PARTIKELDAGARNA GÖTEBORG

Confronting nuclei production mechanisms with balance functions at the LHC

Based on arXiv:2509.03195 [hep-ph]

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Marie Skłodowska-Curie Actions
Funded by the European Union

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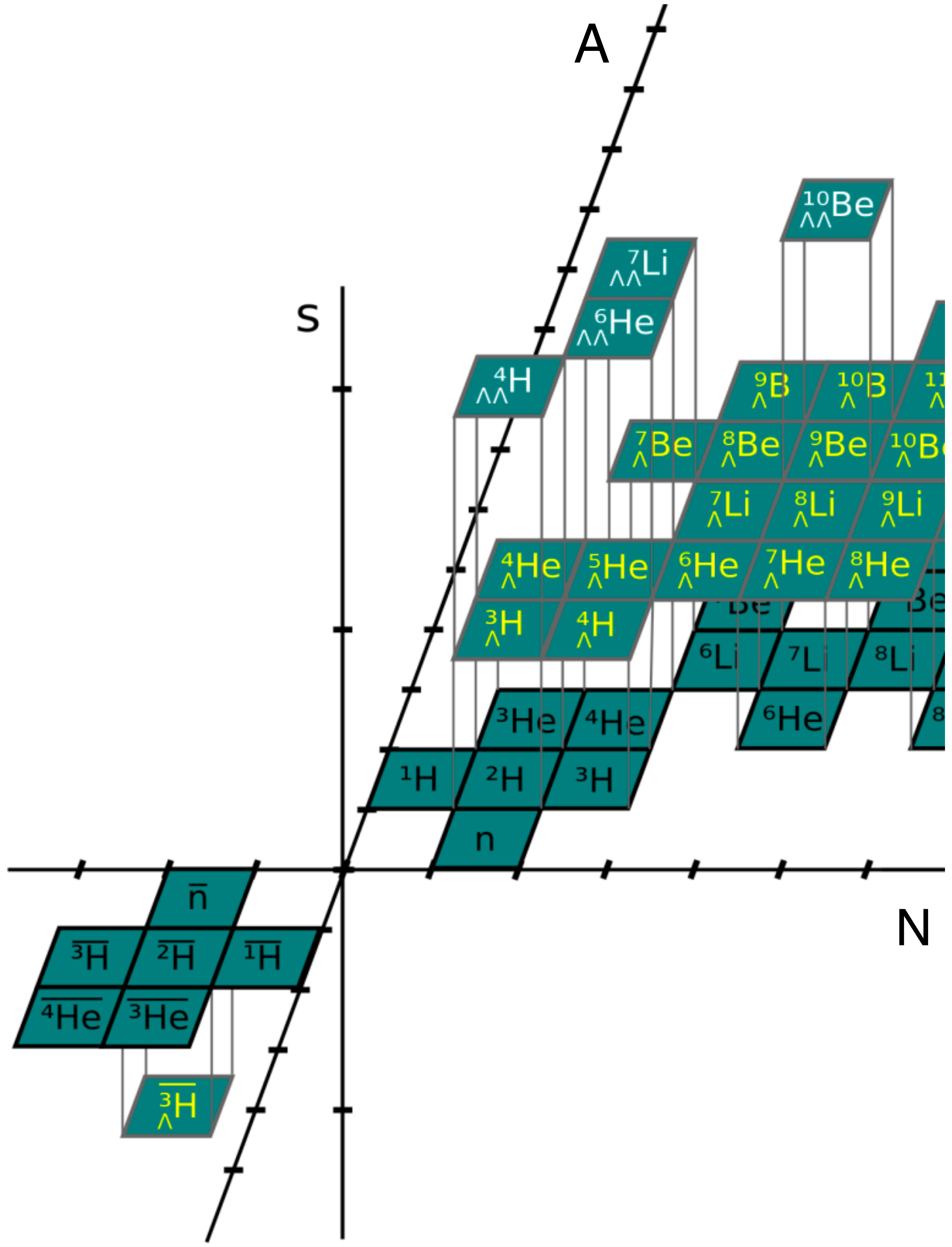
Motivation

- The study of light **nuclei and hypernuclei** production at the LHC is very interesting as the **production mechanism** is still a **puzzle**



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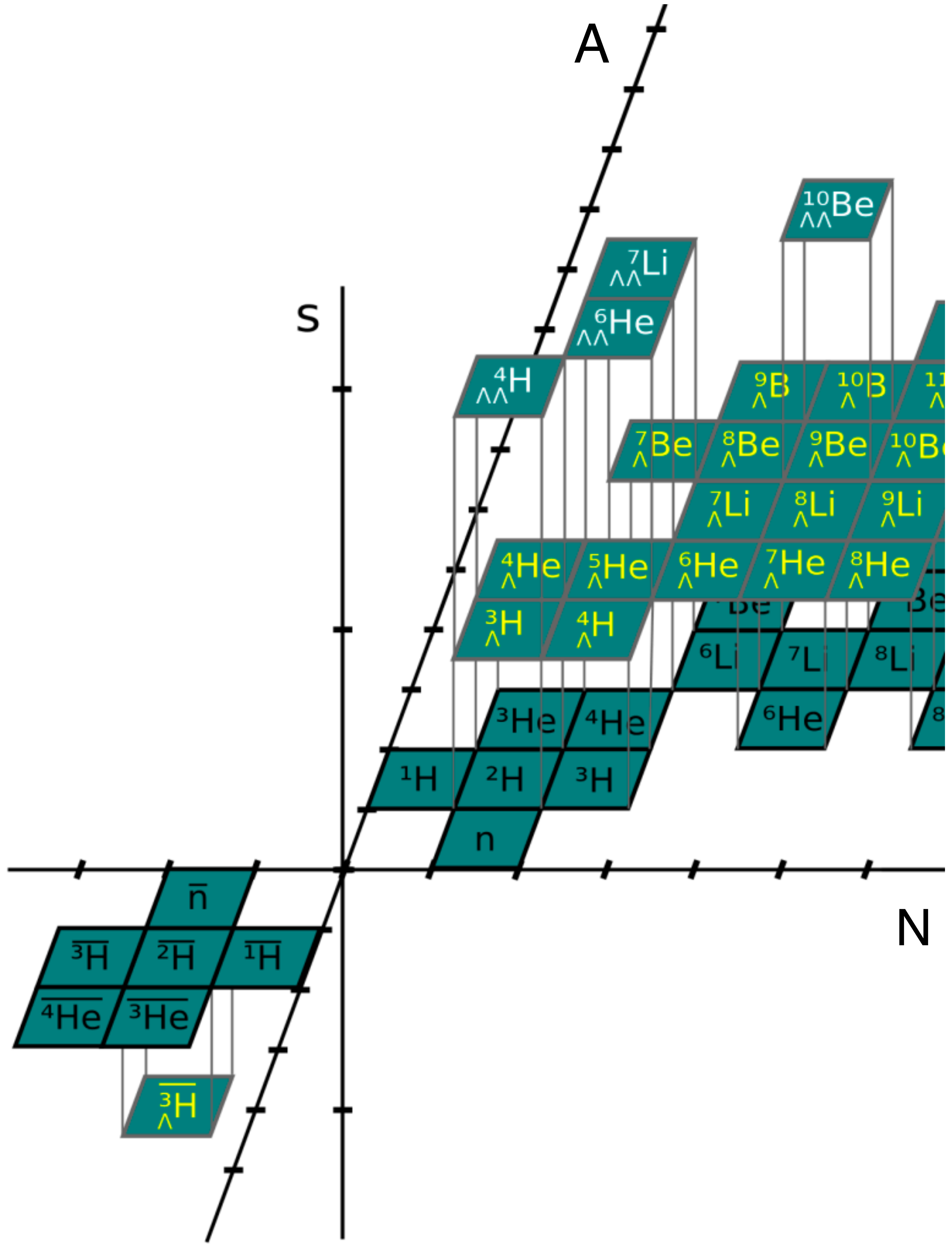
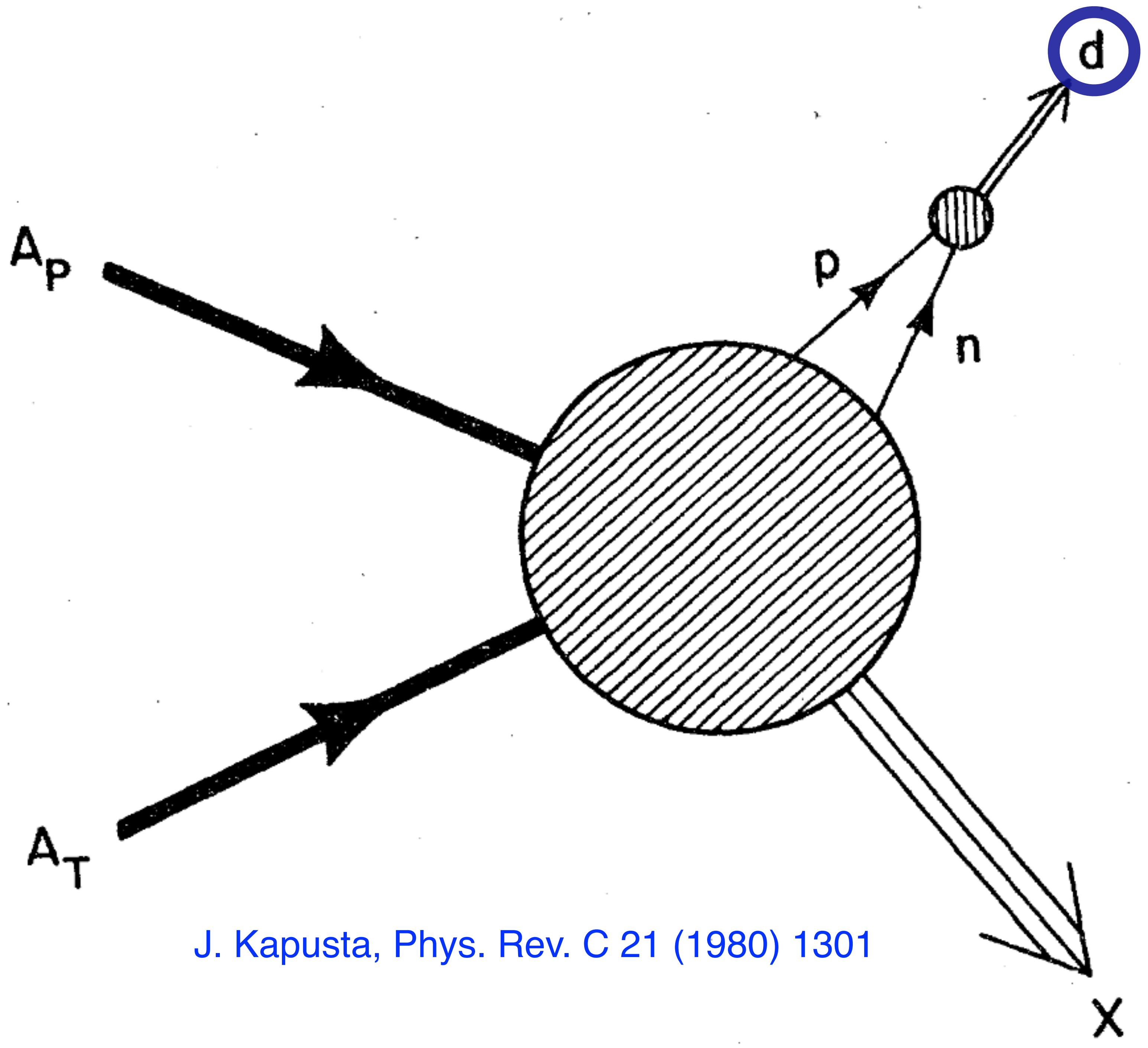
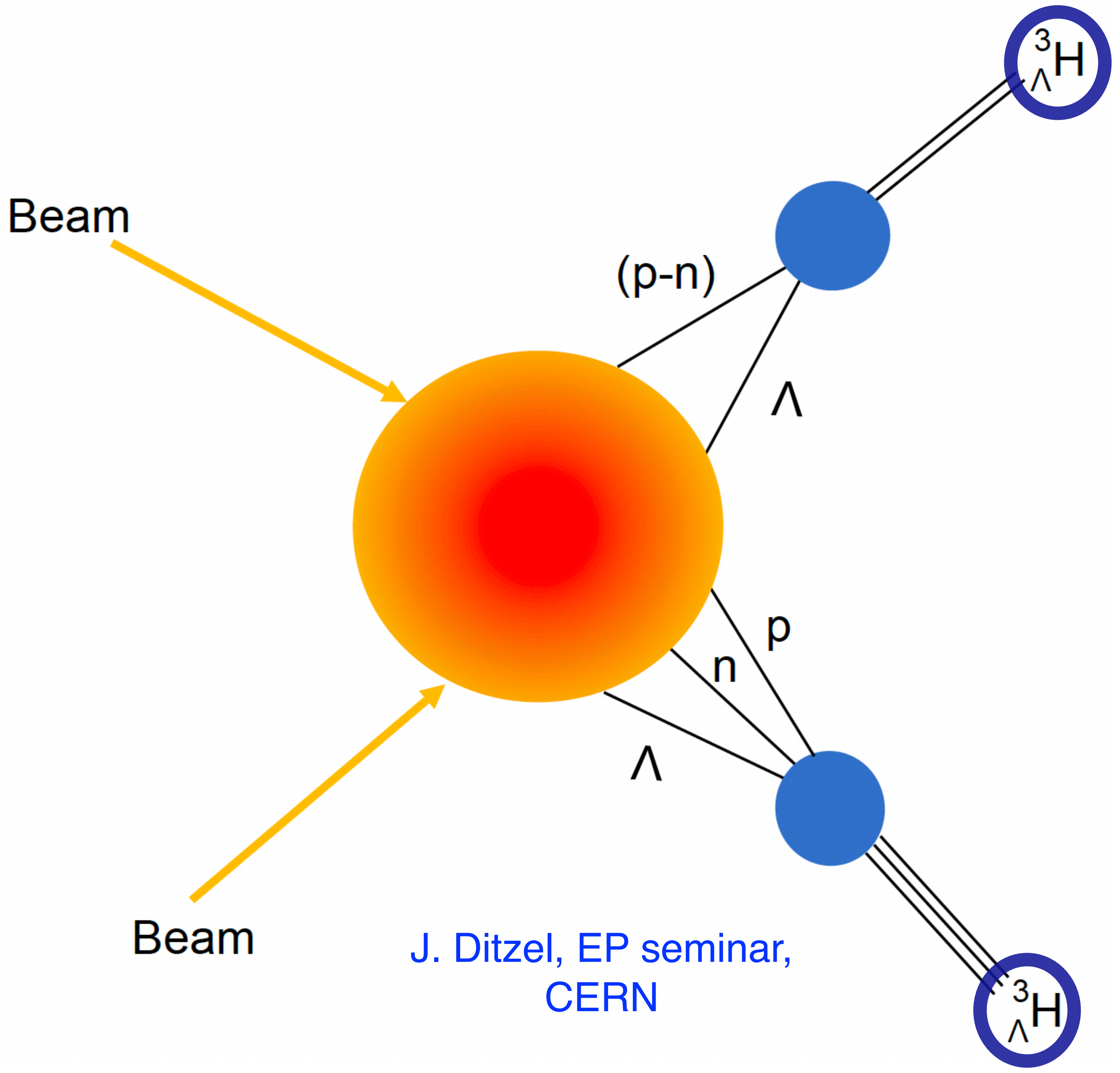


Lightest nuclei: **Deuteron**



J. Kapusta, Phys. Rev. C 21 (1980) 1301

Lightest hypernuclei: **Hypertriton**



J. Ditzel, EP seminar, CERN

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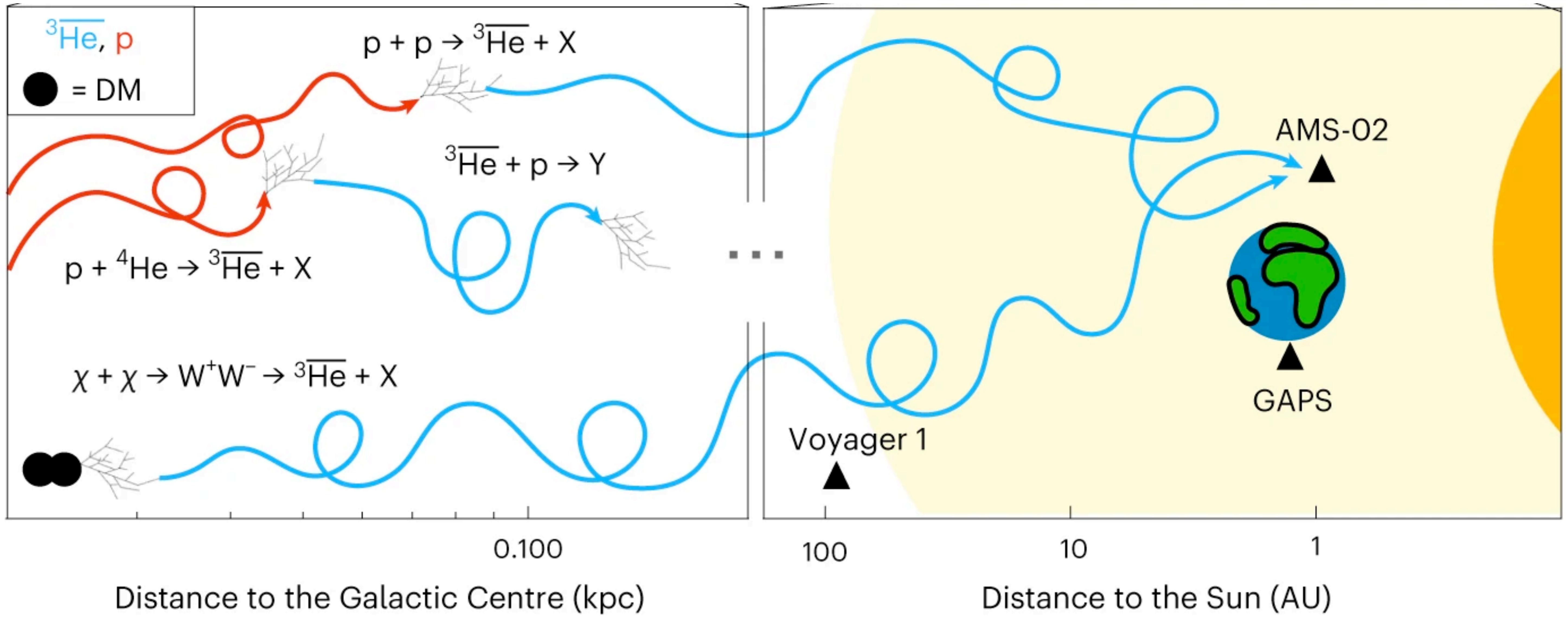
- Antinuclei in space-borne experiments can be a sign of **Dark Matter** annihilation:
  - *Background*: the antinuclei produced by hadronic collisions in space constitutes an irreducible background



ALICE, Nature Phys. 19 (2023) 1, 61

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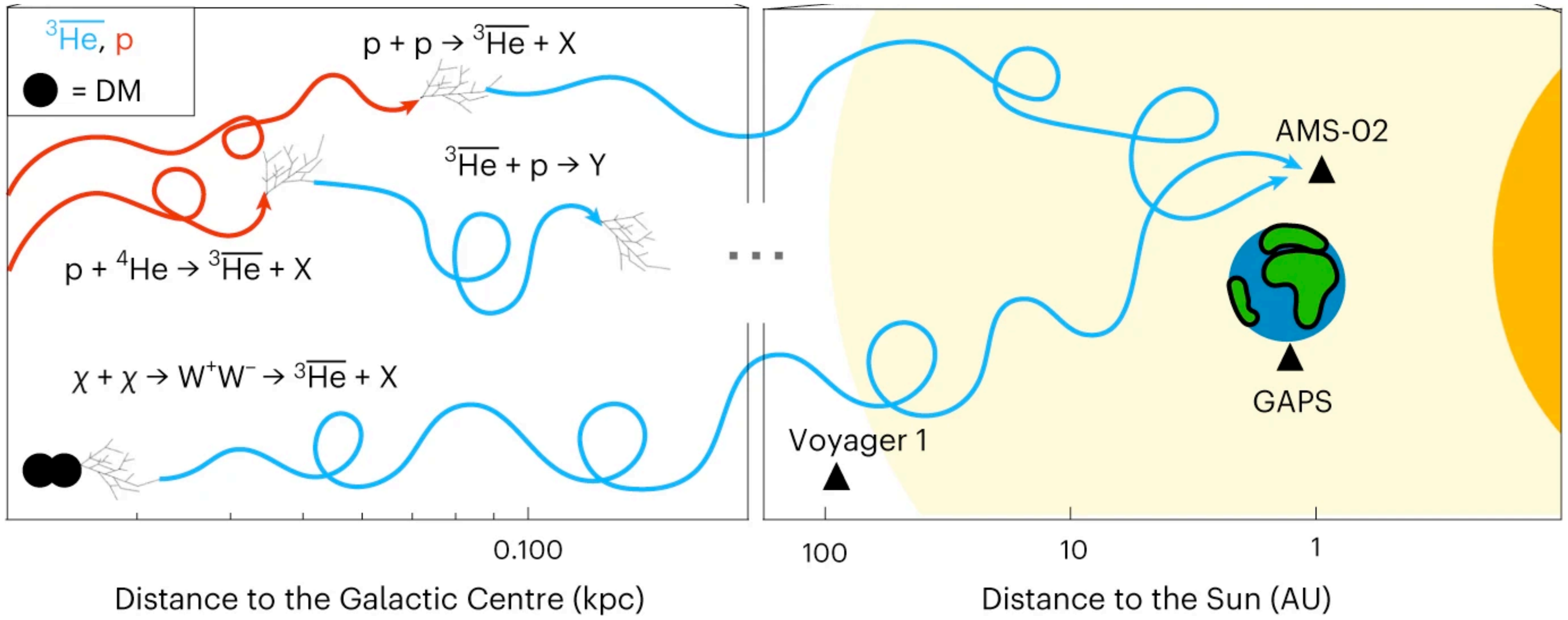

Focus of the talk
How nuclei are formed in collider experiments?

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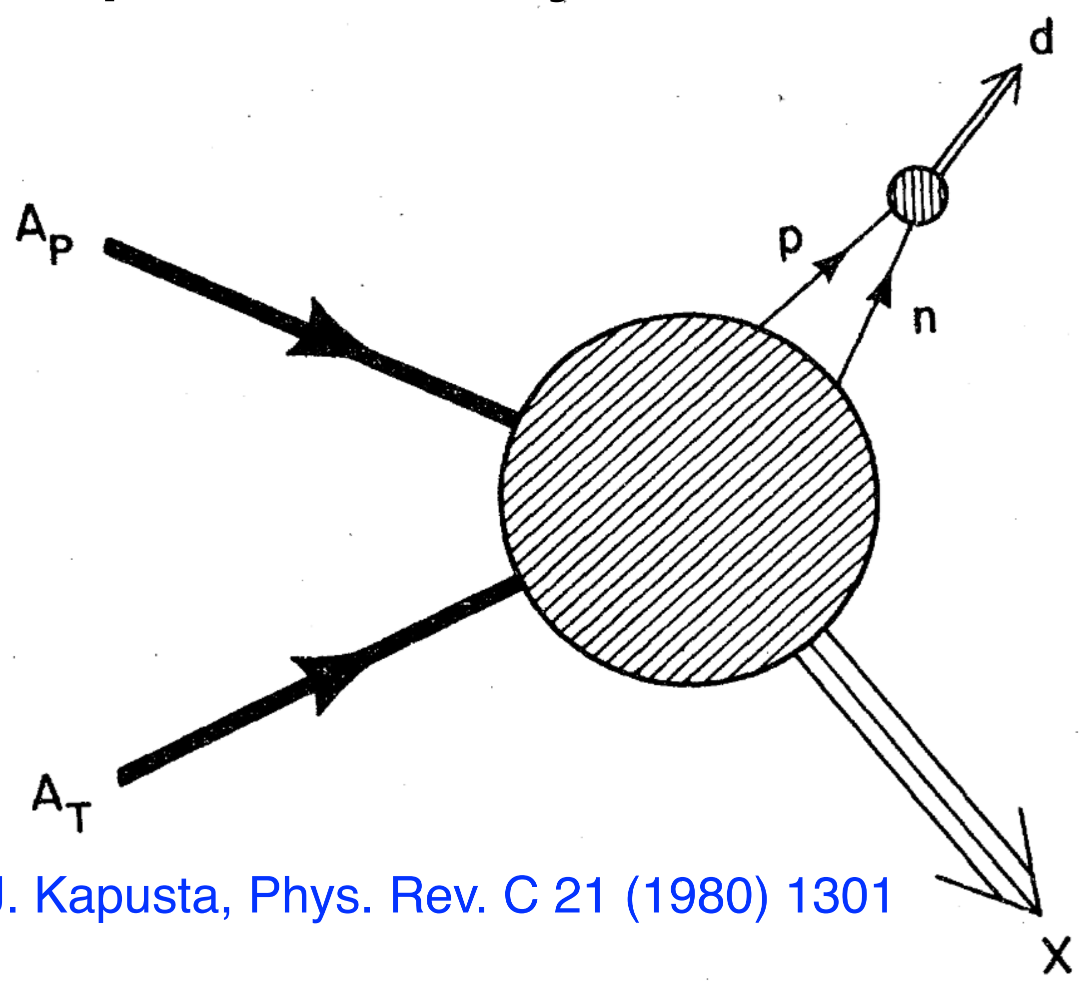
Nuclei synthesis: Coalescence

- **Nuclei** (nuclear clusters) are formed at kinetic freeze-out **if nucleons are close in phase space**
- Convolution between **nucleon phase-space** distribution and **Wigner function** of the nucleus
- **Coalescence parameter** B_2, related to formation probability via coalescence.



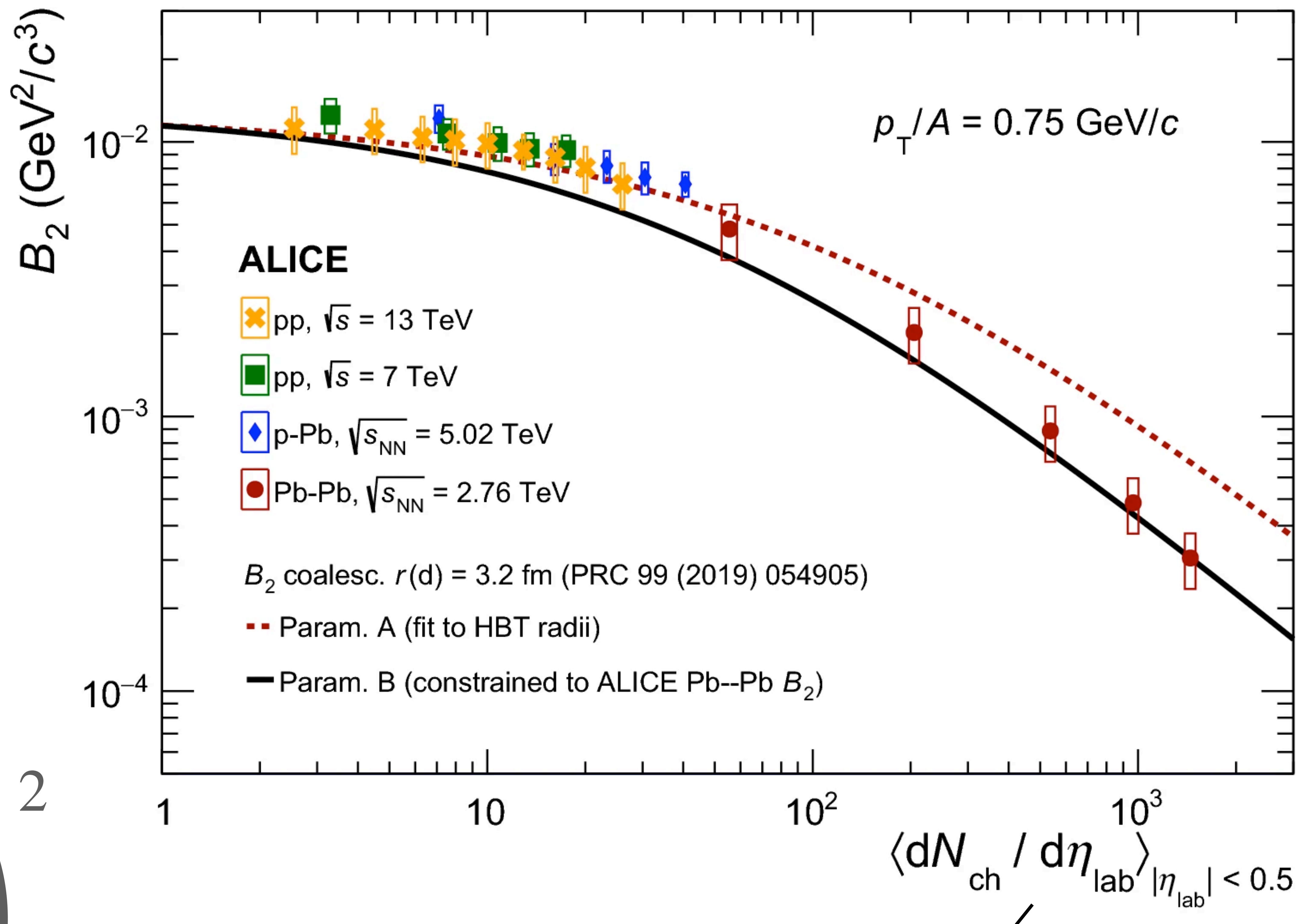
J. Kapusta, Phys. Rev. C 21 (1980) 1301

$$B_2 = E_d \frac{d^3 N_d}{d^3 p_d} \Bigg/ \left(E_p \frac{d^3 N_p}{d^3 p_p} \right)^2$$

Momentum spectra of deuterons

Momentum spectra of protons

ALICE, Eur.Phys.J. C80 (2020) 9, 889



Average charged-particle multiplicity -> proxy for system size

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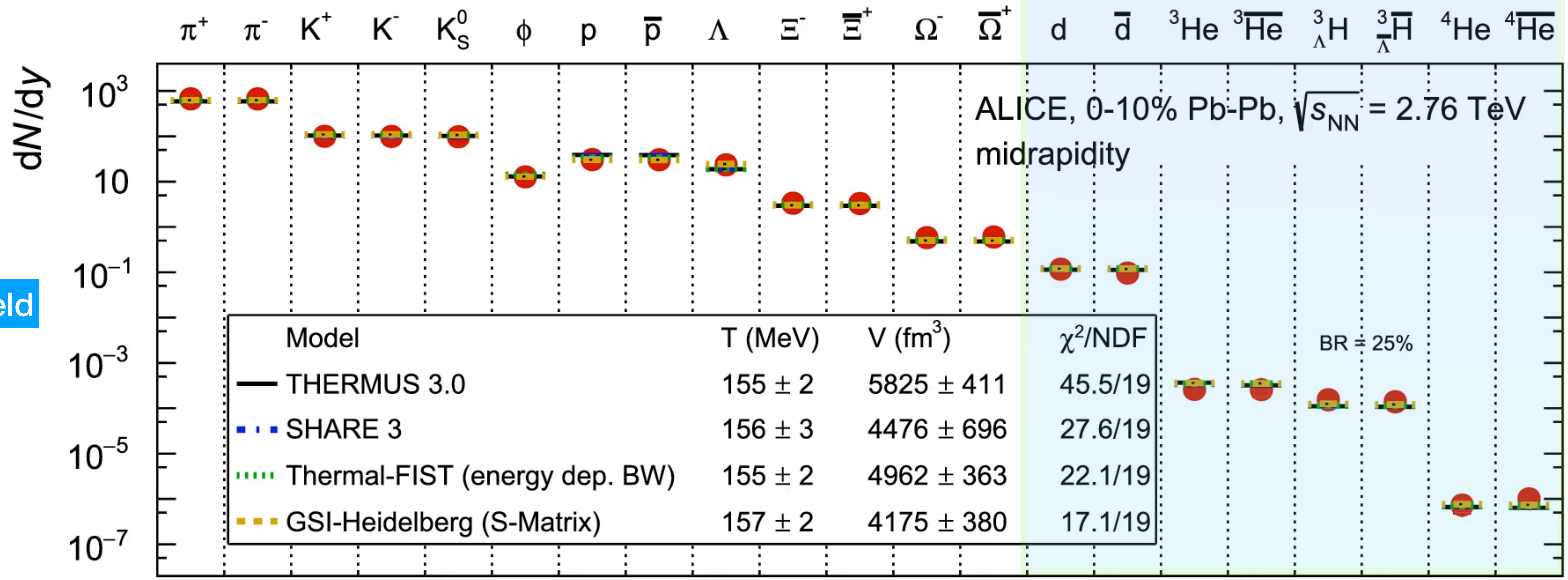
Nuclei synthesis: Thermal model

Integrated yield



ALICE, Eur. Phys. J. C 84 (2024) 813

- Thermal model describes the **yields** of LF hadrons by requiring **thermal** and **chemical equilibrium**
- Provides **very good description** of nuclei production in central Pb-Pb collisions

Nuclei synthesis: Thermal model

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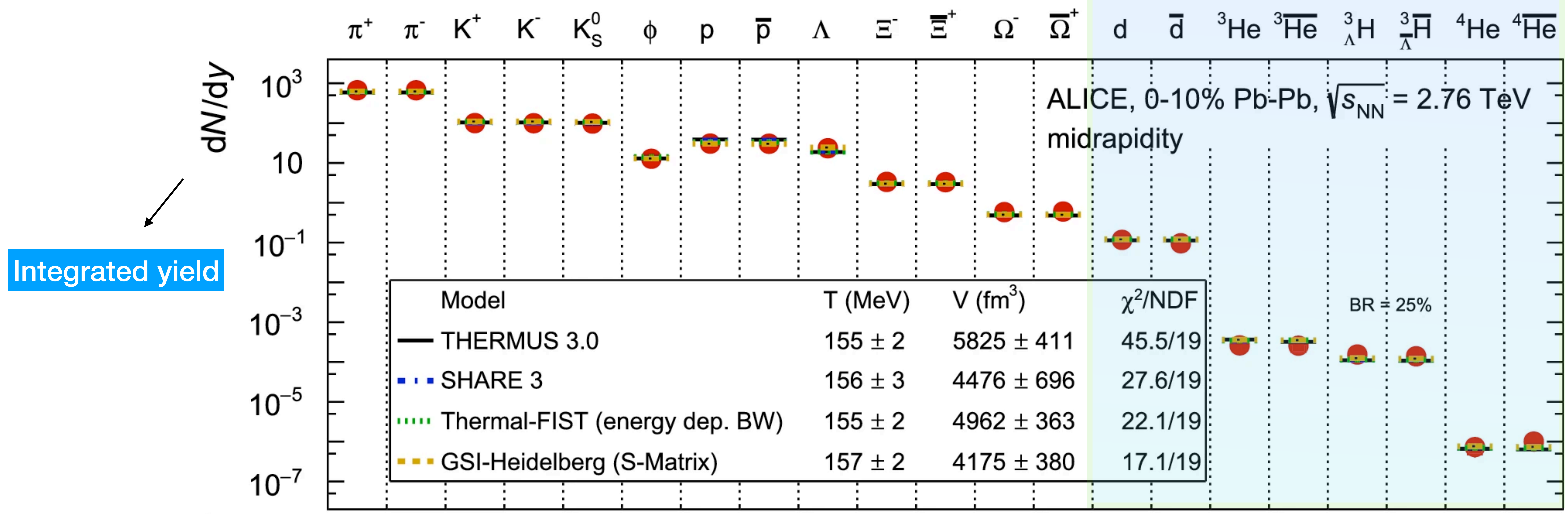

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Temperature of the system ~ 155 MeV
Light nuclei binding energy ~ 1-10 MeV

Snowballs in Hell…

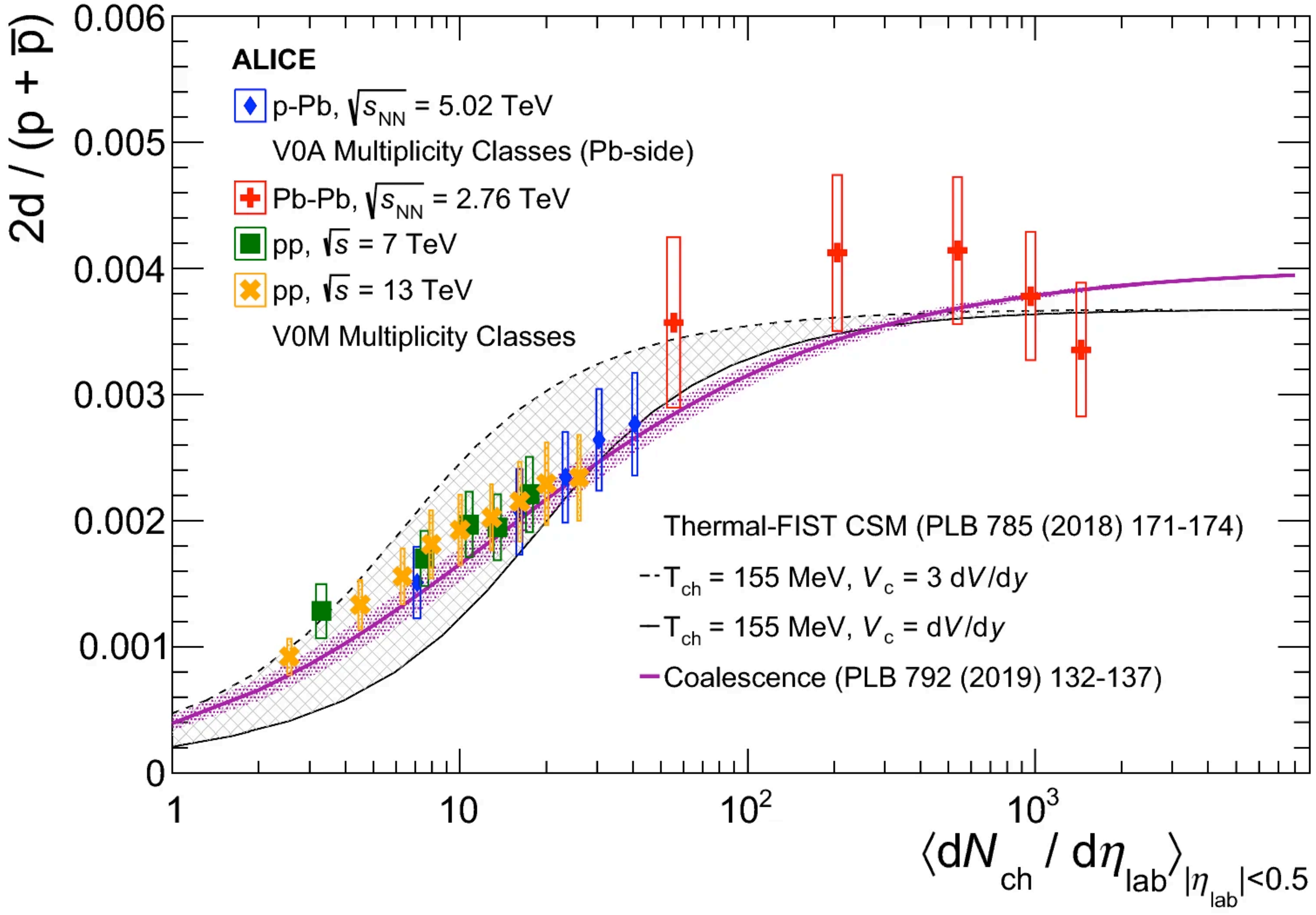
Nuclei synthesis: thermal vs coalescence

- Good description of the deuteron production by both the models

Is it accidental???

How to distinguish between the models?

None of popular generators include the production of nuclei in their default configuration



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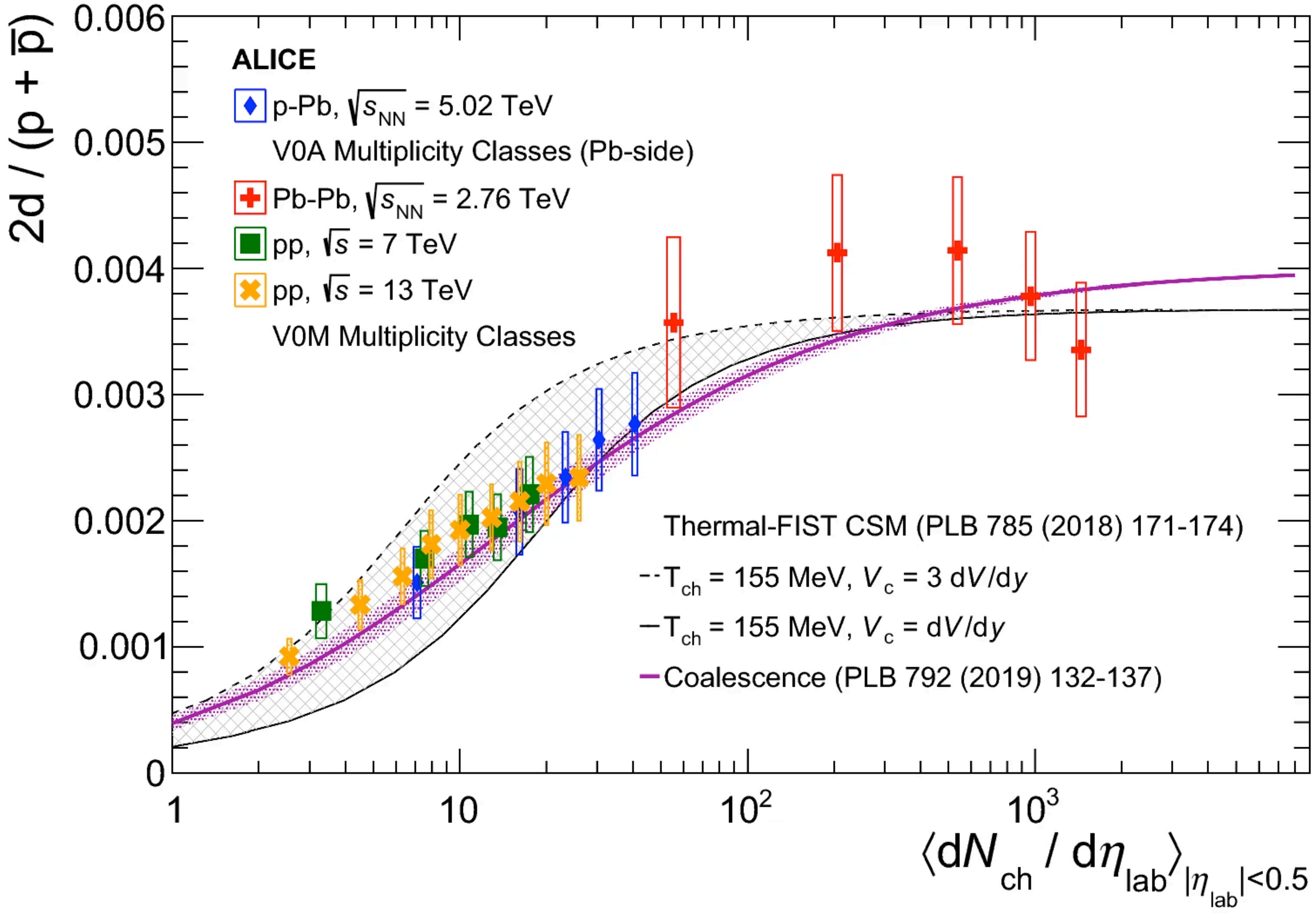
New observable is needed



ALICE, Eur.Phys.J. C80 (2020) 9, 889

Let’s confront the production mechanisms….

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By measuring the baryon number balance

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By measuring the baryon number balance

S. Tripathy, P. Christiansen, arXiv:2509.03195

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Balance functions of protons and deuterons

$$Y(\Delta y, \Delta\varphi) = \frac{1}{N_{\mathrm{trig}}} \frac{d^2 N_{\mathrm{pairs}}}{d\Delta y\, d\Delta\varphi}$$

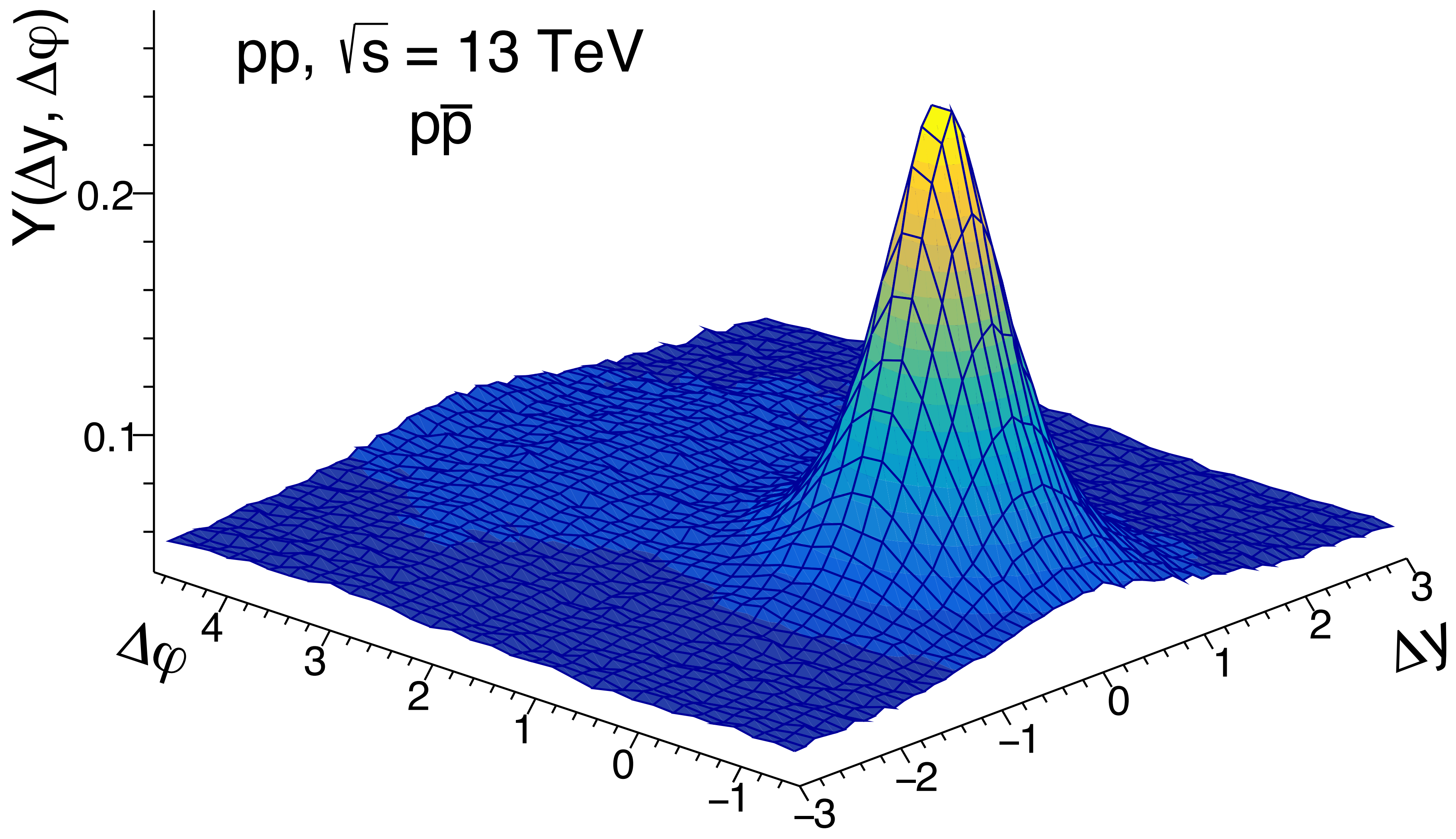
Trigger on protons (p) and deuterons (d)

Measure where baryon number balance end up: antiprotons ($\bar{\mathrm{p}}$), $\bar{\Lambda}$

OS

Subtract the uncorrelated production via the same quantum-number correlations: protons (p), Λ

SS



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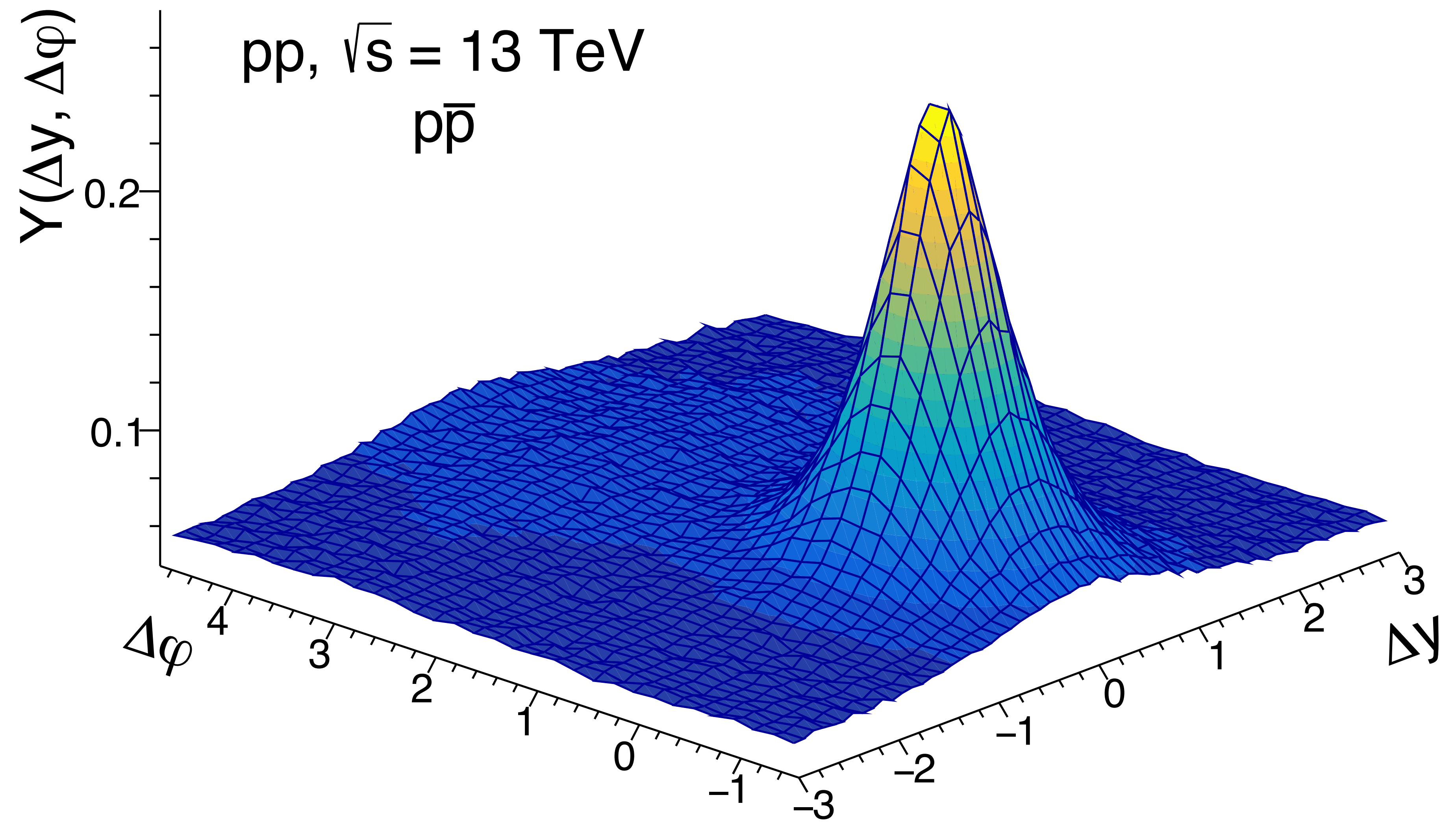

Let's confront the contrasting paradigms: **Thermal-FIST** and PYTHIA8

Thermal production

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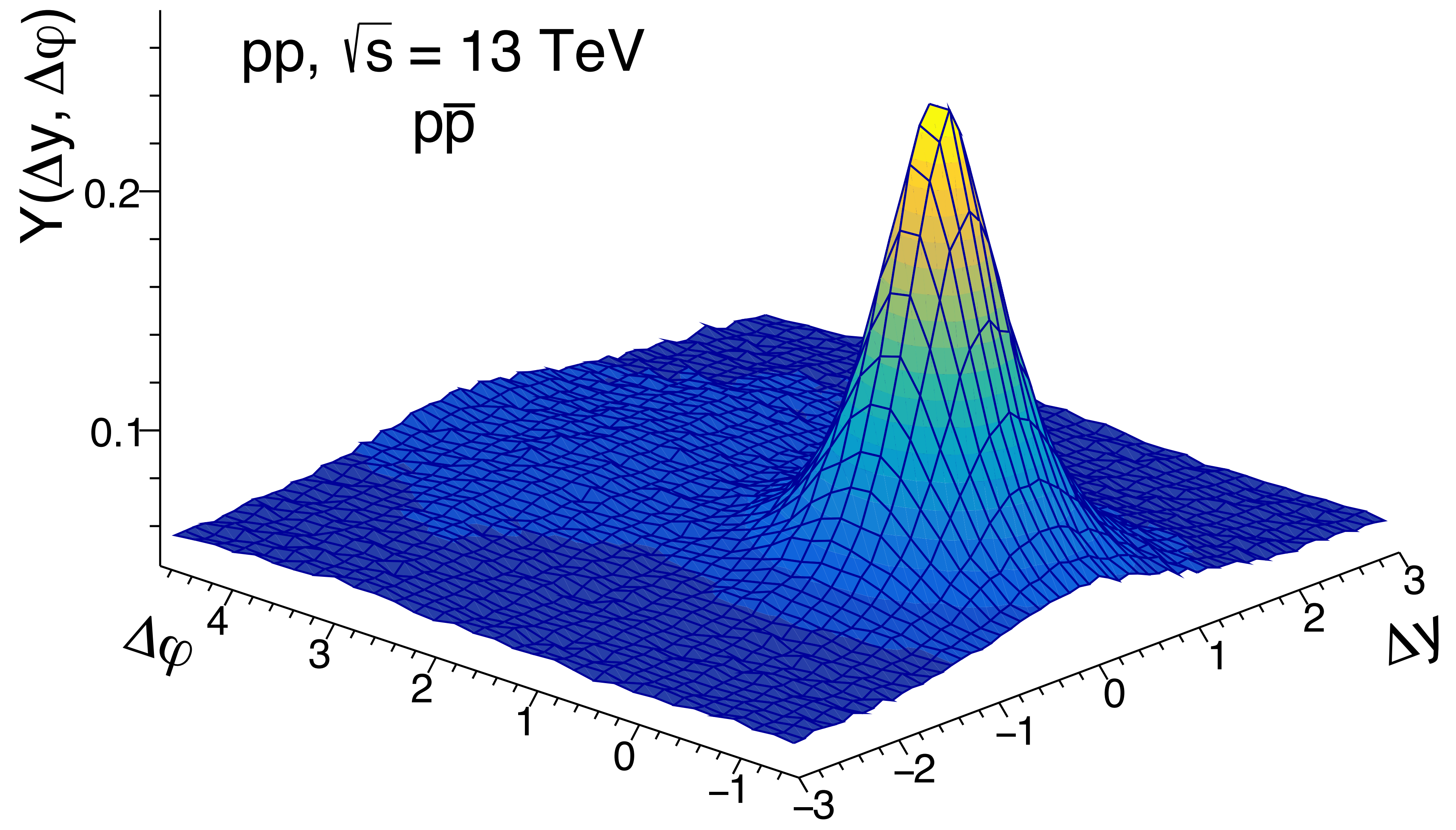


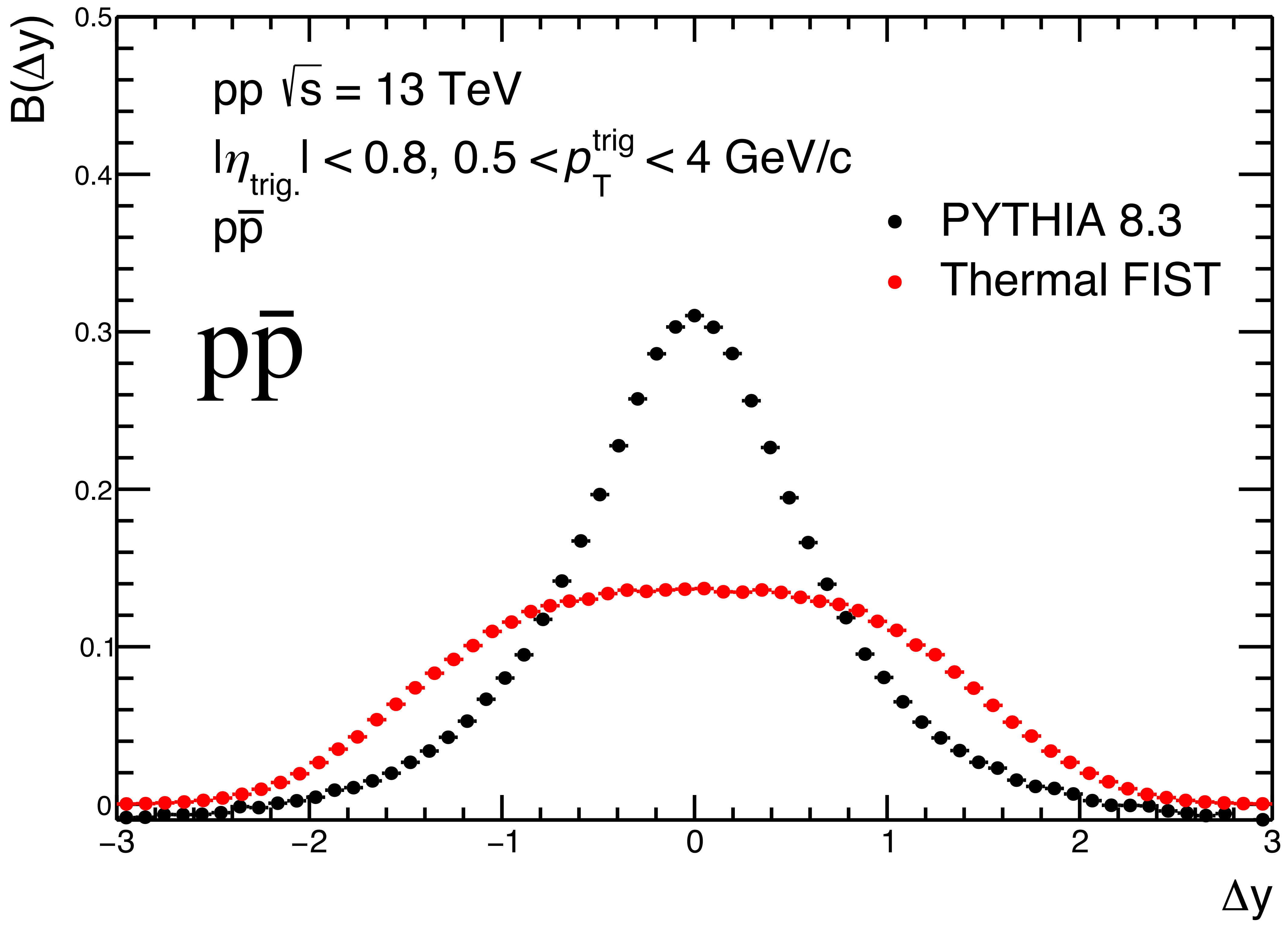
Let's confront the contrasting paradigms: Thermal-FIST and **PYTHIA8**

deuterons with a cross-section based model (only momentum criteria for coalescence)

Balance functions of protons and deuterons

- Cuts on trigger: |eta| < 0.8, **d: 1 < p_T < 8 GeV/c, p: 0.5 < p_T < 4 GeV/c**

$$B(\Delta y) = OS - SS$$



- Clearly different shape of balance functions from Thermal-FIST and PYTHIA 8.
  In Thermal FIST, it is driven by correlation volume (see backup)

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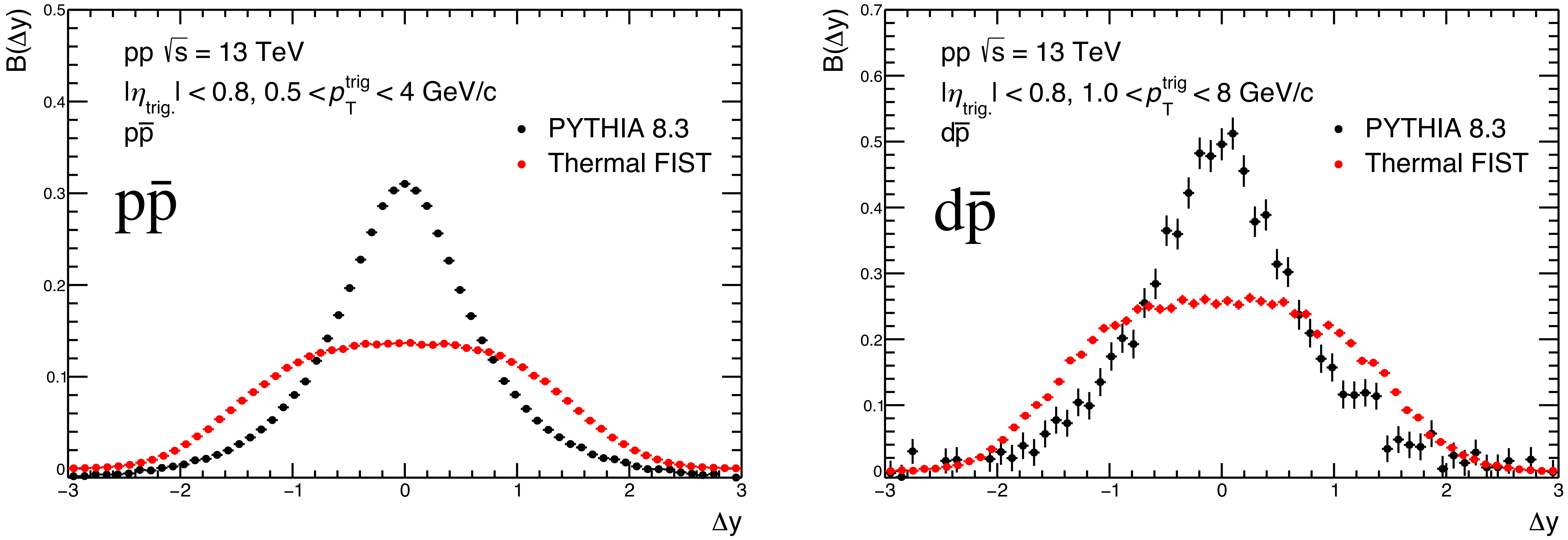
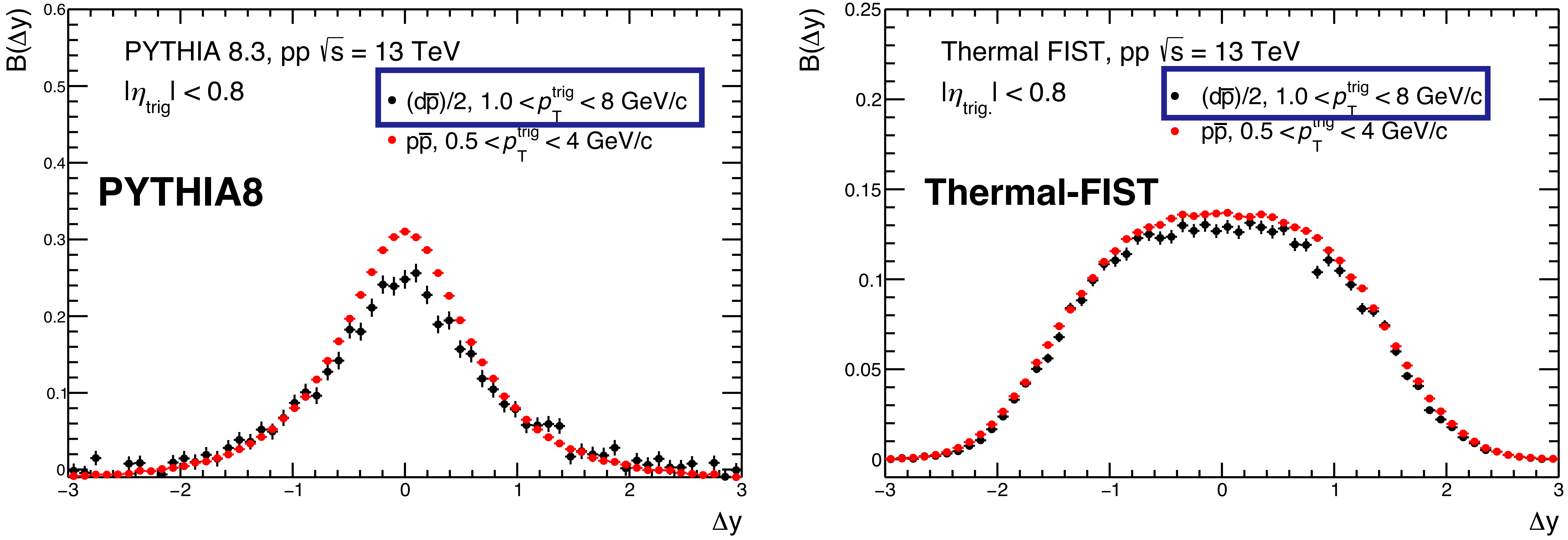


- Clearly different shape of balance functions from Thermal-FIST and PYTHIA 8.
  In Thermal FIST, it is driven by correlation volume (see backup)
- Similar shapes of balance functions for triggered protons and deuterons

Balance functions of protons vs. deuterons

- Cuts on trigger: |eta| < 0.8, **d: 1 < p_T < 8 GeV/c, p: 0.5 < p_T < 4 GeV/c**

$$B(\Delta y) = OS - SS$$



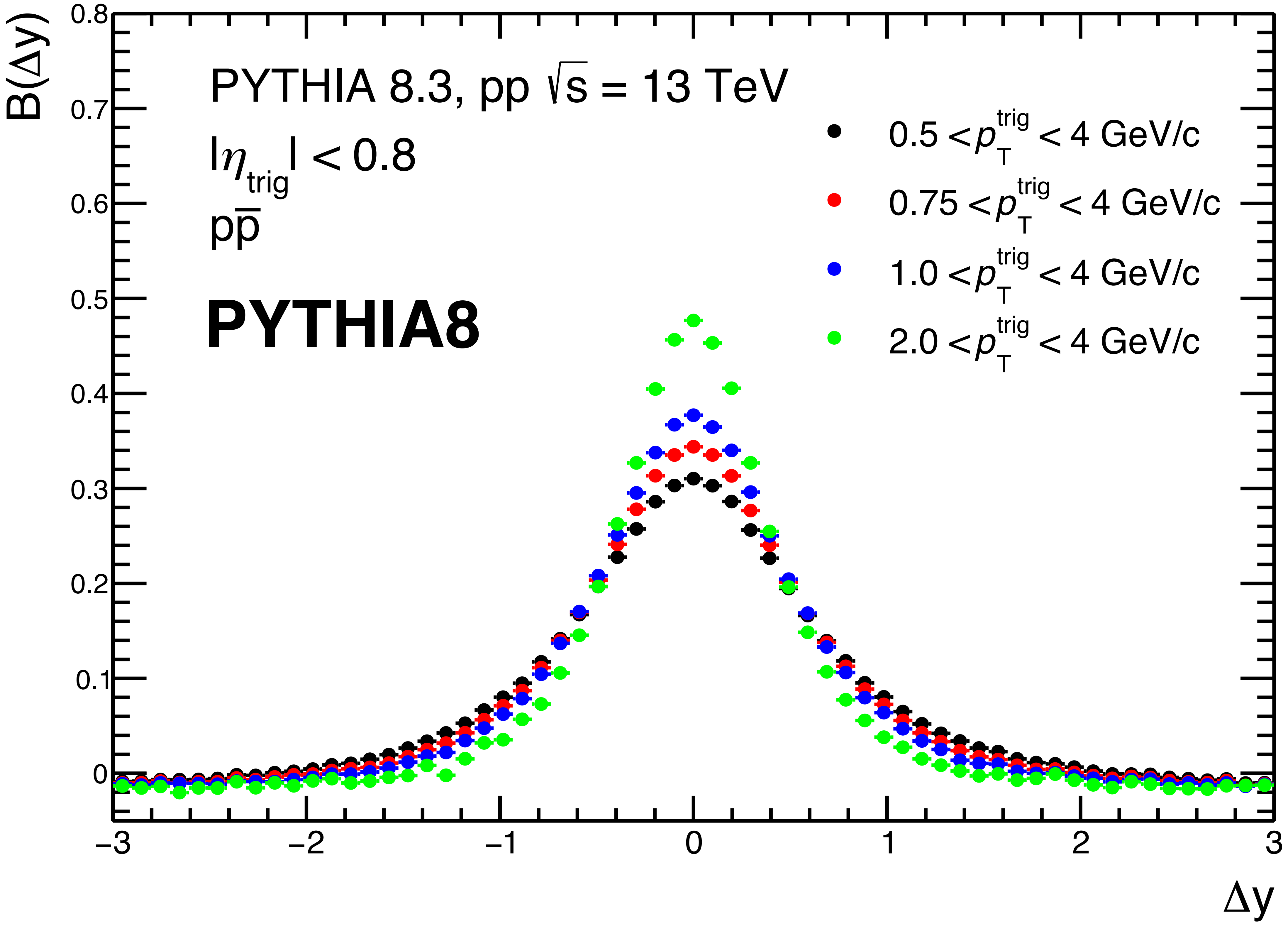
- Since a deuteron consists of two nucleons, its balance function is expected to be twice that of a proton.
- Both models confirm this behavior

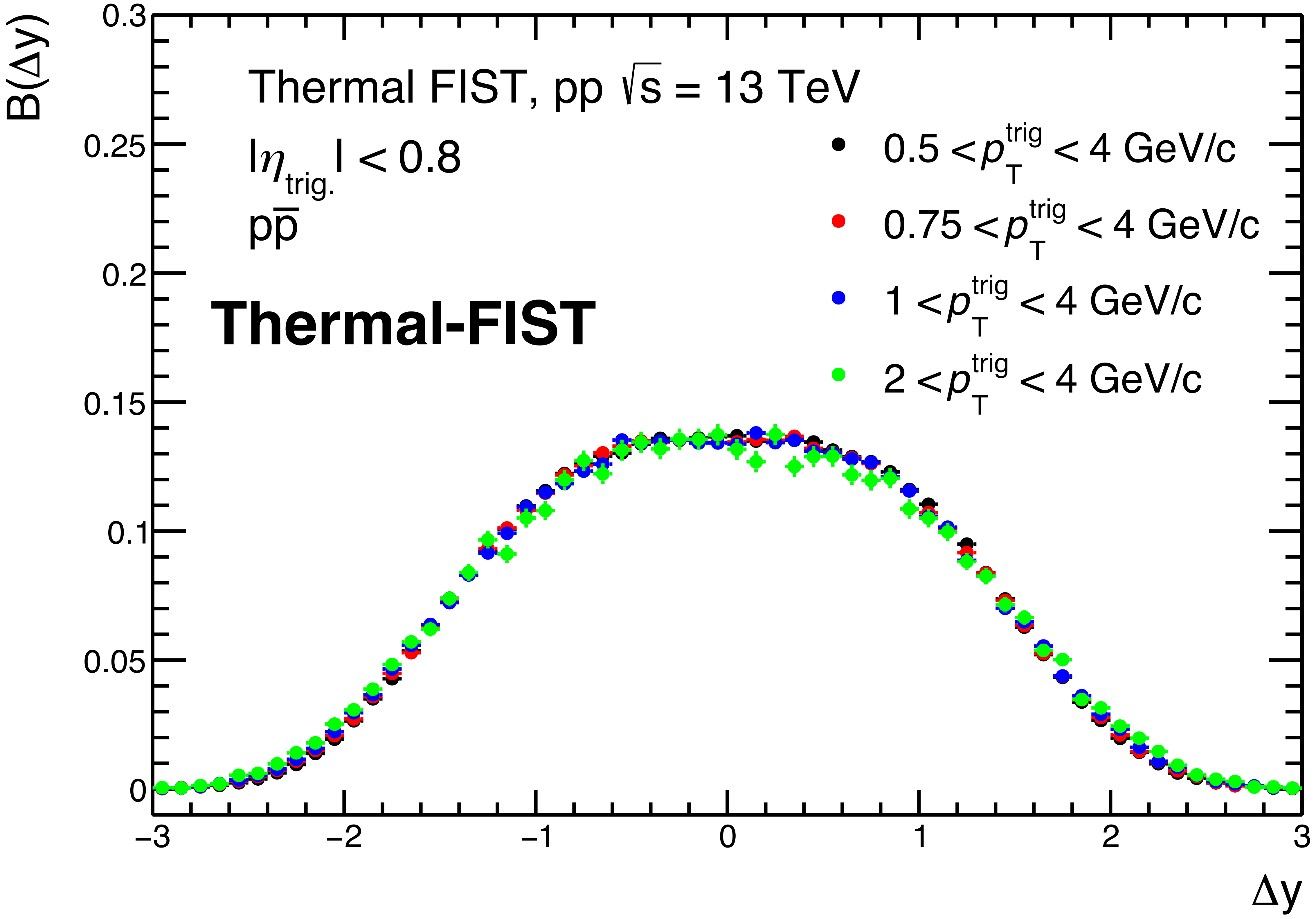
Transverse momentum dependence

$p\bar{p}$

- Now **varying the trigger p_T** in both models for triggered-**protons**

$$B(\Delta y) = OS - SS$$





- **Narrowing in PYTHIA**: the antiproton that balance a proton is produced on the same string as the proton
- **No dependence in Thermal FIST:** quantum number conservation is only imposed globally on the final state

Transverse momentum dependence

$d\bar{p}$

- Now **varying the trigger p_T** in both models for triggered-**deuterons**

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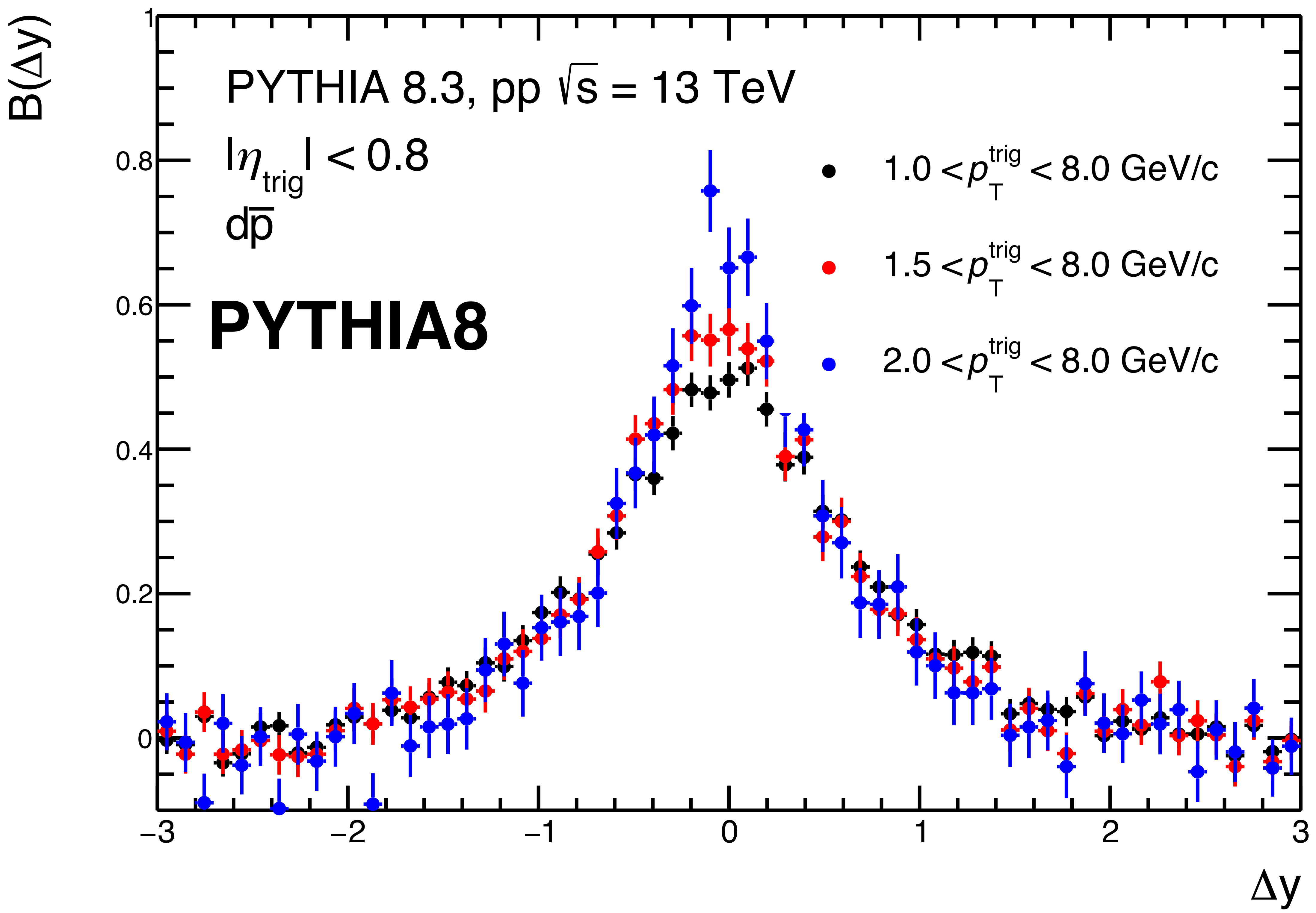
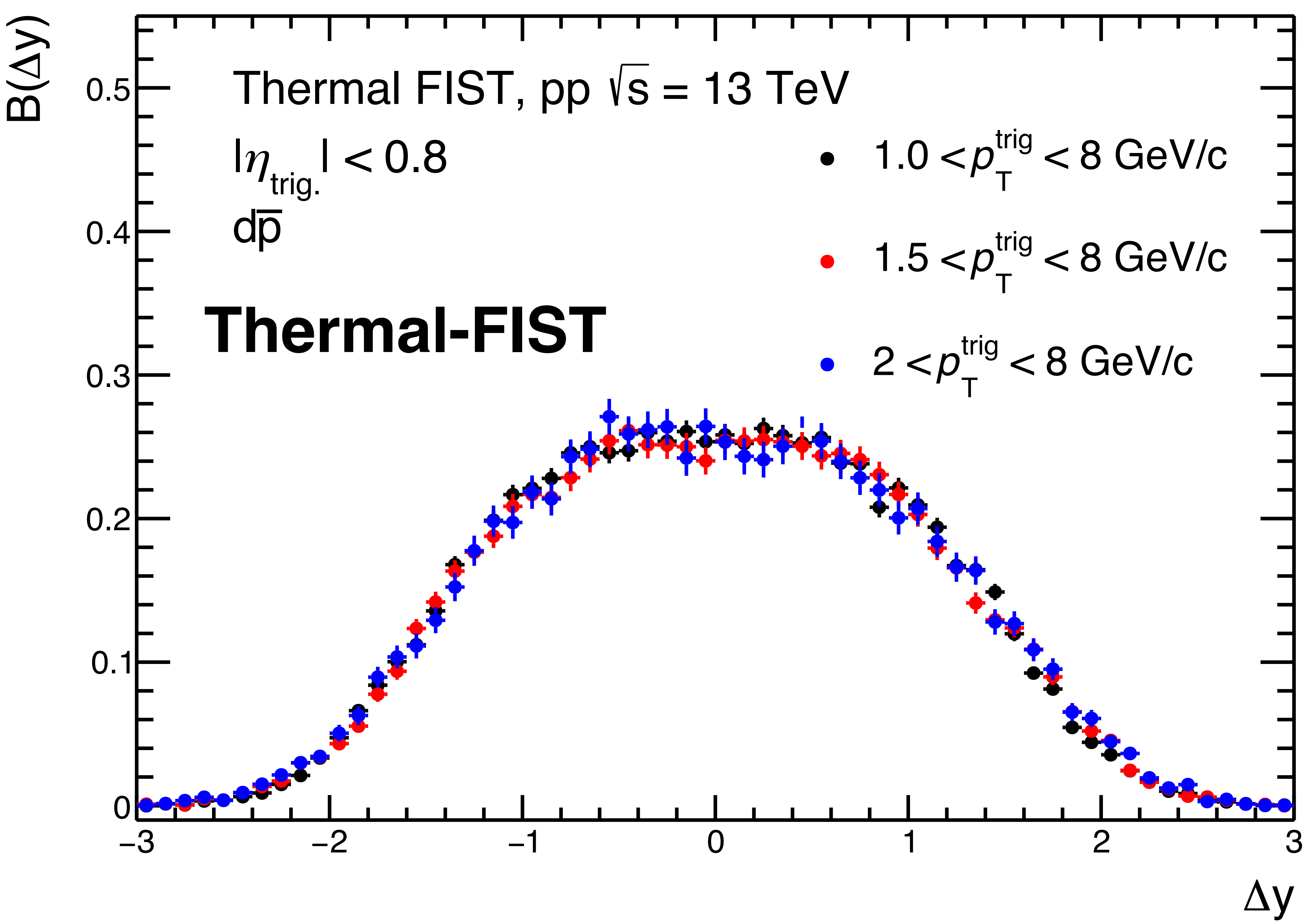




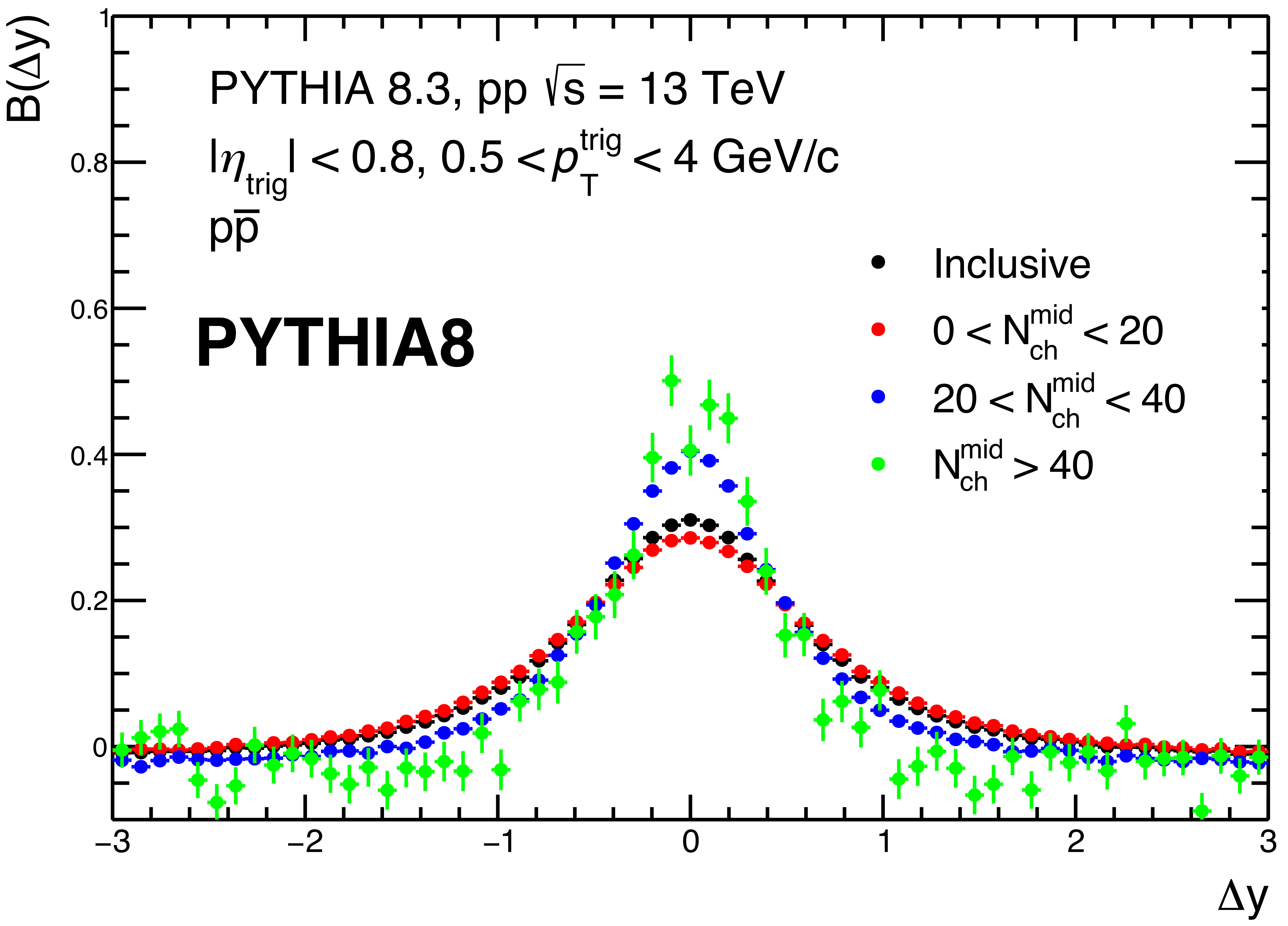
- Same observation is seen for triggered-deuterons
- It will be interesting to study these in experiments.

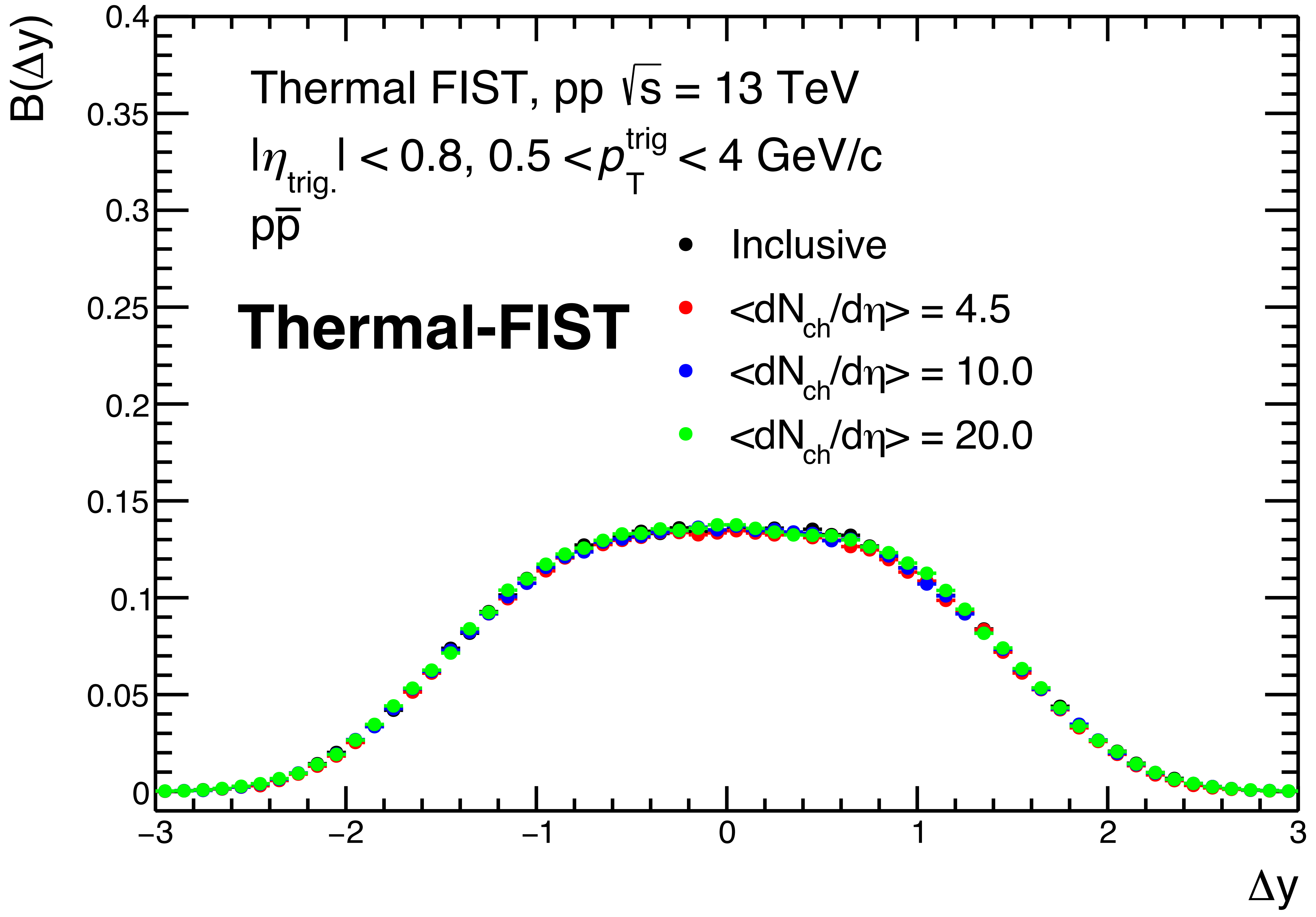
Multiplicity dependence

$p\bar{p}$

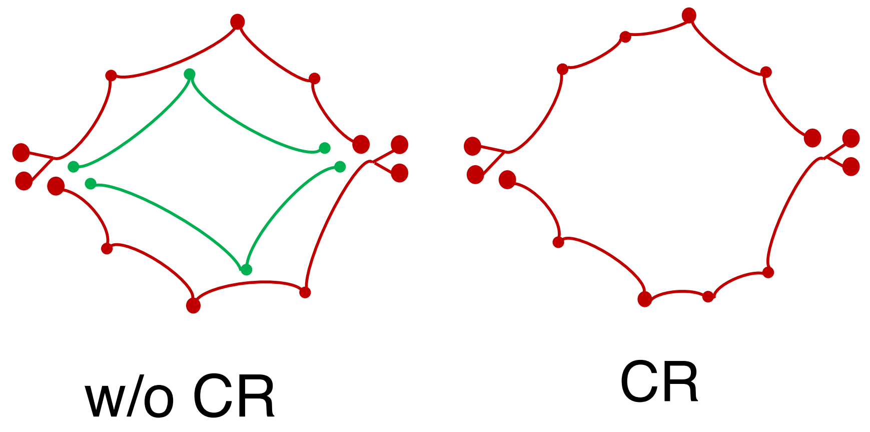
- Now **varying the multiplicity** in both models for triggered-**protons**

$$B(\Delta y) = OS - SS$$





- Moderate multiplicity dependence in PYTHIA 8
- Driven by color reconnection (CR)



Summary

- The **light nuclei production mechanism** is still a **puzzle** at the LHC.
- None of the observables have been successful in pinpointing the production mechanism
- **Proton and deuteron-triggered balance function can be an interesting observable to provide insight into the puzzle**
- A particularly striking difference emerges in the transverse momentum dependence of the balance function: **a promising discriminator**
- **Experimental measurements with ALICE data** is in progress! Stay tuned!

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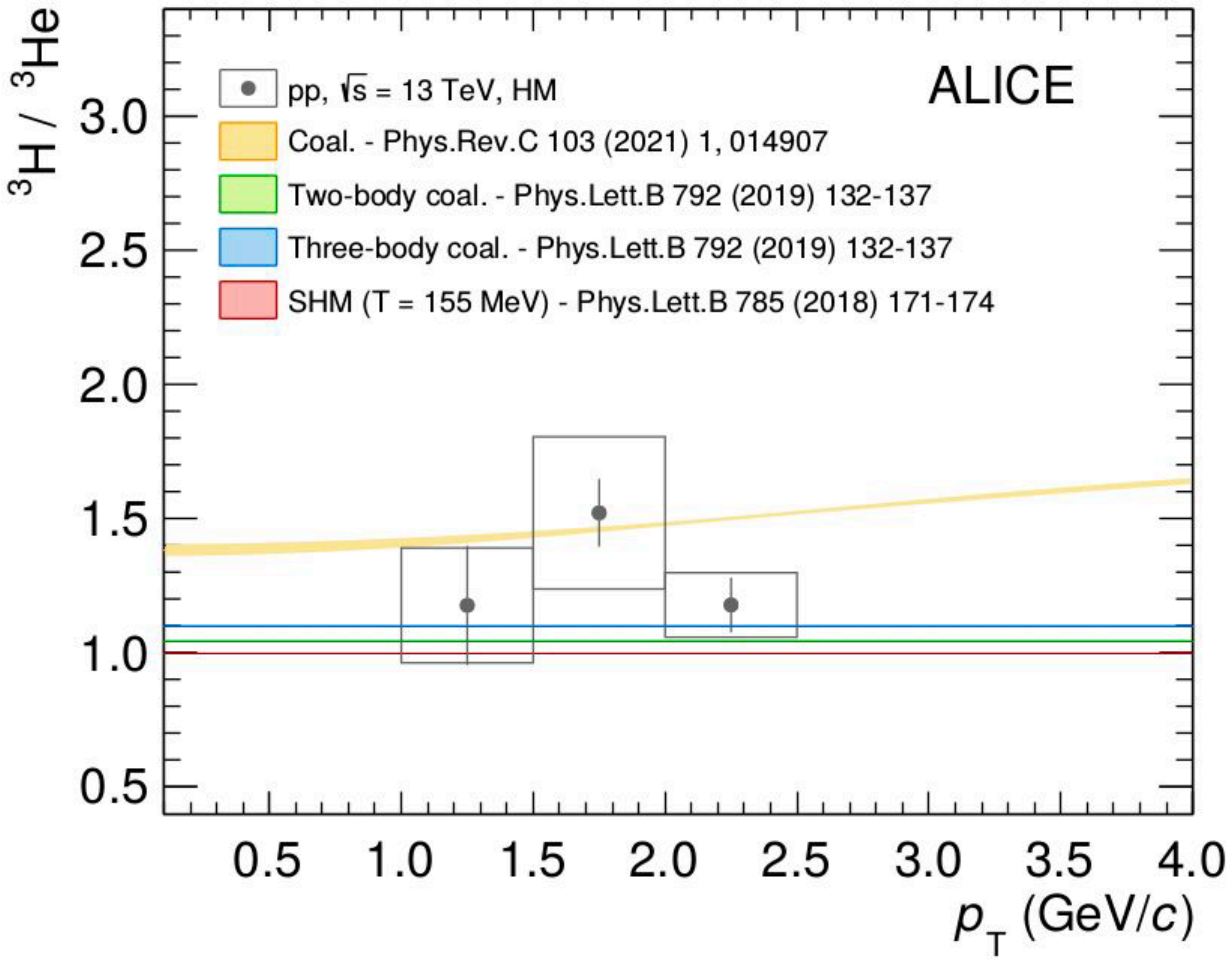
Thank you for your attention!

Backup

Nuclei synthesis: A = 3 nuclei

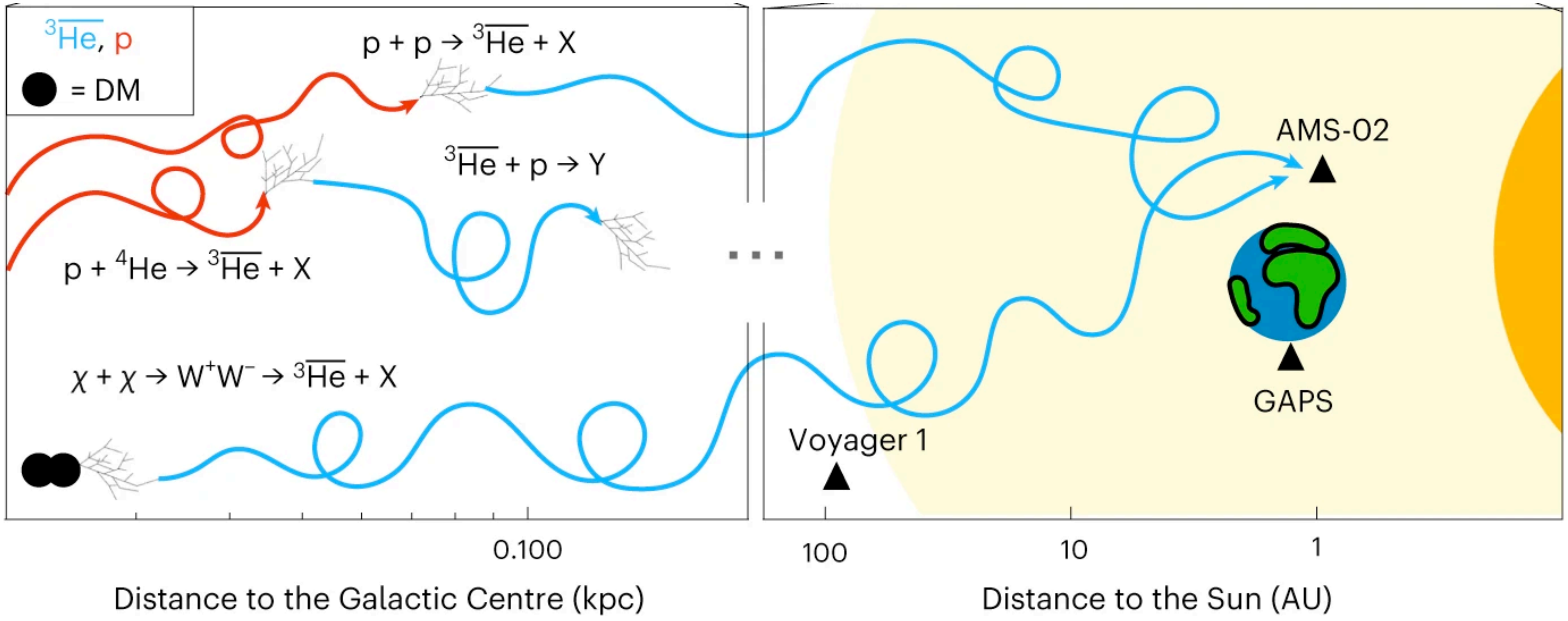
- A = 3 production can be probed by $^3H/^3He$ ratio
- **SHM**: $^3H/^3He \sim 1$ due to similar masses
- **Coalescence**: $^3H/^3He > 1$ due to different source sizes
- No conclusive evidence to distinguish between production mechanisms



ALICE, JHEP 01 (2022) 106

Motivation

- Antinuclei in space-borne experiments can be a sign of **Dark Matter** annihilation:
  - *Background*: the antinuclei produced by hadronic collisions in space constitutes an irreducible background



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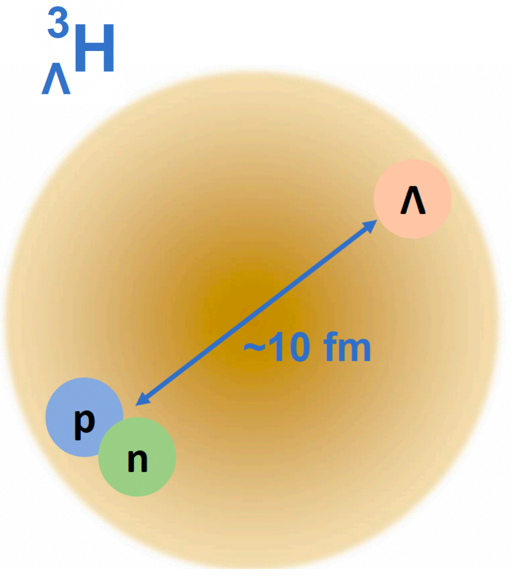
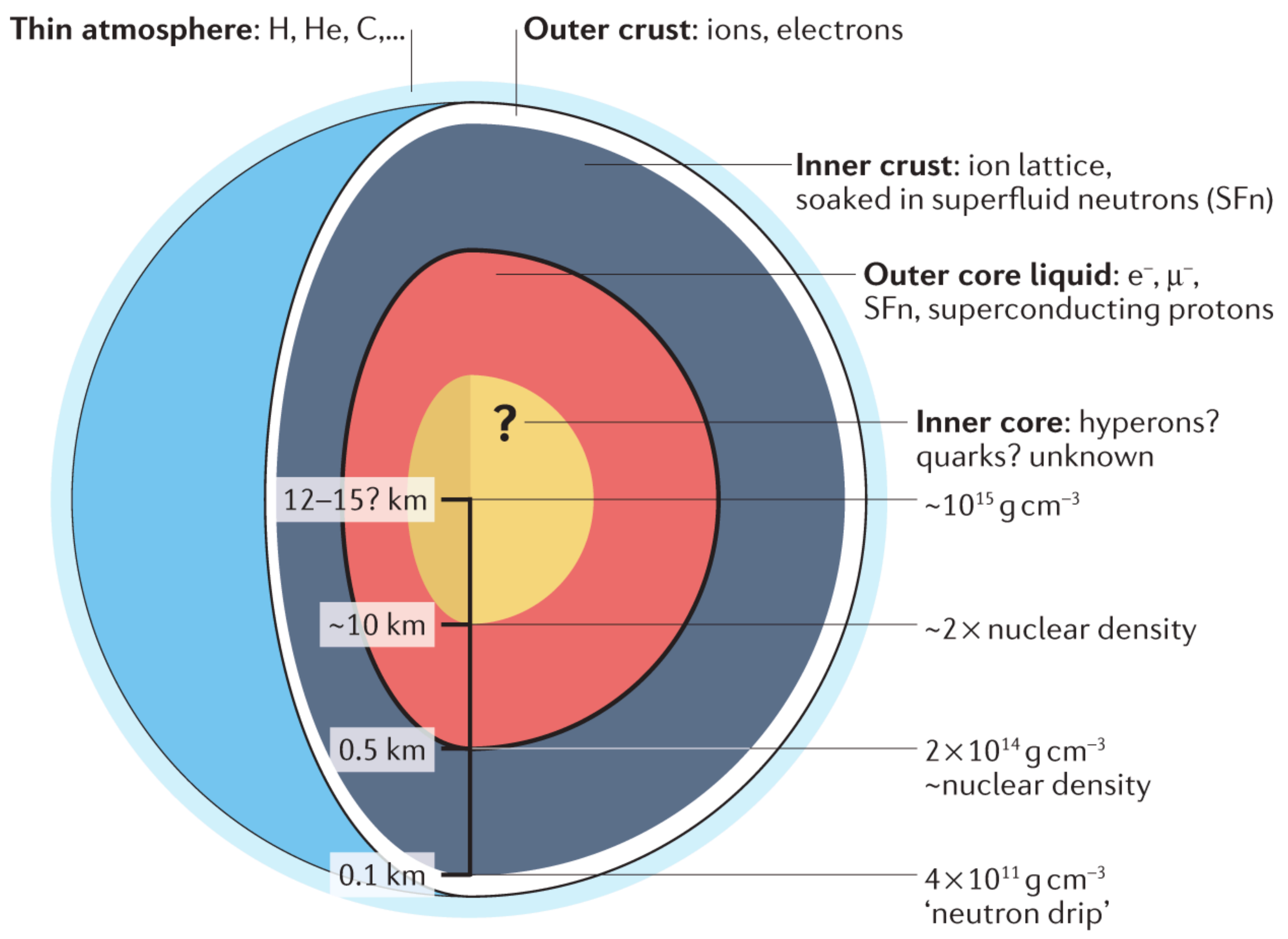
- **Hypernuclei** can be used to study nucleon-hyperon interaction
  - Application for the studies of **neutron stars**



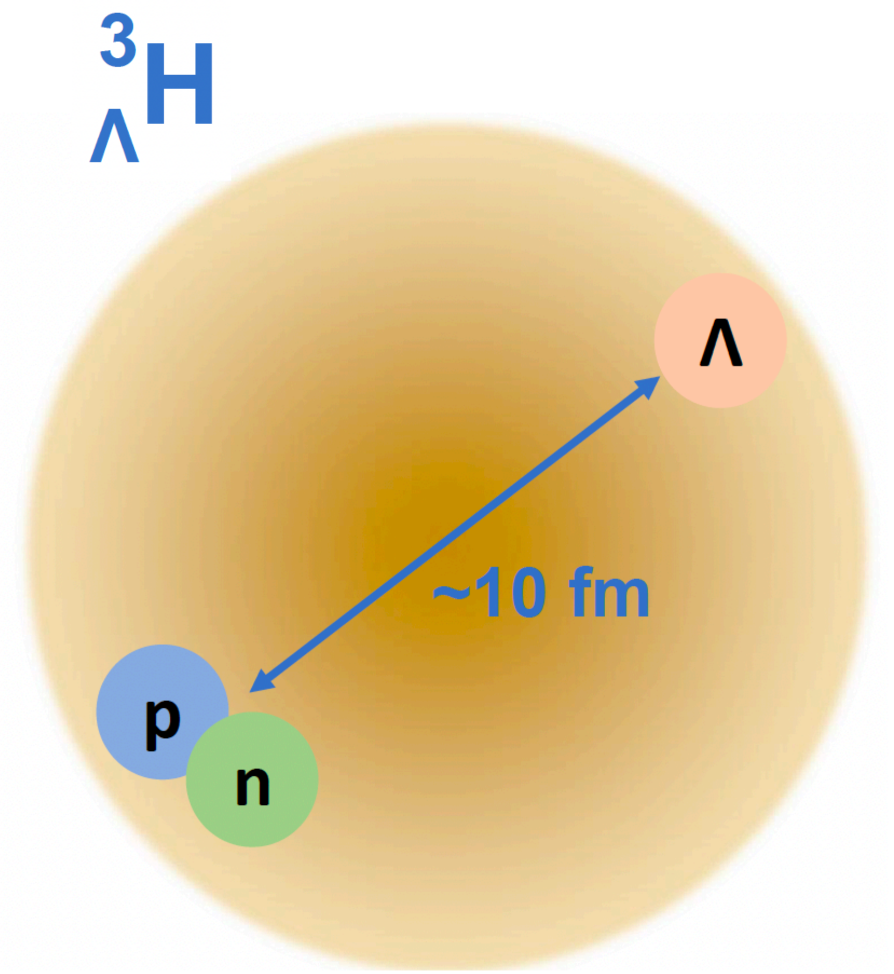


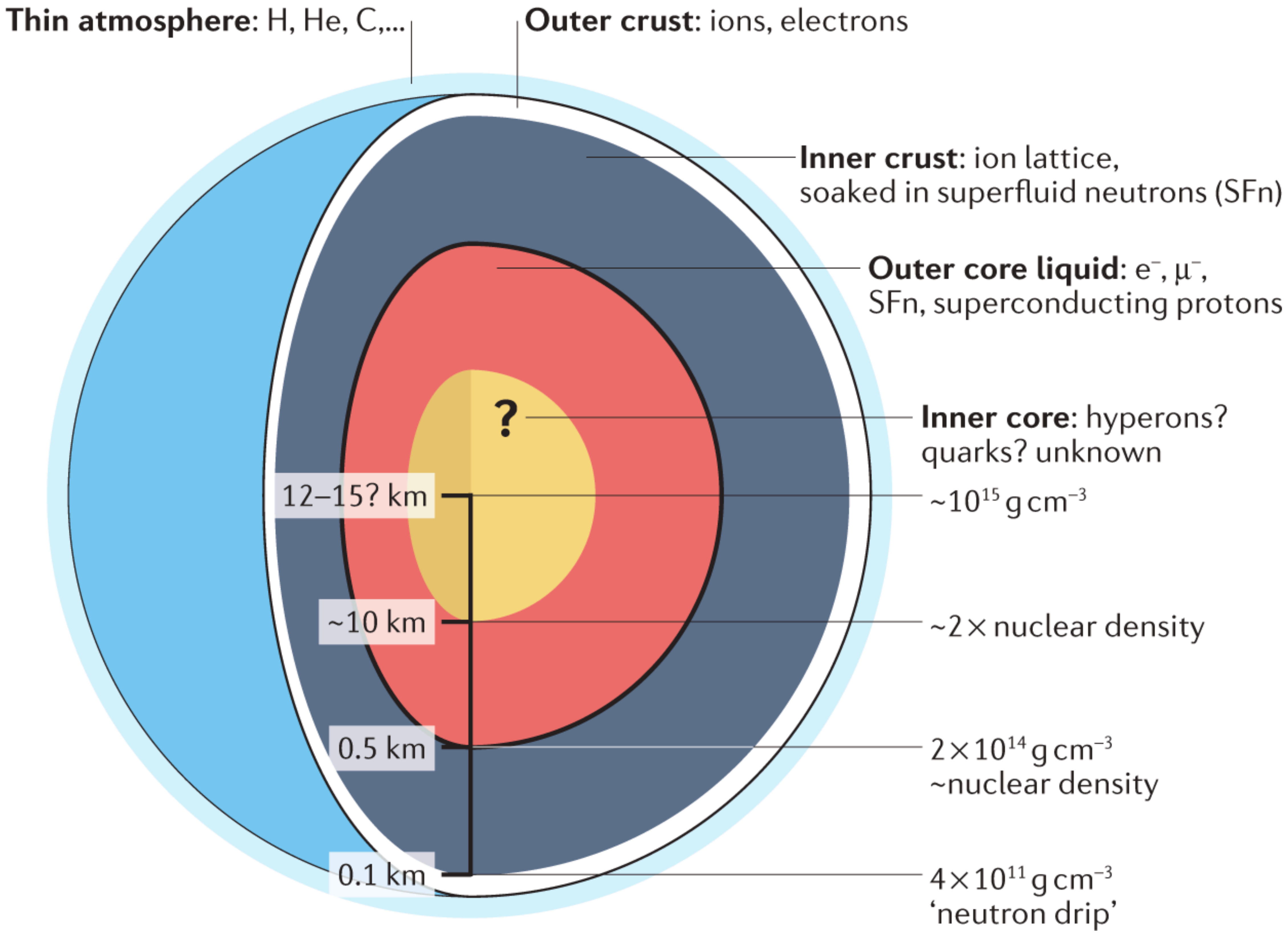
Yunes et. al., Nature Reviews Physics 4, 237(2022)

Focus of the talk
How nuclei are formed in collider experiments?

Motivation

- **Hypernuclei** can be used to study nucleon-hyperon interaction
  - Production of exotic bound states
  - Determination of the **equation of state**
  - Application to **neutron stars**





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Balance functions with pions

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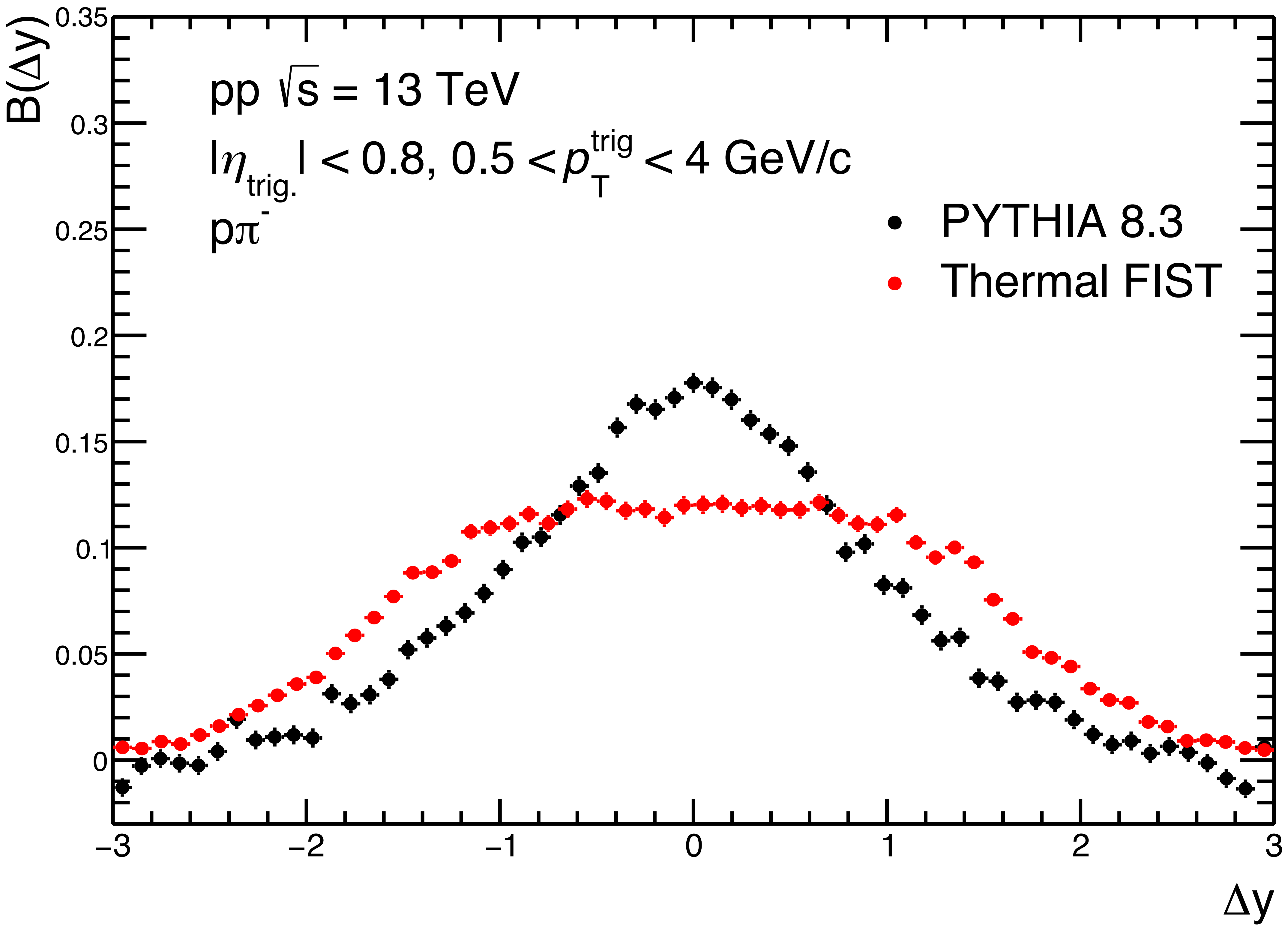
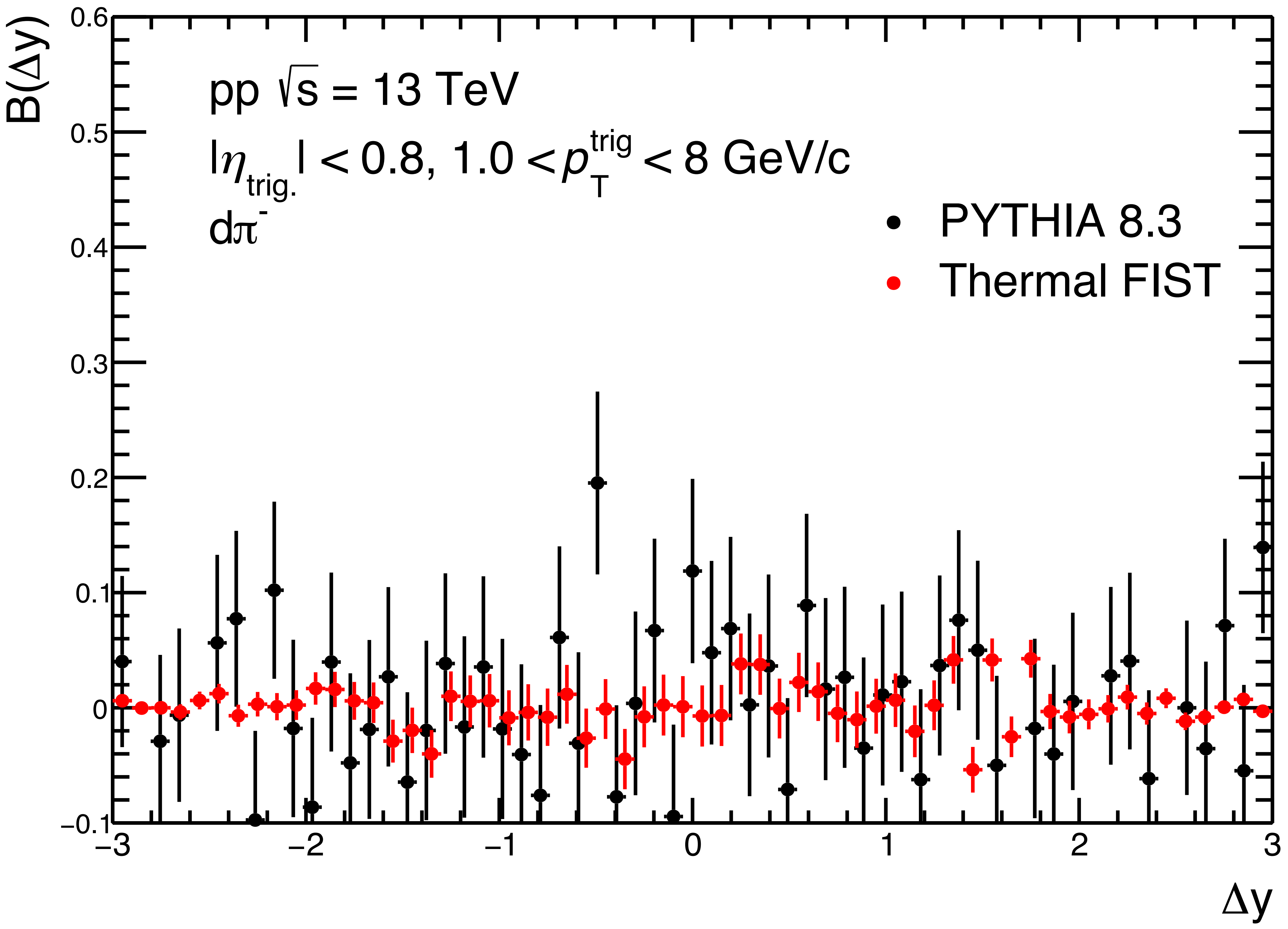
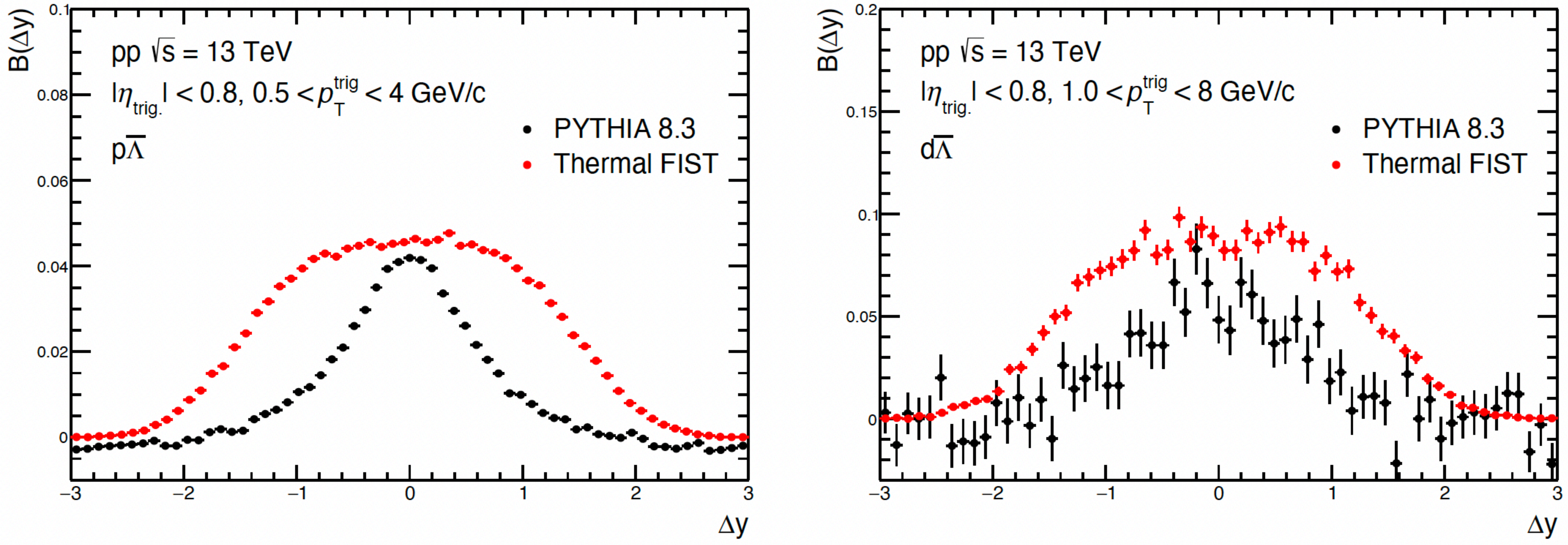
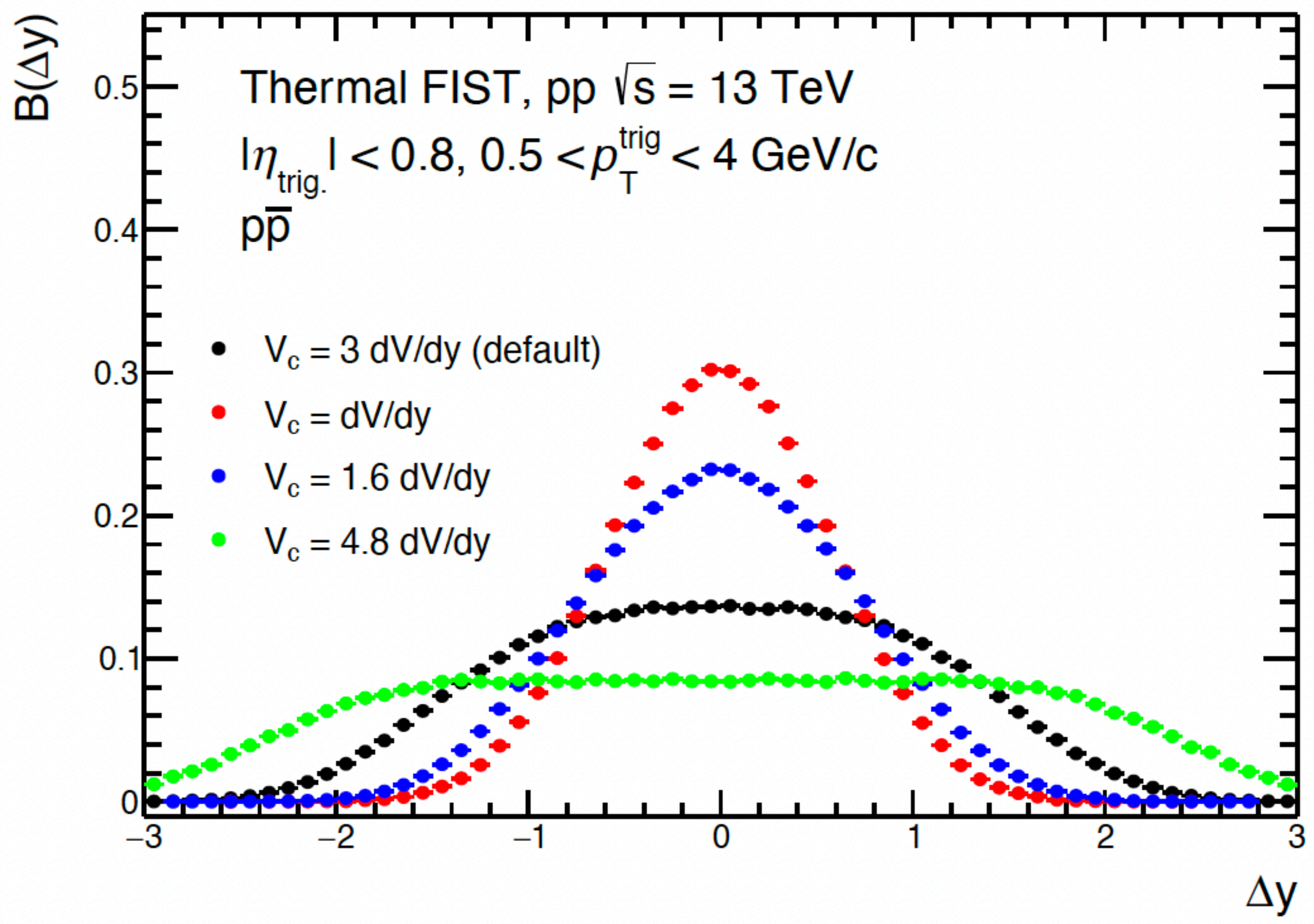


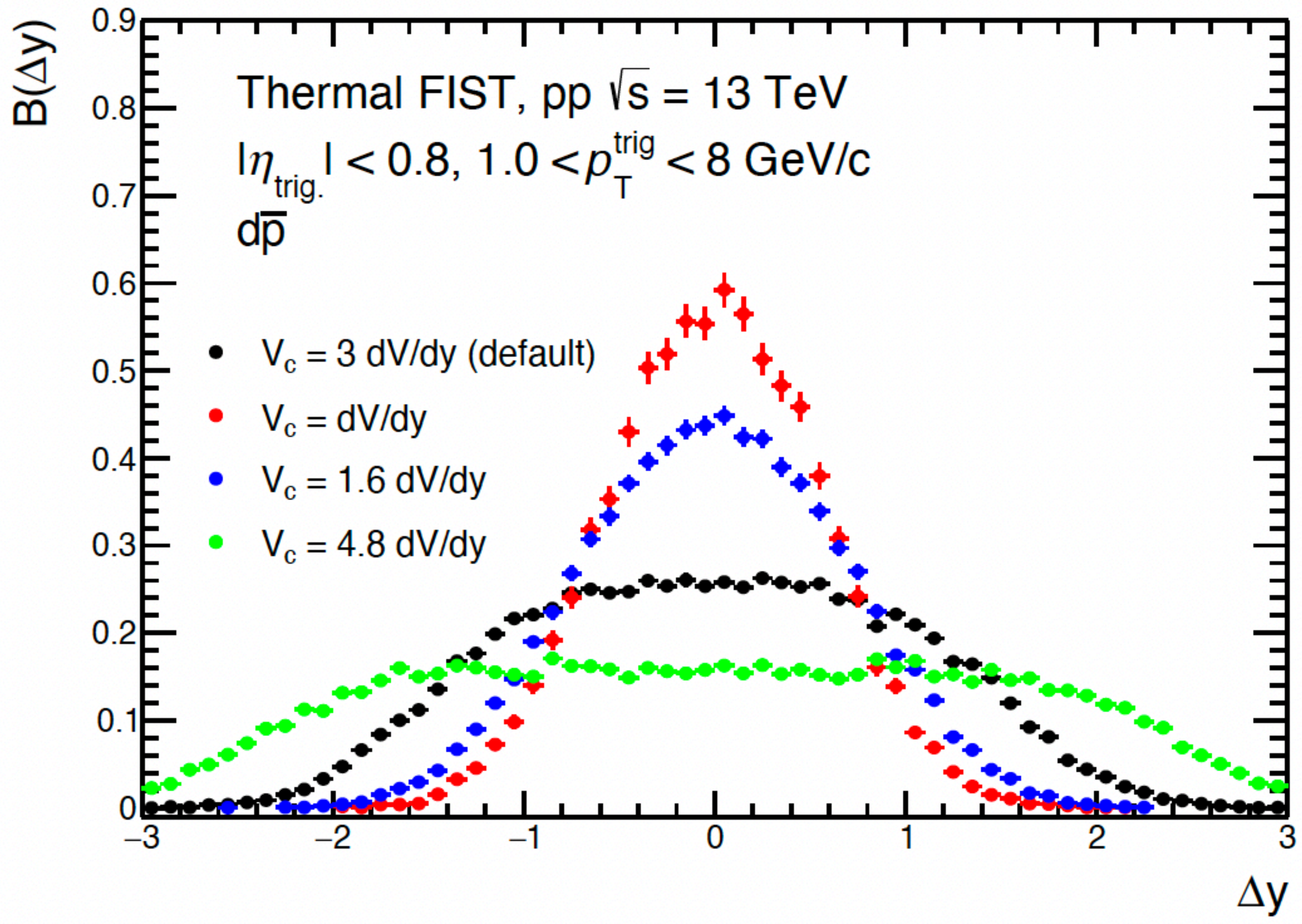


Balance functions with Lambda

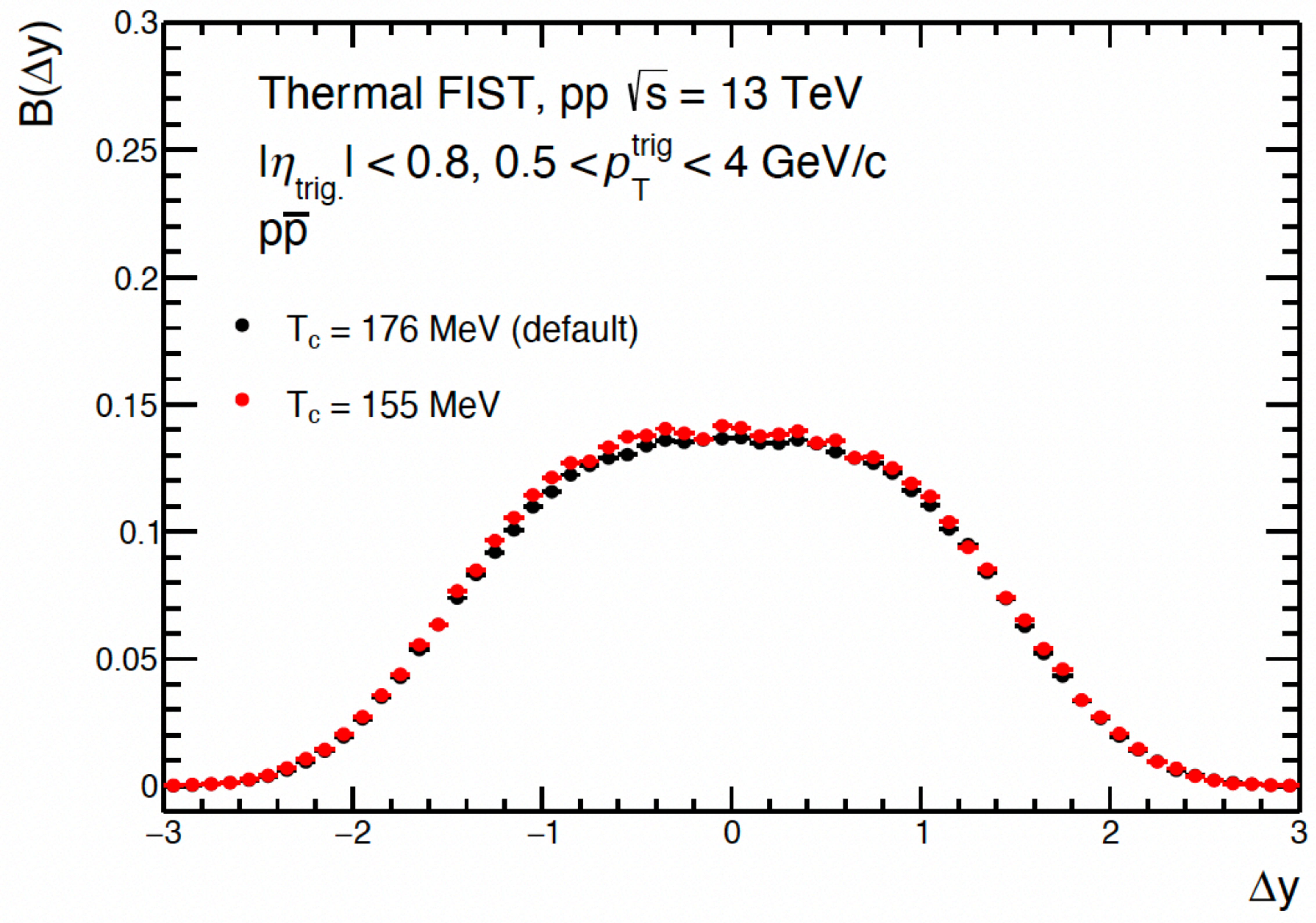


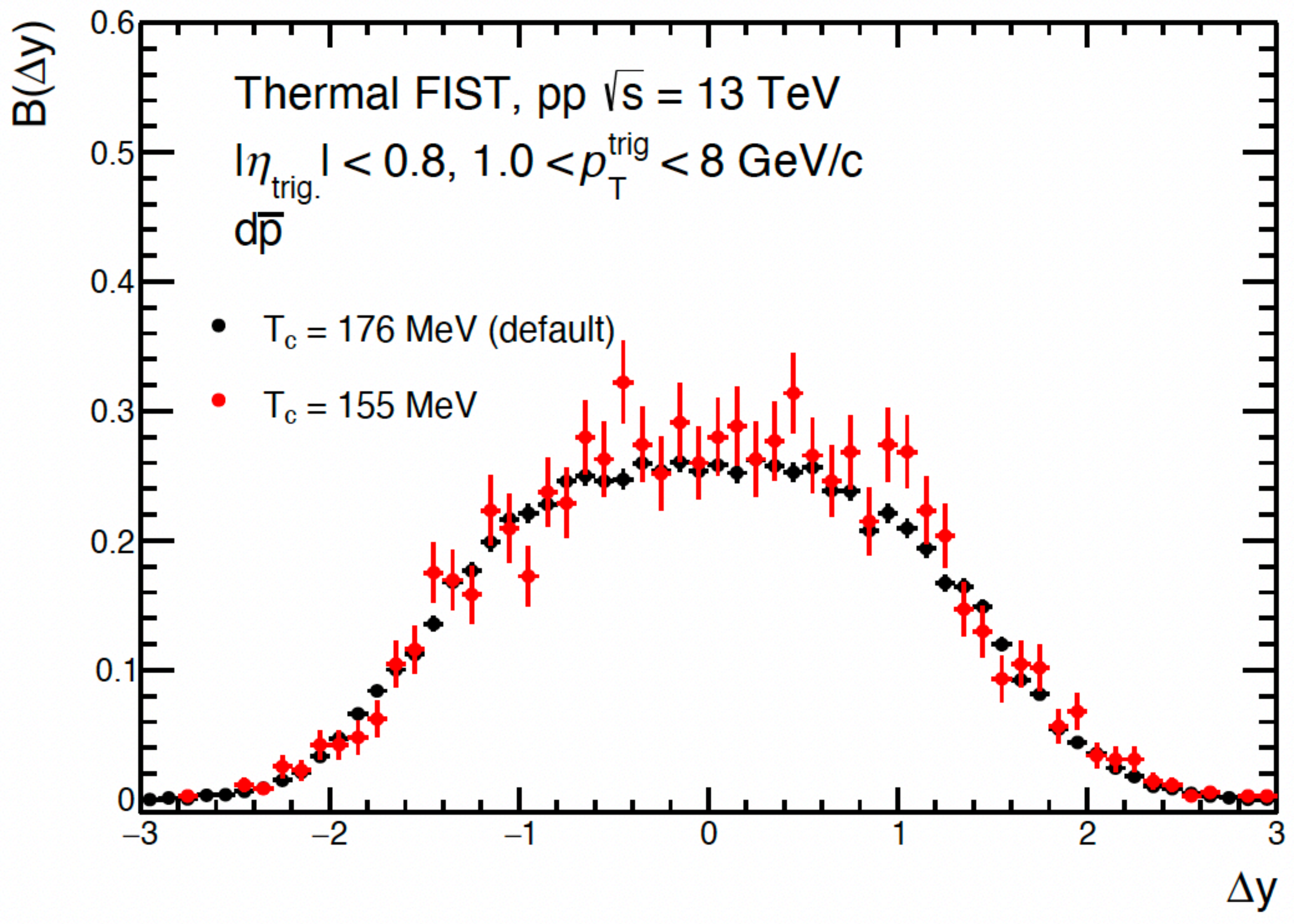
Correlation volume in FIST





Temperature in FIST

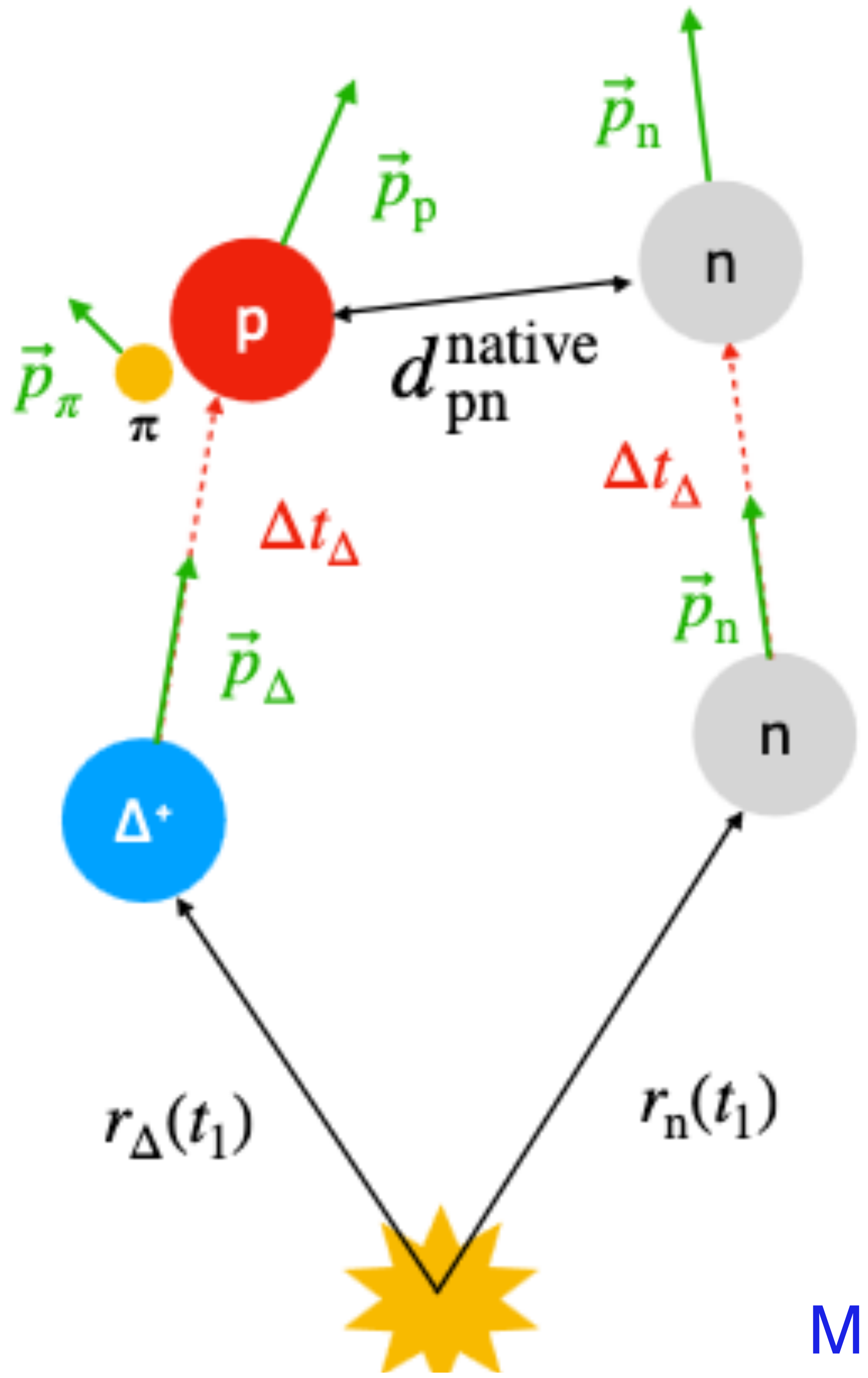




Next step

- PYTHIA produces deuterons with a cross-section based model (only momentum criteria for coalescence)
- Use a realistic coalescence model and obtain the balance functions

E-by-E Wigner approach



M. Mahelin, F. Bellini, S. Tripathy *et. al.*, Eur. Phys. J. C83 (2023) 9, 804

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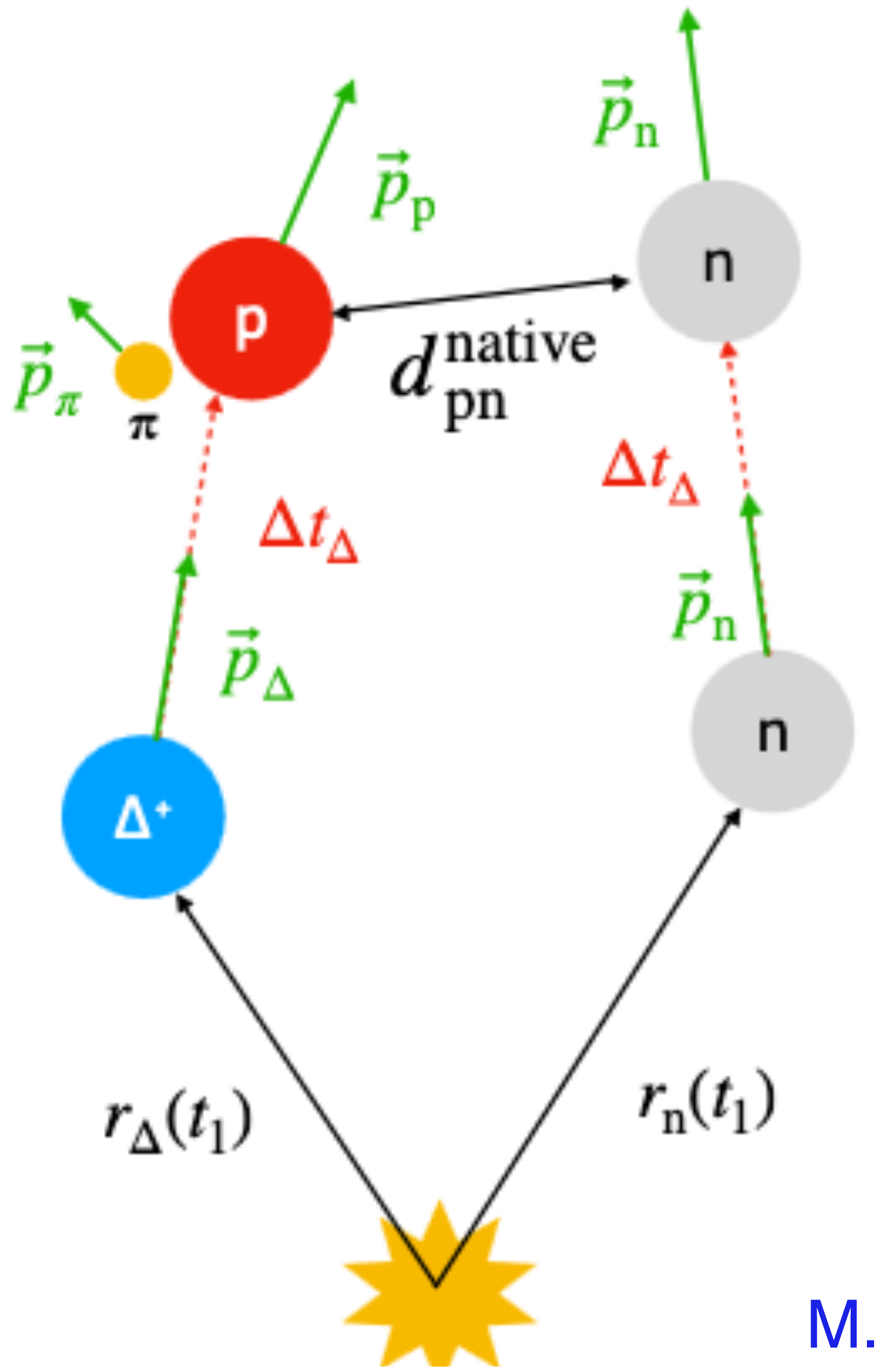
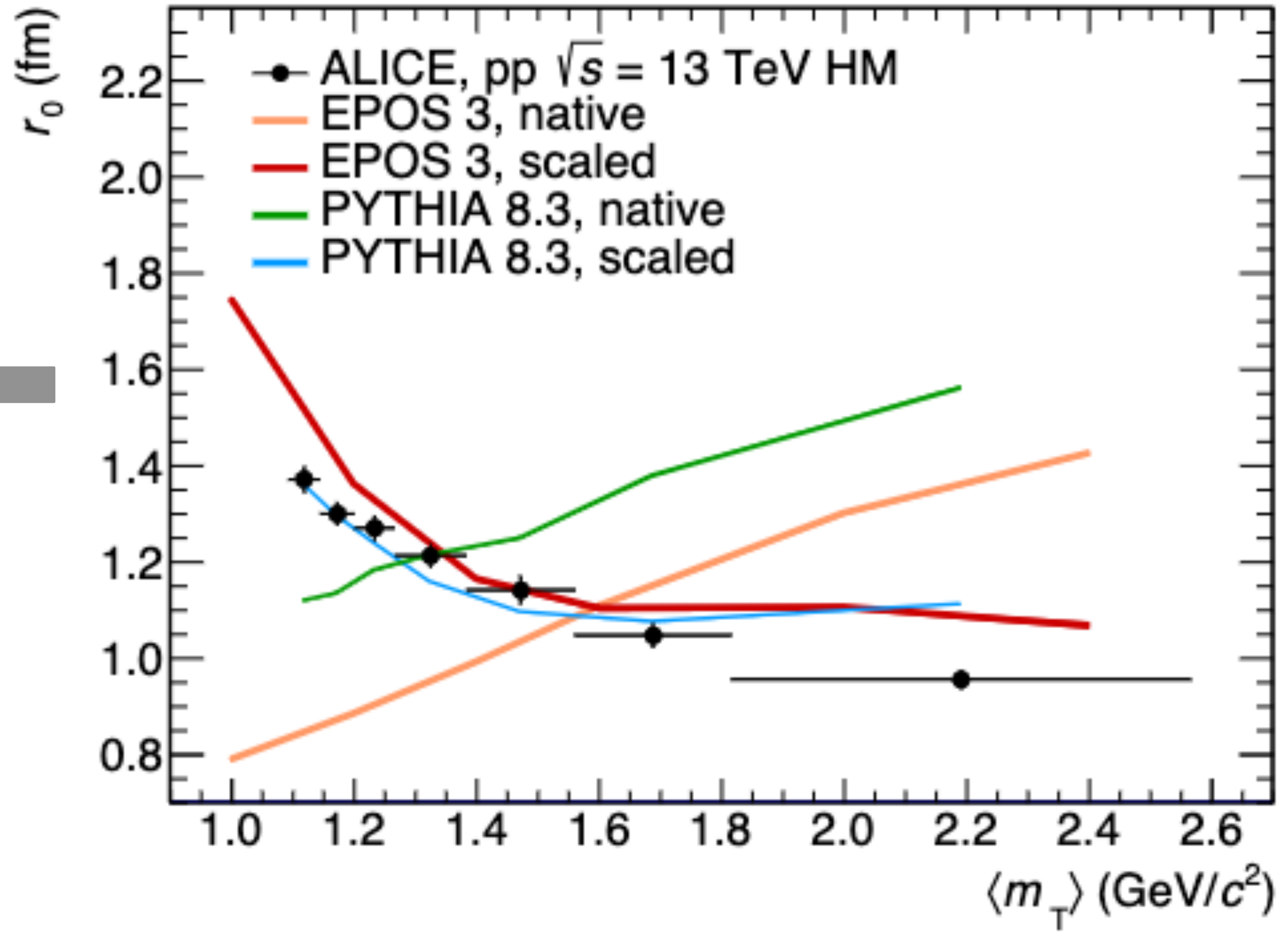


Calibration of emission source size



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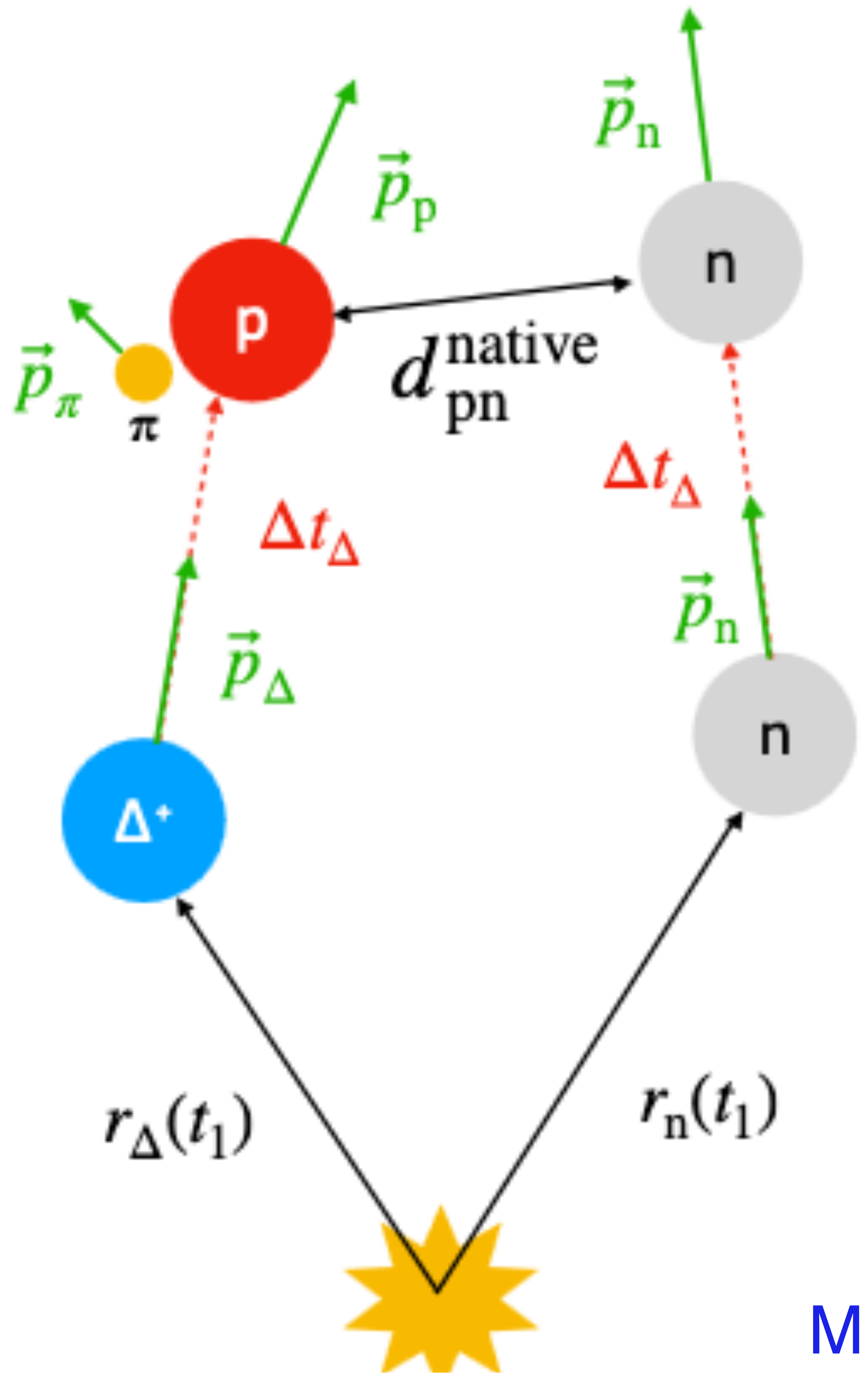

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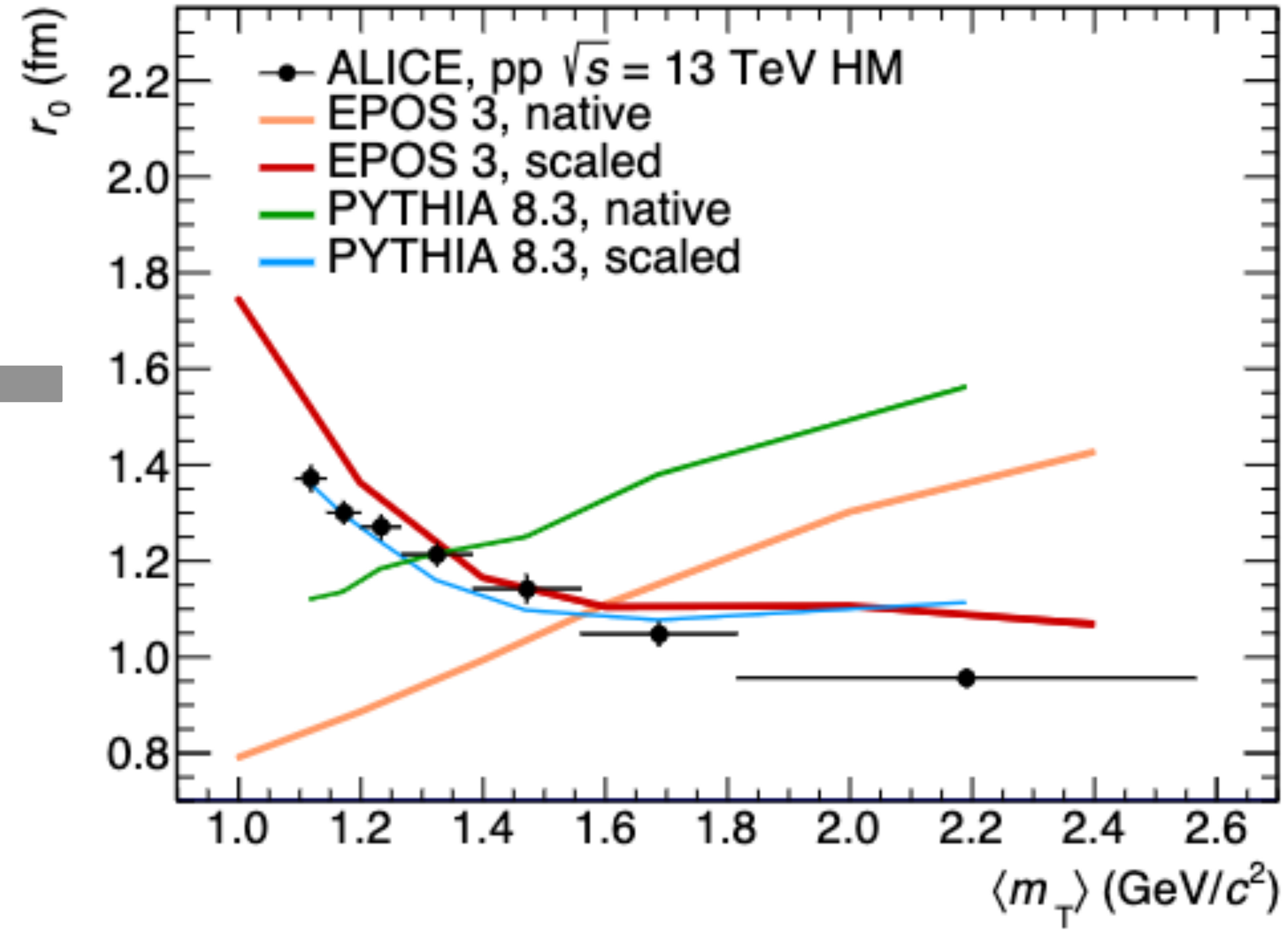

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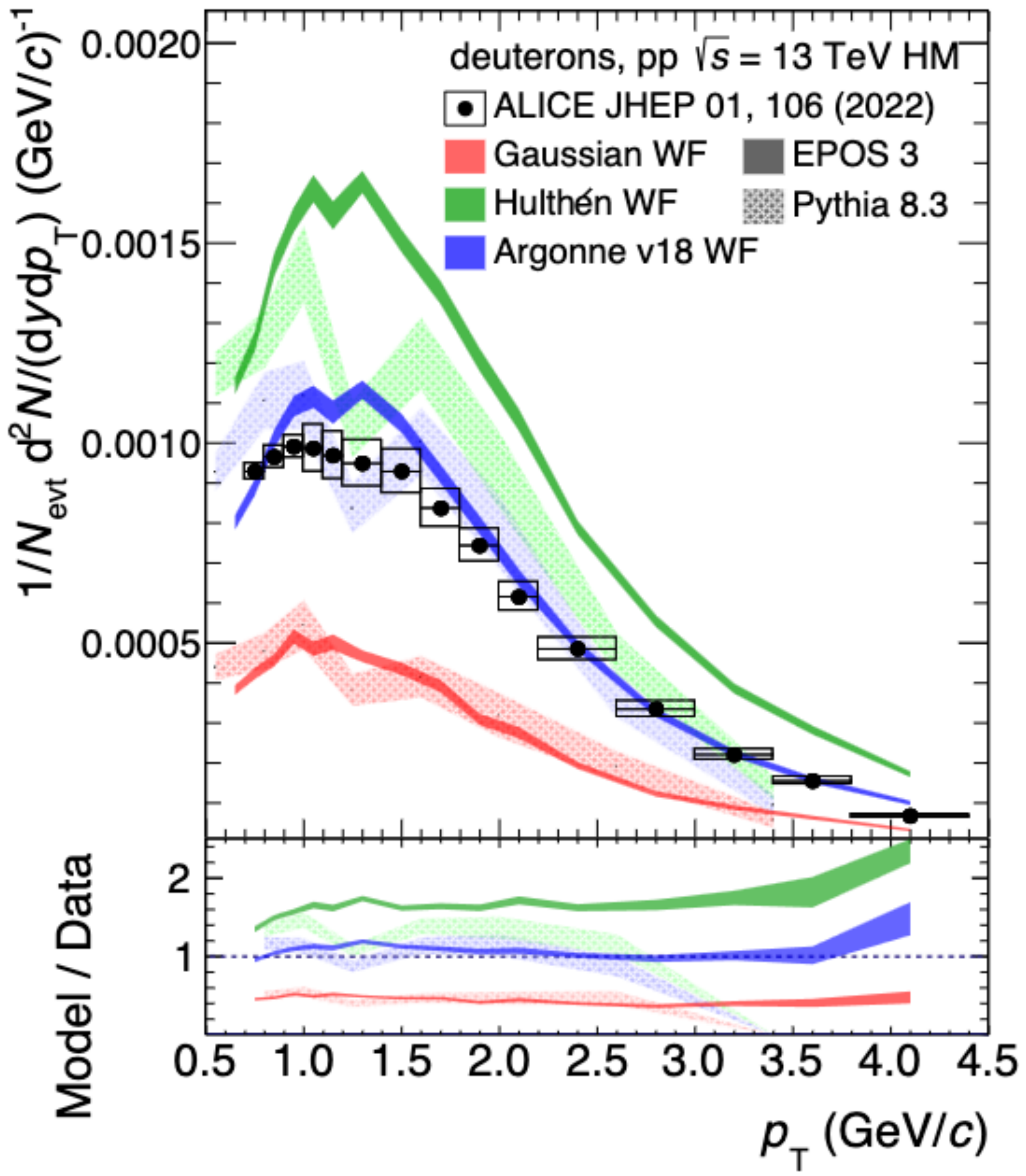
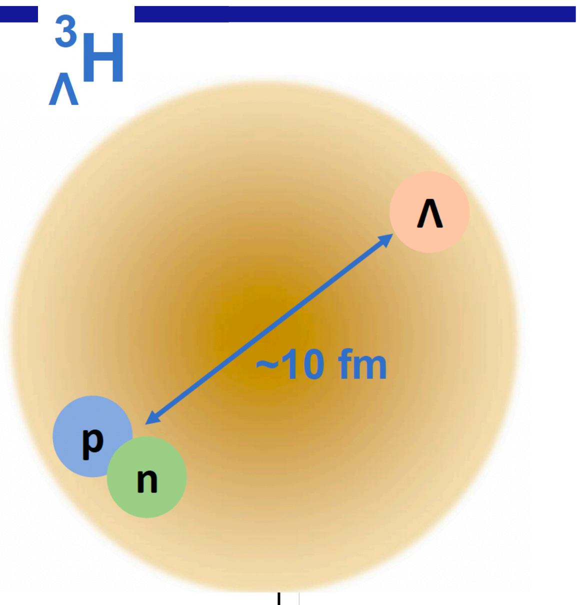
Model with no free parameters

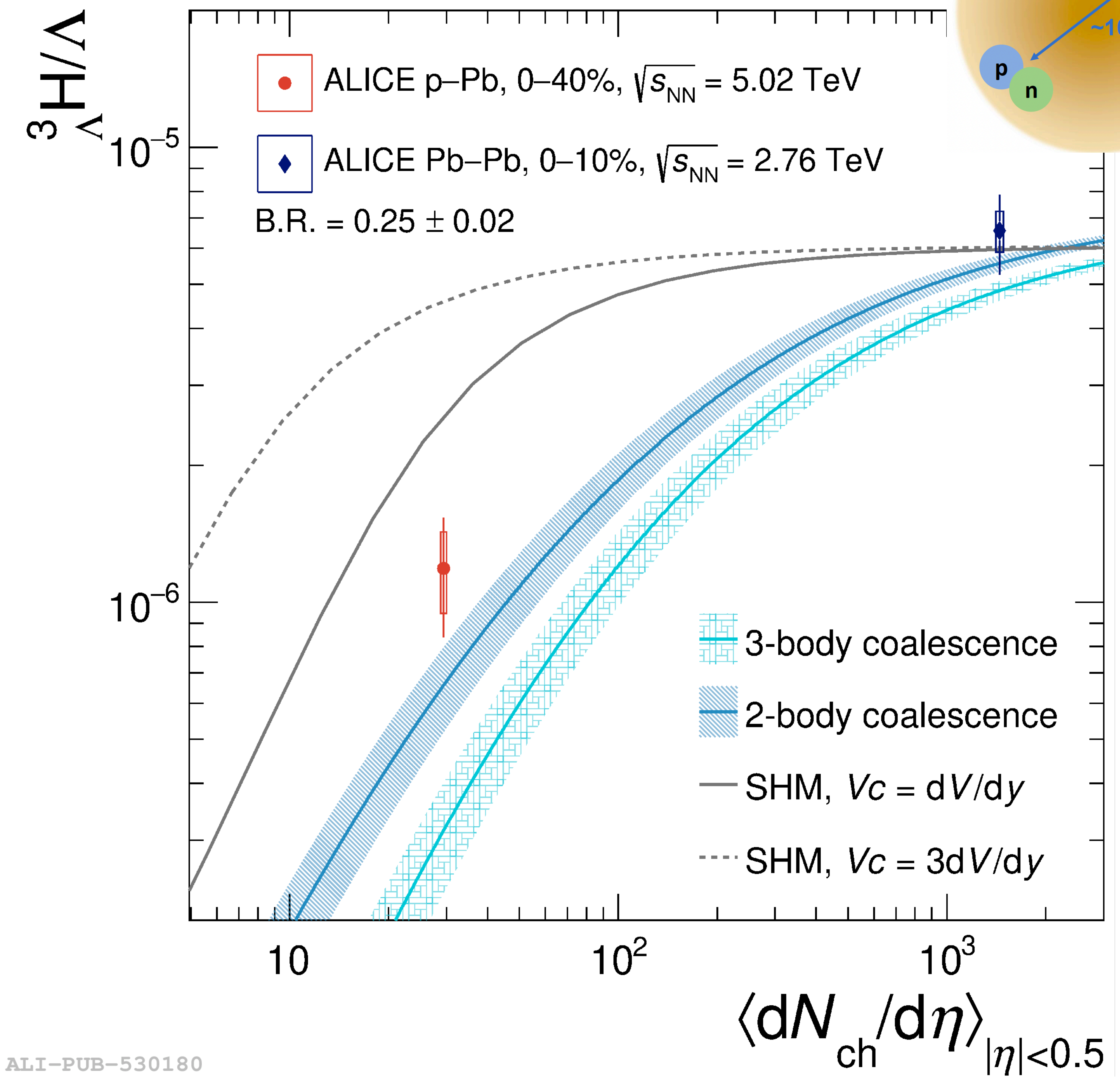


M. Mahelin, F. Bellini, S. Tripathy *et. al.*, Eur. Phys. J. C83 (2023) 9, 804

Hypertriton measurements

- Extremely sensitive to the production mechanism
- In a **coalescence** picture large suppression of the production in small systems expected due to the large object size
- For **SHM** the object size is not relevant→suppression due to canonical conservation of quantum numbers
- Measurements in Run 2 p-Pb collisions favor the coalescence approach





ALICE, Phys. Rev. Lett. 128 (2022) 252003

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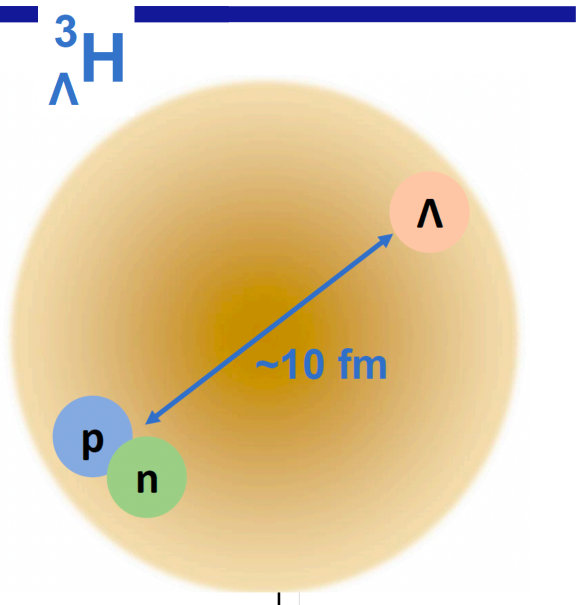
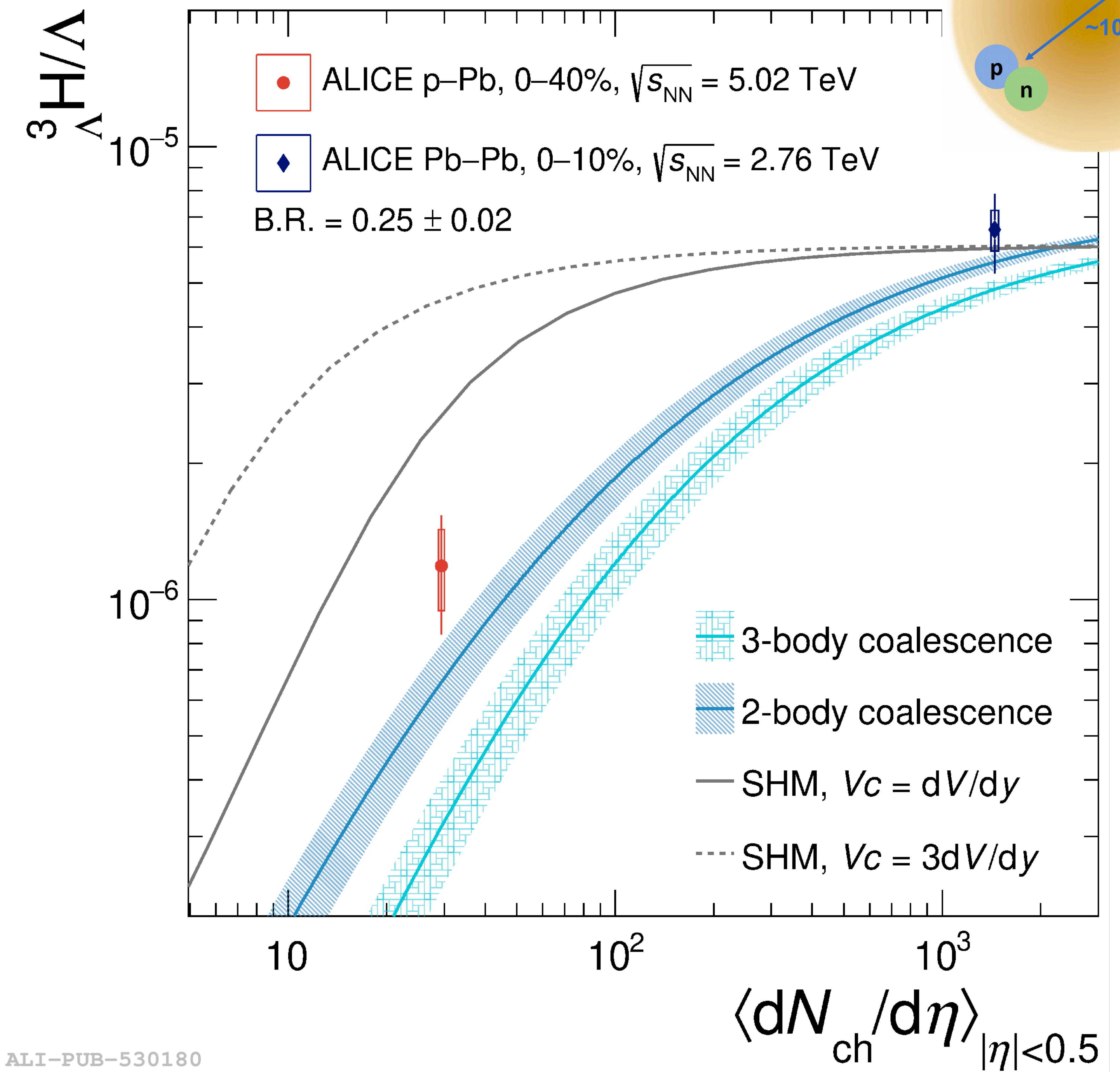
- Measurements in Run 2 p-Pb collisions favor the coalescence approach

Good discriminator but lacks differential and precise measurements



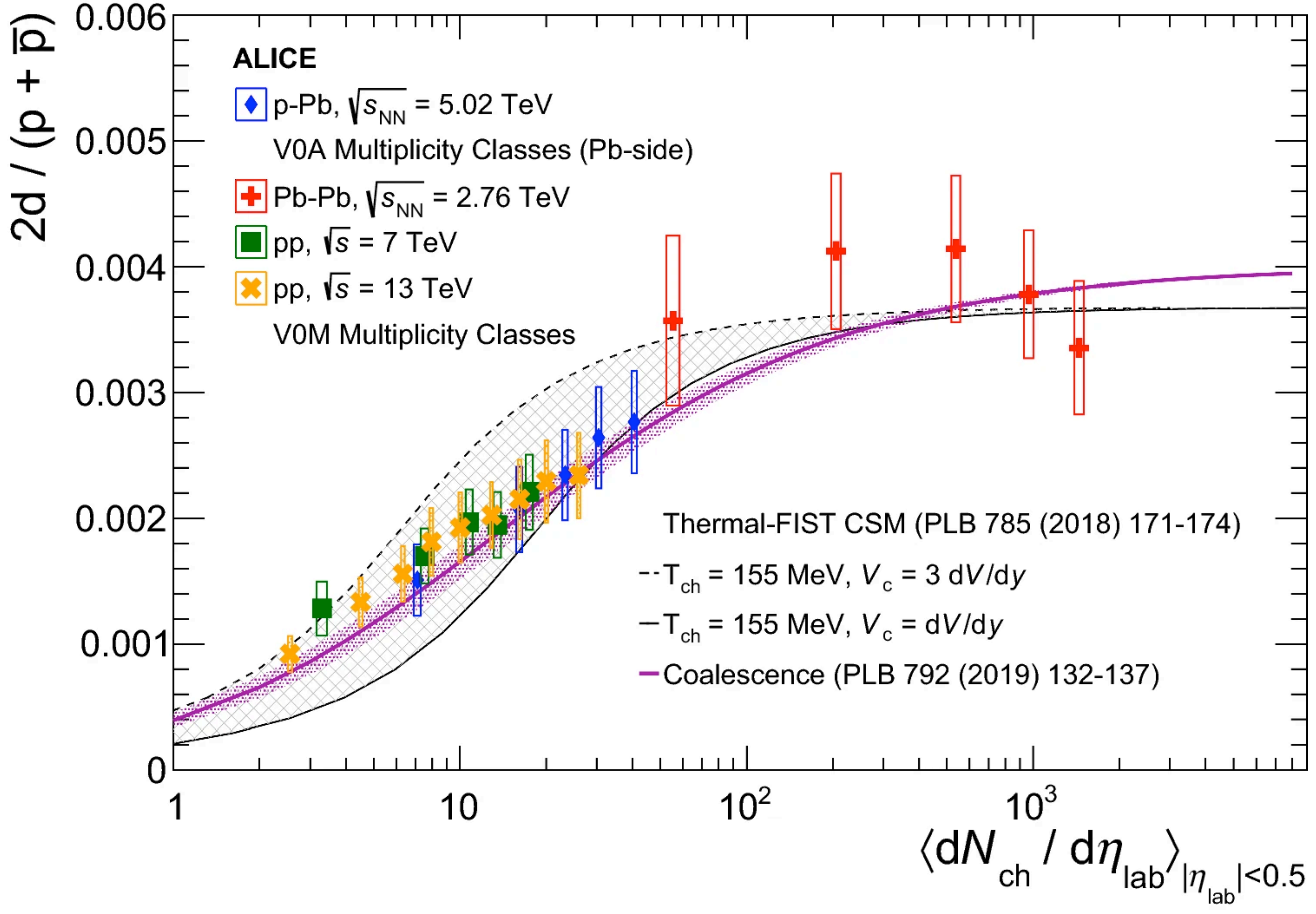


ALICE, Phys. Rev. Lett. 128 (2022) 252003

Nuclei production at the LHC

Good description of the deuteron production by both **thermal models** and **coalescence**

- Thermal Model — requires **thermal** and **chemical equilibrium**
- Coalescence — **Nuclei** clusters are formed at kinetic freeze-out **if nucleons are close in phase space**



ALICE, Eur. Phys. J. C80 (2020) 9, 889