Strangeness and nuclei production in nuclear collisions

Stefania Bufalino - Politecnico and INFN Torino

Outline

- **Physics motivations: what can we learn?**

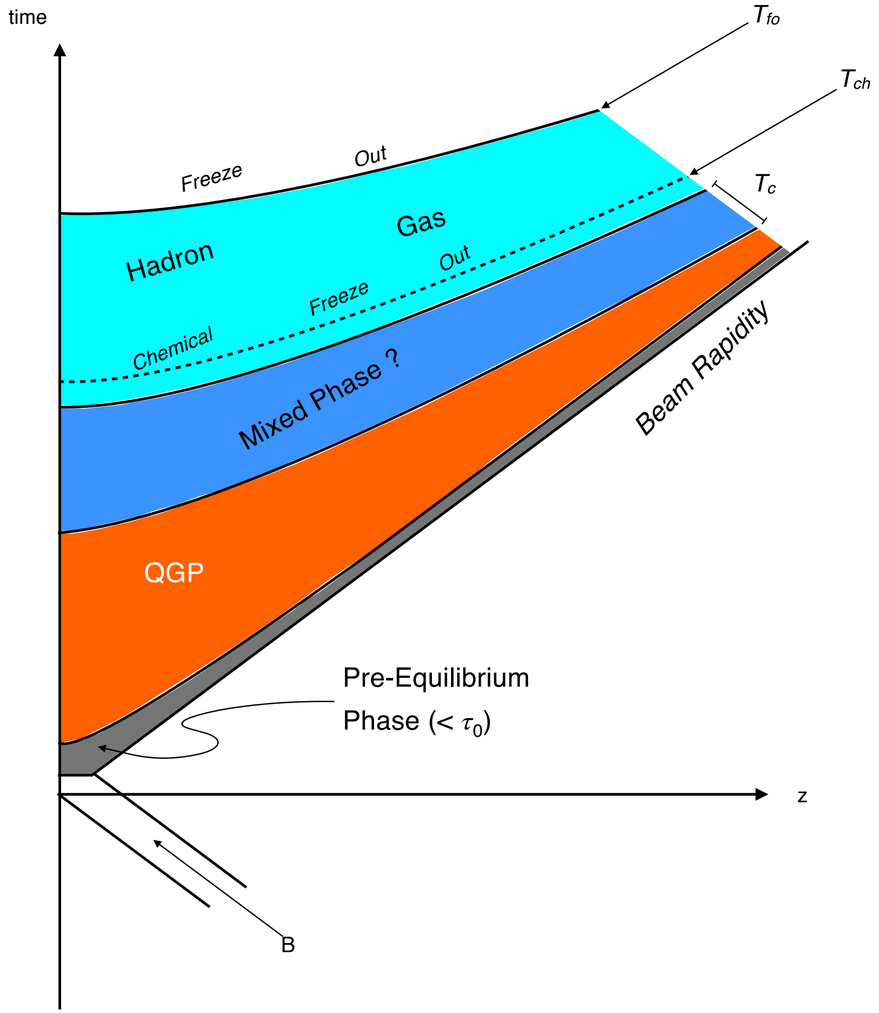
- **Strangeness as QGP signature: from SPS to LHC**
  - enhancement in small systems and model comparison;
  - elliptic flow at RHIC and at the LHC.

- **Light (anti-)nuclei production**
  - p_T spectra and coalescence parameters from ALICE, STAR and HADES;
  - model comparison.

- **(Anti-)hypernuclei in heavy-ion collisions**
  - lifetime measurement from STAR and ALICE;
  - CPT symmetry test via mass difference measurement.

- **Conclusions**

Motivation for strangeness physics



1982 (Rafelski, Muller): Strangeness enhancement relative to elementary collisions proposed as smoking gun for **QGP formation**

- Lower Q-value for $s\bar{s}$ relative to $HsH\bar{s}$ formation
- Faster equilibration in partonic medium

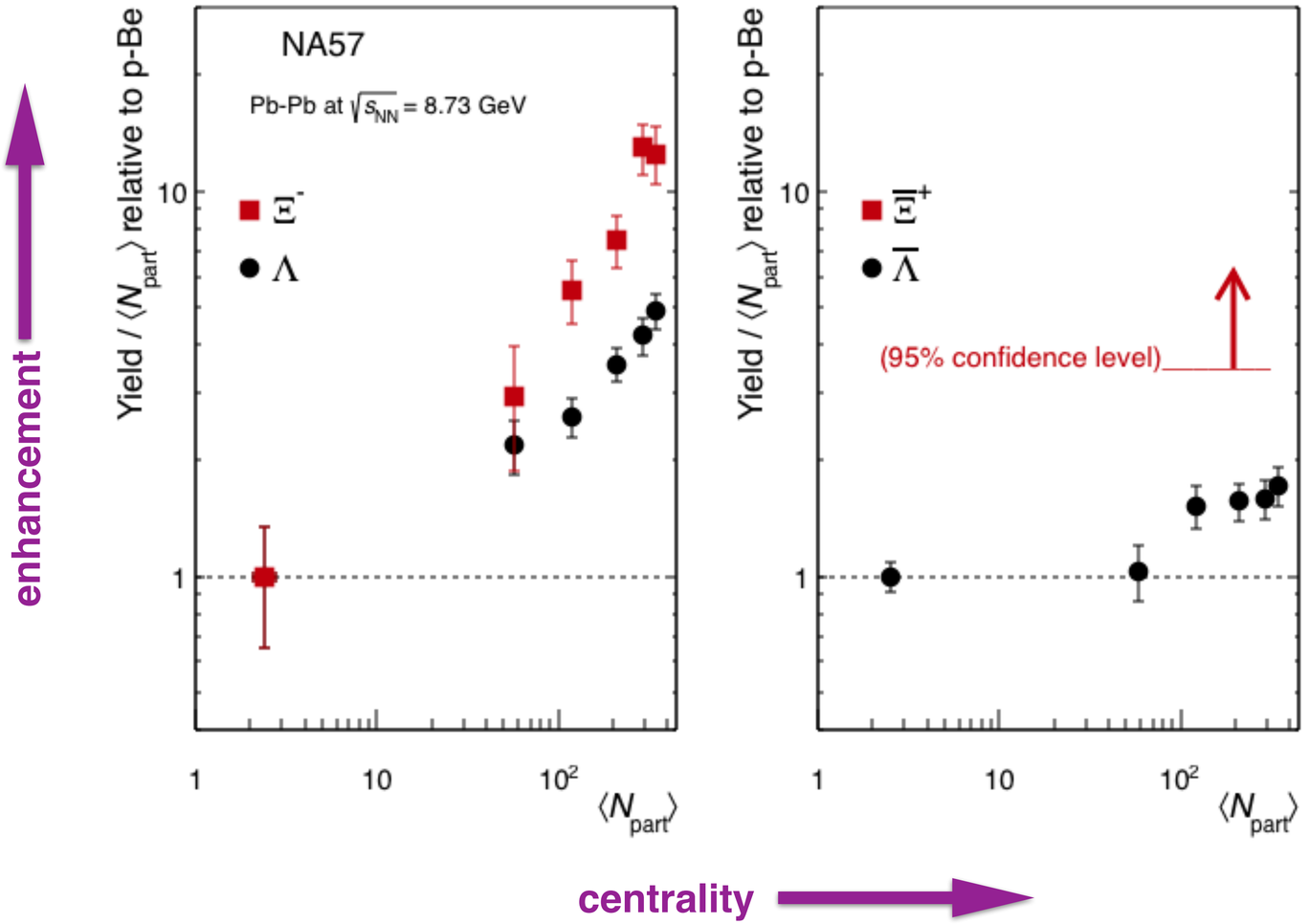
Statistical Hadronization Model describes well hadron formation for very different colliding systems and energies

BUT

What is the microscopical underlying mechanism which brings the system to enhance strangeness?

Can we anyway infer something about the QGP?

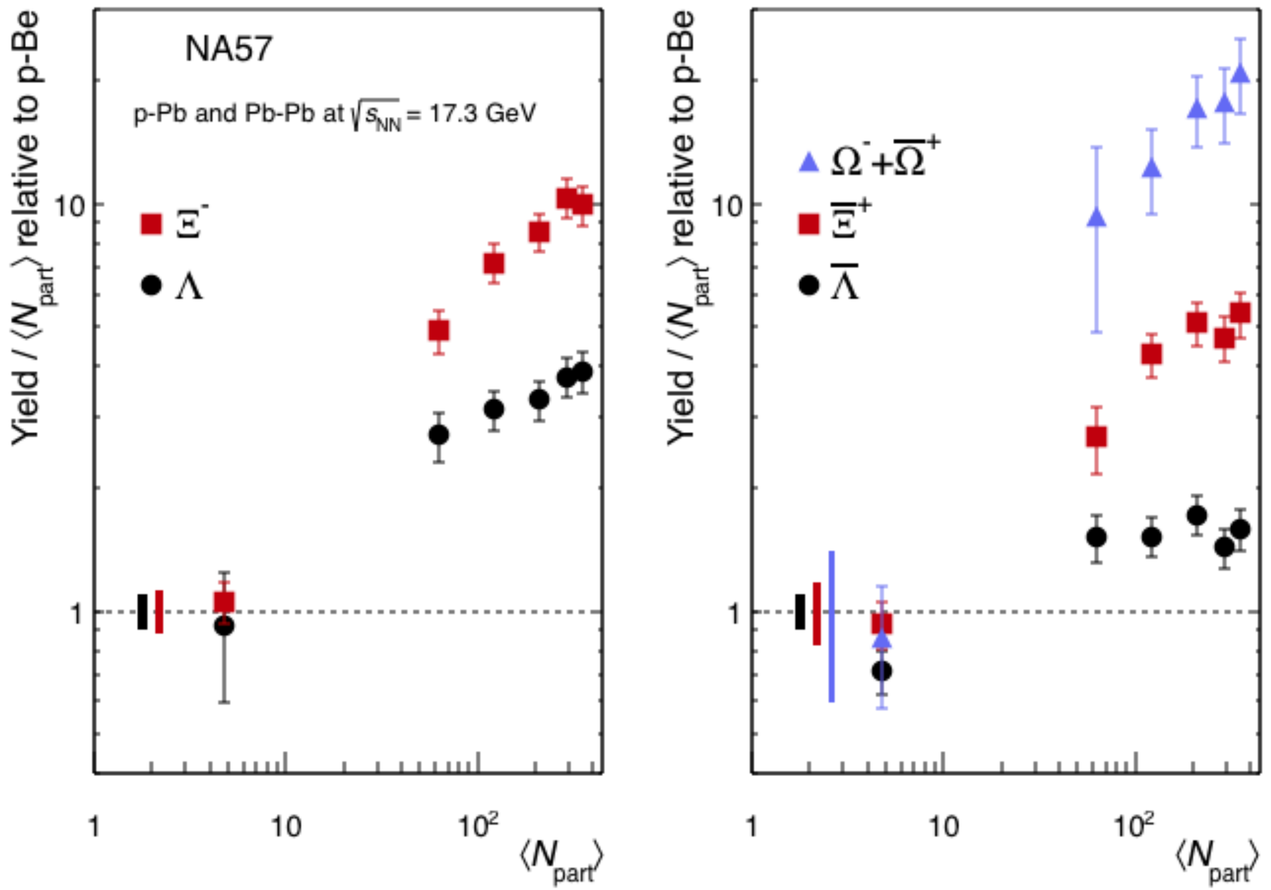
Strangeness enhancement: QGP signature at SPS



- Pb-Pb at SPS - $\sqrt{s_{NN}} = 8.73\ \mathrm{GeV}$
- Higher enhancement when
  - centrality increases
  - the numbers of strange valence quark is higher

NA57 Collaboration, arXiv:1001.1884
J. Phys. G 37 (2010) 045105

Strangeness enhancement: QGP signature at SPS



enhancement

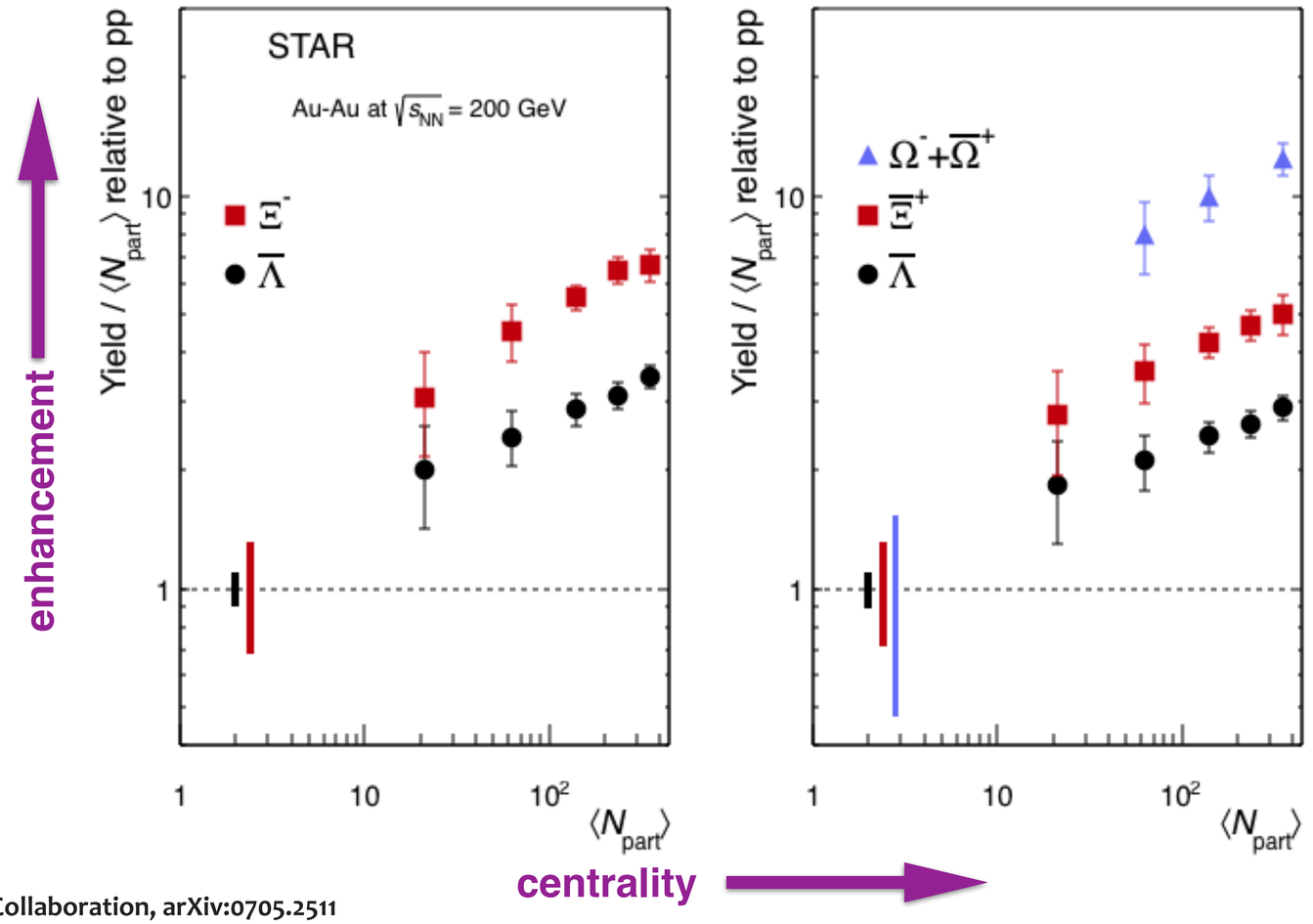
centrality

NA57 Collaboration, nucl-ex/0601021
J. Phys. G 32 (2006) 427

- Pb-Pb at SPS - $\sqrt{s_{NN}} = 8.73$ GeV
- Pb-Pb at SPS - $\sqrt{s_{NN}} = 17.3$ GeV

- Higher enhancement with increasing centrality and when baryons contain a higher numbers of strange valence quark confirmed

Strangeness enhancement: QGP signature at RHIC



STAR Collaboration, arXiv:0705.2511
Phys. Rev. C 77 (2008) 044908

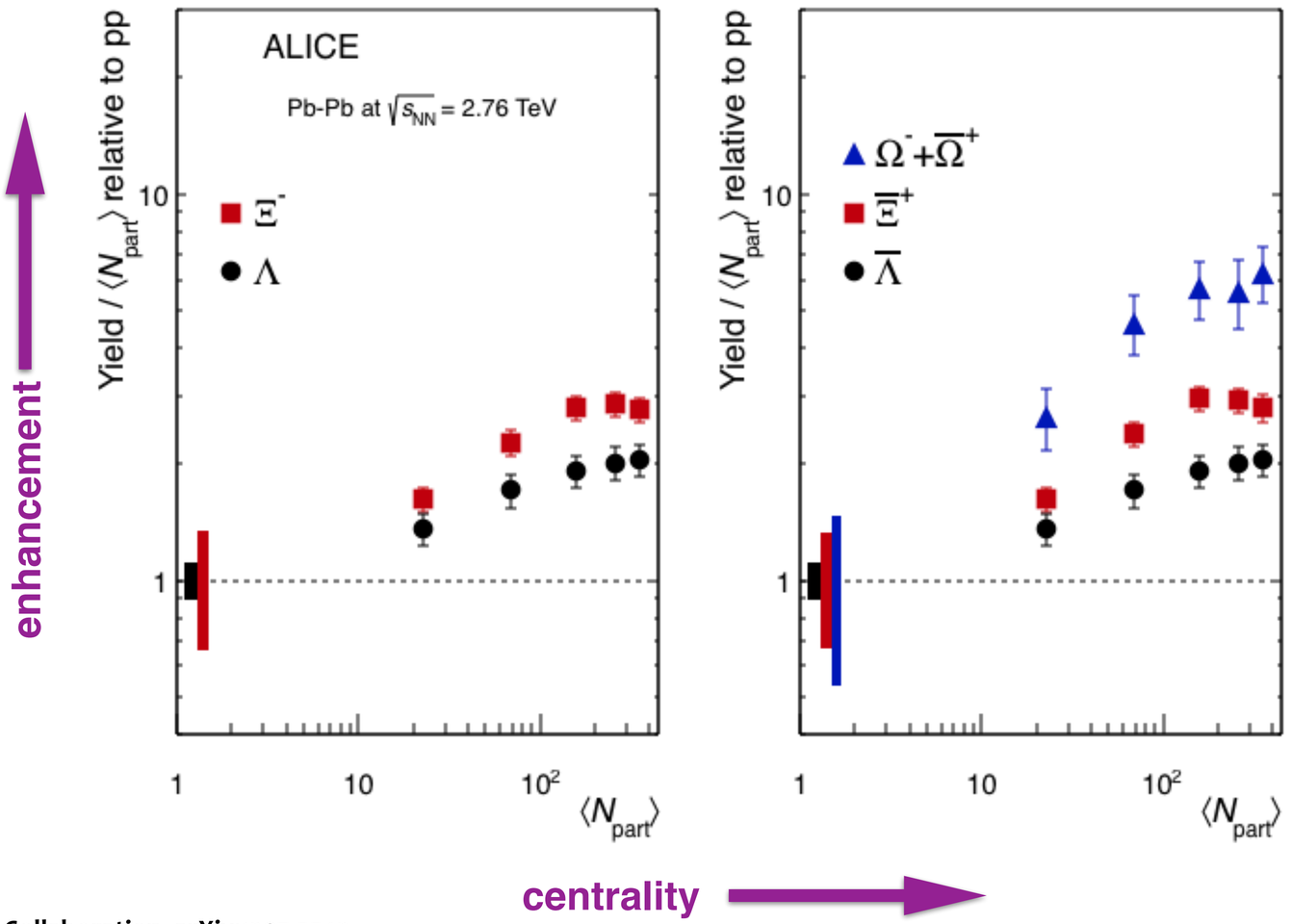
- Pb-Pb at SPS - $\sqrt{s_{NN}} = 8.73$ GeV
- Pb-Pb at SPS - $\sqrt{s_{NN}} = 17.3$ GeV
- Au-Au at RHIC - $\sqrt{s_{NN}} = 200$ GeV

RHIC results confirm the picture:

➡ higher statistics (more precise results) and wider centrality range

➡ BUT: slightly lower enhancement (x15 for the Ω w.r.t. a x20 factor measured at SPS)

Strangeness enhancement: QGP signature at the LHC

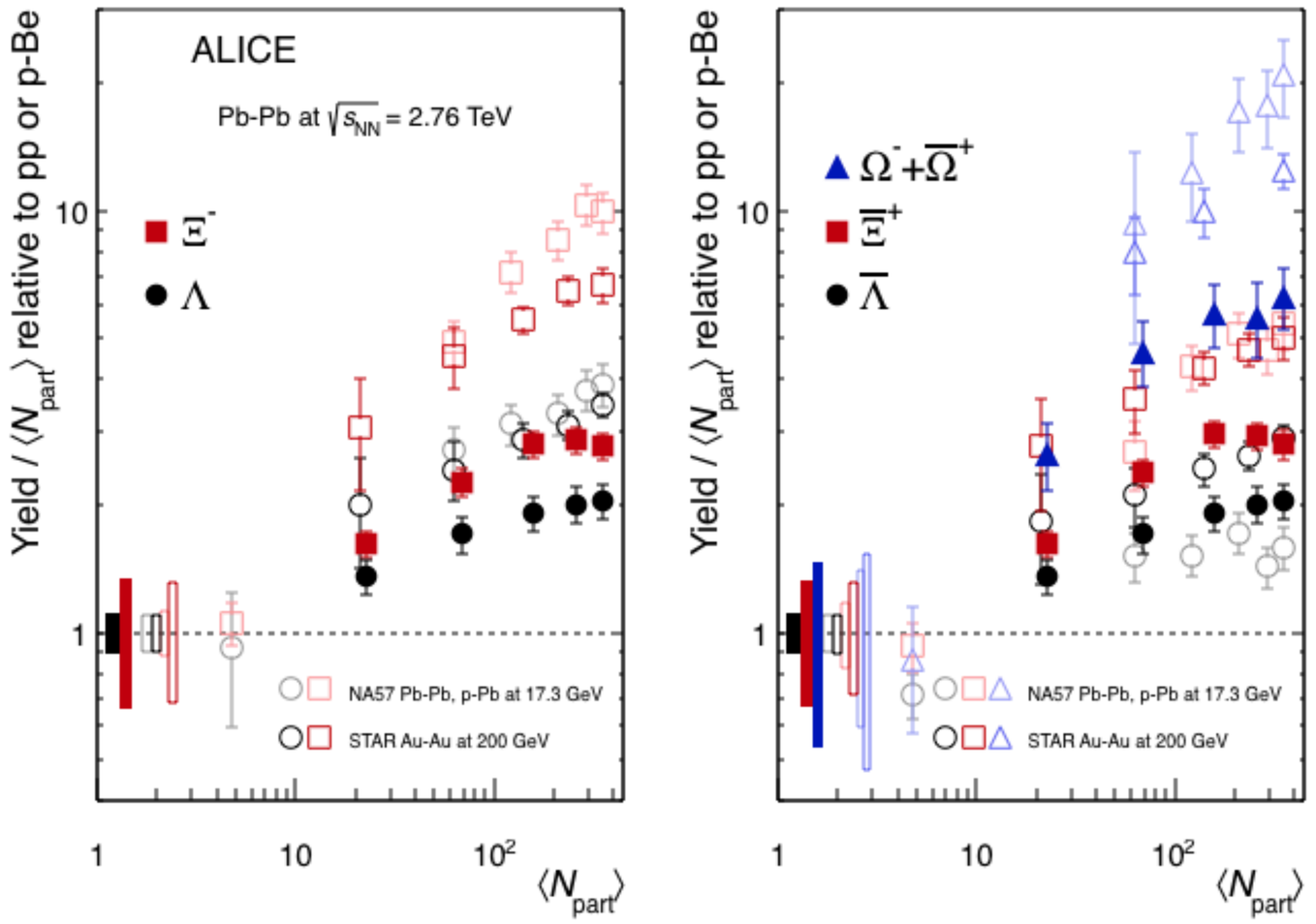


- Pb-Pb at SPS - $\sqrt{s_{NN}} = 8.73$ GeV
- Pb-Pb at SPS - $\sqrt{s_{NN}} = 17.3$ GeV
- Au-Au at RHIC - $\sqrt{s_{NN}} = 200$ GeV
- Pb-Pb at the LHC - $\sqrt{s_{NN}} = 2.76$ TeV

At higher energy confirmed the lower enhancement (x6 for the Ω) observed at RHIC

ALICE Collaboration, arXiv:1307.5543
Phys. Lett. B 728 (2014) 216

Strangeness enhancement: QGP signature

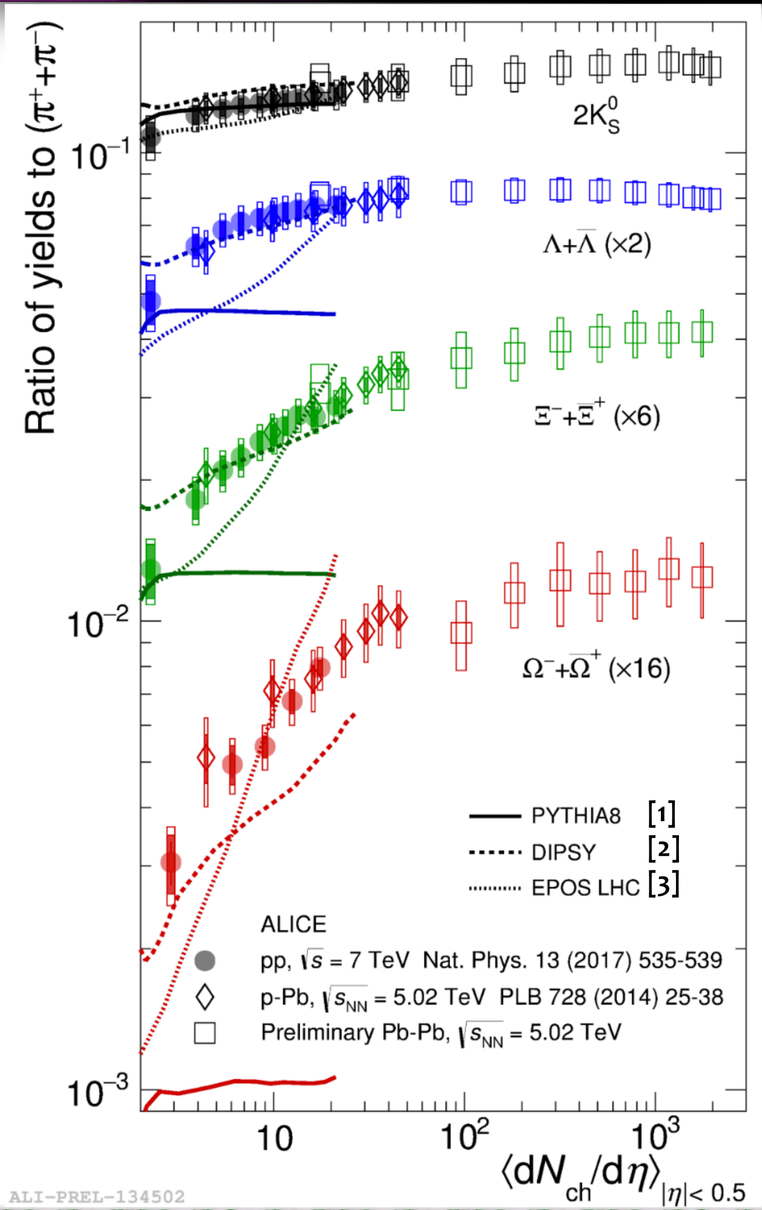


ALICE Collaboration, arXiv:1307.5543
Phys. Lett. B 728 (2014) 216

- Pb-Pb at the LHC - $\sqrt{s_{NN}} = 2.76$ TeV
- Au-Au at RHIC - $\sqrt{s_{NN}} = 200$ GeV
- Pb-Pb at SPS - $\sqrt{s_{NN}} = 17.3$ GeV
- Pb-Pb at SPS - $\sqrt{s_{NN}} = 8.75$ GeV

- Hyperon hierarchy predicted as a signature for QGP confirmed at different energy regimes
- Lower enhancement when collision energy increases

Strangeness enhancement: from small systems to Pb-Pb



- Enhanced production of **strange and multi-strange particles** observed in high-multiplicity pp collisions
- multiplicity dependence of strangeness production is **strikingly similar in pp and p-Pb** and follow the trend of the values corresponding to central Pb-Pb

- MC predictions do not describe satisfactorily the experimental data

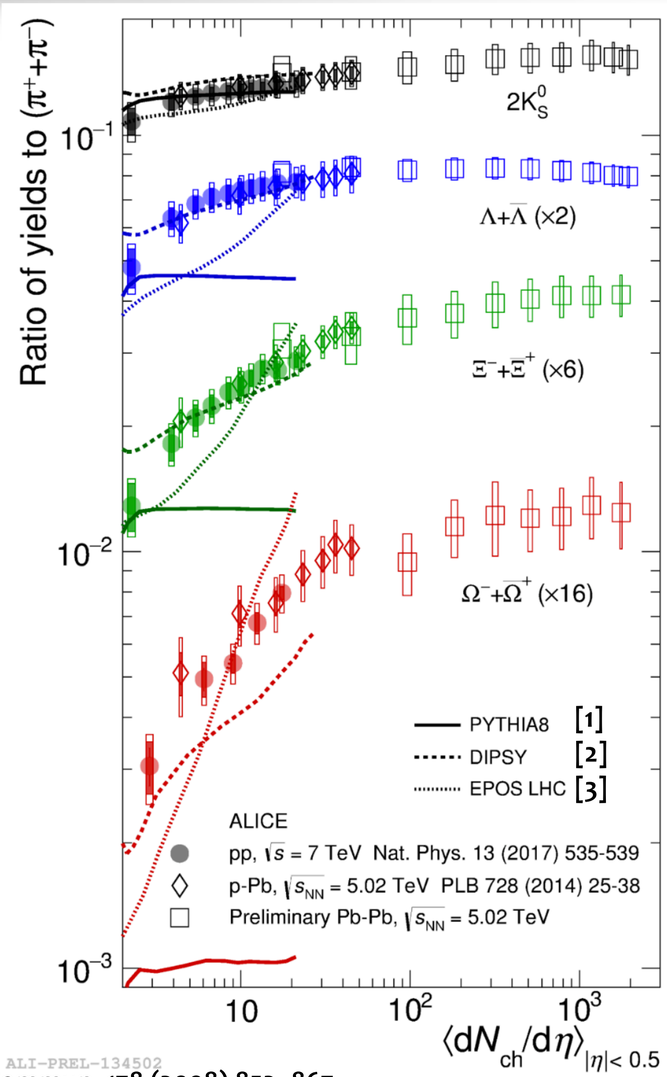
➡ strong disagreement with **PYTHIA8** → Color Reconnection among Multiple Parton Interactions does not help

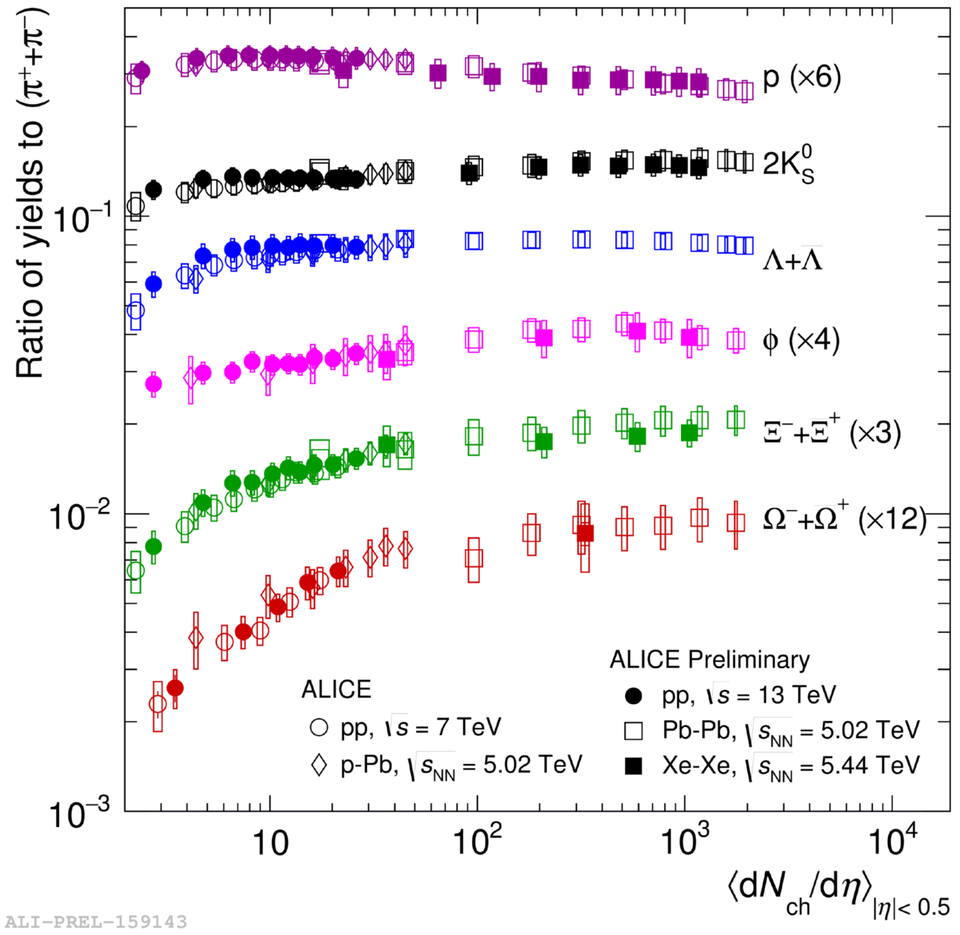
➡ **EPOS LHC** → does not match the data straight away

➡ better agreement with **DIPSY** → BUT deviation for Ω and too much stress on baryon production

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

Strangeness enhancement at the LHC top energy



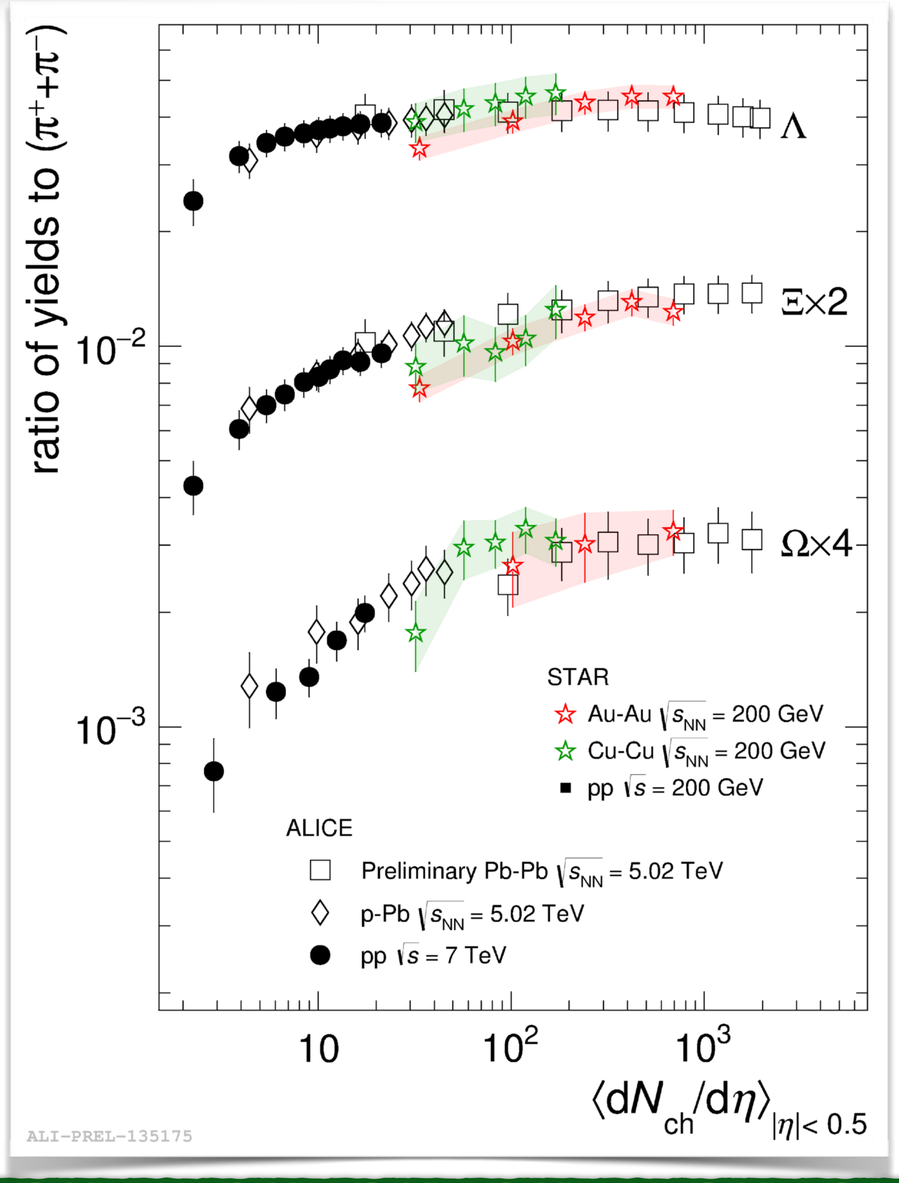


Latest news

Wrap up of measurements available so far: new results from LHC-Run2 for **pp collisions at 13 TeV** and **Xe-Xe collisions at 5.44 TeV**

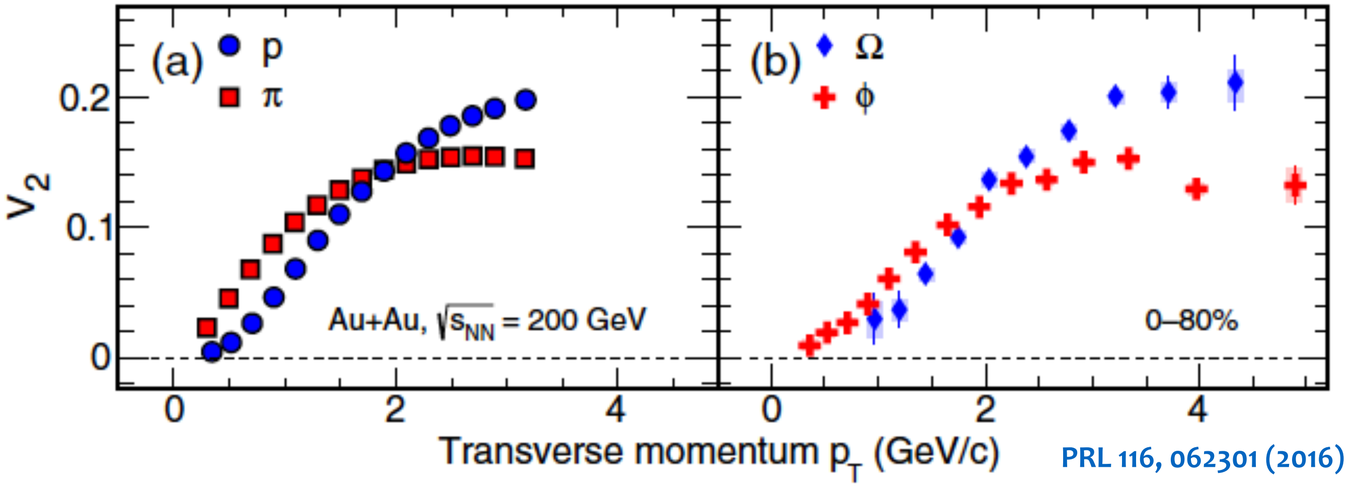
[1] Comput. Phys. Commun. 178 (2008) 852–867
[2] JHEP 08 (2011) 103
[3] Phys. Rev. C 92, 034906 (2015)

Strangeness enhancement: LHC vs RHIC



- High precision measurement at the **LHC** in fair agreement with **STAR** results at high multiplicity
- **Only multiplicity plays a role?** neither energy nor system dependence observed
- Measurements in small system at RHIC could help to understand the experimental hints

v_2 measurements with STAR



PRL 116, 062301 (2016)

- Same v_2 features observed for **strange and non-strange** hadrons
  - mass ordering
  - baryon/meson splitting

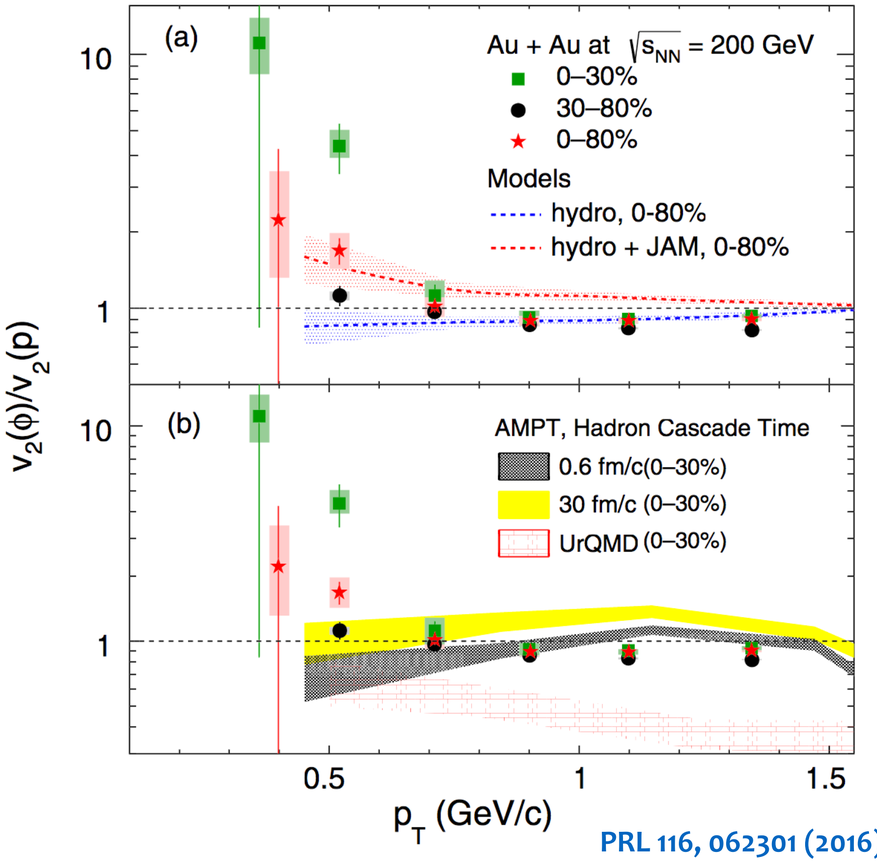
Considering the cross section

—> v_2 driven by initial spatial anisotropy

Data favours hydro at low p_T and coalescence at mid-p_T

- Larger ratio at low p_T: mass ordering breakdown
- comparison with models (0-30%): with increasing hadronic cascade time, the v2(ϕ)/v2(p) ratio increases

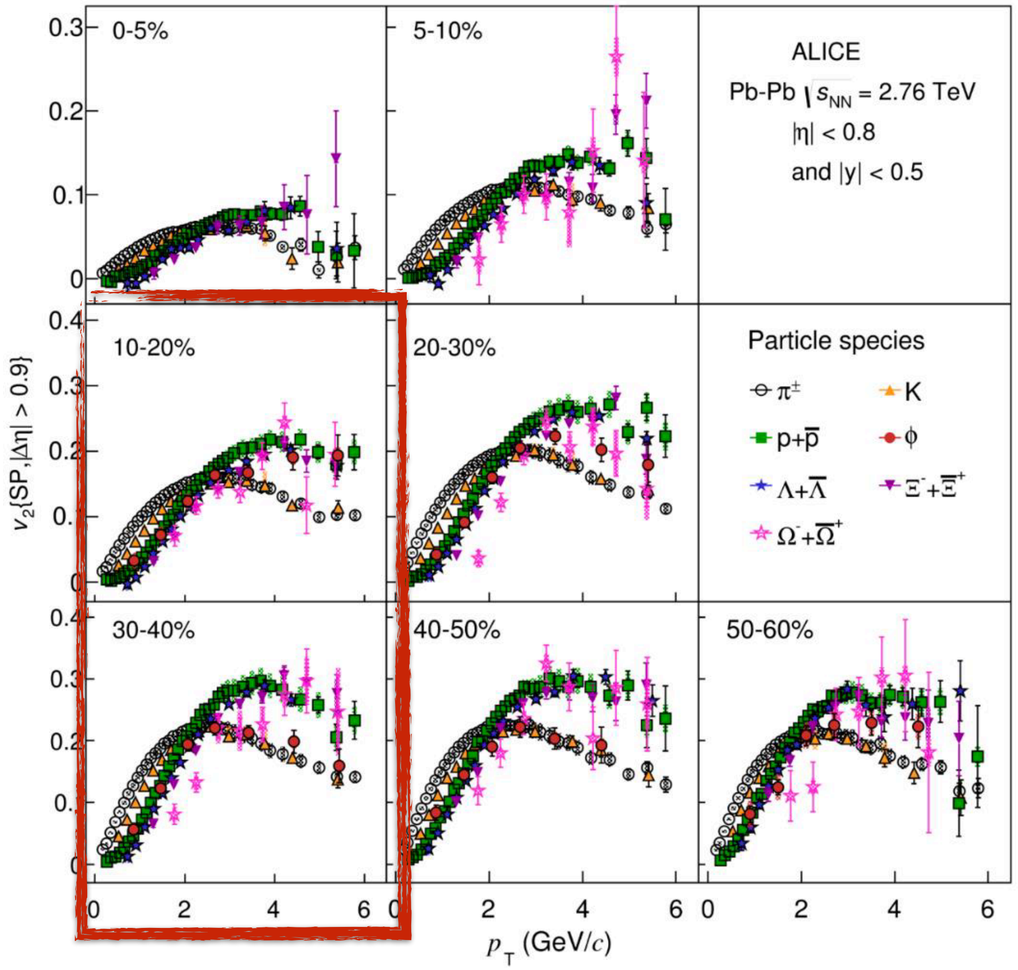
-> more hadronic rescattering for protons?



PRL 116, 062301 (2016)

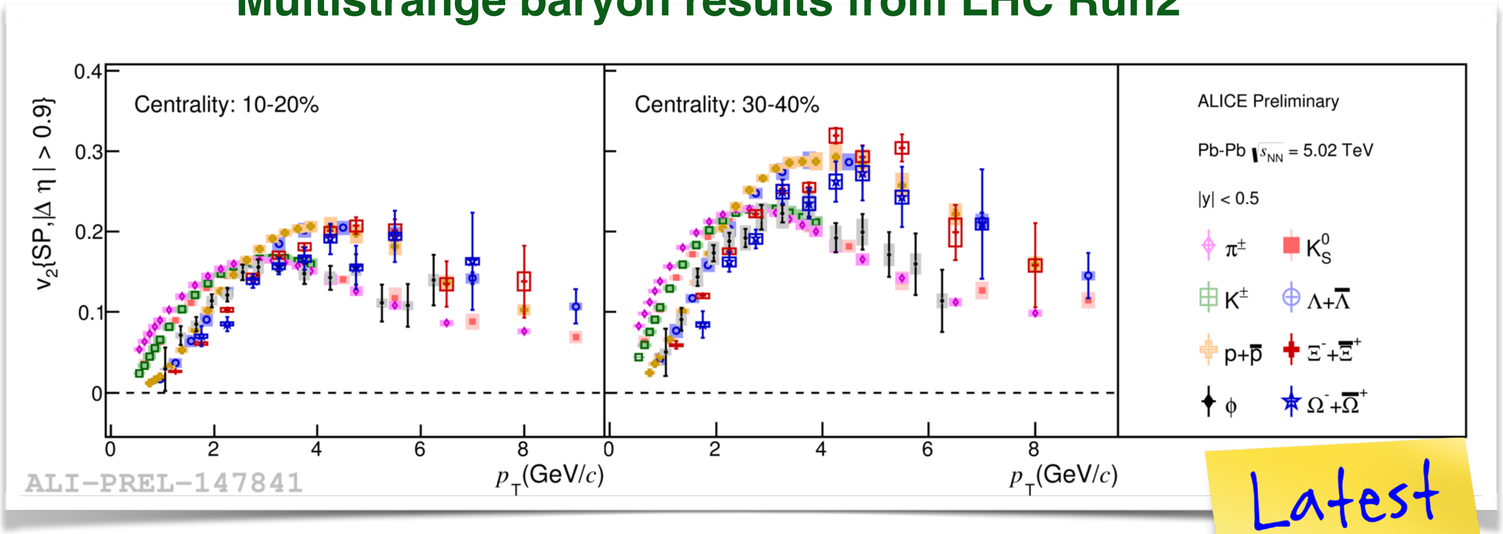
v_2 measurements with ALICE

LHC Run1



JHEP 06 (2015) 190

Multistrange baryon results from LHC Run2



Latest news

- Extended kinematic range of the measurement.
- Mass ordering for p_T < 2 GeV/c.
- Error reduced: better constraint off the theoretical models.
- Run 1 trend confirmed.

Data favours hydro at low p_T and coalescence at mid-p_T

Matter and hyper-matter in URHIC

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Thermal Model

Coalescence Model

Matter and hyper-matter in URHIC

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 $\mathrm{yield} \propto e^{-M/T_{\mathrm{chem}}}$
- The model depends only on T, V and μ_B, which is ~0 at the LHC

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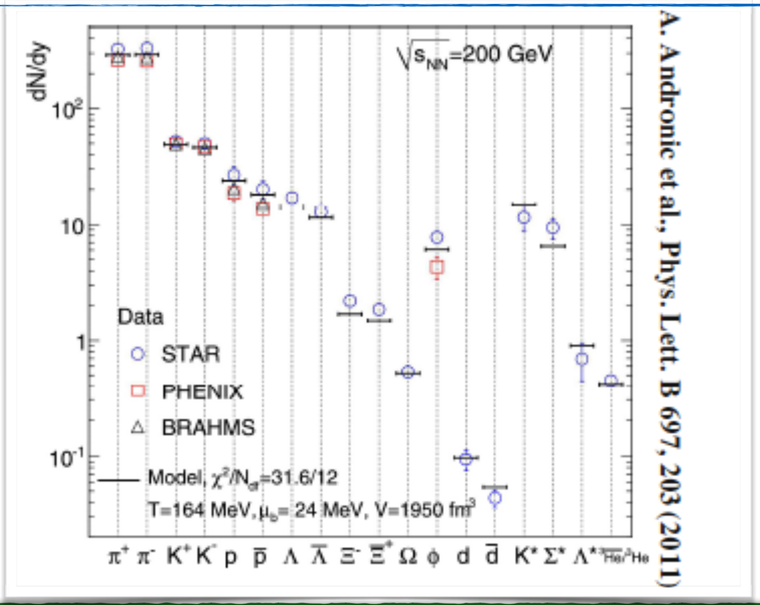

A. Andronic et al., Phys. Lett. B 697, 203 (2011)

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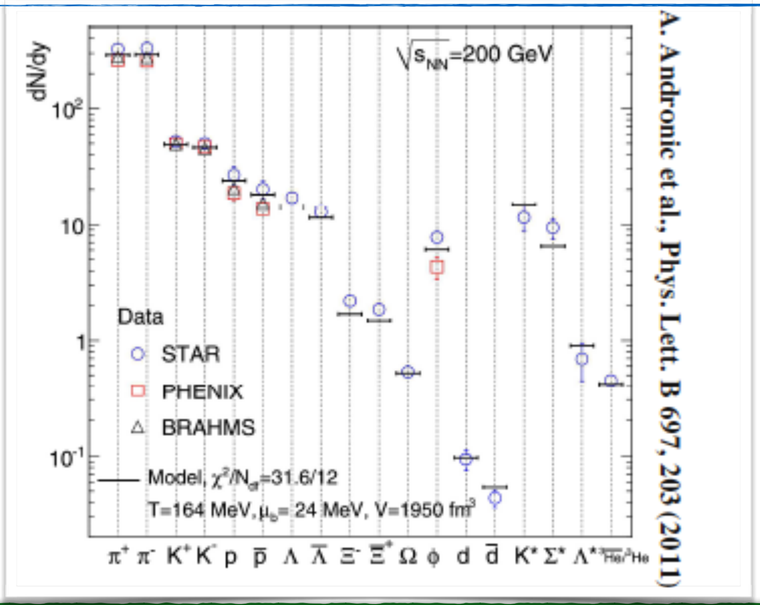

Coalescence Model

- 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

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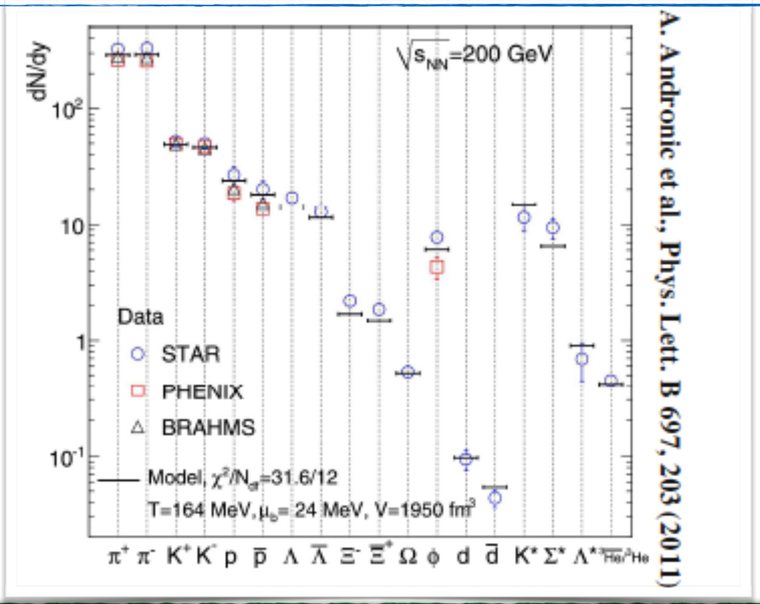

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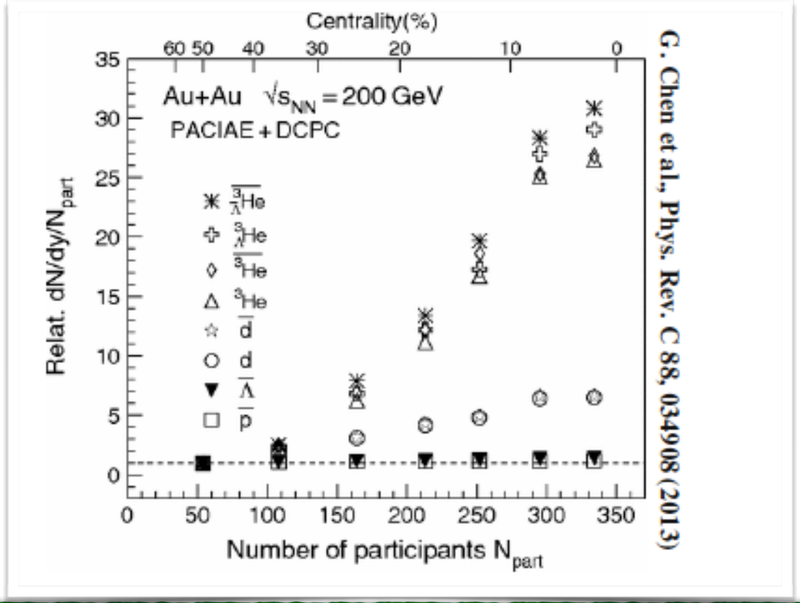
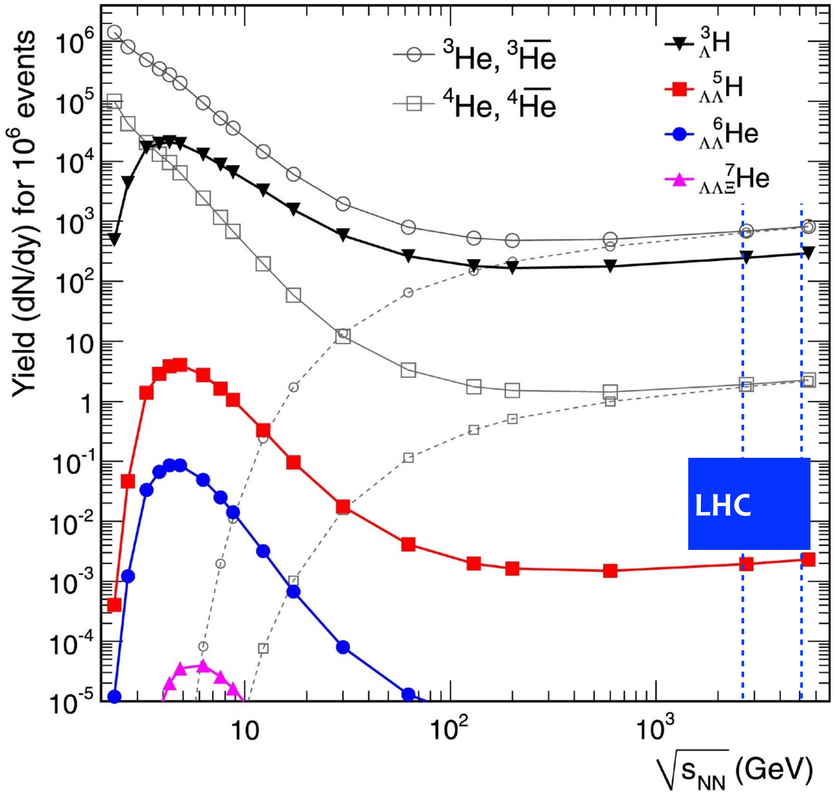
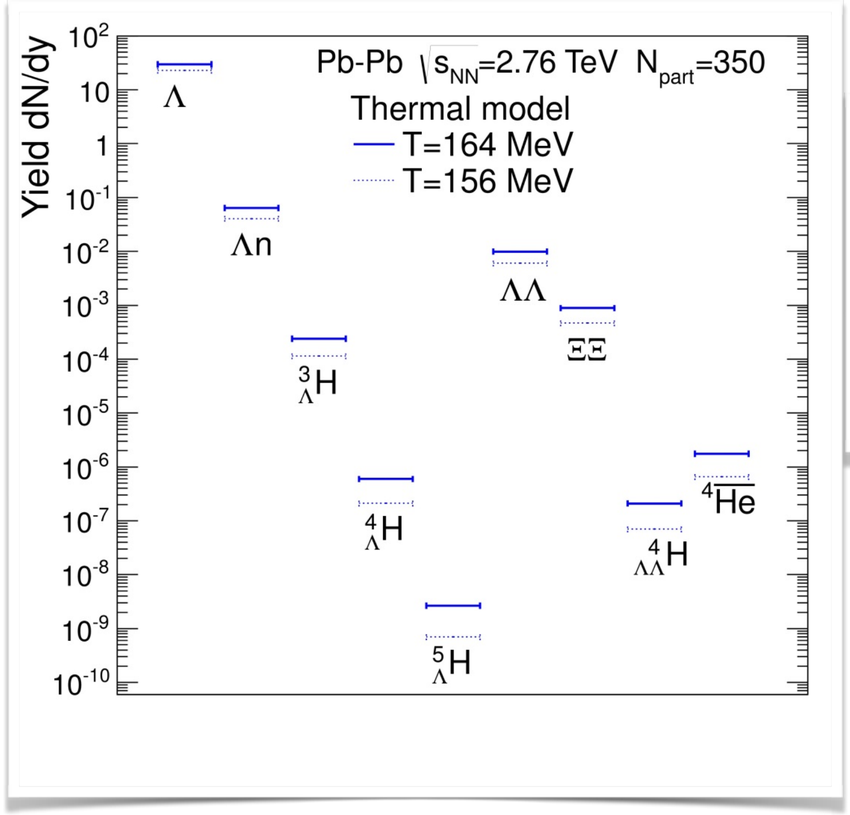


Matter and hyper-matter at the LHC

- Hadrons emitted from the interaction region in statistical equilibrium once the *chemical freeze-out* temperature is reached.
- Production yields estimation for central heavy-ion collisions at LHC energies



Andronic, P. Braun-Munzinger, J. Stachel, H. Stocker. - *Phys. Lett. B* 697, 203 (2011)



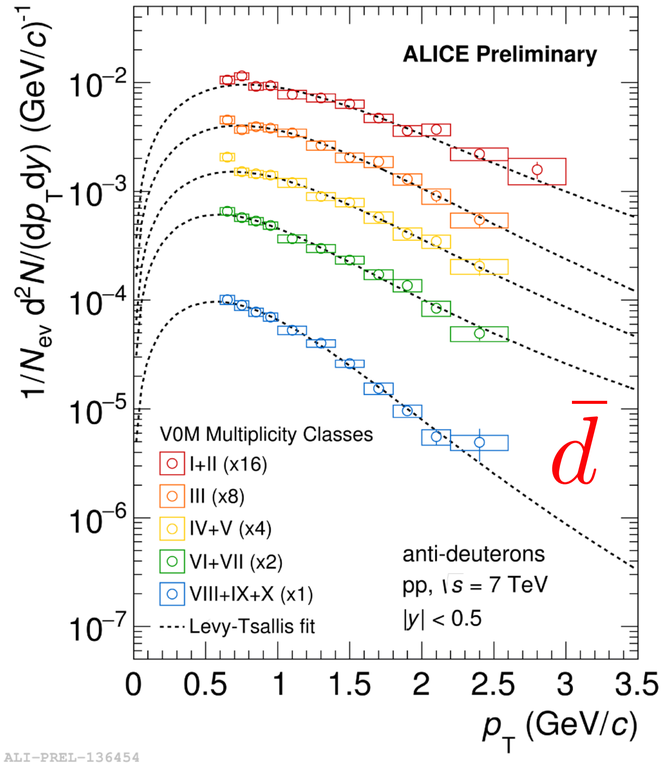
	Yield/event at mid-rapidity and central collisions
π	~800
p	~40
Λ	~30
d	~0.17
^{3}He	~0.01
$^3_\Lambda$H	~0.003

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

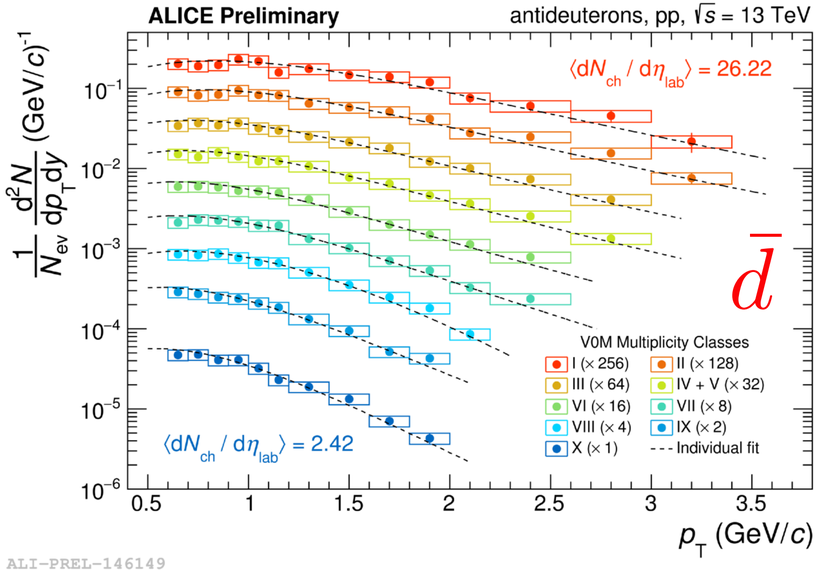
(Anti-)nuclei production in small systems

Latest news

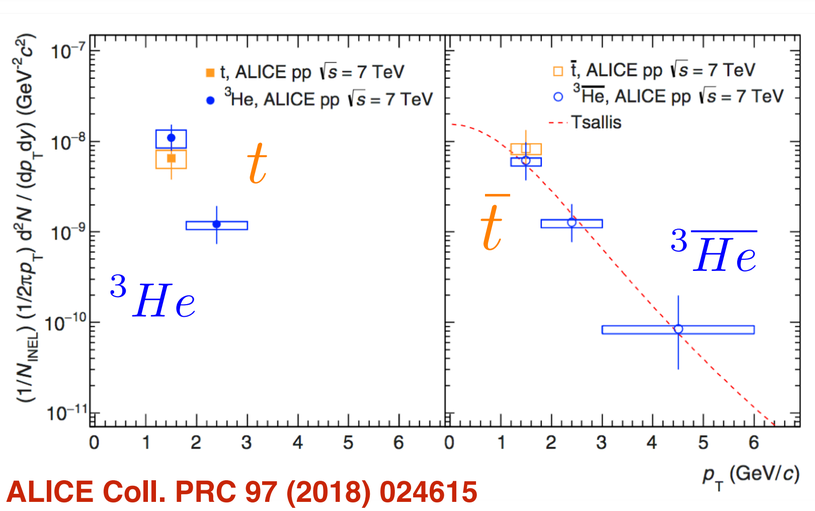
New results from LHC- Run2 at 7 TeV and 13 TeV vs multiplicity and first ever observation of anti-^{3}He in pp collisions from LHC-Run1 data



ALI-PREL-136454



ALI-PREL-146149

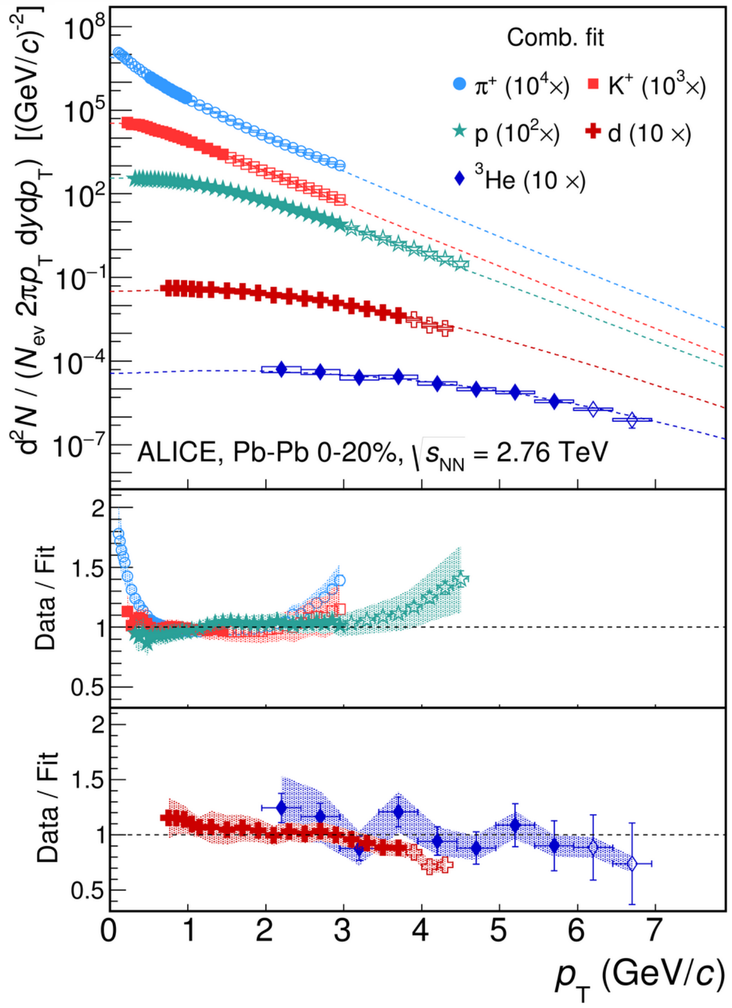


ALICE Coll. PRC 97 (2018) 024615

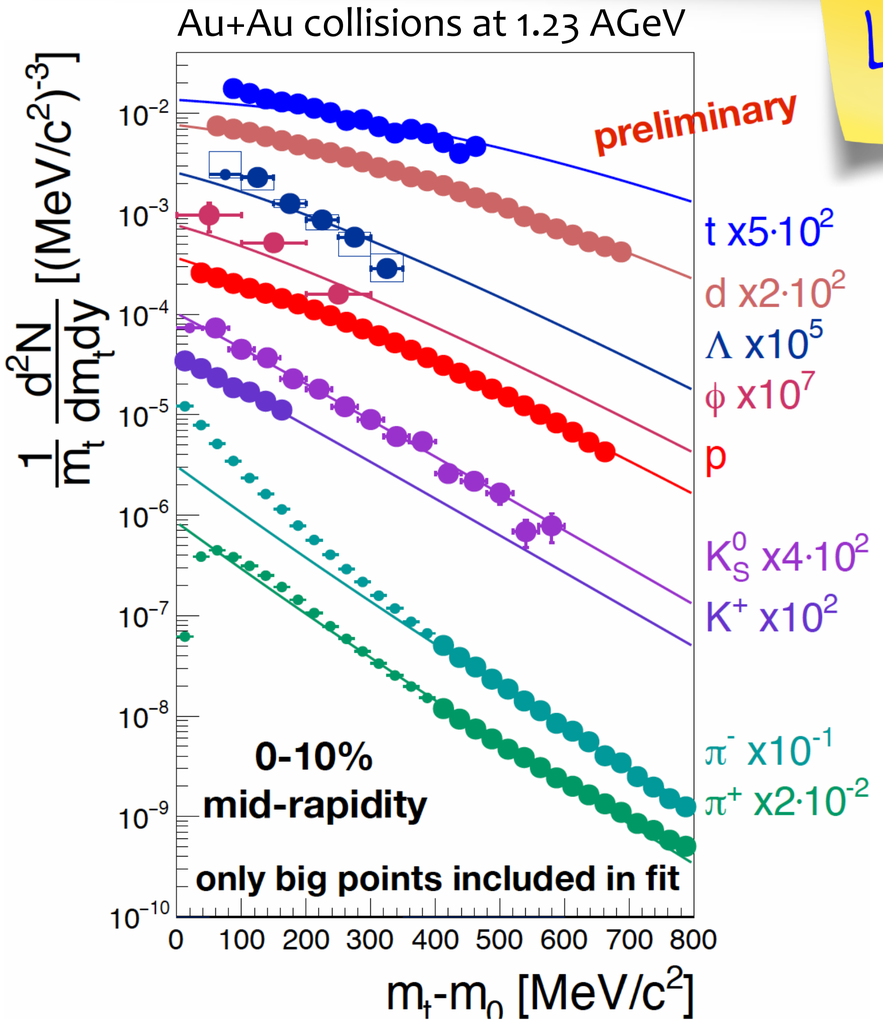
- pp spectrum shows no sign of radial flow (spectra hardening is clearly seen in heavy-ion collisions)
- integrated yields reduced of a factor ~1000 when adding a nucleon

→ it is ~ 300 and ~ 600 in Pb-Pb and p-Pb collisions, respectively

Nuclei production in heavy ion collisions



The hardening of the spectra at the LHC for central collisions is qualitatively well described by the combined BW



Latest news

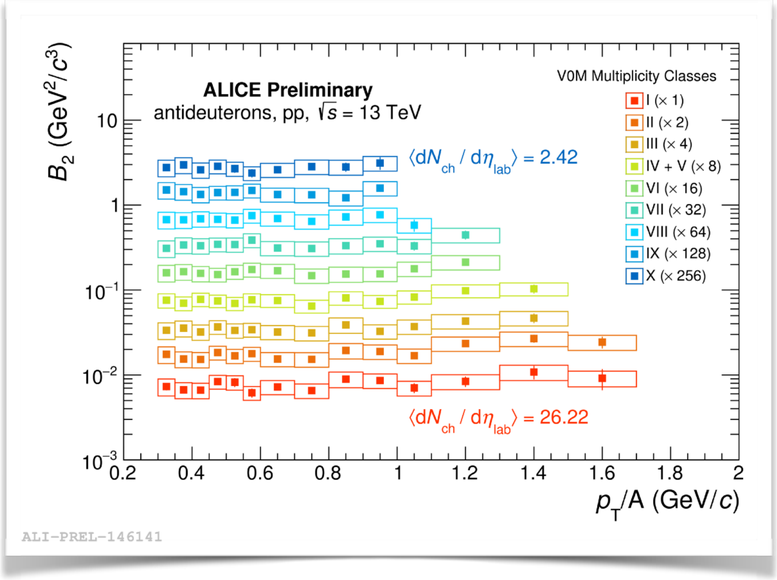
Reasonable description of protons, light nuclei, kaons and pions (at higher m_t)

Coalescence parameters in small systems

Latest news

The formation probability of composite nuclei can be quantified through the coalescence parameter B_A

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



- No p_T dependence as suggested by simple coalescence models

Coalescence parameters in small systems at the LHC

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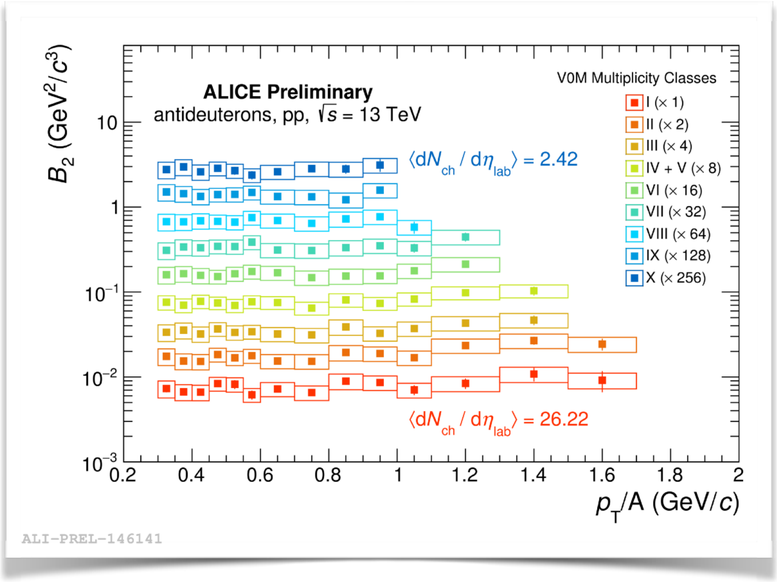
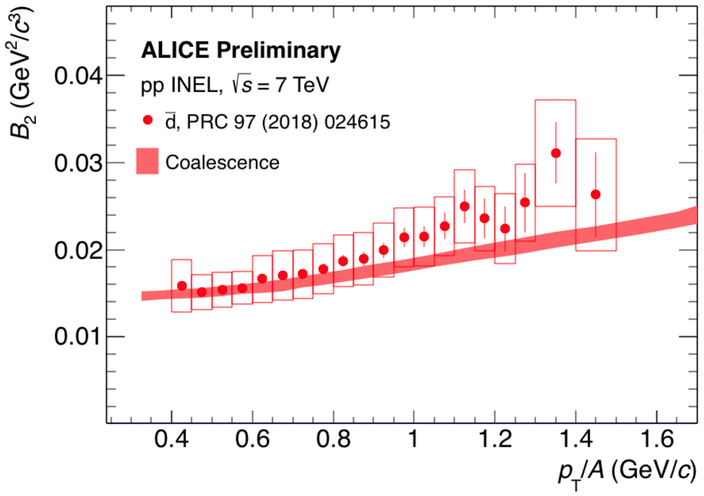


- No p_T dependence as suggested by simple coalescence models

what about the multiplicity integrated B_2 trend?

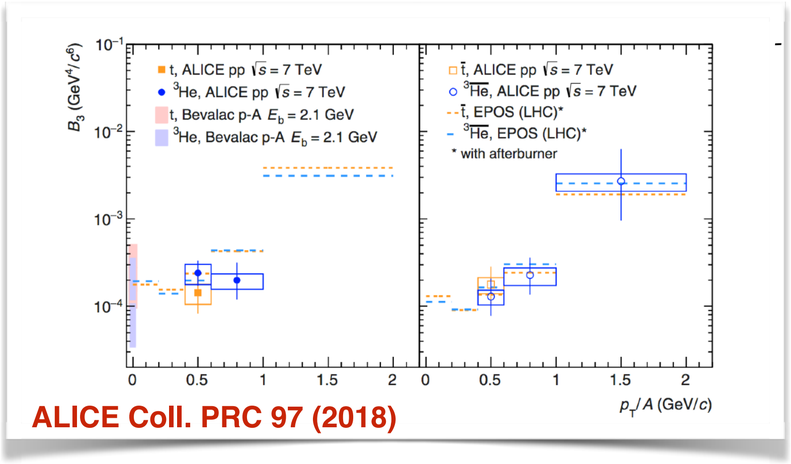
Latest news



Simple Coalescence reproduces the experimental trend

→ **evolution of the primary proton spectra across multiplicity can also explain the result**

→ no need to introduce hard scattering effects



ALICE Coll. PRC 97 (2018)

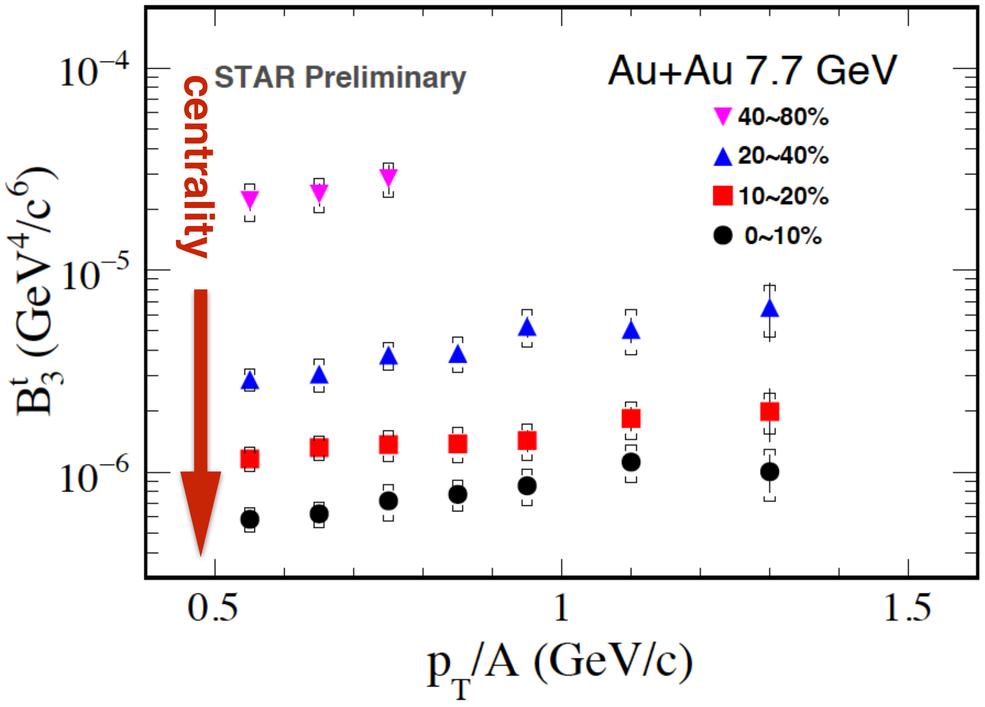
..and what about B_3 ?

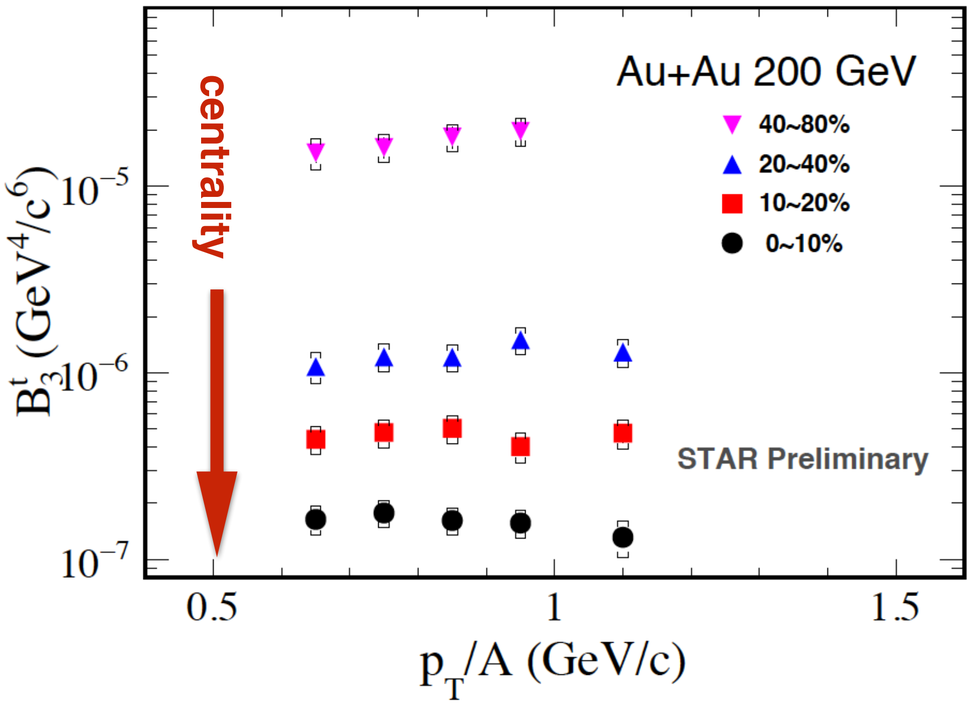
First ever measurement in high energy physics

- reproduced with QCD-inspired event generators with a coalescence-based afterburner
- low p_T values compatible with those obtained in p-C,p-Cu, and p-Pb collisions at Bevalac [Phys. Rev. C 24, 971]

Coalescence parameters for tritons at RHIC

Latest news



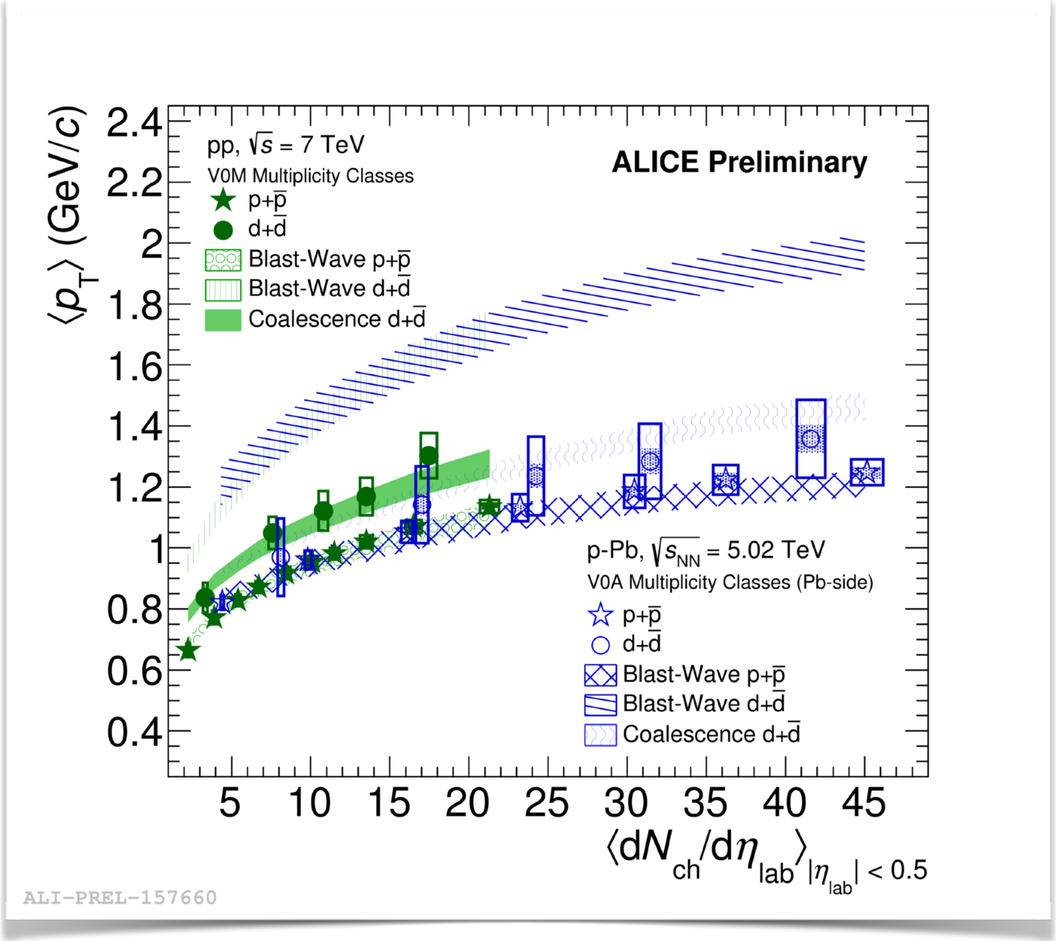


- B_3 of tritons decreases from peripheral to central collisions and when beam energy increase
- It would be important to extend the p_T reach to have a better feeling about the p_T dependence

Triton measurement: quite challenging measurement at the LHC

Testing the models!

Latest news

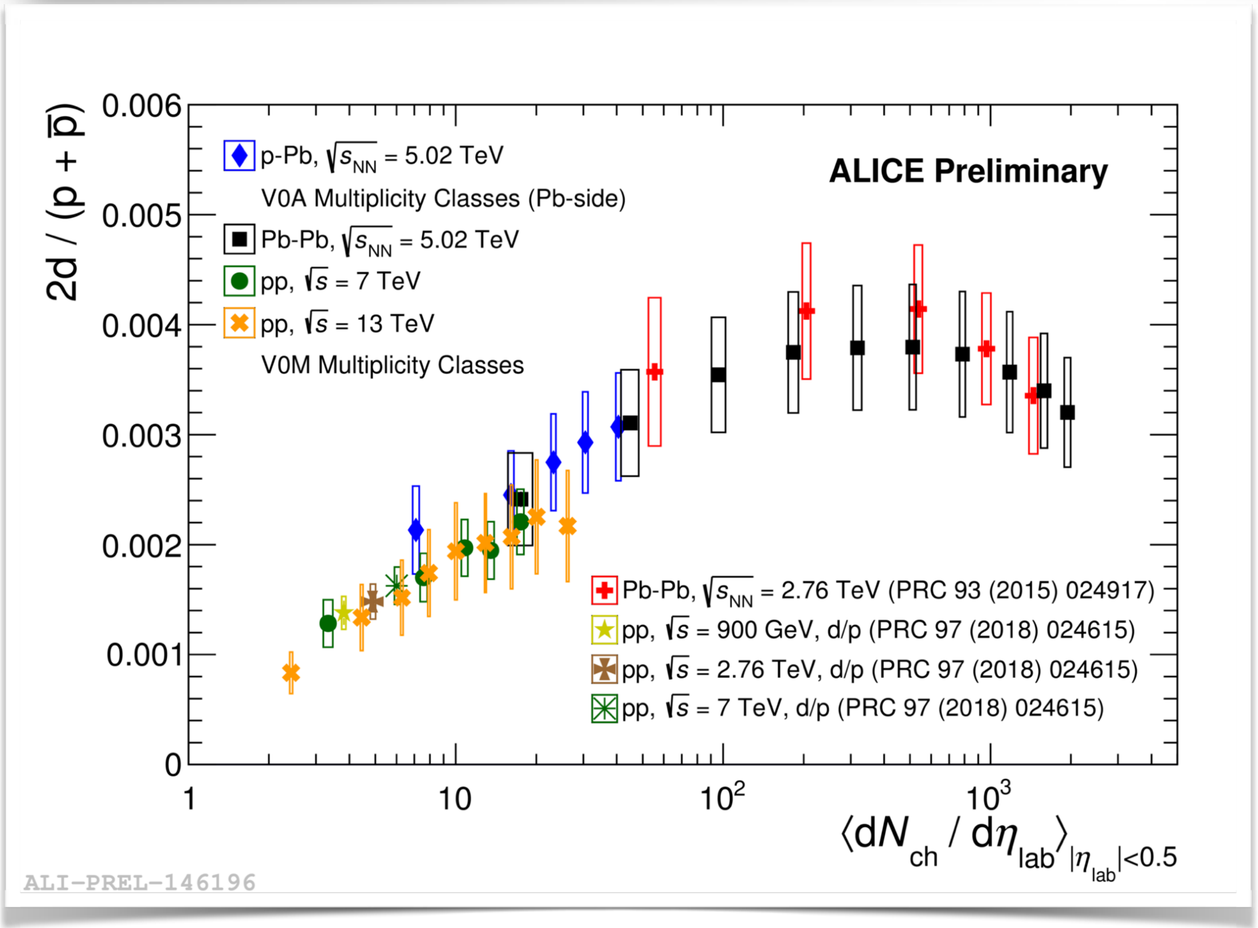


- production in pp and p-Pb: fully inspired-hydrodynamic approach (Blast-Wave[1]) does not describe simultaneously nuclei and protons
- assumption of a radially expanding thermalized source not satisfactory in small systems
- coalescence model reproduce the results in small systems

Blast-Wave model: PRC 48 (1993) 2462

What have we understood?

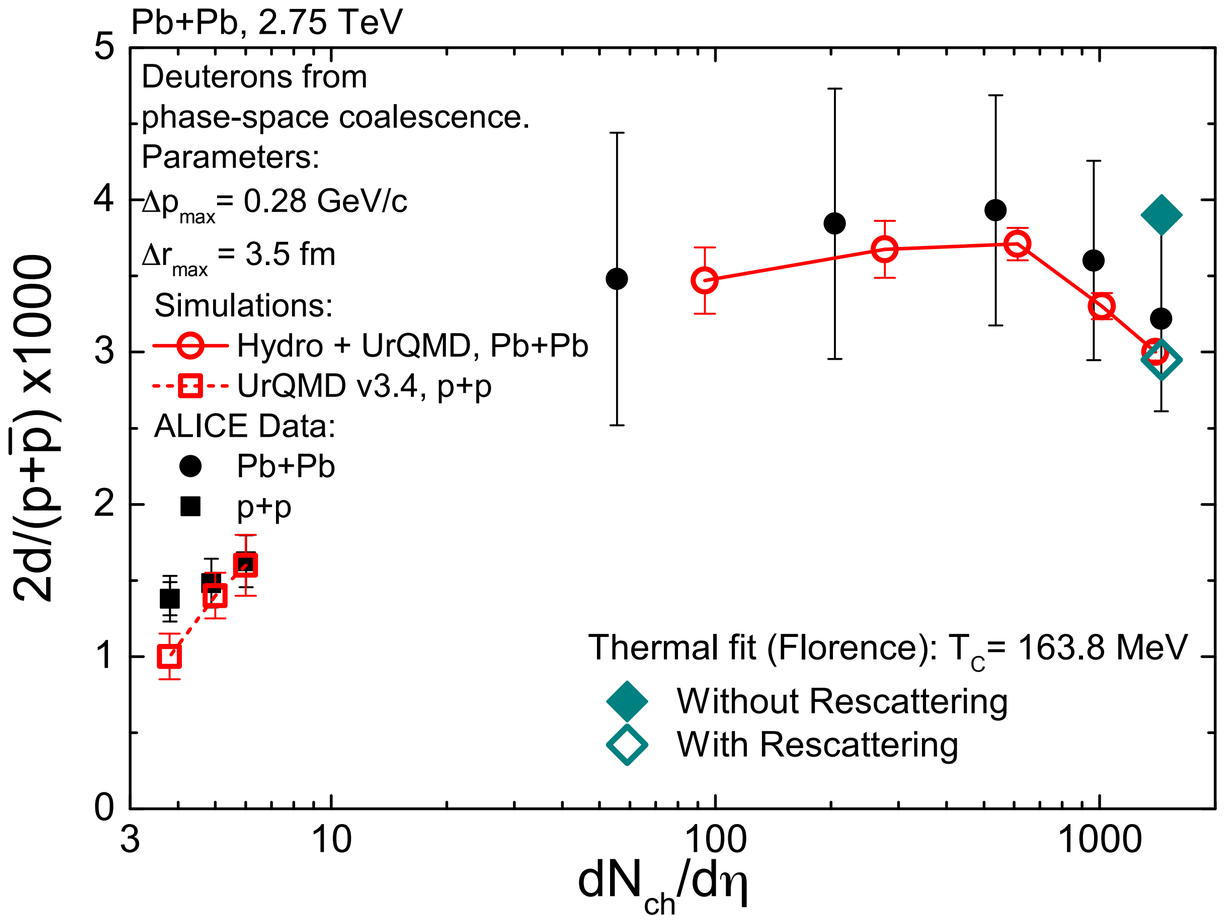
Latest news



- Latest results in pp at 7 TeV and 13 TeV fit the trend drawn by other energies/colliding systems at the LHC
- matching of pp and p-Pb points at similar multiplicities
- **rising** with multiplicity explained in coalescence models as due to an **increased proton and neutron density**

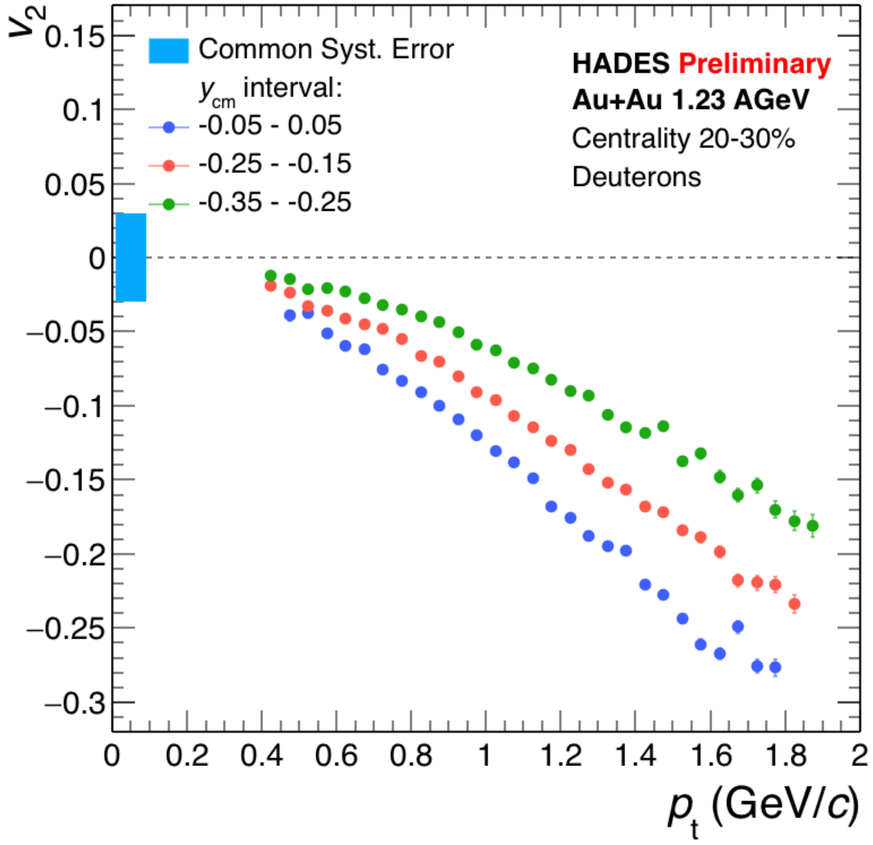
- In pp (and p-Pb) the results point out that the rise in the number of nucleons dominates over the increase in the volume size
- No significant centrality dependence in Pb-Pb collisions in agreement with Thermal-statistical model

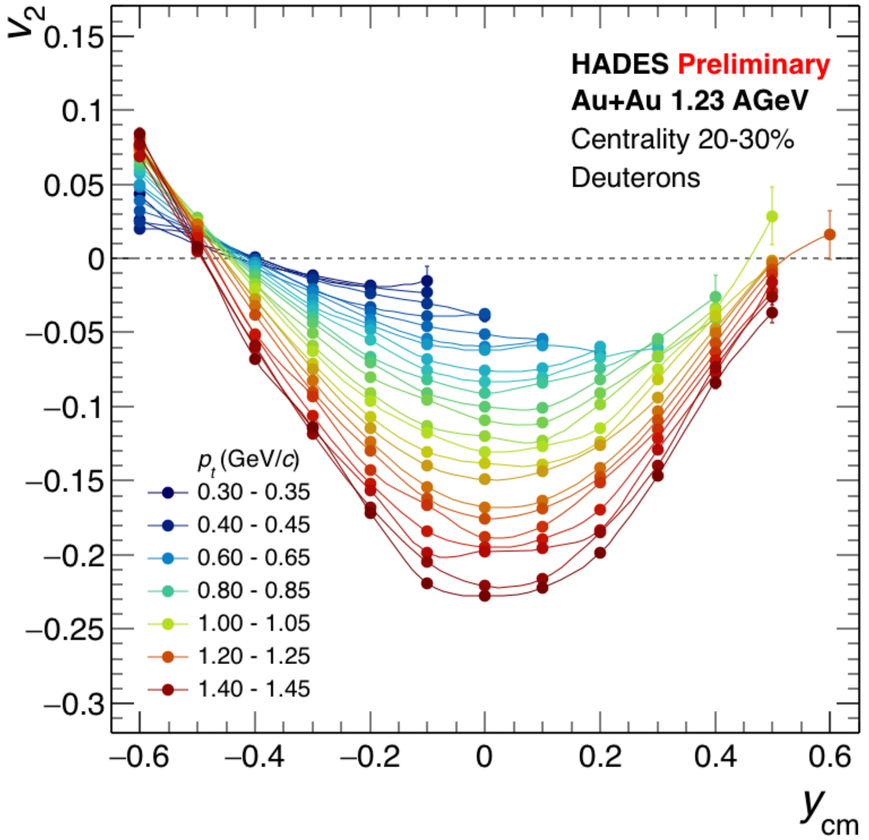
d/p ratio: coalescence in UrQMD and SHM



Elliptic flow with HADES

Latest news





Elliptic flow with HADES

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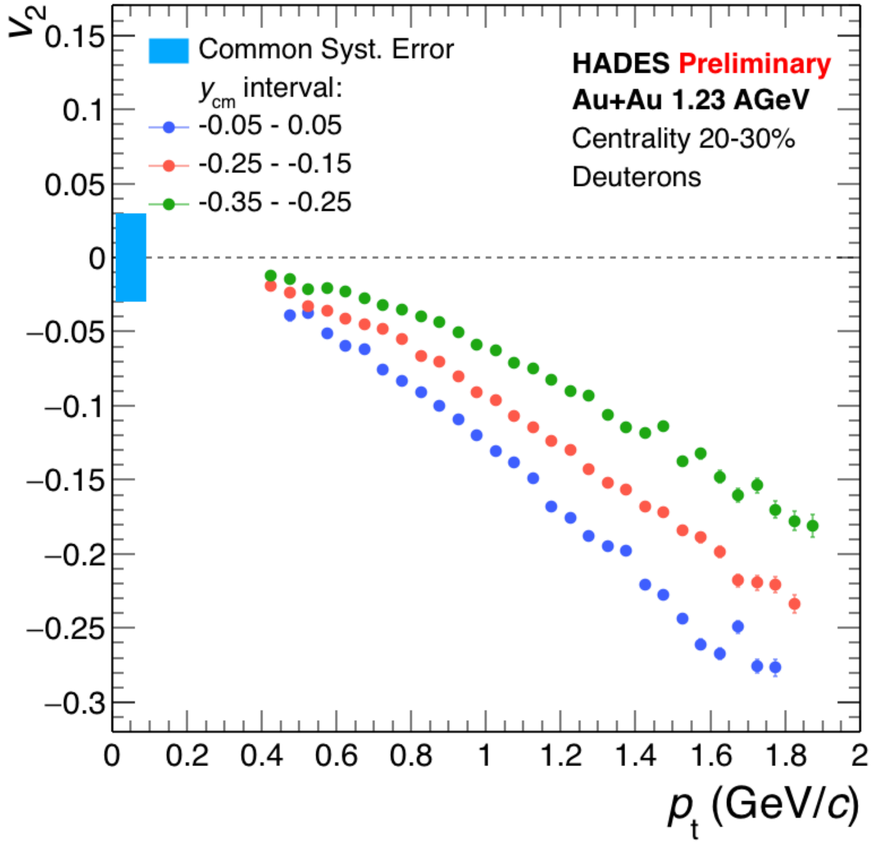
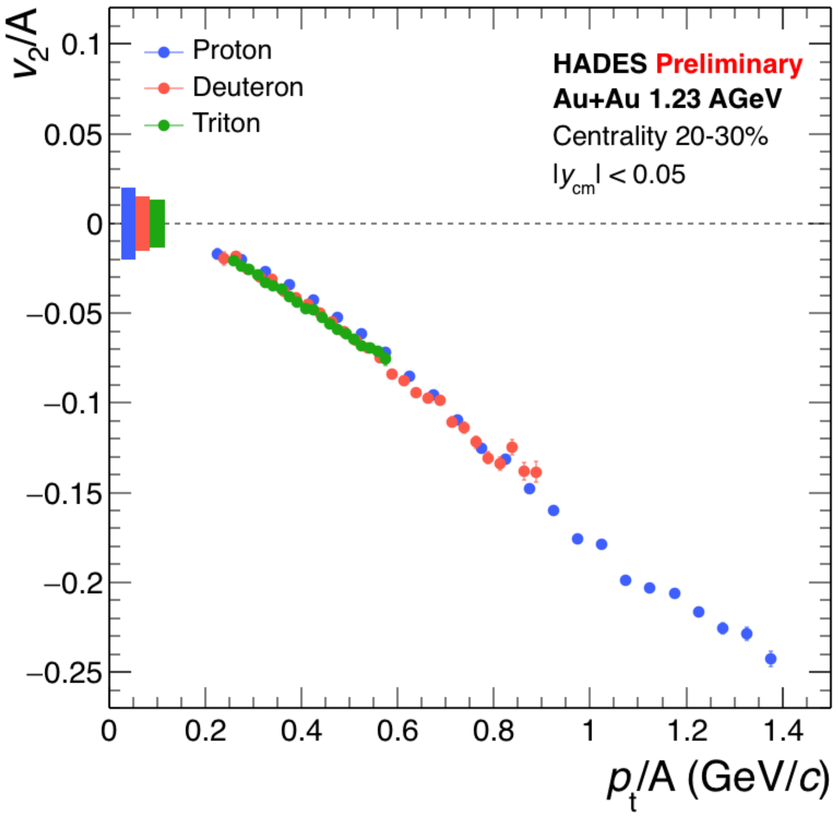


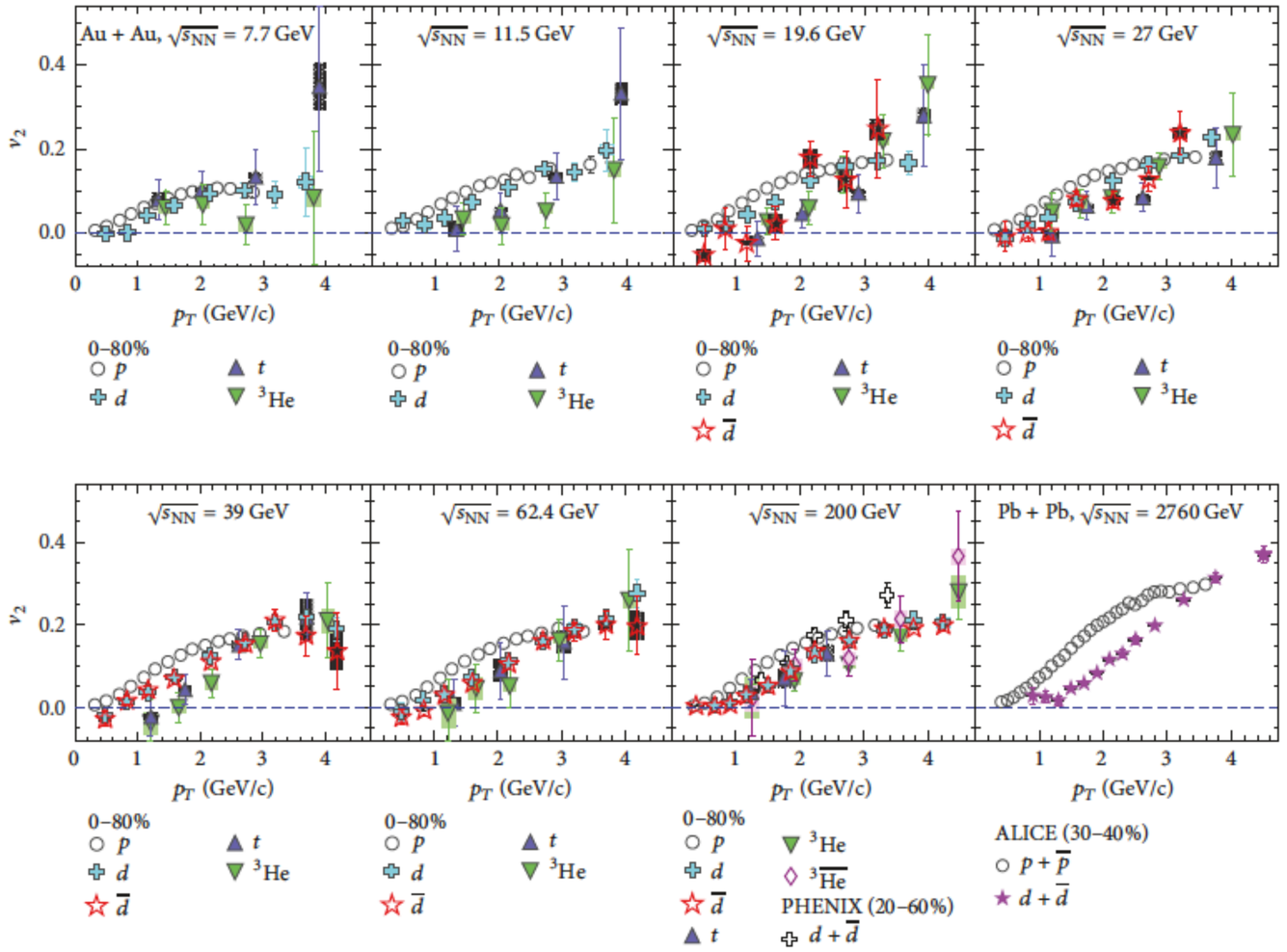


- Comparison of p, d, t elliptic flow at mid-rapidity
- Scaling of v_2 and p_T with nuclear mass number A as expected for nucleon coalescence

Nuclei elliptic flow from ALICE, PHENIX and STAR

Increasing energy →

Increasing energy ↓



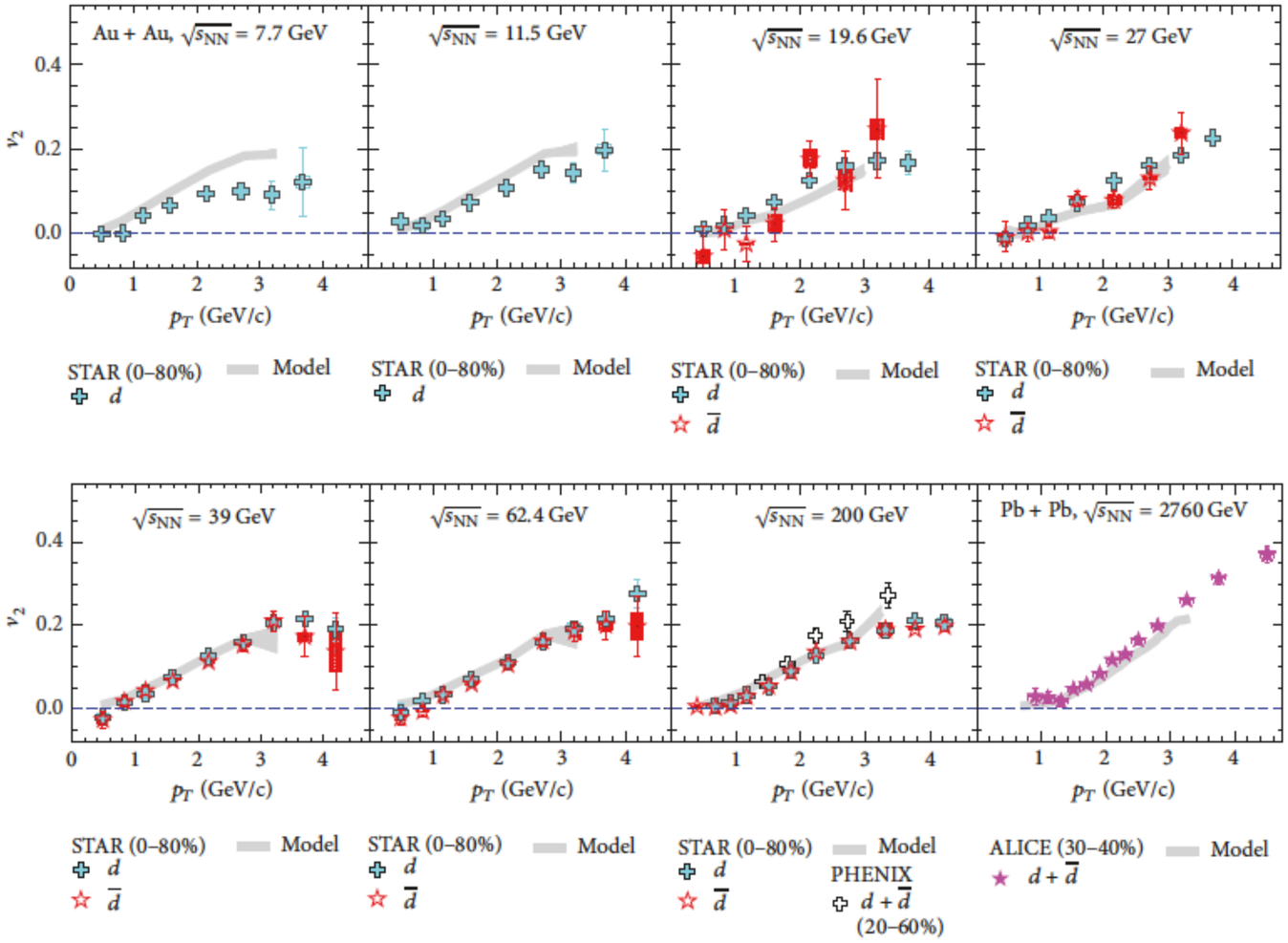
- All species shows similar trend vs p_T
- v_2 of light nuclei shows a mass ordering in particular at low p_T

Advances in High Energy Physics
Volume 2017, Article ID 124856

Nuclei elliptic flow from ALICE, PHENIX and STAR

Increasing energy →

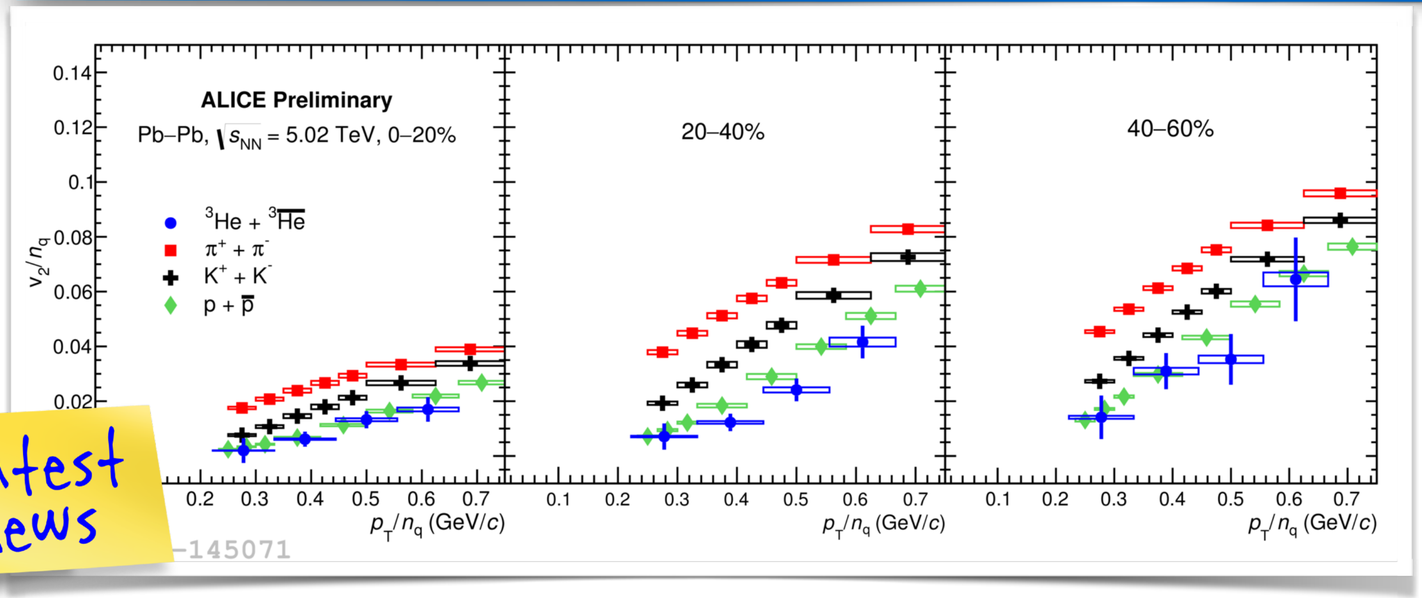
Increasing energy ↓



- mass ordering: expectation typical of thermodynamical models
- a hybrid AMPT + coalescence model fairly reproduce the experimental data at higher energies
- at the LHC energies B-W models reproduce the data

precise measurements of ^{3}He and ^{4}He v_2 can shed light on the nuclei production mechanism in heavy-ion collisions

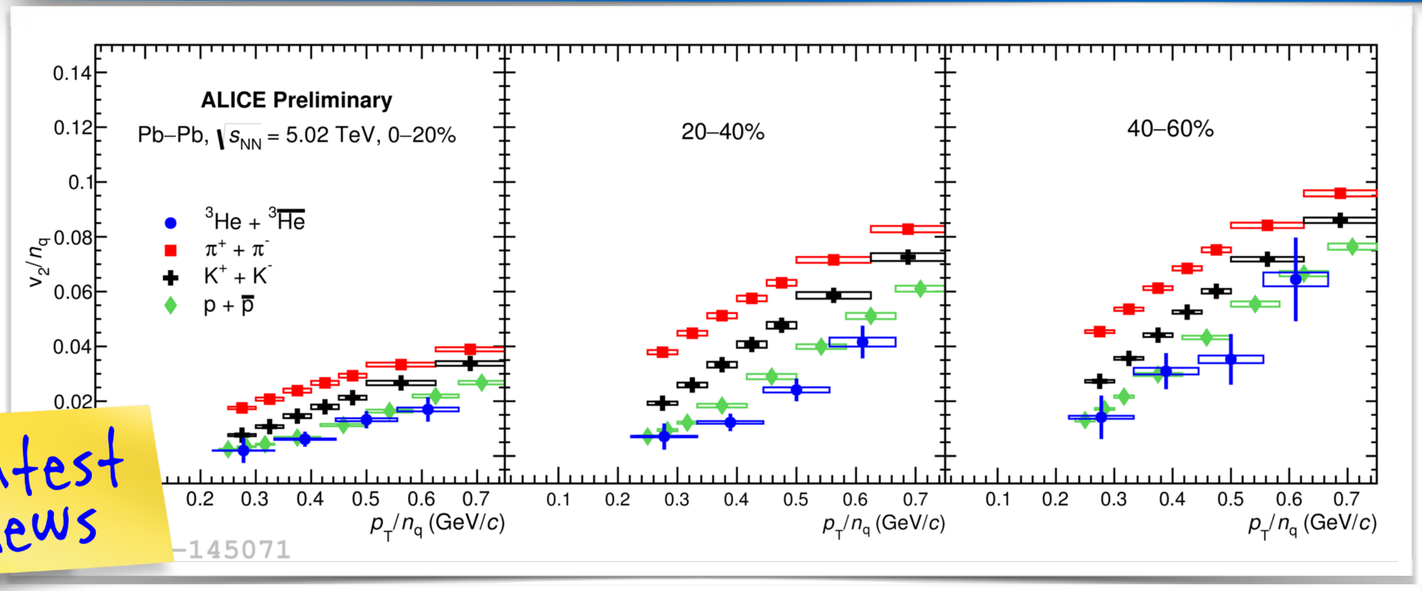
Elliptic flow measurement: d and ^{3}He



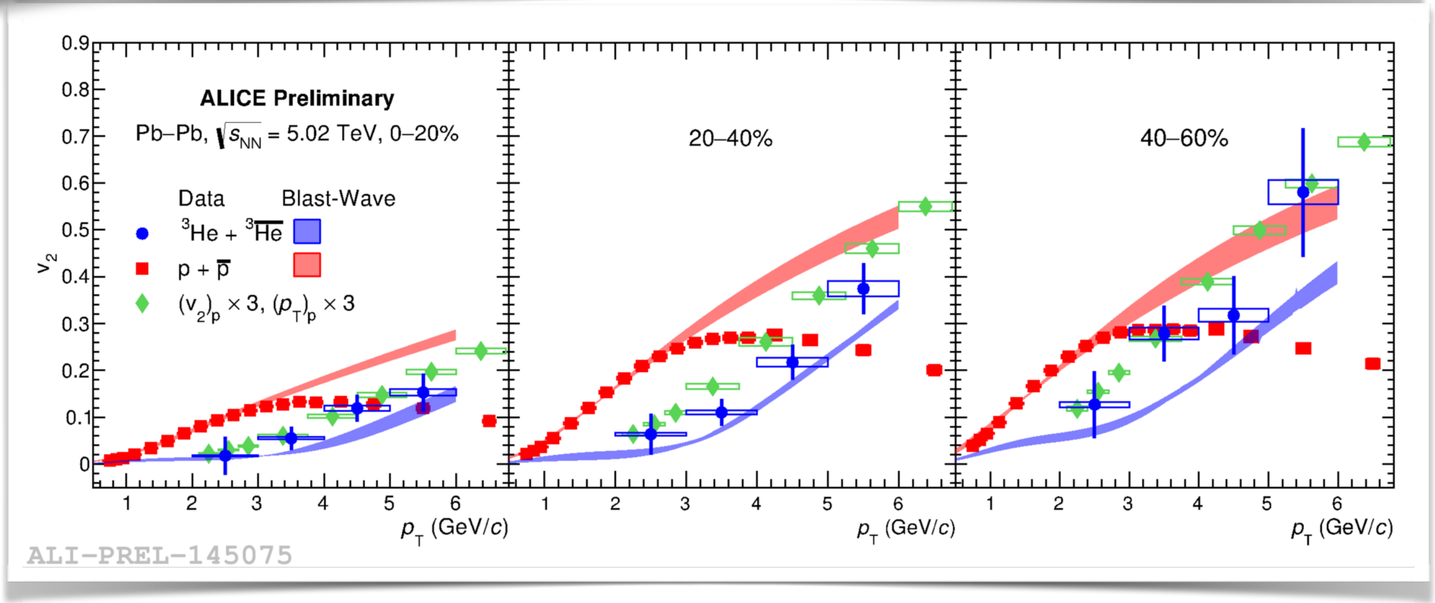
Latest news

As observed for deuterons in Pb-Pb collisions at lower energy, violation of n_q scaling for all charged particles

Elliptic flow measurement: d and ^{3}He

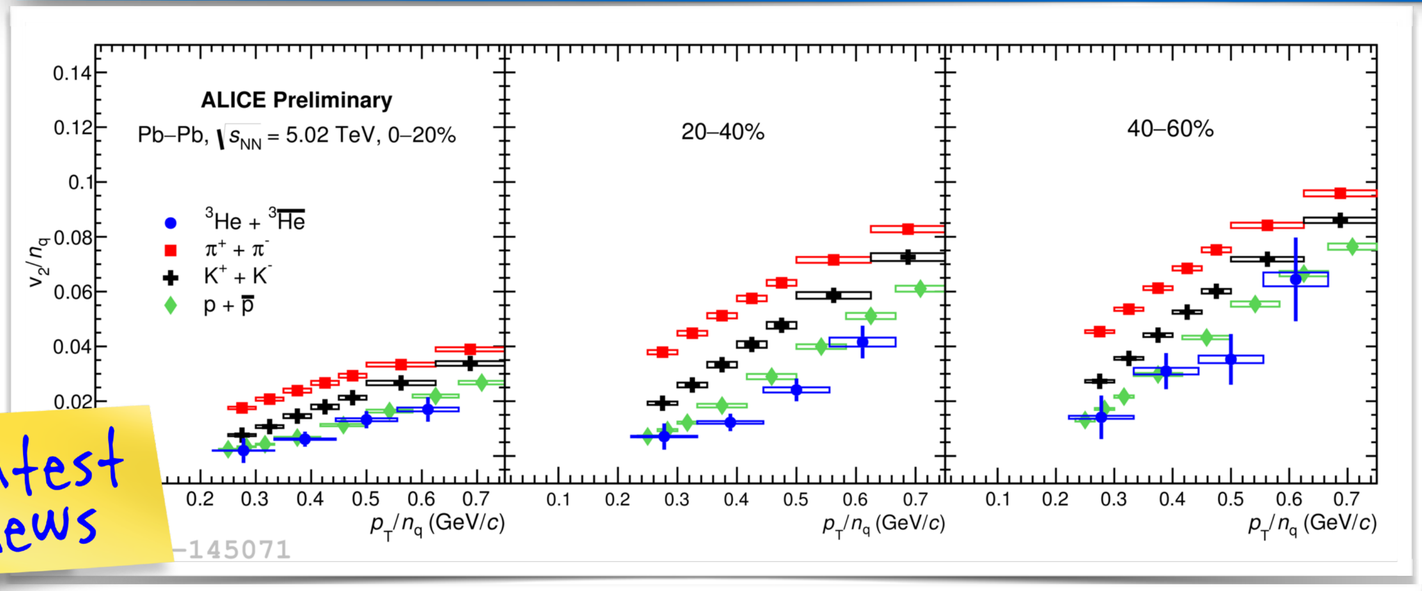


Latest news

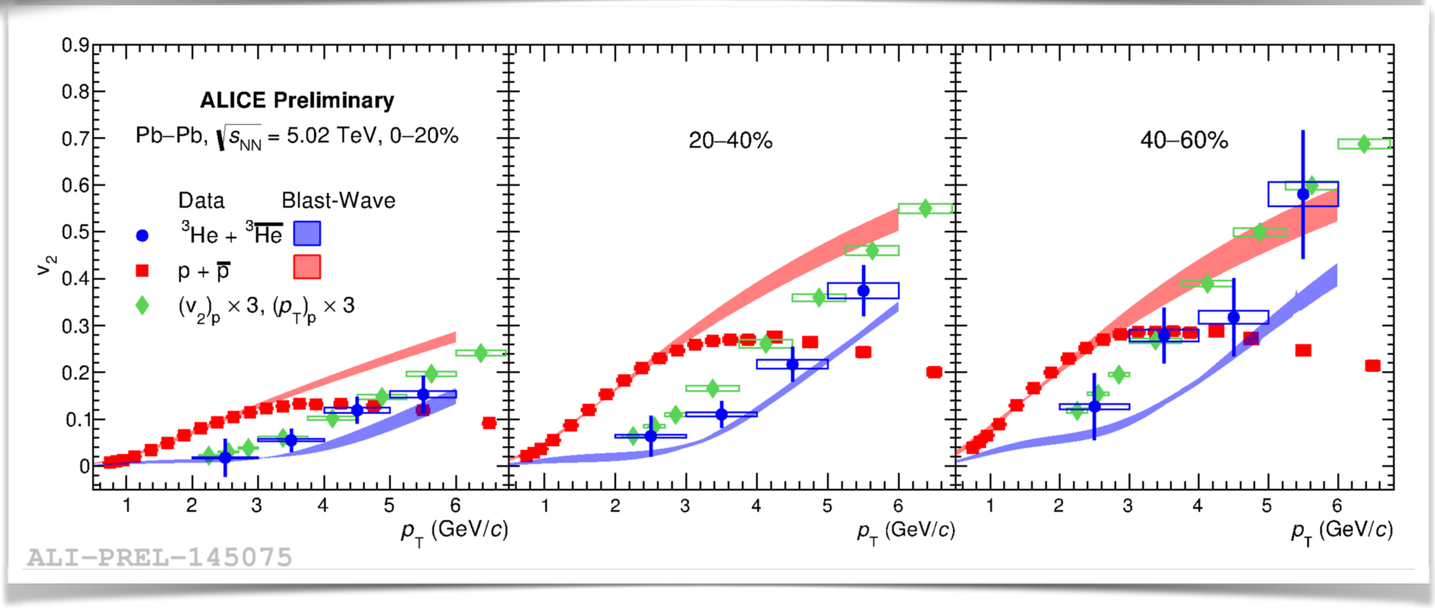


As observed for deuterons in Pb-Pb collisions at lower energy, violation of n_q scaling for all charged particles

Elliptic flow measurement: d and ^{3}He



Latest news

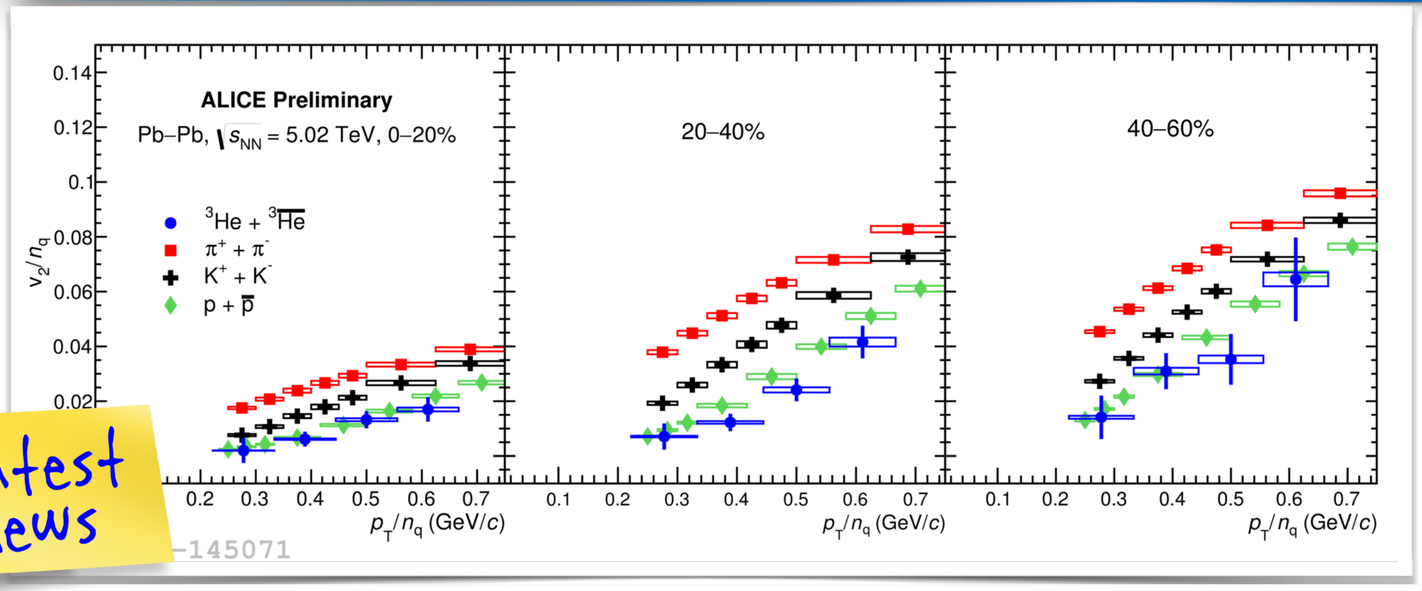


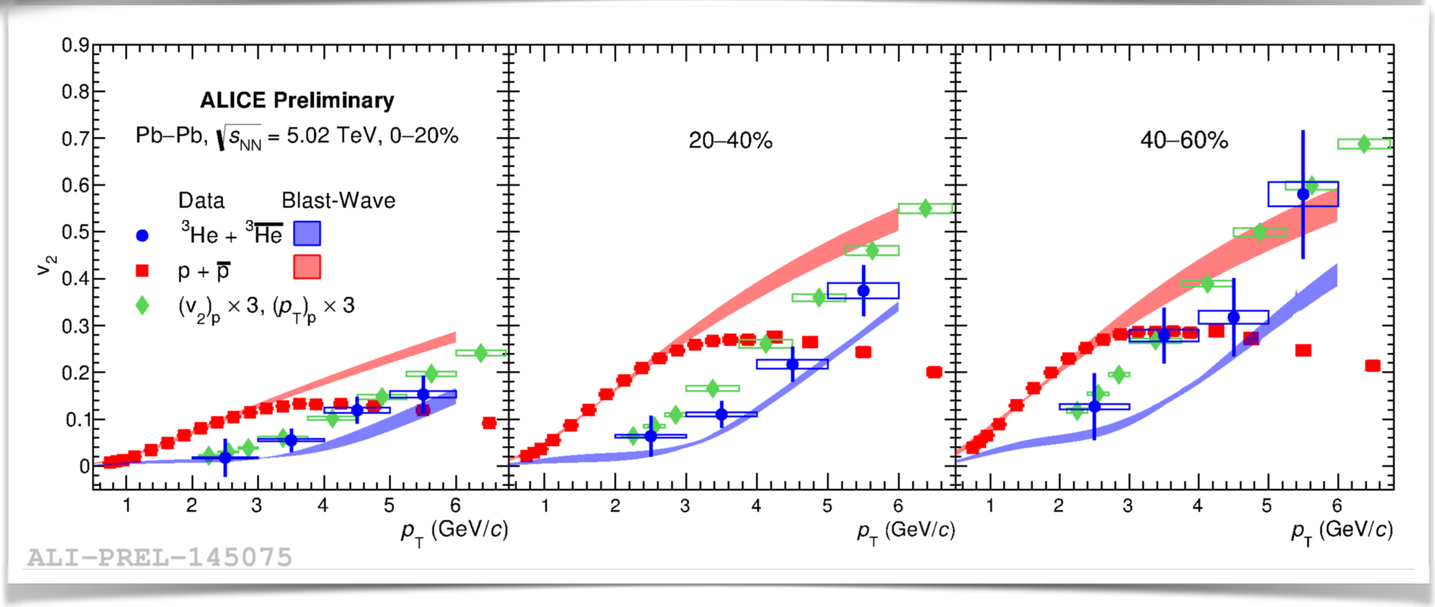
As observed for deuterons in Pb-Pb collisions at lower energy, violation of n_q scaling for all charged particles

^{3}He v_2 trend not described by the Blast-Wave model prediction based on light hadrons

Elliptic flow measurement: d and ^{3}He

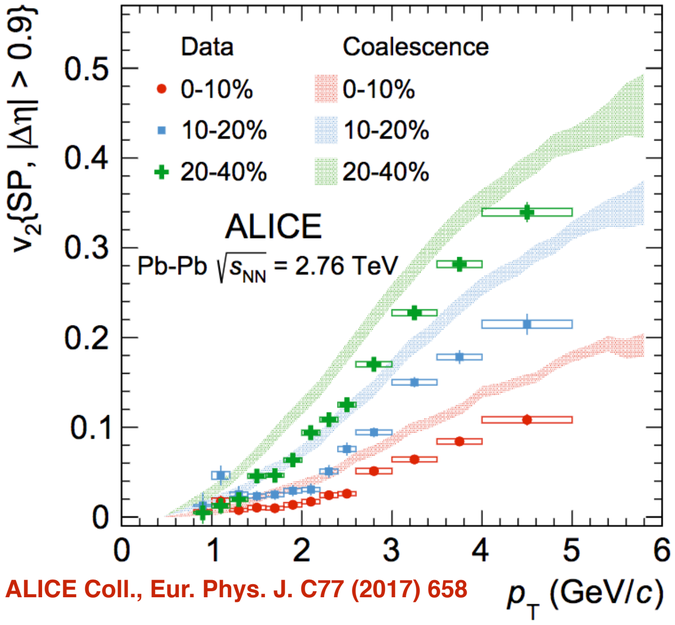
Latest news





As observed for deuterons in Pb-Pb collisions at lower energy, violation of n_q scaling for all charged particles

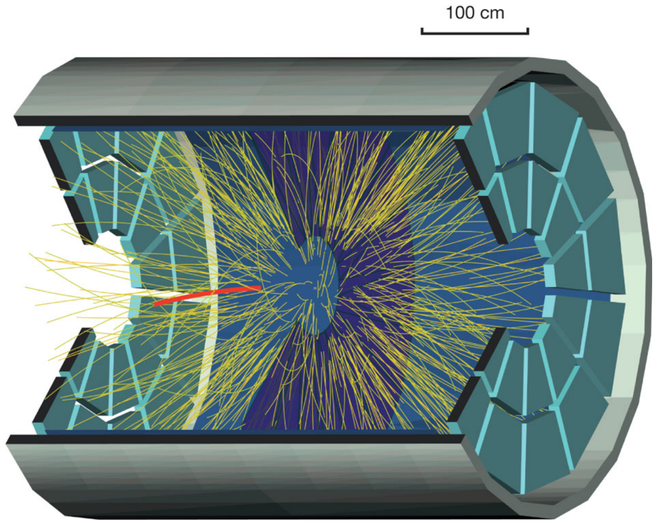
simple coalescence approach does not describe ALICE deuteron measurement in Pb-Pb collisions.

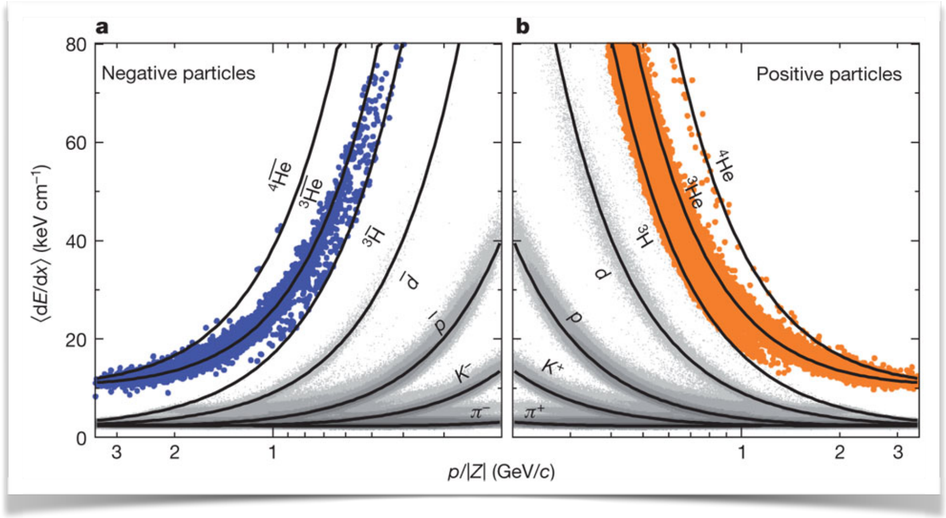


The ALICE Coll., Eur. Phys. J. C77 (2017) 658

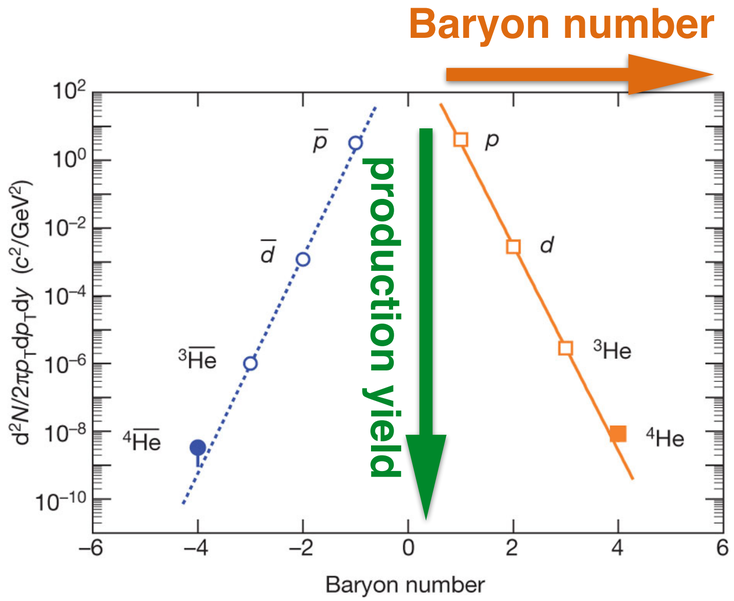
The heaviest stable anti-nucleus observed

anti-^{4}He track in the STAR detector





STAR PID for (anti-nuclei)



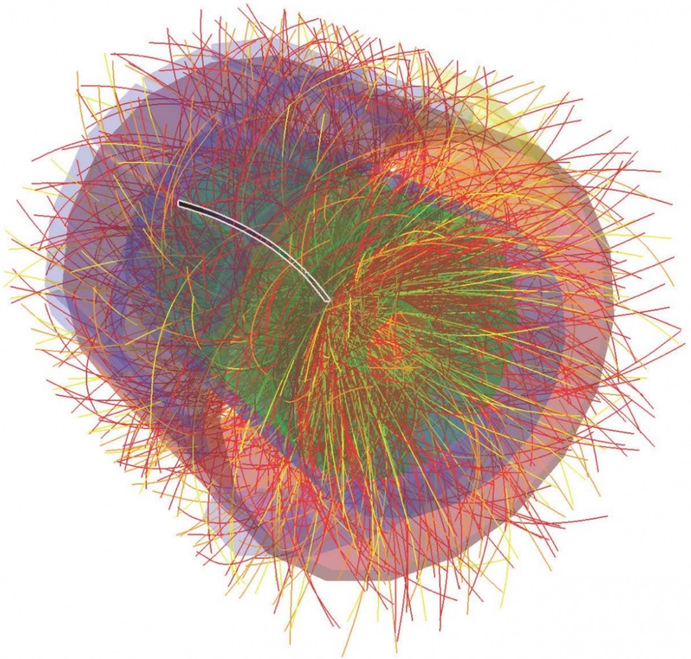
The STAR Collaboration published in 2011 (*Nature* volume 473, pages 353–356) the first observation of anti-^{4}He, measured in Au-Au collisions at 200 GeV and 62 GeV per nucleon–nucleon pair.
The measured production yield is consistent with expectations from thermodynamic[1] and coalescence[2] models

1. Peter Braun-Munzinger, P. & Stachel, J. Nature 448, 302–309 (2007).
2. Sato, H. & Yazaki, K. Phys. Lett. B 98, 153–157 (1981)

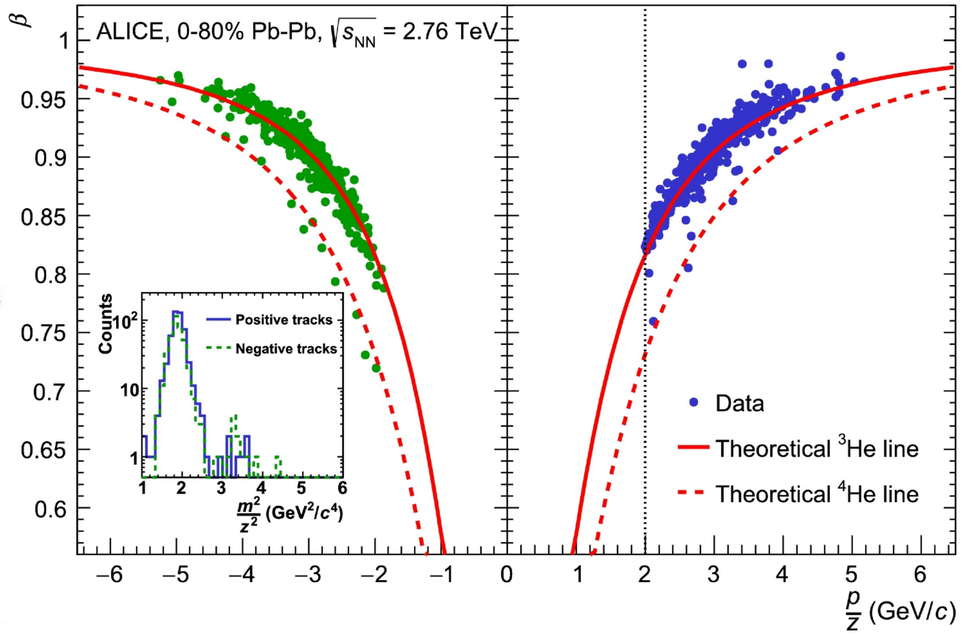
The heaviest stable anti-nucleus observed

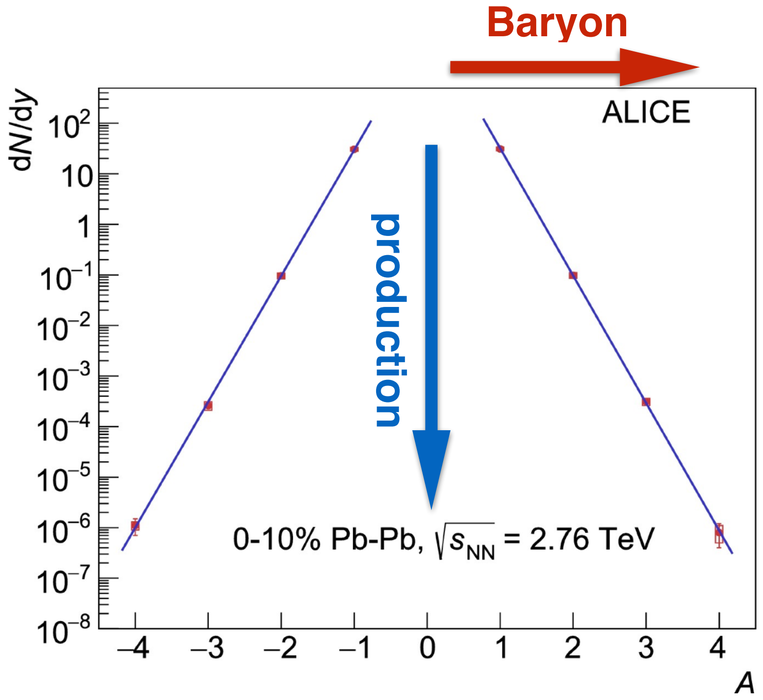
Latest news

^{4}He tracked in the ALICE detector



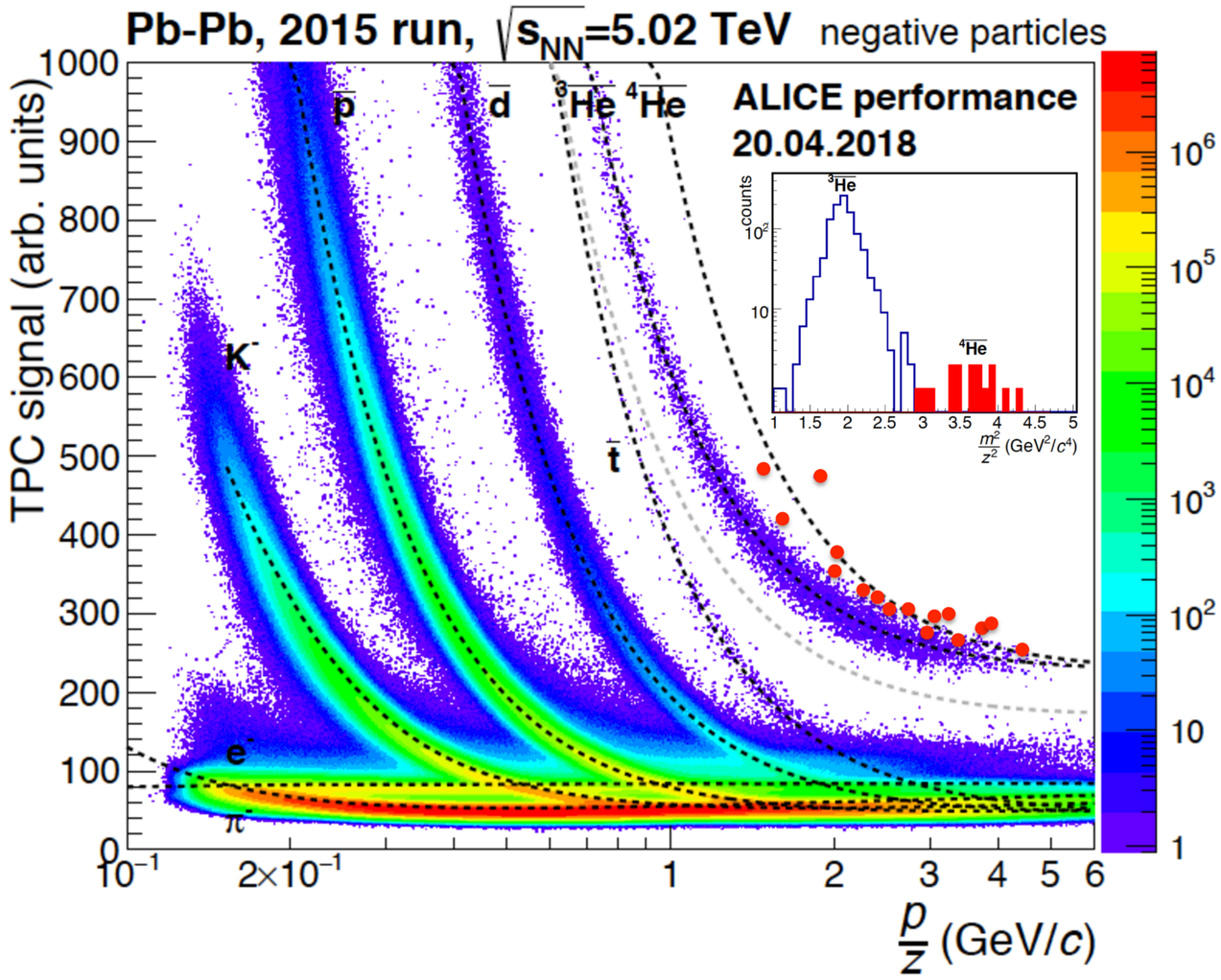
The ALICE Coll., Nucl. Phys, A 971, 1-20





The exponential decrease in nuclei production rate predicted by the Thermal model is confirmed

The heaviest stable anti-nucleus observed



Performances for the ^{4}He measurement using the new Pb-Pb dataset at 5.02 TeV look promising

What about adding the strangeness degree of freedom ?

The *puzzle* of hypertrition lifetime

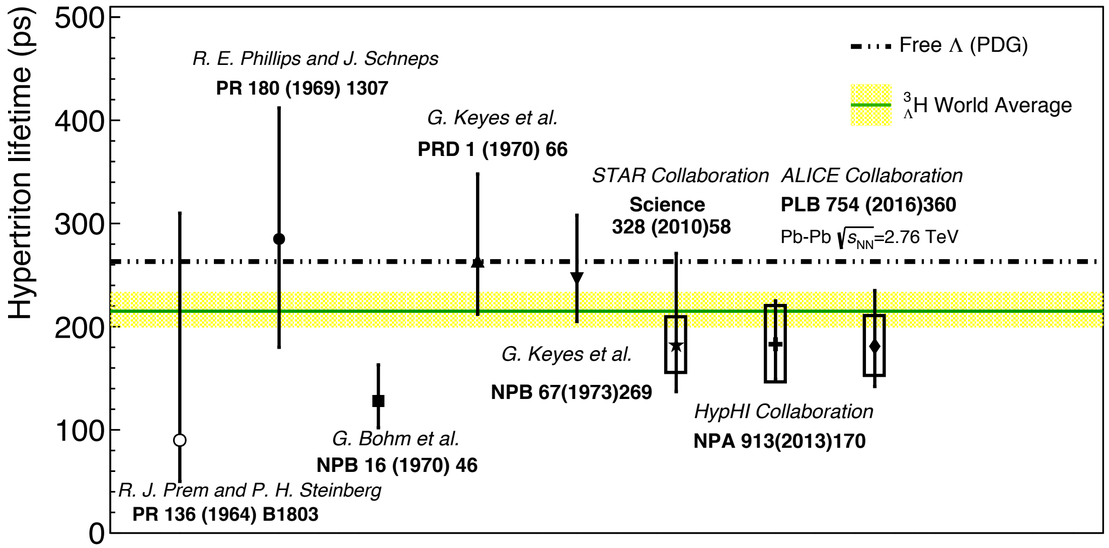
Hypertriton

- bound state of **p**, **n** and **Λ**, is the lightest known hypernucleus
  - **mass** = 2.99131 ± 0.00005 GeV/c^2 [*]
  - **Λ separation energy** E_{B_Λ} = 0.13 ± 0.05 MeV [*]
- Very small E_{B_Λ} (~130 keV) led to the hypothesis that the $^3_\Lambda$H lifetime is slightly below the free Λ lifetime (263.2 ± 2 ps [~])
- Few theoretical predictions available

  - first one by Dalitz and Rayet (1966)

→ τ range **239.3 - 255.5 ps**

  - by Congleton (1992) and Kamada (1998) → **232 ps** and **256 ps**



Re-evaluation of world average including ALICE result:

$\tau = (215^{+18}_{-16})\ ps$

ALICE value compatible with the computed average

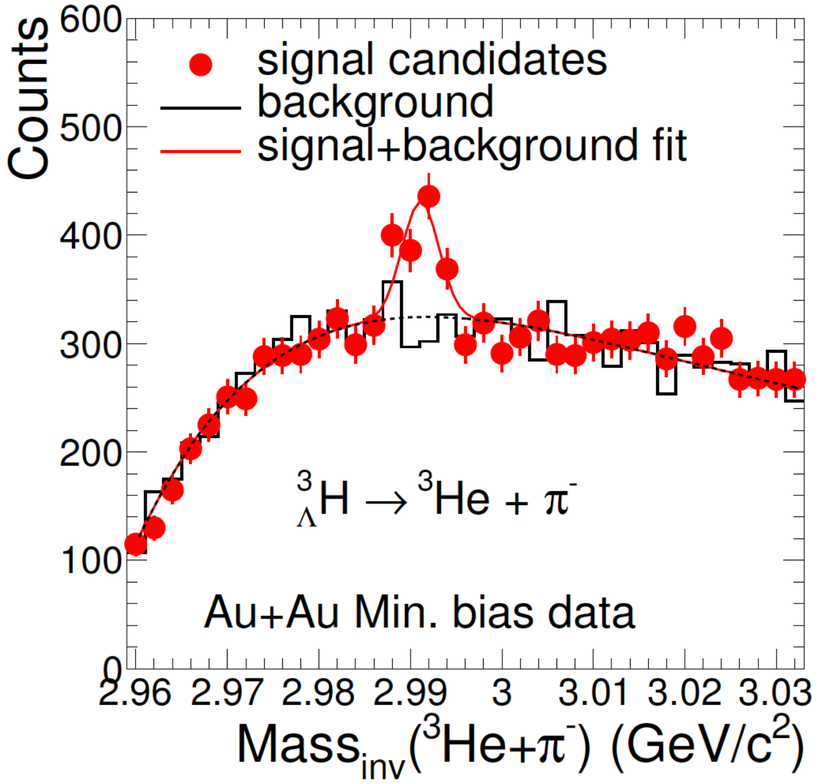
Where we stood last year only published results

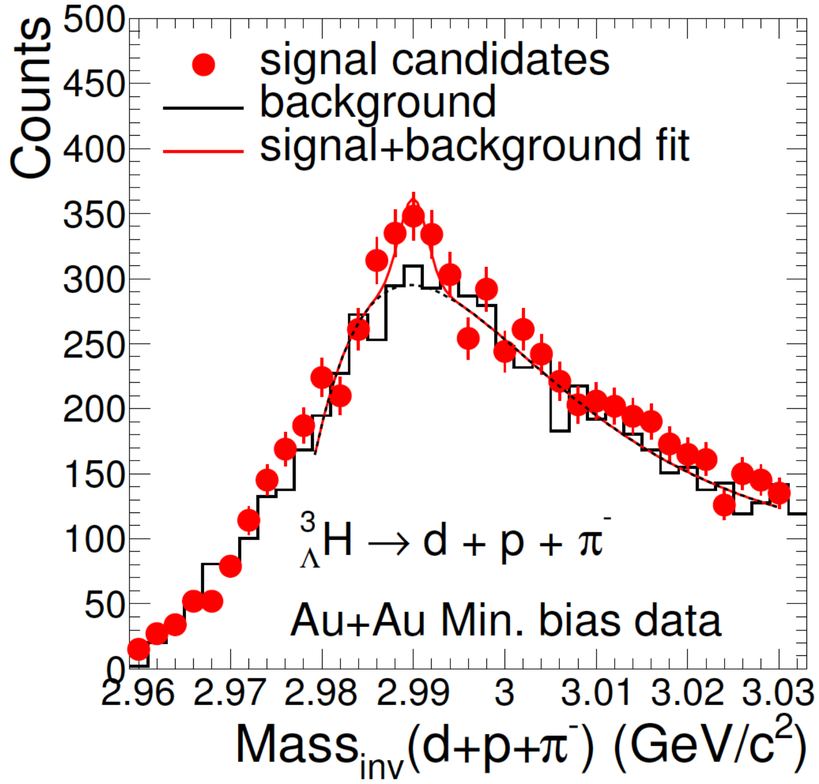
[*] D.H. Davis., Nucl. Phys. A 754 (2005) 3-13

[~] C.Patrignani et al. (Particle Data Group), Chin. Phys. C 40 100001 (2016)

Hypertriton search with STAR at RHIC

Invariant mass spectra from both 2- and 3-body decay

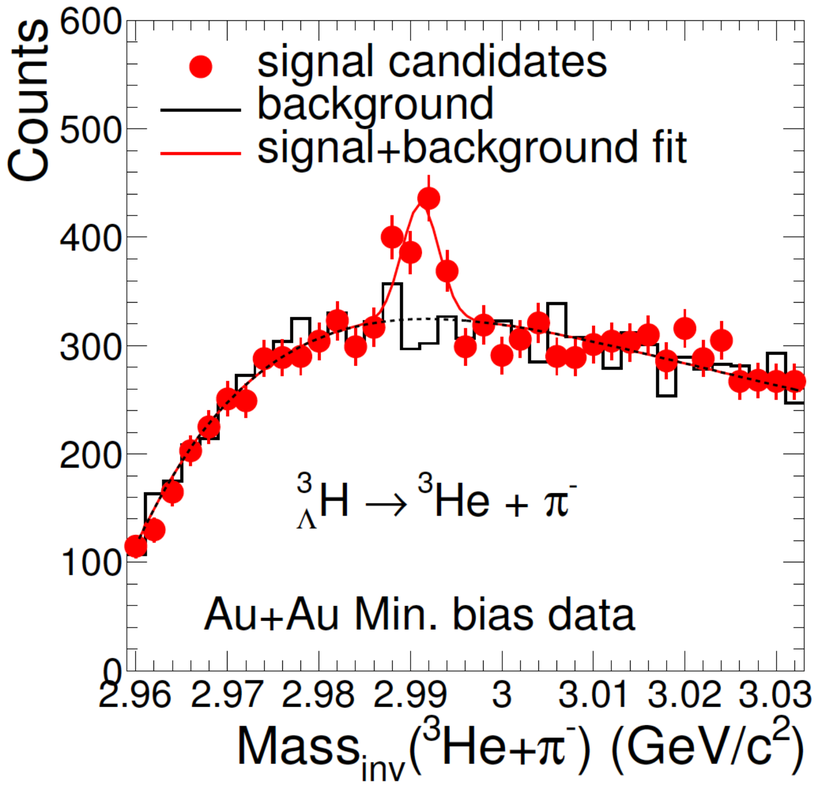


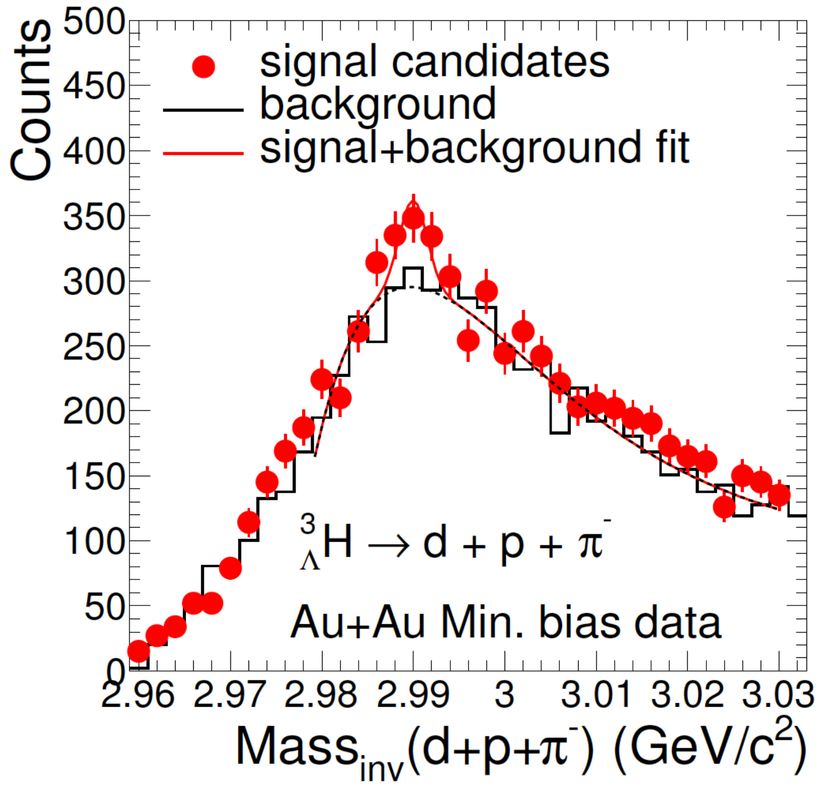


The STAR Collaboration - arXiv:1710.00436 [nucl-ex]

Hypertriton search with STAR at RHIC

Determination of $^{3}_{\Lambda}$H lifetime via both 2- and 3-body decay





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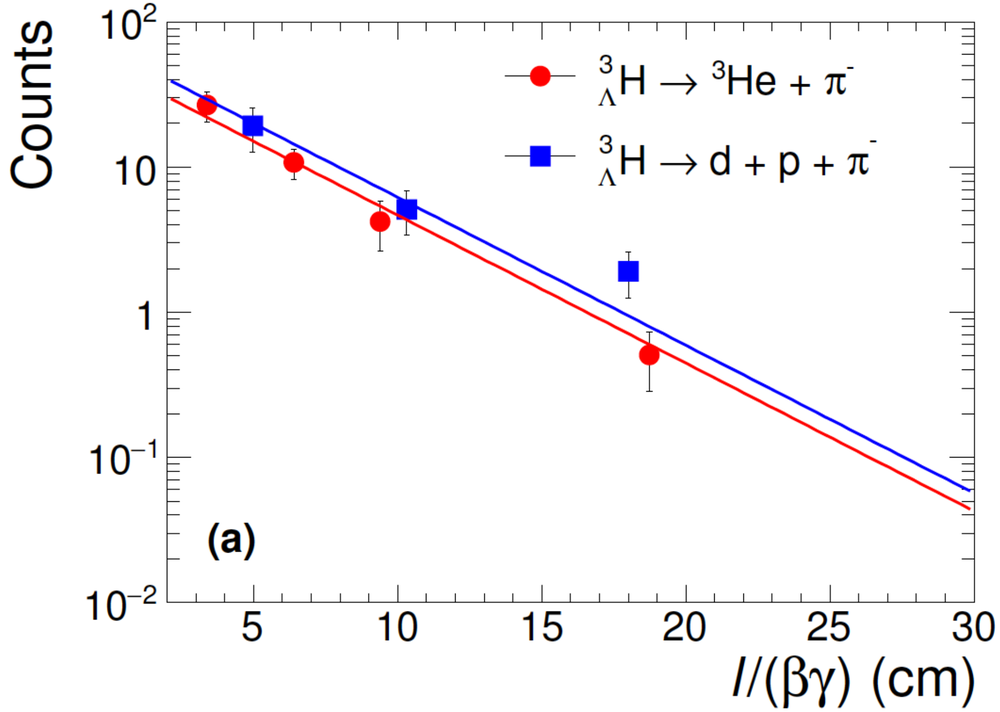
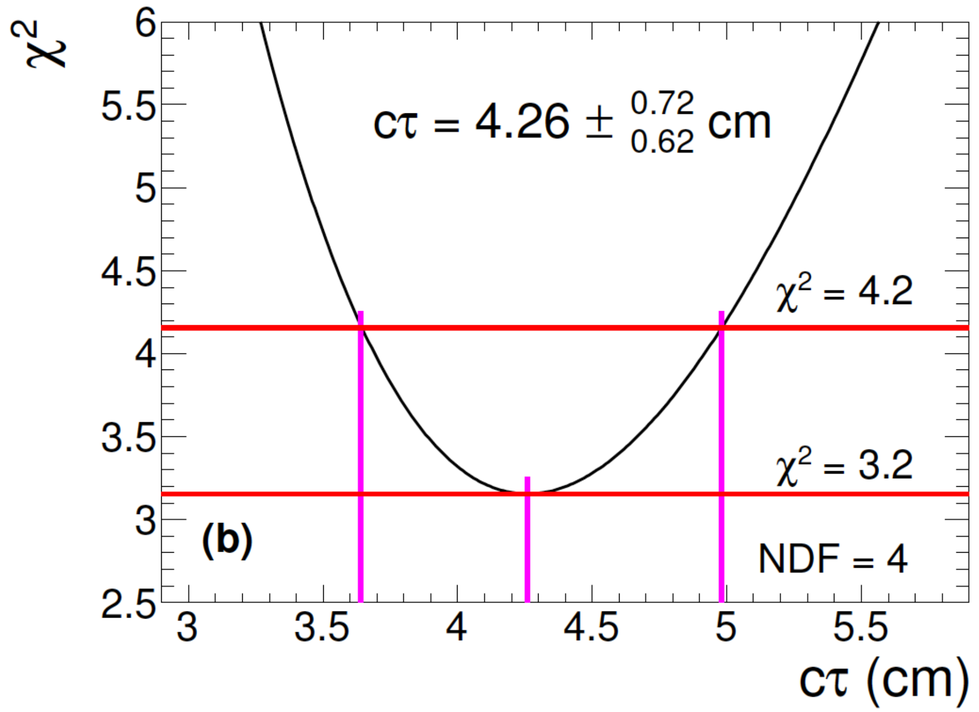
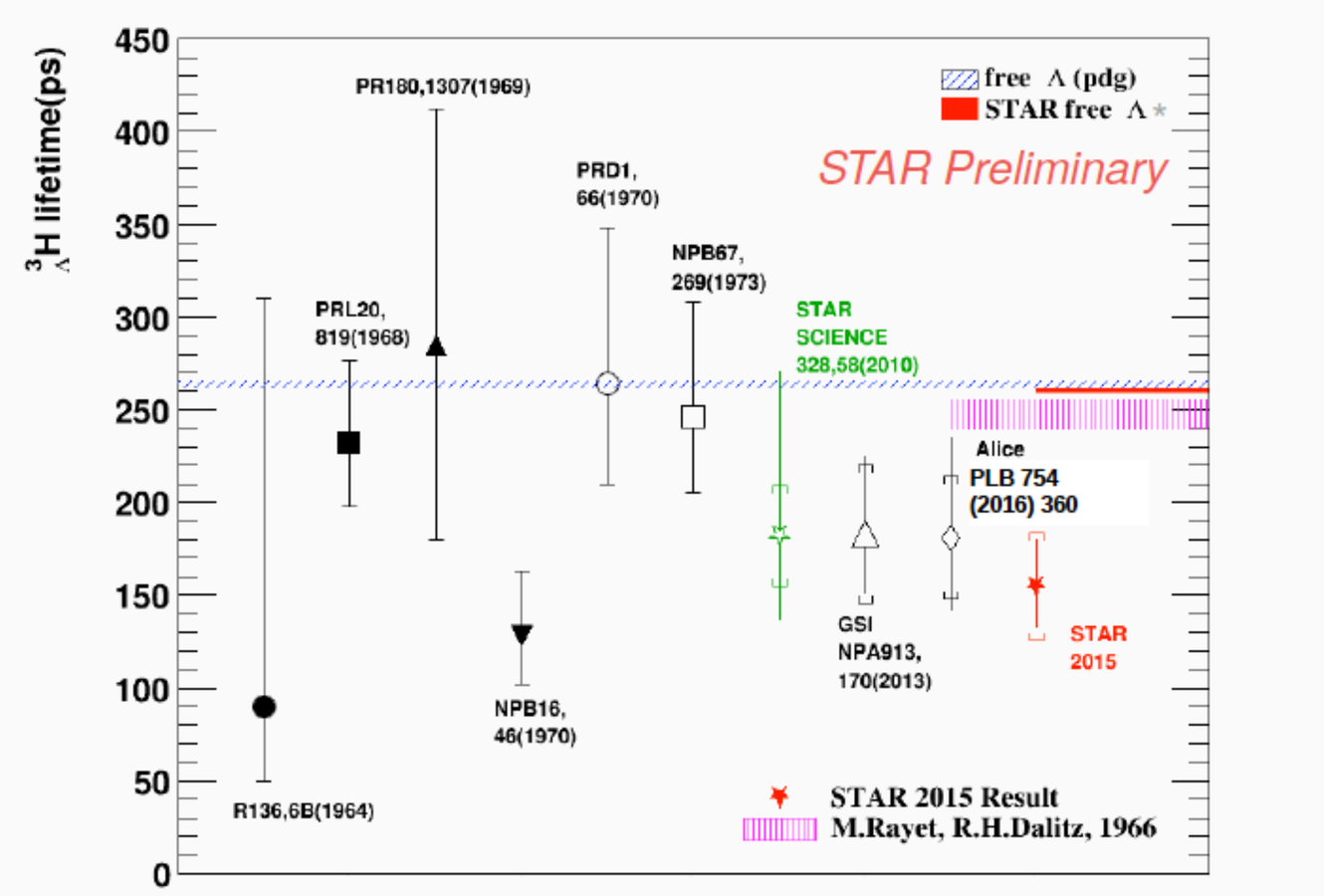




$\tau = 142^{+24}_{-21}(stat) \pm 31\ (sys)\ ps$

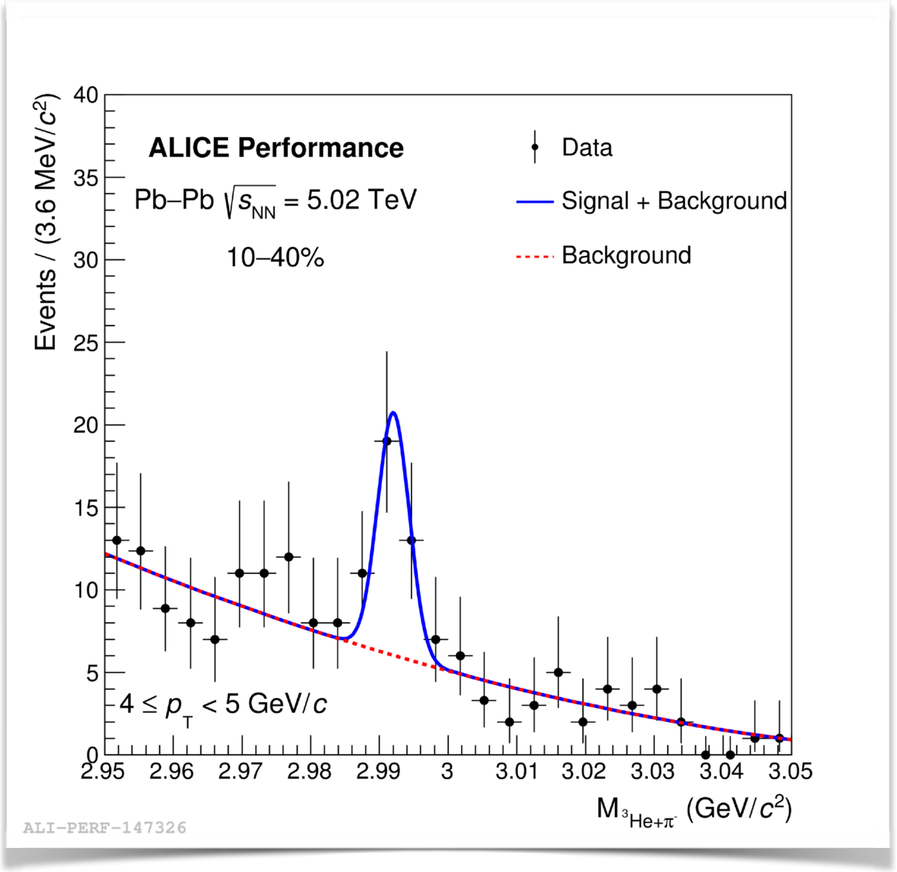
The STAR Collaboration - arXiv:1710.00436 [nucl-ex]

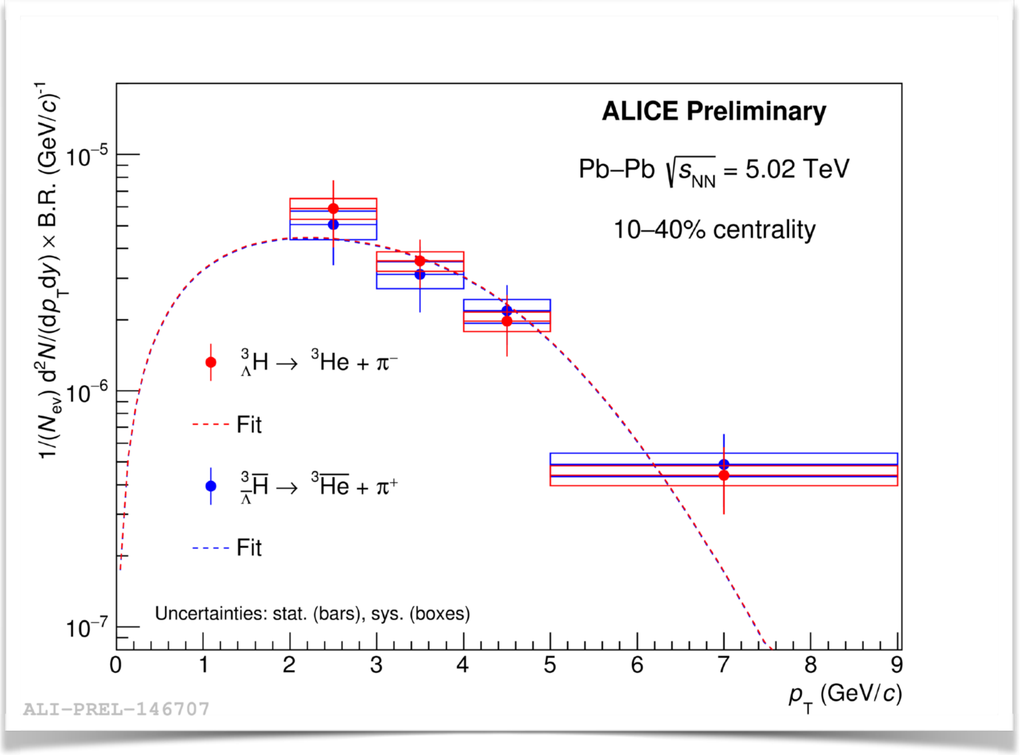
World lifetime avarage adding STAR Preliminary



The STAR Collaboration - arXiv:1710.00436 [nucl-ex]

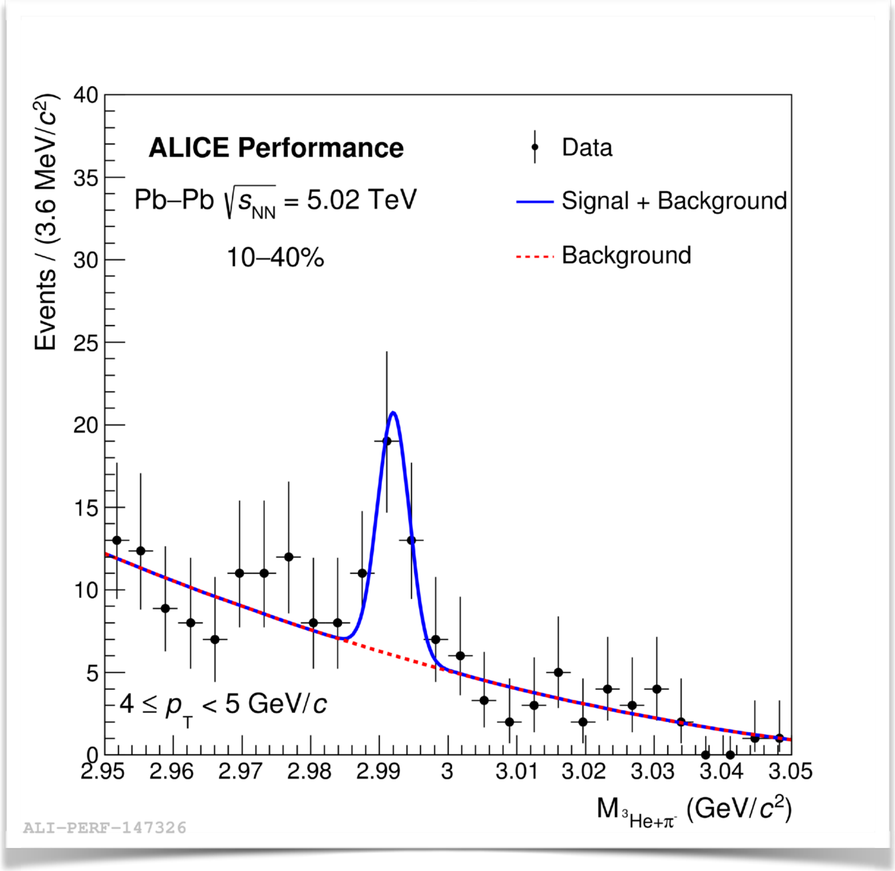
Hypertriton search with ALICE at the LHC

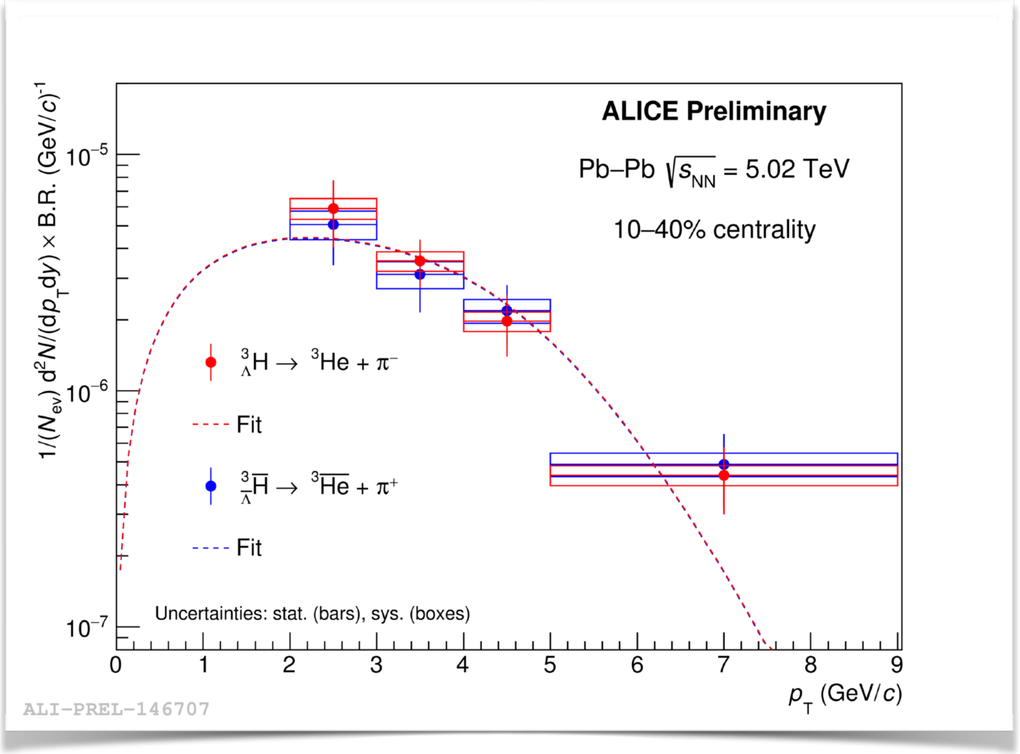




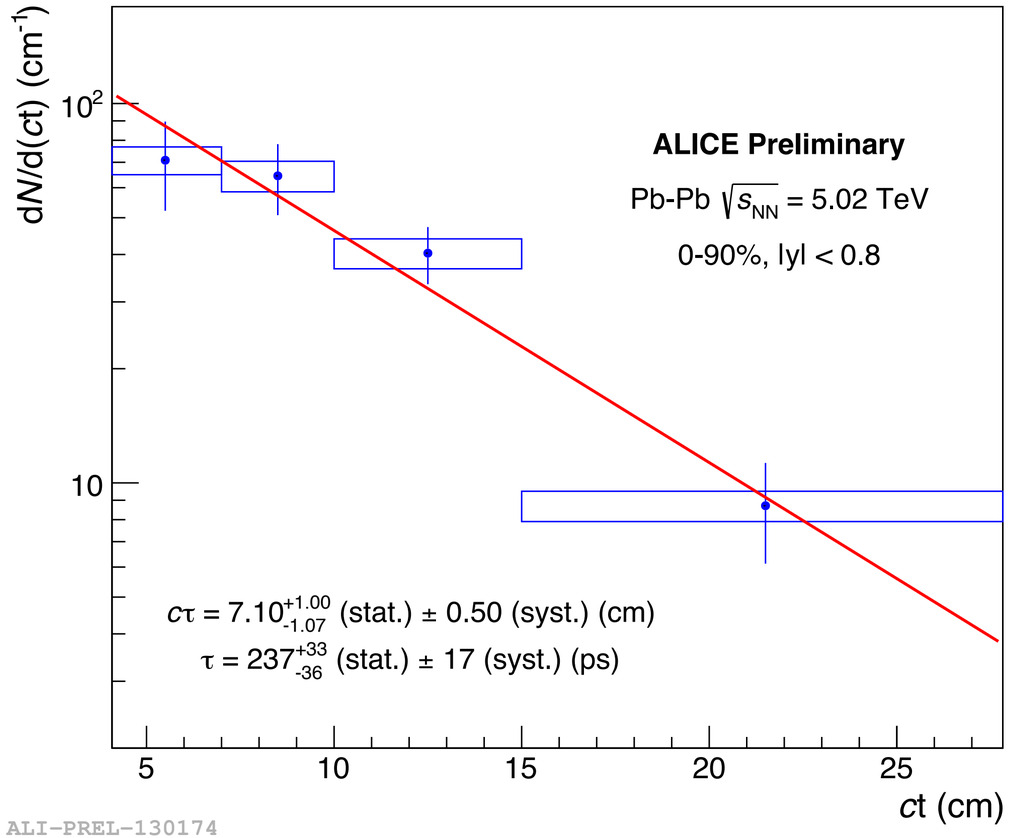
New results on hypertriton production in Pb-Pb collisions at 5.02 TeV

Hypertriton search with ALICE at the LHC

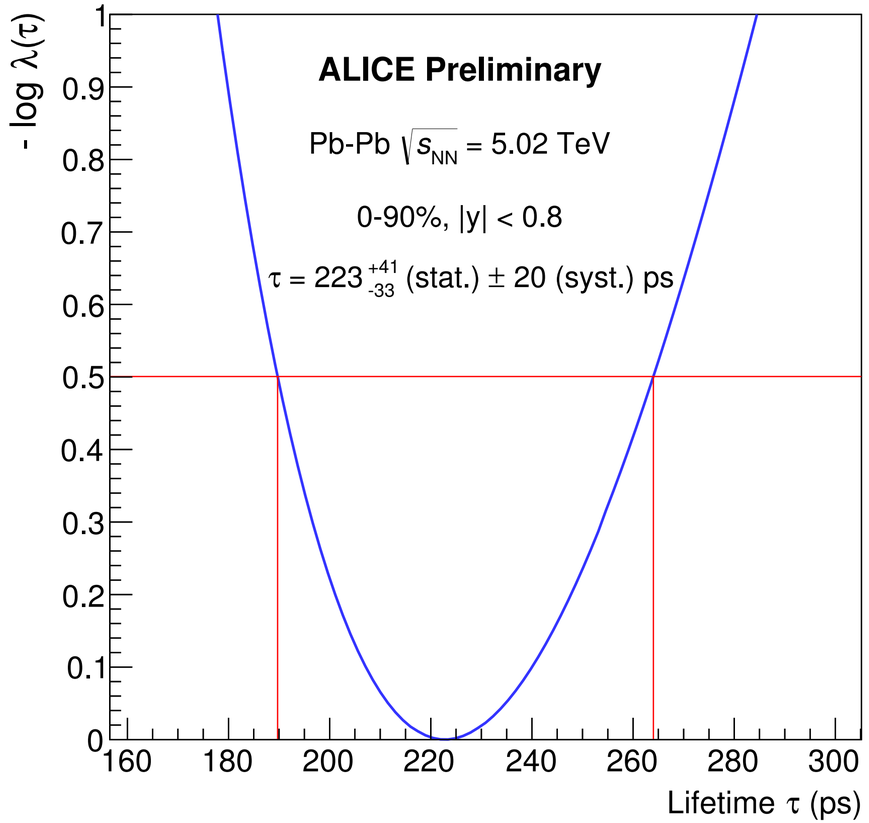




Hypertriton search with ALICE at the LHC



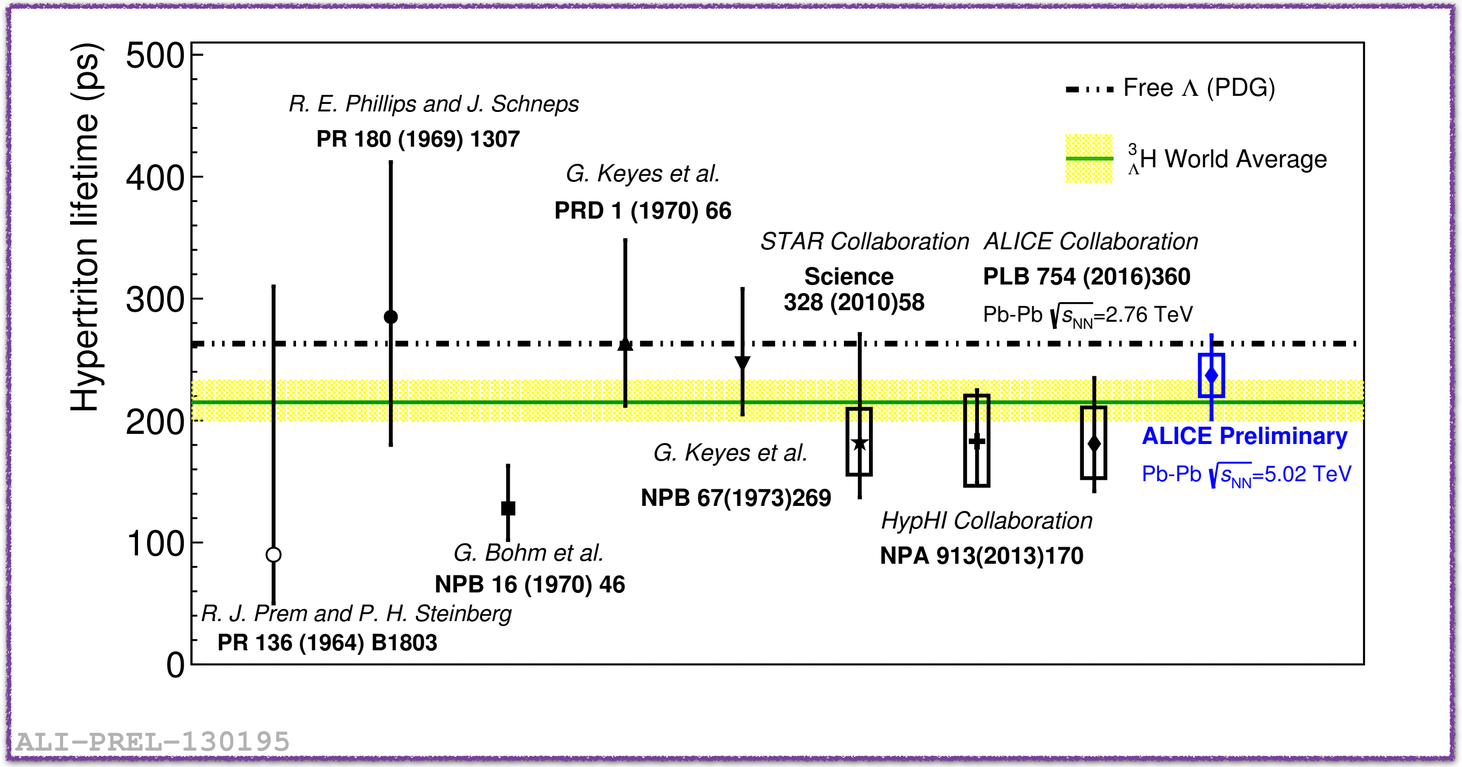
ALI-PREL-130174



ALI-PREL-130191

Hypertriton *lifetime world data*

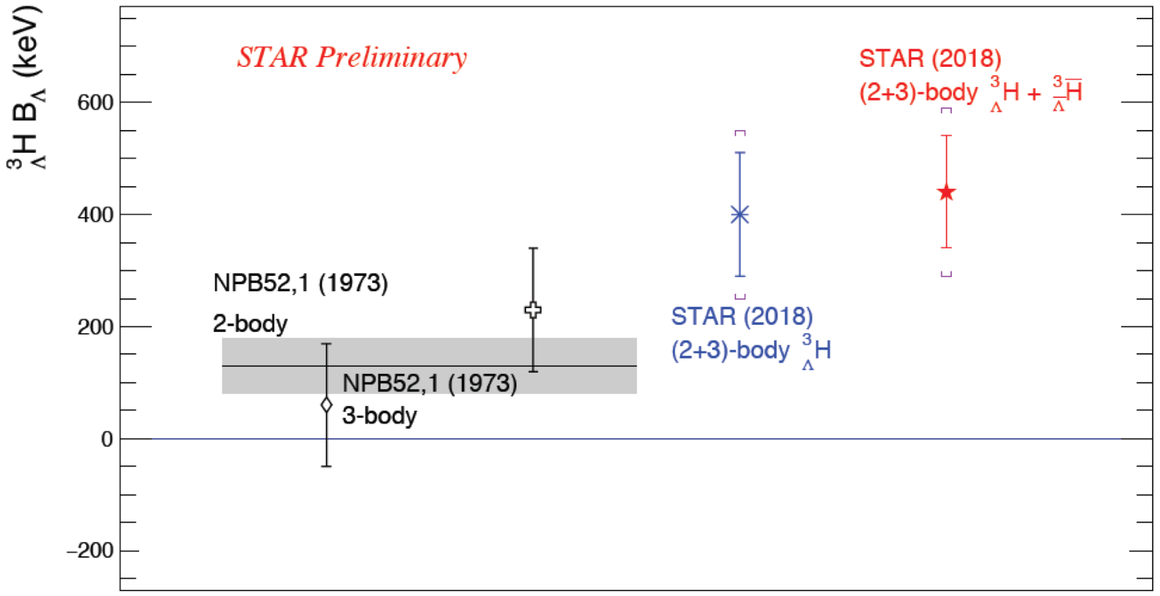
Latest news



- 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 and ~2 σ higher that the latest STAR result (in terms of ALICE uncertainties)
- More precision, reducing the statistical uncertainties can be reached:
  - increasing the statistics
  - lifetime measured in the 3-body decay channel

Hypertriton: news from STAR

Latest news

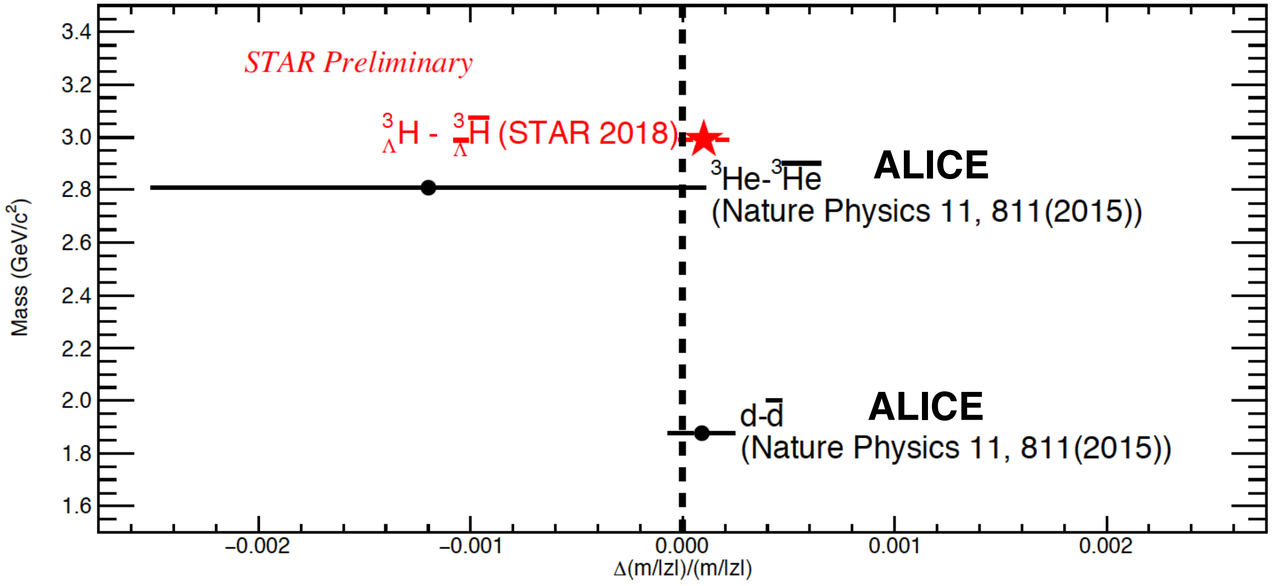


Mean + stat. uncertainty only (NPB 52,1 (1973))

0.13 ± 0.05 (stat. only) MeV

STAR (2018): 0.44 ± 0.10(stat.) ± 0.15(syst.) MeV

Mass difference measurement for hyper-matter confirms the result obtained with light nuclei and it is consistent with CPT prediction.



Conclusions

Strangeness enhancement from pp to Pb-Pb collisions

- no energy and colliding system dependence: driven only by multiplicity?
- BES in different colliding system at RHIC would be beneficial
- What we need to change in microscopic models?

(Anti-)nuclei production

- production in small system well reproduced by coalescence models
- thermal model prediction works nicely for heavy-ion results
- evolution of the results vs multiplicity: is there a common mechanism behind the production in different collisions system ?

(Anti-)hypernuclei production

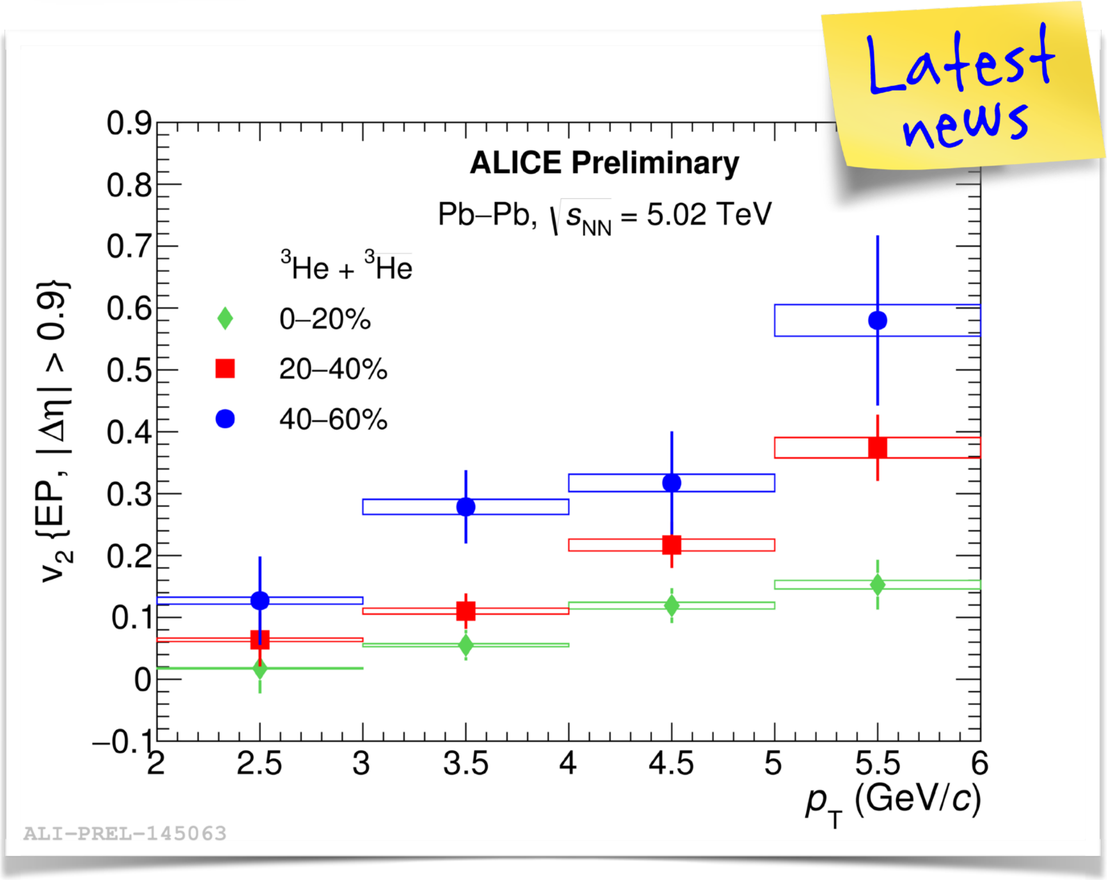
- latest hypertriton lifetime from ALICE closer to the model prediction: more precision is needed to solve the existing puzzle
- hypermatter measurement as a test of CPT symmetry

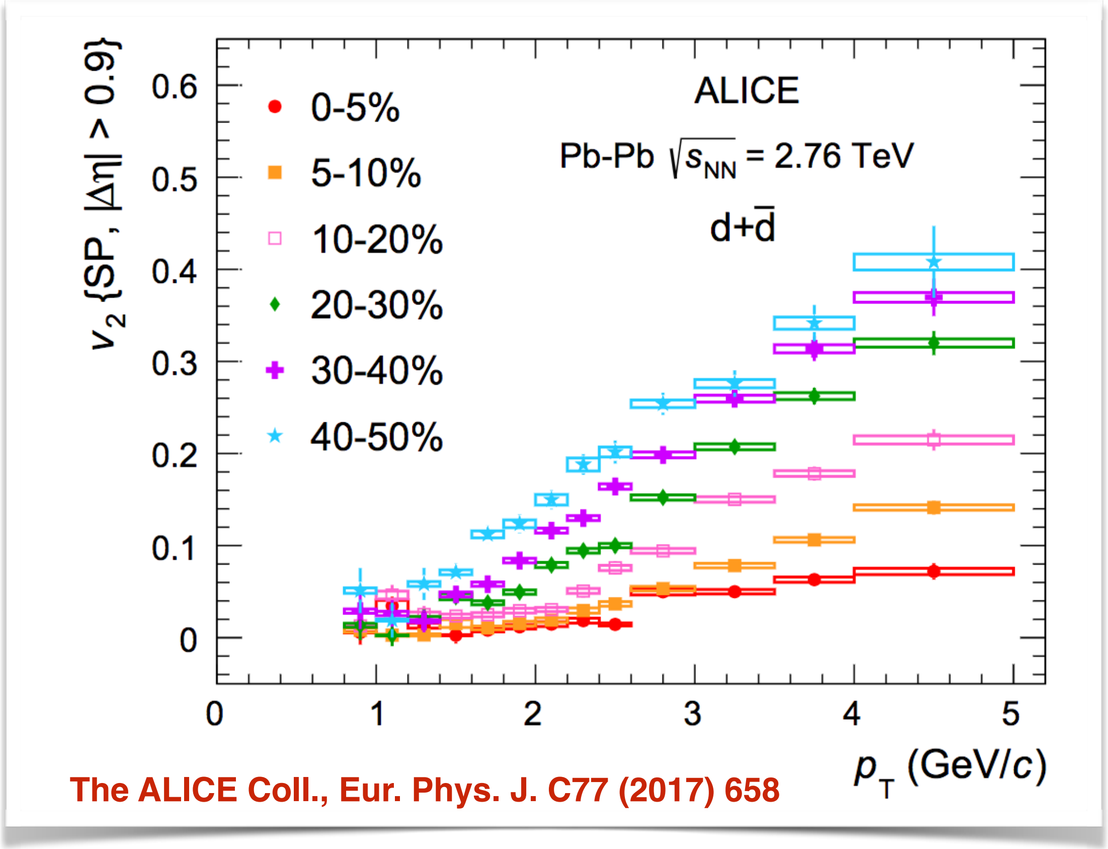
Thank you!

Backup

Elliptic flow measurement: d and ^{3}He

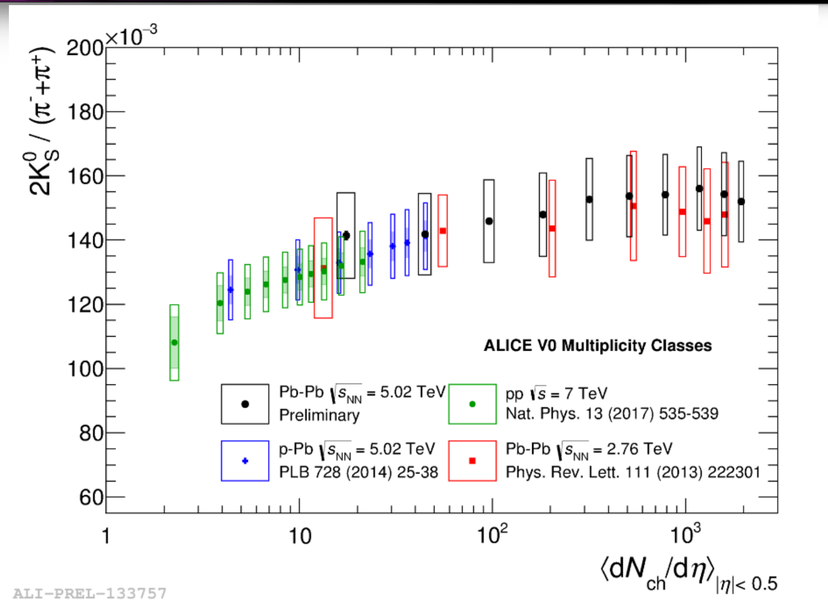
Latest news



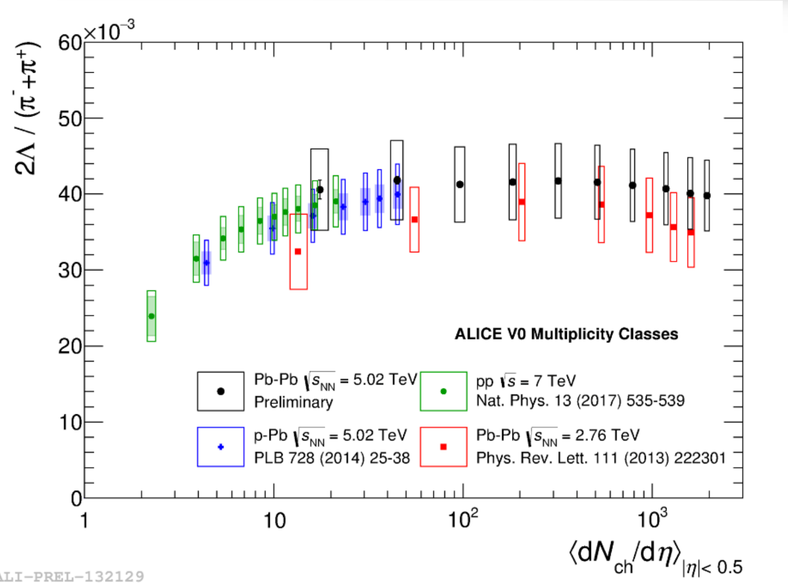


The ALICE Coll., Eur. Phys. J. C77 (2017) 658

Strangeness enhancement: multiplicity dependence



ALI-PREL-133757



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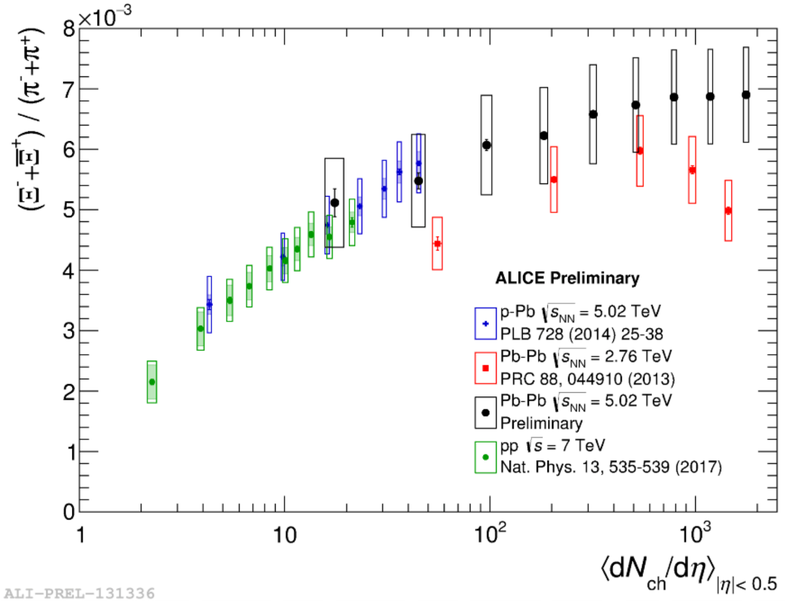

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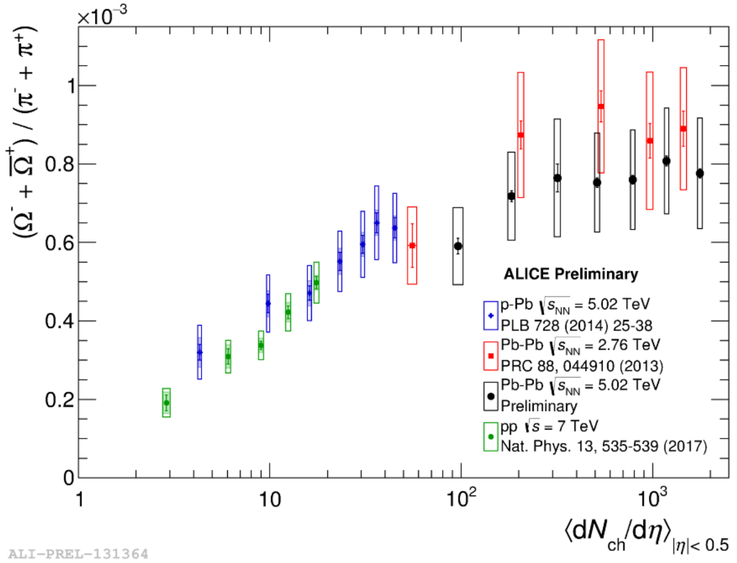

ALI-PREL-131364