Light-nuclei production: experimental measurements vs theoretical predictions

Luca Barioglio

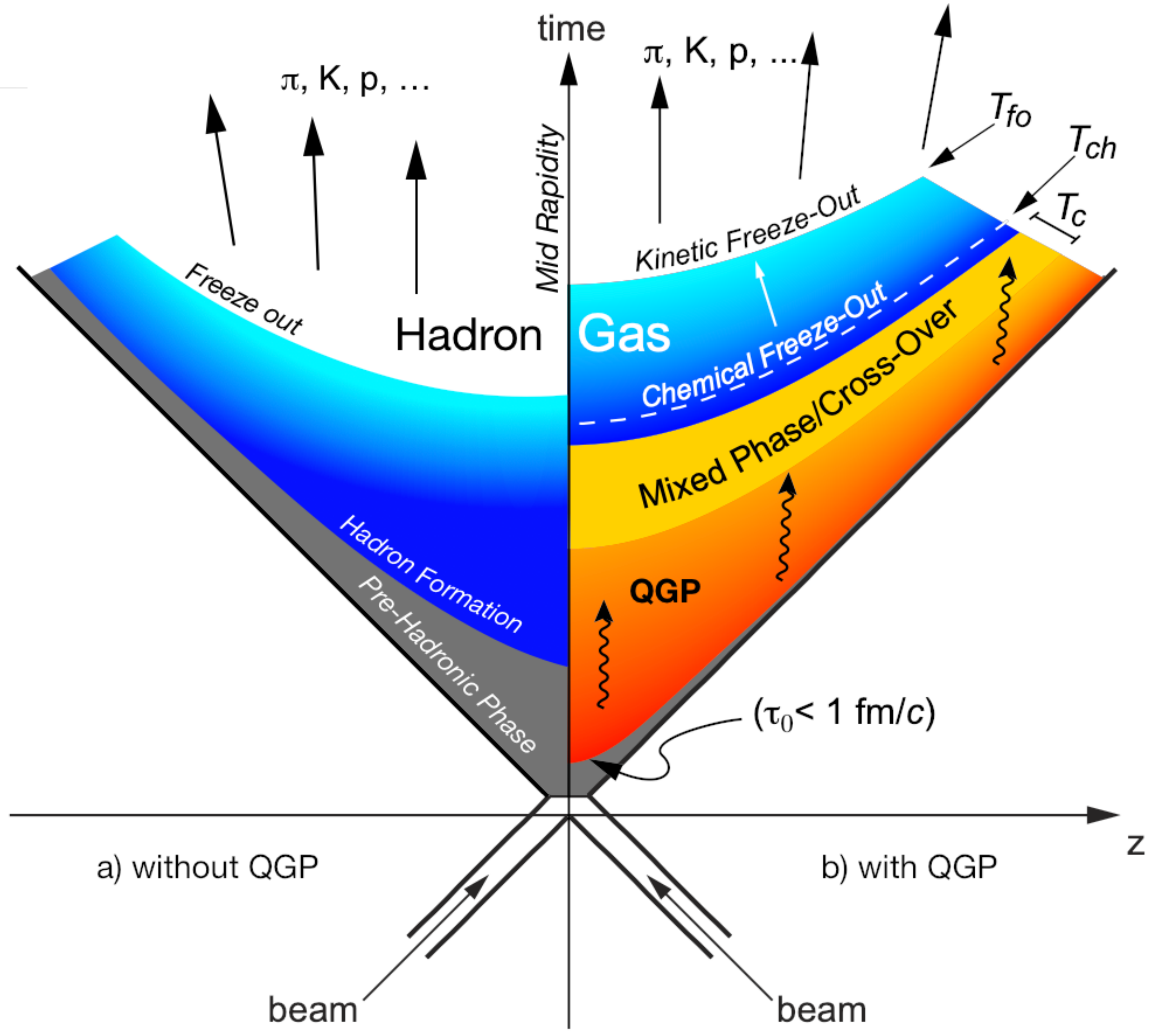
University and INFN - Torino

Origin of nuclear clusters in hadronic collisions

CERN (more or less) - 19/05/2020

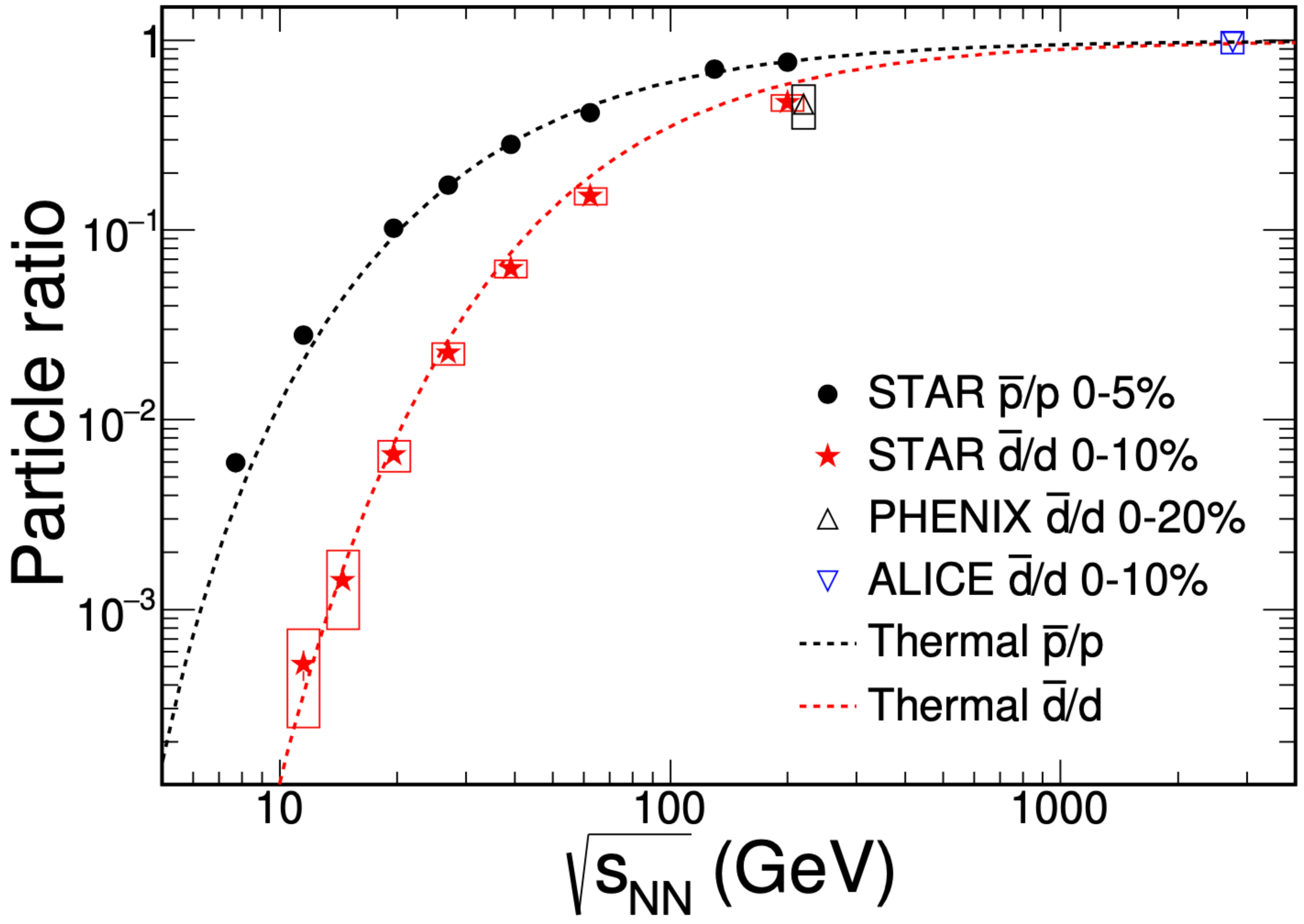
Nuclear matter production

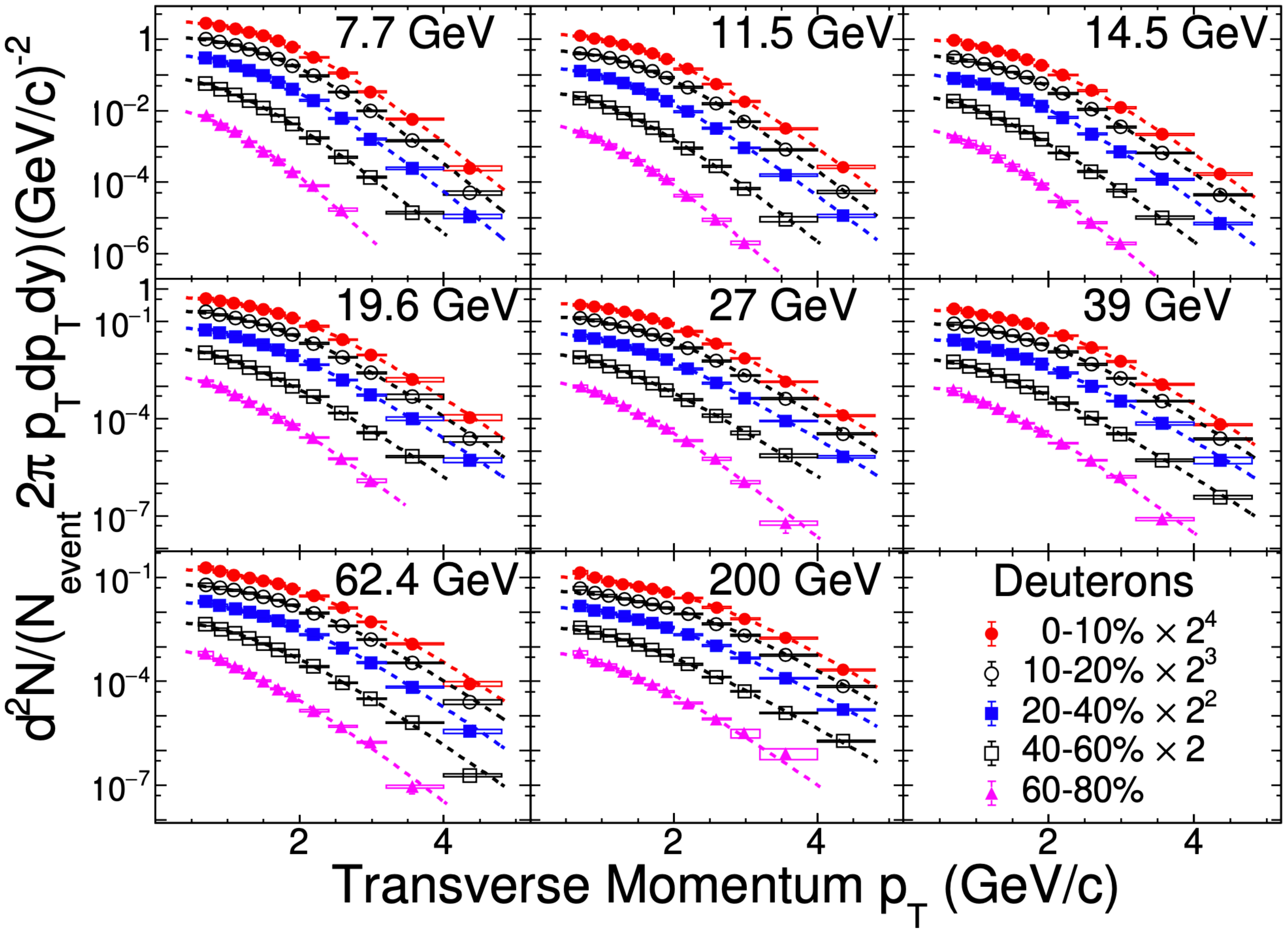
- Light (anti-)nuclei are abundantly produced both at the RHIC and at the LHC in all collision systems and at all the energies
- The **production mechanisms** of light (anti-)nuclei in high-energy physics are still not completely understood
  - light nuclei are characterised by a low binding energy (***E_B* ~ 2 MeV** for d) with respect to the kinetic freeze-out temperature in Pb-Pb (***T_{fo}* ~ 110 MeV**)
- Two classes of models are available:
  - the **coalescence** model
  - the **statistical hadronisation** model



Light nuclei in Au-Au

- p_T spectra described by a **Blast-Wave** function
- **Hardening** with centrality and energy
- Different production of nuclei and anti-nuclei
  - Nuclear stopping

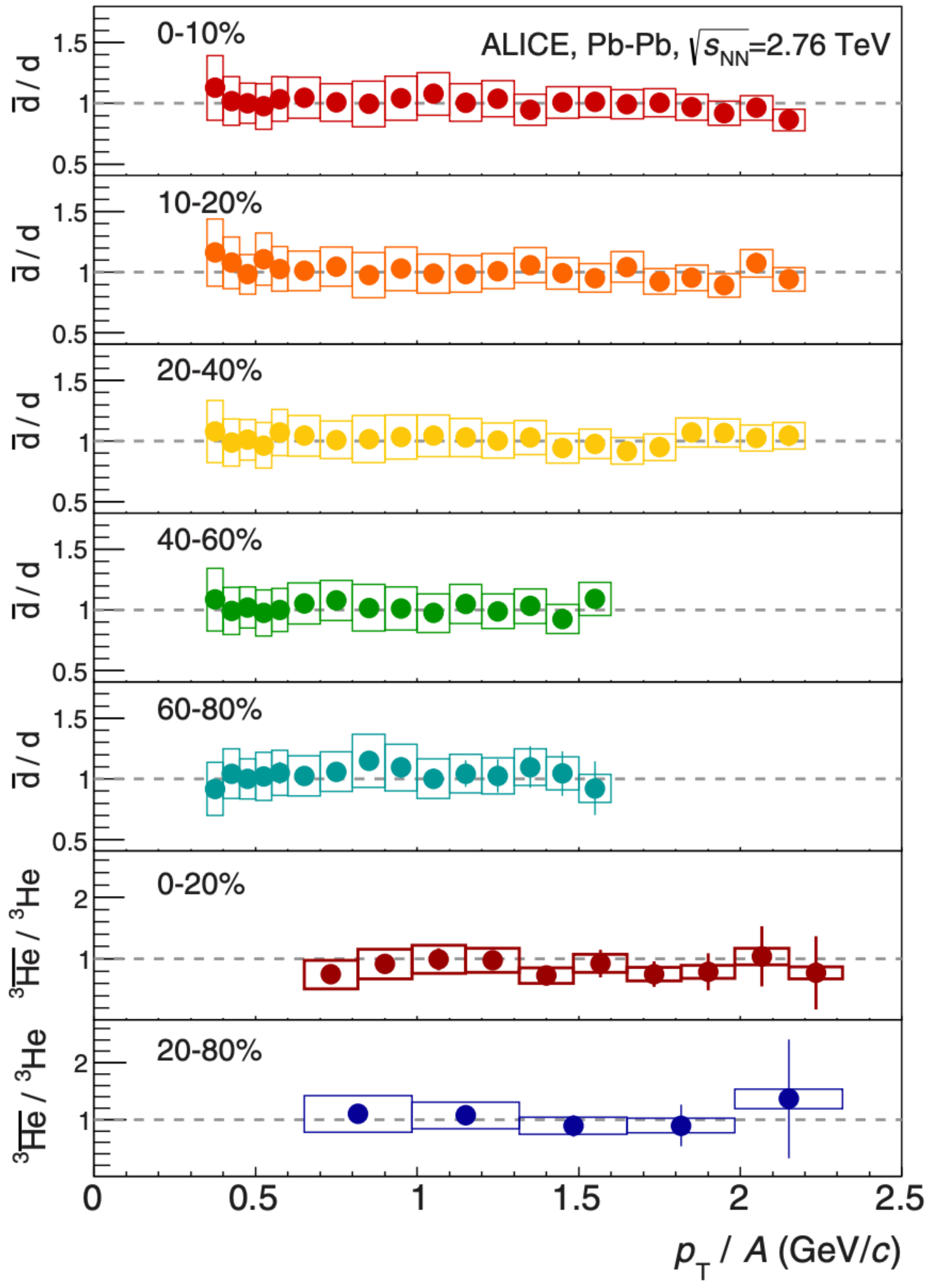


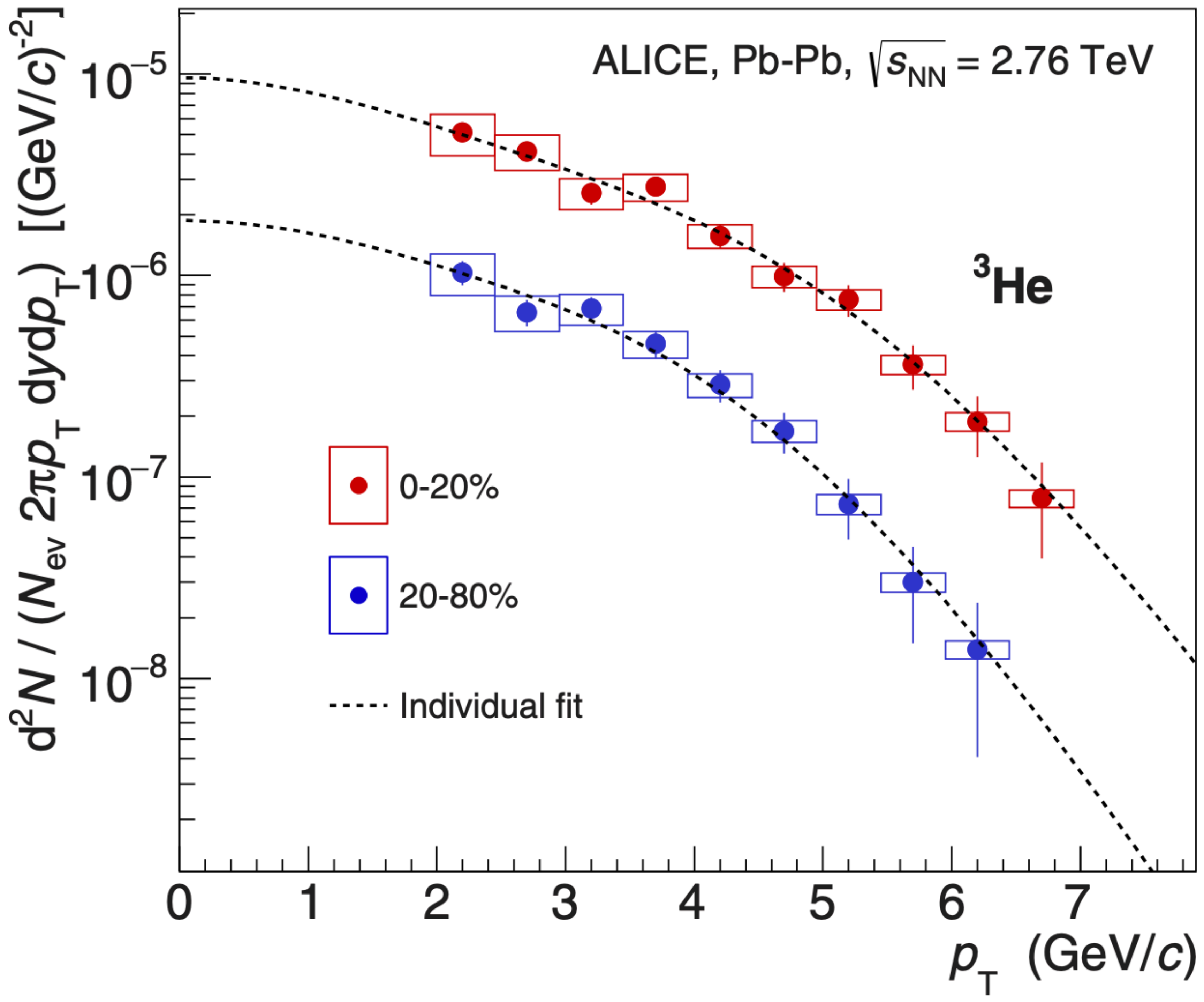


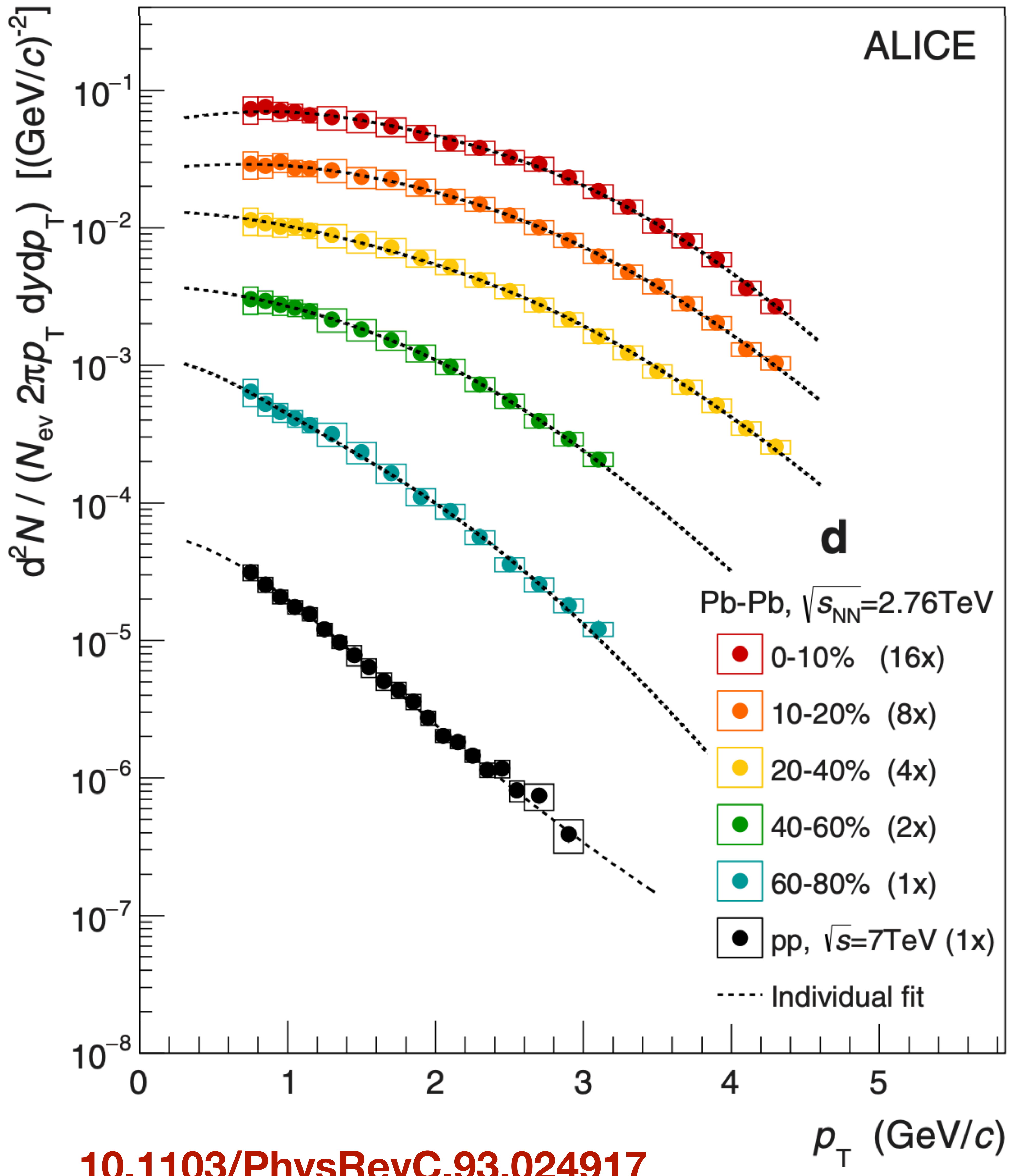
10.1103/PhysRevC.99.064905

Light nuclei in Pb-Pb

- p_T spectra described by a **Blast-Wave** function
- **Hardening** with increasing centrality
- Same production of nuclei and anti-nuclei
  - Nuclear transparency



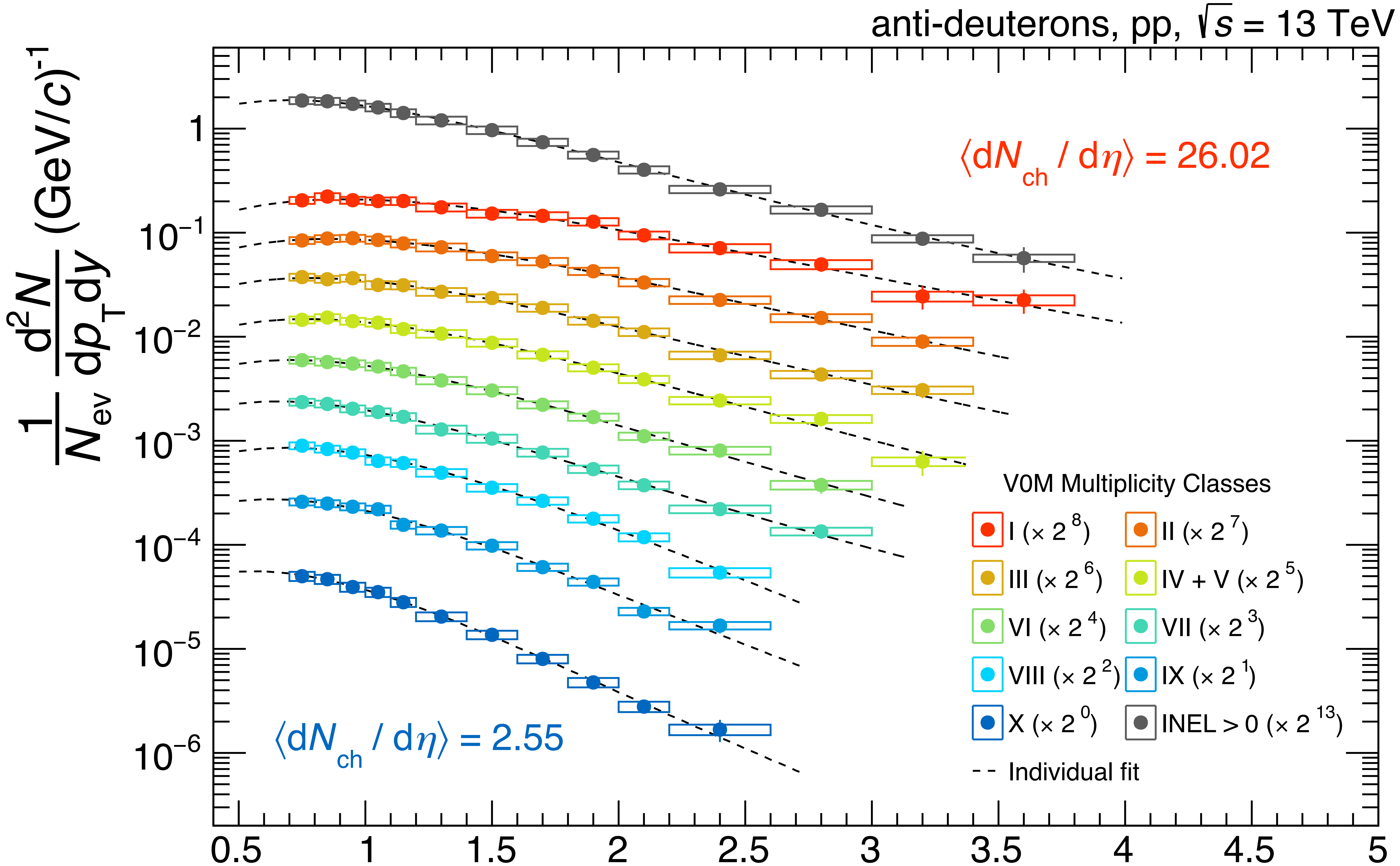




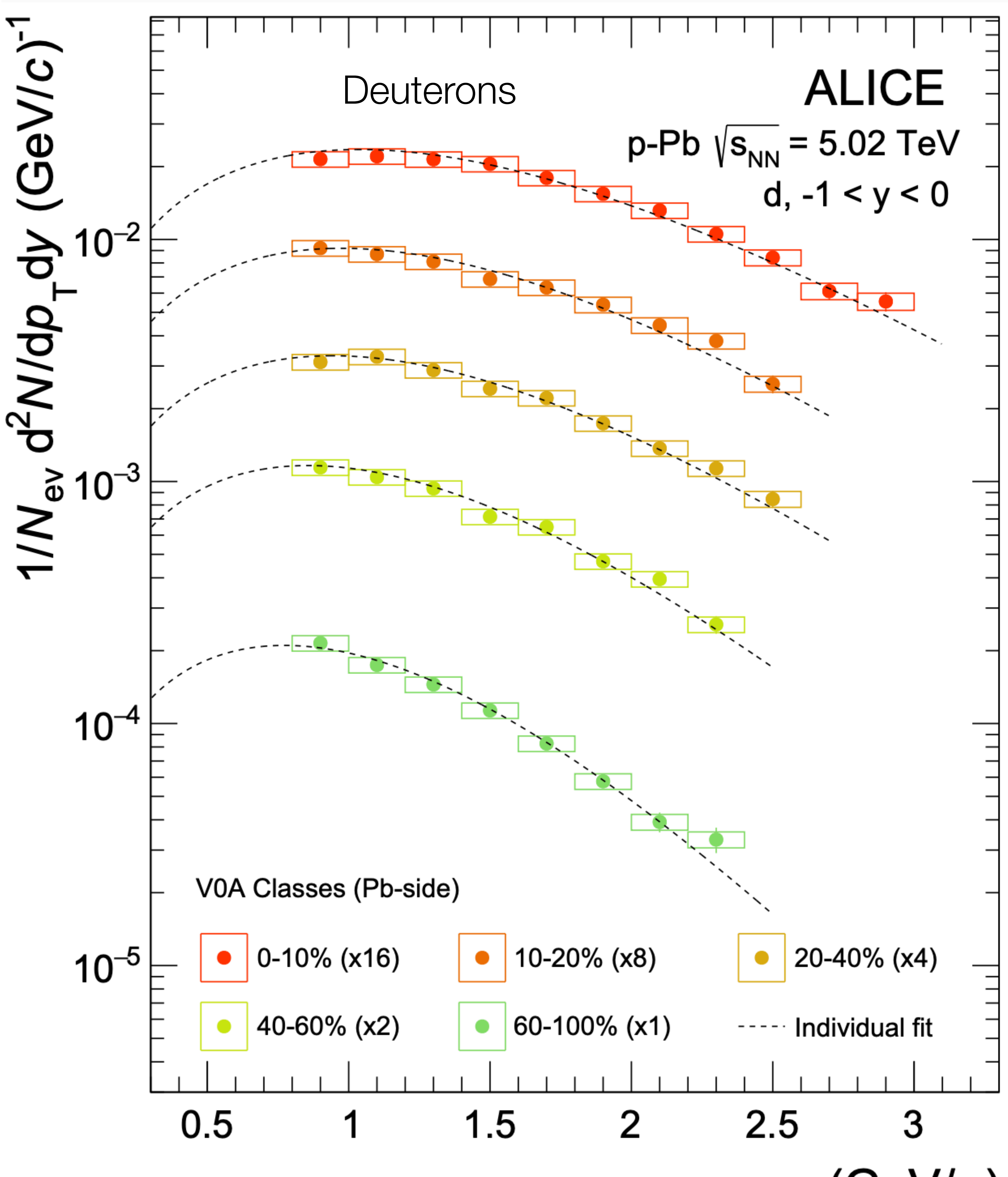
10.1103/PhysRevC.93.024917

Light nuclei in pp and p-Pb

- p_T spectra **NOT** described by a **Blast-Wave** function
- **Hardening** with increasing multiplicity
- Same production of nuclei and anti-nuclei



arXiv:2003.03184



10.1016/j.physletb.2019.135043

Coalescence model

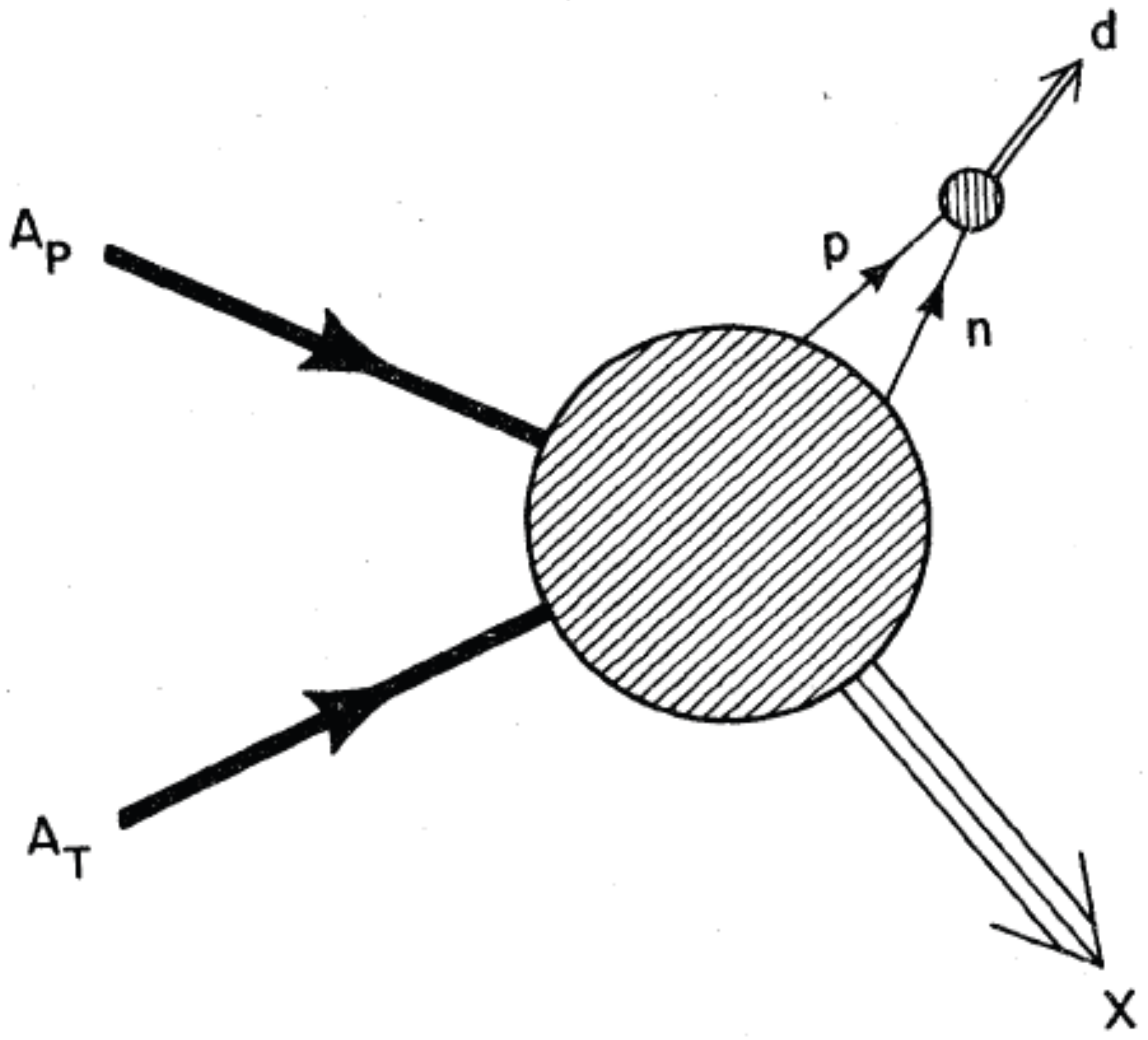
- Nucleons **close in phase space** at the **freeze-out** can form a nucleus via **coalescence**
- Coalescence parameter $\mathbf{B_A}$:

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

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
- **Different implementations** of coalescence model

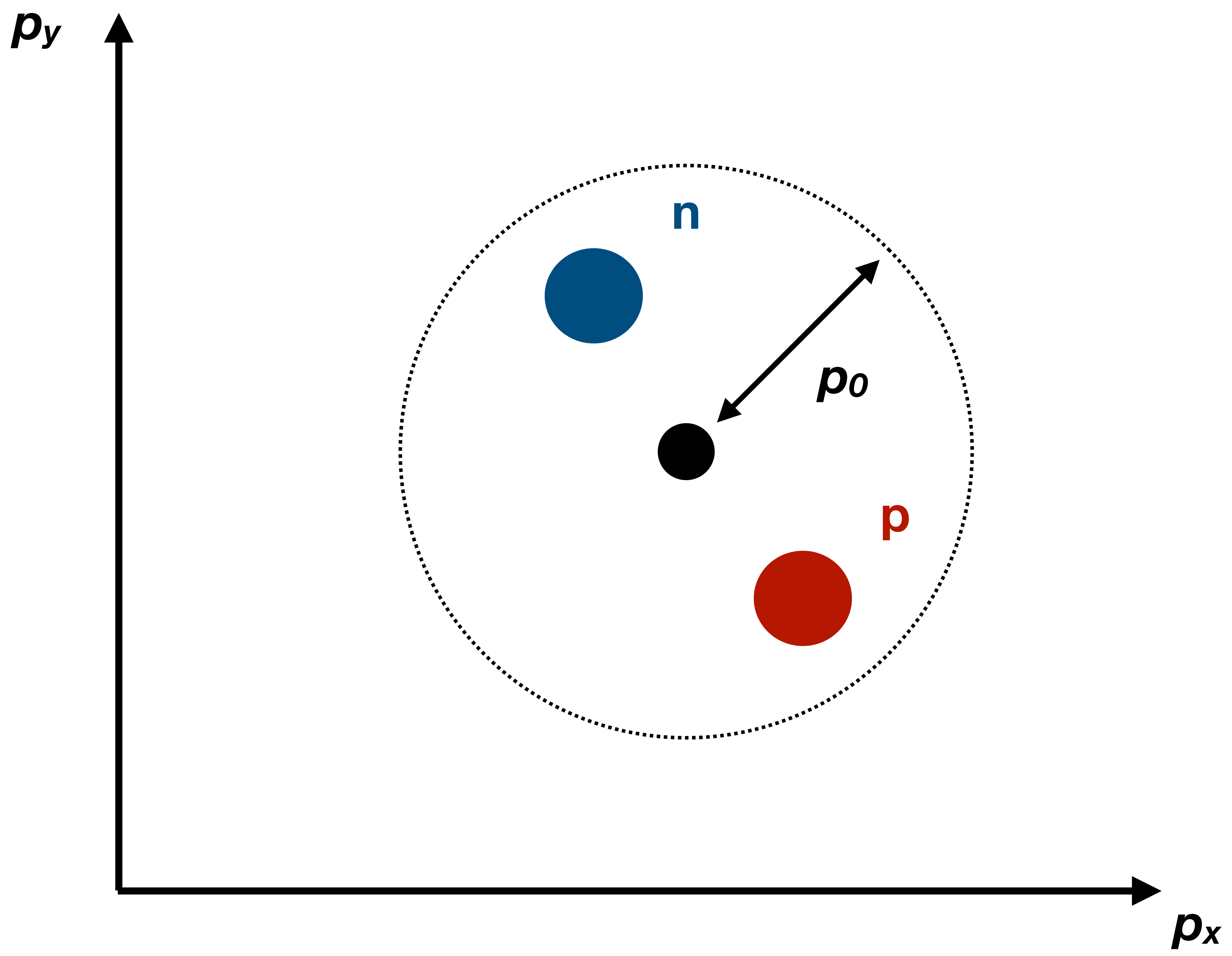


J. I. Kapusta, Phys.Rev.C 21 (1980)

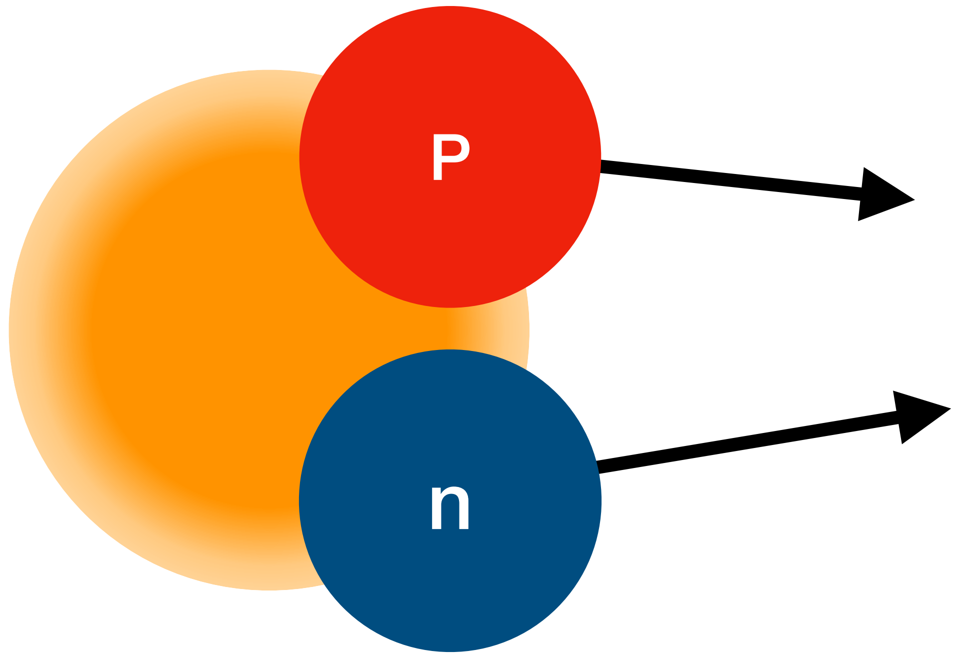
Simplest coalescence model

- Hypotheses:
  - **No space-time** distribution fo the nucleons considered
  - Nucleons with similar momentum (Δ**p** < **p₀**) can form a nucleus

$$B_A = \left(\frac{4\pi}{3}p_0^3\right)^{A-1}\frac{m_A}{m_p^A}$$

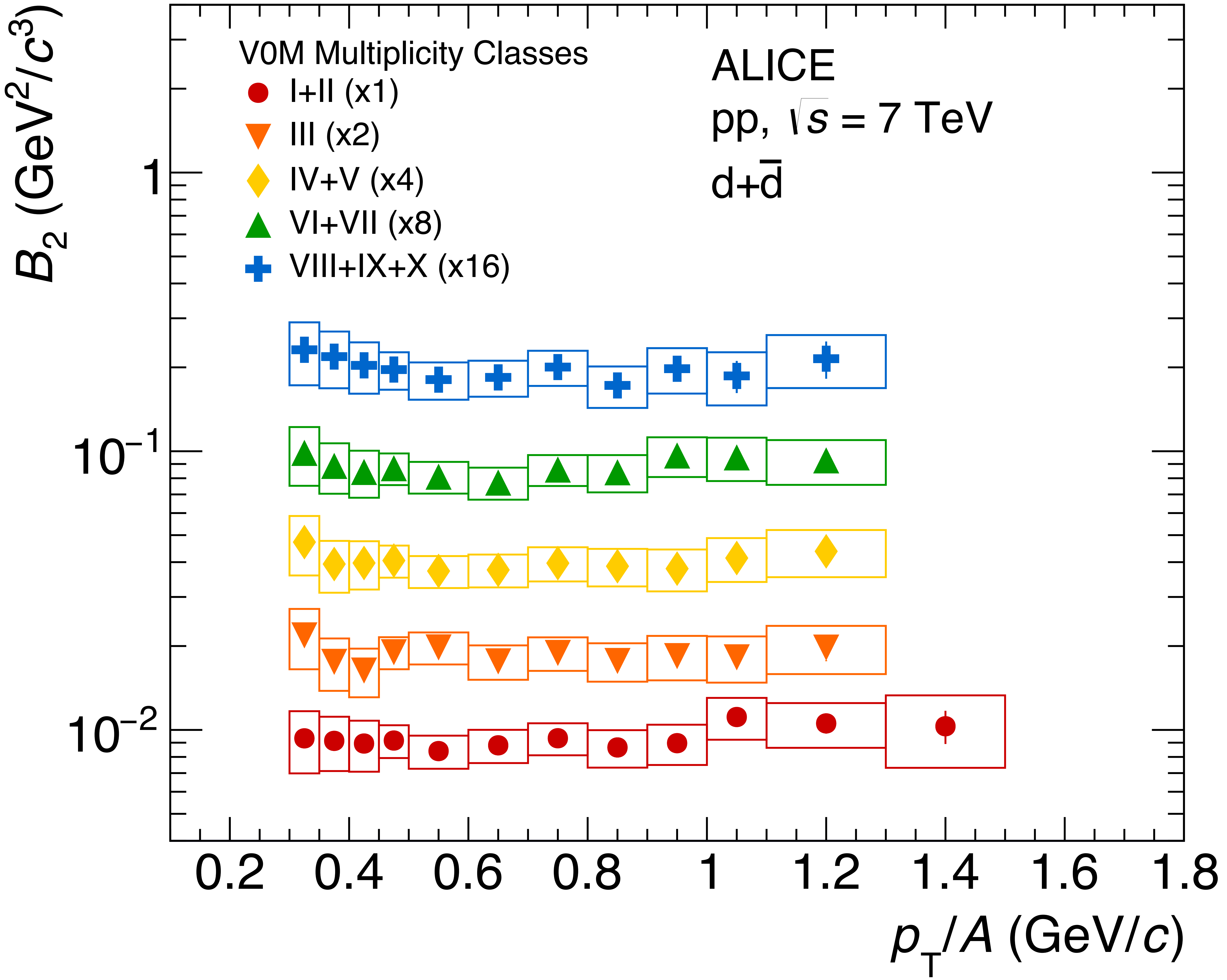


- Consequences:
  - B_A vs p_T is **flat**
- Applications:
  - **pp collisions**: small volume (comparable with nucleus size) → nucleons are alway close to each other



B_2 vs p_T in pp collisions

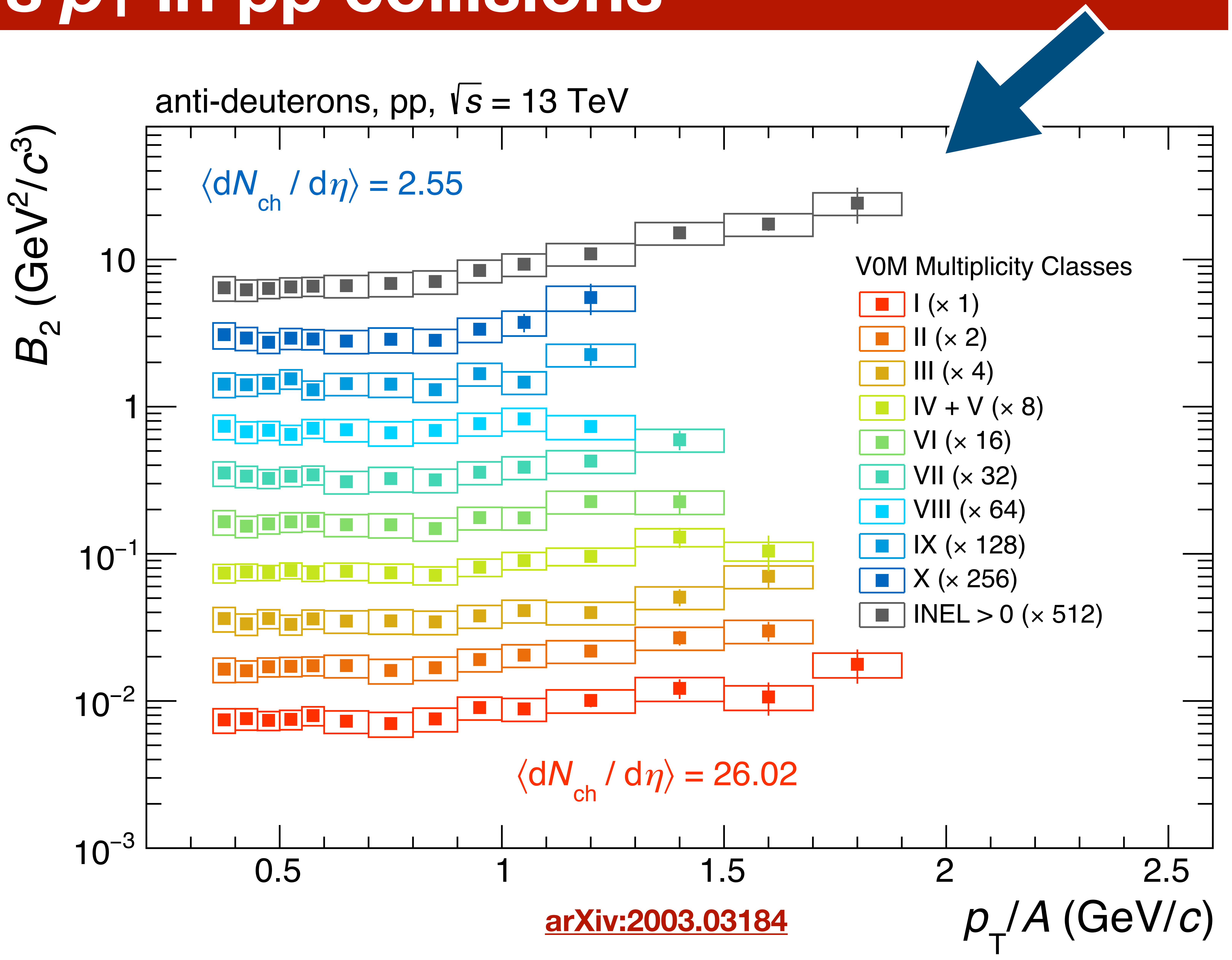
- B_2 vs p_T in **multiplicity** classes:
  - No significant deviations from a **flat** behaviour



10.1016/j.physletb.2019.05.028

B_2 vs p_T in pp collisions

- B_2 vs p_T in **multiplicity** classes:
  - No significant deviations from a **flat** behaviour
- B_2 vs p_T in **MB** analysis:
  - **raise** with p_T

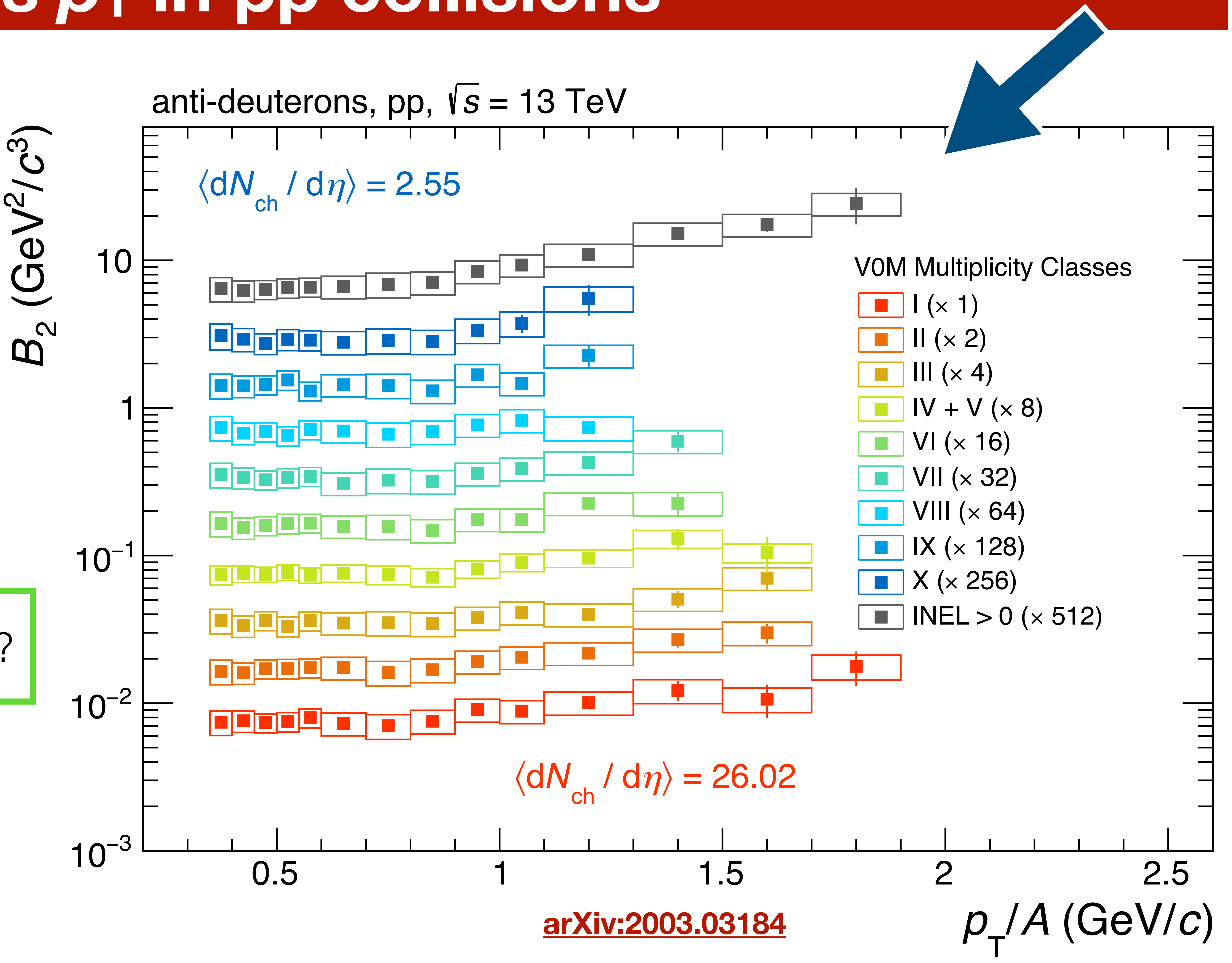


arXiv:2003.03184

B_2 vs p_T in pp collisions

- B_2 vs p_T in **multiplicity** classes:
  - No significant deviations from a **flat** behaviour
- B_2 vs p_T in **MB** analysis:
  - **raise** with p_T

Does it confutate simple coalescence?



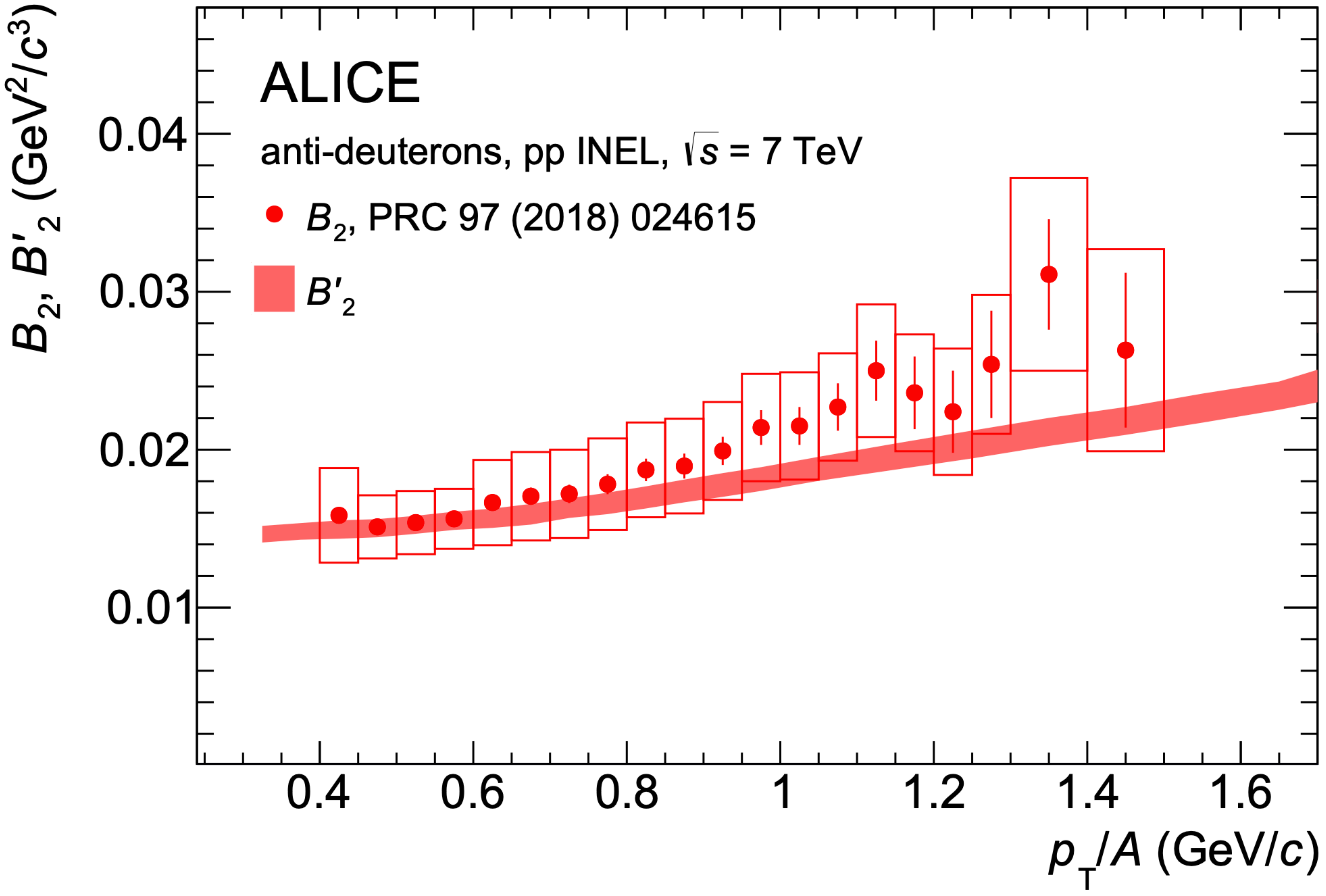
arXiv:2003.03184

B_2 vs B'_2

- An **increasing B'_2** can be obtained from a **flat B_2** in each **multiplicity** class

$$B'_2 = B_2 \frac{\sum_{i=0}^{n} (N_i/N)\, S_{p,i}^2}{\left[\sum_{i=0}^{n} (N_i/N)\, S_{p,i}\right]^2}$$

with $S_{d,i} = B_2\, S_{p,i}^2$



10.1016/j.physletb.2019.05.028

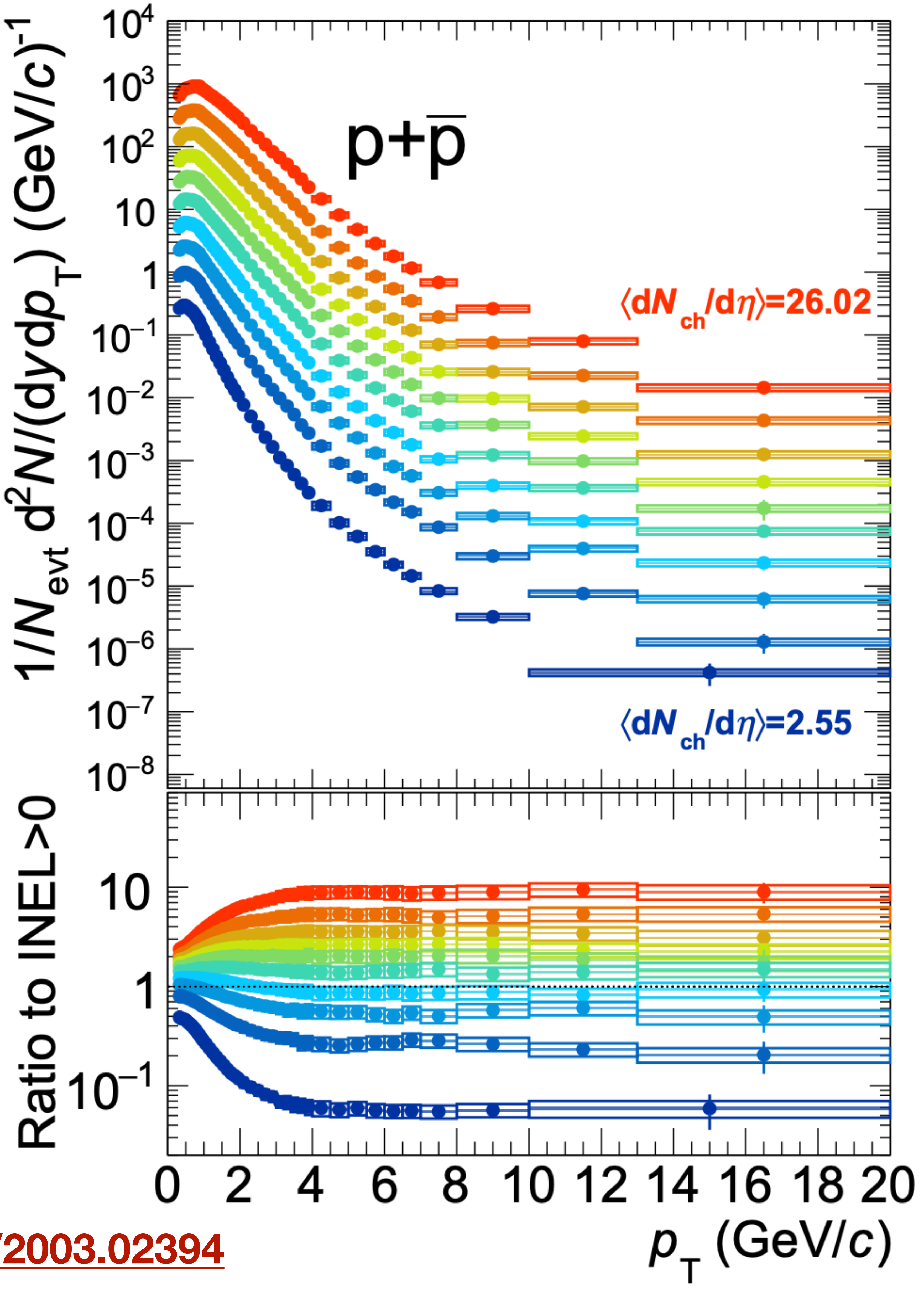
B_2 vs B'_2

- An **increasing B'_2** can be obtained from a **flat B_2** in each **multiplicity** class

$$B'_2 = B_2 \frac{\sum_{i=0}^{n} (N_i/N)\, S_{p,i}^2}{\left[\sum_{i=0}^{n} (N_i/N)\, S_{p,i}\right]^2}$$

with $S_{d,i} = B_2\, S_{p,i}^2$

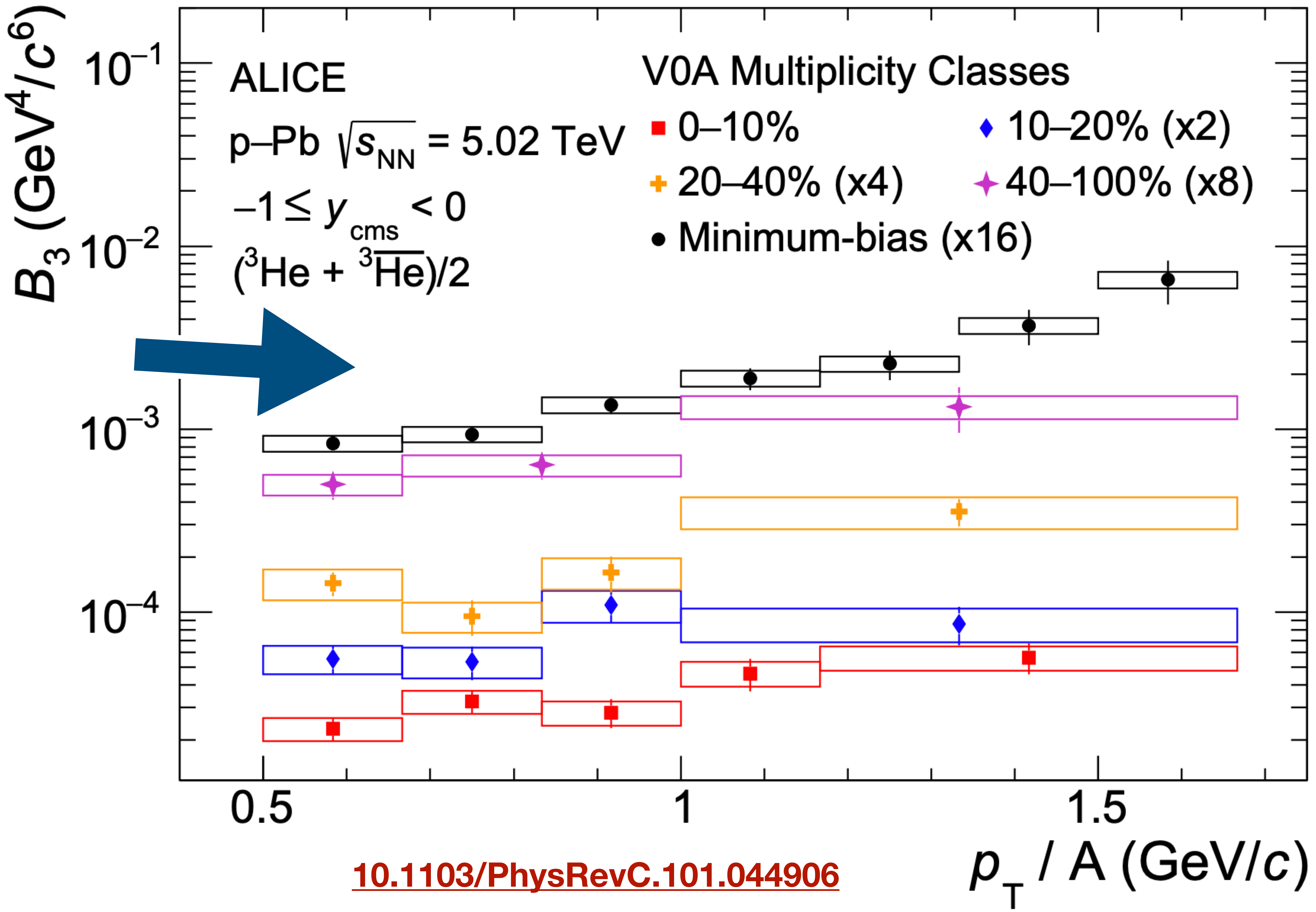
- Consequence of the **hardening** of the **proton spectra** with increasing multiplicity



arxiv.org/2003.02394

B_3 vs p_T in p-Pb collisions

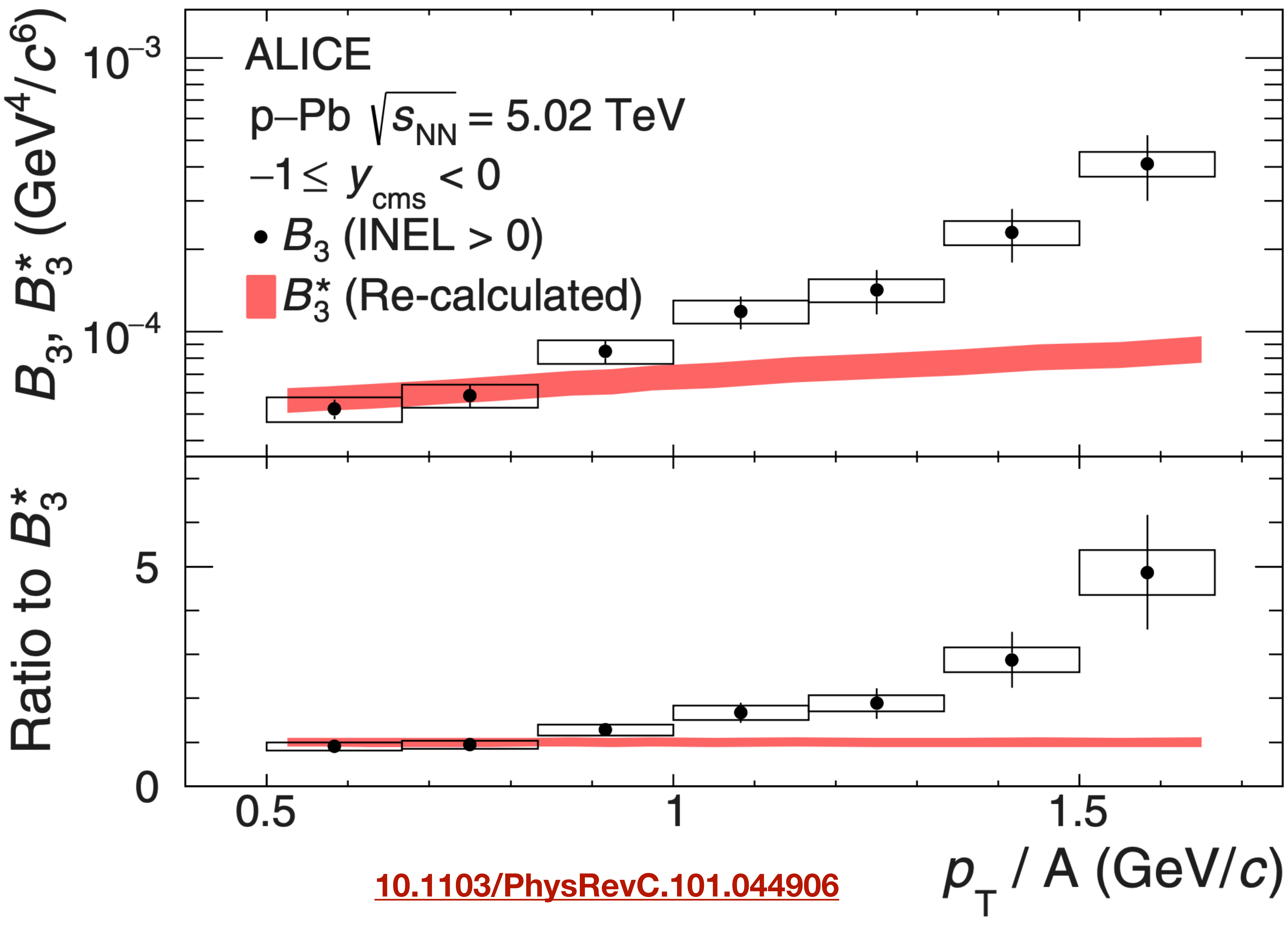
- B_3 vs p_T in **multiplicity** classes:
  - some **deviations** from a **flat** behaviour
  - system volume larger than pp
- B_3 vs p_T in **MB** analysis:
  - **stronger raise** with p_T than in multiplicity classes
- It is worthy to check B'_3 vs p_T



10.1103/PhysRevC.101.044906

B_3 vs B^*_3

- **B^*_3** can be calculated with the same approach used for B'_2
- The raise with p_T cannot be explained only changes in the shape of proton spectra
- Simple coalescence model (no volume dependence) **fails** to describe B_3 vs p_T

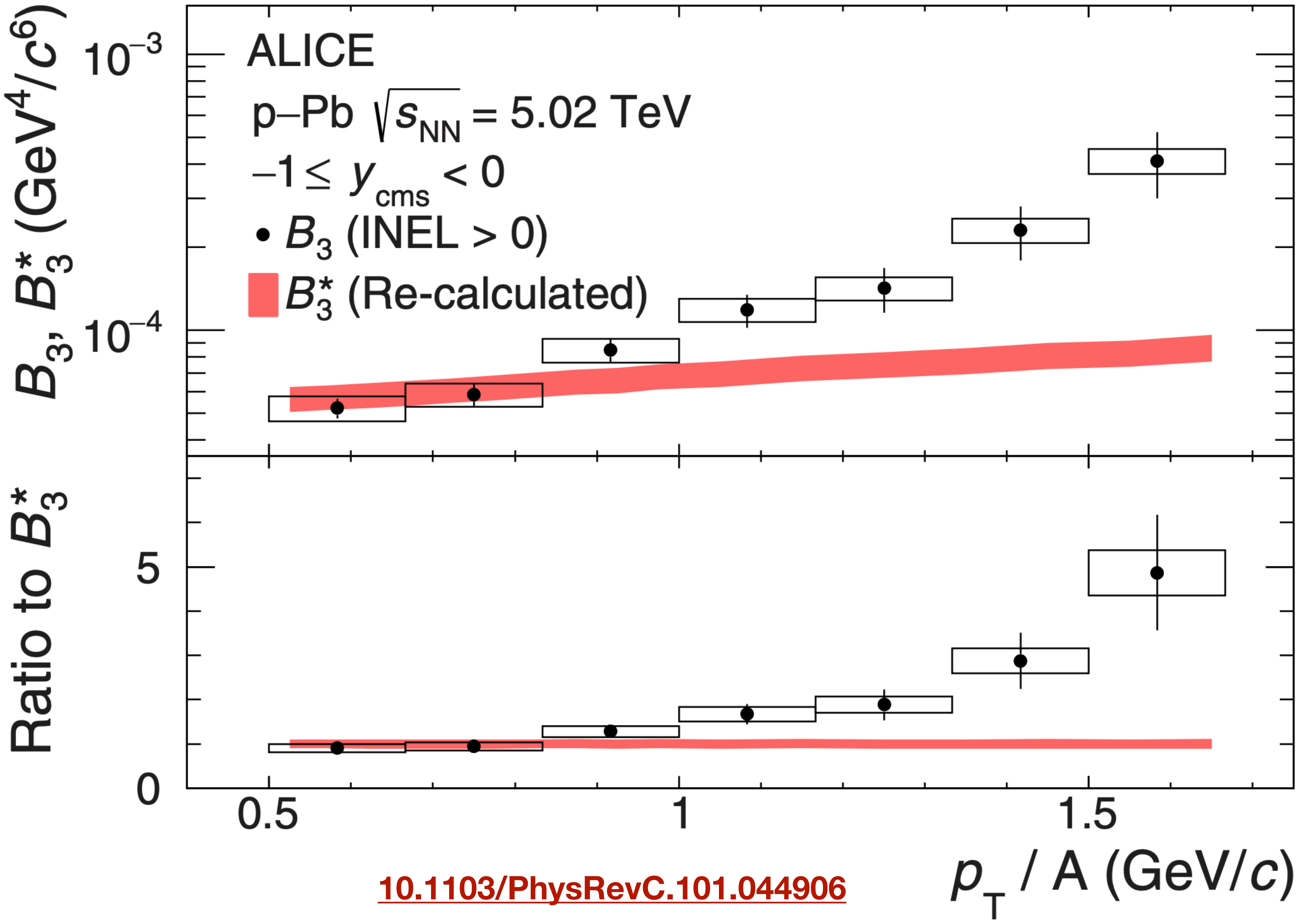


10.1103/PhysRevC.101.044906

B_3 vs B^*_3

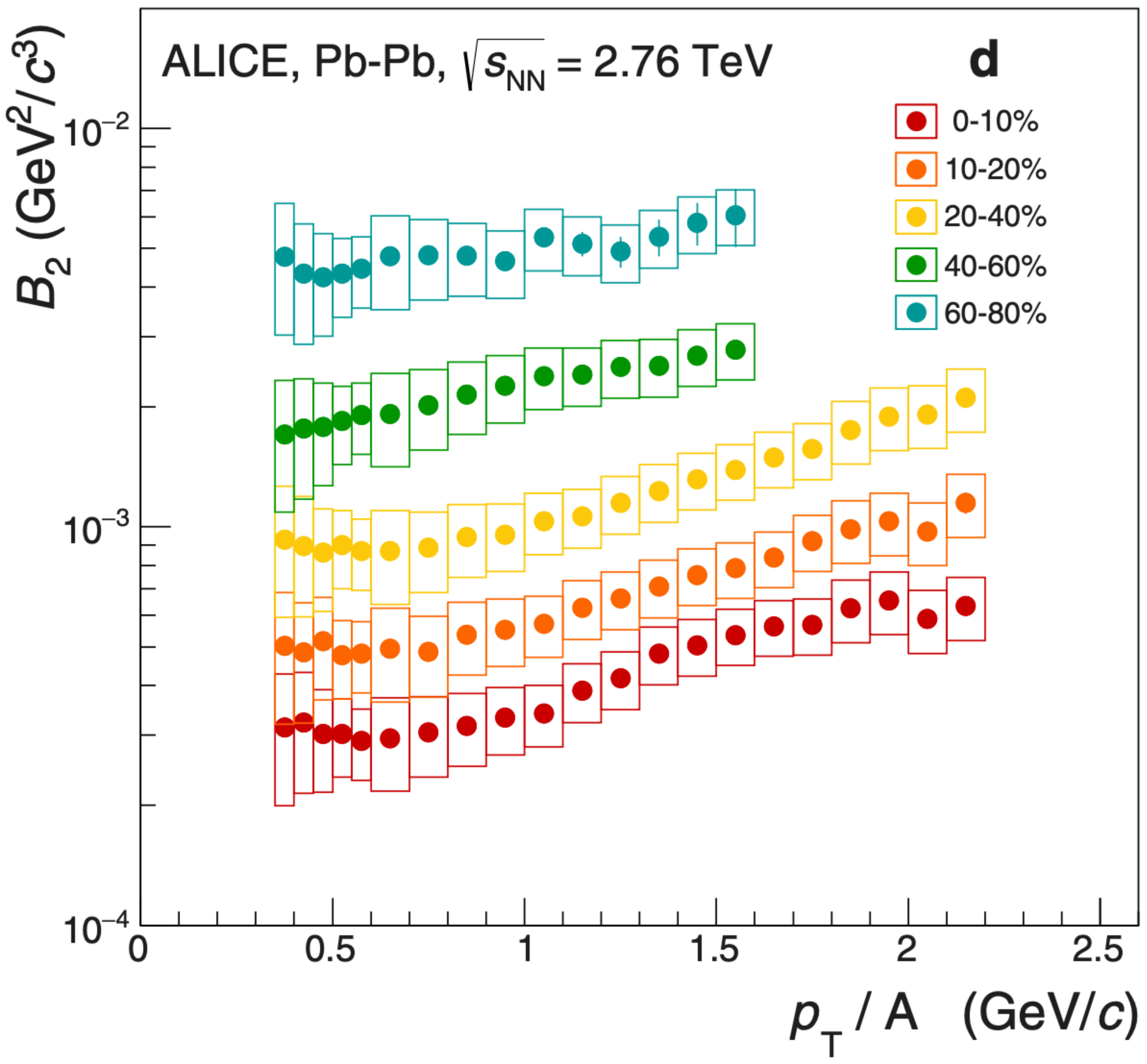
- **B^*_3** can be calculated with the same approach used for B'_2
- The raise with p_T cannot be explained only changes in the shape of proton spectra
- Simple coalescence model (no volume dependence) **fails** to describe B_3 vs p_T

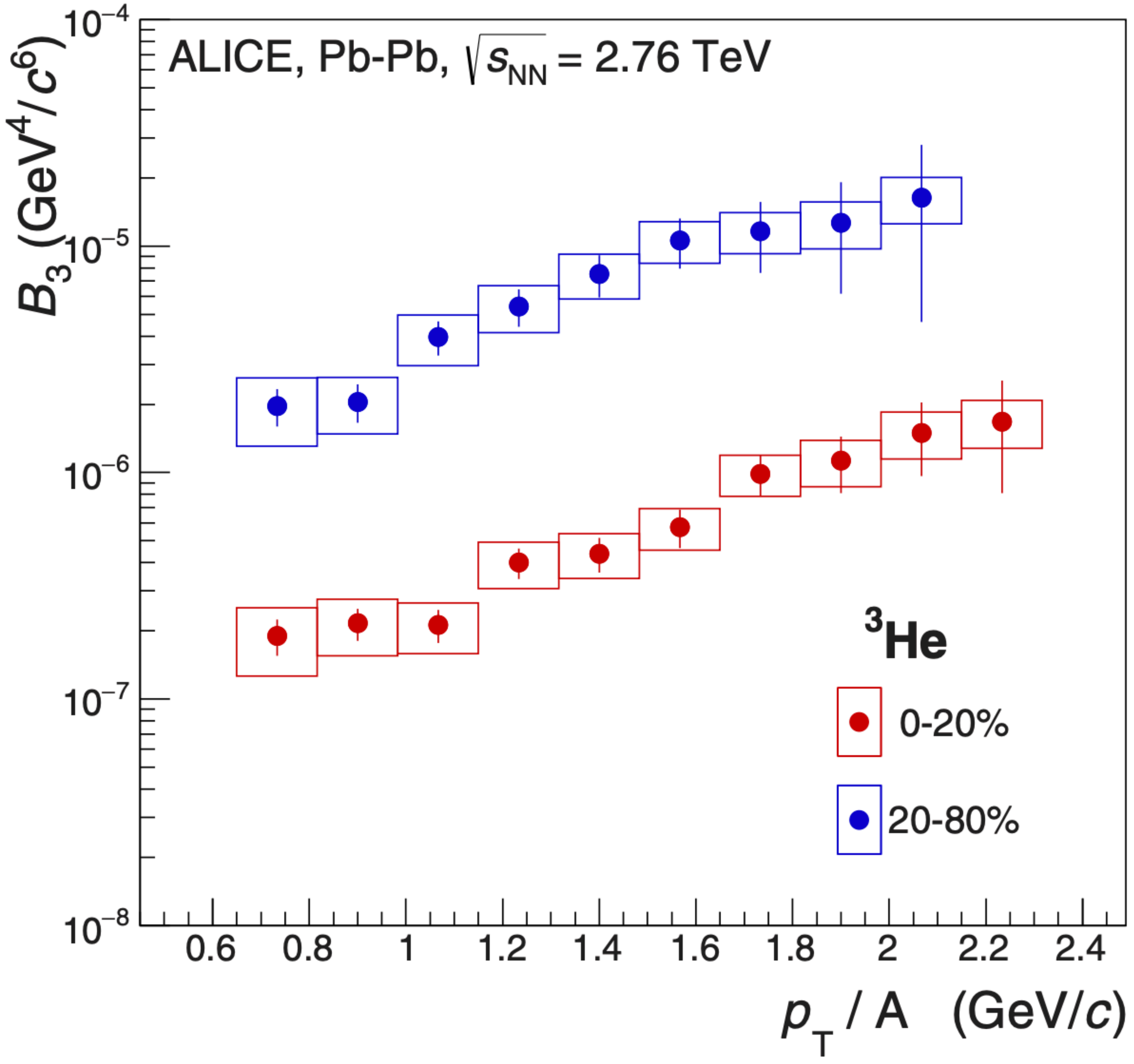
The system size must be taken into account



10.1103/PhysRevC.101.044906

B_A in Pb-Pb collisions





- The raise with p_T is even larger in Pb-Pb collisions

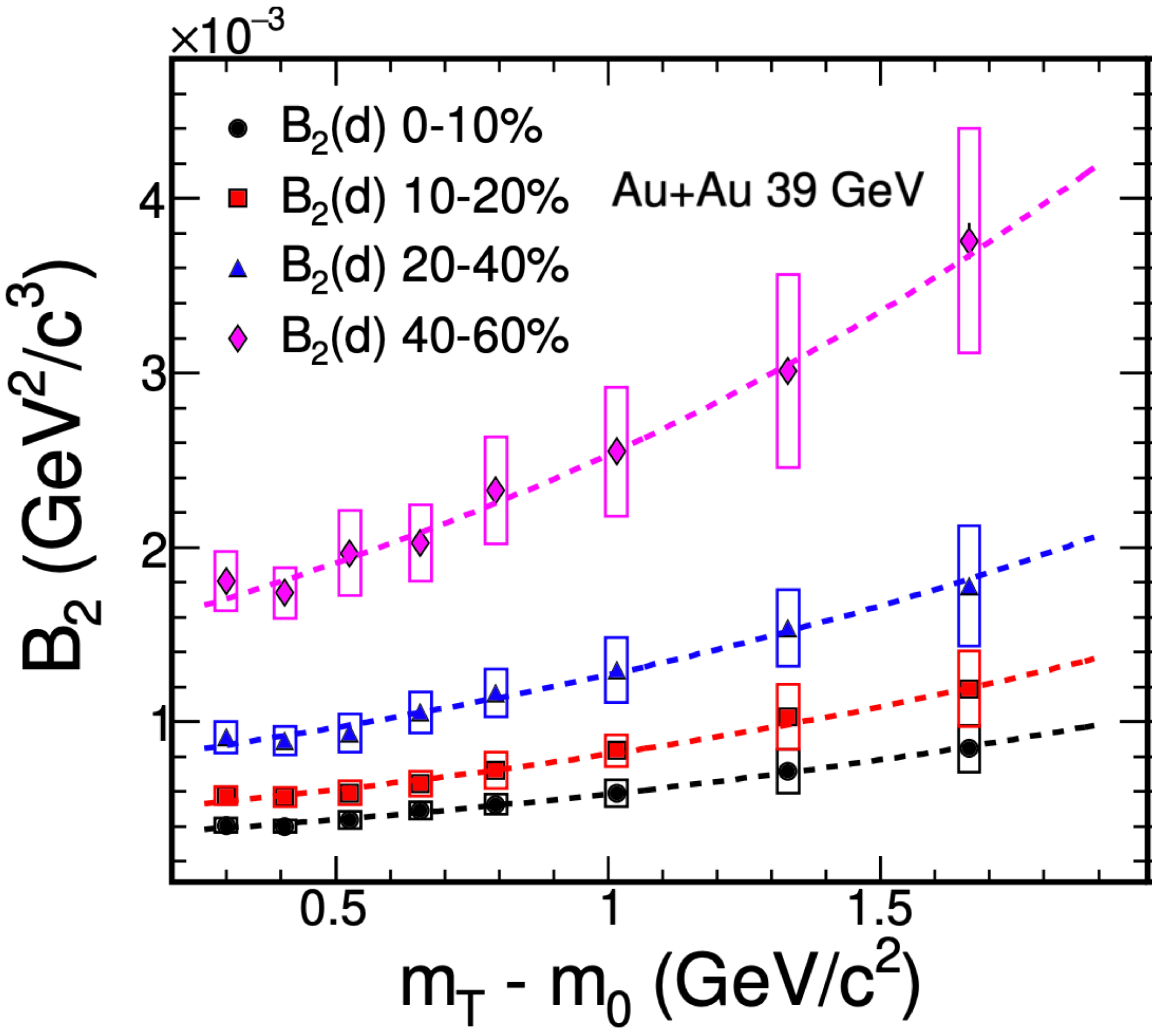
10.1103/PhysRevC.93.024917

Simple coalescence with V

- In simple coalescence model[1]:

$$\frac{4\pi}{3}p_0^3 \leftrightarrow \frac{1}{V} \implies B_A \propto V^{1-A}$$

- V_{HBT} depends on m_T
  - Qualitative description of B_2 vs m_T



10.1103/PhysRevC.99.064905

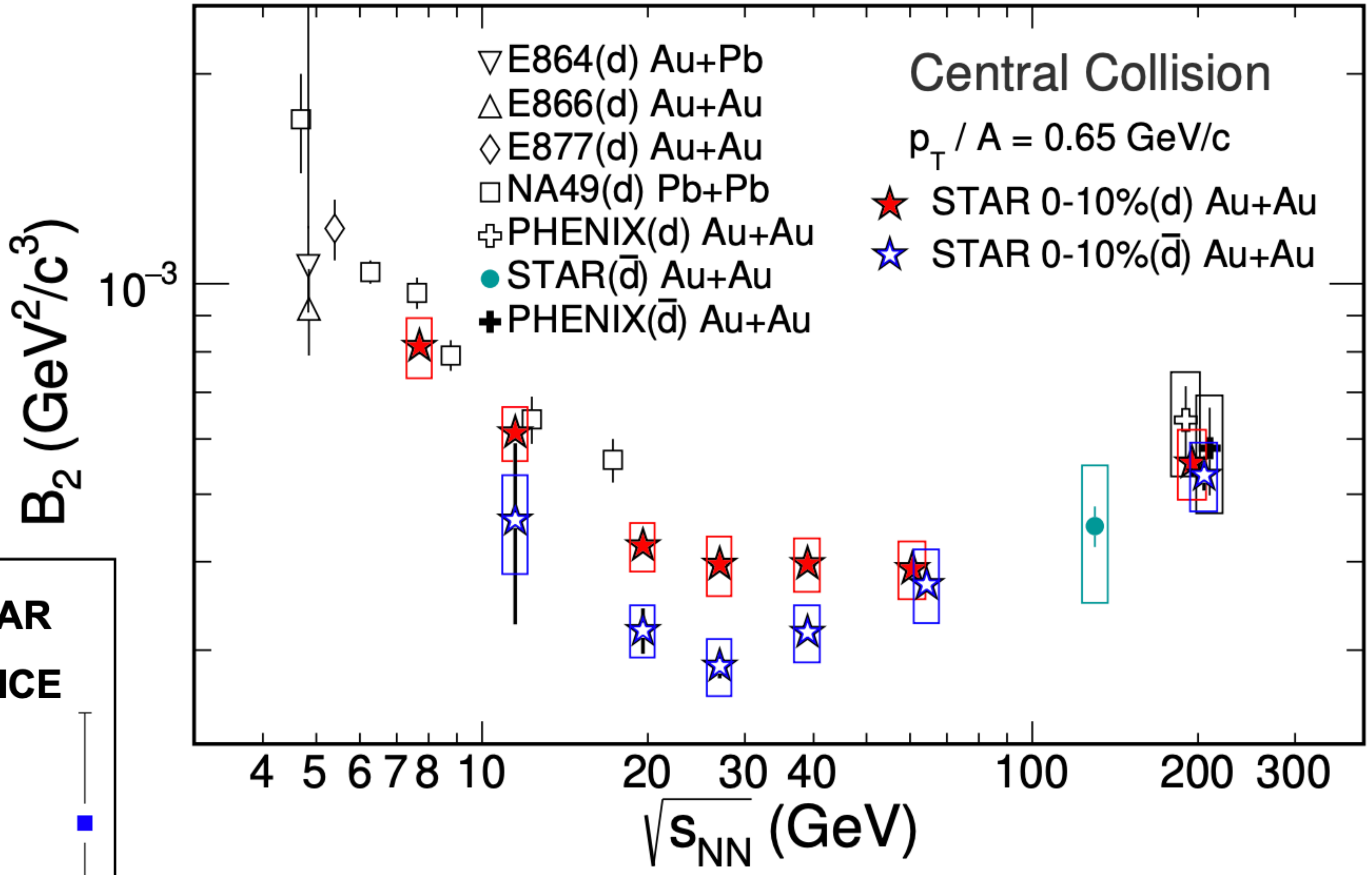
[1] 10.1016/0370-1573(86)90031-1

Simple coalescence with V

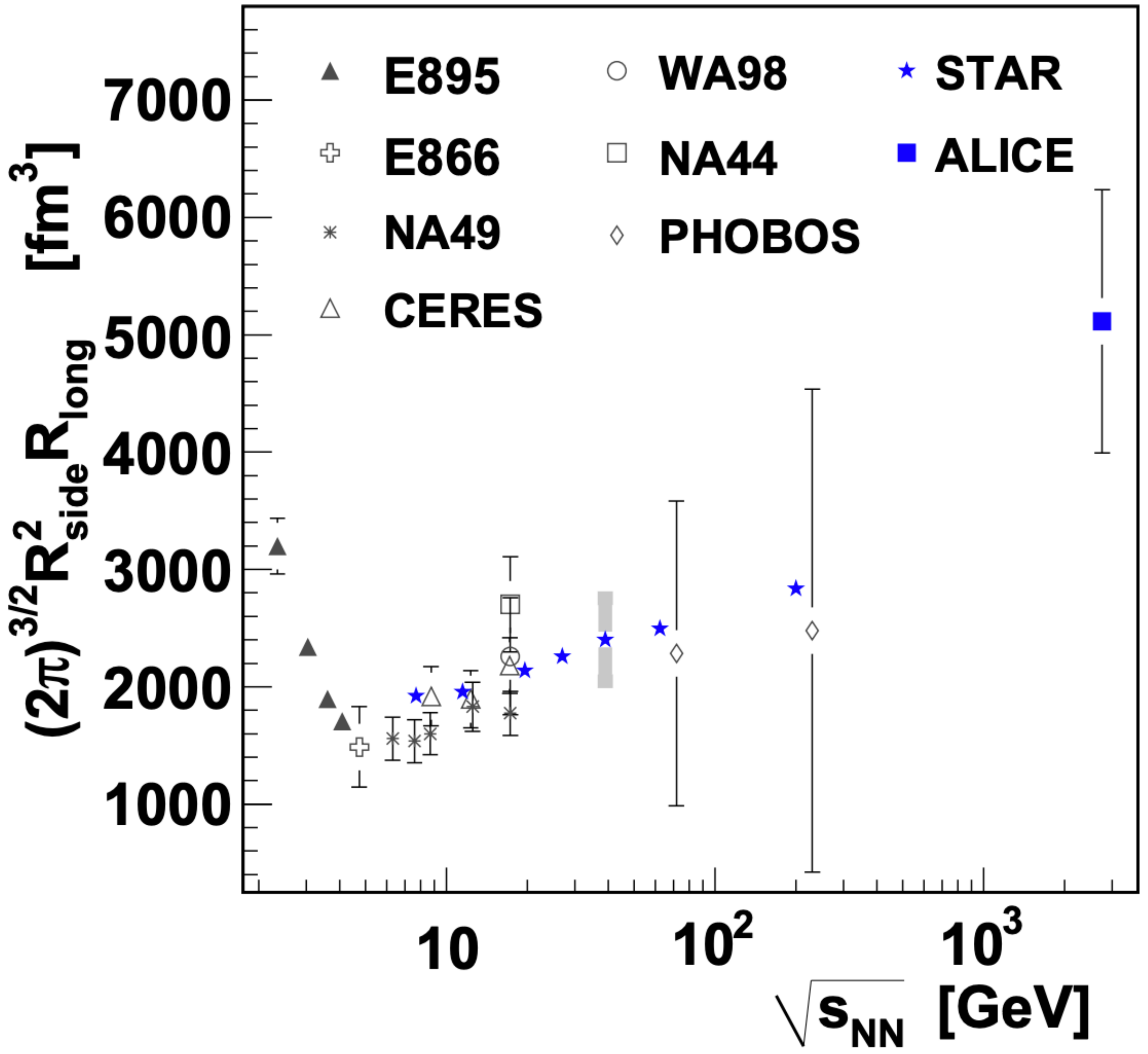
- In simple coalescence model[1]:

$$\frac{4\pi}{3}p_0^3 \leftrightarrow \frac{1}{V} \implies B_A \propto V^{1-A}$$

- V_{HBT} depends on m_T
  - Qualitative description of B_2 vs m_T
- B_2 vs $\sqrt{s_{NN}}$ not described



10.1103/PhysRevC.99.064905



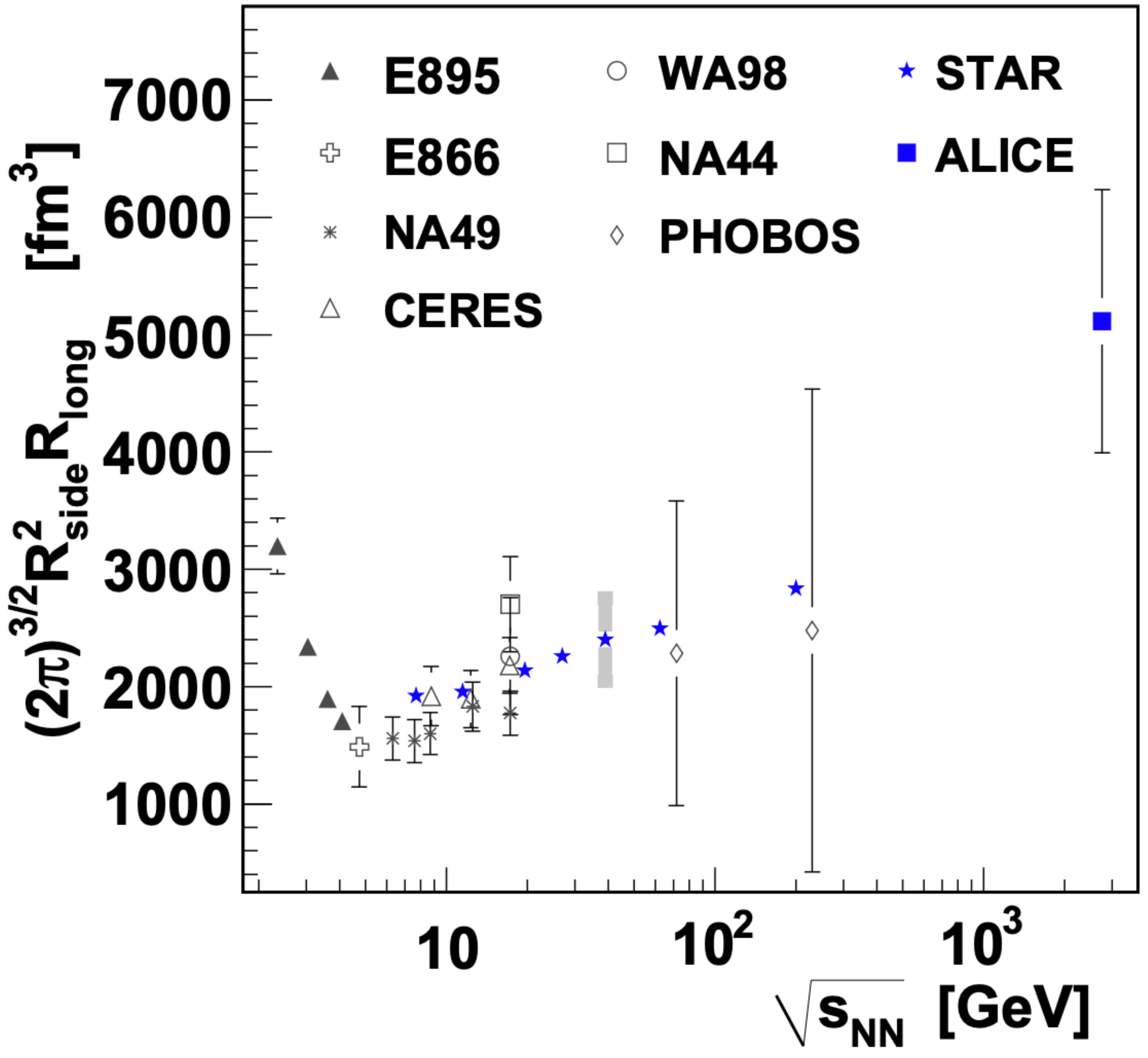
10.1103/PhysRevC.92.014904

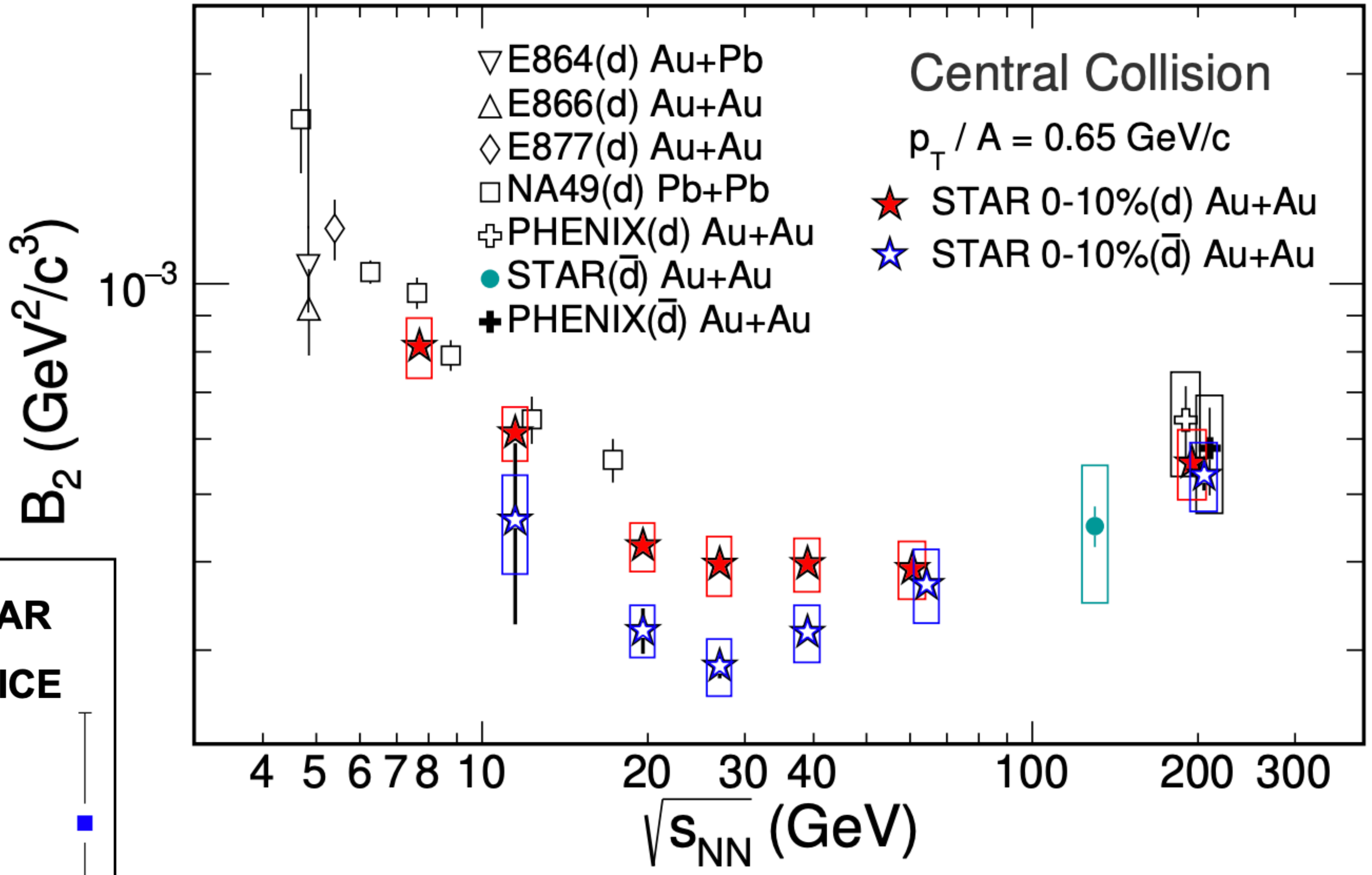
Simple coalescence with V

- In simple coalescence model[1]:

$$\frac{4\pi}{3}p_0^3 \leftrightarrow \frac{1}{V} \implies B_A \propto V^{1-A}$$

- V_{HBT} depends on m_T
    - Qualitative description of B_2 vs m_T
- B_2 vs $\sqrt{s_{NN}}$ not described





10.1103/PhysRevC.99.064905

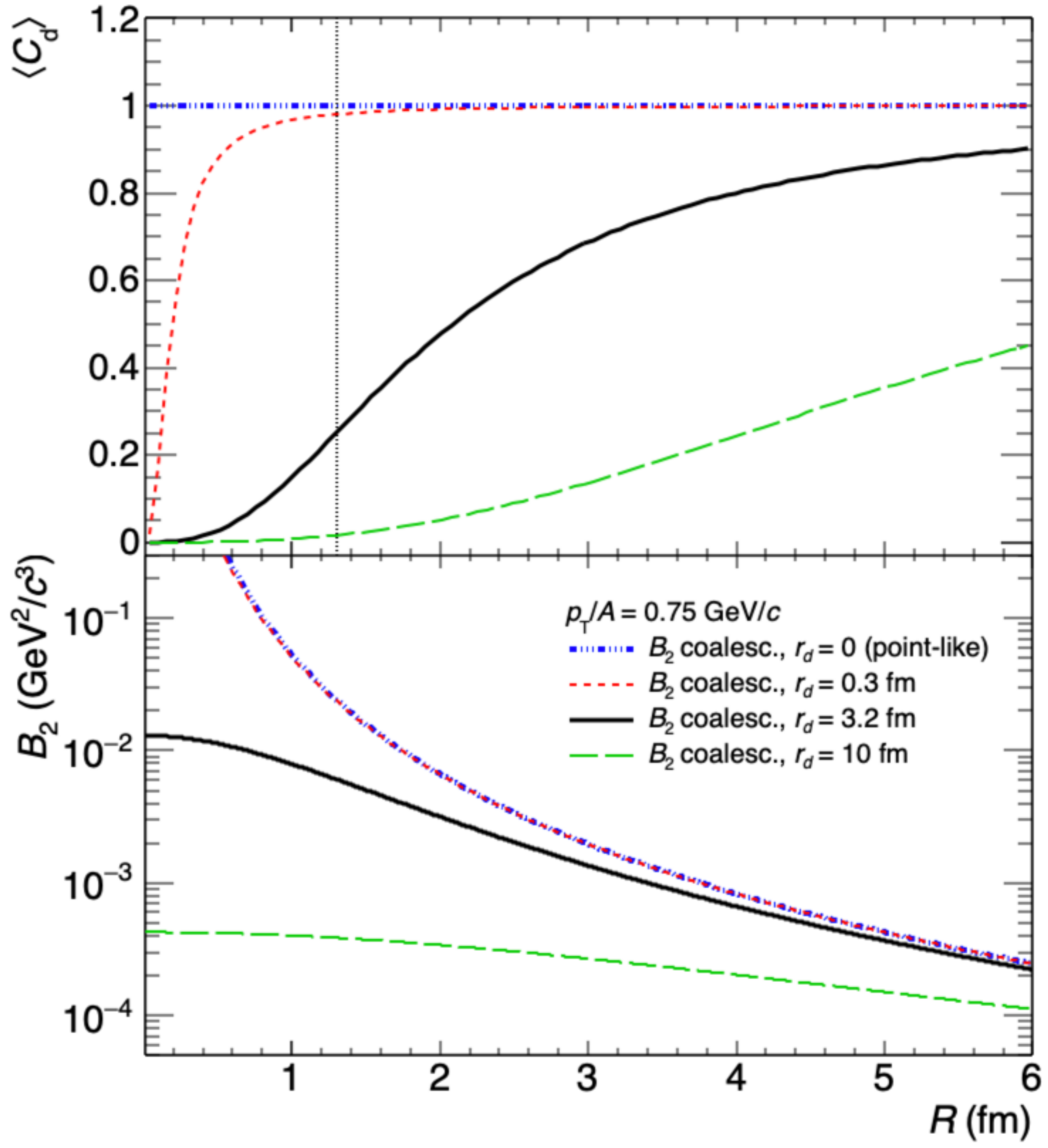
10.1103/PhysRevC.92.014904

More advanced implementations of the coalescence model are needed

An advanced coalescence model

- **Space-time** distribution considered
  - **overlap** between **nucleus wave-function** (Wigner formalism) and **nucleon phase-space distribution**
- Evolution with the system size **R**
- Dependence on the $\boldsymbol{p_T}$

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

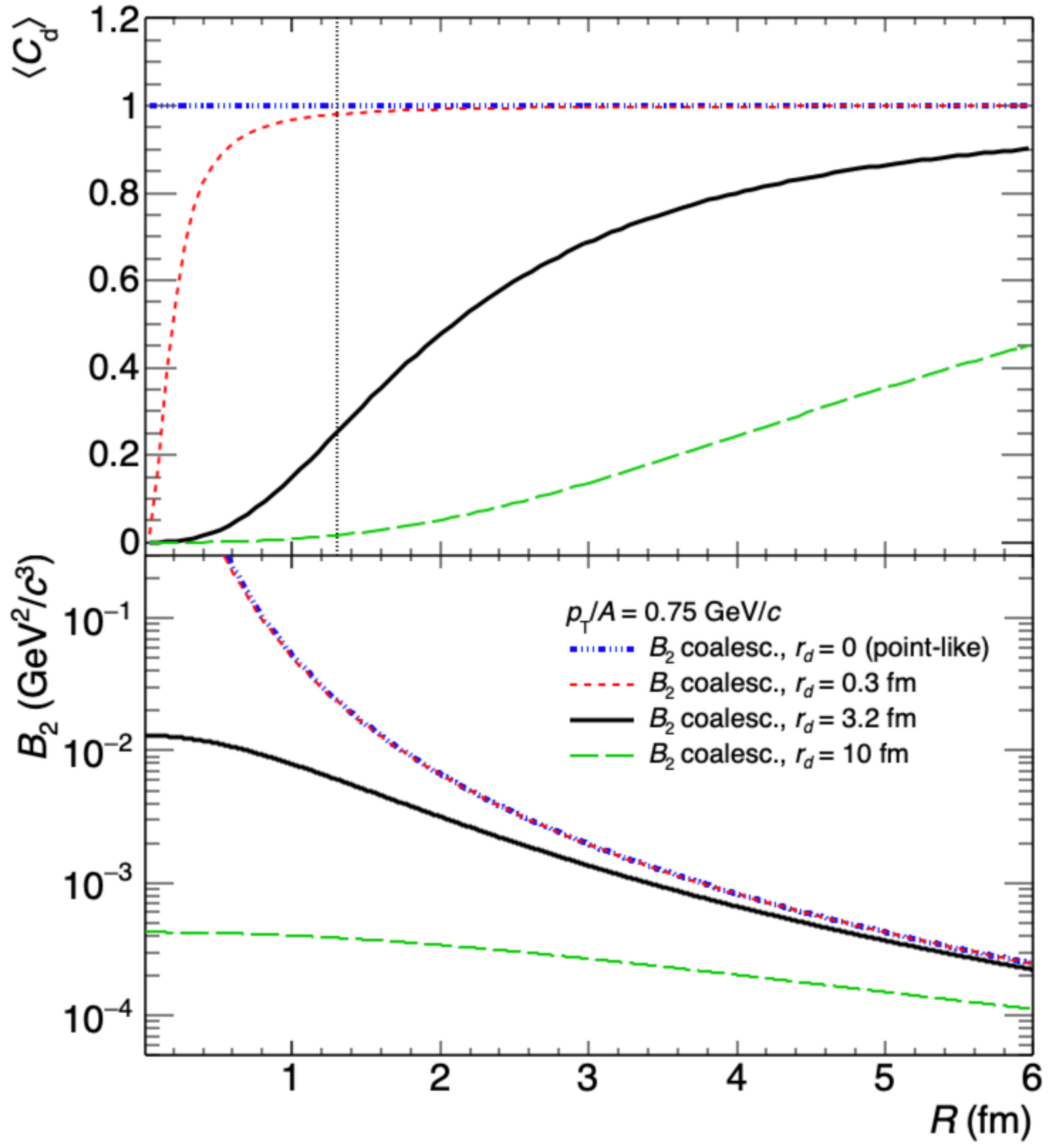


10.1103/PhysRevC.99.054905

An advanced coalescence model

- **Space-time** distribution considered
  - **overlap** between **nucleus wave-function** (Wigner formalism) and **nucleon phase-space distribution**
- Evolution with the system size **R**
- Dependence on the $\boldsymbol{p_T}$

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



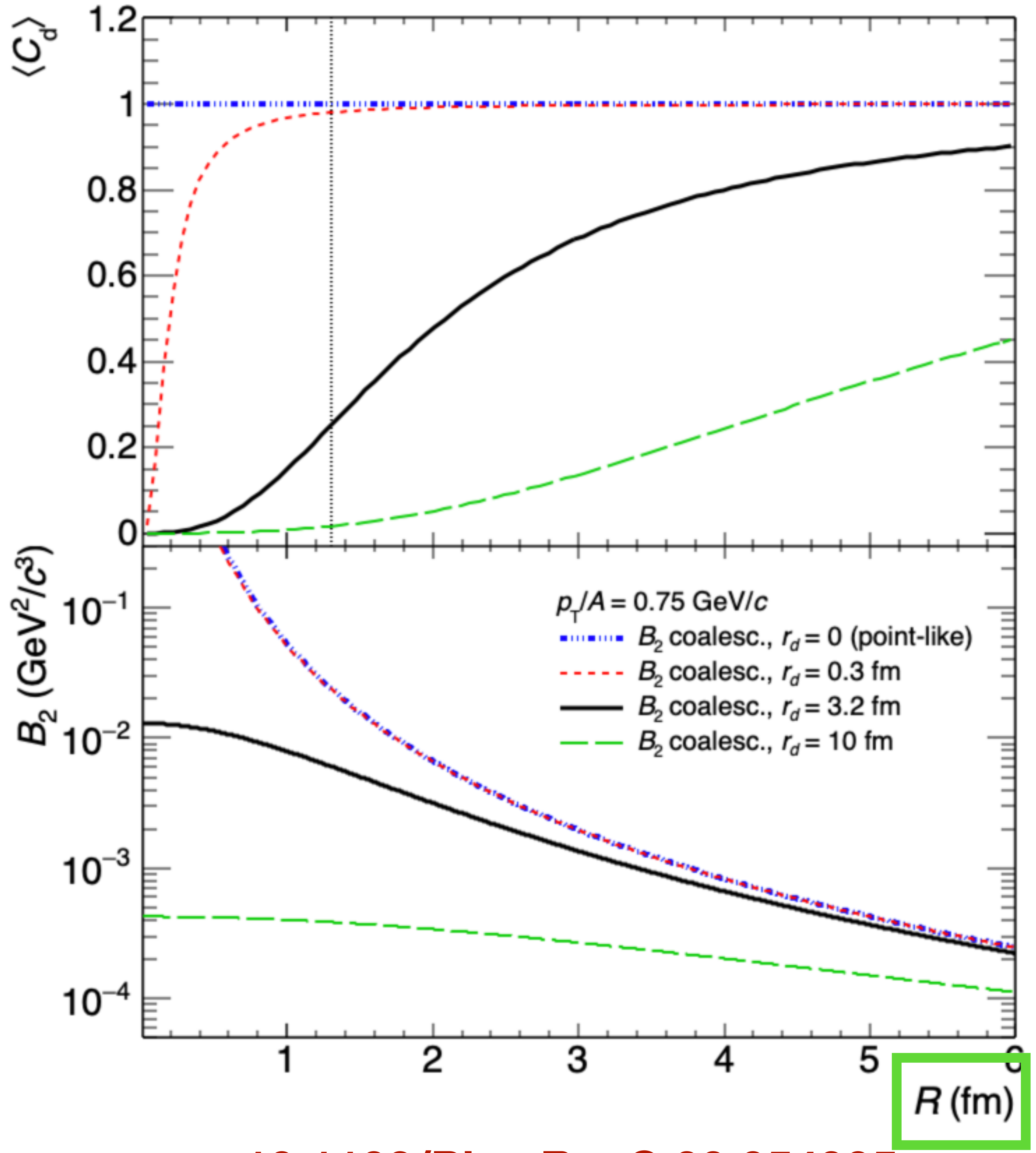
10.1103/PhysRevC.99.054905

An advanced coalescence model

- **Space-time** distribution considered
  - **overlap** between **nucleus wave-function** (Wigner formalism) and **nucleon phase-space distribution**
- Evolution with the system size **R**
- Dependence on the $\boldsymbol{p_T}$

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

How to express system size?



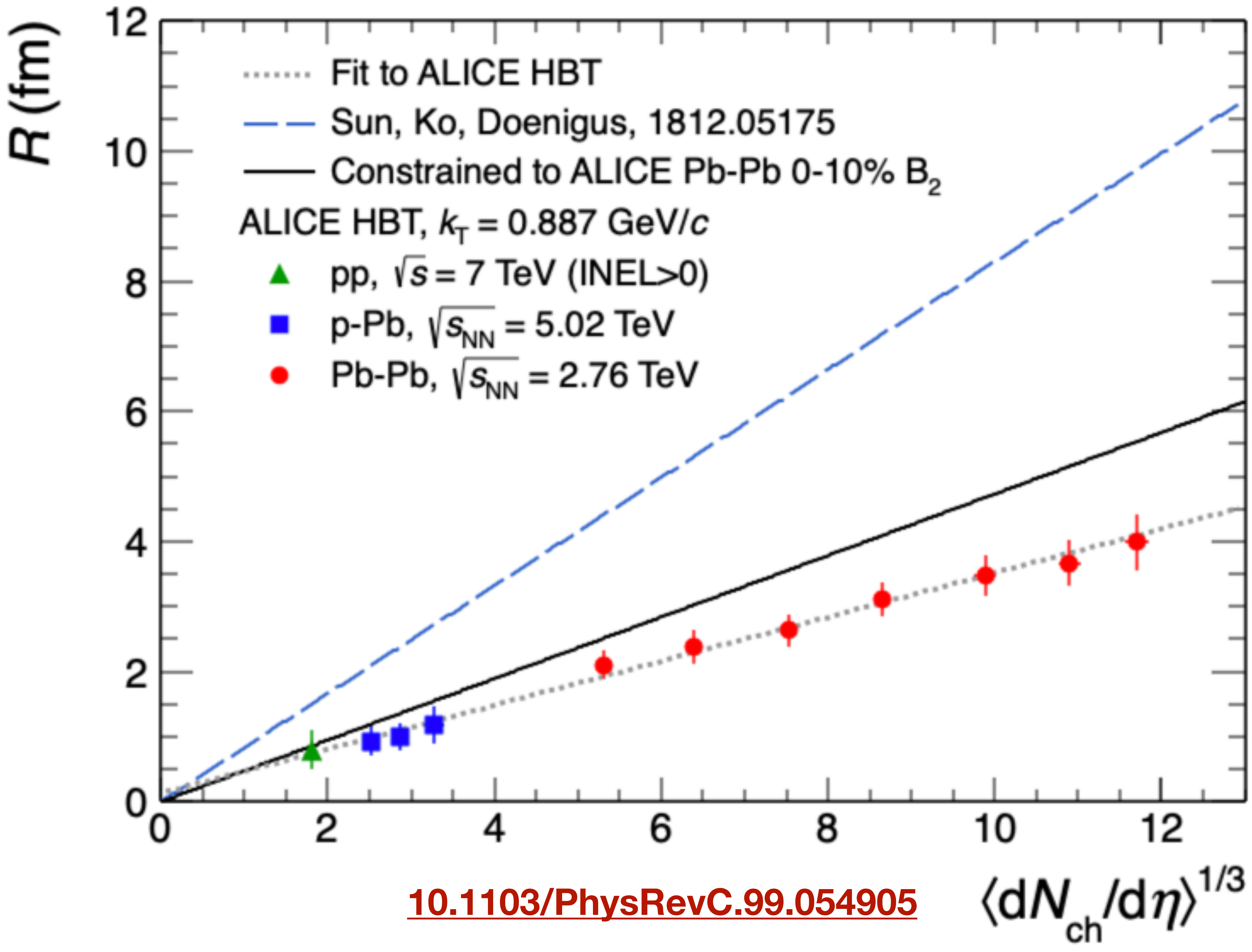
10.1103/PhysRevC.99.054905

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:

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

- Different arguments:
  - **10.1016/j.physletb.2019.03.033** from model parameters (N_p, T_K)



10.1103/PhysRevC.99.054905

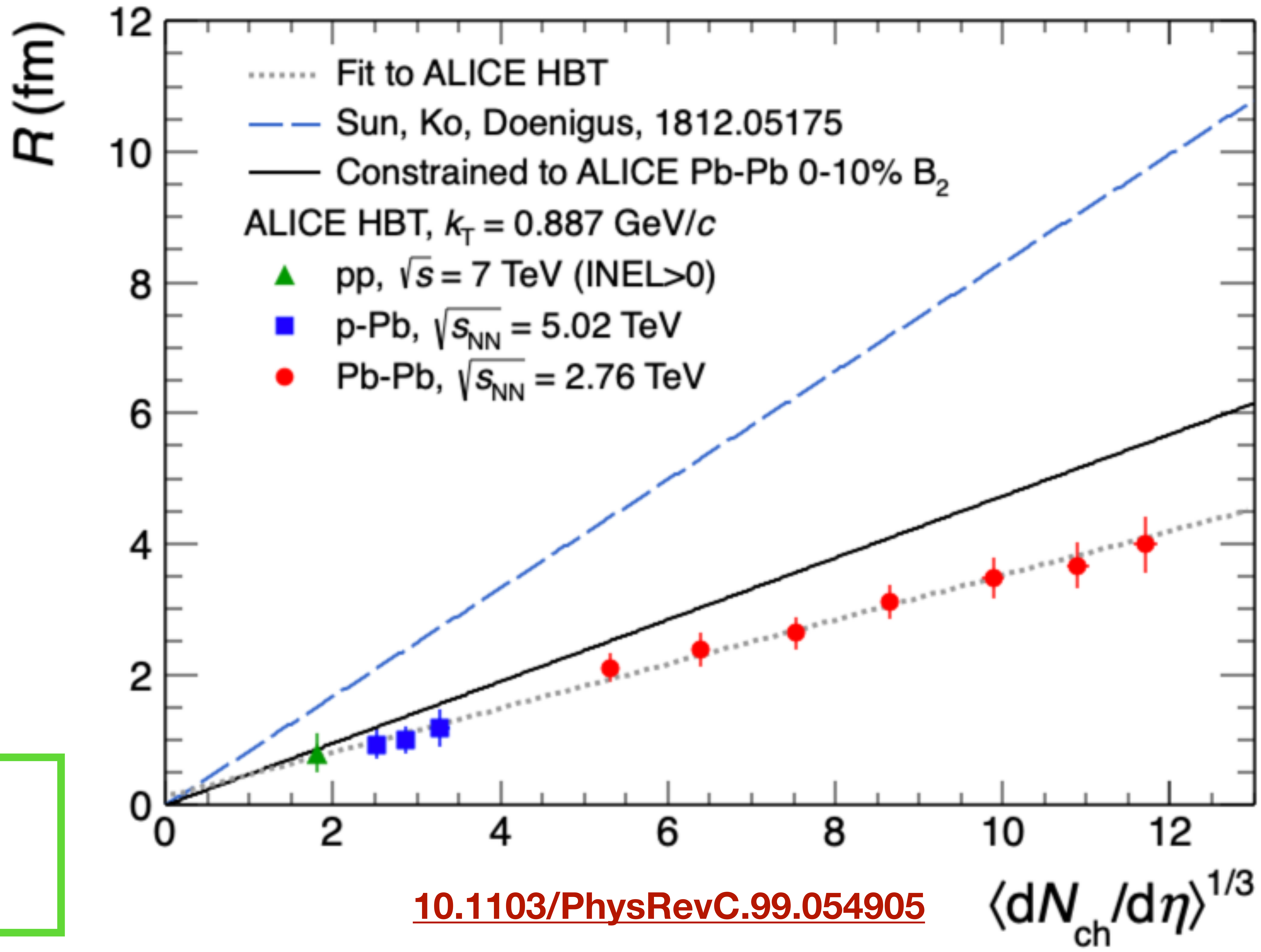
Charged particle multiplicity

- 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:

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

- Different arguments:
  - **10.1016/j.physletb.2019.03.033** from model parameters (N_p, T_K)

The parameterisation of R plays a crucial role in the predictions



10.1103/PhysRevC.99.054905

B_A vs multiplicity

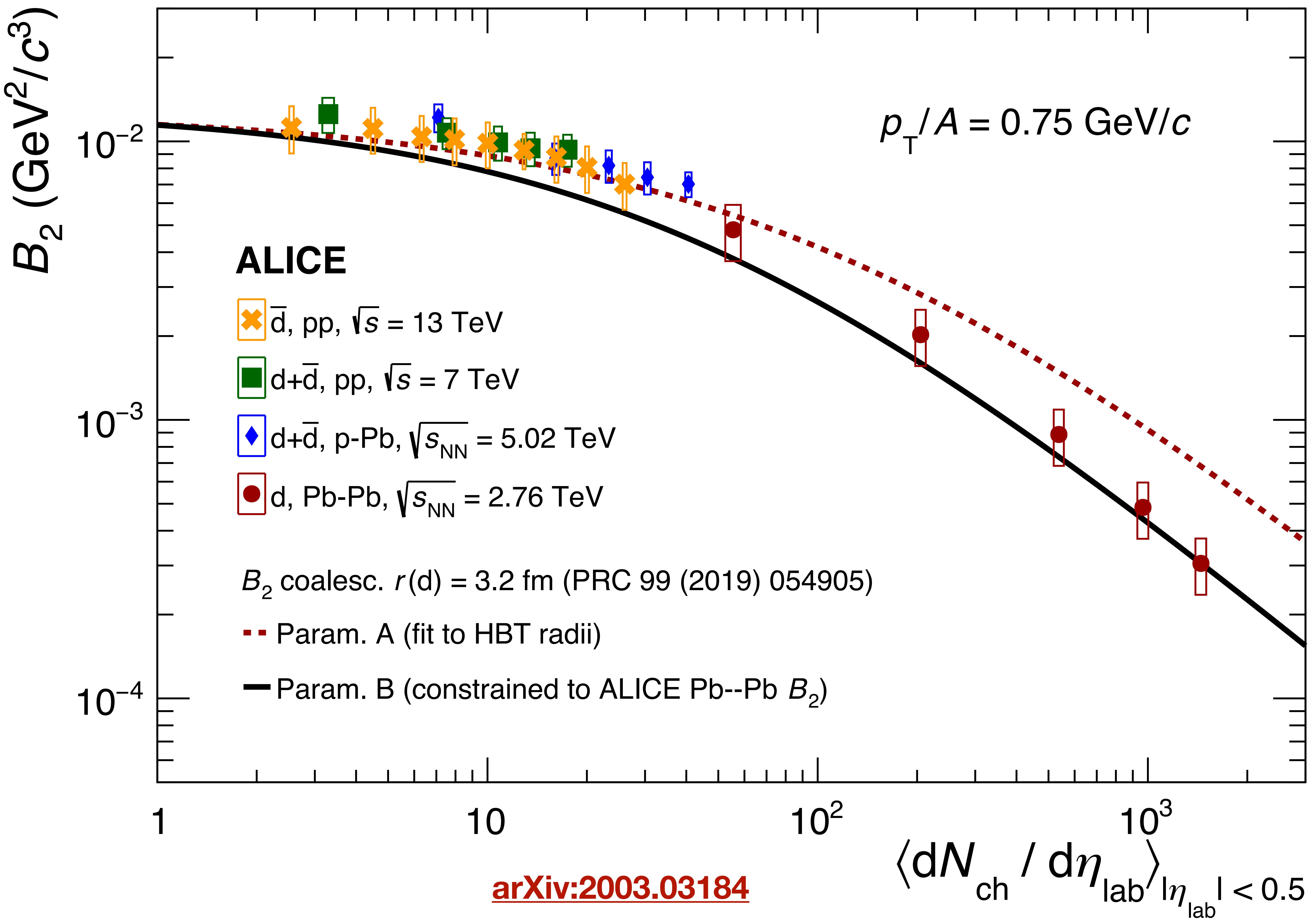
- **B_2** evolves **smoothly** with the **multiplicity**
- Two parameterisations:

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

A. *a* and *b* taken from a **fit** of R vs multiplicity

B. *a* and *b* are **fixed** to reproduce B_2 in 0-10% Pb-Pb

- Neither of the two reproduces B_2 over the full range



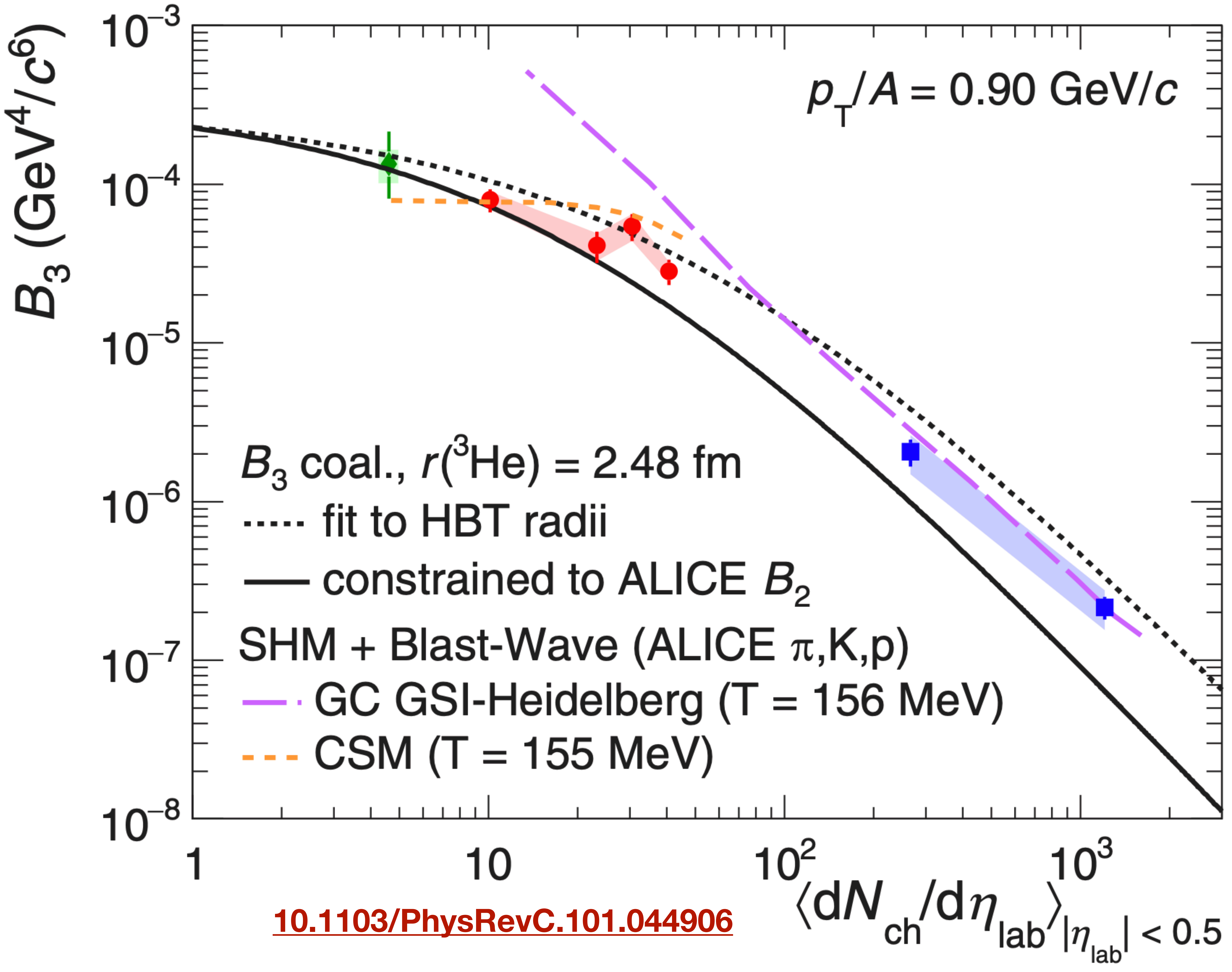
arXiv:2003.03184

B_A vs multiplicity

- **B_2** evolves **smoothly** with the **multiplicity**
- Two parameterisations:

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

  - **A.** *a* and *b* taken from a **fit** of R vs multiplicity
  - **B.** *a* and *b* are **fixed** to reproduce B_2 in 0-10% Pb-Pb
- Neither of the two reproduces B_2 over the full range
- Same for **B_3**



10.1103/PhysRevC.101.044906

B_A vs multiplicity

- B_2 evolves **smoothly** with the **multiplicity**
- Two parameterisations:

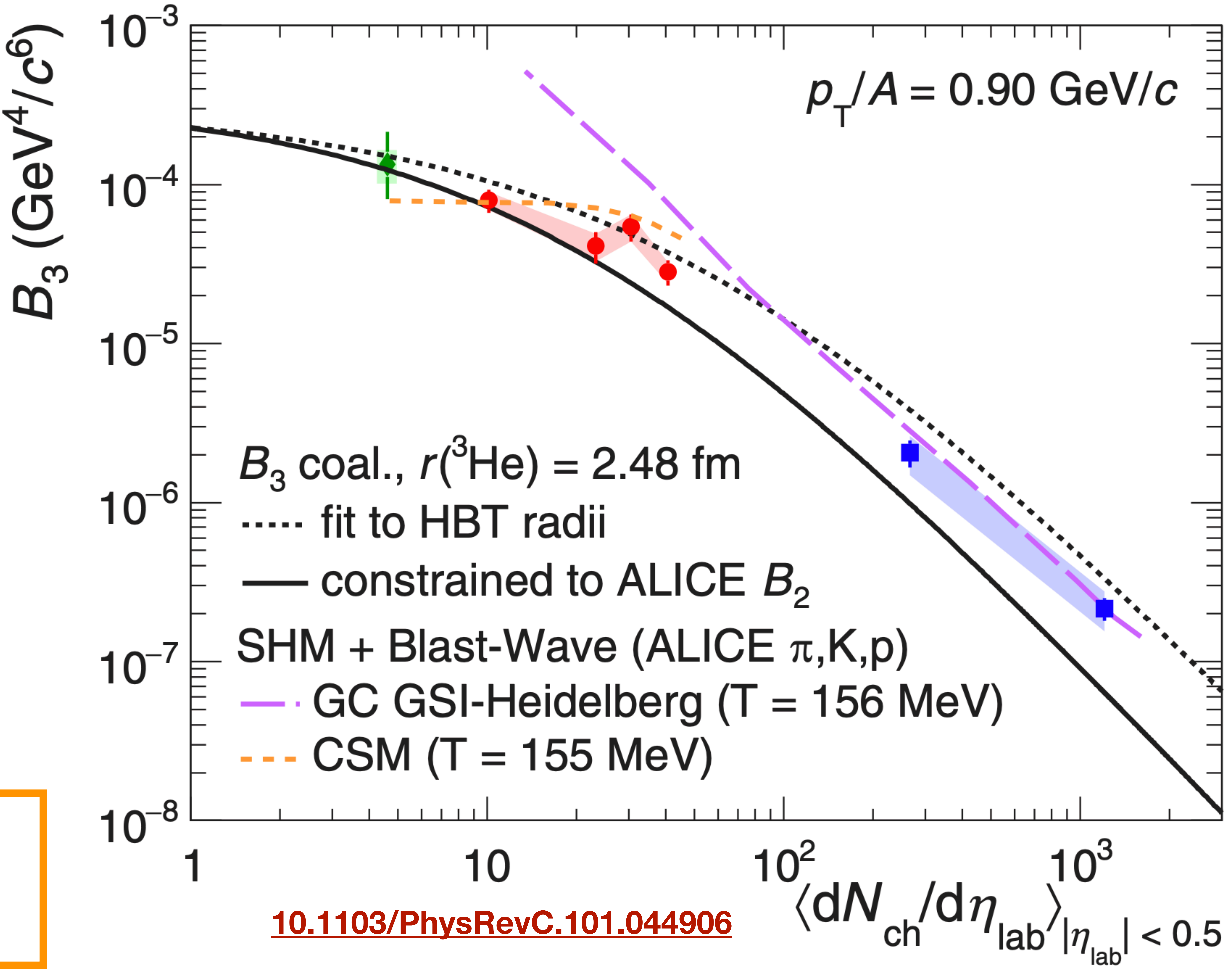
$$R = a \langle \mathrm{d}N/\mathrm{d}\eta \rangle^{1/3} + b$$

  A. *a* and *b* taken from a **fit** of R vs multiplicity

  B. *a* and *b* are **fixed** to reproduce B_2 in 0-10% Pb-Pb

- Neither of the two reproduces B_2 over the full range
- Same for B_3

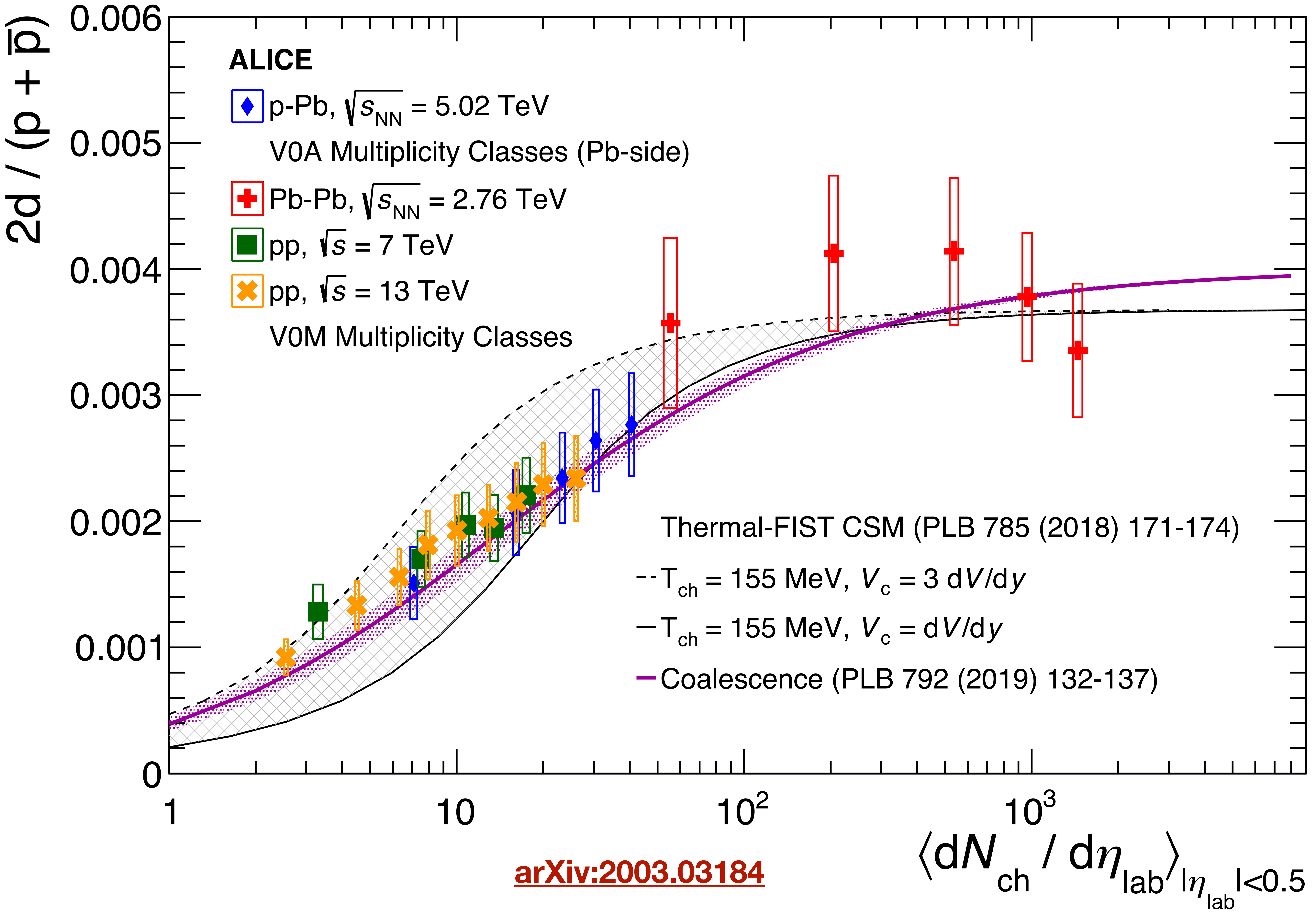
Is a new parameterisation of R needed?



10.1103/PhysRevC.101.044906

A/p vs multiplicity

- Smooth evolution of A/p with multiplicity
- Coalescence can explain well **d/p** over the **full range** of multiplicity

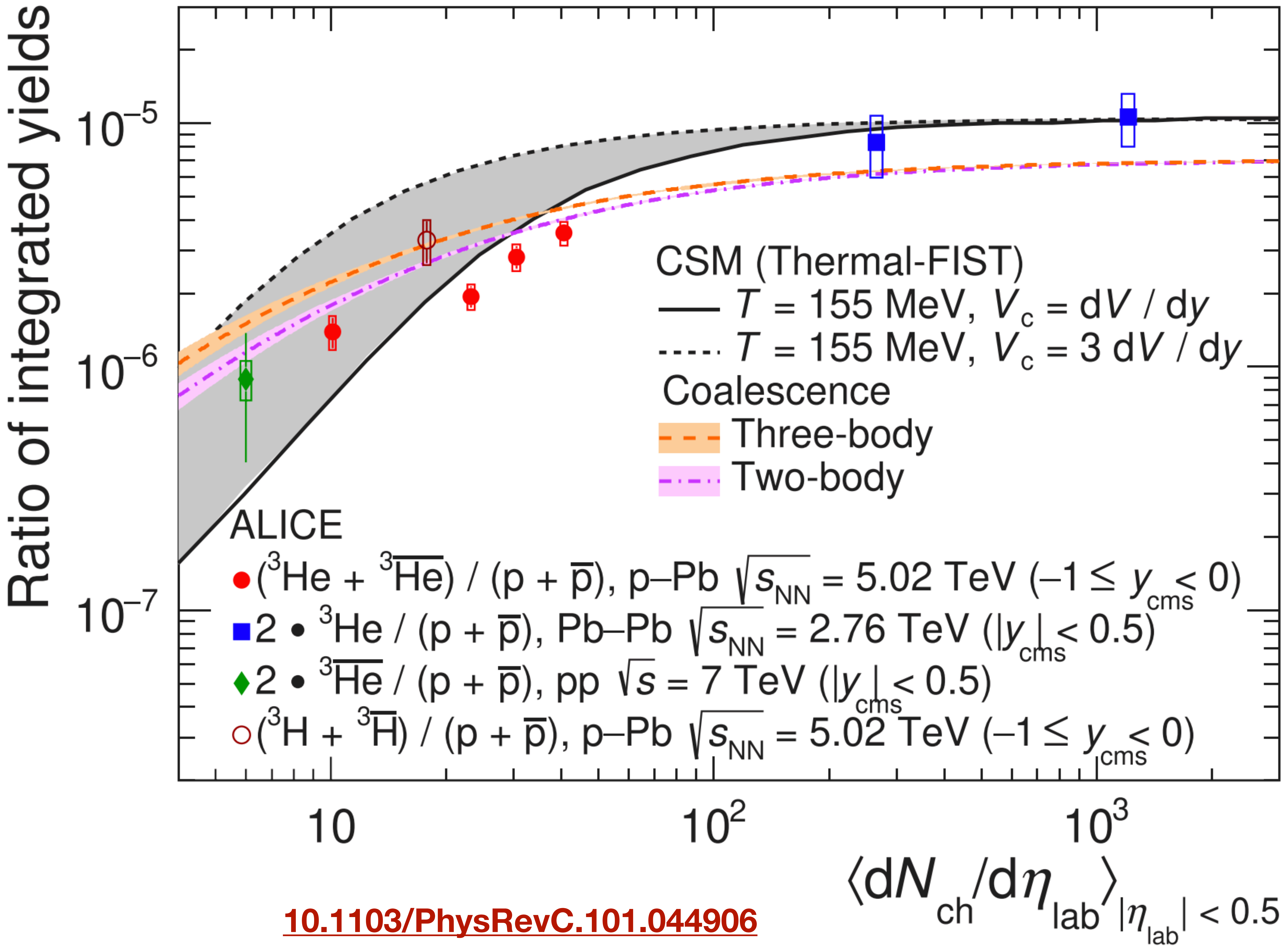


arXiv:2003.03184

A/p vs multiplicity

- Smooth evolution of A/p with multiplicity
- Coalescence can explain well **d/p** over the **full range** of multiplicity
- Coalescence does not describe **^{3}He/p**

Coalescence struggles for A > 2

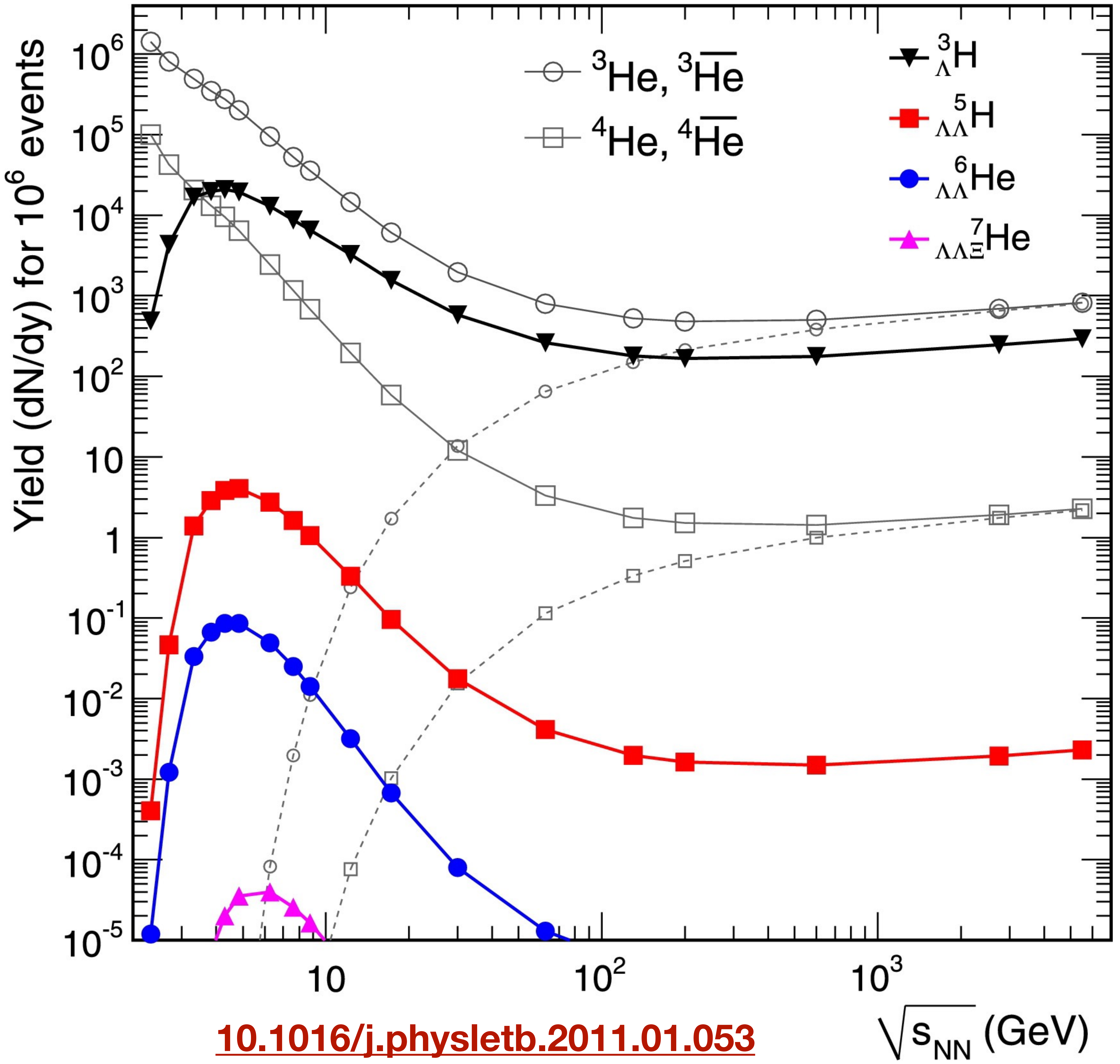


10.1103/PhysRevC.101.044906

The Statistical hadronisation model (SHM)

- Hadron abundances from **statistical equilibrium** at the **chemical freeze-out**
- Large reaction volume ($VT^3 > 1$) in HIC
  - **grand canonical ensemble**
- Successful in describing hadron yields in different collision systems and energies
  - reproduces also nuclei
- Chemical freeze-out temperature (**T_{ch}**) is a key parameter:

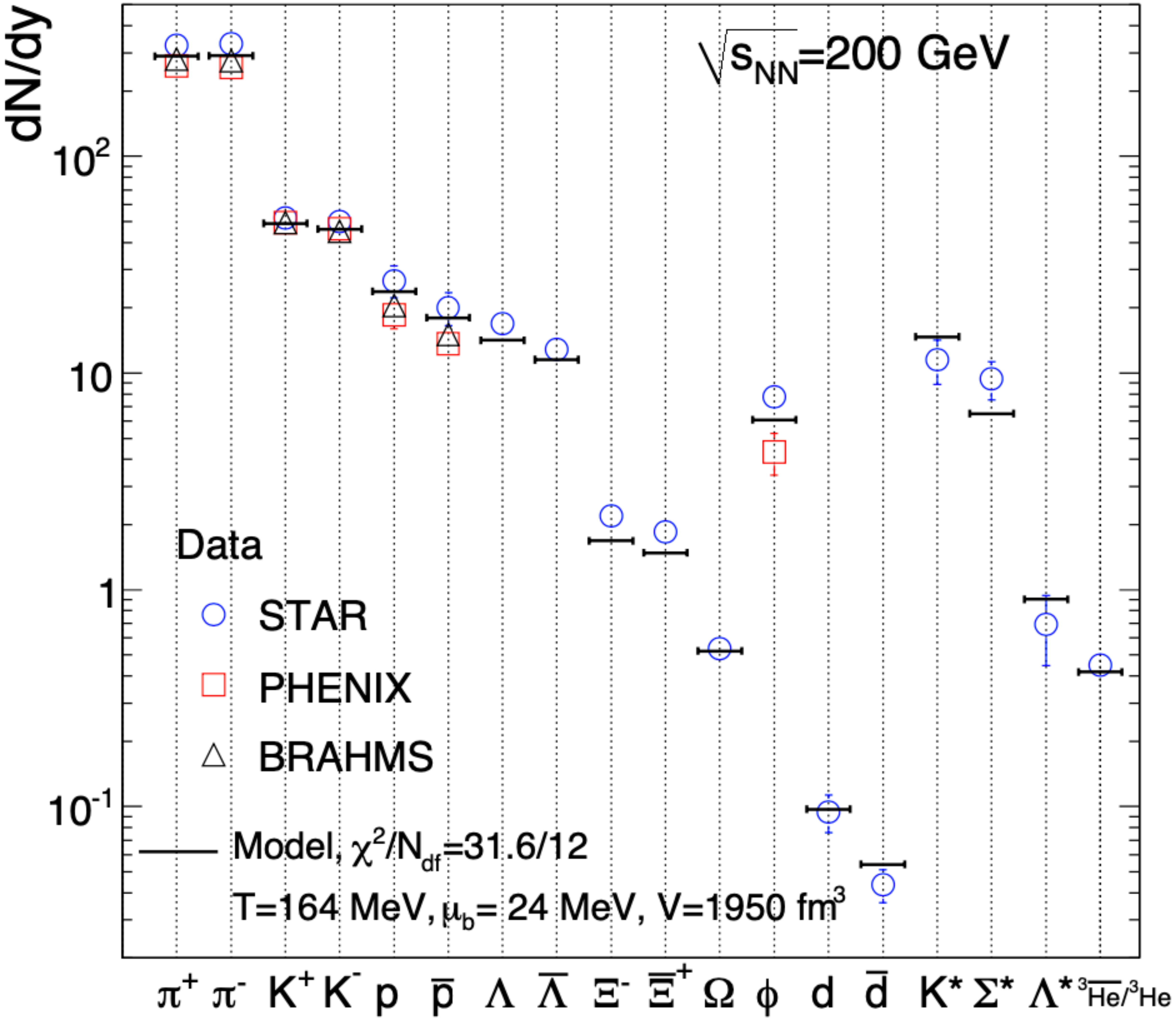
$$dN/dy \propto \exp\left(-m/T_{ch}\right)$$



10.1016/j.physletb.2011.01.053

SHM for Au-Au collisions

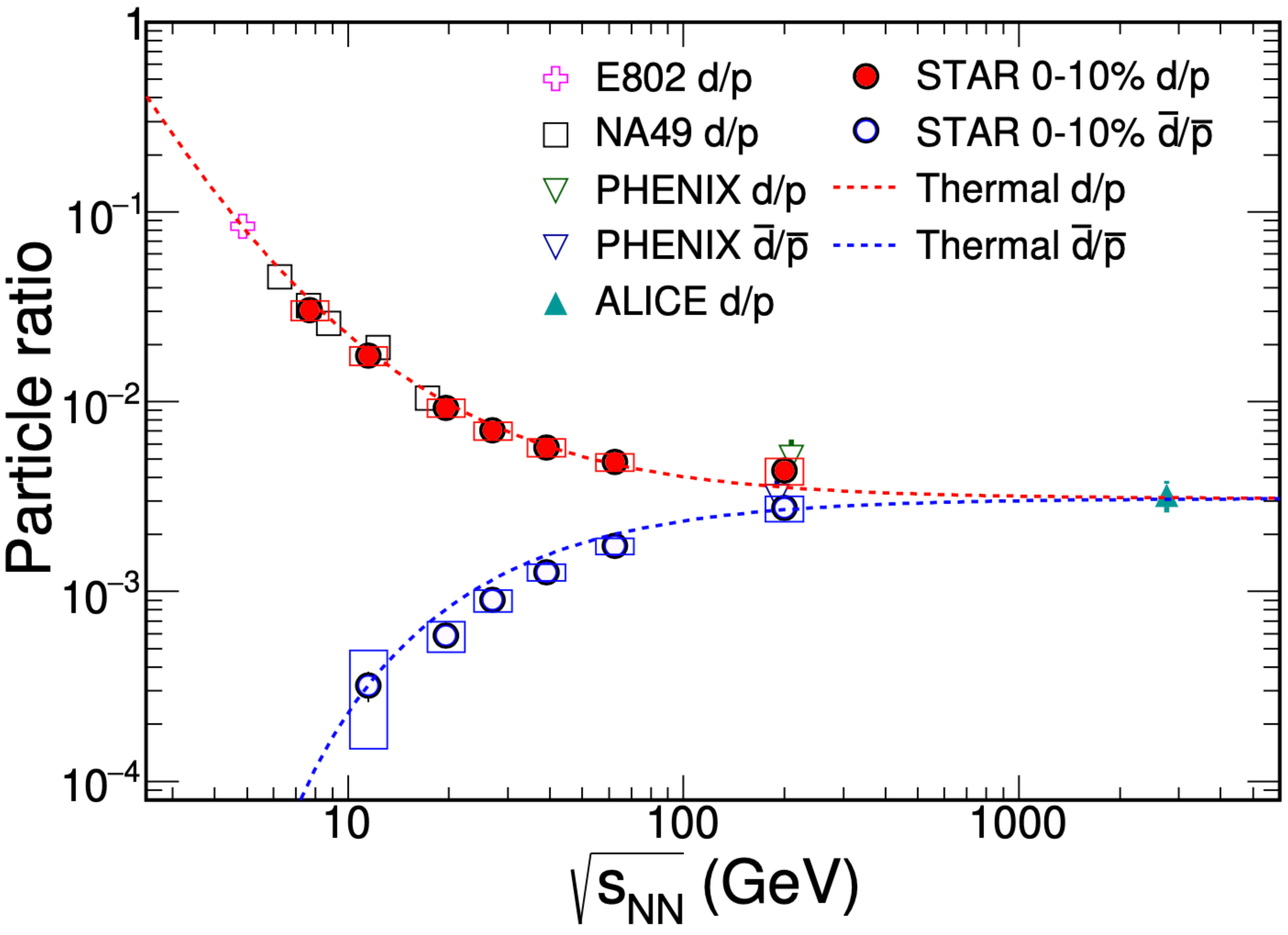
- SHM describes **d*N*/dy** for hadrons, including light nuclei, in HIC

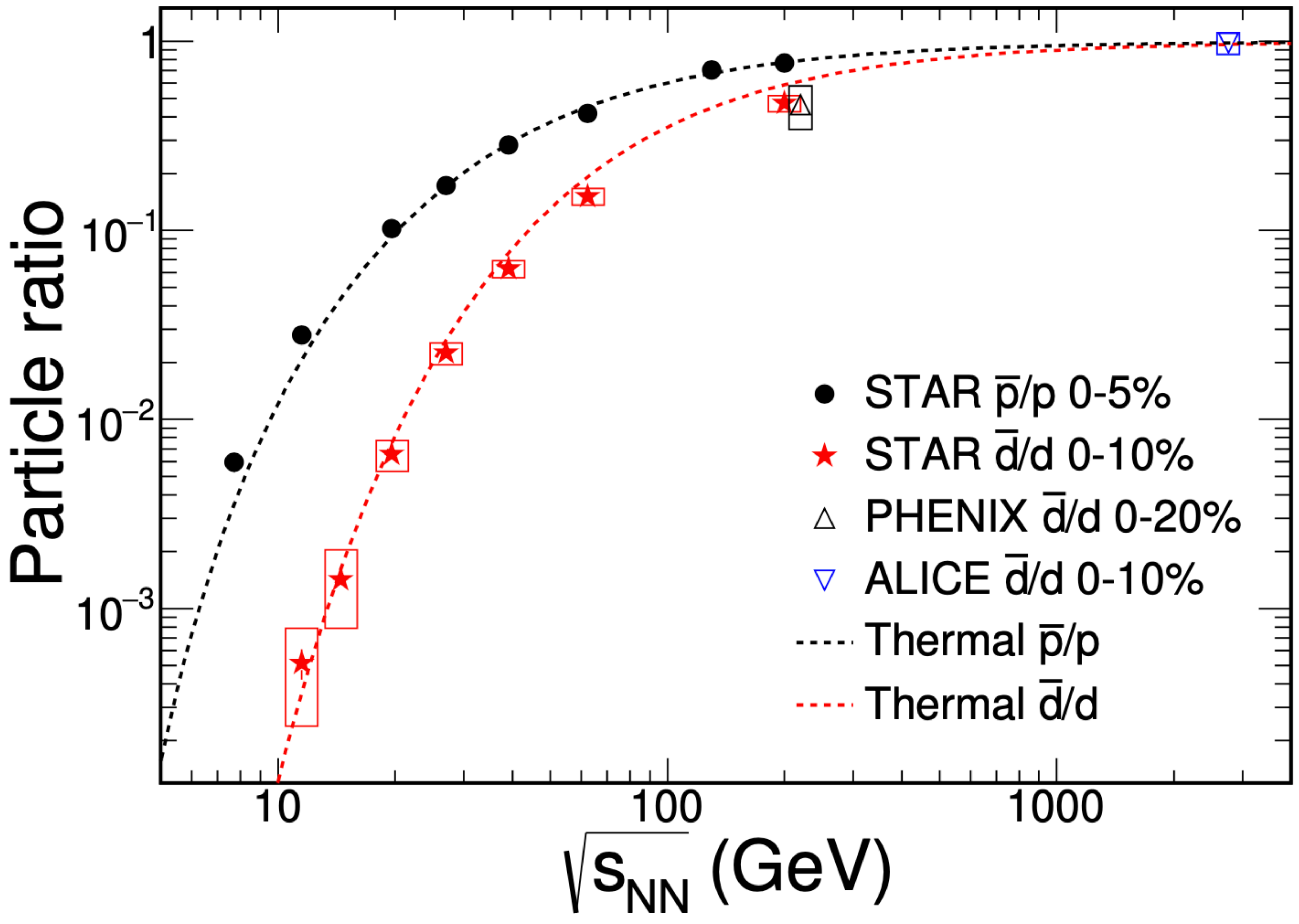


10.1016/j.physletb.2011.01.053

SHM for Au-Au collisions

- SHM describes **d*N*/dy** for hadrons, including light nuclei, in HIC
- **Particle ratios** are well described at different collision energies

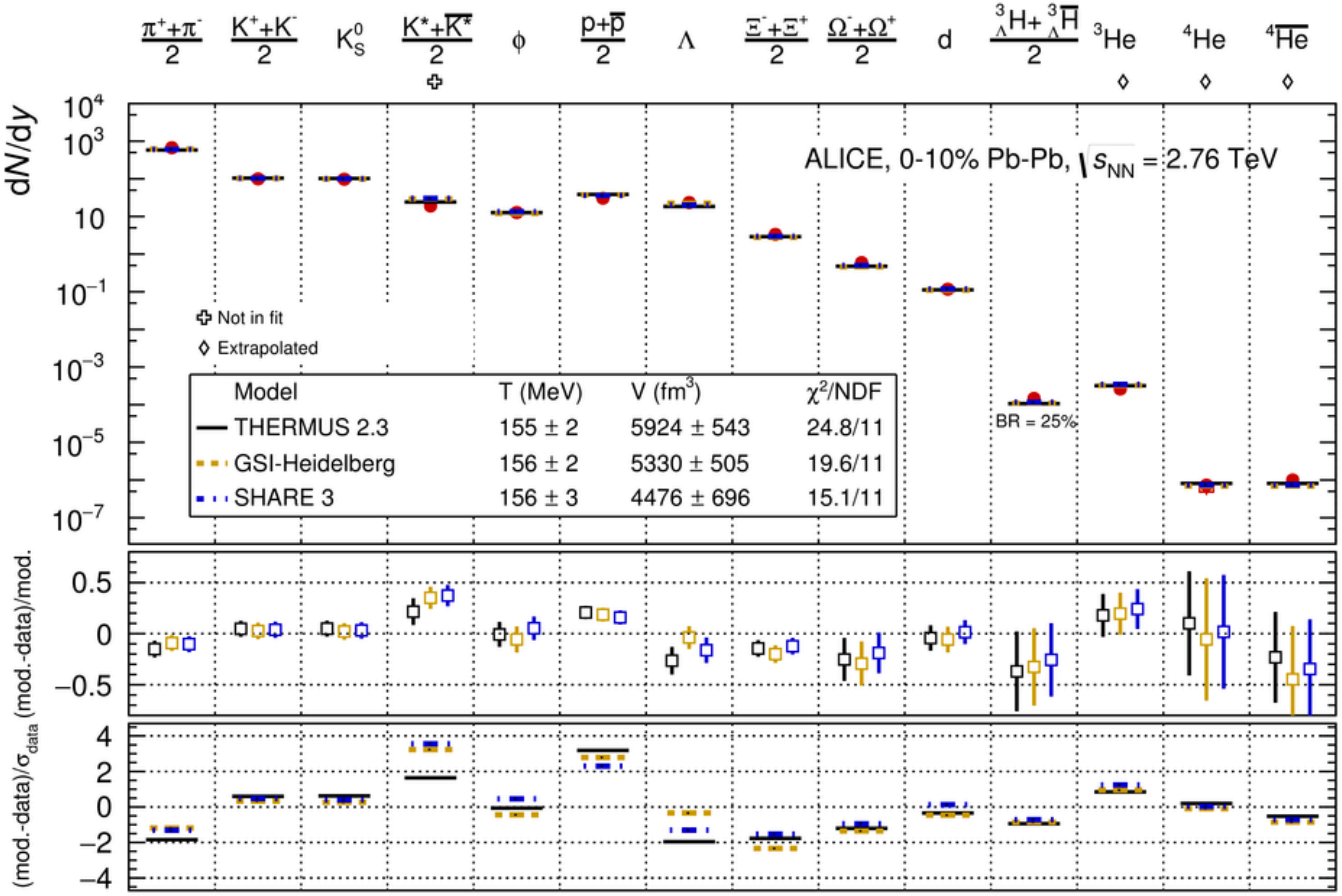




10.1103/PhysRevC.99.064905

SHM for Pb-Pb collisions

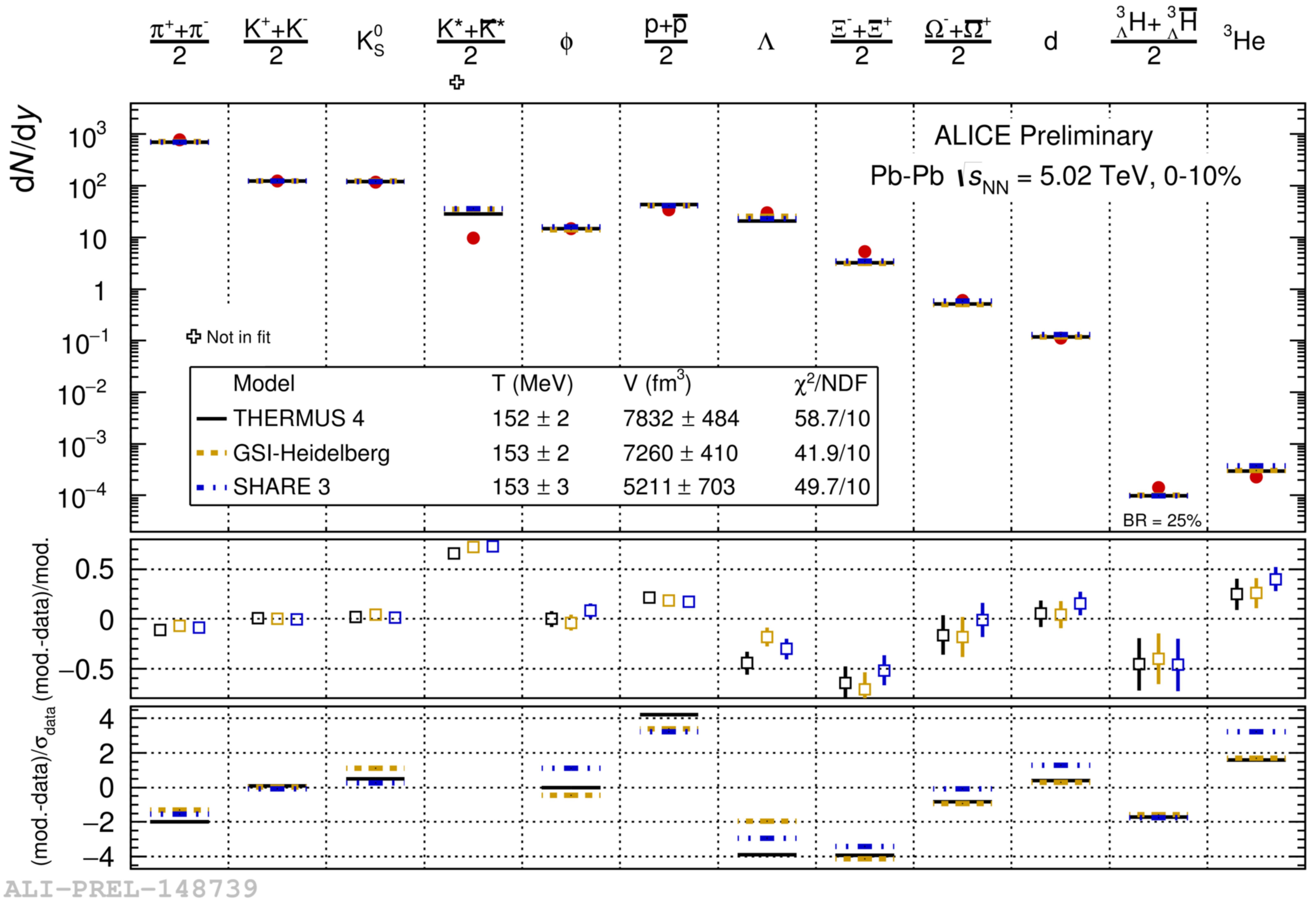
- SHM describes **d*N*/dy** in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV over a wide range of d*N*/dy (**7 orders of magnitude**)
- Nuclei yields are well reproduced
  - thermally produced, together with the other particle species



10.1016/j.nuclphysa.2017.12.004

SHM for Pb-Pb collisions

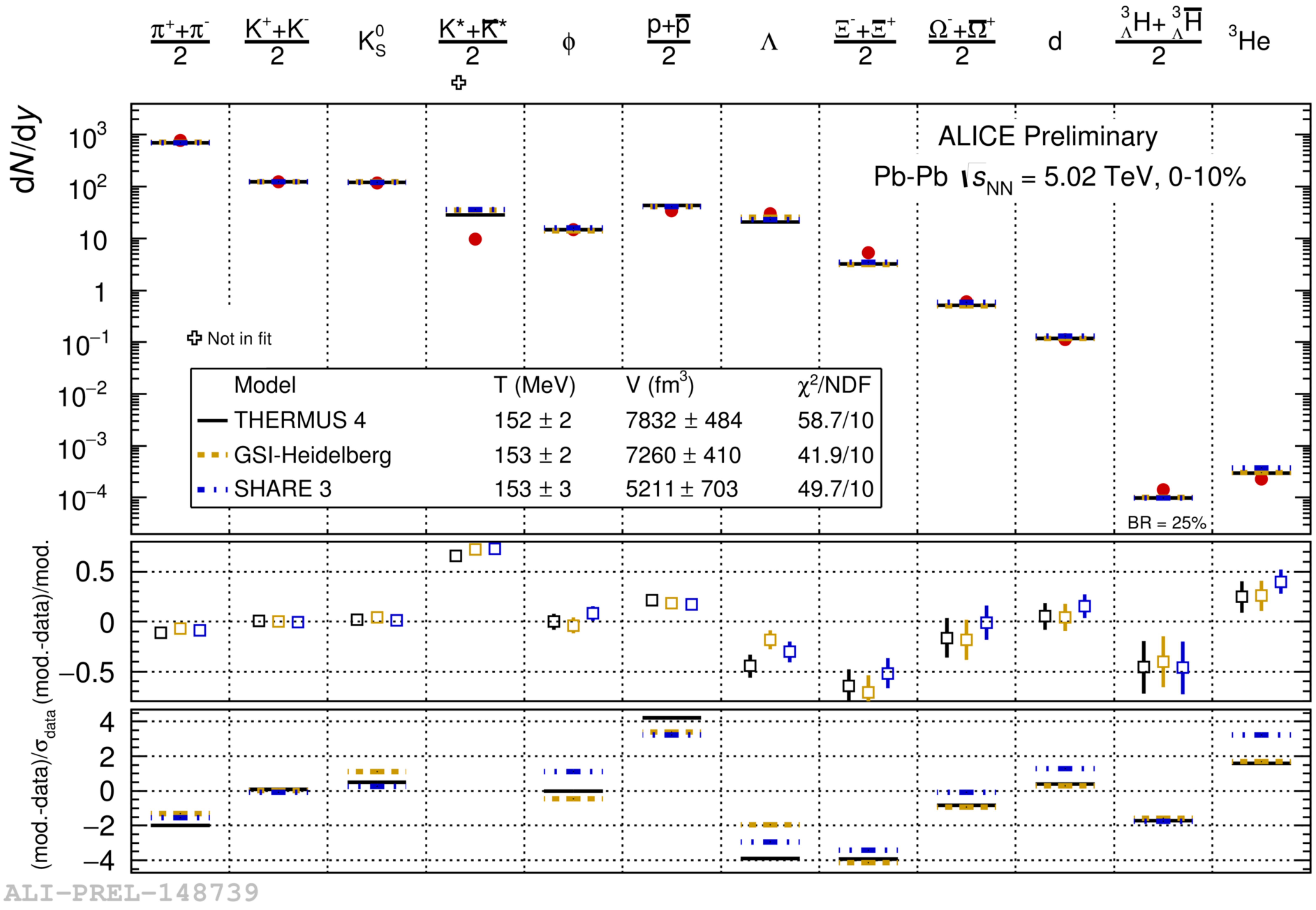
- SHM describes **d*N*/dy** in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV over a wide range of d*N*/dy (**7 orders of magnitude**)
- Nuclei yields are well reproduced
  - thermally produced, together with the other particle species
- In Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5 TeV, tensions between data and model



SHM for Pb-Pb collisions

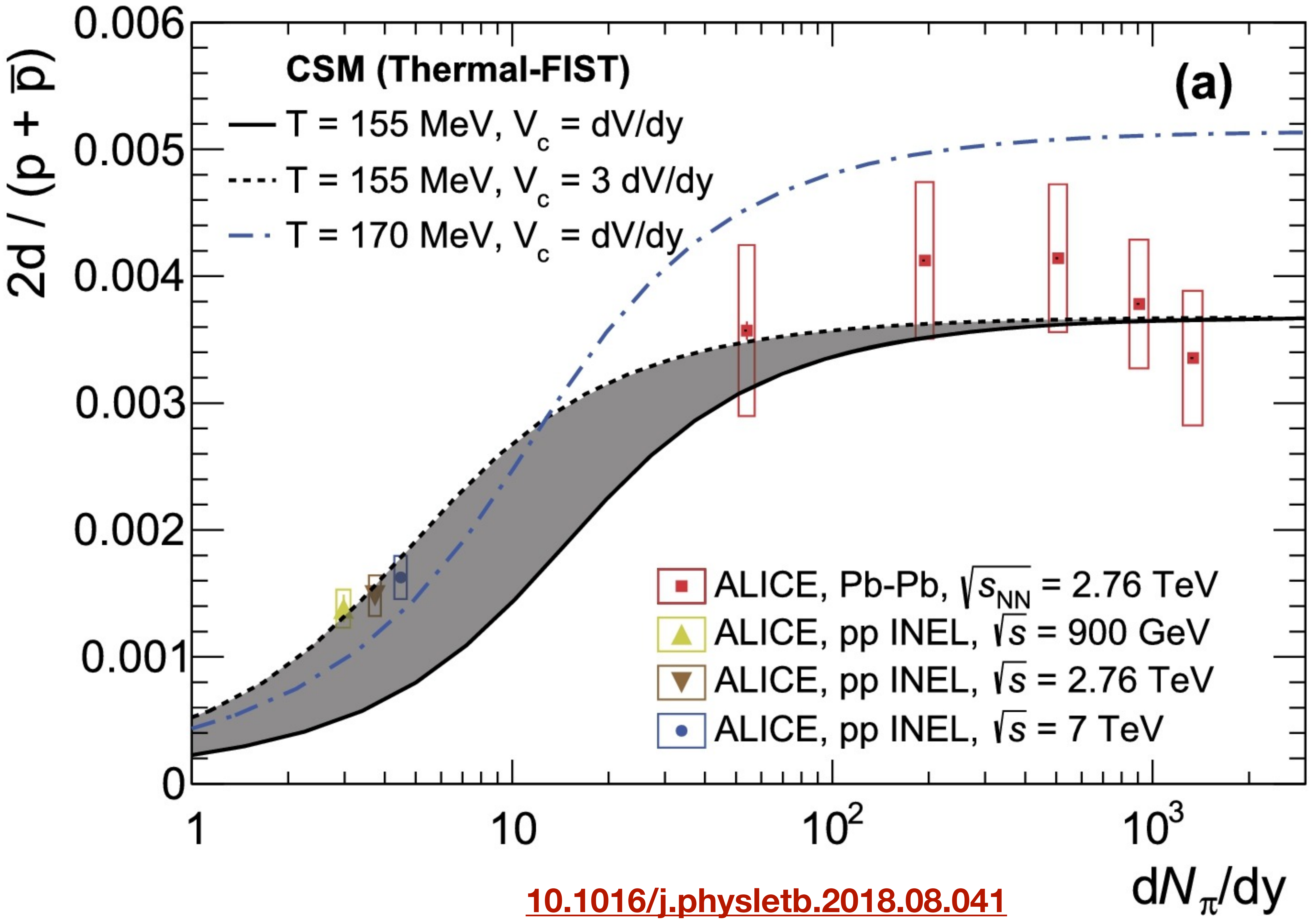
- SHM describes **d*N*/dy** in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV over a wide range of d*N*/dy (**7 orders of magnitude**)
- Nuclei yields are well reproduced
  - thermally produced, together with the other particle species
- In Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5 TeV, tensions between data and model

Is there a way to reduce these tensions?



The canonical statistical hadronisation model (CSM)

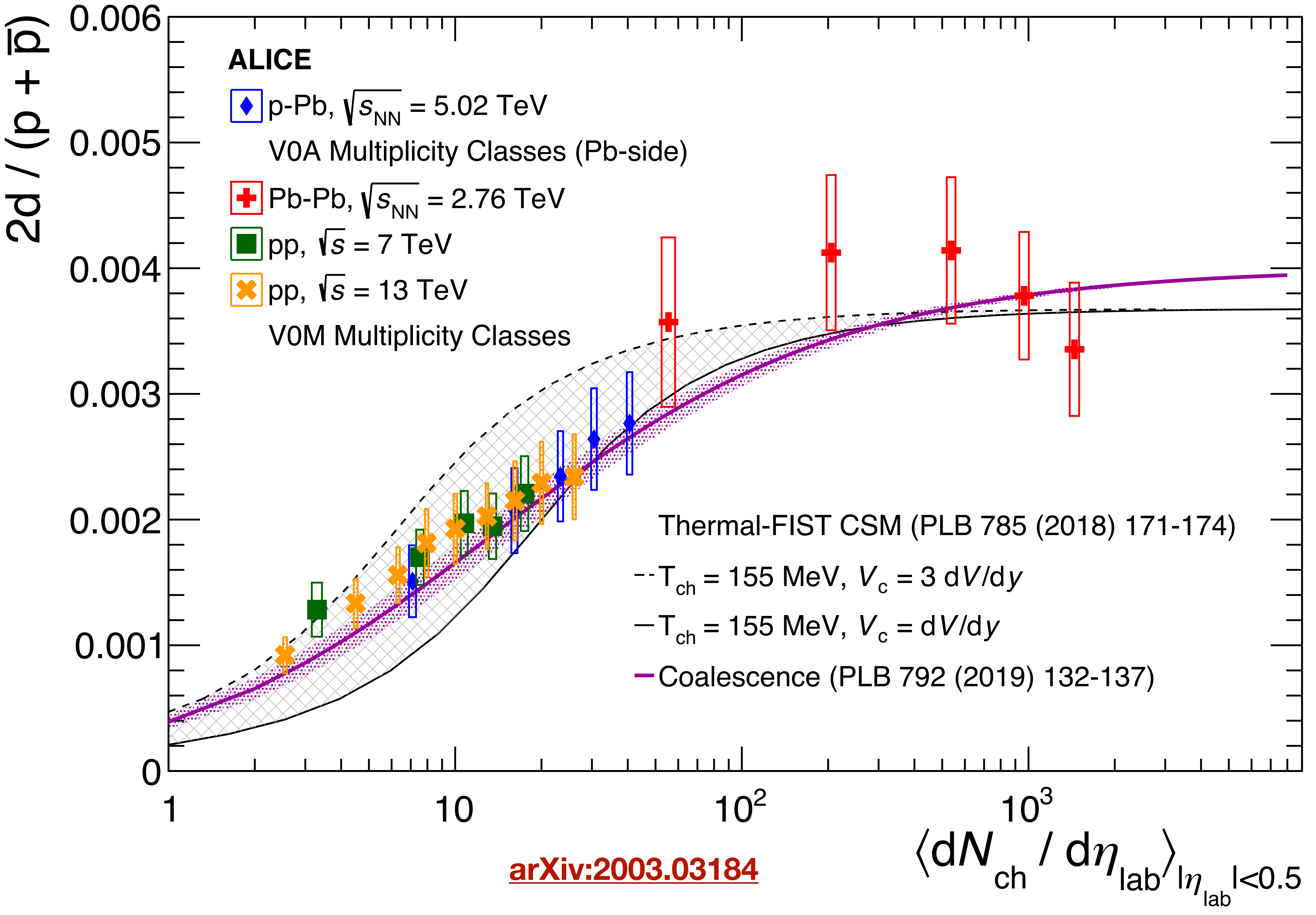
- In **small systems** ($VT^3 < 1$): local conservation of quantum numbers (S, Q and B)
  - **canonical ensemble**
- Small volumes ➝ suppression of particles carrying the conserved charges: **canonical suppression**
- Large volumes ➝ same as SHM
- Production vs multiplicity ➝ dependence on the system size



10.1016/j.physletb.2018.08.041

d/p as a function of multiplicity

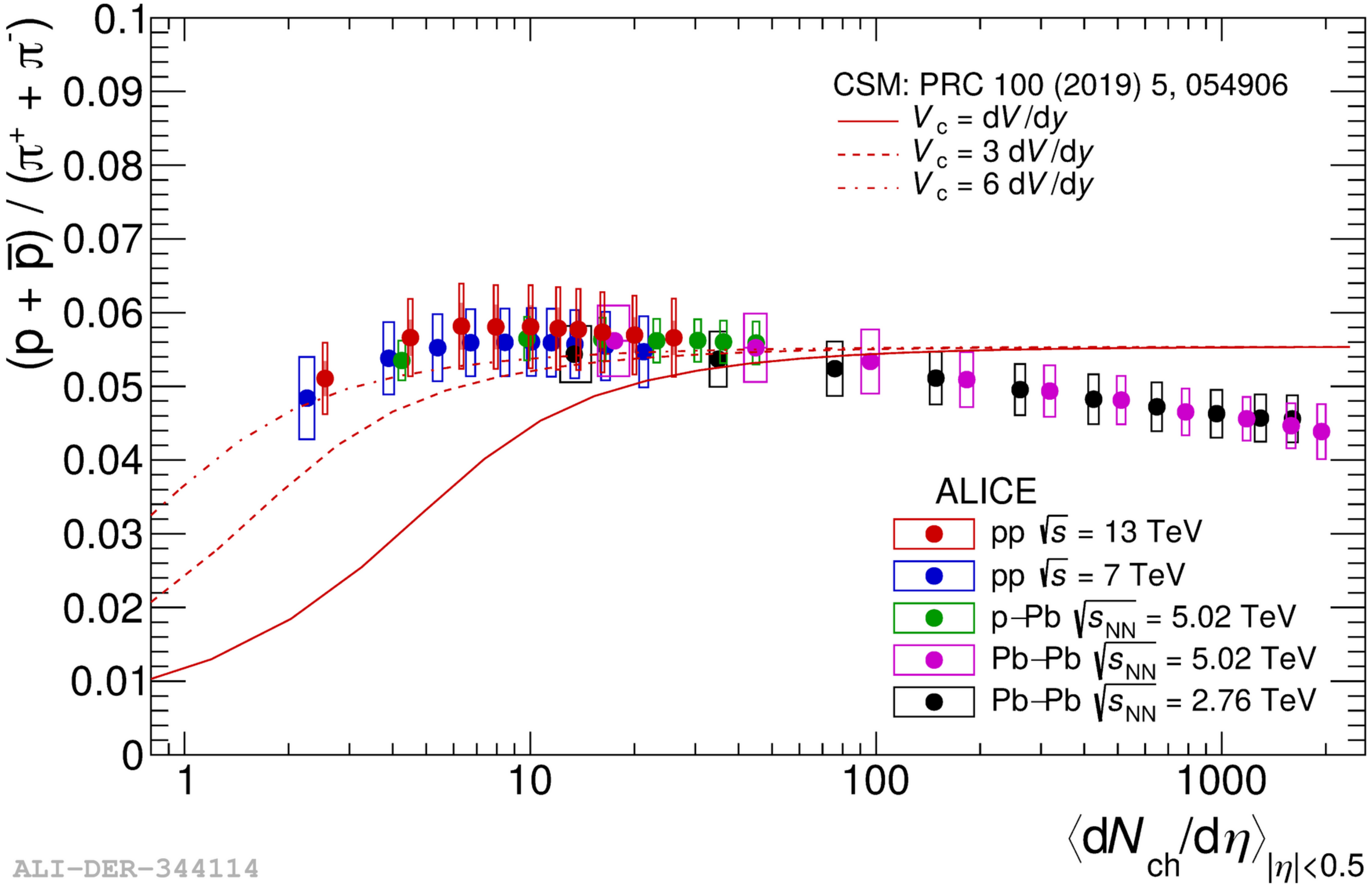
- The measurement of the **d/p** evolves **smoothly** with the **multiplicity**
- Two different regimes:
  1. **increasing:** canonical suppression
  2. **flat:** at high multiplicity there is no dependence of the ratio on the multiplicity



arXiv:2003.03184

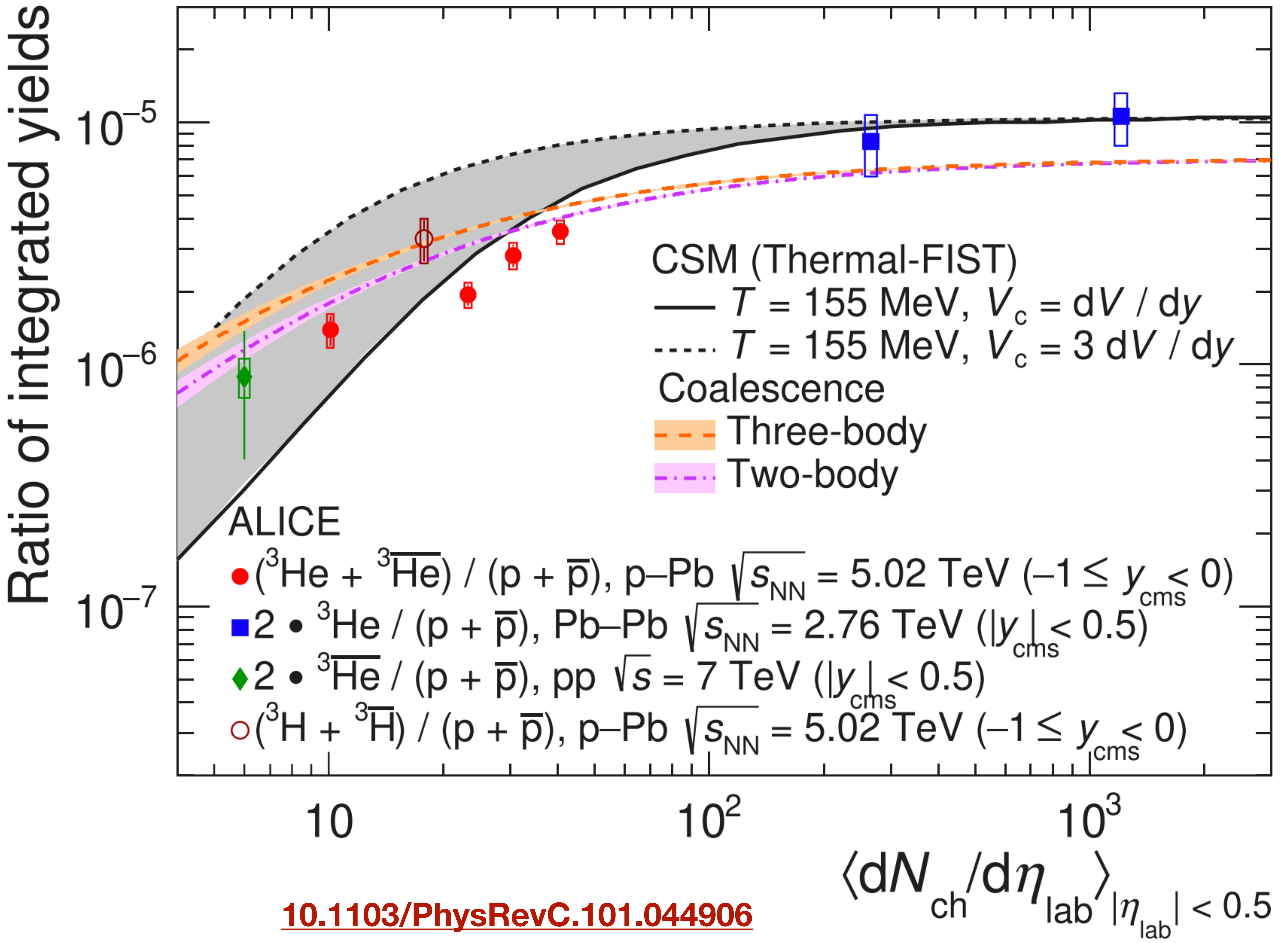
A/p as a function of multiplicity

- The measurement of the **d/p** evolves **smoothly** with the **multiplicity**
- Two different regimes:
  1. **increasing:** canonical suppression
  2. **flat:** at high multiplicity there is no dependence of the ratio on the multiplicity
- **CSM cannot reproduce p/π** with the same correlation volume used for d/p (same baryon content): d*V*/dy < *Vc* < 3 d*V*/dy



A/p as a function of multiplicity

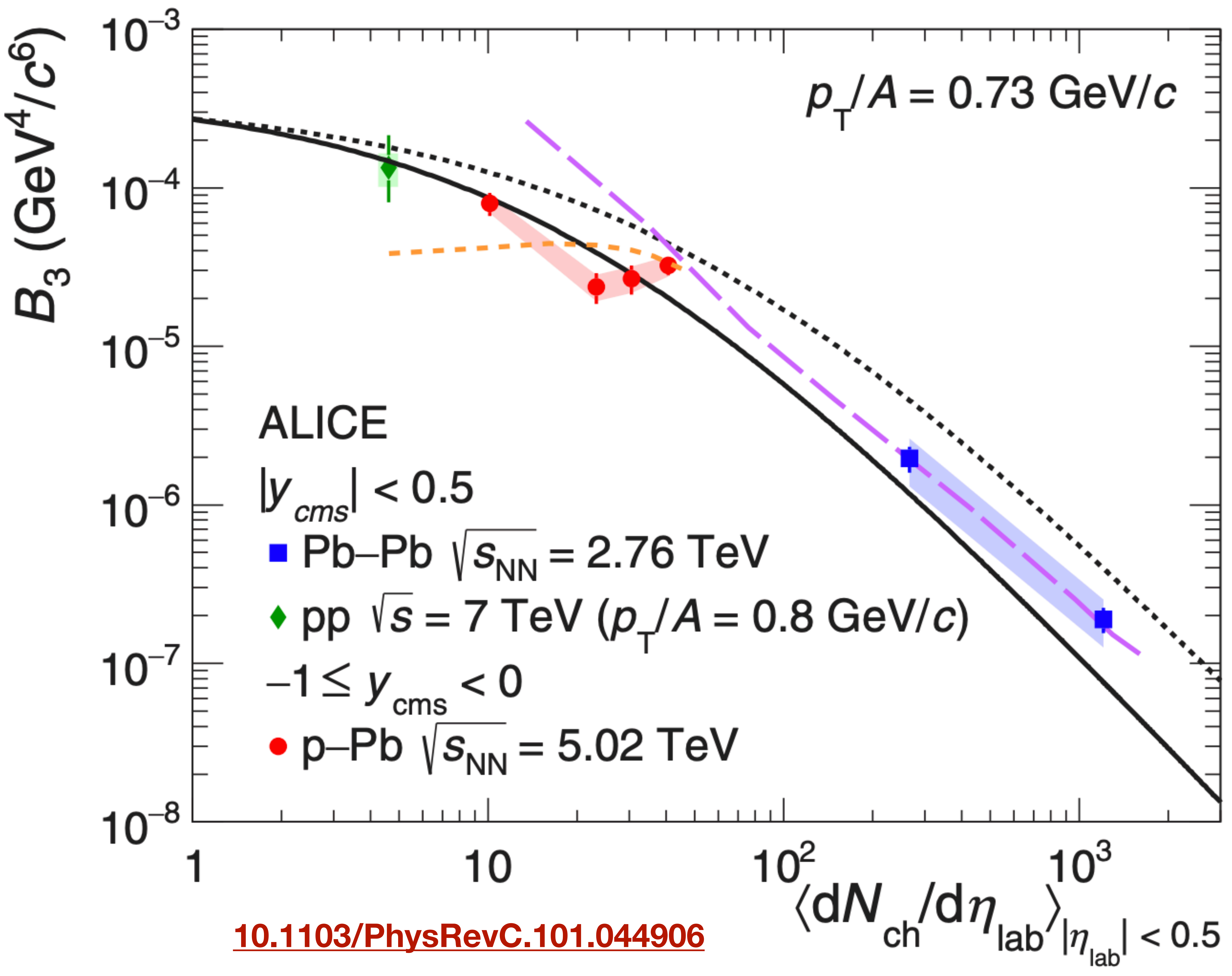
- The measurement of the **d/p** evolves **smoothly** with the **multiplicity**
- Two different regimes:
  1. **increasing:**
     - Thermal model: **canonical suppression**
  2. **flat:** at high multiplicity there is no dependence of the ratio on the multiplicity
- **CSM cannot reproduce p/π** with the same correlation volume used for d/p (same baryon content): d*V*/d*y* < *Vc* < 3 d*V*/d*y*
- **^{3}He/p** shows more tensions than d/p



10.1103/PhysRevC.101.044906

B_A vs multiplicity

- B_2 can also be compared with the predictions of SHM and CSM, with p_T shape from blast-wave
- SHM describes well data at high multiplicity (GCE)
- For small systems the p_T shape of nuclei is bit described by a blast-wave

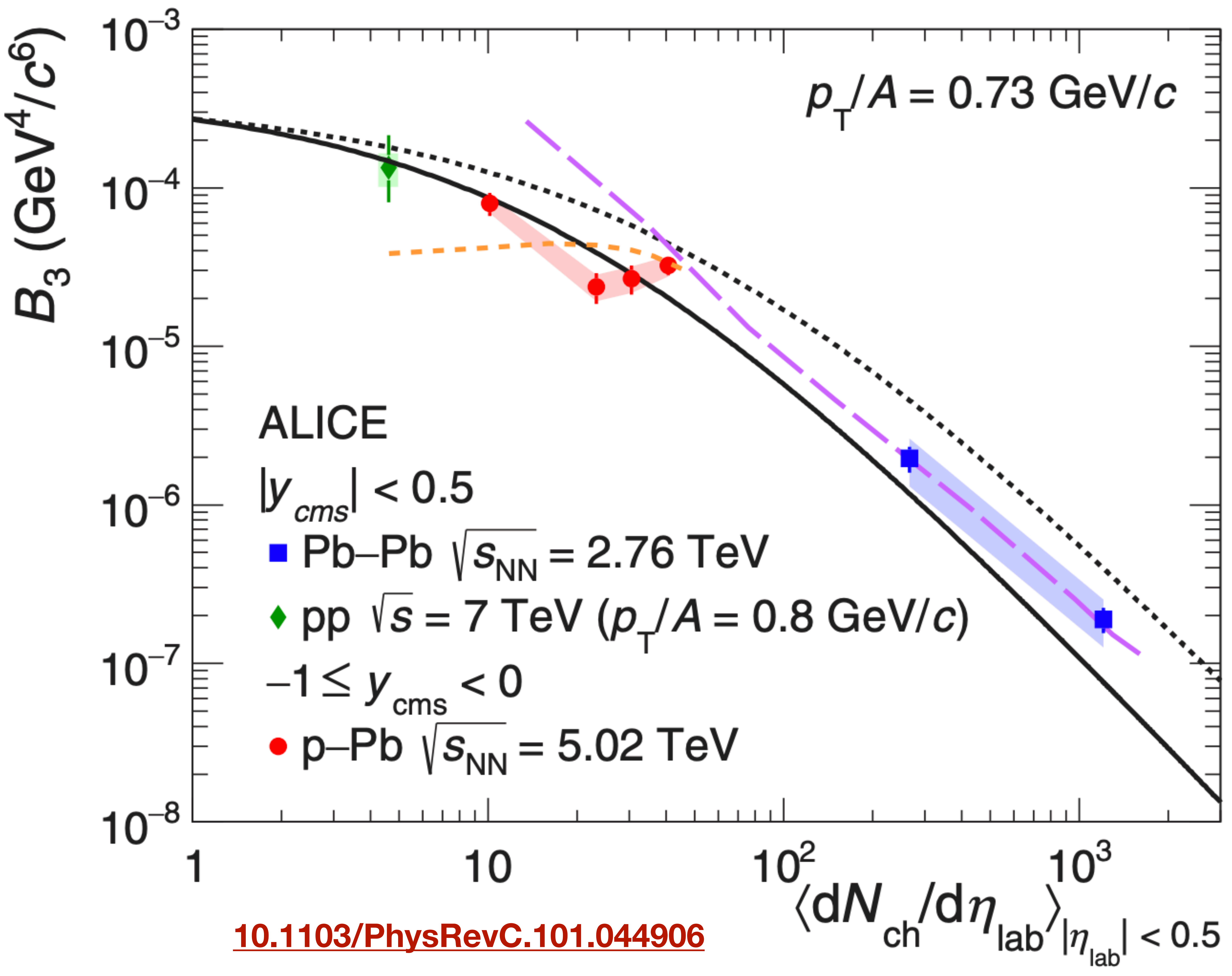


10.1103/PhysRevC.101.044906

B_A vs multiplicity

- **B_2** can also be compared with the predictions of SHM and CSM, with p_T shape from blast-wave
- SHM describes well data at high multiplicity (GCE)
- For small systems the p_T shape of nuclei is bit described by a blast-wave

Is a different comparison with CSM possible over the full range?



10.1103/PhysRevC.101.044906

Conclusions

- **B_A** vs ***p_T***:
  - raise not explained with simple coalescence model
- **B_A** vs **multiplicity**:
  - smooth evolution ➞ production mechanisms dependent on the system size
  - Advanced coalescence cannot describe B_A over the full range
    - New parameterisation of R vs multiplicity needed?
  - CSM does not describe B_A: other hypotheses than BW-shaped p_T spectra needed
- **A/p** vs **multiplicity**:
  - CSM describe d/p, but cannot describe p/π with the same volume
  - CSM struggles a bit in describing ^{3}He/p
  - Advanced coalescence describes d/p but struggles with ^{3}He/p

Conclusions

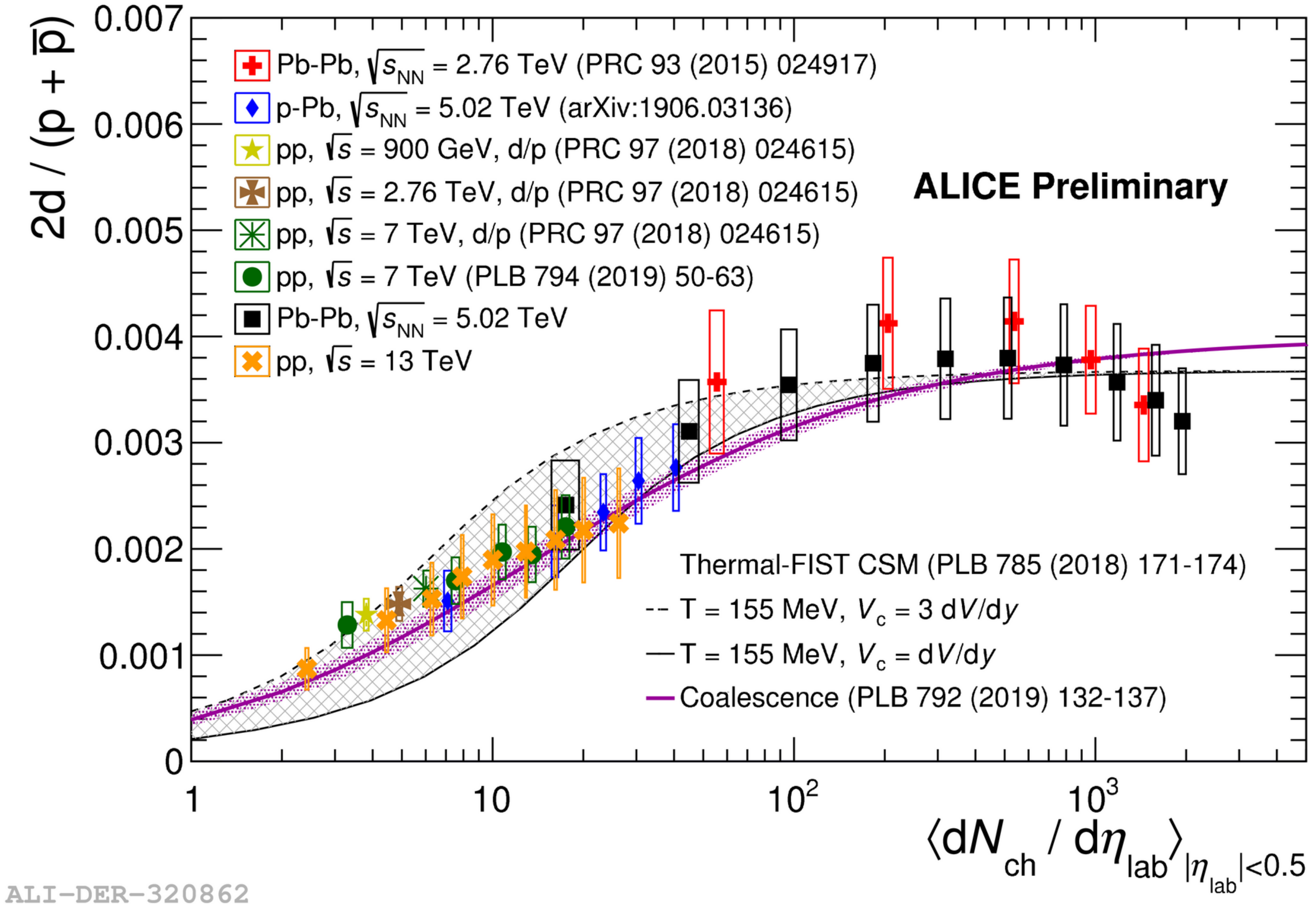
- **B_A** vs ***p_T***:
  - raise not explained with simple coalescence model
- **B_A** vs **multiplicity**:
  - smooth evolution ➞ production mechanisms dependent on the system size
  - Advanced coalescence cannot describe B_A over the full range
    - New parameterisation of R vs multiplicity needed?
  - CSM does not describe B_A: other hypotheses than BW-shaped p_T spectra needed
- **A/p** vs **multiplicity**:
  - CSM describe d/p, but cannot describe p/π with the same volume
  - CSM struggles a bit in describing ^{3}He/p
  - Advanced coalescence describes d/p but struggles with ^{3}He/p

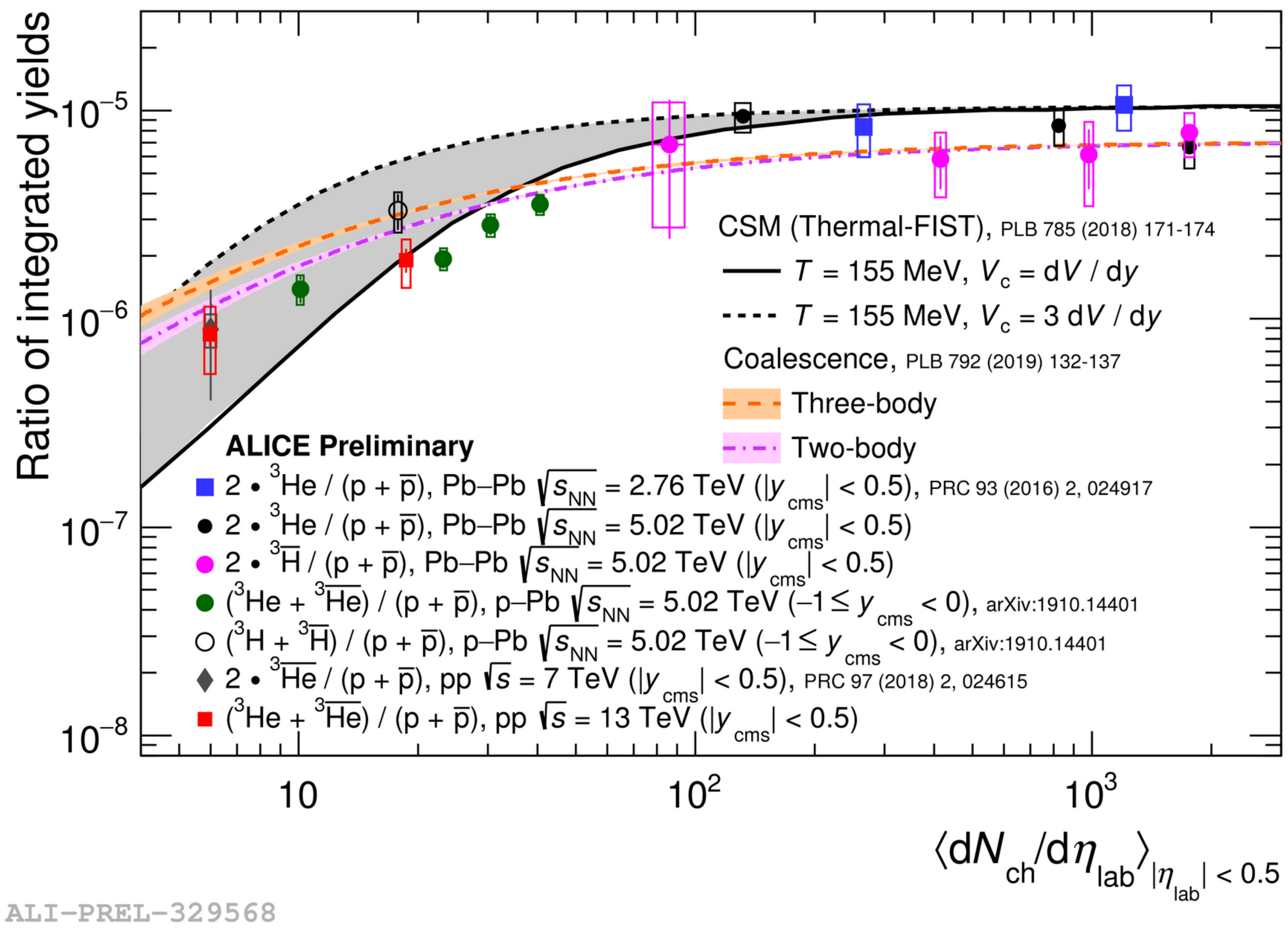
Thank you!

luca.barioglio@cern.ch

Backup

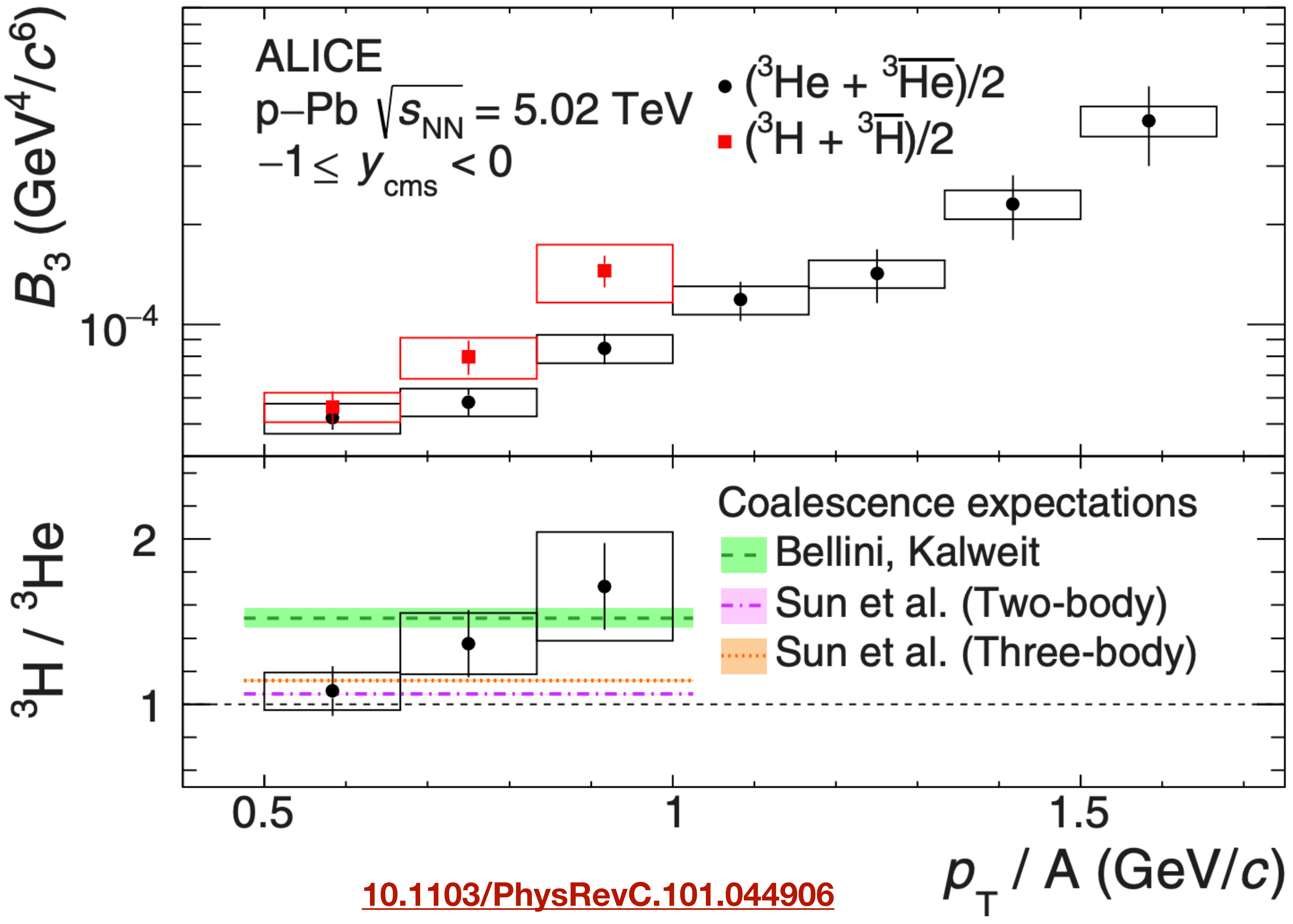
A/p vs multiplicity





B_3: ^{3}He vs ^{3}H

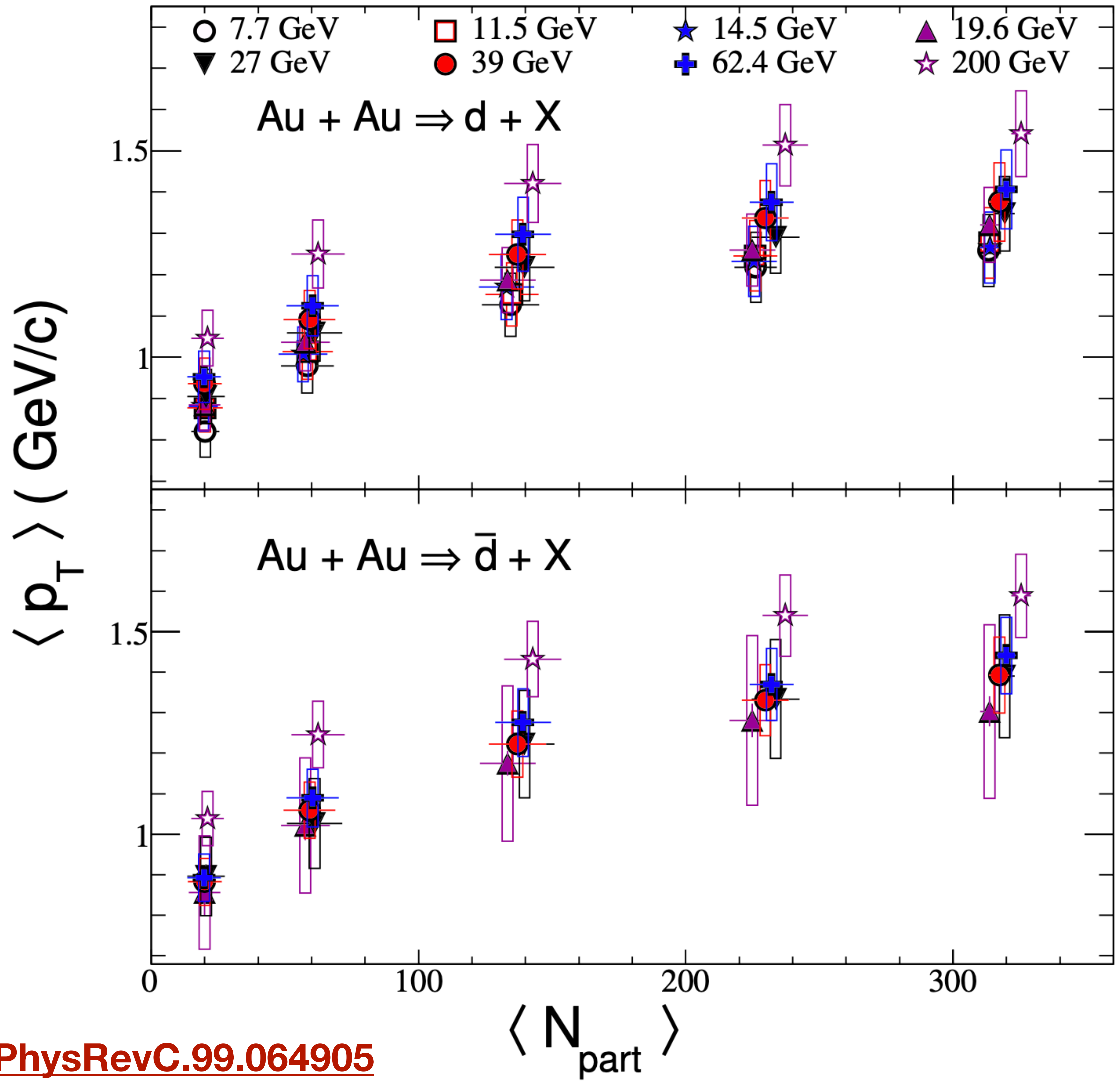
- ^{3}He and ^{3}H have different wave functions
  - B_3 is different



10.1103/PhysRevC.101.044906

Hardening in Au-Au

- p_T spectra show hardening
  - with increasing centrality
  - with increasing energy



10.1103/PhysRevC.99.064905