Probing the (anti)nucleosynthesis via nuclear flow measurements and hypertriton spin determination via the polarisation measurement

Luca Barioglio, on behalf of ALICE
INFN, Sezione di Torino

ICHEP 2024
Prague - 20 July 2024

Physics motivation

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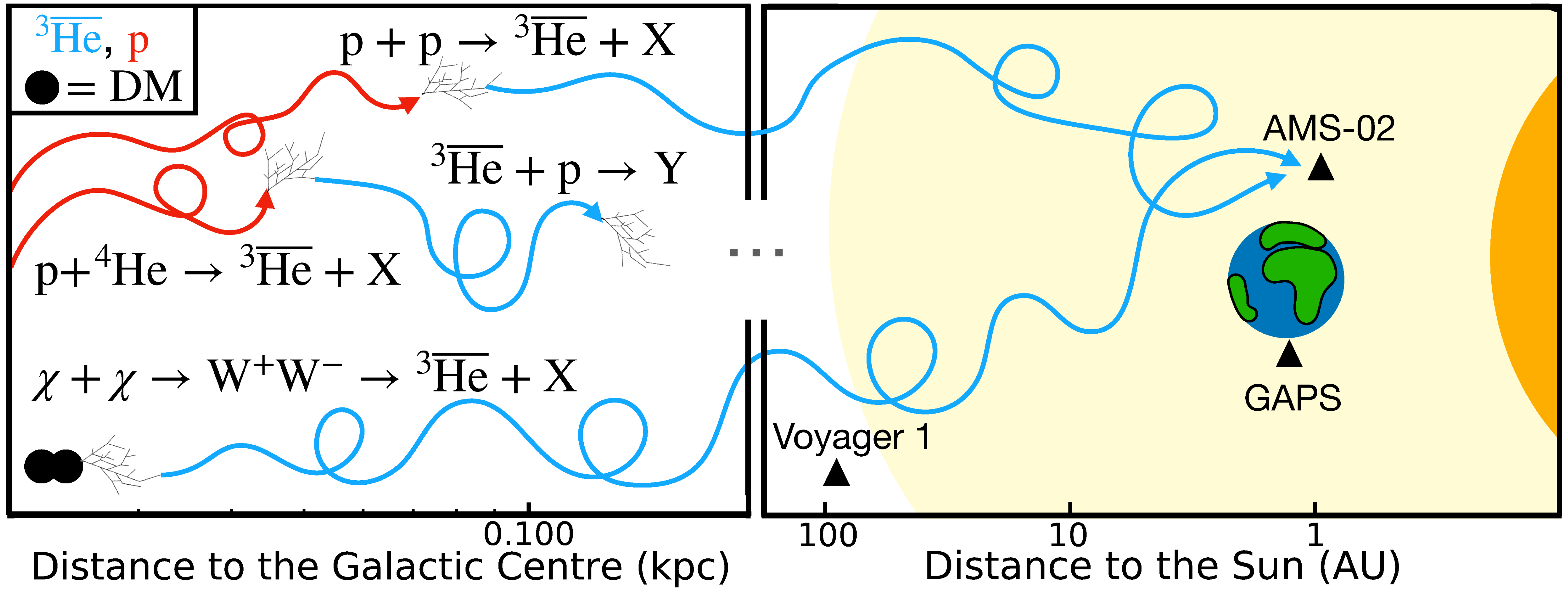
- The study of the production mechanisms of (anti)(hyper)nuclei is not only interesting *per se*
- **Antinuclei** can be a sign of **Dark Matter annihilation**:
  - *Background*: production in the collisions between **cosmic rays** (CR) and the **interstellar medium** (ISM) (pp and p-A collisions)
 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



ALI-PUB-532052

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

Alberto Calivà's presentation about nuclear production in jets
20th July - 10:15

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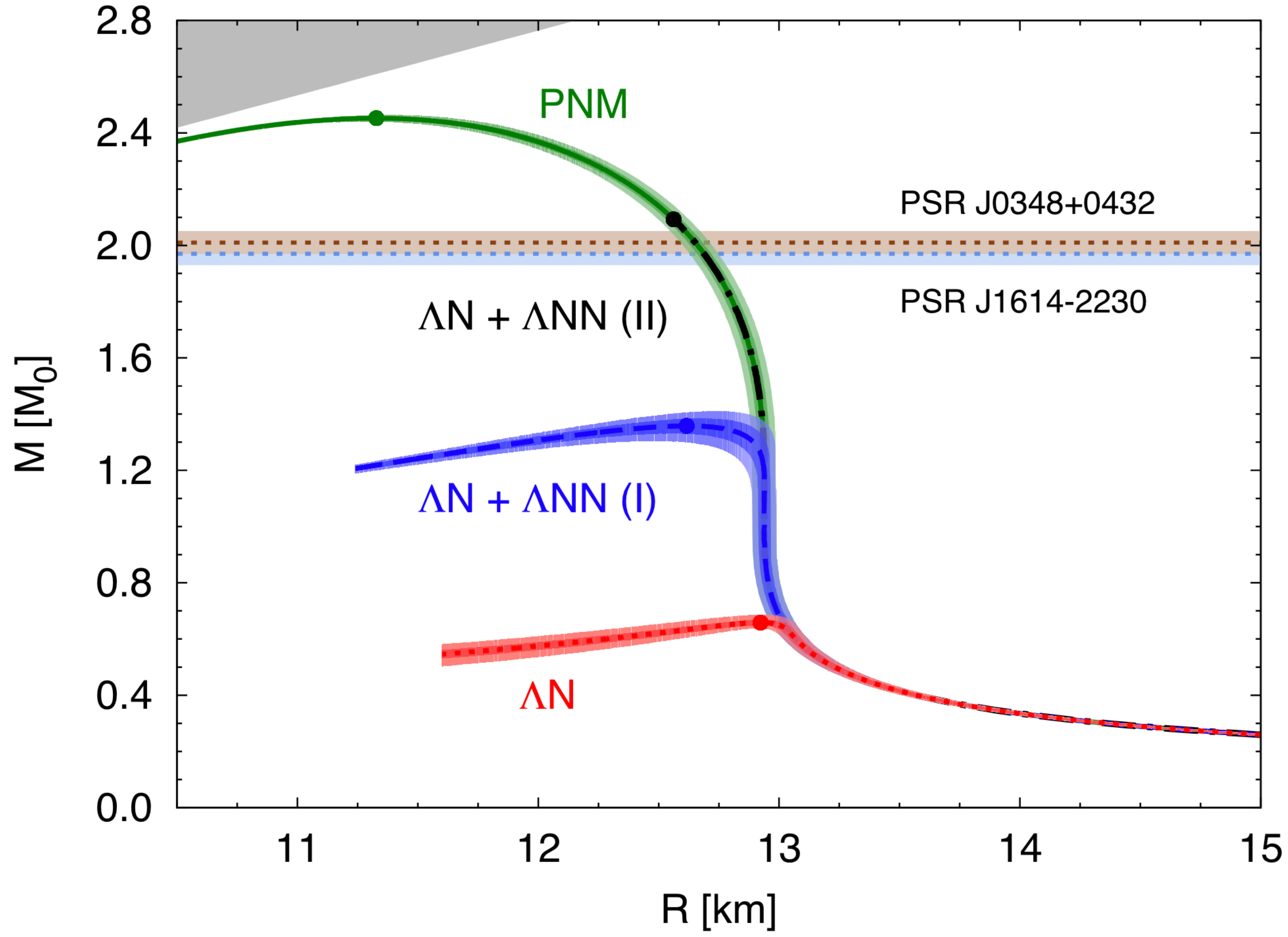
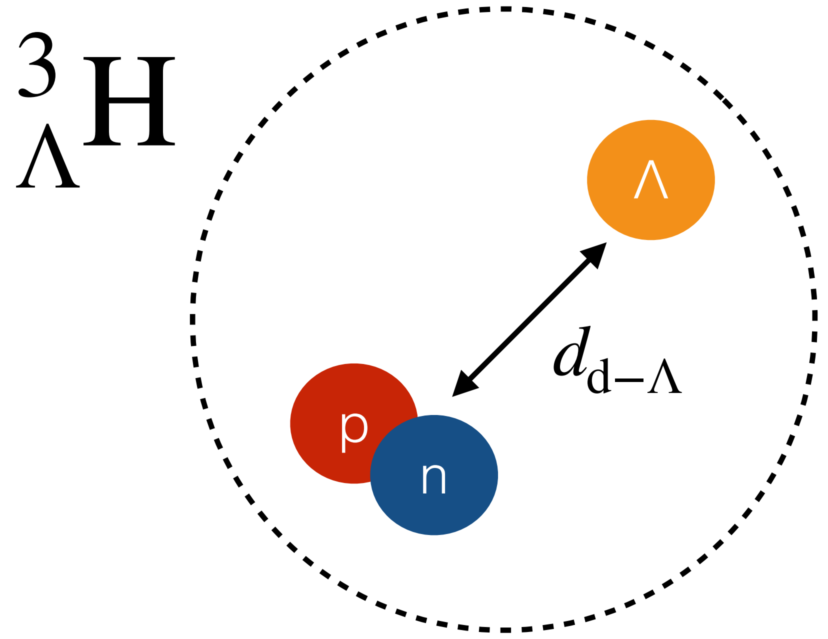
  - *Background*: production in the collisions between **cosmic rays** (CR) and the **interstellar medium** (ISM) (pp and p-A collisions)
    - Nuclear production must be known very well
- **Hypernuclei** can be used to study **nucleon-hyperon interaction**
  - Production of exotic bound states
  - Determination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



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



Janik Ditzel's presentation
about hypernuclei
20th July - 11:00

Statistical Hadronisation Model (SHM)

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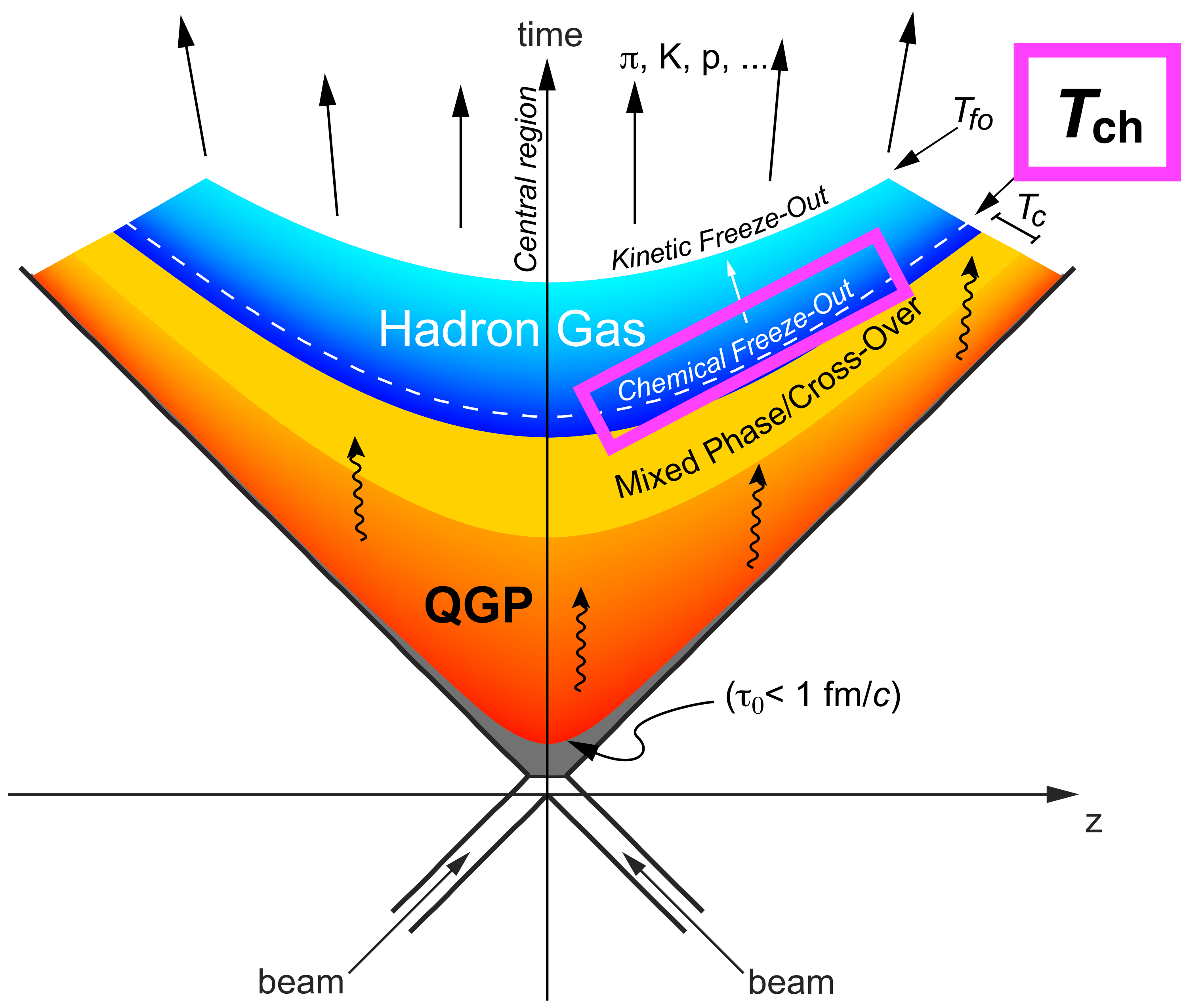
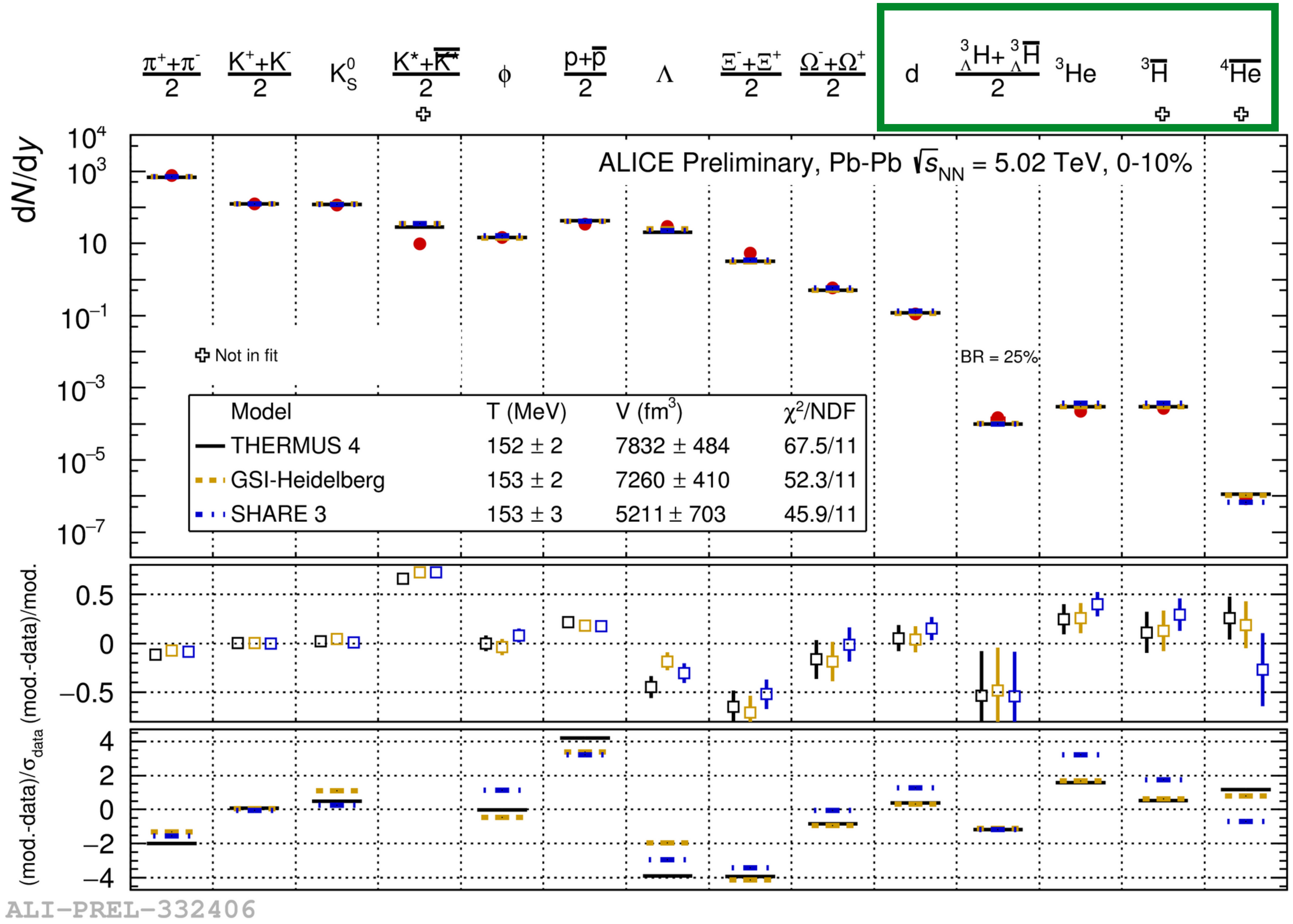
- It describes the **yields** of light-flavoured hadrons by requiring **thermal** and **hadron-chemical equilibrium**
  - Parameters: (T, V, μ_B)
- **Canonical ensemble** (CSM): local conservation of quantum numbers (S, Q and B)
- **Macroscopical model**: no information about how nuclei are produced, together with the other species





THERMUS 4: Comput.Phys.Commun. 180 (2009) 84-106
GSI-Heidelberg: Nucl.Phys.A 772 (2006) 167-199
SHARE 3: Comput.Phys.Commun. 167 (2005) 229-251

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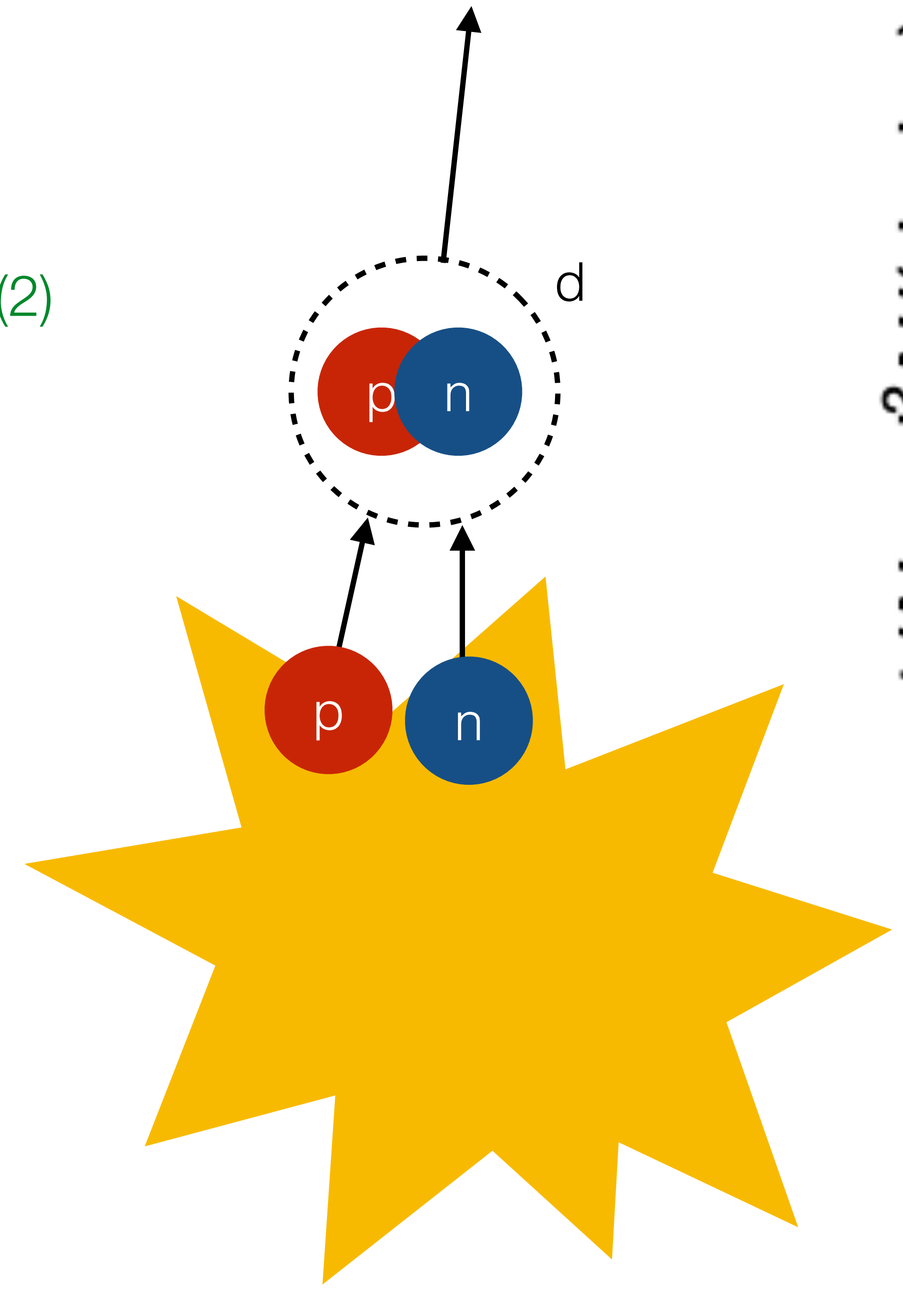
- **Microscopical model**:
  - Nuclei are formed by **nucleons** emitted by a **freeze-out hypersurface**(1)
    - convolution between **nucleon phase-space** distribution and **Wigner function** of the nucleus(2)
- Possible to implement **event-by-event coalescence**, with probability:

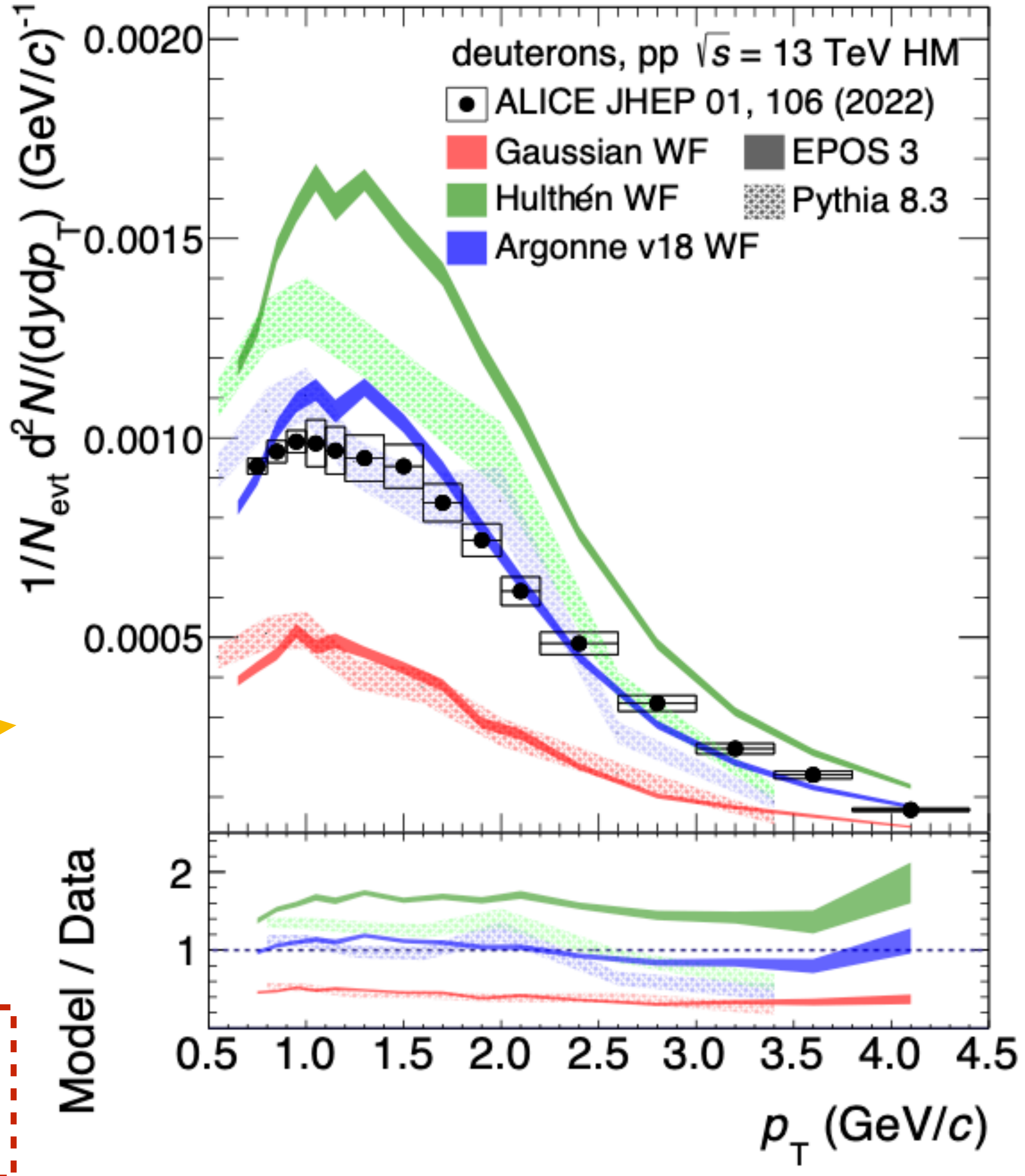
$$\mathscr{P}(r_0, q) = \int d^3r_d \int d^3r \; H_{pn}(\vec{r}, \vec{r}_d; r_0) \; \mathscr{D}(\vec{q}, \vec{r})$$

- 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**



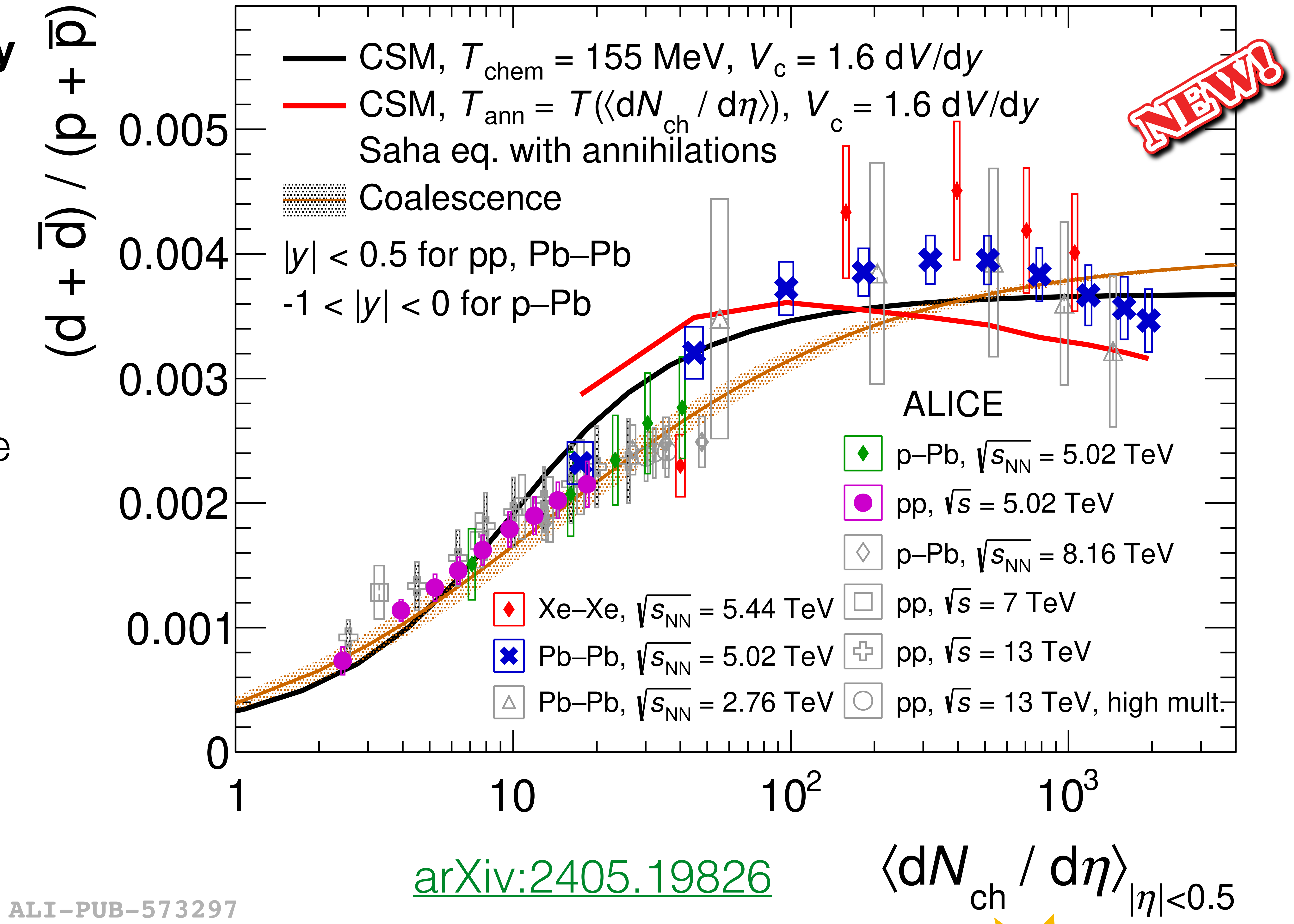


(2) Mahlein et al., EPJC 83 (2023) 9, 804

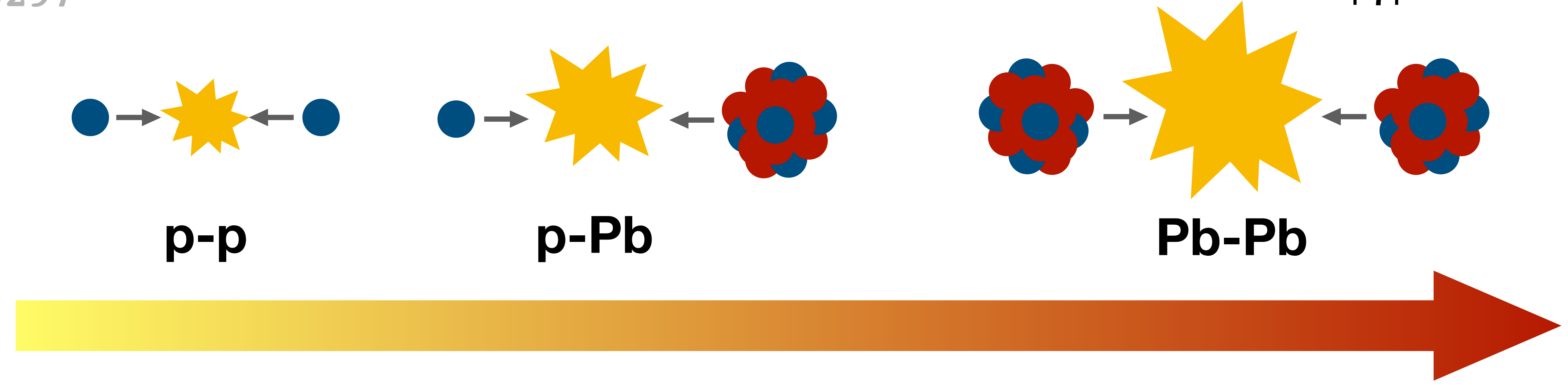
(1) J. I. Kapusta, PRC 21, 1301 (1980)

- Coalescence is a **femtoscopic probe**

- Ratios between p_T-integrated yields (**A/p**) vs **multiplicity**
  - multiplicity is a proxy of the **system size**
- For **d/p** ratio both the models describe the data:
  - CSM: canonical suppression due to baryon number conservation
  - **Coalescence model**: interplay between system size and nuclear size



arXiv:2405.19826



Studying the production via yield ratios

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- Ratios between p_T-integrated yields (**Λ/p**) vs **multiplicity**
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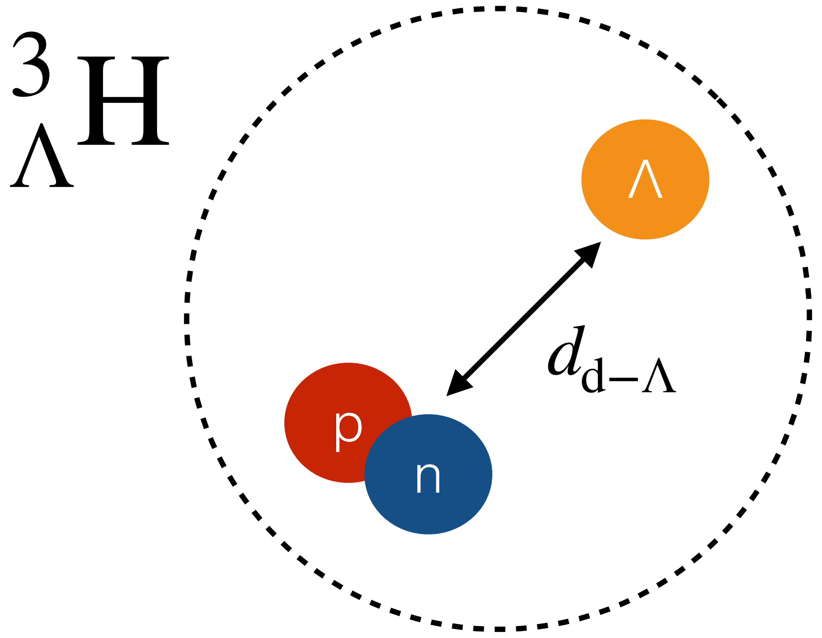
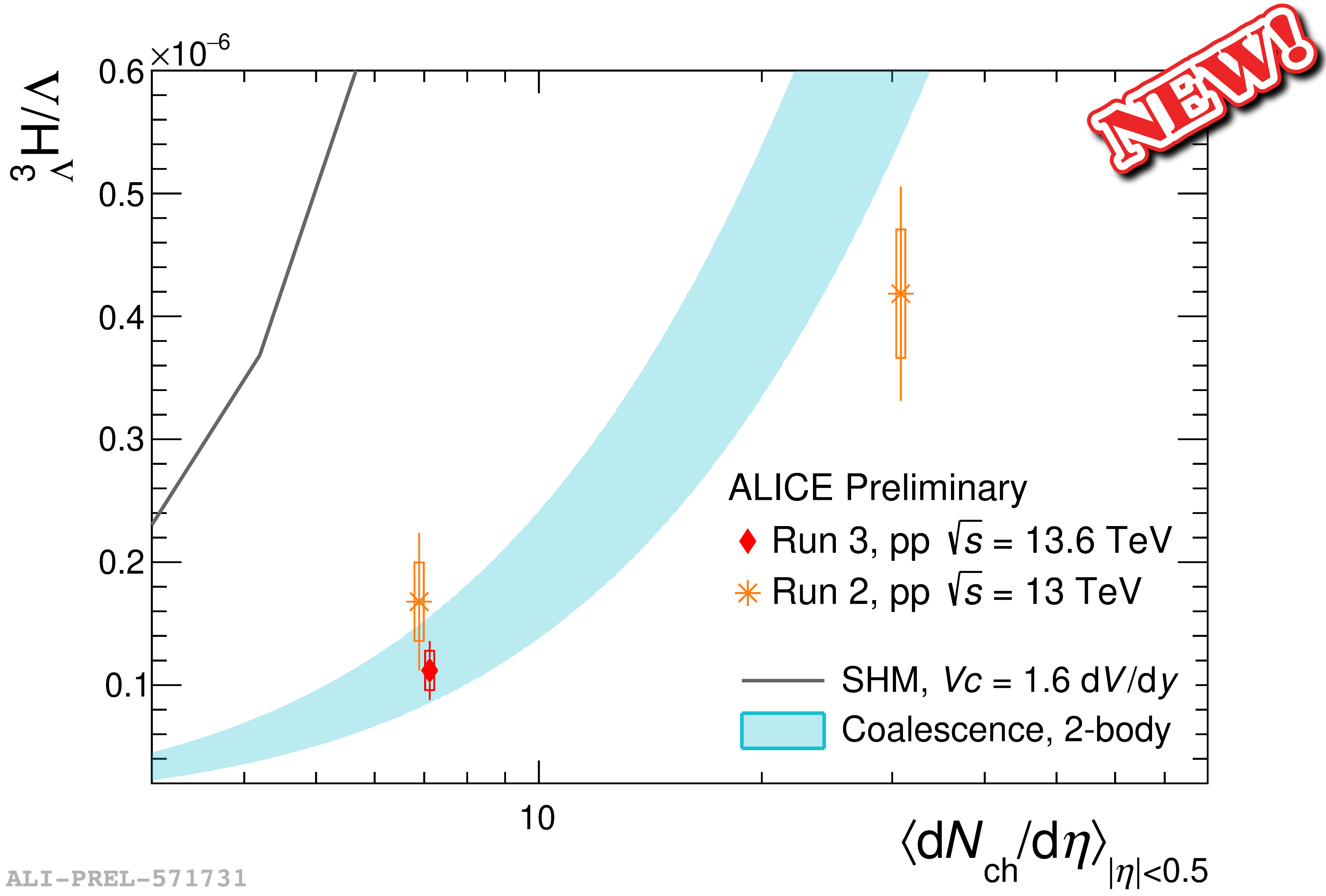


- $^3_\Lambda$H has a large size:
  - $d_{d-\Lambda} = 10.79$ fm [1], $r(\mathrm{d}) = 1.96$ fm
  - **SHM** and **coalescence** predictions for are very **different at low multiplicity**
    - hypertriton in pp collisions favours coalescence



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

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    - **SHM** and **coalescence** predictions for are very **different at low multiplicity**
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- In **Pb-Pb** collisions, system size > nuclear size:
  - Coalescence and CSM gives **similar predictions**
    - Different observables are required

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

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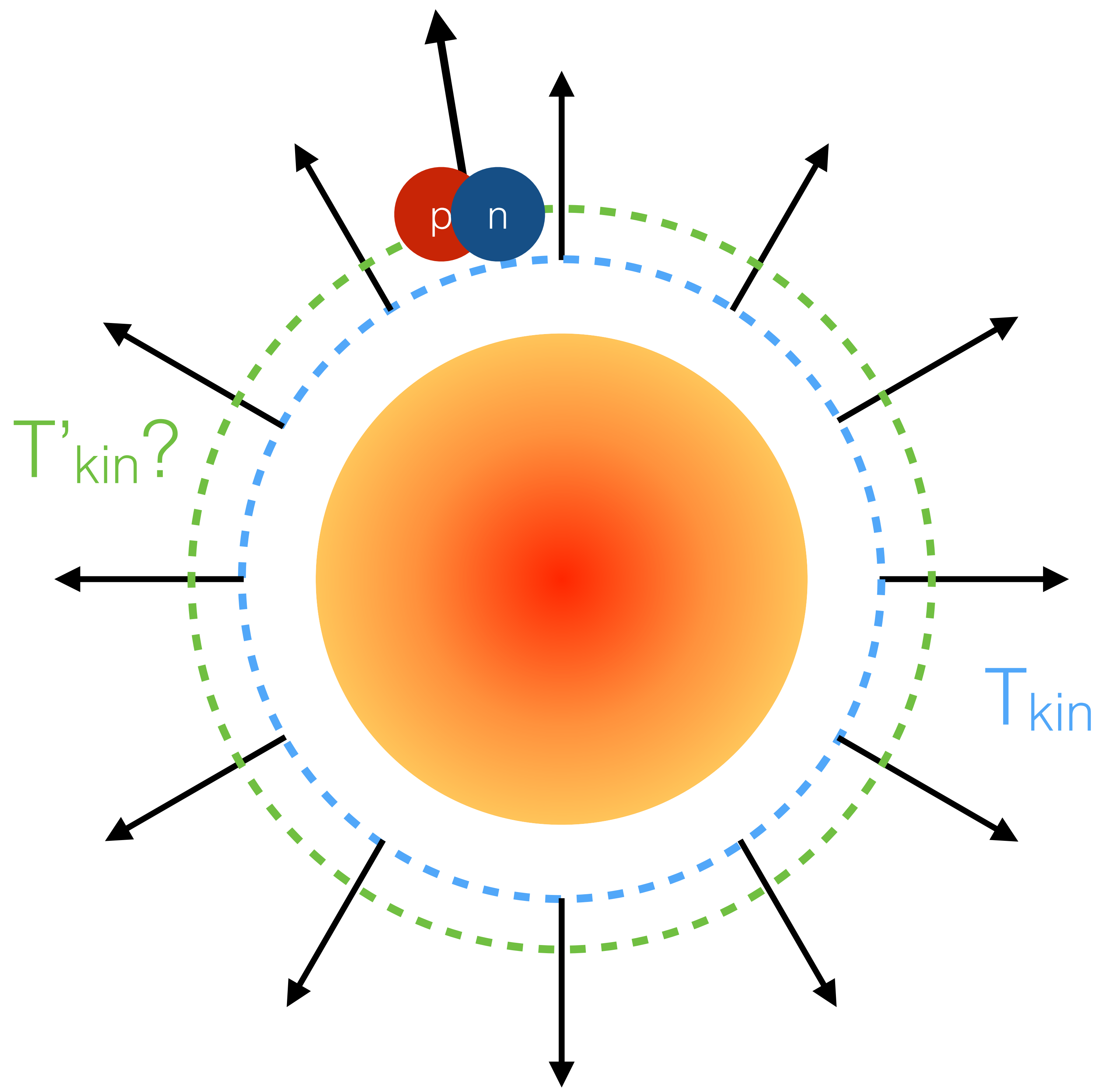
- **Radial flow**:
  - The temperature of the **kinetic freeze-out** (***T*****kin**) can be obtained via a fit to the production spectra with a **blast-wave** (**BW**) fit
    - Do (hyper)nuclei have a **common freeze-out** with the other species?



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- **Radial flow**:
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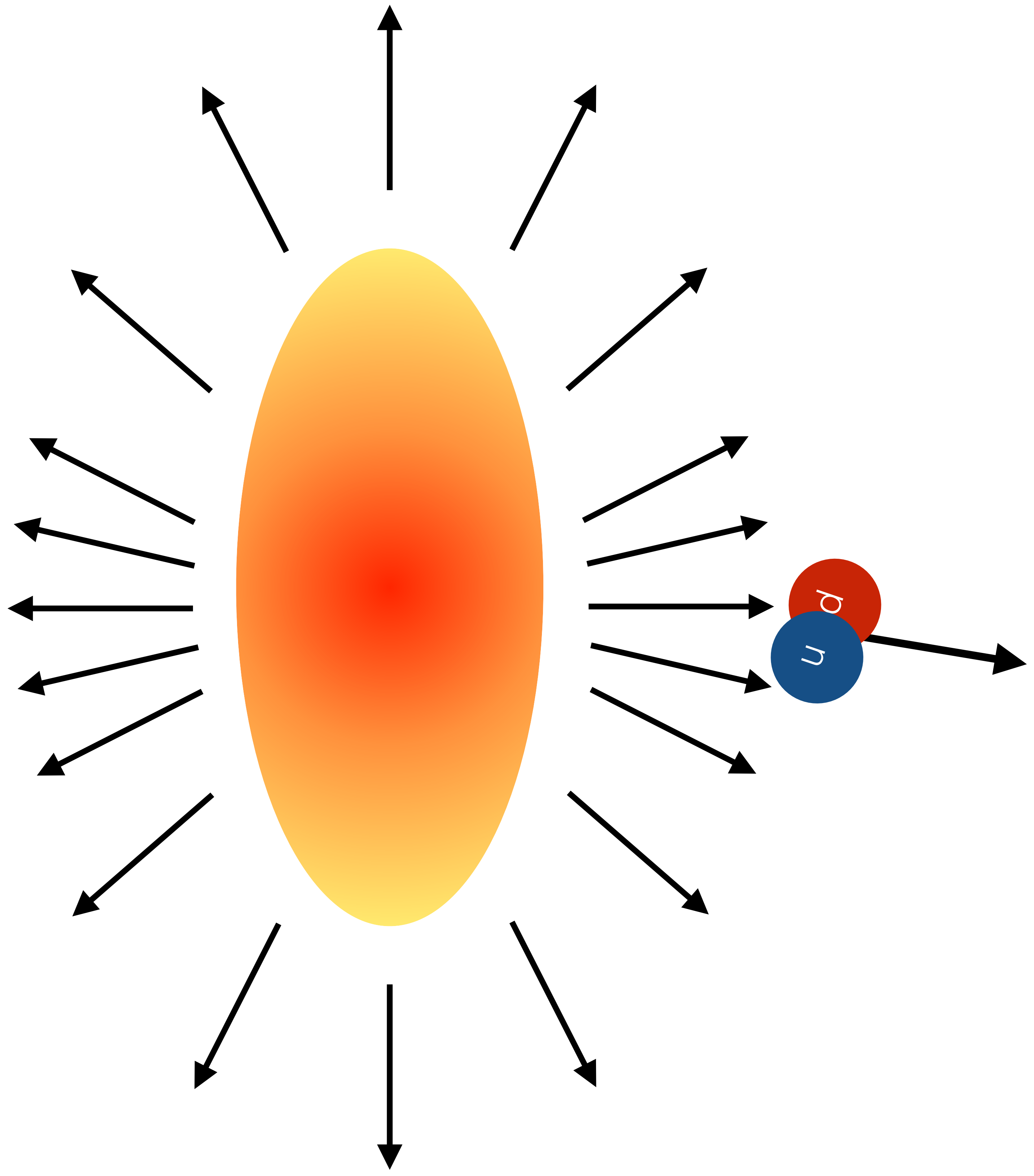
    - Do (hyper)nuclei have a **common freeze-out** with the other species?

- **Anisotropic flow**:
  - **Coalescence** is a femtoscopic probe
    - **phase-space density** of nucleons is a key ingredient
    - sensitive to different production **in-plane** and **out-of-plane** [1]



[1] arXiv:2402.06327

Blast-Wave fits to p_T spectra

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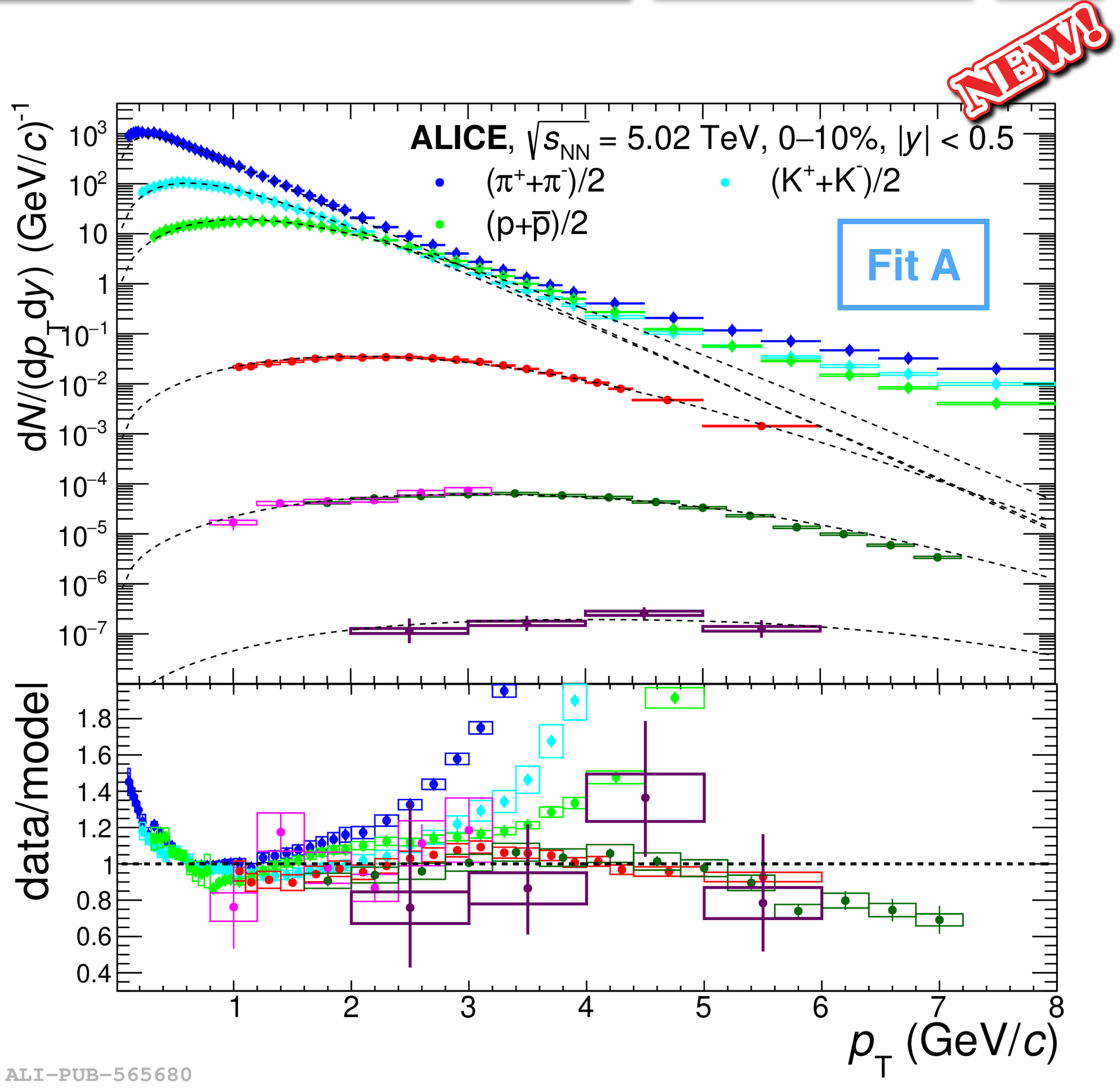
- ALICE has measured the production spectra for d, t, ^{3}He and ^{4}He in Pb-Pb
- p_T spectra of light nuclei and other species are fitted with a **BW** using different options
  - CAVEAT: the blast-wave model is a simplified approach and has limitations (e.g. dependence on the fit range, on the used species)

	Fitted particles	$\langle\beta\rangle$	β_{max}	T_{kin} (MeV)	n	χ^2/ ndf
Fit A	π,K,p,d,t,^{3}He,^{4}He	0.664 ± 0.002	0.873 ± 0.004	108 ± 2	0.63 ± 0.02	381.1 / 92
Fit B	p,d,t,^{3}He,^{4}He	0.670 ± 0.002	0.853 ± 0.004	132 ± 4	0.55 ± 0.02	176.5 / 64
Fit C	d,t,^{3}He,^{4}He	0.684 ± 0.003	0.863 ± 0.005	108 ± 6	0.52 ± 0.02	44.5 / 37
Fit D	π,K,p	0.664 ± 0.002	0.909 ± 0.003	85 ± 4	0.74 ± 0.01	113.0 / 54



arXiv:2311.11758

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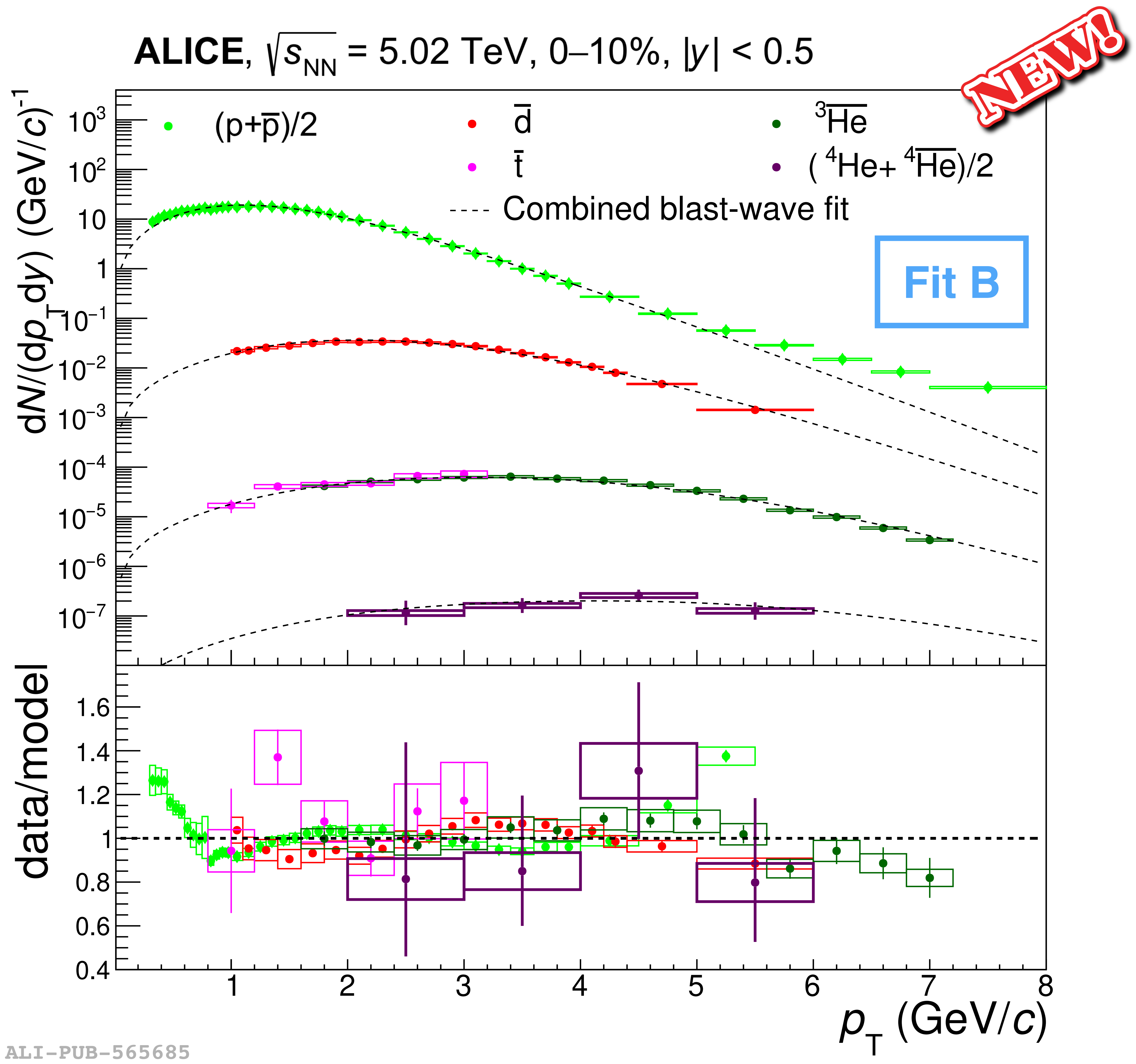
- Fit B describes protons over a larger p_T range than Fit A
- Including π/K/p brings T_{kin} down
  - Resonances not properly handled[(1)]
- Best description from Fit C **only nuclei**, and **not other species**
  - **separate freeze-outs** for nuclei and other species



arXiv:2311.11758

(1) Mazeliauskas and Vislavicius, PRC 101, 014910

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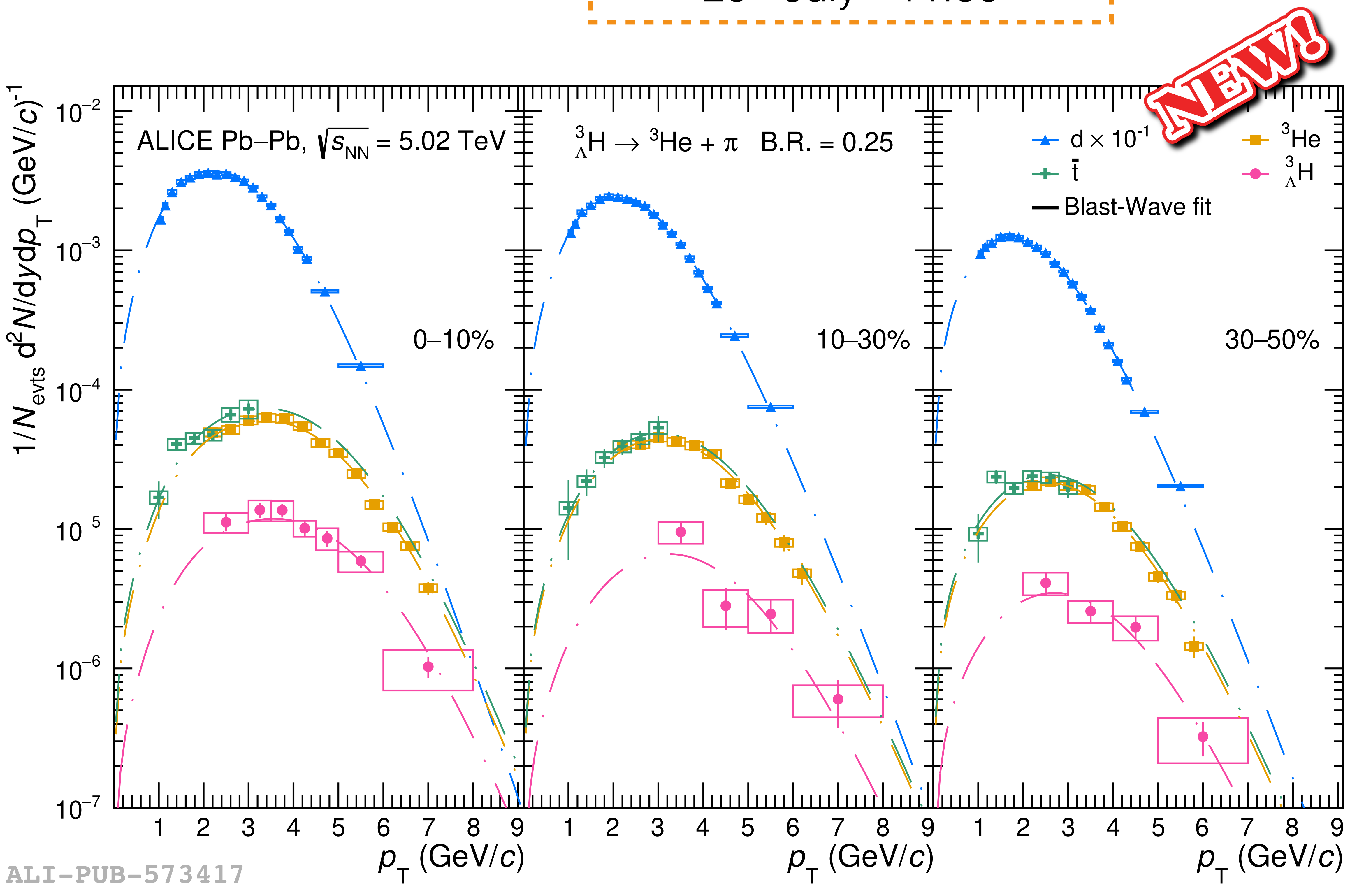

arXiv:2405.19839

- Fit C describes well also hypertriton p_T spectra

v_2 of deuterons

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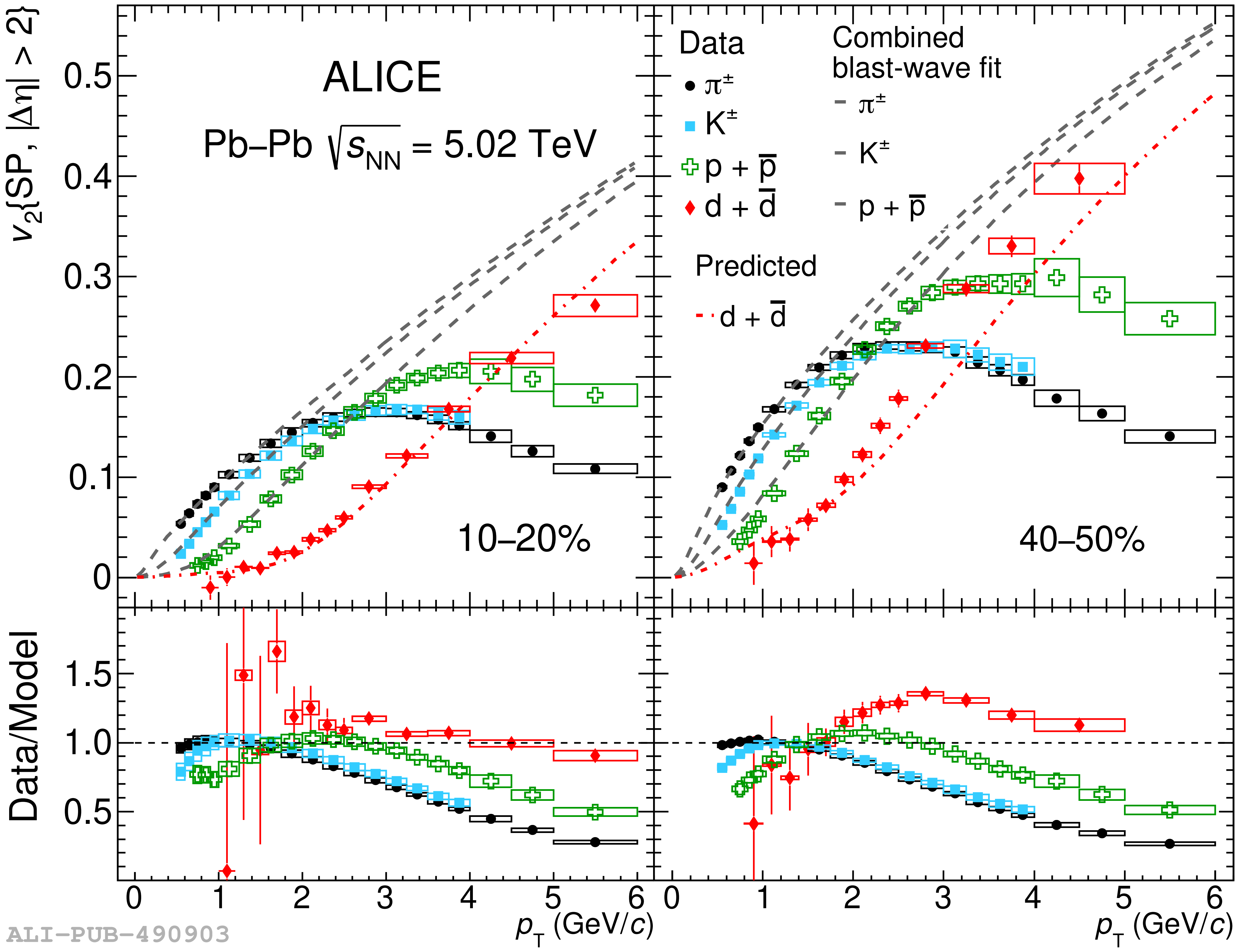
- **v_2** of deuterons measured in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
  - **BW** predictions (fit to π/K/p spectra and v_2):
    - underestimates measurement in semi-central collisions



[PRC 102 (2020) 055203]

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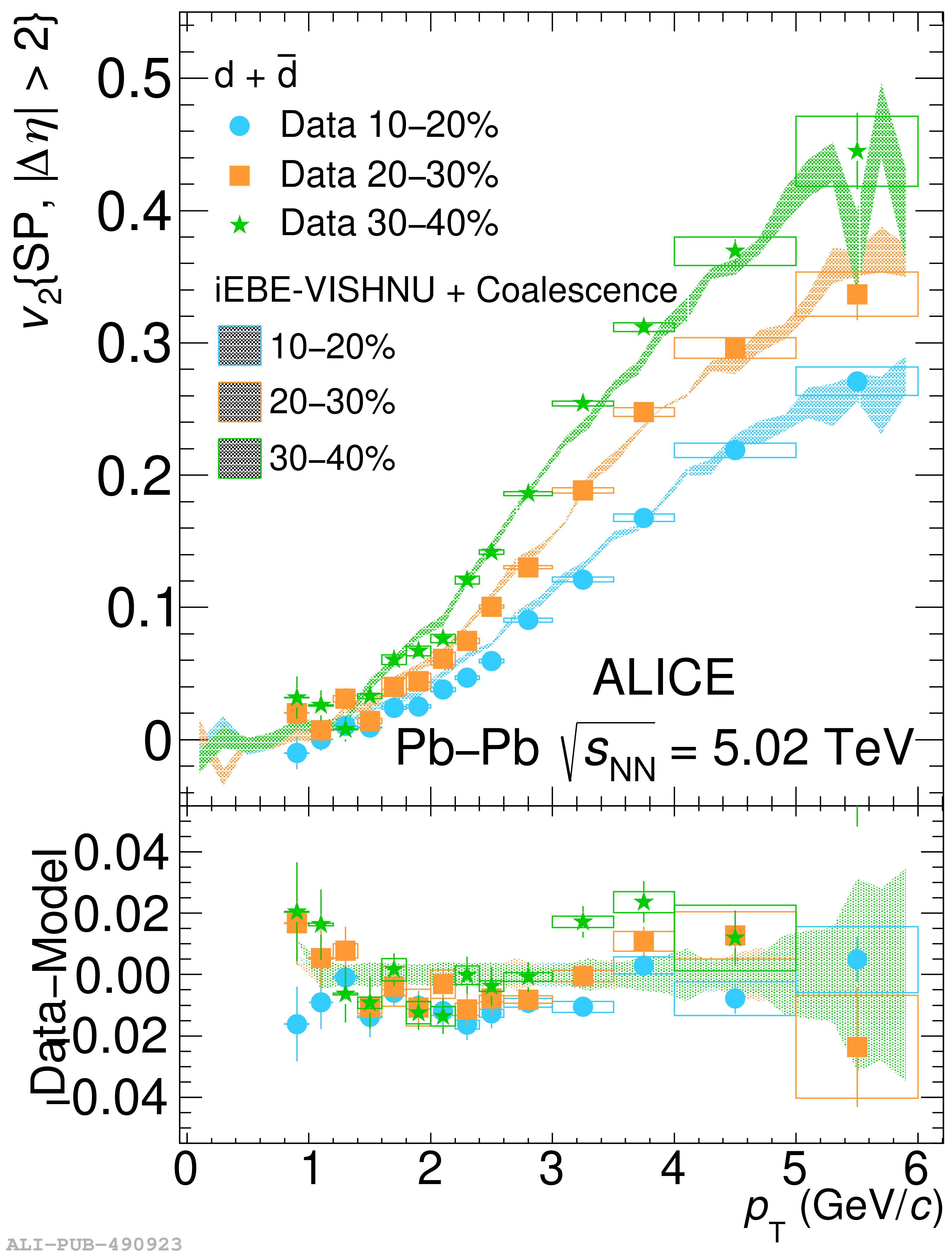
    - Consistent for centrality larger than 20%, 2σ deviations for 10-20%



PRC 102 (2020) 055203

[1] Zhao et al., PRC 98, 054905

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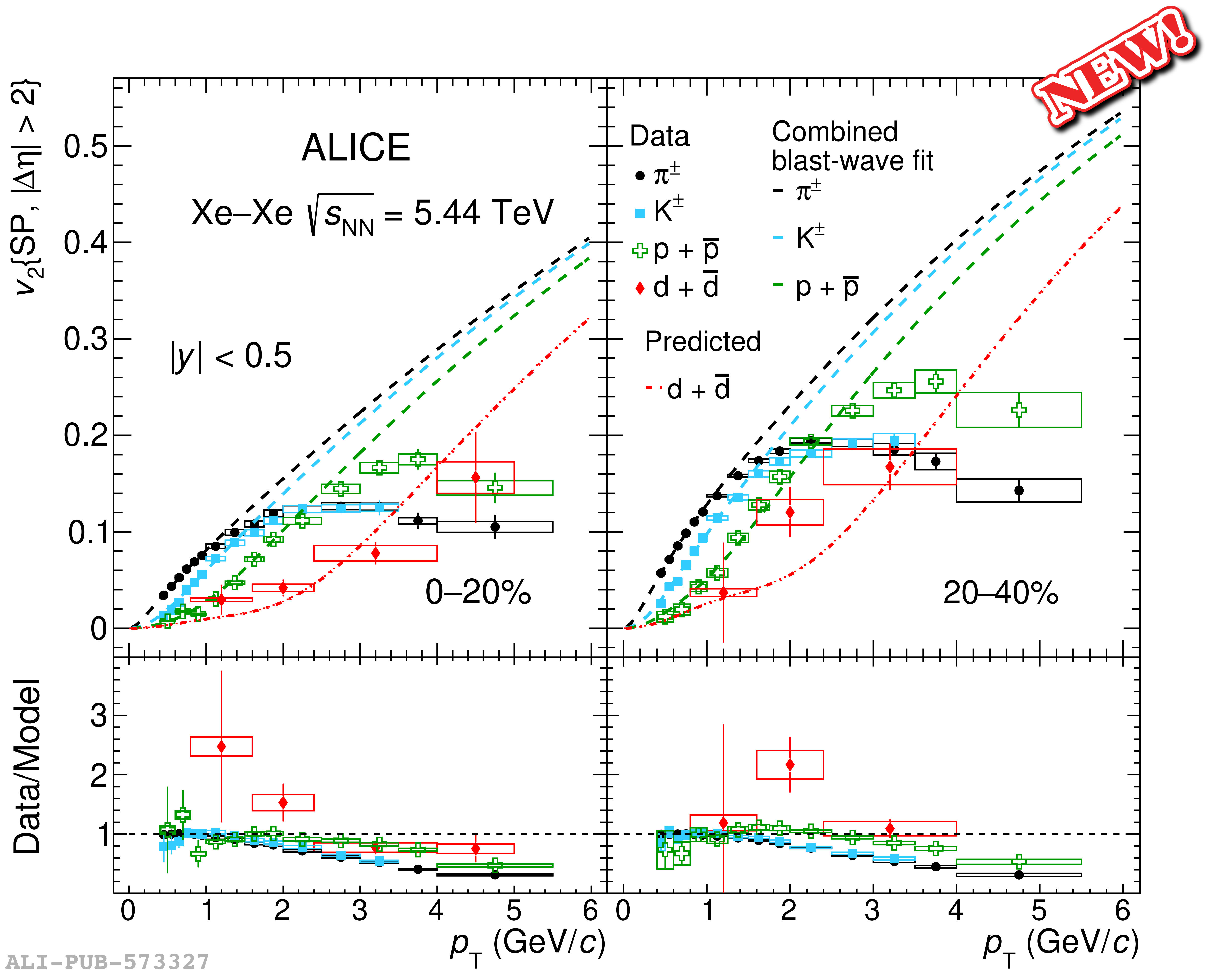
- $\boldsymbol{v_2}$ of deuterons in Xe-Xe collisions recently measured
  - small sensitivity due to large uncertainties



arXiv:2405.19826

v_2 of anti-^{3}He

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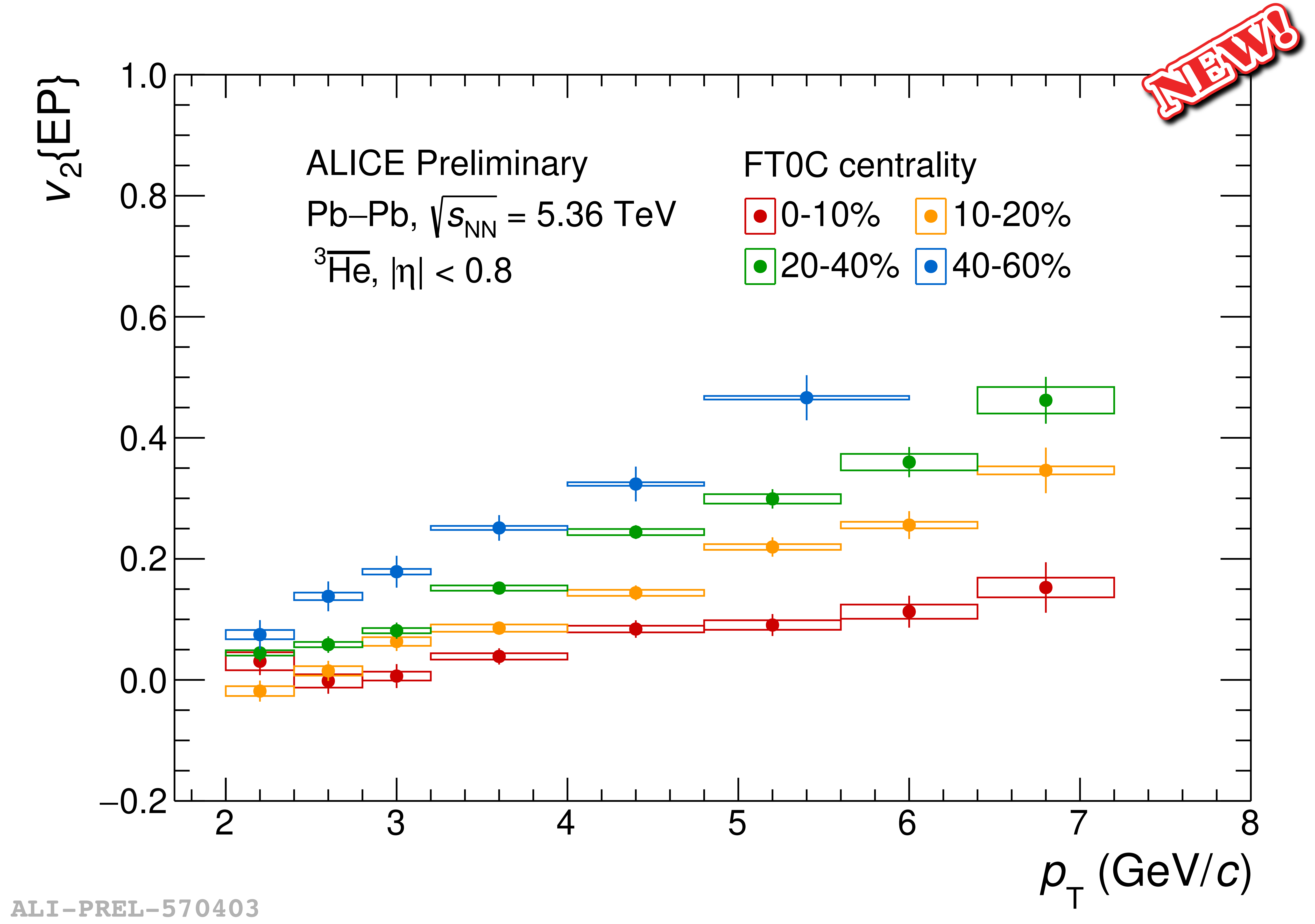
- **v_2** of **anti-^{3}He** in **Run 3 Pb-Pb** collisions at $\sqrt{s_{NN}}$ = 5.36 TeV
  - more differential both in p_T and centrality, more precise than in Run 2(1)



(1) PLB 805 (2020) 135414

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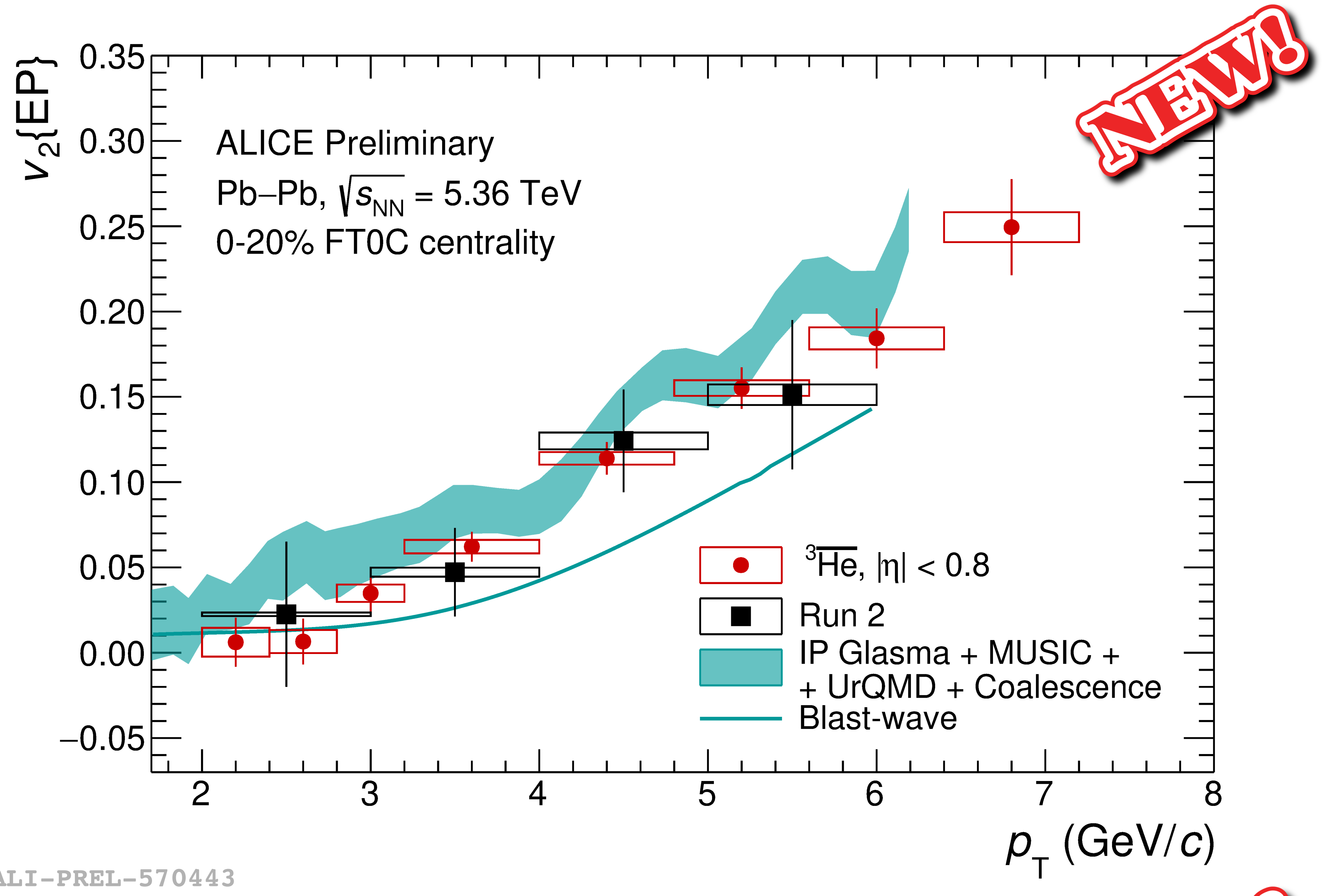
- Data are compared with the predictions from blast-wave and coalescence models
  - with Run 3 precision it is possible to separate the BW (fit to π/K/p spectra and v_2) and coalescence predictions
    - **coalescence** provides a better description



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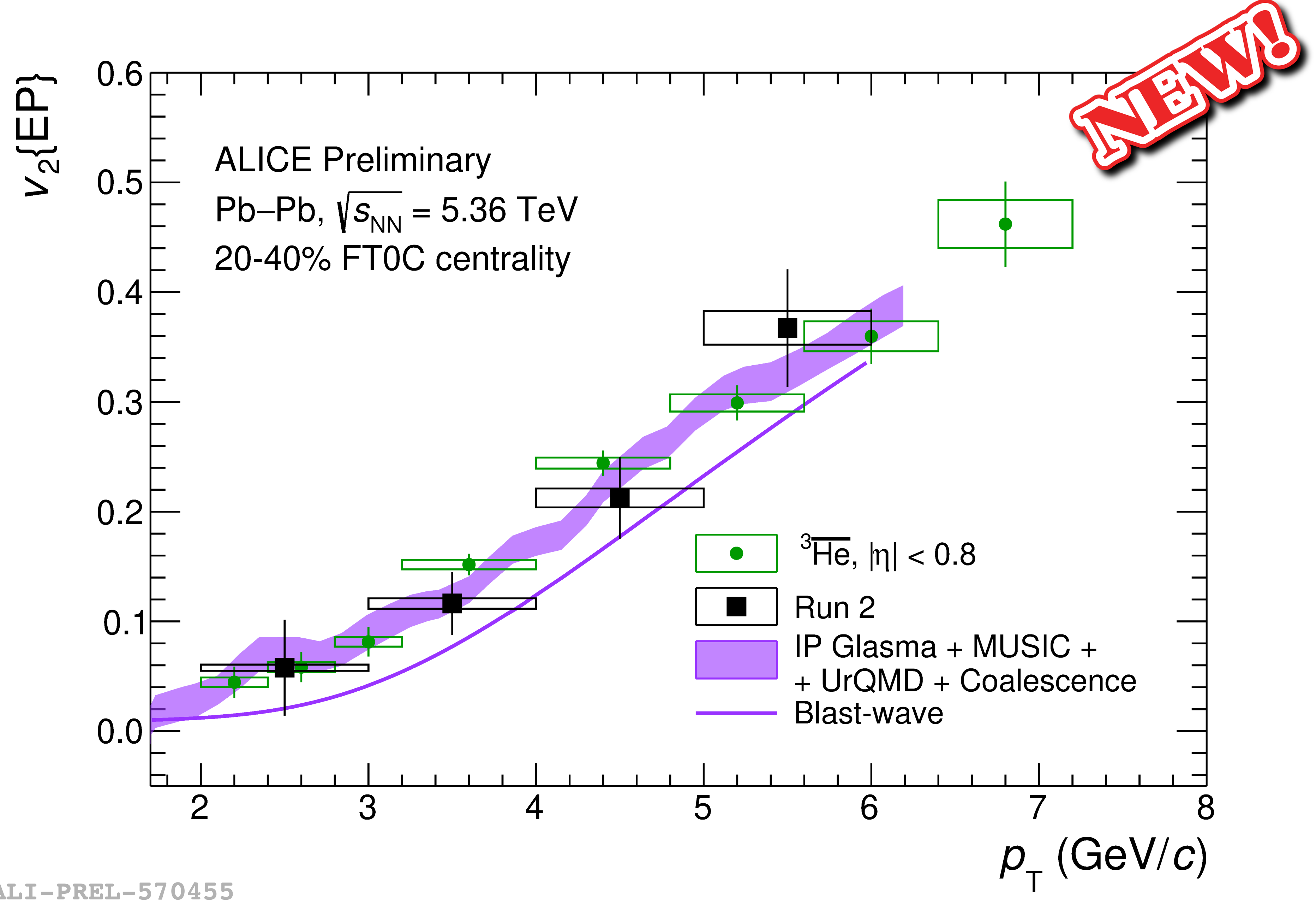

ALI-PREL-570455

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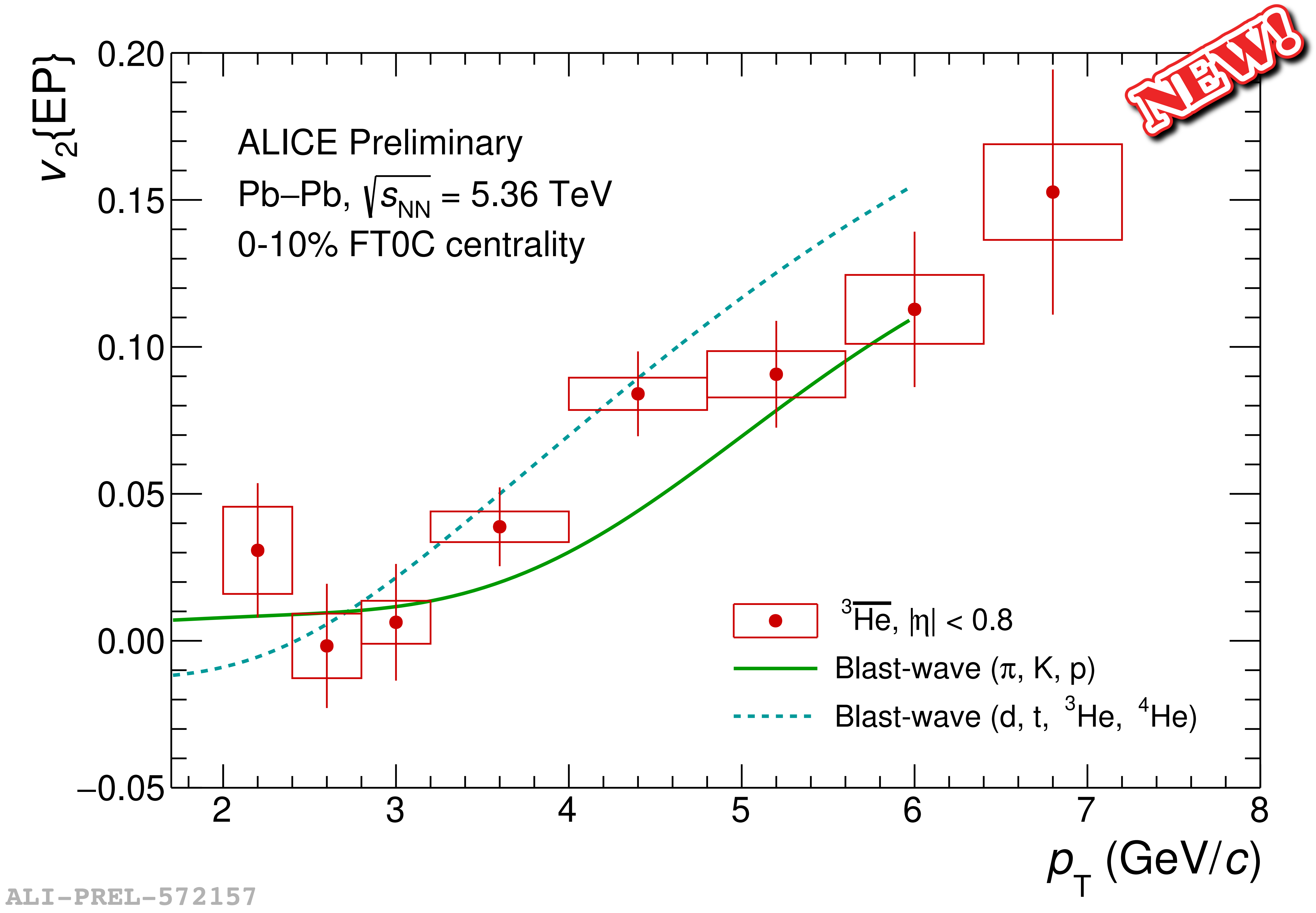
- Data are compared with the predictions from blast-wave and coalescence models
  - with Run 3 precision it is possible to separate the BW (fit to π/K/p spectra and v_2) and coalescence predictions
    - **coalescence** provides a better description
  - Caveat: BW predictions strongly depends on the considered species
    - **dashed line**: fit to spectra of nuclei in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
    - **solid line**: fit to π/K/p spectra and v_2 in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



Flow of hypertriton and towards spin measurement

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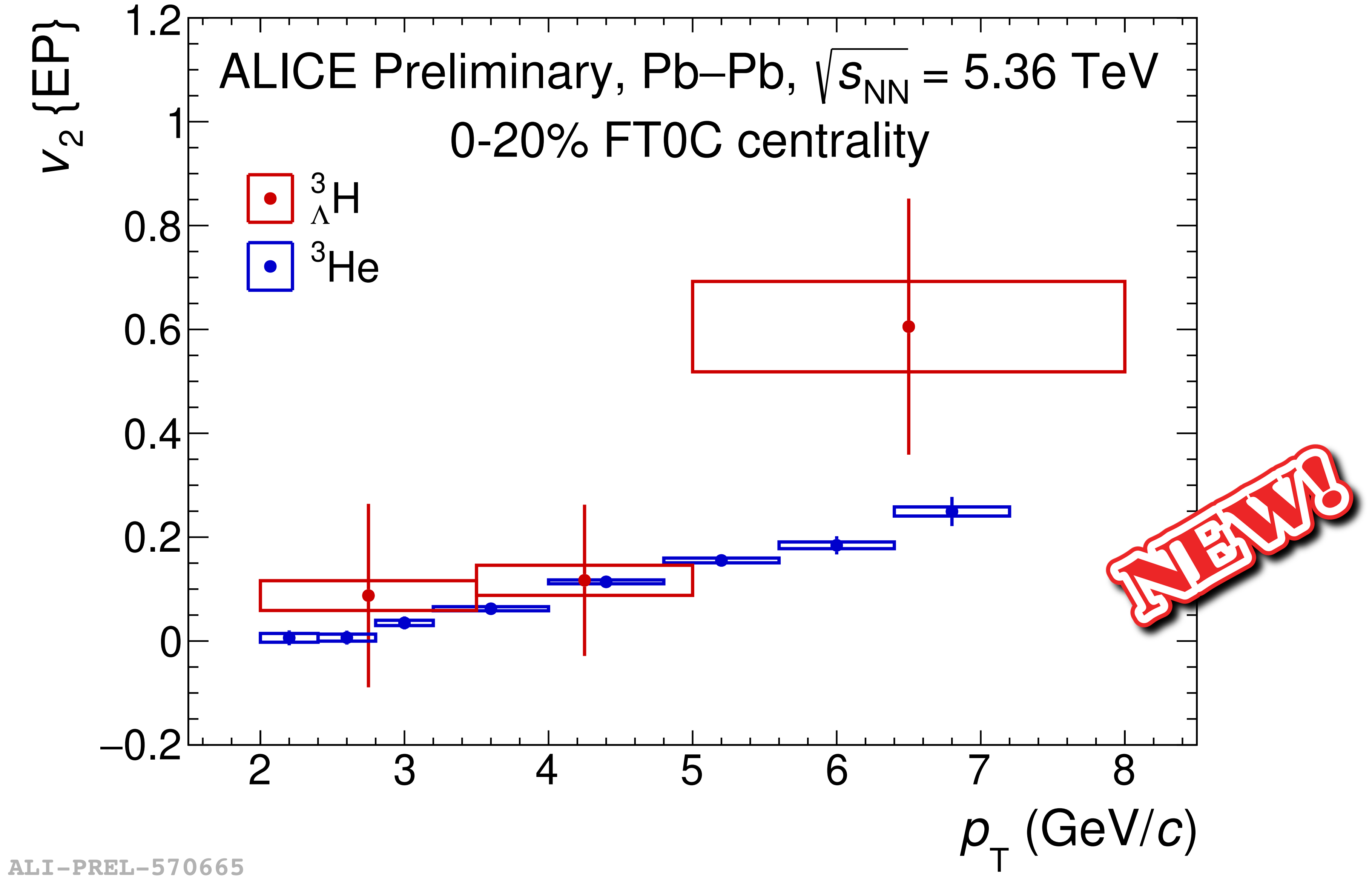
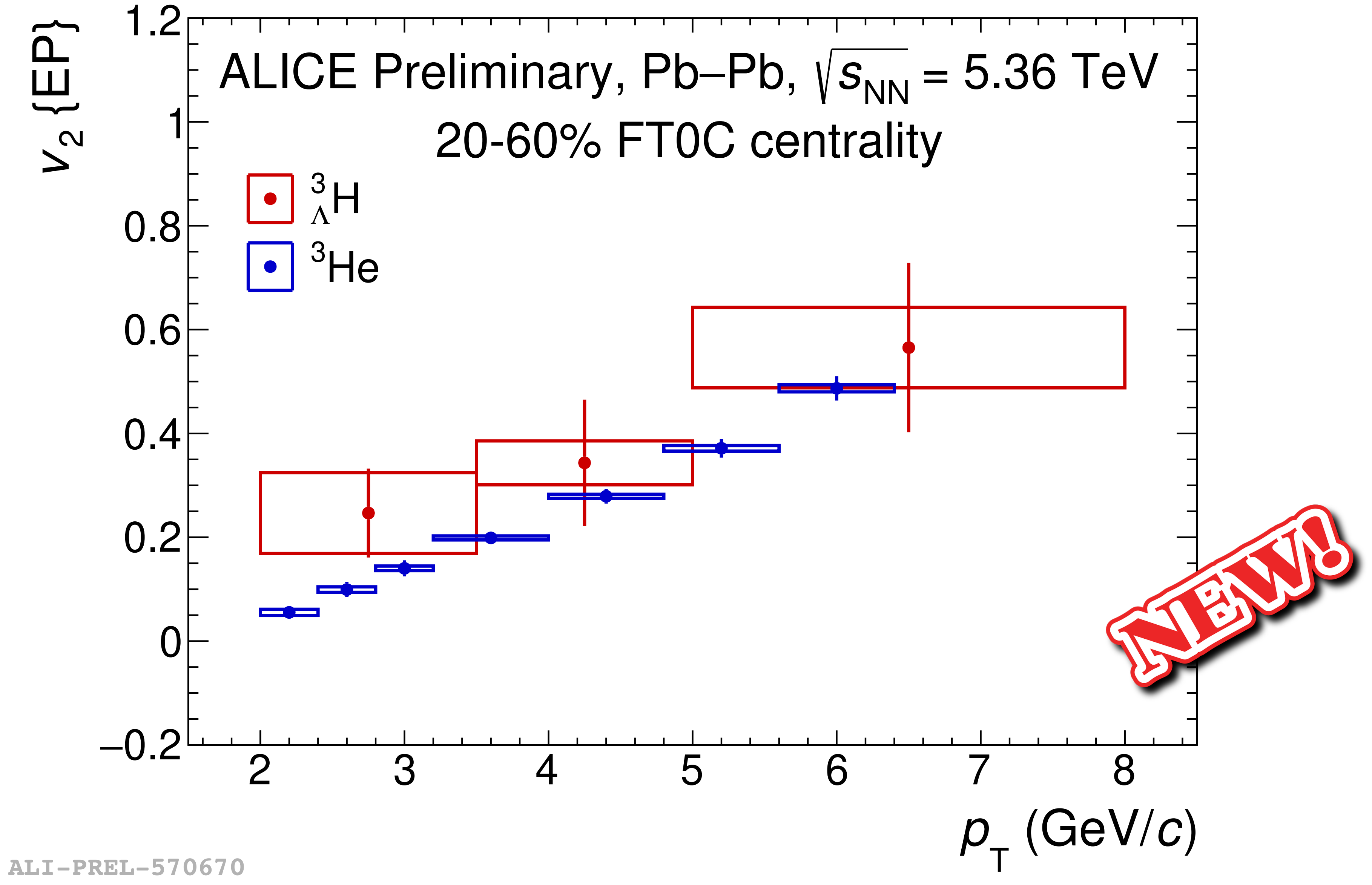
- **Flow** of **hypertriton** has been measured for the first time:
  - compatible with ³He, but still large uncertainties
    - At the end of Run 3 the integrated luminosity will increase of a factor of 4-5 wrt 2023





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- **Flow** of **hypertriton** has been measured for the first time:
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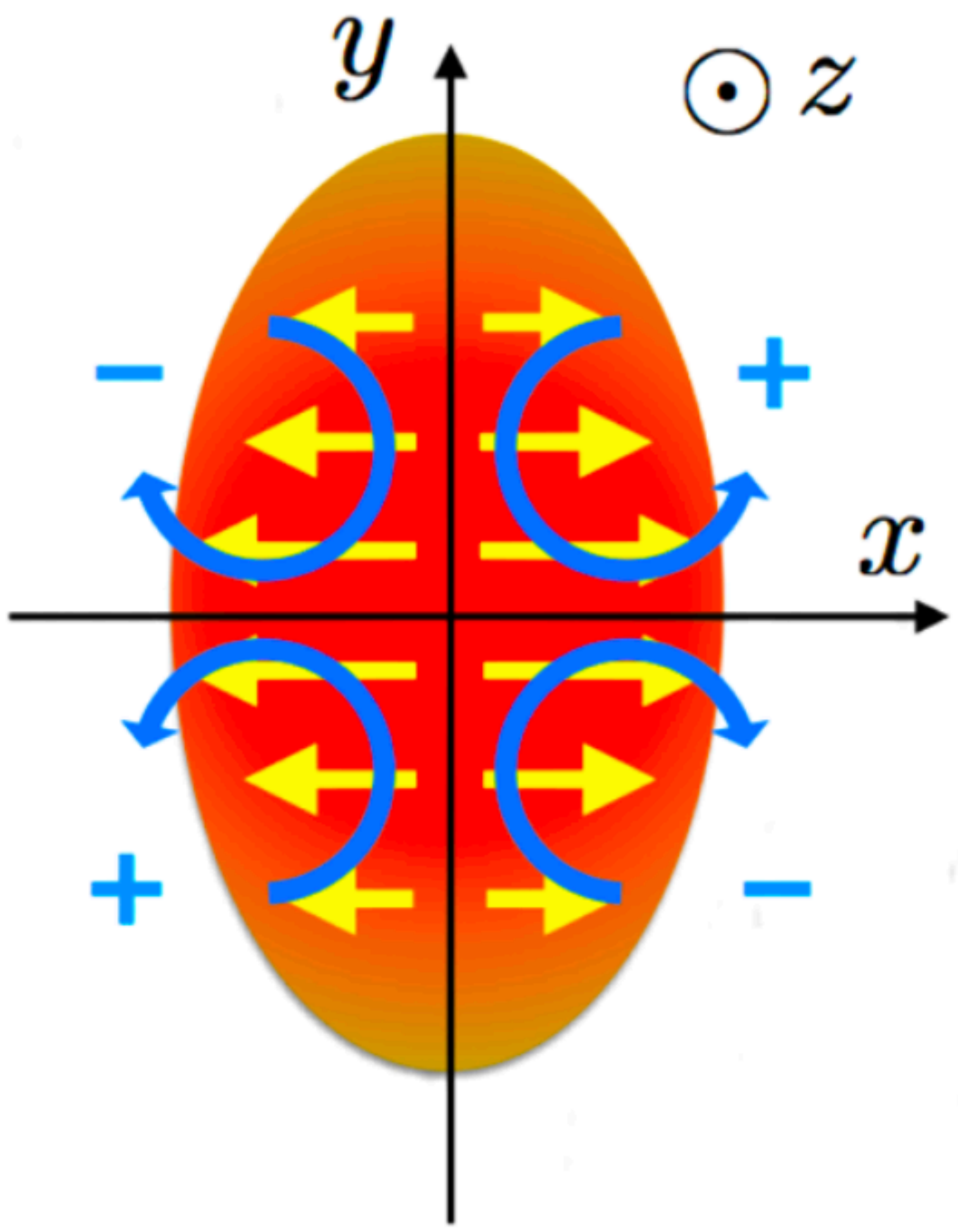
    - At the end of Run 3 the integrated luminosity will increase of a factor of 4-5 wrt 2023
- **Non-zero elliptic flow** generates a **non-zero vorticity** component along the the beam axis (***z***)[(1)]:
    - Particle **spin** tend to be **aligned along *z***
    - $^3_\Lambda$H **spin** can be determined through polarisation:



Voloshin, EPJ Web of Conferences 171, 07002 (2018)

(1) Becattini, Karpenko PRL 120, 012302

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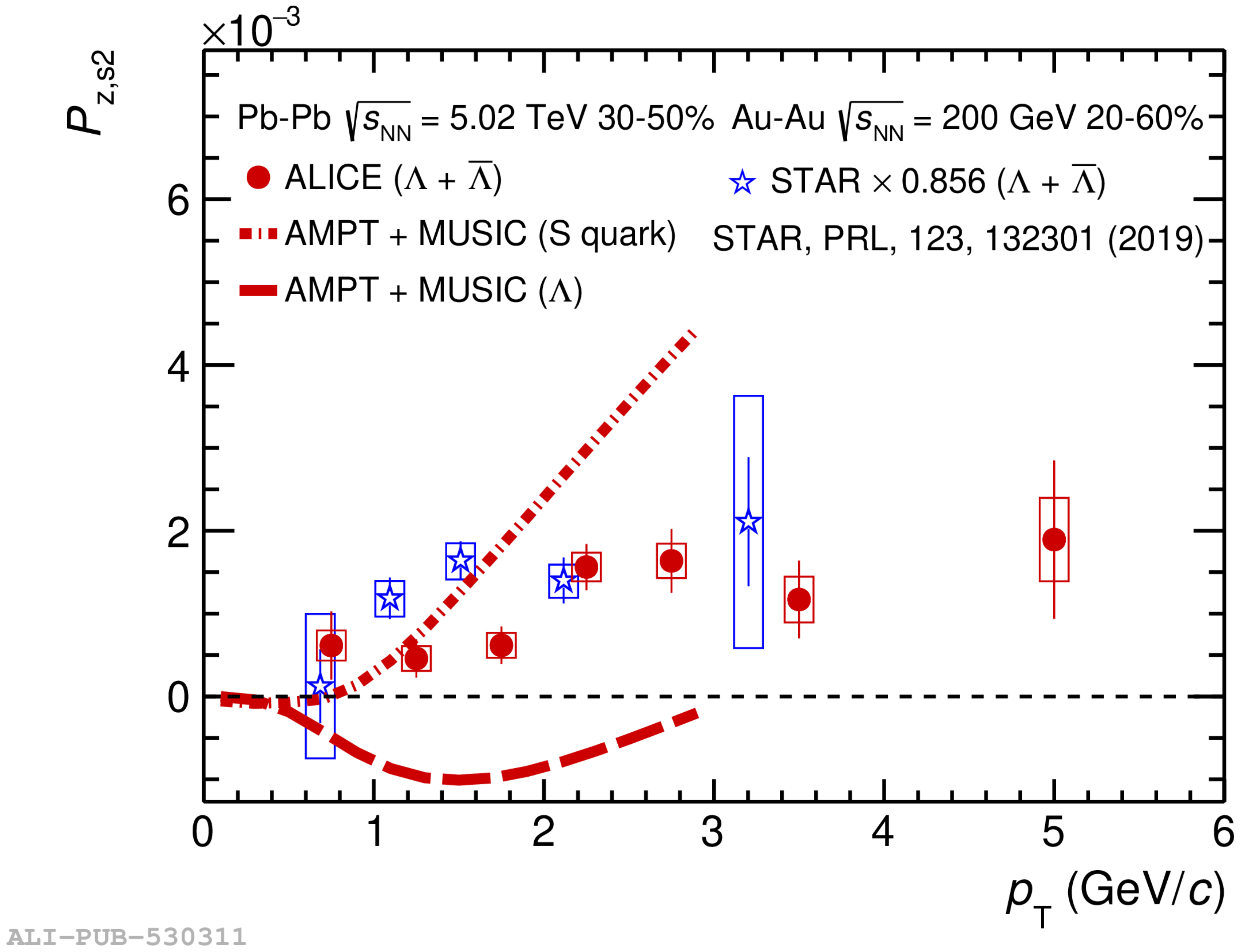
- **Non-zero elliptic flow** generates a **non-zero vorticity** component along the the beam axis (***z***):
  - Particle **spin** tend to be **aligned along *z***
  - $^{3}_{\Lambda}\mathrm{H}$ **spin** can be determined through polarisation:
- The determination of $^{3}_{\Lambda}\mathrm{H}$ spin is important**:**
  - Never measured: 1/2 assumed from theory
  - Determination of production yields
  - Λ-N interaction



PRL 128 (2022) 17, 172005

- Λ polarisation already measured by ALICE:
  - **Coalescence** predicts the **same polarisation** [(1)] for **Λ** and $^{3}_{\Lambda}\mathrm{H}$

(1) arXiv:2405.12015

${}^{3}_{\Lambda}\mathrm{H}$ polarisation

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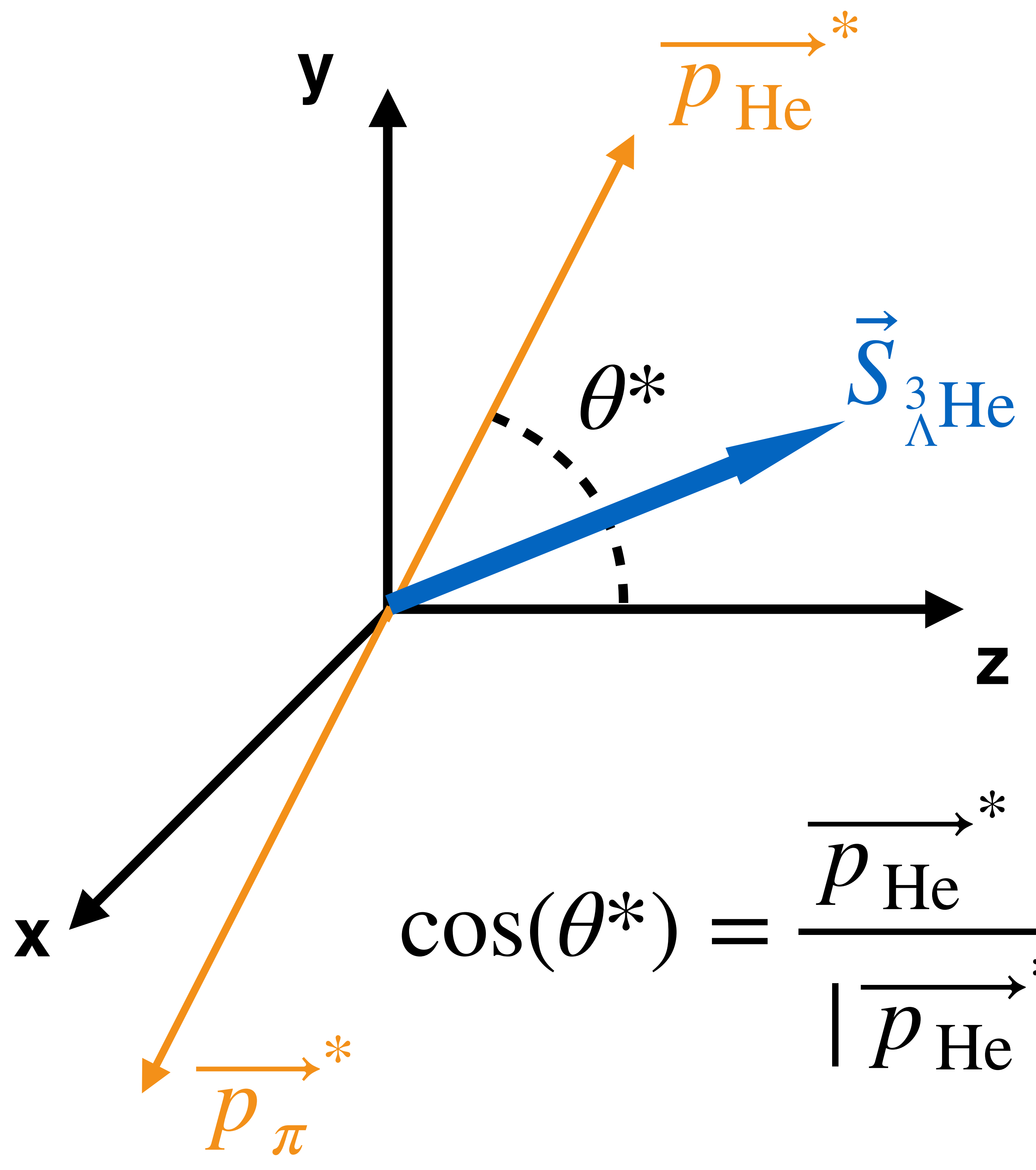
- The two-body decay is considered:
  ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi$
  - ${}^{3}\mathrm{He}$ momentum tends to be aligned to ${}^{3}_{\Lambda}\mathrm{H}$ spin
- The distribution of $\cos(\theta^*)$ is different in case of **Spin = 1/2** and **Spin = 3/2**



$$\cos(\theta^*) = \frac{\vec{p}^{\,*}_{\mathrm{He}} \cdot \hat{z}}{|\vec{p}^{\,*}_{\mathrm{He}}|}$$

$$\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)} \propto 1 + \alpha P \cos(\theta^*)$$

$$\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)} \propto \rho_{33}\,(1 - \cos^2(\theta^*)) + \\ + \rho_{11}\,(1/3 + \cos^2(\theta^*))$$

${}^{3}_{\Lambda}$H polarisation

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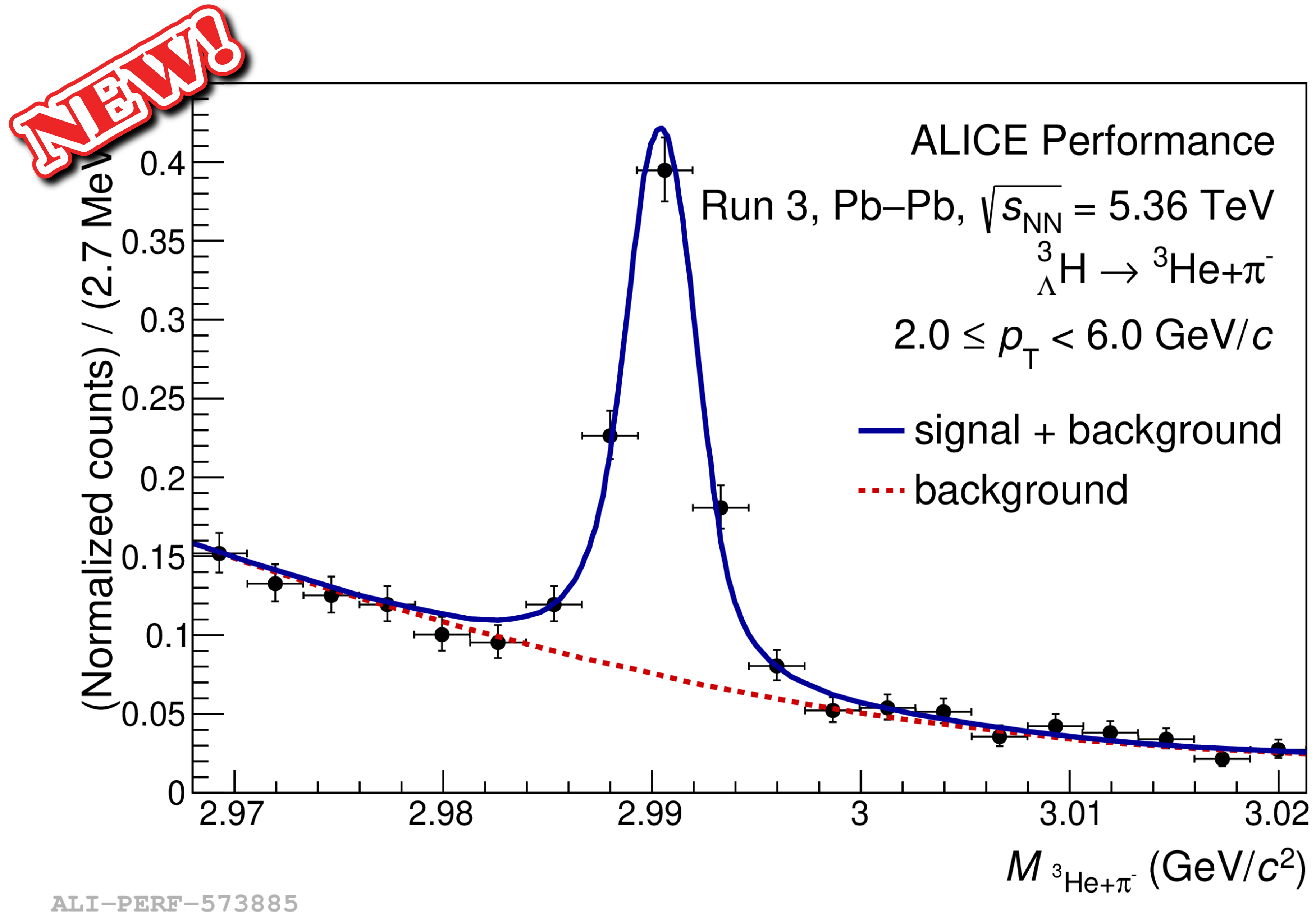
  - ^{3}He momentum tends to be aligned to ${}^{3}_{\Lambda}$H spin
- The distribution of $\cos(\theta^*)$ is different in case of **Spin = 1/2** and **Spin = 3/2**
- Along Run 3 the integrated luminosity will be sufficient to have the first measurement



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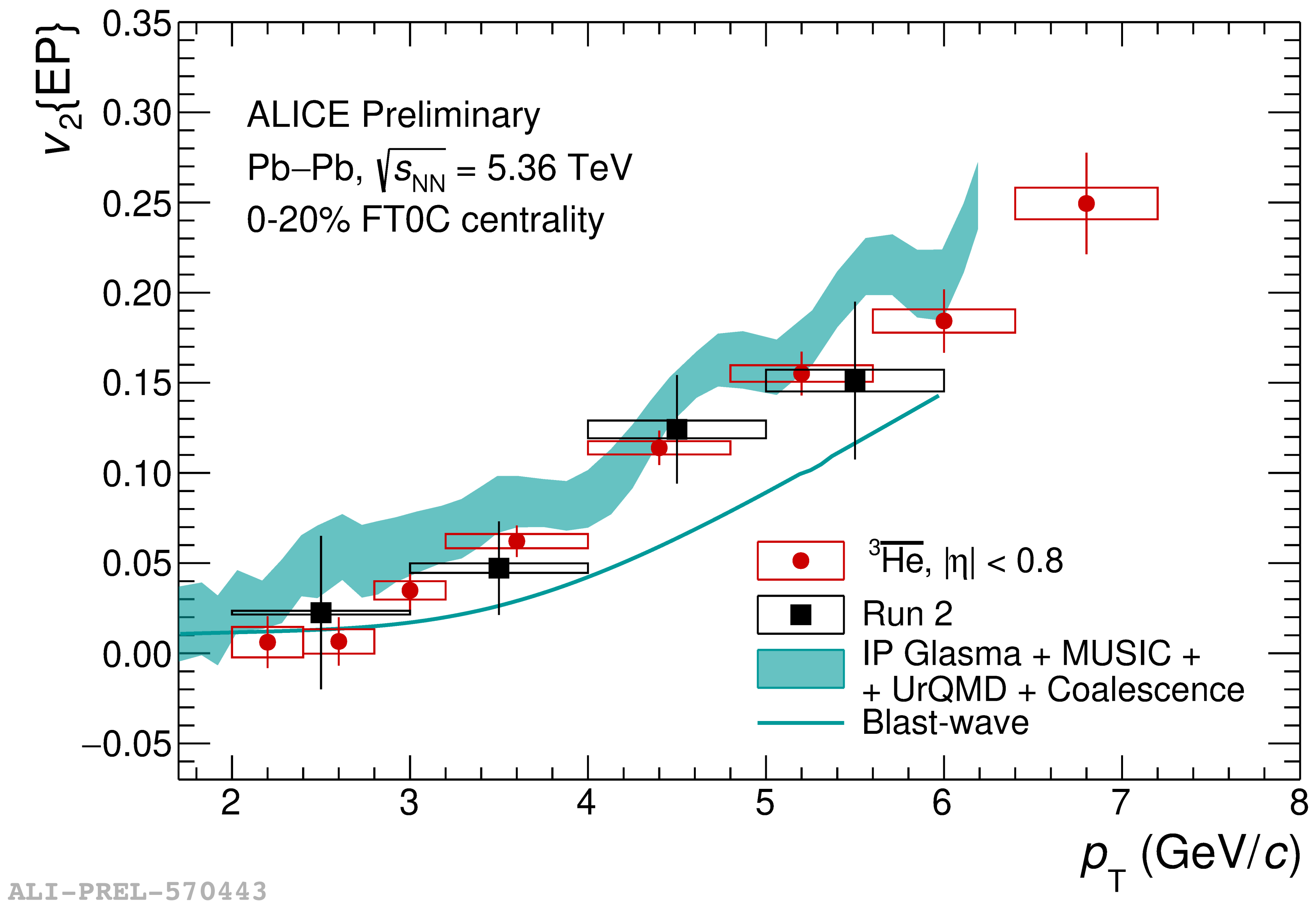
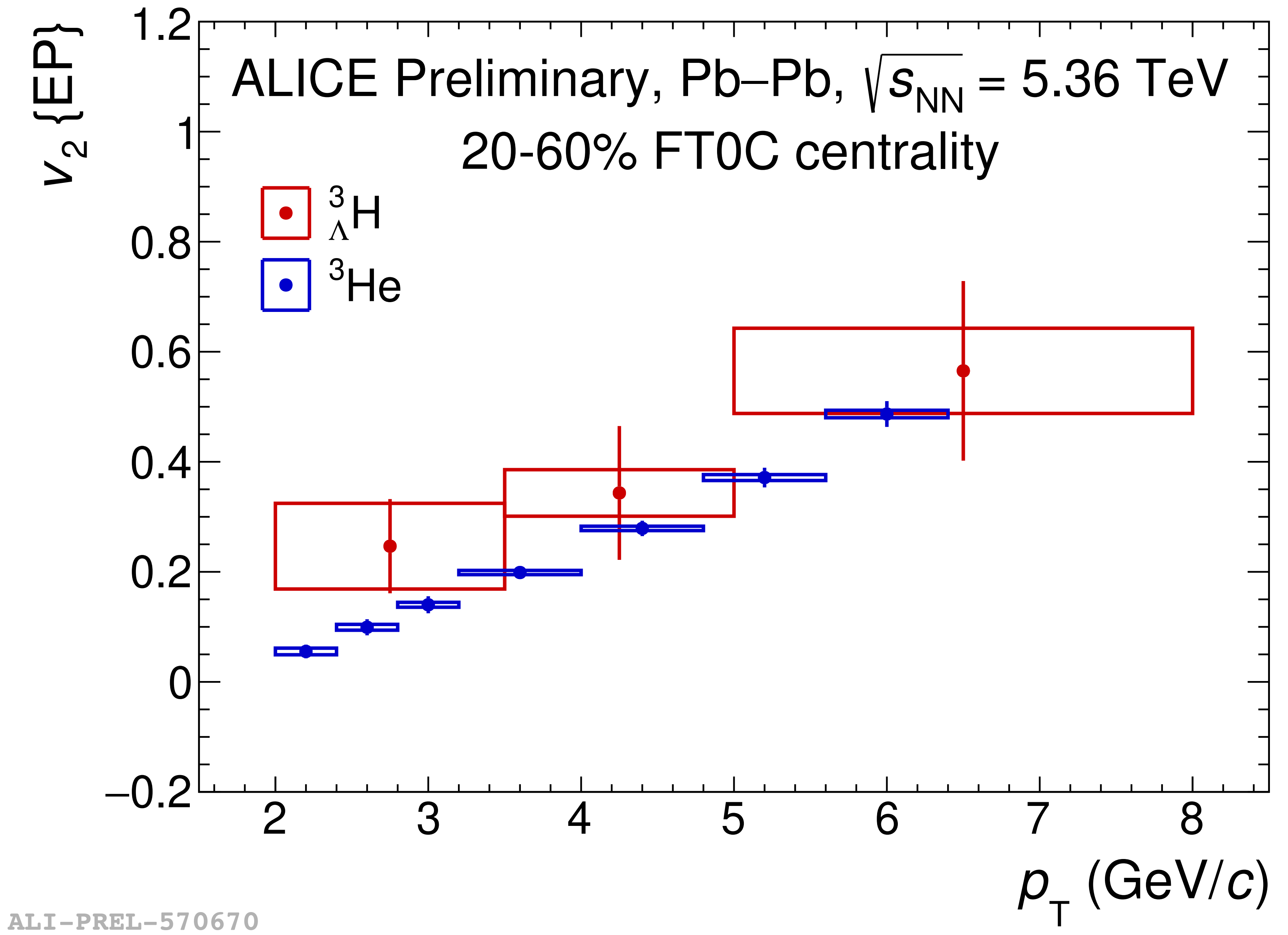
- With flow it is possible to get information about the production of (anti)nuclei
  - BW fits to p_T spectra works better if nuclei are separated from π/K/p
    - CAVEAT: strong dependence on the fit inputs
  - v_2 of nuclei are better reproduced by coalescence than by BW

- With a larger integrated luminosity, ALICE will be able to measure hypertriton v_2 with a better precision wrt the current status and to measure hypertriton spin in Pb-Pb collisions

Thanks for your attention!



ALI-PREL-570443



ALI-PREL-570670

BACKUP

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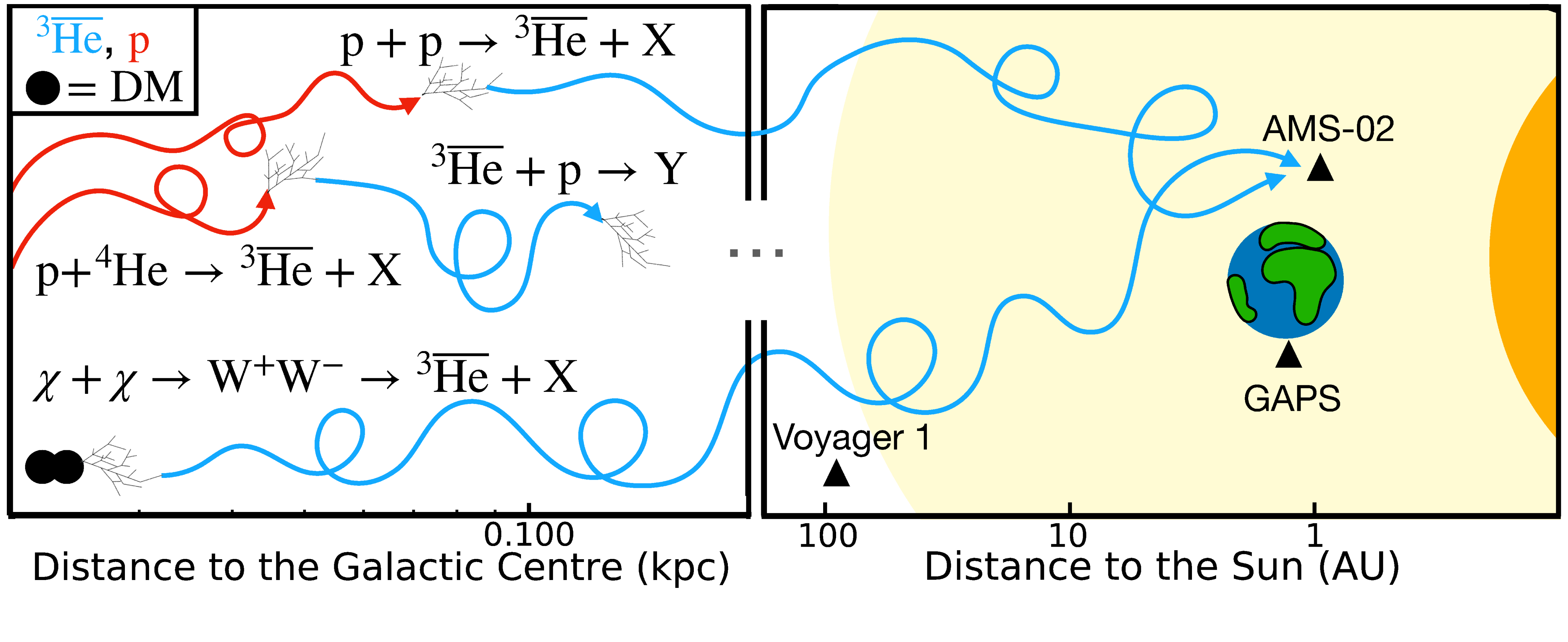
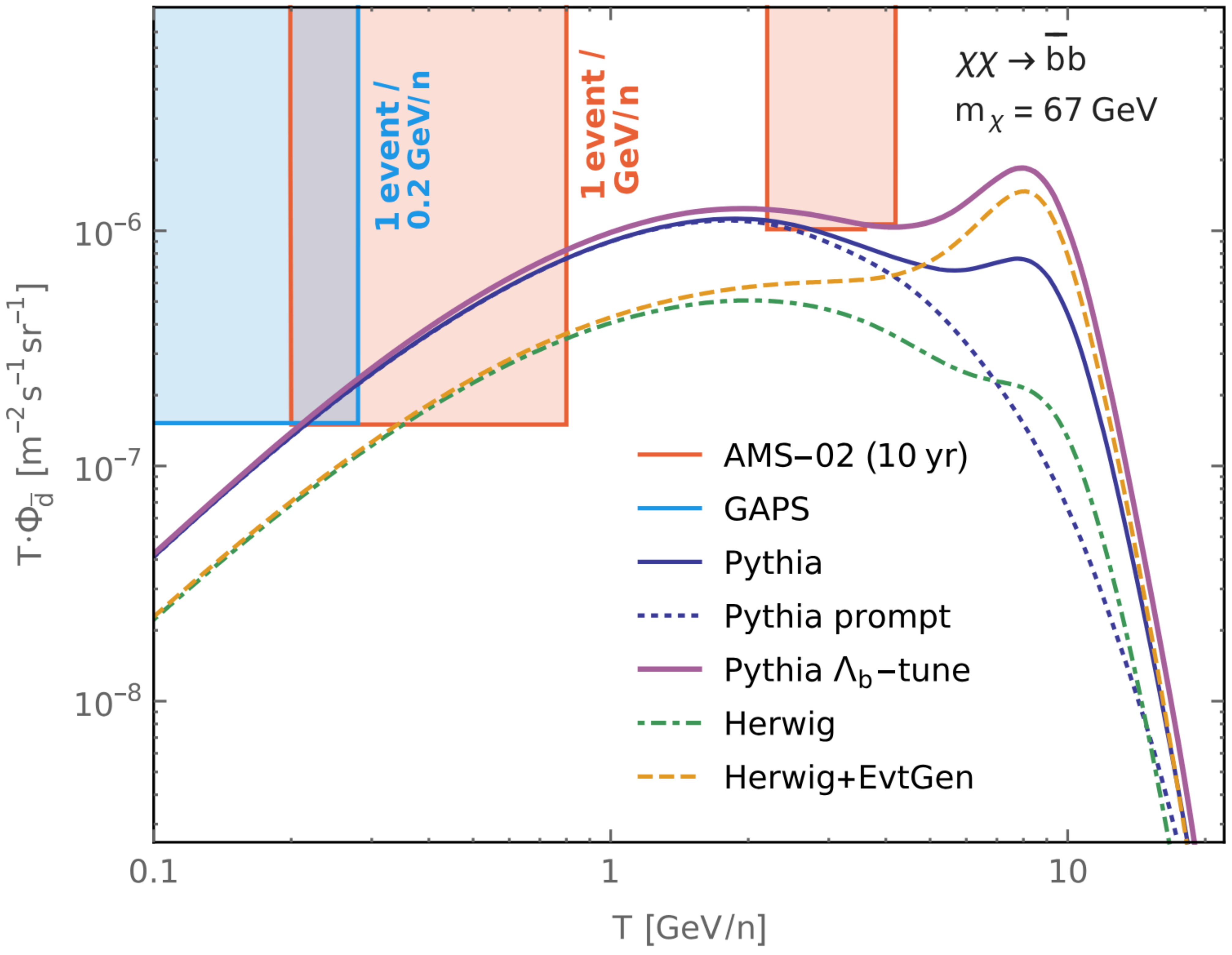
- The study of the production mechanisms of (anti)(hyper)nuclei is not only interesting *per se*
- **Antinuclei** can be a sign of **Dark Matter annihilation**:
  - *Background*: production in the collisions between **cosmic rays** and the **interstellar medium** (pp and pA collisions)
    - Nuclear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





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

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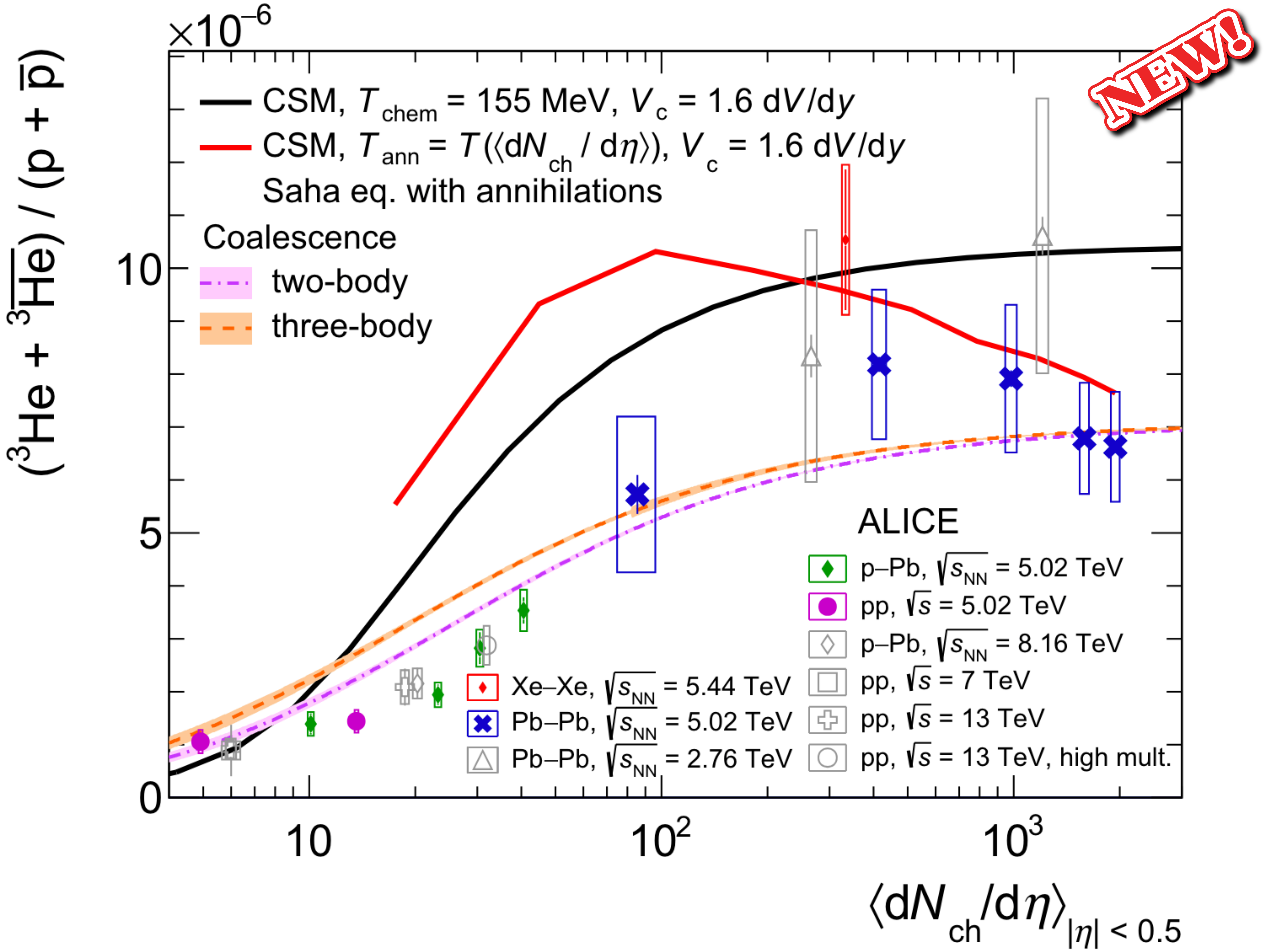
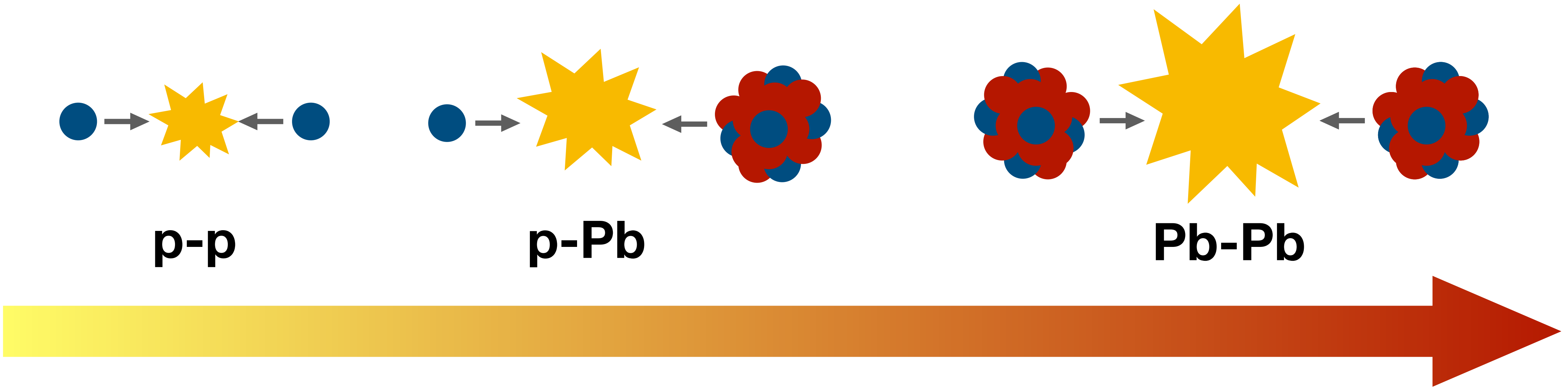
- **d/p** ratio evolves **smoothly** with **multiplicity**
  - dependence on the **system size**
- For **d/p** ratio both the models describe the data:
  - CSM: canonical suppression
  - Coalescence model: interplay between source size and nuclear size
- Also ^{3}**He/p** evolves **smoothly** with **multiplicity**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





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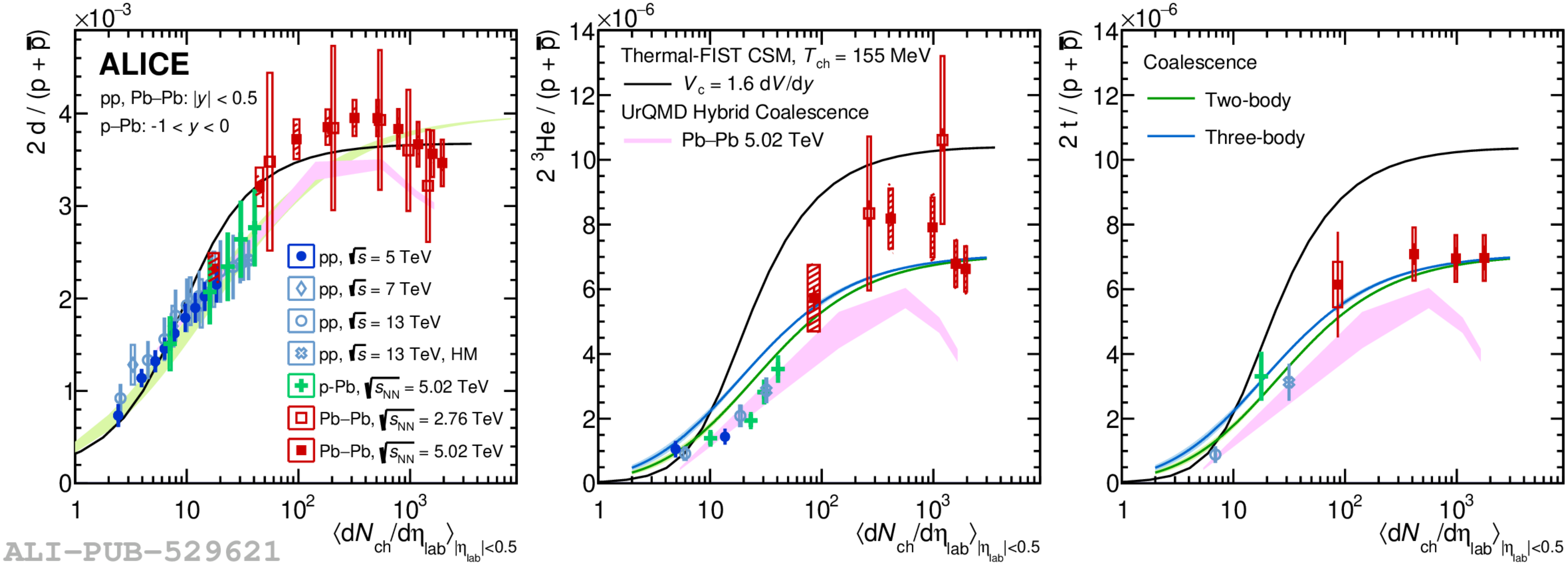
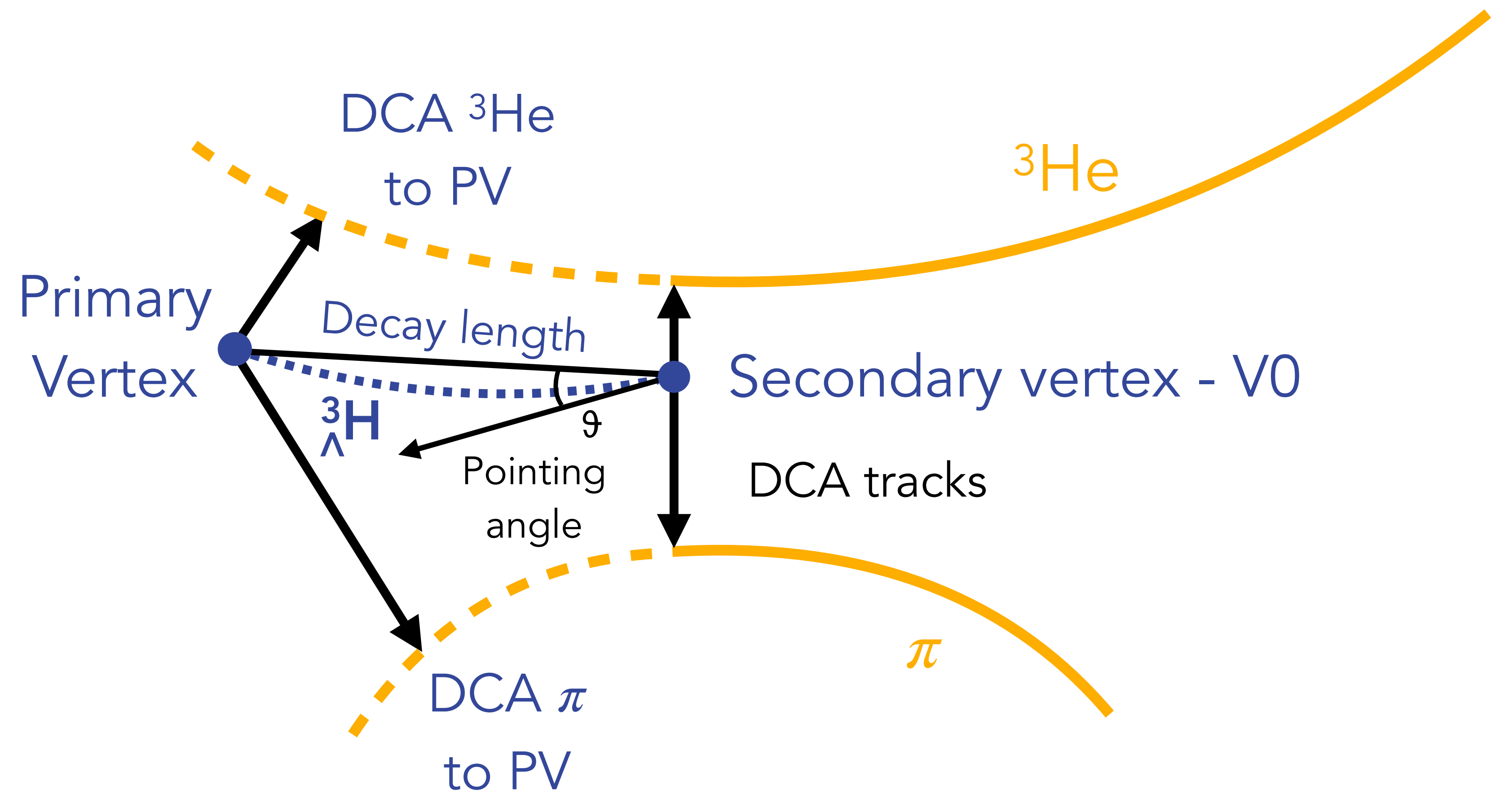
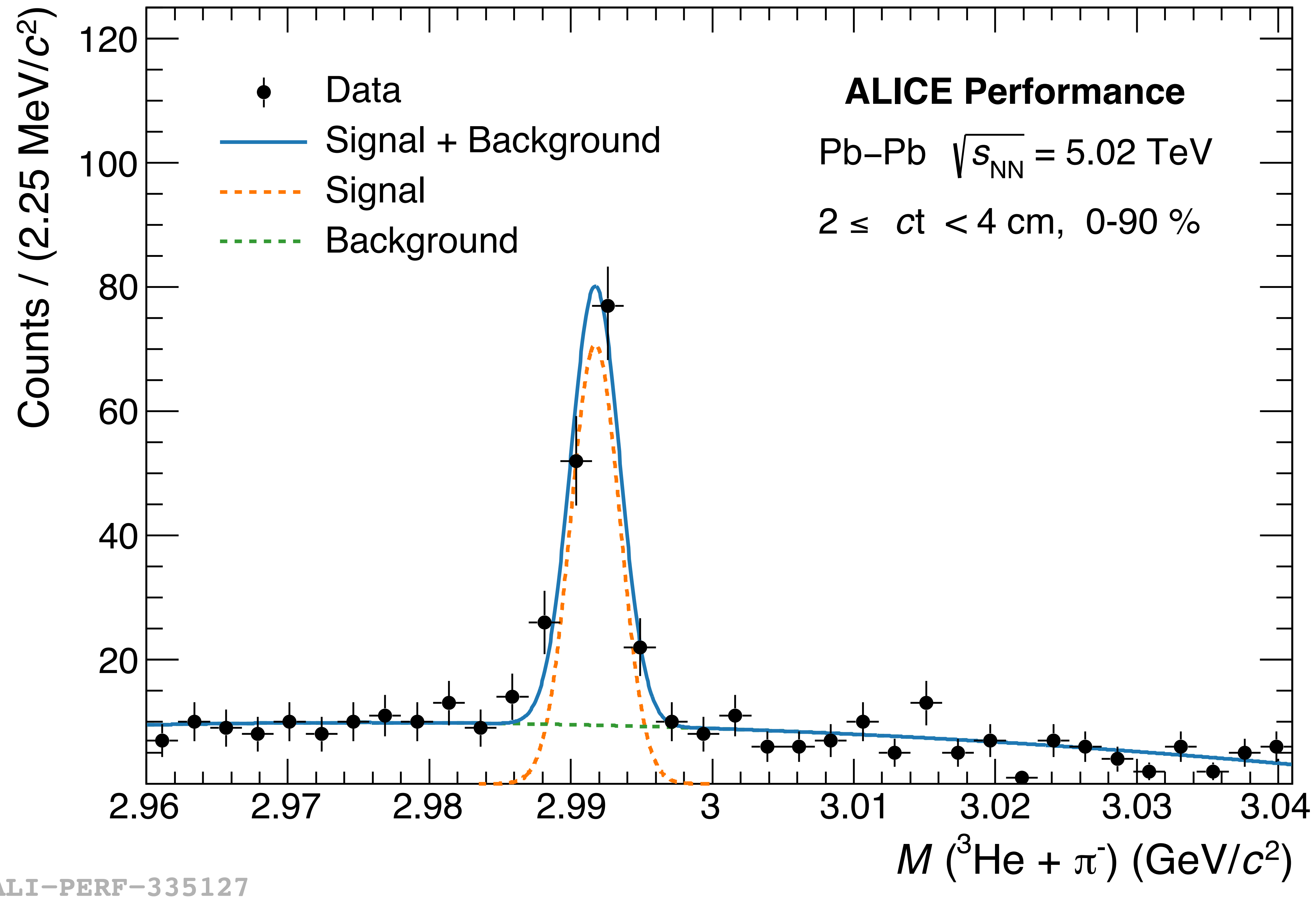


arXiv:2211.14015

Hypertriton reconstruction

- **Hypertriton** is reconstructed through its **two-body** mesonic decay (B.R. 25%):
  - $^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^- \; + \mathrm{c.c.}$
- 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





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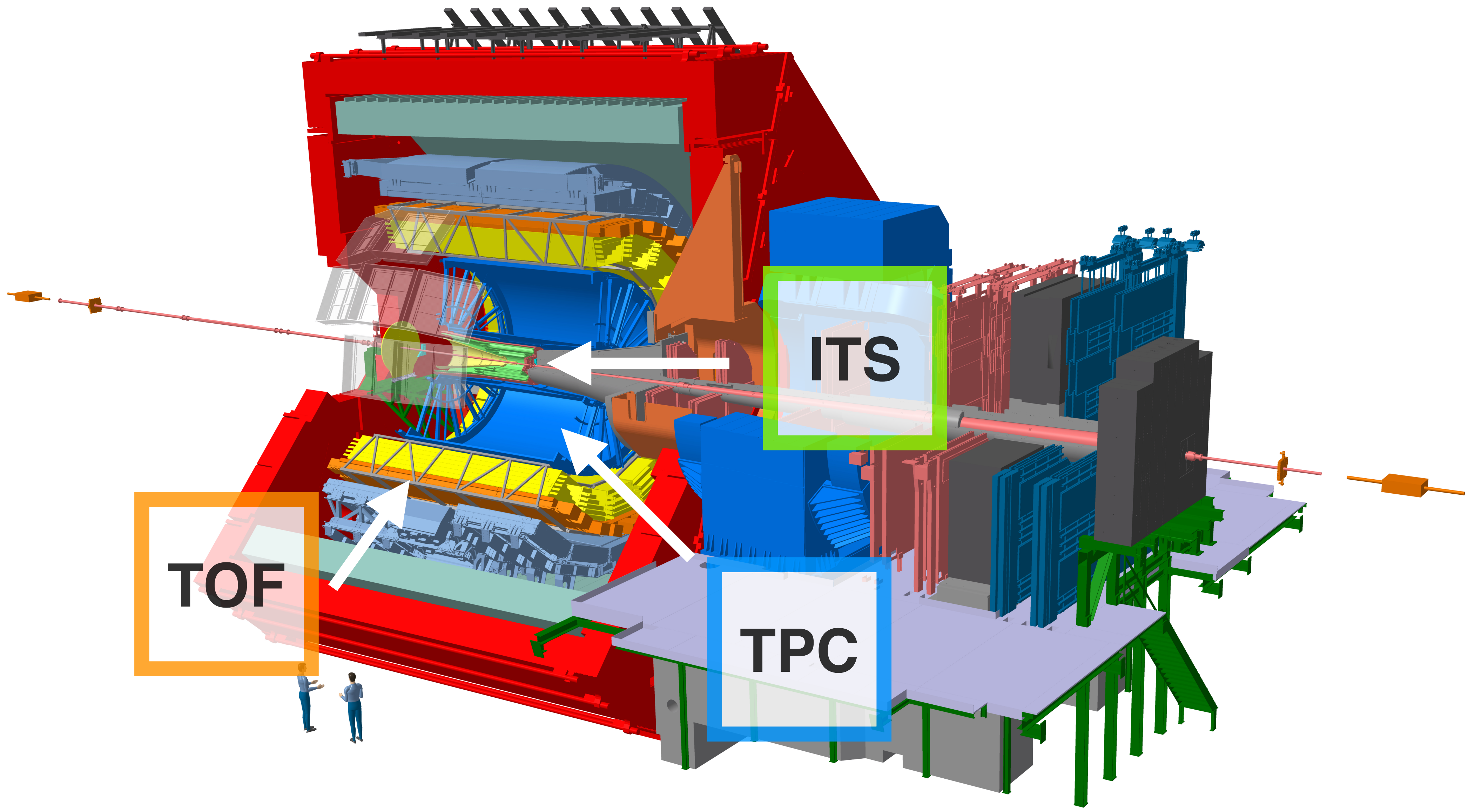
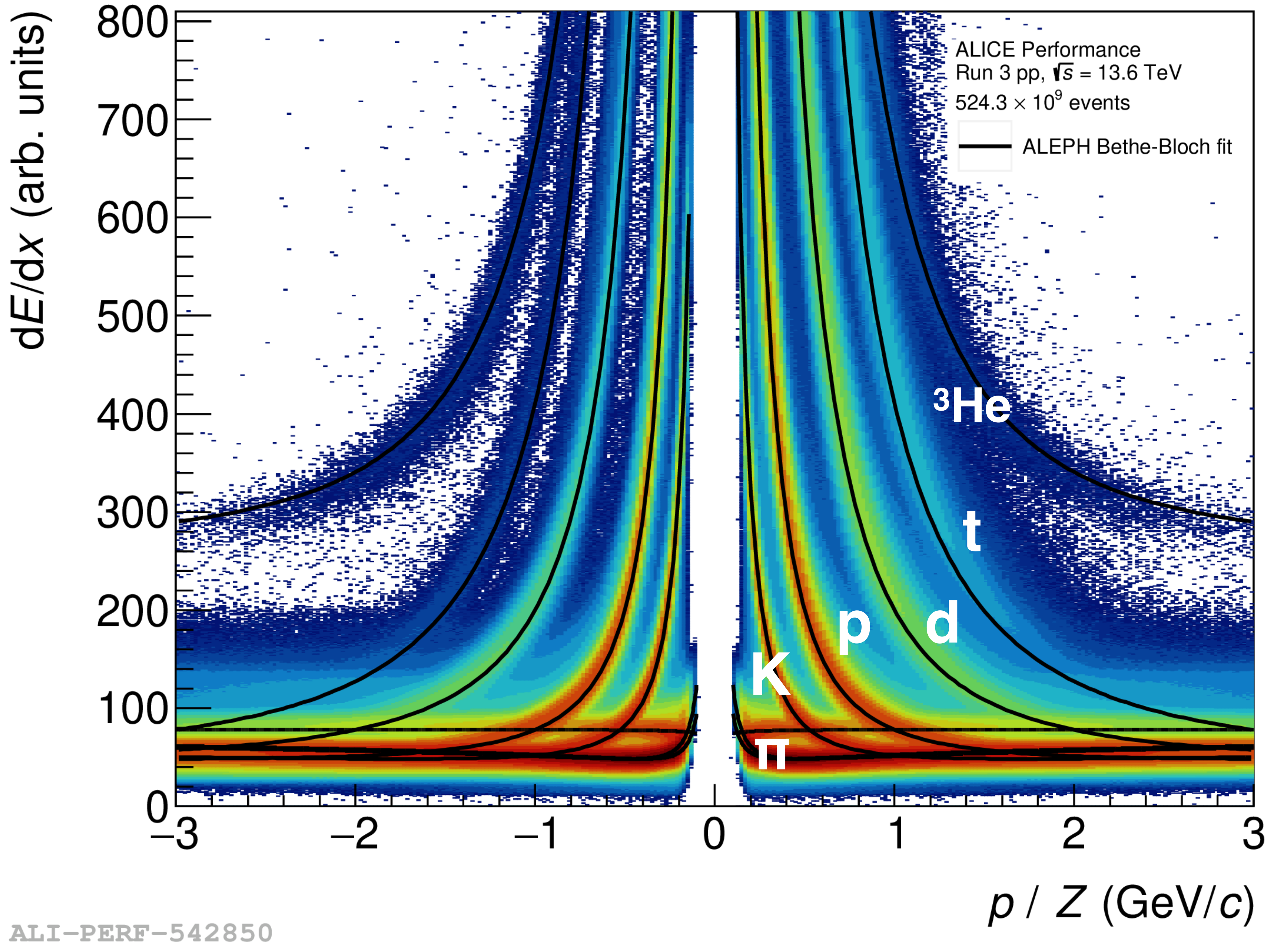
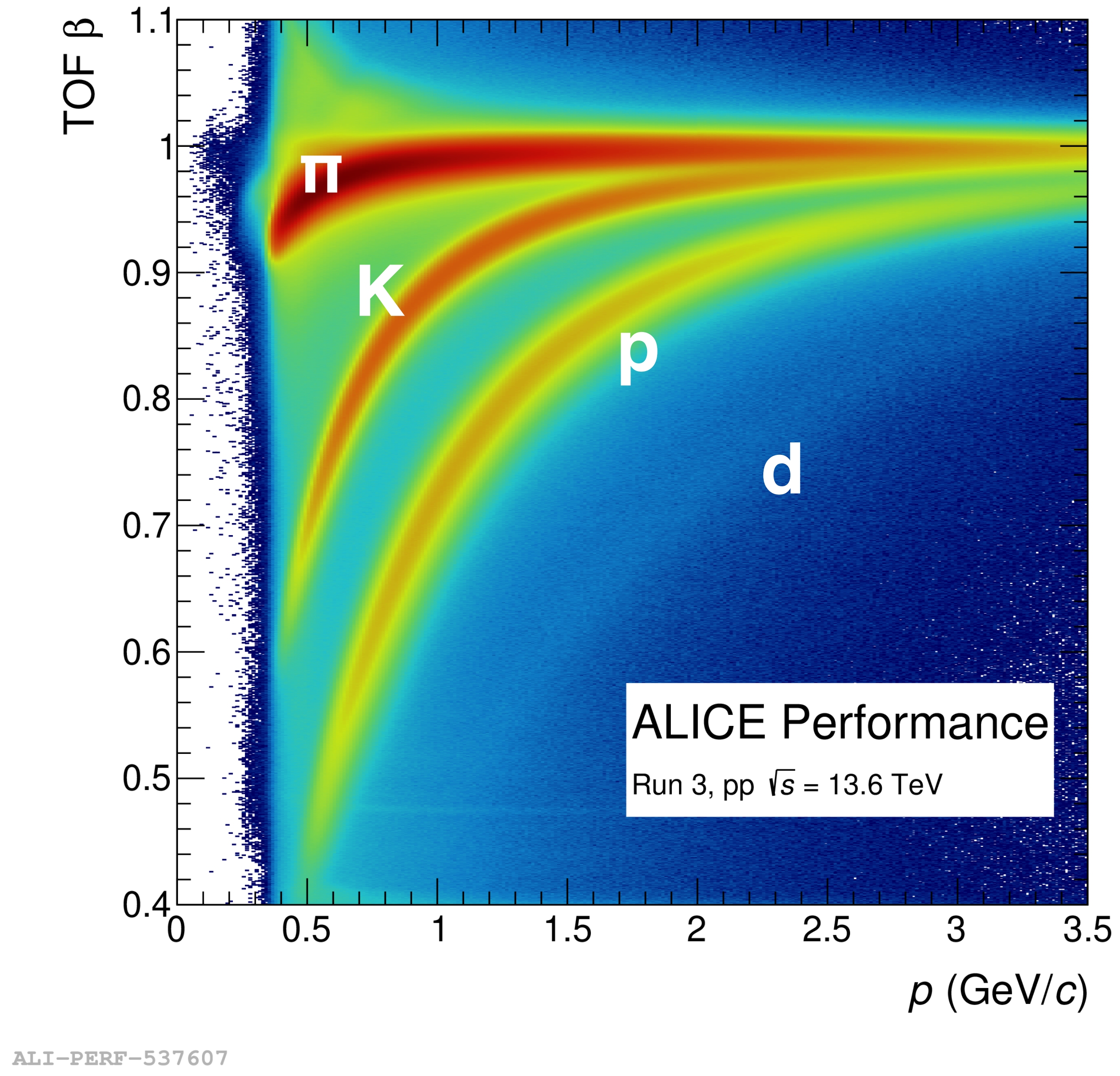
- **ALICE** has been the first experiment at the LHC to measure light (anti)(hyper)nuclei
- Measurements at mid rapidity: **|η| < 0.8**
- Different PID techniques:
  - Specific energy loss **d*E*/dx** in the **TPC** (σ ~ 6%)
  - Time of flight (hence ***β* = Δ*t* / *L***) with the **TOF** (σ ~ 70 ps)







Measure of the source size

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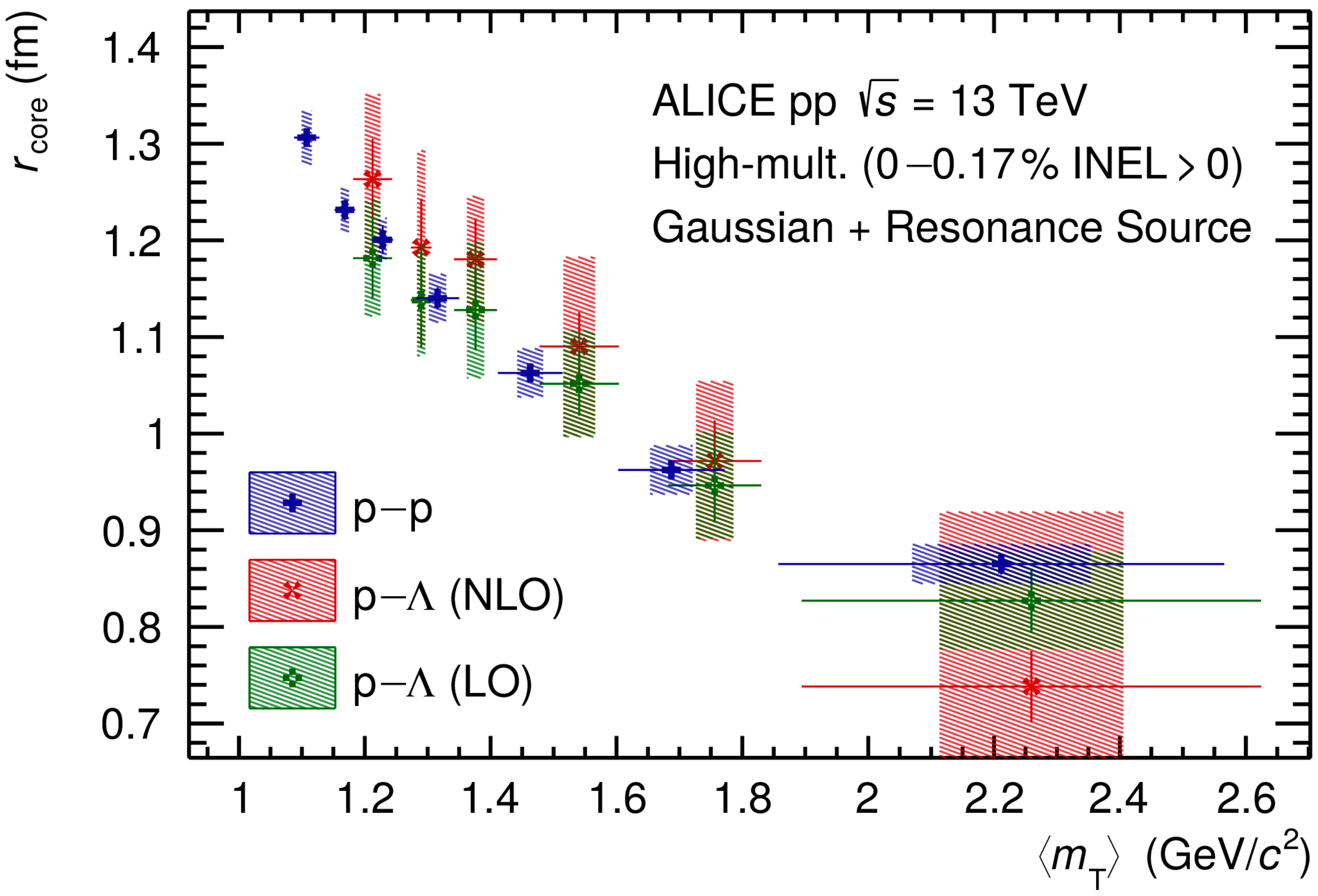
- If the **interaction** is very **well known**, the CF can be used to constrain the **source function**
  - **p-p** and **p-Λ**
- Assumptions:
  - Particle emission from a **Gaussian core** source
- Short-lived strongly decaying **resonances** ($c\tau \approx r_{\mathrm{core}}$) effectively increase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

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



PLB 811 (2020) 135849

B_A vs p_T in HM pp collisions

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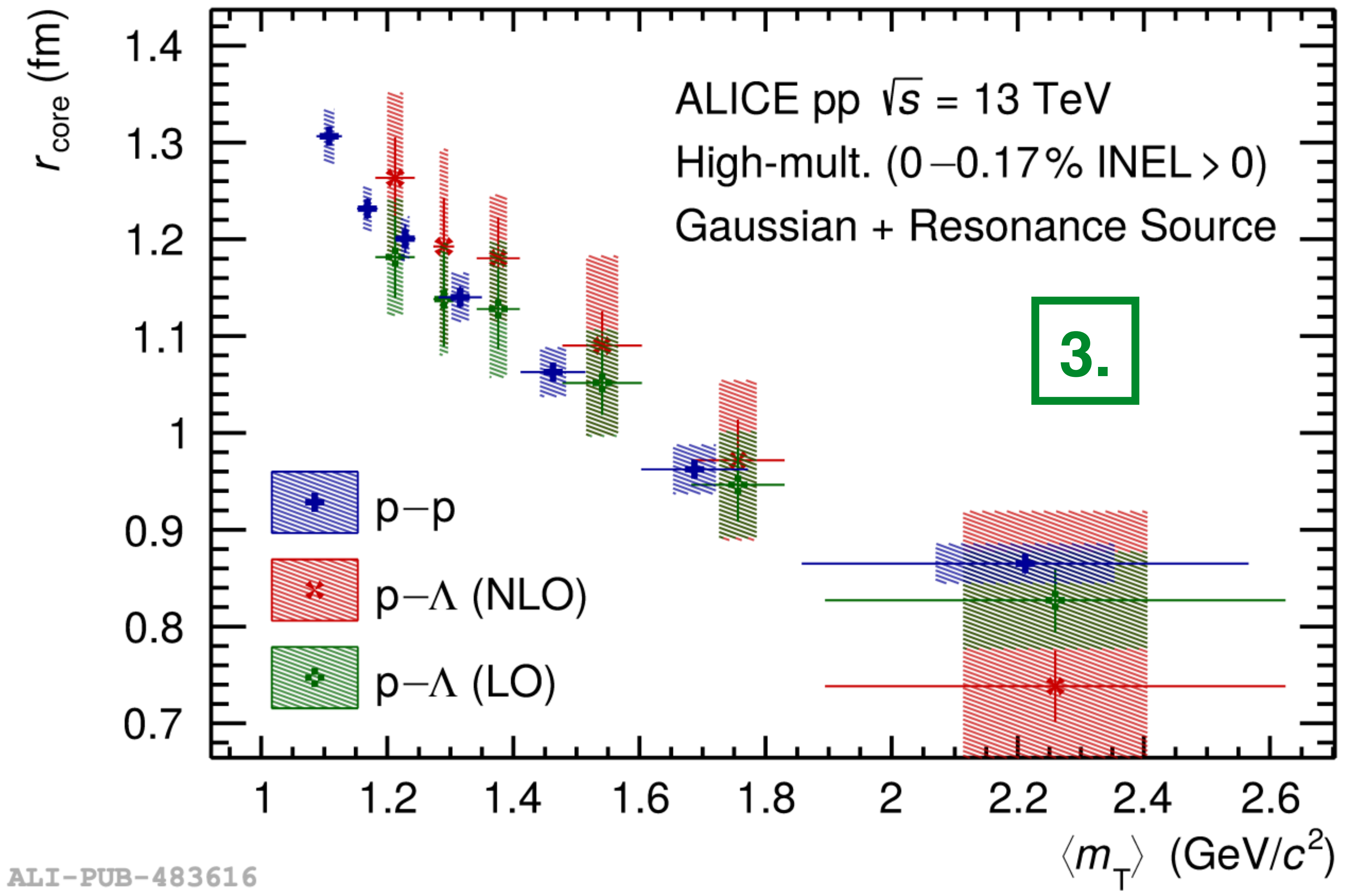
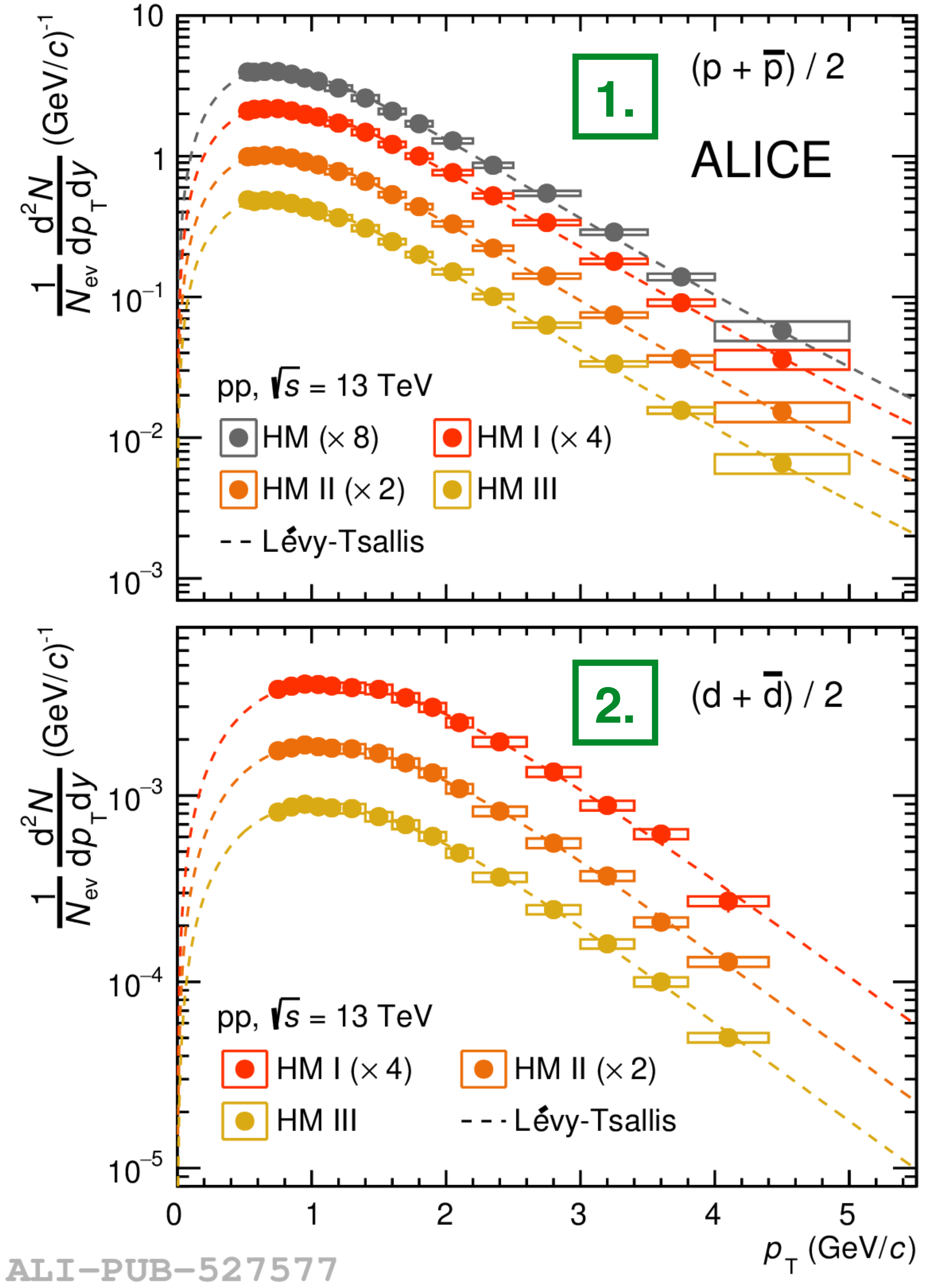
- In **HM pp** collisions, ALICE has measured:
  1. **(anti)proton** production spectra
  2. **(anti)deuteron** production spectra
  3. **size** of the emitting **source** with femtoscopy



PLB 811 (2020) 135849



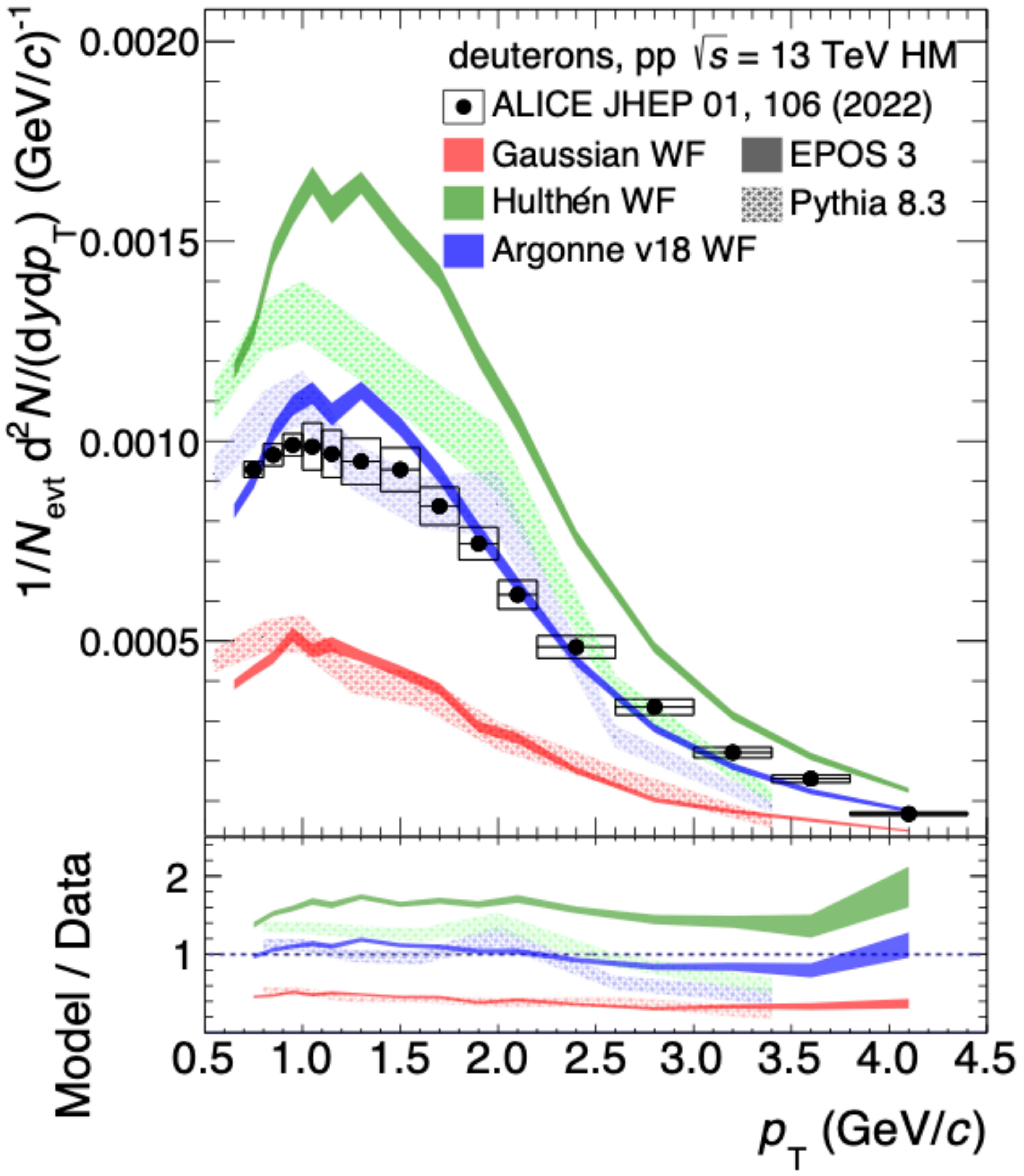
JHEP 01 (2022) 106

- 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

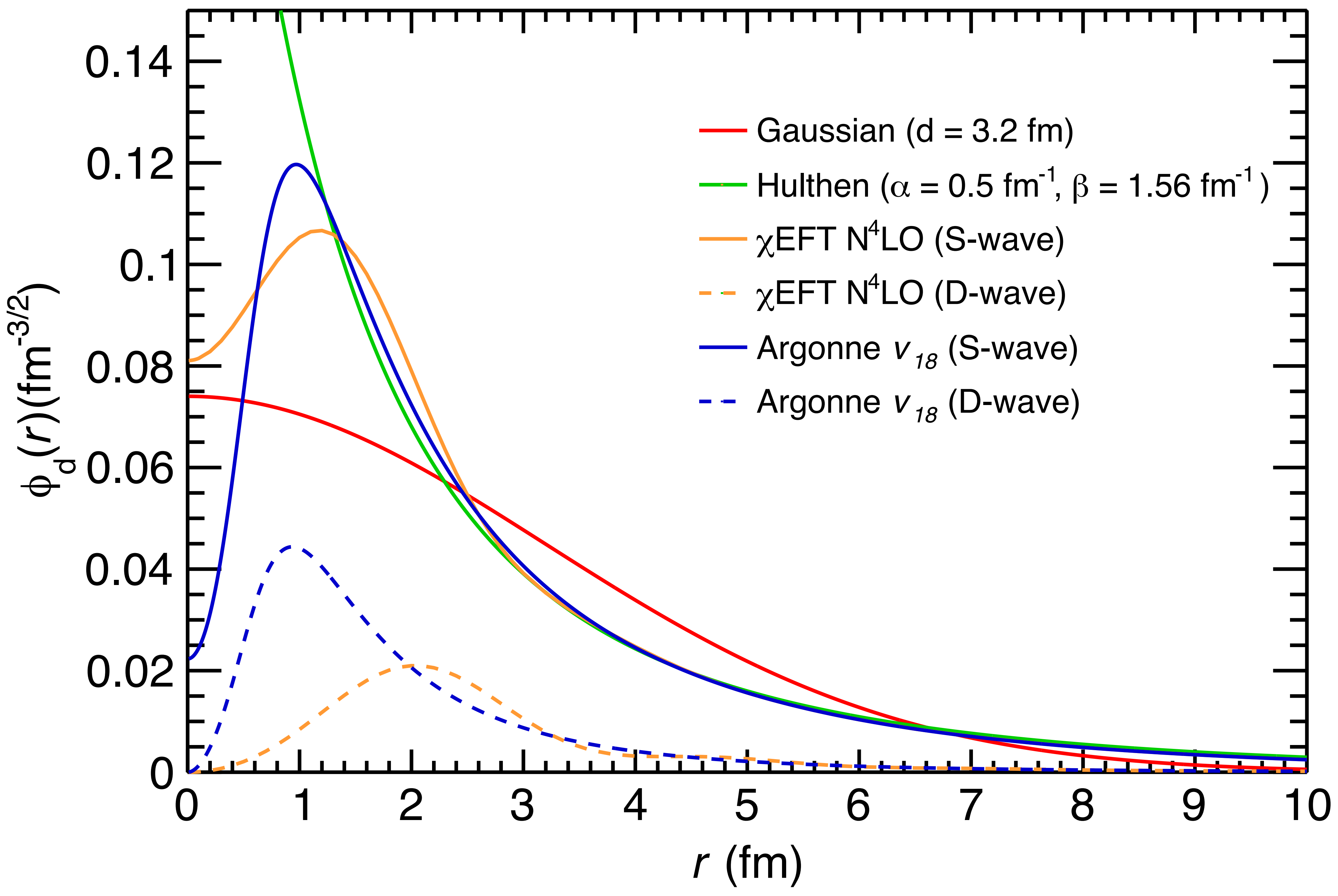
- Coalescence probability $\mathscr{P}(r_0, q)$ is defined as

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

- $H_{pn}(\vec{r}_p, \vec{r}_n) = h(\vec{r}_p)\, h(\vec{r}_n)$ is the two particle emitting-source
  - factorised into two Gaussian sources
- $\mathscr{D}(\vec{q}, \vec{r}) = \int d^3\xi \, e^{-i\vec{q}\cdot\vec{\xi}} \, \varphi_d(\vec{r} + \vec{\xi}/2)\, \varphi_d^*(\vec{r} - \vec{\xi}/2)$

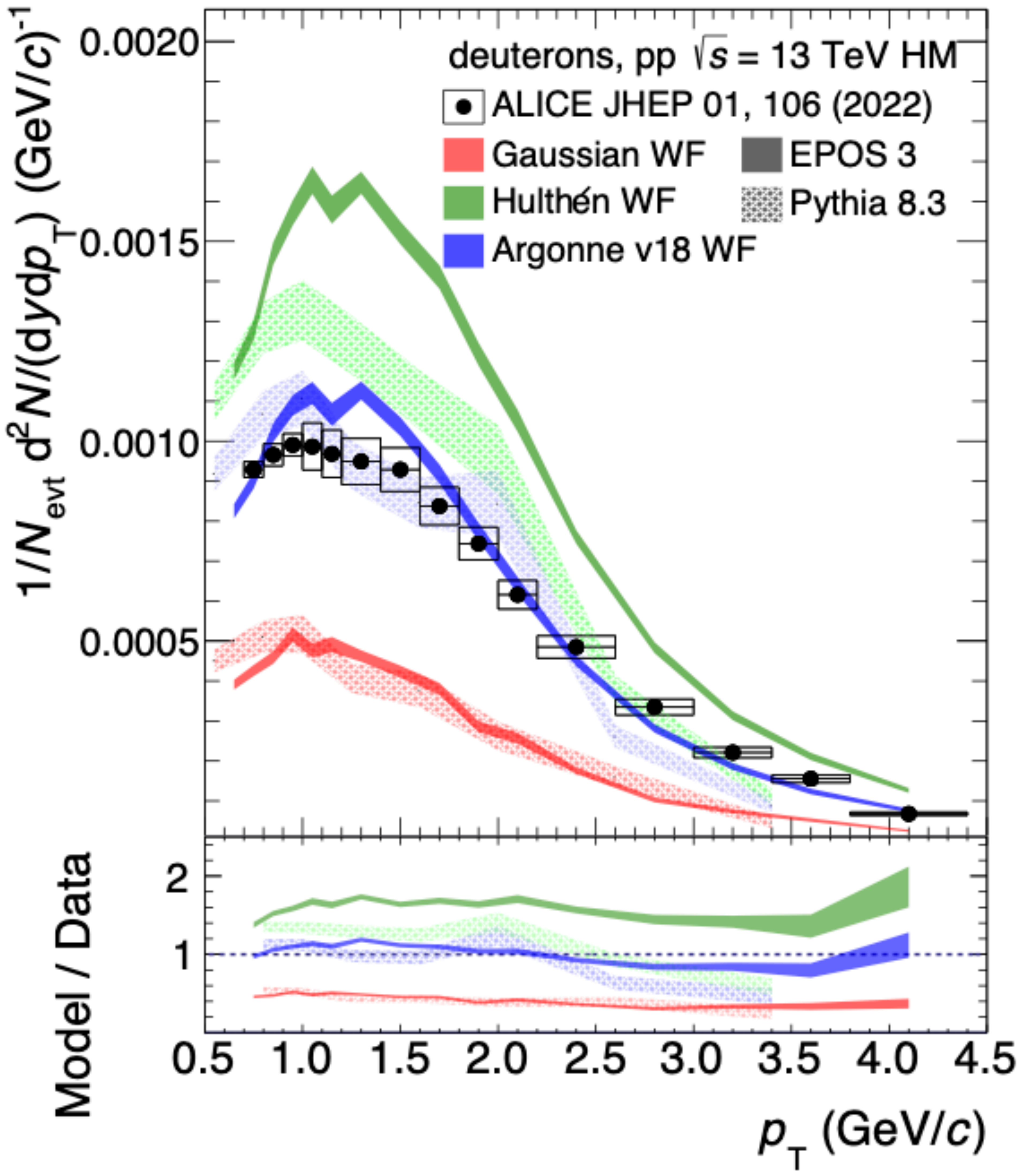
  is the Wigner-transform of the deuteron wavefunction φ_d

➡ test the effect of deuteron wavefunctions on coalescence



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

- 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

Λ separation energy

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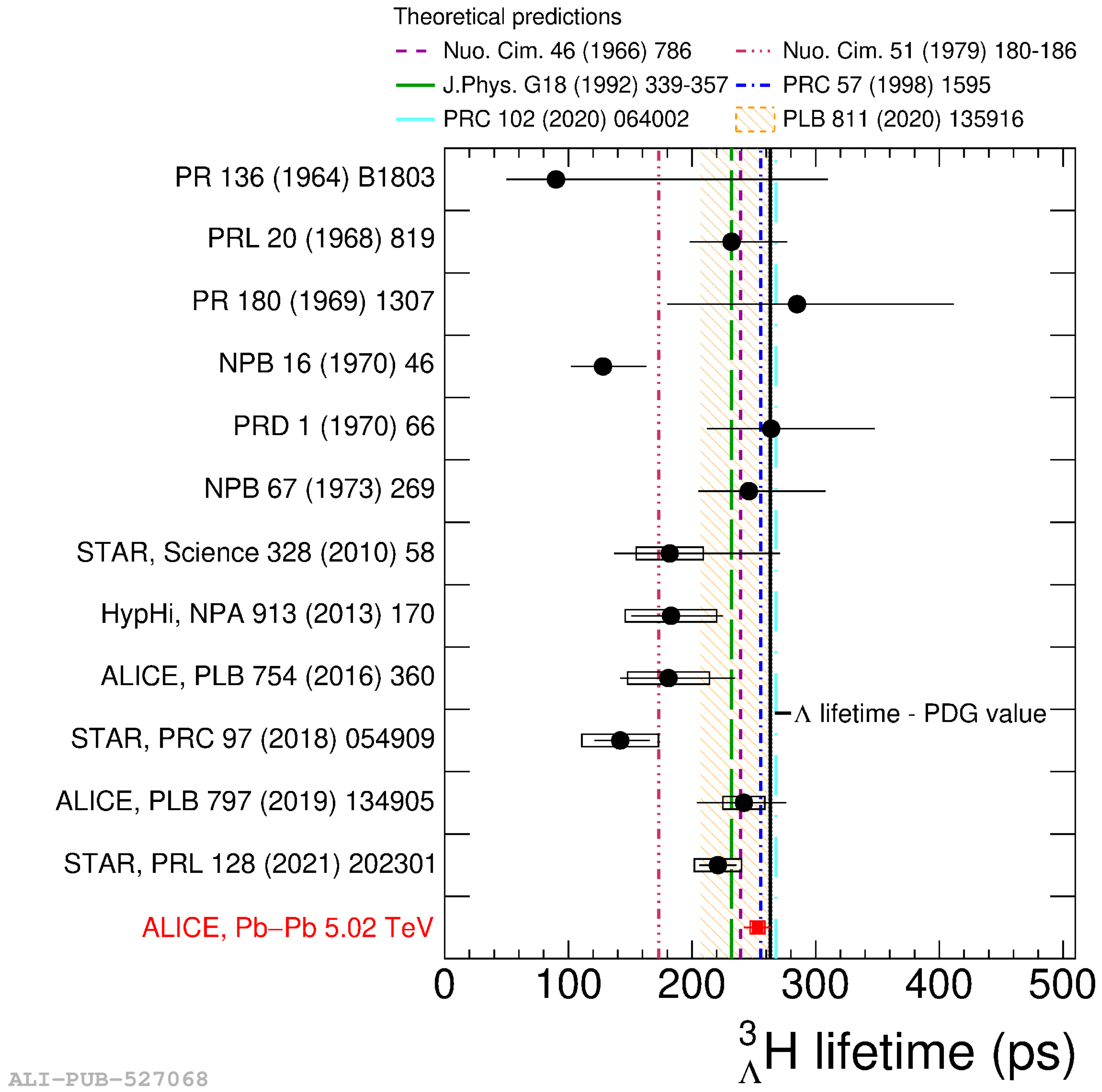
- **Lifetime** measured with the highest precision so far:
  - compatible with that of the **free Λ**
    - **loosely bound** state



PRL 131 (2023) 102302

Λ separation energy

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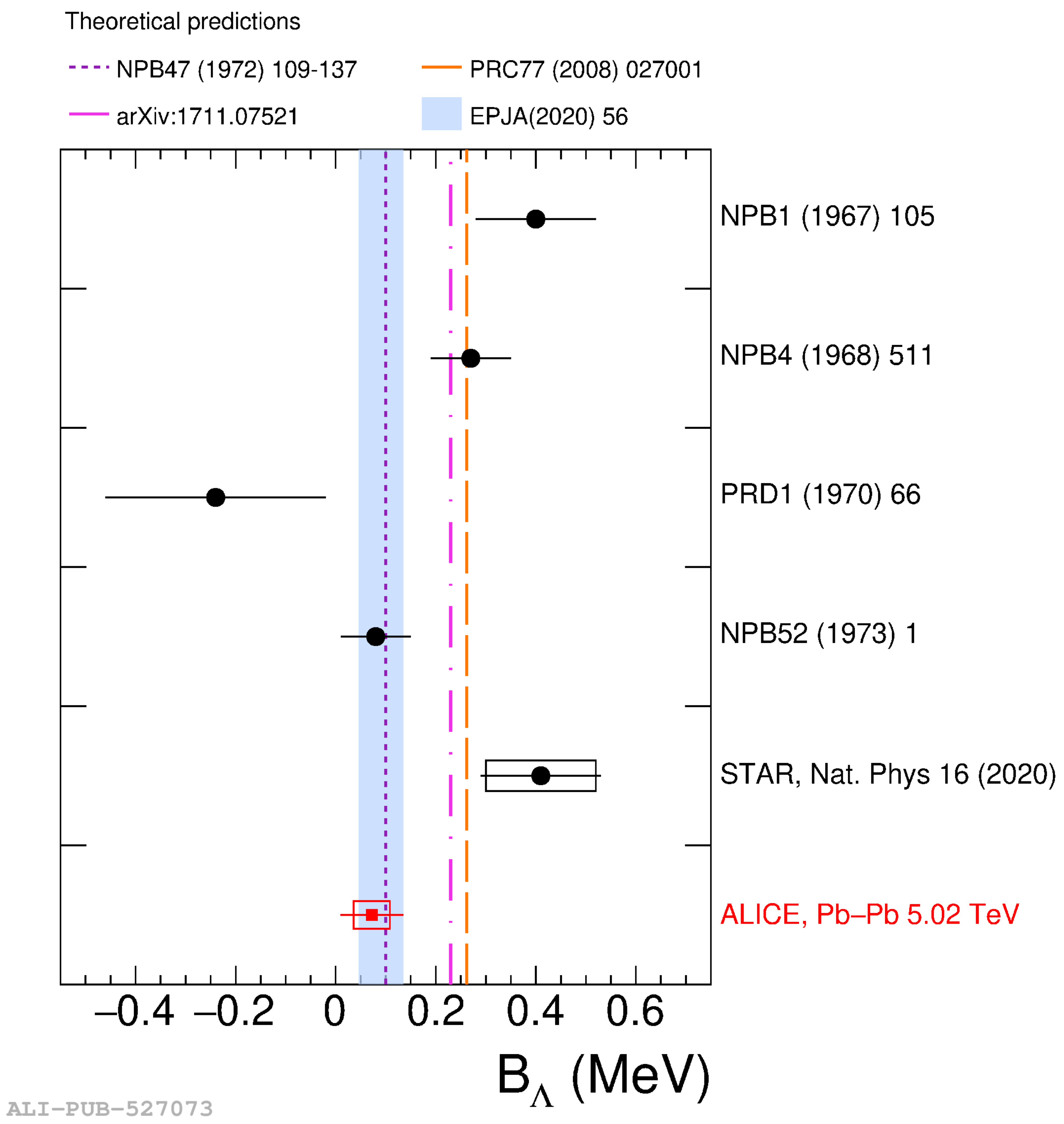
- **Lifetime** measured with the highest precision so far:
  - compatible with that of the **free Λ**
    - **loosely bound** state
- B_Λ has been measured with a **high precision**
  - **1.9 σ** difference w.r.t. last **STAR** results
  - compatible with χEFT and **Dalitz**'s predictions
    - **loosely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



PRL 131 (2023) 102302

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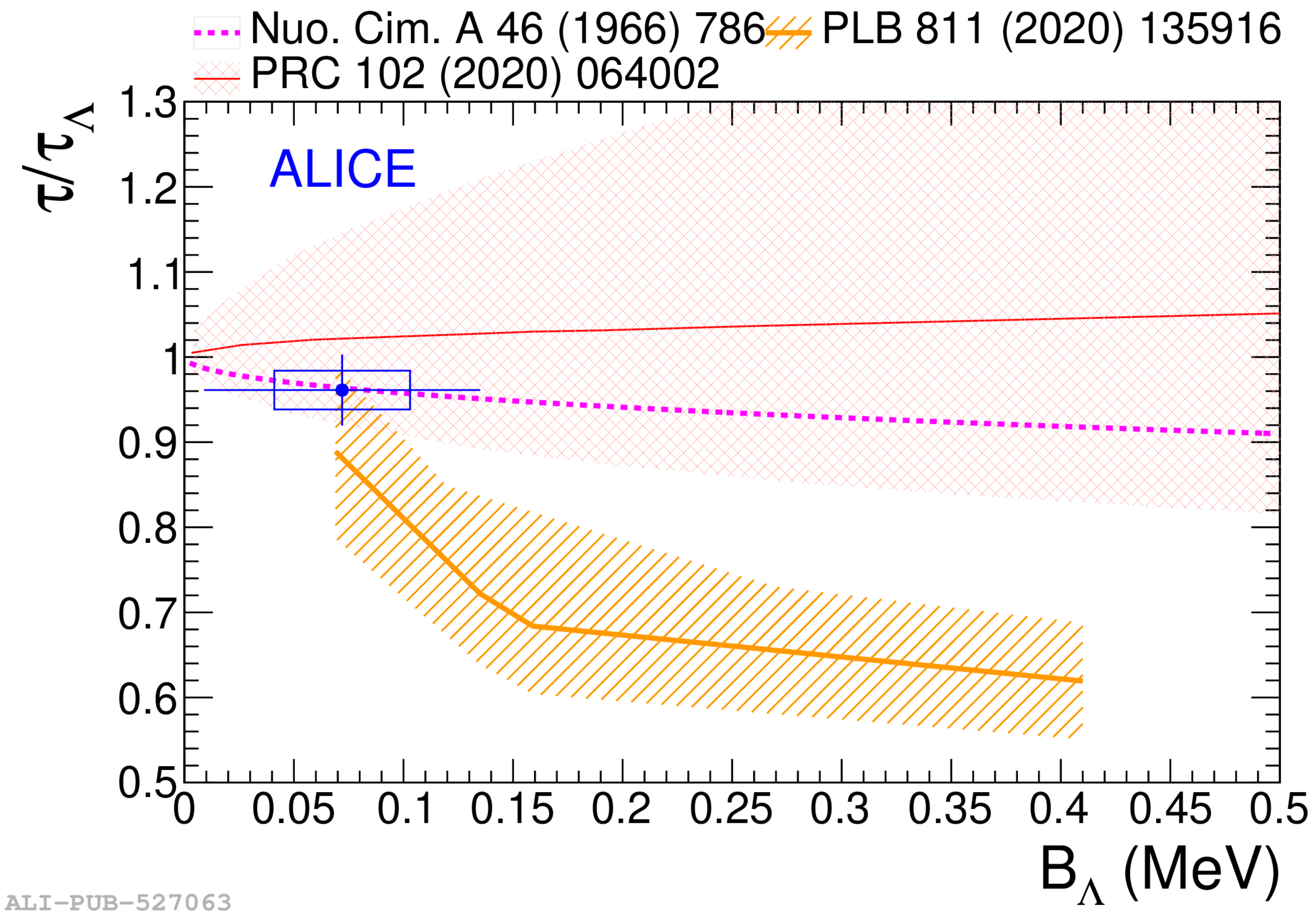
- **B_Λ** has been measured with a **high precision**
  - **1.9 σ** difference w.r.t. last **STAR** results
  - compatible with χ**EFT** and **Dalitz**'s predictions
    - **loosely bound** state
- All the models provide a simultaneous description of τ and **B_Λ**

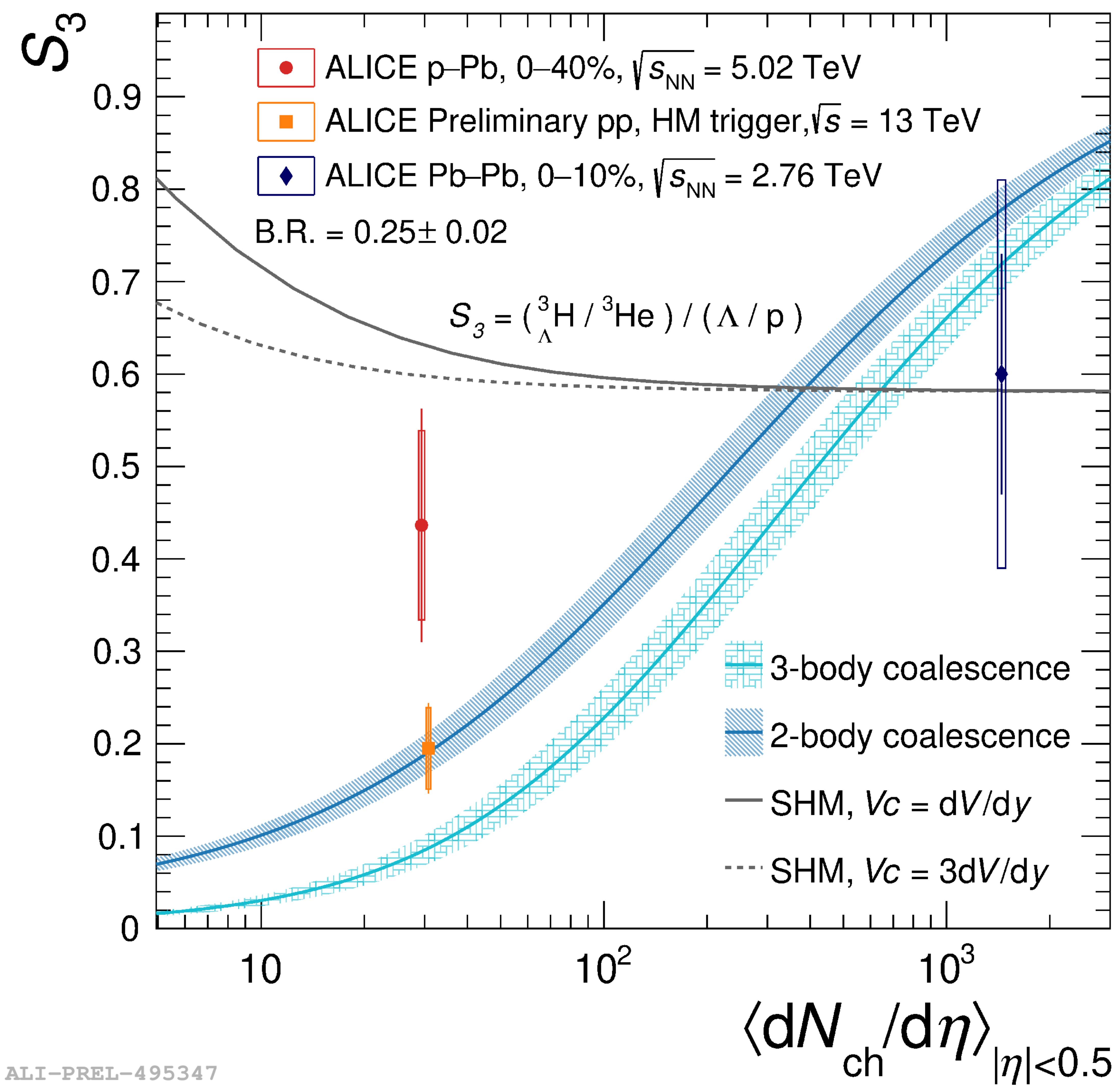


PRL 131 (2023) 102302

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



PRL 128 (2022) 252003

Hypertriton production in Pb-Pb

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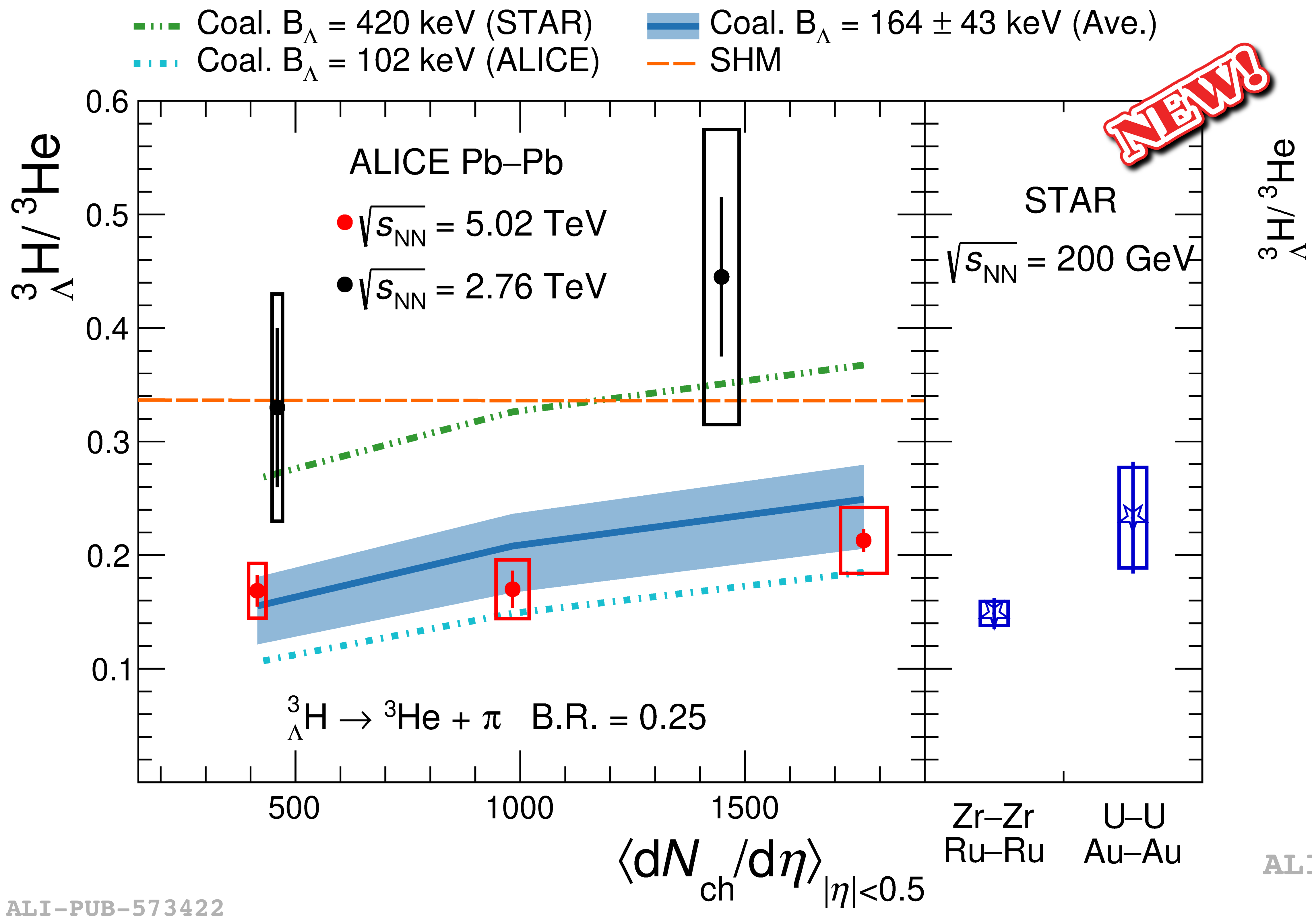
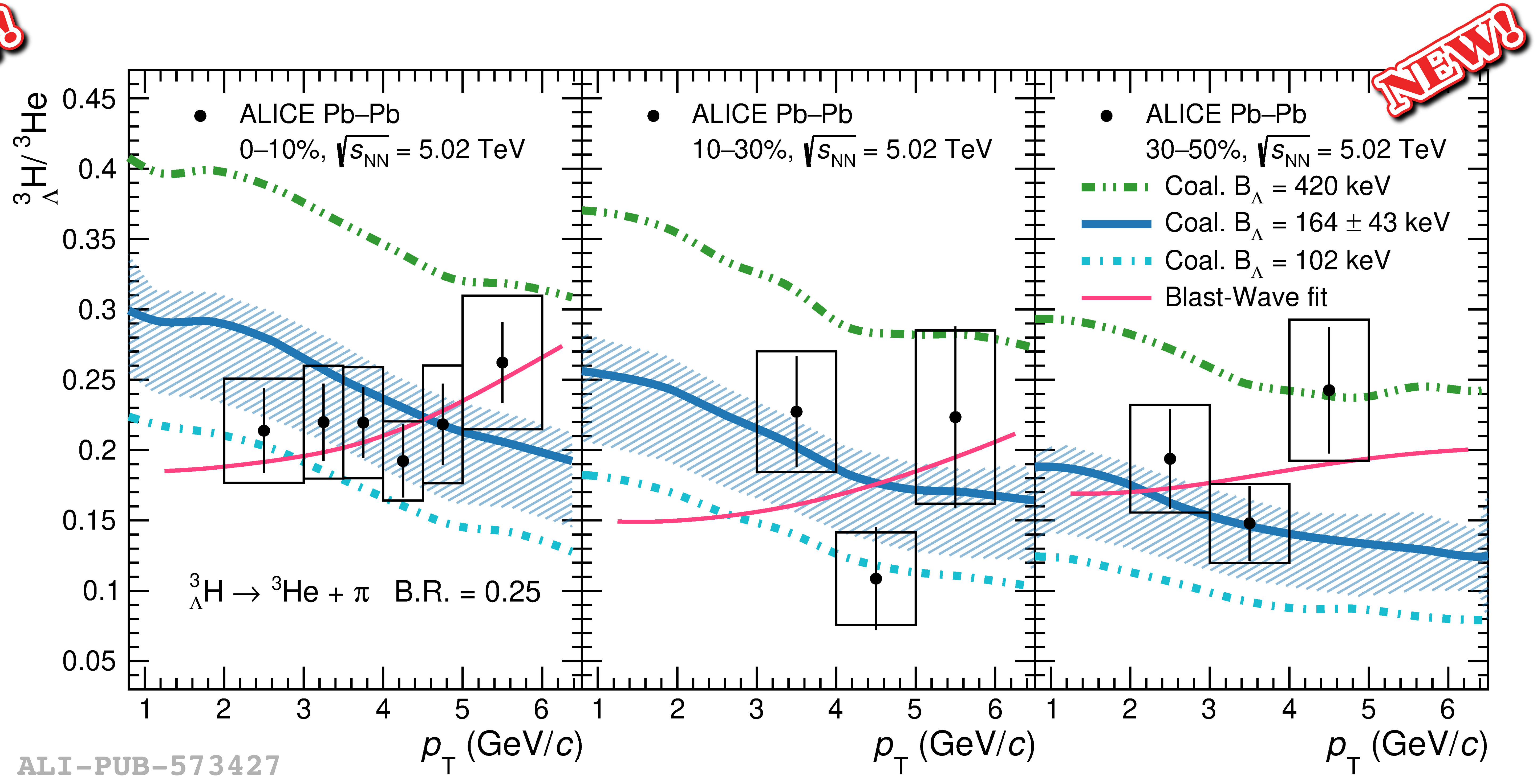
- ${}^{3}_{\Lambda}\mathrm{H}$ has also been recently measured in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5 TeV
  - More precise wrt Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
- ${}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}$ shows good agreement with coalescence, assuming B_Λ < 170 KeV
  - p_T differential measurement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





arXiv:2405.19839

Coalescence parameter B_A

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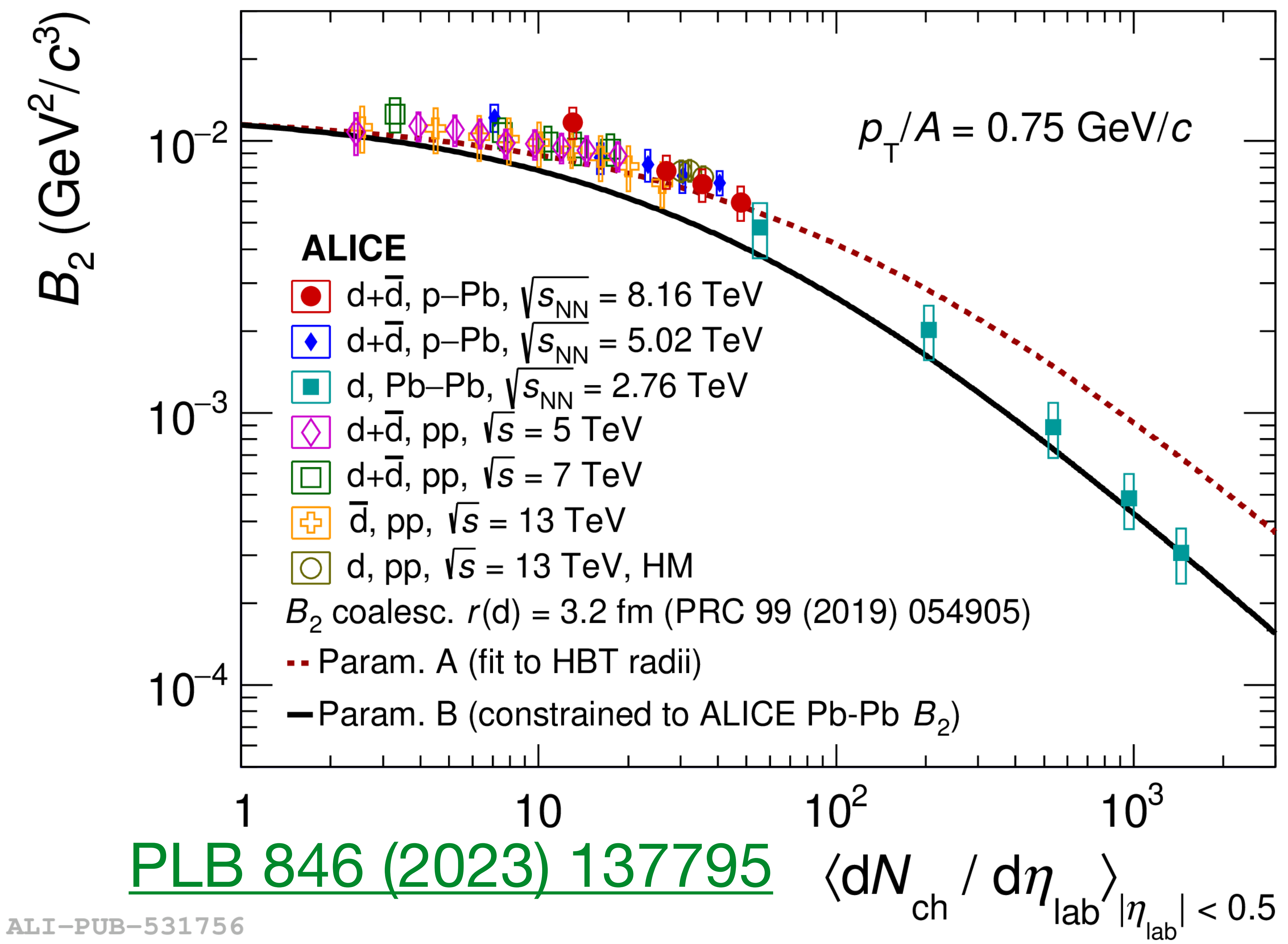
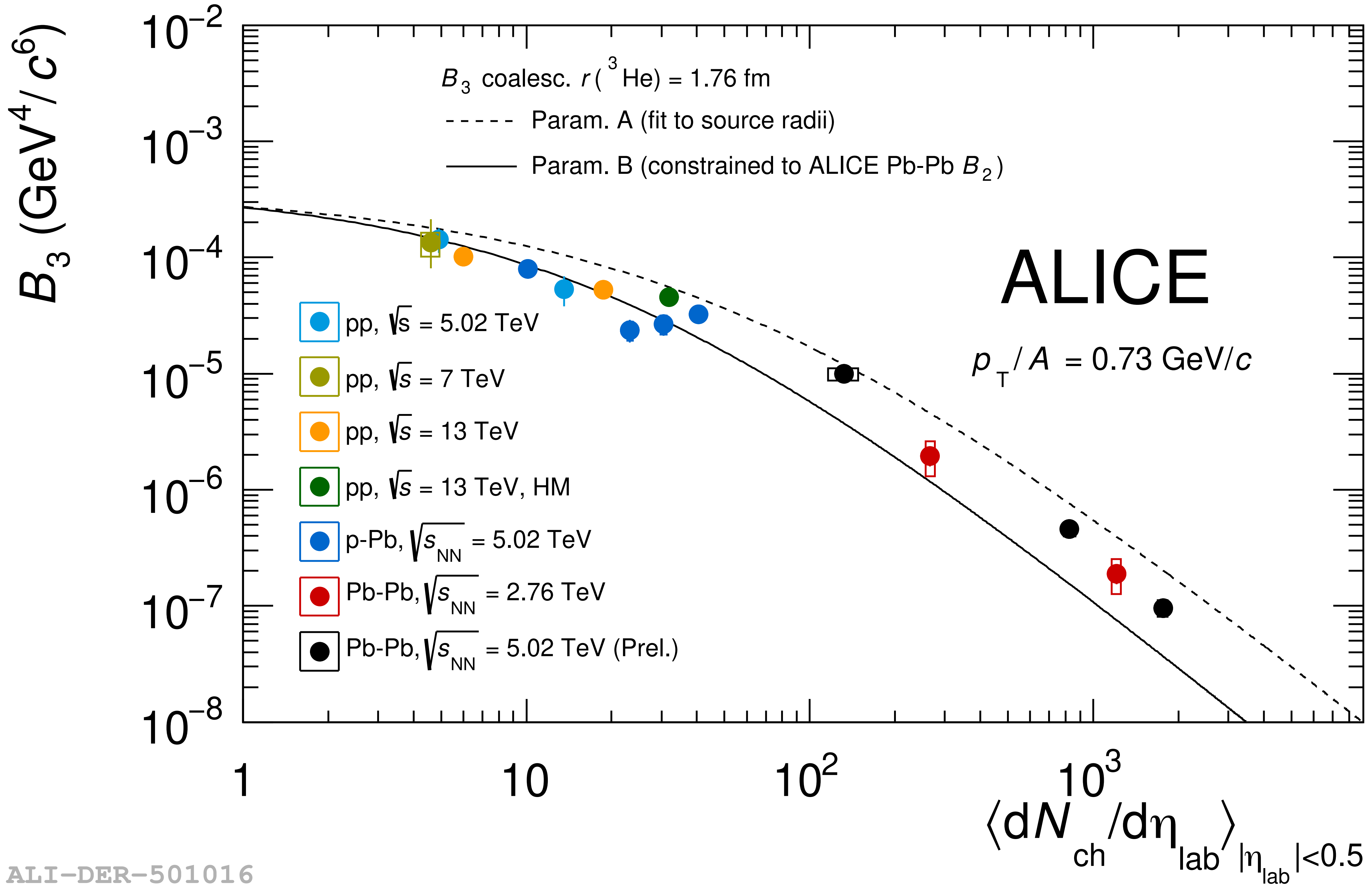
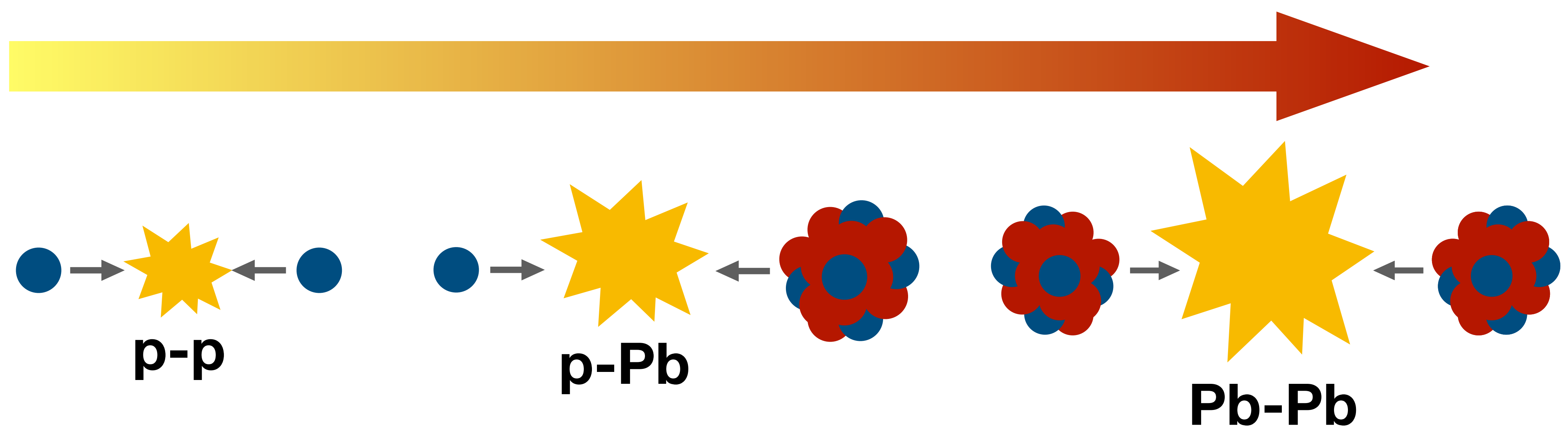


PLB 846 (2023) 137795





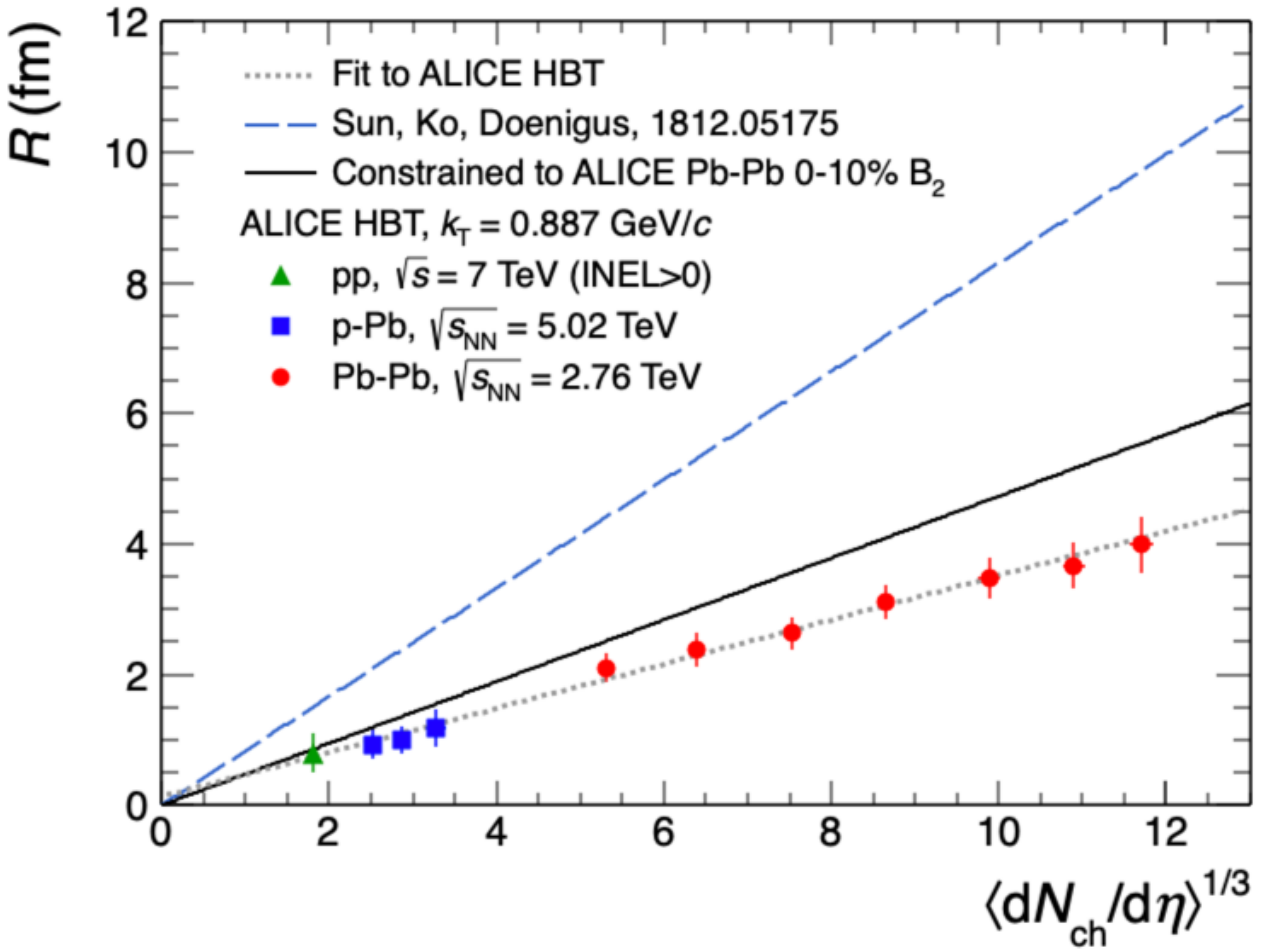
- **B_A** evolves **smoothly** with **multiplicity**
  - dependence on the **system size**
- Comparison with theory:

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

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

- 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

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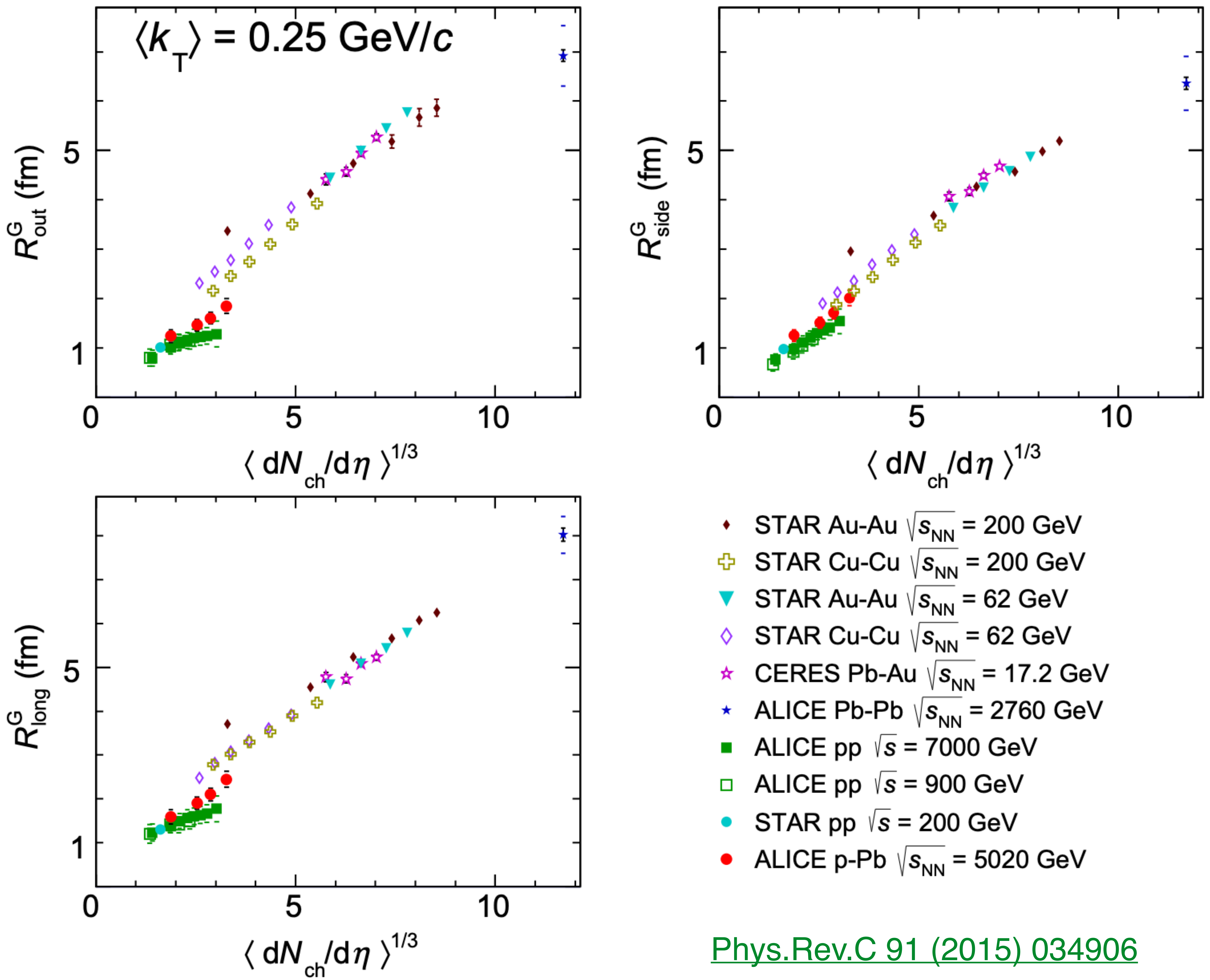
- Adding more points to the *R* vs $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle$, it is visible that the evolution is **not smooth** from pp to p-Pb
- This discontinuity could be the reason why models do not reproduce data along the whole multiplicity range
  - Possible solution: B_2 vs *R*
  - *R*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



Phys.Rev.C 91 (2015) 034906