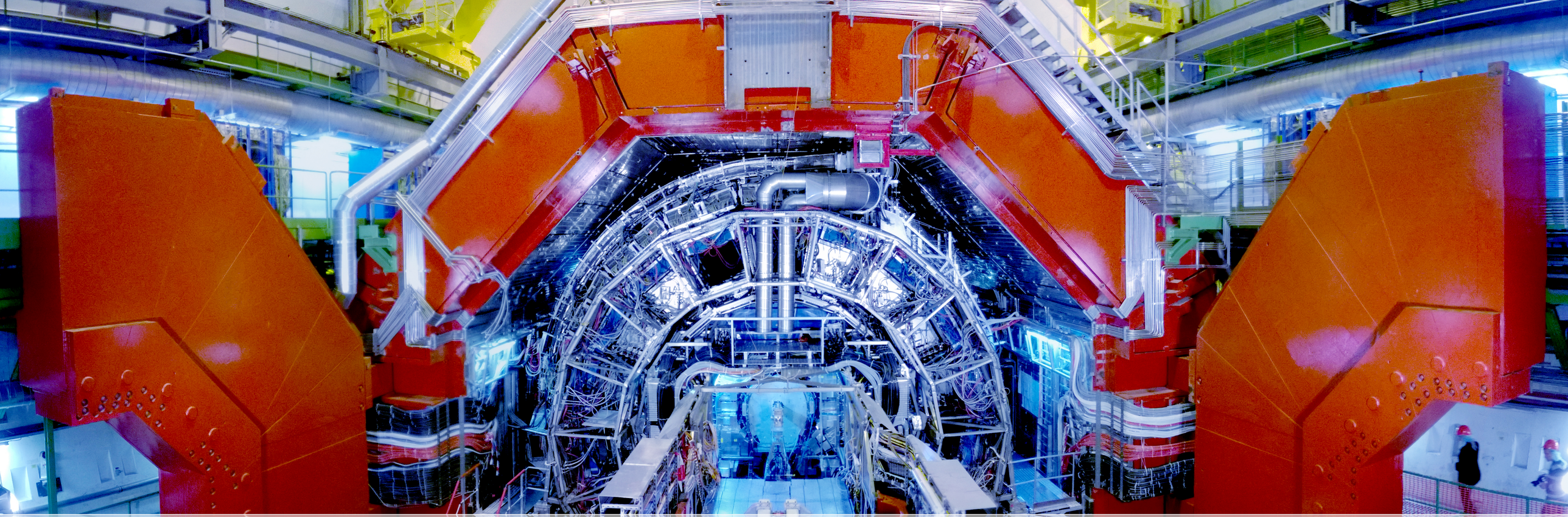
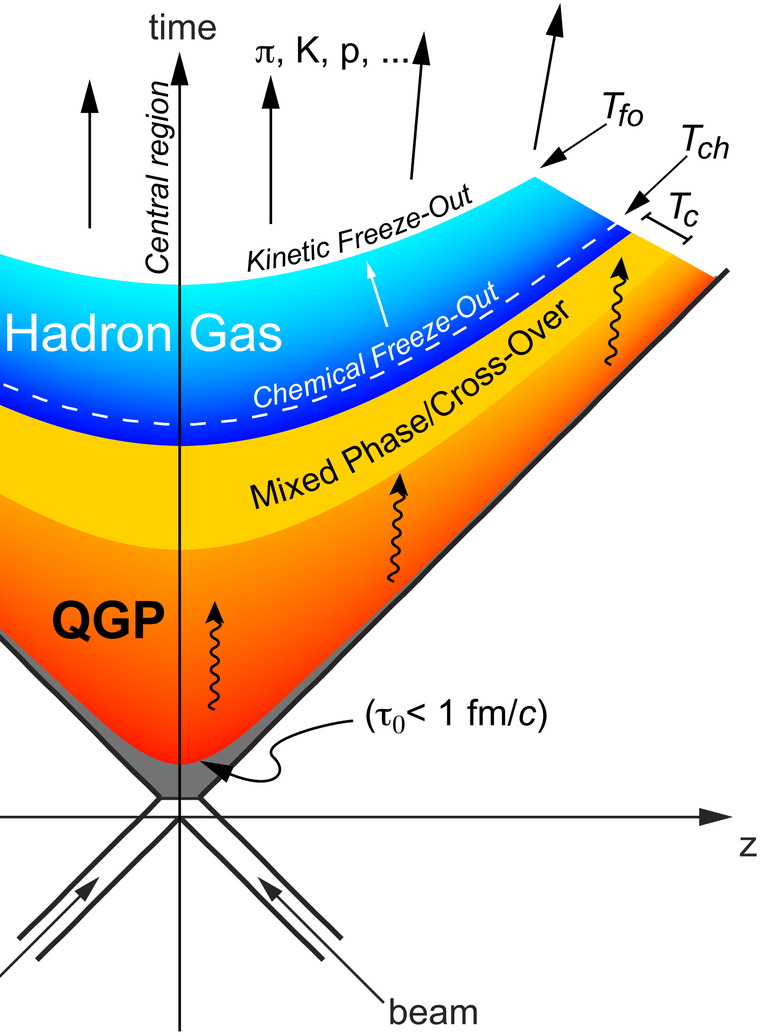


(Anti-)nuclei production and v_2 in heavy ion collisions at the LHC

Maximiliano Puccio on behalf of ALICE Collaboration
University and INFN Torino

Venezia
2018 Quark Matter - 16th May

Why studying nuclei in HIC and why we should care



Question 1: When are light nuclei formed?

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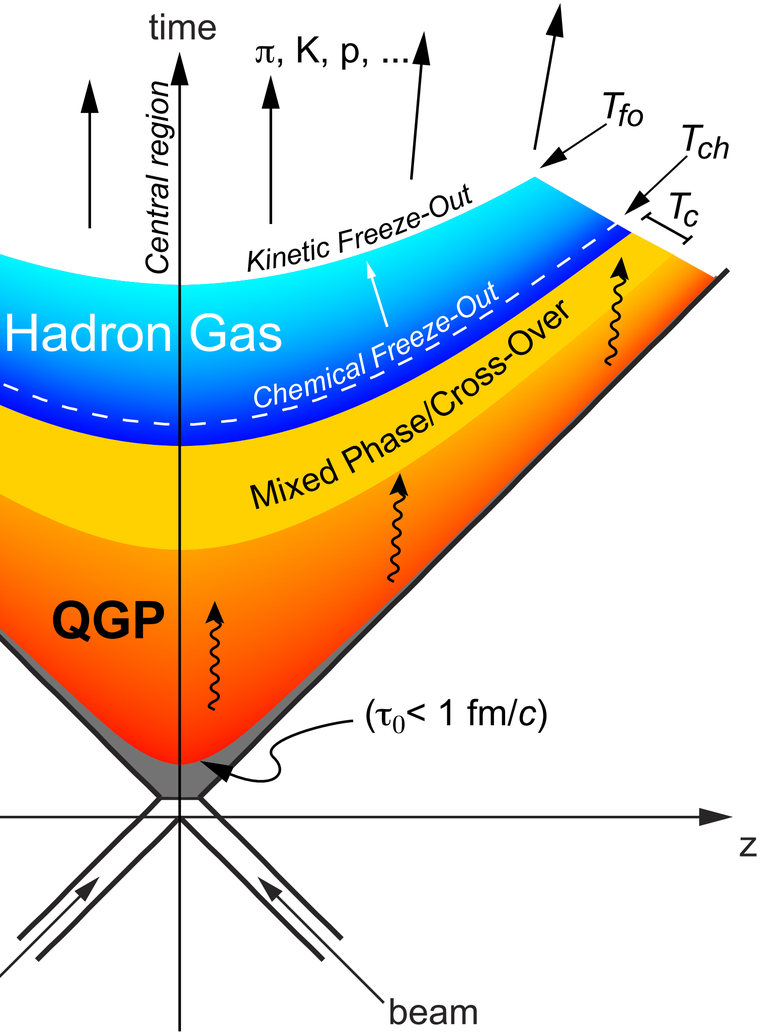

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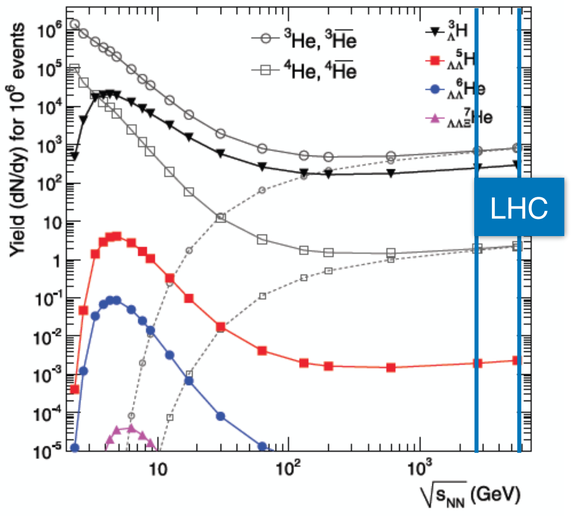
THERMAL MODELS

- Hadrons emitted from the interaction region in statistical equilibrium when the fireball reaches limiting temperature
- Abundances fixed at chemical freeze-out
- Freeze-out temperature T_{chem} is a key parameter
- Abundance of a species $\propto \exp(-m/T_{chem})$:
  - ➡ For nuclei (large m) strong dependence on T_{chem}

A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stoecker, Phys. Lett. B607, 203 (2011), 1010.2995



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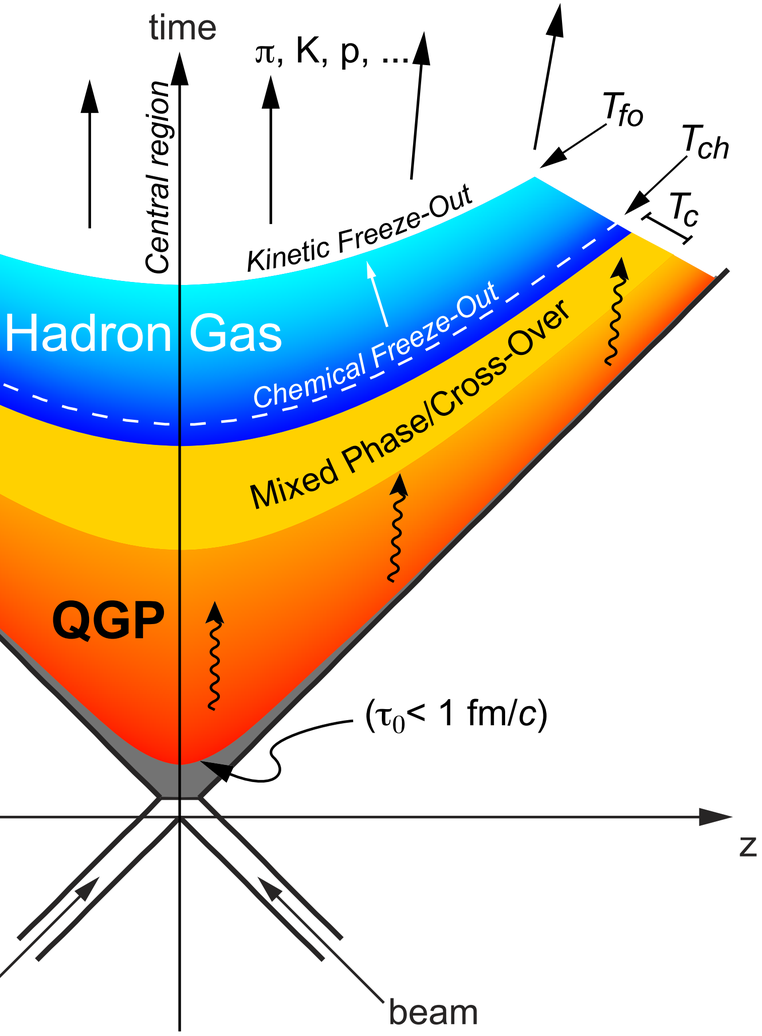

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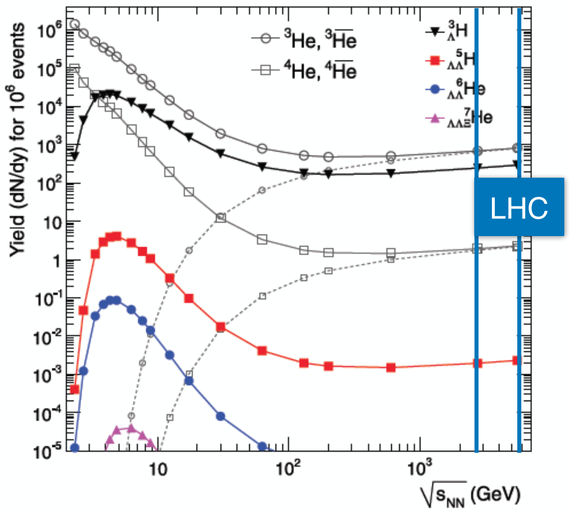

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- If (anti-)baryons are close in phase space after the kinetic freeze-out they can form a (anti-)nucleus
- (Anti-)nuclei produced at the chemical freeze-out might break up and re-form during the time span between the chemical freeze-out and the kinetic freeze-out.

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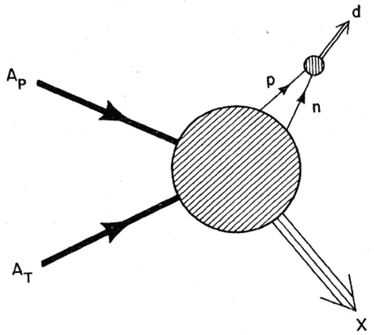

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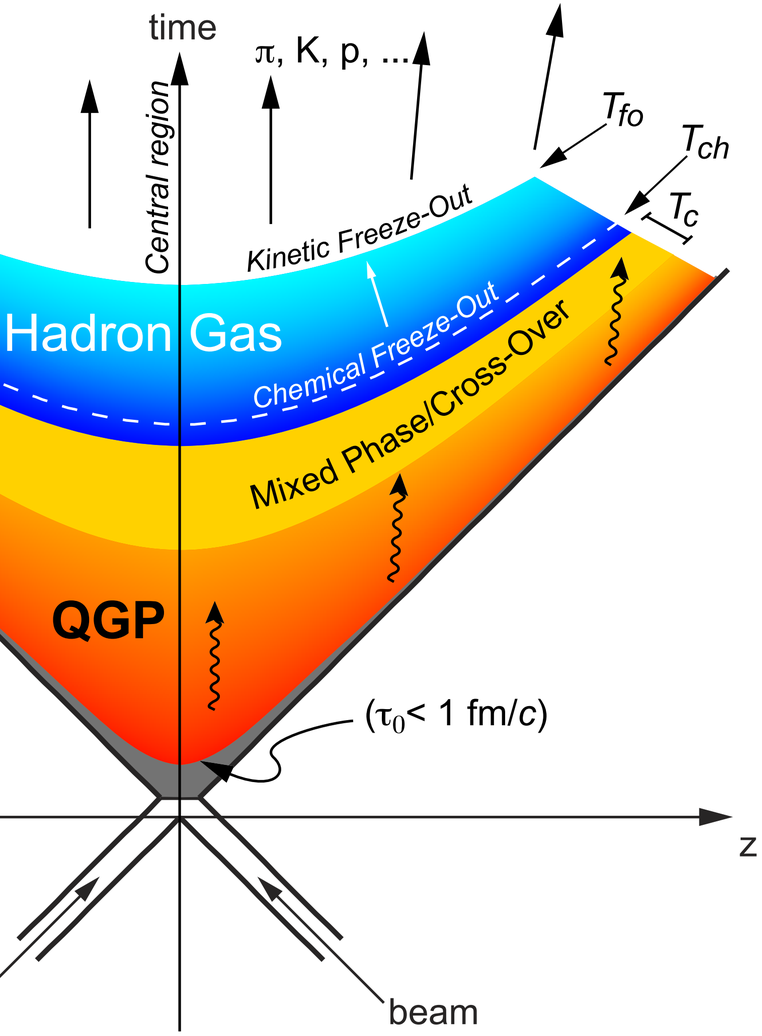

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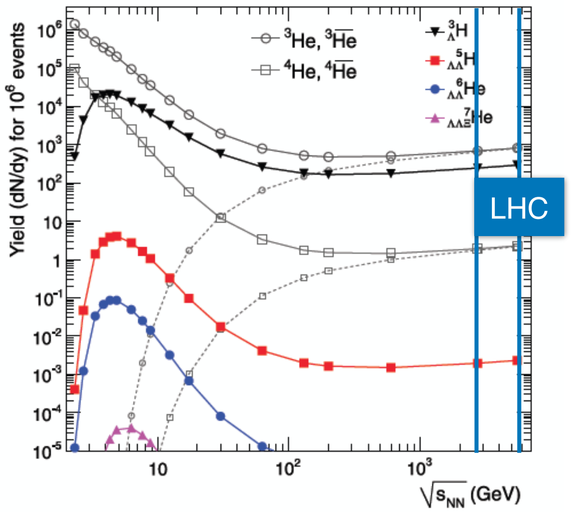

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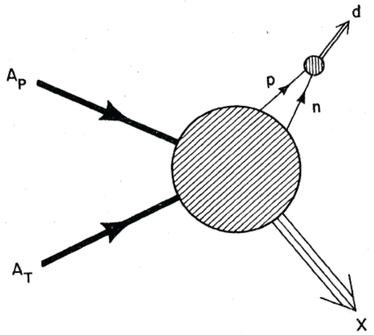

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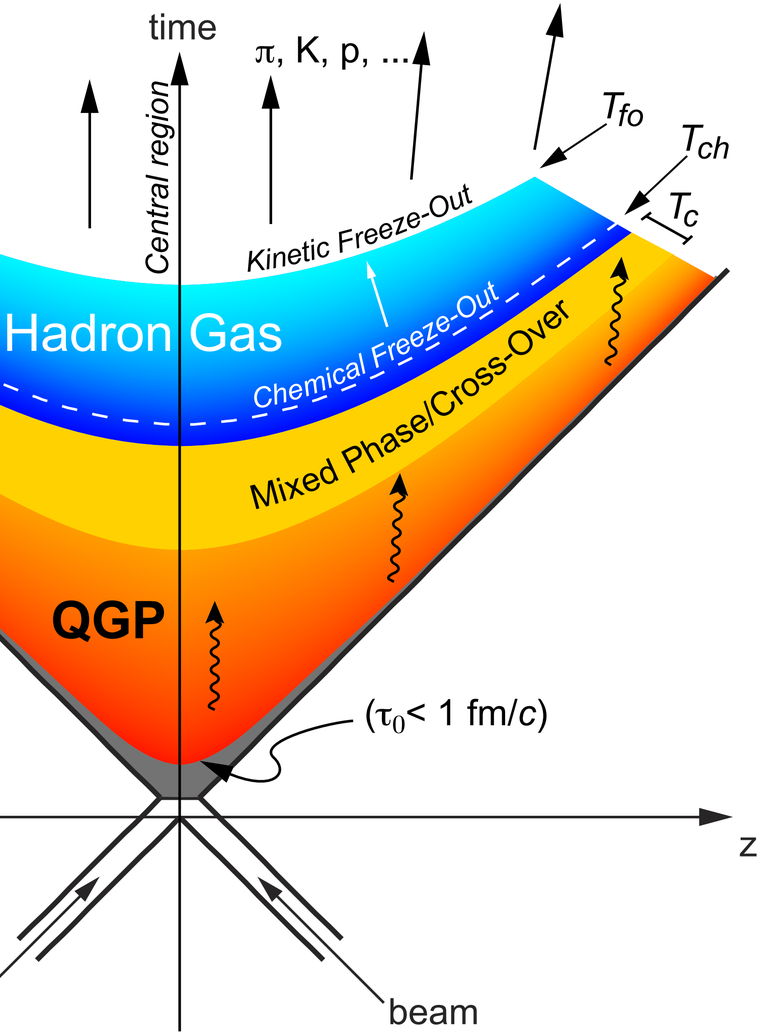

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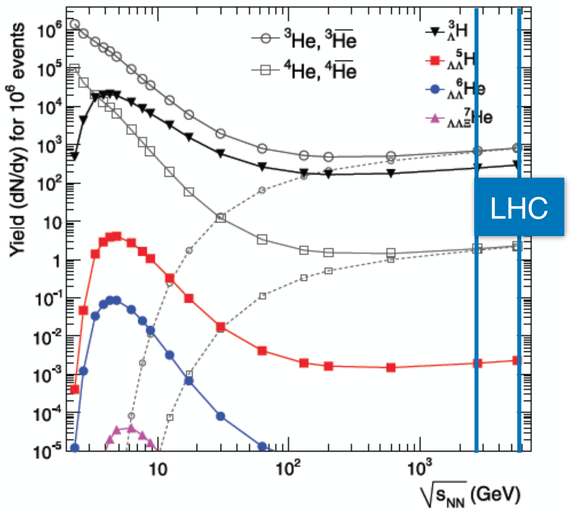

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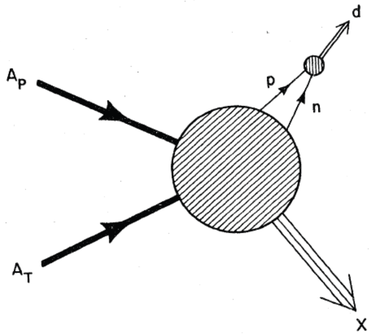

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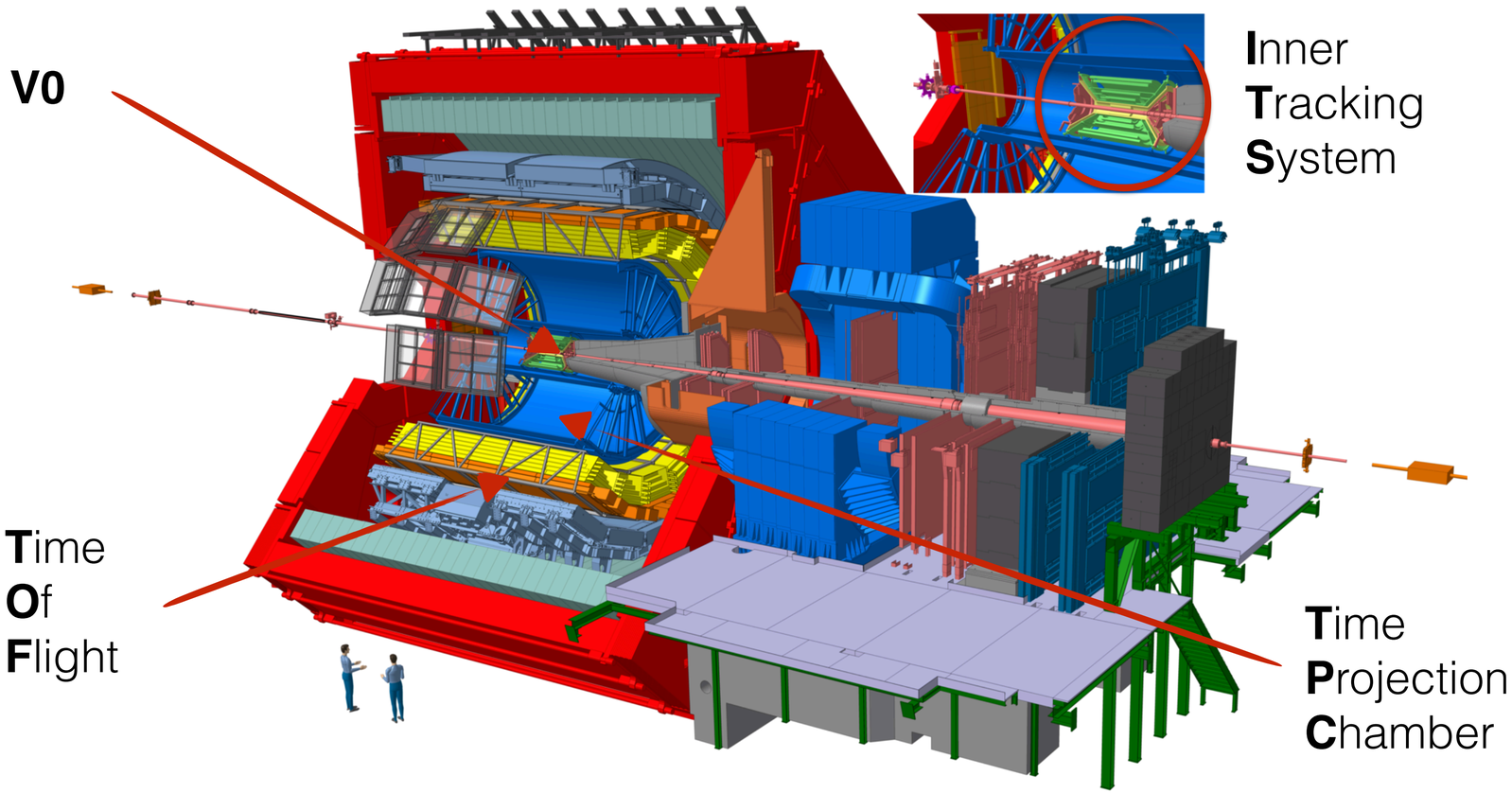
Studying the (Anti-)(Hyper-)Nuclei production properties will help us to understand better our current description of the latest stages of a Heavy Ion collision and will shed light on the nucleosynthesis mechanism at hadron colliders.

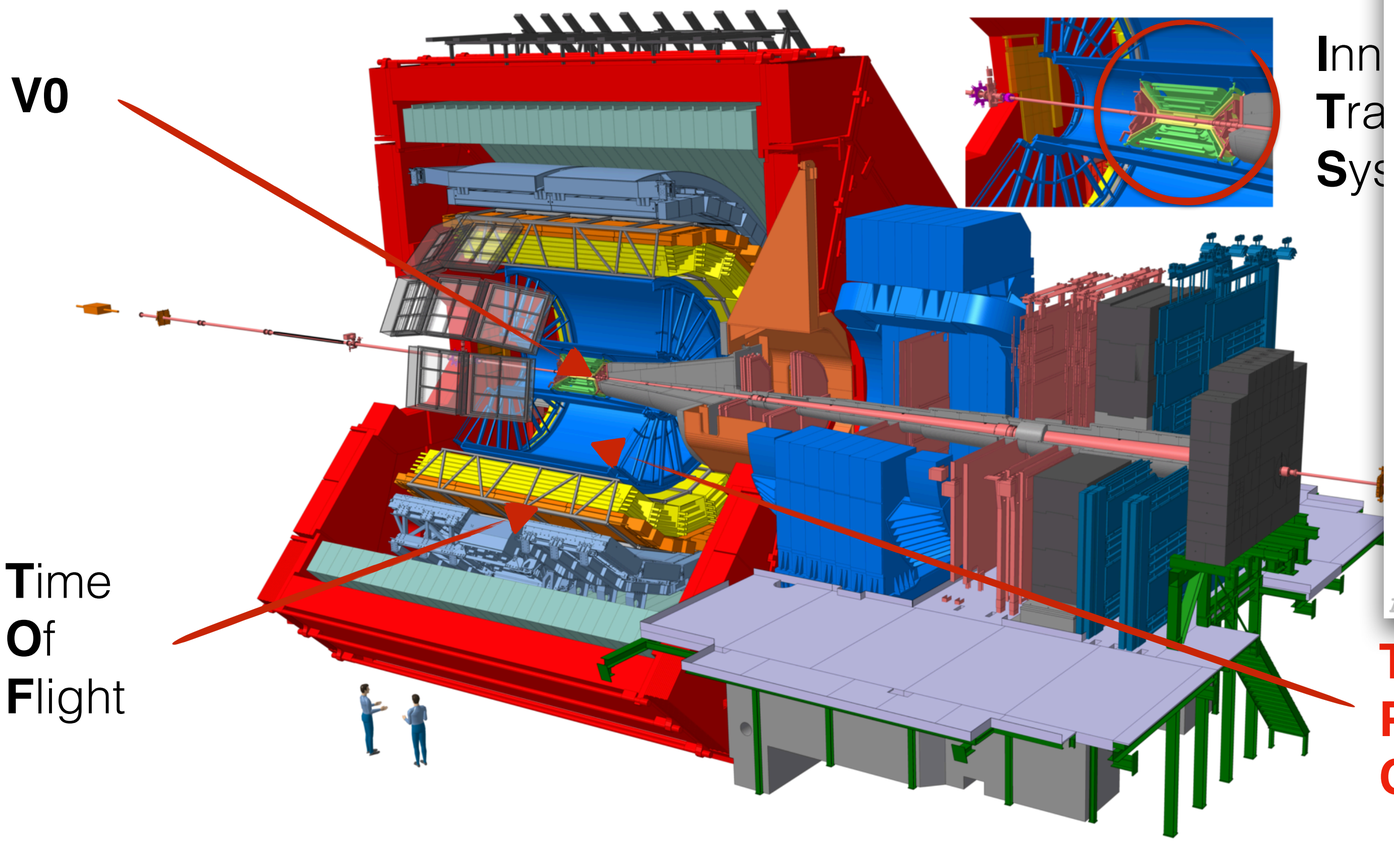
ALICE

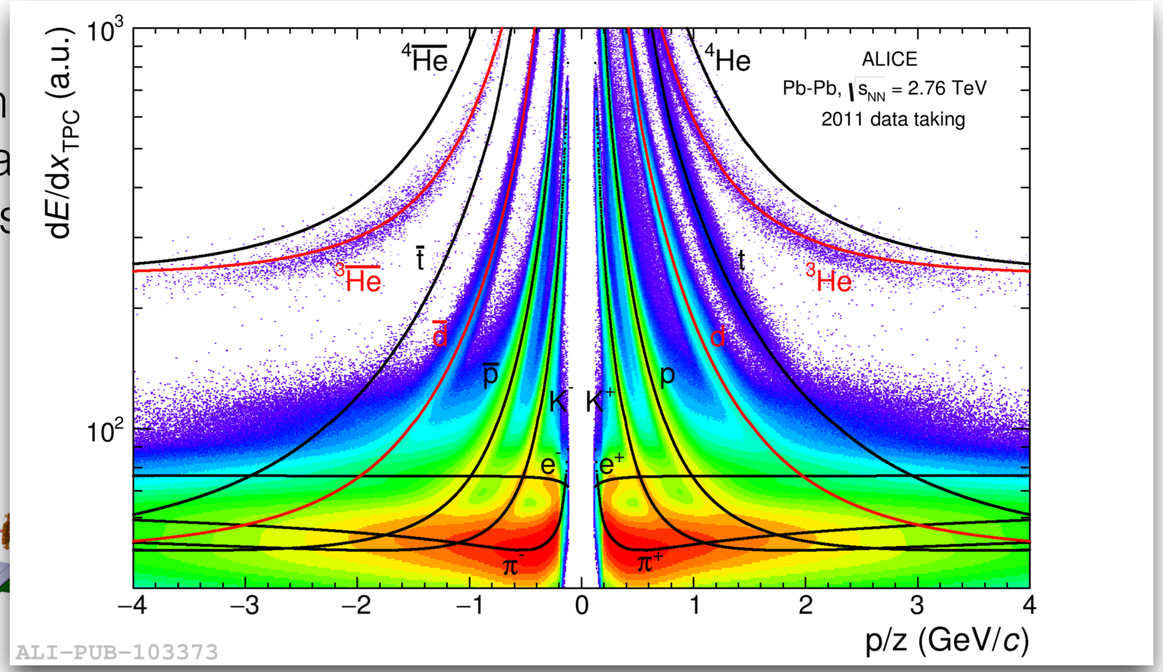


- General purpose heavy ion experiment
- Excellent particle identification (PID) capabilities and low material budget

➡Most suited detector at the LHC to study the (anti-)(hyper-)nuclei produced in pp, p-A and Pb-Pb collisions

ALICE - (Anti-)Nuclei identification

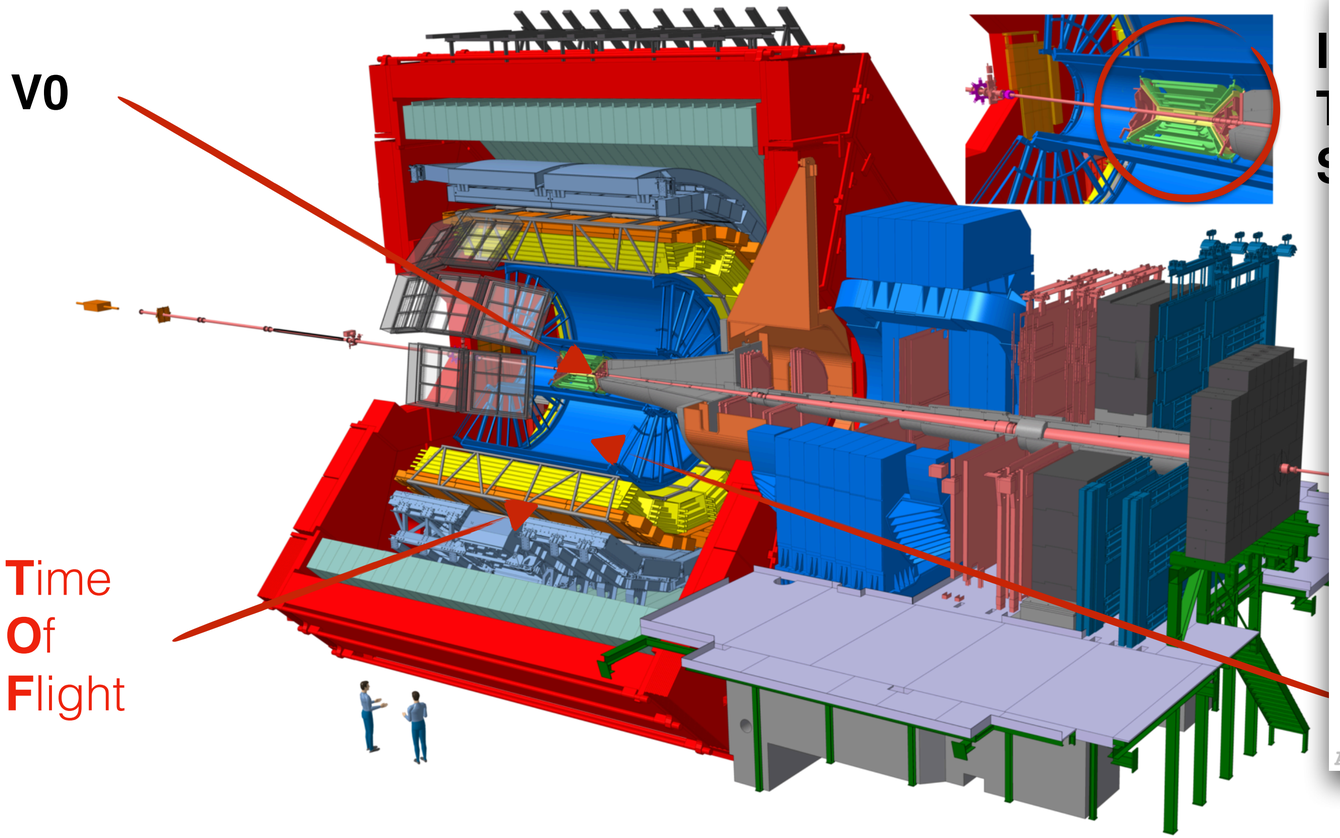


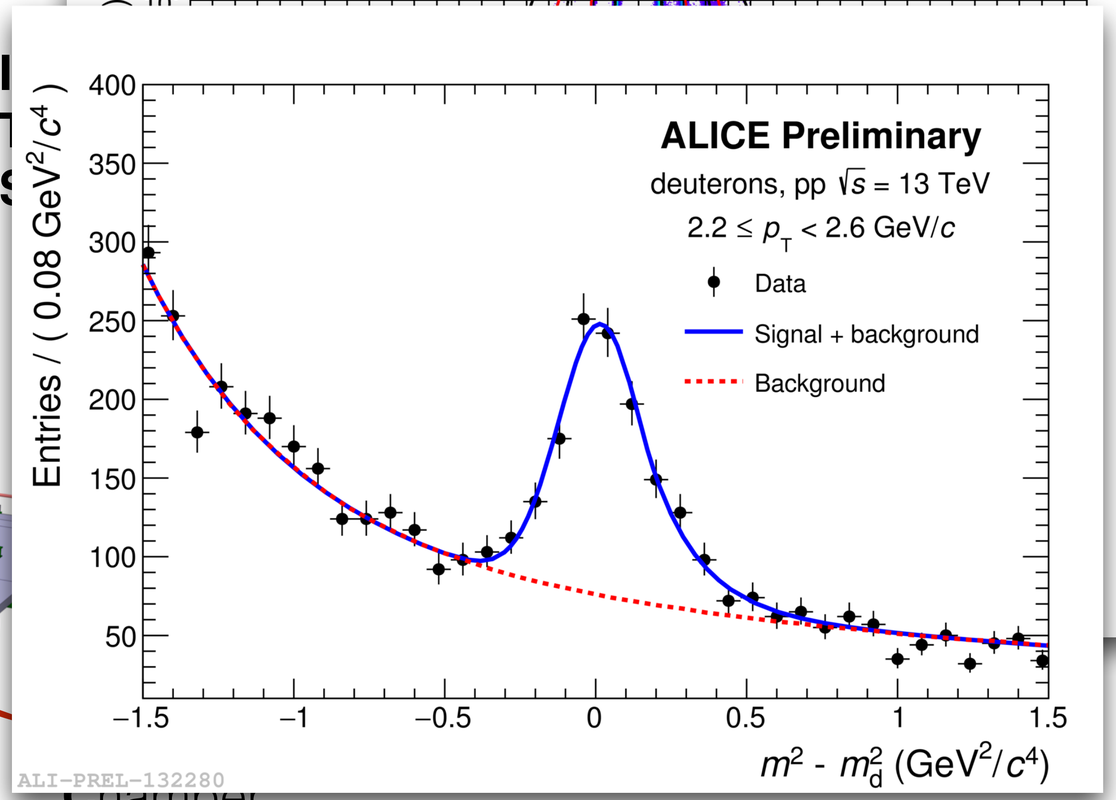


Time
Projection
Chamber

- At $p_T \leq 1.2$ GeV/c the TPC energy loss provides an excellent PID for deuterons
  - ➡$\sigma_{dE/dx}$~6.5% (in Pb-Pb collisions)
- (anti-)^{3}He well separated from the other particle species over the full momentum range
  - Raw yields extracted for each p_T bin from the fit to the nσ distributions

ALICE - (Anti-)Nuclei identification





- At higher p_T the PID is performed using TOF to measure the β of the particle.
  - ➡$\sigma_{TOF\text{-}PID}$~ 85 ps in Pb-Pb collisions
  - ➡$\sigma_{TOF\text{-}PID}$~ 120 ps in pp collisions due to the lower precision on the event start time
- Raw yields extracted for each p_T bin from the TOF mass spectra fit

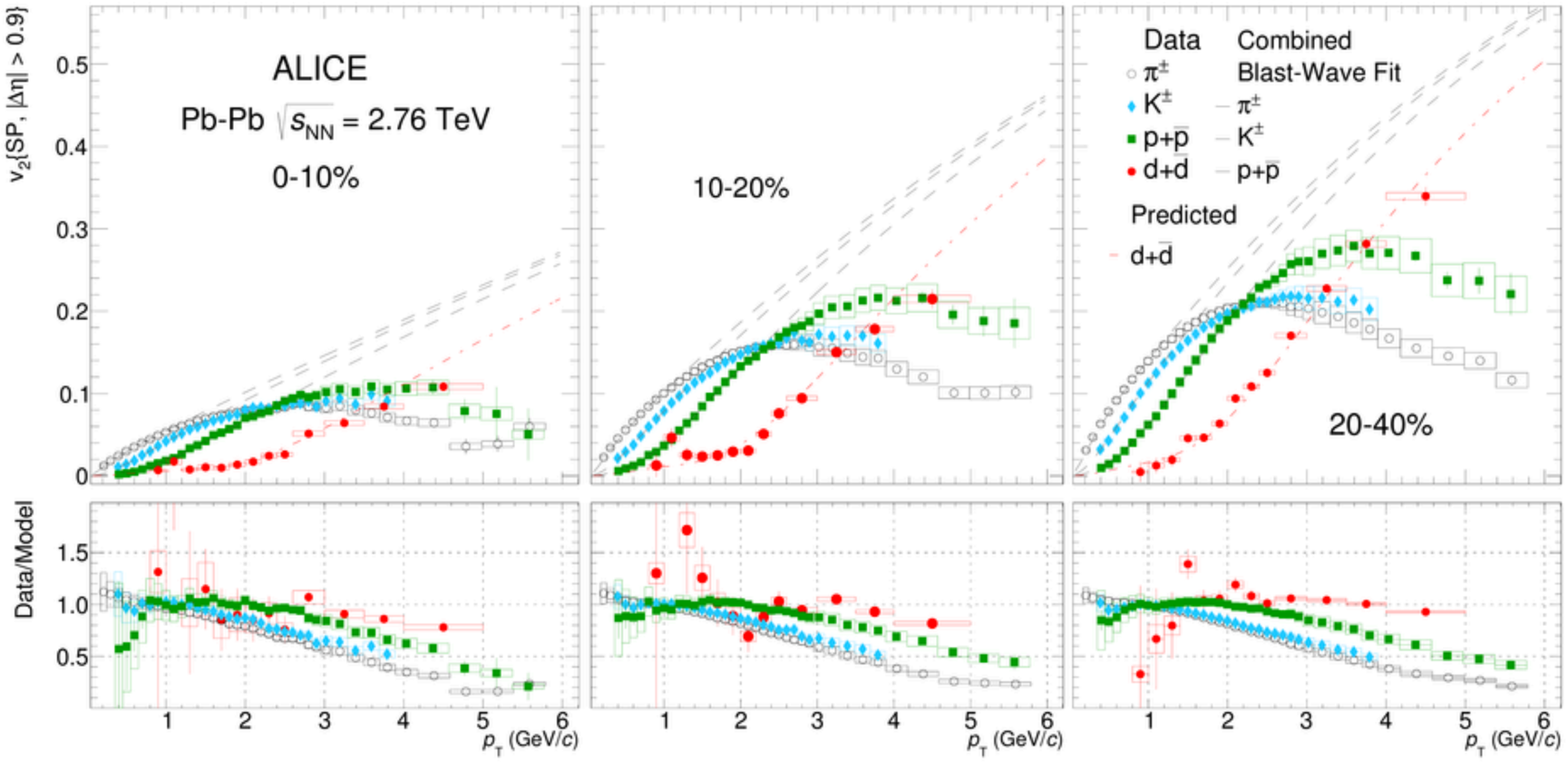
(Anti-)deuteron v_2 and spectra in Pb-Pb

ALICE, 10.1140/epjc/s10052-017-5222-x

Elliptic flow was measured using the scalar product method

- Particles measured by V0A ($2.8 < \eta < 5.1$) and V0C ($-3.7 < \eta < -1.7$) as reference.
- Deuteron candidates are the particles of interest ($|\eta|<0.8$)

$$v_n\{SP\} = \frac{\langle u_{n,i}(p_{\mathrm{T}},\eta)\cdot\frac{Q_n^*}{M}\rangle}{\sqrt{\langle\frac{Q_{n,A}^*}{M_A}\cdot\frac{Q_{n,B}^*}{M_B}\rangle}}$$



The Blast Wave model[1], fitted to the spectra and the v_2 of pions, kaons and protons reproduces reasonably well both the v_2 and the spectra of deuterons

➡**Hint for a common kinetic freeze-out with lighter particles!**

[1]E. Schnedermann et al., 10.1103/PhysRevC.48.2462; STAR, 10.1103/PhysRevLett.87.182301

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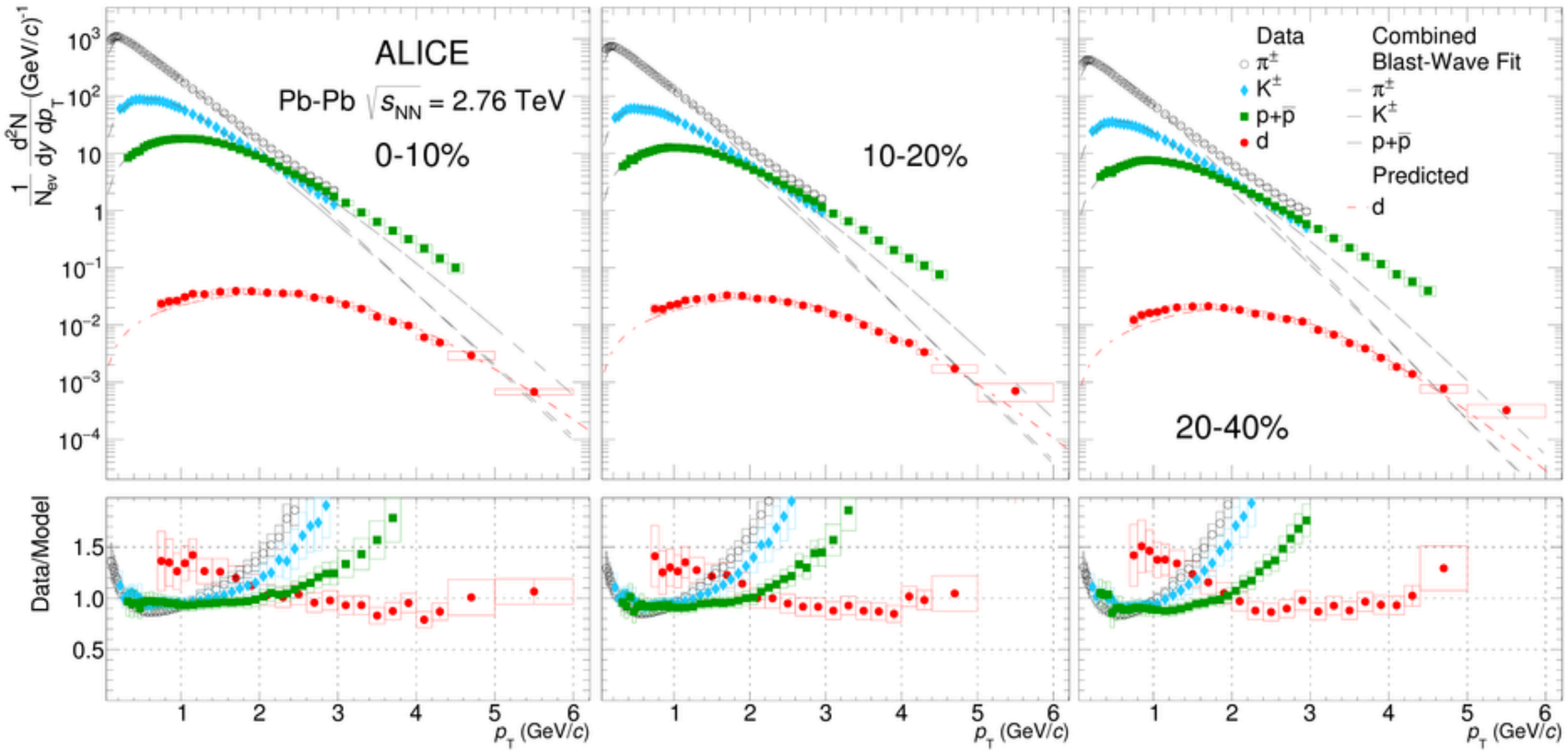

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The coalescence parameter for a nucleus *i* with A nucleons is defined as:

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deuterons →

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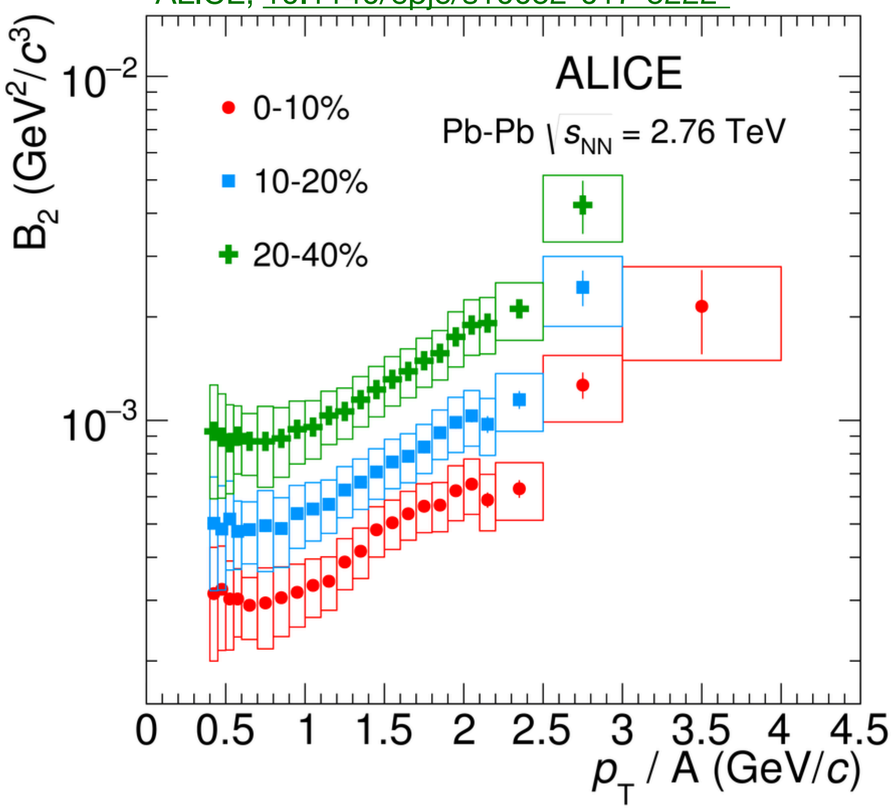
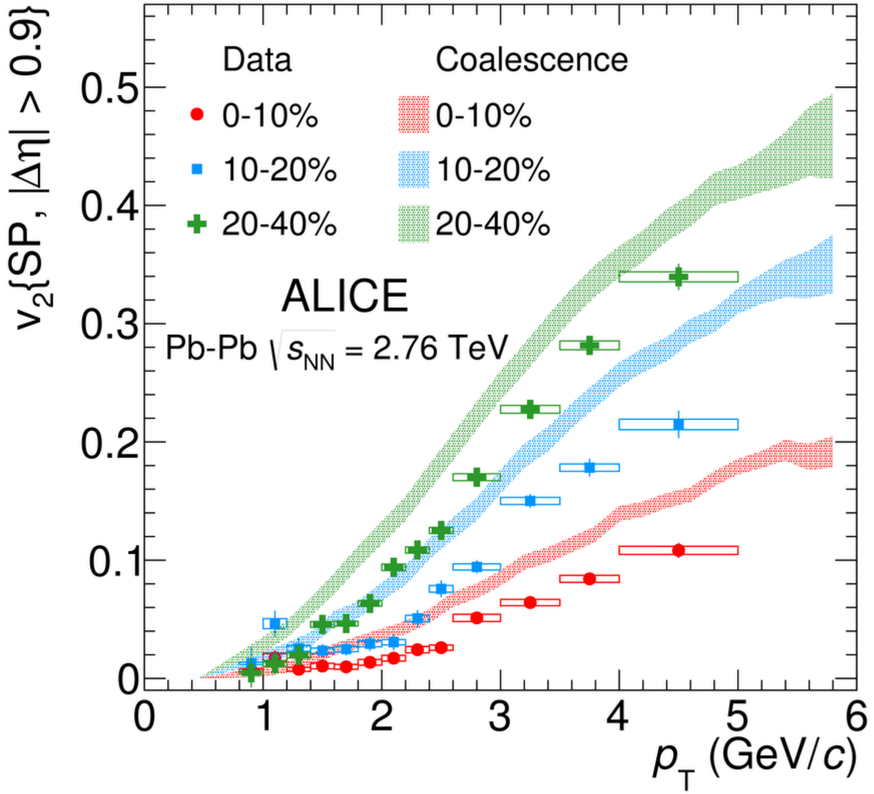
Simple coalescence

- Flat coalescence parameter
- $v^d_2(p^d_T)=2v_2^p(2p^p_T)$

ALICE, 10.1140/epjc/s10052-017-5222-





In general, **simple coalescence does not describe ALICE deuteron measurement in Pb-Pb collisions.**

- Different observation made at lower energies, where simple coalescence is able to describe deuteron v_2 in A-A collisions.
- Flattening of the B_2 in peripheral collisions
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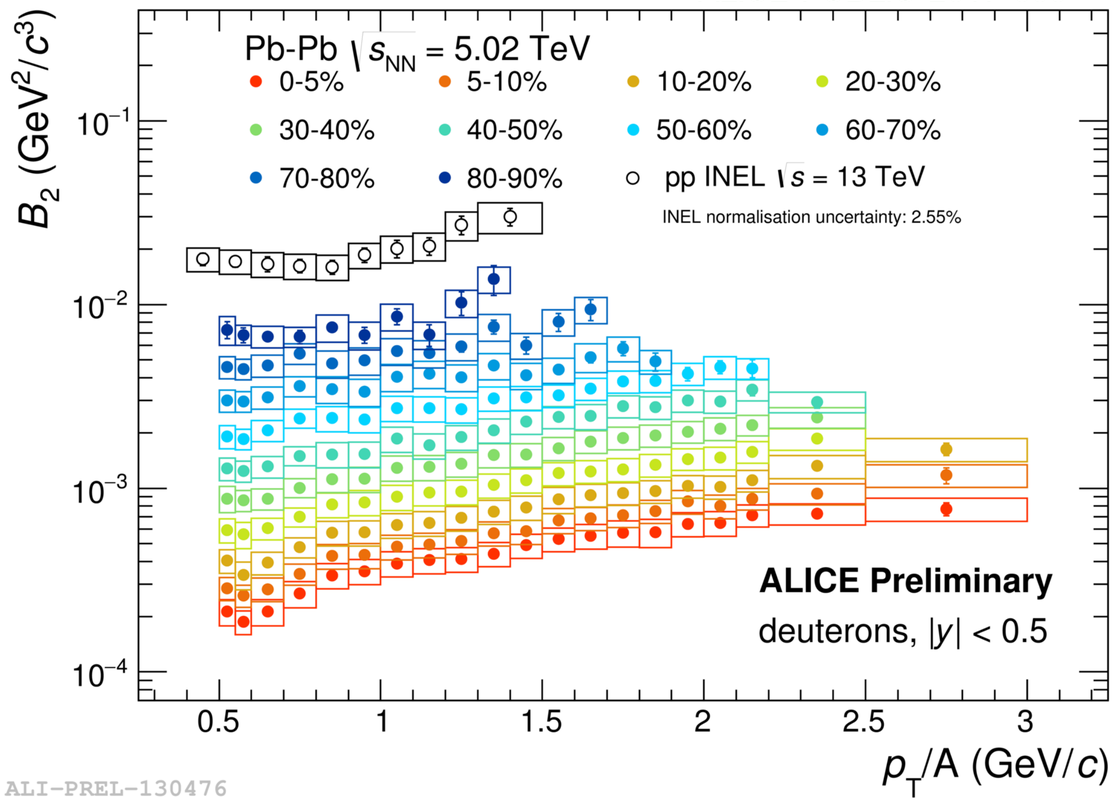

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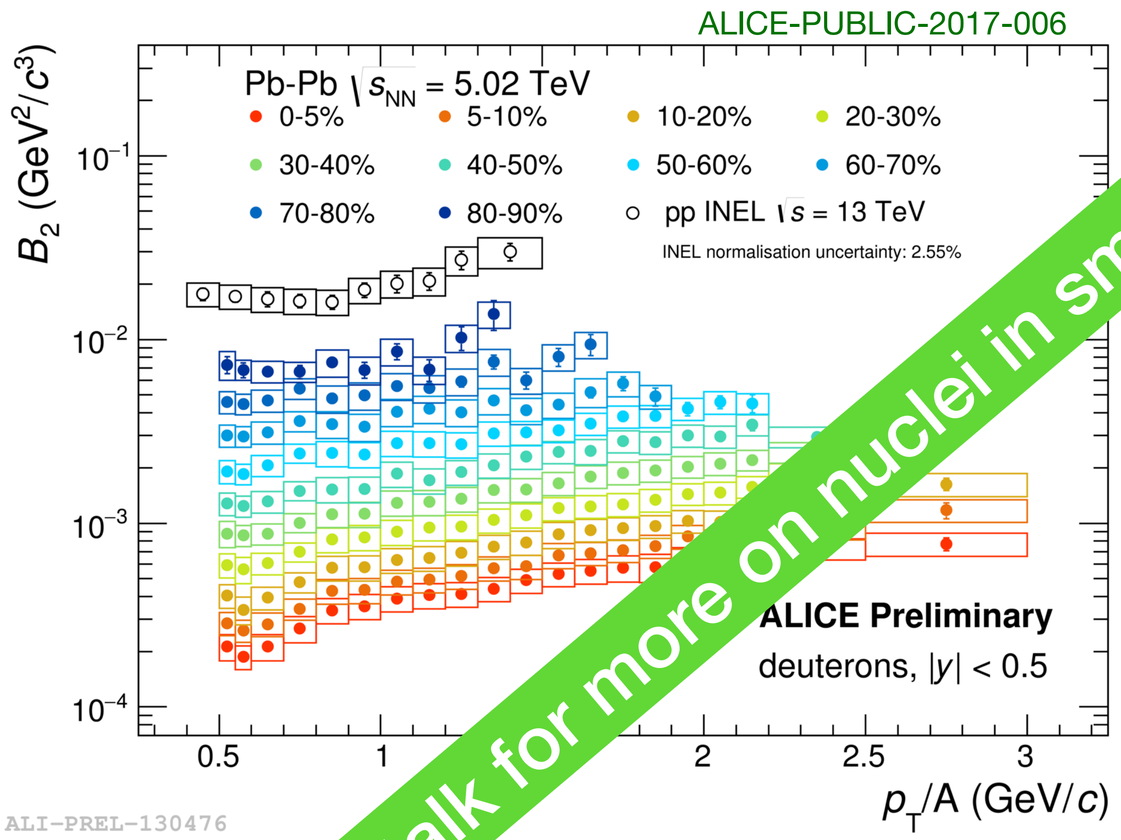

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See M. Colocci talk for more on nuclei in small systems

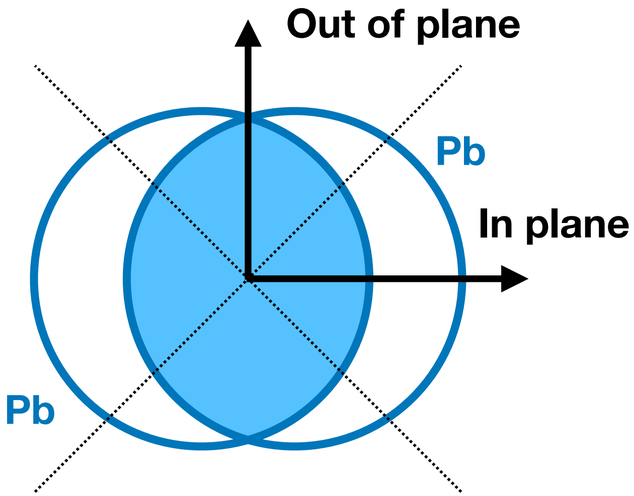
(Anti-)^{3}He v_2 in Pb-Pb

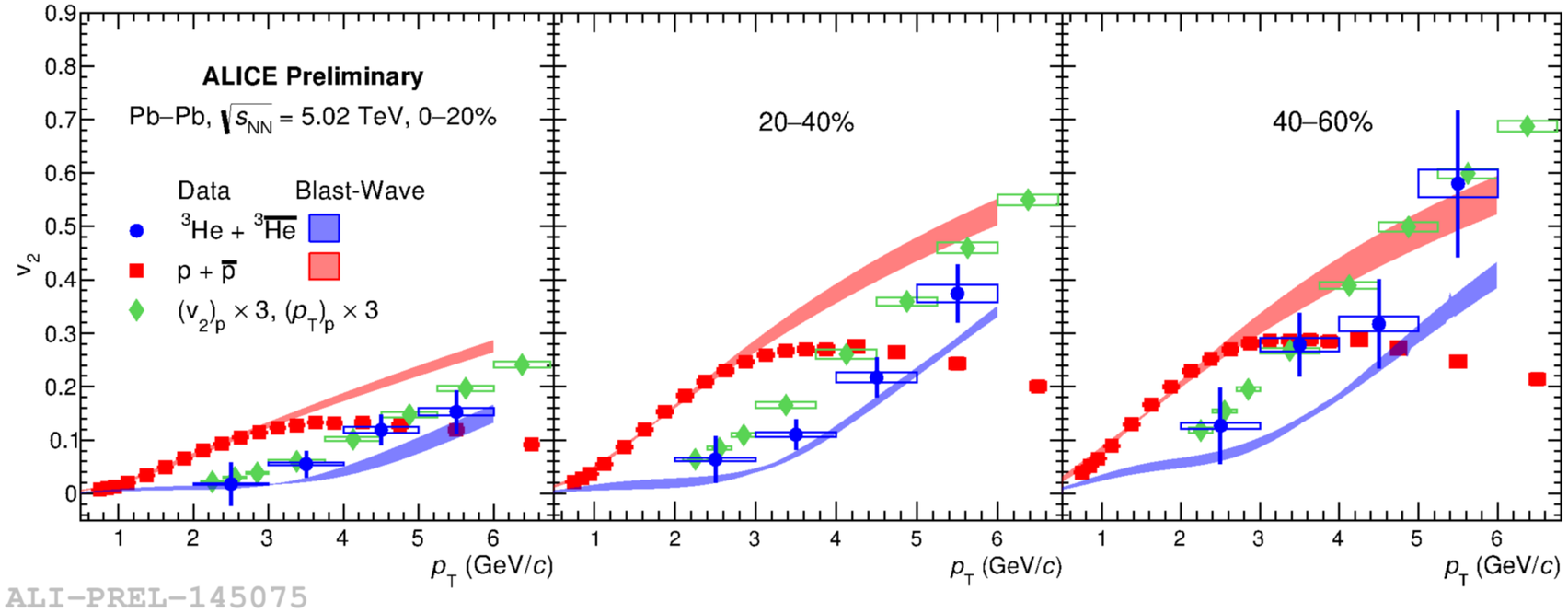
The v_2 of ^{3}He was measured using the Event-Plane method:

1. Reconstruction of the Event Plane (estimator of the Reaction Plane)
2. v_2 computed as:

$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}$$

R_2 is the event plane resolution





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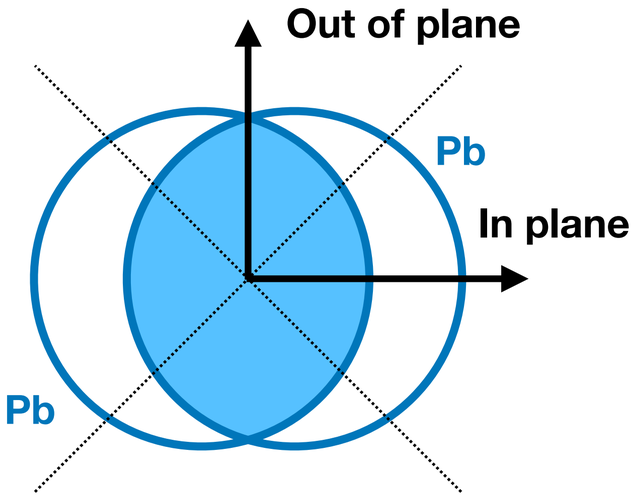

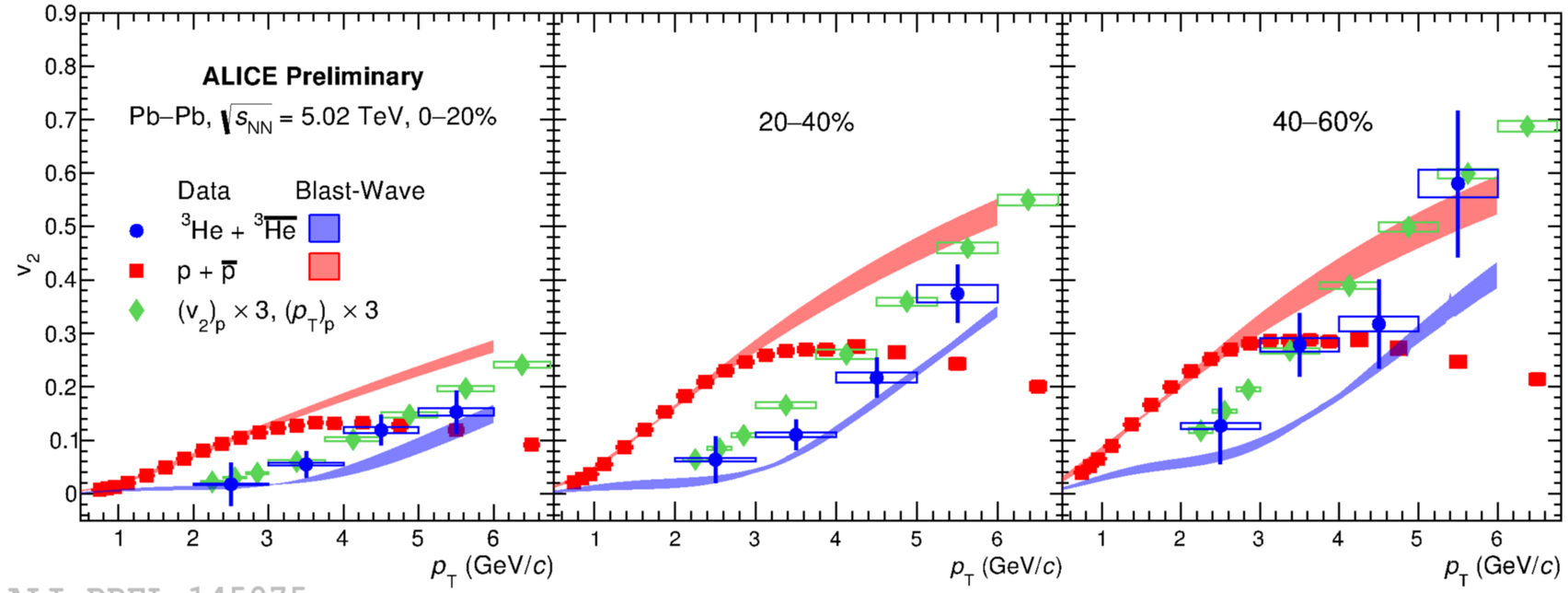

Different behaviour with respect to the deuteron v_2!

- The overall agreement of the Blast-Wave[1] fitted to lighter species prediction for ^{3}He is better in the most central collisions
- The simple coalescence expectation (green points) gets closer to the measured ^{3}He for 40-60% centrality
  - More statistics in the next Pb-Pb run and in the Run3 and Run4 of LHC will help to disentangle this discrepancy!

[1]E. Schnedermann et al., 10.1103/PhysRevC.48.2462; STAR, 10.1103/PhysRevLett.87.182301

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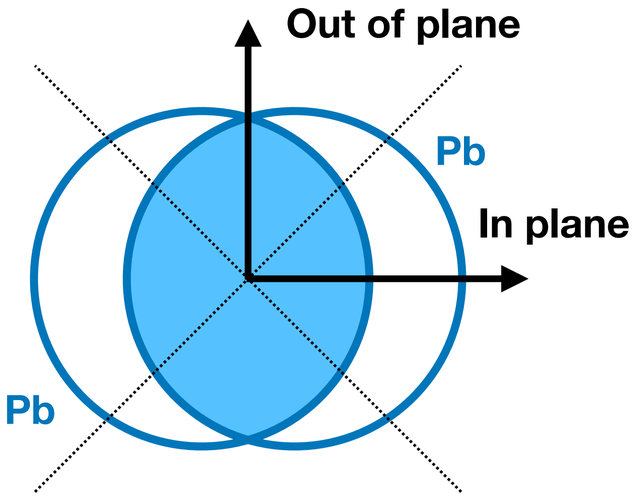

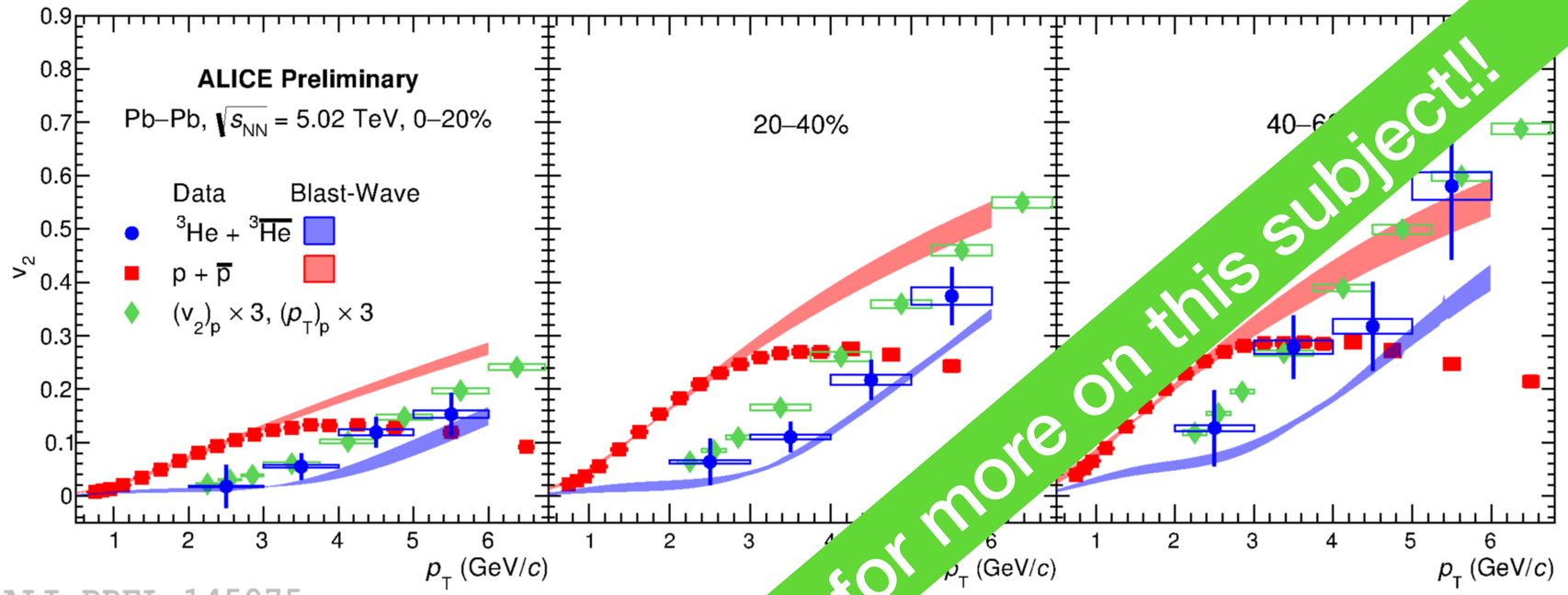

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See A. Calivà poster for more on this subject!!

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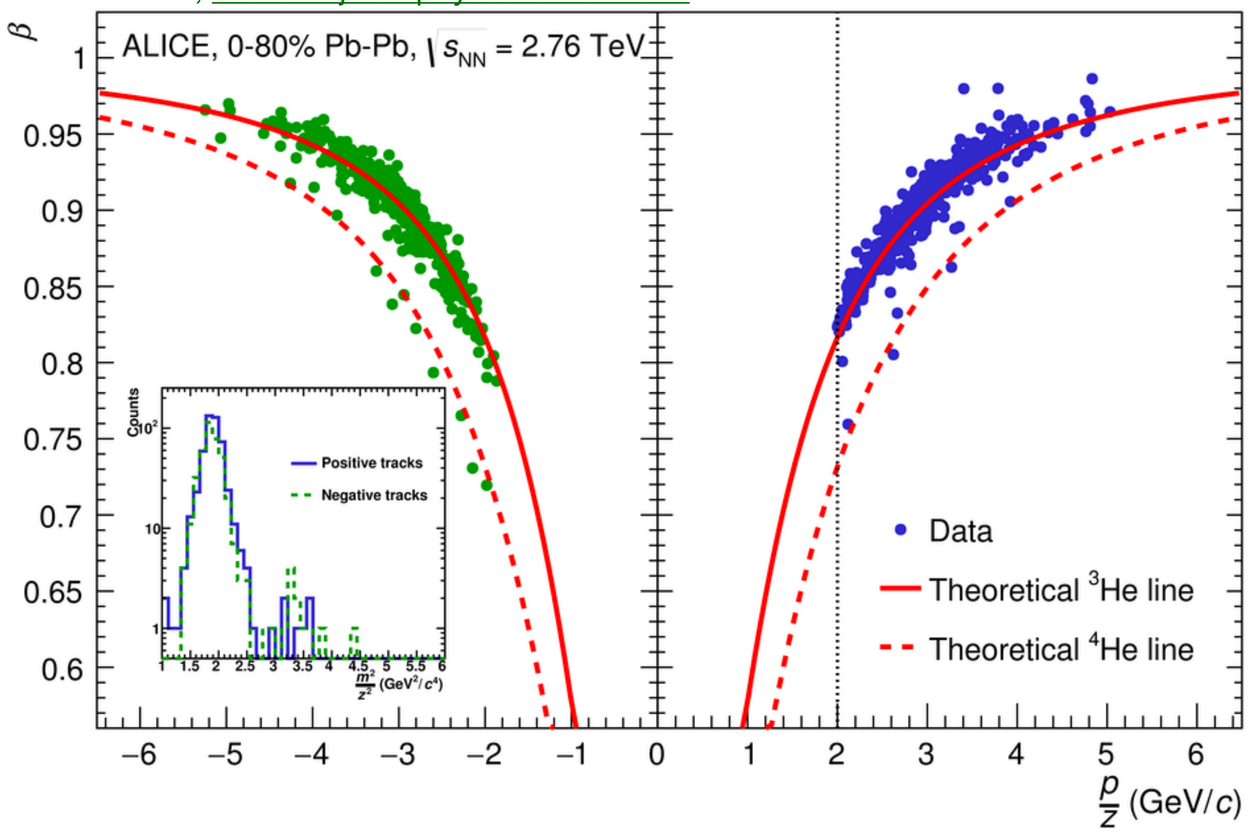
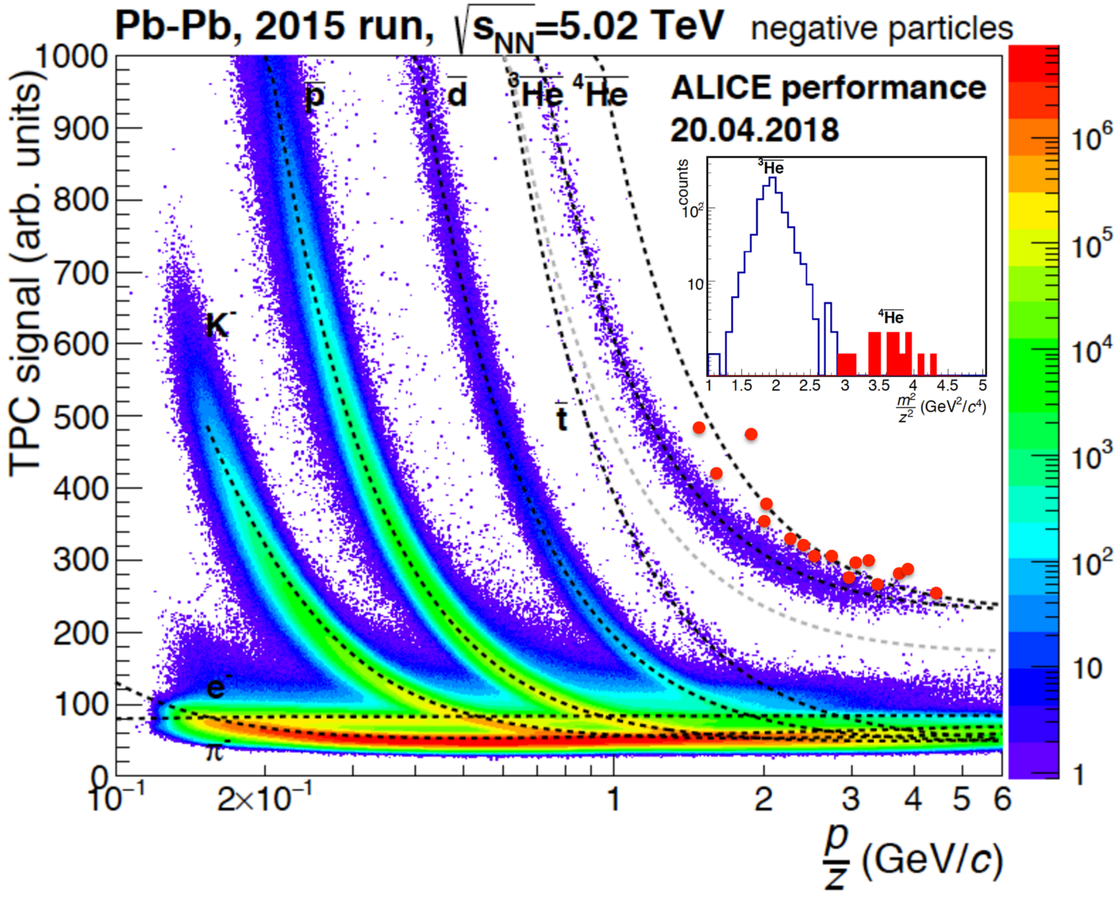
(Anti-)^{4}He production in Pb-Pb

ALICE, 10.1016/j.nuclphysa.2017.12.004

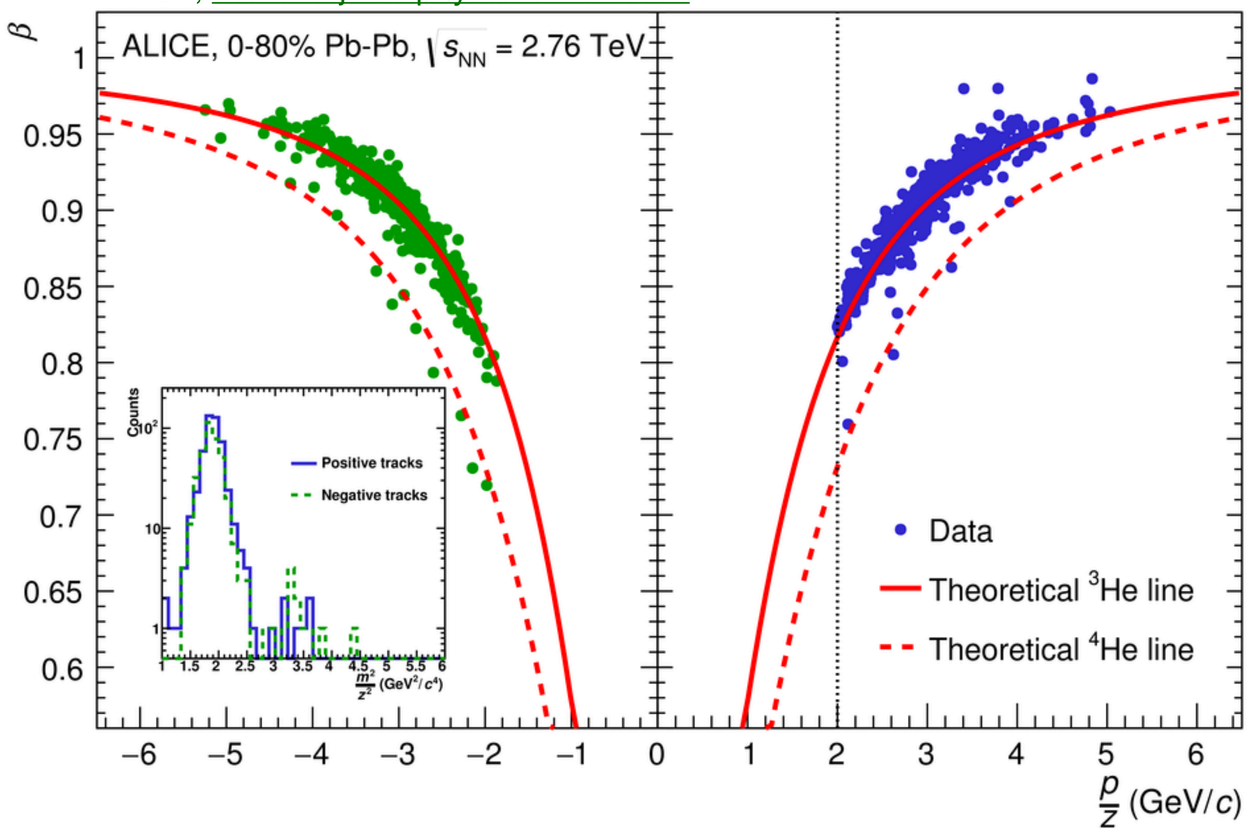


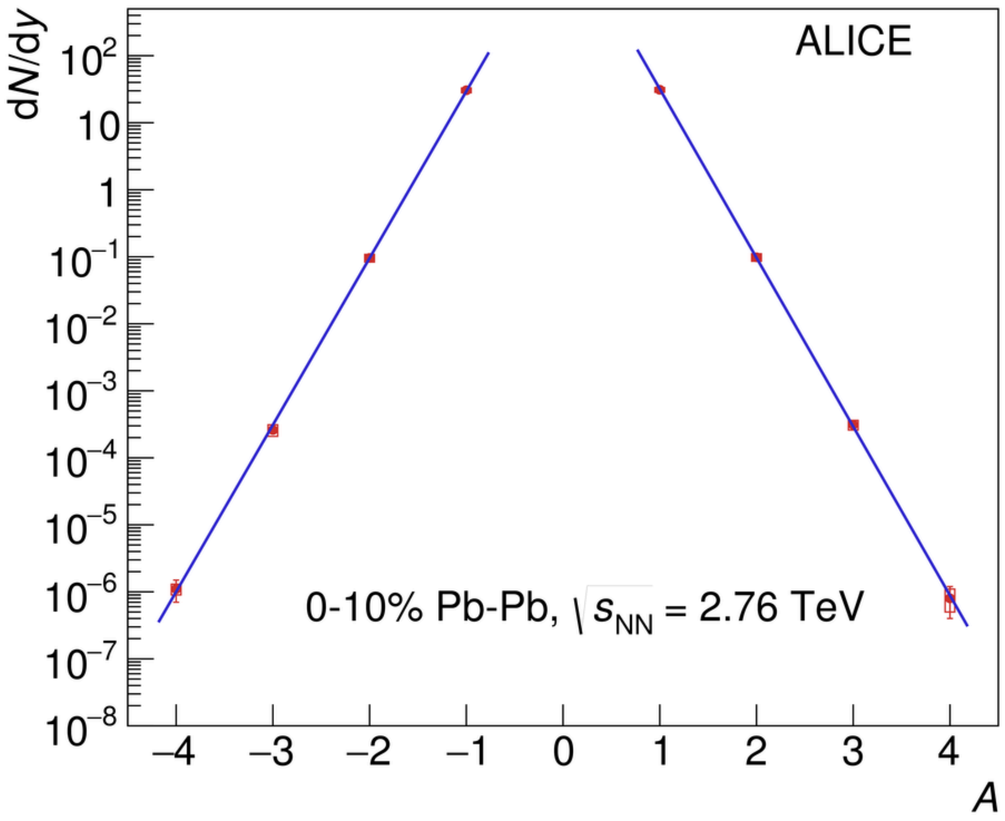


- The production of the heaviest anti-nucleus ever seen has been measured in Pb-Pb@2.76TeV
  - ➡We "rediscovered it" also in the new data sample Pb-Pb@5.02TeV!
- Its production rate is compatible with that of ^{4}He

(Anti-)^{4}He production in Pb-Pb

ALICE, 10.1016/j.nuclphysa.2017.12.004

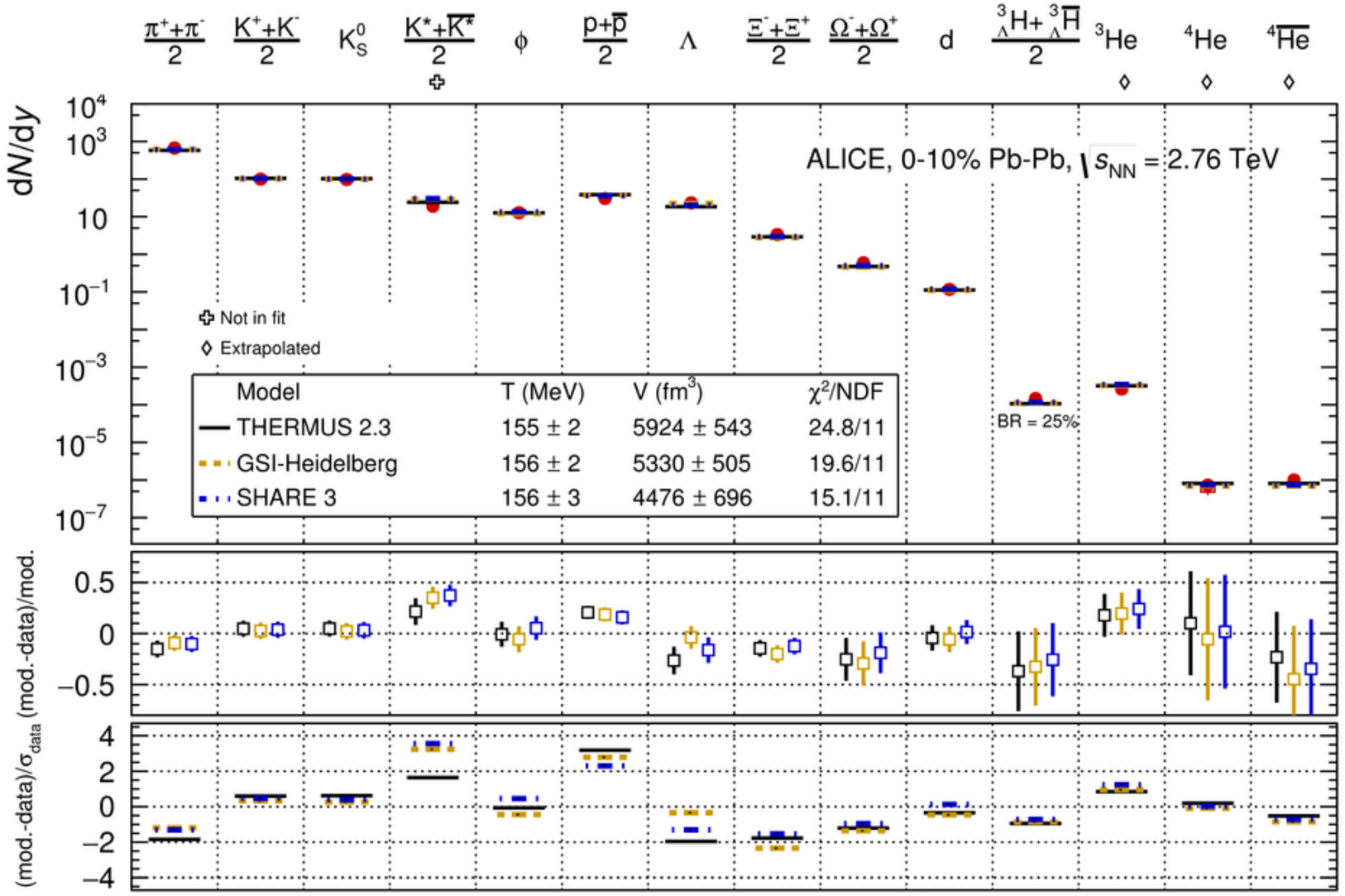




- The production of the heaviest anti-nucleus ever seen has been measured in Pb-Pb@2.76TeV
  - ➡We "rediscovered it" also in the new data sample Pb-Pb@5.02TeV!
- Its production rate is compatible with that of ^{4}He

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

The standard model of particle production in A-A?

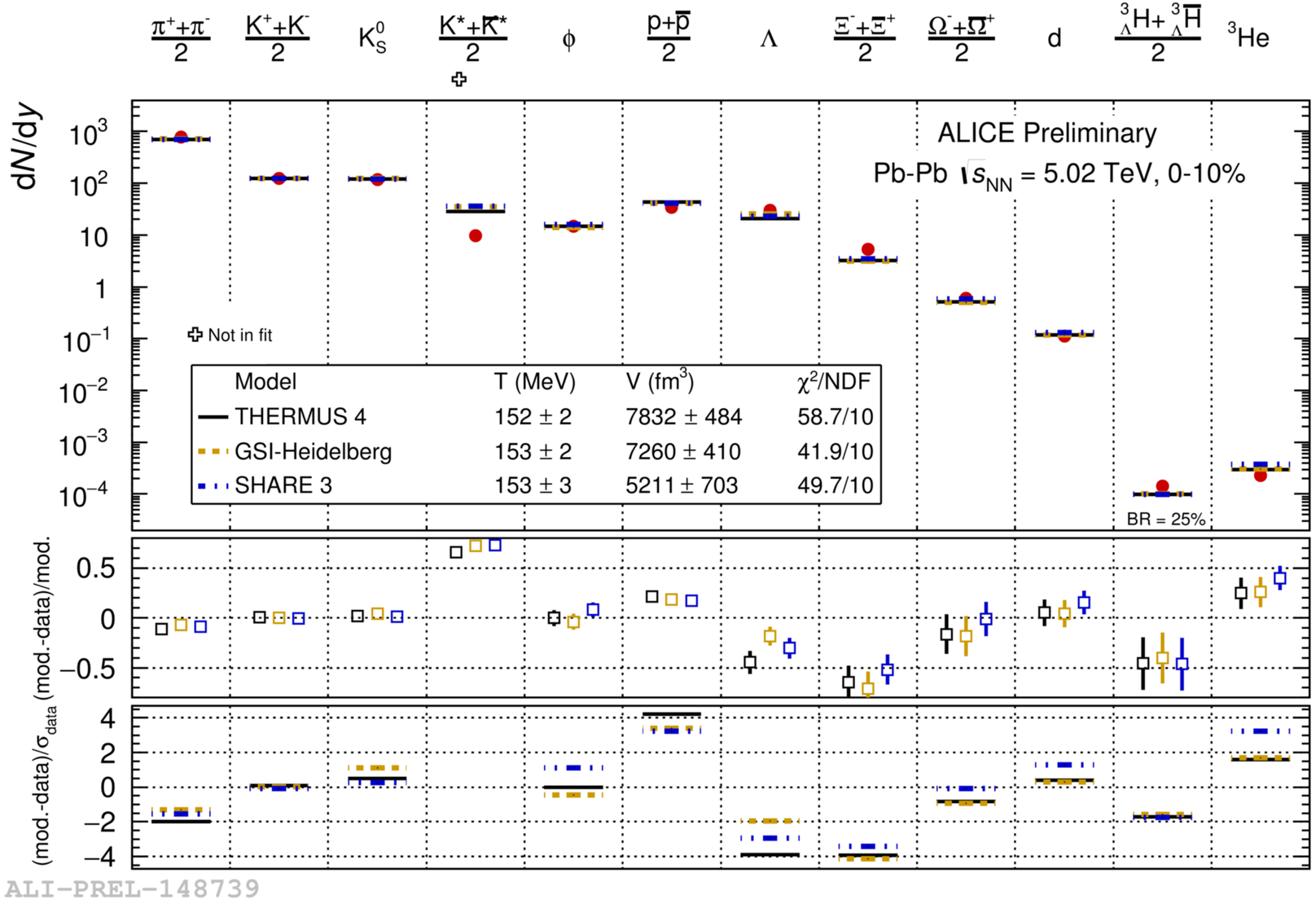


ALICE, 10.1016/j.nuclphysa.2017.12.004

- Thermal model is very successful in reproducing the particle yields measured by ALICE in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV
- (Anti-)nuclei and even hyper-nuclei fit in the thermal picture
- This result, together with the successful Blast-Wave fit to deuteron data suggest that nuclei production happens at the hadronisation, when all the other particles are formed.

The current formulations of the thermal model seems to be the standard model of particle production in Pb-Pb collisions

The standard model of particle production in A-A?

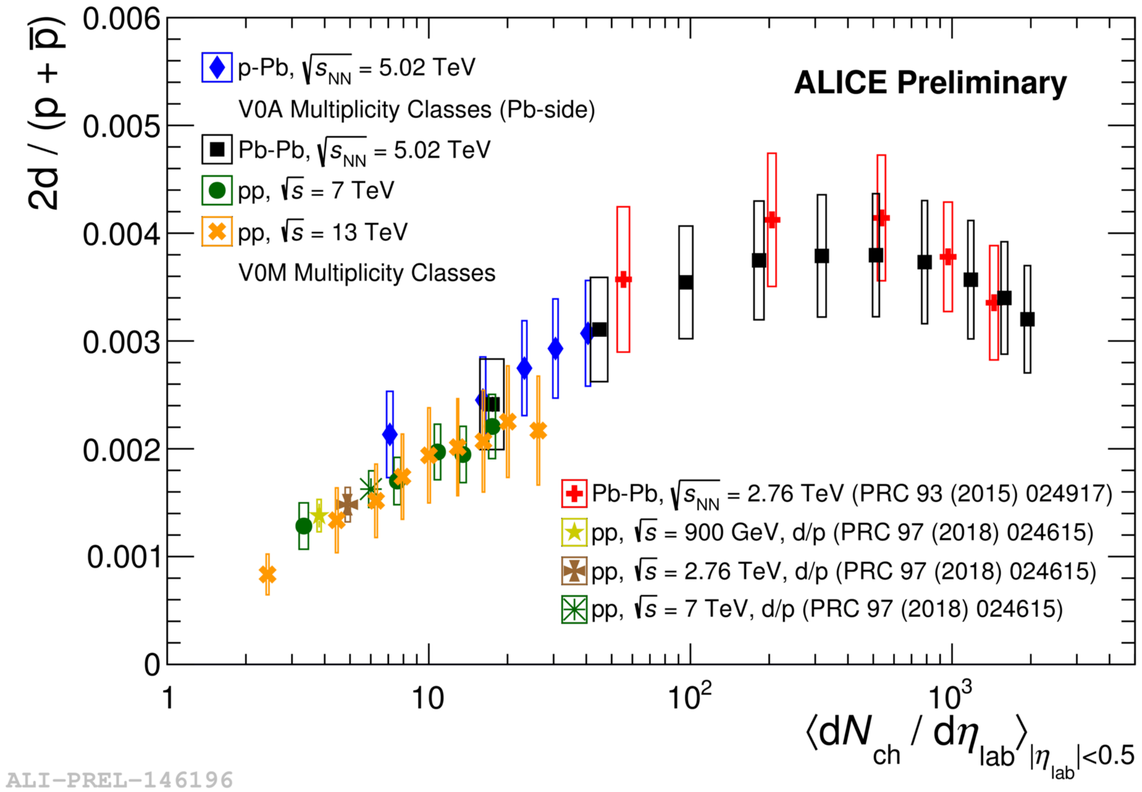


- The larger data sample collected in LHC Run2 and improved reconstruction and analysis techniques reduced the uncertainties.
- The tensions with the thermal model fit to our new preliminary results are now larger

THERMUS 4	5.7σ
GSI-Heidelberg	4.3σ
SHARE 3	5.0σ

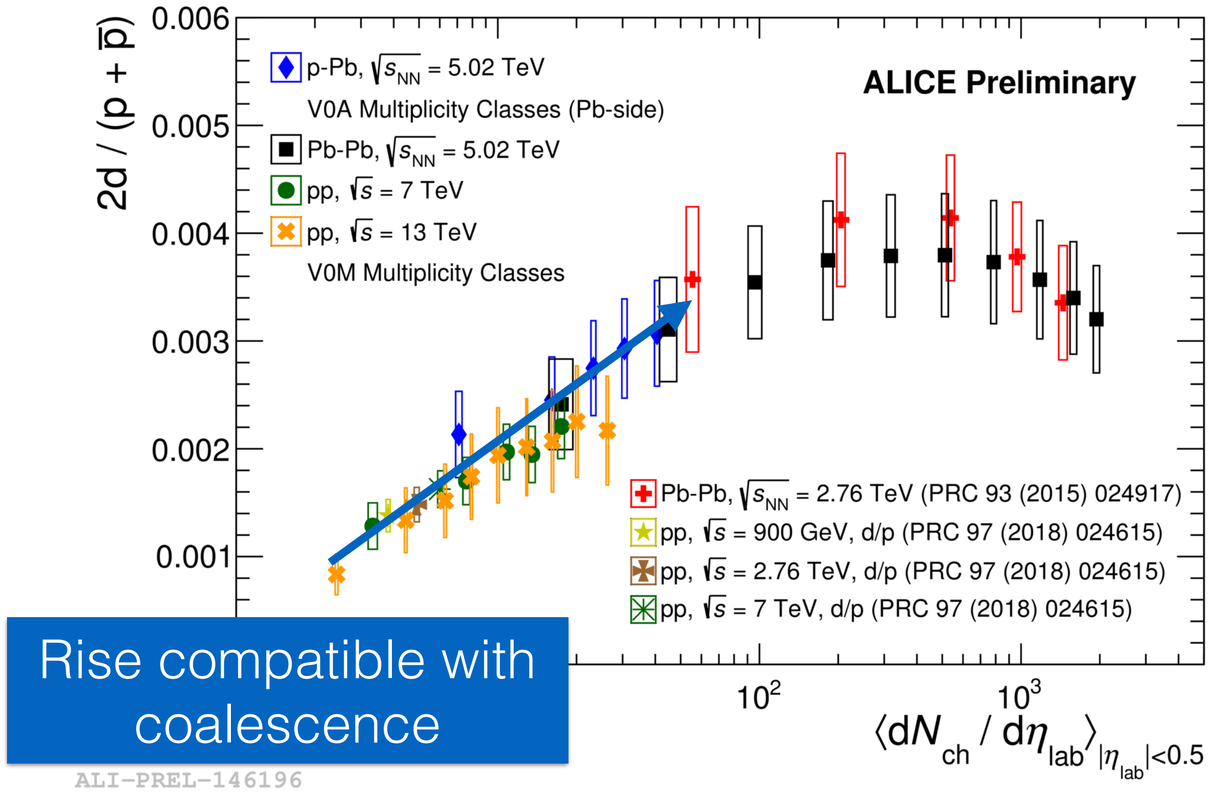
Does the model needs further tuning? Eigen volume corrections, particle lists and corresponding branching ratios, rescattering, S-matrix approach…

Unified description of nucleosynthesis at collider?



- Simple coalescence works in small systems while thermal models describe better the Pb-Pb data
- Hint of deuteron suppression in central collisions (Still not significant with the current uncertainties)
- Is this smooth transition suggesting a single description for the nucleosynthesis in HEP?

Unified description of nucleosynthesis at collider?



Rise compatible with coalescence

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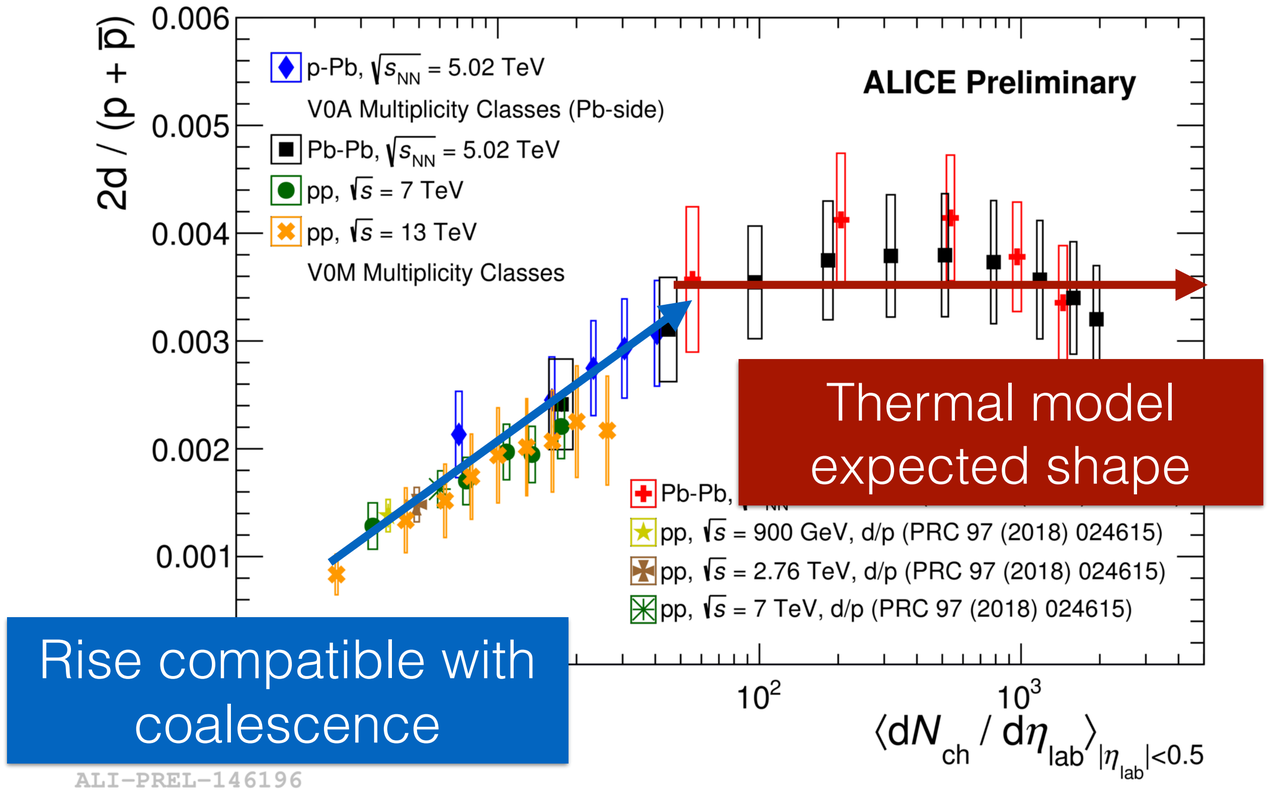

Thermal model expected shape

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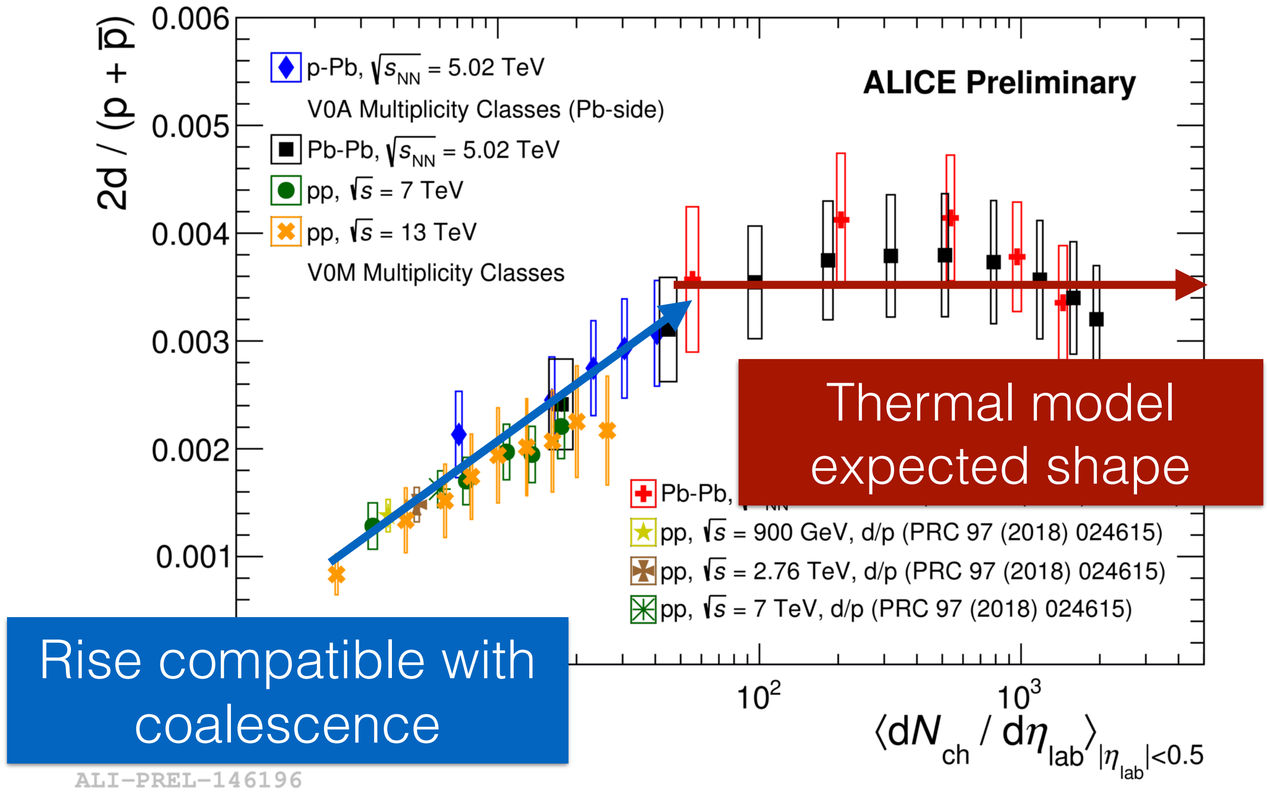
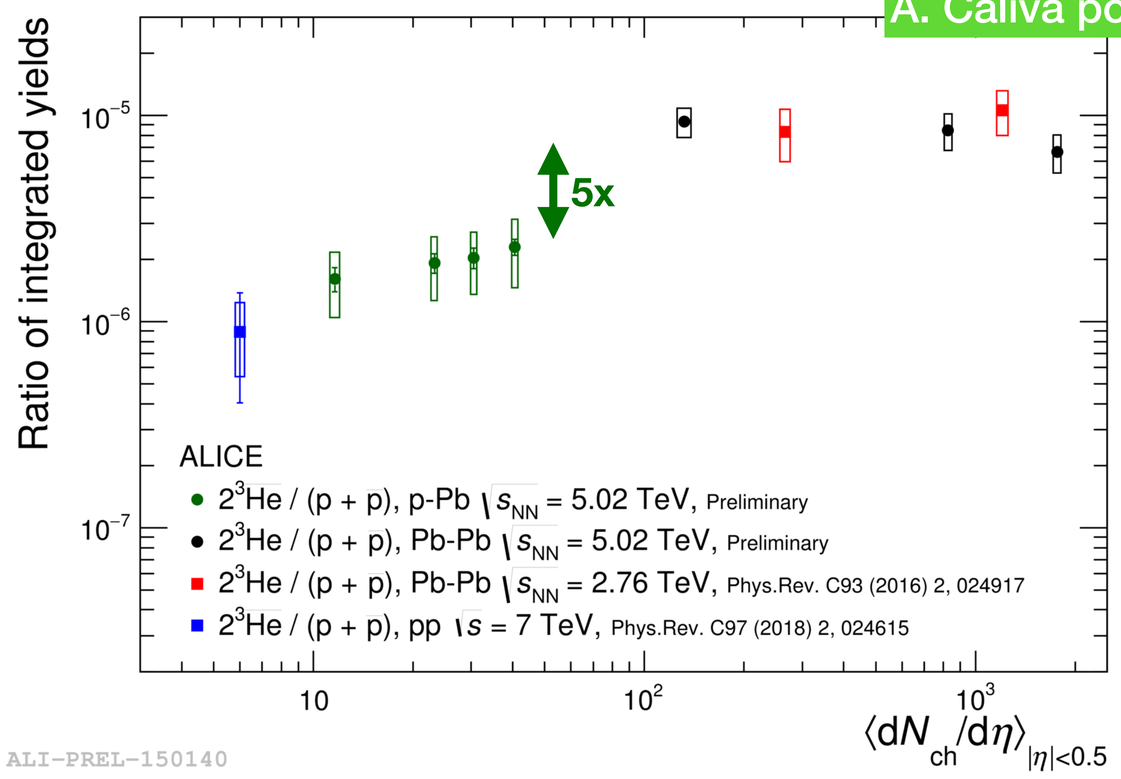
Unified description of nucleosynthesis at collider?

A. Calivà poster





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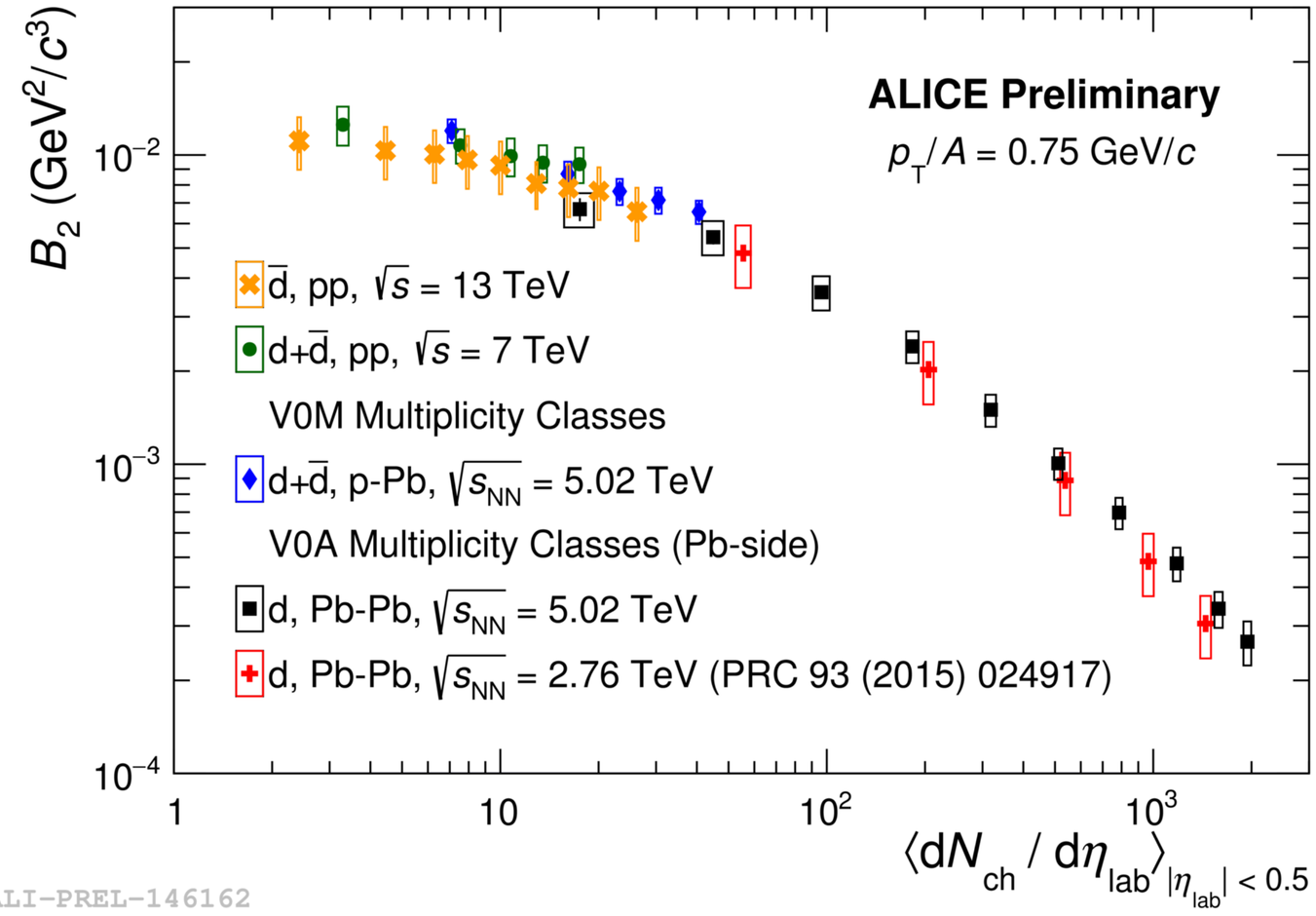
If the factor 5 change in the ^{3}He/p between small systems and Pb-Pb is confirmed by studies on larger data samples, then a unified description will be more challenging.

Unified description of nucleosynthesis at collider?

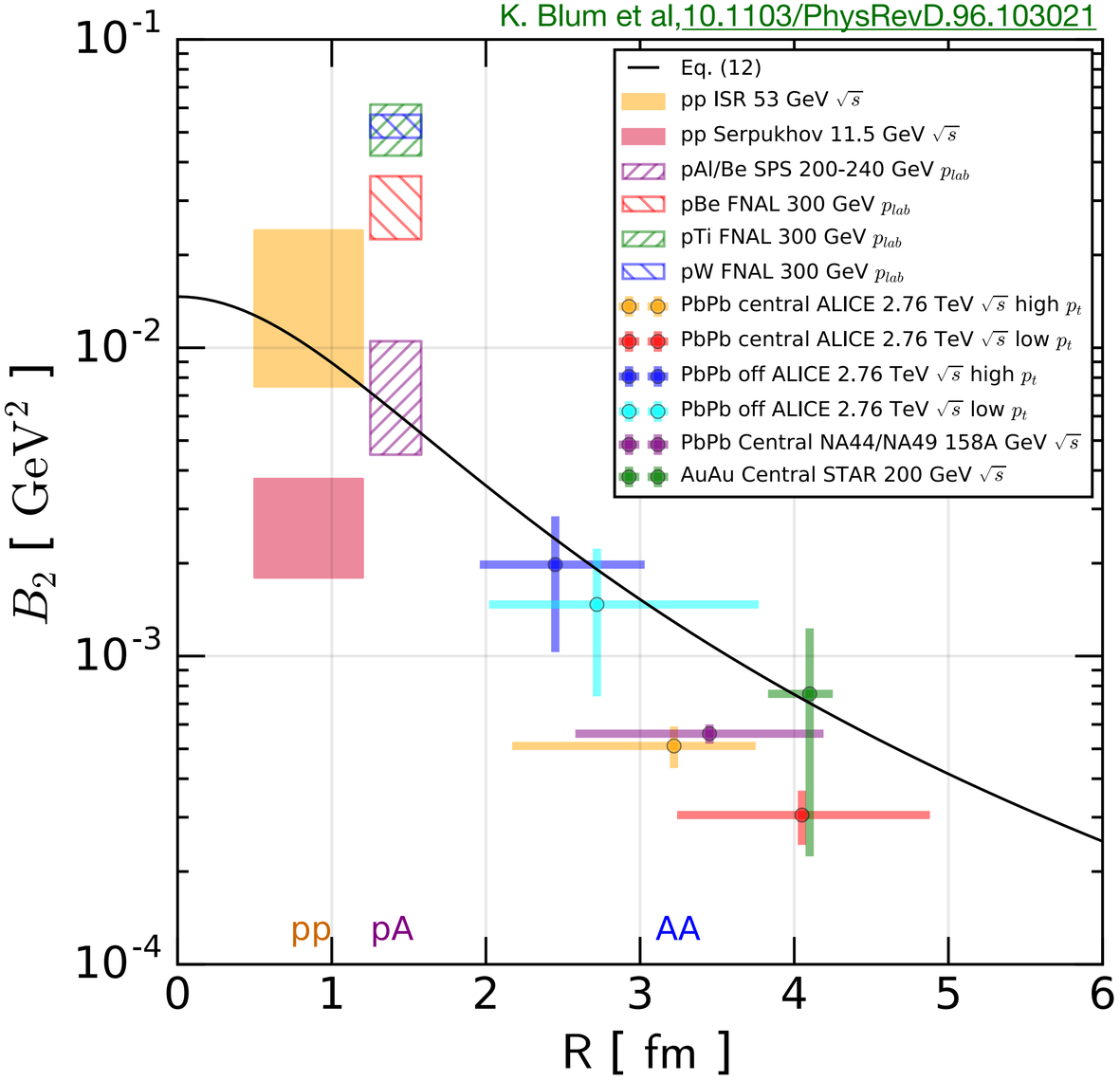


The coalescence parameter evolves smoothly as a function of multiplicity with no discontinuity between different colliding systems

- Another hint of a system size aware production mechanism

Unified description of nucleosynthesis at collider?

K. Blum et al,10.1103/PhysRevD.96.103021



The coalescence parameter evolves smoothly as a function of multiplicity with no discontinuity between different colliding systems

- Another hint of a system size aware production mechanism

This behaviour has been qualitatively described by parametrising the coalescence parameter using the system HBT radius *R*:

$$\frac{B_2}{\mathrm{GeV}^2} \approx 0.068 \left[\left(\frac{R(p_\mathrm{T})}{1\,\mathrm{fm}} \right)^2 + 2.6 \left(\frac{b_2}{3.2\,\mathrm{fm}} \right)^2 \right]^{-3/2}$$

where the numerical factors come from approximations of the nucleus and nucleons sizes

Conclusions

(Anti-)nuclei production measurements at the LHC challenge the traditional production models

- Currently thermal model describes sufficiently well the nuclei production (from proton to ^{4}He)
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Particle chemistry evolution with multiplicity suggests that a single mechanism could be behind the production of hadrons in all systems colliding at the LHC

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Deep scan of all the production properties of nuclei will help to constrain and understand these new models

- Deuteron and ^{3}He v_2 in peripheral collisions ➔ next Pb-Pb run at the end of this year!
- ^{3}He and ^{4}He production at very small multiplicities (in p-Pb and Pb-Pb) ➔ Run3 and beyond!

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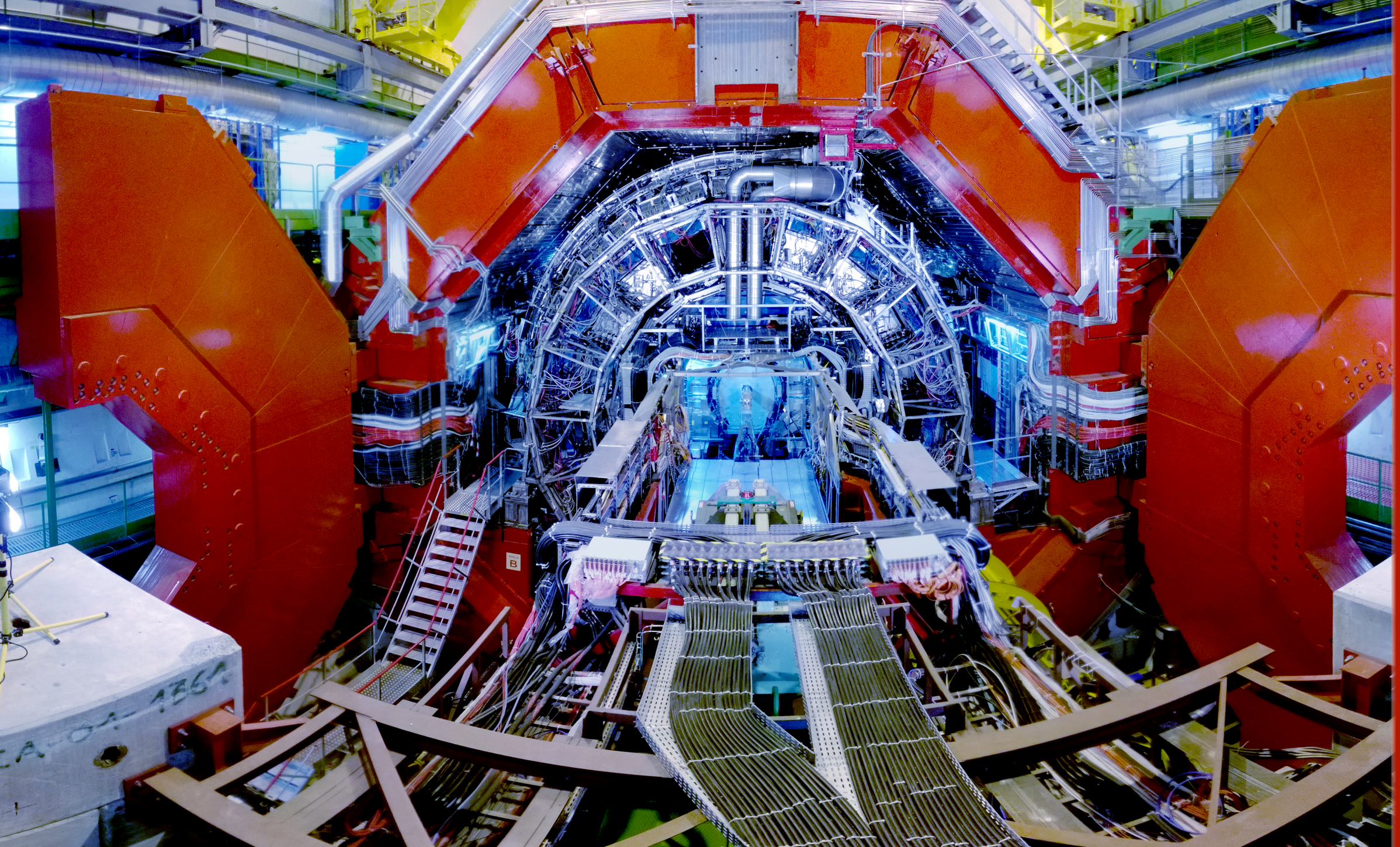
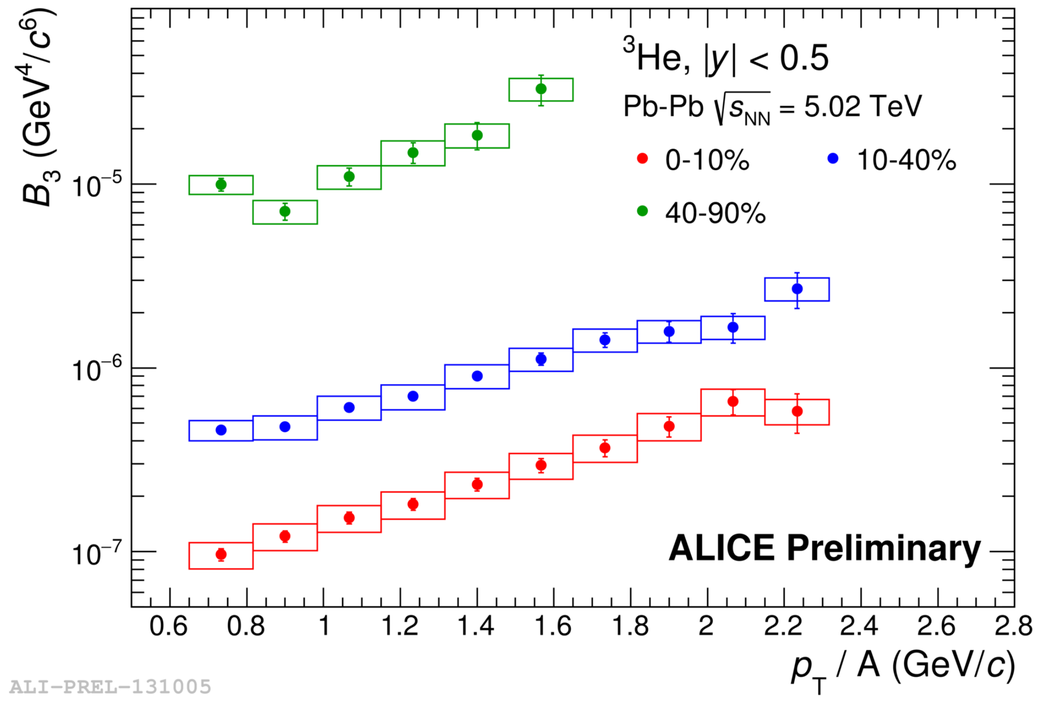
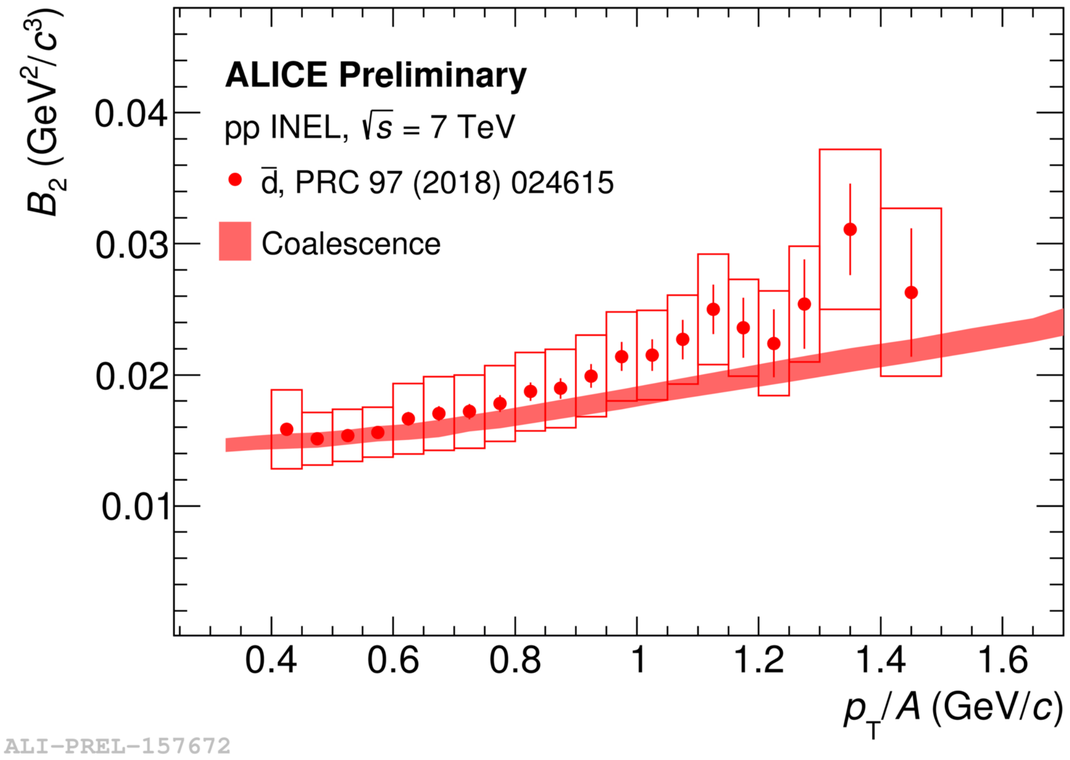
The quest for the understanding of nuclei production is still open, but today we have a much clearer idea of what are the limits of the current models.



Backup

B_3 and proton spectra mathematical bias

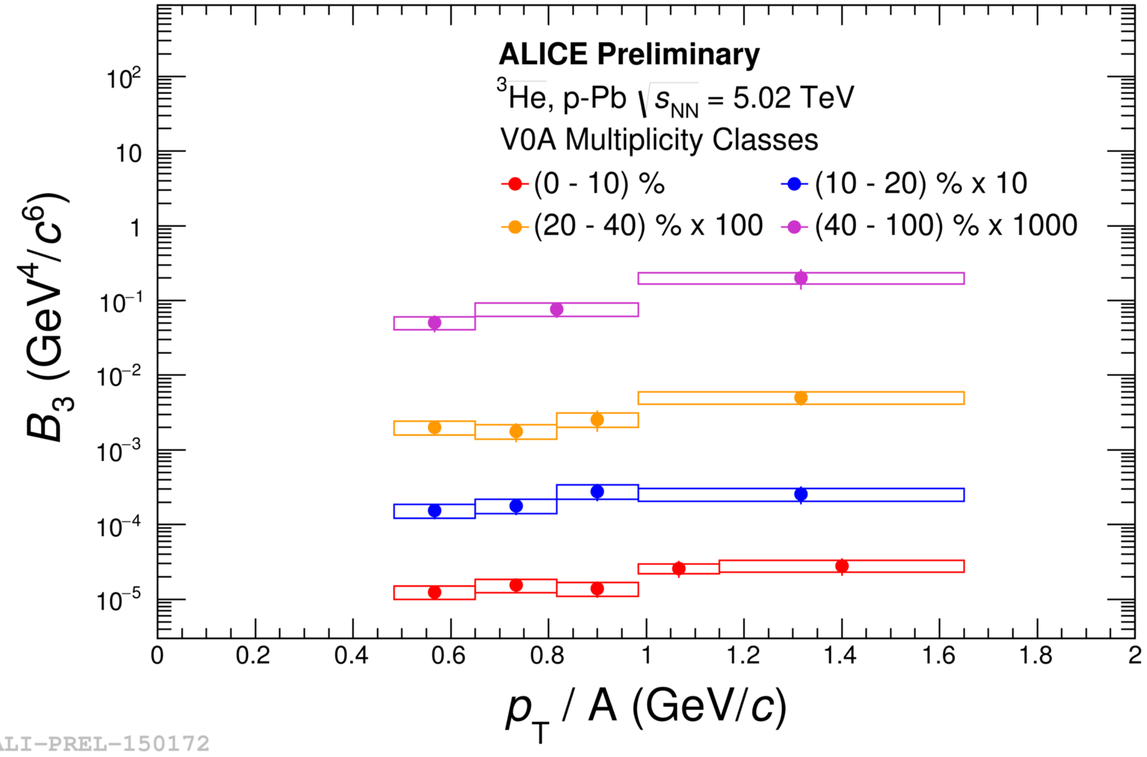


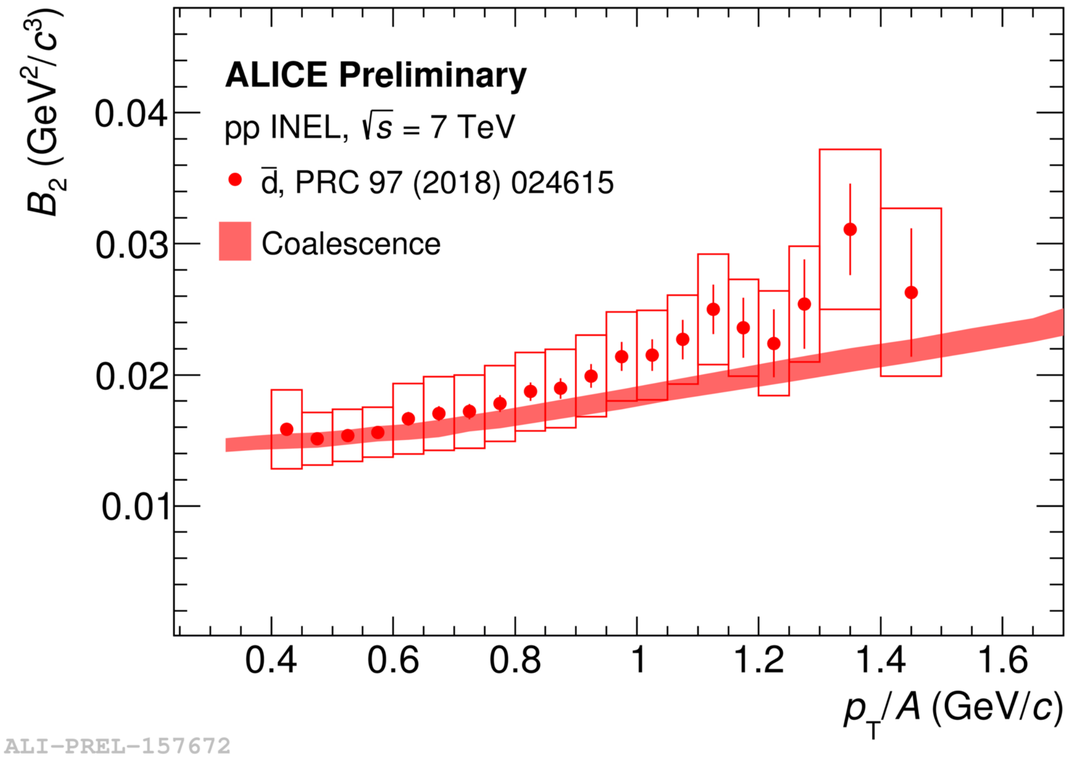


The rising B_3 in Pb-Pb and p-Pb collisions can be partially explained, in the wide centrality bins, by the mathematical bias coming from the proton spectra change as a function of multiplicity.

This effect has been already observed in pp (see M. Colocci talk) and is also affecting the determination of B_A for rare species, where it is not possible to extract the coalescence parameter with the finest centrality bins

B_3 and proton spectra mathematical bias





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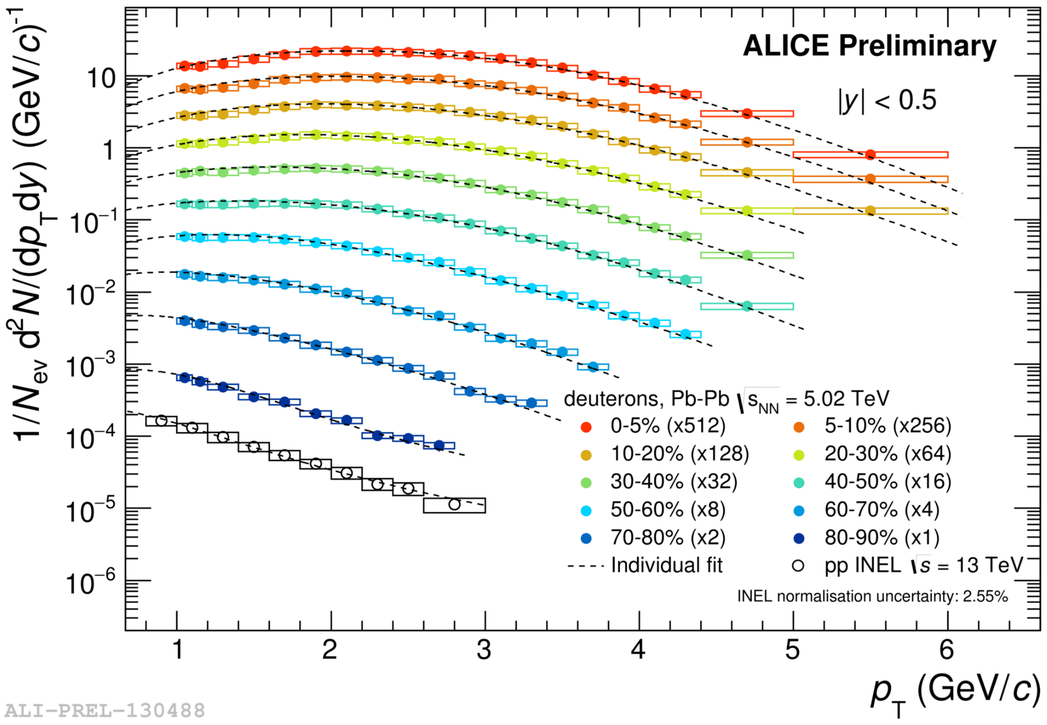
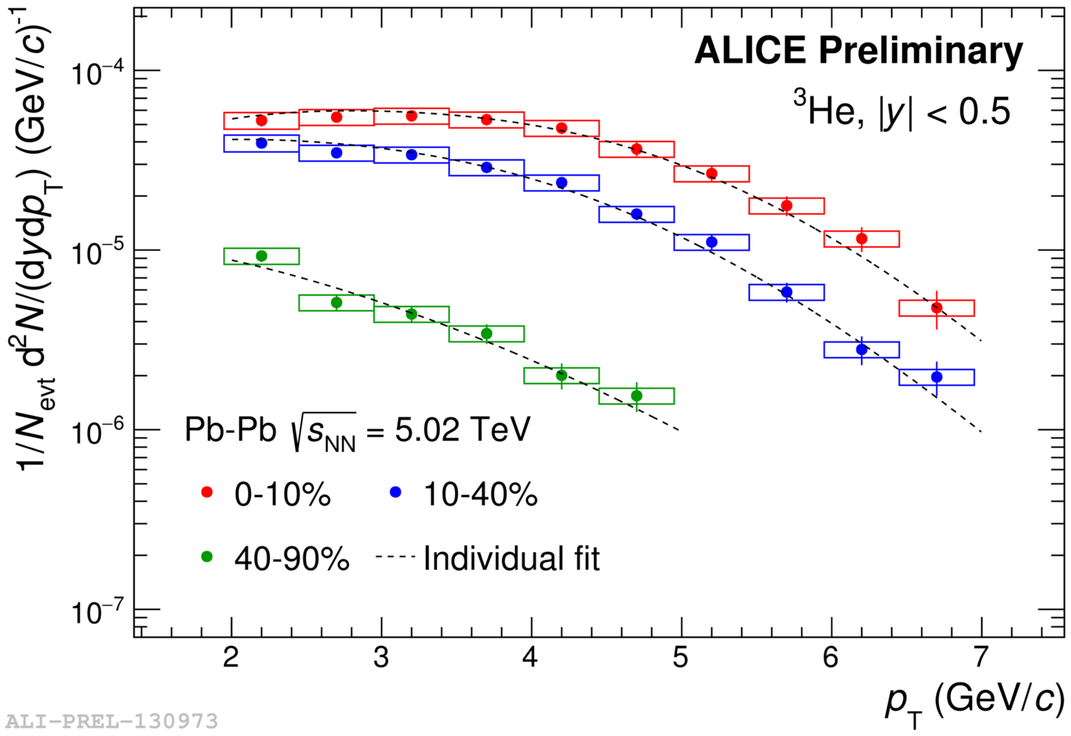
Deuteron and ^{3}He production spectra in Pb-Pb@5TeV





pp

The p_T-differential production spectrum is well fitted by the Levy-Tsallis function

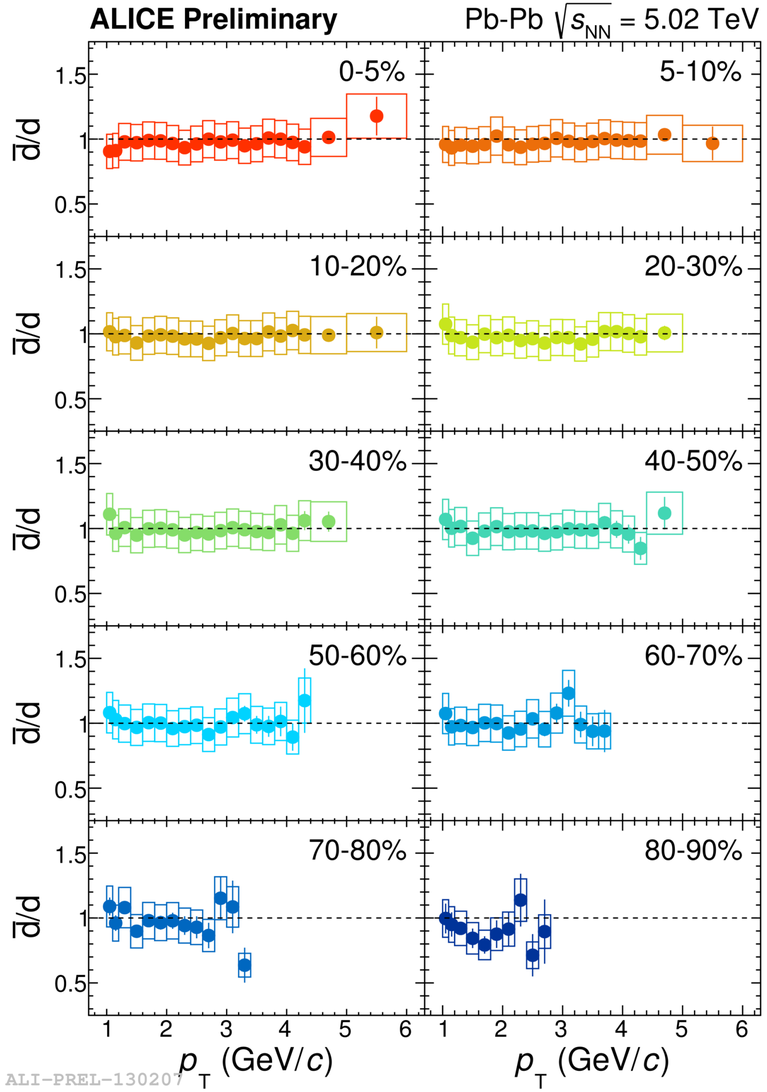
$$\frac{\mathrm{d}^2N}{\mathrm{d}p_\mathrm{T}\mathrm{d}y} = p_\mathrm{T}\frac{\mathrm{d}N}{\mathrm{d}y}\frac{(n-1)(n-2)}{nC(nC+m_0(n-2))}\left(1+\frac{m_\mathrm{T}-m_0}{nC}\right)^{-1}$$

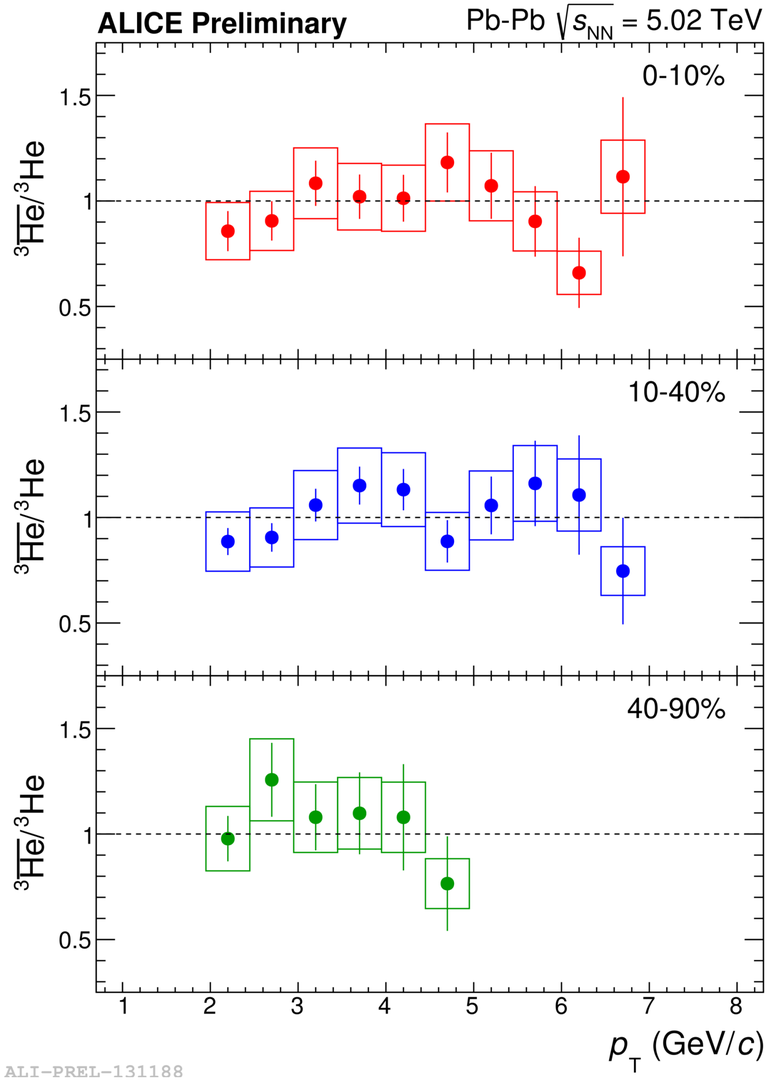
where m_0 is the nominal mass of the deuteron and n,C are fit parameters.

Pb-Pb

- The Blast-Wave (BW) function fits well the data.
- Characteristic hardening of the spectrum with increasing centrality.
  - Radial flow pattern
- These fits are used for the extrapolation of the yield to the unmeasured region at low and high p_T.

Matter/anti-matter ratios





For a nucleus X with mass number A, both coalescence and thermal models predict:

$$\frac{\overline{X}}{X} \approx \left(\frac{\overline{p}}{p}\right)^A$$

The anti-proton over proton ratio is compatible with unity at the LHC ($\mu_B \approx 0$ at mid rapidity)

➡ Measured anti-nuclei over nuclei ratios are in line with theory expectations

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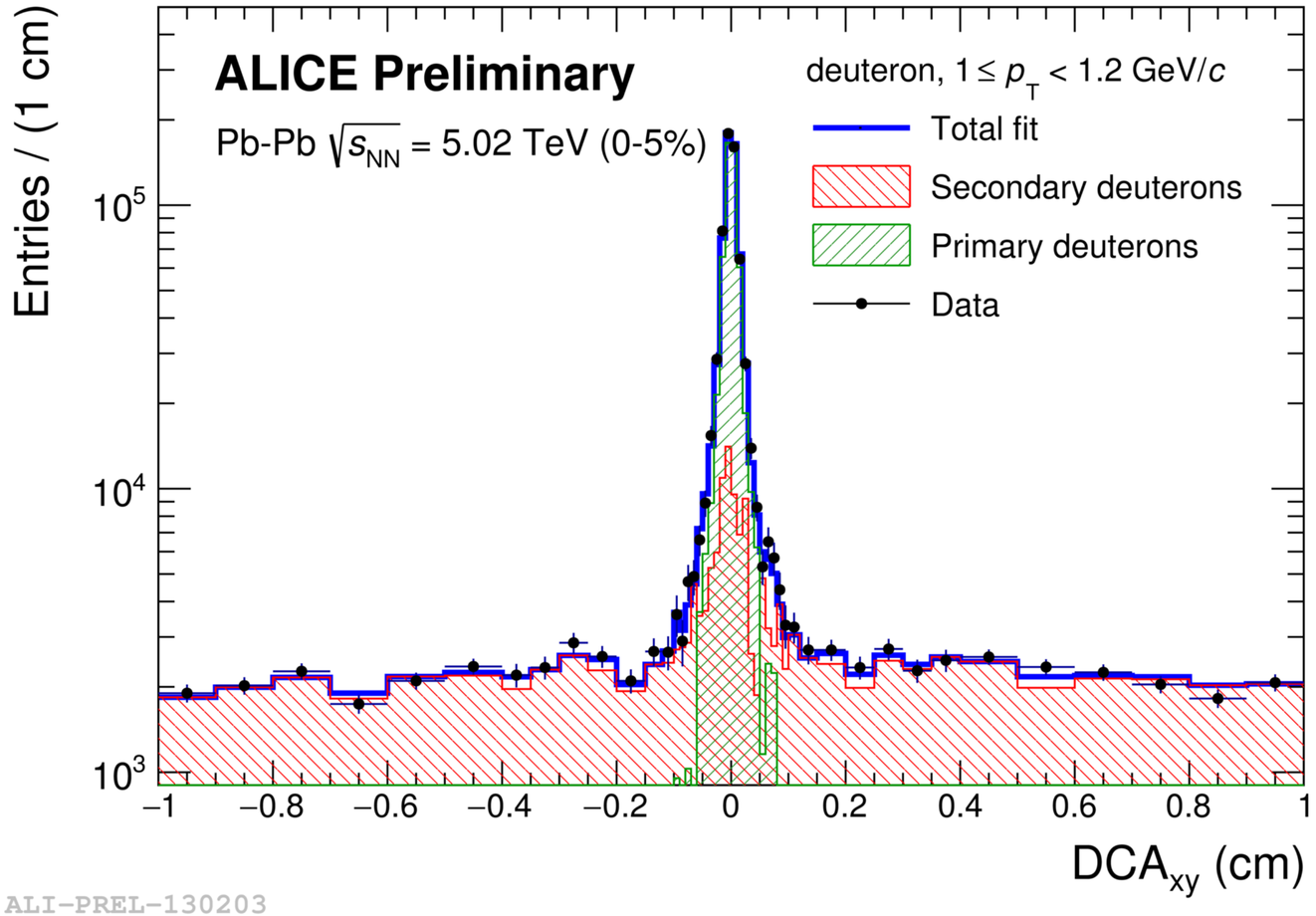
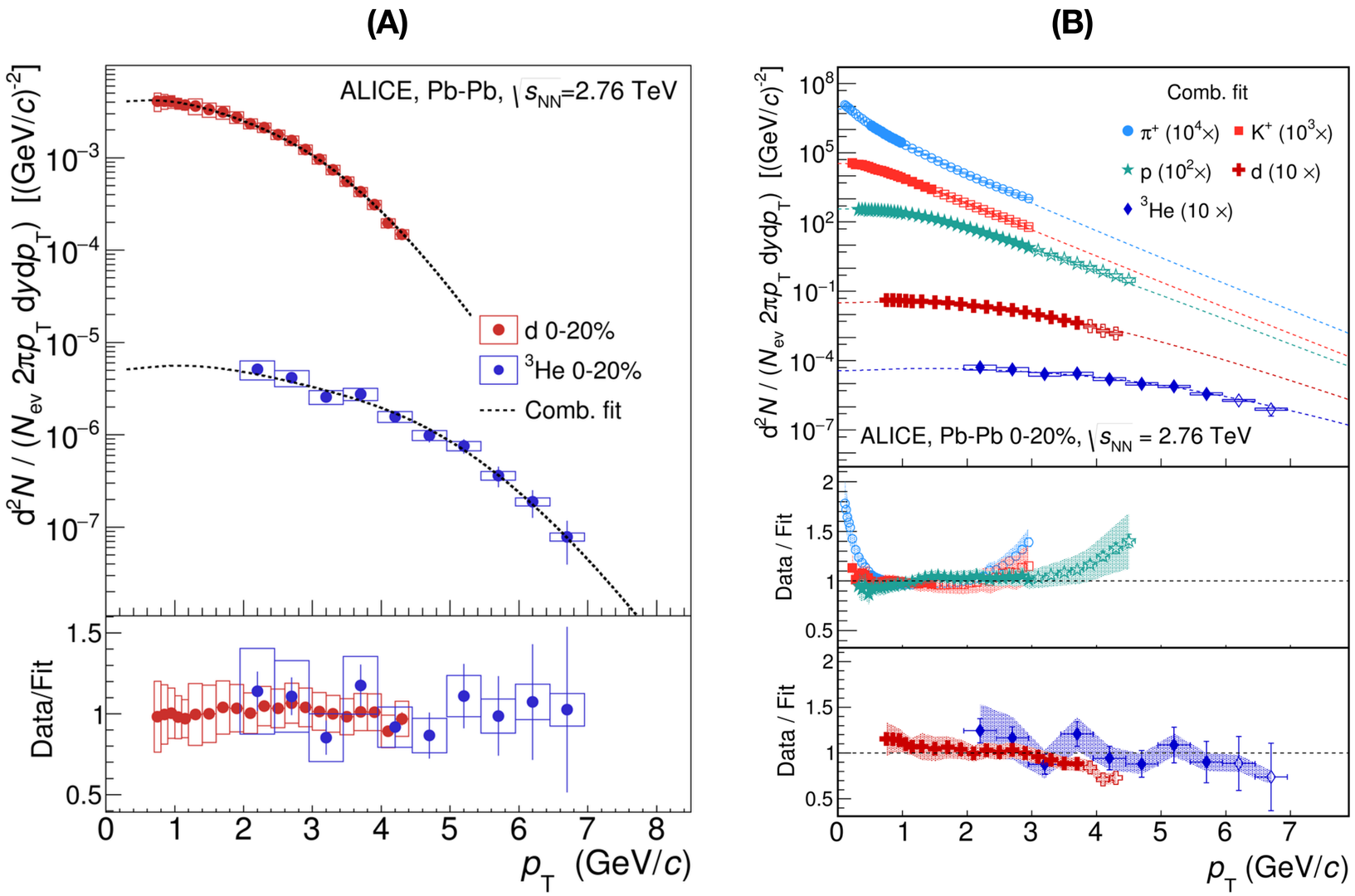
Correction for knock-out nuclei



- Fit on a range of DCA_{xy} wider than the cut used to extract the spectra
- Variable binning used to account for the shape of the primary particles around 0
- Primary fraction extracted from the fitted primary particles template integrated in the DCA_{xy} range corresponding to the analysis cut

Primary particles template and particle from material templates are taken from the MC.

Blast-Wave fit to nuclei spectra



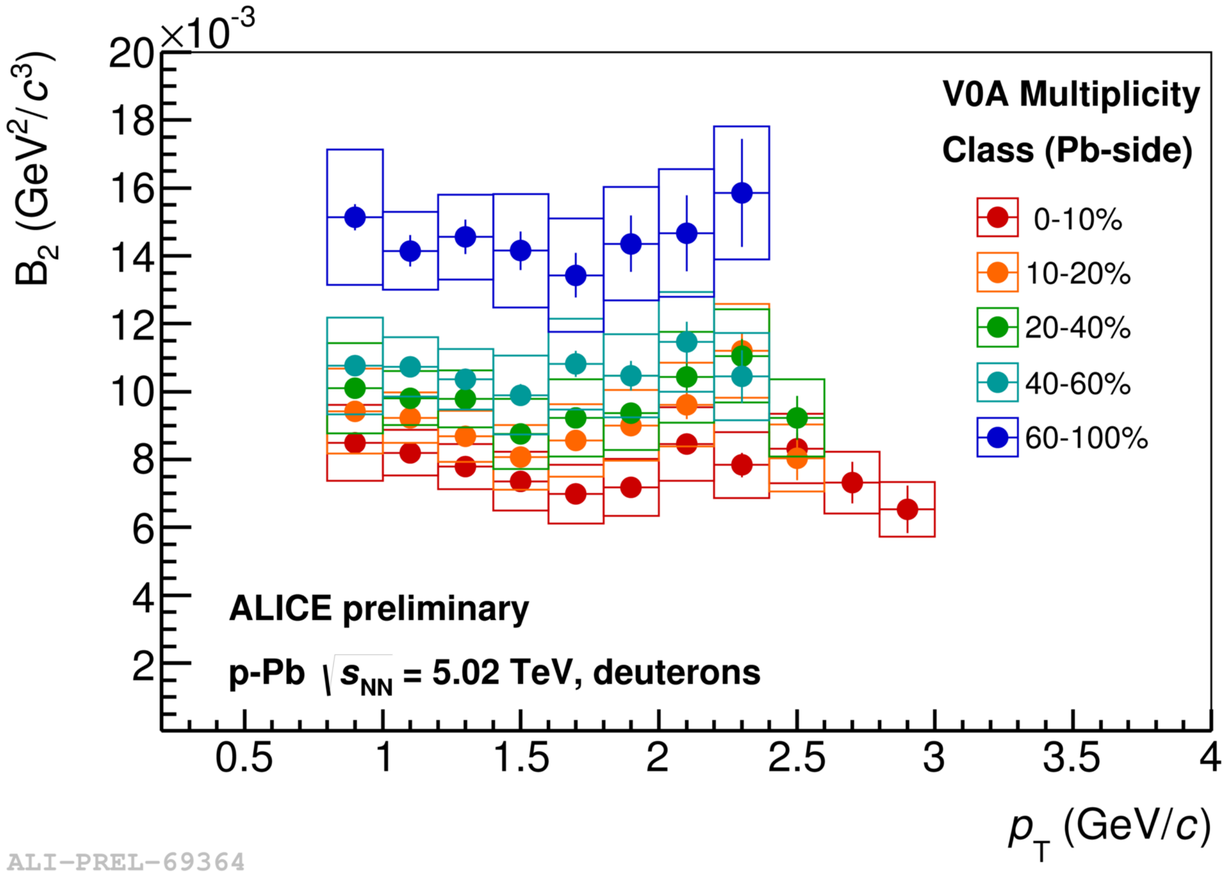
The Blast-Wave combined fit to the ^{3}He and deuteron spectra (**A**) shows a good agreement with the measurements.

- Common freeze-out conditions for light nuclei

The Blast-Wave combined fit to pions, kaons, protons and light nuclei (**B**) works as well

- Common freeze-out conditions even with lighter species!

Coalescence in p-Pb collisions

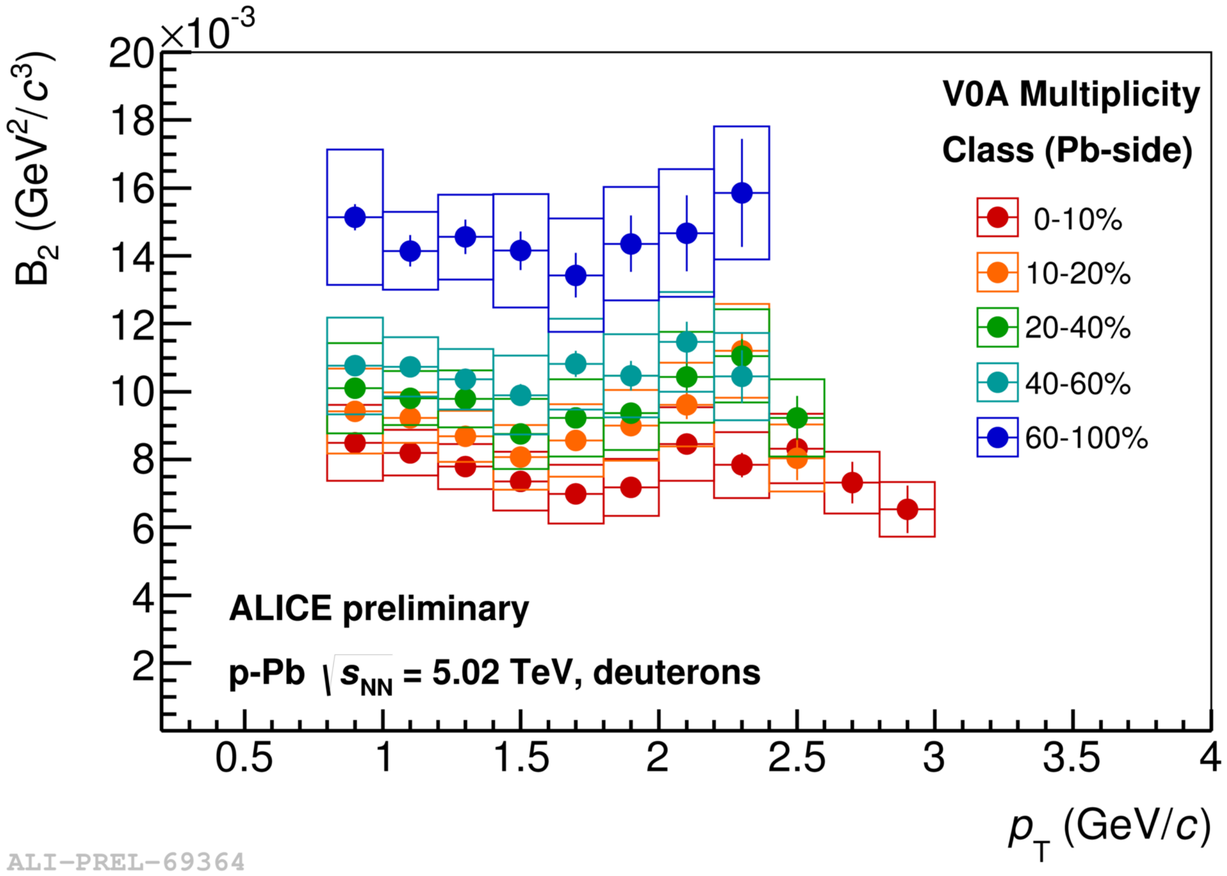


Simple coalescence predictions hold in p-Pb collisions:

- B_2 is p_T independent in all the multiplicity bins investigated

See M. Colocci talk for more on this topic!

Coalescence in p-Pb collisions



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- Mean p_T of the produced deuterons follow the coalescence expectation
  - The Blast Wave expected mean transverse momentum is overestimating systematically our measurements

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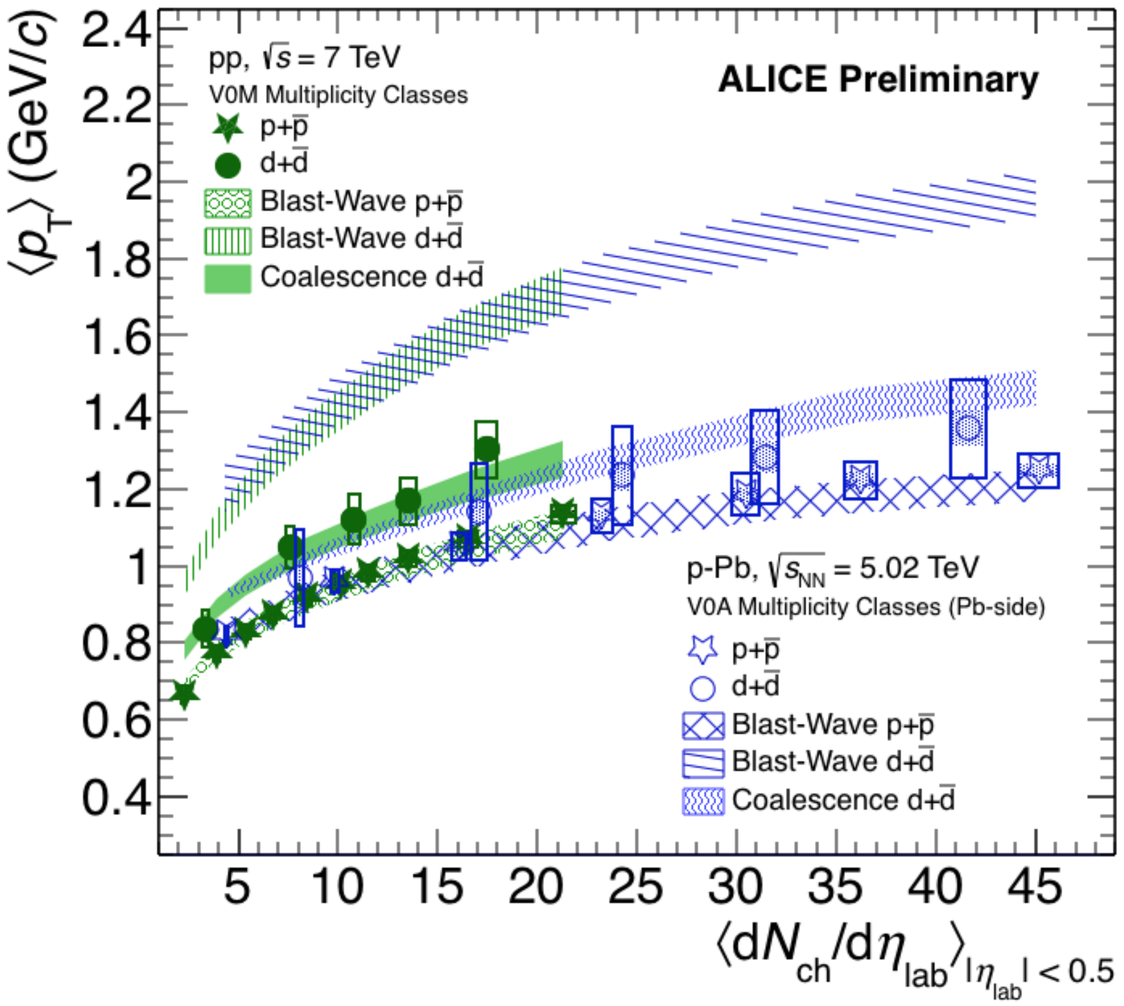

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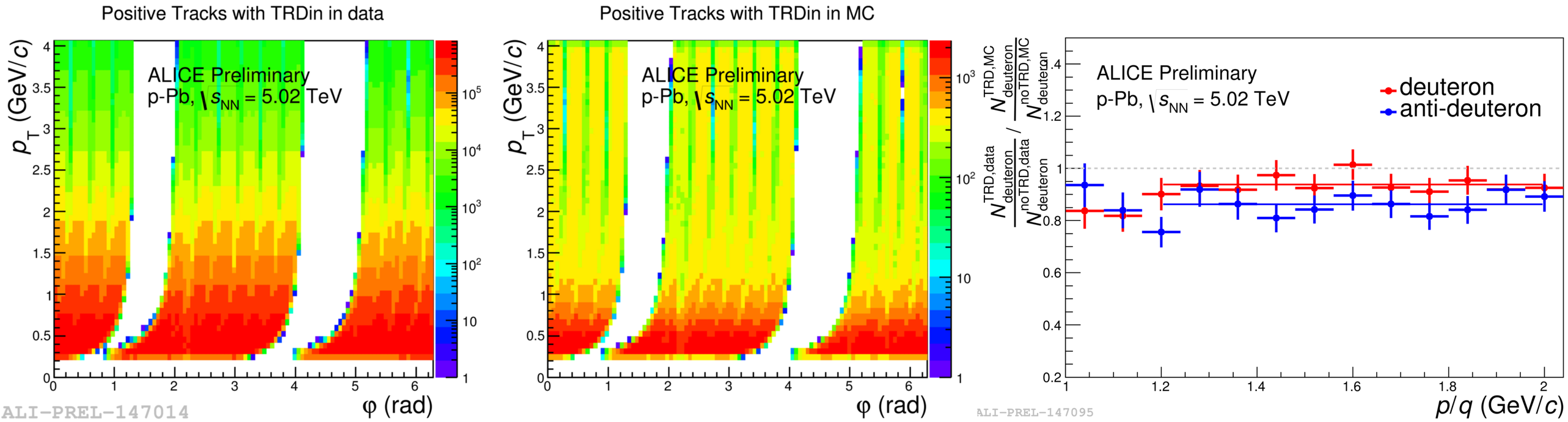
Simple coalescence successfully describes the nuclei production in small systems

See M. Colocci talk for more on this topic!

Improving the (anti-)nuclei production systematics



Ultimate test of production mechanism models will be possible once the (anti-)nuclei interaction with our experiment material will be known precisely

- Efficiencies evaluated on MC using GEANT3 + Optical model and Geant4 are quite different O(10%)
- ALICE is now studying the discrepancies between data and MC using the TRD as inert material where (anti-)nuclei interact
  - First studies show that the current uncertainty can be reduced by applying a better, data driven correction to our measurements.

See Z. Yasin poster for more on this topic

AMPT with enabled rescattering (ART)

ALICE, 10.1140/epjc/s10052-017-5222-x