ALICE

MEASUREMENT OF (ANTI-)HYPERNUCLEI PRODUCTION WITH ALICE AT THE LHC

Stefano Piano on behalf of ALICE Collaboration
INFN sez. Trieste

ALICE

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

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

- (anti-)(hyper)nuclei yields are sensitive to the freeze-out temperature due to their large mass (e.g. in the Thermal Model yield scales roughly $\propto e^{(-M/T_{chem})}$)
- light (anti-)(hyper)nuclei, small binding energy and small Λ separation energy, e.g. $B_{\Lambda}({}^{3}_{\Lambda}H = 0.13 \pm 0.05$ MeV) [H. Bando et al., Int. J. Mod. Phys. A 5 4021 (1990)] :
  - light (anti-)(hyper)nuclei should dissociate in a medium with high T_{chem} (~156 MeV) and be suppressed
  - light (anti-)(hyper)nuclei production determined by the entropy per baryon (fixed at chemical freeze-out)
  - if light (anti-)(hyper)nuclei yields equal to thermal model prediction ⇒ 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) ⇒ Lambda-nucleon correlation (local baryon-strangeness correlation)
  - t / ^{3}He (and anti) ⇒ local charge-baryon correlation
  - YN & YY interaction (strangeness sector of hadronic EOS, cosmology, physics of neutron stars)

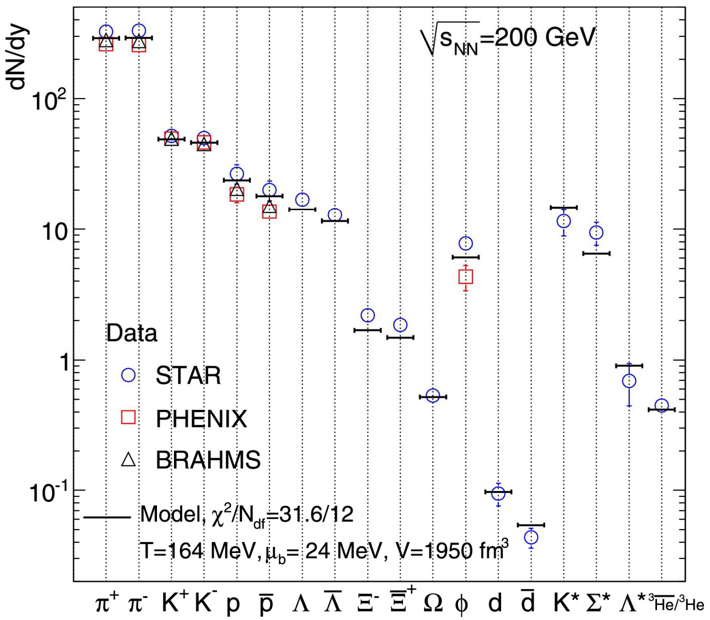
Anti-nuclei in nature:

- matter–antimatter asymmetry [J.~Adam et al. (ALICE Collaboration), Nature Phys. (2015)] (**see Colocci talk**)

(ANTI-)(HYPER)NUCLEI PRODUCTION IN URHIC

Statistical Thermal model

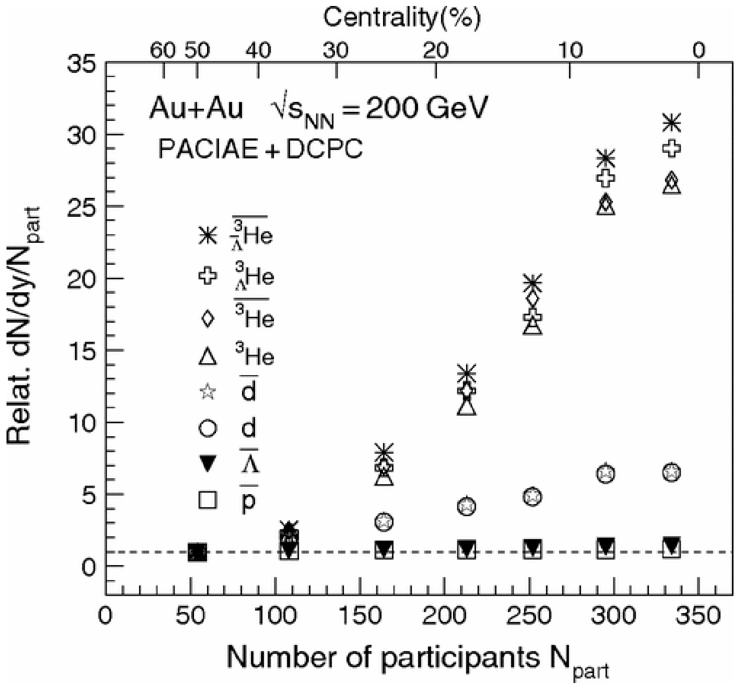
- Thermodynamic approach to particle production in heavy-ion collisions
- Abundances fixed at chemical freeze-out (T_{chem}) (hyper)nuclei are very sensitive to T_{chem} because of their large mass (M)
- Exponential dependence of the yield $\propto e^{(-M/Tchem)}$



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

Coalescence

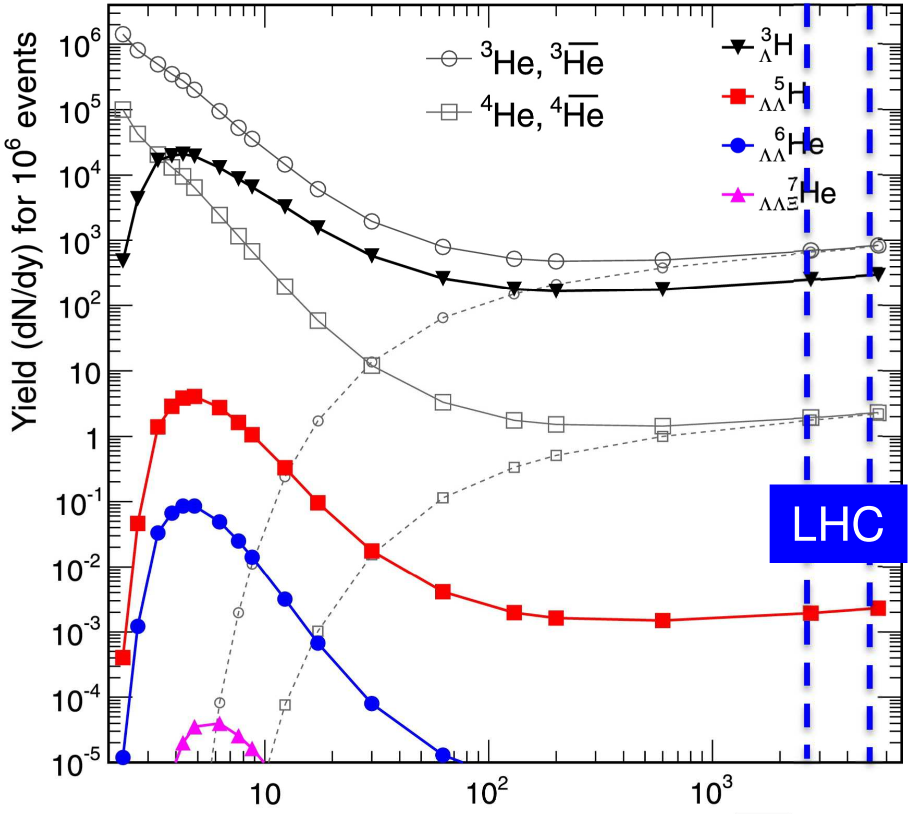
- If baryons at freeze-out are close enough in Phase Space an (anti-)(hyper)nucleus can be formed
- (Hyper)nuclei are formed by protons (Λ) and neutrons which have similar velocities after the freeze-out



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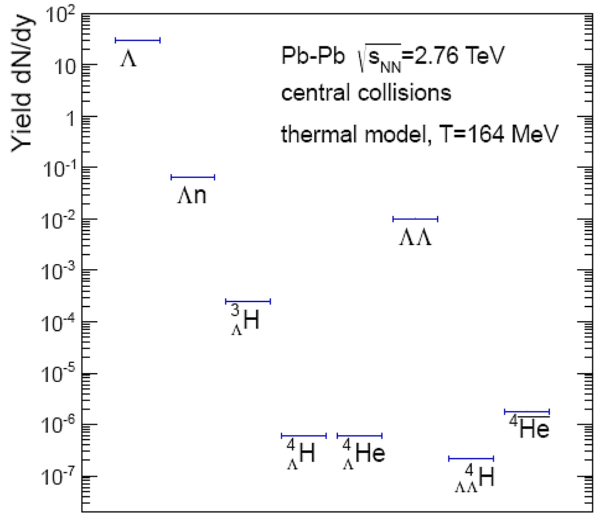
	Yield/event at mid-rapidity and central collisions
π	~800
p	~40
Λ	~30
d	~0.17
^{3}He	~0.01
$^3_\Lambda$H	~0.003

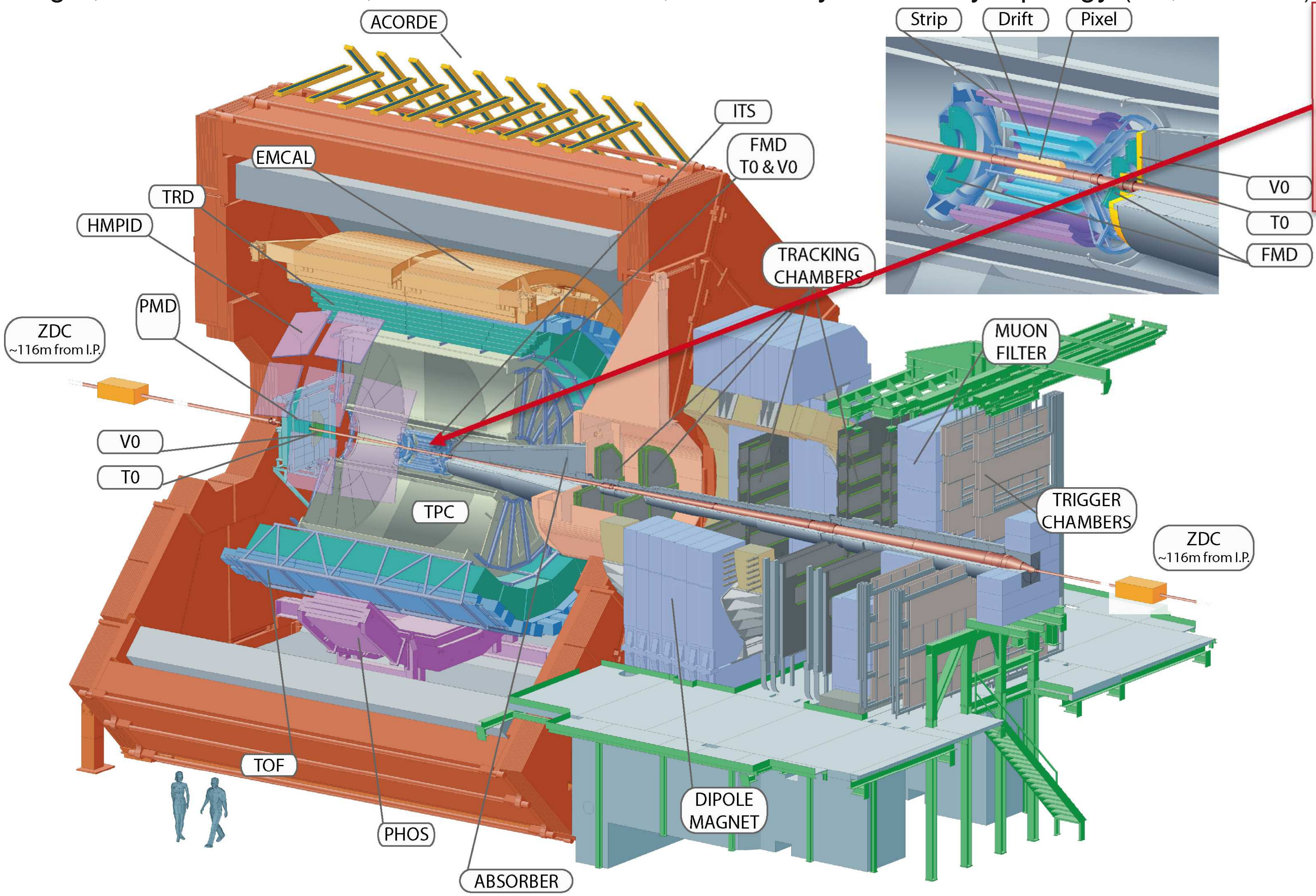
- ✓ Light nuclei (**see Dönigus talk**)
- ✓ Hypertriton
- ✓ Search for: Λn, ΛΛ dibaryons (**see Mastroserio talk**)



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)



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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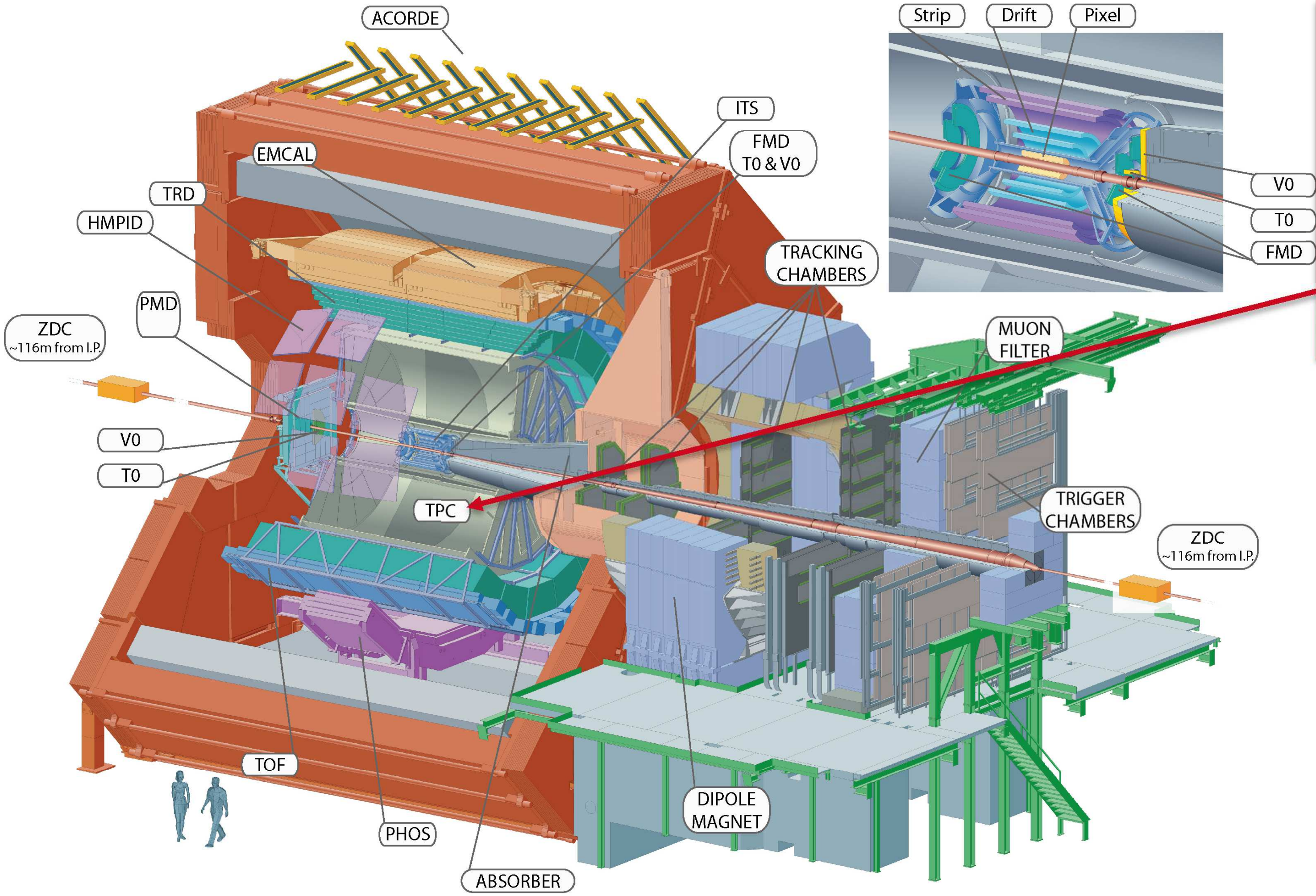

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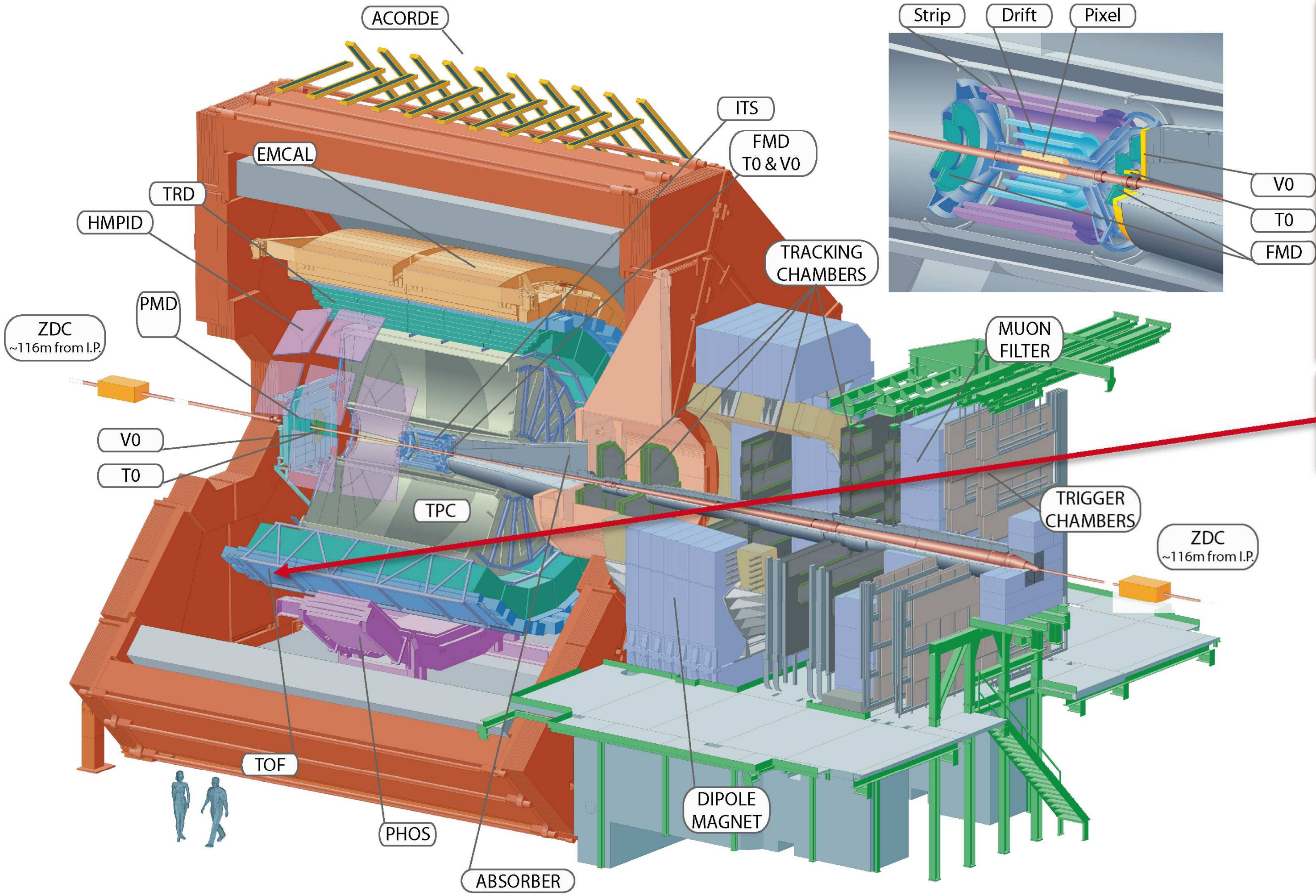

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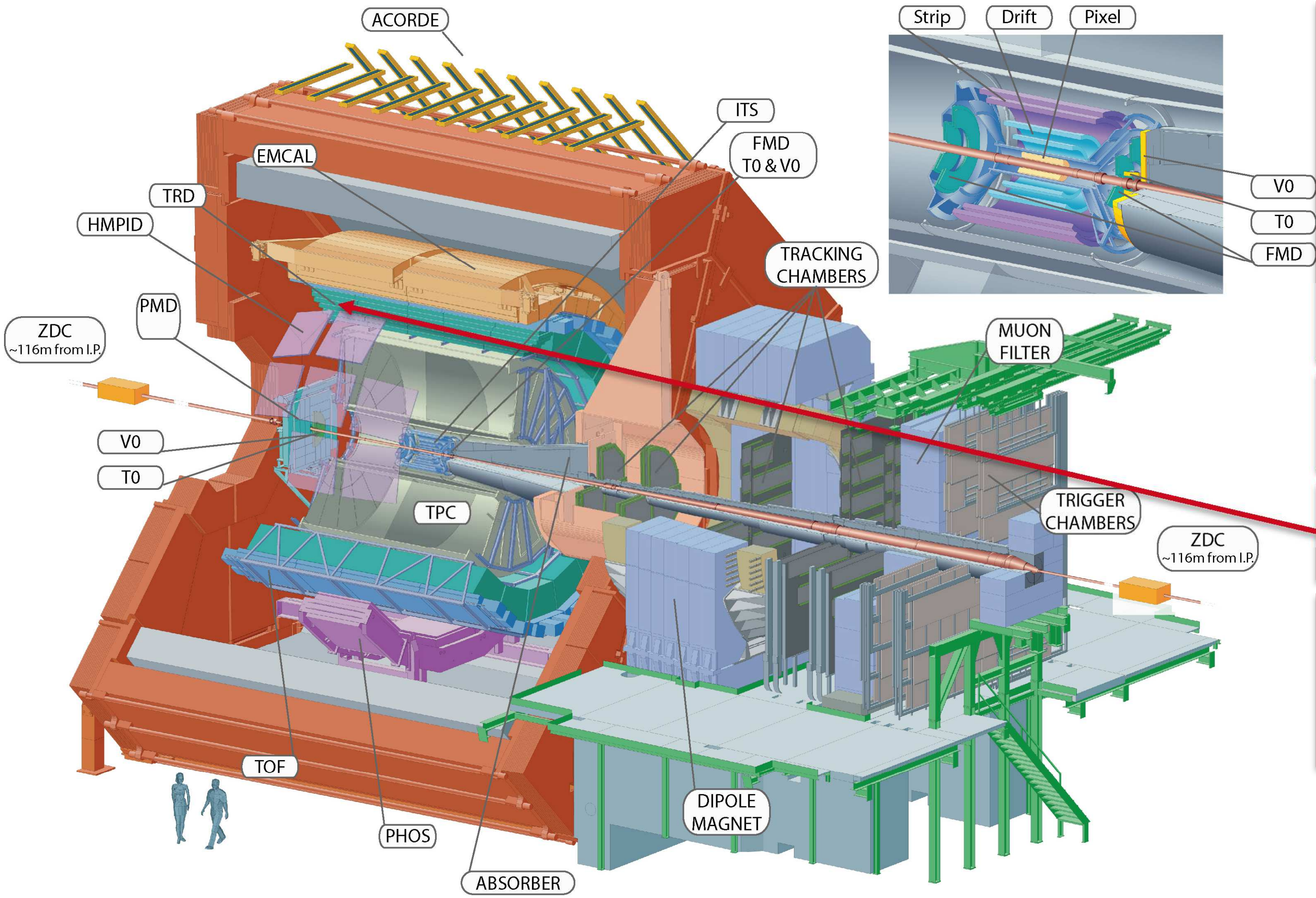

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TRD: electron identification via transition radiation

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

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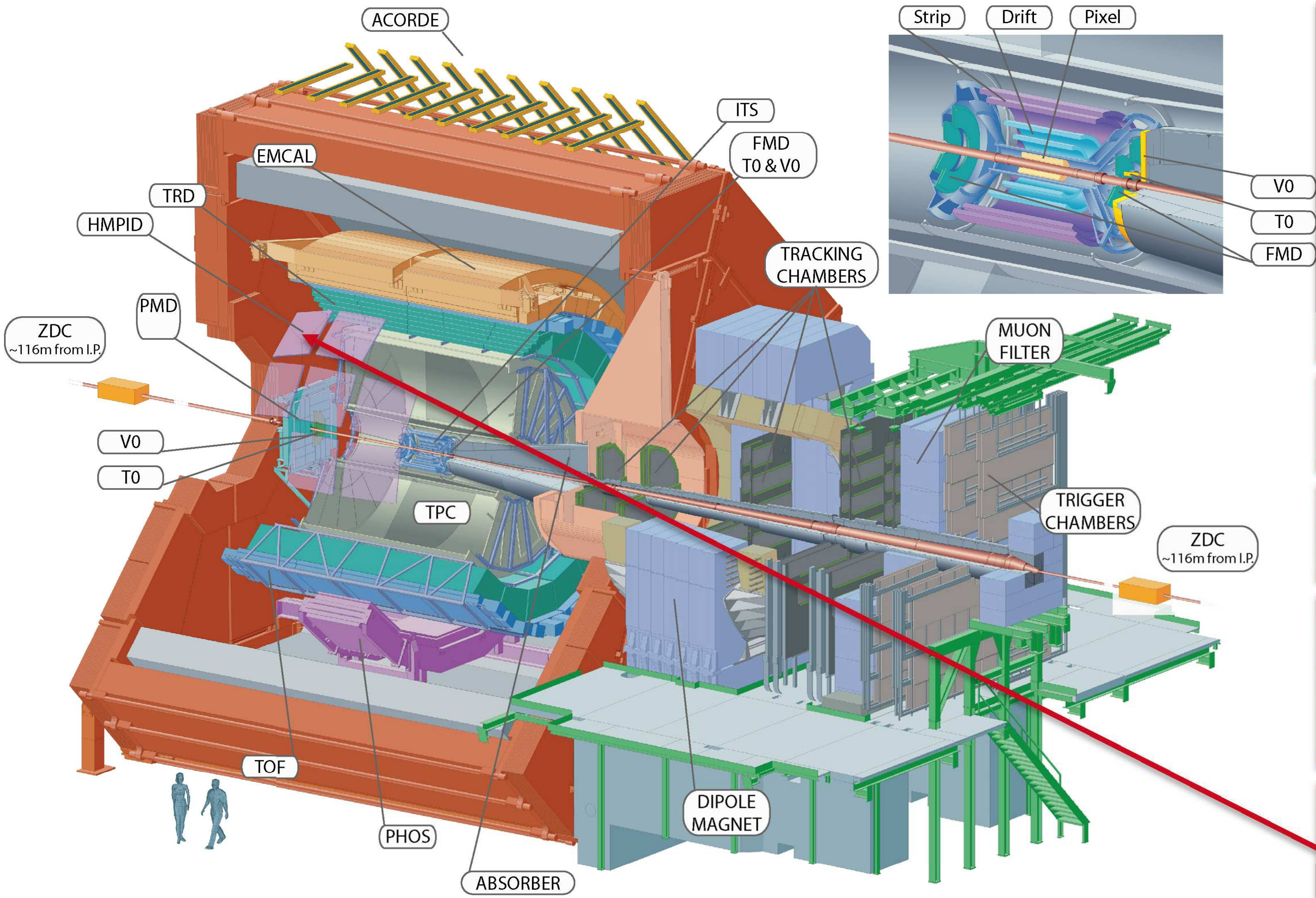

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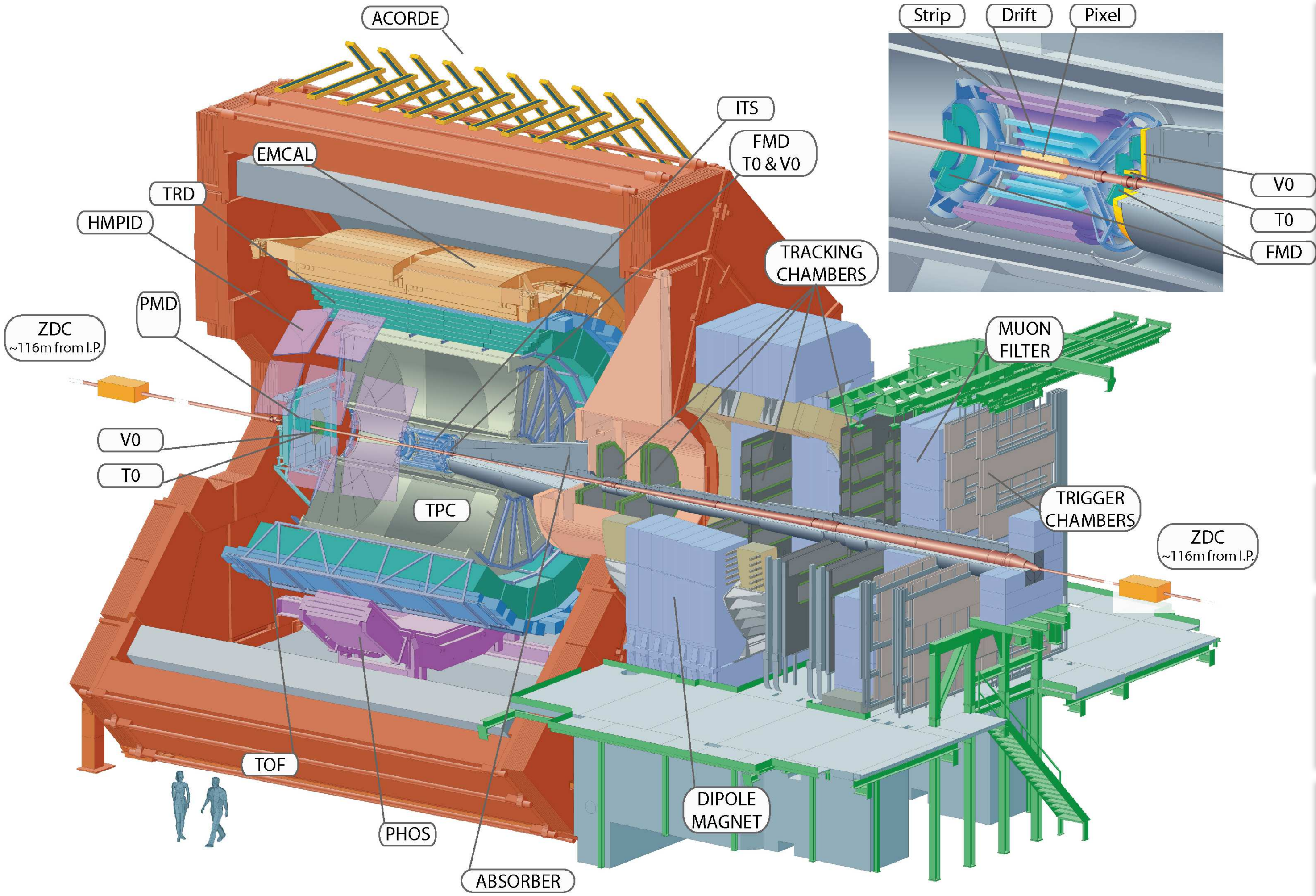

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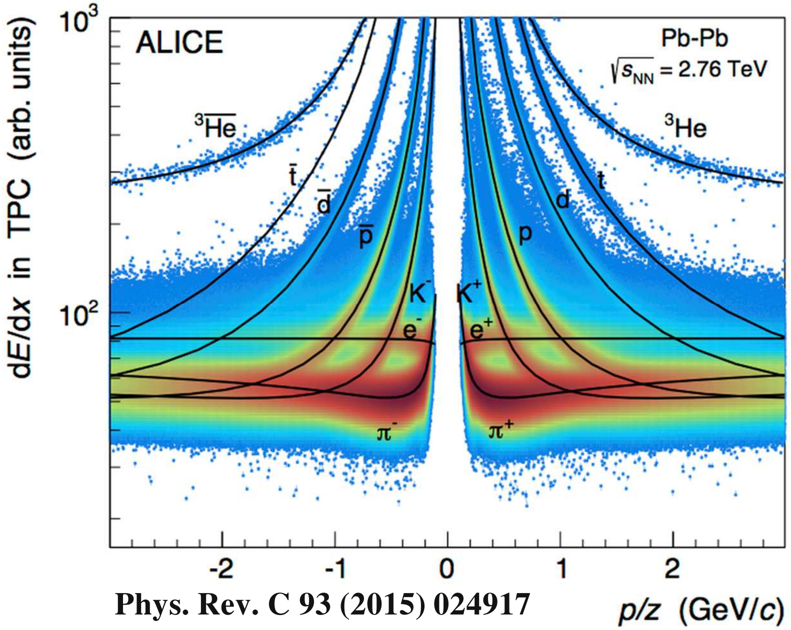
ALICE is ideally suited for the identification of light (anti-)(hyper)nuclei

NUCLEI IDENTIFICATION

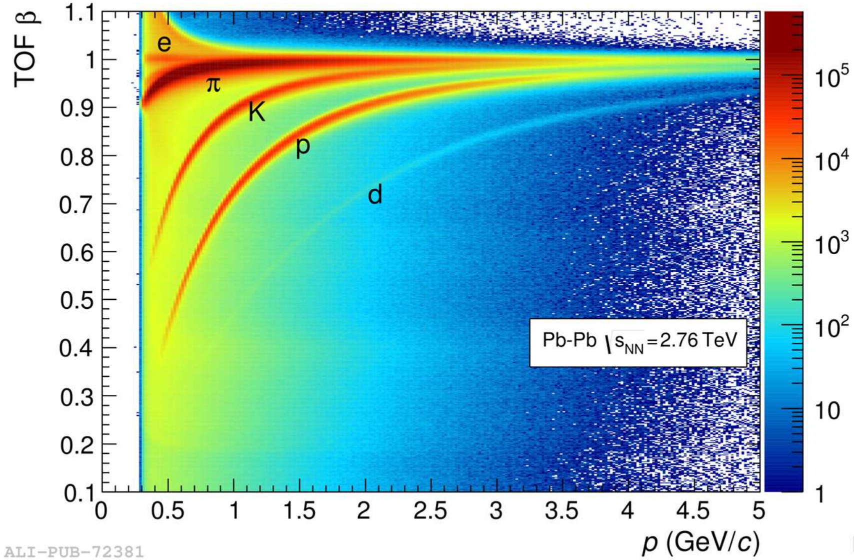


Phys. Rev. C 93 (2015) 024917

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



Higher momenta

Excellent TOF performance:

- σ_{TOF} ≈ 85 ps in Pb-Pb collisions allows identification of light nuclei over a wide momentum range
- Velocity measurement with the TOF detector is used to evaluate the m^2 distribution and to subtract background from the signal in each p_T-bin by fitting the m^2 distribution

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(ANTI)HYPERTRITON IDENTIFICATION

Decay Channels

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

$${}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{H} + \pi^{0} \qquad {}^{3}_{\Lambda}\overline{\mathrm{H}} \to {}^{3}\overline{\mathrm{H}} + \pi^{0}$$

$${}^{3}_{\Lambda}\mathrm{H} \to d + p + \pi^{-} \qquad {}^{3}_{\Lambda}\overline{\mathrm{H}} \to \overline{d} + \overline{p} + \pi^{+}$$

$${}^{3}_{\Lambda}\mathrm{H} \to d + n + \pi^{0} \qquad {}^{3}_{\Lambda}\overline{\mathrm{H}} \to \overline{d} + \overline{n} + \pi^{0}$$

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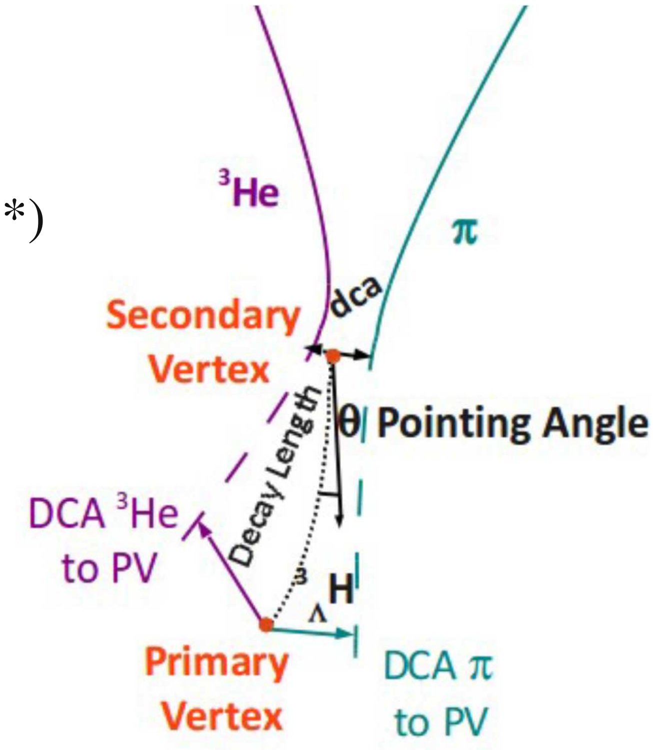

APPLIED CUTS:

- 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

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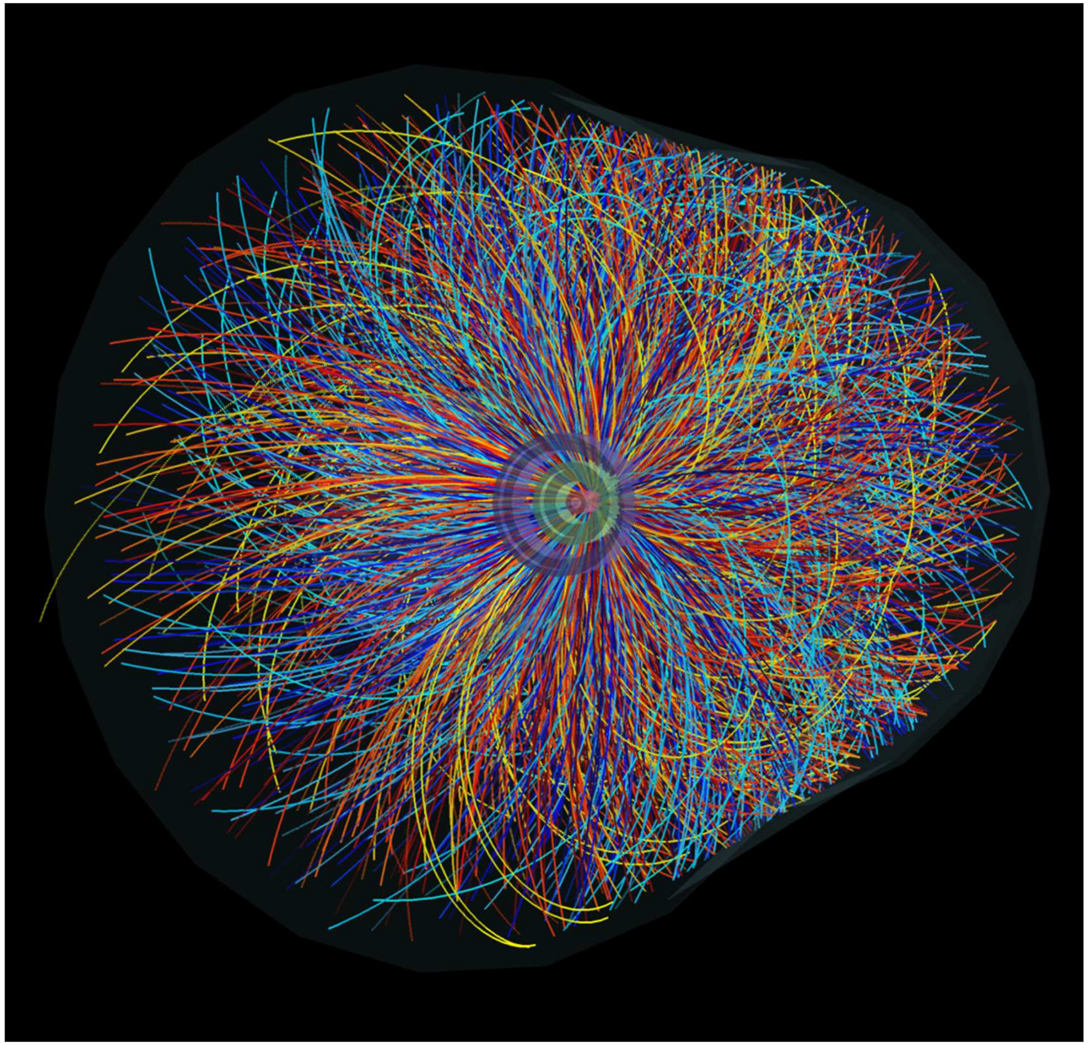
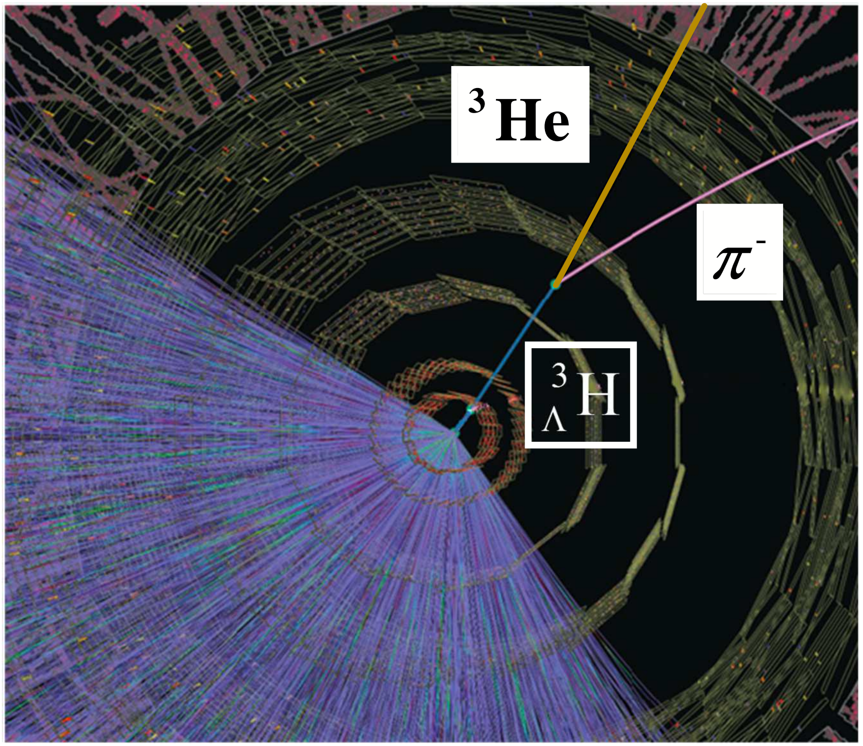
THE EXPERIMENTAL CHALLENGE

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



At $\sqrt{s_{NN}}$ =	2.76 TeV	5.02 TeV
Centrality	$dN_{ch}/d\eta$ ($\|\eta\| < 0.5$)	
0-5 %	1601 ± 60	1943 ± 54



K. Aamodt et al. (ALICE Collaboration) Phys. Rev. Lett. 106, 032301 (2011) ; J. Adam et al (ALICE Collaboration) Phys. Rev. Lett. 116, 222302 (2016)

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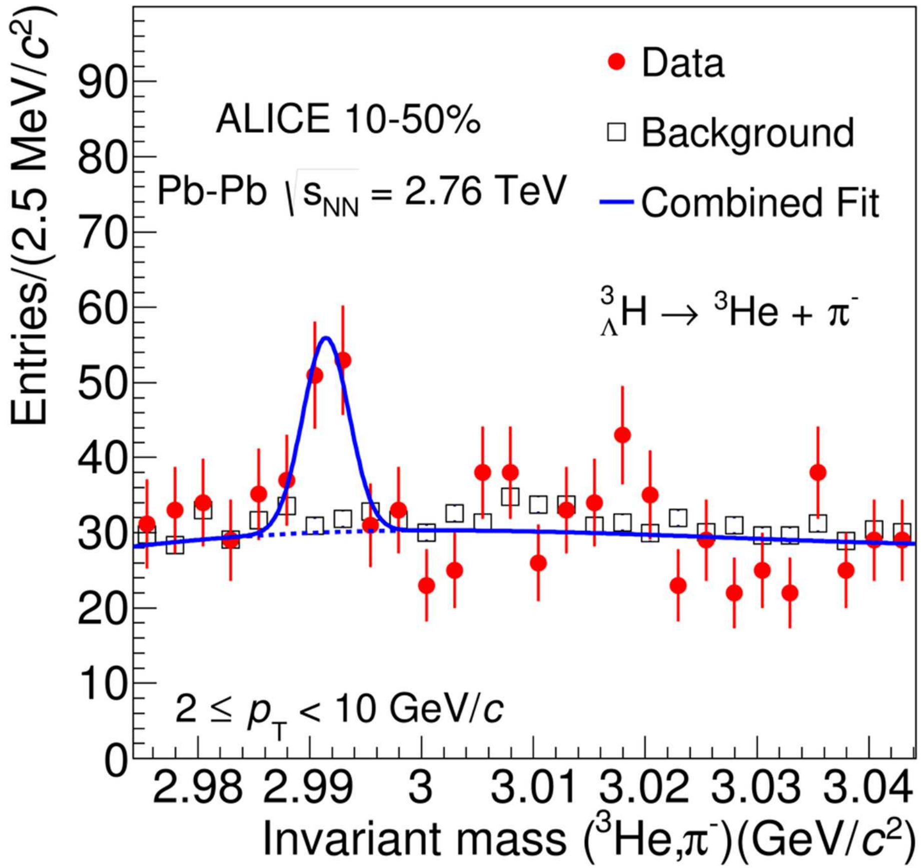

μ = 2.991 ± 0.001 ± 0.003 GeV/c^2
σ= (3.01 ± 0.24)x10^{-3} GeV/c^2

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

(ANTI-)HYPERTRITON IDENTIFICATION

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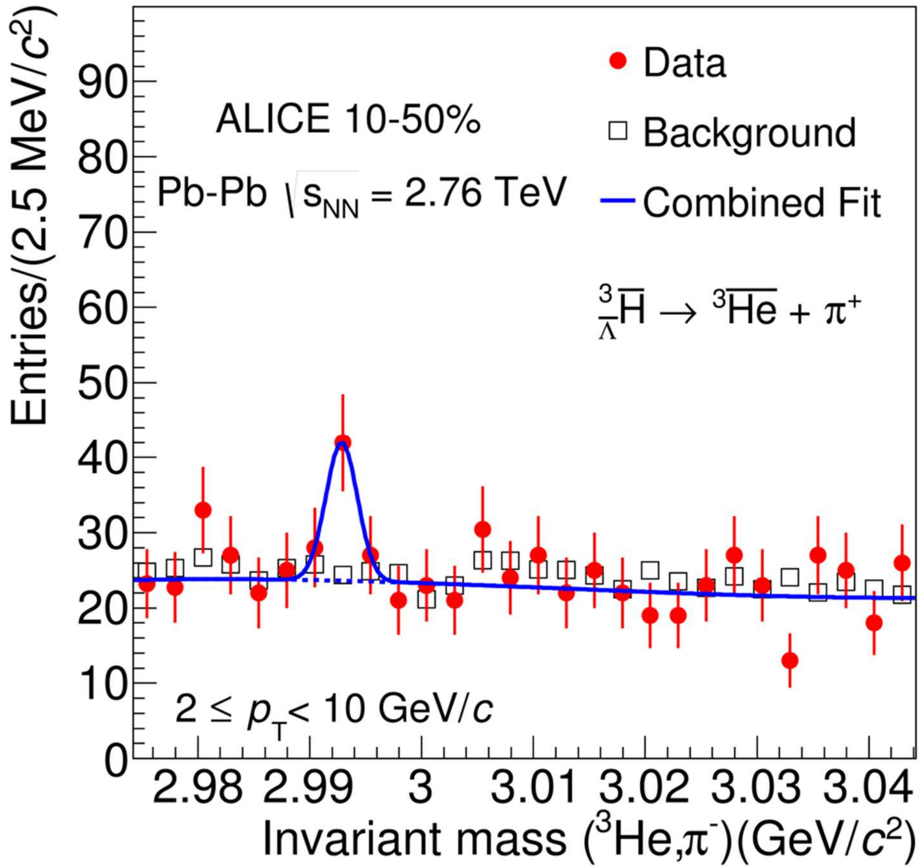

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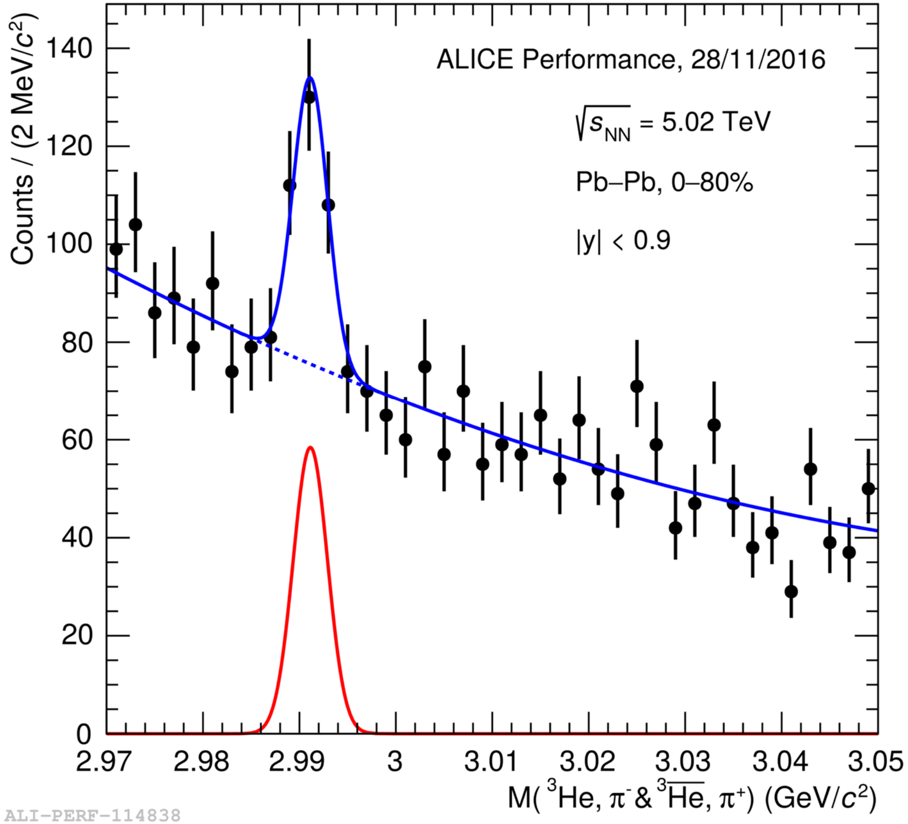
New preliminary results at $\sqrt{s_{NN}}$ = 5.02 TeV



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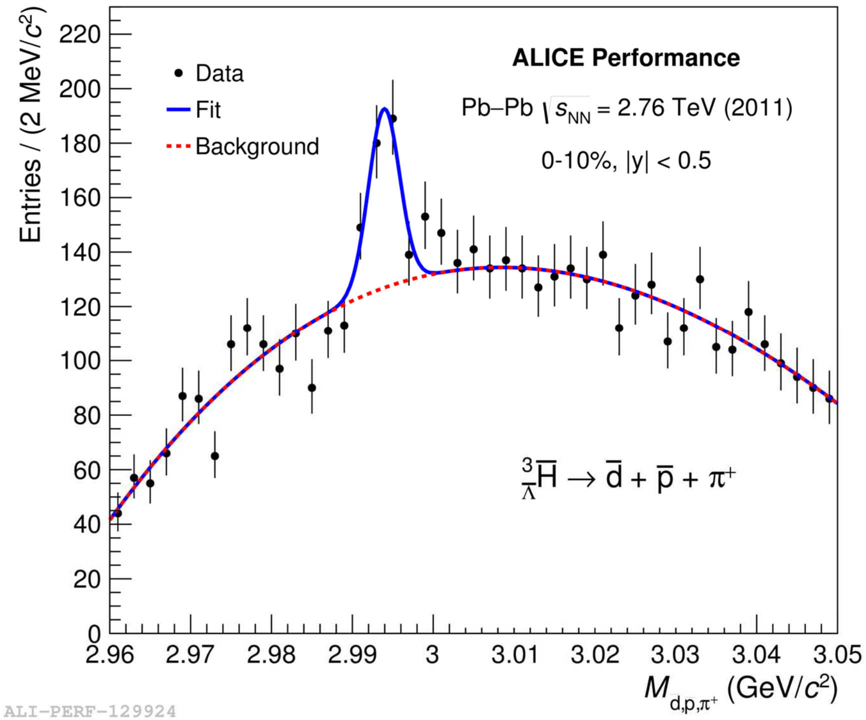
$^{3}_{\Lambda}$H search via three-body decays into charged particles:

- Three body decay: higher combinatorial background but
- Higher B.R. ~ 41% (**Kamada et al., PRC57(1998)4**)
- Charged particles: ALICE acceptance for charged particles (|η|<0.9) higher than for neutrals (|η|<0.7)

Signal Extraction:

- Identify d, p and π and anti
- Evaluate (d,p,π) invariant mass
- Apply topological cuts and background estimation

New preliminary results:
three body decay
at $\sqrt{s_{NN}}$ = 2.76 TeV



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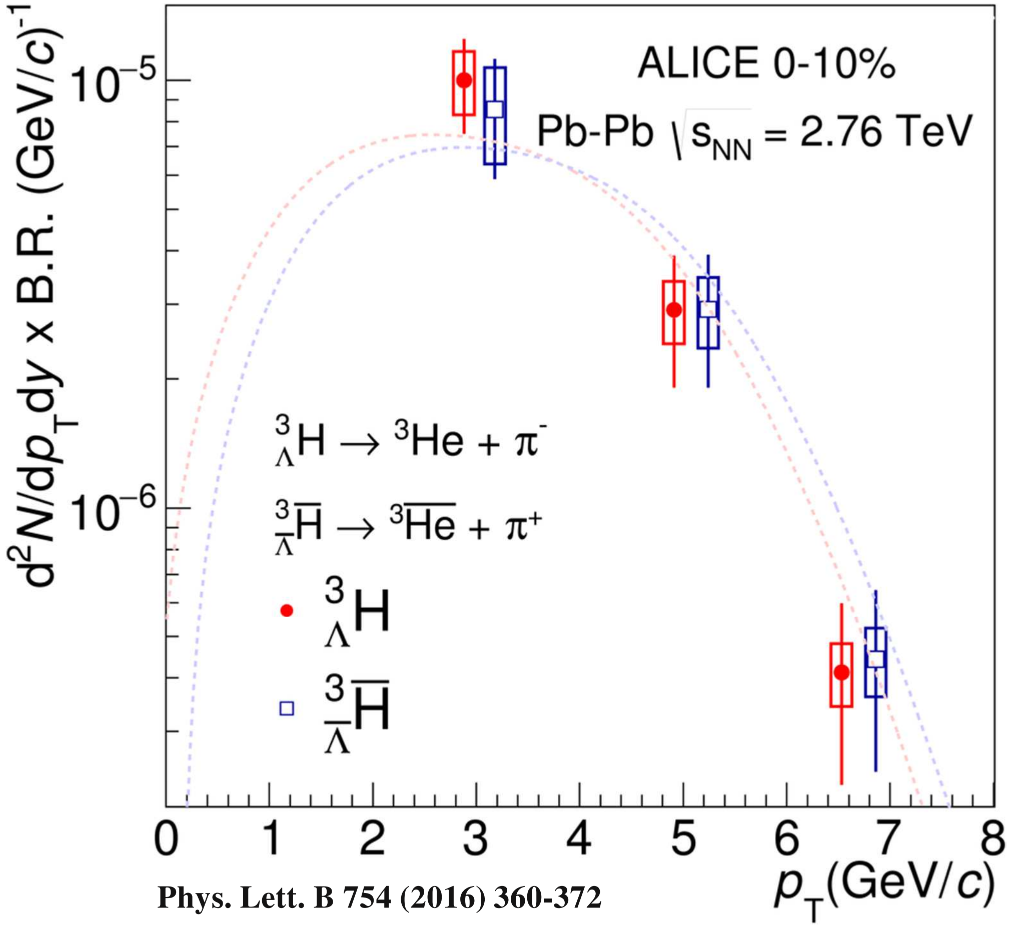
(ANTI-)HYPERTRITON YIELDS



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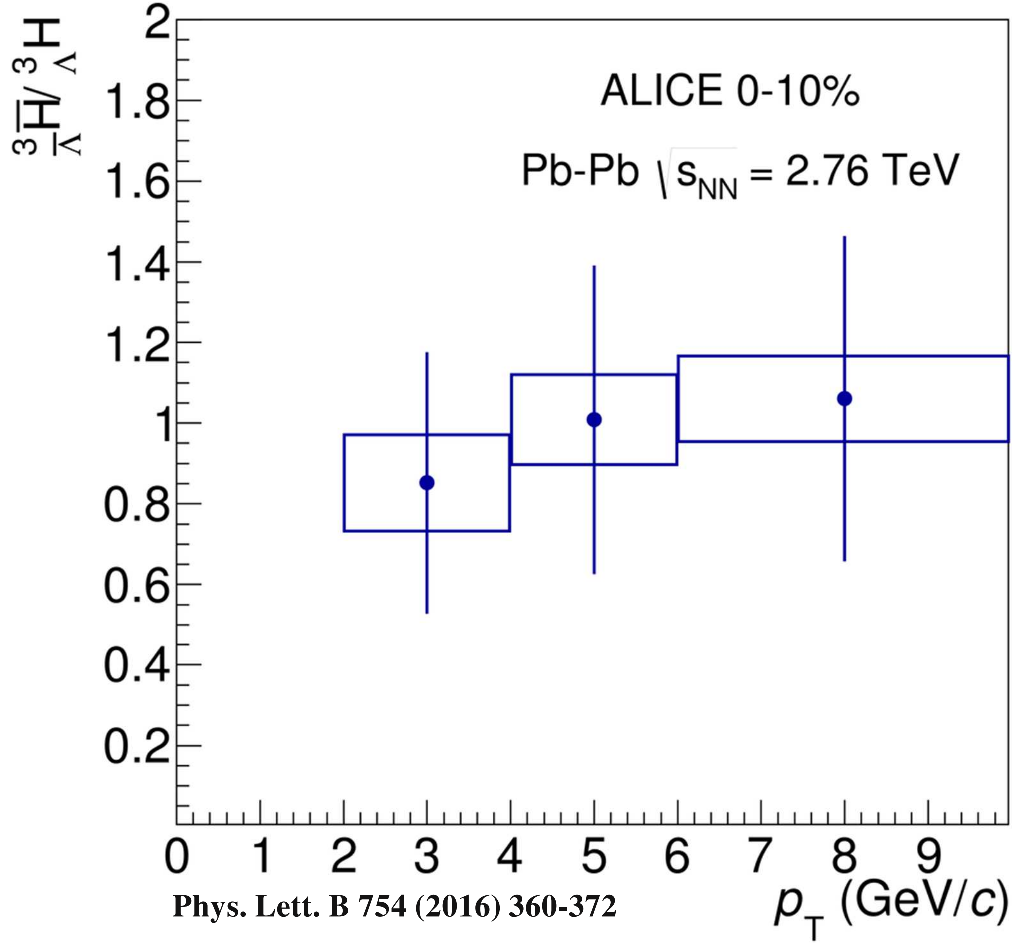

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d*N*/dy x B.R. ($^{3}_{\Lambda}H \rightarrow {}^{3}He\ \pi$) yield extracted in three p_T bins for central (0-10%) events for $^{3}_{\bar{\Lambda}}\bar{H}$ and $^{3}_{\Lambda}H$ separately

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)
COALESCENCE MODEL: $\bar{p}/p \sim \bar{\Lambda}/\Lambda \sim 1$

COMPARISON WITH THEORETICAL PREDICTIONS

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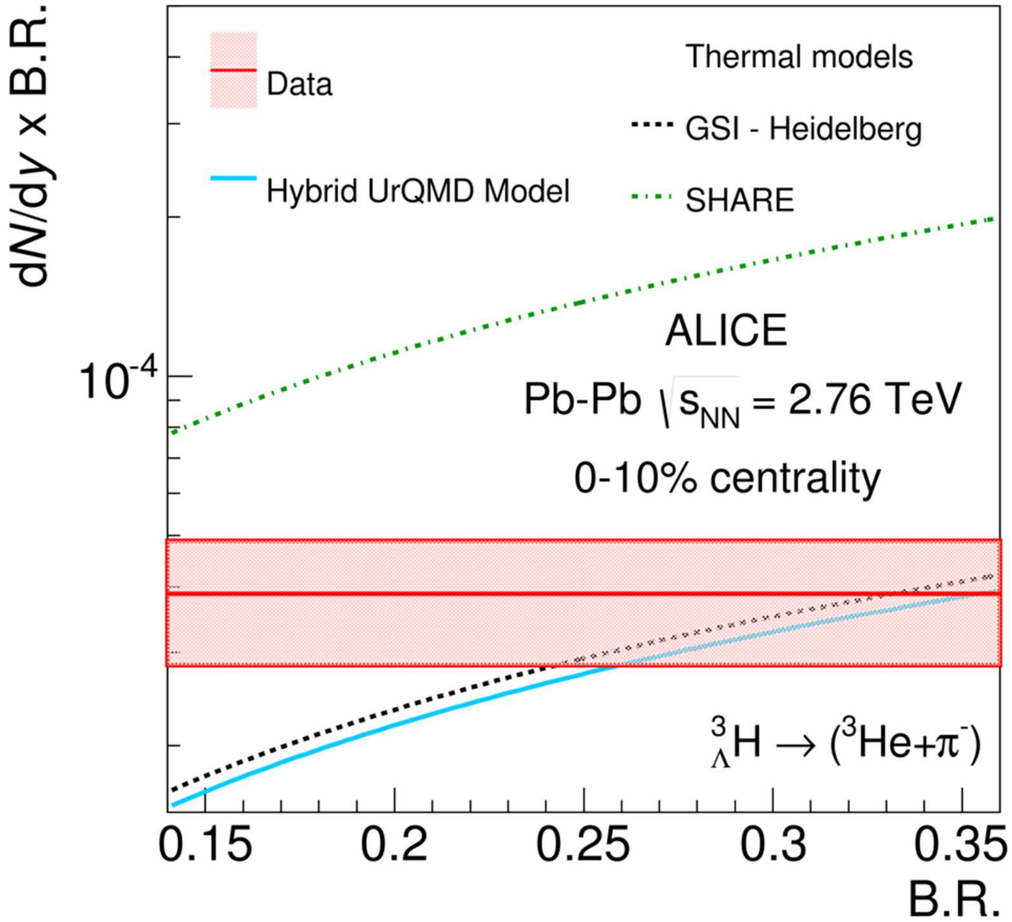


Three different theoretical predictions drawn as a function of BR($^{3}_{\Lambda}H \rightarrow {}^{3}He+\pi^{-}$) after being multiplied by BR:

- ✓ **Hybrid UrQMD**: combines the hadronic transport approach with an initial hydrodynamical stage for the hot and dense medium (**J. Steinheimer et al., Phys. Lett. B 714, 85 (2012)**)
- ✓ **GSI-Heidelberg**: equilibrium statistical model with T_{chem}=156 MeV (**A. Andronic et al., Phys. Lett. B 697, 203 (2011)**)
- – **SHARE**: non-equilibrium thermal model with T_{chem}=138.3 MeV (**M. Petráň et al., Phys. Rev. C 88, 034907 (2013)**)

- ➢ 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 and to Hybrid UrQMD

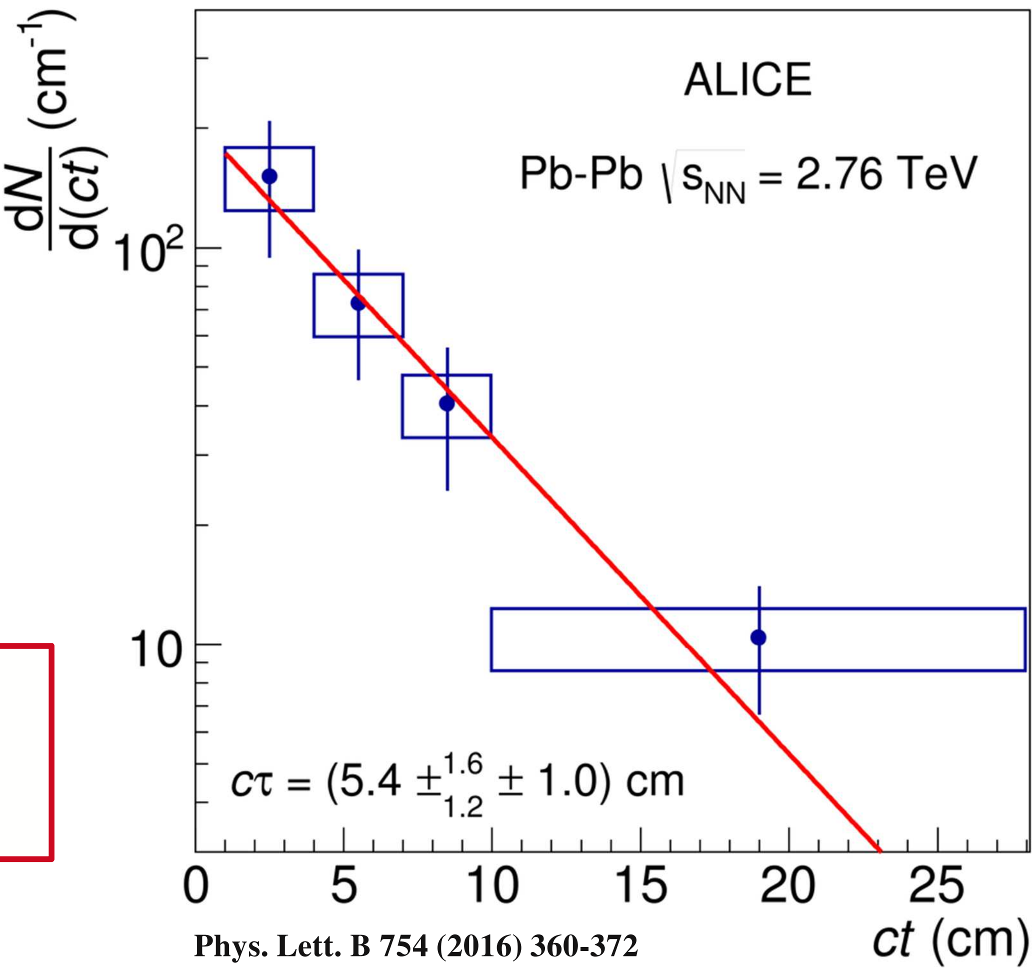
HYPERTRITON LIFETIME DETERMINATION

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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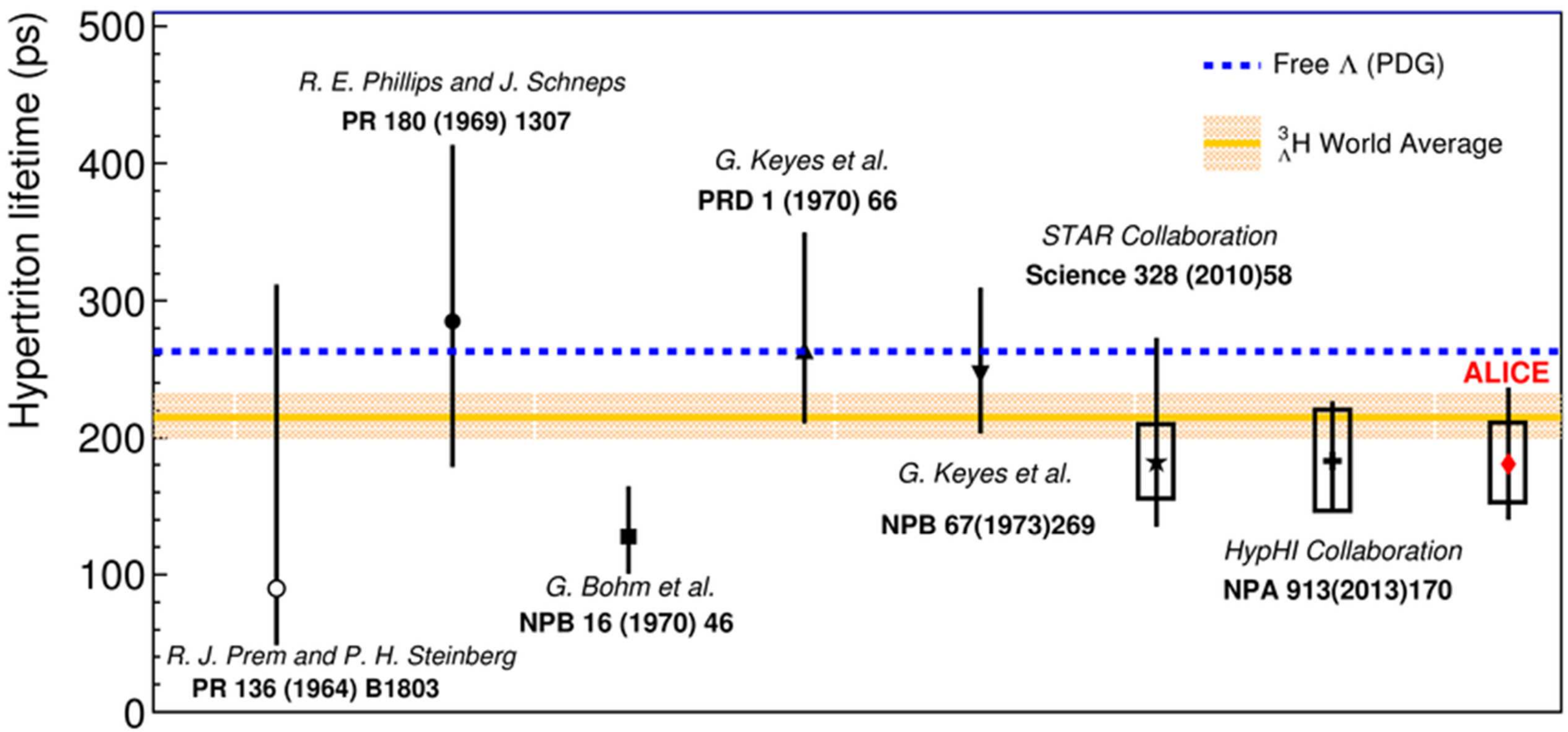
HYPERTRITON LIFETIME WORLD AVERAGE



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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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HYPERTRITON LIFETIME DETERMINATION

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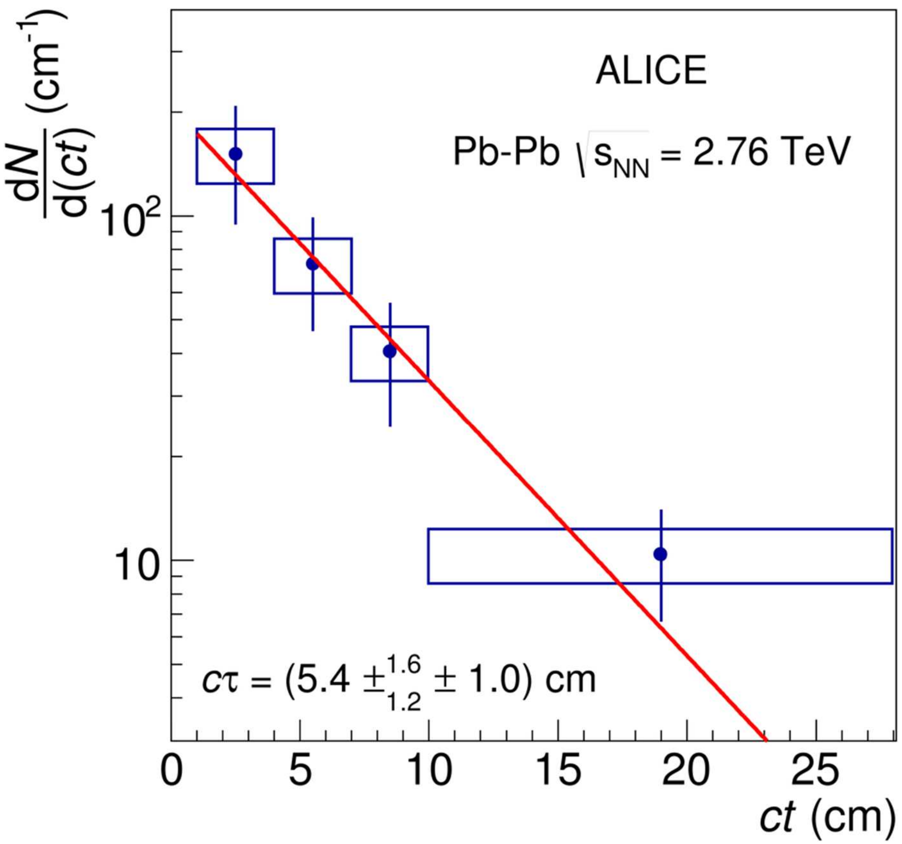
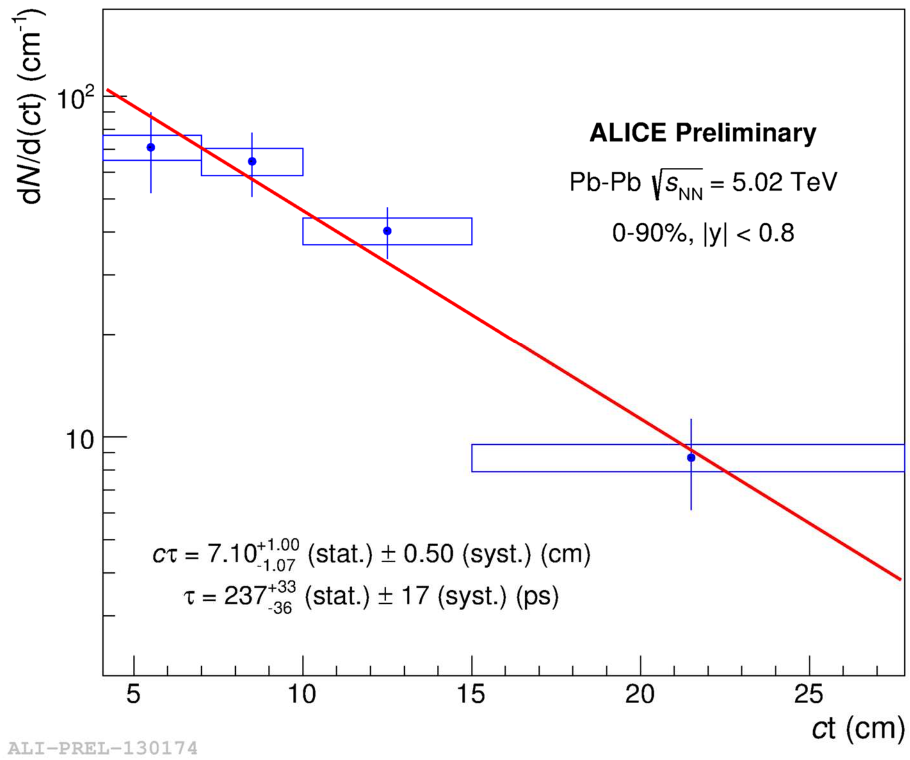


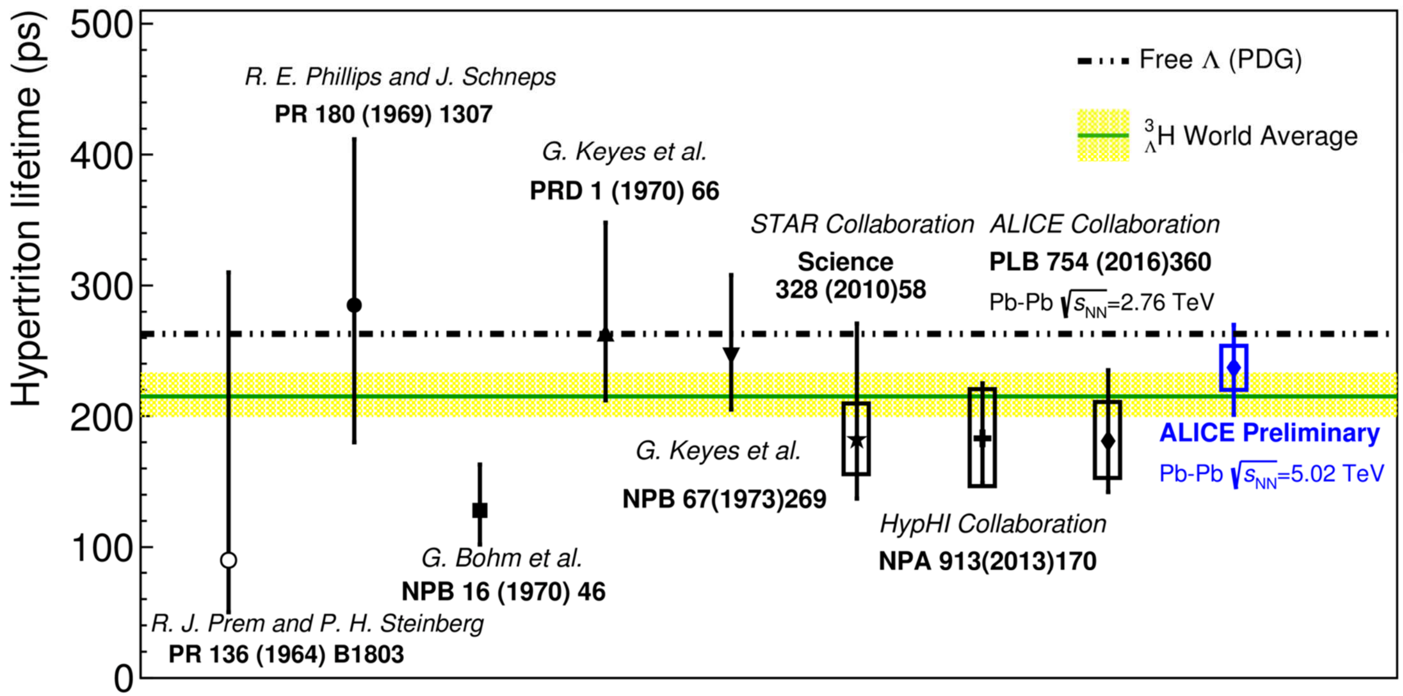
New preliminary results at $\sqrt{s_{NN}}$ = 5.02 TeV



$$c\tau = \left(5.4^{+1.6}_{-1.2}(stat.) \pm 1.00(syst.)\right) cm$$
$$\tau = \left(181^{+54}_{-39}(stat.) \pm 33(syst.)\right) ps$$

$$c\tau = \left(7.10^{+1.00}_{-1.07}(stat.) \pm 0.50(syst.)\right) cm$$
$$\tau = \left(237^{+33}_{-36}(stat.) \pm 17(syst.)\right) ps$$

HYPERTRITON LIFETIME WORLD AVERAGE



ALI-PREL-130195

- Previous heavy-ion experiment results show a trend well below the free Λ lifetime
- ALICE result from Pb-Pb at 5.02 TeV is closer to the free Λ
- More precision, reducing the statistical uncertainties can be reached:
  - Another Pb-Pb data sample will be collected in 2018 at the LHC:
    - ✓ the expected statistics for $^{3}_{\Lambda}$H is >~2x
    - ✓ lifetime in the 3-body decay channel

HYPERTRITON LIFETIME UNCERTAINITIES

ALICE

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

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

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

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 Pb-Pb during RUN2 (Nov. 2018) the expected statistics for $^{3}_{\Lambda}H$ is >2x

During the Long Shutdown 2 (2019-2020):

- **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 (2023) (*)
the expected Integrated Luminosity: ~10 nb^{-1}
the expected statistics for $^{3}_{\Lambda}H$ is ~200x

(*) 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

CONCLUSIONS

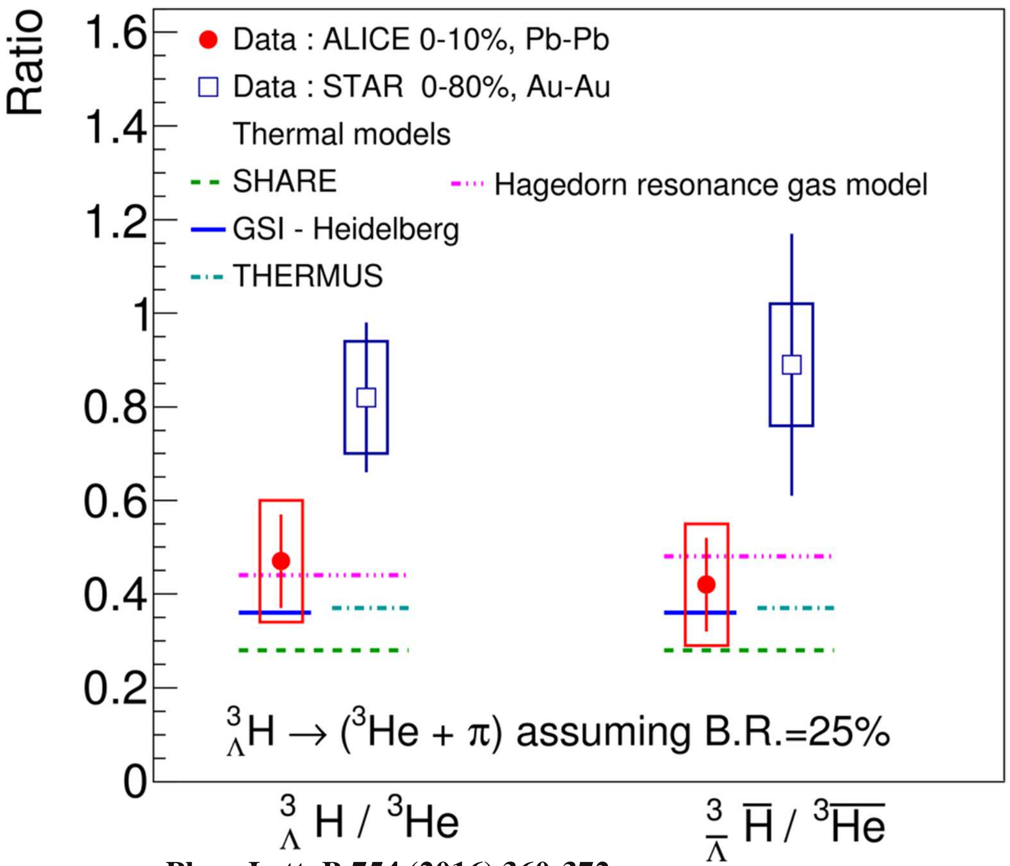
- ✓ Excellent ALICE performance allows for detection of light (anti-)nuclei and (anti-)hypernuclei
- ✓ Blast-Wave fits can be used to extrapolate the yields to the unmeasured p_T region of light hypernuclei in Pb-Pb.
- ✓ Hypertriton yield is in agreement with the current best thermal fit from equilibrium thermal model (T_{chem} = 156 ± 2 MeV)

- ✓ The excellent determination of primary and decay vertices allows for the measurement of lifetime via exponential fit of the proper decay time distribution
- ✓ Re-evaluation of the hypertrion lifetime world average
- ✓ ALICE preliminary result from Pb-Pb at 5.02 TeV is closer to the free Λ

- ✓ Future LHC runs, RUN2 and RUN3, and ALICE upgrades will allow for precise study of (anti)hypertriton production yield and lifetime

ALICE

(ANTI-)HYPERTRITON YIELDS RATIOS



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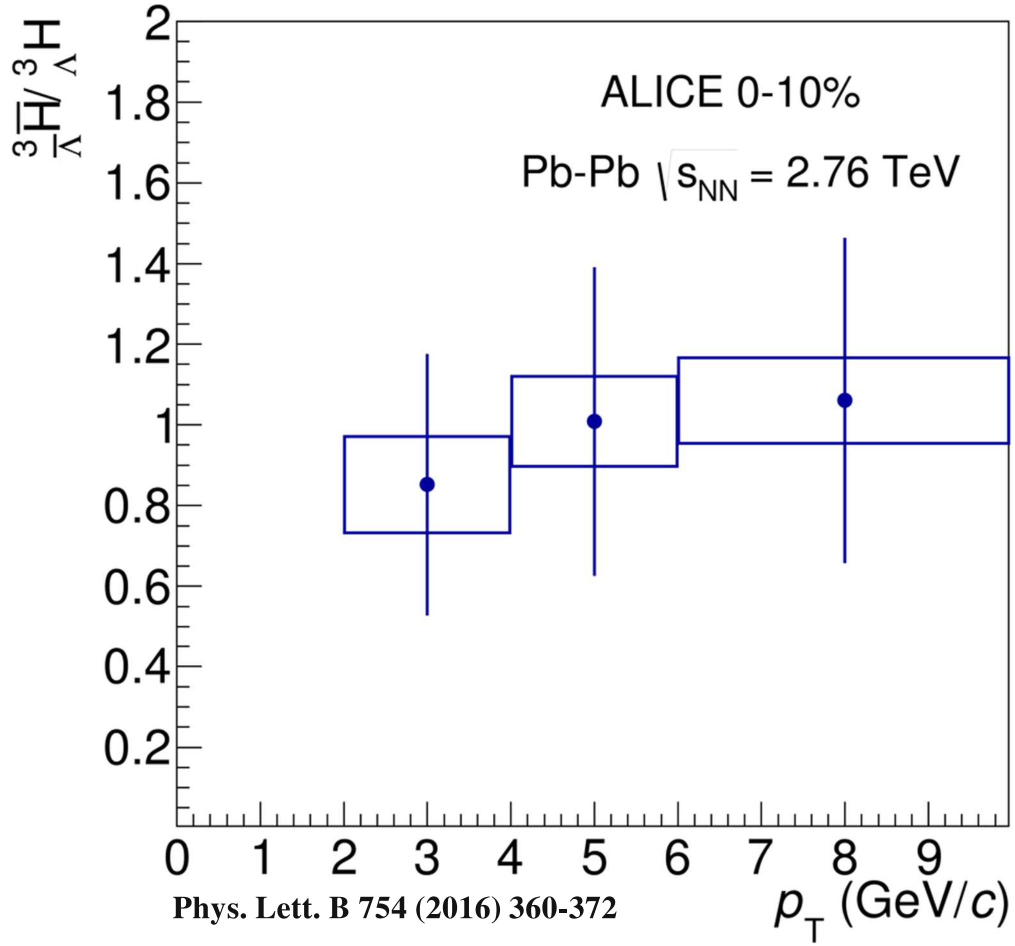

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Hypermatter / Matter Ratio
and
Anti-hypermatter/ Anti-matter Ratio

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

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

HYPERTRITON LIFETIME UNCERTAINITIES

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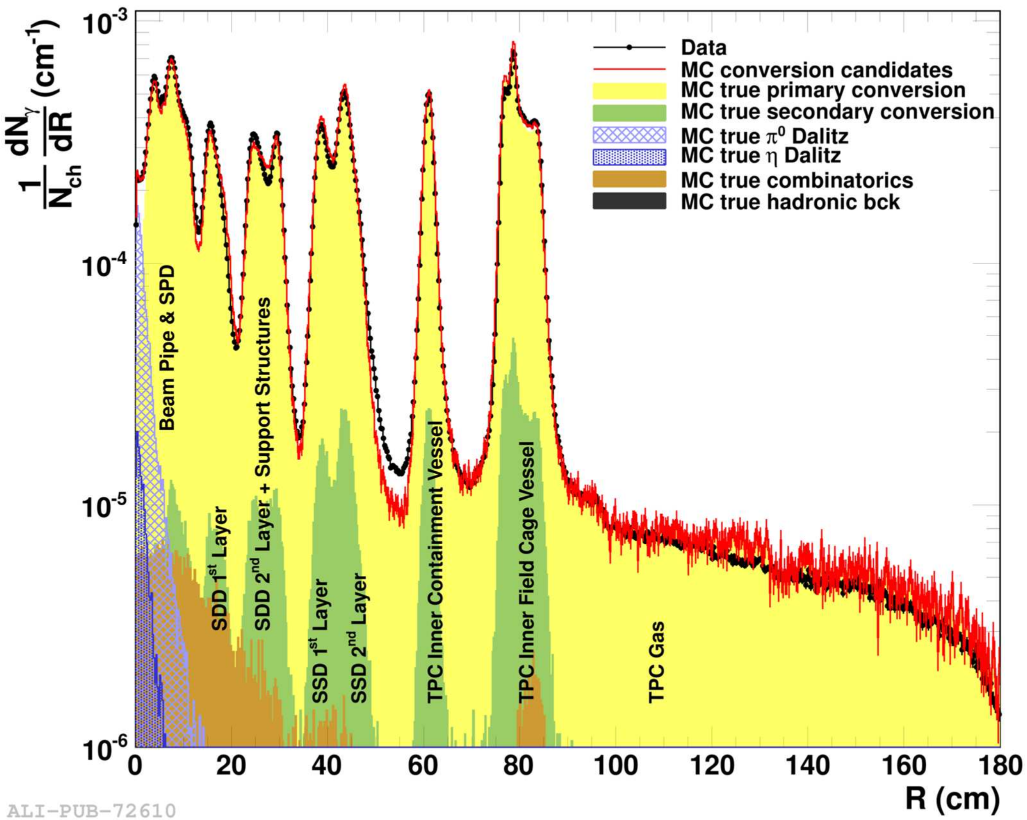
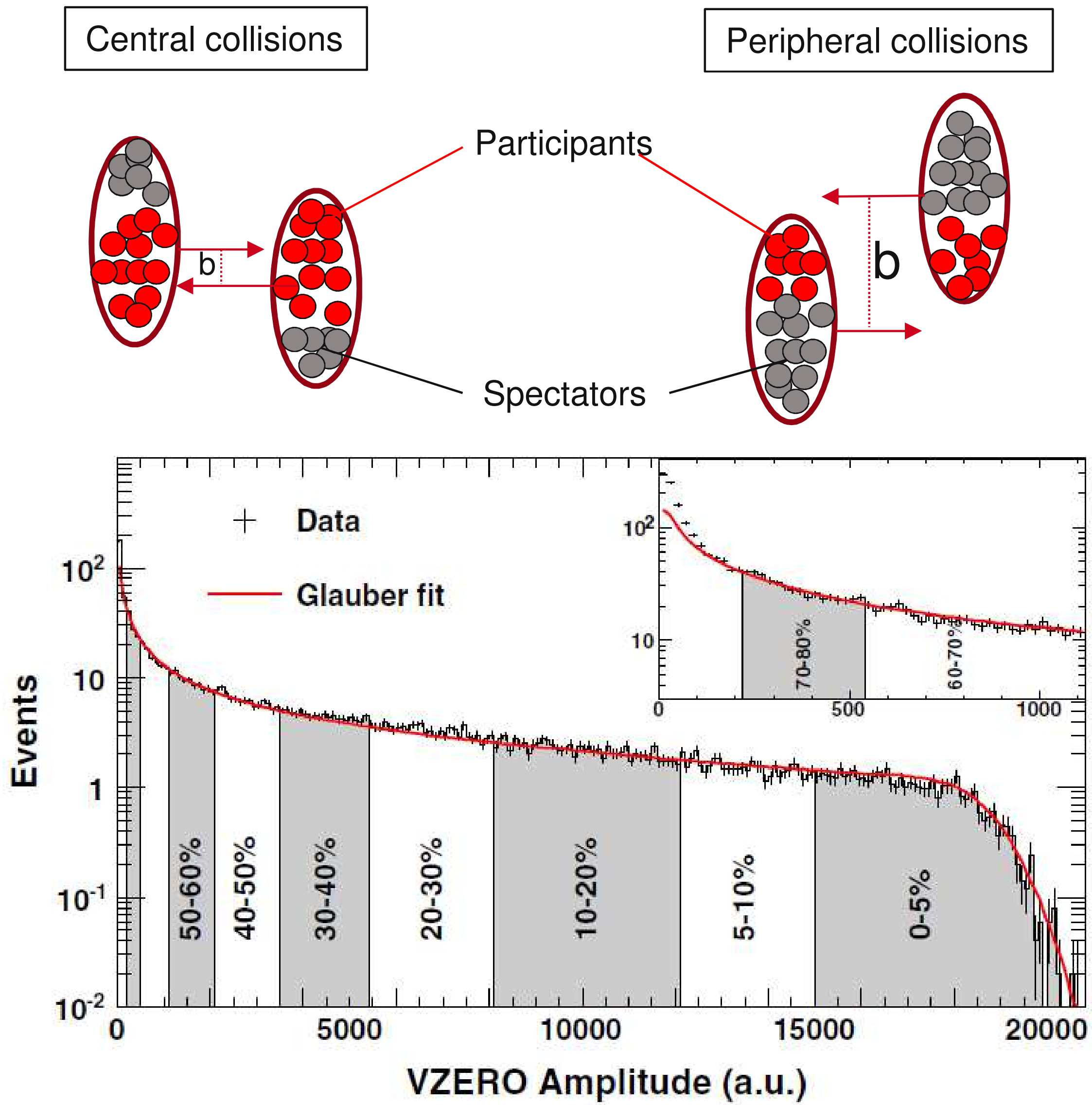


(anti)hypertriton absorption is not negligible:

- (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**

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