2nd EMMI Workshop: Anti-matter, hyper-matter and exotica production at the LHC

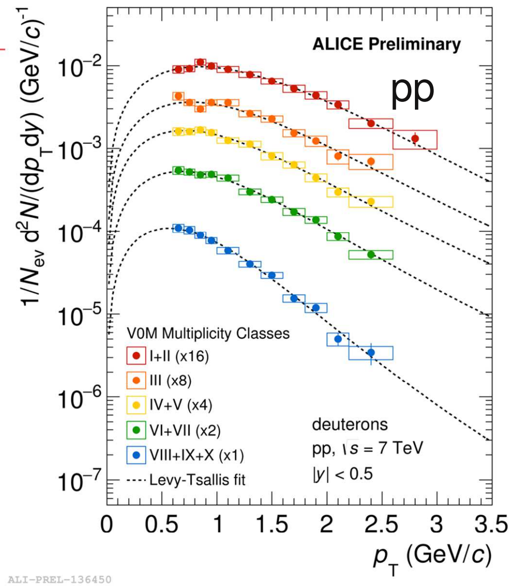
Wrap-up of Monday November 6th

… what to bring home?

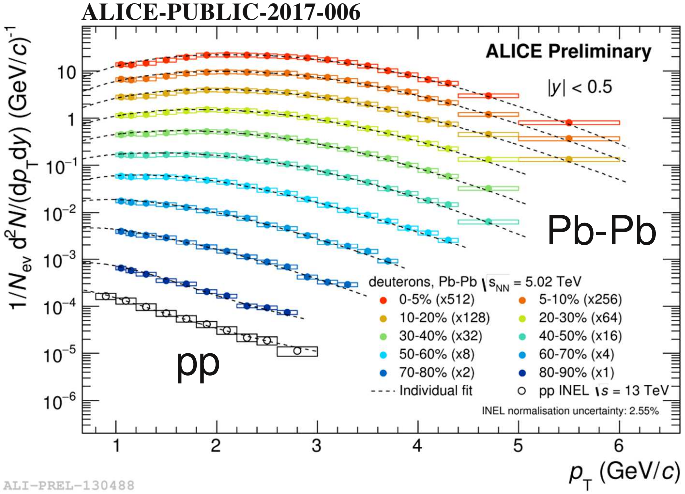
Stefano Piano

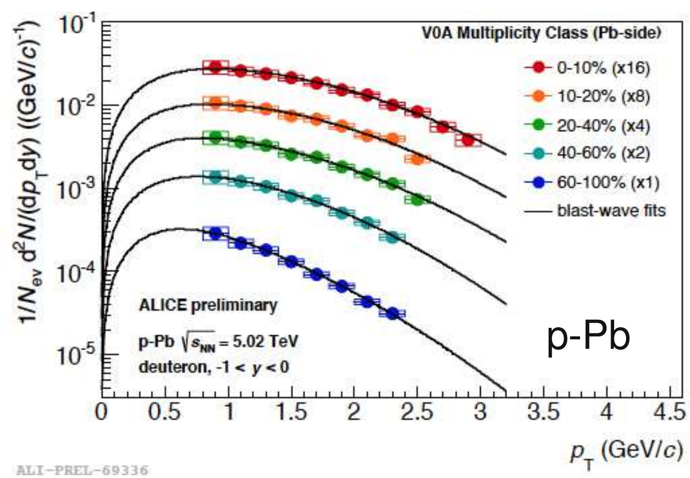
DEUTERON p_T SPECTRA

- Spectra become harder with increasing multiplicity in Pb-Pb and show clear radial flow
- The Blast-Wave fits describe the data well in p-Pb and Pb-Pb
- pp and p-Pb spectrum show no sign of radial flow



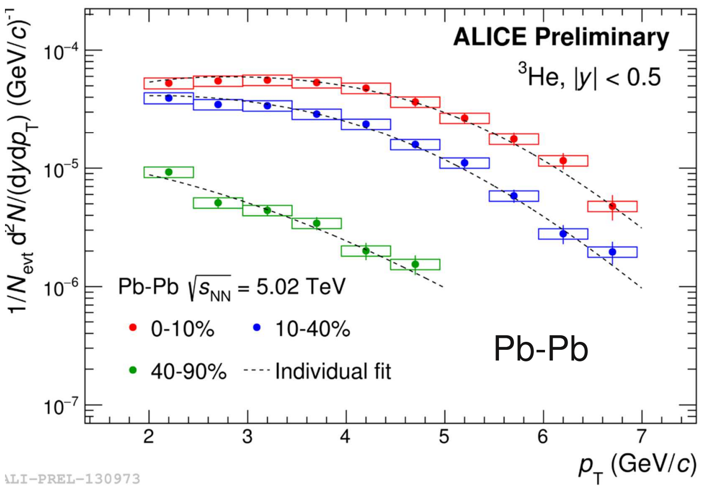
ALICE-PUBLIC-2017-006

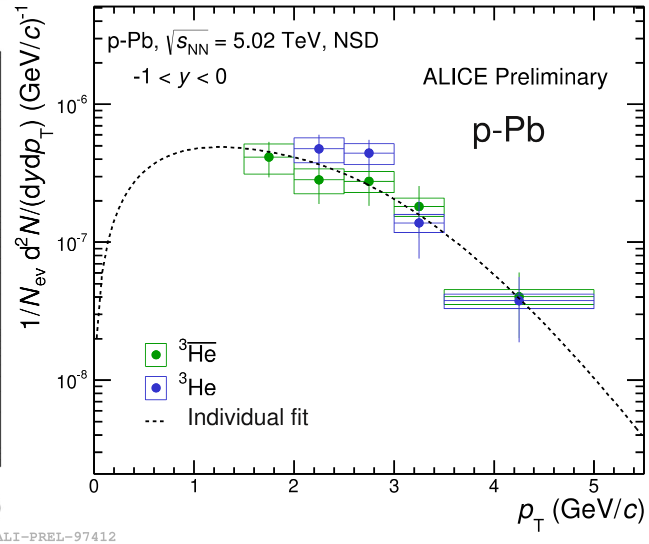




3-HELIUM

ALICE-PUBLIC-2017-006

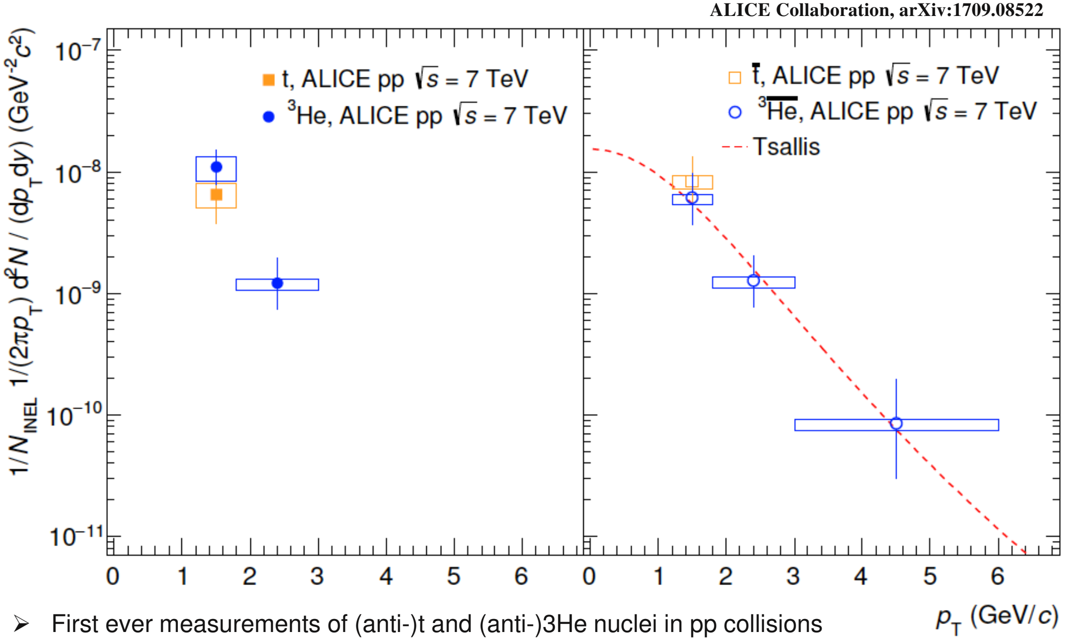




3-HELIUM AND TRITON

ALICE

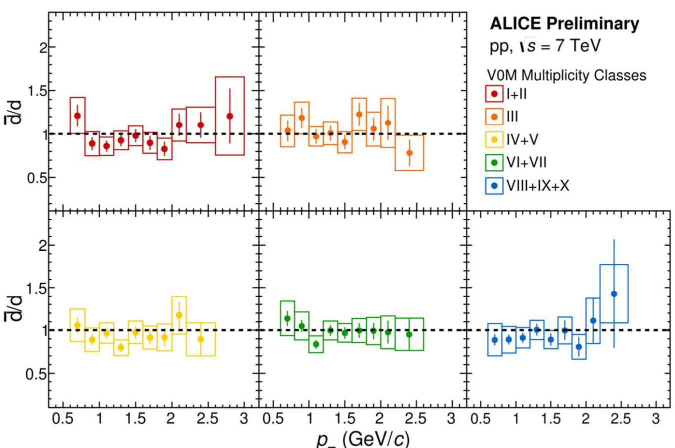
ALICE Collaboration, arXiv:1709.08522



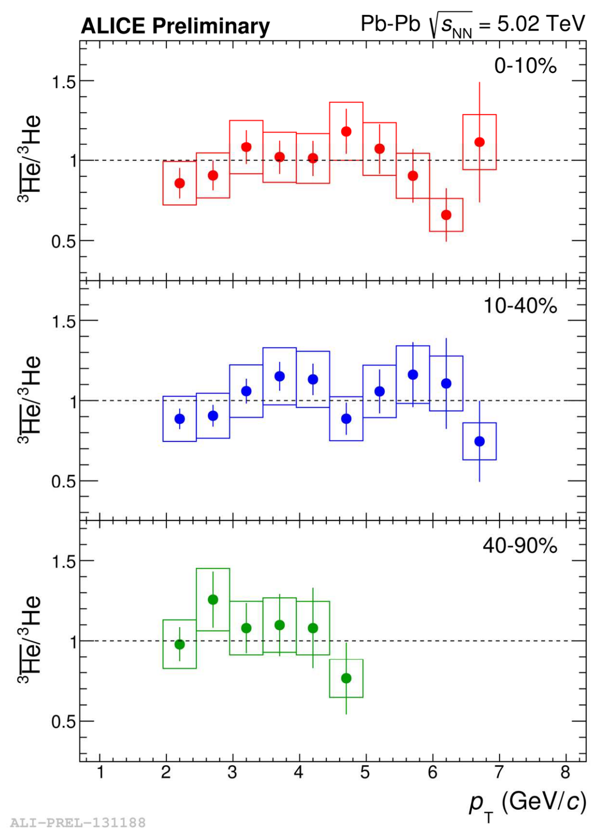
- First ever measurements of (anti-)t and (anti-)3He nuclei in pp collisions

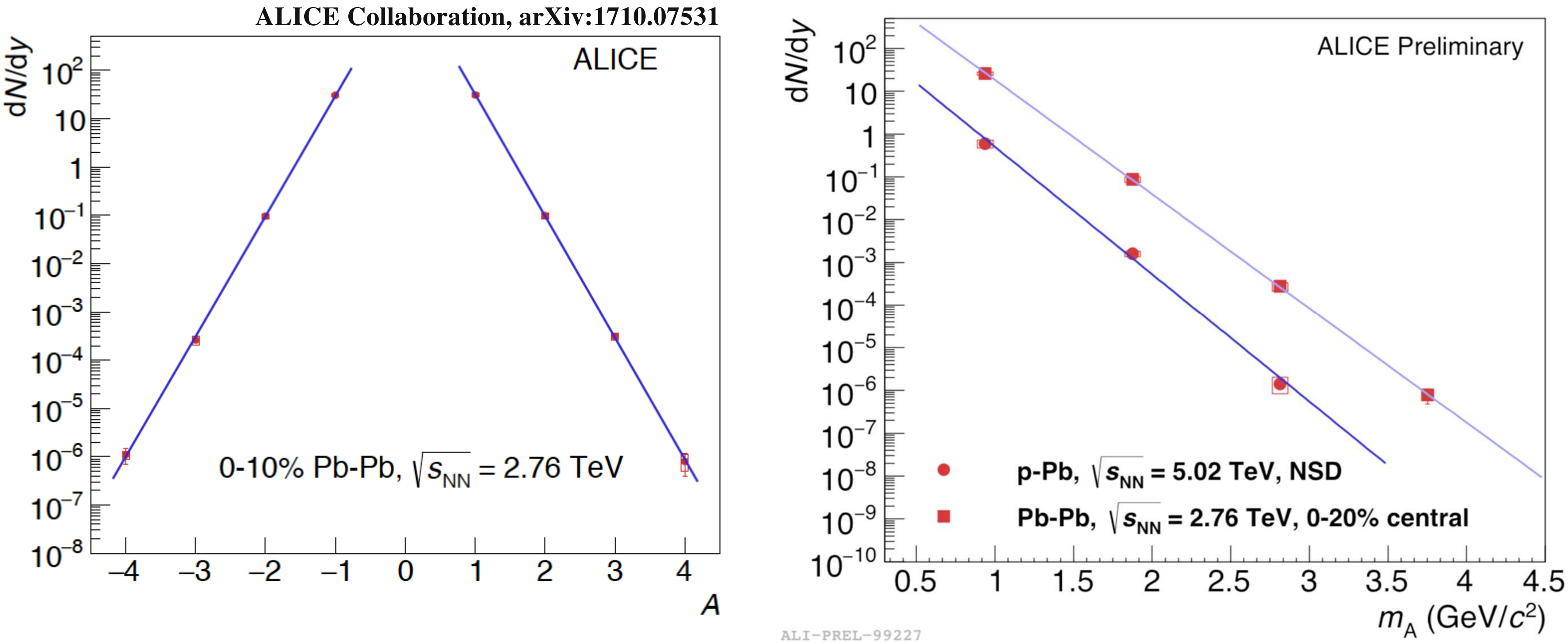
ANTI-NUCLEI PRODUCTION

- Anti-nuclei / nuclei ratios are consistent with unity (similar to other light flavour species)
- Ratios exhibit constant behavior as a function of p_T and centrality
- Ratios are compatible with unity, in agreement with the coalescence and thermal model expectations
- Also in pp multiplicity intervals, anti-deuterons and deuterons are produced equally



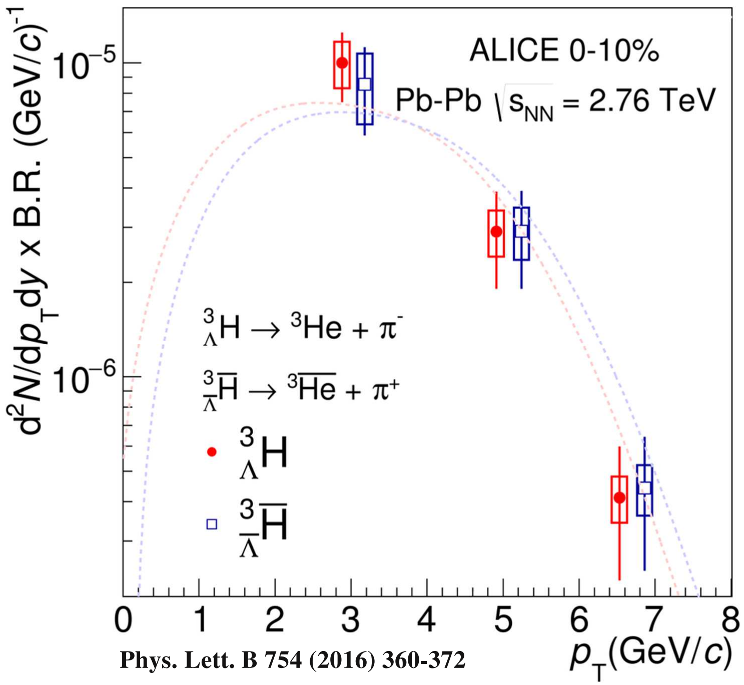
ALICE-PUBLIC-2017-006



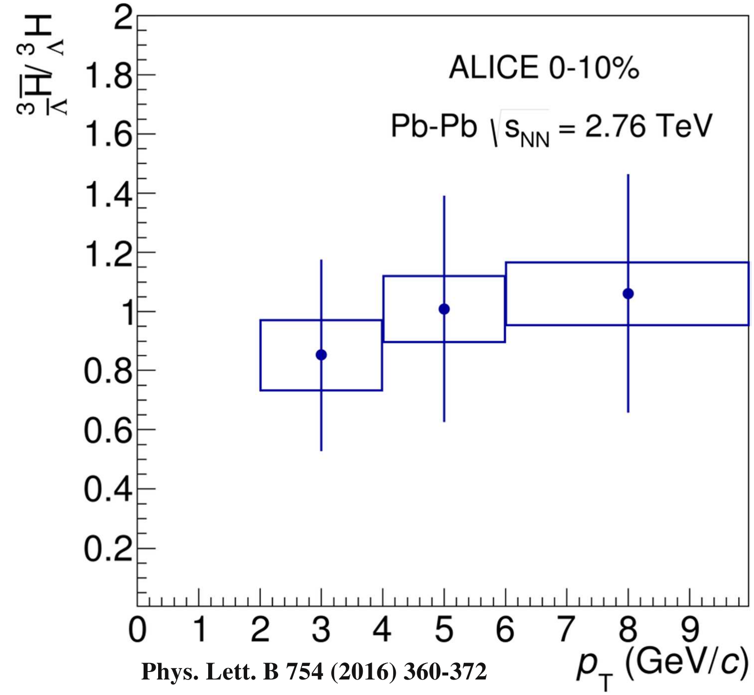


ALICE Collaboration, arXiv:1710.07531
ALICE
dN/dy
0-10% Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
A
ALICE Preliminary
dN/dy
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV, NSD
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV, 0-20% central
m_A (GeV/c^2)
ALI-PREL-99227

(ANTI-)HYPERTRITON YIELDS



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



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

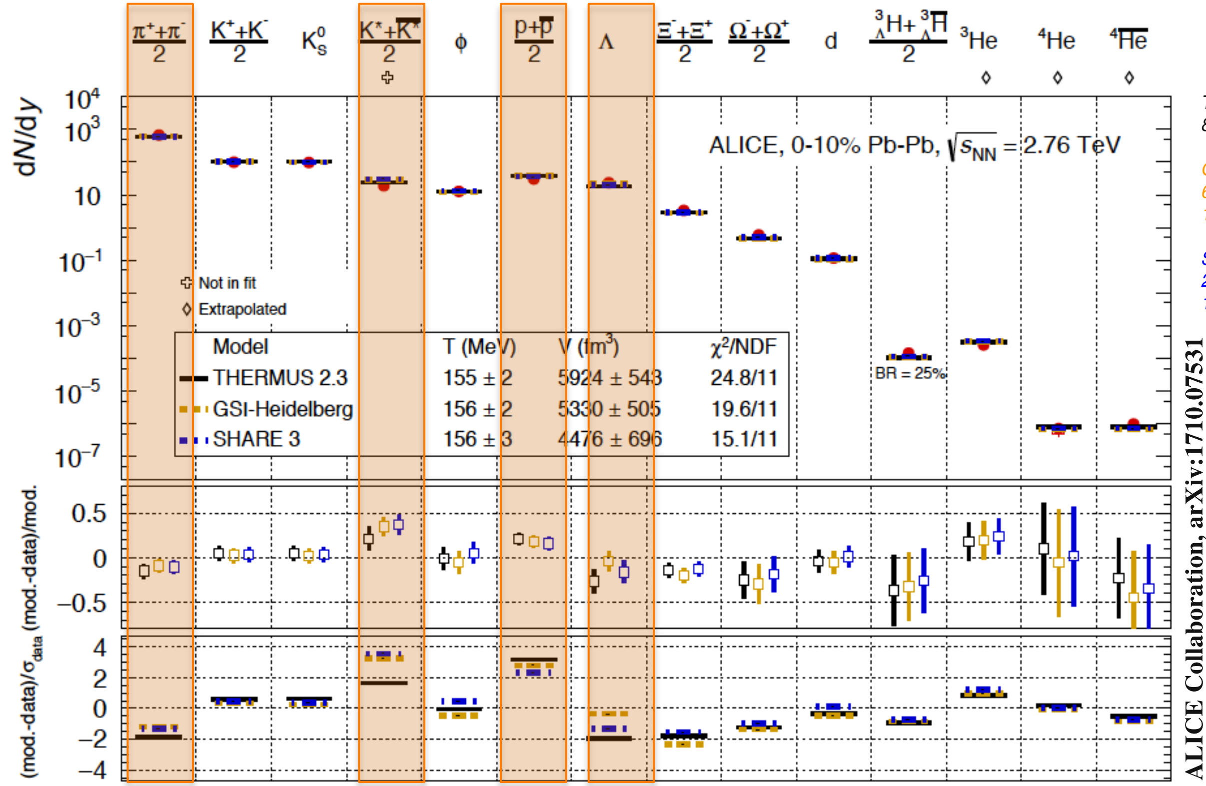
d*N*/d*y* x B.R. (${}^{3}_{\Lambda}H \rightarrow {}^{3}He\ \pi$) yield extracted in three p_T bins for central (0-10%) events for ${}^{3}_{\bar{\Lambda}}\bar{H}$ and ${}^{3}_{\Lambda}H$ separately

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: $\bar{p}/p \sim \bar{\Lambda}/\Lambda \sim 1$

THERMAL MODEL FITS



THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)

GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142

SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)

Different models describe particle yields including light (hyper-)nuclei well with T_{ch} of about 156 MeV

Including nuclei in the fit causes no significant change in T_{ch}

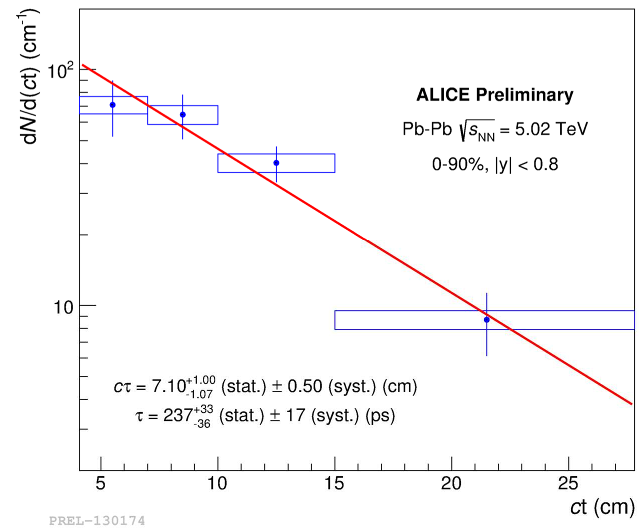
HYPERTRITON LIFETIME DETERMINATION

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

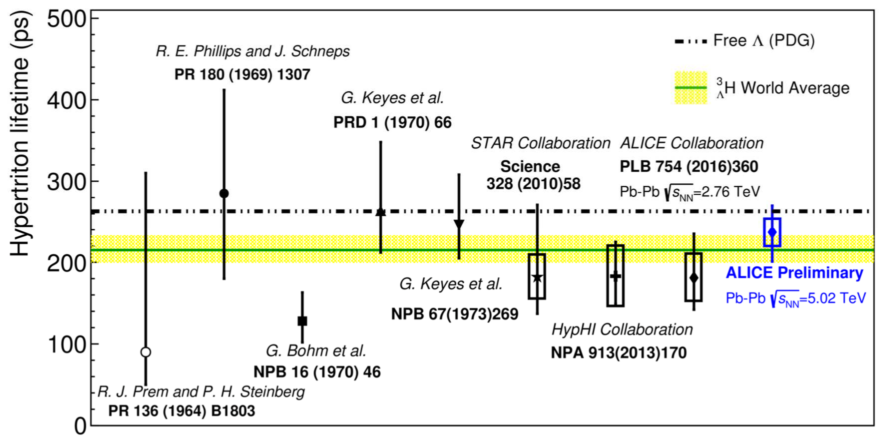
New preliminary results at $\sqrt{s_{NN}}$ = 5.02 TeV



PREL-130174

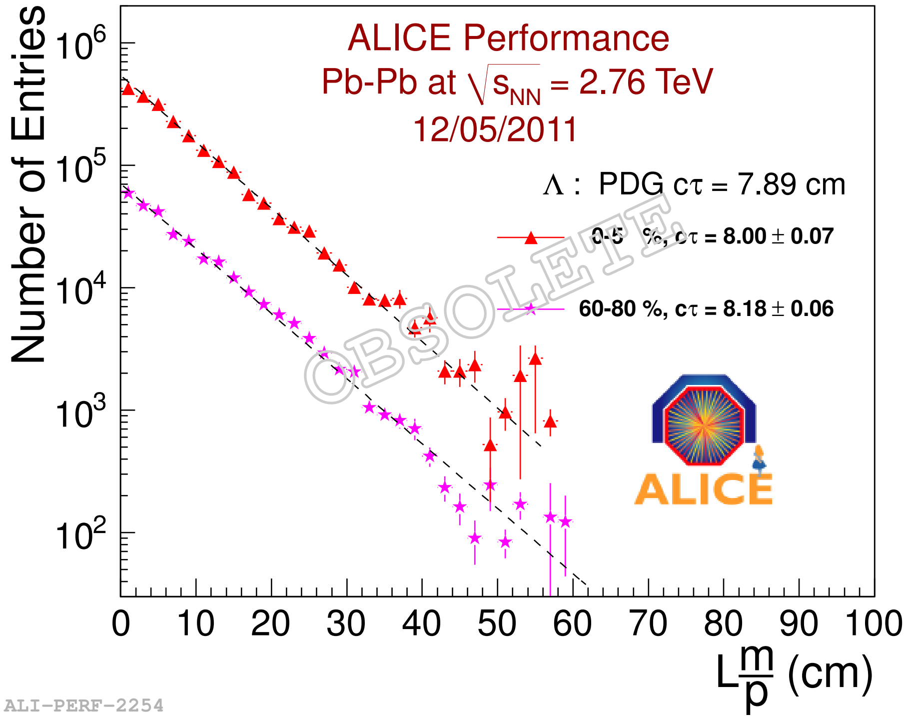
$$c\tau = \left(7.10^{+1.00}_{-1.07}(stat.) \pm 0.50(syst.)\right) cm$$

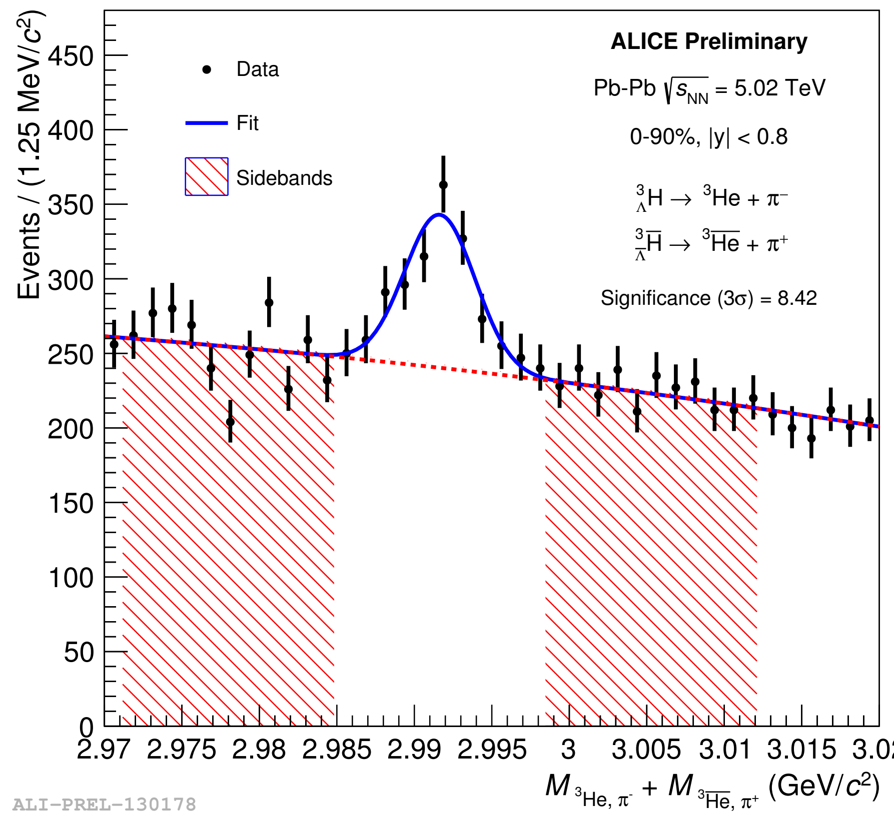
$$\tau = \left(237^{+33}_{-36}(stat.) \pm 17(syst.)\right) ps$$



ALI-PREL-130195

- Previous heavy-ion experiment results show a trend well below the free Λ lifetime
- ALICE preliminary result from Pb-Pb at 5.02 TeV is closer to the free Λ lifetime


ALICE Performance
Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
12/05/2011
Λ : PDG cτ = 7.89 cm
0-5 %, cτ = 8.00 ± 0.07
60-80 %, cτ = 8.18 ± 0.06
OBSOLETE
ALICE
Number of Entries
$L\frac{m}{p}$ (cm)
ALI-PERF-2254

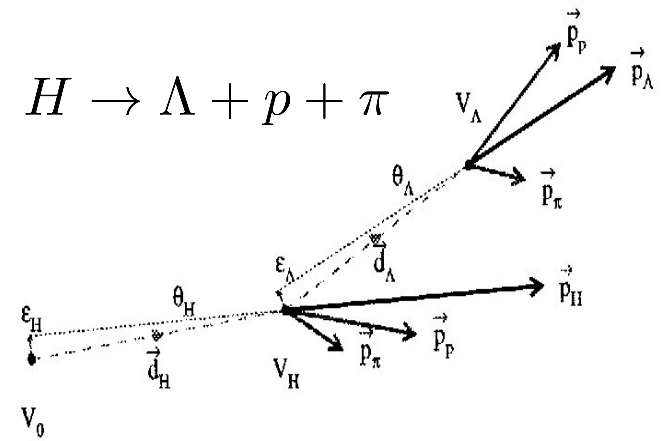

ALICE Preliminary
Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
0-90%, |y| < 0.8
${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$
${}^{3}_{\bar{\Lambda}}\overline{H} \rightarrow {}^{3}\overline{He} + \pi^{+}$
Significance (3σ) = 8.42
Data
Fit
Sidebands
Events / (1.25 MeV/c^2)
$M_{^{3}He,\pi^{-}} + M_{^{3}\overline{He},\pi^{+}}$ (GeV/c^2)
ALI-PREL-130178

Jinhui Chen

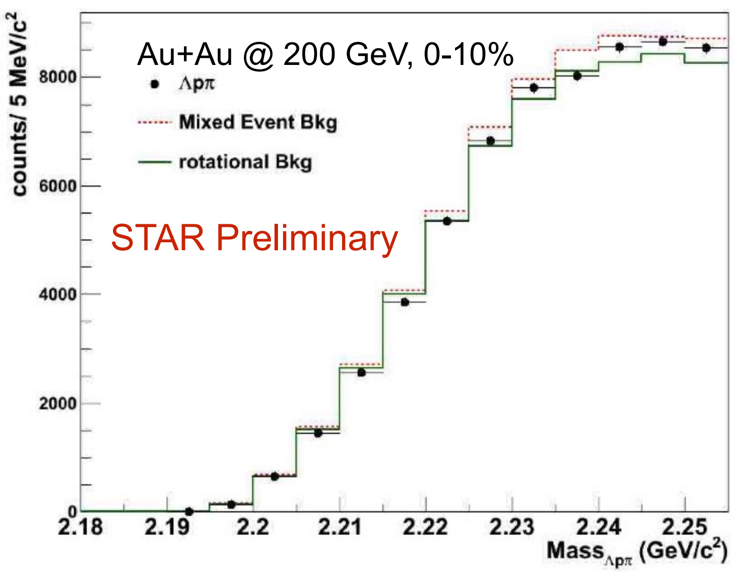
H-dibaryon Invariant Mass Distributions

- Topological reconstruction of $\Lambda p\pi$ to look of H
  - $2.2 < m_H < 2.231$ GeV/c^2
  - No visible signal in the data

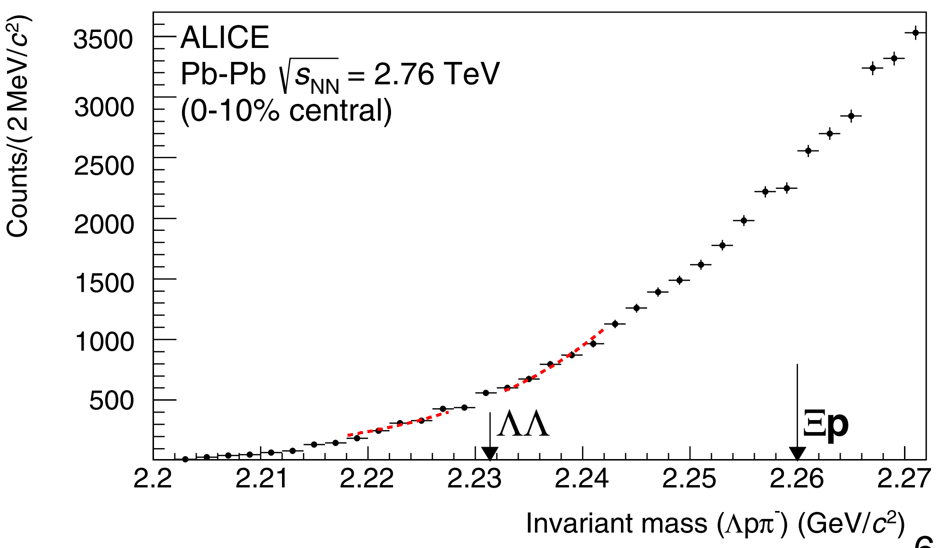
$$H \to \Lambda + p + \pi$$



N. Shah for STAR Col. Nucl. Phys. A 914 (2013) 410



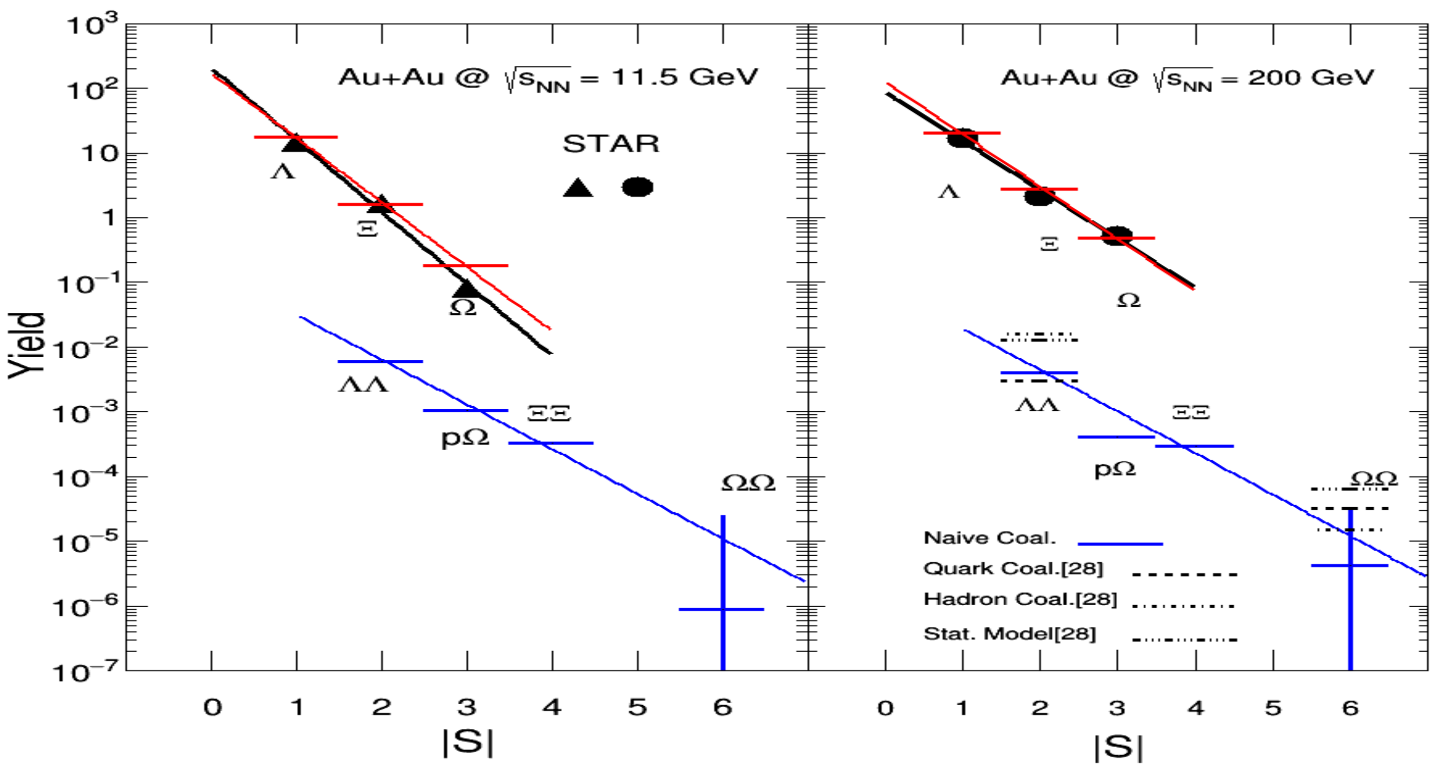
ALICE Col. Phys. Lett. B 752 (2016) 267



NΩ-dibaryon from Heavy-Ion Collisions

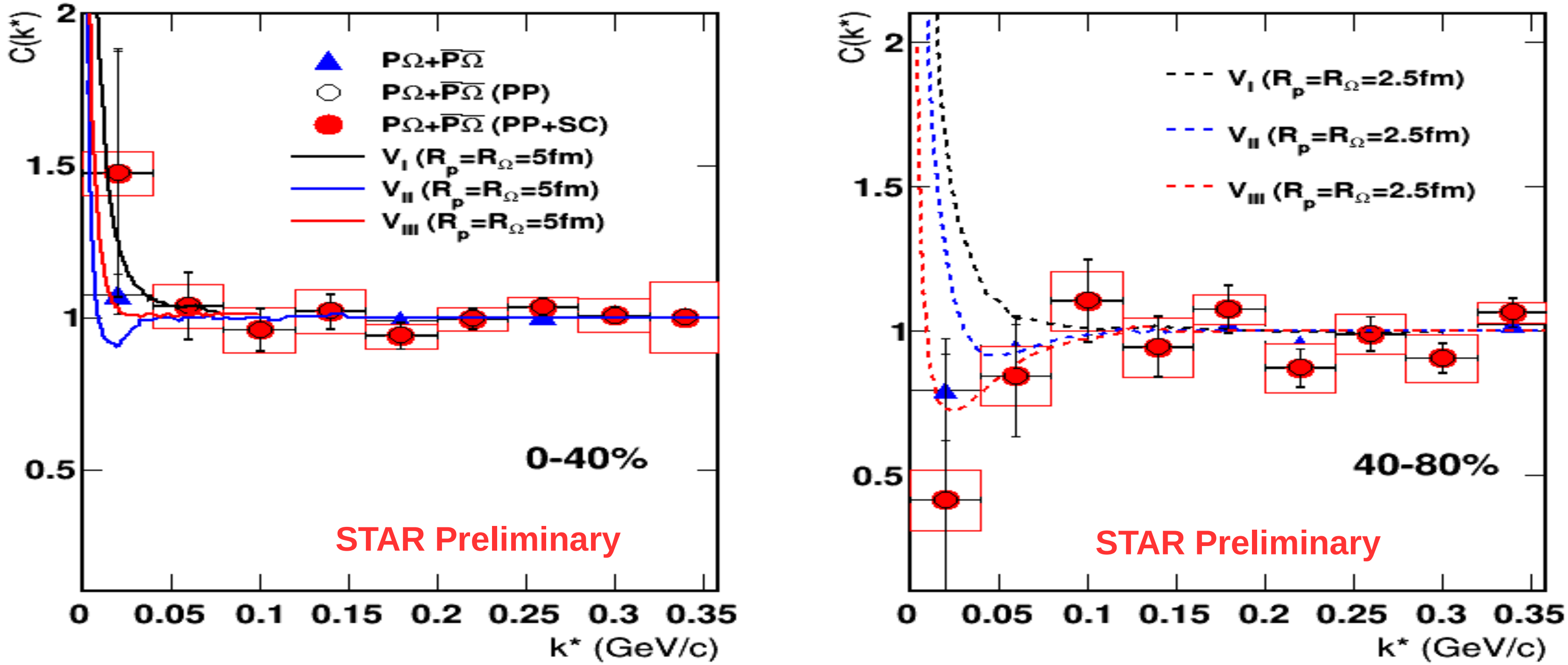
- NΩ-dibaryon is an isospin 1/2 doublet and has both pΩ and nΩ channels possible

Phys. Lett. B 754 (2016) 6



- In experiments, we can look at pΩ channel with two particle correlation analysis or invariant mass analysis (the J=2, S=-3 state weak decay is challenging)
  - Invariant mass
    - Significant combinatorial background

PΩ Correlation Function



PP → Pair Purity Correction
PP+SC → Pair Purity + Mom. Smearing Correction
R → Emission source size
Boxes → systematic uncertainty

Comparison of measured PΩ correlation function from 0-40 and 40-80% centrality with the predictions for PΩ interaction potentials V_I, V_{II} and V_{III}.

Spin-2 pΩ potentials	V_I	V_{II}	V_{III}
Binding energy E_B (MeV)	-	6.3	26.9
Scattering length a_0 (fm)	-1.12	5.79	1.29
Effective range r_{eff} (fm)	1.16	0.96	0.65

Phys. Rev. C 94, 031901 (2016)

Goals of the HypHI phase 0 experiment

The phase 0 experiment:

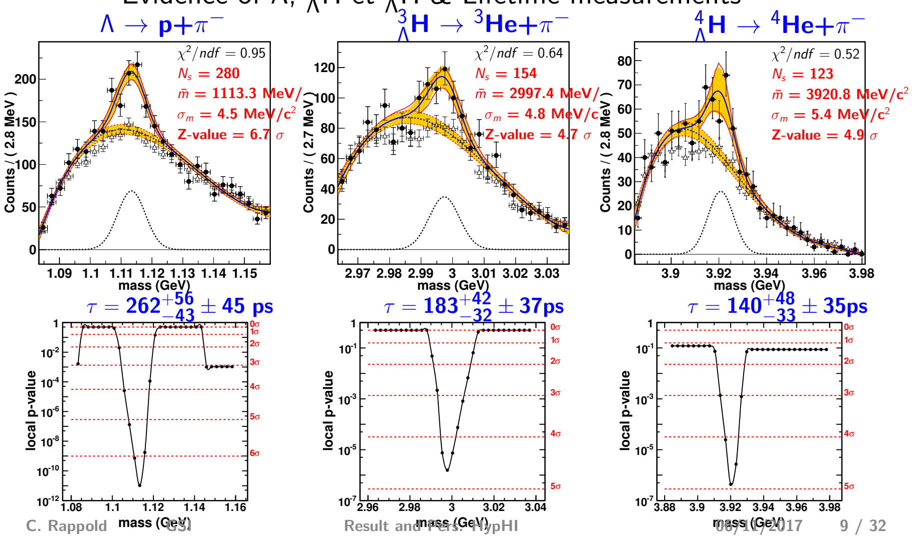
- aimed to demonstrate the feasibility of hypernuclear spectroscopy by means of heavy ion collisions.
- focused on the study of ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, ${}^{5}_{\Lambda}$He
- via a reaction ^{6}Li beam at 2 AGeV on a ^{12}C target.

Christophe Rappold

Hypernuclear spectroscopy from ^{6}Li+^{12}C @ 2 A GeV

[C. Rappold *et al.*, Nucl. Phys. A. **913**, 170 (2013)]

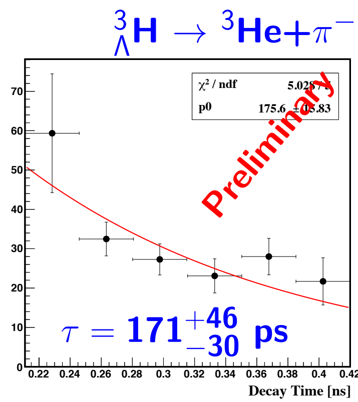
Evidence of Λ, ${}^{3}_{\Lambda}$H et ${}^{4}_{\Lambda}$H & Lifetime measurements



- Average combined lifetime in 2013: ${}^{3}_{\Lambda}$H : 216^{+19}_{-16} ps & ${}^{4}_{\Lambda}$H : 192^{+20}_{-18} ps
- Upper Limit 95 CL% at : ${}^{3}_{\Lambda}$H : 250 ps & ${}^{4}_{\Lambda}$H : 227 ps
- Theory: ${}^{3}_{\Lambda}$H [H. Kamada *et al.* PRC 57 1595 (1998)]: 256 ps
- Theory: ${}^{4}_{\Lambda}$H [T. Motoba *et al.* NPA 534 597 (1991)]: 233 or 244 ps

Second HypHI experiment : Phase 0.5

Fixed target, Reaction : ^{20}Ne+^{12}C @ 2 AGeV or $\sqrt{s_{NN}} = 2.7$ GeV



New perspective: ML for hypernuclear discrimination

Applying ML discrimination for ${}^{3}_{\Lambda}$H lifetime :

- Statistical error: 198 $^{+25}_{-21}$ ps
- published HypHI lifetime : $\tau = \mathbf{183^{+42}_{-32}} \pm \mathbf{37}$ ps
- World average of 2015 : 196^{+14}_{-13} ps

Recent results from HADES

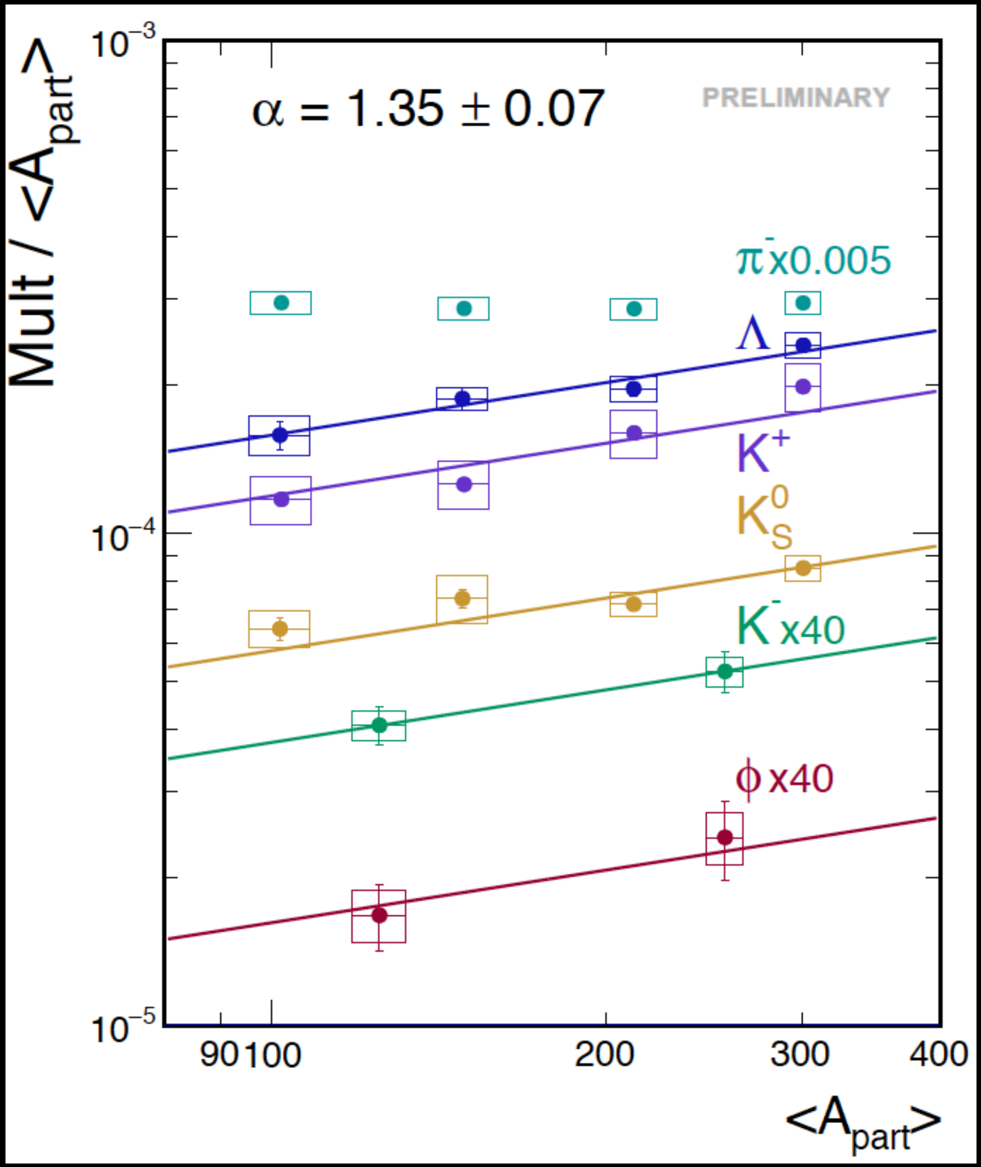
Manuel Lorenz

Heavy-ion collisions a $\sqrt{s_{NN}}$=2.4 GeV

Long interpenetration times
Baryon stopping in the collision zone

→ Baryon dominated system
→ Similar region in the phase diagram as neutron star merger

(Sub-Threshold) Strangeness Production: the Complete Picture

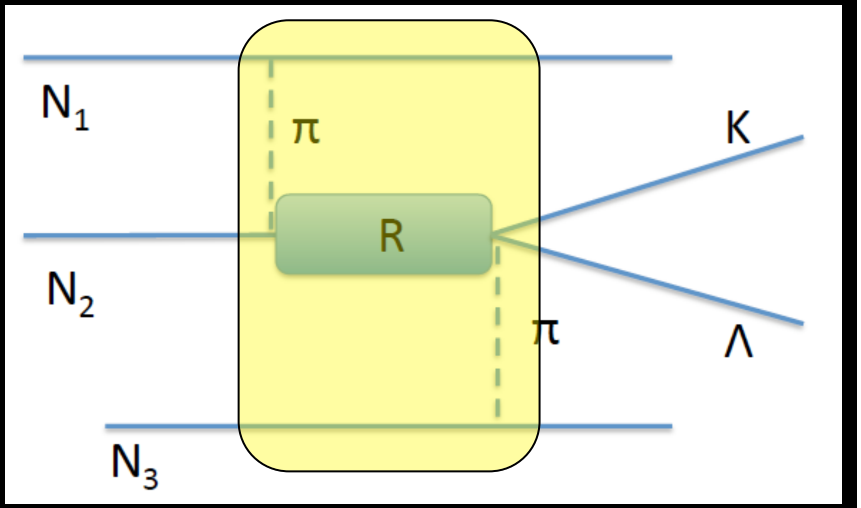


- Strange particle yields rise stronger than linear with $<A_{part}>$ ($M \sim <A_{part}>^{\alpha}$)

- Universal $<A_{part}>$ dependence of strangeness production

→ Hierarchy in production threshold not reflected

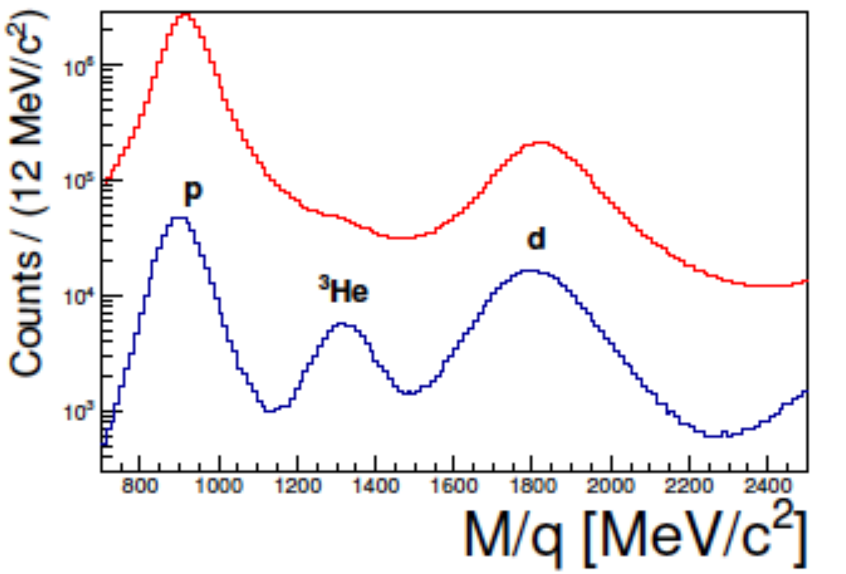
$N \rightarrow NYK^{+}$ $\sqrt{s_{NN}} = 2.55$ GeV
$NN \rightarrow NNK^{+}K^{-}$ $\sqrt{s_{NN}} = 2.86$ GeV

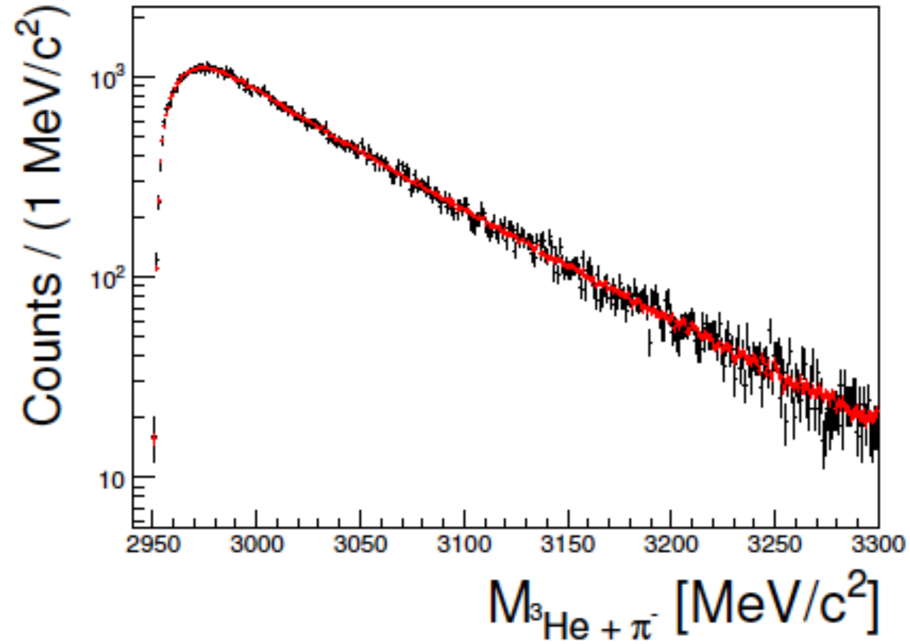


Heat bath

H. Schuldes, T. Scheib

Hypertrition search in Ar+KCl 2.6 GeV





Upper limit:

$$M_{UL} = 1.04 \text{ x } 10^{-3}$$

$^{3}_{\Lambda}He/\Lambda < (2.5 \pm 0.3) \text{ x } 10^{-2}$

Future plans:
Investigate Au+Au data at 2.4 GeV (lower energy but heavier system) and 3 body decay channel

Eur.Phys.J. A49 (2013) 146

Ambiguities in description, potential extraction misleading at the moment.

No indication for sequential K^+K^- freeze-out when correcting for φ feed-down.

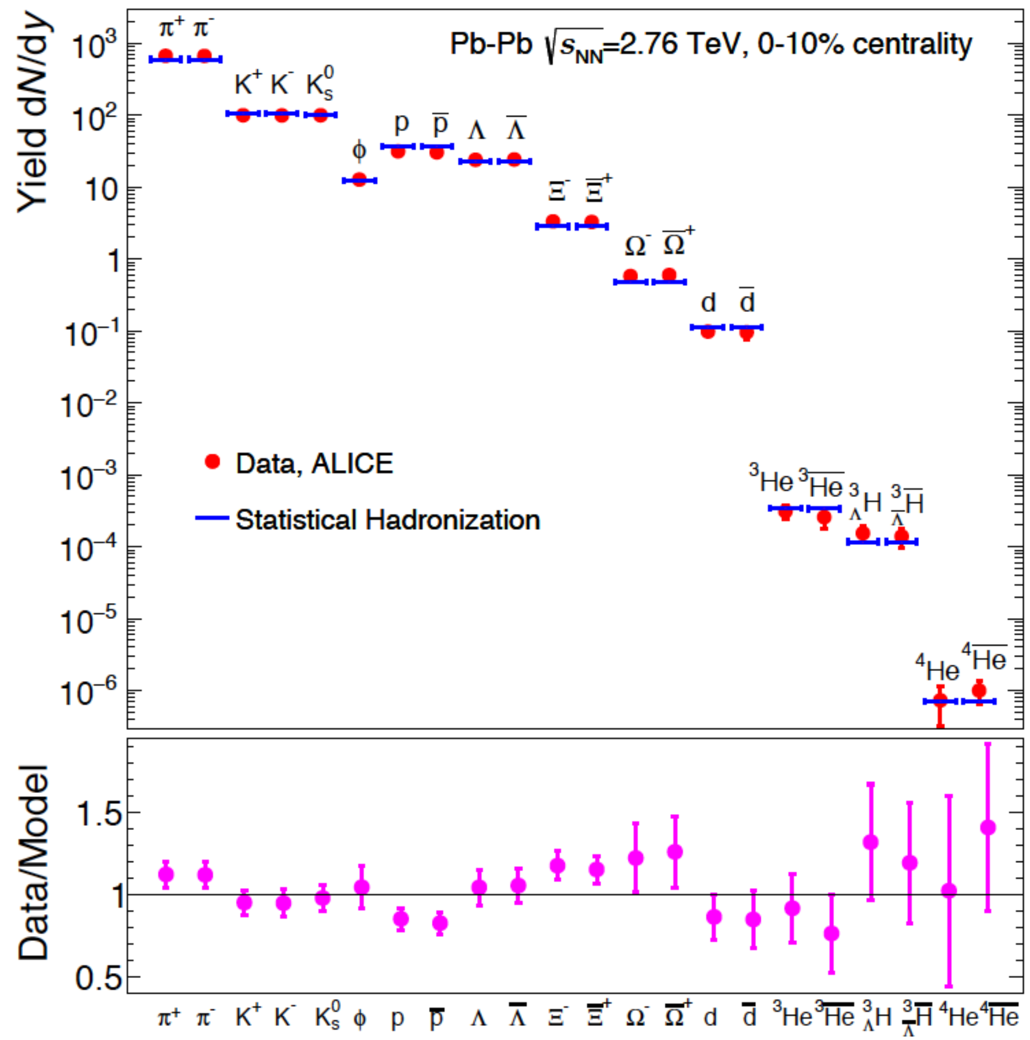
Universal $\langle A_{part} \rangle$ dependence of strange hadrons.

Macroscopic description and Freeze-out Parameter

T_{kin}=62±10 MeV and $\langle \beta_r \rangle$=0.36±0.04 extracted from blast wave fit

July 2017 update: excellent description of ALICE@LHC data

fit includes loosely bound systems such a deuteron and hypertriton
hypertriton is bound-state of (Λ,p,n), Λ separation energy about 130 keV
size about 10 fm, the **ultimate halo nucleus,**
produced at T=156.5 MeV. close to an Efimov state



proton discrepancy 2.8 sigma

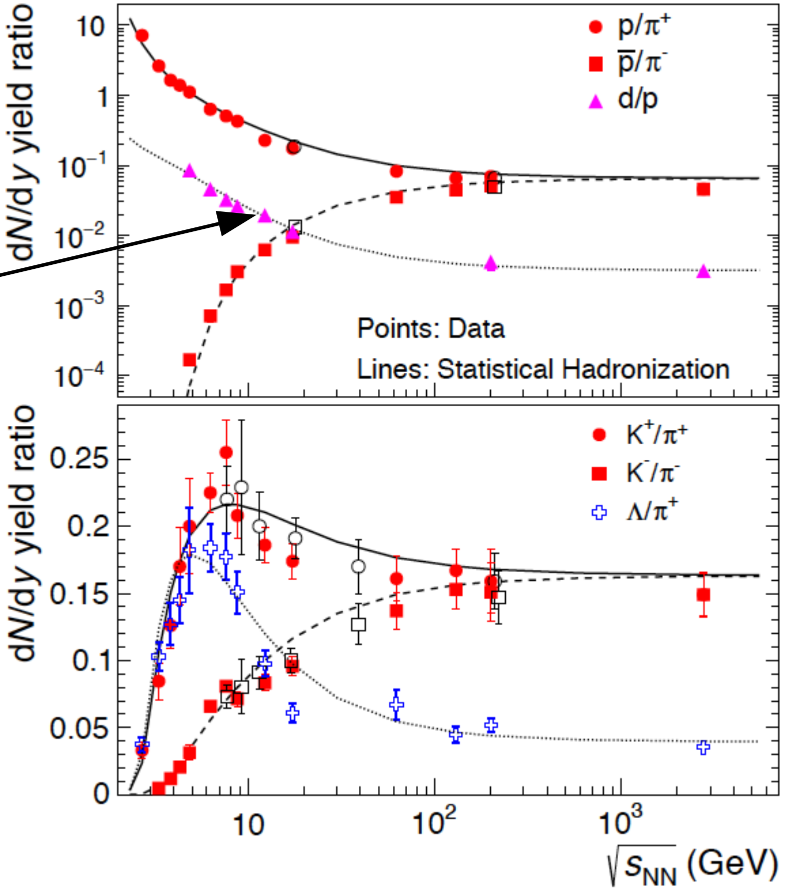
Xi discrepancy?

Andronic, pbm, Redlich, Stache
arXiv :1710.09425

J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich, Confronting LHC data with the statistical hadronization model, J.Phys.Conf.Ser.**509** (2014) 012019, arXiv:1311.4662 [nucl-th].

energy dependence of hadron production described quantitatively

energy dependence of d/p ratio quantitatively described, no new parameters



together with known energy dependence of charged hadron production in Pb-Pb collisions we can predict yield of all hadrons at all energies with < 10% accuracy

no new physics needed to describe K+/pi+ ratio including the 'horn'

Systematic uncertainties in statistical hadronization model

in general, not easy to estimate

from analysis of uncertainties in mass spectrum, and in branching ratios, and considering the Boltzmann suppression, we get:

$\Delta T \leq 5$ MeV at μ_b=0 and T = 156 MeV

The Hypertriton

is coalescence approach an alternative?

coalescence approach, general considerations for loosely bound states

- production yields of loosely bound states is entirely determined by mass, quantum numbers and fireball temperature.

- hyper-triton and 3He have very different wave functions but essentially equal production yields.

- energy conservation needs to be taken into account when forming objects with baryon number A from A baryons.

- delicate balance between formation and destruction; maximum momentum transfer onto hyper-triton before it breaks up: $\Delta Q_{max} < 20$ MeV/c, typical pion momentum p_pi = 250 MeV/c, typical hadronic momentum tranfer > 100 MeV/c

- hyper-triton interaction cross section with pions or nucleons at thermal freeze-out is of order $\sigma > 70\ \mathrm{fm}^2$. For the majority of hyper-tritons to survive, the mfp λ has to exceed 15 fm → density of fireball at formation of hyper-triton $n < 1/(\lambda\ \sigma) = 0.001/\mathrm{fm}^3$. Completely inconsistent with formation at kinetic freeze-out, where n ≈ 0.05

Quark Model Spectroscopy

hypothesis:
all nuclei and hyper-nuclei are formed as compact multi-quark states at the phase boundary. Then slow time evolution into hadronic respresentation.

Andronic, pbm, Redlich, Stachel, arXiv :1710.09425

How can this be tested?

precision measurement of spectra and flow pattern for light nuclei and hyper-nuclei

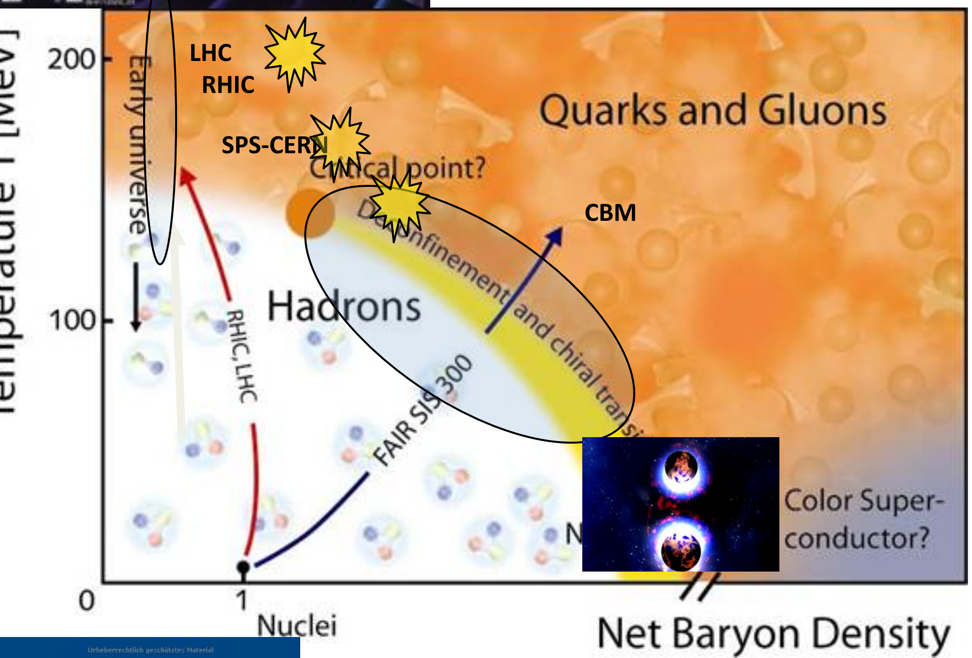
a major new opportunity for ALICE Run3
and for CBM/NICA/JPARC/NA61

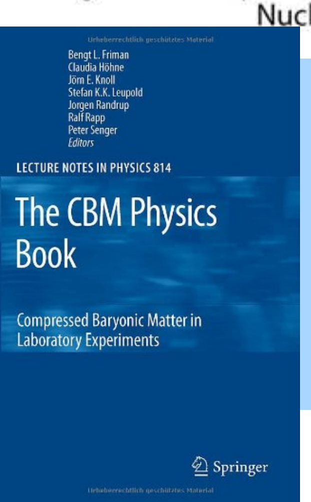
Iouri Vassiliev

Perspectives on strangeness physics with CBM

Extreme IR conditions

Physics case: Exploring the QCD phase diagram





Projects to explore the QCD phase diagram at large μ_B:
RHIC energy-scan, NA61@SPS, MPD@NICA: bulk observables
CBM: bulk and **rare observables, high statistic!**

The equation-of-state at high ρ_B
- collective flow of hadrons
- particle production at threshold energies: **open charm, multi-strange hyperons, HN**

Deconfinement phase transition at high ρ_B
- excitation function and flow of strangeness (K, Λ, Σ, Ξ, Ω) and **charm (J/ψ, ψ', D^0, D_s, $D^\pm$, Λ_c)**

QCD critical endpoint
- excitation function of event-by-event fluctuations (**K/π**, ... **Ξ**/ π, **Ω**/ π)

Onset of chiral symmetry restoration at high ρ_B
- in-medium modifications of hadrons (ρ,ω,ϕ)
- excitation function of **multi-strange (anti)hyperons (PHSD 4.0)**

Volodymyr Vovchenko

Recent thermal model developments

connection of (anti-)nuclei to critical observables

Summary

- Proper modeling of hadronic interactions crucially important for thermal model applications
- Thermal model works very well for light nuclei yields. Only in ideal HRG, however, it does point to a unique freeze-out temperature.
- The van der Waals type interactions between baryons in HRG change qualitative behavior of fluctuations of conserved charges in the crossover region
- LQCD data at both, $\mu = 0$ and imaginary μ, points to overall repulsive baryonic interactions in the crossover region, with an average "eigenvolume" parameter $b \simeq 1$ fm^3
- Imaginary μ_B LQCD data show no evidence for existence of light nuclei at $T \sim 150$ MeV. Partial pressure in $|B| = 2$ sector is dominated by repulsive baryonic interactions.

Five-body structure of heavy pentaquark system

Emiko Hiyama (Kyushu Univ./RIKEN)

- Motivated by the observed Pc(4380) and Pc(4450) systems at LHCb, we calculated energy spectra of qqqcc system using **non-relativistic constituent quark model**. To obtain resonant states, we also use real scaling method.

- Currently, we find no sharp resonant states (penta-quark like) with L=0,S=1/2 ($J^{\pi}=1/2^{-}$) and L=0, S=3/2($J^{\pi}=3/2^{-}$) at observed energy region. However, we have one resonant state at 4690 MeV for $J^{\pi}=1/2^{-}$ and at 4890 MeV for $J^{\pi}=3/2^{-}$. This can be penta-quark state.

From our calculation, we would suggest that the resonant states observed at LHCb are meson-baryon resonant states which we cannot calculate in our model.

If it is possible to produce the penta-quark system at Alice, I would like to ask you what kinds of pentaquark system they can produce.

Thank you to all speakers for very interesting presentations

Thank you to all participants for very interesting discussions