Production of light (anti)(hyper)nuclei at the LHC

Luca Barioglio, on behalf of ALICE and LHCb
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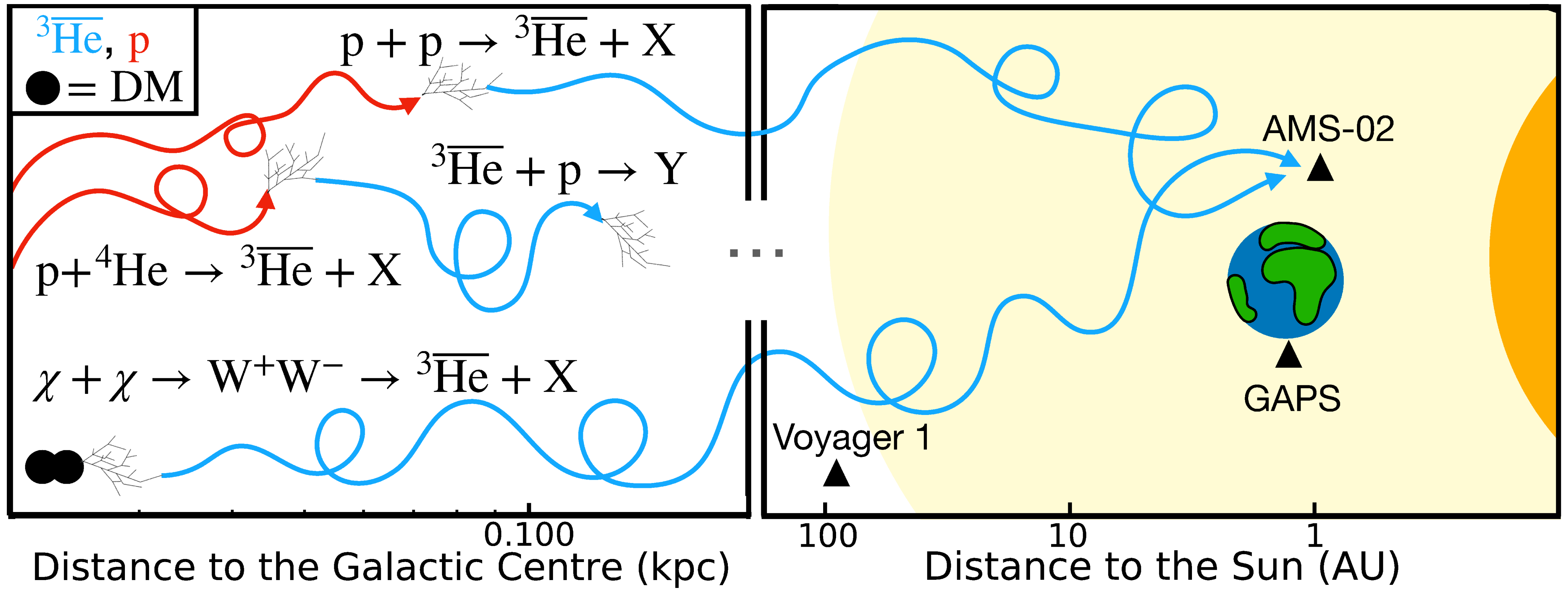
Physics motivation

- The study of the production mechanisms of (anti)(hyper)nuclei is not only interesting *per se*
- **Antinuclei** can be a sign of **Dark Matter annihilation**:
  - *Background*: production in the collisions between **cosmic rays** (CR) and the **interstellar medium** (ISM) (pp and p-A collisions)
    - Nuclear production must be known very well



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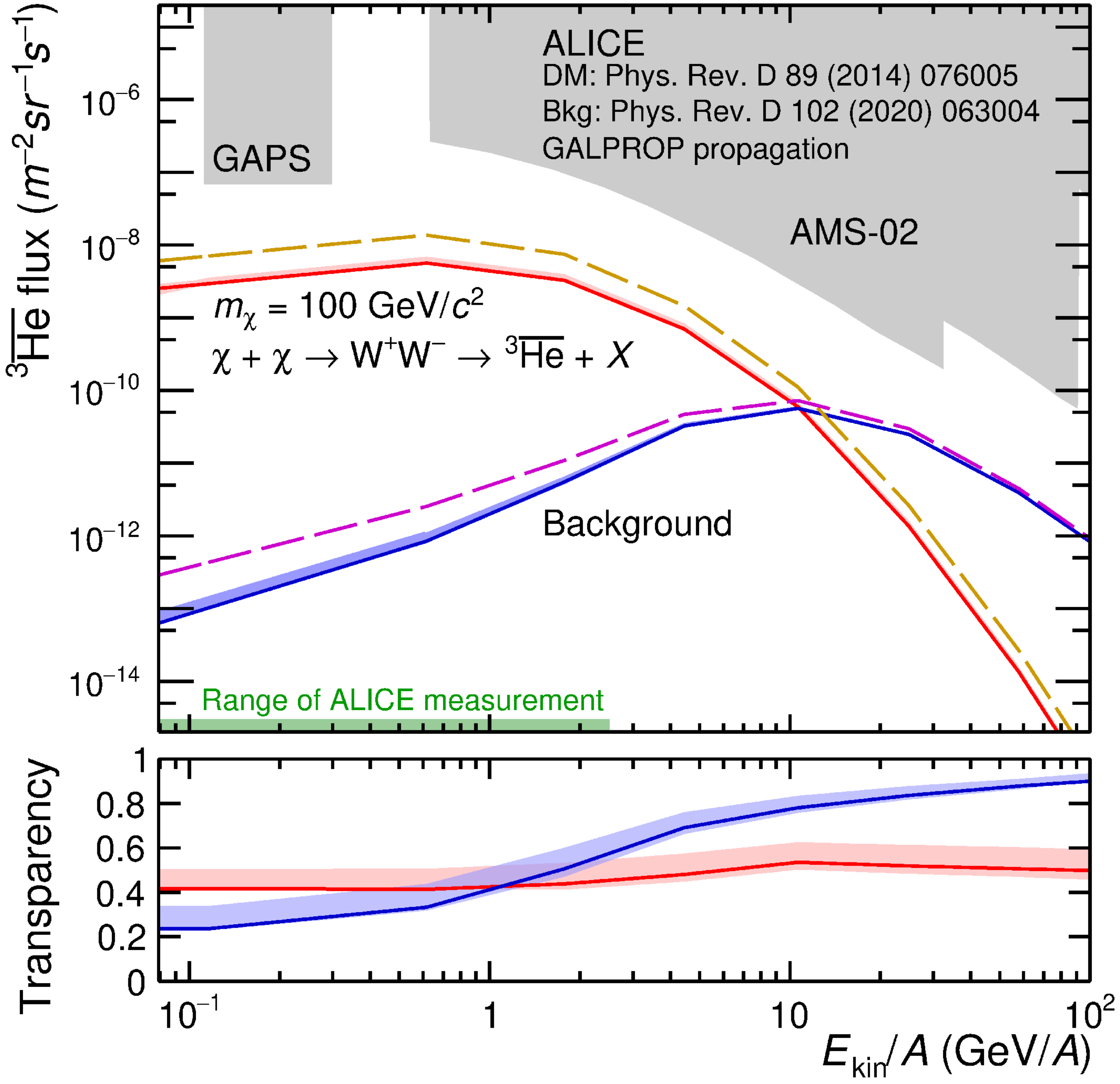

ALI-PUB-532060

Nature Phys. 19 (2023) 1, 61-71

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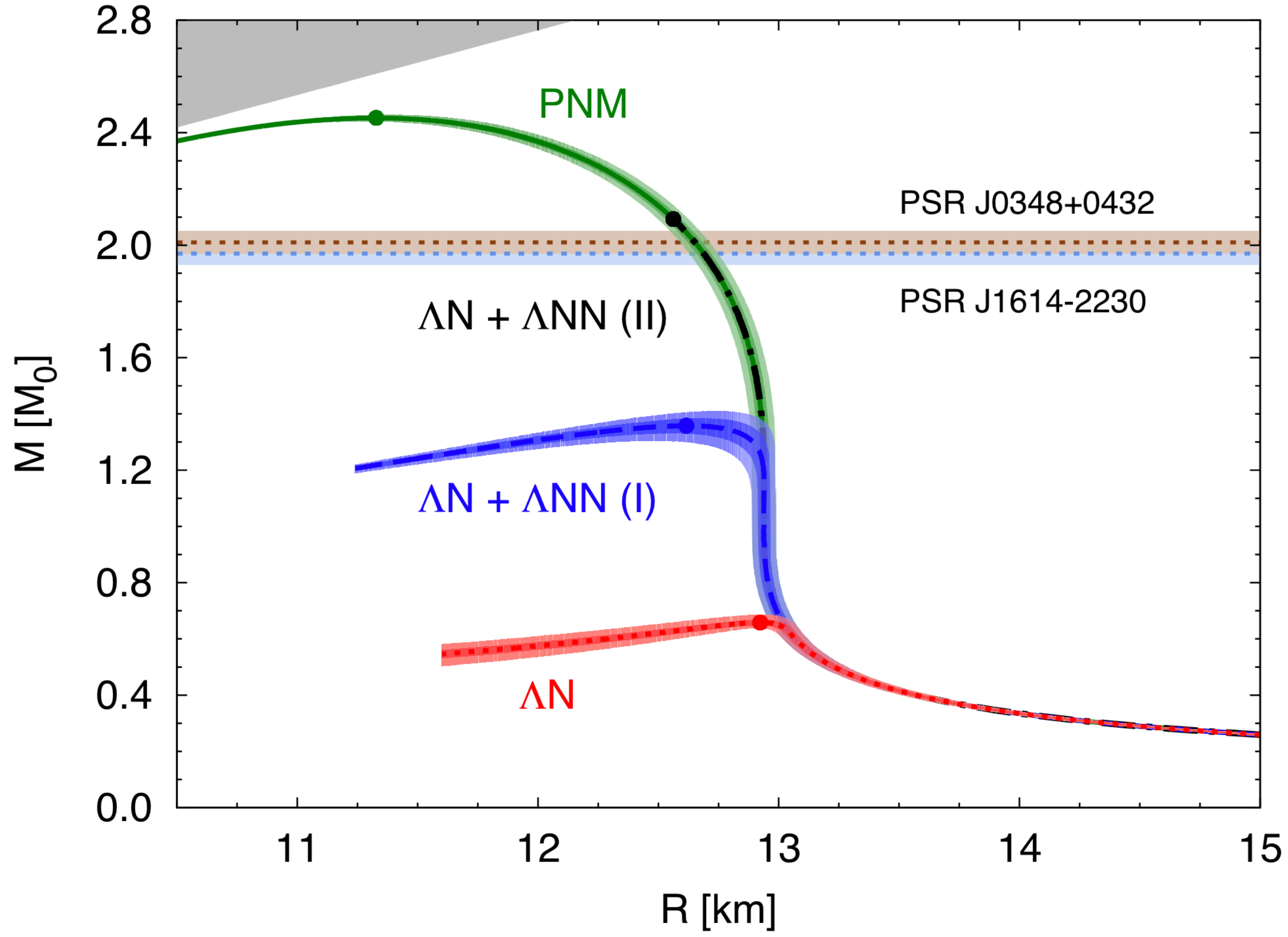
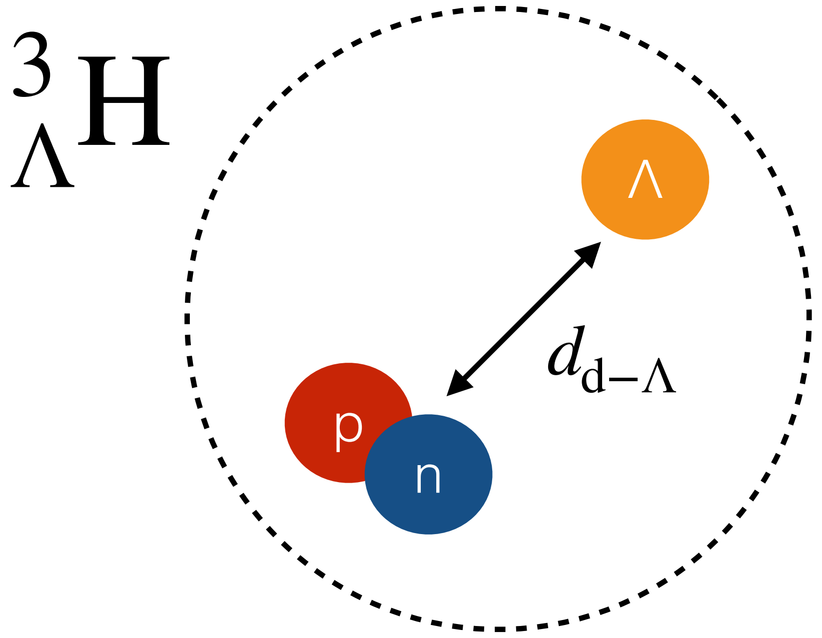
  - *Background*: production in the collisions between **cosmic rays** (CR) and the **interstellar medium** (ISM) (pp and p-A collisions)
    - Nuclear production must be known very well
- **Hypernuclei** can be used to study **nucleon-hyperon interaction**
  - Production of exotic bound states
  - Determination of the **equation of state**
    - Application to **neutron stars**

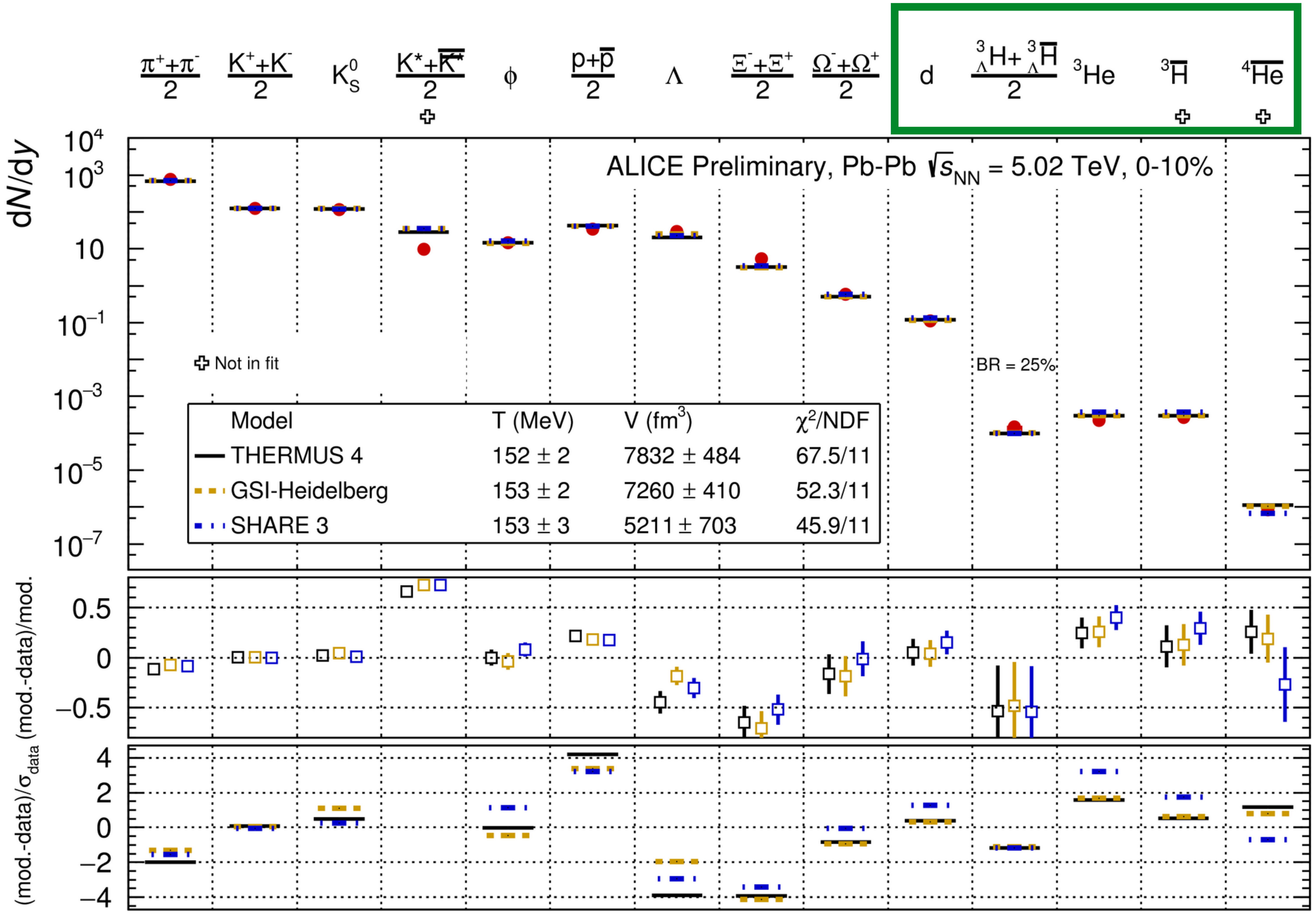


D. Lonardoni et al., PRL 114, 092301 (2015)



Production models

- **Statistical Hadronisation Model** (SHM)
  - describes the **yields** of light-flavoured hadrons by requiring **thermal** and **hadron-chemical equilibrium**
    - Parameters: (T, V, μ_B)
  - **Canonical ensemble** (CSM): local conservation of quantum numbers (S, Q and B)(1)



ALI-PREL-332406

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(1) V. Vovchenko et al., PLB 785 (2018) 171-174

Production models

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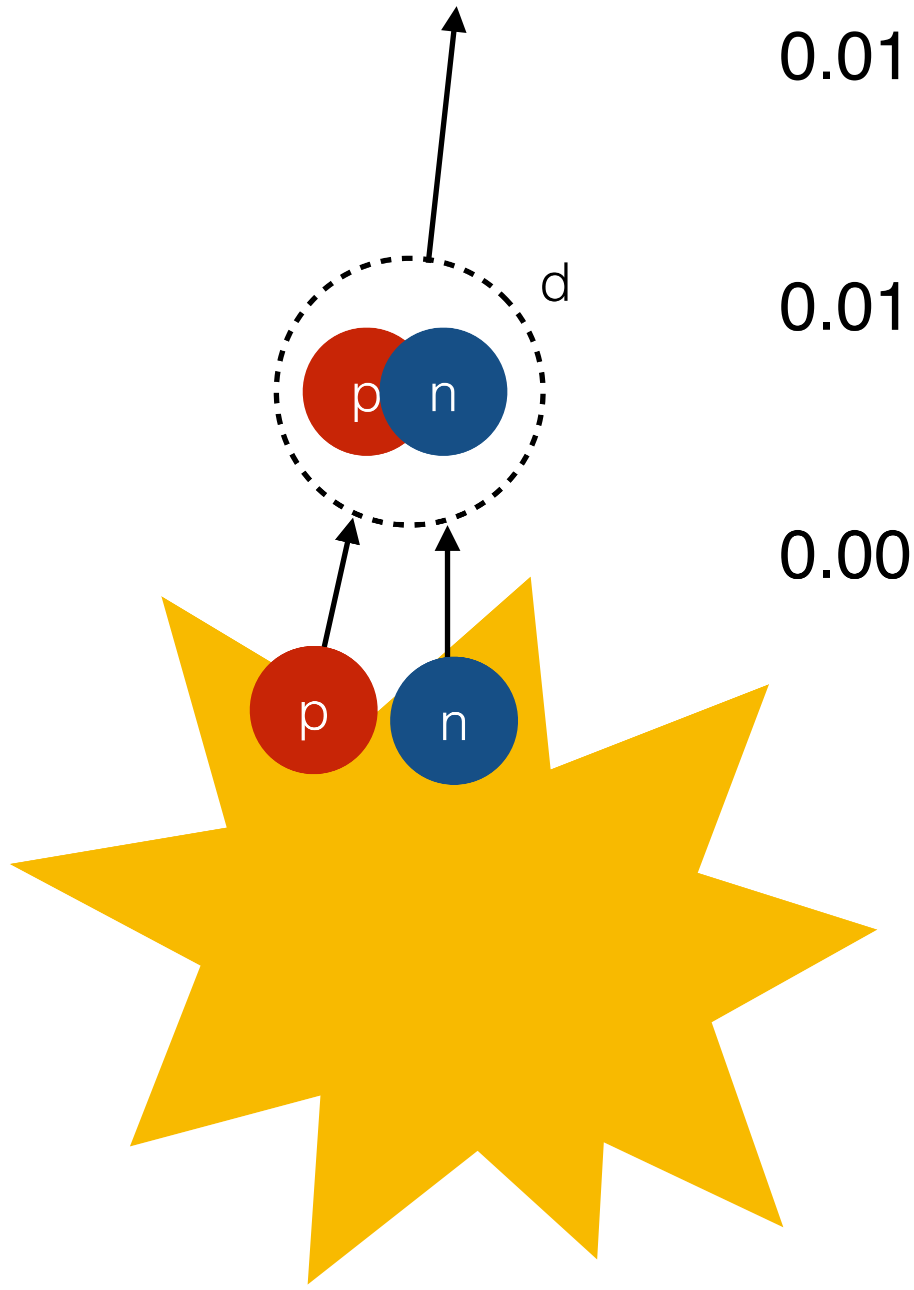
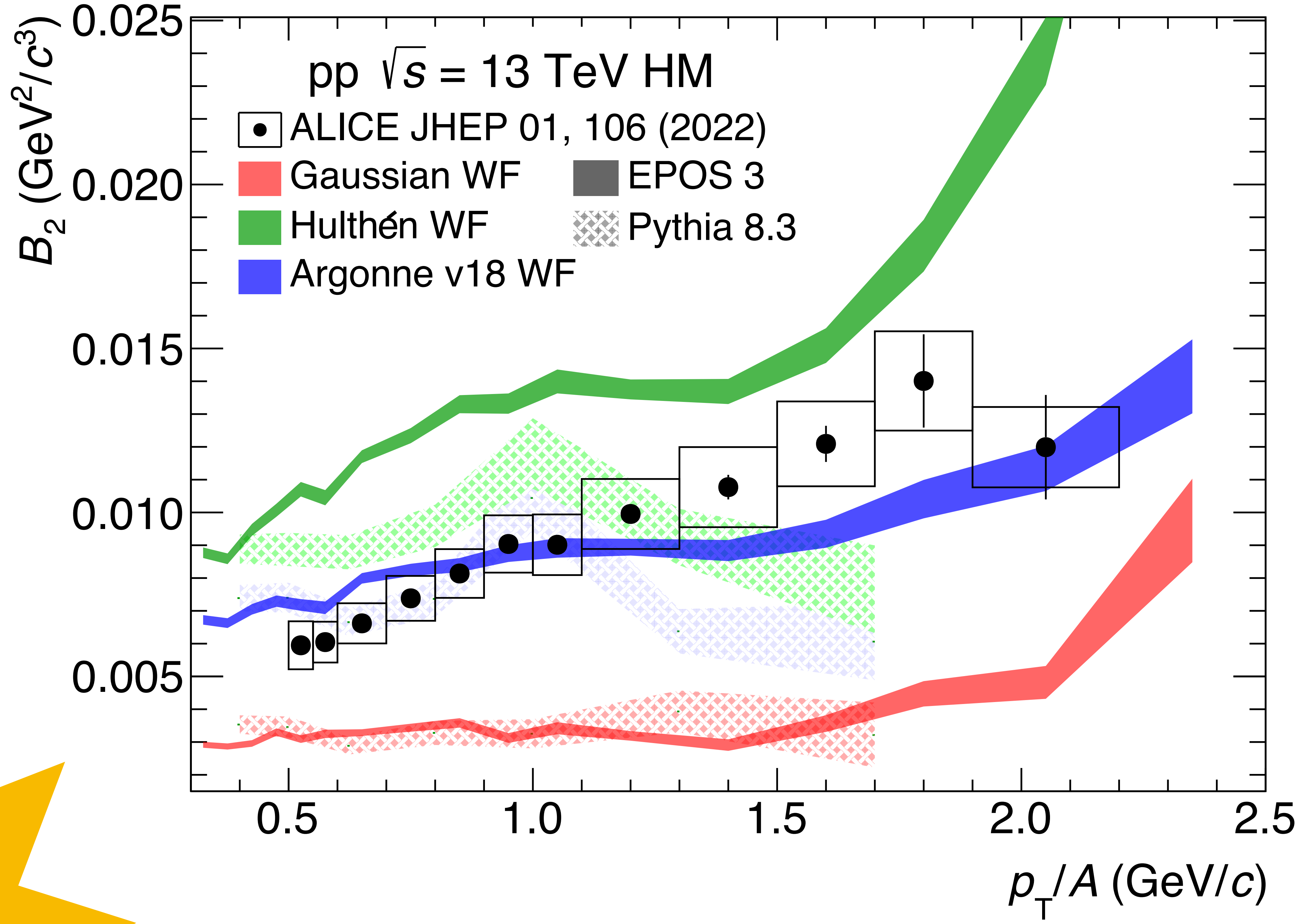
    - Parameters: (T, V, μ_B)
  - **Canonical ensemble** (CSM): local conservation of quantum numbers (S, Q and B)
- **Coalescence**⁽¹⁾:
  - Nuclei are formed by **nucleons** emitted by a **freeze-out hypersurface**
    - convolution between **nucleon phase-space** distribution and **Wigner function** of the nucleus⁽²⁾
  - **Coalescence parameter** B_A, related to formation probability via coalescence:

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



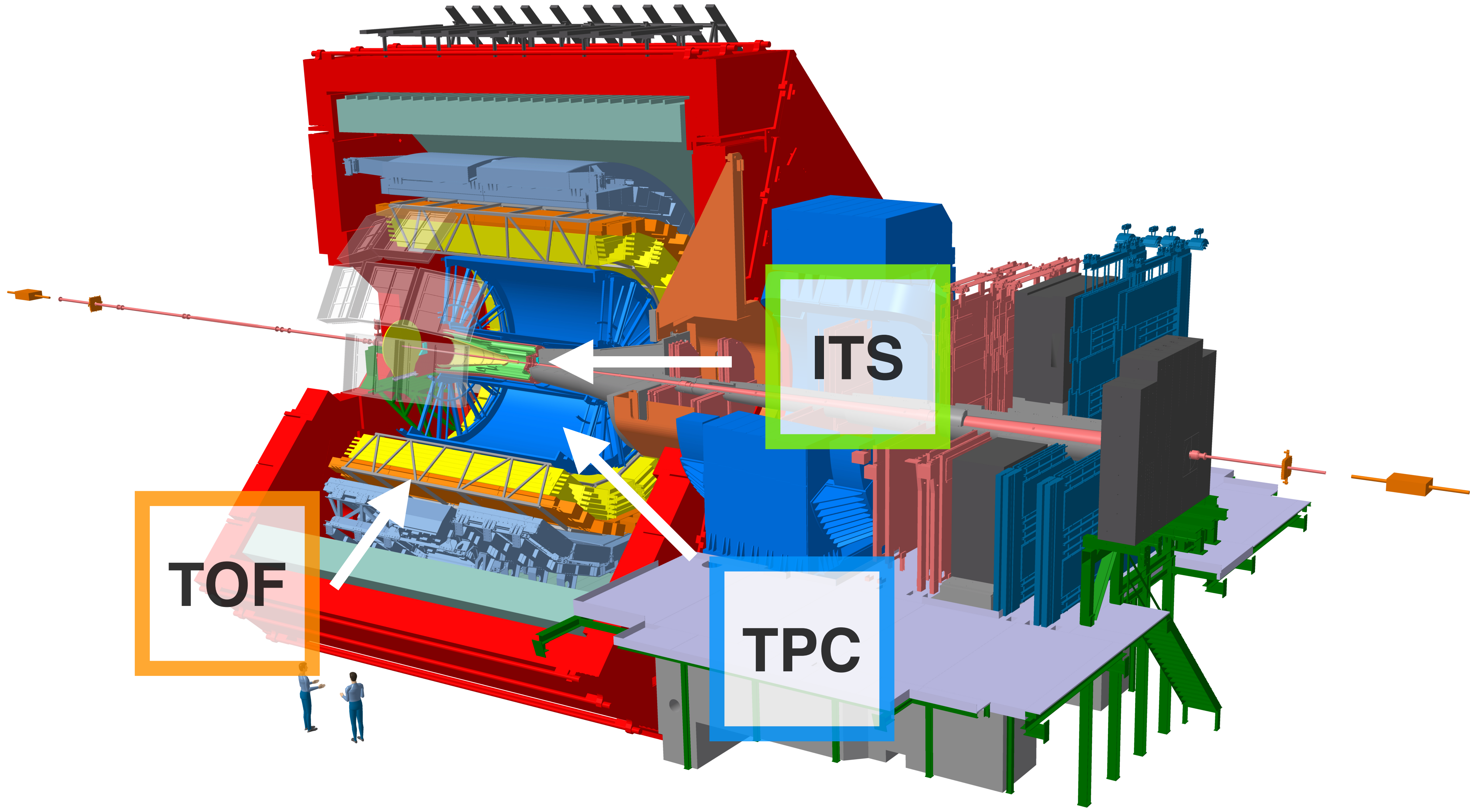


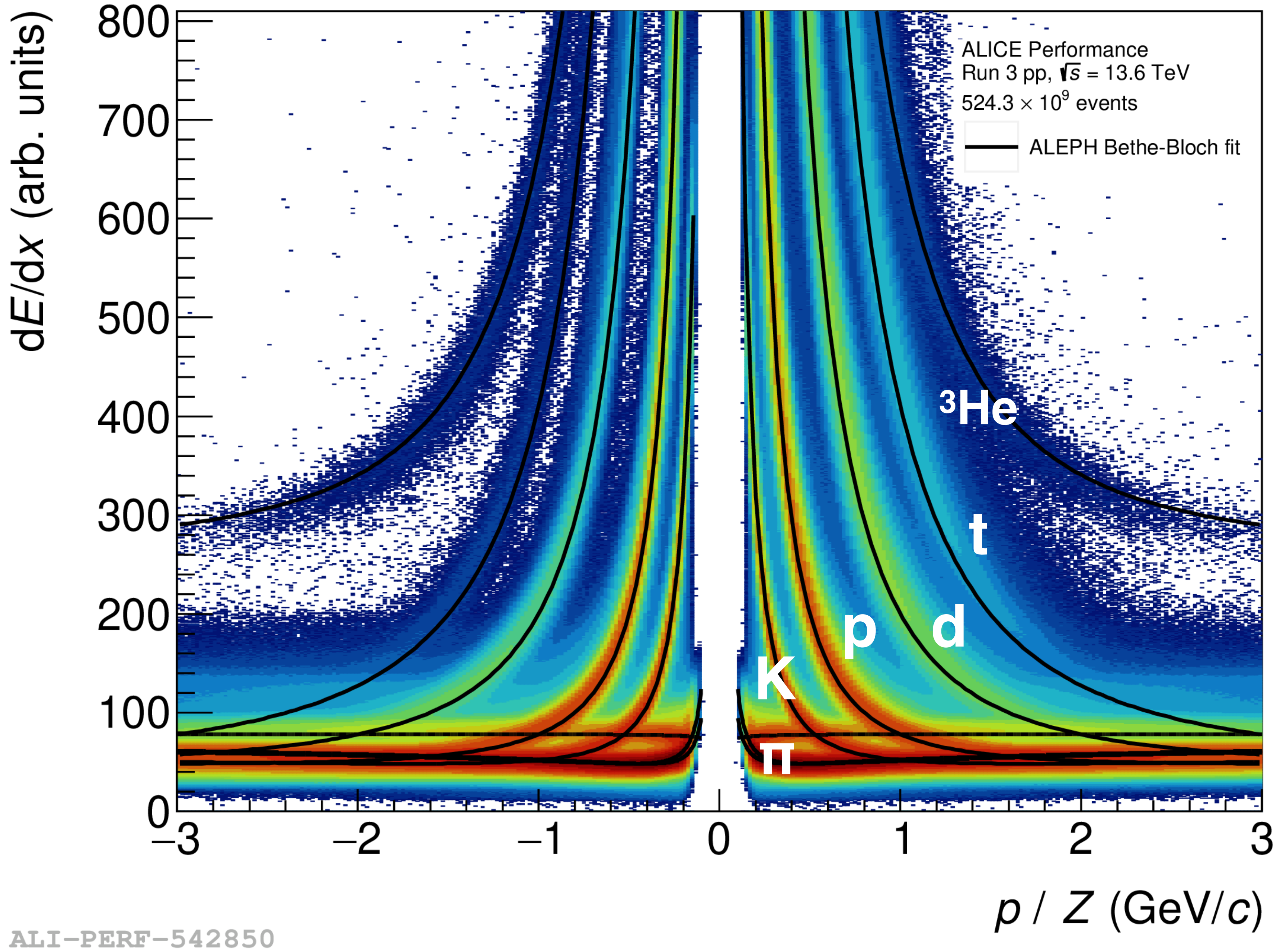
(2) Mahlein et al., EPJC 83 (2023) 9, 804

(1) J. I. Kapusta, PRC 21, 1301 (1980)

The ALICE experiment

- **ALICE** was the first experiment at the LHC to measure light (anti)(hyper)nuclei
- Measurements at mid rapidity: **$|\eta| < 0.8$**
- Different PID techniques:
  - Specific energy loss **d*E*/dx** in the **TPC** ($\sigma \sim 6\%$)
  - Time of flight (hence **$\beta = \Delta t / L$**) with the **TOF** ($\sigma \sim 70$ ps)





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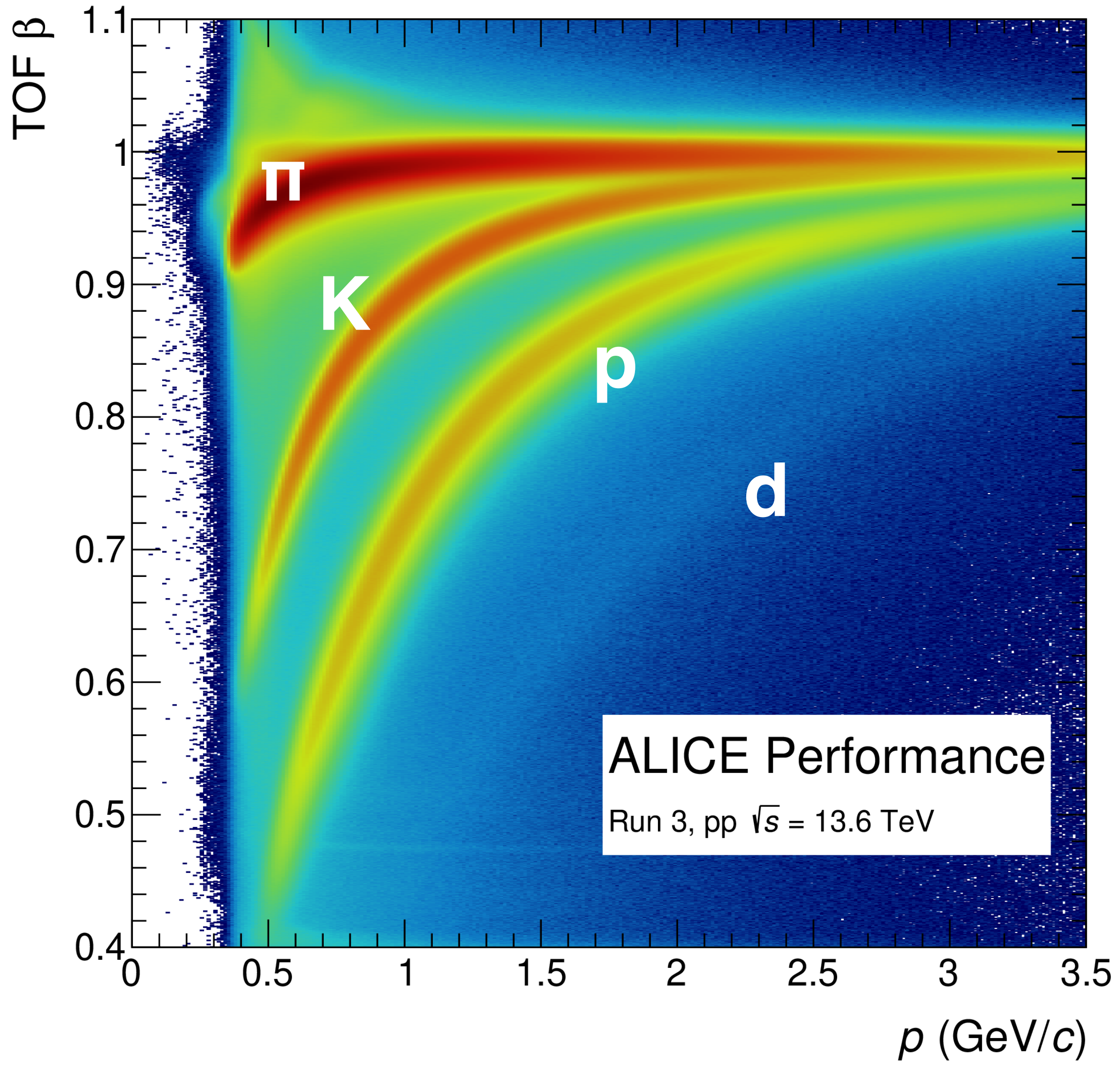

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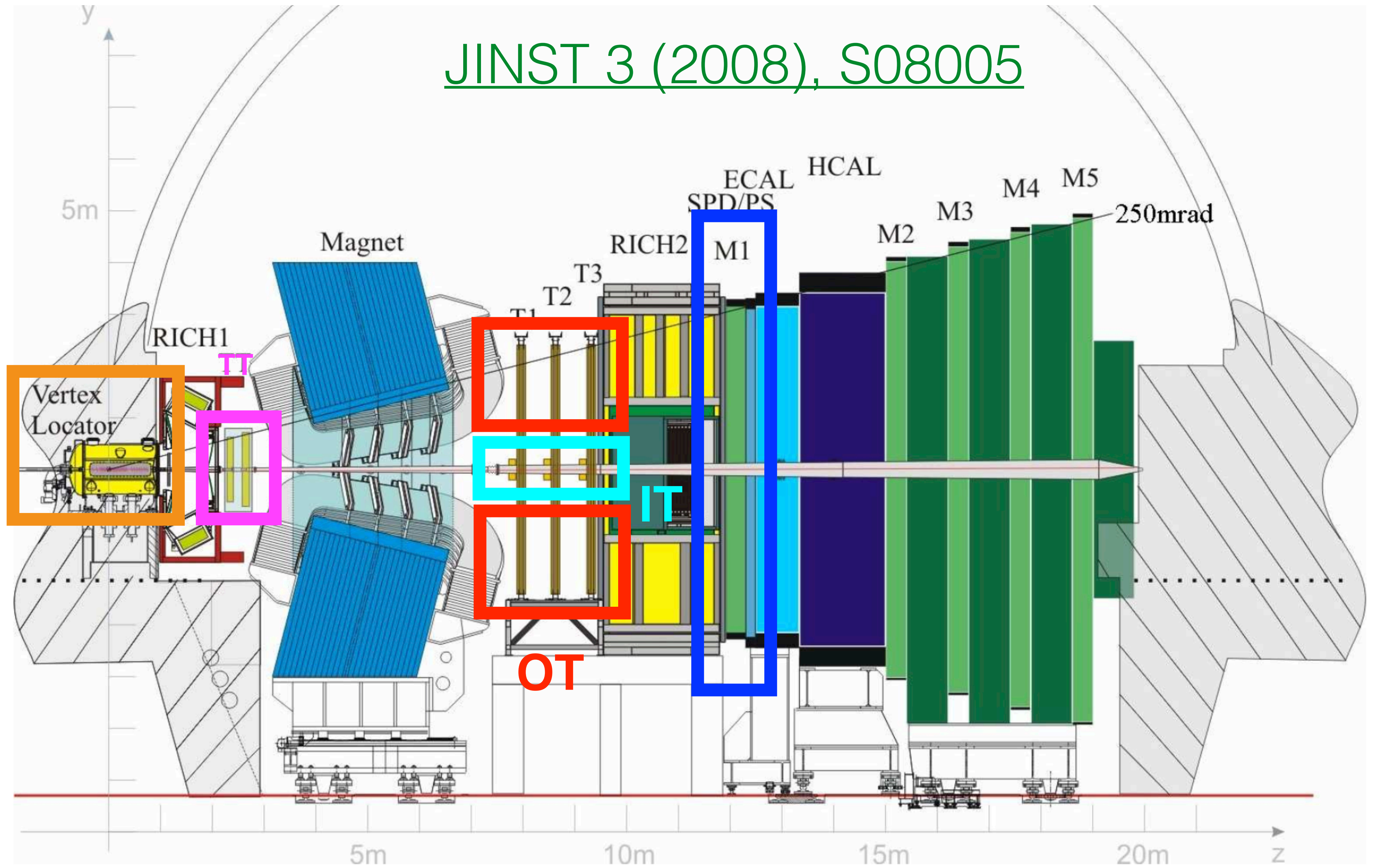
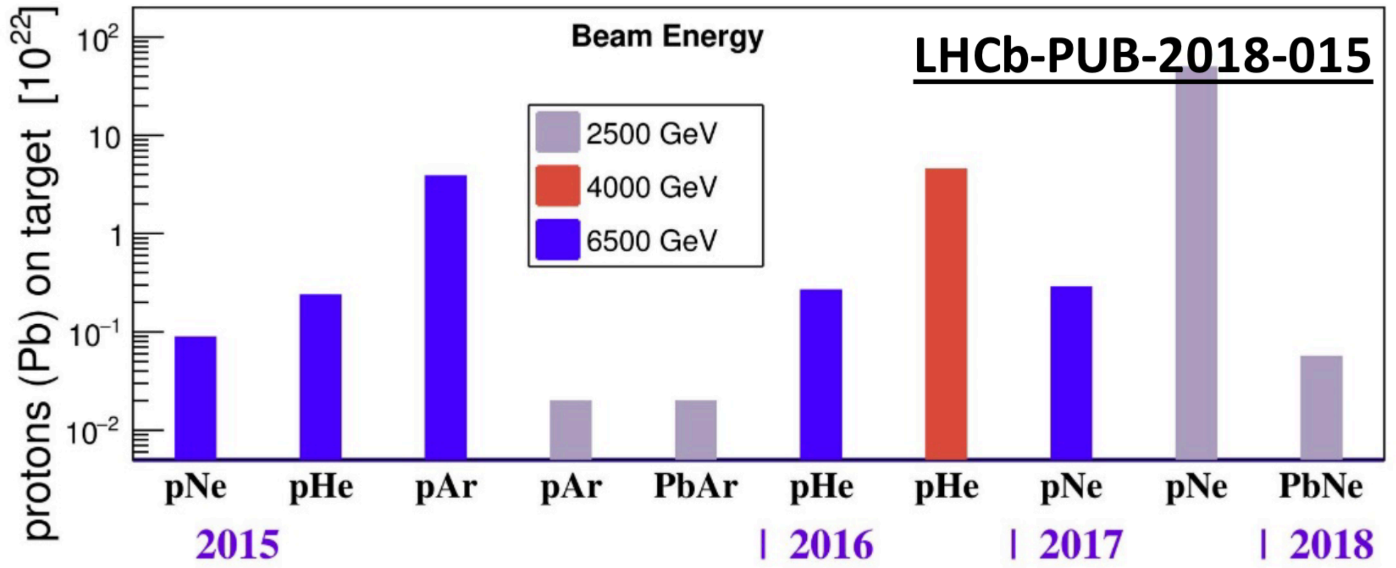
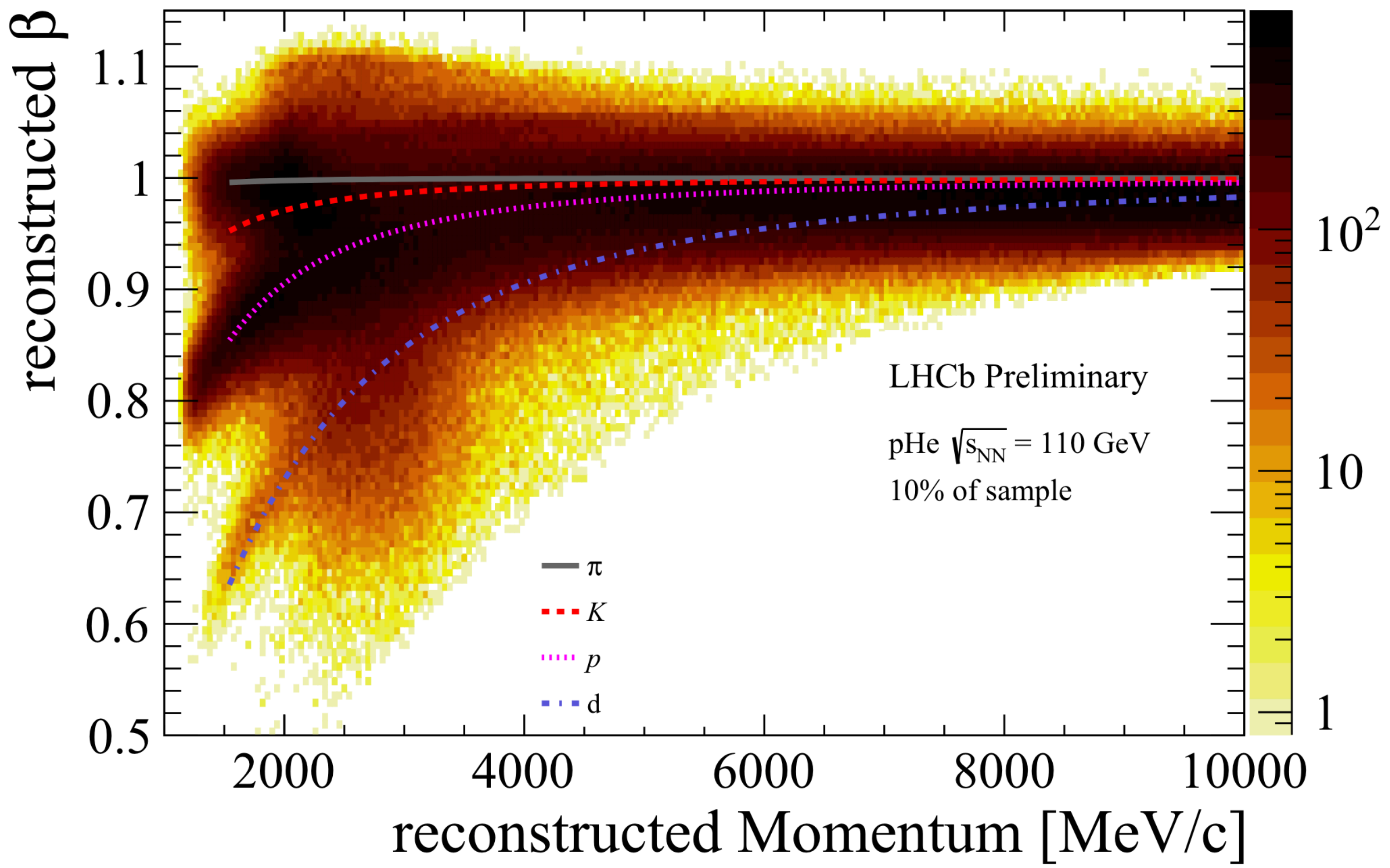
The LHCb experiment

- **LHCb** has recently joined the measurement of light (anti)(hyper)nuclei
- Measurements at forward rapidity: **2 < η < 5**
  - complementary to ALICE!
- With the **SMOG** system can be used as a **fixed-target** experiment
  - Extend the measurement to different systems and energies: $\sqrt{s_{\mathrm{NN}}} \in [30,115]\,\mathrm{GeV}$


JINST 3 (2008), S08005


LHCb-PUB-2018-015

- Different **PID** techniques for **nuclei**:
  - Specific energy loss **d*E*/dx** in **VELO**, **TT**, **IT** and **OT**
    - $\frac{dE}{dx} \propto z^2$ → ^{3}He and ^{4}He are well separated
  - Time of flight (hence **β = Δt / L**) with **OT** and **M1**
    - identify **d**, separate ^{3}He and ^{4}He

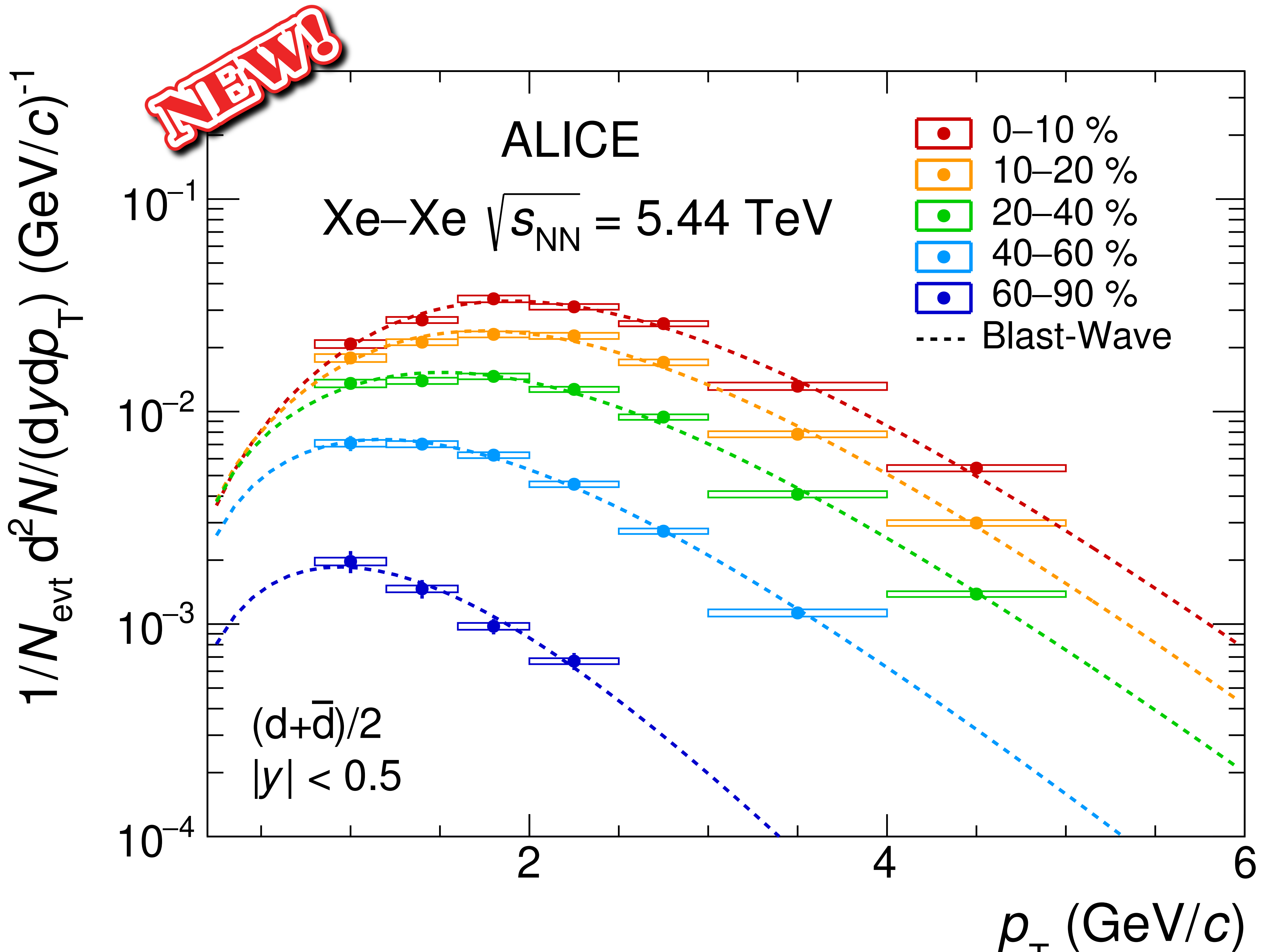

LHCB-FIGURE-2023-017

Production spectra of nuclei at mid rapidity

- ALICE measured production spectra of nuclei in pp, p-Pb, Xe-Xe and Pb-Pb collisions at mid rapidity

- Measurements in classes of multiplicity or centrality
  - related to system size

- Main observables:
  - Ratio of p_T-integrated yields **A/p**
  - Coalescence parameter $\boldsymbol{B_A}$



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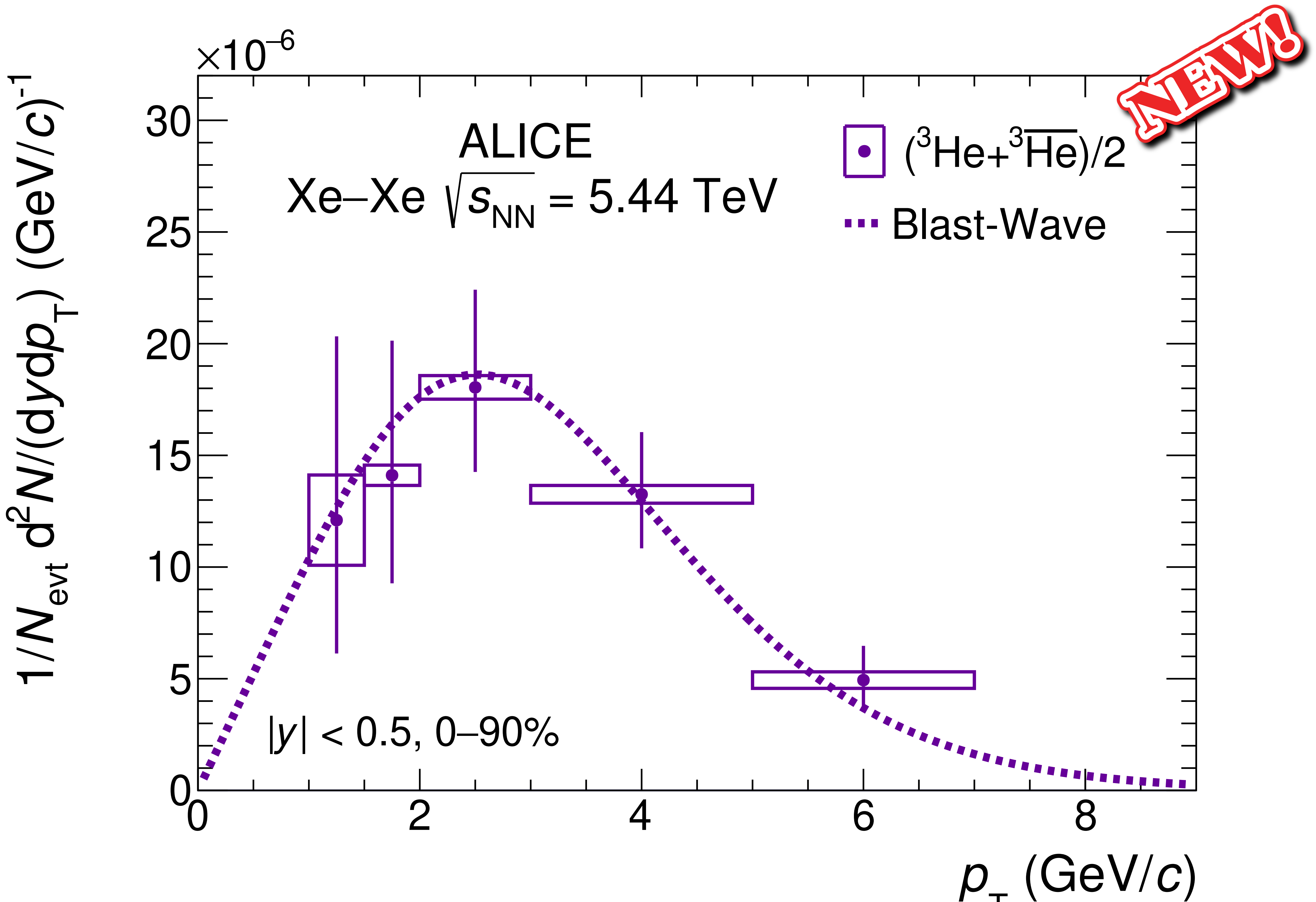
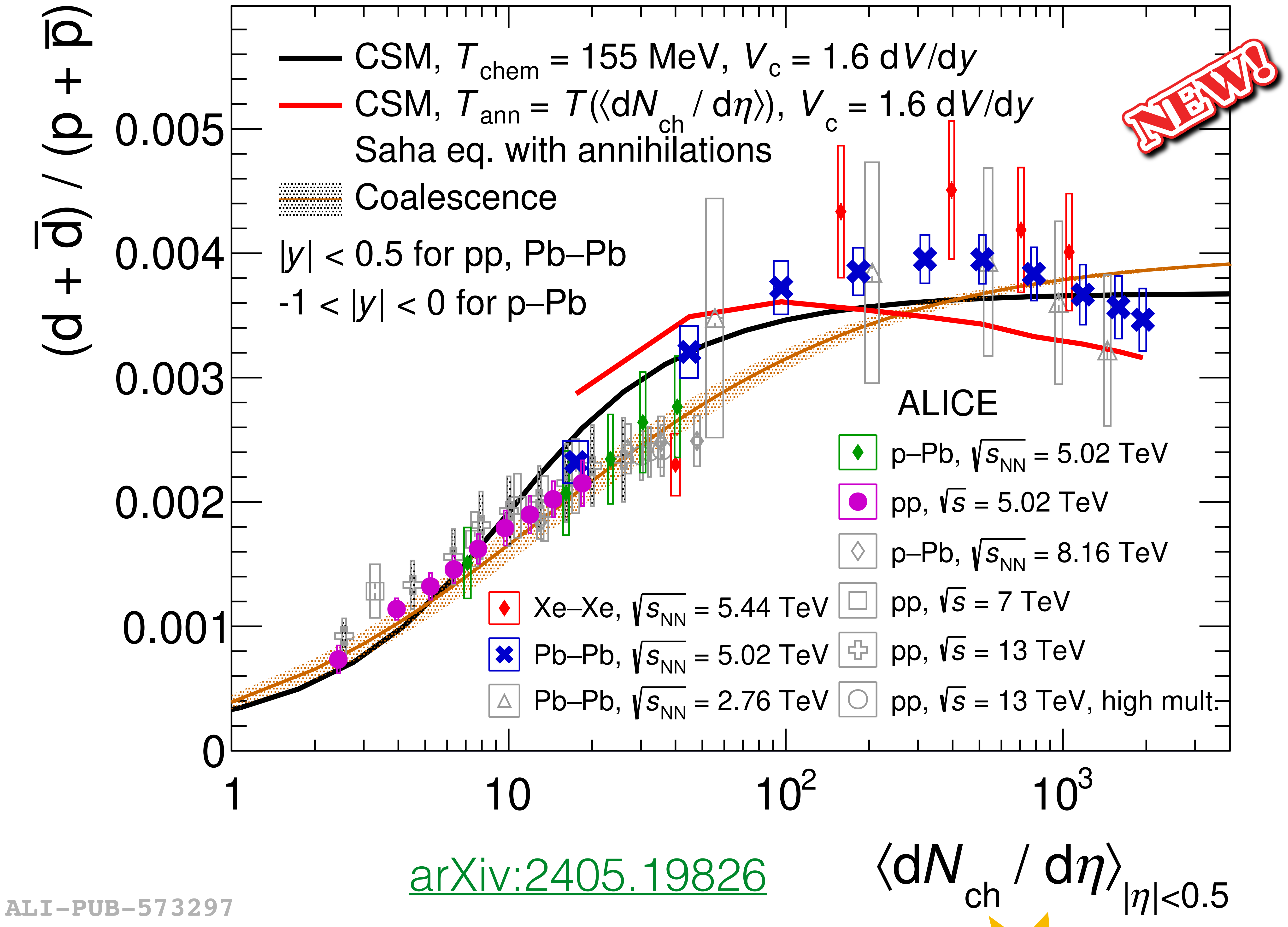


ALI-PUB-573287

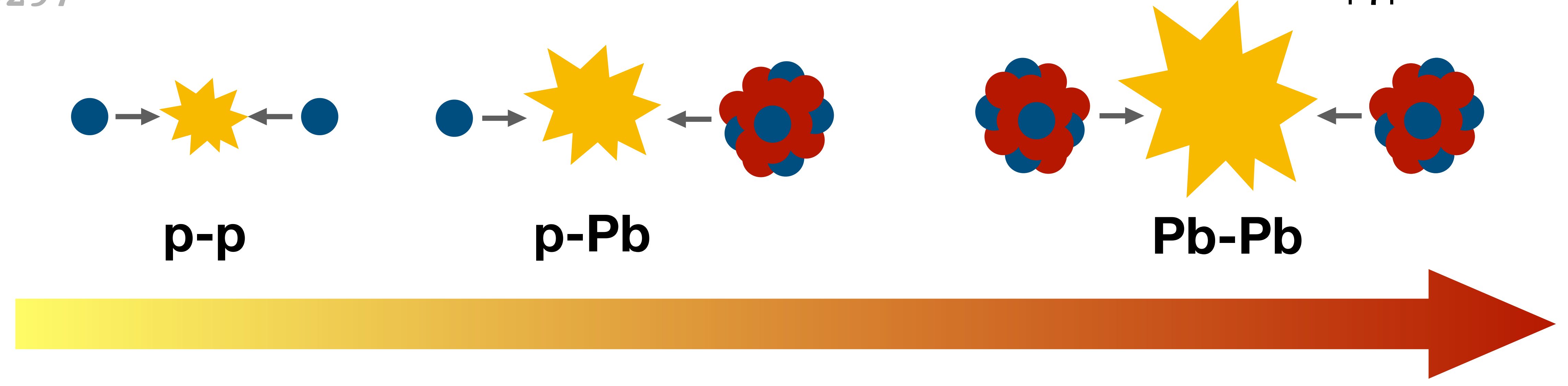
arXiv:2405.19826

The (anti)deuteron

- **d/p** ratio evolves **smoothly** with **multiplicity**
  - dependence on the **system size**
- For **d/p** ratio both the models describe the data:
  - CSM: canonical suppression
  - **Coalescence model**: interplay between system size and nuclear size



arXiv:2405.19826



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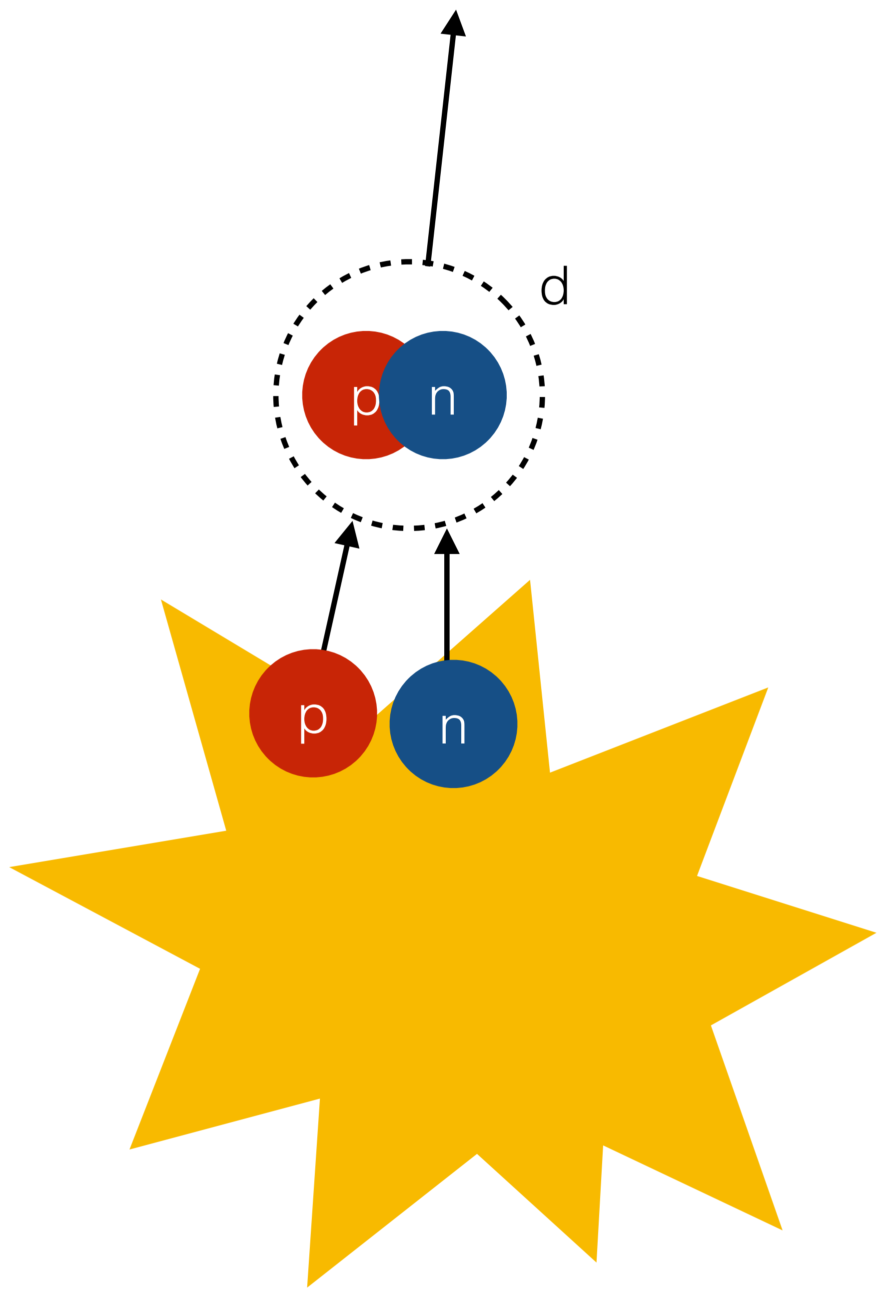
- For **d/p** ratio both the models describe the data:
  - CSM: canonical suppression
  - **Coalescence model**: interplay between system size and nuclear size
- Possible to implement **event-by-event coalescence**, with probability:

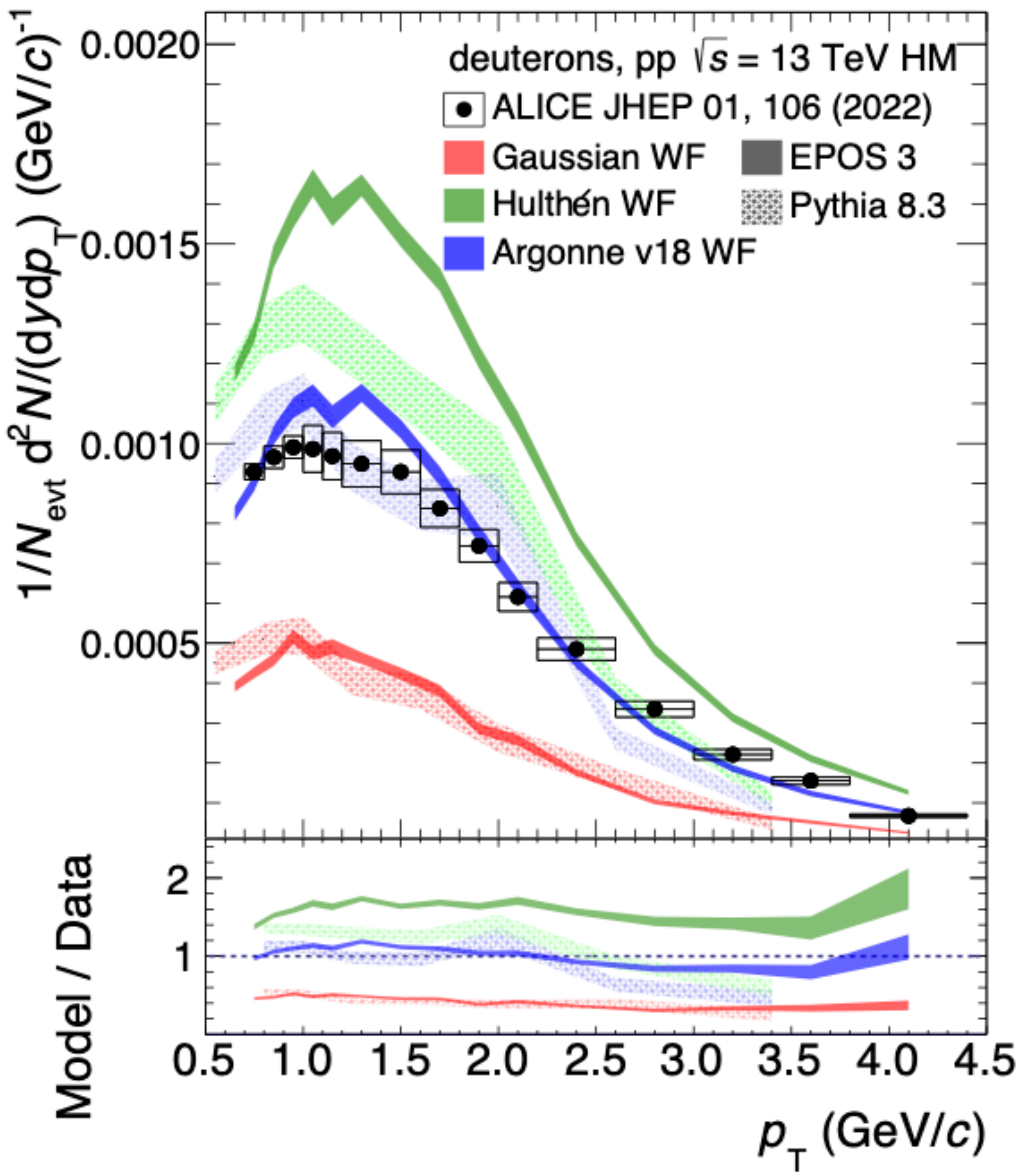
$$\mathscr{P}(r_0, q) = \int d^3r_\mathrm{d} \int d^3r \;\; H_\mathrm{pn}(\vec{r}, \vec{r}_\mathrm{d}; r_0) \;\; \mathscr{D}(\vec{q}, \vec{r})$$

  - ***r*₀** is the size of the emitting source
  - ***q*** is te relative p-n momentum



Two-particle emitting source:
average two-particle distance

Wigner transform of the
deuteron wavefunction

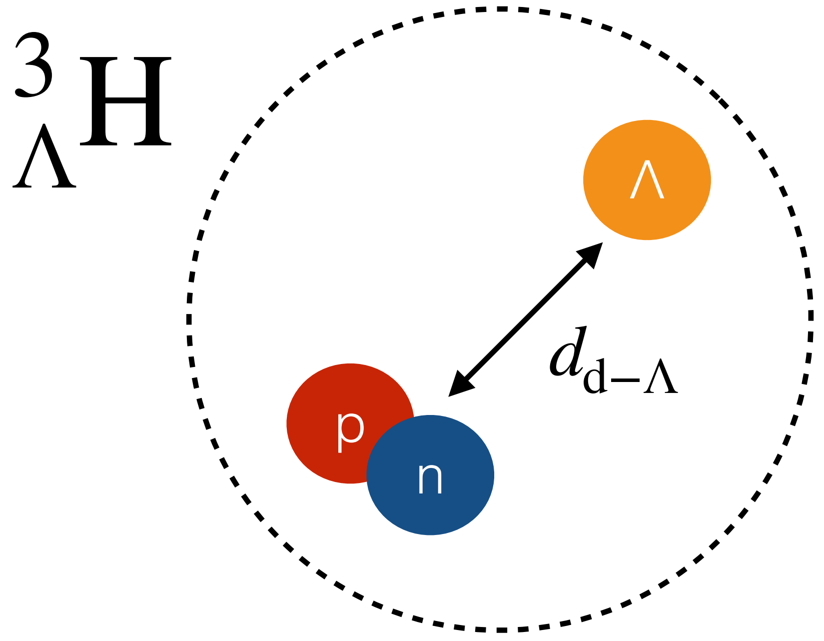


Mahlein et al., EPJC 83 (2023) 9, 804

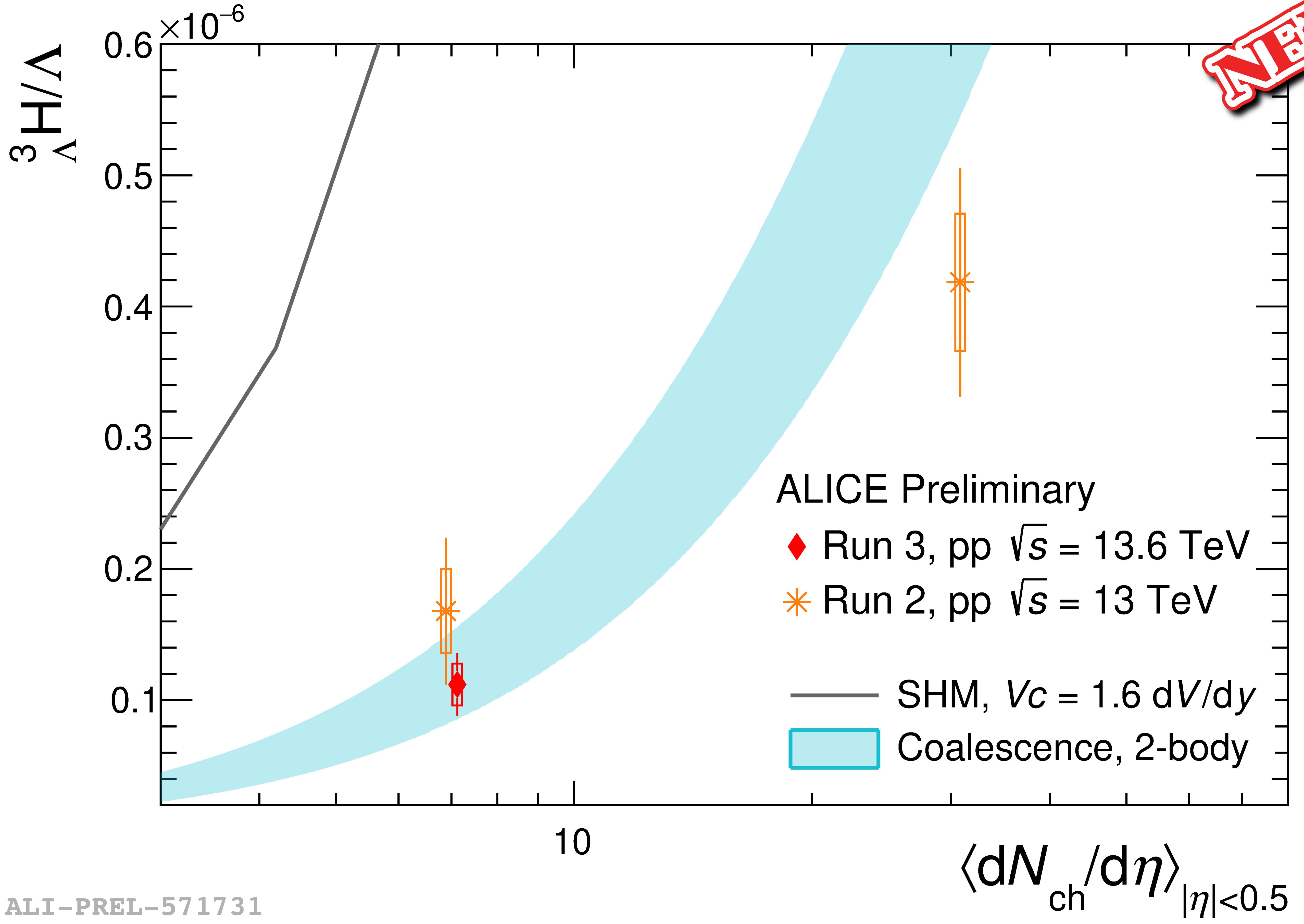
- **production** measurements to constrain the **nuclear wave function**

Hypertriton production in pp

- ${}^{3}_{\Lambda}\mathrm{H}$ has a large size:
  - $d_{\mathrm{d-\Lambda}} = 10.79\ \mathrm{fm}$ (1), $r\left(\mathrm{d}\right) = 1.96\ \mathrm{fm}$
- **SHM** and **coalescence** predictions for Hypertriton are very **different at low multiplicity**
  - measurement in **pp** collisions can be a **conclusive test** for the **production** models
- ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ is compared with the prediction of CSM and coalescence model
  - **Two-body coalescence** model provides the best description of data



NEW!



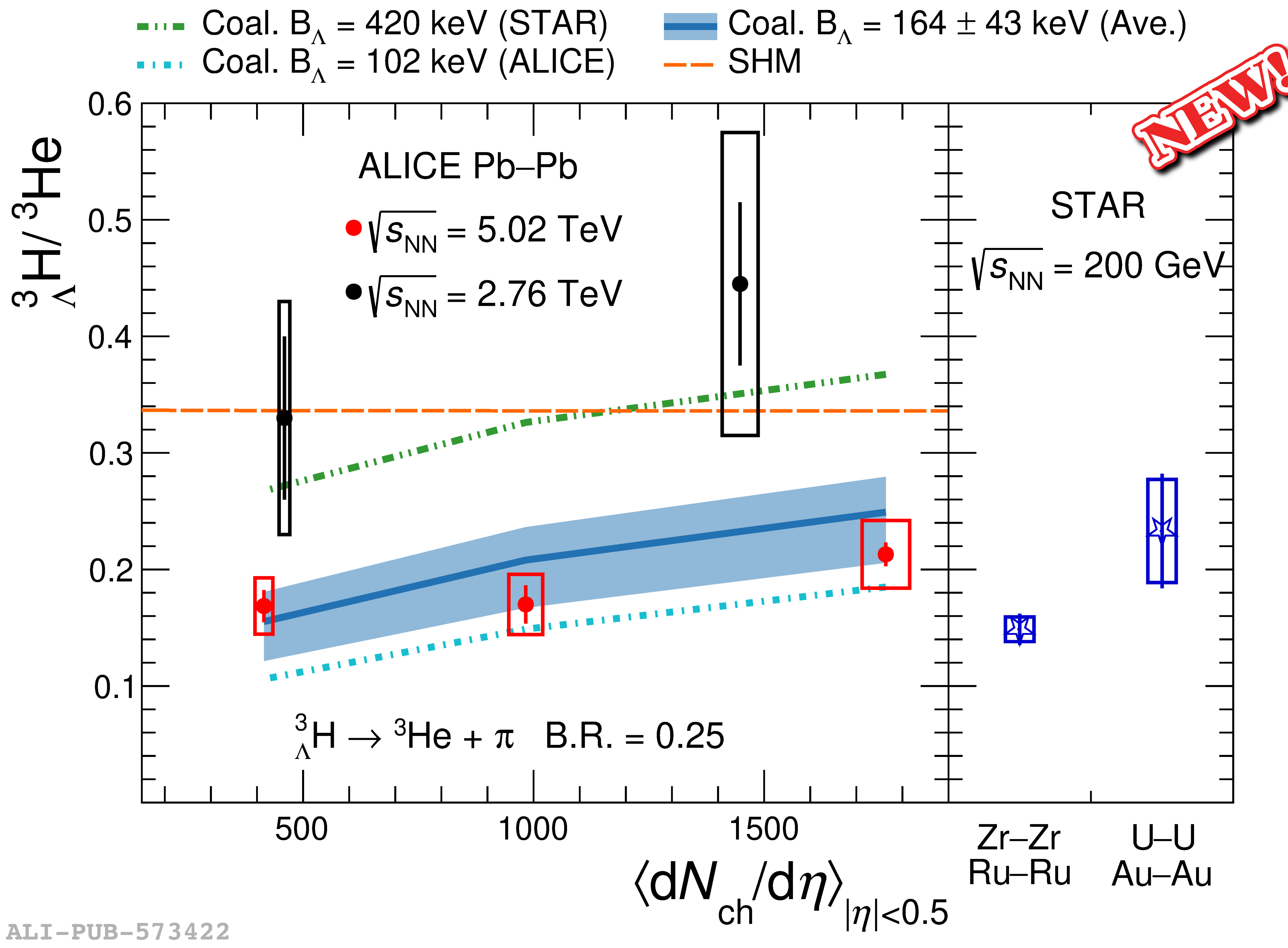
ALI-PREL-571731

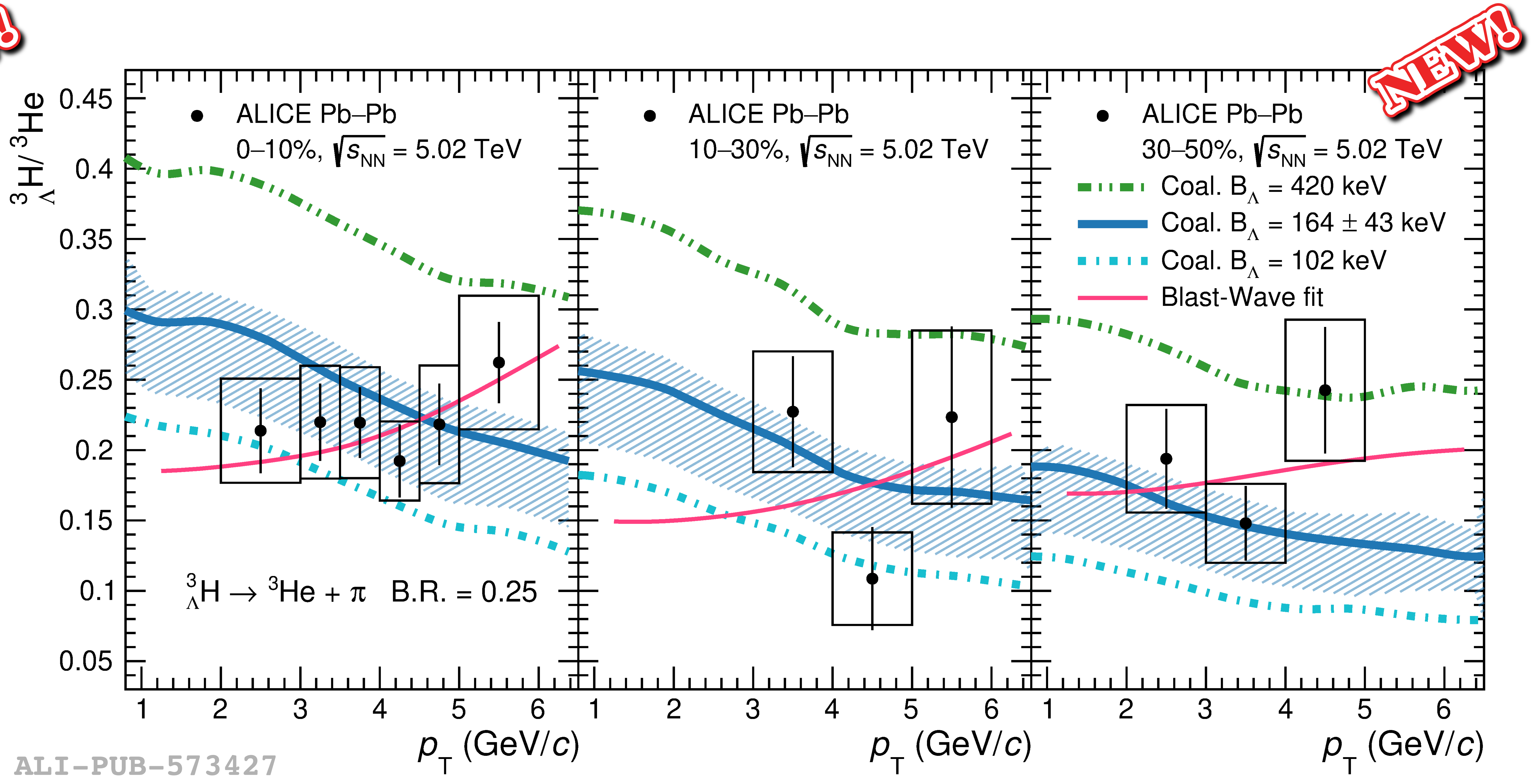
Hypertriton in pp favours coalescence!

(1) F. Hildenbrand and H.-W. Hammer, Phys. Rev. C 100, 034002

Hypertriton production in Pb-Pb

- ${}^{3}_{\Lambda}\mathrm{H}$ has also been recently measured in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5 TeV
  - More precise wrt Pb-Pb at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV
- ${}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}$ shows good agreement with coalescence, assuming $B_{\Lambda} < 170$ KeV
  - p_{T} differential measurement in agreement with blast-wave with common parameters with other nuclei





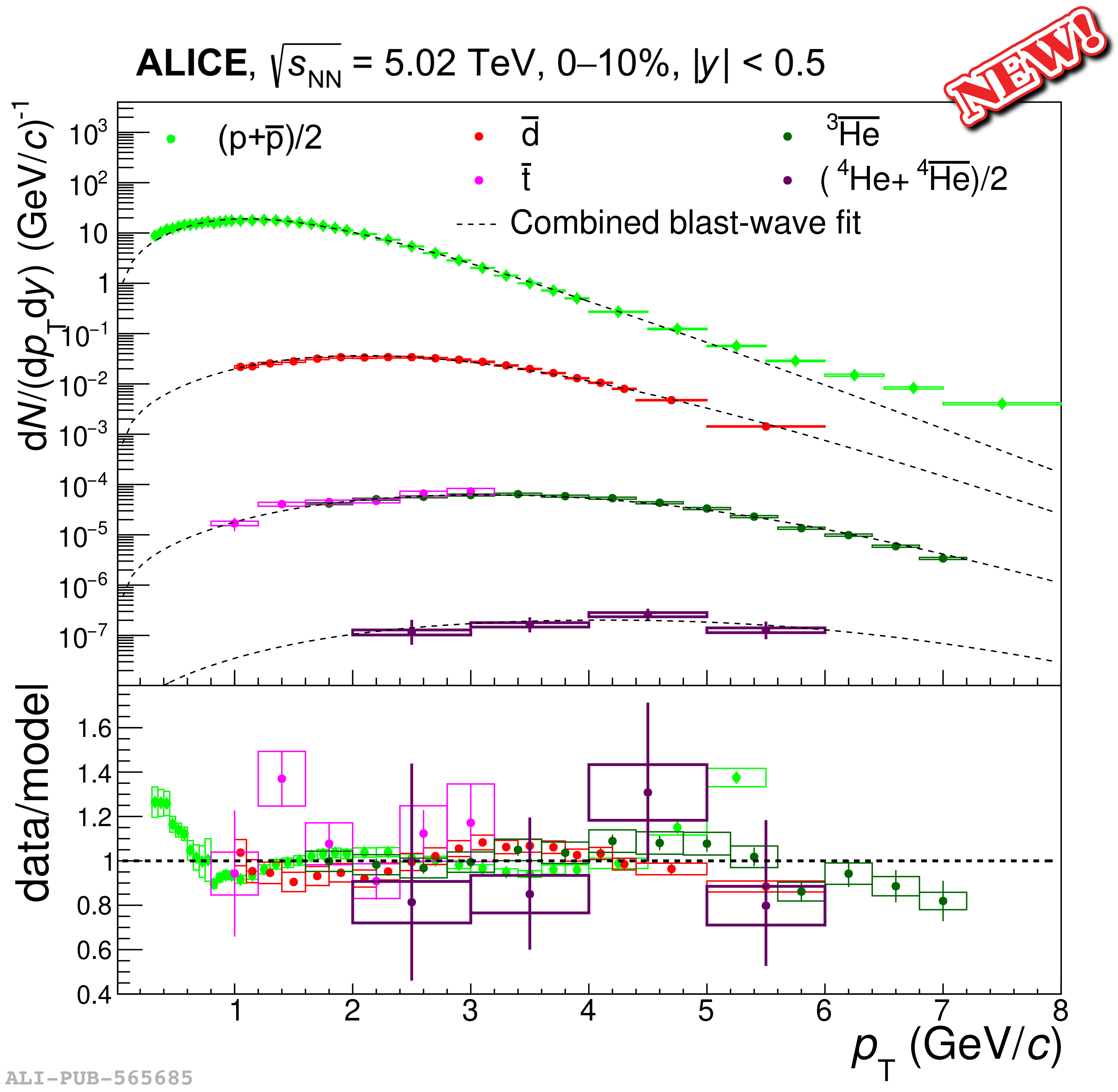
arXiv:2405.19839

^{4}He in Pb-Pb collisions

- ALICE has measured the production spectra for (anti)^{4}He in Pb-Pb
- ^{4}He is more bound and compact than lighter nuclei:
    - $E_B(^4\mathrm{He}) \sim$ 28 MeV, $r(^4\mathrm{He}) \sim$ 1.7 fm
- p_T spectra are well reproduced by a blast wave, using common parameters with the other nuclei

Nucleus	Radius (fm)
d	2.1421 ± 0.0088
t	1.7591 ± 0.0363
^{3}He	1.9661 ± 0.0030
^{4}He	1.6755 ± 0.0028

I. Angeli, K. Marinova, Atom.Data Nucl.Data Tabl. 99 (2013) 1, 69-95



arXiv:2311.11758

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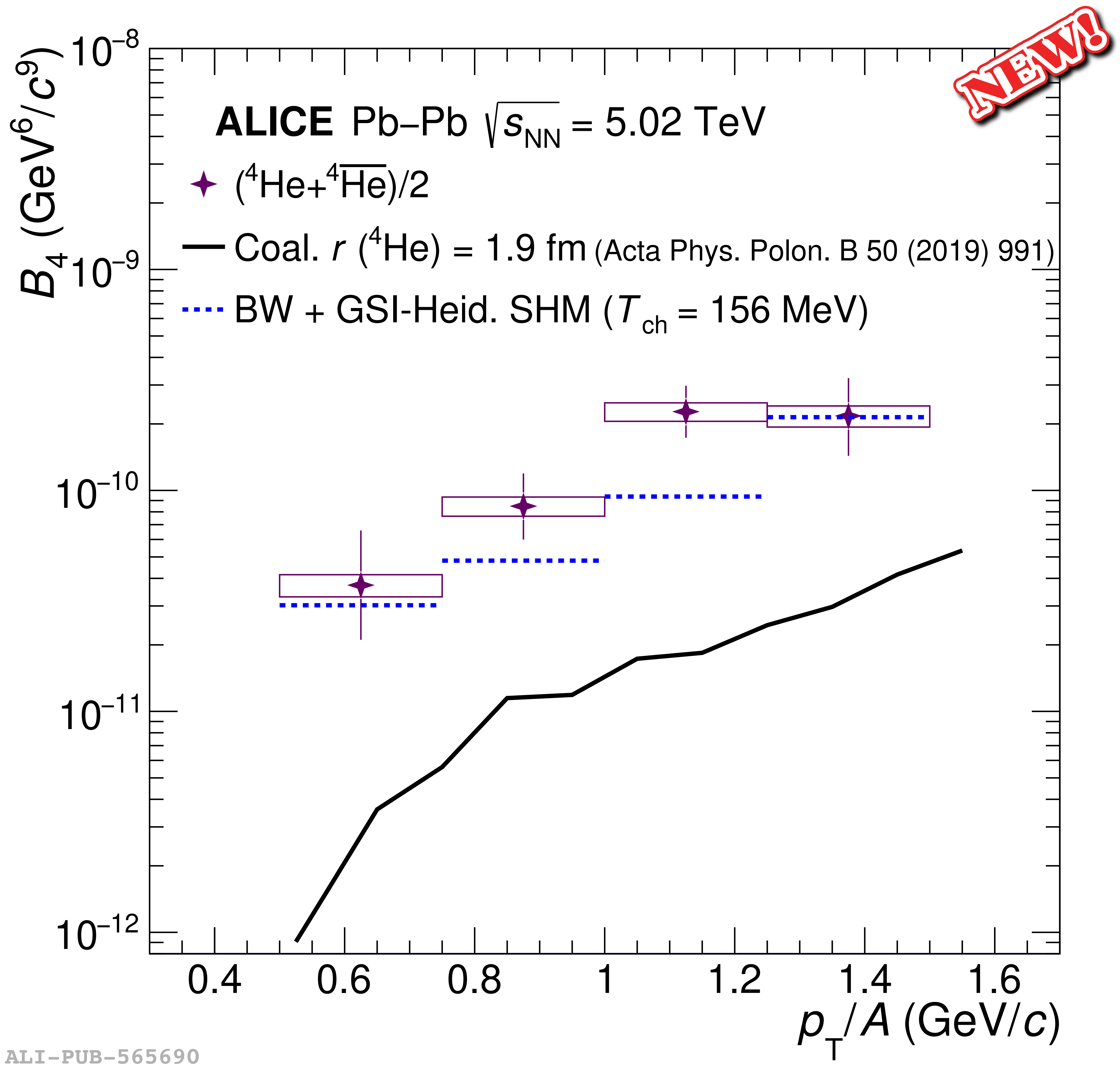
- The coalescence parameter B_4 is compared with SHM and coalescence predictions

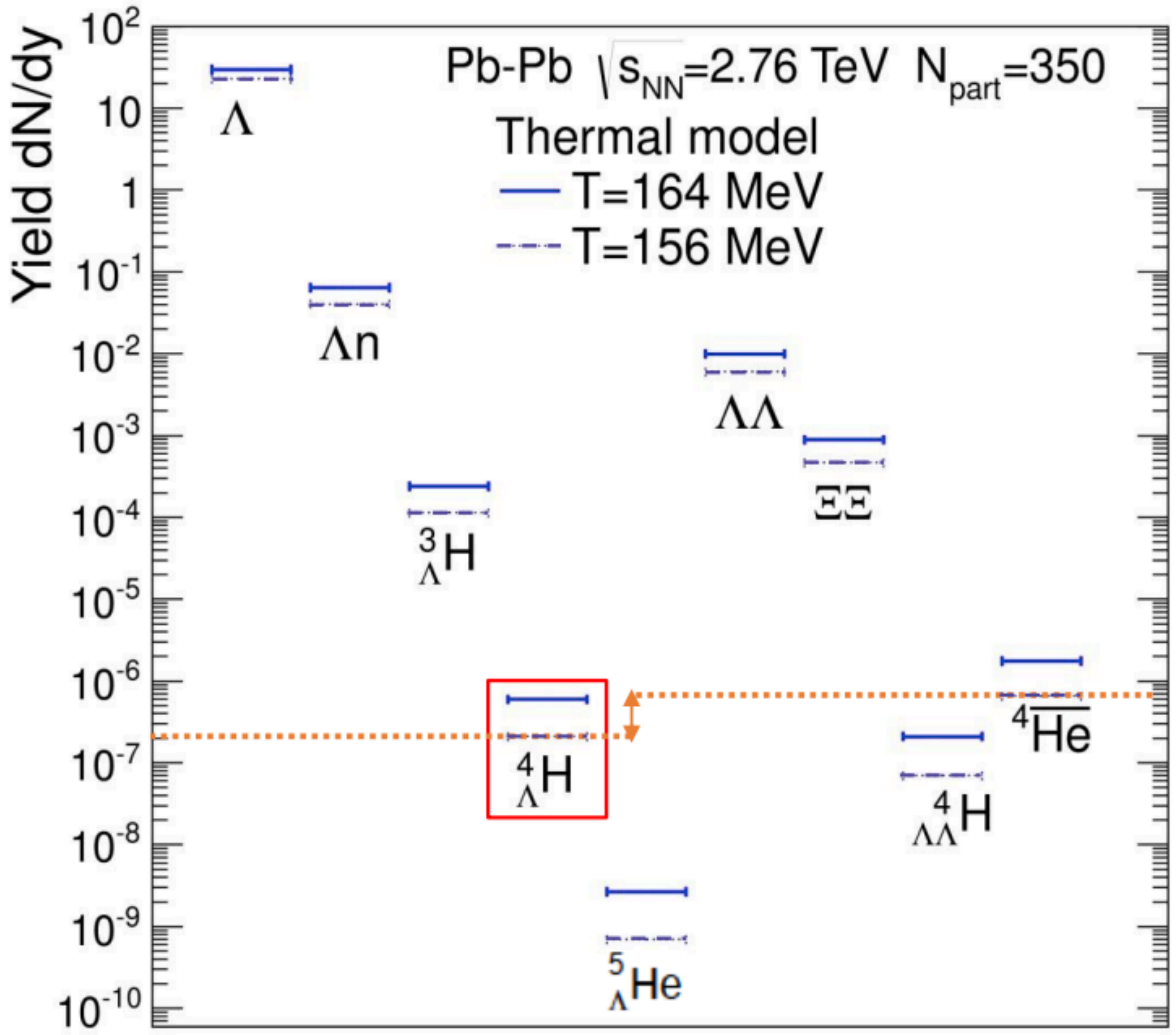
SHM describes better nuclei with A = 4



arXiv:2311.11758

Hypernuclei with A = 4

- **SHM** predicts **hypernuclei** with **A = 4** in Pb-Pb collisions
  - they are rare:
    - penalty factor for increasing A: ~ 300
    - suppression due to strangeness content



A. Adronic, private communication,
A. Andronic et al., PLB 697 (2011) 203-207

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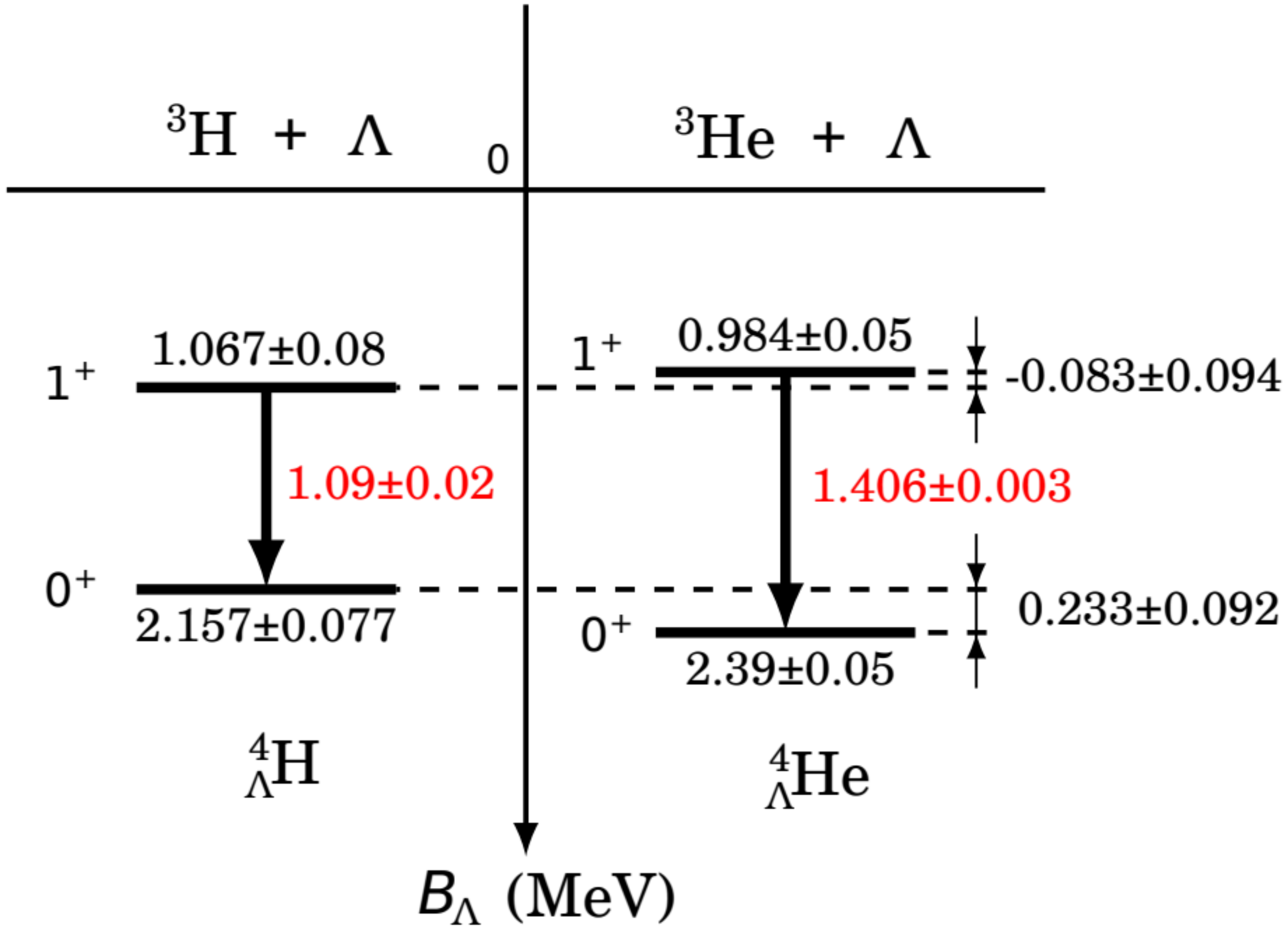
- Some factors may enhance the yield (**x 4**):
  - larger binding energy wrt A = 3
  - existence of excited states
    - spin degeneracy

$$\boxed{\frac{\mathrm{d}N}{\mathrm{d}y} \propto 2J + 1}$$



M. Schäfer et al., PRC 106, L031001 (2022)

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- In Pb-Pb at 5 TeV, ALICE has observed:
  - $^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$
  - $^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + \mathrm{p} + \pi^{-}$

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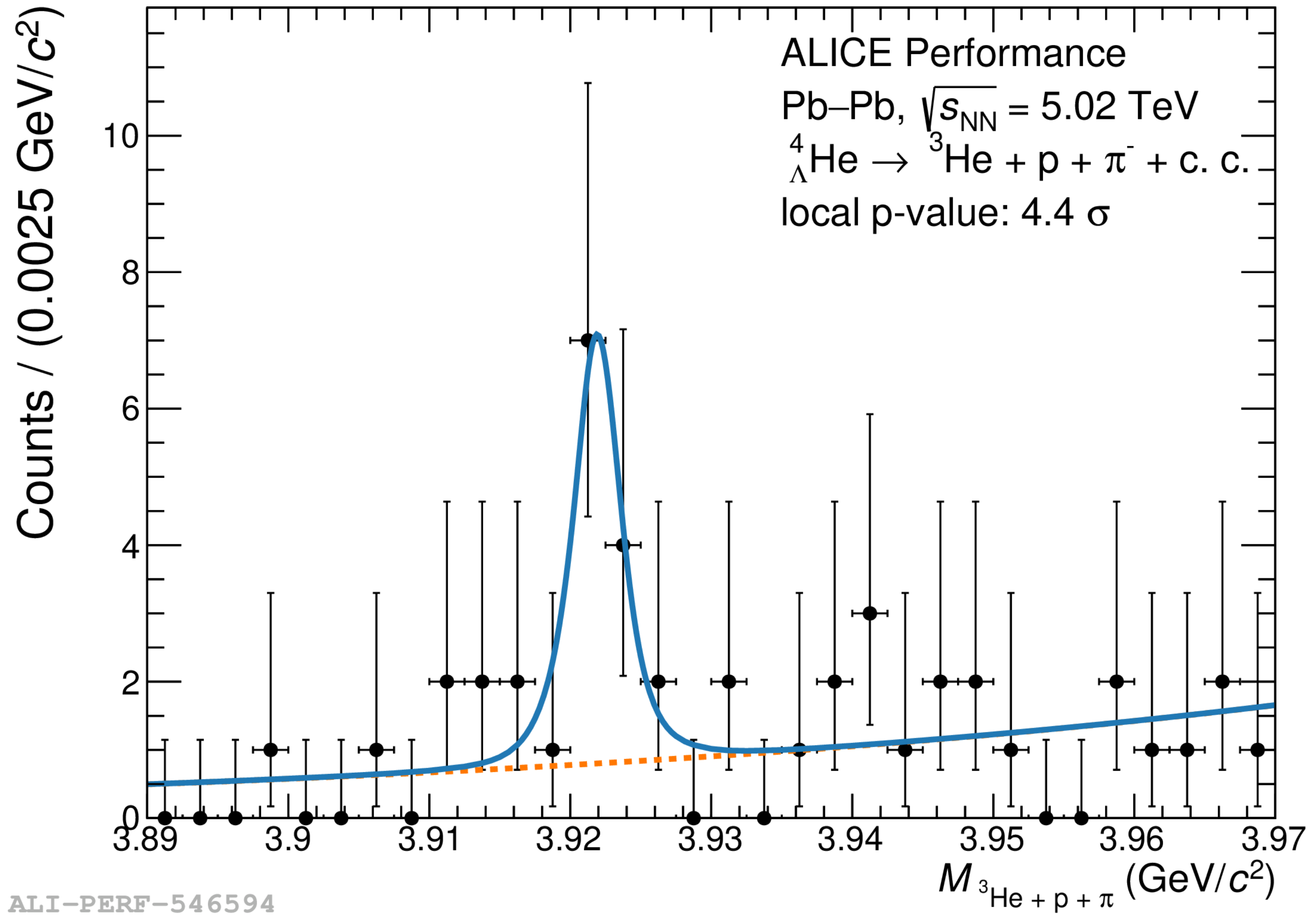

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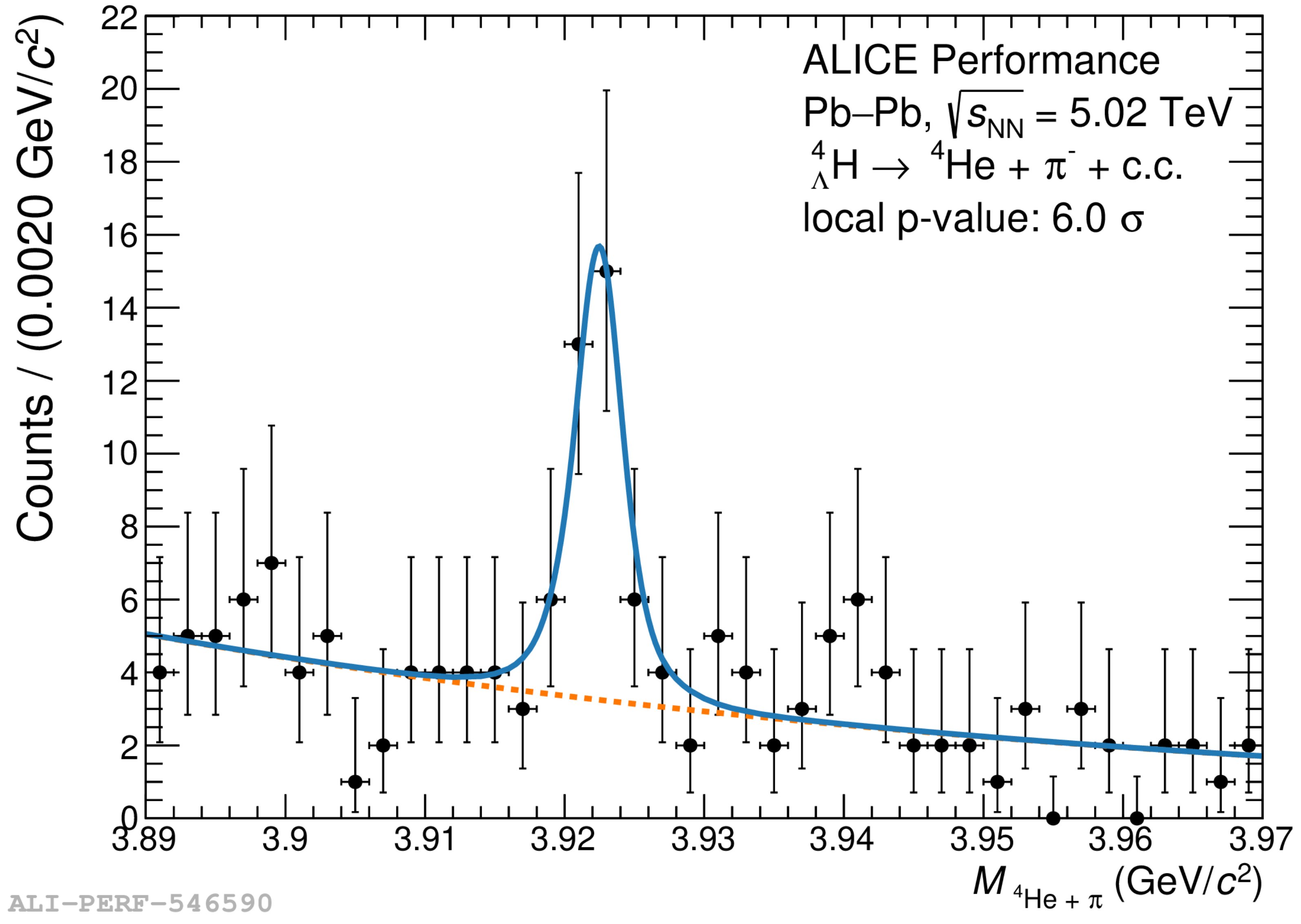

ALI-PERF-546590

Hypernuclei with A = 4

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  - they are rare:
    - penalty factor for increasing A: ~ 300
    - suppression due to strangeness content
- Some factors may enhance the yield (**x 4**):
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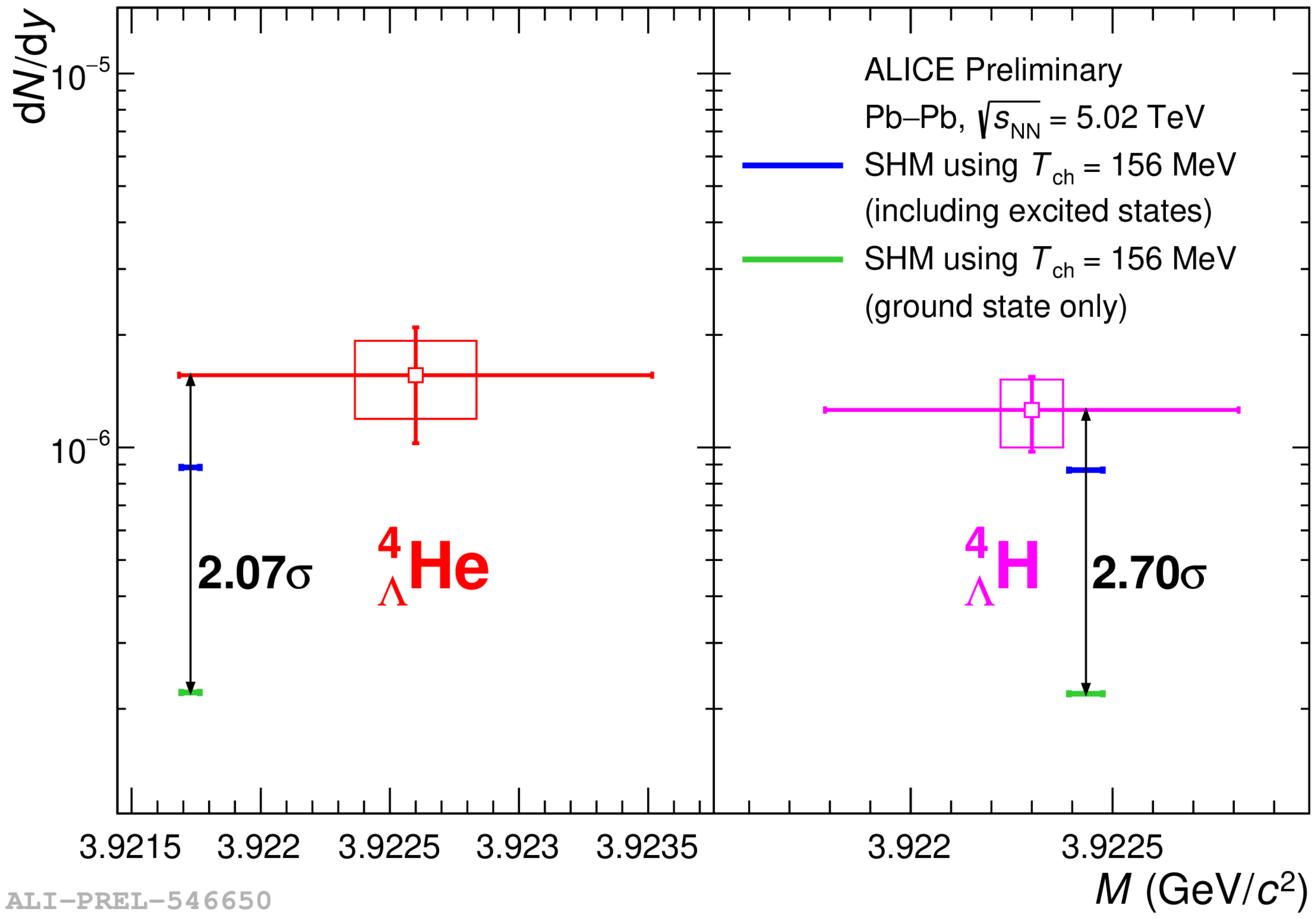
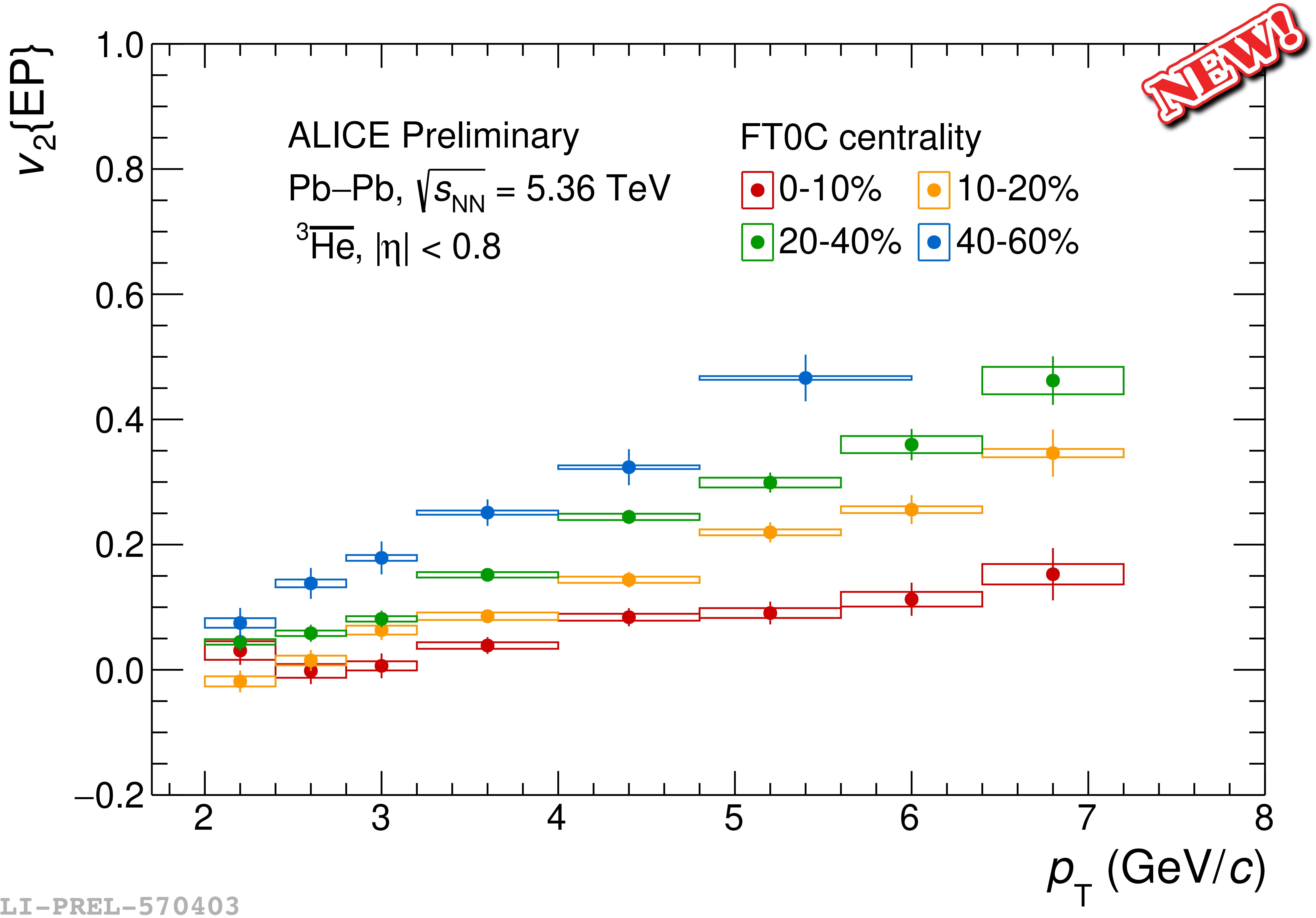
  - ${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$
  - ${}^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + \mathrm{p} + \pi^{-}$
- Yields in agreement with the presence of **excited states**



SHM describes well hypernuclei with A = 4

Flow as a probe for nuclear production

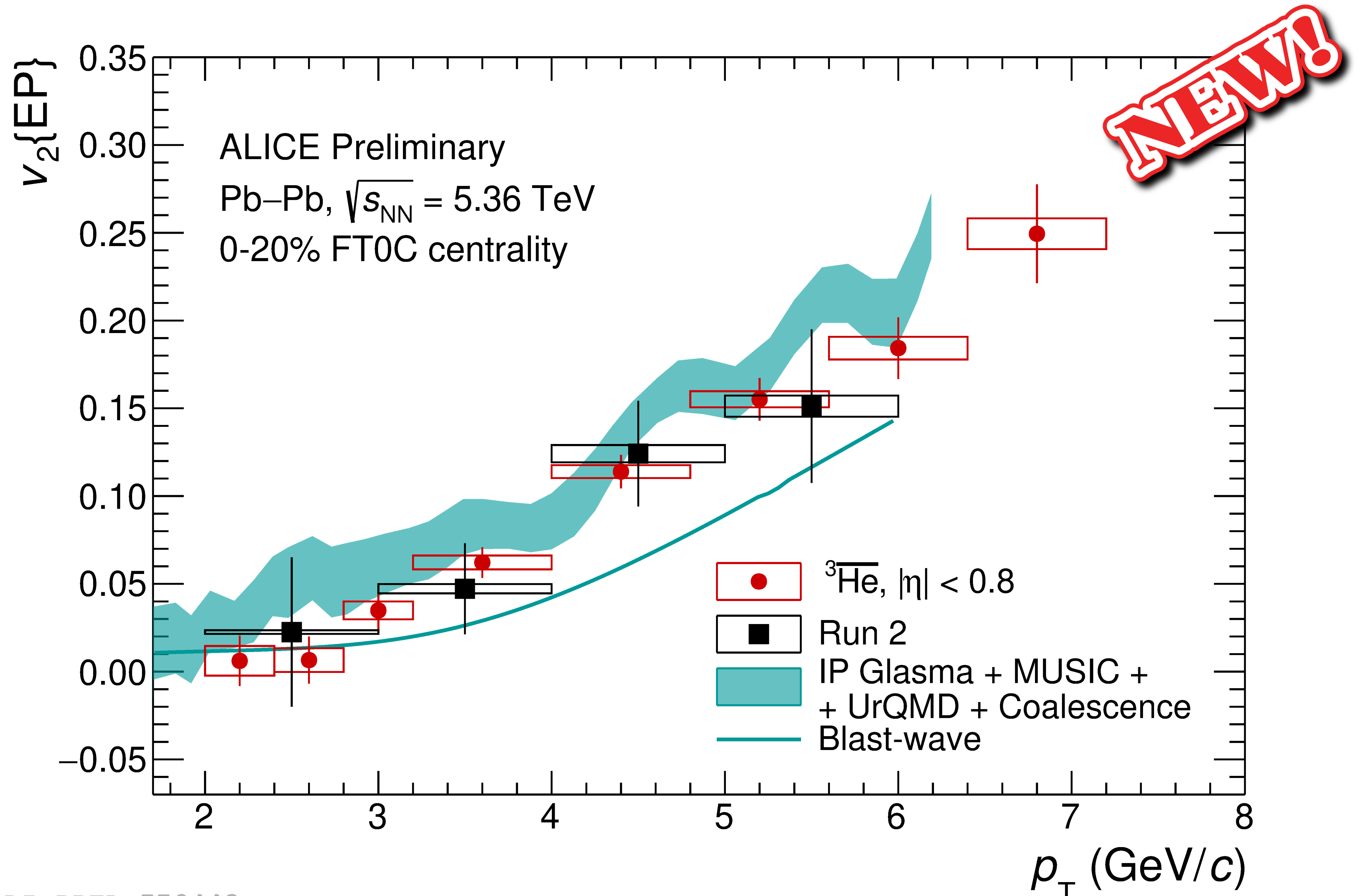
- **Coalescence** is a **femtoscopic probe**:
  - It is sensitive to a different production in-plane and out-of-plane (1)
  - Flow can be used to test production mechanisms
- ALICE has measured ***v*₂** for **anti-³He** in **Run 3 Pb-Pb** collisions at 5.36 TeV
  - more differential both in p_T and centrality, more precise than in Run 2



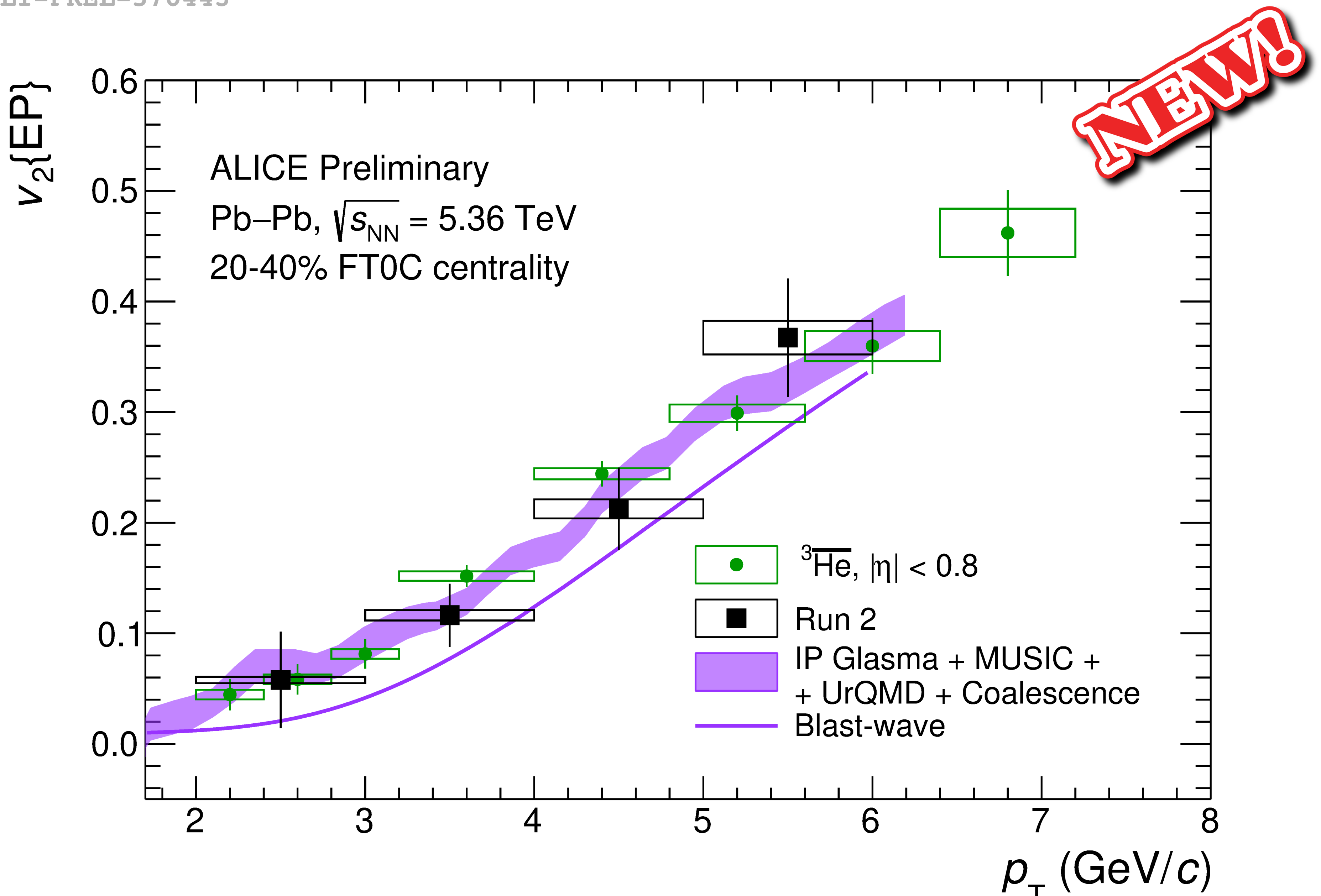
(1) arXiv:2402.06327

Flow as a probe for nuclear production

- **Coalescence** is a **femtoscopic probe**:
  - It is sensitive to a different production in-plane and out-of-plane
  - Flow can be used to test production mechanisms
- ALICE has measured **v_2** for **anti-^{3}He** in **Run 3 Pb-Pb** collisions at 5.36 TeV
  - more differential both in p_T and centrality, more precise than in Run 2
- Data are compared with the predictions of blast wave and coalescence model
  - **coalescence** is favoured



ALI-PREL-570443



ALI-PREL-570455

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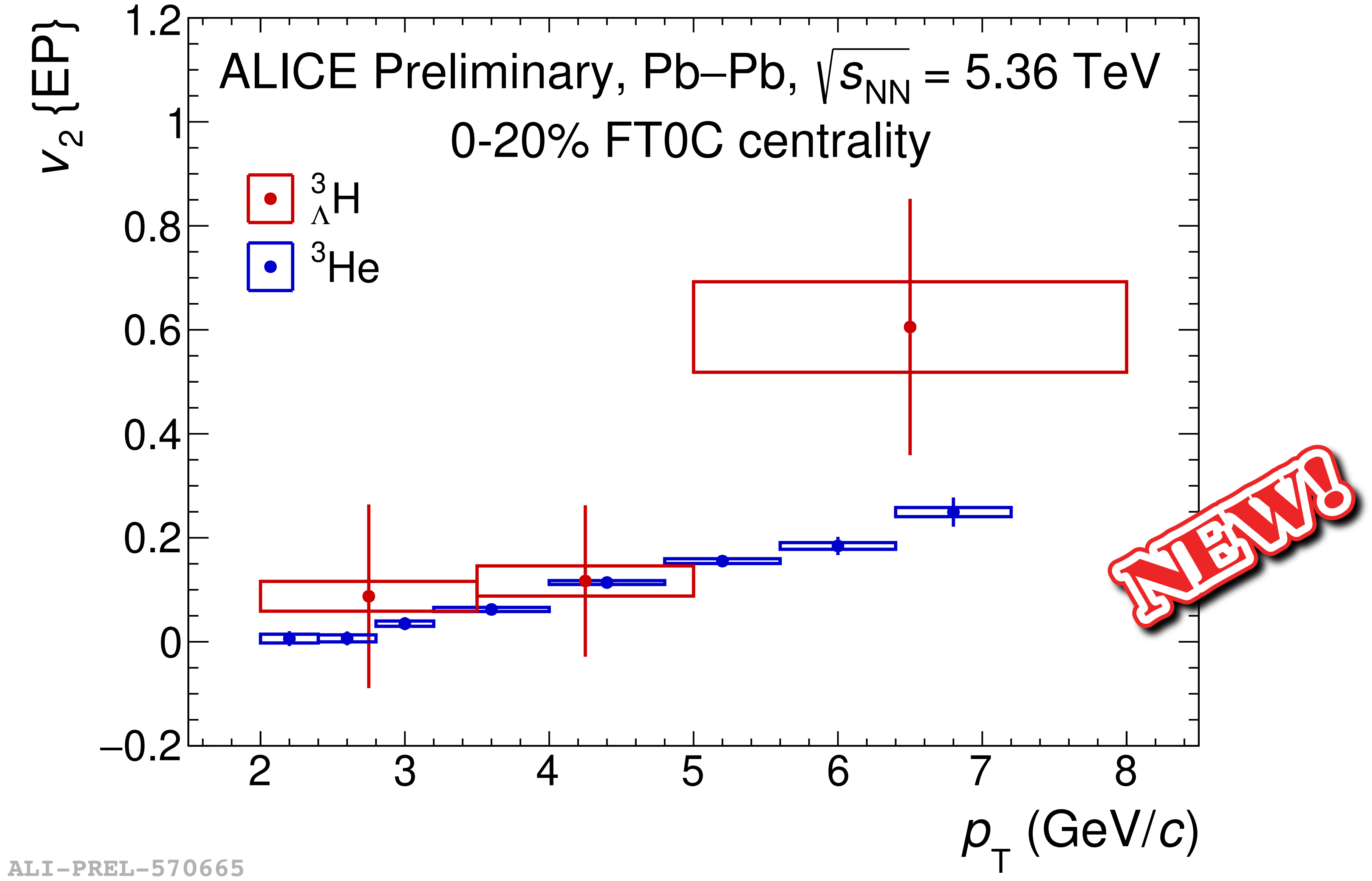
  - more differential both in p_T and centrality, more precise than in Run 2
- Data are compared with the predictions of blast wave and coalescence model
  - **coalescence** is favoured
- **Flow** of **hypertriton** has been measured for the first time:
  - compatible with ^{3}He, but large uncertainties by now



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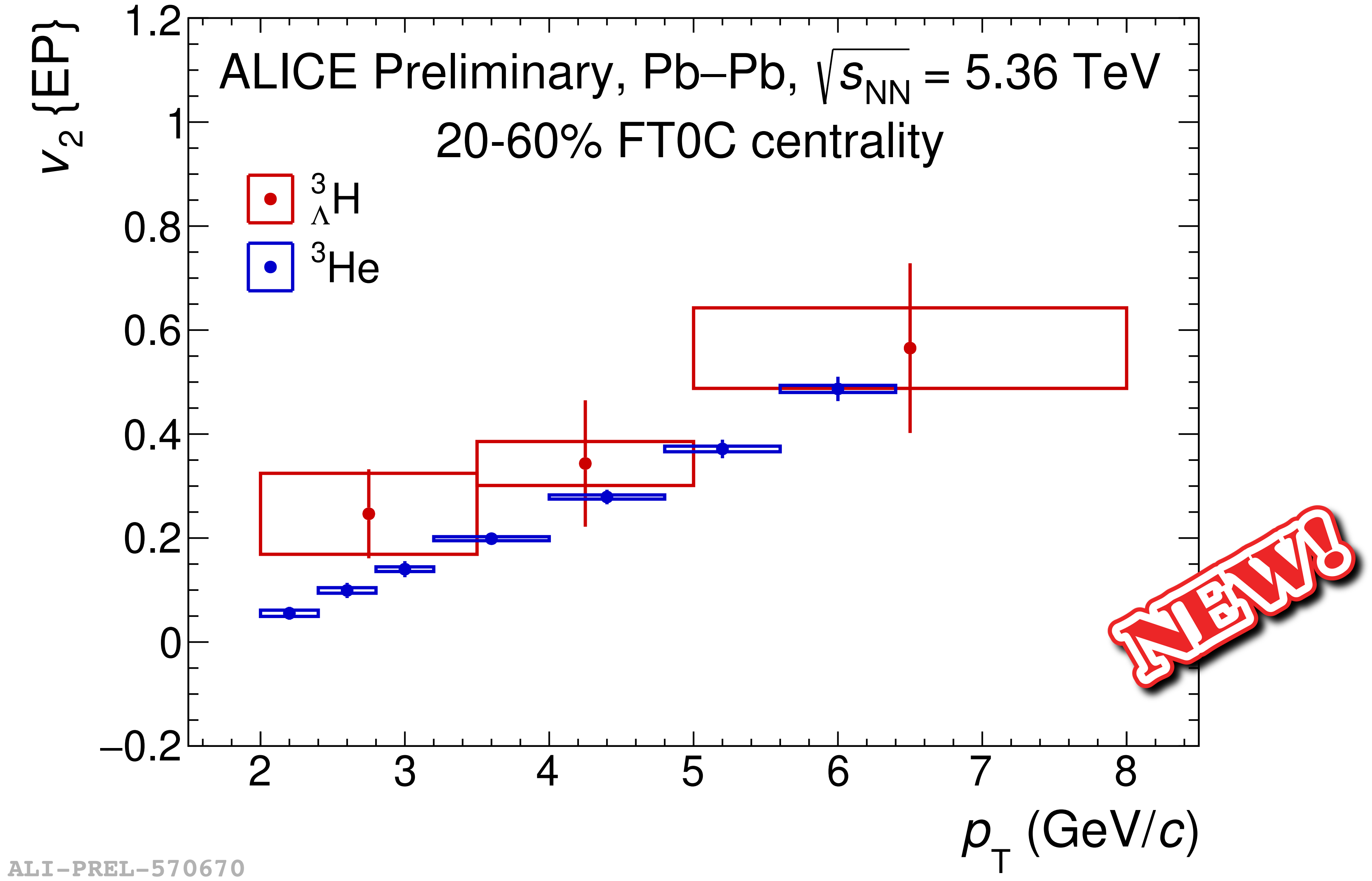

ALI-PREL-570670

Deuteron production vs rapidity

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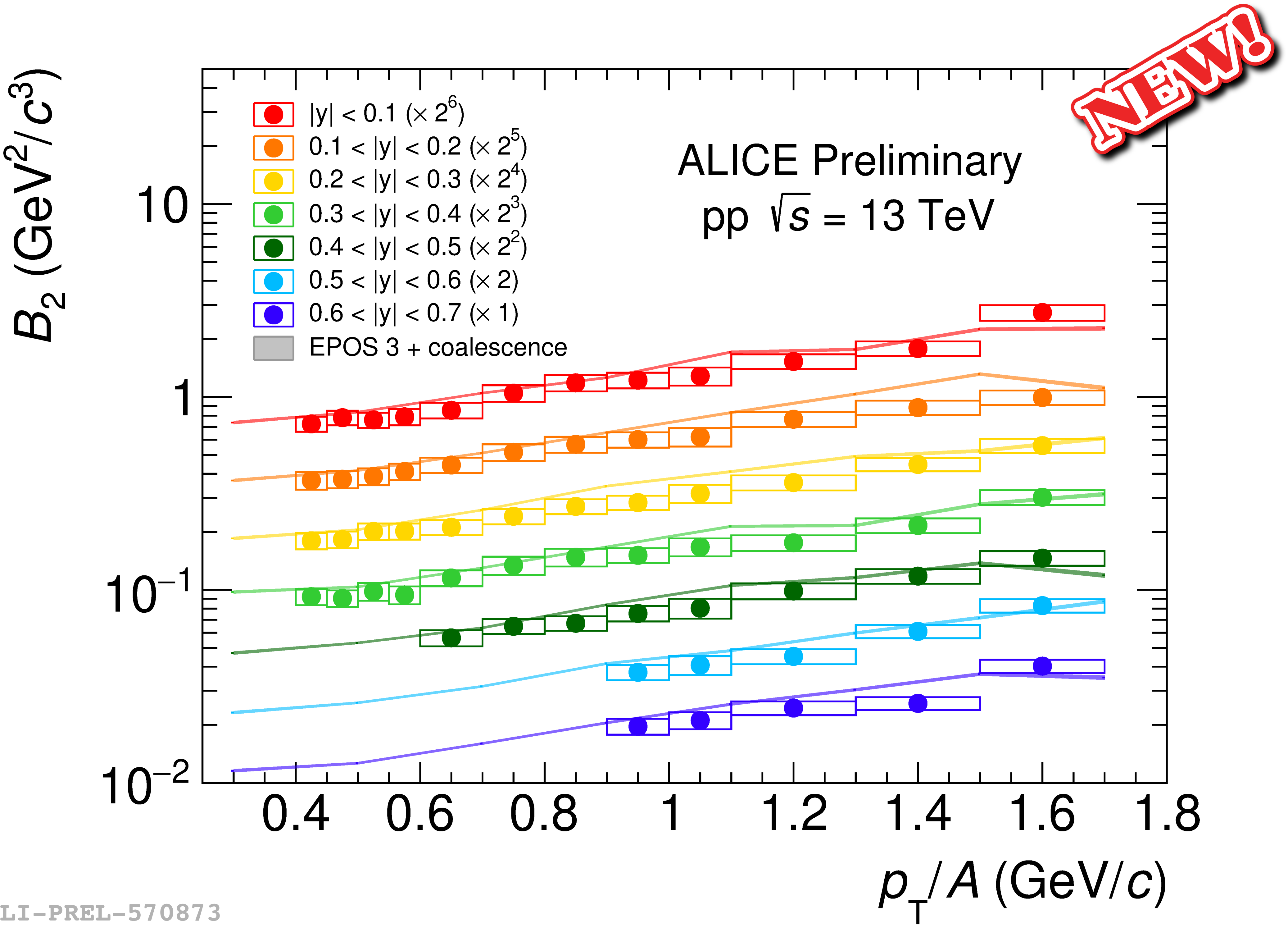
- In **CR - ISM collisions**, (anti)nuclei are mainly produced at **forward rapidity**:
  - important to study nuclear production vs rapidity
- Measurement of **p** and **d** production in **rapidity classes** (|y|<0.7)
- $\boldsymbol{B_2}$ is measured as a function of $\boldsymbol{p_T}$ and **y**:
  - data are compared with predictions from **EPOS + Wigner coalescence afterburner**
    - the shape is correctly reproduced, the magnitude is not



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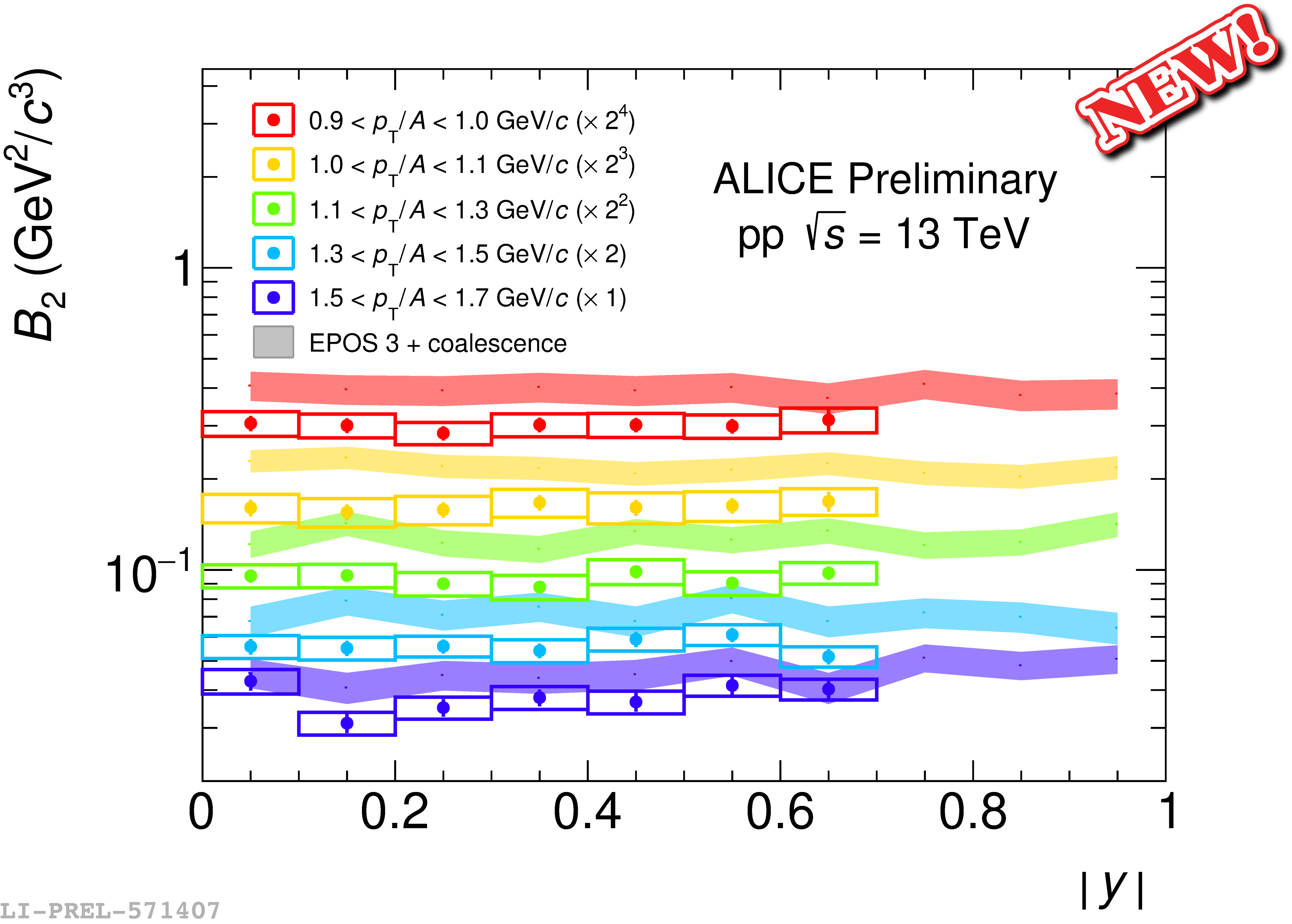
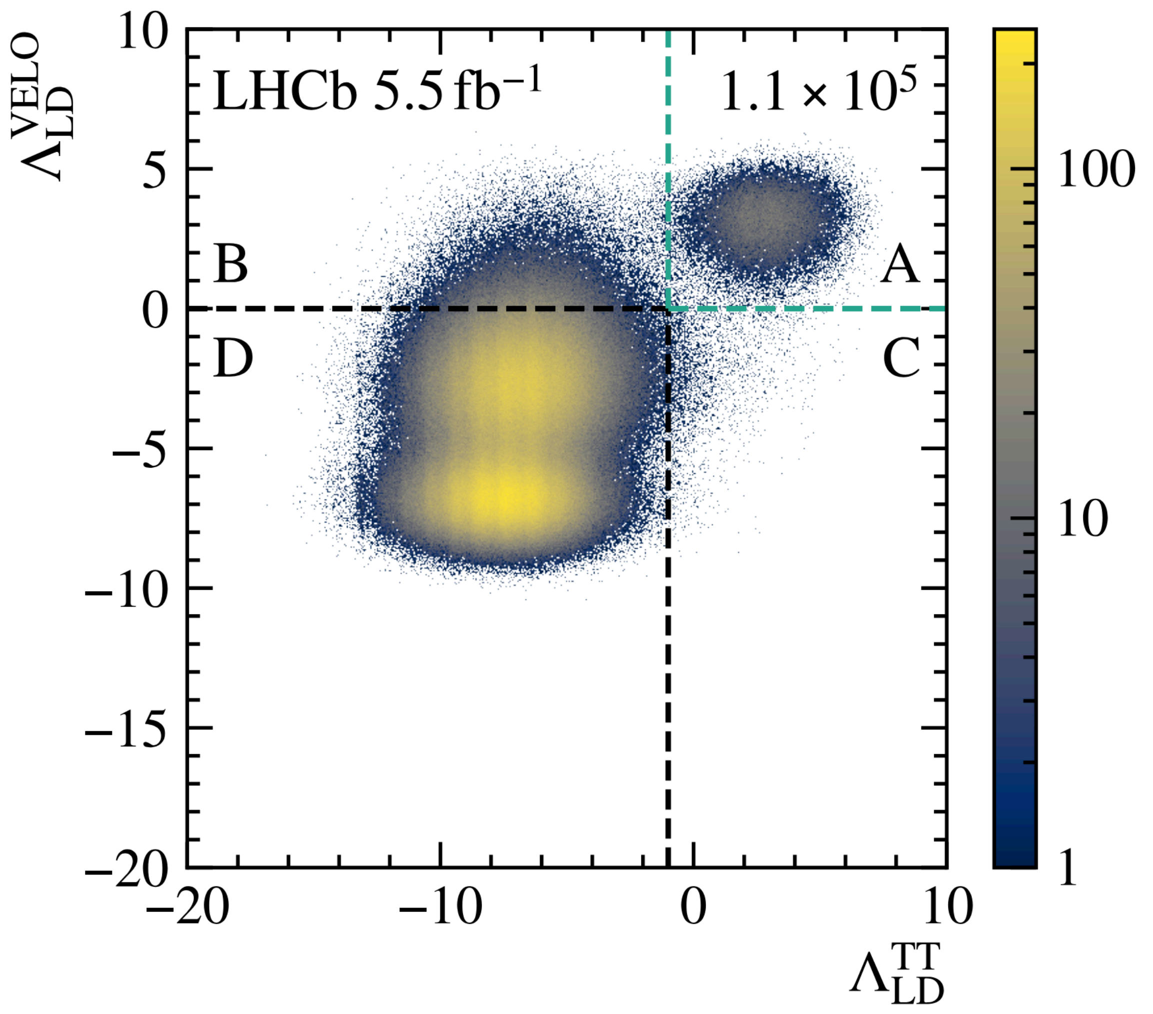


ALI-PREL-571407

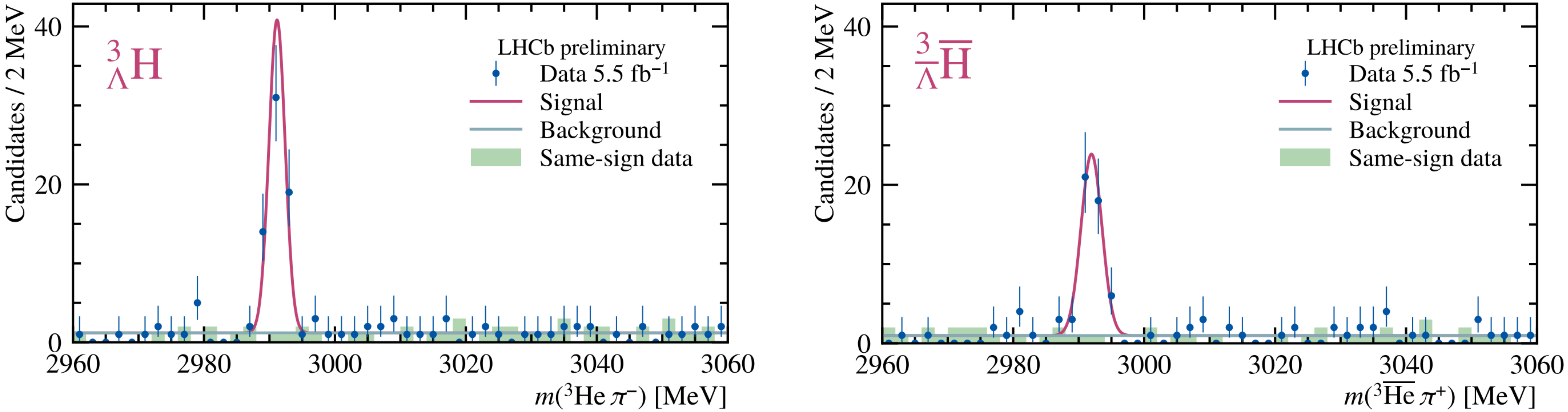
${}^{3}_{\Lambda}\mathrm{H}$ measurement at forward rapidity

- LHCb has recently observed **(anti)hypertriton**
  - Clear separation of ^{3}He via specific energy loss
  - Reconstruction via ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi$
    - ${}^{3}_{\Lambda}\mathrm{H}$: 61 ± 8 candidates, ${}^{3}_{\Lambda}\overline{\mathrm{H}}$: 46 ± 7 candidates
- Possibility to extend the studies at forward rapidity
  - Region of interest for space experiment: $\overline{\Lambda}_b \rightarrow {}^{3}\overline{\mathrm{He}} + \mathrm{X}$ will be accessible

2 < η < 5



JINST 19 (2024) P02010

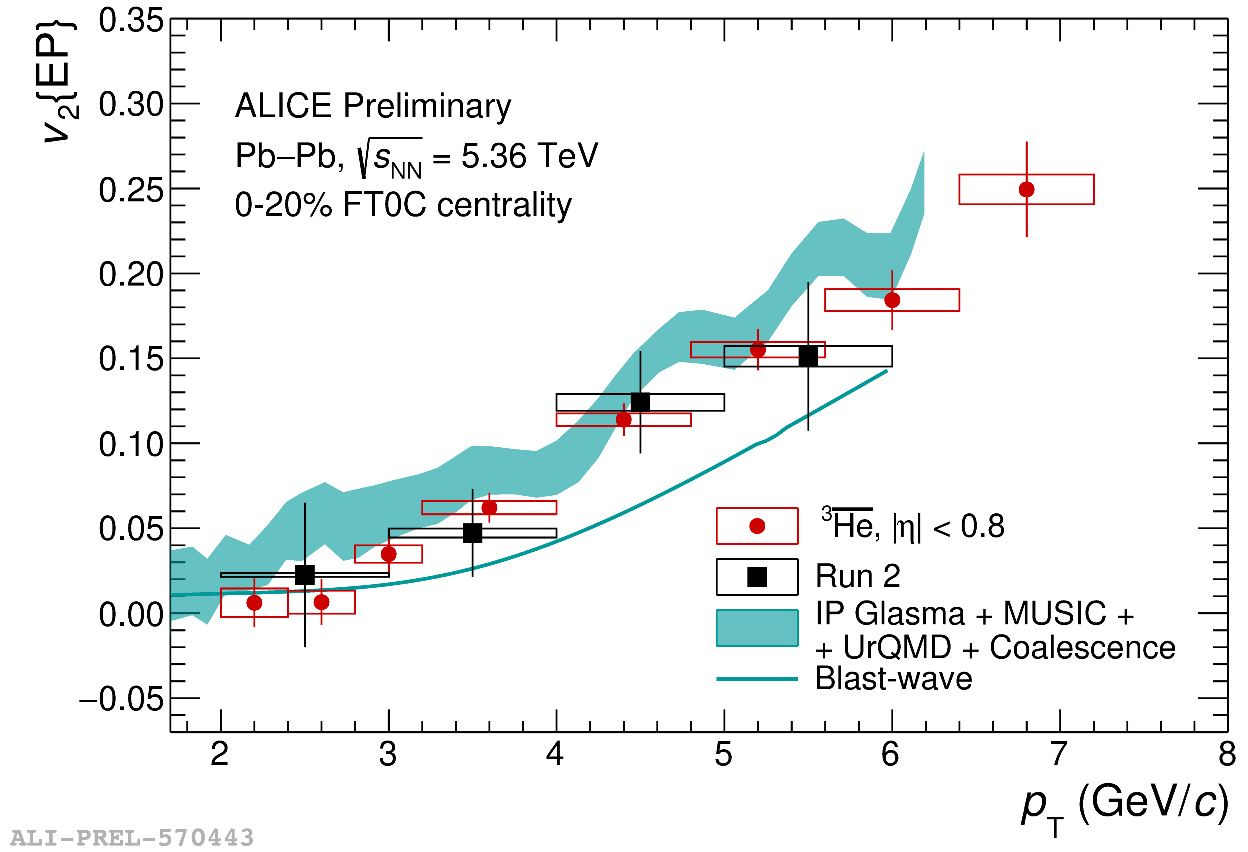


PoS EPS-HEP2023 (2024) 254

Summary

- Production of (anti)(hyper)nuclei measured at mid rapidity in pp, p-Pb, Xe-Xe and Pb-Pb
  - SHM and coalescence reproduce (anti)nuclei with A < 4
  - Hypertriton in small systems favour scoalescence
- SHM reproduces better nuclei with A = 4, but only in large systems
- With LHCb, production can be study at forward rapidity
  - important for astrophysics
- With Run 3, some measurements that were possible only in Pb-Pb collisions will be accessible also in small systems

Thanks for your attention!



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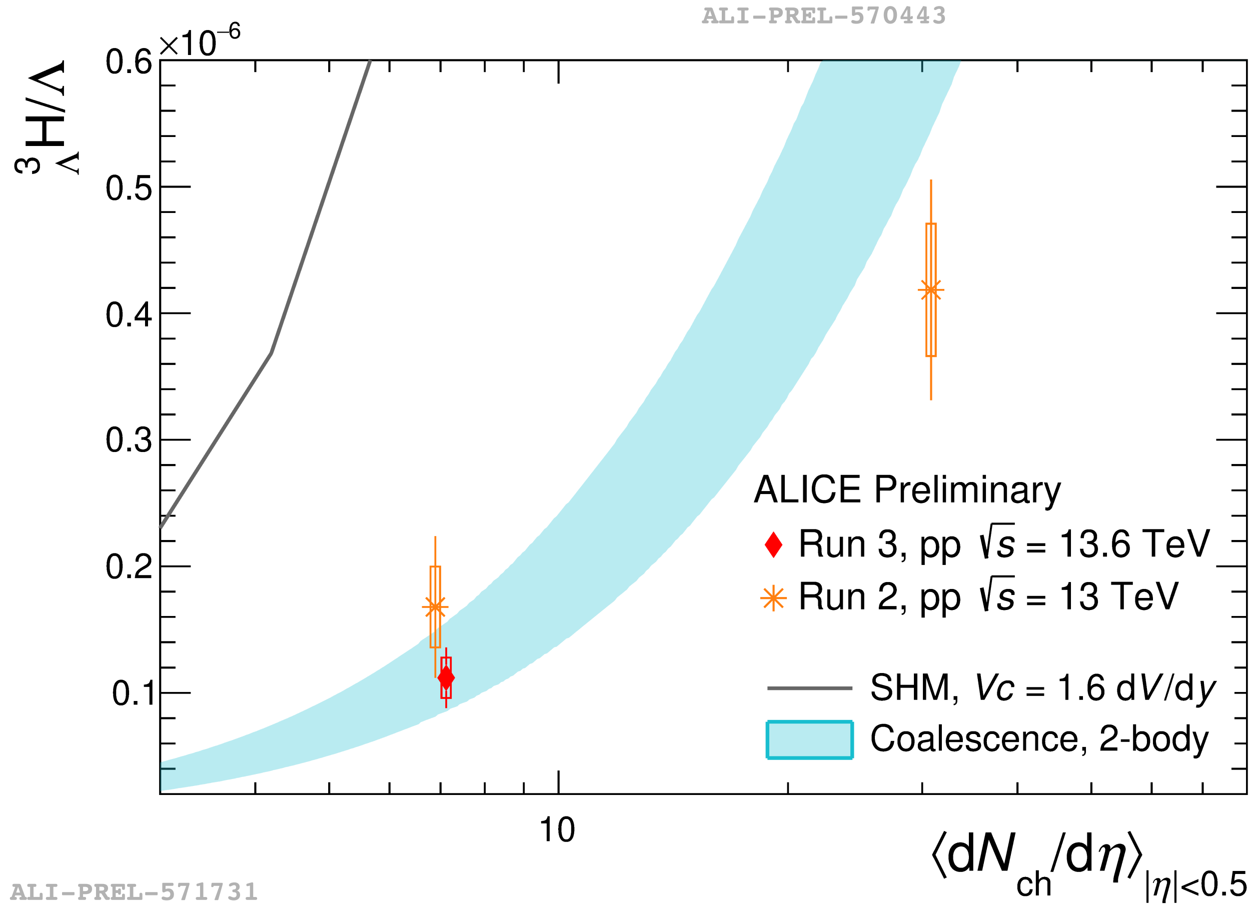

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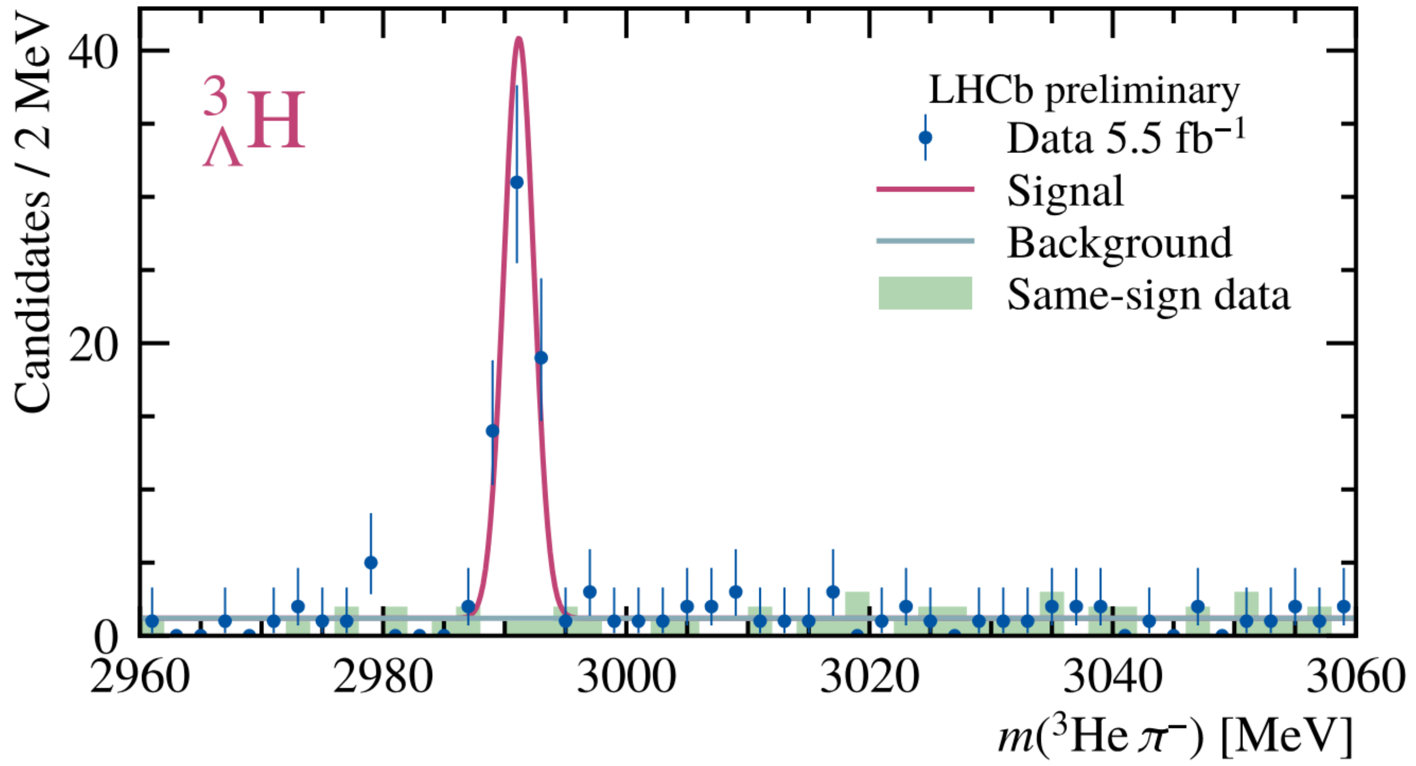
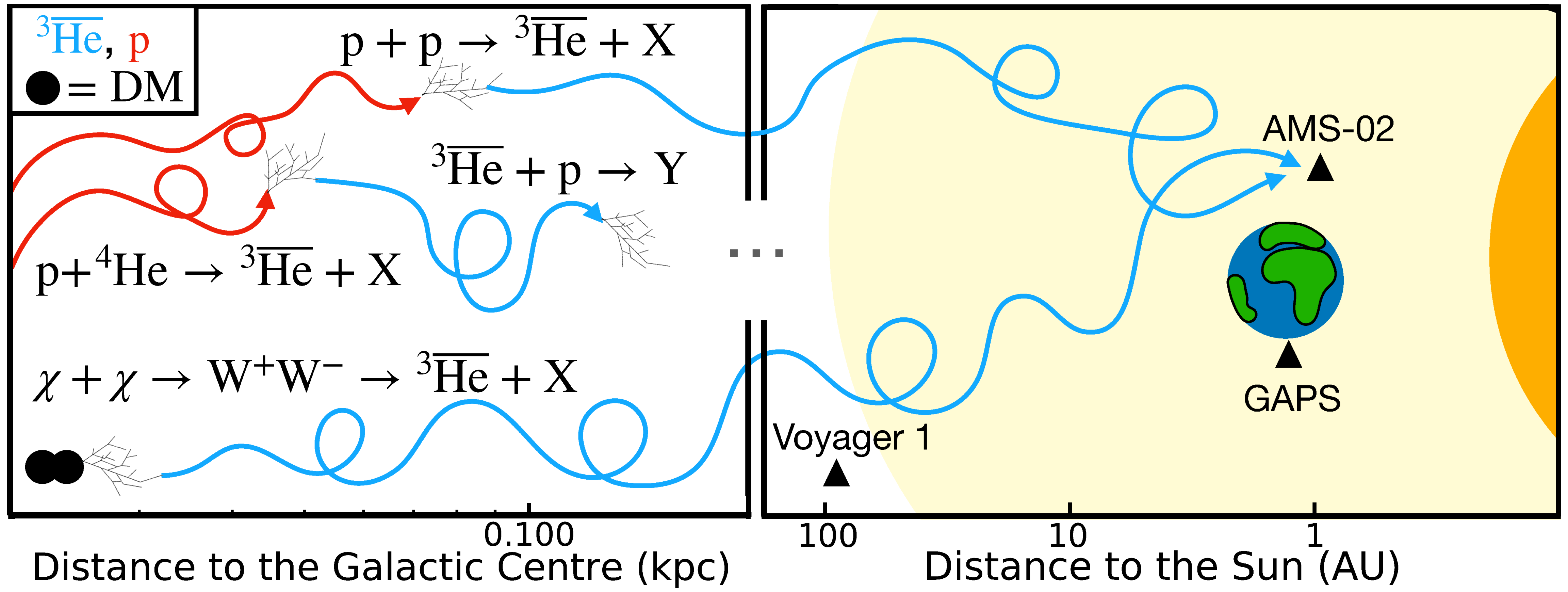
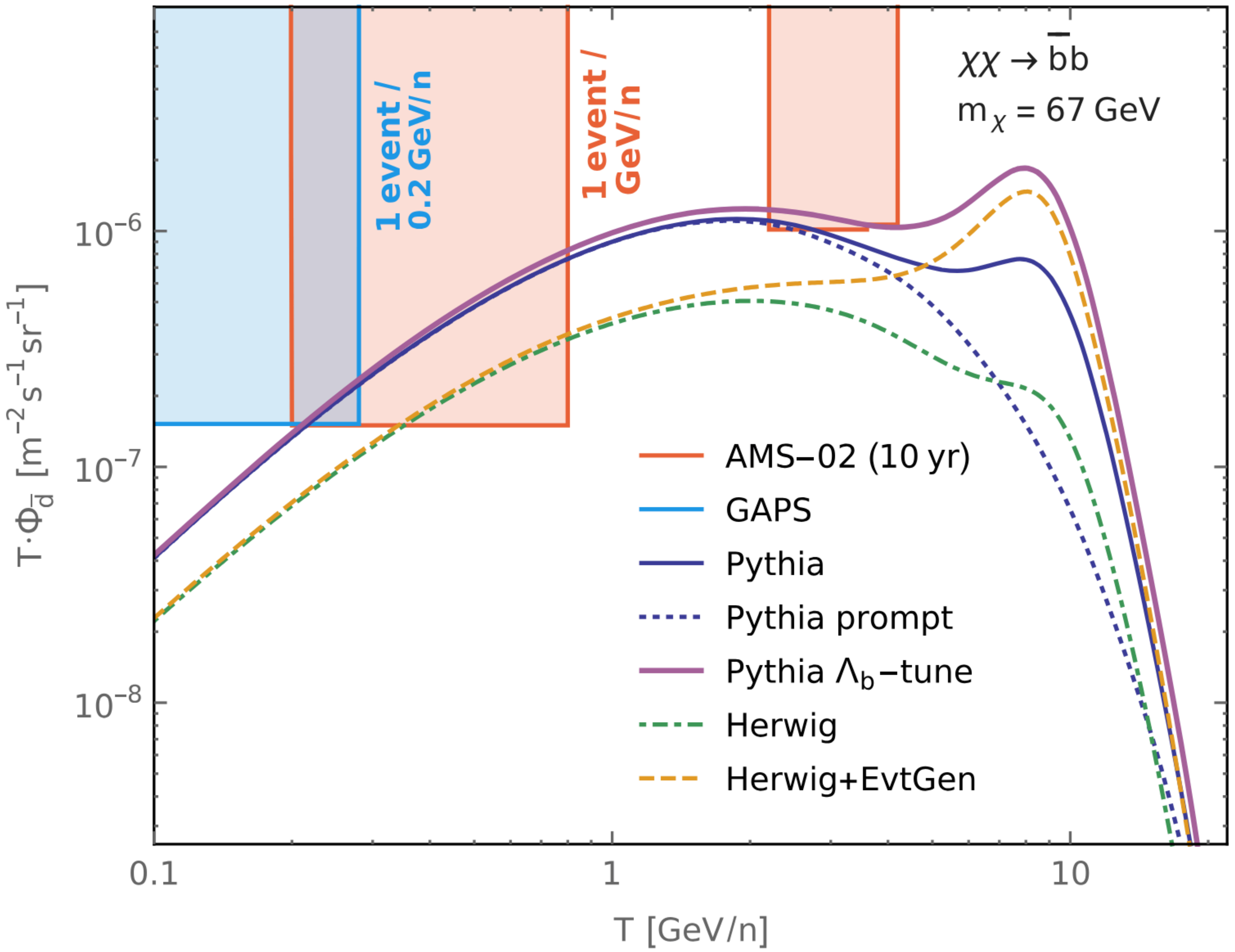


BACKUP

Physics motivation

- The study of the production mechanisms of (anti)(hyper)nuclei is not only interesting *per se*
- **Antinuclei** can be a sign of **Dark Matter annihilation**:
  - *Background*: production in the collisions between **cosmic rays** and the **interstellar medium** (pp and pA collisions)
    - Nuclear production must be known very well

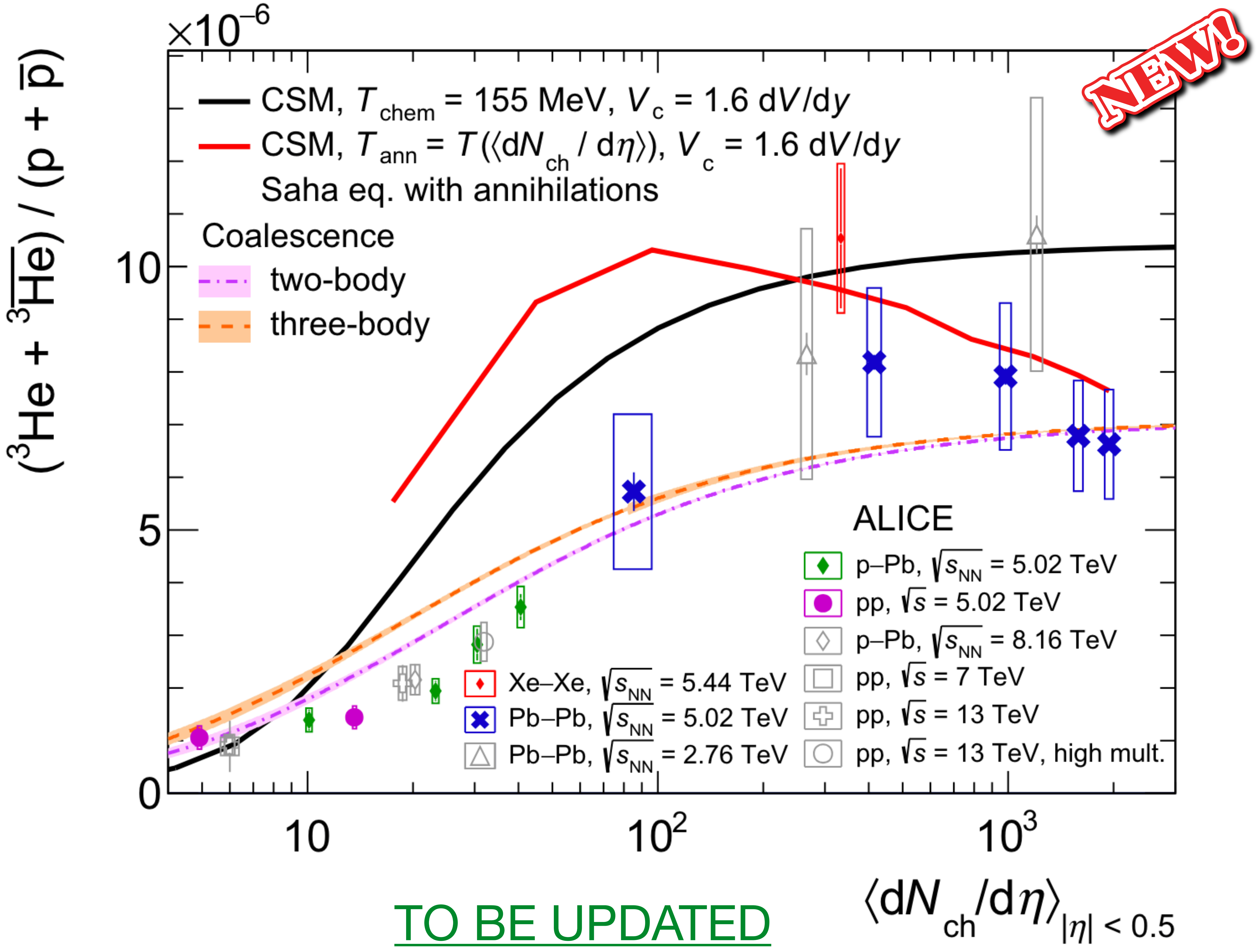




M. Winkler and T. Linden, PRL 126, 101101

Yield ratios

- **d/p** ratio evolves **smoothly** with **multiplicity**
  - dependence on the **system size**
- For **d/p** ratio both the models describe the data:
  - CSM: canonical suppression
  - Coalescence model: interplay between source size and nuclear size
- Also ^{3}**He/p** evolves **smoothly** with **multiplicity**
  - But there are more tensions between data and models
- Coalescence seems to describe better data for A > 2



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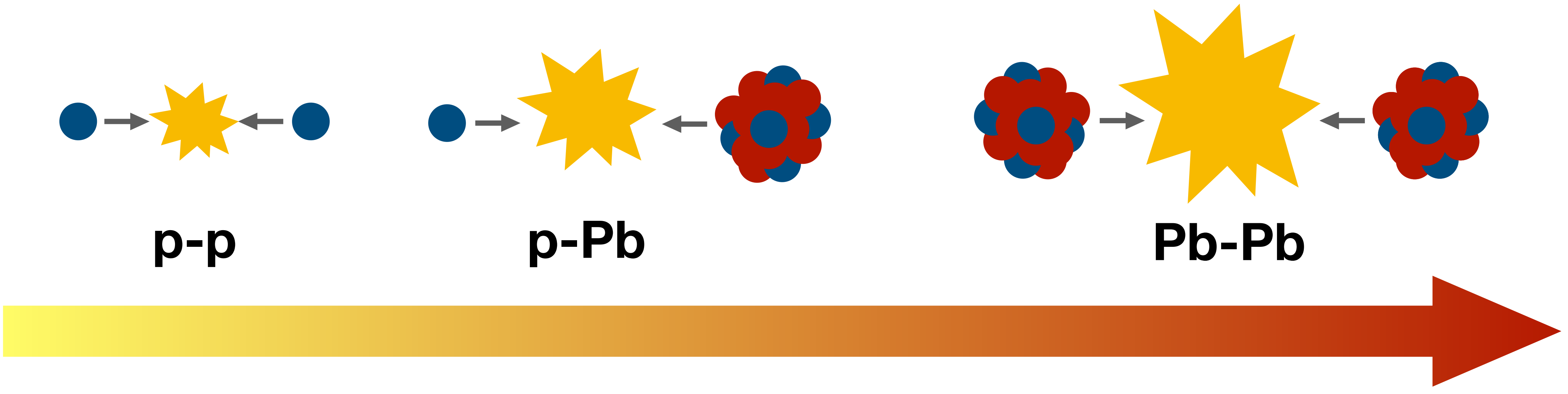
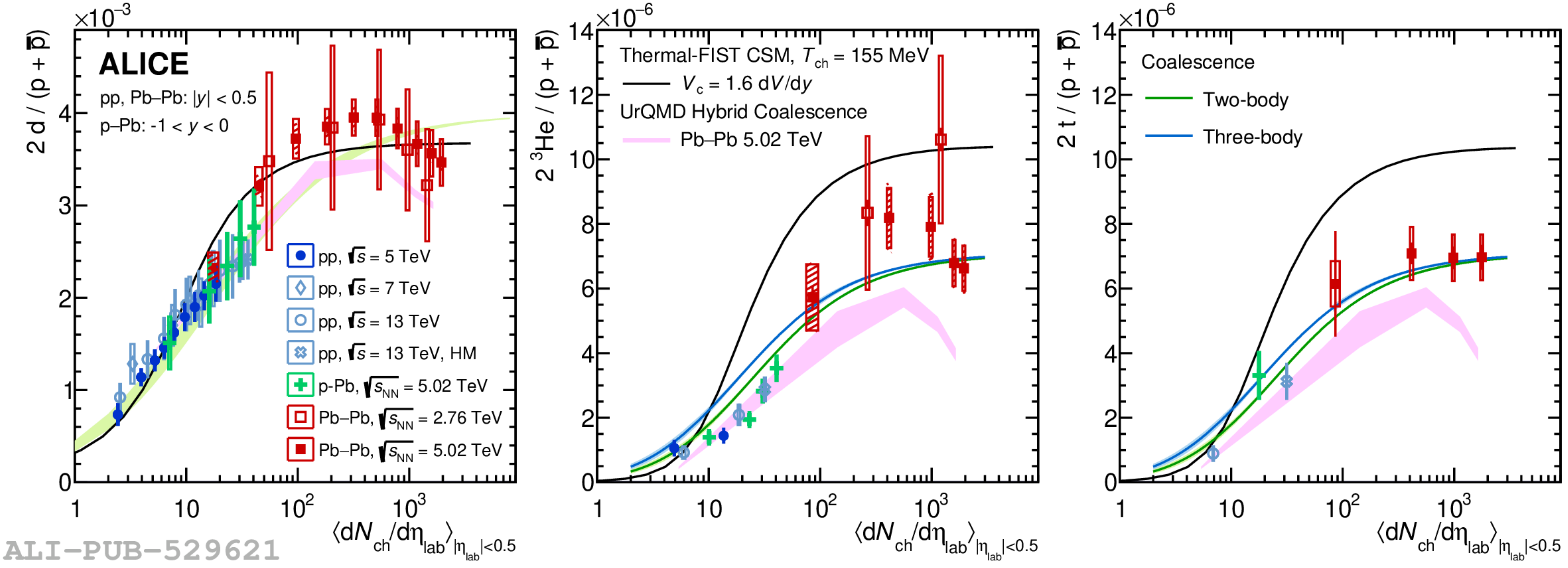


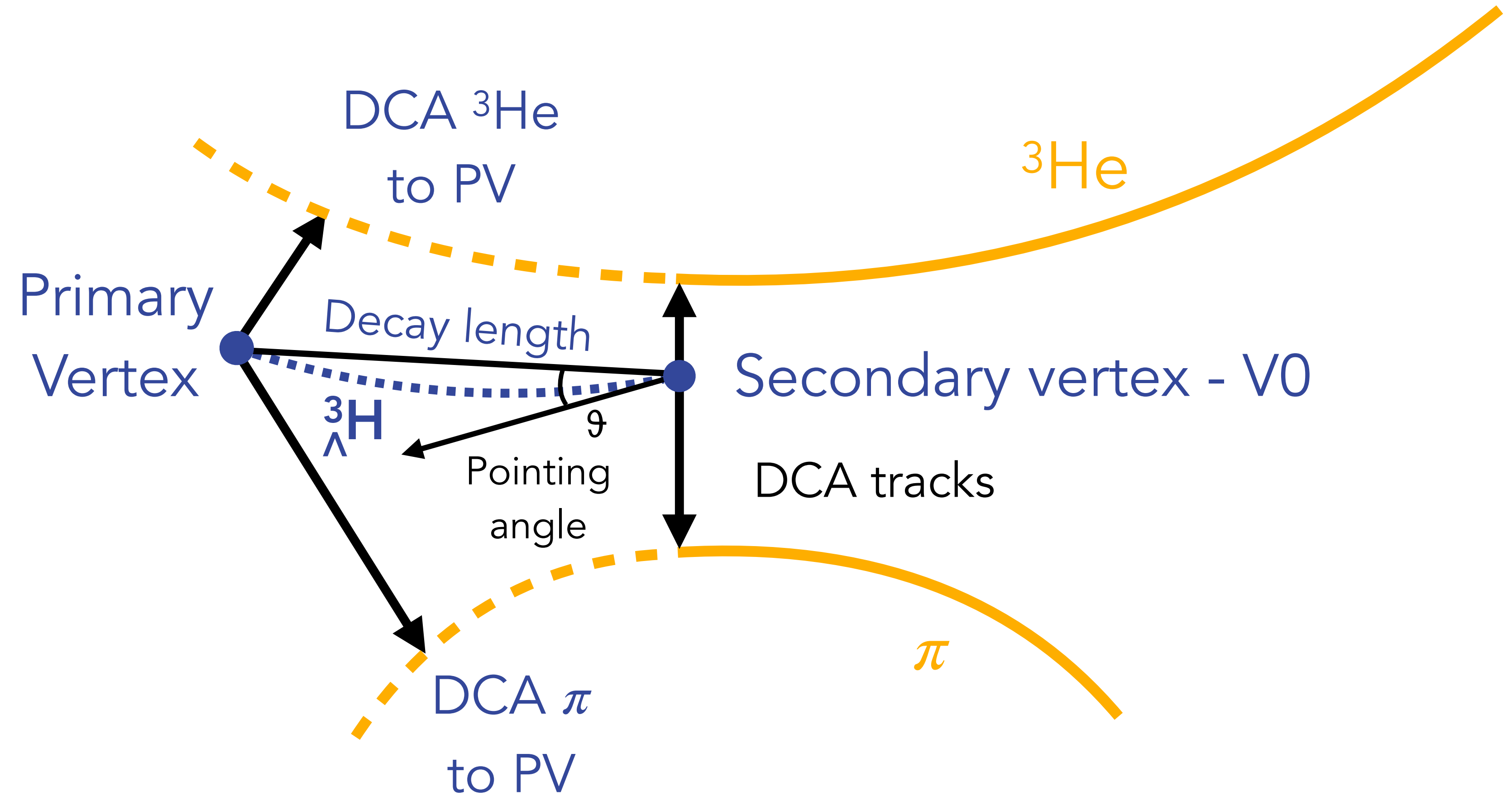
Yield ratios

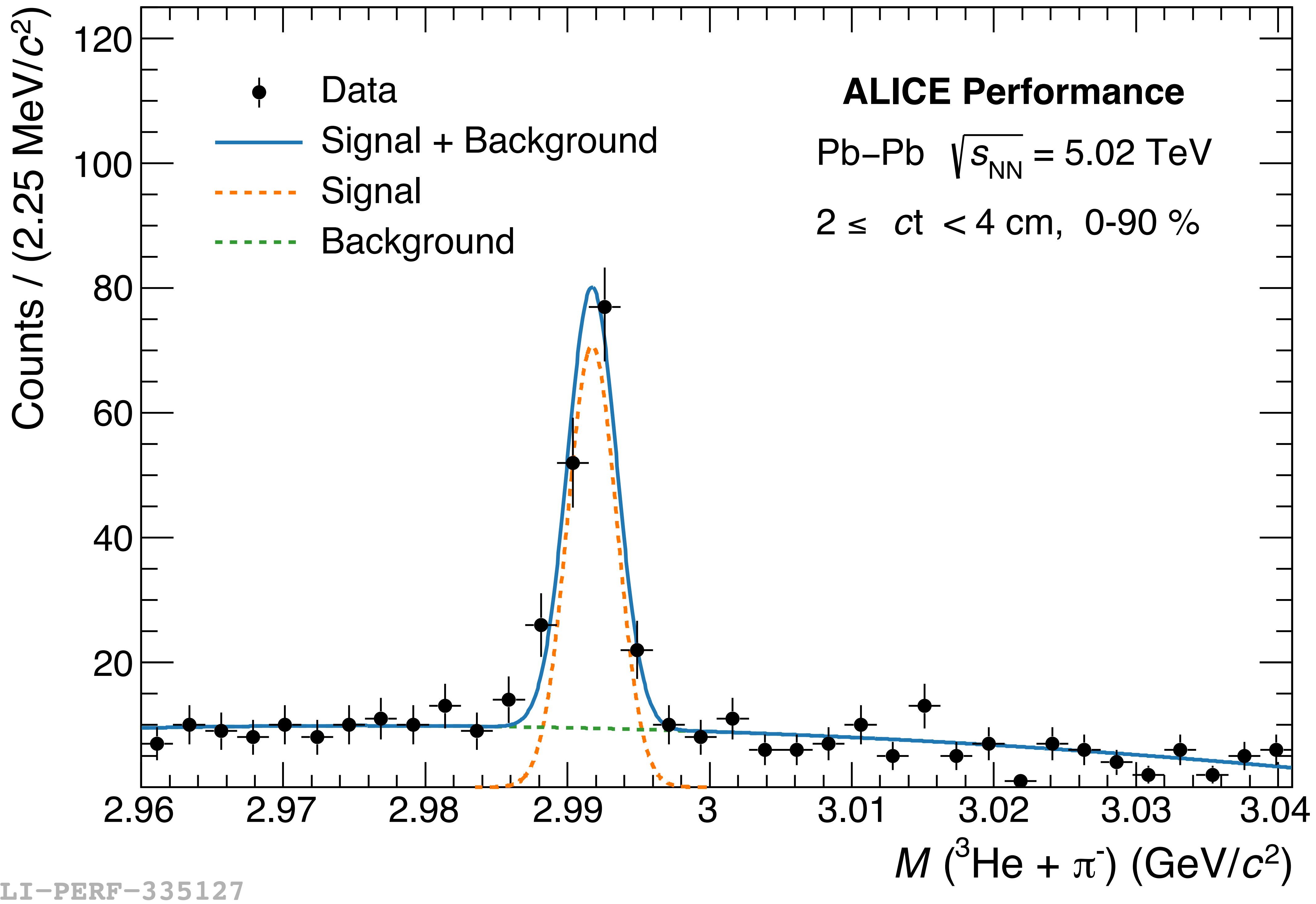


arXiv:2211.14015

Hypertriton reconstruction

- **Hypertriton** is reconstructed through its **two-body** mesonic decay (B.R. 25%):
  - $^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-} \quad + \mathrm{c.c.}$
- Candidates are selected with:
  - Standard selections on **single-track** and **topological** variables
  - **Boosted Decisions Trees** (BDT) models, trained on dedicated MC samples used to discriminate signal and background
    - BDT selections are optimised to **improve** the **significance** of the signal
    - Use of the package hipe4ML





ALI-PERF-335127

Measure of the source size

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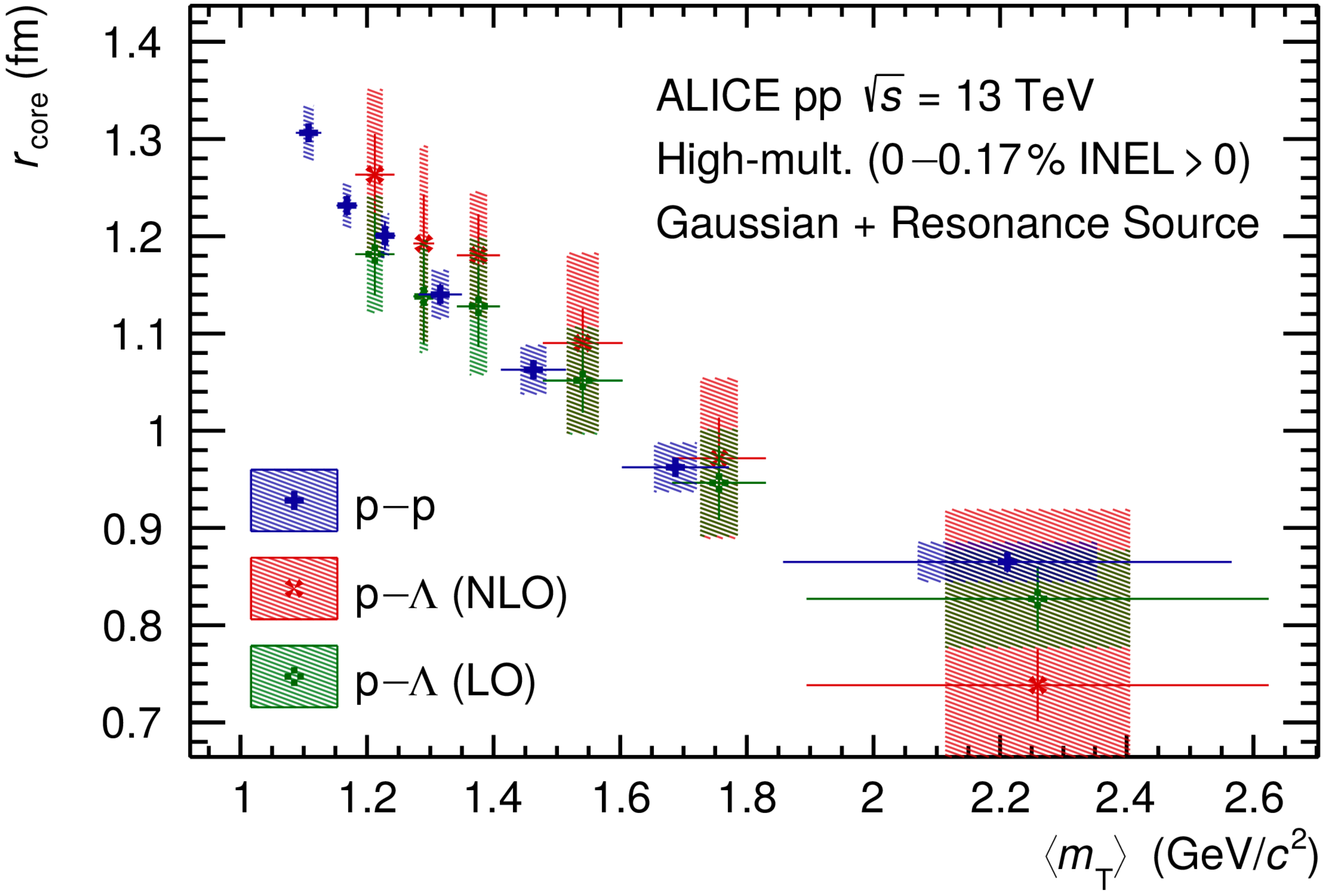
- If the **interaction** is very **well known**, the CF can be used to constrain the **source function**
  - **p-p** and **p-Λ**
- Assumptions:
  - Particle emission from a **Gaussian core** source
- Short-lived strongly decaying **resonances** ($c\tau \approx r_{\mathrm{core}}$) effectively increase the source radius
  - e.g. Δ-resonances for protons
- **Universal source model**
  - r_{core} fixed for each pair based on $\langle m_{\mathrm{T}} \rangle$

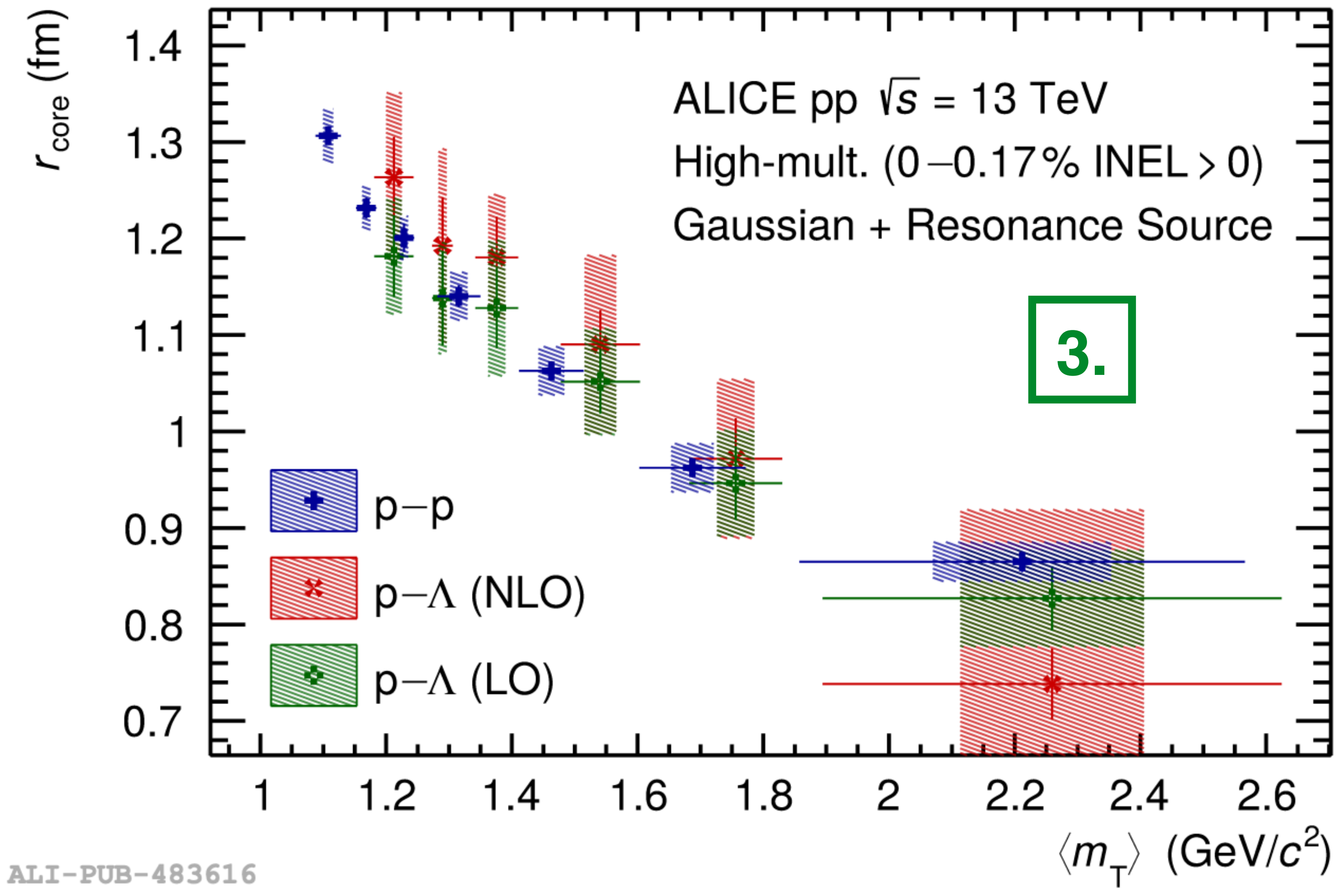
$$C(k^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2\, \mathrm{d}^3 r^* = \mathcal{N}\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

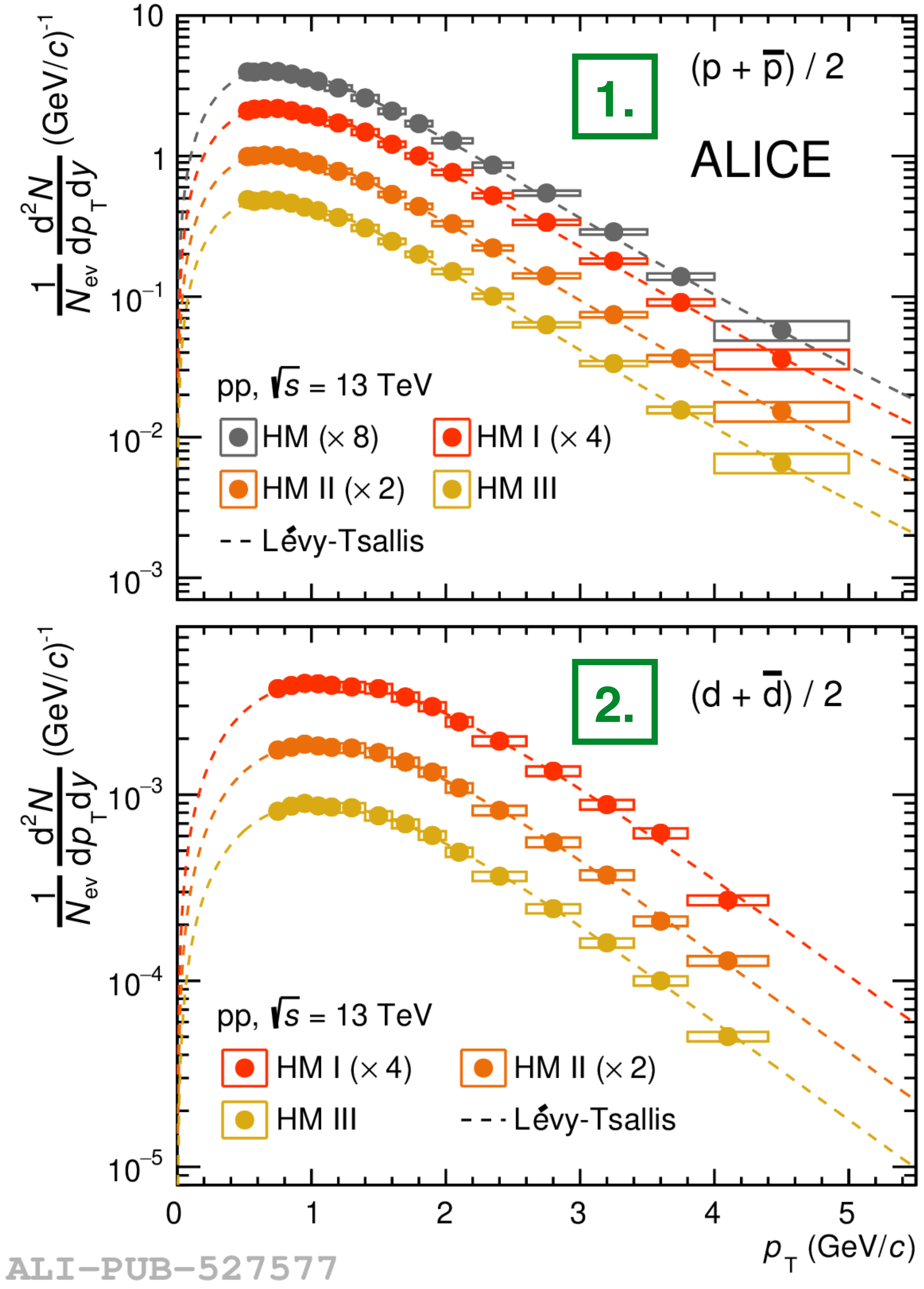


PLB 811 (2020) 135849

B_A vs p_T in HM pp collisions

- In **HM pp** collisions, ALICE has measured:
    1. **(anti)proton** production spectra
    2. **(anti)deuteron** production spectra
    3. **size** of the emitting **source** with femtoscopy





PLB 811 (2020) 135849

JHEP 01 (2022) 106

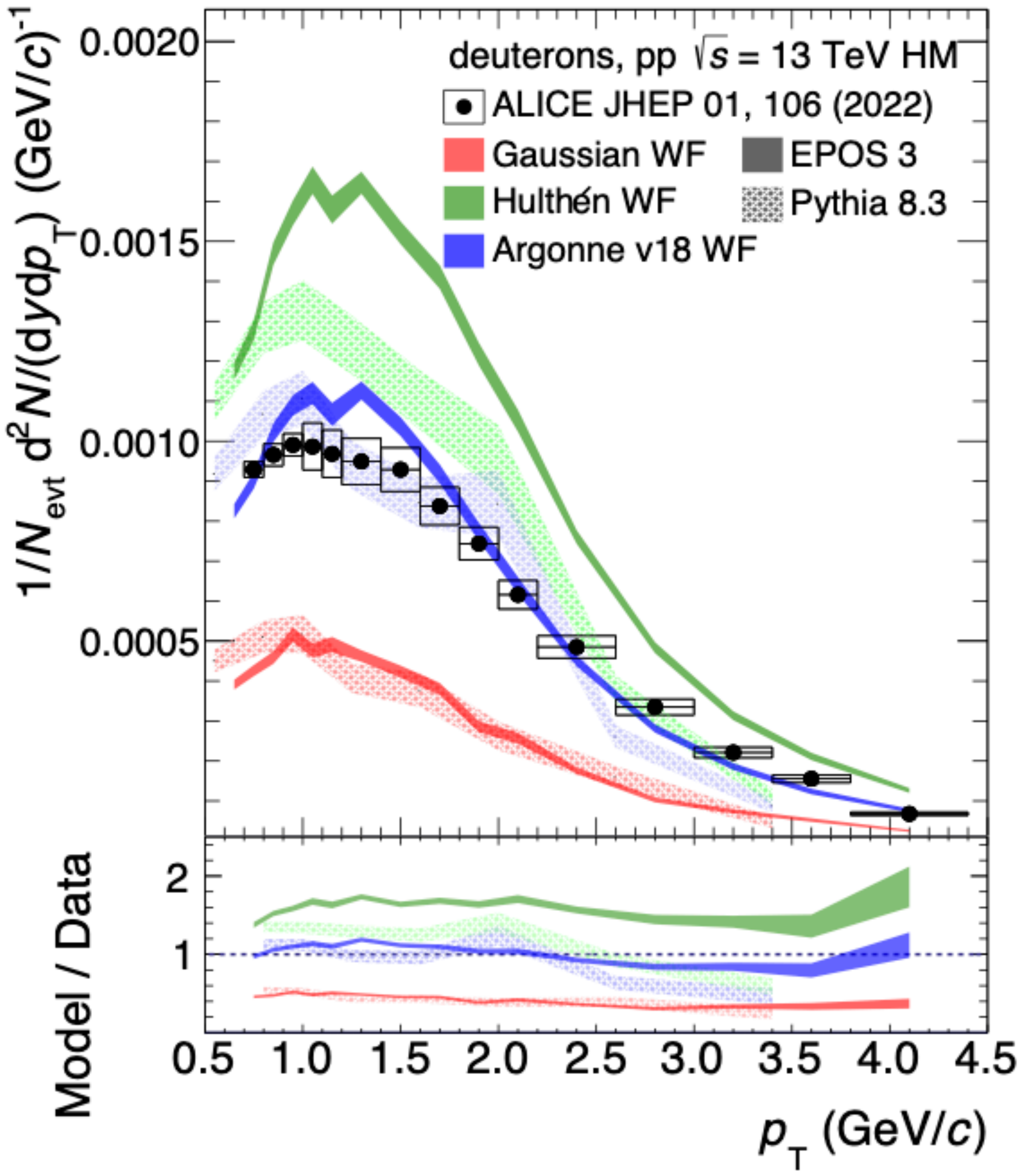
B_A vs p_T in HM pp collisions

- In **HM pp** collisions, ALICE has measured:
  1. **(anti)proton** production spectra
  2. **(anti)deuteron** production spectra
  3. **size** of the emitting **source** with femtoscopy

➡ theoretical predictions for the spectra of (anti)deuterons obtained via coalescence:

$$\frac{d^3N_d}{dP_d^3} = S_d \int d^3q \; \mathscr{P}(r_0, q) \; \frac{G_{np}(\overrightarrow{P}_d/2 + \vec{q}, \overrightarrow{P}_d/2 - \vec{q})}{(2\pi)^6}$$

1. S_d is a degeneracy factor (3/8 for deuterons)
2. G_{np} is the proton-neutron momentum distribution
3. $\mathscr{P}(r_0, q)$ is the coalescence probability
   - r_0 is the size of the emitting source
   - q is the relative momentum of the p-n pair



Mahlein et al., EPJC 83 (2023) 9, 804

B_A vs p_T in HM pp collisions

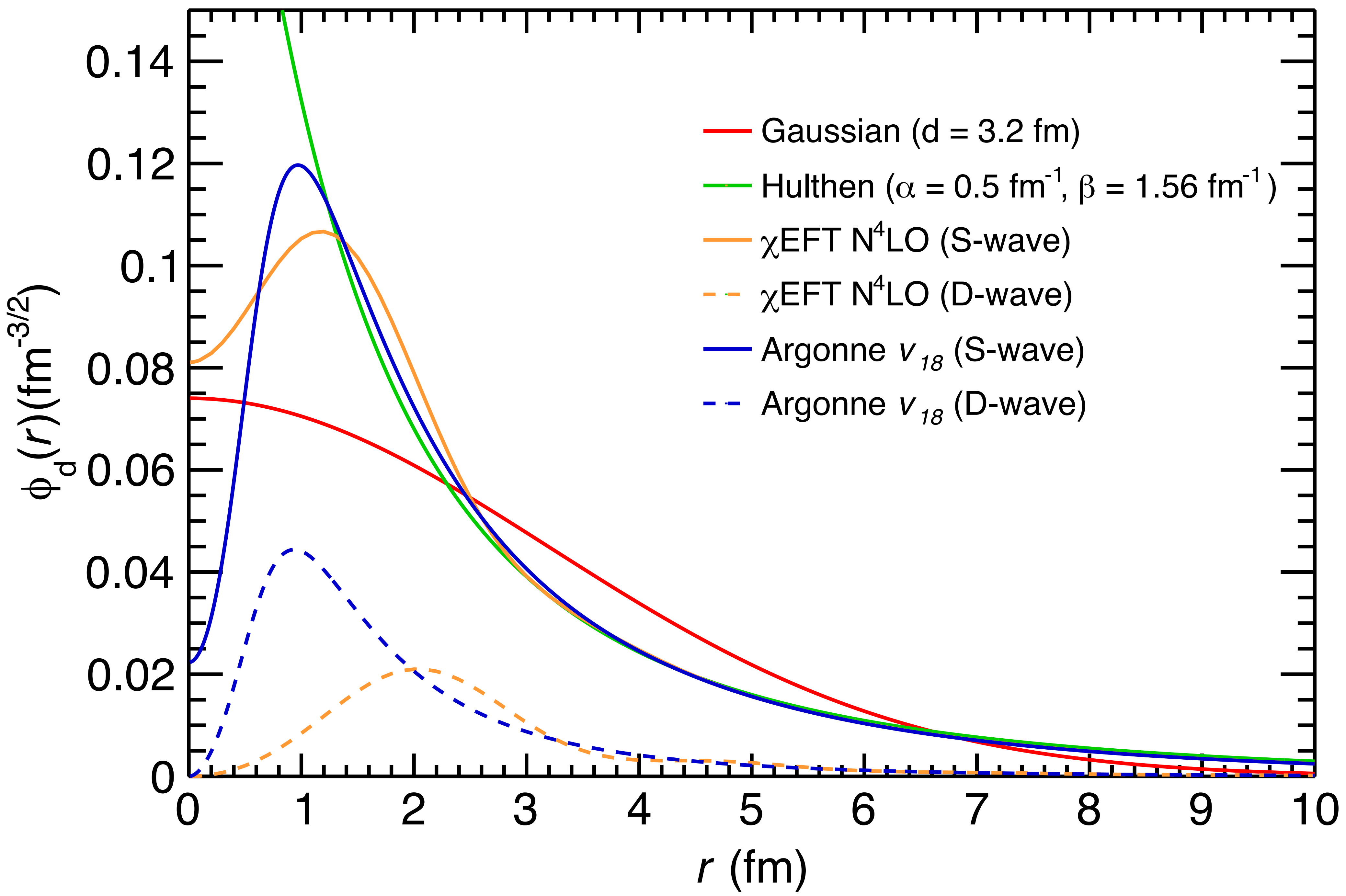
- Coalescence probability $\mathscr{P}(r_0, q)$ is defined as

$$\mathscr{P}(r_0, q) = \int d^3 r_\mathrm{d} \int d^3 r \; H_\mathrm{pn}(\vec{r}, \vec{r}_\mathrm{d}; r_0) \; \mathscr{D}(\vec{q}, \vec{r})$$

- $H_\mathrm{np}(\vec{r}_\mathrm{p}, \vec{r}_\mathrm{n}) \; = h(\vec{r}_\mathrm{p})\, h(\vec{r}_\mathrm{n})$ is the two particle emitting-source
  - factorised into two Gaussian sources
- $\mathscr{D}(\vec{q}, \vec{r}) \; = \int \mathrm{d}^3\xi \, e^{-i\,\vec{q}\cdot\vec{\xi}} \, \varphi_\mathrm{d}(\vec{r} + \vec{\xi}/2)\, \varphi^*_\mathrm{d}(\vec{r} - \vec{\xi}/2)$

  is the Wigner-transform of the deuteron wavefunction φ_d

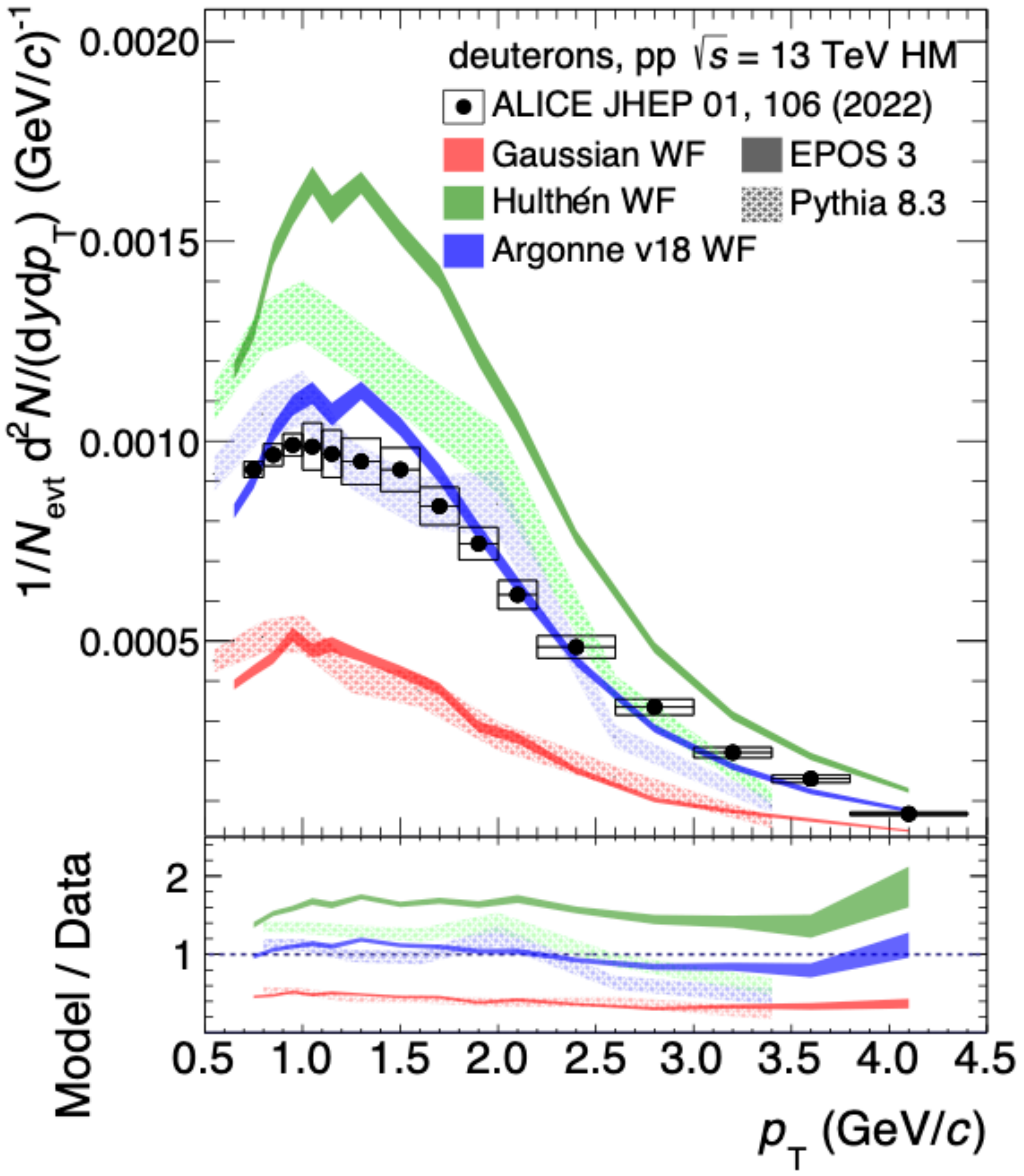
➡ test the effect of deuteron wavefunctions on coalescence



Mahlein et al., EPJC 83 (2023) 9, 804

B_A vs p_T in HM pp collisions

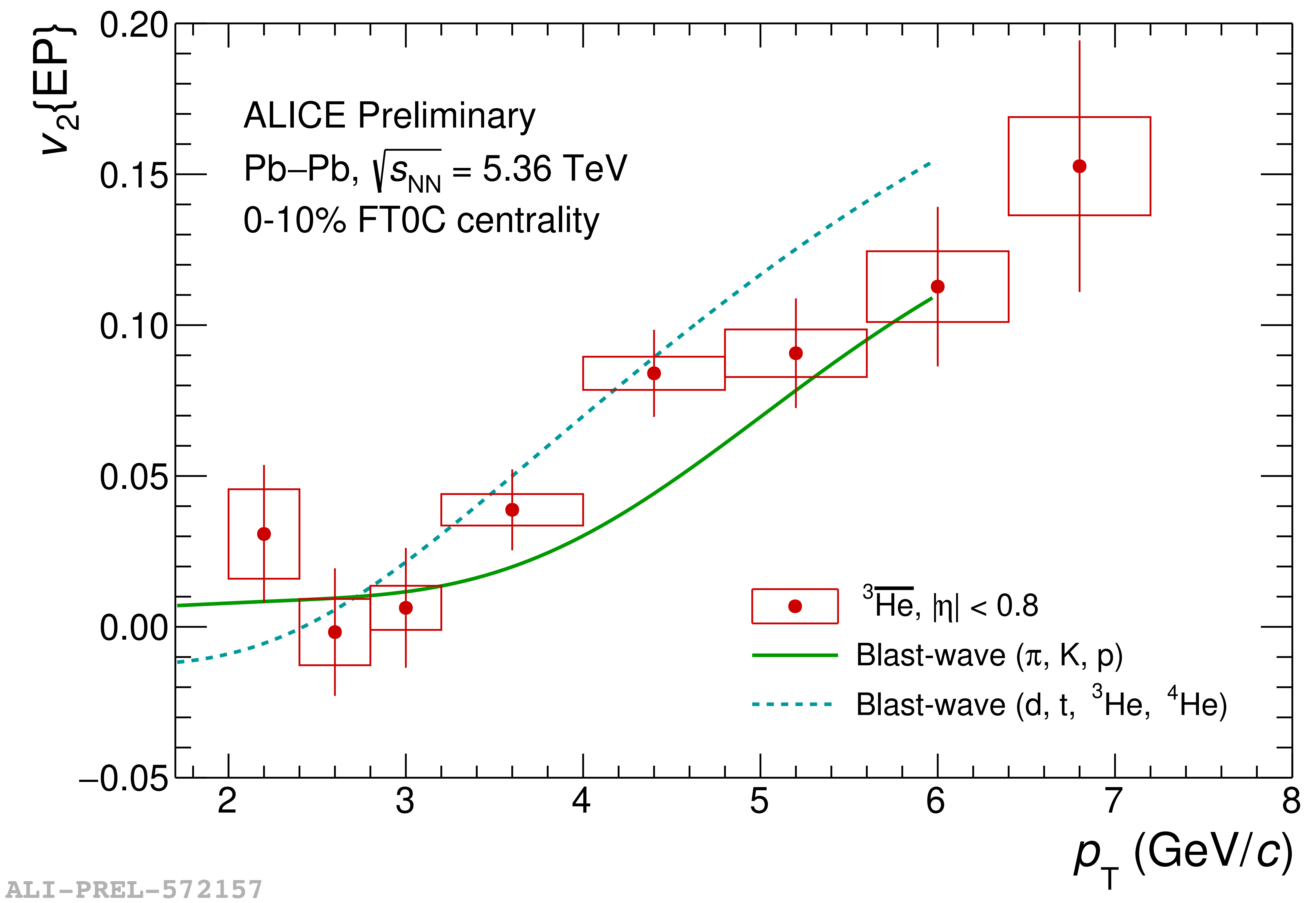
- Coalescence is implemented on a single-event base:
  1. The event is simulated with a MC generator
  2. The p-n momentum distribution G_{np} (hence relative momentum q) is taken from the generator
  3. p and n spectra are re-weighted to reproduce ALICE measurements
  4. The p-n distance is re-weighted to reproduce the source size r_0 measured by ALICE
  5. The coalescence probability $\mathscr{P}(r_0, q)$ is evaluated and used in a rejection method
- Argonne v18 wavefunction (which is the most realistic) provides a good description of data



Mahlein et al., EPJC 83 (2023) 9, 804

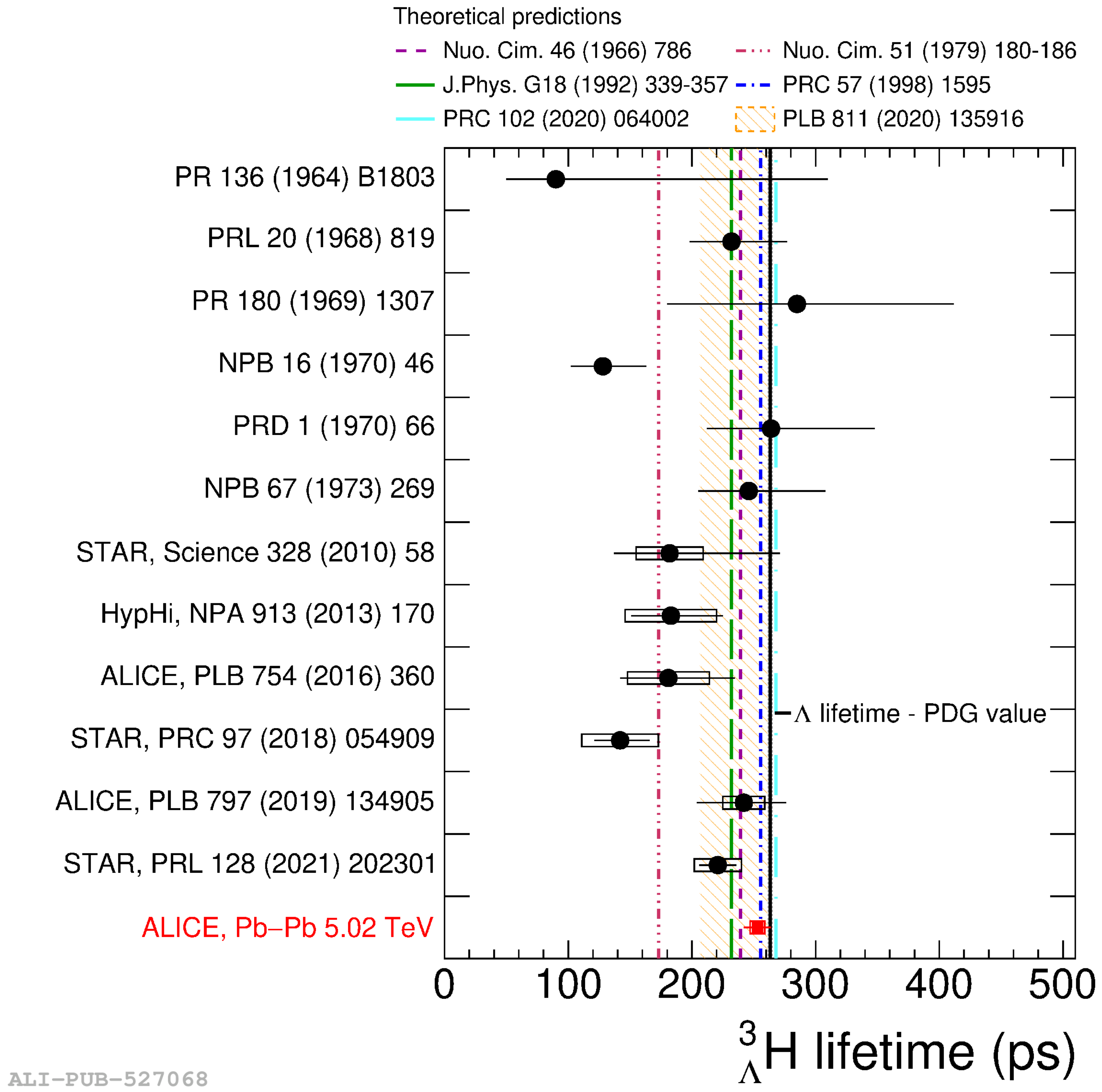
Flow as a probe for nuclear production

- **Coalescence** is a **femtoscopic probe**:
  - It is sensitive to a different production in-plane and out-of-plane
  - Flow can be used to test production mechanisms
- ALICE has measured ***v*₂** for **anti-³He** in **Run 3 Pb-Pb** collisions at 5.36 TeV
  - more differential both in p_T and centrality, more precise than in Run 2
- Data are compared with the predictions of blast wave and coalescence model
  - **coalescence** is favoured



Λ separation energy

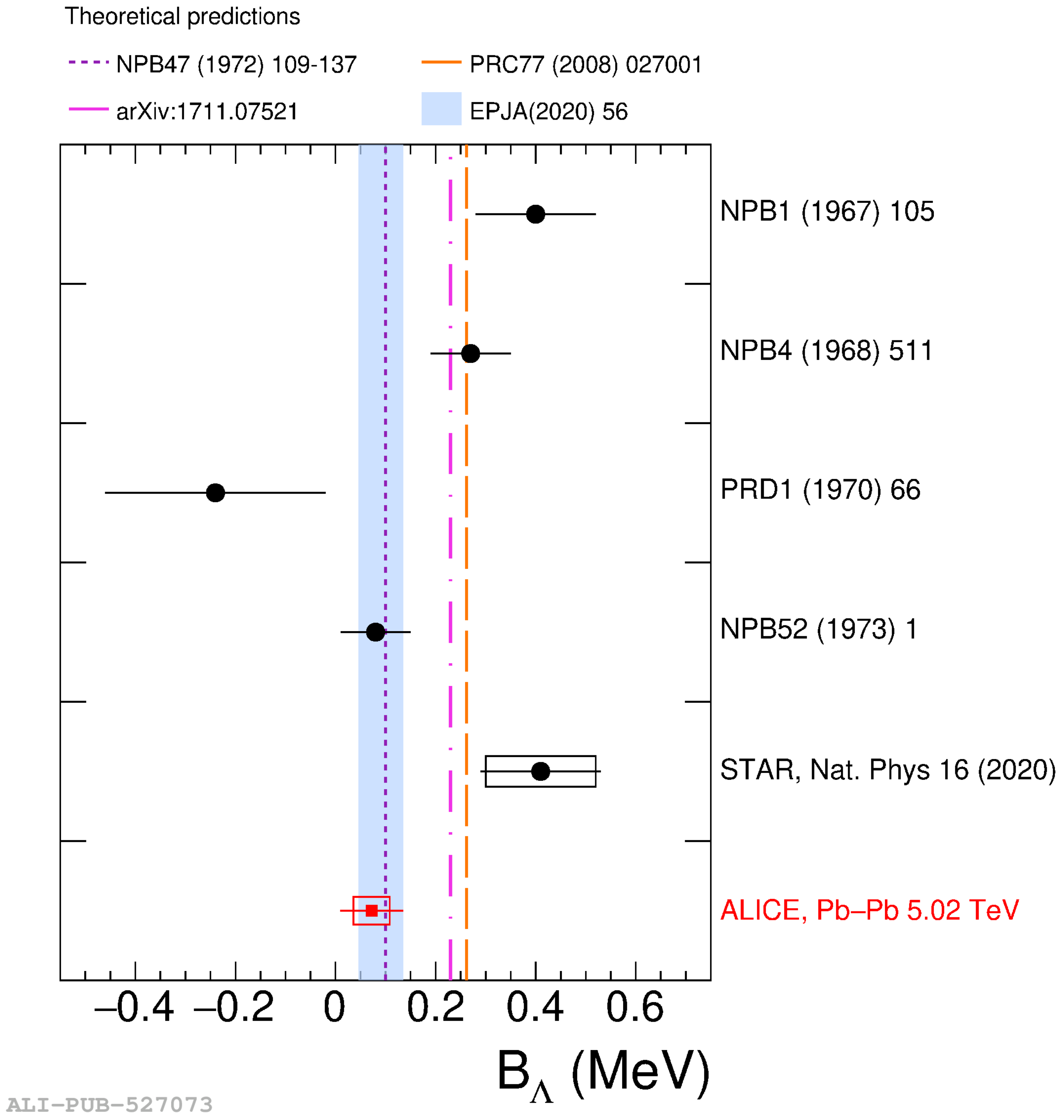
- **Lifetime** measured with the highest precision so far:
  - compatible with that of the **free Λ**
    - **loosely bound** state



PRL 131 (2023) 102302

Λ separation energy

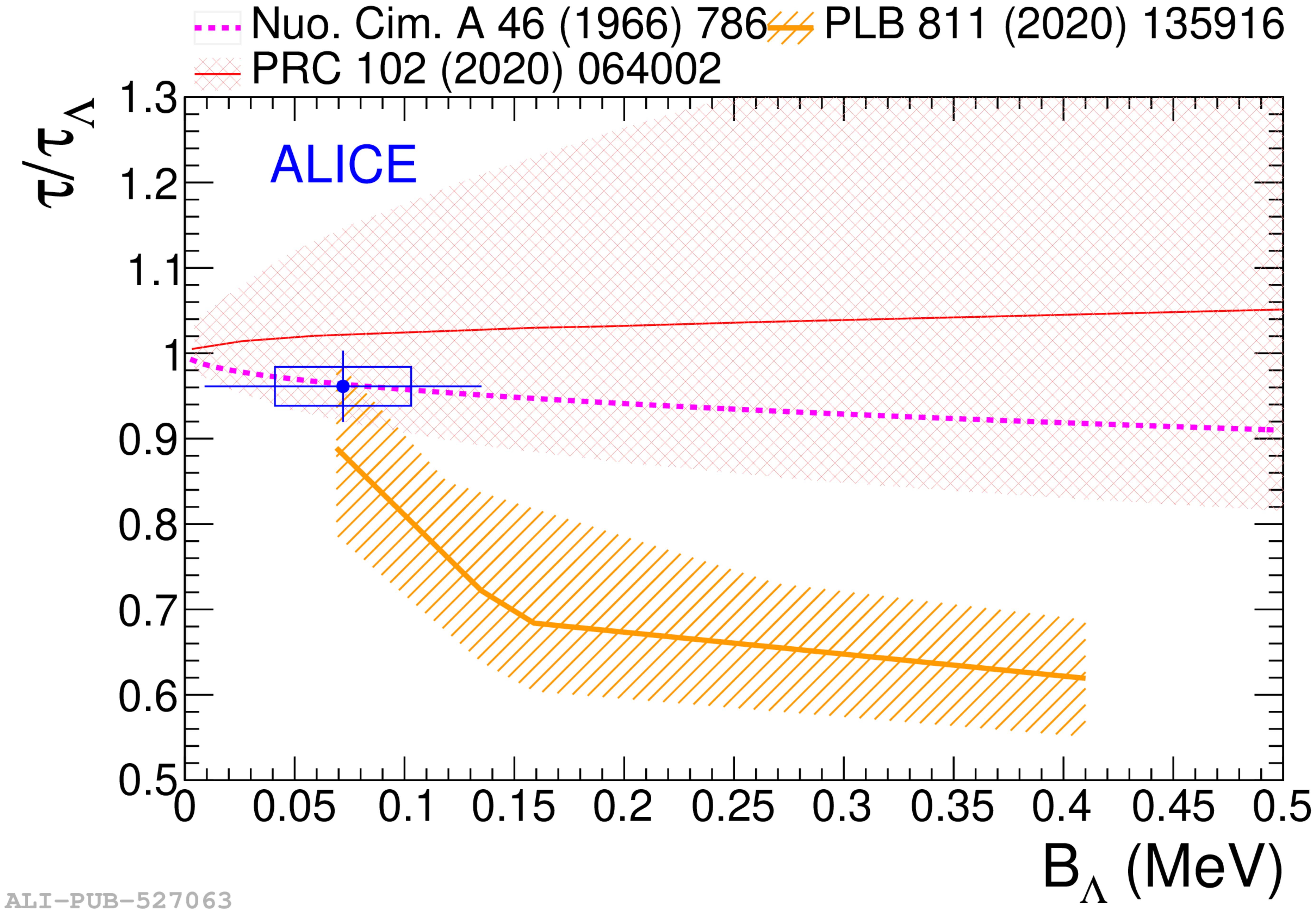
- **Lifetime** measured with the highest precision so far:
  - compatible with that of the **free Λ**
    - **loosely bound** state
- B_Λ has been measured with a **high precision**
  - **1.9 σ** difference w.r.t. last **STAR** results
  - compatible with χEFT and **Dalitz**'s predictions
    - **loosely bound** state



PRL 131 (2023) 102302

Λ separation energy

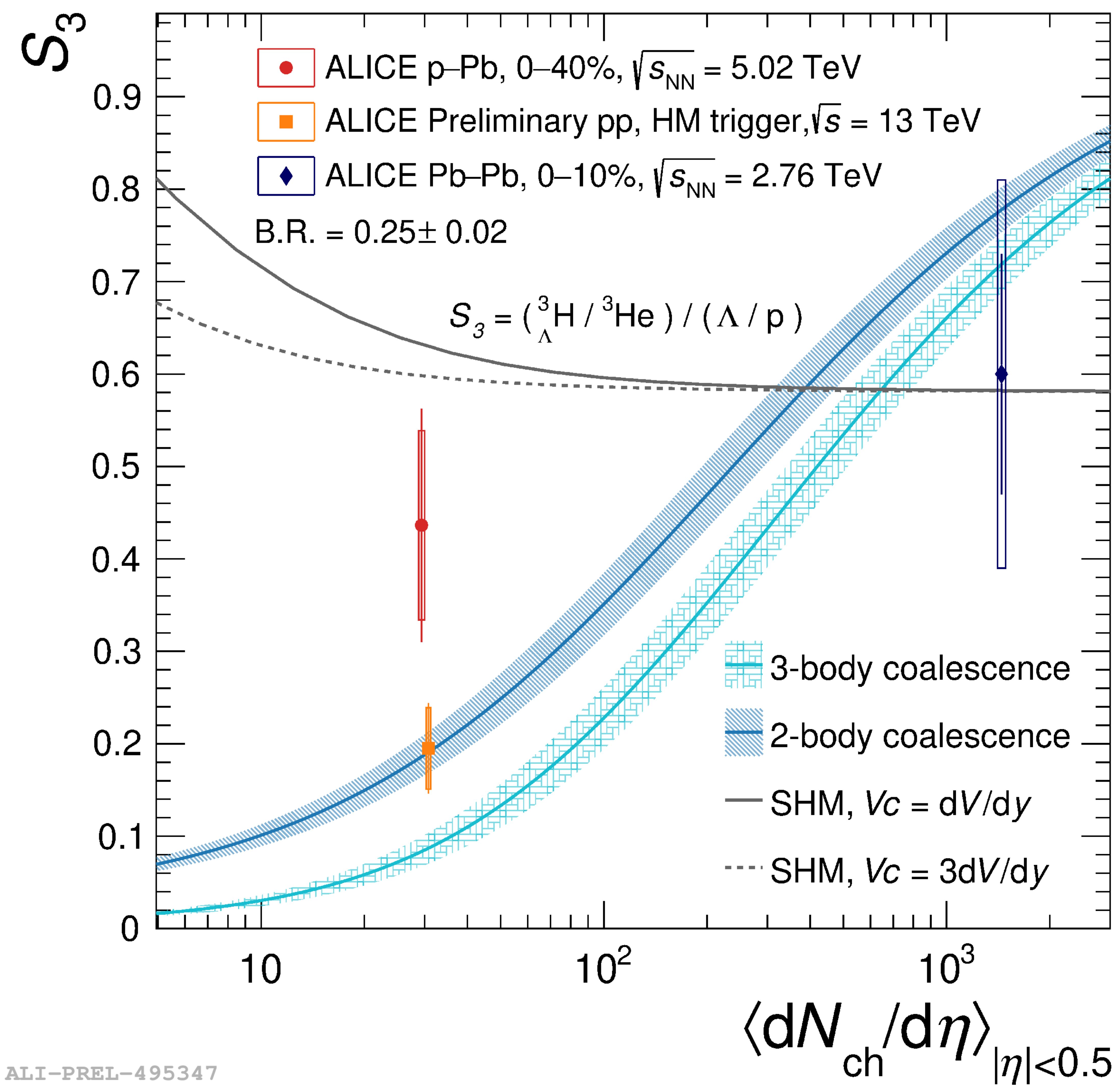
- **Lifetime** measured with the highest precision so far:
  - compatible with that of the **free Λ**
    - **loosely bound** state
- **B$_\Lambda$** has been measured with a **high precision**
  - **1.9 σ** difference w.r.t. last **STAR** results
  - compatible with χ**EFT** and **Dalitz**'s predictions
    - **loosely bound** state
- All the models provide a simultaneous description of τ and **B$_\Lambda$**



PRL 131 (2023) 102302

Hypertriton production in small systems

- ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ is compared with the prediction of CSM and coalescence model
  - **Two-body coalescence** model provides the best description of data
- Also $S_3 = \dfrac{{}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}}{\Lambda/\mathrm{p}}$ is a valuable observable to discriminate between production mechanisms
  - Also in this case **coalescence** is favoured, even though with less sensitivity



ALI-PREL-495347

PRL 128 (2022) 252003

Coalescence parameter B_A

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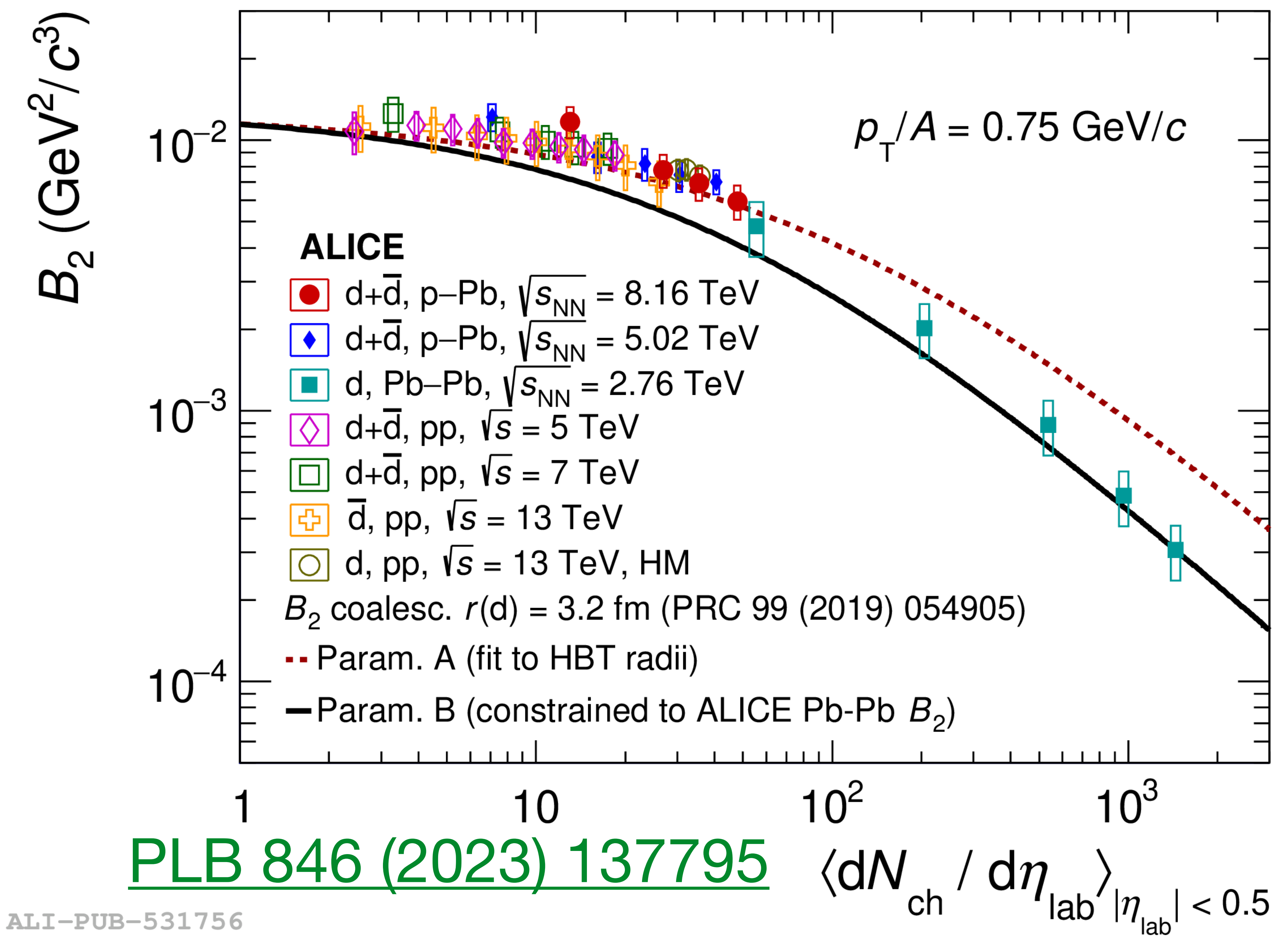
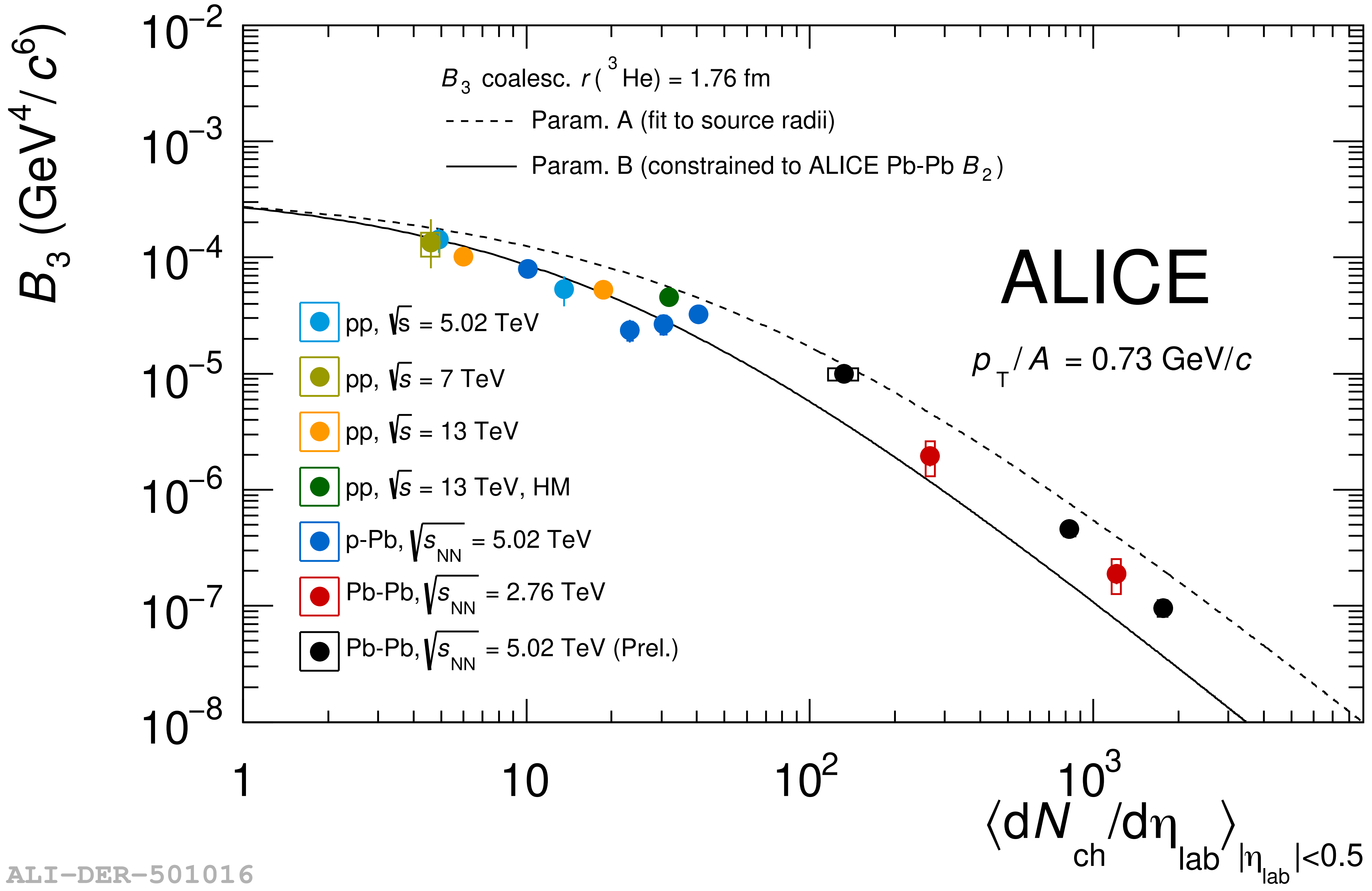
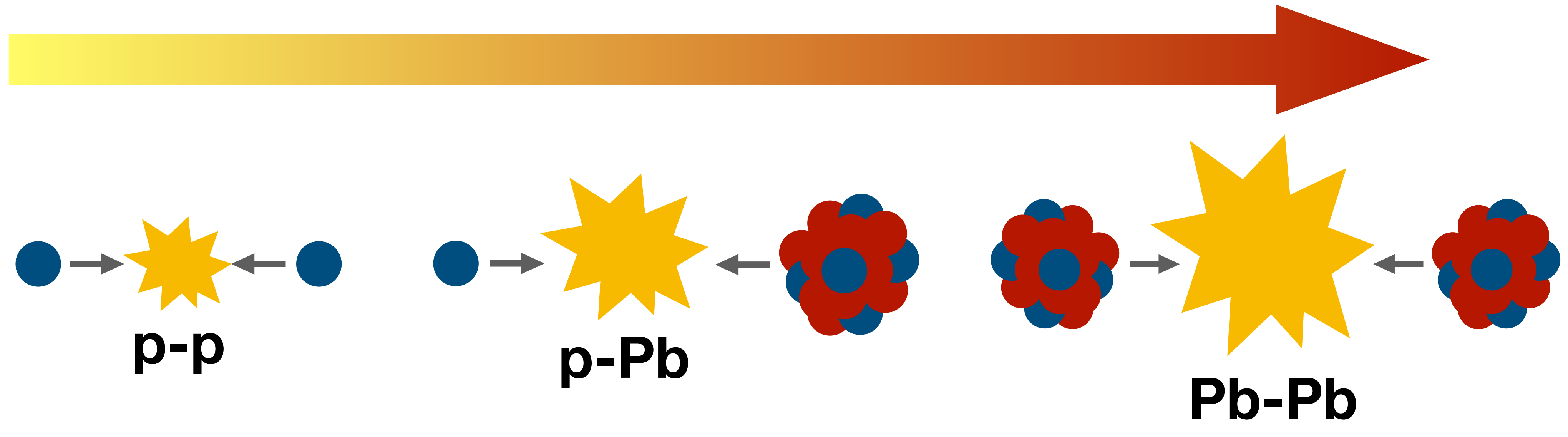


PLB 846 (2023) 137795





- B_A **evolves smoothly** with **multiplicity**
  - dependence on the **system size**
- Comparison with theory:

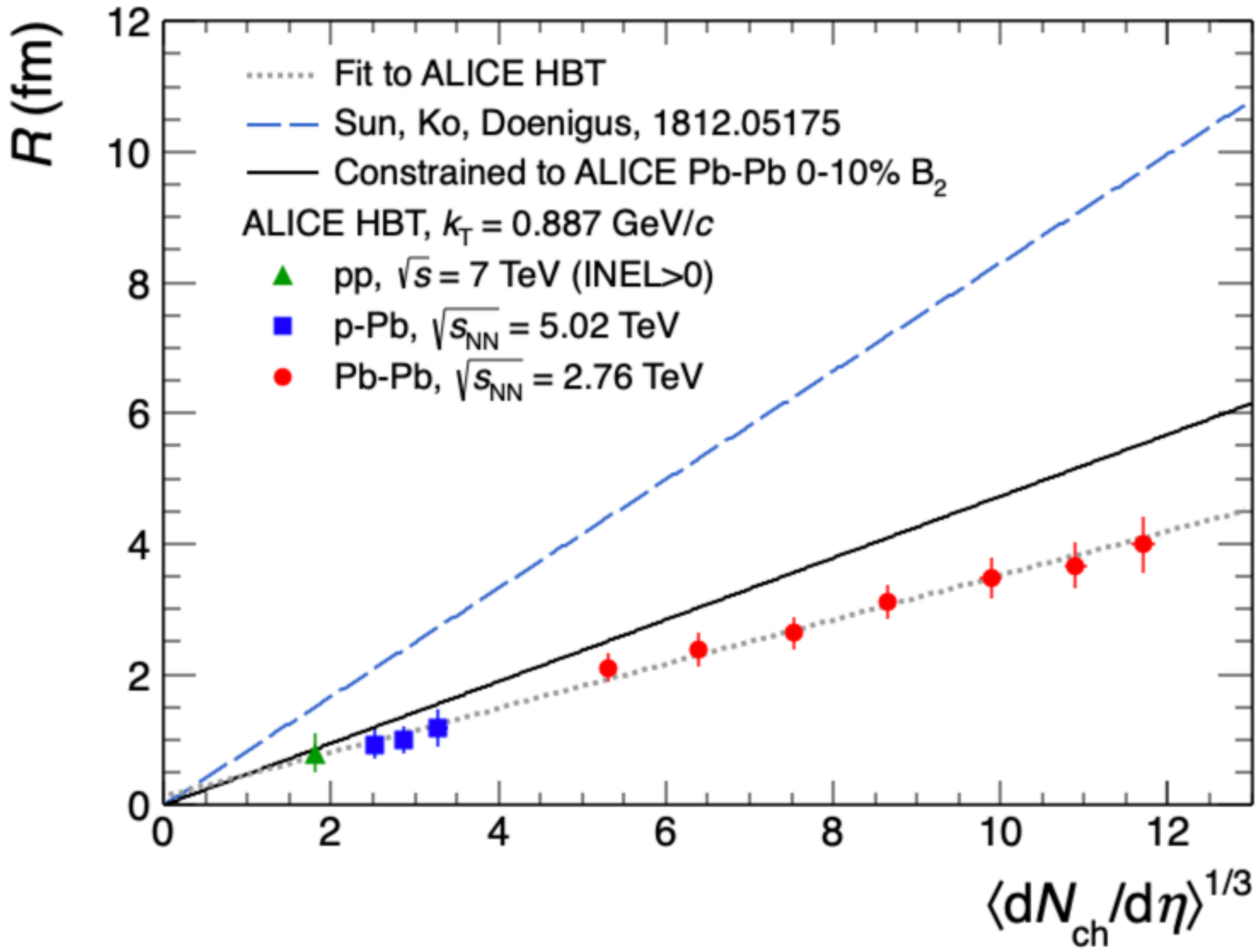
$$B_A = \frac{2J_A + 1}{2^A\sqrt{A}} \frac{1}{m^{A-1}} \left[\frac{2\pi}{R^2(m_T) + \left(r_A/2\right)^2}\right]^{\frac{3}{2}(A-1)}$$

- **Two** different parameterisations for **d*N*/d*η*** vs ***R***
  - None of them can describe simultaneously B_2 and B_3

Charged particle multiplicity

- Measurements are carried out vs multiplicity
- $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle \leftrightarrow$ **system size**
- System size: **HBT radius R**
  - R vs multiplicity:

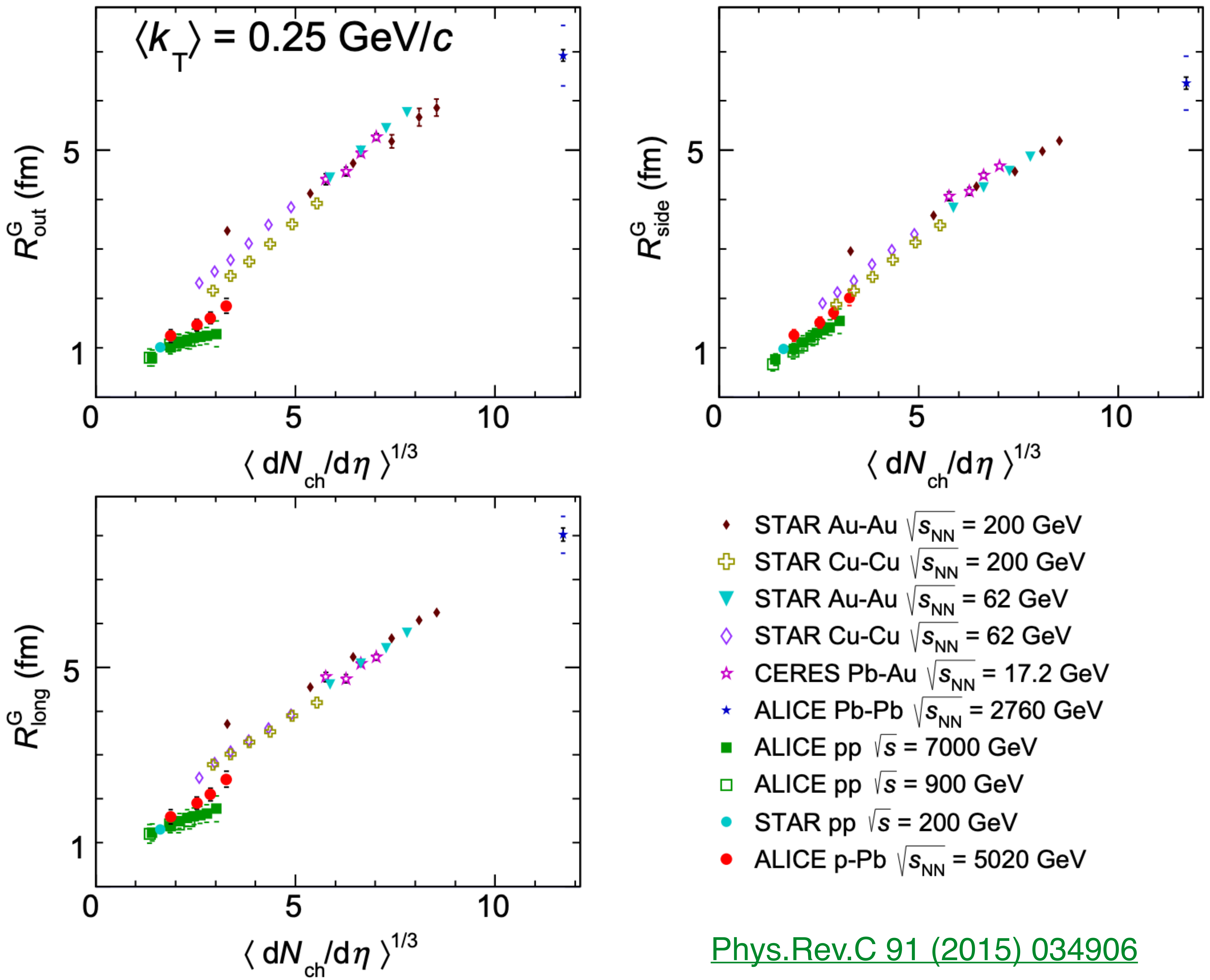
$$R = a \, \langle \mathrm{d}N/\mathrm{d}\eta \rangle^{1/3} + b$$



Phys.Rev.C 99 (2019) 5, 054905

Charged particle multiplicity

- Adding more points to the R vs $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle$, it is visible that the evolution is **not smooth** from pp to p-Pb
- This discontinuity could be the reason why models do not reproduce data along the whole multiplicity range
  - Possible solution: B_2 vs R
  - R vs $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle$ needed



Phys.Rev.C 91 (2015) 034906