Light (Hyper-)Nuclei production at the LHC measured with ALICE

TECHNISCHE UNIVERSITÄT DARMSTADT

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EMMI Physics Days 2014

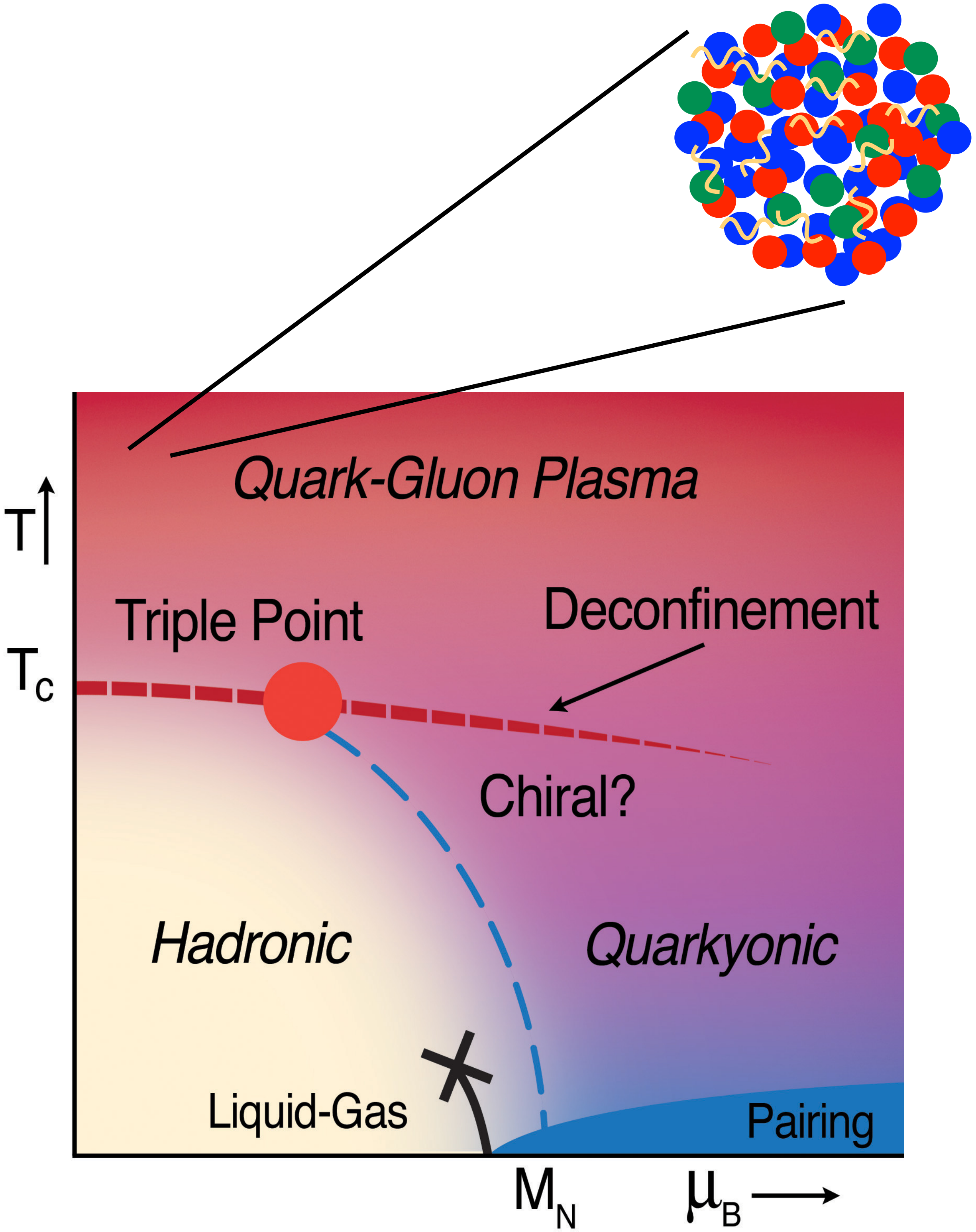
EMMI

GSI

ALICE

H-QM Helmholtz Research School Quark Matter Studies

Phase diagram of nuclear matter



A.Andronic et al., Nucl. Phys. A 837 (2009) 65

Quark-Gluon Plasma

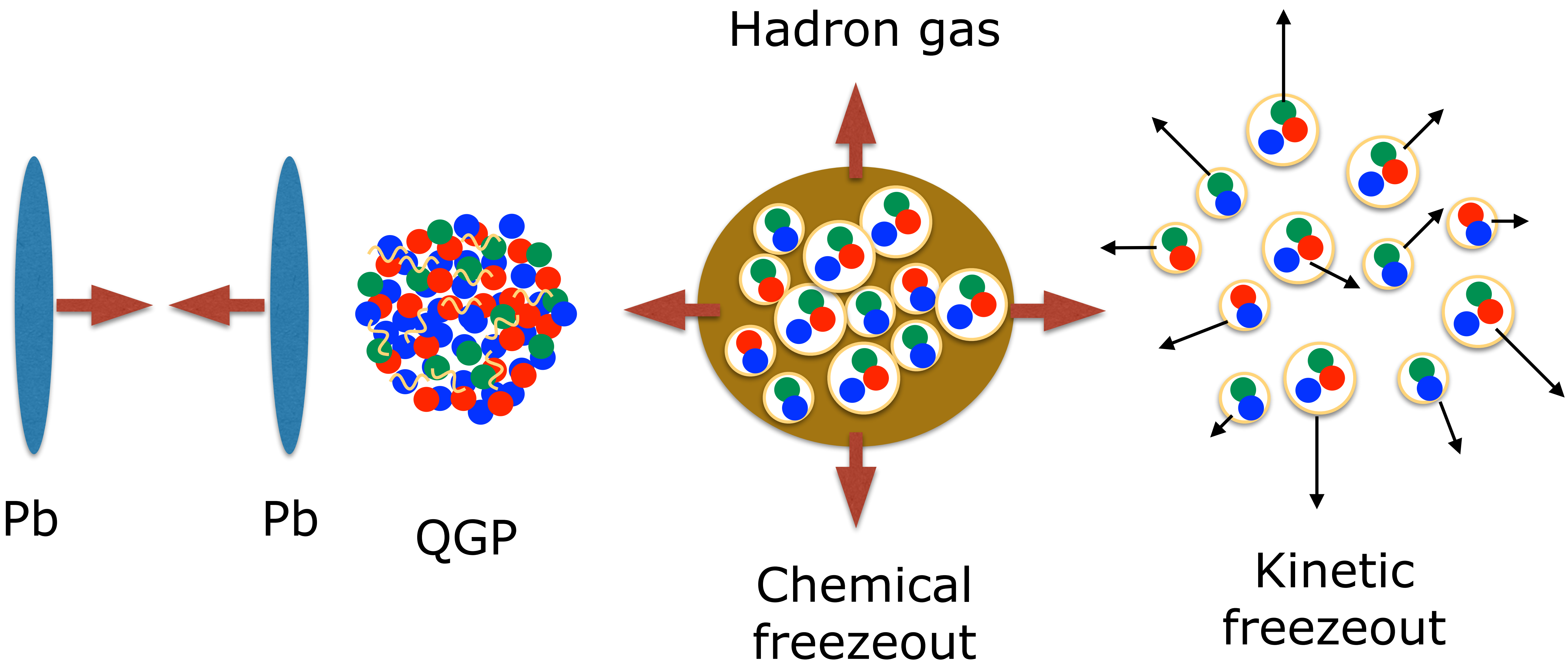
Our tool to produce the Quark-Gluon Plasma (QGP) are Heavy-Ion Collisions (HIC)

QGP in laboratory

Large Hadron Collider (LHC) ~ 27 km circumference

pp collisions at $\sqrt{s}$ = 900 GeV, 2.76 TeV, 7 TeV and 8 TeV
Pb—Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
p—Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

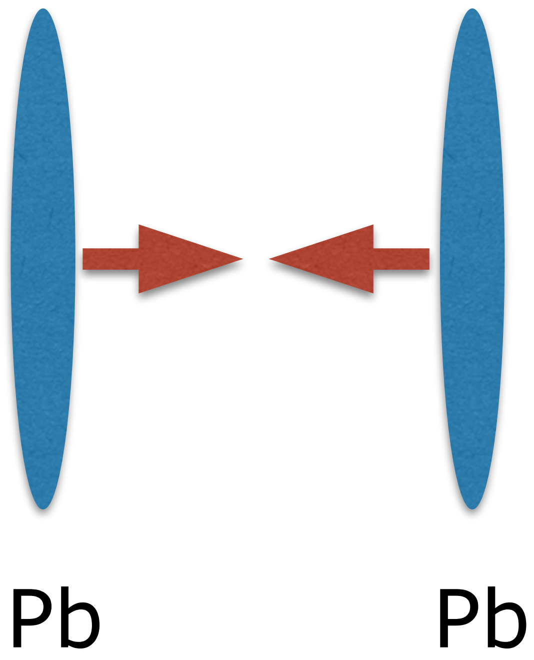
Heavy Ion Collision



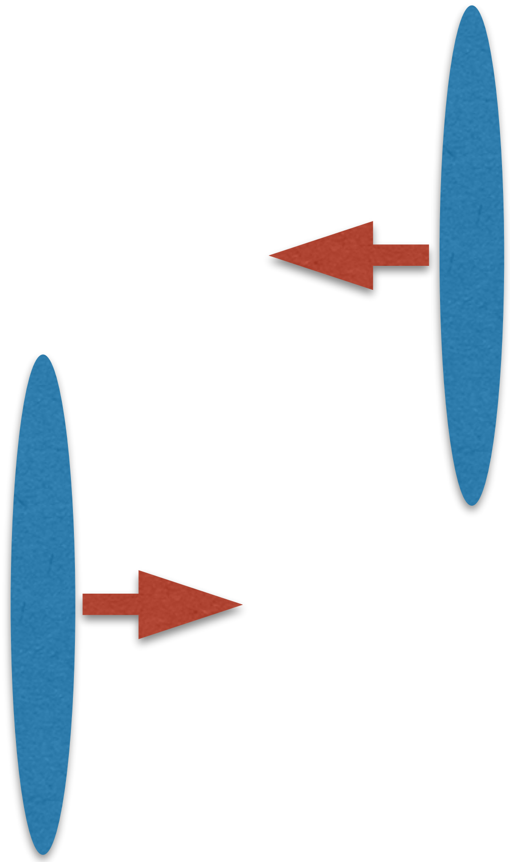
Particle composition fixed

Particle momenta fixed

Centrality in a HIC



Central Pb—Pb collision
high multiplicity = high number of tracks
(more than 2000 charged tracks in the detector)



Peripheral Pb—Pb collision
low multiplicity = low number of tracks
(few tens of charged tracks in the detector)

Multiplicity in a HIC

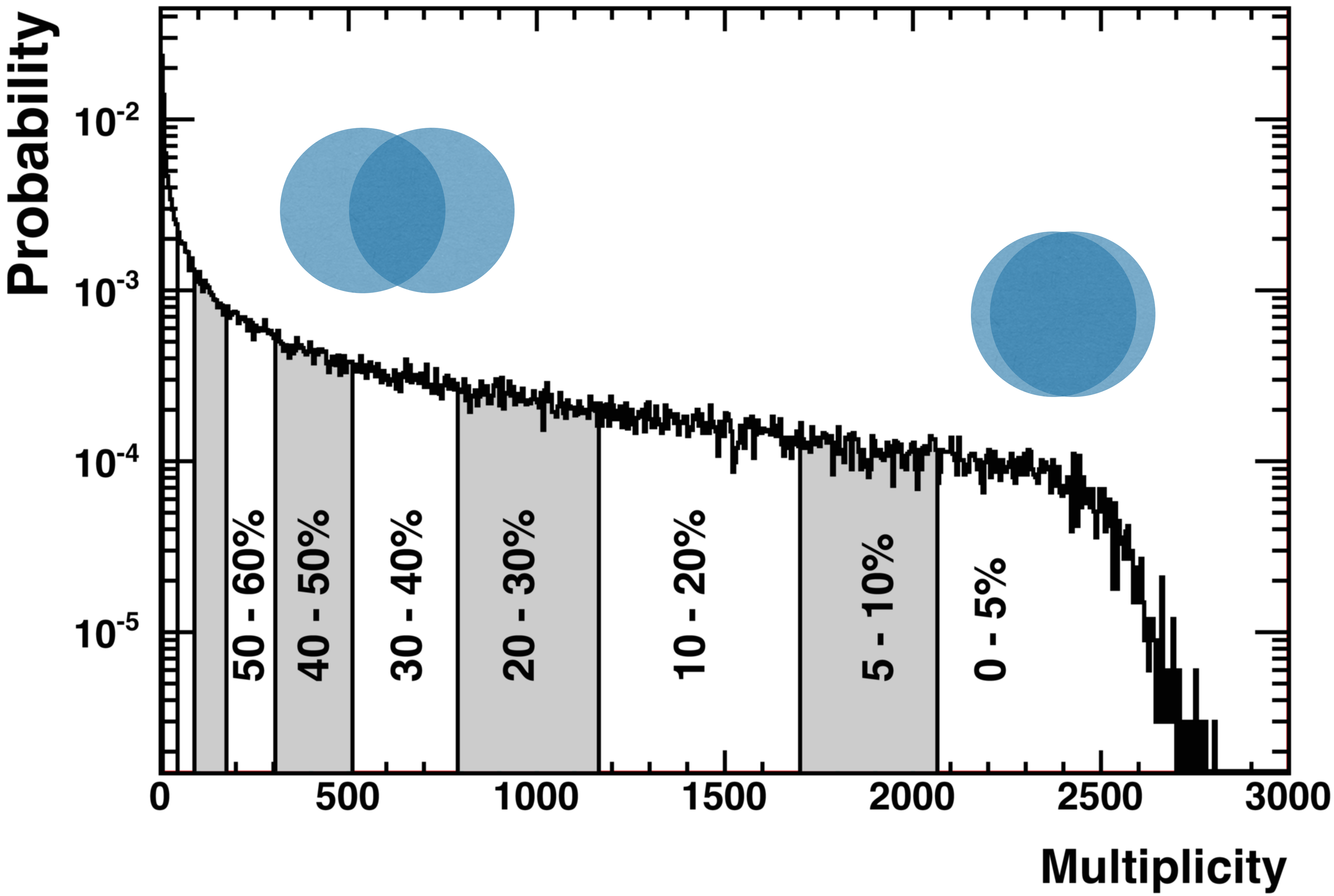


Table of nuclides

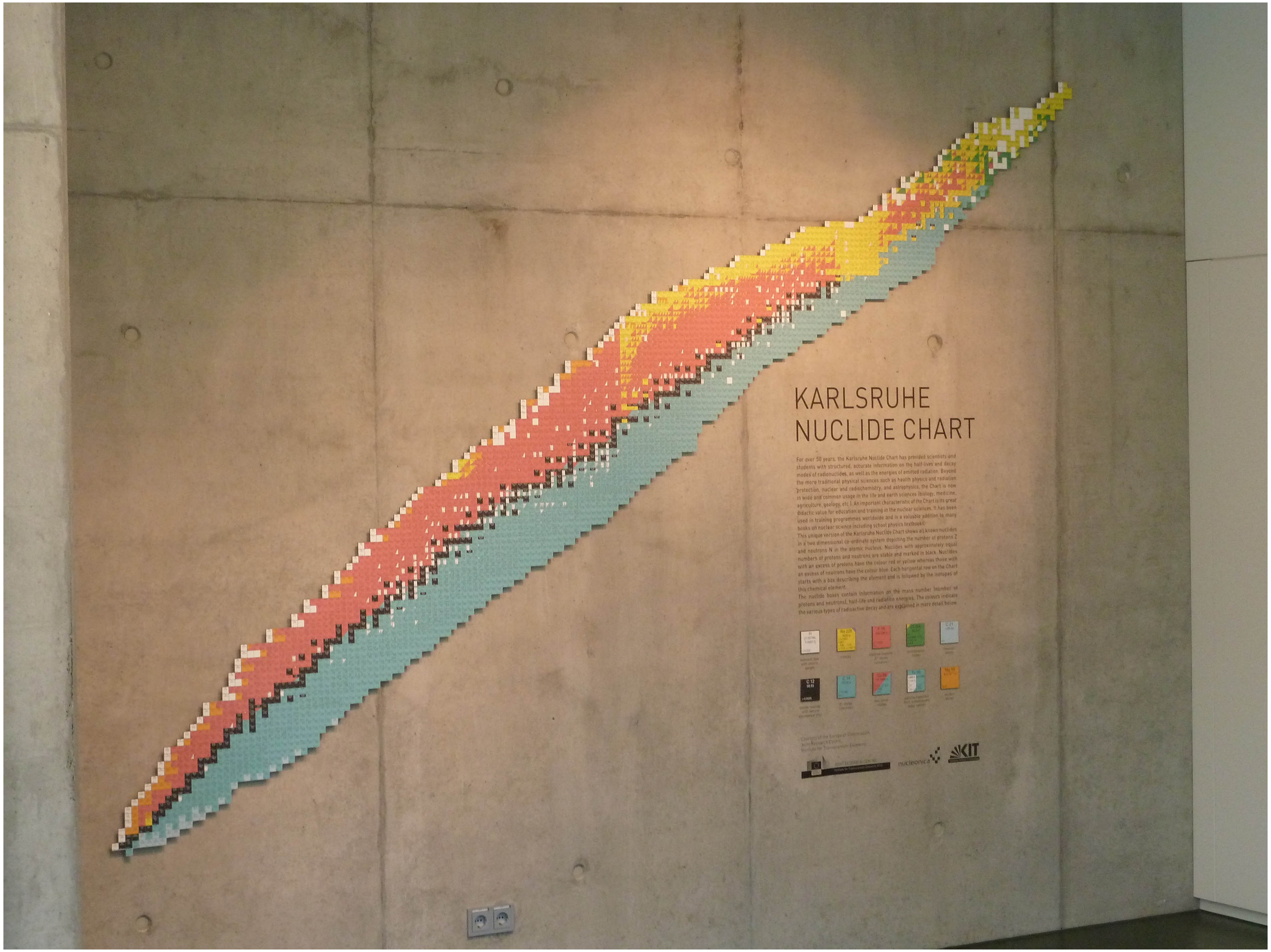
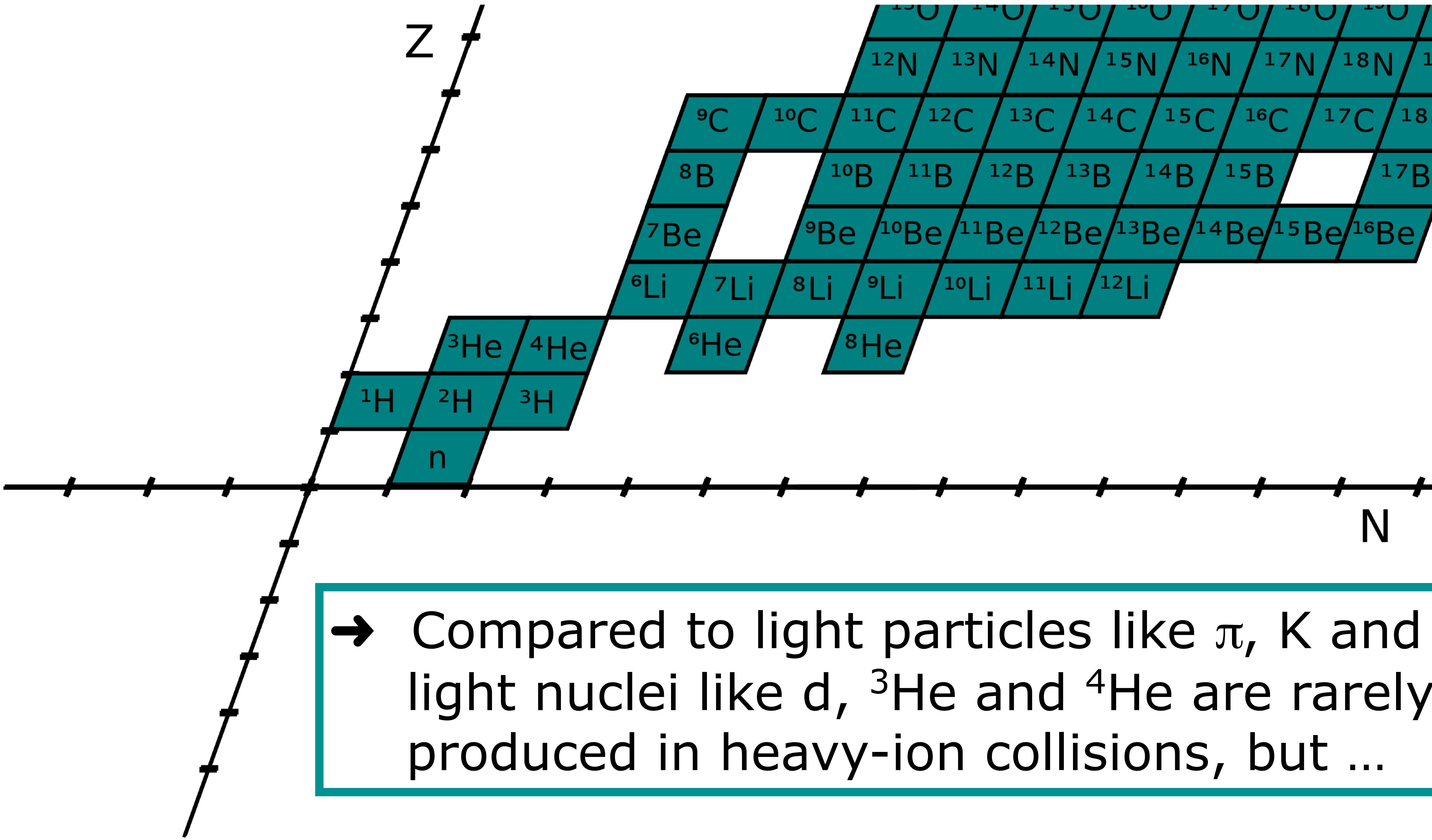
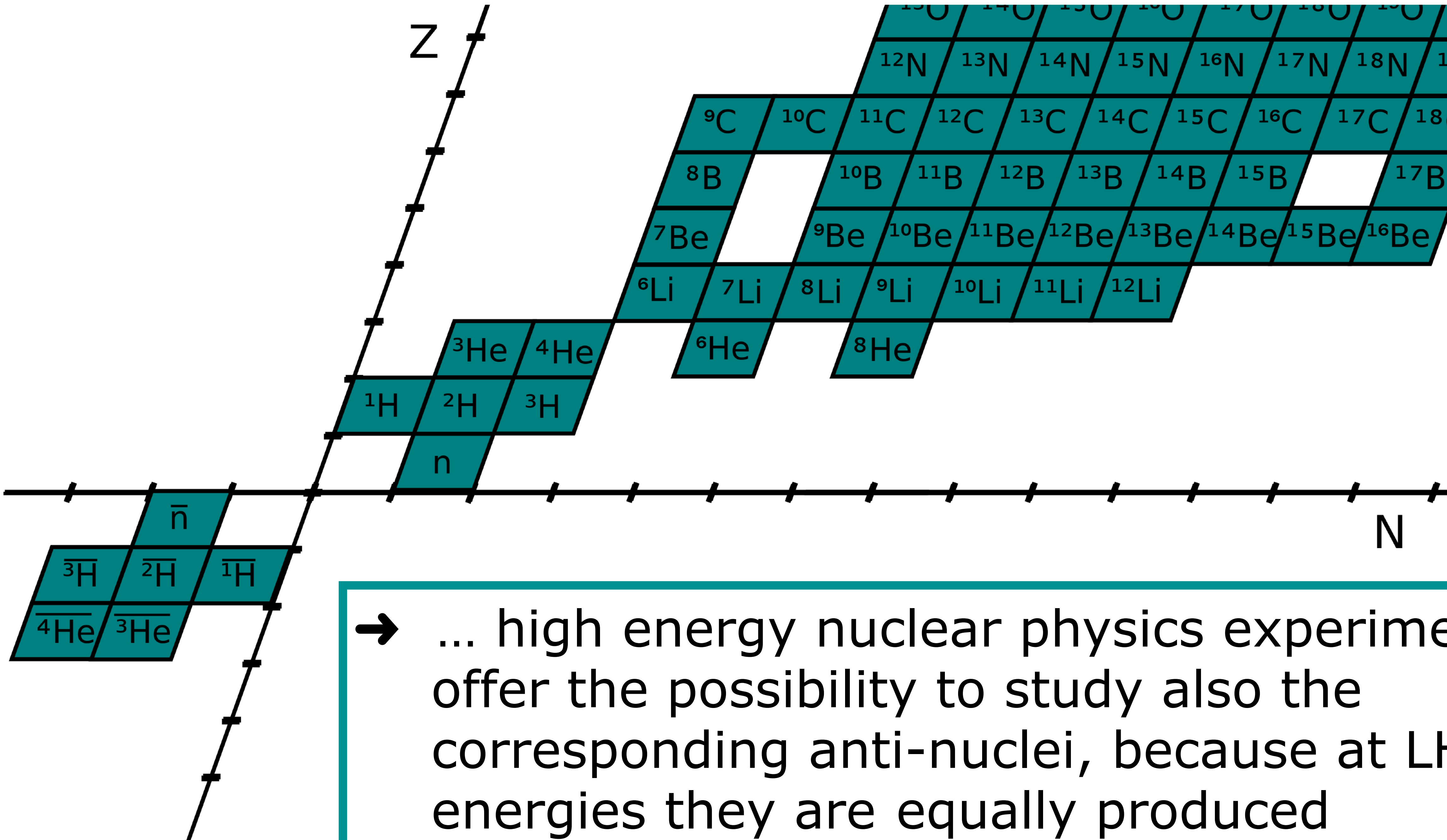


Table of nuclides



➜ Compared to light particles like π, K and p light nuclei like d, ^{3}He and ^{4}He are rarely produced in heavy-ion collisions, but …

Table of nuclides



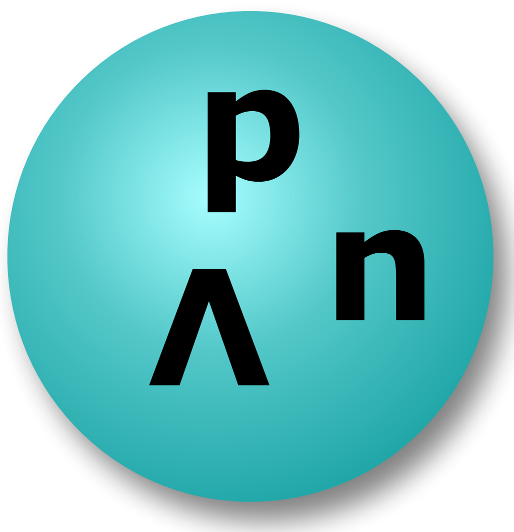
➜ … high energy nuclear physics experiments offer the possibility to study also the corresponding anti-nuclei, because at LHC energies they are equally produced

Hypernuclei

- Hyperons: Baryons, which have at least one s-quark as one of their 3 valence-quarks for example Λ, Σ, Ξ, or Ω

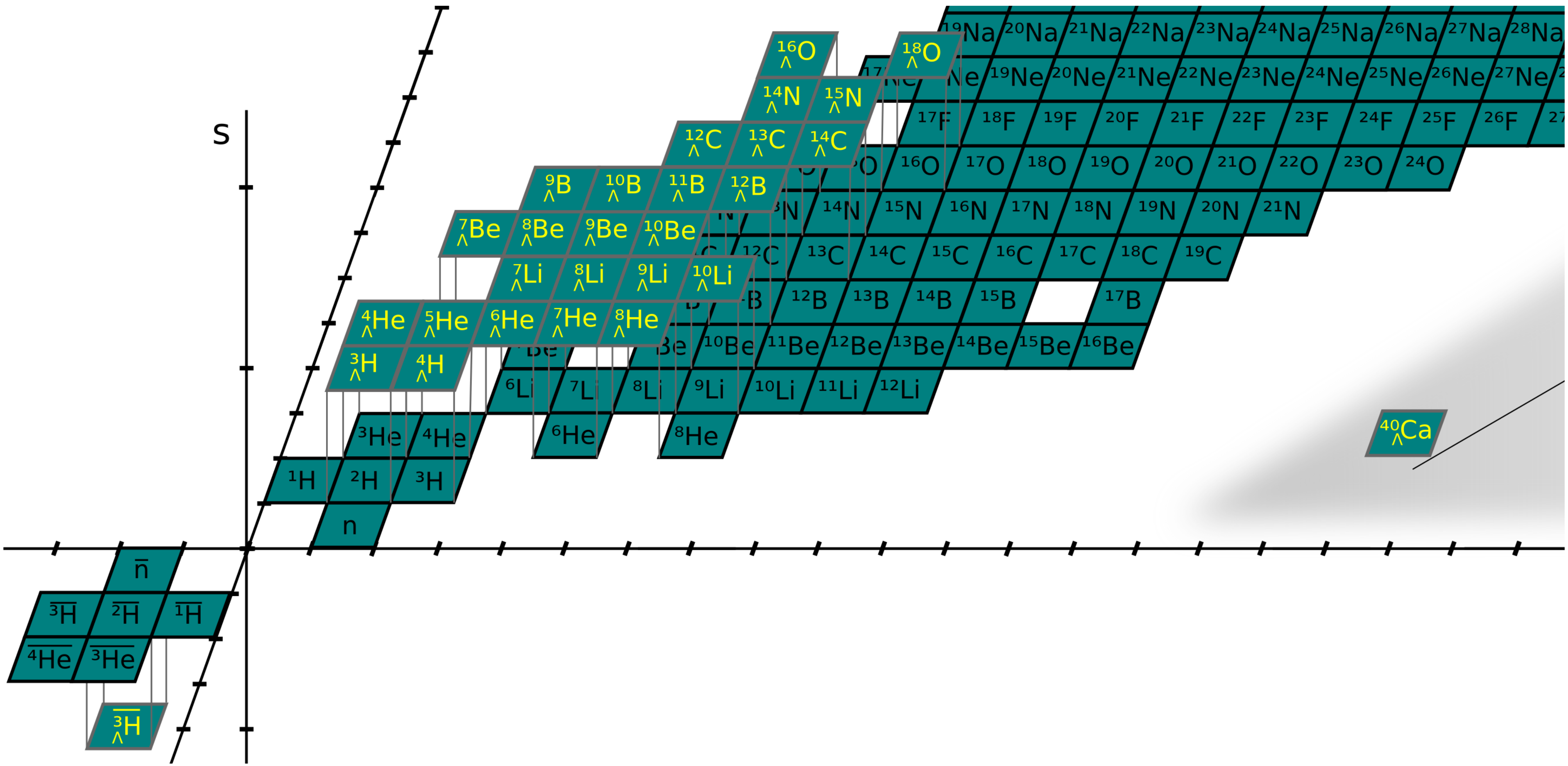
- Hypernuclei: nuclei, in which at least one neutron is replaced by a hyperon

Hypertriton



→ All hypernuclei are unstable

Table of nuclides



➜ table of nuclei can be extend to include also hypernuclei

Models I

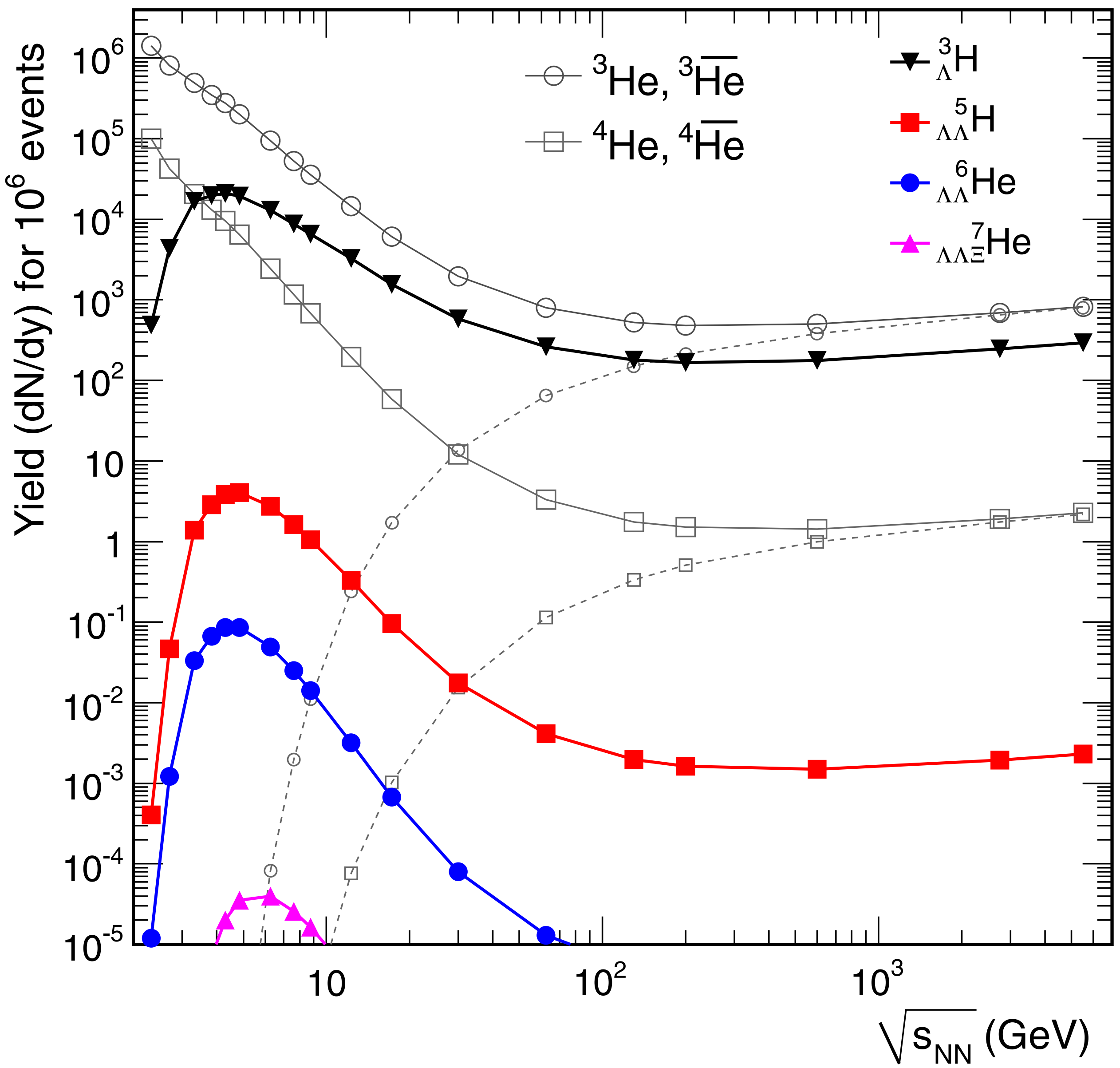
Thermal model:

Key parameter at LHC energies: chemical freeze-out temperature T_{chem}

Strong sensitivity of abundance of nuclei to choice of T_{chem} due to:

1. large mass m
2. exponential dependence of the yield ~ exp($-m/T_{chem}$)

yield determined by T_{chem}, if expansion after T_{chem} is isotropic



A. Andronic, P. Braun-Munzinger, J. Stachel, and H. Stoecker, Phys. Lett. B697, 203 (2011), 1010.2995

Models II

Coalescence model:

Nuclei are formed by protons and neutrons which are nearby and have similar velocities (after kinetic freeze-out)

Nuclei produced at chemical freeze-out

➜ can break apart

➜ created again by final-state coalescence

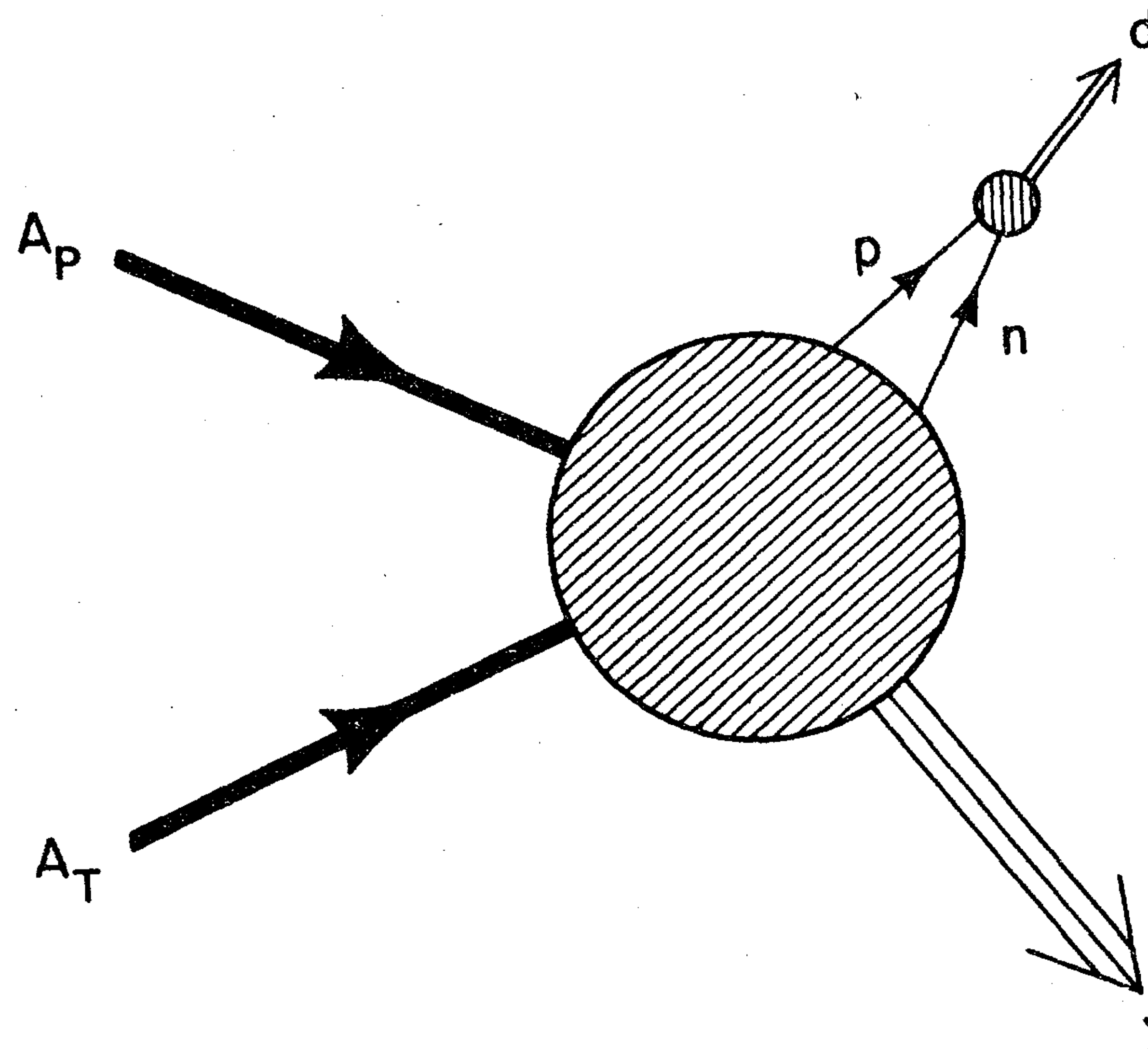


FIG. 1. Schematic for the production of a deuteron in the final state of a relativistic collision between two heavy nuclei.

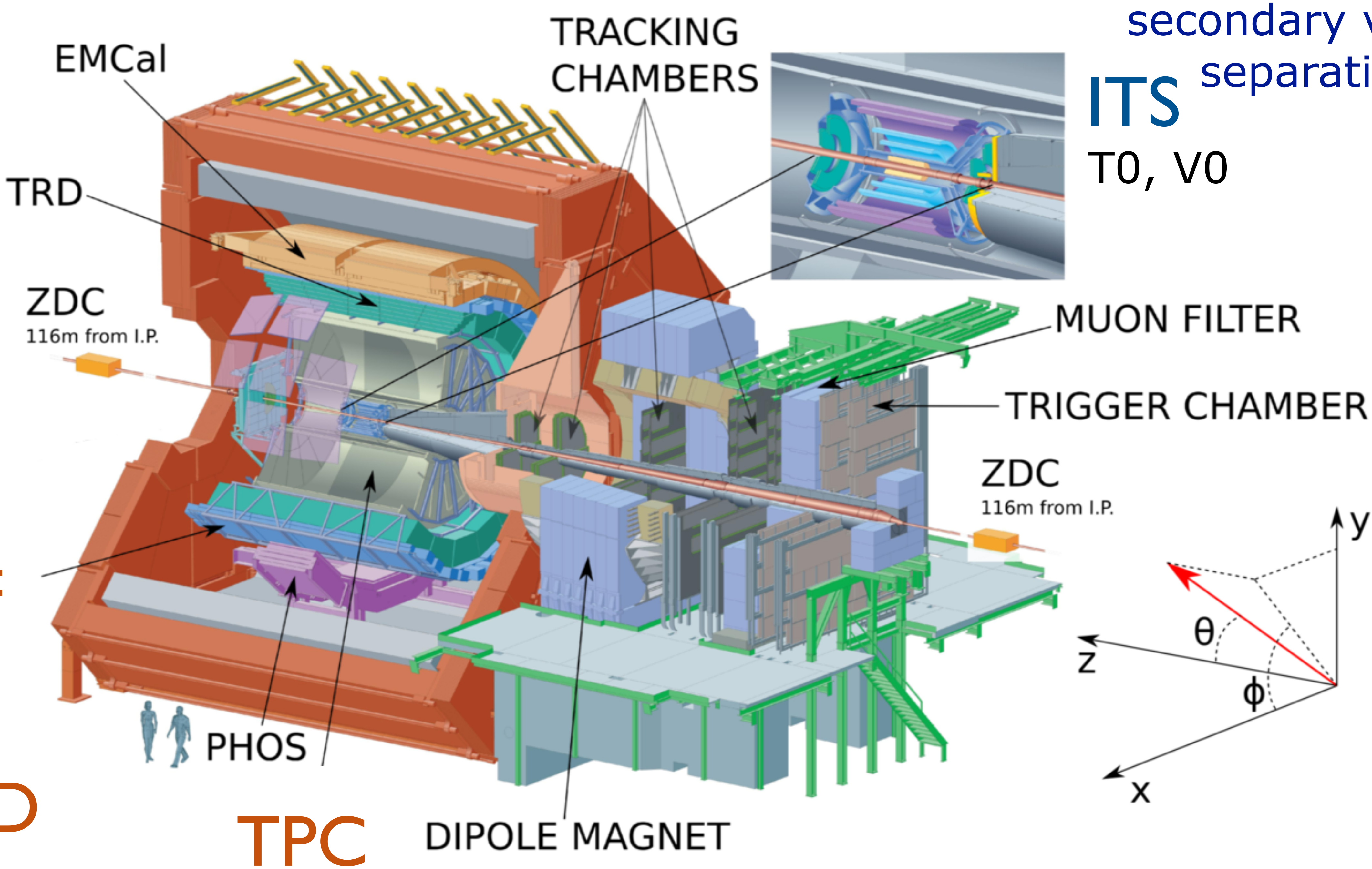
J. I. Kapusta, Phys.Rev. C21, 1301 (1980)

Analysis strategy

primary and
secondary vertex
separation

ITS

T0, V0

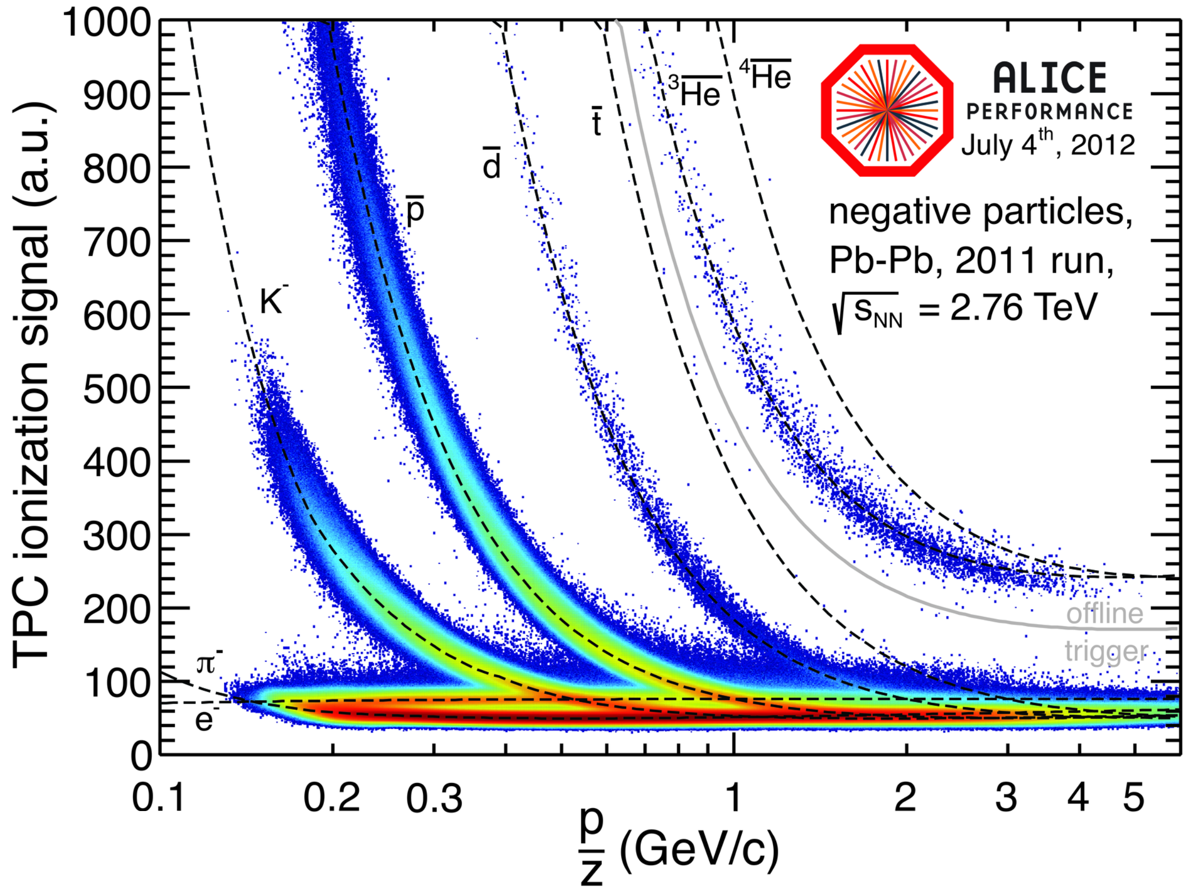


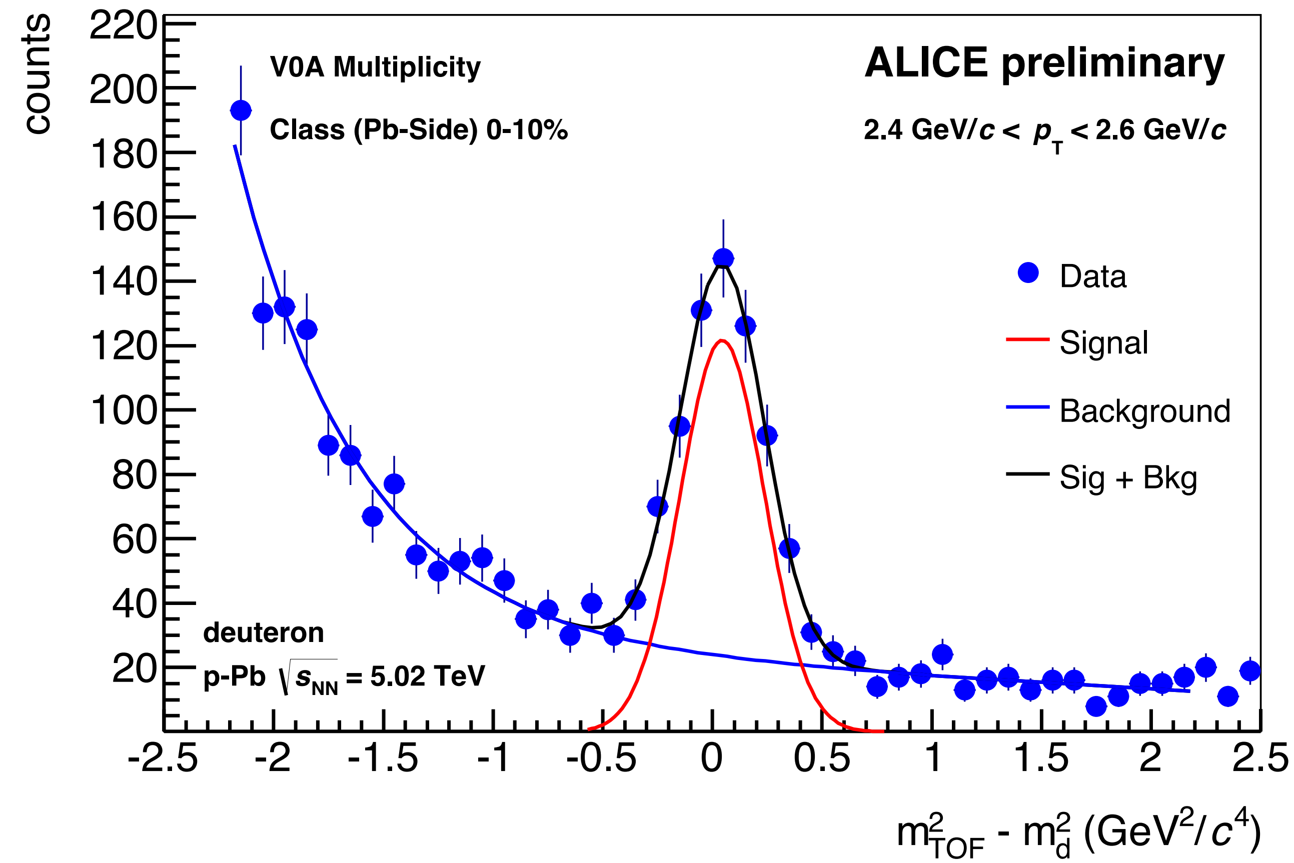
TOF

PID

TPC

Particle identification

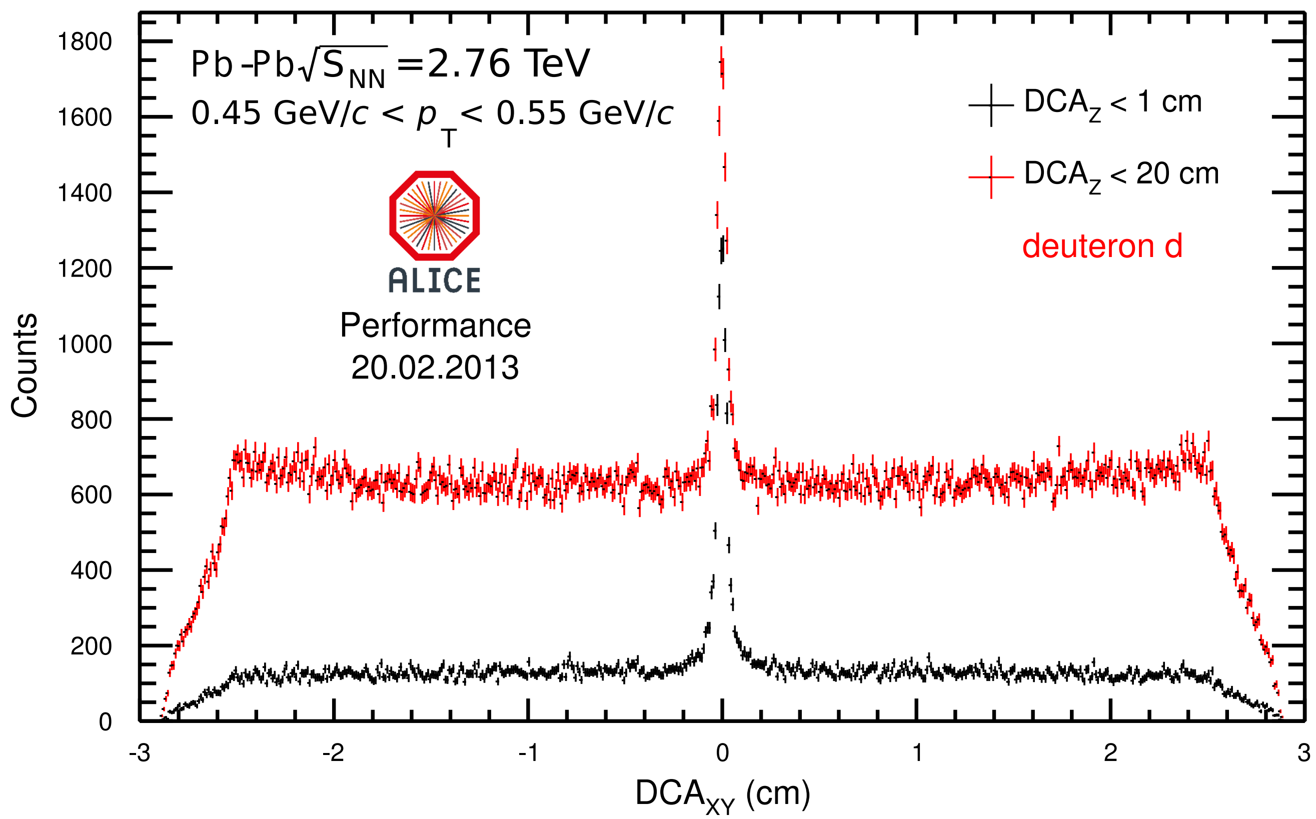


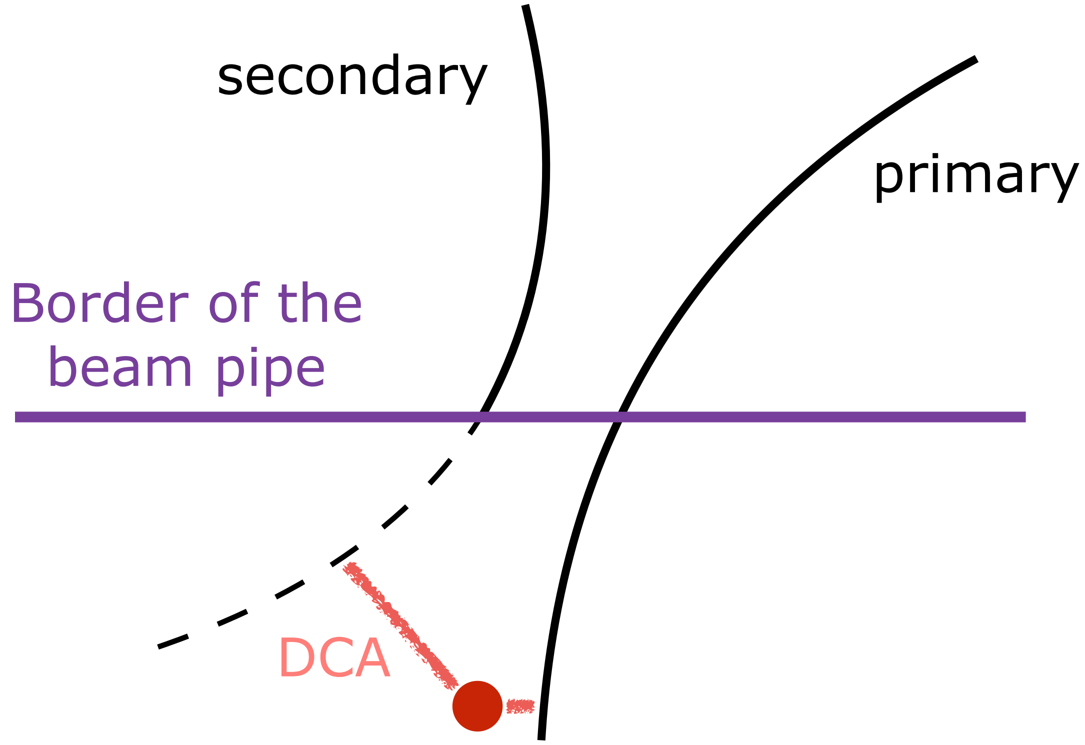


Low momenta:
Nuclei are identified using the d*E*/d*x* measurement in the Time Projection Chamber

Higher momenta:
Velocity measurement with the Time of Flight detector is used to calculate the m^2 distribution

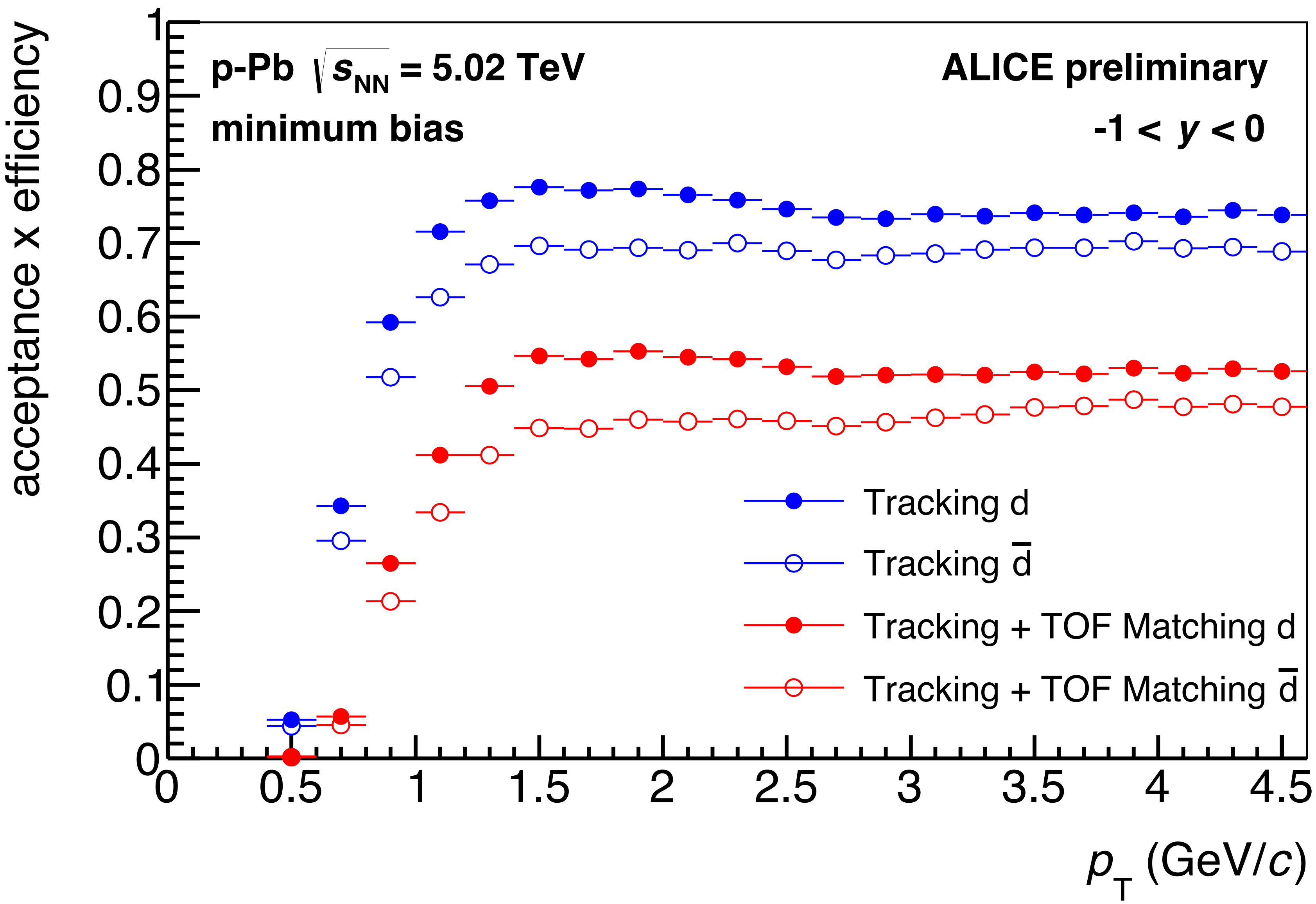
Primaries vs. Secondaries





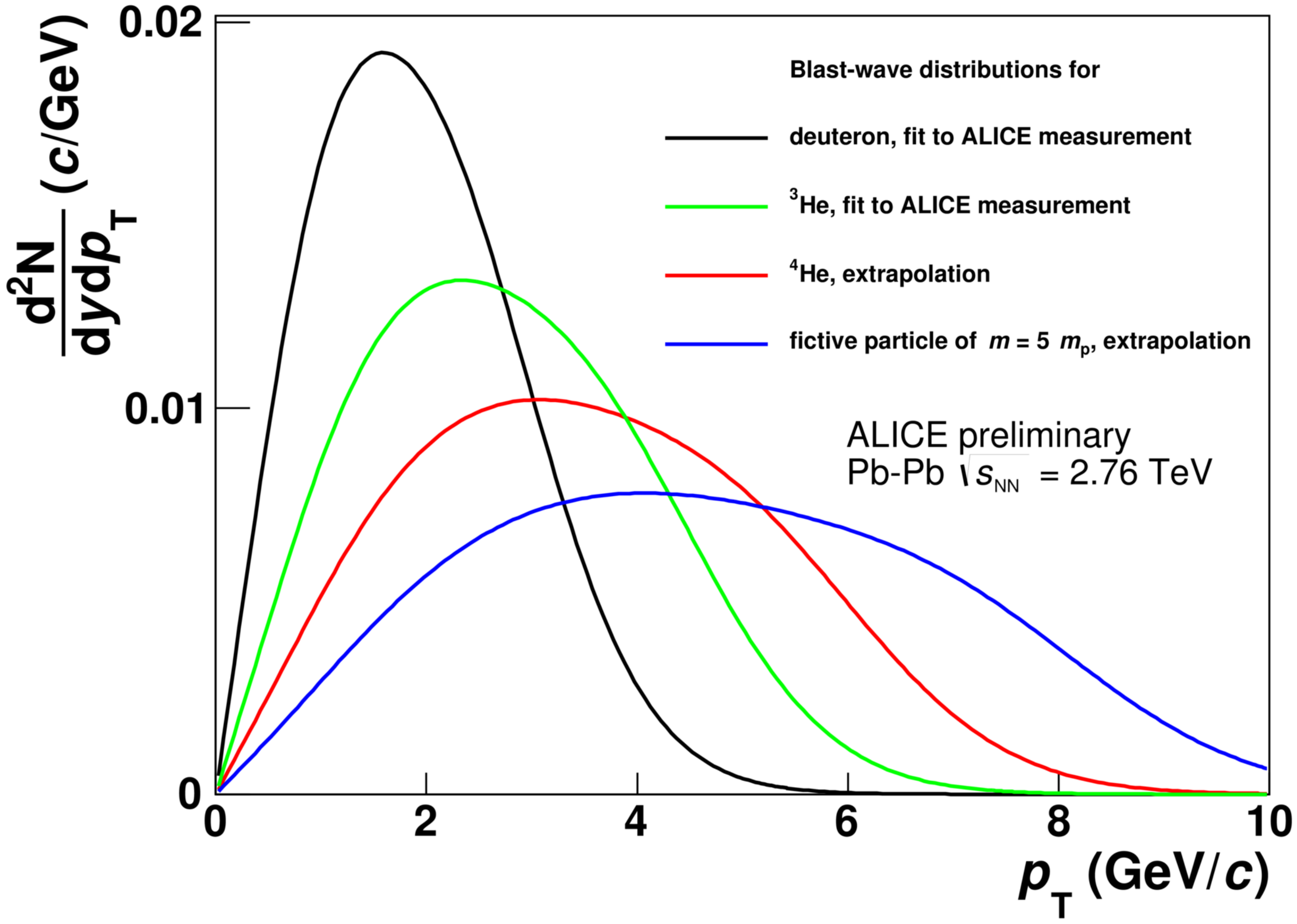
- ➜ Distance-of-Closest-Approach (DCA) distributions can be used to separate primary particles (produced in the collision) from secondary particles (from knock-out of the material e.g. the beam pipe)
- ➜ Knock-out significant problem at low p_T, but only for nuclei not for anti-nuclei

Efficiency correction



The measured raw yields have to be corrected for efficiency and acceptance.

Blast-Wave model

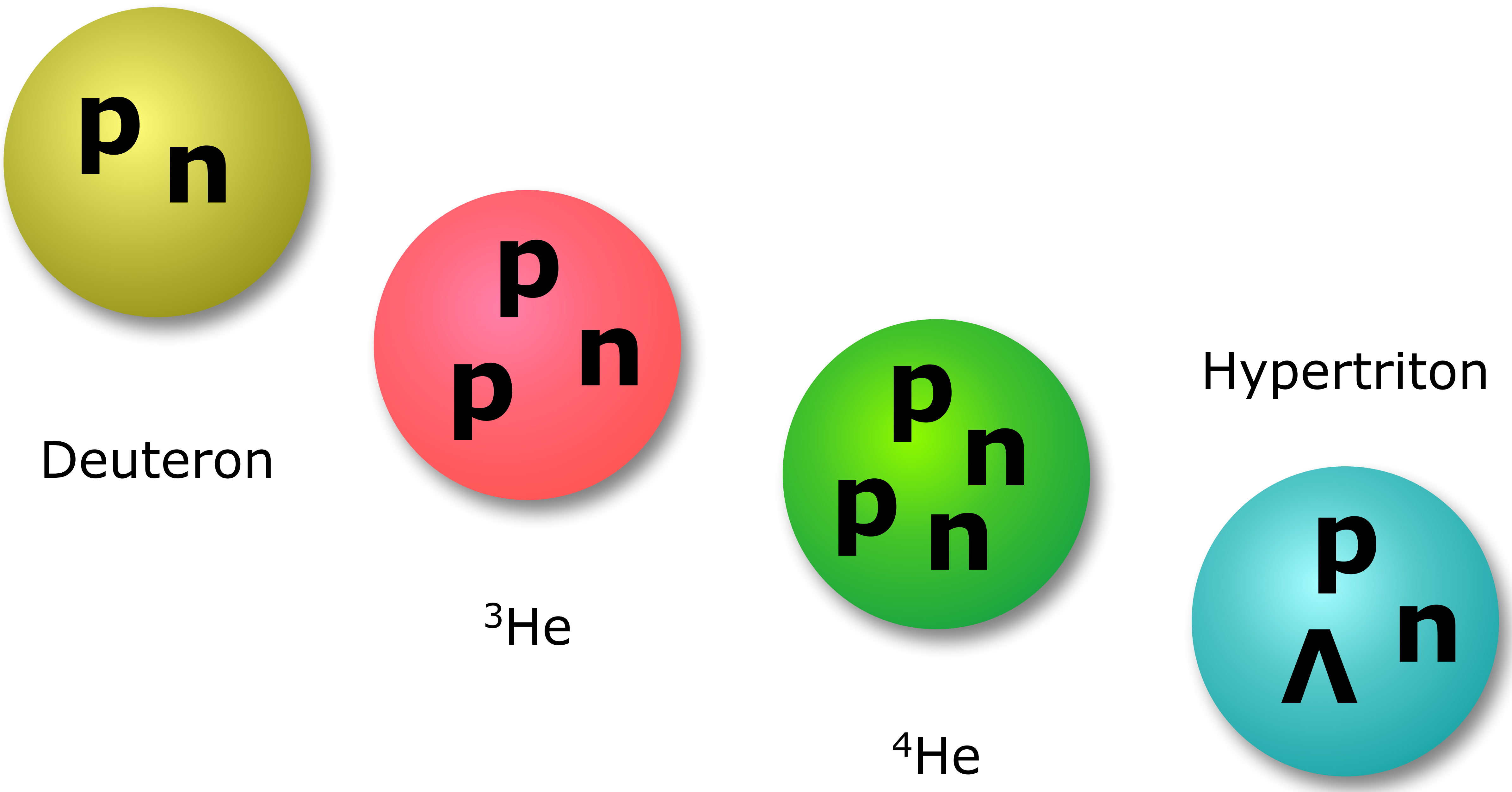


A Blast-wave function is a parameterized description of hydrodynamic flow.

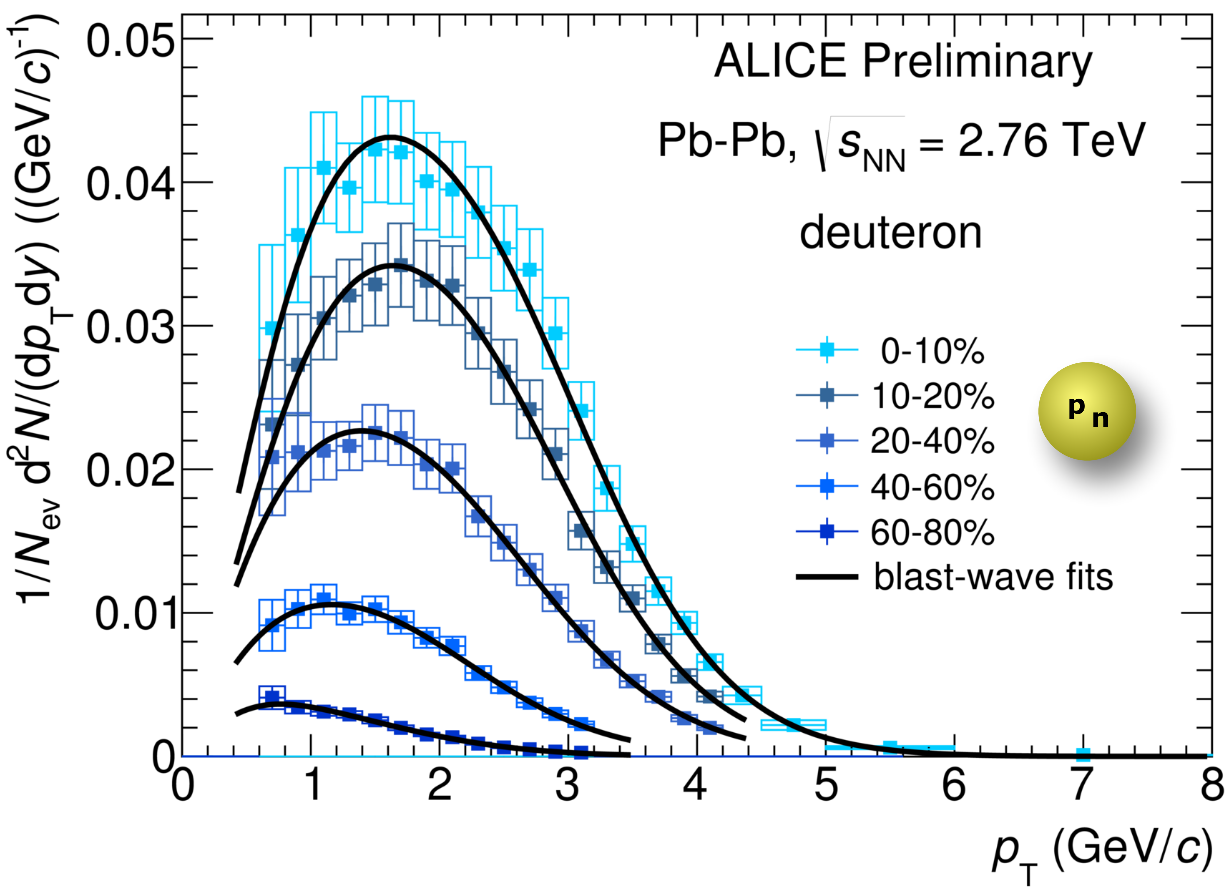
It can be used to describe the shape of transverse momentum p_T spectra in heavy-ion collisions.

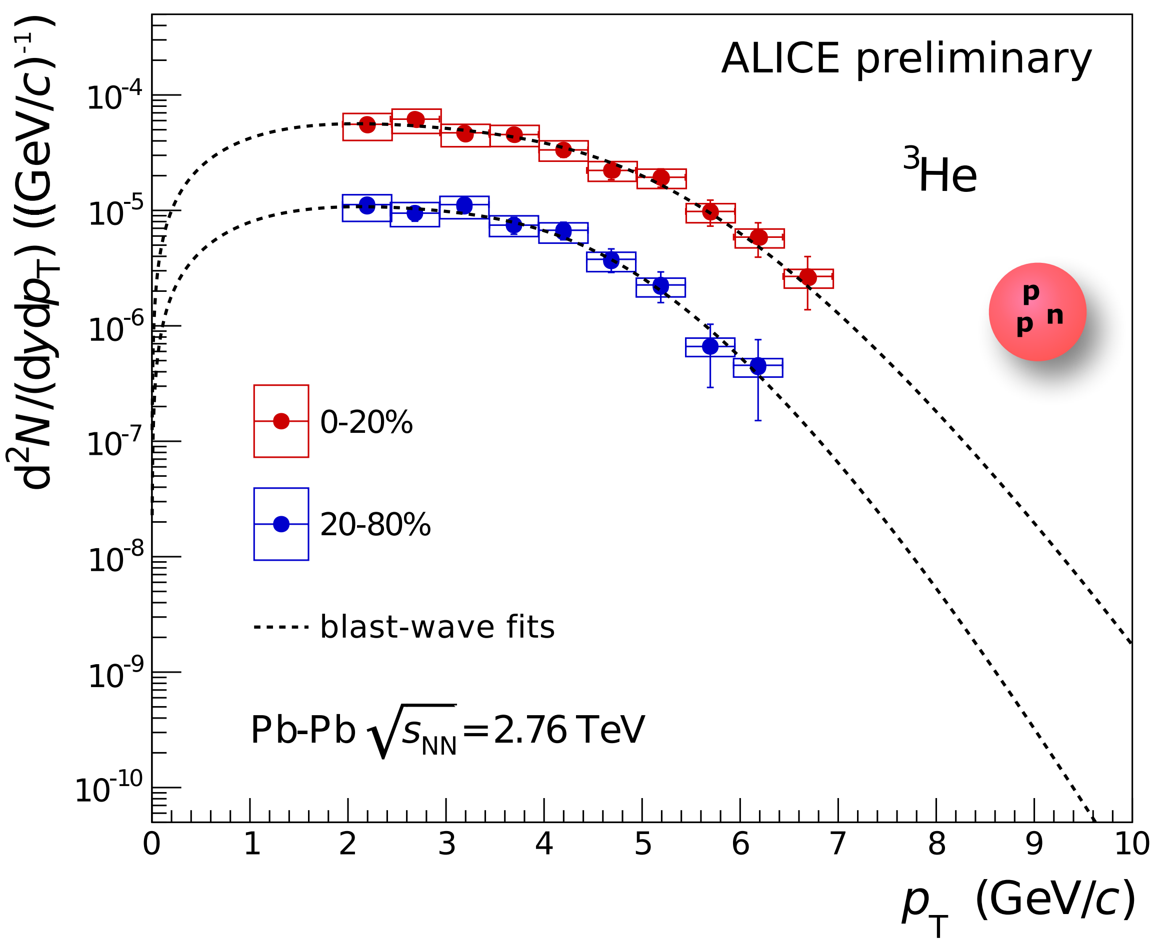
Works quite well, since the blast-wave describes the thermal part and the radial flow visible in p_T spectra

Nuclei and hypernuclei **measurements**



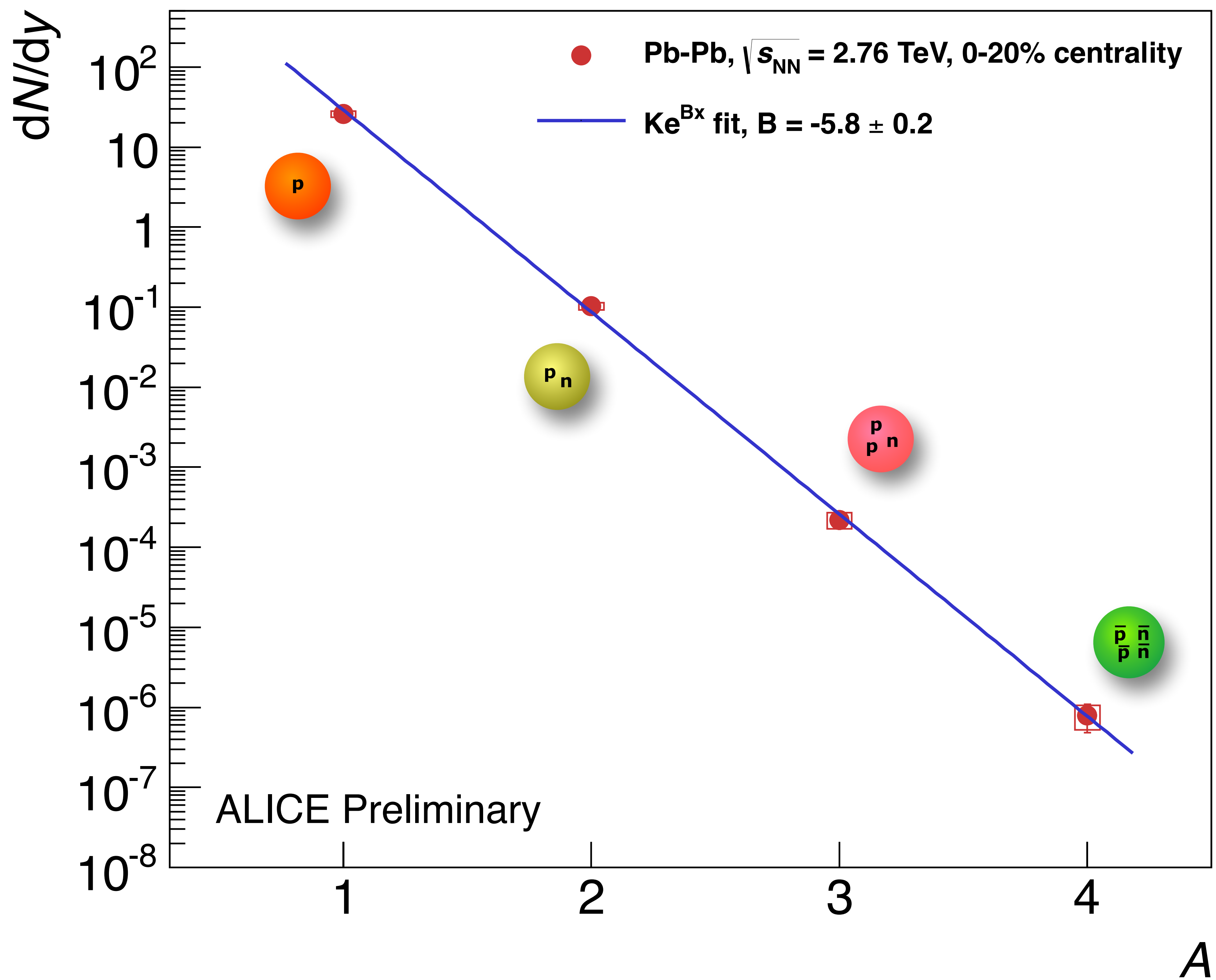
Deuterons and ^{3}He in Pb-Pb





➜ Spectra are fitted with blast-wave functions in different centrality bins and show radial flow

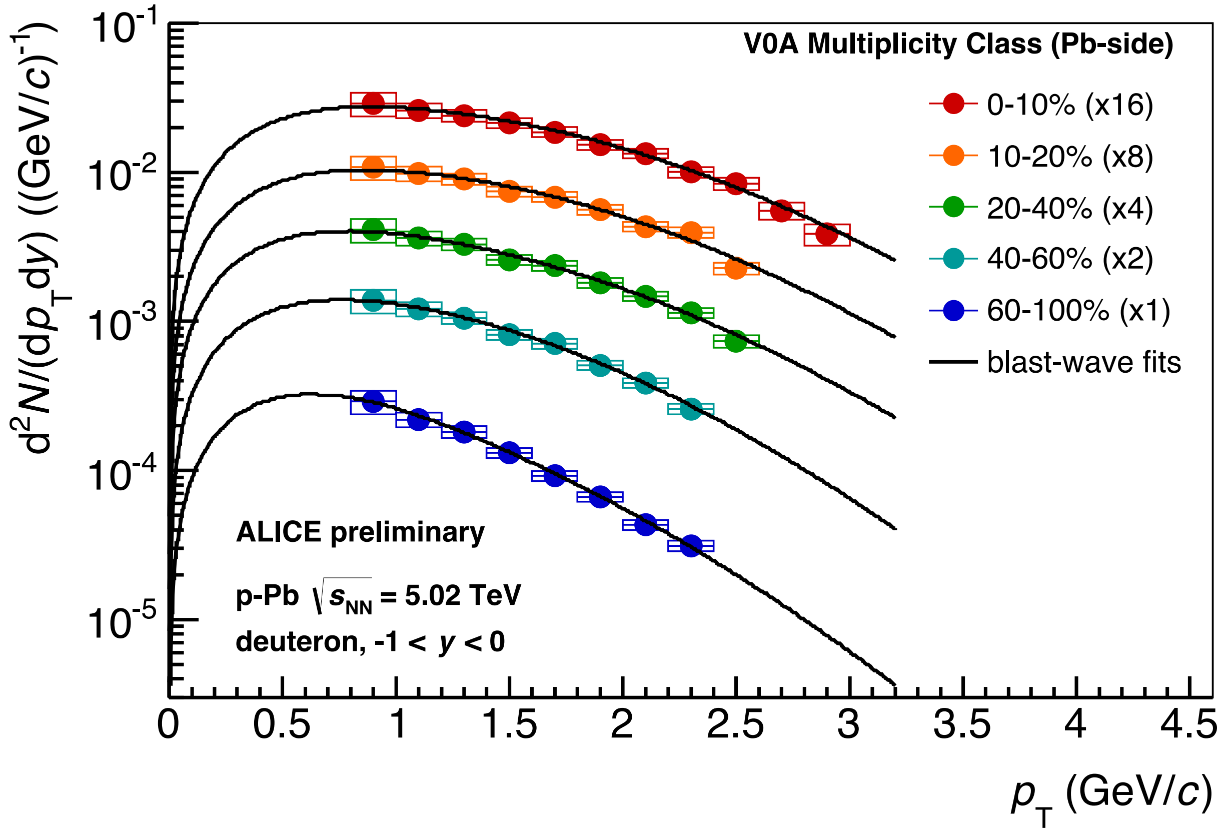
Nuclei in Pb-Pb

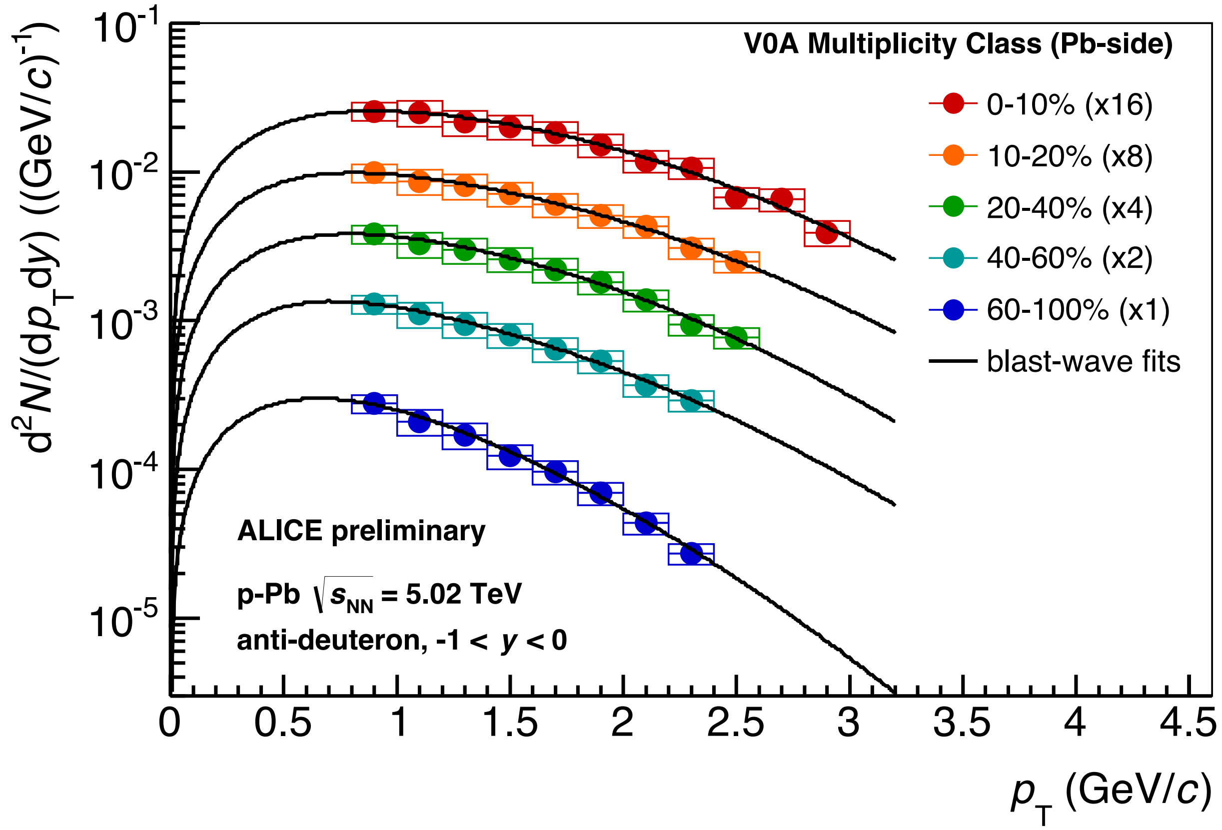


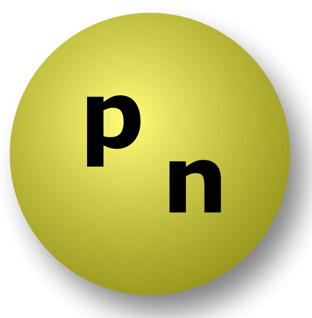
Nuclei yields measured down to $^{4}\overline{He}$

Penalty factor ~330 for each additional nucleon

Deuterons in p-Pb

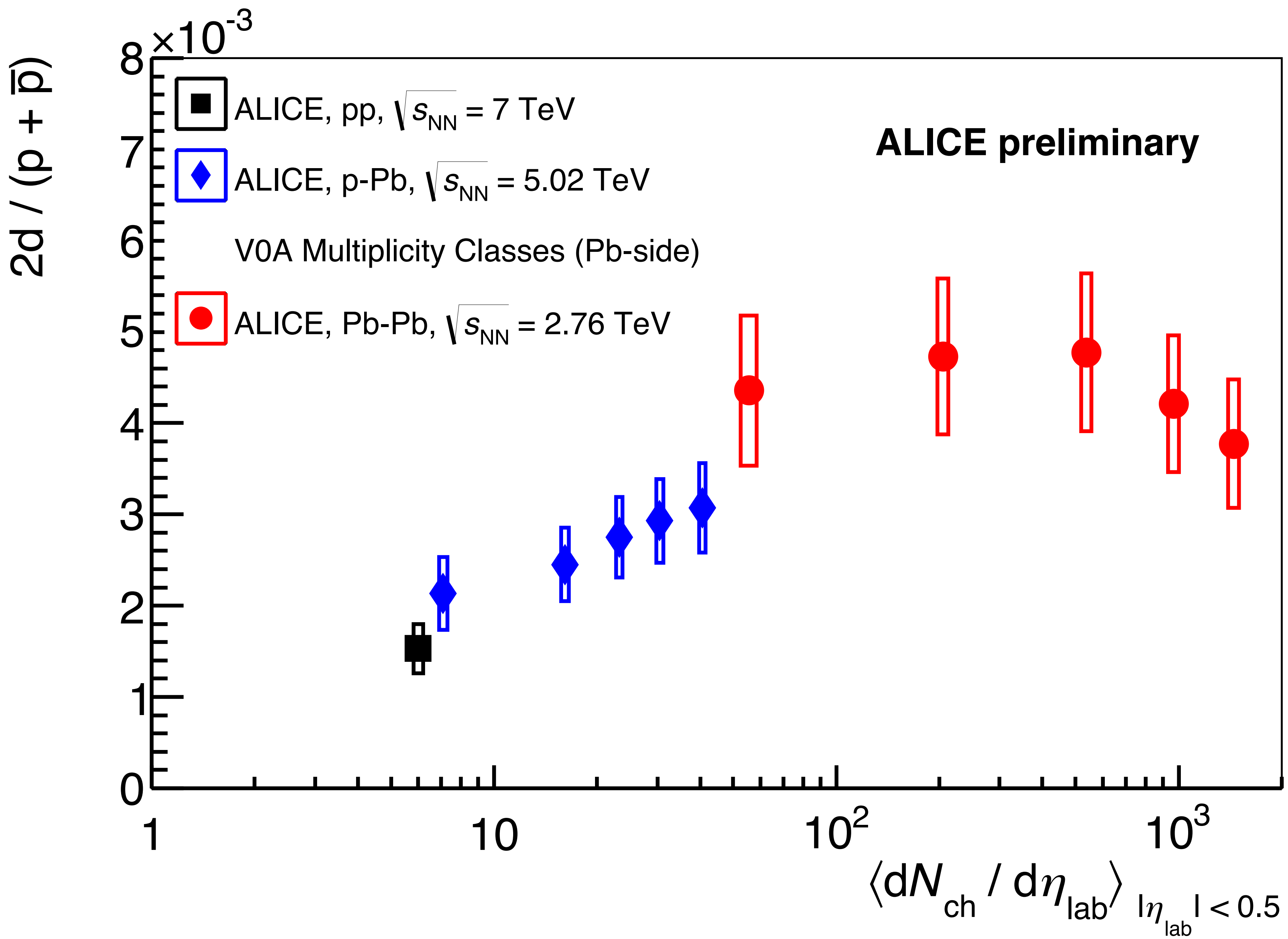






➜ Spectra become harder with increasing multiplicity

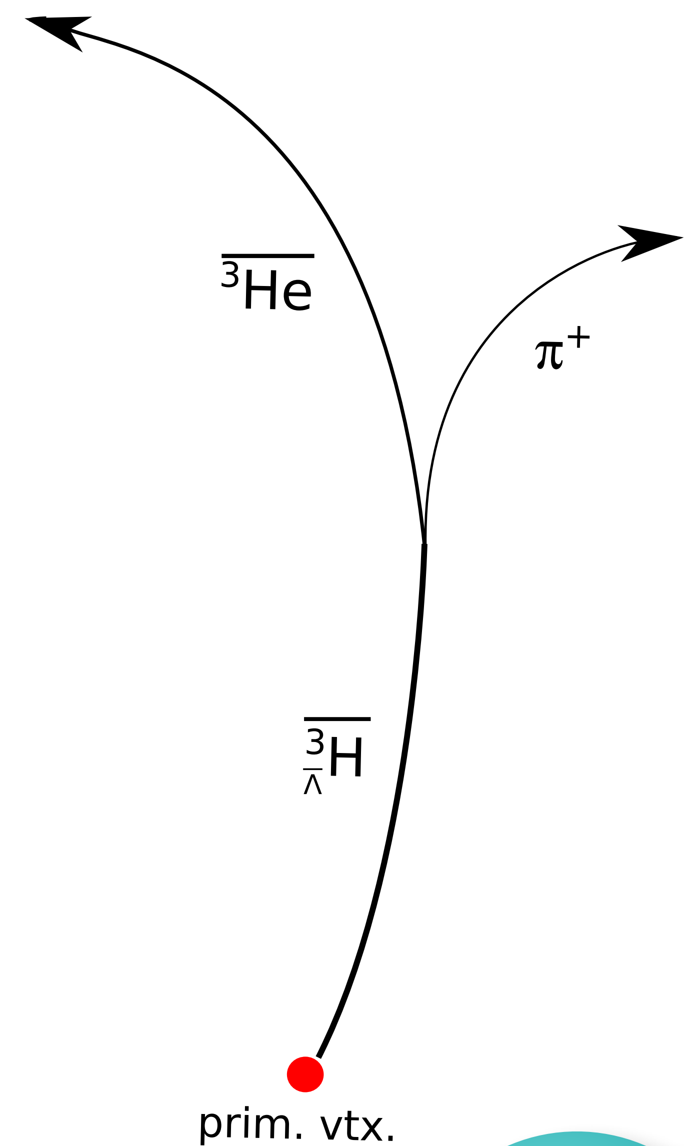
Deuteron to proton ratio



Rise with multiplicity

No further increase in Pb-Pb collisions within errors

Hypertriton

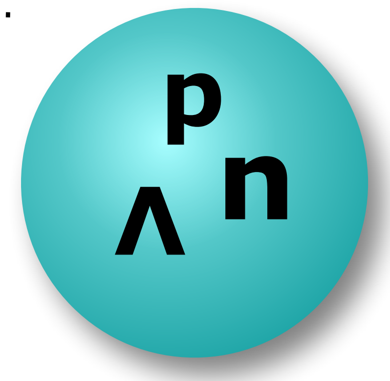


Identification of light nuclei which are daughter tracks originating from decay vertices

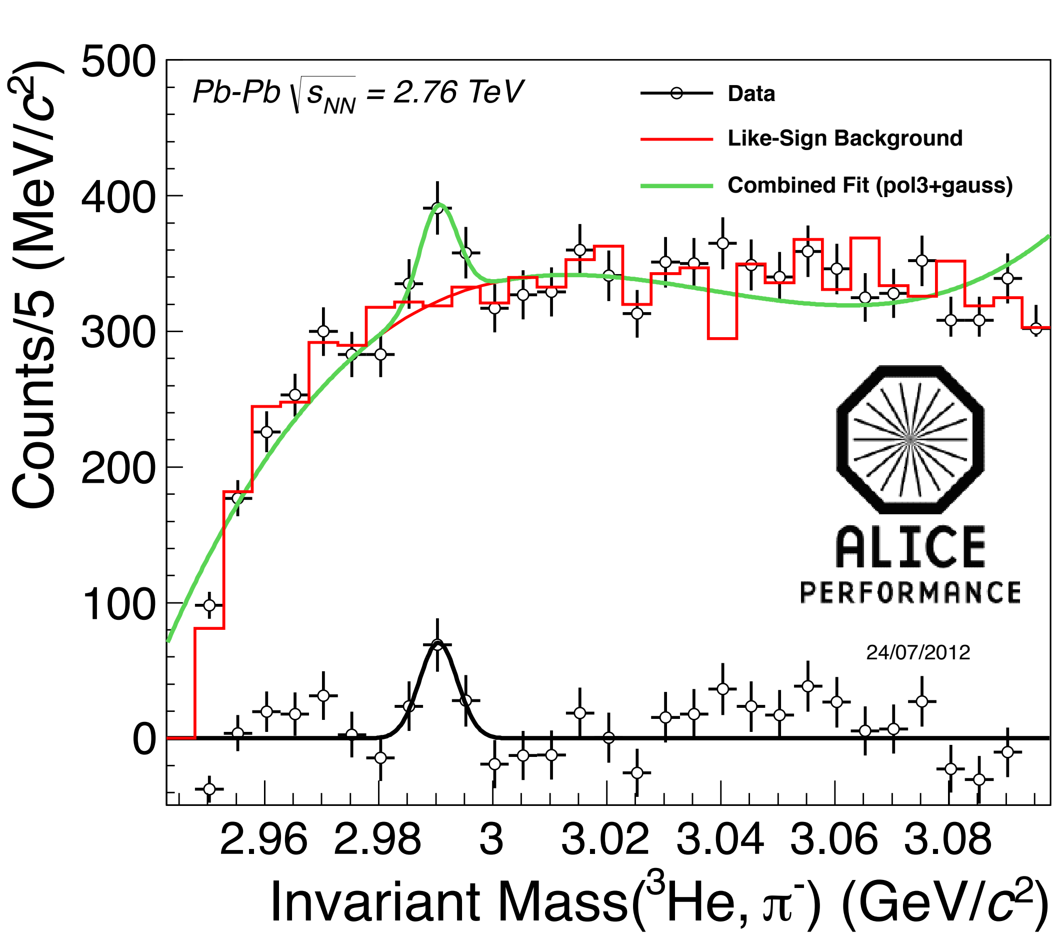
Lifetime similar to lifetime of free Λ

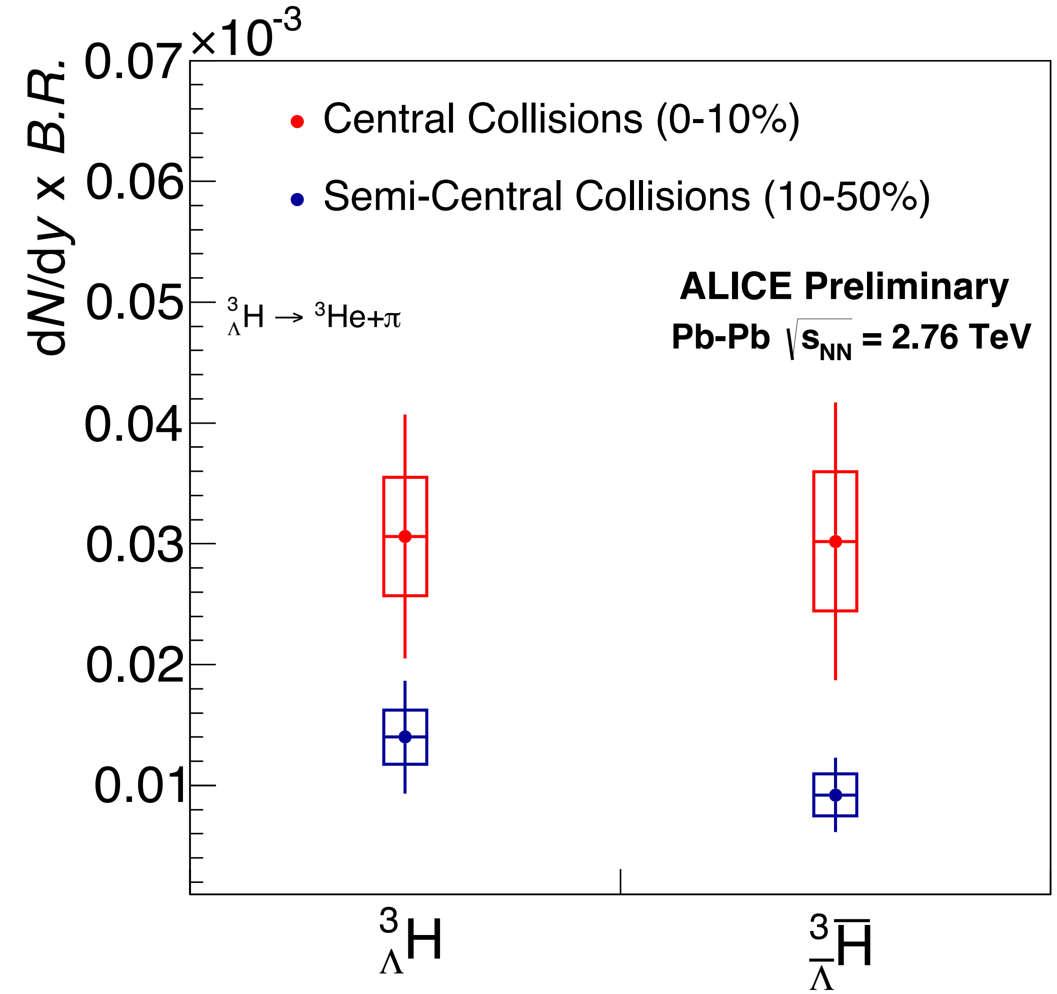
m(Hypertriton) = 2.991 ± 0.002 GeV/c^2

investigated decay channel:
Hypertriton → $^3He + \pi^-$



Hypertriton





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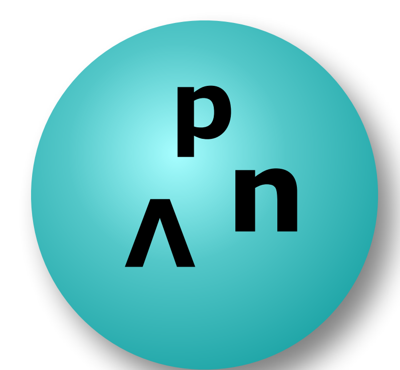
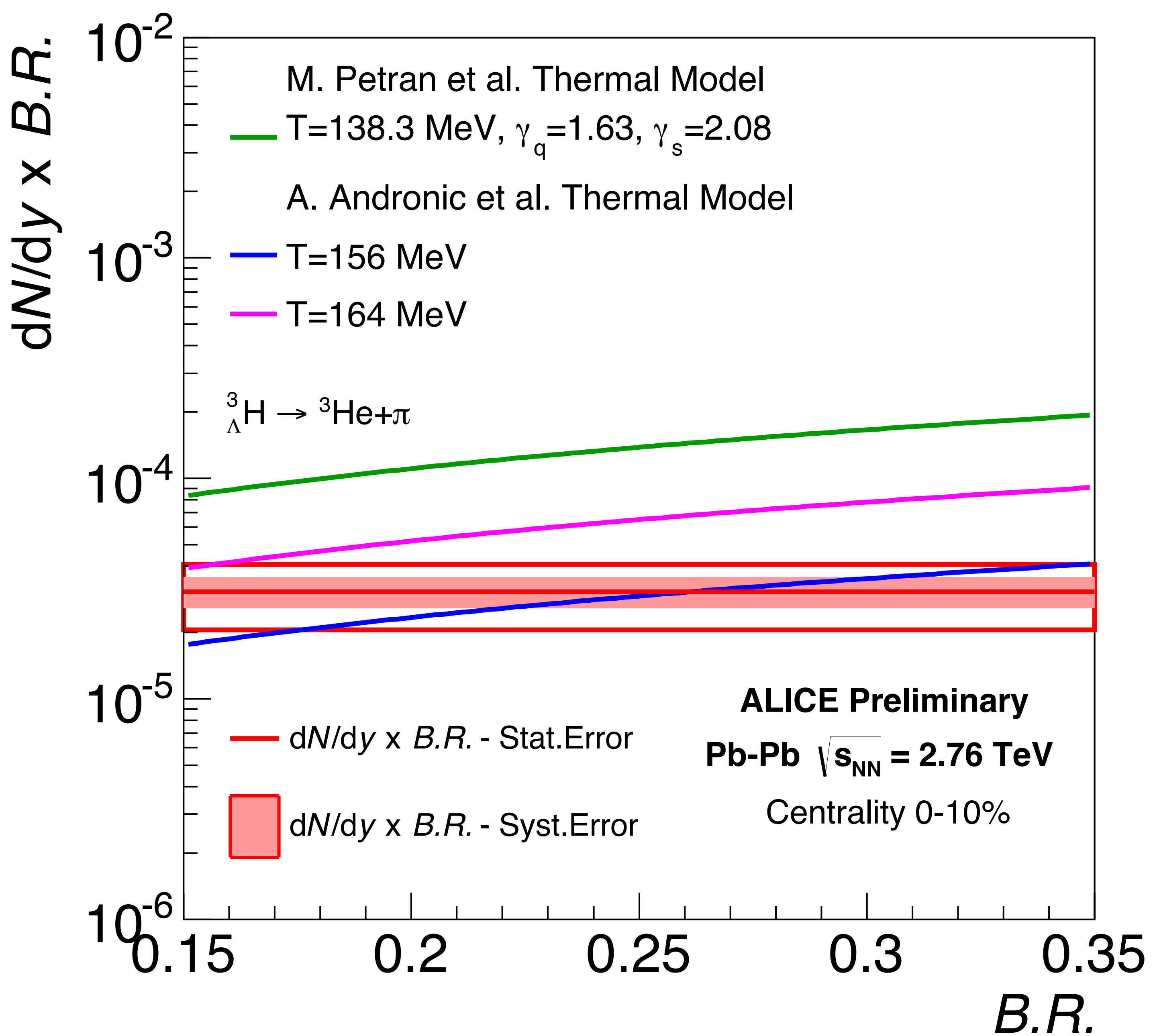
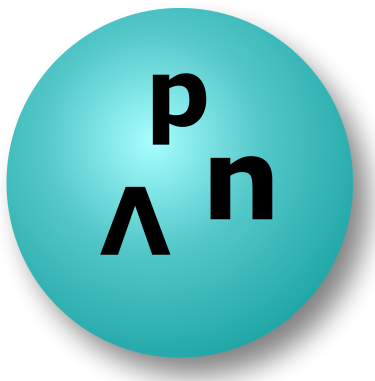


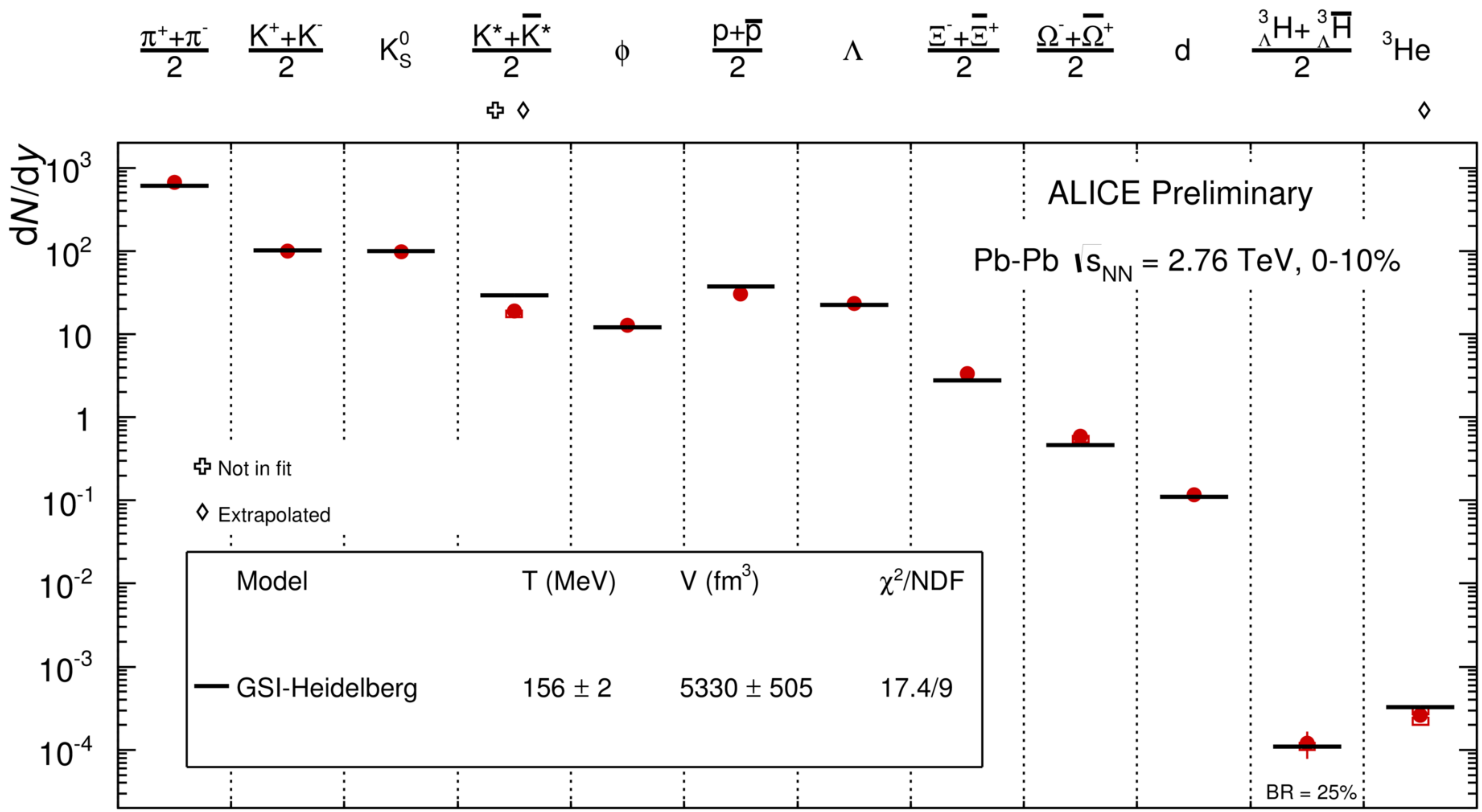
Hypertriton



dN/dy in good agreement with thermal model prediction from Andronic *et al.* for T = 156 MeV



d*N*/dy comparison



$\mu_B = 0$

Searches
for weakly decaying exotic bound states

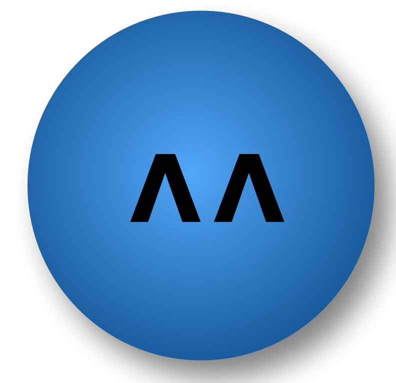
ΛΛ

Λn

Exotica - Introduction

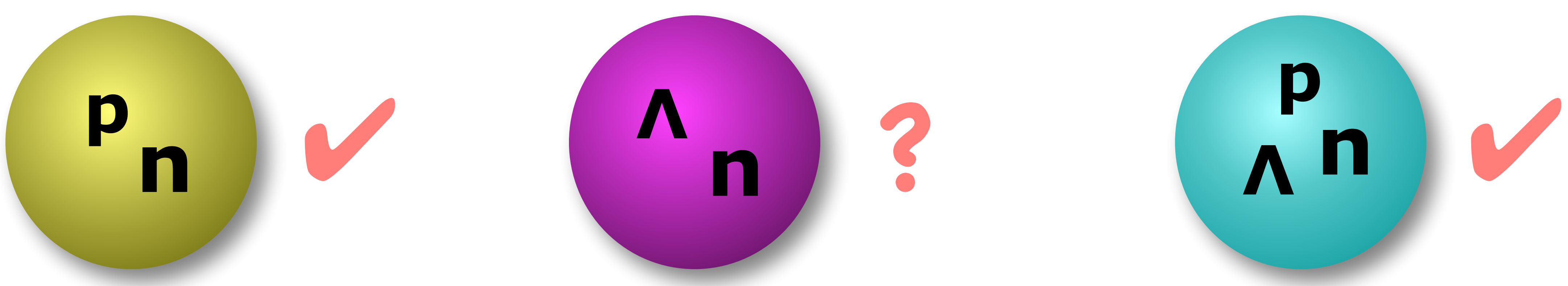
H-dibaryon:

First predicted by Jaffe in a bag model calculation
(Jaffe, PRL 38, 617 (1977))



Recent lattice calculations suggest bound state or a resonance close to the Ξp threshold

Λn bound state:



H-dibaryon

Expected H-dibaryons ($H \rightarrow \Lambda p \pi^-$):

ΛΛ

$$N_{H^0} = \underbrace{1.38 \cdot 10^7}_{events} \cdot \underbrace{0.0385}_{eff.} \cdot \underbrace{0.64}_{BR(\Lambda)} \cdot \underbrace{3.1 \cdot 10^{-3}}_{dN/dy} \cdot \underbrace{2}_{dy} \approx 2110$$

BR(H-dibaryon)

strongly bound H: $2110 \cdot 0.1 = 211$ lightly bound H: $2110 \cdot 0.64 = 1350$

H-dibaryon

Expected H-dibaryons (H → $\Lambda p \pi^-$):

ΛΛ

$$N_{H^0} = \underbrace{1.38 \cdot 10^7}_{\textit{events}} \cdot \underbrace{0.0385}_{\textit{eff.}} \cdot \underbrace{0.64}_{BR(\Lambda)} \cdot \underbrace{3.1 \cdot 10^{-3}}_{dN/dy} \cdot \underbrace{2}_{dy} \approx 2110$$

BR(H-dibaryon)

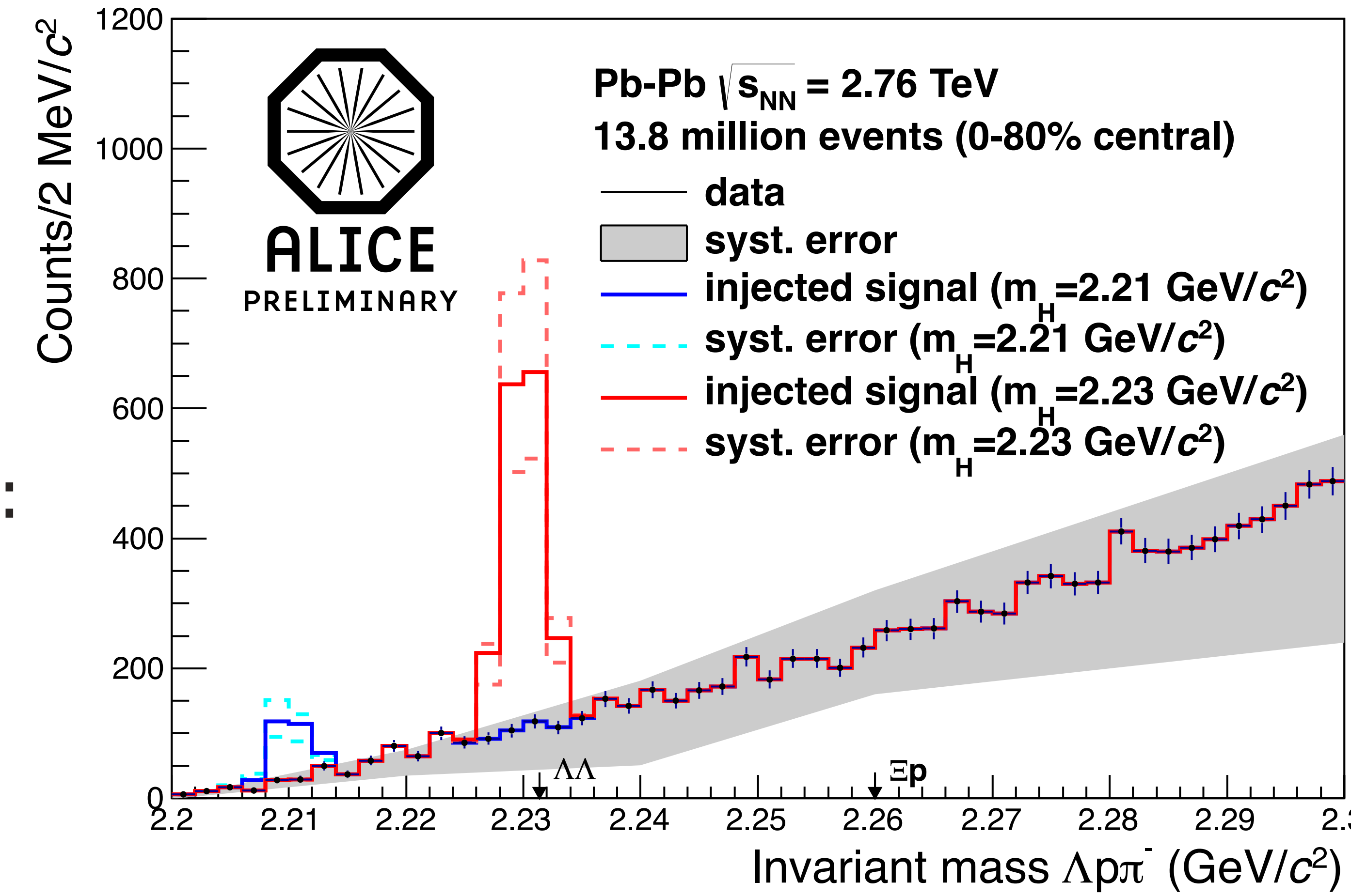
strongly bound H: 2110 · 0.1 = 211 lightly bound H: 2110 · 0.64 = 1350

No signal visible

From the non-observation we obtain as **upper limits**:

For a strongly bound (20 MeV) H:
➜ $dN/dy \leq 8.4 \cdot 10^{-4}$ (99% CL)

For a lightly bound (1 MeV) H:
➜ $dN/dy \leq 2 \cdot 10^{-4}$ (99% CL)



$\overline{\Lambda}$n bound state

Expected $\overline{\Lambda}$n bound states ($\overline{\Lambda}n \rightarrow \bar{d}\pi^+$):

$$N_{\overline{\Lambda}n} = \underbrace{1.38 \cdot 10^7}_{events} \cdot \underbrace{0.0255}_{eff.} \cdot \underbrace{0.35}_{BR} \cdot \underbrace{1.6 \cdot 10^{-2}}_{dN/dy} \cdot \underbrace{2}_{dy} \approx 4000$$

$\overline{\Lambda}$n bound state

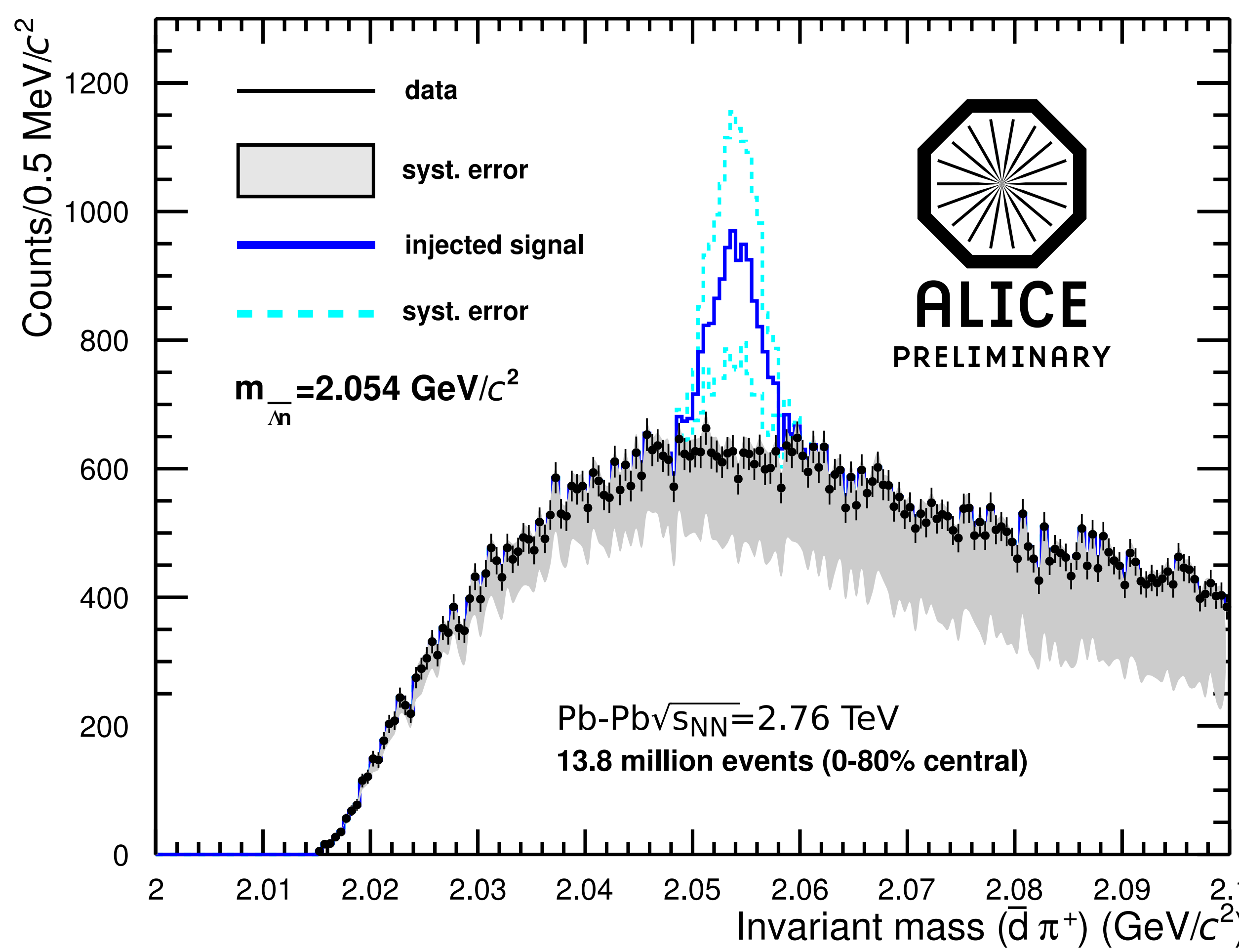
Expected $\overline{\Lambda}$n bound states ($\overline{\Lambda}n \rightarrow \bar{d}\pi^+$):

$$N_{\overline{\Lambda}n} = \underbrace{1.38 \cdot 10^7}_{events} \cdot \underbrace{0.0255}_{eff.} \cdot \underbrace{0.35}_{BR} \cdot \underbrace{1.6 \cdot 10^{-2}}_{dN/dy} \cdot \underbrace{2}_{dy} \approx 4000$$

No signal visible

From the non-observation we obtain as **upper limit**:

➜ $dN/dy \leq 1.5 \cdot 10^{-3}$ (99% CL)



Comparison to models

The $\overline{\Lambda n}$ bound state and the H-dibaryon are not observed

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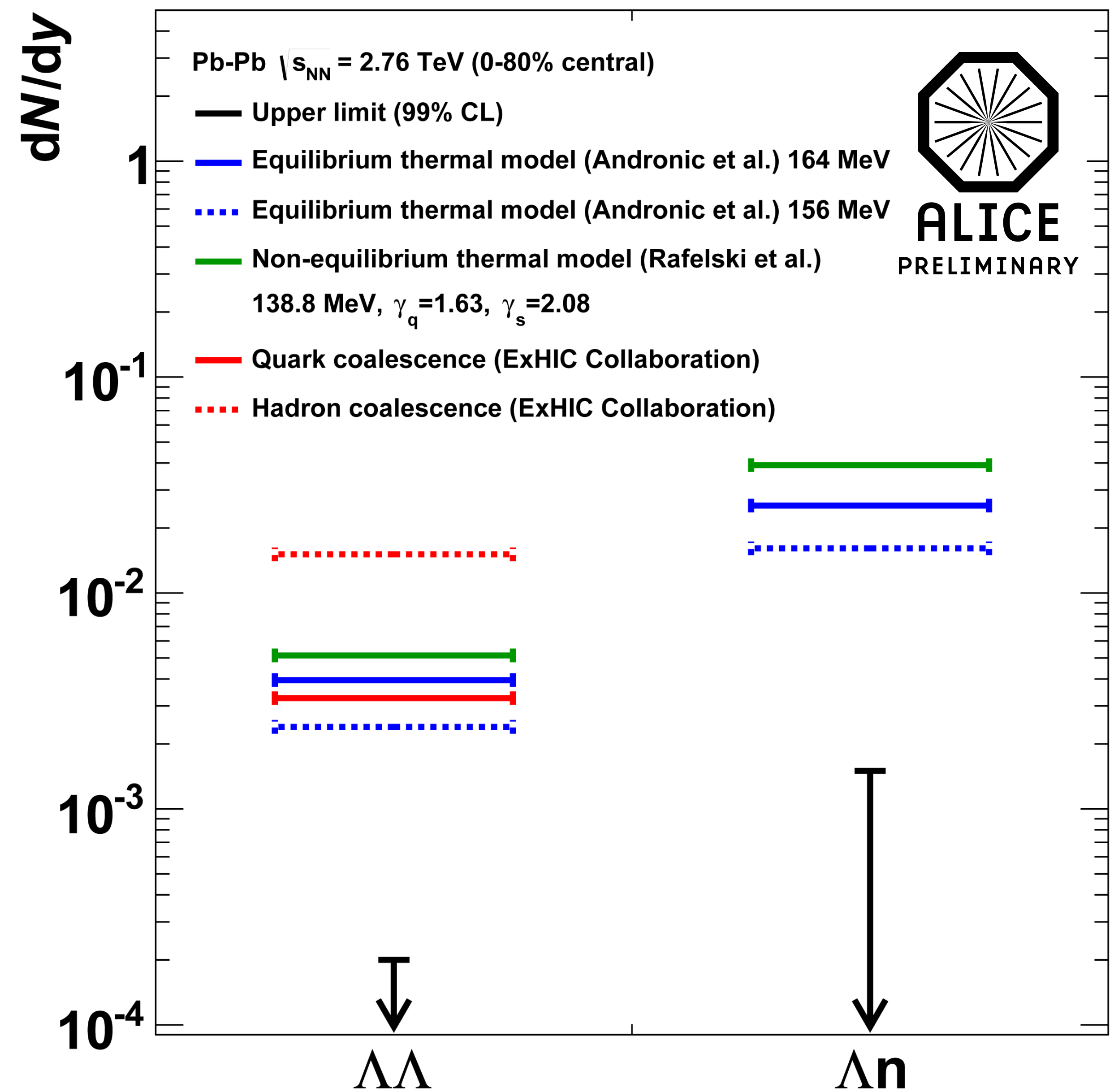
Different model predictions are of the same order

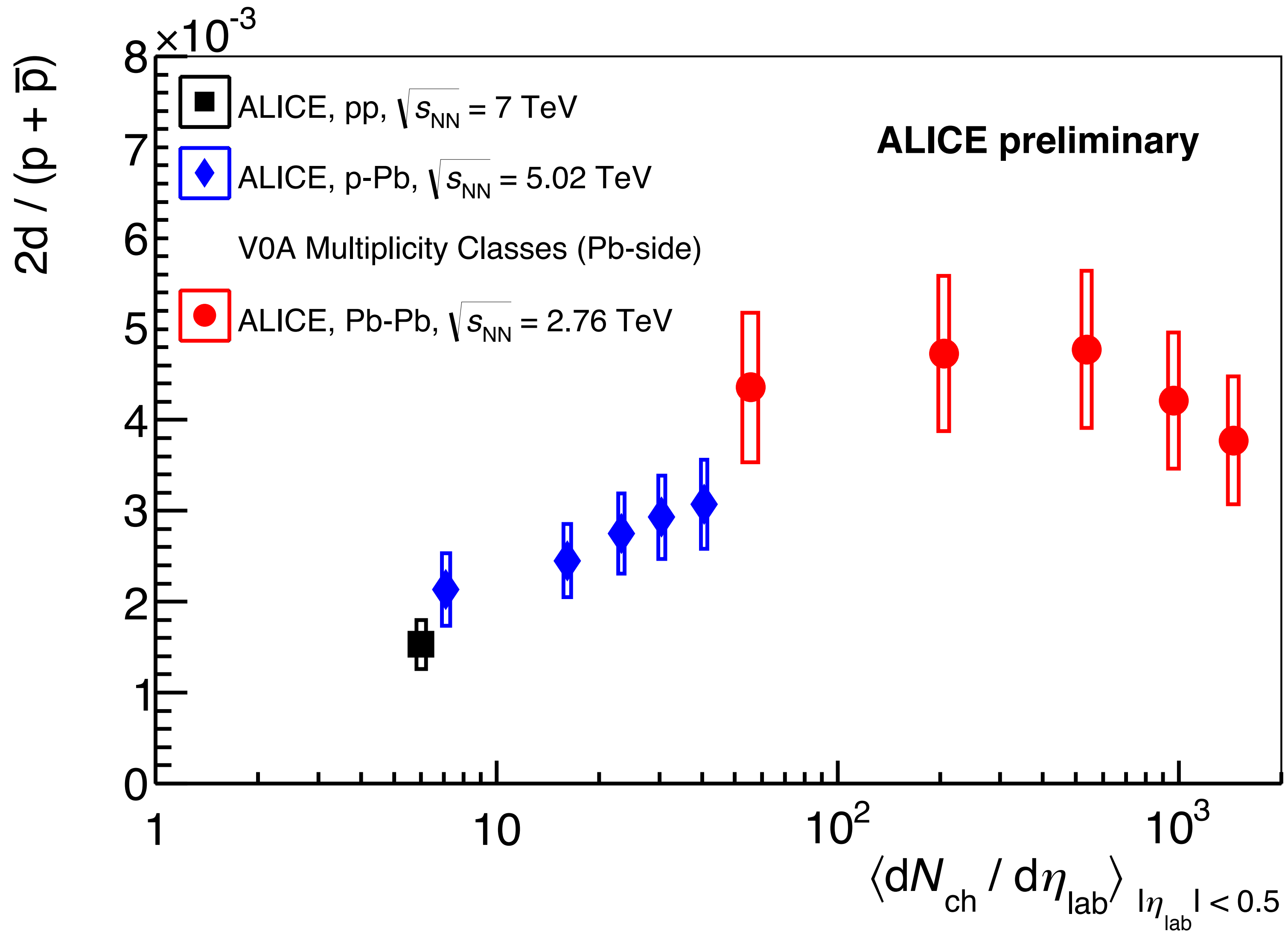
Upper limits for the two particles are set, at least a factor 10 below model predictions



➜ Existence of these particles with the assumed properties (BR, mass, lifetime) is questionable

Conclusion I

The increase of the d/p-ratio with charged particle multiplicity is qualitatively consistent with the coalescence picture.

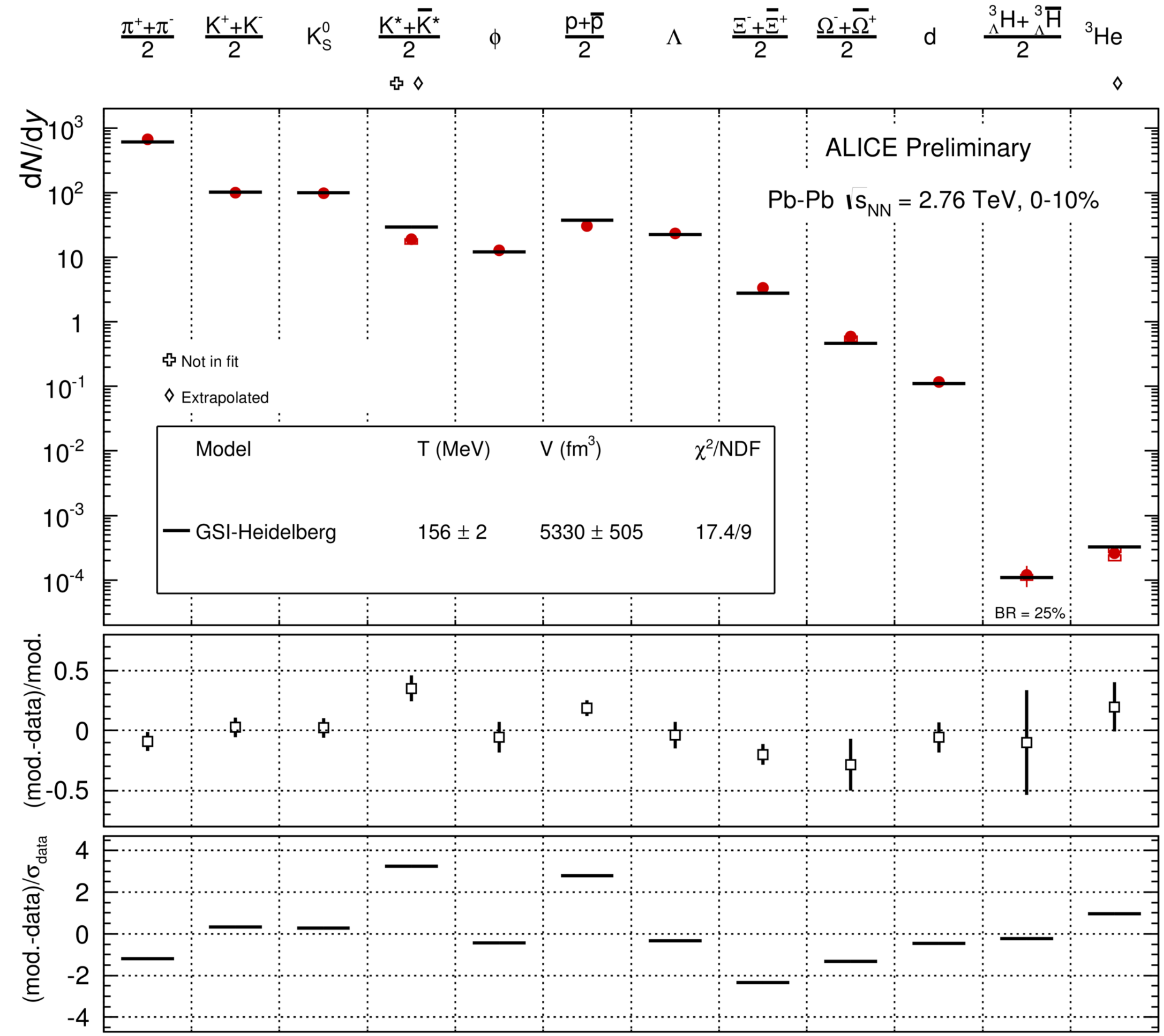


Conclusion II

Loosely bound hypertriton is observed

Absolute yields (dN/dy) of light nuclei and hypertriton production in Pb-Pb collisions is in good agreement with thermal model calculation

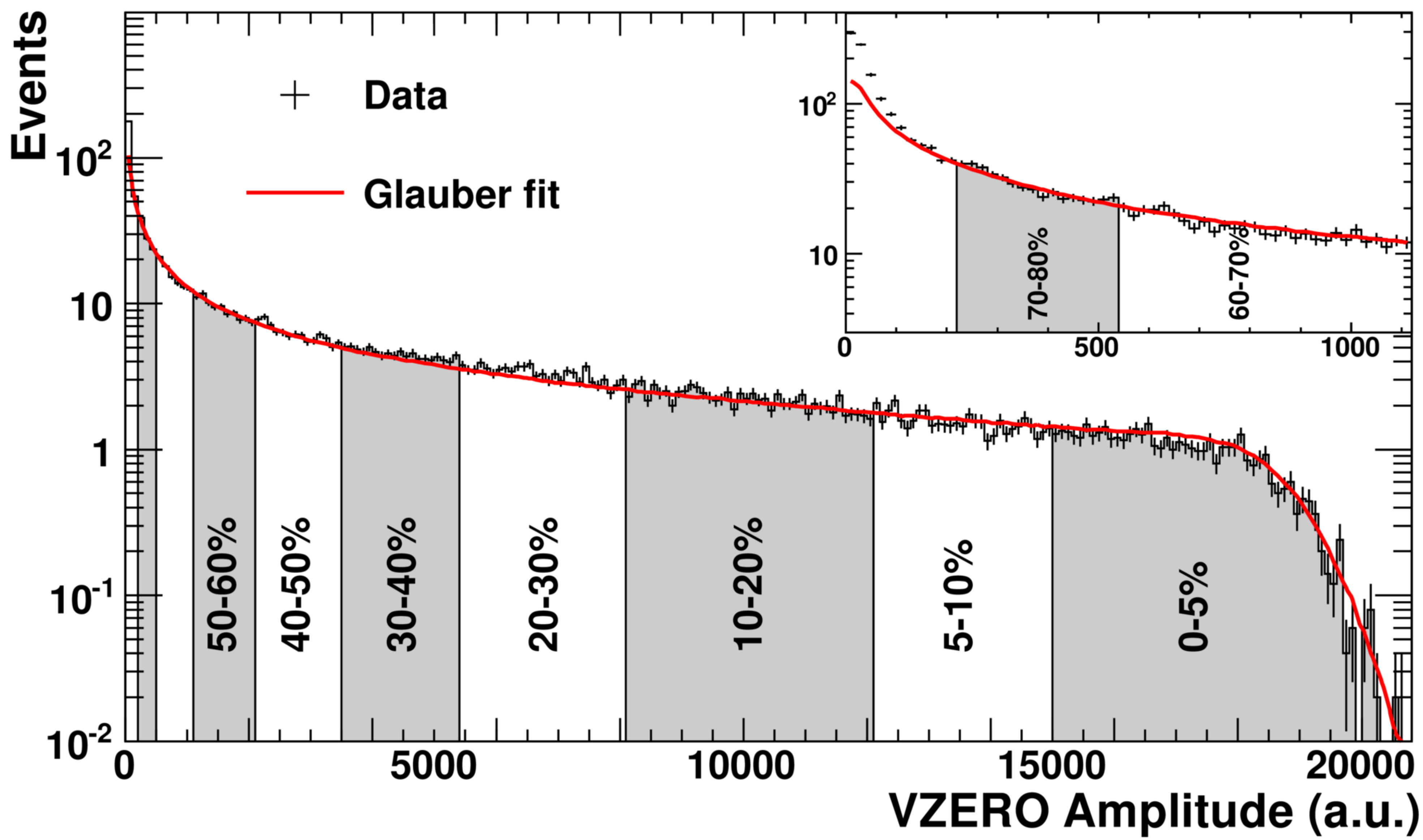
Thermal model predictions using the temperature which fits the measured nuclei and hypertriton yields are above obtained exotica limits



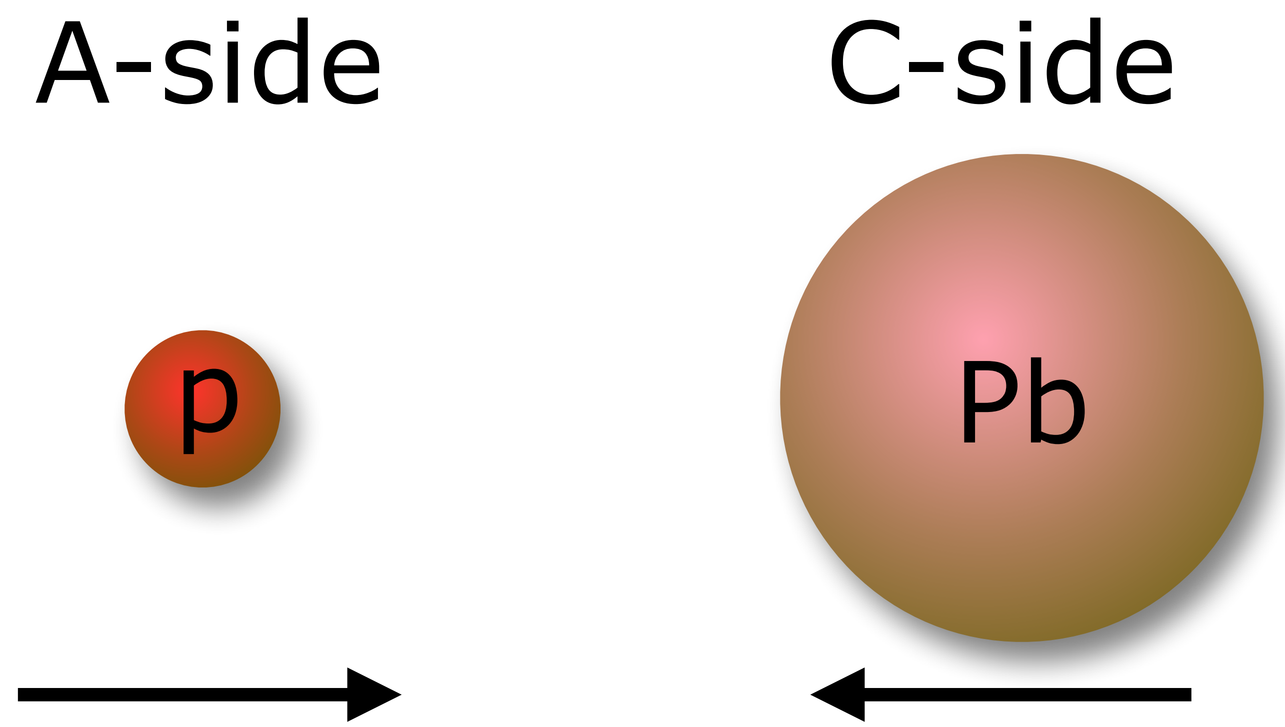
➜ Data provide no support for existence of $\overline{\Lambda n}$ and H-dibaryon

Centrality in a HIC

VZERO detectors: Two scintillation hodoscopes, which are placed on either side of the interaction point



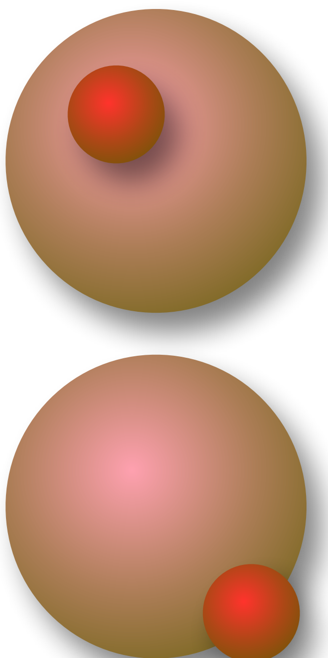
Rapidity definition in p-Pb



$$\overrightarrow{y_{\mathrm{cms,NN}}} = -0.465$$

Asymmetric energy/nucleon in the two beams
➜ cms moves with rapidity $y_{\mathrm{cms}} = -0.465$

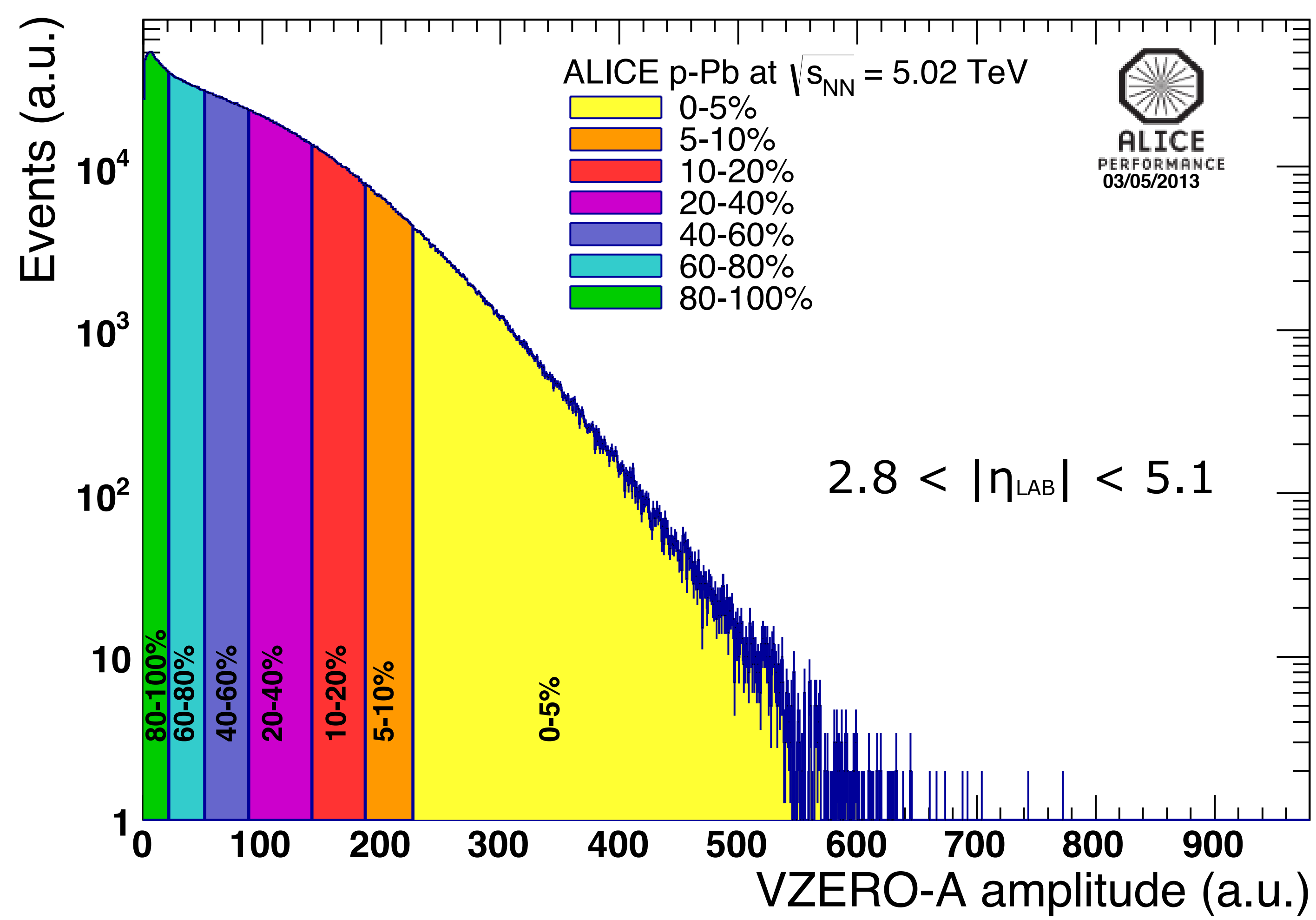
multiplicity classes in p-Pb



central

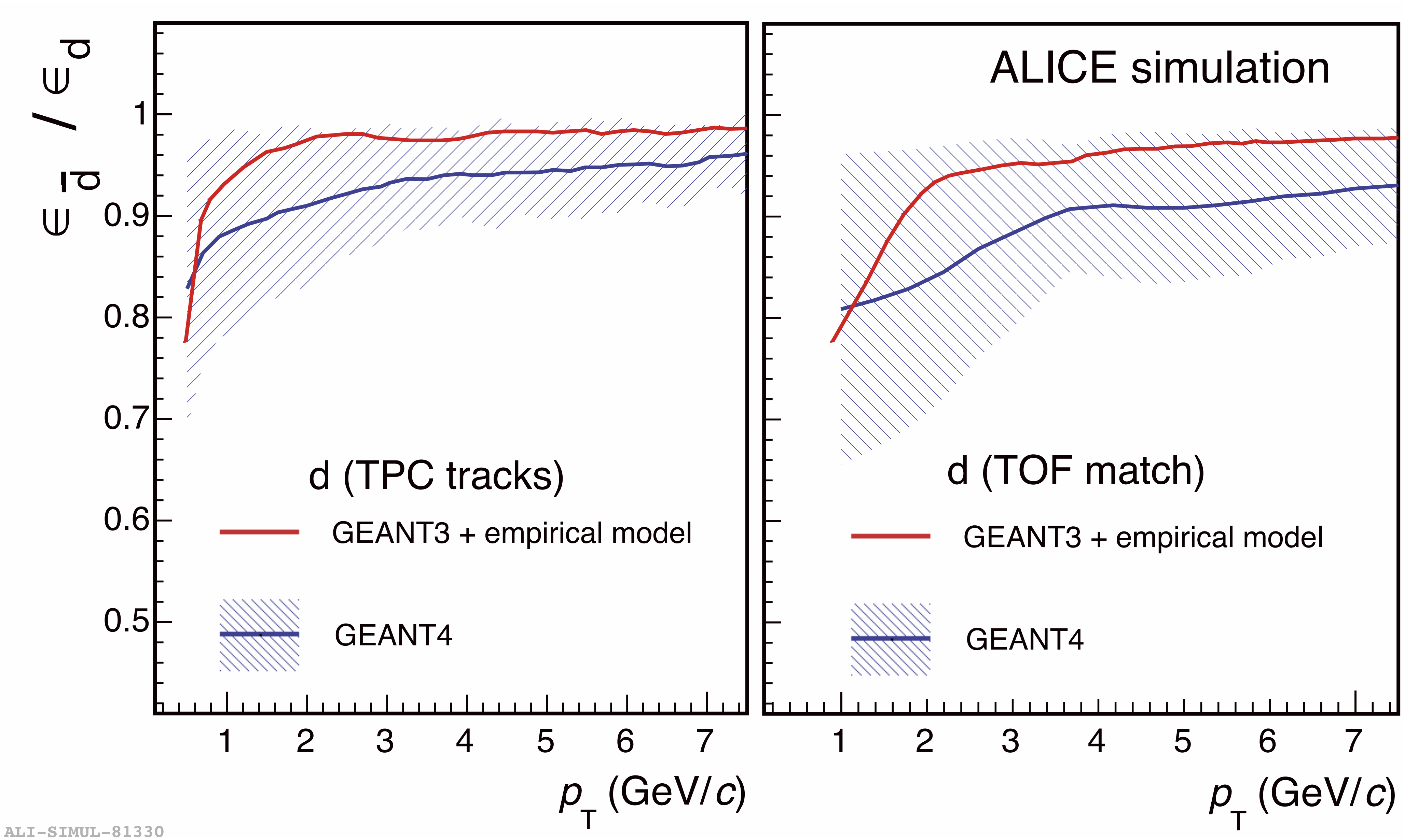
peripheral

Definition of seven multiplicity classes:
➜ slices in VZERO-A (V0A) amplitude



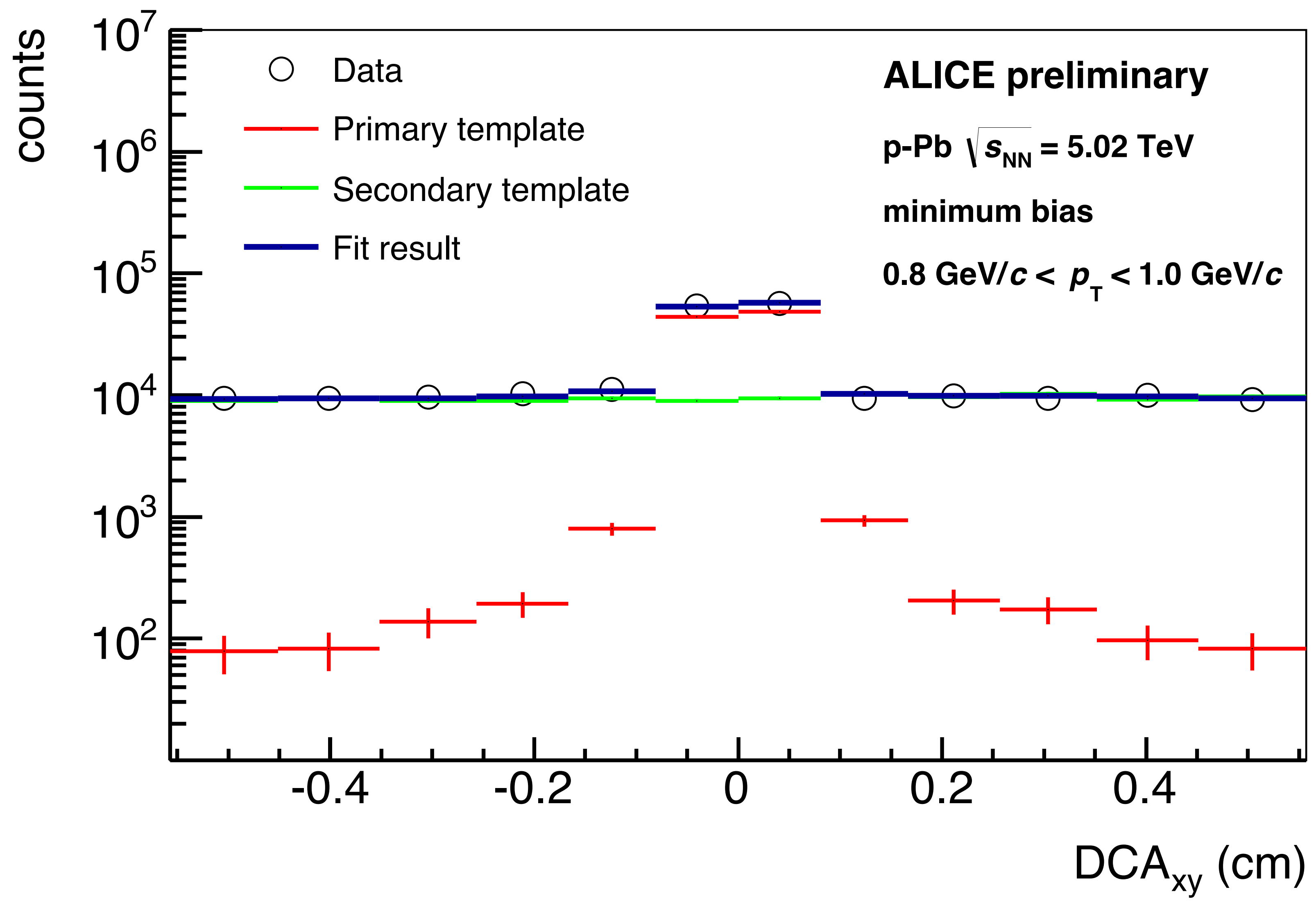
Correlation between impact parameter and multiplicity is not as straight-forward as in Pb-Pb

Absorption correction



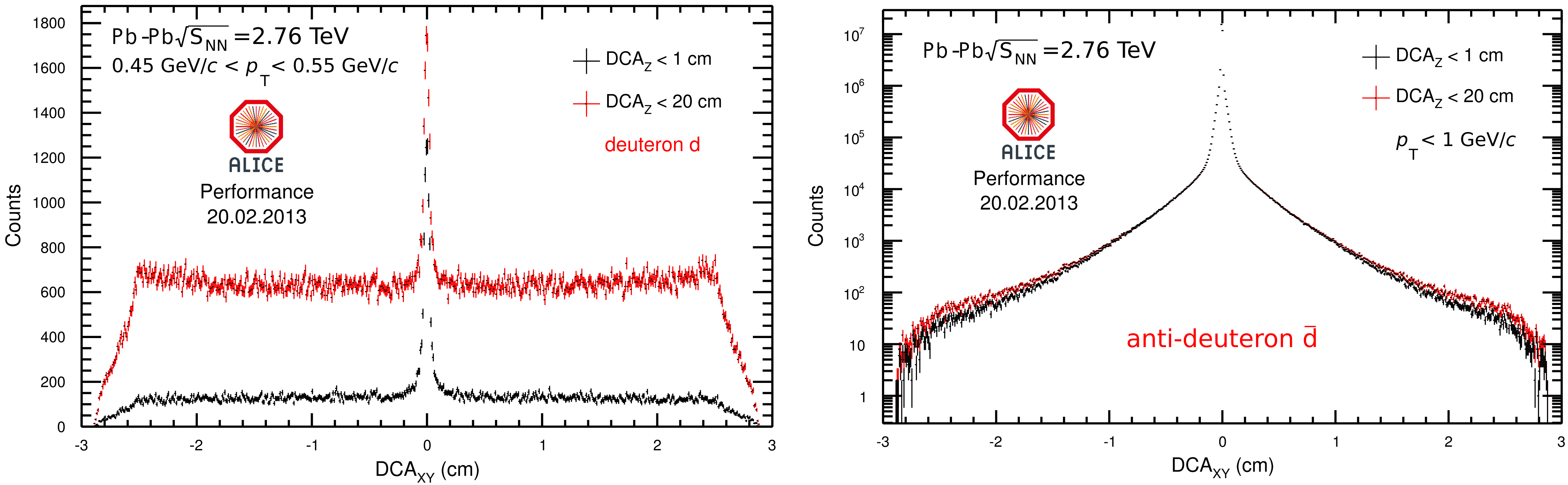
Anti-nuclei:
Additional correction for absorption

Secondary correction



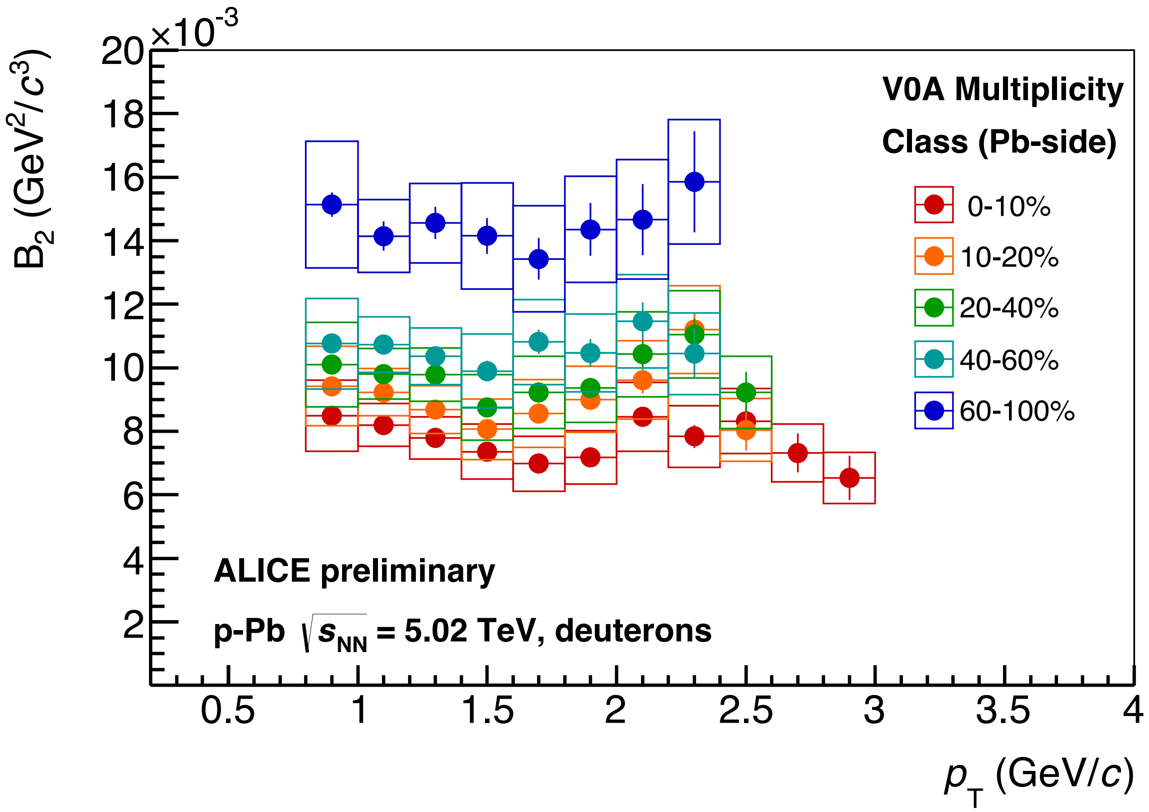
Nuclei:
Additional correction for secondaries

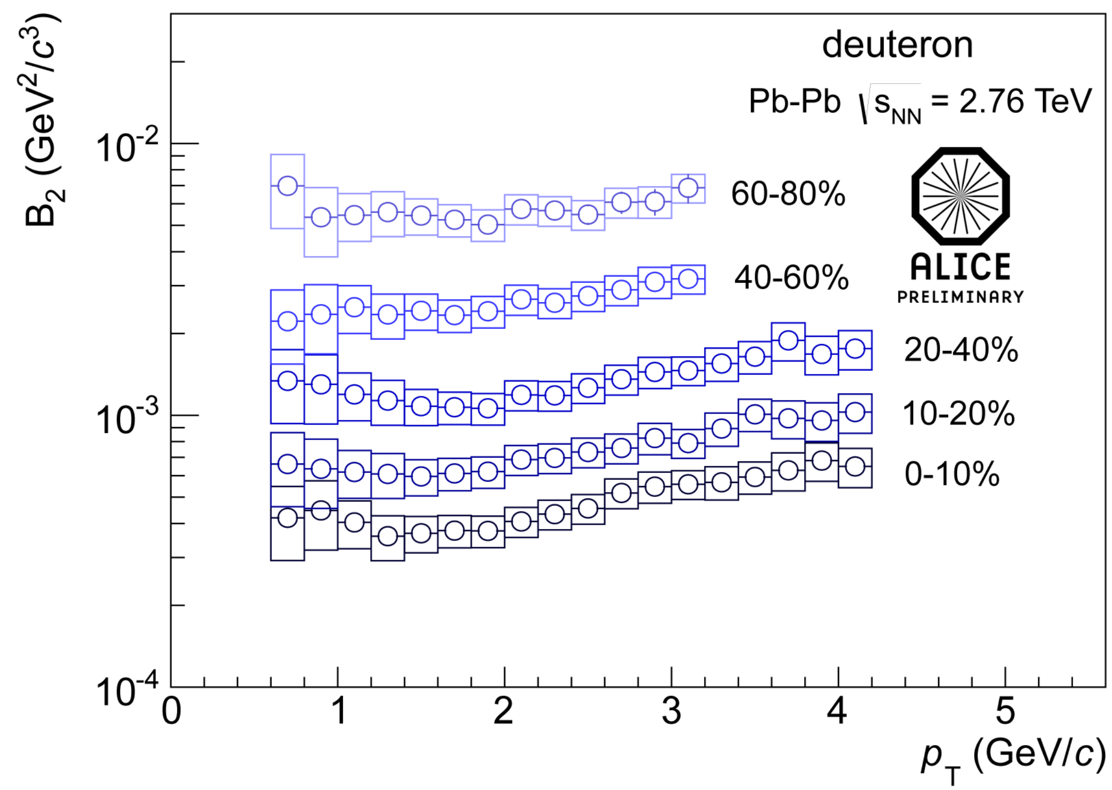
Nuclei vs. Anti-Nuclei



- ➜ Due to the non-existing knock-out, the search for anti-nuclei is often easier than the search for the corresponding nuclei
- ➜ But efficiency corrections easier for nuclei, because of the unknown anti-nuclei absorption

Coalescence parameter B_2

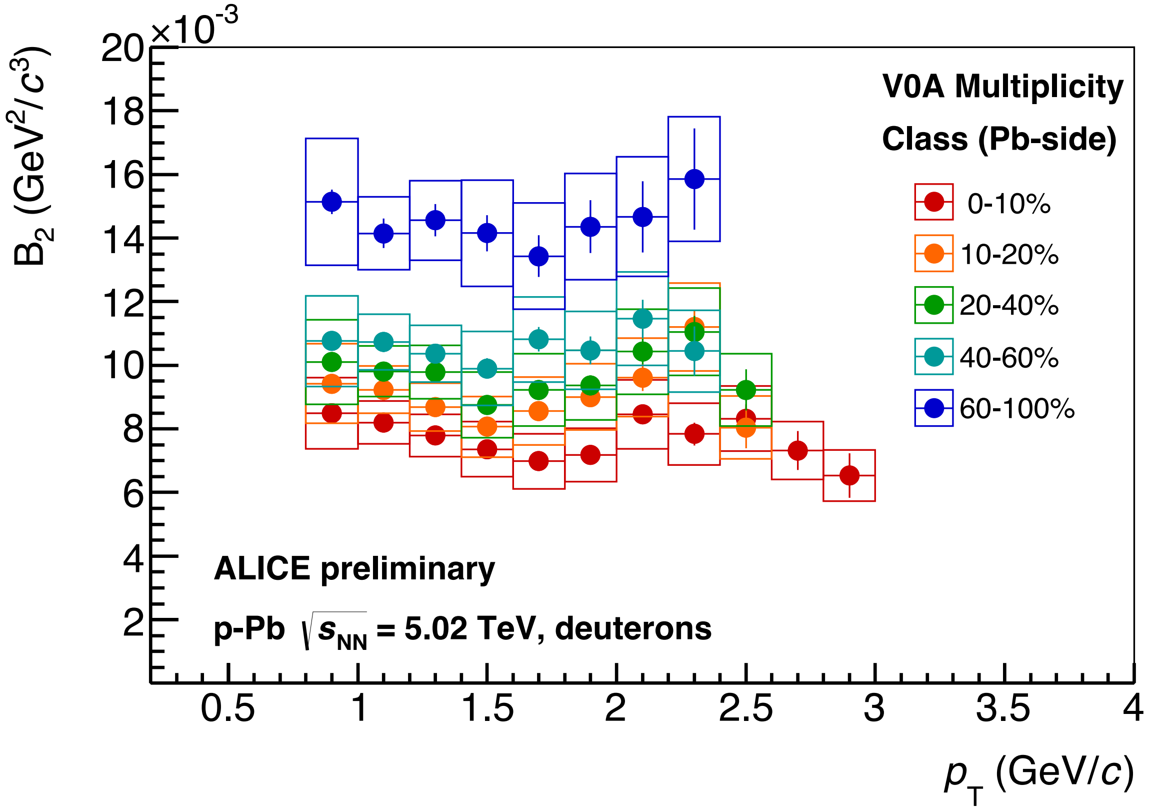


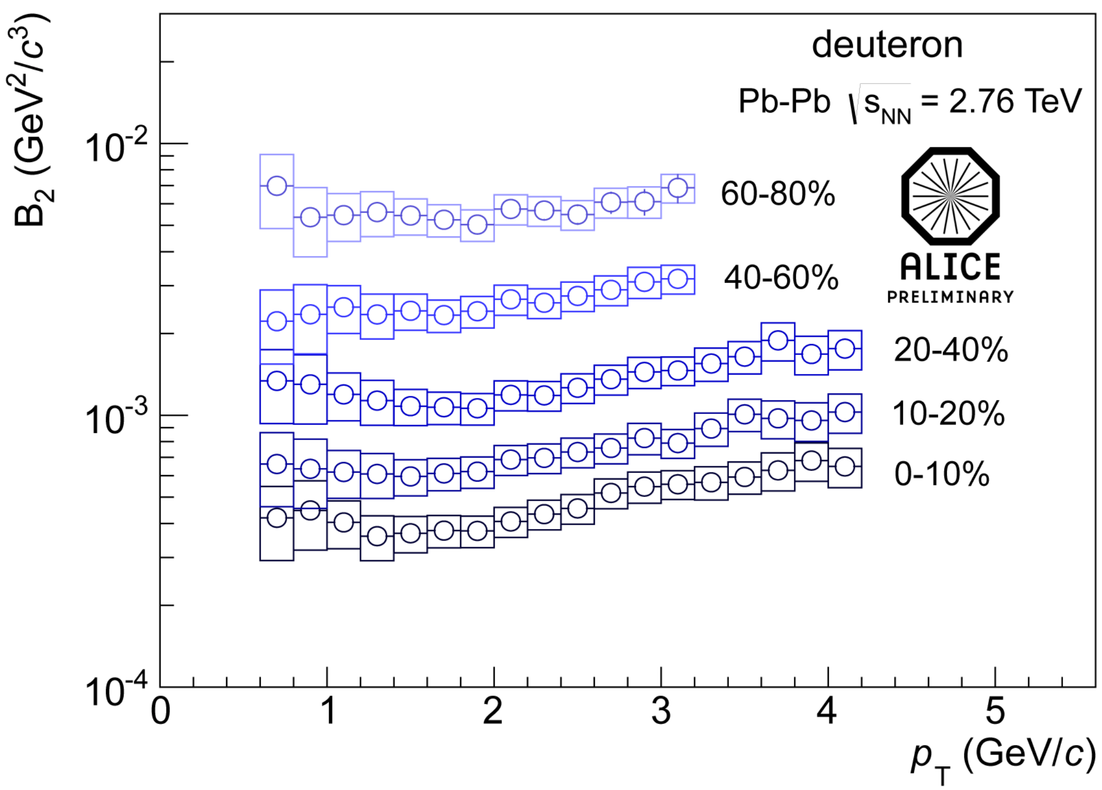


$$B_2 = \frac{E_d \frac{d^3N_d}{dp_d^3}}{\left(E_p \frac{d^3N_p}{dp_p^3}\right)^2}$$

First order prediction of coalescence model:
B_2 independent of p_T
➜ Observed in p-Pb and peripheral Pb-Pb

Coalescence parameter B_2





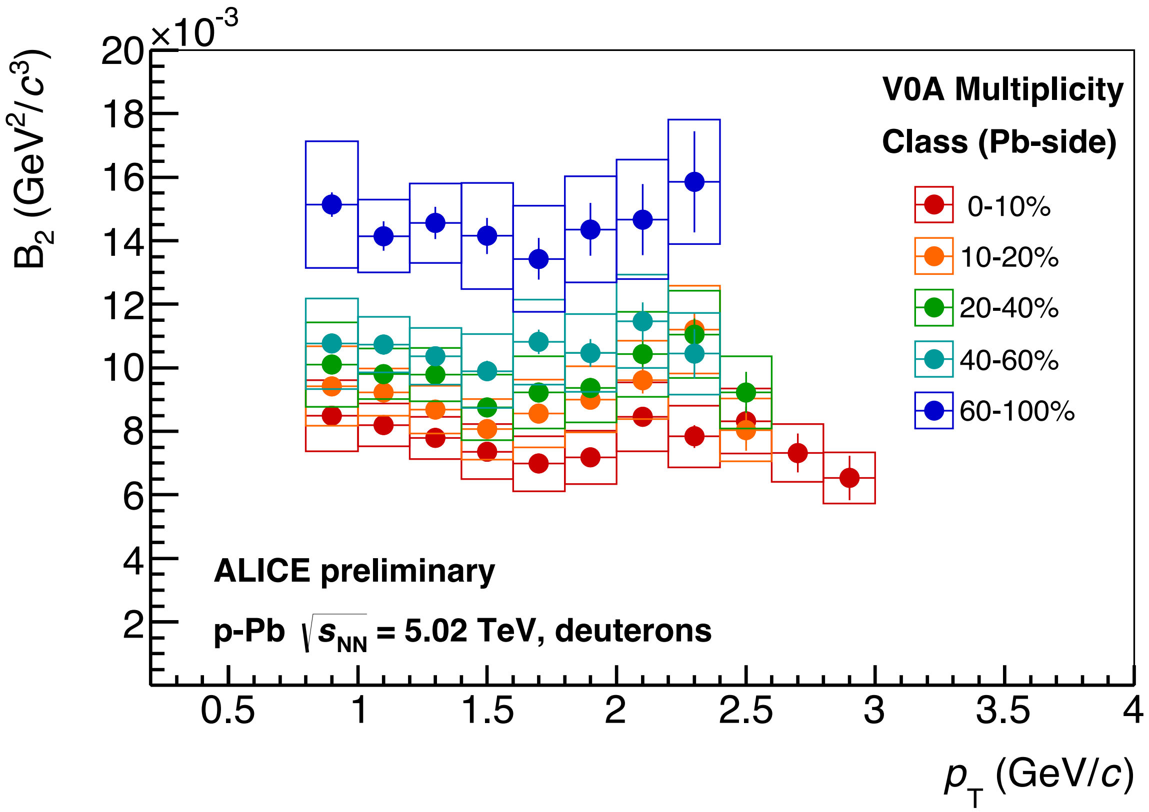
In second order: B_2 scales like the HBT radii

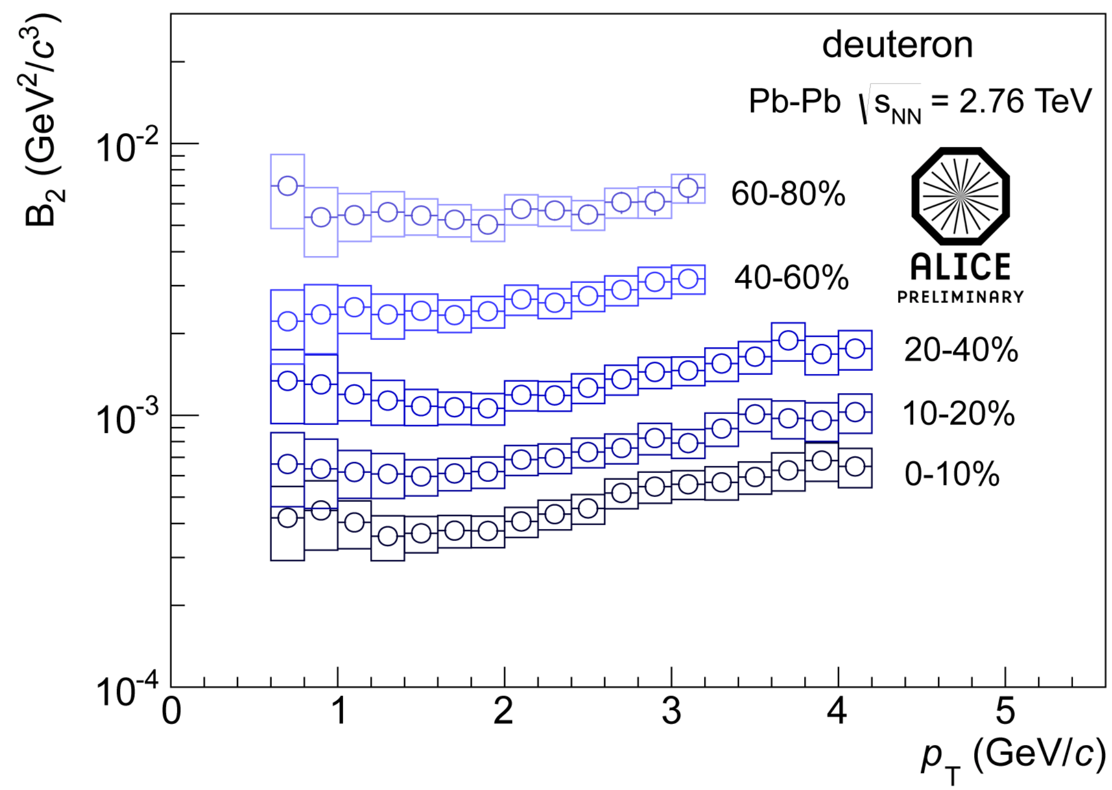
➜ Decrease with centrality in Pb-Pb is understood as an increase in the source volume

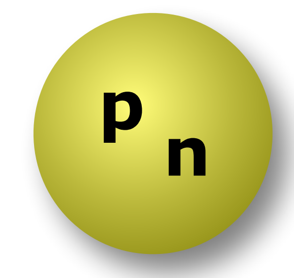
$$B_2 = \frac{3\pi^{3/2} \langle C_d \rangle}{2 m_T R_\perp^2(m_T) R_{||}(m_T)}$$

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

Coalescence parameter B_2







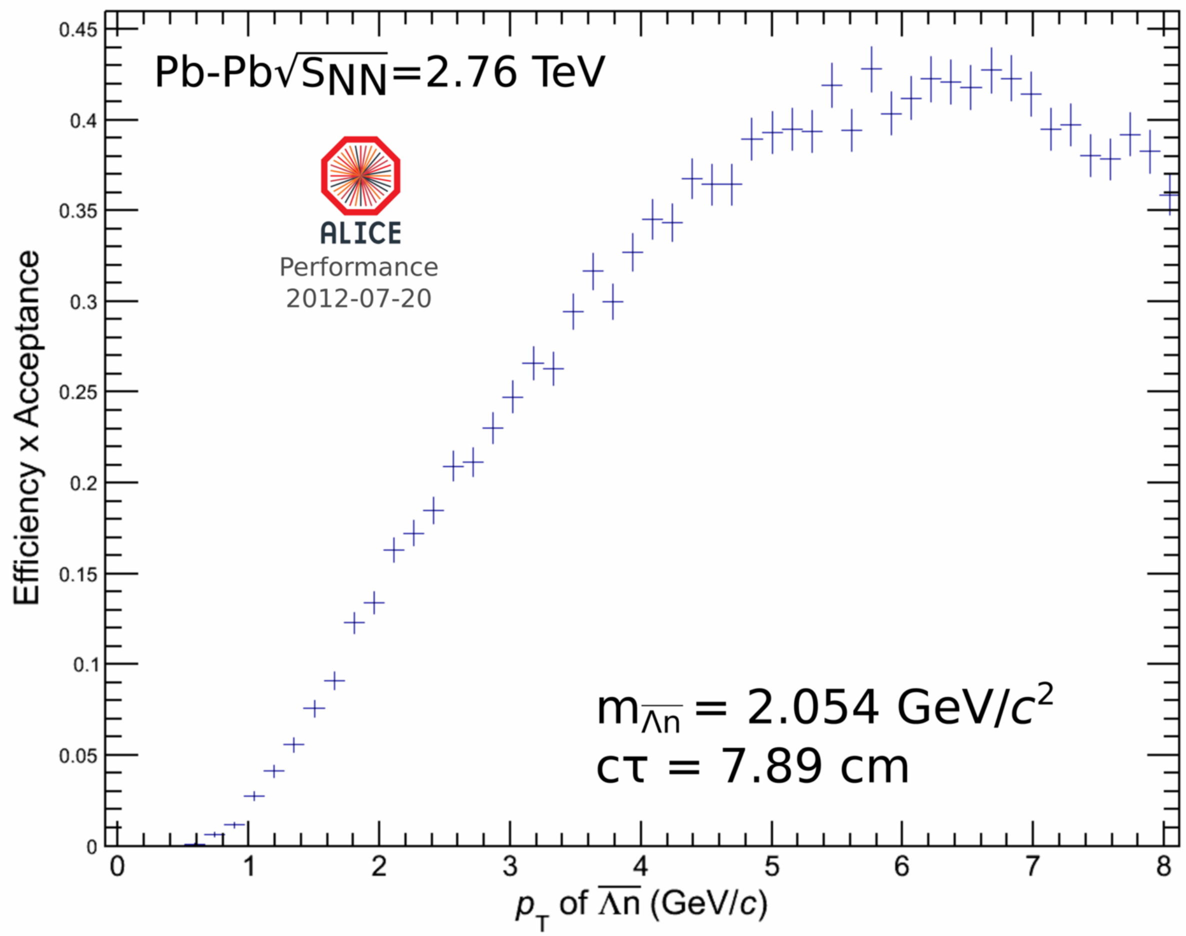
In second order: B_2 scales like the HBT radii

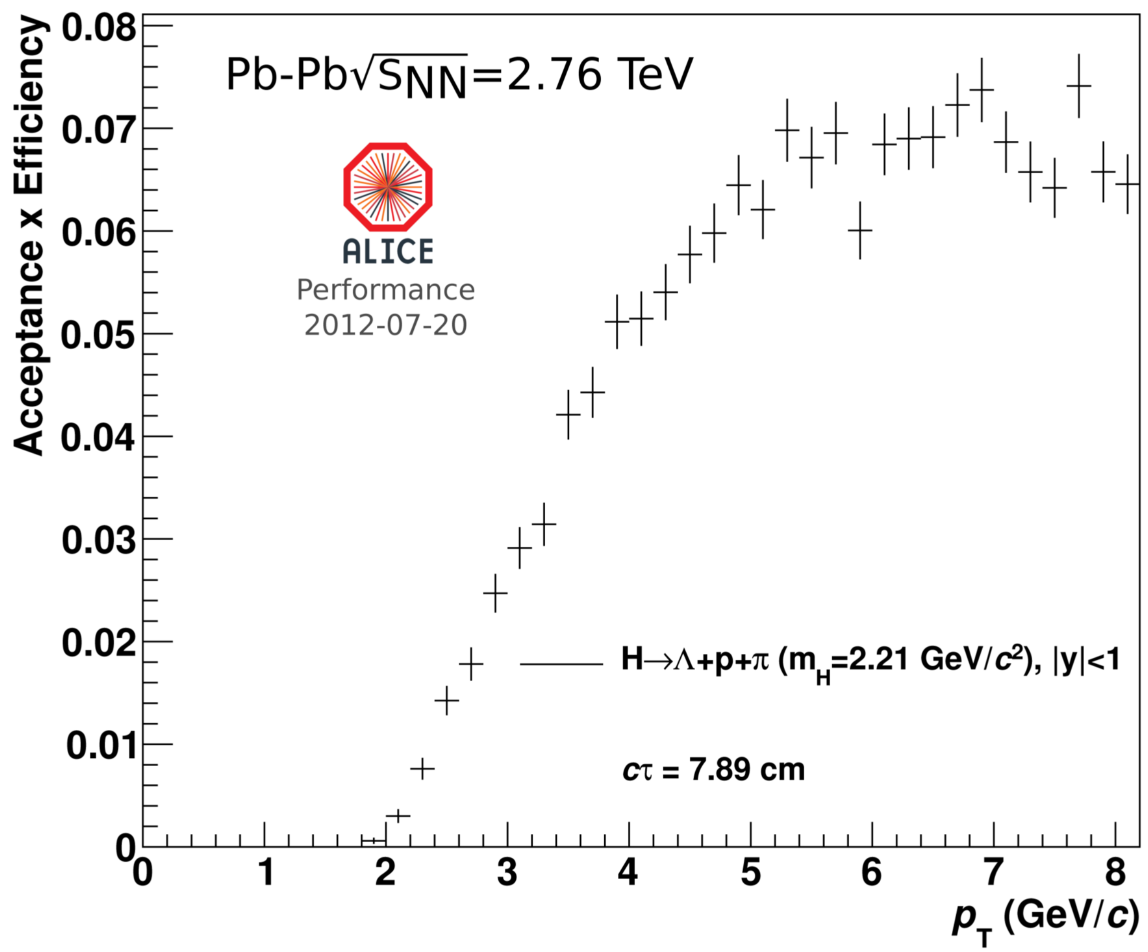
➜ p_T-slope which develops in central Pb-Pb reflects the k_T-dependence of the homogeneity volume in HBT

$$B_2 = \frac{3\pi^{3/2}\langle C_d\rangle}{2m_T R_\perp^2(m_T) R_{||}(m_T)}$$

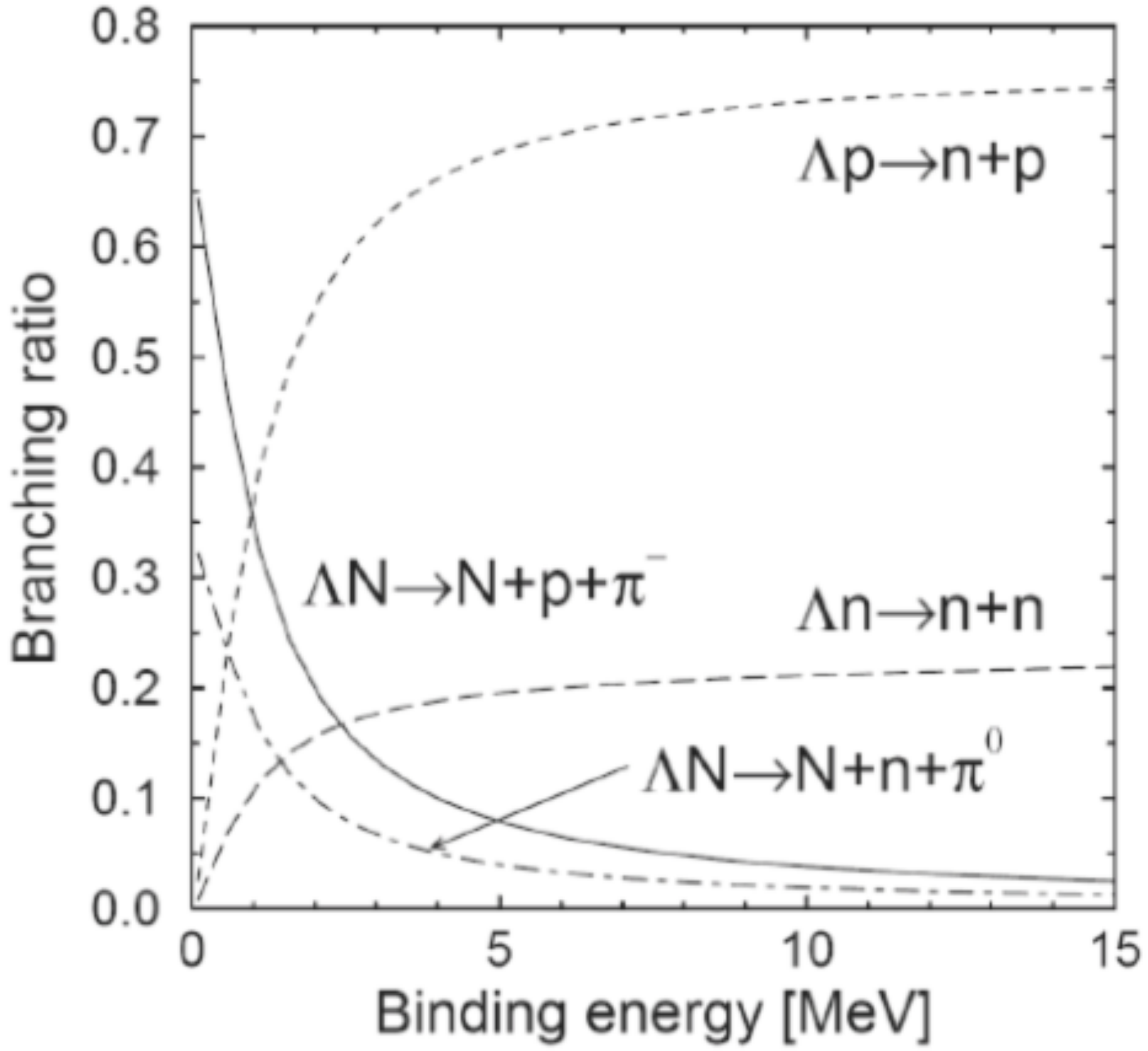
R. Scheibl and U. Heinz, Phys.Rev. C59, 1585 (1999)

Efficiencies exotica

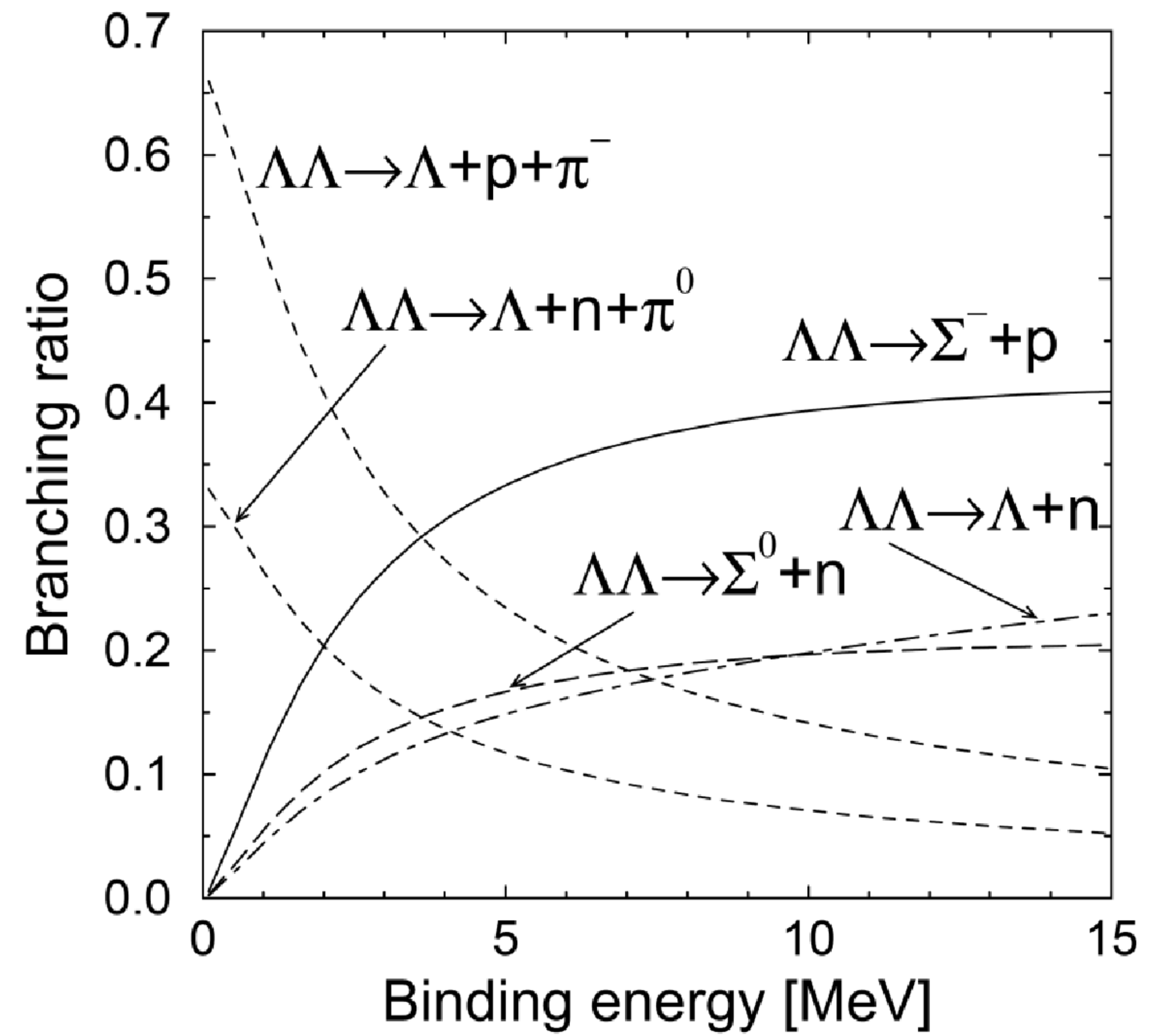




Branching ratios exotica



Jürgen Schaffner-Bielich, private communication

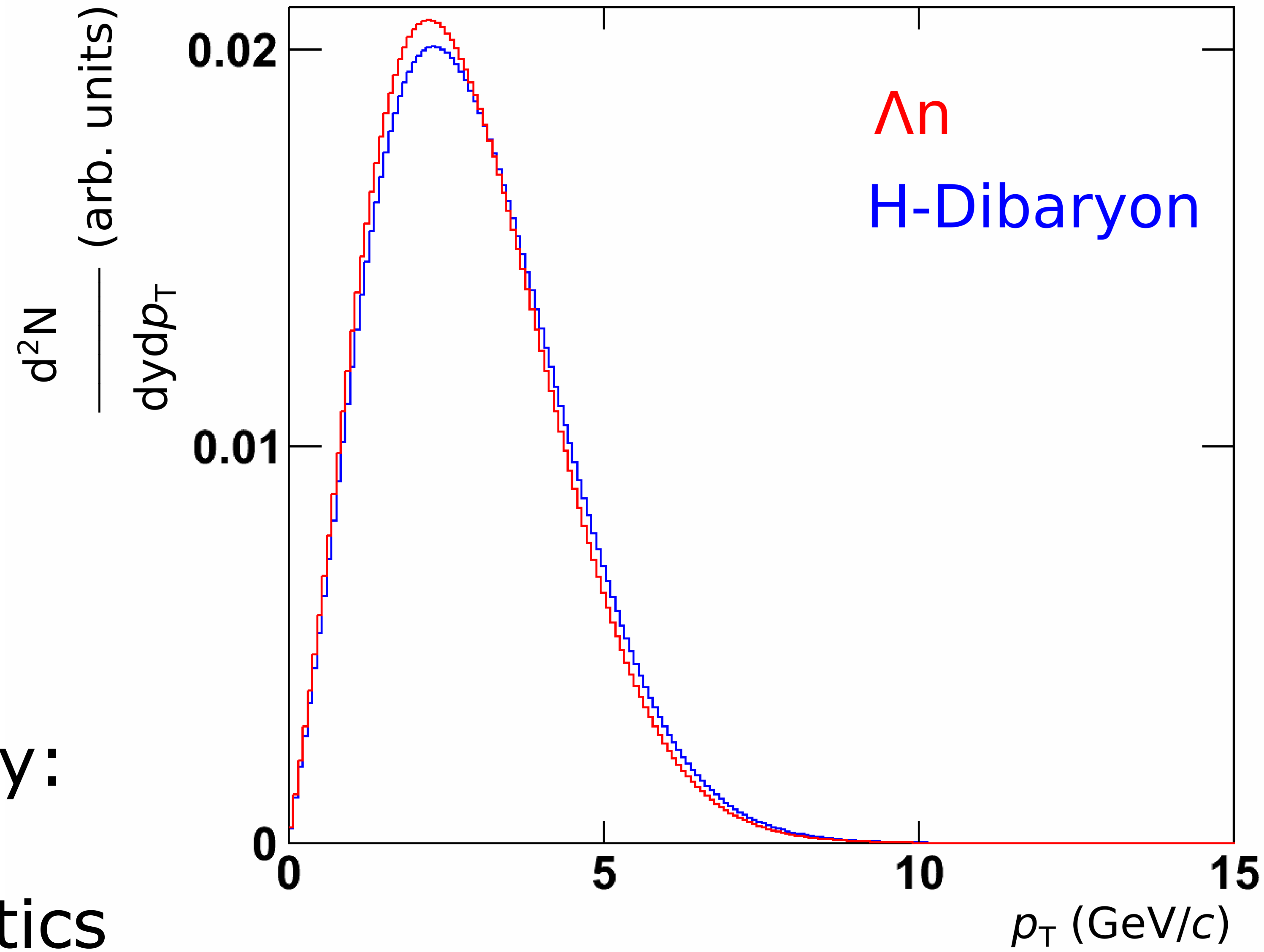


Jürgen Schaffner-Bielich et al., PRL 84, 4305 (2000)

Blast-Wave exotica

p_T-shape of the Λn bound state and the H-dibaryon estimated from the extrapolation of Blast-Wave fits for π,K,p

Normalized to unity and convoluted with Acceptance x Efficiency to get a weighted Efficiency



Unknown p_T-shape is the main source of uncertainty: Therefore used different functions for the systematics (limiting cases: Blast-Wave of deuteron and ^{3}He)

Lifetime dependence exotica

$\Lambda\Lambda$

Lifetime (s)	Decay length (cm)	Efficiency	Upper limit d*N*/dy 99% CL
$1.3 \cdot 10^{-10}$	3.95	0.0531	0.00061
$2.63 \cdot 10^{-10}$	7.89	0.0385	0.0084
$5.2 \cdot 10^{-10}$	15.8	0.0308	0.0011
$1.4 \cdot 10^{-9}$	42	0.0154	0.0017

$\bar{\Lambda}\bar{n}$

Lifetime (s)	Decay length (cm)	Efficiency	Upper limit d*N*/dy 99% CL
$1.3 \cdot 10^{-10}$	3.95	0.0220	0.001708
$2.63 \cdot 10^{-10}$	7.89	0.0255	0.001474
$5.2 \cdot 10^{-10}$	15.8	0.0320	0.001174
$1.4 \cdot 10^{-9}$	42	0.0440	0.000854