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

ALICE

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 $\propto e^{(-M/Tchem)}$)
- 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:

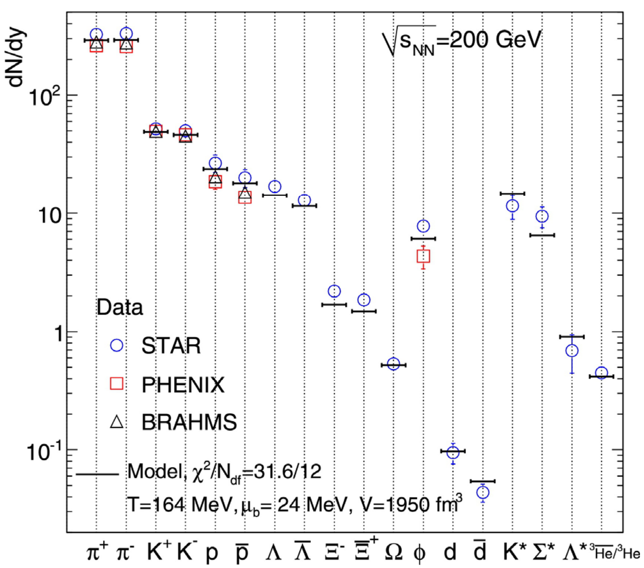
- matter–antimatter asymmetry [J.~Adam et al. (ALICE Collaboration), Nature Phys. (2015)]
- anti-d are rare in cosmic rays, a clear excess in anti-d flux would be suggestive of dark matter: measurements like anti-d production in pA collisions correspond to the background of dark matter search

(ANTI-)(HYPER)NUCLEI PRODUCTION IN URHIC

ALICE

Statistical Thermal model

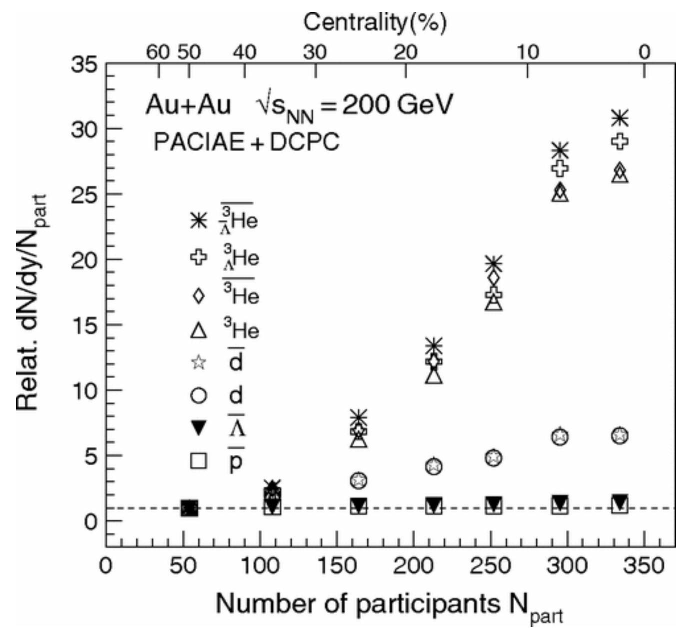
- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out (T_{chem}) (hyper)nuclei are very sensitive to T_{chem} because of their large mass (M)
- Exponential dependence of the yield $\propto e^{(-M/Tchem)}$



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

Coalescence

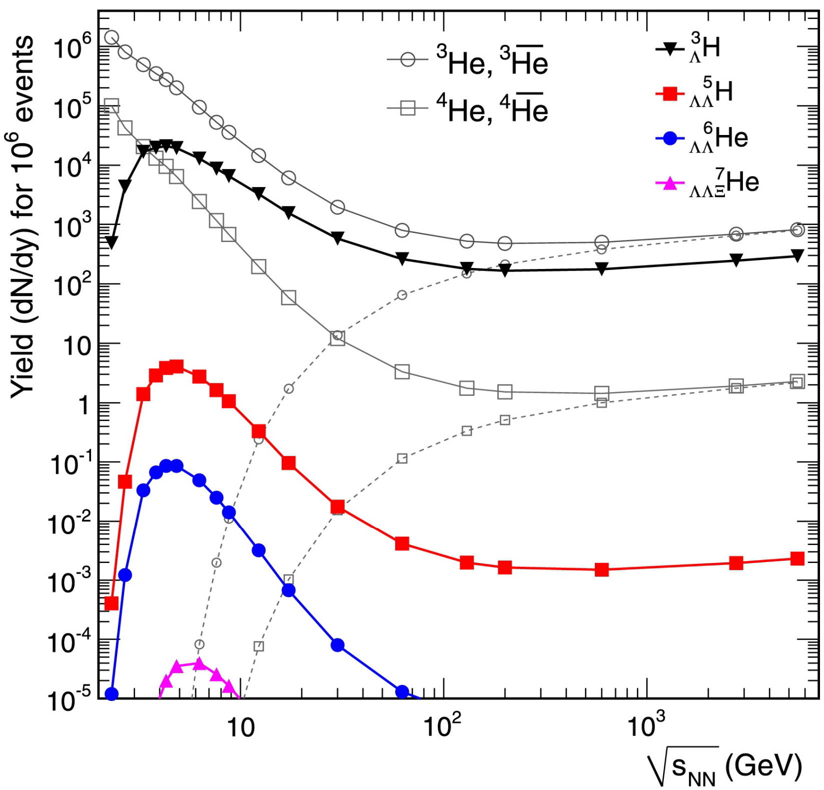
- If baryons at freeze-out are close enough in Phase Space an (anti-)(hyper)nucleus can be formed
- (Hyper)nuclei are formed by protons (Λ) and neutrons which have similar velocities after the freeze-out



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

(ANTI-)(HYPER)NUCLEI PRODUCTION AT LHC

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



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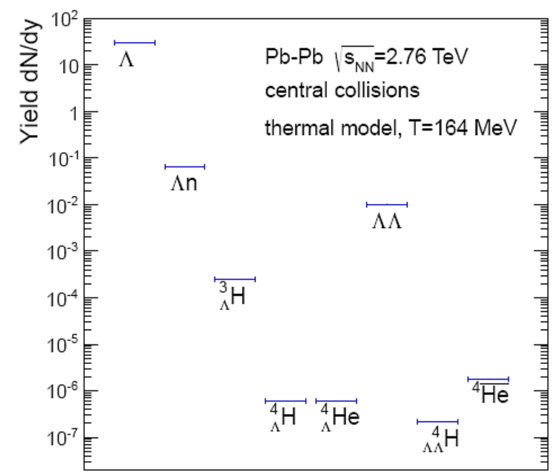
	Yield/event at mid-rapidity
π	~800
p	~40
Λ	~30
d	~0.17
^{3}He	~0.01
$^3_\Lambda$H	~0.003

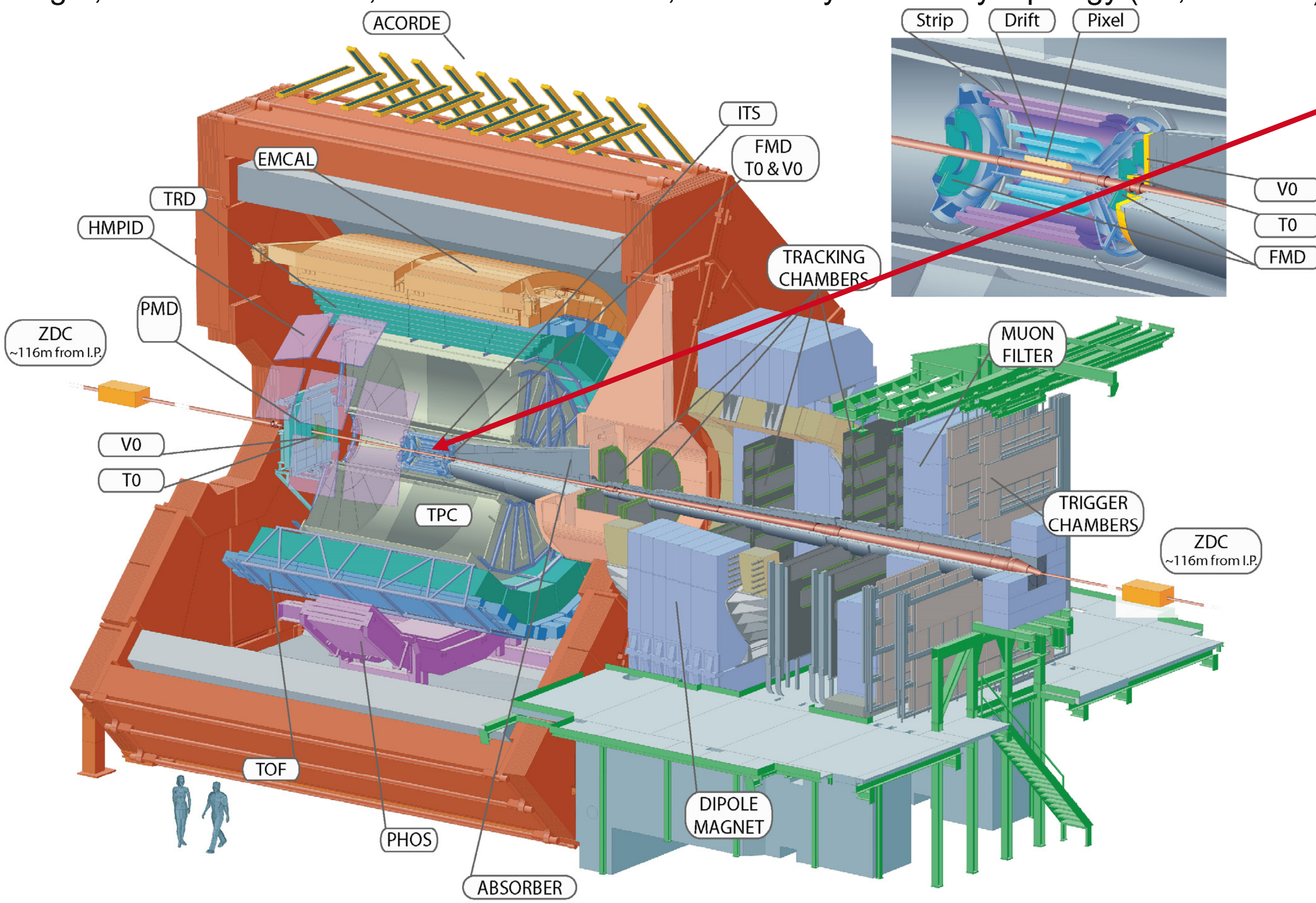
- ✓ Light nuclei
- ✓ Hypertriton
- ✓ Search for: Λn, ΛΛ dibaryons



A. Andronic, private communication

A LARGE ION COLLIDER EXPERIMENT

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



ITS: precise separation of primary particles and those from weak decays (hyper-nuclei) or knock-out from material

K. Aamodt et al. (ALICE Collaboration), JINST 3 (2008) S08002
B. B. Abelev et al. (ALICE Collaboration), Int. J. Mod. Phys. A 29 (2014) 1430044

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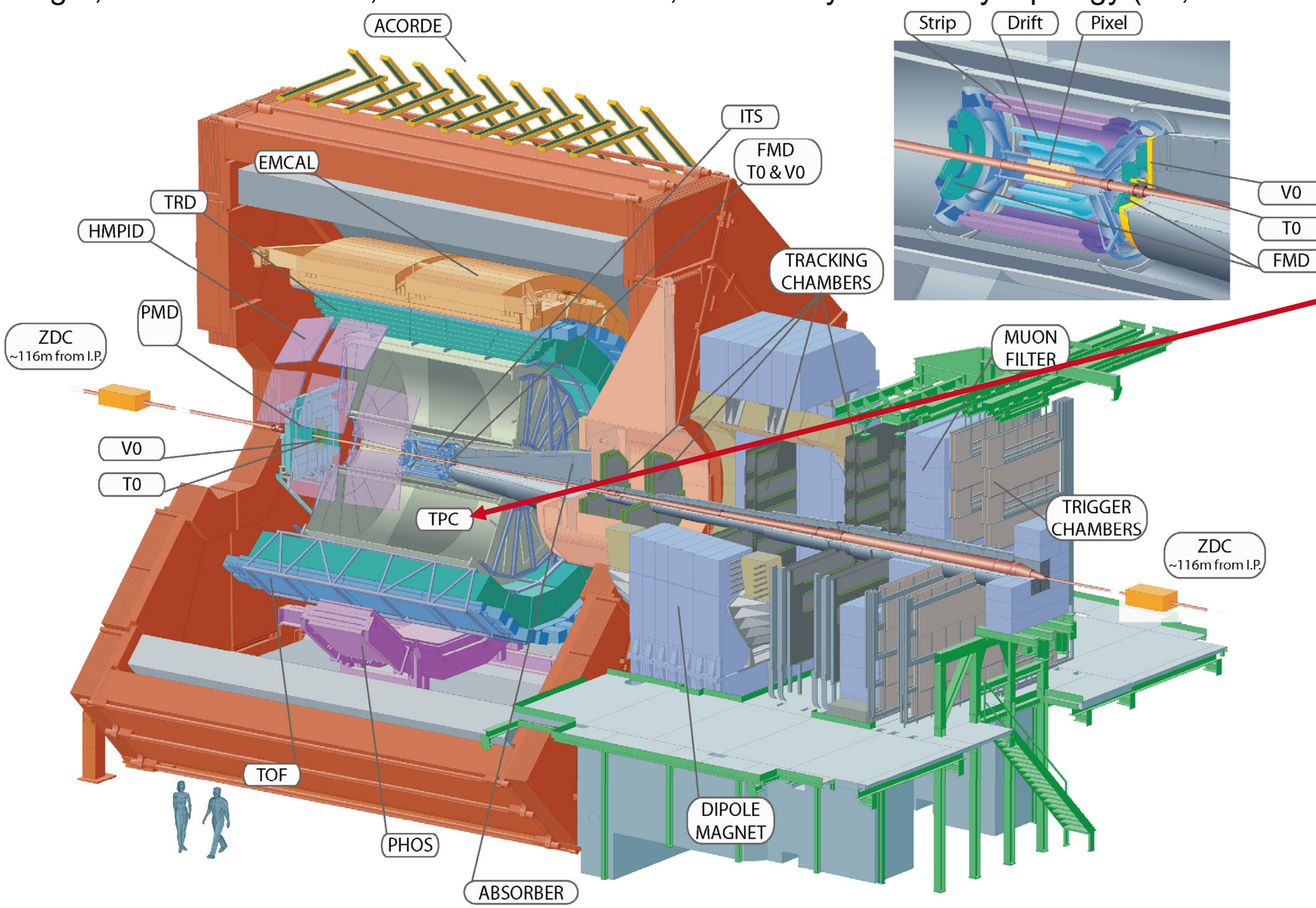

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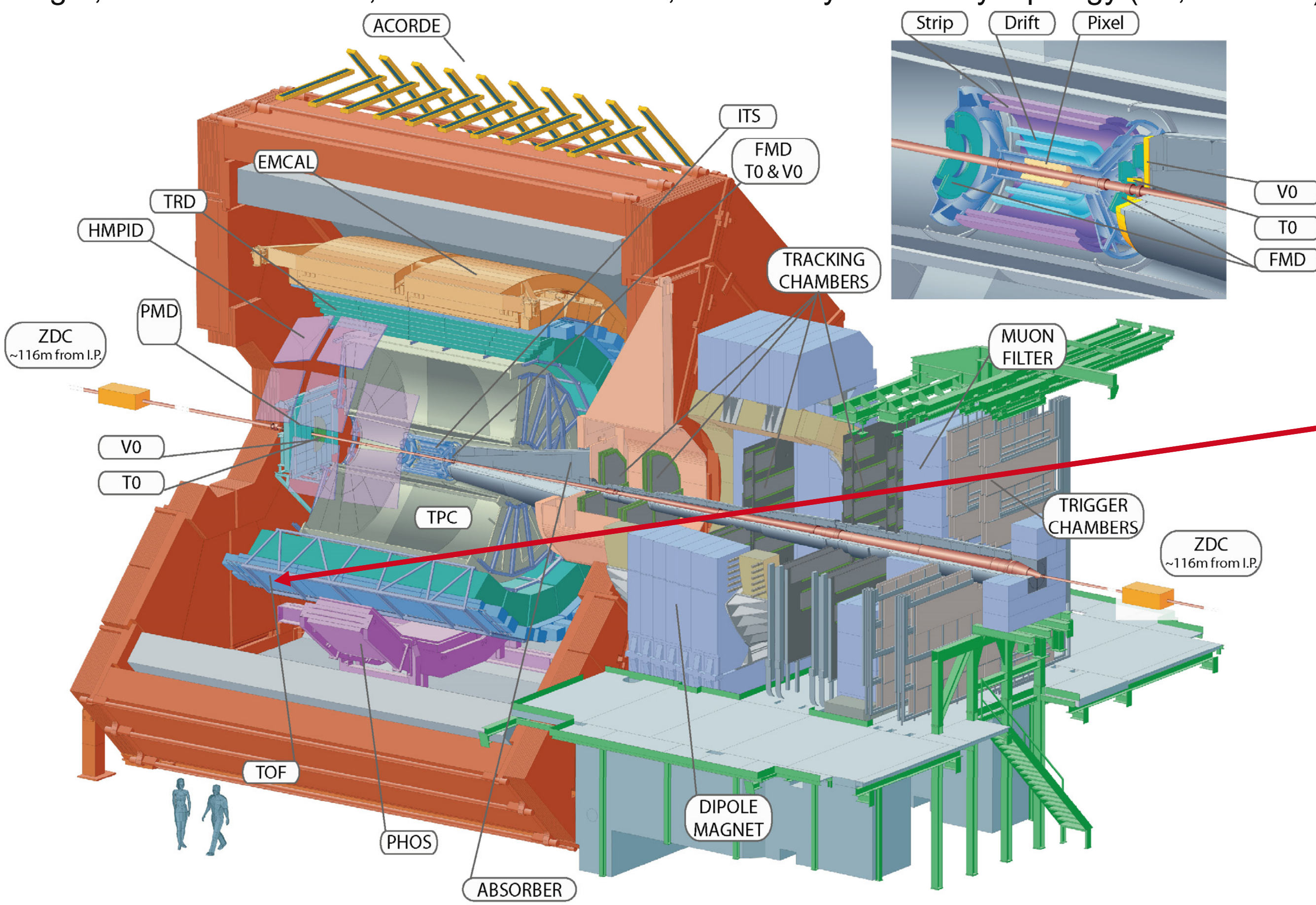

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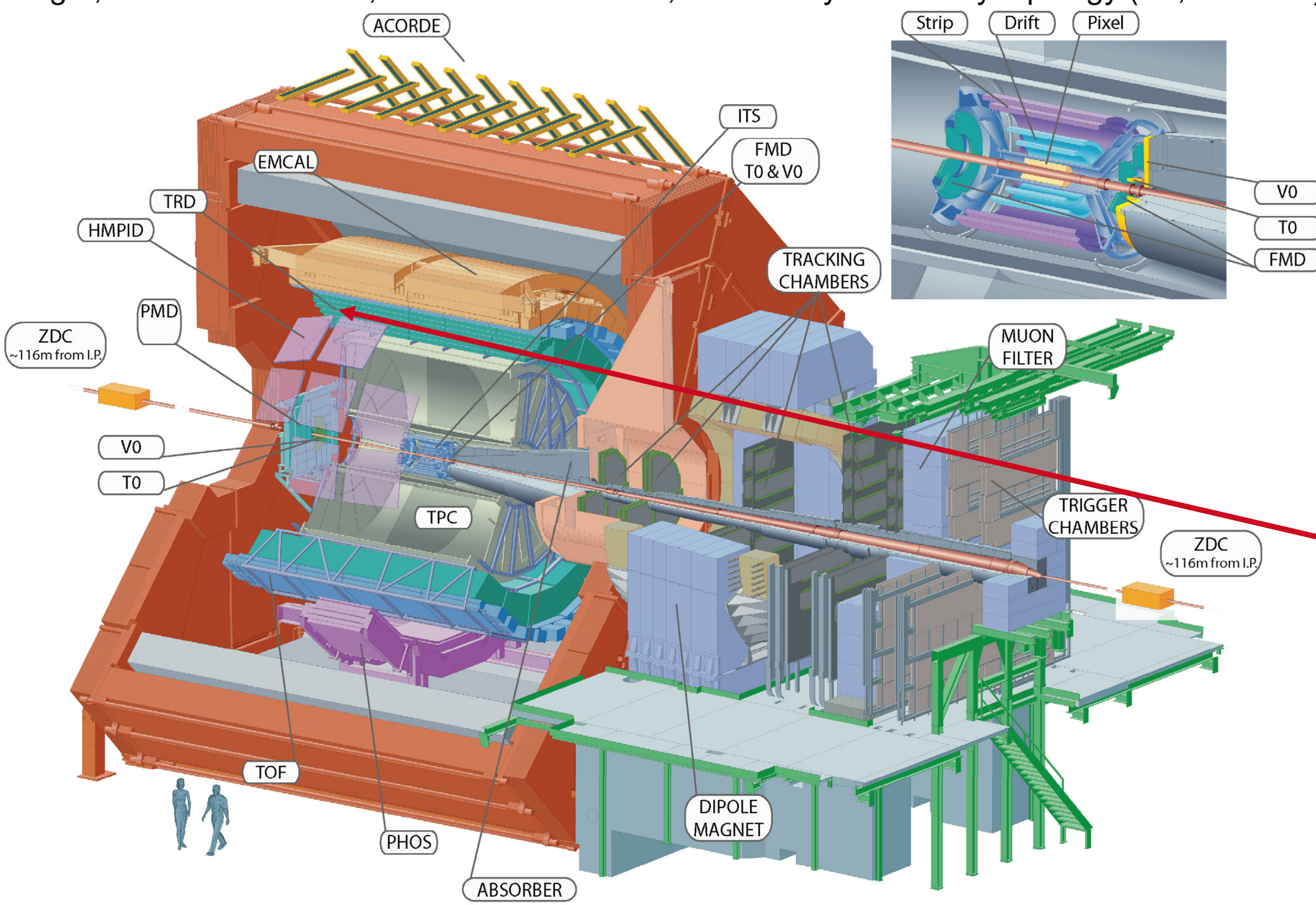

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ITS+TPC+TRD: excellent track reconstruction capabilities in a high track density environment

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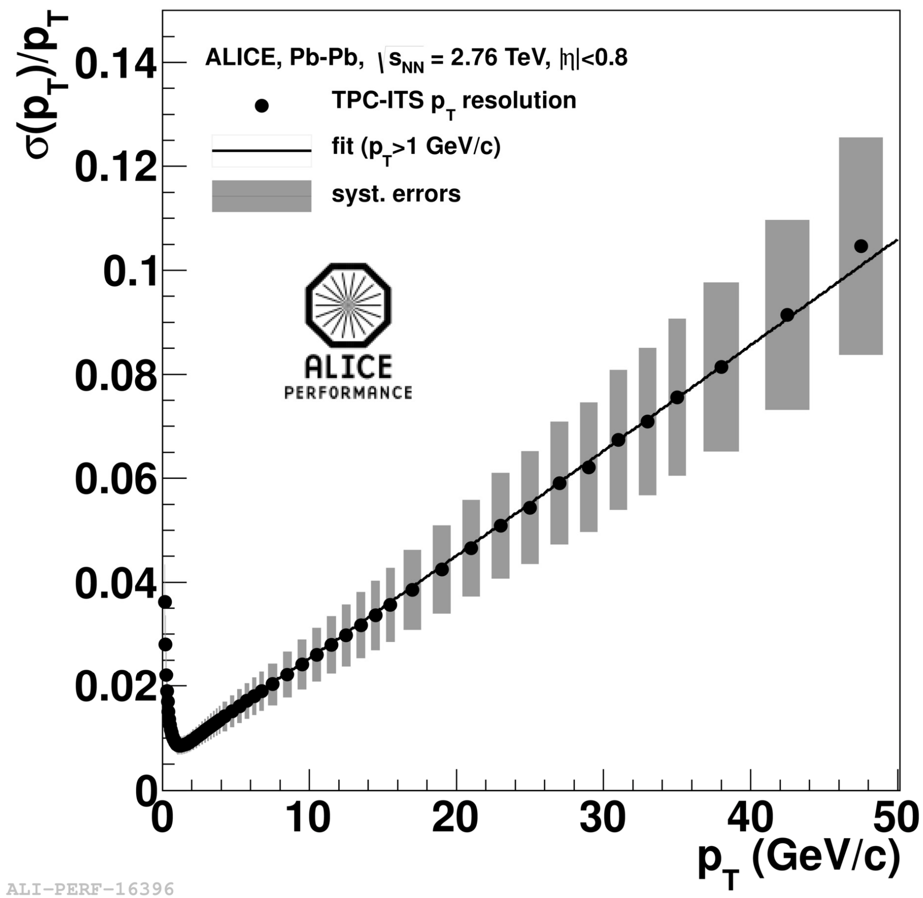

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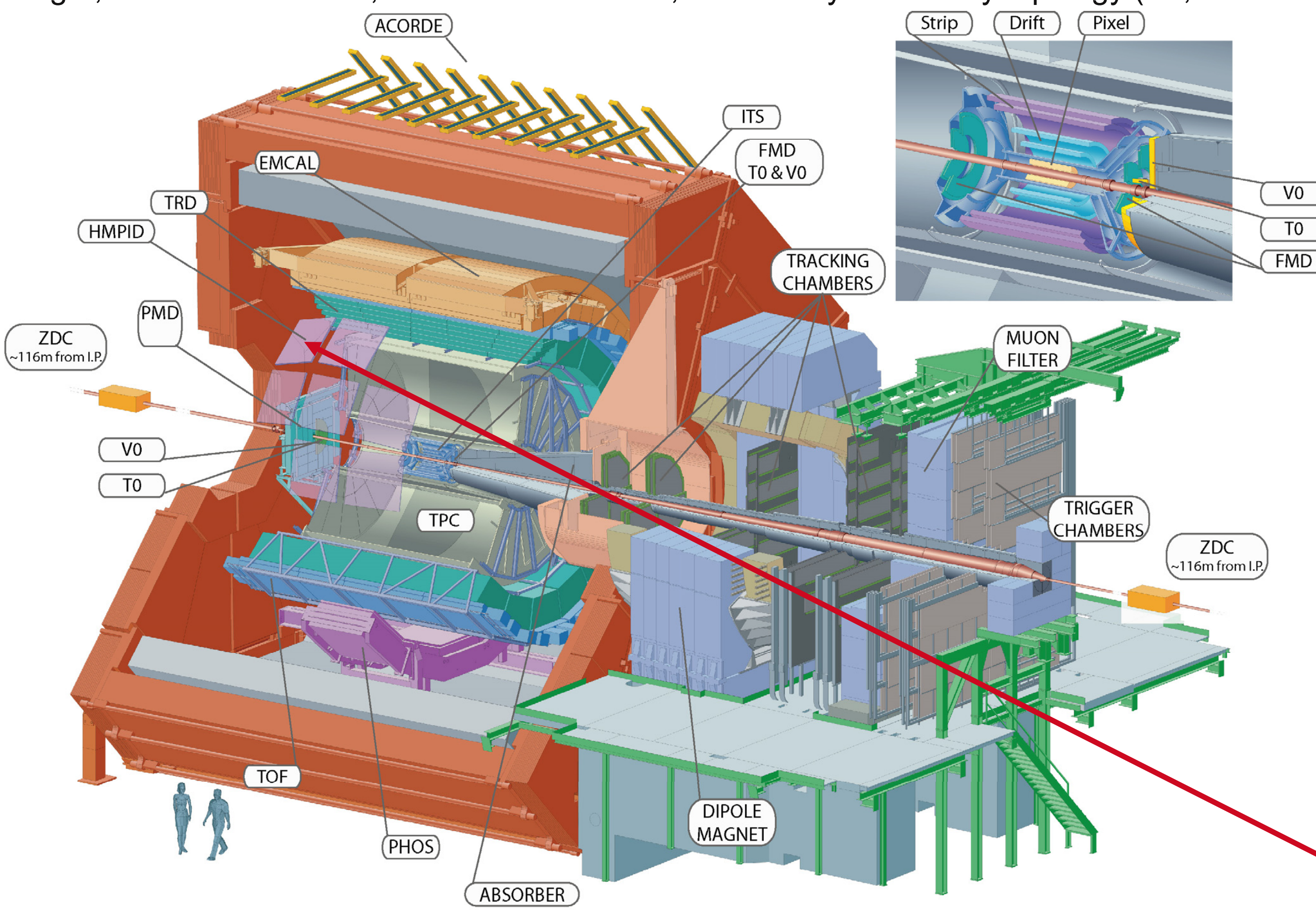

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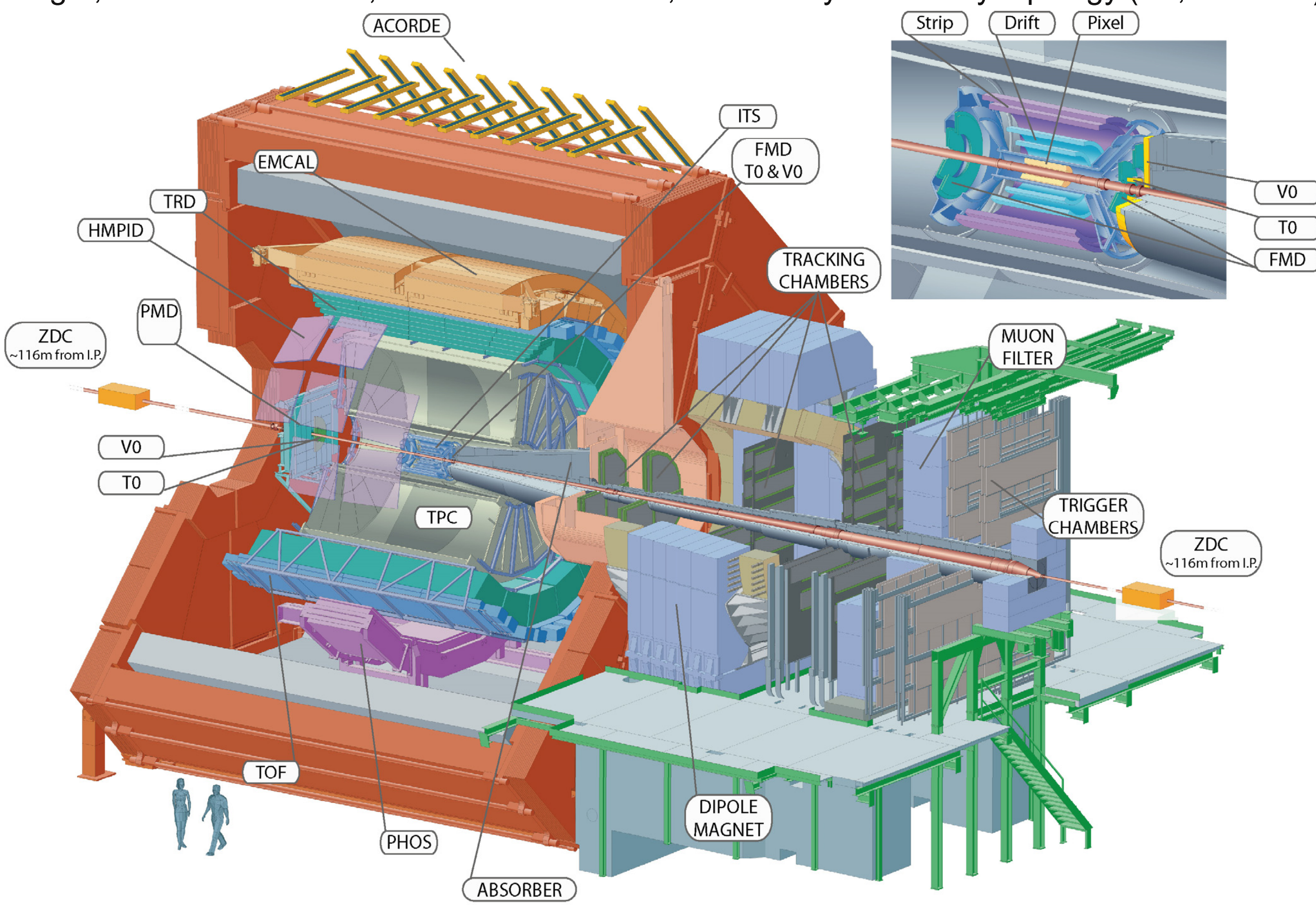

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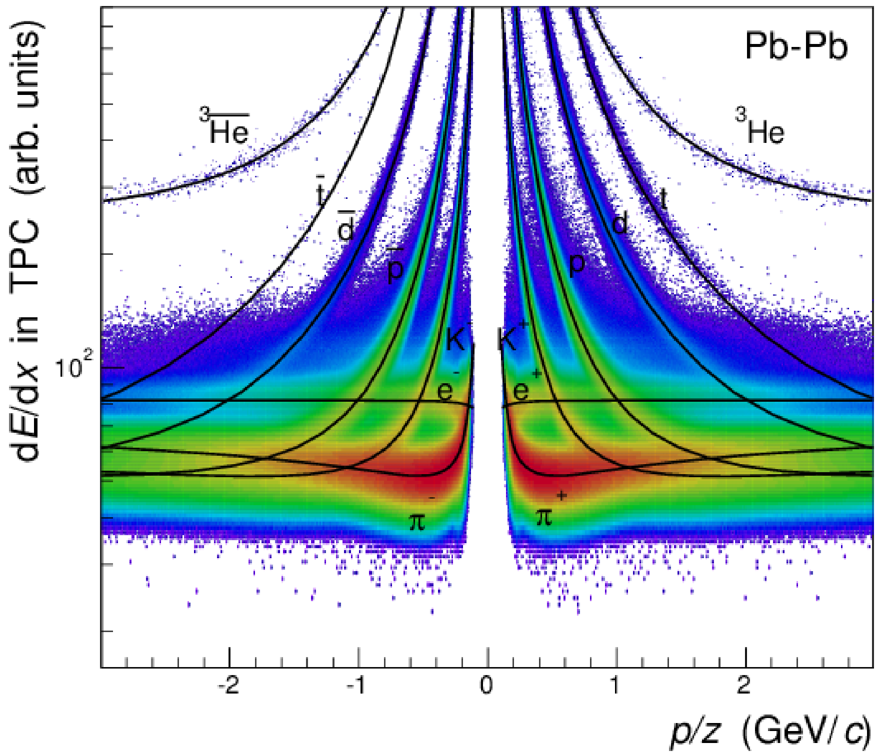
ALICE is ideally suited for the identification of light (anti-)(hyper)nuclei

NUCLEI IDENTIFICATION



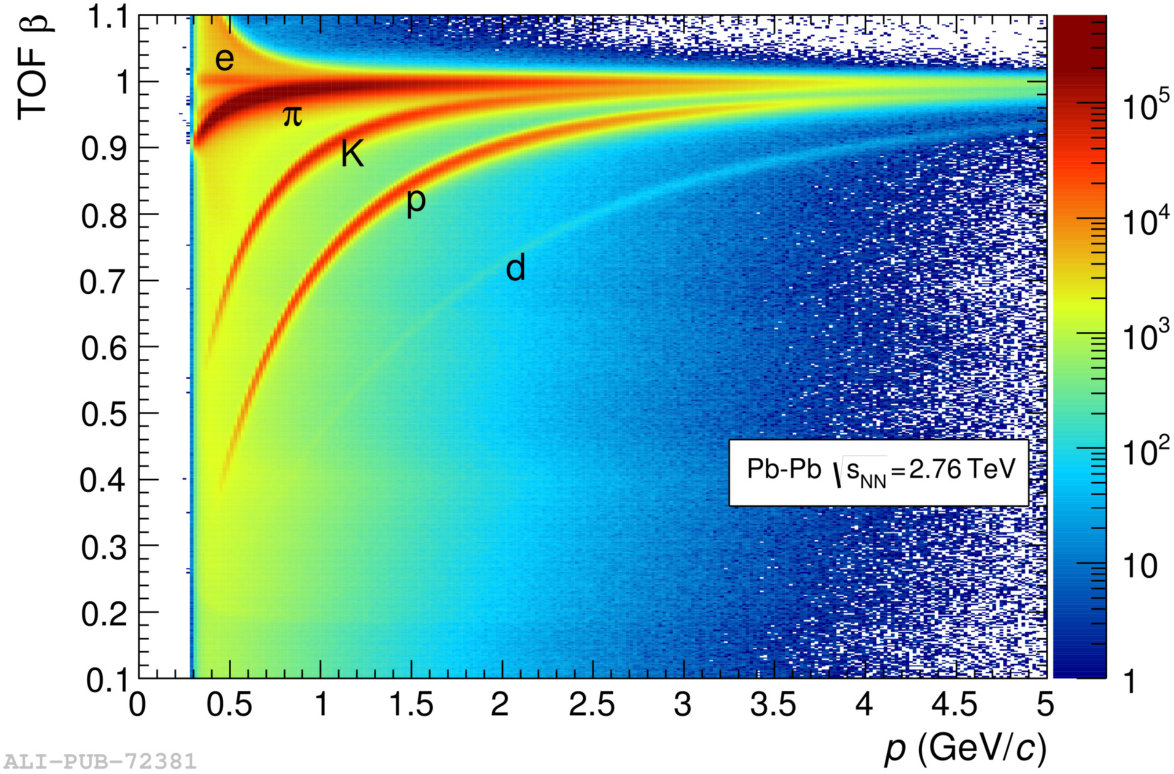
arXiv:1506.08951

Low momenta

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

- d*E*/d*x* 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



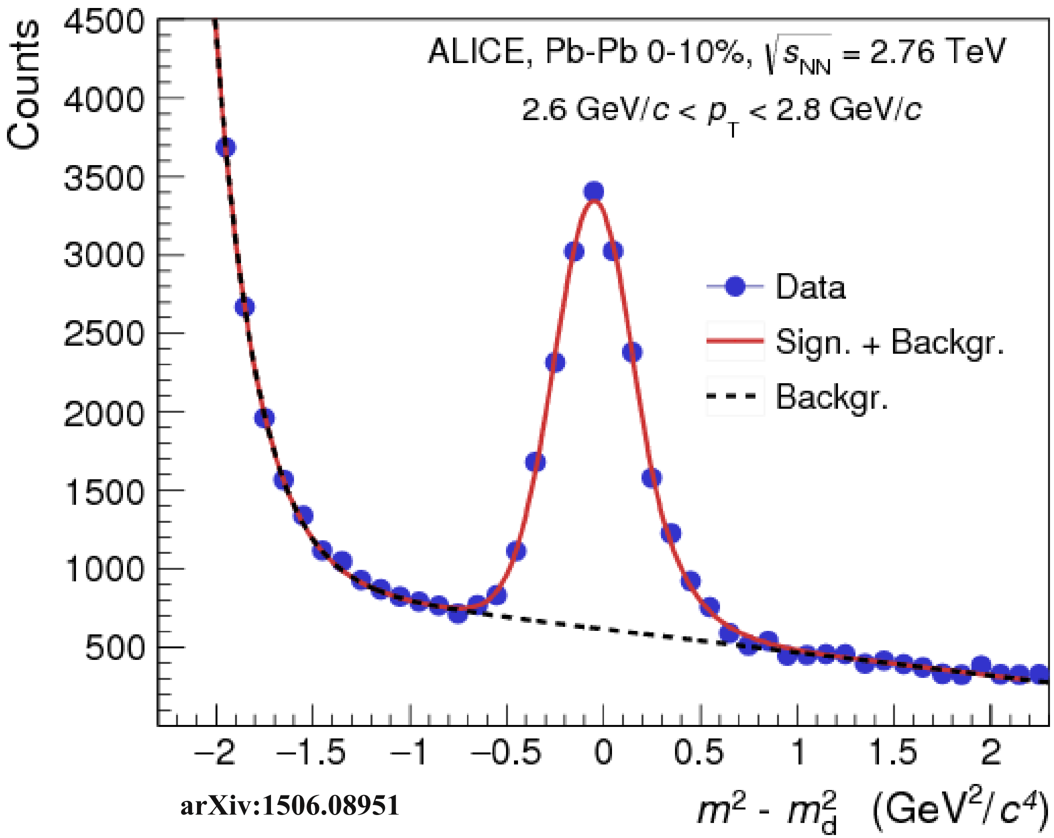
ALI-PUB-72381

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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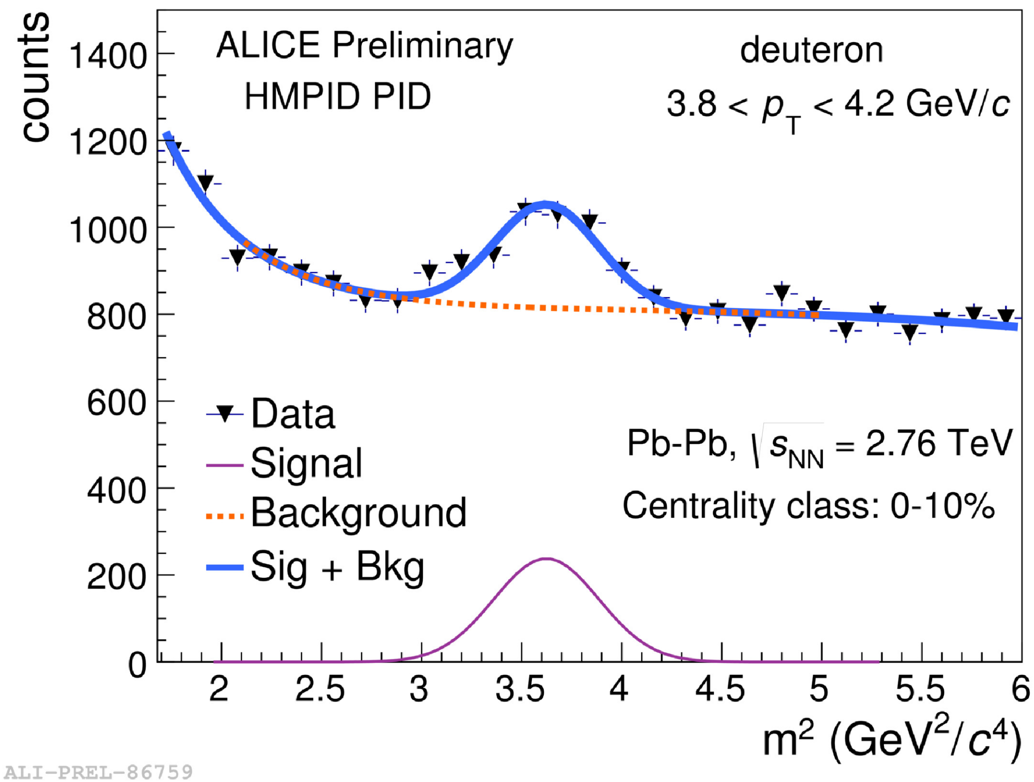

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At even higher momenta nuclei in central Pb-Pb collisions are identified on the basis of Cherenkov radiation with HMPID (deuteron spectrum up to 8 GeV/c)

(ANTI)HYPERTRITON IDENTIFICATION

Decay Channels

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

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

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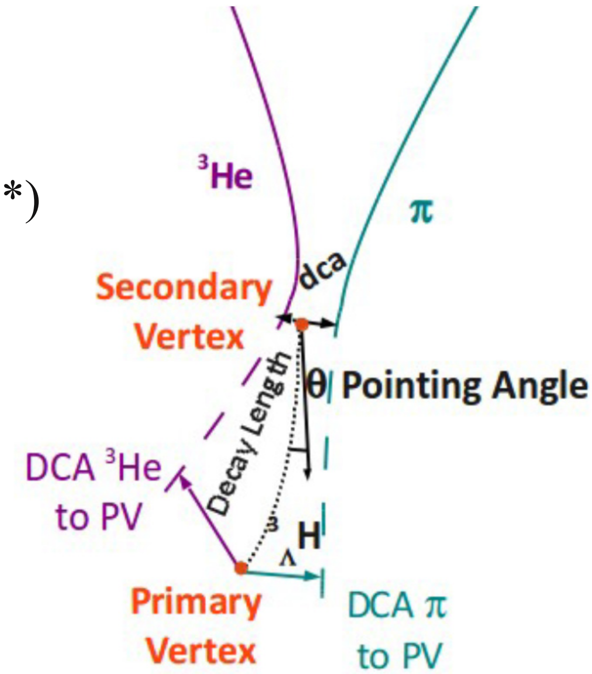
${}^{3}_{\Lambda}$H search via two-body decays into charged particles:

- 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



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

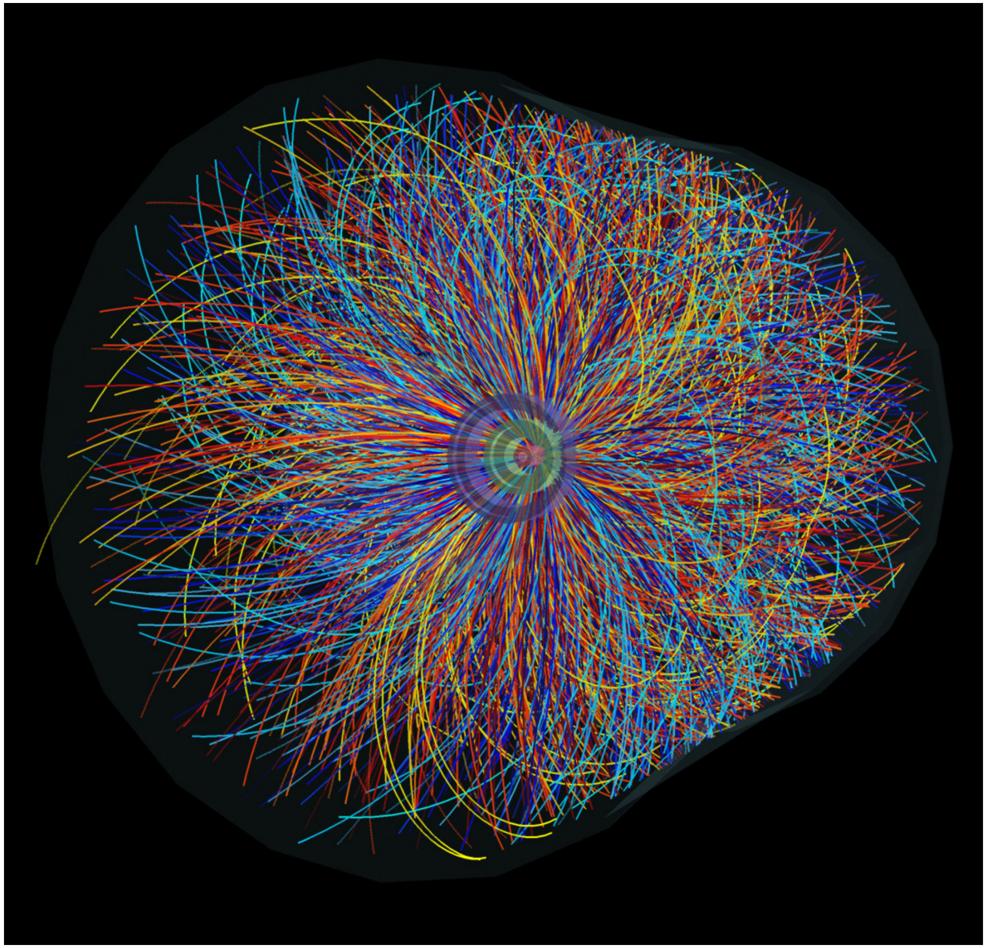
(*) Kamada et al., PRC57(1998)4

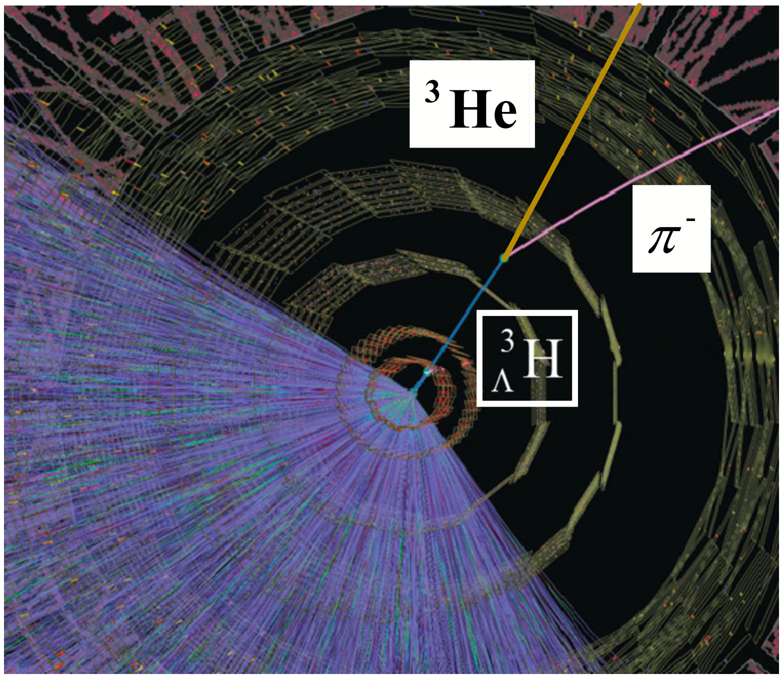
THE EXPERIMENTAL CHALLENGE

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)





ALICE

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

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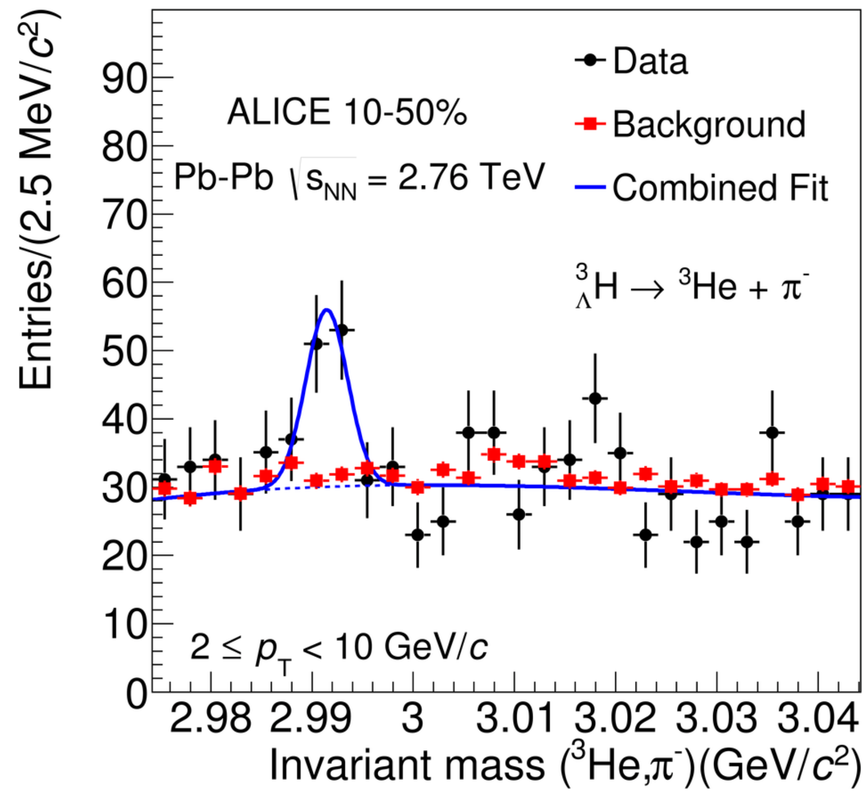

arXiv:1506.08453

μ = 2.991 ± 0.001 ± 0.003 GeV/c^2

σ= (3.01 ± 0.24)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)]

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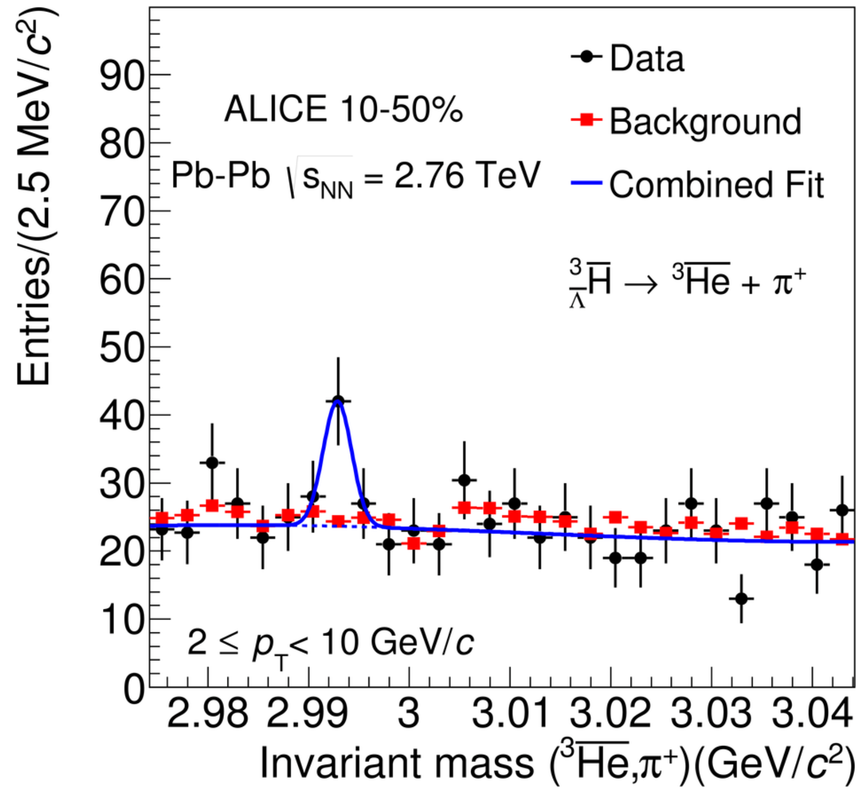

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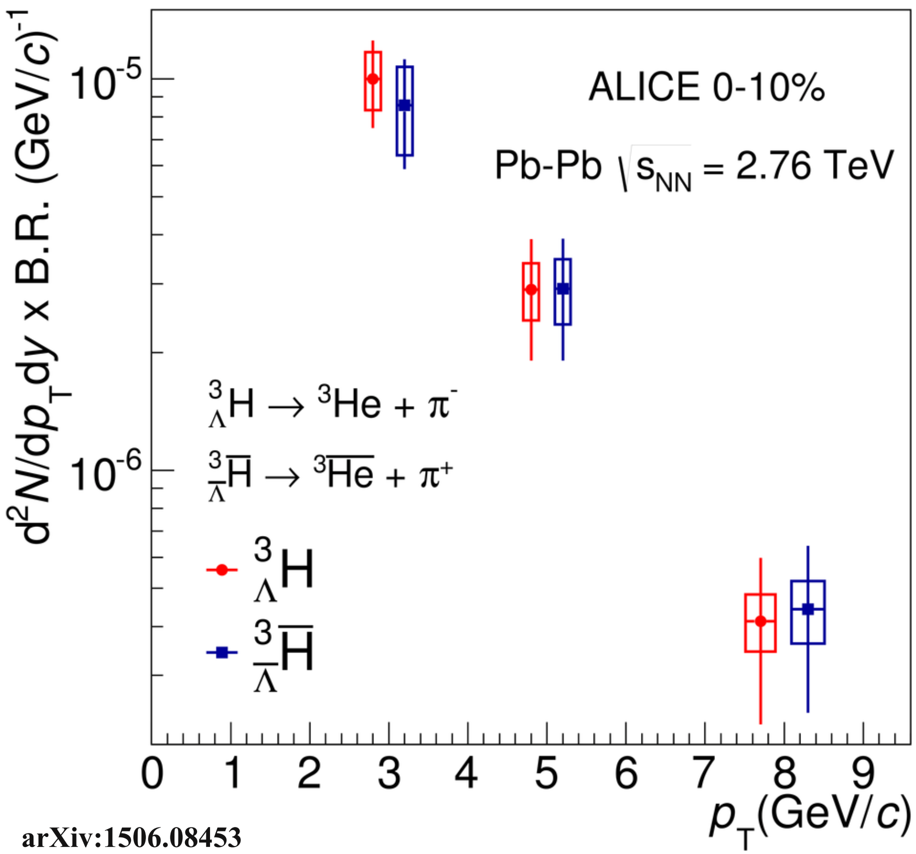
(ANTI-)HYPERTRITON YIELDS



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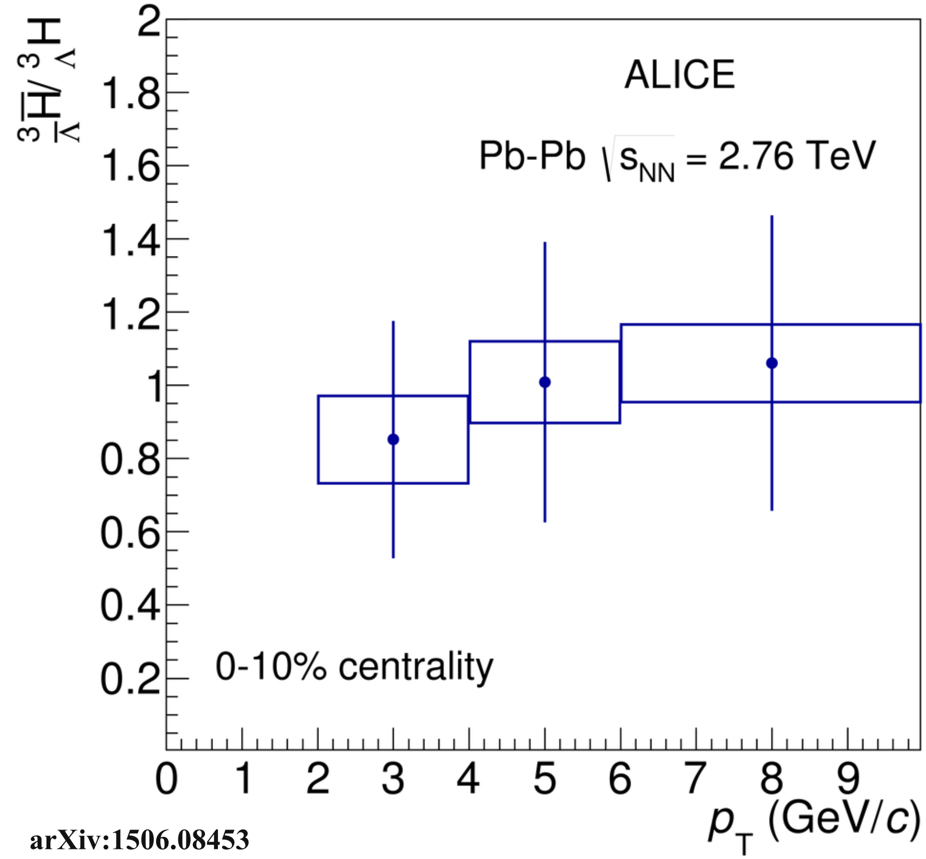
dN/dy x B.R. ($^{3}_{\Lambda}H \rightarrow {}^{3}He\ \pi$) yield extracted in three p_T bins for central (0-10%) events for $^{3}_{\bar{\Lambda}}\bar{H}$ and $^{3}_{\Lambda}H$ separately



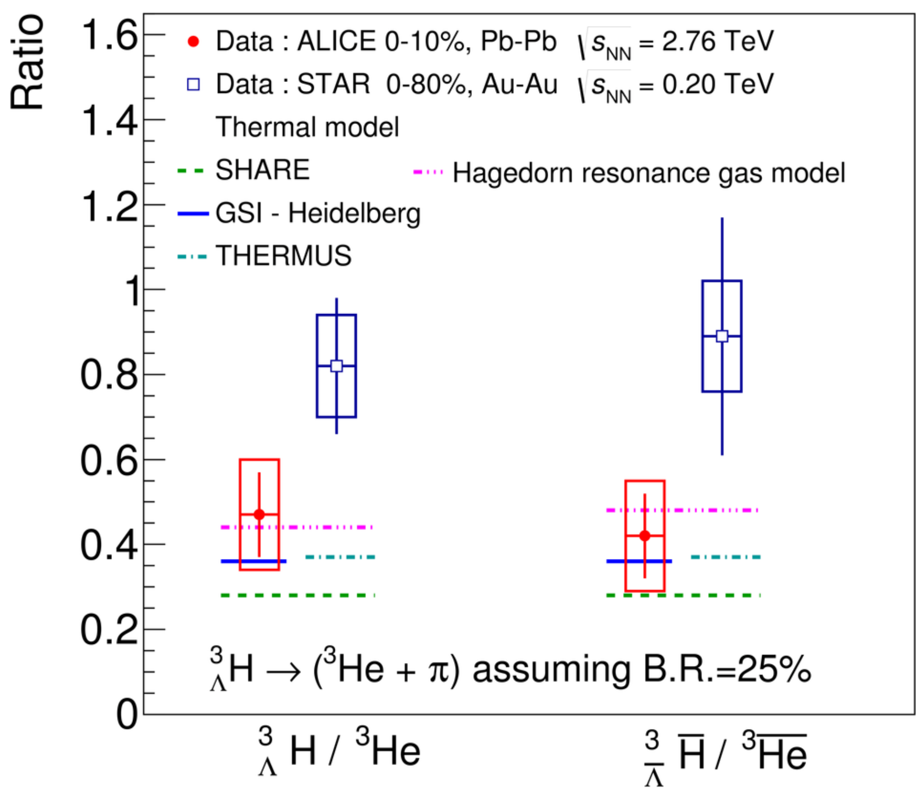
arXiv:1506.08453

Anti-hypermatter / Hypermatter Ratio: $R = \frac{^{3}_{\bar{\Lambda}}\bar{H}}{^{3}_{\Lambda}H}$

STATISTICAL-THERMAL MODEL: R=0.95

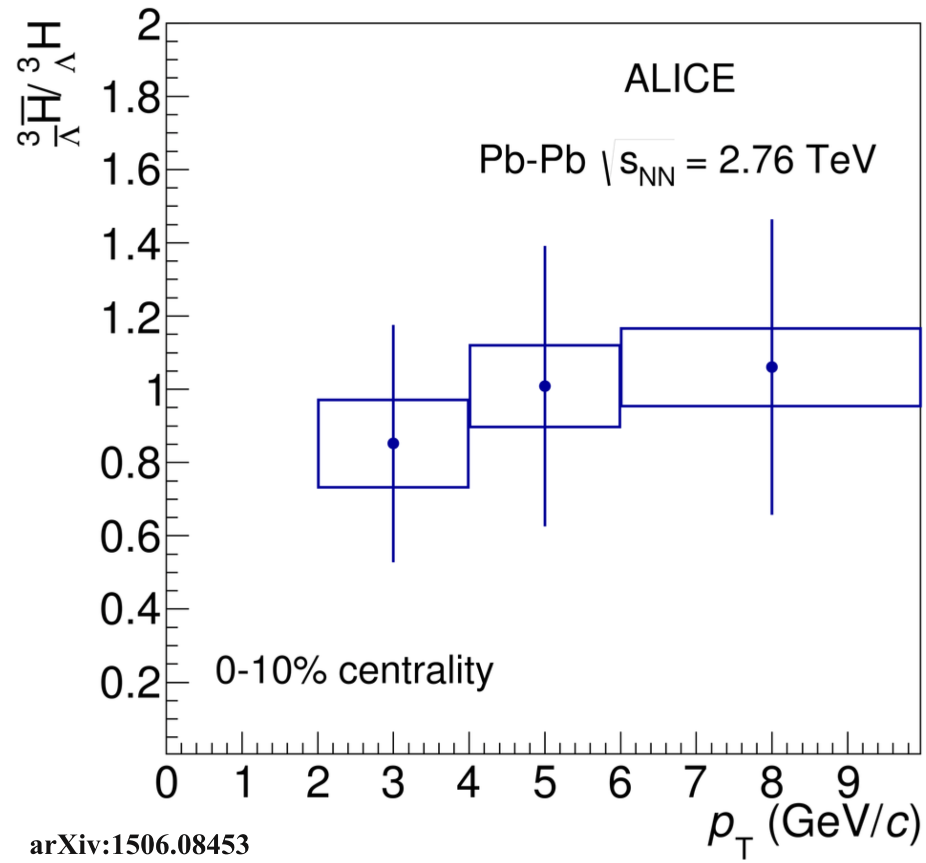
(Cleymans et al, PRC84(2011) 054916)

(ANTI-)HYPERTRITON YIELDS RATIOS



arXiv:1506.08453

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



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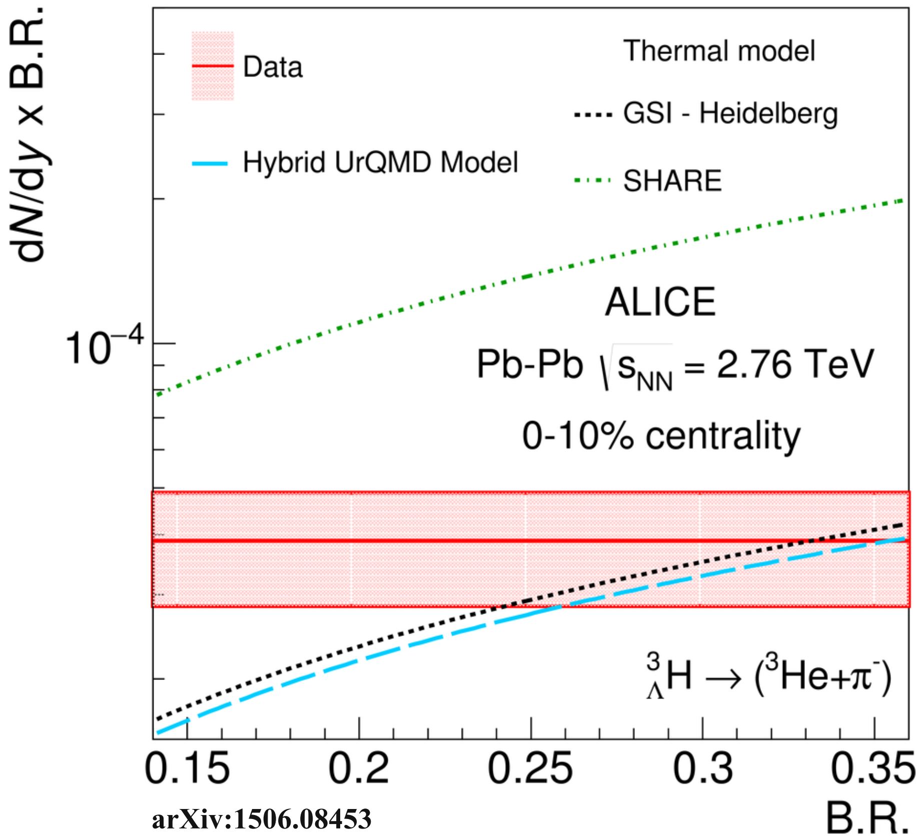
COMPARISON WITH THEORETICAL PREDICTIONS



arXiv:1506.08453

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 statistical thermal model (Petran-Rafelsky SHARE) provides better global fitting (χ^2~1) to lower mass hadrons but **misses $^{3}_{\Lambda}$H** and light nuclei
- Experimental data closest to equilibrium thermal model with T_{chem} = 156 MeV

M. Petráň et al., Phys. Rev. C 88, 034907 (2013)
A. Andronic et al., Phys. Lett. B 697, 203 (2011)

HYPERTRITON LIFETIME DETERMINATION

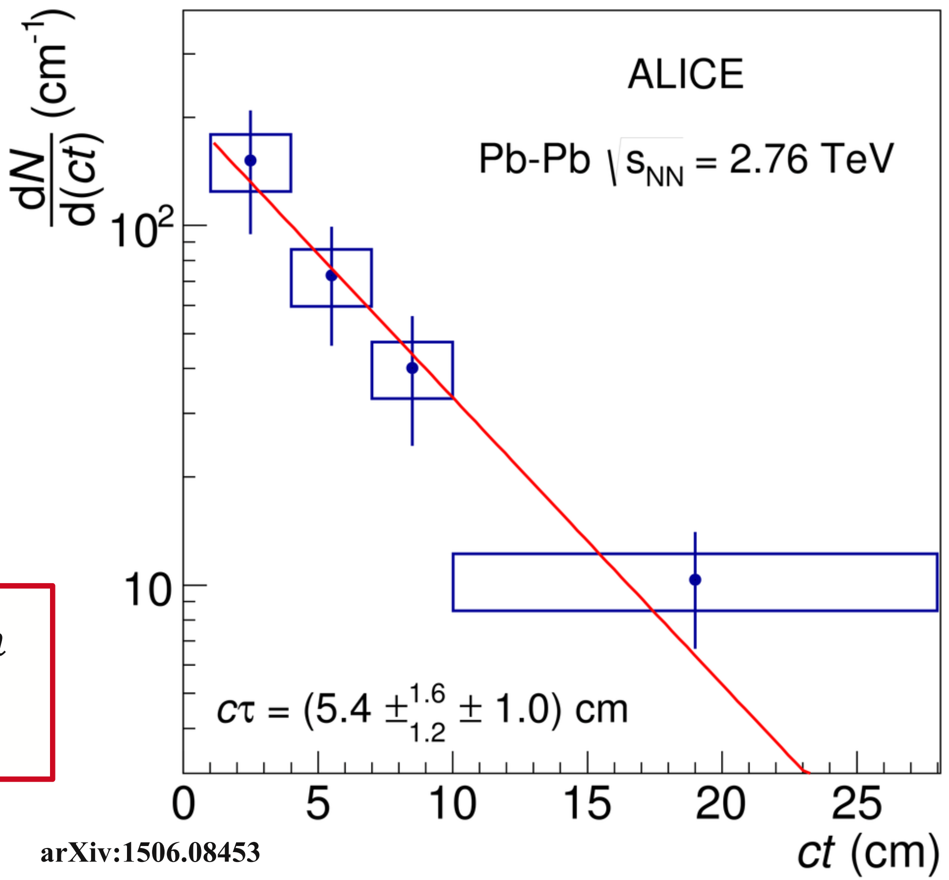
Direct decay time measurement is difficult (~ps), but the excellent determination of primary and decay vertex allows measurement of lifetime via:

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

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

$$c\tau = \left(5.4^{+1.6}_{-1.2}(stat.) \pm 1.00(syst.)\right) cm$$

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



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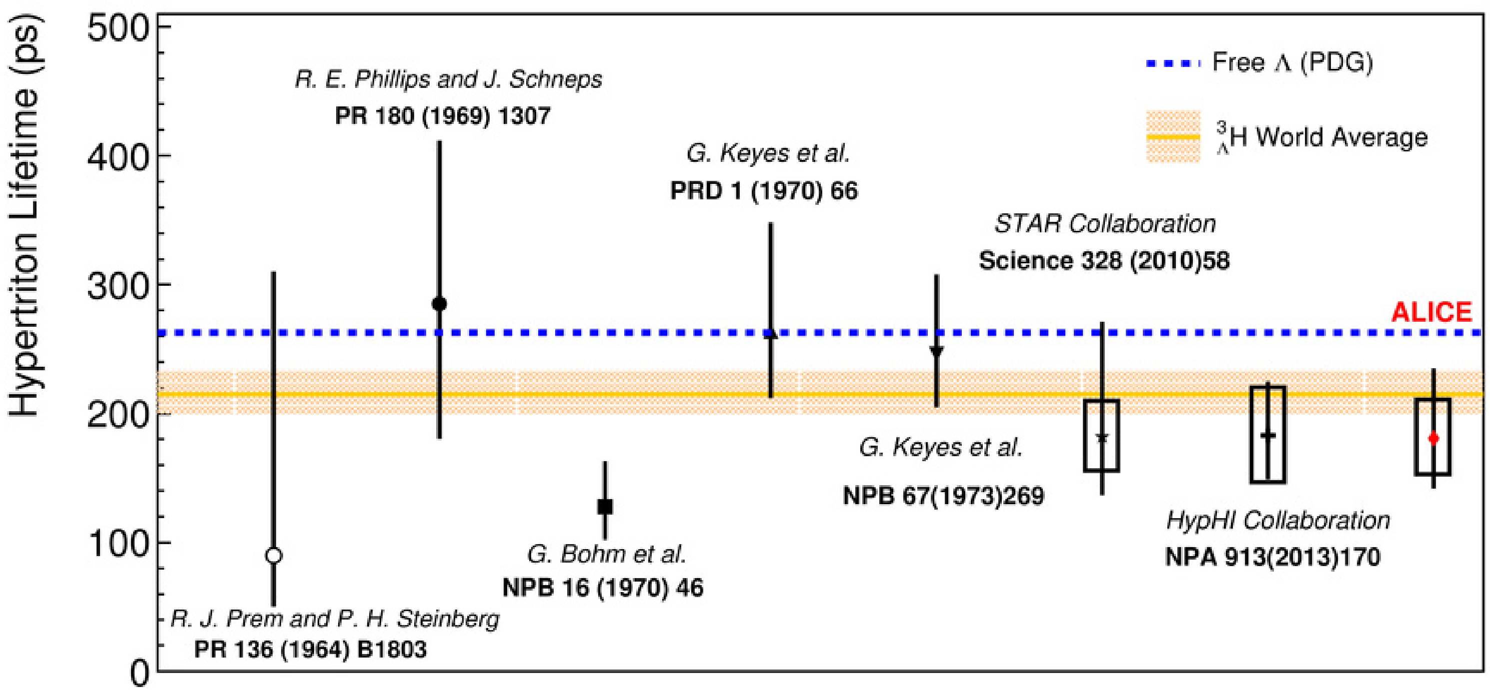
HYPERTRITON LIFETIME WORLD AVERAGE



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Re-evaluation of world average including ALICE result:

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

ALICE value compatible with the computed average

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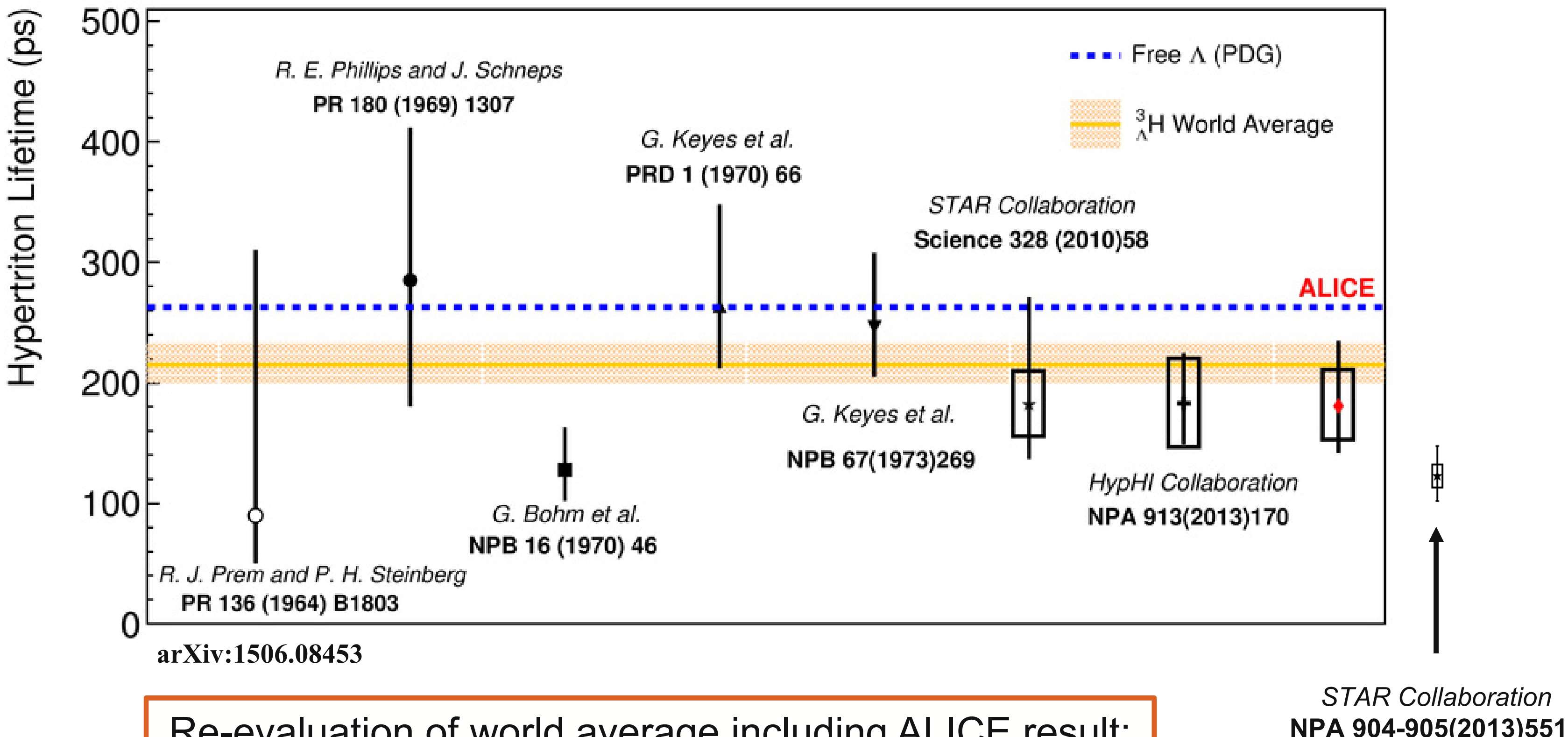

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Stat:		***+30% - 22%***
Syst:		*18%*
	Signal Extraction	*9%*
	Tracking Efficiency	*10%*
	Absorption	*12%*

arXiv:1506.08453

At the end of Pb-Pb during RUN2 (Dec. 2015) the expected statistics for $^{3}_{\Lambda}H$ is >2x

During the Long Shutdown 2 (2018-2019):

- New Inner Tracking System (ITS)
  - ✓ improved pointing precision
  - ✓ less material -> thinnest tracker at the LHC
- Upgrade of Time Projection Chamber (TPC):
  - ✓ new GEM technology for readout chambers
  - ✓ continuous readout
  - ✓ faster readout electronics
- High Level Trigger (HLT):
  - ✓ new architecture
  - ✓ on line tracking & data compression
  - ✓ 50kHz PbPb event rate

At the end of RUN3 (2022) the expected statistics for $^{3}_{\Lambda}H$ is ~200x

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arXiv:1506.08453

At the end of RUN3:
Statistical uncertainty will be negligible

With the LS2 ALICE upgrades:
Signal extraction and tracking efficiency uncertainties will be strongly reduced

At the end of RUN2 (Dec. 2015)
the expected statistics for $^{3}_{\Lambda}H$ is >2x

During the Long Shutdown 2 (2018-2019):

- New Inner Tracking System (ITS)
  - ✓ improved pointing precision
  - ✓ less material -> thinnest tracker at the LHC
- Upgrade of Time Projection Chamber (TPC):
  - ✓ new GEM technology for readout chambers
  - ✓ continuous readout
  - ✓ faster readout electronics
- High Level Trigger (HLT):
  - ✓ new architecture
  - ✓ on line tracking & data compression
  - ✓ 50kHz PbPb event rate

At the end of RUN3 (2022)
the expected statistics for $^{3}_{\Lambda}H$ is ~200x

ALICE

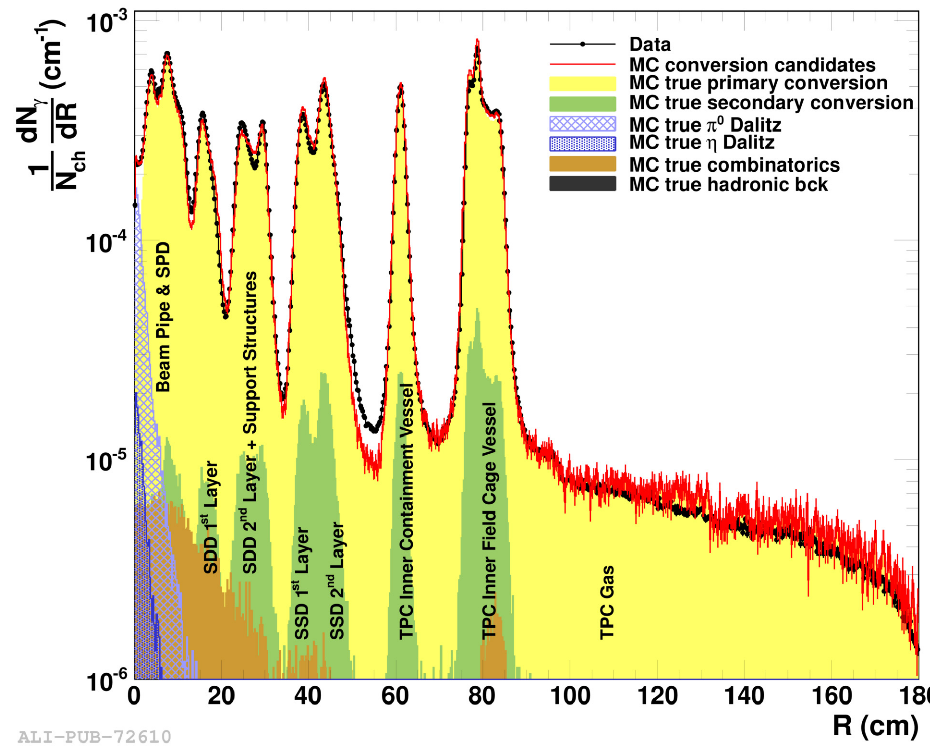
HYPERTRITON LIFETIME UNCERTAINITIES

$$c\tau = \left(5.4^{+1.6}_{-1.2}(stat.) \pm 1.00(syst.)\right) cm$$

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

Stat:		***+30% - 22%***
Syst:		*18%*
	Signal Extraction	*9%*
	Tracking Efficiency	*10%*
	Absorption	*12%*

arXiv:1506.08453



(anti)hypertriton absorption is not negligible:

- (anti)hypertriton is barely bound: stronger absorption in matter than *t* or ^{3}He
- distribution of the material well known from the distribution of reconstructed photon conversions
- **more precise evaluation of absorption cross section of $^3_\Lambda$H and ^{3}He is needed**

OUTLOOK FOR HYPERNUCLEAR STUDIES

ALICE

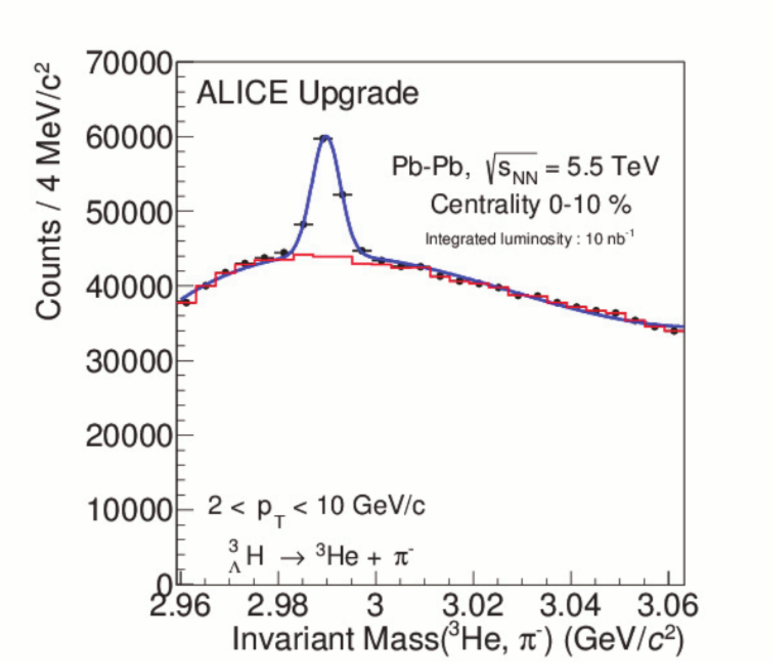
After the upgrade, ALICE will be able to collect data with better performance at higher luminosity:

- Expected Integrated Luminosity: ~10 nb^{-1} (~ $8x10^9$ 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 for 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 (*)

(*) 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

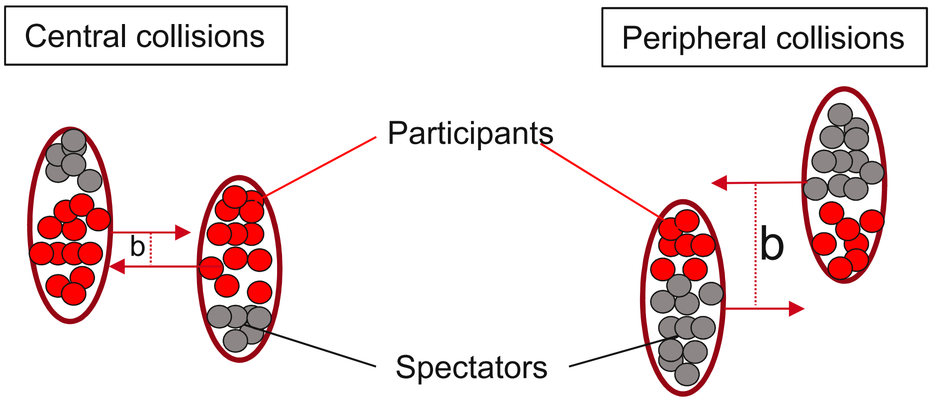


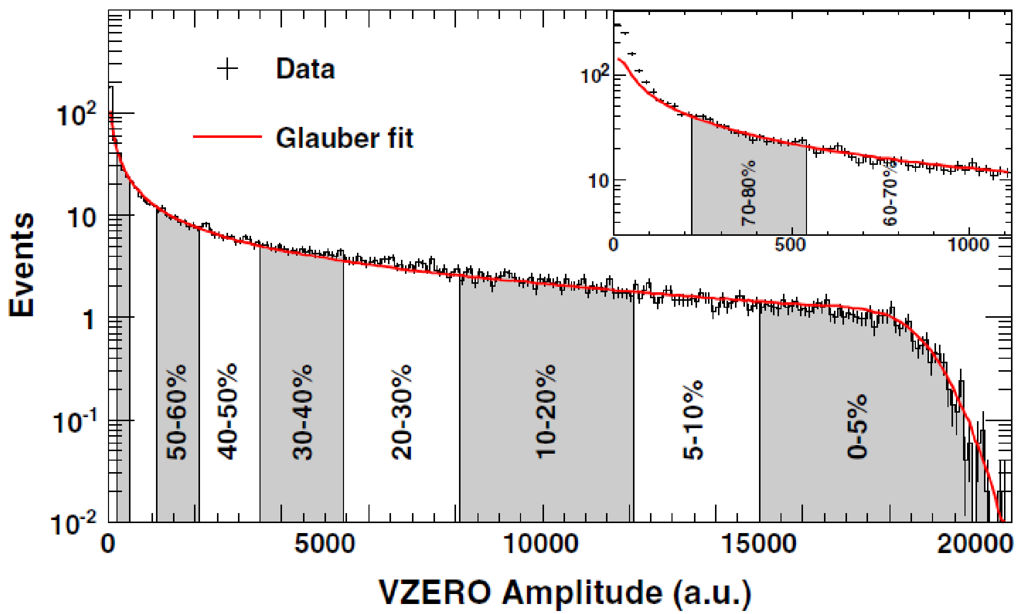
Expected invariant mass distribution for $^3_\Lambda$H (plus antiparticle) from (*)

CONCLUSIONS

- ✓ Excellent ALICE performance allows for 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
- ✓ Hypertriton yield is in agreement with the current best thermal fit from equilibrium thermal model (T_{chem} = 156 MeV)
- ✓ The excellent determination of primary and decay vertices allows for the measurement of lifetime via exponential fit of the proper decay time distribution
- ✓ The measured hypertriton lifetime is consistent with previous measurement
- ✓ Re-evaluation of the hypertrion lifetime world average
- ✓ Future LHC runs, RUN2 and RUN3, and ALICE upgrades will allow for precise study of (anti)hypertriton production yield and lifetime

COLLISION GEOMETRY





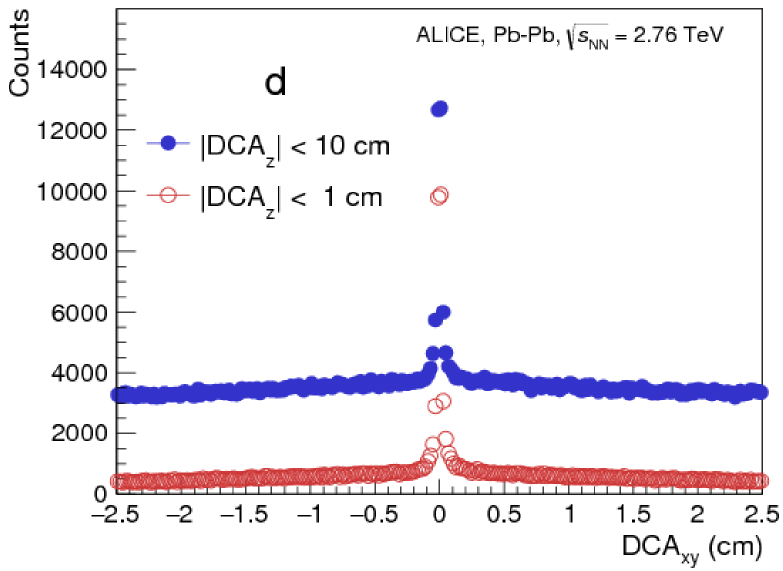
K. Aamodt et al. (ALICE Collaboration), Phys. Rev. Lett. 106, 032301 (2011)

- 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

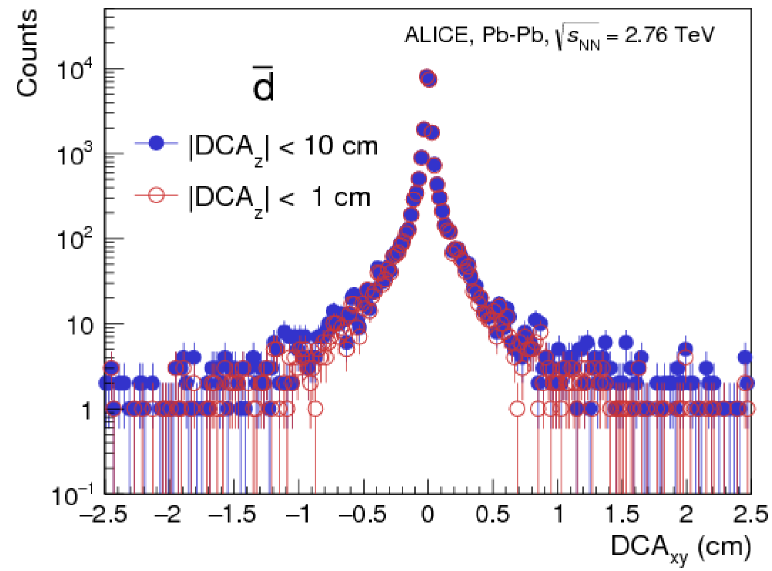
SECONDARIES

deuterons



arXiv:1506.08951

anti-deuterons



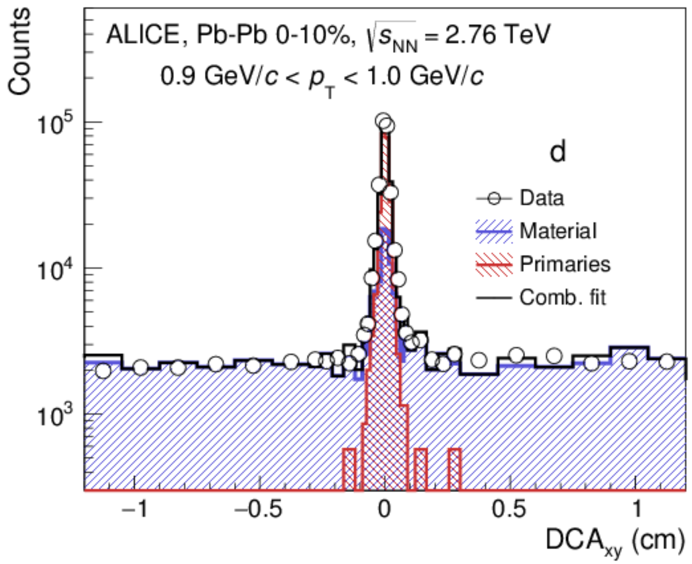
arXiv:1506.08951

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

SECONDARIES

deuterons



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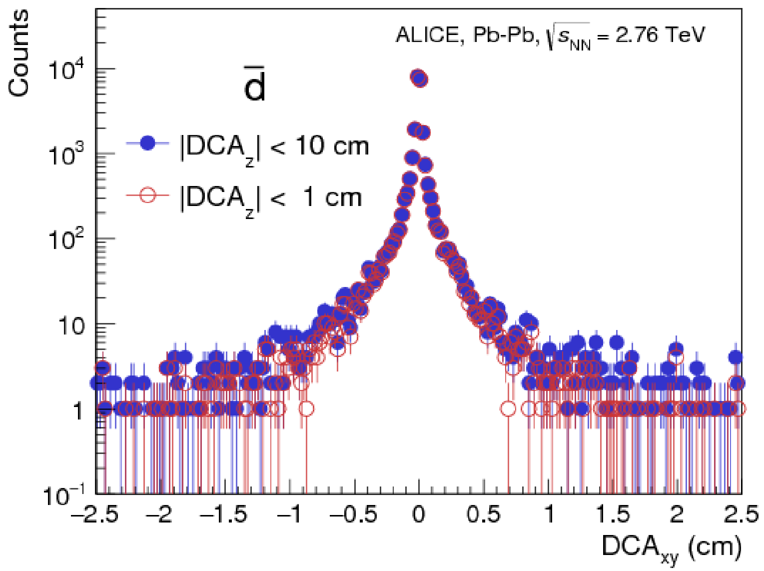

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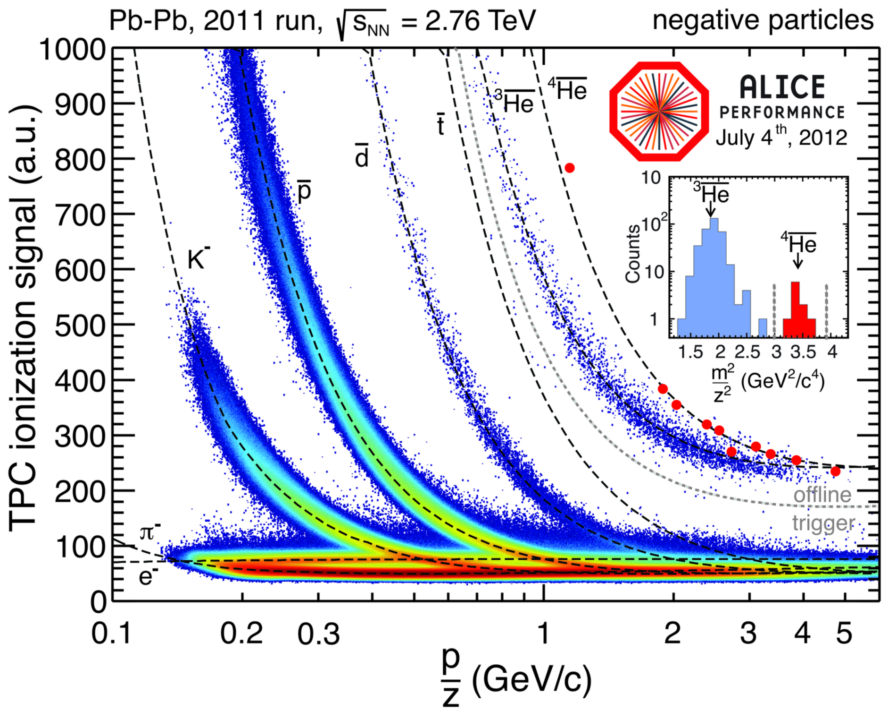
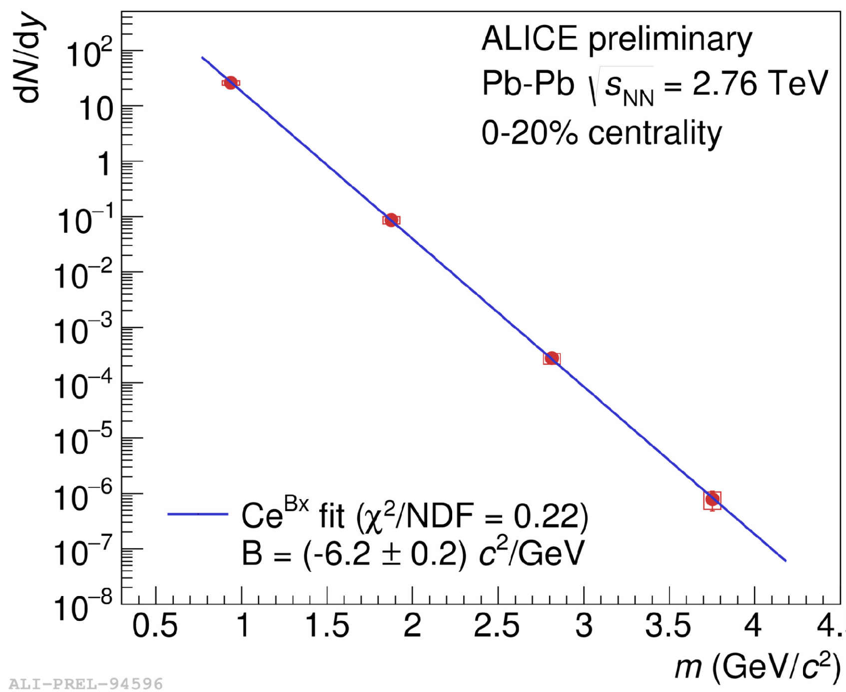
(ANTI-)NUCLEI IN Pb–Pb





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

SEARCHES FOR WEAKLY DECAYING EXOTIC BOUND STATES

Λn and H-Dibaryon search

H-Dibaryon: hypothetical *udsuds* bound state

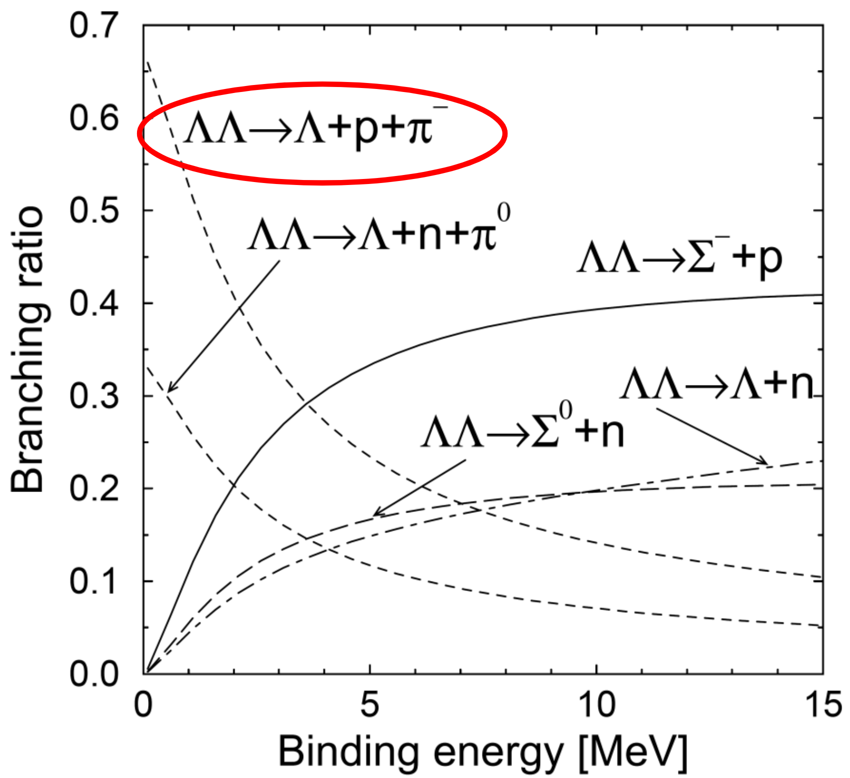
- First predicted by Jaffe [Jaffe, PRL 38, 195617 (1977)]
- Several predictions of bound and also resonant states.
- Recent Lattice models predict weakly bound states [Inoue et al., PRL 106, 162001 (2011), Beane et al., PRL 106, 162002 (2011)]

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

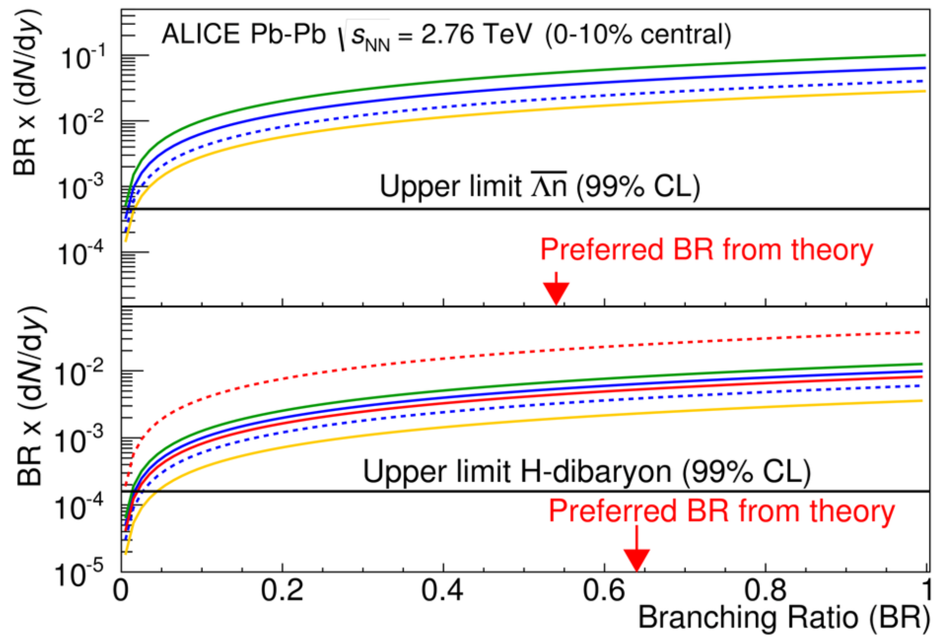
No signal visible

- 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:

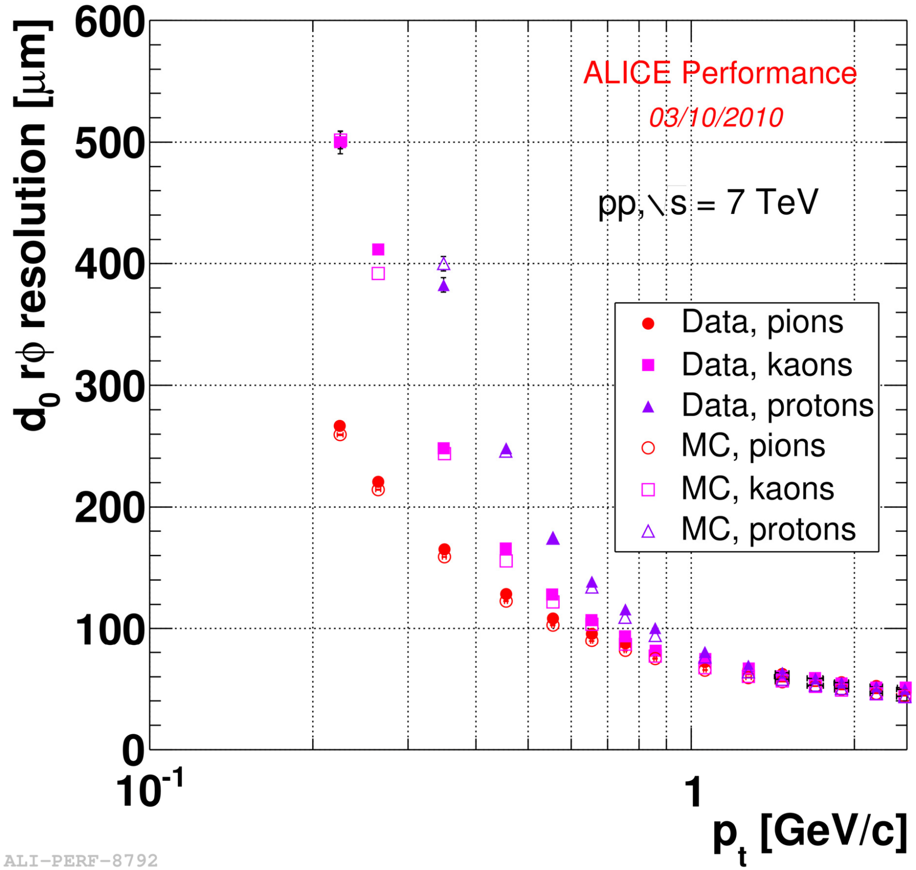
  dN/dy ≤ 1.5x10^{-3} (99% CL)
- The upper limits for exotica are lower than the thermal model expectation by a factor 10
- Thermal model with the same temperature describe precisely the production yield of deuterons, ^{3}He and $^3_\Lambda$H
- The existence of such states with the assumed B.R., mass and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



A LARGE ION COLLIDER EXPERIMENT

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

ITS: precise separation of primary particles and those from weak decays (hyper-nuclei) or knock-out from material



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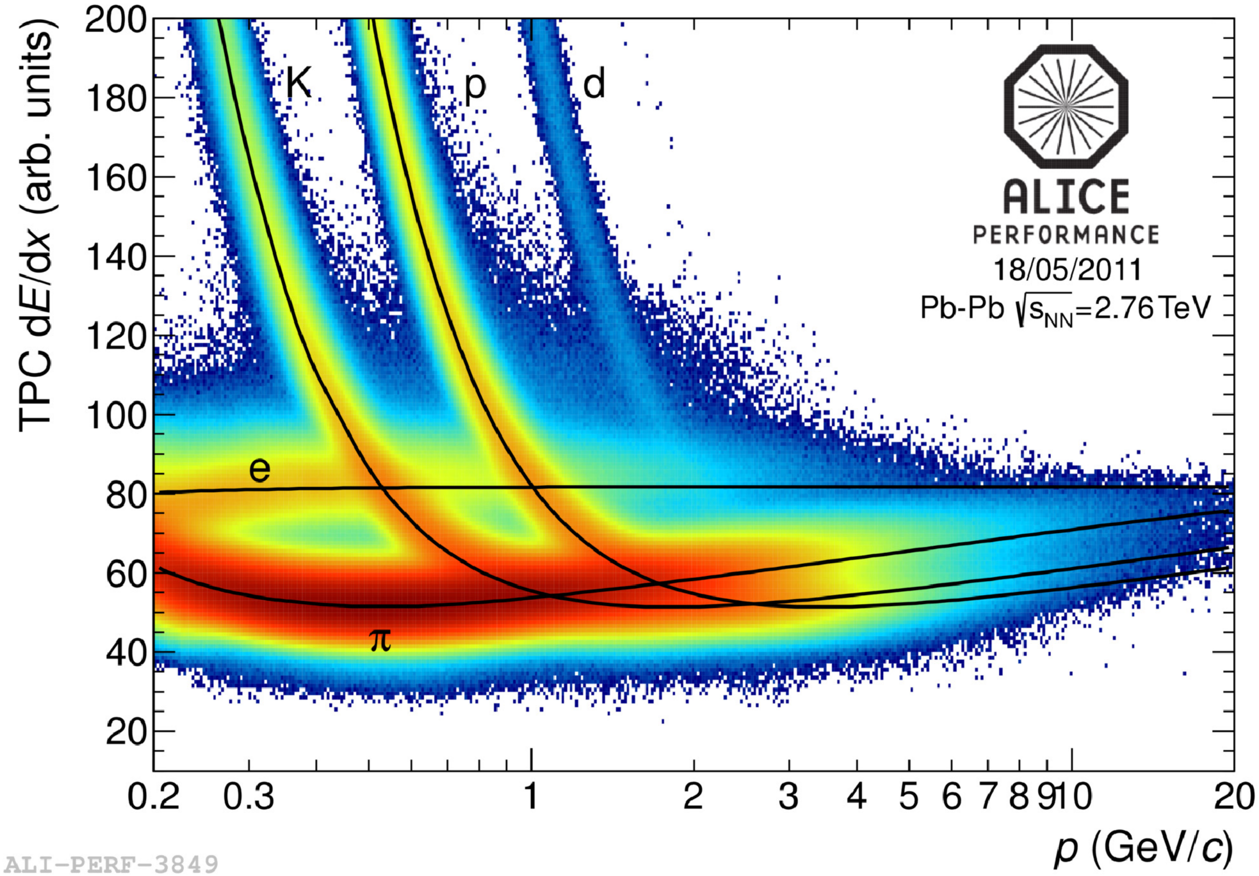

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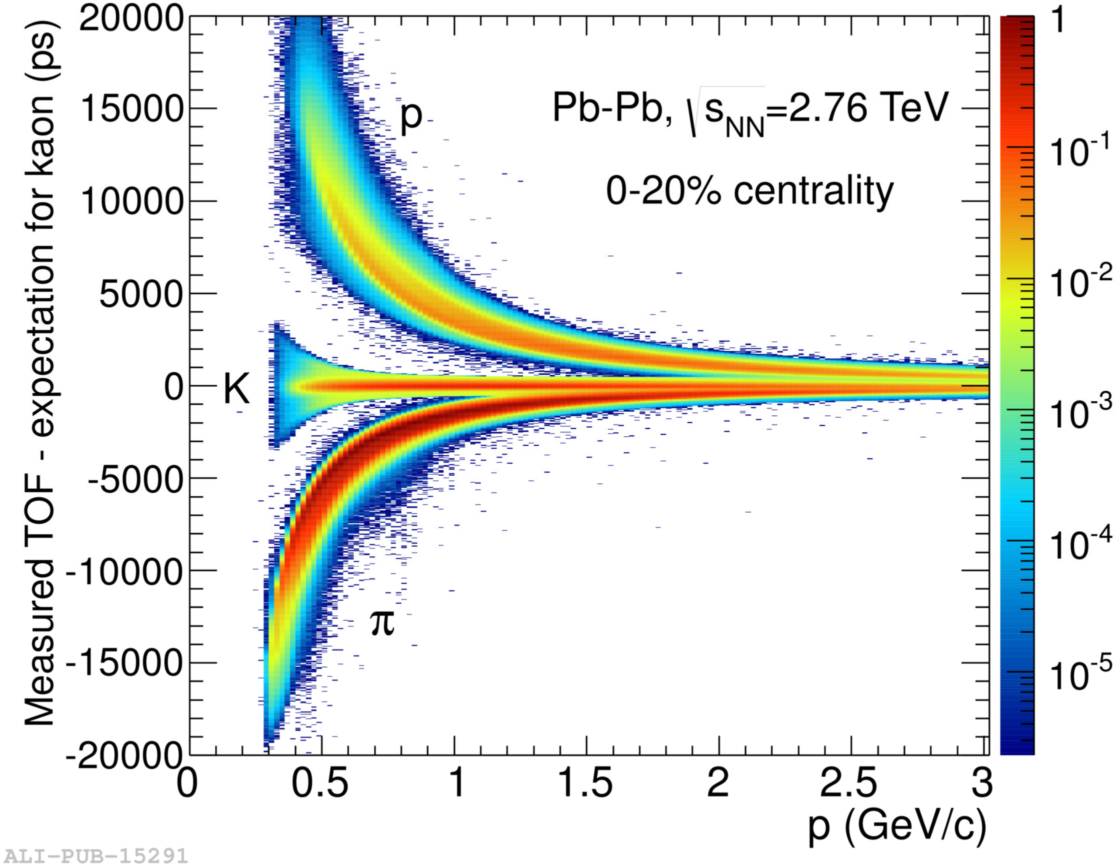
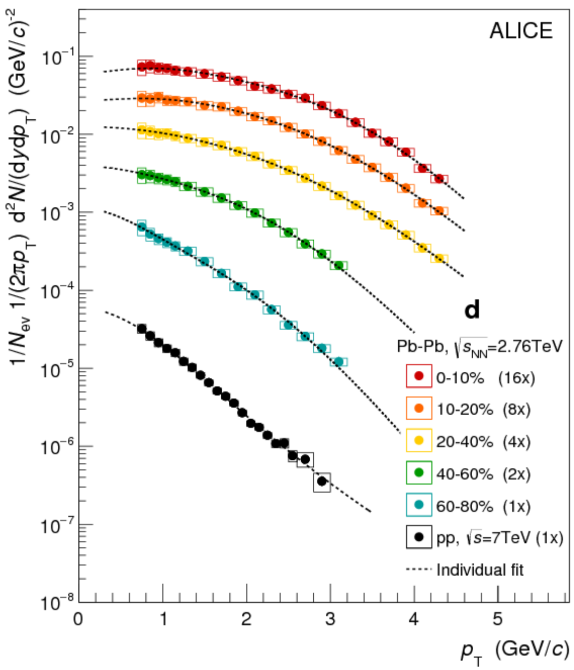


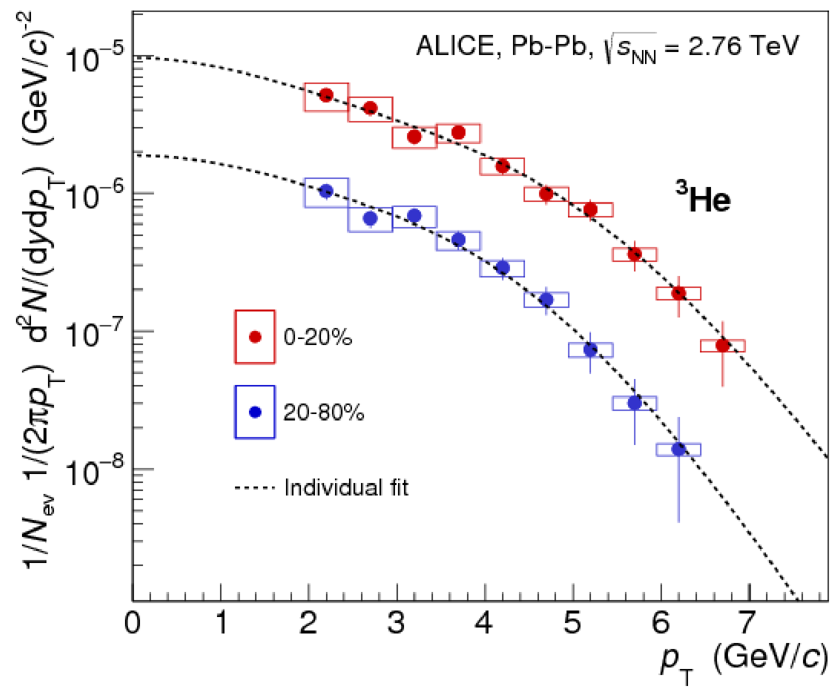
ITS: precise separation of primary particles and those from weak decays (hyper-nuclei) or knock-out from material

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

TOF: particle identification via time-of-flight

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)