PRODUCTION OF (ANTI-)(HYPER)NUCLEI IN Pb-Pb COLLISIONS MEASURED WITH ALICE AT THE LHC

Stefano Piano on behalf of ALICE Collaboration
INFN sez. Trieste

MOTIVATION TO MEASURE (ANTI-)(HYPER)NUCLEI IN Pb-Pb COLLISIONS WITH ALICE AT THE LHC

ALICE aims to study the formation of Quark-Gluon Plasma, its properties and the evolution:

- (anti-)(hyper)nuclei yields are sensitive to the freeze-out temperature due to their large mass (e.g. in the Thermal Model: yield $\propto e^{(-M/T_{chem})}$)
- light (anti-)nuclei, small binding energy (e.g. (anti-)d ~ 2.2 MeV):
  - light (anti-)nuclei should dissociate in a medium with high T_{chem} (~160 MeV) and be suppressed
  - light (anti-)nuclei production determined by the entropy per baryon (fixed at chemical freeze-out)
  - if light (anti-)nuclei yields equal to thermal model prediction $\Rightarrow$ sign for adiabatic isentropic expansion in the hadronic phase
- A=3 (anti-)(^{3}He, t, $^3_\Lambda$H), a simple system of 9 valence quarks:
  - $^3_\Lambda$H / ^{3}He and $^3_\Lambda$H / t (and anti) $\Rightarrow$ Lambda-nucleon correlation (local baryon-strangeness correlation)
  - t / ^{3}He (and anti) $\Rightarrow$ local charge-baryon correlation

Anti-nuclei in nature:

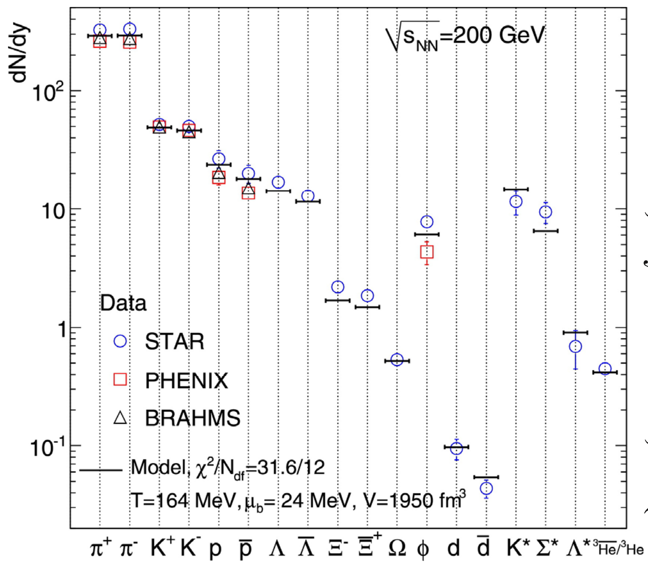
- matter–antimatter asymmetry
- anti-d are rare in cosmic rays, a clear excess in anti-d flux would be suggestive of dark matter: measurements like anti-d production in pA collisions correspond to the background of dark matter search

(ANTI-)(HYPER)NUCLEI PRODUCTION IN URHIC

ALICE

Statistical Thermal model

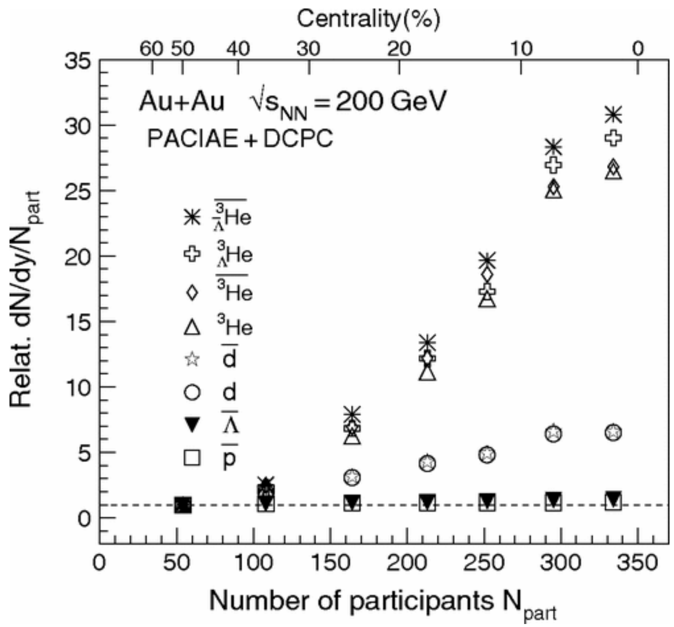
- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out (T_{chem}) (hyper)nuclei are very sensitive to T_{chem} because of their large mass (M)
- Exponential dependence of the yield $\propto e^{(-M/Tchem)}$



A. Andronic et al., Phys. Lett. B 697, 203 (2011)

Coalescence

- If baryons at freeze-out are close enough in Phase Space an (anti-)(hyper)nucleus can be formed
- (Hyper)nuclei are formed by protons (Λ) and neutrons which have similar velocities after the kinetic freeze-out

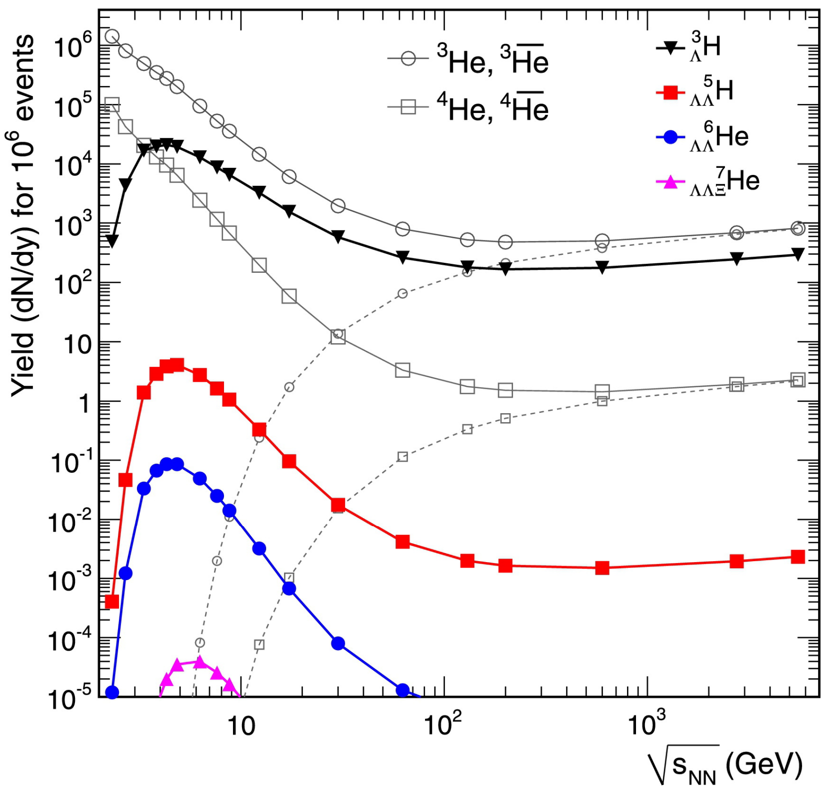


G. Chen et al., Phys. Rev. C 88, 034908 (2013)

(ANTI-)(HYPER)NUCLEI PRODUCTION AT LHC

ALICE

Production yield estimate (thermal model) of (anti-)(hyper)nuclei in central heavy ion collisions at LHC energy:



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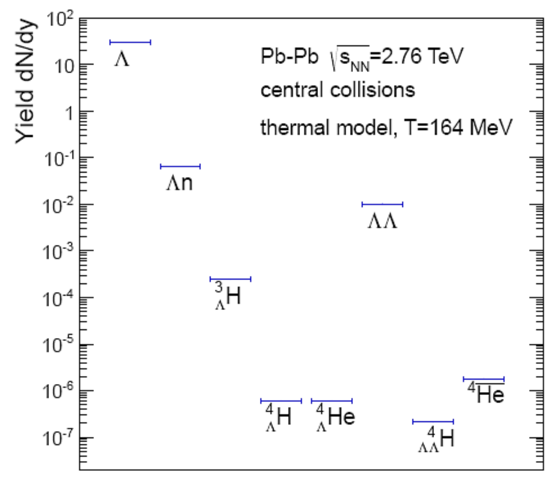
	Yield/event at mid-rapidity
π	~800
p	~40
Λ	~30
d	~0.17
^{3}He	~0.01
$^3_\Lambda$H	~0.003

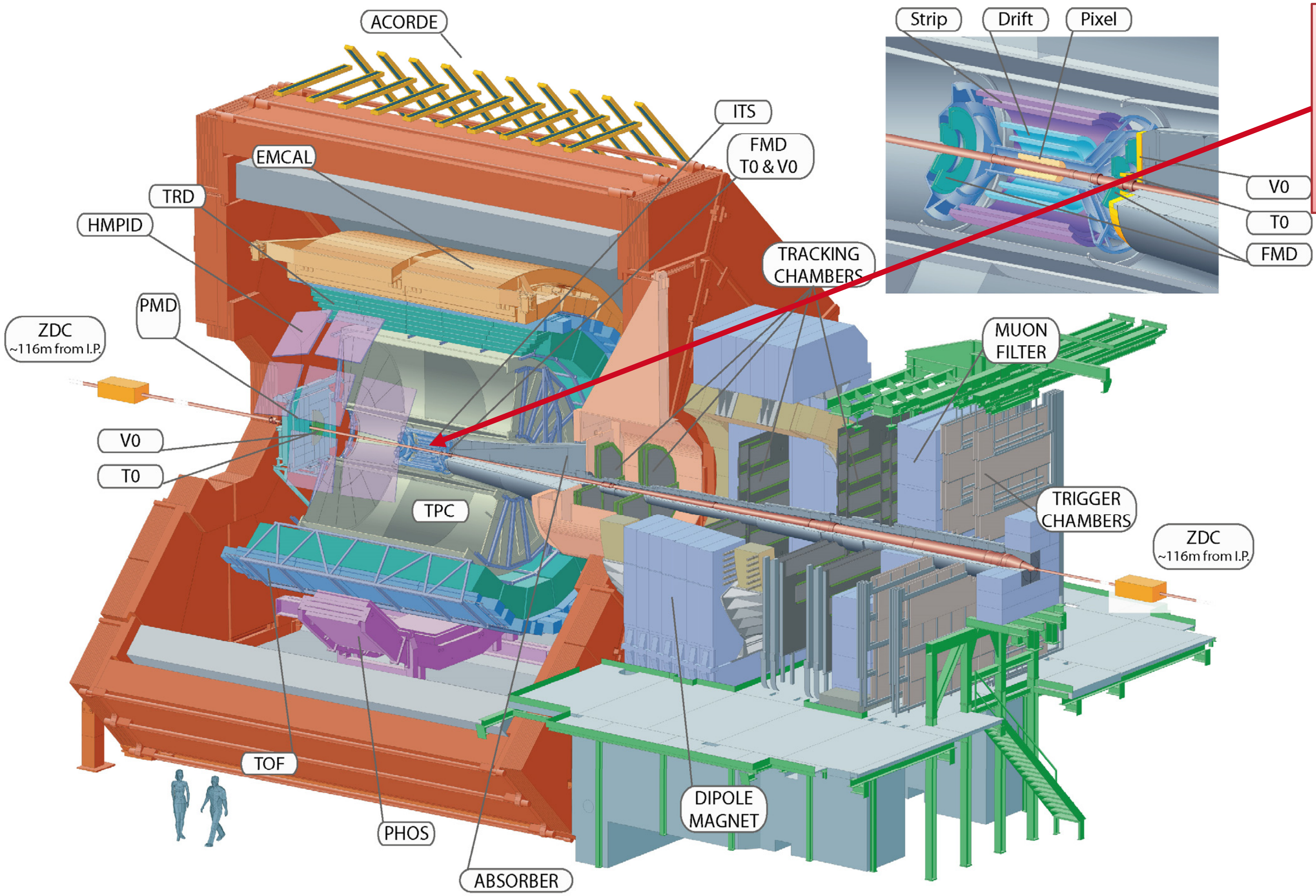
- ✓ Light nuclei
- ✓ Hypertriton
- ✓ Search for: Λn, ΛΛ dibaryons



A. Andronic, private communication

A LARGE ION COLLIDER EXPERIMENT

ALICE particle identification capabilities are unique. Almost all known techniques are exploited: dE/dx, time-of-flight, transition radiation, Cherenkov radiation, calorimetry and decay topology (V0, cascade)



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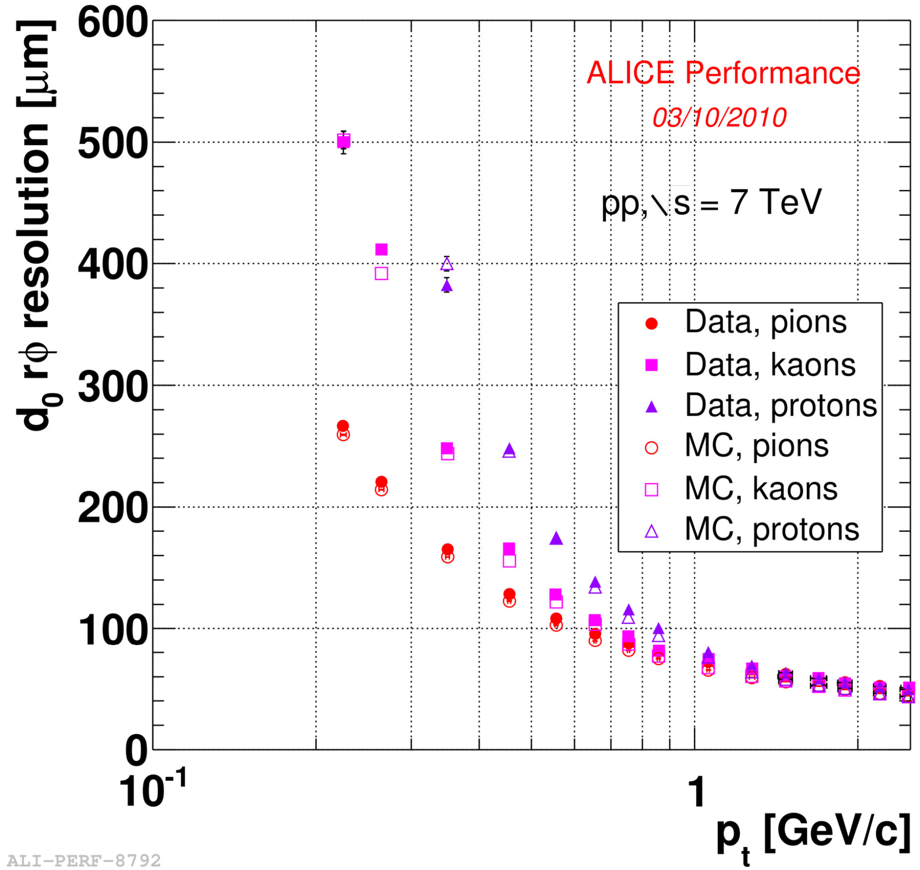

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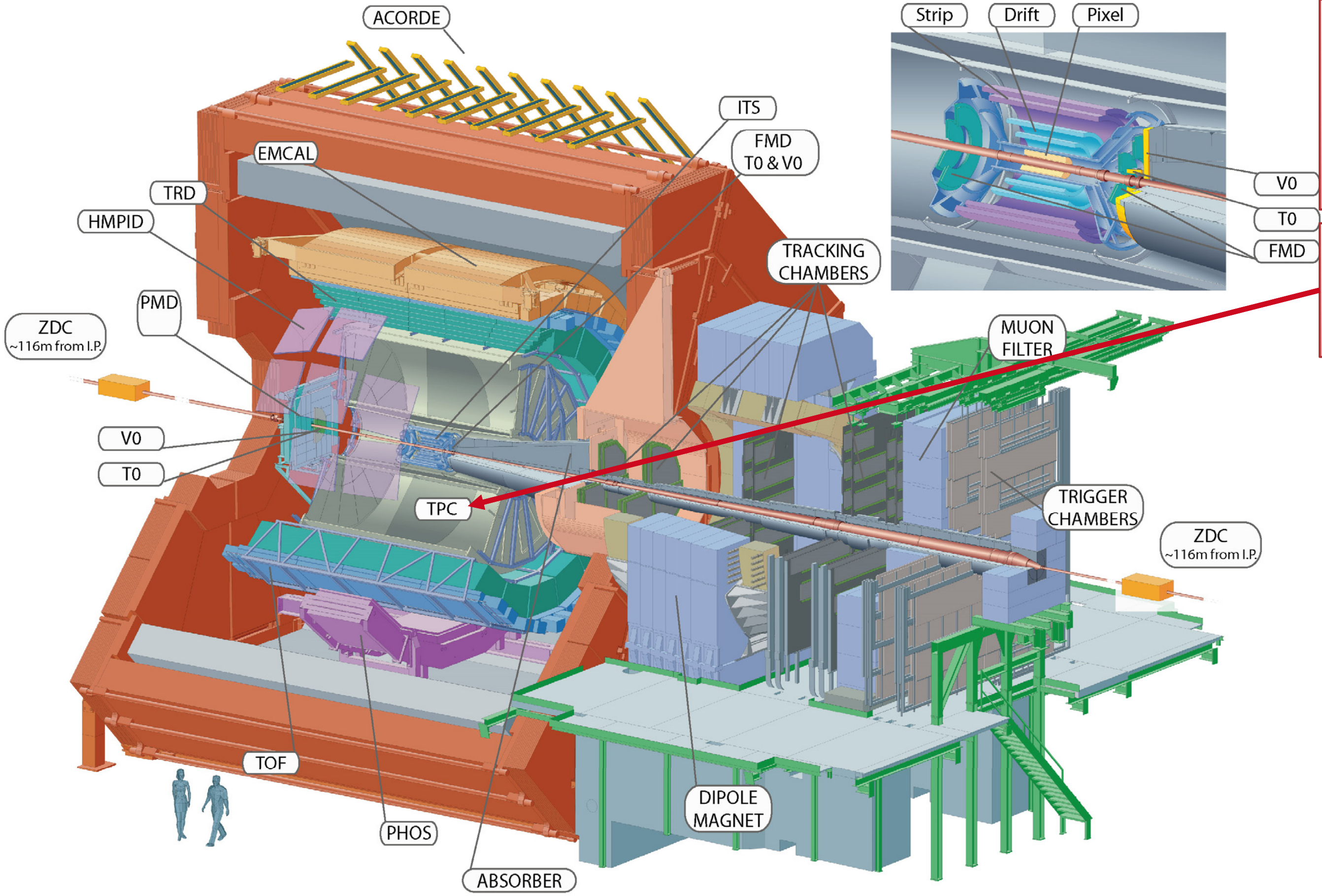

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TPC: particle identification via d*E*/dx (allows also separation of charges).

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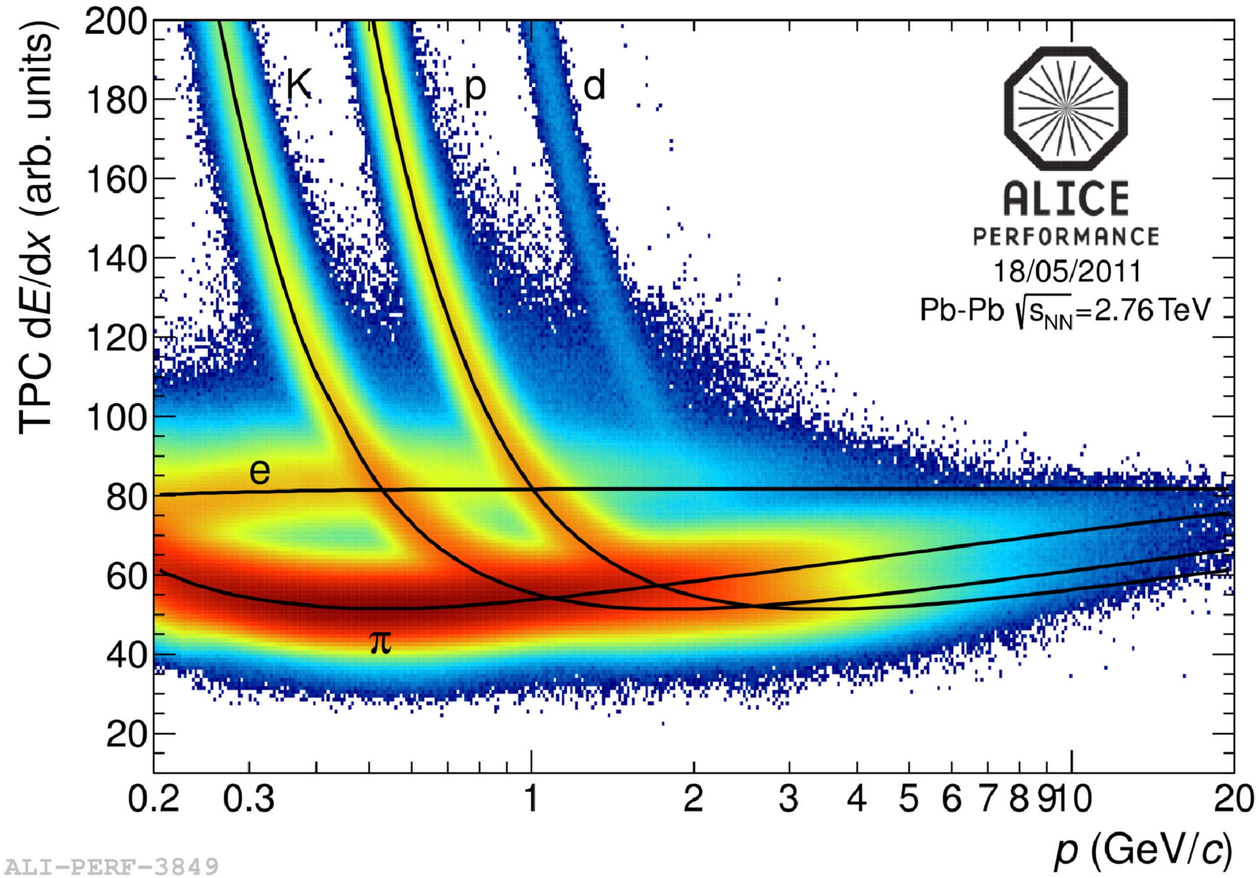

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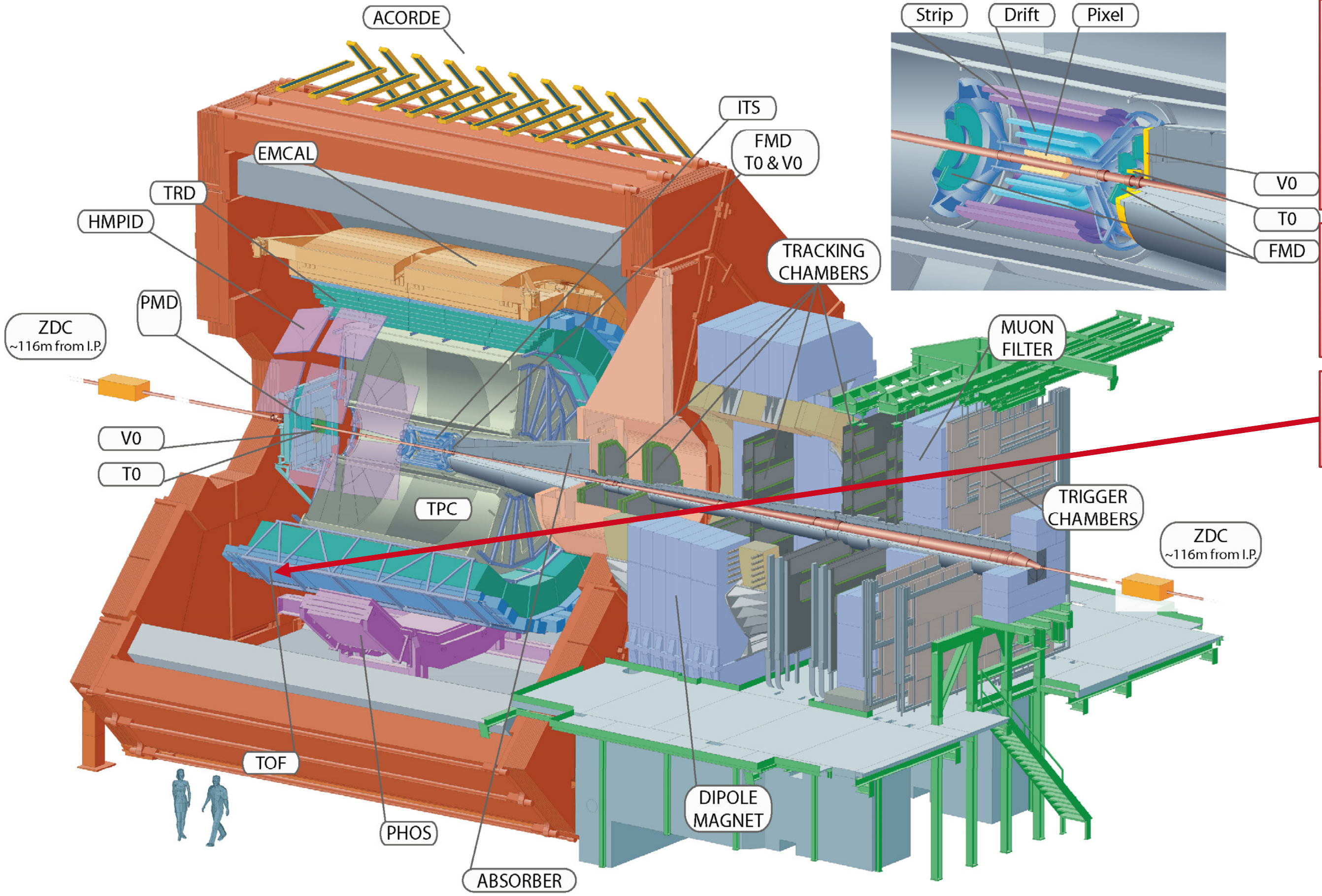

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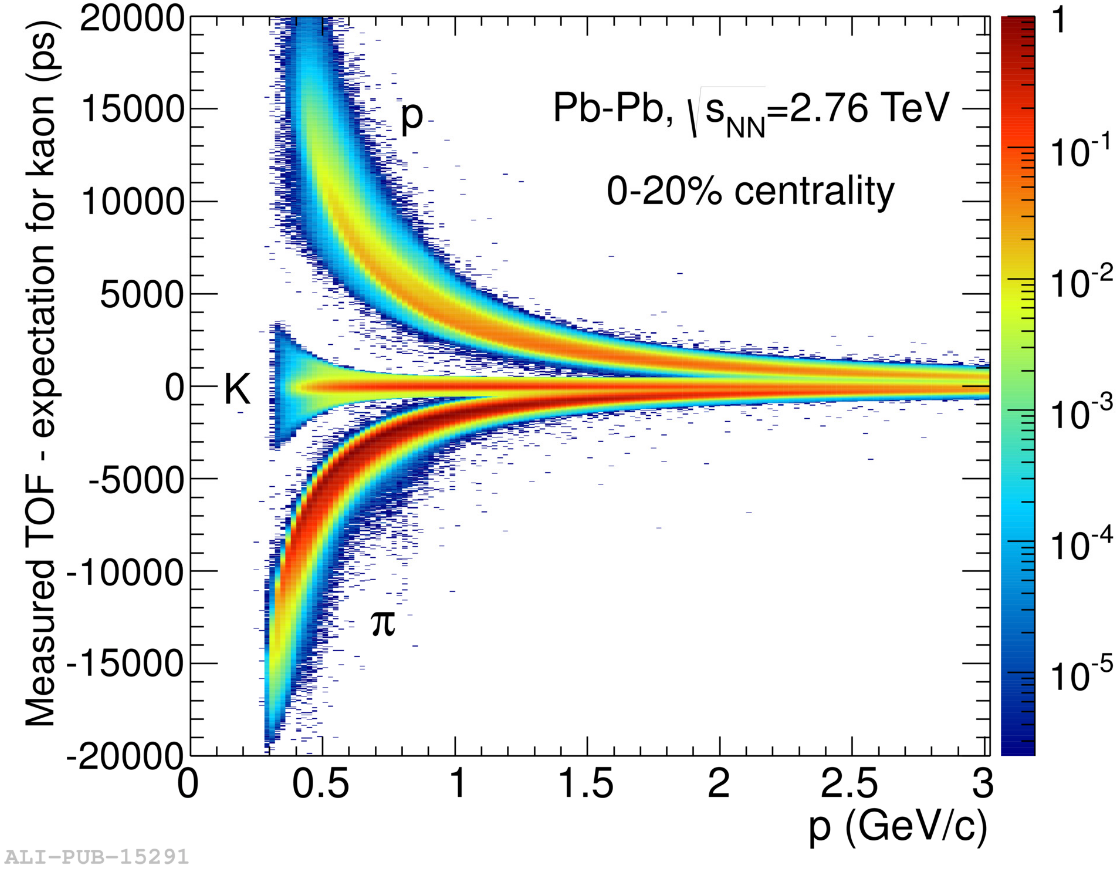

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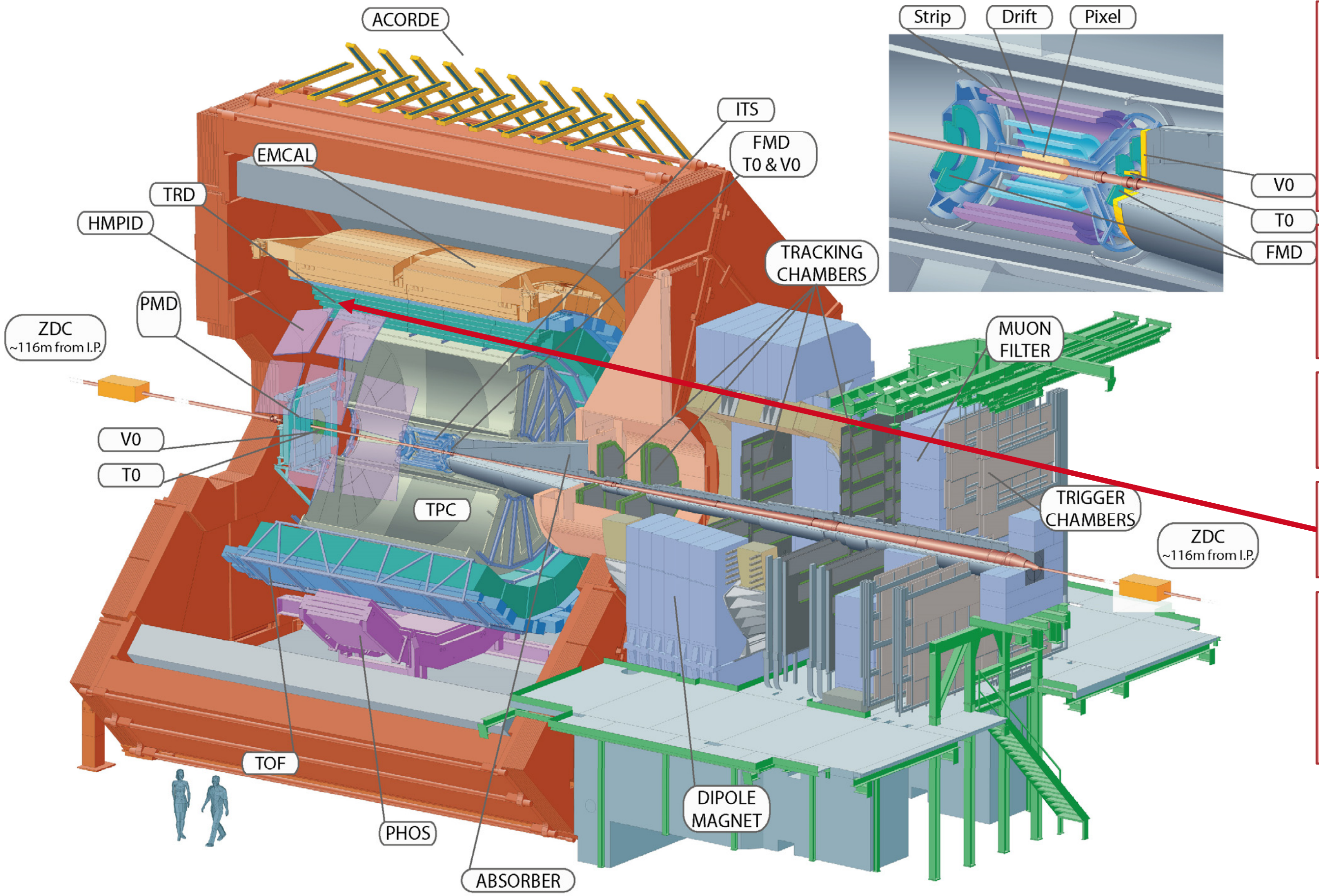

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TRD: electron identification via transition radiation

ITS+TPC+TRD: excellent track reconstruction capabilities in a high track density environment

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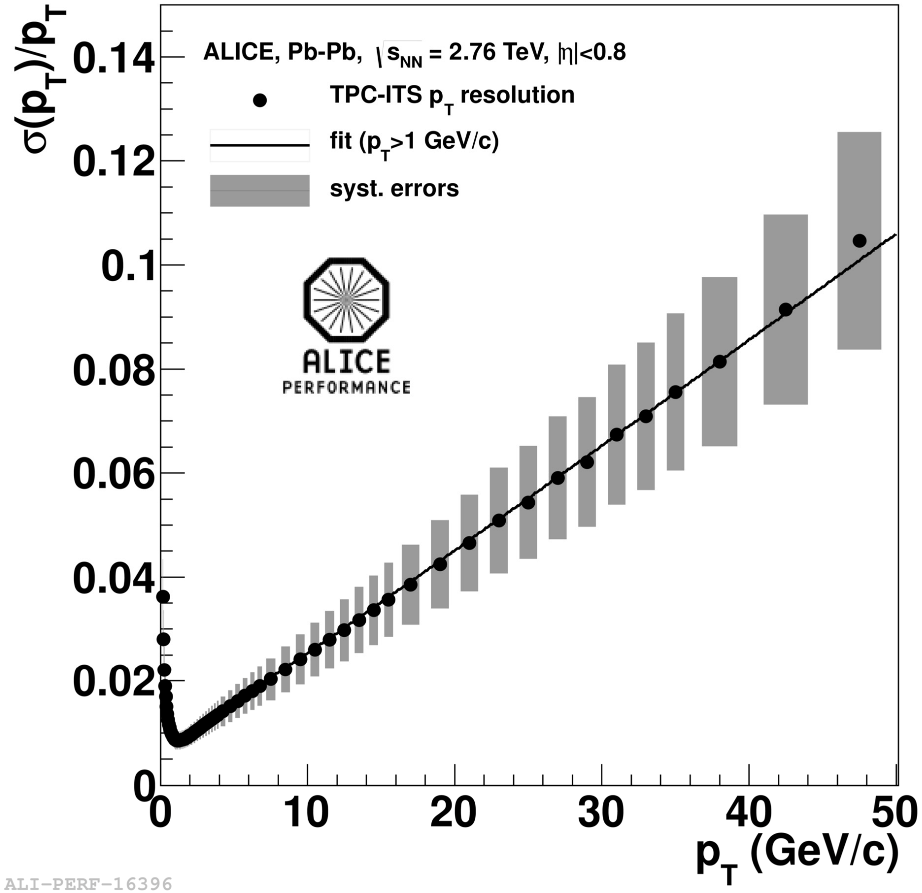

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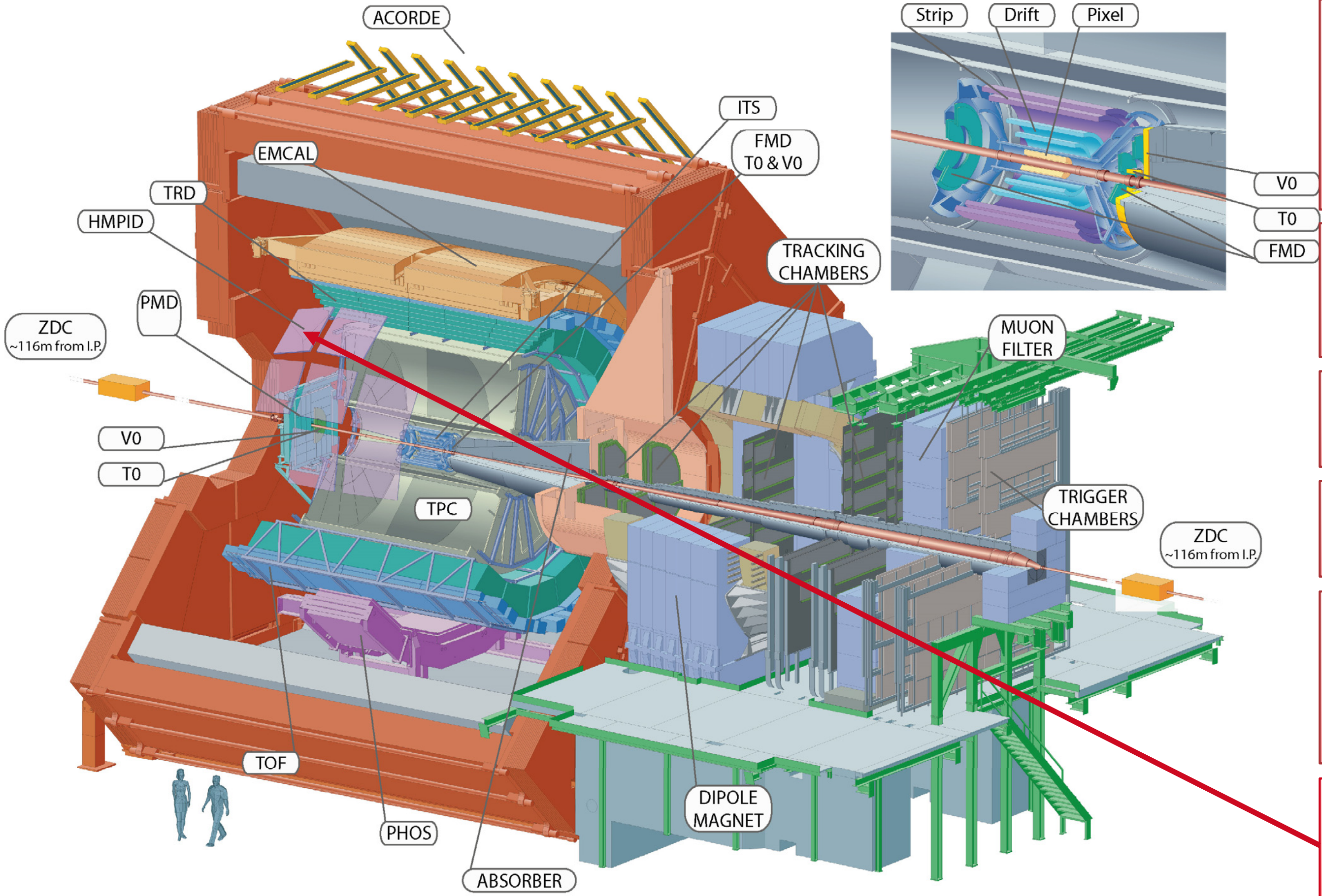

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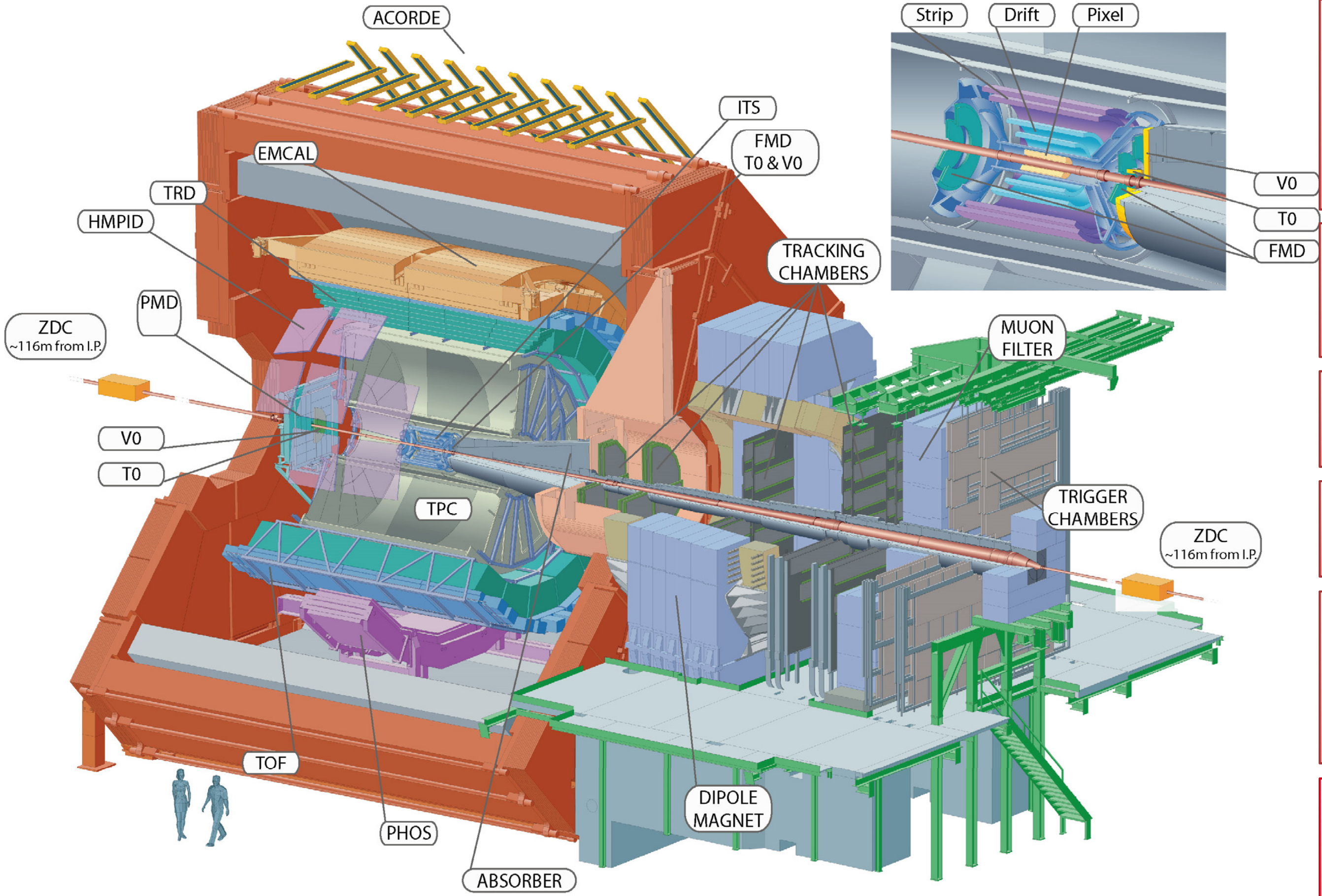

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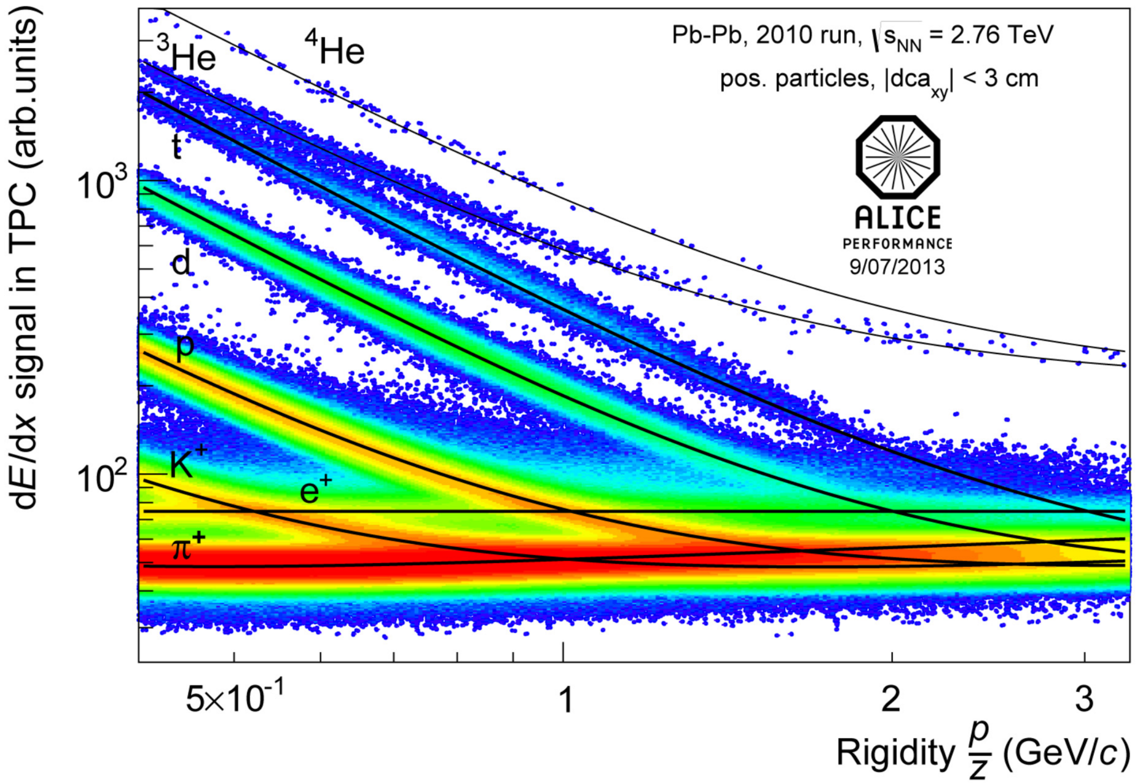
ALICE is ideally suited for the identification of light (anti-)(hyper)nuclei

NUCLEI IDENTIFICATION

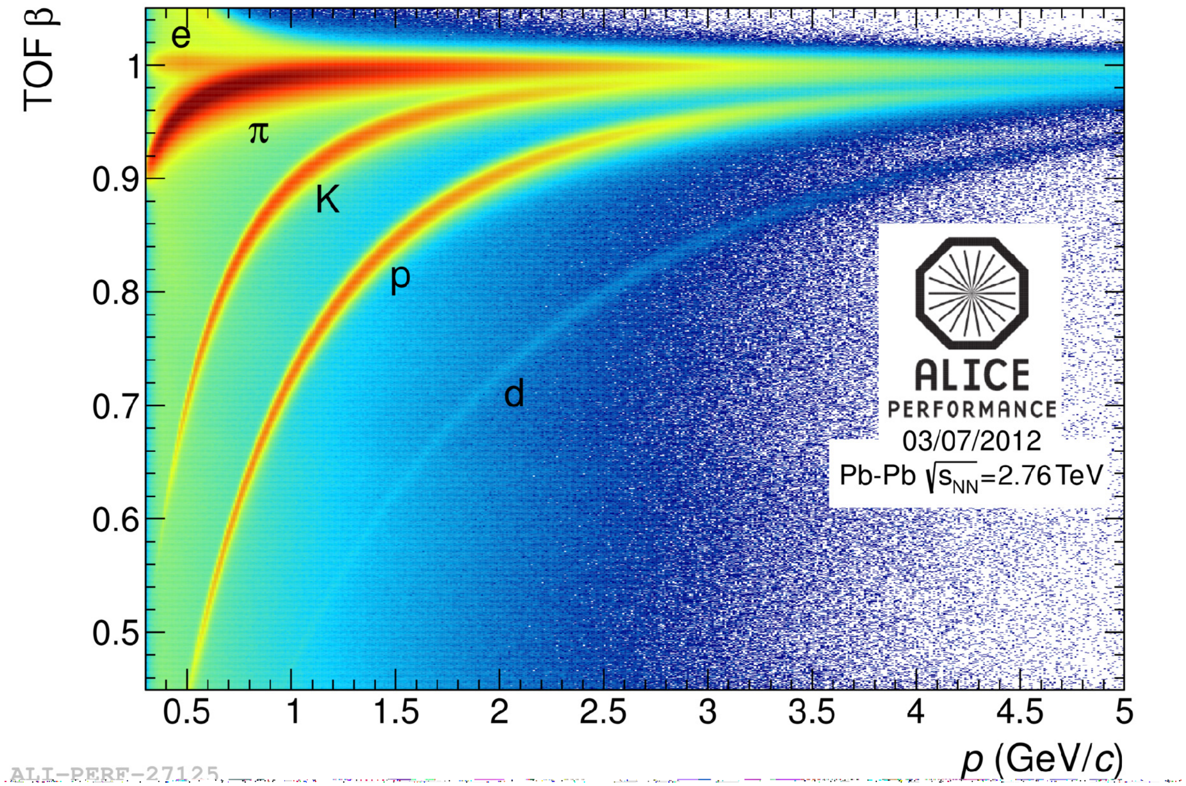


Low momenta

Nuclei identification via d*E*/d*x* measurement in the TPC:

- d*E*/dx resolution in central Pb-Pb collisions: ~7%
- Excellent separation of (anti-)nuclei from other particles over a wide momentum range
- About 10 anti-alpha candidates identified out of 23x10^6 events by combining TPC and TOF particle identification

NUCLEI IDENTIFICATION



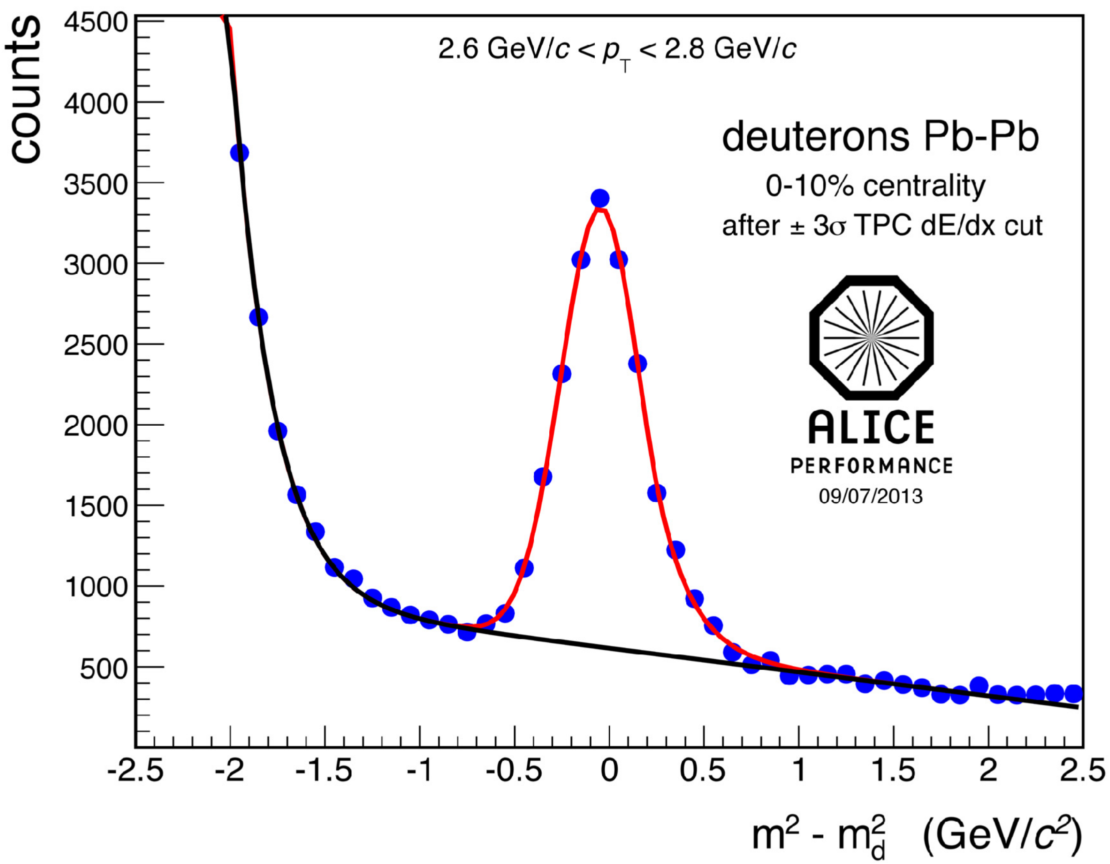
Higher momenta

Velocity measurement with the Time Of Flight detector is used to evaluate the m^2 distribution

- Excellent TOF performance:

  $\sigma_{TOF} \approx 85$ ps in Pb-Pb collisions allows identification of light nuclei over a wide momentum range

NUCLEI IDENTIFICATION



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

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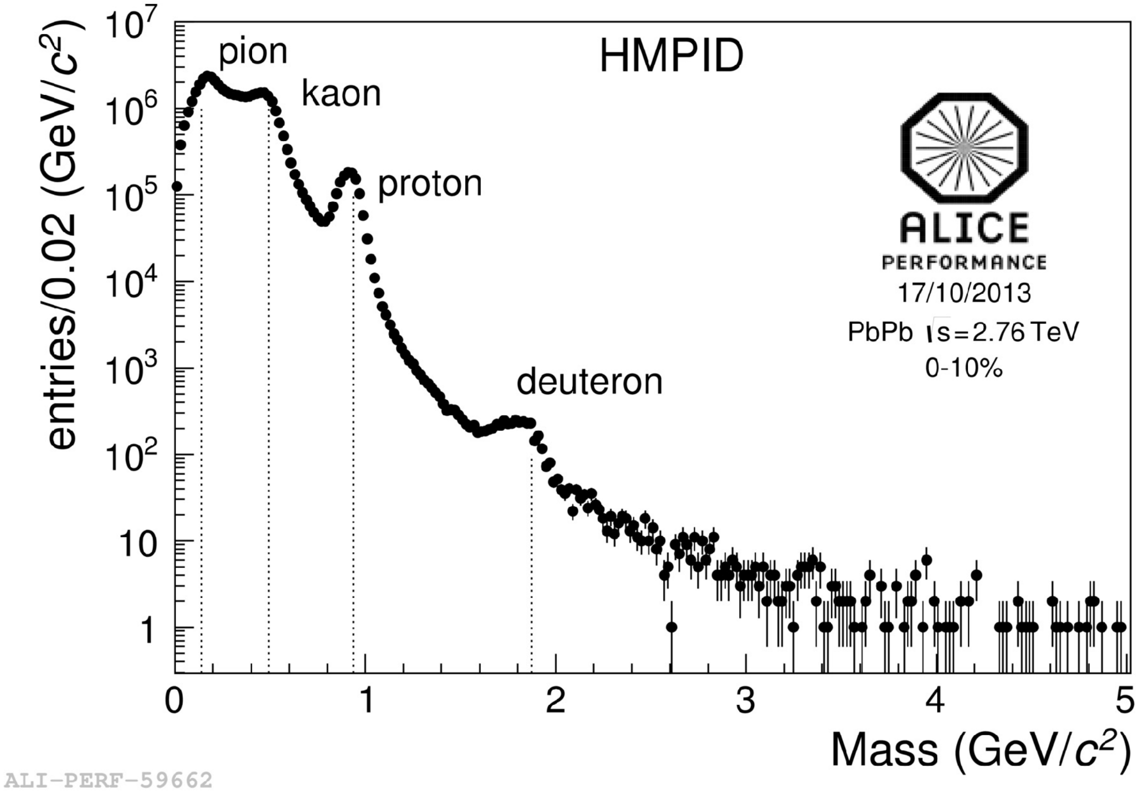

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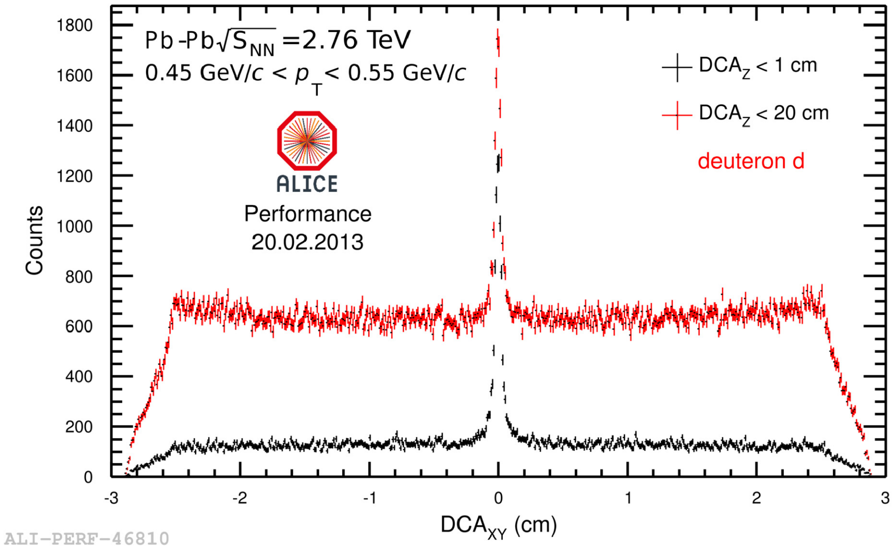
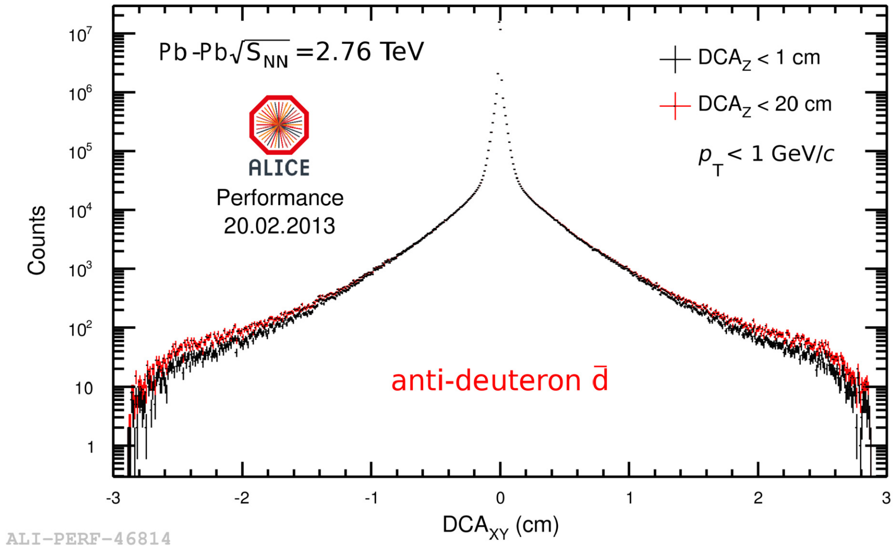
At even higher momenta nuclei in central Pb-Pb collisions are identified on the basis of Cherenkov radiation with HMPID (deuteron spectrum up to 8 GeV/*c*)

SECONDARIES





The measurement of nuclei is strongly affected by background from knock-out from material:

- Rejection is possible by applying a cut on DCA_Z and fitting the DCA_{XY} distribution
- Not relevant for anti-nuclei. However, their measurement suffers from large systematics related to unknown hadronic interaction cross-sections of anti-nuclei in material

ALICE

(ANTI)HYPERTRITON IDENTIFICATION

Decay Channels

$$ {}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-} \quad {}^{3}_{\Lambda}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+} $$ BR = 0.25 (*)

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

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

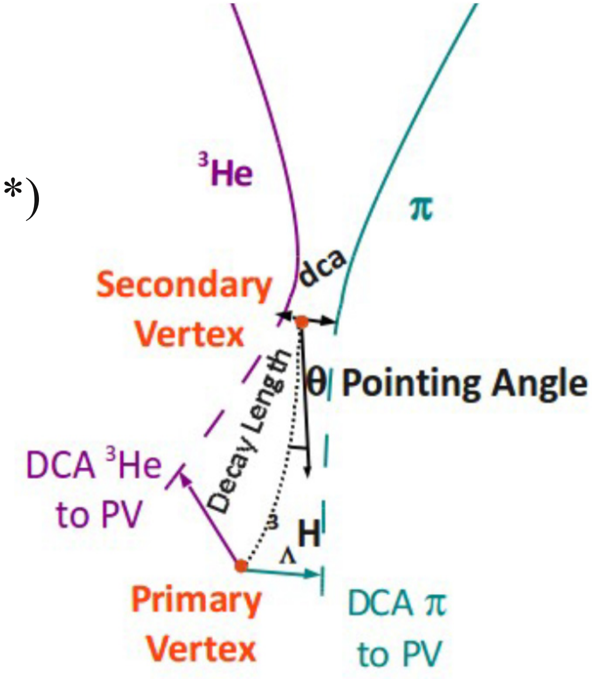
$$ {}^{3}_{\Lambda}H \rightarrow d + n + \pi^{0} \quad {}^{3}_{\Lambda}\overline{H} \rightarrow \overline{d} + \overline{n} + \pi^{0} $$

${}^{3}_{\Lambda}H$ search via two-body decays into charged particles:

- Two body decay: lower combinatorial background
- Charged particles: ALICE acceptance for charged particles (|η|<0.9) higher than for neutrals (|η|<0.7)

Signal Extraction:

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



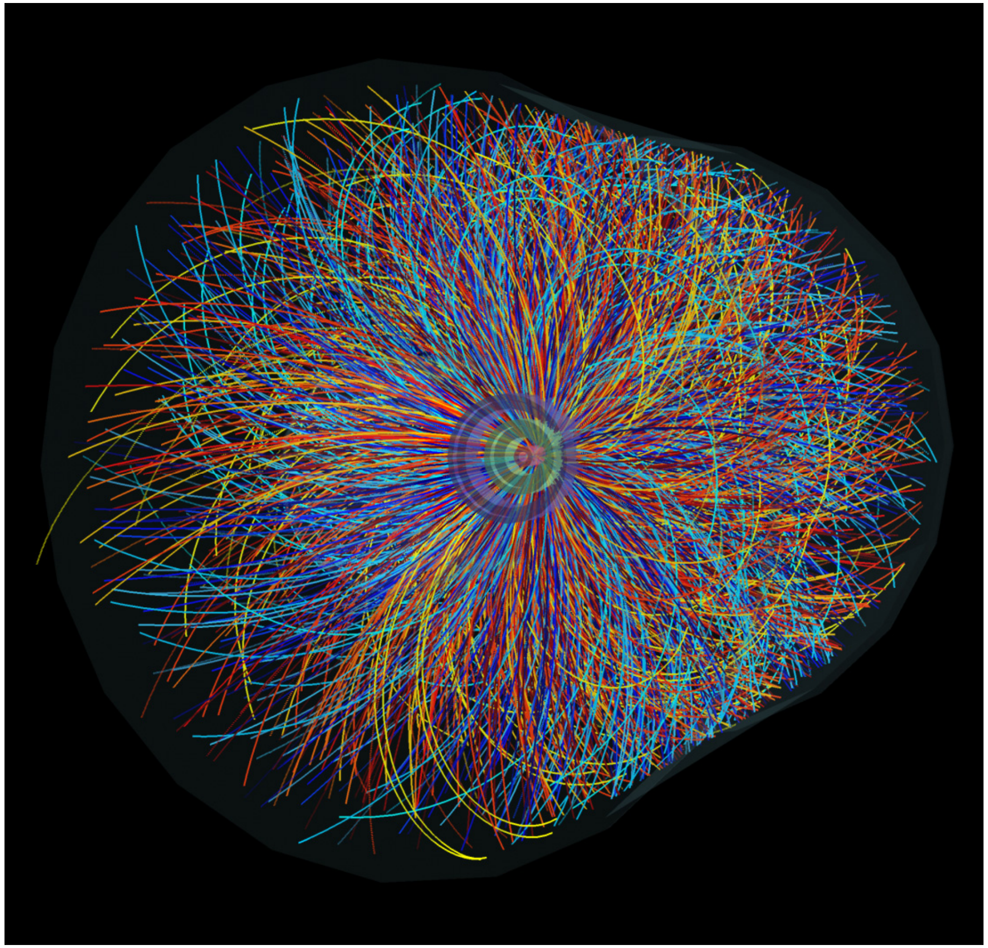
APPLIED CUTS:

- Cos(Pointing Angle) > 0.99
- DCA π to PV > 0.4 cm
- DCA between tracks < 0.7 cm
- (${}^{3}He$,π) p_T> 2 GeV/c
- |y| ≤ 1
- cτ > 1 cm

(*) Kamada et al., PRC57(1998)4

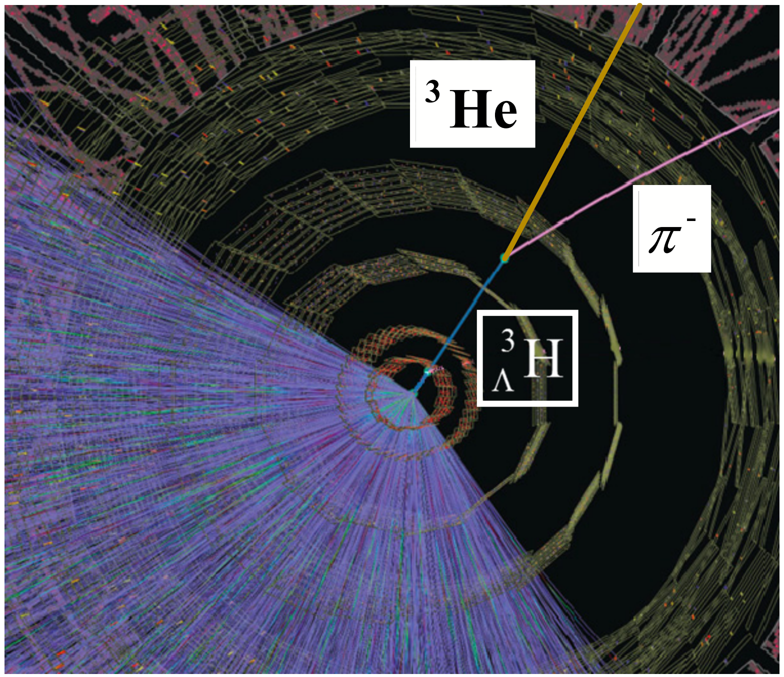
THE EXPERIMENTAL CHALLENGE

The challenge: extract the ${}^{3}_{\Lambda}H$ signal from an overwhelming background



Centrality	$dN_{ch}/d\eta$
0-5 %	1601 ± 60
0-80%	546 ± 30

K. Aamodt et al. (ALICE Collaboration) Phys. Rev. Lett. 106, 032301 (2011)



(ANTI-)HYPERTRITON IDENTIFICATION

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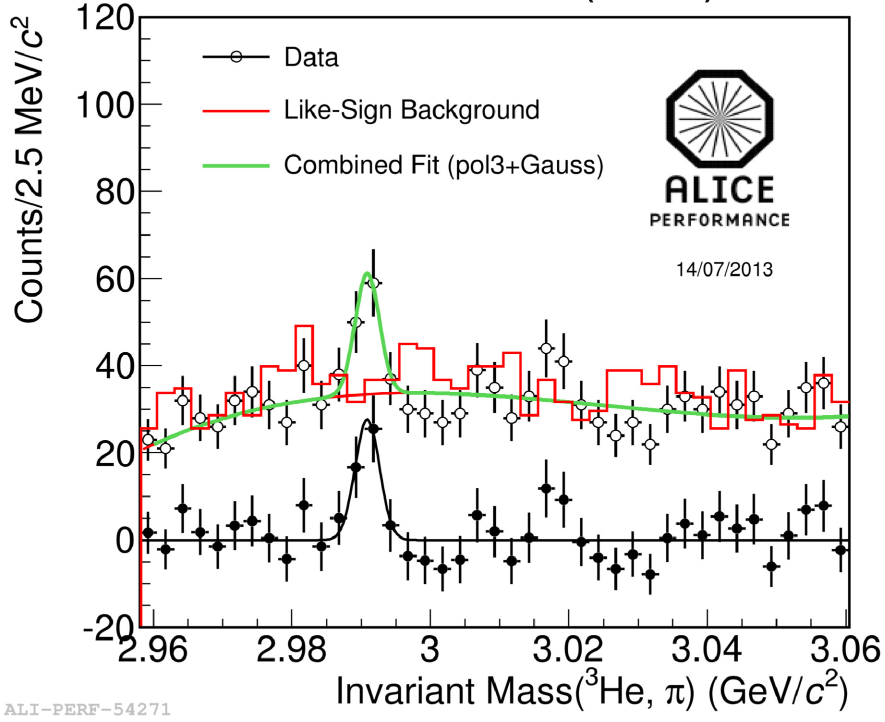
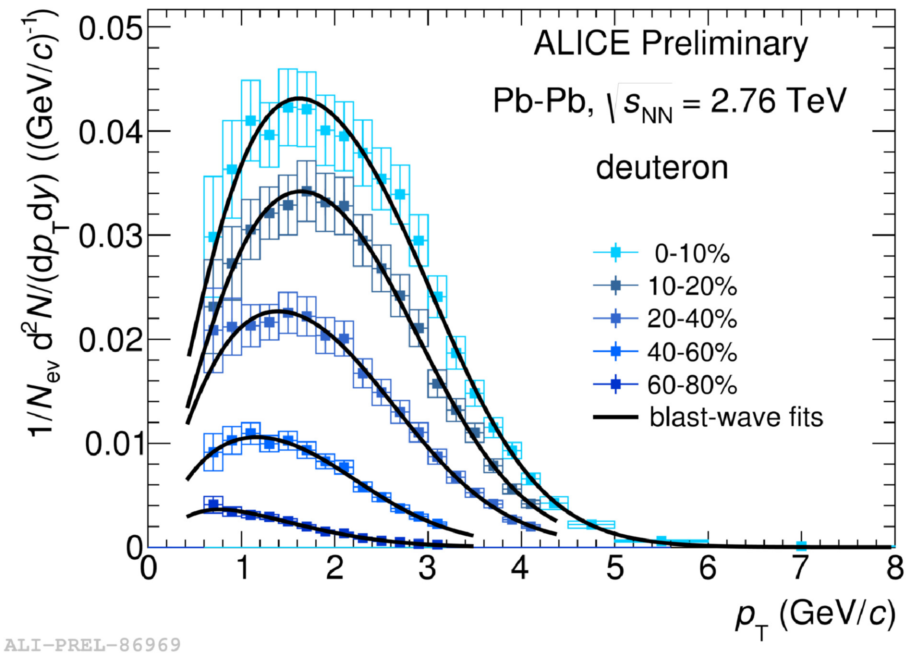
[(^{3}He,π^{-})+ ($^{3}\overline{\mathrm{He}}$, π^{+})] Invariant Mass spectrum
Semi-Central Events (10-50%)

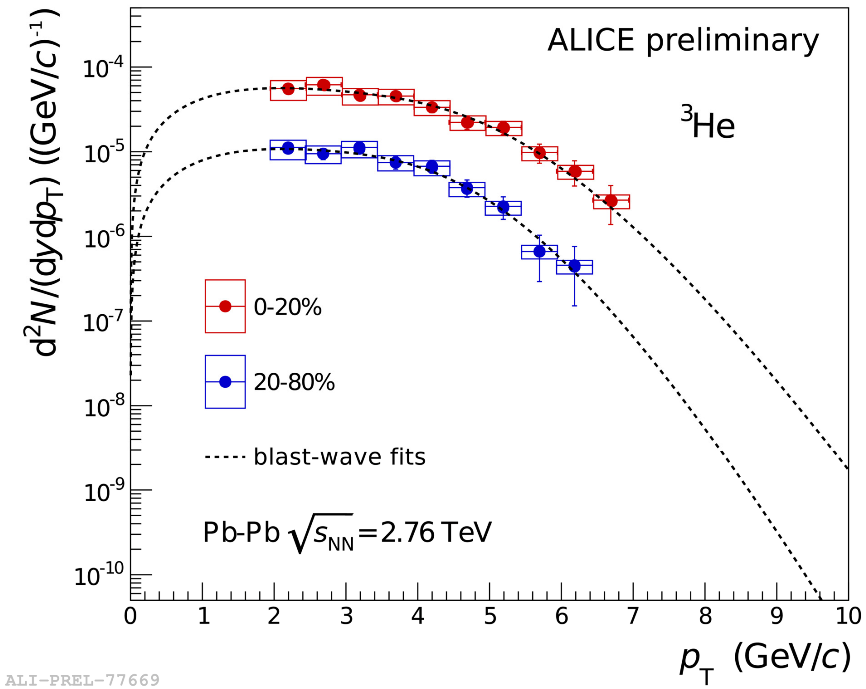


μ = 2.992 ± 0.002 GeV/c^2
σ= (2.08 ± 0.50)x10^{-3} GeV/c^2

To be compared to literature value:
μ= 2.99131 ± 0.00005 GeV/c^2
[Juric, Nucl. Phys. B 52, 1 (1973)]

DEUTERONS AND ^{3}HE SPECTRA IN Pb-Pb





Spectra are extracted in different centrality bins and fitted with a Blast-Wave function (simplified hydro model (*)) for the extraction of yields (extrapolation to unmeasured region at low and high p_T)

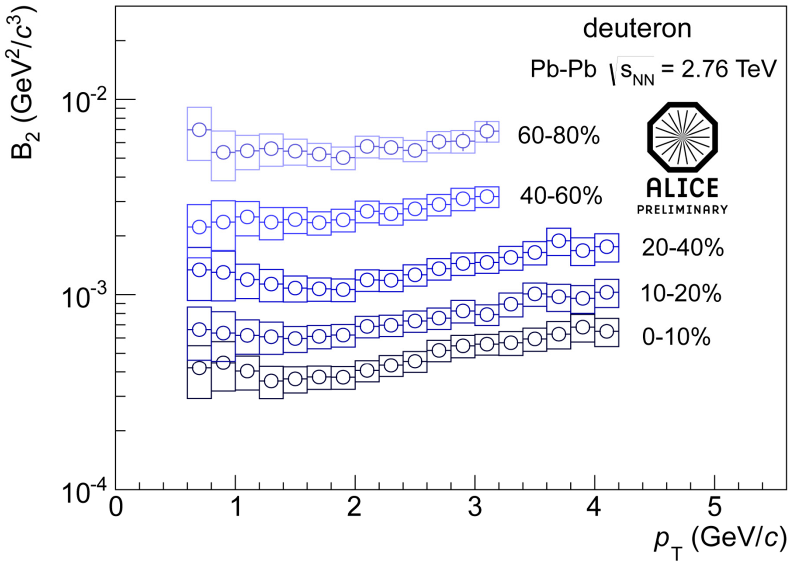
- A hardening of the spectrum with increasing centrality is observed as expected in a hydrodynamic description of the fireball as a radially expanding source

(*) **Schnedermann et al., Phys. Rev. C 48, 2462 (1993)**

DEUTERONS B_2

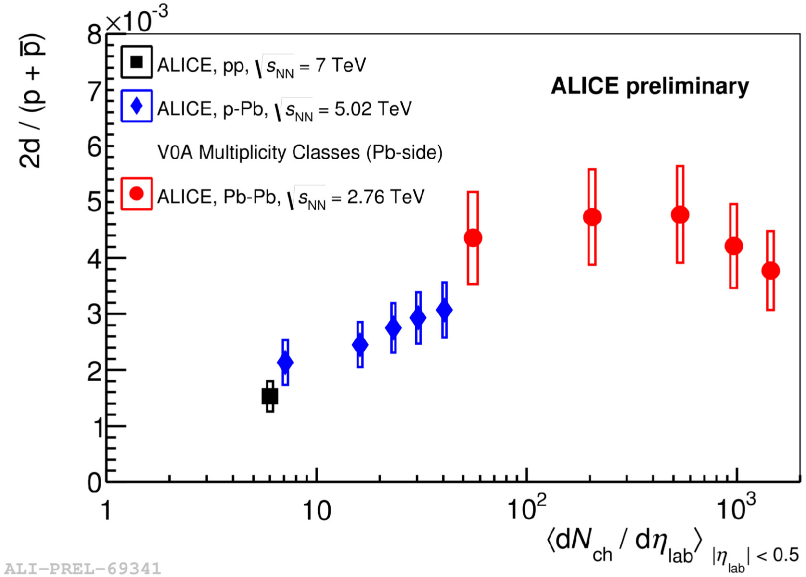
Within a coalescence approach, the formation probability of deuterons can be quantified through the parameter B_2:

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



In first order, B_2 is expected to depend only on the maximum difference in the momentum of the two constituents ("pure nuclear physics") (*).

- B_2 should be flat vs. p_T and should not depend on multiplicity/centrality
- The d/p ratio should strongly increase with multiplicity/centrality



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

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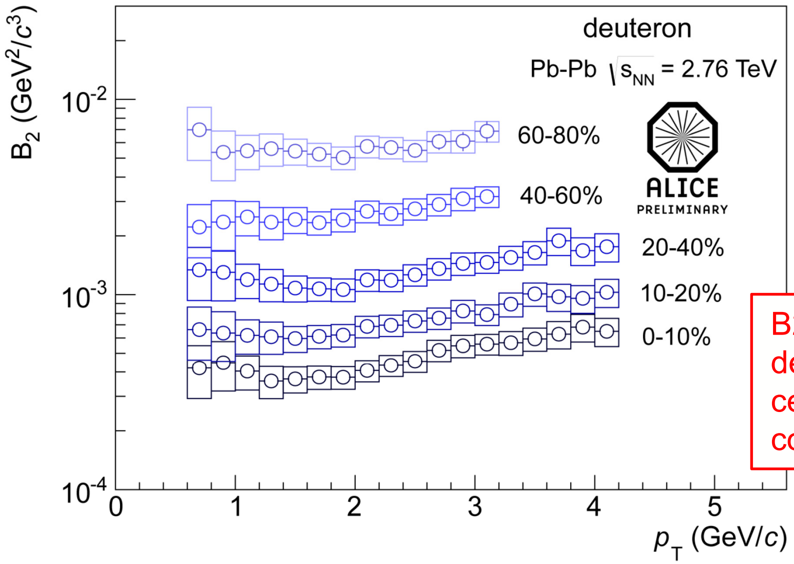
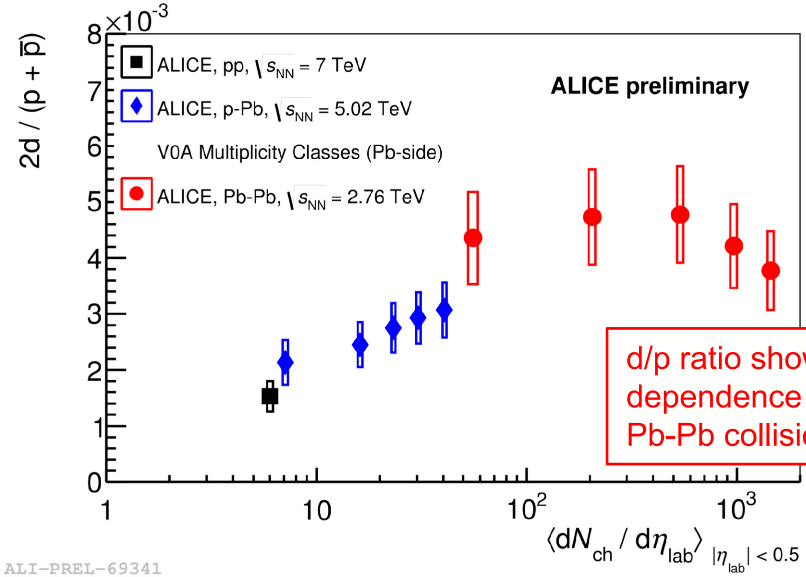


B2 is strongly decreasing with centrality in Pb-Pb collisions.



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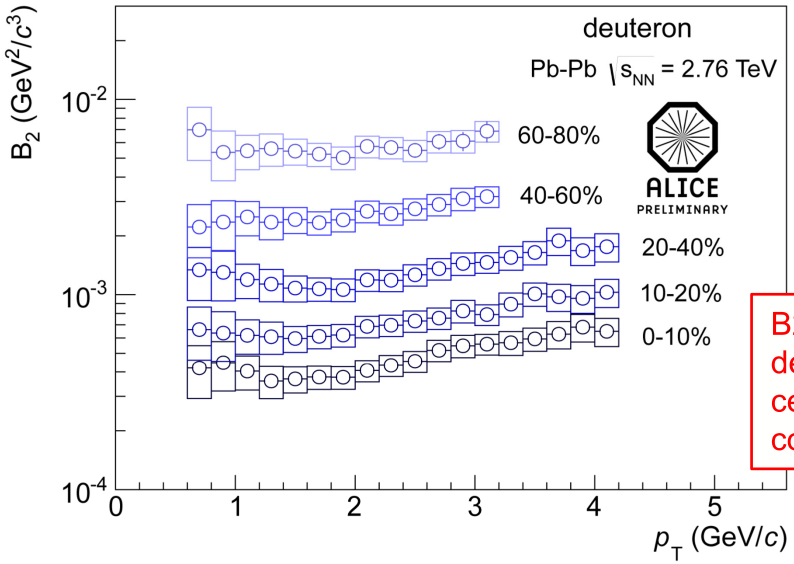

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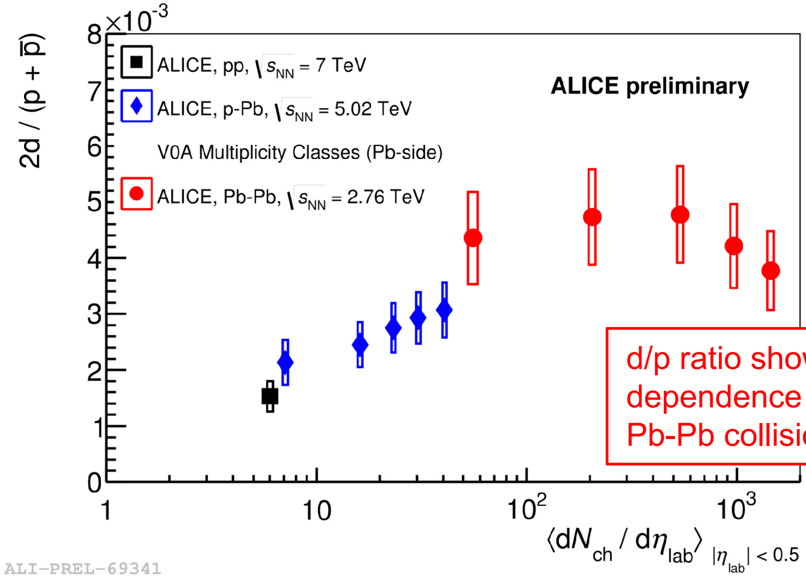
In second order, B_2 scales like HBT radii (*):

- decrease with centrality in Pb-Pb is explained as an increase in the source volume
- increasing with p_T in central Pb-Pb reflects the k_T-dependence of the homogeneity volume in HBT



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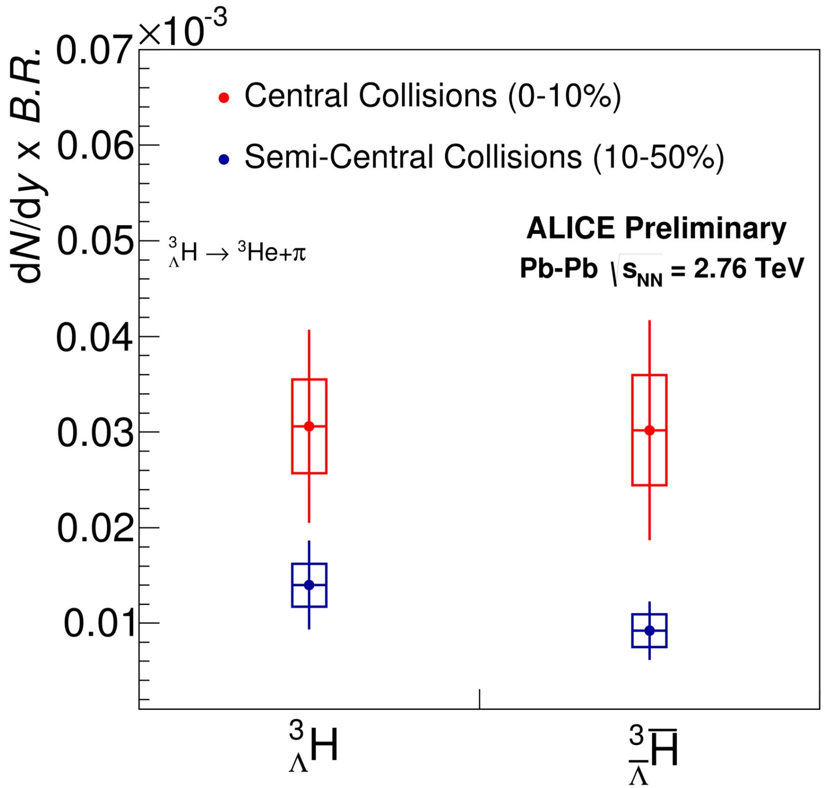
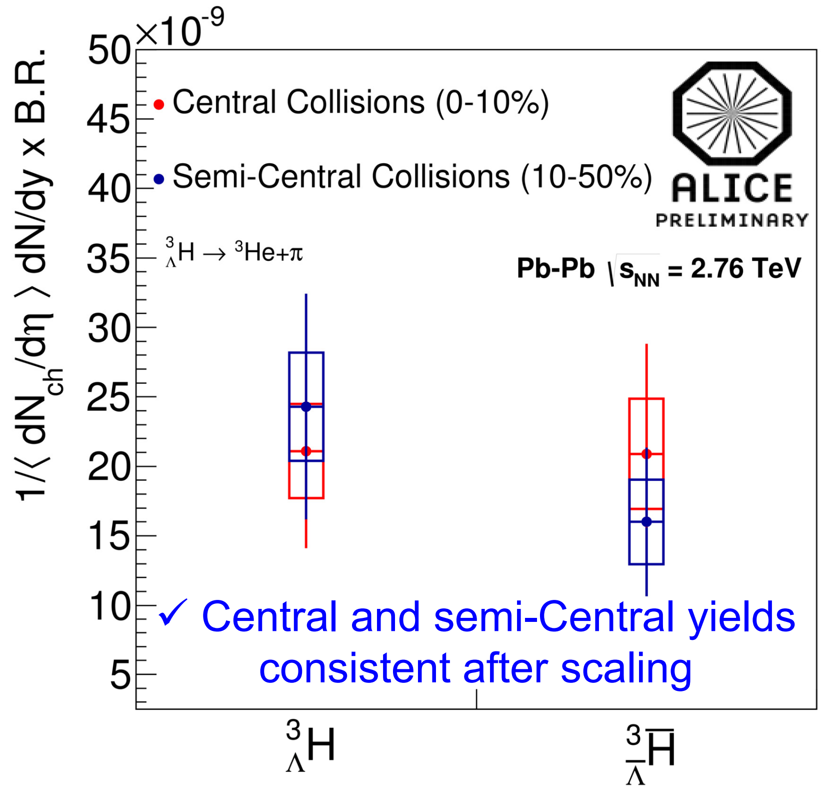
(ANTI-)HYPERTRITON YIELDS



ALI-PREL-54275



ALI-PREL-54279

dN/dy x B.R. ($^{3}_{\Lambda}H \rightarrow {}^{3}He\ \pi$) yield extracted in two centrality bins for Central (0-10%) and Semi-central (10-50%) events for $^{3}_{\bar{\Lambda}}\bar{H}$ and $^{3}_{\Lambda}H$ separately

Assuming particle production scales with centrality, yields were renormalized by $\langle dN_{ch}/d\eta \rangle$ (*)

N_{ch}:number of charged particles

(*) K. Aamodt et al. (ALICE Collaboration) Phys. Rev. Lett. 106, 032301 (2011)

(ANTI-)HYPERTRITON YIELD RATIOS

ALICE

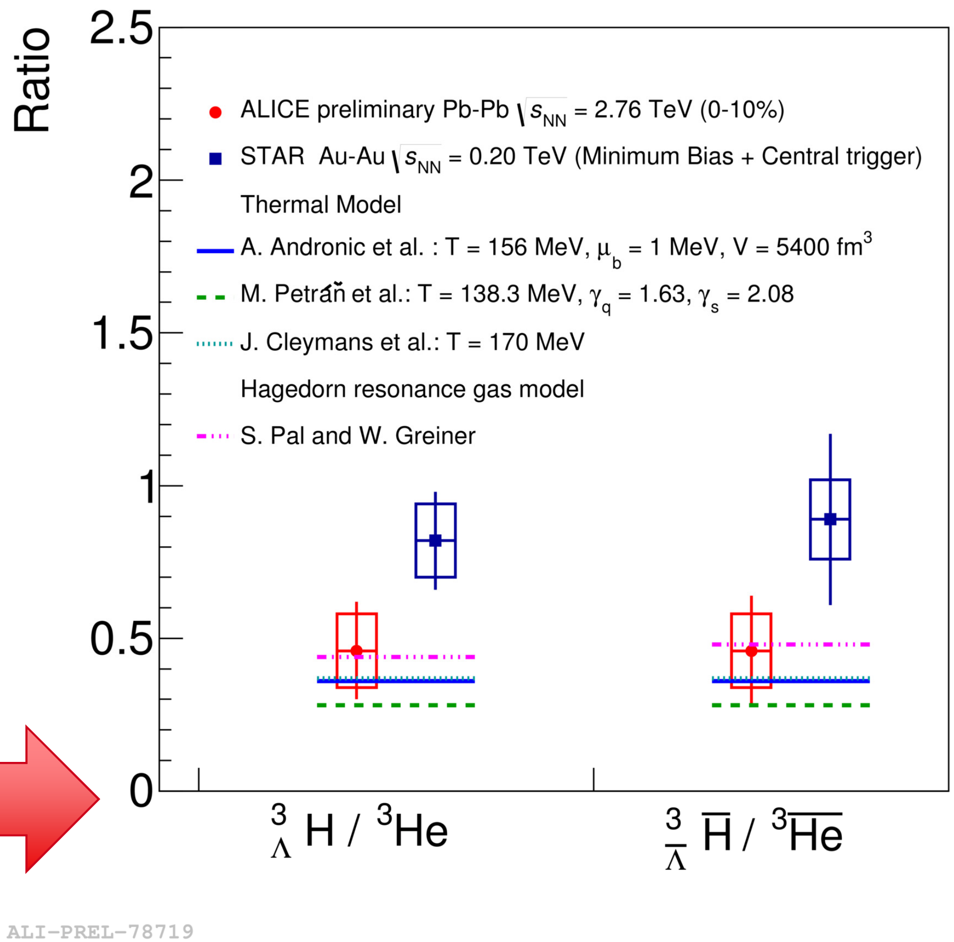
Anti-hypermatter / Hypermatter Ratio:

$$R = \frac{{}^{3}_{\bar{\Lambda}}\bar{H}}{{}^{3}_{\Lambda}H}$$

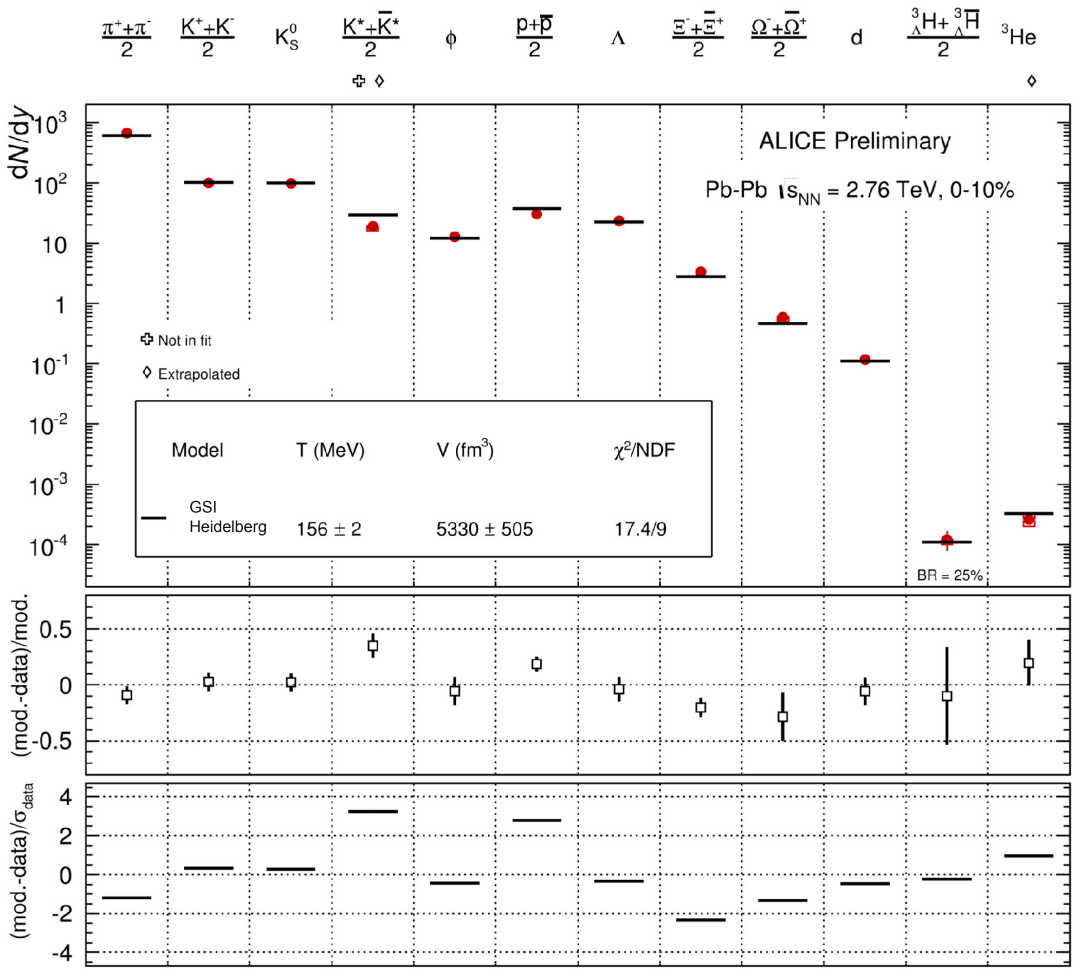
STATISTICAL-THERMAL MODEL:
R=0.95
(Cleymans et al, PRC84(2011) 054916)

At $\sqrt{s_{NN}}$=200GeV
STAR: R=0.49 ± 0.18 ± 0.07
STATISTICAL-THERMAL MODEL :
R=0.48

Hypermatter / Matter Ratio
and
Anti-hypermatter/ Anti-matter Ratio



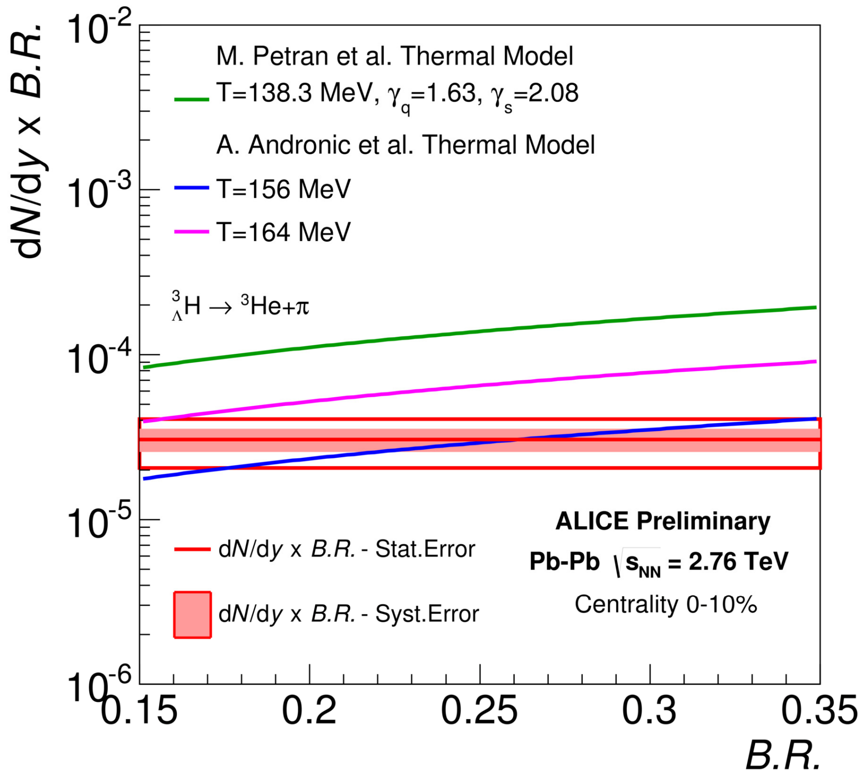
ABUNDANCES AND THE THERMAL MODEL



ALI-PREL-75448

- Particle yields of light flavor hadrons (including nuclei) are described with a common chemical freeze-out temperature:
  T_{chem} = 156 ± 2 MeV best value for LHC
- K^{*0} not used in global fit
- ${}^{3}_{\Lambda}H$ value normalized by BR(${}^{3}_{\Lambda}H \rightarrow {}^{3}He+\pi$) =0.25;
- deuteron, ^{3}He and ${}^{3}_{\Lambda}H$ yields: model predictions OK
- The p_T-integrated yields and ratios can be interpreted in terms of statistical (thermal) models

COMPARISON WITH THEORETICAL PREDICTIONS



ALI-PREL-54321

M. Petráň et al., Phys. Rev. C 88, 034907 (2013)

A. Andronic et al., Phys. Lett. B 697, 203 (2011)

Theoretical Predictions drawn as a function of BR($^{3}_{\Lambda}H \rightarrow {}^{3}He+\pi^{-}$) after being multiplied by BR:

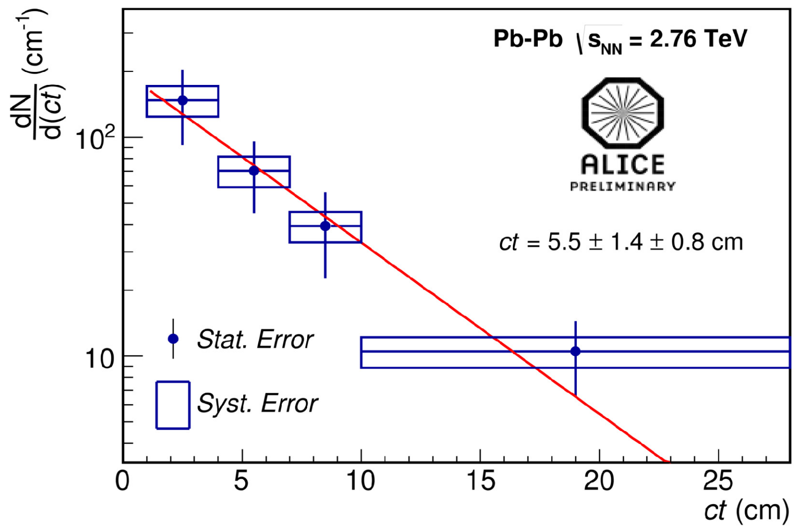
- Great sensitivity to theoretical models parameters
- Non–equilibrium SHM model (Petran-Rafelsky) provides better global fitting ($\chi^2 \sim 1$) to lower mass hadrons but **misses $^{3}_{\Lambda}$H** and light nuclei
- Experimental data closest to equilibrium thermal model with lower T_{chem} (156 MeV)

HYPERTRITON LIFETIME DETERMINATION

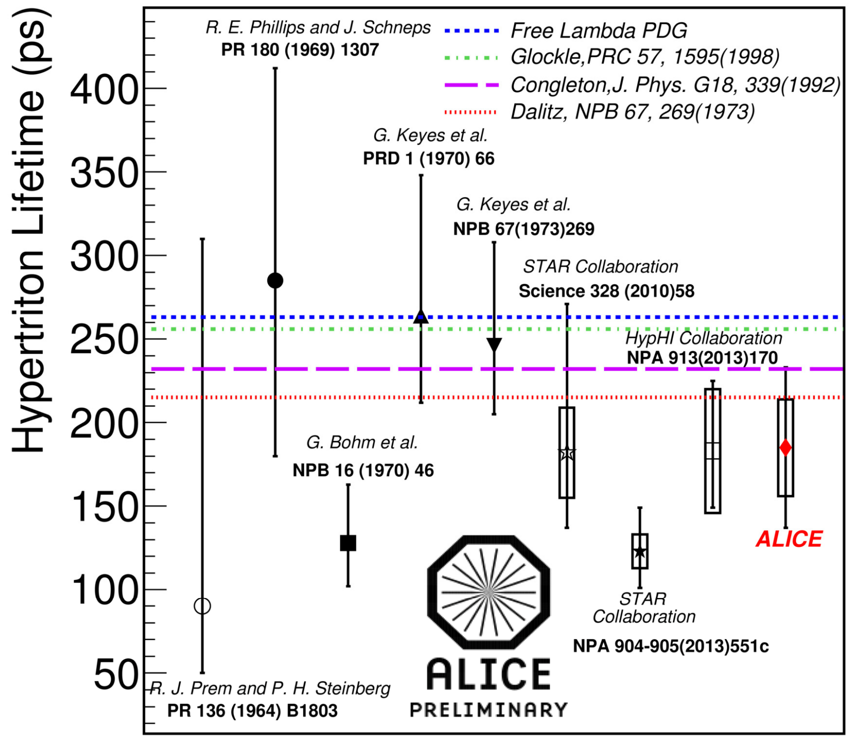
Direct decay time measurement is difficult (~ps), but the excellent determination of primary and decay vertex allows measurement of lifetime via:

$$N(t) = N(0)\, e^{-\frac{t}{\tau}}$$

where $t = L/(\beta\gamma c)$ and $\beta\gamma c = p/m$ with m the hypertriton mass, p the total momentum and L the decay length

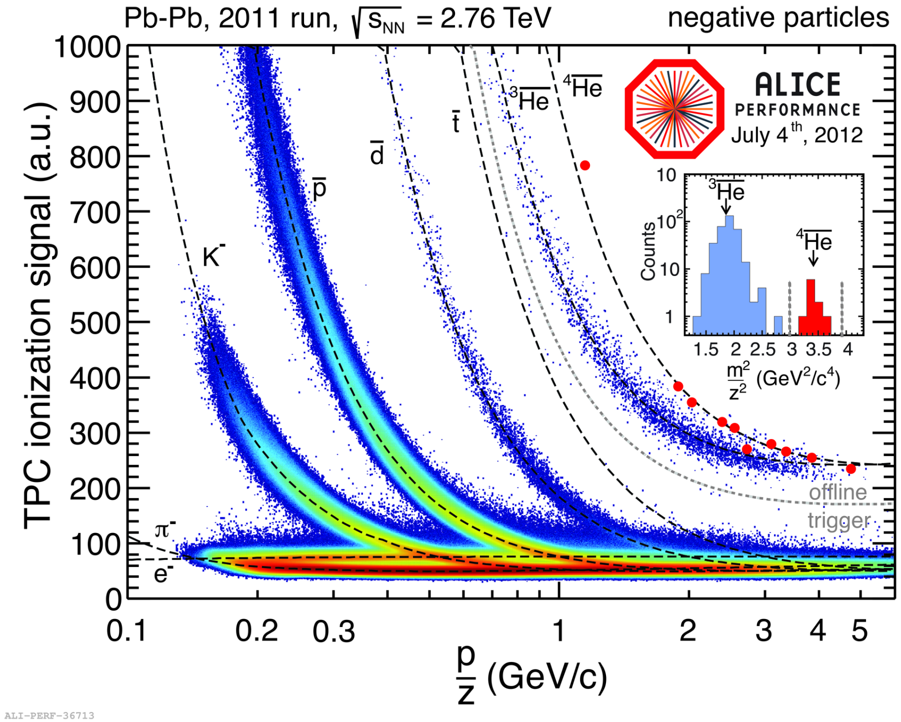


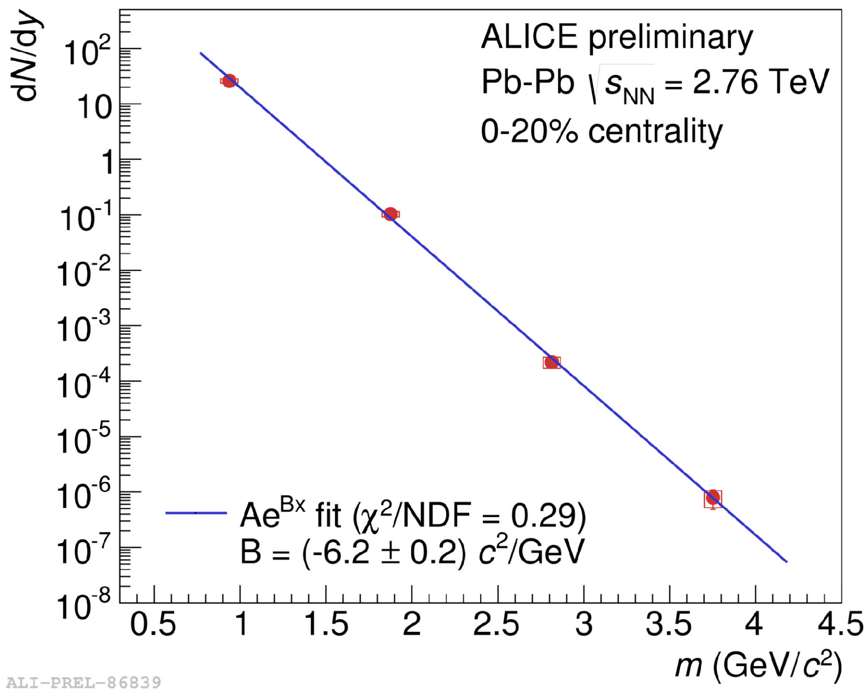
ALI-PREL-54387



ALI-PREL-54325

(ANTI-)NUCLEI IN Pb–Pb





About 10 anti-alpha candidates identified

Thermal model prediction: $\frac{dN}{dy} \propto \left(-\frac{M}{T_{chem}}\right)$

Nuclei follow nicely the exponential fall predicted by the model

Each added baryon gives a factor ~300 less production yield

ALICE

SEARCHES FOR WEAKLY DECAYING EXOTIC BOUND STATES

Λn and H-Dibaryon search

H-Dibaryon: hypothetical *udsuds* bound state

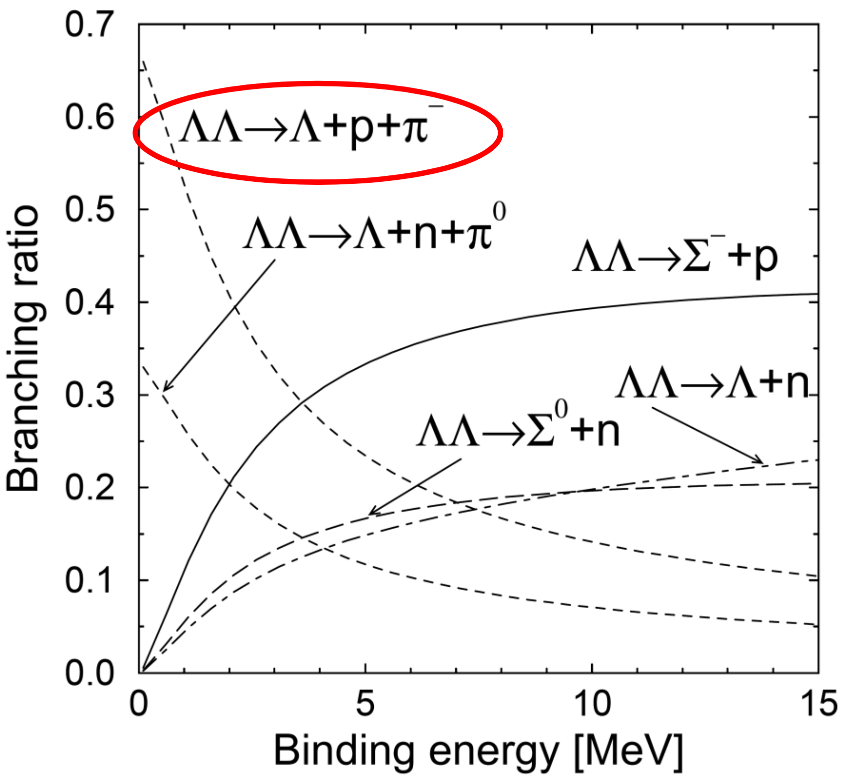
- First predicted by Jaffe [Jaffe, PRL 38, 195617 (1977)]
- Several predictions of bound and also resonant states.
- Recent Lattice models predict weakly bound states [Inoue et al., PRL 106, 162001 (2011), Beane et al., PRL 106, 162002 (2011)]

If H-Dibaryon is bound: $m_H < \Lambda\Lambda$ threshold

- measurable channel H → Λpπ but BR depends on binding energy, two cases considered:
  - weakly bound
  - strongly bound

Bound state of **Λn** ?

- HypHI experiment at GSI sees evidence of a new state: **Λn → d+ π⁻** [C. Rappold et al. (HypHI collaboration), Phys. Rev. C88, 041001(R) (2013)]



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

Λn AND H-DIBARYON SEARCH

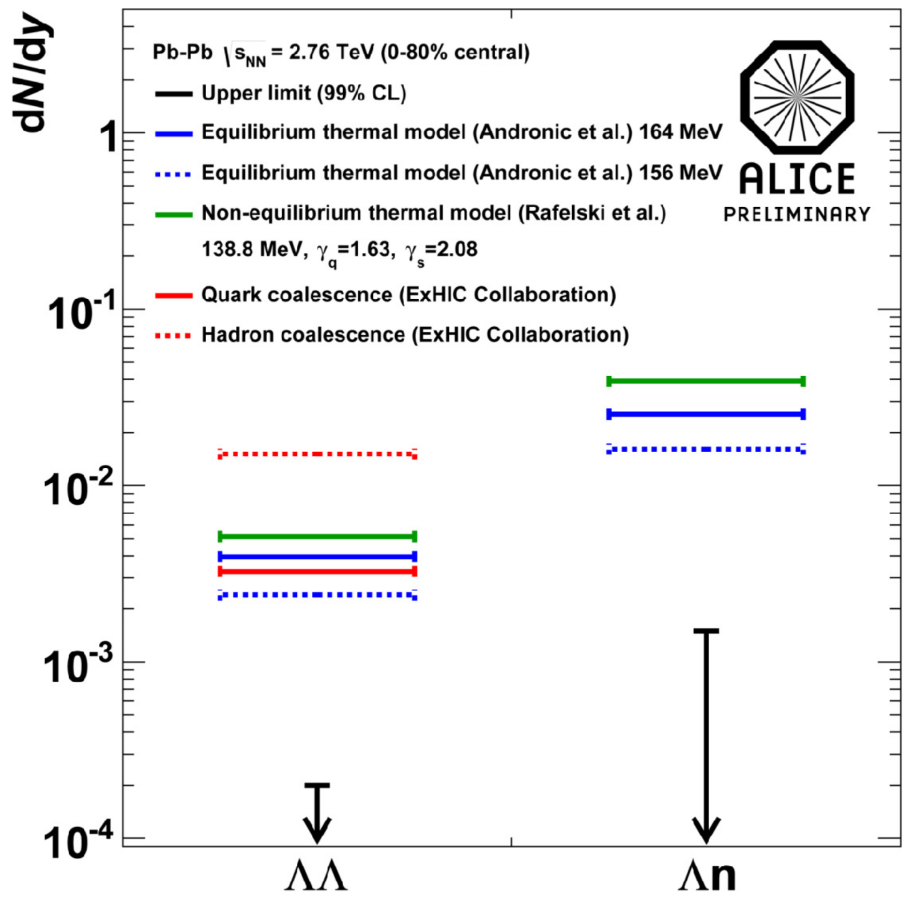
No signal visible

- Obtained upper limits:
  - Strongly bound H (m=2.21 GeV/c^2):

    dN/dy ≤ 8.4x10^{-4} (99% CL)
  - Lightly bound H:

    dN/dy ≤ 2x10^{-4} (99% CL)
  - Λn bound state:

    dN/dy ≤ 1.5x10^{-3} (99% CL)
- The upper limits for exotica are lower than the thermal model expectation by a factor 10
- Thermal model with the same temperature describe precisely the production yield of deuterons, ^{3}He and $^{3}_{\Lambda}$H
- The existence of such states with the assumed B.R., mass and lifetime is questionable



CONCLUSIONS

- ✓ Excellent ALICE performance allows detection of light (anti-)nuclei, (anti-)hypernuclei and other exotic bound states
- ✓ Blast-Wave fits can be used to extrapolate the yields to the unmeasured p_T region of light nuclei in Pb-Pb. A hardening of the spectrum with increasing centrality is observed in Pb-Pb collisions
- ✓ The d/p ratio has not a significant centrality dependence in Pb-Pb collisions
- ✓ Coalescence parameter B_2 is independent from p_T in peripheral Pb-Pb collisions, while it increases with p_T in central Pb-Pb collisions. A decrease with centrality is also observed in Pb-Pb collisions
- ✓ The measured hypertriton lifetime is consistent with previous measurement
- ✓ Measured deuteron, ^{3}He and hypertriton yields are in agreement with the current best thermal fit from equilibrium thermal model (T_{chem} = 156 MeV)
- ✓ H-Dibaryon and Λn search in Pb-Pb with ALICE: upper limits are at least an order of magnitude lower than predictions of several models

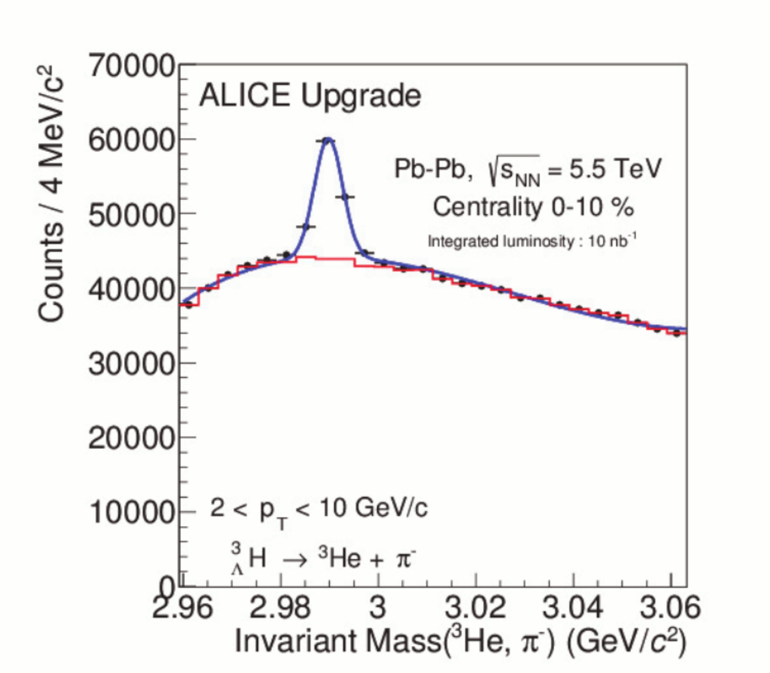
OUTLOOK

After the upgrade, ALICE will be able to collect data with better performance at higher luminosity:

- Expected Integrated Luminosity: ~10 nb^{-1} (~ 8×10^9 collisions in the 0-10% centrality class)
- Expected S/B ~ 0.1 and significance ~ 60 for p_T > 2 GeV/*c*
- Expected yields will allow detailed study of hypertriton characteristics
- Performed analysis relevant for future study of strange and multi-strange states

State	dN/dy [81]	B.R.	$\langle Acc \times \varepsilon \rangle$	Yield
$^3_\Lambda H$	1×10^{-4}	25 % [82]	11 %	44000
$^4_\Lambda H$	2×10^{-7}	50 % [82]	7 %	110
$^4_\Lambda He$	2×10^{-7}	32 % [83]	8 %	130

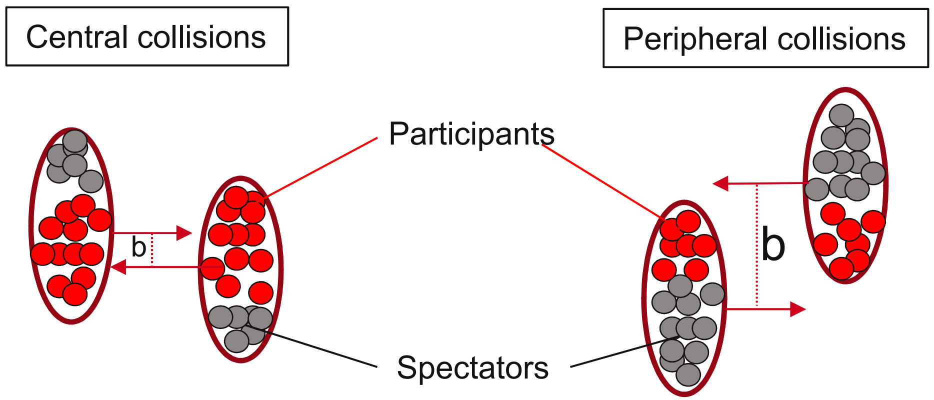
Expected yields for three hypernuclear states (plus their antiparticles) for central Pb-Pb collisions (0-10 %) at $\sqrt{s_{NN}}$ = 5.5TeV from (*)

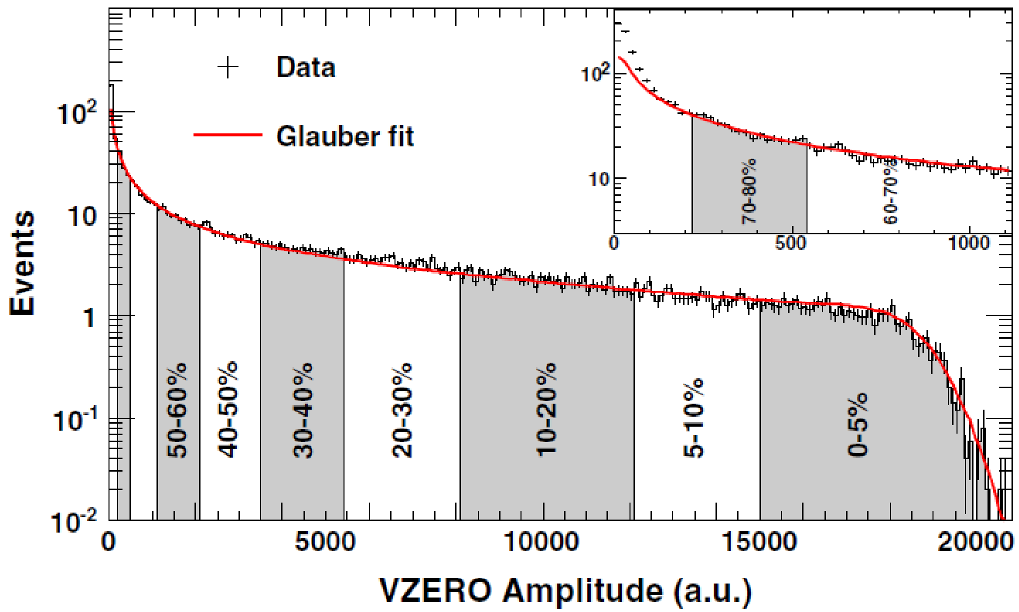


Expected invariant mass distribution for $^3_\Lambda H$ (plus antiparticle) from (*)

(*) Technical Design Report for the Upgrade of the ALICE Inner Tracking System
B. Abelev *et al.* (The ALICE Collaboration)
2014 *J. Phys. G: Nucl. Part. Phys.* 41 087002

COLLISION GEOMETRY





K. Aamodt et al. (ALICE Collaboration)
Phys. Rev. Lett. 106, 032301 (2011)

- Nuclei are extended objects
- Geometry not directly measurable
- Centrality (percentage of the total cross section of the nuclear collision) connected to observables via Glauber model

- Data classified into centrality percentiles for which the average impact parameter, number of participants, and number of binary collisions can be determined