Testing coalescence and thermal models with the production measurement of light (anti-)nuclei as function of collision system size with ALICE at the LHC

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on behalf of the **ALICE Collaboration**

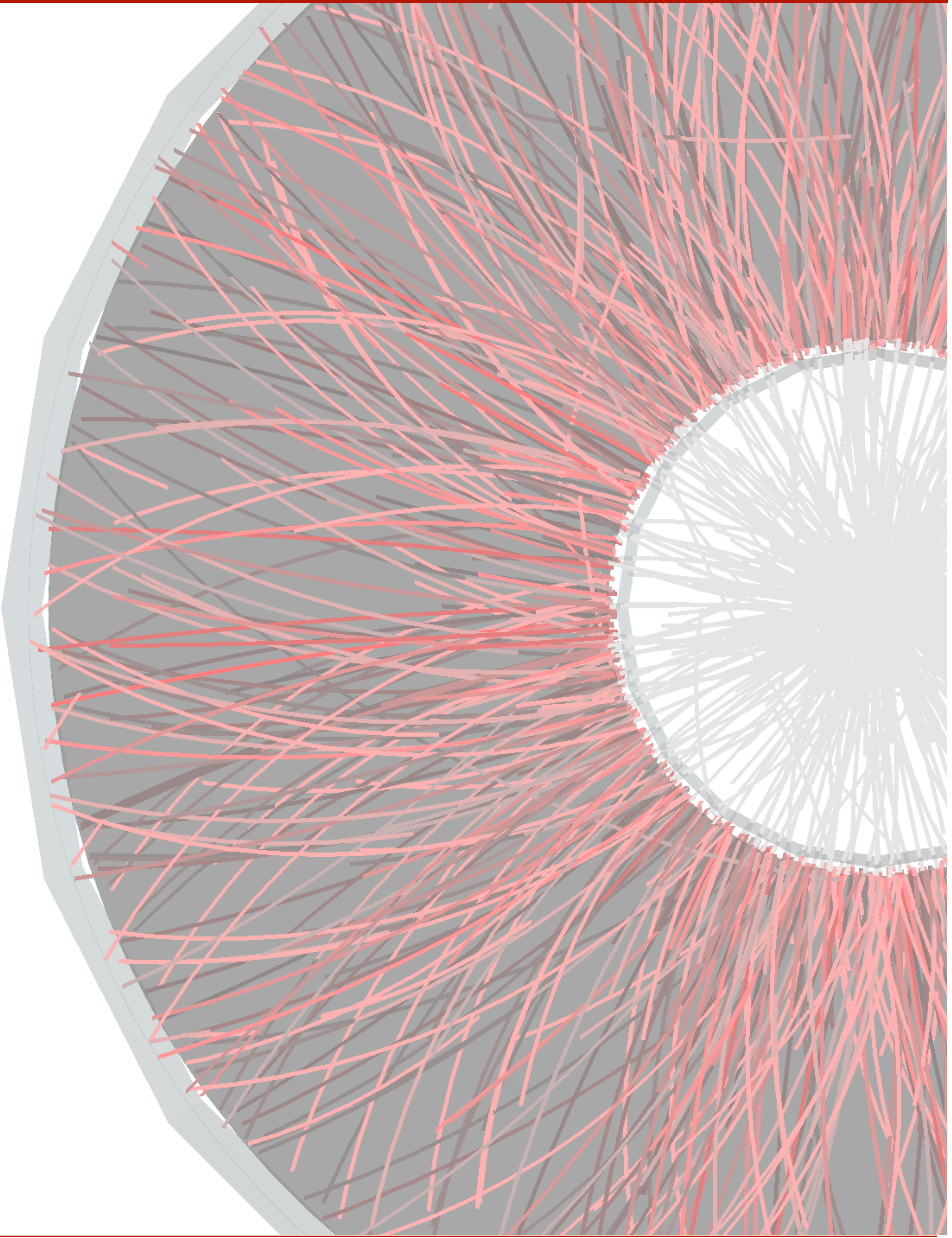
ALICE

INFN

STRANGENESS IN QUARK MATTER
SQM
Bari
2019

Outline

- **Phenomenological models**
  - The **Statistical-thermal** model
  - The **Coalescence** model



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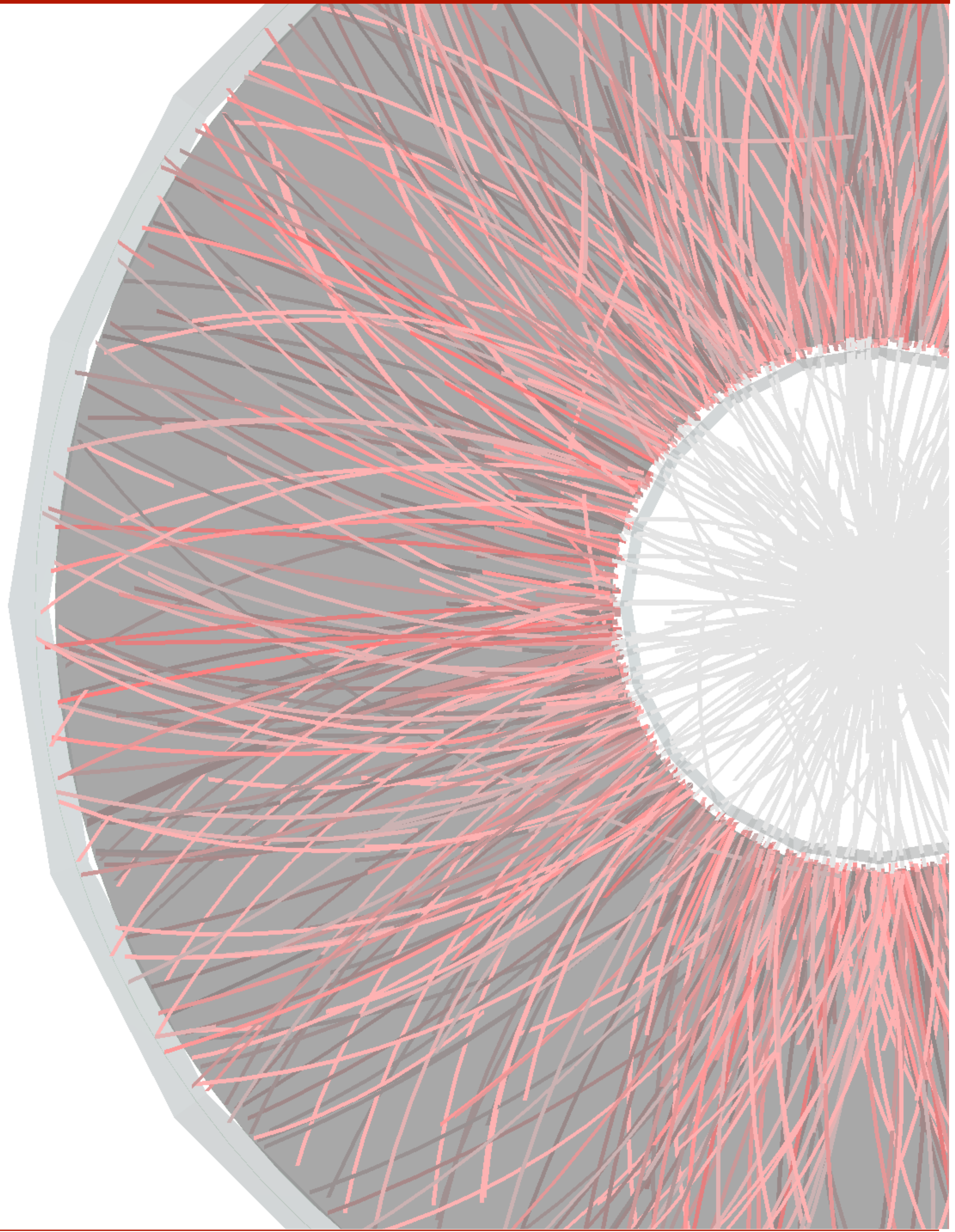
  - **Identification** of nuclei



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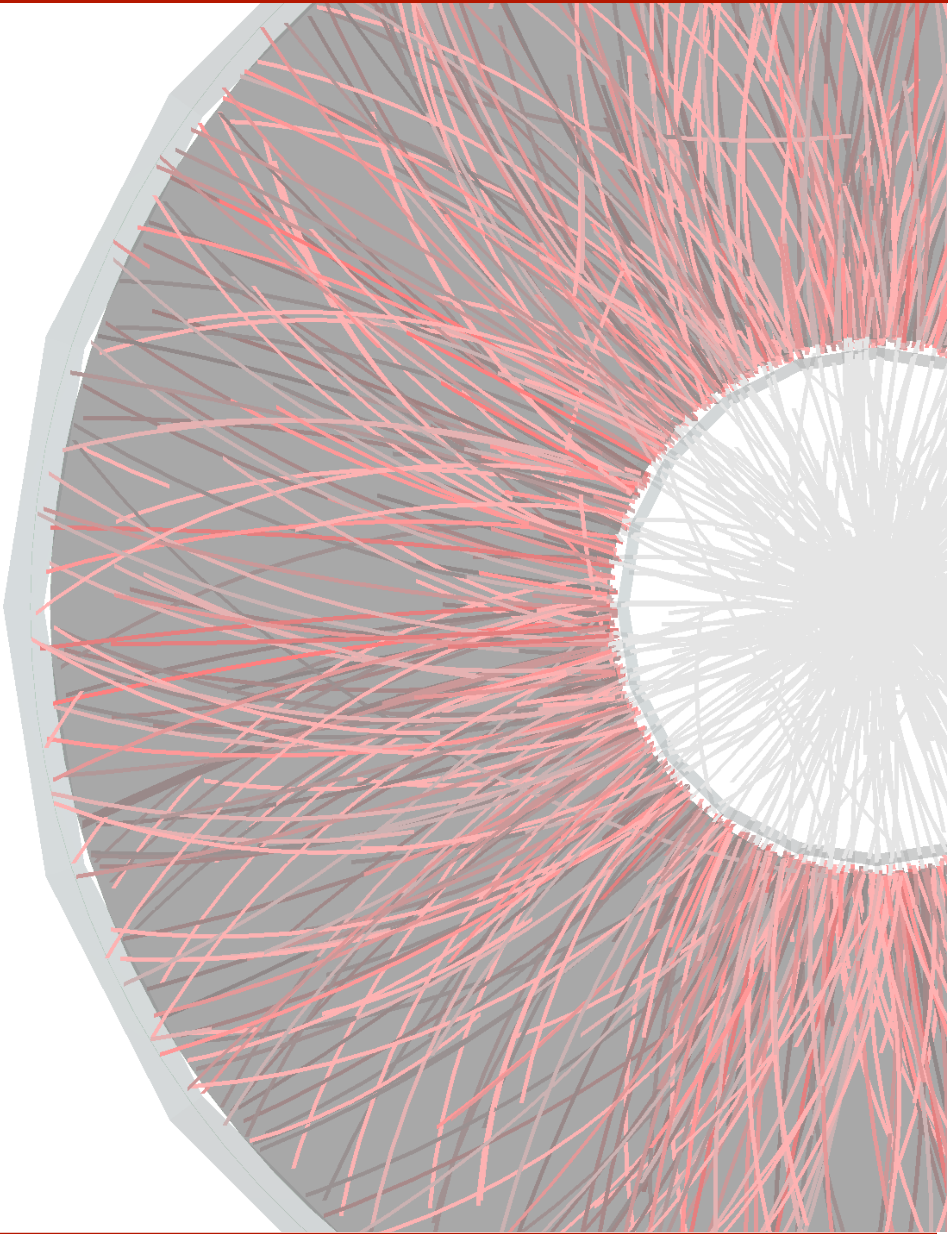
  - **Antimatter/matter** ratio in Pb-Pb and pp collisions



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  - **p_T spectra** in Pb-Pb, p-Pb and pp collisions
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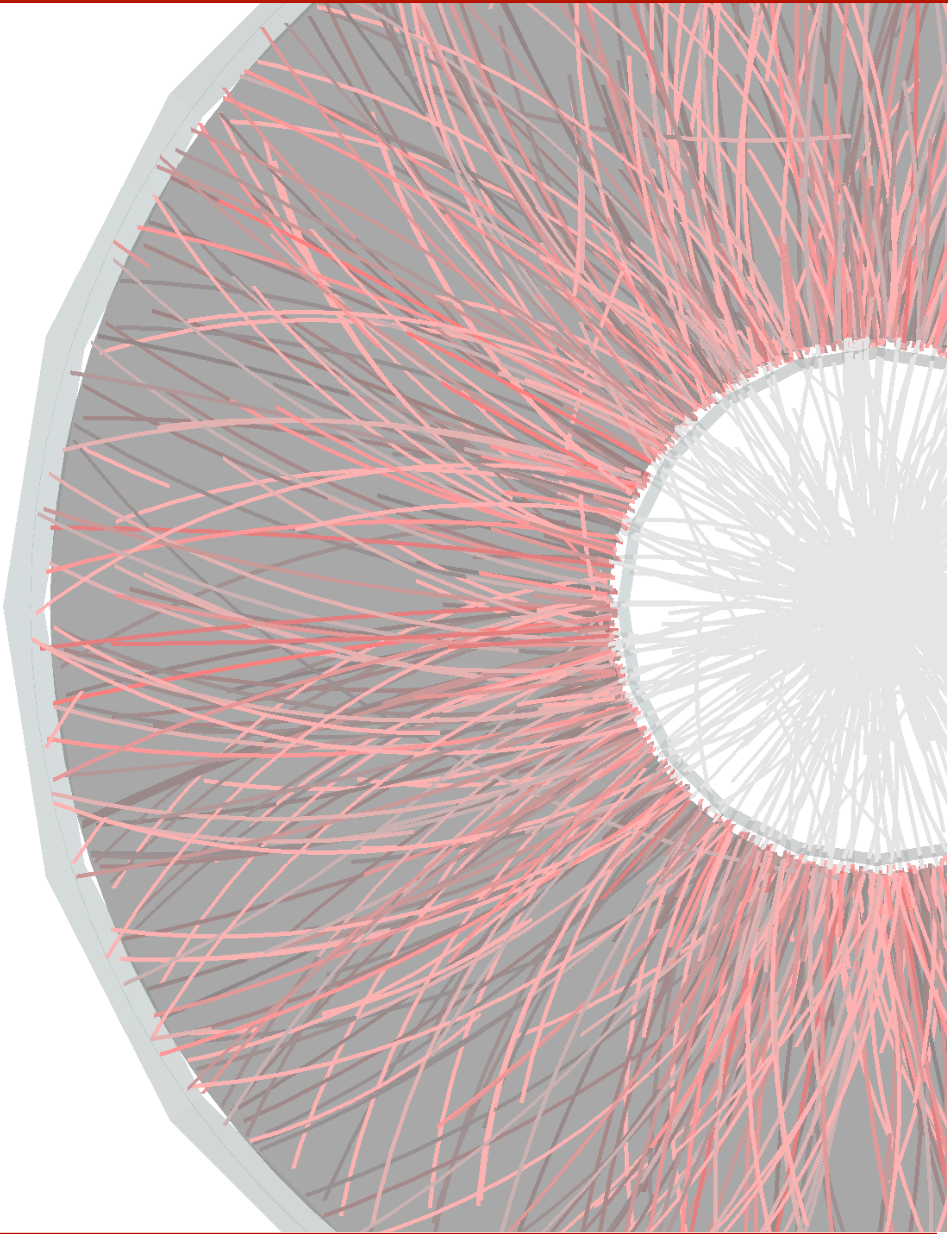
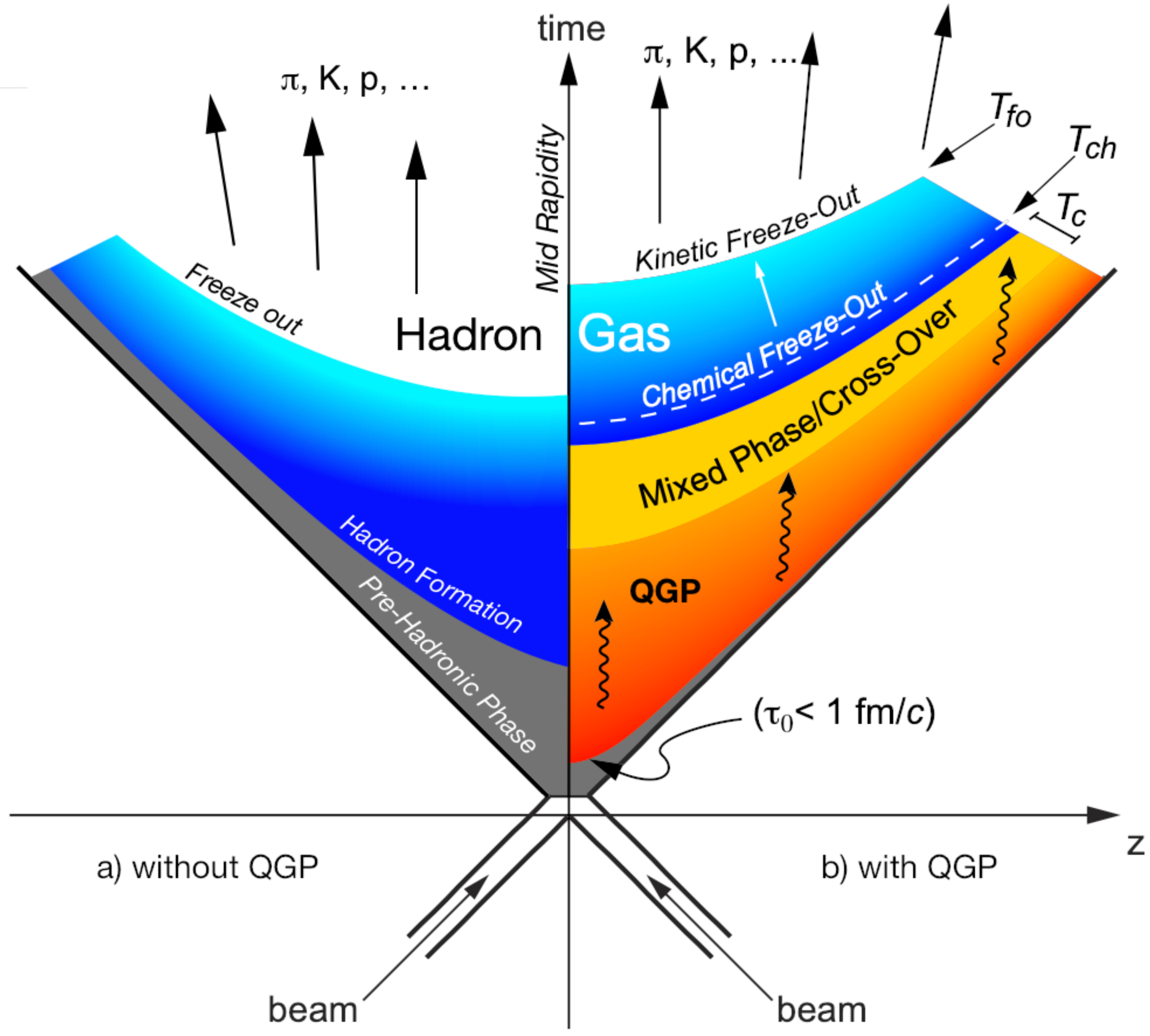
- Testing the models
  - Coalescence parameter **B_A** vs multiplicity
  - **d/p** and **^{3}He/p** vs multiplicity



Nuclear matter production

- Light (anti-)nuclei are significantly produced at the LHC in pp, p-Pb and Pb-Pb collisions
- The **production mechanisms** of light (anti-)nuclei in high-energy physics are still not completely understood
  - light nuclei are characterised by a low binding energy (**E_B ~ 1 MeV**) with respect to the kinetic freeze-out temperature (**T_{fo} ~ 100 MeV**)
- Two classes of models are available:
  - the **statistical-thermal** model
  - the **coalescence** model

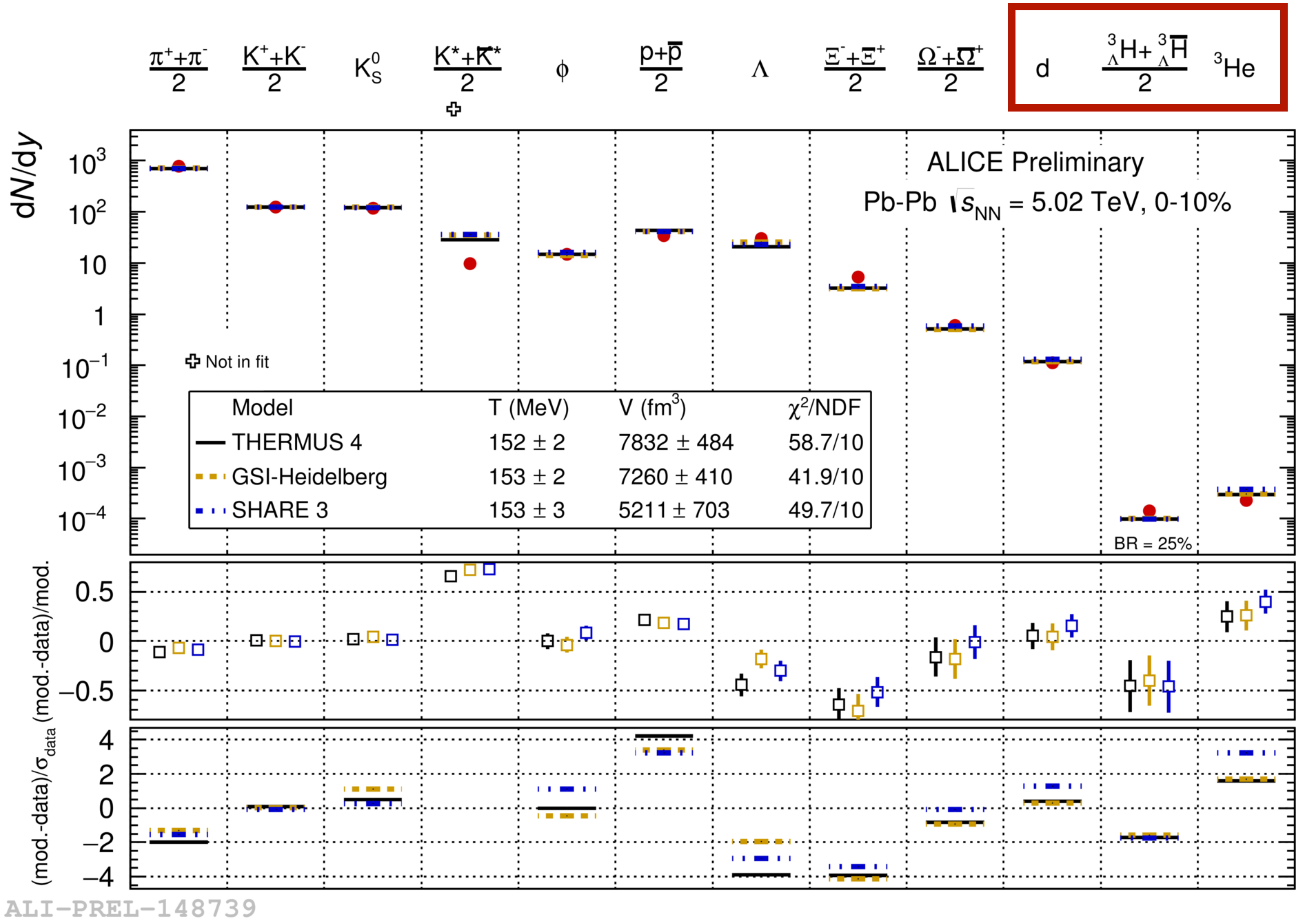


The Statistical-thermal model

- Hadrons are emitted from the interaction region in **statistical equilibrium** at the **chemical freeze-out**
- It describes the production yields **dN/dy** in central Pb-Pb collisions over a wide range of dN/dy (**7 orders of magnitude**), including nuclei
- In **Pb-Pb** collisions a **grand canonical** approach is used
- In **small systems** ($VT^3 < 1$) a local conservation of quantum numbers is necessary, therefore a **canonical** approach is used
- The chemical freeze-out temperature (***T***T_{ch}) is a key parameter:

$$\mathrm{d}N/\mathrm{d}y \propto \exp(-\frac{m}{T_{ch}})$$

- For nuclei (large *m*) there is **strong dependence** on T_{ch}



The coalescence model

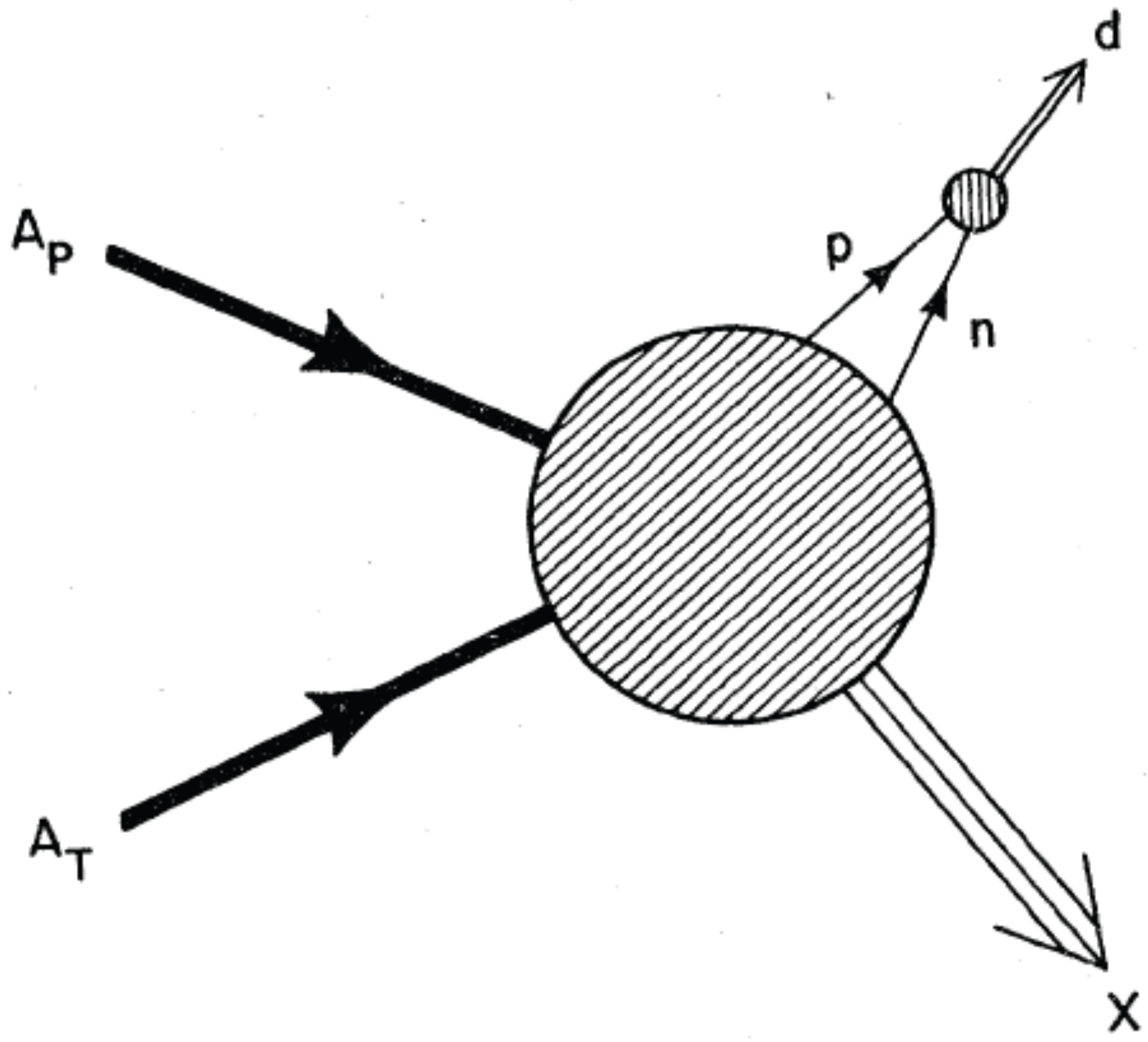
- Nucleons that are **close in the phase space** at the **freeze-out** can form a nucleus via **coalescence**
- The key concept is the overlap between the **nucleus wave-function** and the **phase space** of the **nucleons**
- The main parameter of the coalescence is the $\mathbf{B_A}$, defined as:

$$B_A = \frac{E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3}}{\left(E_p \frac{\mathrm{d}^3 N_p}{\mathrm{d}p_p^3}\right)^A}$$

where:

- A is the mass number of the nucleus
- $p_p = p_A / A$

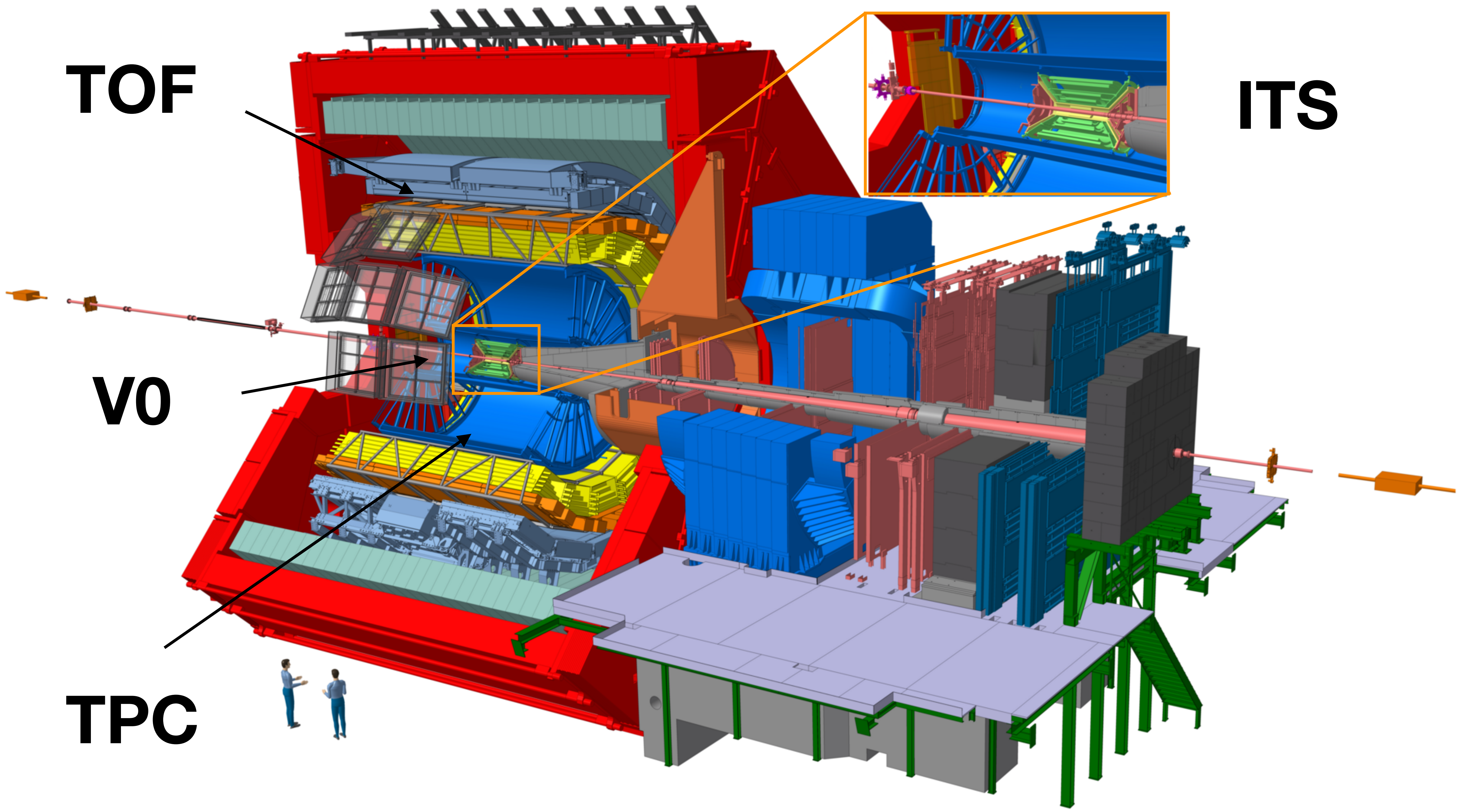
- $\mathbf{B_A}$ is related to the **probability** to form a nucleus via coalescence



J. I. Kapusta, Phys.Rev. C21, 1301 (1980)

The ALICE experiment

- General purpose heavy-ion experiment
  - 19 different sub-detectors
  - Excellent particle identification (**PID**)
  - Most suited LHC experiment for studying the production of nuclei



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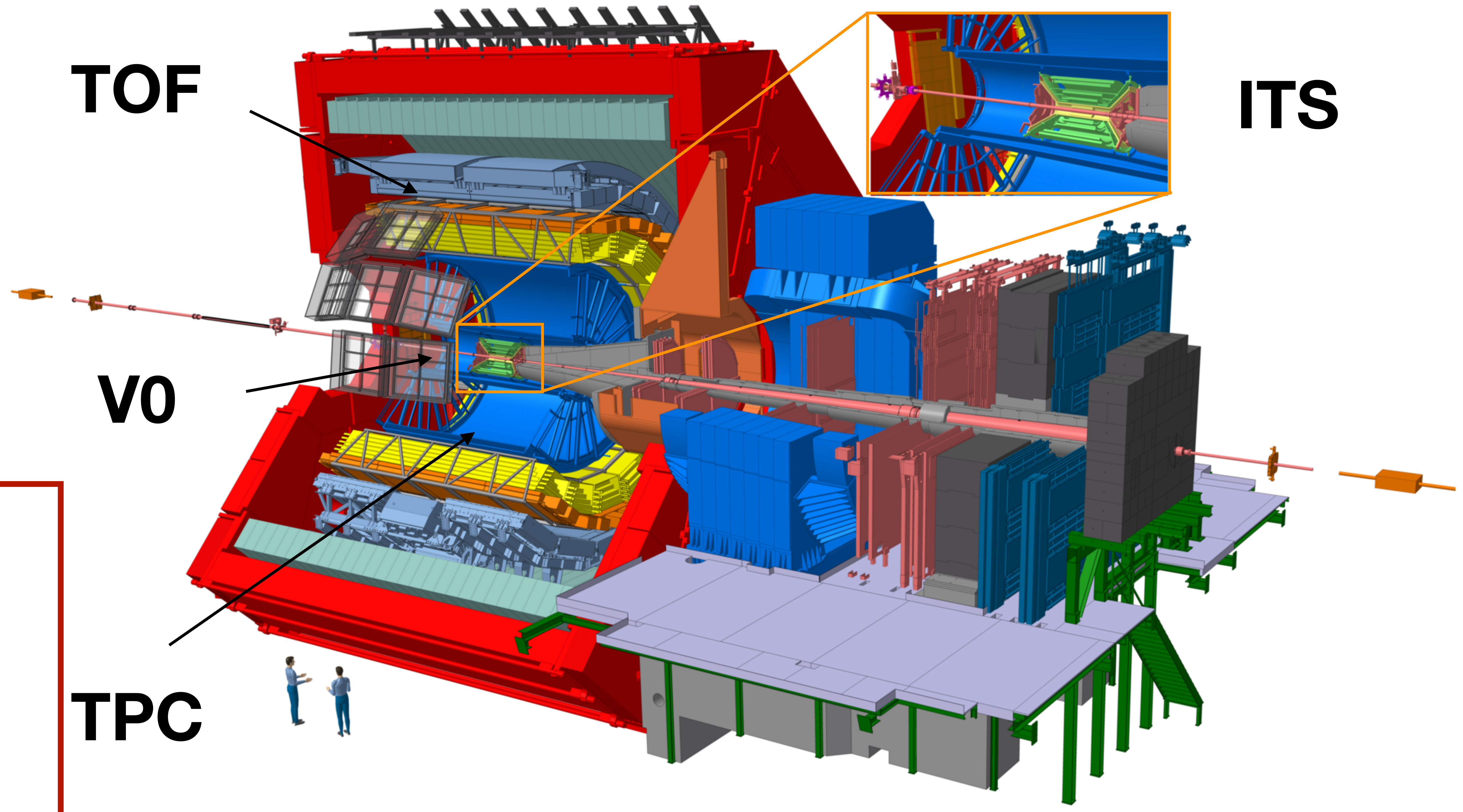

Inner **T**racking **S**ystem

- **Tracking** and **Vertex** reconstruction
- $\boldsymbol{\sigma_{DCA_{xy}} < 100\ \mu m}$ for $p_T > 0.5$ GeV/c in Pb-Pb
  - Separation of **primary** and **secondary vertices**
  - Separation of **secondary nuclei** (from material knock-out)

V0

- **Multiplicity/centrality** determination

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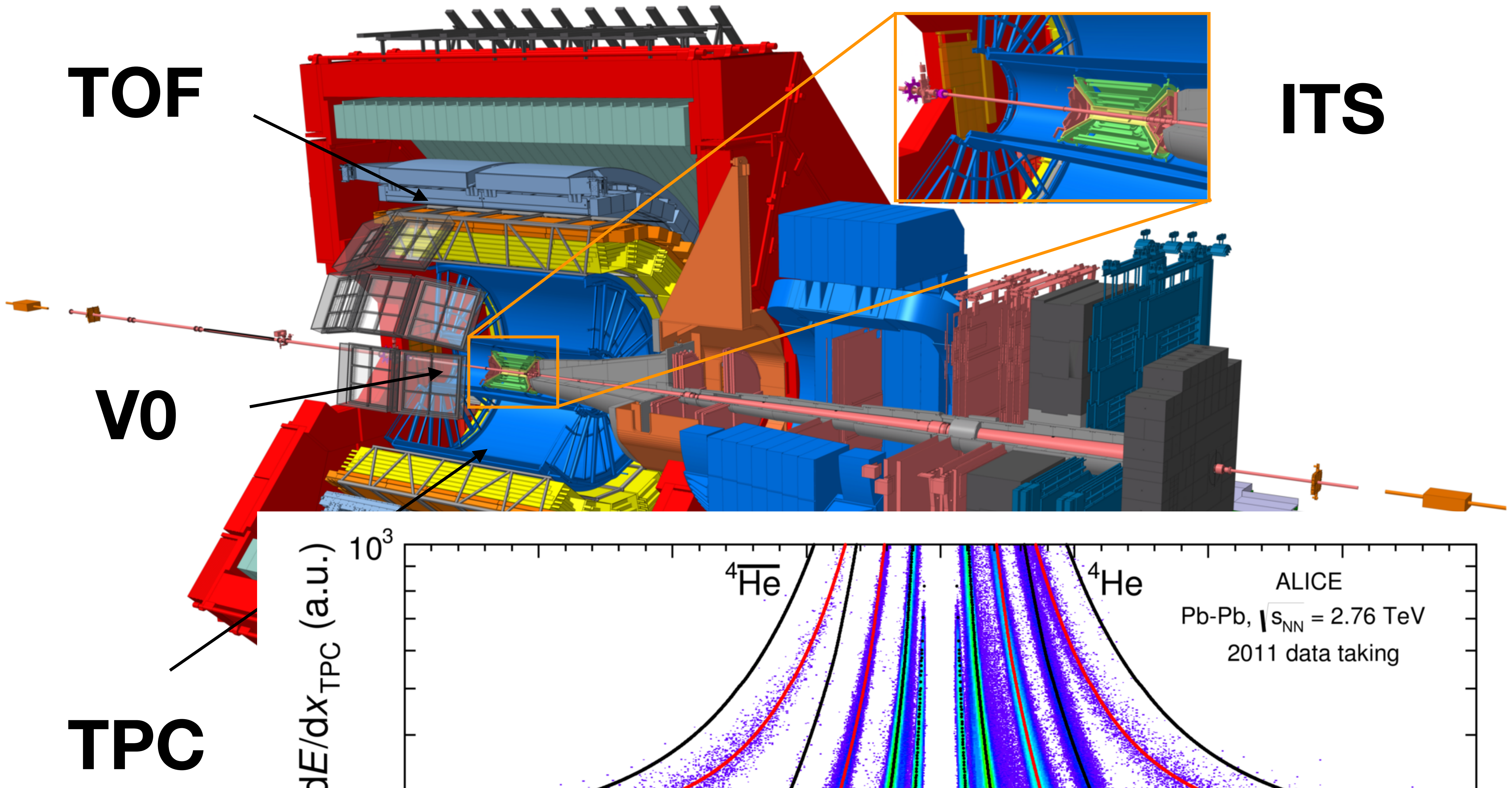
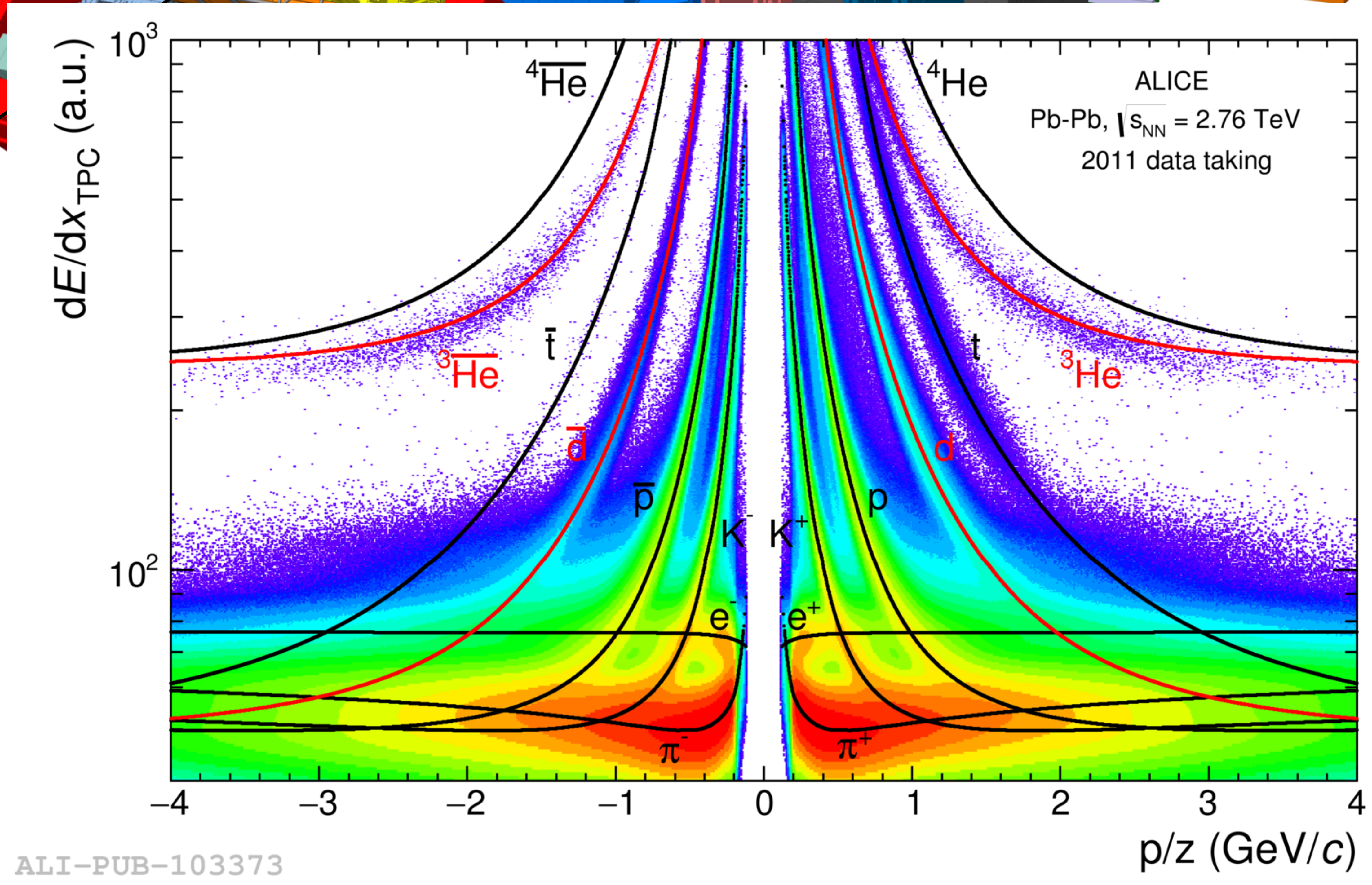


Time **P**rojection **C**hamber

- **Tracking**
- **PID** via **d*E*/dx** measurement
  - **$\sigma_{dE/dx}$ ~ 7%** (in Pb-Pb collisions)
- Raw yields extracted for each p_T bin from the nσ distributions



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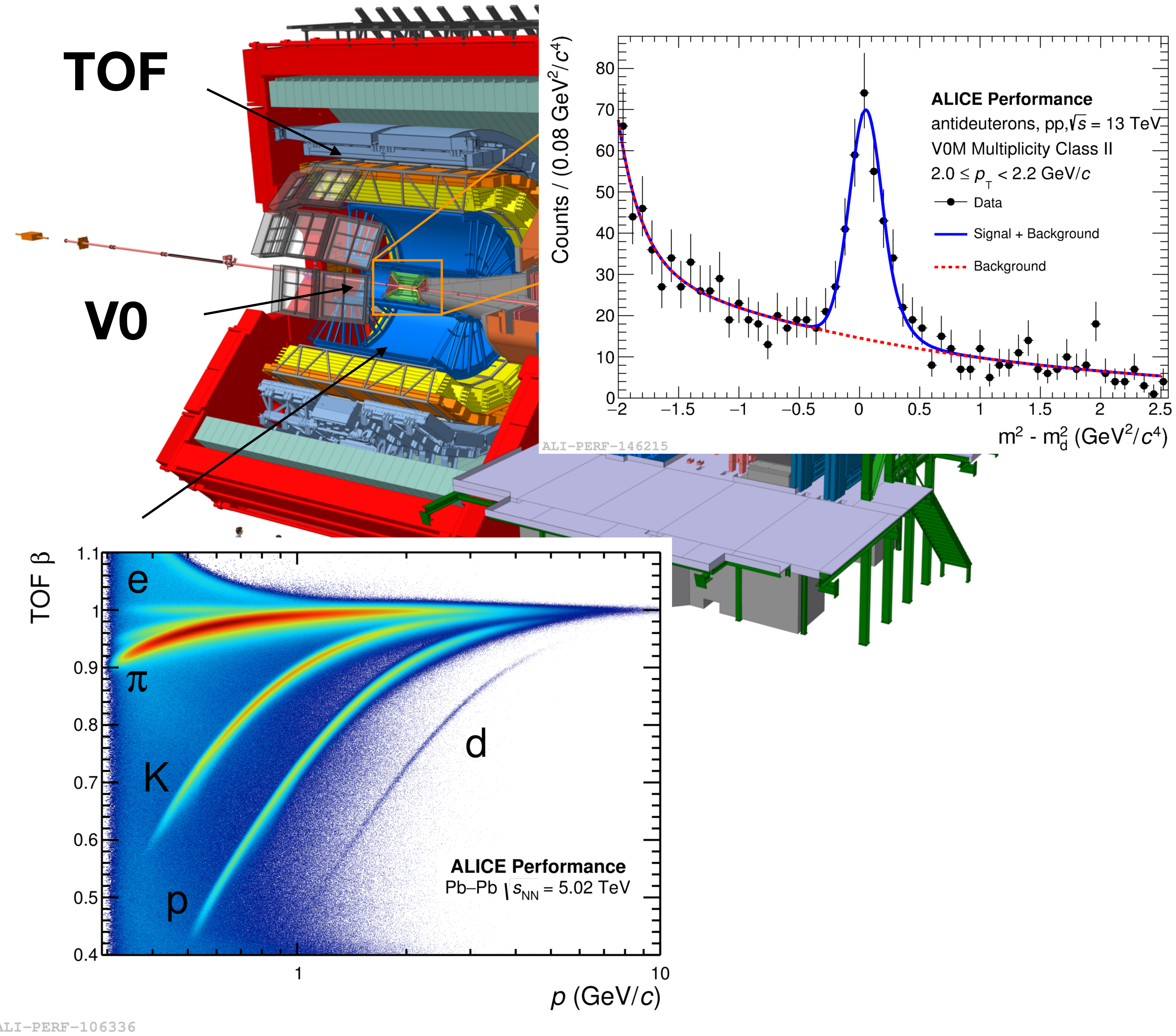
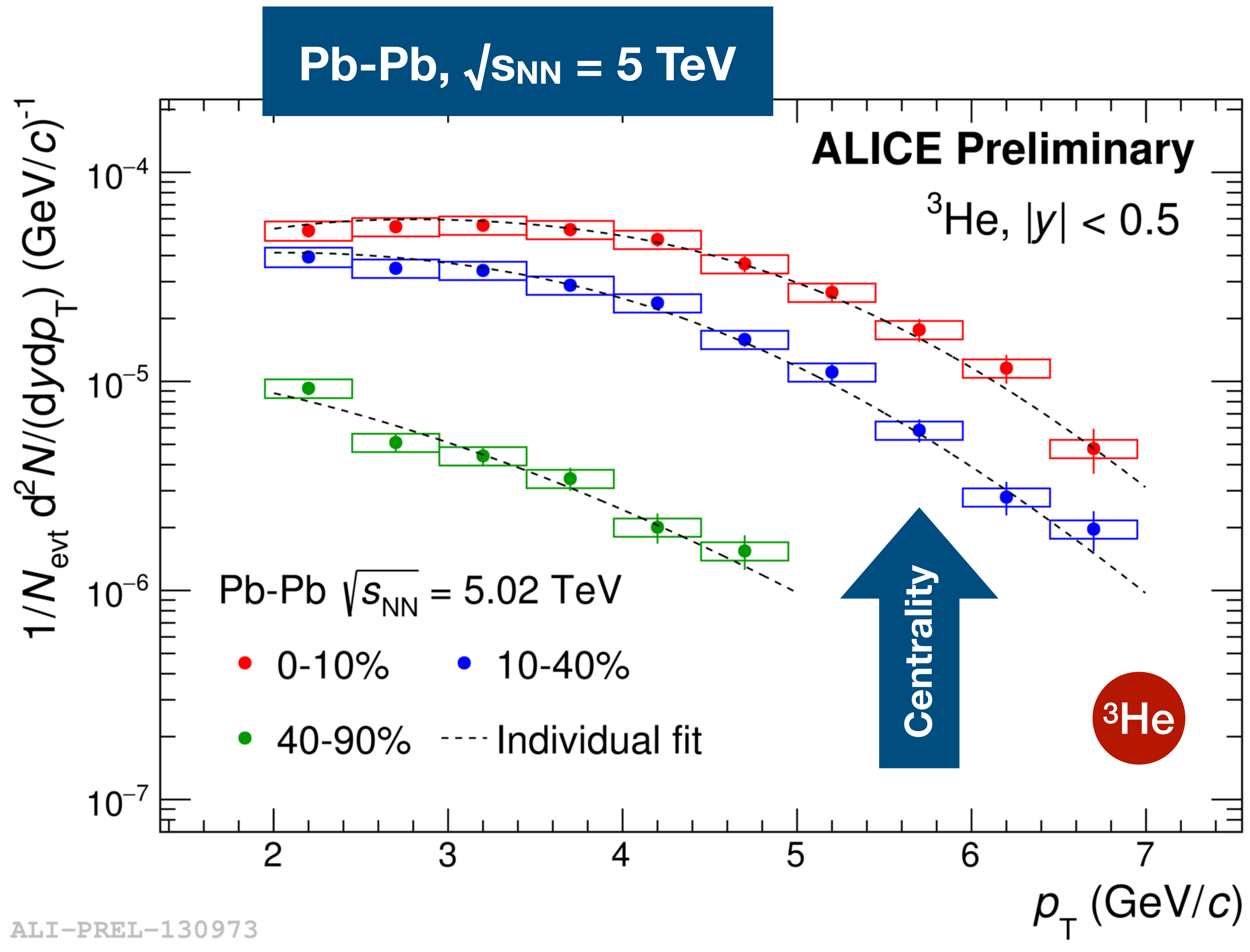
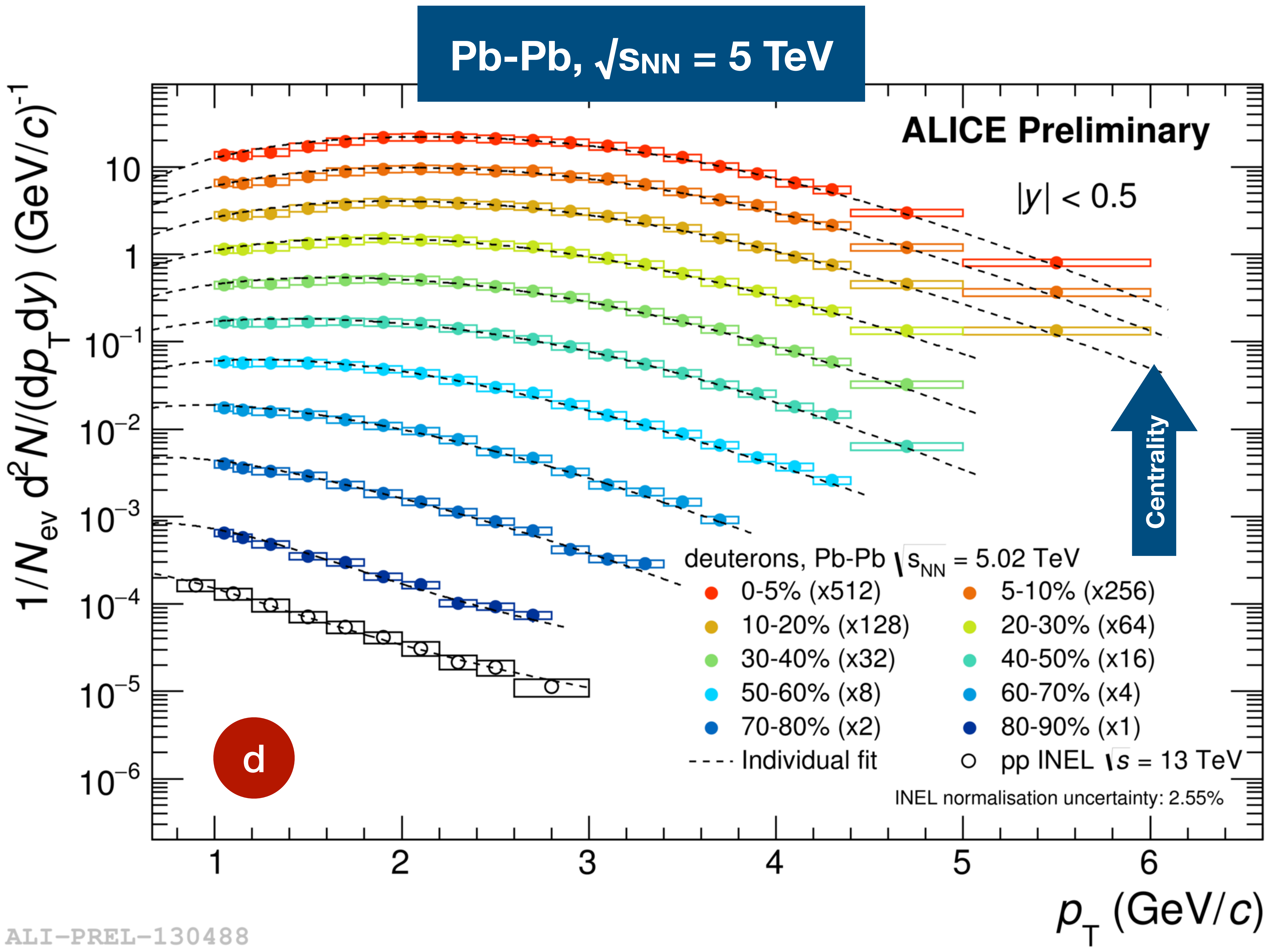


Time **O**f **F**light

- **PID** via **β** measurement
    - **$\sigma_{TOF\text{-}PID}$ ~ 85 ps** in **Pb-Pb** collisions
    - **$\sigma_{TOF\text{-}PID}$ ~ 120 ps** in **pp** collisions (lower precision on event start-time)
- Raw yields extracted for each p_T bin from the TOF mass spectra distribution

Deuteron and ^{3}He spectra in Pb-Pb





- Pb-Pb at $\sqrt{s_{NN}}$ = 5 TeV
- **p_T spectra** are fitted with a **Blast-Wave**[1] function, used for the extrapolation of the yield to unmeasured p_T regions
- Evident spectra **hardening** with increasing centrality/multiplicity→ **radial flow**.

[1] **E. Schnedermann et al., 10.1103/PhysRevC.48.2462**

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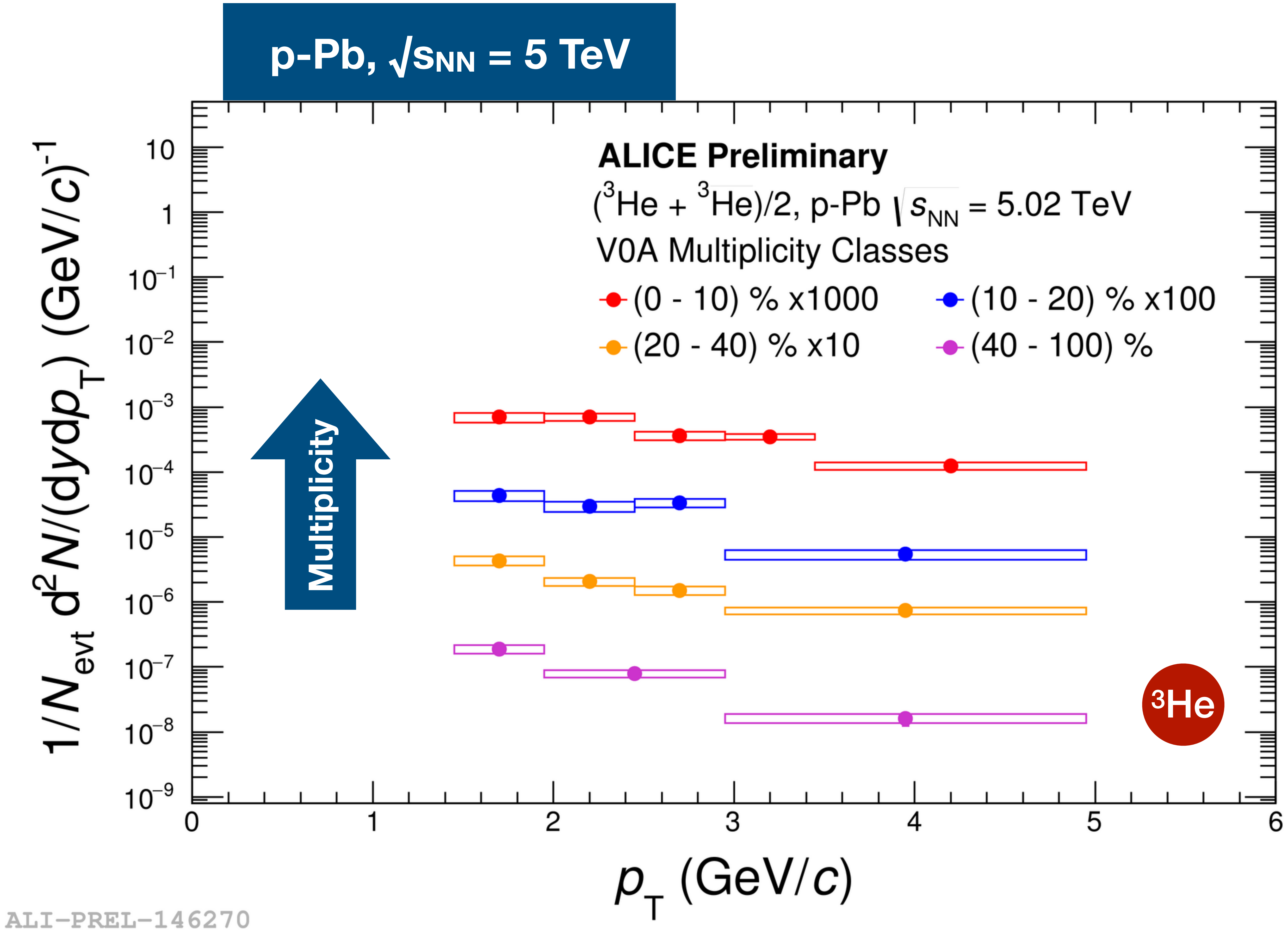
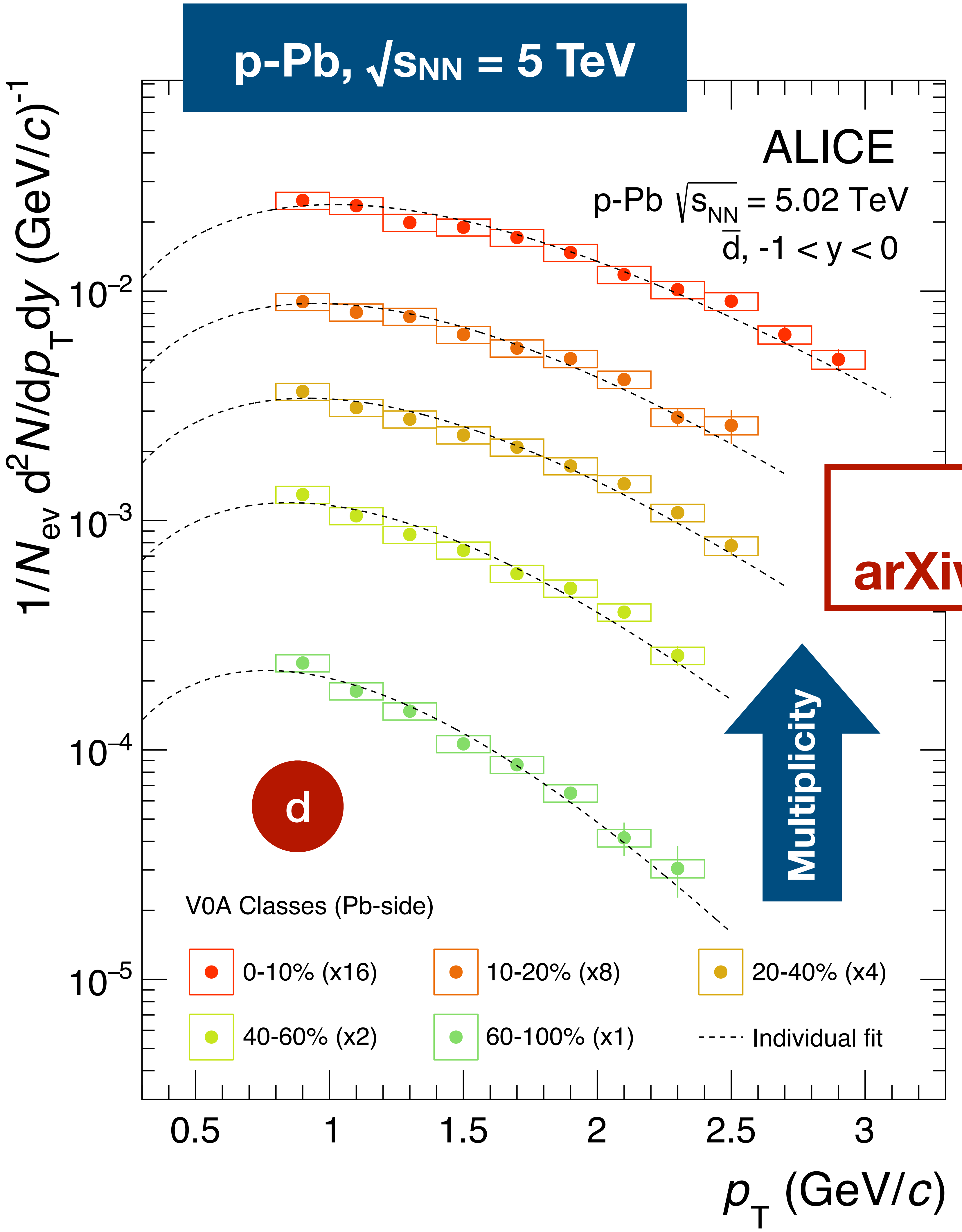
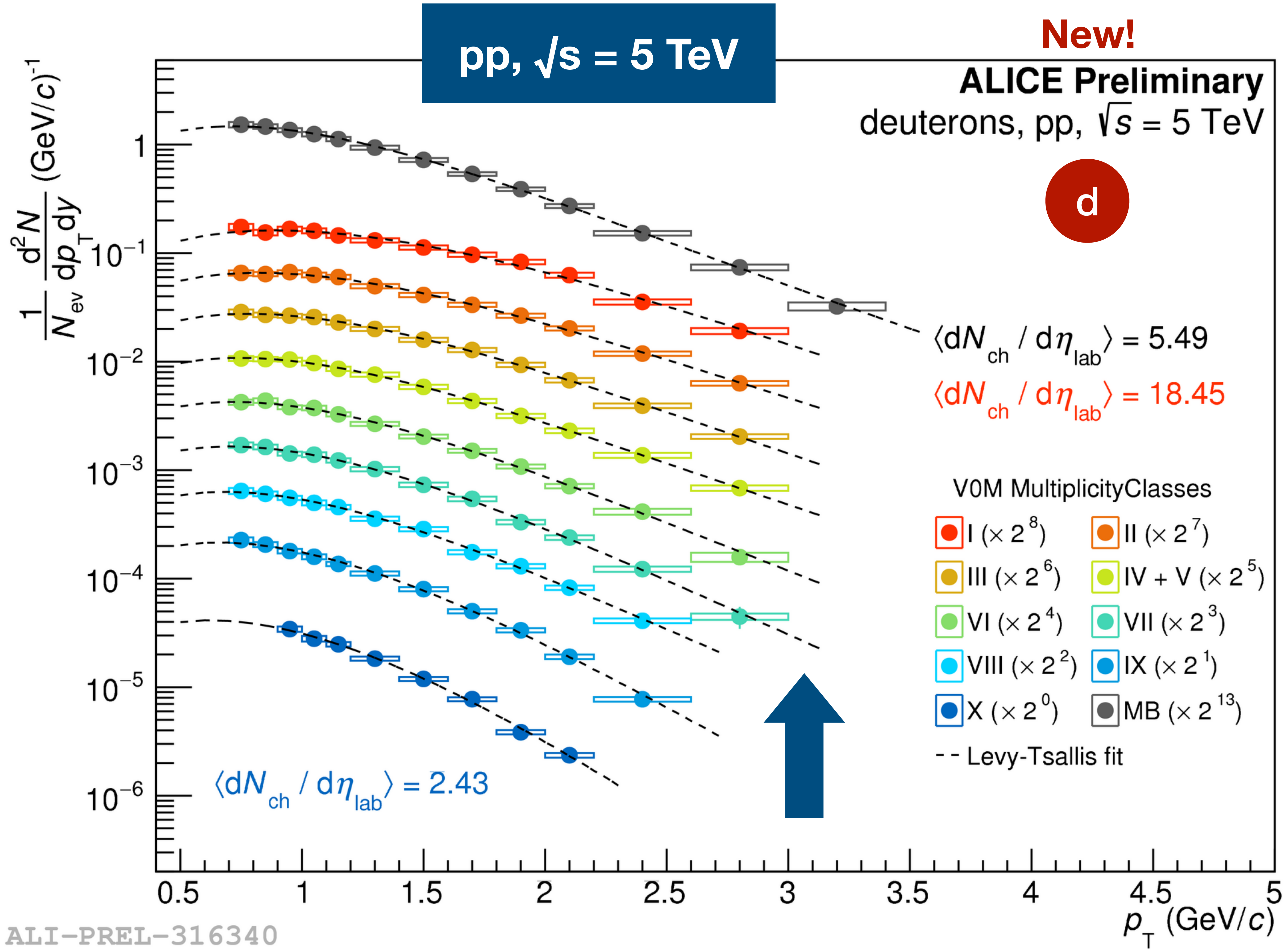


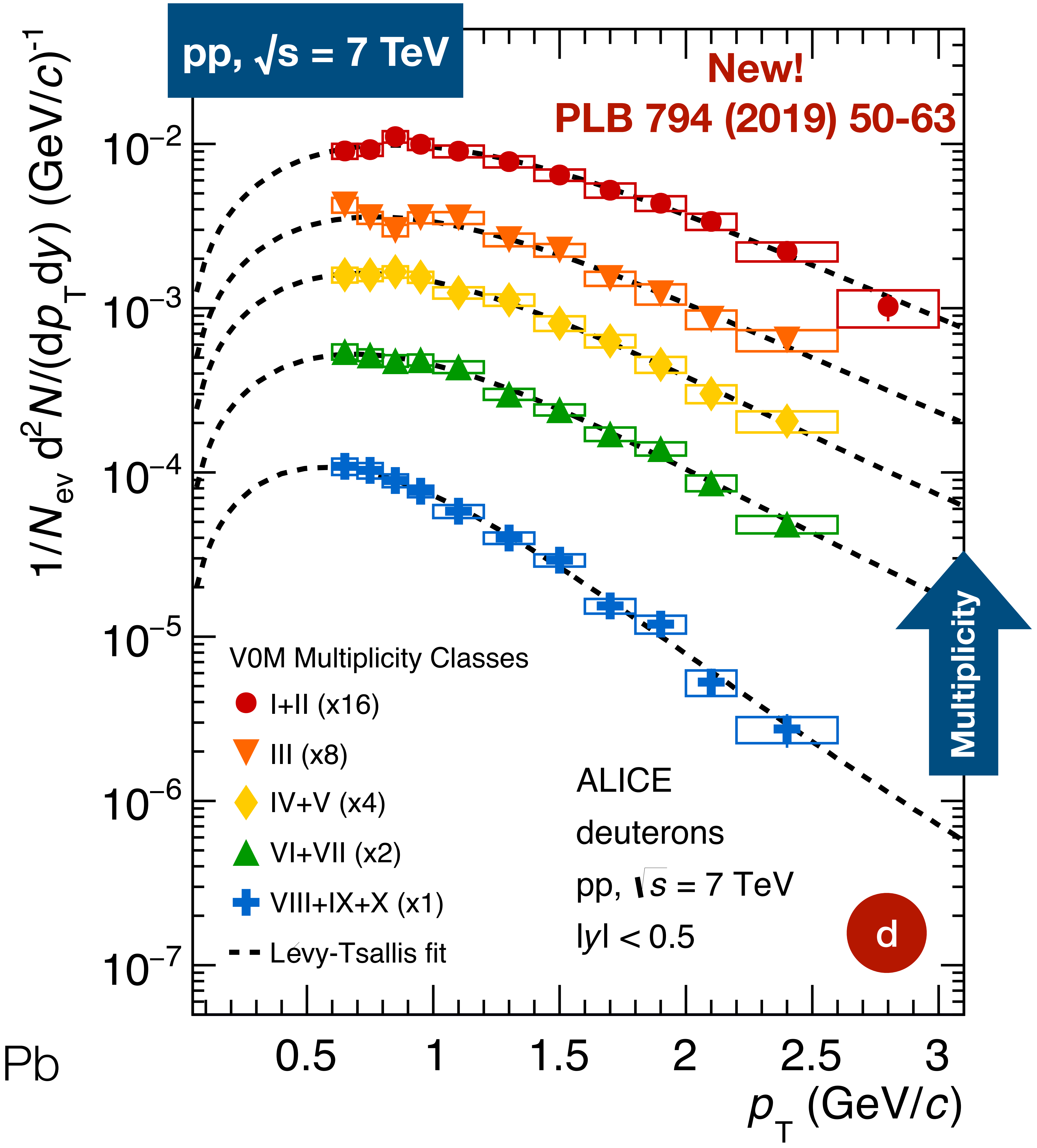


New!
arXiv:1906.03136

- p-Pb at $\sqrt{s_{NN}}$ = 5 TeV
- ***p_T* spectra** are fitted with a ***m_T*-exponential** function, used for the extrapolation of the yield to unmeasured p_T regions

Deuteron spectra in pp

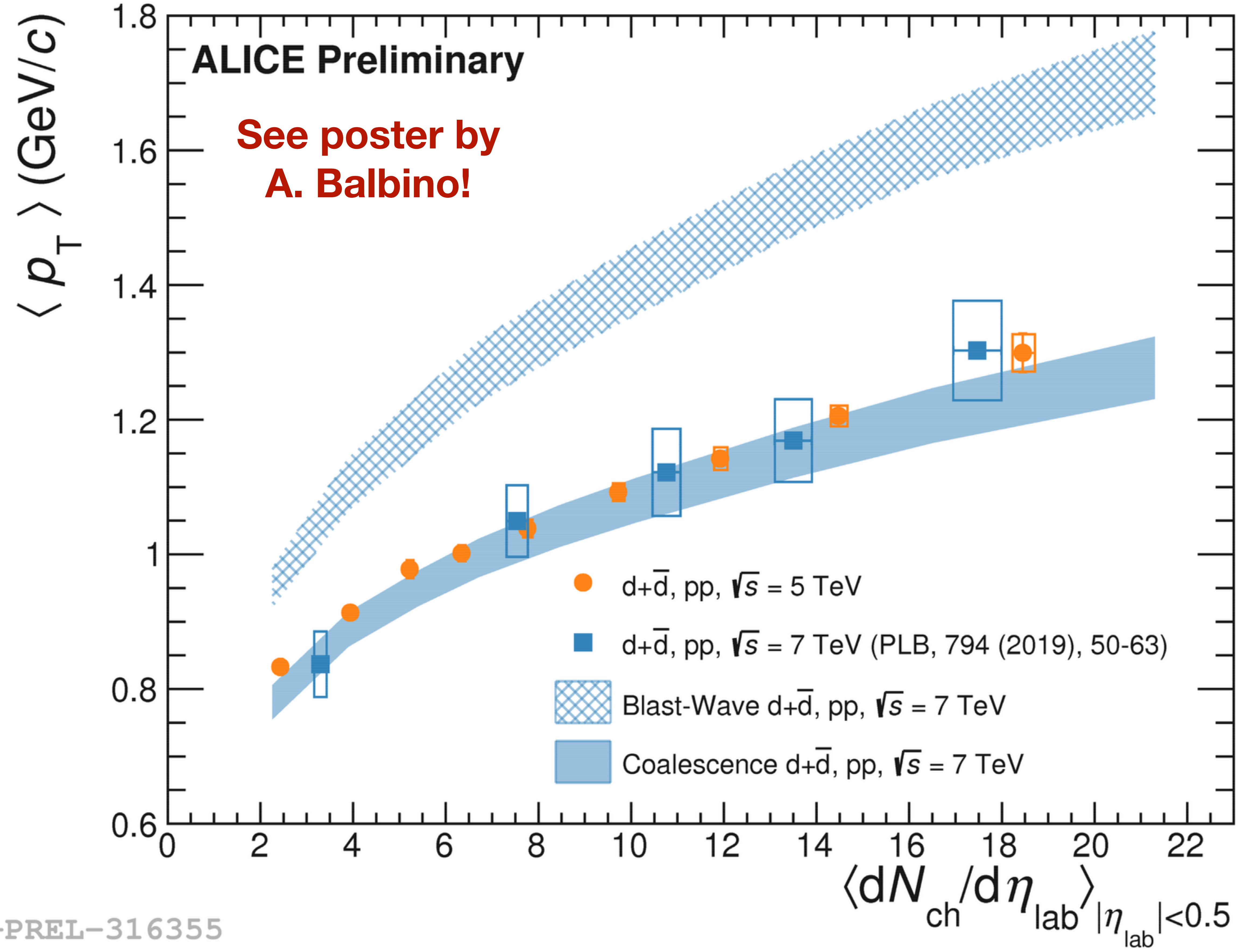


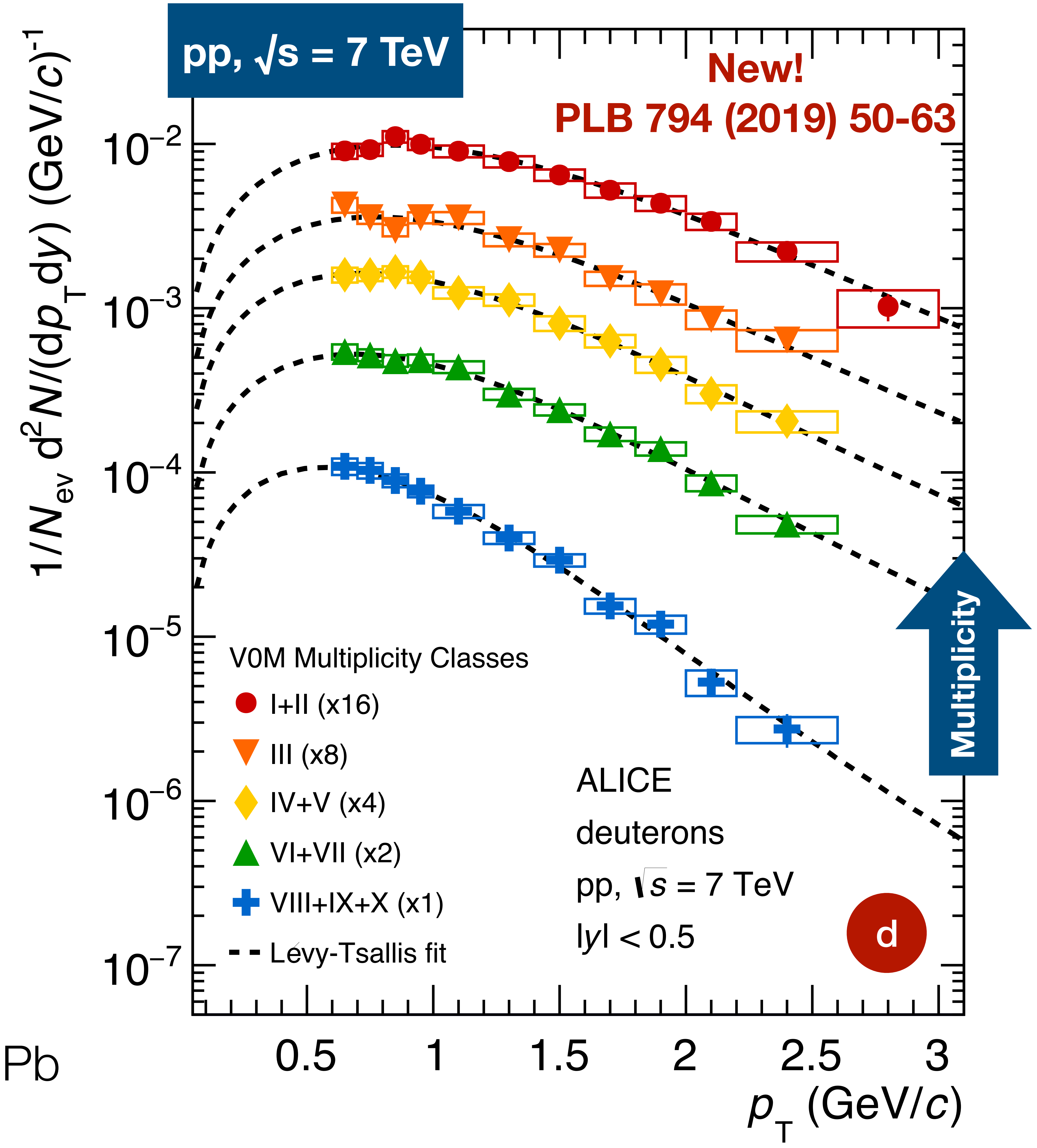


- **p_T spectra** are fitted with a **Levy-Tsallis**[1] function
- **Hardening** with increasing multiplicity, **less pronounced** than in Pb-Pb

[1]C. Tsallis. J. Stat. Phys. 52, 479 (1988)

Deuteron spectra in pp





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- **Hardening** with increasing multiplicity, **less pronounced** than in Pb-Pb
  - in agreement with coalescence model predictions

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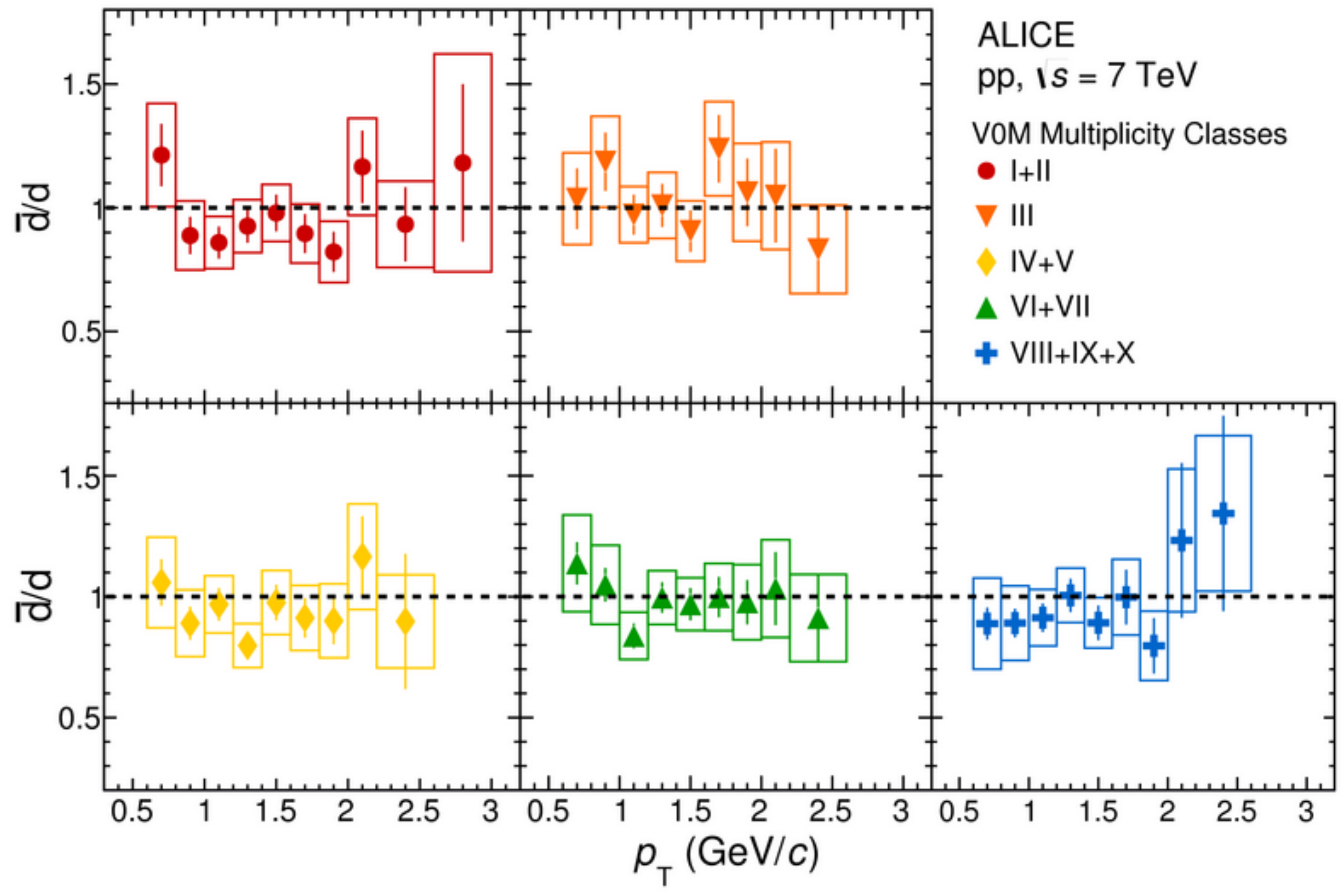
Anti-nuclei / nuclei ratio

- At the LHC energies the **antiproton/ proton** ratio is compatible with the **unity**:
  - the regime of **nuclear transparency** is reached: evanescent baryochemical potential (**$\mu_B \sim 0$**) in the central rapidity region
- Both **thermal** and **coalescence** models predict for a nucleus X with mass number A:

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

- The measurements of **$\overline{d}/d$** and **$^3\overline{He}/^3He$** in **Pb-Pb**, **p-Pb** and **pp** collisions confirm the predictions:
  - **matter and anti-matter produced with the same abundances**



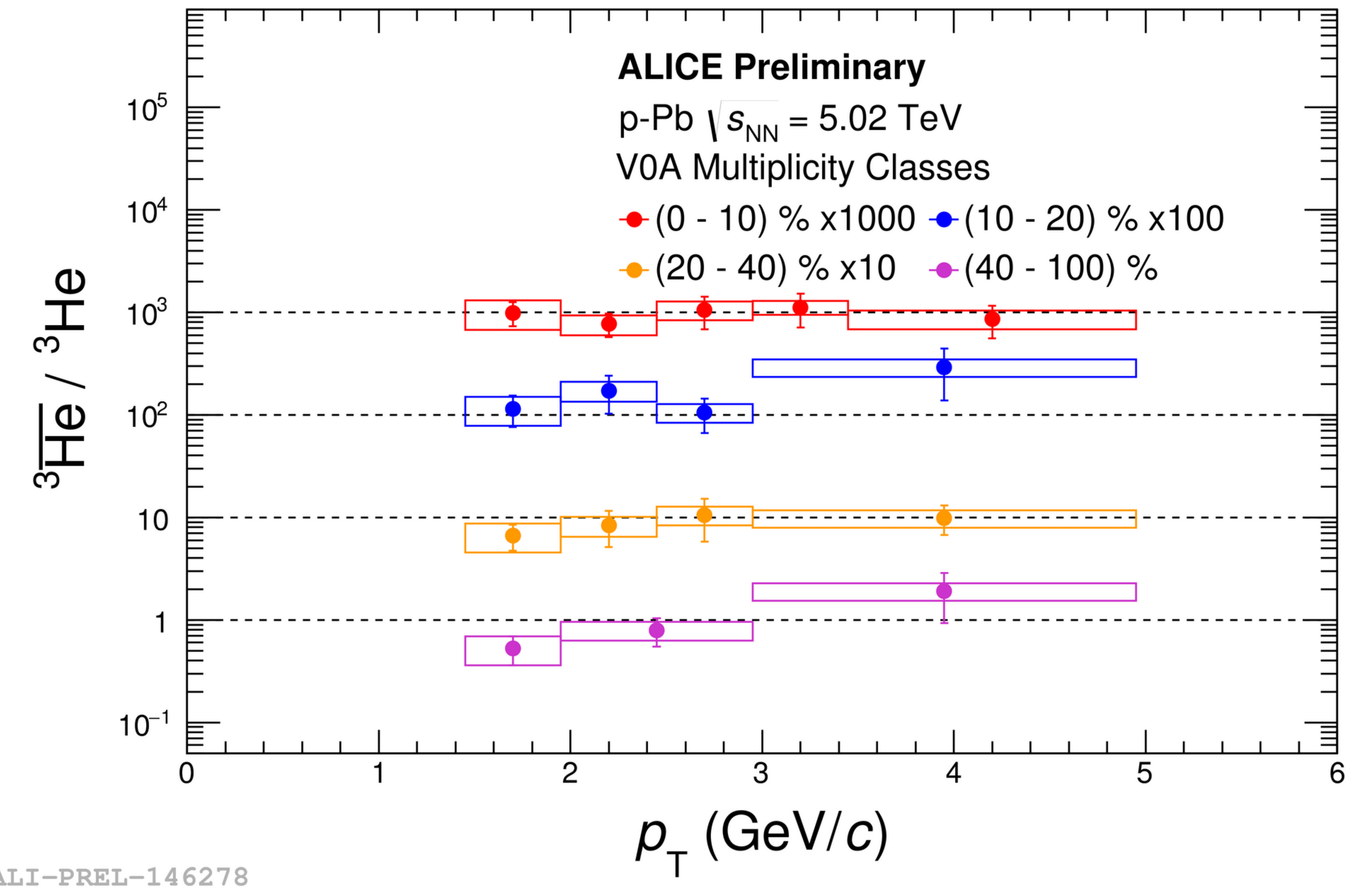
pp, √s = 7 TeV

PLB 794 (2019) 50-63

d

p-Pb, $\sqrt{s_{NN}}$ = 5 TeV

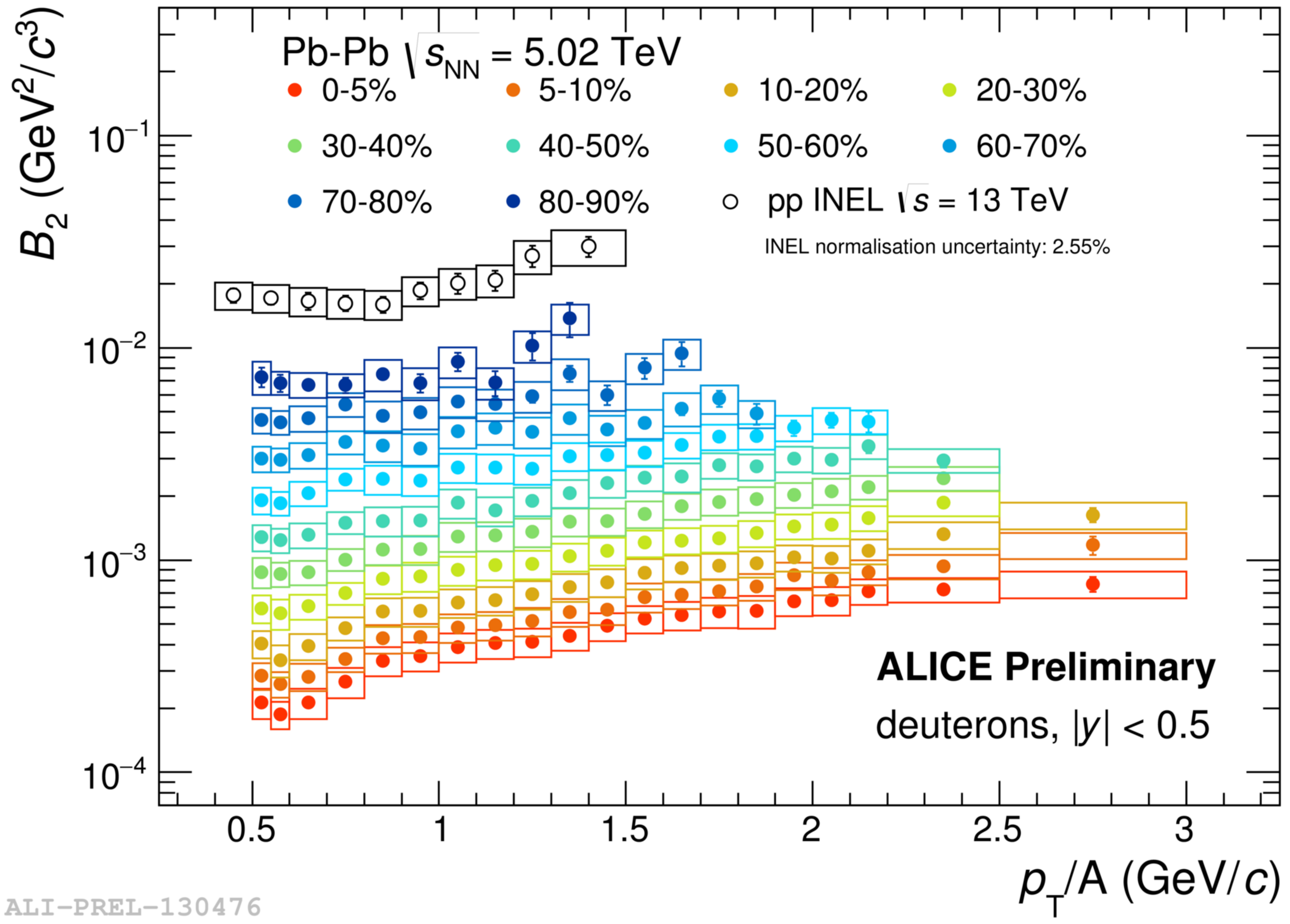
^{3}He



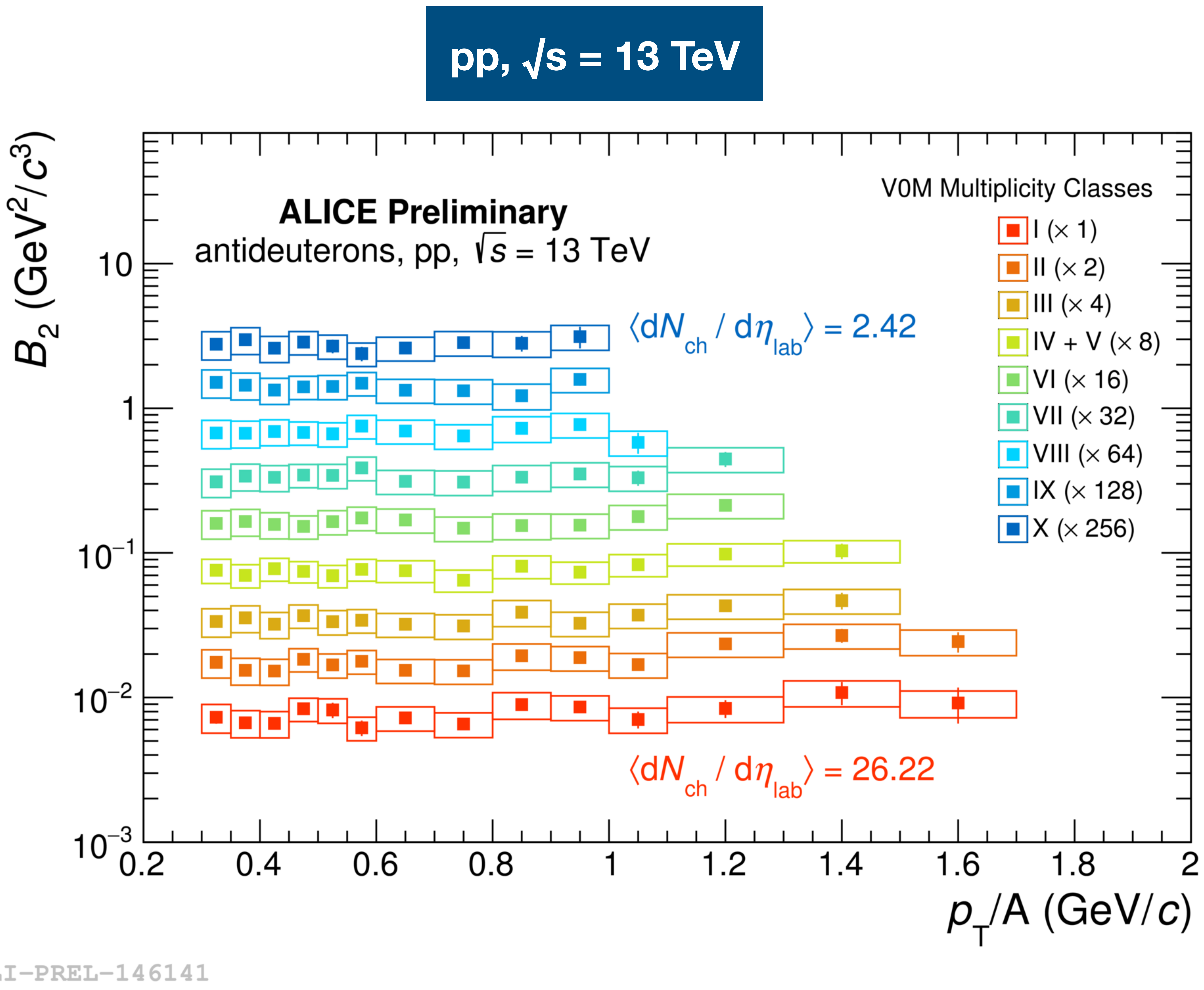
The coalescence parameter B_A

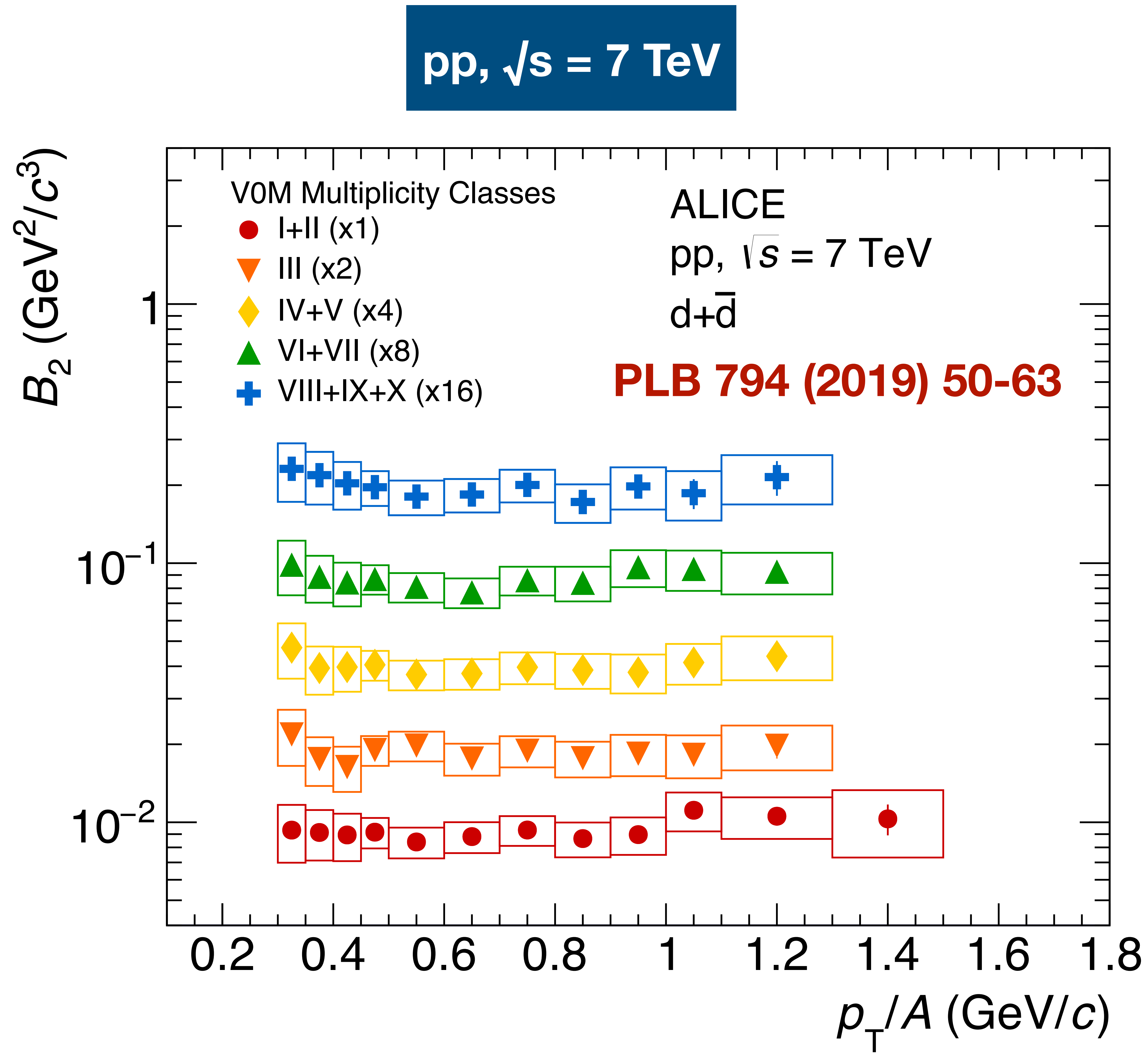
- The **probability** to form a nucleus via coalescence can be quantified by the **coalescence parameter B_A**
- According to **simple coalescence** predictions, the **B_A** is **flat in p_T**
  - Simple coalescence **does not describe** the behaviour observed in **Pb-Pb** collisions
- Moving from central to peripheral collisions (i.e. towards **lower multiplicities**), the rise in p_T becomes milder

Pb-Pb, $\sqrt{s_{NN}}$ = 5 TeV



The coalescence parameter B_2





- In **pp** collisions, the $\mathbf{B_2}$ is **flat in $\boldsymbol{p_T}$**, in agreement with the **simple coalescence** model

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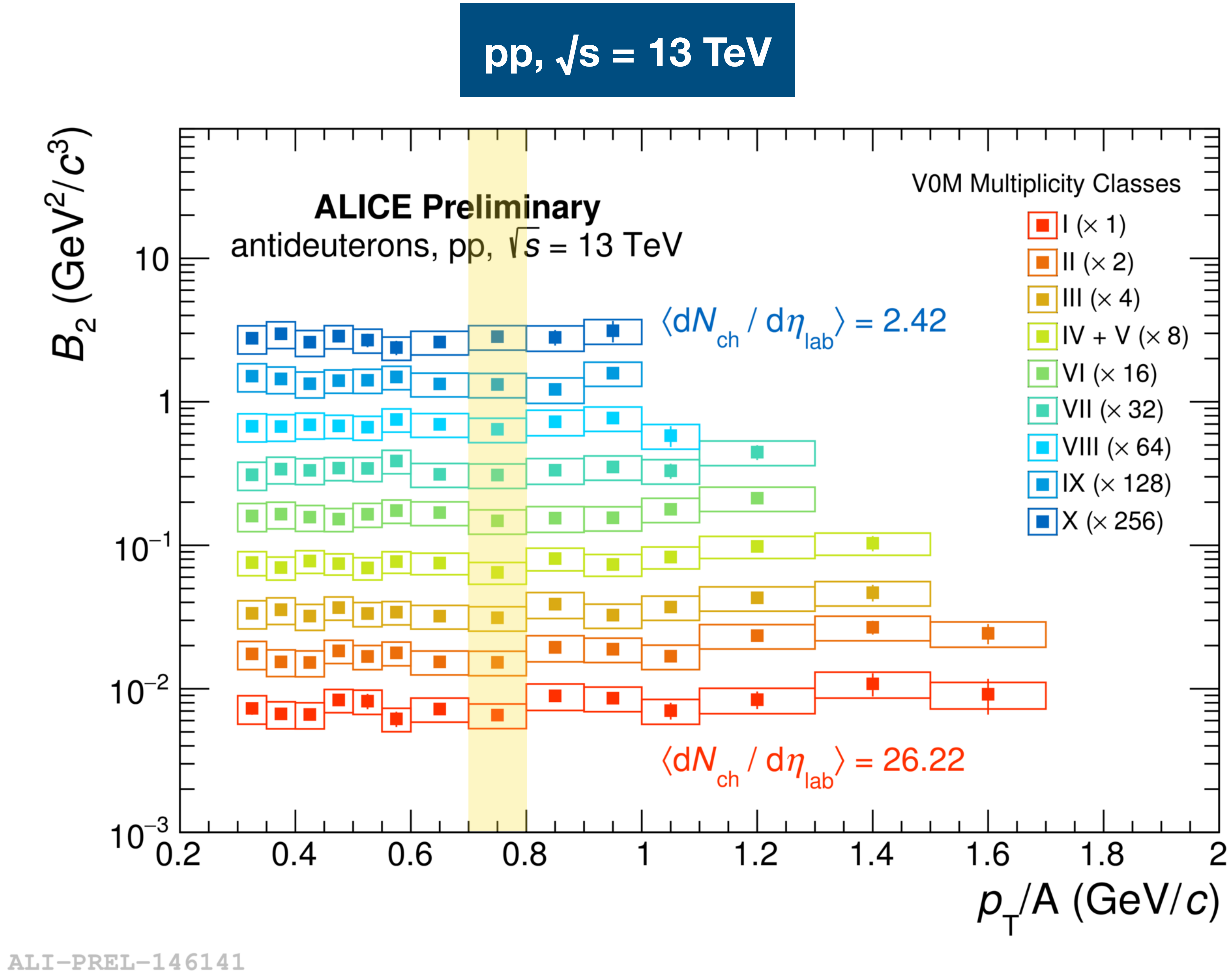

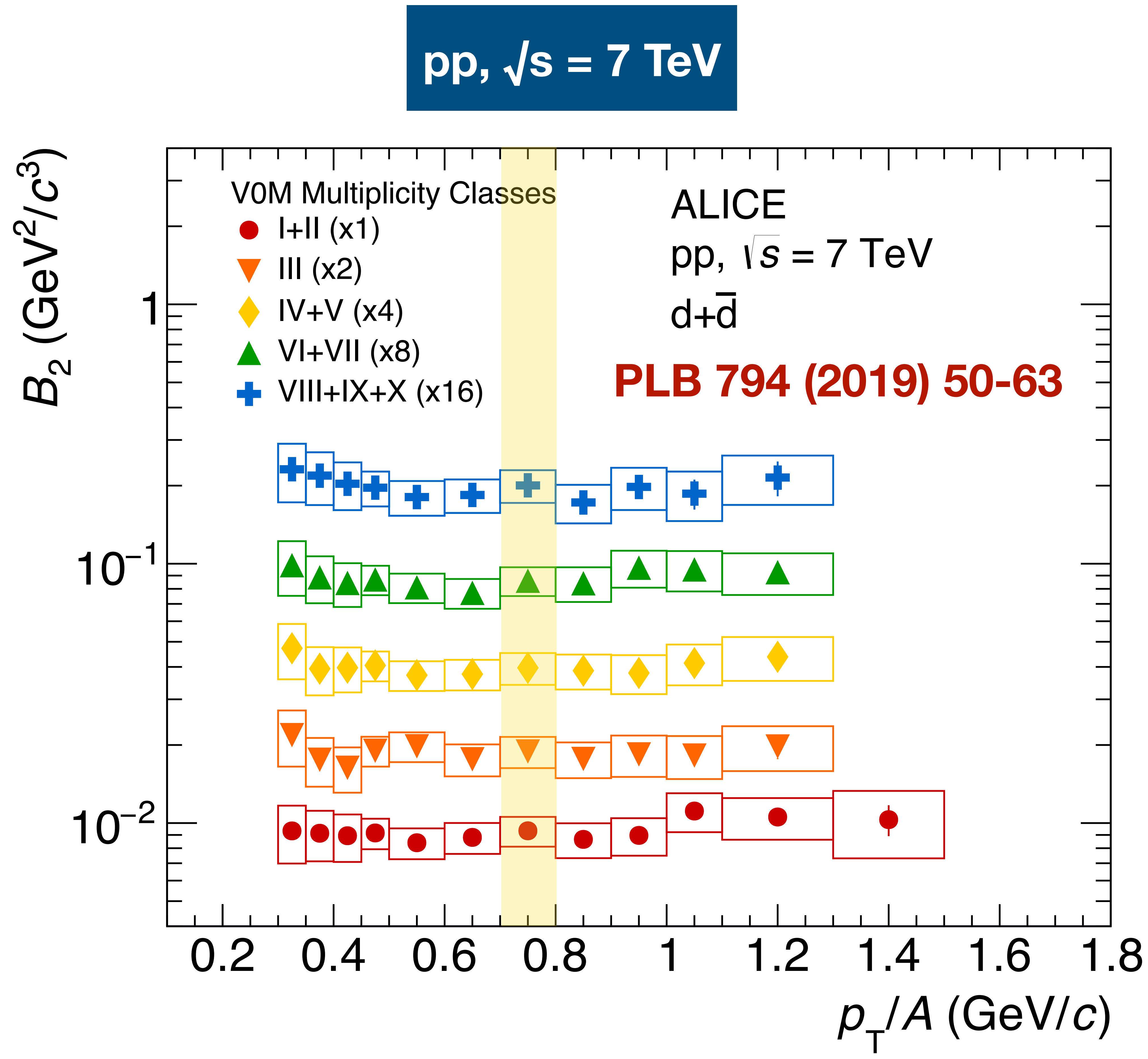

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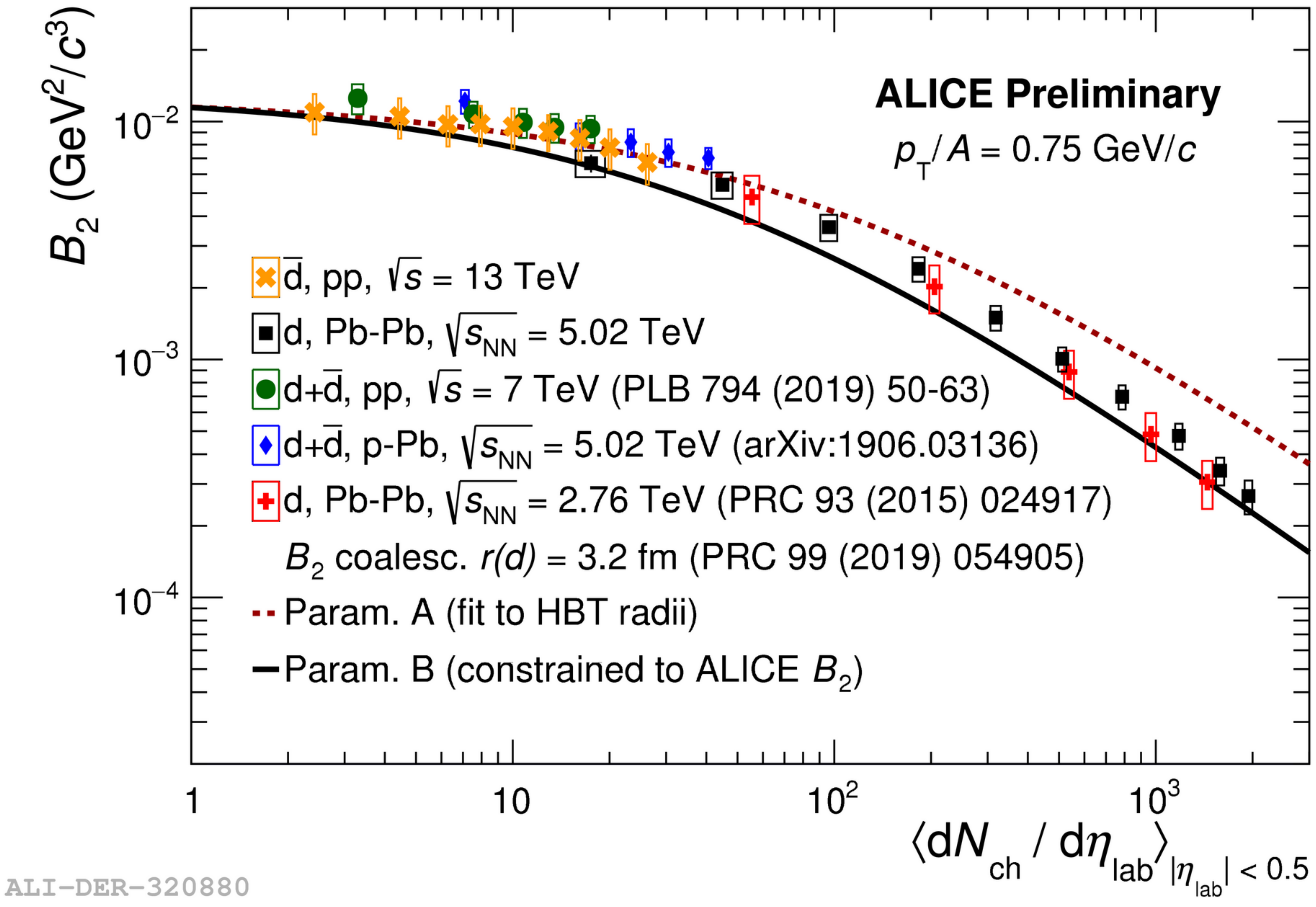
Multiplicity dependence of B_2

- The measurement of the **B_2 does not show discontinuity** between different colliding systems and different energies:
  it evolves **smoothly** with the **multiplicity**:
  - **Hint of a unique production mechanism depending only on the system size**



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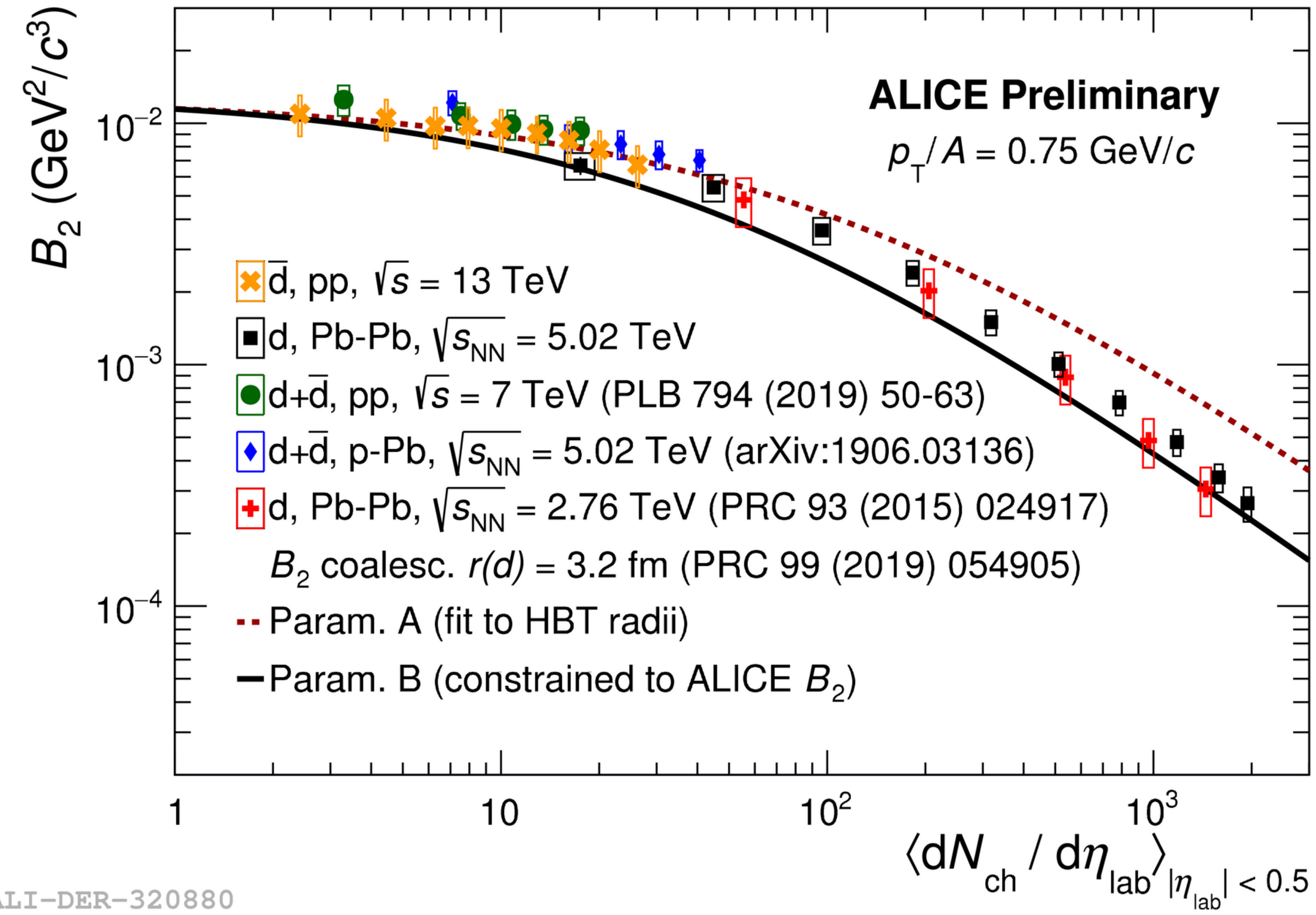

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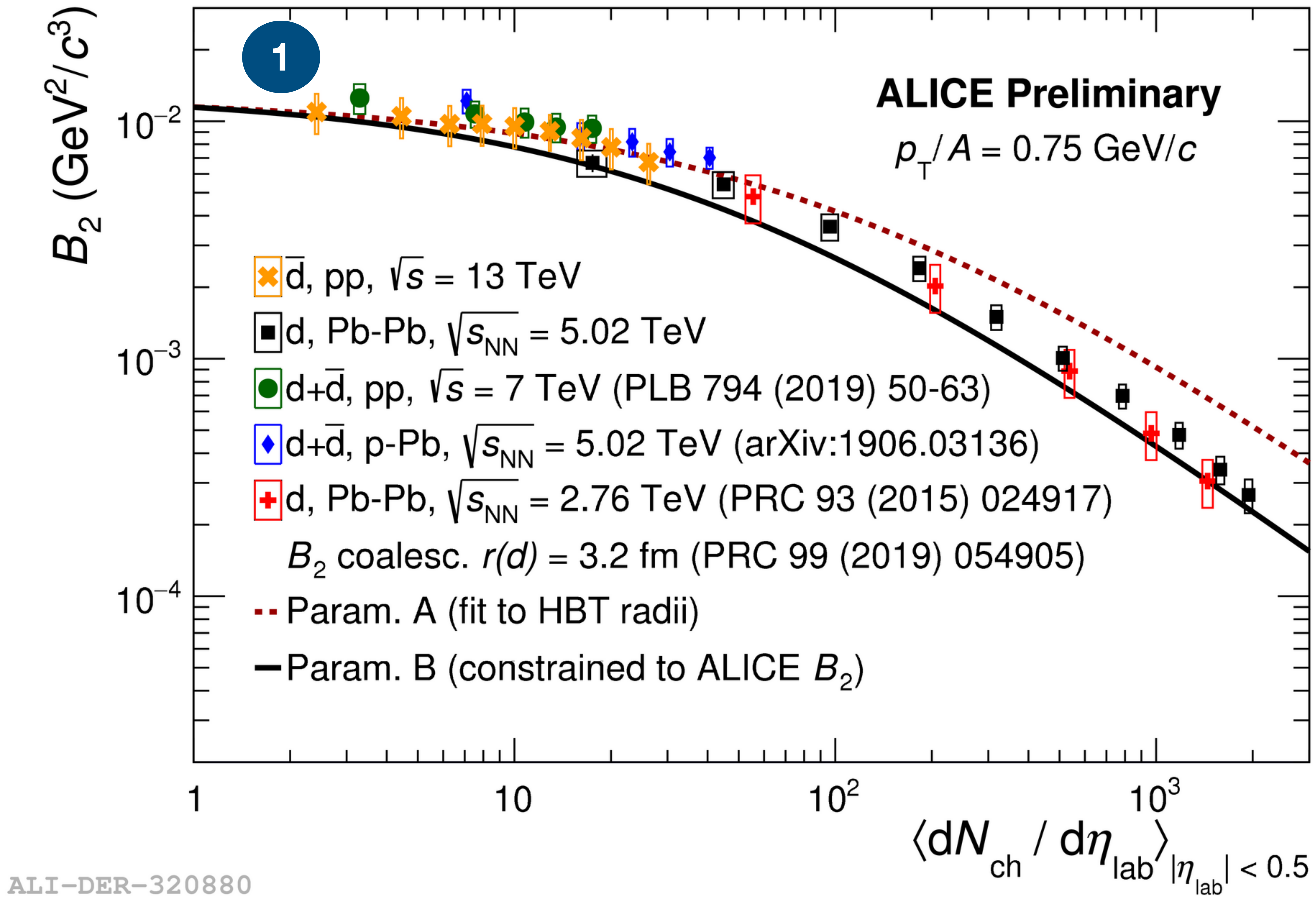

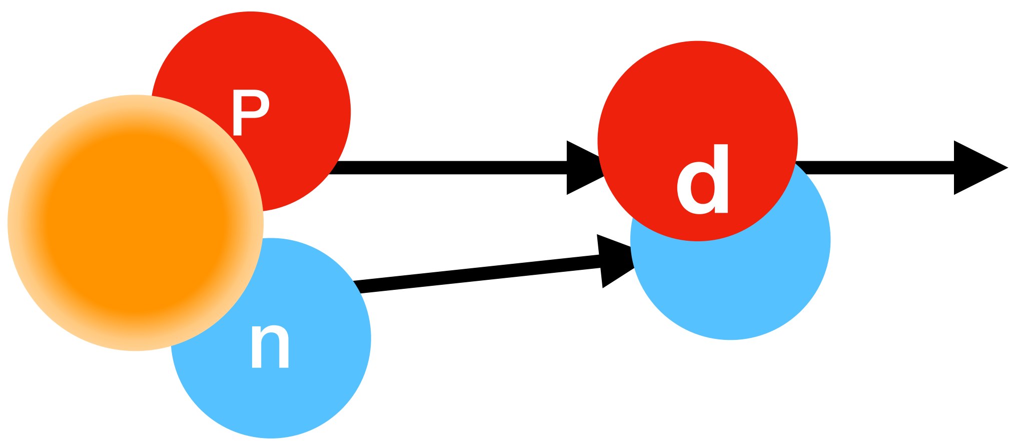

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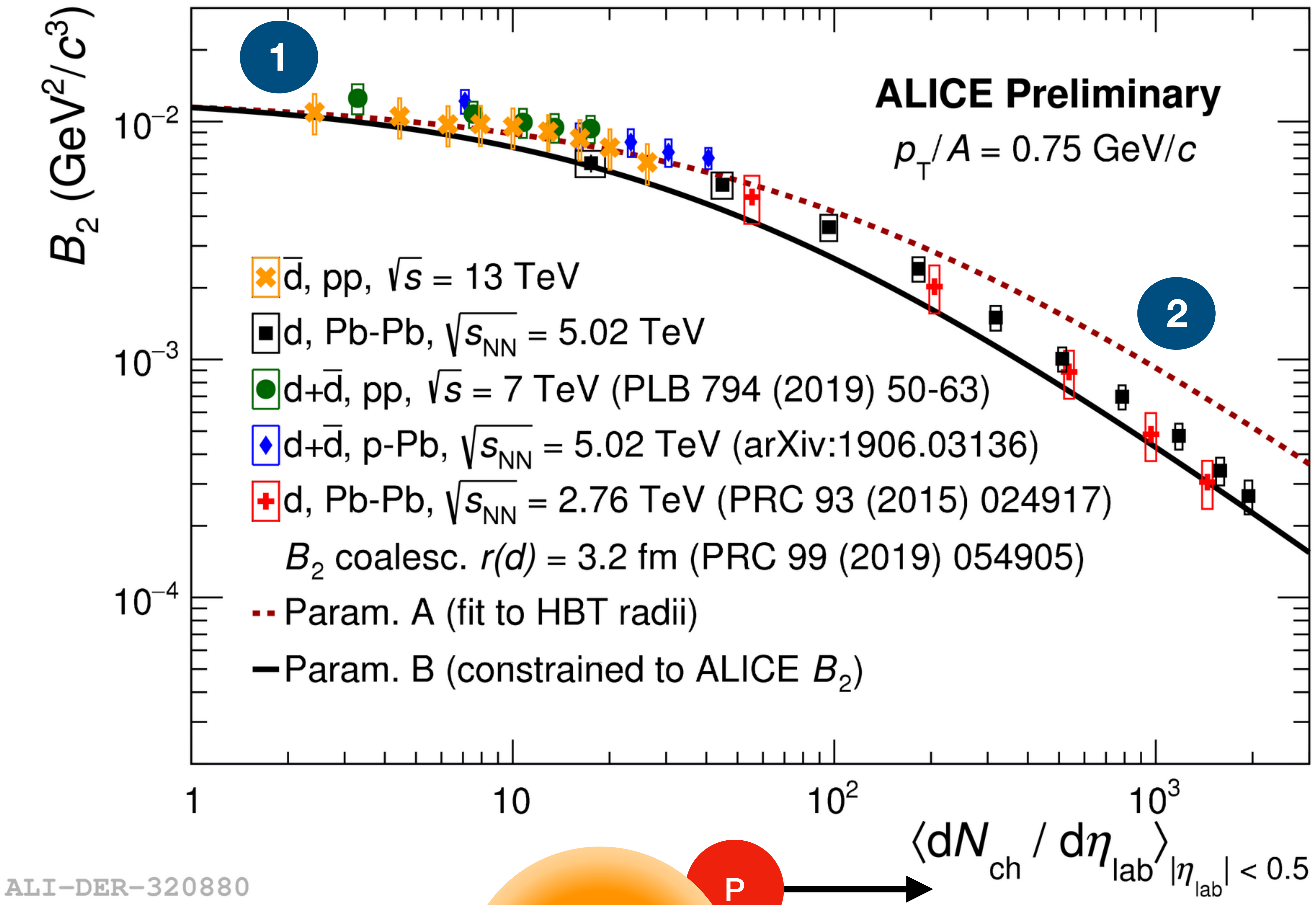

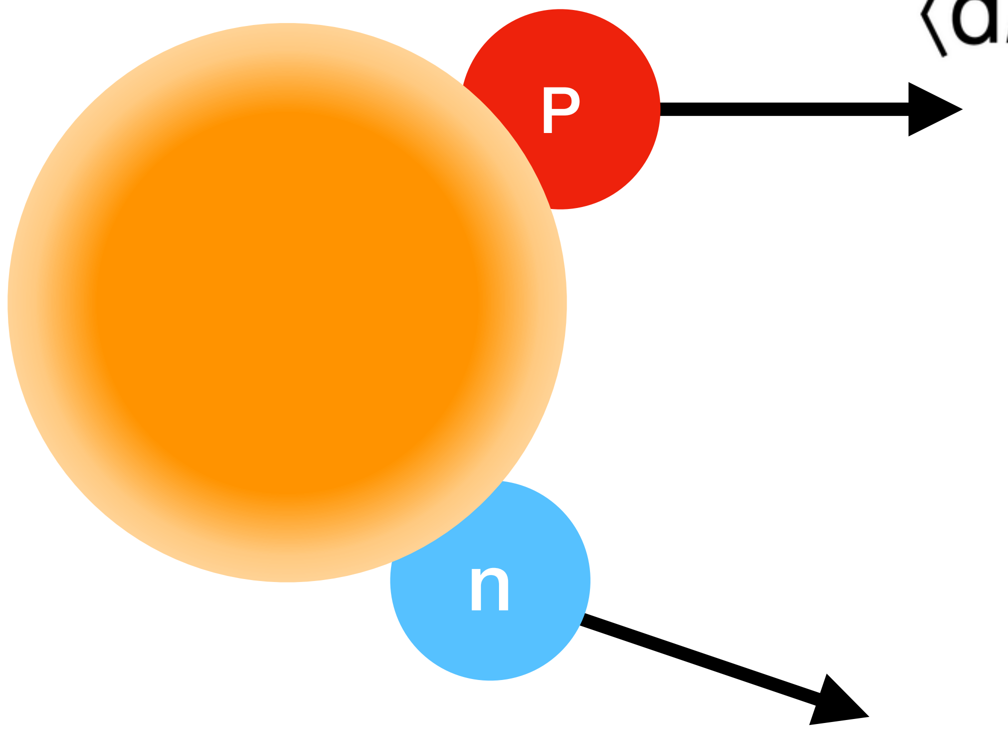

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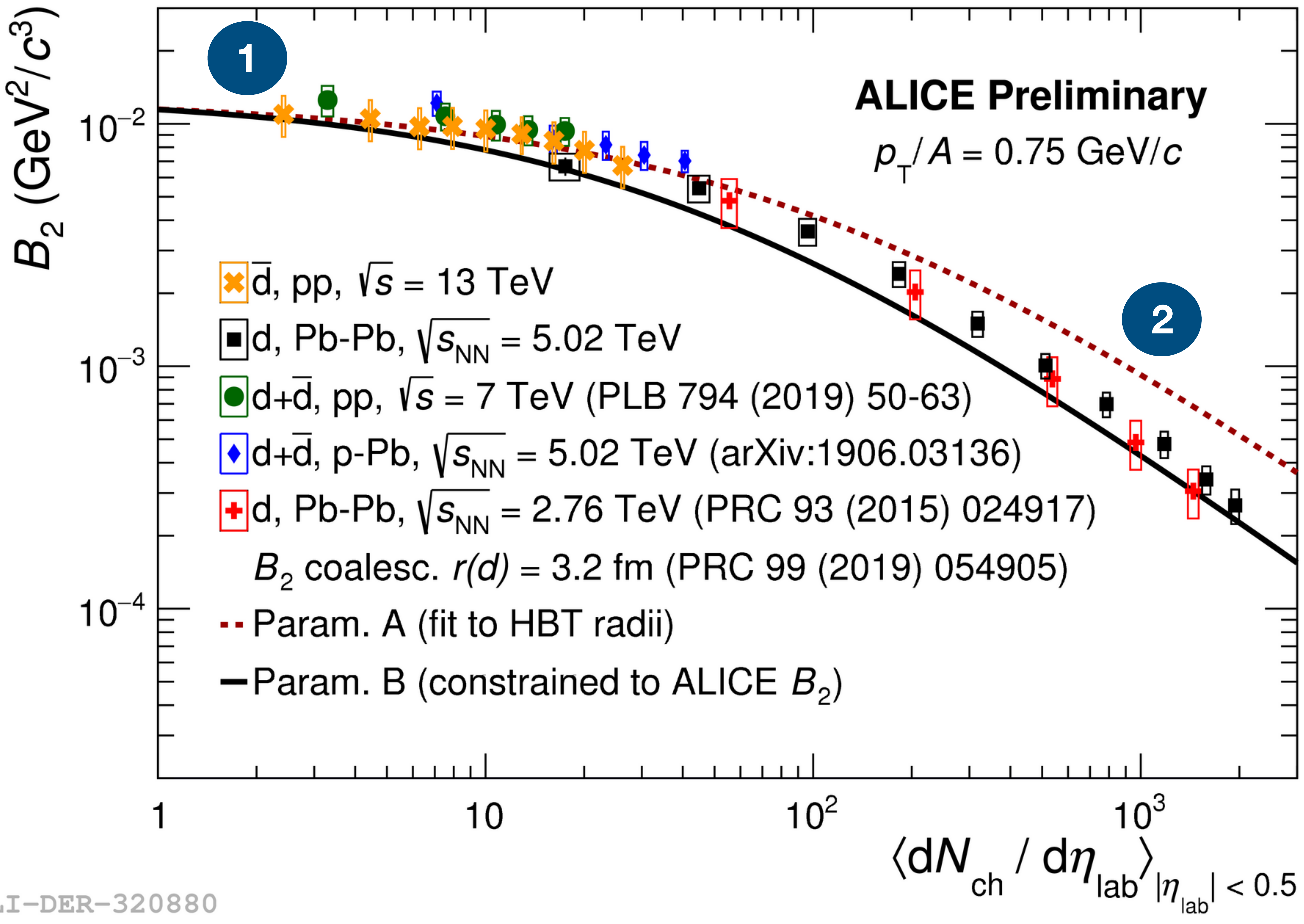
- Two regimes observed:
  1. **flat:** the system size is smaller than the deuteron size
  2. **decreasing:** the system size is larger than the deuteron size
- Through the coalescence model it is possible to predict the **B_A** as a function of the **system volume**, parameterised from the dN/dη

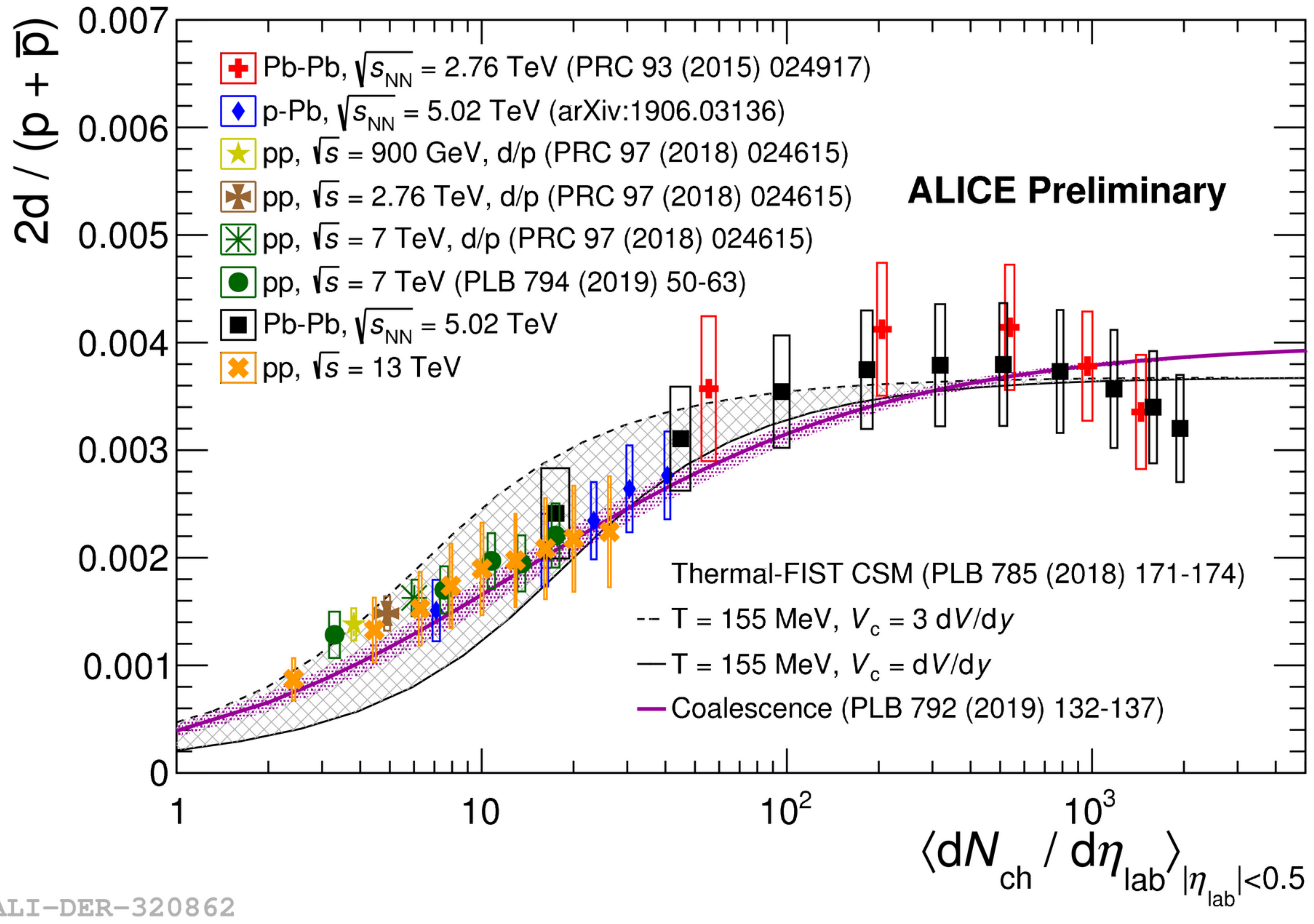


ALI-DER-320880

$$B_2 = \frac{3\pi^{3/2}\langle C_d\rangle}{2m_T R^3(m_T)} \quad \text{with} \quad \langle C_d\rangle \approx \left[1 + \left(\frac{r_d}{2R(m_T)}\right)^2\right]^{-3/2}$$

Deuteron over proton ratio

- The measurement of the **d/p** ratio **does not show discontinuity** between different colliding systems and different energies: it evolves **smoothly** with the **multiplicity**
  - **Hint of a unique production mechanism depending only on the system size**



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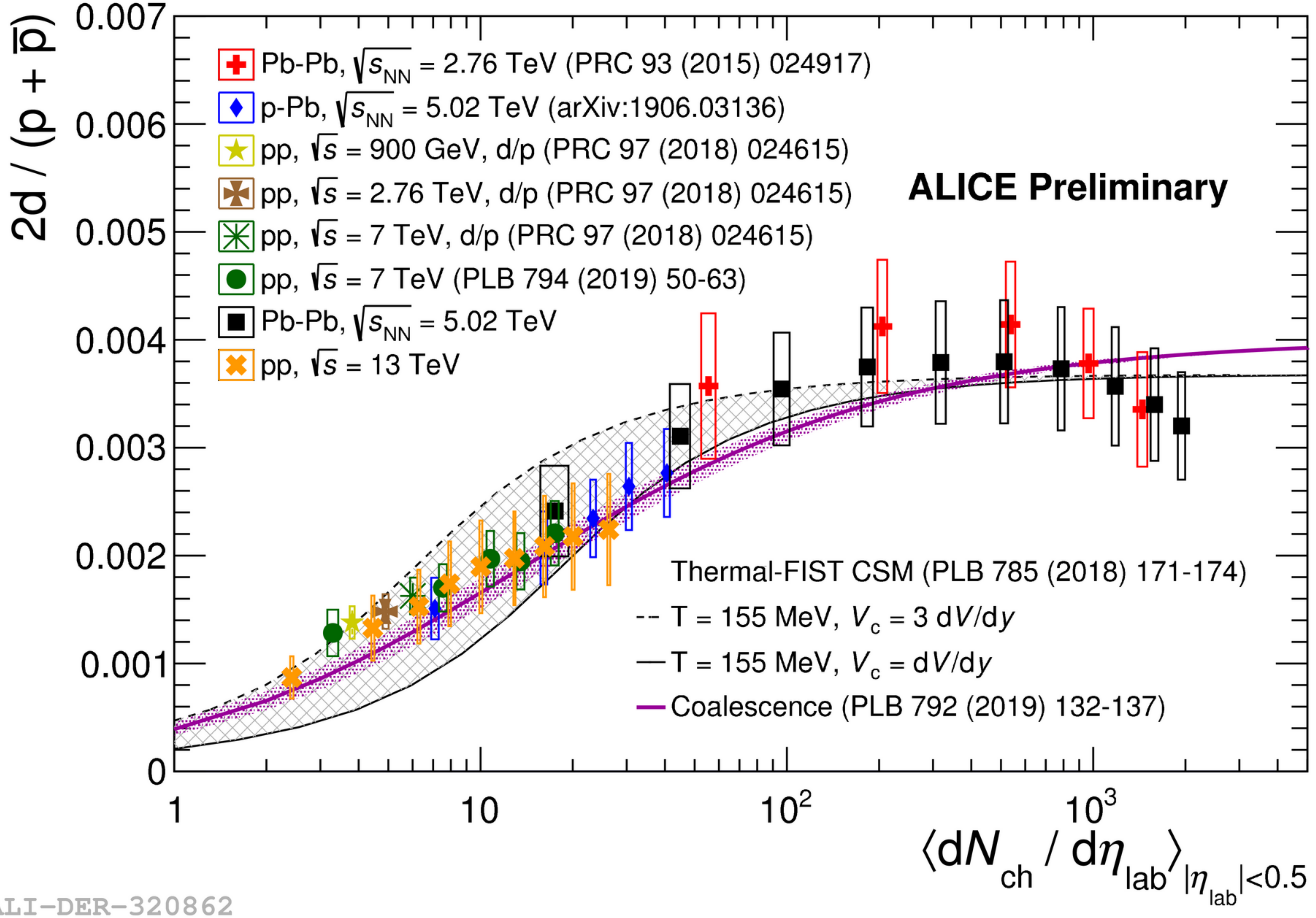

ALI-DER-320862

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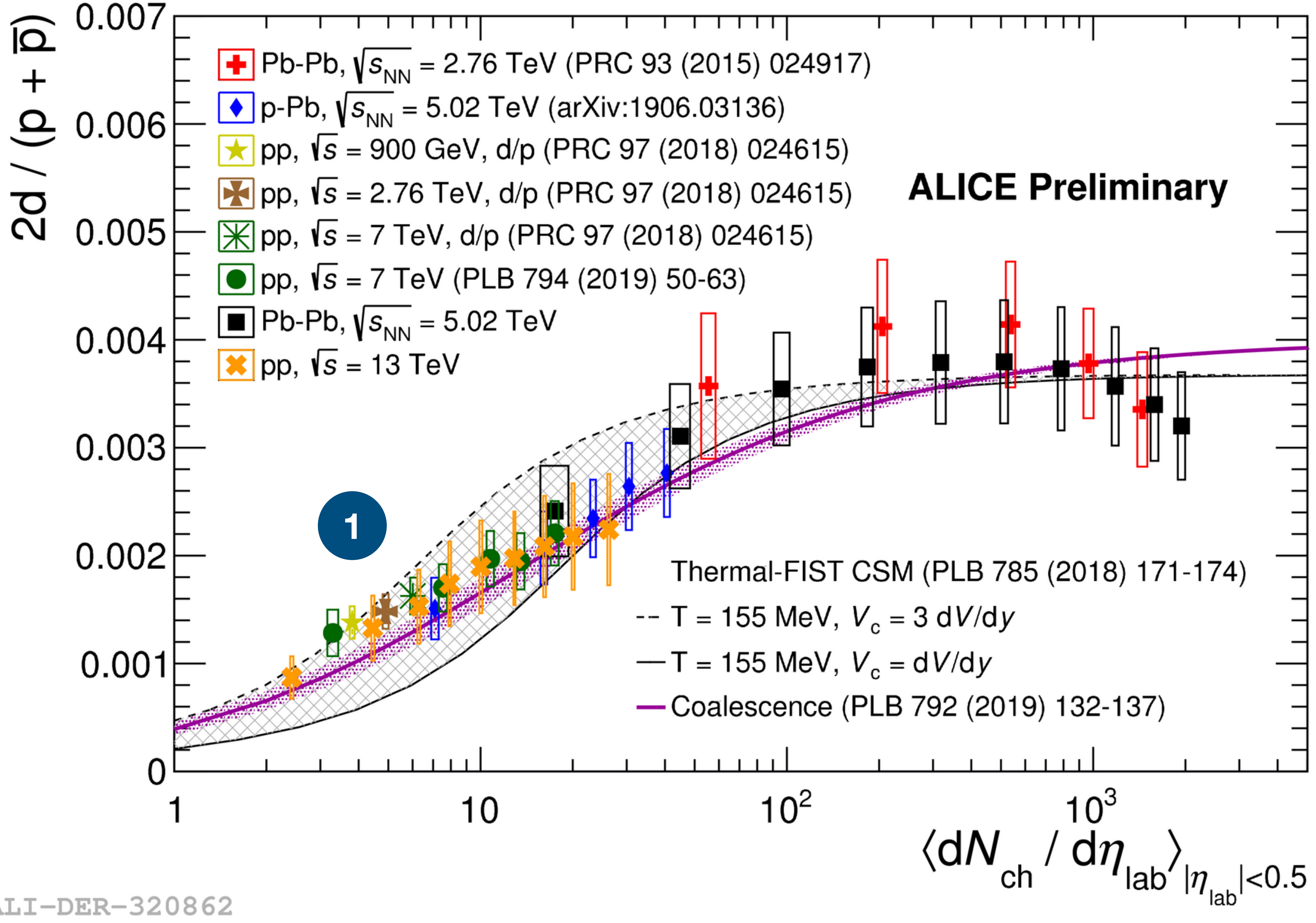
   - Thermal model: **canonical suppression**
   - Coalescence: **small phase space**



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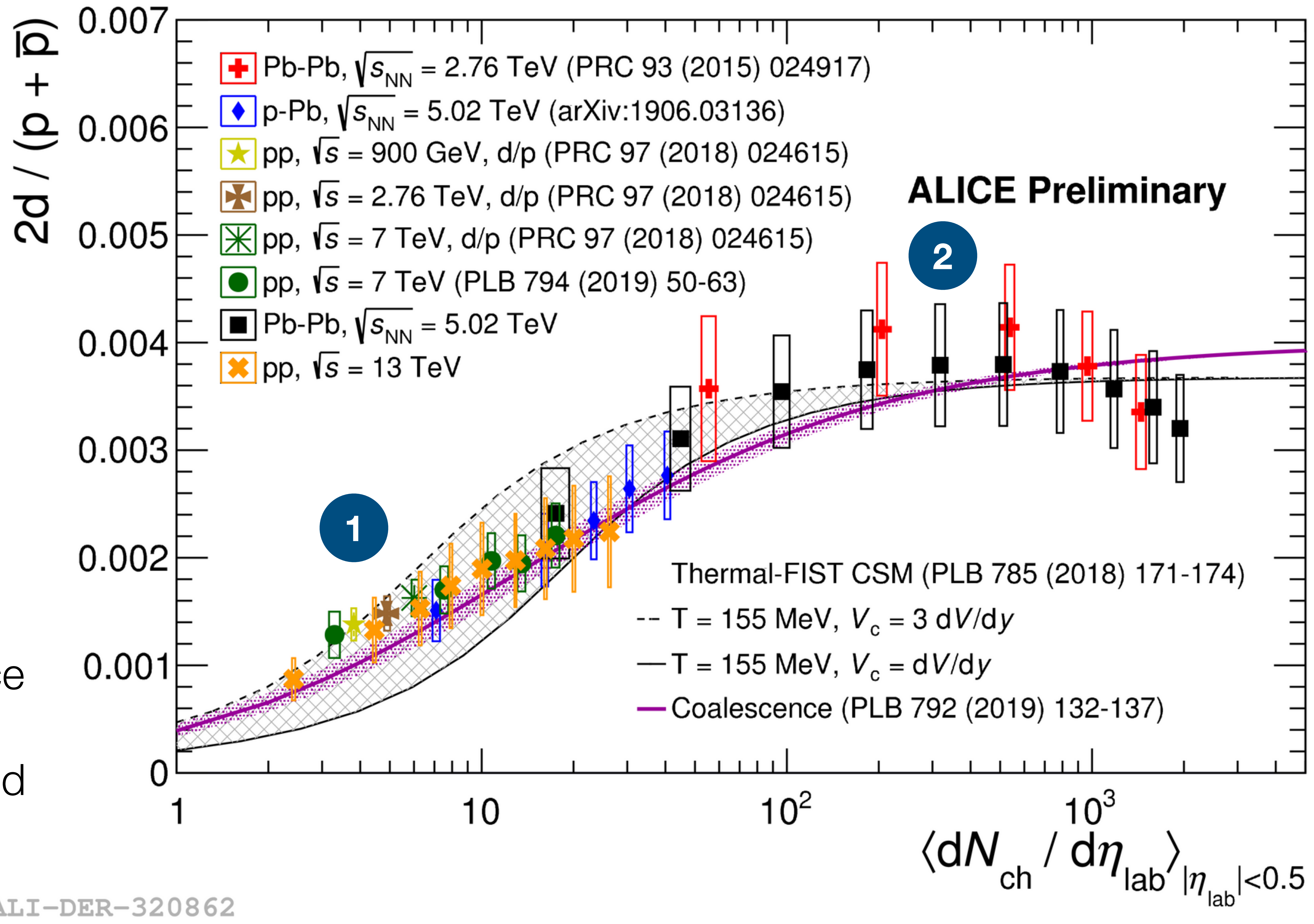

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- Two different regimes: (or three?)

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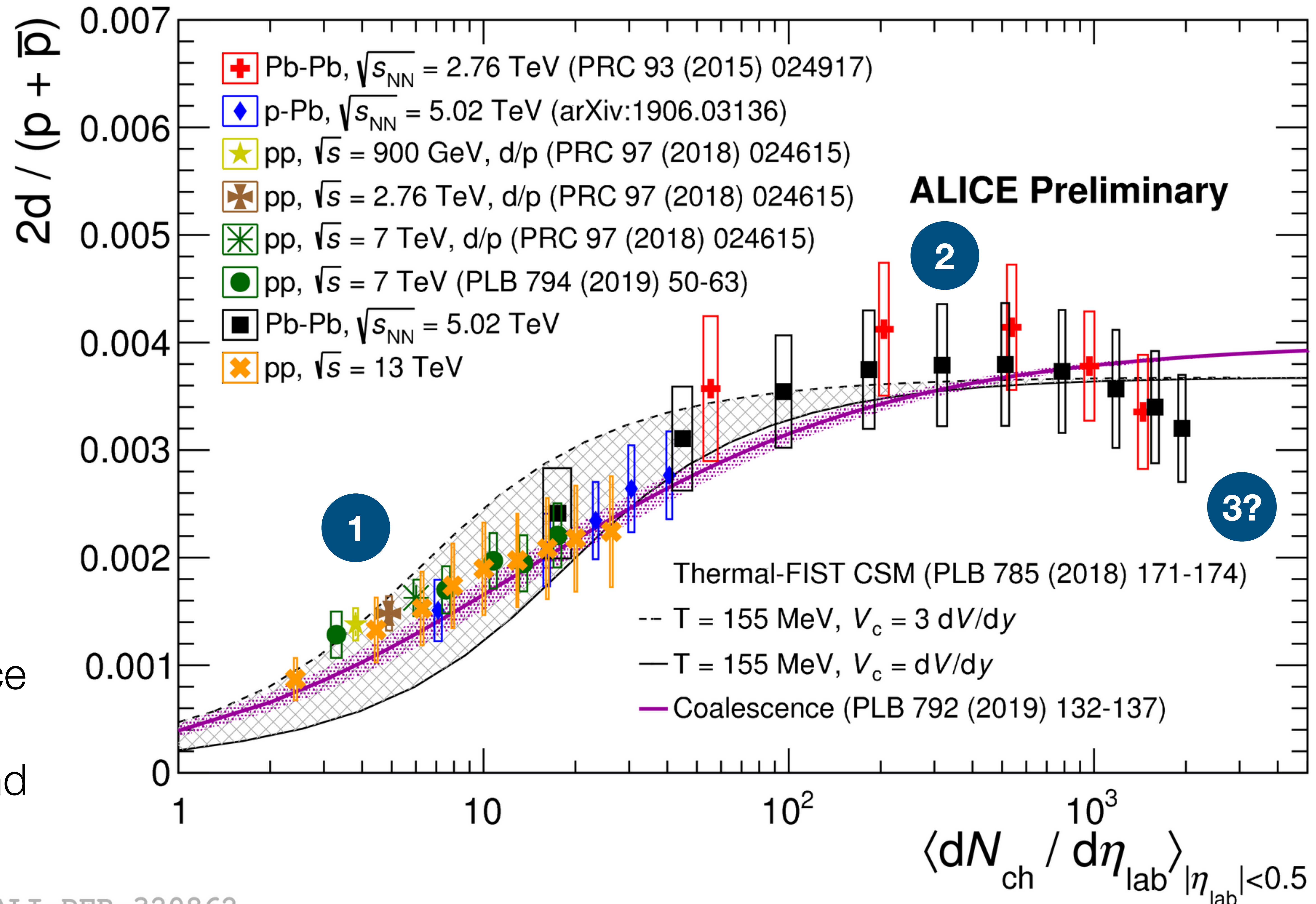
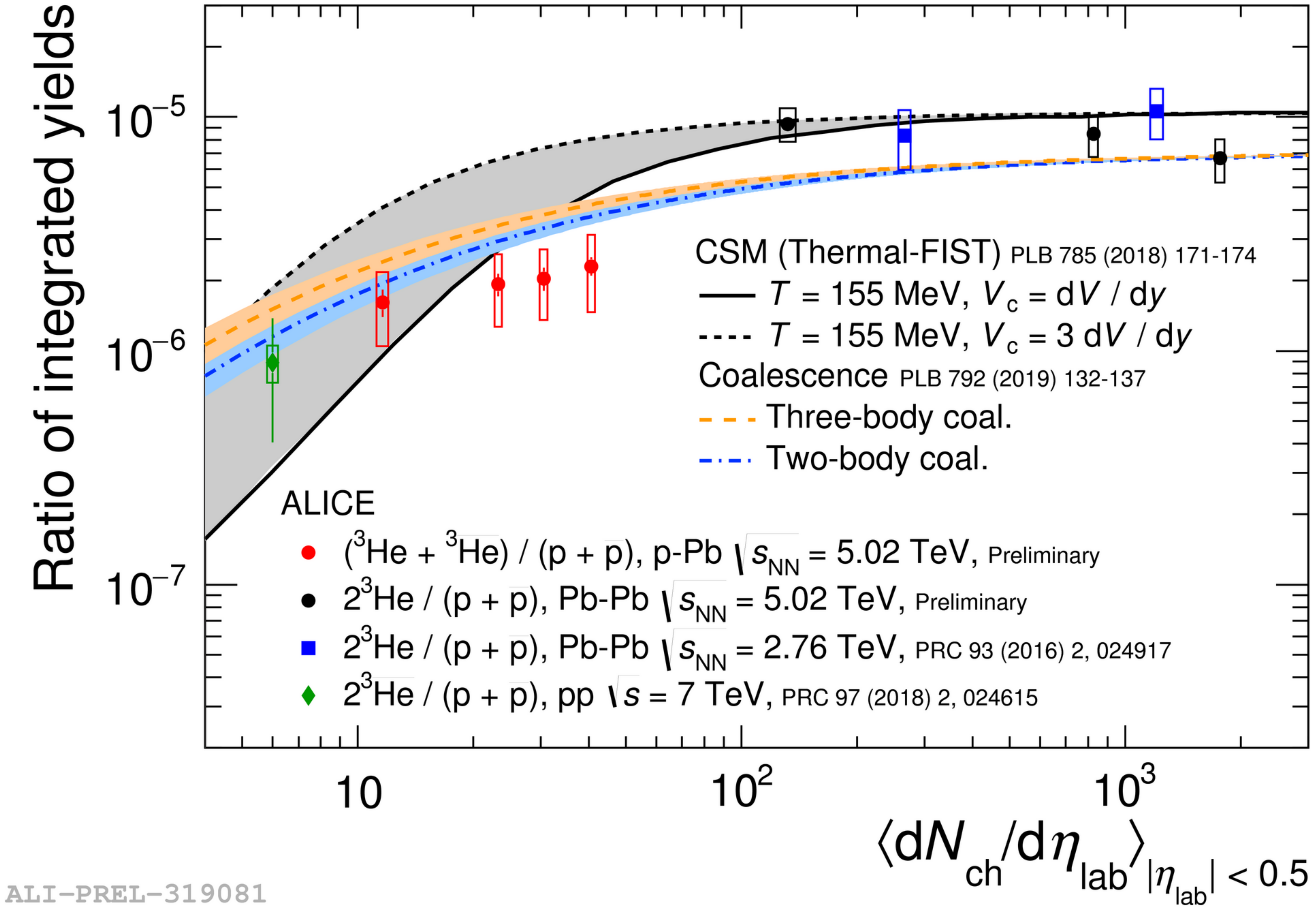
3. **(suppression?)**: too large uncertainties for a conclusion



ALI-DER-320862

^{3}He over proton ratio

- Also for **^{3}He/p** we see a **smooth evolution** with the multiplicity, regardless of the collision system



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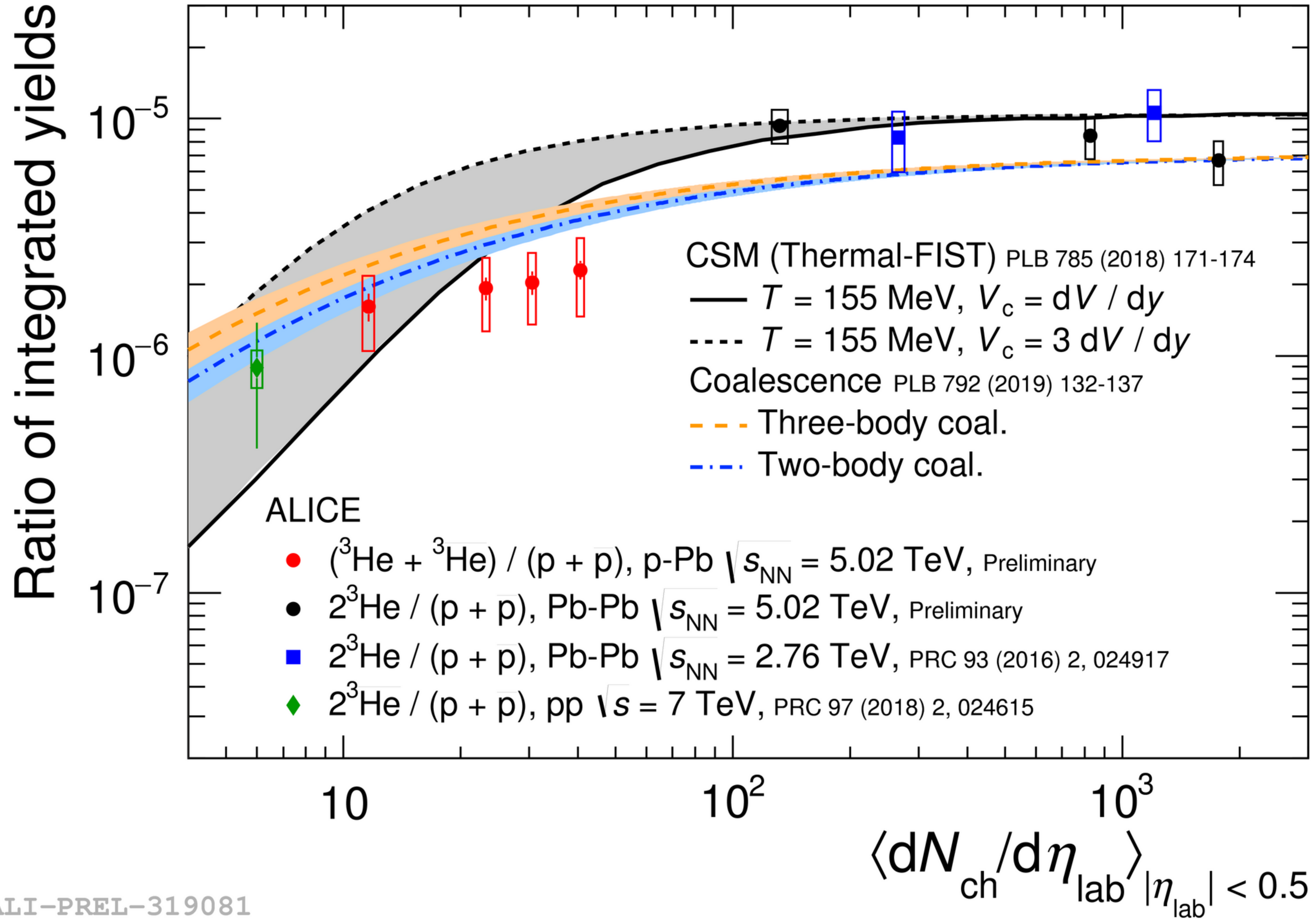
- We see again two different regimes:



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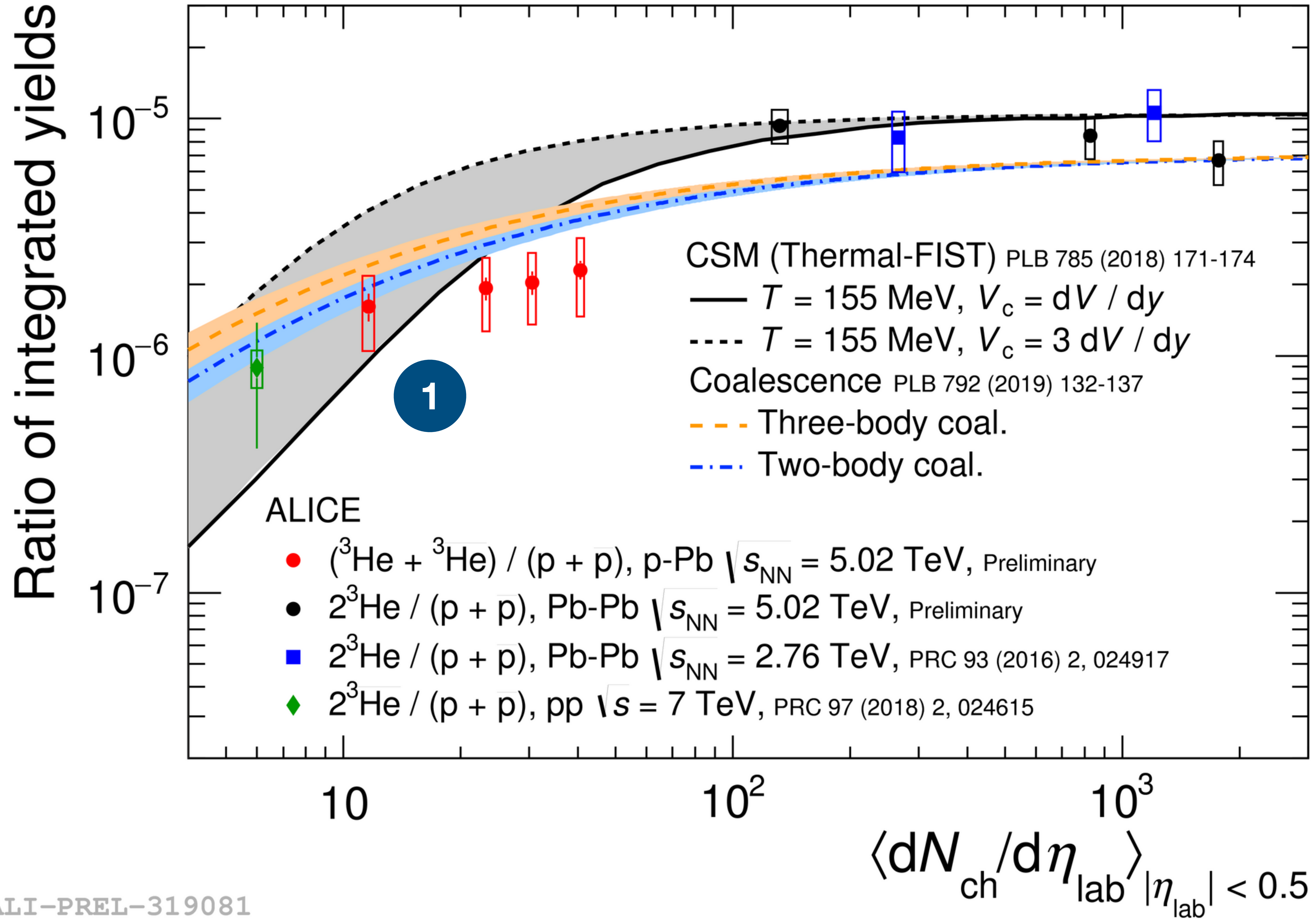

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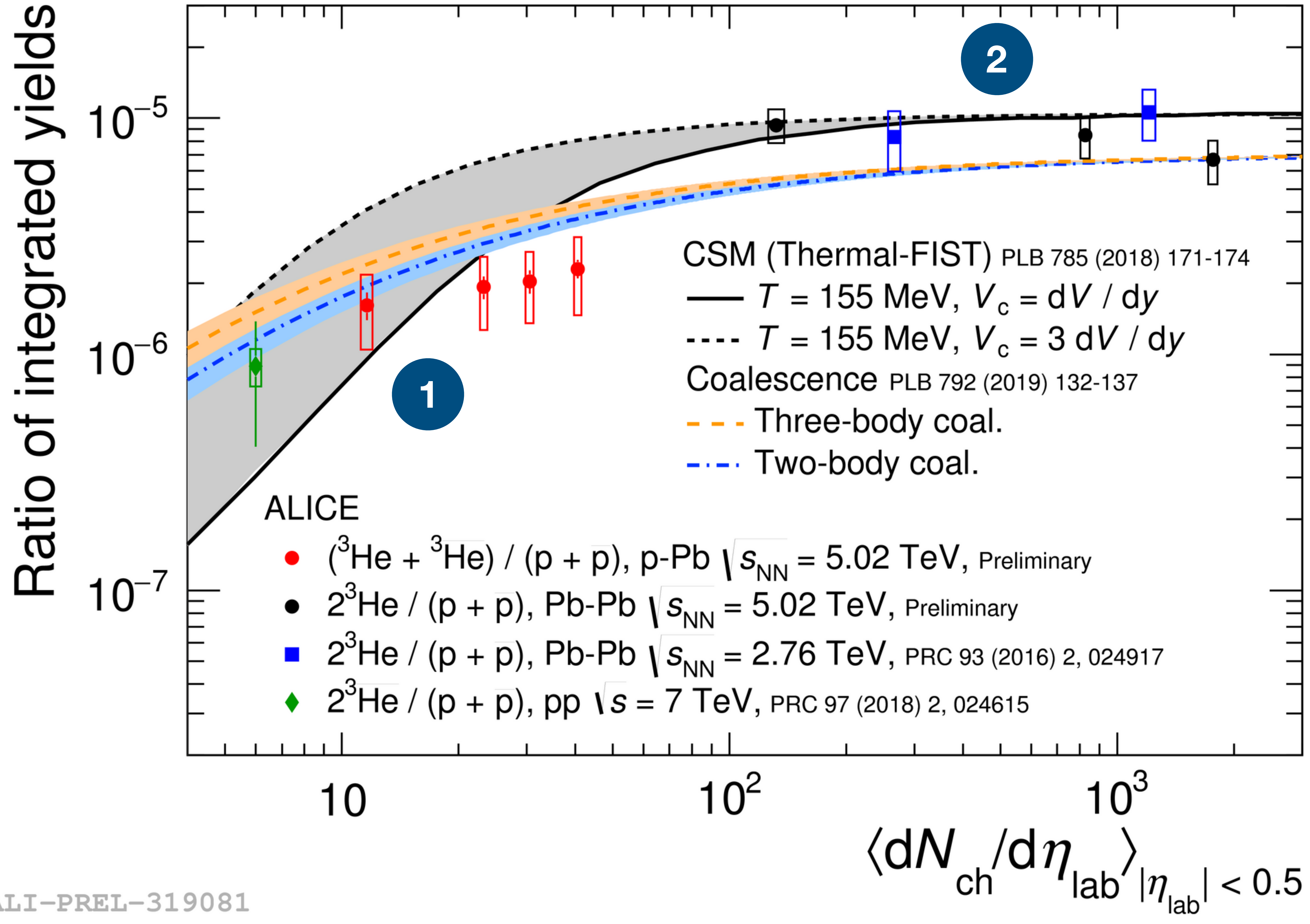
    - Coalescence: **small phase space**
2. **flat:** at high multiplicity there is no dependence of the ratio on the multiplicity, in agreement with the predictions of the **thermal model** and **coalescence**



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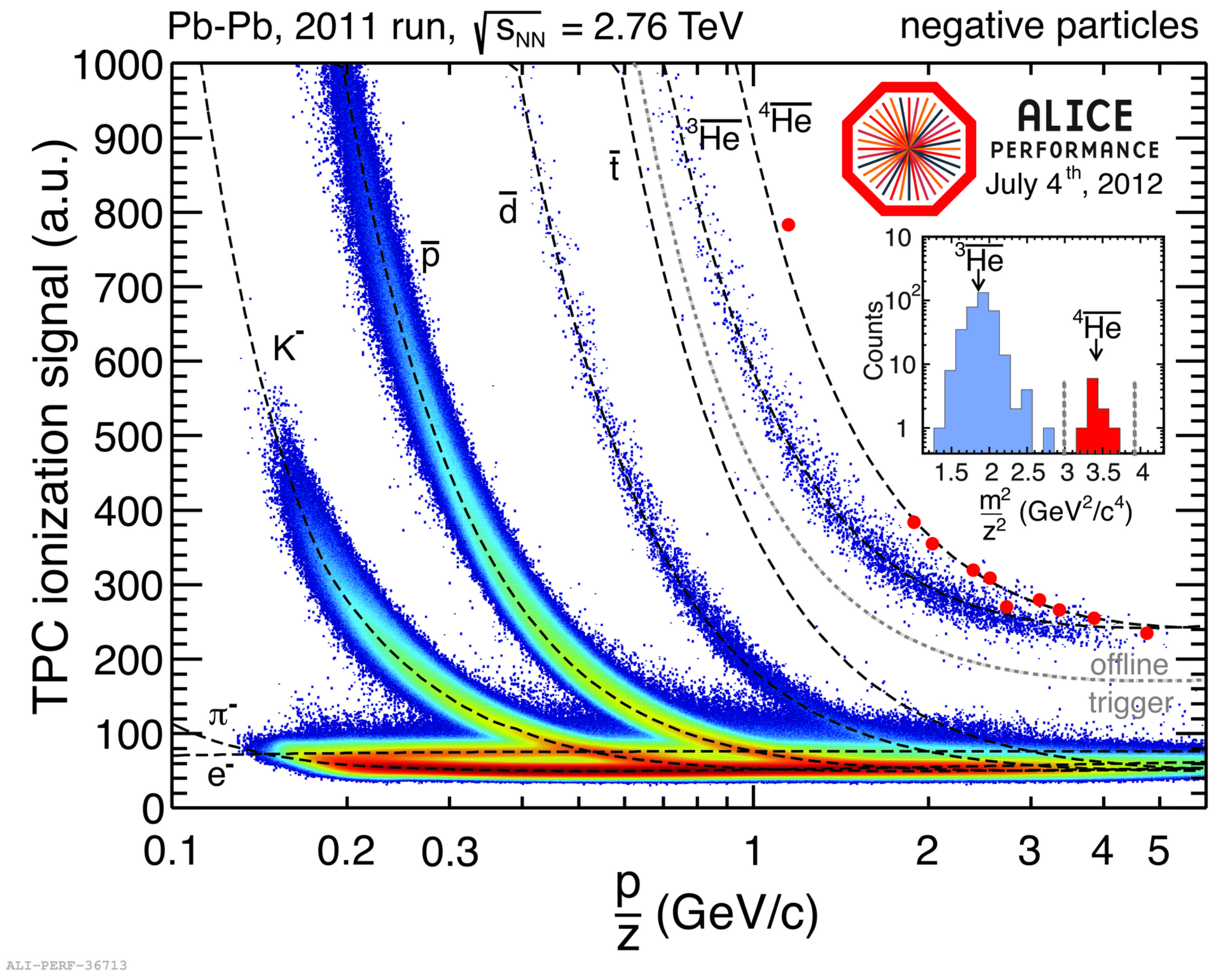
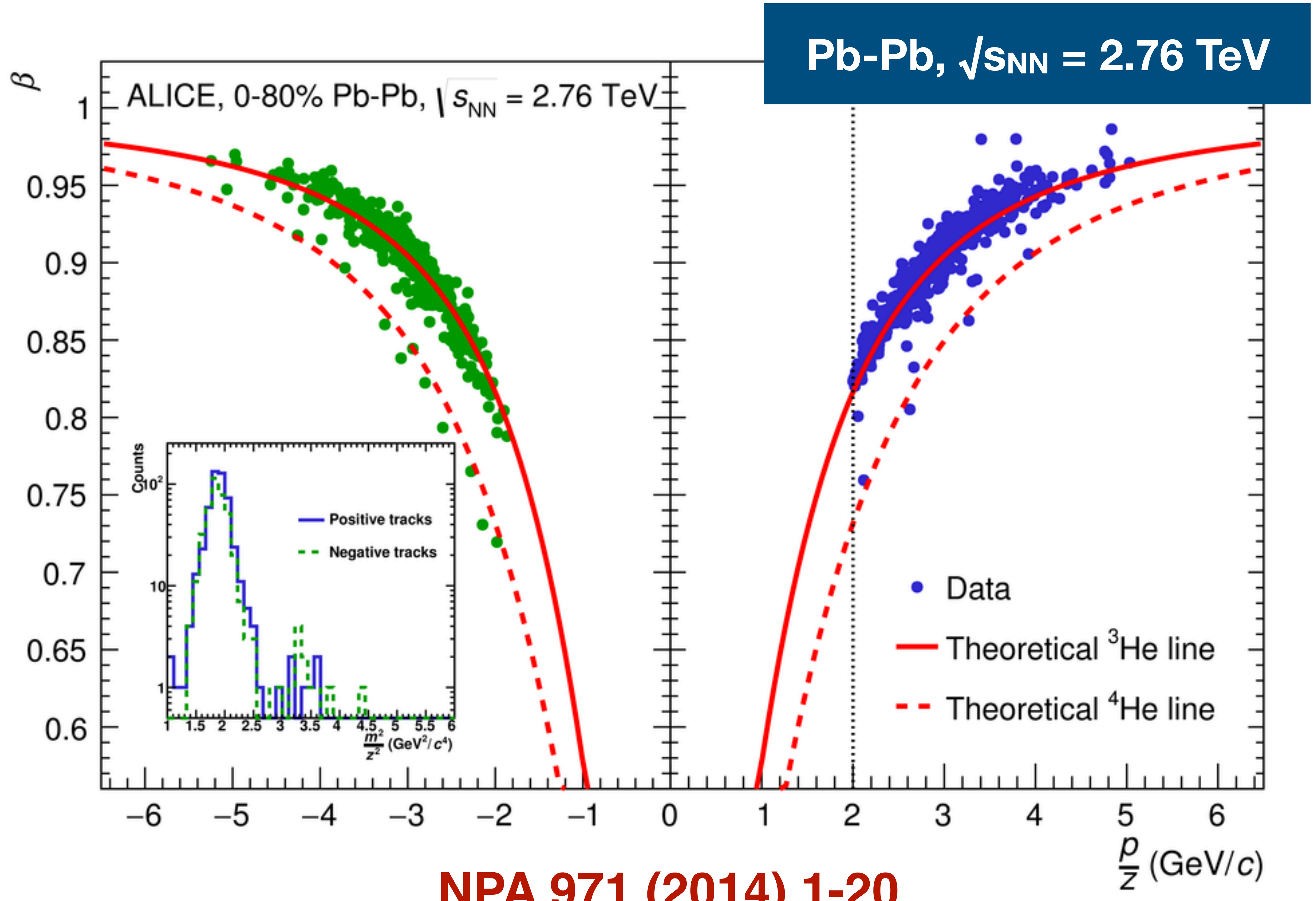
(Anti-)^{4}He in Pb-Pb





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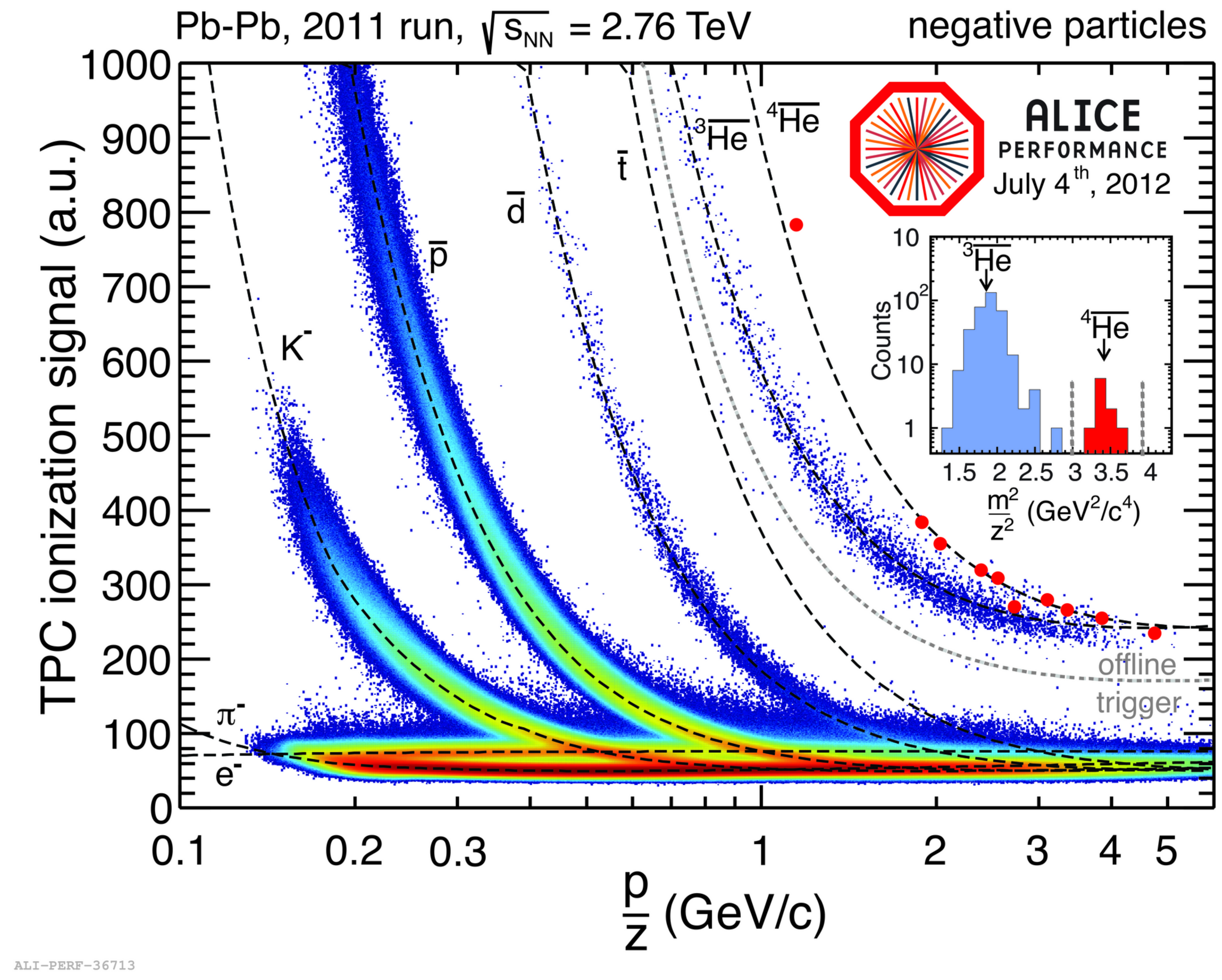
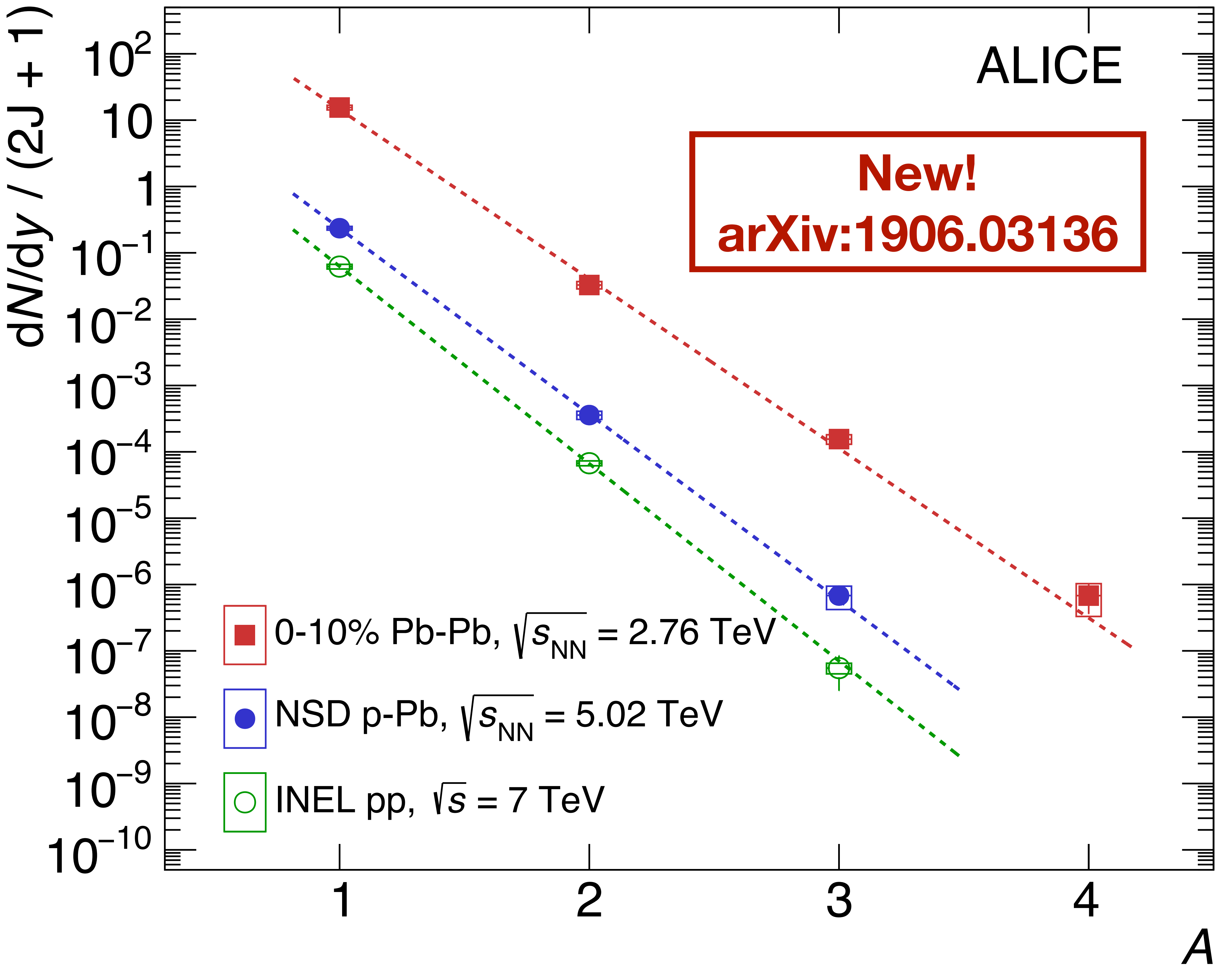
- The **(anti-)^{4}He** yield has been measured in Pb-Pb collisions

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





- The **(anti-)^{4}He** yield has been measured in Pb-Pb collisions
- The **exponential decrease** in the particle rate predicted by the **thermal model** is confirmed:
  - **Penalty factor** of **~300** for each additional nucleon in **Pb-Pb**
  - **Larger** penalty factor in **p-Pb** (**~600**) and **pp** collisions (**~1000**)

Conclusions

- ALICE has measured the production of light (anti-)nuclei in different collision systems and at different energies
- The measurements of **B_A** and of **d/p** of **^{3}He/p** as a function of multiplicity suggest a **common production** mechanism that depends only on the **system size**
- The **simple coalescence** model can explain both the evolution of **B_A** and of **d/p** and of **^{3}He/p** with multiplicity.
- With a **canonical approach** for small systems, also the **thermal model** can describe the evolution of **d/p** and **^{3}He/p** with multiplicity.
- **More data** and **more precise model calculations** are needed to understand the production of light (anti-)nuclei in high energy physics.

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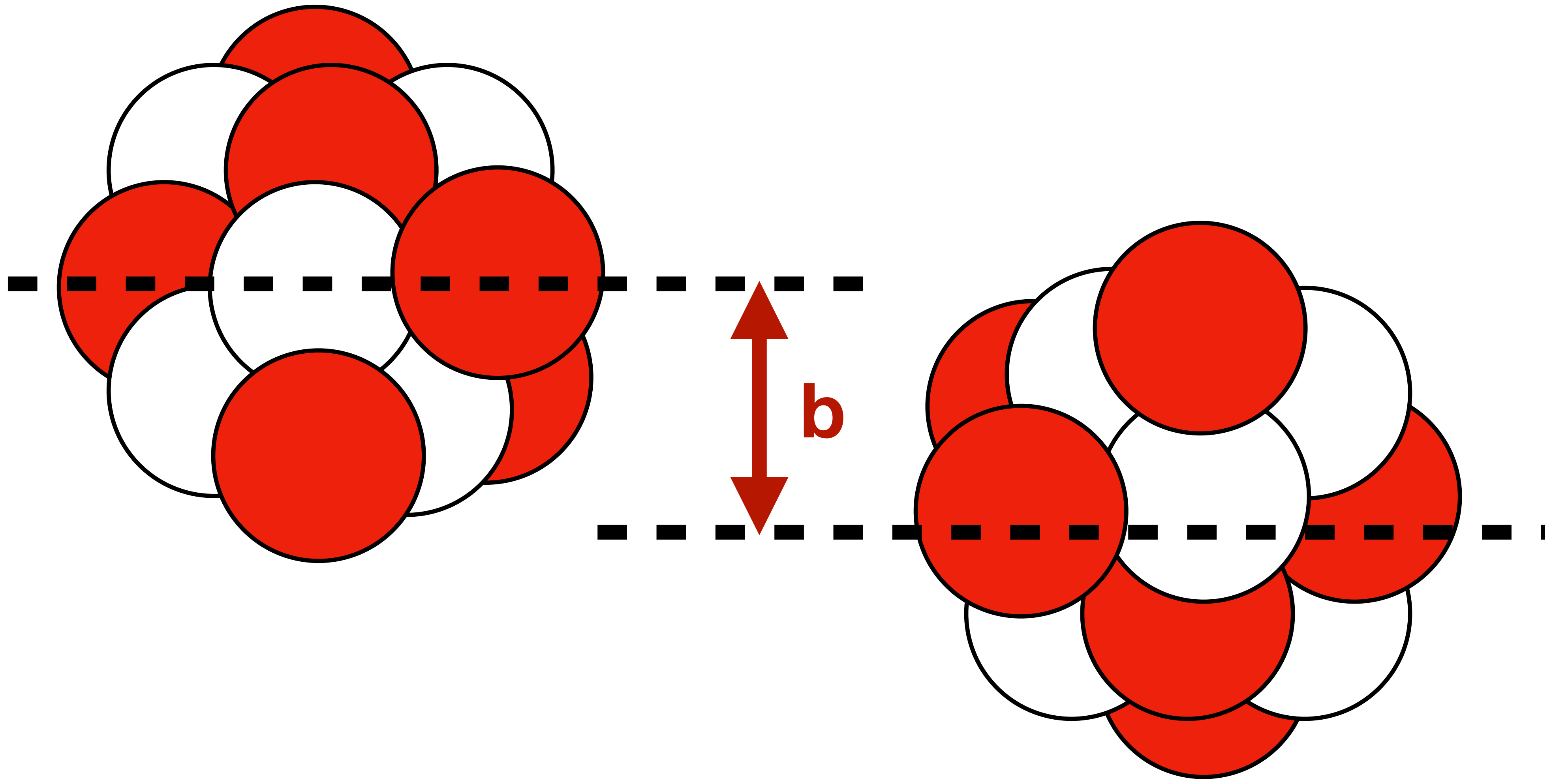
Thanks for your attention!

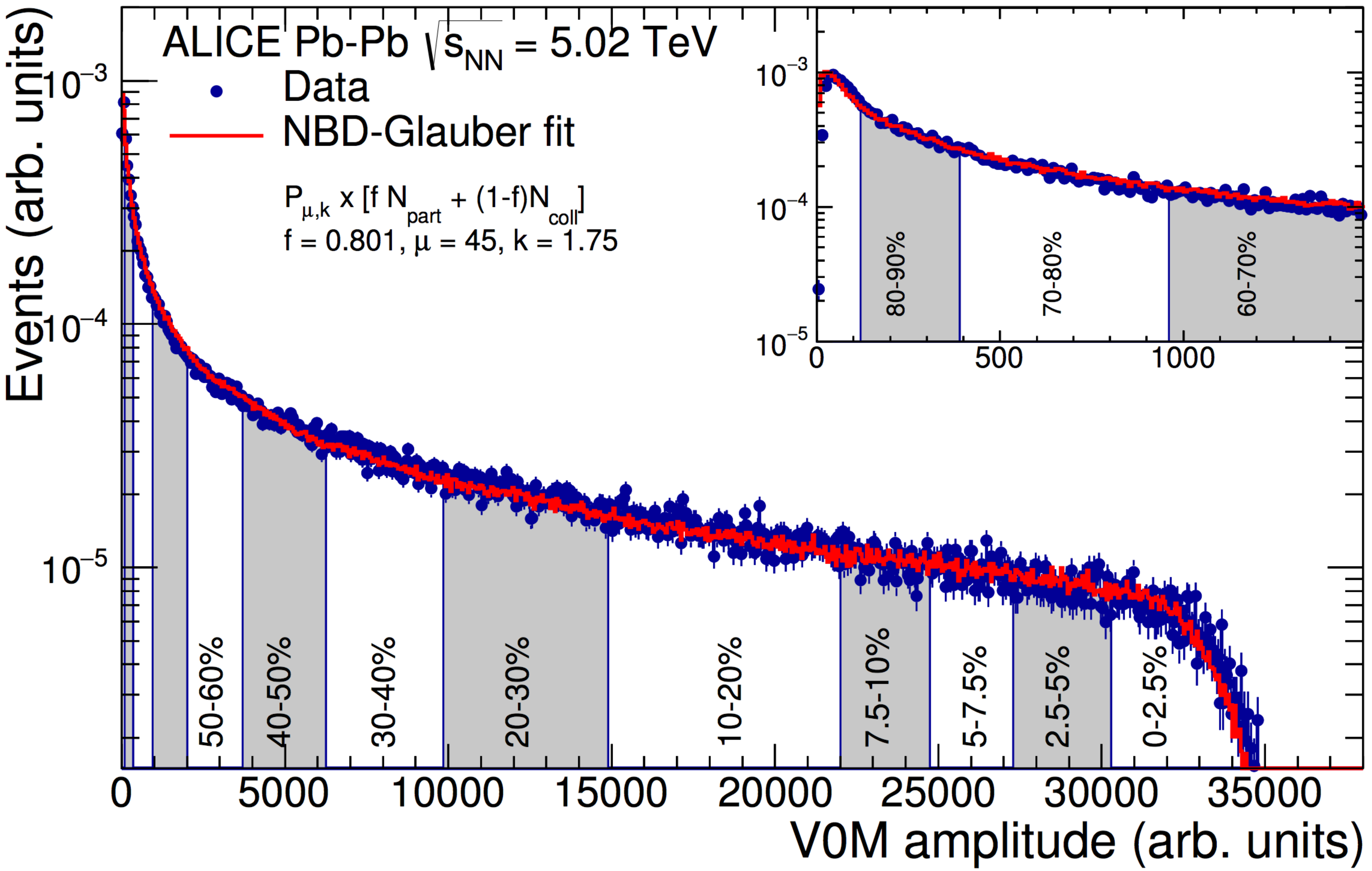
Backup

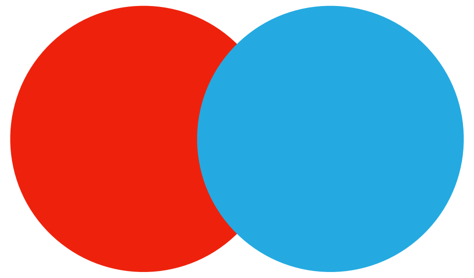
Centrality determination

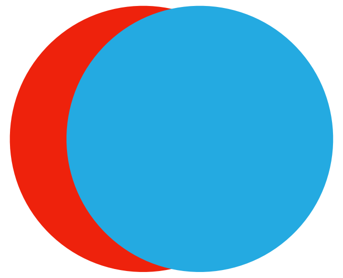
- The centrality if a Pb-Pb collision is described by the impact parameter **b**
- The estimation of the impact parameter is obtained from the track multiplicity, fitting the data with the predictions of the **Glauber model**



ALICE, ALICE-PUBLIC-2015-008 (2015)

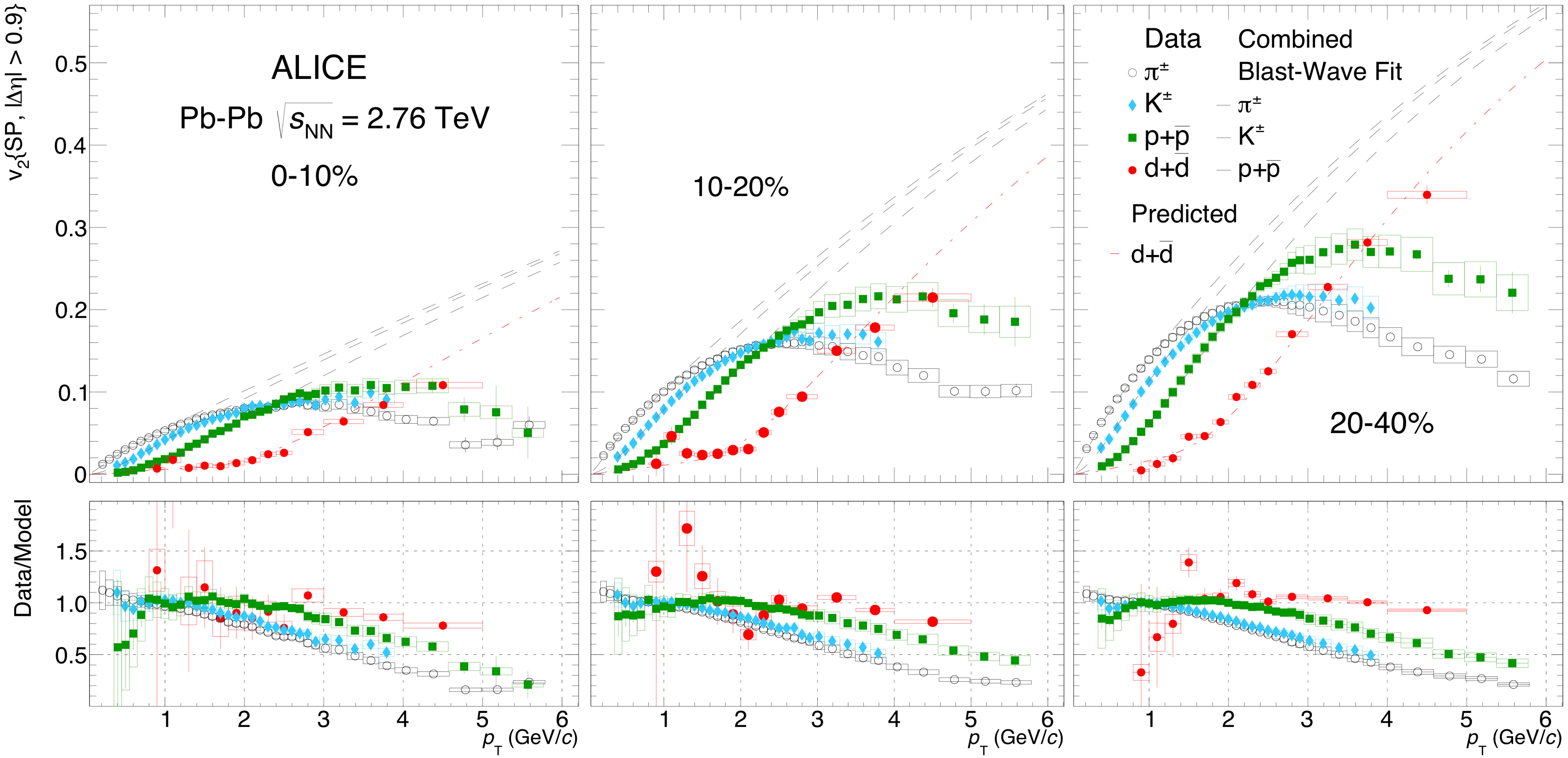






Nuclei v_2 in Pb-Pb

Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV



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- The v_2 of the deuteron is compatible with the prediction of the **Blast-Wave** model, obtained scaling the BW fits to the π/K/p spectra to the mass of the deuteron
  - **Hint of a common thermal production**

v_2 computed with the scalar product method

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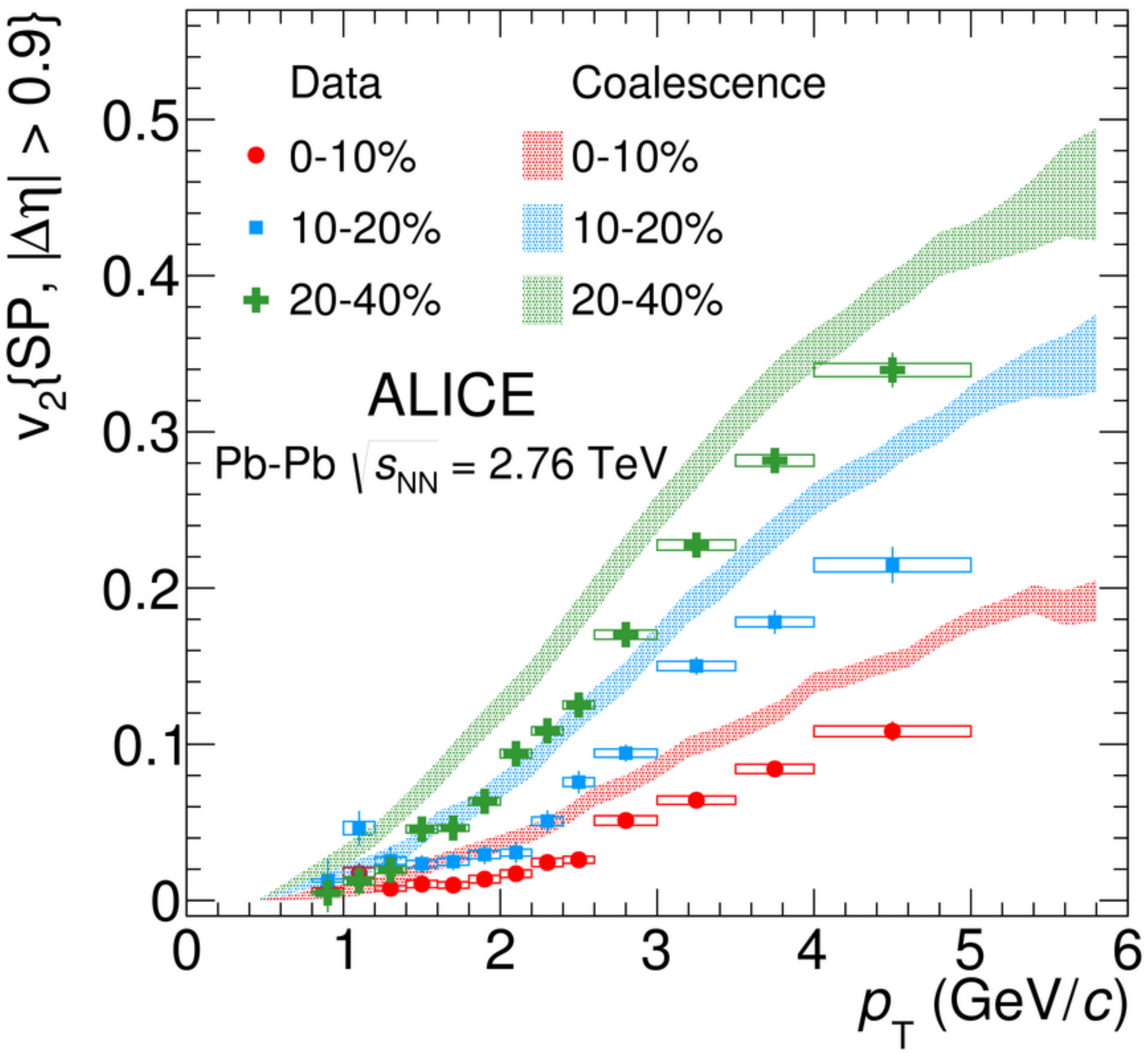


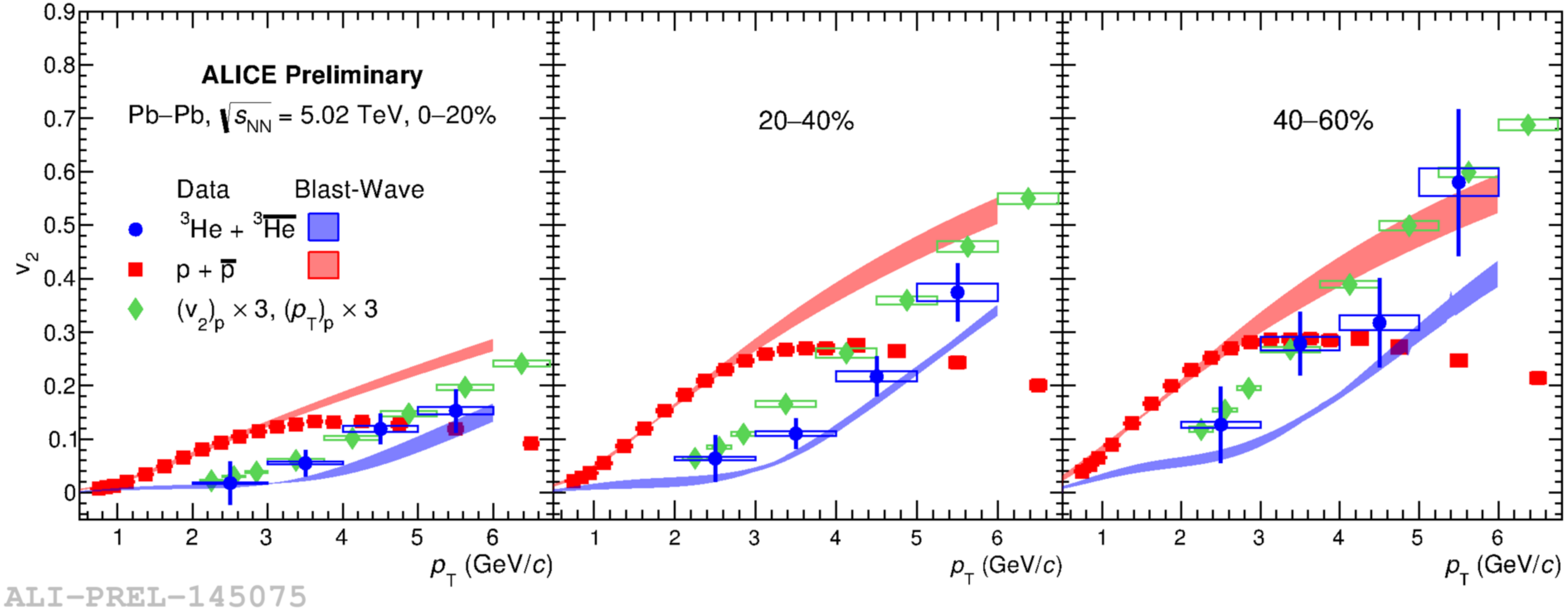
ALICE, Eur. Phys. J. C77 (2017) 658

- The v_2 of the deuteron is compatible with the prediction of the **Blast-Wave** model, obtained scaling the BW fits to the π/K/p spectra to the mass of the deuteron
  - **Hint of a common thermal production**
- The **simple coalescence** model does **not describe** the v_2 of the deuterons

v_2 computed with the scalar product method

Nuclei v_2 in Pb-Pb

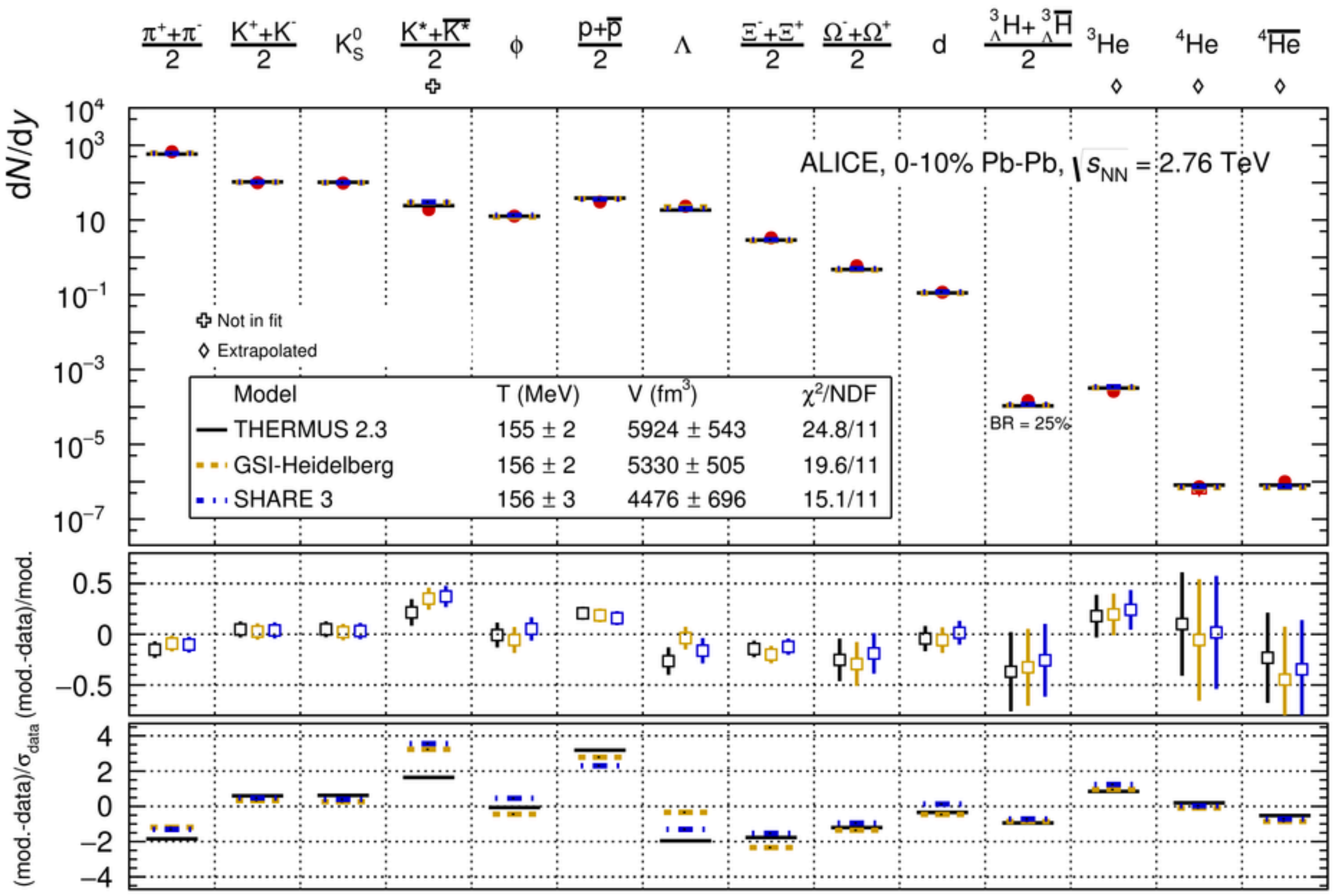
Pb-Pb, $\sqrt{s_{NN}}$ = 5 TeV



v_2 computed with the event-plane method

- The prediction of the **Blast-Wave** model, obtained scaling the BW fits to the π/K/p spectra to the mass of the ^{3}He, does **not** seem to **reproduce** the data at **low centrality**
- The **simple coalescence** prediction (green points) seems to show a slightly **better agreement** to the measurement
  - **More data is needed** to distinguish between the two models

Thermal fit - Pb-Pb @ $\sqrt{s_{NN}}$ = 2.76 TeV



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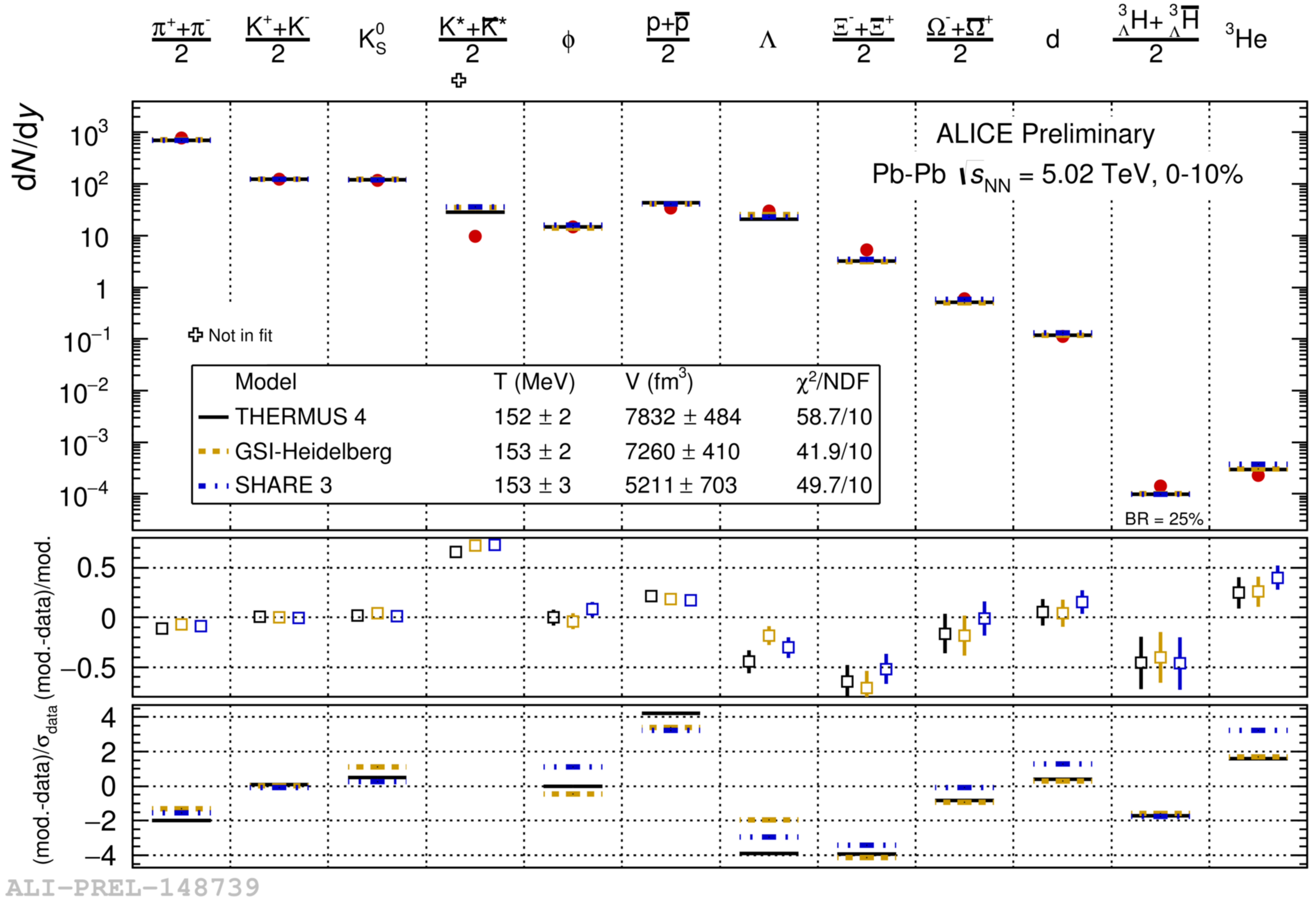
- The thermal model describes the production yields d*N*/dy in Pb-Pb collisions over a wide range of d*N*/dy (7 orders of magnitude)
- Also the yields of the nuclei are well reproduced
  - nuclei are thermally produced in the hadronisation, together with the other particle species

Thermal fit - Pb-Pb @ $\sqrt{s_{NN}}$ = 5 TeV



- In Run2 the uncertainties on the particle yields have been reduced, thanks to a larger data sample and to the improvement in the analysis techniques
- Although describing qualitatively well the particle yields, there is less agreement between the thermal model prediction and the particle yields

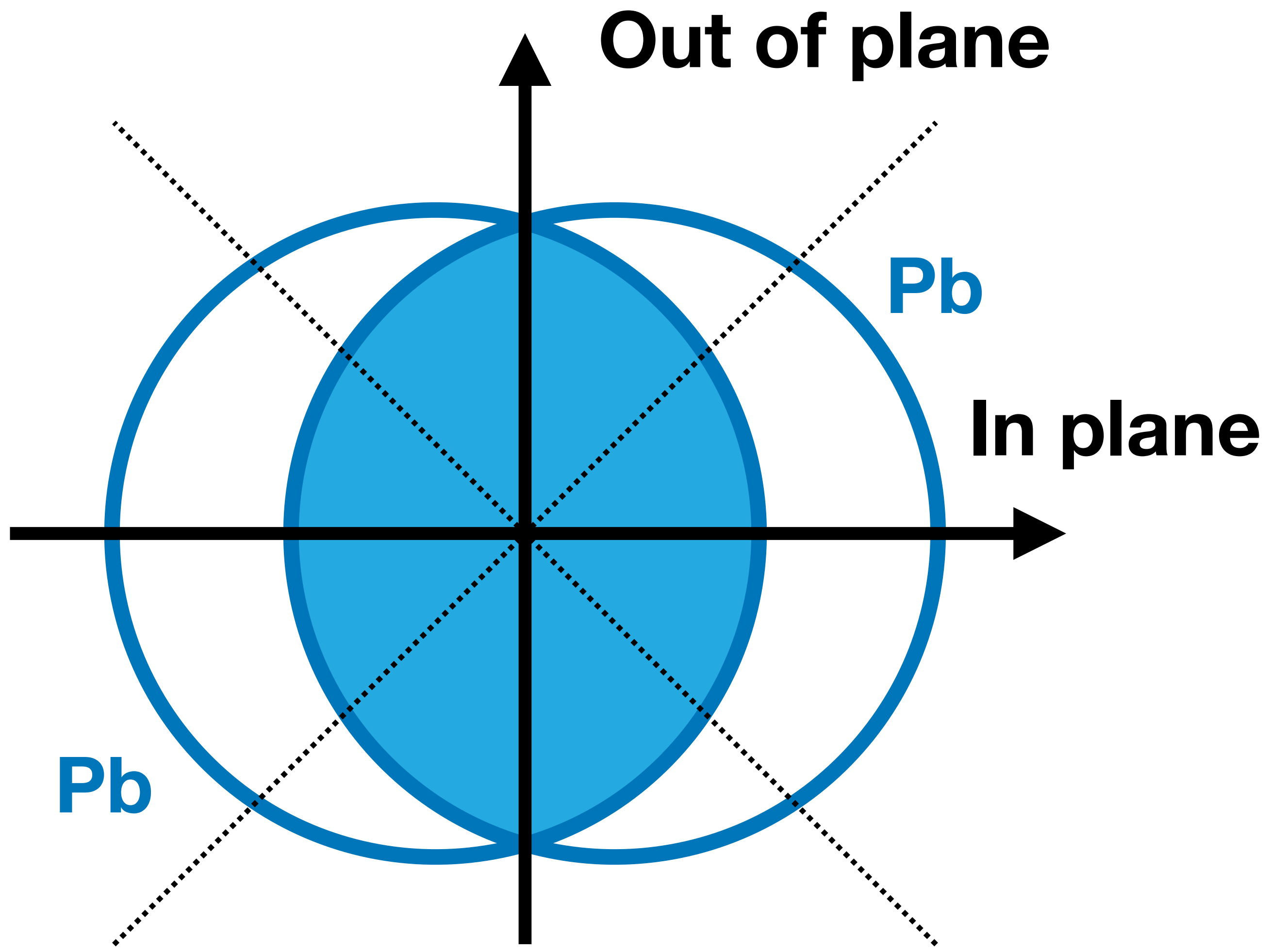
Methods for the v_2 computation

- **Event-Plane method:**

1. the Event Plane is reconstructed and taken as the estimator of the reaction plane
2. v_2 is computed as:

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

where R_2 is the event plane resolution



- **Scalar product method:**

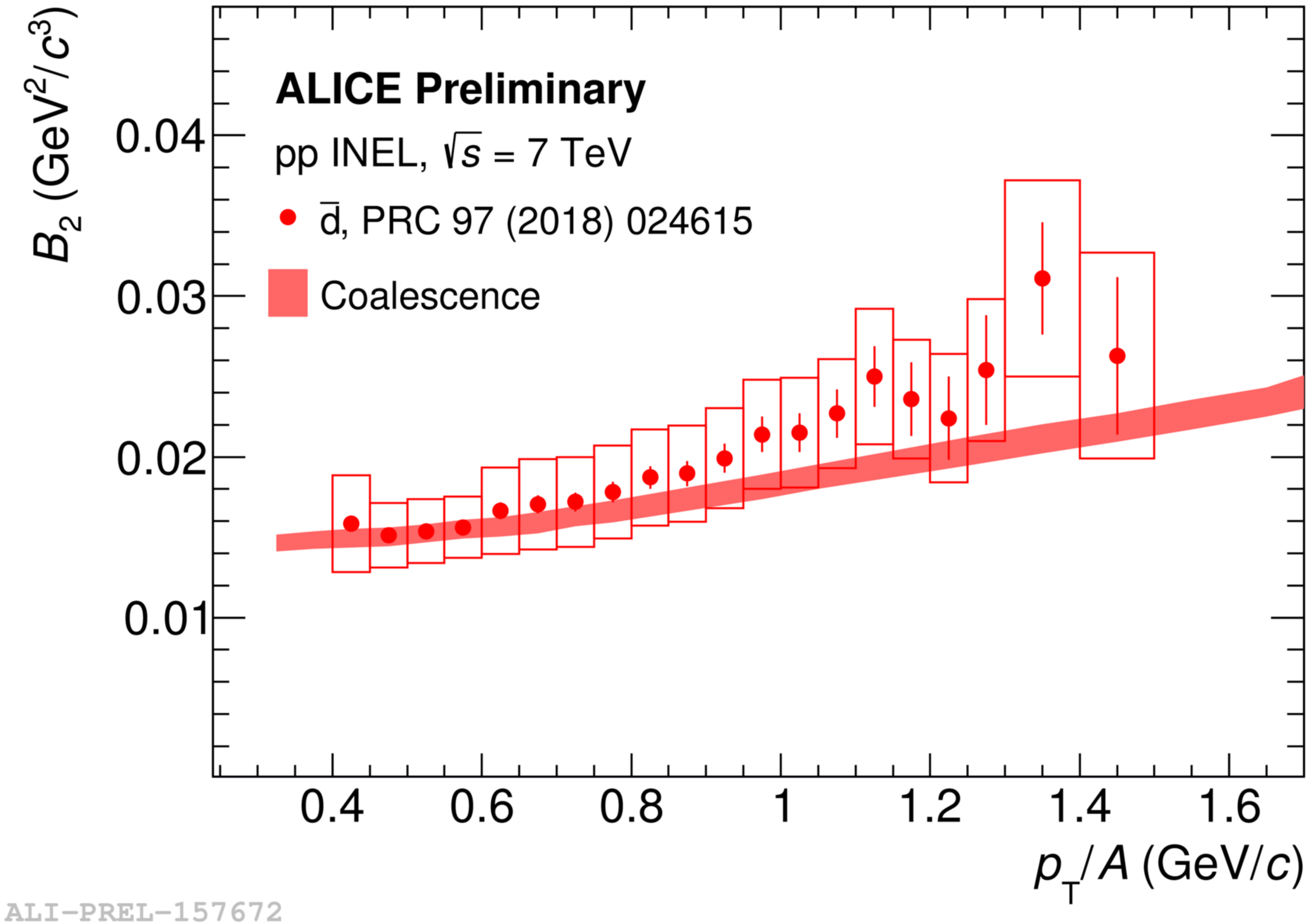
1. Particles measured by V0A ($2.8 < \eta < 5.1$) and V0C ($-3.7 < \eta < -1.7$) as reference.
2. v_2 is computed as:

$$v_2\{SP\} = \frac{\left\langle u_{2,i}\left(p_{\mathrm{T}}, \eta\right) \cdot \frac{Q_2^*}{M} \right\rangle}{\sqrt{\left\langle \frac{Q_{2,A}^*}{M_A} \cdot \frac{Q_{2,B}^*}{M_B} \right\rangle}}$$

where:

- $u_{2,i}$ is the momentum unit vector
- Q_2 is the flux vector
- M is the multiplicity
- A, B are two subevents

Multiplicity integrated B_2



ALI-PREL-157672

- A rising in the multiplicity integrated B_2 as a function of p_T can be obtained even if the B_2 of all the multiplicity classes is flat in p_T
- Indeed, a consistent change in the proton spectra with the multiplicity determines a mathematical bias in the computation of the multiplicity integrated B_2