Microscopic origin of light nuclei production at the LHC

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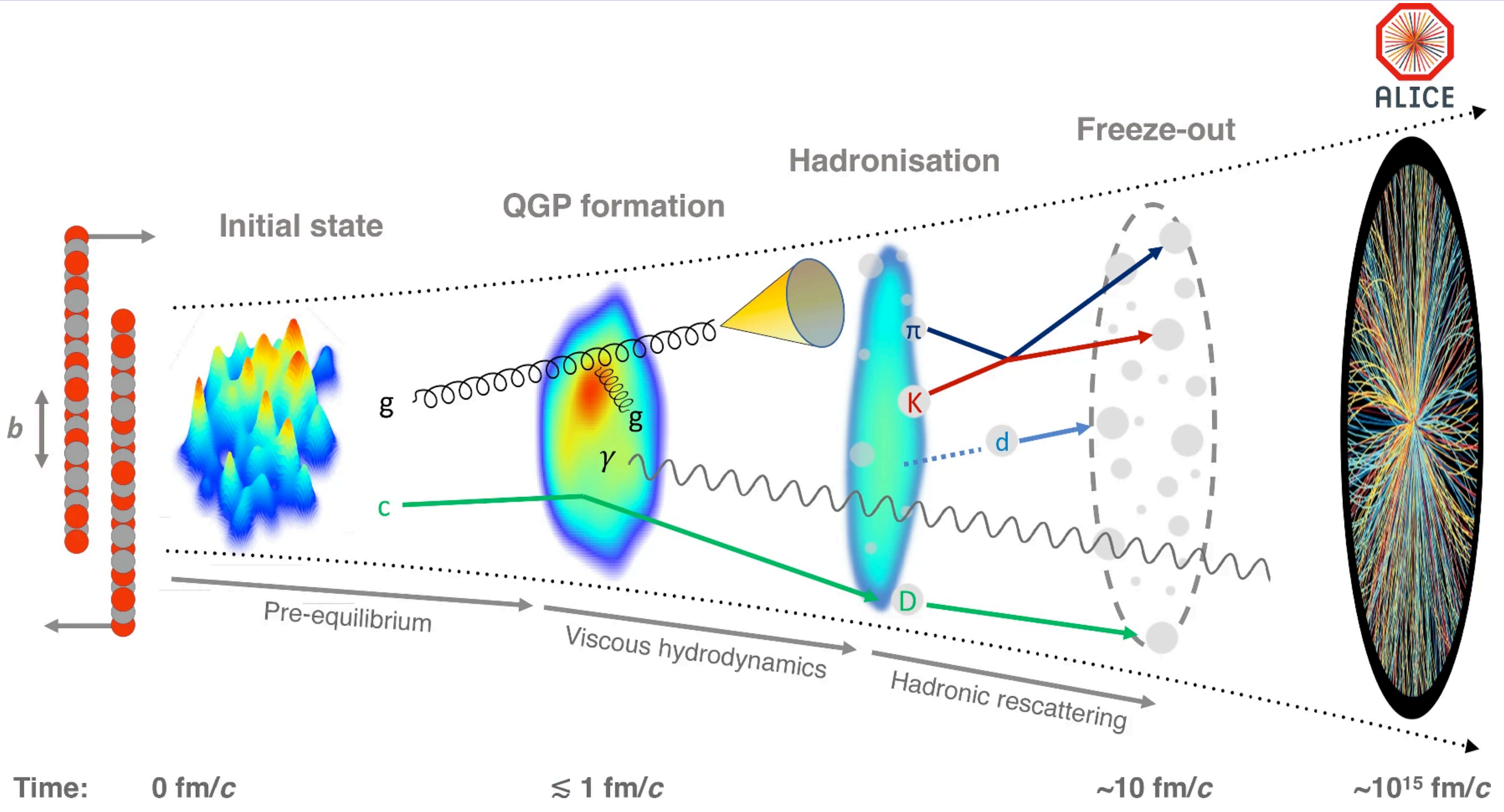
Marie Skłodowska-Curie Actions
Funded by the European Union

QCD at its extreme conditions



Due to **high-energy density** in **relativistic heavy-ion collisions**, a deconfined strongly-interacting matter can be formed → quark-gluon plasma (QGP)

ALICE experiment: a journey through QCD, EPJC 84 (2024) 8, 813

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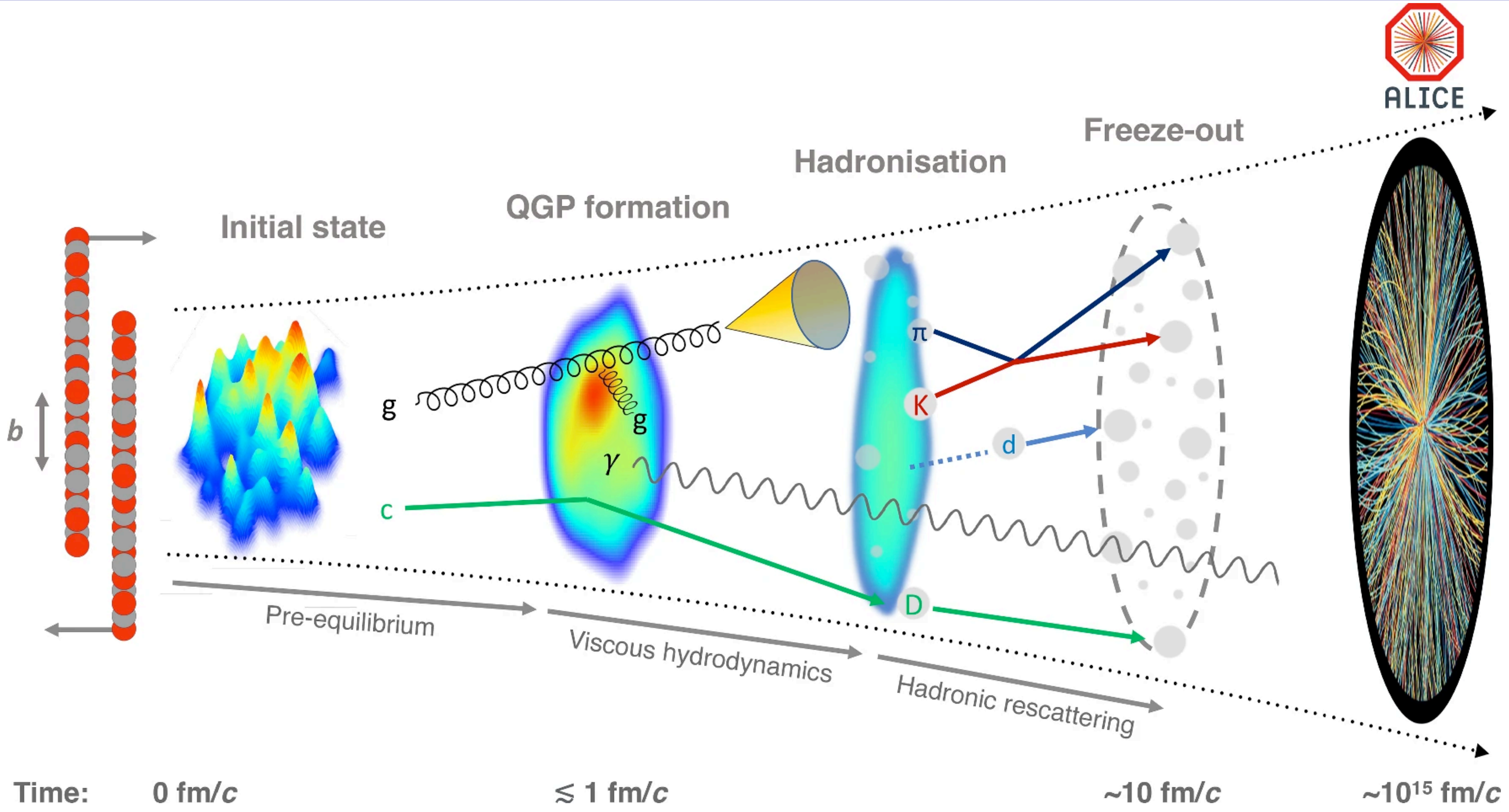

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ALICE experiment: a journey through QCD, EPJC 84 (2024) 8, 813

- Heavy-ion physics experiments investigate the **QGP** and the **stages of heavy-ion collisions** using final-state observables
  - Hadronisation, Hadrochemistry and bulk properties of the medium
  - Medium interactions with hard probes
- **Small systems** serve as both reference and probes of collective-like effects

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Motivation: nuclei puzzle

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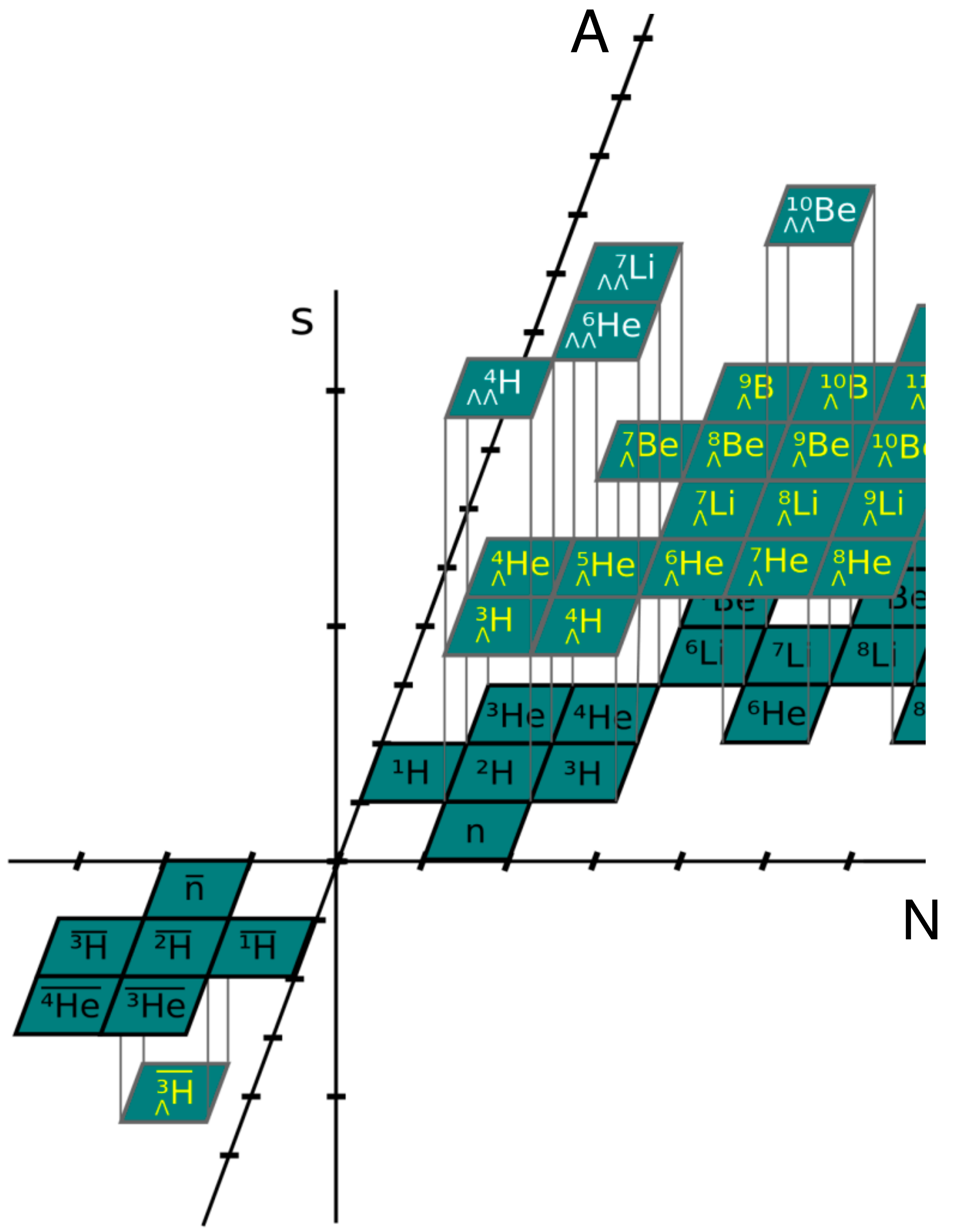
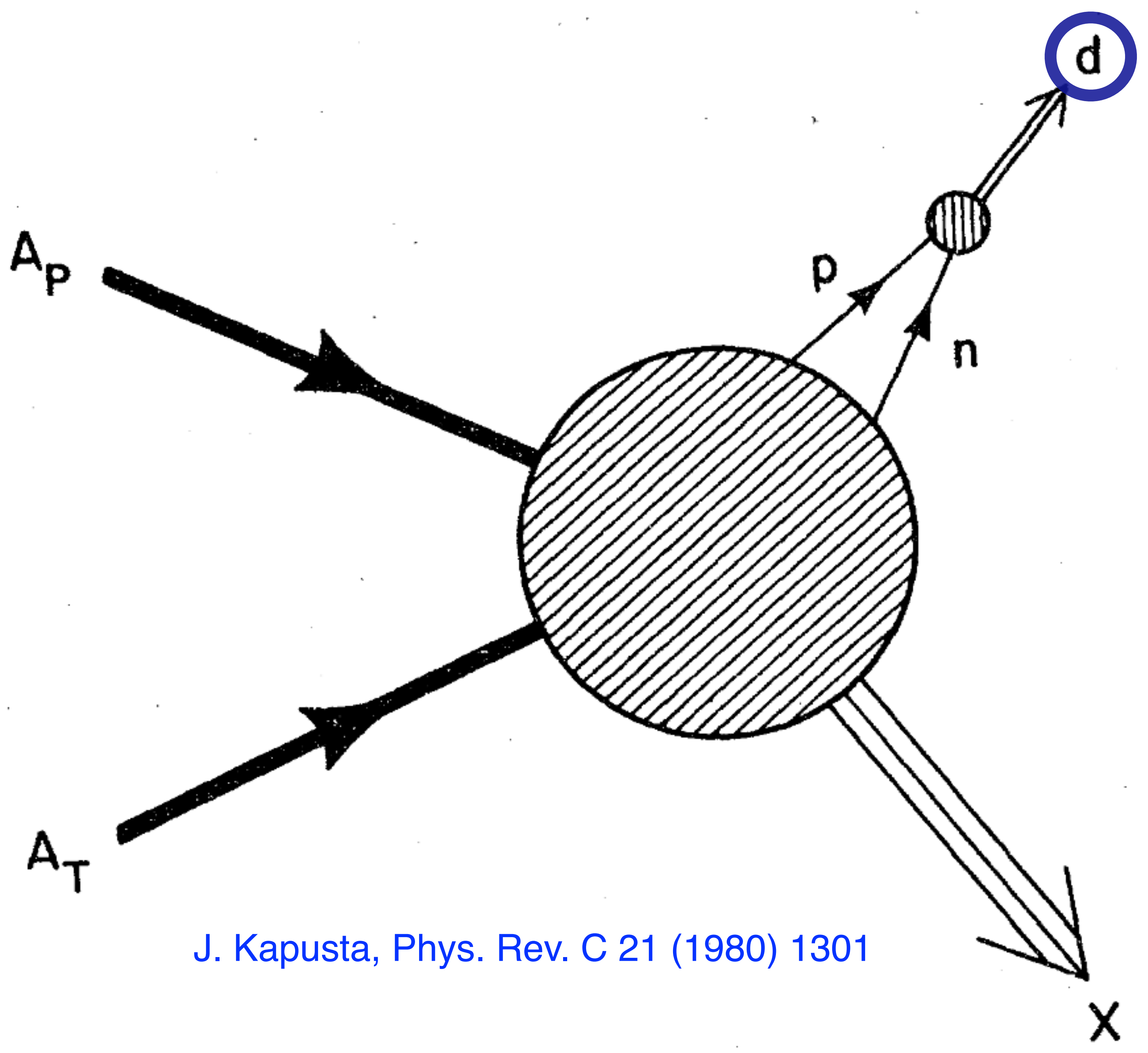
- The study of light **nuclei** production at the LHC is interesting as the **production mechanism** is still a **puzzle**
- **None of popular generators include the production of nuclei in their default configuration**



Lightest nuclei: **Deuteron**

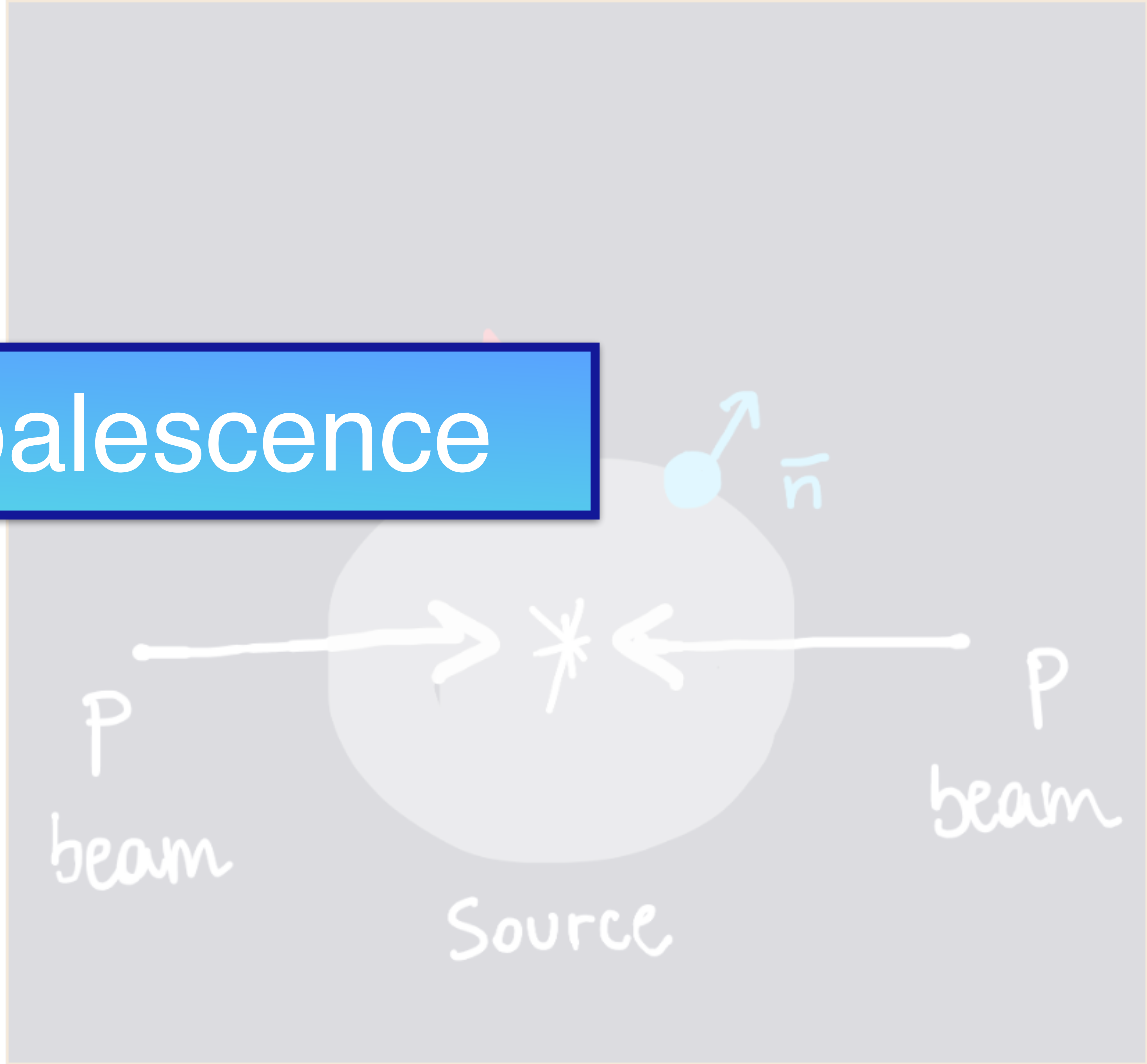


J. Kapusta, Phys. Rev. C 21 (1980) 1301

Nuclei synthesis: coalescence

- **Nuclei** are formed at kinetic freeze-out **if nucleons are close in phase space.**

- The formation of a $\bar{\mathrm{d}}$ by coalescence is the result of final state interactions between a $\bar{\mathrm{p}}$ and a $\bar{\mathrm{n}}$.



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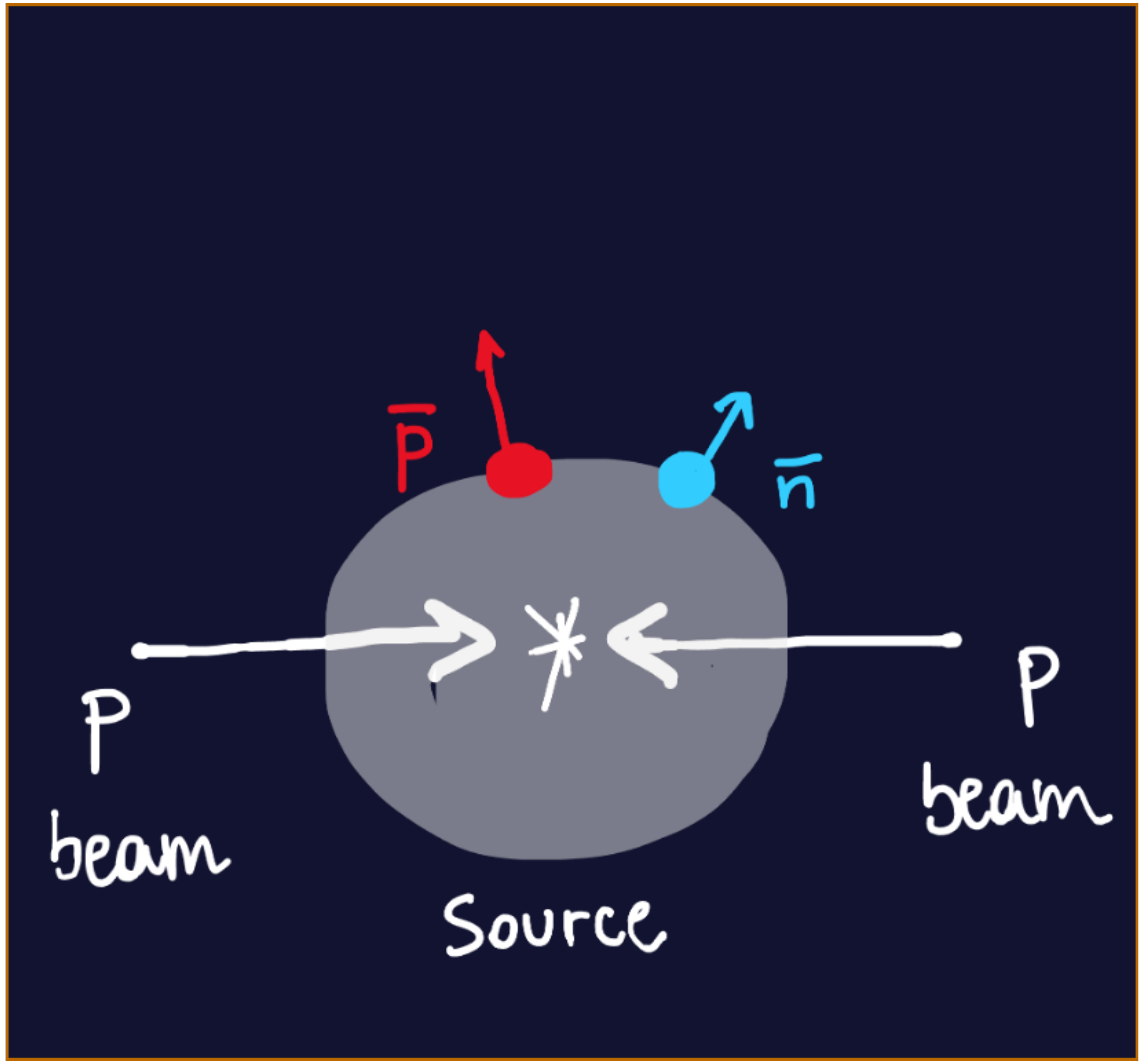

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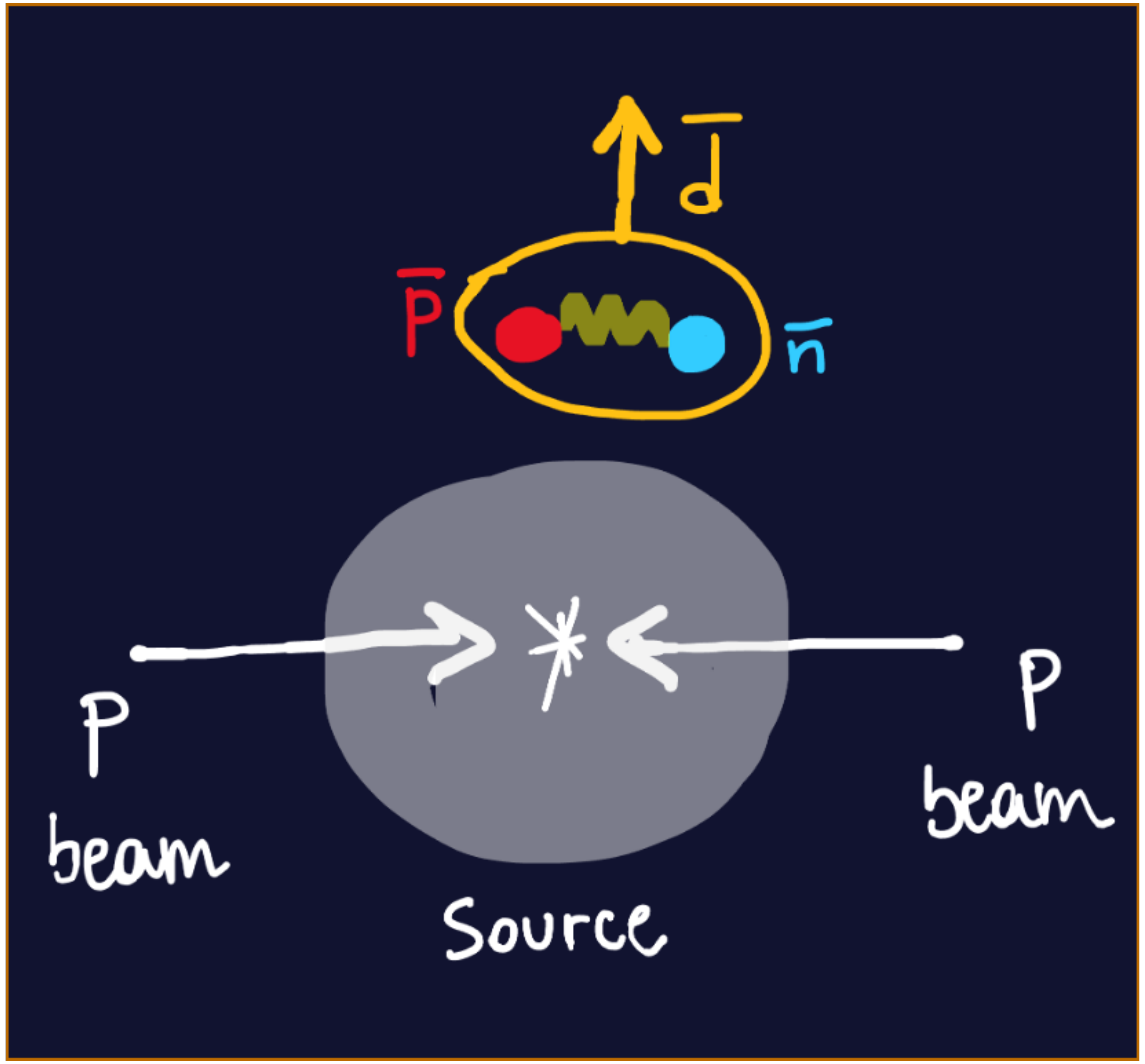

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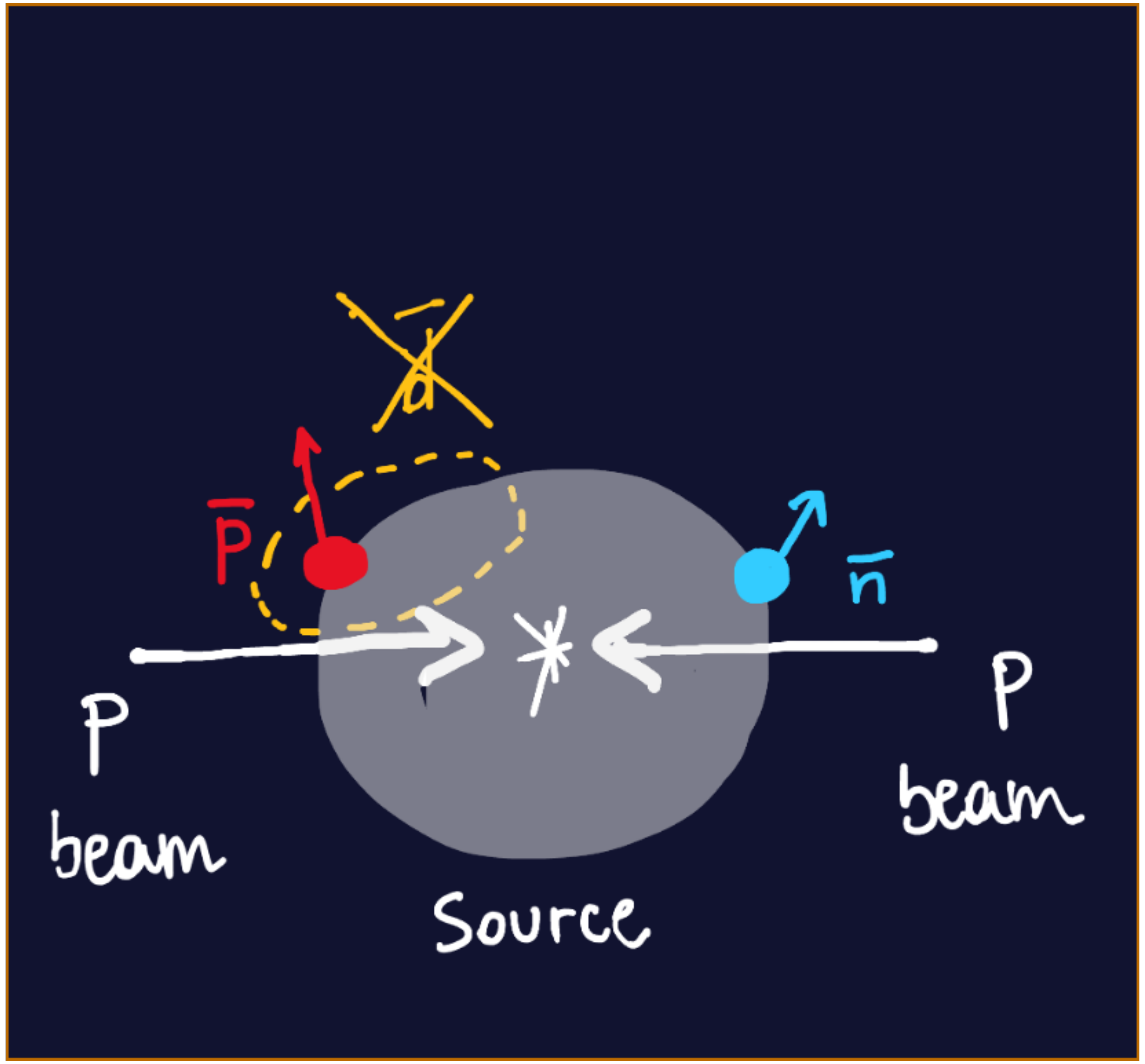

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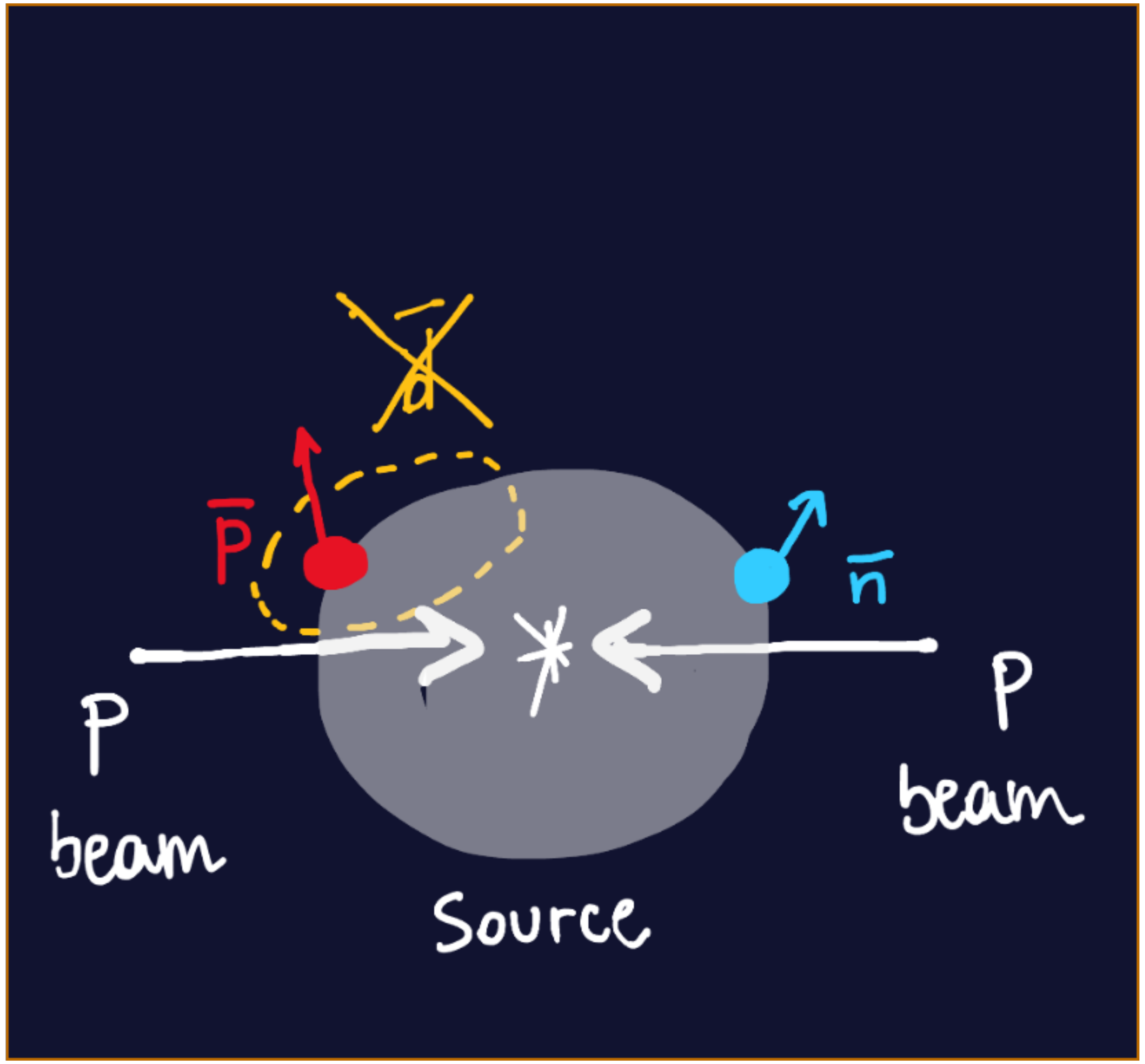
→ Wigner formalism exploited in state-of-the-art calculations



Coalescence probability depends on

- **the momentum**
- the **size of the nucleon source**
- the **nucleus wavefunction**

Nuclei synthesis: coalescence

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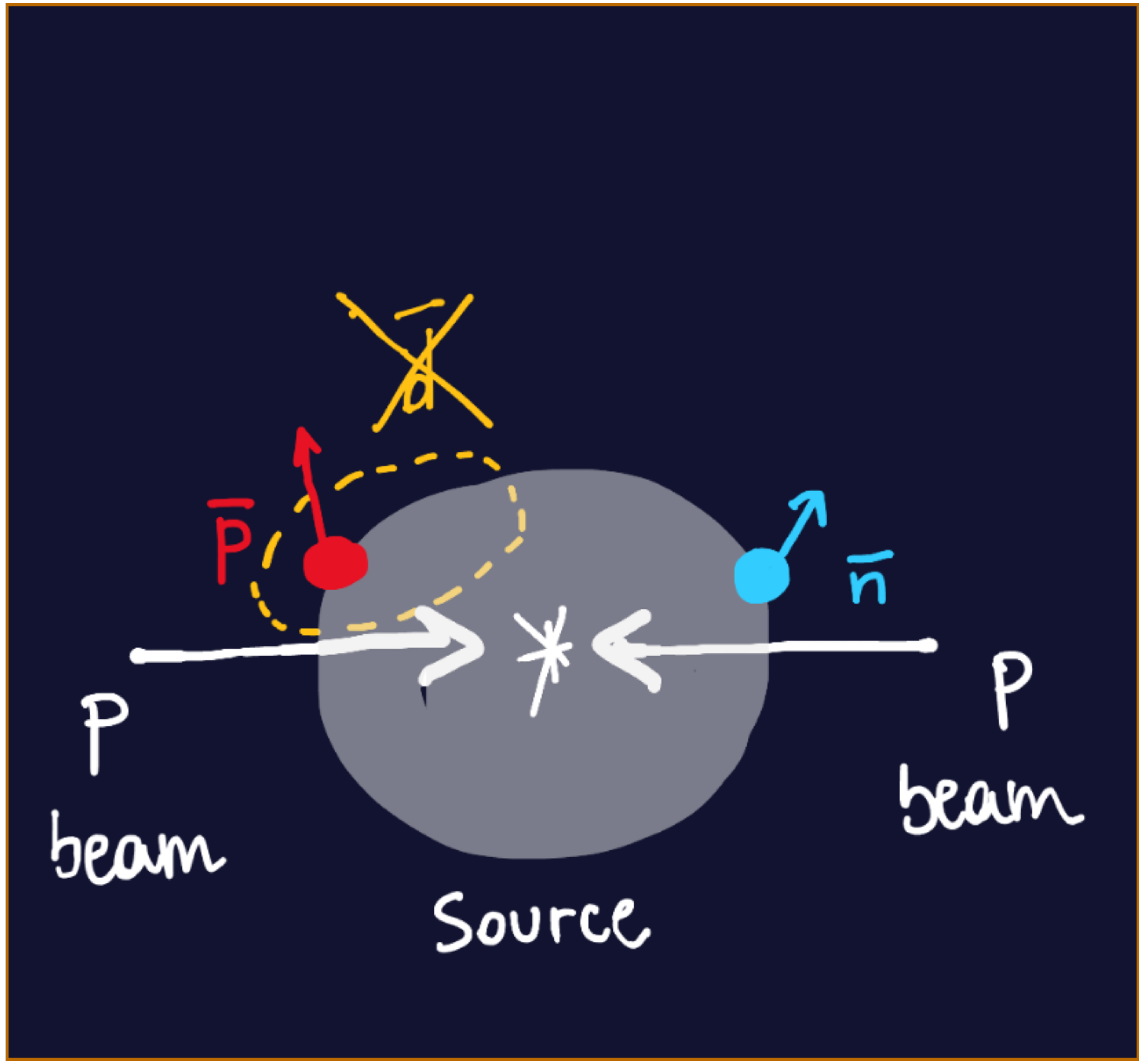
Phase space distributions of p/n (obtained from hydro)

$$\frac{dN_d}{dP_d^3} = g_d \int d^3x_1 d^3p_1 d^3x_2 d^3p_2 \, f_p(x_1,p_1) f_n(x_2,p_2) \times \rho_d^W(\rho, P_\rho) \delta(P_d - p_1 - p_2)$$

Wigner function of deuteron

$$\rho_d^W(\mathbf{r},\mathbf{k}) = \int \phi(\mathbf{r}+\frac{\mathbf{R}}{2})\phi^*(\mathbf{r}-\frac{\mathbf{R}}{2}) \exp(-i\mathbf{k}\cdot\mathbf{R}) d\mathbf{R}$$

wave function



Nuclei synthesis: coalescence

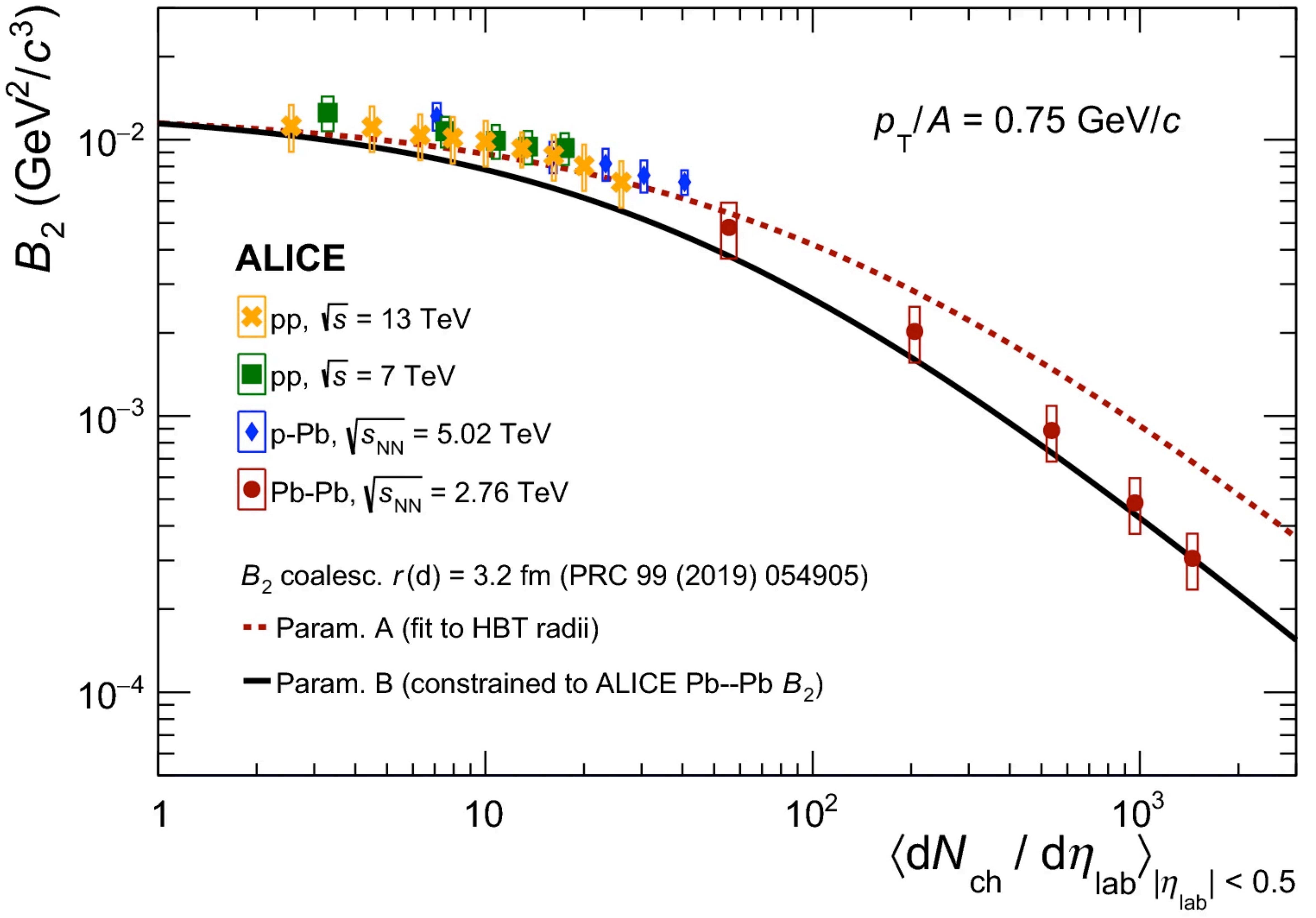
- **Coalescence parameter** *B*2, related to formation probability via coalescence.

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

Momentum spectra of deuterons

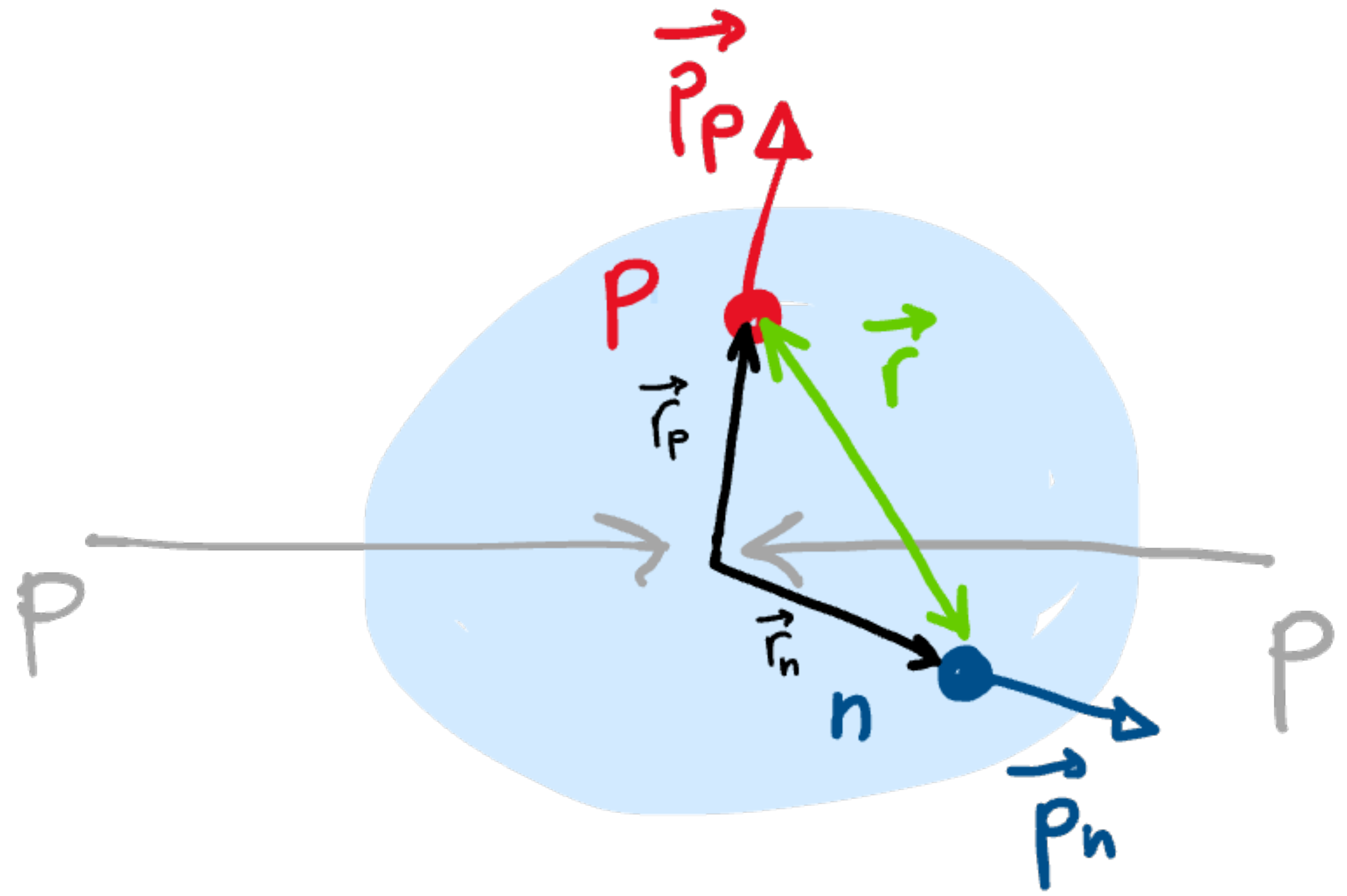
Momentum spectra of protons

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

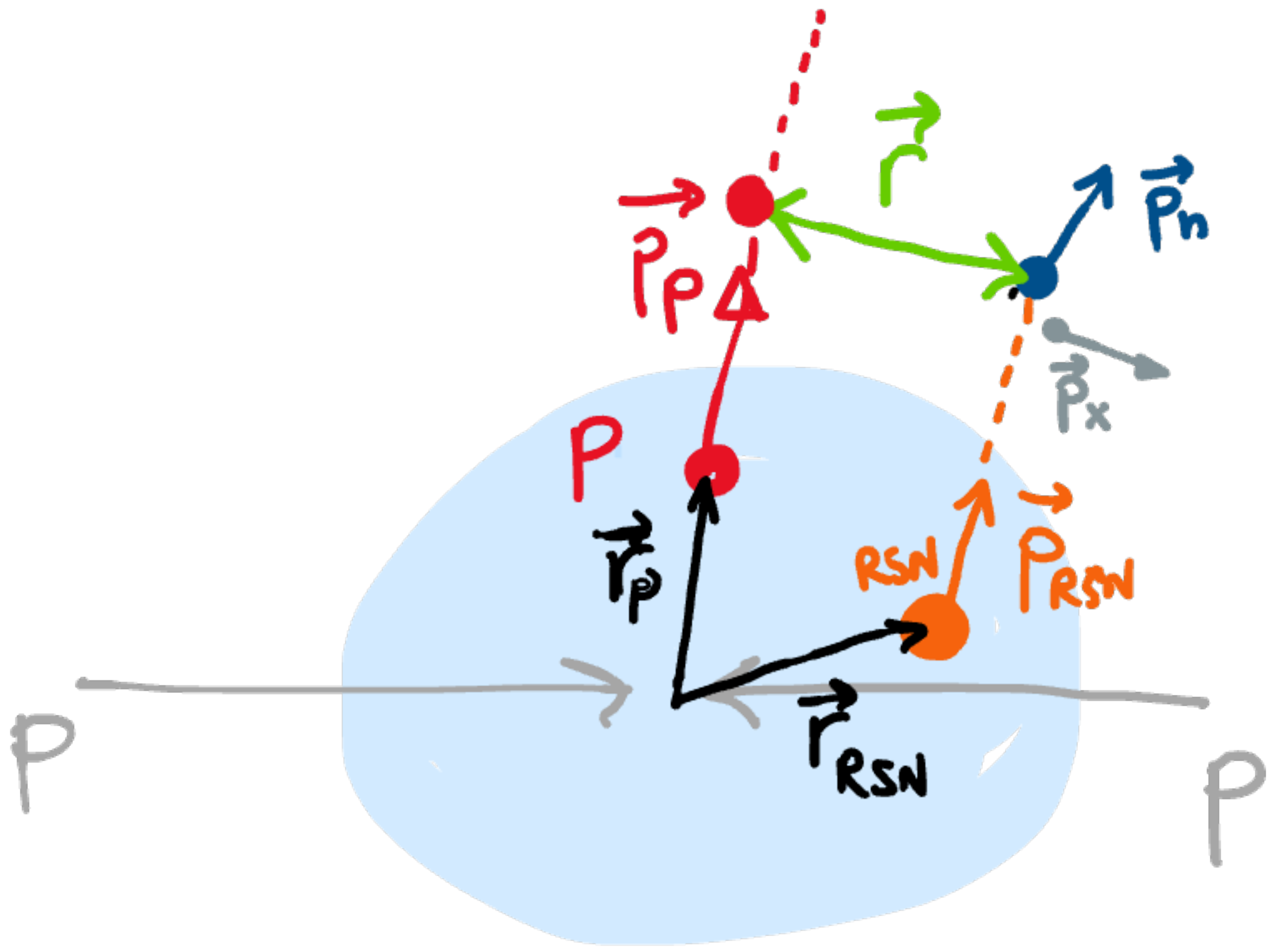


Coalescence is supported by ALICE measurements

Nuclei synthesis: coalescence

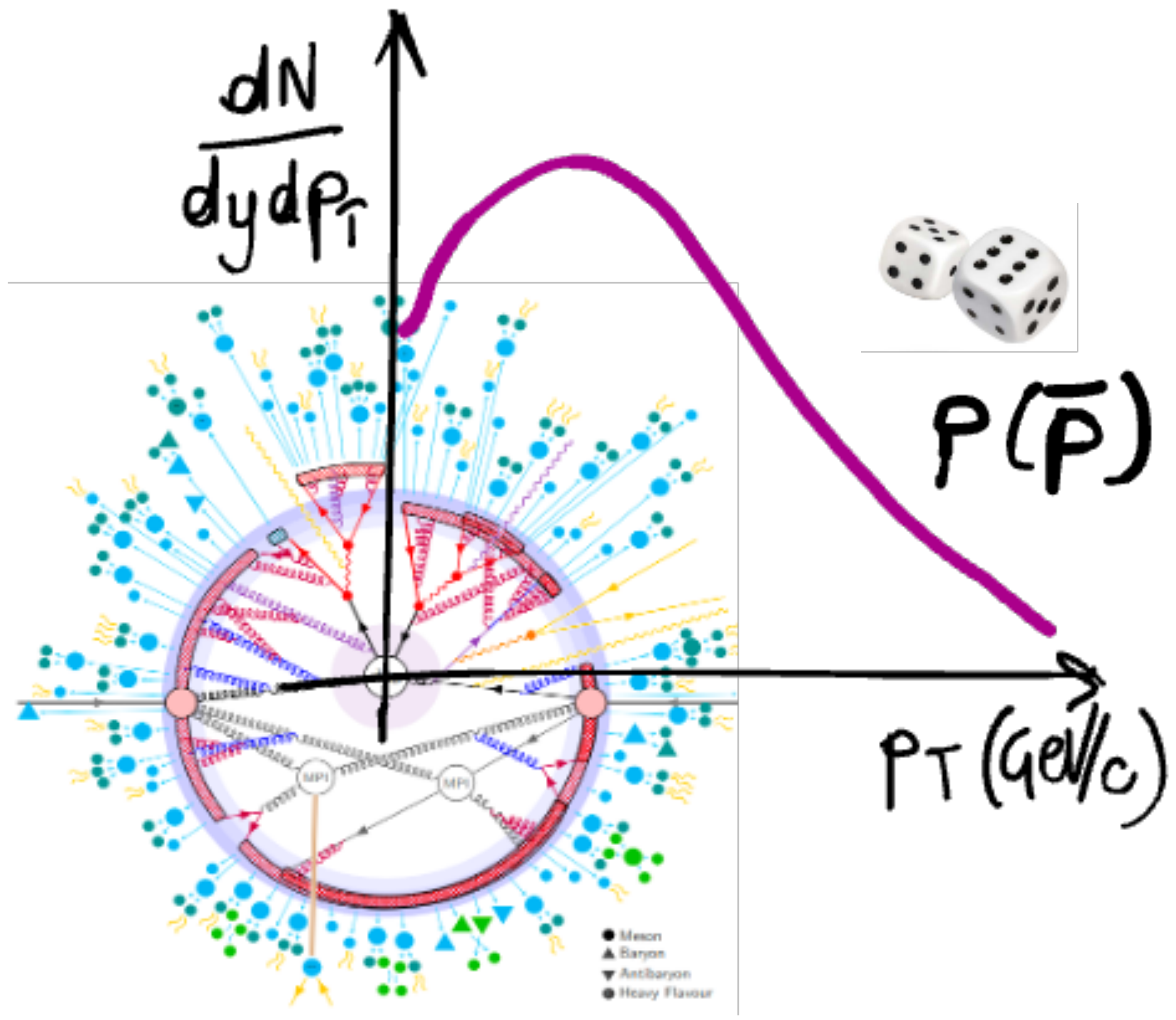


Prompt p(bar) + prompt n(bar)



Prompt p(bar) + n(bar) from resonances

Nuclei synthesis: coalescence afterburner



A realistic coalescence model for deuteron production,
M. Mahelin, L. Fabietti, F. Bellini, S. Tripathy *et. al.*, Eur. Phys. J. C83 (2023) 9, 804

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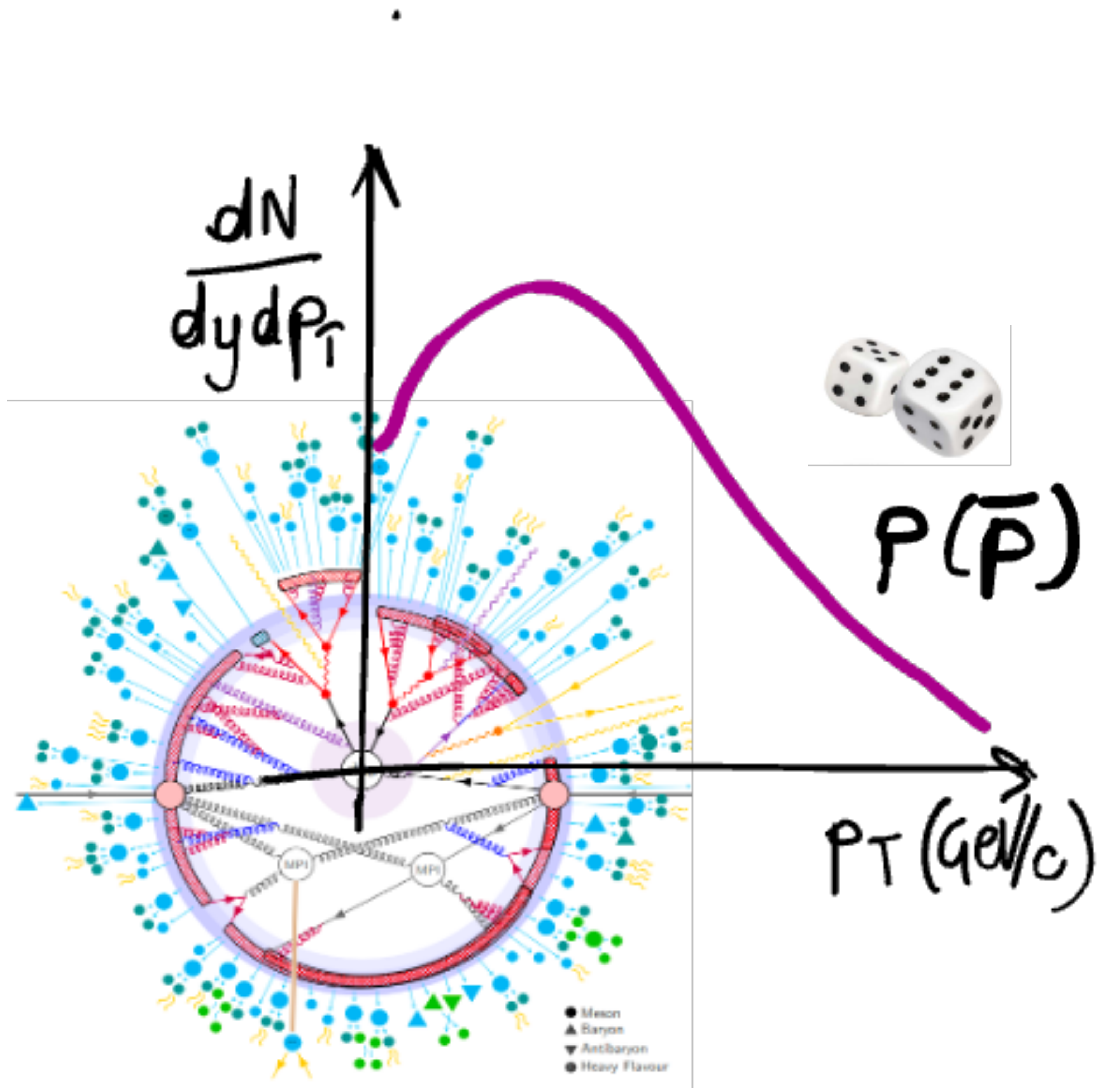

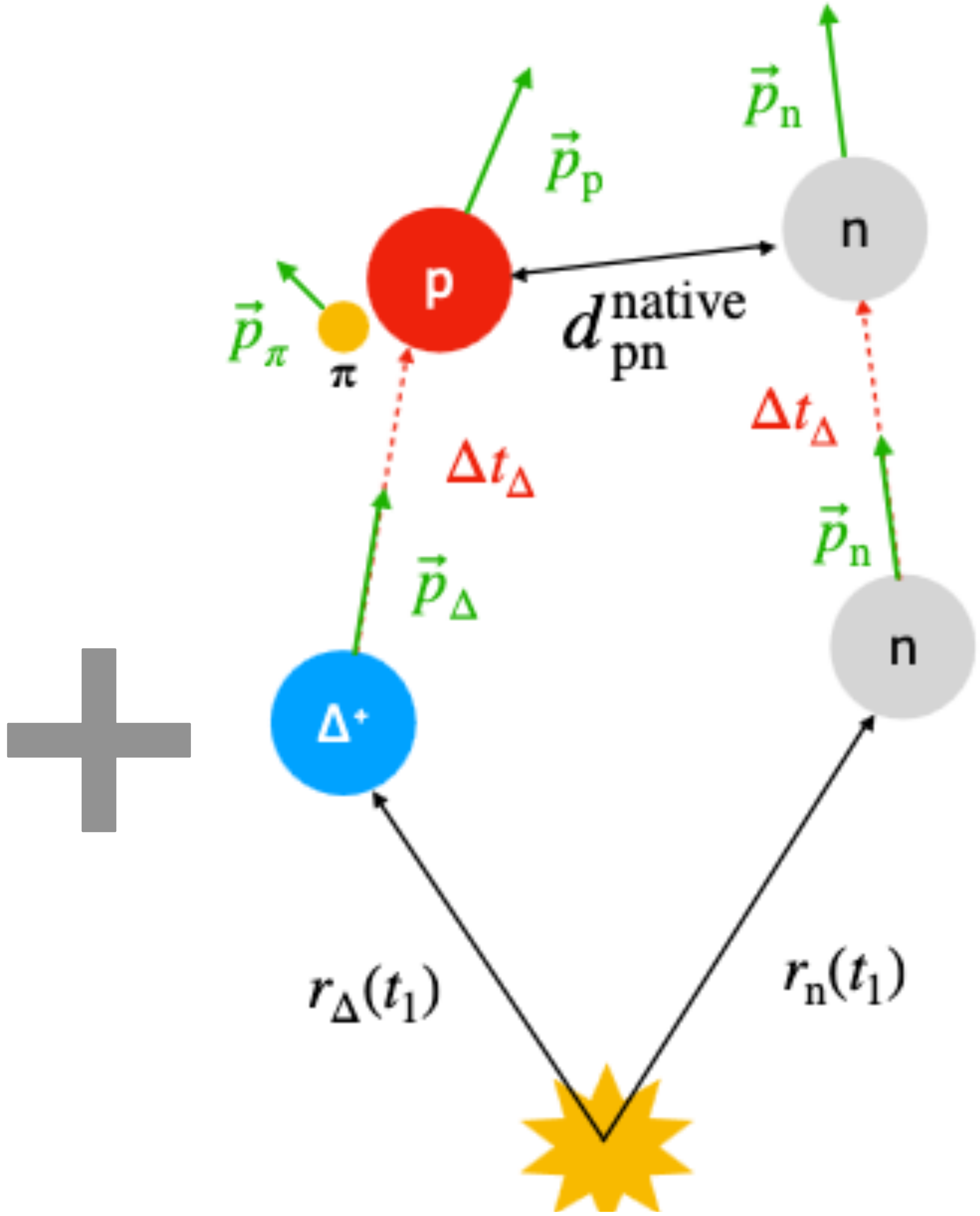

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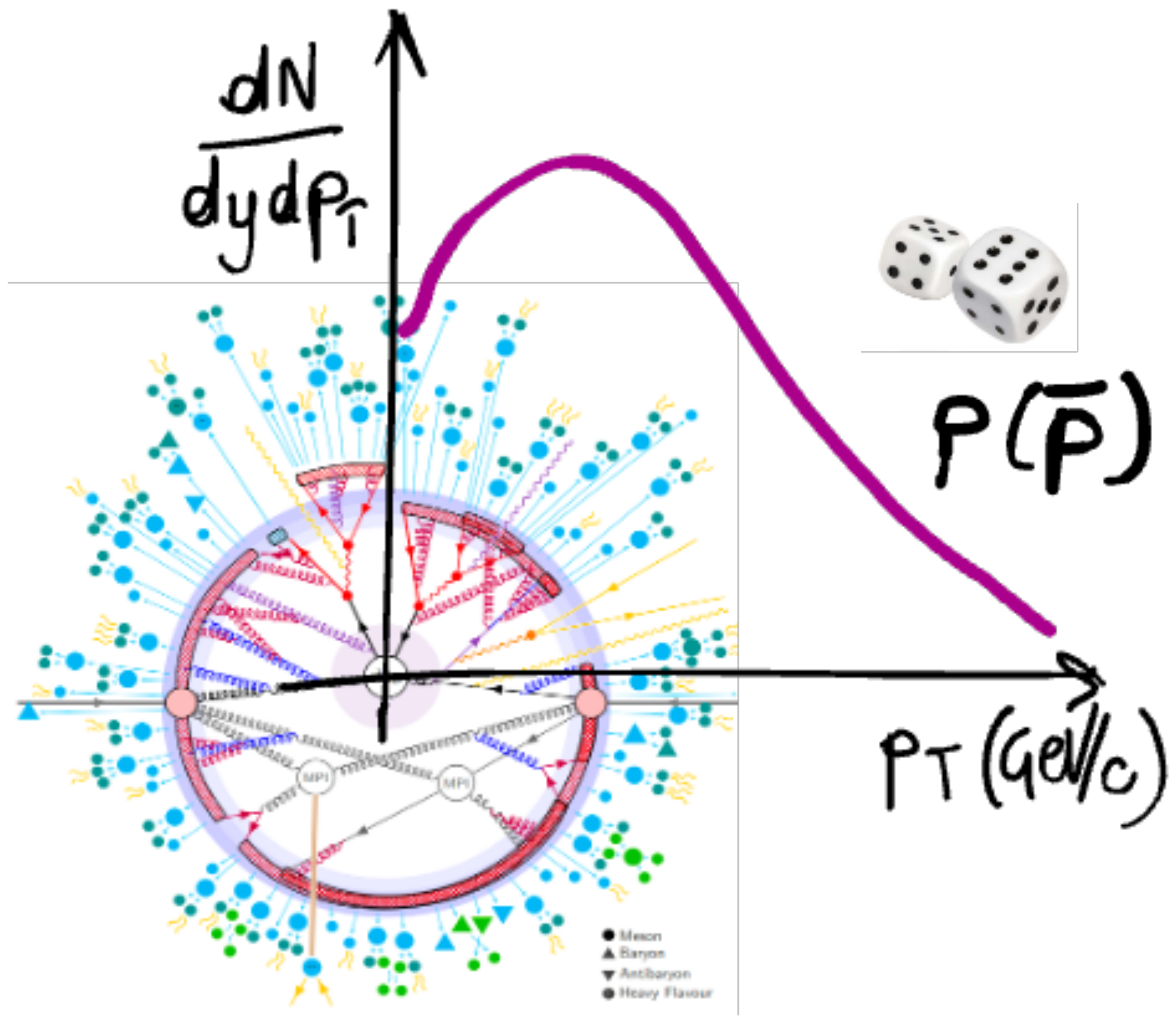

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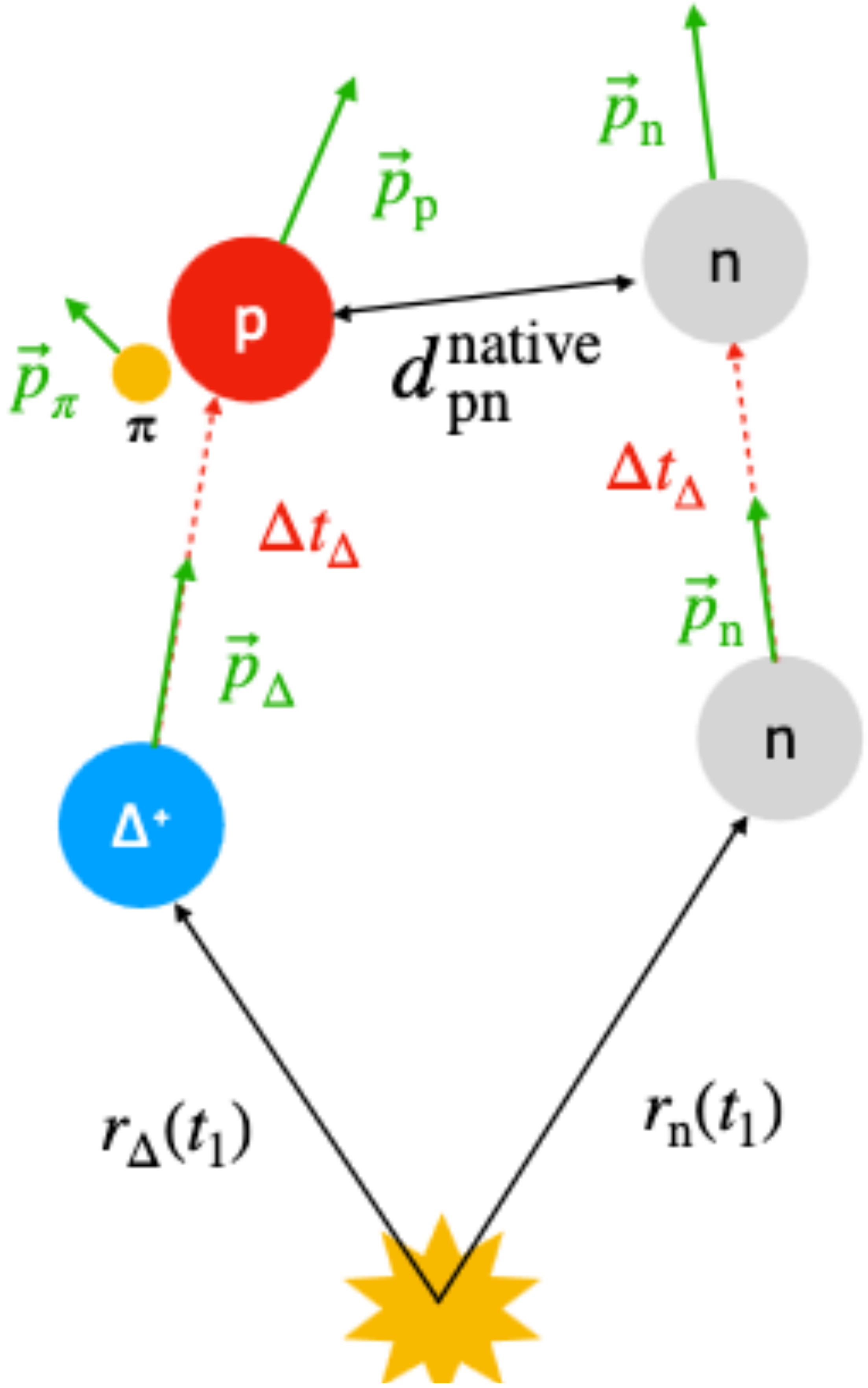

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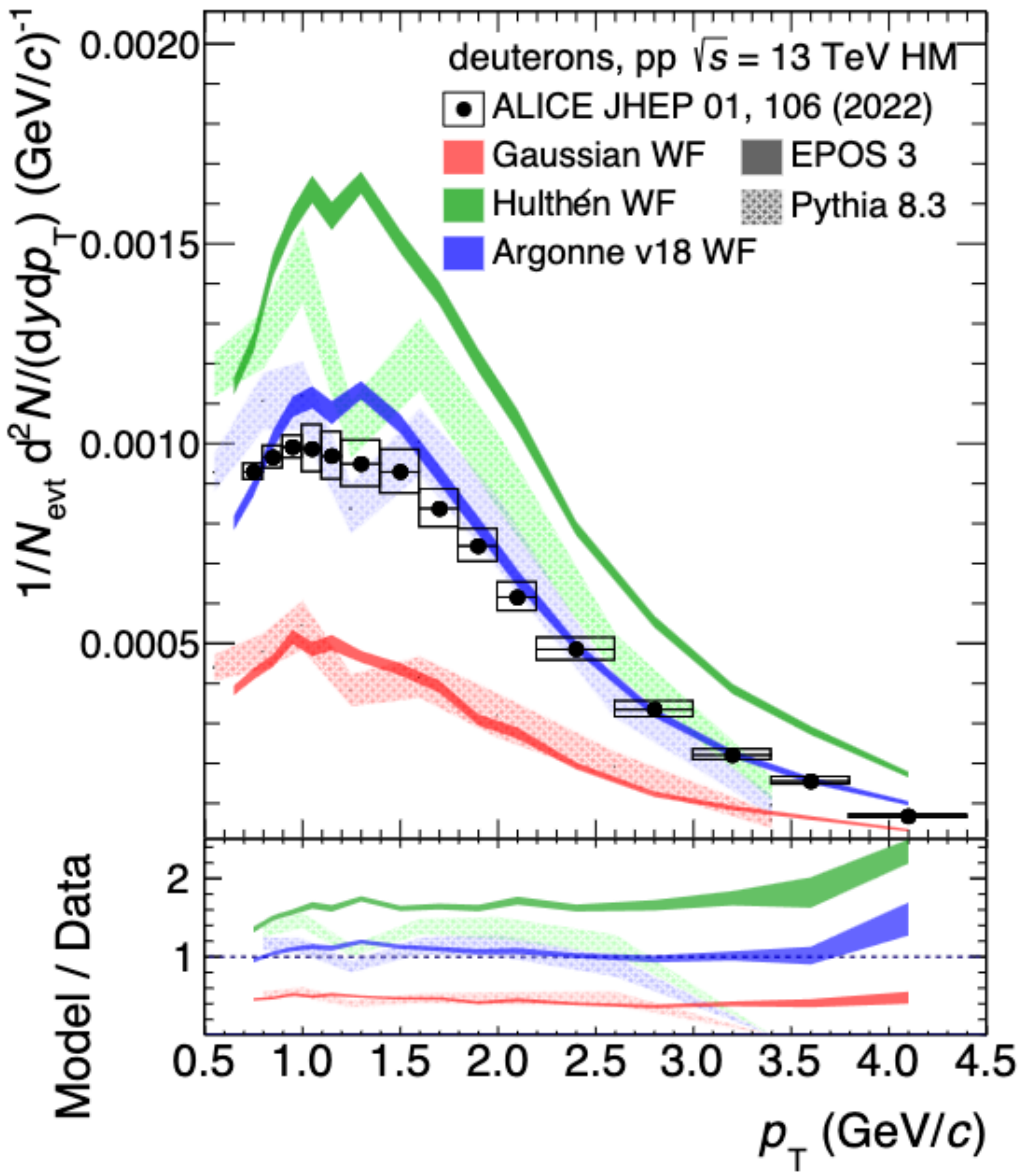
Model with no free parameters



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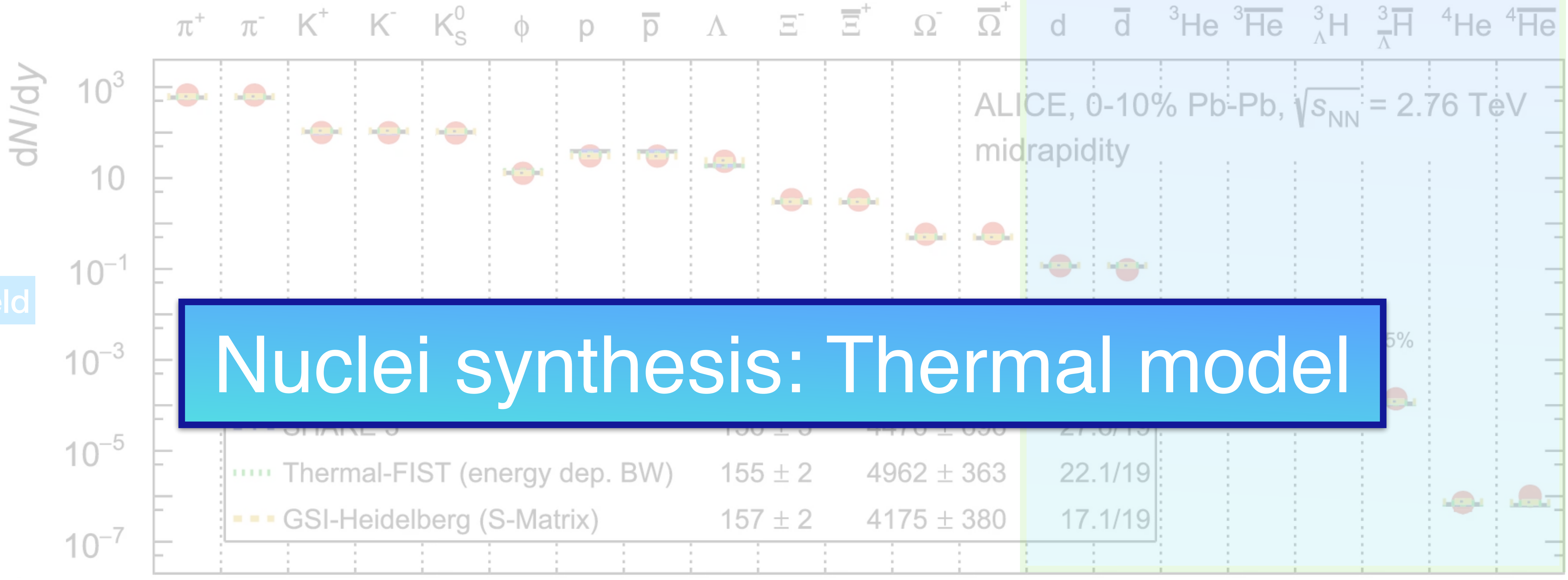
Nuclei synthesis: Thermal model



Integrated yield

Nuclei synthesis: Thermal model

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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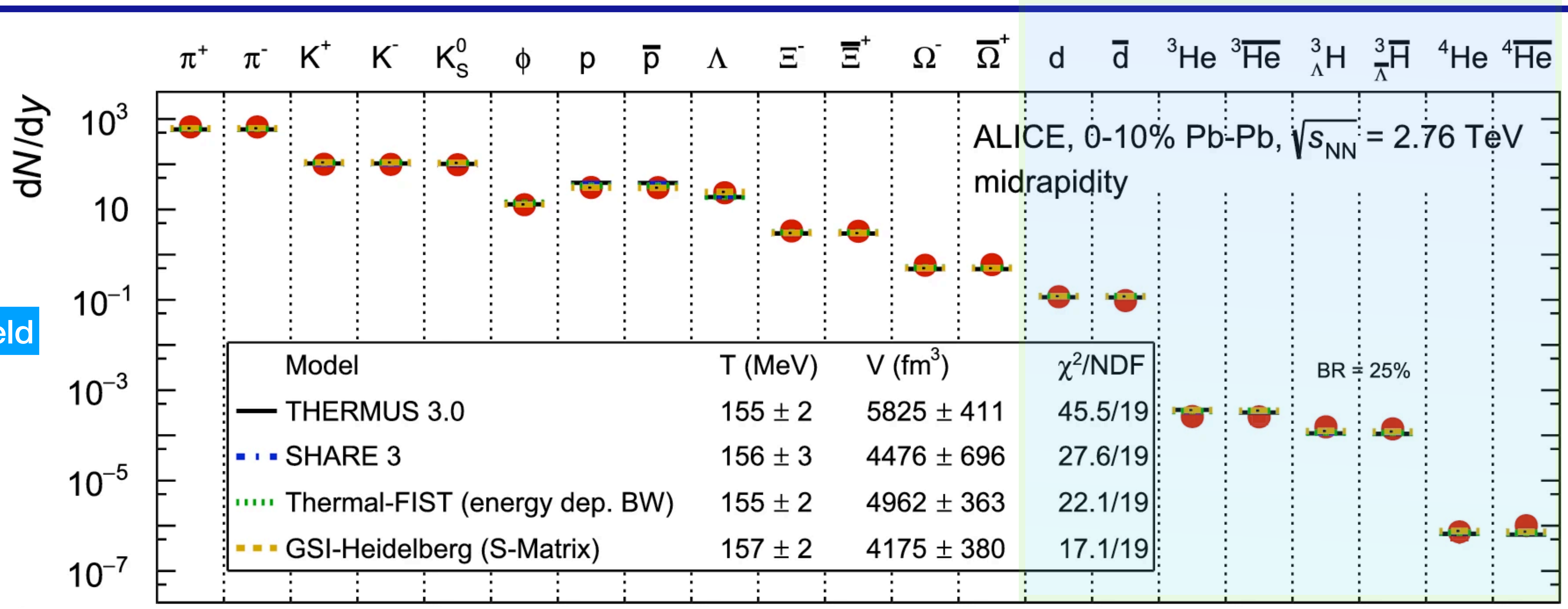

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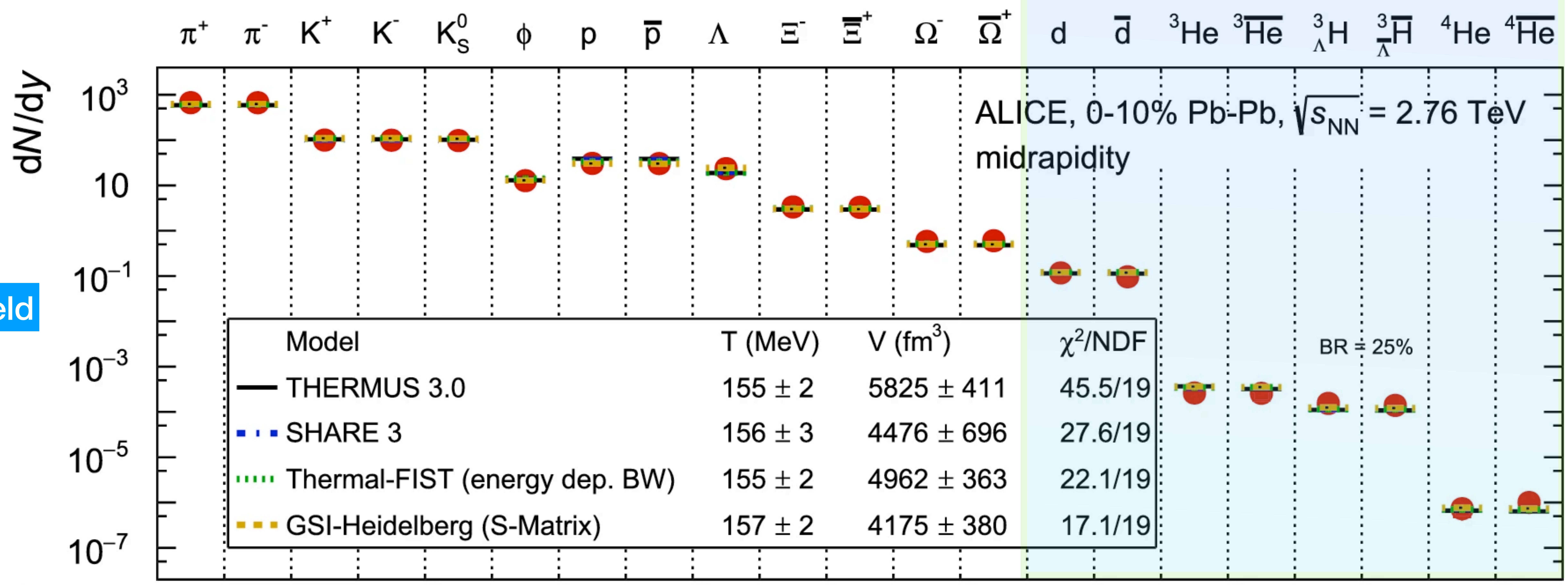

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Temperature of the system ~ 155 MeV
Light nuclei binding energy ~ 1-10 MeV

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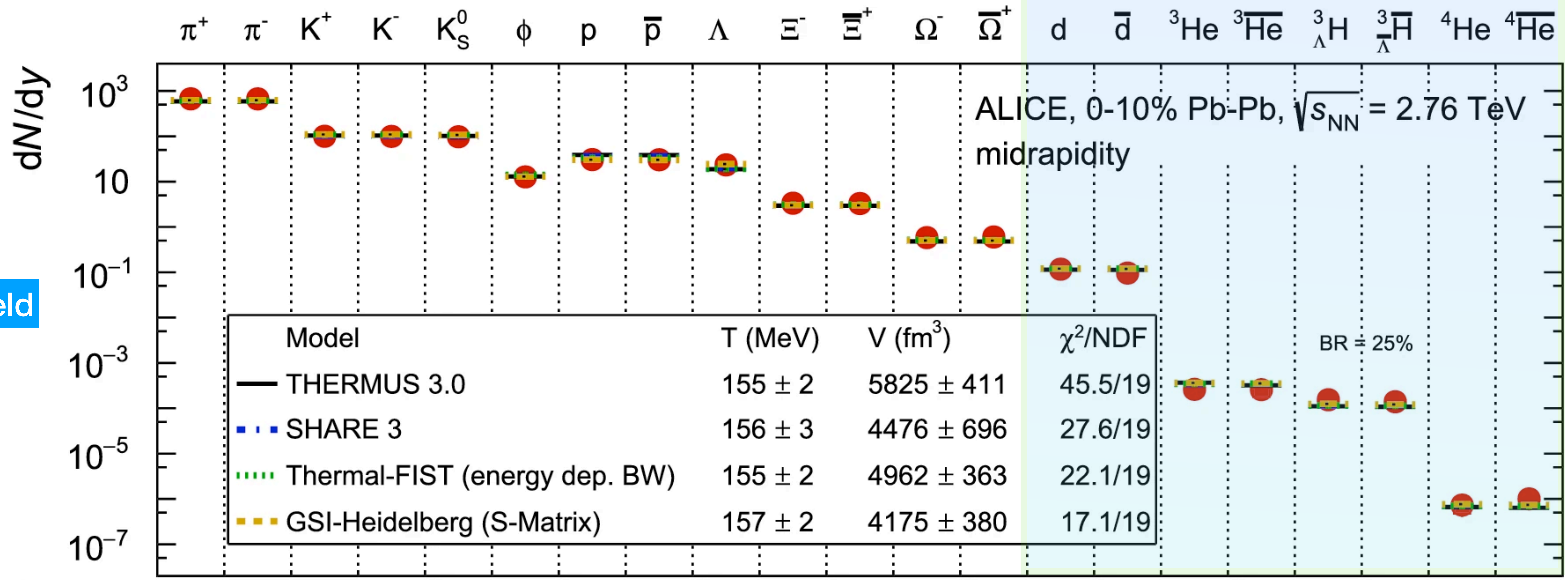

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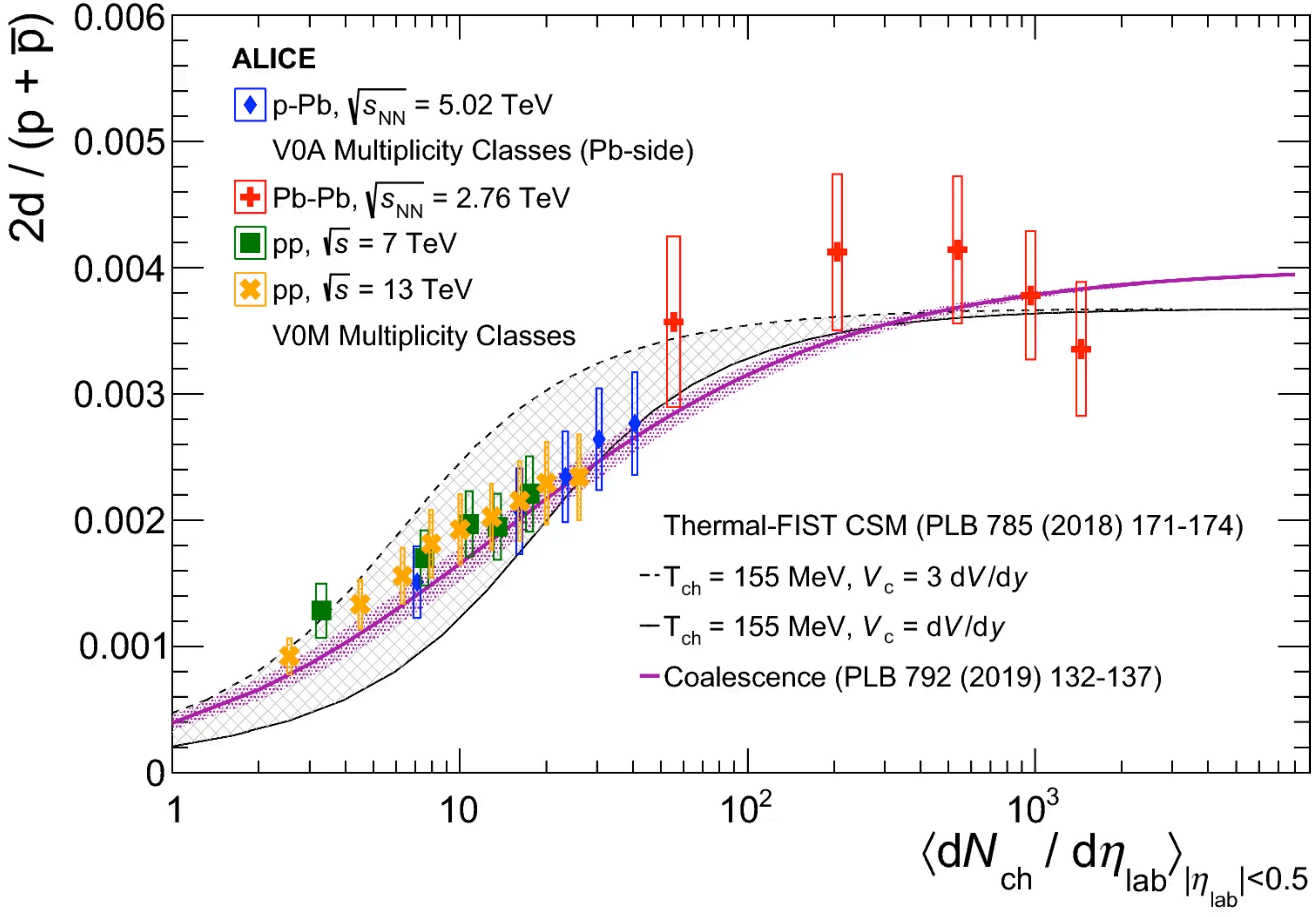
Snowballs in Hell…

Nuclei synthesis: thermal vs coalescence

- Good description of the deuteron production by both the models



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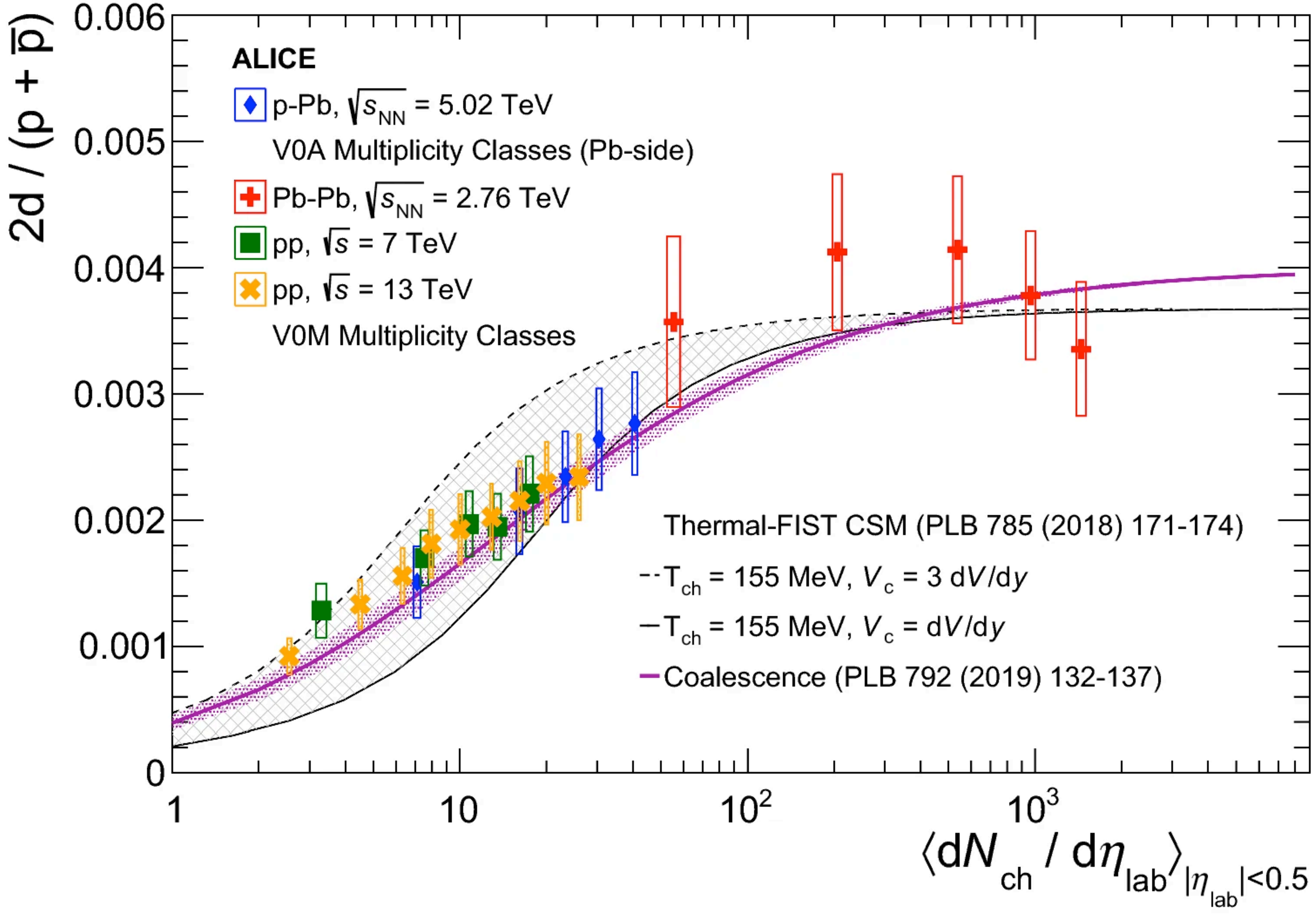
Is it accidental???

How to distinguish between the models?

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



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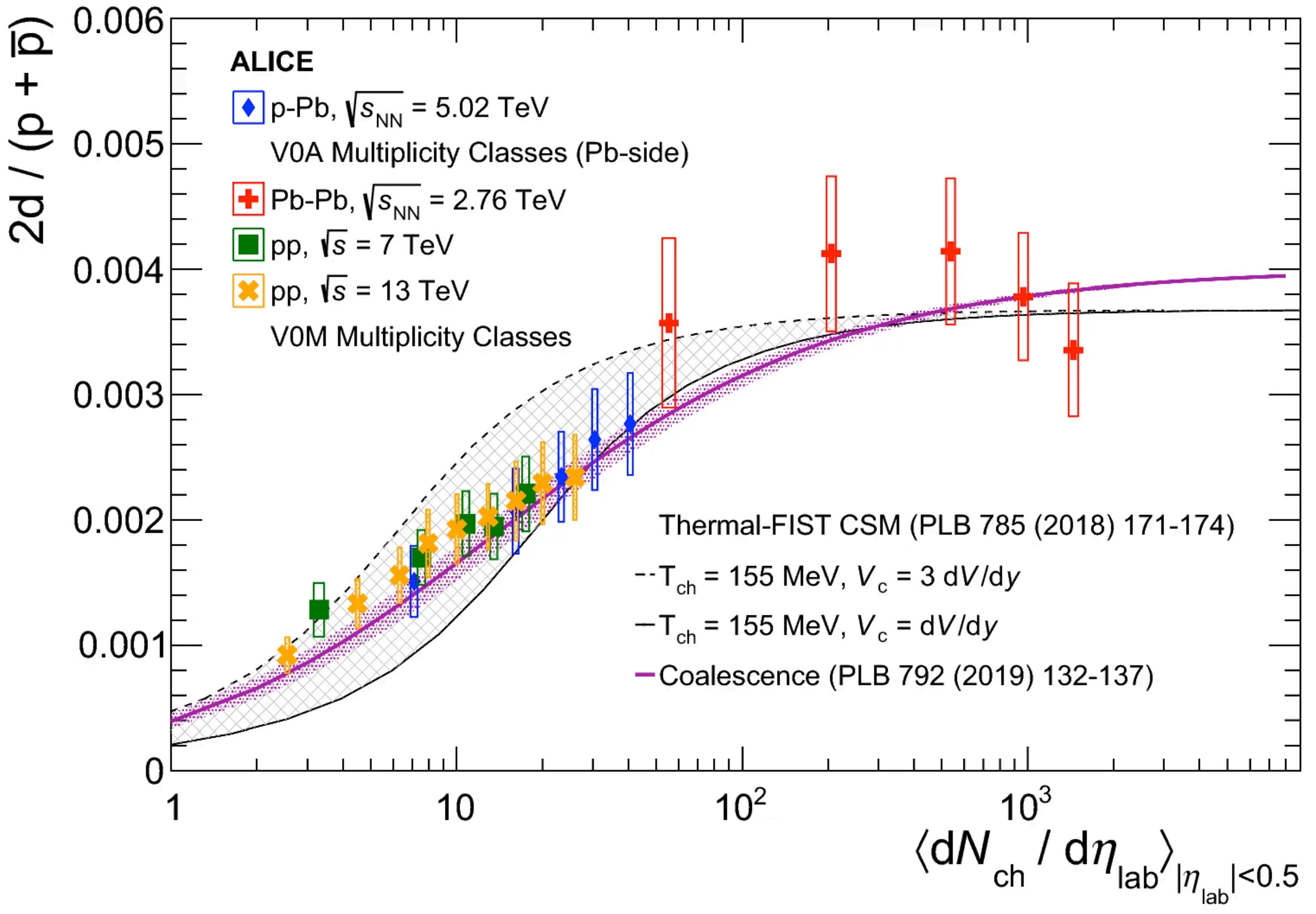

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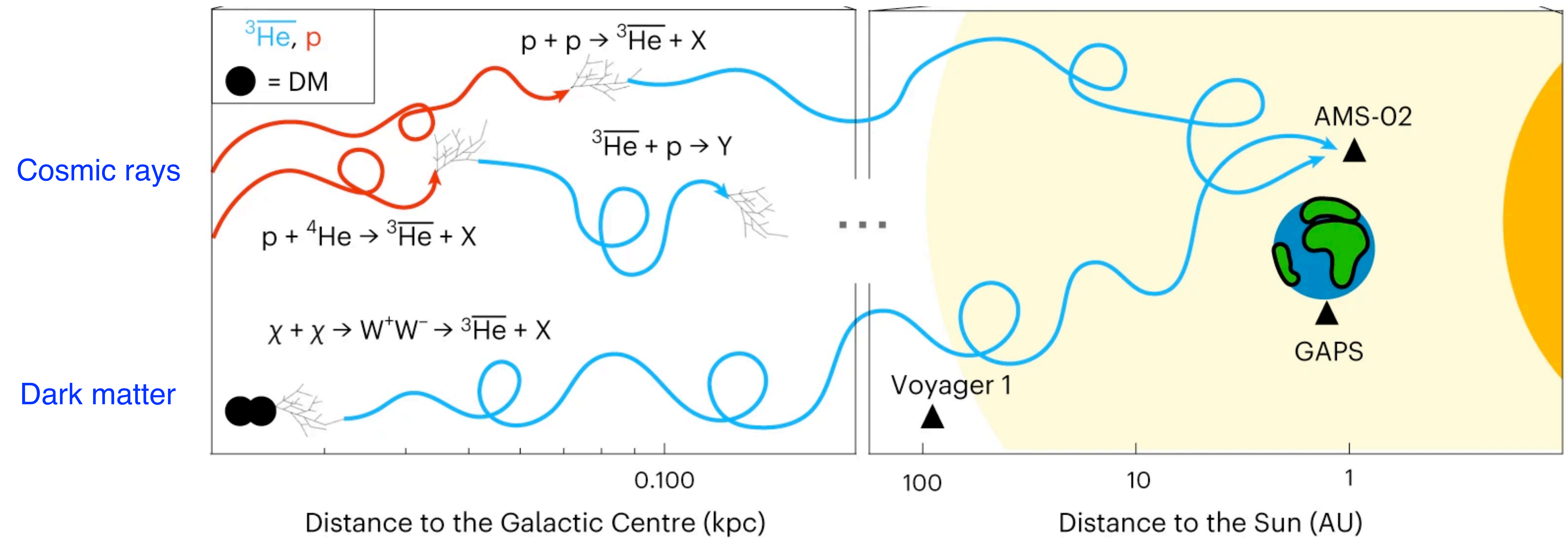
What is their microscopic origin?

Motivation: beyond heavy-ion collisions

- 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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Let’s confront the production mechanisms….

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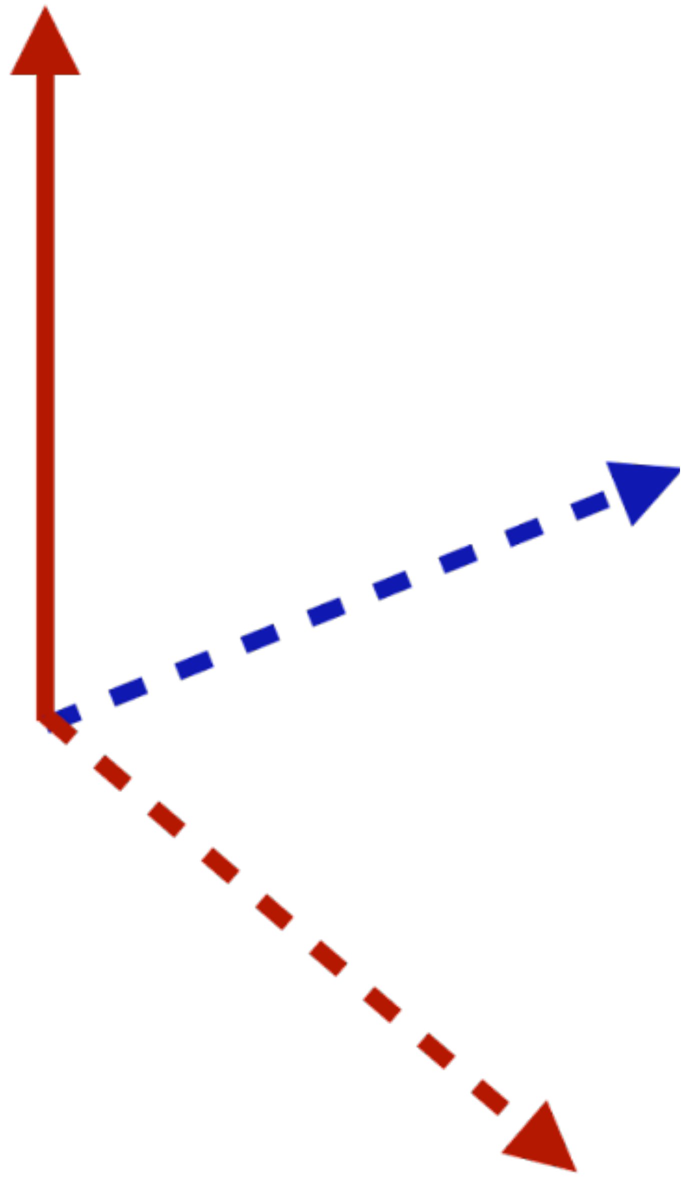
By measuring the baryon number balance

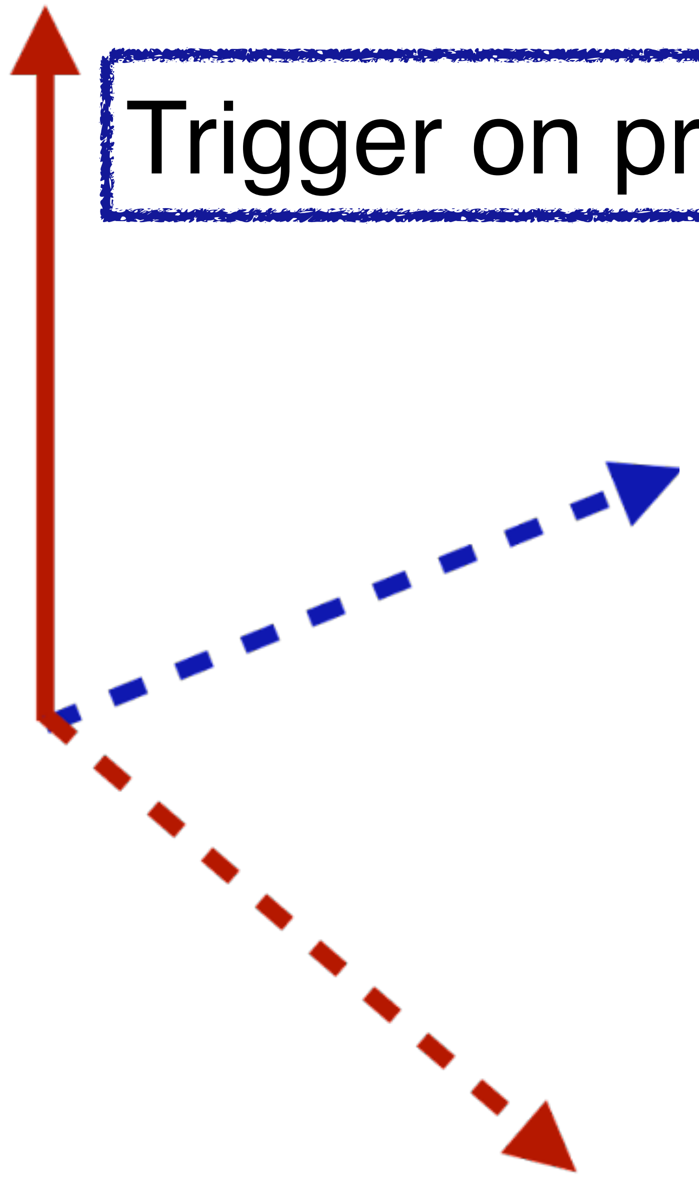
S. Tripathy, P. Christiansen, arXiv:2509.03195

Balance functions of protons and deuterons



Balance functions of protons and deuterons

Trigger on protons (p) and deuterons (d)



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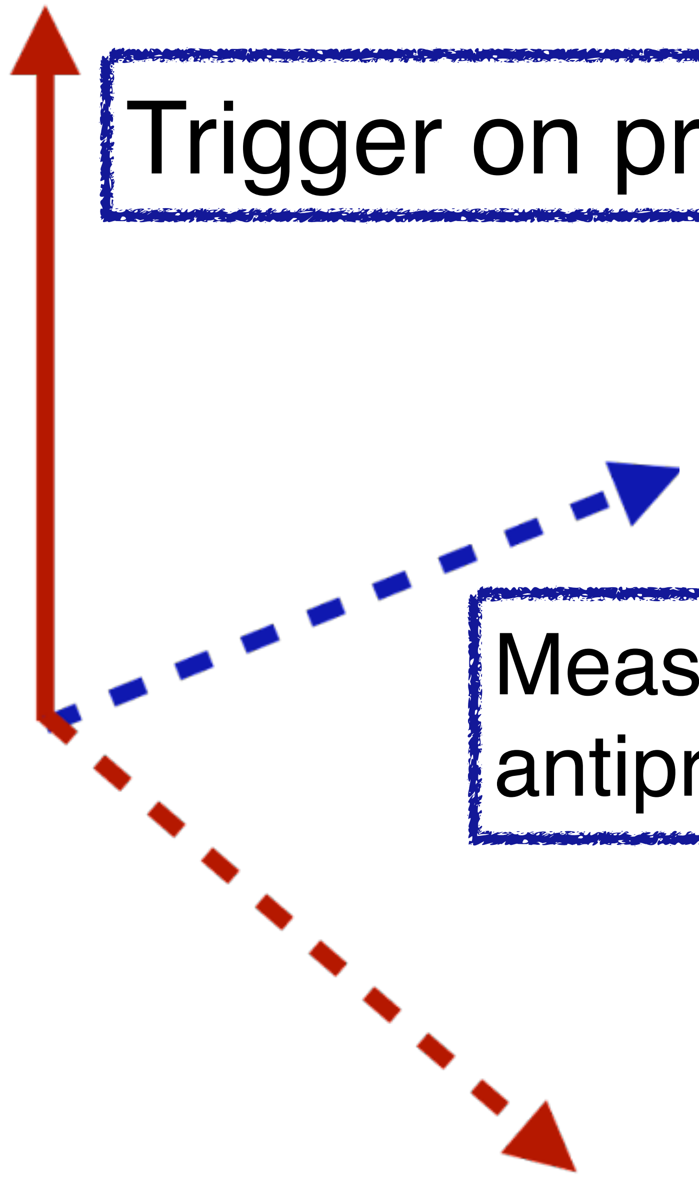

Trigger on protons (p) and deuterons (d)

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

OS

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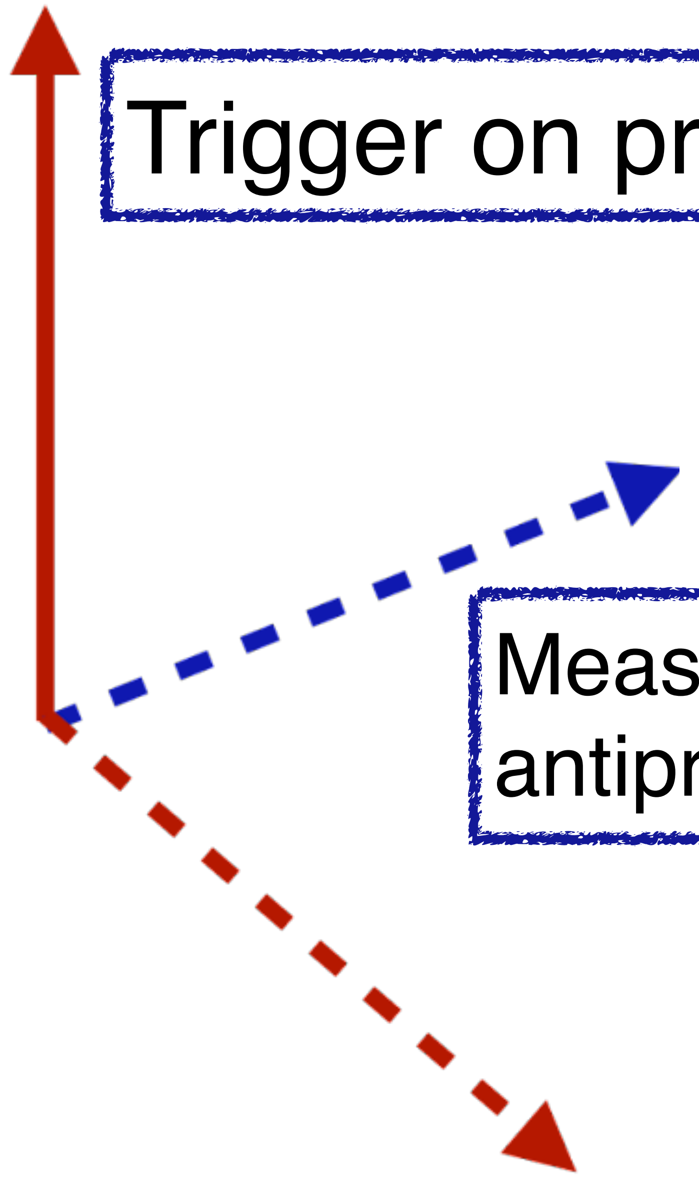

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Subtract the uncorrelated production via the same
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SS

Balance functions of protons and deuterons

Trigger on protons (p) and deuterons (d)

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

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

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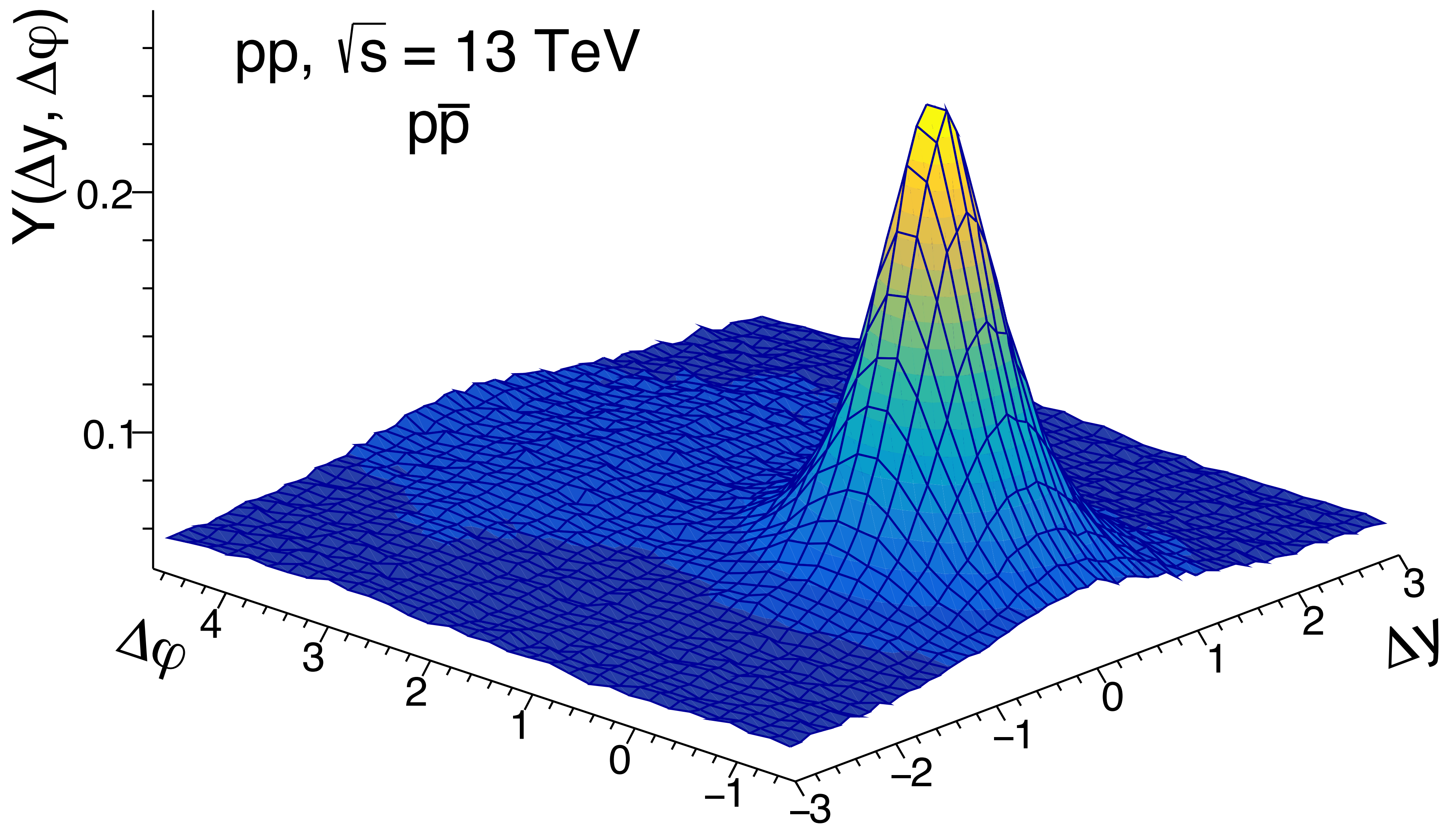

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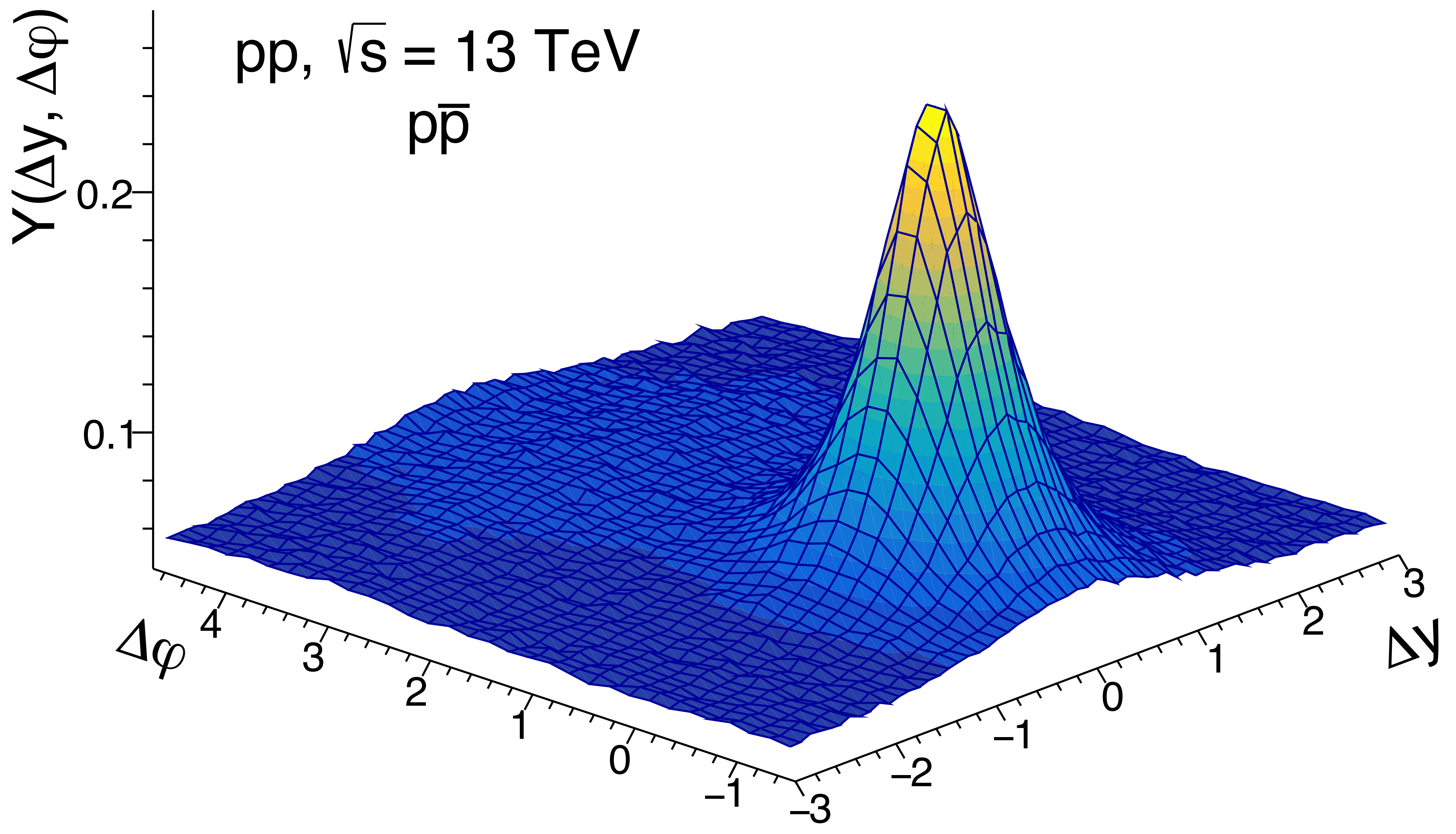

Let's confront the contrasting paradigms: **Thermal-FIST** and PYTHIA8

Thermal production

Balance functions of protons and deuterons

Trigger on protons (p) and deuterons (d)

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

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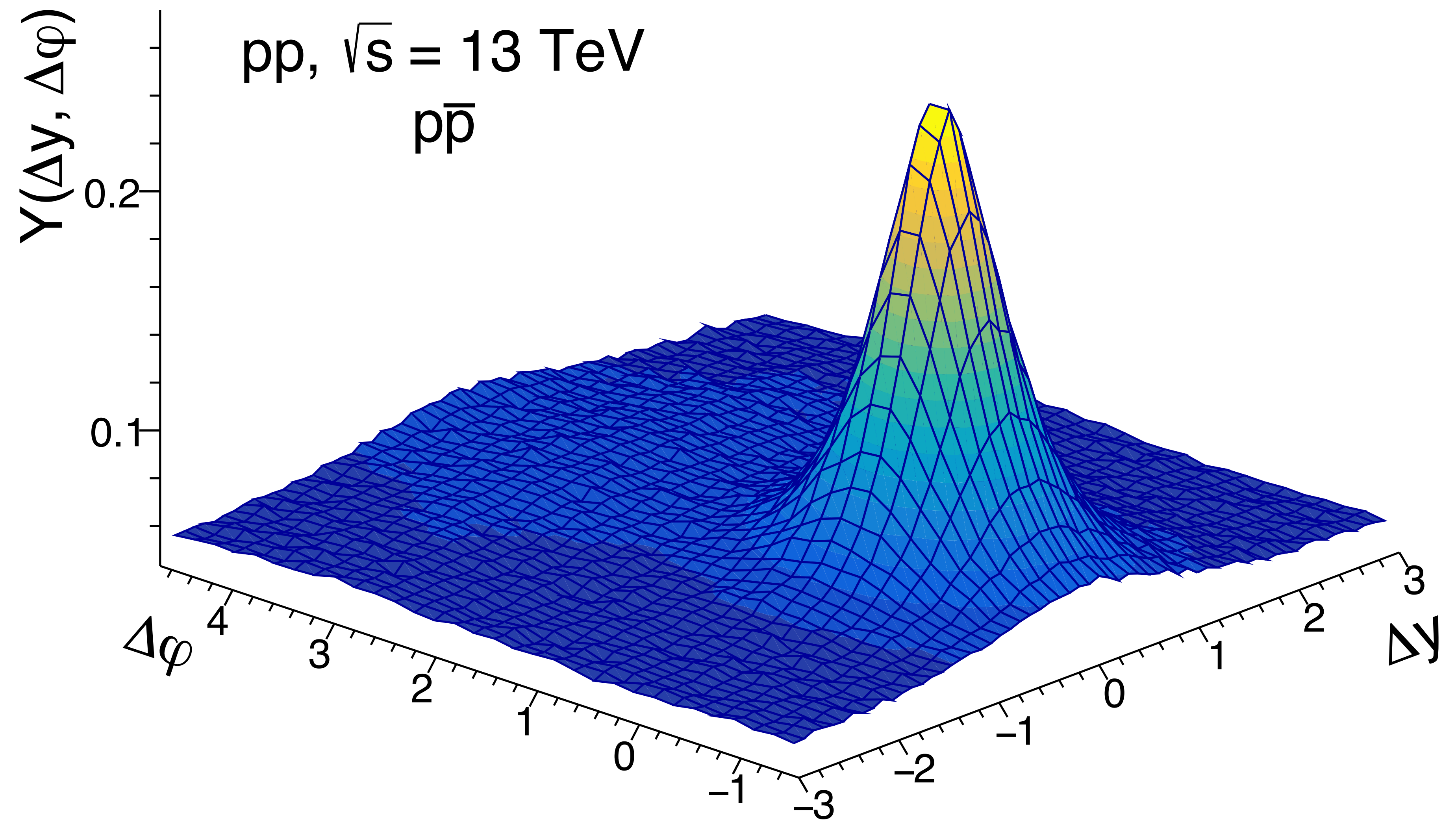


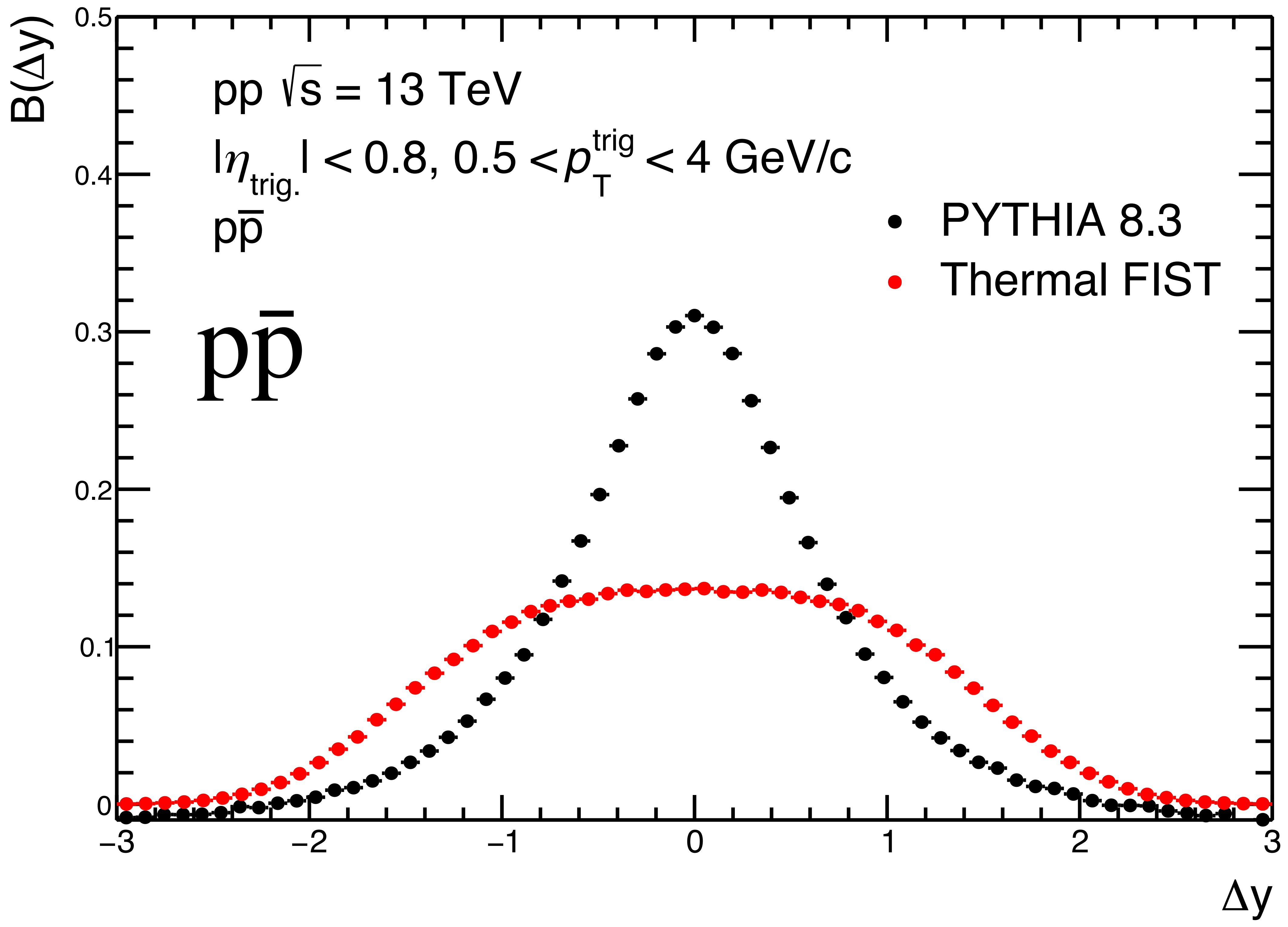
Let's confront the contrasting paradigms: Thermal-FIST and **PYTHIA8**

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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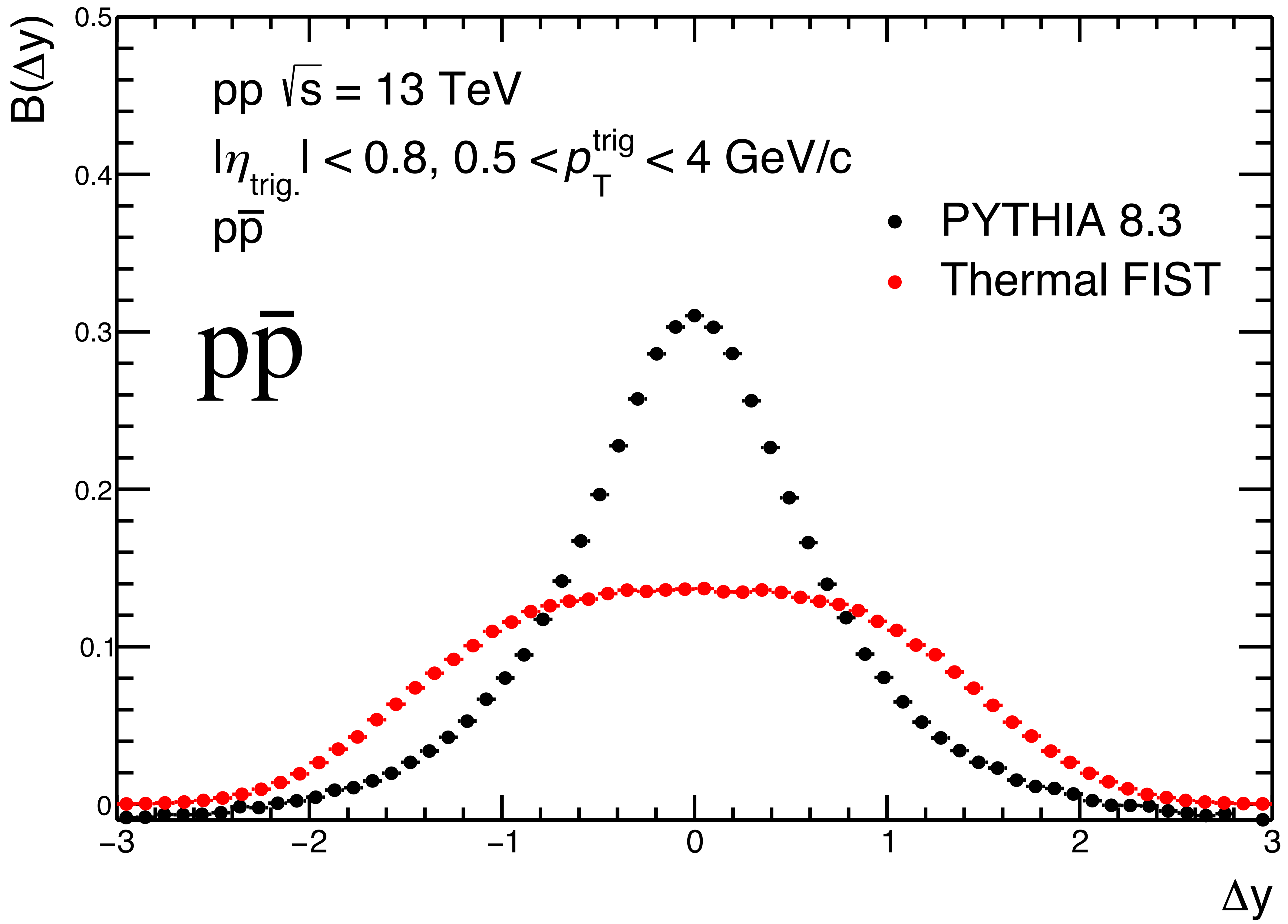

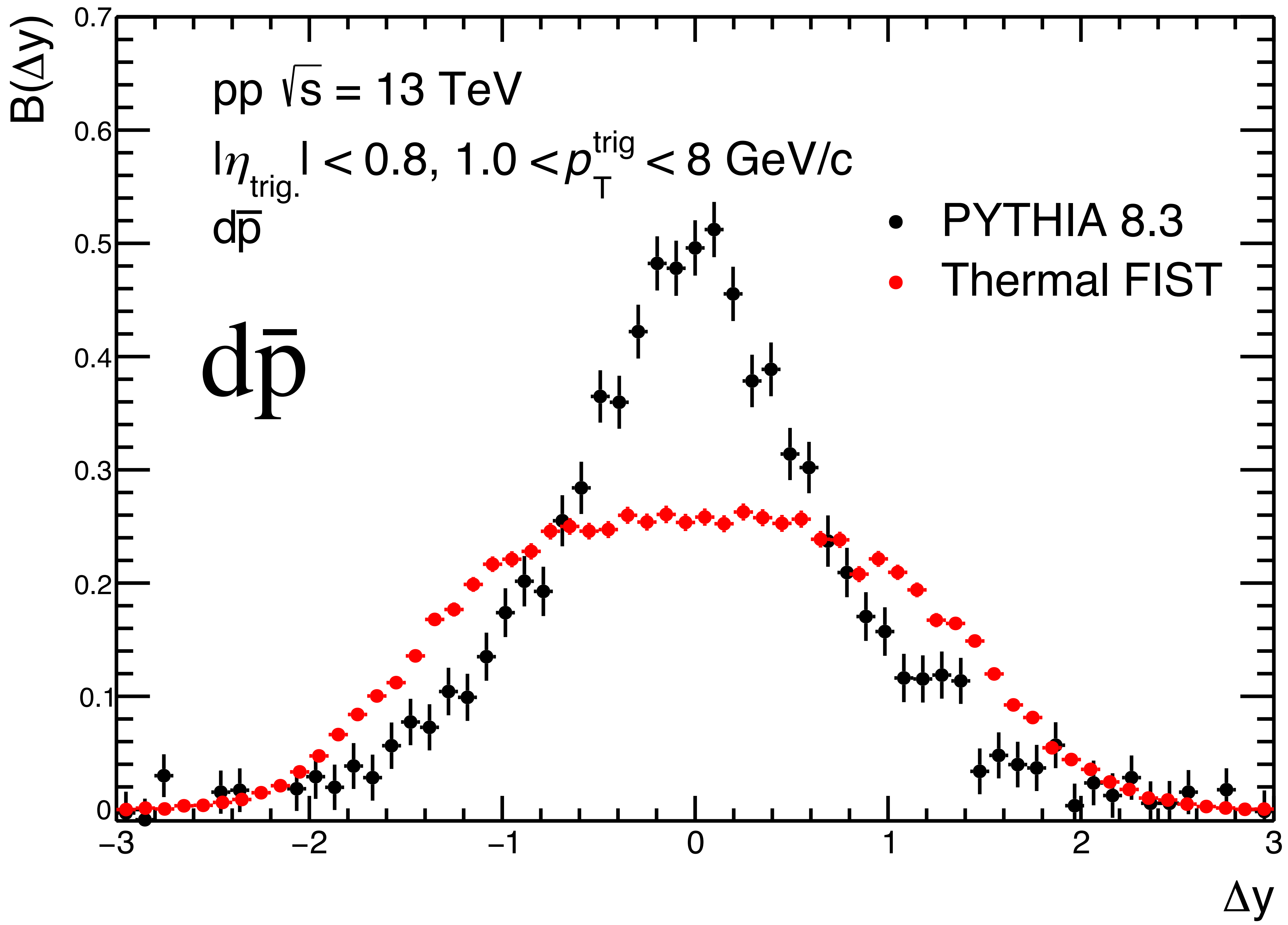

- Clearly different shape of balance functions from Thermal-FIST and PYTHIA 8.
  In Thermal FIST, it is driven by correlation volume (see backup)
- Similar shapes of balance functions for triggered protons and deuterons

Balance functions of protons and deuterons

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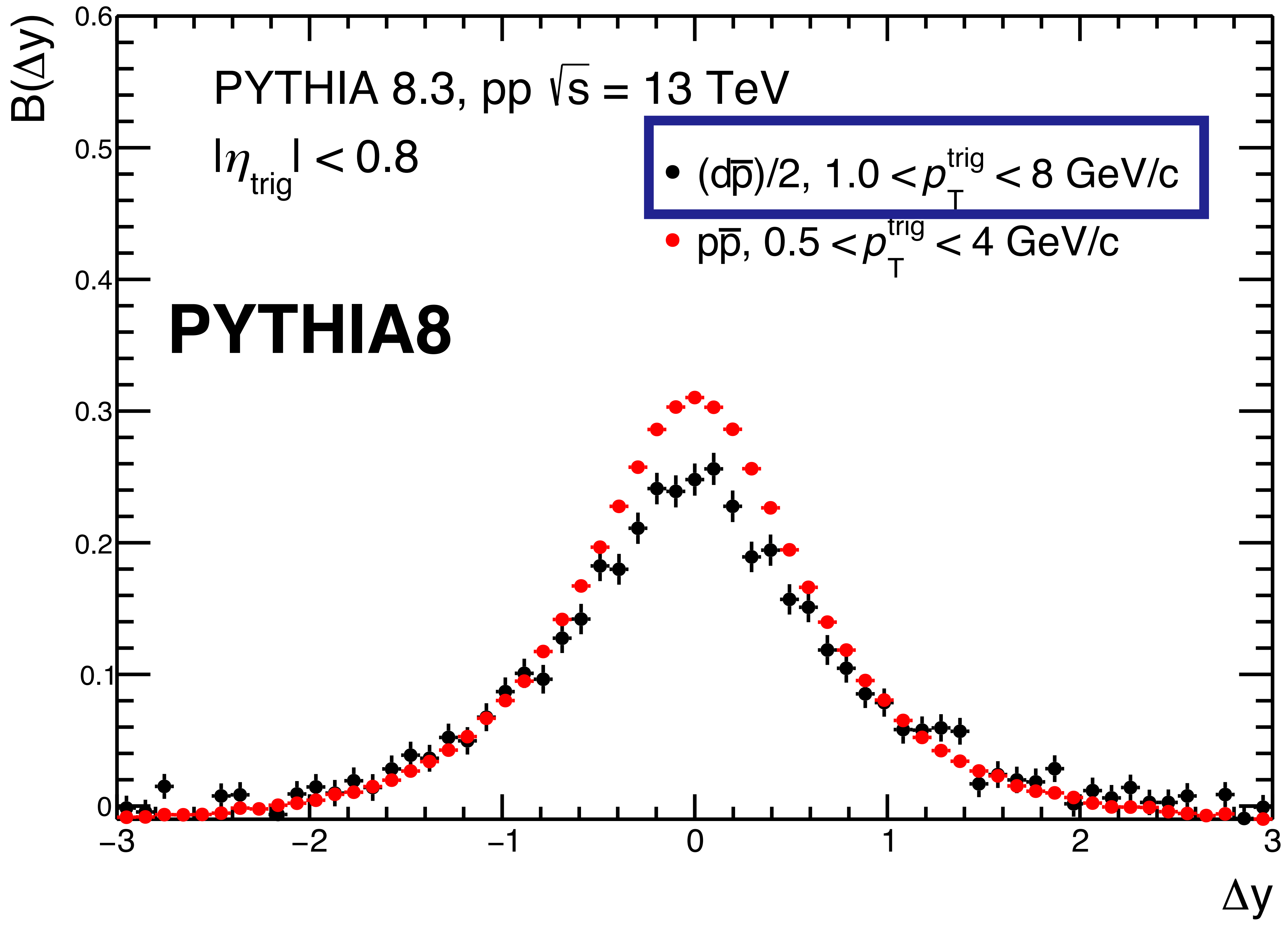
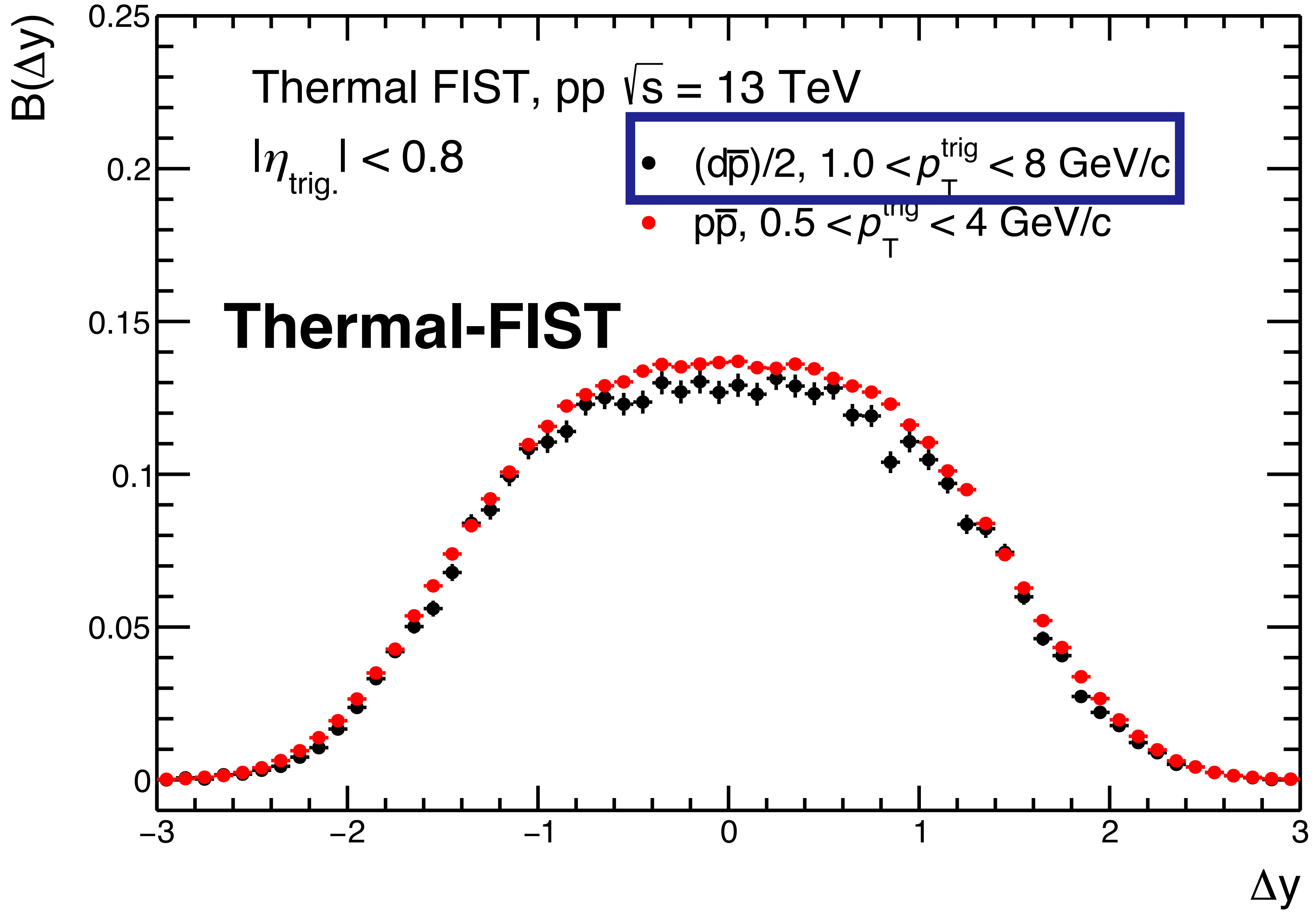




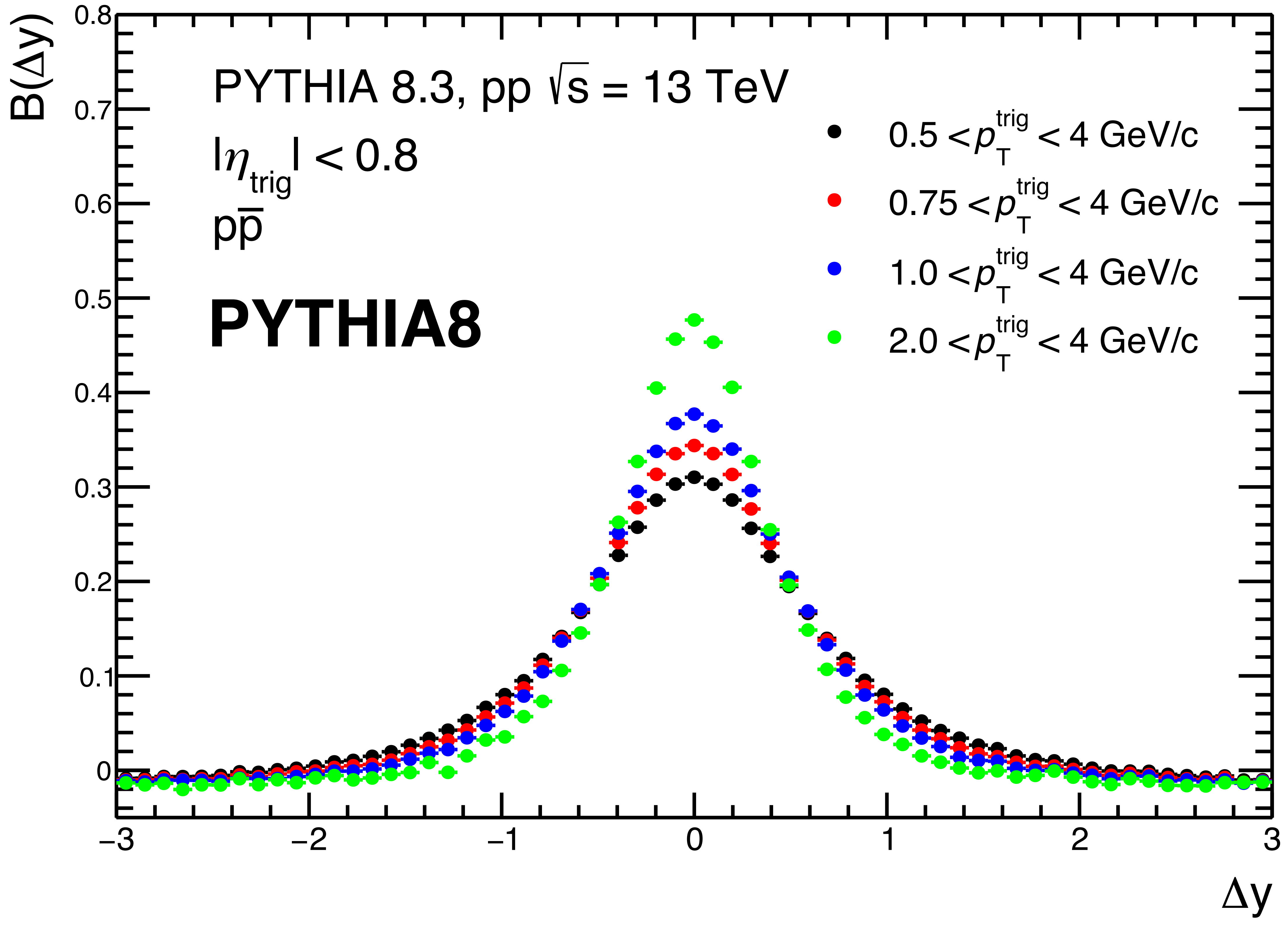
- Since a deuteron consists of two nucleons, its balance function is expected to be twice that of a proton.
- Both models confirm this behavior

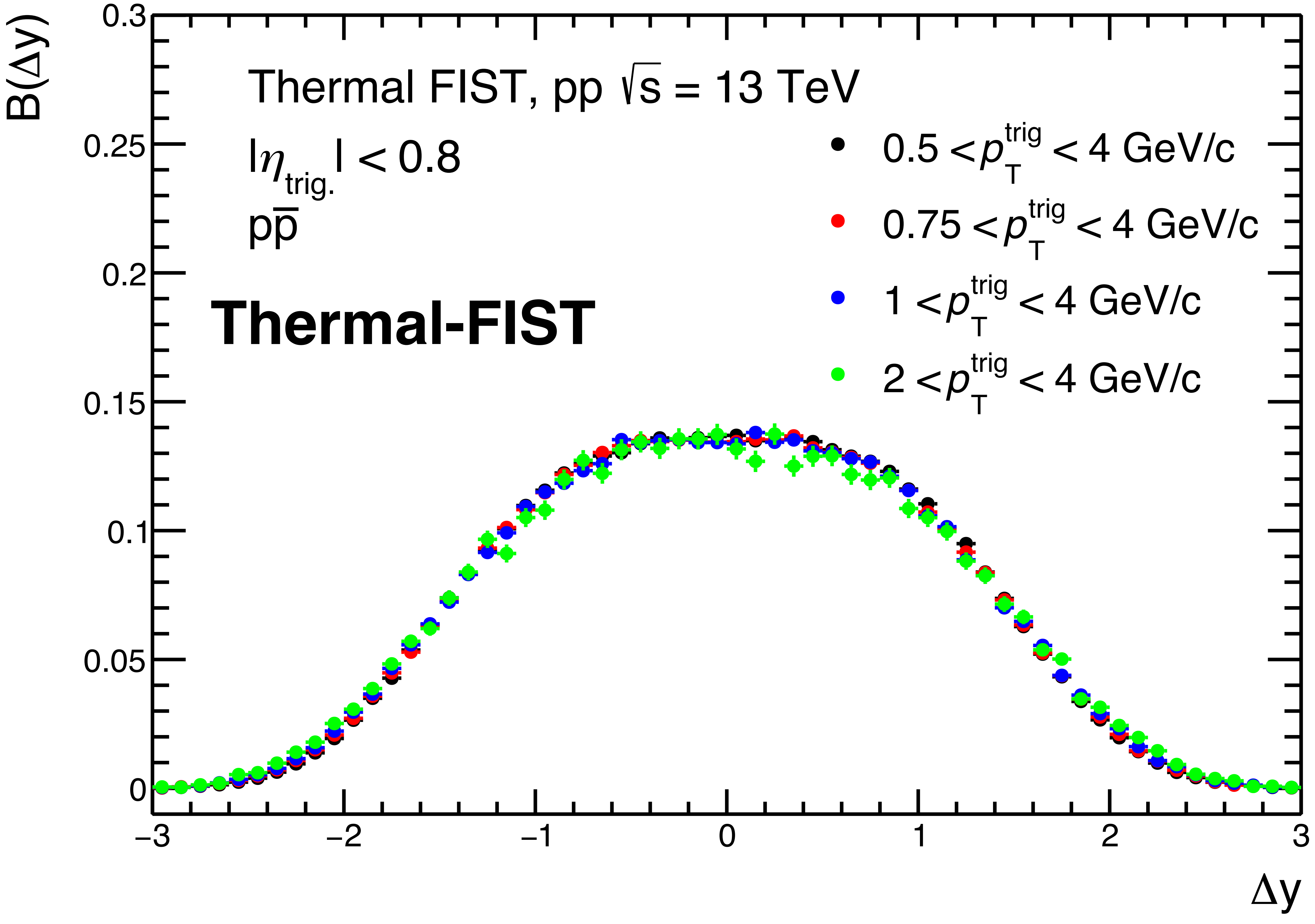
Transverse momentum dependence

$p\bar{p}$

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

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





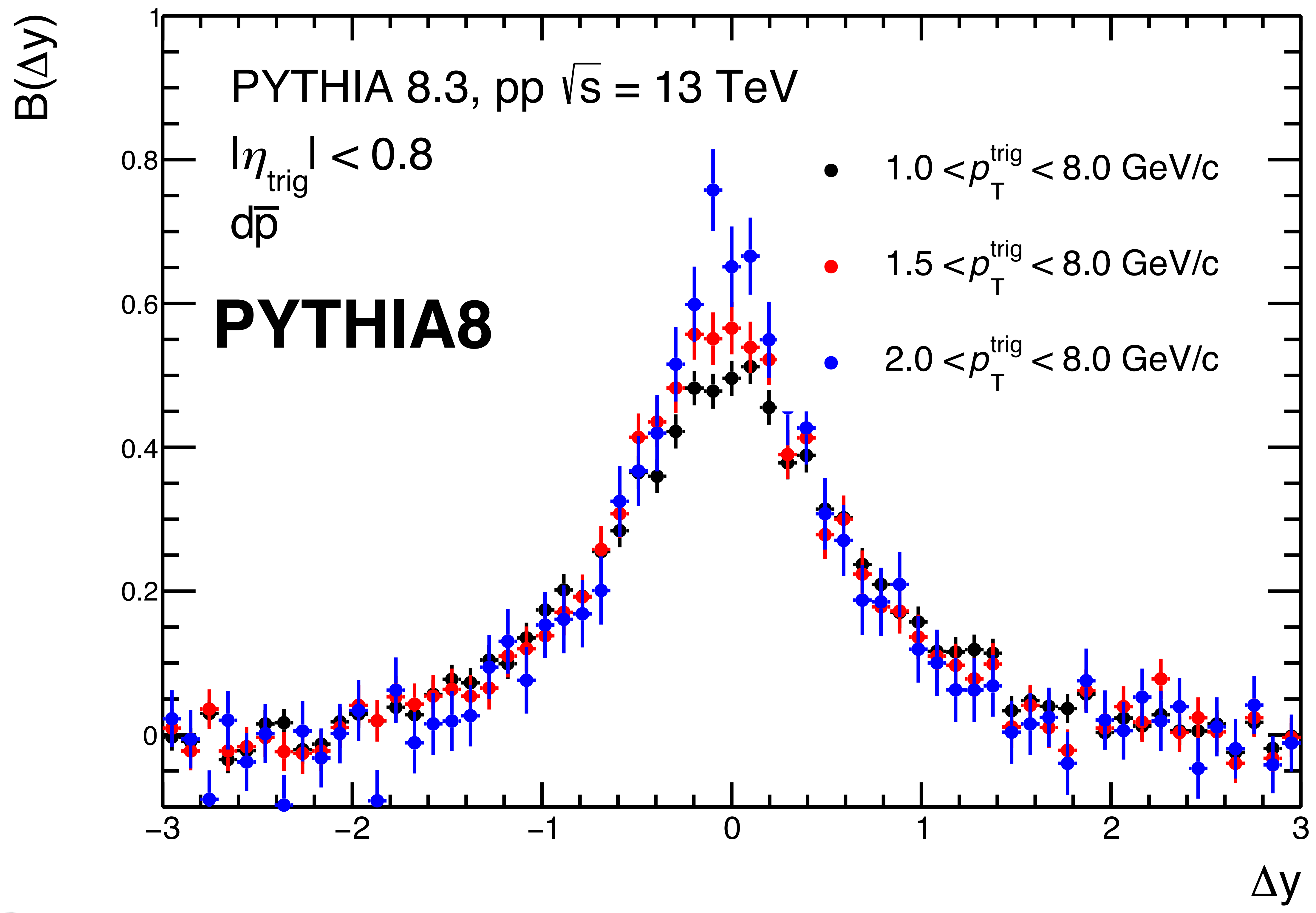
- **Narrowing in PYTHIA**: the antiproton that balance a proton is produced on the same string as the proton
- **No dependence in Thermal FIST:** quantum number conservation is only imposed globally on the final state

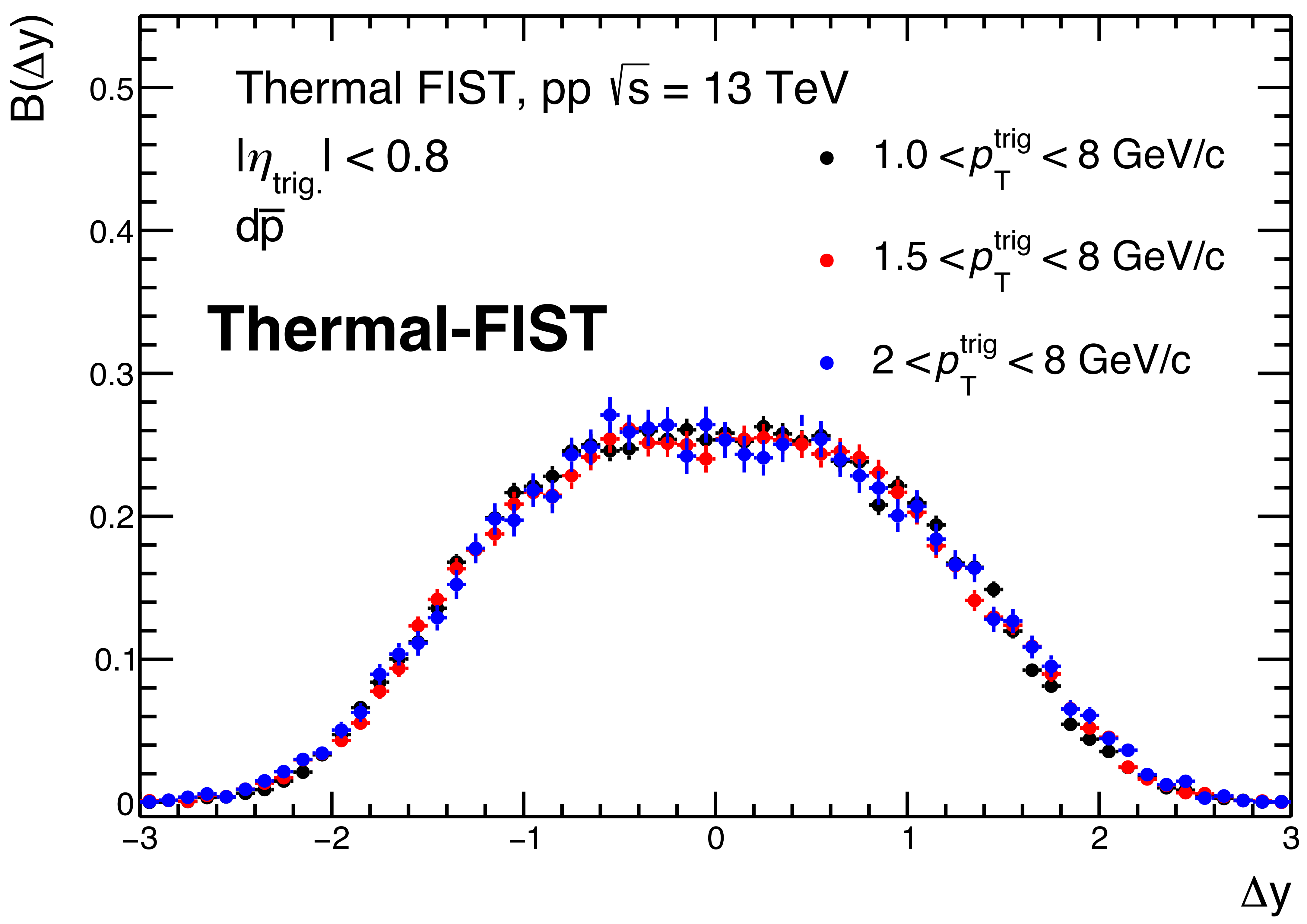
Transverse momentum dependence

$d\bar{p}$

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

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





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

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Observation of origin from resonance-decay nucleons

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Observation of origin from resonance-decay nucleons

formation

The ALICE Collaboration

Nature **648**, 306–311 (2025) | Cite this article

Most of the observed deuterons are produced in nuclear reactions following the decay of short-lived resonances, such as the $\Delta(1232)$

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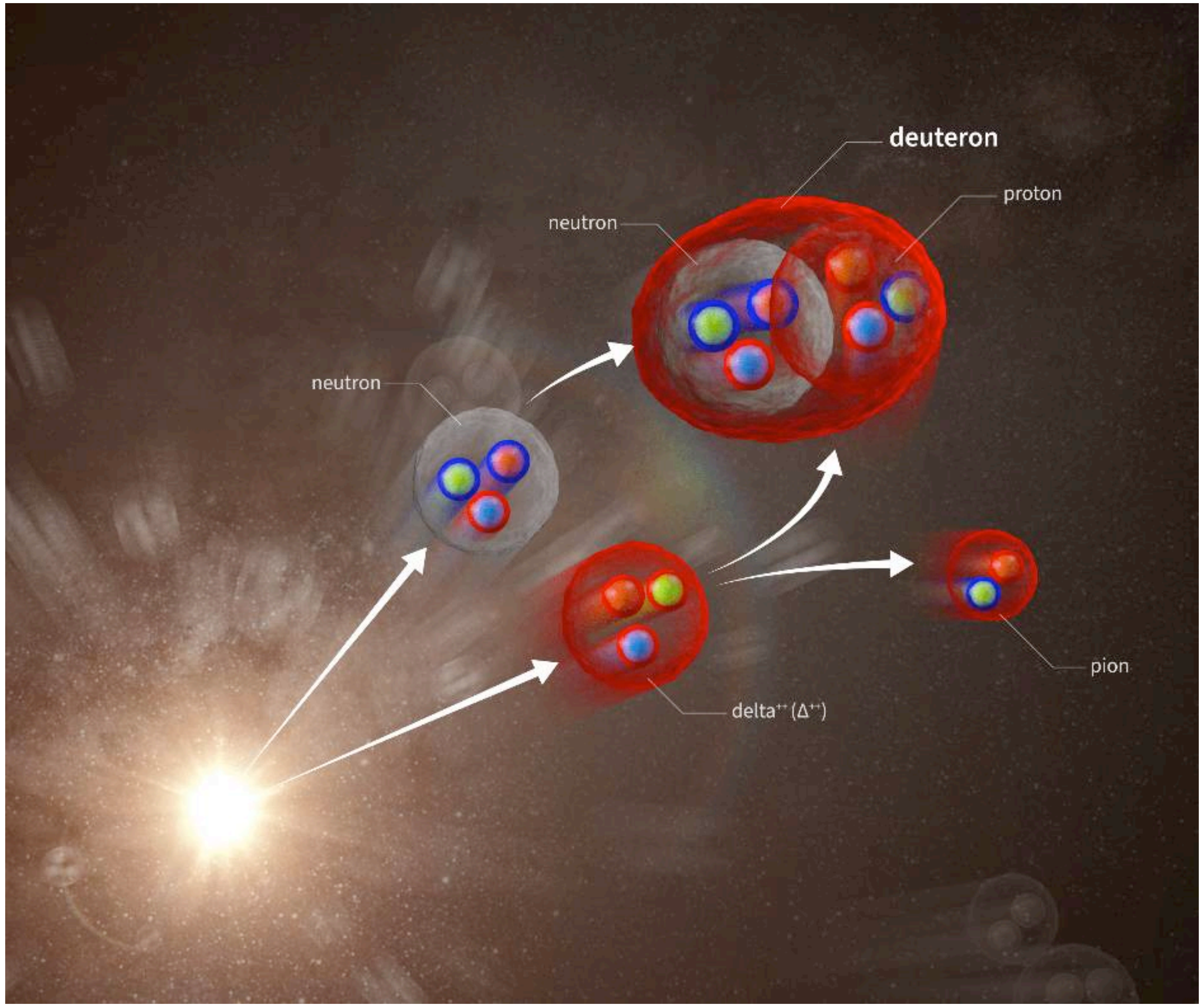
Observation of origin from resonance-decay nucleons



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Observation of deuteron and antideuteron formation from resonance-decay nucleons

The ALICE Collaboration

Nature **648**, 306–311 (2025) | Cite this article

Most of the observed deuterons are produced in nuclear reactions following the decay of short-lived resonances, such as the $\Delta(1232)$

Observation of origin from resonance-decay nucleons

ALICE, Nature 648 306 (2025)

Pion-deuteron correlations as microscope

$$C(k^*) = N \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

k* is the single-particle momentum in the pair rest frame

For non-interacting particles, C(k*) ≈ 1 everywhere

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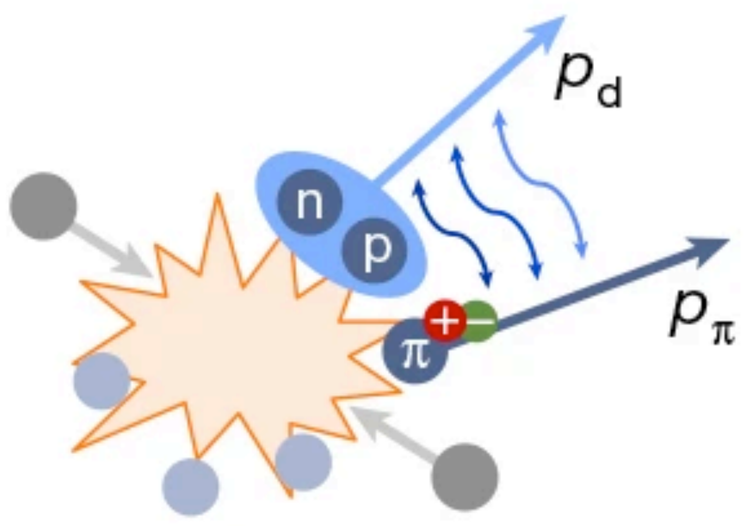
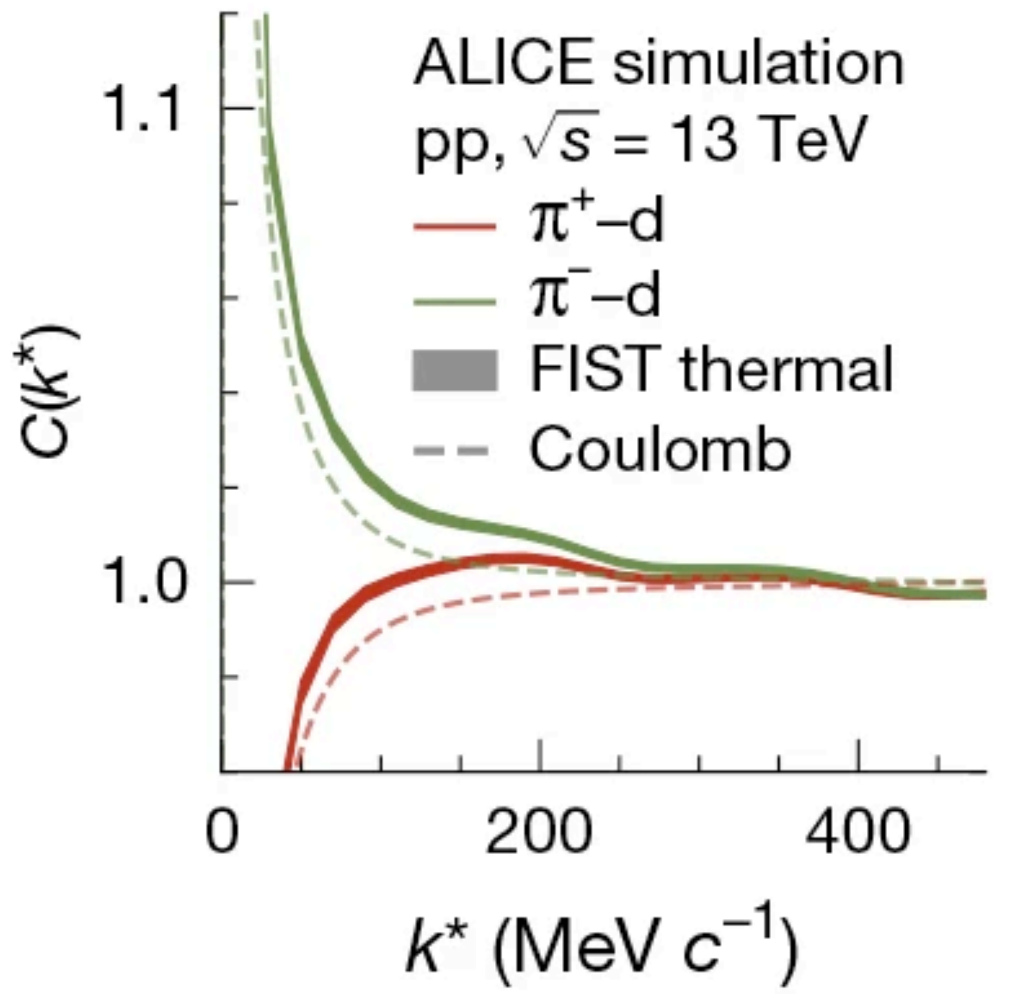


Pure thermal π + d, only Coulomb FSI



1. **For pure thermal π + d correlations,**
   - π and d produced independently
   - only Coulomb effect (attractive for OS, repulsive for SS)

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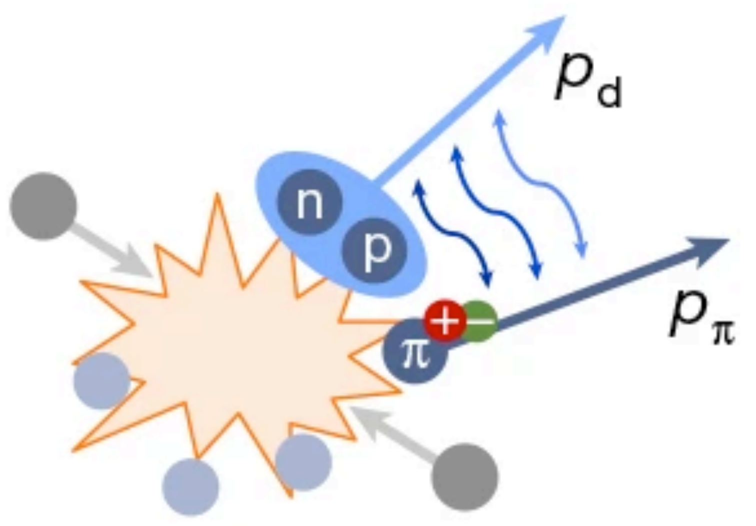

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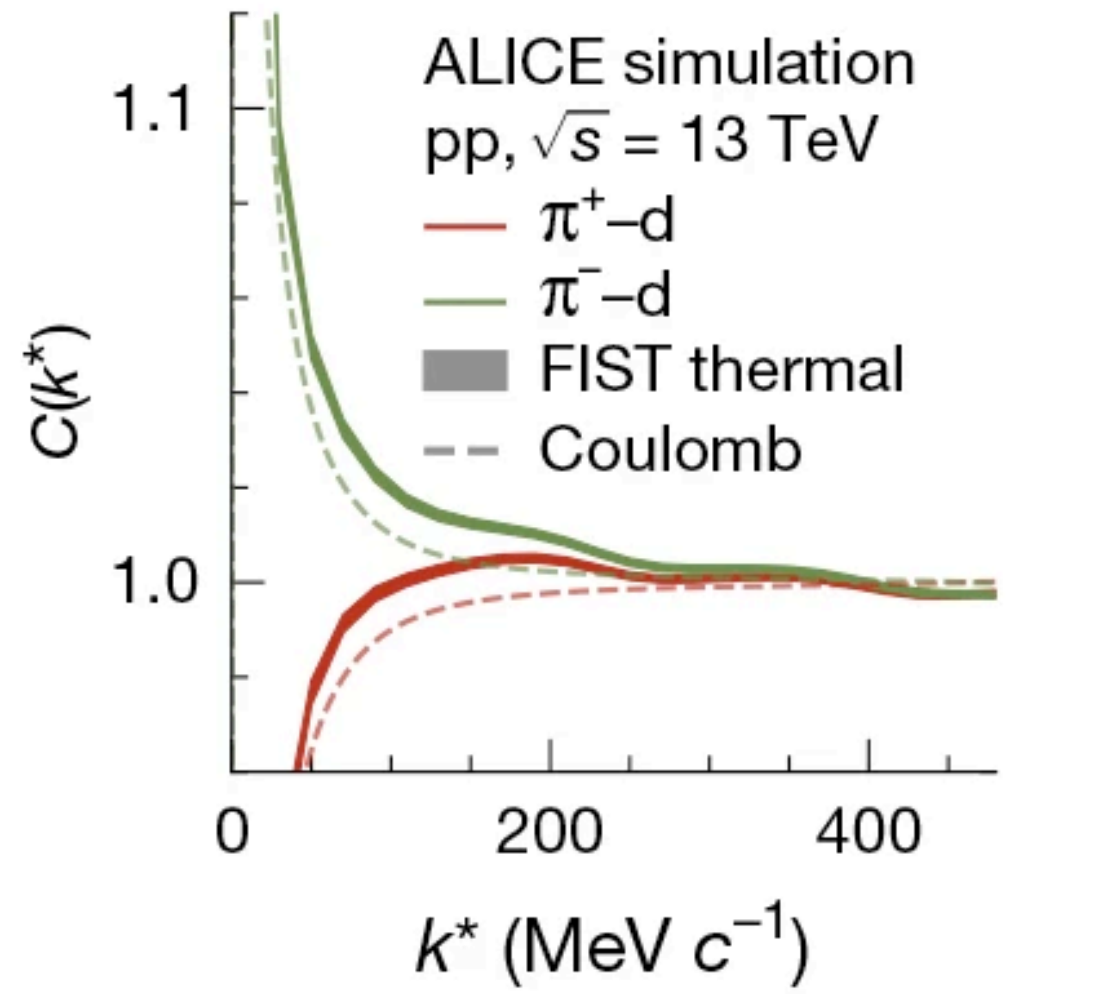
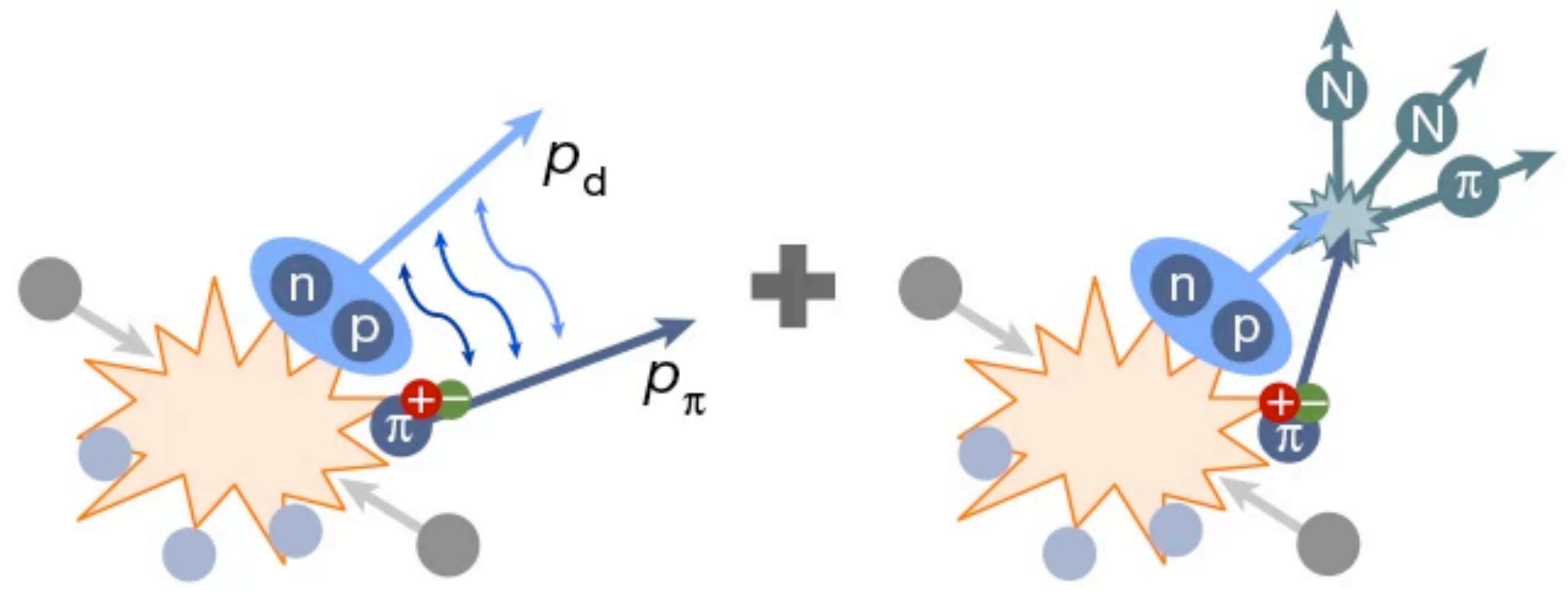
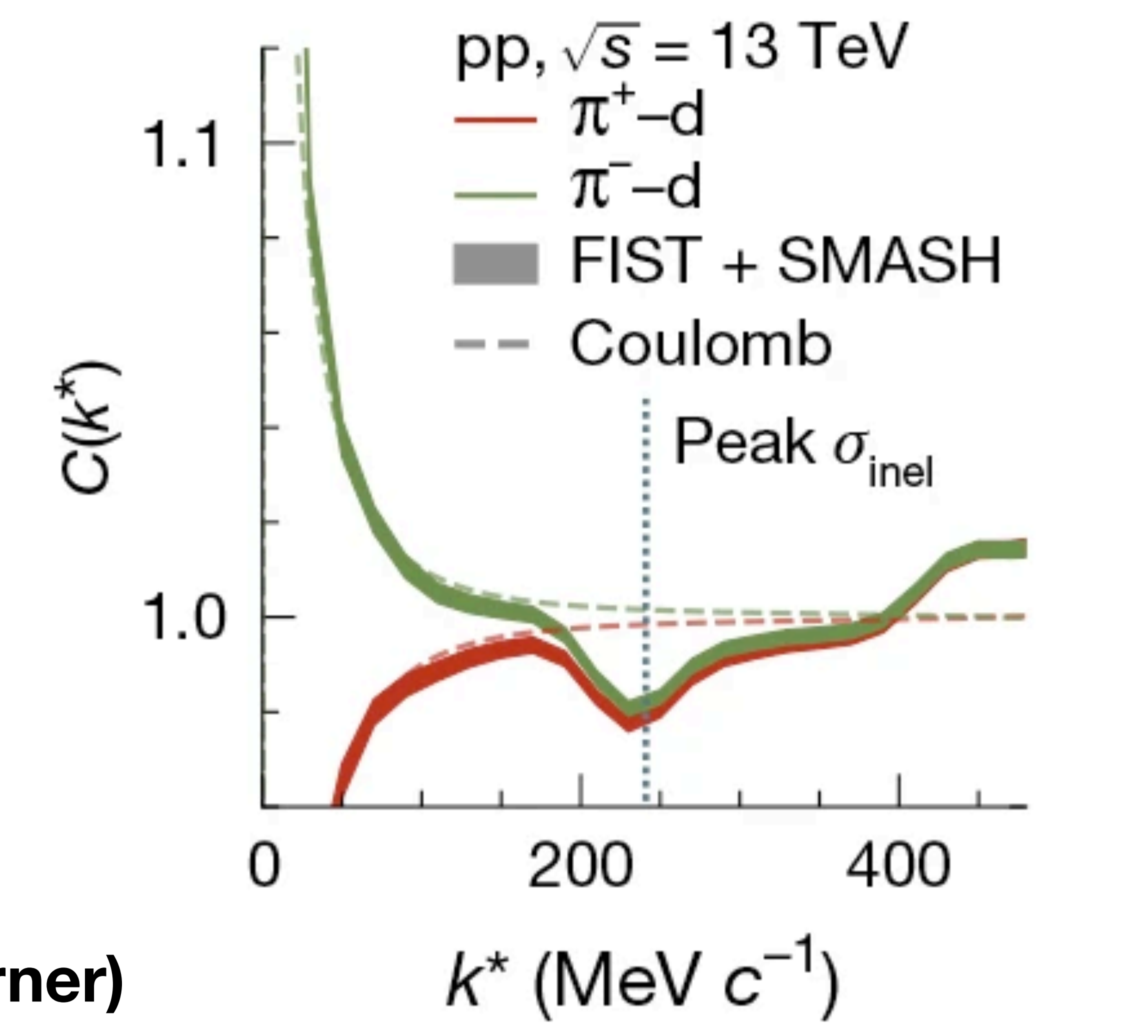


1. **For pure thermal π + d correlations,**
   - π and d produced independently
   - only Coulomb effect (attractive for OS, repulsive for SS)

2. **Thermal + SMASH**
   - Elastic scattering keeps k* unchanged
   - Inelastic π–d → deuteron breakup
   - Inelastic cross section peaks at the Δ mass → peak



Thermal π + d,
including elastic + inelastic π–d scattering (SMASH afterburner)



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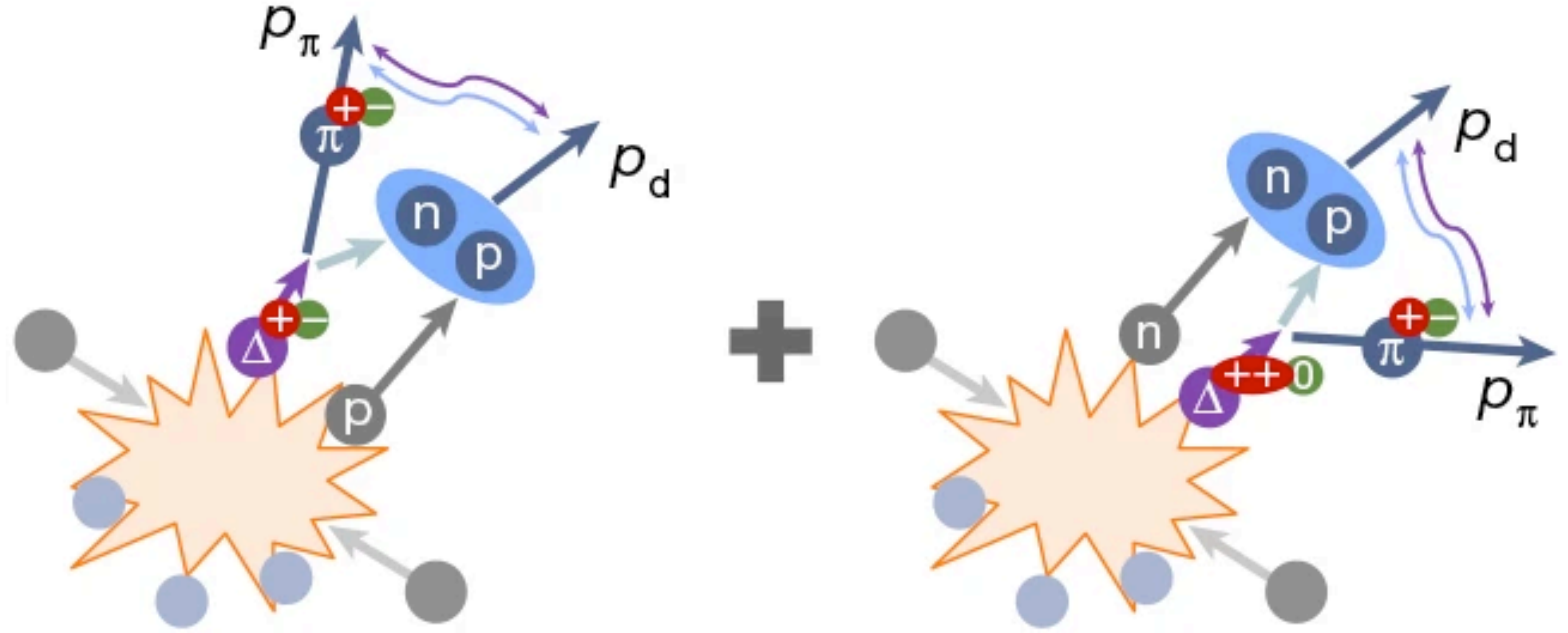
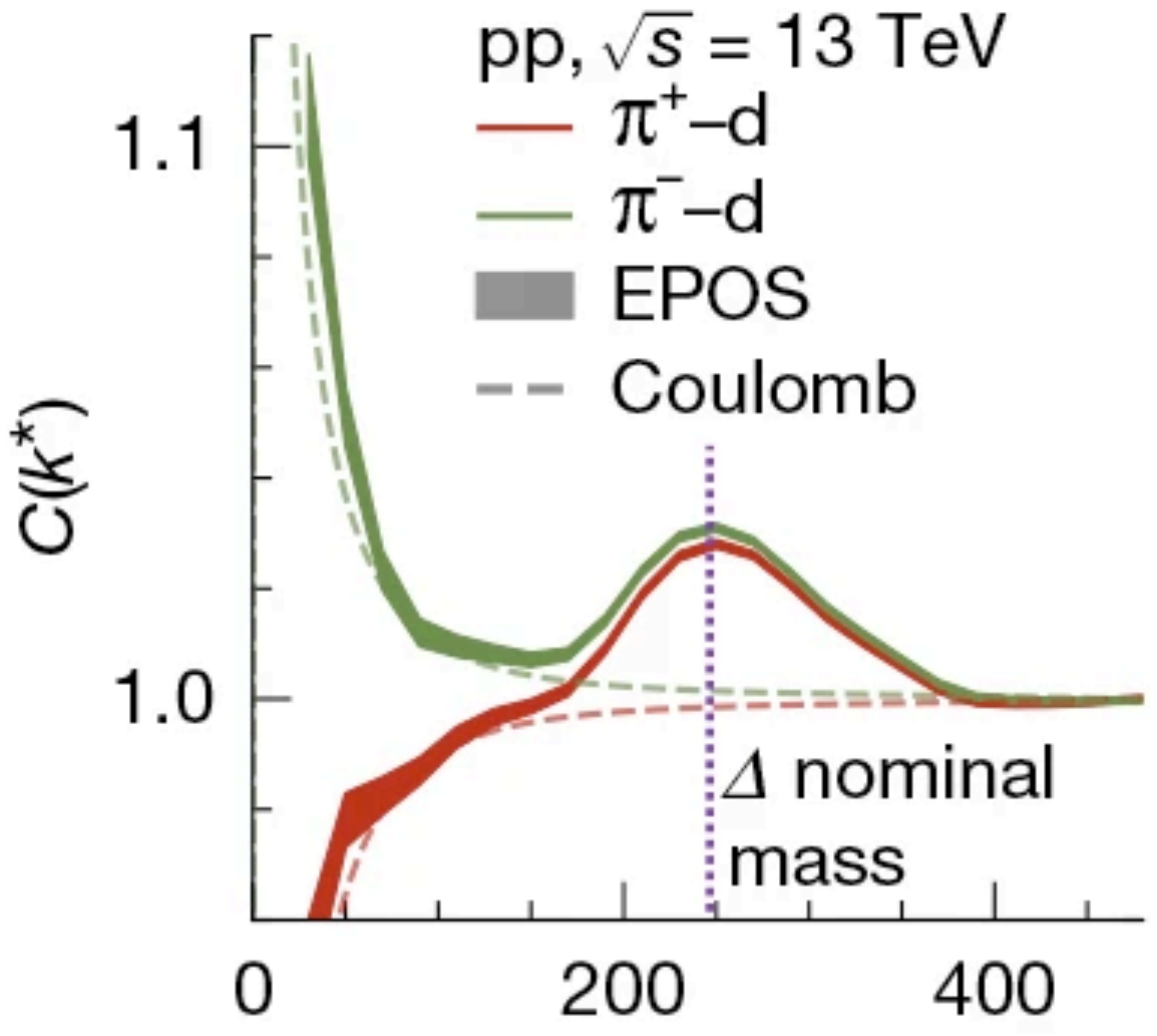
3. **EPOS + coalescence afterburner***
   - the nucleon from the decay coalesces with another nucleon to form d
   - a **peak** in C(k*) near the Δ nominal mass





*A realistic coalescence model for deuteron production,
M. Mahelin, L. Fabietti, F. Bellini, S. Tripathy *et. al.*, Eur. Phys. J. C83 (2023) 9, 804

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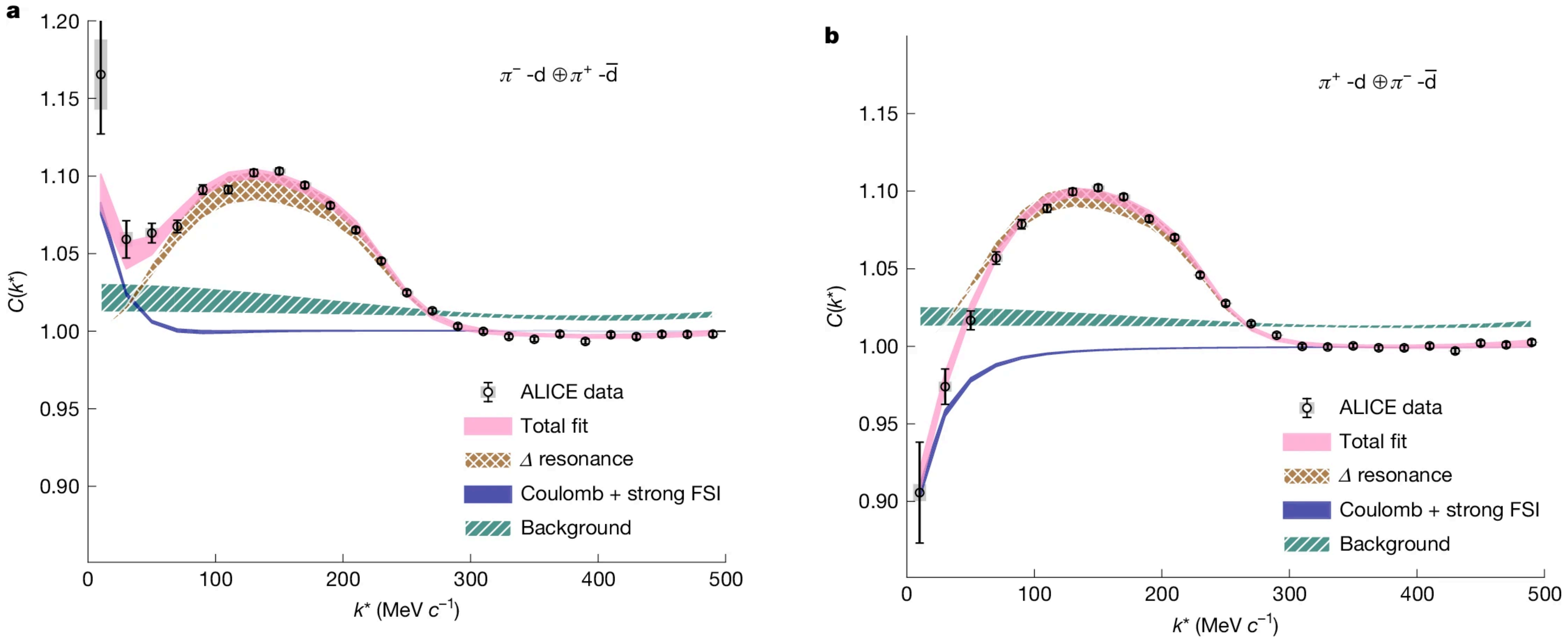
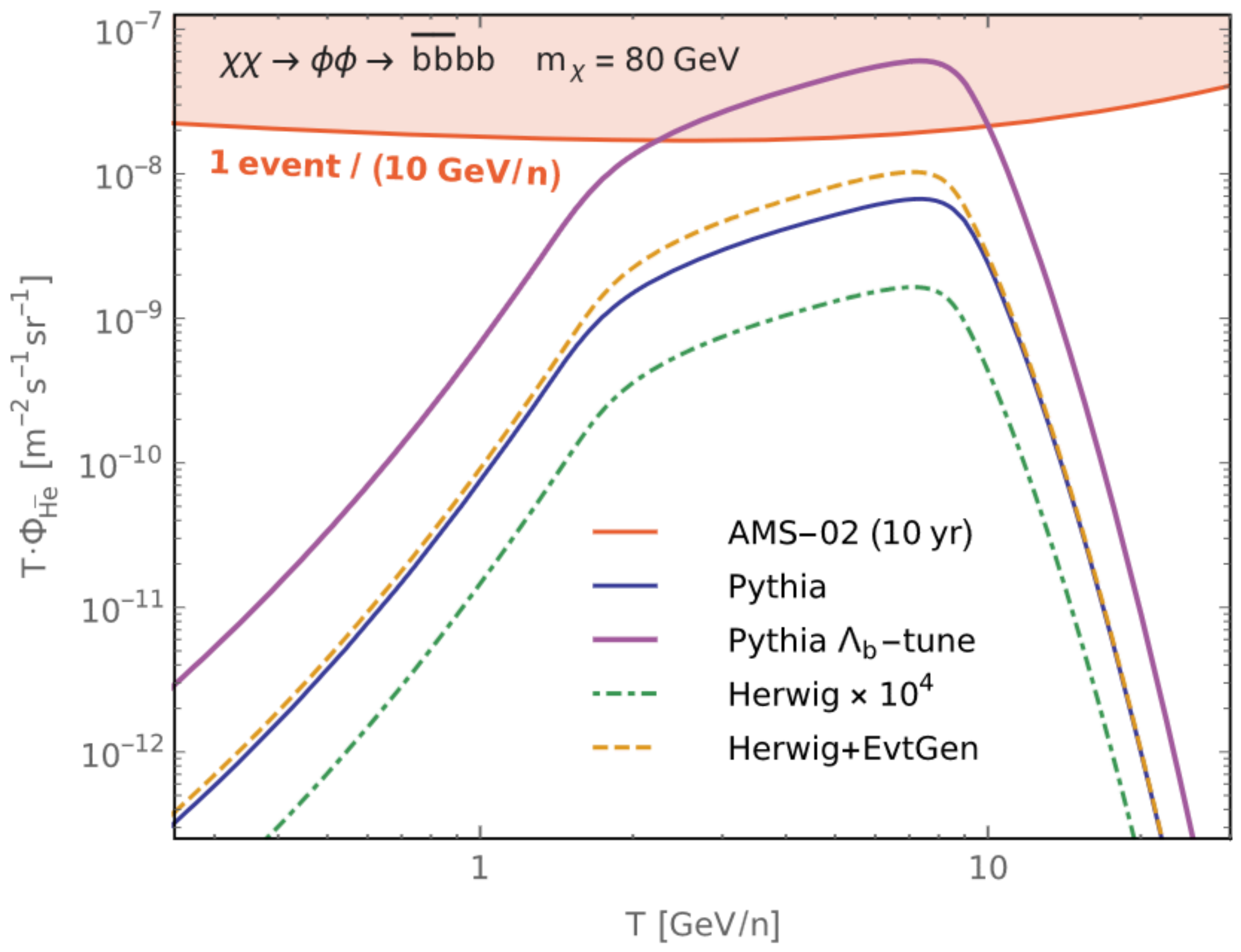


- **Clear peak at Δ nominal mass and no dip nor the coulomb FSI shape**
- Most of deuterons are just **snowballs** which do not try to survive hottest phase as they form in a much cooler stage.

Nuclei production in $\bar{\Lambda}_b^0$ decays

Winkler & Linden, PRL 126 (2021) 101101



Antibaryons from the same $\bar{\Lambda}_b^0$ decay can form $^3\overline{\mathrm{He}}$ and enhance cosmic anti helium

Relevant for dark matter searches

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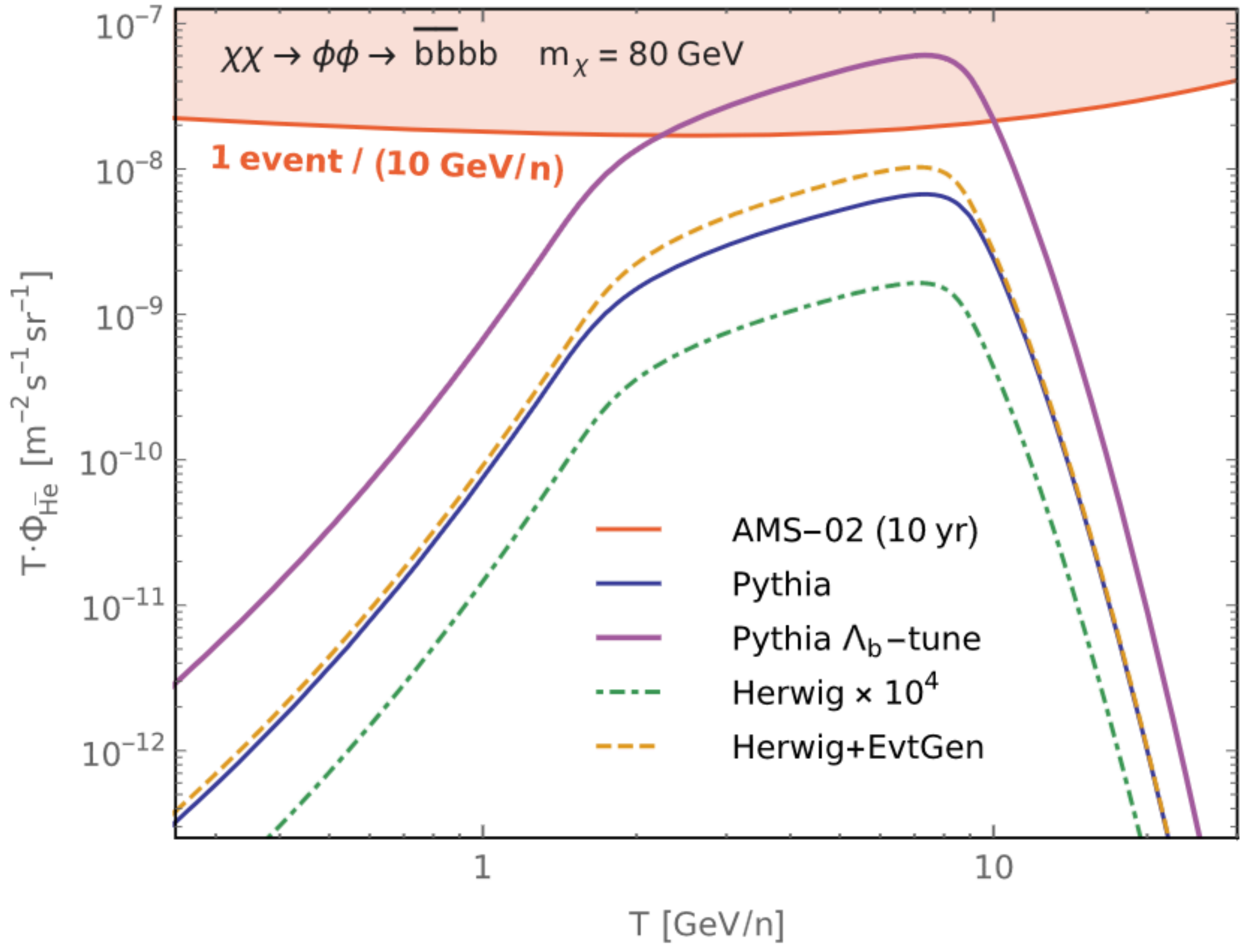
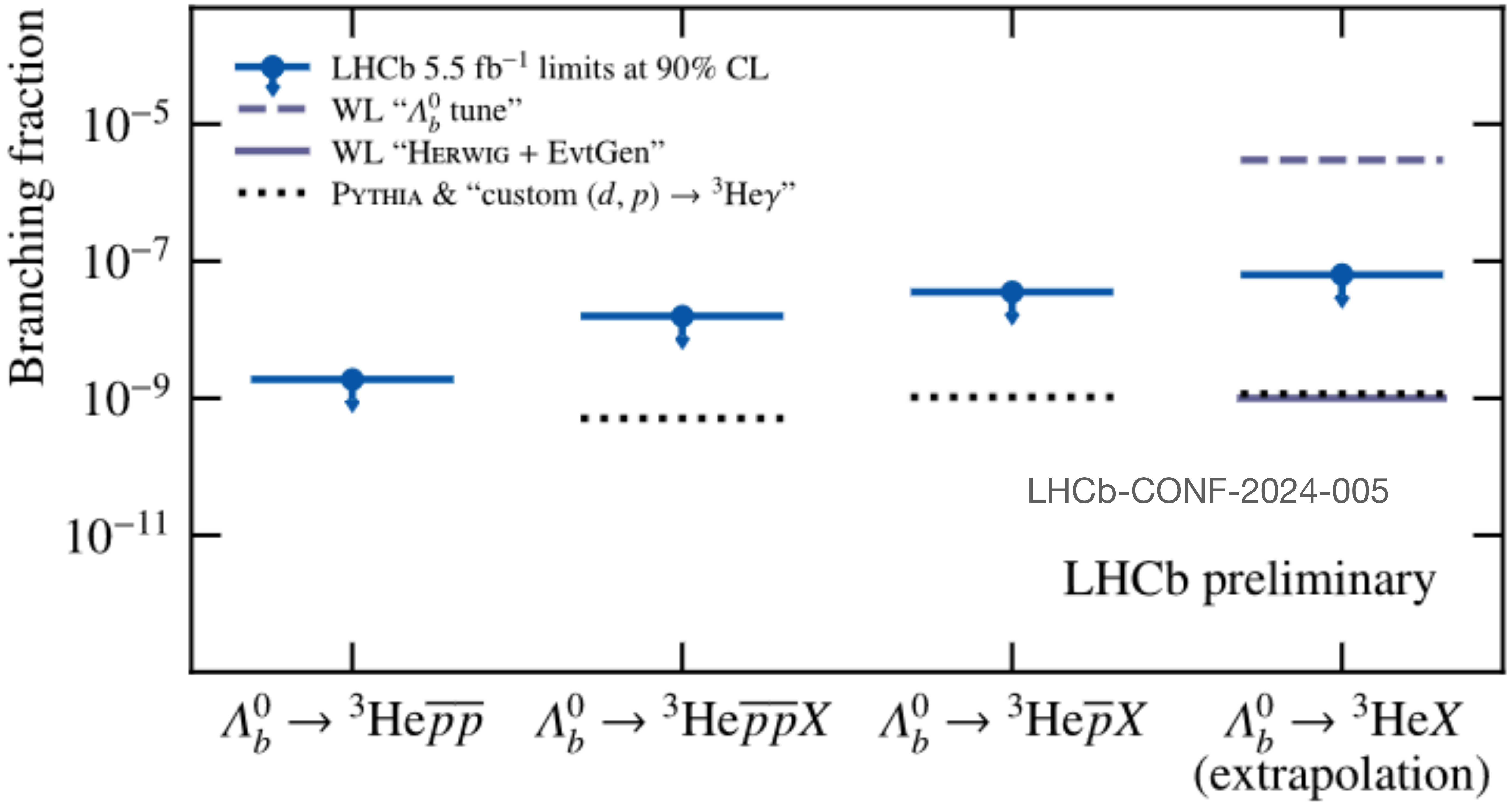


Antibaryons from the same $\bar{\Lambda}_b^0$ decay can form $^3\overline{\mathrm{He}}$ and enhance cosmic anti helium

Relevant for dark matter searches

- No ^{3}He signals has been observed in Λ_b^0 decays so far by LHCb
- No significant excess was found; upper limits reach the 10^{-8}-10^{-9} level



LUND UNIVERSITY

Marie Skłodowska-Curie Actions

Summary and outlook

- Light nuclei production at the LHC remains a microscopic puzzle.
- Both thermal and coalescence approaches reproduce key yield observables.
- Proton/deuteron balance functions can provide strong separation between production mechanisms.
- Pion–deuteron correlations study by ALICE support an important role of resonance-decay nucleons.
- Future precision measurements can establish the microscopic origin of light nuclei and improve inputs for dark matter searches

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Thank you for your attention!

Backup

Quantification

$$R^{(\mathrm{d}/2)\mathrm{K}}_{\Lambda^*}(p_\mathrm{T}) = \frac{Y^{(\mathrm{d}/2)\mathrm{K}}_{\Lambda^*}}{Y^{\mathrm{pK}}_{\Lambda^*}}$$

- R ~ 0, if deuterons are produced independently
- R ~ 1, coalescence and the idea works

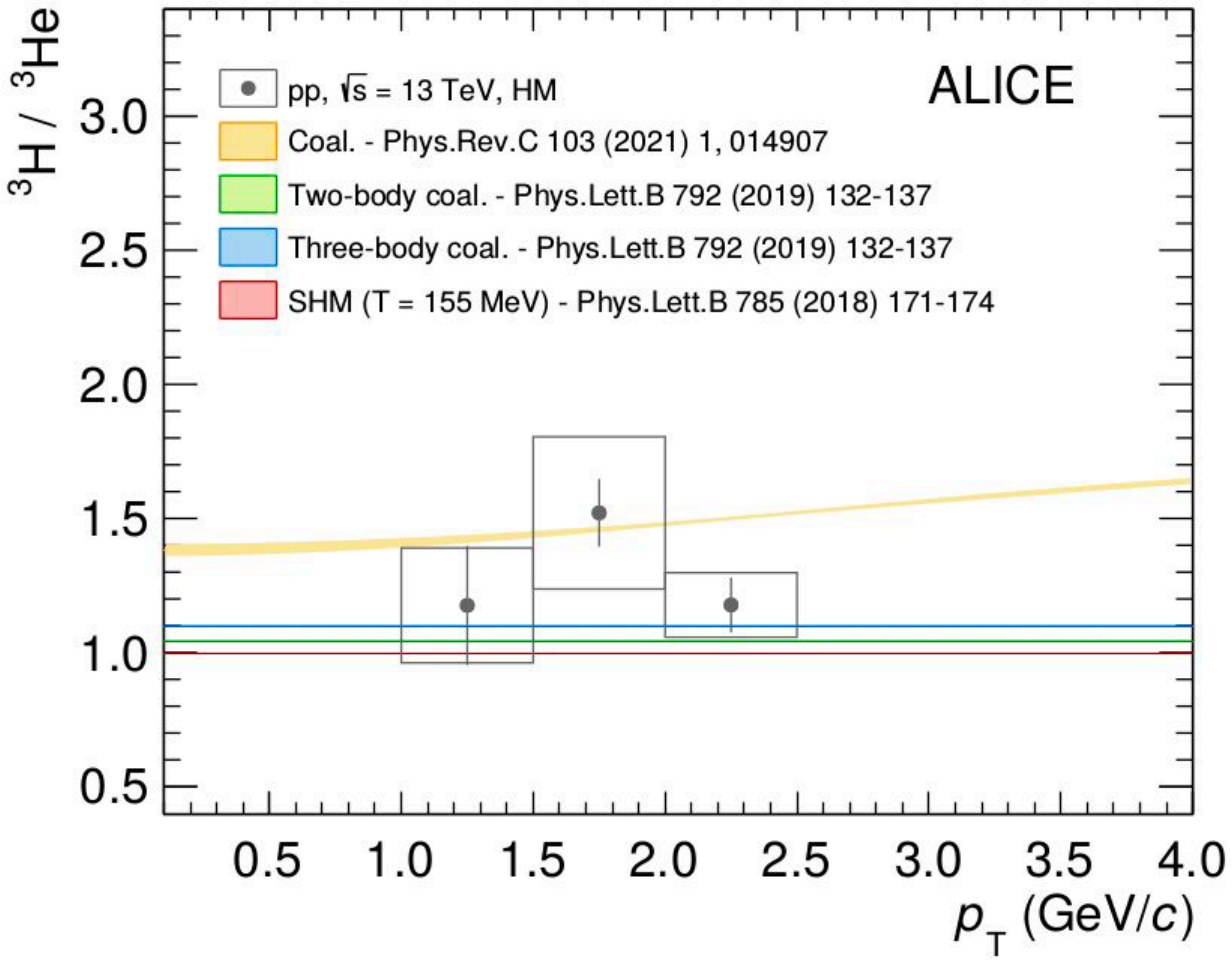
Work in progress

Yield is calculated in the range of $M_\mathrm{PDG} \pm 3\Gamma_\mathrm{PDG}$

Models	$R^{(\mathrm{d}/2)\mathrm{K}}_{\Lambda^*}$
Thermal-FIST	~ 0
Simple Coalescence	0.981437 ± 0.546984 (p_0 = 0.1 GeV/c) 0.953468 ± 0.0301501 (p_0 = 0.2 GeV/c)
Gaussian WF	0.948608 ± 0.349003
Argonne v18 WF	0.926634 ± 0.0884558

Nuclei synthesis: A = 3 nuclei

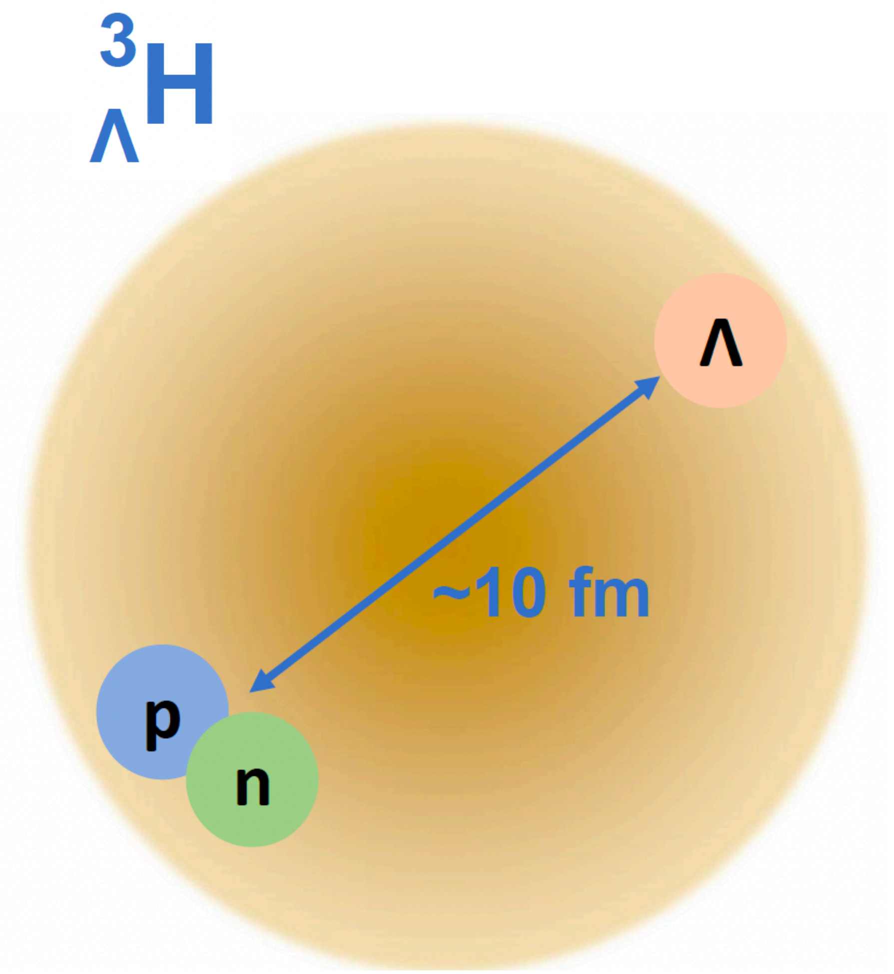
- A = 3 production can be probed by $^{3}H/^{3}He$ ratio
- **SHM**: $^{3}H/^{3}He \sim 1$ due to similar masses
- **Coalescence**: $^{3}H/^{3}He > 1$ due to different source sizes
- No conclusive evidence to distinguish between production mechanisms

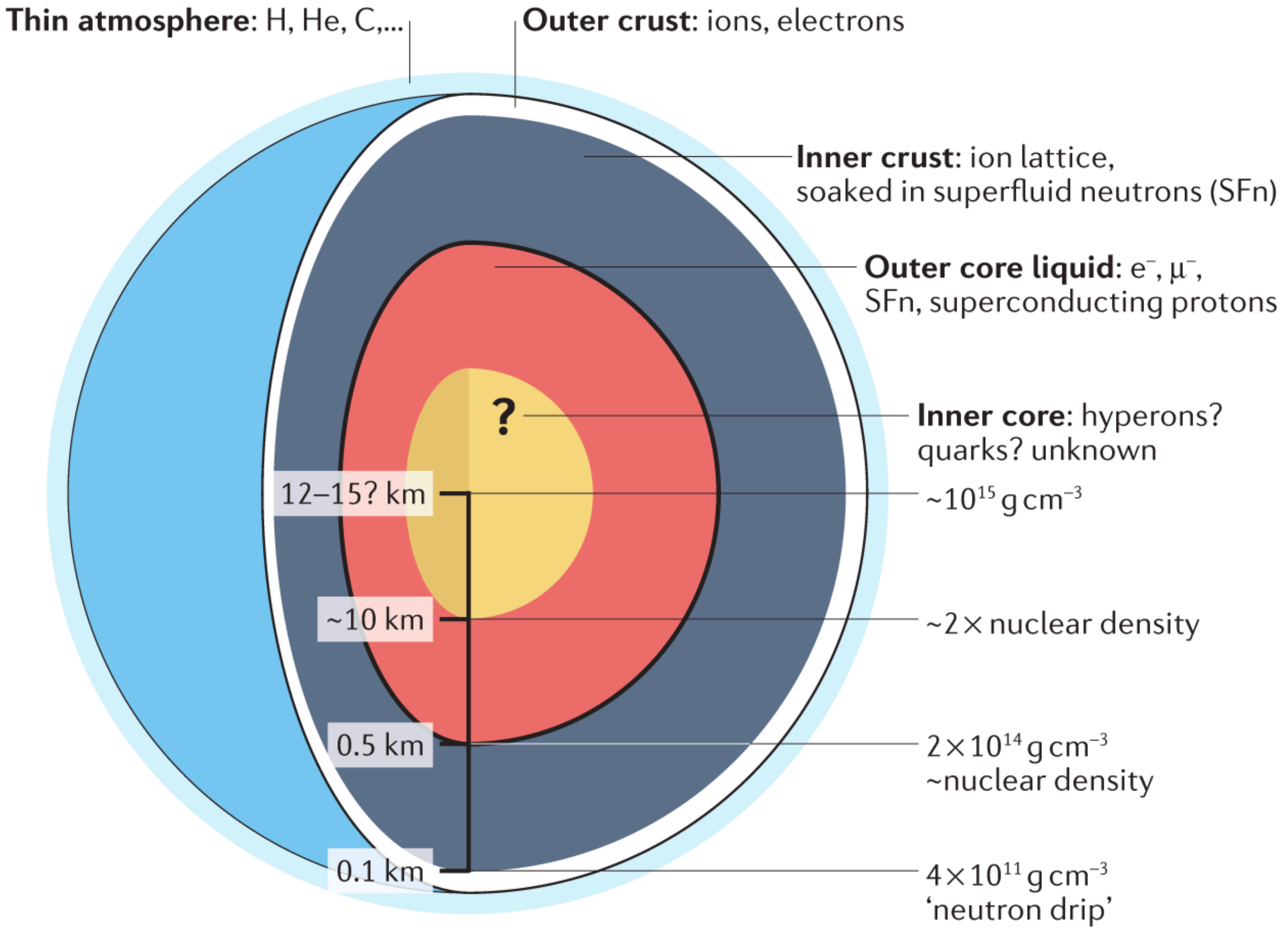


ALICE, JHEP 01 (2022) 106

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**

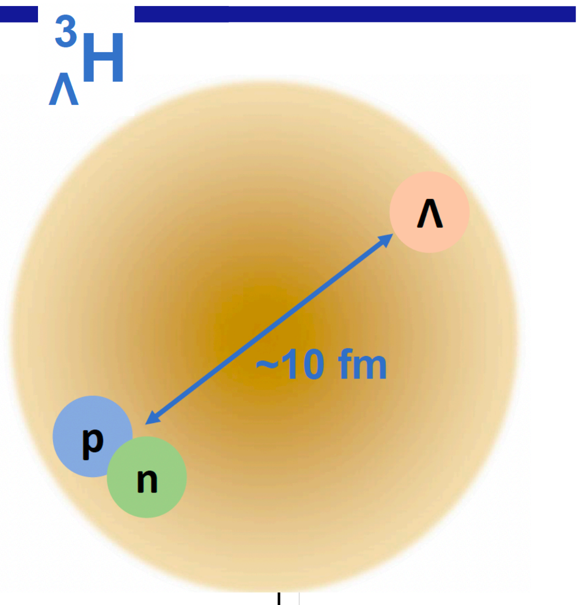


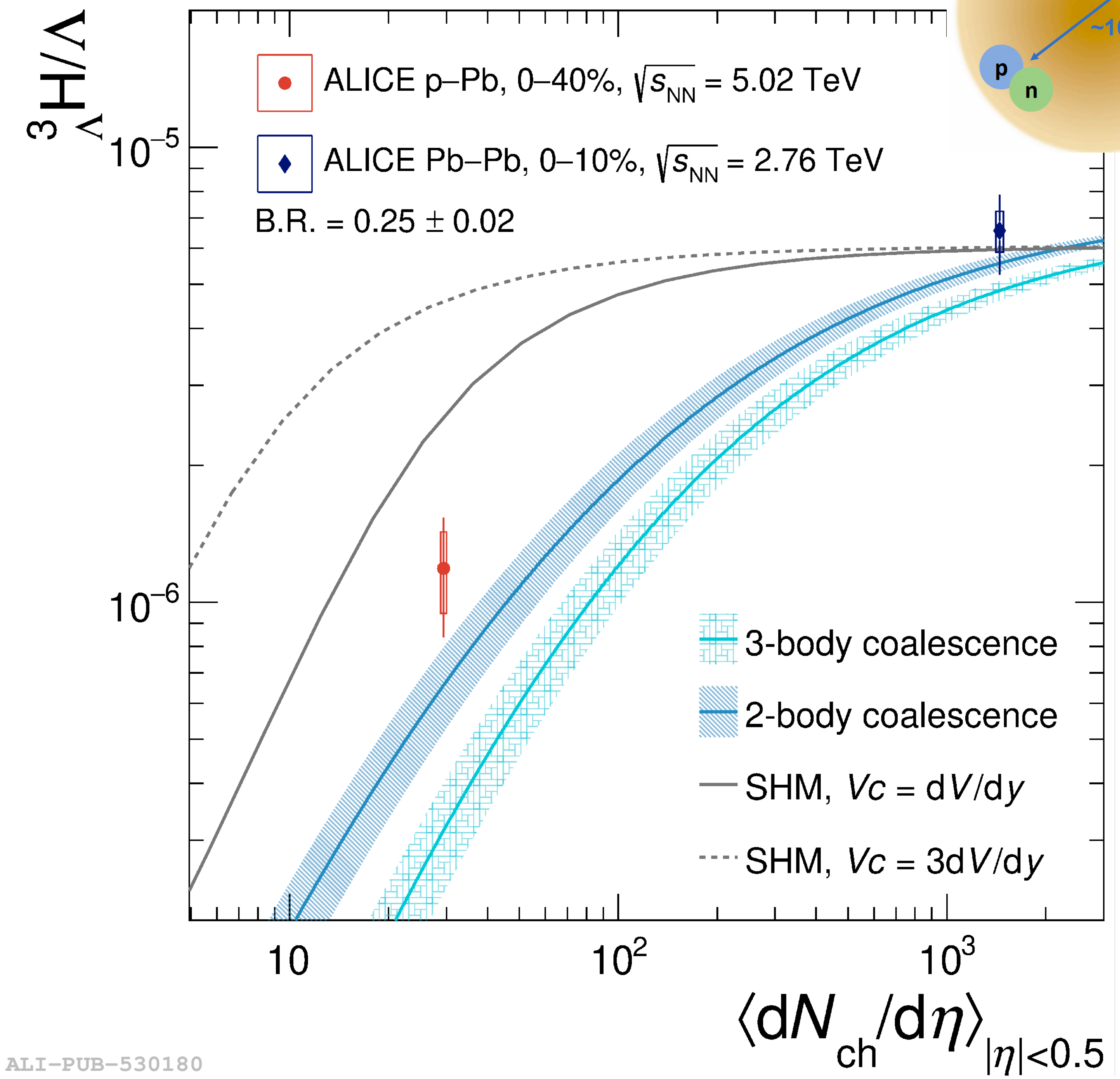


Yunes et. al., Nature Reviews Physics 4, 237(2022)

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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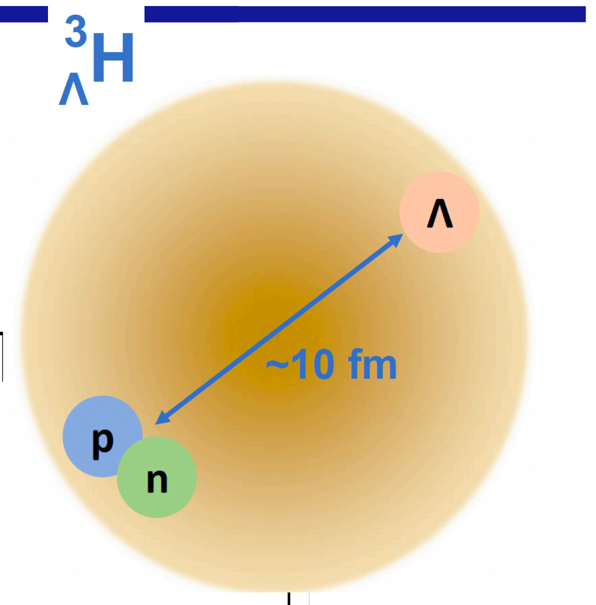
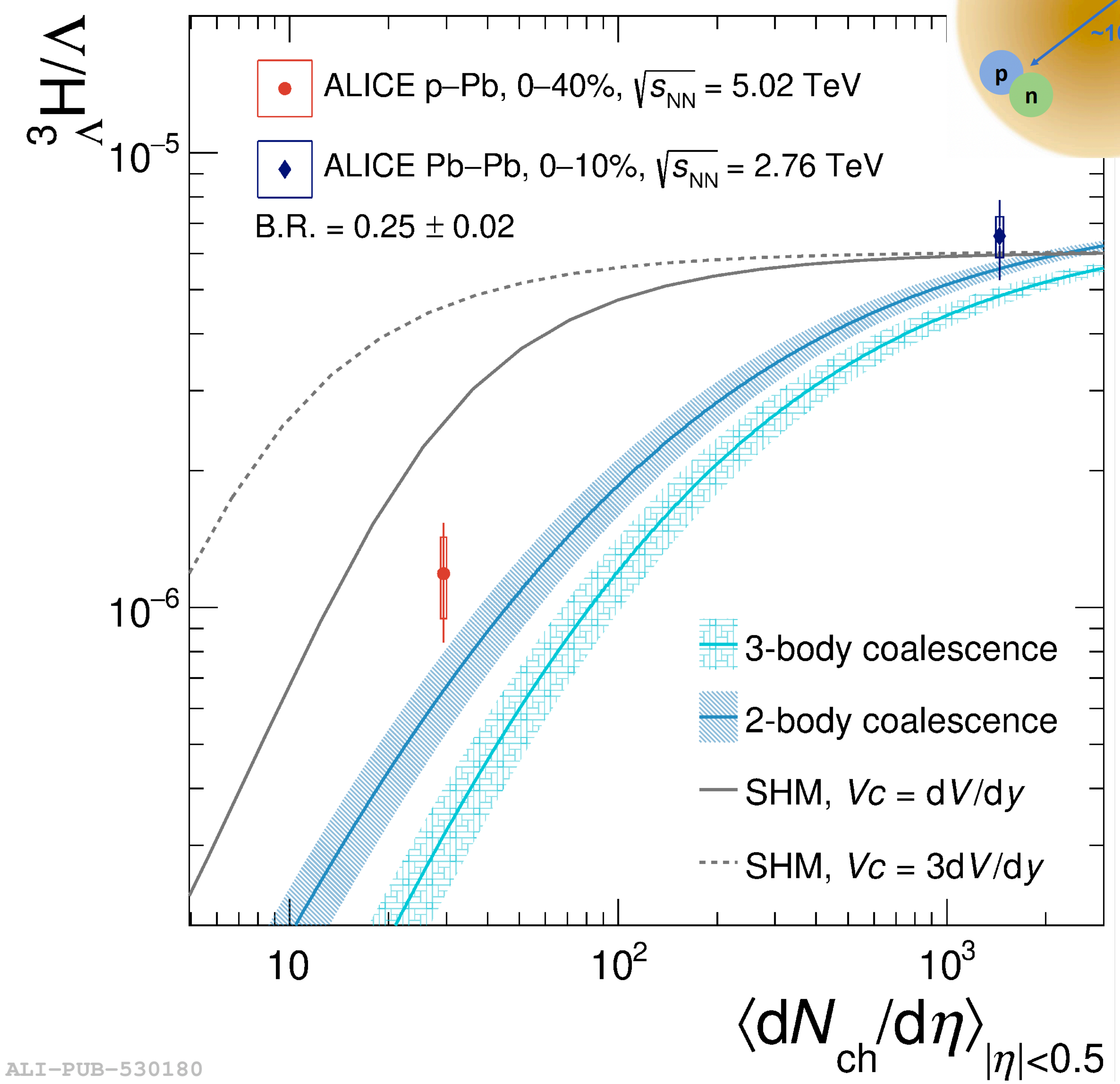
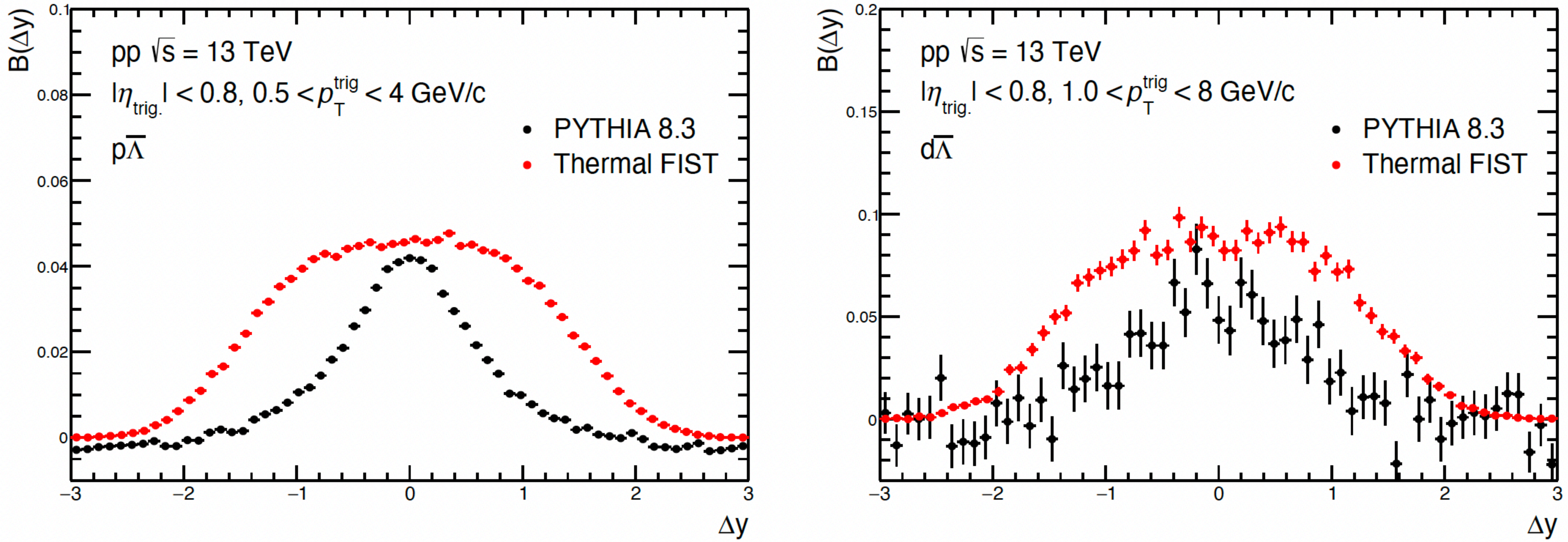




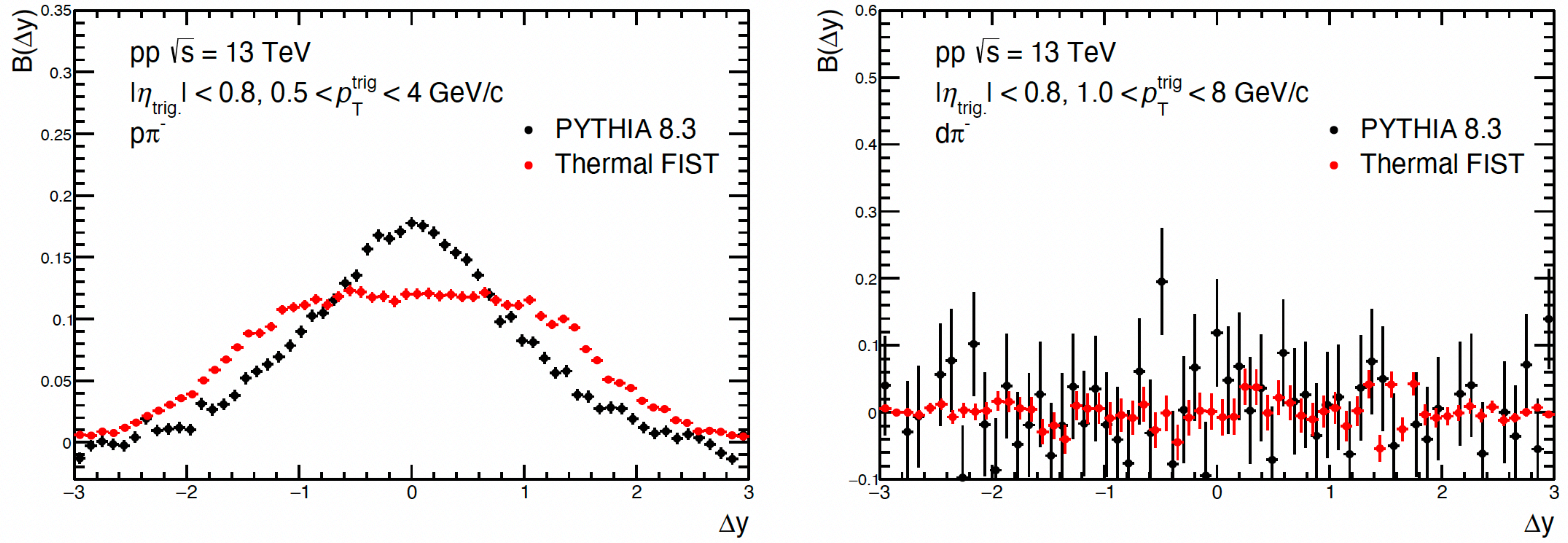
Good discriminator but lacks differential and precise measurements

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

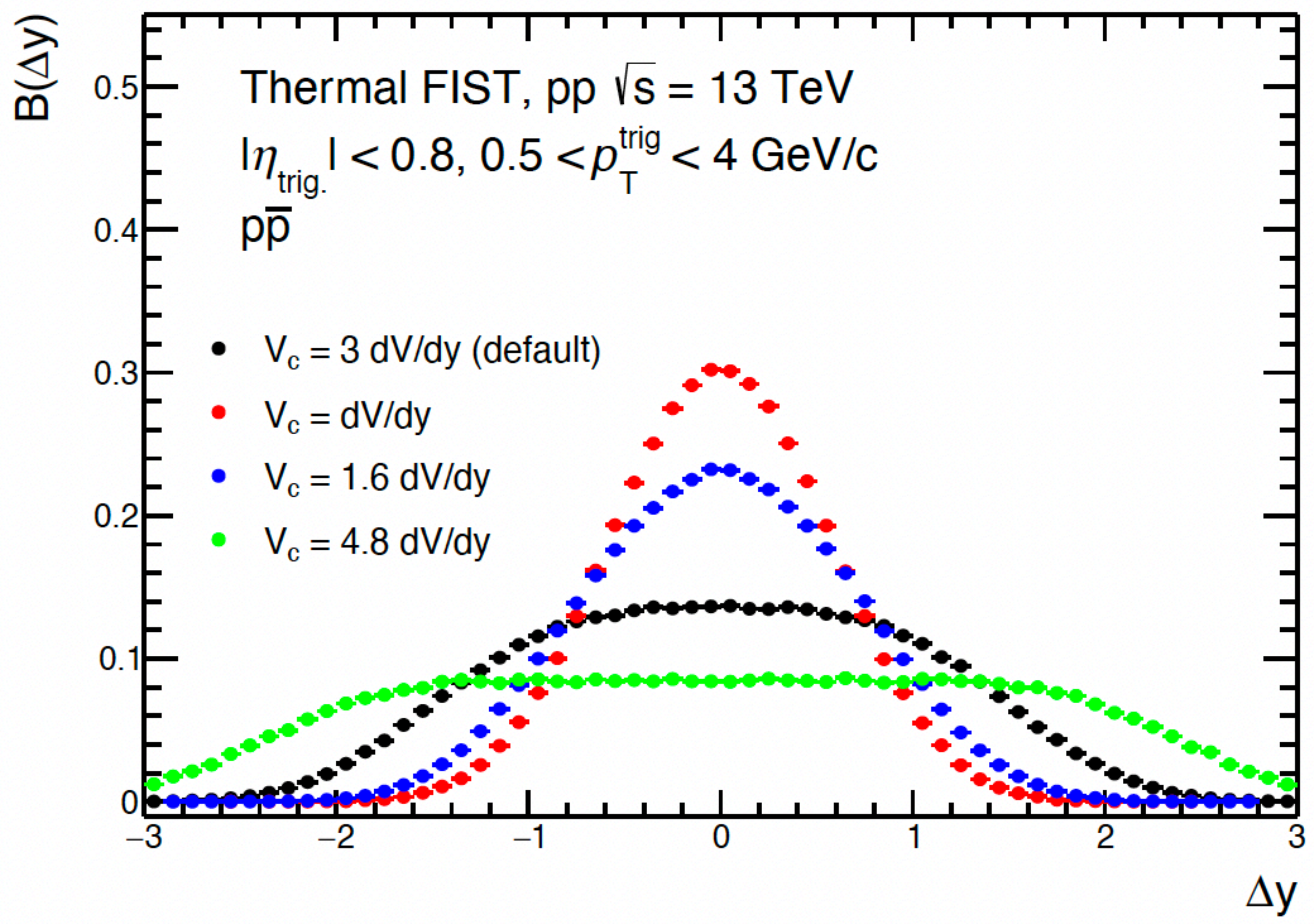
Balance functions with Lambda

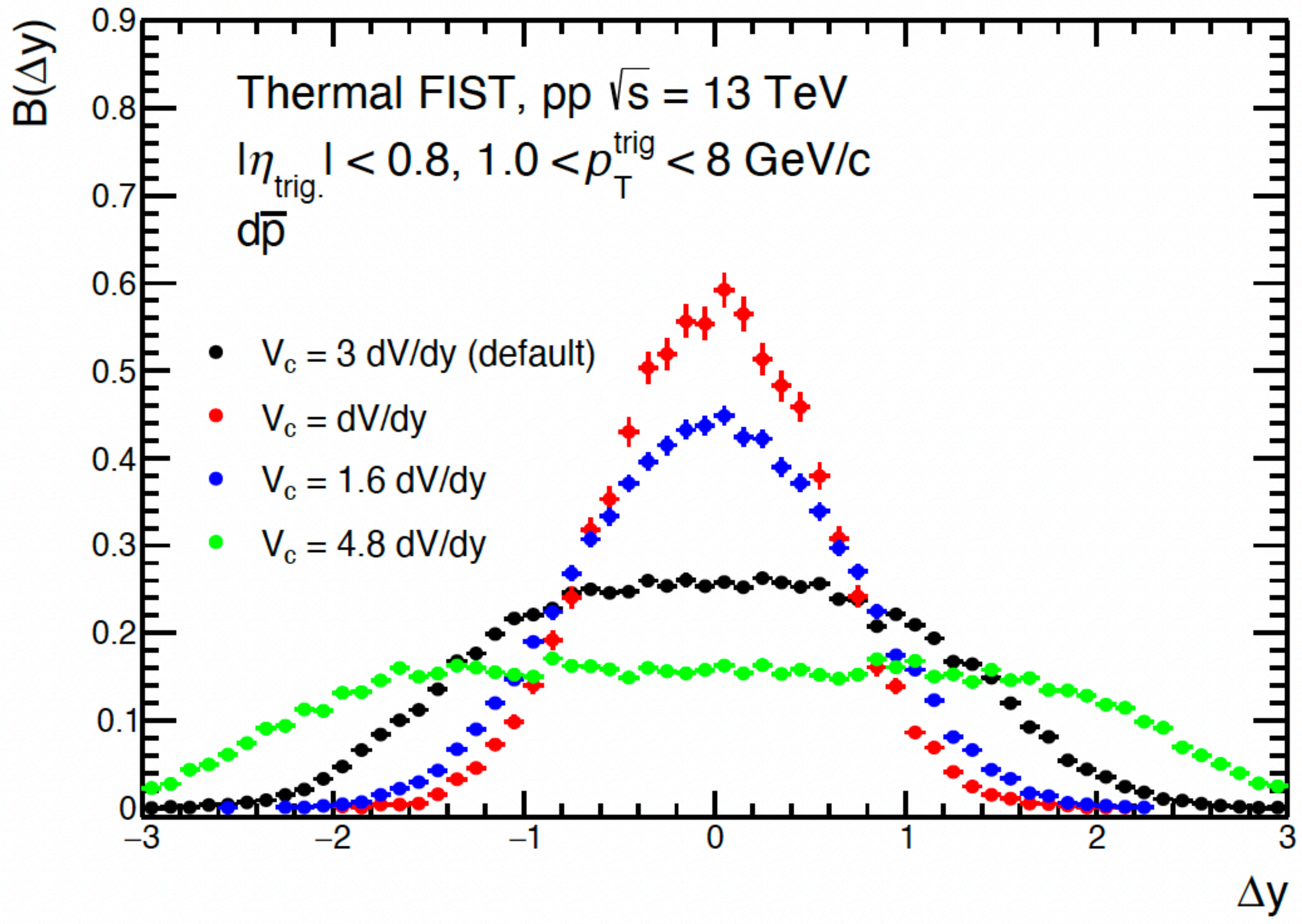


Balance functions with Pions

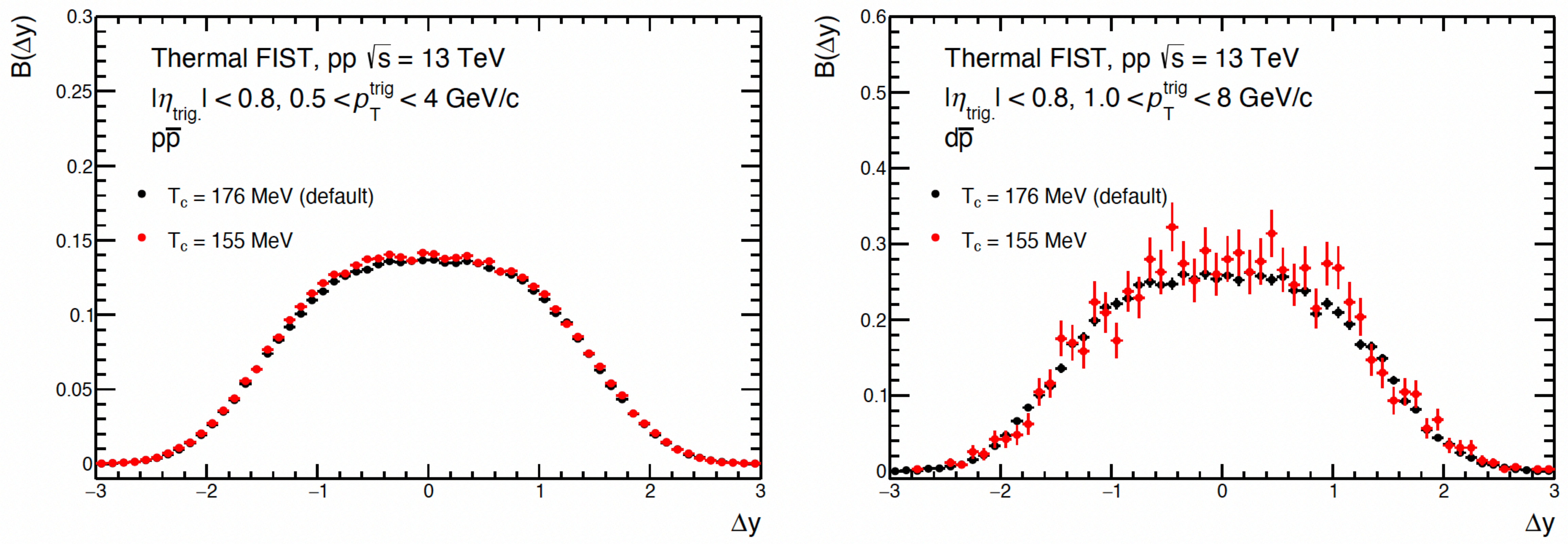


Correlation volume in FIST





Temperature in FIST



Microscopic origin of light nuclei production at the LHC

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Joined ALICE collaboration (Jan, 2016)

Marie Skłodowska-Curie Actions

Funded by the European Union

deuteron

proton

neutron

pion