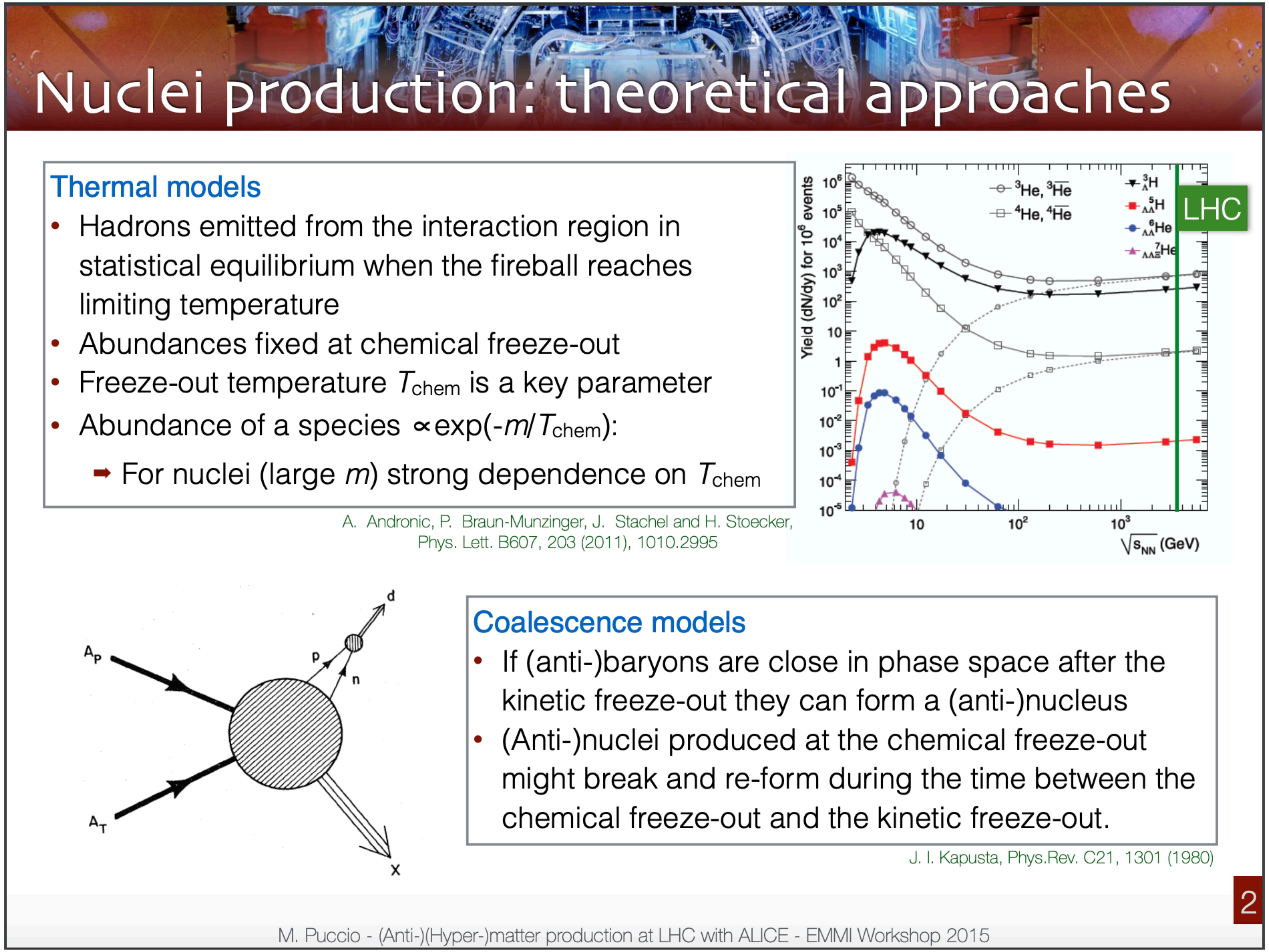
(Anti-)nuclei, hyper-nuclei and exotica production with ALICE

Maximiliano Puccio on behalf of ALICE Collaboration

2015, same workshop

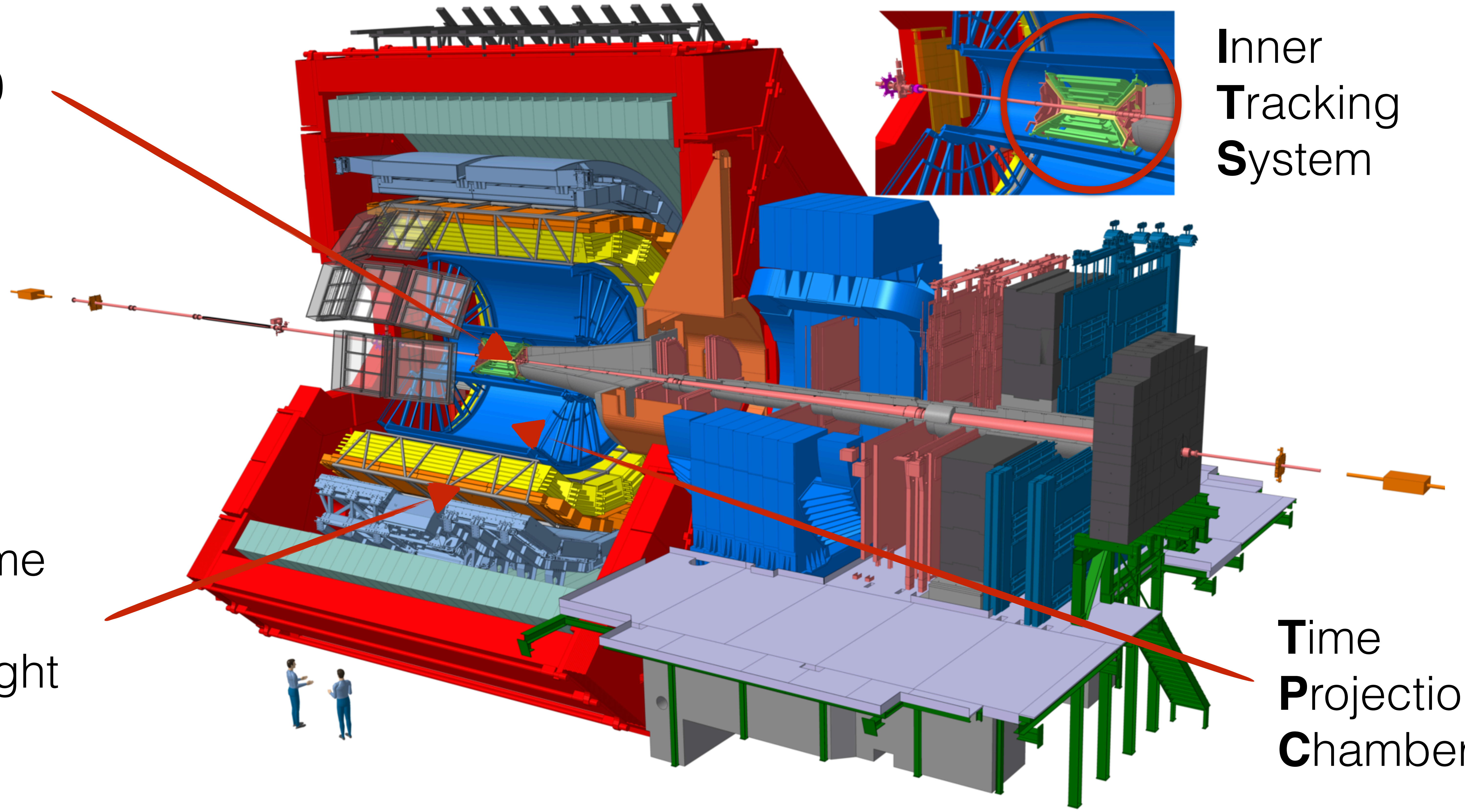


… and if you look at the latest ALICE talks on nuclei you get very similar overview of the theoretical models:

- Coalescence/thermal model dichotomy
- Many new theoretical developments since then
  - CSM
  - Phase shifts in the thermal model
  - Transport models
  - Educated coalescence

What do new data tell us?

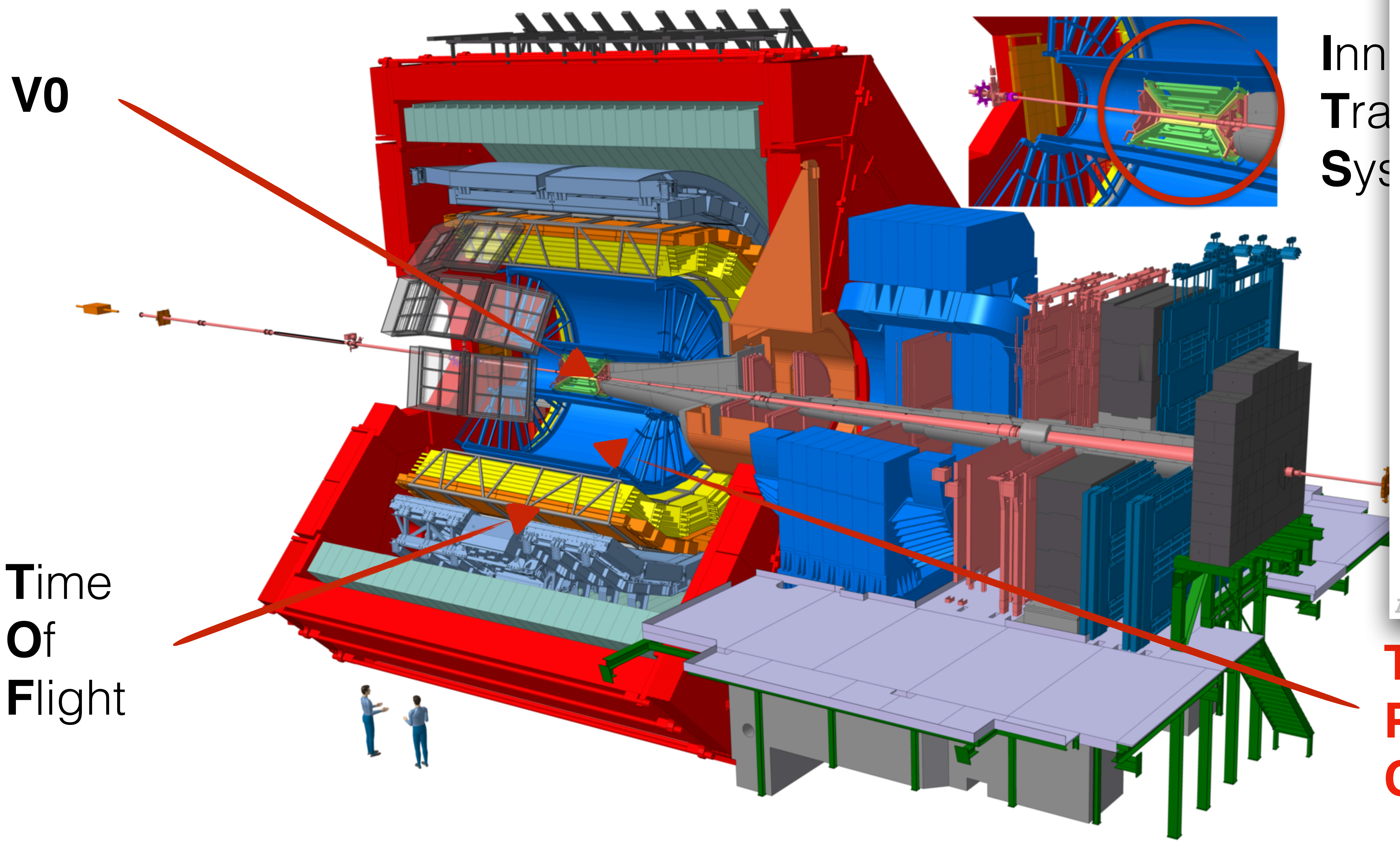
ALICE

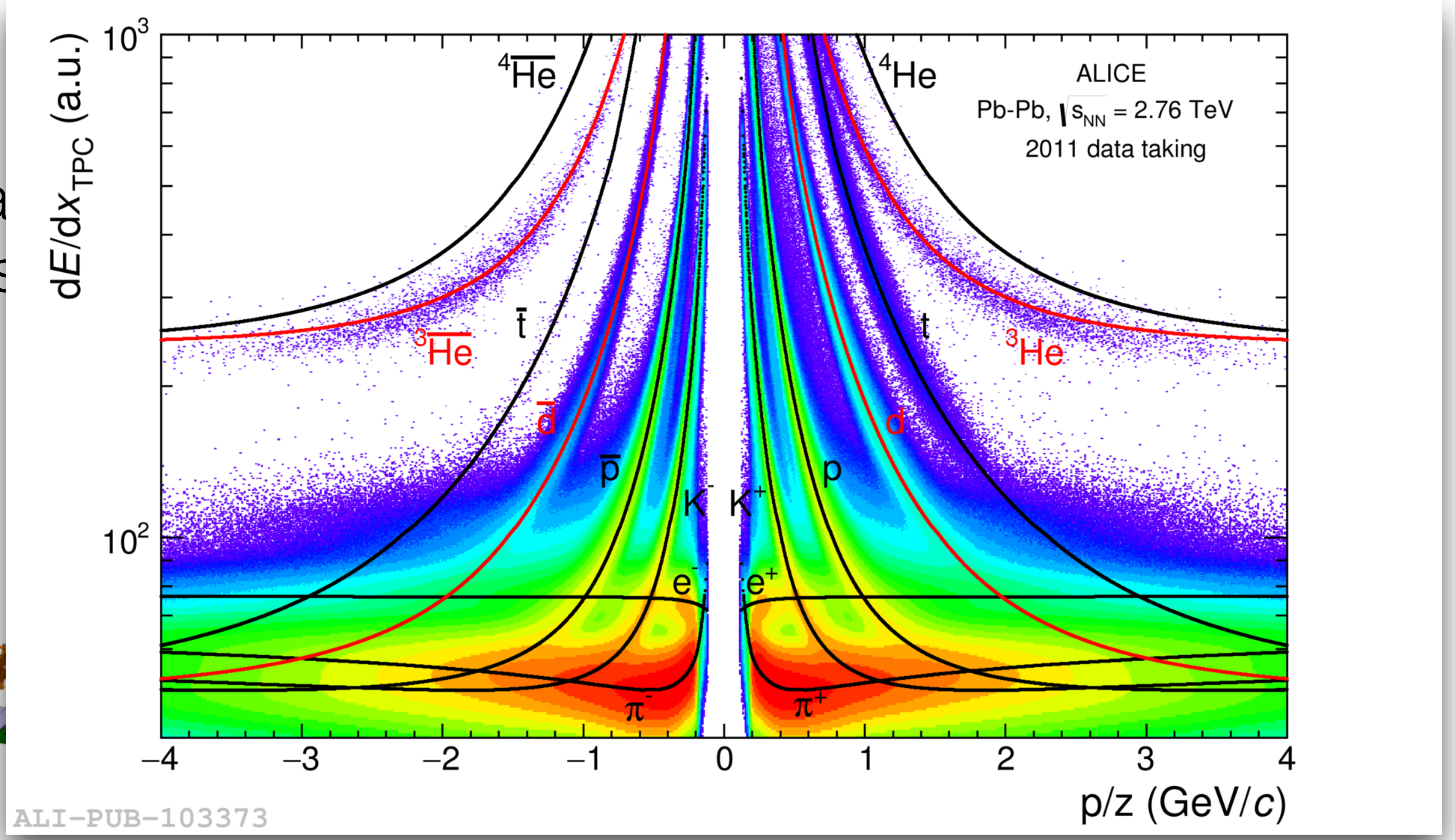


- General purpose heavy ion experiment
- Excellent particle identification (PID) and tracking capabilities + low material budget

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

ALICE - (Anti-)Nuclei identification

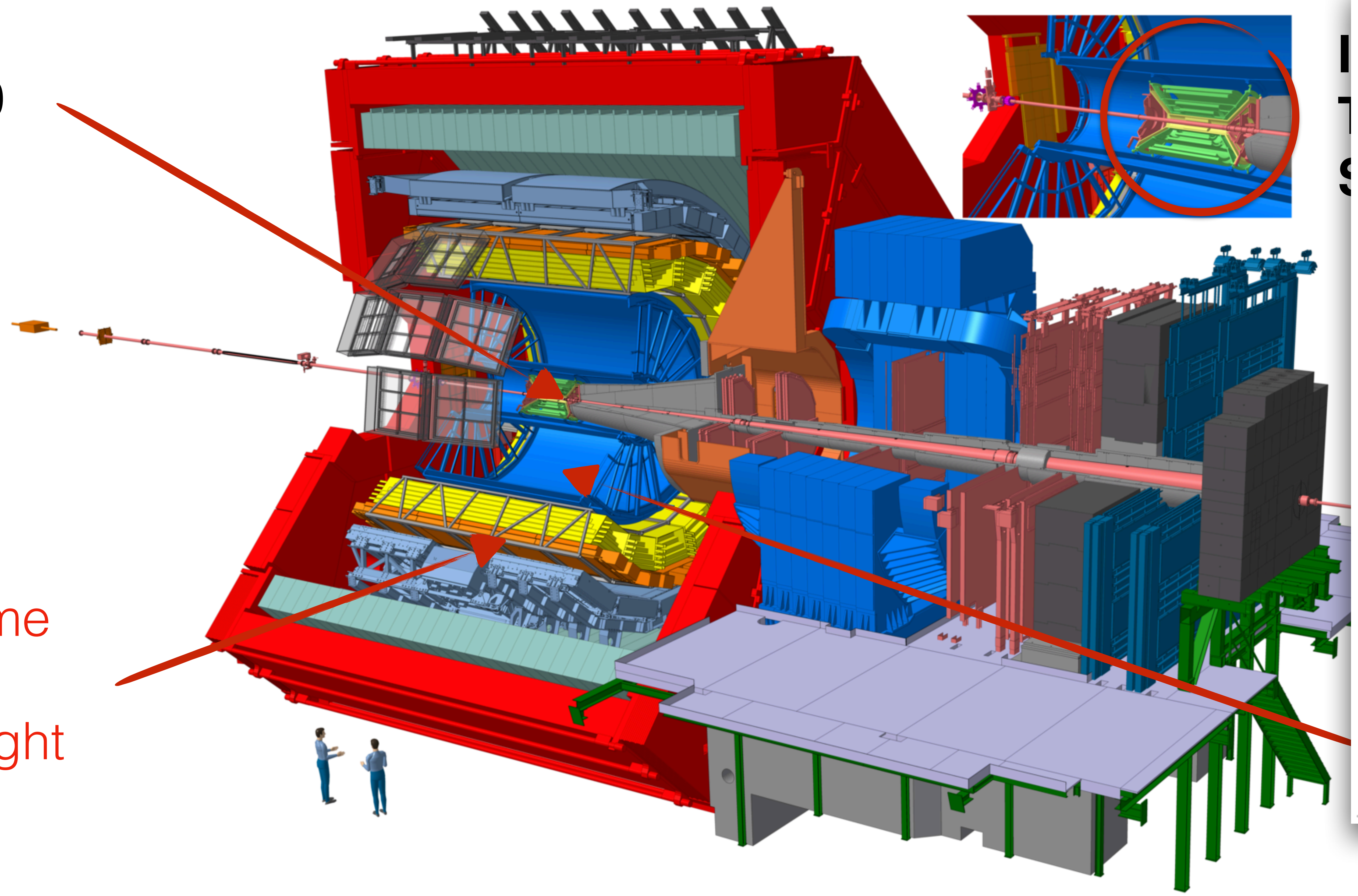




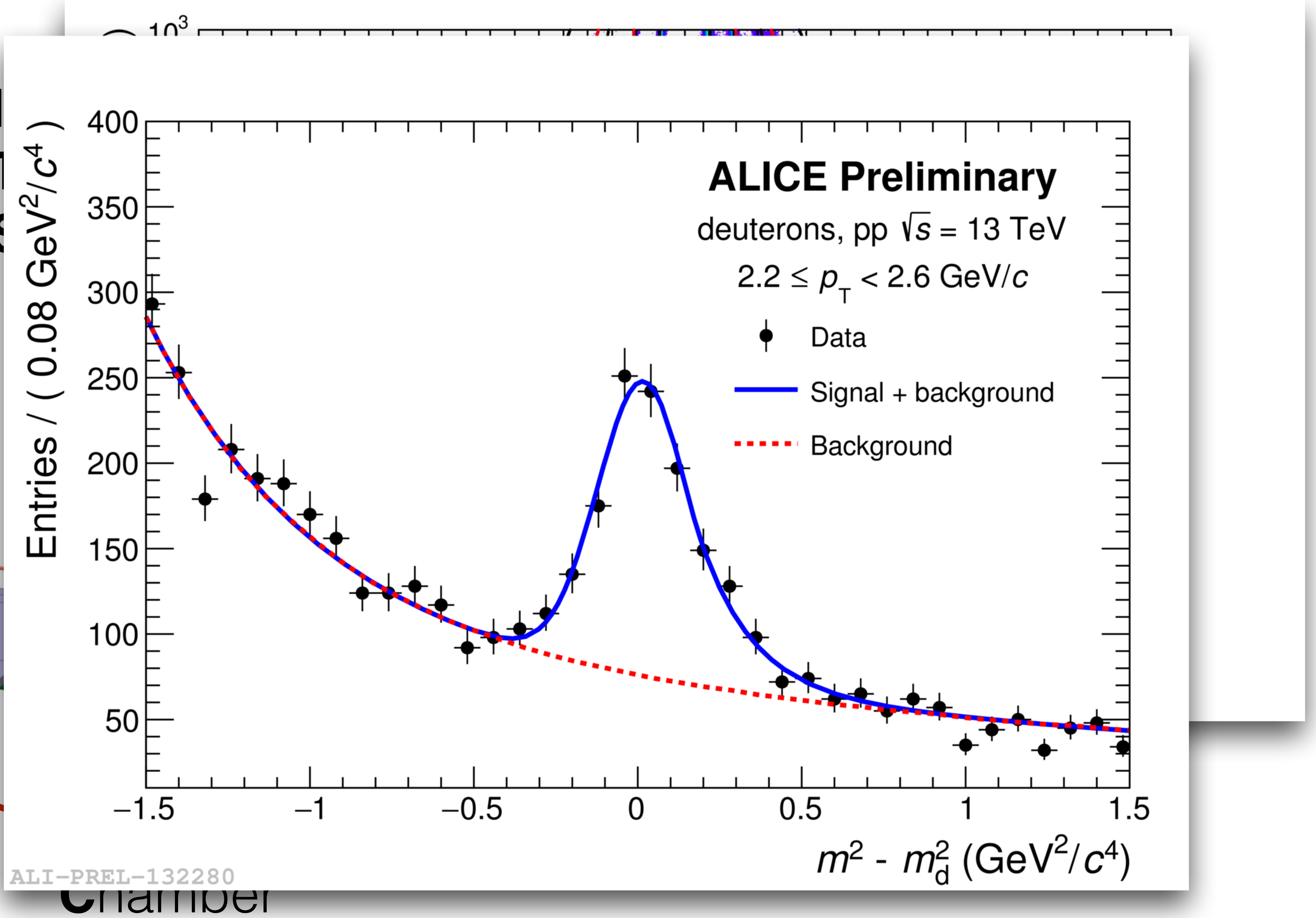
- At $p_T \leq$ 1.2 GeV/c the specific energy loss measured by TPC provides excellent PID for deuterons
  - ➡$\sigma_{dE/dx}$~6.5% (in Pb-Pb collisions)
- (anti-)^{3}He well separated from the other particle species over the full momentum range
  - Raw yields extracted for each p_T bin from the fit to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

ALICE - (Anti-)Nuclei identification

V0



Time
Of
Flight



- 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

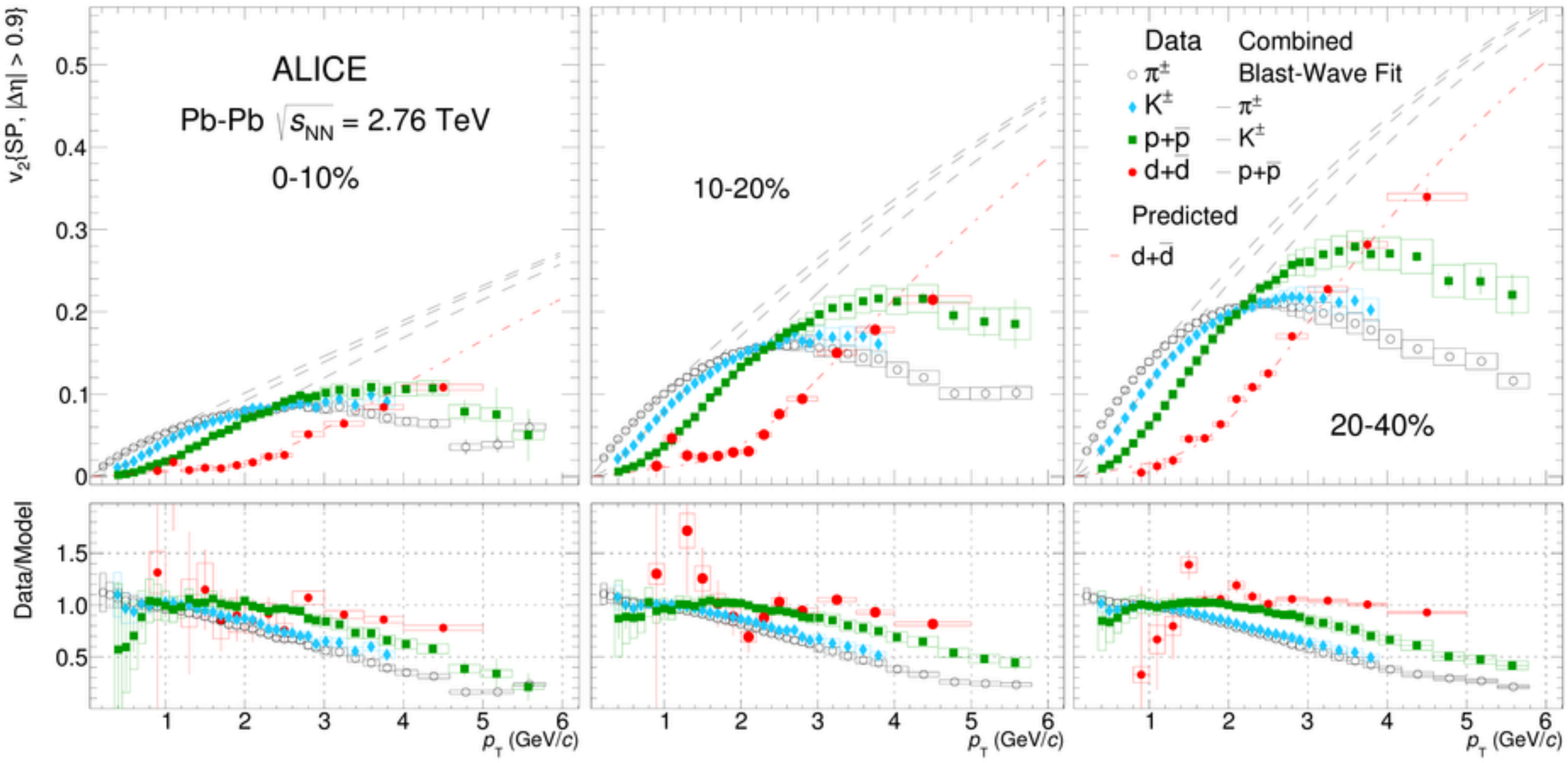
(Anti-)deuteron v_2 and spectra in Pb-Pb

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 ($|\eta|<0.8$)

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

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

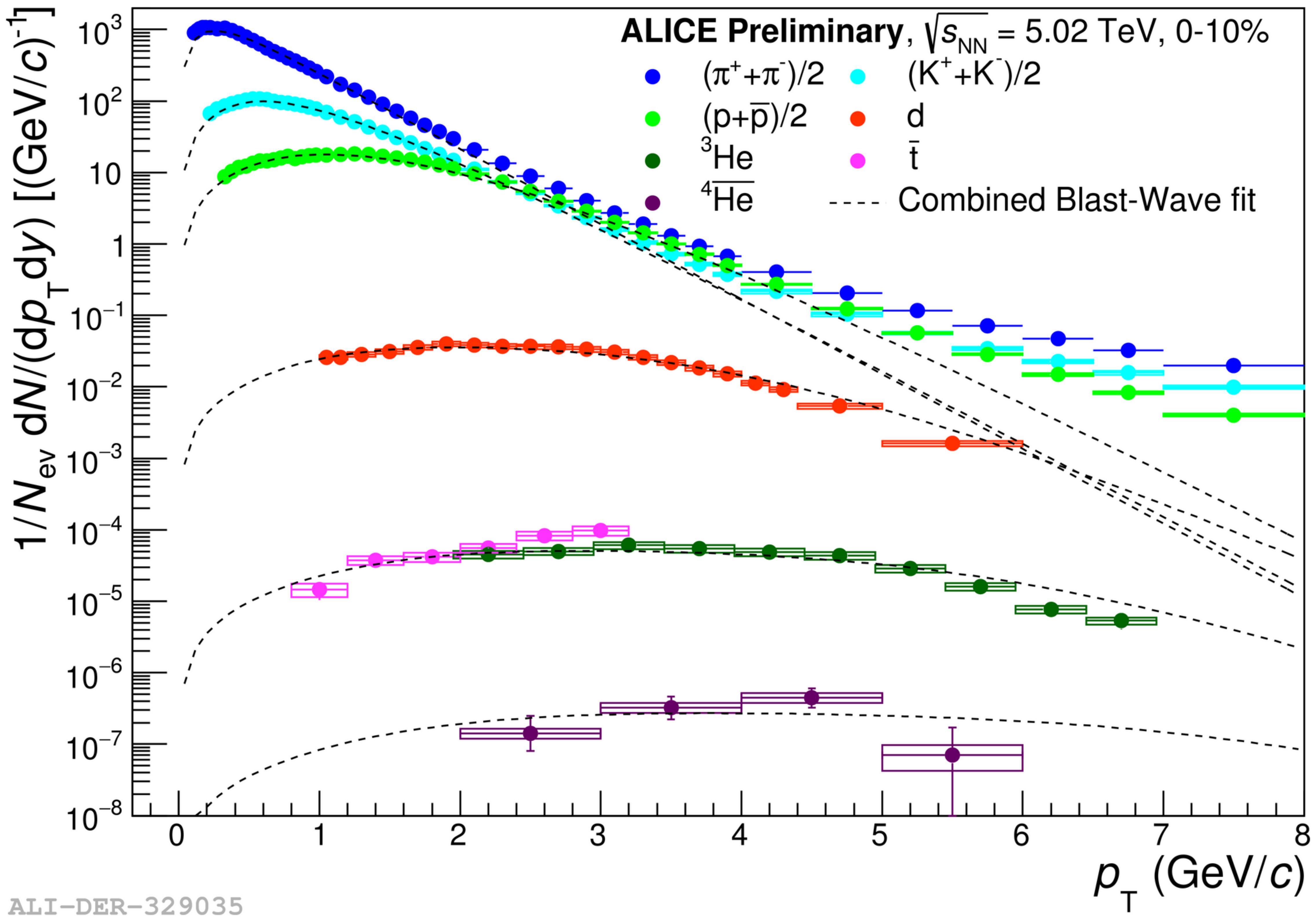


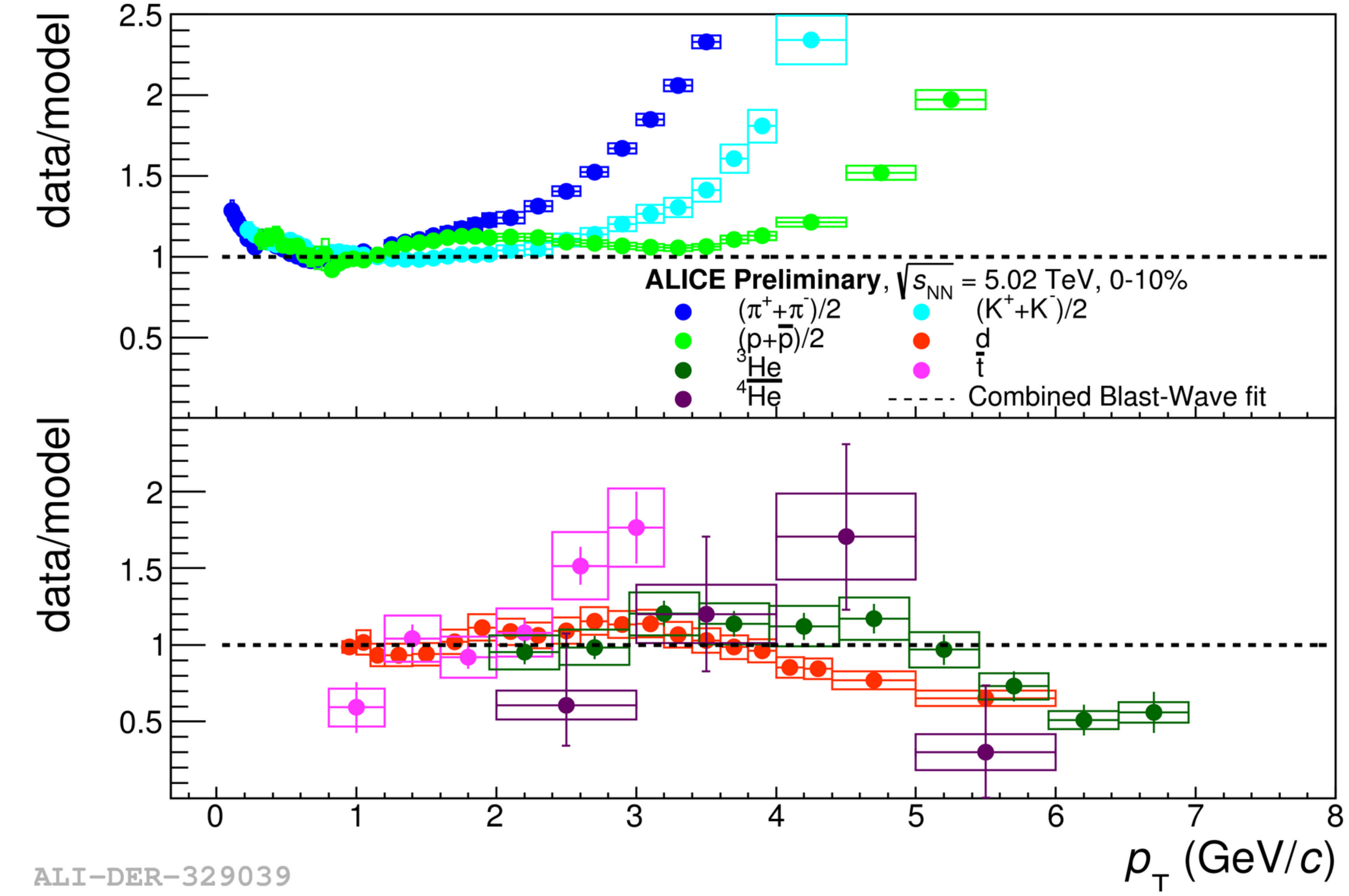
The Blast Wave model[1], fitted to the spectra and the v_2 of pions, kaons and protons reproduces reasonably well both the v_2 and the spectra of deuterons

➡**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

Common kinetic freeze-out?





- First measurement of (anti)alpha p_T spectrum
- Common Blast-Wave fit to light flavoured particles gives
  - Decent description of the observed spectra at the low-intermediate transverse momenta
  - Similar to what is observed in Pb-Pb 2.76 TeV
  - Is this enough to claim a common freeze-out surface?

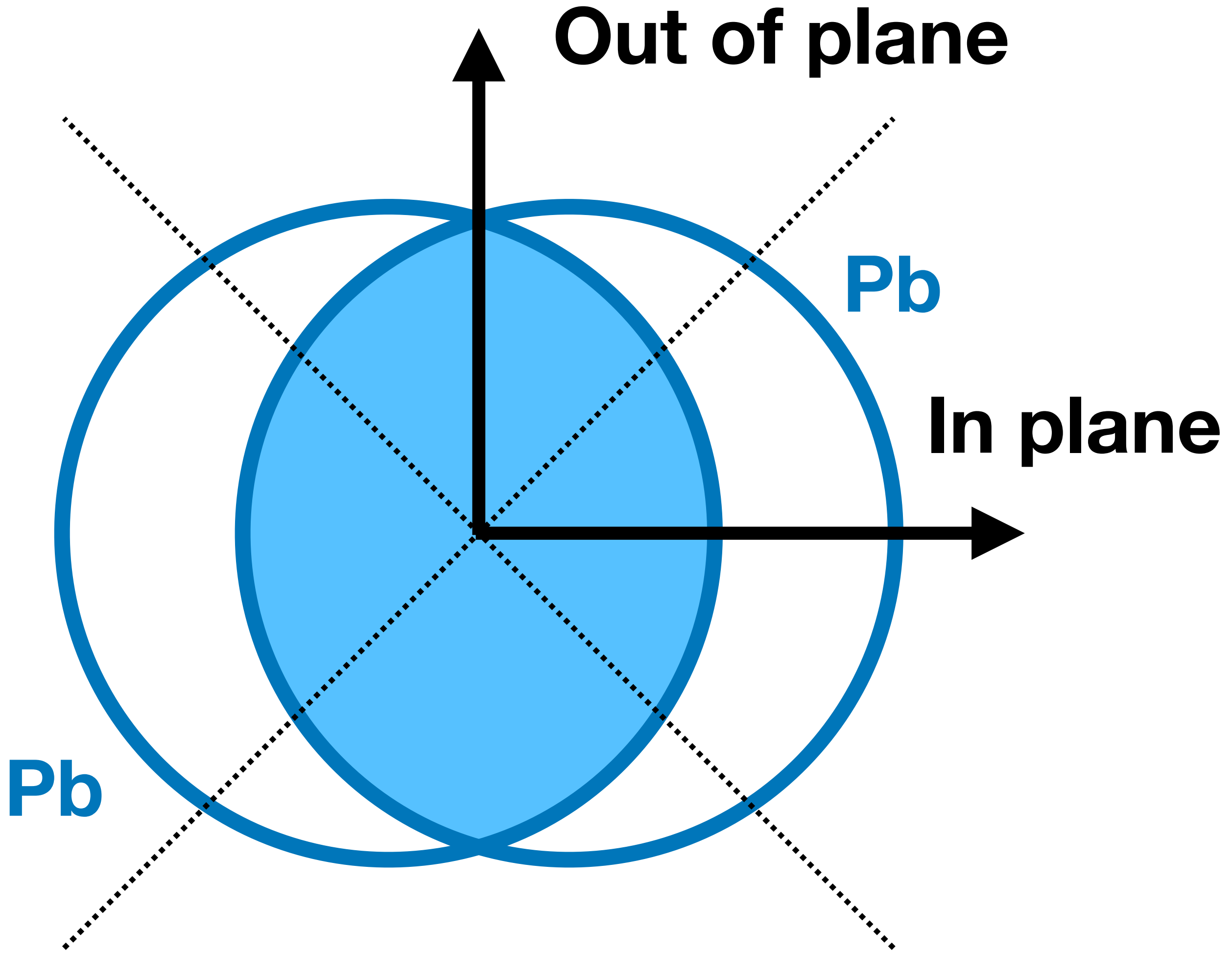
Maybe no: (anti-)^{3}He v_2 in Pb-Pb

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

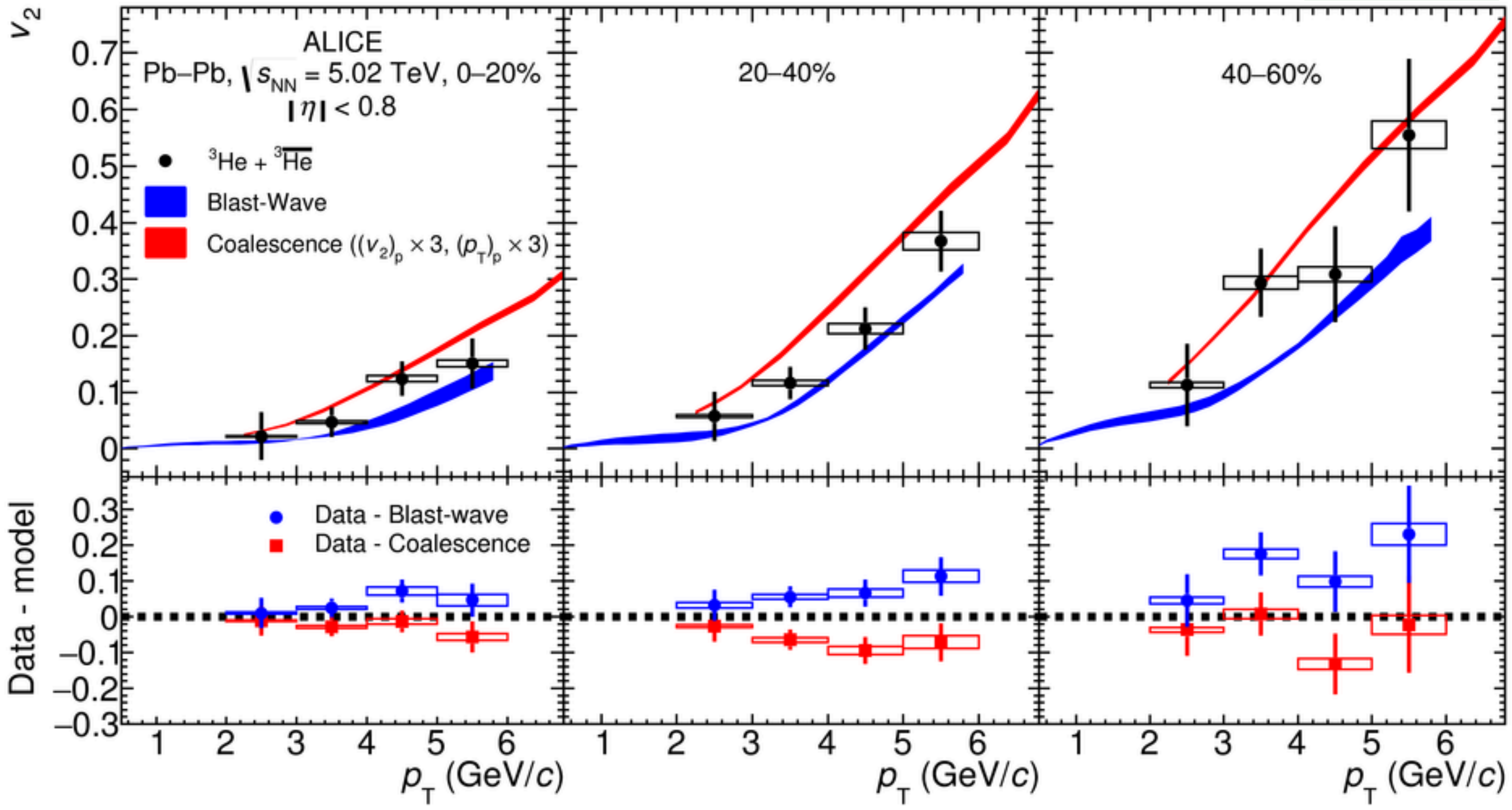
1. Reconstruction of the Event Plane (estimator of the Reaction Plane)
2. v_2 computed as:

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

R_2 is the event plane resolution



arXiv:1910.09718



- 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 (red points) gets closer to the measured ^{3}He for 40-60% centrality

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

Testing coalescence: the coalescence parameter

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

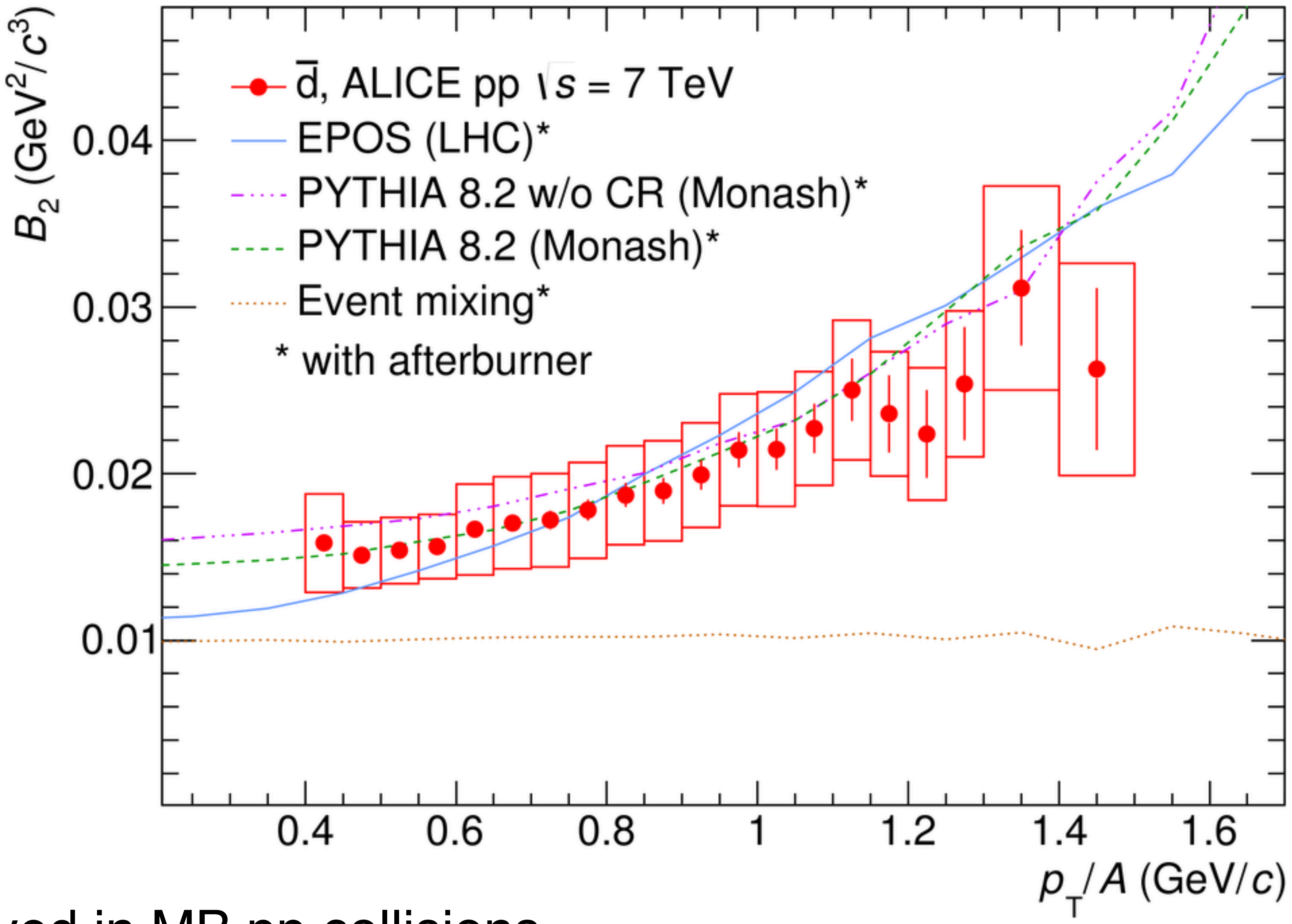
$$E_i \frac{\mathrm{d}^3 N_i}{\mathrm{d}p_i^3} = B_A \left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^A$$

deuterons

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

Simplistic coalescence

- Flat coalescence parameter
- $v^{\mathrm{d}}_2(p^{\mathrm{d}}_\mathrm{T})=2v_2^{\mathrm{p}}(2p^{\mathrm{p}}_\mathrm{T})$



Flat coalescence parameter in p_T is not observed in MB pp collisions

- Coalescence afterburner on top of QCD inspired generators describes both B_2 and B_3

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10.1016/j.physletb.2019.05.028

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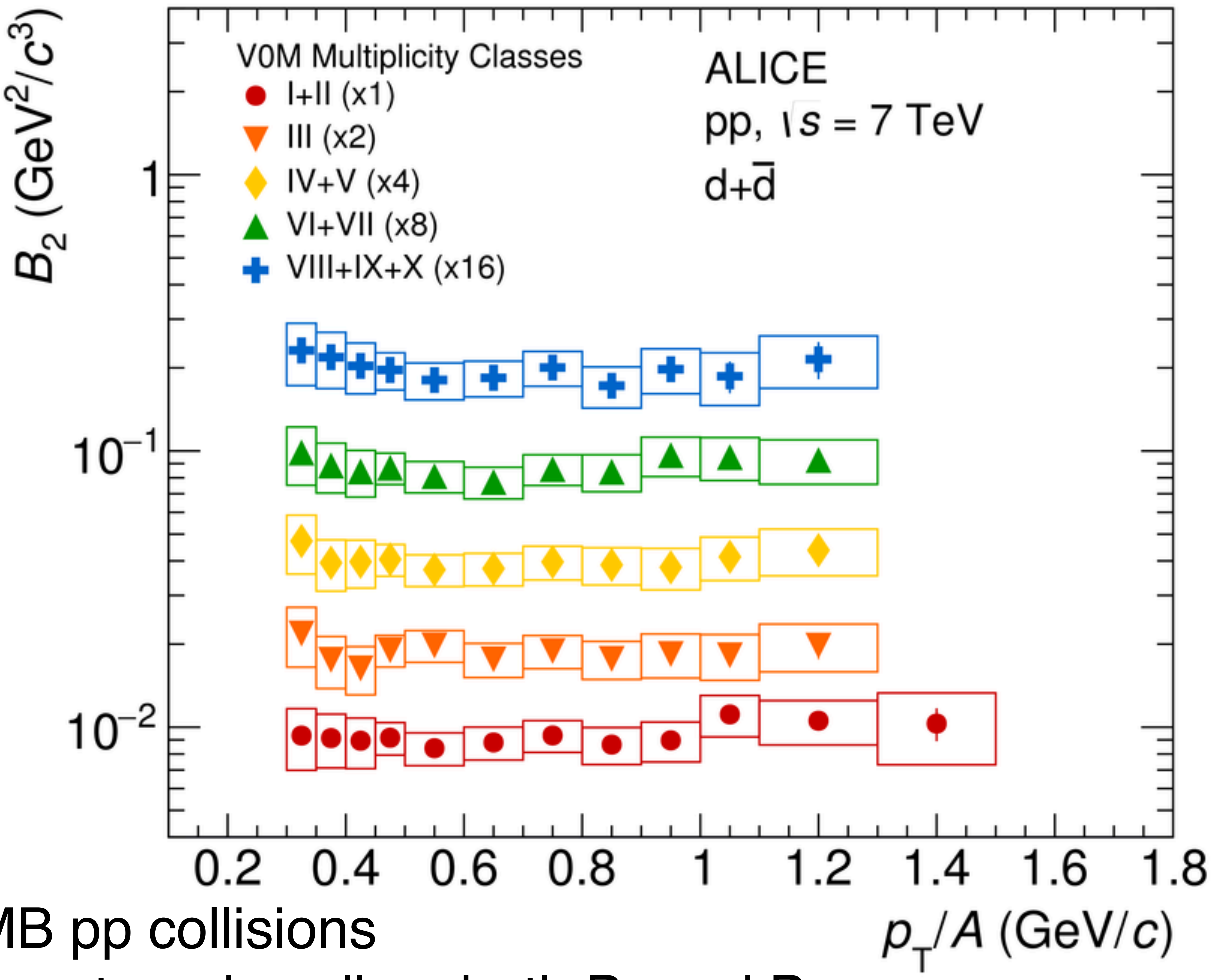

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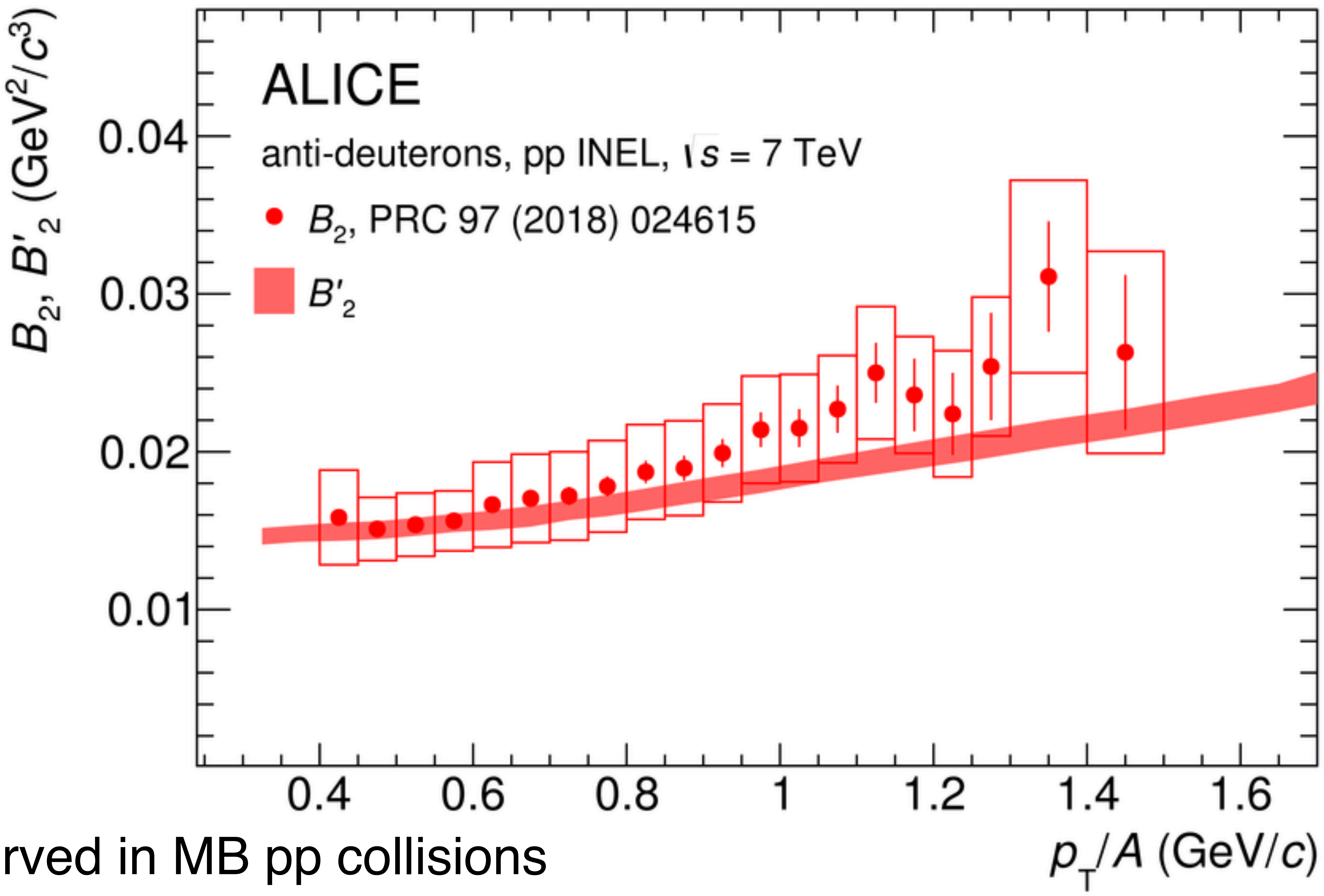

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- **Coalescence afterburner on top of QCD inspired generators describes both B_2 and B_3**

But the observed rise in MB collision is not seen when looking at the B_2 in multiplicity bins

- The rise in MB (partially) comes from the change of the proton spectra shape as a function of multiplicity

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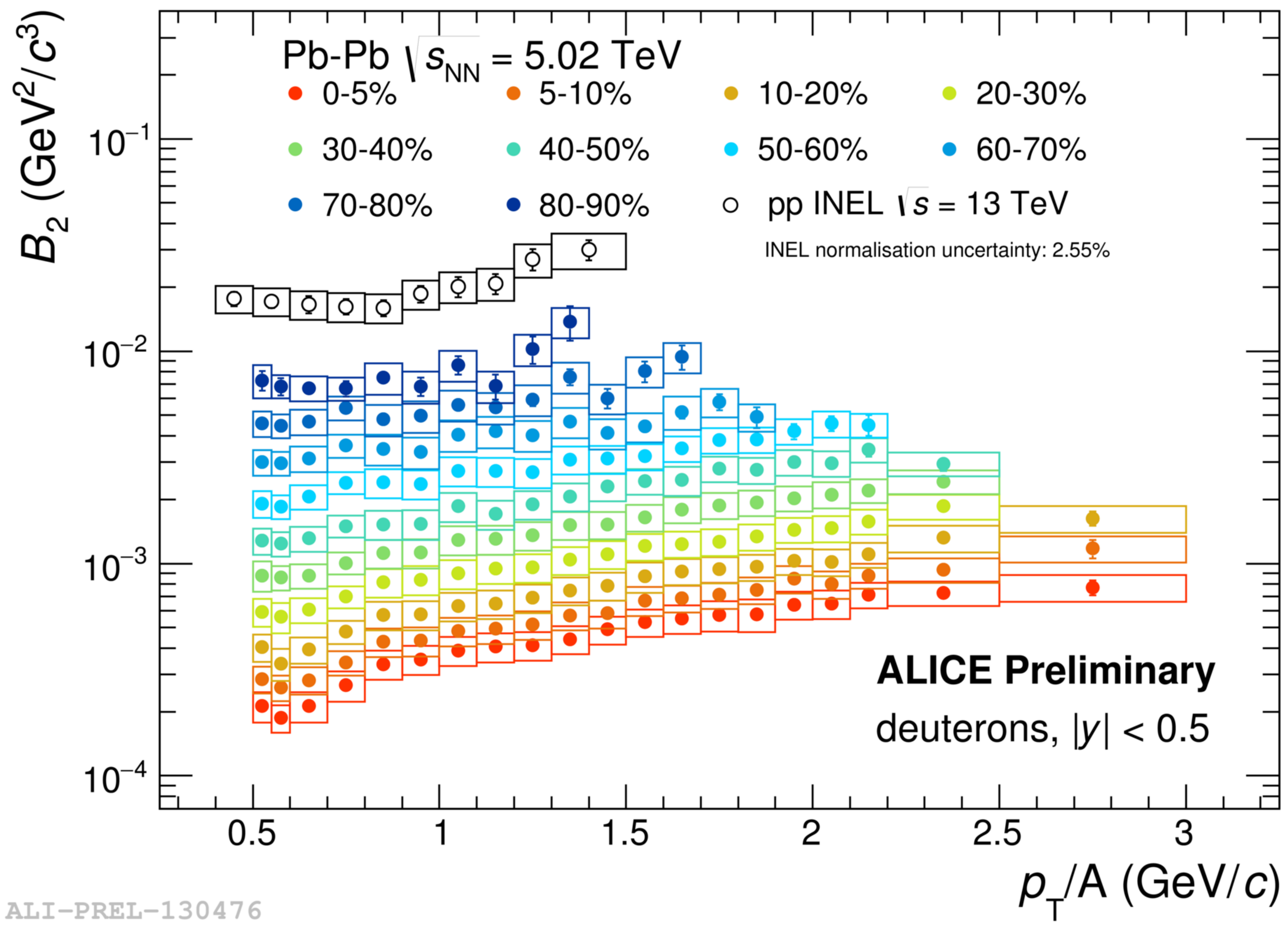
ALICE-PUBLIC-2017-006

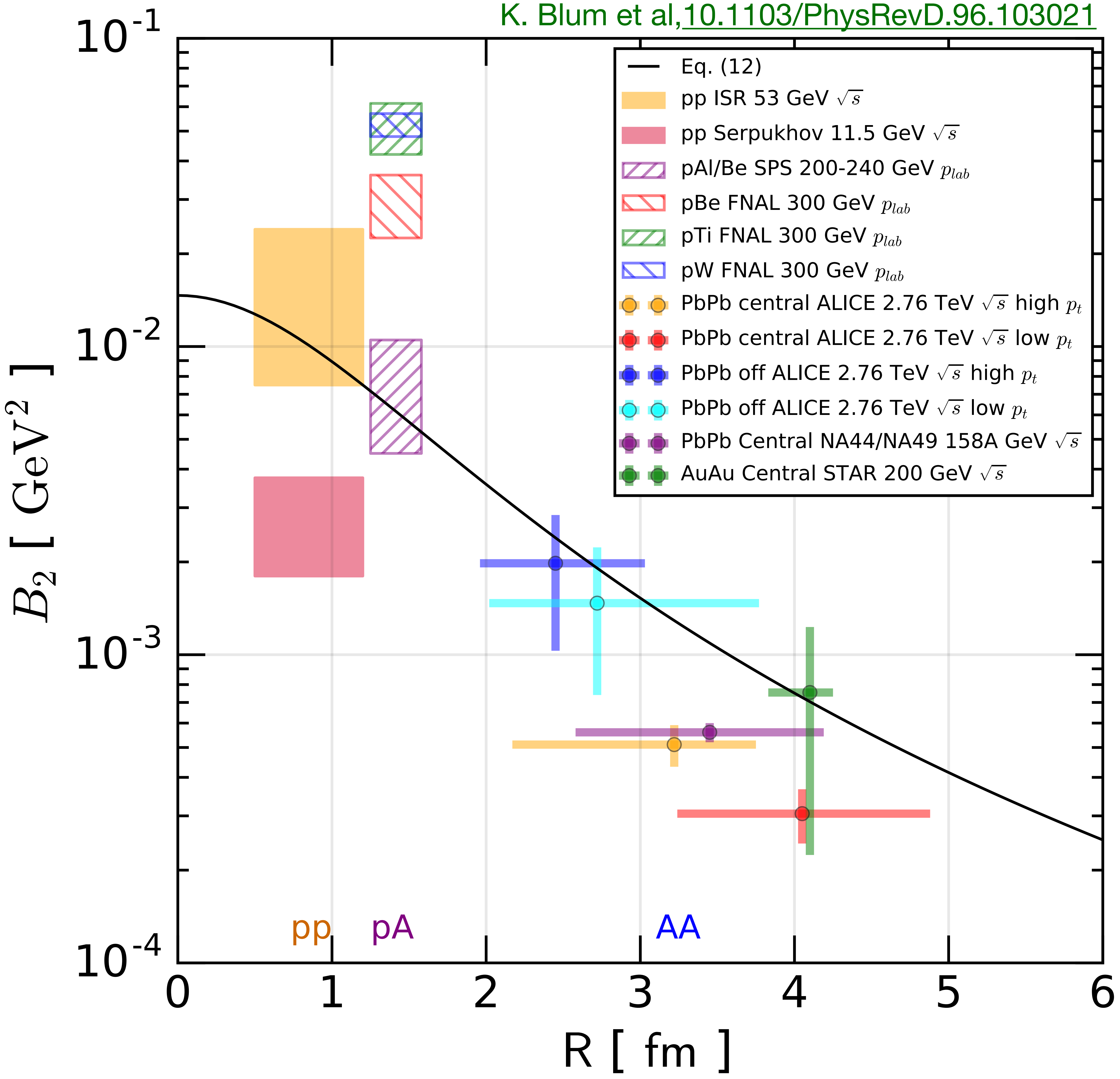


In general, **simplistic coalescence does not describe ALICE deuteron measurement in Pb-Pb collisions.**

- **Fine centrality binning:** the proton spectra does not change within the centrality bins considered
- Flattening of the B_2 in peripheral collisions
  - System size dependency in the nuclei production mechanism
    - ➡ High p_T -> small emission volume -> higher coalescence parameter

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

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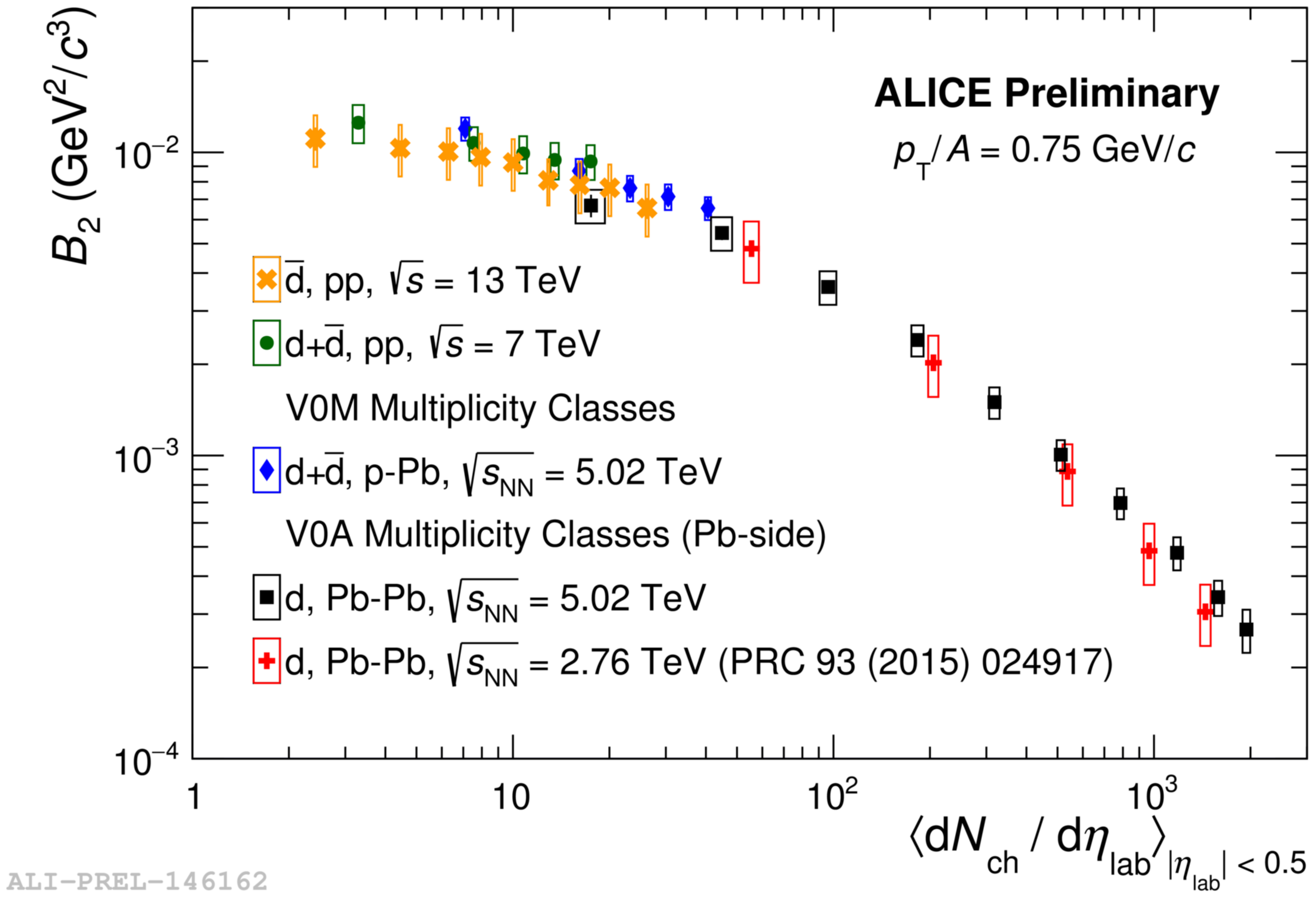

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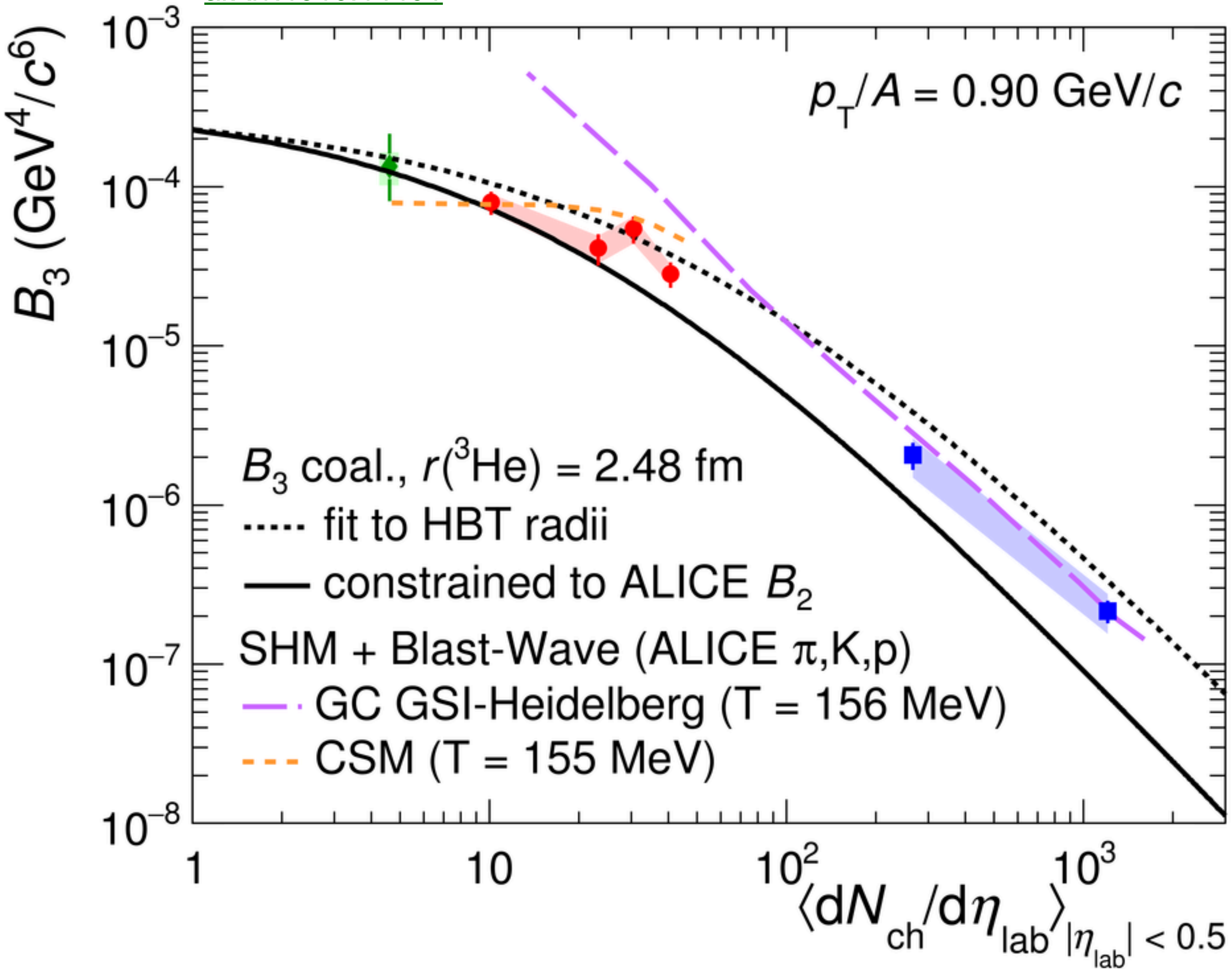
arXiv:1910.14401



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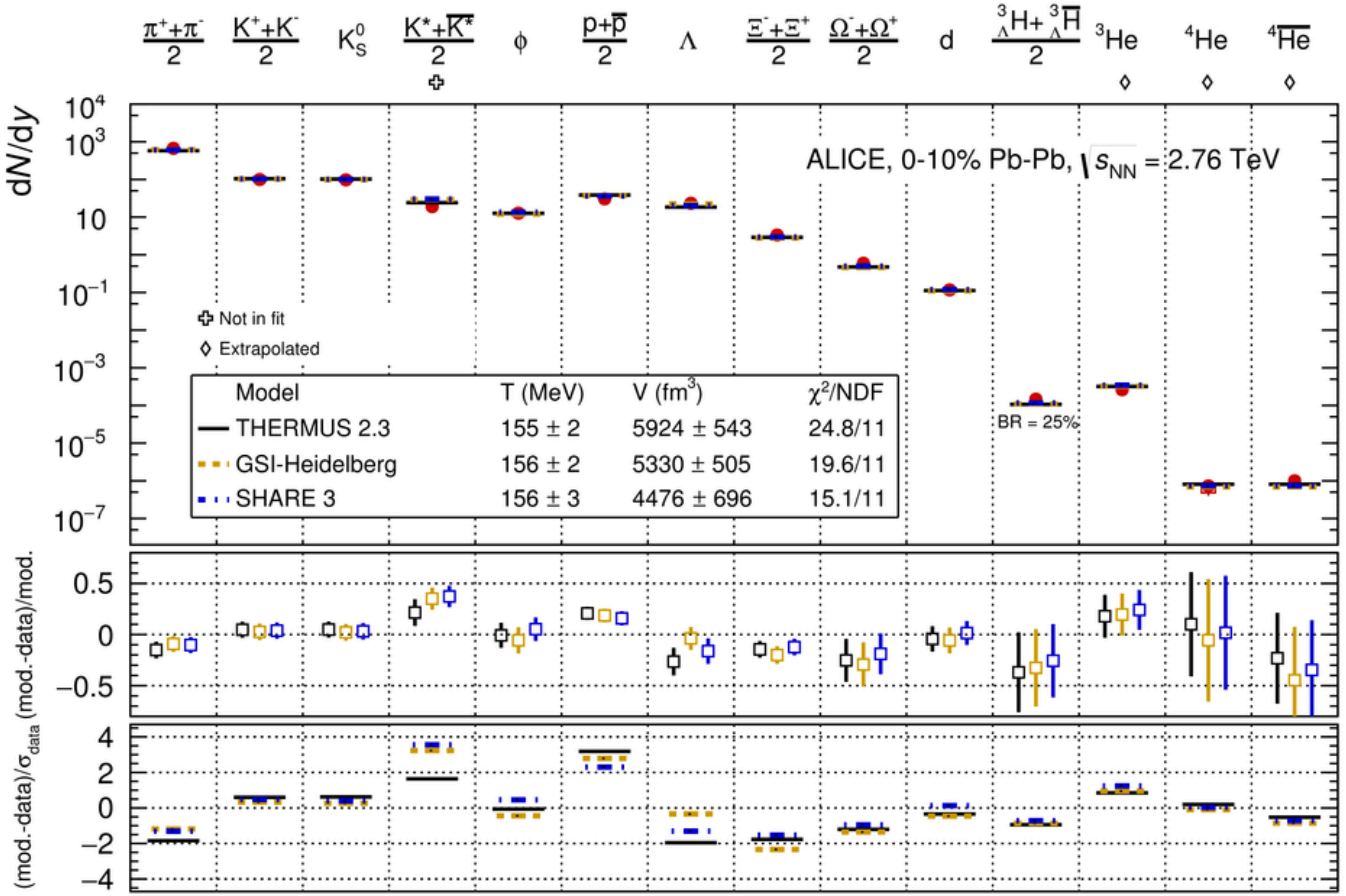
The standard model of particle production in A-A?

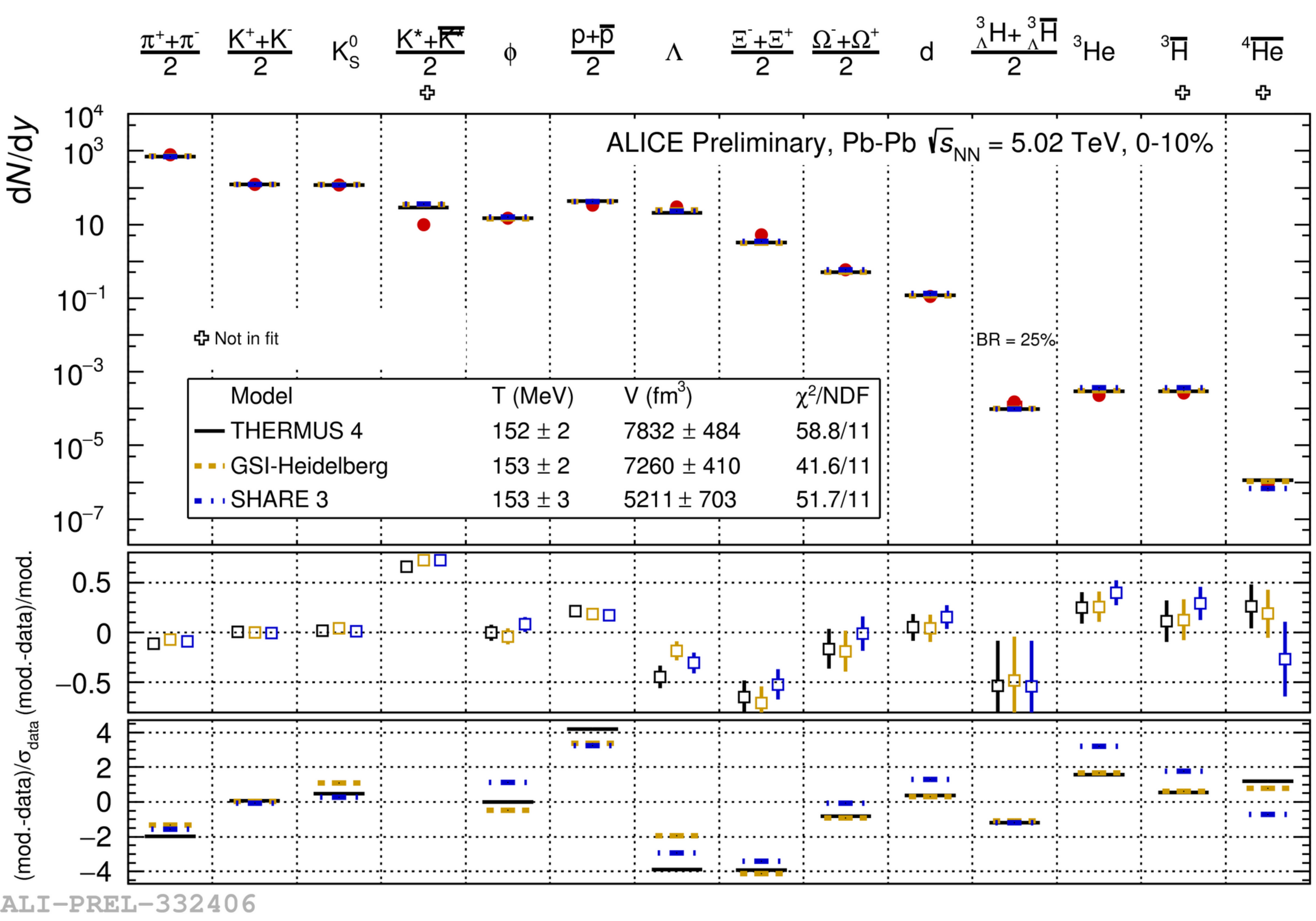


ALICE, 10.1016/j.nuclphysa.2017.12.004

- 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 formulation 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?

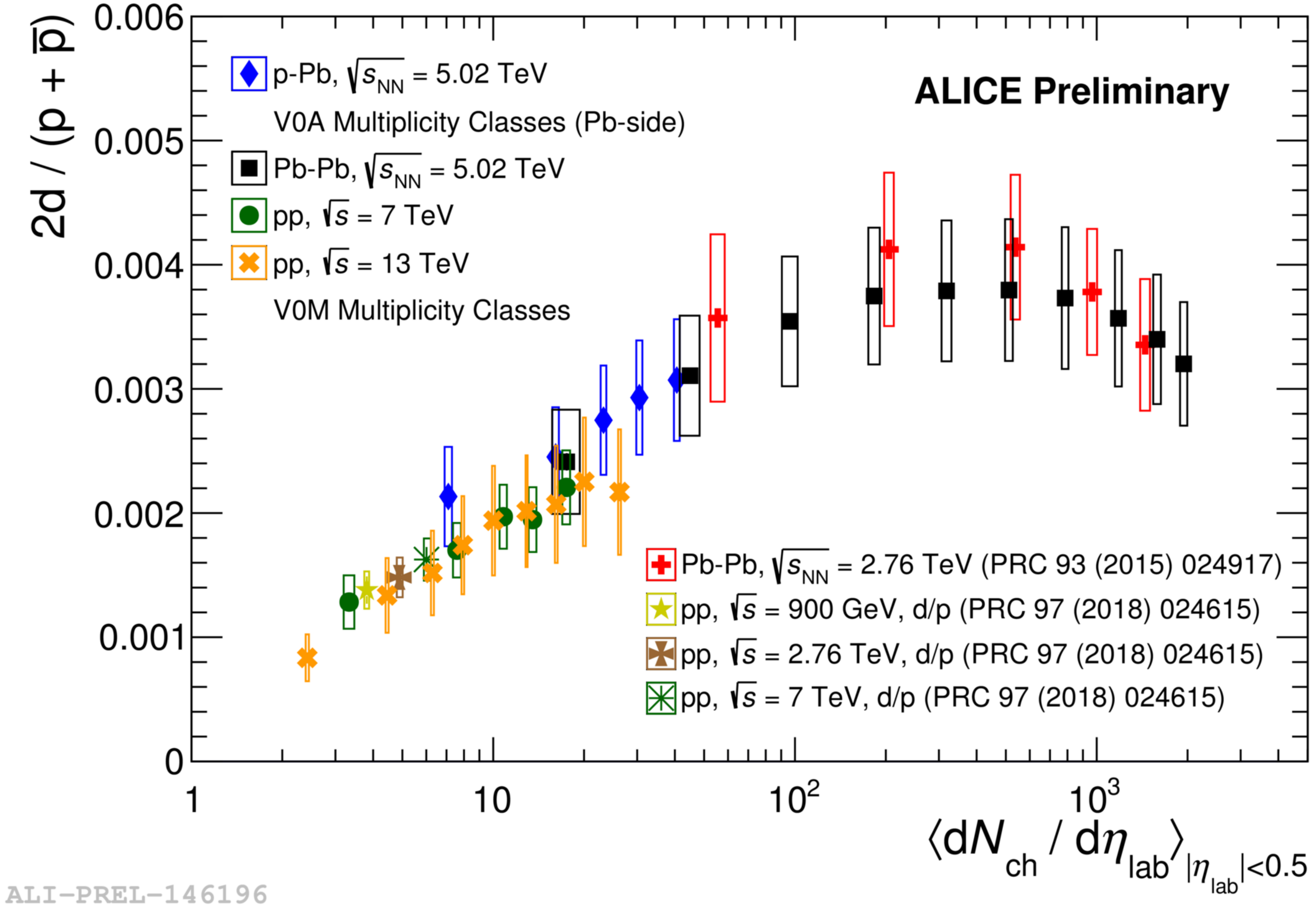


- The larger data sample collected in LHC Run2 and improved reconstruction and analysis techniques reduced the uncertainties.
- The tensions with the thermal model fit to our new preliminary results are now larger due to the smaller uncertainties

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

Simple thermal fits shown here, the tensions get solved with more sophisticated approaches (e.g. S-Matrix approach)

Unified description of nucleosynthesis at collider?



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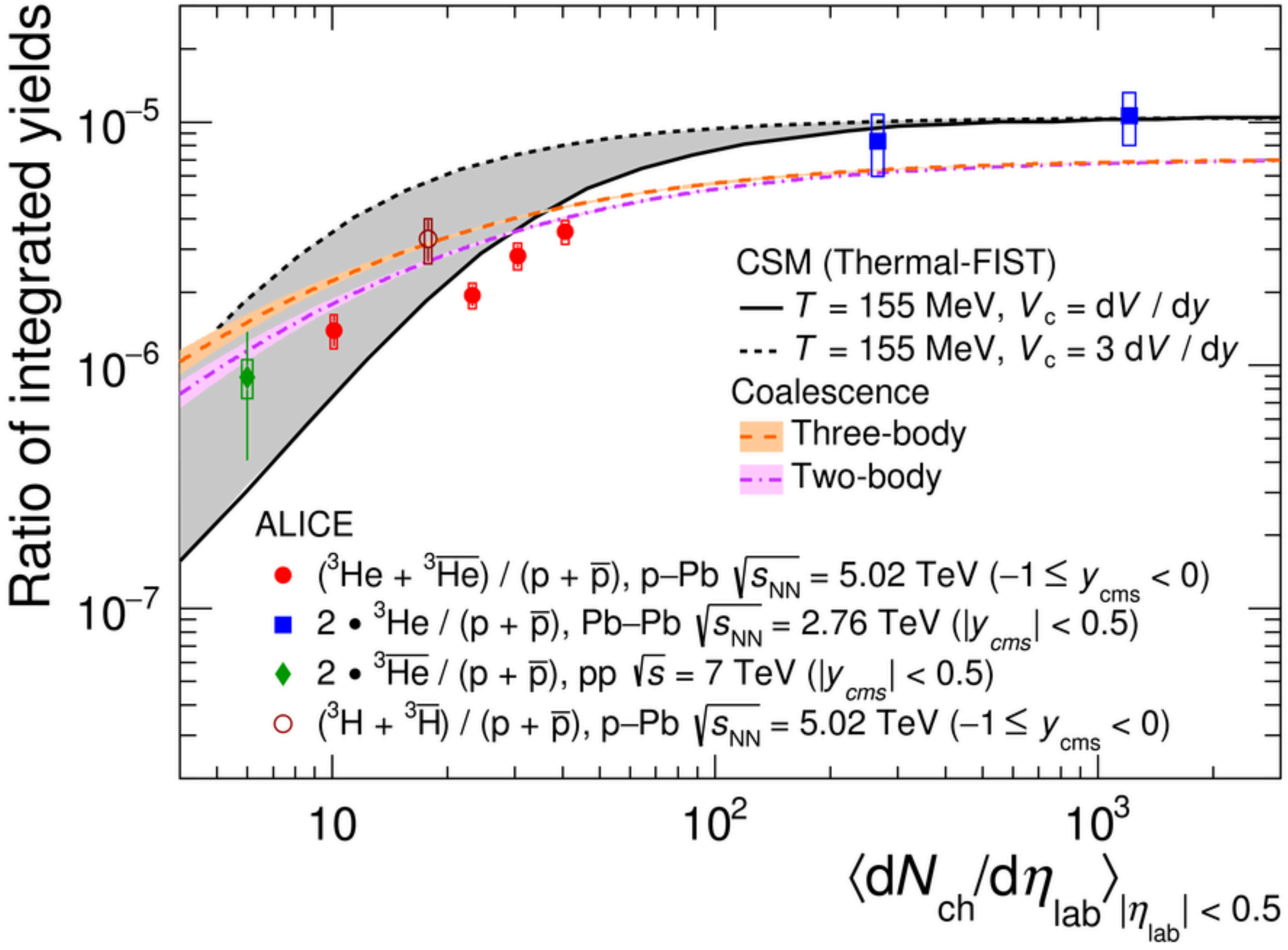
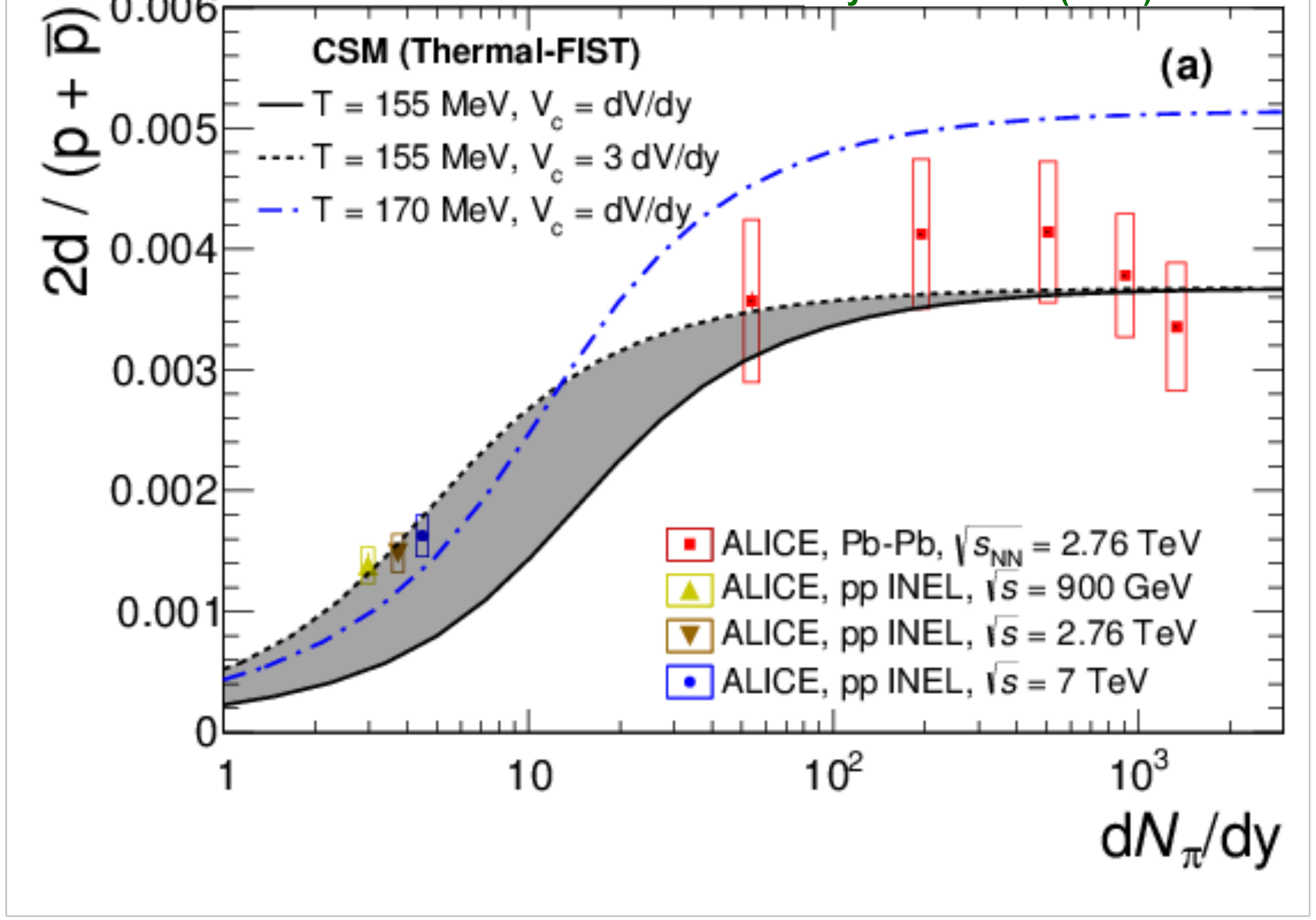


- Is this smooth transition suggesting a single description for the nucleosynthesis in HEP?
  - Thermal model with canonical suppression gets the rise of the nucleus/proton ratio

Unified description of nucleosynthesis at collider?

Phys.Lett. B785 (2018) 171-174



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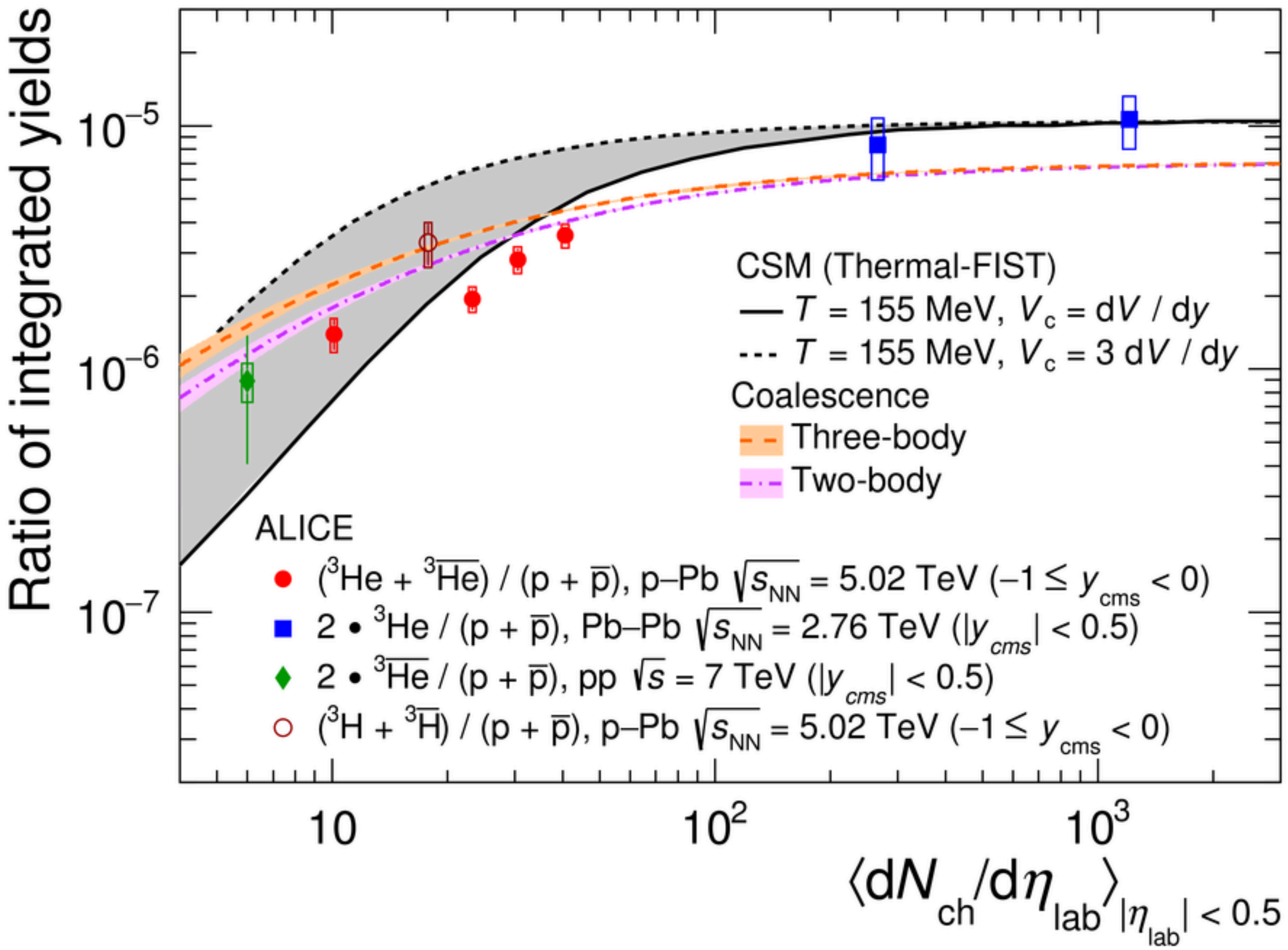

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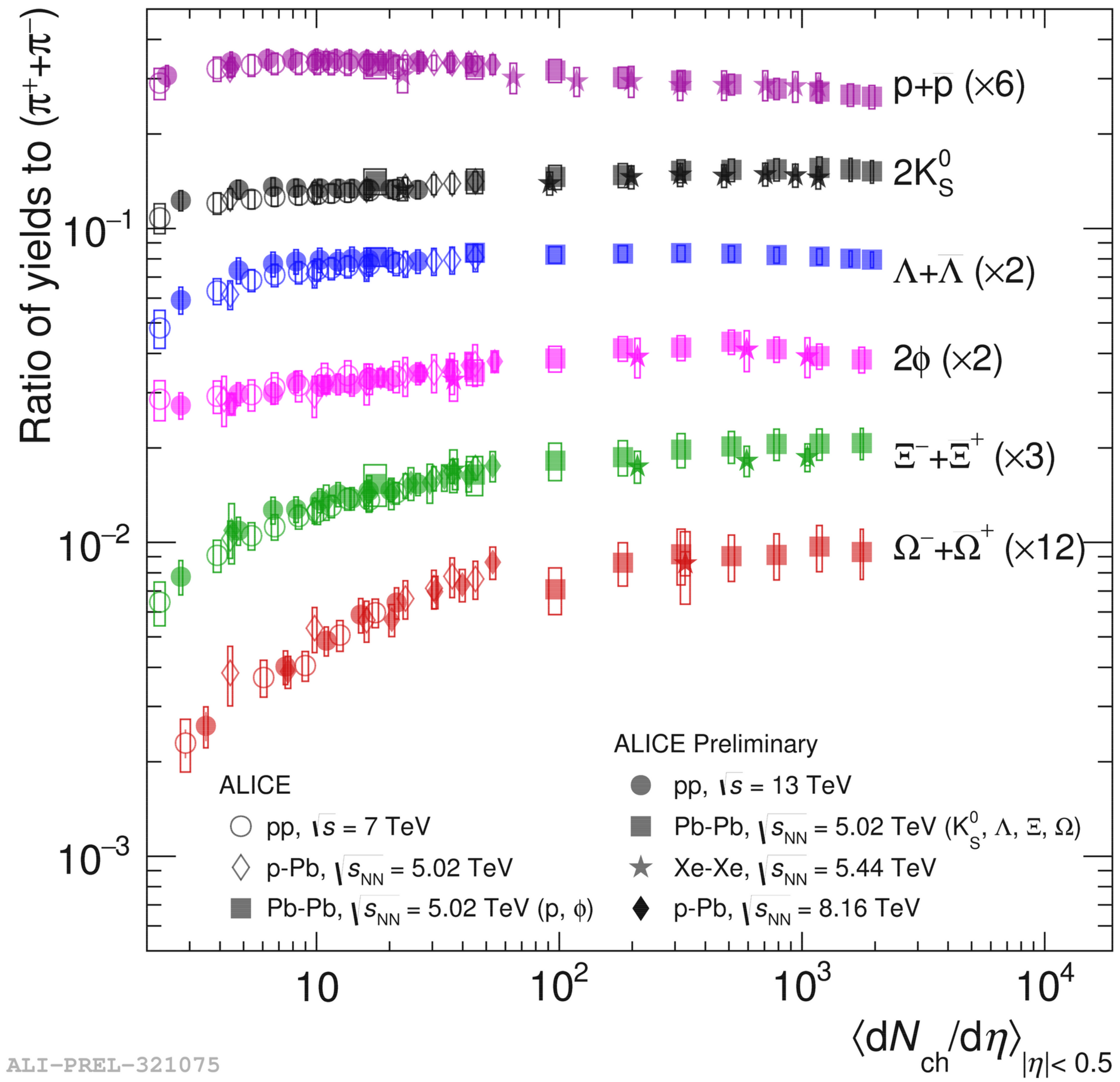

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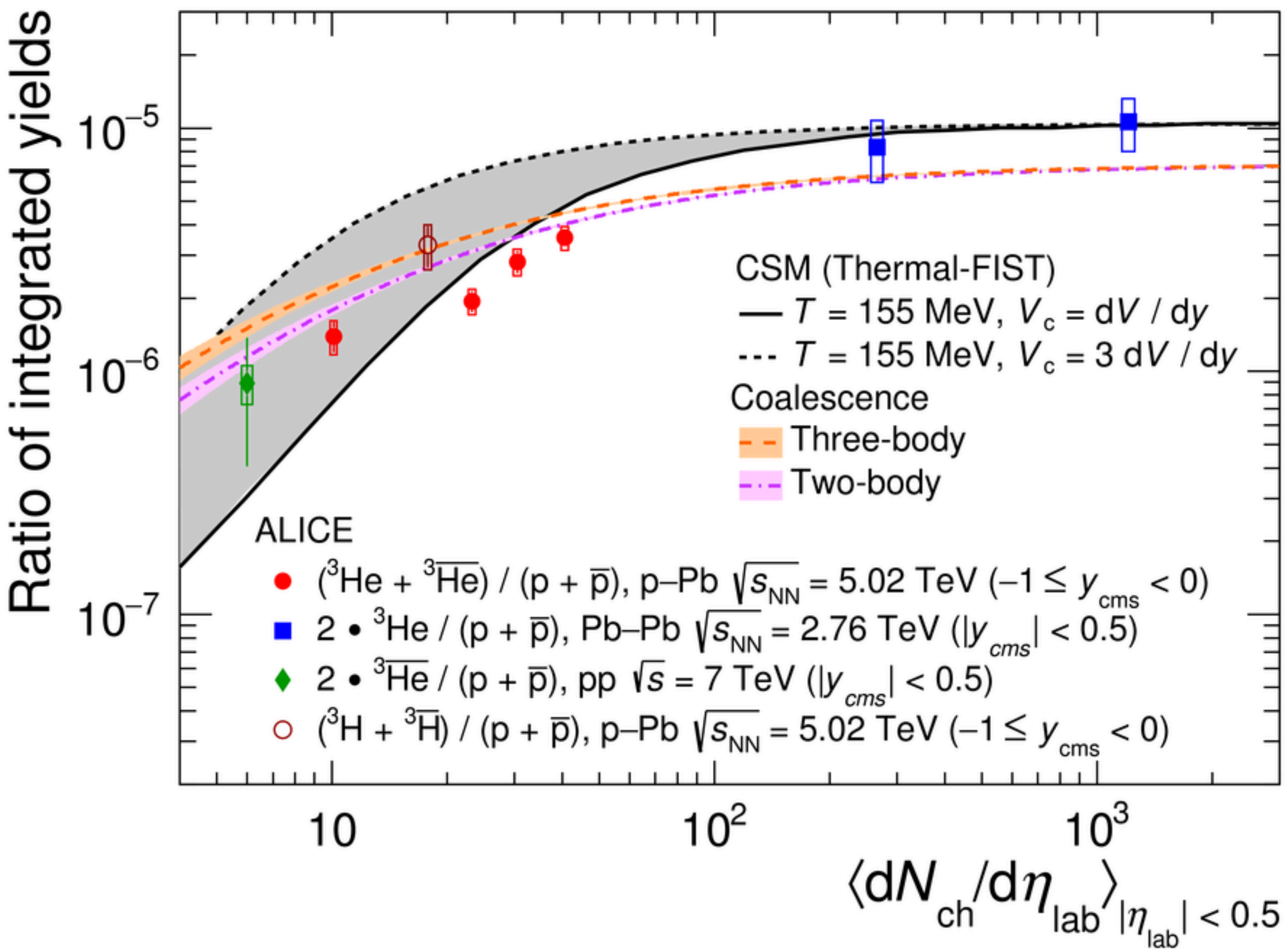

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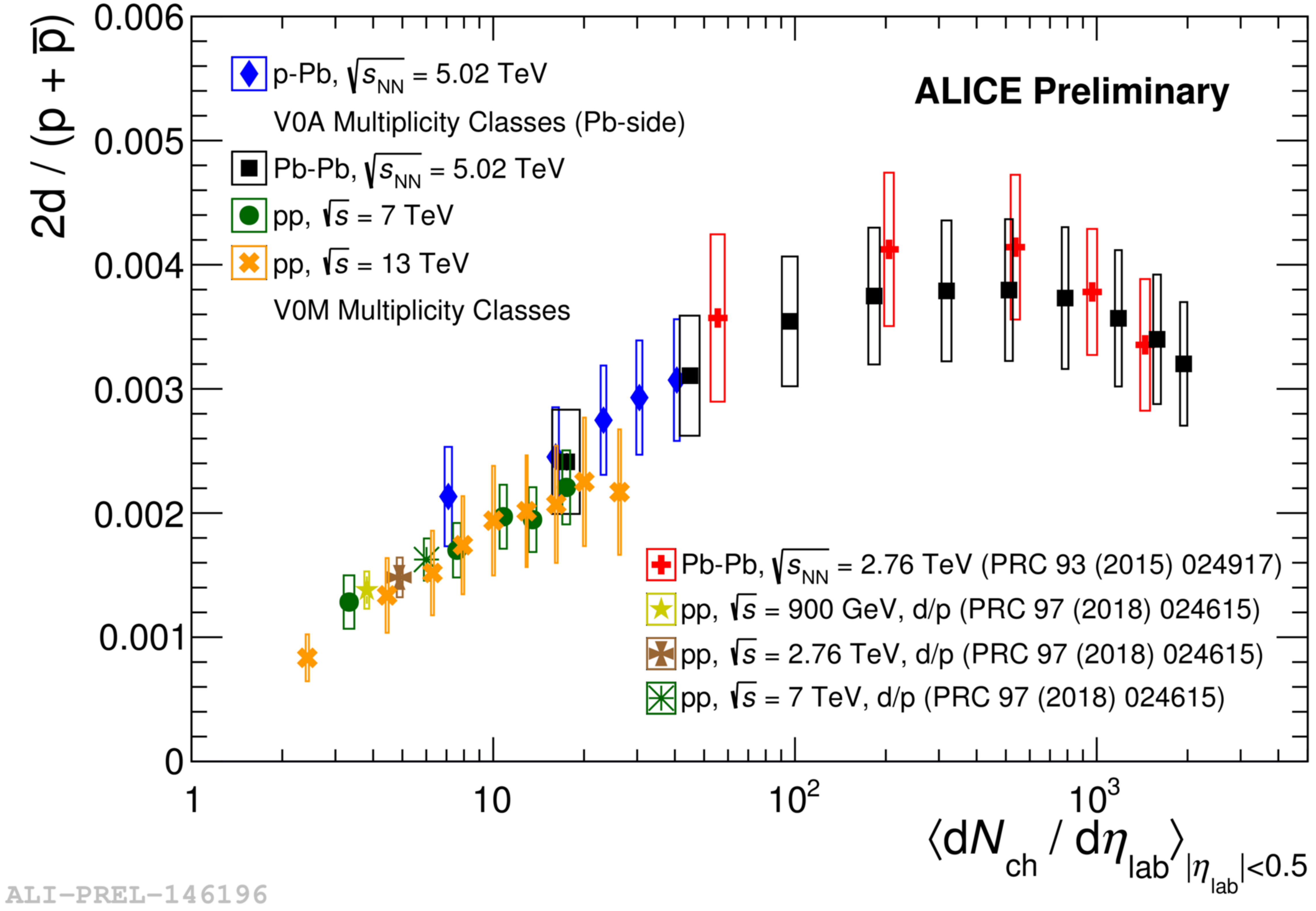
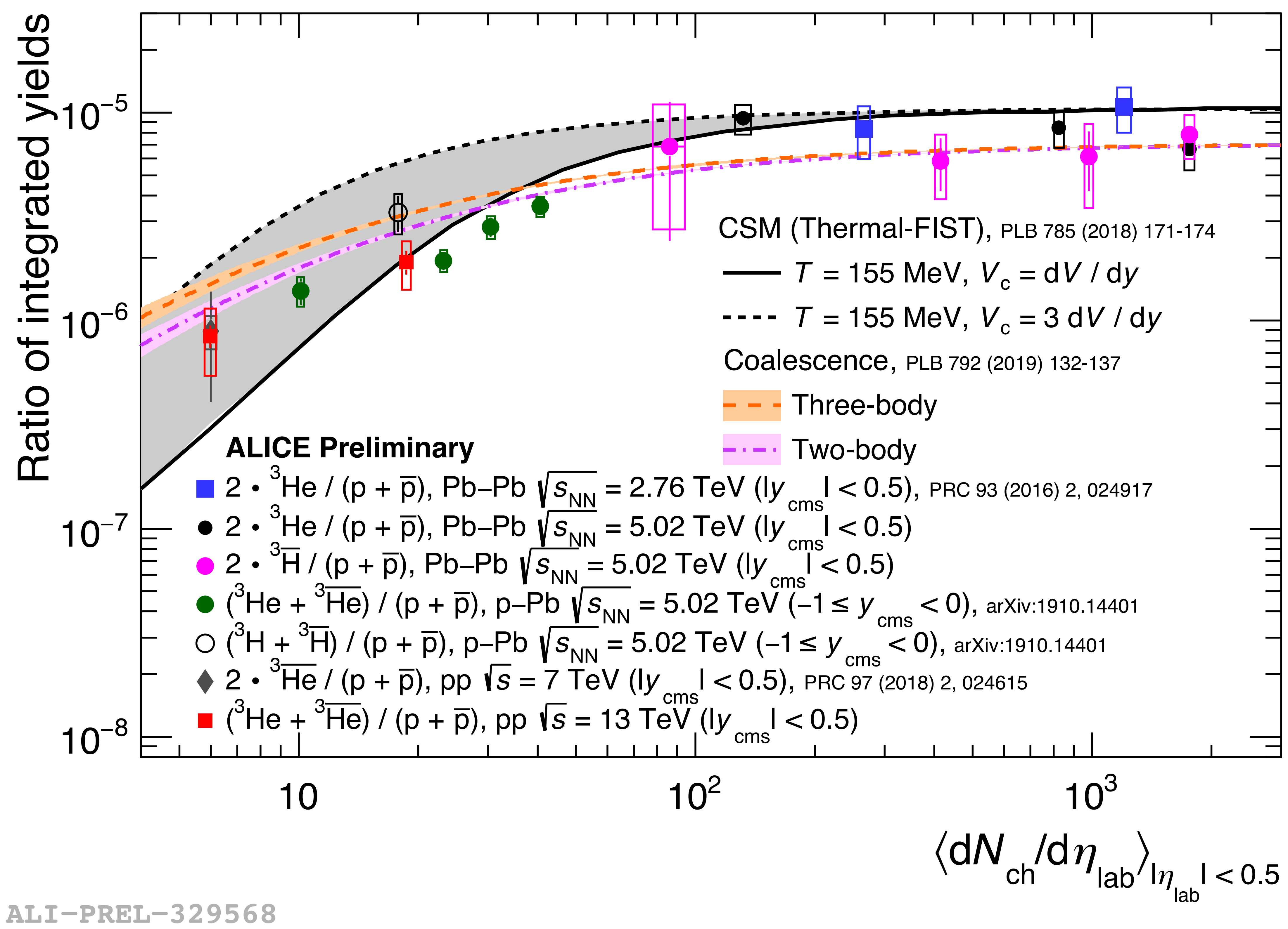
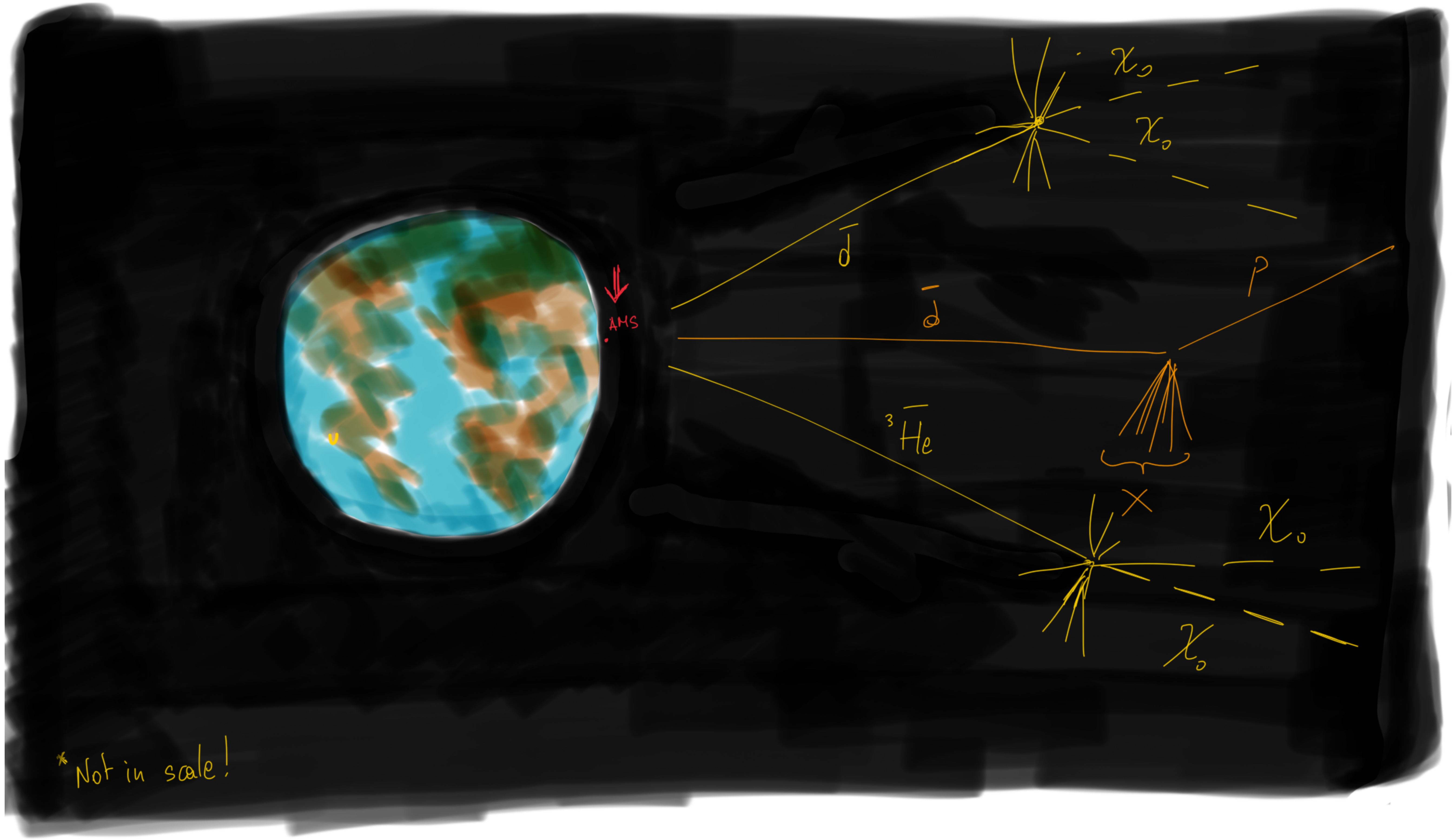




- Is this smooth transition suggesting a single description for the nucleosynthesis in HEP?
  - Thermal model with canonical suppression gets the rise of the nucleus/proton ratio
    - However the proton over pion ratio does not show any increase with multiplicity
- Advanced nuclei coalescence can describe the d/p ratio but struggle with the Z=2 nuclei

Anti-nuclei relevance in other fields

K. Blum et al., 10.1103/PhysRevD.96.103021
F.Donato et al.,10.1103/PhysRevD.62.043003

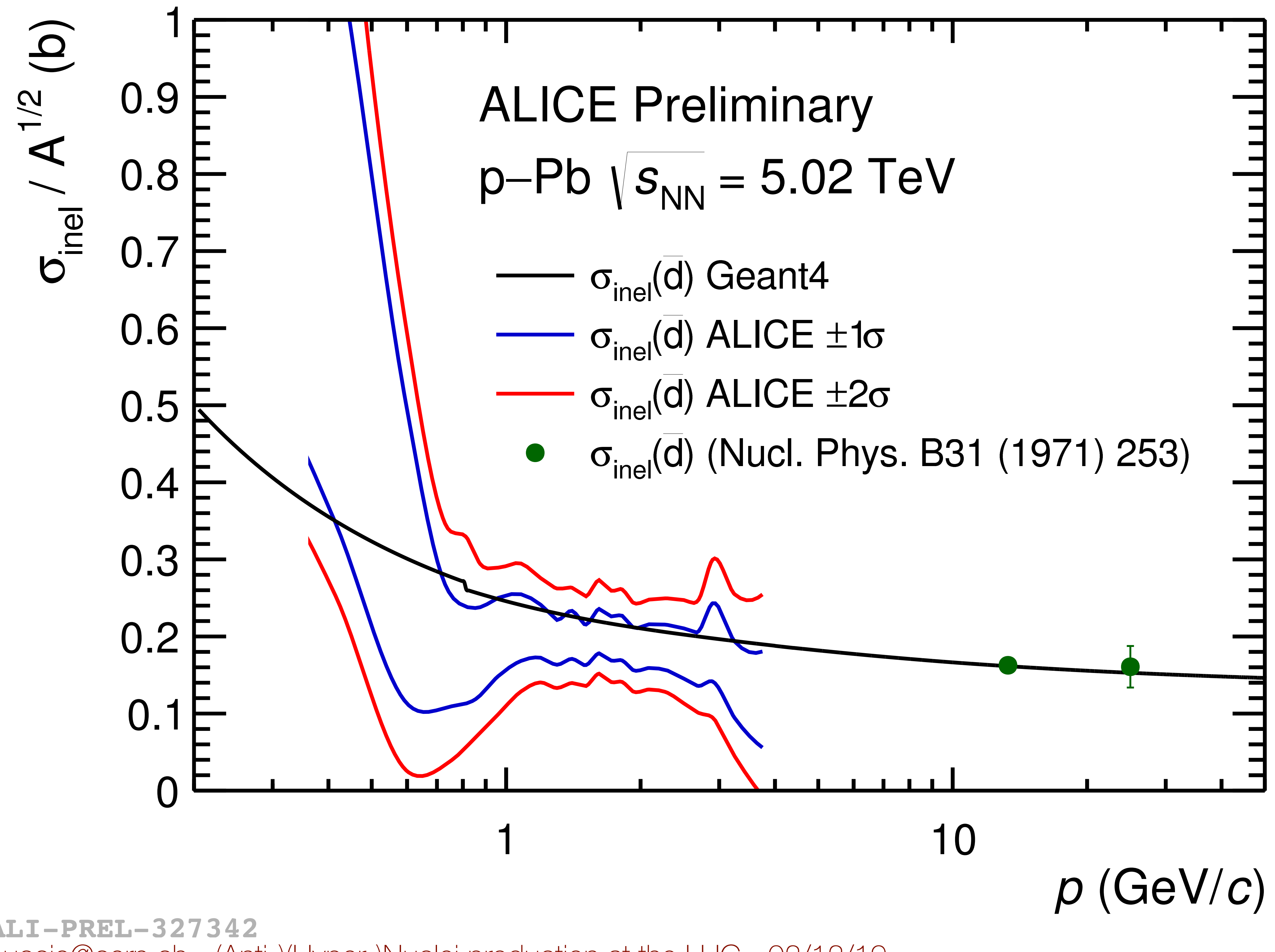


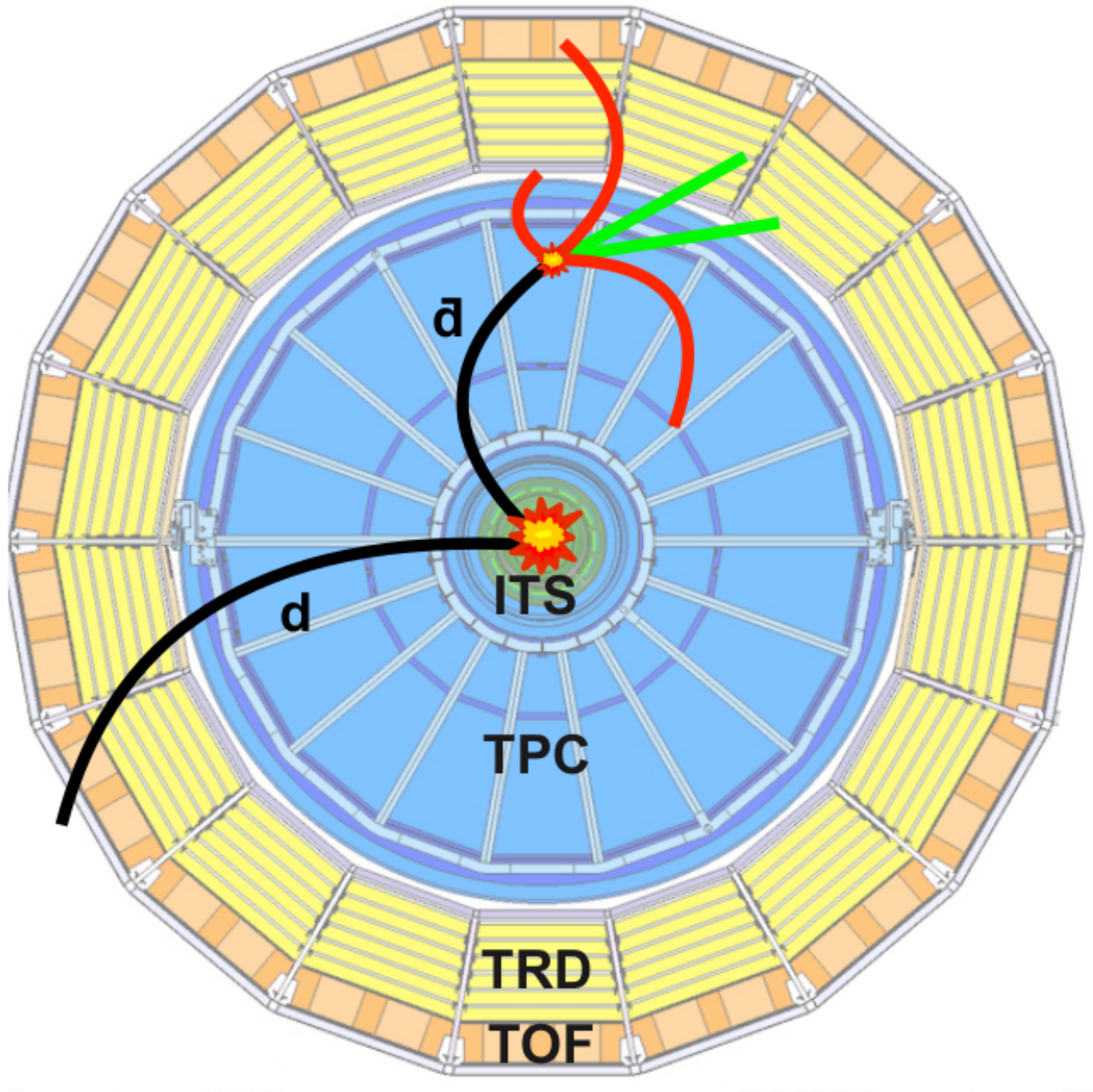
- Long standing prediction: anti-nuclei as unambiguous probe of dark matter annihilation in the universe
- Main background: *secondary* production from ordinary matter collision (what we measure!)
- Large uncertainties though on the propagation of these antinuclei

Anti-deuteron inelastic cross section

Second ingredient: anti-matter inelastic interaction cross section at low momentum with ordinary matter

- Required to constrain transport of both primary and secondaries through the galaxies
- Measured only at high momentum in the 70s





Idea: use the ALICE detector as target material

- Use full GEANT4 transport, scale to determine $\sigma_{inel}(\bar{d})$
- Obtained limits on the cross section down to ~0.5GeV/c, *far below the previously measured cross sections*

Hypertriton lifetime in the high precision era

Hyper-triton is the lightest hyper-nucleus. ALICE collaboration measured its production in the charged 2 body decay channel.

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

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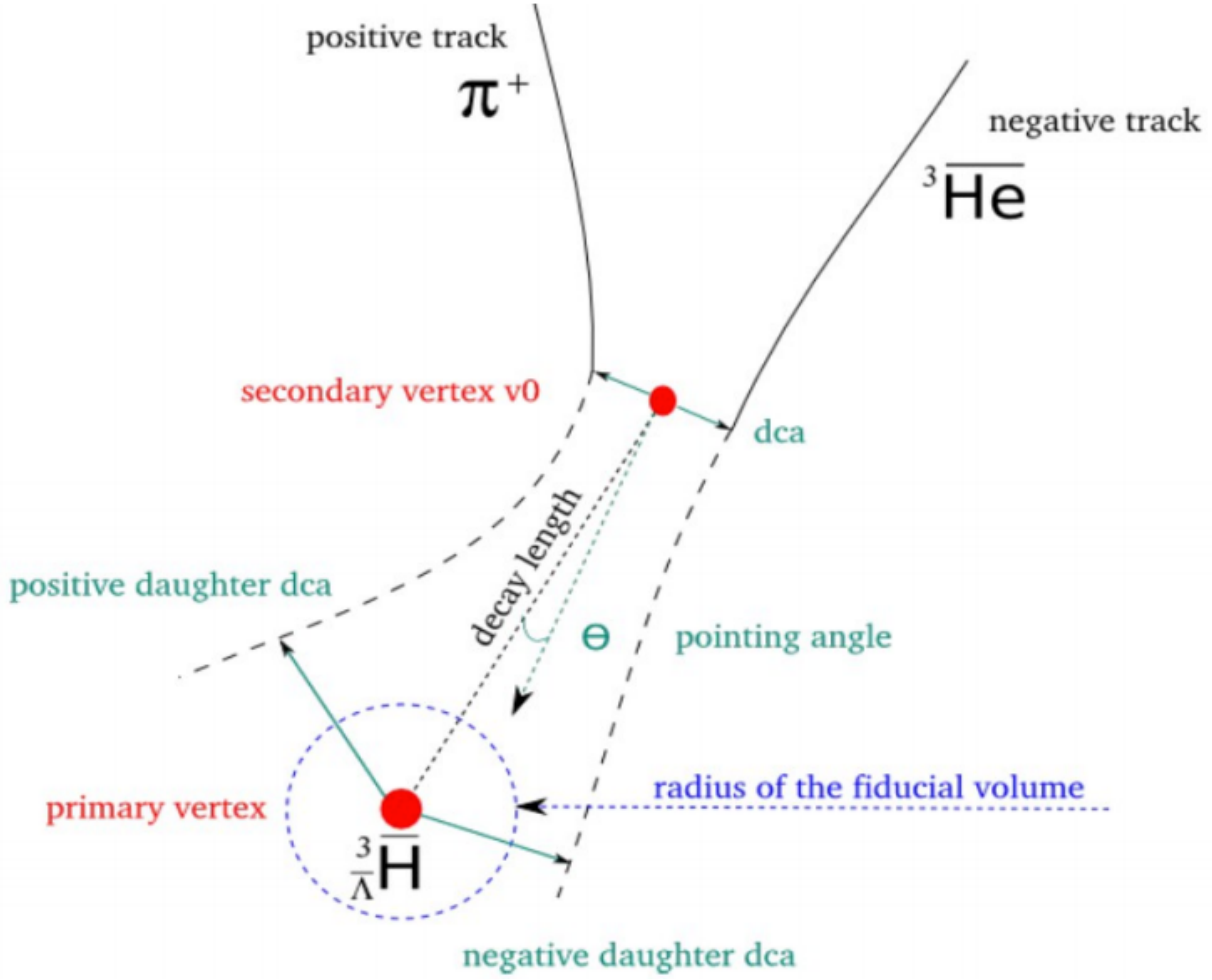

Signal Extraction:

- Identify ^{3}He and π
- Evaluate (^{3}He,π) invariant mass
- Apply topological cuts in order to:
  - identify secondary decay vertex
  - reduce combinatorial background
- Or… train a ML discriminator

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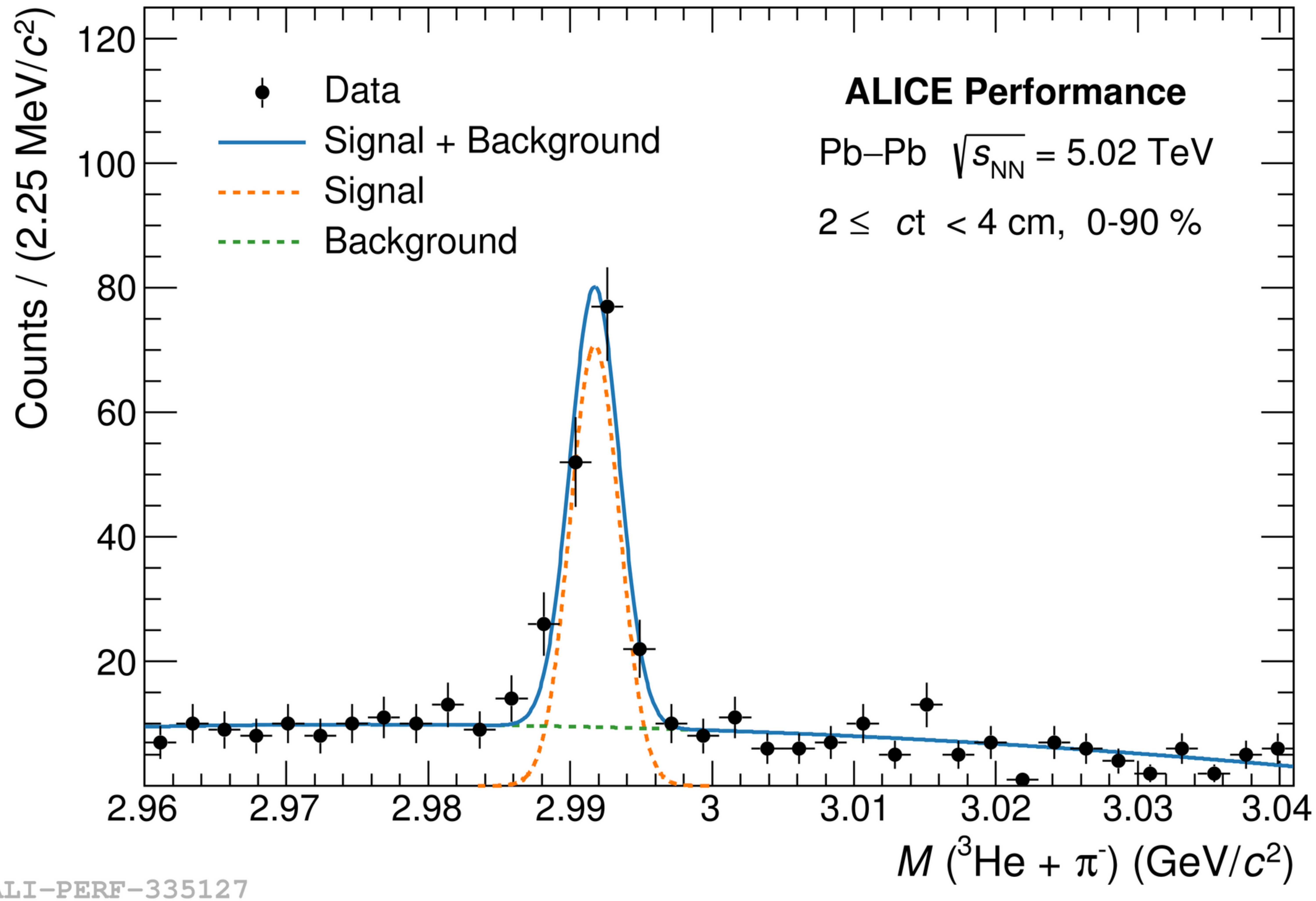

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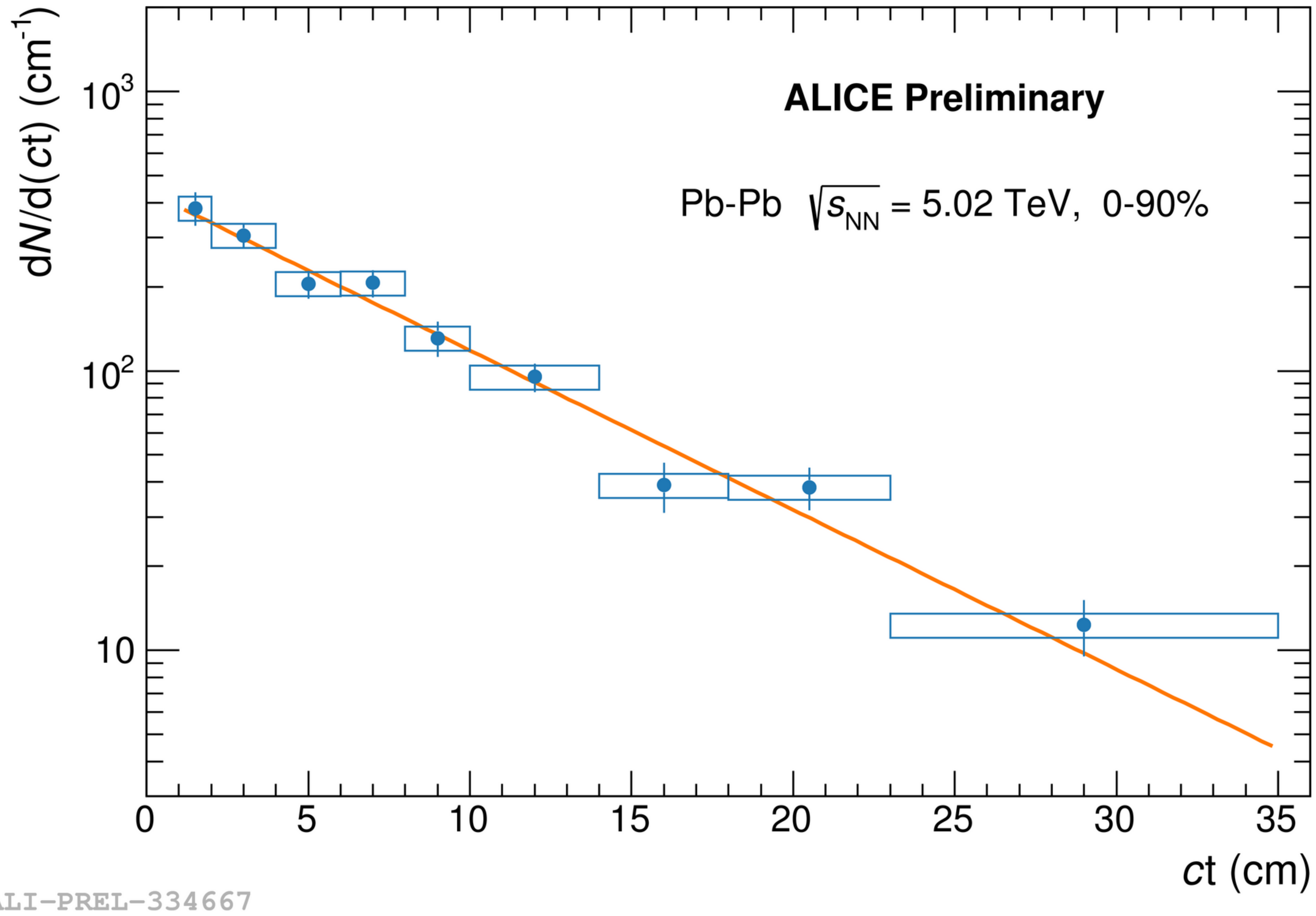
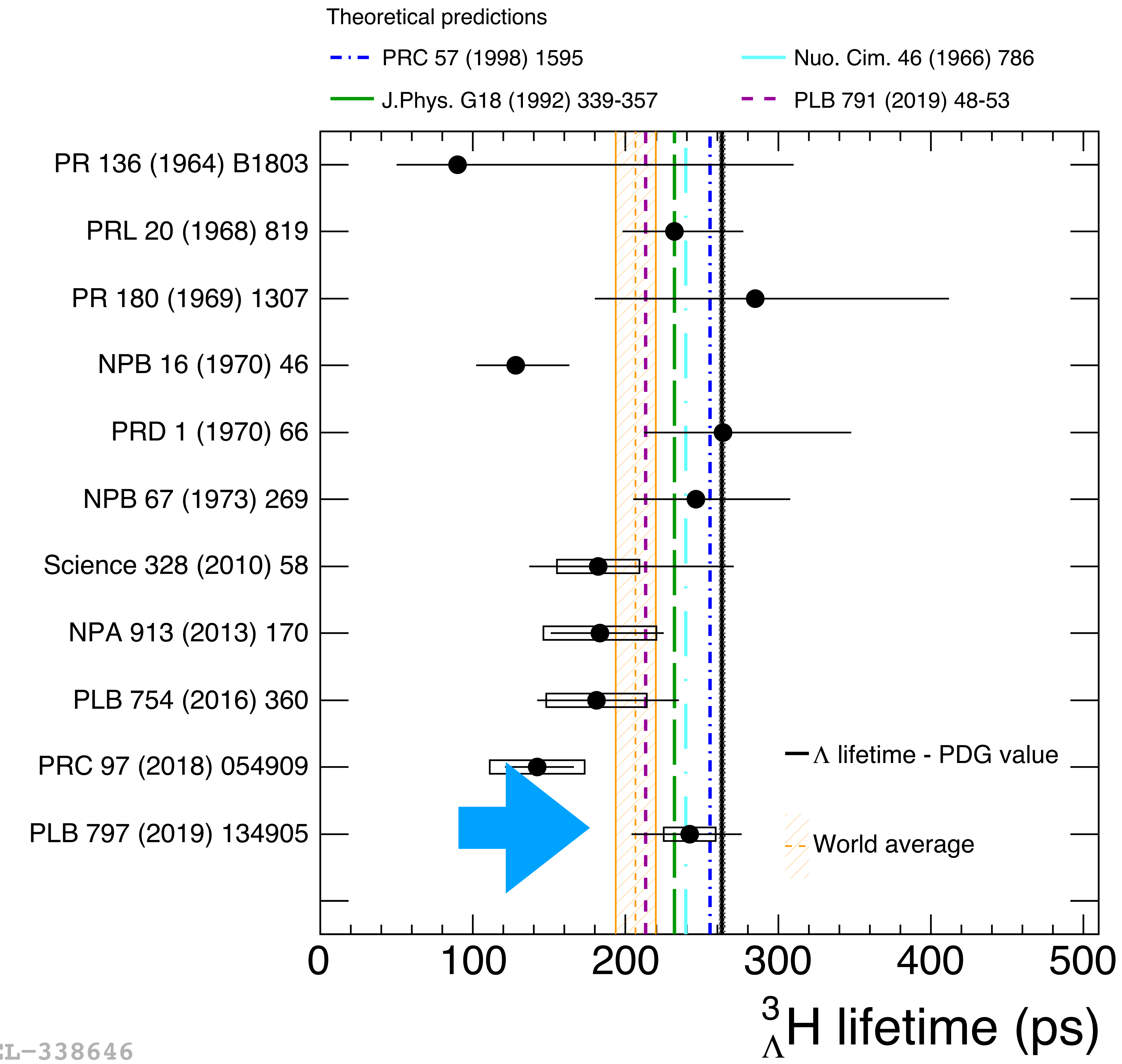


(Anti-)Hypertriton lifetime measurement



ALI-PREL-338646

ALICE measurement setting new standards:

- Pb-Pb 2015 dataset already published

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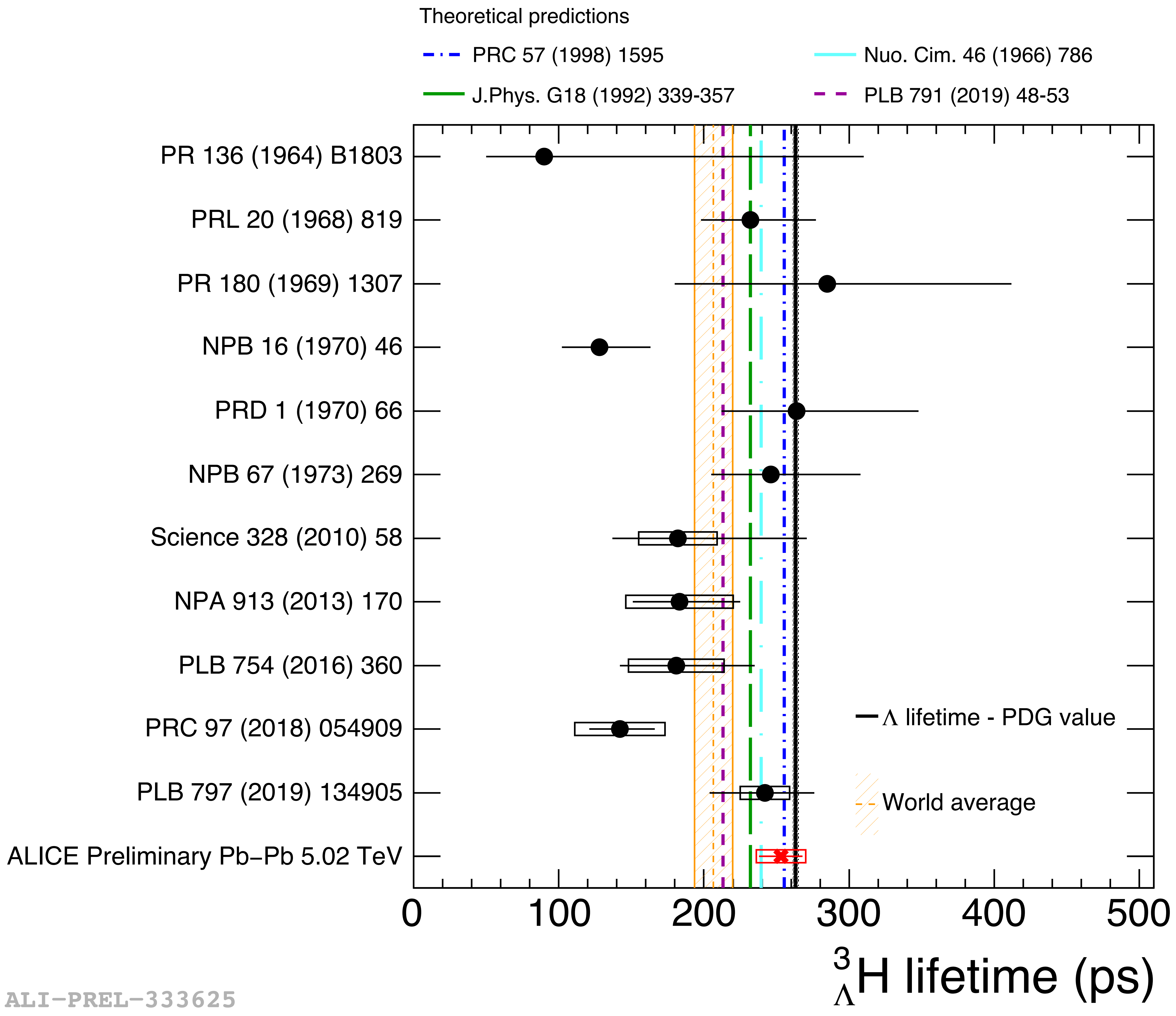


ALICE measurement setting new standards:

- Pb-Pb 2015 dataset already published

Using the 2018 Pb-Pb data + Machine Learning methods

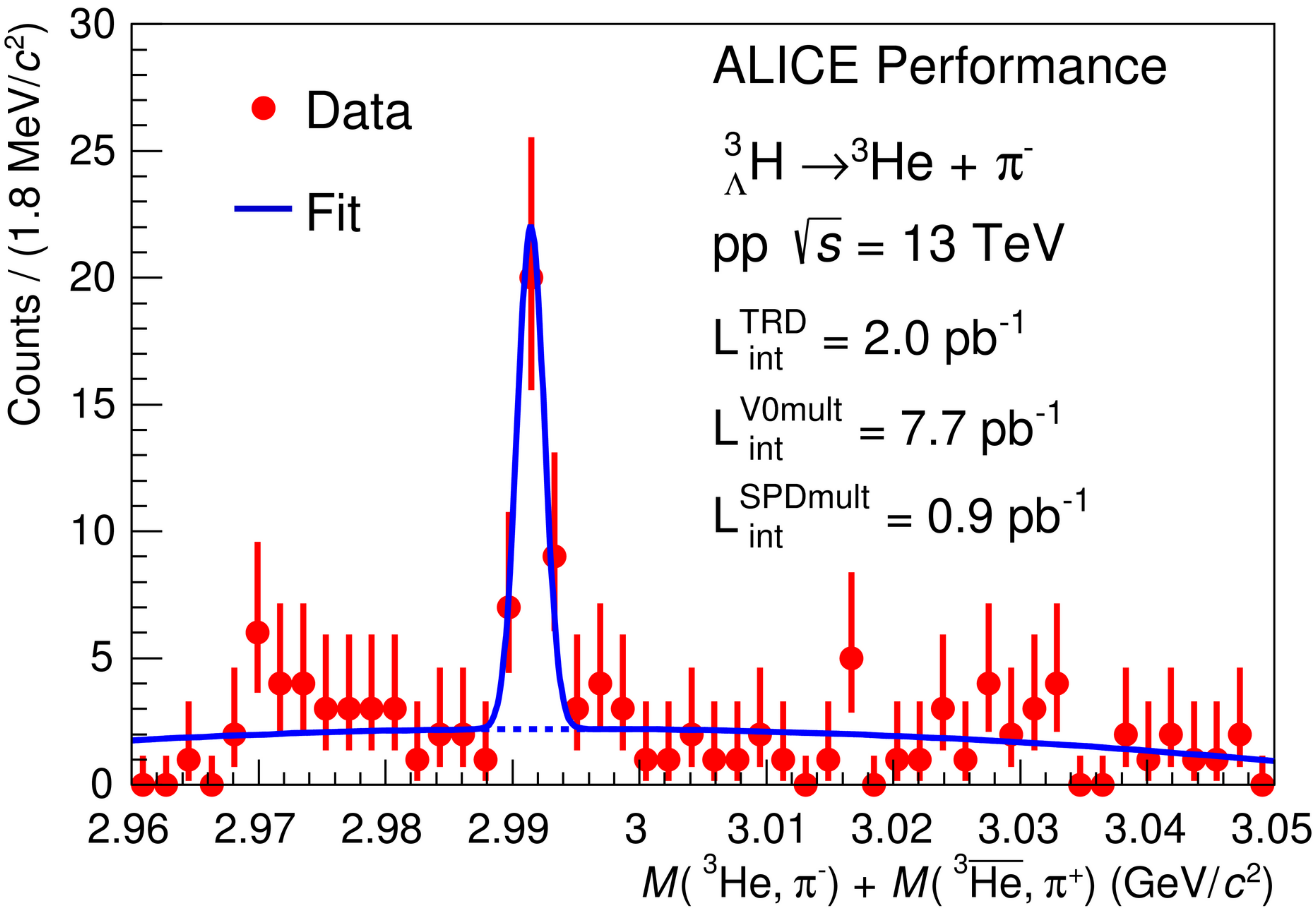
- single measurement same relative error as world average

➡Exclude large deviations from free Λ life time

➡Test of different models with different Hypertriton structure and final state interaction

(Anti-)Hypertriton in small systems

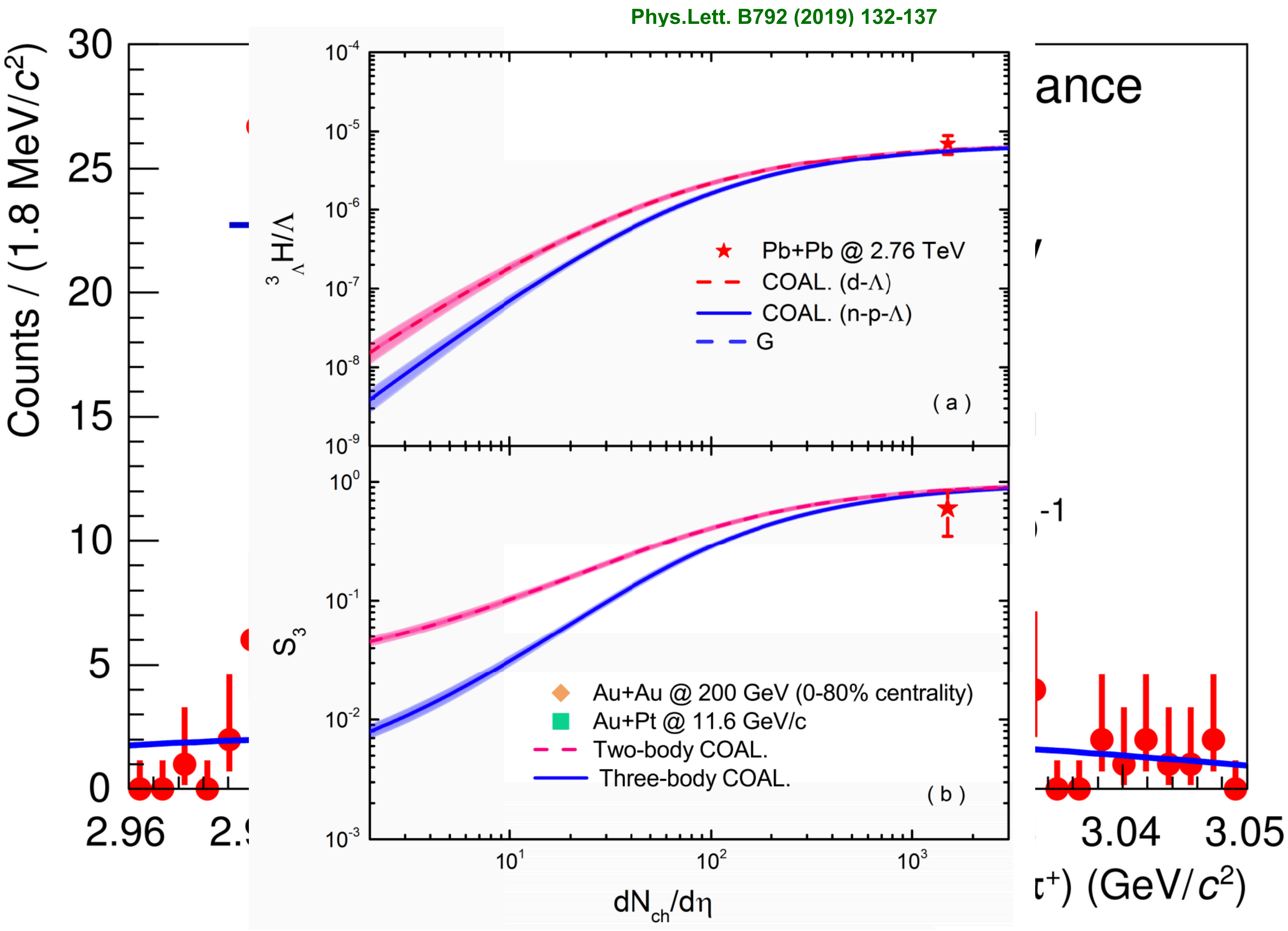
- **First observation of (anti-)hyper-nuclei production in pp collisions at the LHC**
- Extremely rare: dedicated trigger for heavily ionising particles devised in the ALICE Transition Radiation Detector



(Anti-)Hypertriton in small systems

- **First observation of (anti-)hyper-nuclei production in pp collisions at the LHC**
- Extremely rare: dedicated trigger for heavily ionising particles devised in the ALICE Transition Radiation Detector

- **Soon to come:** yield and then strangeness population factor measurement to clearly distinguish among different production mechanisms



Conclusions: 2019 vs 2015

Great evolution of the field of (anti-)(hyper-)nuclei in HEP in the last years

- We certainly learned a lot about our measurements
  - Even about implicit biases in some of the observables like the coalescence parameter
- We put tighter and tighter constraints on the models

A>=2 nuclei are now the battleground for experiments/models

- ^{3}He/p as a function of multiplicity shows interesting deviations from models
- ^{3}He flow and ^{4}He spectra requires more data to have a clearer picture

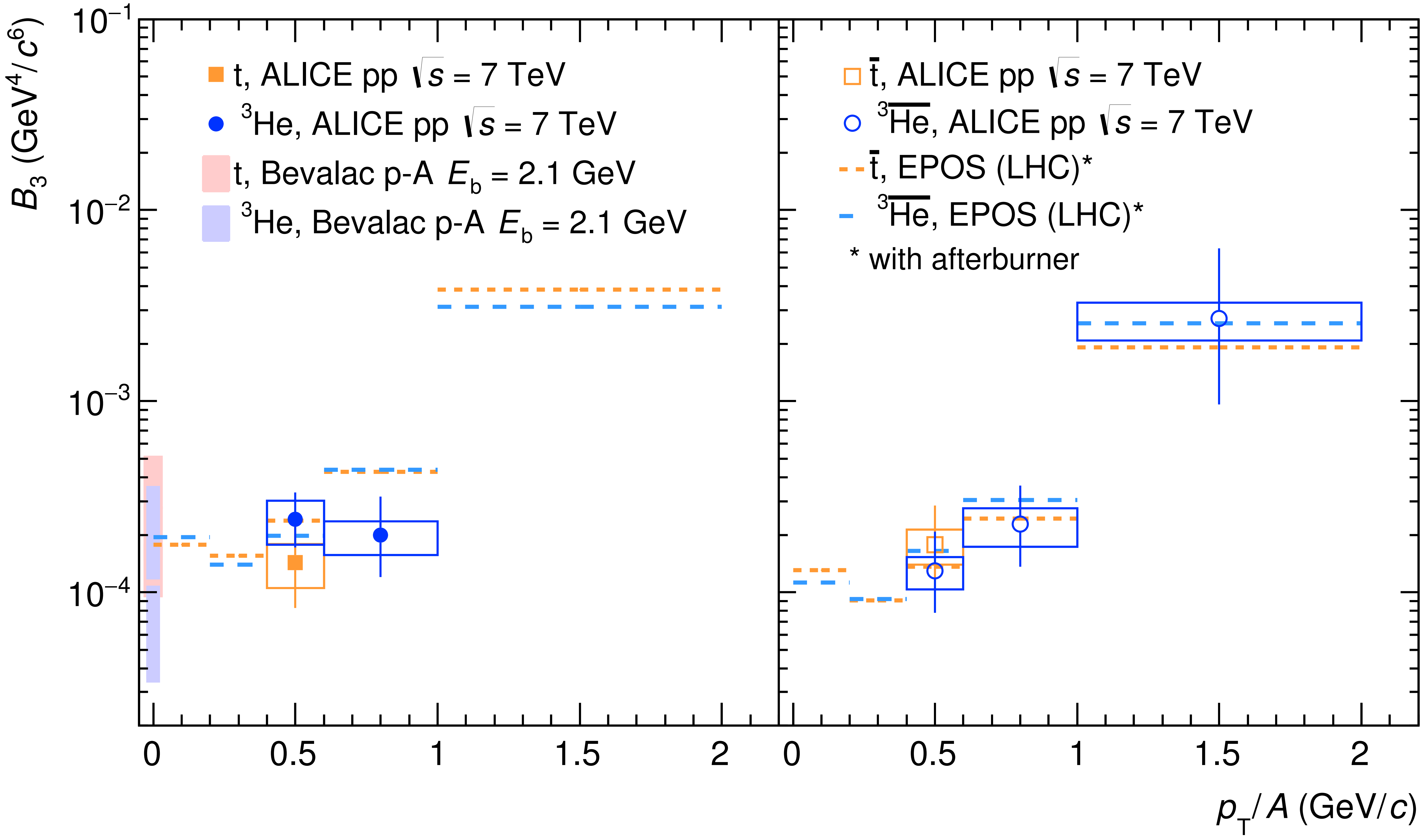
More observables are coming up

- (anti-)hypertriton production in small systems is sensitive to different coalescence scenarios
- deuteron-proton, deuteron-lambda femtoscopy to understand the dynamics of the nucleosynthesis at collider

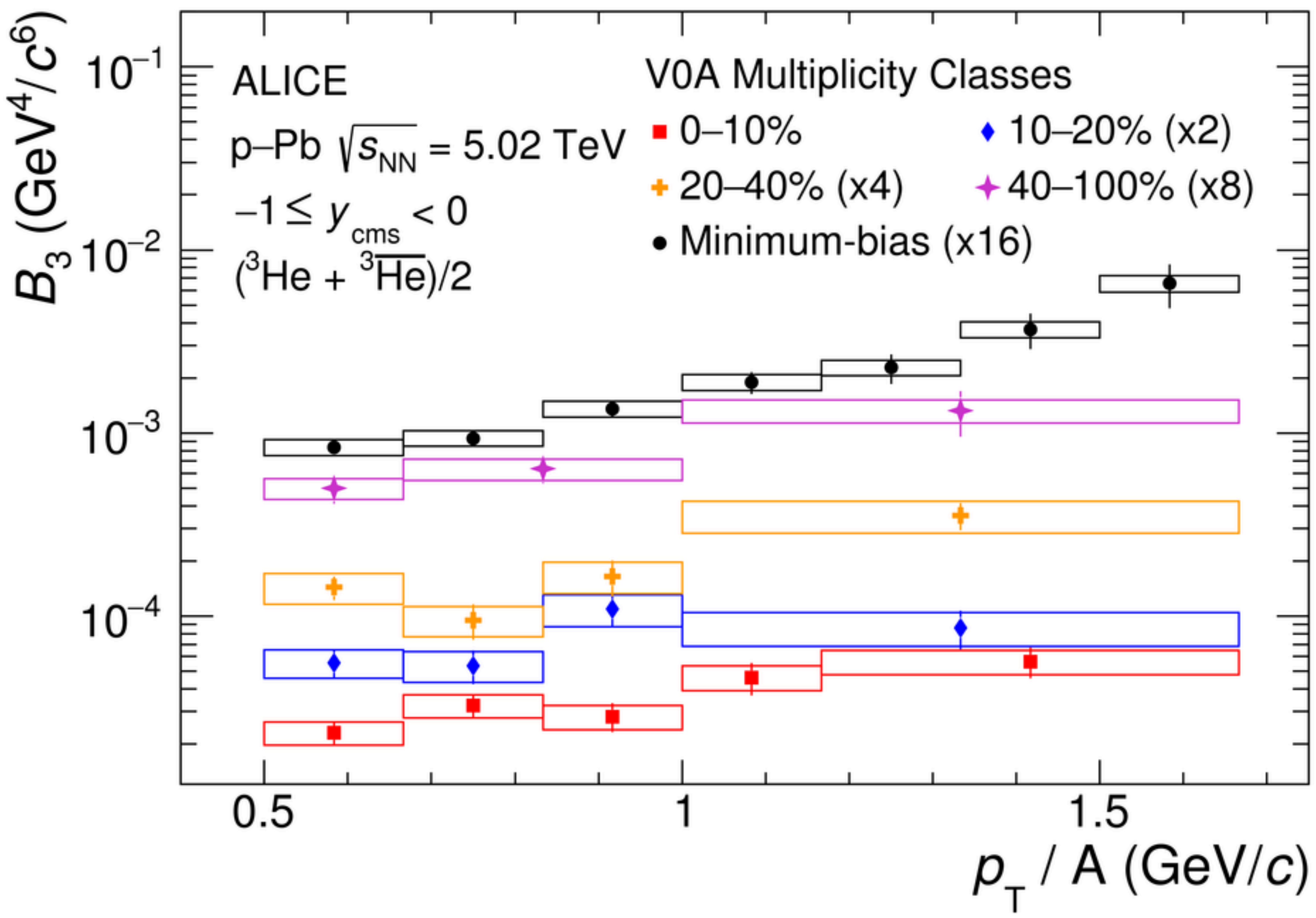
➡Even larger data samples in both pp and heavy ion collisions coming with the LHC Run 3

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.

B_3



B_3 (GeV^4/c^6)
t, ALICE pp $\sqrt{s}$ = 7 TeV
^{3}He, ALICE pp $\sqrt{s}$ = 7 TeV
t, Bevalac p-A E_b = 2.1 GeV
^{3}He, Bevalac p-A E_b = 2.1 GeV
$\bar{t}$, ALICE pp $\sqrt{s}$ = 7 TeV
$^3\overline{He}$, ALICE pp $\sqrt{s}$ = 7 TeV
$\bar{t}$, EPOS (LHC)*
$^3\overline{He}$, EPOS (LHC)*
* with afterburner
p_T/A (GeV/c)



ALICE
p–Pb $\sqrt{s_{NN}}$ = 5.02 TeV
$-1 \leq y_{cms} < 0$
(^{3}He + $^3\overline{He}$)/2
V0A Multiplicity Classes
0–10%
10–20% (x2)
20–40% (x4)
40–100% (x8)
Minimum-bias (x16)
B_3 (GeV^4/c^6)
p_T / A (GeV/c)