Constraining the production mechanism of light (anti-)nuclei in small systems with ALICE at the LHC

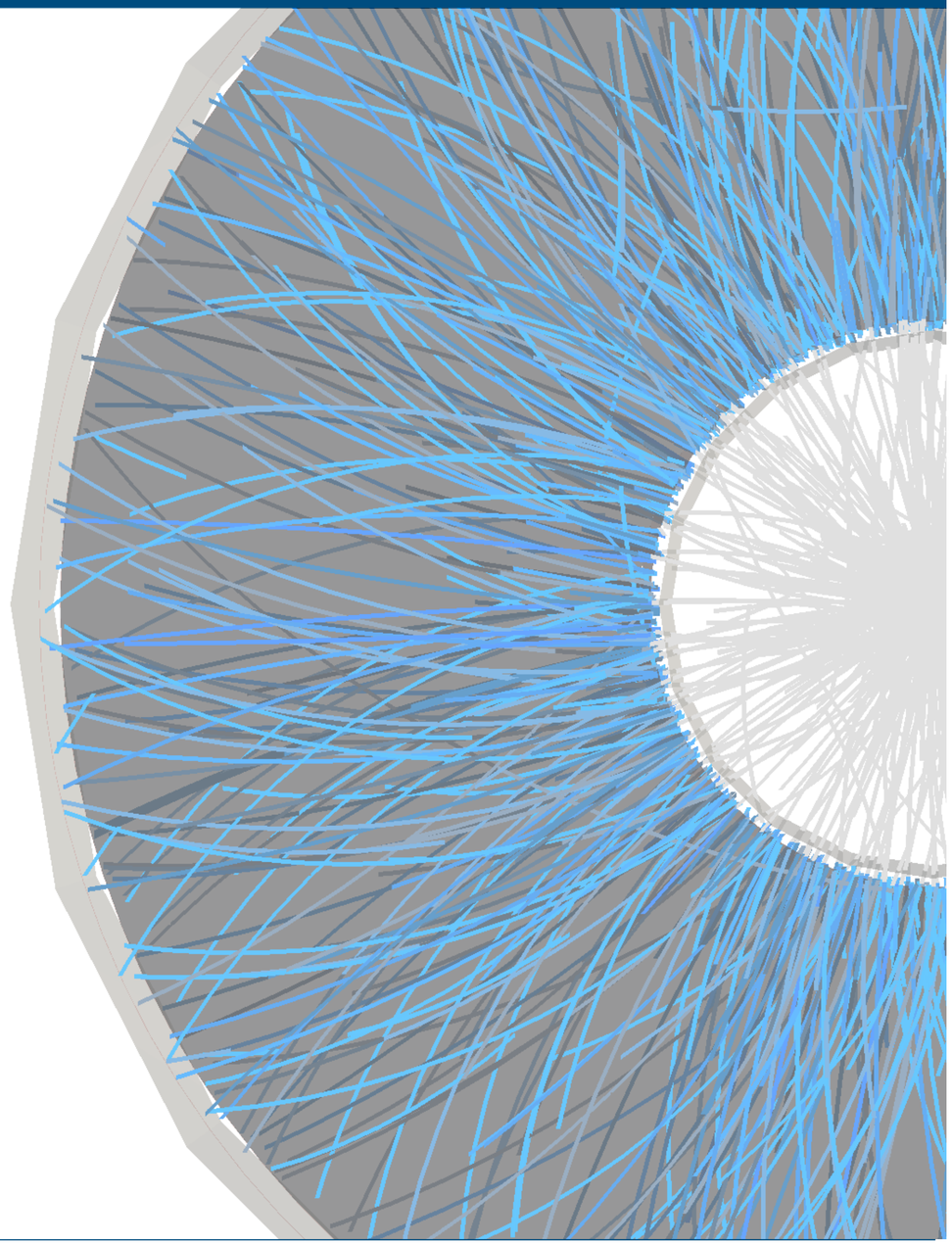
Luca Barioglio

University and INFN - Torino

on behalf of the **ALICE Collaboration**

Outline

- **Phenomenological models**
  - The **statistical hadronisation** model
  - The **coalescence** model



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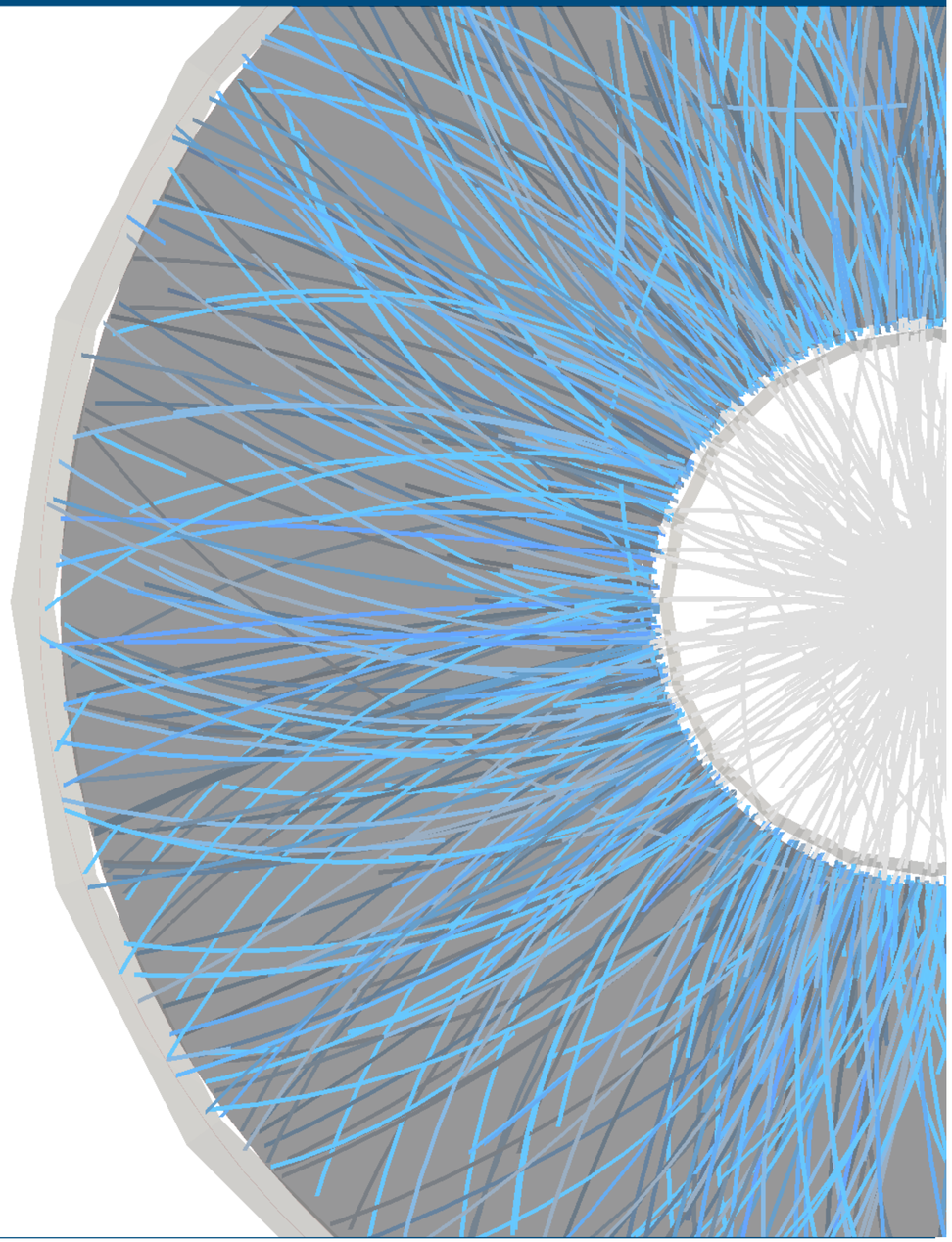
  - **Identification** of nuclei



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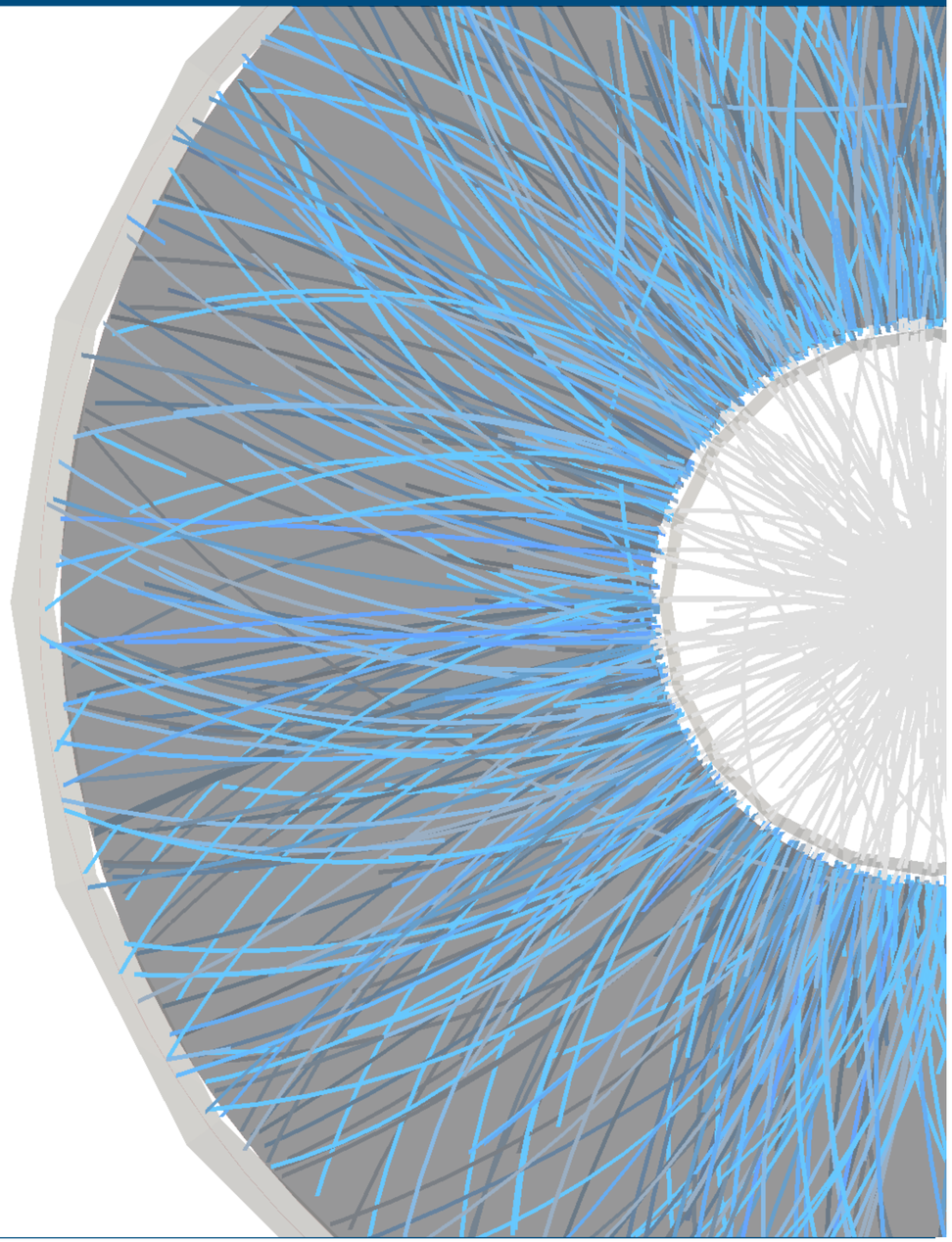

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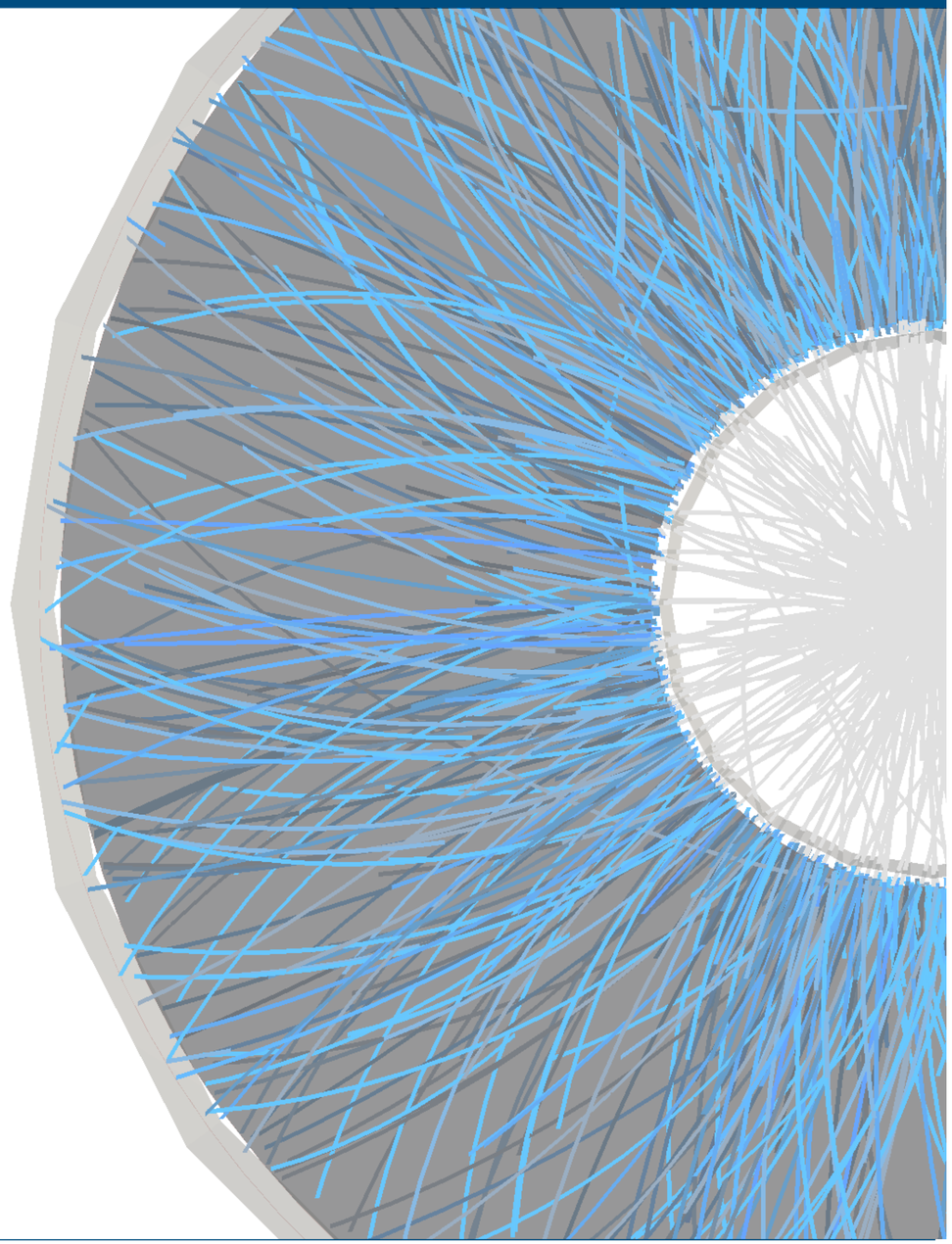
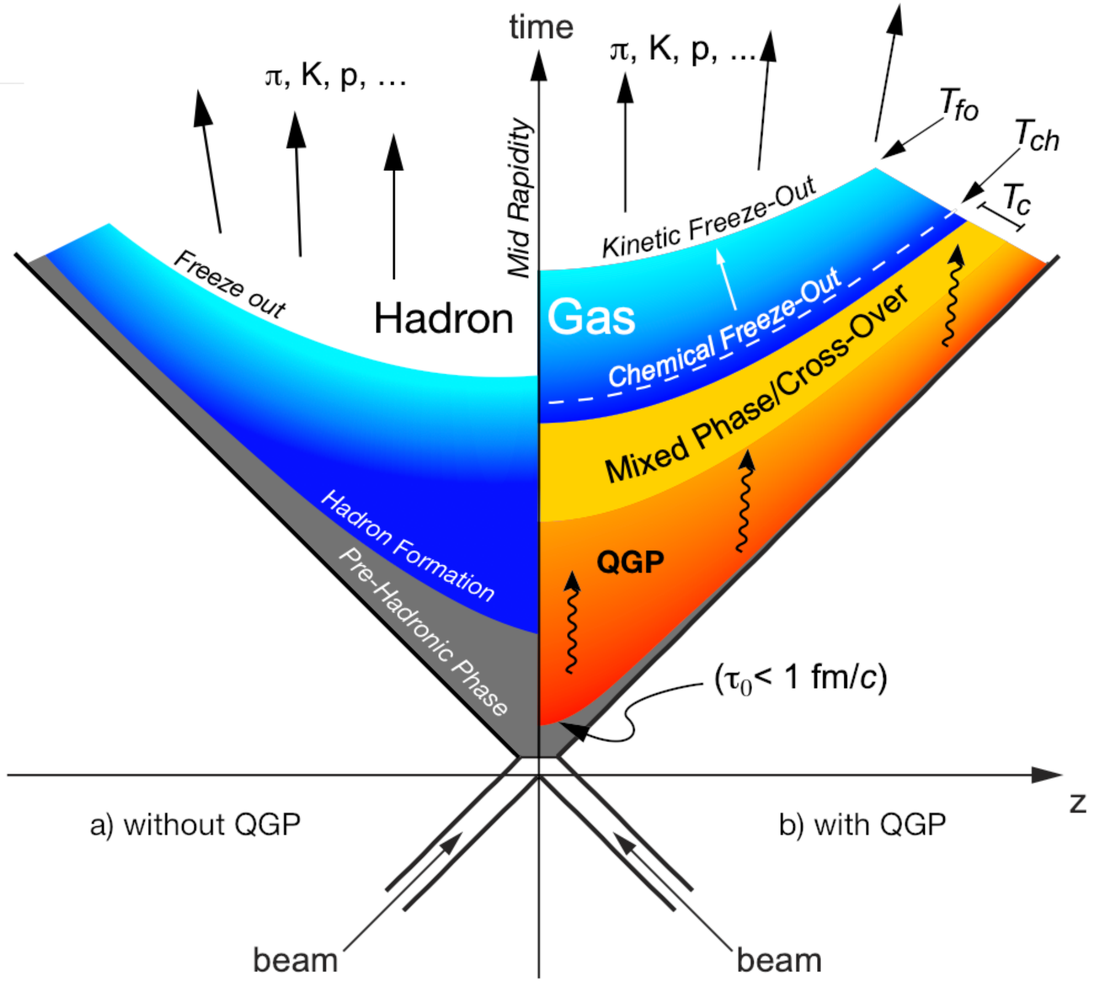
- **(Anti-)nuclei** production:
  - **p_T spectra** in pp and p-Pb collisions
- Testing the models
  - Coalescence parameter B_A vs multiplicity
  - **d/p** and **^{3}He/p** vs multiplicity



Nuclear matter production

- Light (anti-)nuclei are abundantly 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 hadronisation** model
  - the **coalescence** model

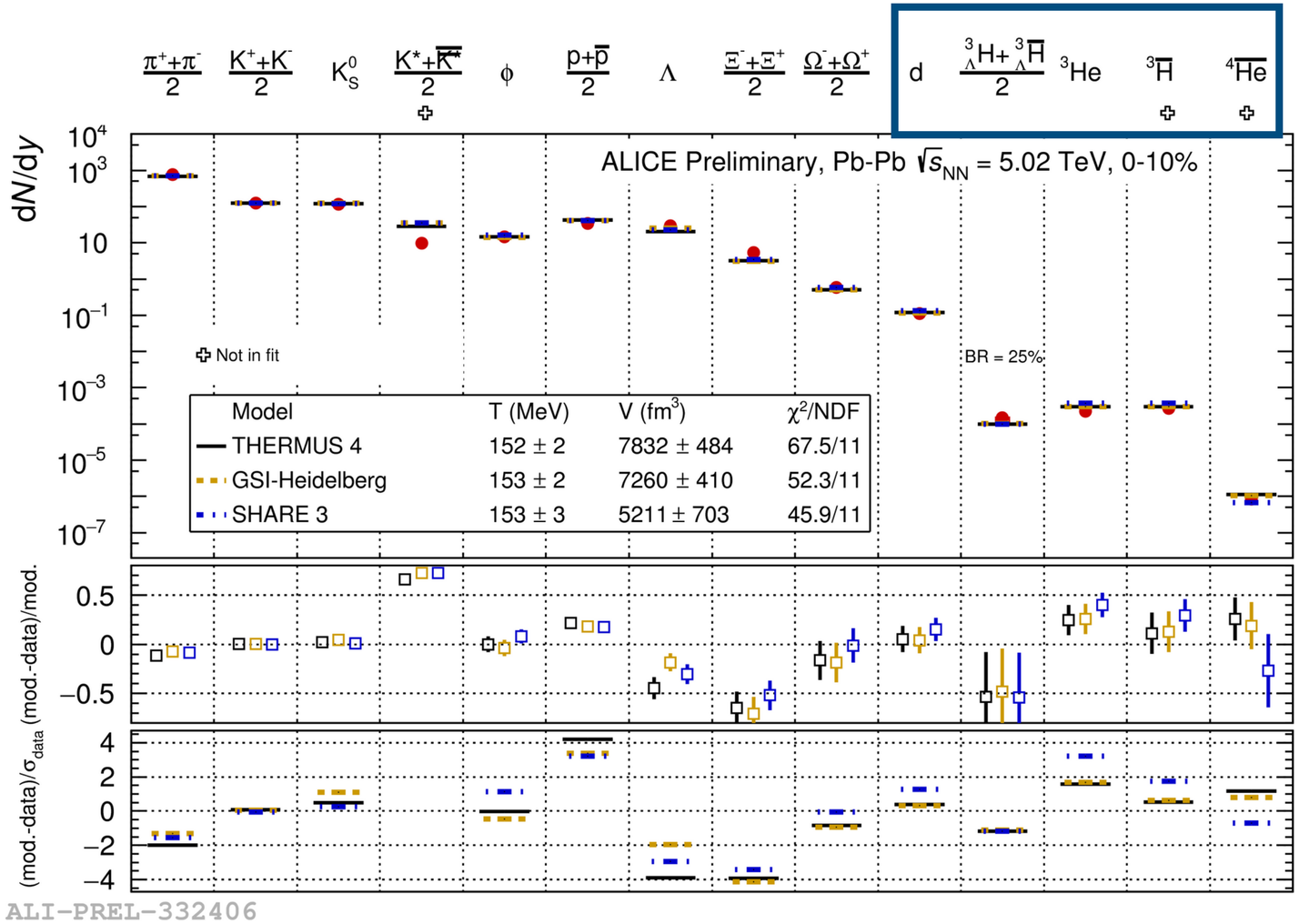


The Statistical Hadronisation Model (SHM)

- It assumes hadron abundances from **statistical equilibrium** at the **chemical freeze-out**
- The chemical freeze-out temperature (***T_{ch}***) is a key parameter:

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

- Large reaction volume ($VT^3 > 1$) in Pb-Pb collisions
  - **grand canonical ensemble**
- Production yields **d*N*/d*y*** in central Pb-Pb collisions described over a wide range of d*N*/d*y* (**7 orders of magnitude**), including nuclei
- In **small systems** ($VT^3 < 1$) a local conservation of quantum numbers (*S*, *Q* and *B*) is necessary
  - **canonical ensemble**



The coalescence model

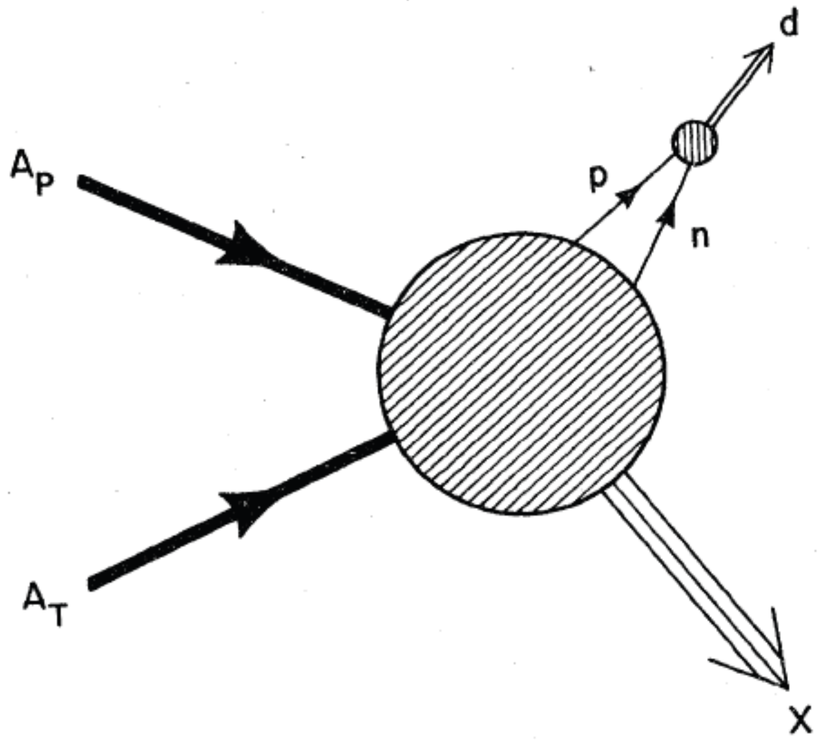
- Nucleons that are **close in the phase space** at the **freeze-out** can form a nucleus via **coalescence**
- The key concept is the overlap between the **nucleus wave-function** and the **phase space** of the **nucleons**
- The main parameter of the coalescence is the $\boldsymbol{B_A}$, defined as:

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

where:

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

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



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

The ALICE experiment

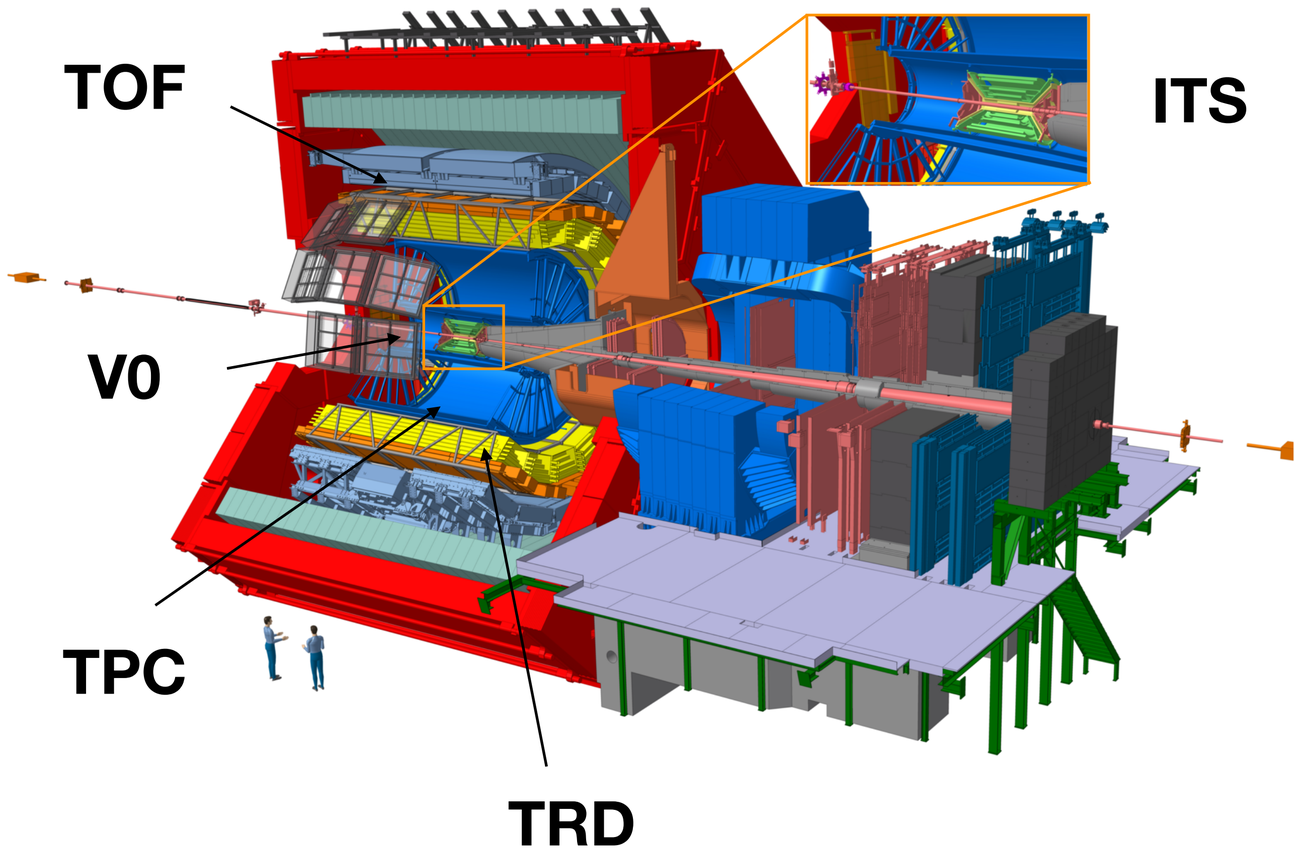
- General purpose heavy-ion experiment
  - 19 different sub-systems
  - Excellent particle identification (**PID**)
  - Most suited LHC experiment for studying the production of nuclei

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

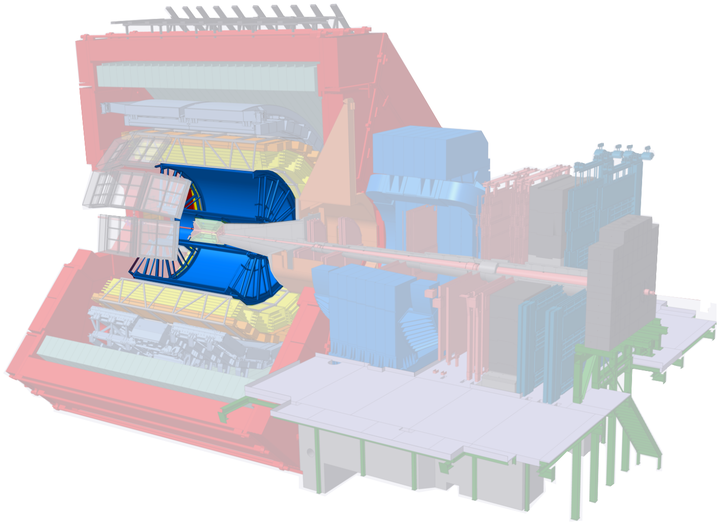
- **Tracking** and **Vertex** reconstruction
- $\sigma_{DCA_{xy}}$ **< 100 μm** for $p_T > 0.5$ GeV/c in Pb-Pb
  - Separation of **primary** and **secondary nuclei** (coming from material knock-out)

V0

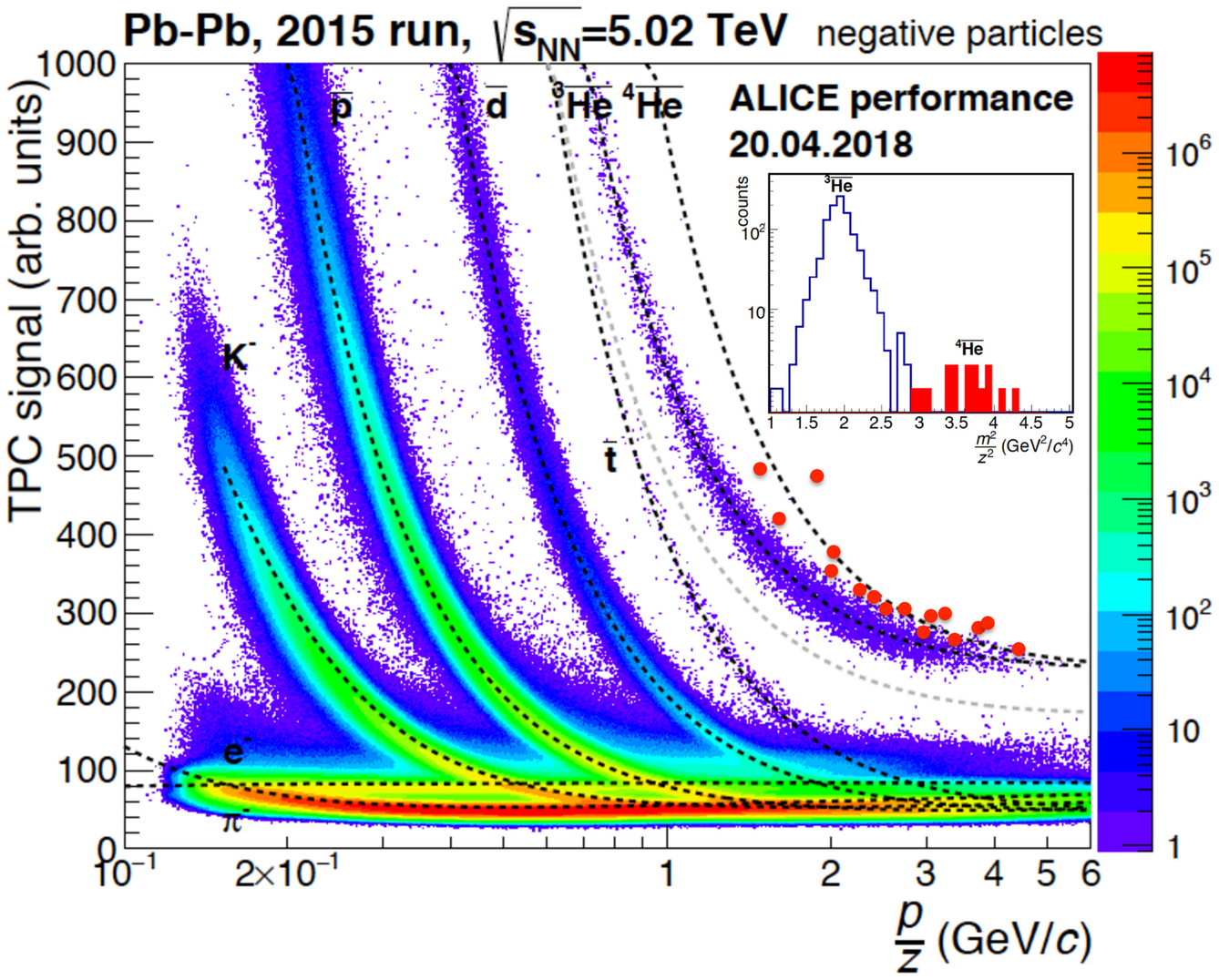
- **Multiplicity/centrality** determination



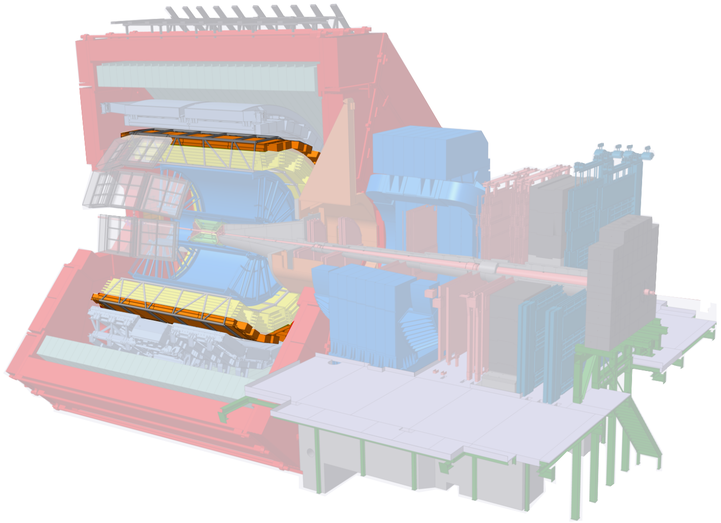
PID with the Time Projection Chamber



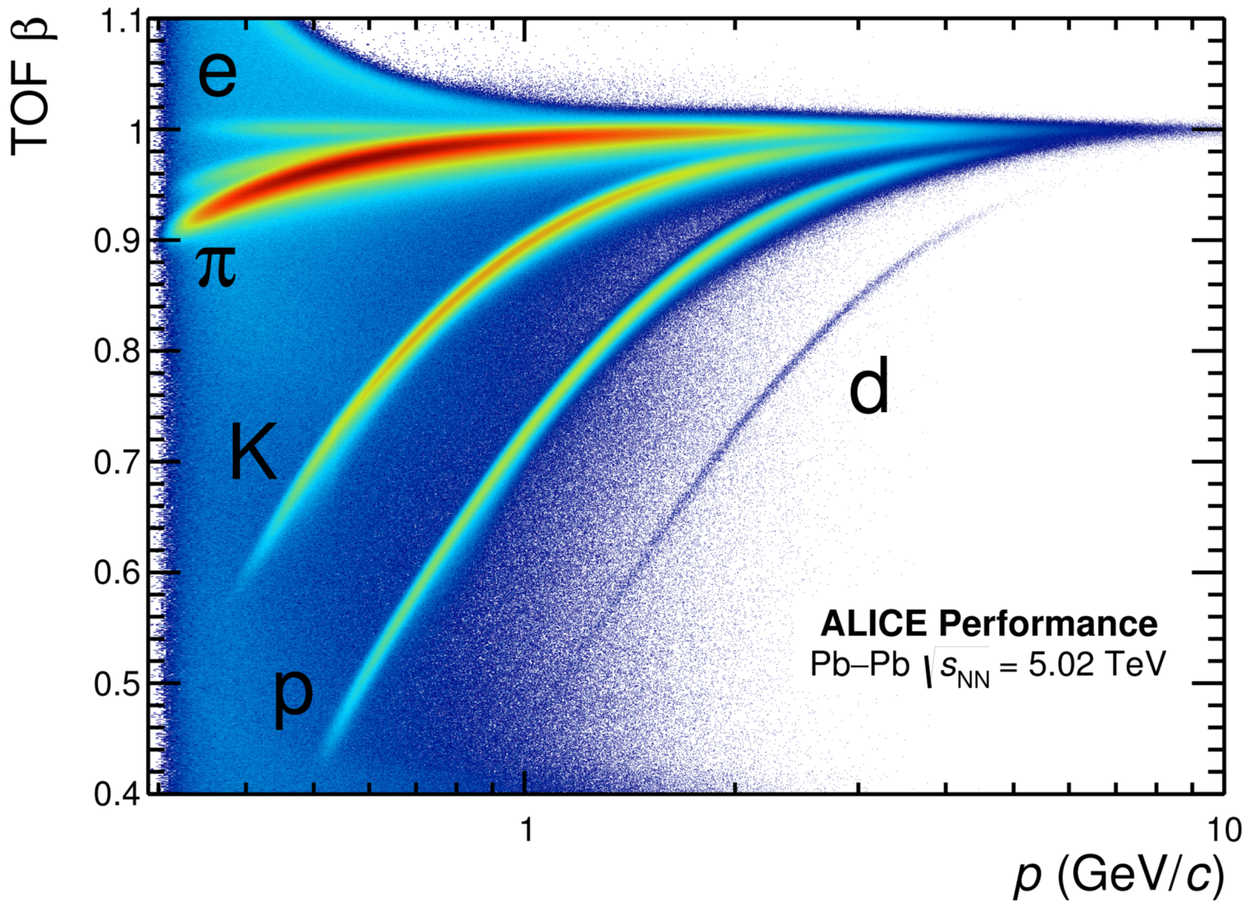
- **Tracking**
- **PID** via **d*E*/d*x*** measurement
  - $\sigma_{dE/dx}$ **~ 5.5%** (in pp collisions)
  - $\sigma_{dE/dx}$ **~ 7%** (in Pb-Pb collisions)
- Raw yields extracted for each p_T bin from the nσ distributions
- ^{3}He and ^{4}He well separated



PID with the Time Of Flight



- **PID** via **β** measurement
  - **$\sigma_{TOF\text{-}PID}$ ~ 60 ps** in **Pb-Pb** collisions
  - **$\sigma_{TOF\text{-}PID}$ ~ 70 ps** in **pp** collisions (lower precision on event collision time)
- Raw yields extracted for each p_T bin from the TOF mass spectra distribution



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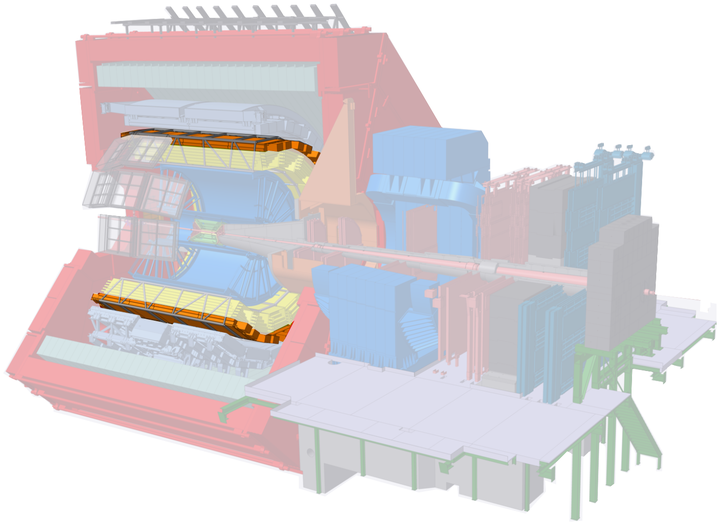

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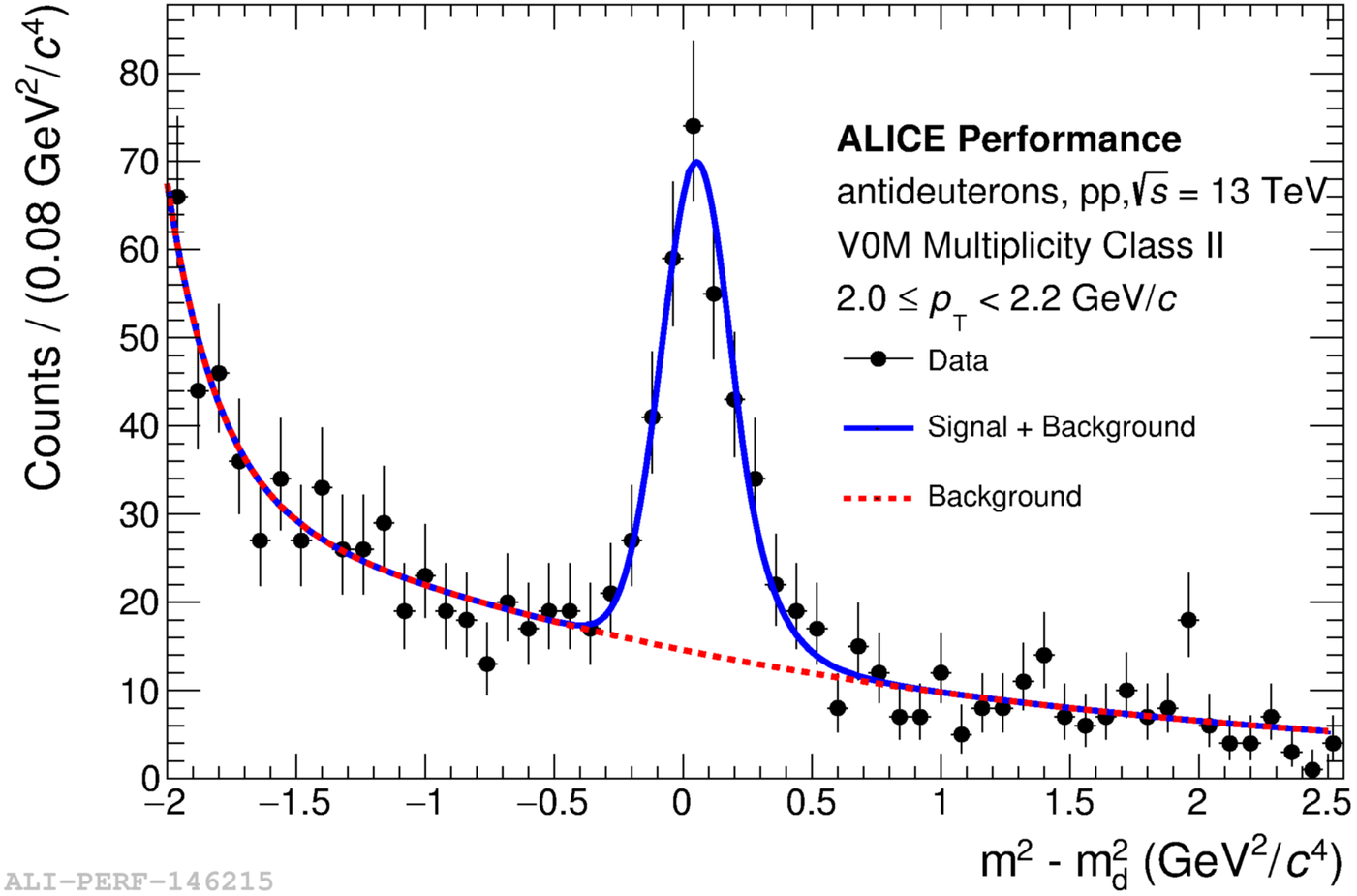
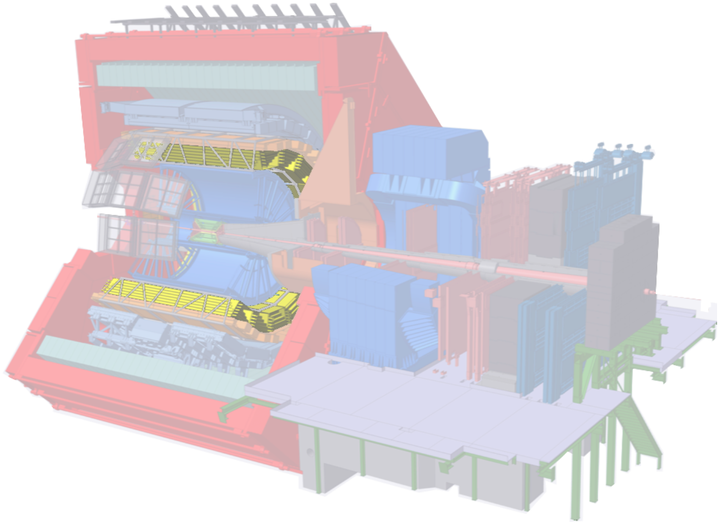
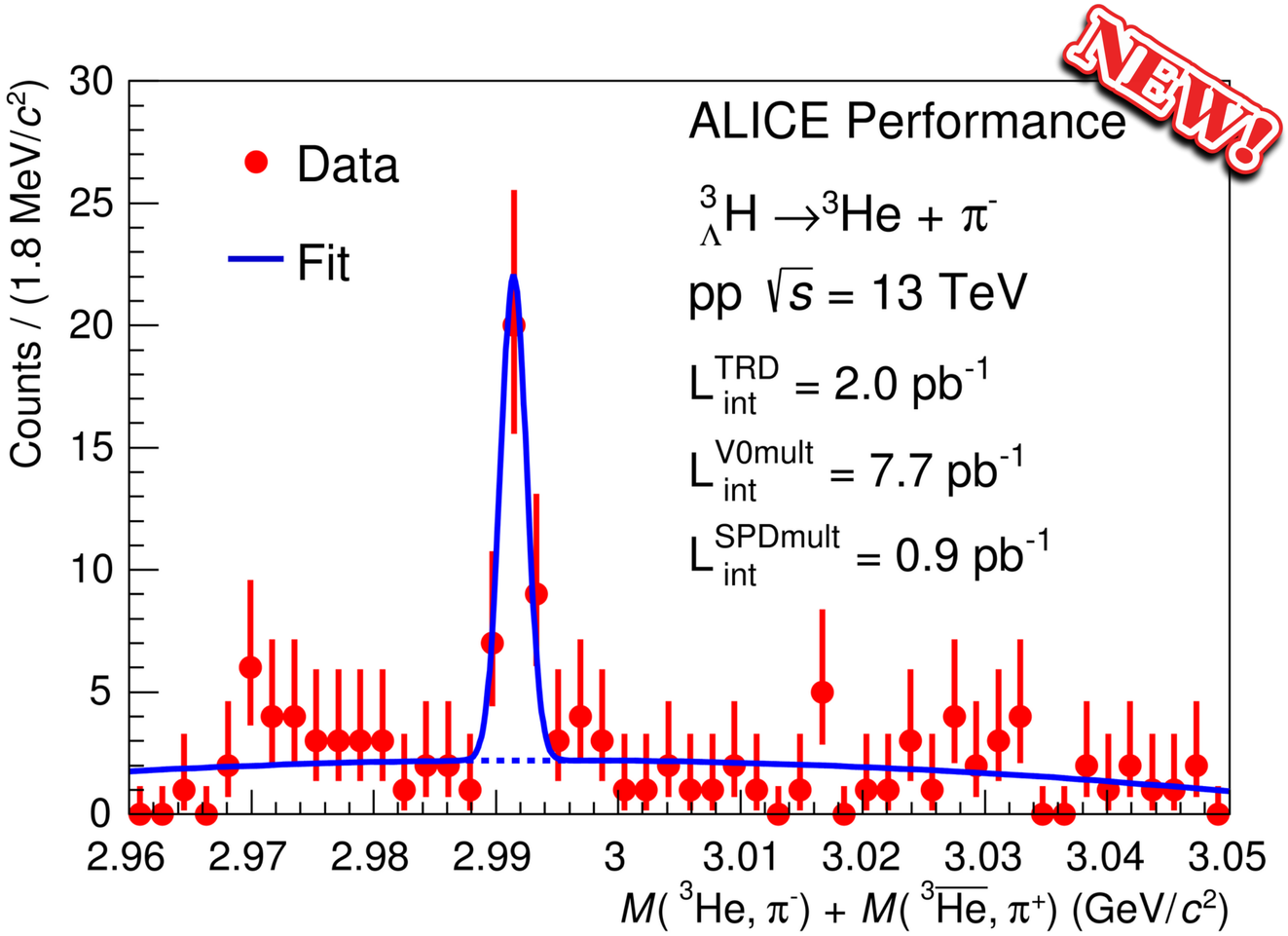


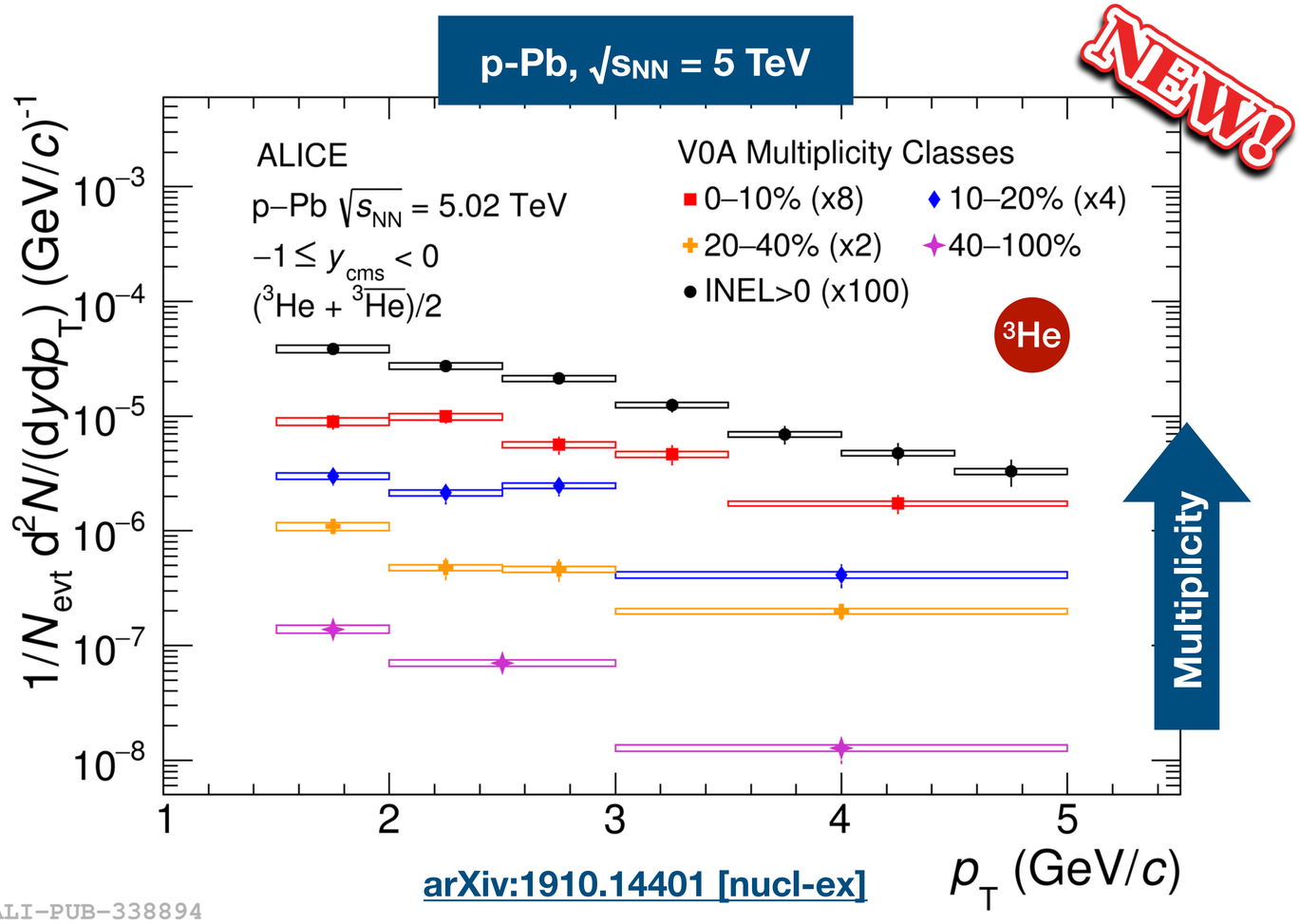
Trigger for nuclei with the Transition Radiation Detector



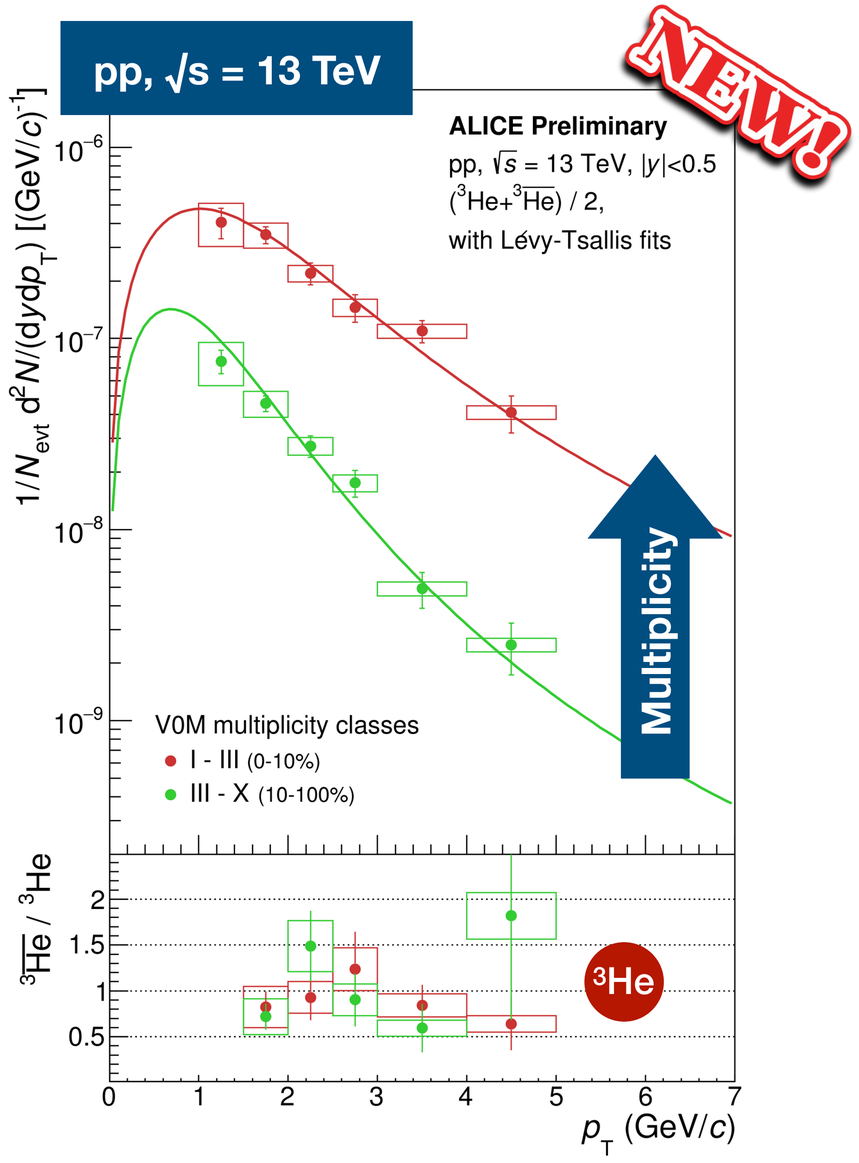
- **TRD** can be used as **trigger** for **nuclei**
  - Only events with a nucleus candidate are selected → **background reduced**
- With TRD trigger it is possible to measure:
  - **$^{3}_{\Lambda}$H** in **pp** collisions
  - **(anti-)^{4}He** in **pp** collisions (in the future)



^{3}He spectra in p-Pb and pp



arXiv:1910.14401 [nucl-ex]



- **^{3}He** p_T spectra measured in **pp**, **p-Pb** and Pb-Pb collisions
  - A comparison between different systems can be performed

^{3}H spectra in p-Pb

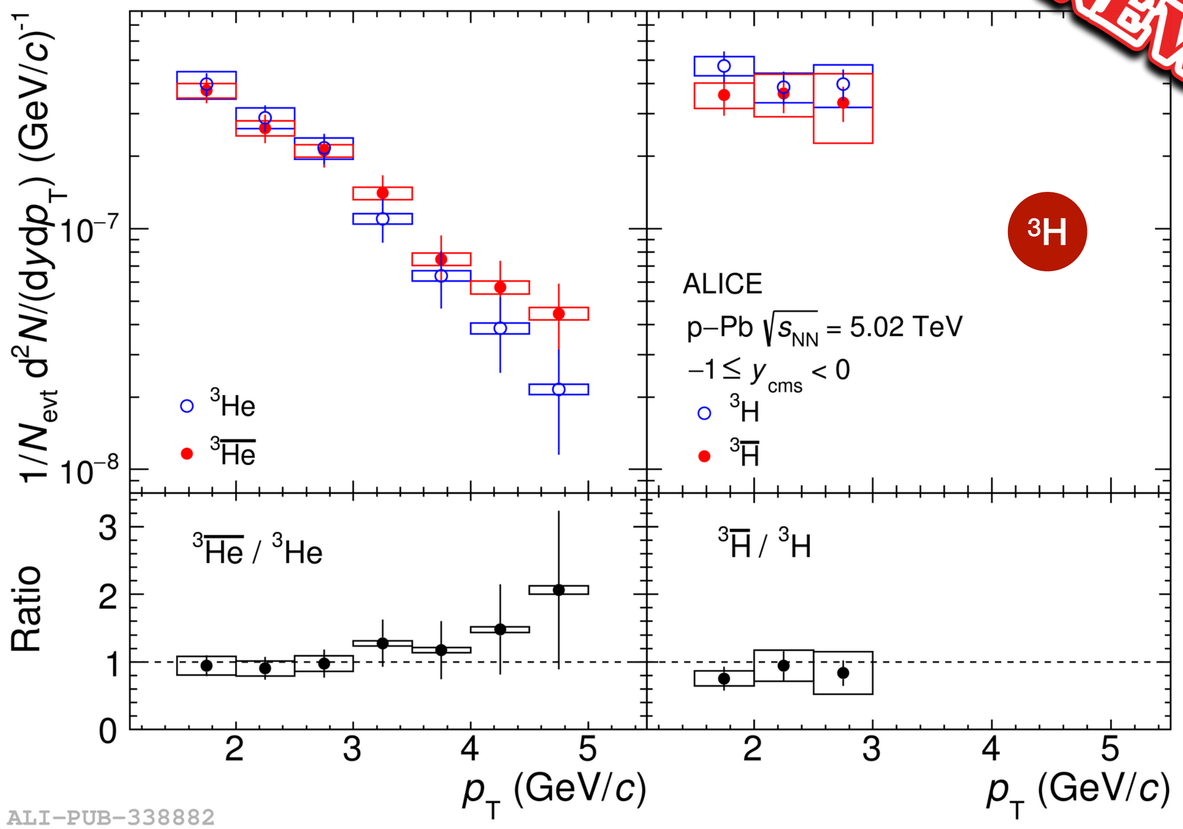
- **^{3}H** p_T spectra measured in **p-Pb** collisions
- Comparison with ^{3}He spectra is a cross-check for the isospin-invariance in the production mechanisms
- **^{3}H** p_T spectra measured also in **Pb-Pb** collisions
  - see **Esther's talk**:

    "New results on light (anti-)(hyper-)nuclei production and hypertriton lifetime in Pb-Pb collisions at the LHC"

    - Collective dynamics II session
    - on 05.10.2019 at 15:40

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

NEW!



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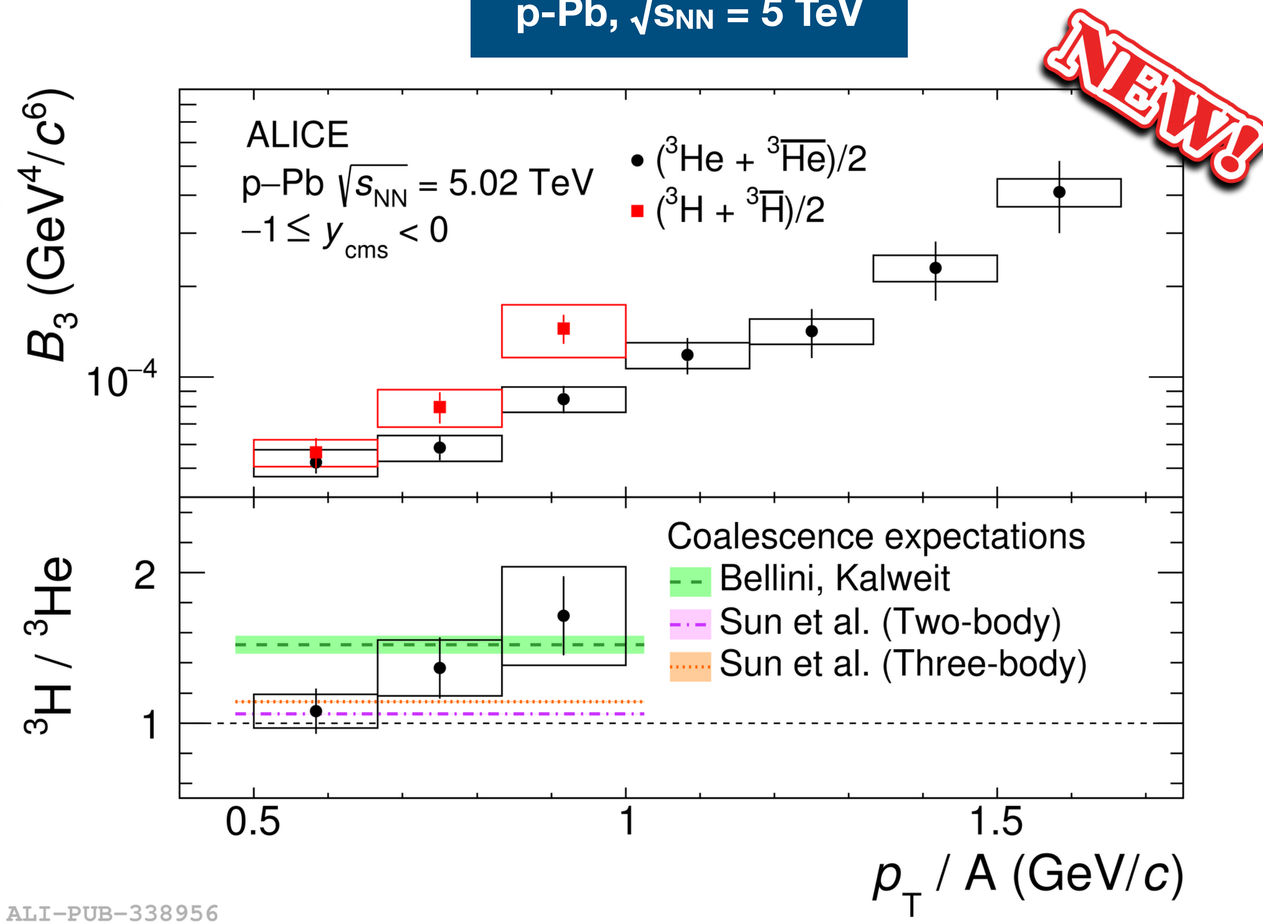

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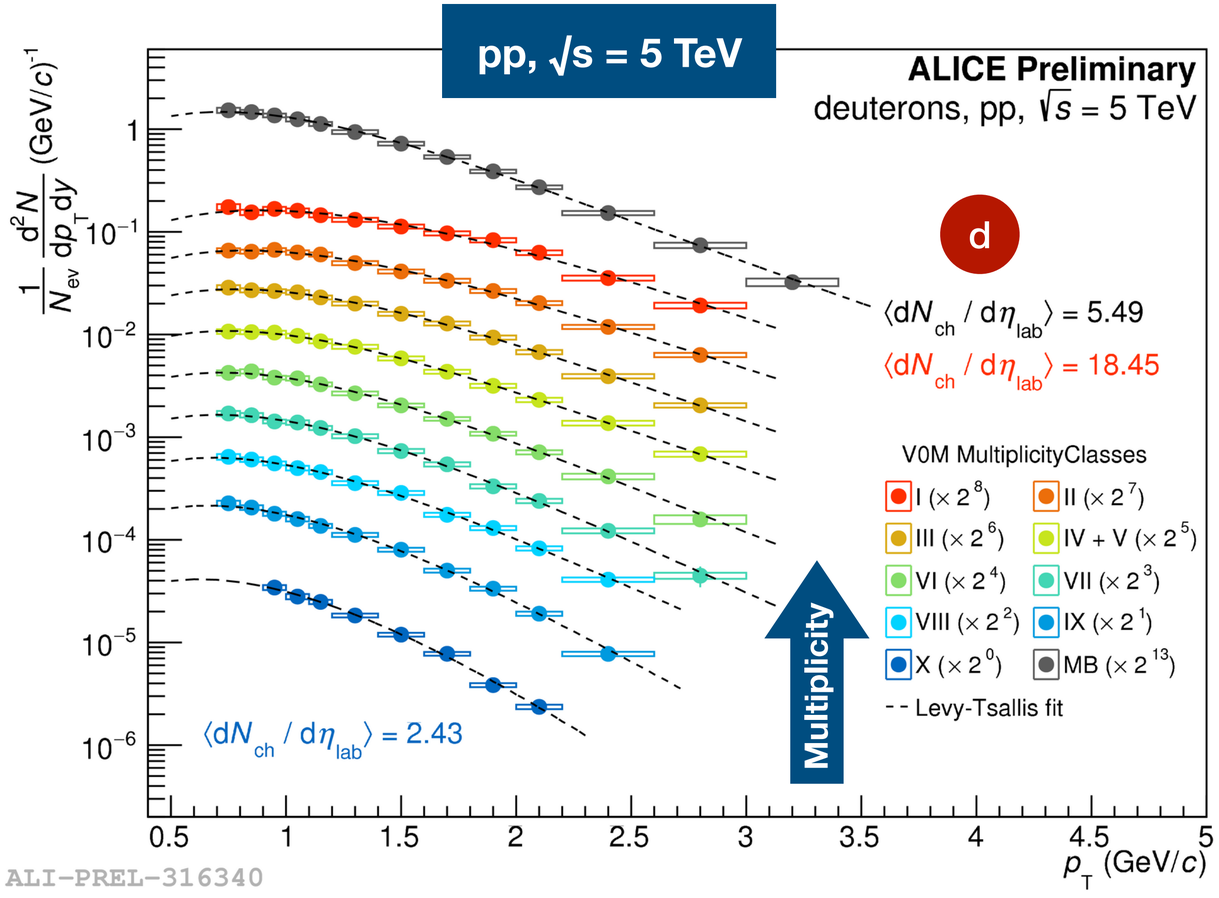
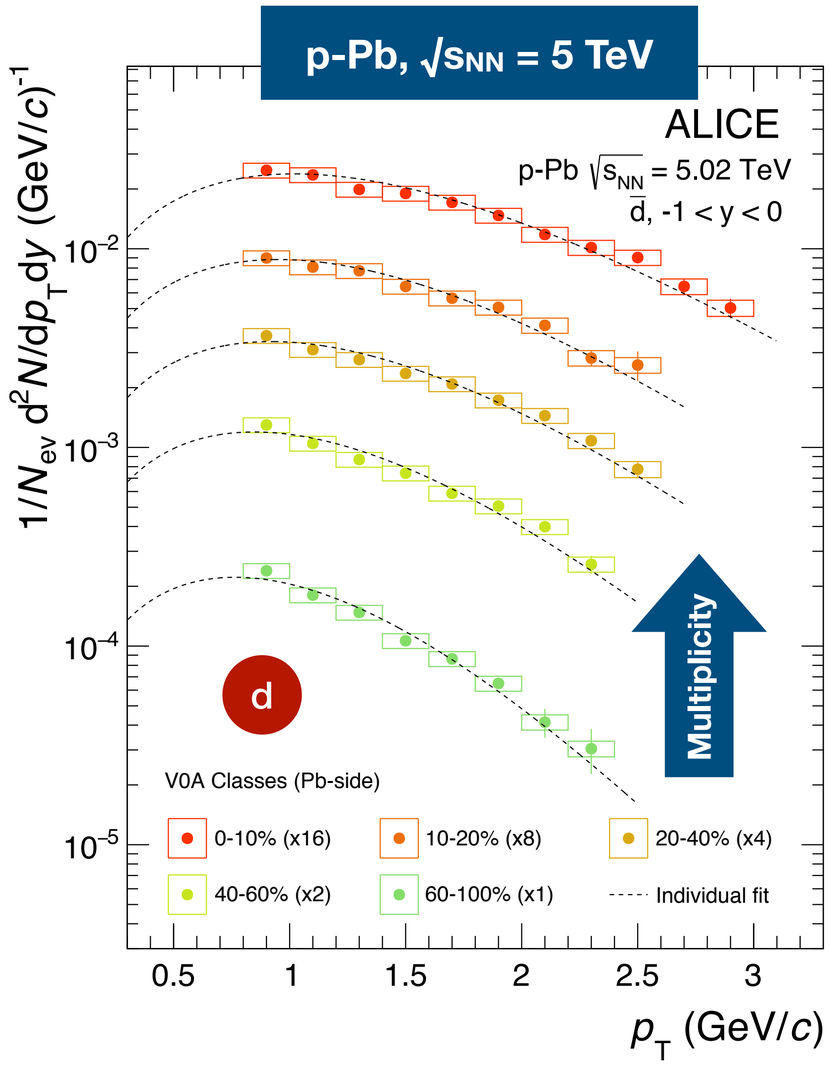
Deuteron in pp and p-Pb





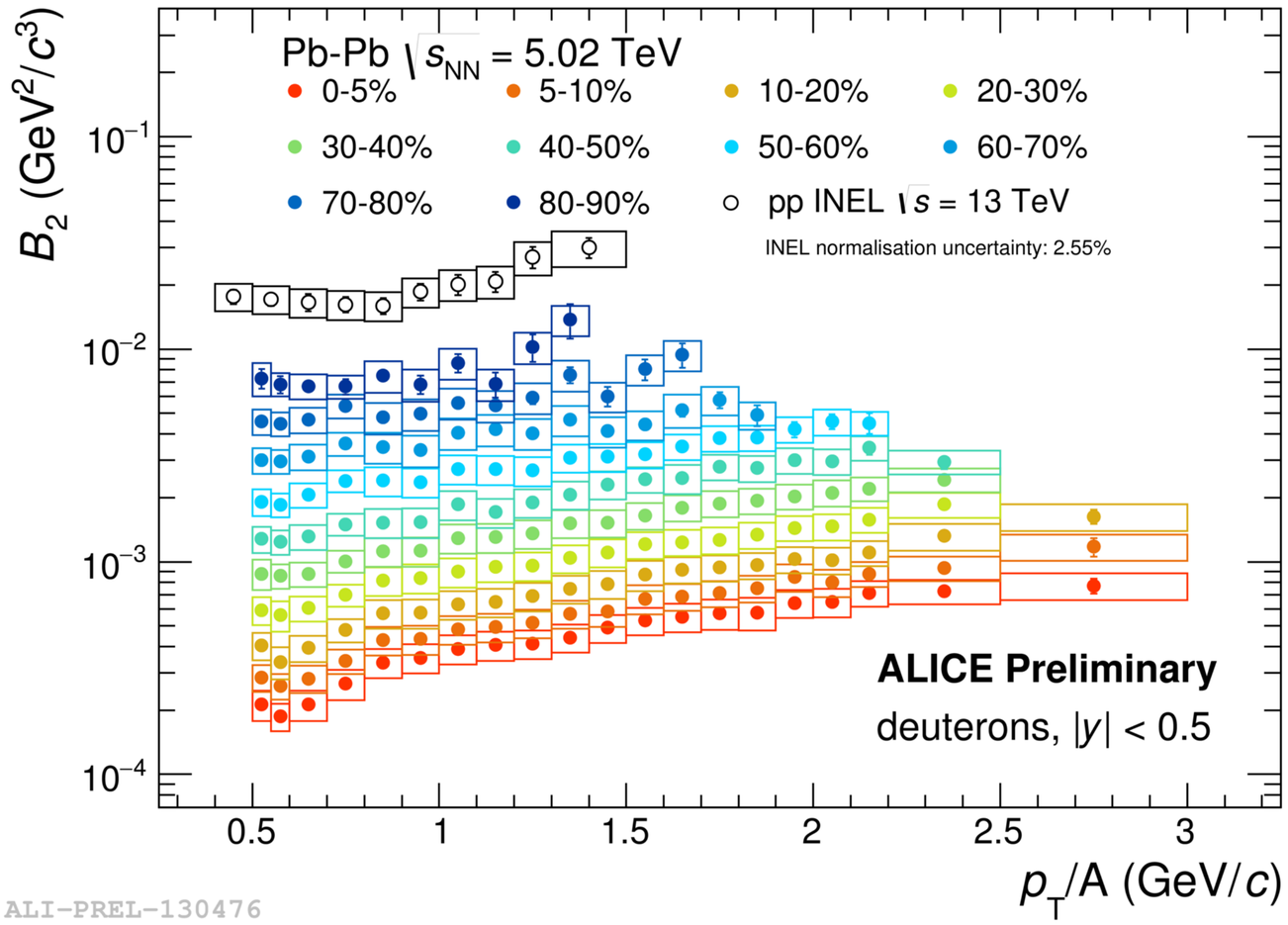
- **deuteron** p_T spectra have been measured in pp, p-Pb and Pb-Pb collisions
  - Comparison with **proton spectra →** constrain to production mechanisms

arXiv:1906.03136 [nucl-ex]

The coalescence parameter B_A

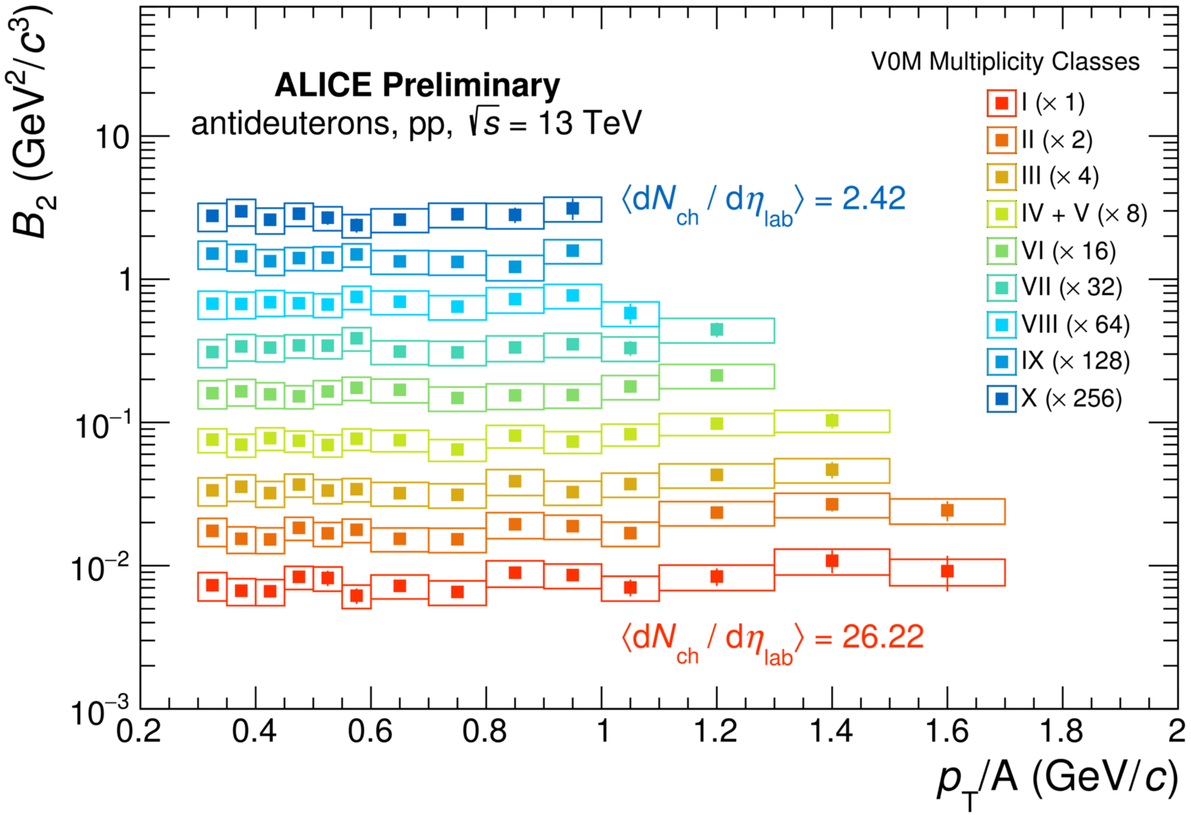
- The **probability** to form a nucleus via coalescence can be quantified by the **coalescence parameter B_A**
- According to **simple coalescence** predictions, the B_A is **flat in p_T**
  - Simple coalescence **does not describe** the behaviour observed in **Pb-Pb** collisions
- Moving from central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

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

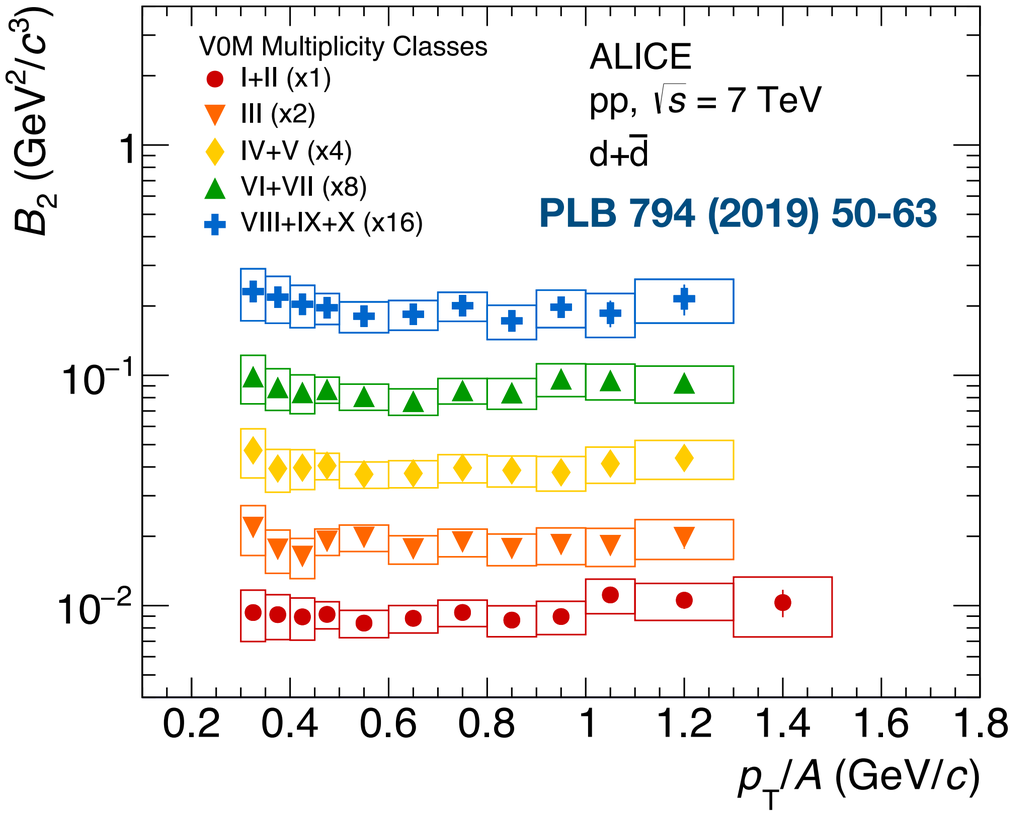


The coalescence parameter B_2

pp, √s = 13 TeV



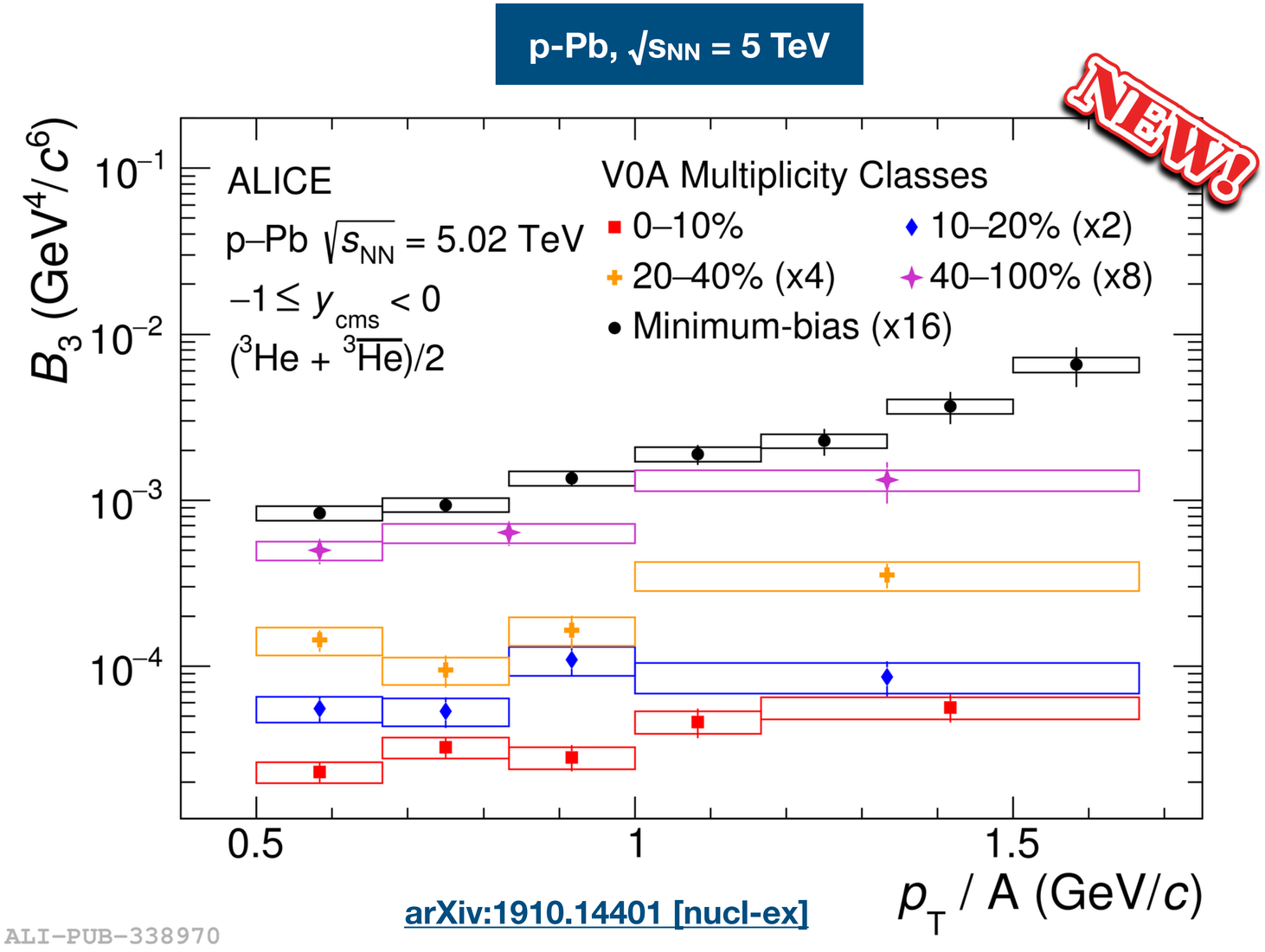
pp, √s = 7 TeV



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

The coalescence parameter B_3

- B_3 has also been measured in **pp** and in **p-Pb** collisions
- Comparison of the B_3 in different **collision systems** and at different **multiplicities**
  - Dependence of the coalescent production on the **system size**



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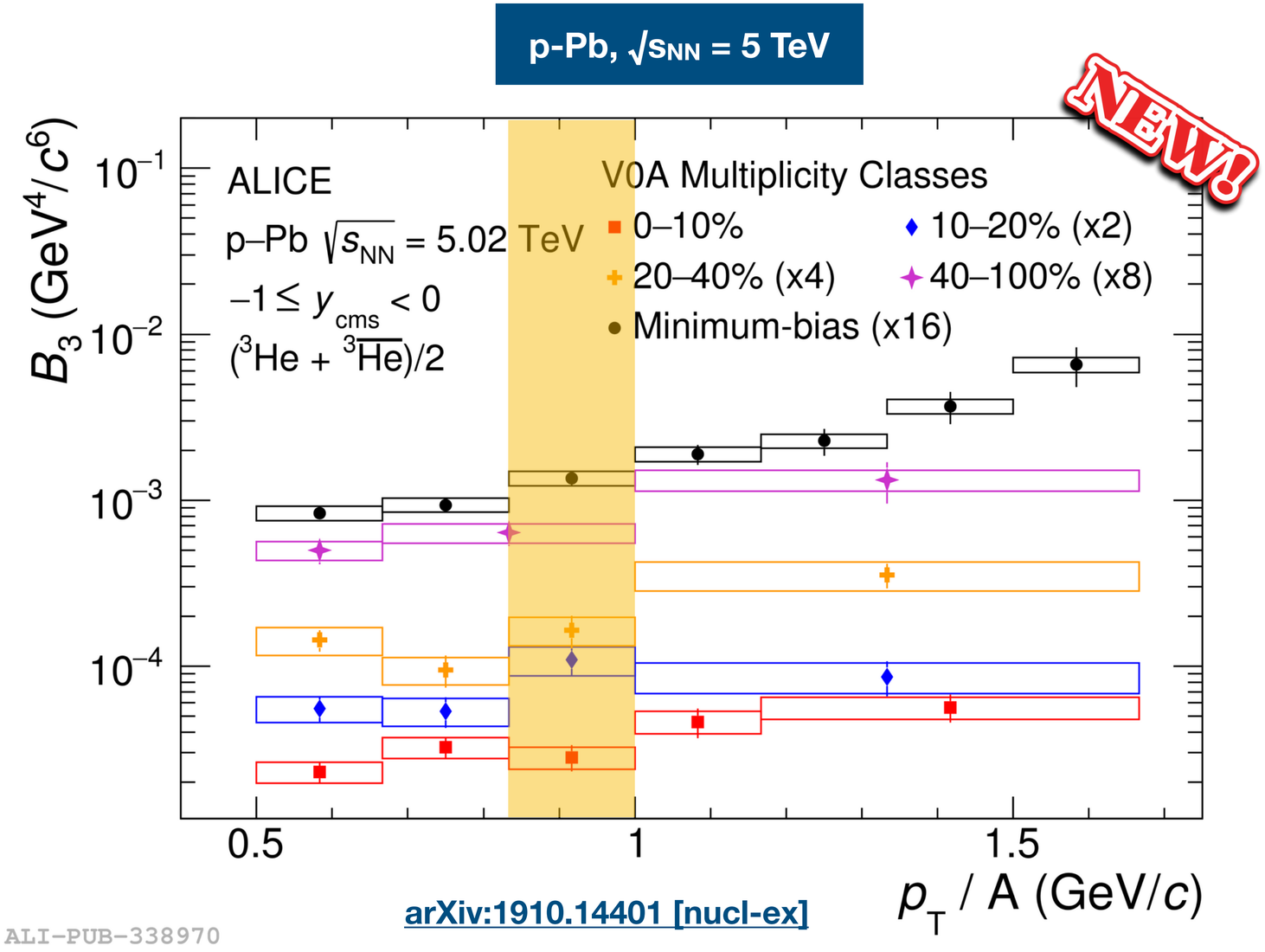

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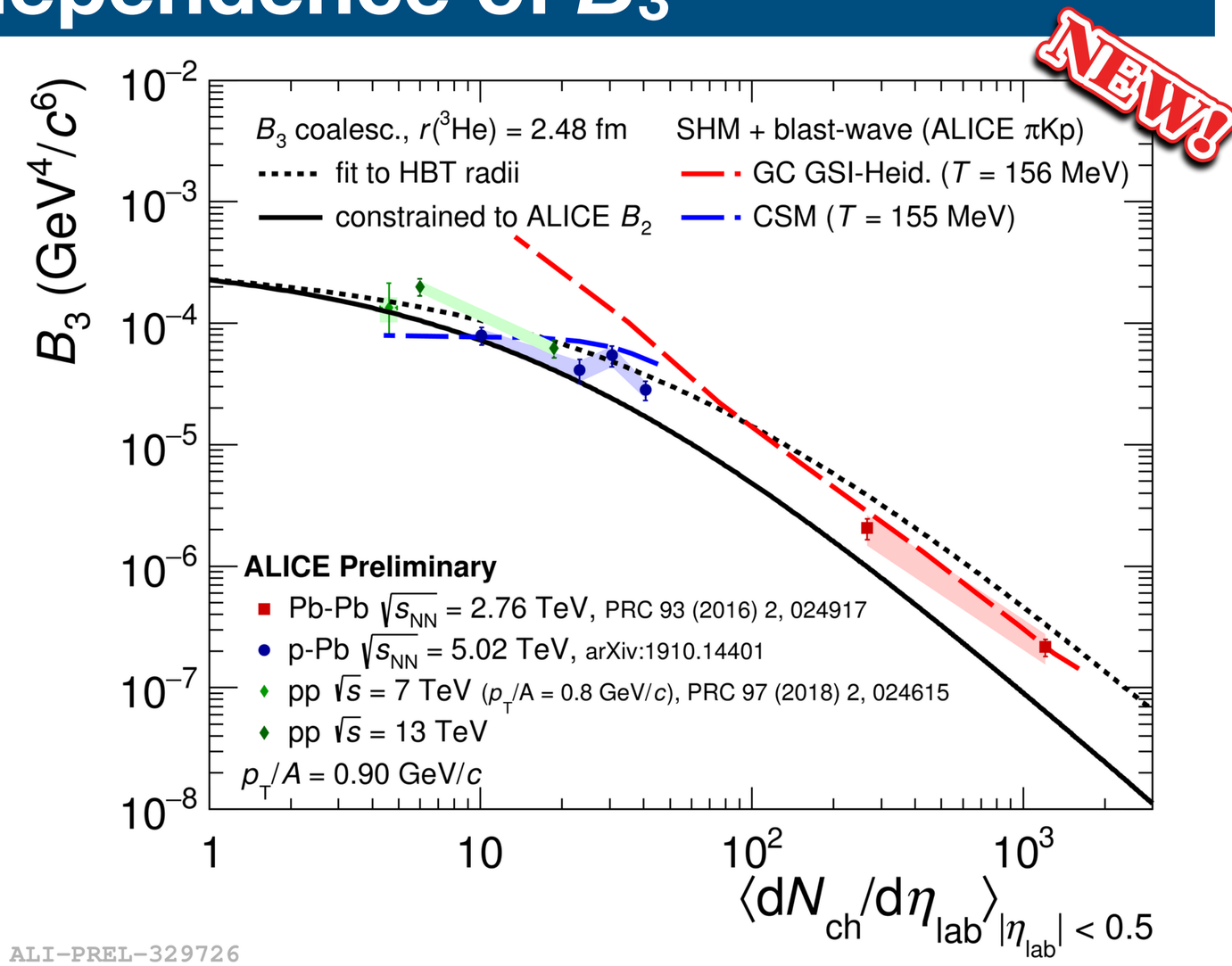
Multiplicity dependence of B_3

- B_3 evolves **smoothly** with **multiplicity**, regardless of the collision system:



Multiplicity dependence of B_3

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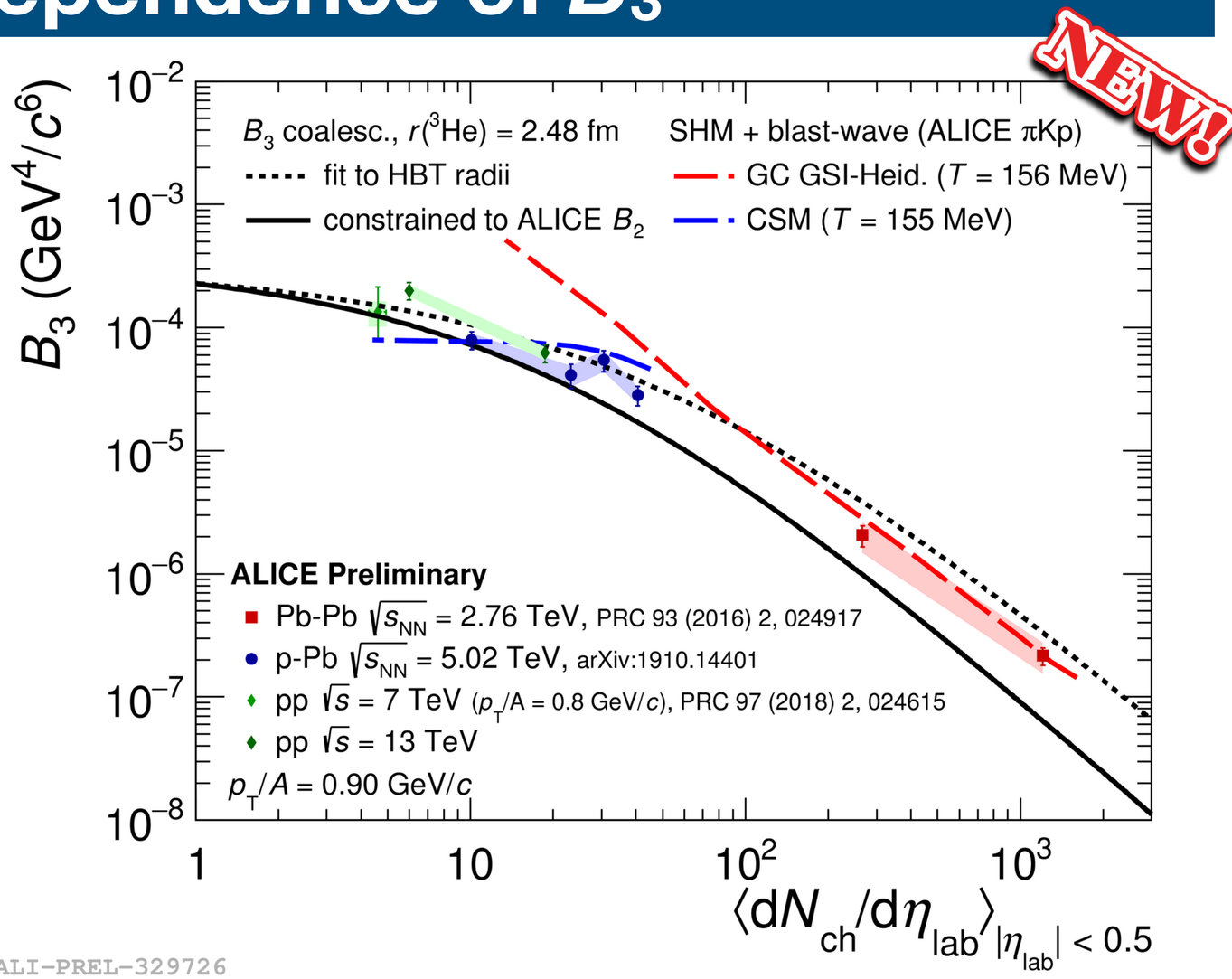

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- B_3 evolves **smoothly** with **multiplicity**, regardless of the collision system:
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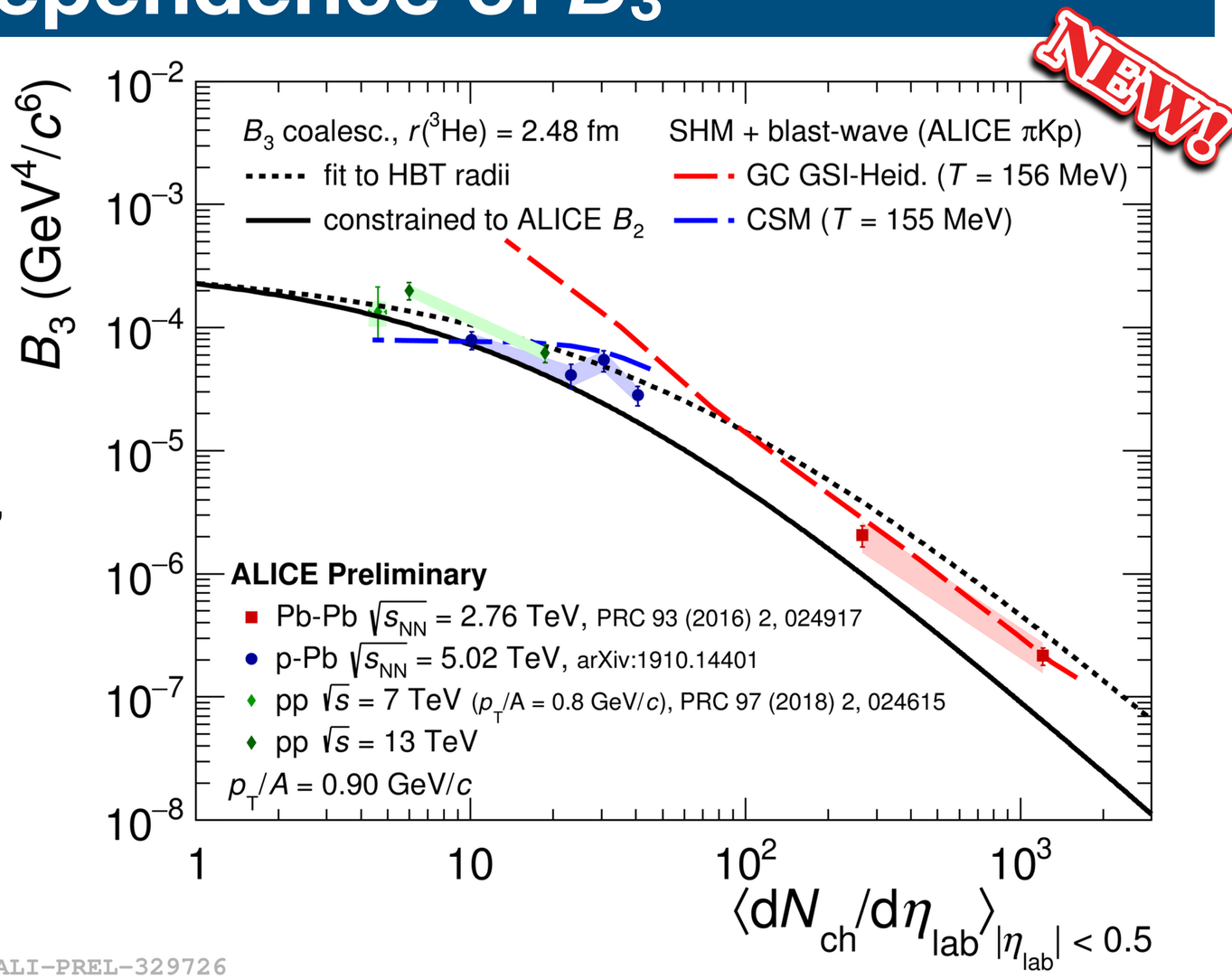
- Through the coalescence model it is possible to predict the B_A as a function of the **system volume**, parameterised from the dN/dη



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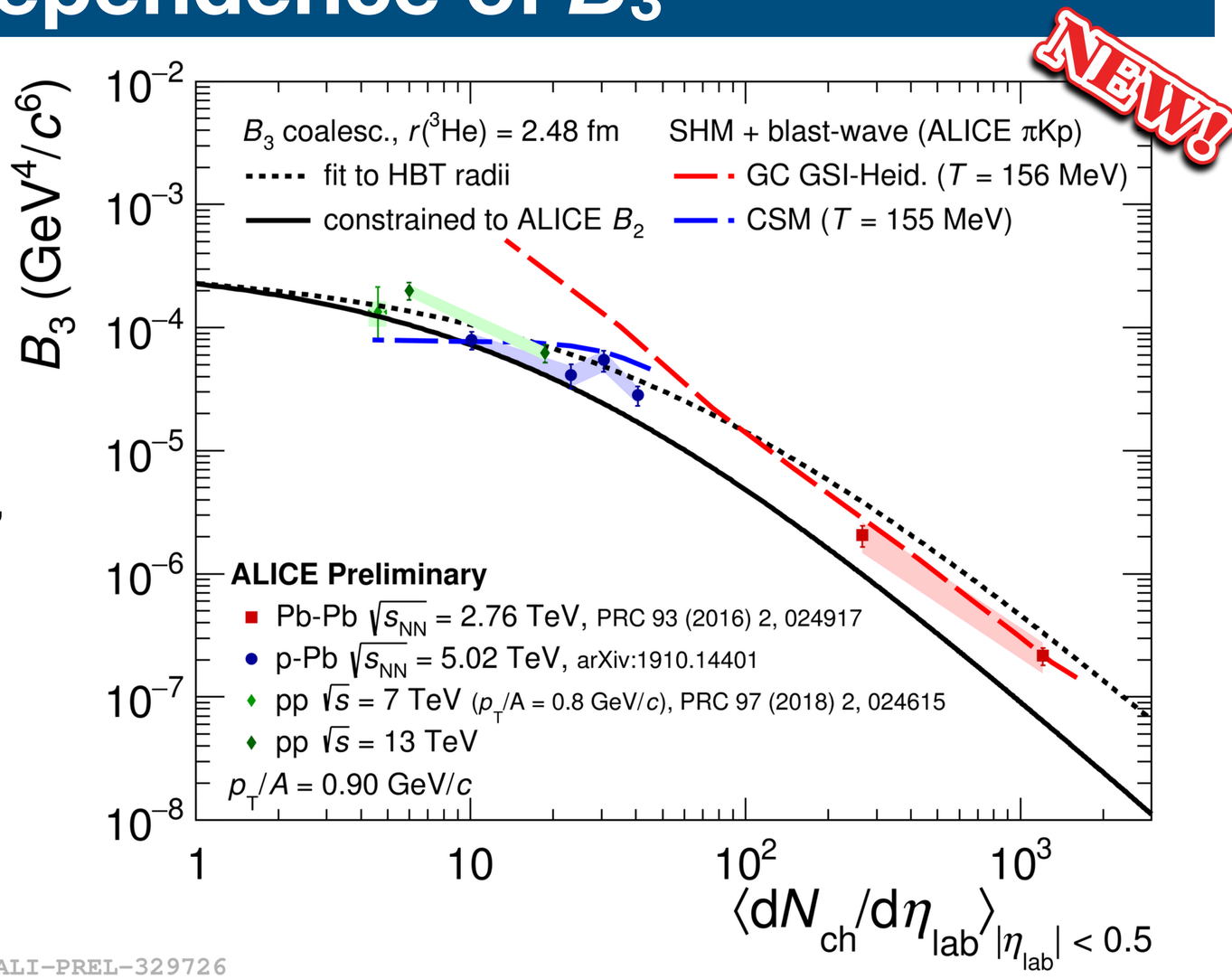

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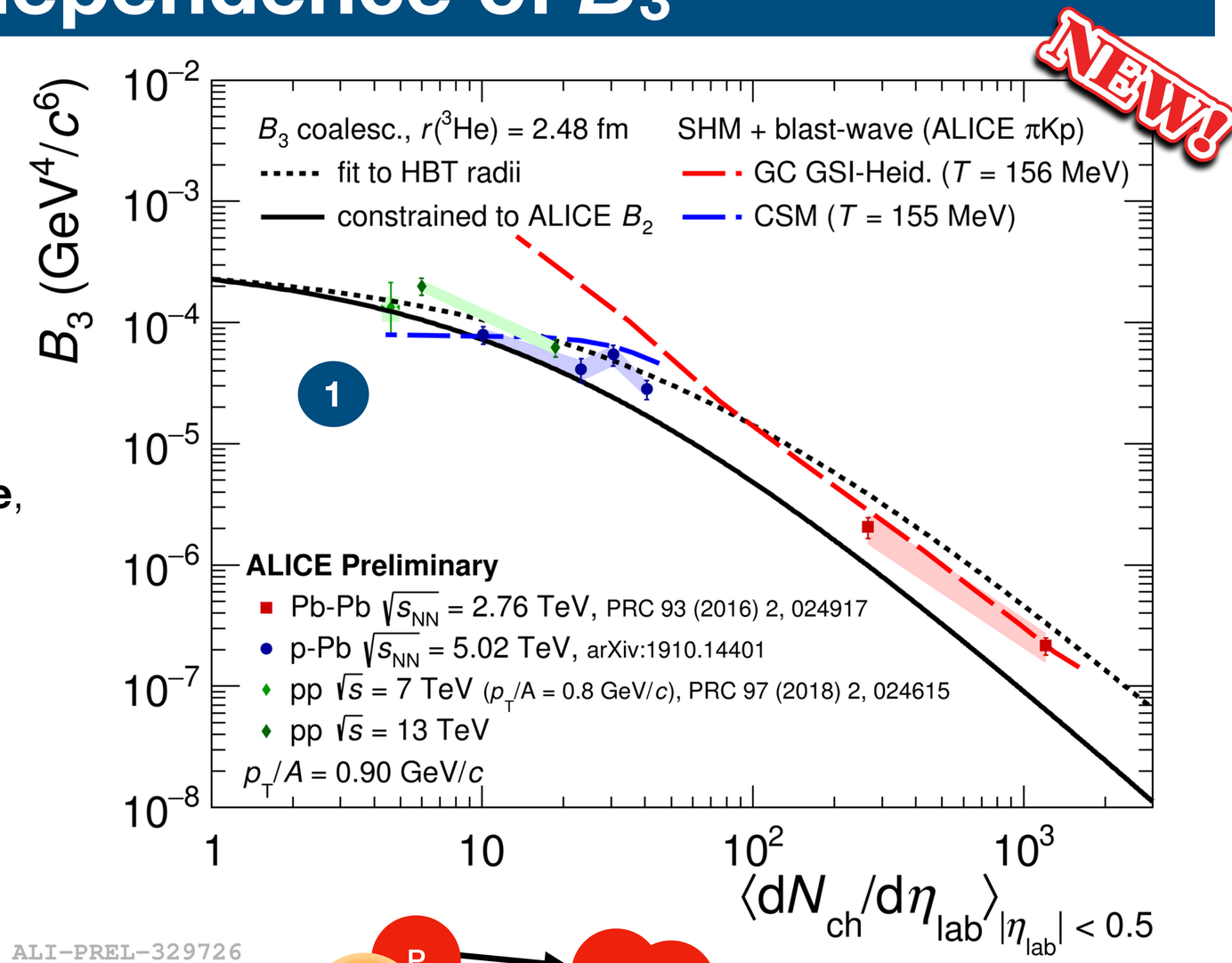

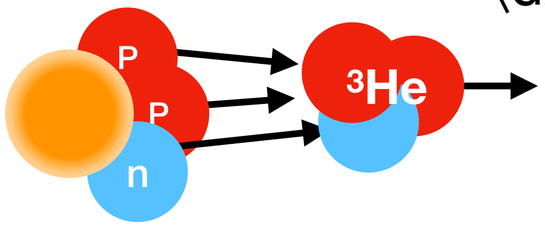

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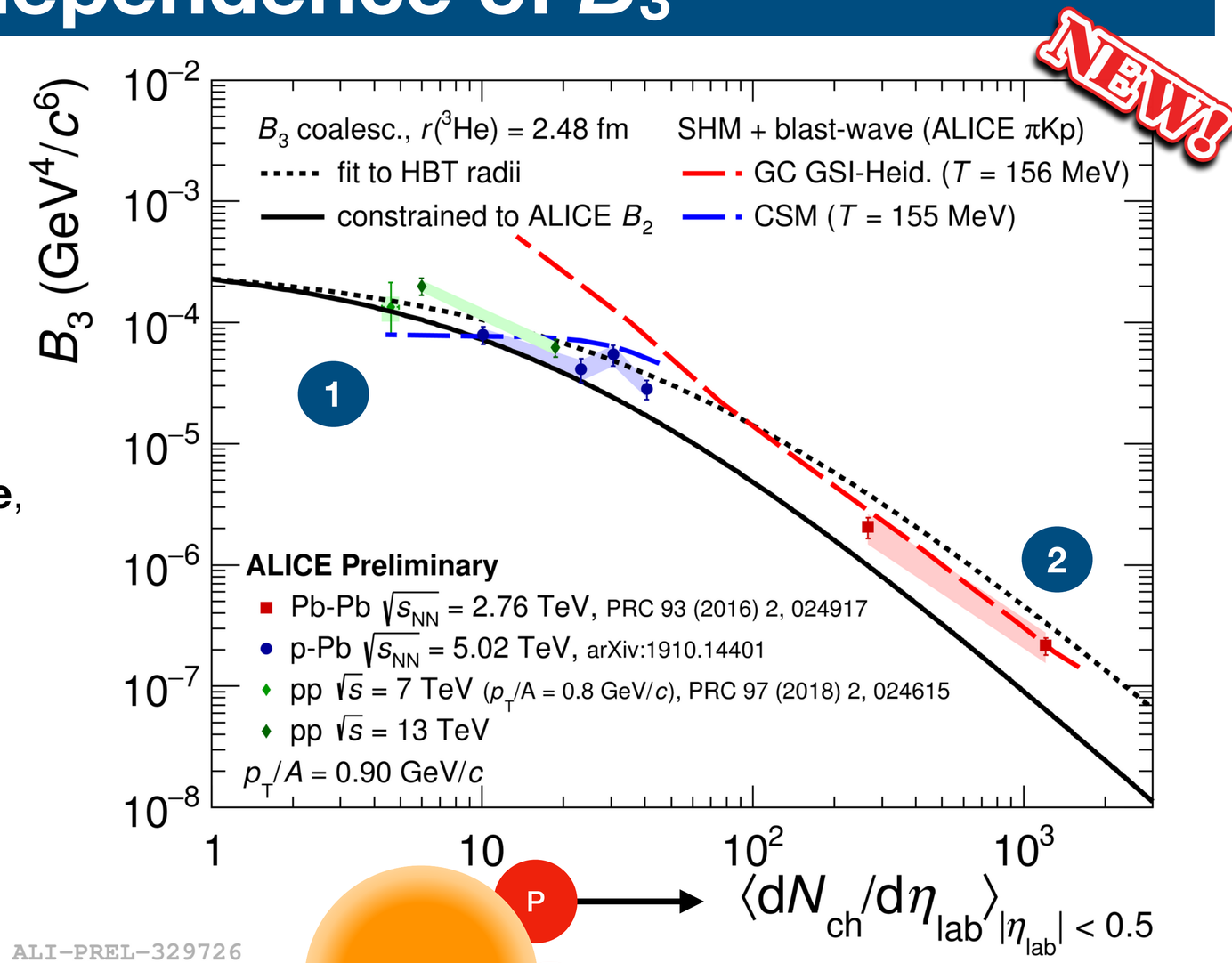
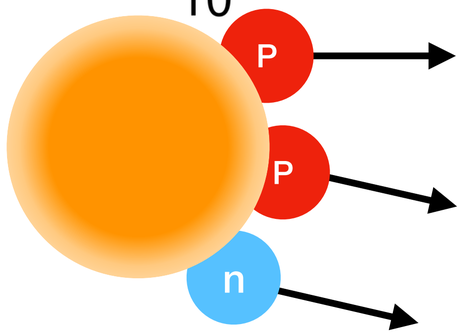
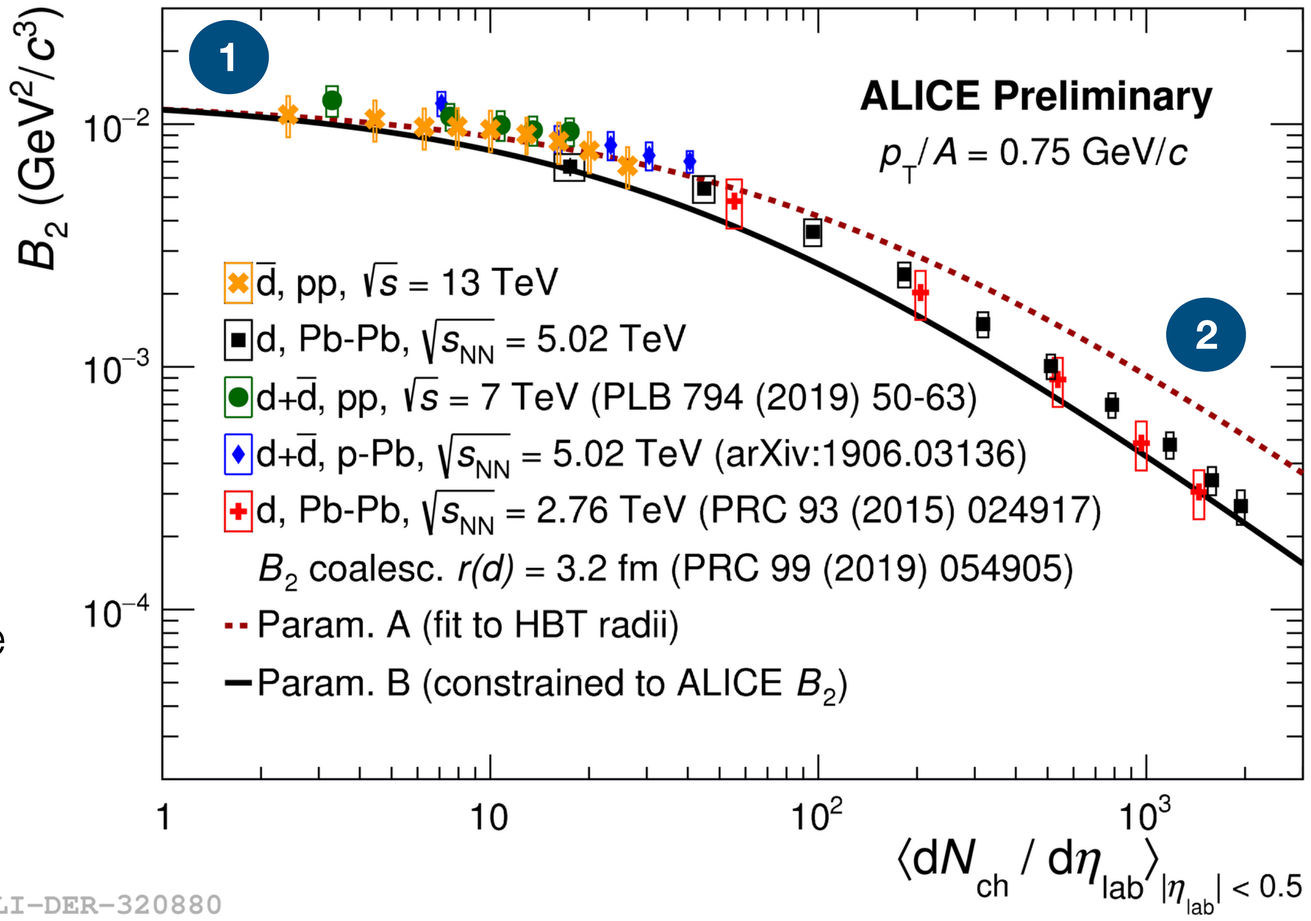
- Through the coalescence model it is possible to predict the B_A as a function of the **system volume**, parameterised from the dN/dη
- Two regimes observed:
  1. **flat**: the system size is smaller than the nucleus size
  2. **decreasing**: the system size is larger than the nucleus size





Multiplicity dependence of B_2

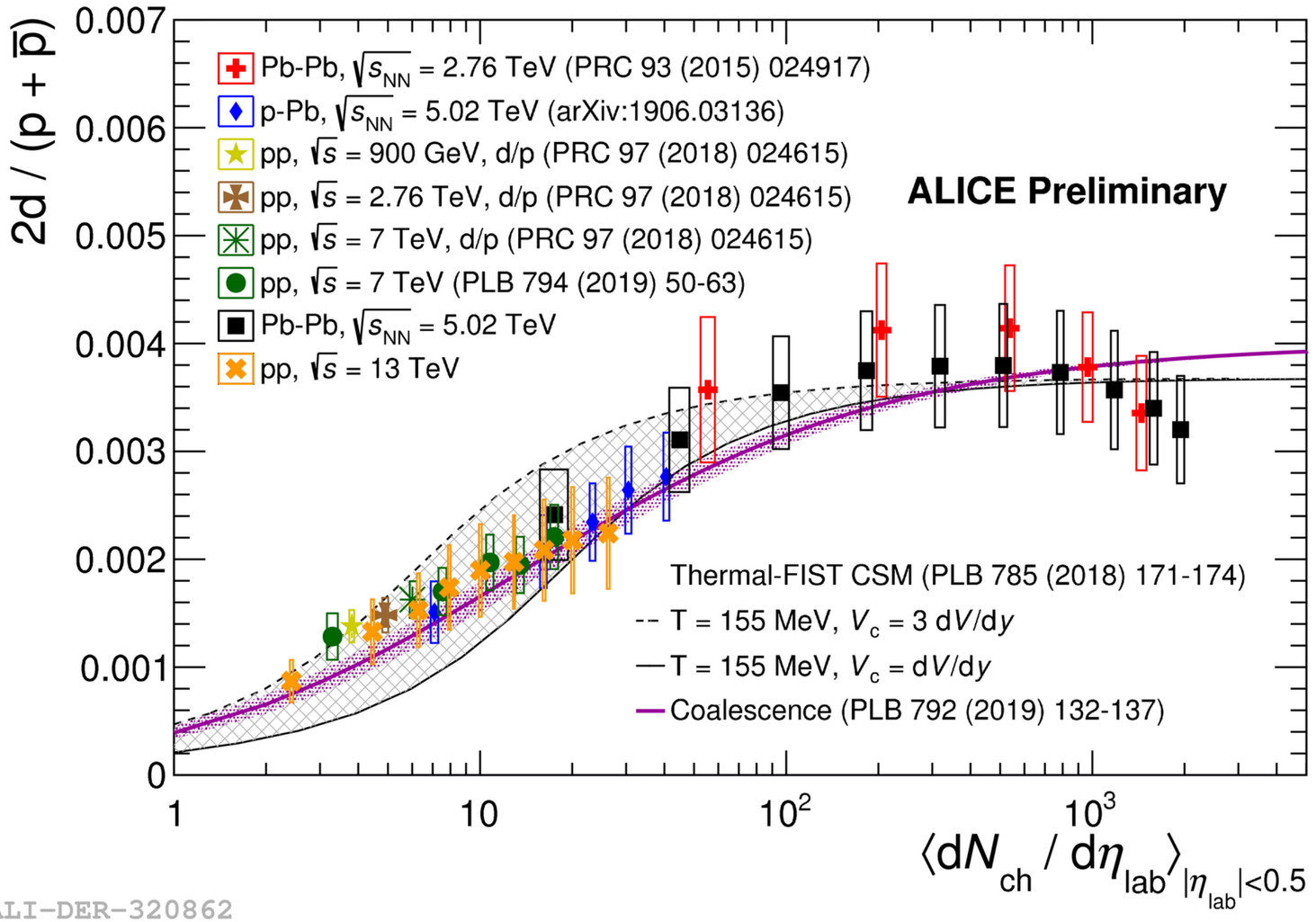
- Also B_2 shows a **smooth evolution** with **multiplicity**
- B_2 can be predicted as a function fo the **system volume**, parameterised from dN/dη
- Two regimes observed:
  1. **flat**: the system size is smaller than the deuteron size
  2. **decreasing**: the system size is larger than the deuteron size



ALI-DER-320880

Deuteron over proton ratio

- **d/p** ratio evolves **smoothly** with **multiplicity**, regardless of the collision system:
  - **production mechanism depending only on the system size**



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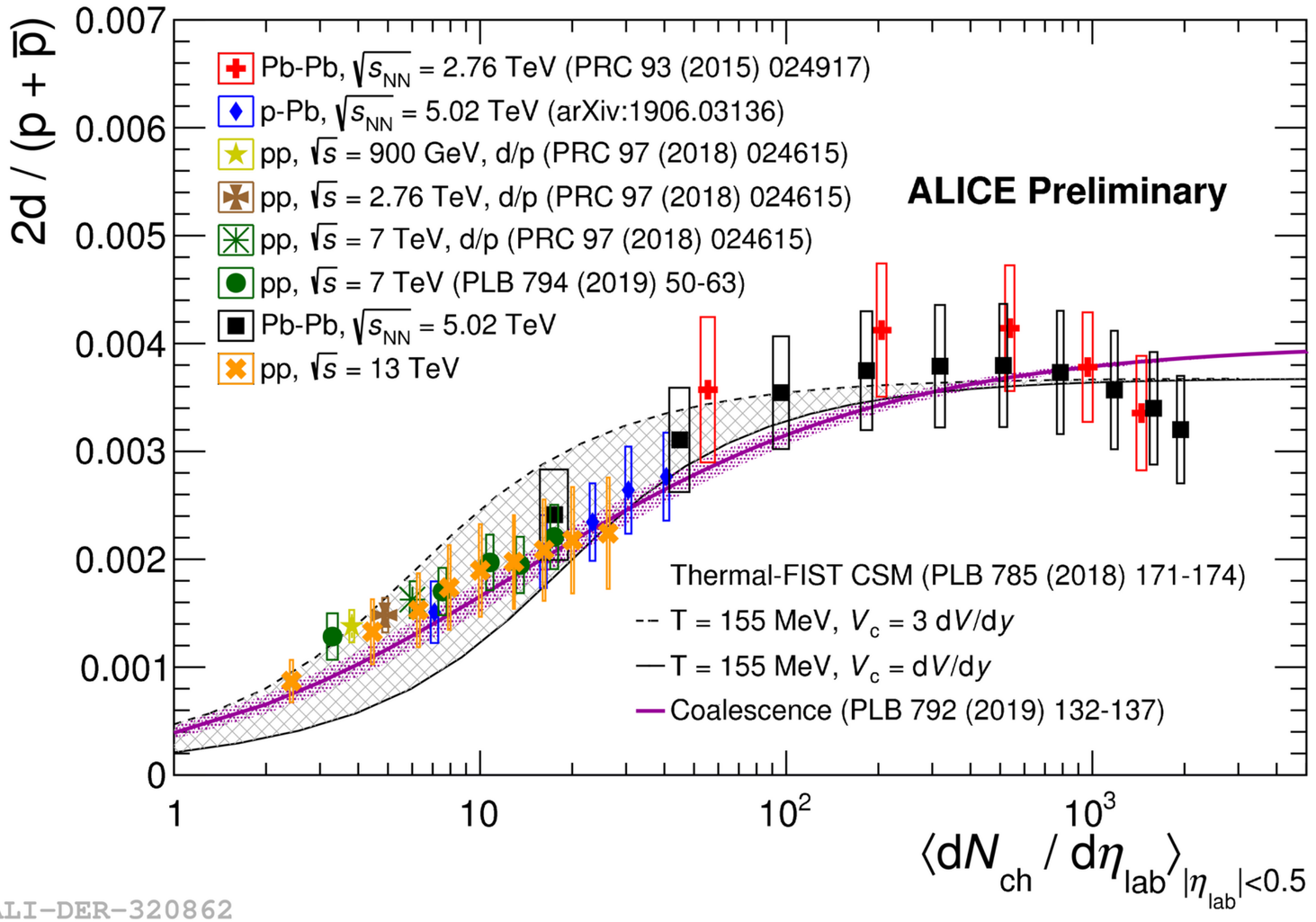

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- **d/p** ratio evolves **smoothly** with **multiplicity**, regardless of the collision system:
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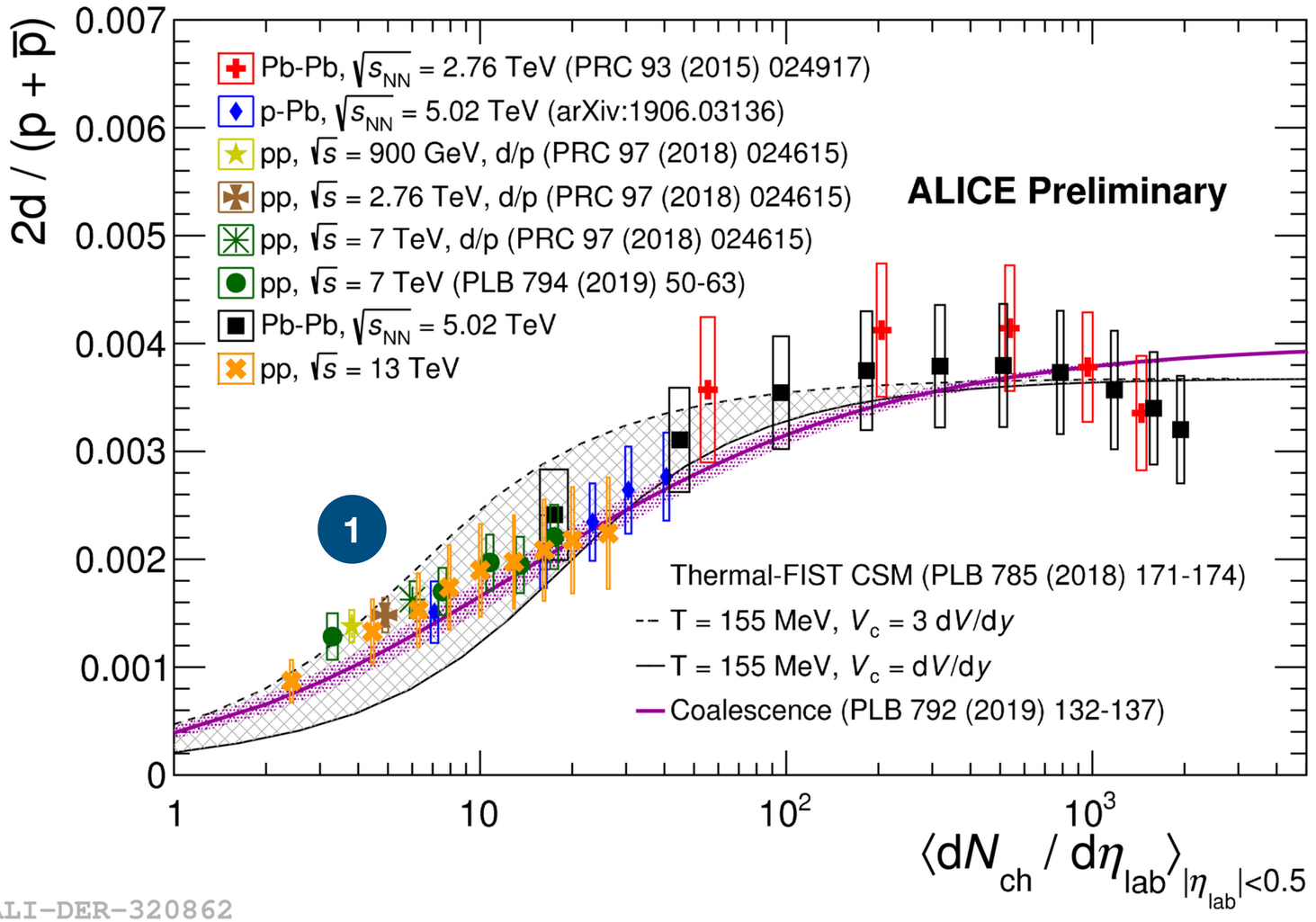
- Two different regimes:
  1. **increasing**:
     - Thermal model: **canonical suppression**
     - Coalescence: **small phase space**



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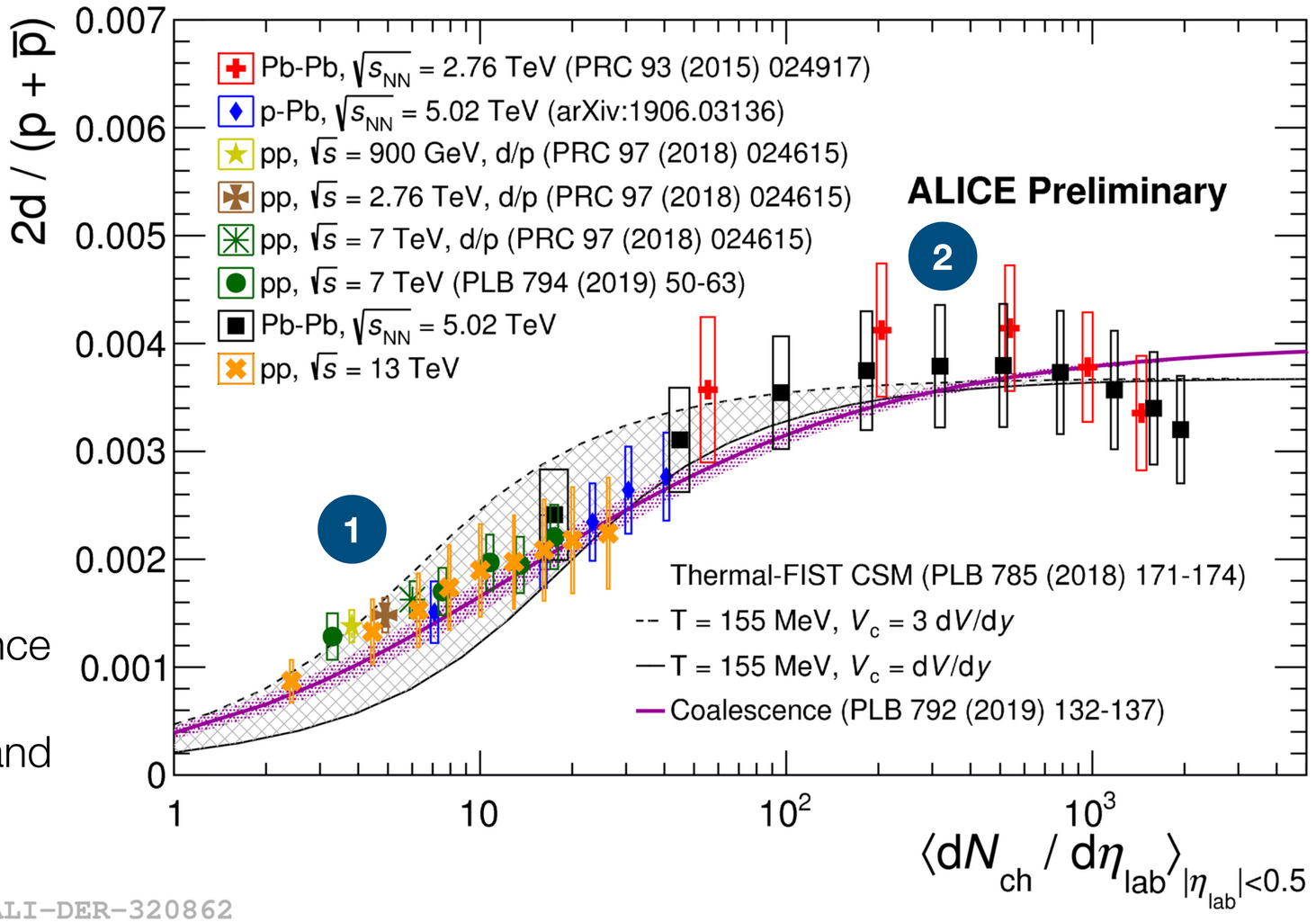
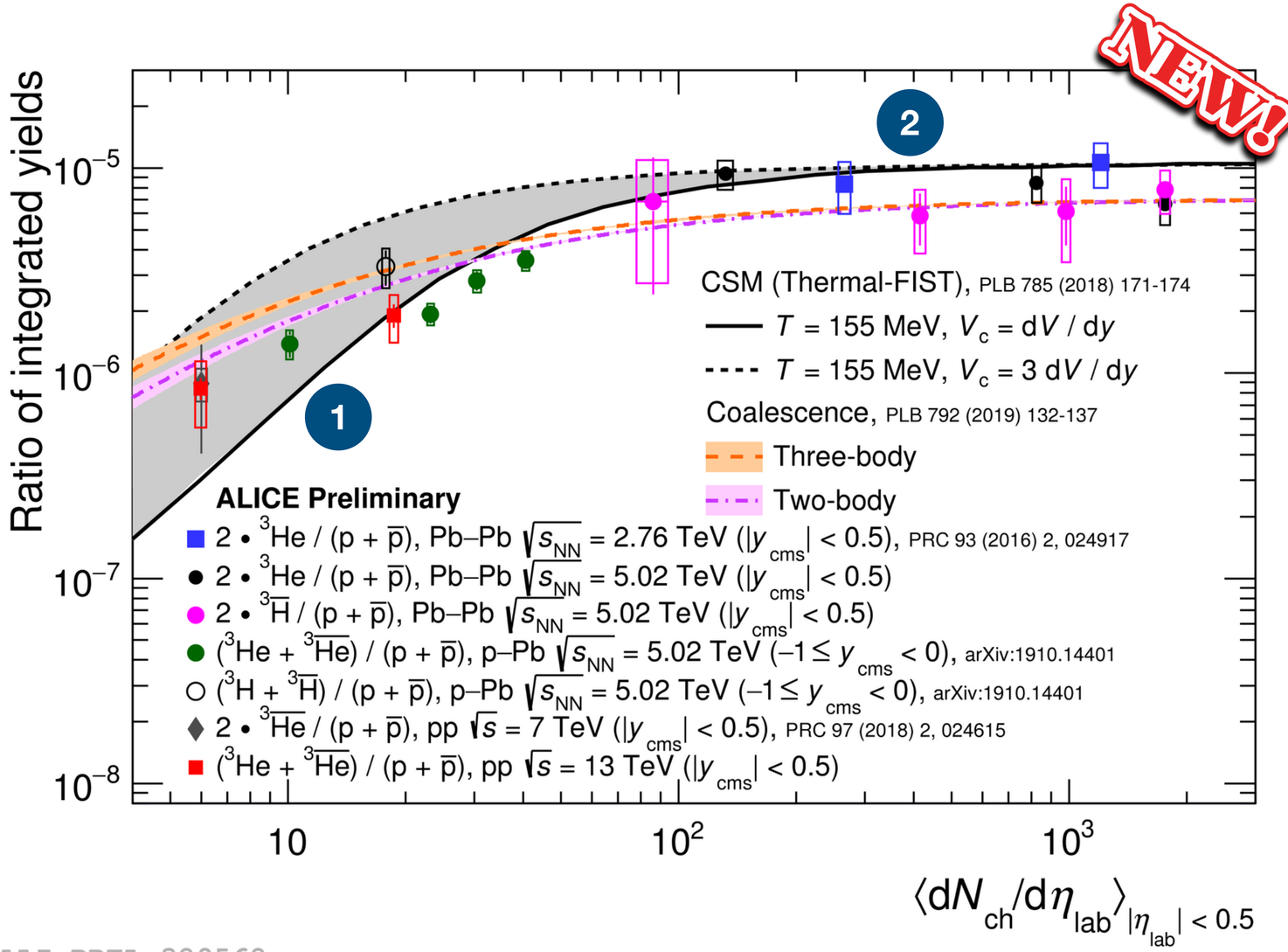
     - Thermal model: **canonical suppression**
     - Coalescence: **small phase space**
  2. **flat**: at high multiplicity there is no dependence of the ratio on the multiplicity, in agreement with the predictions of the **thermal model** and **coalescence**



^{3}He over proton ratio

- Also for **^{3}He/p** we see a **smooth evolution** with the multiplicity, regardless of the collision system
- Two kinds of coalescence:
  - **2-body** coalescence
  - **3-body** coalescence
- As for d/p, two different regimes:

1. **increasing:**
   - Thermal model: **canonical suppression**
   - Coalescence: **small phase space**
2. **flat:** in agreement with both models



Conclusions

- ALICE has measured the production of light (anti-)nuclei in different collision systems and at different energies.
- The measurements of $\boldsymbol{B_A}$, **d/p** and **^{3}He/p** as a function of multiplicity suggest a **common production** mechanism that depends only on the **system size**.
- The **coalescence** model can explain both the evolution of $\boldsymbol{B_A}$, **d/p** and **^{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 hadron collisions.

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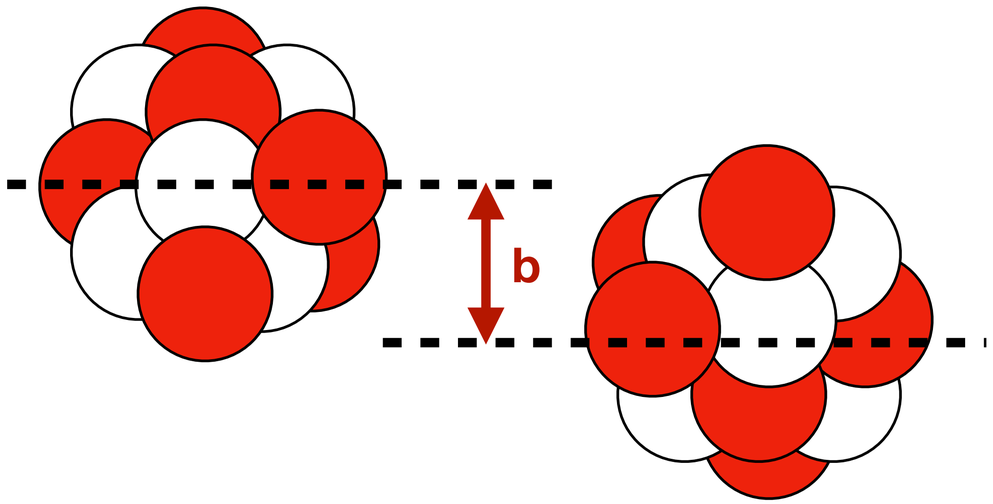
Thanks for your attention!

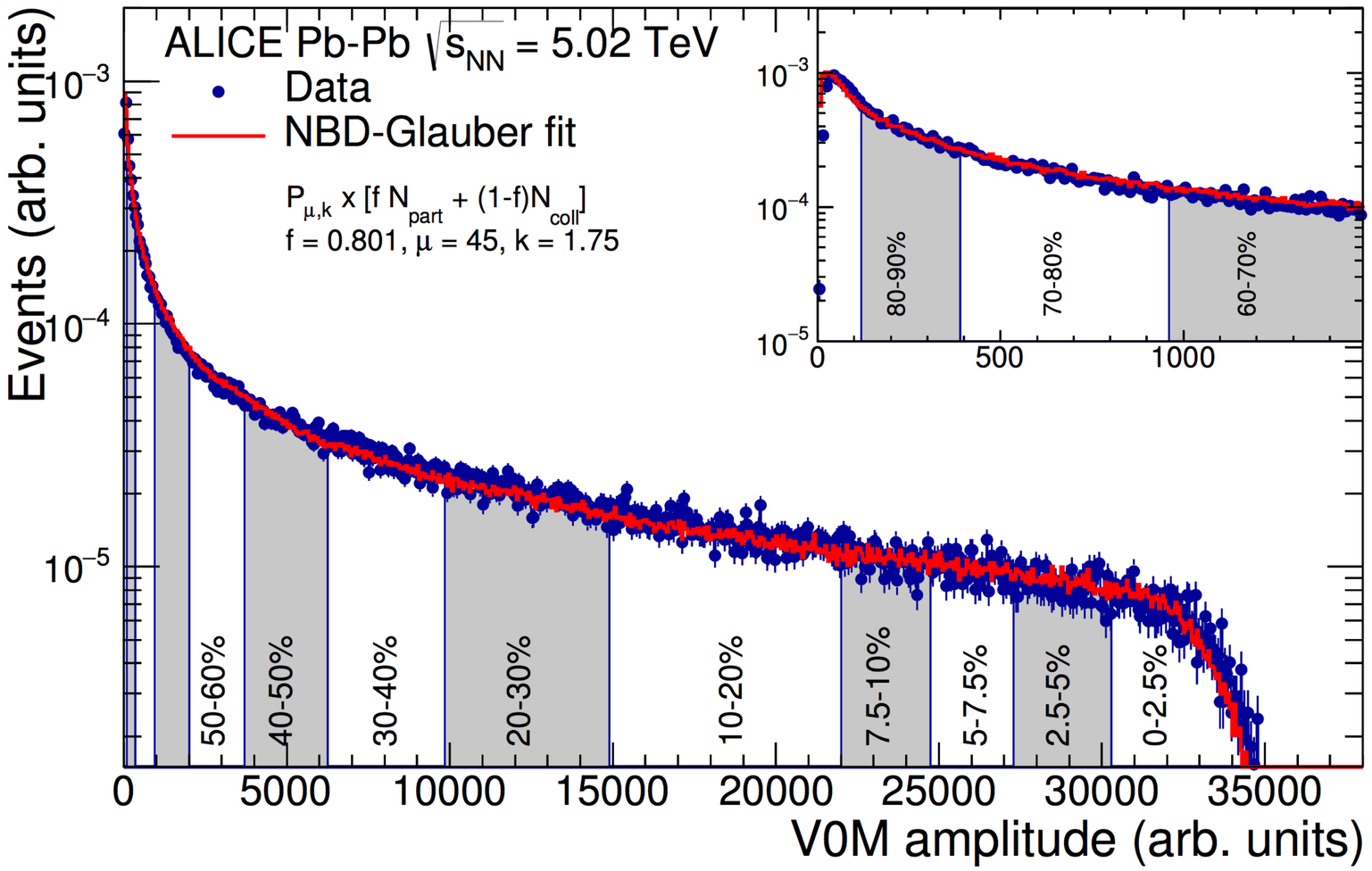
Backup

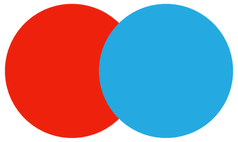
Centrality determination

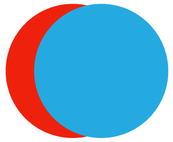
- The centrality if a Pb-Pb collision is described by the impact parameter **b**
- The estimation of the impact parameter is obtained from the track multiplicity, fitting the data with the predictions of the **Glauber model**



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





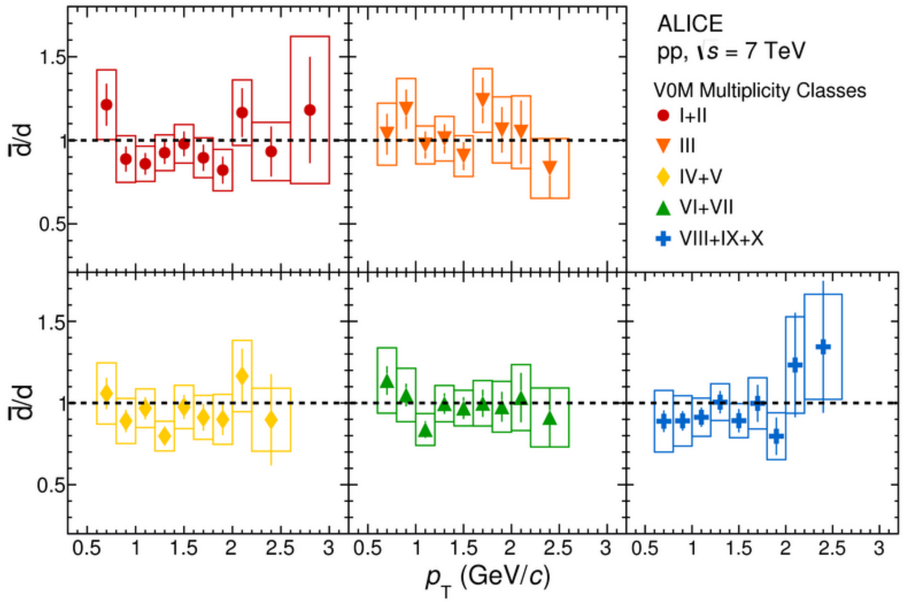


Anti-nuclei / nuclei ratio

- At the LHC energies the **antiproton/ proton** ratio is compatible with the **unity**:
  - the regime of **nuclear transparency** is reached: evanescent baryochemical potential (**μ_B ~ 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

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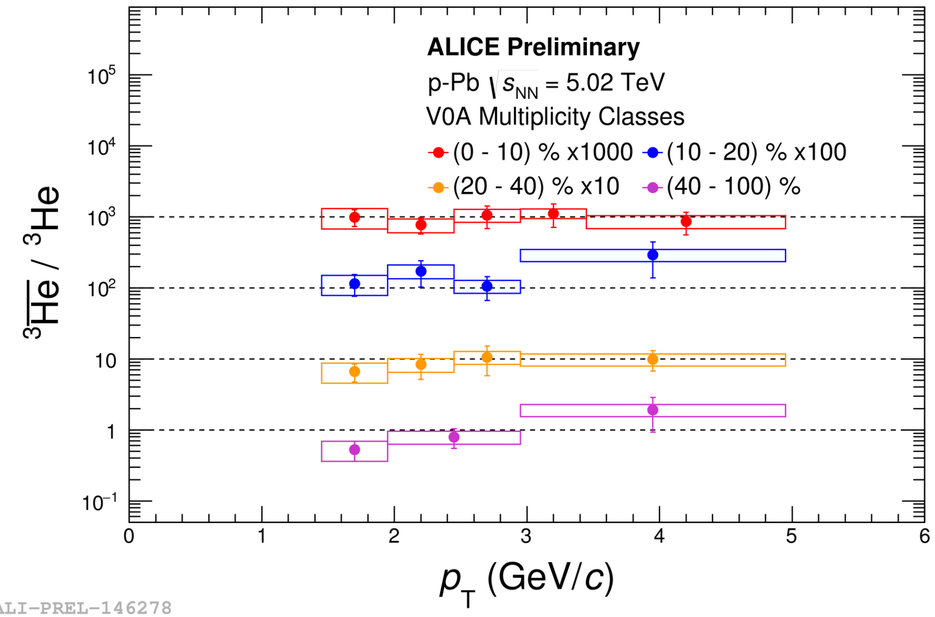
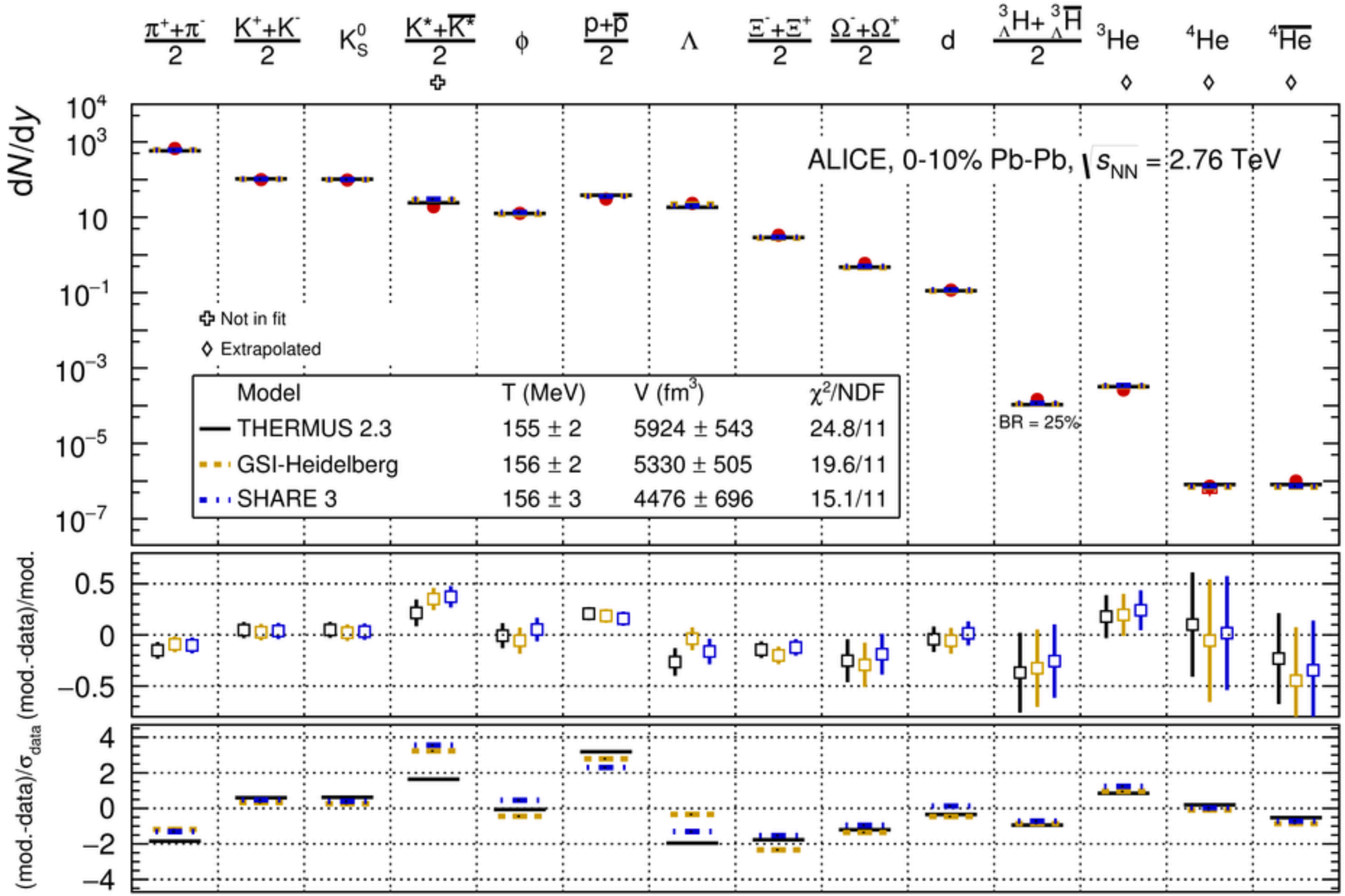
d

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

^{3}He



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



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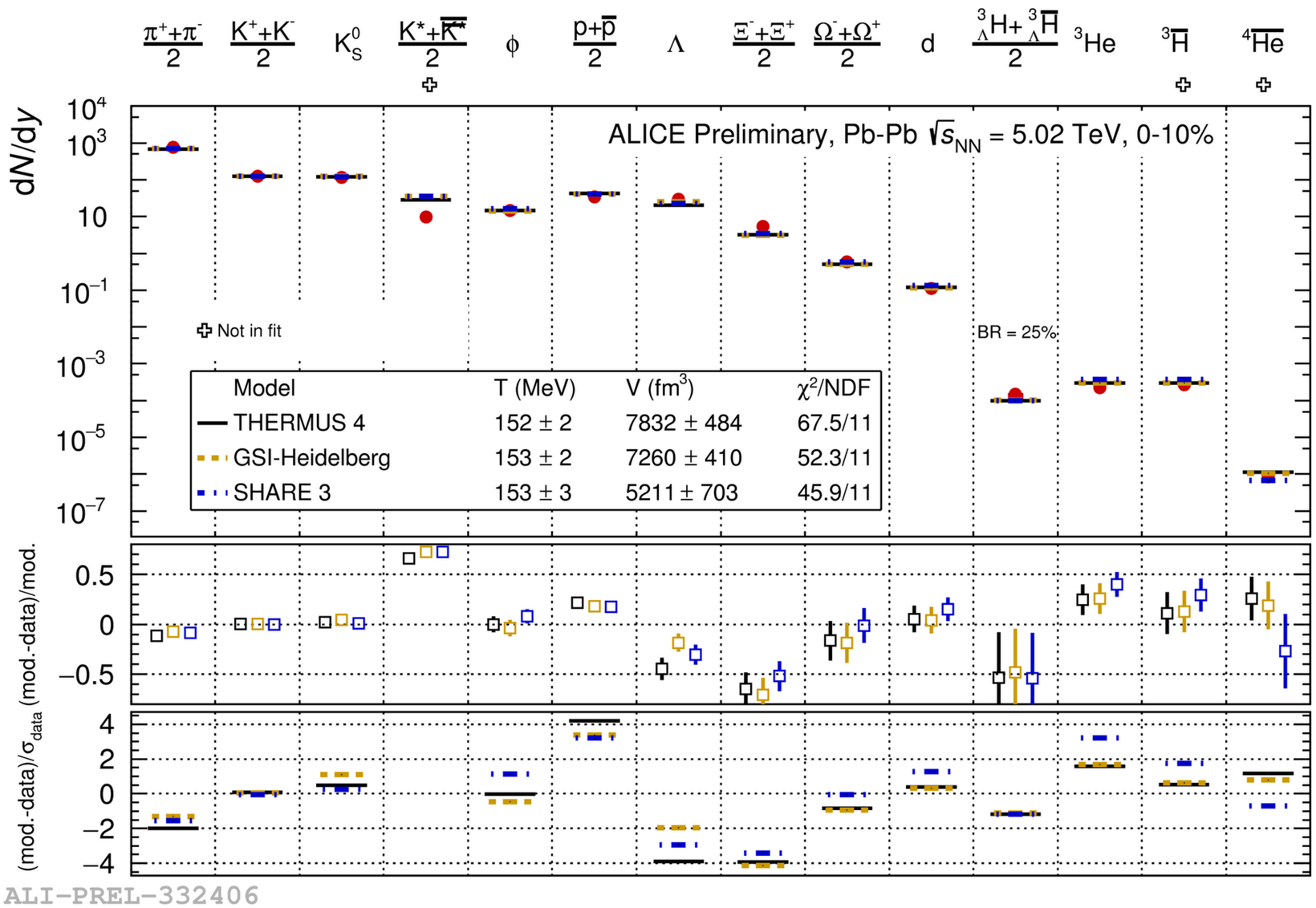
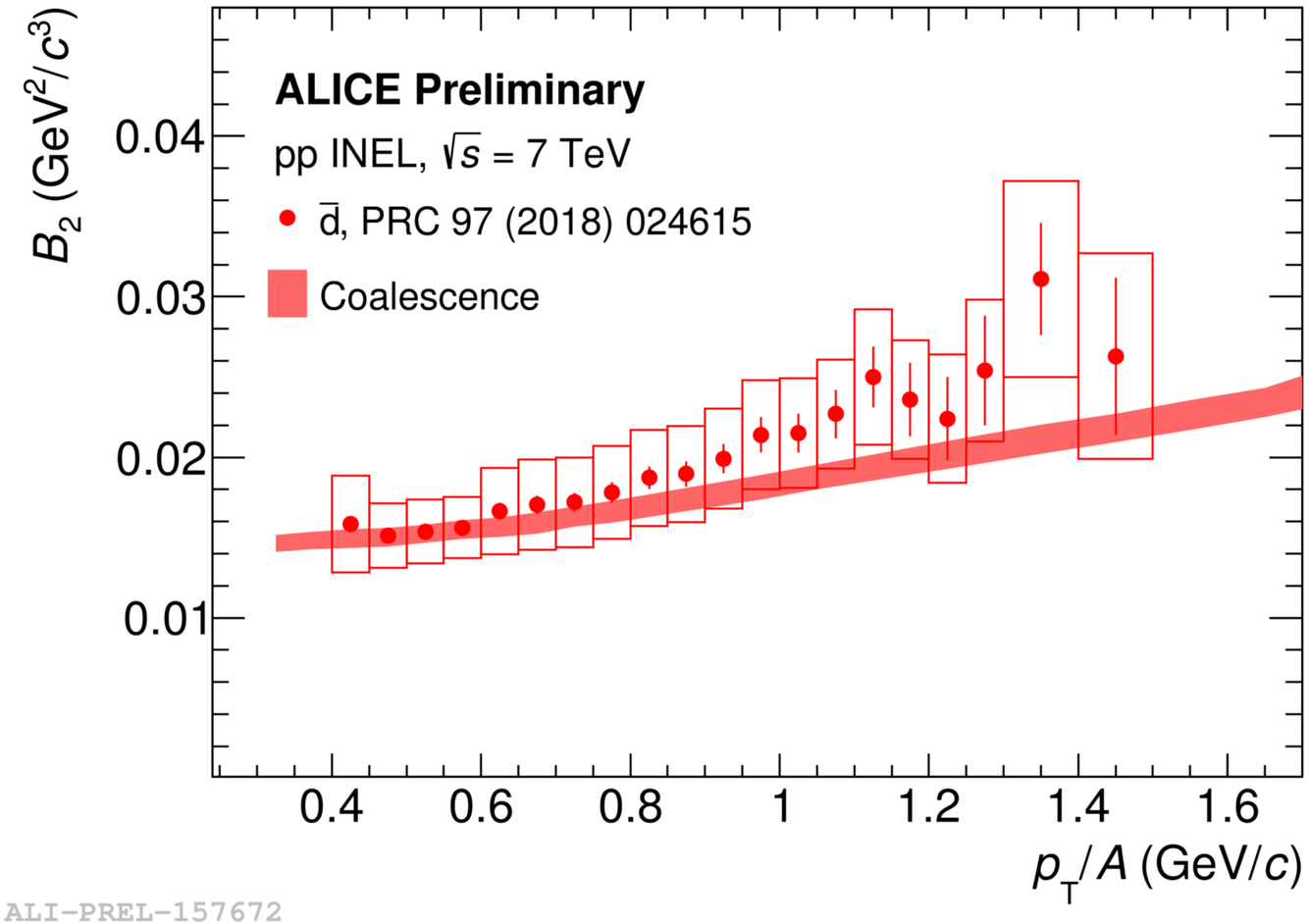
- The thermal model describes the production yields d*N*/d*y* in Pb-Pb collisions over a wide range of d*N*/d*y* (7 orders of magnitude)
- Also the yields of the nuclei are well reproduced
  - nuclei are thermally produced in the hadronisation, together with the other particle species

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

Multiplicity integrated B_2



- 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