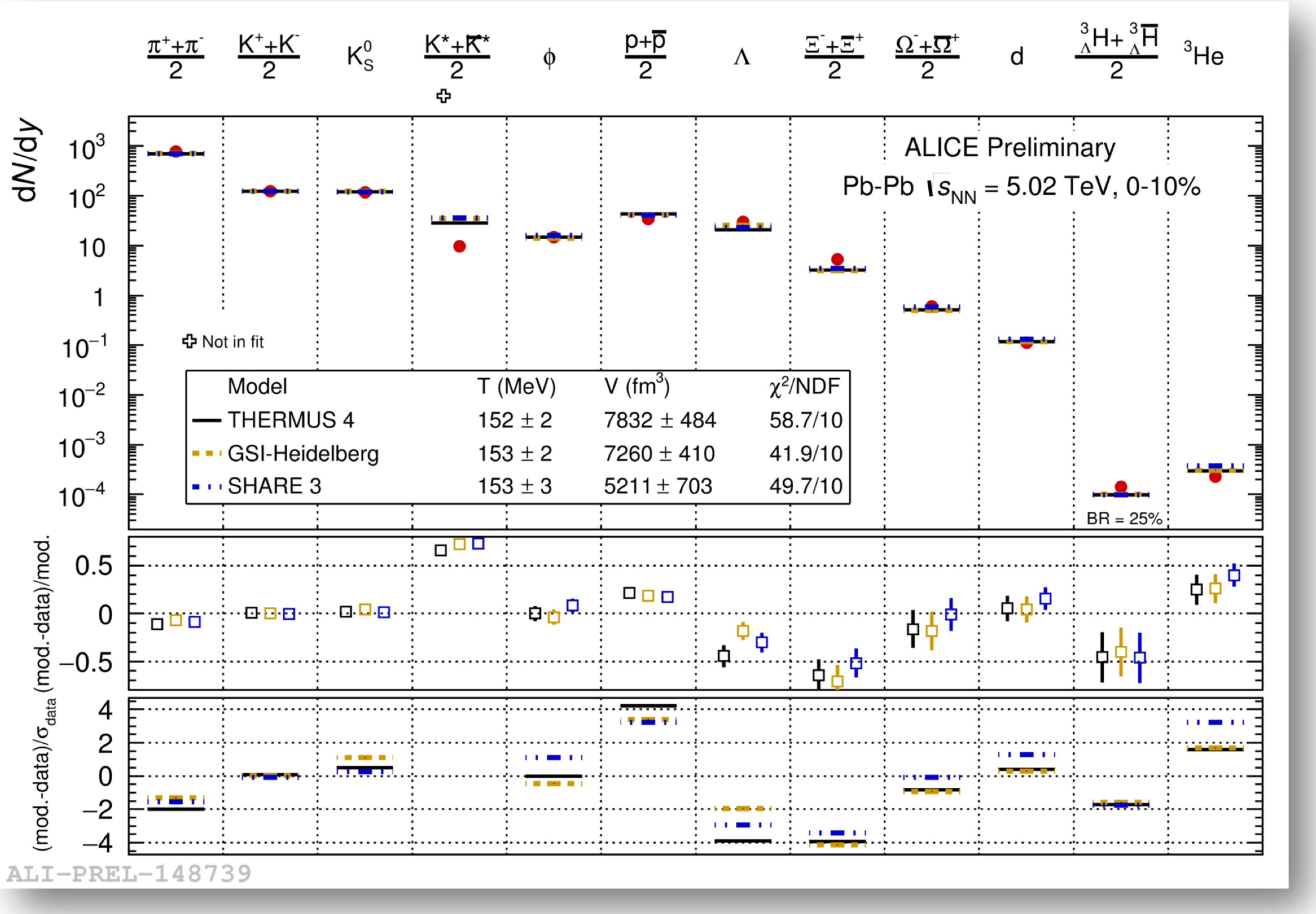
Light flavor hadron production from small to large systems at LHC energies

A. Kalweit, *CERN*

Introduction

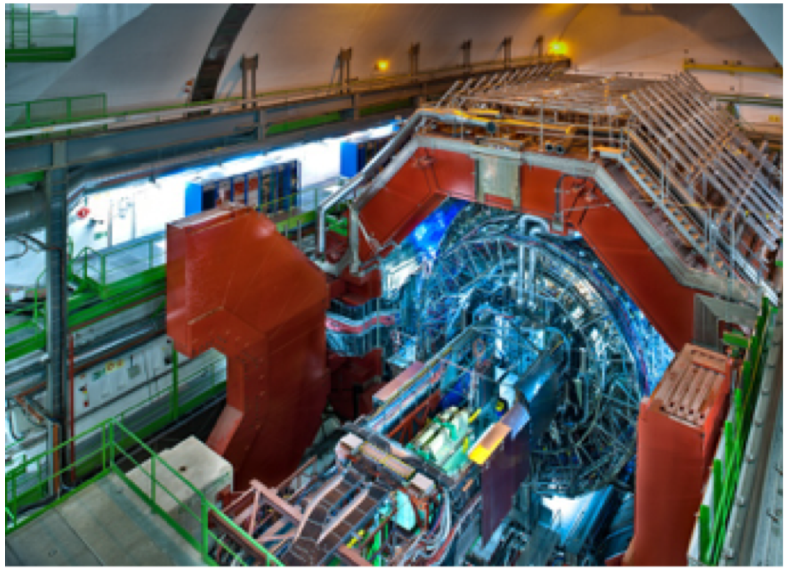
This fantastic plot is probably the most shown plot at this workshop! It seems everything can be described in Pb-Pb collisions.

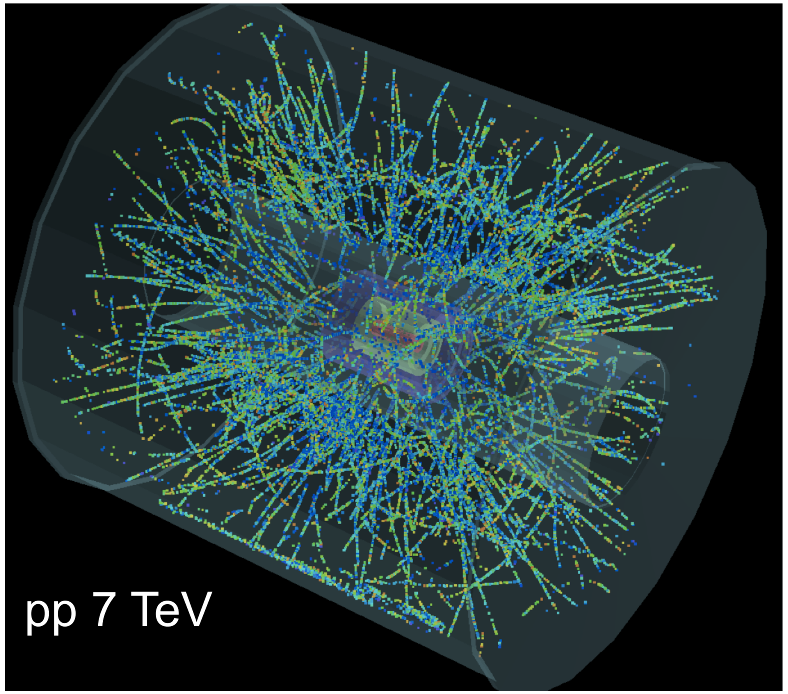
- Is there still any open question?
- Does this picture break down in small systems?
- What are the future directions?
- What should we measure in future?



Overview

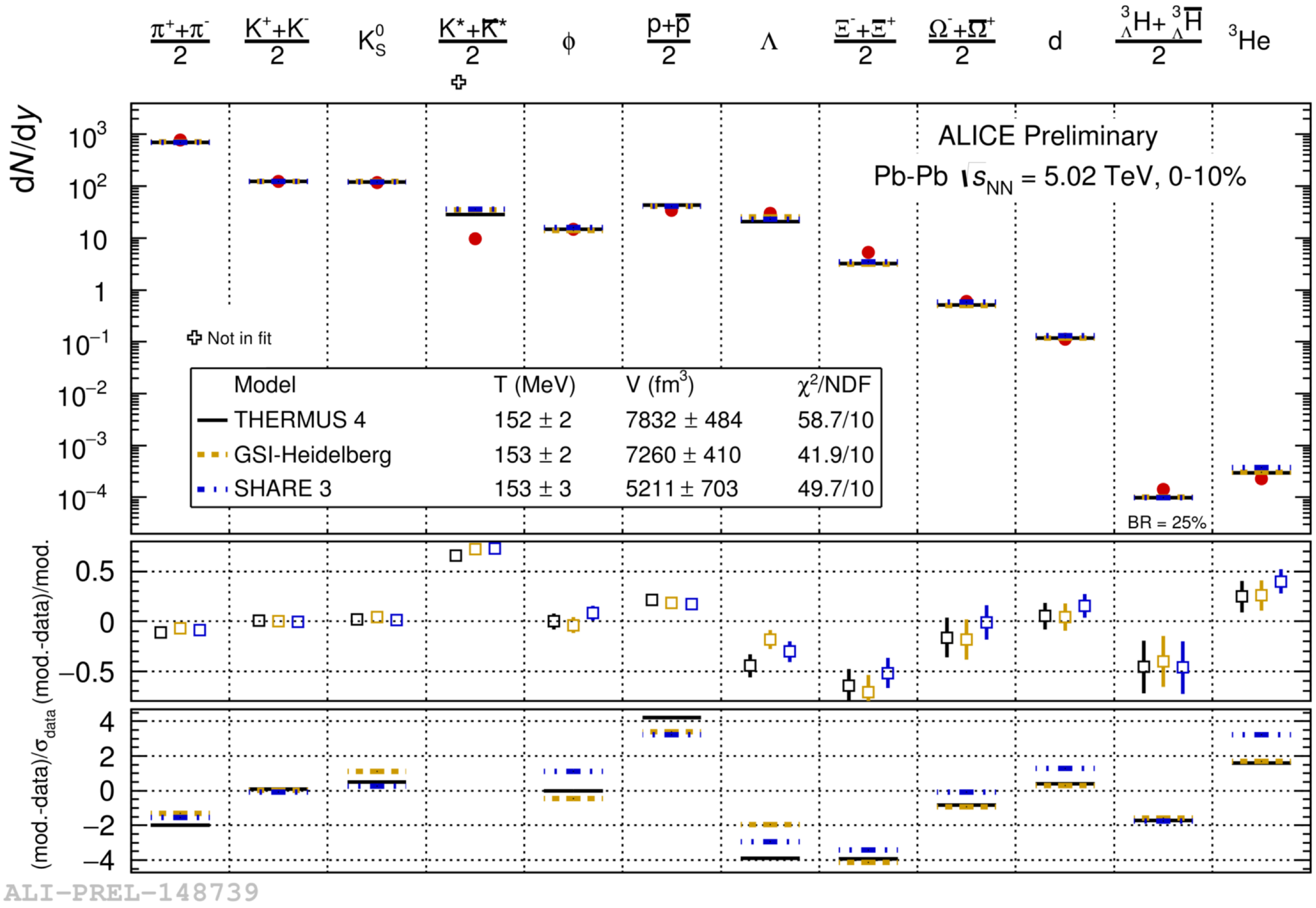
1. The origin and understanding of strangeness enhancement.
2. Towards intermediate p_T: Particle production via recombination of strangeness and charm.
3. The (anti-)hyper-triton as the one particle which will clarify all questions.





1. Origin and understanding of strangeness enhancement

Thermal statistical model fits Pb-Pb 5.02 TeV



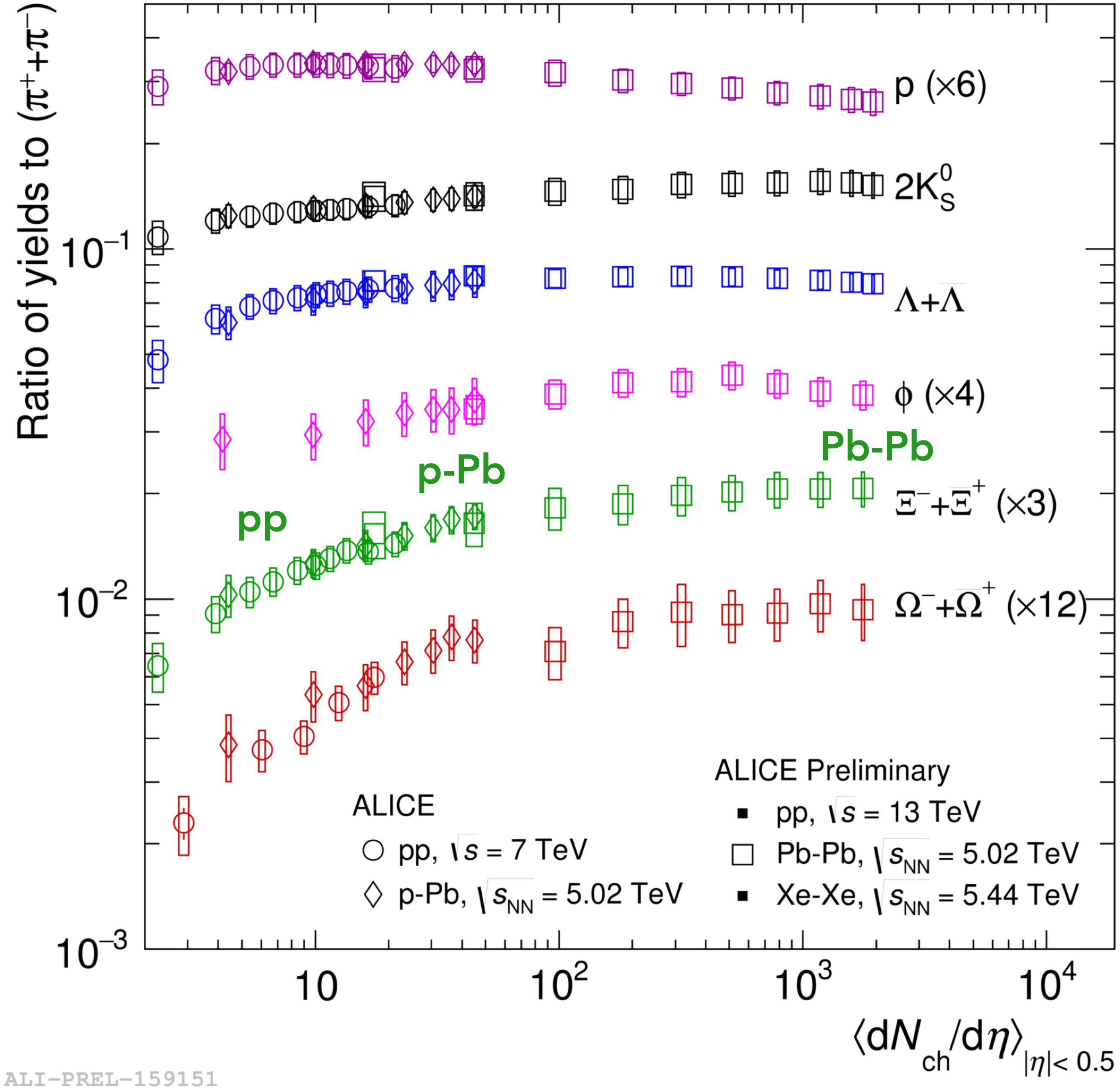
→ Also at 5.02 TeV, yields of light flavor hadrons are qualitatively well described by equilibrium thermal models over 7 orders of magnitude.

→ Fit at 5.02 TeV converges to slightly lower T_{ch} than at 2.76 TeV (153 w.r.t to 156 MeV) due to proton yield.

Particle chemistry across system size (1)

→ Smooth evolution of particle chemistry from small to large systems as function of charged particle multiplicity
⇒ common origin in all systems?

→ Increasing strangeness production with increasing multiplicity until saturation (grand-canonical plateau) is reached.

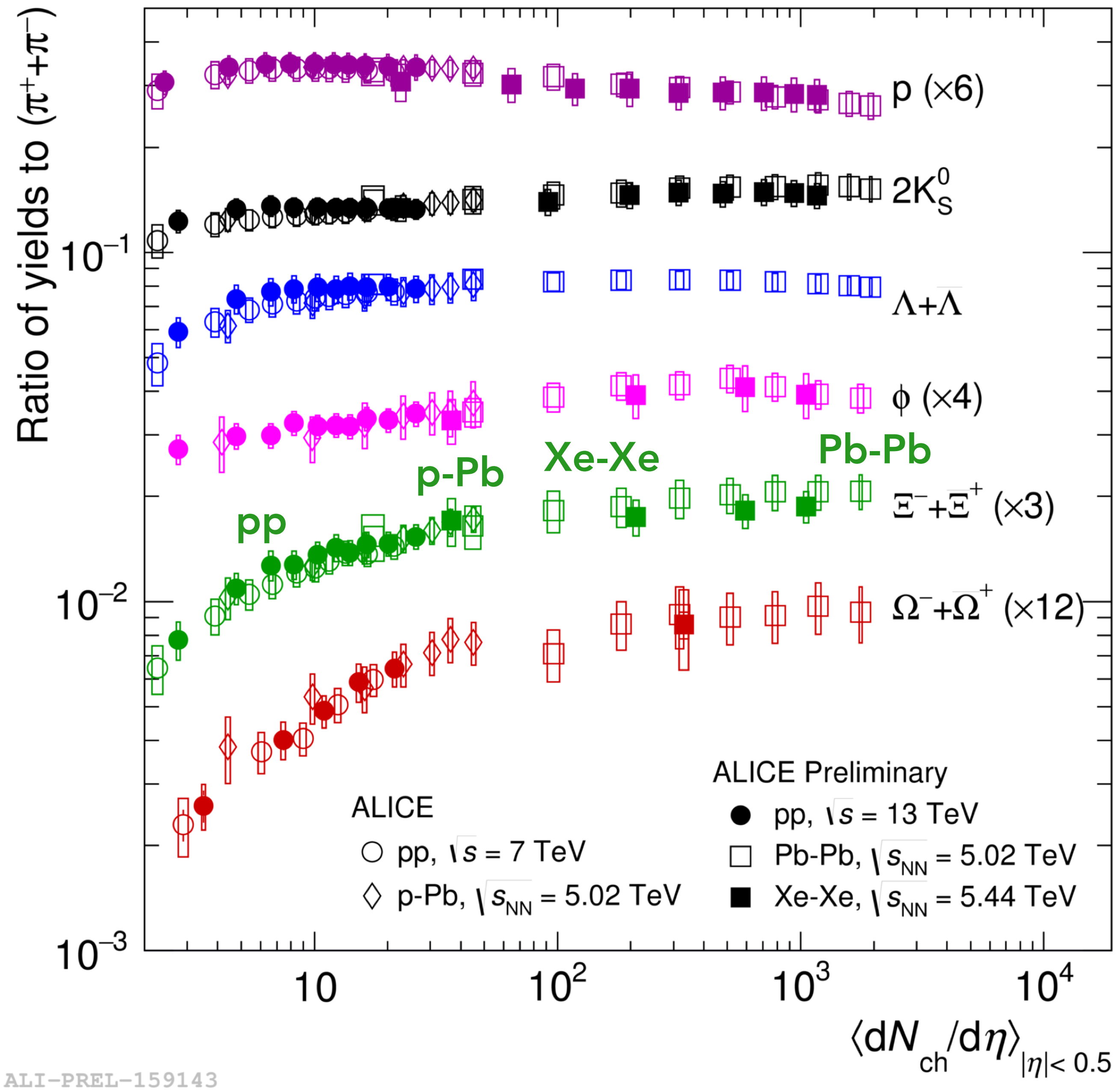


Particle chemistry across system size (2)

→ Smooth evolution of particle chemistry from small to large systems as function of charged particle multiplicity
⇒ common origin in all systems?

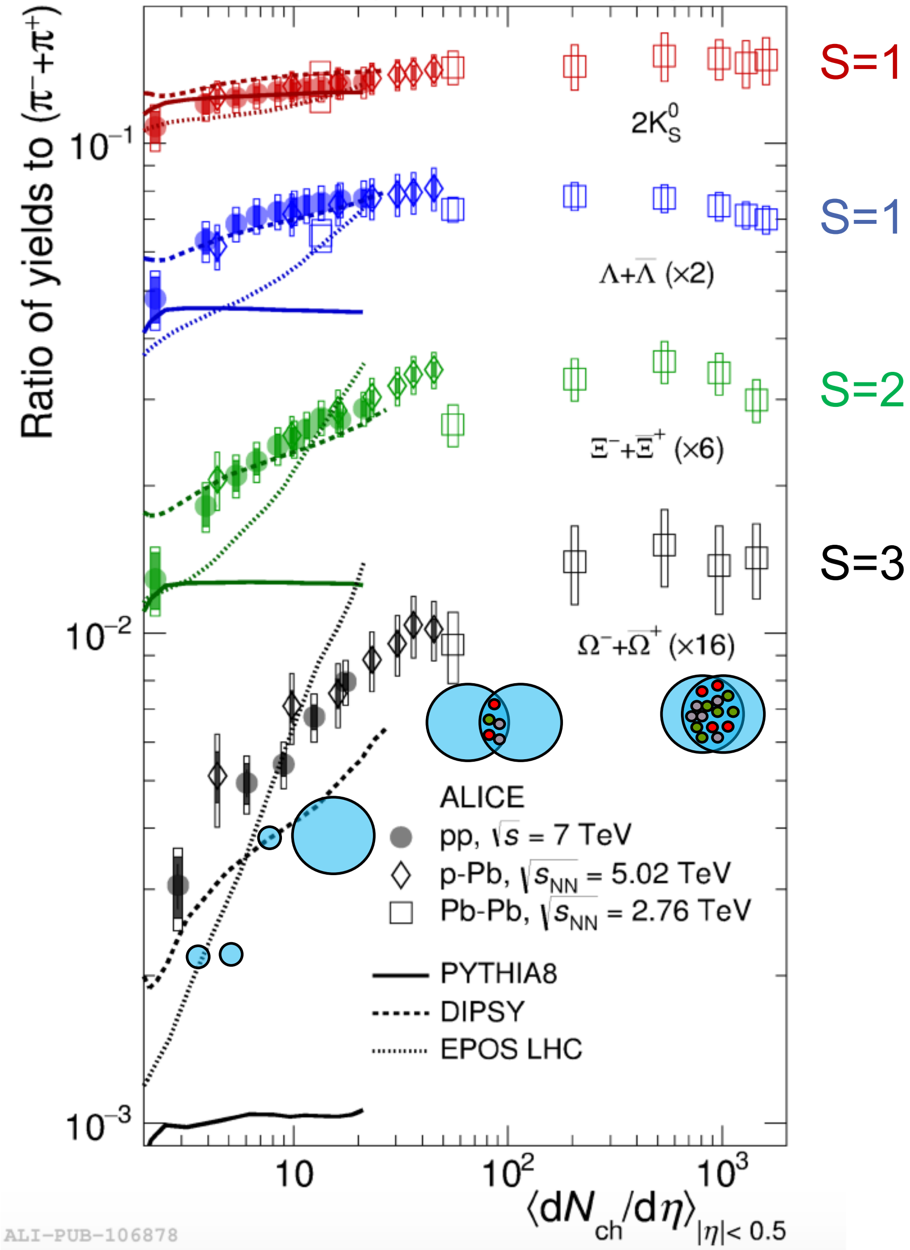
→ Increasing strangeness production with increasing multiplicity until saturation (grand-canonical plateau) is reached.

→ **Confirmed with new pp $\sqrt{s}$=13 TeV and Xe-Xe data!**



Hadrochemistry and strangeness enhancement (1)

Nature Physics (2017) doi:10.1038/nphys4111

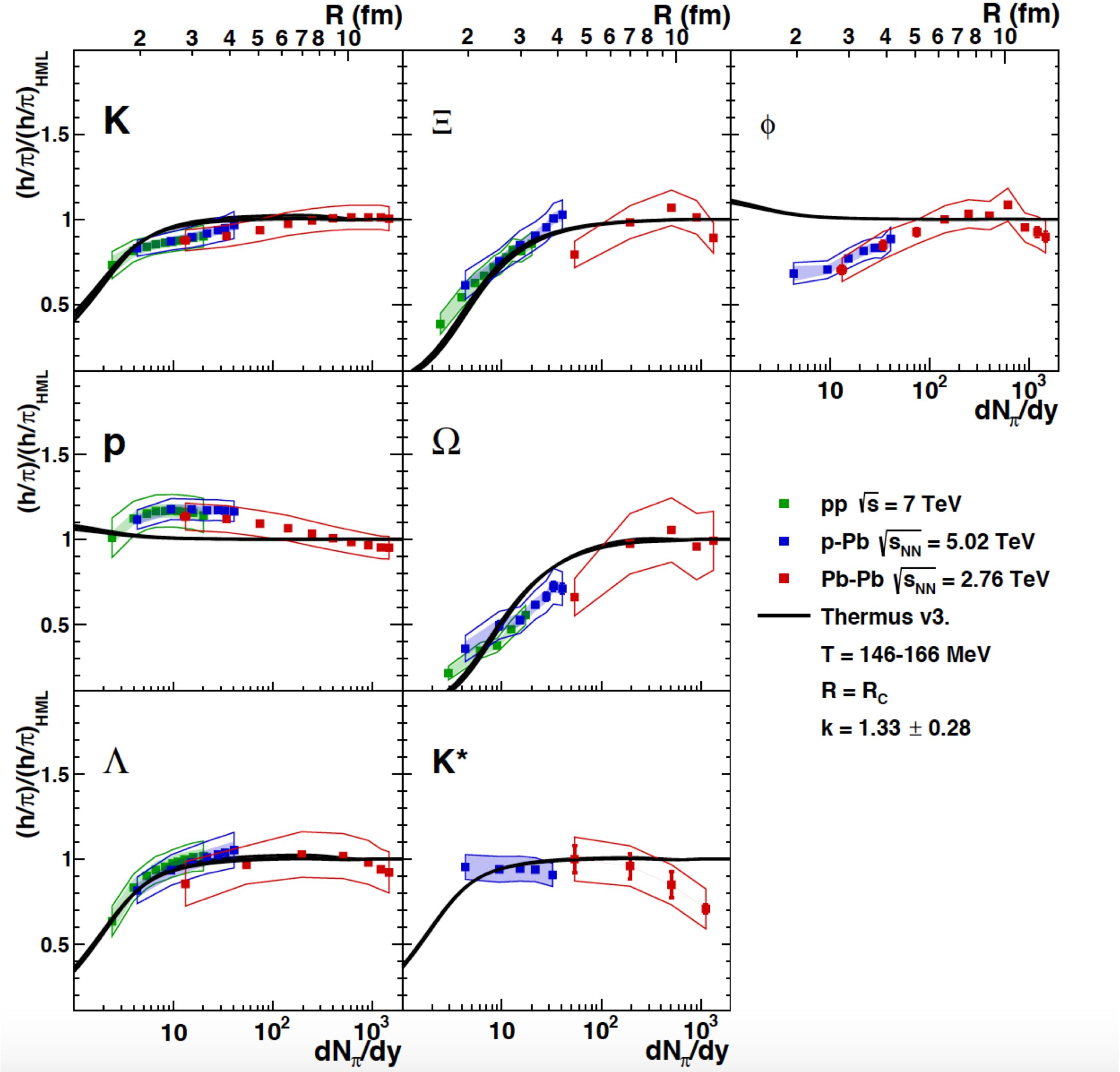


- Smooth evolution of hadrochemistry observed from pp to pPb to Pb-Pb collisions as a function of charged particle multiplicity.
- Significant enhancement of strange to non-strange particle production observed in pp collisions.
- pp collision data allows to compare to a plethora of QCD inspired event generators:
  - **PYTHIA8** completely **misses** the behavior of the data (independent of switching ON/OFF color reconnection)
  - **DIPSY** (color ropes) describes the increase in strangeness production qualitatively but fails to predict protons correctly in its original version..
  - **EPOS-LHC** (core-corona) only qualitatively describes the trend.

Hadrochemistry (2)

- Heavy-ion view: the thermal-statistical hadronisation picture can be extended to smaller collision systems (strangeness canonical suppression).

- Does strangeness canonical enhancement explain everything? Is there any need for a microscopic modeling?



[V. Vislavicius, AK, arXiv:1610.03001]

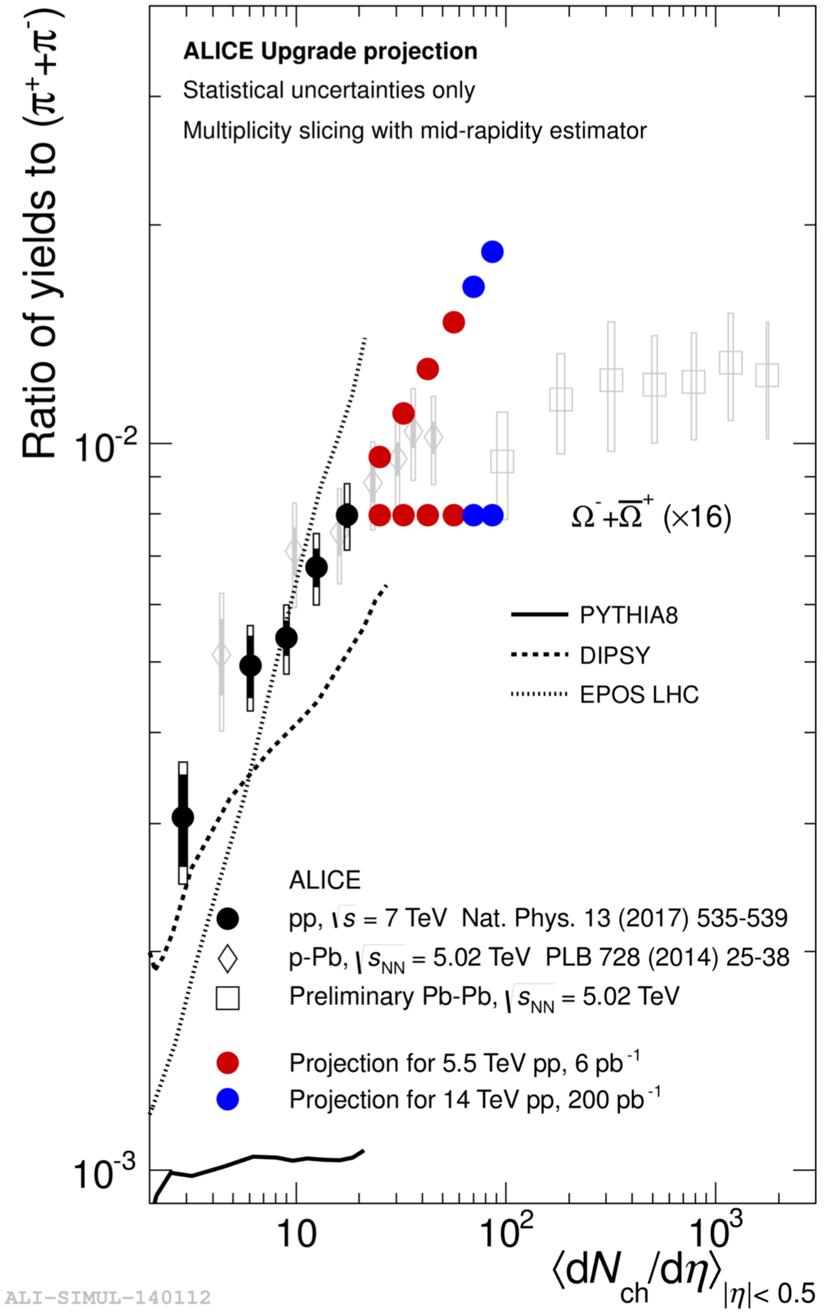
Hadrochemistry (3)

- Omega baryon is the most sensitive probe (needs ~10M events for spectrum and dN/dy in highest multiplicity class).

- Run 3 and 4 will provide crucial tests:

  Is the grand-canonical limit for particle production universally respected or is it violated in very high multiplicity pp collisions?

- Caveats:
  - Multiplicity estimators and selection biases.
  - Particle production in jets versus bulk
  - …



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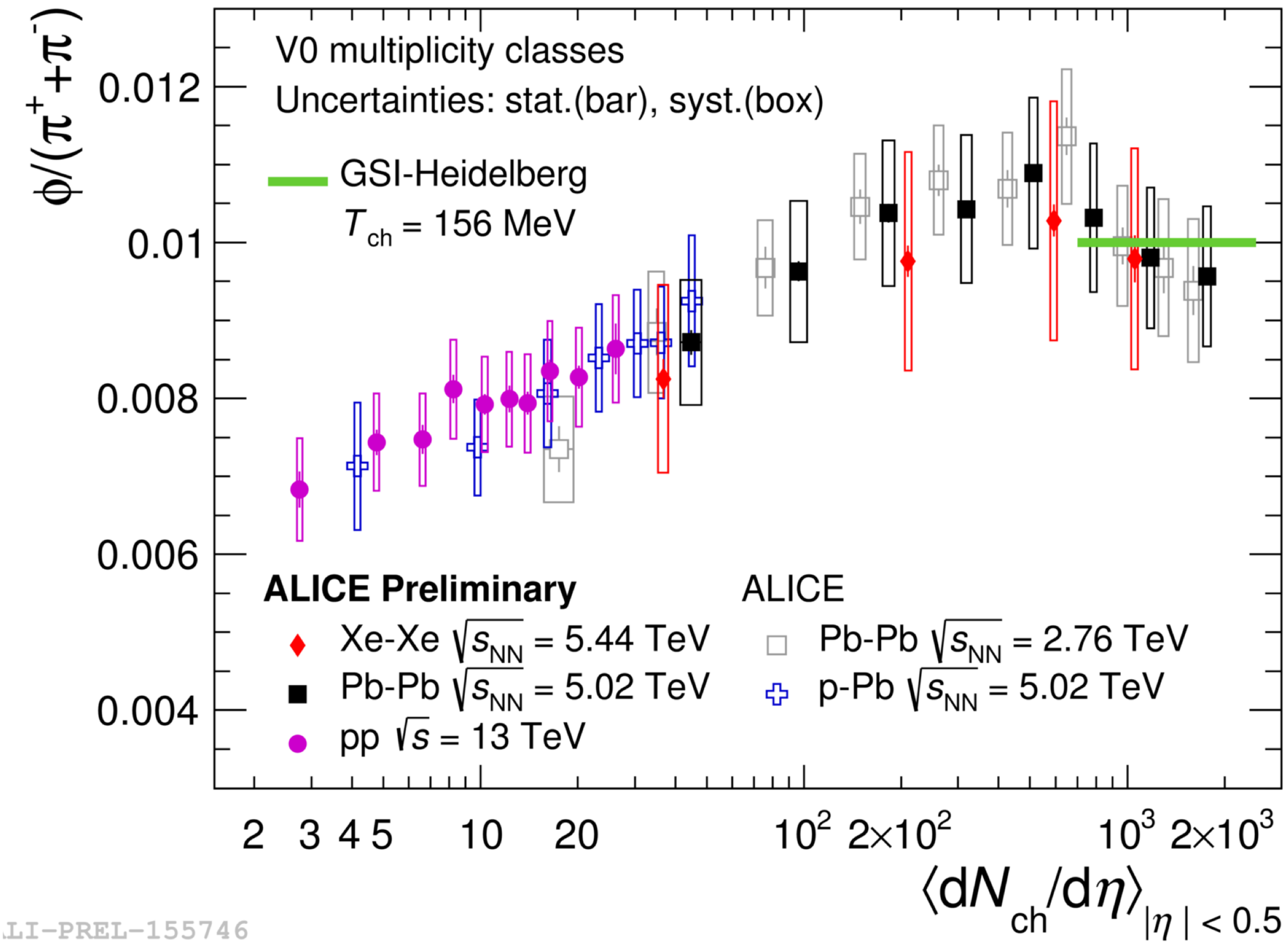
The Φ meson

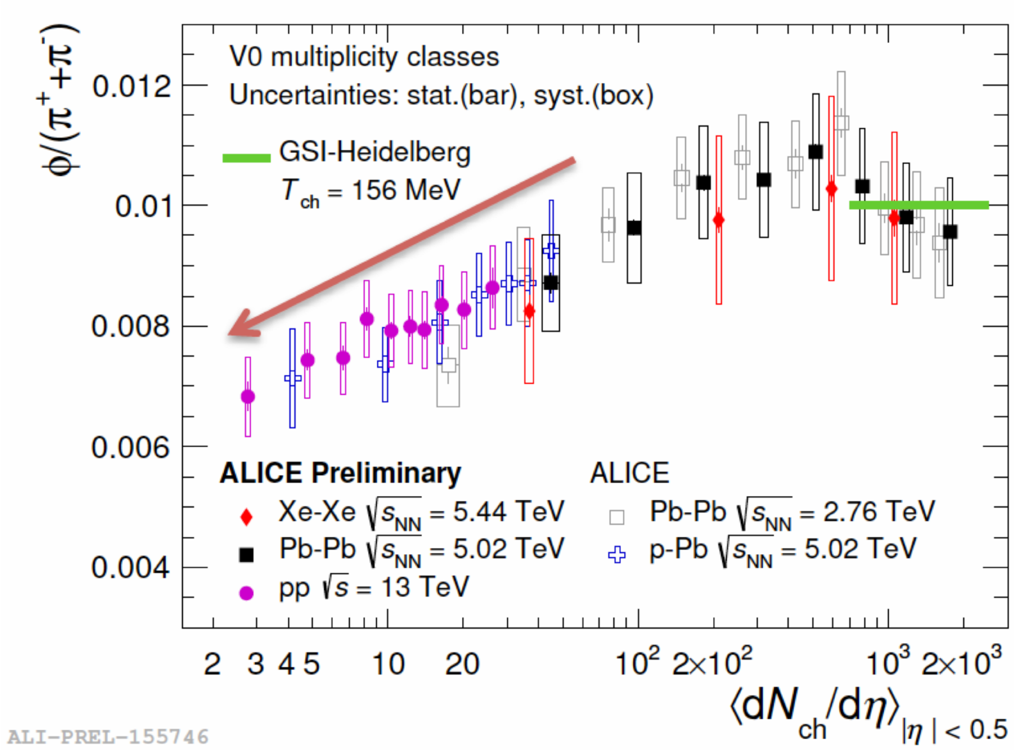


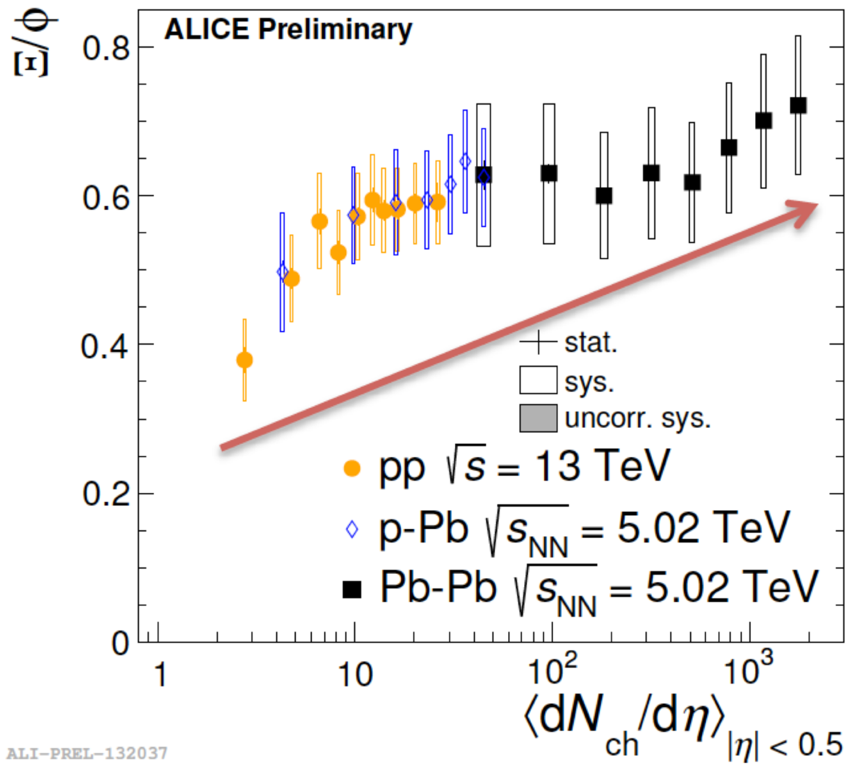
Significantly increasing trend of ϕ-meson ($s\bar{s}$) to pion ratio with increasing multiplicity

→ In contrast to expectation from simple strangeness canonical suppression: favors non-equilibrium production of either only the ϕ or of all strange particles (γ_s)

→ Pivotal role of the ϕ-meson in the understanding of strangeness production with thermal-statistical, core-corona, and MC models.

The Φ production meson in detail

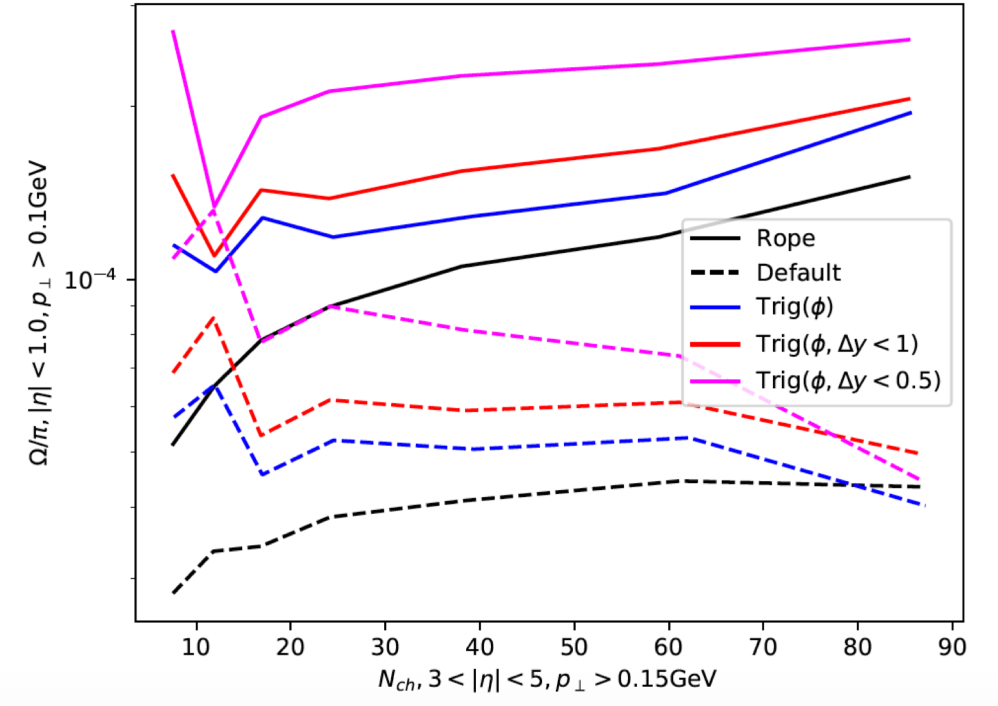


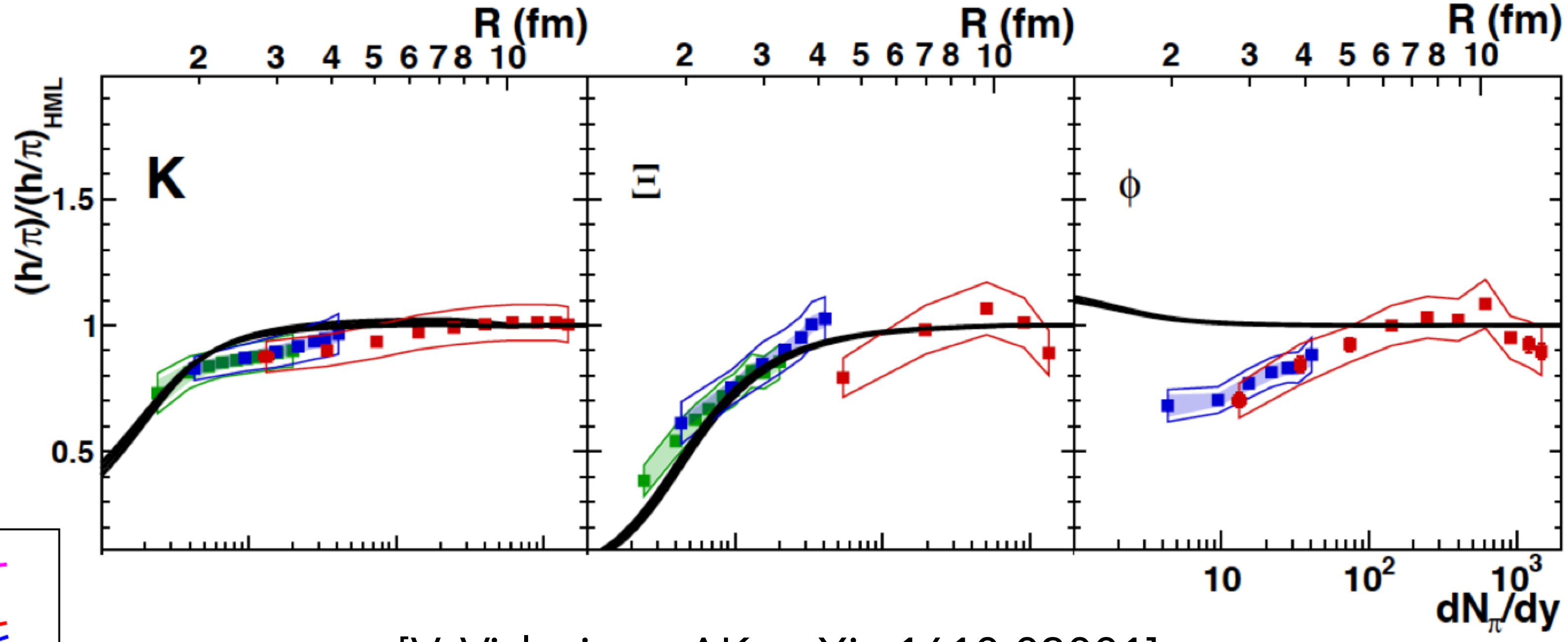


- ***ϕ(S=0) yield in agreement with thermal model expectation in central Pb-Pb collisions***
- ***But decreases towards smaller multiplicity in contrast to the expectation from strangeness canonical suppression***
- ***Ξ(S=2)/ϕ(S=0) increases as a function of multiplicity in contrast to expectation from non-equilibrium production as quantified with strangeness suppression factor.***

Understanding Φ-meson production

[C. Bierlich (Lund&CPH) at *Light Up! 2018 workshop*]

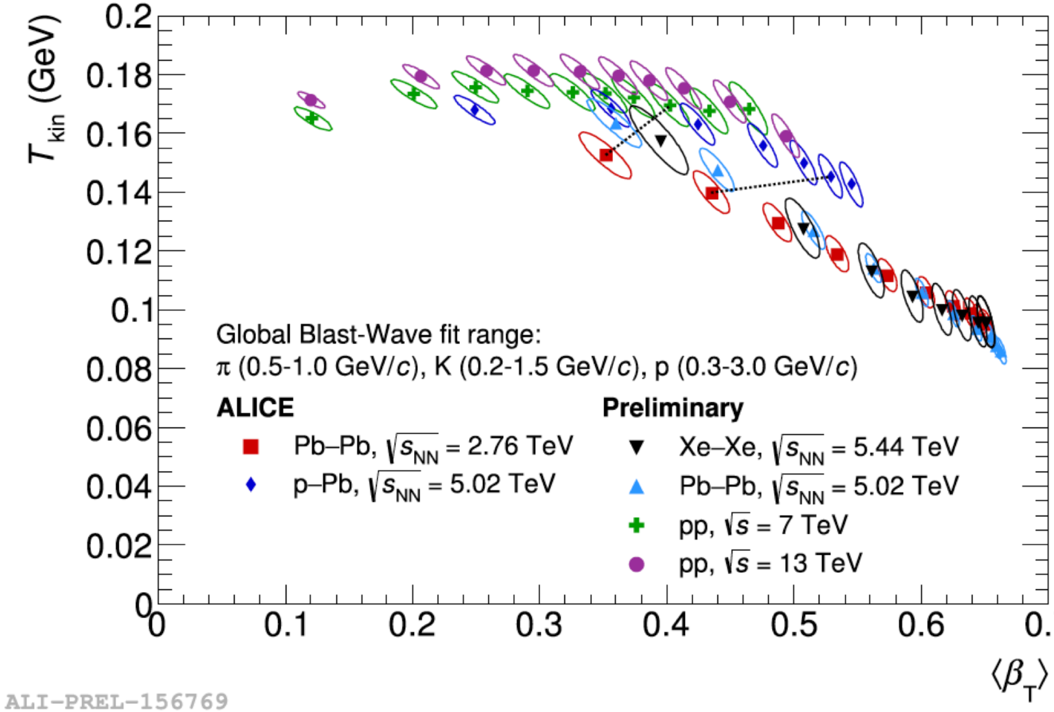




[V. Vislavicus, AK, arXiv:1610.03001]

2. Towards intermediate pT: recombination

Blast-wave and hydro



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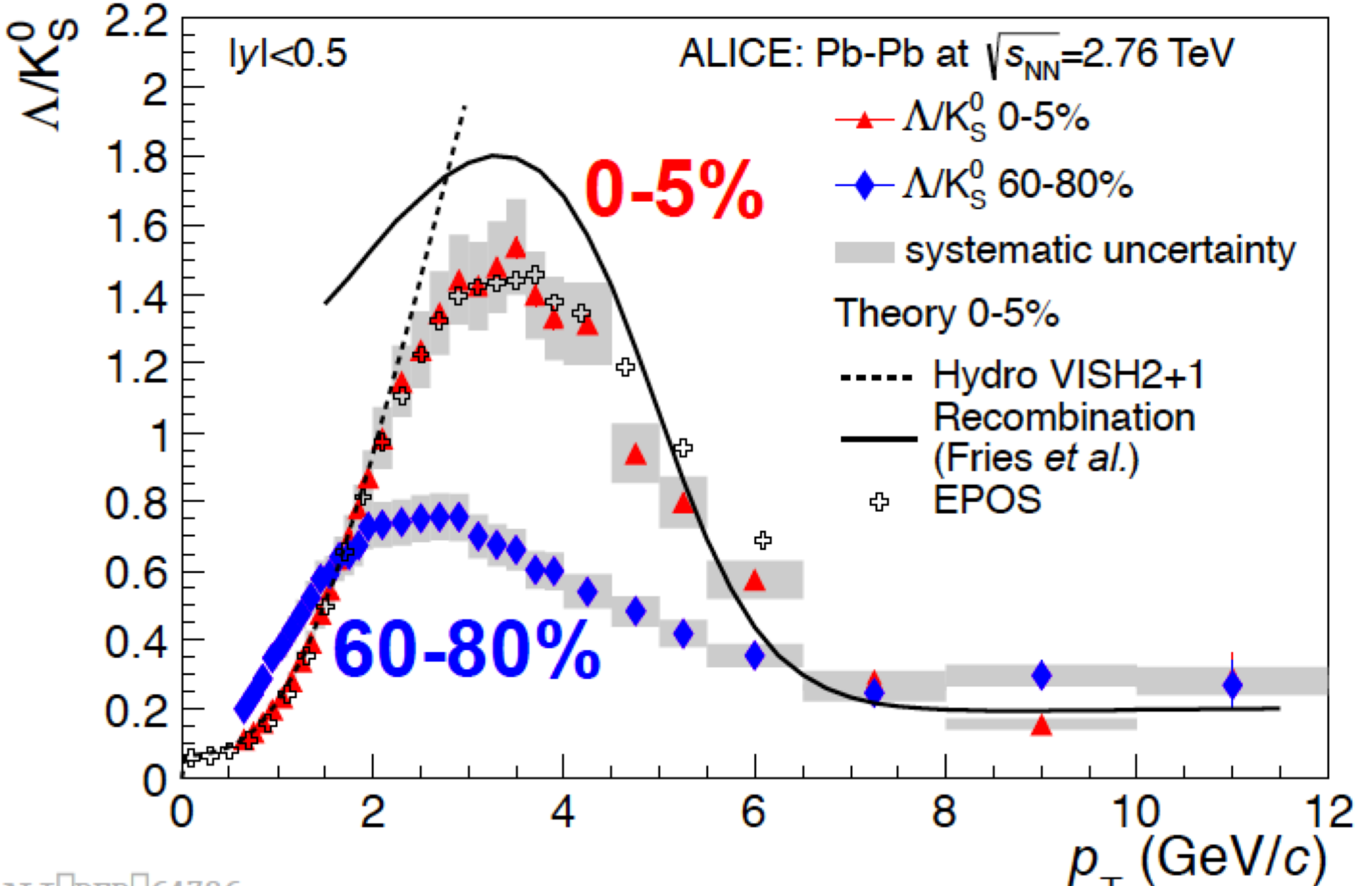

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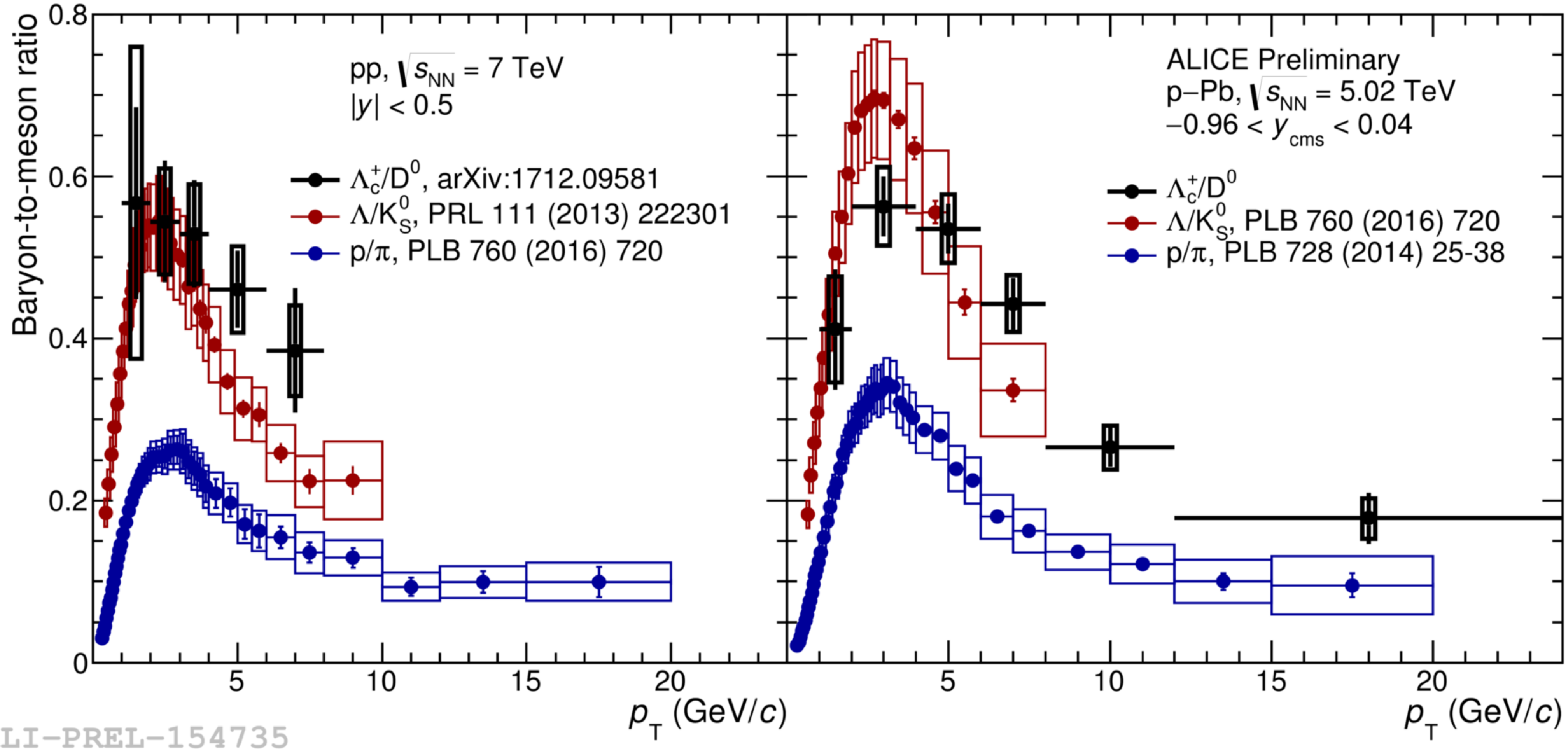
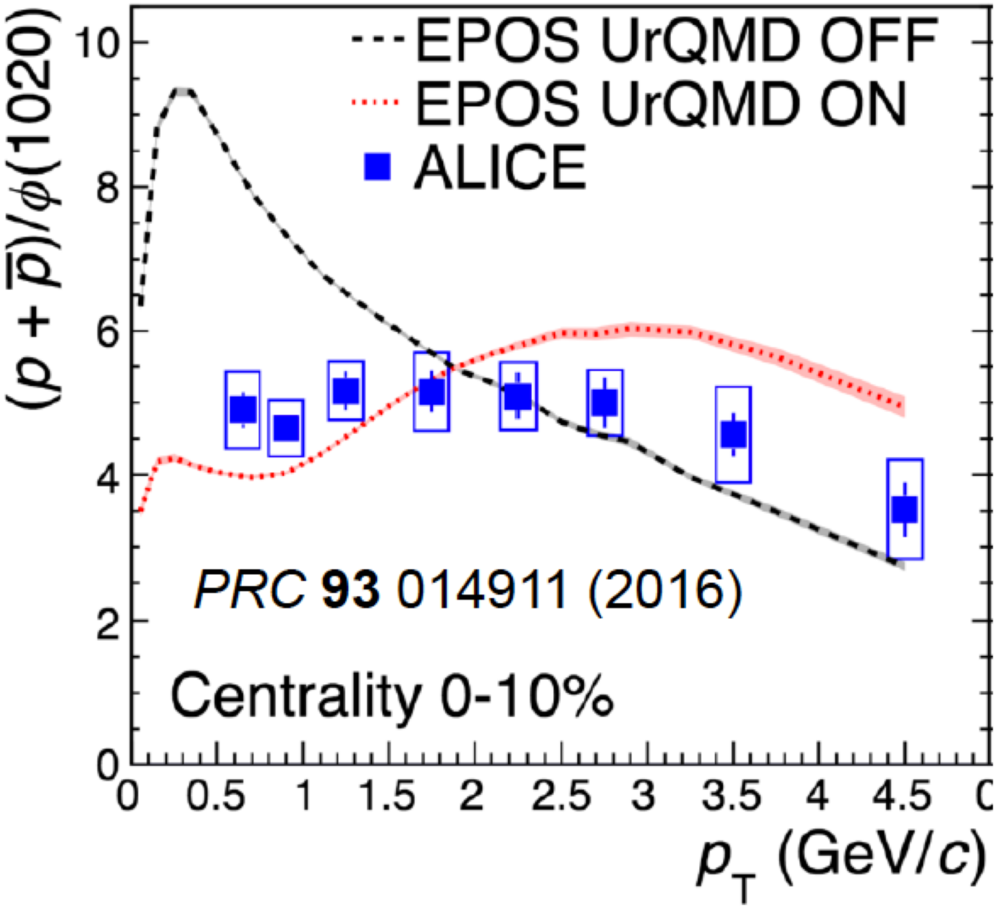
Baryon to meson ratios in pp and p-Pb collisions

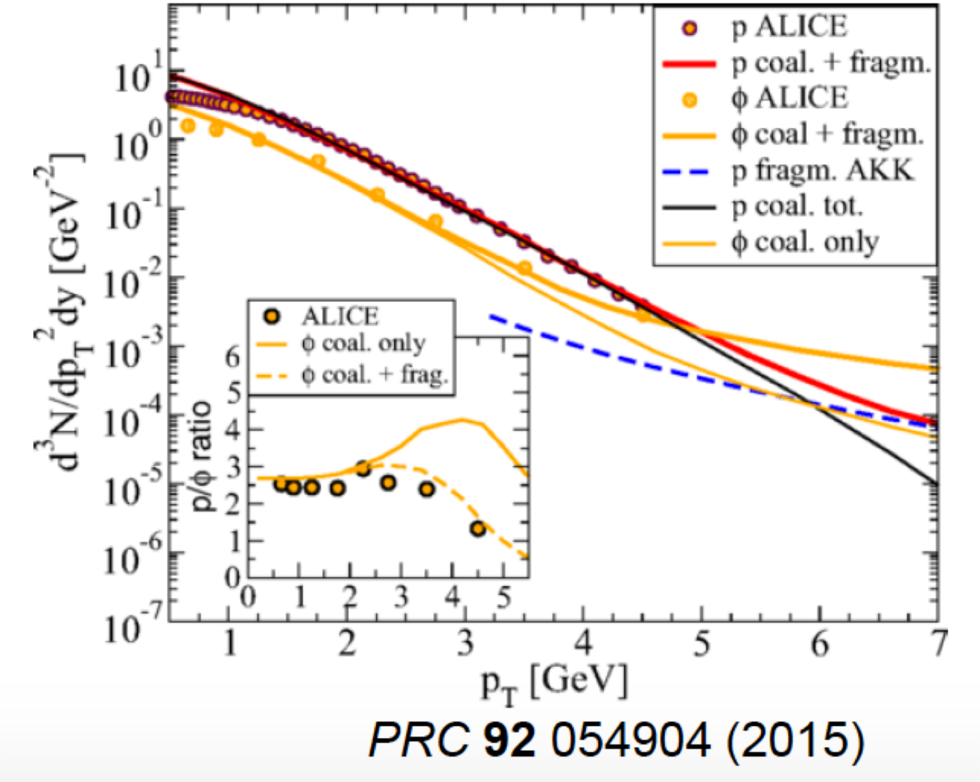


→ Remarkable similarities of baryon to meson ratio in the charm sector with light flavor results.

Φ meson

- Also here the Φ has a special as it is often argued that it is a meson with the same mass as the proton (a baryon) and thus should be flat in the hydro picture, but is this a coincidence?

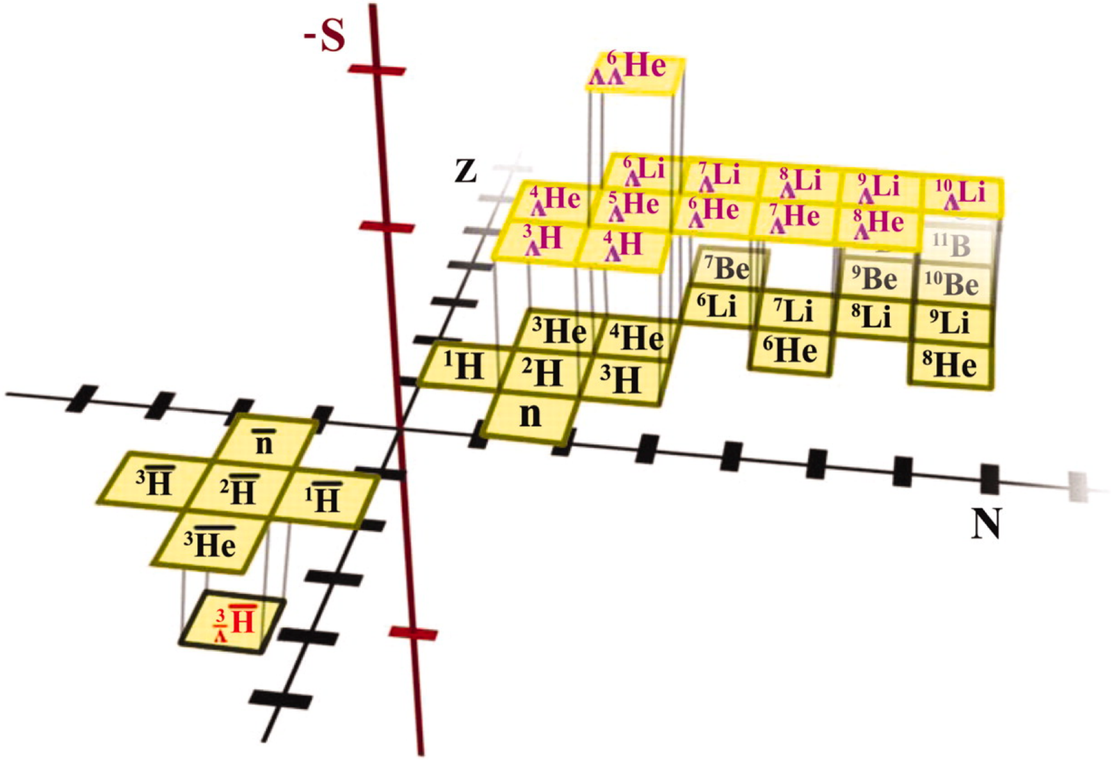


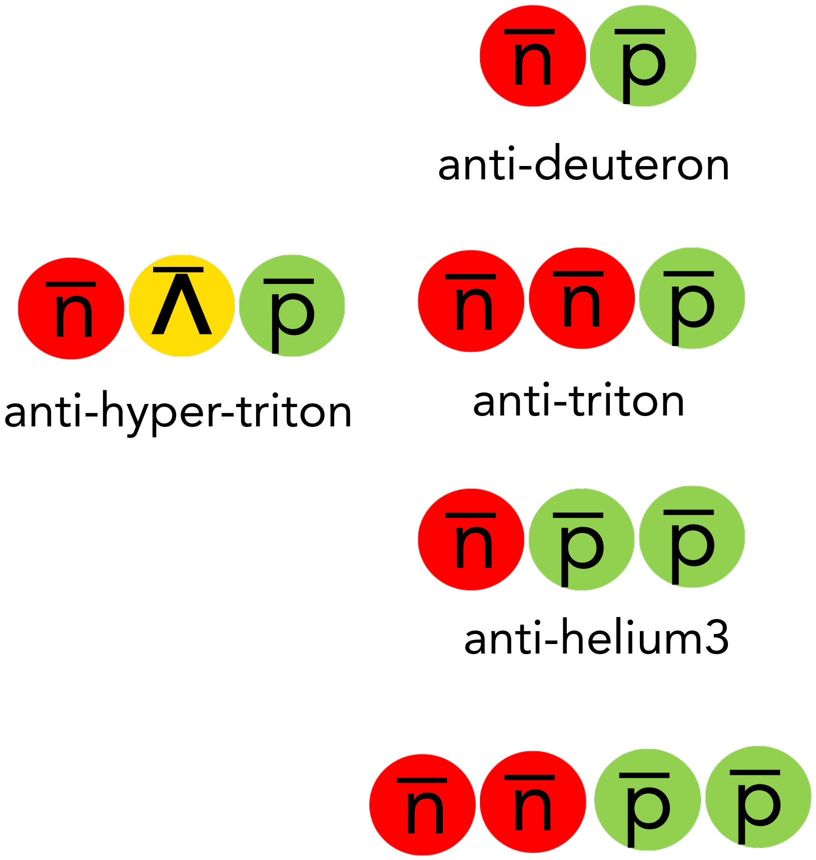


PRC **92** 054904 (2015)

4. The hyper-triton

Light (anti-)nuclei





anti-deuteron

anti-hyper-triton

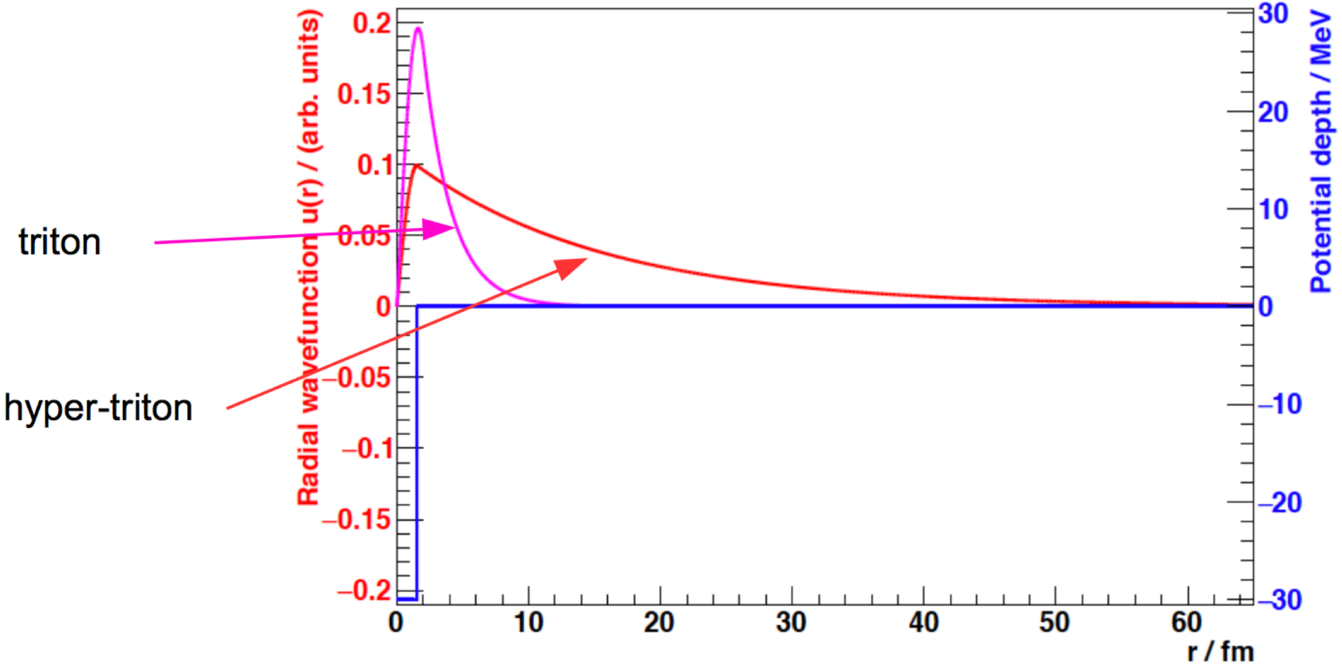
anti-triton

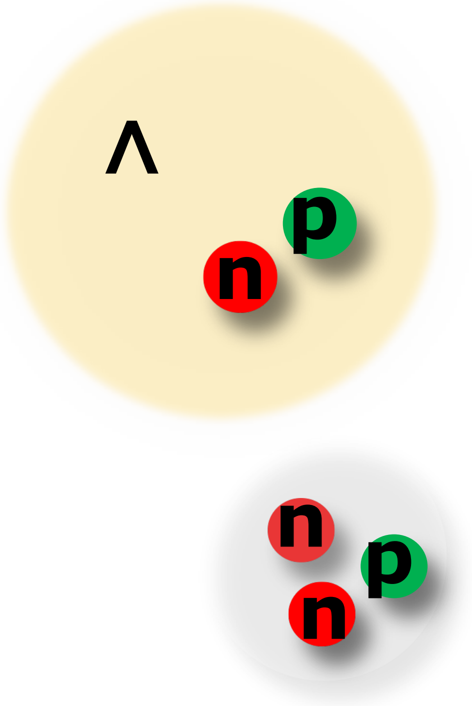
anti-helium3

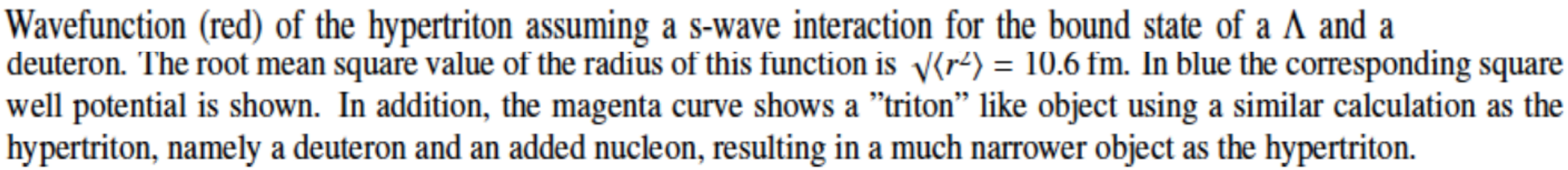
anti-alpha

Object size and wave function

B. Donigus, August 2017



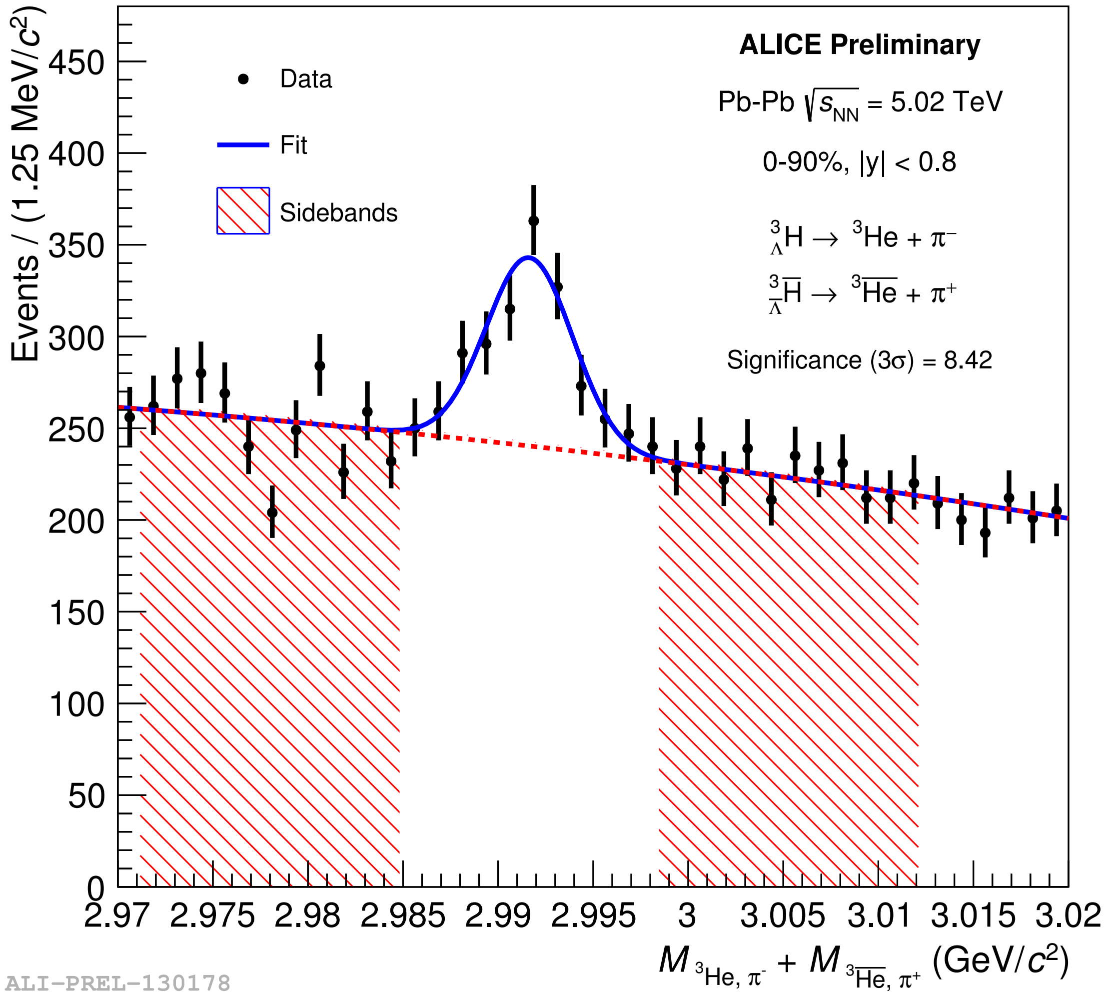


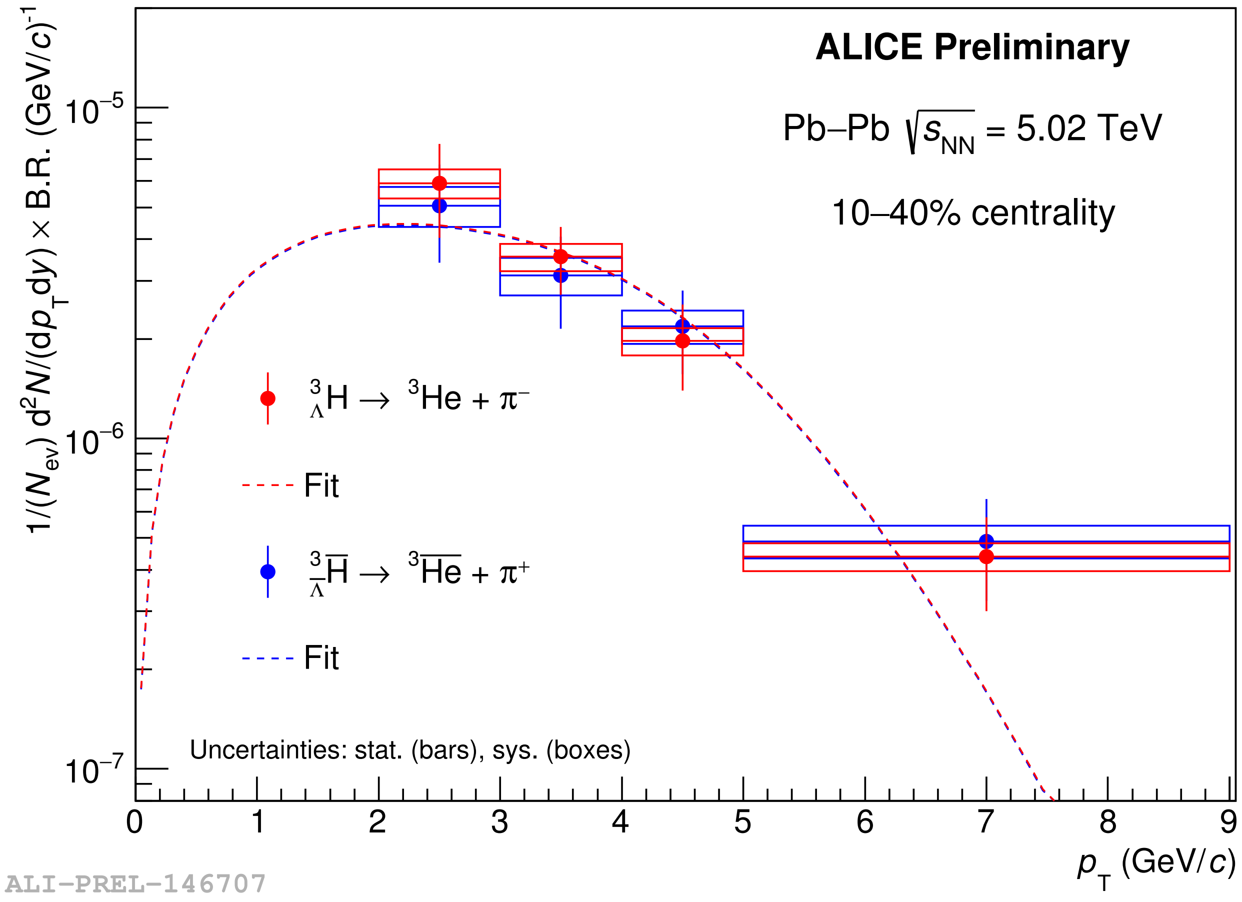


Wavefunction (red) of the hypertriton assuming a s-wave interaction for the bound state of a Λ and a deuteron. The root mean square value of the radius of this function is $\sqrt{\langle r^2 \rangle} = 10.6$ fm. In blue the corresponding square well potential is shown. In addition, the magenta curve shows a ”triton” like object using a similar calculation as the hypertriton, namely a deuteron and an added nucleon, resulting in a much narrower object as the hypertriton.

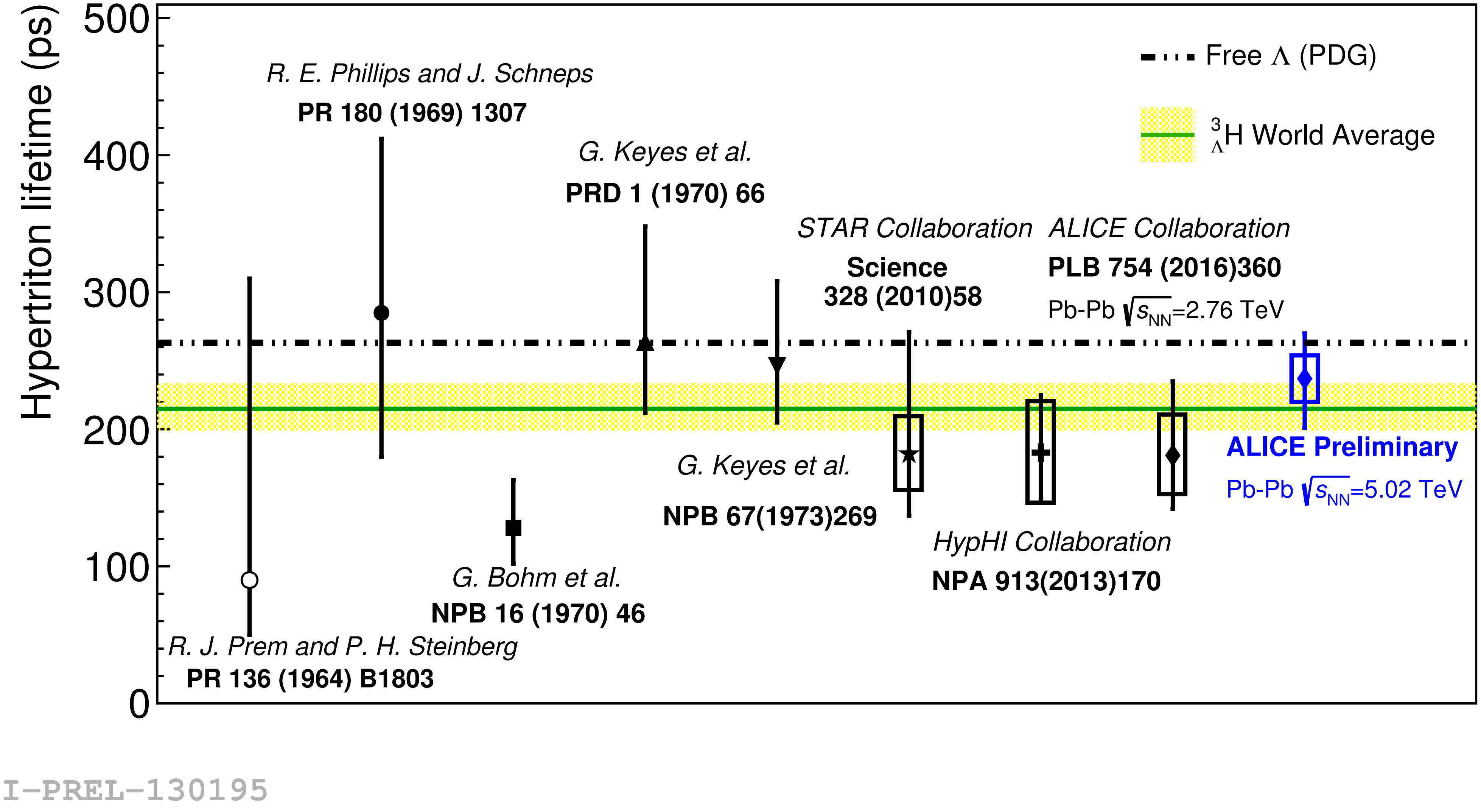
See EMMI workshop,
https://indico.gsi.de/event/6301/session/2/contribution/4/material/slides/0.pdf

Hyper-triton

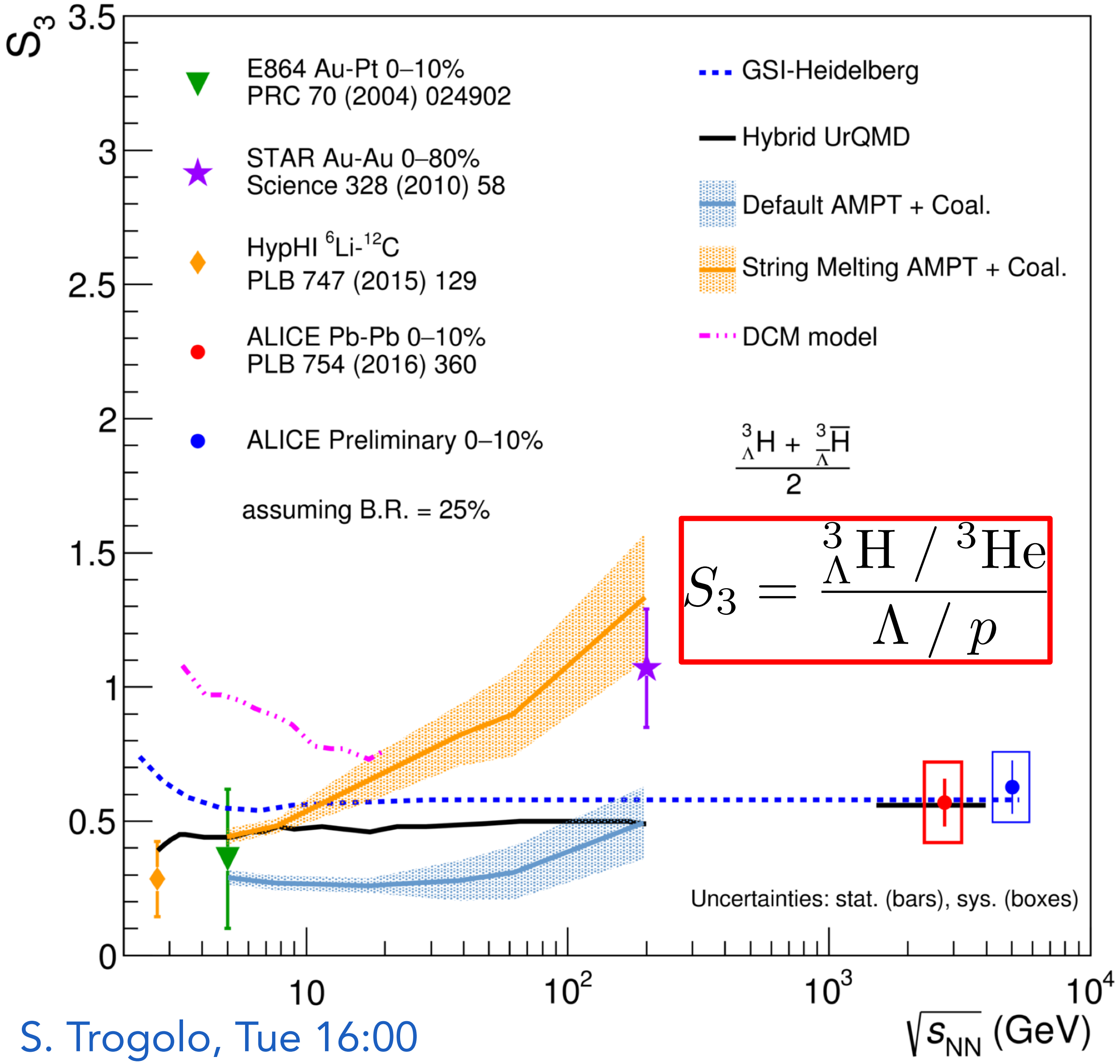




Hyper-triton lifetime

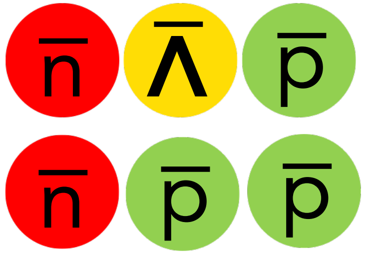


(anti-)hyper-triton in Pb-Pb collisions at 5.02 TeV



$$\frac{{}^{3}_{\Lambda}\mathrm{H} + {}^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}}{2}$$

$$\boxed{S_3 = \frac{{}^{3}_{\Lambda}\mathrm{H} \;/\; {}^{3}\mathrm{He}}{\Lambda \;/\; p}}$$



anti-hyper-triton

anti-^{3}He

→ Yields of heavy and fragile objects such as (anti-)(hyper-)nuclei in agreement with thermal-statistical model predictions at *chemical* freeze-out.

→ No re-scattering of anti-nuclei in hadronic phase despite large dissociation cross-section.

→ Final-state coalescence after kinetic freeze-out requires more detailed modeling: *naive coalescence* ($S_3 \approx 1$) does not describe data.

S. Trogolo, Tue 16:00

Production models in a nutshell

Thermal production at chemical freeze-out/phase boundary

- Key parameters are mass and chemical freeze-out temperature: **$dN/dy \sim \exp(-m/T_{ch})$**
- Model provides yields but no p_T spectra (no dynamics)

→ *works in Pb-Pb collisions→ but how can loosely bound states survive?*

Coalescence of nucleons at kinetic freeze-out

- Key parameters are nuclear wave functions, size of the (hyper)nucleus
- Production probability quantified by **coalescence parameter B_A**
- Model provides spectra

→ *works in small systems → but how can "large" objects be created in a small system?*

Production in the hadronic phase

→ *Are they in contrast? Up to which extent?*
→ *For which system(s) do they provide a valid description?*
→ *Can they describe all "objects" in their scope of validity?*

The (anti-)nuclei riddle

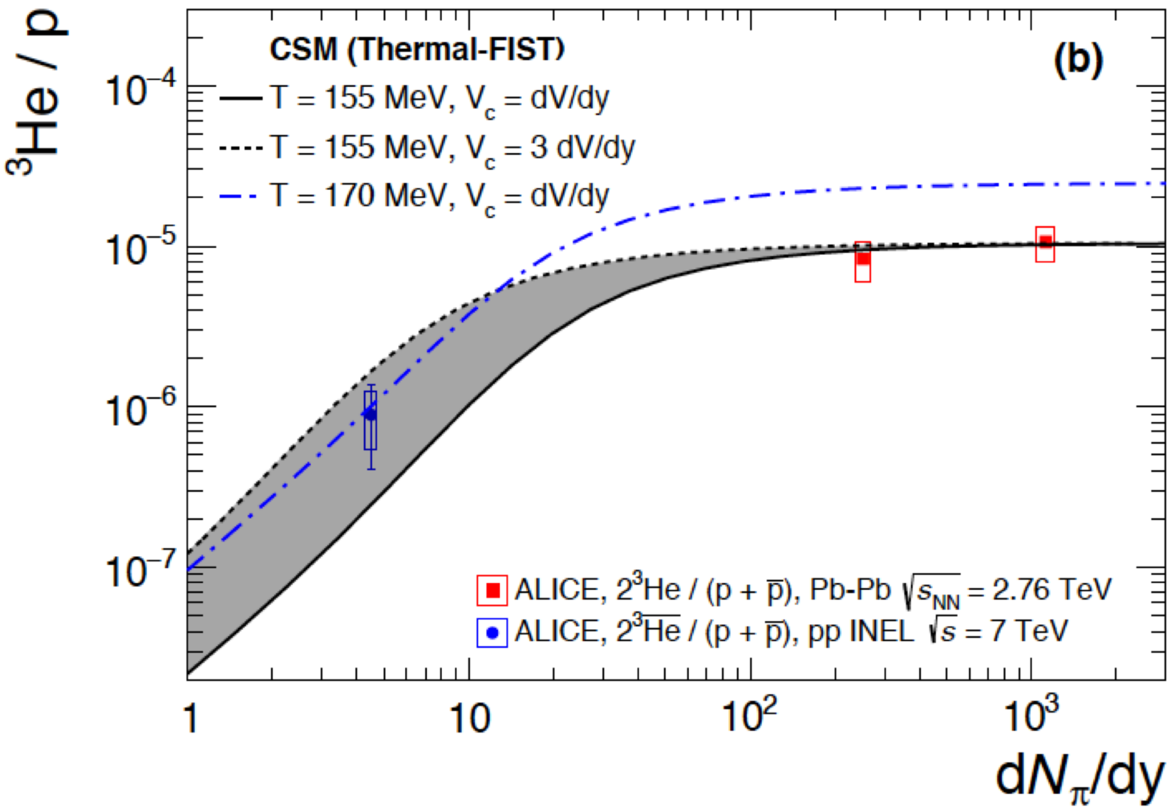
- Fragile objects such as anti-nuclei should not be produced in thermal equilibrium at 156 MeV together with the non-composite objects, but why are they in perfect agreement with the model?

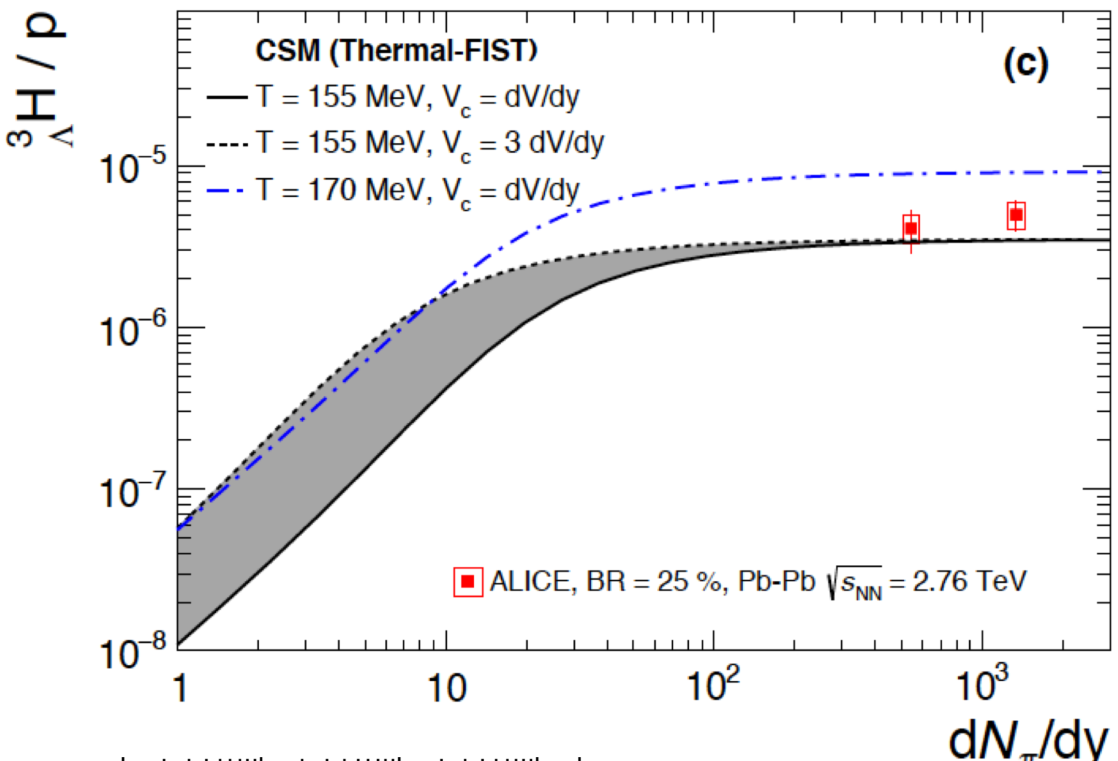
- Is it just a coincidence? Can coalescence models explain this? In my opinion, there is no convincing calculation on the market at the moment.

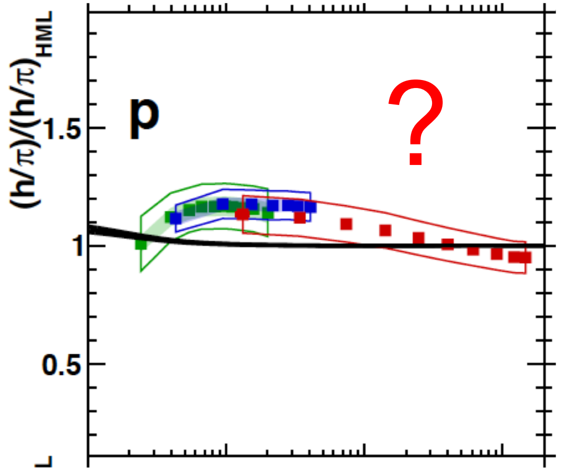
- N.B.: production rates in quantum mechanical coalescence models depend crucially on the size of the object with respect to the system size!

- Are multi-quark bags the way out (see [A. Andronic *et al.*, arXiv:1710.09425])?

Full canonical calculations





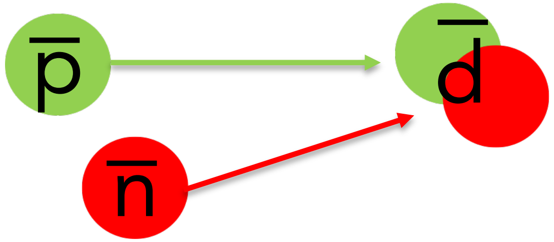


Vovchenko, Donigus, Stoecker, arXiv:1808.05245

Coalescence parameters B_A

- (anti-)nuclei production by coalescence of (anti-)protons and (anti-)neutrons which are close by in momentum and position space. Roughly speaking: *“deuteron ∝ proton x neutron => deuteron ∝ proton^2”*

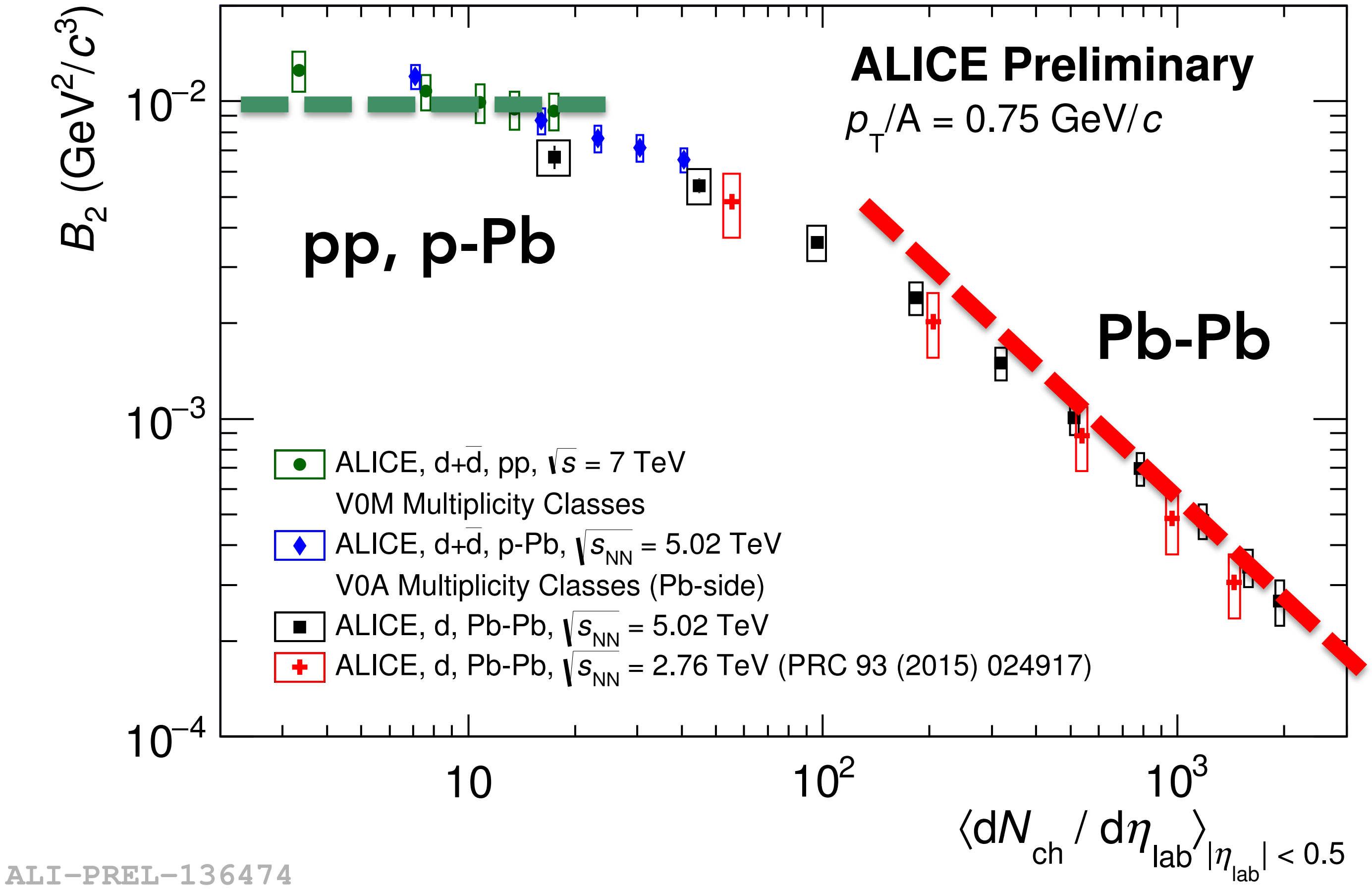
$$\boxed{E_{\mathrm{d}} \frac{\mathrm{d}^3 N_{\mathrm{d}}}{\mathrm{d}p_{\mathrm{d}}^3} = B_2 \left(E_{\mathrm{p}} \frac{\mathrm{d}^3 N_{\mathrm{p}}}{\mathrm{d}p_{\mathrm{p}}^3} \right)^2}$$



- Spherical approximation: maximum momentum difference (coalescence momentum p_0) is approx. 100 MeV (5.3 MeV kinetic energy of a nucleon in the rest frame of the other).

→ Can be implemented as an *afterburner* to standard event generators.

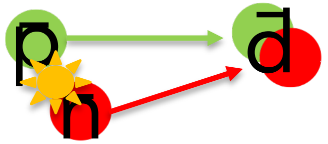
Coalescence models in heavy-ion (1)



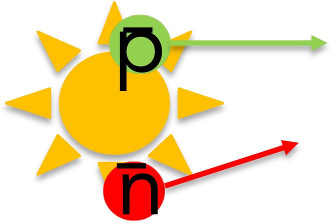
→ Very strong dependence of B_2 on collision geometry.

→ Two production regimes observed:

(a.) system size < deuteron size



(b.) system size > deuteron size



Fermi momentum and uncertainty principle

- “Close in phase-space” <-> “Close in configuration and momentum space” sounds nice, but is quantum-mechanically ill defined due to the uncertainty principle!

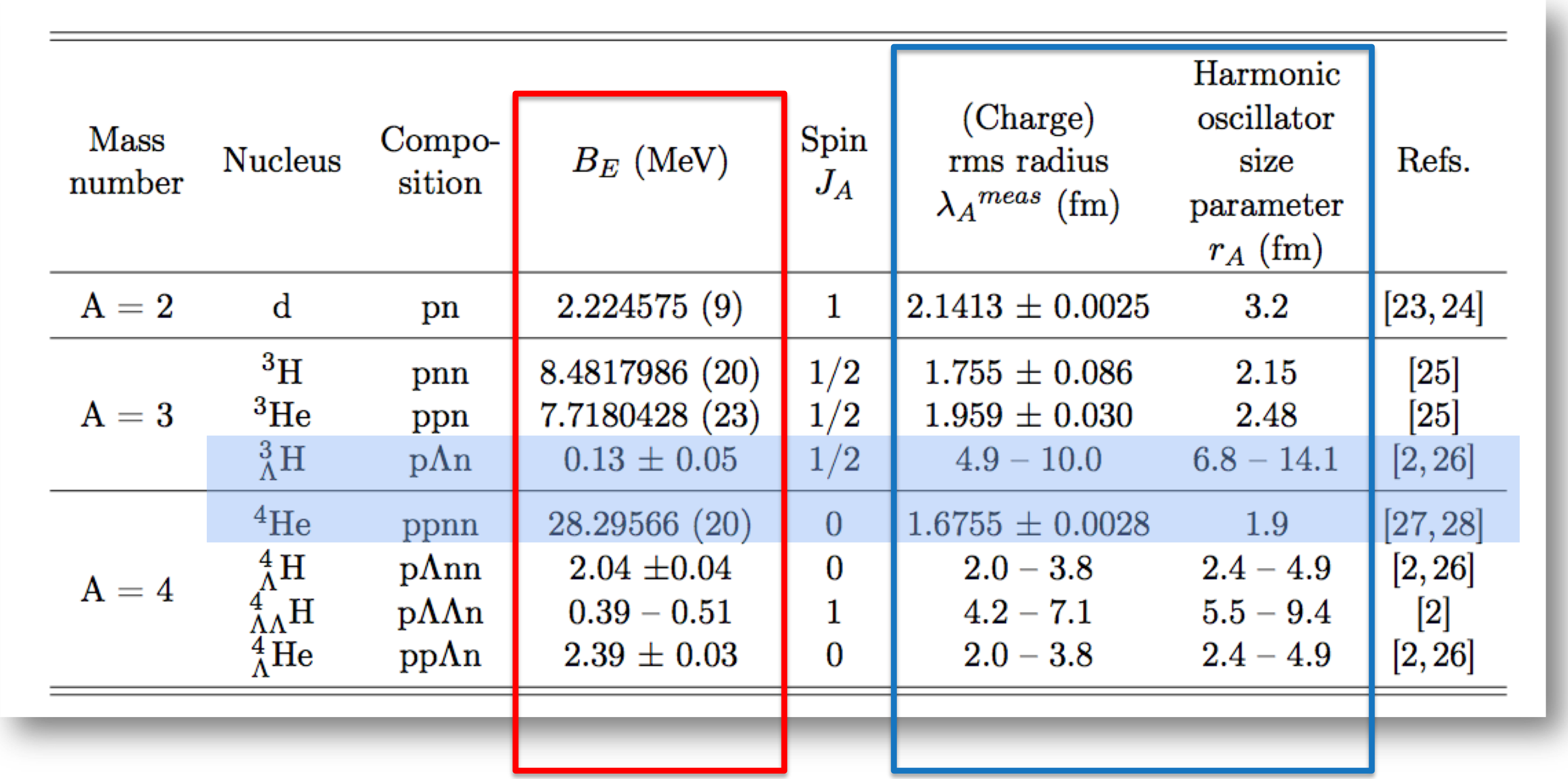
- Imagine a point-like emission source (pp): phase-space reduces to momentum space and the **coalescence momentum**, becomes equal to the momentum of the nucleons in the bound nucleus (the “Fermi momentum” in large nuclei).

- Quantum-mechanically correct treatment: overlap of the source function with the **Wigner-function** of the nucleus.

$$P(x,p) = \frac{1}{\pi\hbar}\int_{-\infty}^{\infty} dy\, \psi^*(x+y)\psi(x-y)e^{2ipy/\hbar}$$

E. Wigner

Properties of (hyper-)nuclei for A≤4



Mass number	Nucleus	Composition	B_E (MeV)	Spin J_A	(Charge) rms radius $\lambda_A{}^{meas}$ (fm)	Harmonic oscillator size parameter r_A (fm)	Refs.
$A = 2$	d	pn	2.224575 (9)	1	2.1413 ± 0.0025	3.2	[23, 24]
$A = 3$	^{3}H	pnn	8.4817986 (20)	1/2	1.755 ± 0.086	2.15	[25]
	^{3}He	ppn	7.7180428 (23)	1/2	1.959 ± 0.030	2.48	[25]
	${}^3_\Lambda$H	pΛn	0.13 ± 0.05	1/2	4.9 – 10.0	6.8 – 14.1	[2, 26]
$A = 4$	^{4}He	ppnn	28.29566 (20)	0	1.6755 ± 0.0028	1.9	[27, 28]
	${}^4_\Lambda$H	pΛnn	2.04 ± 0.04	0	2.0 – 3.8	2.4 – 4.9	[2, 26]
	${}^4_{\Lambda\Lambda}$H	p$\Lambda\Lambda$n	0.39 – 0.51	1	4.2 – 7.1	5.5 – 9.4	[2]
	${}^4_\Lambda$He	ppΛn	2.39 ± 0.03	0	2.0 – 3.8	2.4 – 4.9	[2, 26]

“Fragile” objects!!!

Different size parameters!!!

Coalescence

R. Scheibl, U. Heinz, (1999) PRC 59 (1999) 1585-1602
K. Blum et al., PRD 96 (2017) 103021

- Nuclei form by coalescence of nucleons close enough in phase-space
- Density matrix approach used to calculate the coalescence probability
  - The source is rapidly expanding under radial flow (hydrodynamics)
  - The coalescence process is governed by the same correlation volume which can be extracted from HBT interferometry
  - For the source, $R_\perp \approx R_\parallel \approx R$ is assumed
  - Gaussian wave-functions (size parameter = r_A) for nuclei are assumed → *see next slides*

$$B_A = \frac{2J_A+1}{2^A}\frac{1}{\sqrt{A}}\langle C_A\rangle \left(\frac{(2\pi)^{3/2}}{m_T\prod_{i=1,2,3}R_i}\right)^{A-1}$$

- The size of the source enters in the B_A and in the quantum-mechanical correction factor, $\langle C_A\rangle$
- $\langle C_A\rangle$ accounts for the size of the object being produced (r_A) → *see next slides*

$$\langle C_A\rangle = \prod_{i=1,2,3}\left(1+\boxed{\frac{r^2}{4R_i^2}}\right)^{-\frac{1}{2}(A-1)}$$

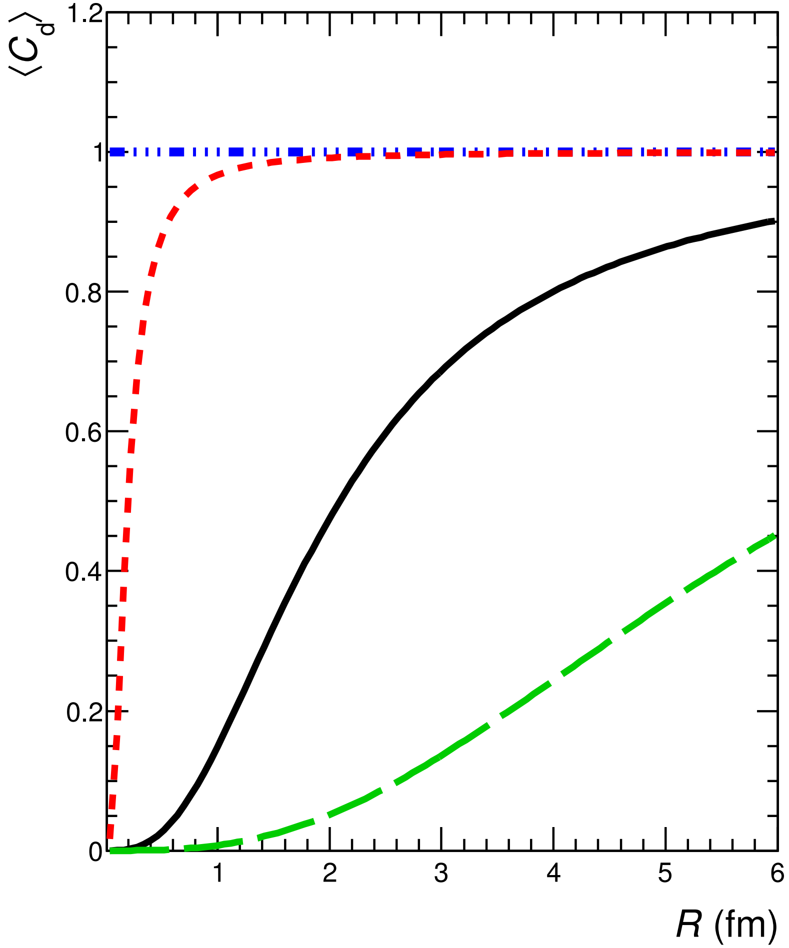
Length scale defined by the size of the object relative to the size of the system

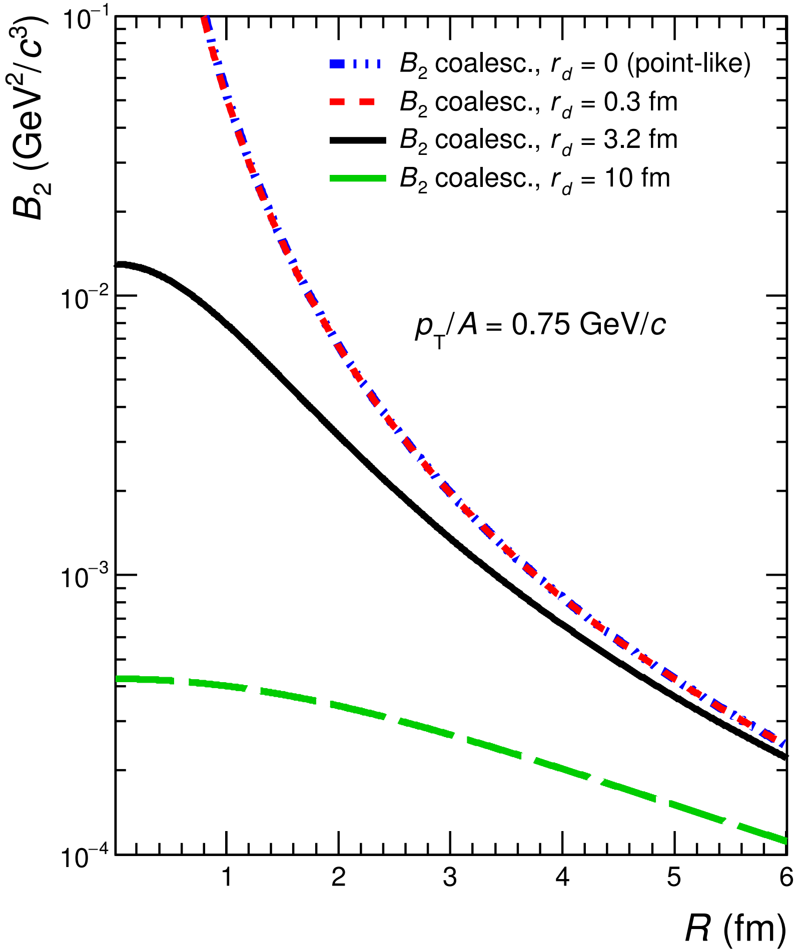
Deuteron case

F. Bellini, AK, arXiv:1807.05894

$$\langle C_d \rangle \approx \left[1 + \left(\frac{r_d}{2R(m_T)}\right)^2\right]^{-3/2}$$

$$B_2 = \frac{3\pi^{3/2}\langle C_d \rangle}{2m_T R^3(m_T)}$$





Coalescence model:
- analytic expression for B_A
- explicit dependence on R, r_A, m_T

$$\boxed{B_A = \frac{2J_A+1}{2^A}\frac{1}{\sqrt{A}}\frac{1}{m_T^{A-1}}\left(\frac{2\pi}{R^2+(\frac{r_A}{2})^2}\right)^{3/2(A-1)}}$$

Thermal model + blast-wave:
- Spectral shape of (hyper-)(anti-)nuclei and p from BW
- Normalization of spectra from thermal model
- Multiplicity → radius mapping from parameterization

$$\boxed{E_i\frac{\mathrm{d}^3N_i}{\mathrm{d}p_i^3} = B_A\left(E_\mathrm{p}\frac{\mathrm{d}^3N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3}\right)^A}$$

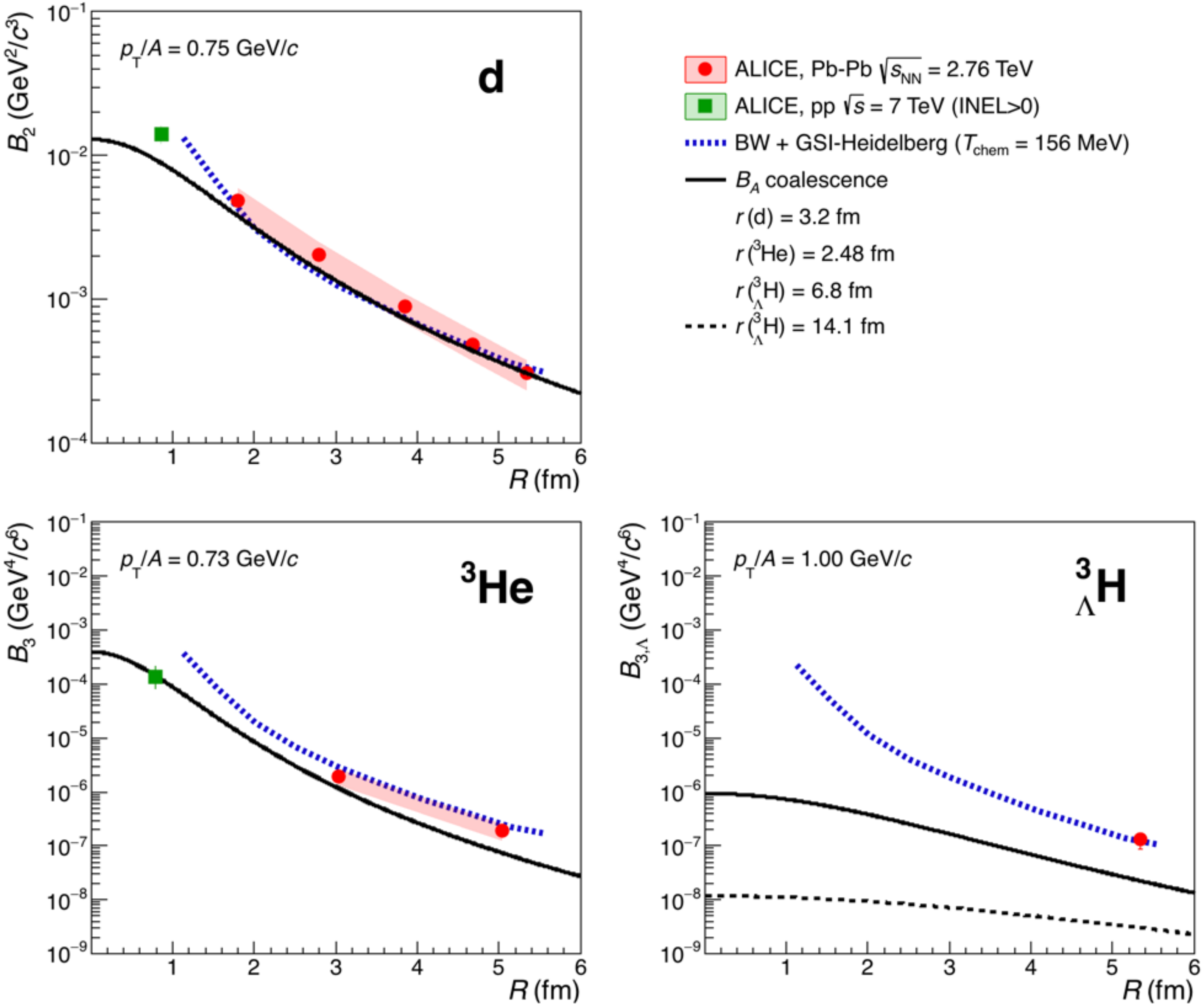
Data:
- B_A from measured (Hyper-)(anti-)nuclei and p spectra
- Multiplicity → radius mapping from parameterization

B_A vs R

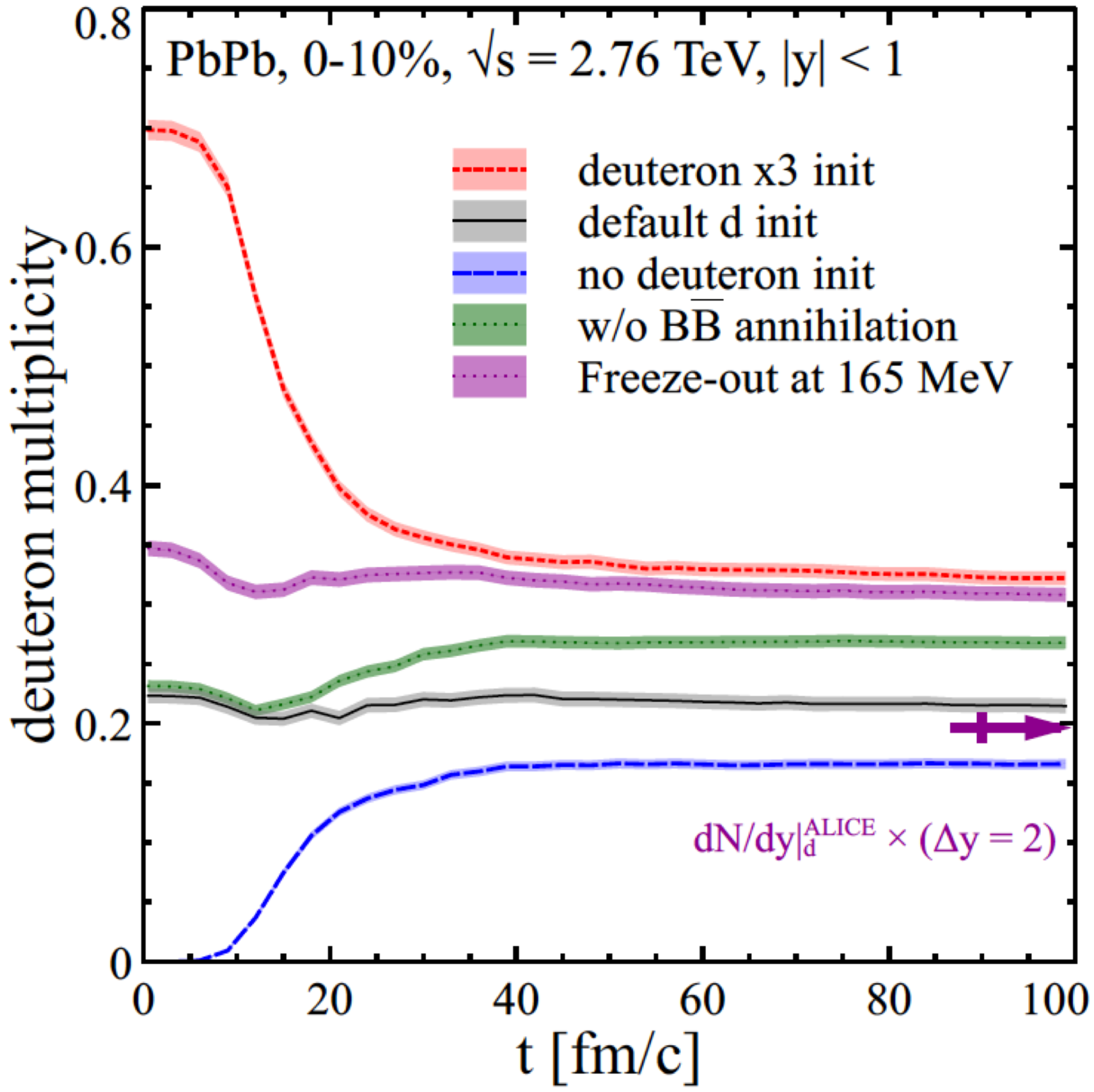
1. Thermal+BW and coalescence are fully consistent only for d and R > 1.6 fm, where they are also reproducing data

2. Difference between data and coalescence worsens for ^{3}He and $^{3}_{\Lambda}$H
   - *Wave function assumption?*
   - *Two-steps coalescence?*
   - *Excited state of the $^{3}_{\Lambda}$H?*

3. *$^{3}_{\Lambda}$H suppressed by about 2 orders of magnitude wrt ^{3}He in pp!*
   - Size of $^{3}_{\Lambda}$H?



It would be nice to see this for hyper-triton!

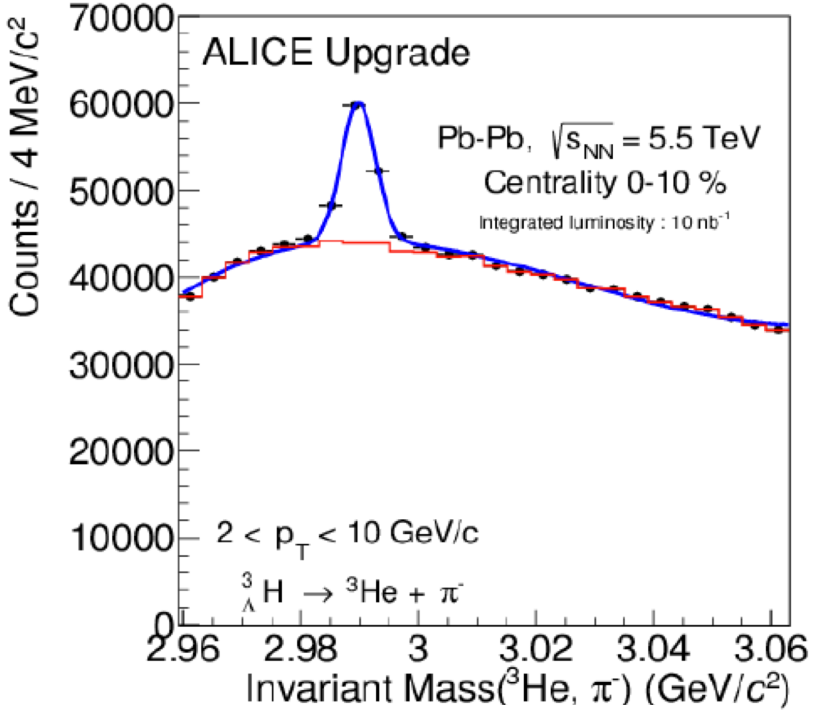


D. Ollichenko, Hot Quarks 2018 and respective publication.

Hyper-nuclei yield reach in Run 3+4

- High statistics sample of min bias Pb-Pb
- Improved tracking resolution from the ALICE ITS upgrade
- **$^{3}_{\Lambda}$H reconstruction** feasible in 2-body and 3-body decay with charged products
  - Lower background but also lower B.R. for 2-body

- B.R. not well known [1,2]
- precise evaluation of absorption cross section of $^{3}_{\Lambda}$H and ^{3}He is needed



ALICE ITS upgrade TDR, *CERN-LHCC-2013-024*

	Mass (GeV/c^2)	**Decay channel (B.R.)**	**d*N*/dy (SHM)**
$^{3}_{\Lambda}$H	2.991	**$^{3}_{\Lambda}$H → ^{3}He + π^- (25% [1])** $^{3}_{\Lambda}$H → d + p + π^- (41% [1])	1 x 10^{-4}
$^{4}_{\Lambda}$H	3.931	$^{4}_{\Lambda}$H → ^{4}He + π^- (50% [1])	2 x 10^{-7}
$^{4}_{\Lambda}$He	3.929	$^{4}_{\Lambda}$He → ^{3}He + p + π^- (32% [2])	2 x 10^{-7}

[1] H. Kamada et al., PRC 57, 1595 (1998), [2] H. Outa et al., NPA 639 (1998) 251-260

Outlook to LHC Run 3 and 4

The measurement of the **coalescence parameters** for composite objects with **different sizes** studied as a function of the **multiplicity** can be used to compare the light (anti-)(hyper-)nuclei production scenarios

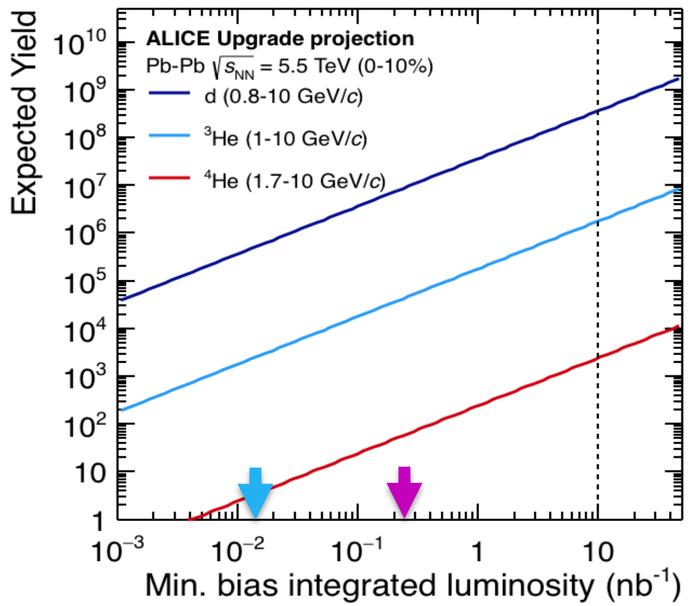
Physics case for Run3&4:

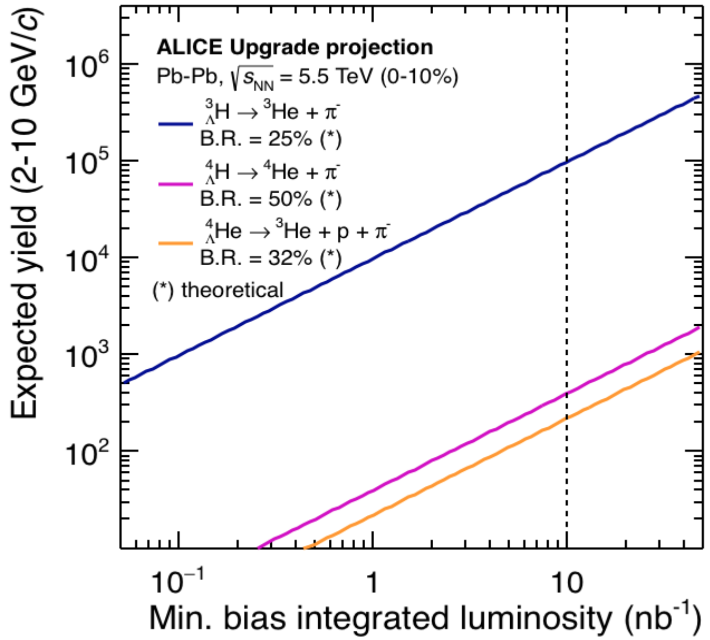
→ Measure centrality dependence of the hypertriton in Pb-Pb

→ Can we produce at all the hypertriton in pp collisions?

→ Go more differential for A = 3

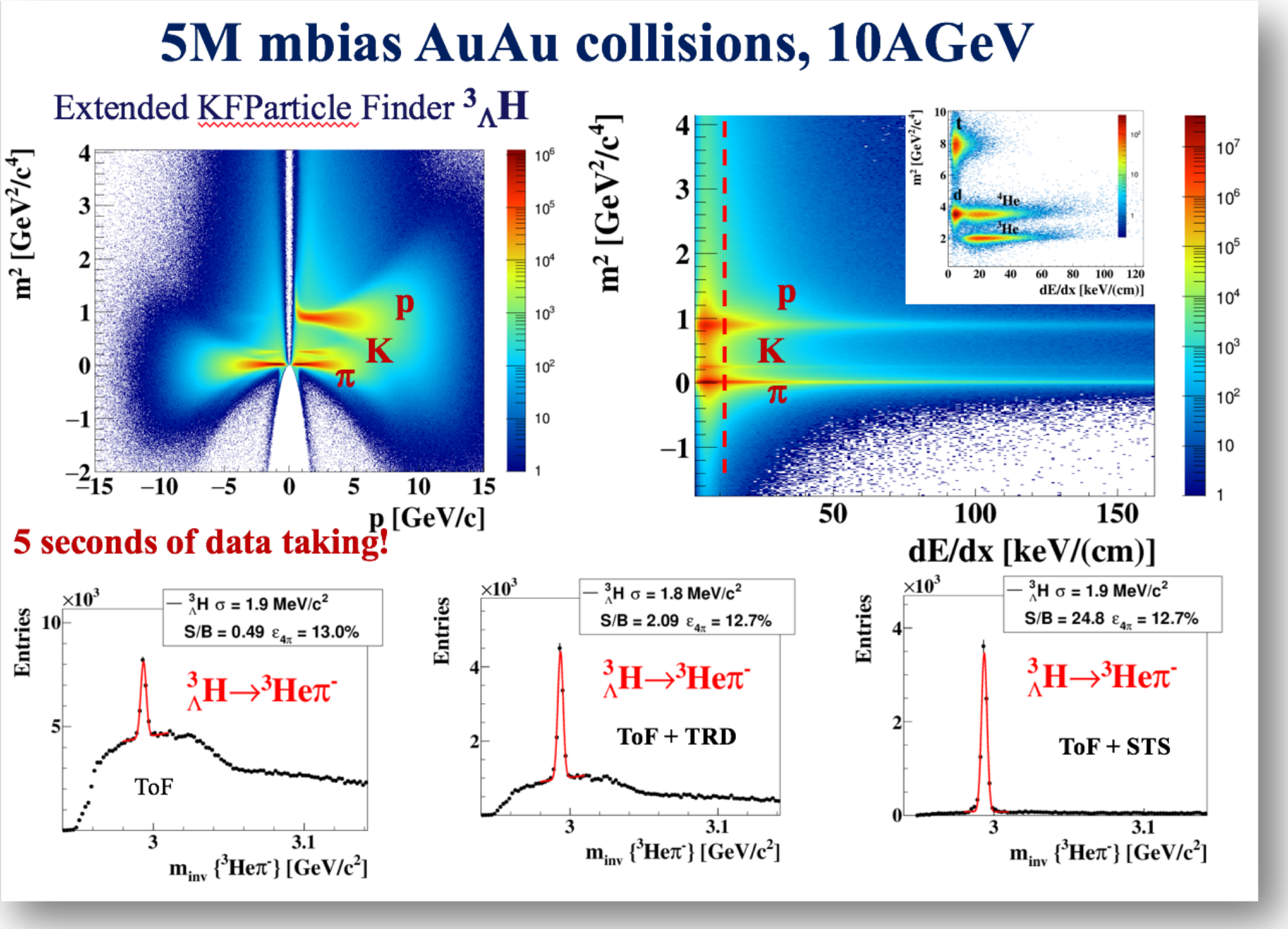
→ Measure B_4 for ^{4}He, $^{4}{}_{\Lambda}$H, $^{4}{}_{\Lambda}$He

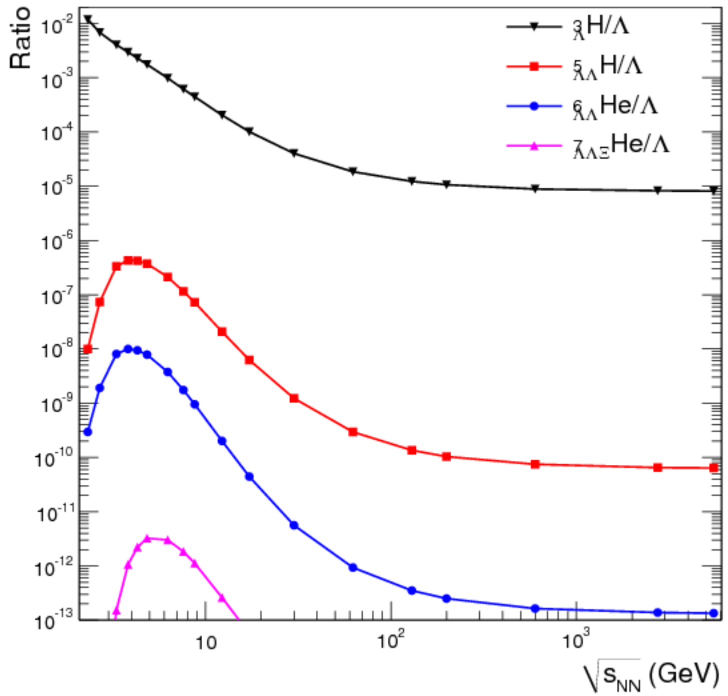




Possibilities at FAIR

- Largest production probability of hyper-nuclei is at FAIR energies.
- See excellent talk of I. Vassiliev at EMMI Torino workshop:
  https://indico.gsi.de/event/6301/session/2/contribution/5/material/slides/0.pptx





A. Andronic et al:
Phys.Lett. B697 (2011) 203-207

Summary and conclusions

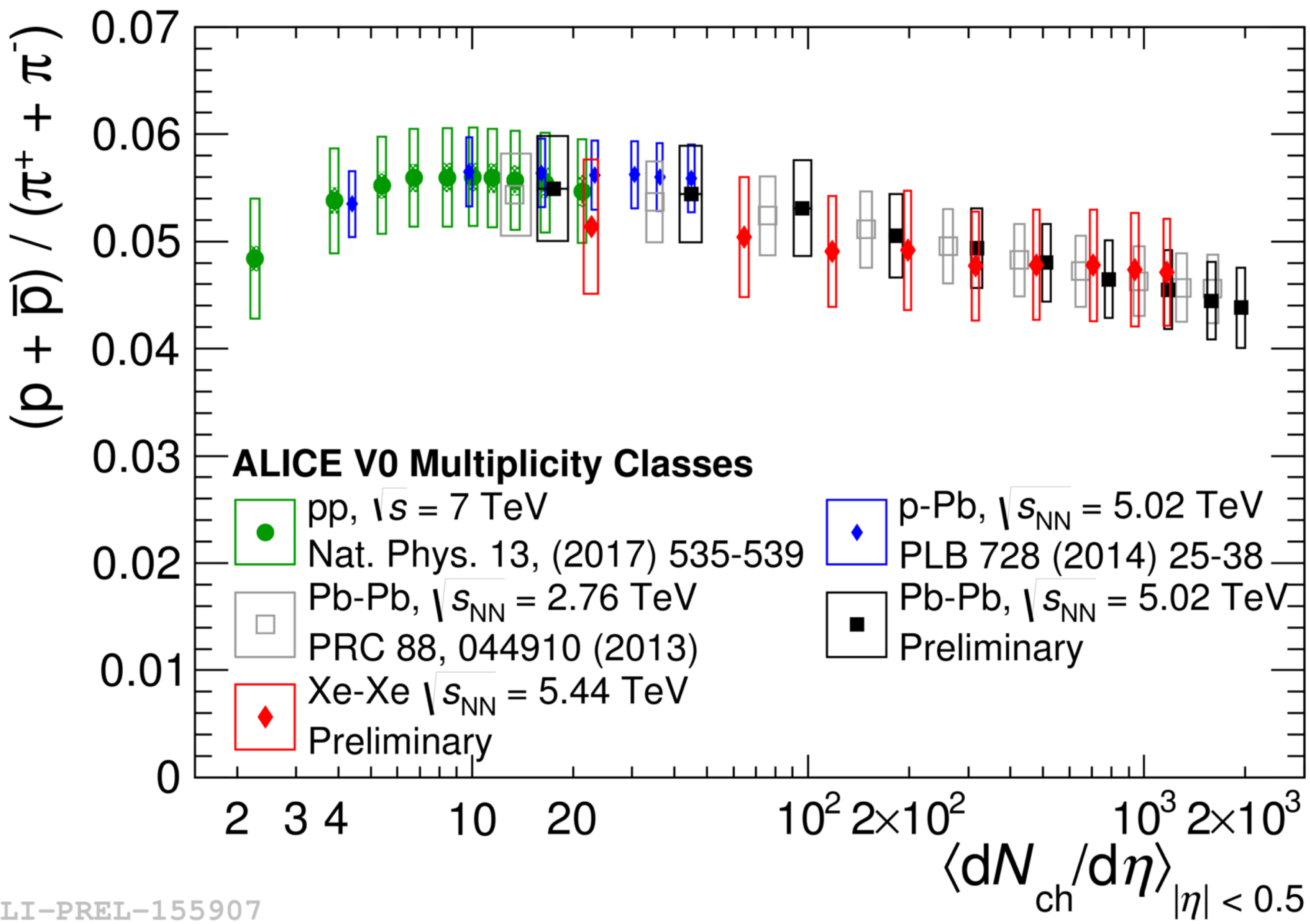
Summary and conclusions

- ALICE has measured a wealth of results on the production of light favor hadron production.

- Beautiful picture established in central heavy-ion collisions, but there is still a lot to do and to understand at *several frontiers:*
  - Anti- and hyper-nuclei production
  - Small systems and the phi meson
  - Intermediate p_T

Thank you!

Proton-to-pion ratio



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