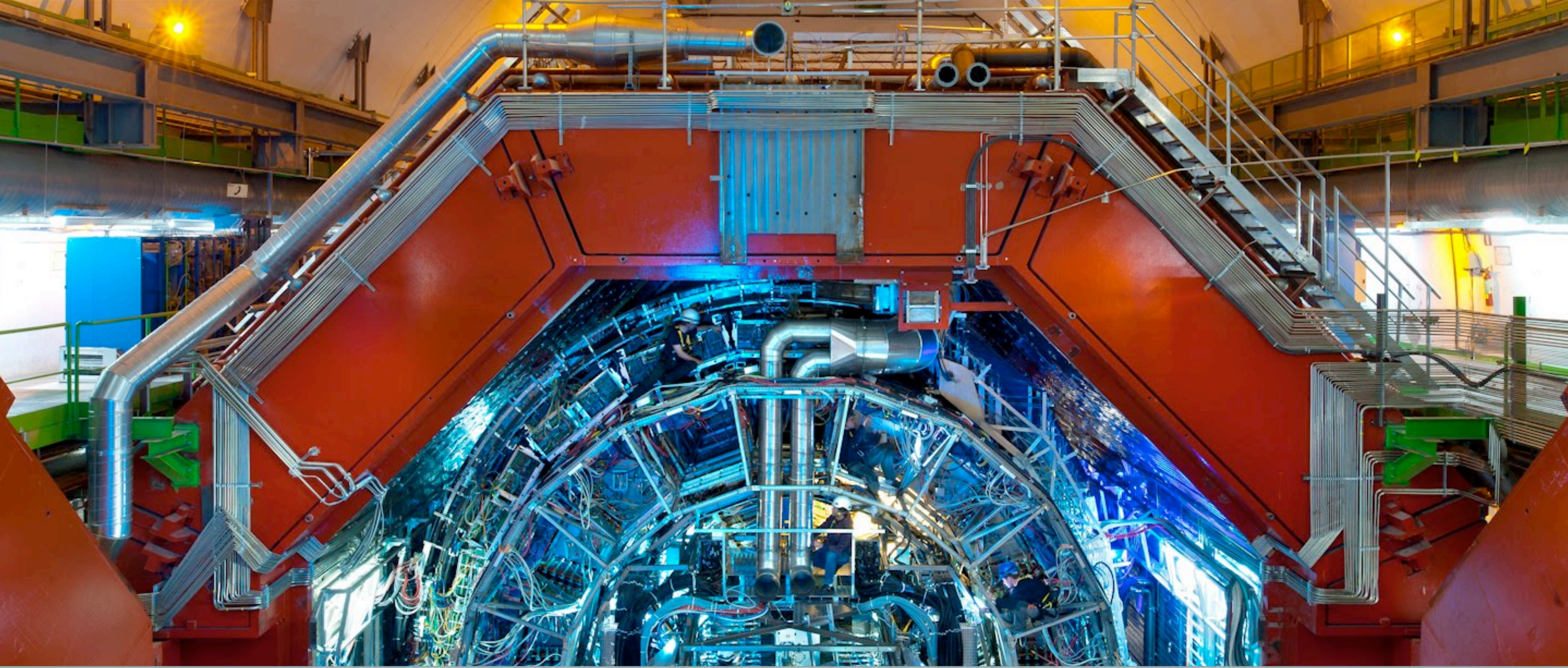


(Anti-)(hyper-)nuclei production with ALICE at the LHC

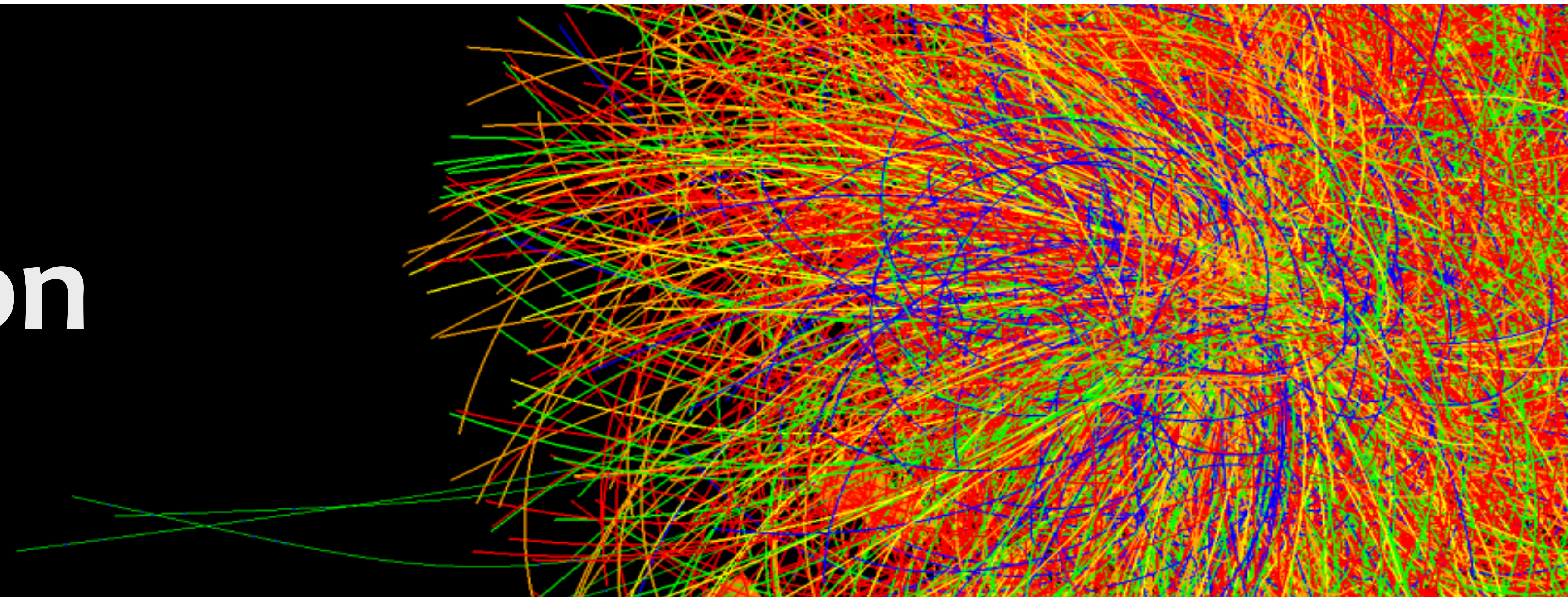
Stefano Trogolo

University and INFN - Torino

Nuclear Physics Colloquium

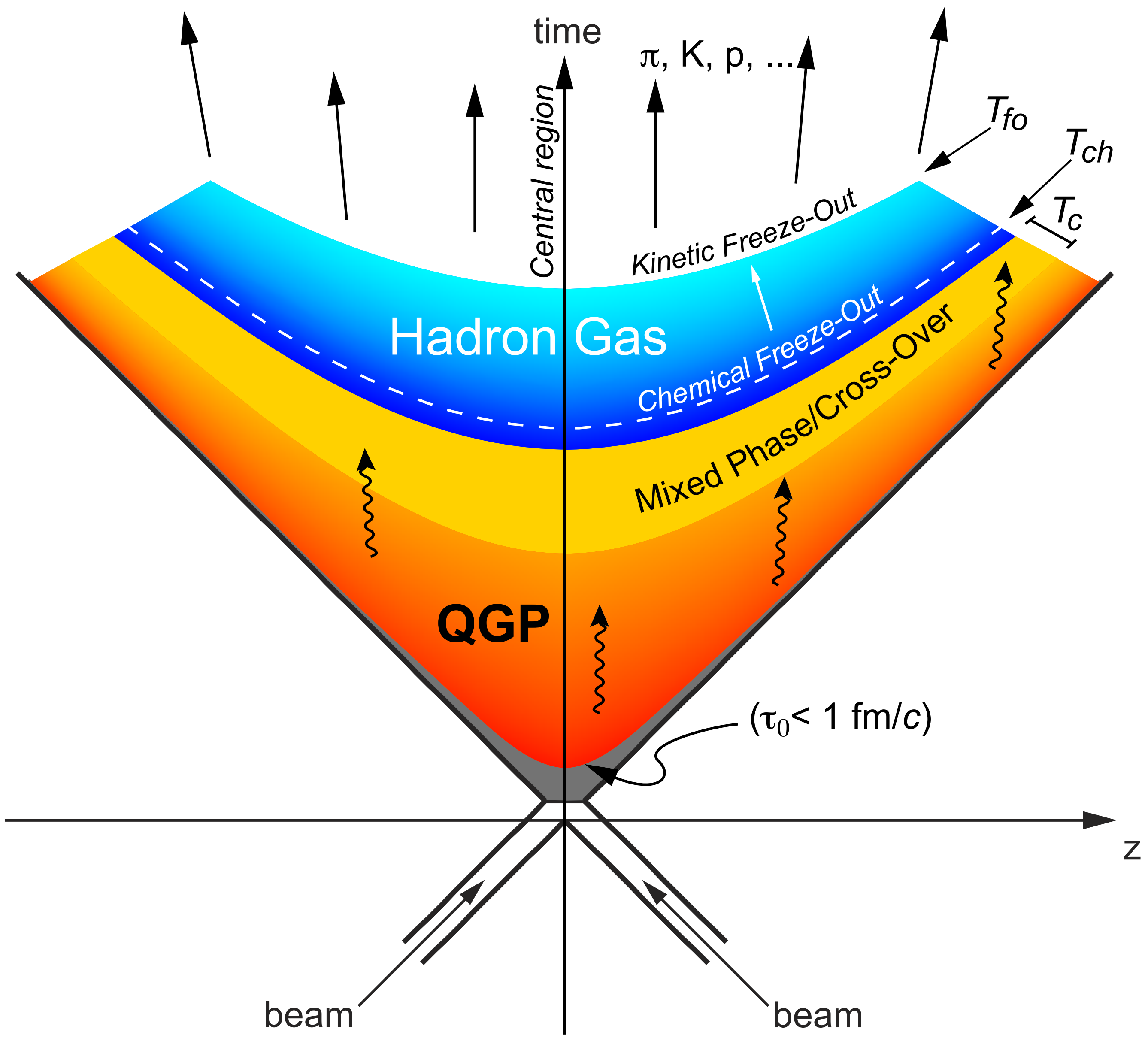
Frankfurt University - December 13th,2018

Introduction



Heavy Ion collisions

- study of hadronic matter under conditions of high energy density (~18 GeV/fm^3) and temperature (~300 MeV)
- a hot and dense partonic medium is created that undergoes a radial expansion
- rapid expansion described using hydrodynamical models



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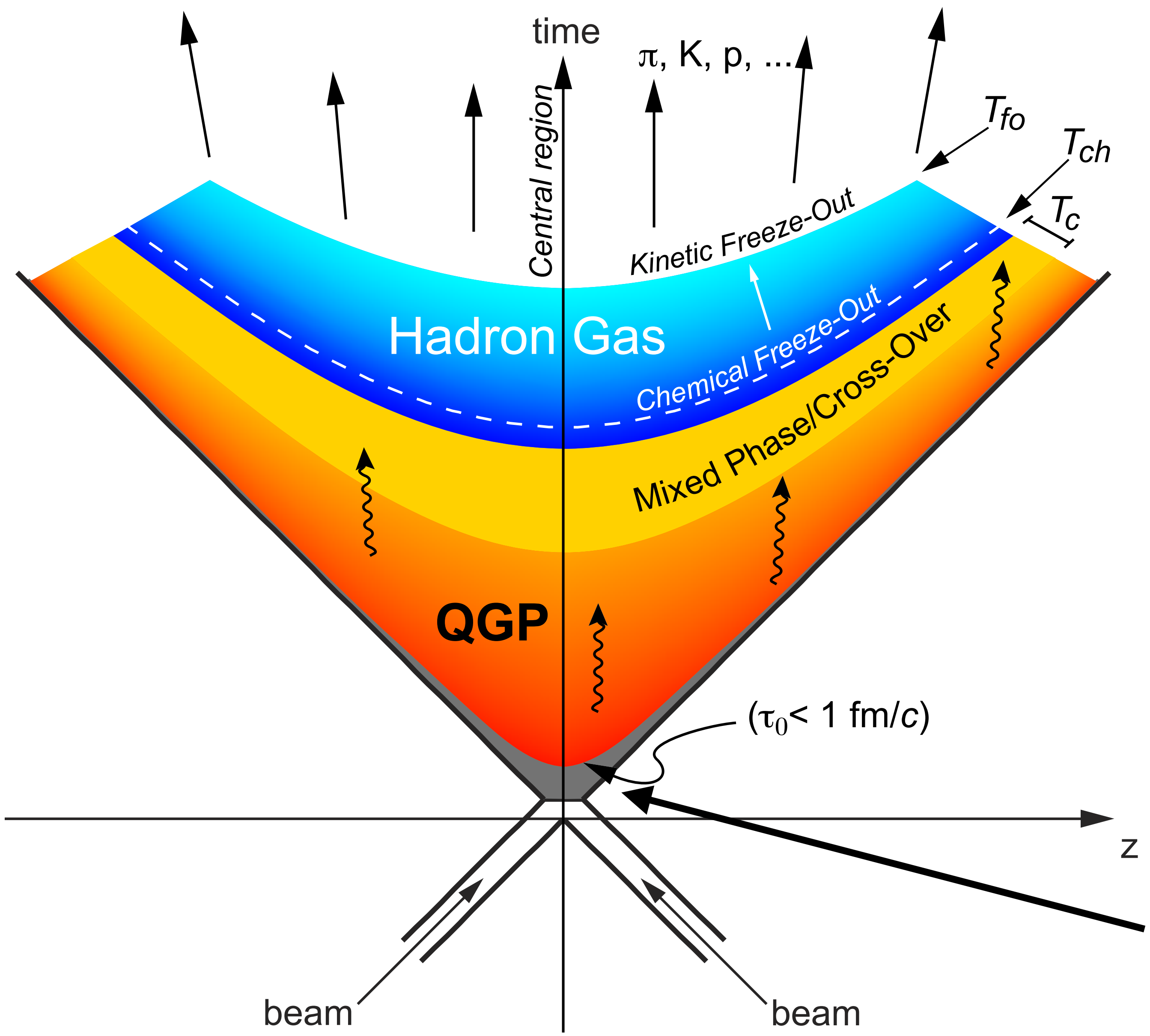

Thermalization time (LHC) $\tau_0 < 1$ fm/c

- centre-of-mass energy dependent

Hard processes

- probe the whole evolution of the collision

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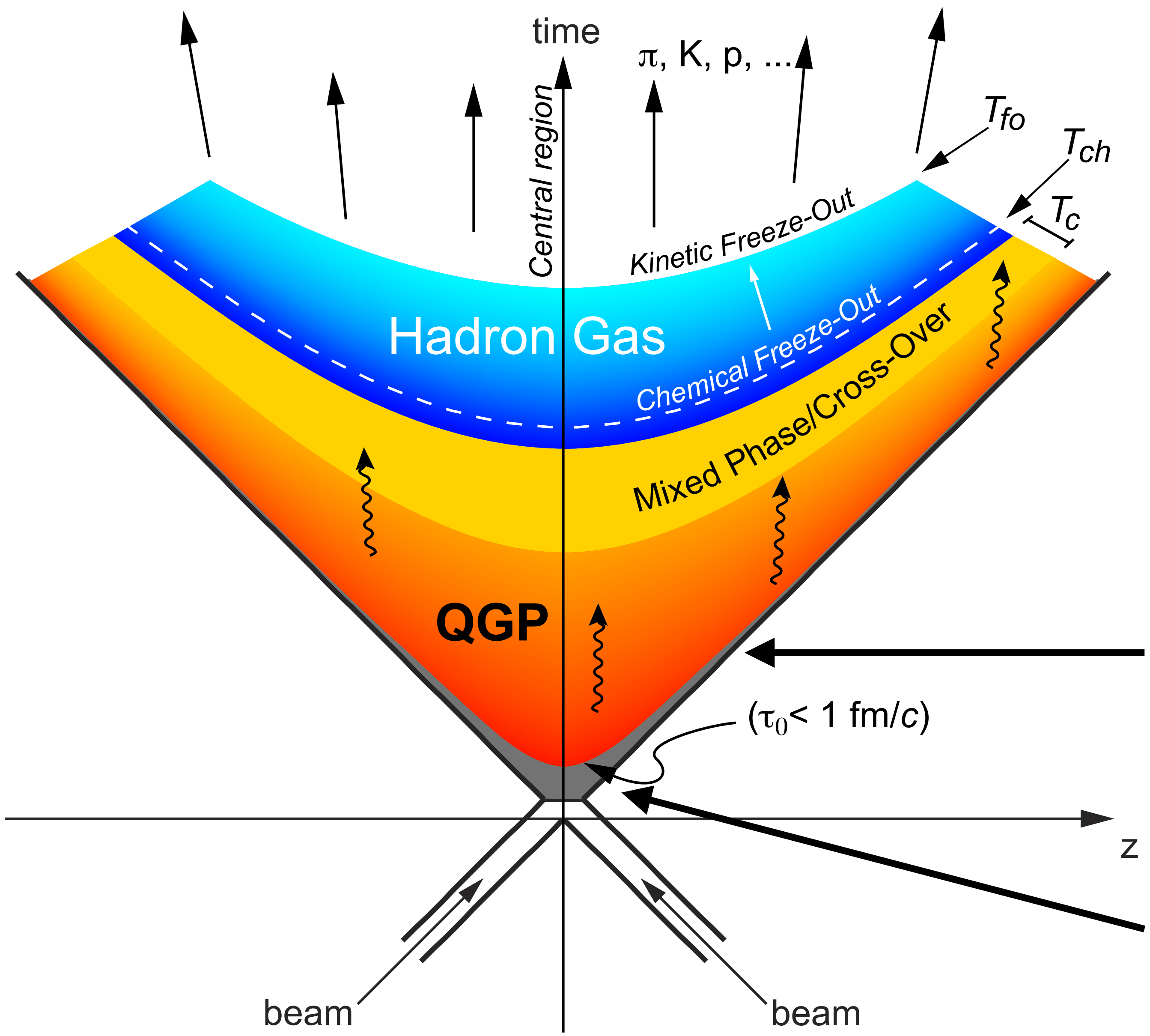

System expansion 1 fm/c < τ < 10 fm/c

- Hydrodynamics laws
- Temp. (T) and energy density (ε) drop down

Thermalization time (LHC) τ_0 < 1 fm/c

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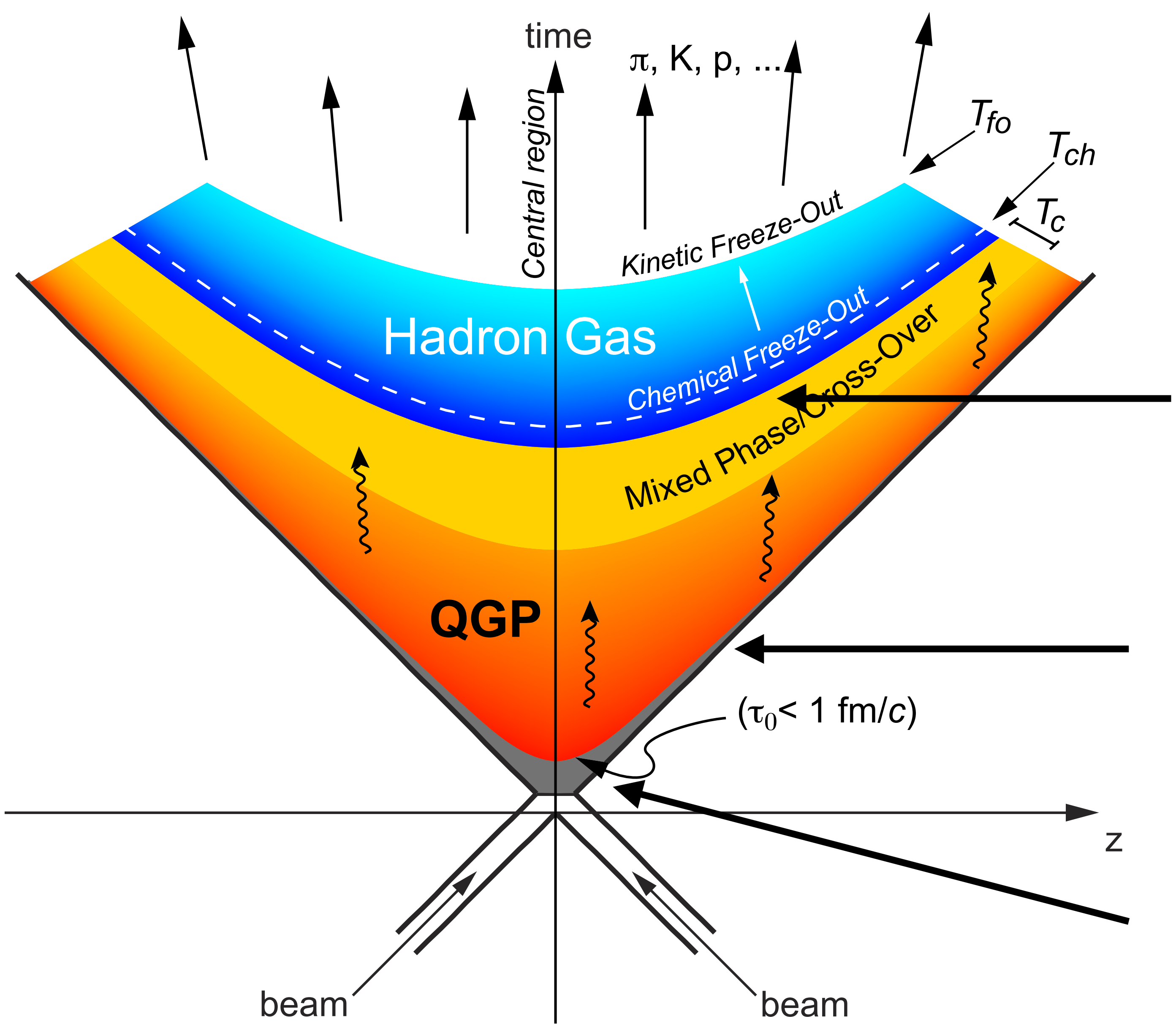

Hadronization

- $T_c \cong 160 \div 170$ MeV
- Confinement of quarks and gluons

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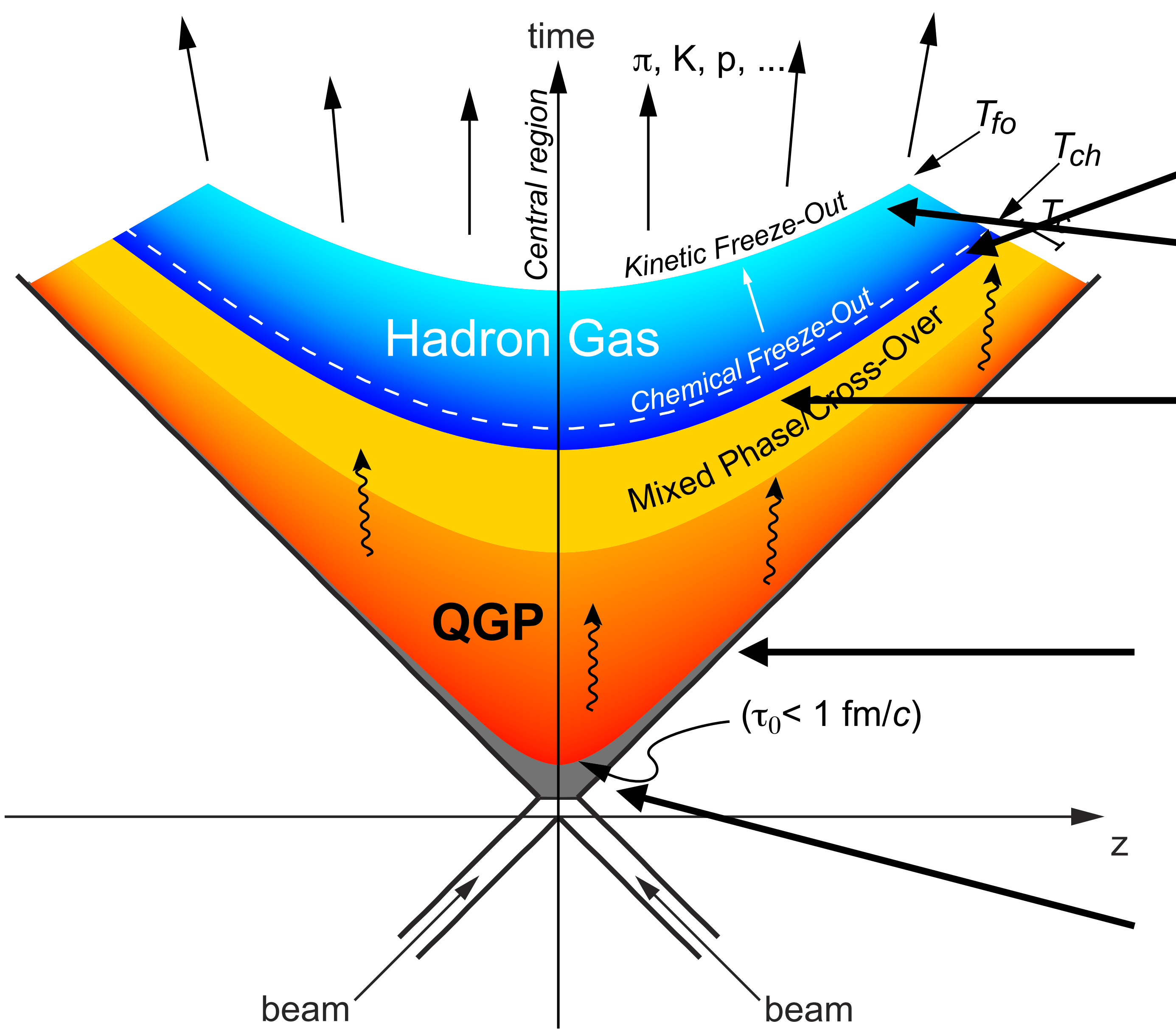

Freeze-out (fo)

- *Chemical*: particle composition is fixed (inel. coll. ceased) ⟶ $T_{ch} \cong 150 \div 155$ MeV
- *Kinetic*: momentum spectra are fixed (elas. coll. ceased) ⟶ $T_{fo} \cong 110 \div 130$ MeV

Hadronization

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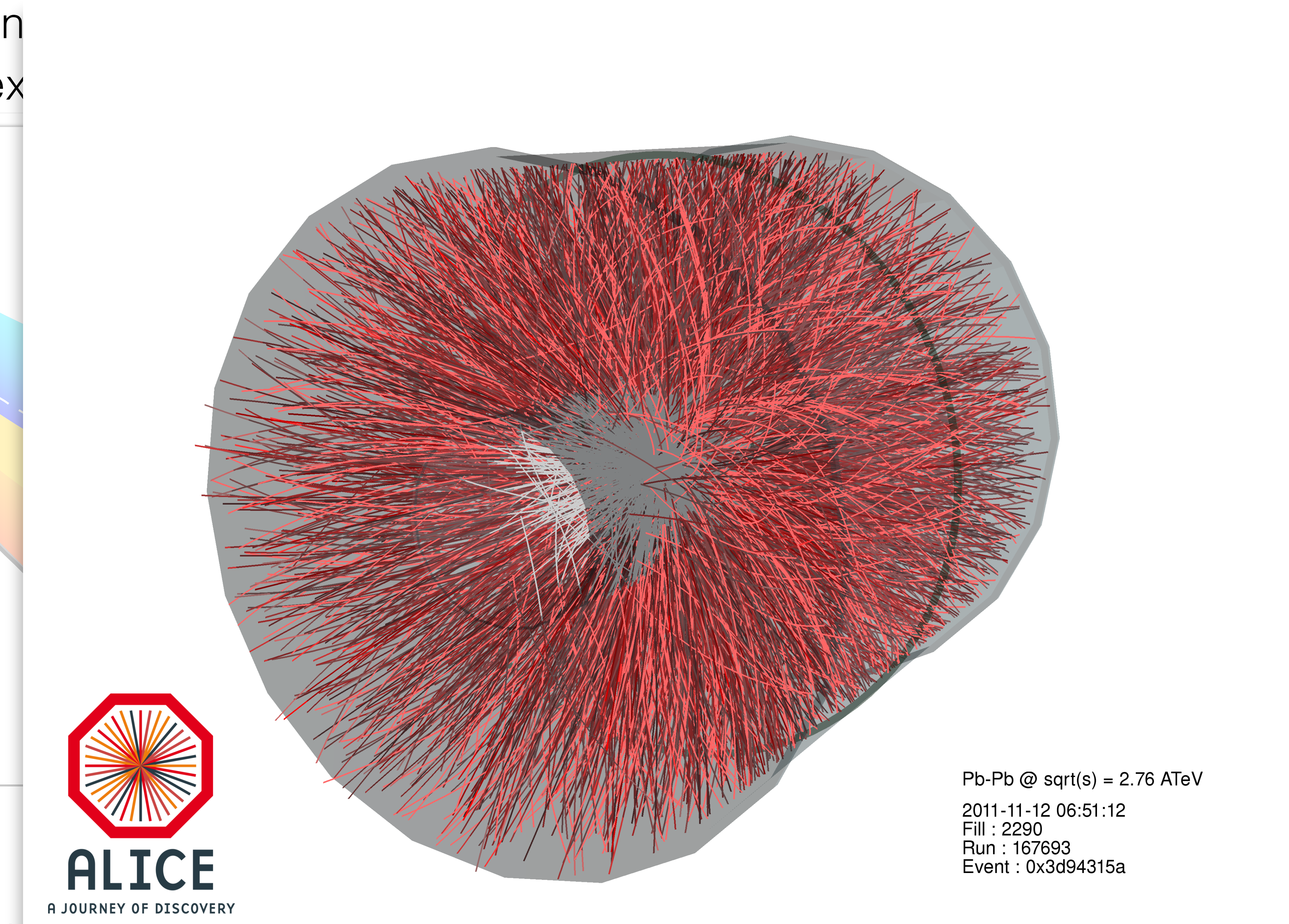

fixed (inel. coll.

ed (elas. coll.

fm/c

drop down

m/c

- probe the whole evolution of the collision

Heavy Ion collisions

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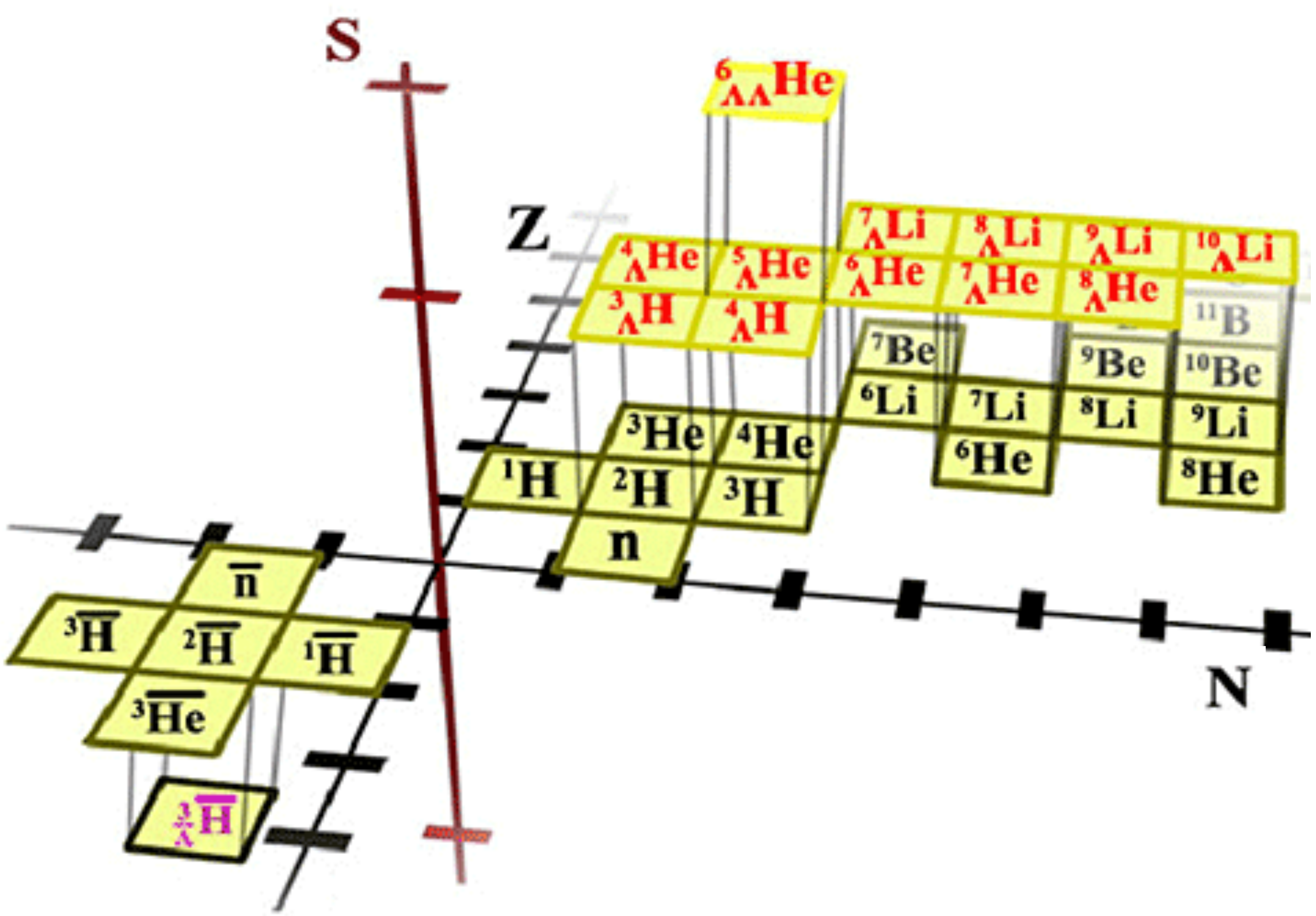


Soft Probes

- Low p_T ($p_T < 2$ GeV/c) **light flavoured** objects coming from the interaction region
- They are produced in the **late stage** of the collision
- Useful to study the **freeze-out** conditions

Light (anti-)(hyper-)nuclei are soft probes and it is interesting to investigate their production in HIC since they are **loosely bound** objects

- U. W. Heinz, "Concepts of heavy ion physics" (2004)
- C. A. Salgado, "Lectures on high-energy heavy-ion collisions at the LHC" (2009)

What is an hypernucleus?

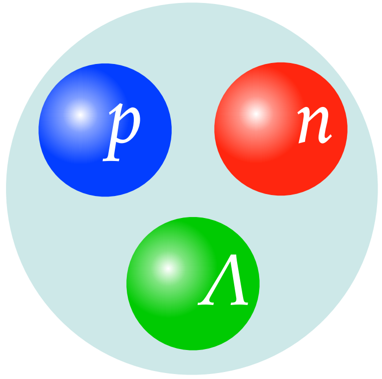
Hypernucleus

a nucleus that contains at least one hyperon in addition to nucleons

First observation in 1952 by Danysz and Pniewski Phil. Mag. 44 (1953) 348

Hypertriton ($^{3}_{\Lambda}$H): bound state of **p**, **n** and **Λ**, is the lightest known hypernucleus

- **Mass** = 2.99116 ± 0.00005 GeV/c^2 [1]
- **Λ binding energy** = 0.13 ± 0.05 MeV [1]
- **lifetime**: world average = 216 $^{+16}_{-19}$ ps [2]
- **decay channels**: ➡ Mesonic (**MWD**)
  ➡ Non Mesonic (**NMWD**)



Mesonic channels

Channels	^{3}He+π^- ^{3}H+π^0	d+p+π^- d+n+π^0	n+p+p+π^- n+n+p+π^0
Branching Ratio [3]	37,3%	60,1%	0,94%

Study of the production in the accessible decay channels (charged products only)

➡ 2-body (B.R. ≅ 25%)

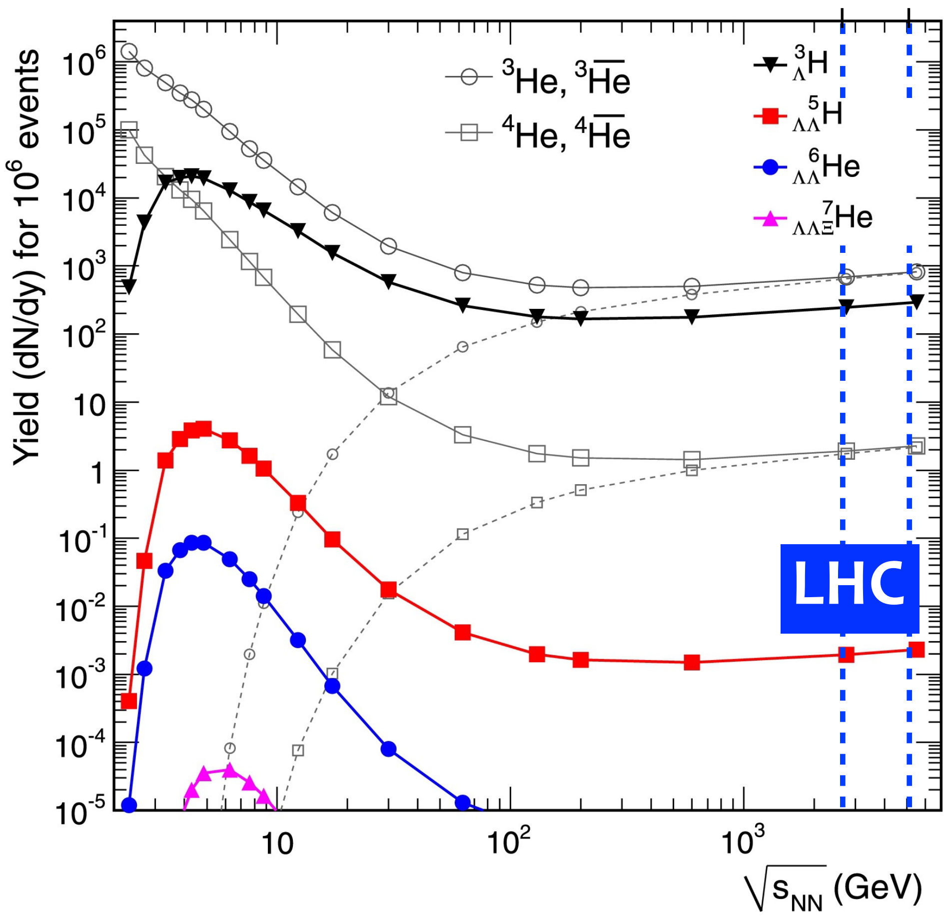
➡ 3-body (B.R. ≅ 41%)

[1] D.H. Davis., Nucl. Phys. A 754 (2005) 3-13

[2] C. Rappold et al., Phys. Lett. B 728, 543 (2014)

[3] H. Kamada et al., Phys. Rev. C 57 (1998) 1595-1603

How (hyper-)nuclei can be produced?



Thermal model

- Hadrons emitted from the interaction region in statistical equilibrium once the *chemical freeze-out* temperature is reached
- Key parameter is *chemical freeze-out* temperature T_{chem}
- Abundance of a species $\propto \exp(-m/T_{chem})$

➡ For hypernuclei (large *m*) strong dependence on T_{chem}

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stoecker. Phys. Lett. B 697, 203 (2011)

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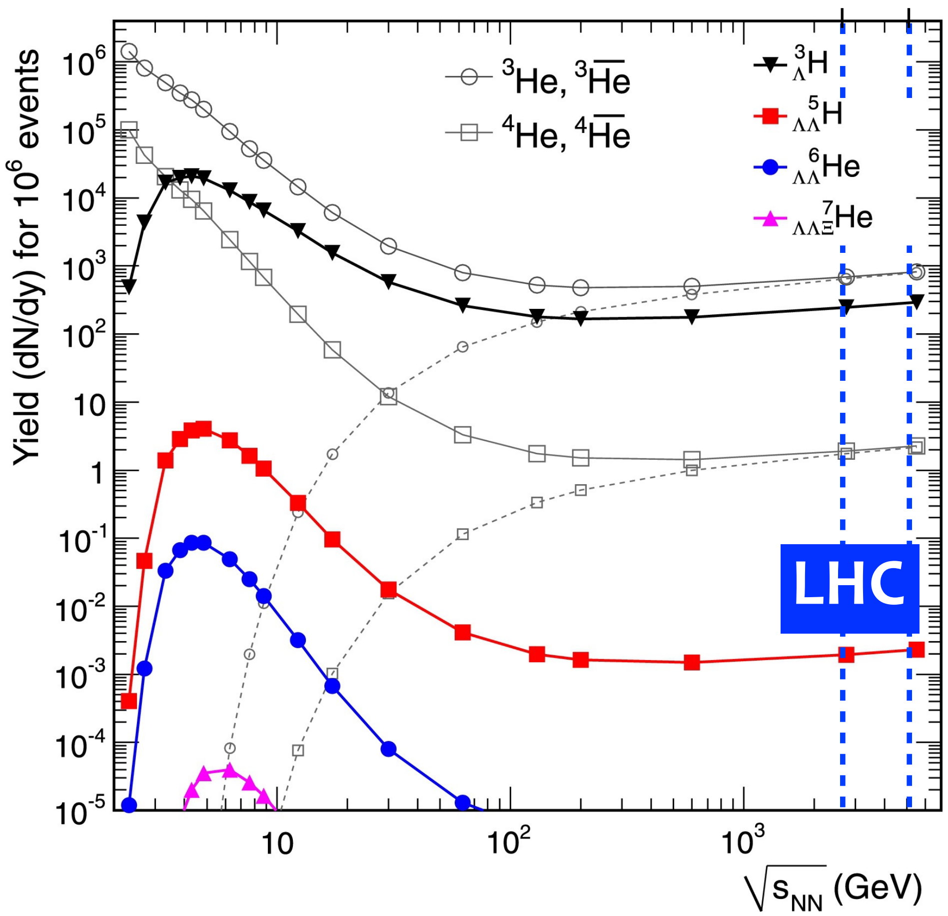

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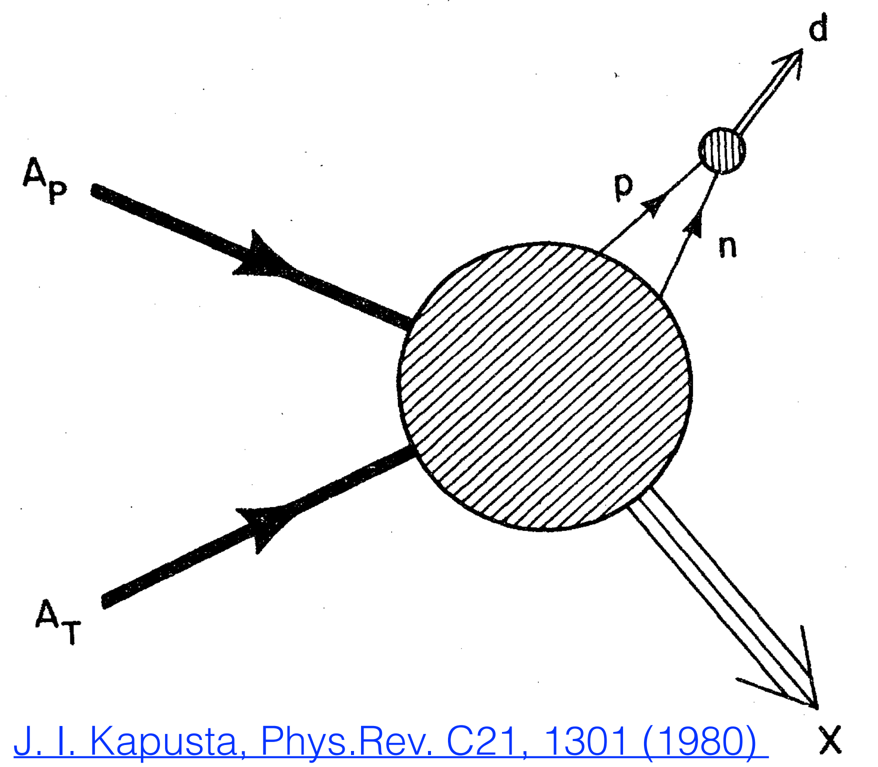
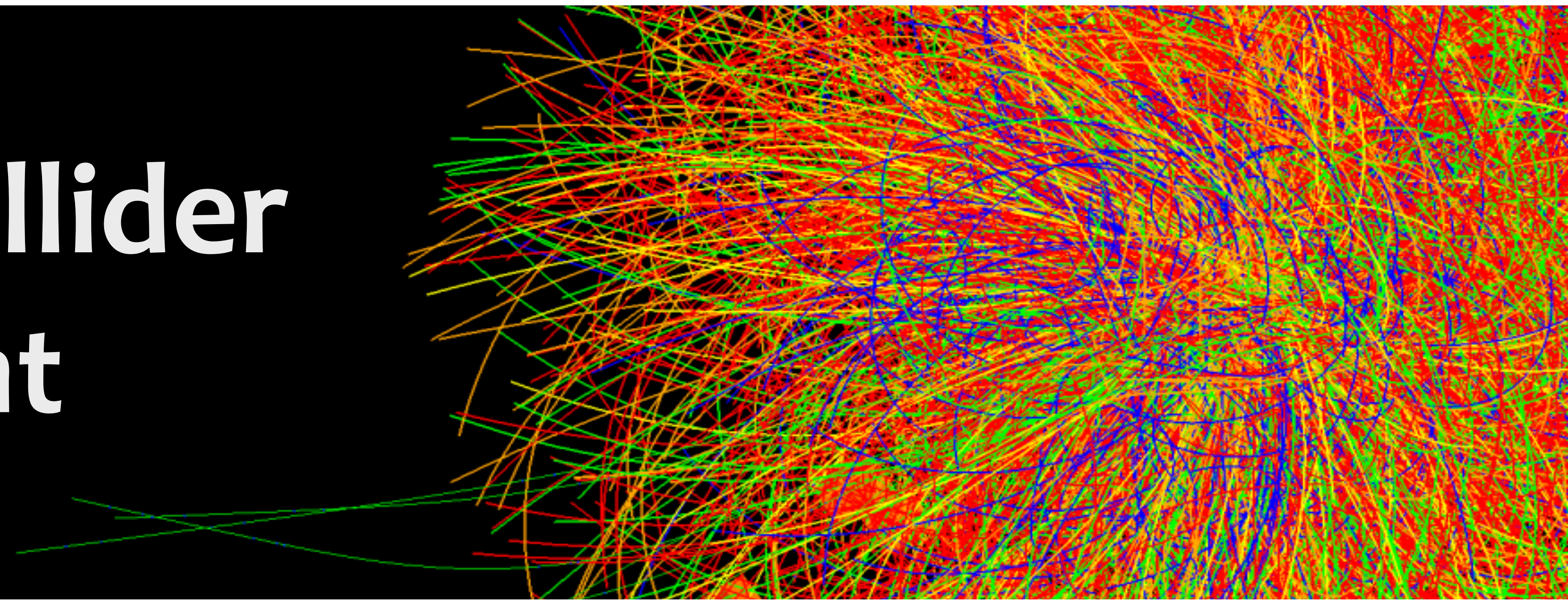
Coalescence model

- (Anti-)baryons close in phase space at the *kinetic freeze-out* can form a (anti-)(hyper-)nucleus
- (Anti-)(hyper-)nuclei formed at the *chemical freeze-out*:
  - might break up
  - regenerate in the time interval between *chemical* and *kinetic freeze-out*



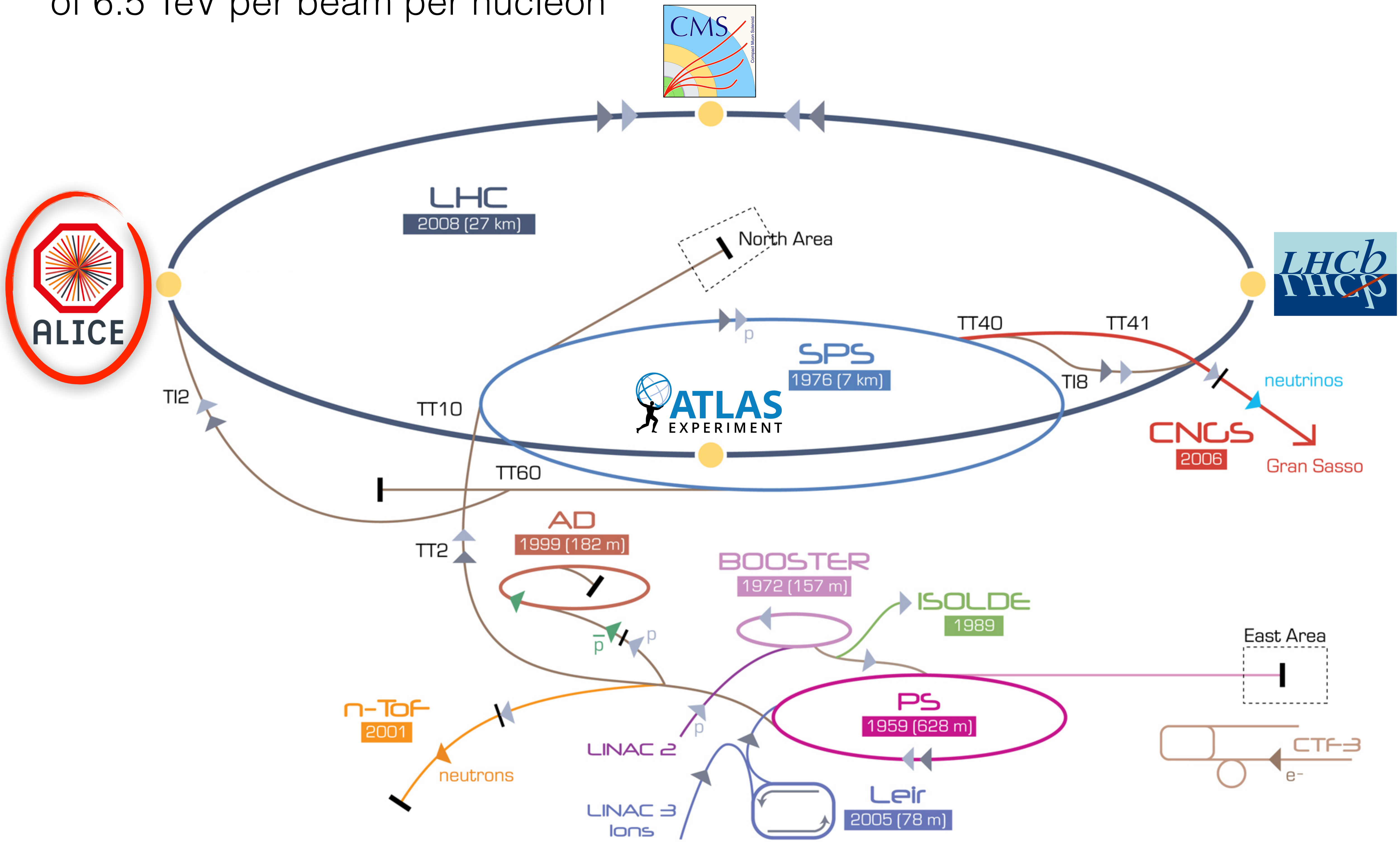
J. I. Kapusta, Phys.Rev. C21, 1301 (1980)
J. Steinheimer et al. Phys. Lett. B 714, 85-91 (2012)

A Large Ion Collider Experiment



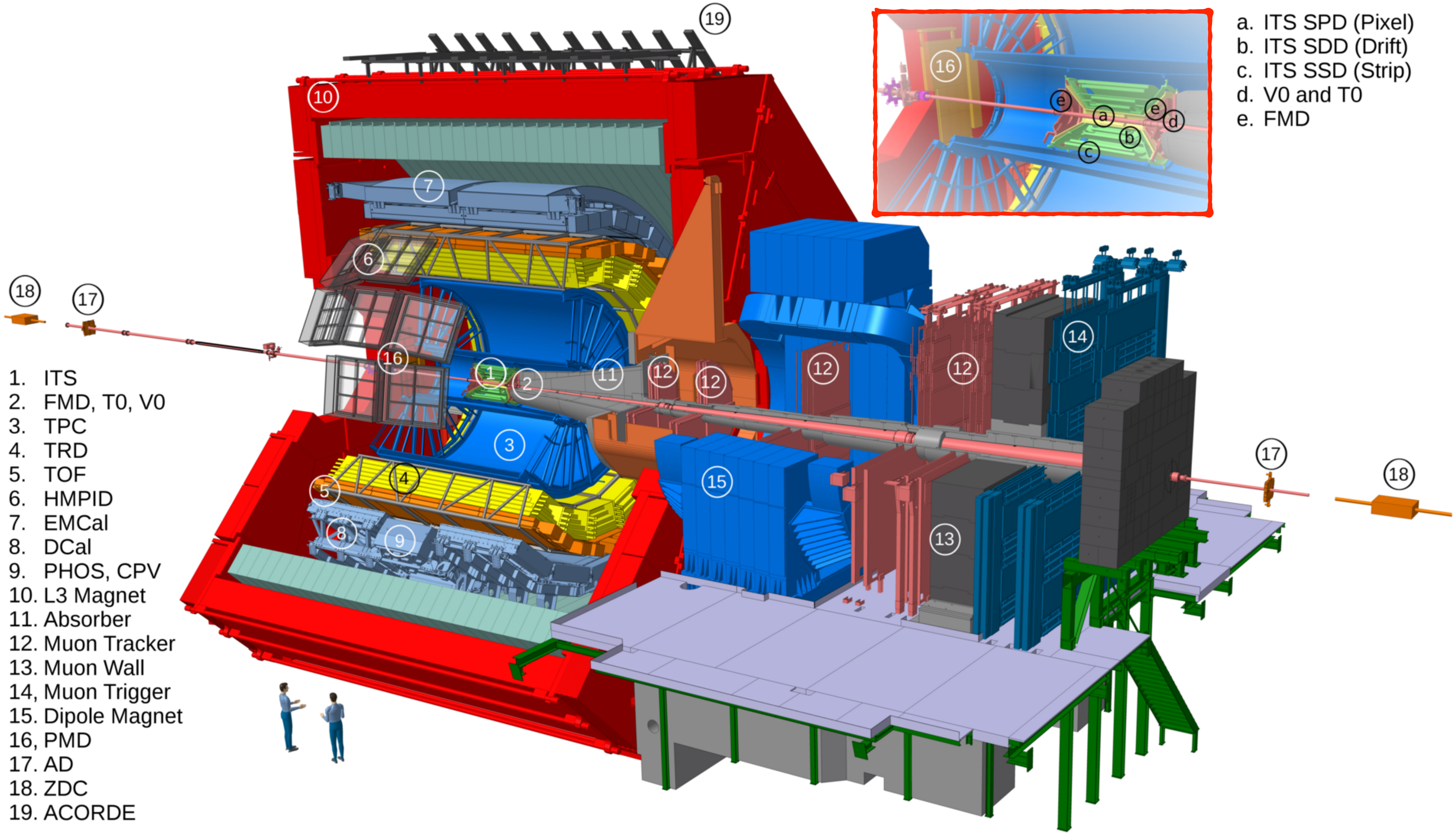
Large Hadron Collider

- In the **LHC** particle beams (protons and Pb ions) are accelerated up to the energy of 6.5 TeV per beam per nucleon



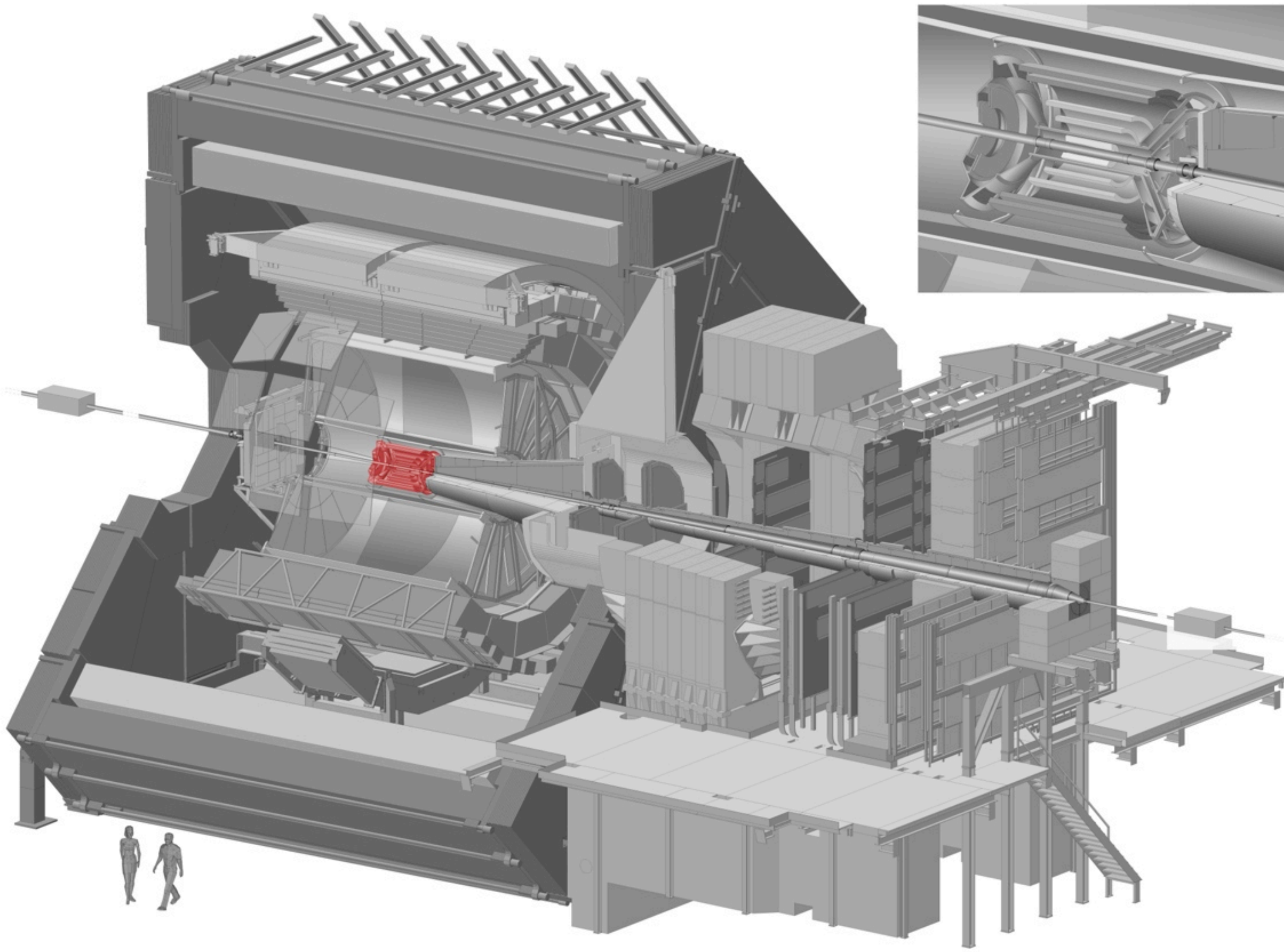
https://cds.cern.ch/record/1997193 CERN acceleration chain

A Large Ion Collider Experiment



- General purpose heavy ion apparatus
- Excellent particle identification (PID) capabilities (σ ~ 5-7%) and low material budget (~ 7.26% X/X_0)
- Most suited detector at the LHC to study the (anti-)(hyper-)nuclei production in the collisions

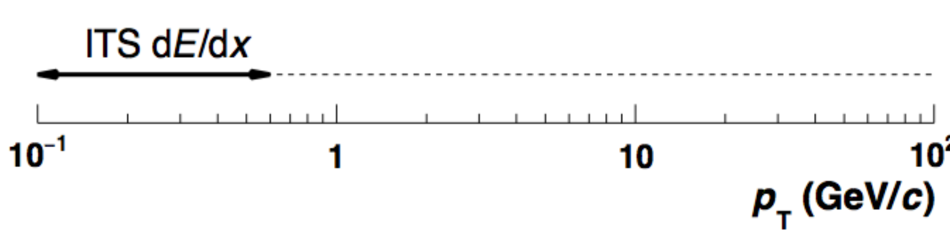
A Large Ion Collider Experiment

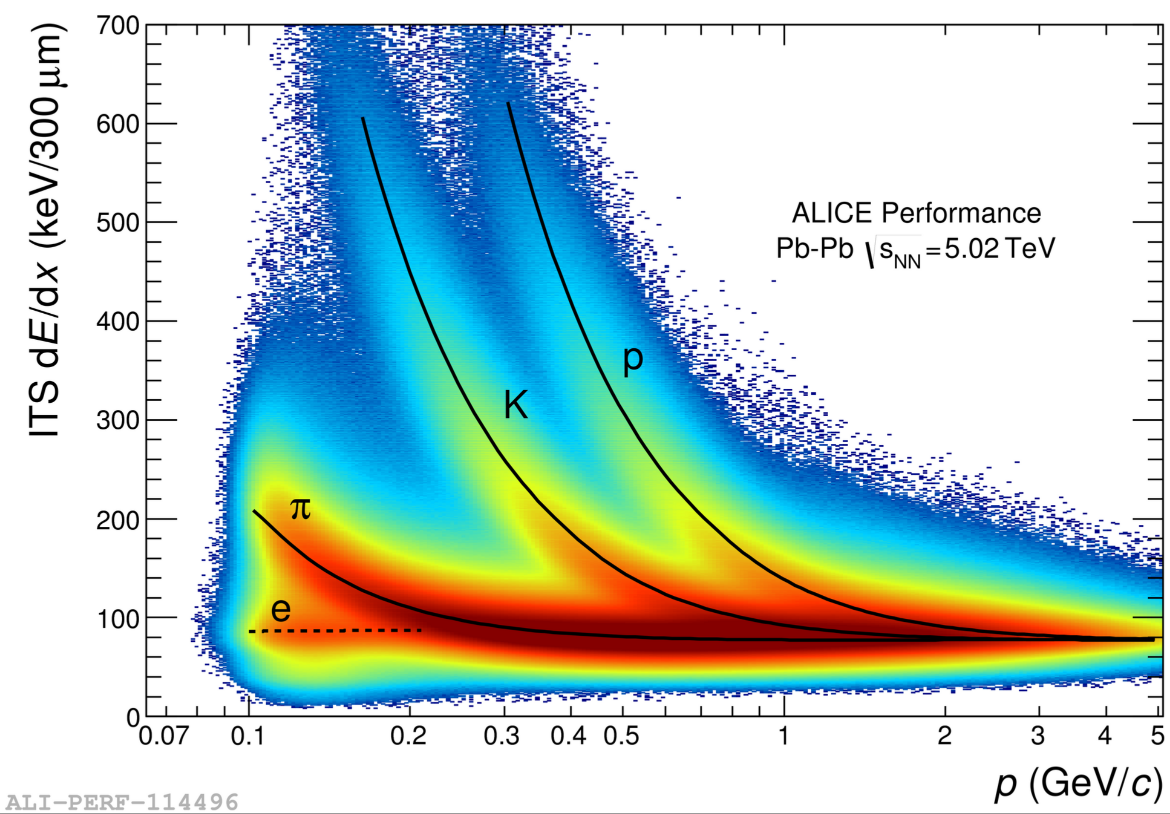


Inner **T**racking **S**ystem

- 6 Layers of silicon detectors
  - Pixel, Drift and Strip detectors
  - r_{min} = 3.9 cm, r_{max} = 43 cm
  - $|\eta| < 0.9$
- Main purposes:
  - Trigger, vertexing and tracking
  - PID via d*E*/d*x*

More details on ITS:
ALICE Collaboration, JINST 5 (2010) P03003





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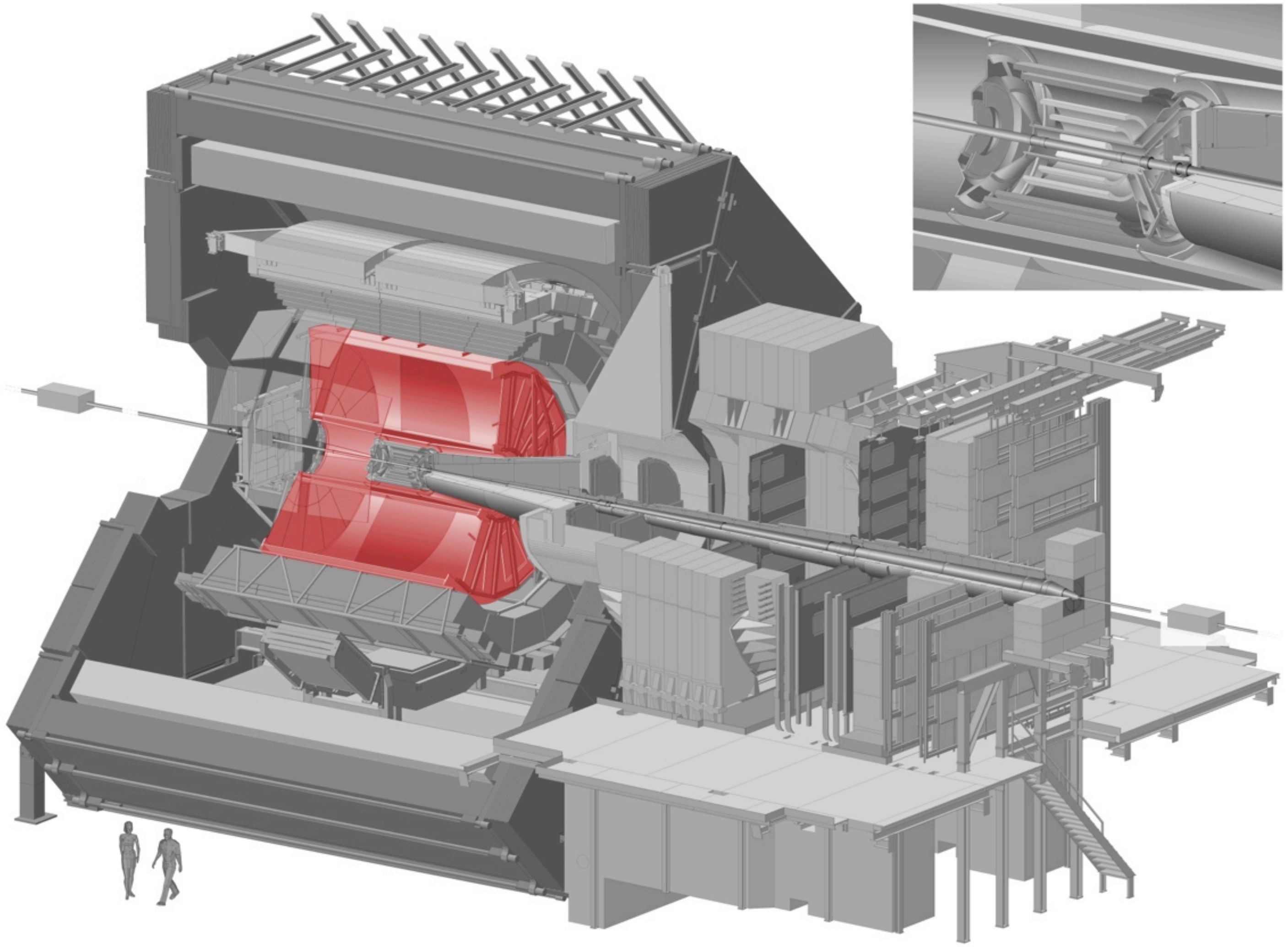
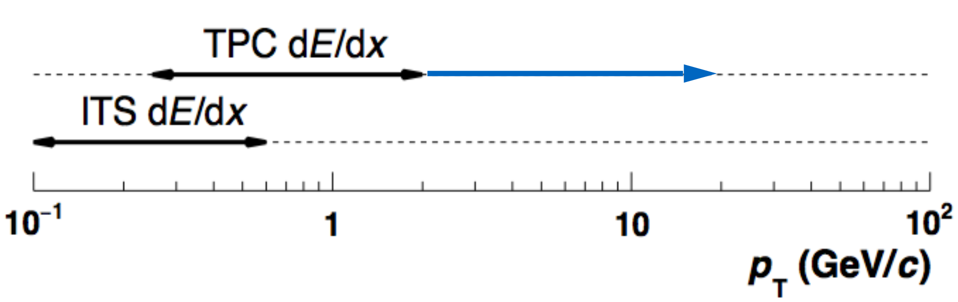


Time Projection Chamber

- Gas-filled ionization detection volume
  - 90 m^3 of Ne-CO_2 or Ar-CO_2
  - r_{min} = 85 cm, r_{max} = 247 cm
  - $|\eta| < 0.9$
- Main purposes:
  - Tracking and vertexing
  - Weak decay reconstruction (e.g. Λ)
  - PID via d*E*/d*x*

More details on TPC:
J. Alme et al., Nucl. Instrum. Methods A 622 (2010) 316-367



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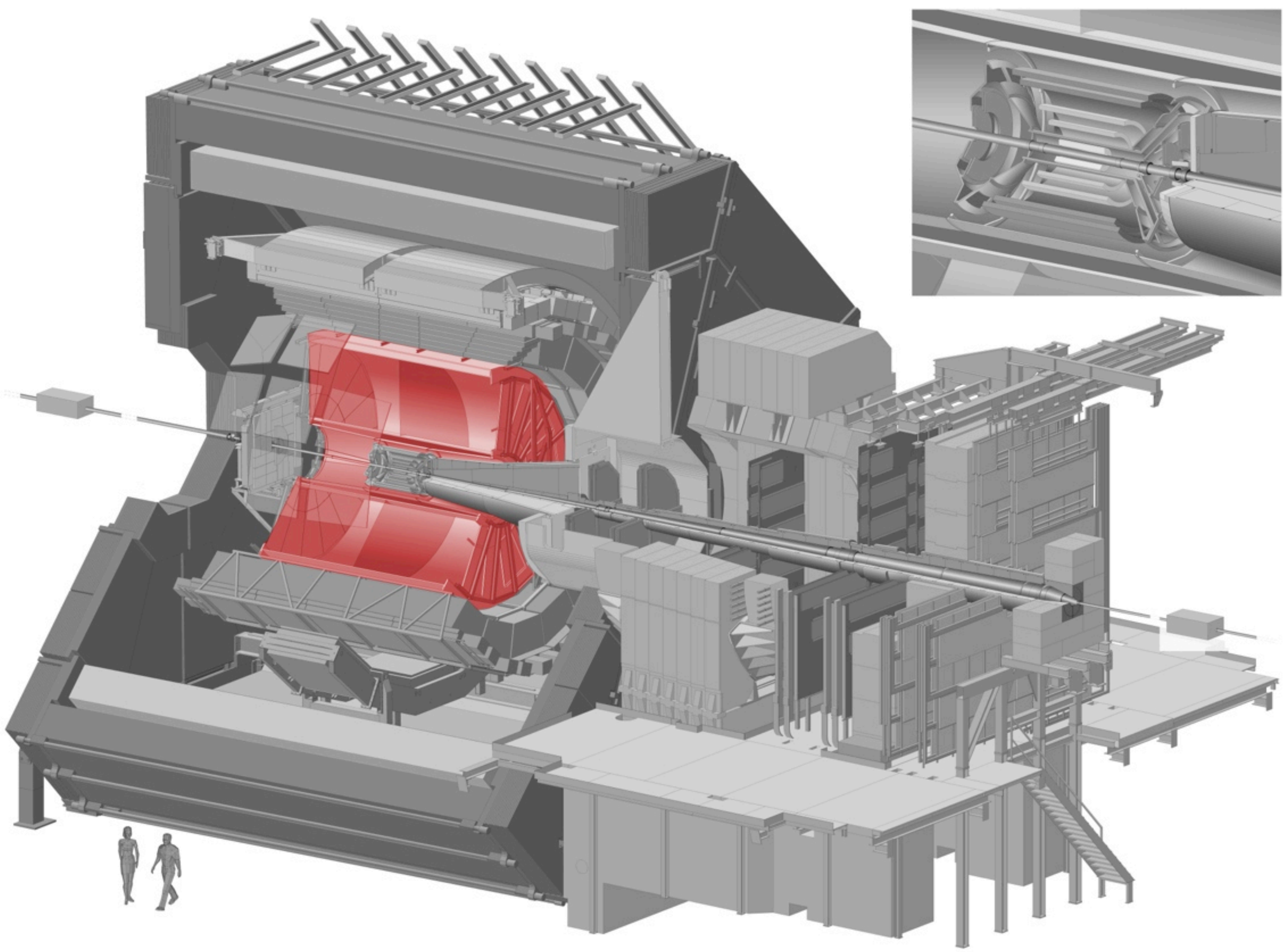
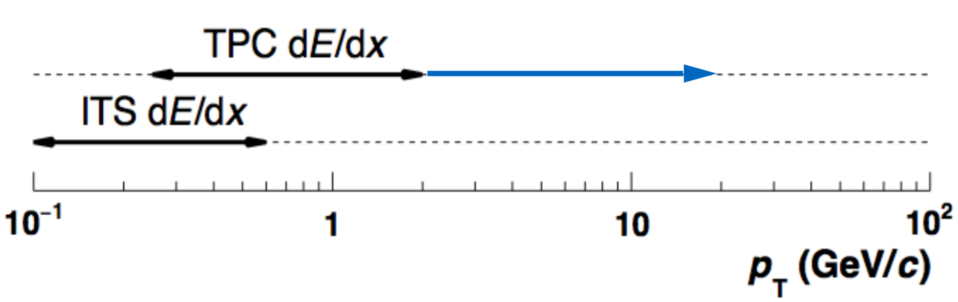


More details on TPC:
[J. Alme et al., Nucl. Instrum. Methods A 622 (2010) 316-367]



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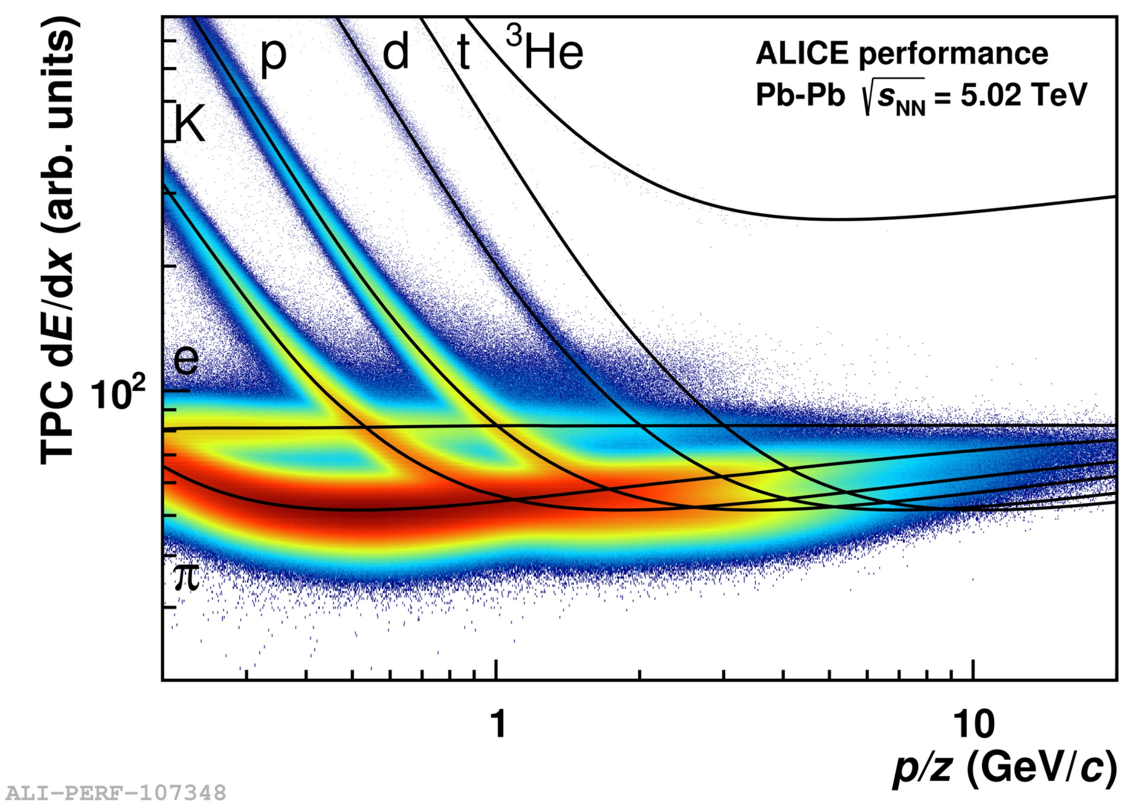

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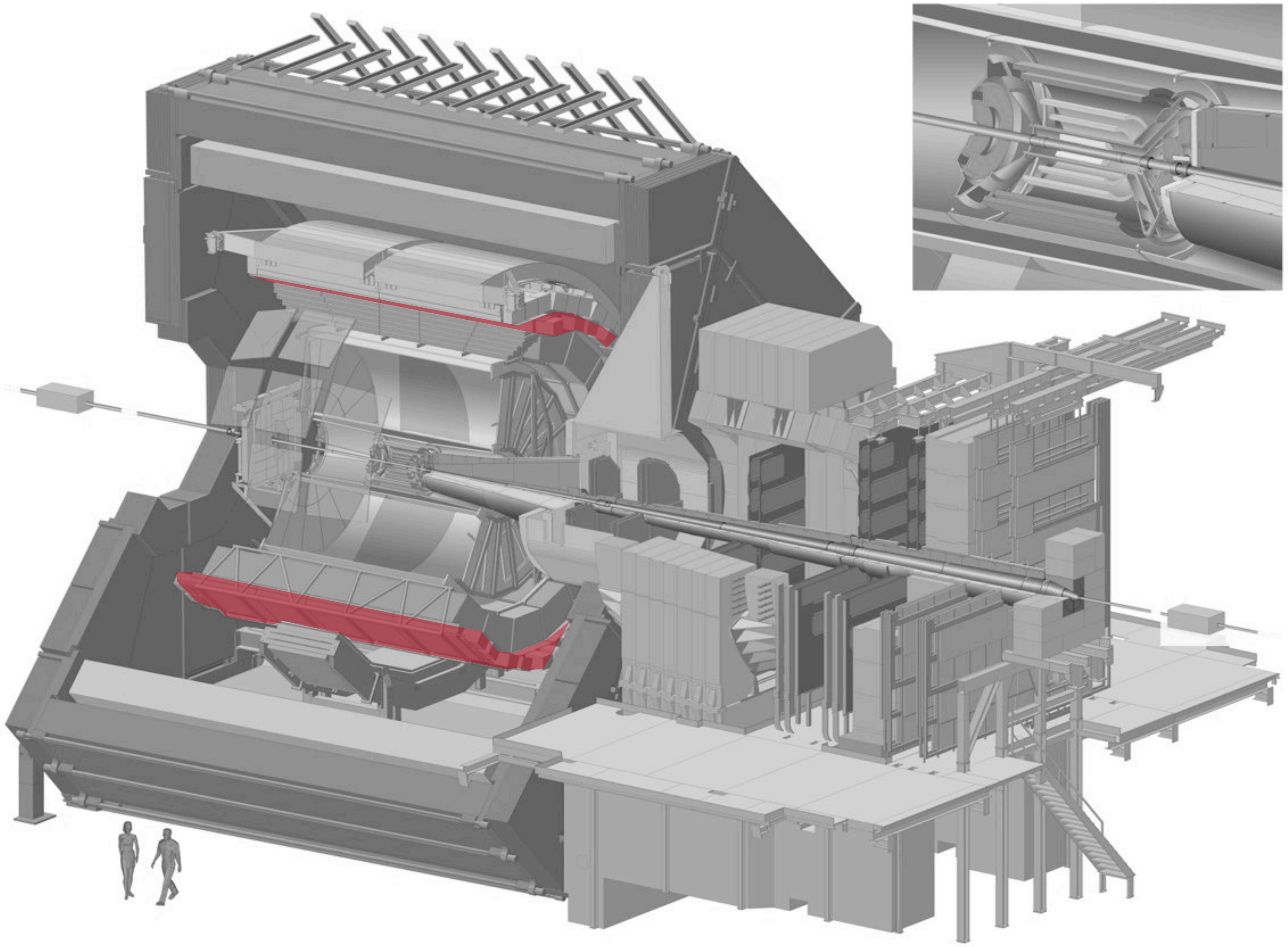
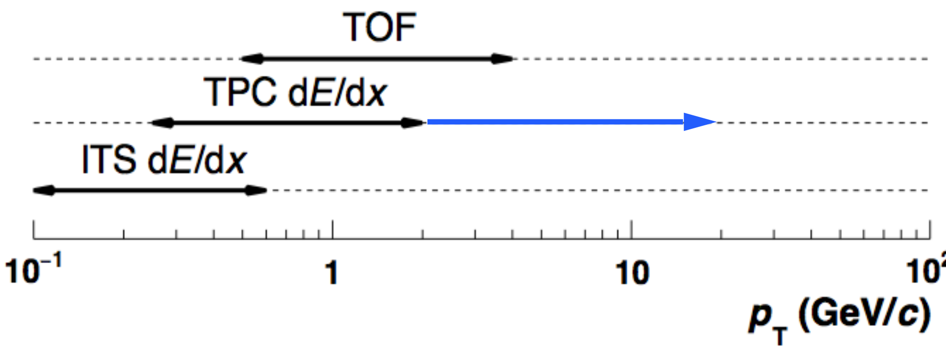
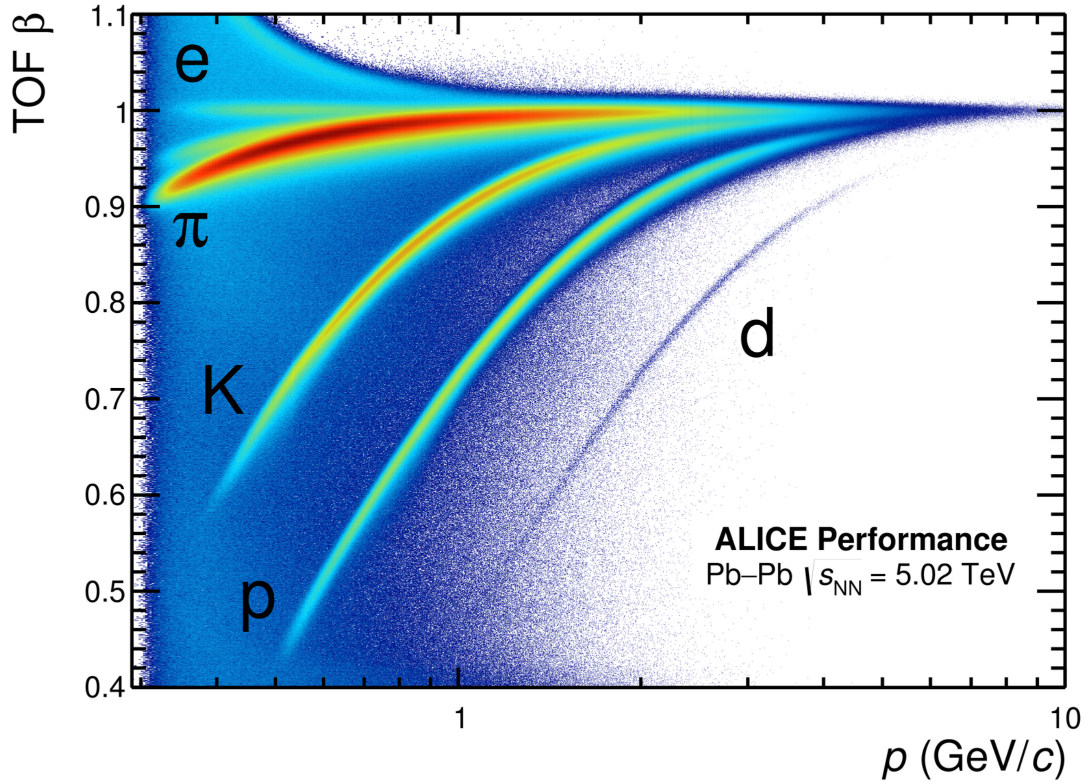


More details on TOF:
[ALICE Collaboration, JINST 3 (2008) S08002]



Time-Of-Flight

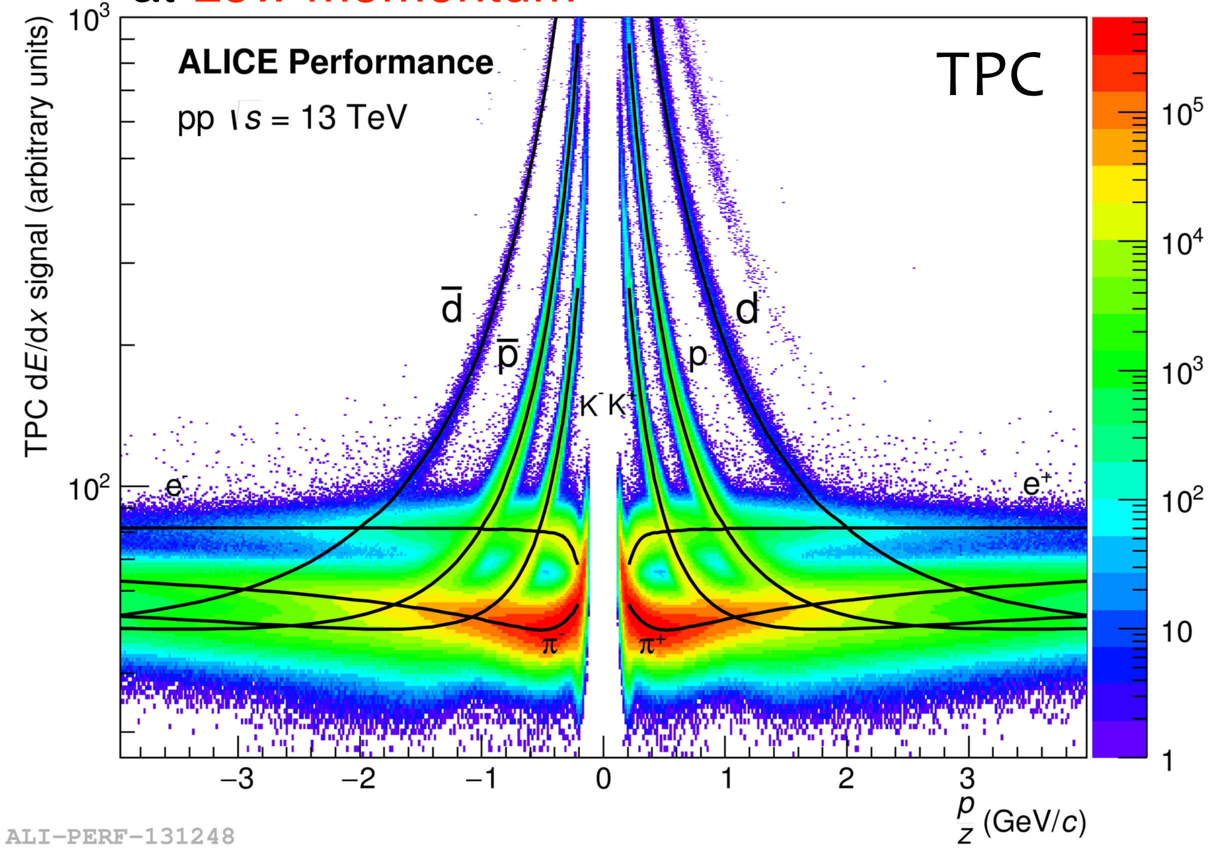
- Multi-gap resistive plate chambers
  - r_{min} = 370 cm, r_{max} = 399 cm
  - $|\eta| < 0.9$
- PID in the intermediate momentum range:
  - via velocity determination
  - time resolution σ_{TOF} ~ 80 ps

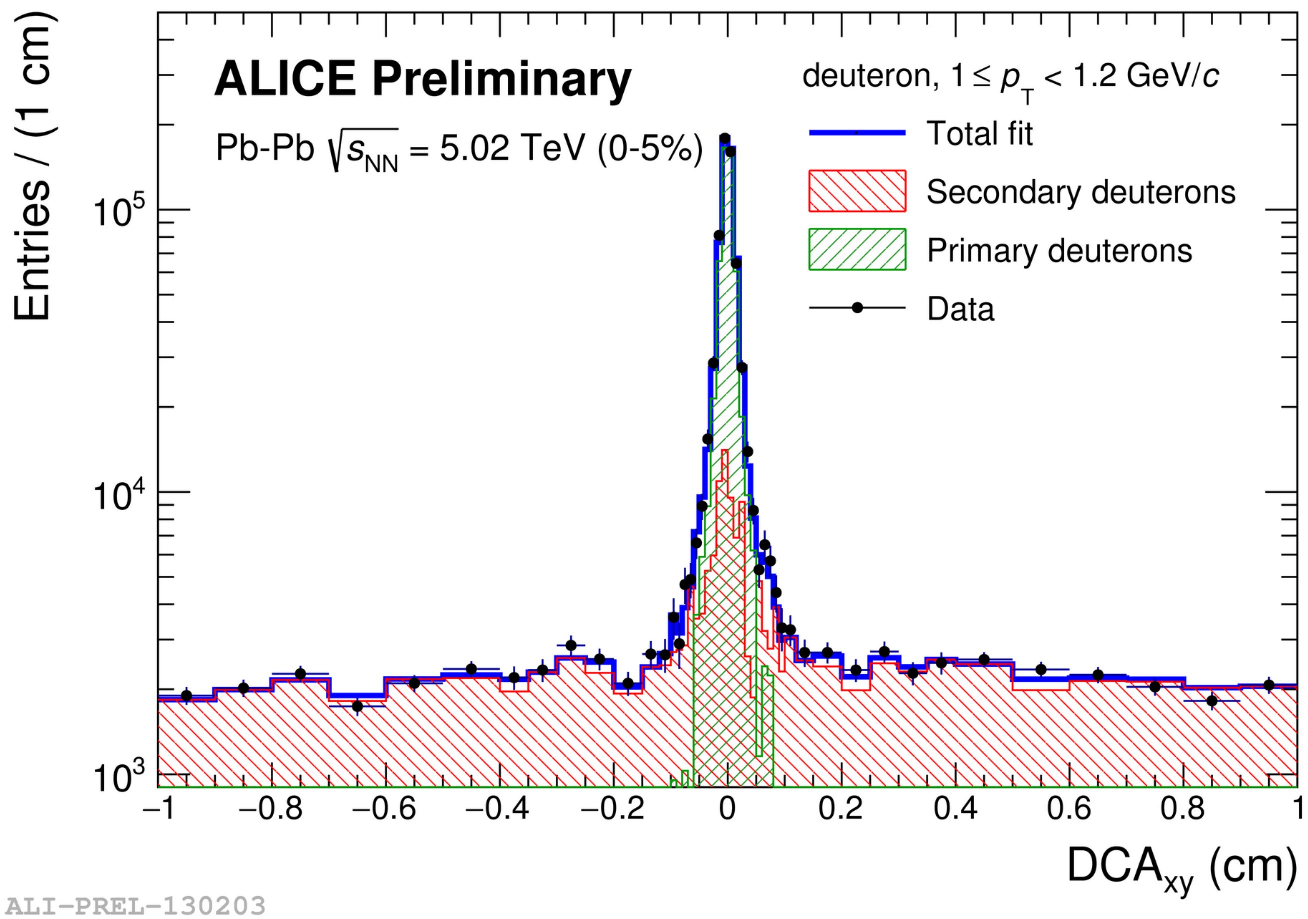


Nuclei identification

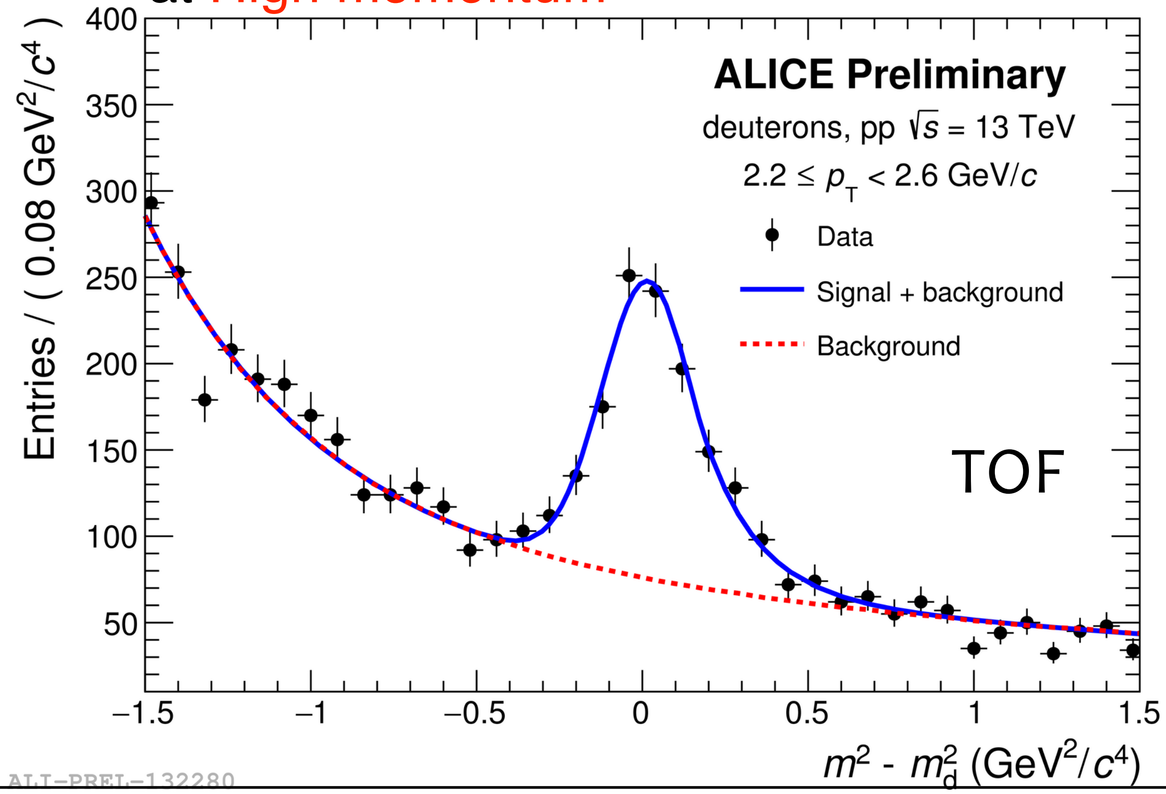
- Nuclei production studies performed via:
  - Particle IDentification (TPC, TOF)
  - Topological selection
- Distance-of-Closest-Approach (DCA) distributions used to separate primary particles from secondary particles (e.g. knock-out from material)

at Low momentum





at High momentum



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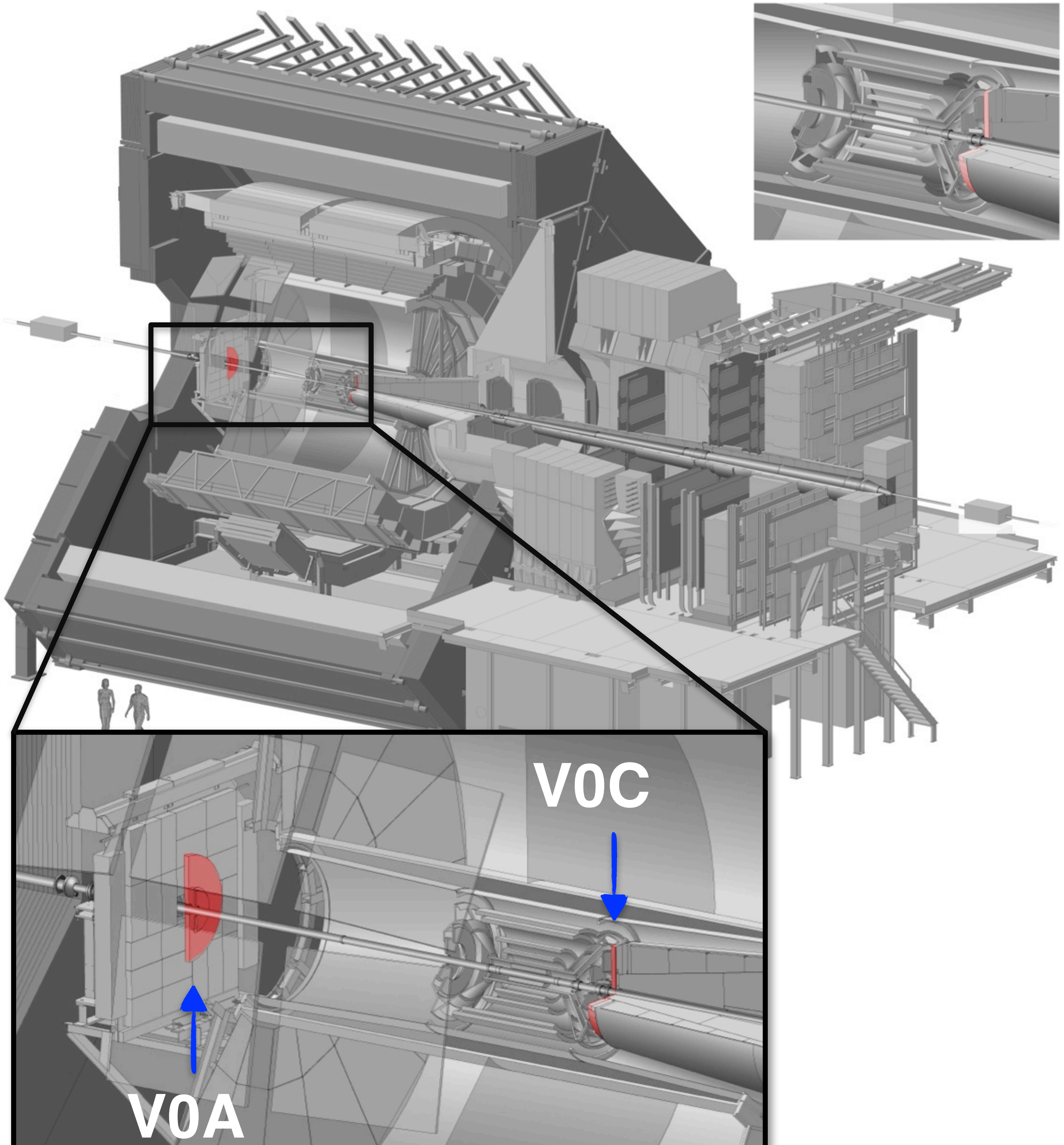
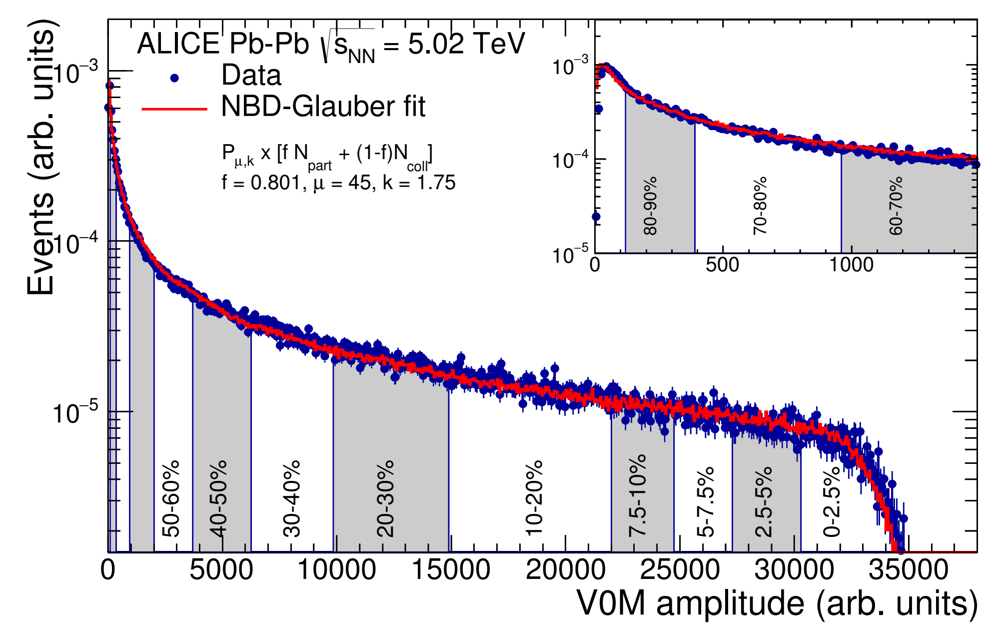


More details on V0:
[ALICE Collaboration, JINST 8 (2013) P10016](#)

V-ZERO

- Two arrays of scintillator detectors
  - V0A ($2.8 < \eta < 5.1$) and V0C ($-3.7 < \eta < -1.7$)
- Main purposes:
  - trigger, beam-gas rejection
  - centrality and multiplicity estimator
- Event selection based on total charge deposited in the **V0A** and **V0C** detectors ("V0M")



Centrality of a collision

Theory

The centrality of the collision is defined by the absolute value of the impact parameter vector ***b***

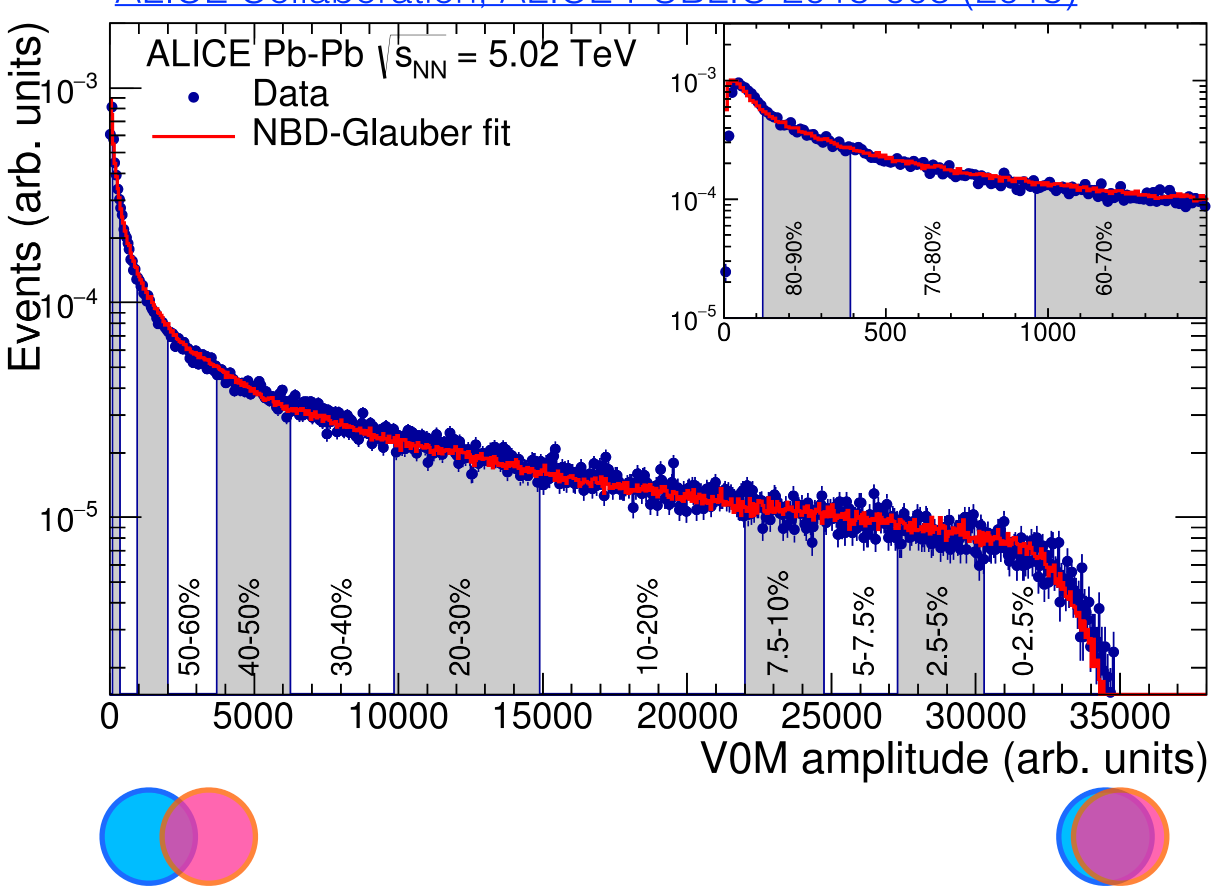
Most central collision ⟺ Smallest *b*

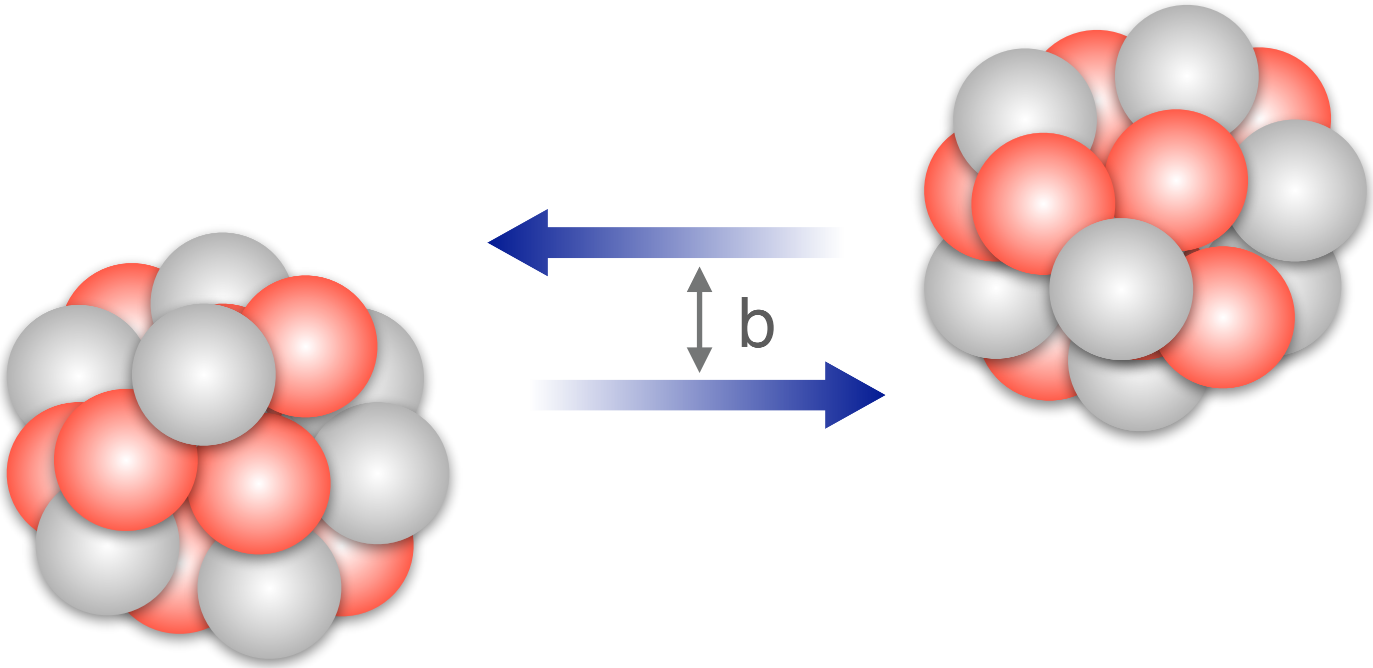
Experimentally

It is possible to correlate the charged particle multiplicity to an impact parameter value by fitting data with predictions from Glauber model

- centrality class defined as percentile of the total cross-section

[ALICE Collaboration, ALICE-PUBLIC-2015-008 (2015)]





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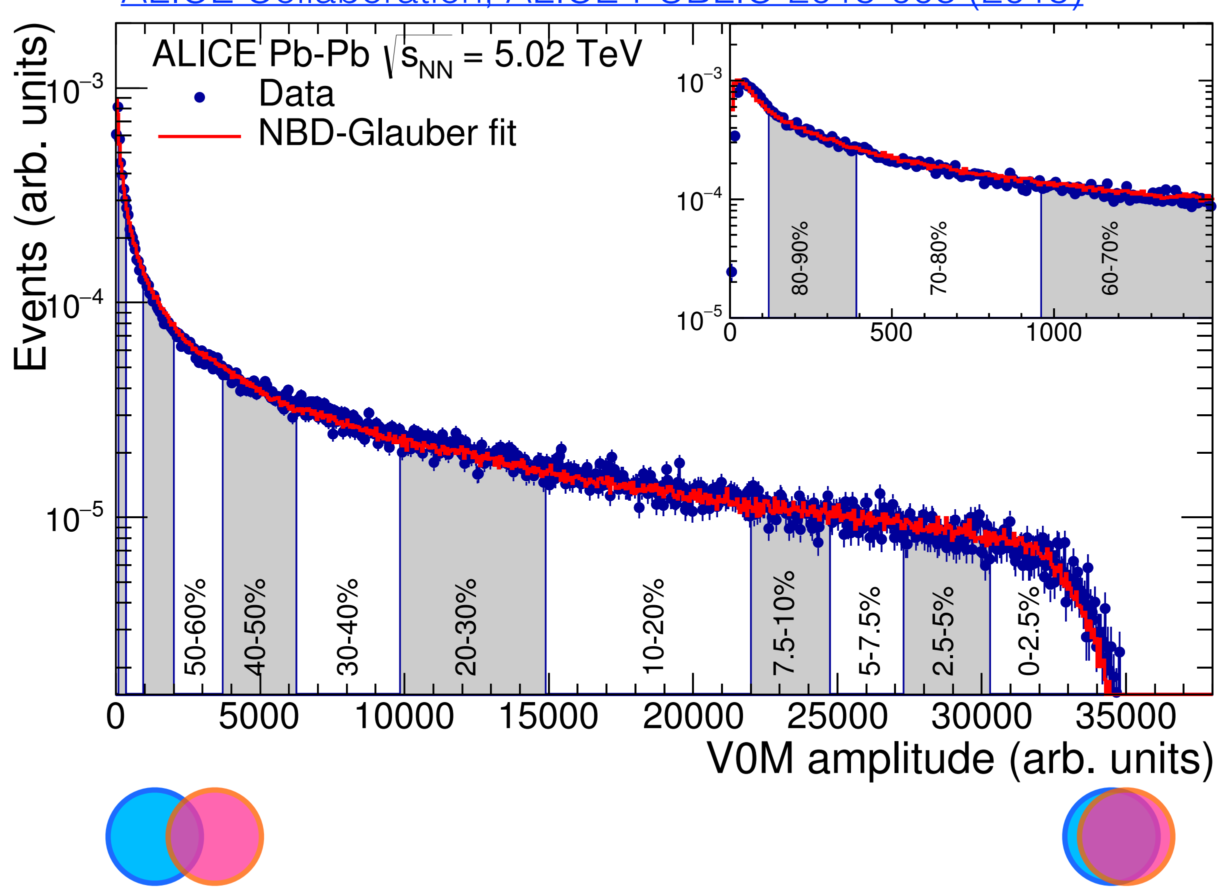
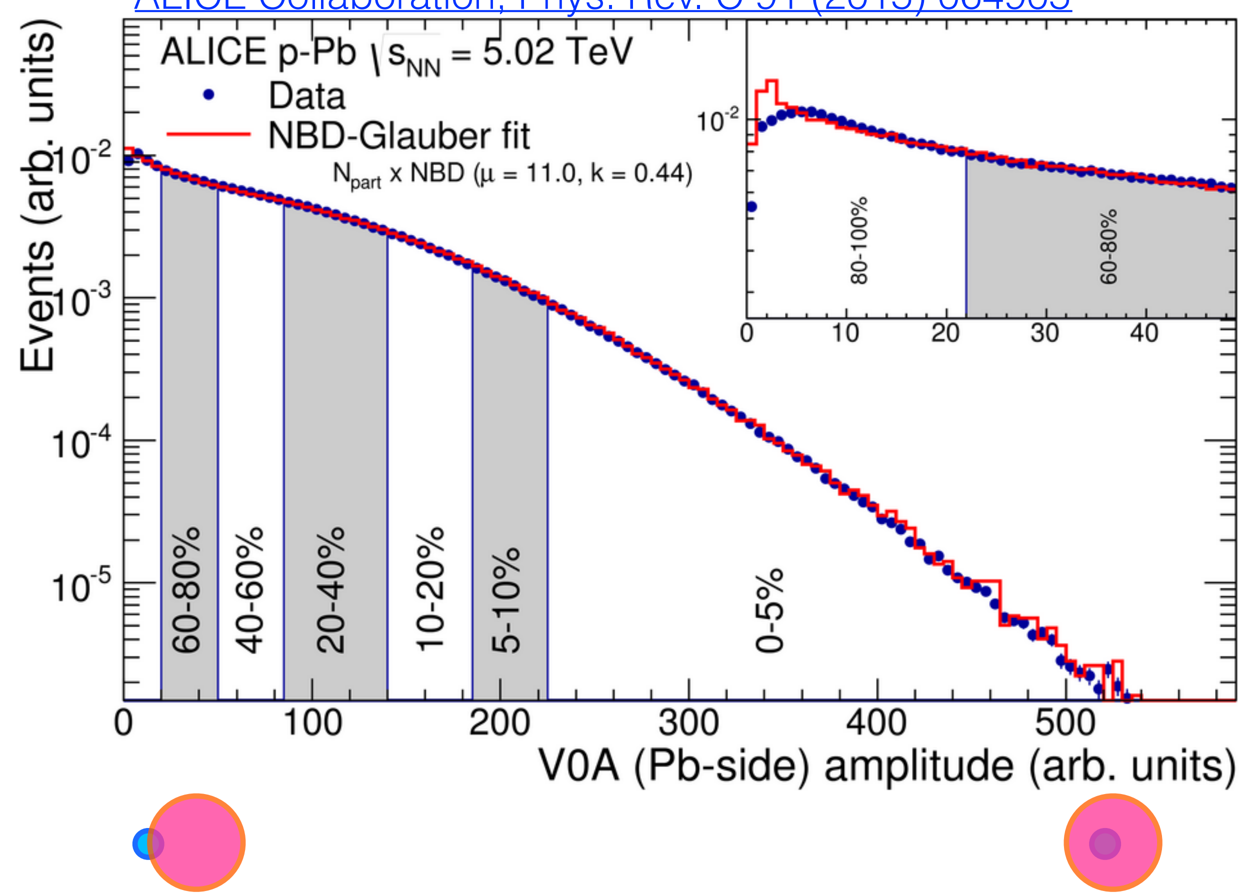
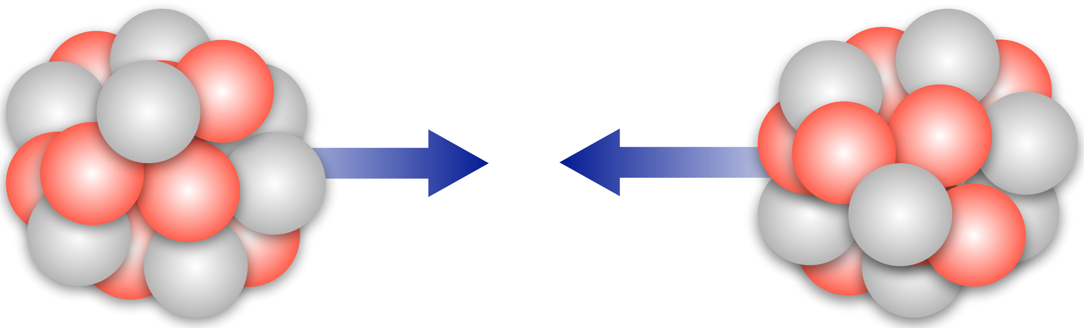


ALICE Collaboration, Phys. Rev. C 91 (2015) 064905



Collision systems at the LHC

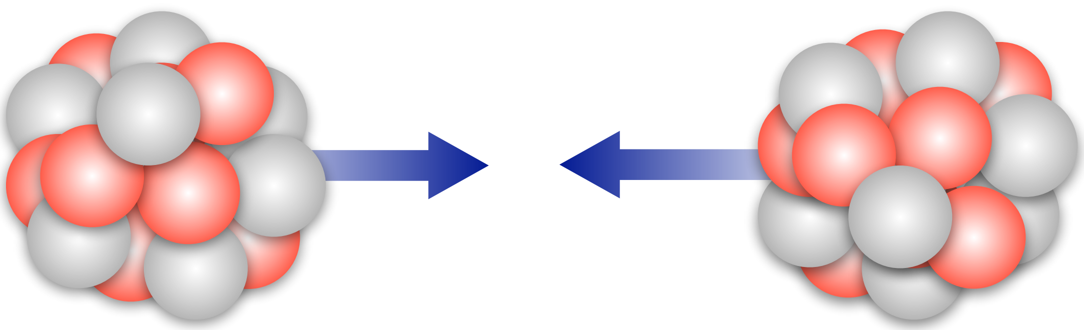


	$\sqrt{s_{NN}}$
Pb-Pb	2.76 TeV
	5.02 TeV
Xe-Xe	5.44 TeV

Study of the hot and dense matter

Study of these three collision systems is fundamental to improve our knowledge of hadronisation and strong interaction at extreme regimes of energy density

Collision systems at the LHC



Pb-Pb

Xe-Xe

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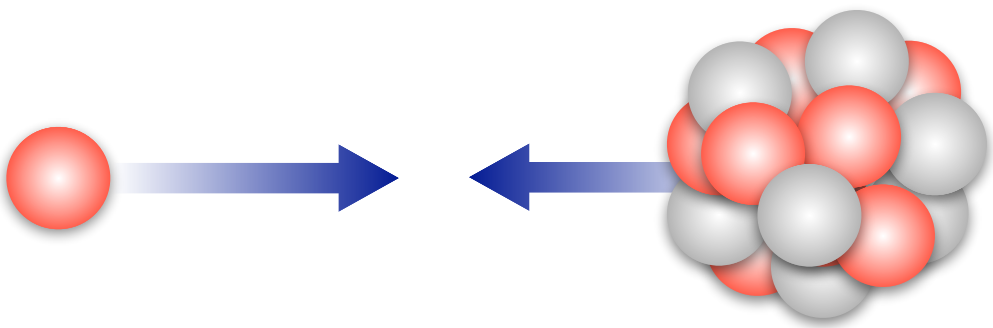


p-Pb

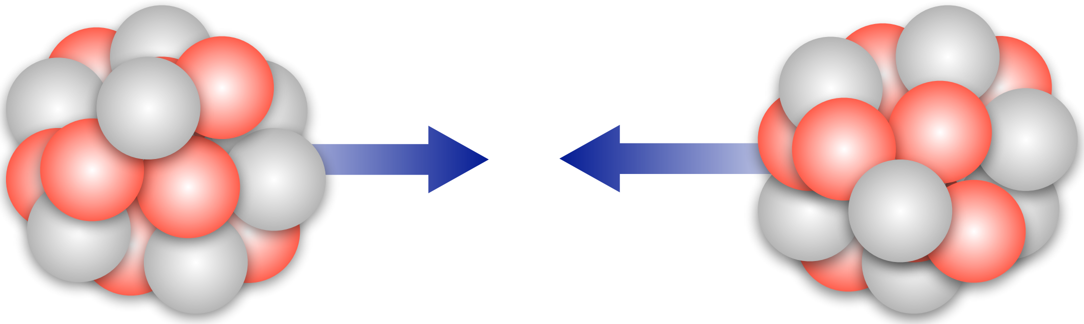
Pb-p

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

Study of nuclear matter effects

Study of these three collision systems is fundamental to improve our knowledge of hadronisation and strong interaction at extreme regimes of energy density

Collision systems at the LHC

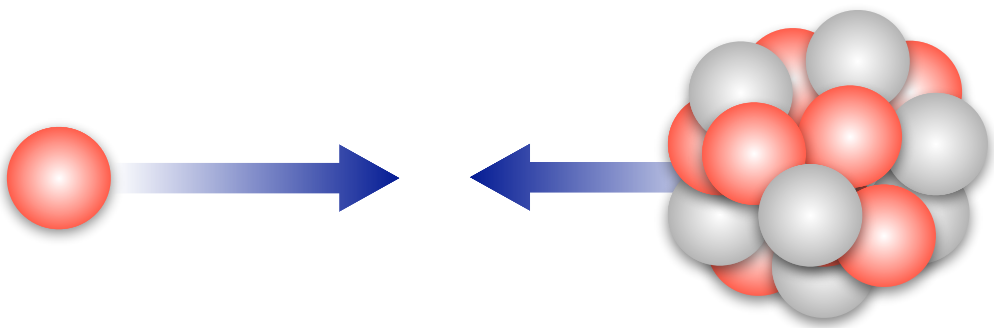


Pb-Pb

Xe-Xe

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

Study of the hot and dense matter



p-Pb

Pb-p

$\sqrt{s_{NN}}$
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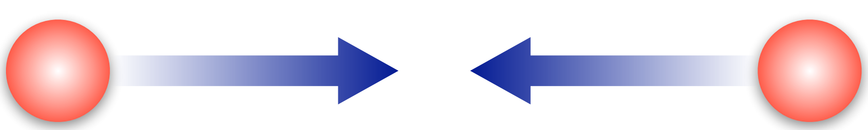
Study of nuclear matter effects



p-p

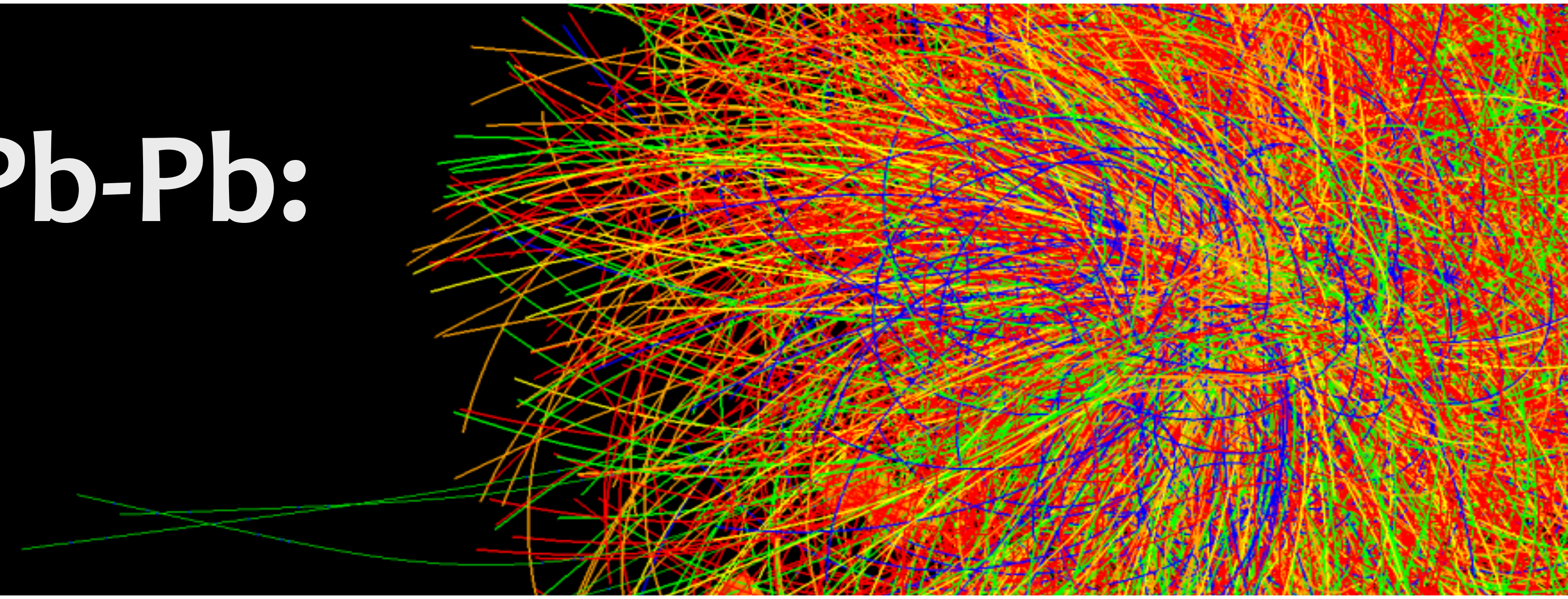
$\sqrt{s_{NN}}$
0.9 TeV
2.76 TeV
5 TeV
7 TeV
13 TeV

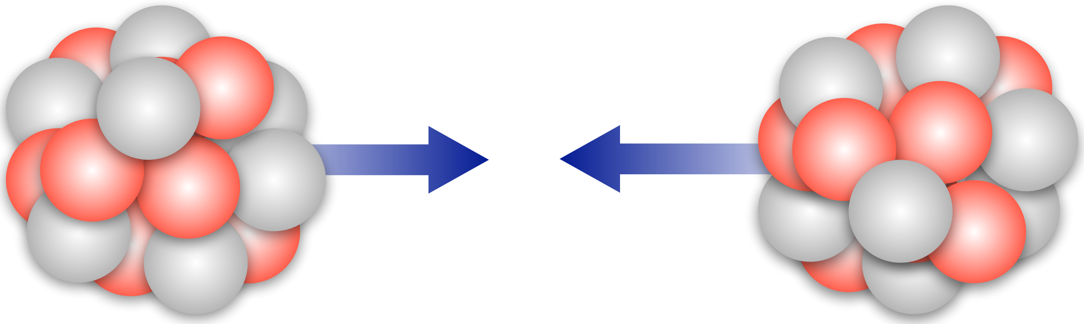
Reference for measurements in other systems

Study of these three collision systems is fundamental to improve our knowledge of hadronisation and strong interaction at extreme regimes of energy density

Production in Pb-Pb:

Nuclei

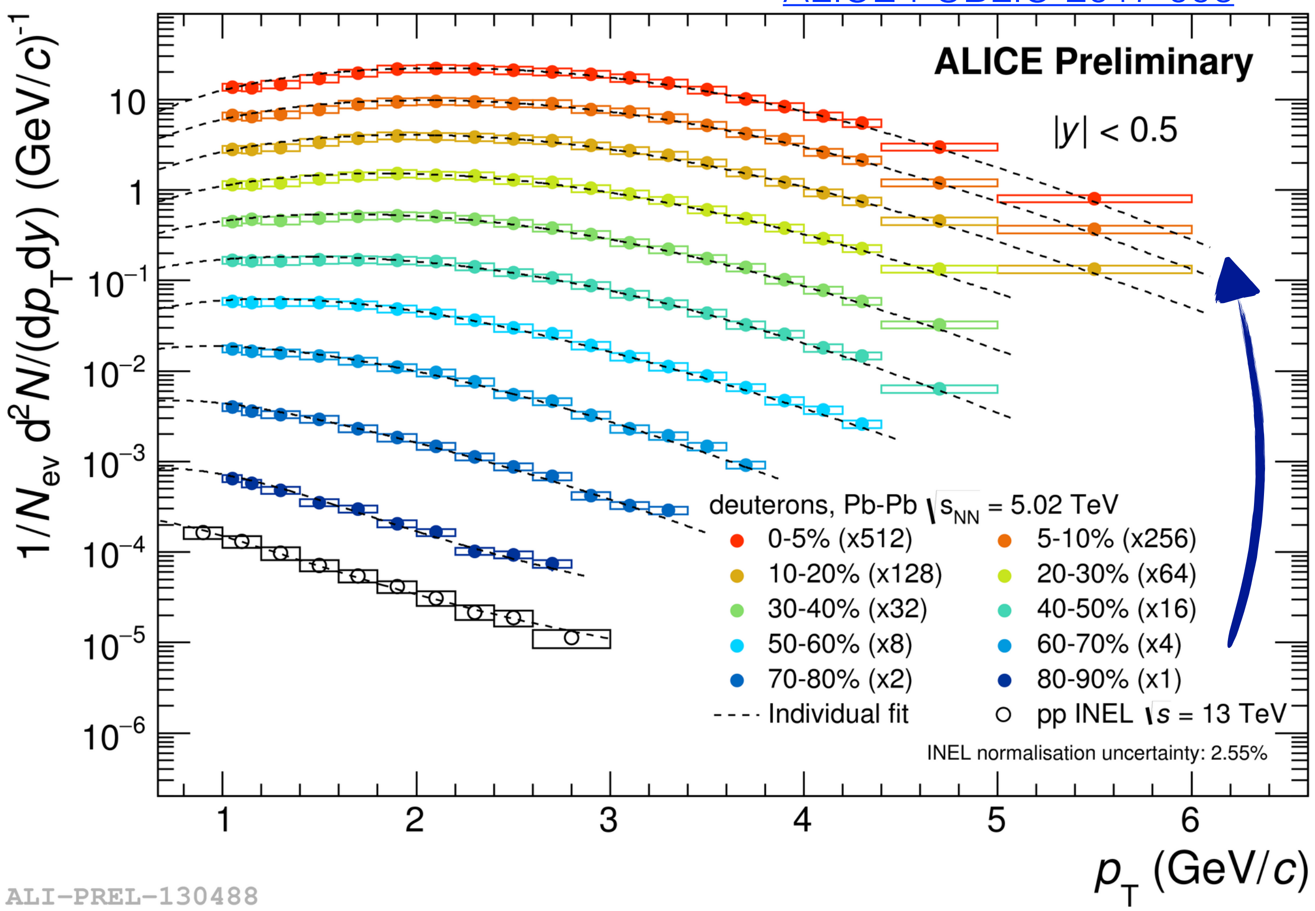


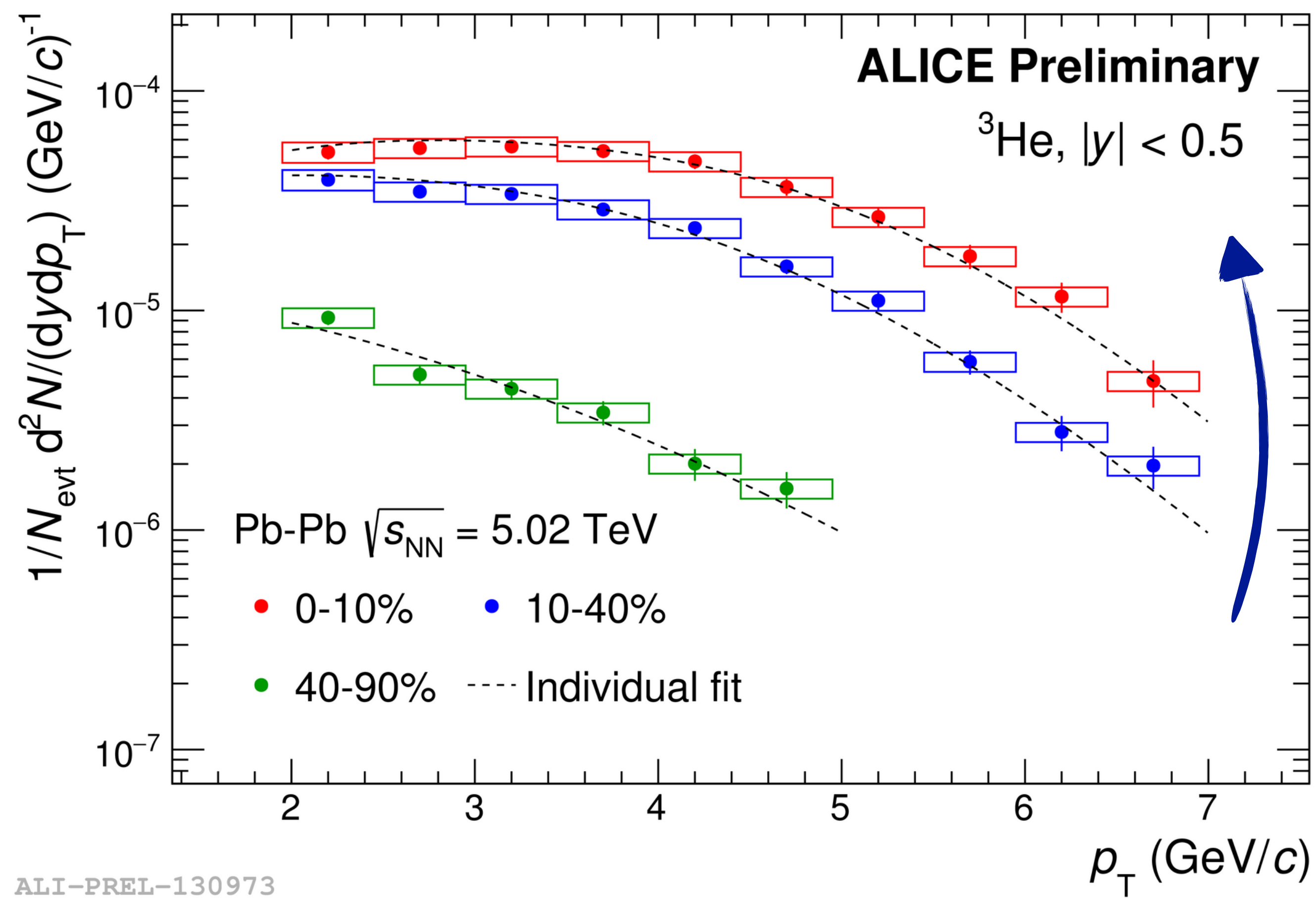


Deuteron and ³He spectra

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

ALICE-PUBLIC-2017-006





- deuteron and ³He spectra measured as a function of centrality classes
- Pronounced hardening of deuteron and ³He p_T spectra with increasing centrality → radial flow
- p_T spectra are fitted with the Blast-Wave [4] function → yield extrapolation to unmeasured regions

[4] E. Schnedermann et al. Phys. Rev. C 48, 2462 (1993)

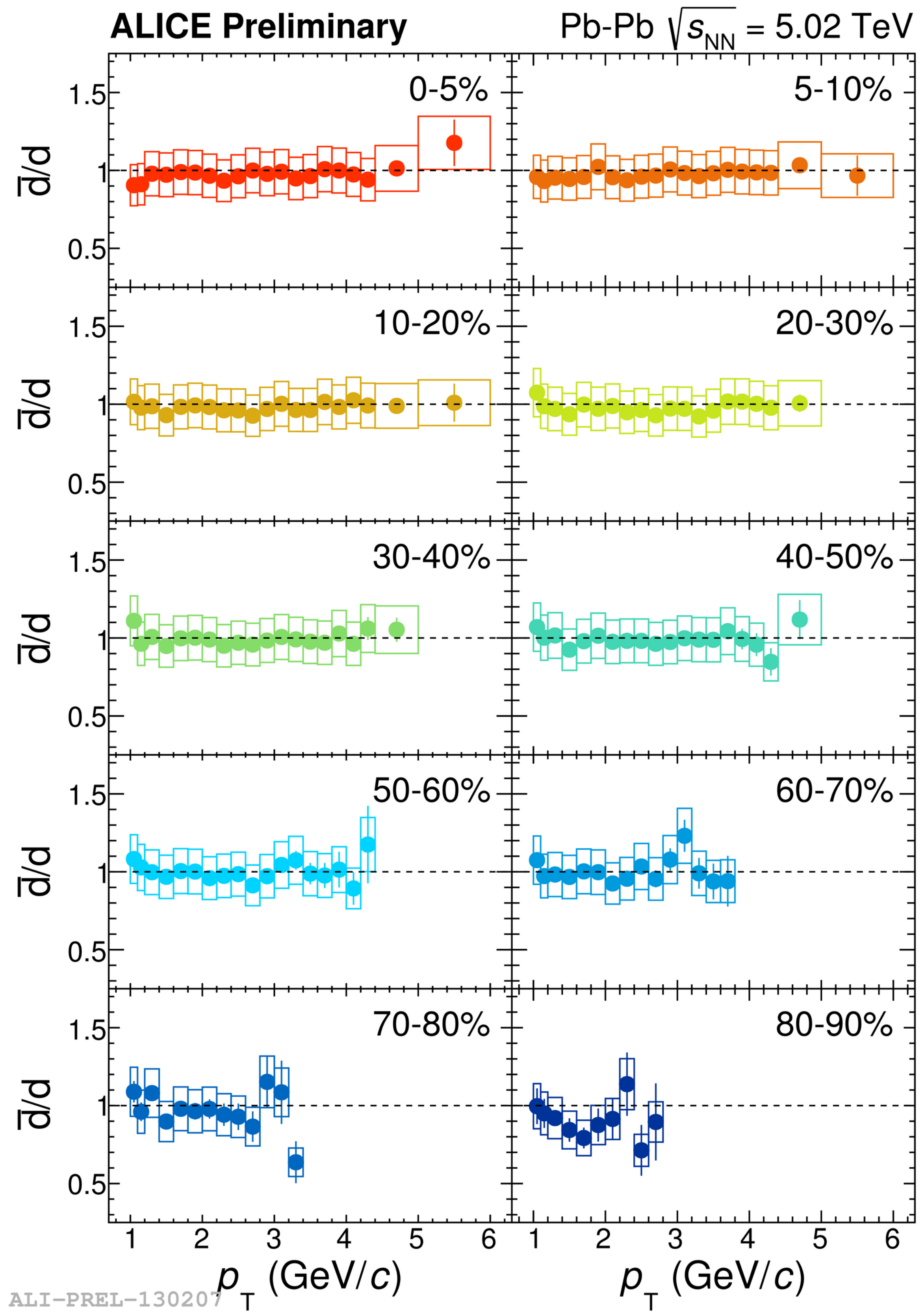
Anti-nuclei/nuclei ratio

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

- At the LHC energies the antiproton/proton ratio [5] is compatible with the unity:
  - regime of nuclear transparency is reached → evanescent baryo-chemical (μ_B~0) potential in the mid-rapidity region
- Thermal and coalescence models predict for a nucleus X with mass number A:

$$\frac{\overline{X}}{X} \approx \left(\frac{\overline{p}}{p}\right)^A$$

- Results of $\overline{d}$/d and $^3\overline{He}$/^{3}He in Pb-Pb collisions confirm the prediction:
  - p_T and centrality independent



[5] ALICE Collaboration, Phys. Rev. C 88 (2013) 044910

ALICE-PUBLIC-2017-006

Anti-nuclei/nuclei ratio

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

- At the LHC energies the antiproton/proton ratio [5] is compatible with the unity:
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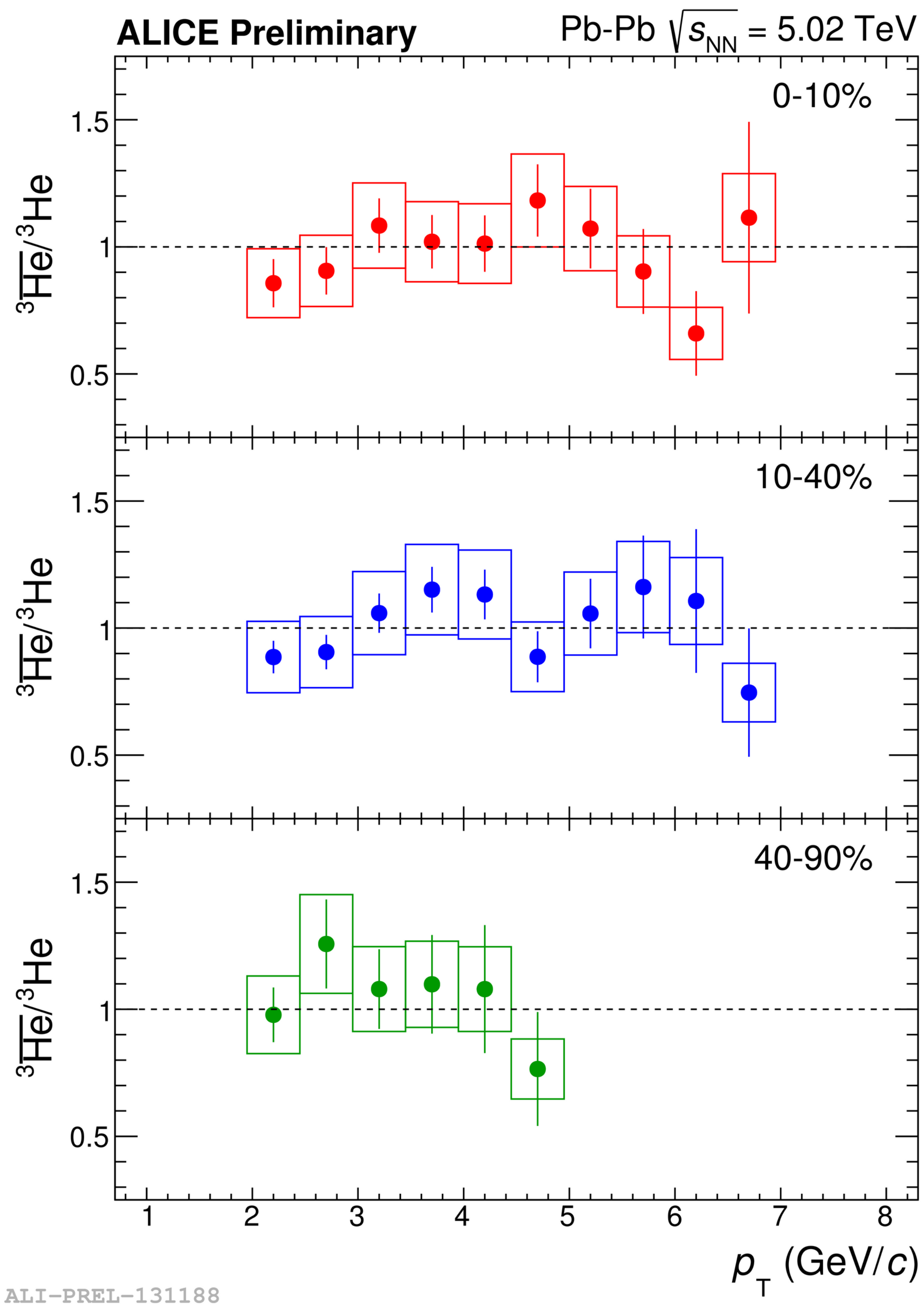
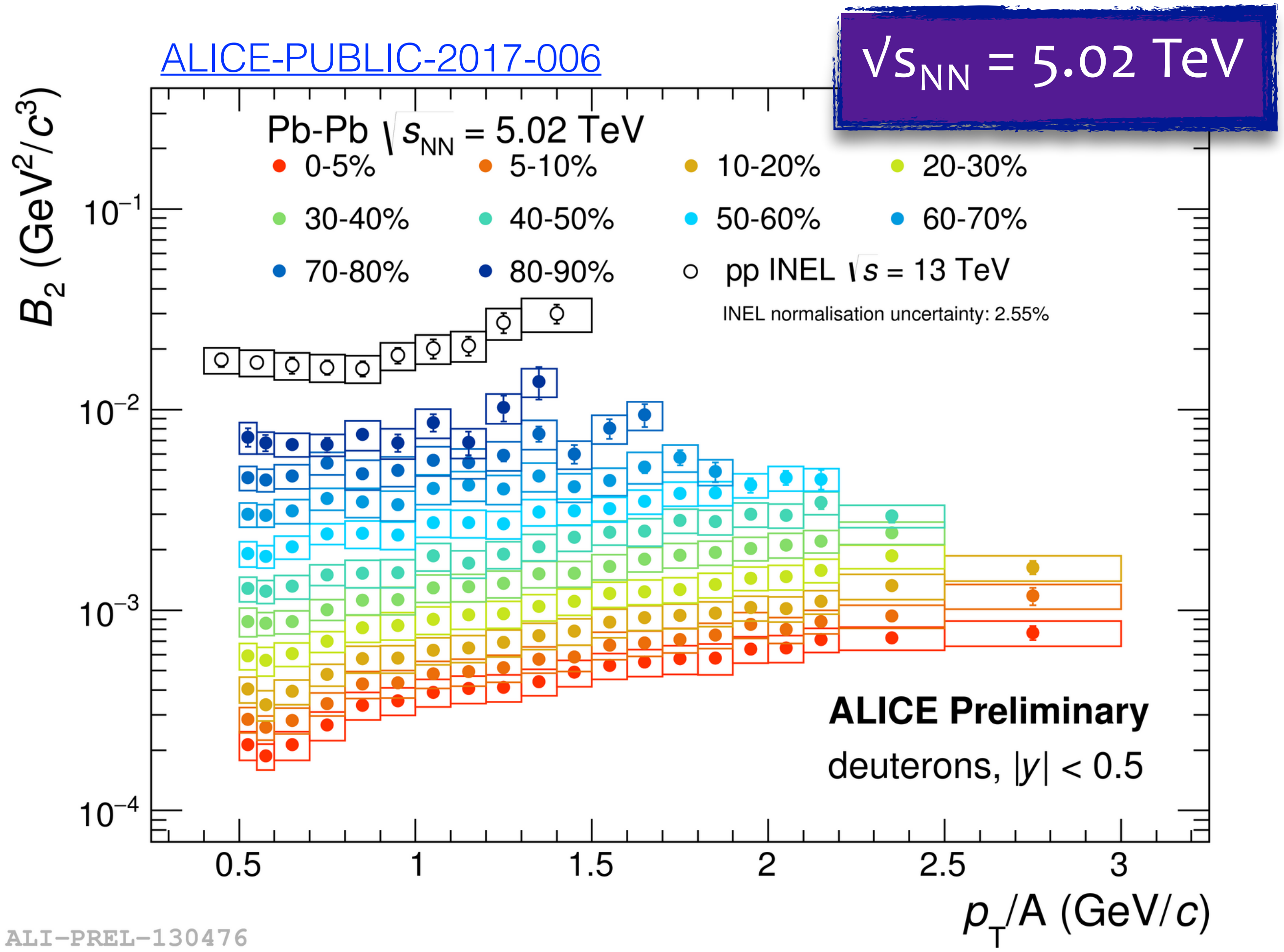
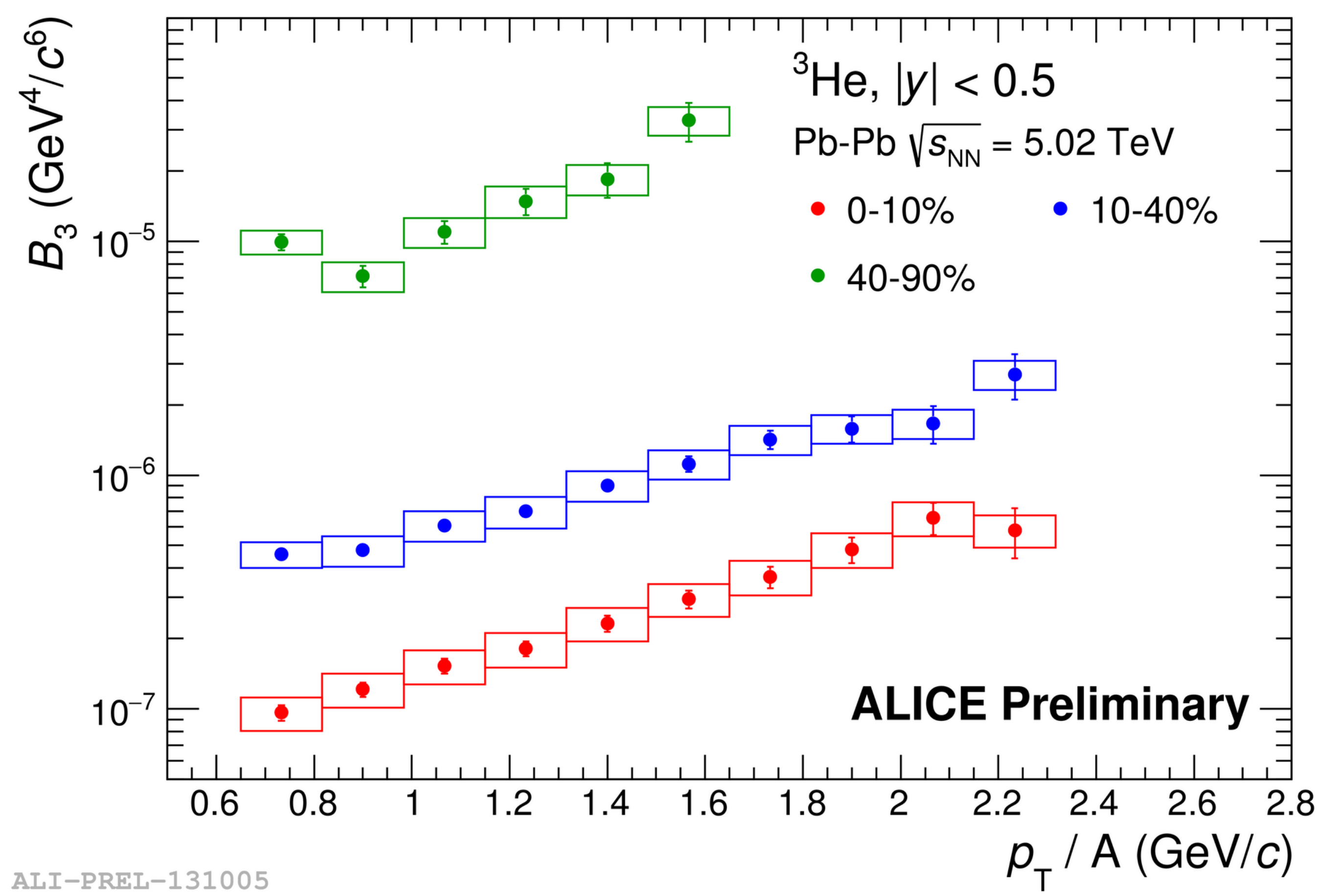


[5] ALICE Collaboration, Phys. Rev. C 88 (2013) 044910

Coalescence parameter B_A





- The **probability** to form a nucleus via coalescence can be quantified by the **coalescence parameter B_A**:

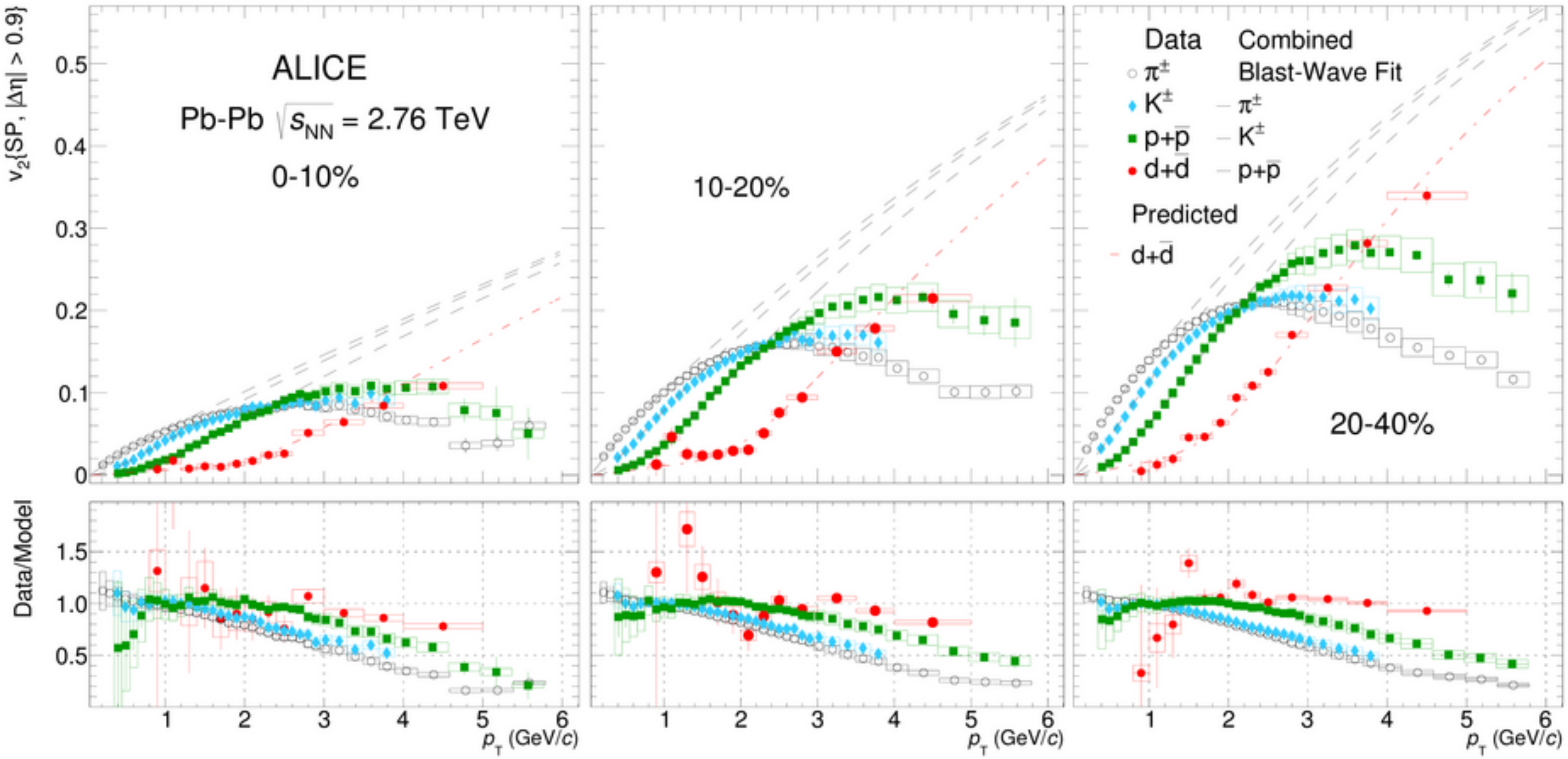
$$B_A = E_A \frac{d^3N_A}{dp_A^3} \Big/ \left(E_p \frac{d^3N_p}{dp_p^3} \right)^A$$

  - A is the mass number
  - $p_p = p_A/A$

- According to **simple coalescence** predictions **B_A** is **p_T flat**:
  - simple coalescence **does not describe** the trend observed in Pb-Pb collisions
- The **rise in p_T** becomes milder moving from central to peripheral collisions

Deuteron elliptic flow

√s$_{NN}$ = 2.76 TeV



ALICE Collaboration, Eur. Phys. J. C 77 (2017) 658

Elliptic flow measured with scalar product method

$$v_n\{SP\} = \frac{\langle u_{n,i}(p_T, \eta) \cdot \frac{Q_n^*}{M} \rangle}{\sqrt{\langle \frac{Q_{n,A}^*}{M_A} \cdot \frac{Q_{n,B}^*}{M_B} \rangle}}$$

- The v_2 of the deuteron is compatible with the prediction of the Blast-Wave model:
  - scale the BW fits to π/K/p spectra to the deuteron mass → hint of a common thermal production

Deuteron elliptic flow

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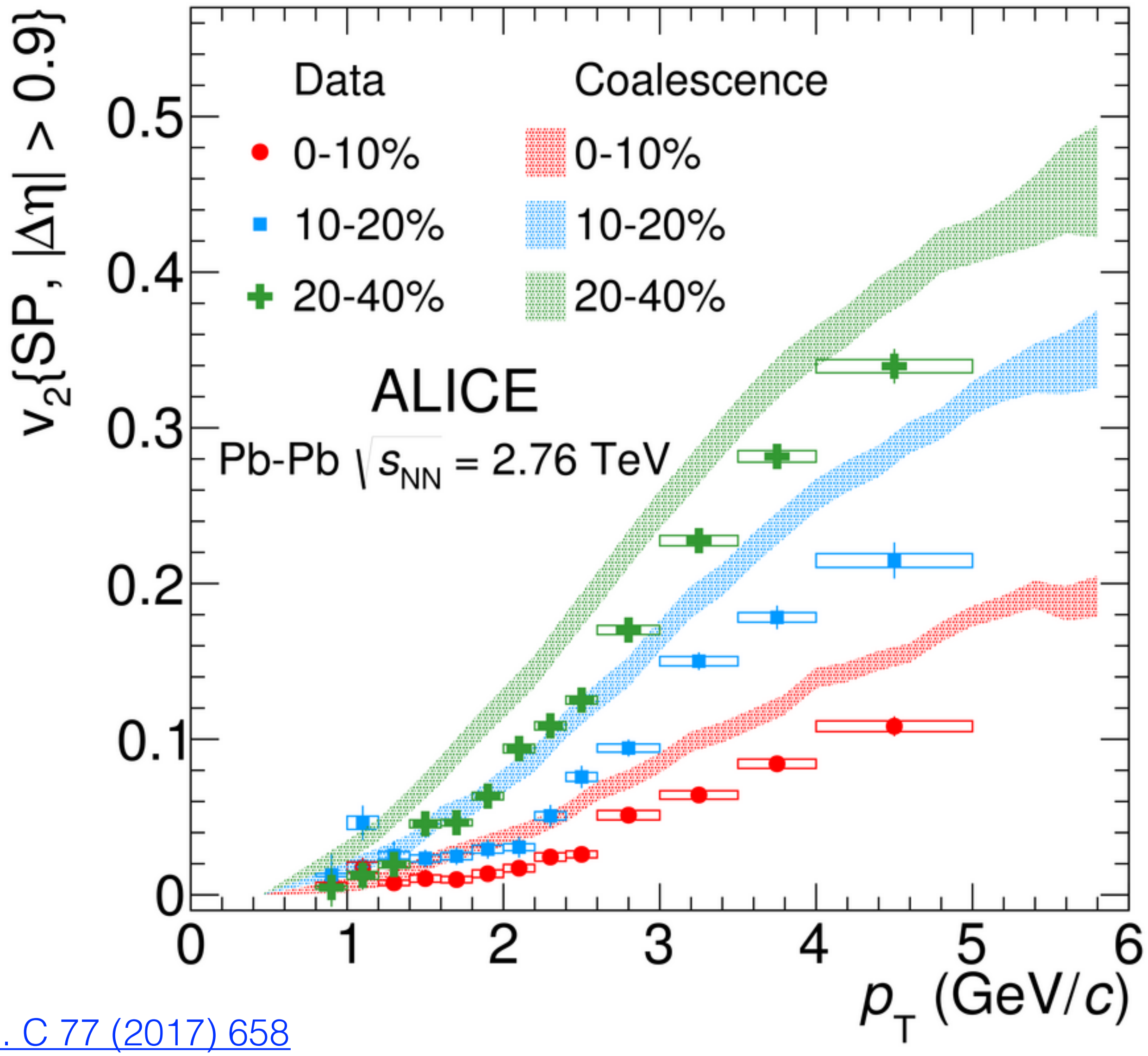

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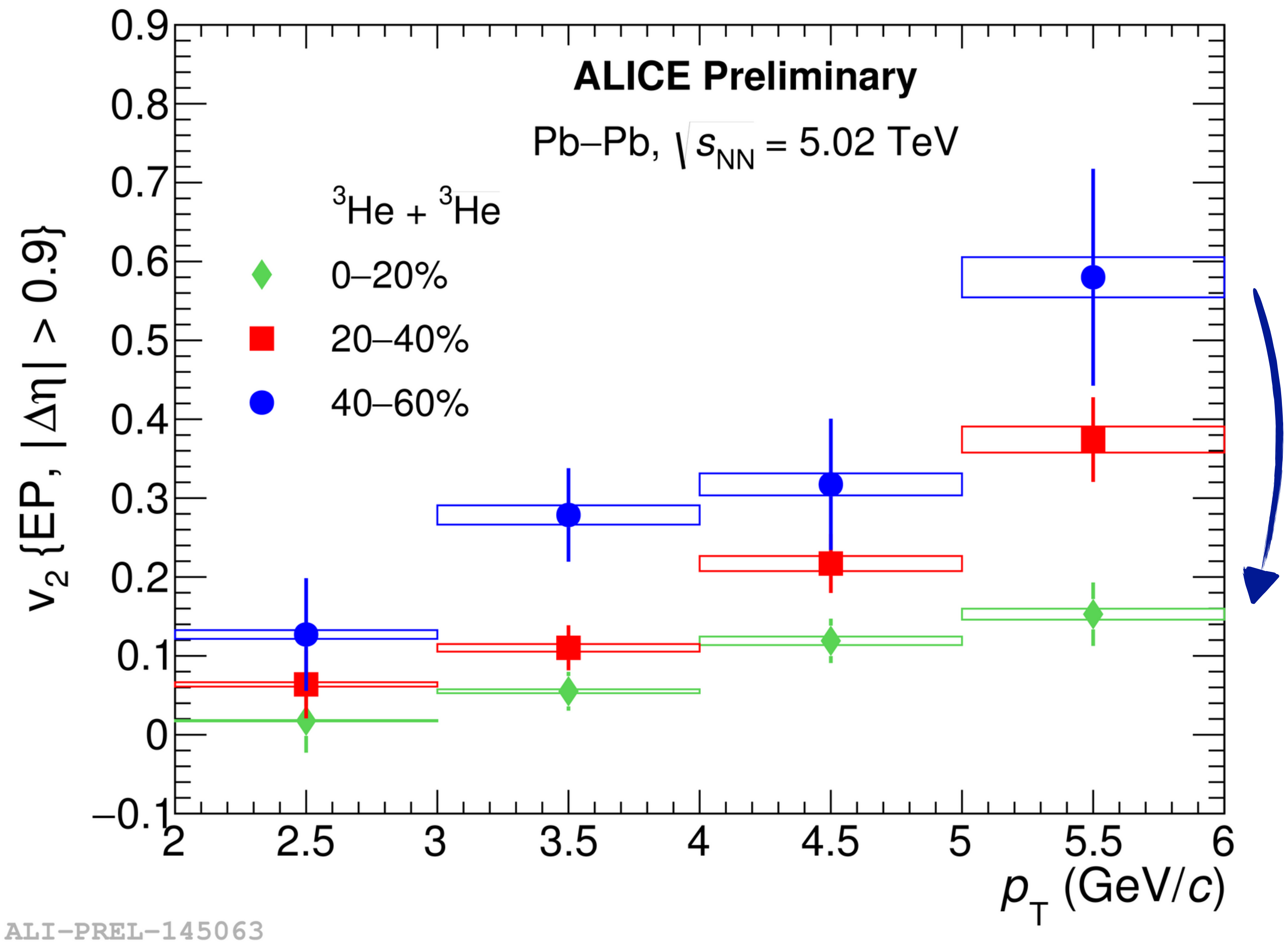
ALICE Collaboration, Eur. Phys. J. C 77 (2017) 658

- The v_2 of the deuteron is compatible with the prediction of the Blast-Wave model:
  - scale the BW fits to π/K/p spectra to the deuteron mass → hint of a common thermal production
- The simple coalescence model does not describe the v_2 of the deuterons:
  - $v_2^d(p_T^d) = 2 \cdot v_2^p(2p_T^p)$ → at lower energies able to describe deuteron v_2

^{3}He elliptic flow

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

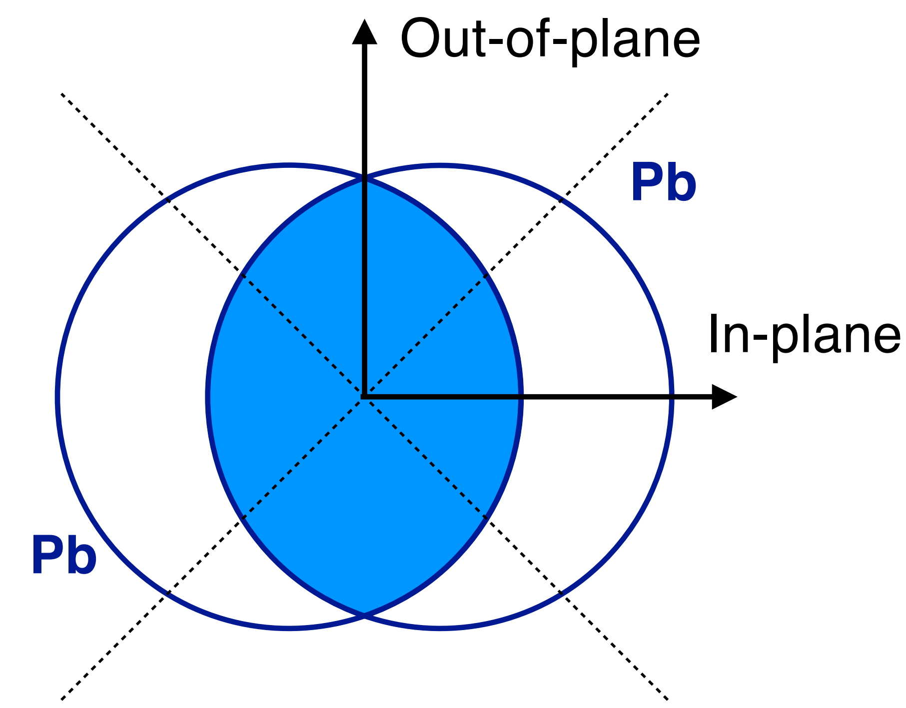


The v_2 of 3He is measured using the Event-Plane method:

- Reconstruction of the Event Plane (estimator of the Reaction Plane)
- v_2 computed as:

$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}$$

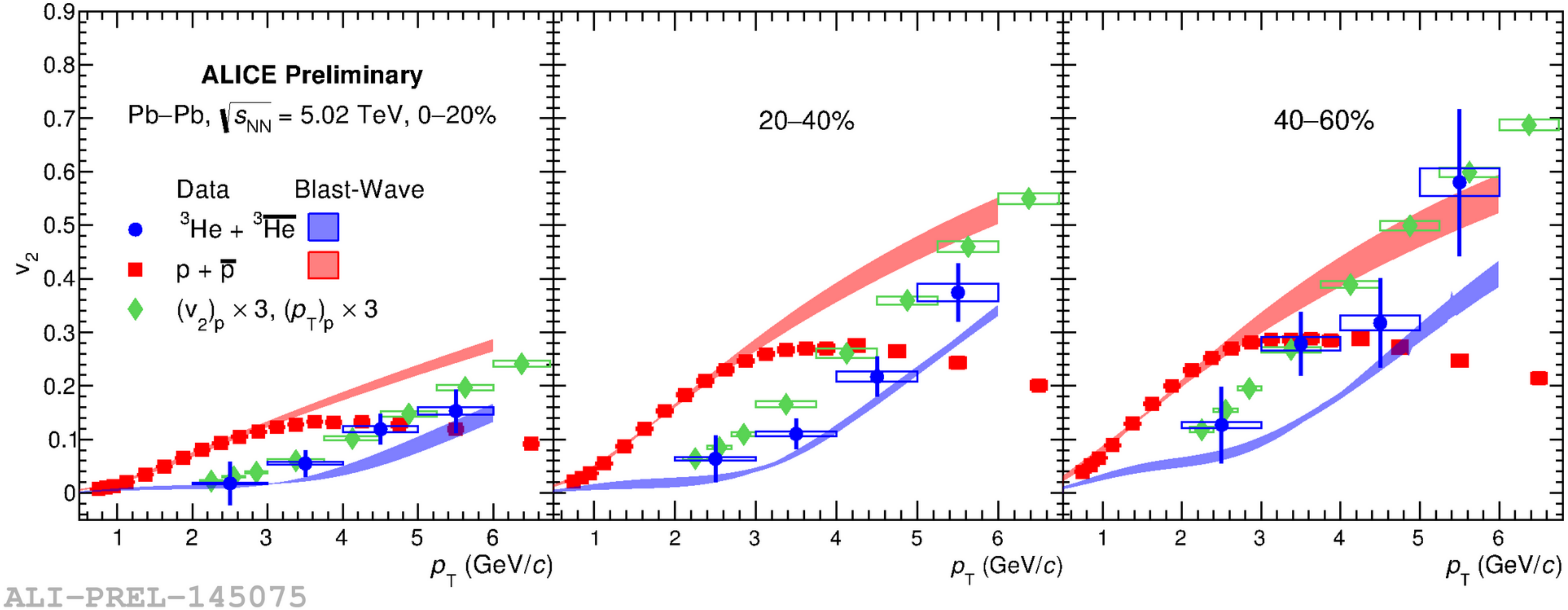
R_2 is the event plane resolution



- v_2 of ^{3}He measured in three centrality classes:
  - increase while going to peripheral collisions
  - smooth rise with p_T

^{3}He elliptic flow

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

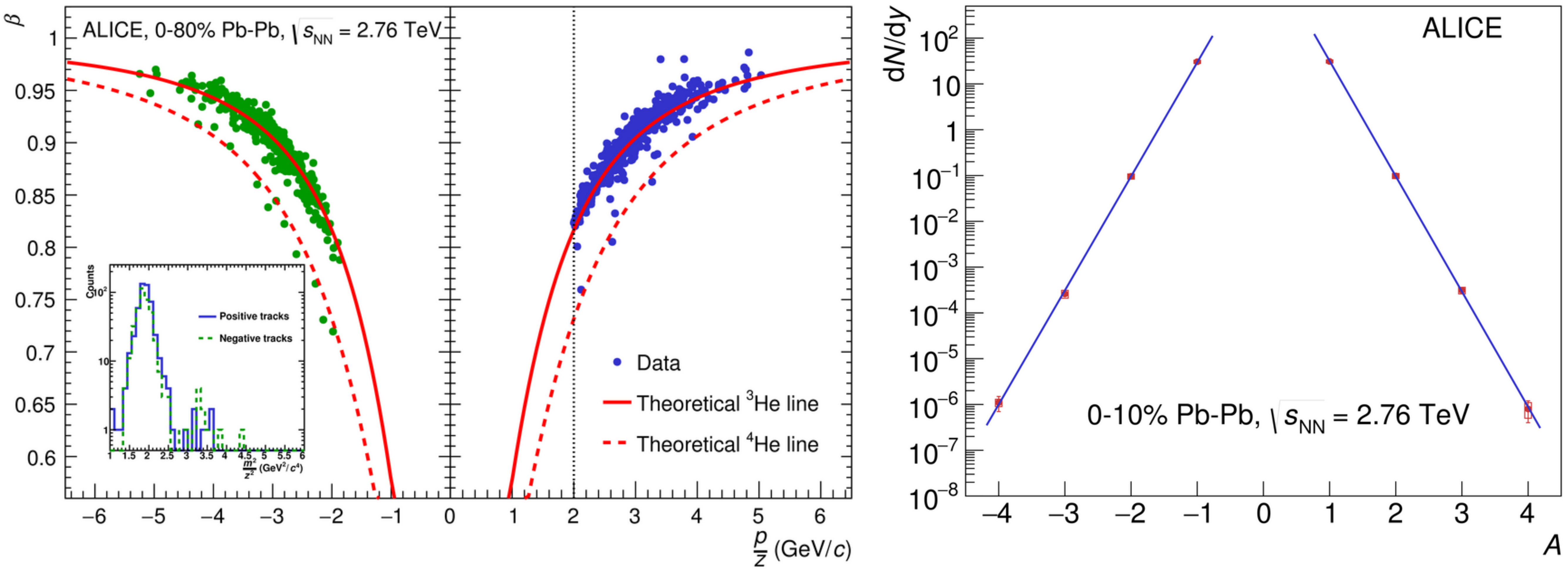


- v_2 of ^{3}He shows a different behavior with respect to v_2 of deuteron
  - overall agreement of the prediction from Blast-Wave fit to lighter species is better in the most central collisions
  - simple coalescence expectation (green points) is closer for the results in 40-60% centrality

^{4}He production yields

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

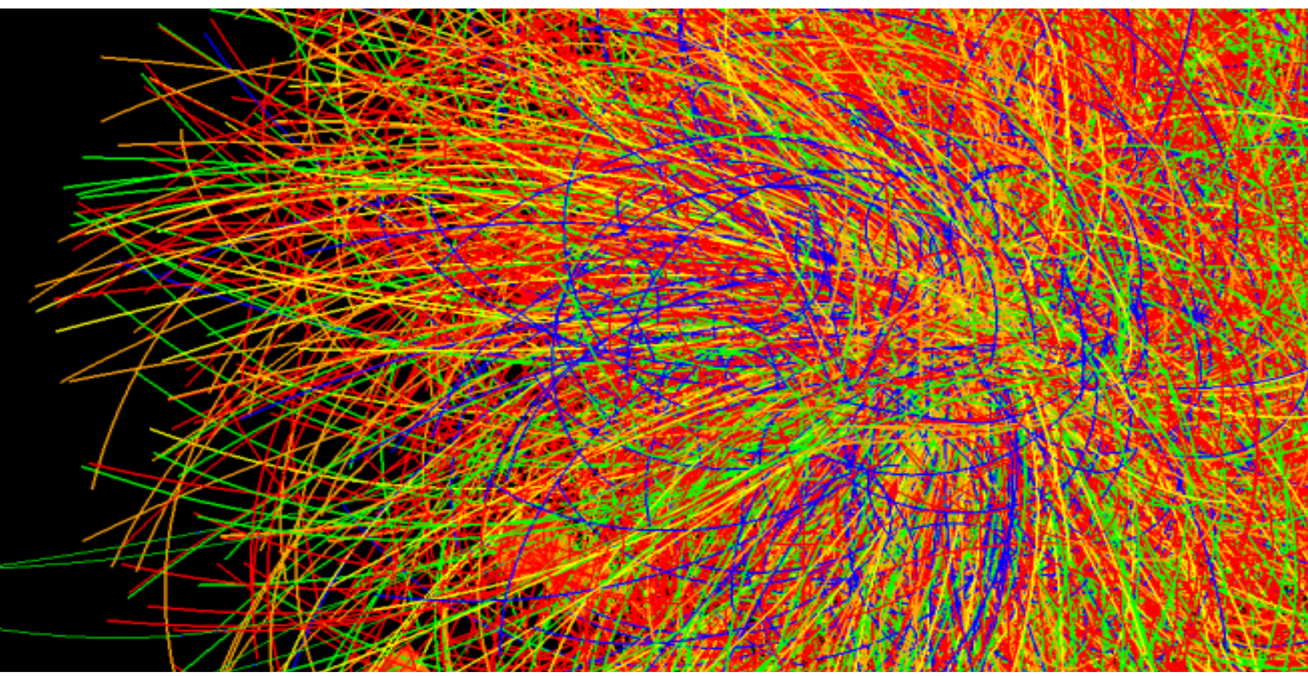
ALICE Collaboration, Nucl. Phys. A 971 (2018) 1-20

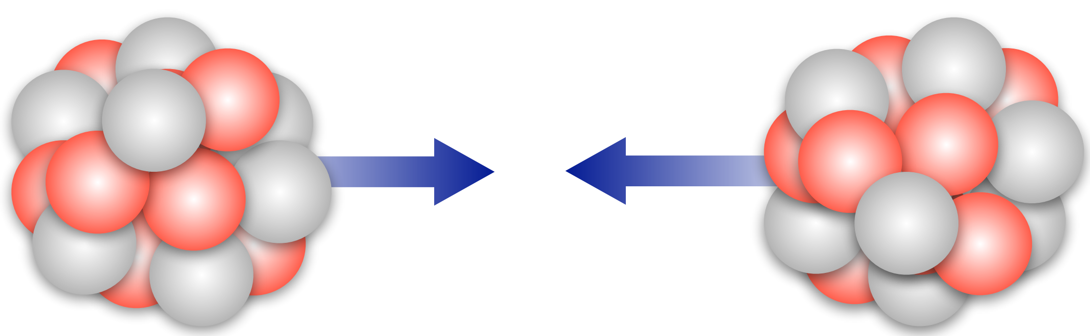


- the production of the **heaviest anti-nucleus** ever has been measured in **Pb-Pb at 2.76 TeV** and "rediscovered" also in **Pb-Pb at 5.02 TeV**
- the prediction by the **thermal model** of **exponential decrease** in nuclei production rate is **confirmed**
  - in Pb-Pb the **penalty factor** for adding one baryon is **~ 300**

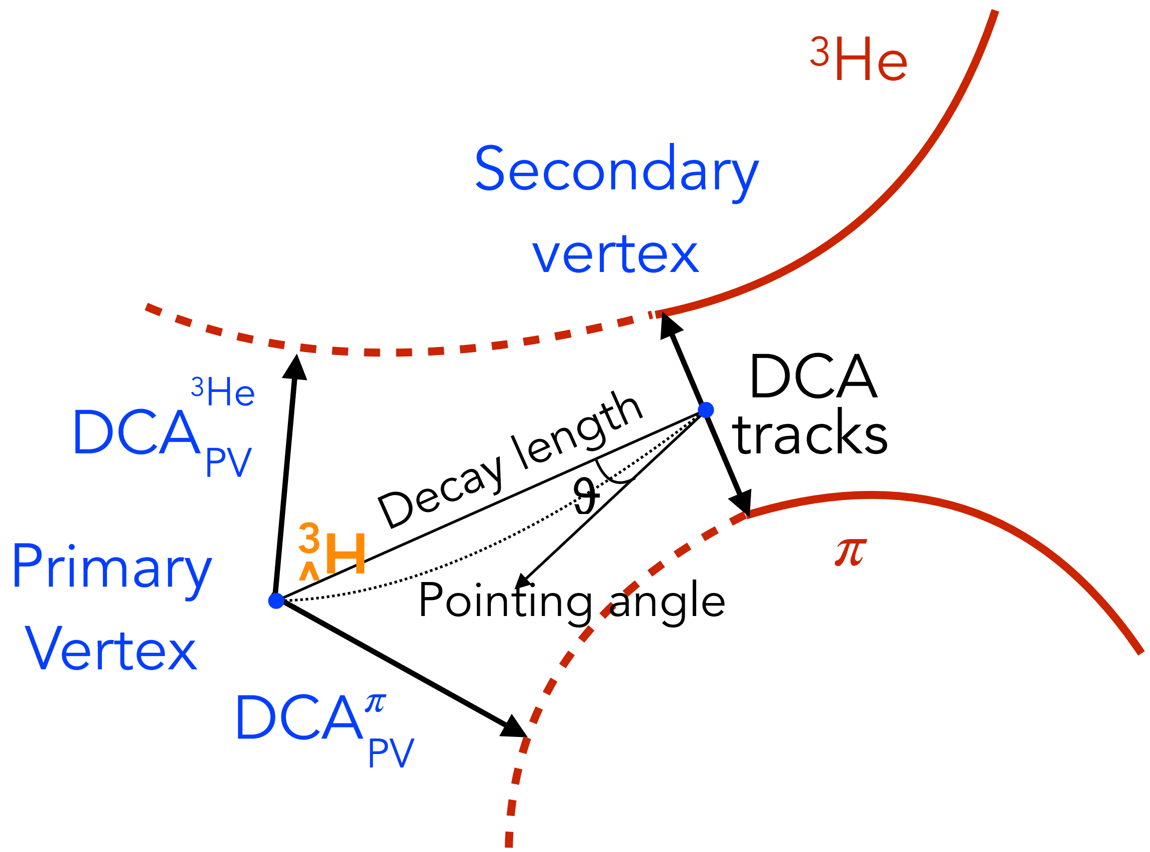
Production in Pb-Pb:

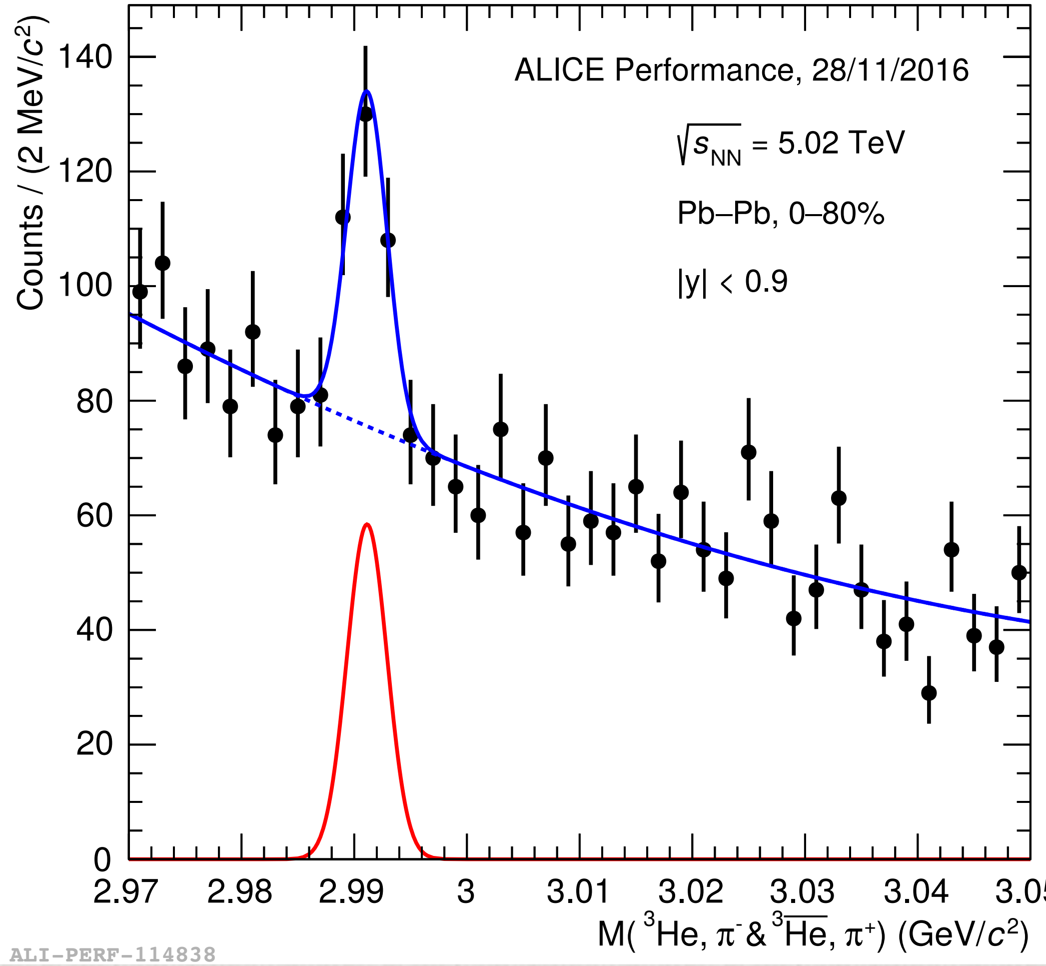
Hypertriton





Hypertriton identification





- (Anti-)hypertriton **production** studies performed via two charged body decay channel

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

- ^{3}He and π tracks identified via specific energy loss in TPC
- **Secondary vertex** reconstructed exploiting the algorithm used for the V0 topology
- **Signal raw yields** extracted with a fit to the invariant mass distribution:

$$ f(m) = N_{sig} \cdot f_{sig}(m) + N_{bkg} \cdot f_{bkg}(m) $$

- Method used both for **production** and **lifetime** analysis

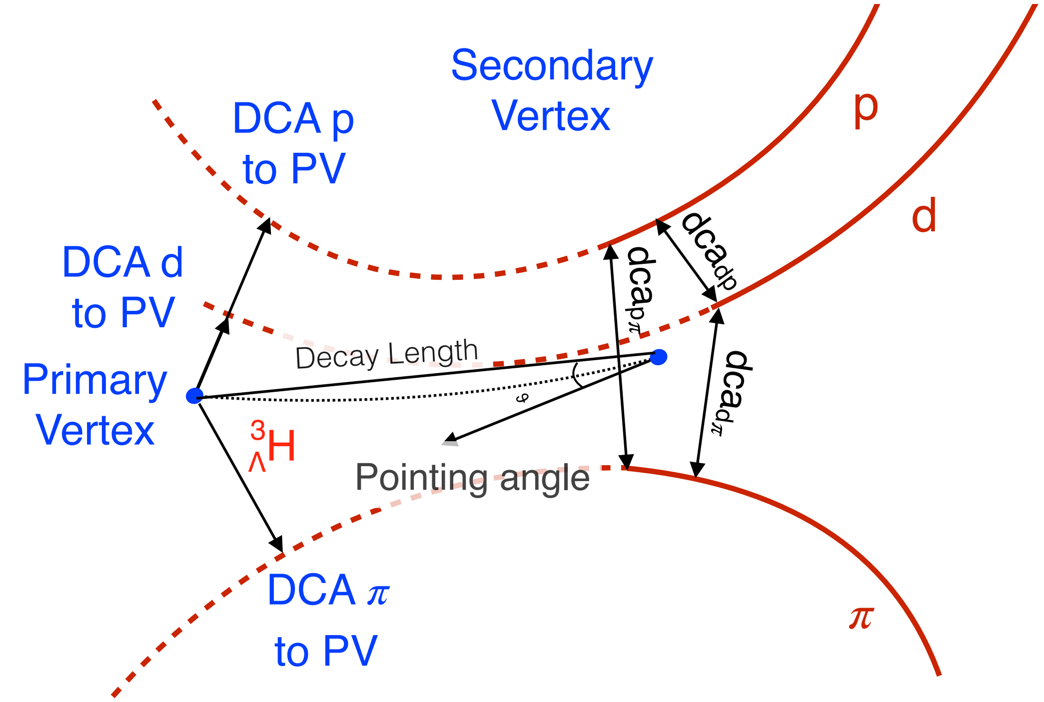
Hypertriton identification

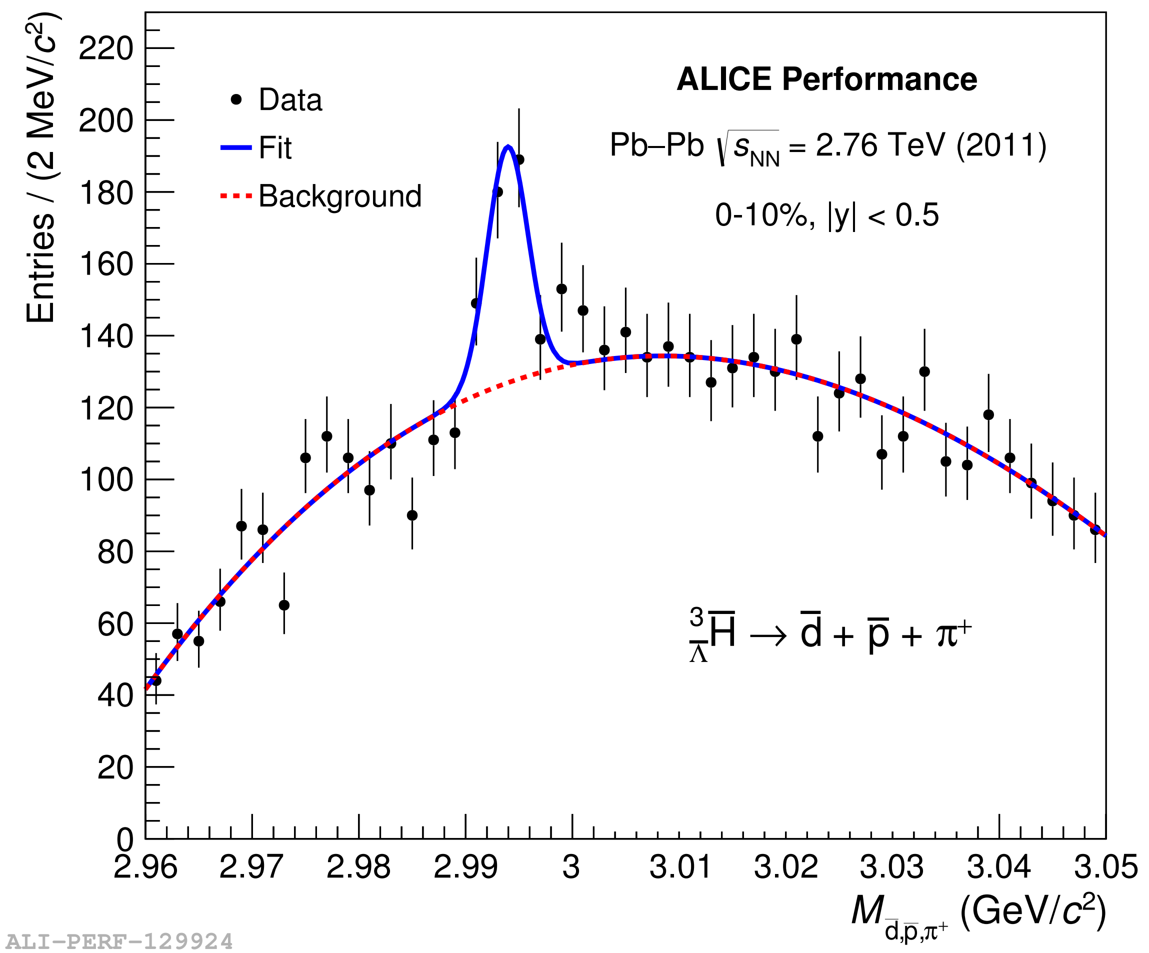
- (Anti-)hypertriton **production** studies performed via **three charged body** decay channel

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

  - higher Branching Ratio compared to the two body, but also larger combinatorial background

- d, p and π tracks identified via specific energy loss in TPC
- Topological and kinematical selections on the daughter tracks
- Secondary vertex reconstructed as the point at minimum distance to the selected tracks
- Signal raw yields extracted with a fit to the invariant mass distribution, as previously shown

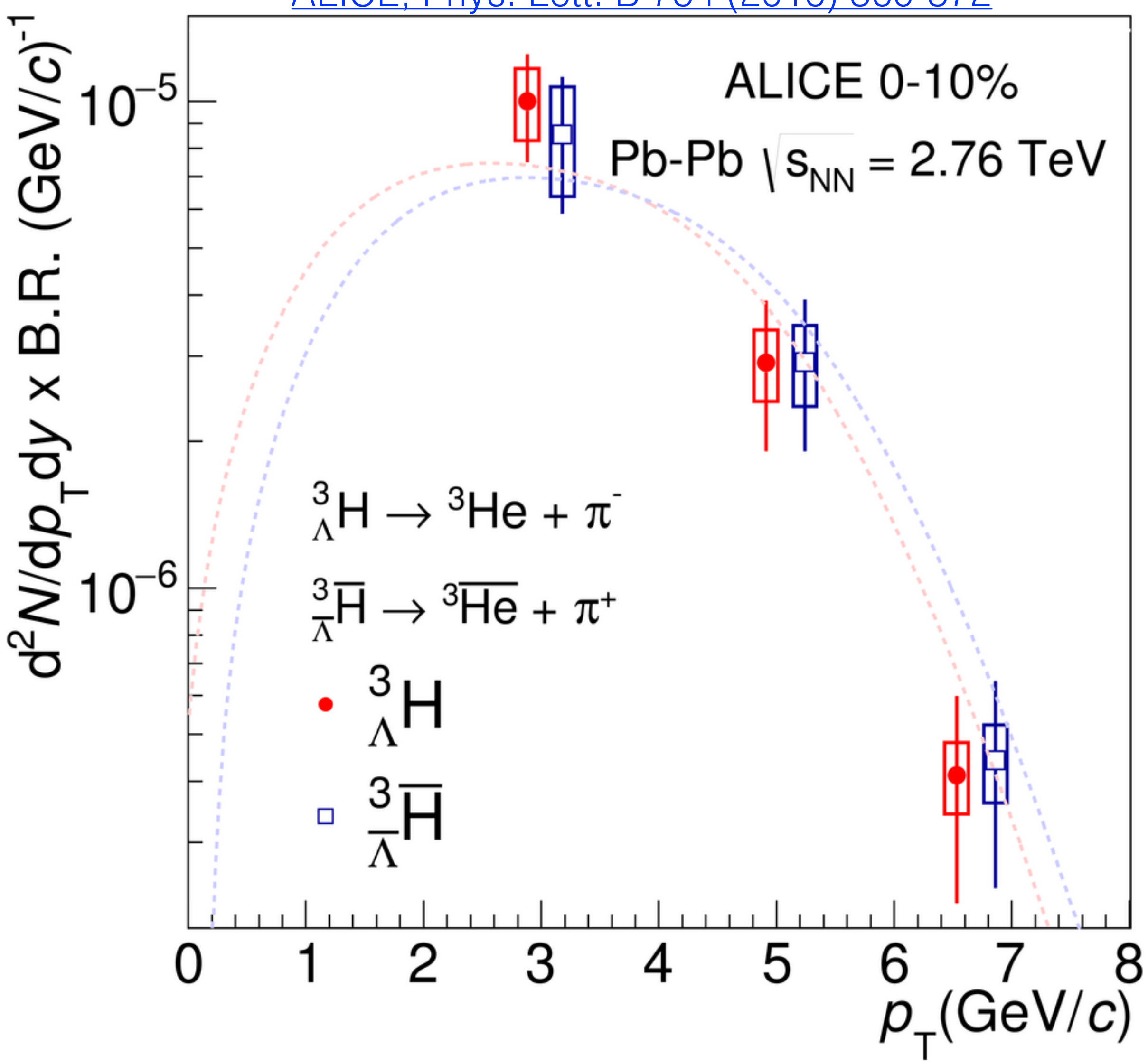




${}^{3}_{\Lambda}H$ production

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

ALICE, Phys. Lett. B 754 (2016) 360-372

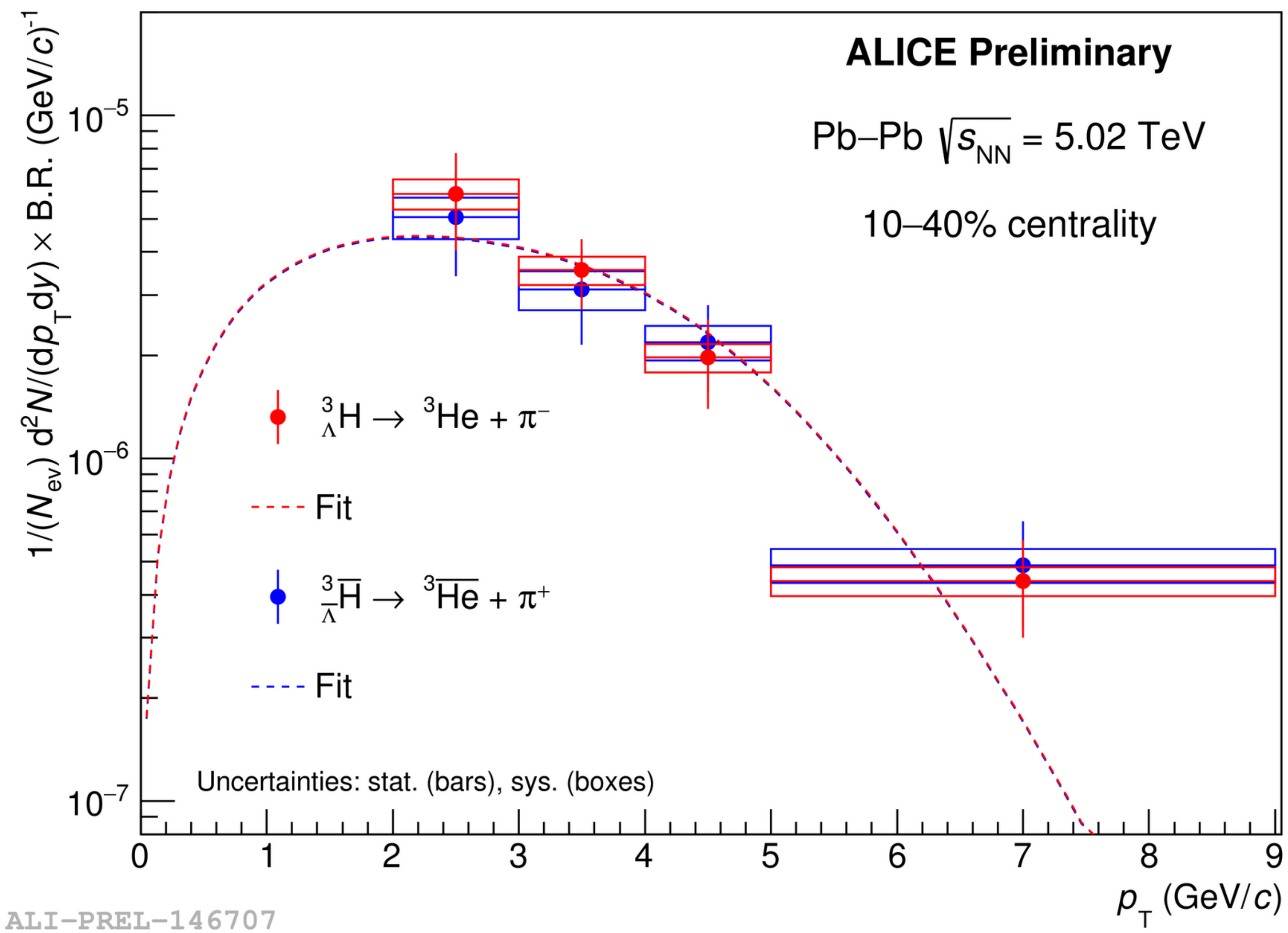


Antimatter-to-matter ratio in agreement with unity within the uncertainties

- p_T spectra were measured in **most central** collisions at **2.76 TeV**:
  - **Blast-Wave** fit to extrapolate yield in the unmeasured regions
- Similarly p_T spectra have been measured in **semi-central** collisions at **5.02 TeV**
- In Pb-Pb collisions at **5.02 TeV** yields measured as a function of the **charged particle multiplicity**:
  - dN/dy in three centrality classes
  - increasing trend can be interpreted in the thermal model as related to the volume of the created medium

${}^{3}_{\Lambda}H$ production

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



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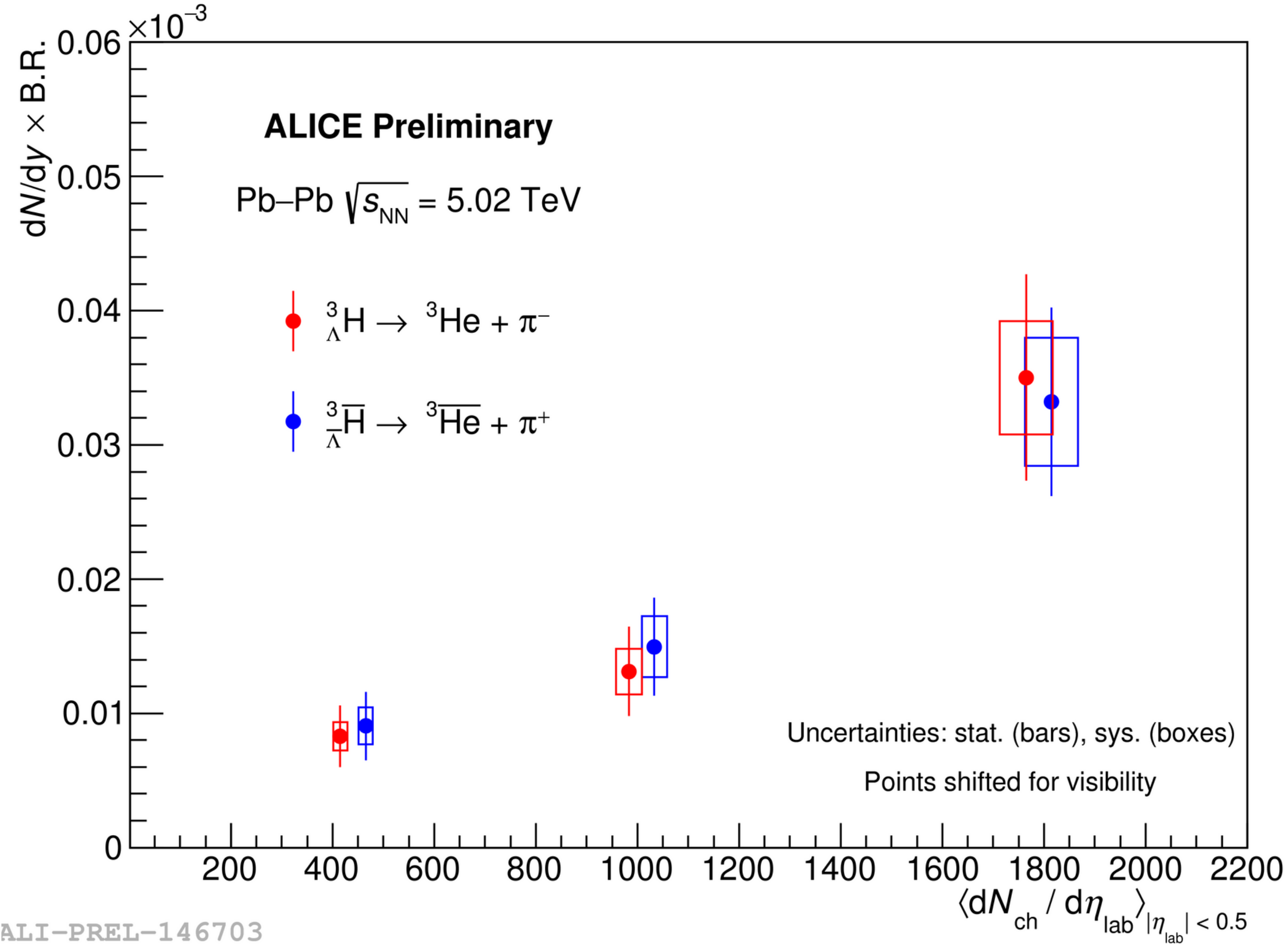

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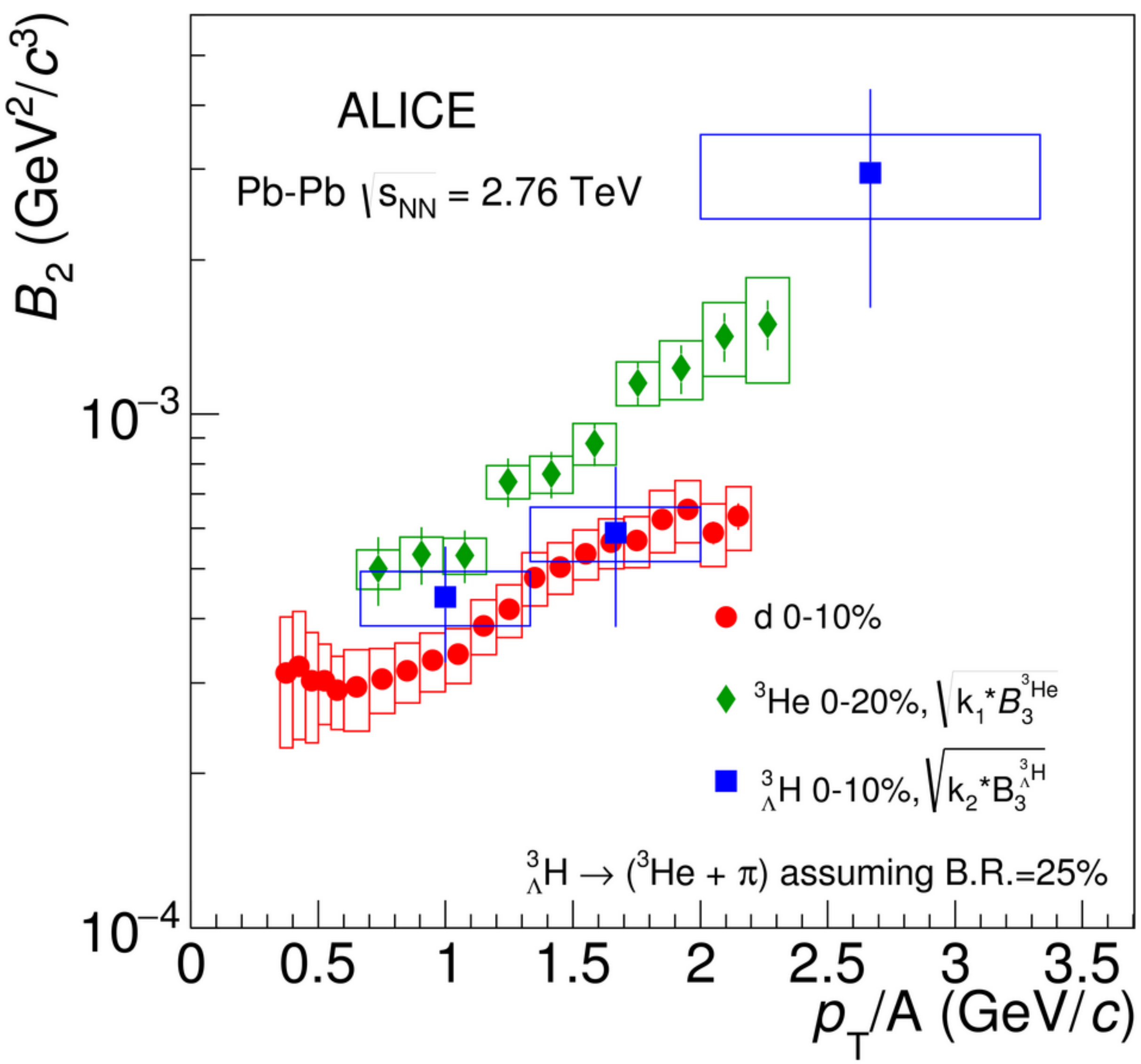
${}^{3}_{\Lambda}H$ coalescence parameter

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

ALICE, Phys. Lett. B 754 (2016) 360-372

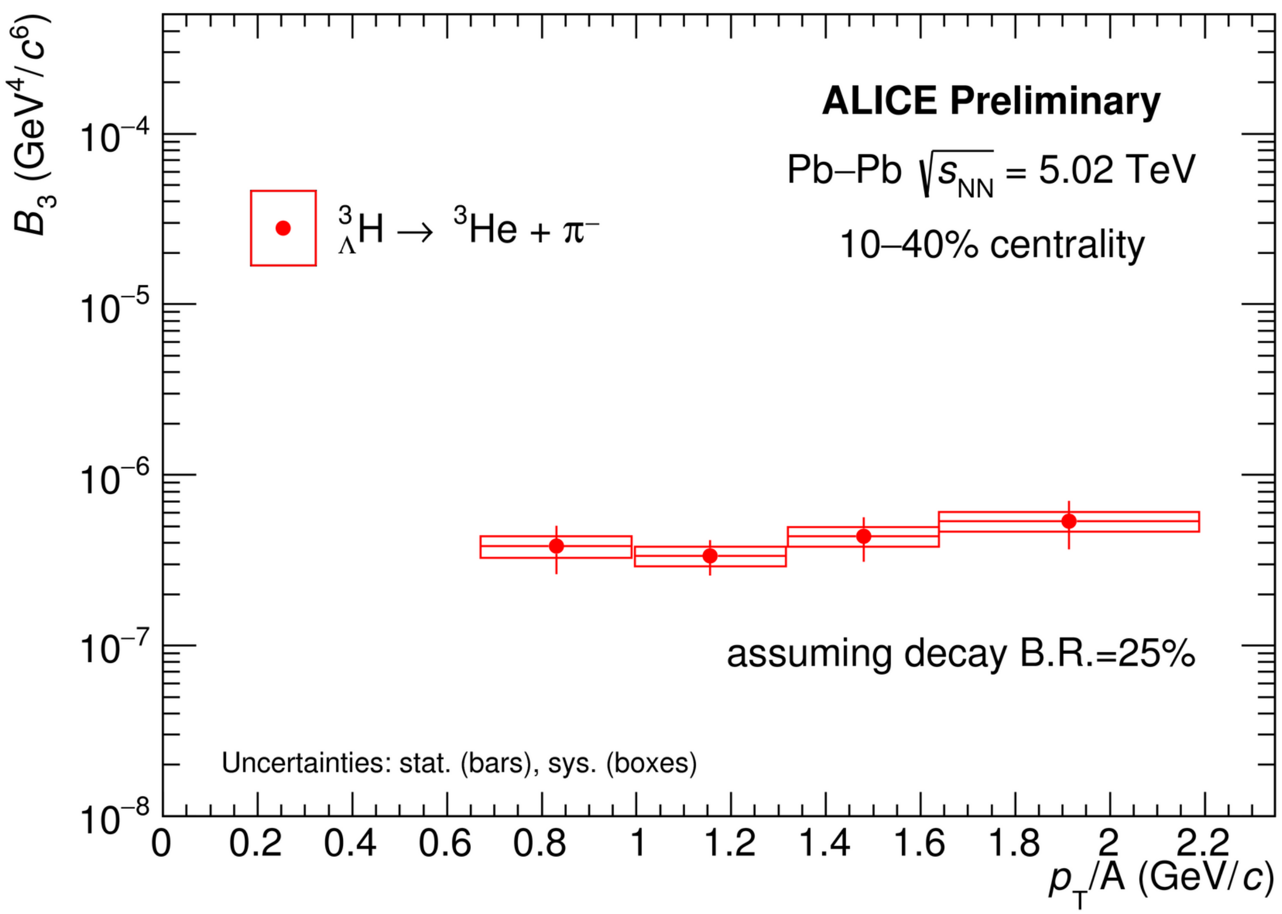


Proton and Λ spectra used the calculations are measured at the same energies

- (Anti-)hypertriton B_3 measured in central collisions at 2.76 TeV:
  - rescaled for a comparison with deuteron B_2
  - rise with p_T not expected by simple coalescence
- In Pb-Pb collisions at 5.02 TeV B_3 measured in semi-central collisions:
  - separately for matter and anti-matter
  - almost flat behavior as a function of p_T as supposed in coalescence picture
- Despite the different energies B_3 is higher in semi-central than in central collisions

${}^{3}_{\Lambda}$H coalescence parameter

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



ALI-PREL-146743

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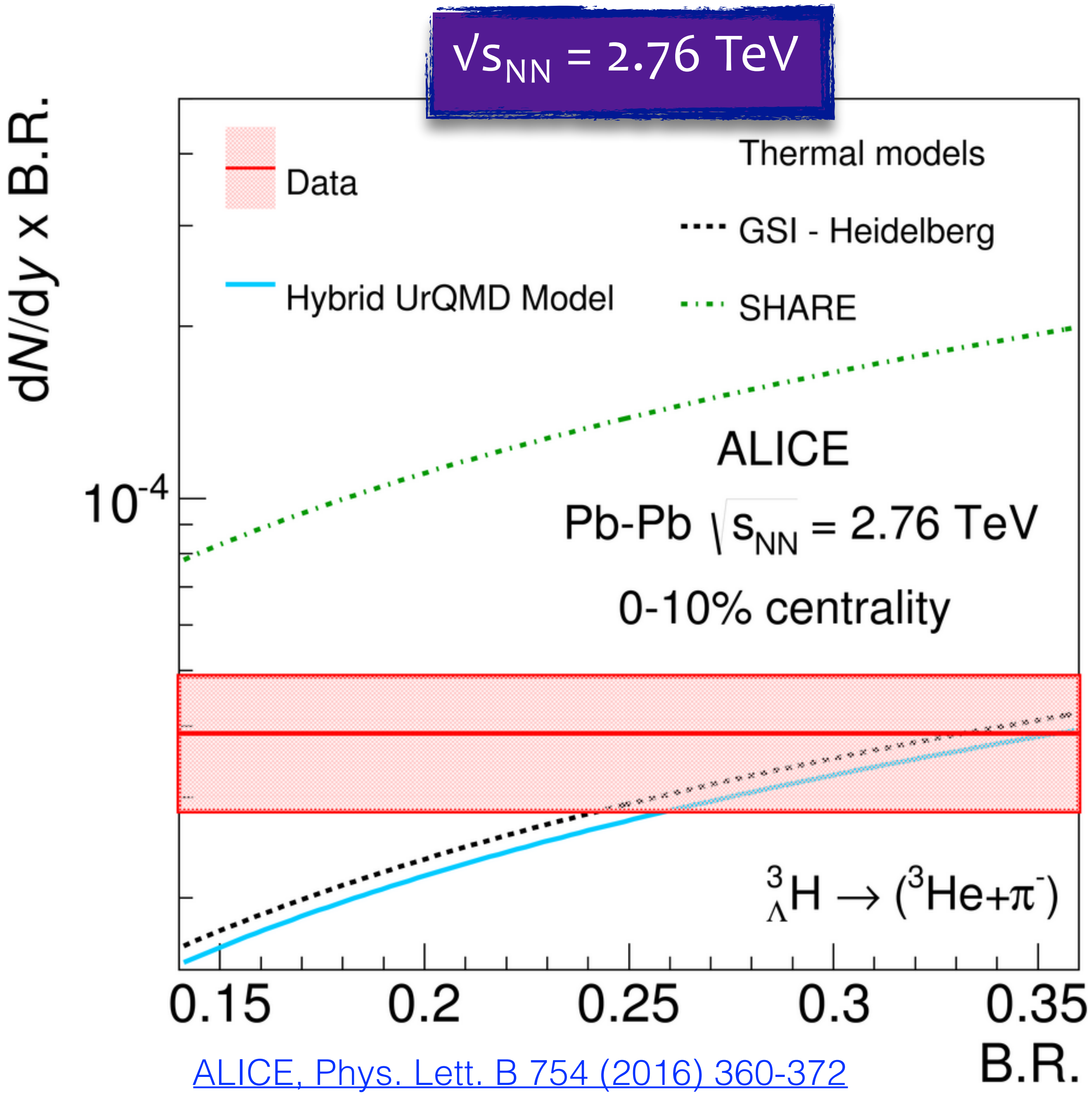
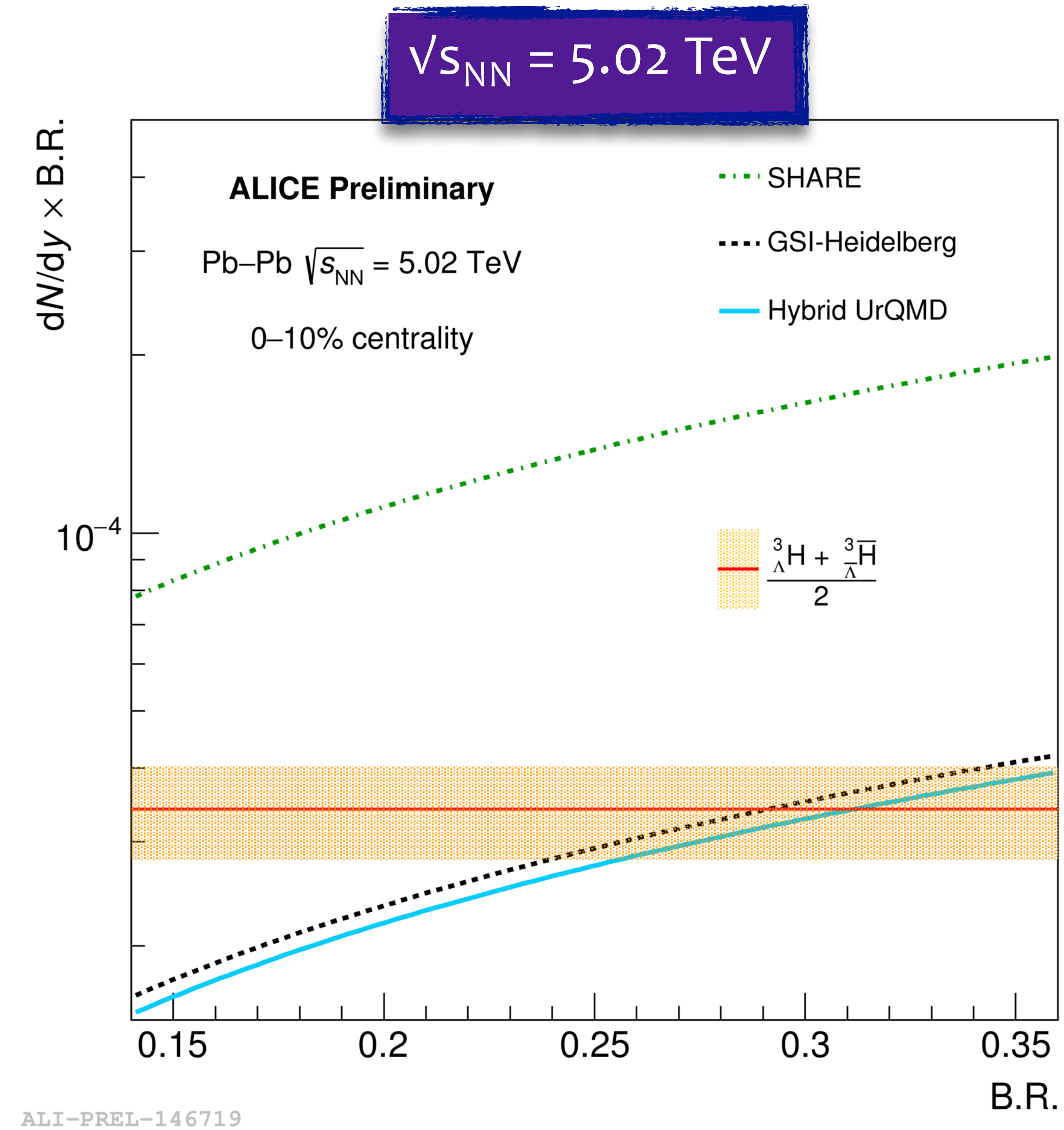
dN/dy vs B.R.



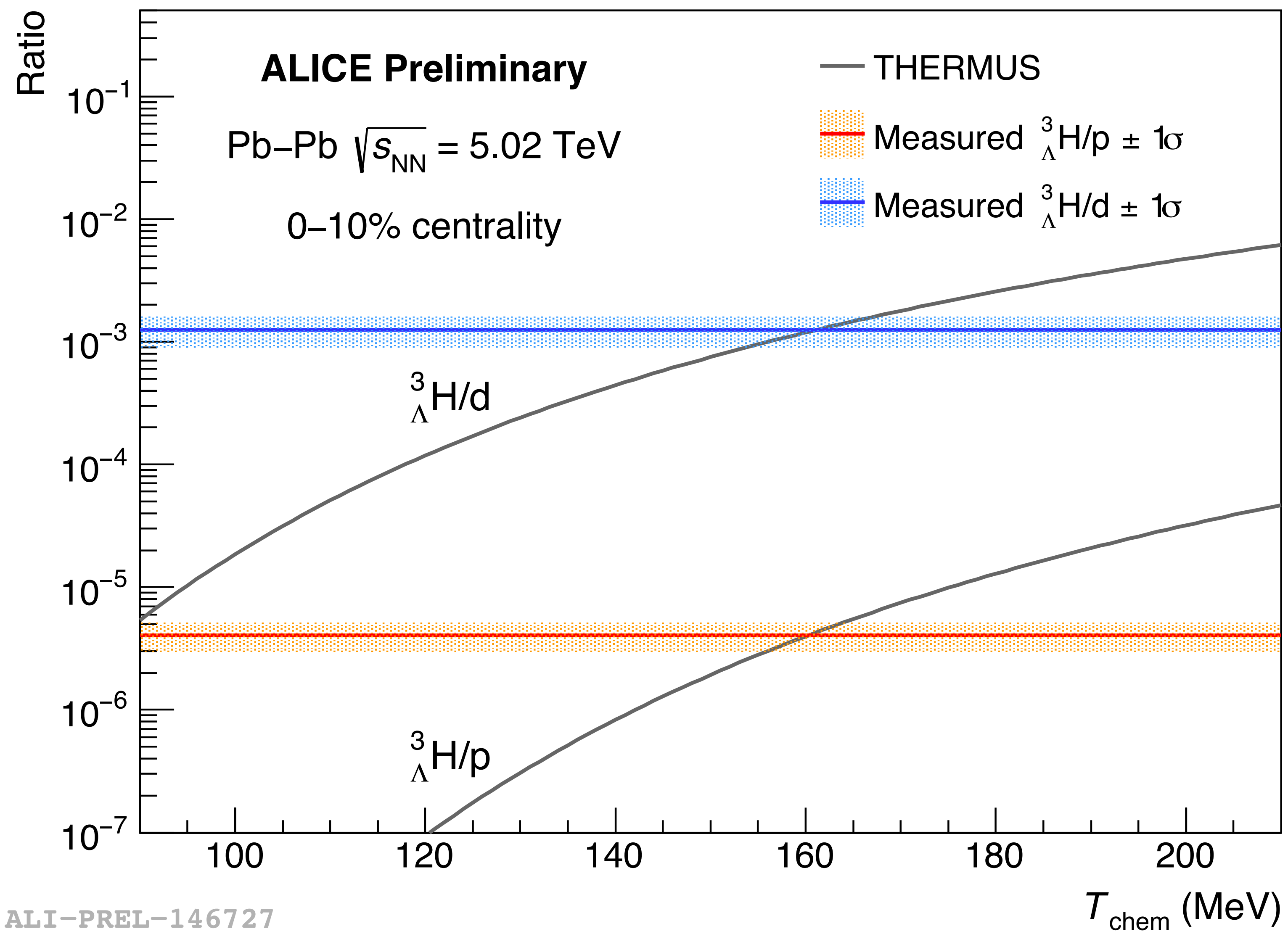
ALICE, Phys. Lett. B 754 (2016) 360-372



- (Anti-)hypertriton **Branching Ratio** is not precisely known
  - only constrained by the ratio between all charged channels containing a pion
- **Thermal model predictions** done for different **B.R.** values → agreement in the range **0.24 - 0.35** with equilibrium thermal models

${}^{3}_{\Lambda}H$ ratios to light hadron yields

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

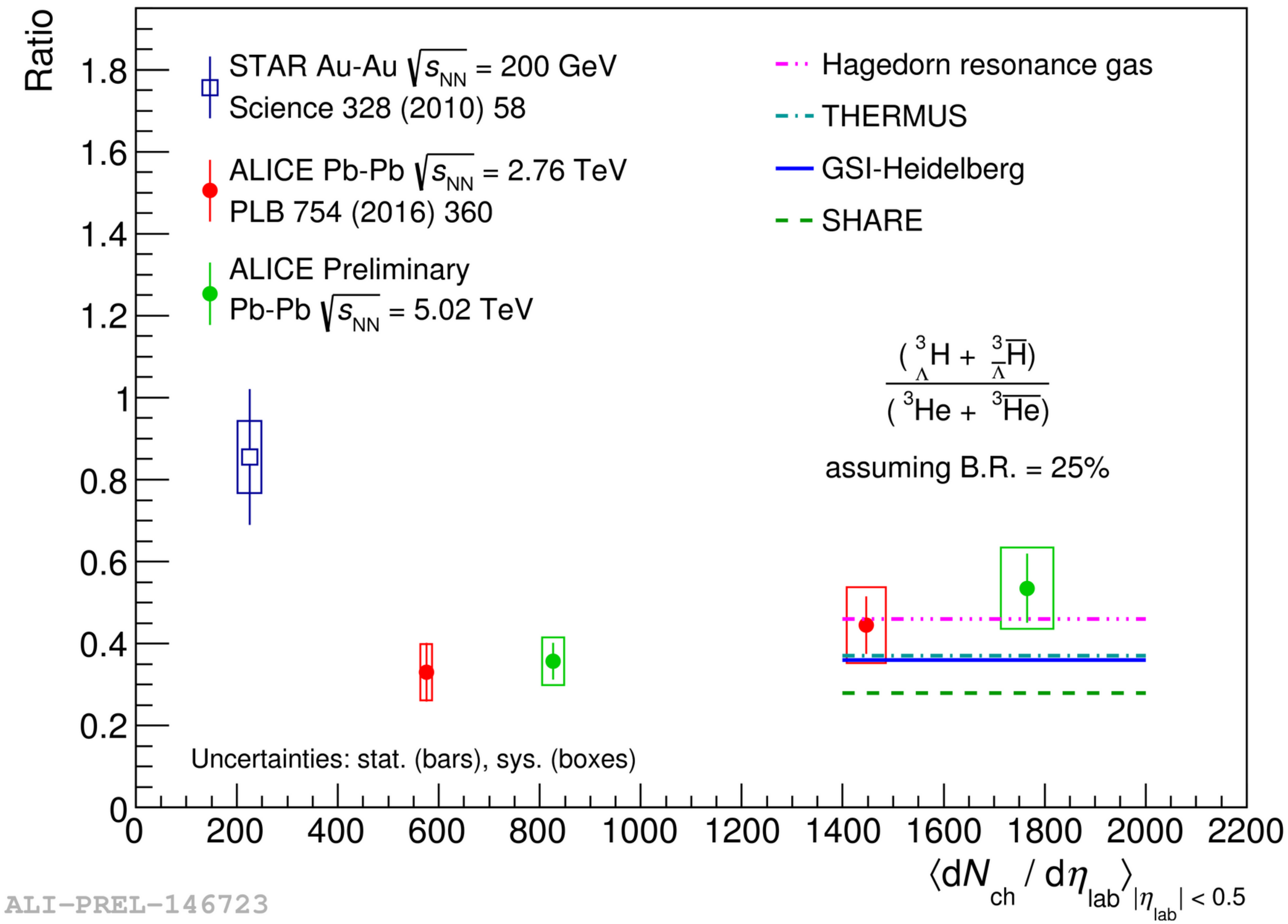


THERMUS:
S. Wheaton, et al.,CPC180, 84 (2009)

- Ratio to **light hadron yields** more sensitive to the **chemical freeze-out temperature**
- ${}^{3}_{\Lambda}H/p$ and ${}^{3}_{\Lambda}H/d$ compared with THERMUS predictions as a function of T_{chem}
- Range T_{chem} = 153-165 MeV in agreement with T_{chem} = 156 MeV obtained at 2.76 TeV

${}^{3}_{\Lambda}$H-to-^{3}He ratio

- Ratios for **most central collisions** ($\sqrt{s_{NN}}$ = 2.76 TeV and $\sqrt{s_{NN}}$ = 5.02 TeV) are in agreement with predictions from **Hagedorn resonance gas** (HRG) and **thermal models**
- The new result at **5.02 TeV** might give a hint for an evolution with **charged particle multiplicity**
- Predictions from **coalescence** and for **lower multiplicities** are needed



THERMUS: S. Wheaton, et al., CPC180, 84 (2009)

GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142

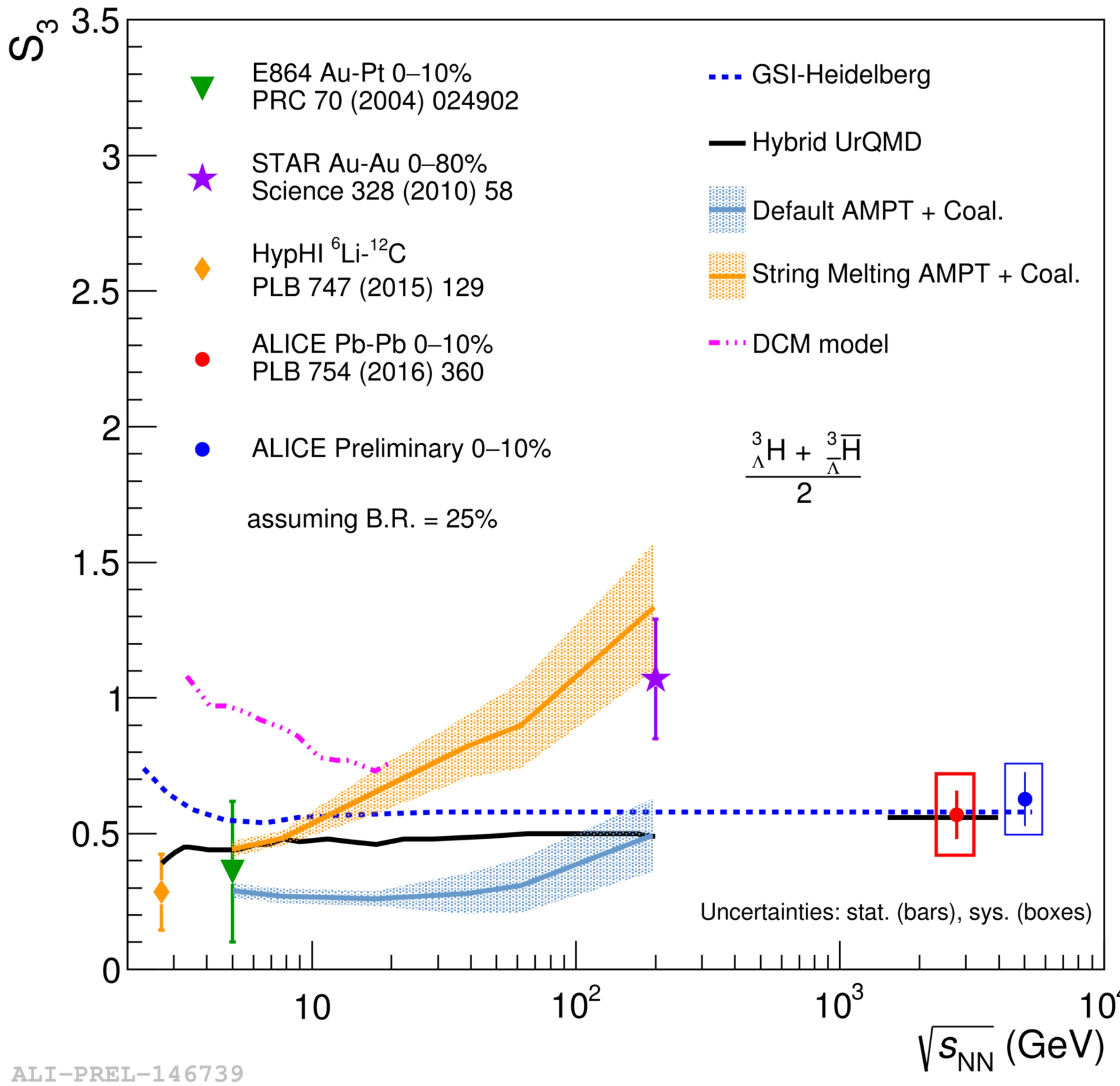
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC185, 2056 (2014)

Strangeness population factor

Strangeness population factor S_3 [6,7] is defined as:

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

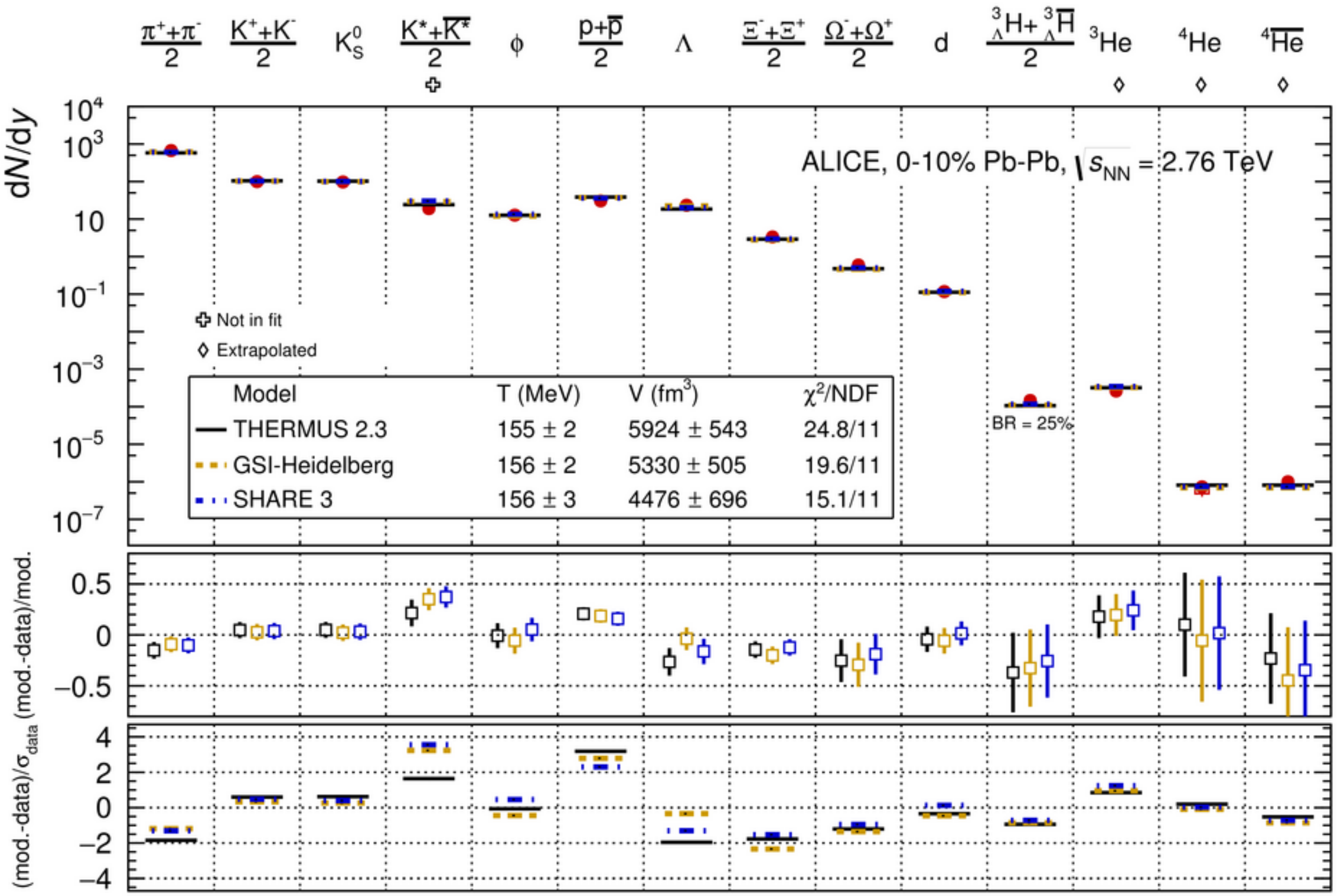
- **independent** on the **chemical potential** of the particles and additional canonical correction factor for **strangeness** is cancelled
- ALICE results at 5.02 TeV is:
  - **compatible** with the published results at 2.76 TeV and with those at lower energies
  - **in agreement** with the prediction of the equilibrium thermal model
- **Coalescence** predictions available only up to top RHIC energies



[6] E864 Collaboration, T. A. Armstrong et al. Phys. Rev. C 70, 024902 (2004)

[7] S. Zhang et al. Phys. Lett. B 684, 224-227 (2010)

The standard model for A-A collisions?



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

ALICE Collaboration, Nucl. Phys. A 971 (2018) 1-20

THERMUS: S. Wheaton, et al., CPC180, 84 (2009)

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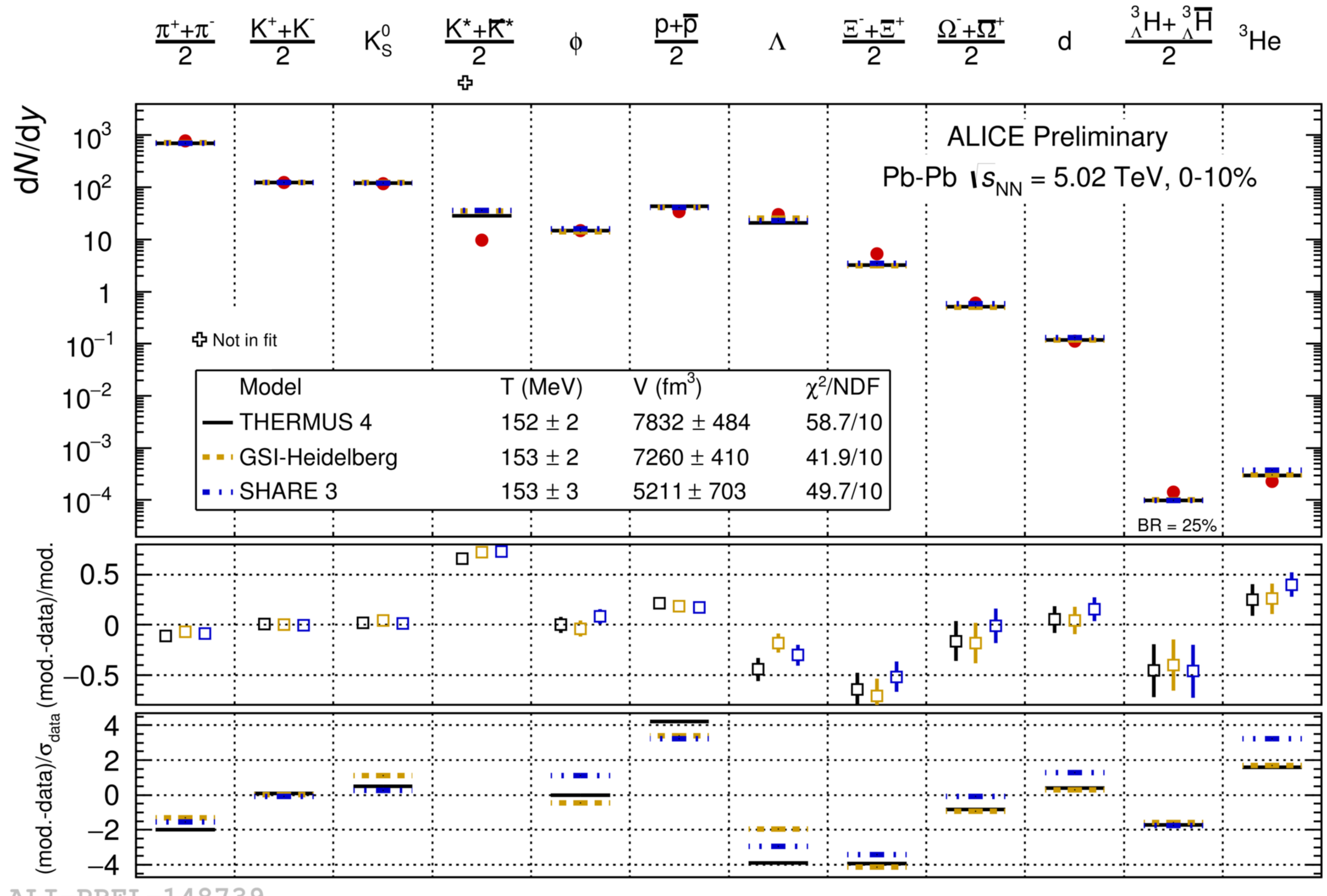
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC185, 2056 (2014)

- **Thermal model** successful in reproducing the **particle yields** measured in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV → (anti-)(hyper-)nuclei included in the fit
- This result suggests that (hyper-)nuclei production happens at the **hadronisation**
- **The present formulation of thermal model seems to be the standard model of particle production in A-A collisions**

The standard model for A-A collisions?

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



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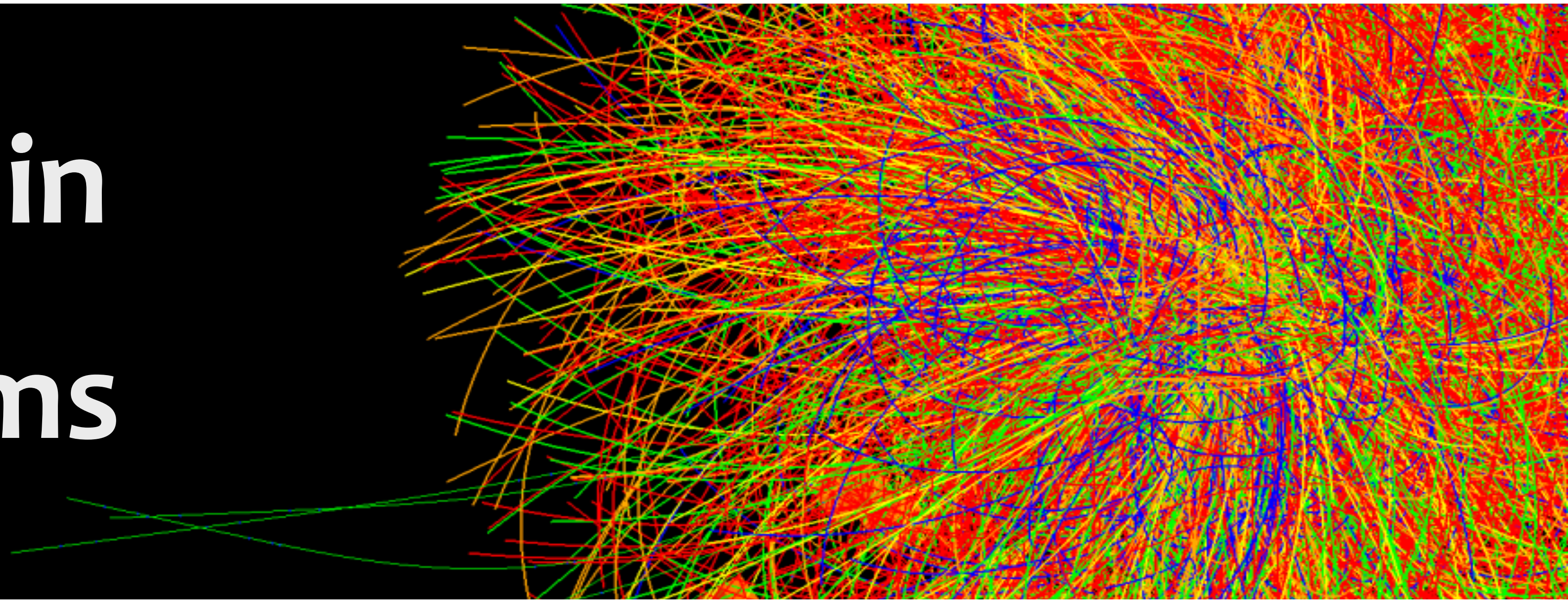
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC185, 2056 (2014)

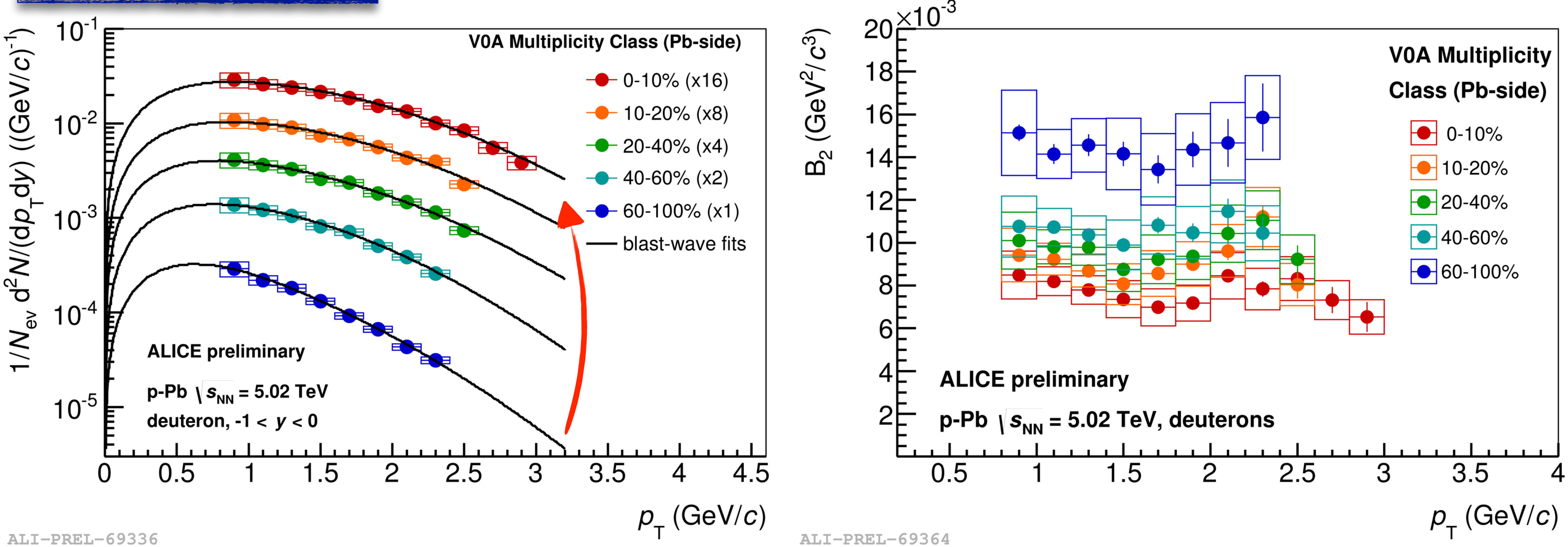
- Larger data sample collected in LHC Run2 and improved reconstruction and analysis techniques reduced the uncertainties.
- Although describing qualitatively well the particle yields, there is less agreement between the thermal model prediction and the particle yields
- **Does the model need further tuning and improvement?**

Production in small systems



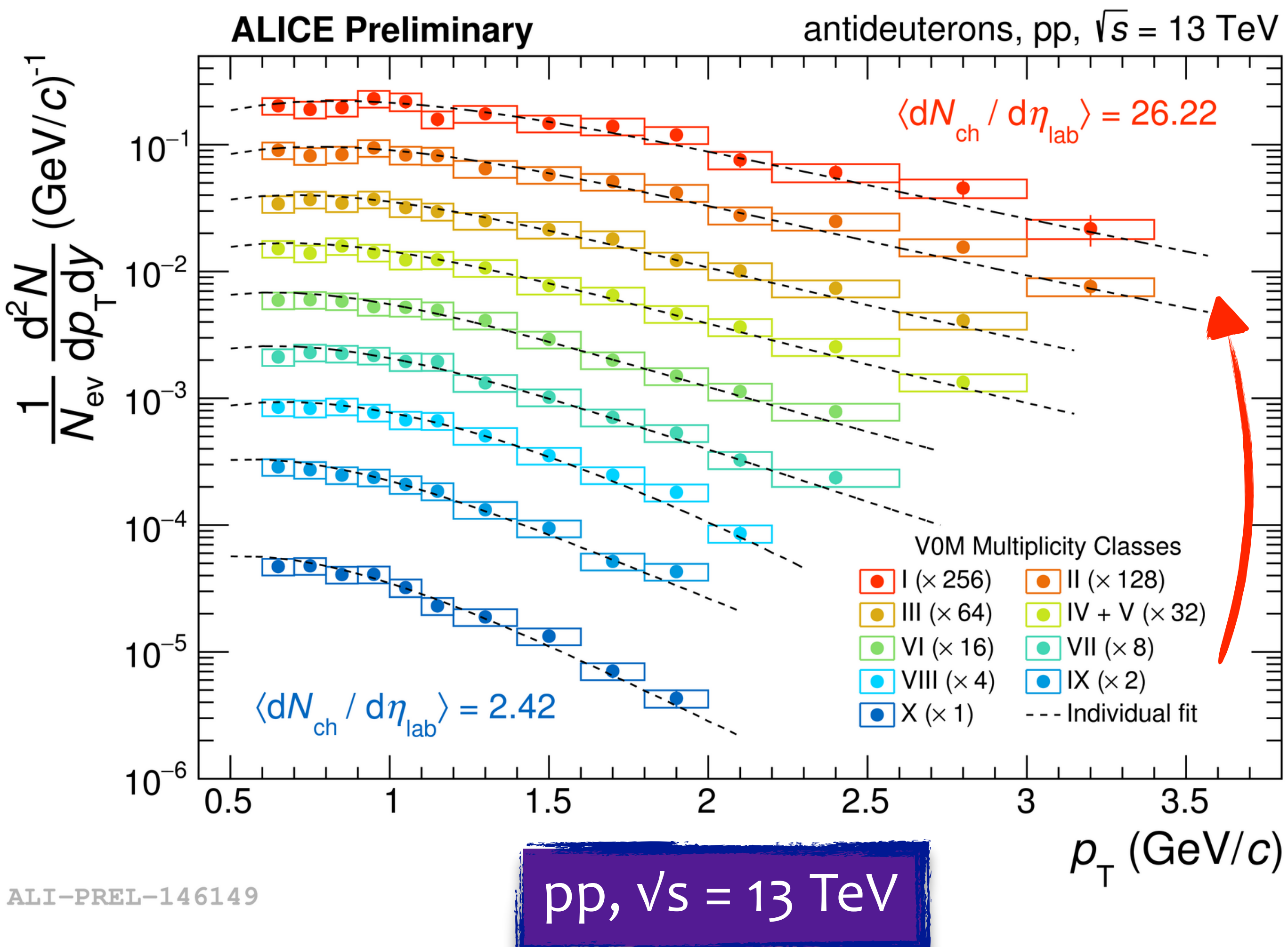
Deuteron production

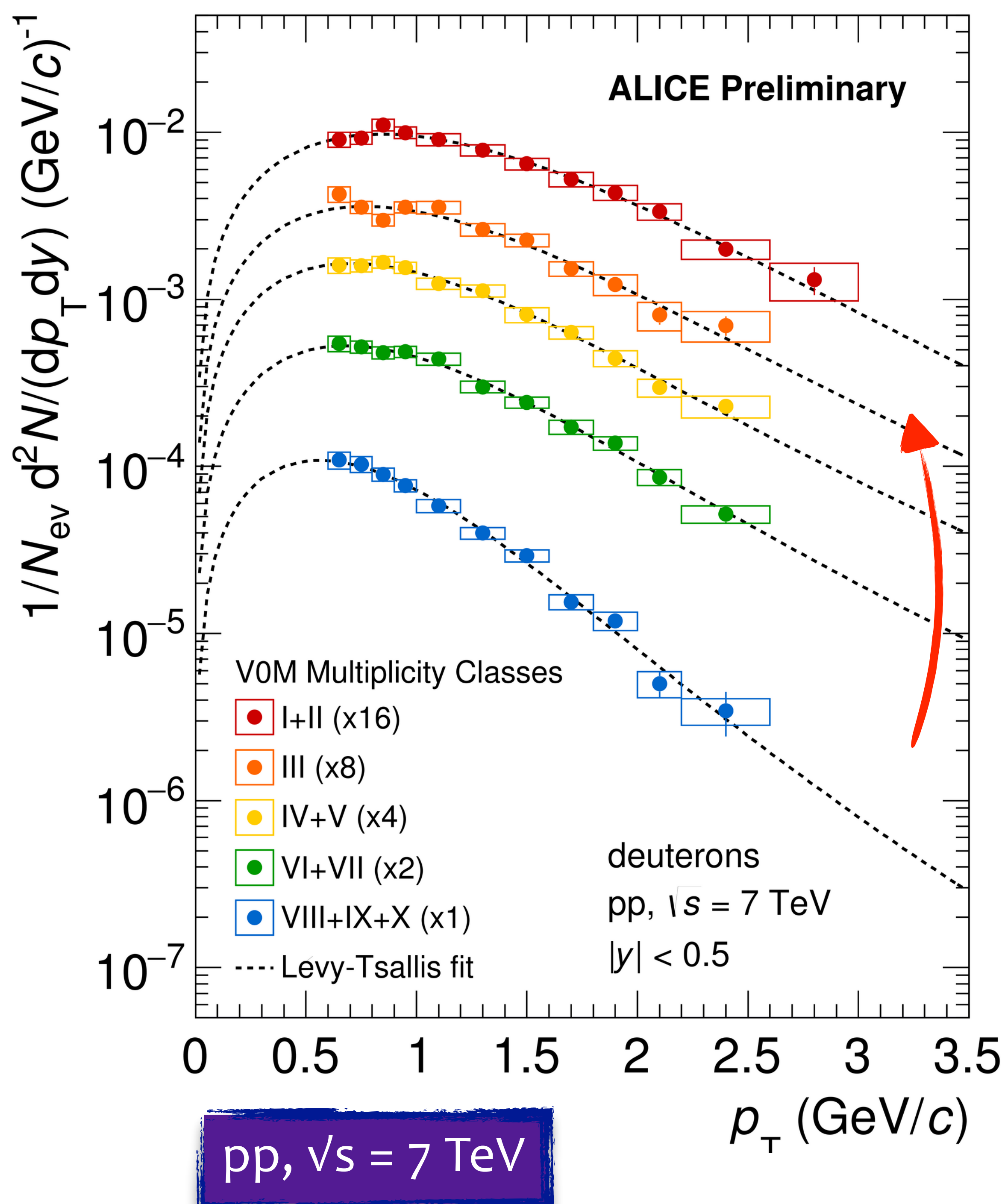
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV



- p_T spectra becomes harder with increasing multiplicity in p-Pb → hint of radial flow
  - the Blast-Wave (BW) function describe the data well in p-Pb and is used for the yield extrapolation to the unmeasured regions
- deuteron B_2 is almost flat as a function of p_T while it increase while going to lower multiplicity in p-Pb → compatible with simple coalescence picture

Deuteron production

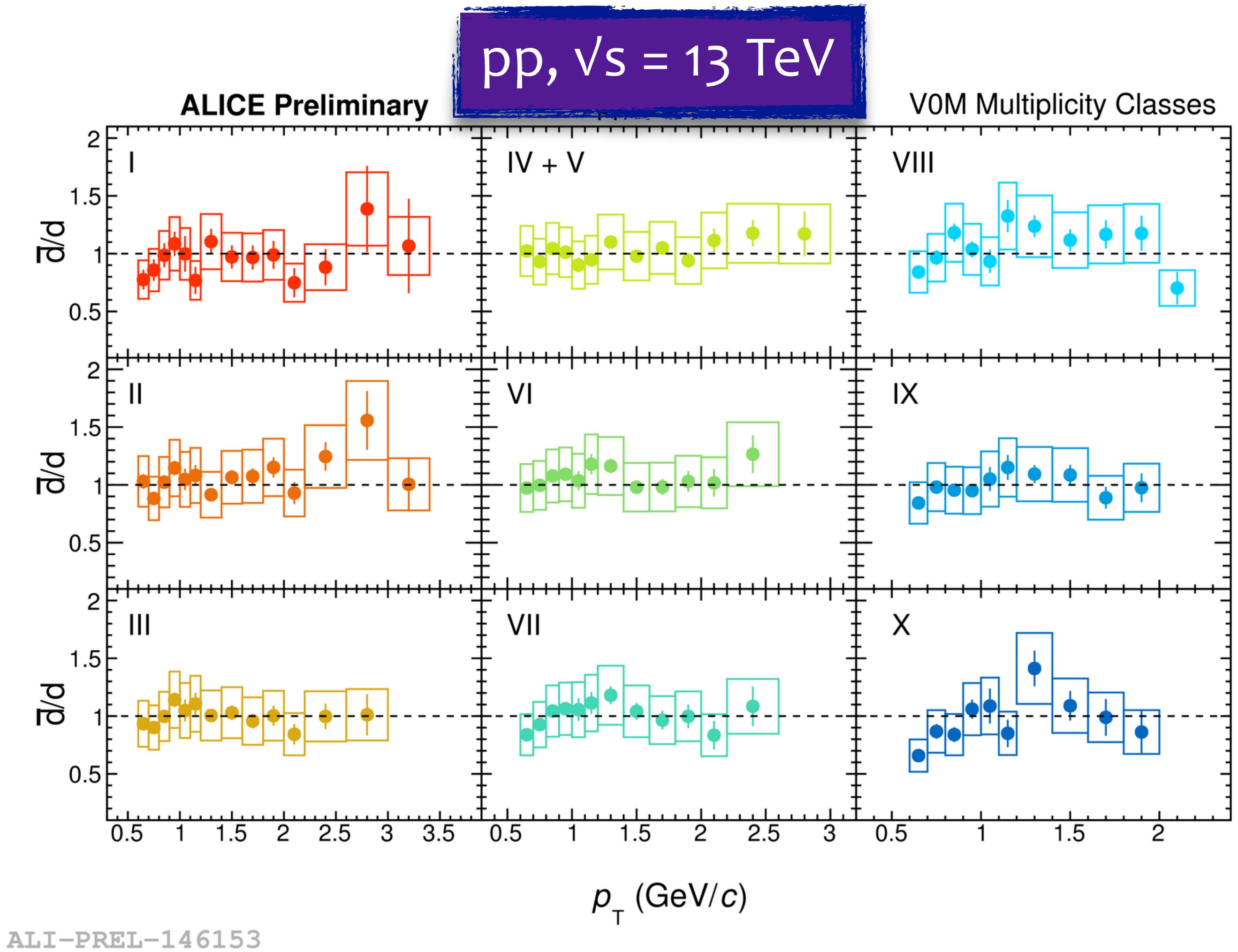


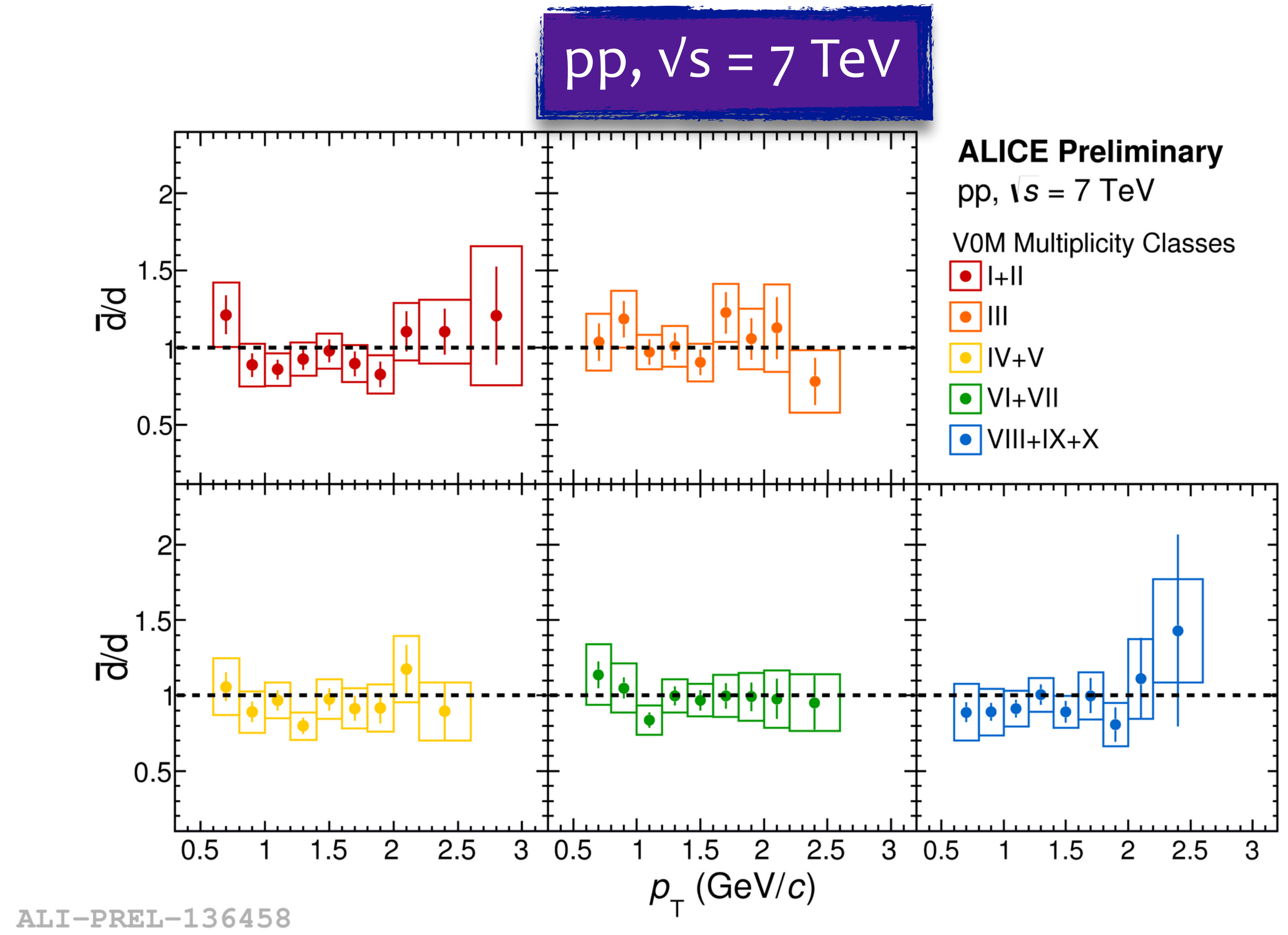


- The fit is performed with a Levy-Tsallis function [8] used for the yield extrapolation to the unmeasured regions
- Also the p_T spectra as a function of charged particle multiplicity do not show a pronounced hardening

[8] C. Tsallis, J. Stat. Phys. 52 (1988) 479

Anti-deuteron/deuteron ratio



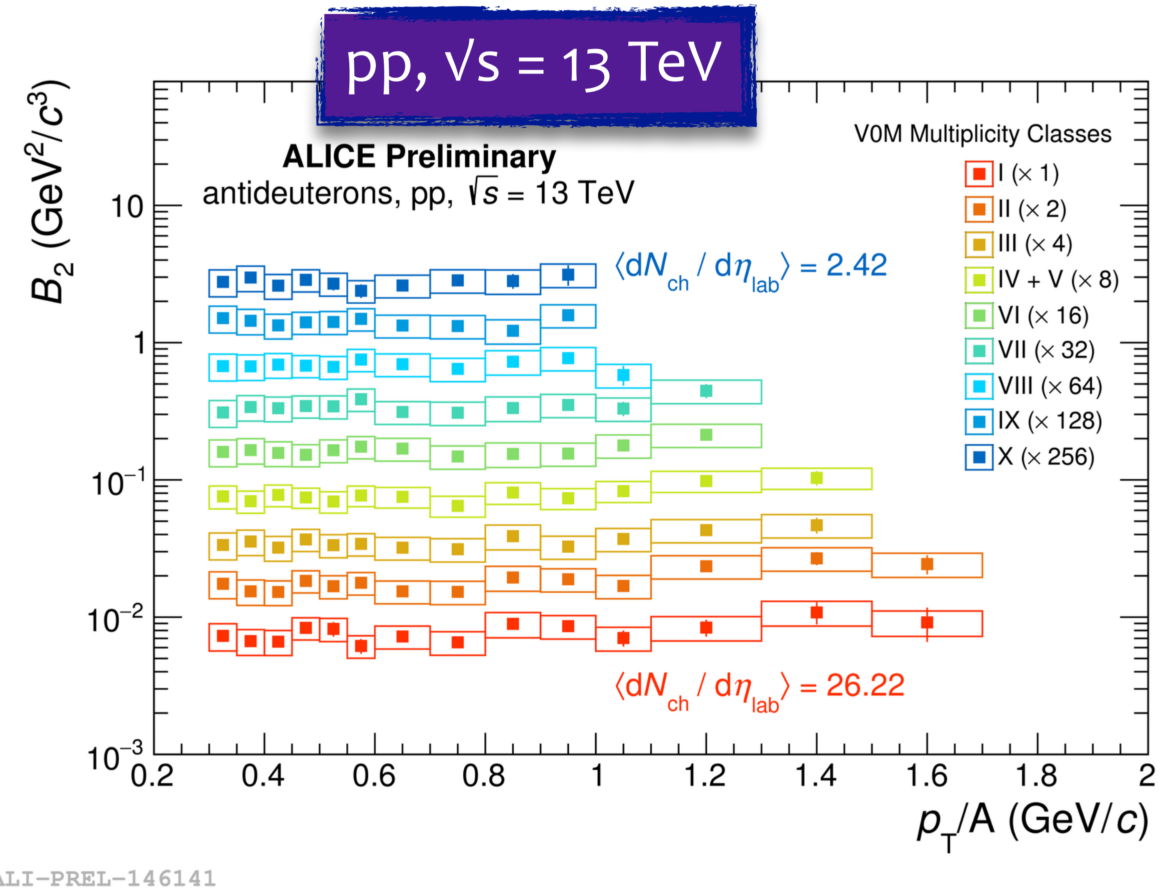


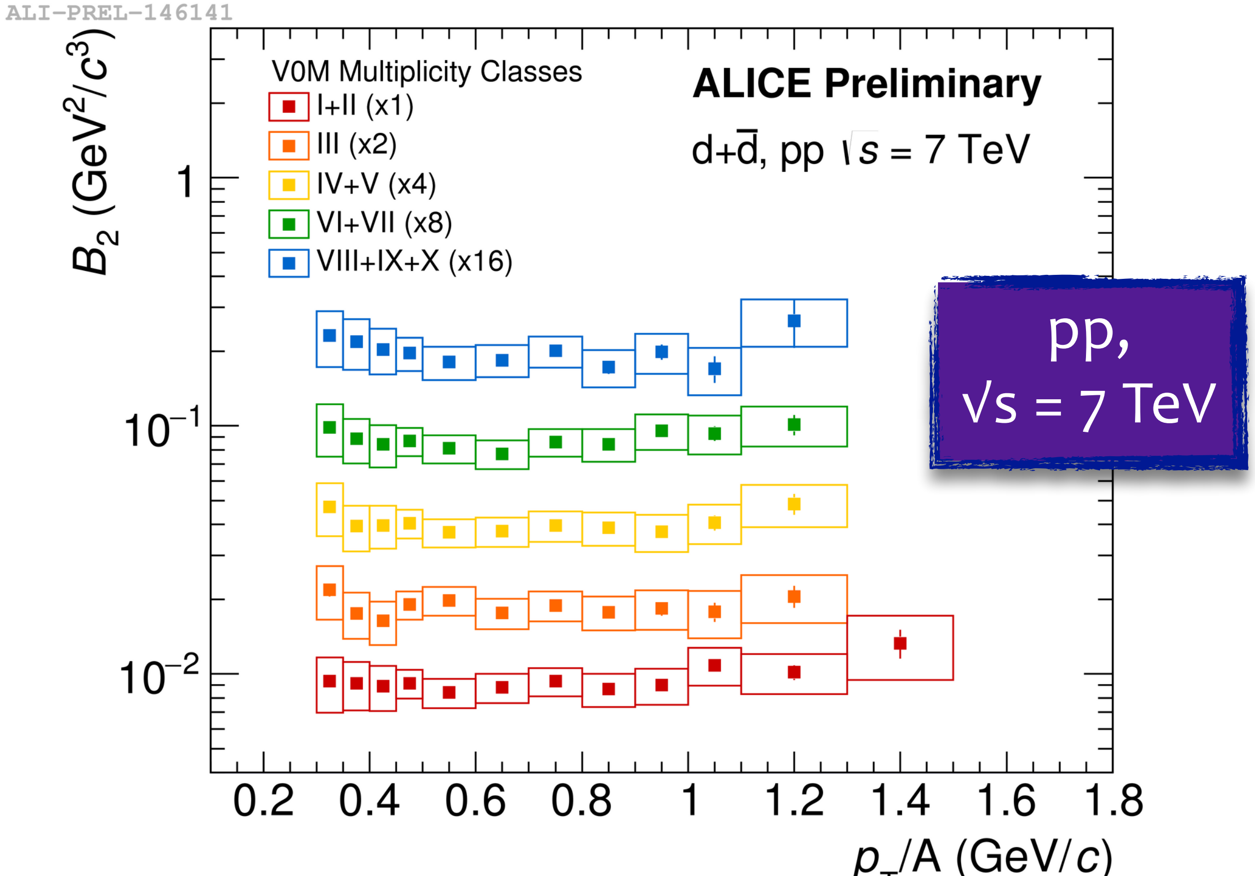
- In the regime of nuclear transparency thermal and coalescence models predict for a nucleus X with mass number A:

$$\frac{\overline{\mathrm{X}}}{\mathrm{X}} \approx \left(\frac{\overline{\mathrm{p}}}{\mathrm{p}}\right)^{\mathrm{A}}$$

- Results of d̄/d in p-p collisions confirm the prediction:
  - p_T and multiplicity independent

Coalescence parameter B_2





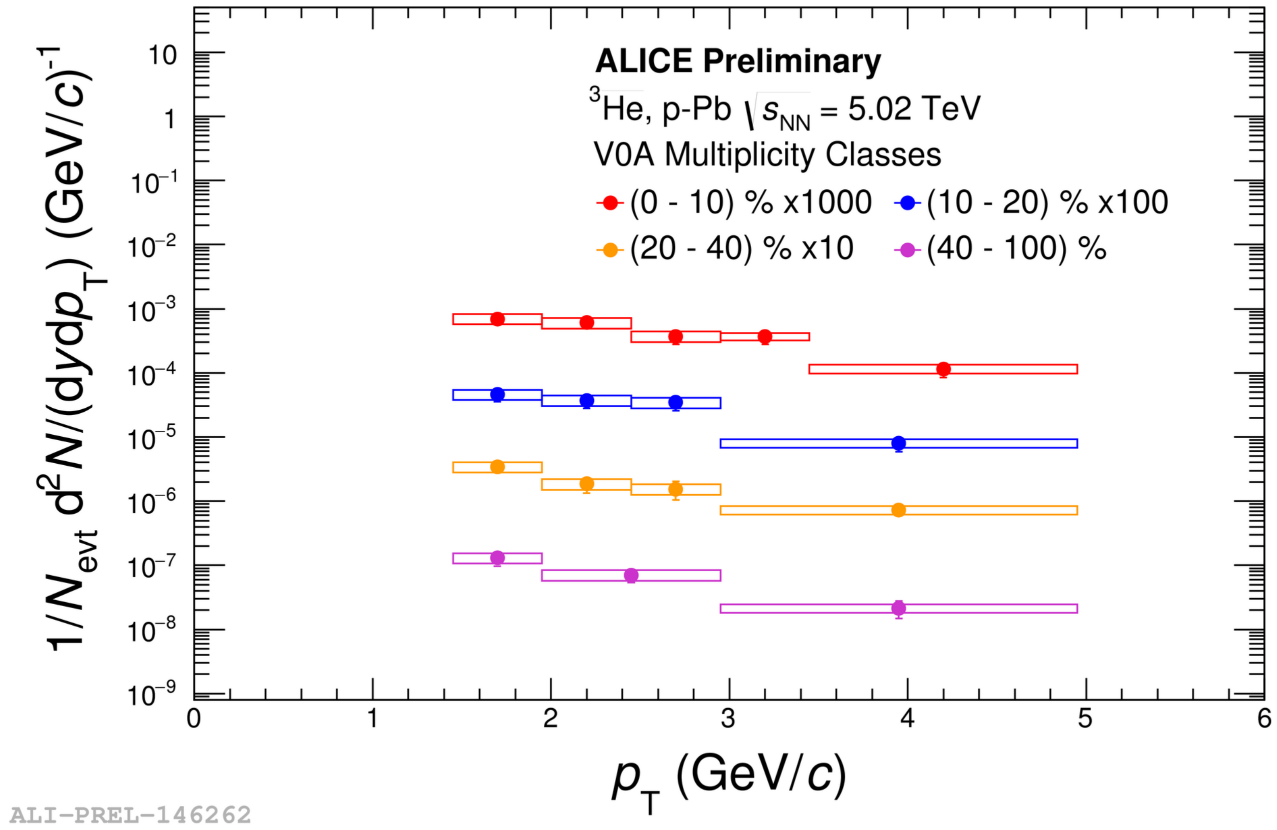
- The probability to form a (anti-)deuteron via coalescence can be quantified by the coalescence parameter B_2:

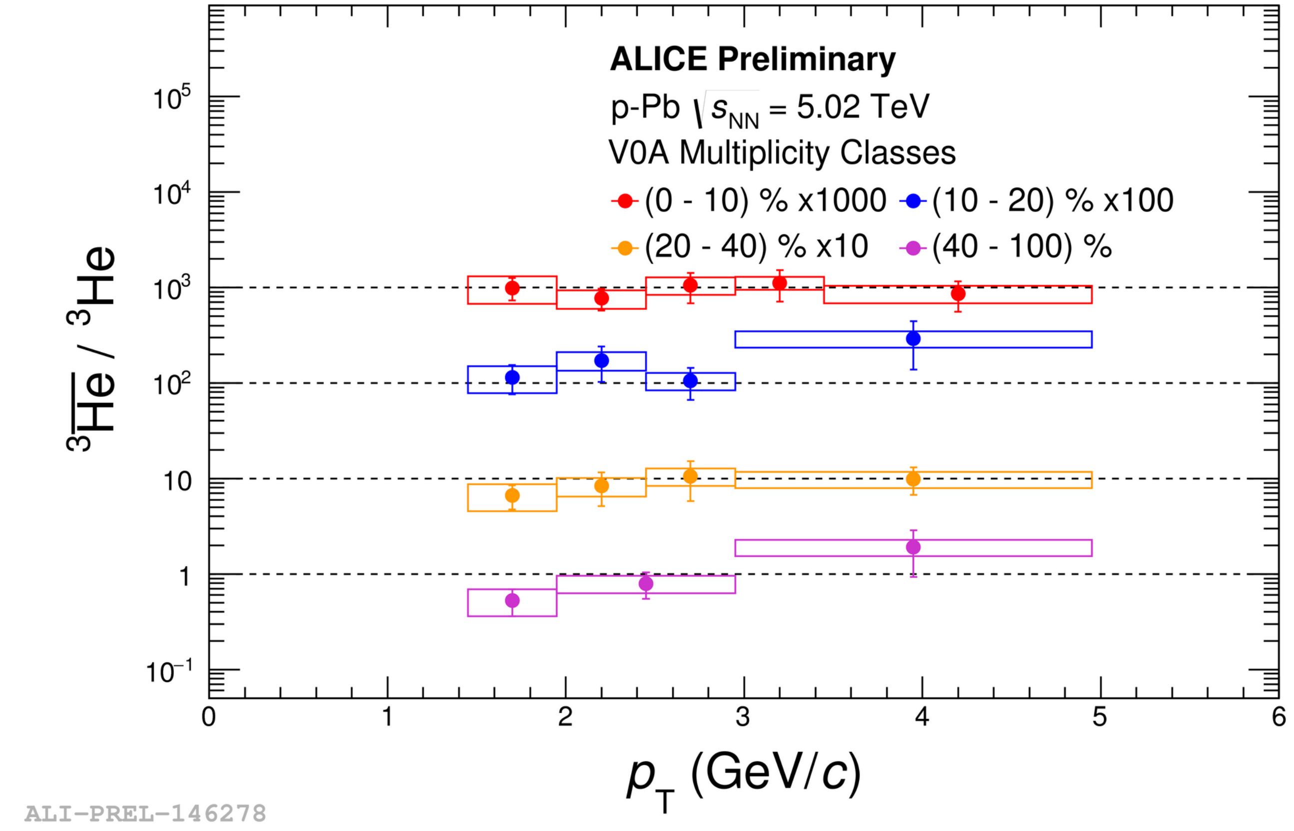
$$B_A = E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3} \Big/ \left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}p_p^3} \right)^A$$

- B_2 measured in p-p collisions as a function of charged particle multiplicity:
  - B_2 is flat as a function of p_T
  - B_2 increases while going to lower multiplicities
- This behavior is in agreement with the simple coalescence model

^{3}He production

p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

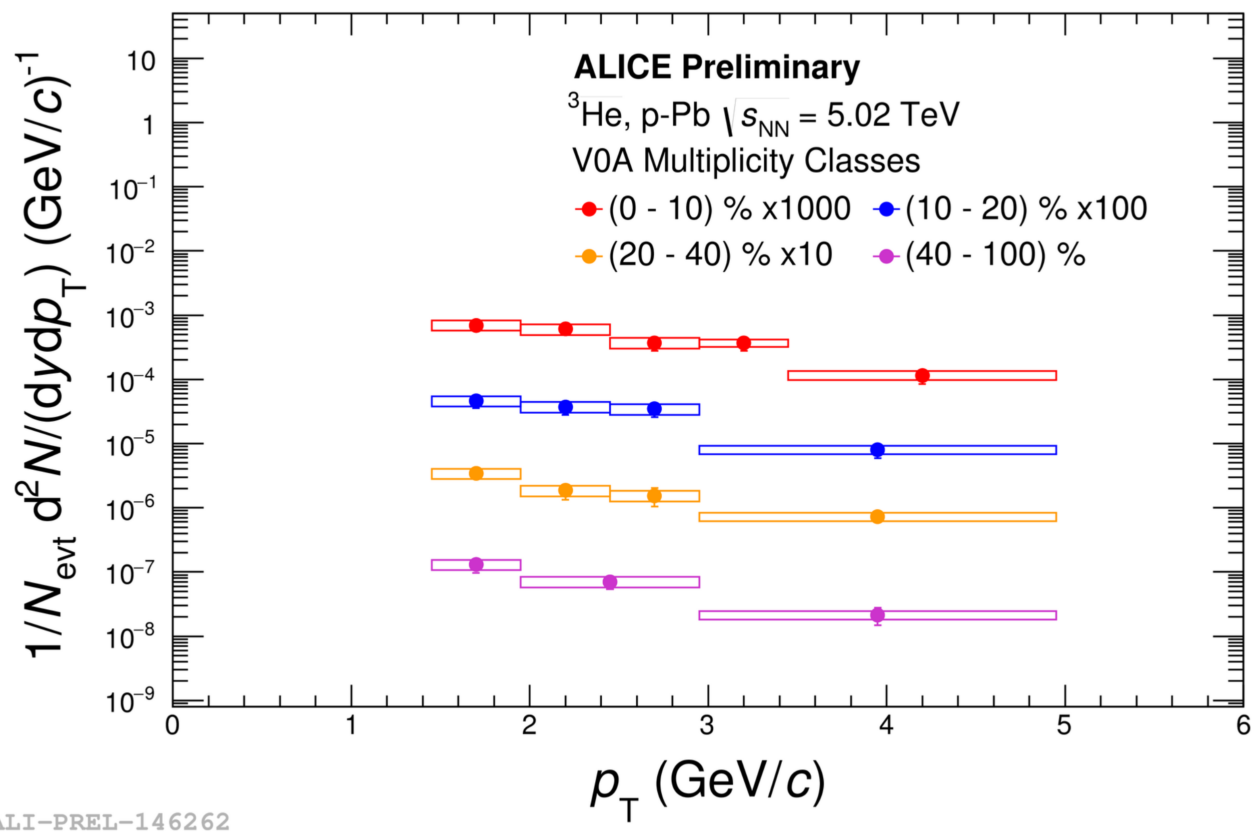


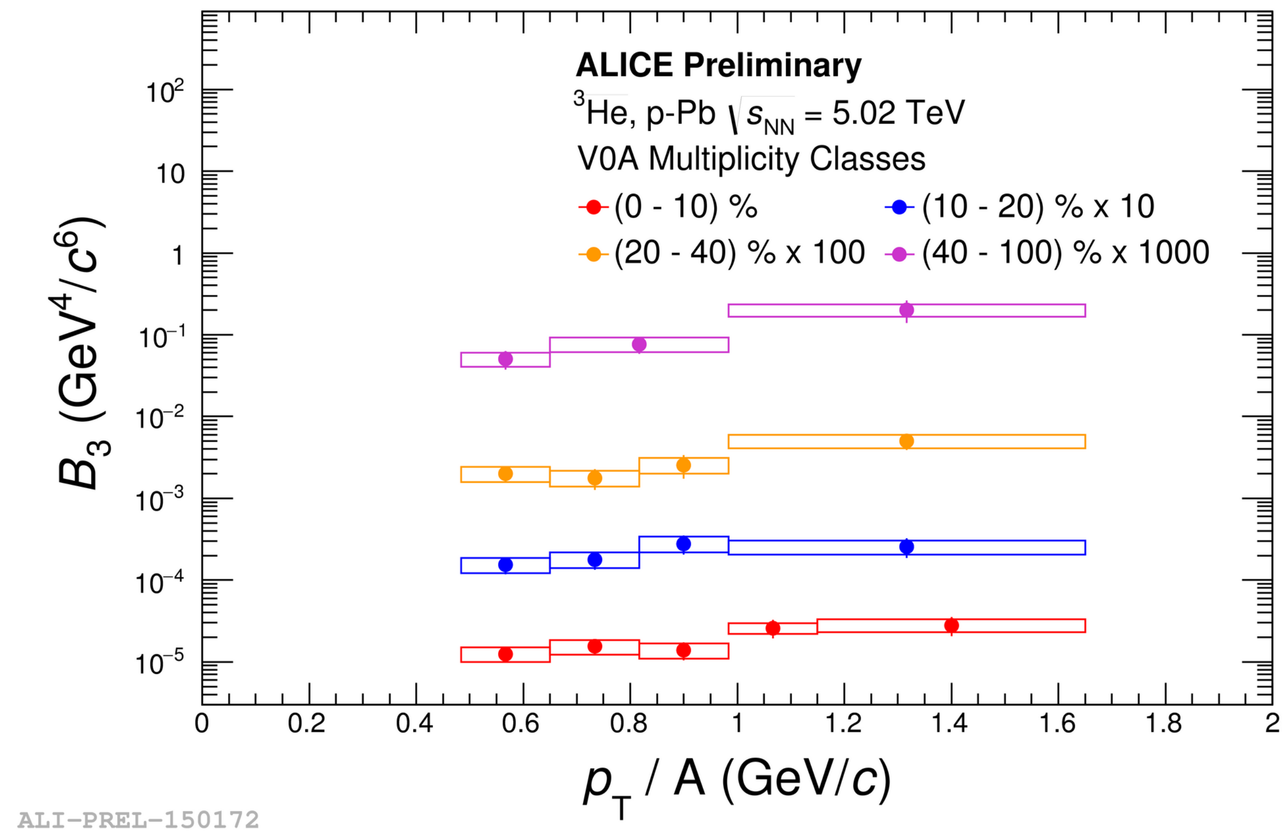


- p_T spectra measured in 4 multiplicity bins in p-Pb
  - show a hardening with increasing multiplicity
- $^3\overline{He}/^3He$ ratio in agreement with unity as a function of p_T and multiplicity
- B_3 measured in p-Pb collisions as a function of charged particle multiplicity:
  - almost flat as a function of p_T, except for the lowest multiplicity class

^{3}He production

p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV





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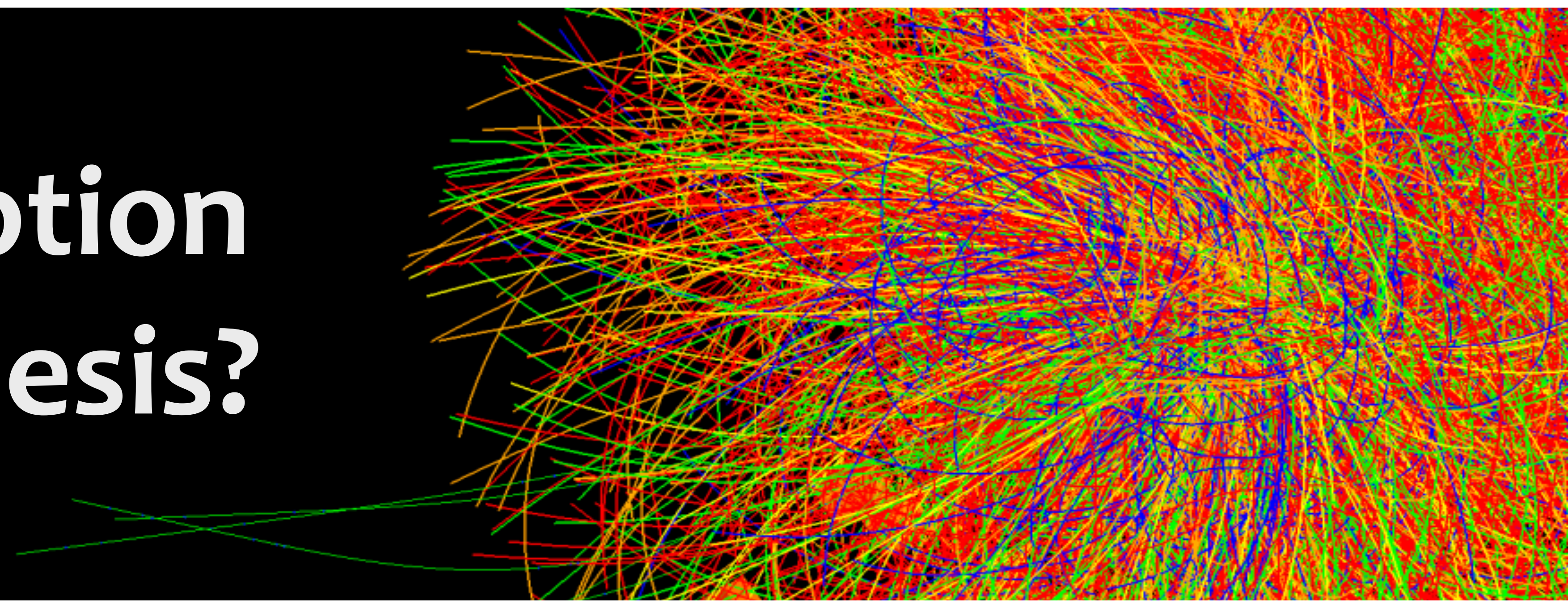
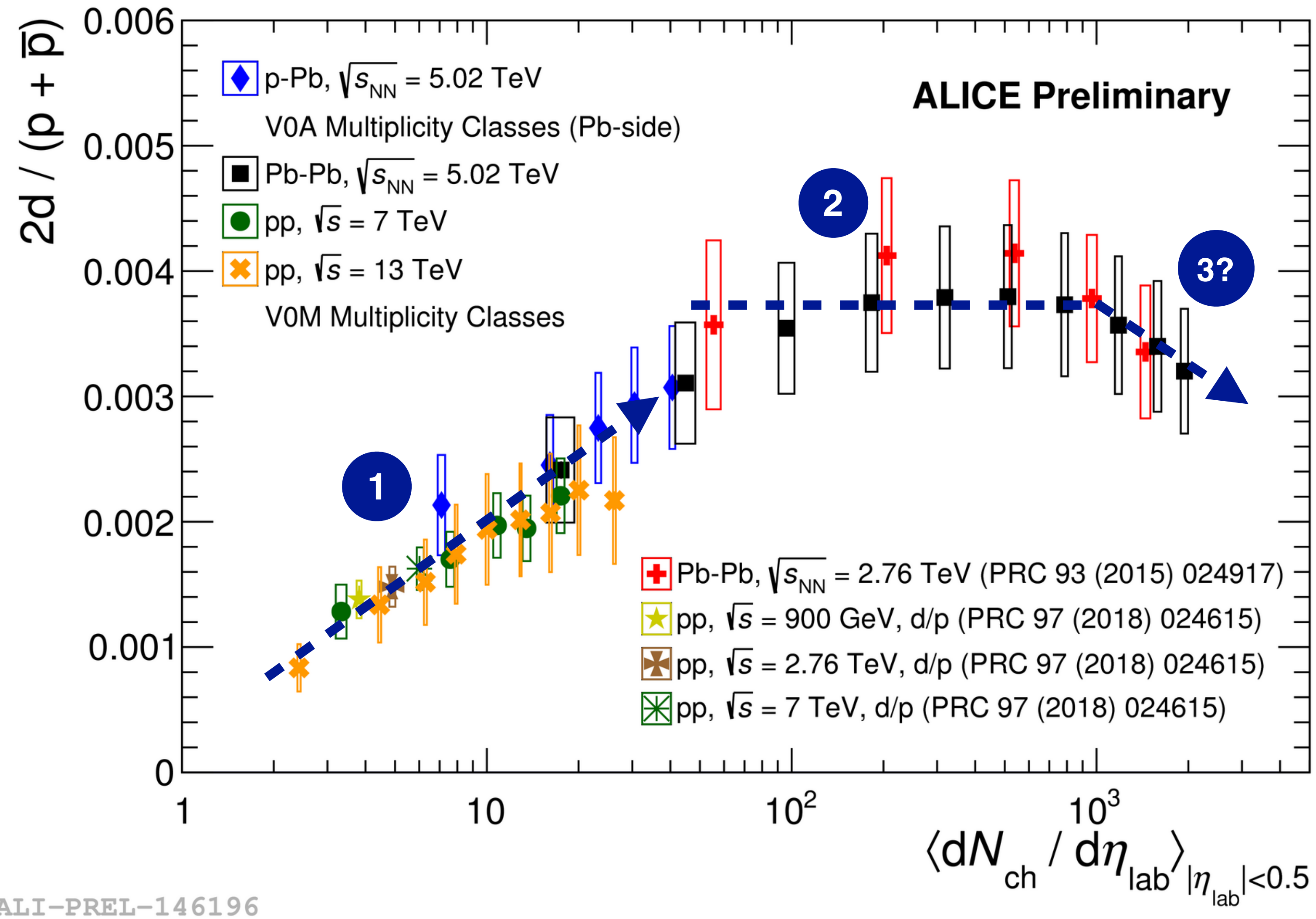
Unified description of nucleosynthesis?



Nucleus over proton ratio

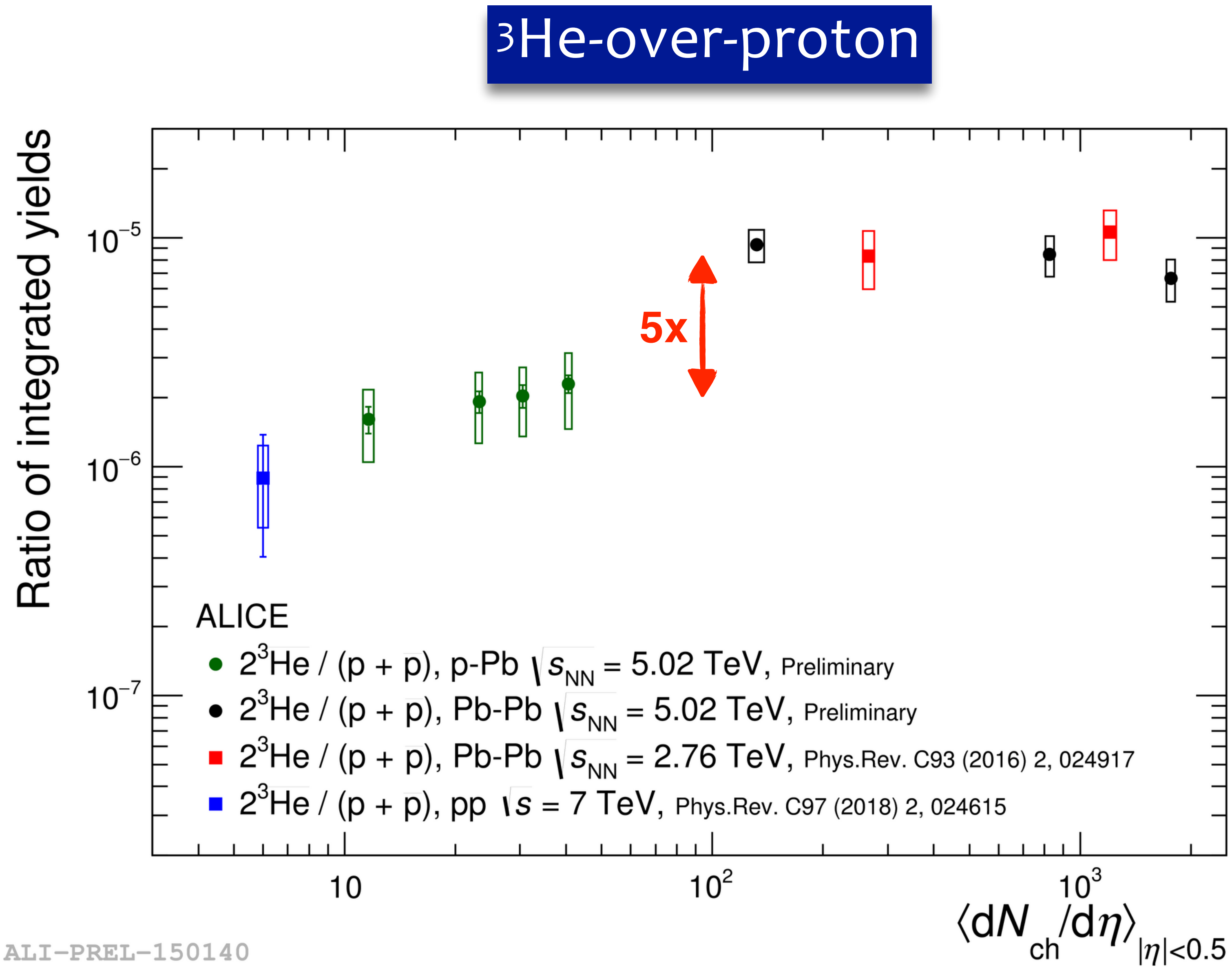
deuteron-over-proton



Is there a unique production mechanism depending only on the system size?

- d/p ratio does not show discontinuity between different colliding systems
- Two different regimes:
  1. **Increasing**: rise at low multiplicity compatible with the description of the coalescence models
  2. **Flat**: at high multiplicity there is no dependence of the ratio on the multiplicity, in agreement with thermal model predictions
  3. **Suppression(?)**: still not significant with these uncertainties
- On the other hand ^{3}He/p ratio shows factor 5 step between small systems and Pb-Pb

Nucleus over proton ratio



If the factor 5 is confirmed by studies on larger data samples, then a unified description will be more challenging

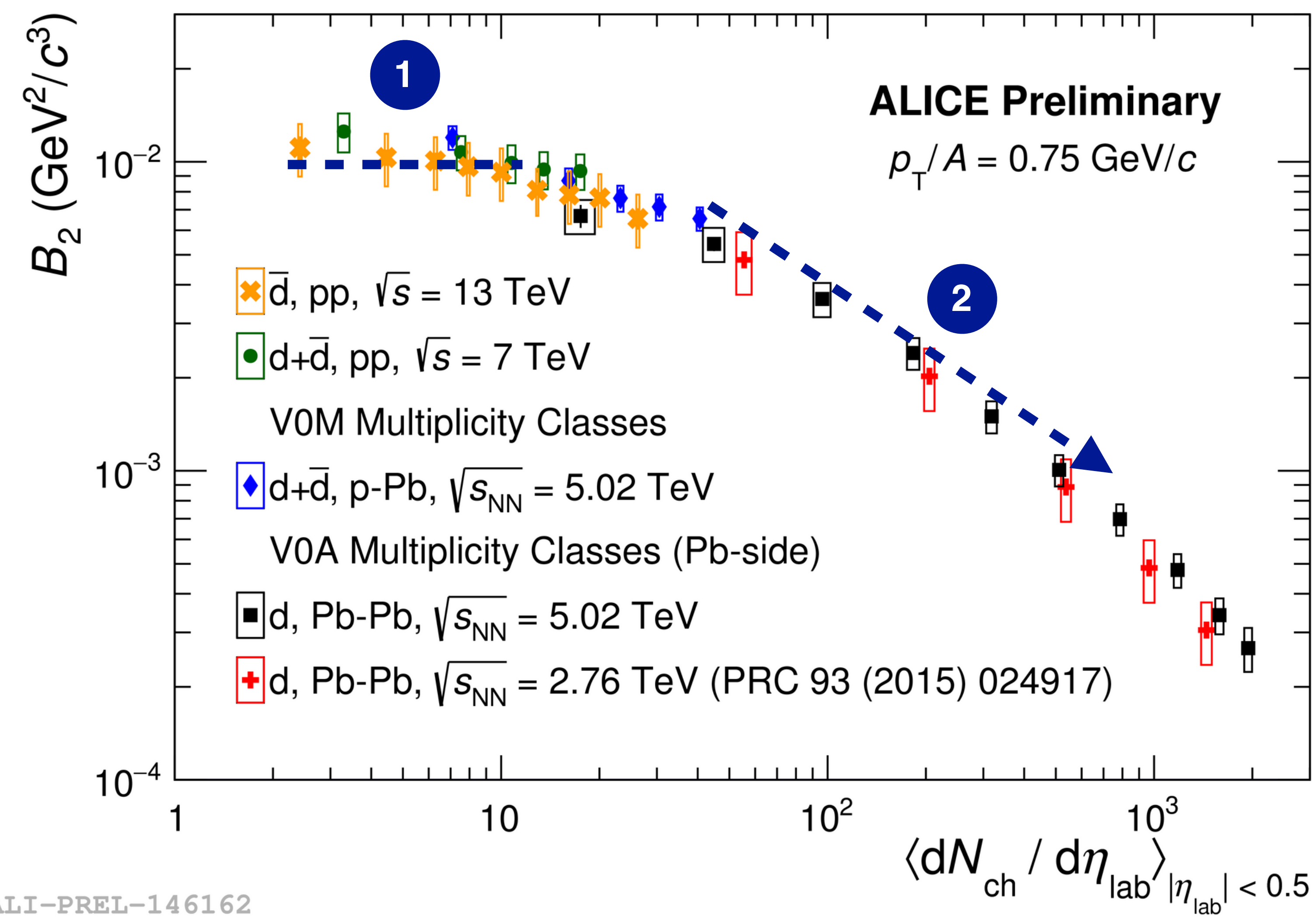
- d/p ratio does not show discontinuity between different colliding systems
- Two different regimes:
  1. **Increasing**: rise at low multiplicity compatible with the description of the coalescence models
  2. **Flat**: at high multiplicity there is no dependence of the ratio on the multiplicity, in agreement with thermal model predictions
  3. **Suppression(?)**: still not significant with these uncertainties
- On the other hand $^{3}He/p$ ratio shows factor 5 step between small systems and Pb-Pb

Multiplicity dependence of B_A

- The measurement of B_2 does not show discontinuity between different colliding systems
- Two different regimes:
  1. **Flat**: the system size is smaller than deuteron size
  2. **Decreasing**: the system size gets larger than the deuteron size
- This behavior has been qualitatively described by parametrizing the coalscence parameter using the system HBT radius *R*:

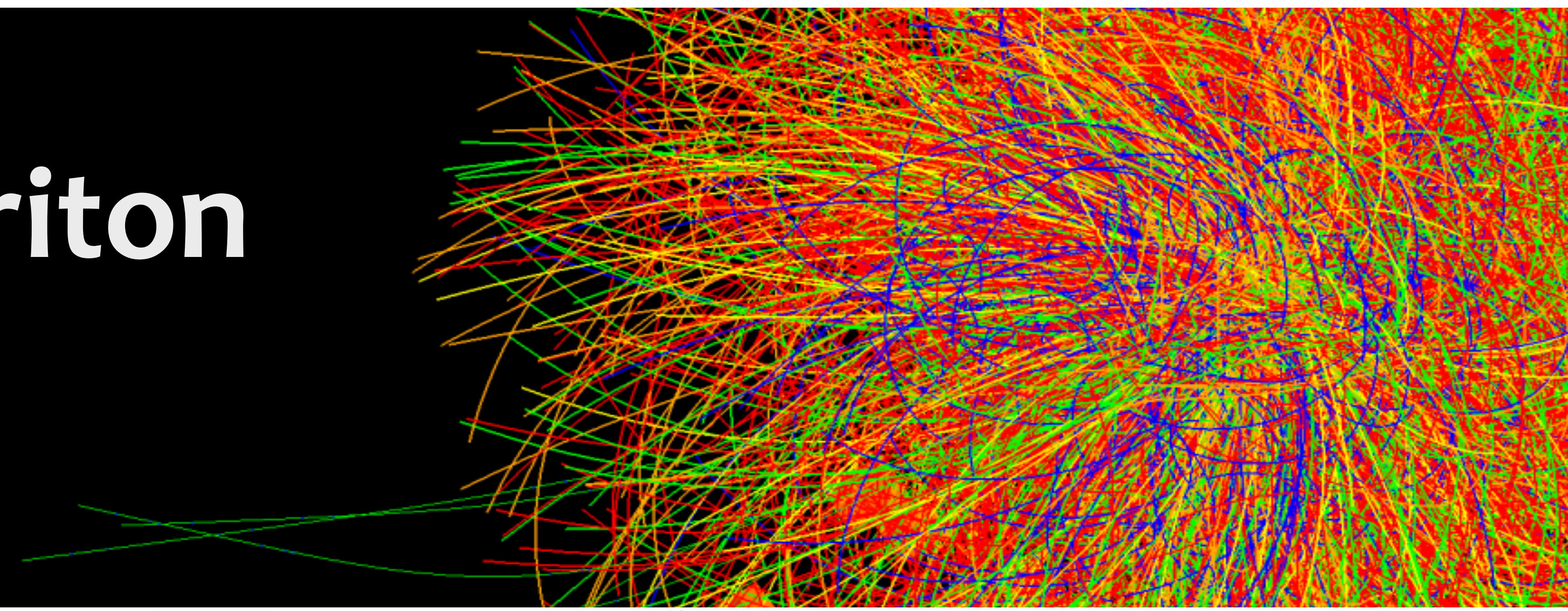
$$\frac{B_2}{\mathrm{GeV}^2} \approx 0.068 \left[\left(\frac{R(p_\mathrm{T})}{1\mathrm{fm}} \right)^2 + 2.6 \left(\frac{b_2}{3.2\mathrm{fm}} \right)^2 \right]^{-3/2}$$

K. Blum et al., Phys. Rev. D 96 (2017) 103021



Is there a unique production mechanism depending only on the system size?

(Anti-)hypertriton lifetime



Can we still talk about a puzzle?

Hypertriton

Hypertriton ($^{3}_{\Lambda}$H): bound state of **p**, **n** and **Λ**, is the lightest known hypernucleus

- Mass = 2.99116 ± 0.00005 GeV/c^2 [1]
- Λ binding energy = 0.13 ± 0.05 MeV [1]
- lifetime: world average = 216^{+16}_{-19} ps [2]
- decay channels: ➡ Mesonic (**MWD**)
  ➡ Non Mesonic (**NMWD**)

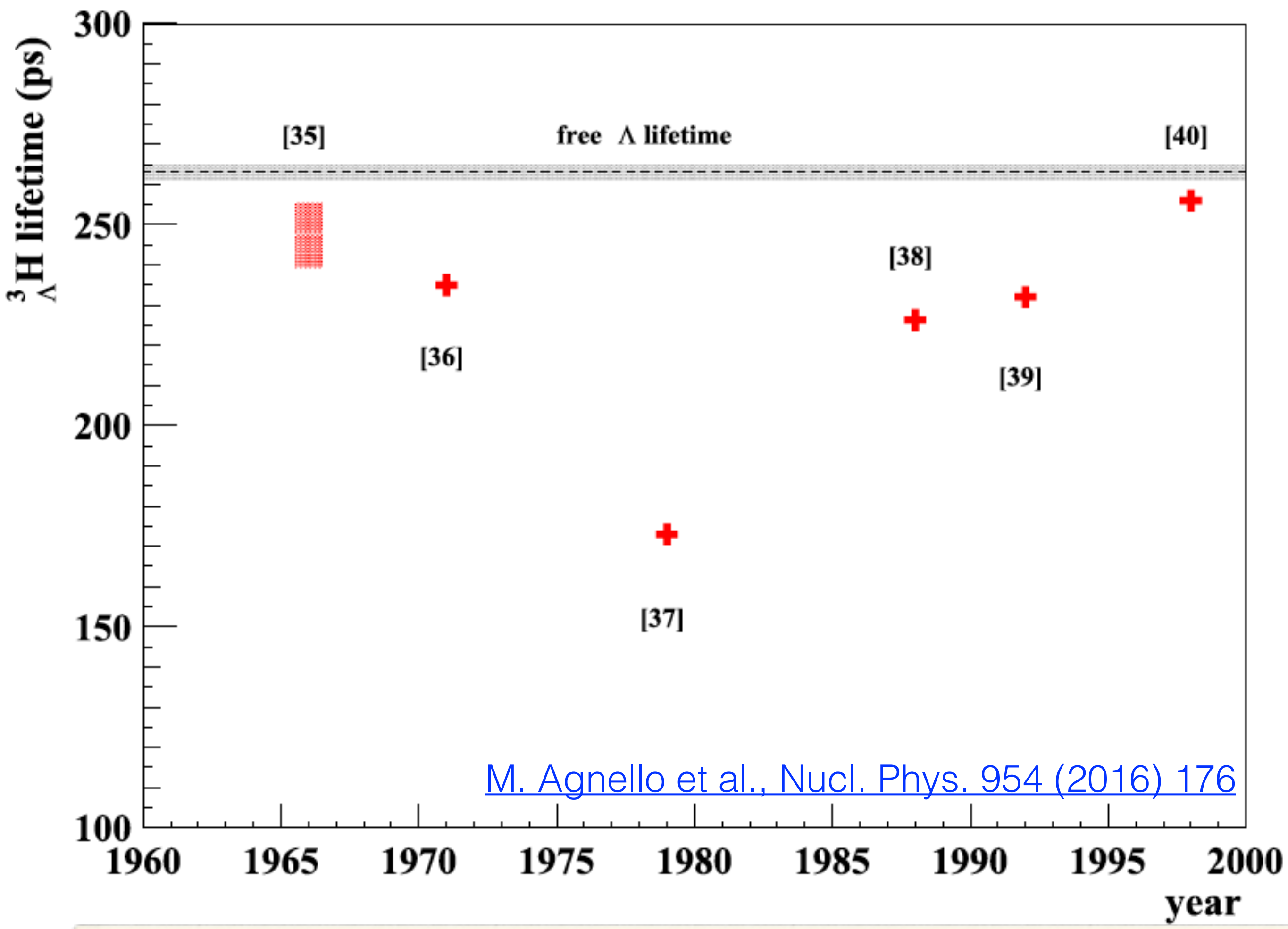
Mesonic channels

Channels	Branching Ratio [3]
^{3}He+π^- ^{3}H+π^0	37,3%
d+p+π^- d+n+π^0	60,1%
n+p+p+π^- n+n+p+π^0	0,94%

- Very small Λ separation energy led to the hypothesis that the $^{3}_{\Lambda}$H lifetime is slightly below the free Λ hyperon lifetime (263.2 ± 2 ps [3])
  - consequence of the fact that the Λ spends most of the time far from the deuteron core due to very small value of B_Λ
  - many theoretical calculations support this hypothesis

[1] D.H. Davis., Nucl. Phys. A 754 (2005) 3-13
[2] C. Rappold et al., Phys. Lett. B 728, 543 (2014)
[3] H. Kamada et al., Phys. Rev. C 57 (1998) 1595-1603

Theoretical predictions

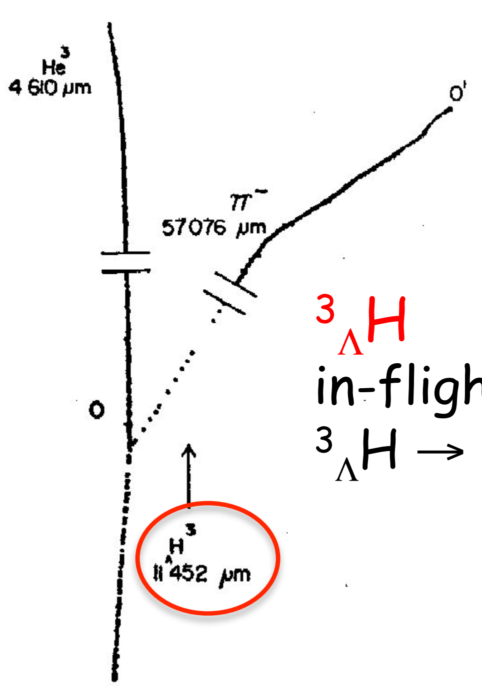


- [35] *M. Rayet, R.H. Dalitz, Il Nuovo Cim. A 46 (1966) 786*
  - values for τ in the range from **239.3 - 255.5 ps**
  - phase space factor, Pauli principle effect, corrections for final-state pion scattering and for NMWD included
- [36] *M. Ram, W.Williams, Nucl. Phys. B 28 (1971) 566*
  - calculated a value of **235 ps**
  - investigation whether hard core corrections in ΛN and NN potentials used to calculate the wave functions could affect the values of τ
- [37] *H. Manosur, K. Higgins, Il Nuovo Cim. A 51 (1979) 180*
  - lower value of **173 ps**
  - calculation based on explicit inclusion of the nucleon induced pionic emission
- [38] *N. Kolesnikov, V. Kopylov, Sov. Phys. J 31 (1988) 210*
  - values for τ of **226.3 ps**
  - Using wave functions found by multi-parameter variation calculations employing 5 different ΛN potential
- [39] *J.G. Congleton, J. Phys. G., Nul. Part. Phys. 18 (1992) 339*
  - obtained a value of **232 ps**
  - using updated values for the NN and YN potentials to determine the wave functions
- [37] *H. Kamada et al., Phys. Rev. C 57 (1998) 1595*
  - prediction of a value of **256 ps**
  - calculation based on rigorous solution of three-body Faddeev equations for the hypernucleus wave function and for the 3N scattering states, where realistic NN and YN interactions were used.

Lifetime measurements: *visualizing techniques*

Hypernuclei discovered1953 in photographic emulsion, through the MWD

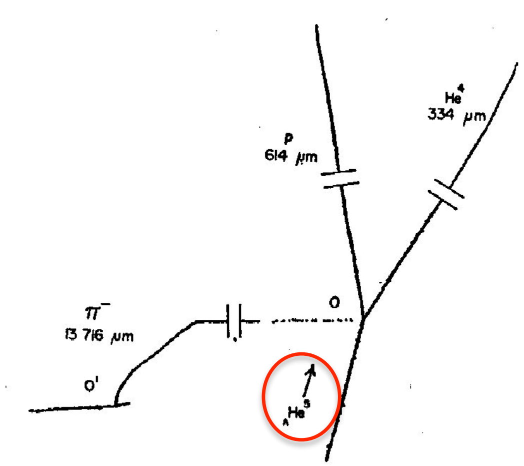
- At the beginning light hypernuclei/hyperfragments identified via their π^- MWD with visualizing techniques
  - emulsion/bubble chambers exposed to energetic K^- beams
  - observation of charged decay modes
- In the first experiments:
  - assignment of spin/parity to light hypernuclei ground state ($^3_\Lambda$H, $^4_\Lambda$H, $^4_\Lambda$He, $^8_\Lambda$Li, $^{11}_\Lambda$B and $^{12}_\Lambda$B) through properties of π^- MWD ($^7_\Lambda$Li)
  - study of the Λ-N spin dependent interaction ($J_{hyp\ g.s.} = J_{core} - 1/2$)



$^3_\Lambda$H
in-flight decay
$^3_\Lambda H \rightarrow {}^3He + \pi^-$

First experiments:
Lifetime obtained from the spatial distribution of the **π–MWD** vertices around the formation point of the hypernucleus

$^5_\Lambda$He
in-flight decay
$^5_\Lambda He \rightarrow {}^4He + p + \pi^-$



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  - study of the Λ-N spin dependent interaction ($J_{hyp\ g.s.} = J_{core} - 1/2$)
- Limitations of visualizing techniques:
  - ✘ no timing information
  - ✘ no neutron, γ detection → only charged WD channels
  - ✘ number of formed hypernuclei not counted → no Branching Ratio determination
  - ✘ spatial distribution of the π^- MWD vertices around the formation point

Lifetime measurements: *counter experiment - I*

Studies with counter experiments at accelerators (BNL AGS, KEK PS) from ’80 on

- high intensity K^- / π^+ beams for hypernuclei production via:

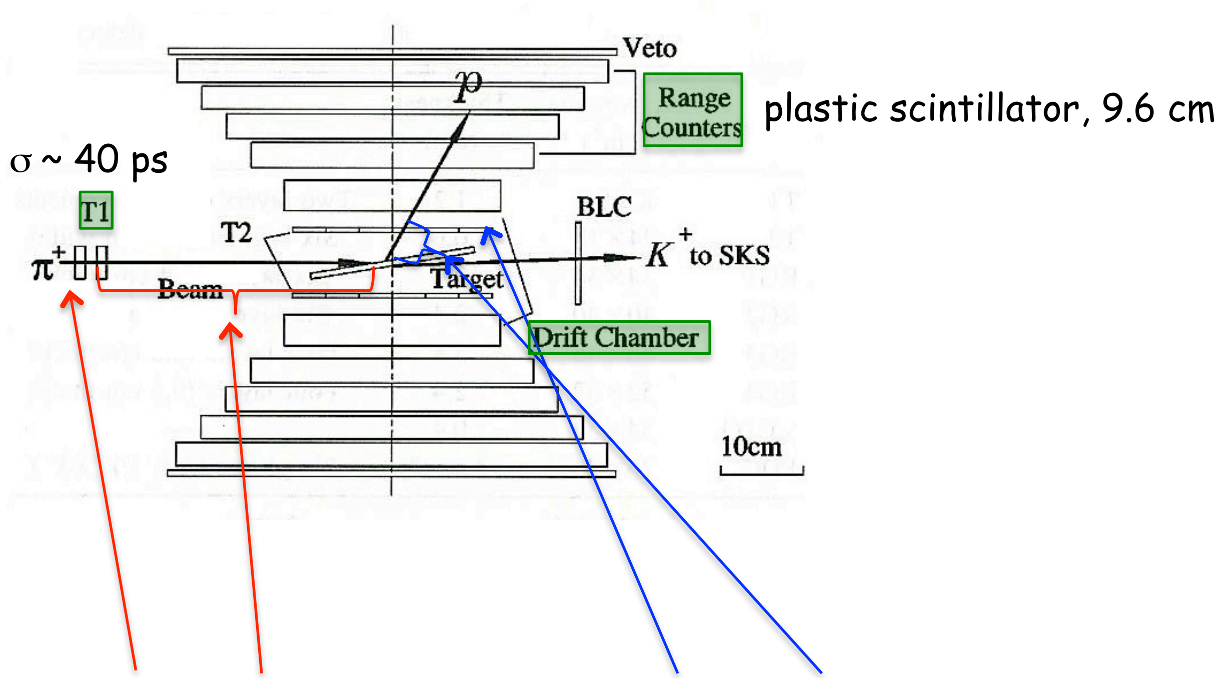
$$K^- + N \to \Lambda + \pi$$

Strangeness exchange

$$\pi^+ + n \to \Lambda + K^+$$

Associated production

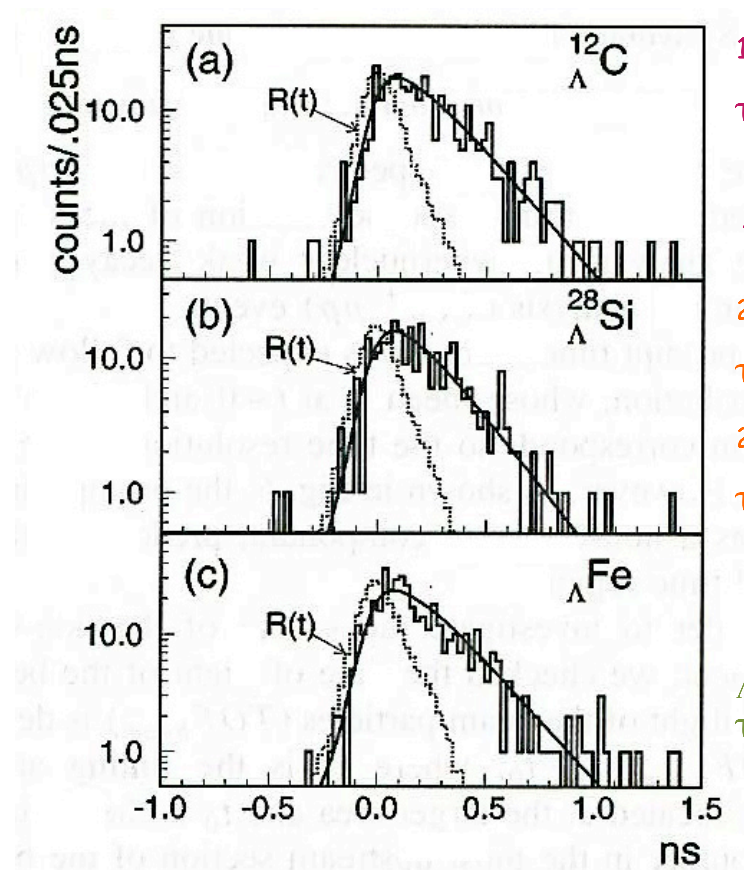
- Coincidence measurements with large solid angle spectrometer and direct timing measurement techniques



$t_p = t_1 + t_{fb}$ $\quad$ $t_d = t_2 - t_{fd}$

$\Delta t = t_d - t_p$

Medium Mass Number hypernuclei



$^{12}_{\Lambda}C$ τ = 231±15 ps

$^{11}_{\Lambda}B$ τ = 211±13 ps

$^{28}_{\Lambda}Si$ τ = 206±12 ps

$^{27}_{\Lambda}Al$ τ = 203±10 ps

$_{\Lambda}Fe$ τ = 215±14 ps

Studies with counter experiments at accelerators (BNL AGS, KEK PS) from '80 on

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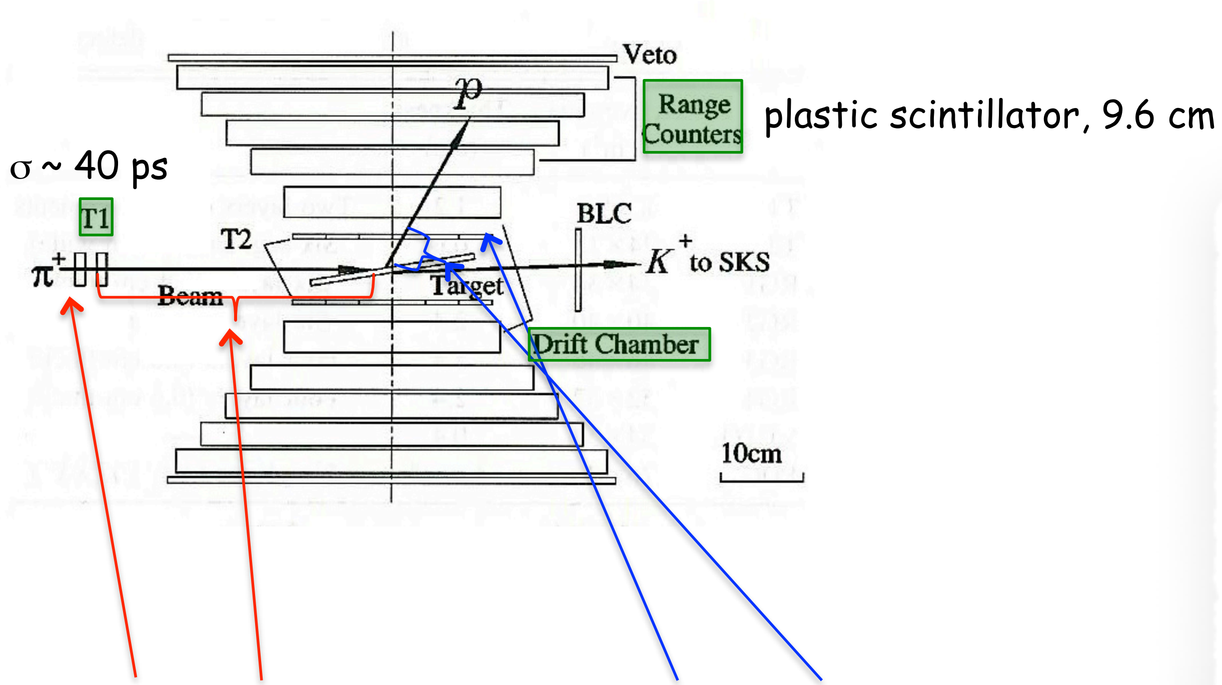


$t_p = t_1 + t_{fb}$ $\quad$ $t_d = t_2 - t_{fd}$

$$\Delta t = t_d - t_p$$

✘ This experimental technique could not be applied to the hydrogen hyperisotopes

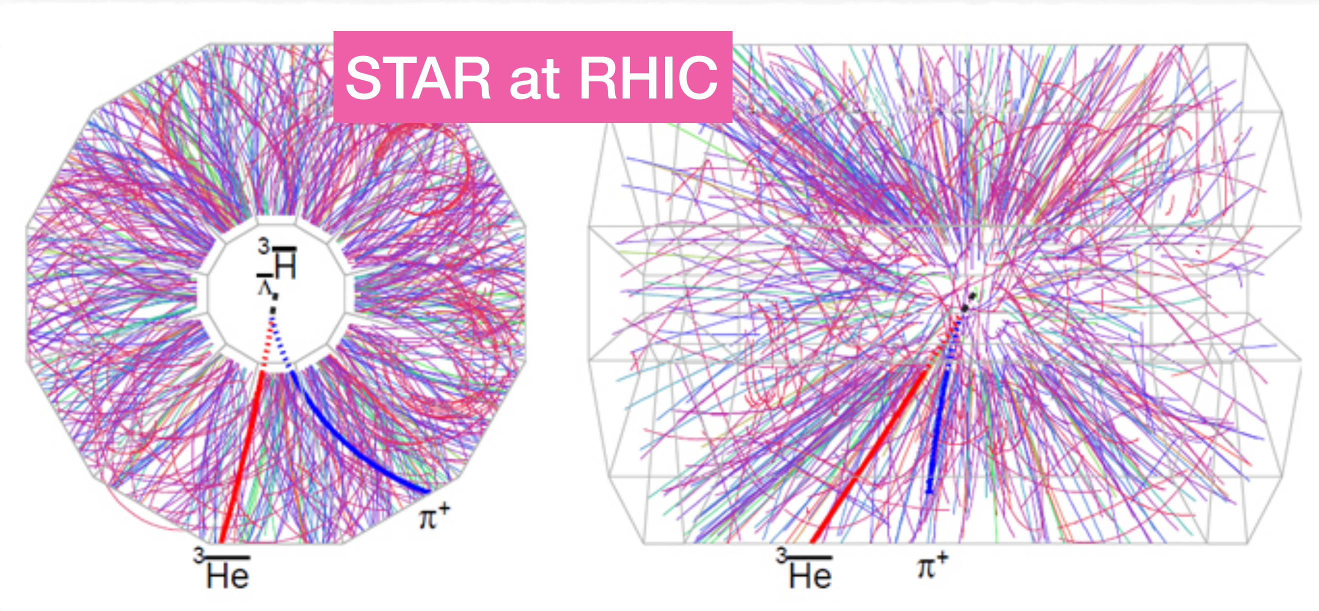
✘ The two-body reactions require targets

- ^3H → radioactive, hard to deal with
- ^4H → does not exist

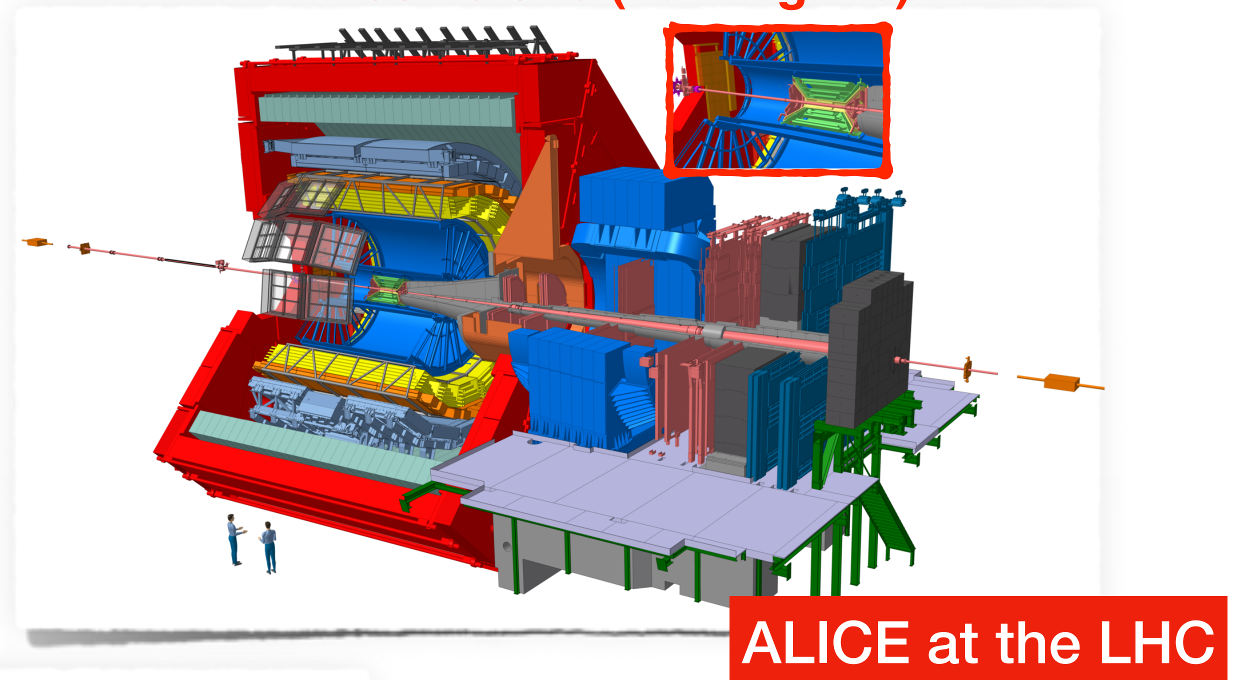
Lifetime measurements: *counter experiment - II*

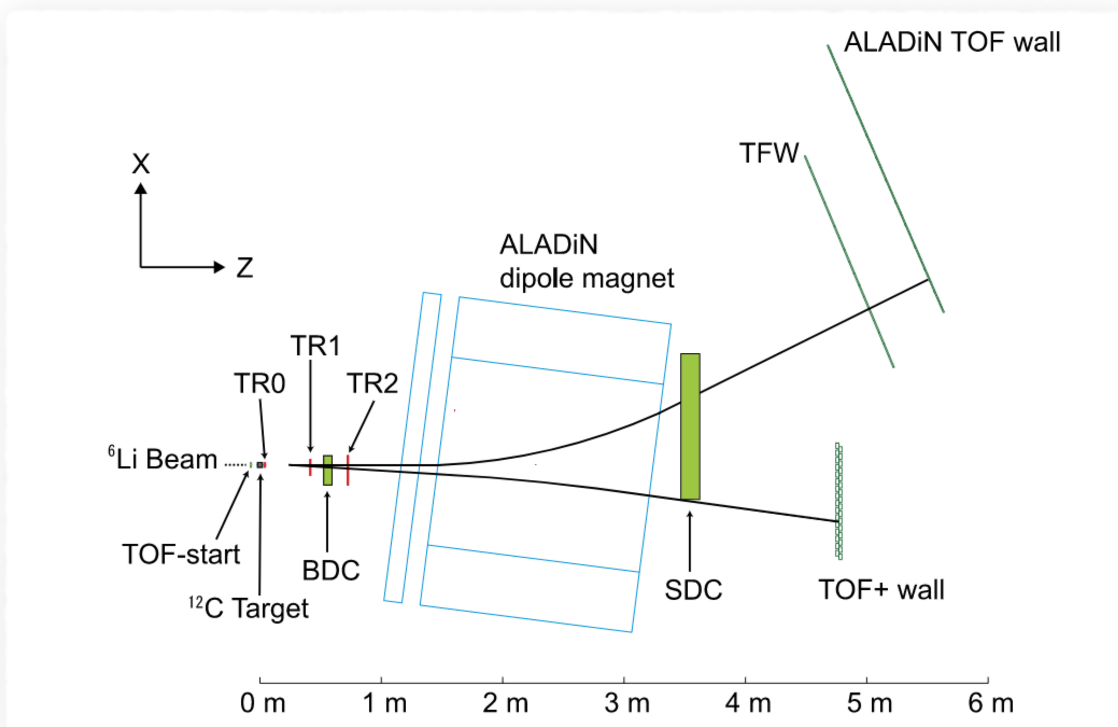
Heavy ion collisions: production of light (anti-)hypernuclei measured via invariant mass of decay products in mesonic decay channels

Au-Au collisions (GeV regime)



Pb-Pb collisions (TeV regime)



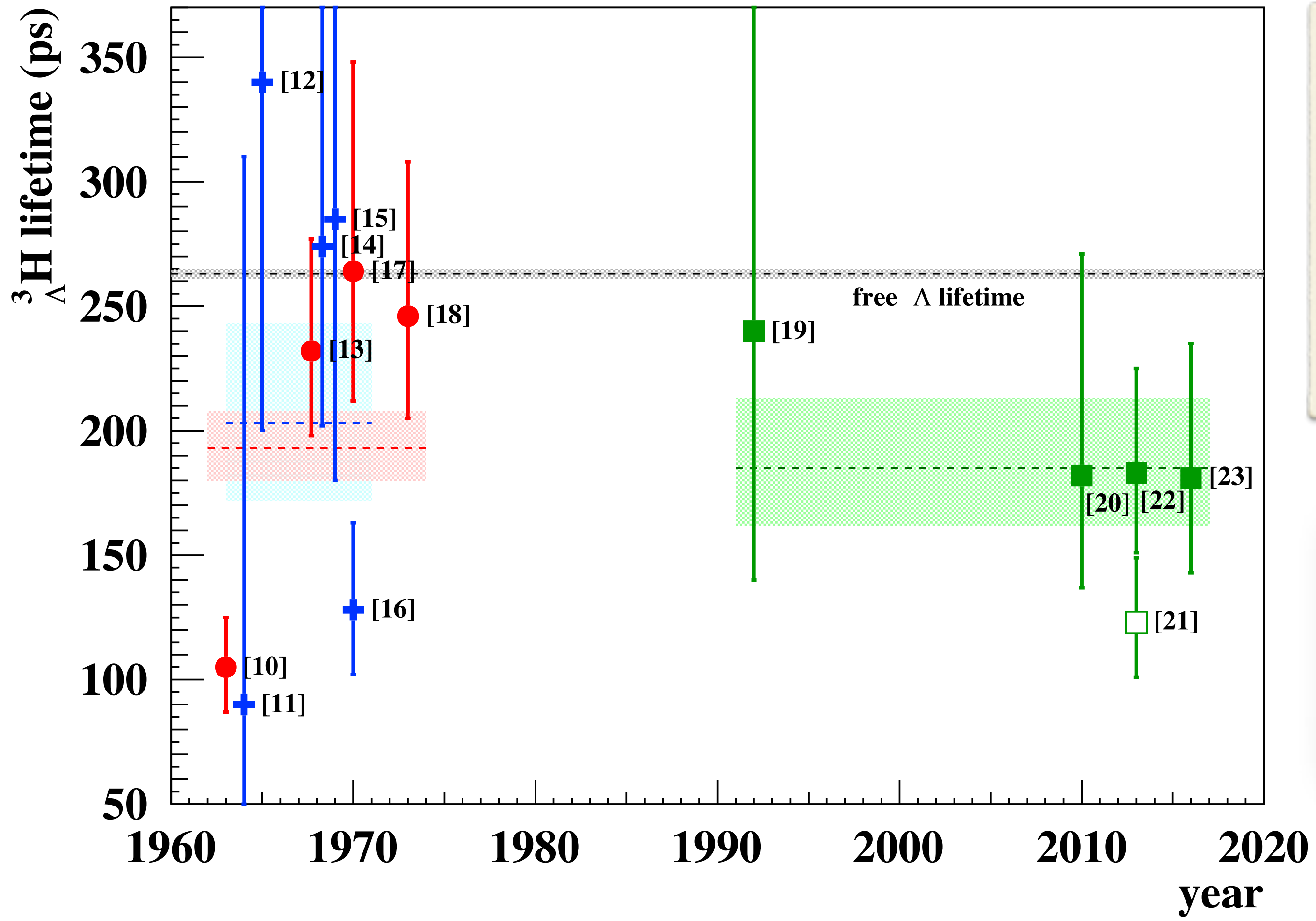


HypHI at GSI

projectile fragmentation reactions of ^{6}Li at 2 AGeV delivered on a carbon target.

Experimental knowledge

M. Agnello et al., Nucl. Phys. 954 (2016) 176



emulsion technique: 203^{+40}_{-31} ps

He Bubble Chamber: 195^{+15}_{-13} ps

Electronic techniques: 185^{+28}_{-23} ps without [21]

Electronic techniques: 163^{+18}_{-16} ps with [21]

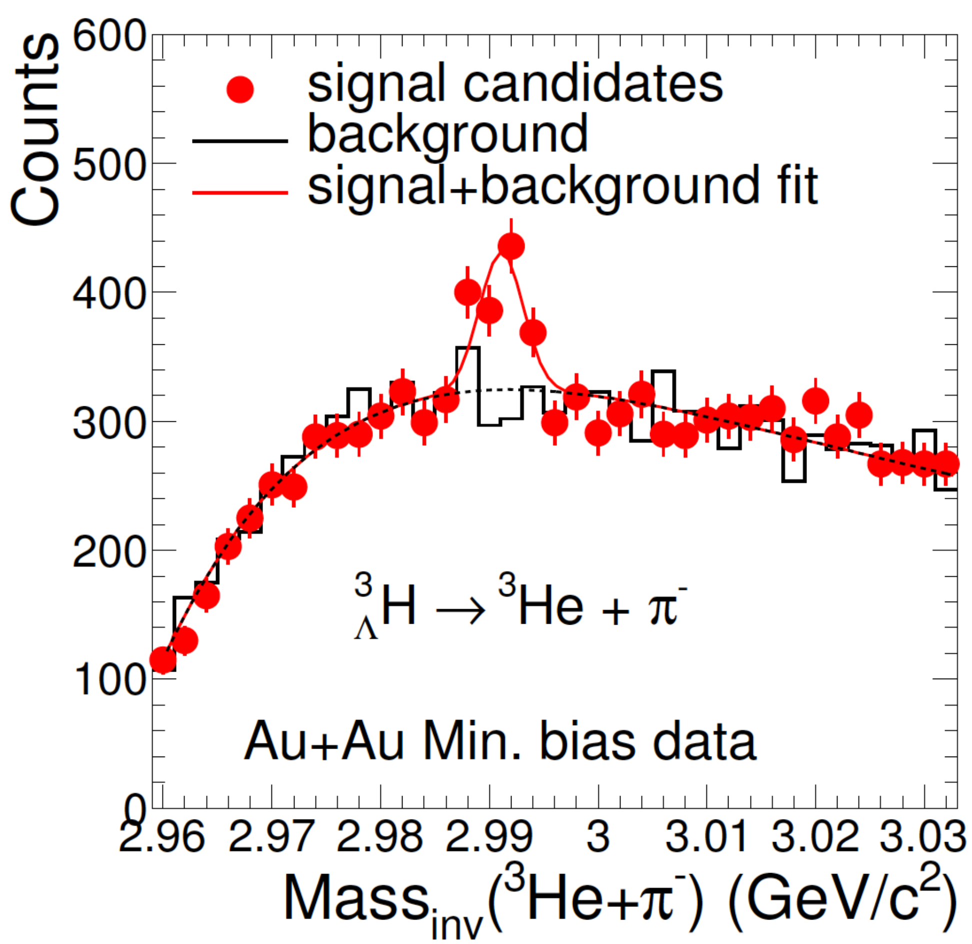
CAVEAT:

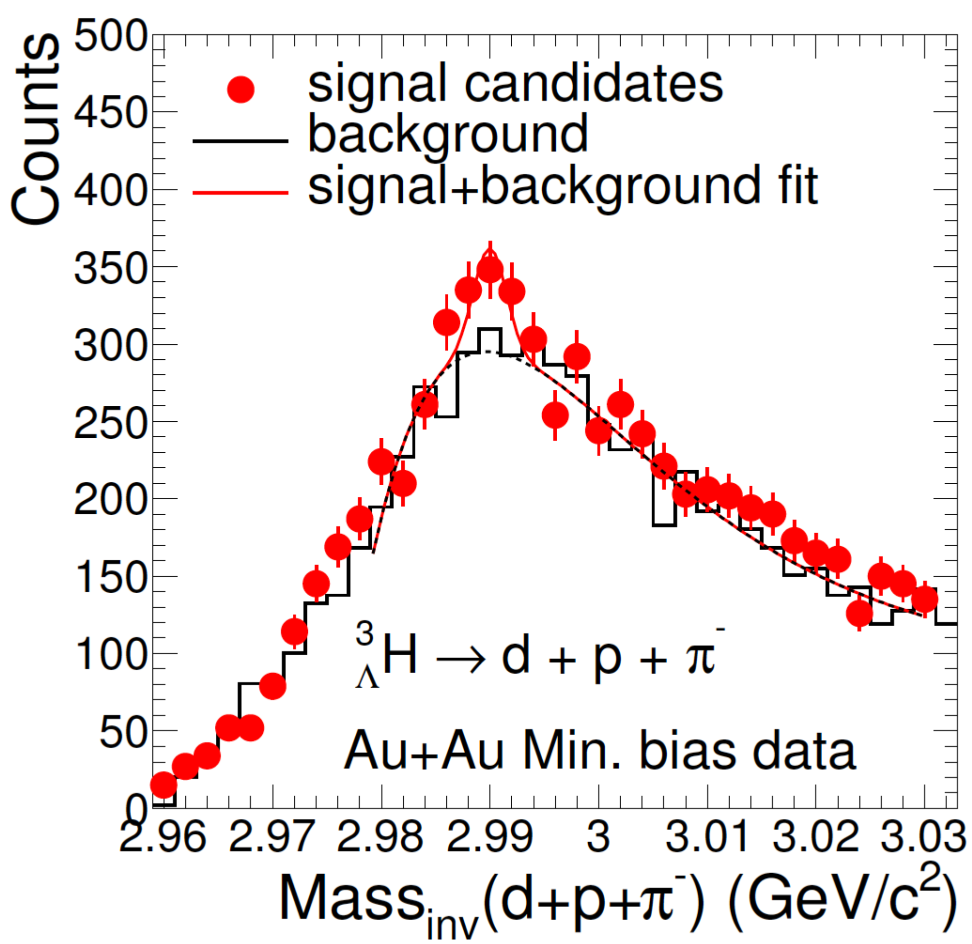
The citations close to each marker are related to the review where the plot is shown

- Visualizing techniques (emulsion and ^{3}He Bubble chamber):
  - values closer and in agreement with the free Λ lifetime
  - large uncertainties due to the limited data sample
- Electronic techniques (heavy-ion experiments):
  - larger data sample led to a reduction of the uncertainties
  - measured values are below the expectations

Latest results: STAR

- Invariant mass spectra from 2- and 3-body decay:
  - analysis of the Au-Au collisions data sample from beam energy scan (BES)
  - large uncertainties due to the limited data sample
- Lifetime determination with both decay modes





STAR Collaboration, Phys. Rev. C 97 (2018) 054909

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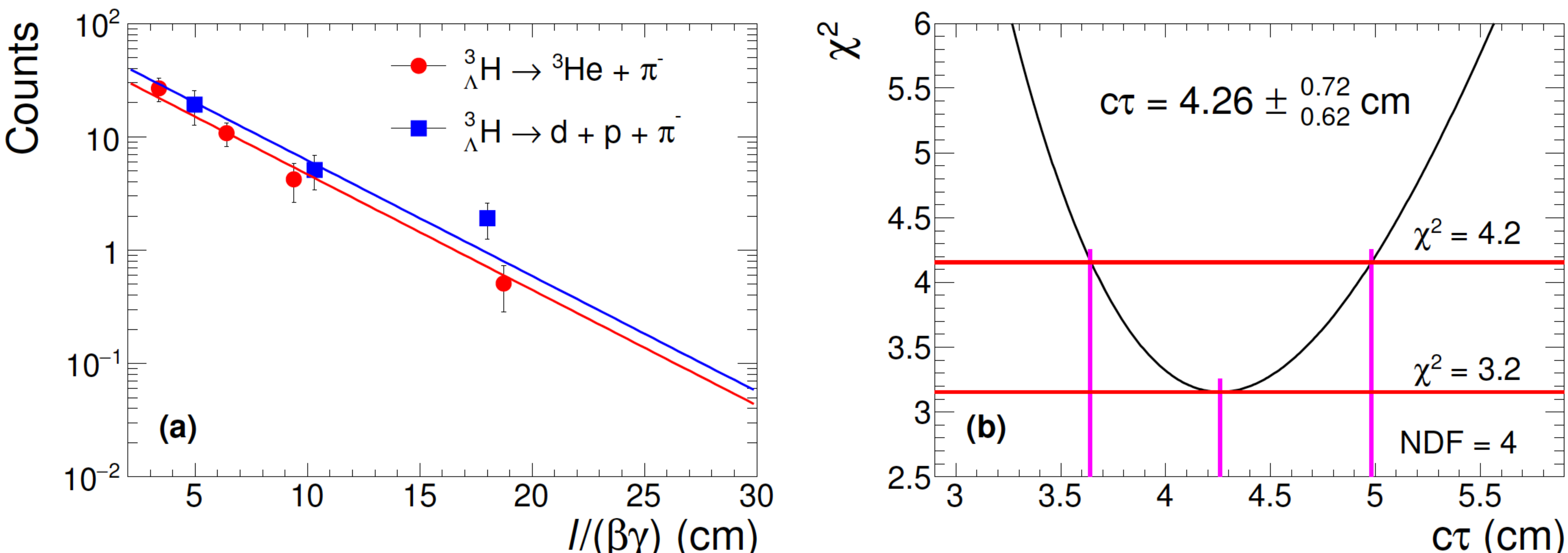
  - large uncertainties due to the limited data sample
- Lifetime determination with both decay modes

2-body $\tau = 123^{+26}_{-21}(stat.)ps$

3-body $\tau = 193^{+82}_{-48}(stat.)ps$

Final value

$\tau = 142^{+24}_{-21}(stat.) \pm 29(syst.)ps$



STAR Collaboration, Phys. Rev. C 97 (2018) 054909

Latest results: *ALICE*

The lifetime estimate is performed:

- using the full data sample of Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected in 2015
- selecting both hypertriton and anti-hypertriton candidates
- using two methods: "ct spectra" (default) and unbinned fit (crosscheck)

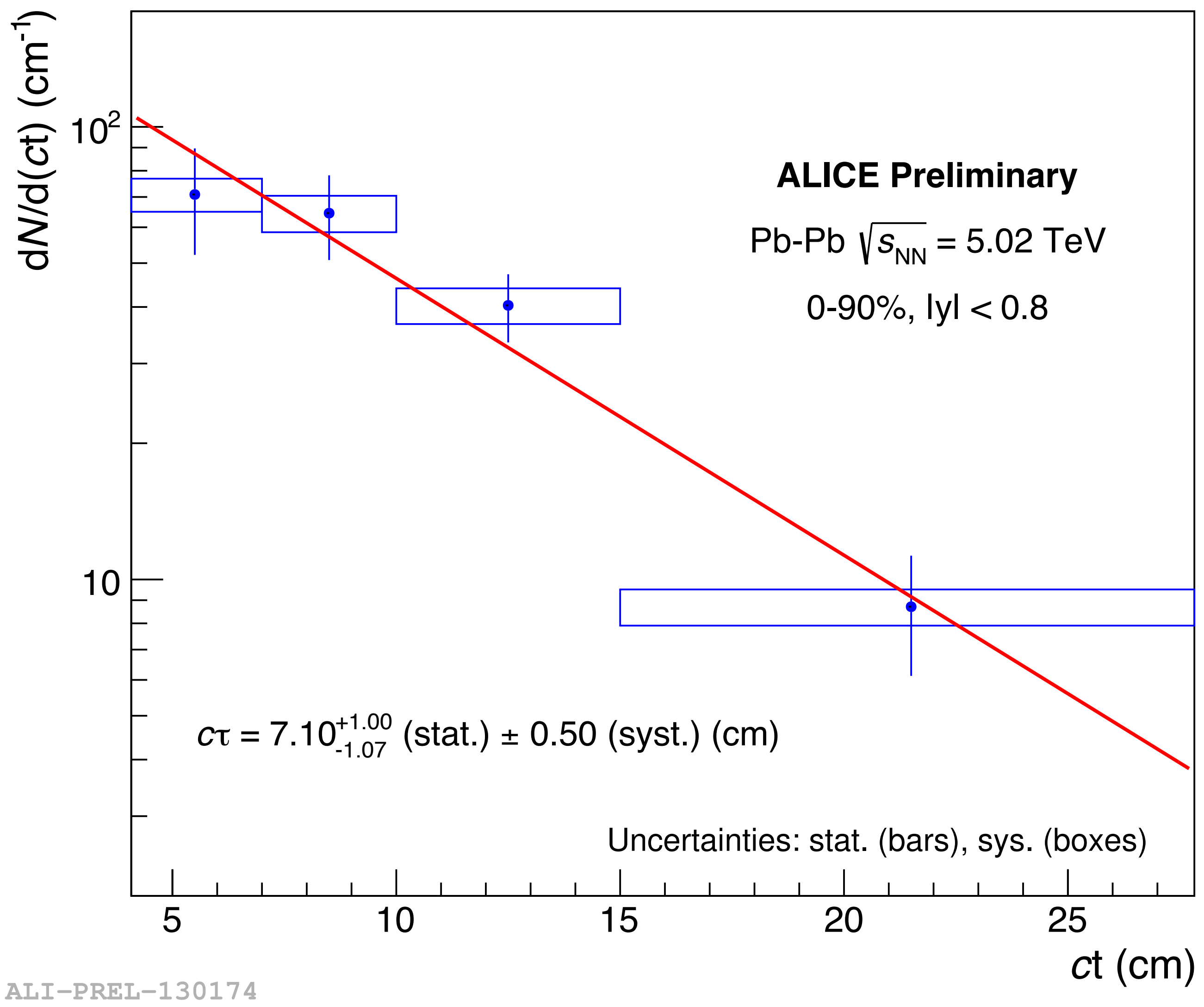
Latest results: *ALICE*

ct spectra (*default*)

- Signal extraction in four different *ct* bins
  - 4-7, 7-10, 10-15, 15-28 cm
- Exponential fit to the corrected d*N*/*ct* spectrum for the lifetime estimate

$$\tau = 237^{+33}_{-36}(stat.) \pm 17(syst.)\text{ps}$$

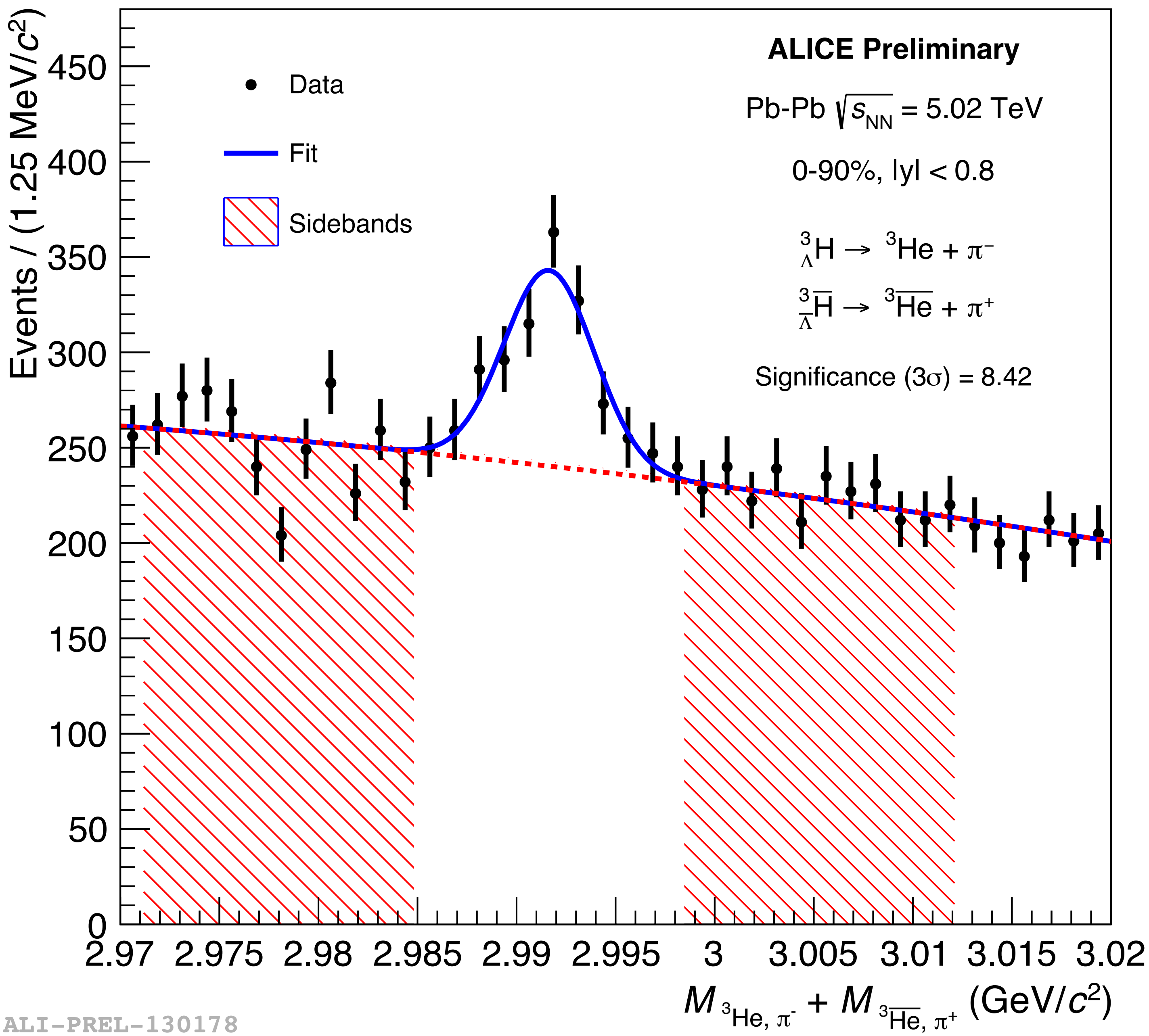
- Result with the highest precision at the moment
  - improved resolutions with respect to the previous result at 2.76 TeV
- Lifetime estimate with an alternative method as a crosscheck



ALICE results (Pb-Pb at 2.76 TeV)

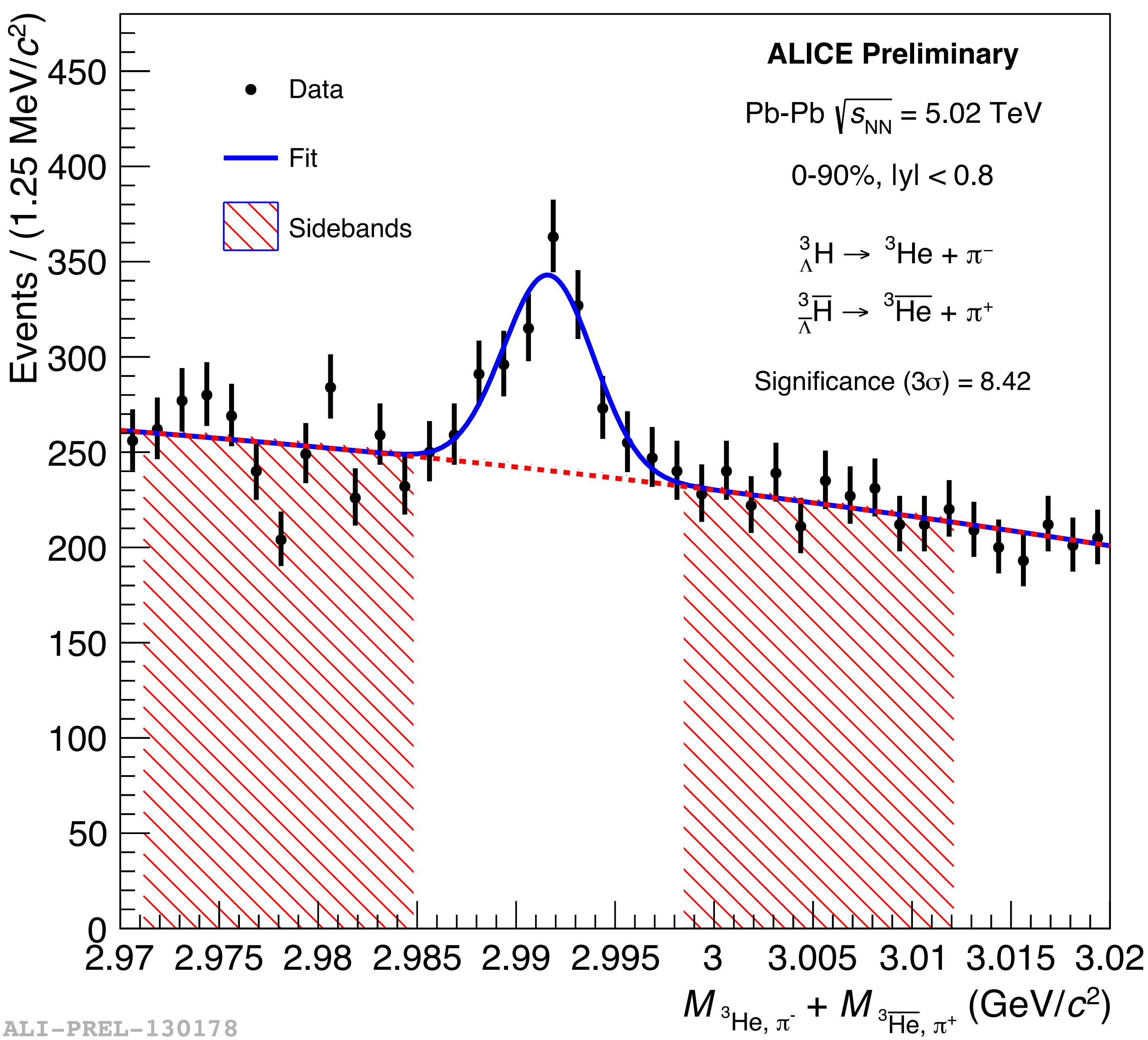
$$\tau = 181^{+54}_{-38}(stat.) \pm 33(syst.)ps$$

Latest results: *ALICE*



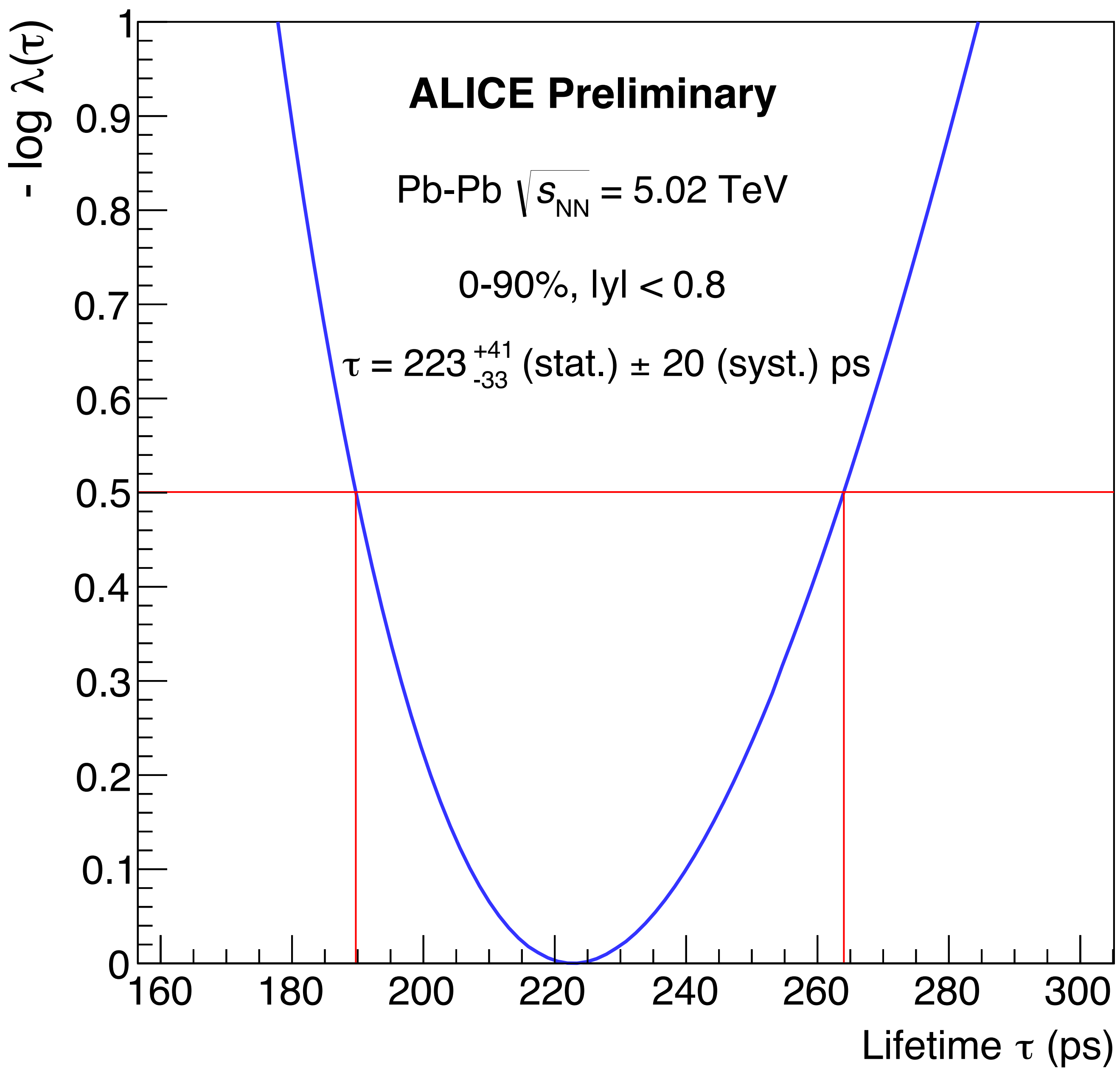
- Fit to the invariant mass distribution to define the signal range and the sidebands

Latest results: *ALICE*



- Fit to the invariant mass distribution to define the signal range and the sidebands
- Fit in the sidebands with two exponential is performed (background)
- Fit in the signal range for the lifetime estimate
  - *signal*: exponential function multiplied for the efficiency
  - *background*: from the sidebands fit

Latest results: *ALICE*



ALI-PREL-130191

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- Fit in the sidebands with two exponential is performed (background)
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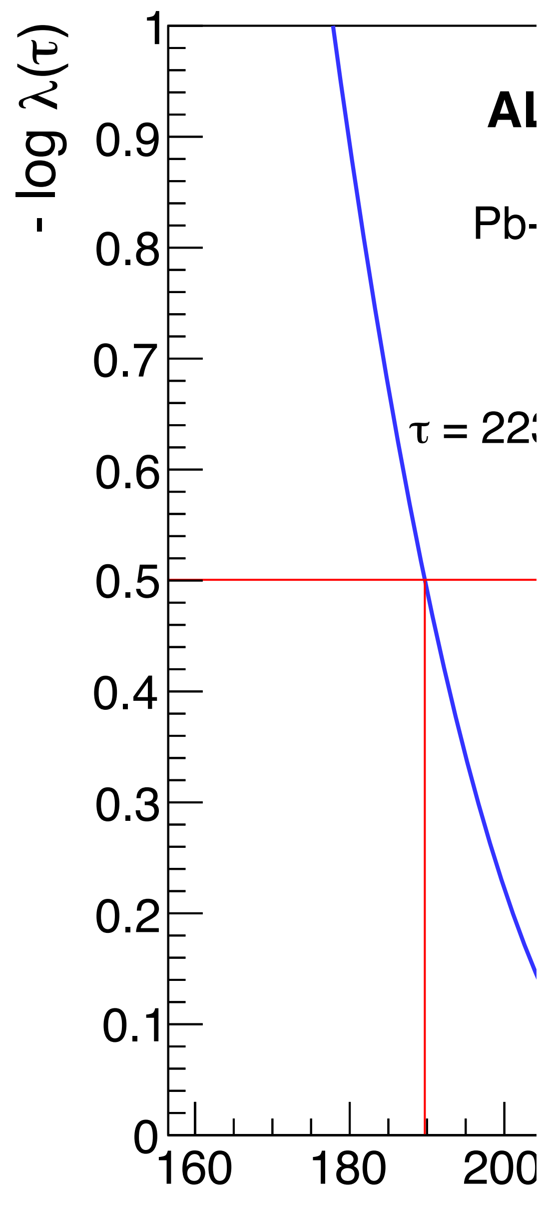
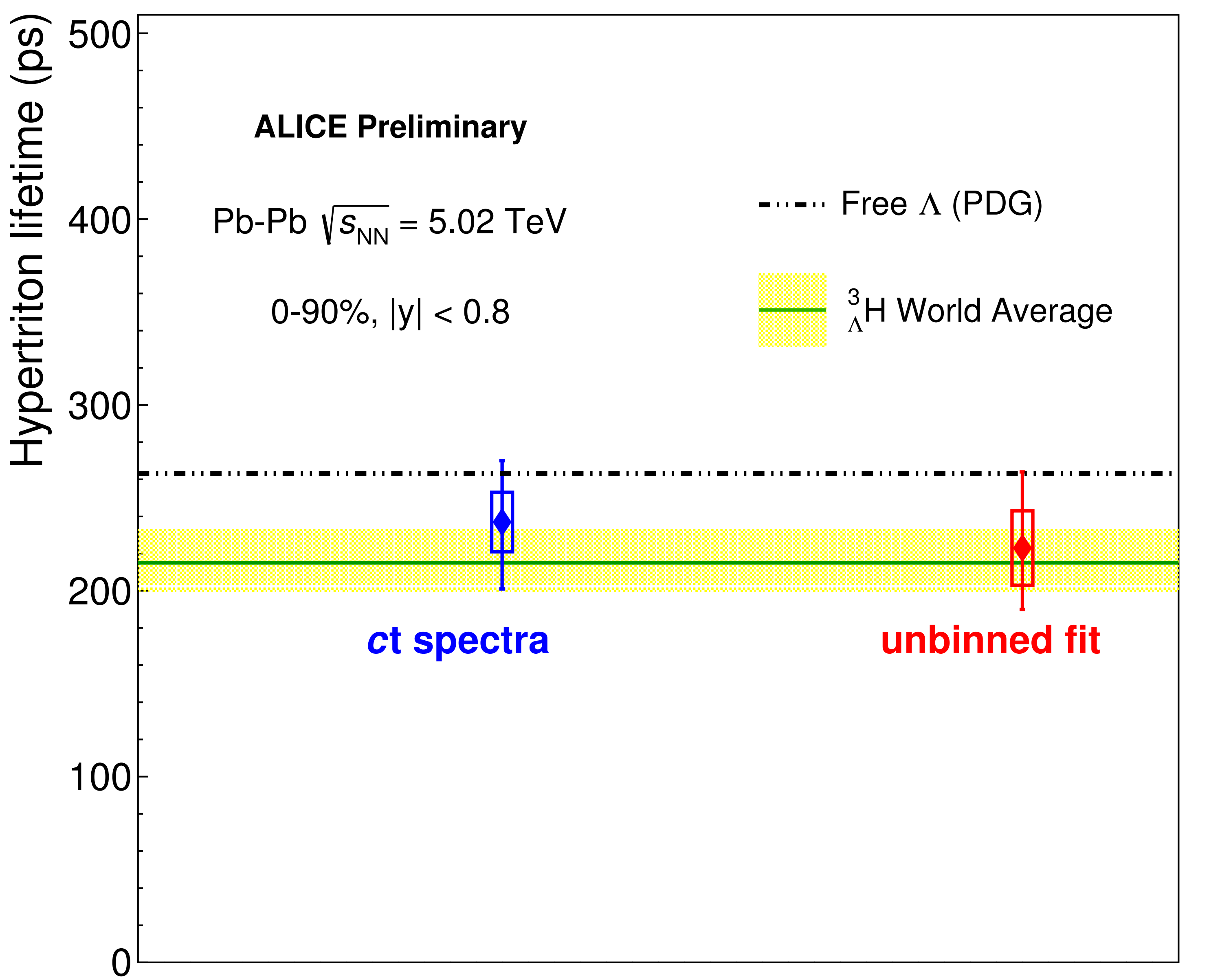
  - *background*: from the sidebands fit

Lifetime value estimate

$$\tau = 223^{+41}_{-33}(stat.) \pm 20(syst.)\text{ps}$$

Latest results: *ALICE*





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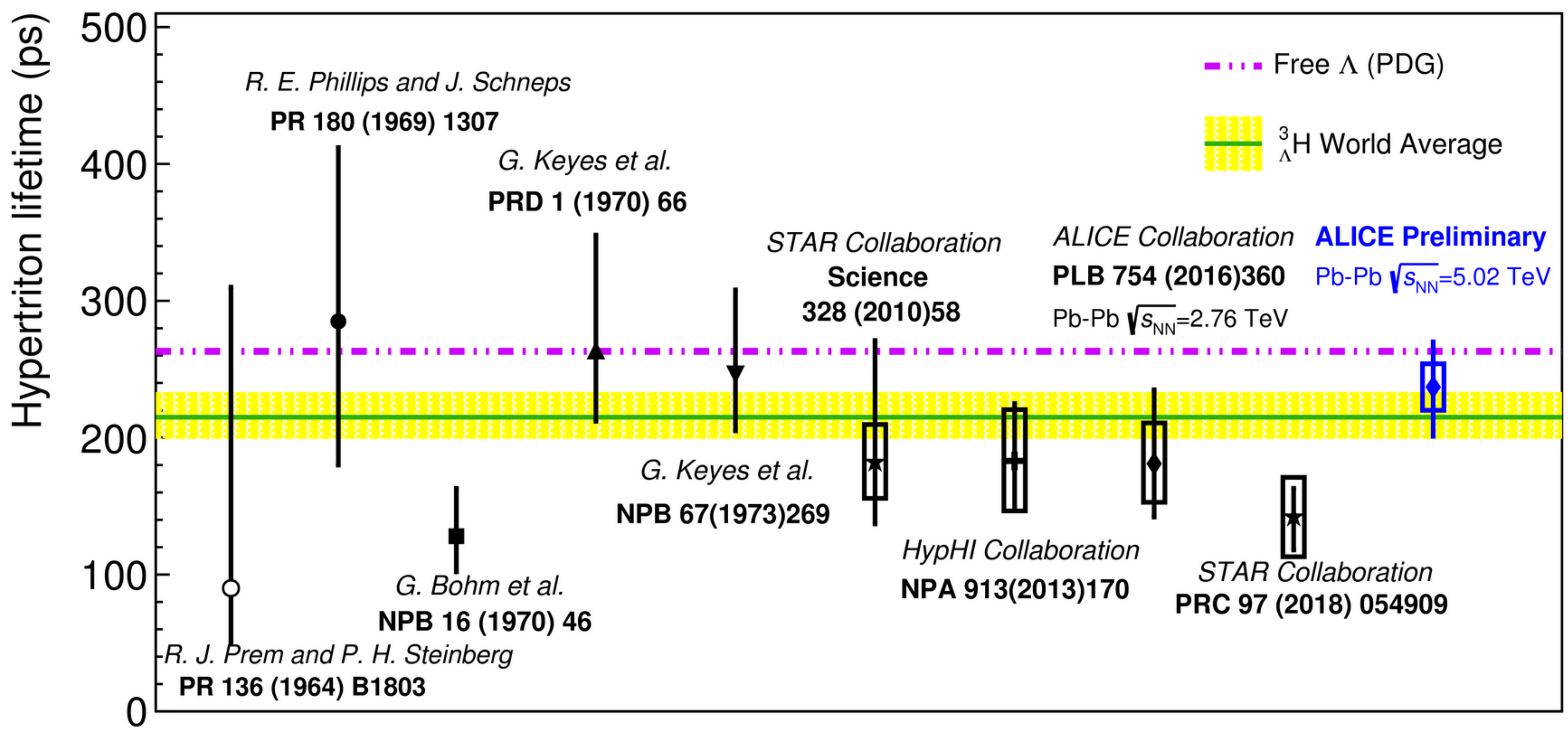
estimate

$\tau = 223_{-33}(stat.) \pm 20(syst.)\mathrm{ps}$

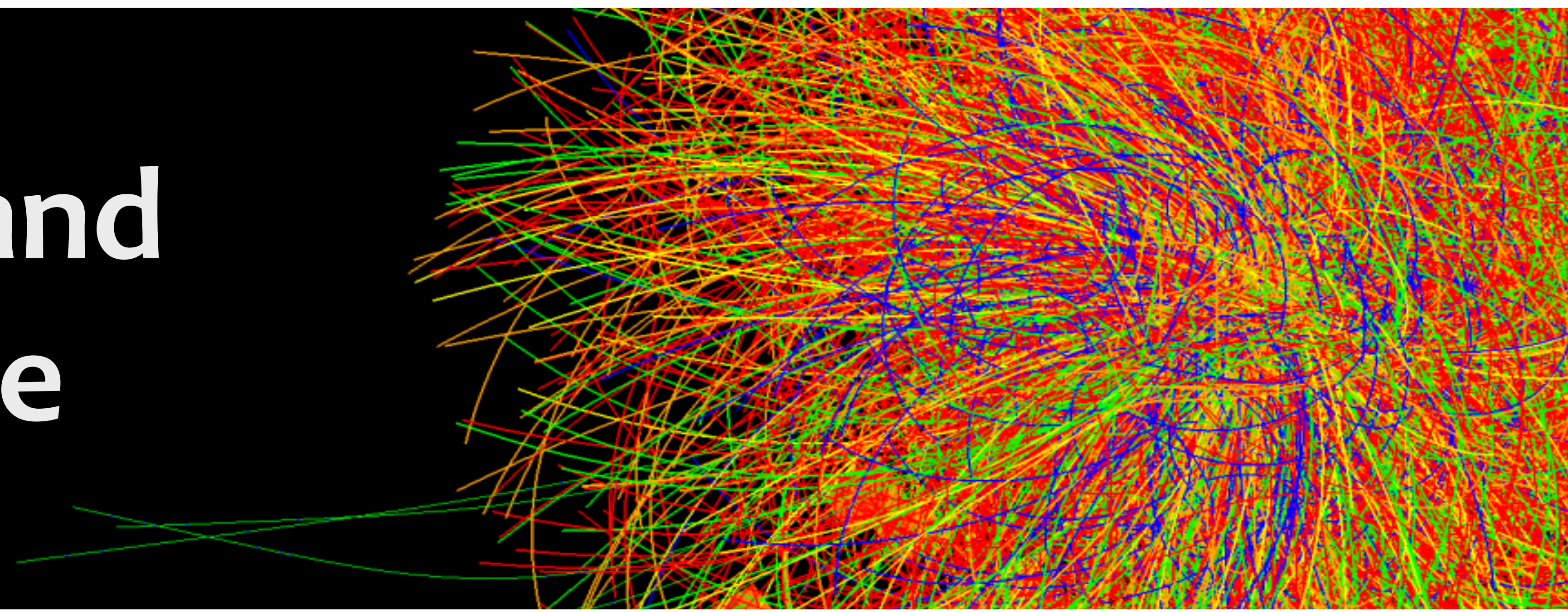
Lifetime collection



ALI−DER−161043

- ALICE result, obtained from the analysis Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV data sample, show an improved precision with respect to previous heavy ion experiment
  - it is compatible with the world average and, in particular, with the free Λ hyperon lifetime
- Further improvements will come from:
  - from lifetime measured in the 3-body decay channel
  - upgrade of the ALICE experiment for LHC Run3 and Run4

Conclusion and perspective



Conclusion and perspective

☑ Production

- Both thermal and coalescence models can describe particular aspects of (hyper-)nuclei measurements in three different collision systems
- Huge experimental effort is going on to provide more precise results to investigate a possible unified description of nucleosynthesis
- Theoretical predictions are needed especially for comparison with small systems

Conclusion and perspective

Production

- Both thermal and coalescence models can describe particular aspects of (hyper-)nuclei measurements in three different collision systems
- Huge experimental effort is going on to provide more precise results to investigate a possible unified description of nucleosynthesis
- Theoretical predictions are needed especially for comparison with small systems

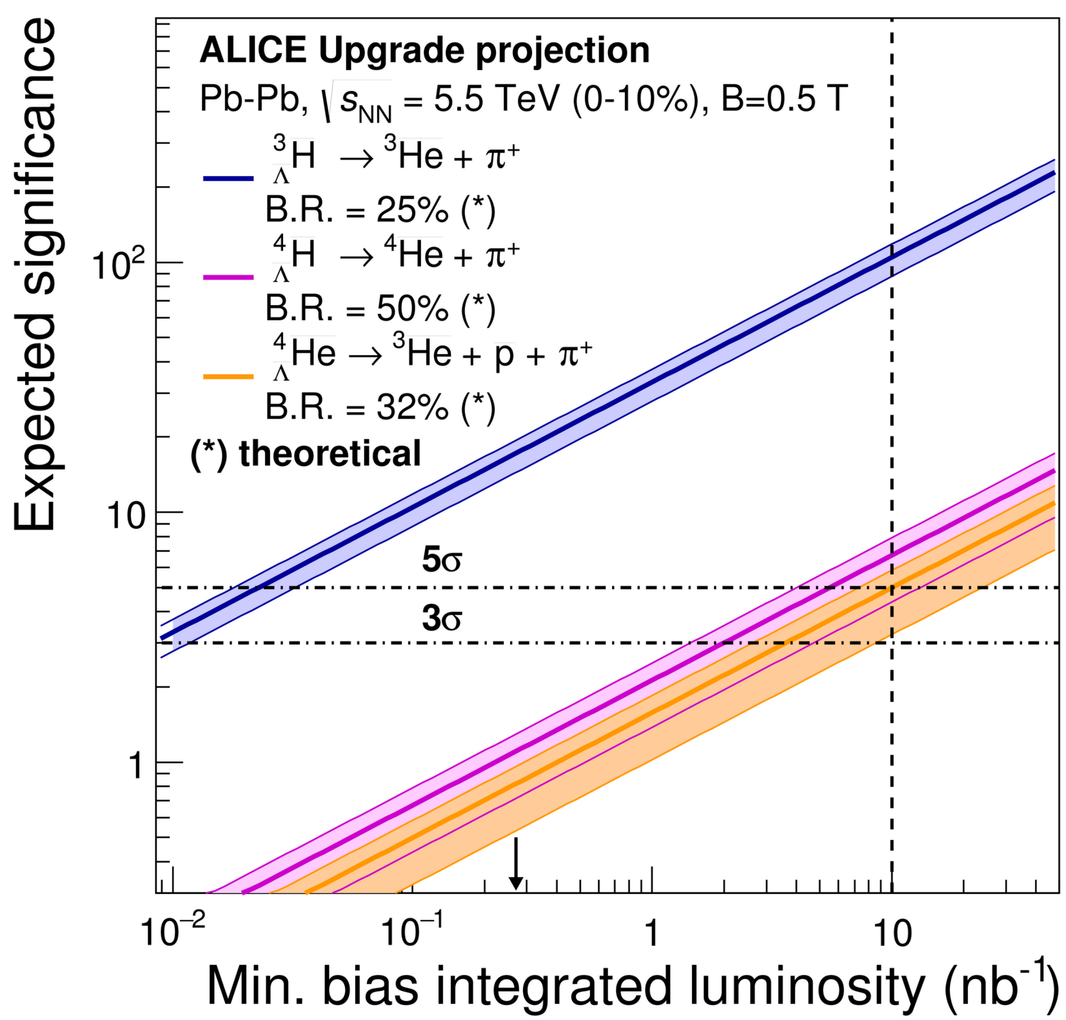
Lifetime puzzle

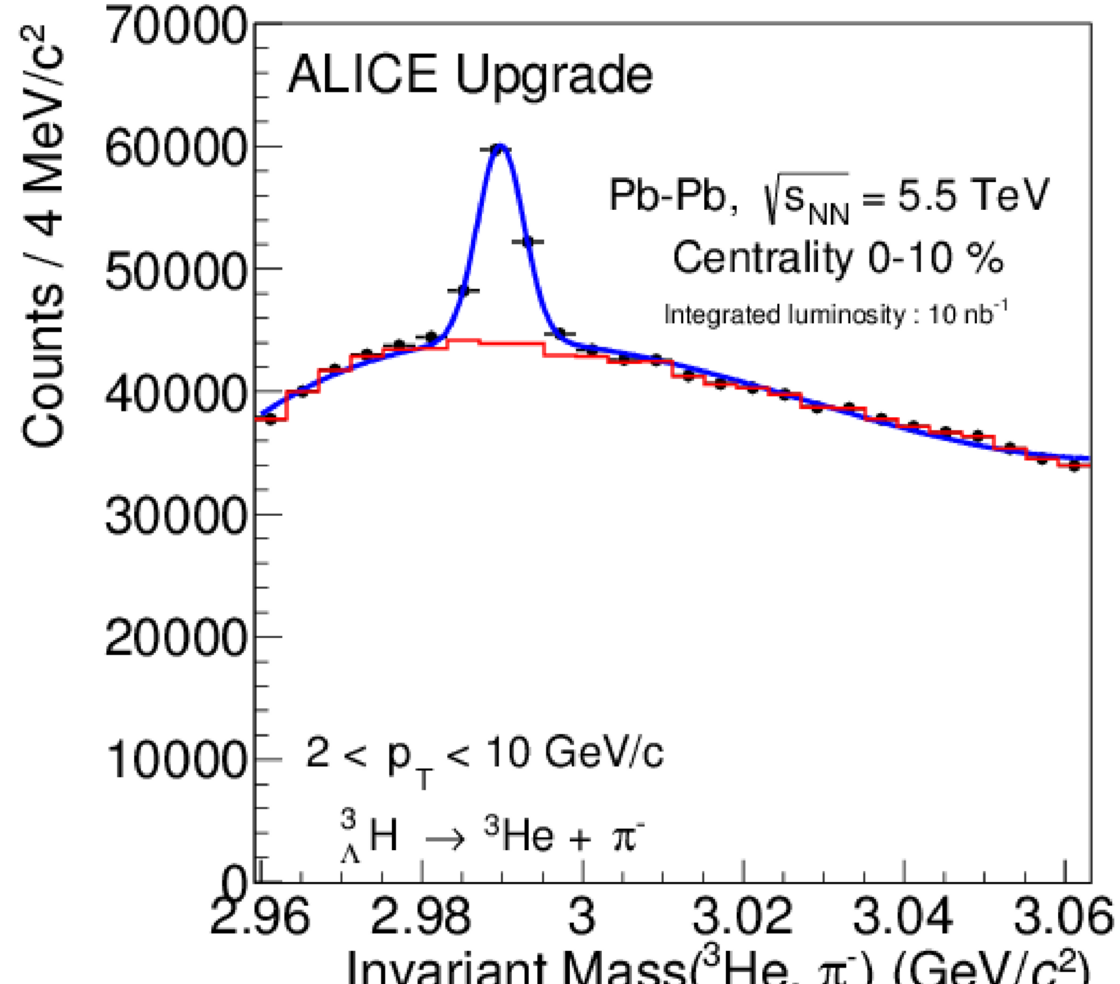
- Latest ALICE result at 5.02 TeV is the most precise and is closer to the theoretical expectation → this raise the question "*can we still talk about a puzzle?*"
- Challenge faced by other experiments to measure the lifetime and also the Λ binding energy with higher precision
- In the next LHC Run3 and Run4 ALICE is expected to collect a larger data sample to reduce the uncertainties below 5%

Conclusion and perspective

Outlook

- ALICE has started a huge upgrade of the main detectors in preparation of LHC Run3 and Run4 → expected Pb-Pb $\mathcal{L}_{DEL} = 13\ nb^{-1}$ at 50 kHz collision rate
- Improvements on the results for A=3 and possibility to investigate A=4 (hyper-)nuclei production



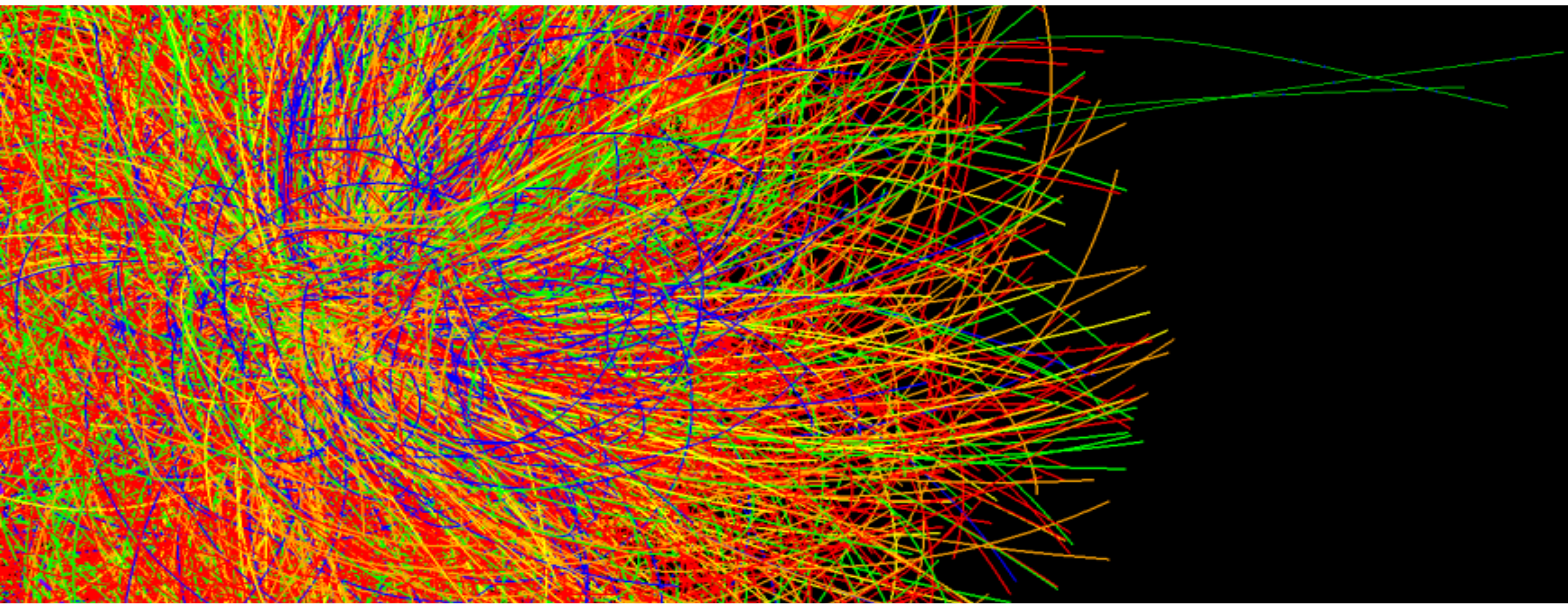


ALICE Collaboration, J. Phys. G 41, 087002 (2014)

Thank you for your attention

and

Best Wishes!

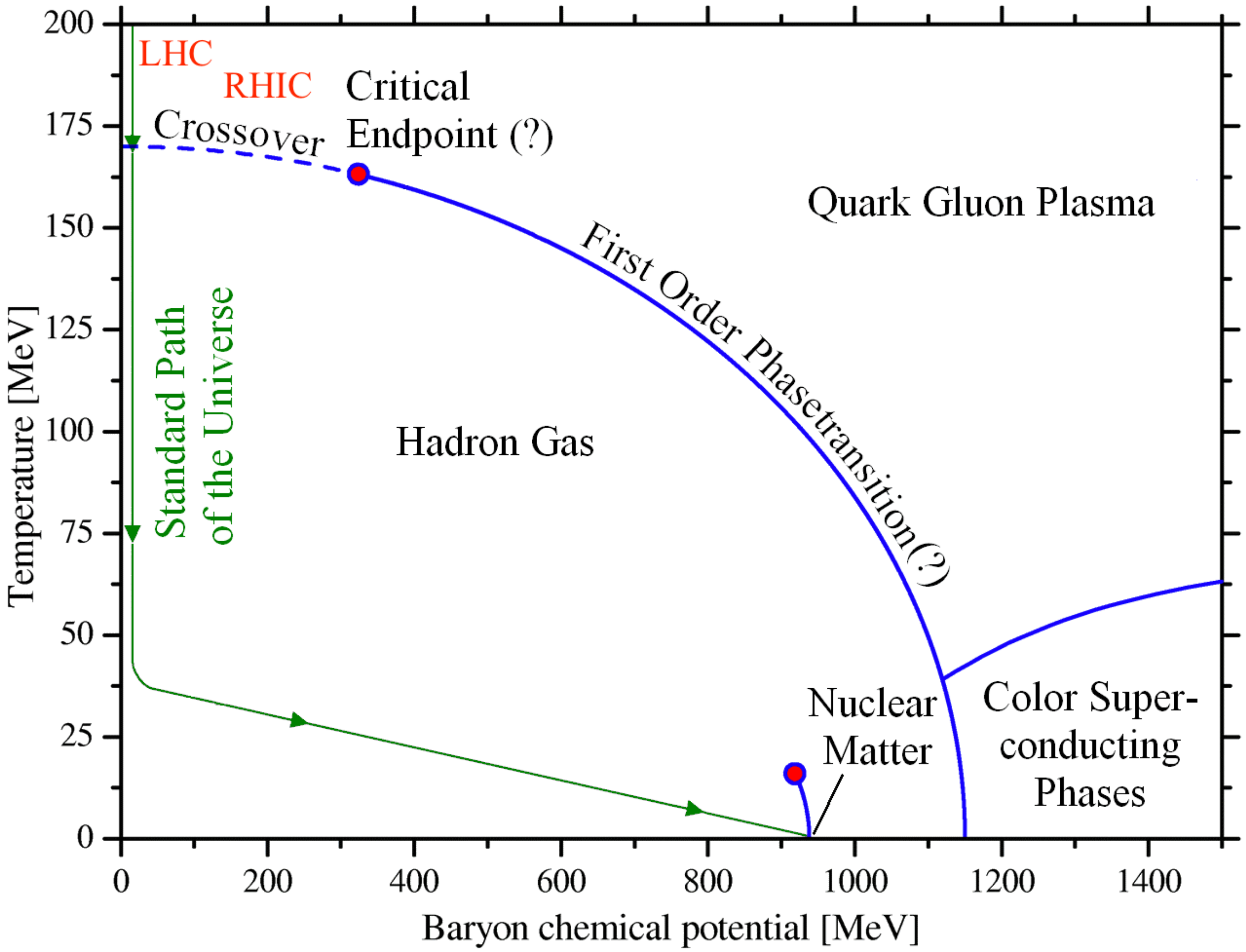


Backup

Why heavy ion collisions?

Everyday matter comes in various form and we distinguish between solid, liquid and gas phases…

T. Boeckel and J. Schaffner-Bielich, Phys. Rev. D 85, 103506 (2012)



- E. Fermi, Prog. Theor. Phys. 5, 570 (1950)
- R. Stock, "Relativistic Nucleus-Nucleus Collisions and the QCD Matter Phase Diagram" (2008)
- J. Rafelski and J. Birrell, J. Phys. Conf. 509, 012014 (2014)

QCD phase diagram

- Consequence of the **running of α_s** is the existence of a phase transition:
  - Hadron gas ⇔ Quark Gluon Plasma
- In the QGP **quarks** and **gluons** are no longer confined in colour singlets:
  - probably existed in the early universe, 10 μs after the Big Bang
- The phase transition is expected to be:
  - first order transition at *high μ_B* (FAIR)
  - crossover at *small μ_B* and *high T* (LHC, RHIC)

Blast Wave distribution

- Distribution based on the phenomenological model for hadronic matter production in heavy collision, described in
  [E. Schnedermann, J. Sollfrank, and U. Heinz, Phys. Rev. C 48, 2462 (1993)]
- It describes particle production spectra both at RHIC and LHC energies
- Description for hadron spectra from HIC in terms of few collective variables

$$\frac{1}{p_{\mathrm{T}}}\frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}} \propto \int_0^R r\mathrm{d}r m_{\mathrm{T}} I_0\left(\frac{p_{\mathrm{T}} sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_{\mathrm{T}} cosh\rho}{T_{kin}}\right)$$

where

- $m_{\mathrm{T}} = \sqrt{p_{\mathrm{T}}^2 + m^2}$ is the transverse mass
- I_0, K_1 are the modified Bessel functions
- r is the radial distance on the transverse plane
- T_{kin} is the kinetic freeze-out temperature
- ρ is the velocity profile → $\rho = tanh^{-1}\left(\left(\frac{r}{R}\right)^n \beta_S\right)$
- β_s is the transverse expansion velocity at the system surface

Centrality class

- Centrality of a collision estimated using the particle multiplicities (N_{ch}) and correlated to the impact parameter using the Glauber model
- In literature, the centrality is defined as **percentage** of the total hadronic cross section σ_{AA}

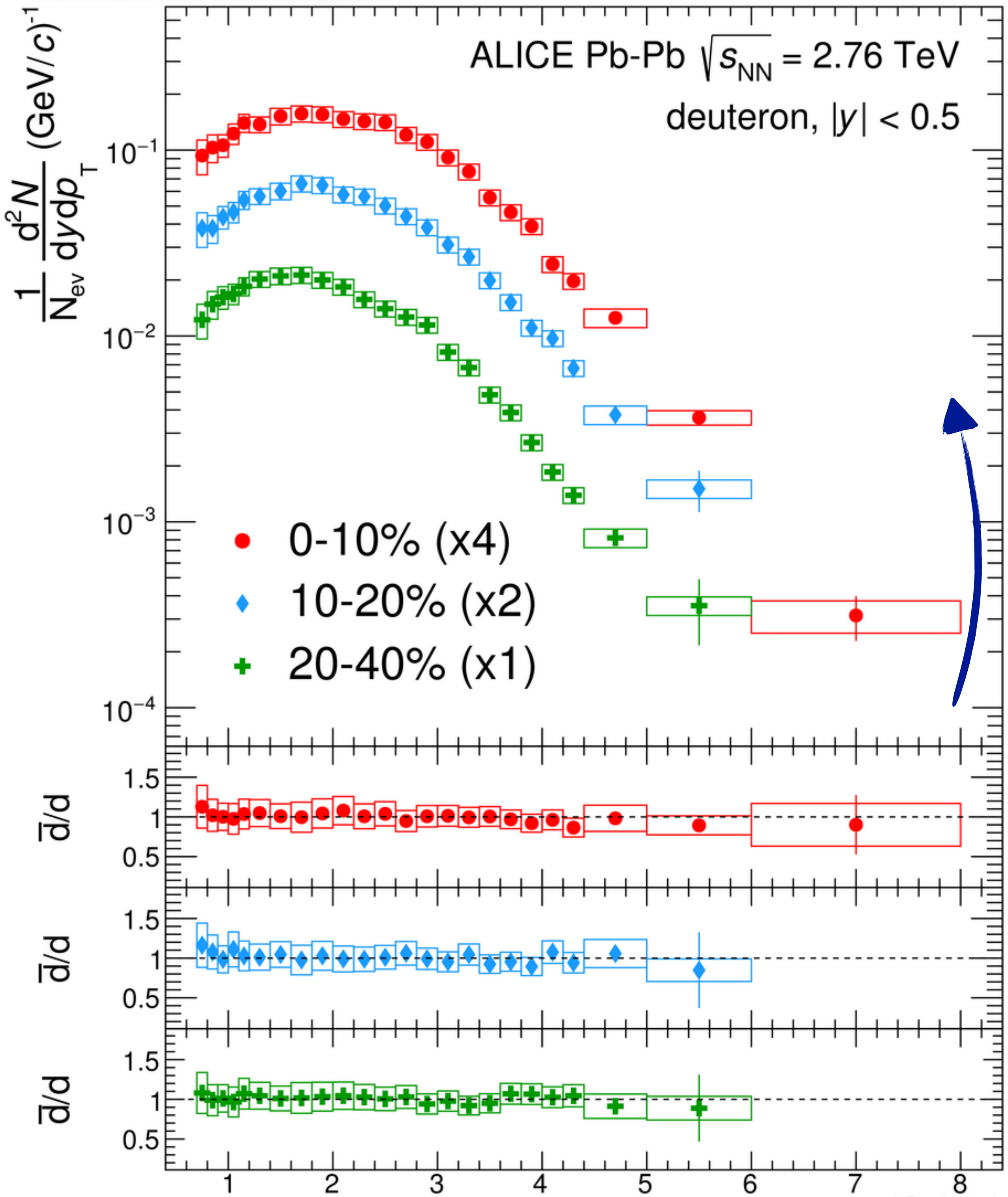
$$c(b) = \frac{\int_0^b \frac{d\sigma}{db'} db'}{\int_0^\infty \frac{d\sigma}{db'} db'} = \frac{1}{\sigma_{AA}} \int_0^b \frac{d\sigma}{db'} db'$$

- Assuming a monotonic dependence of the charged particle multiplicity on the overlap volume, the centrality can be expressed as:

$$c(b) \approx \frac{1}{\sigma_{AA}} \int_{N_{ch}}^\infty \frac{d\sigma}{dN'_{ch}} dN'_{ch}$$

Deuteron spectra

√s_{NN} = 2.76 TeV



ALICE Collaboration, Eur. Phys. J. C 77 (2017) 658

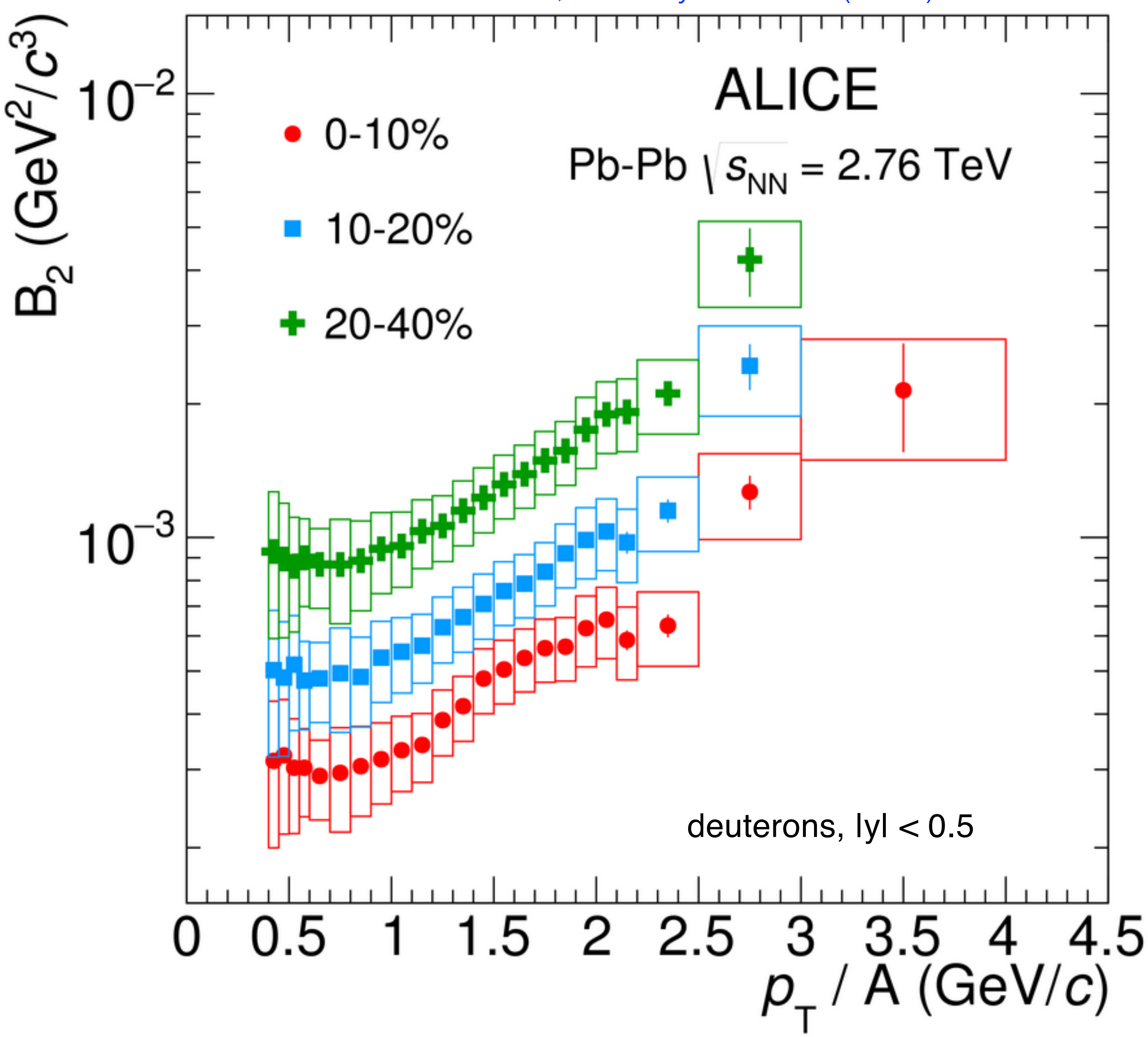
- p_T **spectra** measured for deuteron and anti-deuteron in three different centrality classes
  - pronounced hardening of the spectra visible for increased centrality → **radial flow**
- **Integrated yield** and **mean** p_T are extracted by fitting the spectra with the **Blast-Wave** [4] (BW) function
- Ratio $\bar{d}$/d in agreement with unity within the uncertainties
  - confirms equal production of matter and anti-matter at the LHC energies

[4] E. Schnedermann et al. Phys. Rev. C 48, 2462 (1993)

Coalescence parameter B_A

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

ALICE Collaboration, Eur. Phys. J. C 77 (2017) 658



- The **probability** to form a nucleus via coalescence can be quantified by the **coalescence parameter B_A**:

$$B_A = E_A \frac{d^3 N_A}{dp_A^3} \Big/ \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

  - A is the mass number
  - $p_p = p_A/A$

- According to **simple coalescence** predictions **B_A** is **p_T flat**:
  - simple coalescence **does not describe** the trend observed in Pb-Pb collisions

- The **rise in p_T** becomes milder moving from central to peripheral collisions

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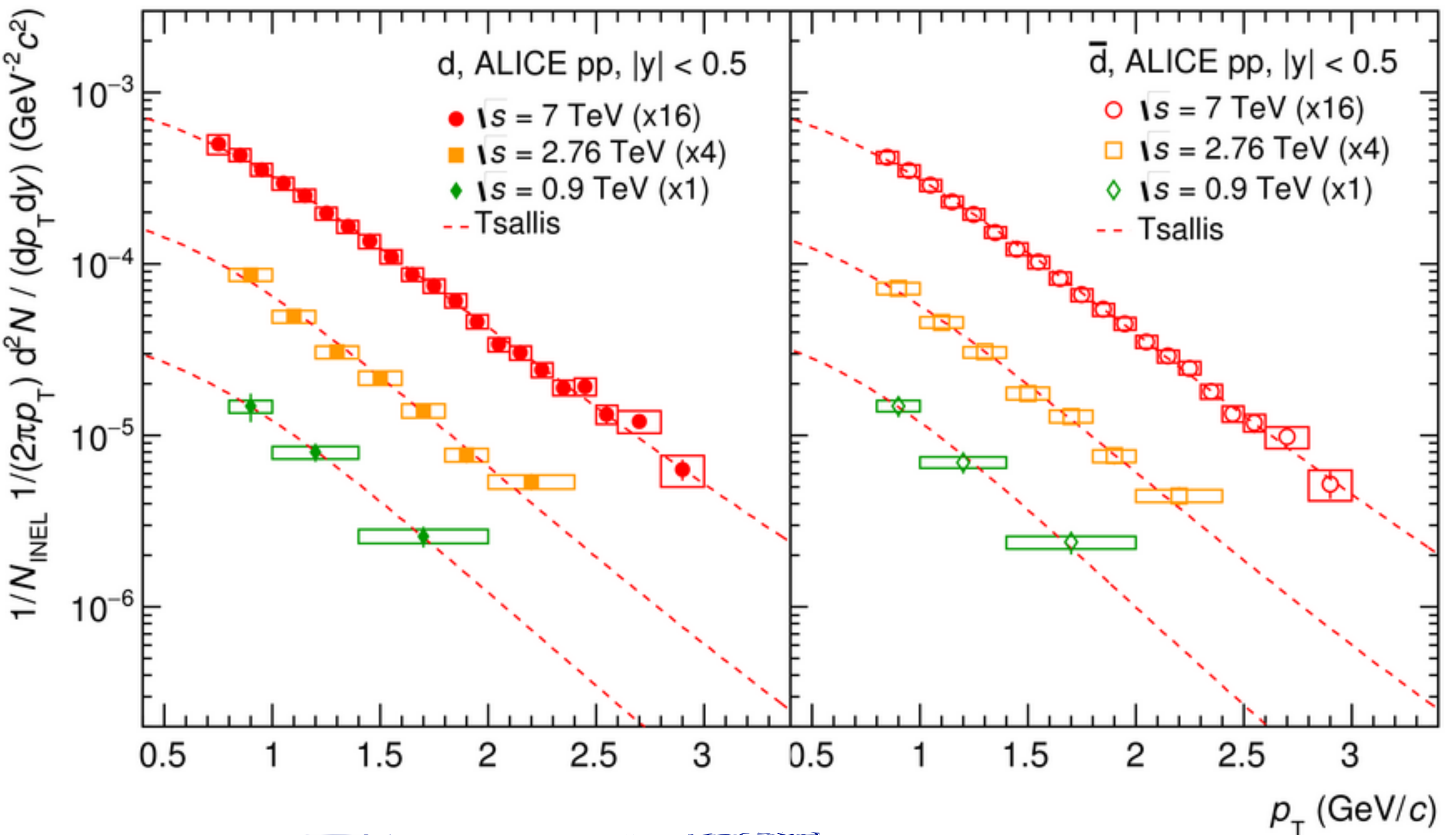
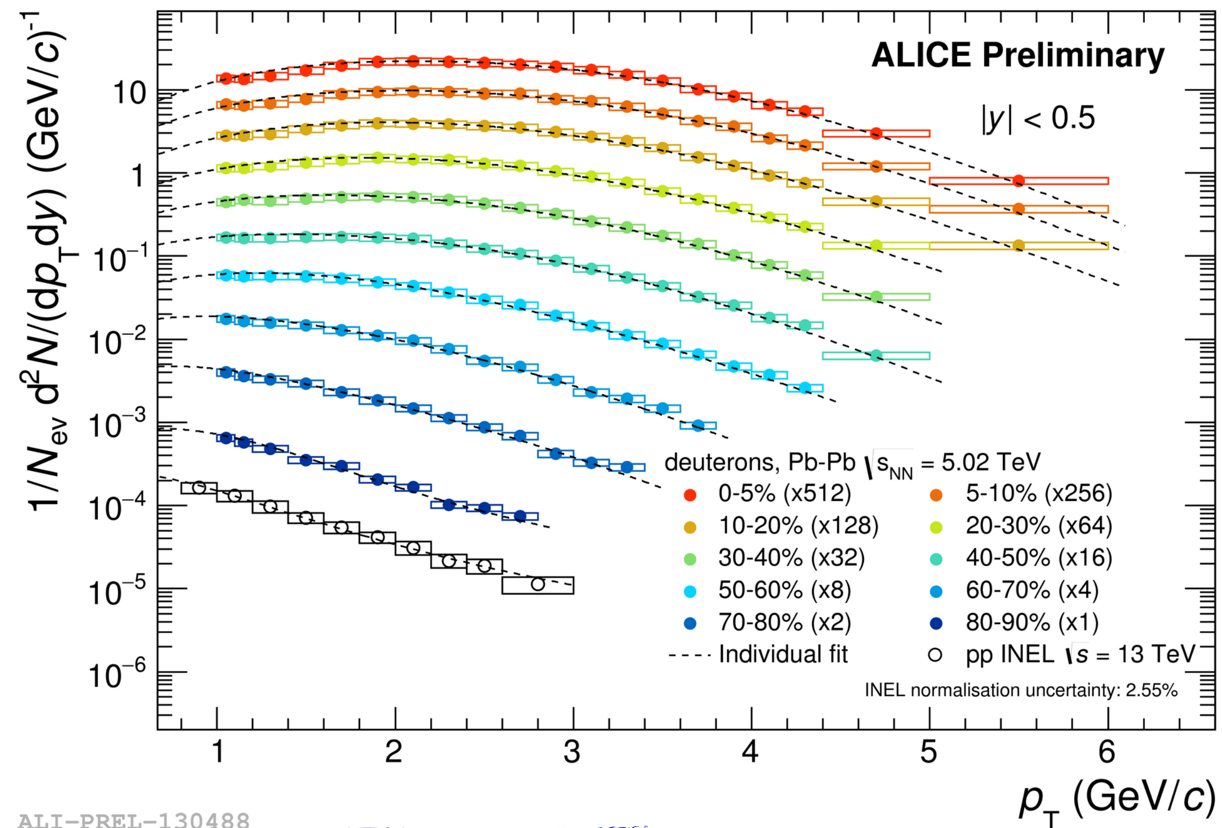
Deuteron production

ALICE Collaboration, Phys. Rev. C 97 (2018) 024615



pp, √s = 0.9, 2.76, 7 TeV

ALICE-PUBLIC-2017-006

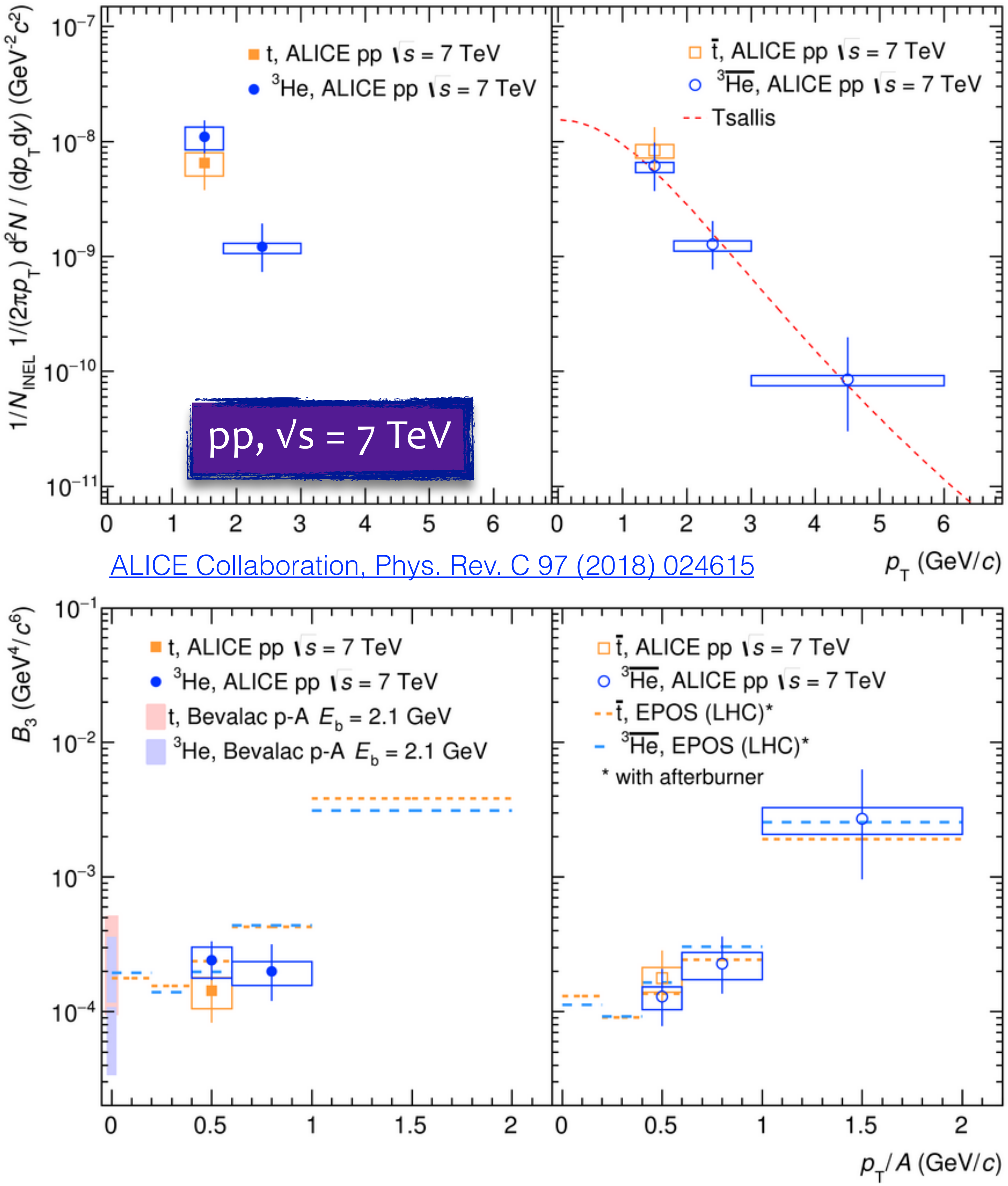


pp, √s = 7 TeV

- Minimum Bias p_T spectra in pp collisions show no sign of radial flow
- The fit is performed with a Tsallis function [8] used for the yield extrapolation to the unmeasured regions

[8] C. Tsallis, J. Stat. Phys. 52 (1988) 479

^{3}He and ^{3}H production



- First (anti-)^{3}He spectrum measured in pp collisions
  - fit performed with the Levy-Tsallis function
- (anti-)^{3}H measurement extremely difficult
- Antimatter-to-matter ratios agrees with unity
- B_3 measured in p-p collisions and compared with:
  - predictions of EPOS-LHC with afterburner
  - Bevalac measurements, shown as vertical bands

Summary: *thermal production*

Nuclei and hypernuclei production			
	Pb-Pb	p-Pb	pp
Thermal (+hydro)	✓ p_T spectra ✓ particle yields ✓ antinucleus/nucleus ✓ deuteron v_2 ✓ ^{3}He v_2 ✓ d/p and ^{3}He/p ✓ dN/dy mass depend. ✗ B_2 and B_3 factor	✓ p_T spectra ✓ antinucleus/nucleus ✗ d/p and ^{3}He/p ✓ dN/dy mass depend. ✗ B_2 and B_3 factor	✓ p_T spectra ✓ antinucleus/nucleus ✗ d/p and ^{3}He/p ✗ B_2 and B_3 factor
	✓ p_T spectra ✓ particle yields ✓ ^{3}H/^{3}H ✓ ^{3}H/p, ^{3}H/d and ^{3}H/^{3}He ✓ S_3 factor ✗ B_3 factor		

Legend: ✓ = well described; ✓ = described with some tension; ✗ = not described/missing prediction

Summary: *production via coalescence*

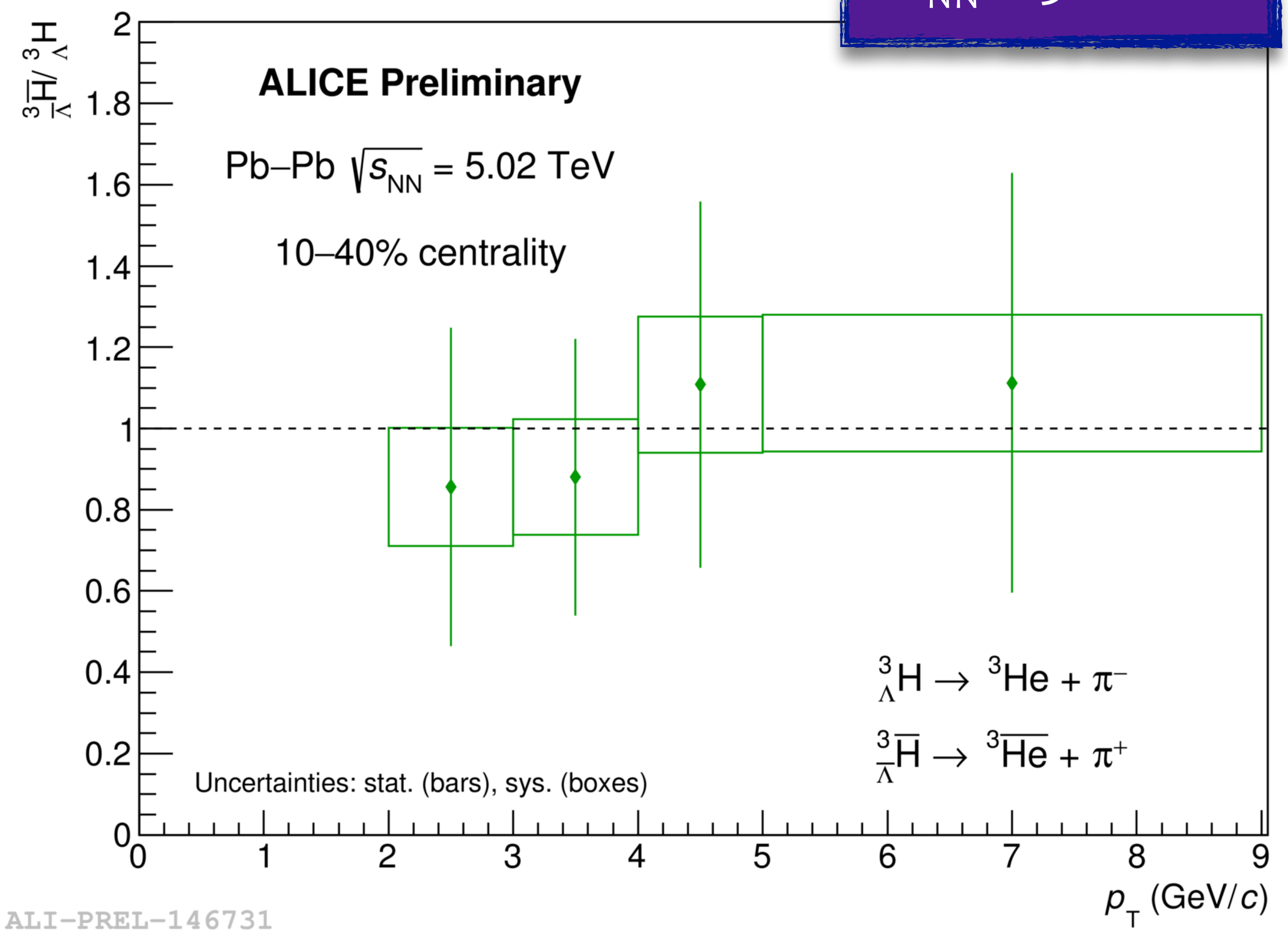
Nuclei and hypernuclei production

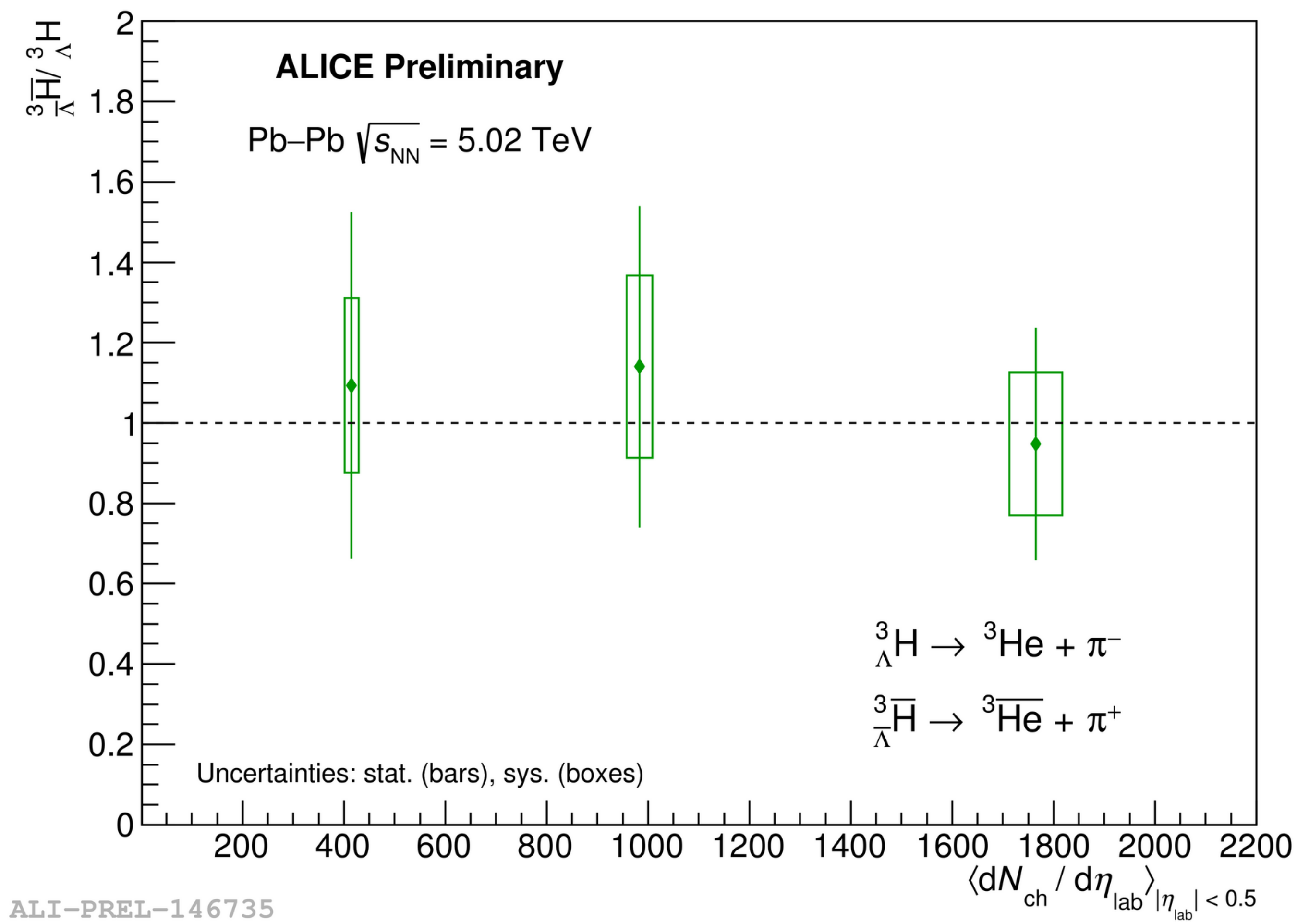
	Pb-Pb	p-Pb	pp
Coalescence model	✓ (orange) p_T spectra ✓ (orange) particle yields ✓ (green) antinucleus/nucleus ✗ deuteron v_2 ✓ (green) ^{3}He v_2 ✗ d/p and ^{3}He/p ✗ dN/dy mass depend. ✓ (orange) B_2 and B_3 factor	✓ (orange) p_T spectra ✓ (green) antinucleus/nucleus ✓ (green) d/p and ^{3}He/p ✗ dN/dy mass depend. ✓ (green) B_2 and B_3 factor	✓ (orange) p_T spectra ✓ (green) antinucleus/nucleus ✗ d/p and ^{3}He/p ✓ (green) B_2 and B_3 factor
	✓ (orange) p_T spectra ✓ (orange) particle yields ✓ (green) ^{3}H/^{3}H ✗ ^{3}H/p, ^{3}H/d and ^{3}H/^{3}He ✗ S_3 factor ✓ (green) B_3 factor		

Legend: ✓ (green) = well described; ✓ (orange) = described with some tension; ✗ = not described/missing prediction

${}^{3}_{\bar{\Lambda}}\overline{\text{H}}/{}^{3}_{\Lambda}\text{H}$ ratio

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





- The ratio has been measured as a function of p_{T} and of the **charged particle multiplicity**
- **Anti-hypertriton/hypertriton** ratio is in agreement with unity → confirm the predictions from **thermal** and **coalescence models**

${}^{3}_{\Lambda}$H lifetime knowledge

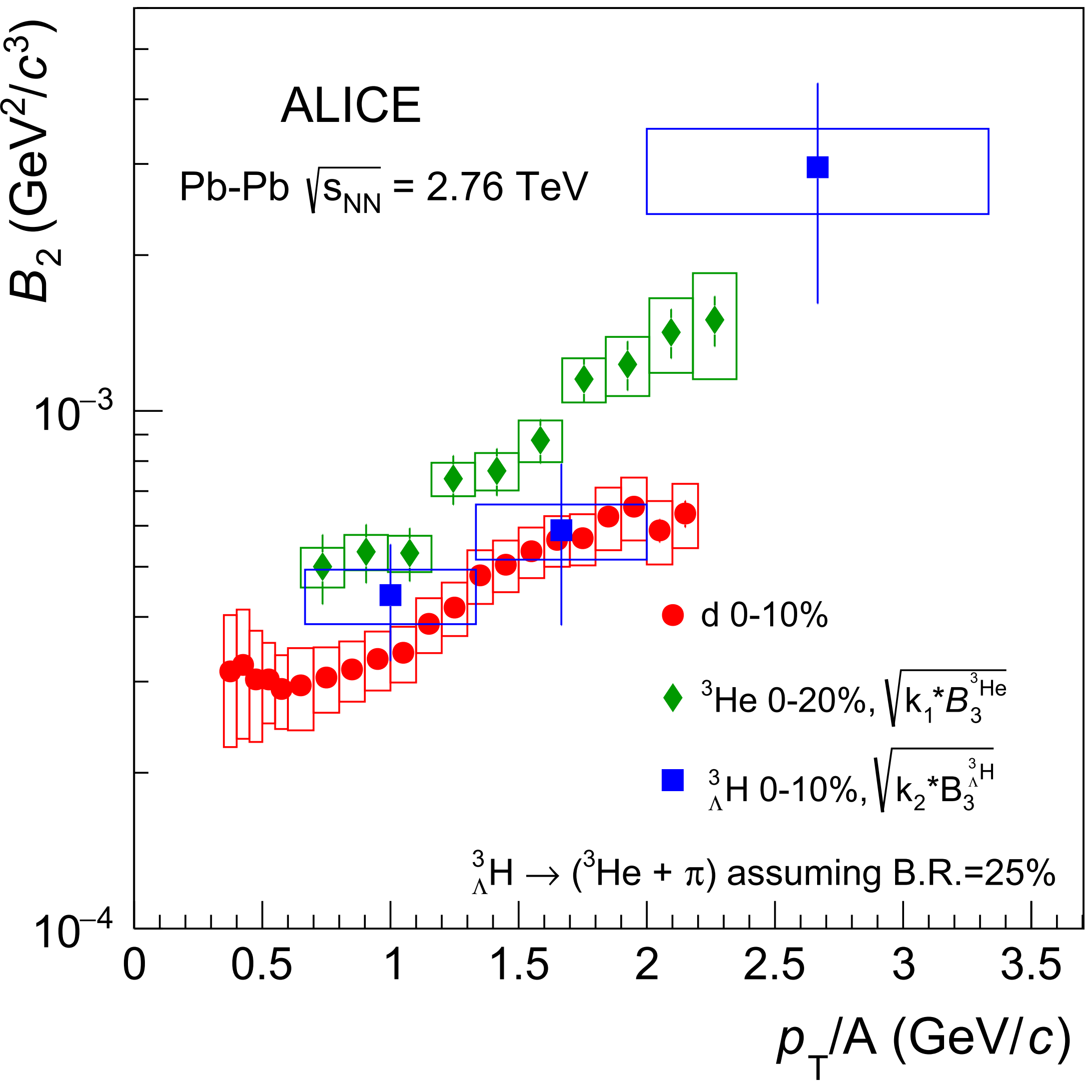
M. Agnello et al., Nucl. Phys. 954 (2016) 176

Year	Laboratory	Beam	Exp. method	Lifetime (ps)	Reference
1963	LBL Bevatron	stopped K^-	He bubble chamber	105^{+20}_{-18}	[10]
1964	BNL AGS	K^-, 2.3–2.5 GeV/c	ph. emulsions	90^{+220}_{-40}	[11]
1965	BNL AGS and LBL Bevatron	K^-, 2.3 GeV/c K^- 790 MeV/c	ph. emulsions	340^{+820}_{-140}	[12]
1968	ANL ZGS	stopped K^-	He bubble chamber	232^{+45}_{-34}	[13]
1968	LBL Bevatron	K^- 1.1 GeV/c	ph. emulsions	274^{+110}_{-72}	[14]
1969	BNL AGS	K^- 1.1 GeV/c	ph. emulsions	285^{+127}_{-105}	[15]
1970	CERN PS	stopped K^-	ph. emulsions	128^{+35}_{-26}	[16]
1970	ANL ZGS	stopped K^-	He bubble chamber	264^{+84}_{-52}	[17]
1973	ANL ZGS	stopped K^-	He bubble chamber	246^{+62}_{-41}	[18]
1992	Dubna Synchrophasotron	He, Li ions 2.2–5 AGeV rHIc	counter experiment	240^{+170}_{-100}	[19]
2010	BNL RHIC	Au–Au $\sqrt{s_{NN}} = 200$ GeV central urHIc	counter experiment	182^{+89}_{-45}	[20]
2013	BNL RHIC	Au–Au $\sqrt{s_{NN}} = 7.7$–200 GeV central urHIc	counter experiment	123^{+26}_{-22}	[21]
2013	GSI SIS	Li ions 2 AGeV peripheral rHIc	counter experiment	183^{+42}_{-32}	[22]
2016	CERN LHC	Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV central urHIc	counter experiment	181^{+54}_{-38}	[23]

[10] M.M. Block, et al., in: Proc. of the International Conference on Hyperfragments, St. Cergue, 28–30 March 1963, p.63.
[11] R.J. Prem, P.H. Steinberg, Phys. Rev. 136 (1964) B1803.
[12] Y.V. Kang, et al., Phys. Rev. 139 (1965) B401.
[13] G. Keyes, et al., Phys. Rev. Lett. 20 (1968) 819.
[14] R.J. Phillips, J. Schneps, Phys. Rev. Lett. 20 (1968) 1383.
[15] R.J. Phillips, J. Schneps, Phys. Rev. 180 (1969) 1307.
[16] G. Bohm, et al., Nucl. Phys. B 16 (1970) 46.
[17] G. Keyes, et al., Phys. Rev. D 1 (1970) 66.
[18] G. Keyes, et al., Nucl. Phys. B 67 (1973) 269.
[19] S. Avramenko, et al., Nucl. Phys. A 547 (1992) 95c.
[20] STAR Collaboration, Science 328 (2010) 58.
[21] J. Zhu, Nucl. Phys. A 904 (2013) 551c.
[22] C. Rappold, et al., Nucl. Phys. A 913 (2013) 170.
[23] ALICE Collaboration, J. Adam, et al., Phys. Lett. B 754 (2016) 360.

${}^{3}_{\Lambda}H$ coalescence parameter details

- Λ, p and n close in the phase space at the *kinetic freeze-out* can form a(n) (anti-)hypertriton
- B_A is expected to be independent from p_T and centrality



- B_3 is computed for ${}^{3}_{\Lambda}H$ according to the above equation
  - ${}^{3}H$ measured p_T spectra from this analysis
  - p and Λ spectra respectively from [9] and [10]
- $B_3^{{}^3_{\Lambda}H}$ is compared with B_2^{d} and $B_3^{{}^3He}$ obtained in [11]
  - ${}^{3}He$ B_3 is scaled to B_2 through the scaling factor k_1
  - ${}^{3}_{\Lambda}H$ B_3 is scaled to B_2 through the scaling factor k_2

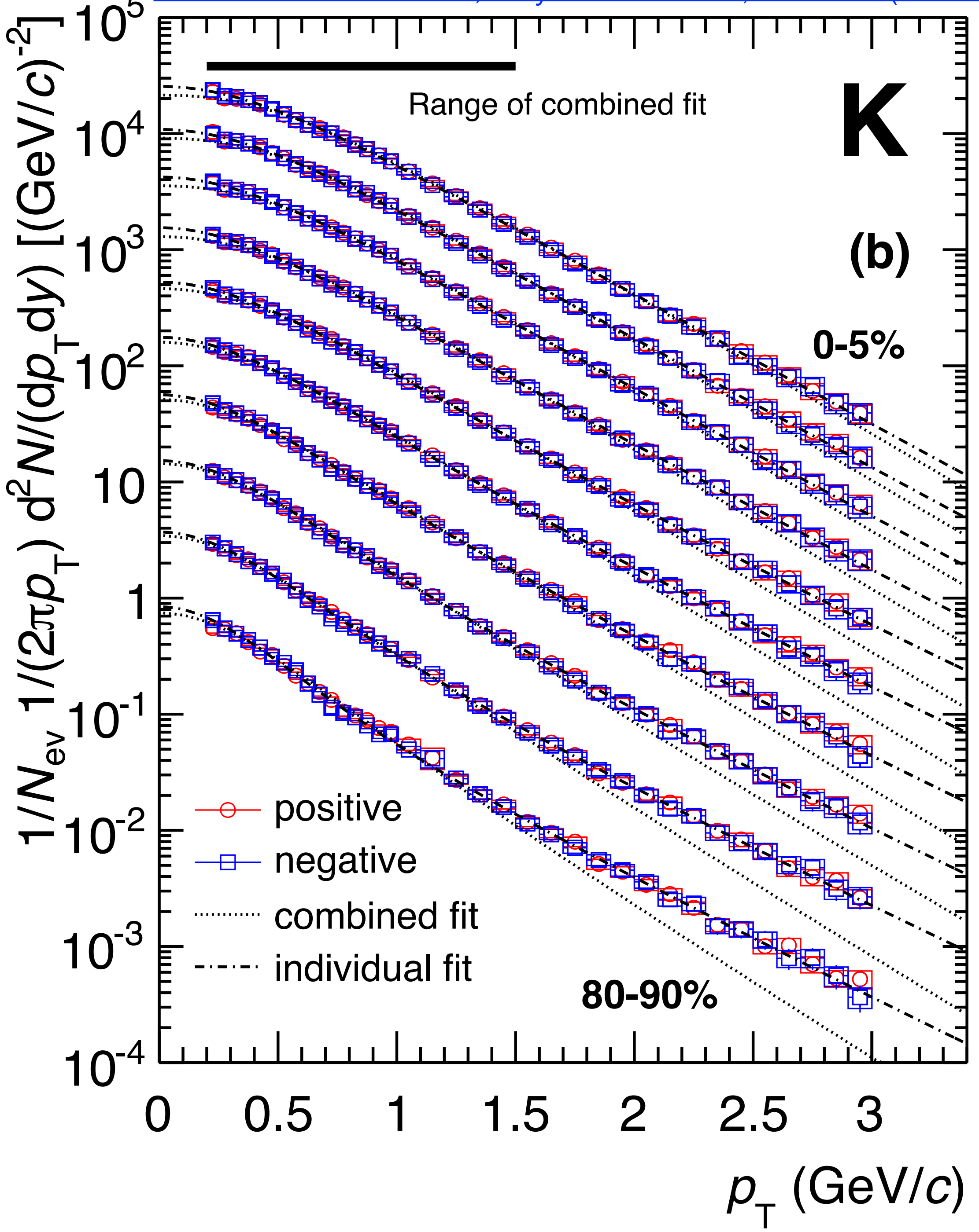
$$k_1 = \frac{m_d^2}{M_{{}^3He} m_p} \qquad k_2 = \frac{m_d^2 m_\Lambda}{m_p^2 M_{{}^3_{\Lambda}H}}$$

- ${}^{3}H$ coalescence parameter is not flat as function of p_T contrary to the simple coalescence model predictions
- Model does not take into account characteristics of the emitting source
- Behaviour similar to the one observed for d and ${}^{3}He$

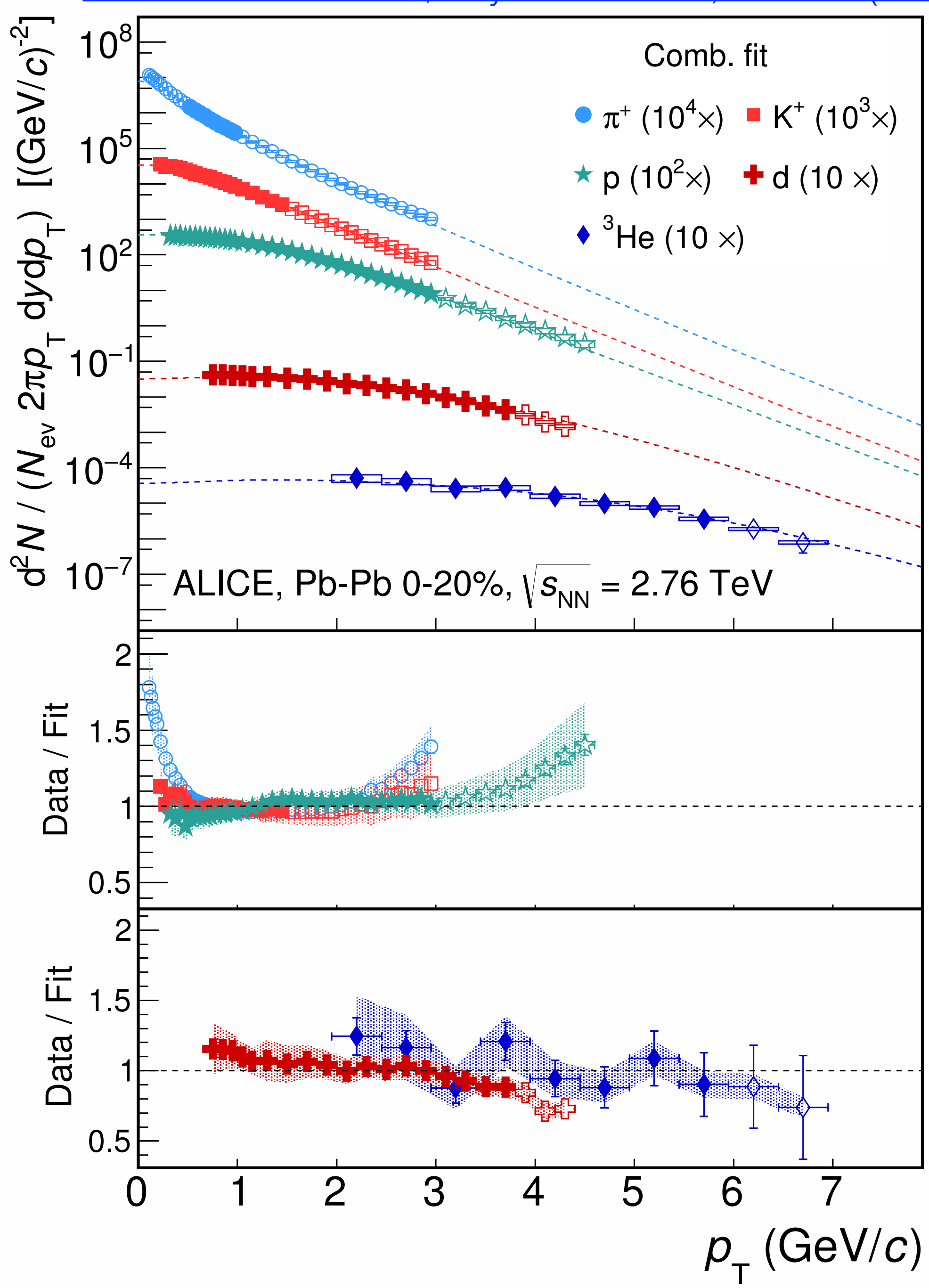
[9] ALICE Collaboration Phys. Rev. C 88, (2013) 044910
[10] ALICE Collaboration Phys. Rev. Lett. 11, (2013) 22301
[11] ALICE Collaboration Phys. Rev. C 93 (2016) 024917

Blast Wave distribution

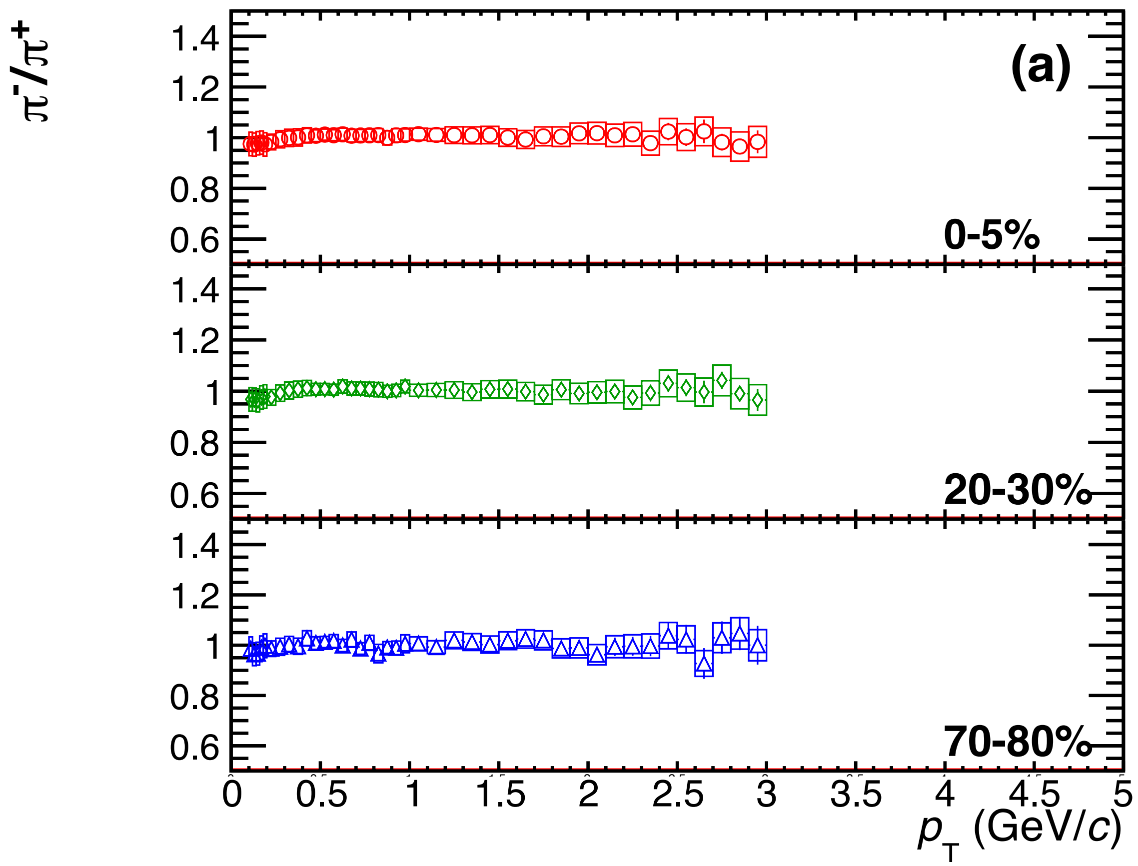
ALICE Collaboration, Phys. Rev. C 88, 044910 (2013)

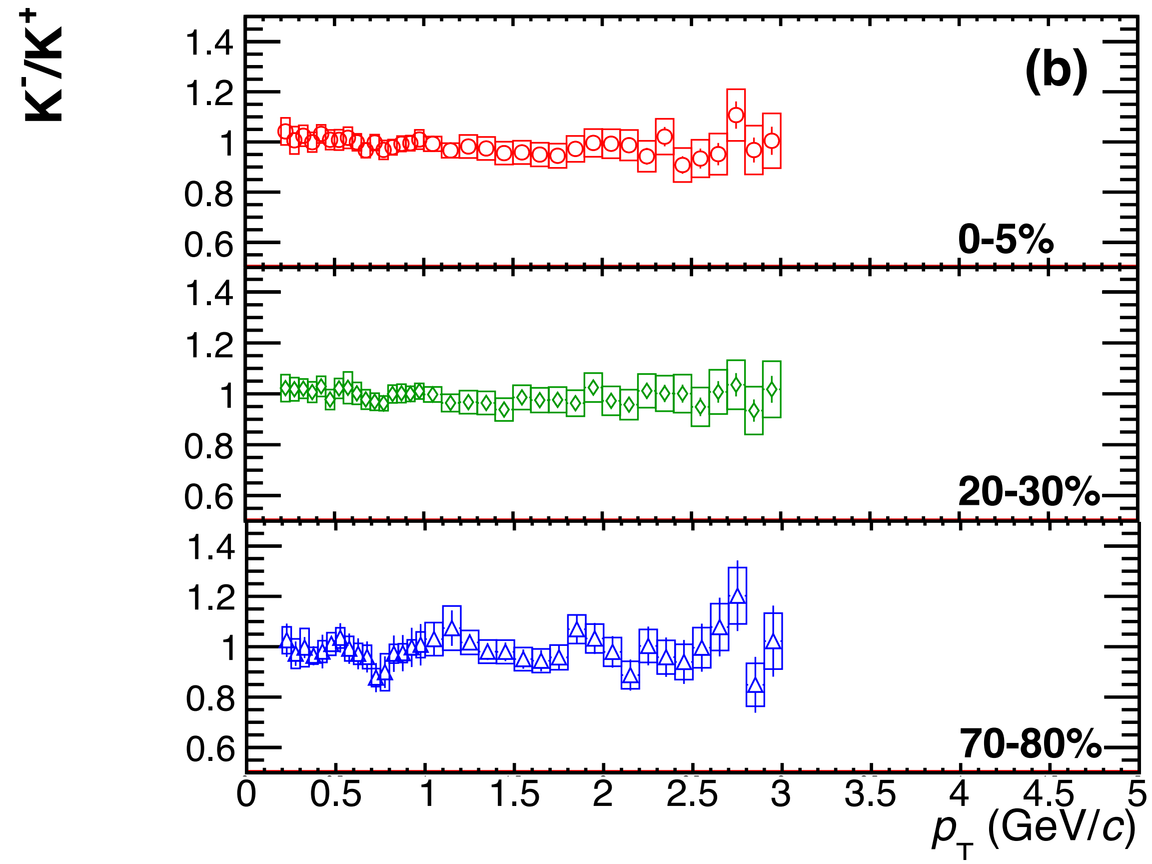


ALICE Collaboration, Phys. Rev. C 93, 024917 (2015)

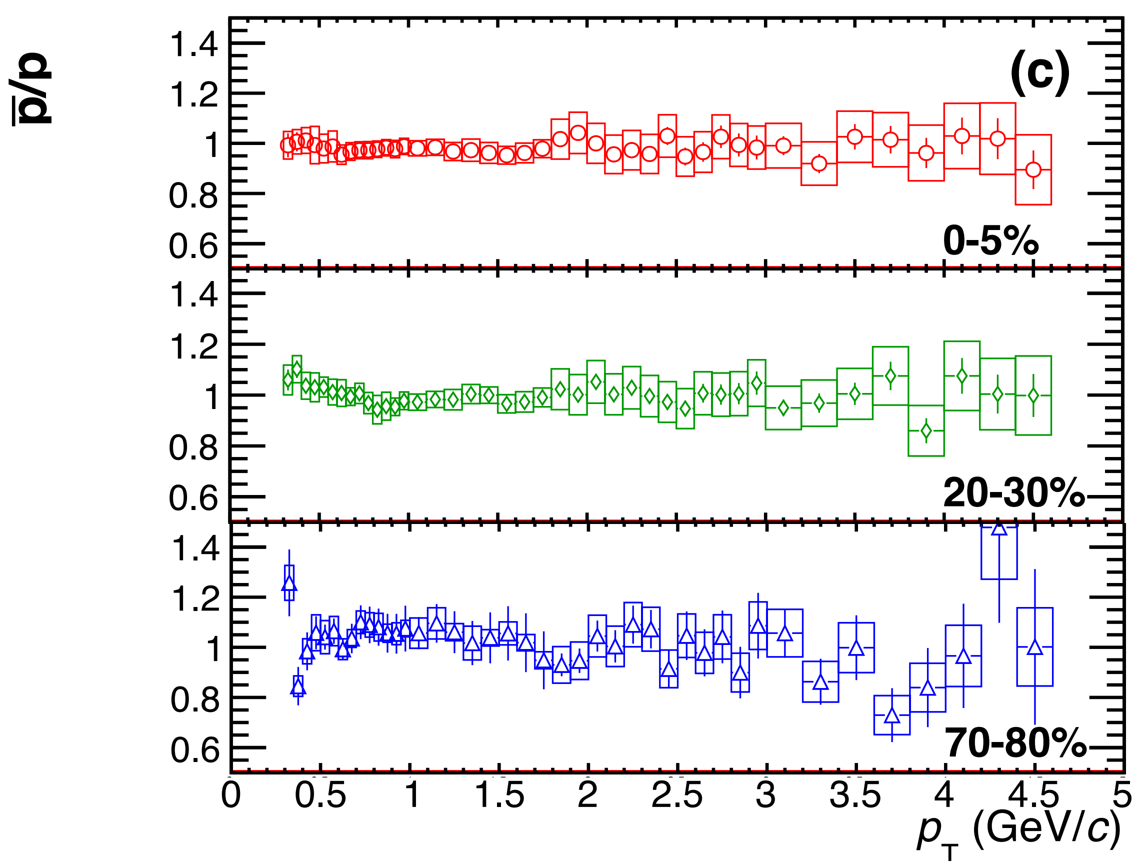


Antimatter-to-matte ratio





ALICE Collaboration, Phys. Rev. C 88, 044910 (2013)



Hypernuclei production mechanisms

Strangeness exchange

$$K^- + N \rightarrow \Lambda + \pi$$

- A transfer of the s-quark from the incident meson to the struck baryon

Associated production

$$\pi^+ + n \rightarrow \Lambda + K^+$$

- Proceeds by the creation of $s\bar{s}$ pair by the incident meson

Electroproduction

$$e + p \rightarrow e^{'} + \Lambda + K^+$$

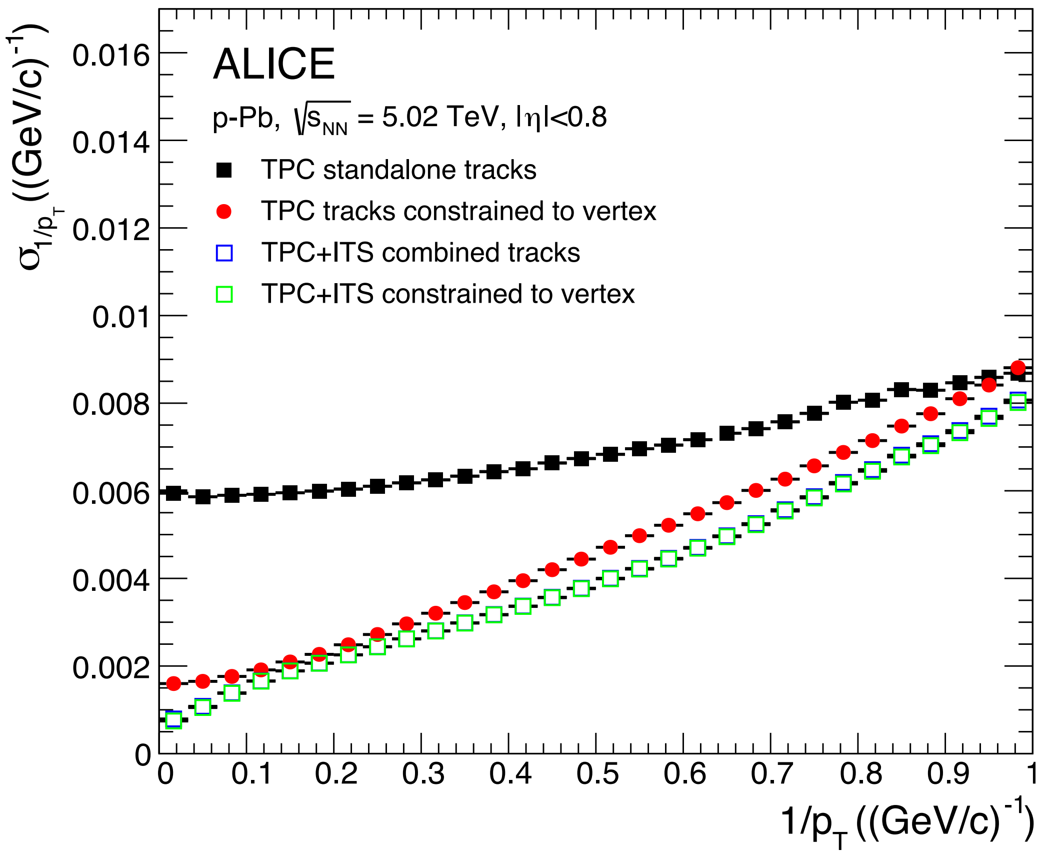
- Electroproduction of strangeness on protons in the very forward direction
- Virtual photon associated can be regarded as quasi-real

Glauber model

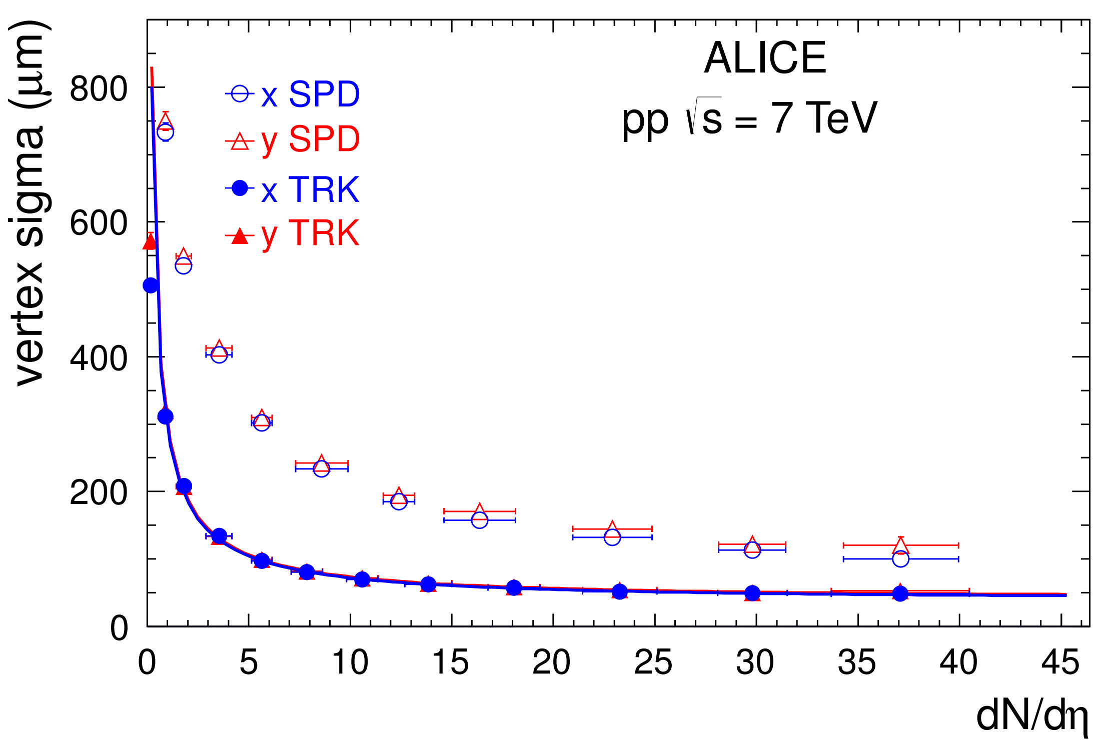
- Heavy ion collision as the superposition of the interactions between the constituent nucleons of colliding nuclei
- Key parameters:
  - N_{part}: number of nucleons participating in the interactions
  - N_{coll}: number of binary collisions between nucleons

    ➡ correlated with impact parameter of the collision
- Assumptions:
  - nucleons point like and independent inside the colliding nuclei
  - only hadronic interactions are considered
  - each interaction does not deflect the trajectories of colliding nucleons
- It allows to calculate:
  - the interaction probability
  - N_{coll} and N_{part}
  - Size of the overlap region between the colliding nuclei

Tracking



- Momentum resolution $\frac{\sigma_{p_T}}{p_T} = p_T \; \sigma_{1/p_T}$
  - TPC standalone tracks 1-6% (1-10 GeV/*c*)
  - resolution improved when constraining the tracks to the primary vertex and when requiring the ITS



- Primary vertex resolution
  - better resolution with full tracks than using only SPD
  - scale with the charged particle multiplicity