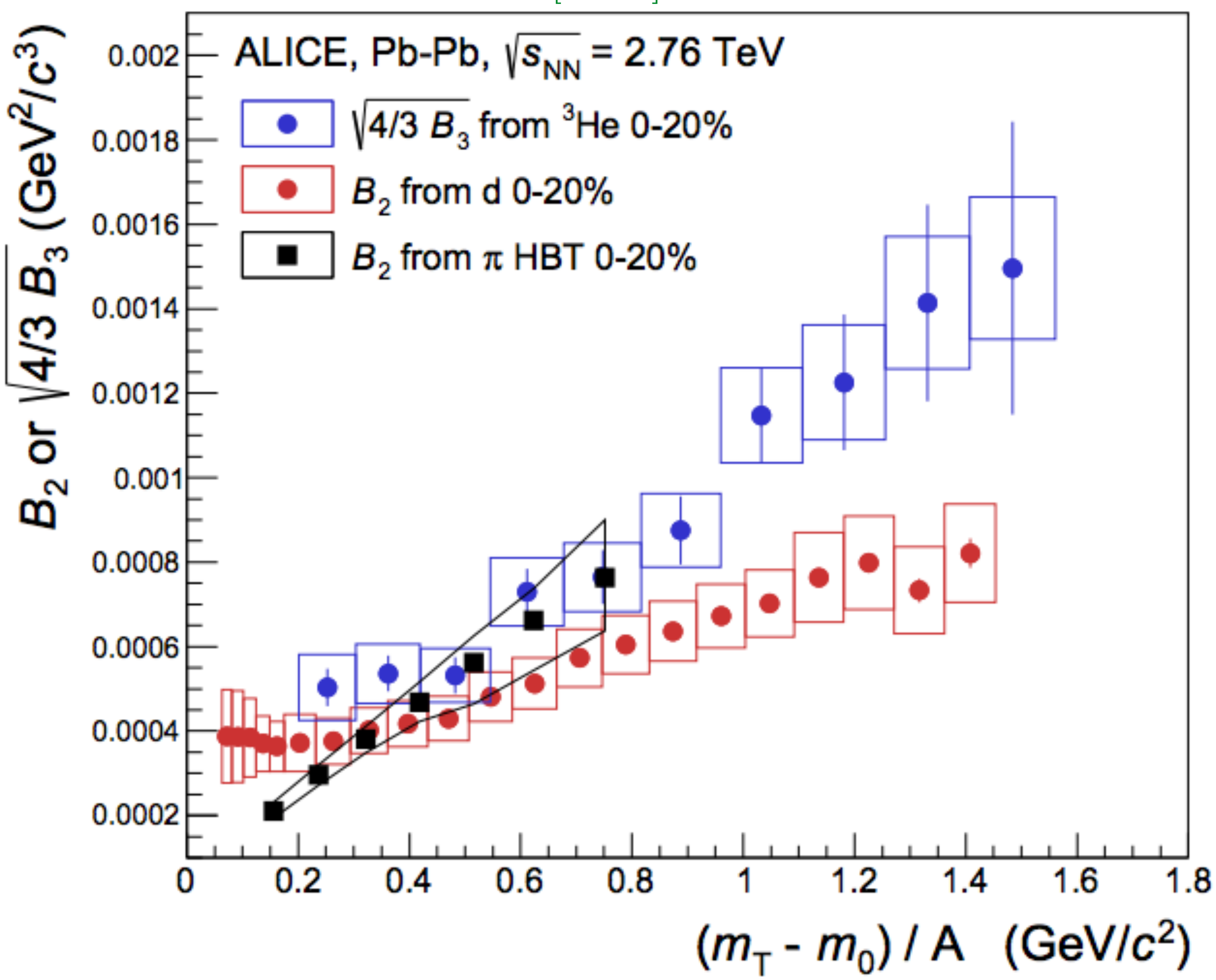
The coalescence parameter can be expressed as a function of the HBT radii:

$$B_2 = \frac{3\pi^{3/2}\langle C_\mathrm{d}\rangle}{2m_\mathrm{T}R_\perp^2(m_\mathrm{T})R_\parallel(m_\mathrm{T})}$$

R. Scheibl and U. Heinz, Phys.Rev. C59, 1585 (1999)

A rough agreement is found in terms of magnitude and the dependence on p_T.

ALICE Coll. arXiv:1506.08951 [nucl-ex]



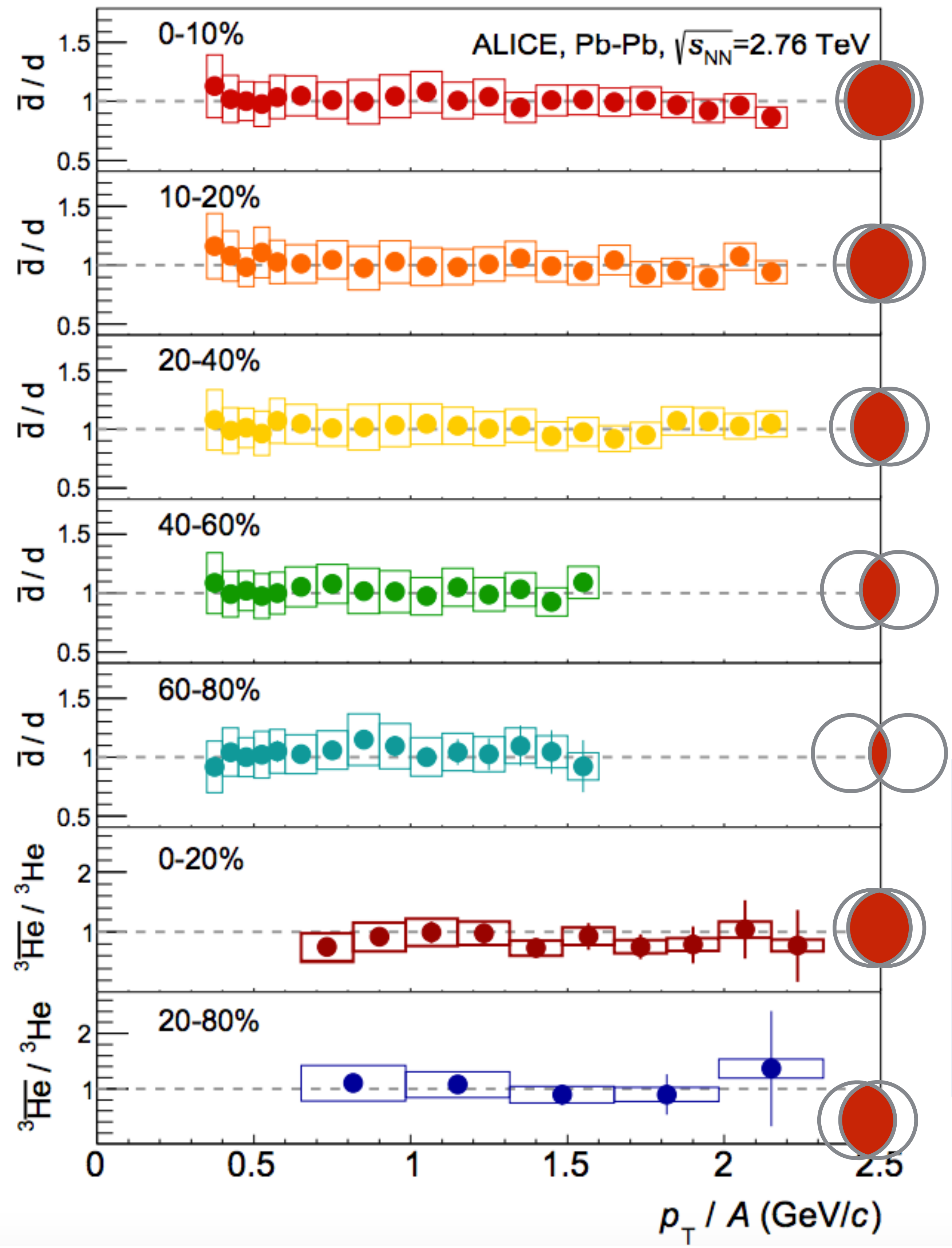
The coalescence parameter for a nucleus *i* with A nucleons is defined as:

$$E_i\frac{\mathrm{d}^3N_i}{\mathrm{d}p_i^3} = B_A\left(E_\mathrm{p}\frac{\mathrm{d}^3N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3}\right)^A$$

From this it is possible to derive a recursive formula. For instance for the ^{3}He:

$$B_3 = B_2^2\left(\frac{M_{^3He}\cdot m}{M_d^2}\right) \approx \frac{3}{4}B_2^2$$

Ratio matter/ antimatter



The ratio nuclei / anti-nuclei is compatible with one at mid-rapidity

The same ratio is seen for other particle species measured at the LHC

A large fraction of the systematic uncertainties on the determination of the ratios is due to the limited knowledge of the cross sections of anti-nuclei interacting with the material of the detector.

Combined Blast Wave fit

BW model fit:

- gives insight into the kinetic freeze-out conditions
- does not describe hard processes that contribute to particle production at high p_T

Fit parameters
$\langle\beta\rangle = 0.632 \pm 0.01$
T_{kin} = 113 ± 12 MeV
n = 0.72 ± 0.03

With respect to the fit performed without the nuclei the $\langle\beta\rangle$ decreased while the T_{kin} increased but they are compatible within the uncertainties.

Solid symbols denote the spectra points used for the fit.

ALICE Coll. arXiv:1506.08951 [nucl-ex]