Production of hypernuclei in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with ALICE at the LHC

Ramona Lea
Dipartimento Di Fisica, Università di Trieste e INFN, Sezione Trieste
For the ALICE collaboration
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Strangeness in Quark Matter
Birmingham, 21-27/07/2013

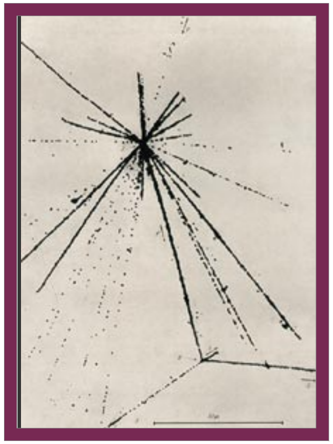
Outline

- Introduction to (double) Λ - hypernuclei
- Hypertriton ($^{3}_{\Lambda}H$) and H-Dibaryon
- ALICE detector and PID
- $^{3}_{\Lambda}H$ and $^{3}_{\bar{\Lambda}}\overline{H}$ signal in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
- $^{3}_{\Lambda}H$ in $c\tau$ bins
- H-Dibaryon search with ALICE
- Conclusions and Outlook

Hypernuclei

A hypernucleus is a nucleus which contains at least one hyperon (a baryon containing one or more strange quarks) in addition to nucleons.

Photographic emulsion
(M. Danysz and J. Pniewski, Phil. Mag. 44 (1953) 348)



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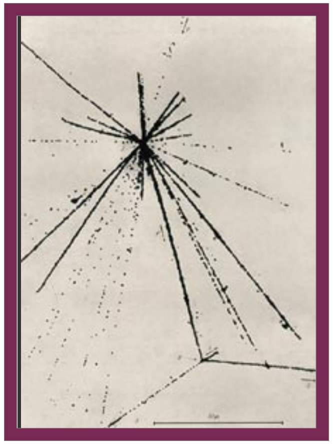
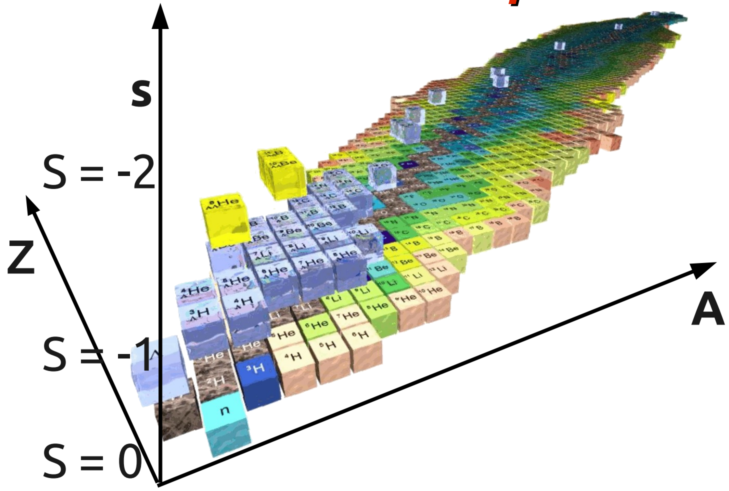


1952: first observation of hypernuclear decay from cosmic rays data.

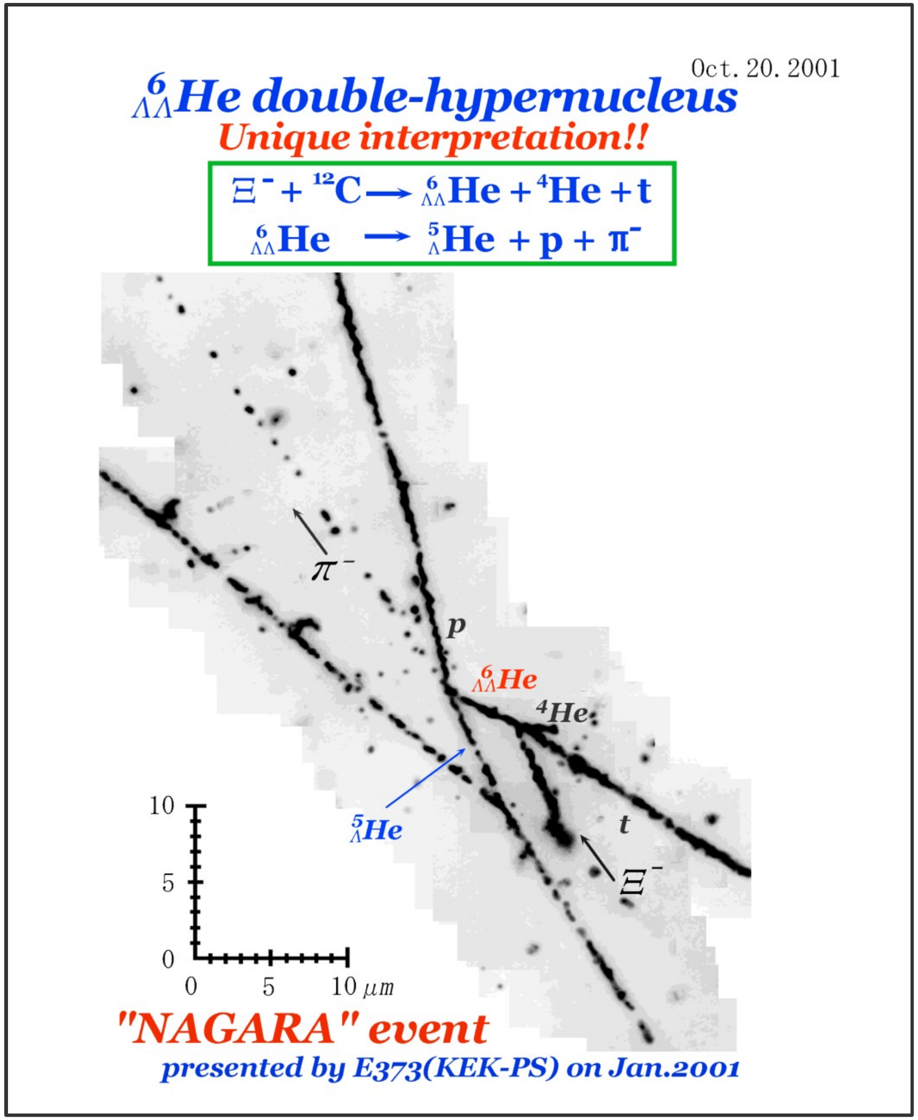
Main goals of hypenuclear physics:
- Extension of nuclear chart;
- Understand the baryon-baryon interaction in strangeness sector;
- Study the structure of multi-strange systems

3D nuclear landscape



http://wwwa1.kph.uni-mainz.de/Hyp2006/poster.html

ΛΛ hypernuclei



Oct. 20. 2001

$^{6}_{\Lambda\Lambda}$He double-hypernucleus

Unique interpretation!!

$$\Xi^- + {}^{12}C \longrightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$$

$$^{6}_{\Lambda\Lambda}He \longrightarrow {}^{5}_{\Lambda}He + p + \pi^-$$

"NAGARA" event

presented by E373(KEK-PS) on Jan.2001

Double-Λ hypernuclei

- have been observed in 1963 by Danysz et al.
- give valid experimental constraint on the possible binding energy of the H-Dibaryon or the ΛΛ bound state
- In total only 7 candidate events worldwide
- Most prominent example is the “NAGARA” event which is restricting the binding of the H-Dibaryon energy from the experimental side

Hypernuclei production

In high-energy heavy-ion collisions the cluster is formed at the freeze-out of the system.

The production yield can be estimated using:

- coalescence mechanism
- thermal models

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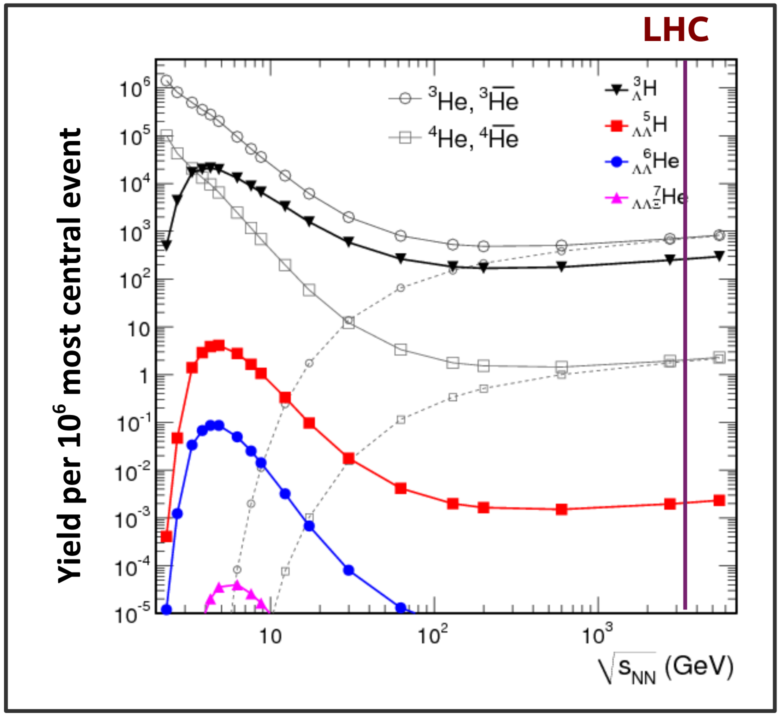

A=3

A=4

A=5

A.Andronic et al., PLB 697, 203 (2011)

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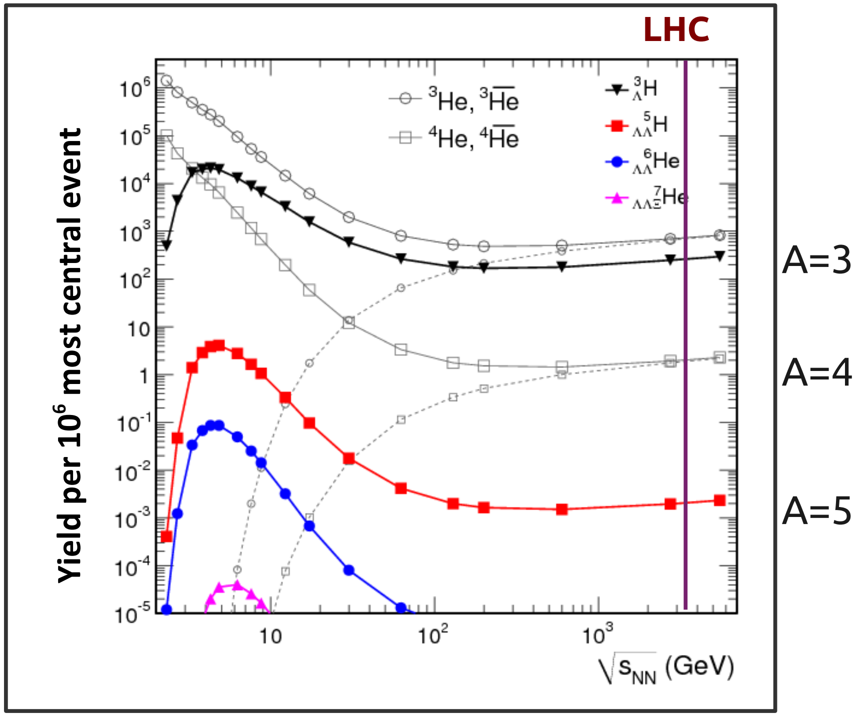

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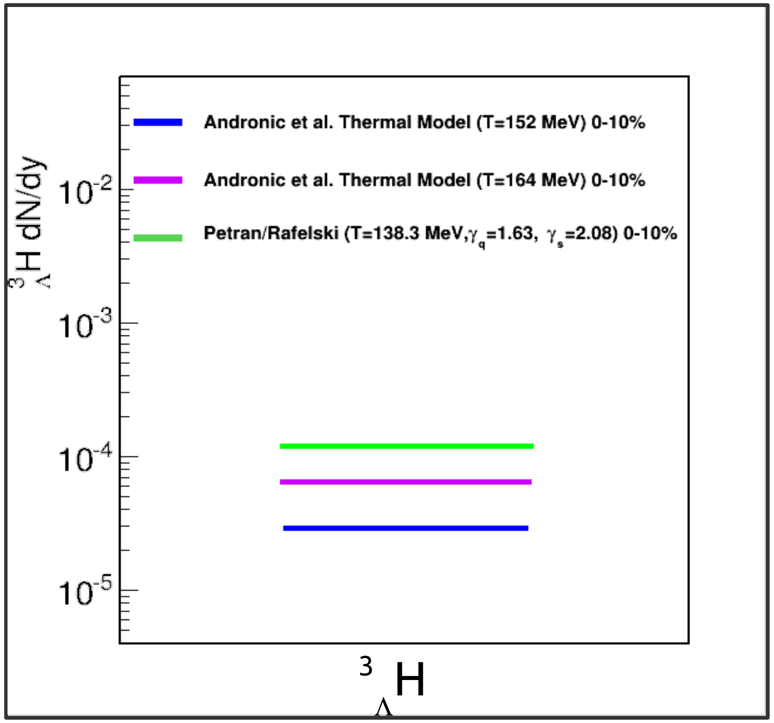
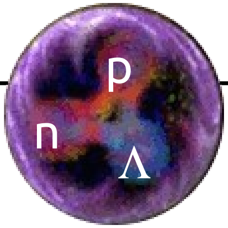


🟦 A.Andronic, private communication
🟪 A.Andronic *et al.*, PLB 697, 203 (2011)
🟩 J.Rafelski *et al.* ArXiv:1303.2098v1

In a thermal model scenario, the hypernuclei production yield is sensitive to temperature and γ_s.

Measurements of $^{3}_{\Lambda}$H



($^{3}_{\Lambda}\overline{\text{H}}$) $^{3}_{\Lambda}$H is the lightest known hypernucleus and is formed by (p,n,Λ).

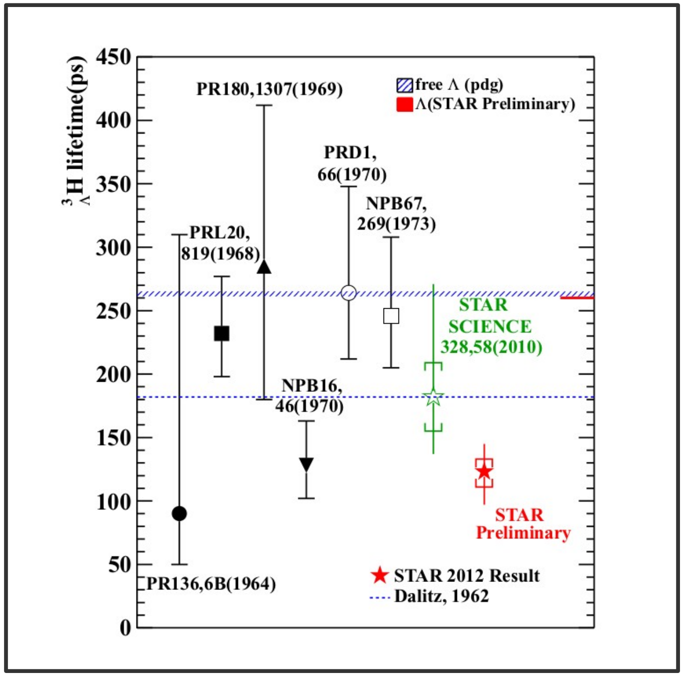
Mass = 2.991 GeV/c^2

B_{Λ} = 0.13 ± 0.05 MeV

Lifetime ~ 263 ps

($^{3}_{\Lambda}\overline{\text{H}}$) $^{3}_{\Lambda}$H is unstable under weak decay.
Possible (anti)hypertriton decay modes:

$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-} \qquad {}^{3}_{\Lambda}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+}$$
$$^{3}_{\Lambda}H \rightarrow {}^{3}H + \pi^{0} \qquad {}^{3}_{\Lambda}\overline{H} \rightarrow {}^{3}\overline{H} + \pi^{0}$$
$$^{3}_{\Lambda}H \rightarrow d + p + \pi^{-} \qquad {}^{3}_{\Lambda}\overline{H} \rightarrow \overline{d} + \overline{p} + \pi^{+}$$
$$^{3}_{\Lambda}H \rightarrow d + n + \pi^{0} \qquad {}^{3}_{\Lambda}\overline{H} \rightarrow \overline{d} + \overline{n} + \pi^{0}$$



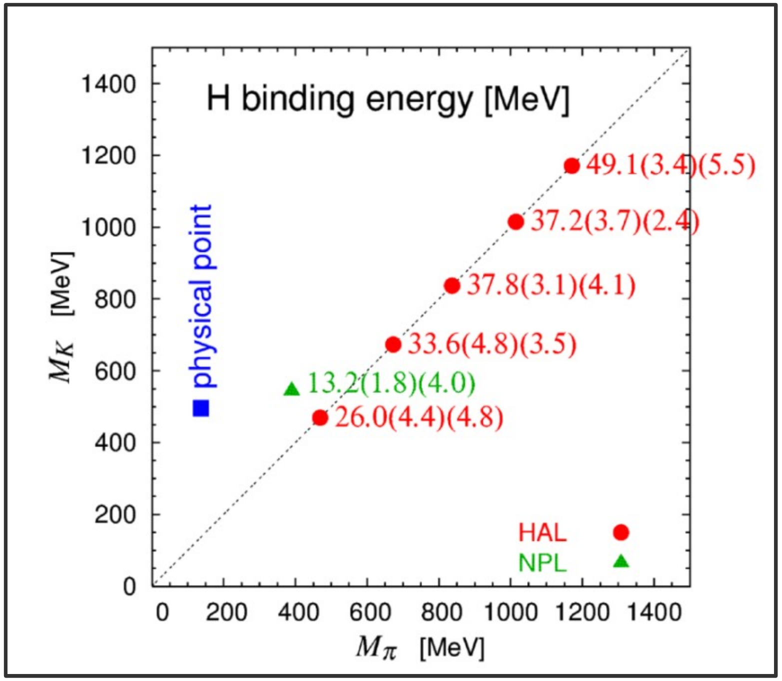
Nuclear Physics A 904-905 (2013)551c -554c

H-Dibaryon

- Hypothetical bound state of *uuddss* (ΛΛ)
- First predicted by Jaffe in a bag model calculation (***Jaffe, PRL 38, 195 + 617 (1977)***)
- Recent lattice calculations suggest (***Inoue et al., PRL 106, 162001 (2011) and Beane et al., PRL 106, 162002 (2011)***) a bound state (20-50 MeV/c^2 or 13 MeV/c^2)

- ***Shanahan et al., PRL 107, 092004 (2011)*** **and** ***Heidenbauer, Meißner, PLB 706, 100 (2011)*** made chiral extrapolation to a physical pion mass and got as result:
  - the H is unbound by 13±14 MeV/c^2, respectively lies close to the Ξp threshold

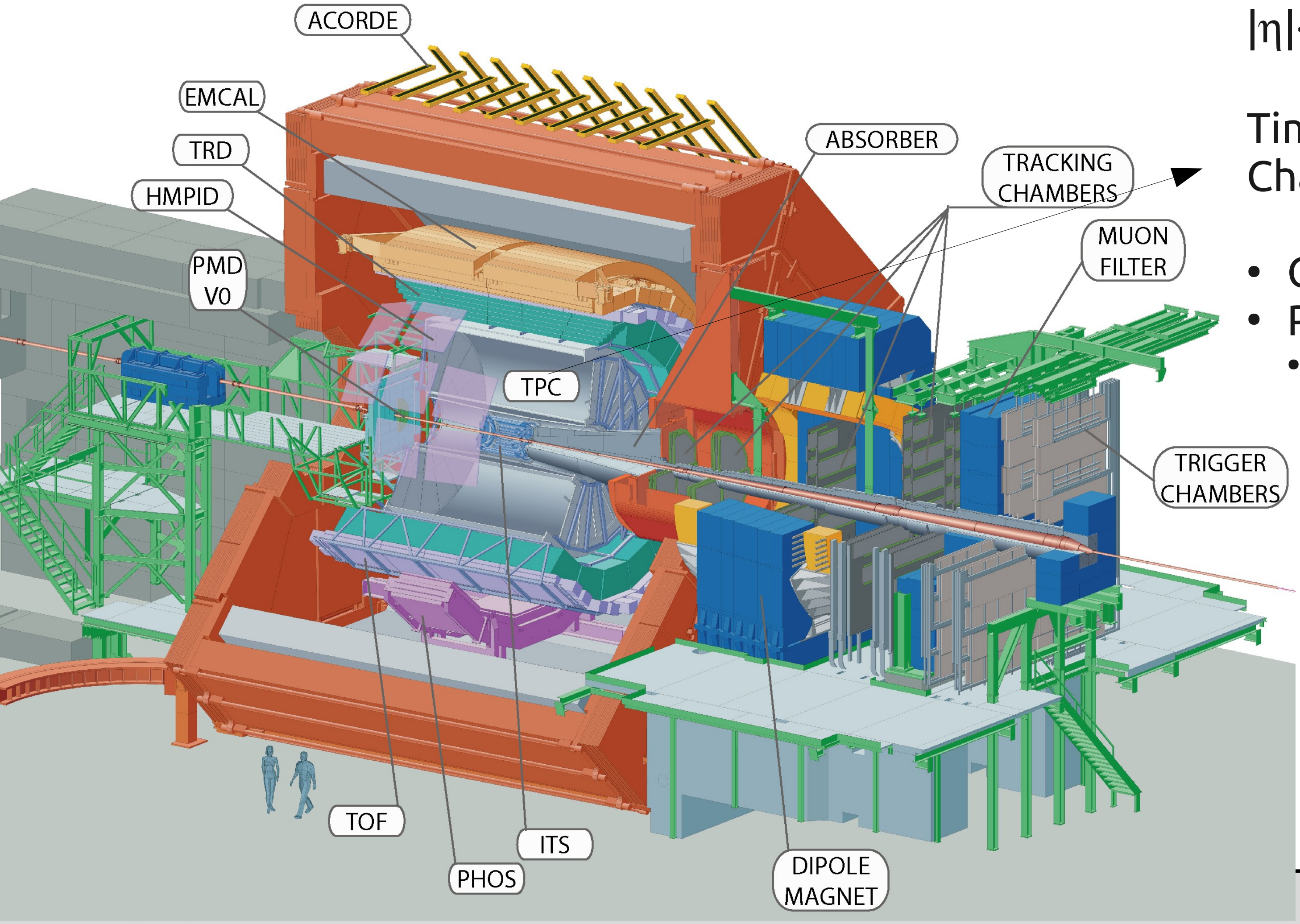
→ Renewed interest in experimental searches



T. Inoue, private communication

ALICE

ALICE particle identification capabilities are unique. Almost all known techniques are exploited: dE/dx, Time Of Flight, Transition Radiation, Cherenkov Radiation, calorimetry and topological decay (V0, cascade).



Central Barrel :
$|\eta| < 0.9$; B = 0.5 T

Time Projection Chamber (TPC):

- Global tracking;
- PID via dE/dx
  - dE/dx resolution in central Pb-Pb collisions: 7.2% (2011).

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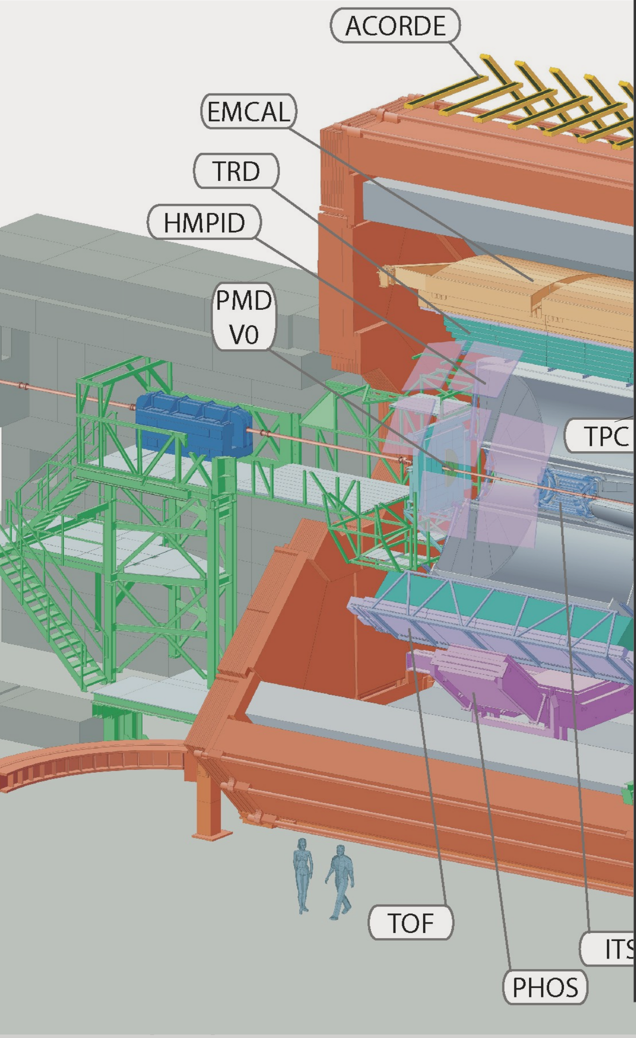
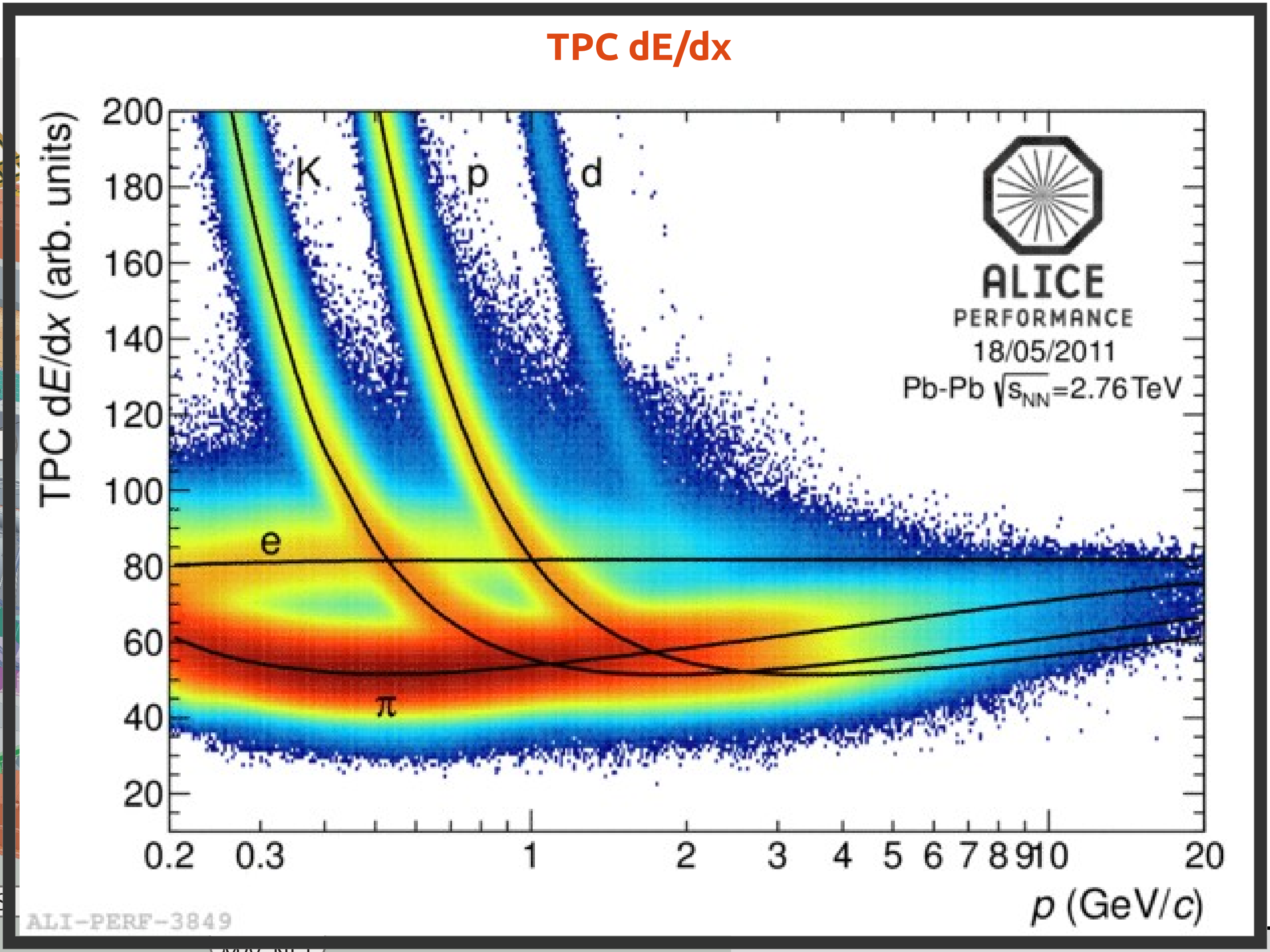




$({}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}})\,{}^{3}_{\Lambda}\mathrm{H}$ analysis

Analysis Technique

DATA SAMPLE:

Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV collected by ALICE during 2011.

Events selected for the analysis:

~21 x 10^6 central events (0-10%)

~18 x 10^6 semi-central events (10-50%)

ANALYSIS METHOD:

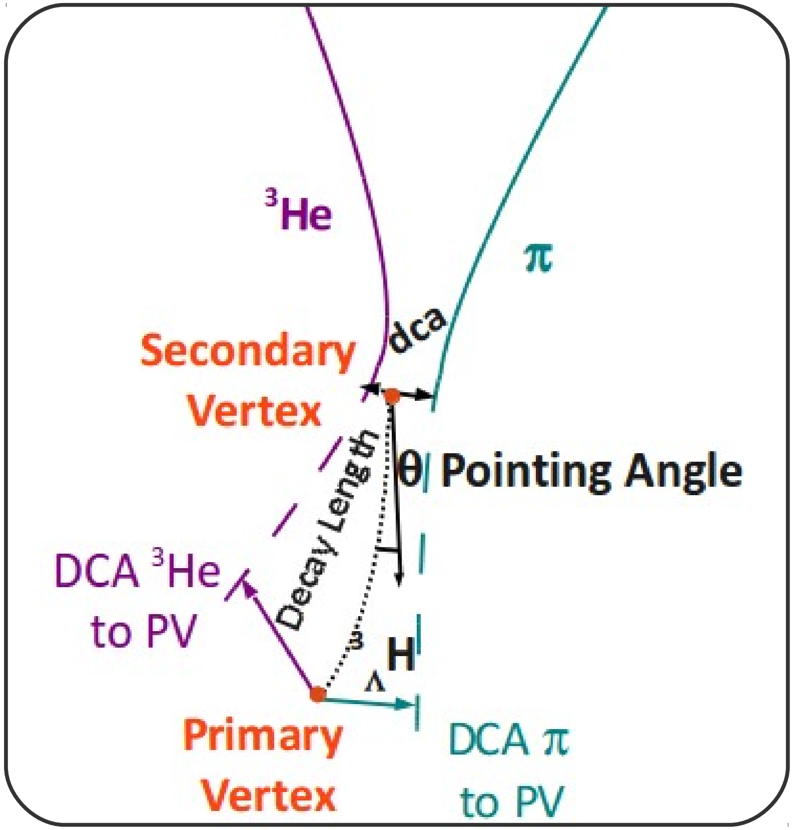
Find pion and ^{3}He pairs and apply appropriate topological cuts

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
- $|y| \leq 1$
- cτ > 1 cm

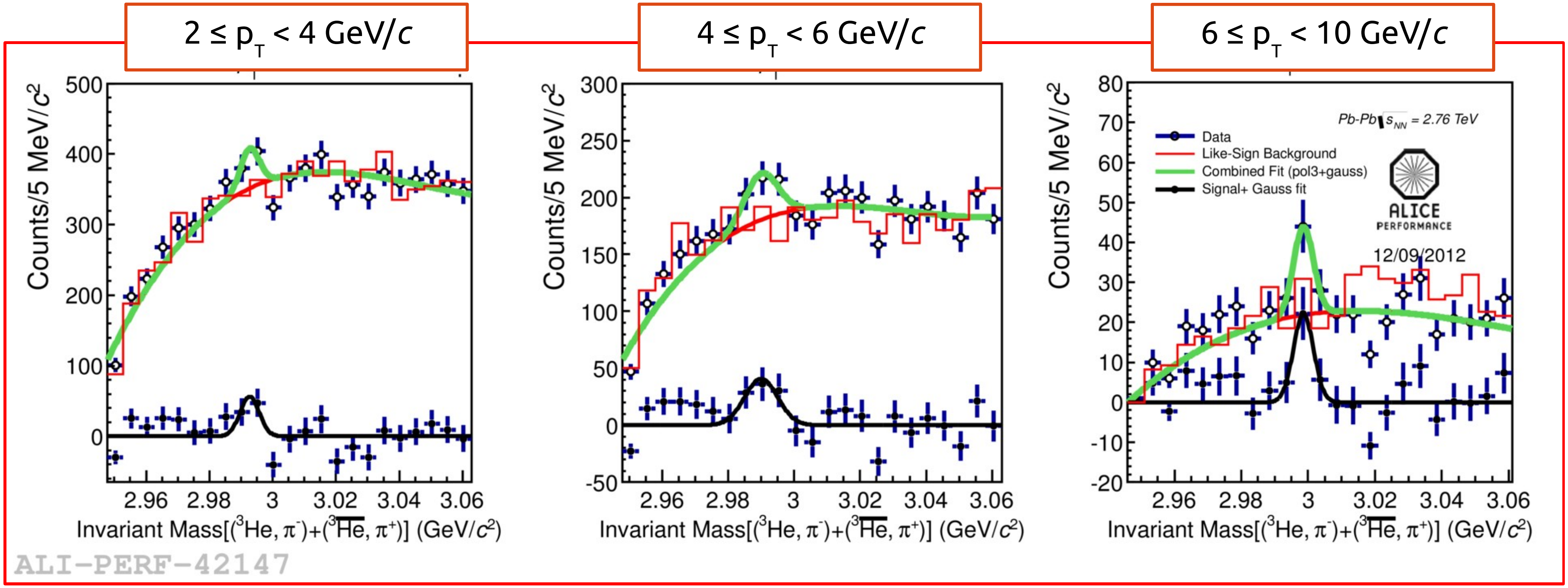
$$ {}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-} $$

$$ {}^{3}_{\bar{\Lambda}}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+} $$



Invariant Mass Distributions vs p_T

$[(^3He,\pi^-) + (^3\overline{He},\pi^+)]$ Invariant Mass spectrum : **Central Events (0-10%)**


$2 \le p_T < 4$ GeV/c

$4 \le p_T < 6$ GeV/c

$6 \le p_T < 10$ GeV/c

$\mu = 2.993 \pm 0.001$ GeV/c^2
$\sigma = (3.00 \pm 1.5) \times 10^{-3}$ GeV/c^2

$\mu = 2.990 \pm 0.002$ GeV/c^2
$\sigma = (4.00 \pm 1.7) \times 10^{-3}$ GeV/c^2

$\mu = 2.998 \pm 0.002$ GeV/c^2
$\sigma = (3.00 \pm 1.6) \times 10^{-3}$ GeV/c^2

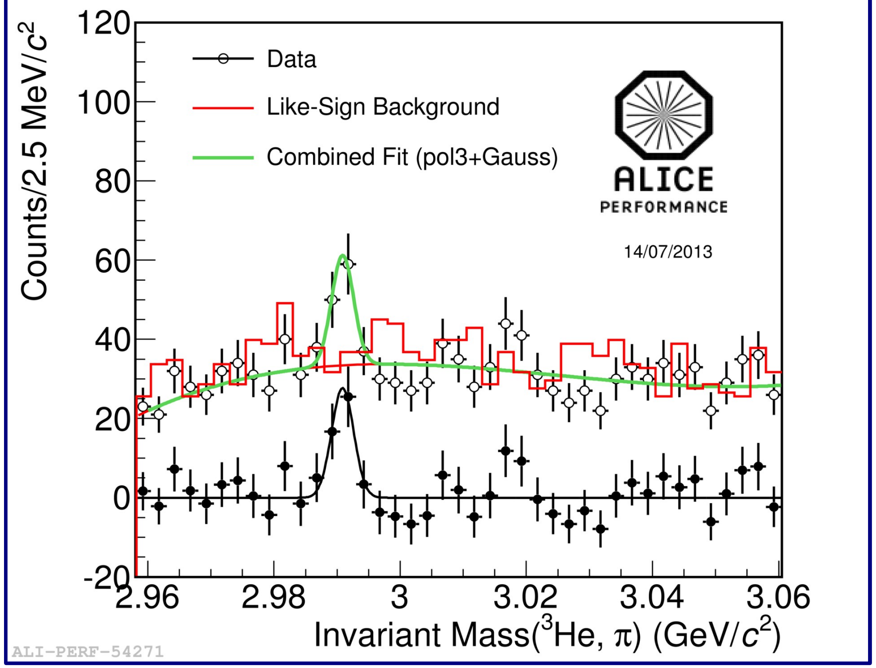
Number of selected events:
~20 x 10^6

Stat. Uncertainties Only

Invariant Mass Distributions

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

p_T integrated invariant mass spectrum



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

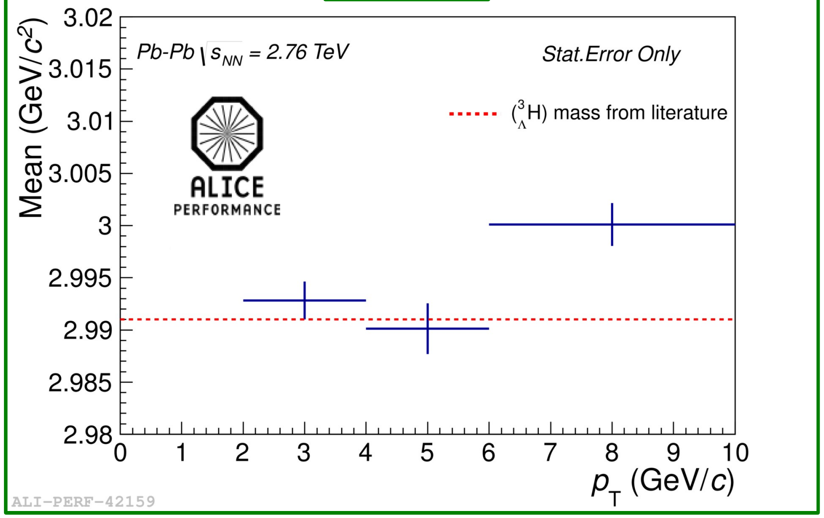
Number of selected events:
~18 x 10^6

$^{3}_{\Lambda}\mathrm{H}$ and $^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$: μ and σ vs p_{T}

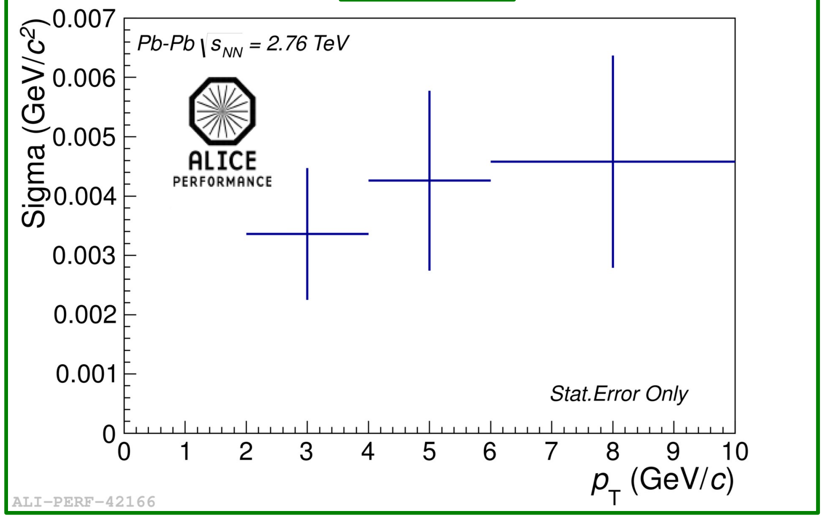
Quality checks on the stability of mean and width of (anti)hypertriton vs pT.
Only statistical errors shown.

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

Mean

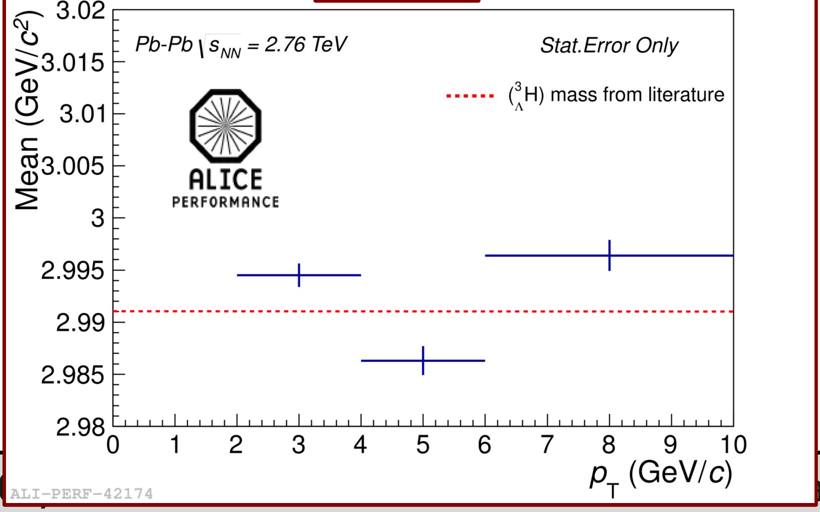


Width

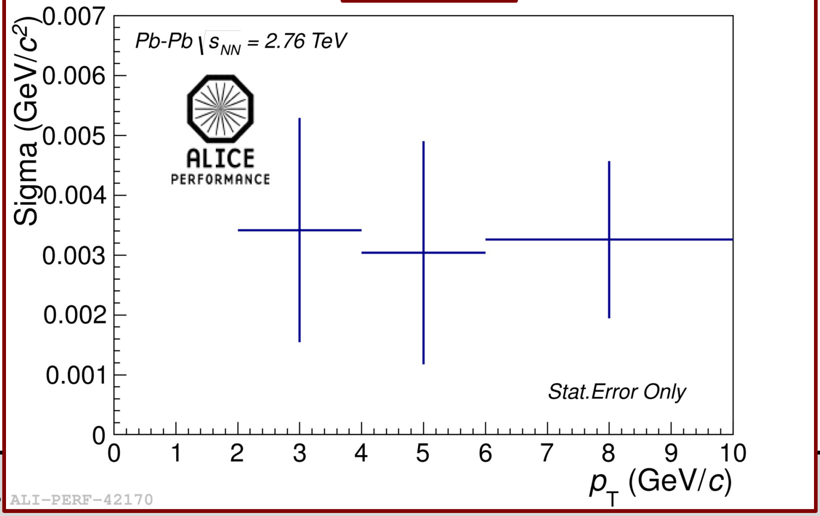


$^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$

Mean

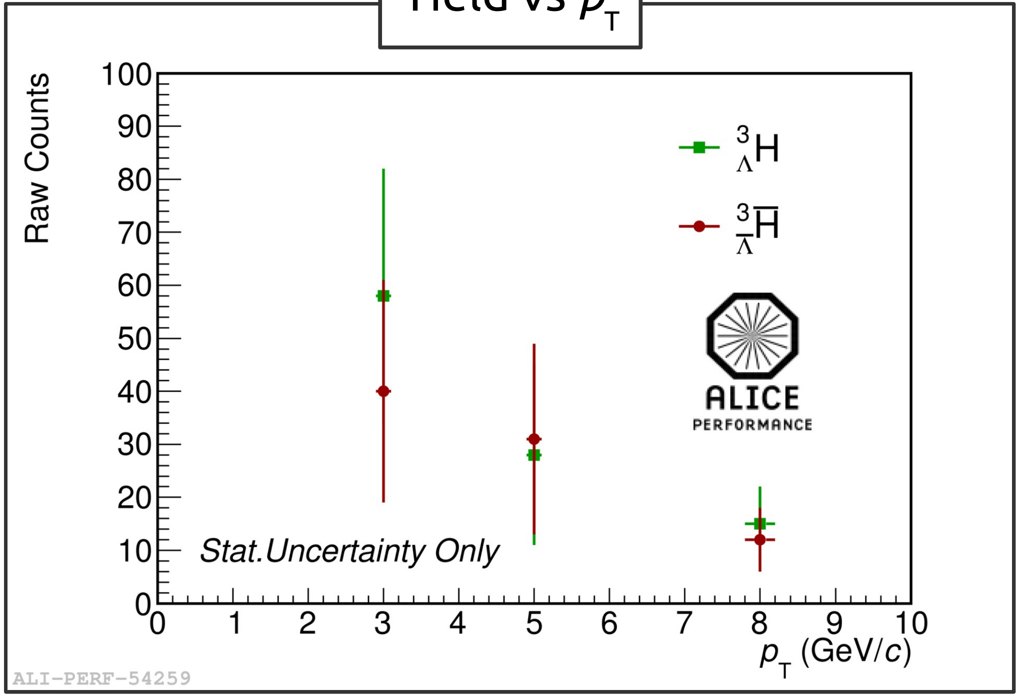


Width

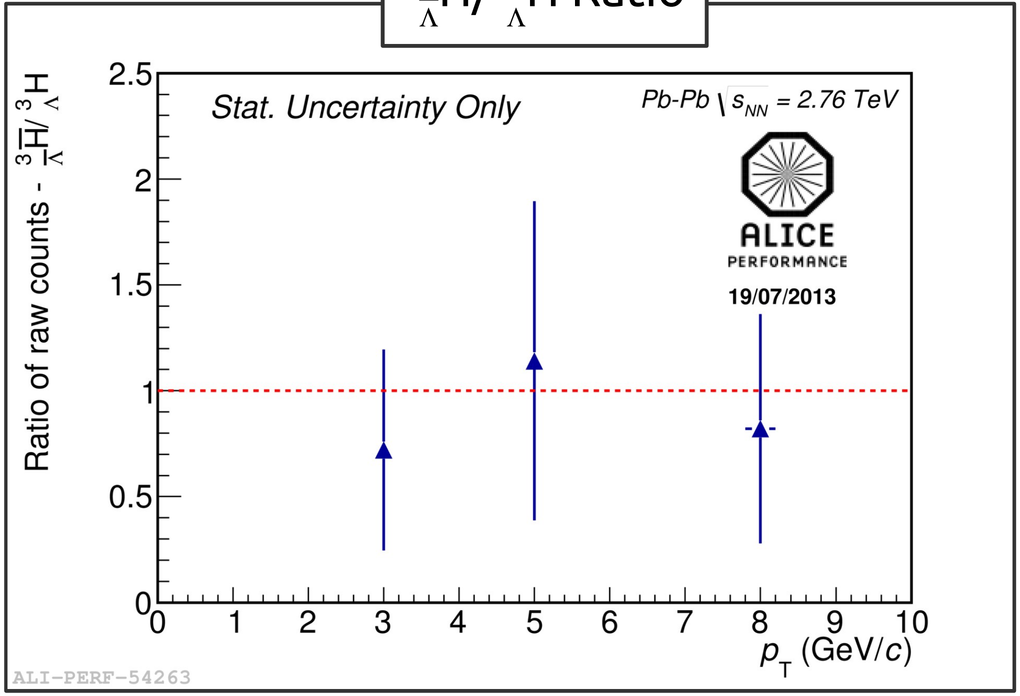


${}^{3}_{\Lambda}$H and ${}^{3}_{\bar{\Lambda}}\overline{\text{H}}$ vs p_T: Counts and ratio

Yield vs p_T

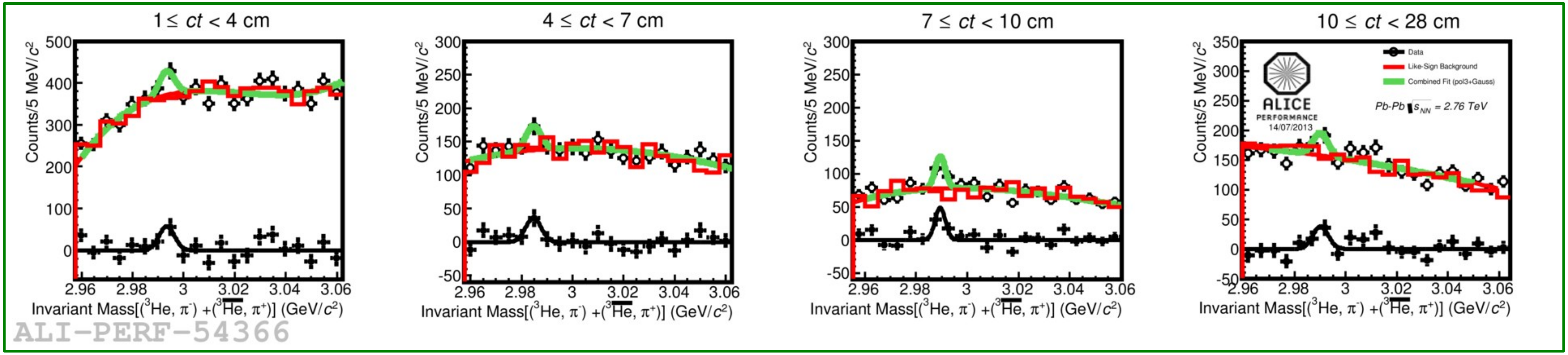


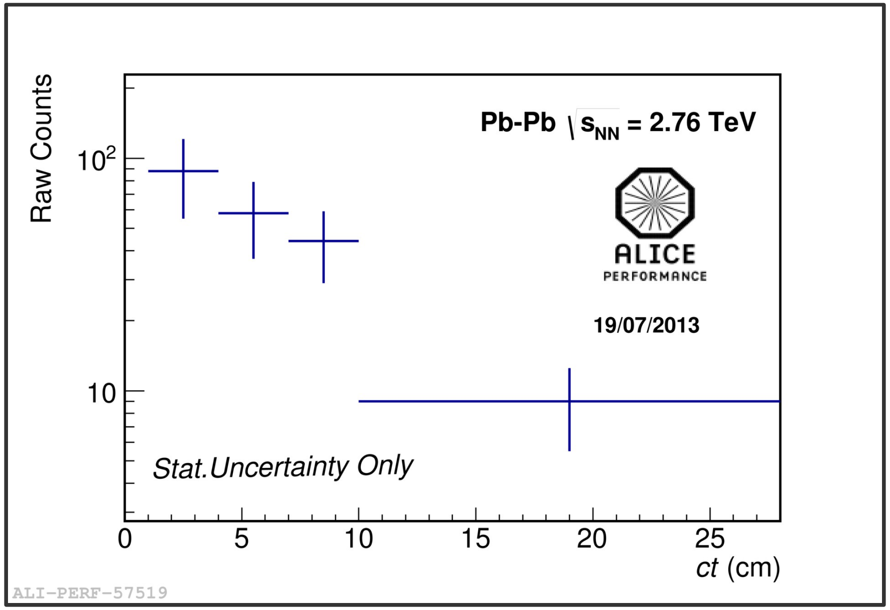
${}^{3}_{\bar{\Lambda}}\overline{\text{H}}/{}^{3}_{\Lambda}$H Ratio



Raw ratio consistent with 1

$^{3}_{\Lambda}$H Lifetime determination





$$N(t)=N(0)e^{\frac{-t}{\tau}}=N(0)e^{-\frac{\frac{l}{\beta\gamma}}{c\tau}}$$

ct is defined as:
ct = mL/p (cm)

Efficiency correction ongoing to get corrected lifetime

H-Dibaryon search

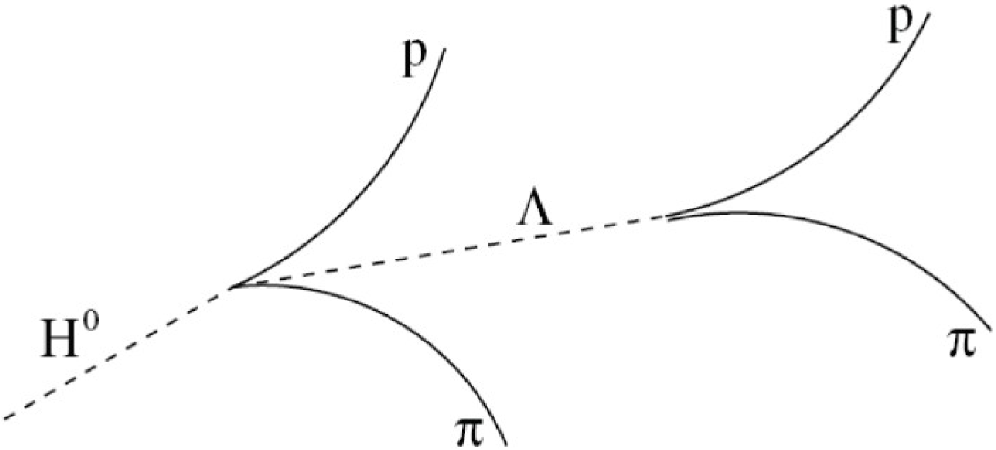
DATA SAMPLE:
Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV collected by ALICE during 2010.

Events selected for the analysis:
~14 x 10^6 Minimum bias events (0-80%)

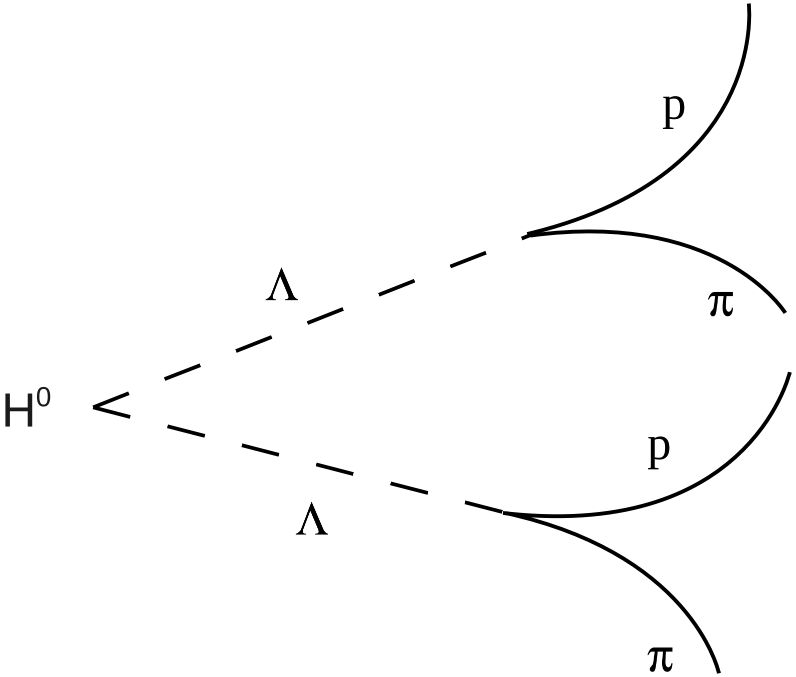
H-Dibaryon

Two cases:

- $m_H < \Lambda\Lambda$ threshold
  - weakly bound:
    measurable channel
    $H \rightarrow \Lambda p \pi$
  - $2.2\ \mathrm{GeV}/c^2 < m_H < 2.231\ \mathrm{GeV}/c^2$



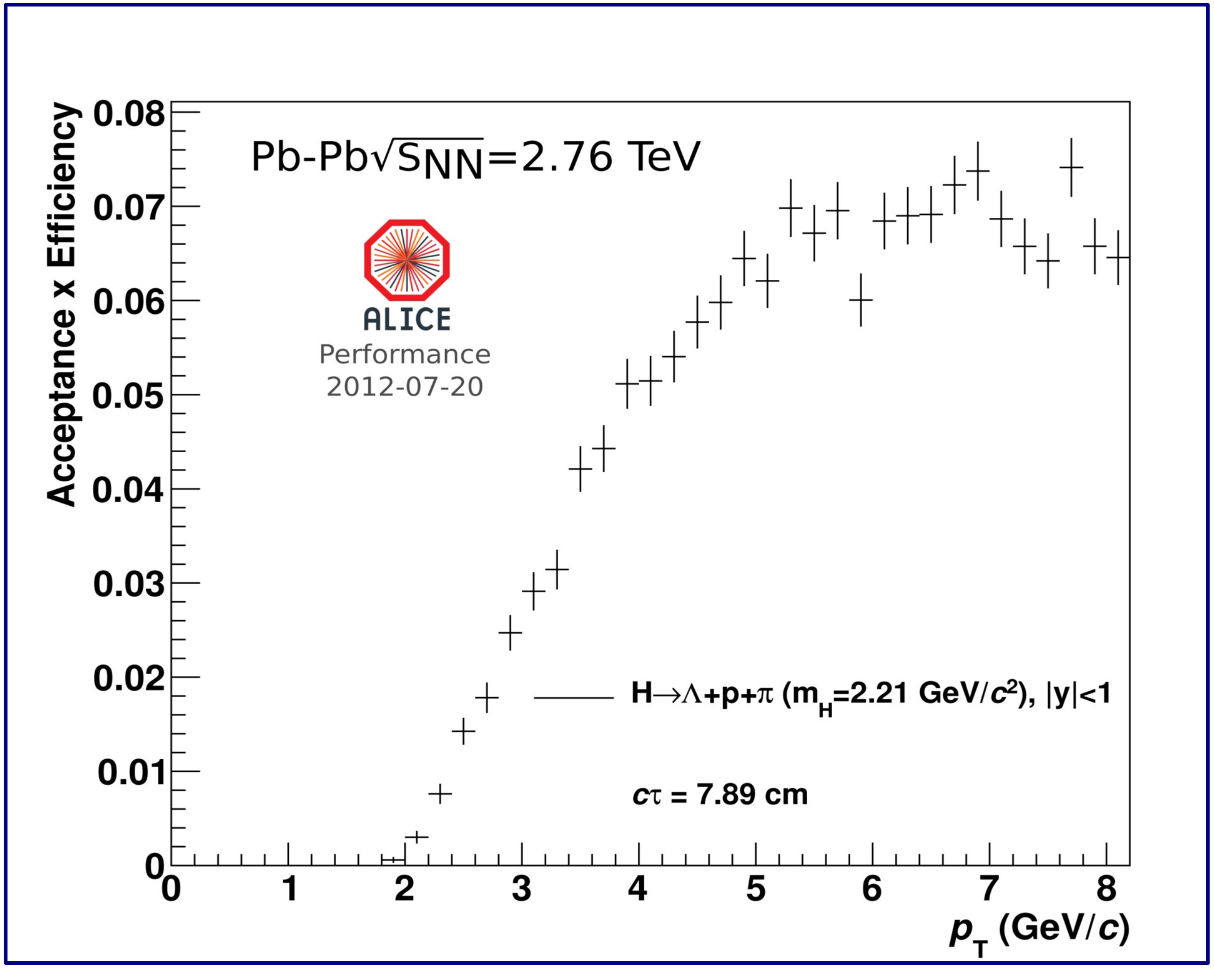
- $m_H > \Lambda\Lambda$ threshold
  - resonant state:
    measurable channel
    $H \rightarrow \Lambda\Lambda$
  - $m_H > 2.231\ \mathrm{GeV}/c^2$



H-Dibaryon

Efficiency estimation from Monte Carlo simulation (generated flat in *y* and p_T) for the detection of the H-Dibaryon

Assuming the lifetime to be that of the Λ



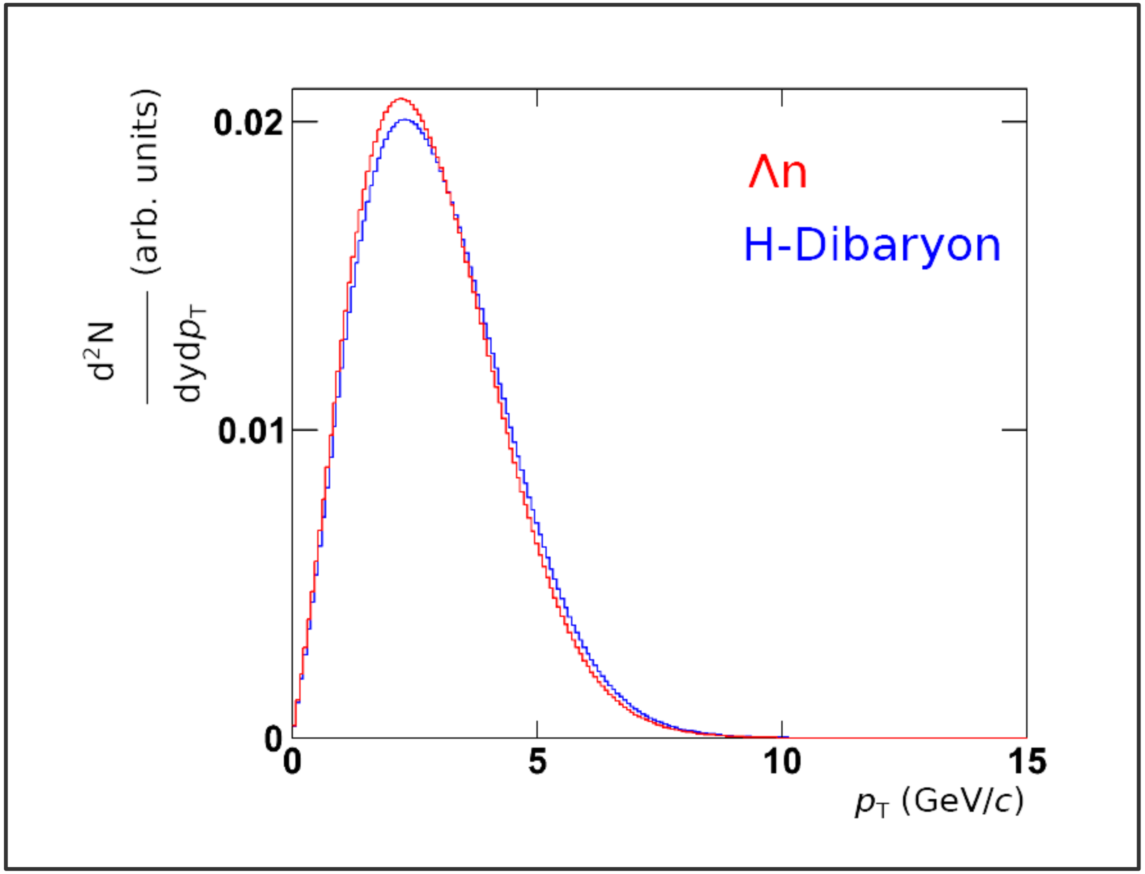
H-Dibaryon

p_T-shape of the H-Dibaryon estimated from the extrapolation of blast-wave fits for p,K,π.

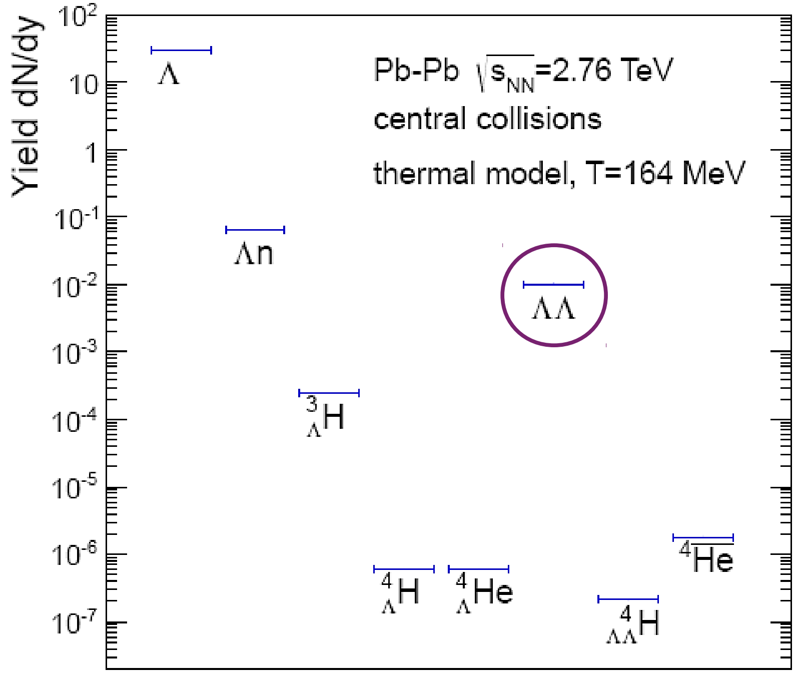
Normalized to 1 and convoluted with Acceptance x Efficiency to get a weighted efficiency

Unknown p_T-shape is the main source of uncertainty: Therefore used different functions for the systematics

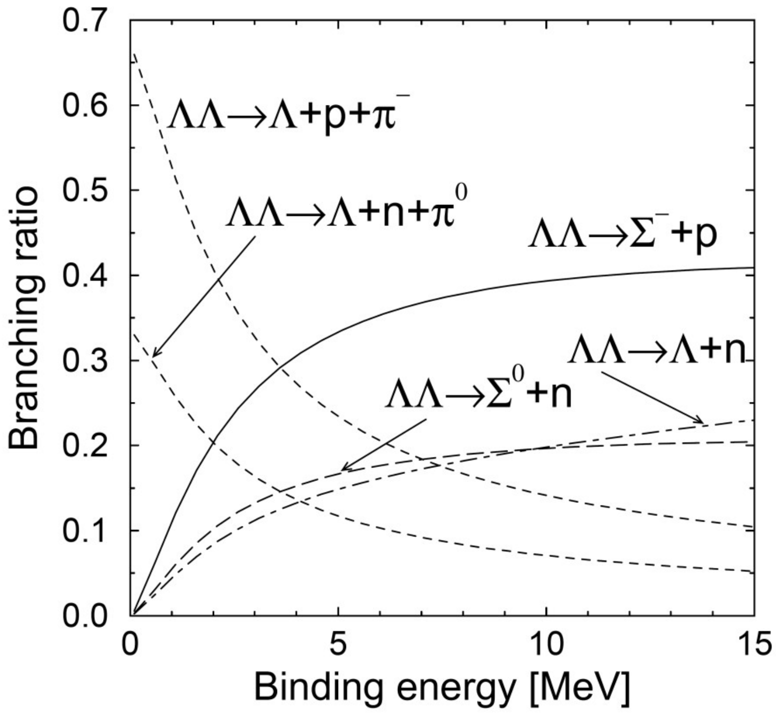
(limiting cases: blast-wave of deuteron and helium-3)



H-Dibaryon



A. Andronic, private communication



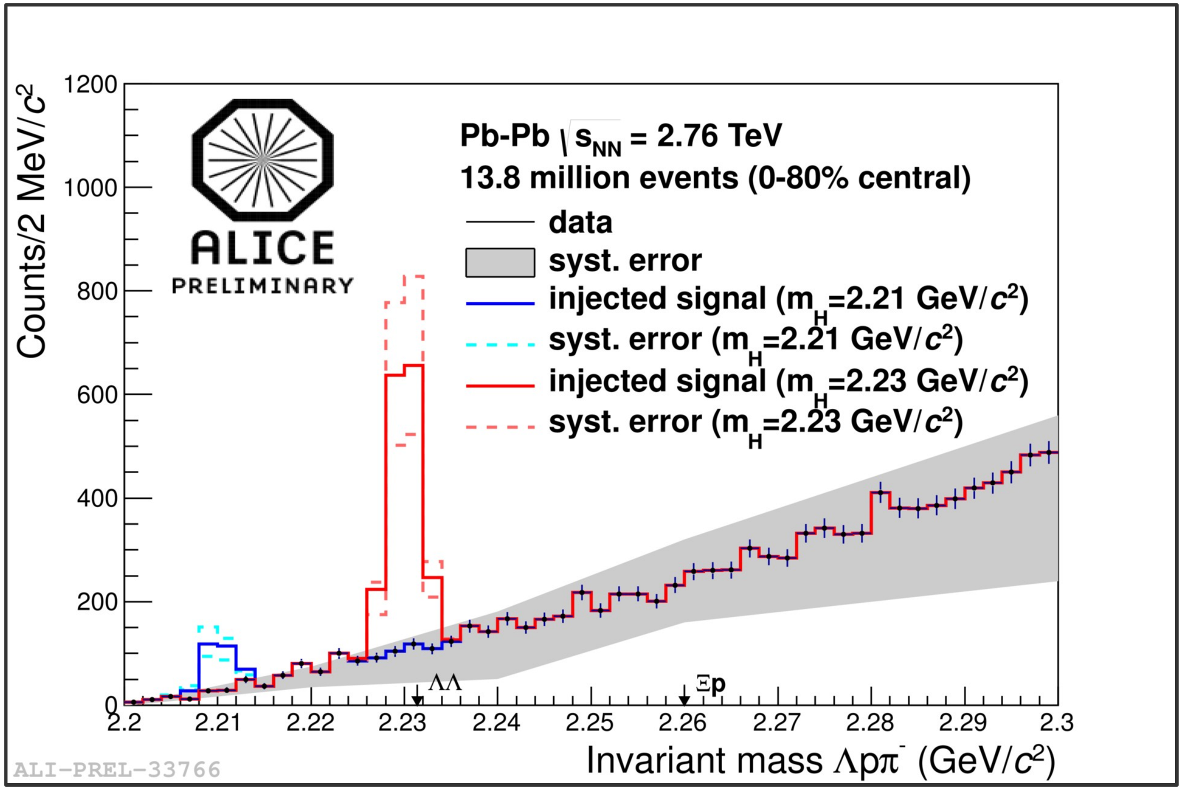
Schaffner-Bielich et al., PRL 84, 4305 (2000)

$$N = \underbrace{3.1\cdot10^{-3}}_{dN/dy} \times \underbrace{2}_{y} \times \underbrace{1.38\cdot10^{7}}_{events} \times \underbrace{0.0385}_{Eff.} \times \underbrace{0.64}_{BR(\Lambda)} = 2110$$

strongly bound: 2110 x 0.1 = 211

lightly bound: 2110 x 0.64 = 1350

H-Dibaryon



- No signal visible

From the non-observation we obtain as upper limits:

For a strongly bound H:
→ $dN/dy \leq 8.4\text{x}10^{-4}$ (99% CL)

For a lightly bound H:
→ $dN/dy \leq 2\text{x}10^{-4}$ (99% CL)

Thermal model prediction is $dN/dy = 3.1\text{x}10^{-3}$ → thermal model would need to be wrong by a factor ~10
But the model describes the hypertriton yields measured with STAR correctly within uncertainties ***(Andronic et al., PLB 697, 203 (2011) and Cleymans et al., PRC 84, 054916 (2011))***

See B.Doenigus's talk for comparison with more models

Outlook - ALICE Upgrade

After the Upgrade (2018) ALICE will be able to collect higher luminosity.

Expected Integrated Luminosity: ~10 nb^{-1} (~ 10^{10} Central collisions)

Expected yield of Exotica

Particle	Yield
${}^{3}_{\Lambda}\mathrm{H}$	3.0×10^{5}
${}^{4}_{\Lambda}\mathrm{H}$	8.0×10^{2}
${}^{4}_{\Lambda\Lambda}\mathrm{H}$	3.4×10^{1}
${}^{5}_{\Lambda}\mathrm{H}$	3.0
${}^{5}_{\Lambda\Lambda}\mathrm{H}$	0.2

Letter of Intent for the Upgrade of the ALICE Experiment
CERN-LHCC-2012-012 ; LHCC-I-022

Expected yields of exotica per 10^{10} central collisions computed in the framework of the statistical hadronization model.

Predictions done assuming 8% as efficiency per detected baryon.

Summary & Outlook

- The (^{3}He,π^-) and ($^3\overline{\mathrm{He}}$,π^+) invariant mass distributions have been studied in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
- ${}^3_\Lambda\mathrm{H}$ and ${}^3_{\bar{\Lambda}}\overline{\mathrm{H}}$ signals extracted in central (0-10%) and semi-central (10-50%) events;
- Raw ${}^3_{\bar{\Lambda}}\overline{\mathrm{H}}/{}^3_\Lambda\mathrm{H}$ ratio consistent with unity
- (${}^3_\Lambda\mathrm{H}+{}^3_{\bar{\Lambda}}\overline{\mathrm{H}}$) signal can be extracted also in 4 *ct* bins.

- H-Dibaryon search in Pb-Pb with ALICE: no visible signal → Upper limits H-Dibaryon is significantly lower than thermal model predictions

- ${}^3_\Lambda\mathrm{H}$ Efficiency correction:

  A dedicated Monte Carlo production is needed in order to evaluate efficiency and acceptance corrections.

  Studies are ongoing to get corrected yield and lifetime.