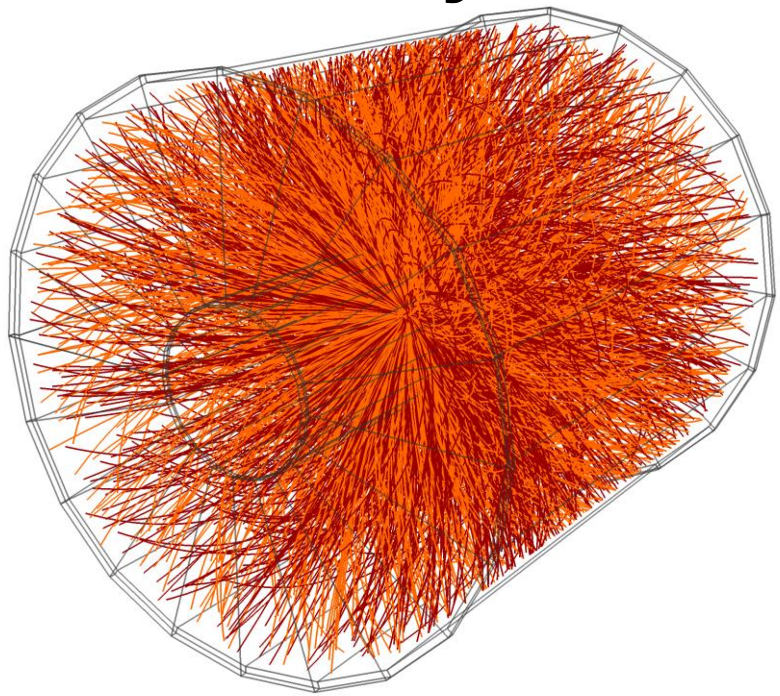
Light Flavour Hadron Production at the LHC: Equilibrium Thermodynamics at Work



Excited Hyperons in QCD Thermodynamics at Freeze-Out
YSTAR2016
November 16-17, 2016
JLab, Newport News, VA

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Goethe Universität Frankfurt

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- Introduction
- Strangeness
- Resonances
- (Hyper-)Nuclei
- Exotica
- Summary

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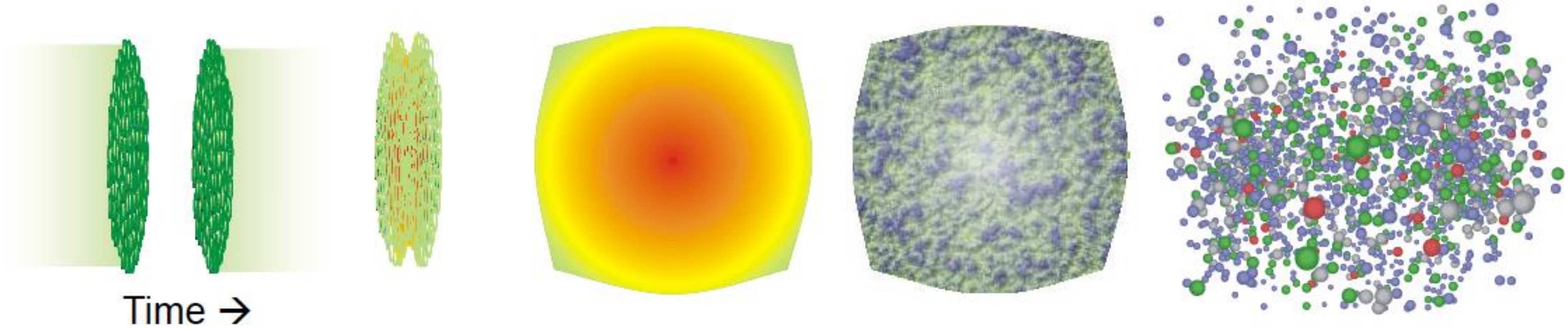
Introduction



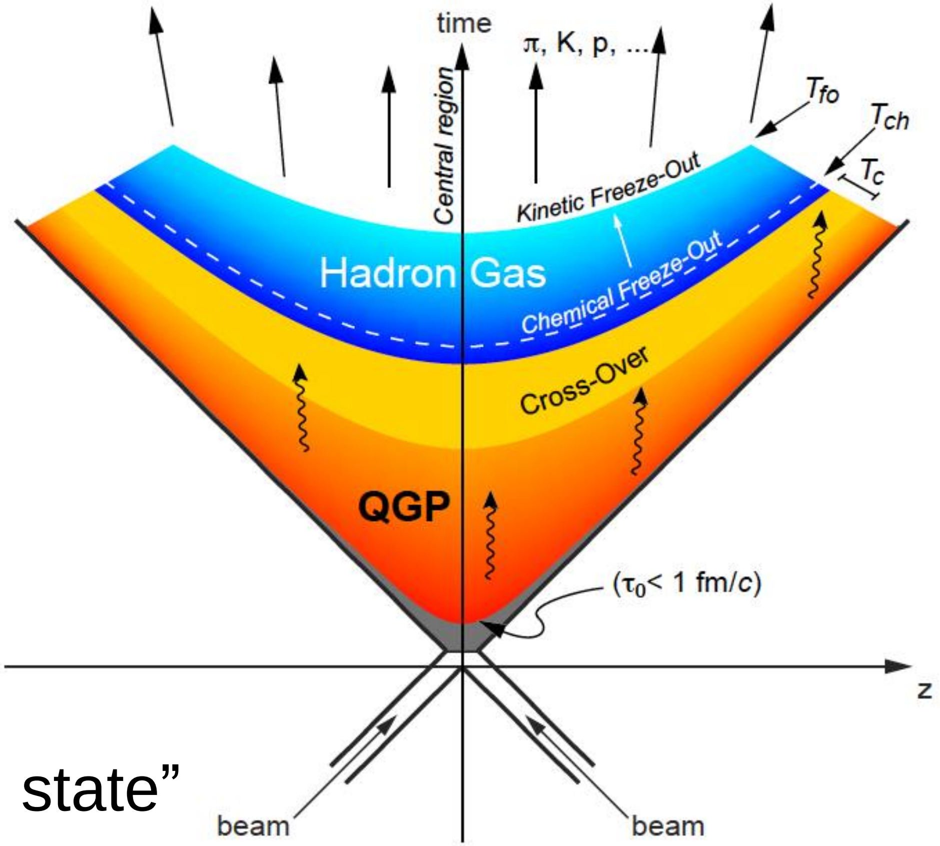
Cartoon of an ultra-relativistic heavy-ion collision

Left to right:

- the two Lorentz contracted nuclei approach,
- collide,
- form a Quark-Gluon Plasma (QGP),
- the QGP expands and hadronizes,
- finally hadrons rescatter and freeze

Plot by S. Bass, Duke University; http://www.phy.duke.edu/research/NPTheory/QGP/transport/evo.jpg

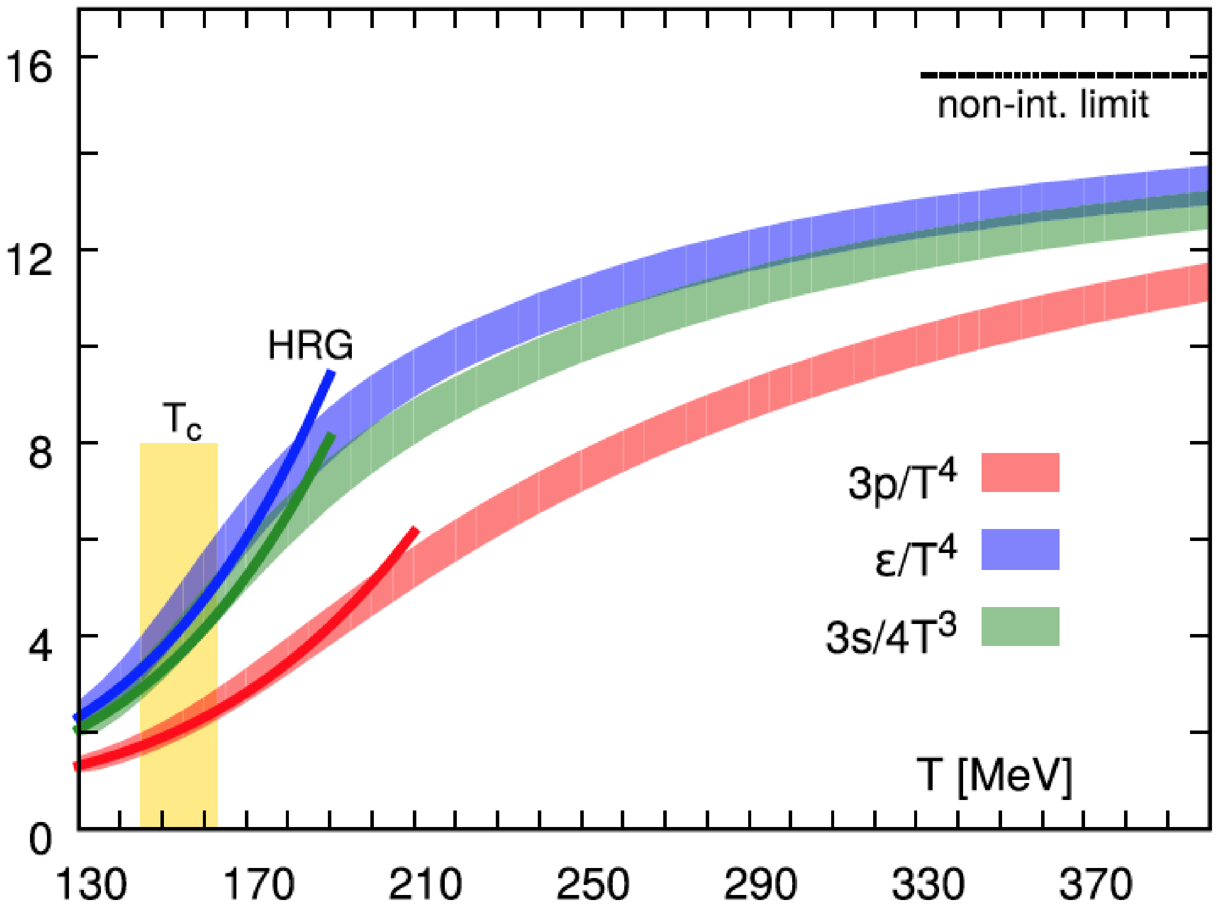
Introduction



The fireball evolution:

- Starts with a “pre-equilibrium state”
- Forms a Quark-Gluon Plasma phase (if T is larger than T_c)
- At *chemical freeze-out,* T_{ch}, *hadrons stop being produced*
- At *kinetic freeze-out,* T_{fo}, *hadrons stop scattering*

Lattice QCD results



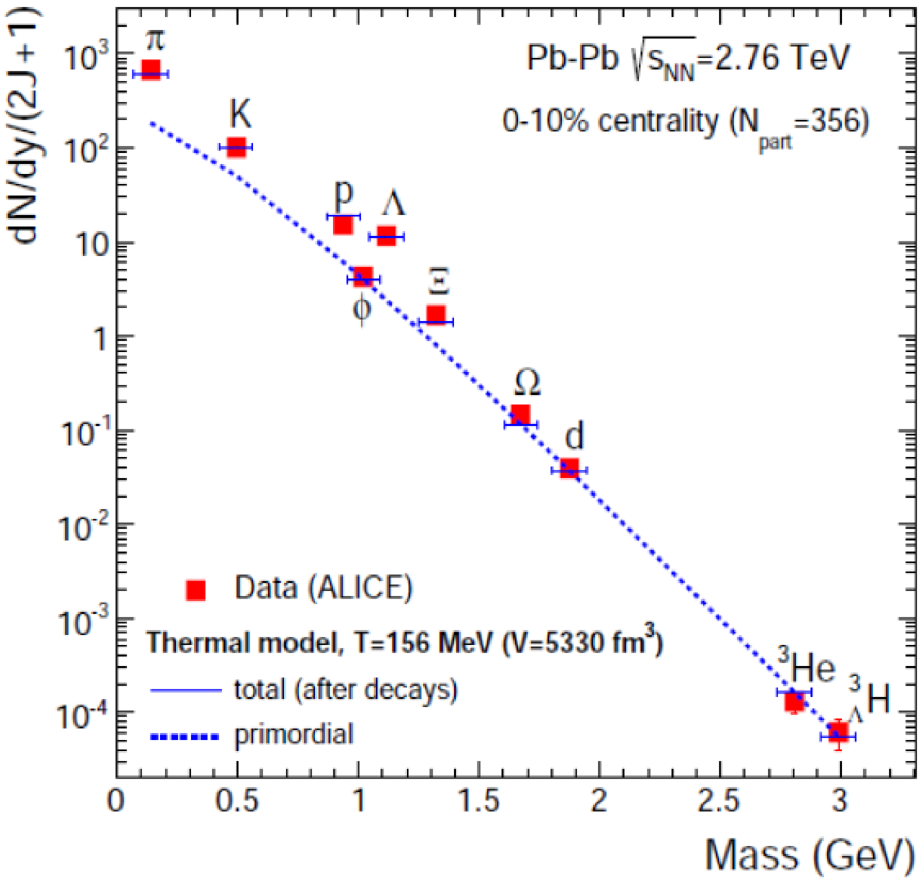
Lattice QCD tells us where to expect the phase transition

Critical energy density:
$\varepsilon_C = 0.34 \pm 0.16$ GeV/fm^3

Critical temperature
$T_C = (154 \pm 9)$ MeV

A. Bazavov et al. (hotQCD) Phys. Rev. D90 (2014) 094503
Similar results from Budapest-Wuppertal group: S. Borsányi et al. JHEP 09 (2010) 073

Temperature of the source



Plot by A. Andronic, GSI-Heidelberg group
arXiv:1407.5003 [nucl-ex]

Analogy:

Light source → particle source

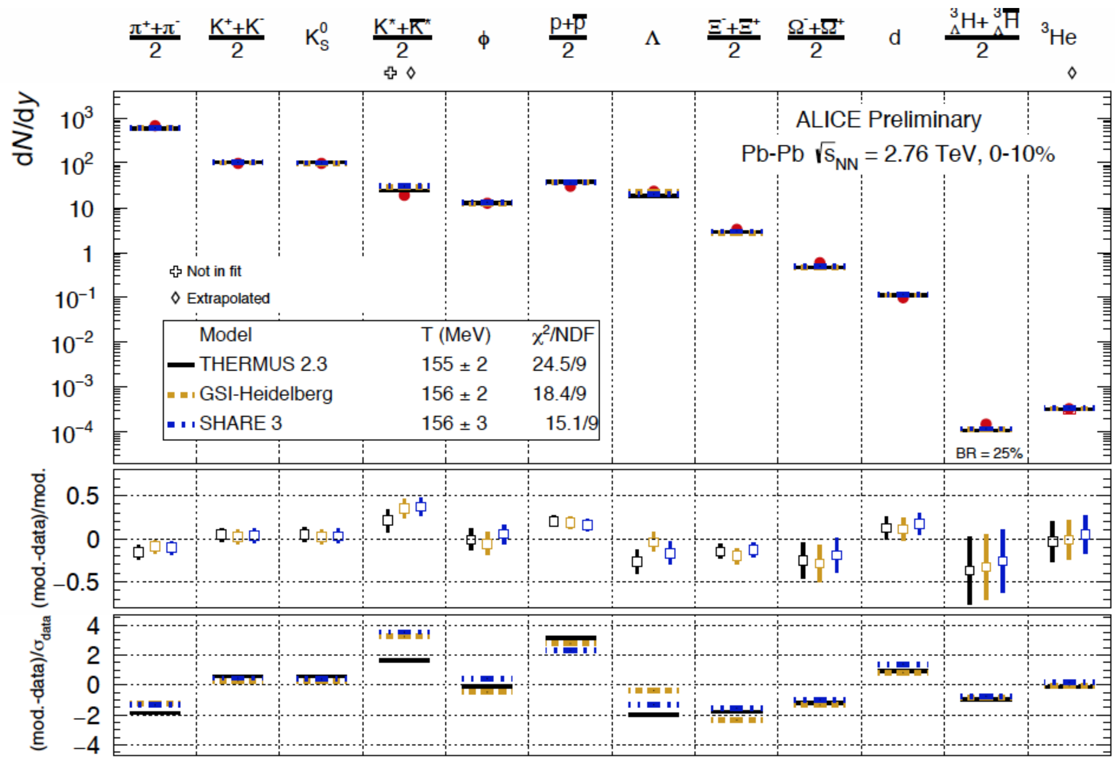
- Multiplicity described best with
  T = 1 900 000 000 000 ^{o}C
  (1.9 trillion degree centigrade)

→ 100 000 times hotter than in the interior of the sun!

1/40 eV = 20 ^{o}C

Thermal model

- Statistical (thermal) model with only three parameters able to describe particle yields (grand canonical ensemble)

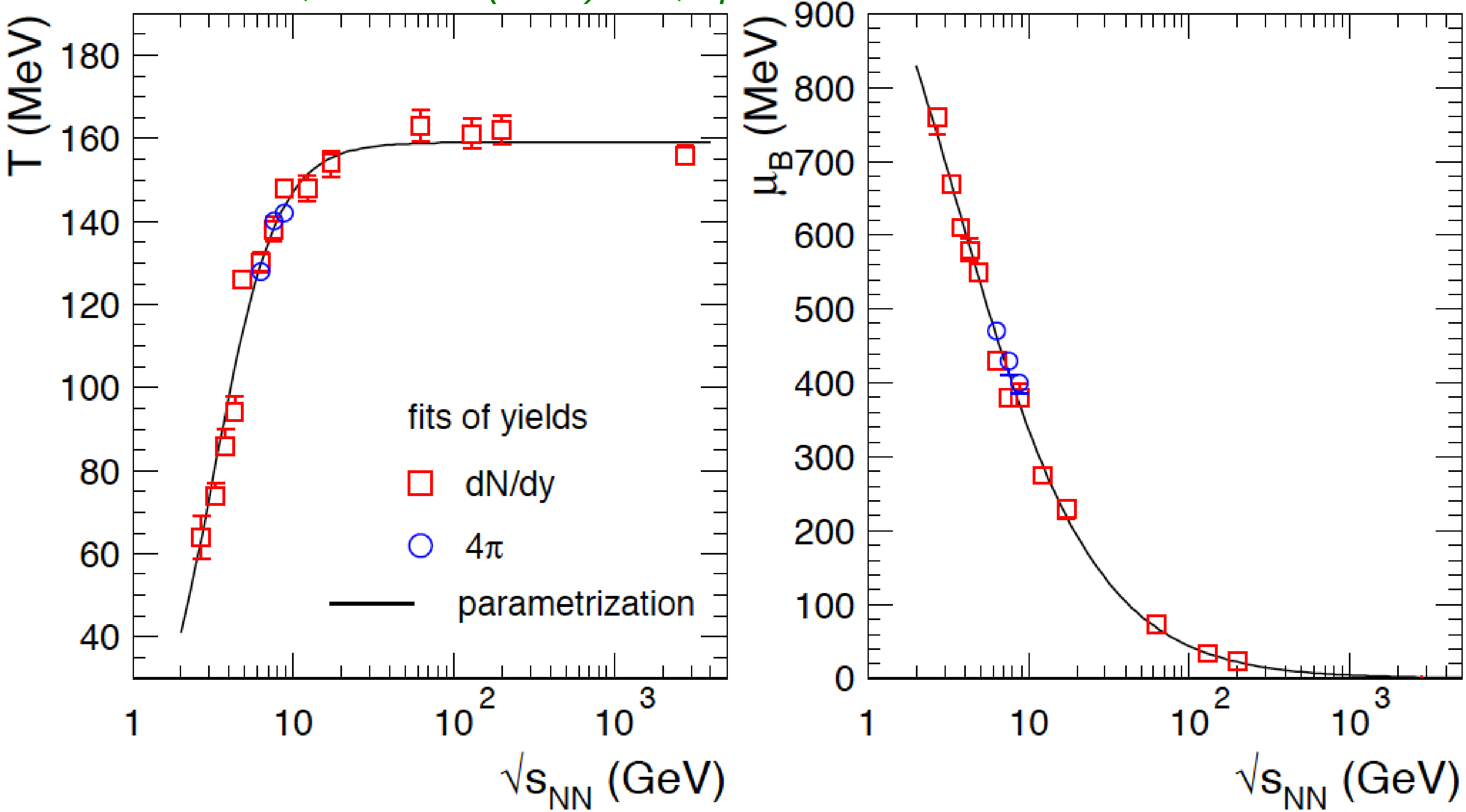


- chemical freeze-out temperature T_{ch}
- baryo-chemical potential μ_B
- Volume V

→ Using particle yields as input to extract parameters

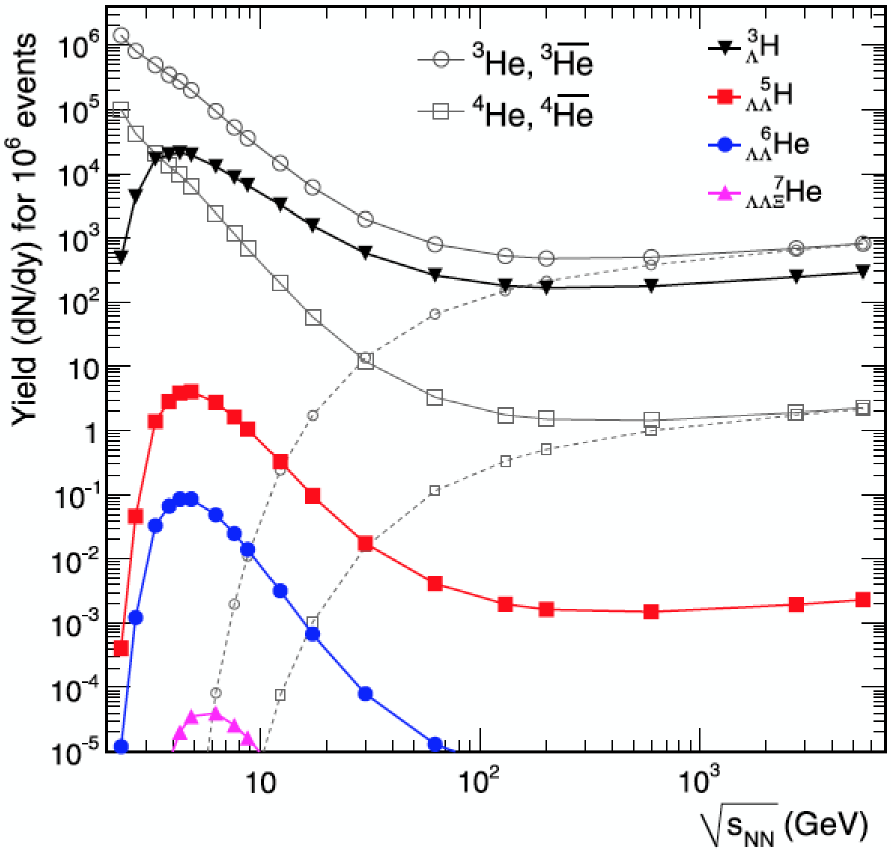
Energy dependence

A. Andronic et al., PLB 673 (2009) 142, updated



Thermal model fits show limiting temperature: T_{lim} = (159 ± 2) MeV

Predicting yields of bound states



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

Key parameter at LHC energies:

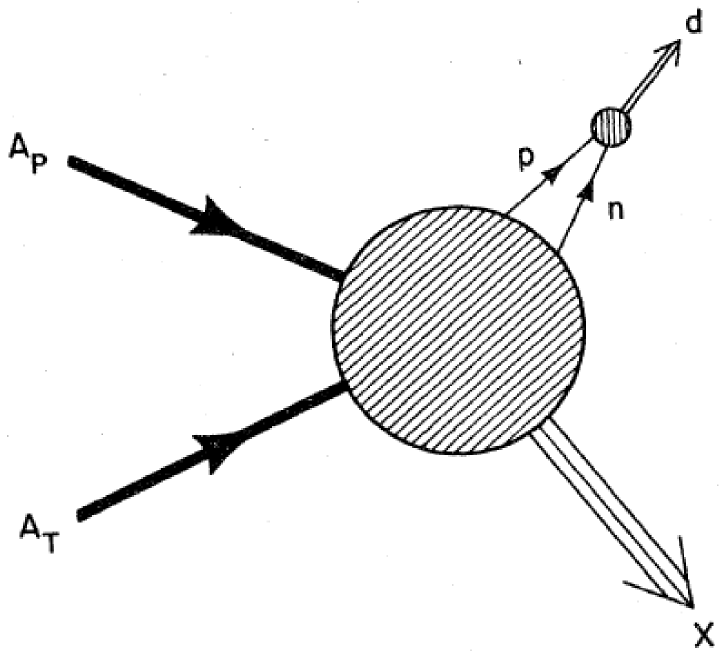
chemical freeze-out temperature T_{ch}

Strong sensitivity of abundance of nuclei to choice of T_{ch} due to:

1. large mass *m*
2. exponential dependence of the yield ~ $\exp(-m/T_{ch})$

→ Binding energies small compared to T_{ch}

Coalescence



J. I. Kapusta, PRC 21, 1301 (1980)

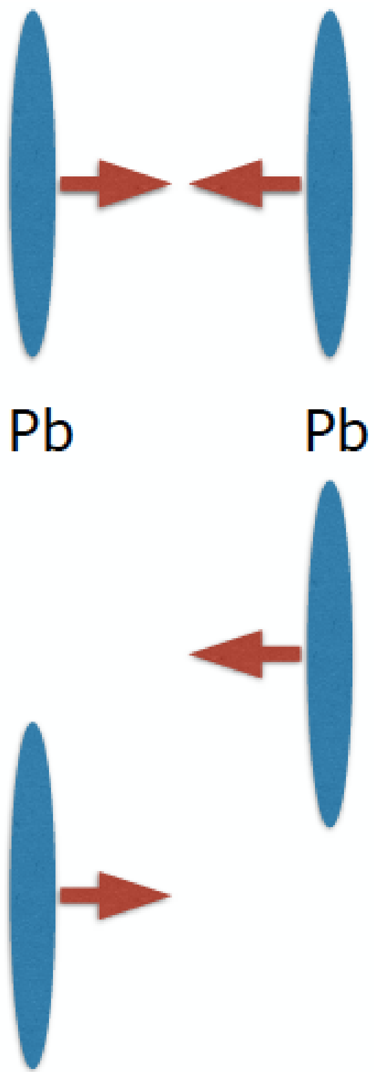
- Nuclei are formed by protons and neutrons which are nearby and have similar velocities (after kinetic freeze-out)

- Produced nuclei

➜ can break apart

➜ created again by final-state coalescence

Interlude: Centrality



Central Pb-Pb collision:

High multiplicity = large <dN/dη>

High number of tracks

(more than 2000 tracks in the detector)

Peripheral Pb-Pb collision:

Low multiplicity = small <dN/dη>

Low number of tracks

(less than 100 tracks in the detector)

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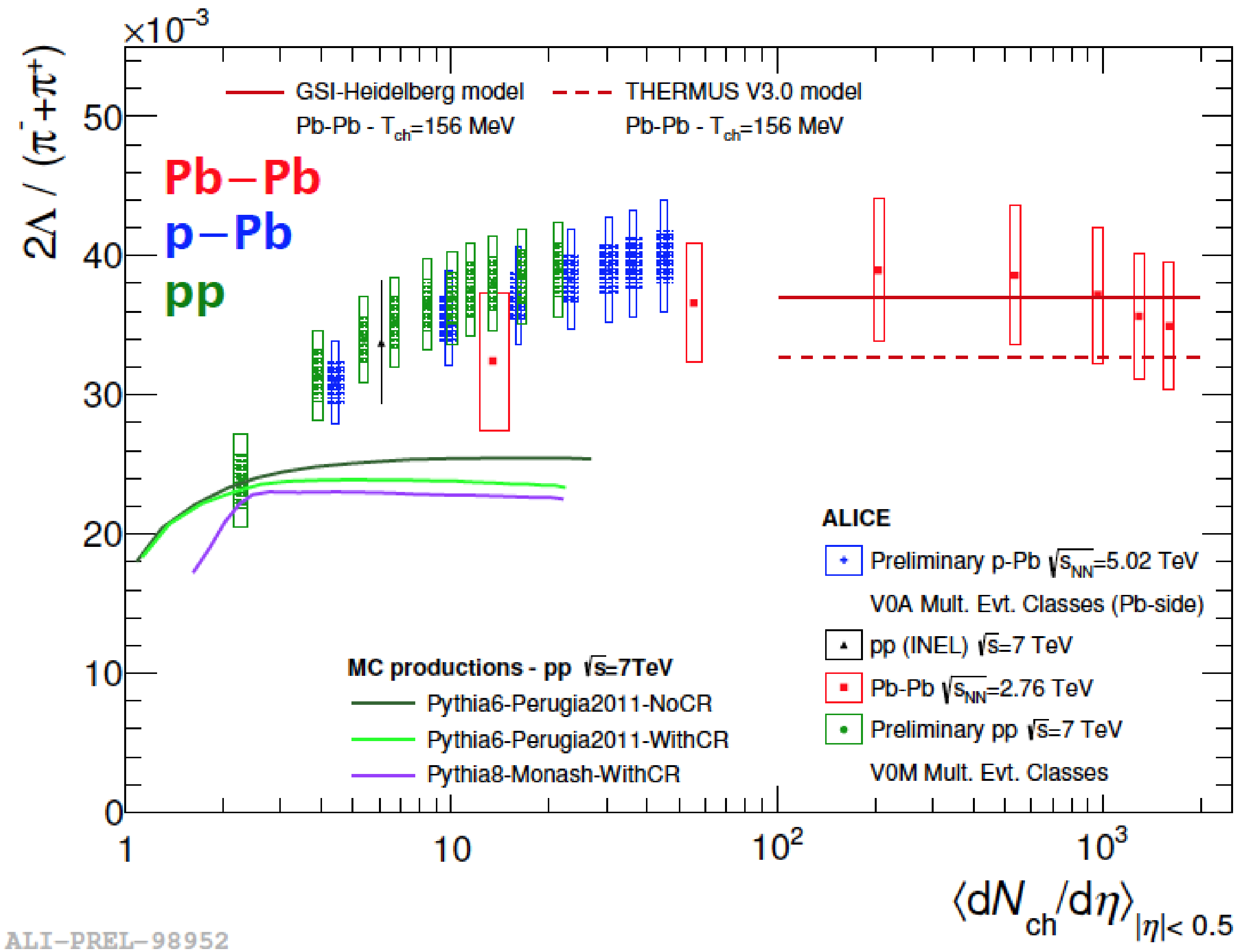
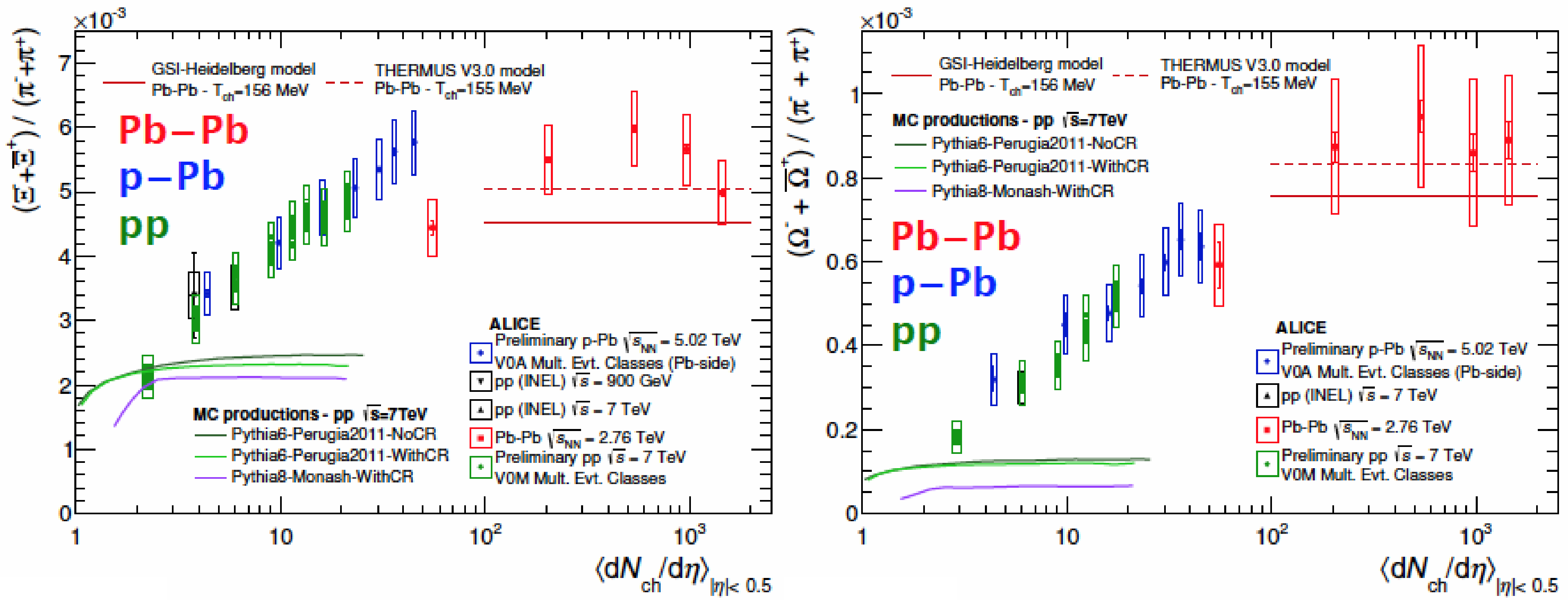
Strangeness: Λ/π

- Observation when Λ/π ratio is compared for different collision systems as function of multiplicity



→ Values approach thermal model expectation also in high-multiplicity pp and p-Pb events

Strangeness: Ξ/π & Ω/π

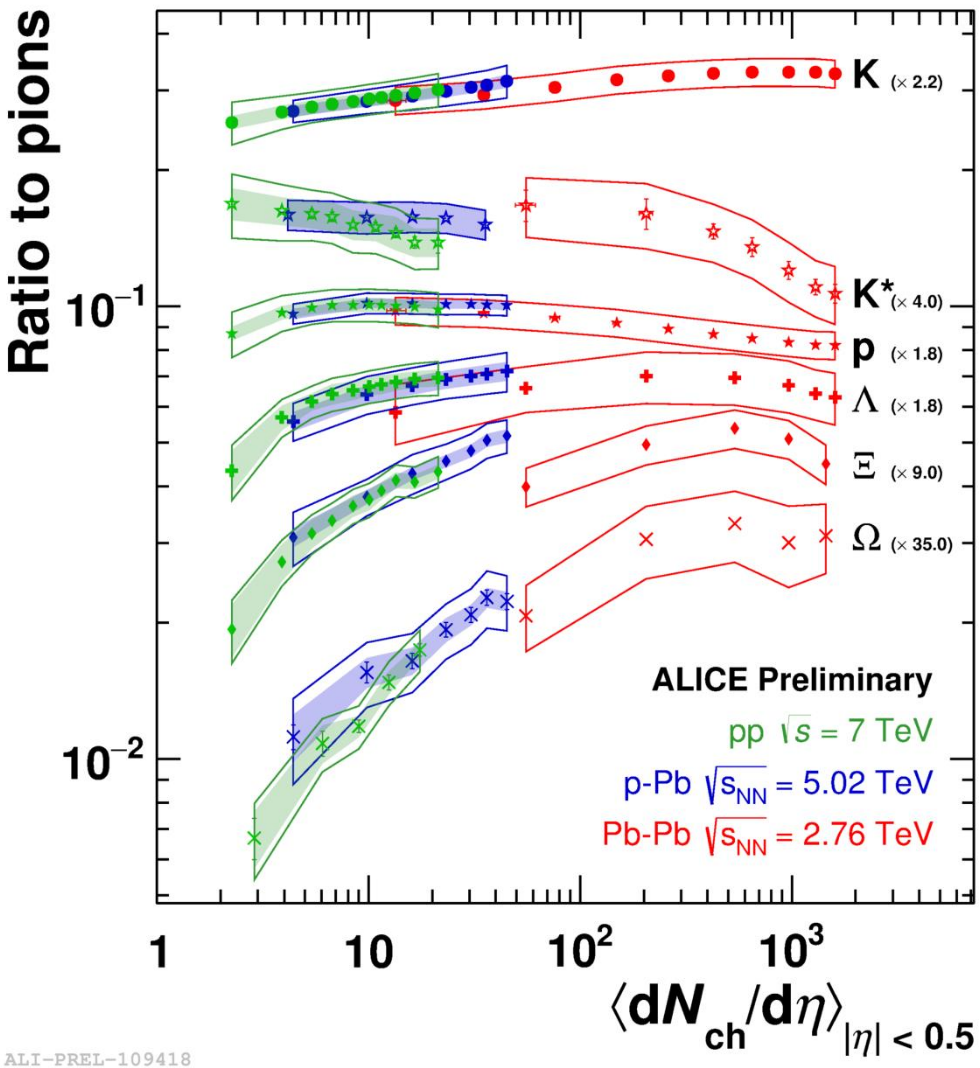


- Similar trend observed for the Ξ/π and Ω/π ratios

→ Saturation reached at the grand canonical limit in Pb-Pb collisions

Ratios in different systems

- Small systems:
  - Strangeness enhancement
  - Relative decrease of K^{*0}
  - No multiplicity dependence of baryon/meson ratio
- Towards central Pb-Pb:
  - Strangeness abundance constant
  - K^{*0} abundance decreases further
  - Baryon/meson decreases



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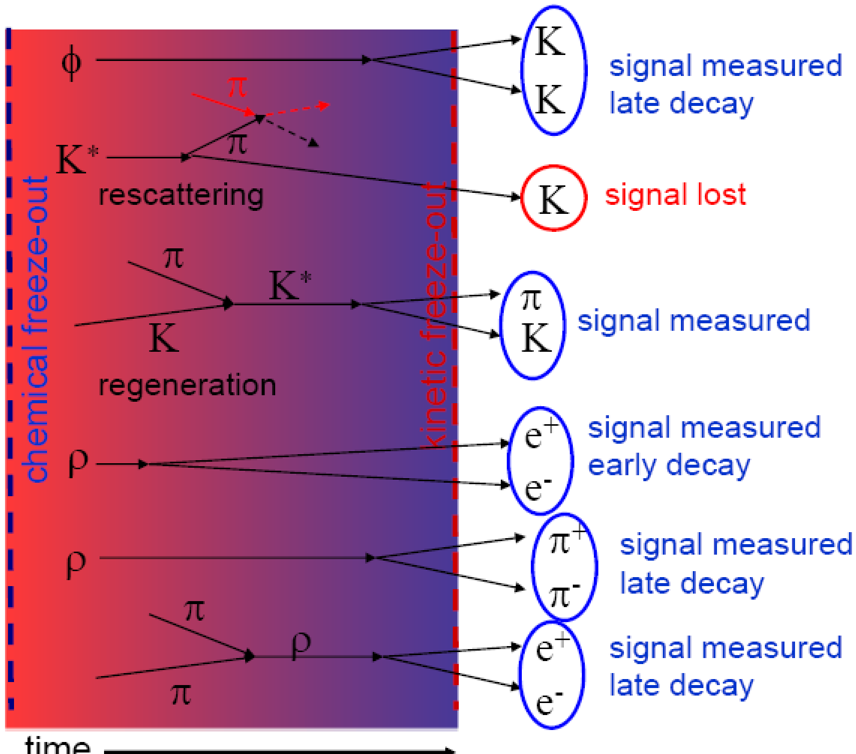
Resonances in HIC

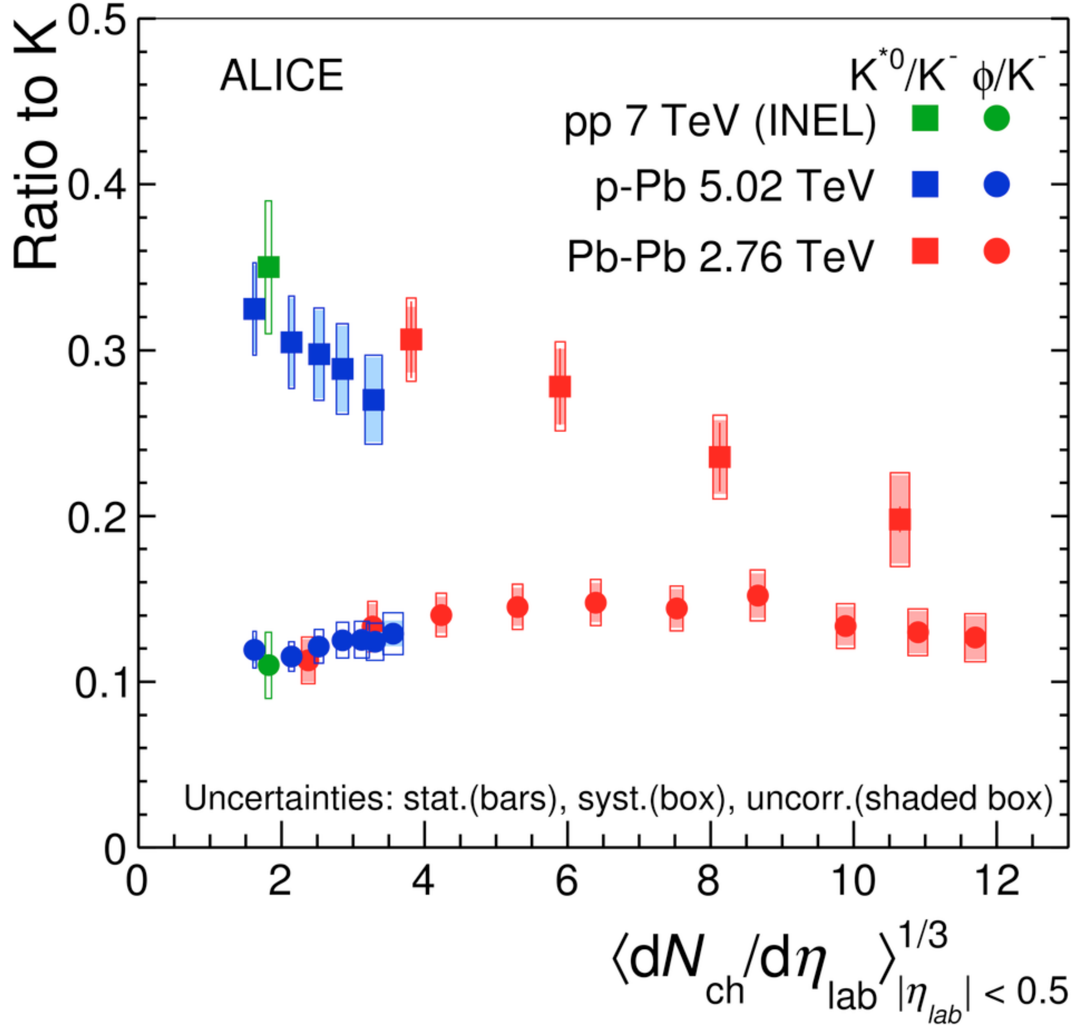


C. Markert

- Resonances lifetimes typically shorter than the lifetime of the fireball, i.e. 10 fm/*c*
- Resonances can decay inside the fireball and can either be lost or regenerated
- Resonances are used as probes for the lifetime of the hadronic phase, because of their different lifetimes
- Resonances are aimed to measure chiral symmetry restauration in the medium

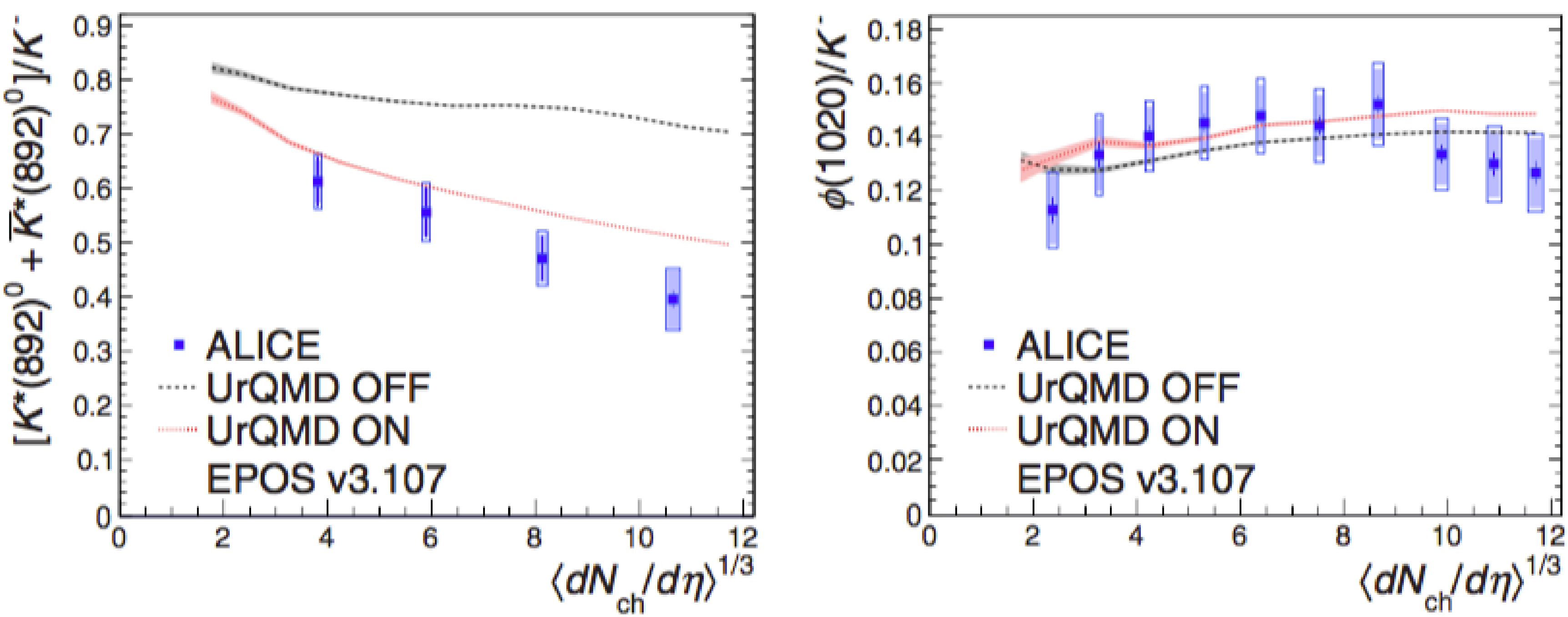
Re-scattering of K* and Φ

- Clear trend in p-Pb and Pb-Pb, but also in high mult. pp collisions
- Can there be re-scattering in such a small system as p-Pb?
- → In principle a medium is needed for the discussed scenario
- Could there be an alternative mechanism at play which does not require a dense and long lived hadronic phase?
- More data and more resonances needed to get a complete picture



Re-scattering of K* and Φ

- The effect can be semi-quantitatively described by EPOS with an UrQMD afterburner for the hadronic phase.



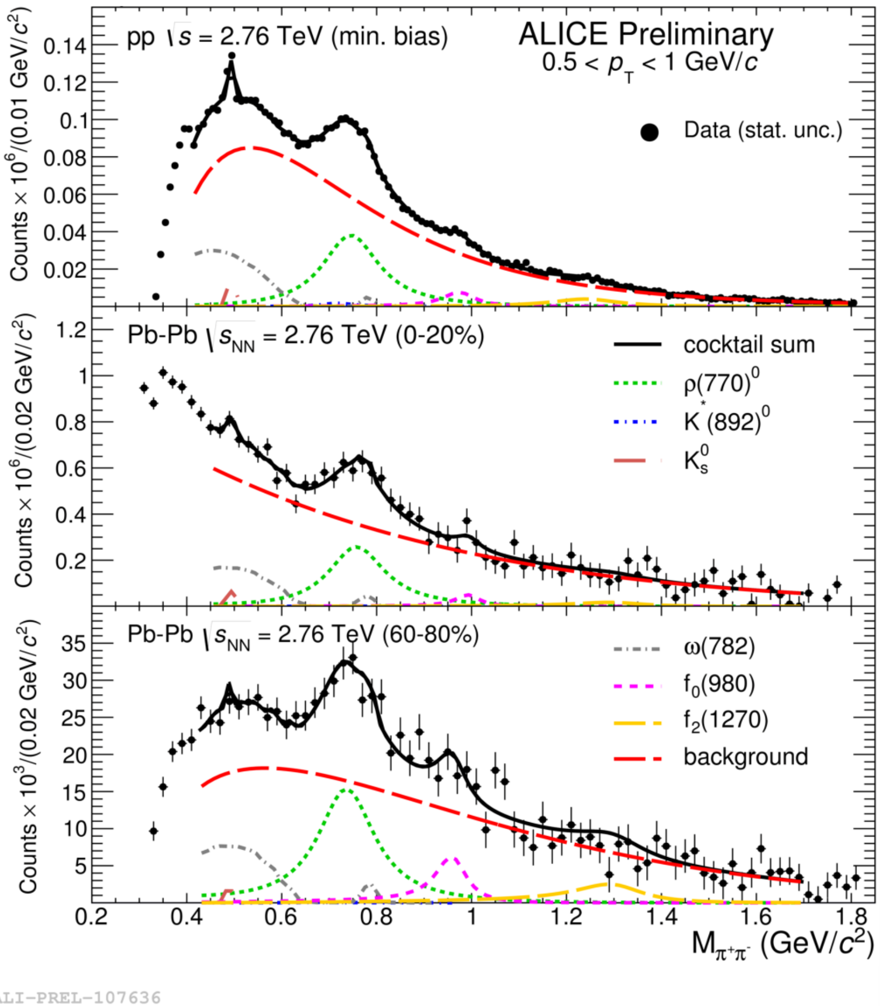
A. G. Knospe *et al.*, PRC 93 (2016) 014911.

Re-scattering of $\rho(770)$

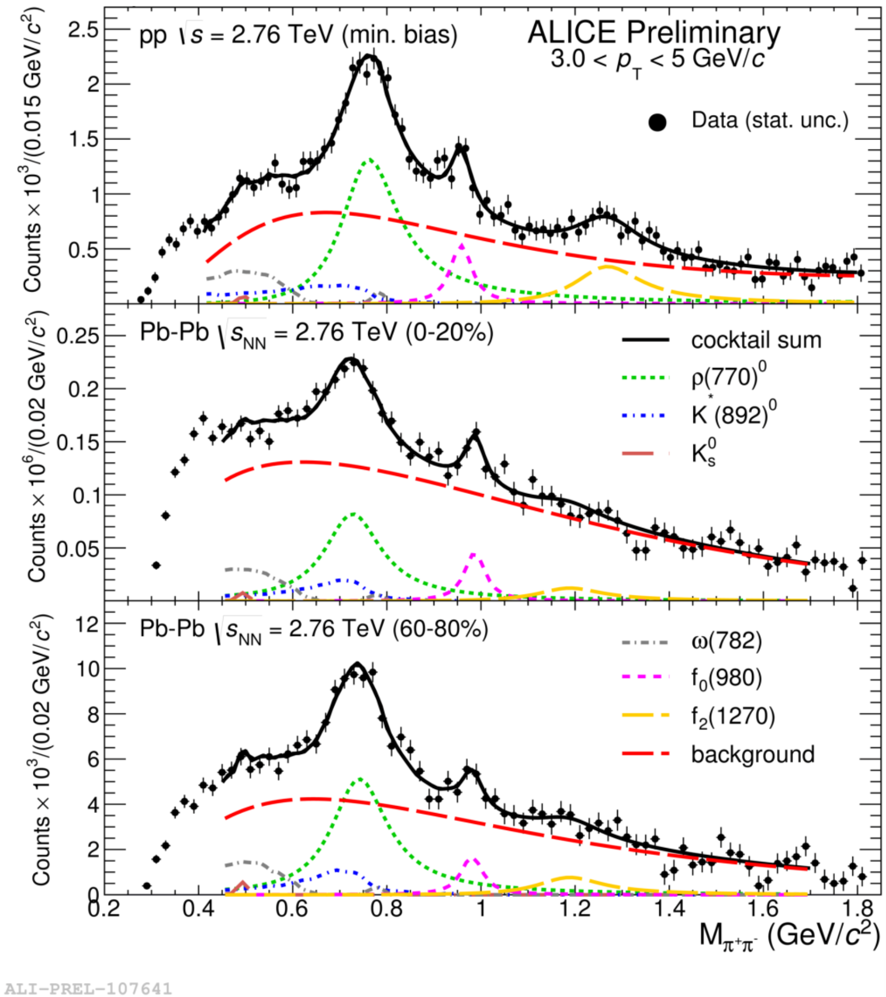
	$\rho(770)$	$K^*(892)$	$\Sigma(1385)$	$\Lambda(1520)$	$\Xi(1530)$	$\phi(1020)$
$c\tau$ (fm/c)	1.3	4.2	5.5	12.7	21.7	46.2
$\sigma_{rescatt}$	$\sigma_\pi\sigma_\pi$	$\sigma_\pi\sigma_K$	$\sigma_\pi\sigma_\Lambda$	$\sigma_K\sigma_p$	$\sigma_\pi\sigma_\Xi$	$\sigma_K\sigma_K$

- $\rho(770)$-resonance should be affected in a similar way like the K* (shorter lifetime, but σ_π instead of σ_K)
- The analysis is very complicated and challenging:
  - Accumulate invariant mass distribution for $\pi^+\pi^-$ pairs.
  - Subtract like-sign background.
  - Describe remaining background as sum of:
    - smooth background:
    - sum of templates for K_s, K* and ω each normalised to measured yield and corrected for acceptance x efficiency.
    - reject contributions from η, η'm and Φ by limiting fit range $M < 0.45$ GeV/c^2
    - use peak models for ρ, f_0, and f_2

ρ(770) signal



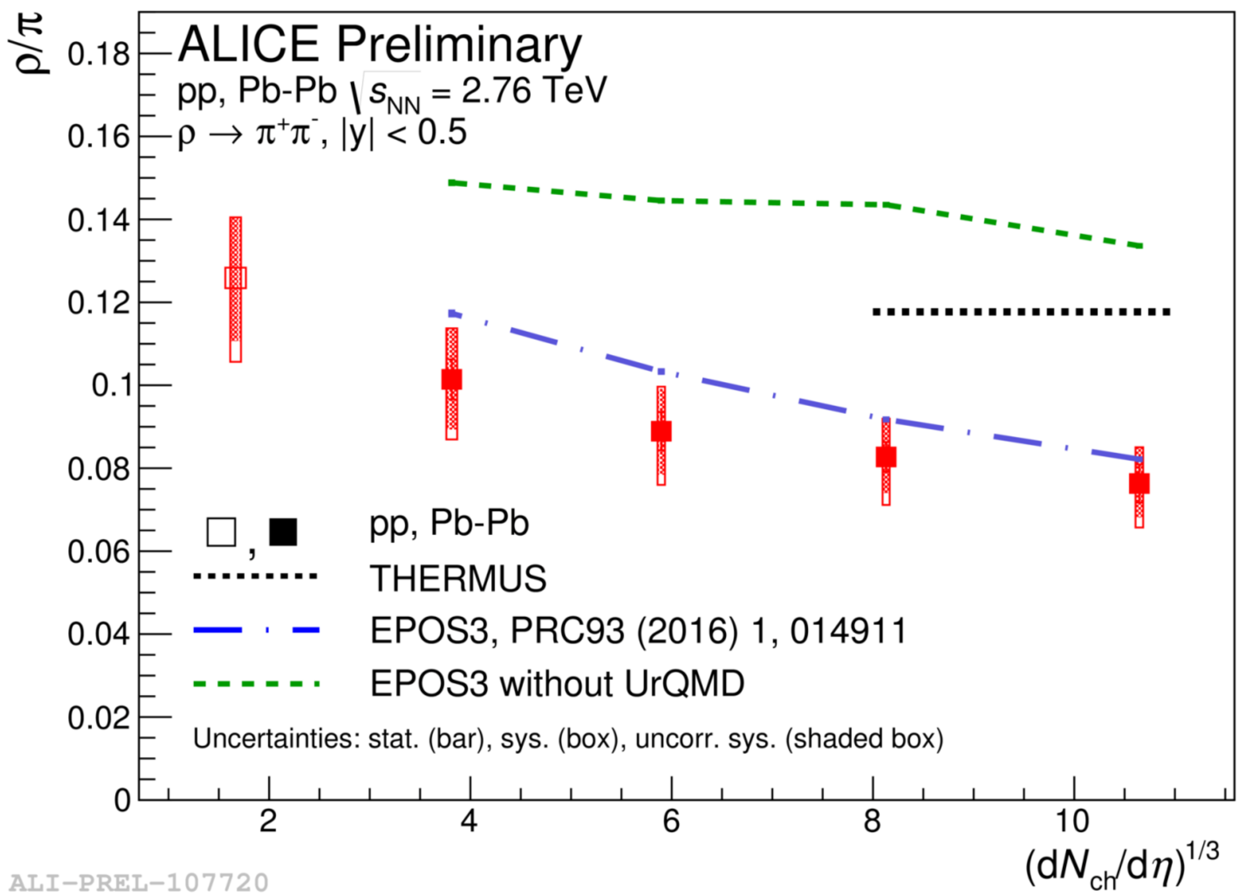
pp √s = 2.76 TeV (min. bias)
ALICE Preliminary
0.5 < p_T < 1 GeV/c
Data (stat. unc.)
Pb-Pb √s_NN = 2.76 TeV (0-20%)
cocktail sum
ρ(770)^0
K*(892)^0
K^0_s
Pb-Pb √s_NN = 2.76 TeV (60-80%)
ω(782)
f_0(980)
f_2(1270)
background
Counts × 10^6/(0.01 GeV/c^2)
Counts × 10^6/(0.02 GeV/c^2)
Counts × 10^3/(0.02 GeV/c^2)
M_π+π- (GeV/c^2)
ALI-PREL-107636



pp √s = 2.76 TeV (min. bias)
ALICE Preliminary
3.0 < p_T < 5 GeV/c
Data (stat. unc.)
Pb-Pb √s_NN = 2.76 TeV (0-20%)
cocktail sum
ρ(770)^0
K*(892)^0
K^0_s
Pb-Pb √s_NN = 2.76 TeV (60-80%)
ω(782)
f_0(980)
f_2(1270)
background
Counts × 10^3/(0.015 GeV/c^2)
Counts × 10^6/(0.02 GeV/c^2)
Counts × 10^3/(0.02 GeV/c^2)
M_π+π- (GeV/c^2)
ALI-PREL-107641

$\rho(770)$ suppression

- Trend is also qualitatively well described by EPOS+UrQMD



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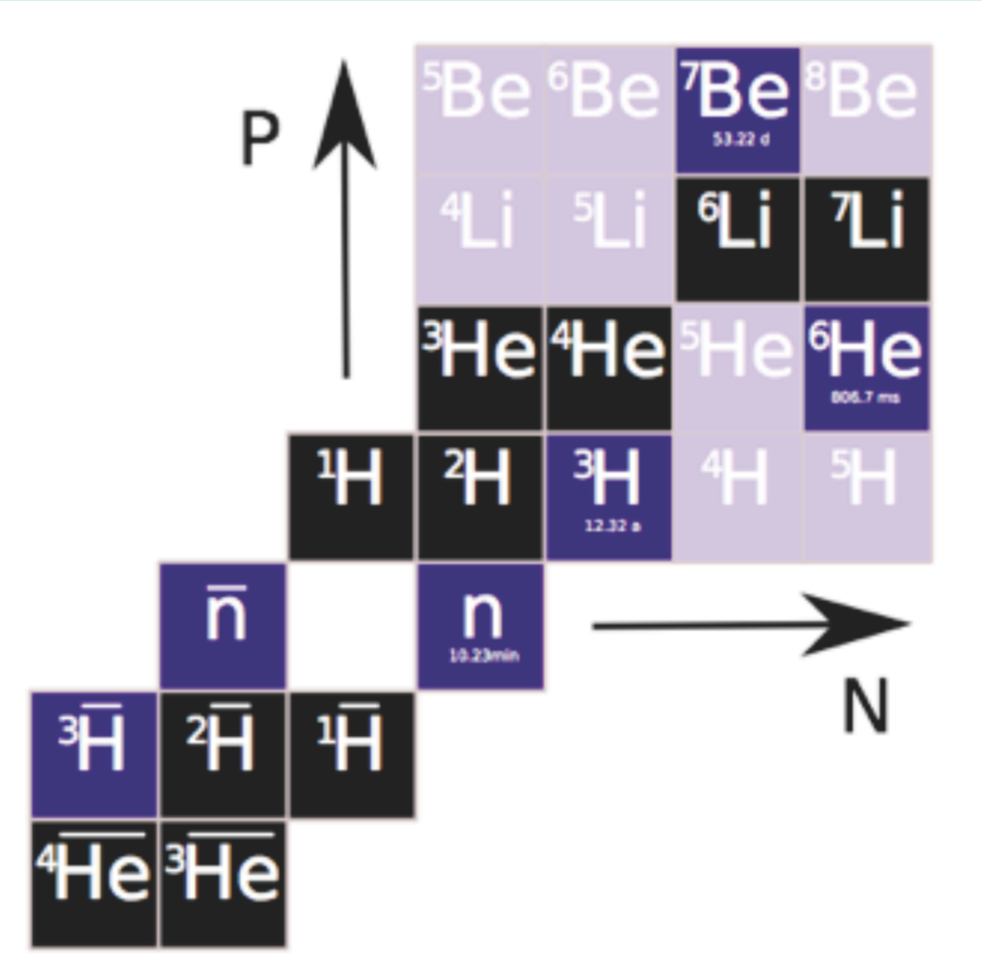
(Anti-)Nuclei

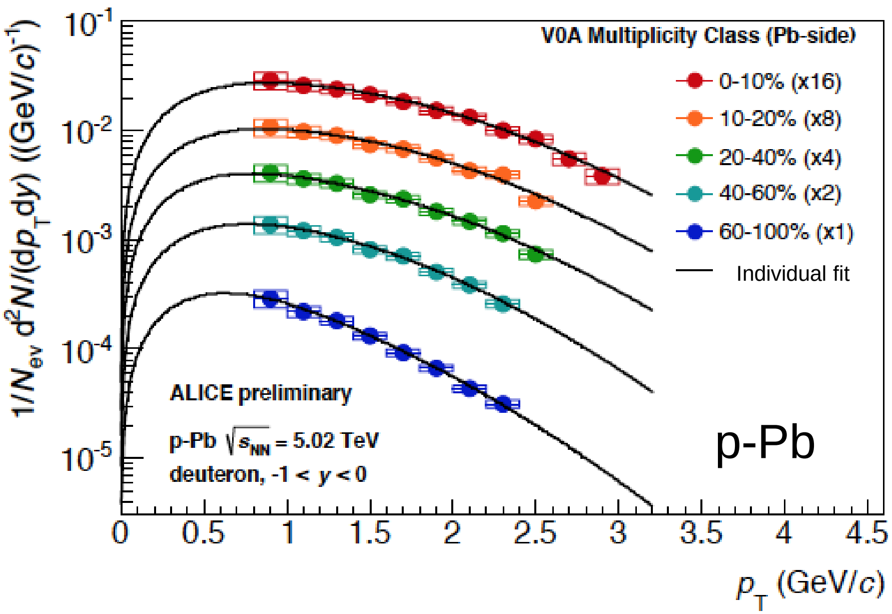


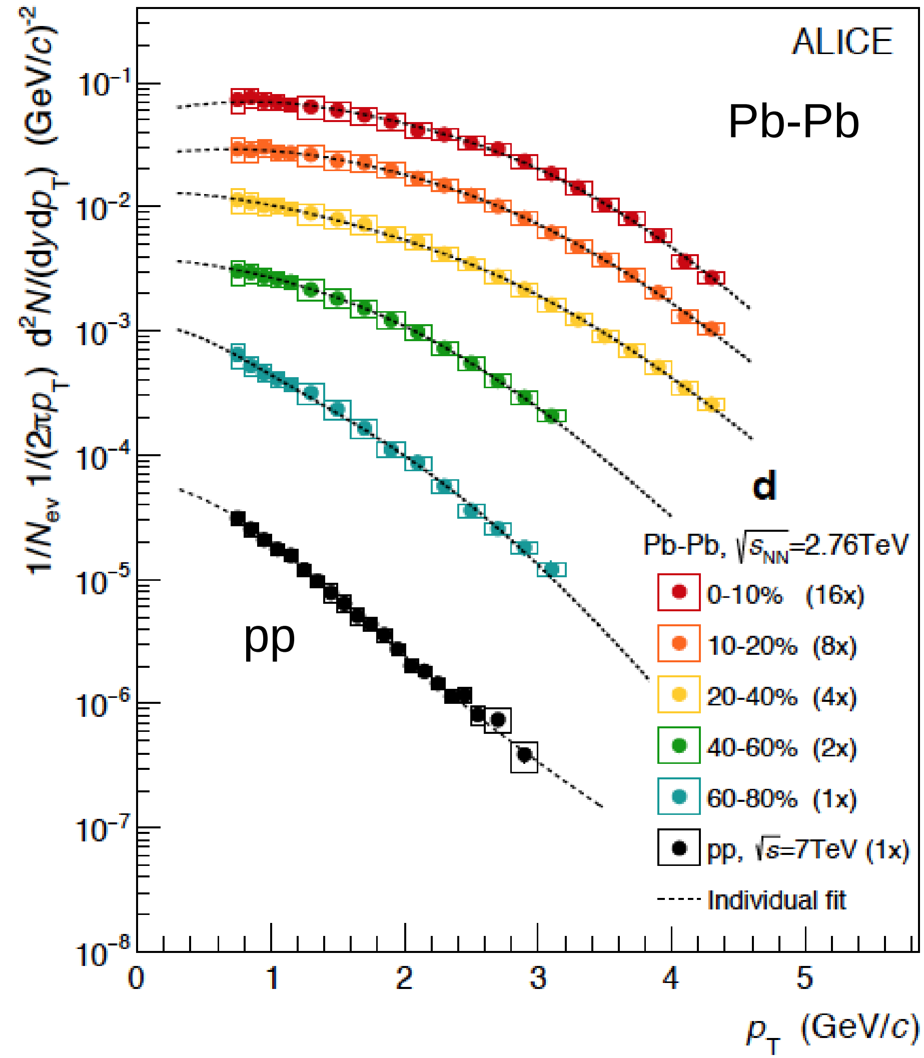
P
N
^{5}Be
^{6}Be
^{7}Be
53.22 d
^{8}Be
^{4}Li
^{5}Li
^{6}Li
^{7}Li
^{3}He
^{4}He
^{5}He
^{6}He
806.7 ms
^{1}H
^{2}H
^{3}H
12.32 a
^{4}H
^{5}H
$\bar{n}$
n
10.23min
$^{3}\overline{H}$
$^{2}\overline{H}$
$^{1}\overline{H}$
$^{4}\overline{He}$
$^{3}\overline{He}$

Deuterons

ALICE Collaboration: PRC 93, 024917 (2016)

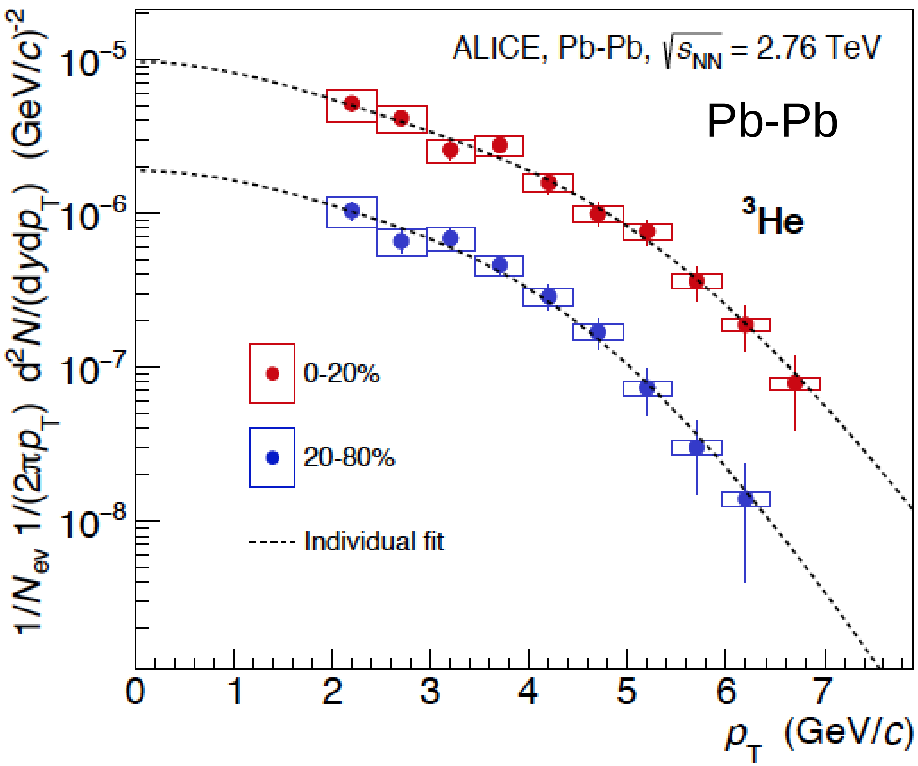
- Spectra become harder with increasing multiplicity in p-Pb and Pb-Pb and show clear radial flow
- The Blast-Wave fits describe the data well in p-Pb and Pb-Pb
- pp spectrum shows no sign of radial flow

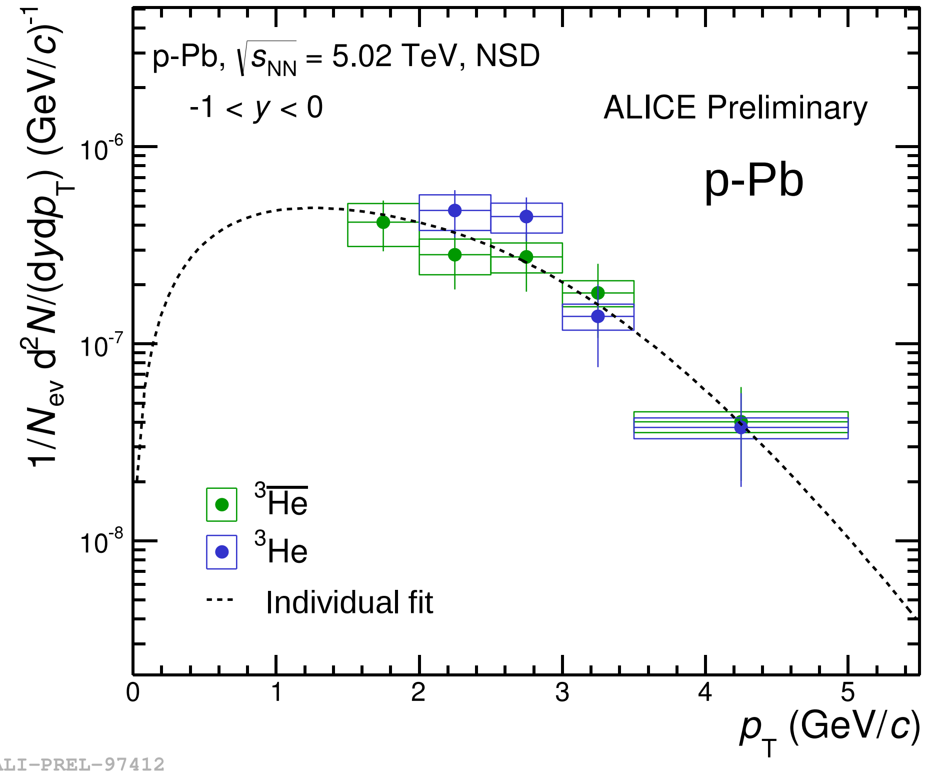




^{3}He

ALICE Collaboration: PRC 93, 024917 (2016)





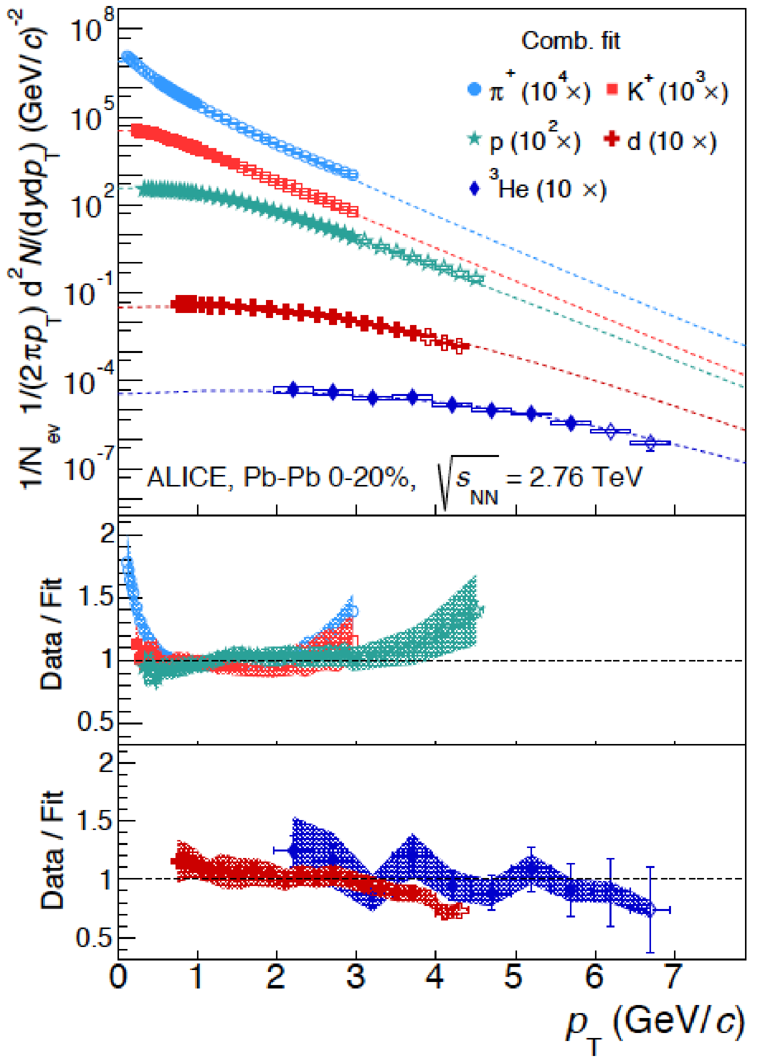
- Dashed curve represents individual Blast-Wave fits
- Spectrum obtained in 2 centrality classes in Pb-Pb and for NSD collisions in p-Pb

Combined Blast-Wave fit

ALICE Collaboration: J. Adam et al., PRC 93 (2016) 024917

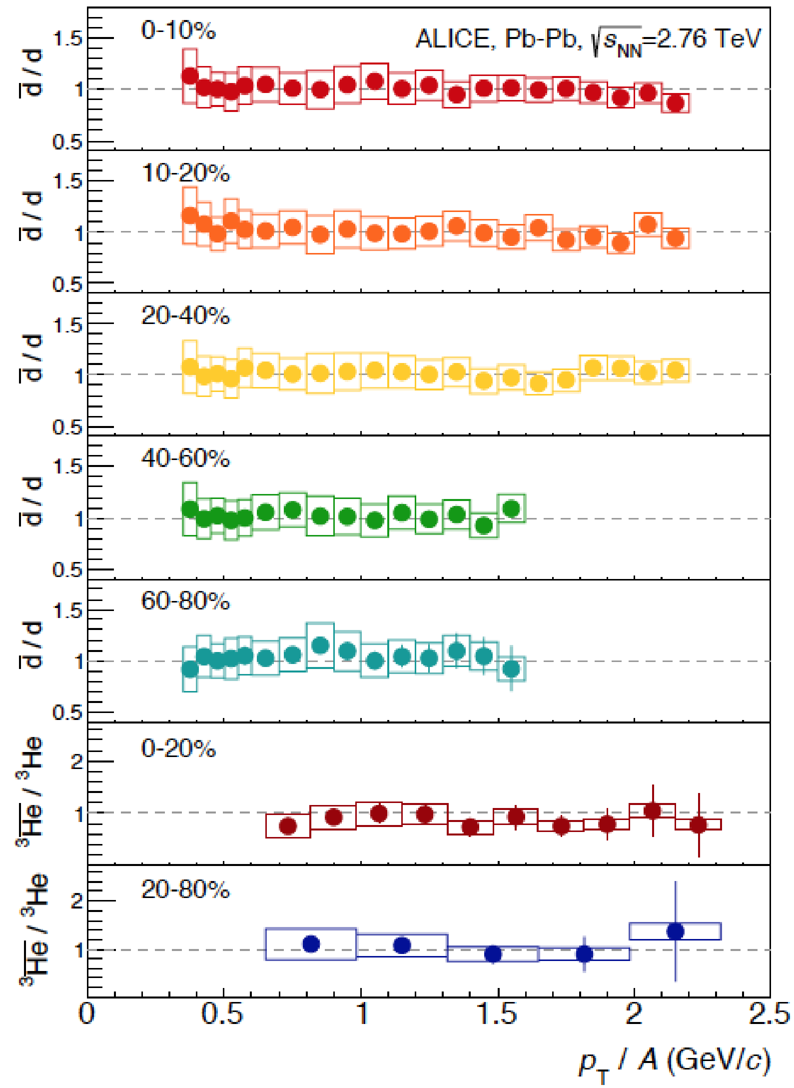
Simultaneous Blast-Wave fit of π^+, K^+, p, d and ^{3}He spectra for central Pb-Pb collisions leads to values for $<\beta>$ and T_{kin} close to those obtained when only π,K,p are used

All particles are described rather well with this simultaneous fit



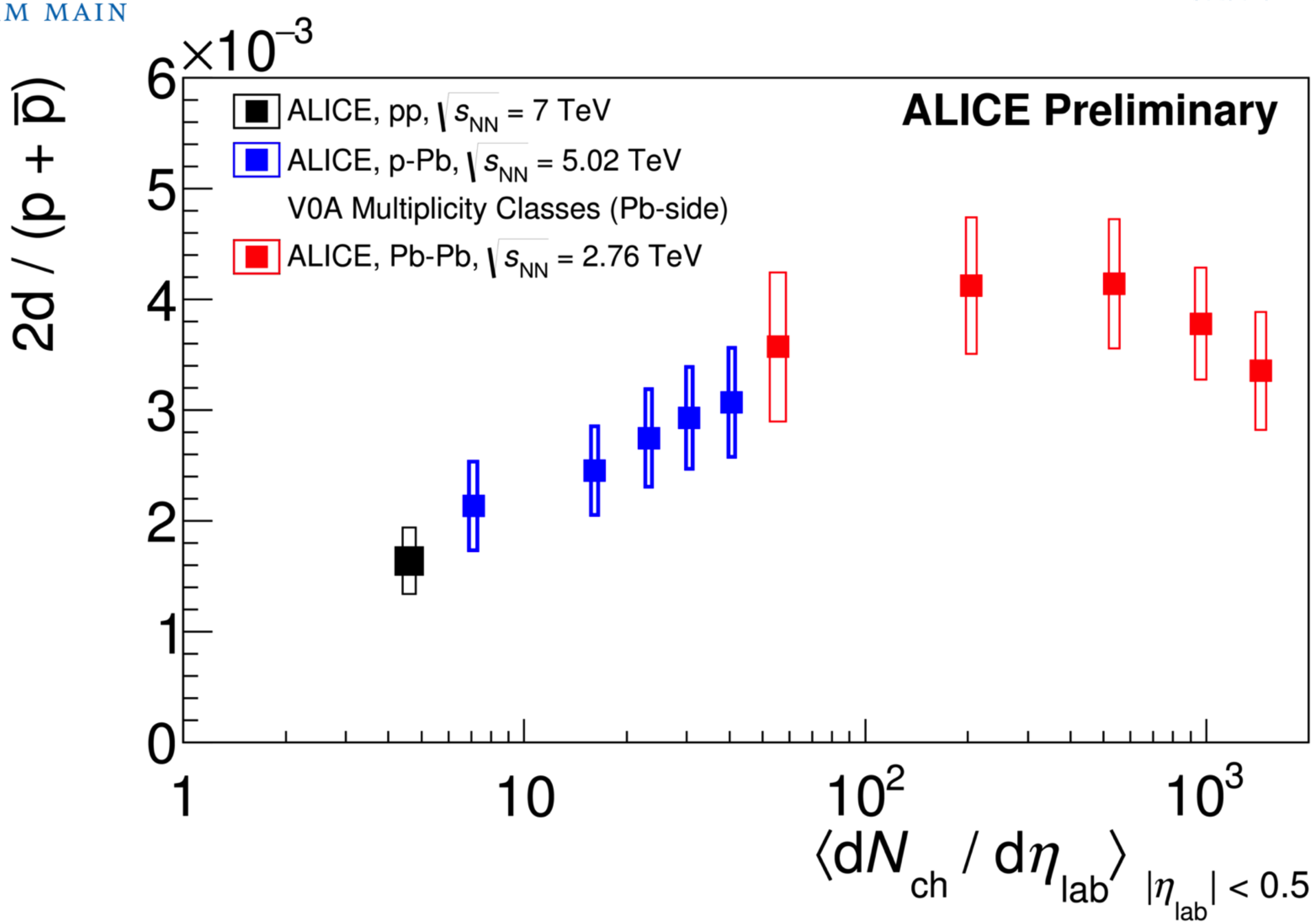
LHC: factory for anti-matter and matter

- Anti-nuclei / nuclei ratios are consistent with unity (similar to other light particle species)
- Ratios exhibit constant behavior as a function of p_T and centrality
- Ratios are in agreement with the coalescence and thermal model expectations



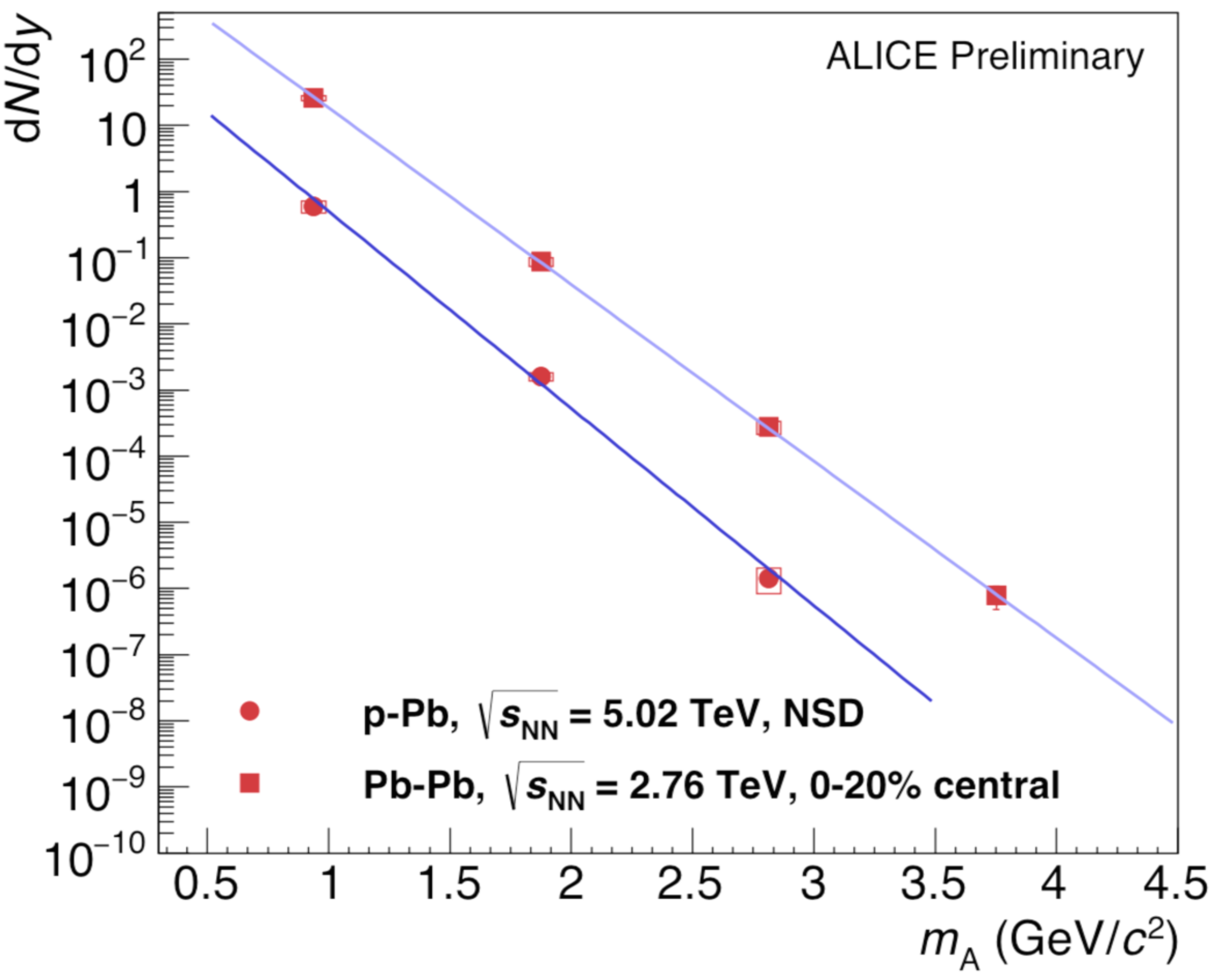
ALICE Collaboration: PRC 93, 024917 (2016)

d/p vs. multiplicity



d/p ratio increases when going from pp to p-Pb, until it reaches the grand canonical thermal model value (d/p=3x10^{-3} at 156 MeV)

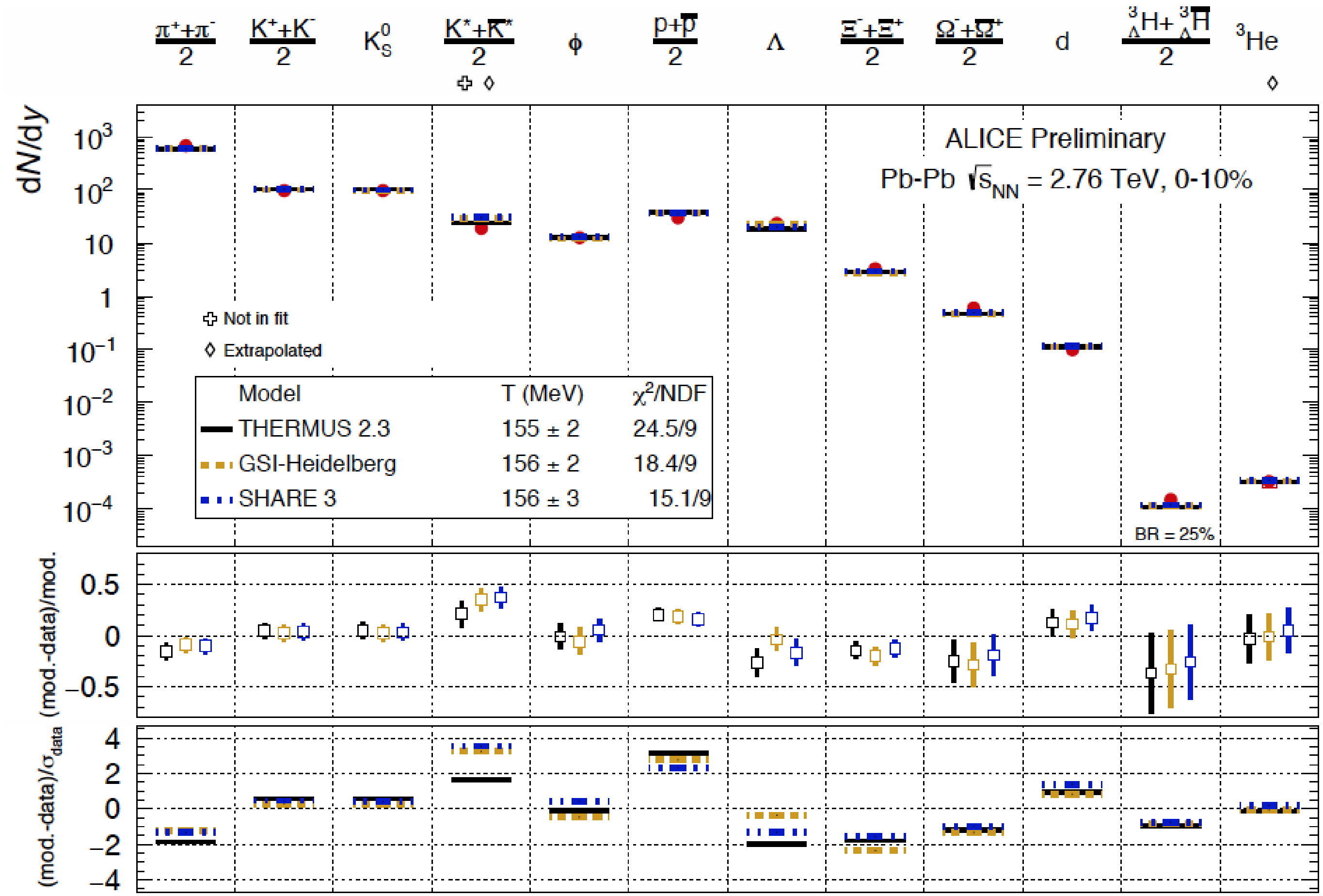
Mass dependence



- Nuclei production yields follow an exponential decrease with mass as predicted by the thermal model
- In Pb-Pb the penalty factor for adding one baryon is ~300 and for p-Pb ~600

Thermal model fits

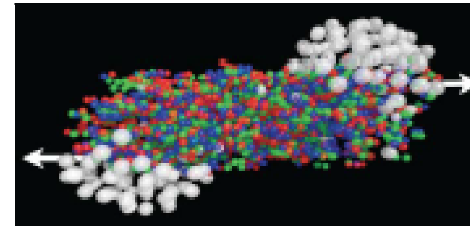
THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)

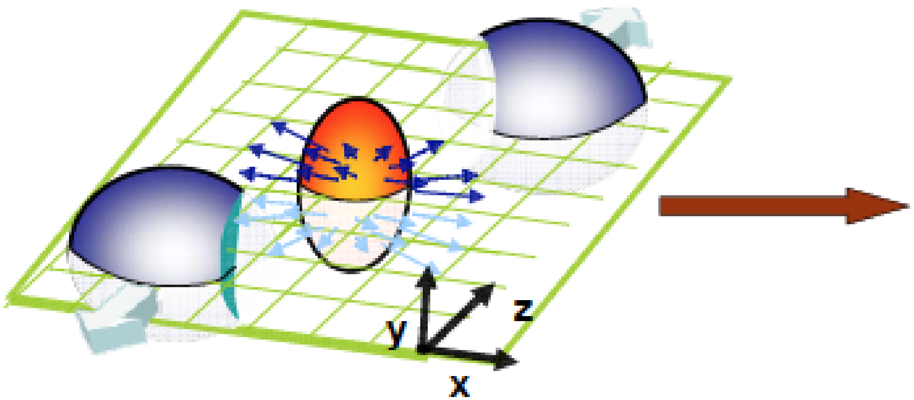


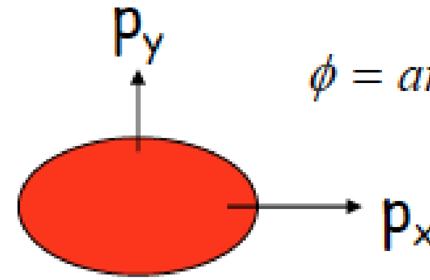
Model	T (MeV)	χ^2/NDF
THERMUS 2.3	155 ± 2	24.5/9
GSI-Heidelberg	156 ± 2	18.4/9
SHARE 3	156 ± 3	15.1/9

- 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}

Elliptic flow







$$\phi = arc\tan\frac{p_y}{p_x}$$

$$\varepsilon = \frac{\langle y^2\rangle - \langle x^2\rangle}{\langle y^2\rangle + \langle x^2\rangle}$$

Initial coordinate-space anisotropy

$$v_2 = \left\langle \frac{p_x^{\,2} - p_y^{\,2}}{p_x^{\,2} + p_y^{\,2}} \right\rangle$$

Final momentum-space anisotropy

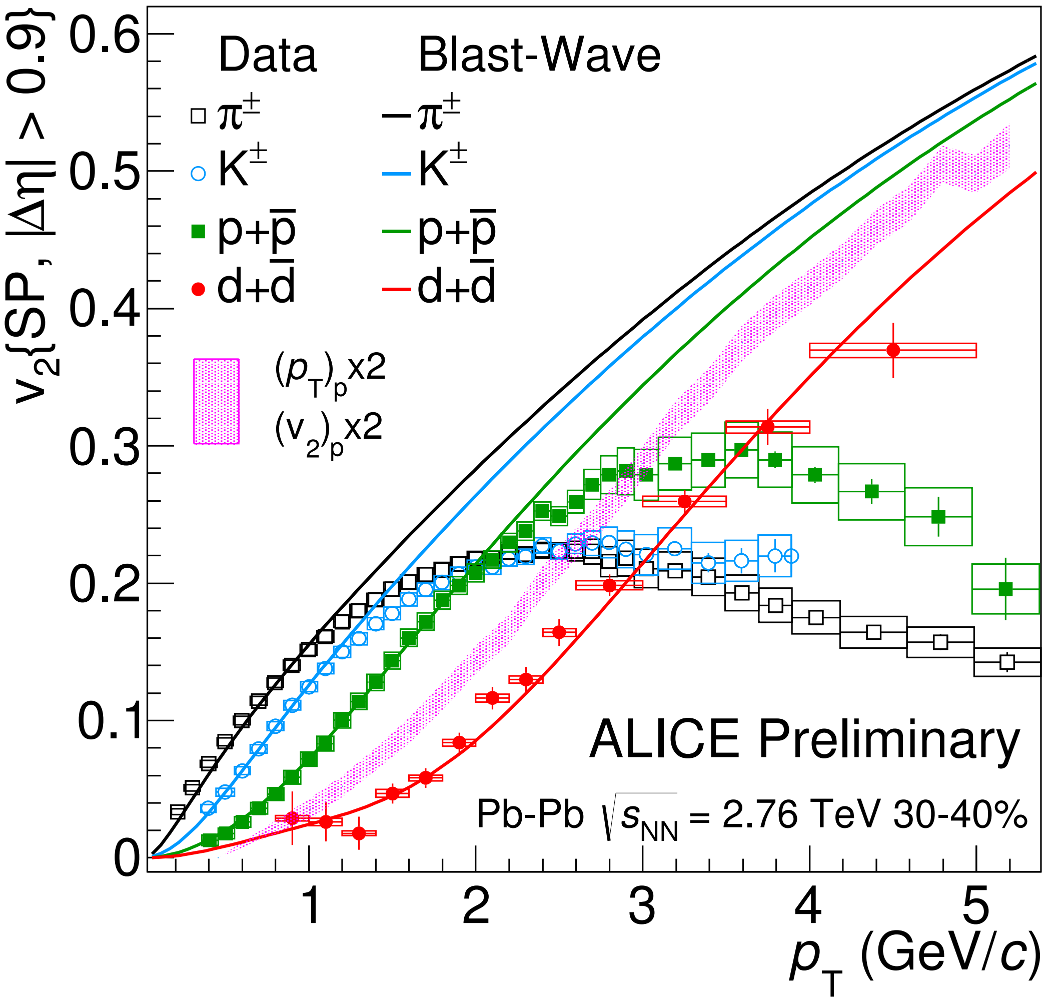
$$\frac{dN}{d\phi} \propto 1 + 2v_2\cos[2(\phi - \Psi_R)] + 2v_4\cos[4(\phi - \Psi_R)] + \ldots$$

Elliptic term

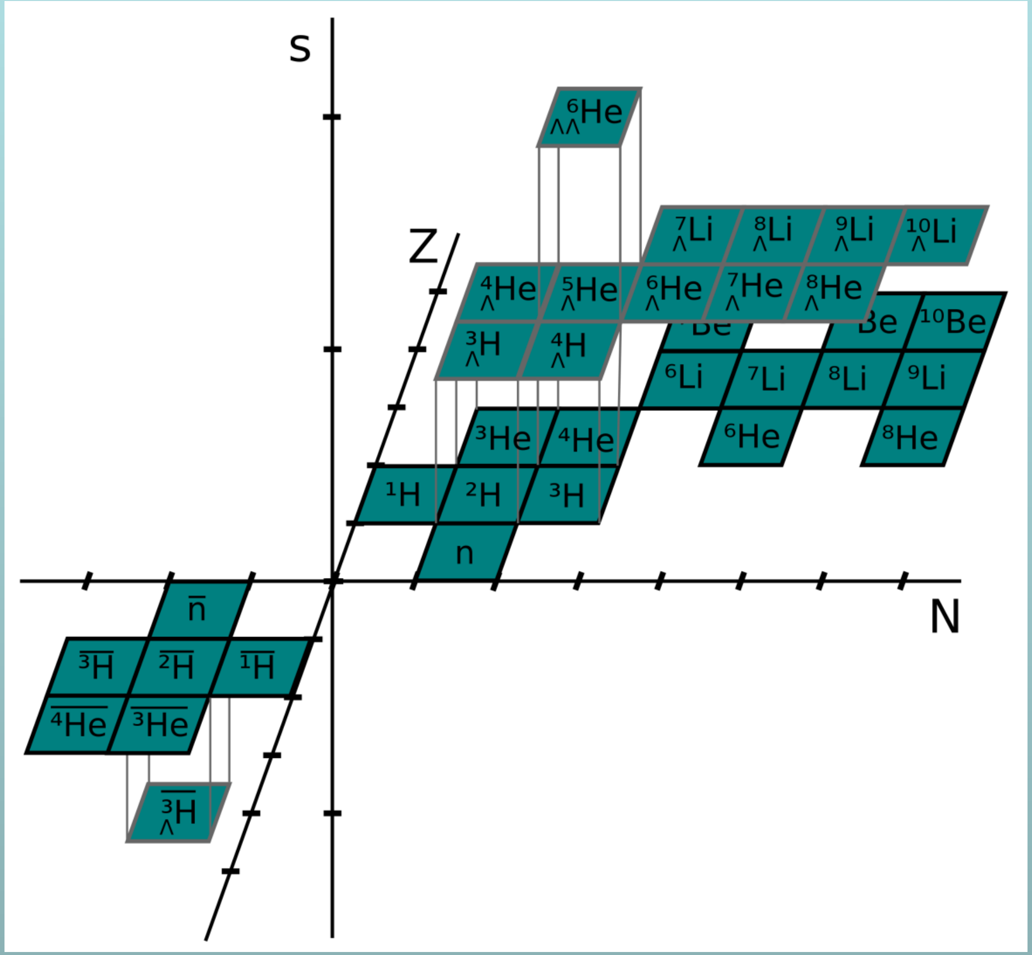
Anisotropy self-quenches, so v_2 is sensitive to early times

Deuteron flow

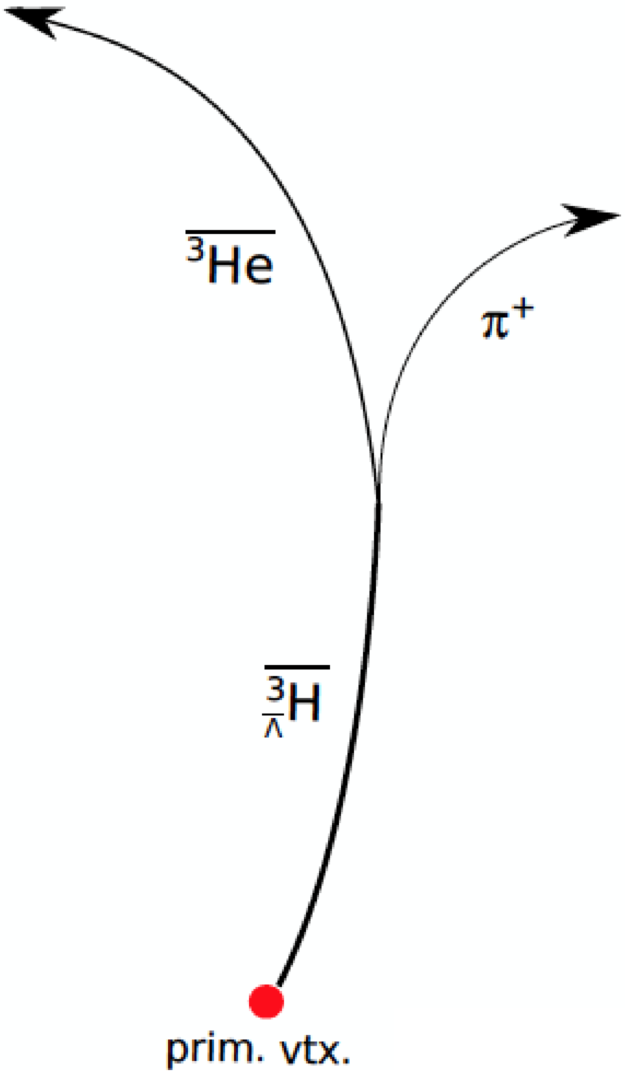
- Deuterons show a significant v_2
- Also the v_2 of deuterons follows the mass ordering expected from hydrodynamics
- A naive coalescence prediction is not able to reproduce the deuteron v_2
- A Blast-Wave prediction is able to describe the v_2 reasonably well



Hypernuclei



Hypertriton identification



Bound state of Λ, p, n

m = 2.991 GeV/c^2 (B_Λ =130 keV)

→ rms radius: 10.3 fm

Decay modes:

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

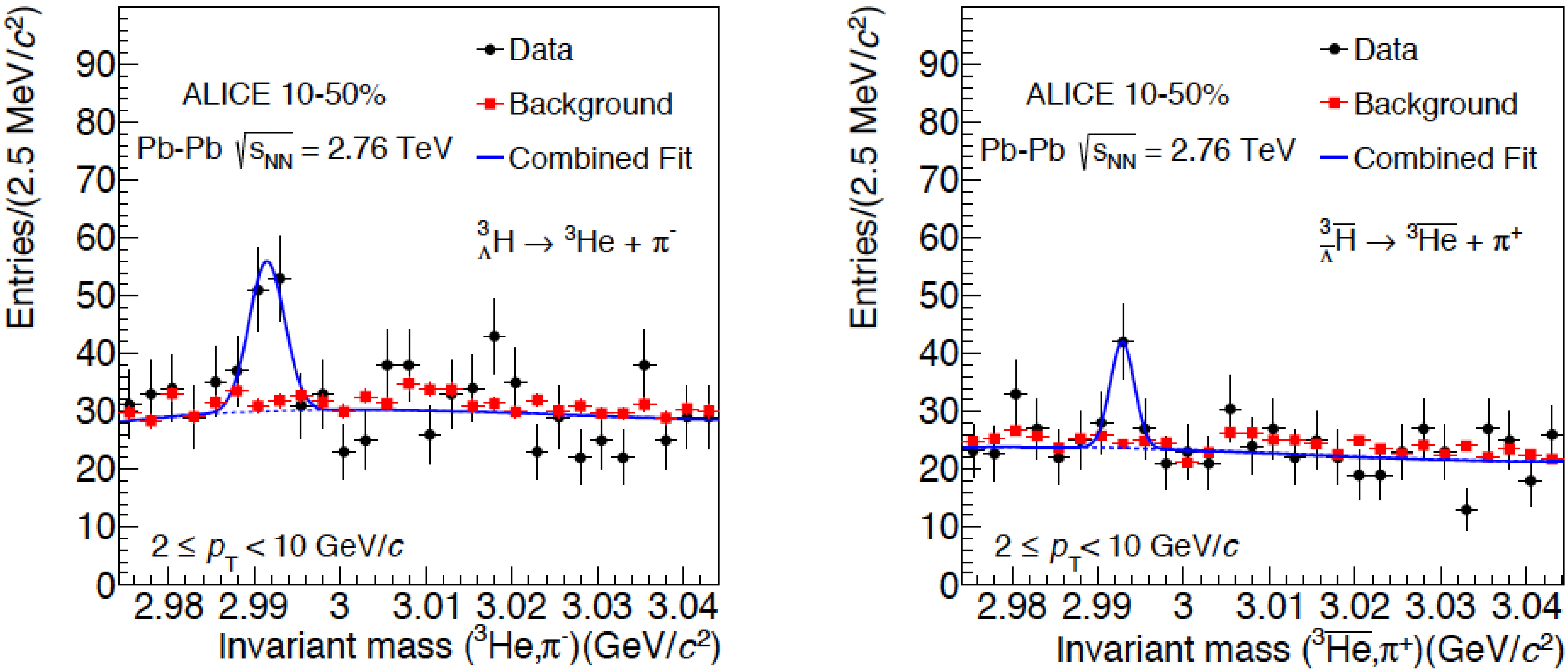
+ anti-particles

→ Anti-hypertriton was first observed by the STAR Collaboration:

Science 328,58 (2010)

Hypertriton signal

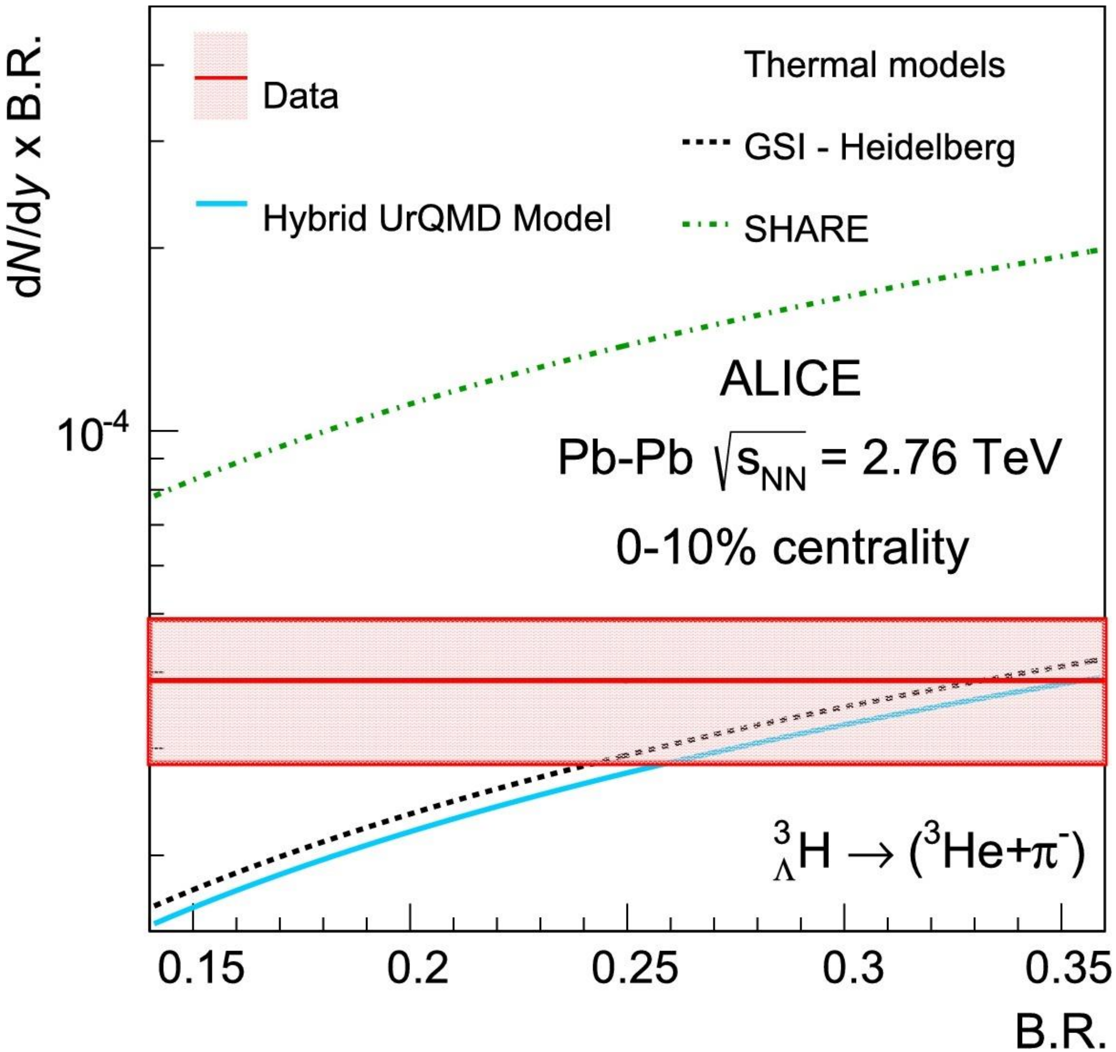
ALICE Collaboration: PLB 754, 360 (2016)



- Peaks are clearly visible for particle and anti-particle
  - → Extracted yields in 3 p_T bins and 2 centrality classes

Hypertriton yield vs. B.R.

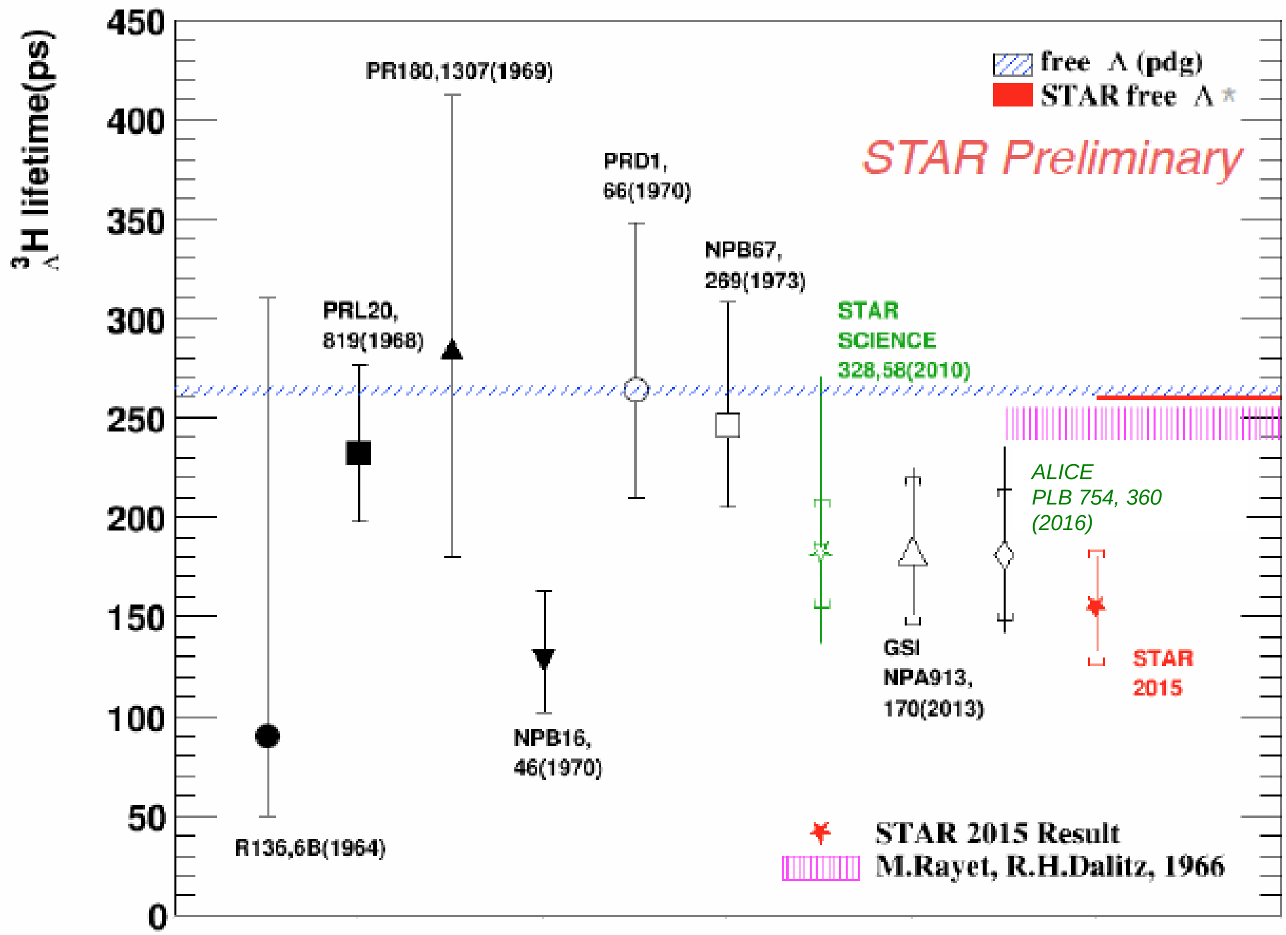
ALICE Collaboration: PLB 754, 360 (2016)



- The hypertriton branching ratio is not well known, only constrained by the ratio between all charged channels containing a pion
- Theory which prefers a value of around 25% gives a lifetime of the hypertriton close to the one of the free Λ

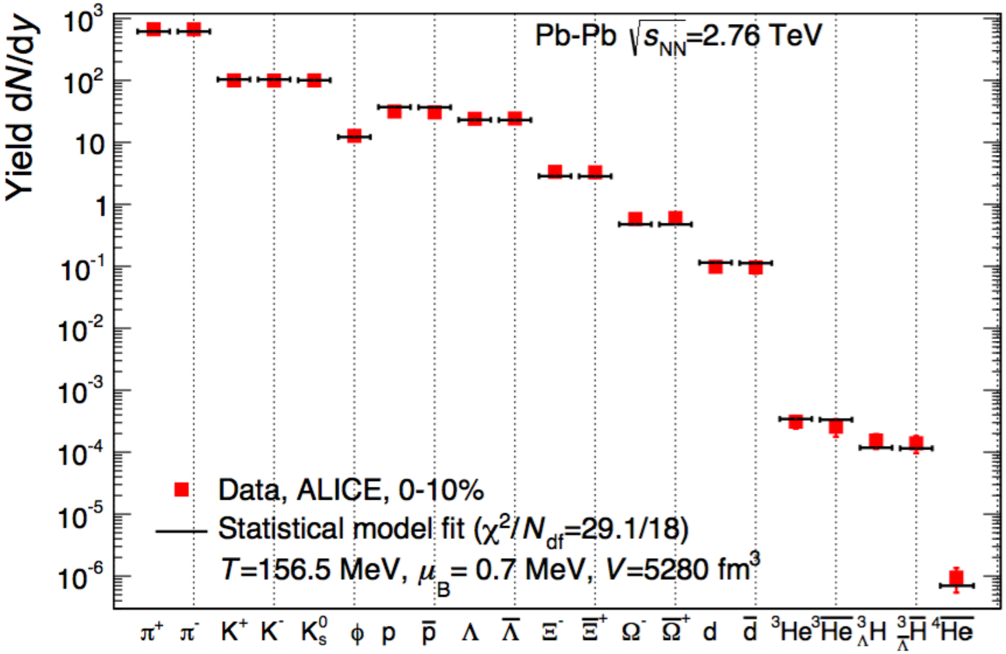
Hypertriton „puzzle“

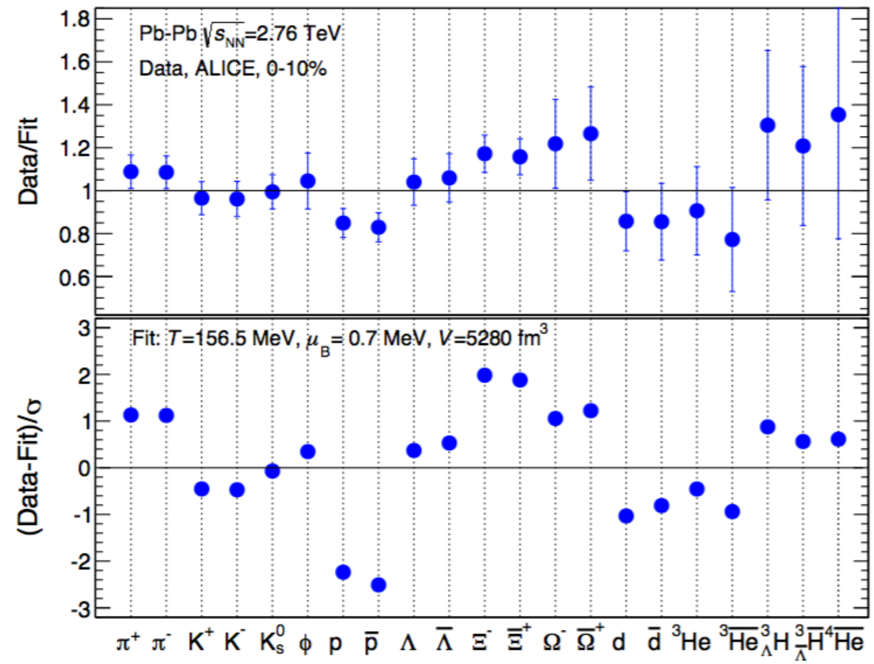
- Recently extracted lifetimes significantly below the free Λ lifetime
  - Not expected from theory!
  - Data before 2010 from emulsions
  - Currently most precise data coming from heavy-ion collisions
  - Better precision expected from larger data samples to be taken



As shown by Yifei Xu at HYP2015 conference

Thermal model at the LHC





Particle yields of light flavor hadrons are described over 9 orders of magnitude within 20% with a common chemical freeze-out temperature of $T_{ch} \approx$ 156 MeV.

Largest deviations observed for **protons** (would prefer lower T_{ch}) and for **Ξ** (would prefer higher T_{ch}).

Light (anti-)(hyper-)nuclei yields in agreement with equilibrium thermal model predictions: help in (a.) distinguishing equilibrium from non-equilibrium and (b.) stabilise the fit for different eigenvolume corrections.

A. Kalweit/A. Andronic

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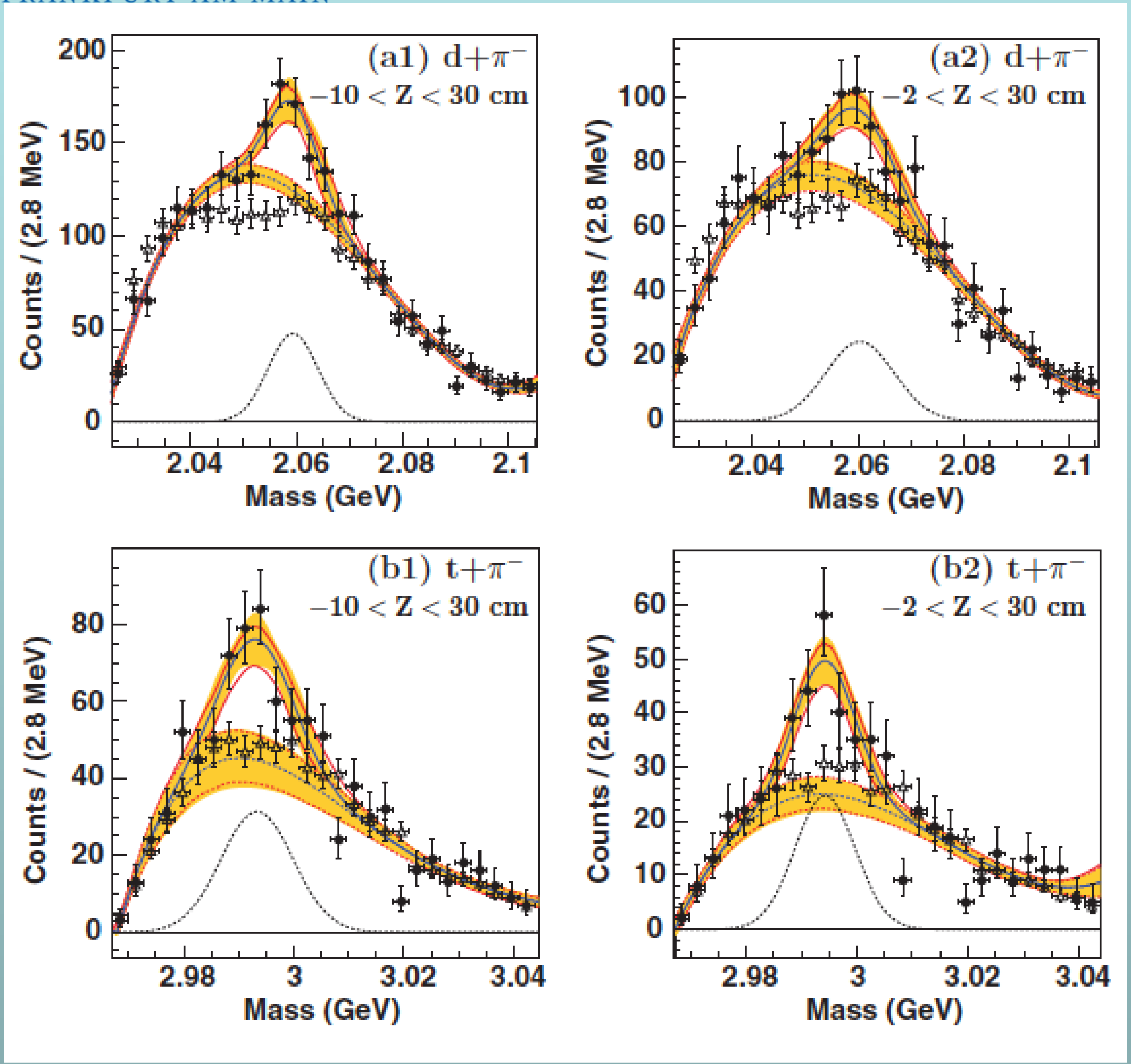
- Summary

Exotica

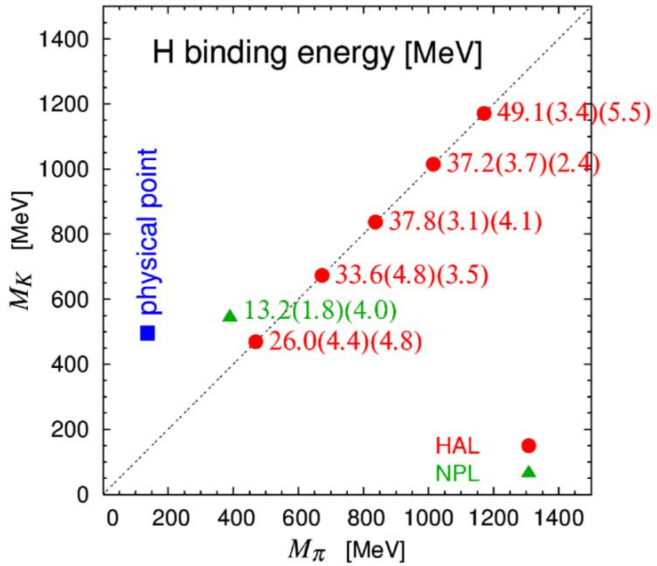


HypHI Collaboration observed signals in the t+π and d+π invariant mass distributions

C. Rappold et al.,
PRC 88, 041001 (2013)

H-Dibaryon

- Hypothetical bound state of *uuddss* ($\Lambda\Lambda$)
- First predicted by Jaffe in a bag model calculation (*PRL 195, 38 +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 Haidenbauer, 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 or lies close to the Ξp threshold

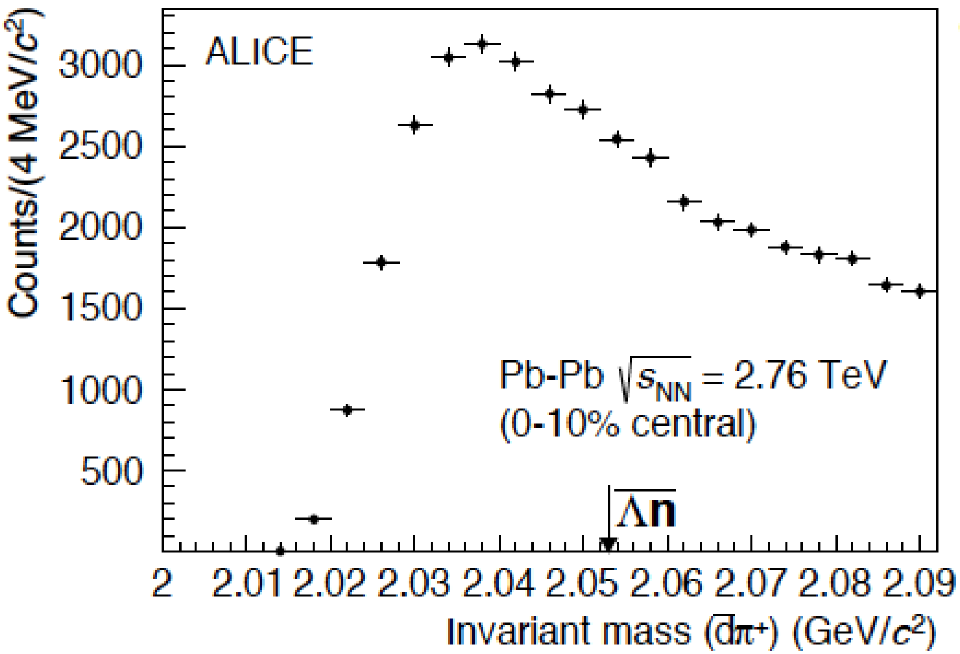


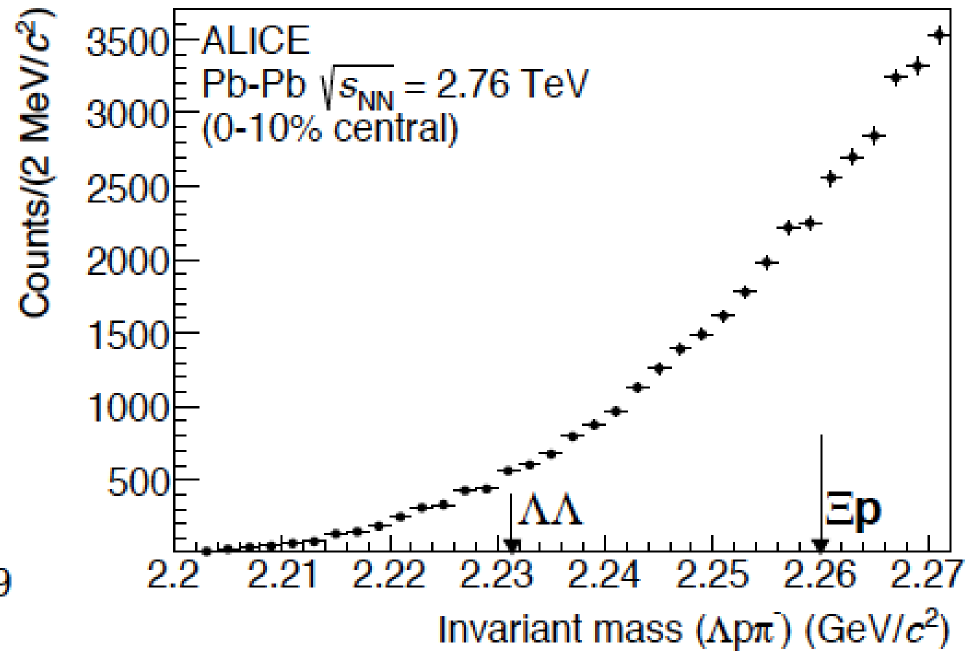
T. Inoue, private communication

→ Renewed interest in experimental searches

Searches for bound states

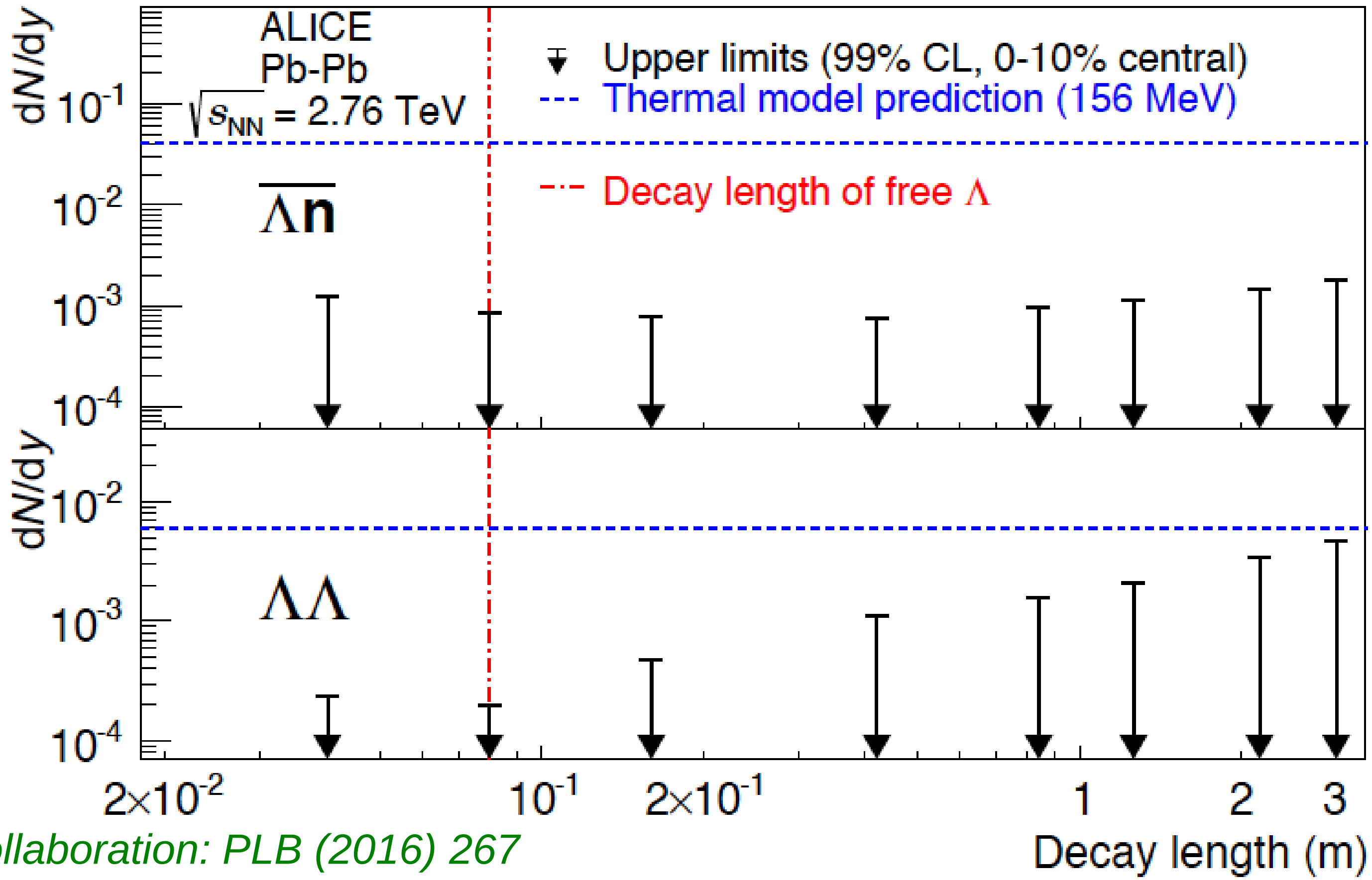
ALICE Collaboration: PLB 752, 267 (2016)





Invariant mass analyses of the two hypothetical particles lead to no visible signal → Upper limits set

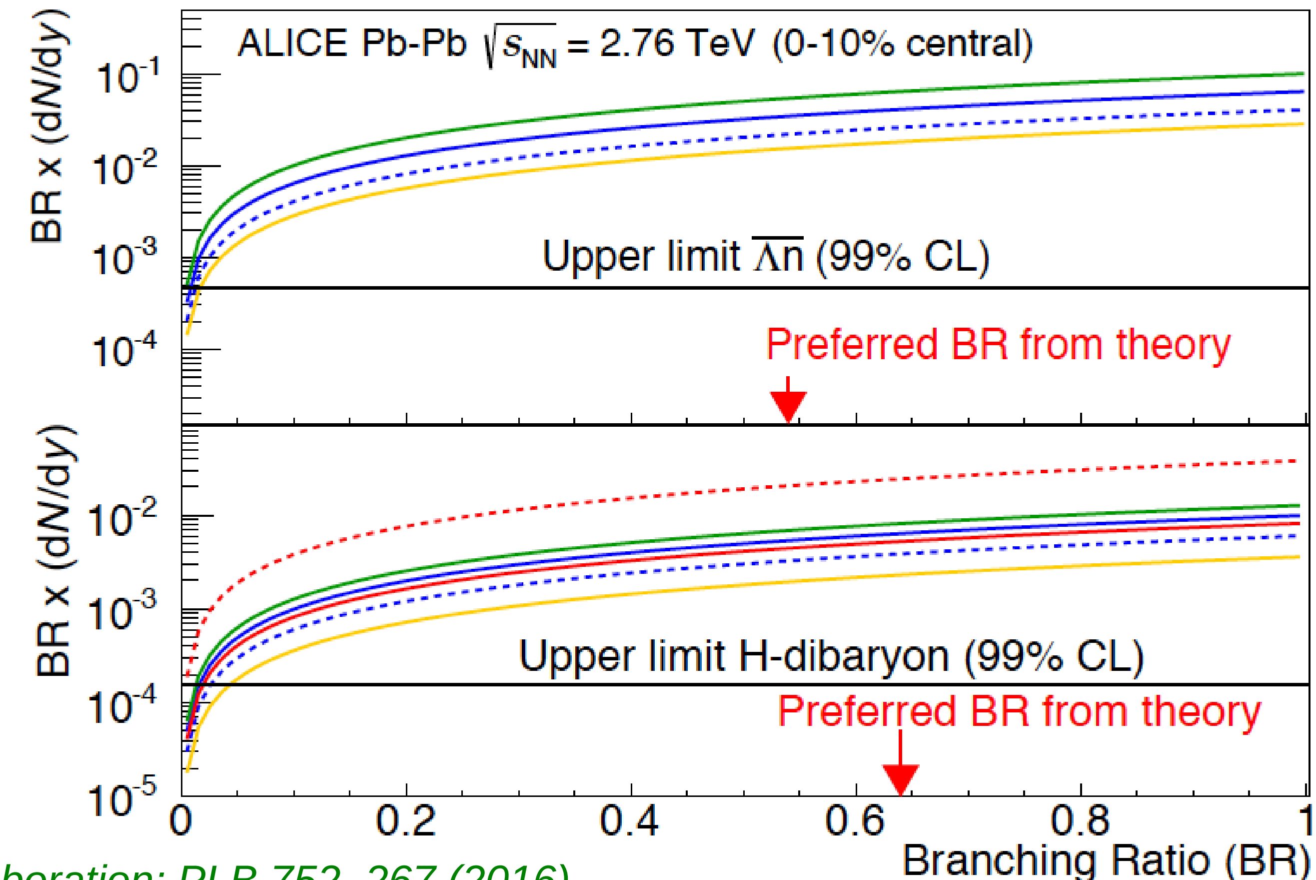
Decay length dependence



ALICE Collaboration: PLB (2016) 267

Search for a bound state of Λn and ΛΛ, shows no hint of signal
→ upper limits set (for different lifetimes assumed for the bound states)

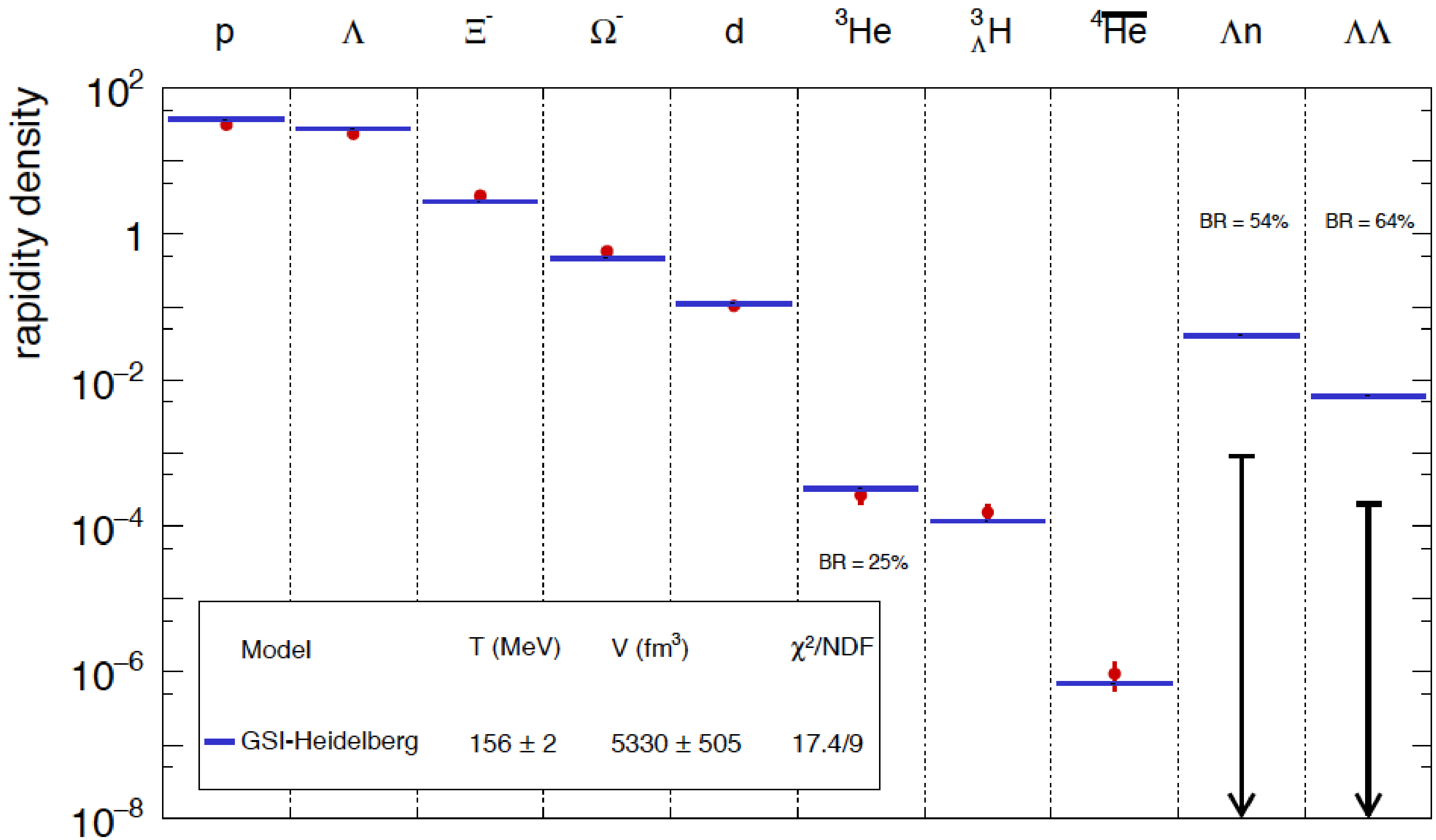
Dependence on BR



ALICE Collaboration: PLB 752, 267 (2016)

If the Λ lifetime is assumed, the upper limits are away from the expectations, as long as the branching ratio stays reasonable

Comparison with fit



Simplified plot, from the CERN Courier (September 2015)

Hypertriton (B_Λ: 130 keV) and Anti-Alpha (B/A: 7MeV) yields fit well with the thermal model expectations

→ Upper limits of $\Lambda\Lambda$ and Λn are factors of >25 away from the model

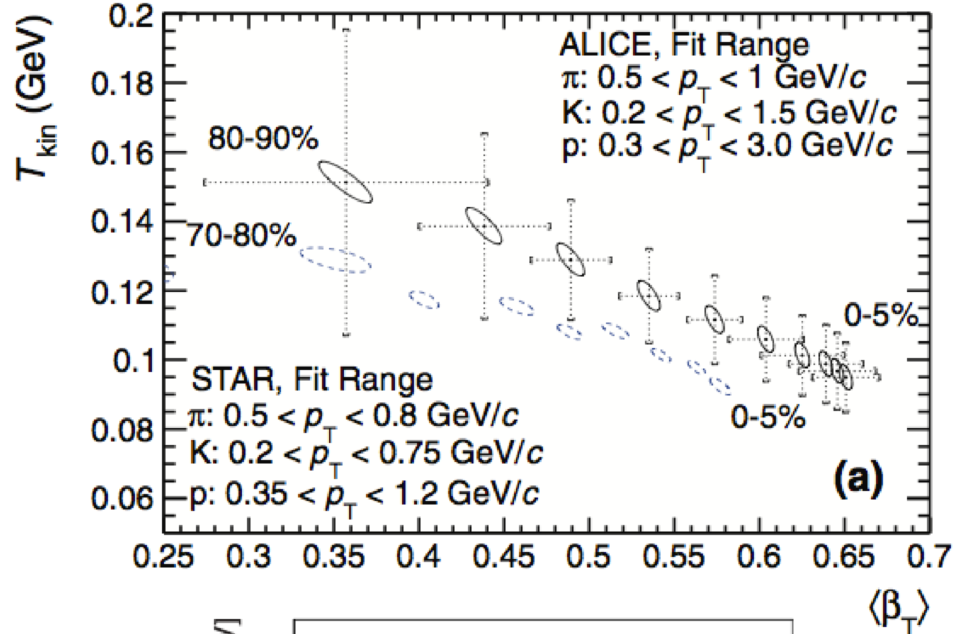
Conclusion

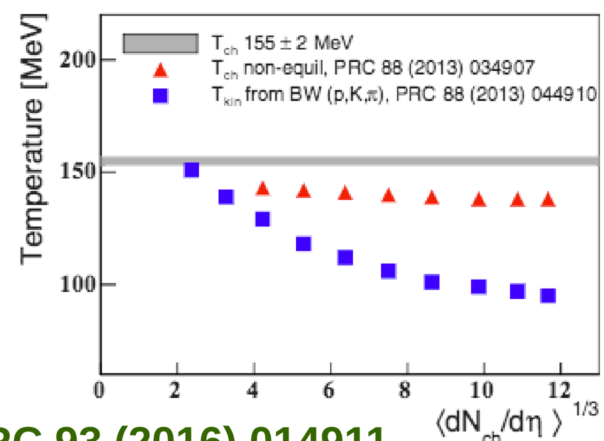
- Interesting physics observed in the strangeness sector in all collision systems at the LHC
- Resonances show a clear suppression with increasing centrality/multiplicity
- Copious production of loosely bound objects measured by ALICE as predicted by the thermal model
- Thermal and coalescence models describe the (anti-)(hyper-)nuclei data rather well
- Upper limits for searched exotica are 25 times below the thermal model expectation
- More data and more studies are needed in order to establish a scenario which seamlessly describes all observations

Backup

Is there a hadronic phase?

- Most often, it is argued that the kinetic freeze-out temperature is lower than the chemical freeze-out temperature.
- But this is model dependent and might be less striking than the survival of the deuteron in the fireball!
- The combined blast-wave fit proves that different particles have *identical* freeze-out conditions, but the kinetic freeze-out temperature is not constrained and depends strongly on the pion fit range.
- Fine, but what about re-scattering of resonances?





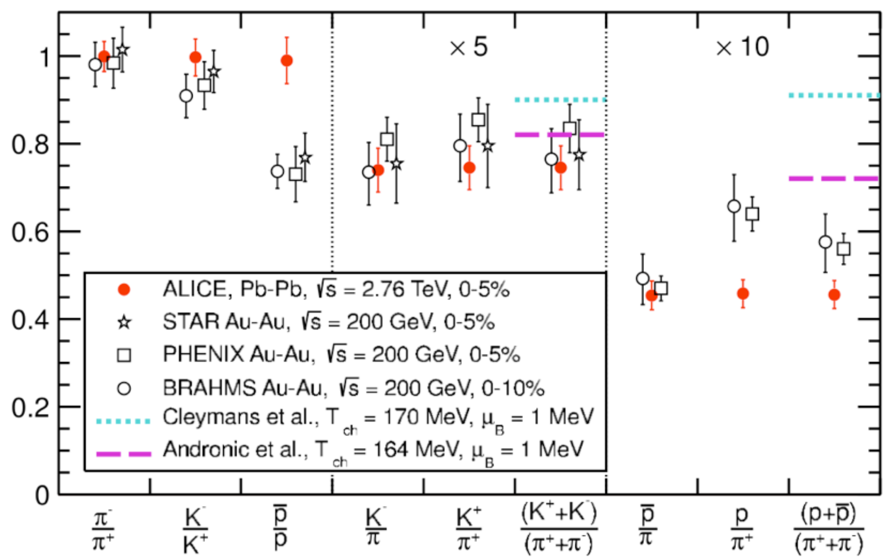
PRC 93 (2016) 014911

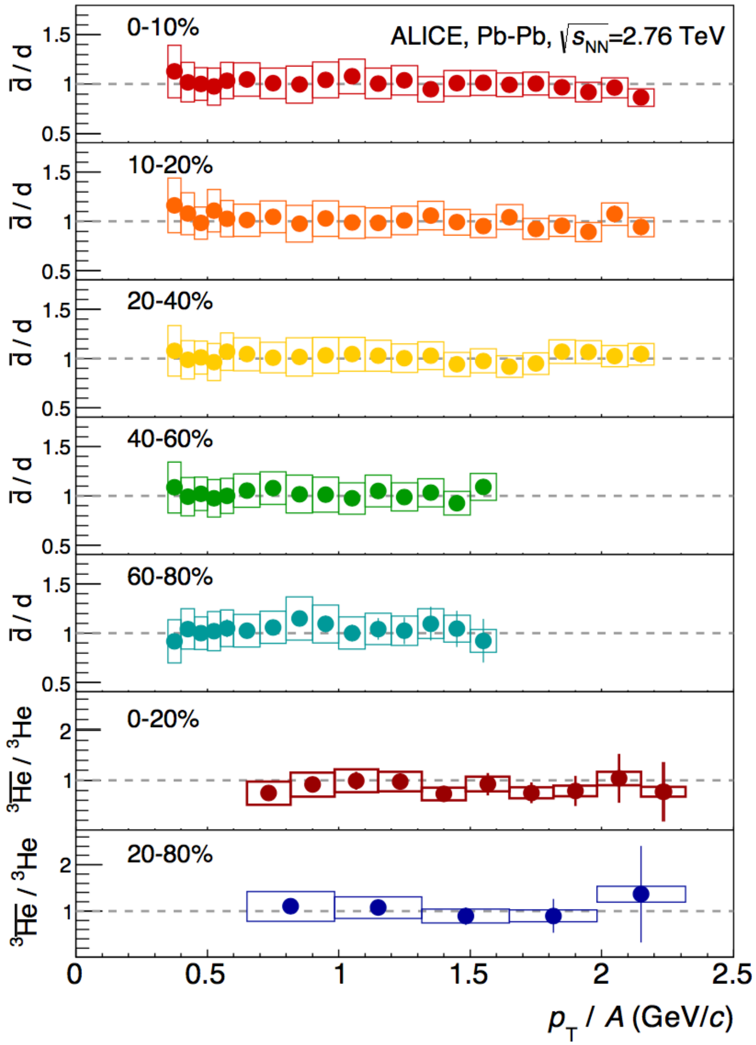
Matter & anti-matter

Particle production in pp, p-Pb, and Pb-Pb collisions shows an equal abundance of matter and anti-matter in the central rapidity region: $\mu_B \approx 1$ MeV.

$$\frac{n_{\bar{p}}}{n_p} = e^{-(2\mu_B)/T} \qquad \frac{n_{^3\overline{\mathrm{He}}}}{n_{^3\mathrm{He}}} = e^{-(6\mu_B)/T}$$

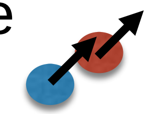
PRL 109 (2012) 252301

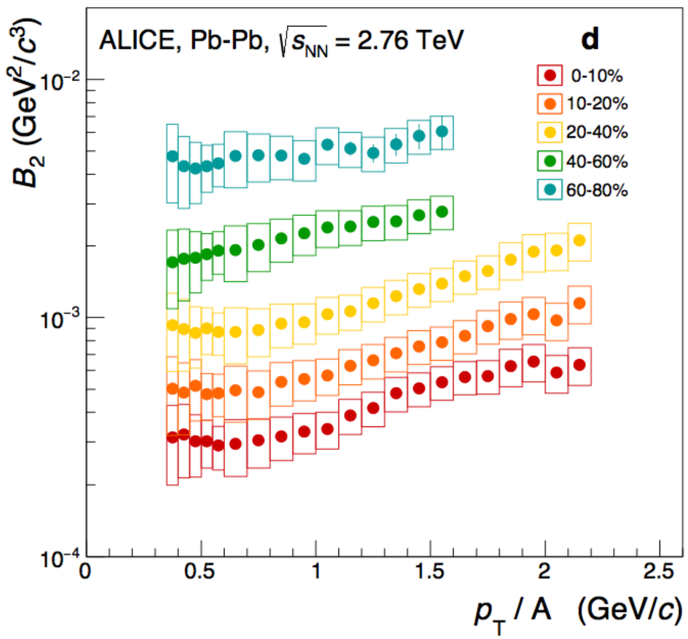


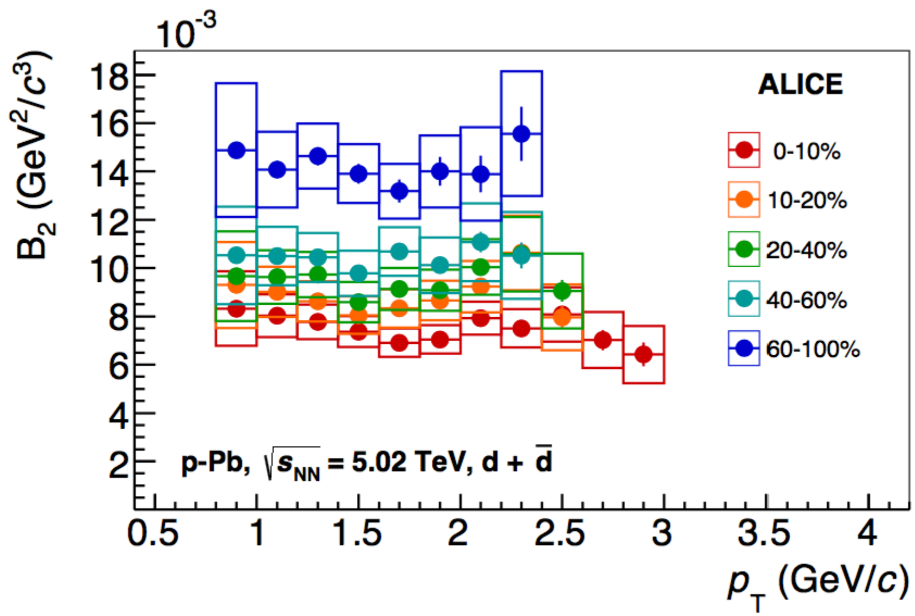


Coalescence (1)

- Production of nuclei by coalescence of nucleons which are close in phase space:







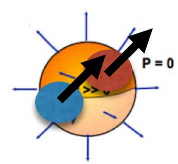
$$B_A = \frac{E_A \frac{d^3N_A}{dp_A^3}}{\left(E_p \frac{d^3N_p}{dp_p^3}\right)^A}$$

B_2 is flat vs. p_T in p-Pb collisions and in peripheral Pb-Pb collisions.

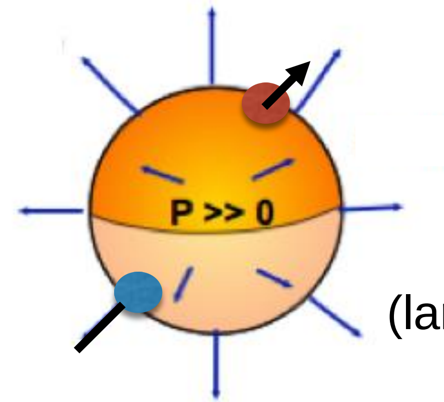
B_2 is strongly decreasing with centrality in Pb-Pb collisions. d/p ratio shows no significant dependence with centrality.
→ **physics beyond a *simple* coalescence model.**

Coalescence (2)

- Clearly, the size of the emitting volume has to be taken into account.



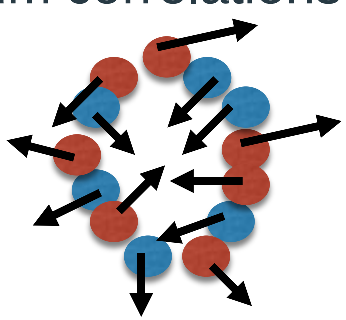
(small fireball)

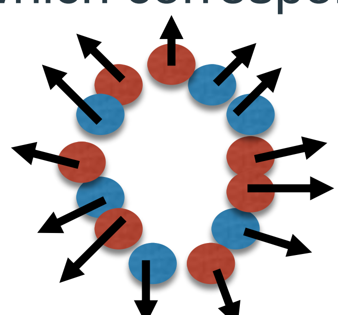


(large fireball)

- The strong decrease of B_2 with centrality in Pb-Pb collisions can be naturally explained as an increase in the emitting volume: Particle densities are relevant and not absolute multiplicities.
- The increase with transverse momentum can be explained by space-momentum correlations which correspond to the radial flow.

purely thermal source: position and momentum of particles completely uncorrelated





collective radial expansion: momentum and position are partially linked

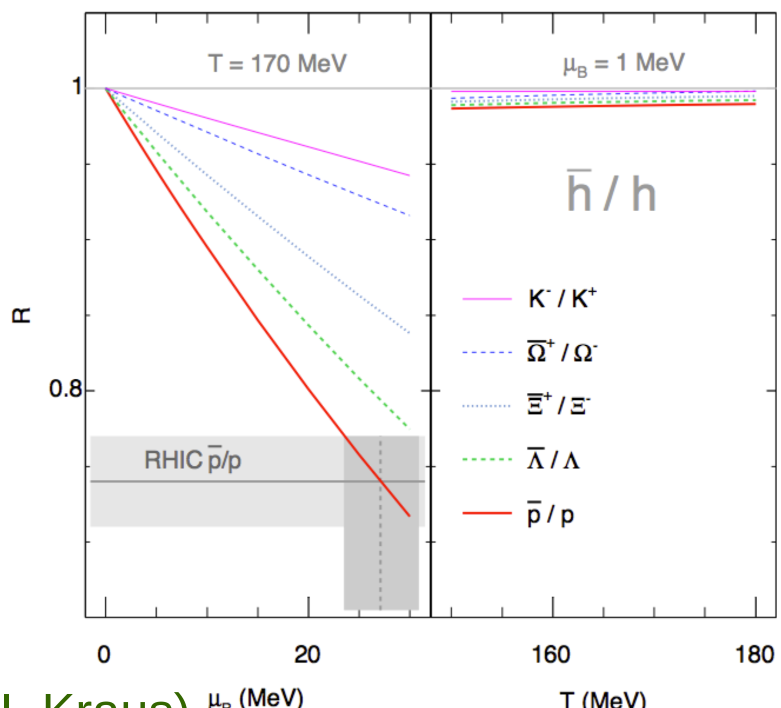
A. Polleri *et al.*, PLB 419 (1998) 19

The baryochemical potential μ_B

- In contrast to the chemical freeze-out temperature T, the baryochemical potential is a less intuitive quantity…
- It quantifies the net-baryon content of the system (baryon number transport to midrapidity):

$$dU = T\,dS - p\,dV + \Sigma \mu_i\,dn_i \quad .$$

$$\Rightarrow \mu_i := \left(\frac{\partial U(S,V,n_j)}{\partial n_i}\right)_{S,V,n_{j\neq i}}$$



(I. Kraus)

at LHC: $\mu_B \approx 0$ => $\bar{p}/p \approx 1$

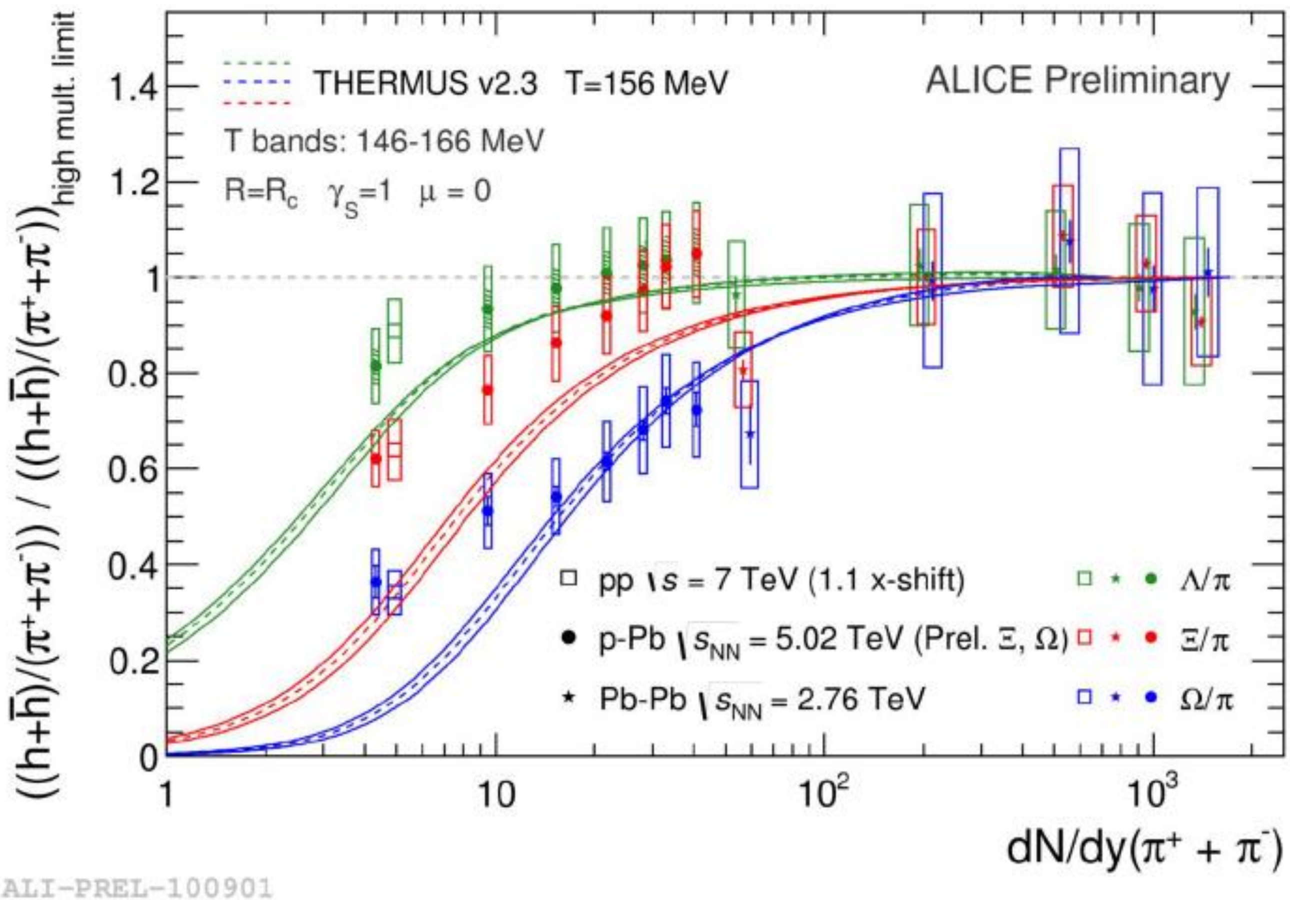
However, (anti-)nuclei are more sensitive:

$$\frac{n_{\bar{p}}}{n_p} = e^{-(2\mu_B)/T}$$

$$\frac{n_{\bar{d}}}{n_d} = e^{-(4\mu_B)/T}$$

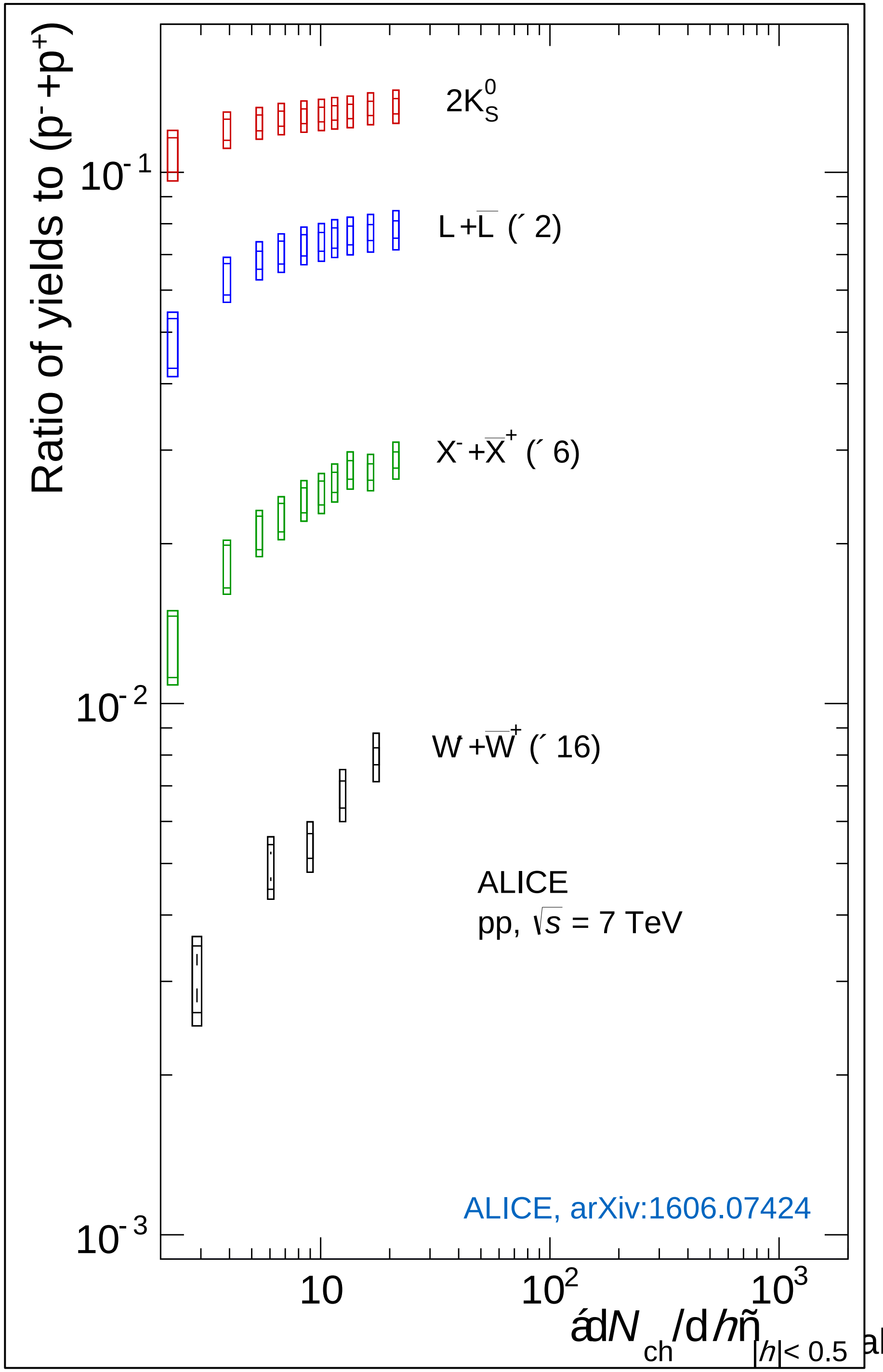
$$\frac{n_{^3\overline{He}}}{n_{^3He}} = e^{-(6\mu_B)/T}$$

Canonical suppression



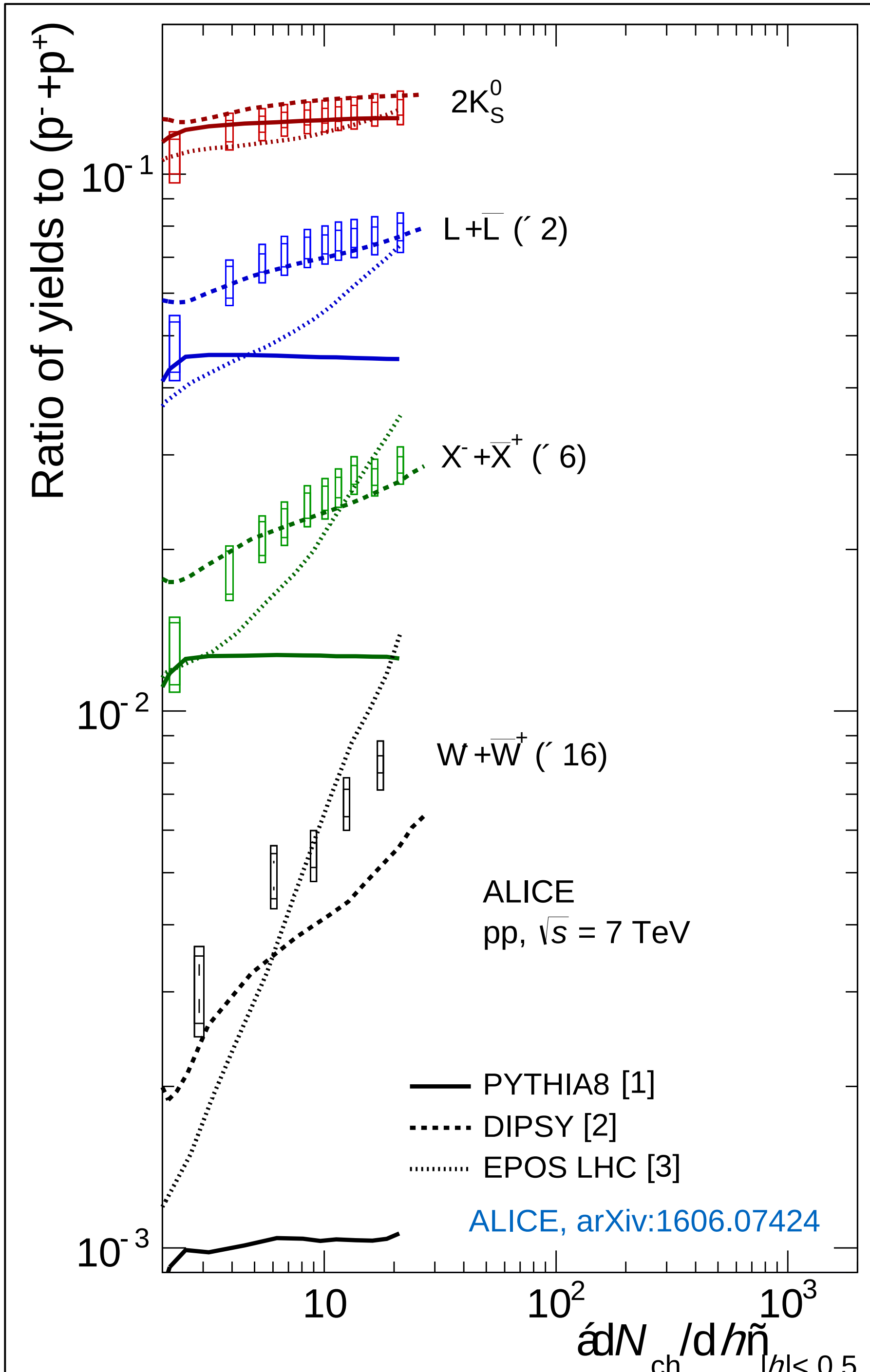
- Can be interpreted as the lifting of the canonical suppression of strangeness

→ Trend qualitatively reproduced within a thermal model with additional local conservation of strangeness



Relative Strangeness Production

- Quantified via strange to non-strange integrated particle ratios vs.
- Significant enhancement of strange and multi-strange particle production



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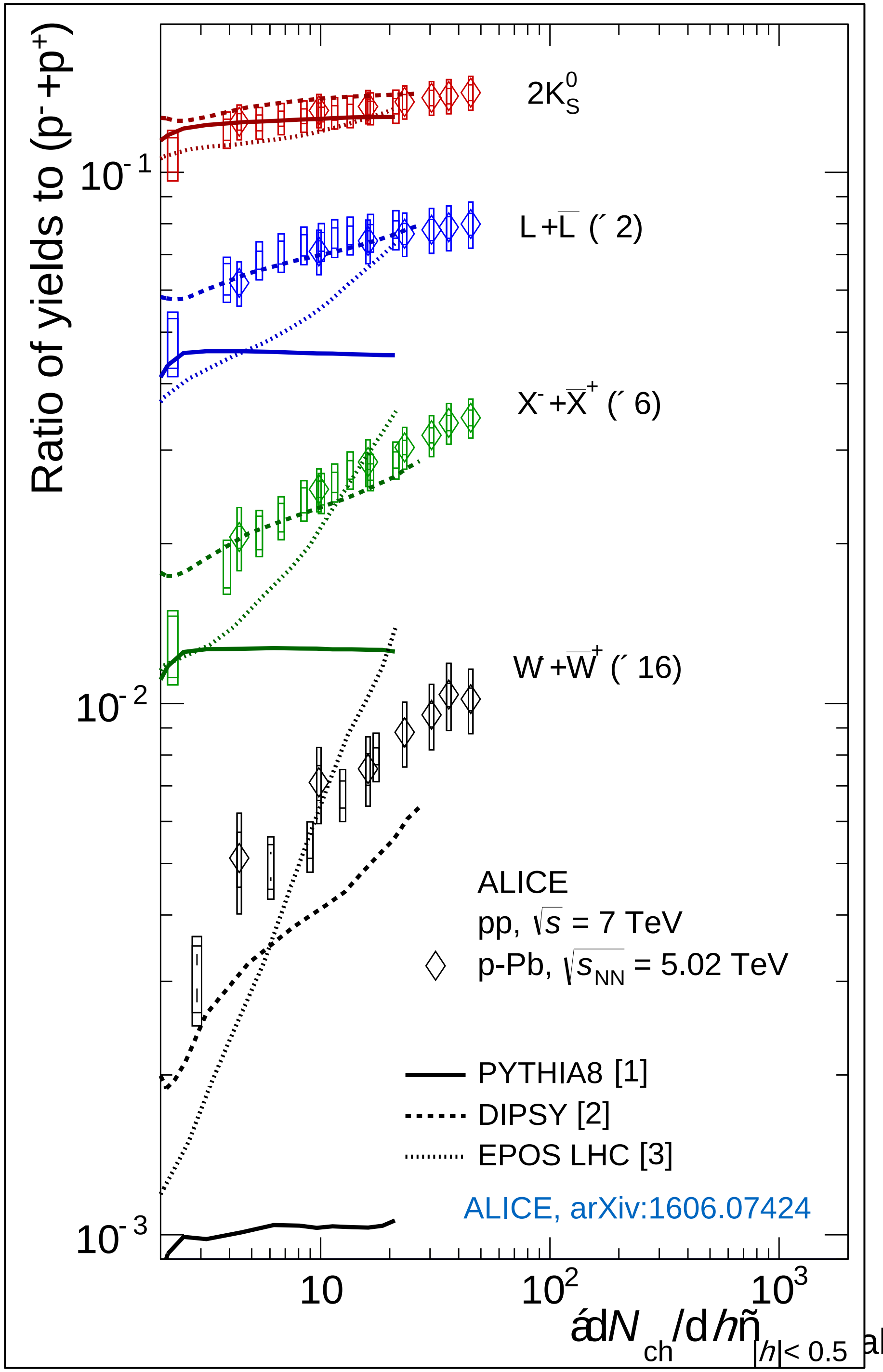
- MC predictions do not describe this observation satisfactorily

[1] Comput. Phys. Commun. 178 (2008) 852–867
[2] JHEP 08 (2011) 103
[3] Phys. Rev. C 92, 034906 (2015)



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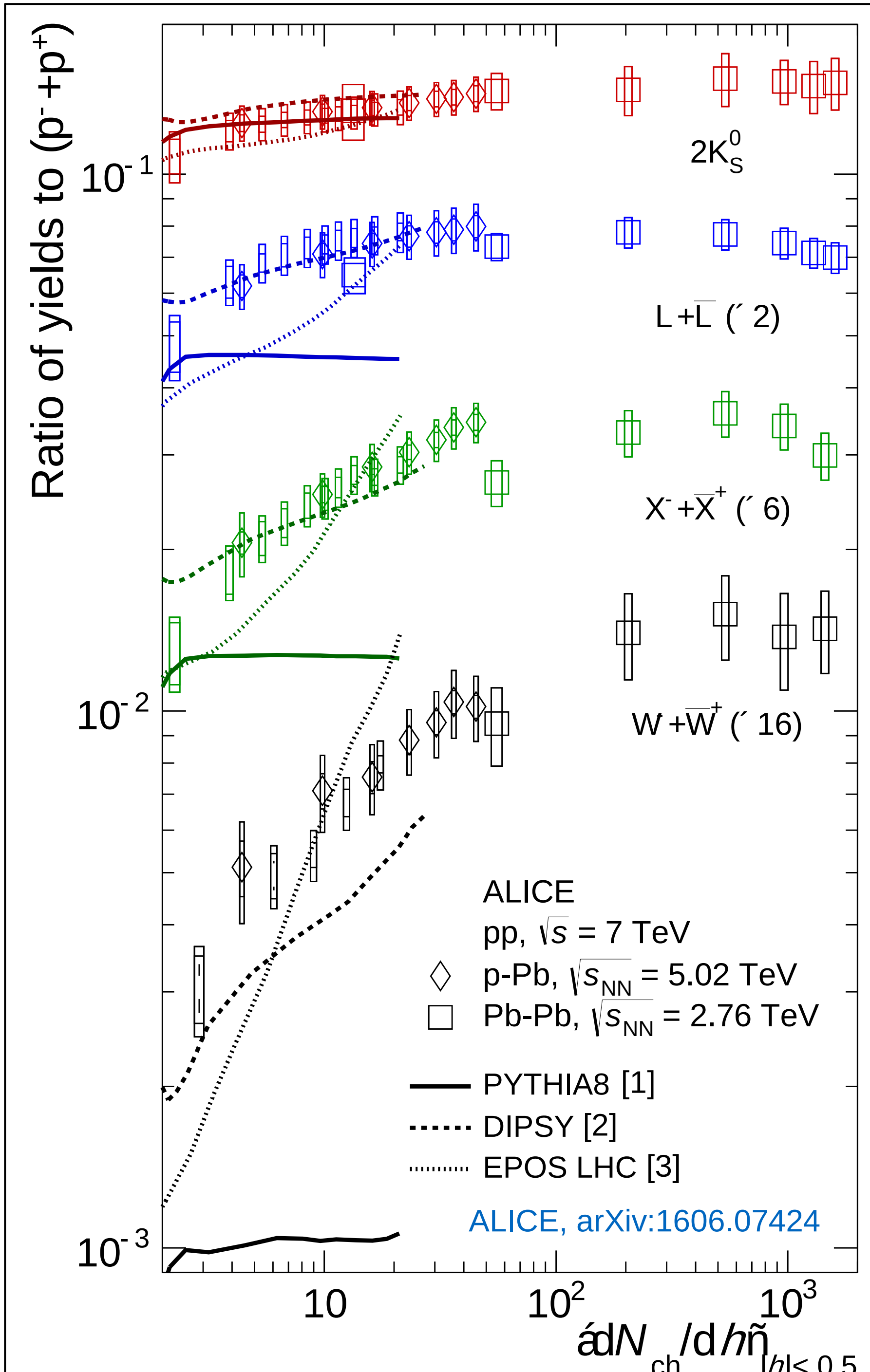

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- Significant enhancement of strange and multi-strange particle production
- MC predictions do not describe this observation satisfactorily
- Follows the trend observed in p-Pb, despite differences in initial state
- Particle ratios reach values that are similar to those observed in central Pb-Pb collisions

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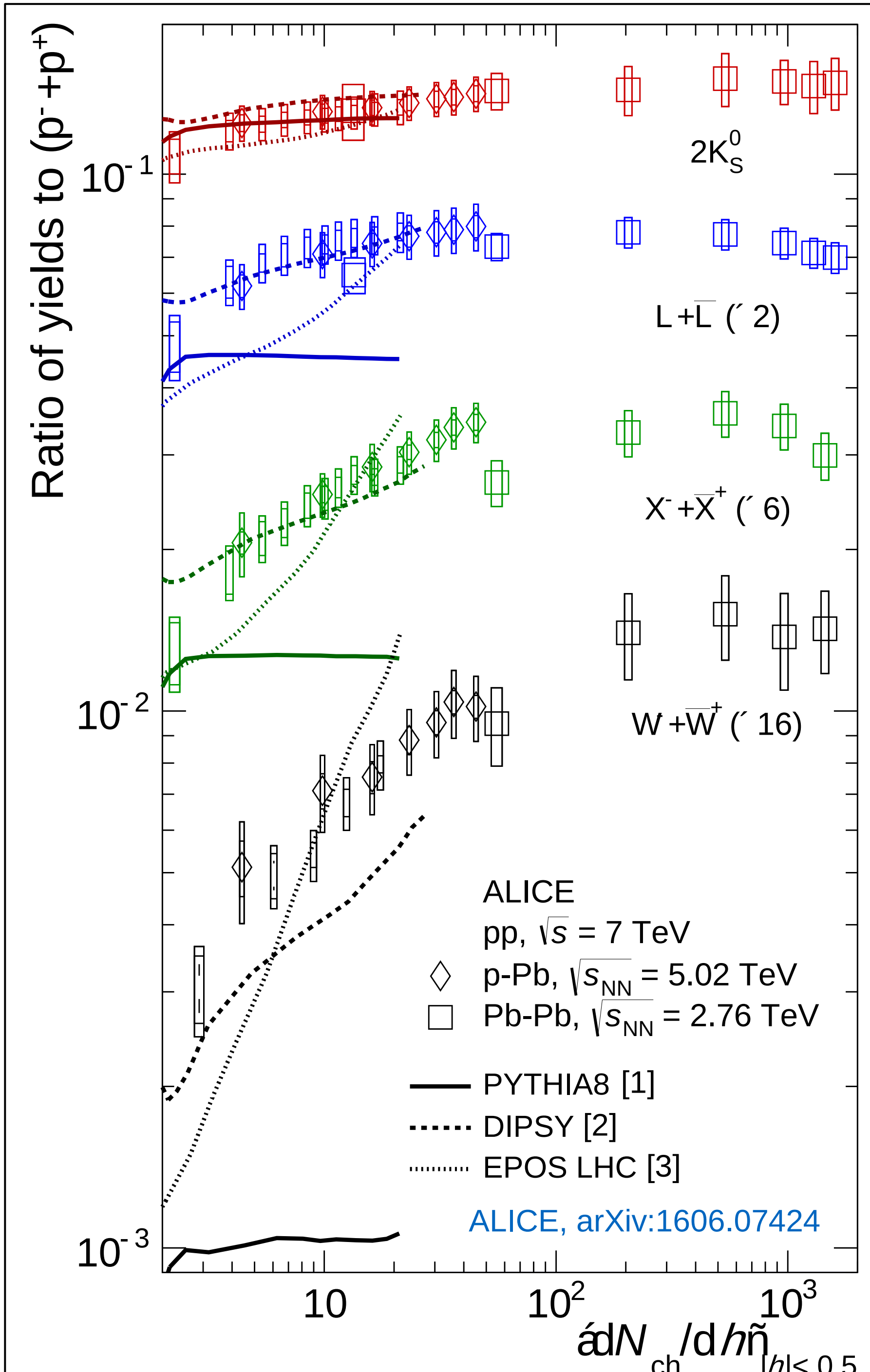

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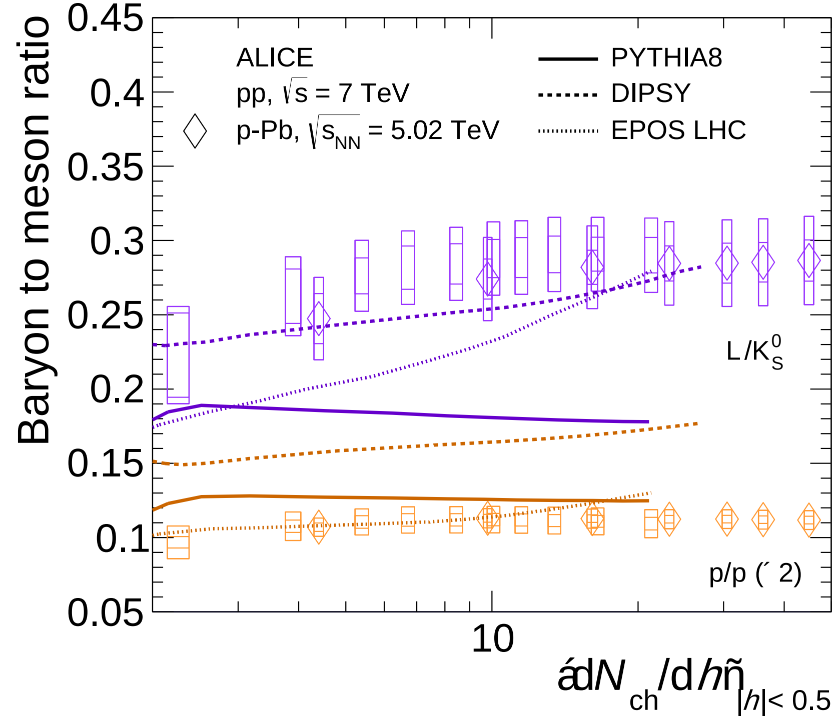

- No increase for protons (non-strange), contrary to models such as DIPSY

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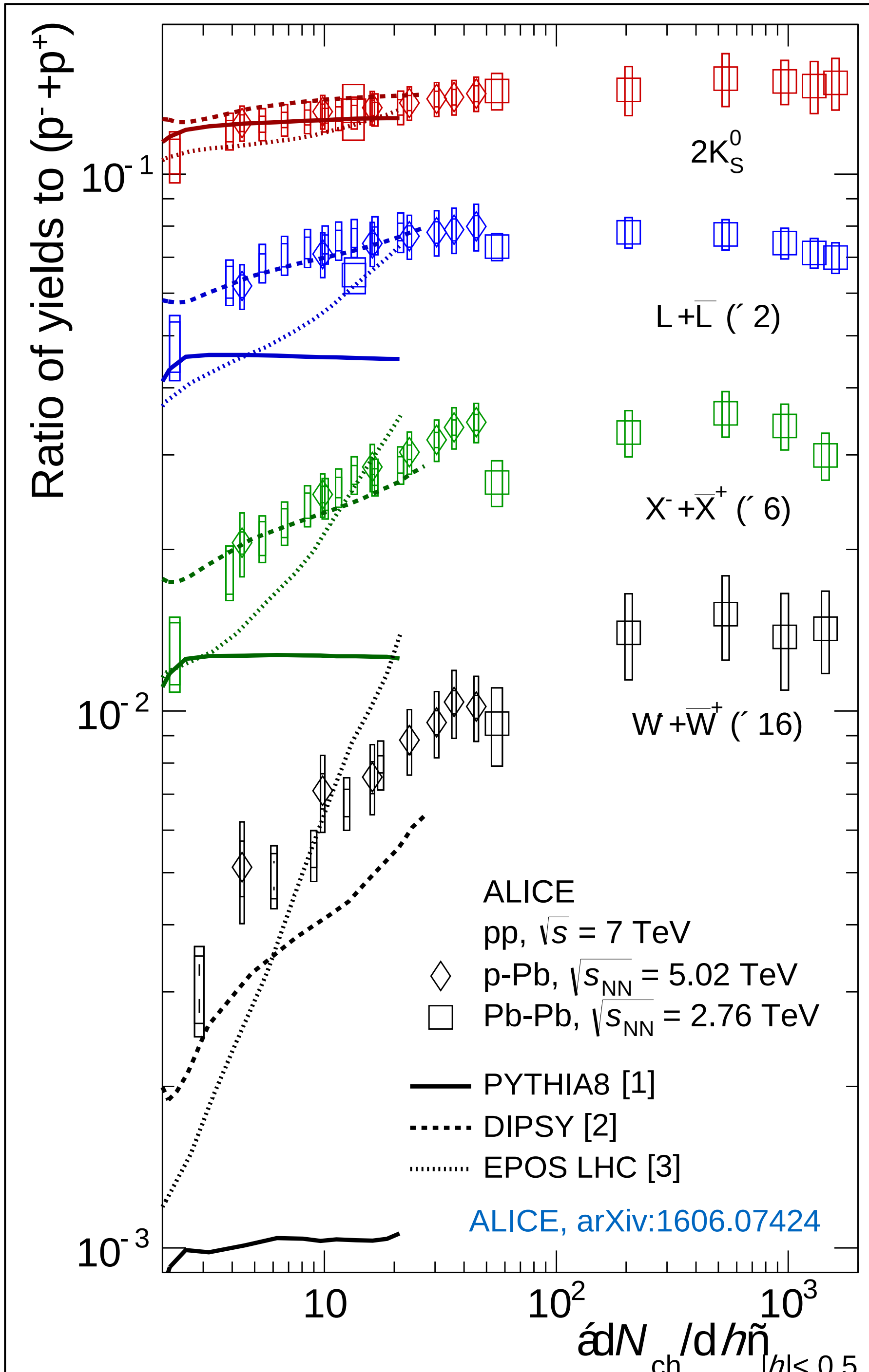

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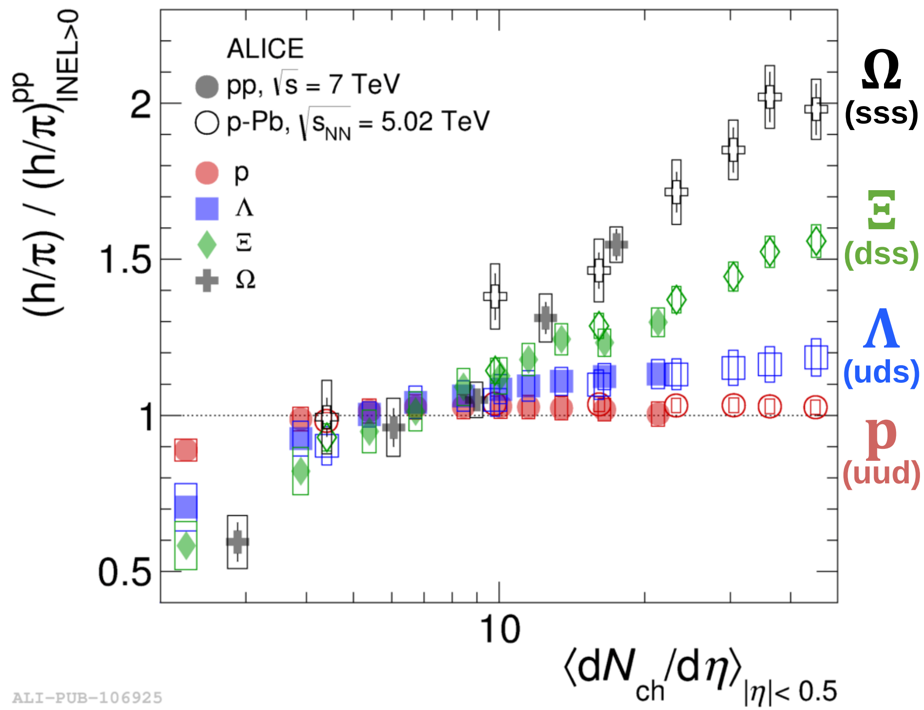

- No increase for protons (non-strange), contrary to models such as DIPSY
- Observed increase is more pronounced for baryons with higher strangeness content