(Anti)nucleosynthesis in the laboratory: recent measurements of deuteron production and absorption with ALICE

Maximiliano Puccio (CERN)

Based mainly on arXiv:1910.14401, arXiv:2003.03184 and arxiv:2004.08018

EP-LHC seminar - CERN@Home - 28th April 2020

Outline

What this talk is about:

- A nuclear physics problem: (anti)nuclei formation in high energy collisions is not clear
- Antinucleosynthesis to understand the evolution of the system created in the collisions
- Implications of collider measurements on the understanding of cosmic ray antinuclei
- Collider environment is suited for studying the interaction of antinuclei with the material
- While this aspects are studied also in Pb-Pb, today focus on pp and p-Pb collisions

(Anti)nucleosynthesis at collider: how?

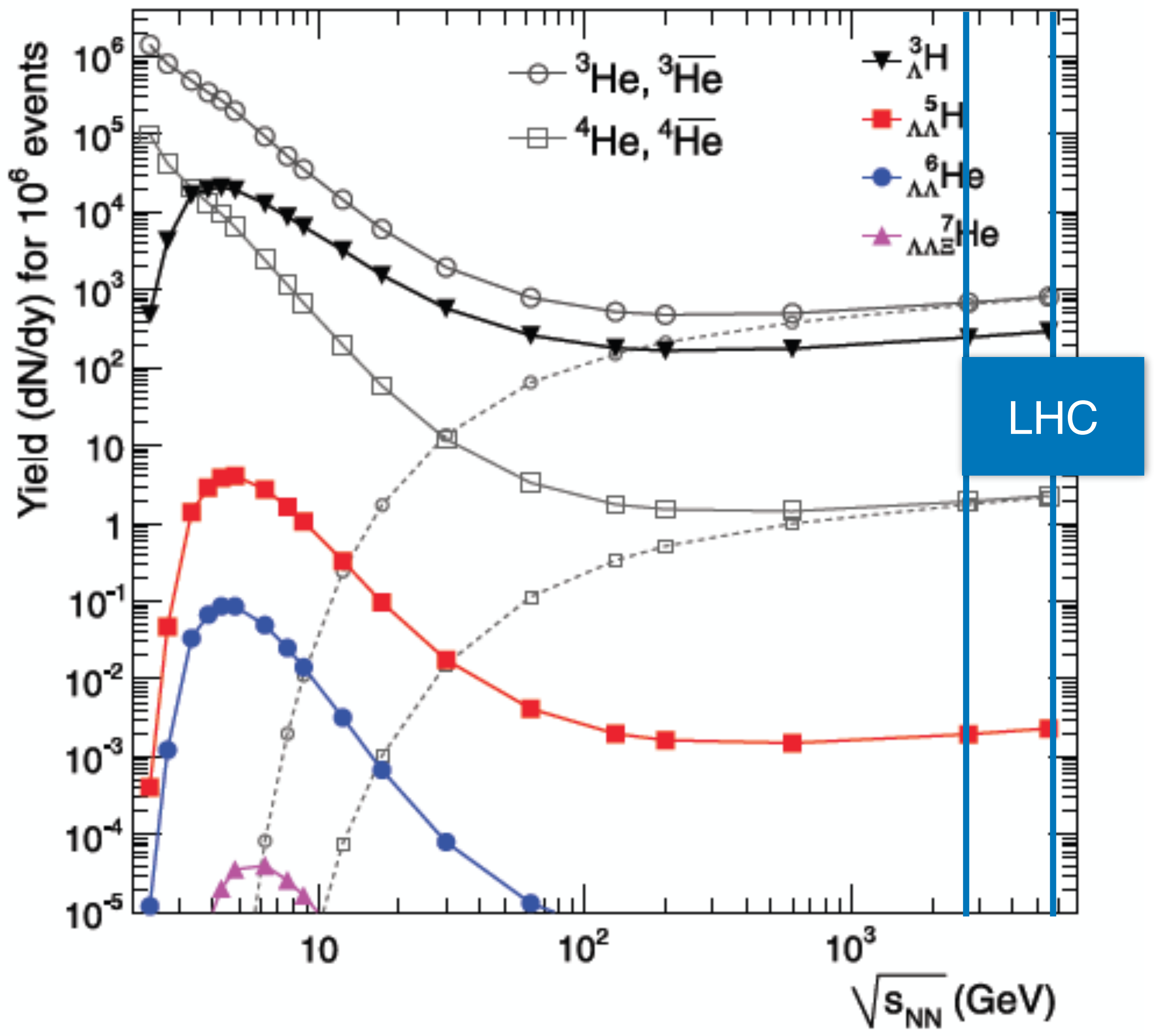
(Anti)nucleosynthesis at collider: how?

THERMAL MODELS

- Hadrons emitted from the interaction region in statistical equilibrium when the system reaches a limiting temperature
- Freeze-out temperature T_{chem} is a key parameter
- Abundance of a species $\propto \exp(-m/T_{chem})$:
  - ➡For nuclei (large m) strong dependence on T_{chem}

Mainly used for Pb-Pb, it can be used in smaller systems by using the canonical ensemble

A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stoecker, Phys. Lett. B607, 203 (2011), 1010.2995



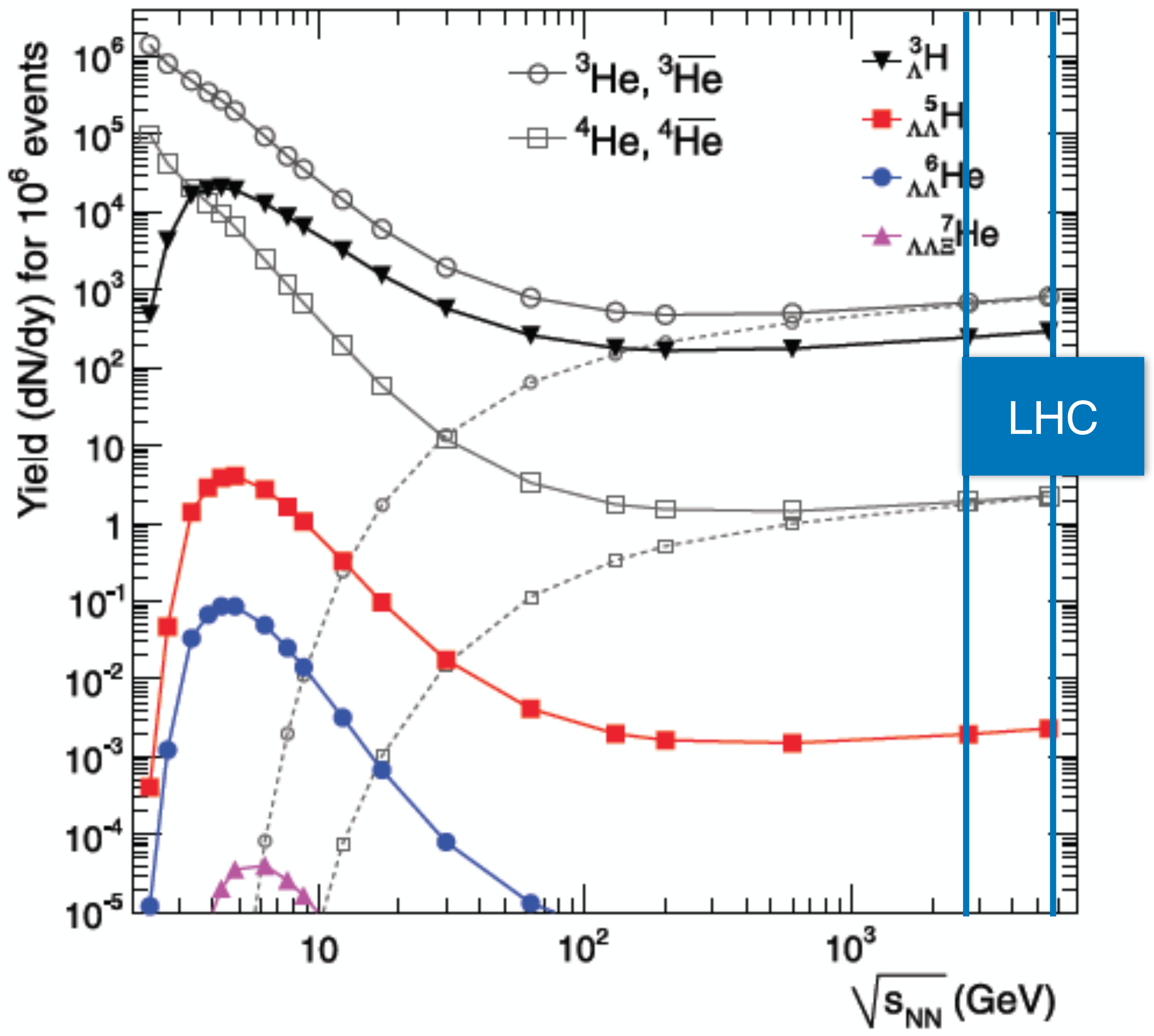
(Anti)nucleosynthesis at collider: how?

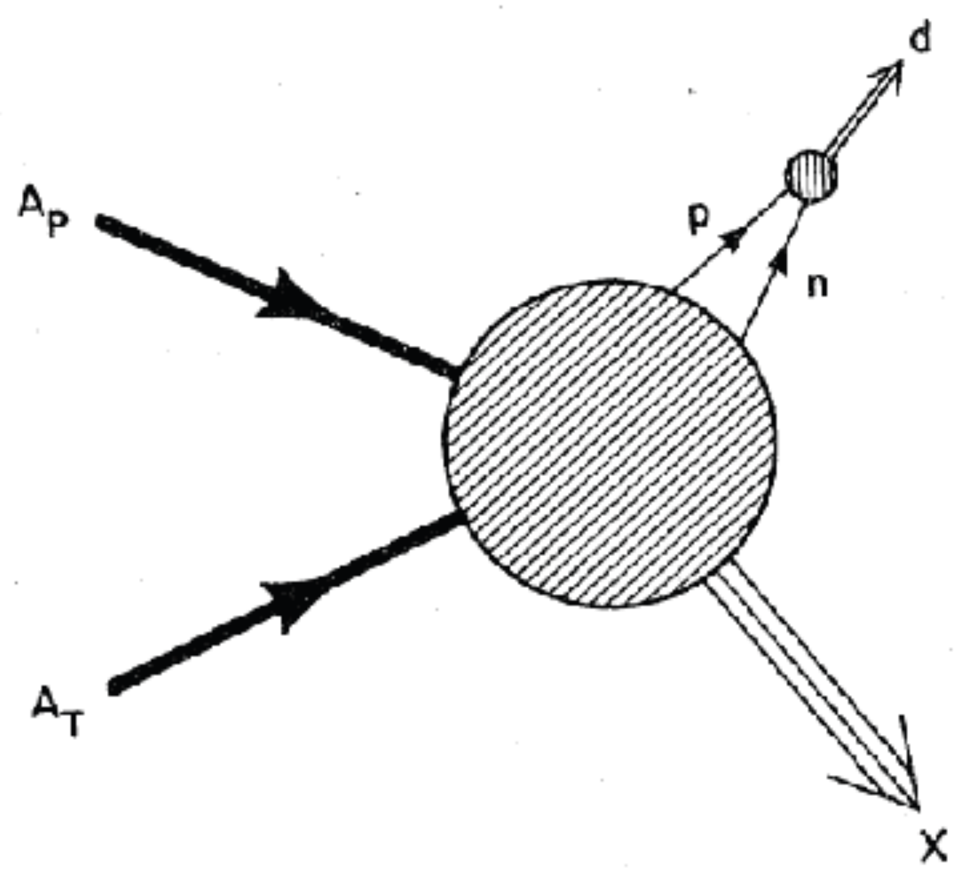
THERMAL MODELS

- Hadrons emitted from the interaction region in statistical equilibrium when the system reaches a limiting temperature
- Freeze-out temperature T_{chem} is a key parameter
- Abundance of a species $\propto \exp(-m/T_{chem})$:
  - ➡For nuclei (large m) strong dependence on T_{chem}

Mainly used for Pb-Pb, it can be used in smaller systems by using the canonical ensemble

A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stoecker, Phys. Lett. B607, 203 (2011), 1010.2995





COALESCENCE

- If (anti)baryons are close in phase space they can form a (anti)nucleus
- Interplay between the configuration of the phase space of (anti)baryons and the wave function of the (anti)nuclei to be formed

J. I. Kapusta, Phys.Rev. C21, 1301 (1980)

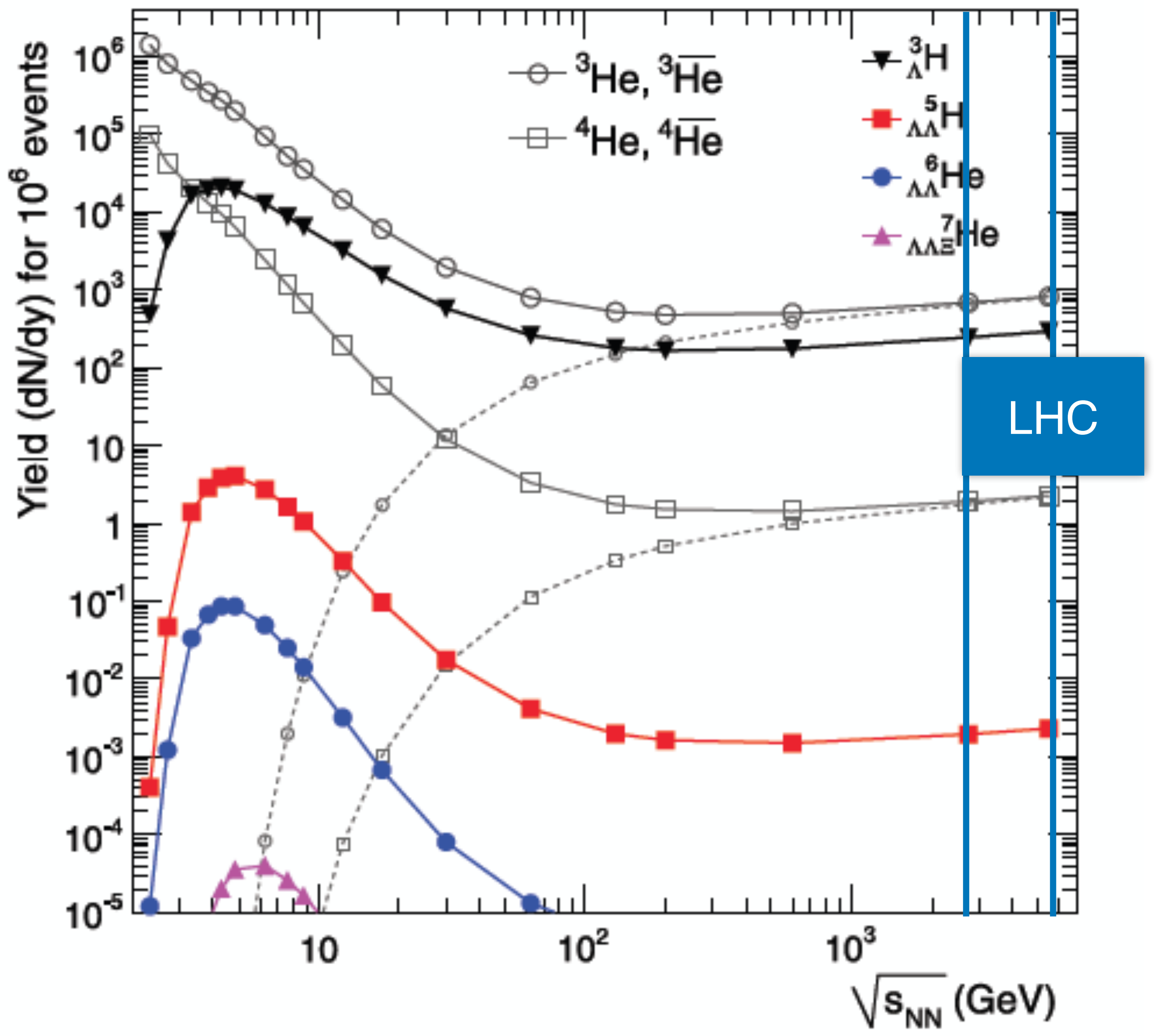
(Anti)nucleosynthesis at collider: how?

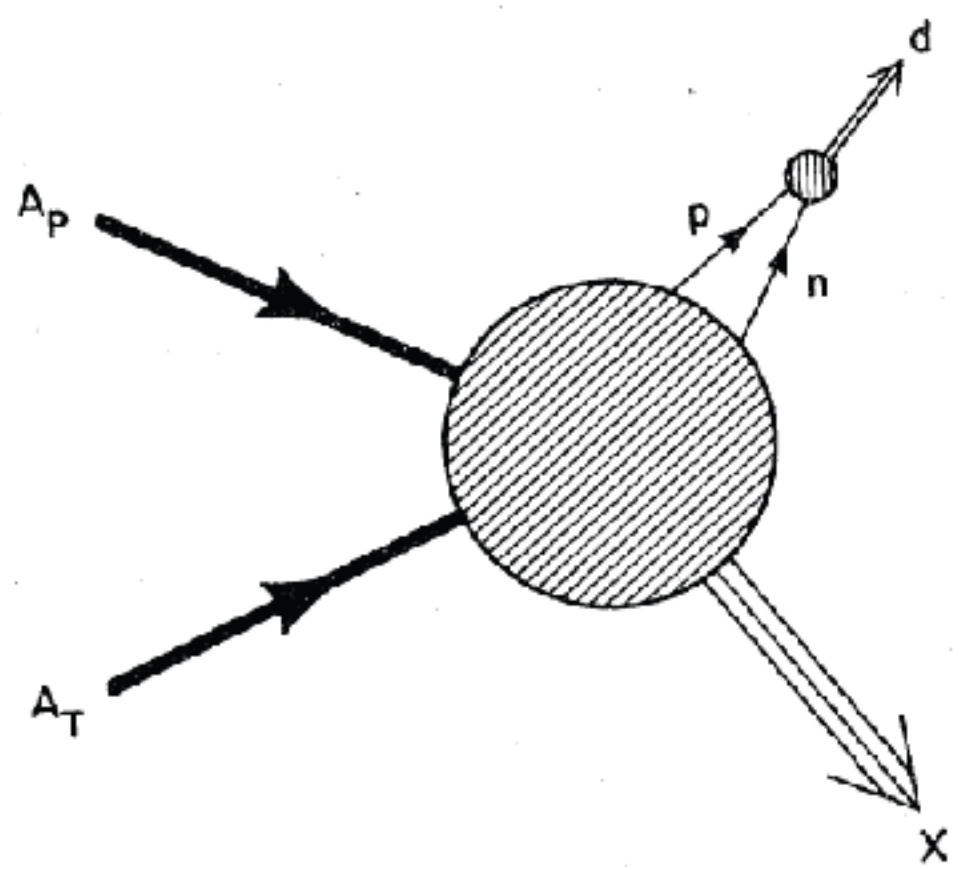
THERMAL MODELS

- Hadrons emitted from the interaction region in statistical equilibrium when the system reaches a limiting temperature
- Freeze-out temperature T_{chem} is a key parameter
- Abundance of a species $\propto \exp(-m/T_{chem})$:
  - ➡ For nuclei (large m) strong dependence on T_{chem}

Mainly used for Pb-Pb, it can be used in smaller systems by using the canonical ensemble

A. Andronic, P. Braun-Munzinger, J. Stachel and H. Stoecker, Phys. Lett. B607, 203 (2011), 1010.2995





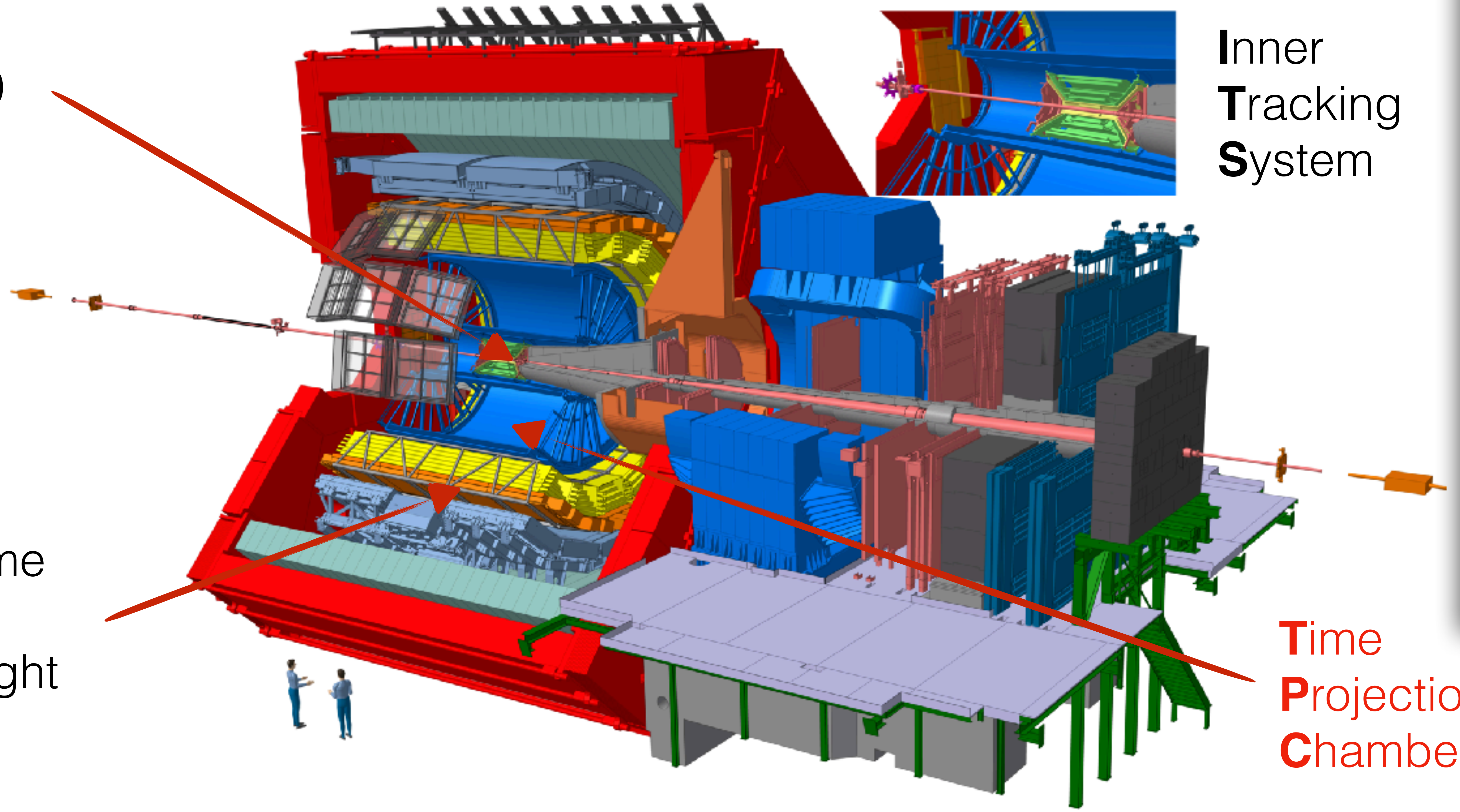
COALESCENCE

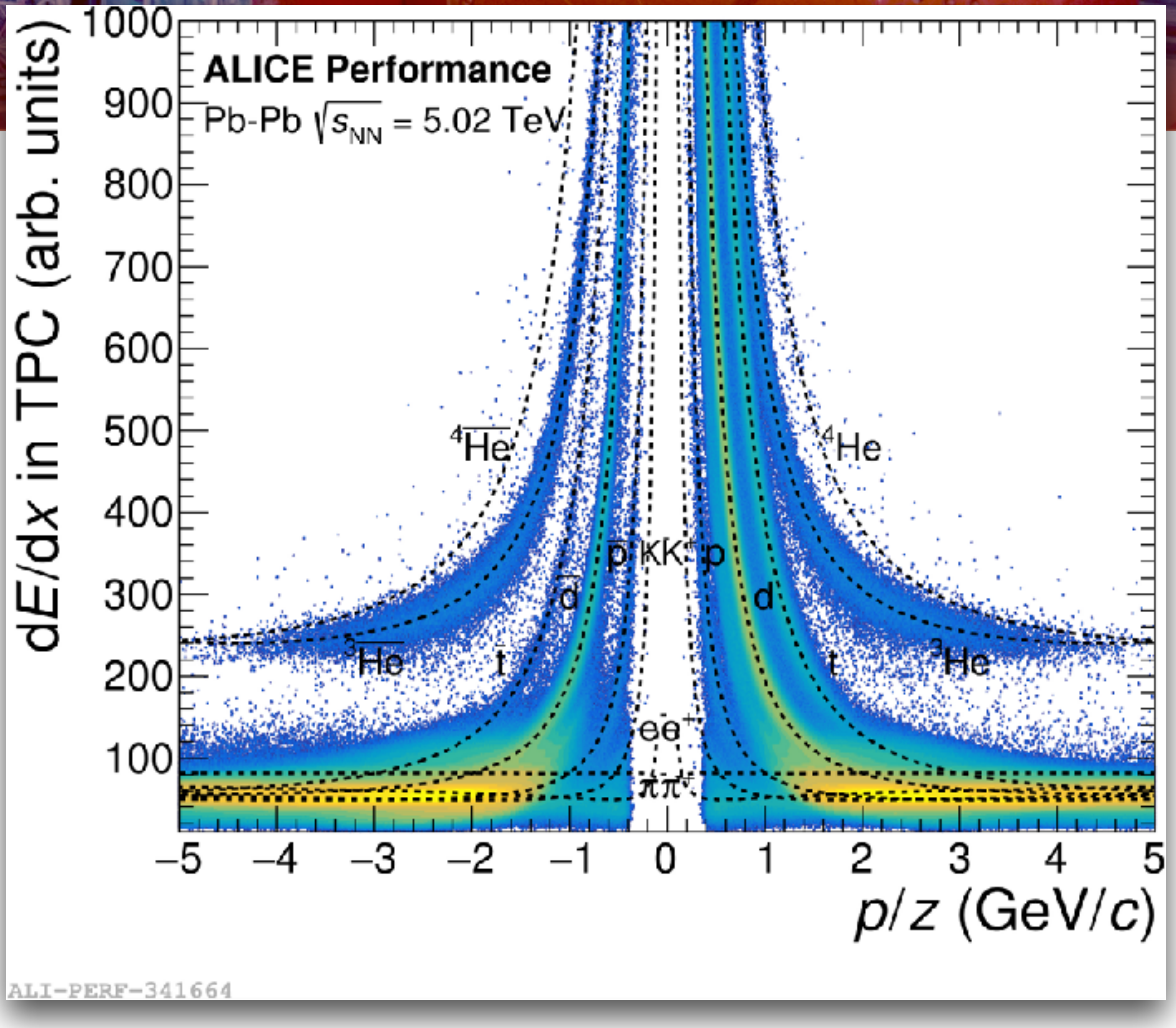
- If (anti)baryons are close in phase space they can form a (anti)nucleus
- Interplay between the configuration of the phase space of (anti)baryons and the wave function of the (anti)nuclei to be formed

J. I. Kapusta, Phys.Rev. C21, 1301 (1980)

This two pictures give quantitative predictions for high energy collisions

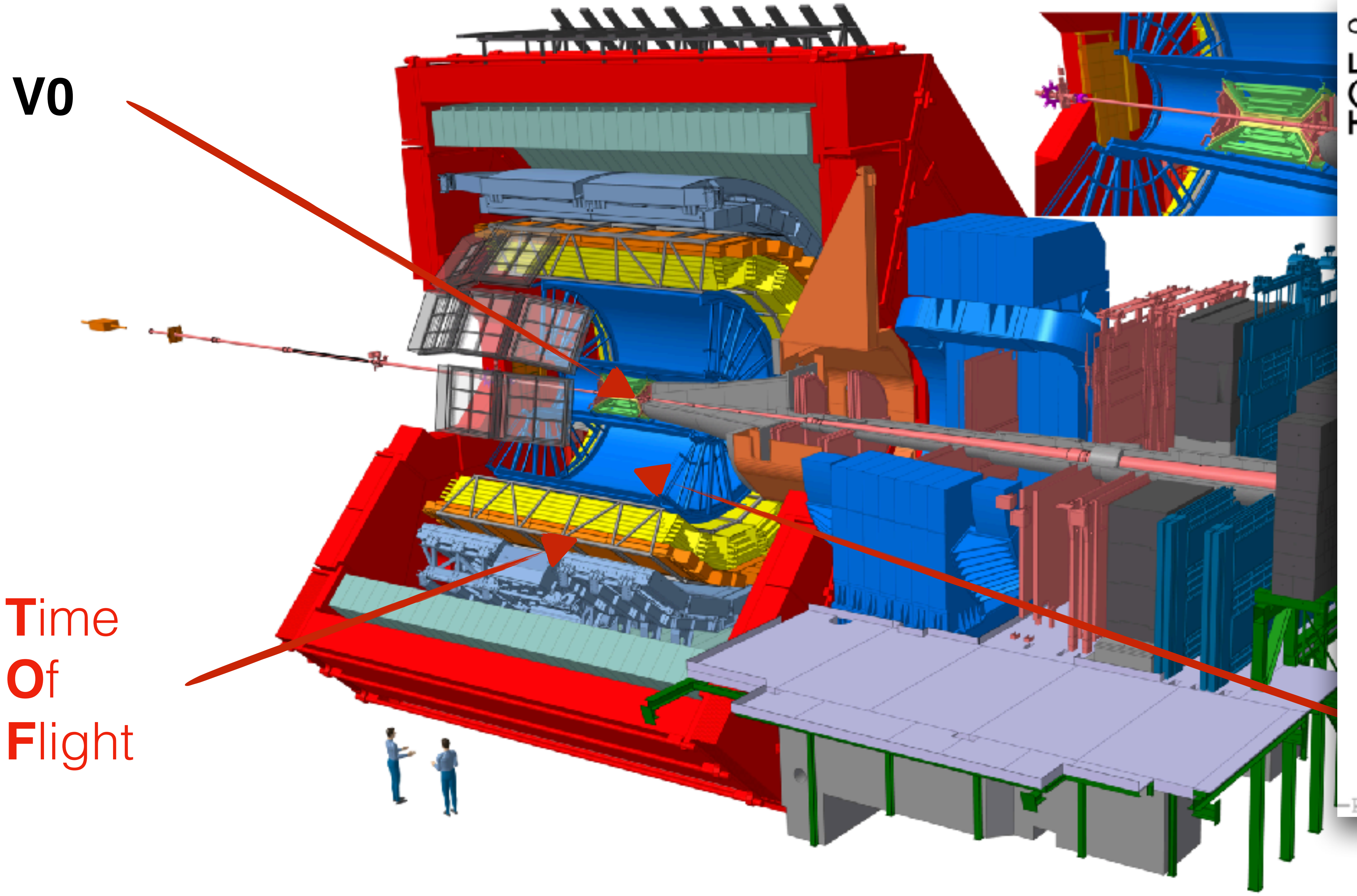
(Anti)Nuclei identification

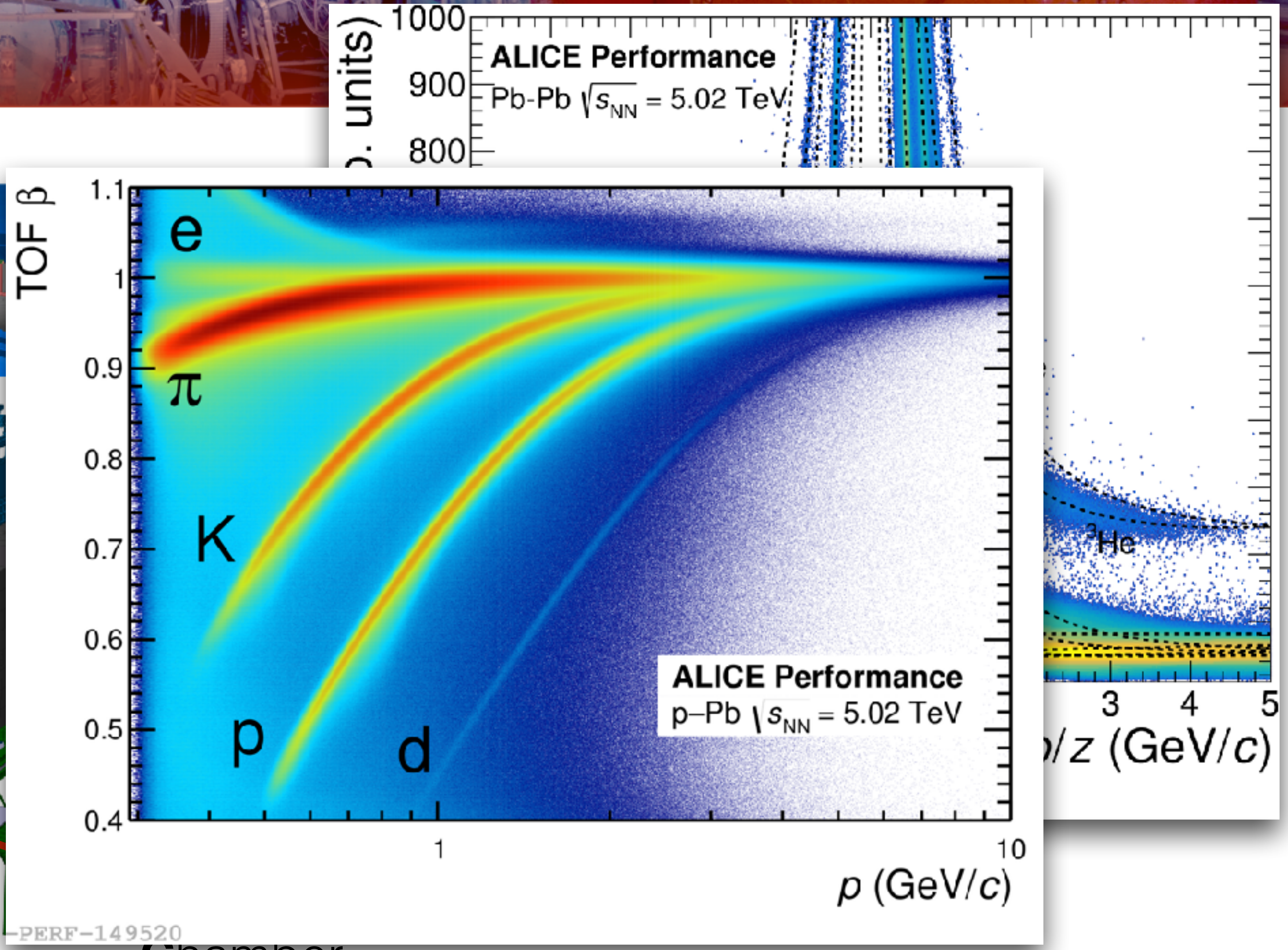




- At $p_T \leq 1.2$ GeV/c the specific energy loss measured by TPC provides excellent PID for deuterons
  - ➡$\sigma_{dE/dx}$~6.5% (in Pb-Pb collisions)
- (anti)^{3}He well separated from the other particle species over the full momentum range

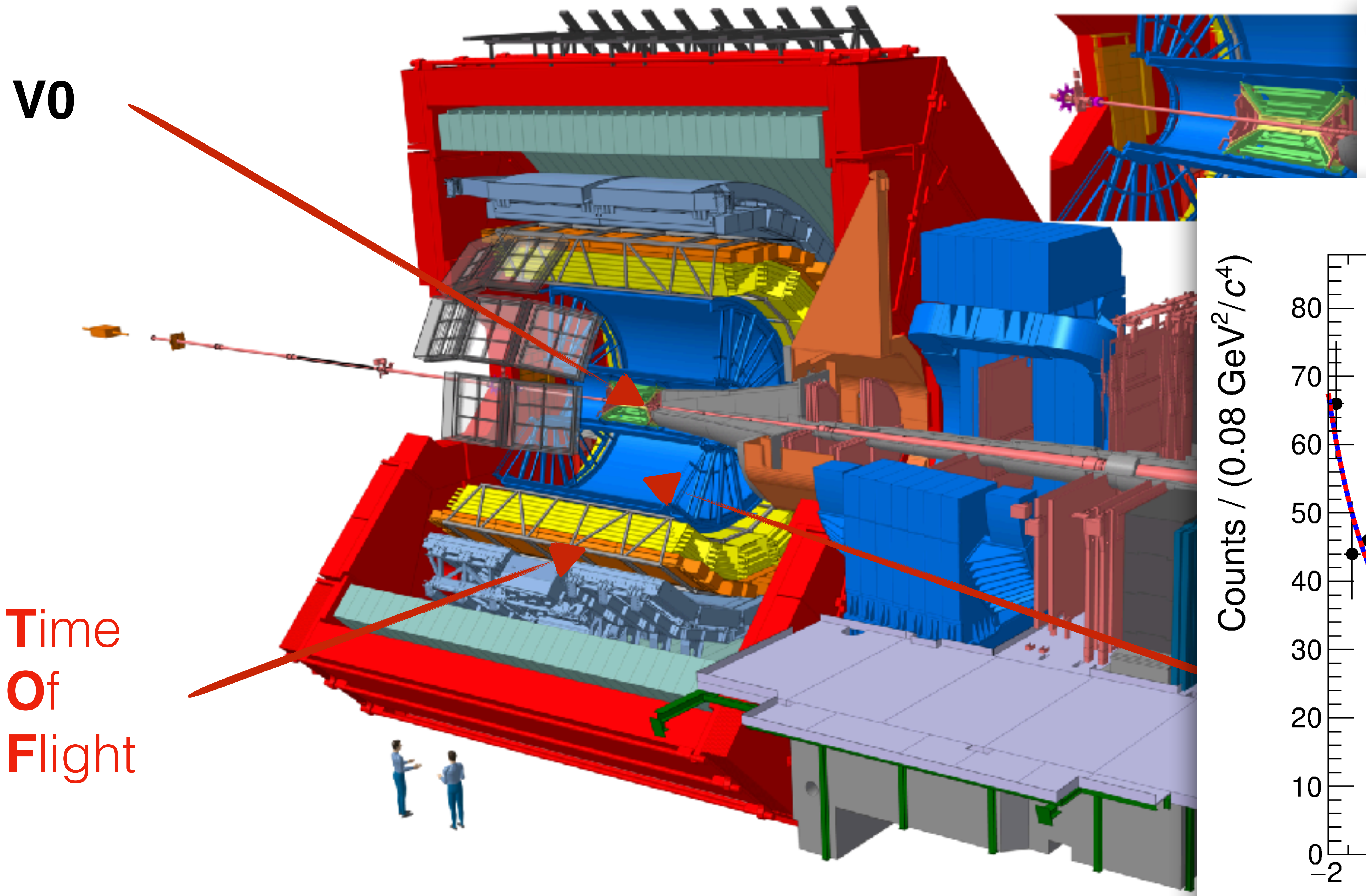
(Anti)Nuclei identification

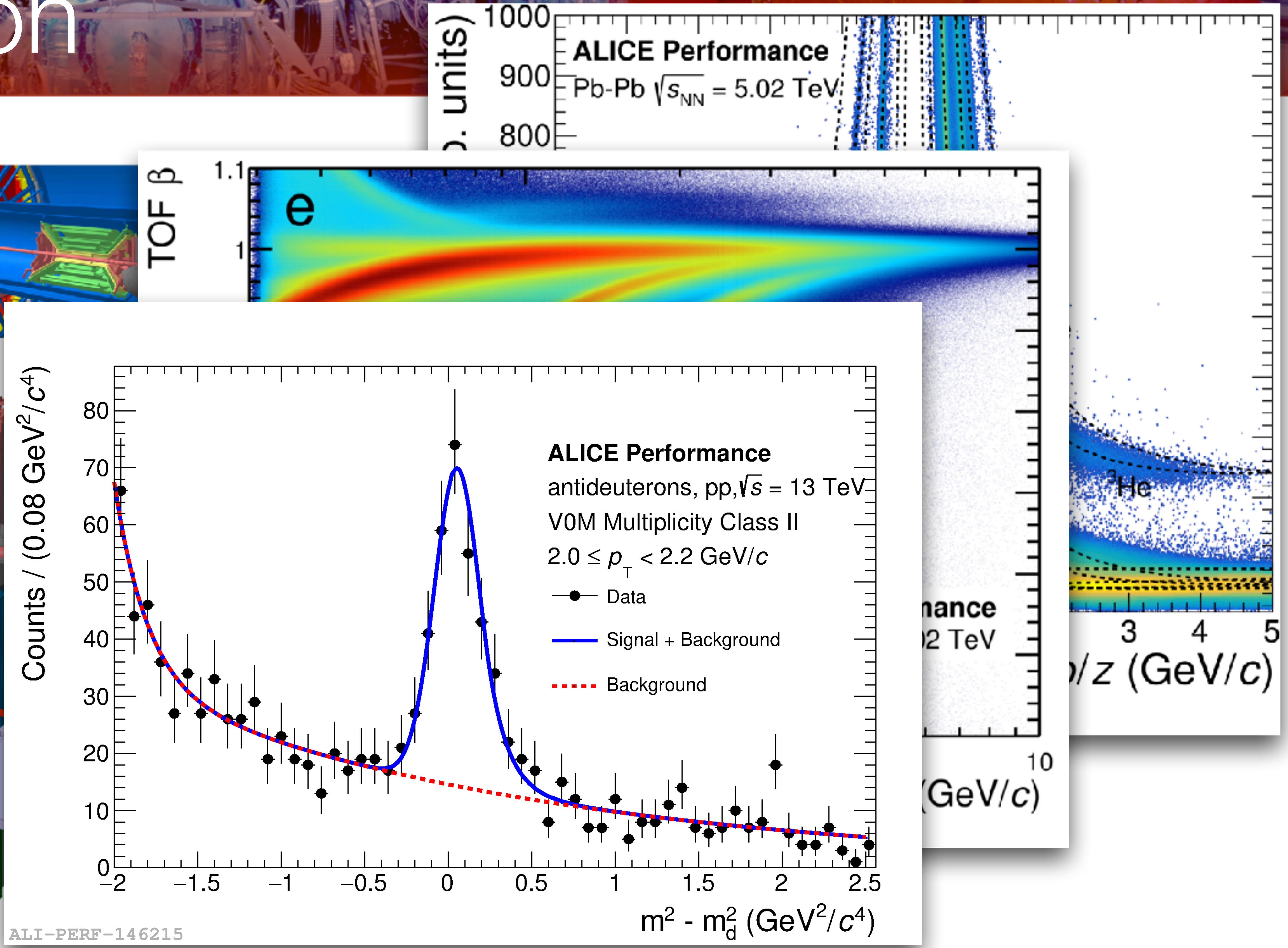




- At higher p_T the PID is performed using TOF to measure the β hence the mass of the particle.
  - ➡$\sigma_{TOF-PID}$~ 65 ps in Pb-Pb collisions
  - ➡$\sigma_{TOF-PID}$~ 120 ps in pp collisions due to the lower precision on the event start time

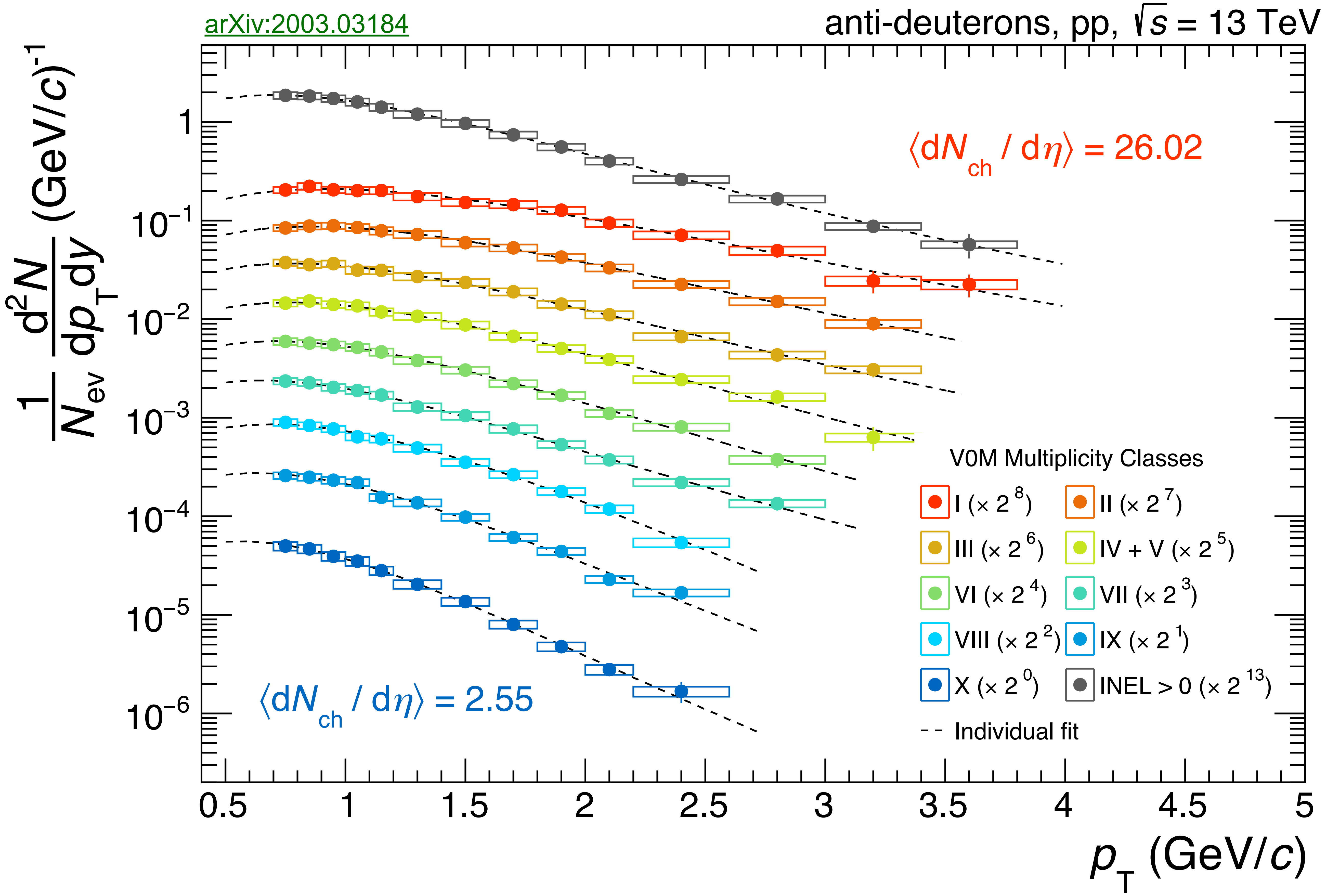
(Anti)Nuclei identification

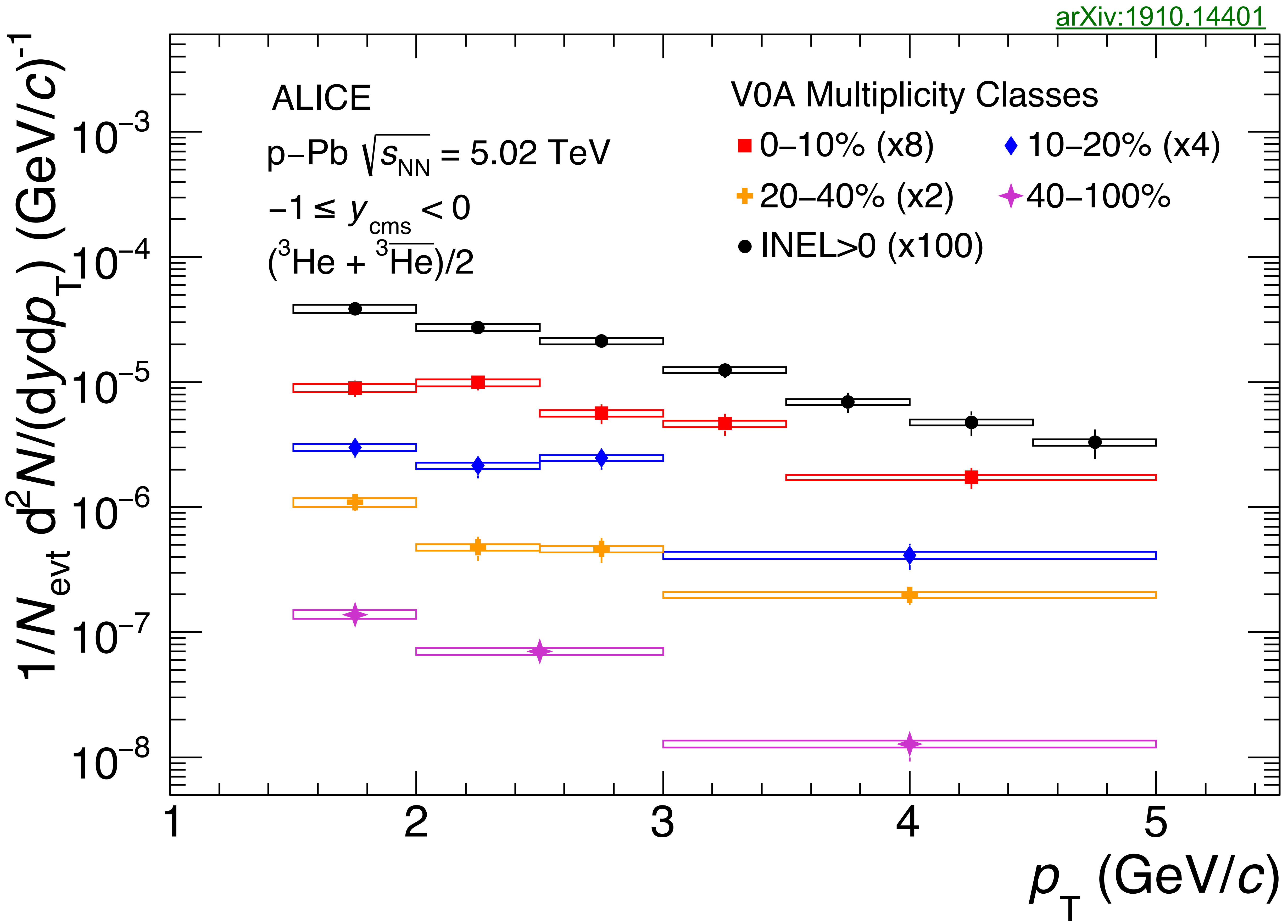




- At higher p_T the PID is performed using TOF to measure the β hence the mass of the particle.
  - ➡$\sigma_{TOF\text{-}PID}$~ 65 ps in Pb-Pb collisions
  - ➡$\sigma_{TOF\text{-}PID}$~ 120 ps in pp collisions due to the lower precision on the event start time

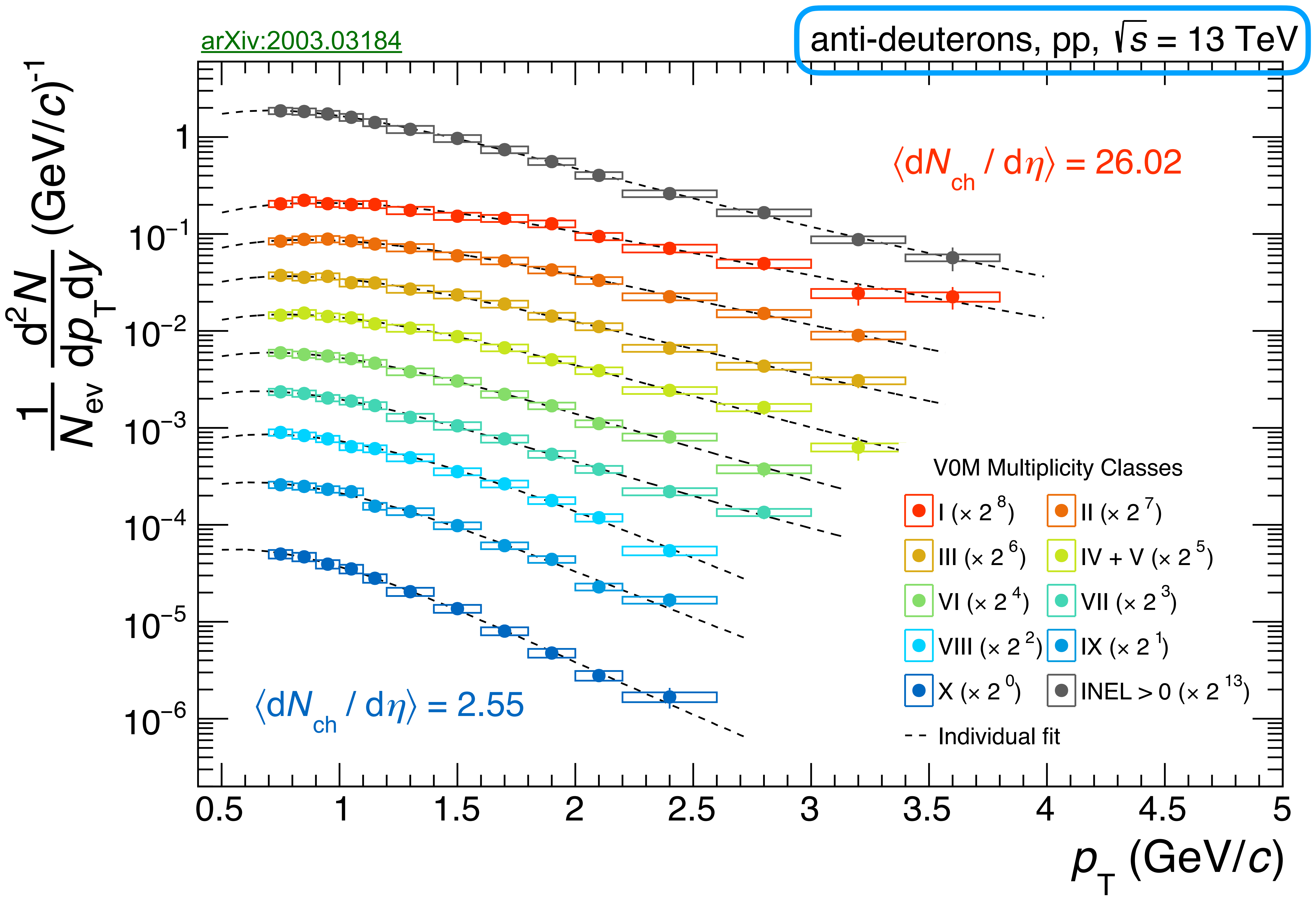
Production spectra of (anti)deuterons and (anti)^{3}He

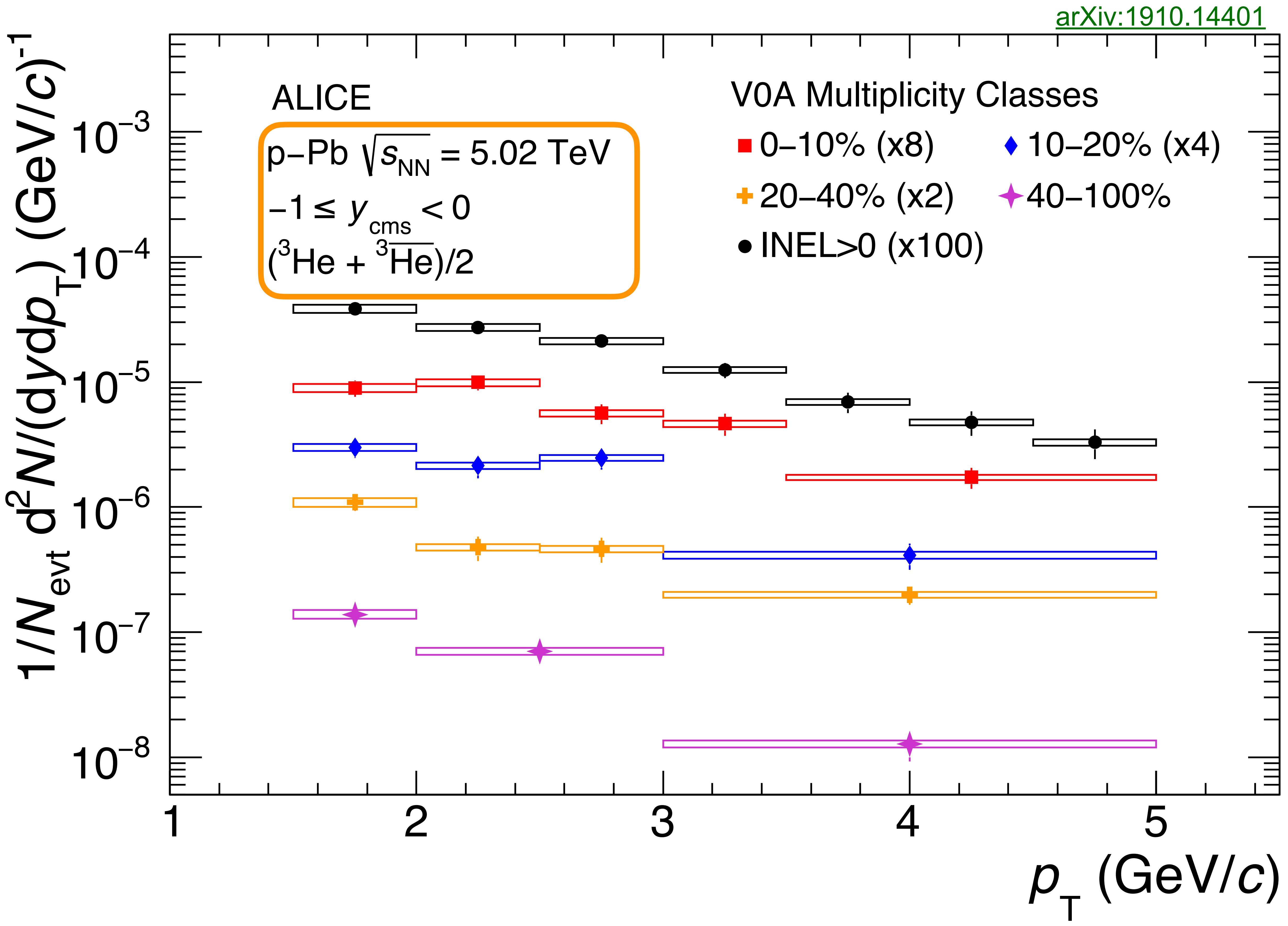




- ALICE extends with light nuclei the already complete set of light flavour hadrons measurements as a function of charged particle multiplicity in all collision systems now available
- Remarkable similarities across collision systems are observed.

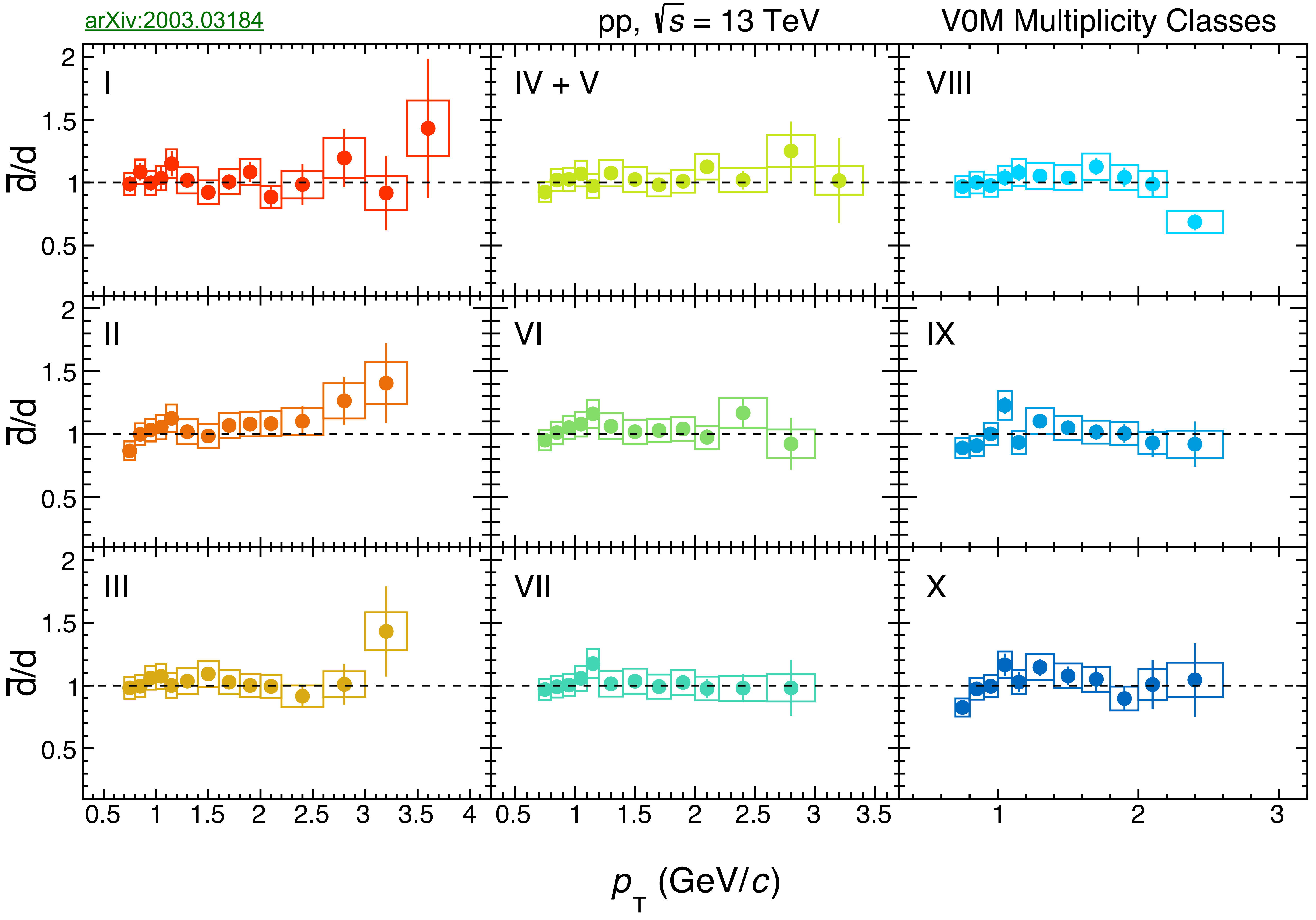
Production spectra of (anti)deuterons and (anti)^{3}He





- ALICE extends with light nuclei the already complete set of light flavour hadrons measurements as a function of charged particle multiplicity in all collision systems now available
- Remarkable similarities across collision systems are observed.

The ~~LHC~~ antimatter factory



For a nucleus X with mass number A, both coalescence and thermal models predict:

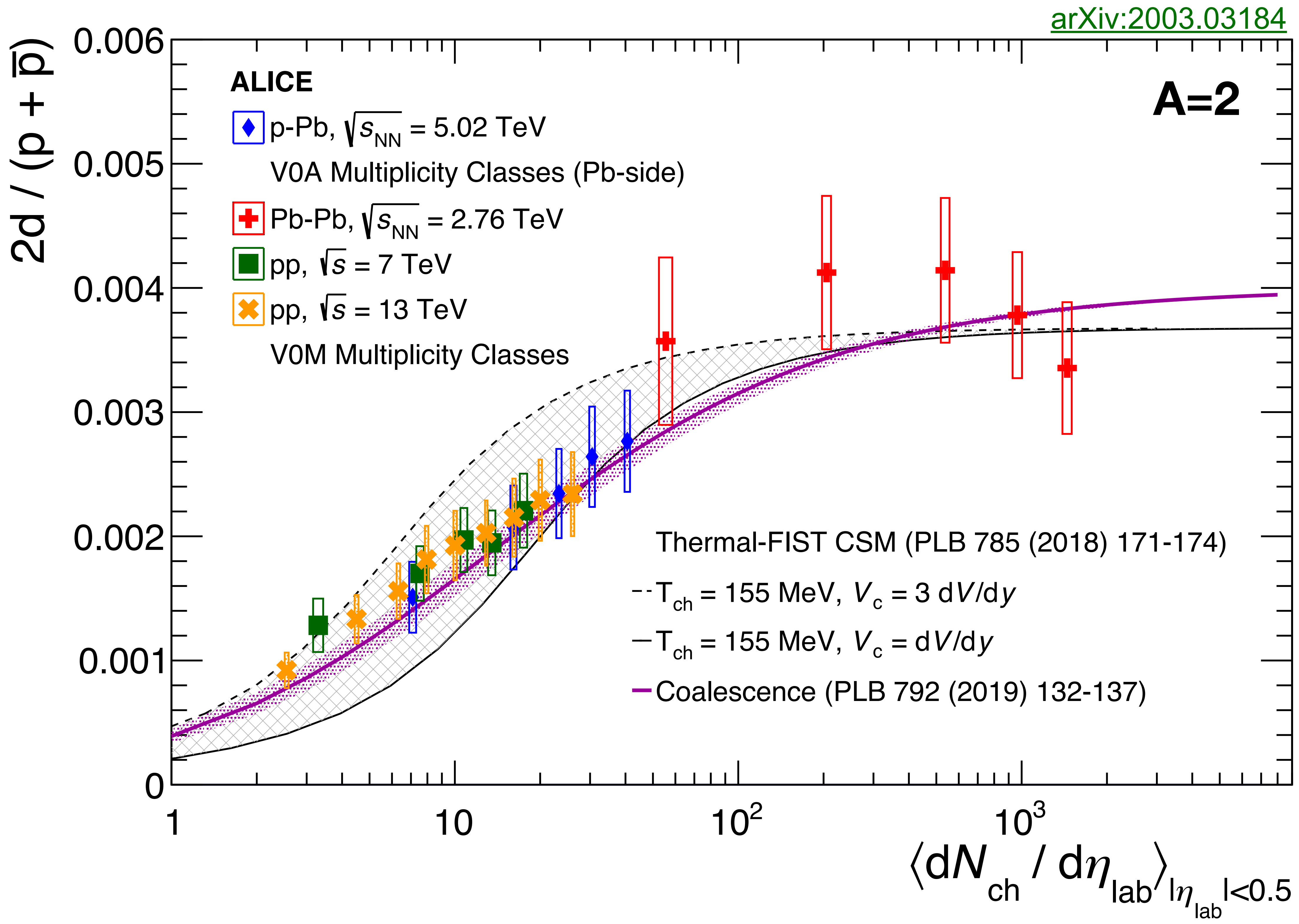
$$\frac{\overline{X}}{X} \approx \left(\frac{\overline{p}}{p}\right)^A$$

The antiproton / proton ratio is compatible with unity at the LHC

- ➡ Measured anti-nuclei over nuclei ratios are in line with theory expectations
- ➡ Valid also for A=3 in p-Pb!
- ➡ Systematics dominated by the poorly known interaction cross section of antinuclei with the detector material

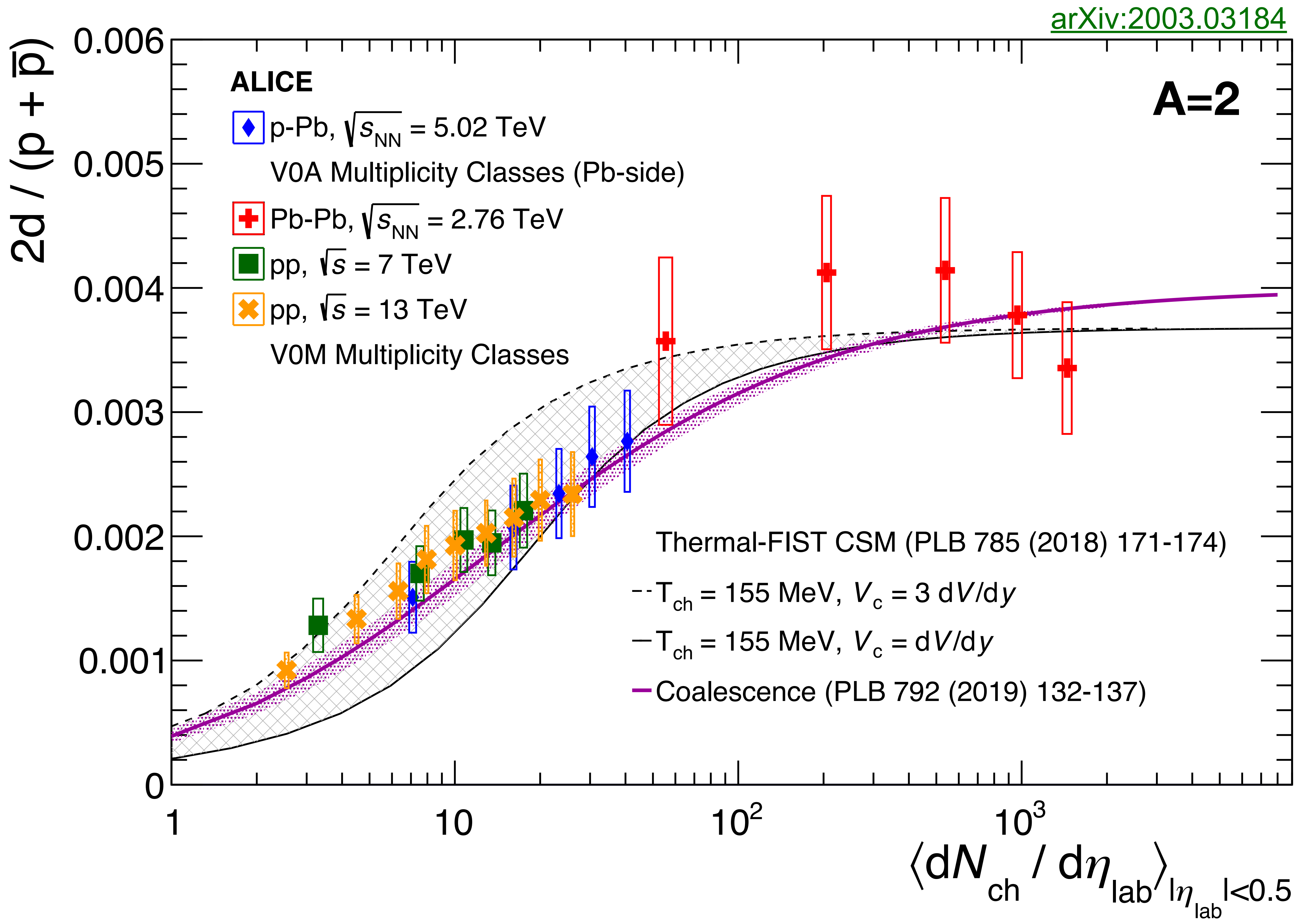
At the LHC matter and antimatter are produced in equal abundance at mid rapidity

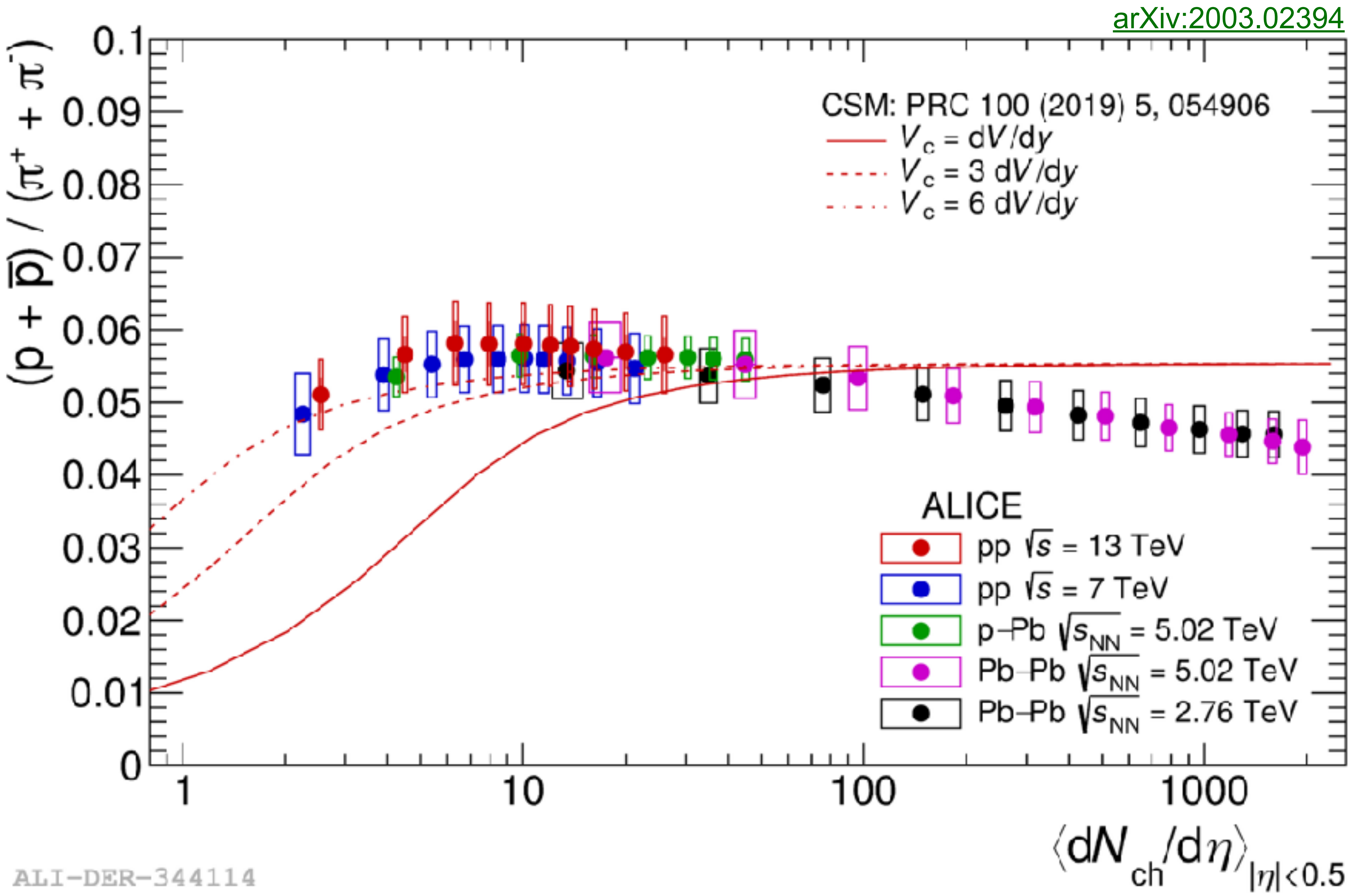
Thermal model vs coalescence



- Is this smooth transition suggesting a single description for the nucleosynthesis in HEP?
  - Thermal model with canonical suppression gets the rise of the nucleus/proton ratio

Thermal model vs coalescence

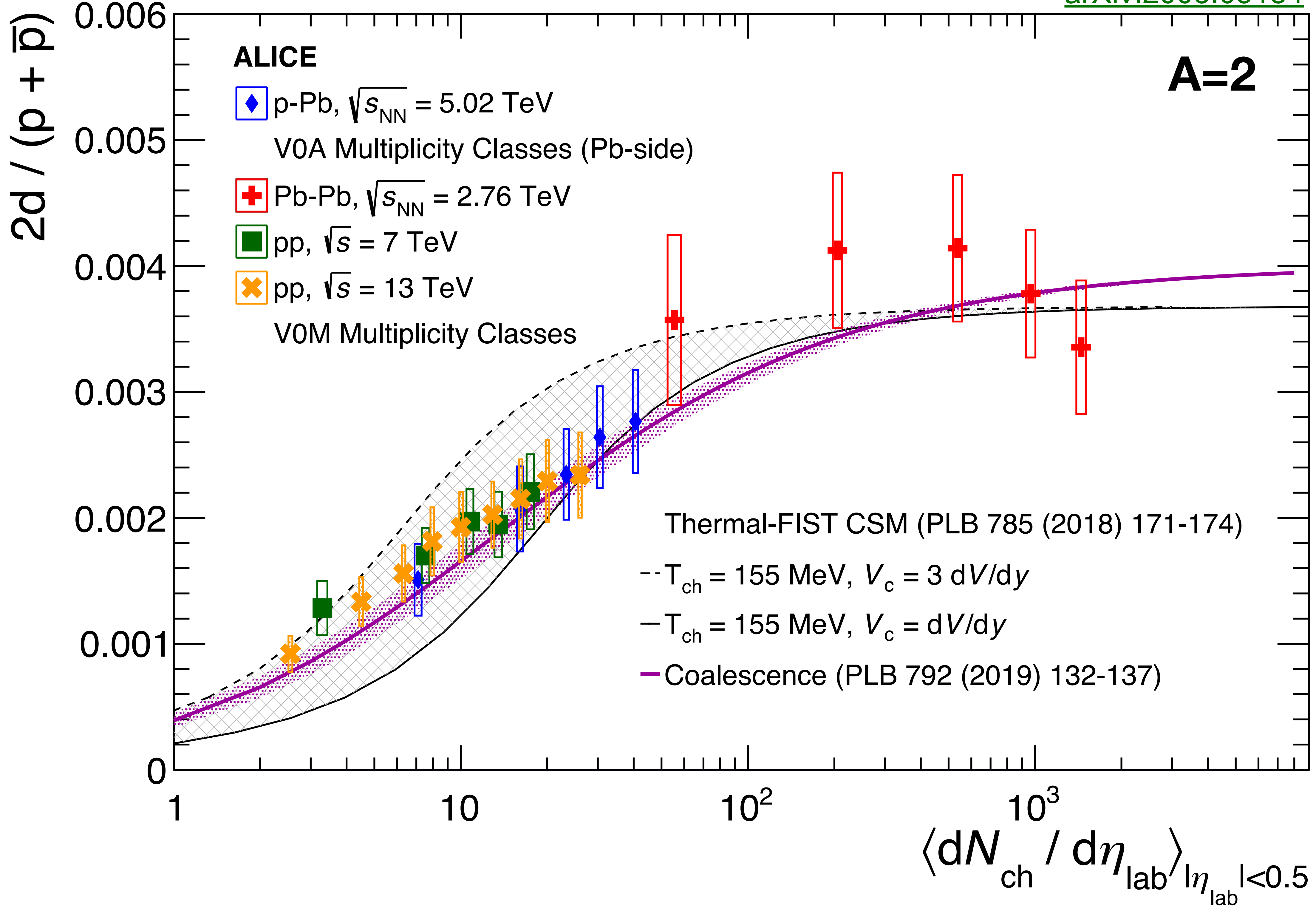




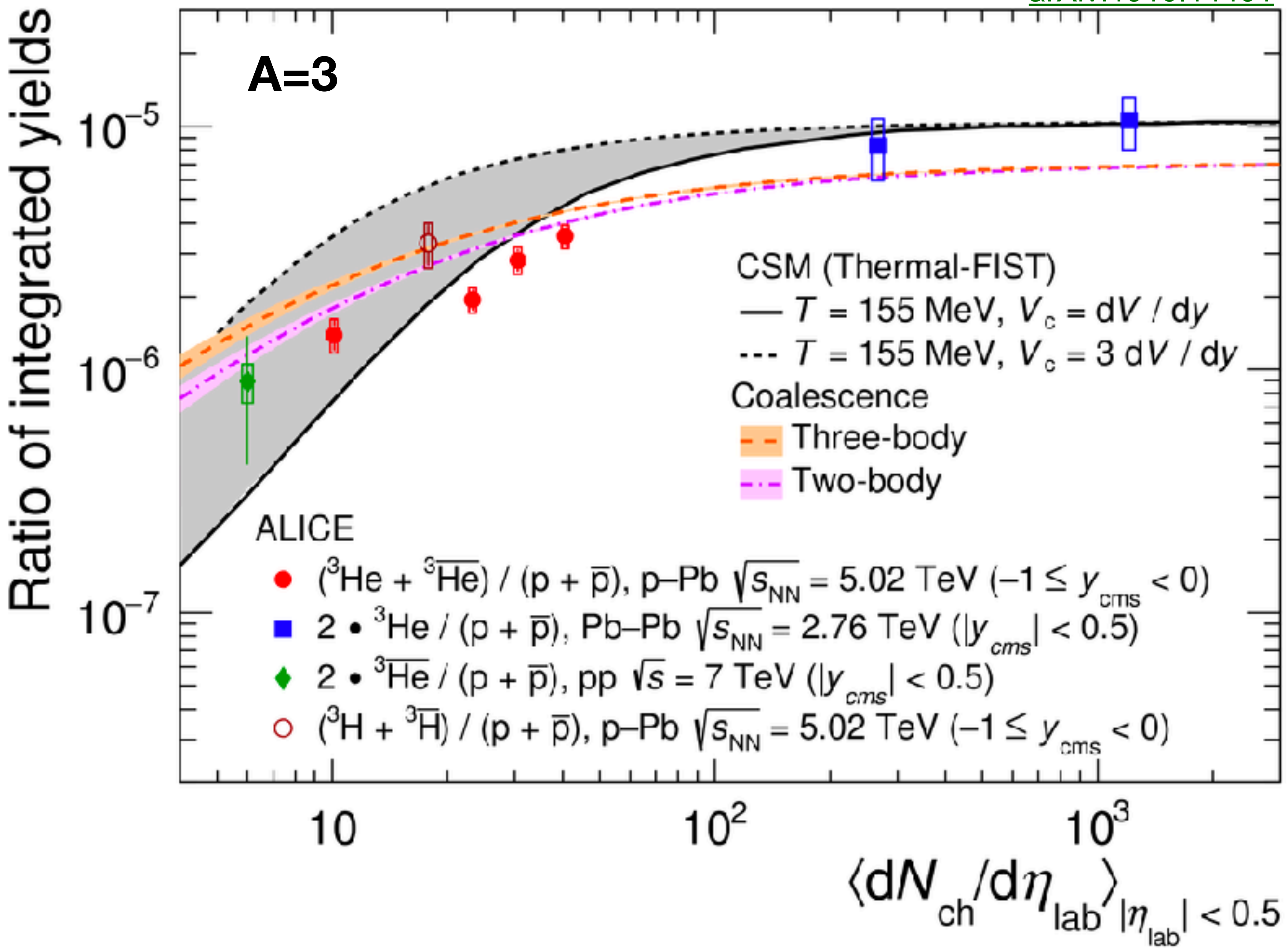
- Is this smooth transition suggesting a single description for the nucleosynthesis in HEP?
  - Thermal model with canonical suppression gets the rise of the nucleus/proton ratio
    - However with the same parameters proton over pion ratio is not reproduced at low multiplicity

Thermal model vs coalescence

arXiv:2003.03184



arXiv:1910.14401



- Is this smooth transition suggesting a single description for the nucleosynthesis in HEP?
  - Thermal model with canonical suppression gets the rise of the nucleus/proton ratio
    - However with the same parameters proton over pion ratio is not reproduced at low multiplicity
- Advanced nuclei coalescence can describe the d/p ratio but again struggle with the A=3 nuclei

The coalescence parameter

The coalescence parameter for a nucleus *i* with A nucleons is defined as:

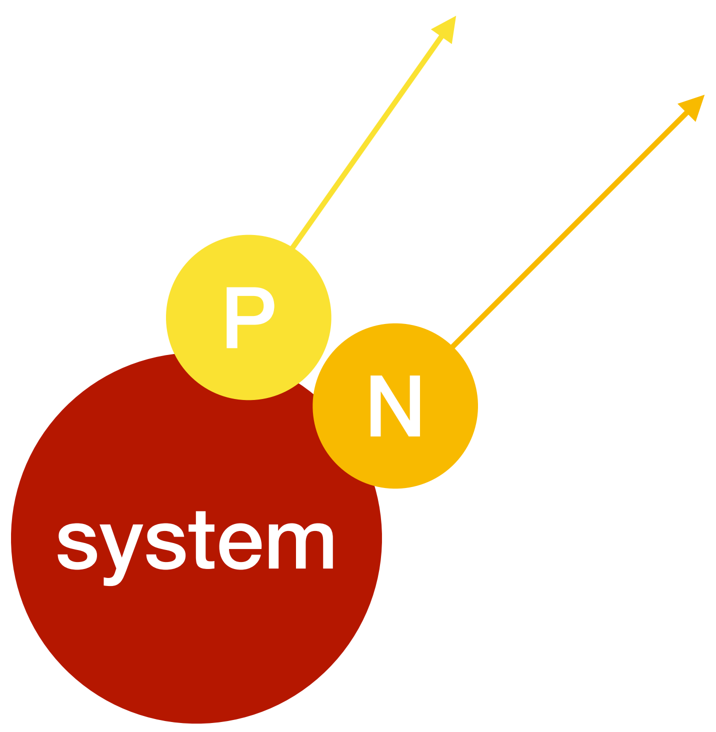
$$E_i \frac{\mathrm{d}^3 N_i}{\mathrm{d}p_i^3} = B_A \left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^A \quad \xrightarrow{\text{deuterons}} \quad B_2 = \frac{E_\mathrm{d} \frac{\mathrm{d}^3 N_\mathrm{d}}{\mathrm{d}p_\mathrm{p}^3}}{\left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^2}$$

Experimental parameter that is tightly connected to the coalescence probability:

Larger B_A $\Longleftrightarrow$ Larger coalescence probability

The closer the nucleons are in phase space the higher is the coalescence probability

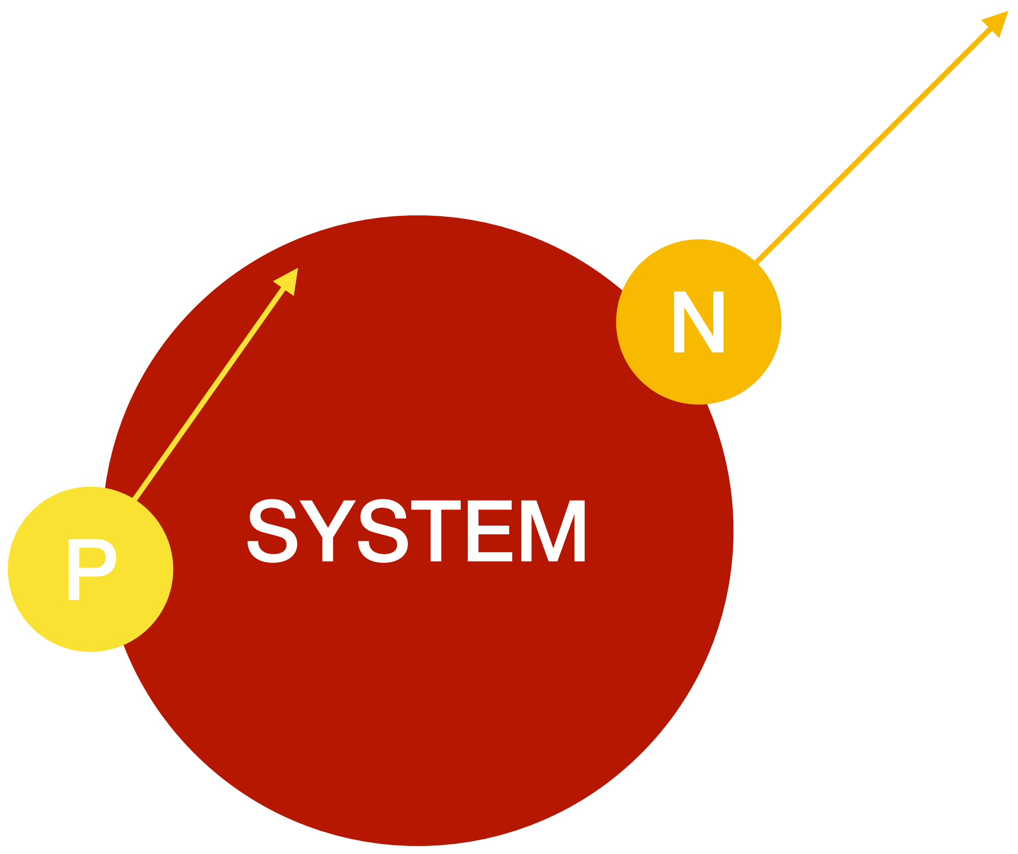
SCHEMATIC VIEW



Small systems
=
Small distance in space

Only momentum correlation matters

Expect larger B_A

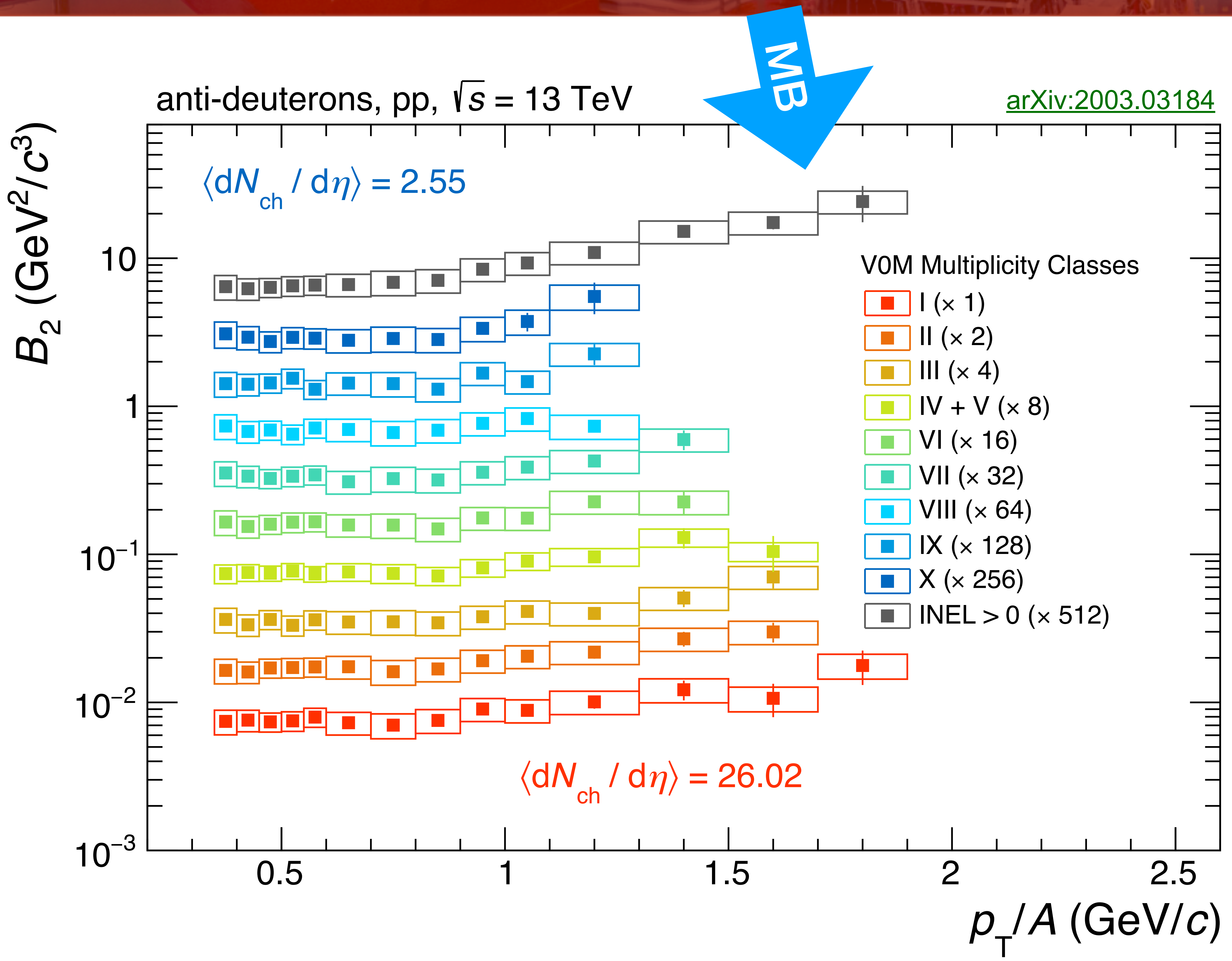


Large systems
=
Large distance in space

Both momentum and space correlations matter

Expect smaller B_A

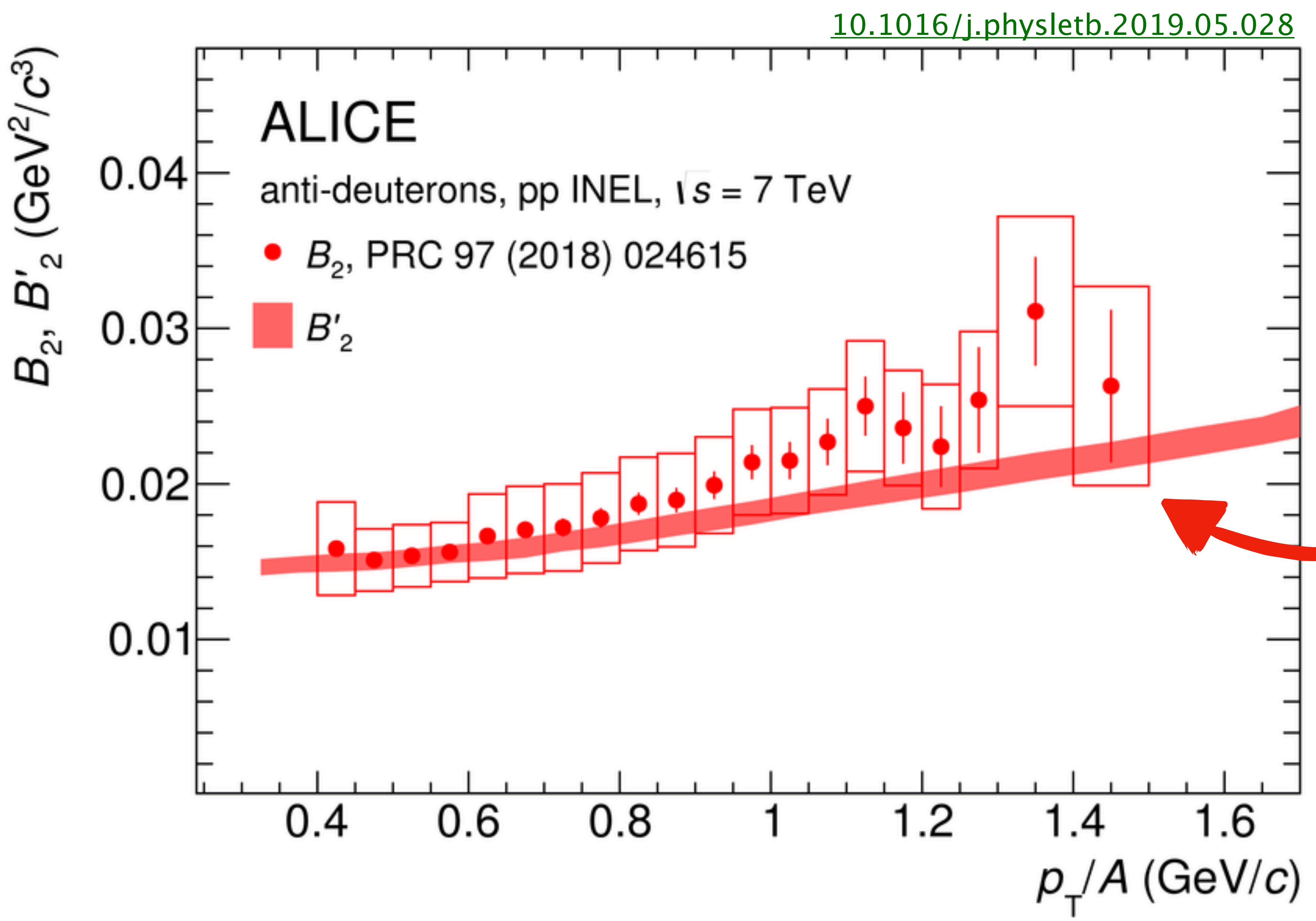
Testing coalescence with B_A

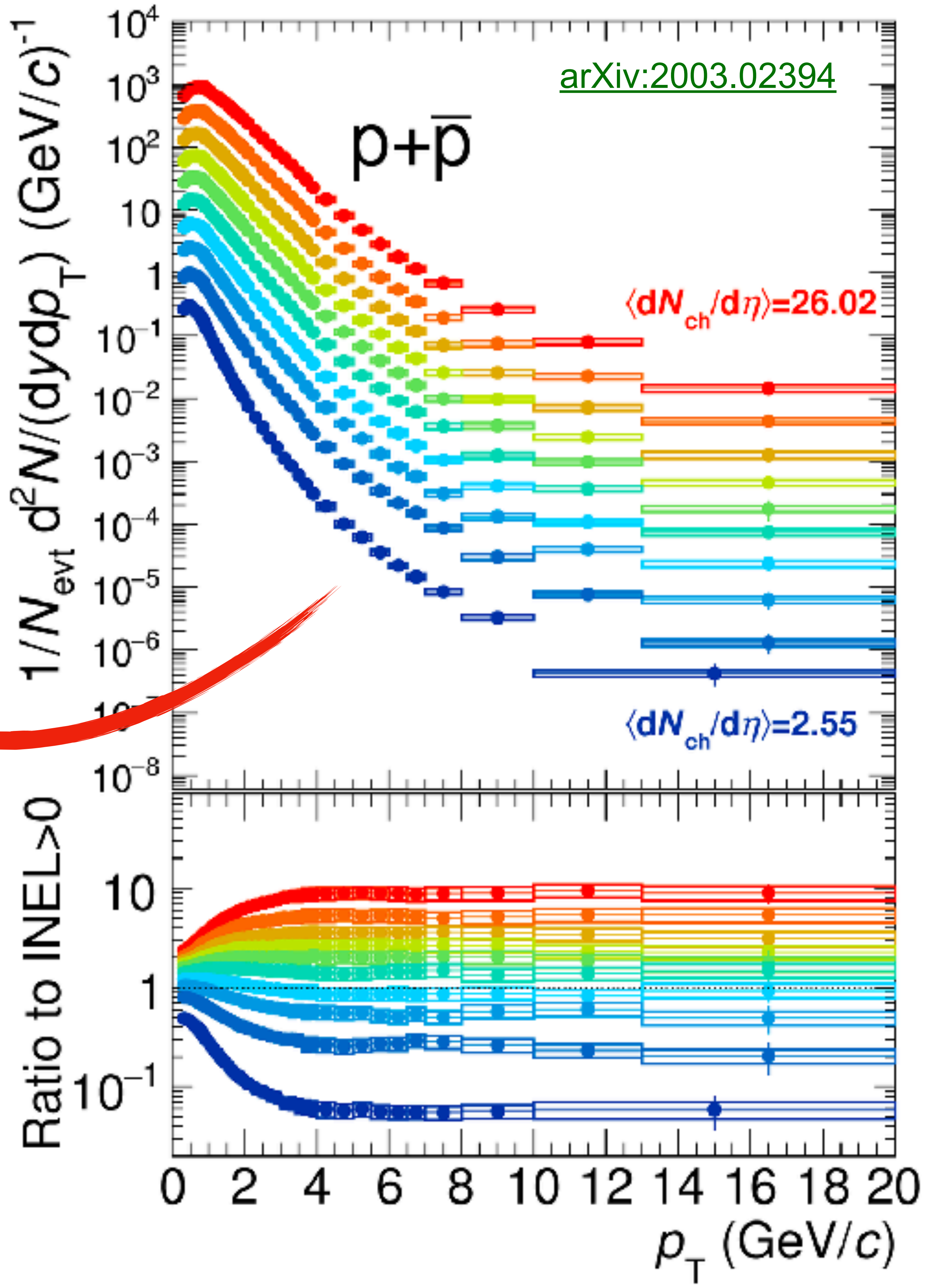


Simplest coalescence: B_A flat in momentum

- Not observed for MB collision but observed in multiplicity intervals

Testing coalescence with B_A





$$S_{d(i)} = B_2 S_{p(i)}^2$$

With $S_{d(i)}$ and $S_{p(i)}$ = proton and deuteron spectra in the mult interval *i*

$$B_2' = B_2 \frac{N \sum_{i=0}^{n} N_i S_{p(i)}^2}{\left(\sum_{i=0}^{n} N_i S_{p(i)}\right)^2}$$

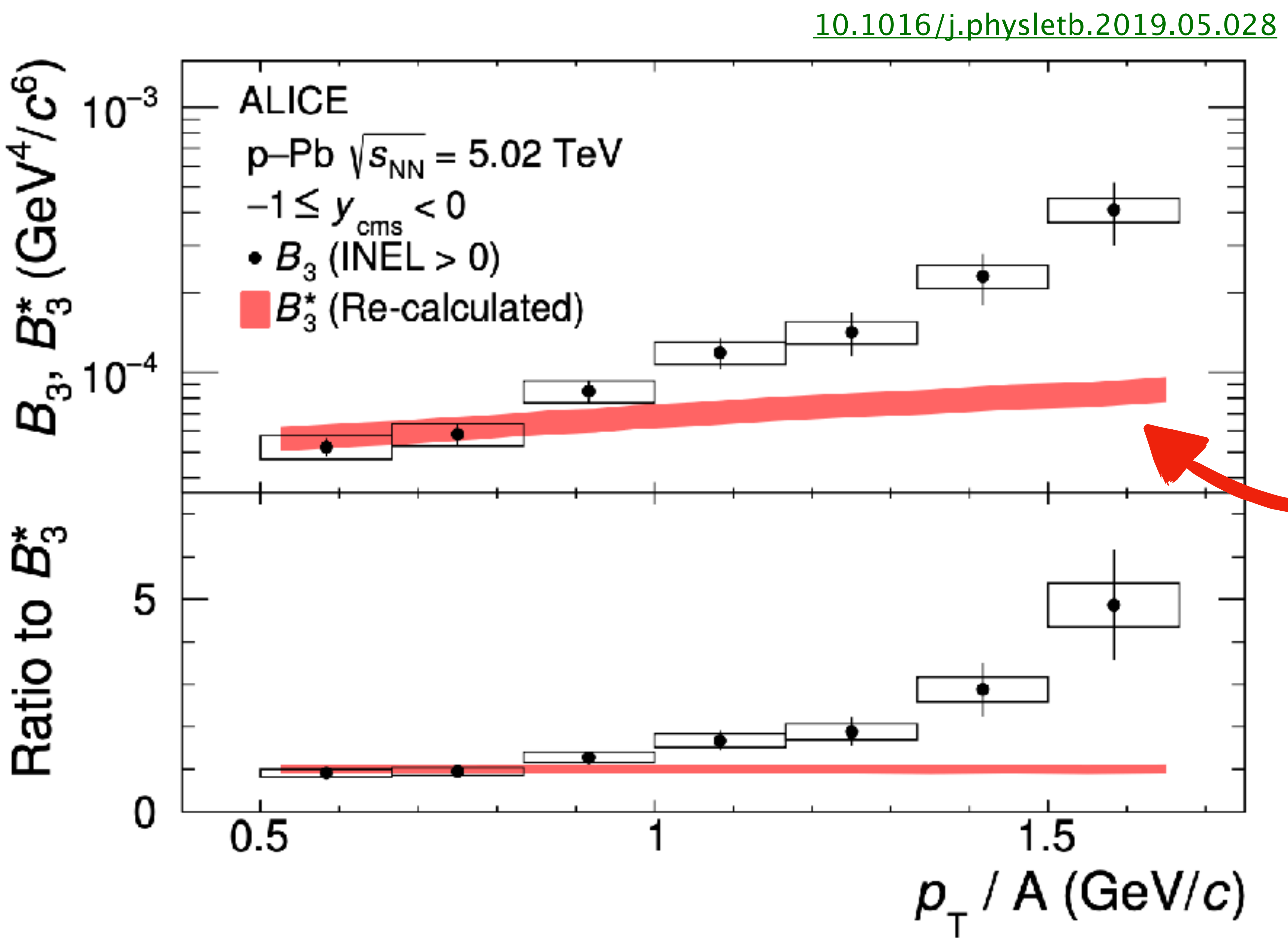
Simplest coalescence: B_A flat in momentum

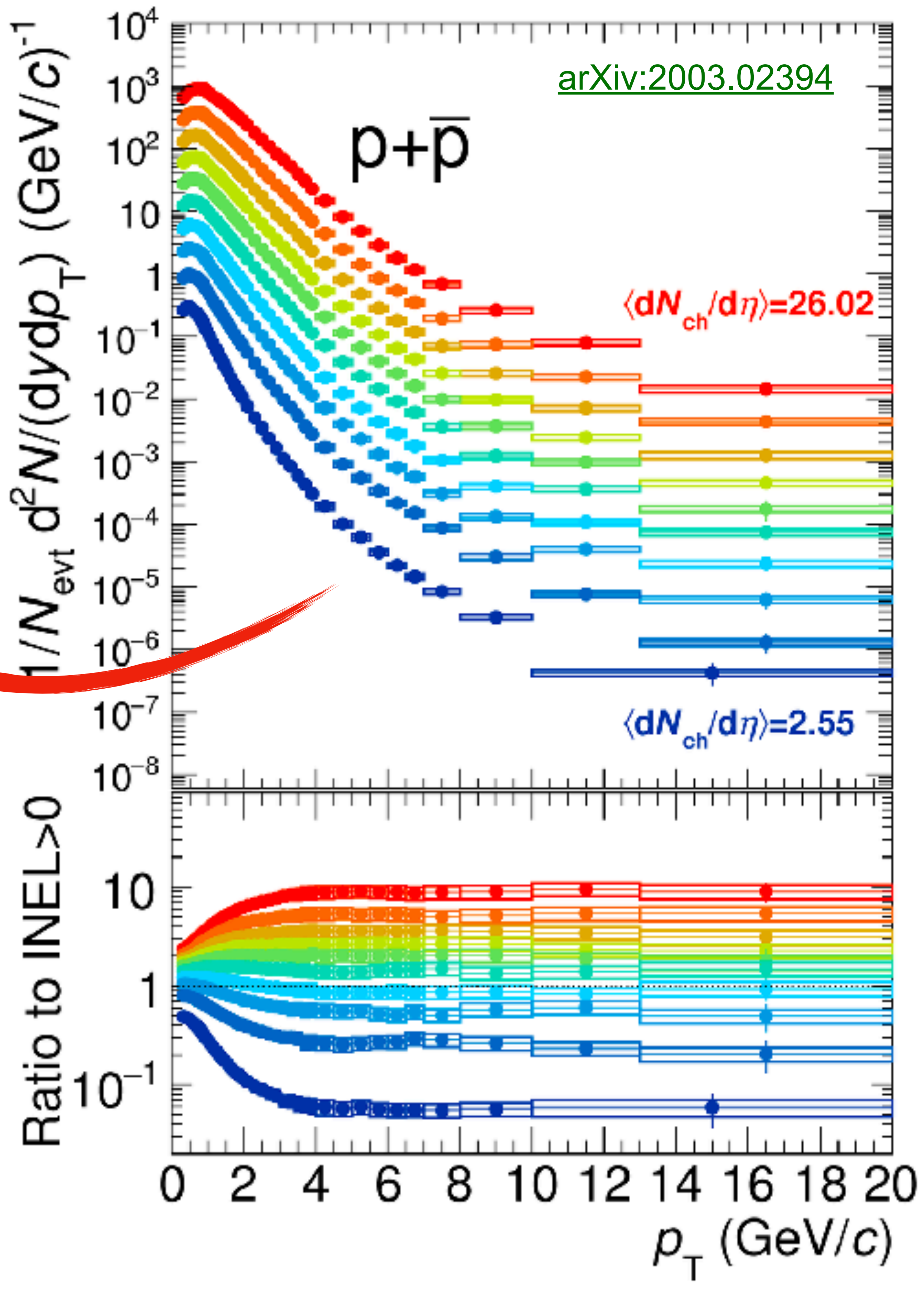
- Not observed for MB collision but observed in multiplicity intervals

The rise in MB is partially due to the change of the proton spectra shape as a function of multiplicity

- But this alone cannot explain the B_3 evolution as a function of momentum

Testing coalescence with B_A





$$S_{d(i)} = B_3 S^3_{p(i)}$$

With $S_{d(i)}$ and $S_{p(i)}$ = proton and deuteron spectra in the mult interval *i*

$$B_3^* = B_3 \frac{N \sum_{i=0}^{n} N_i S^3_{p(i)}}{\left(\sum_{i=0}^{n} N_i S_{p(i)}\right)^3}$$

Simplest coalescence: B_A flat in momentum

- Not observed for MB collision but observed in multiplicity intervals

The rise in MB is partially due to the change of the proton spectra shape as a function of multiplicity

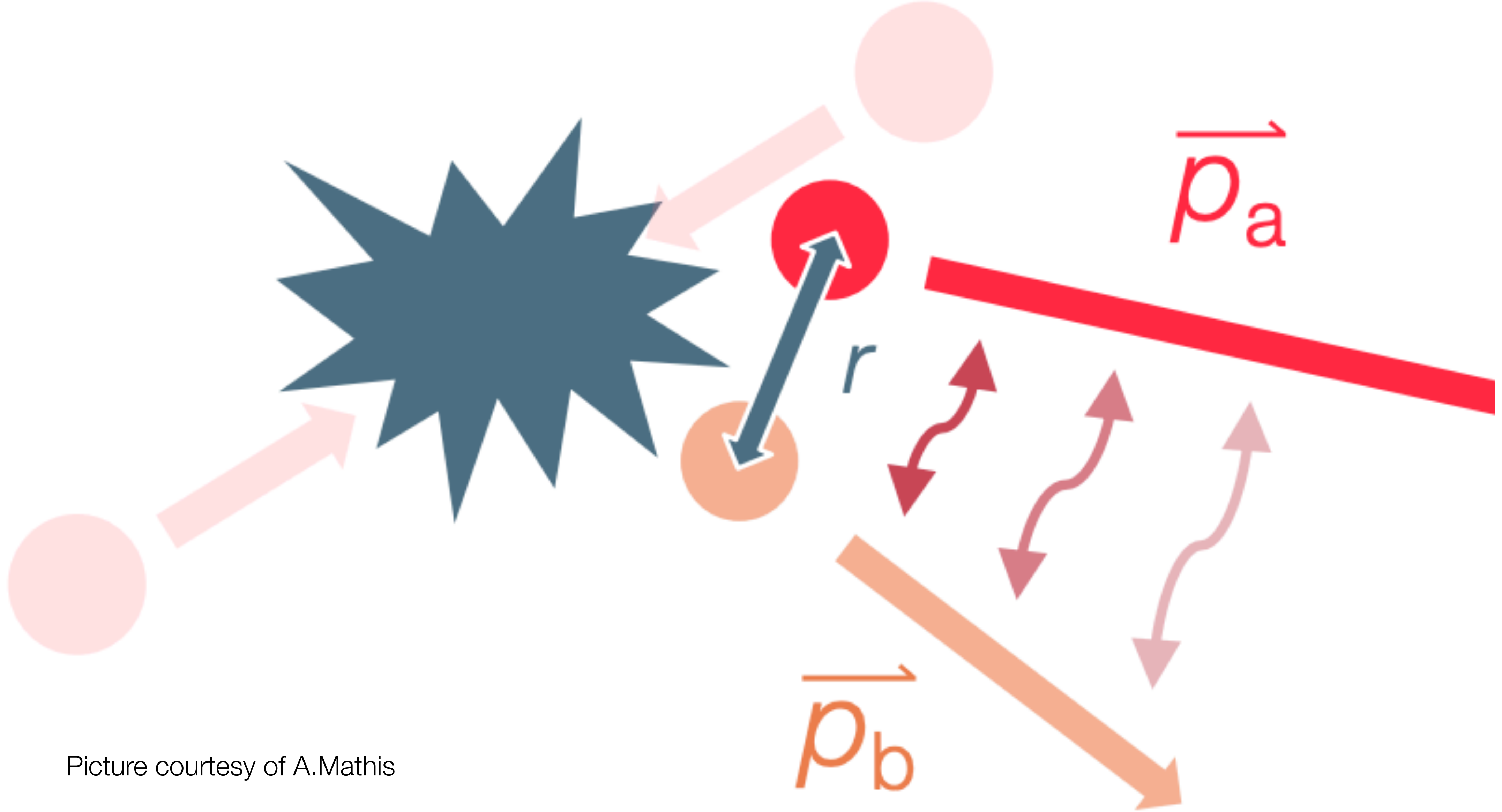
- But this alone cannot explain the B_3 evolution as a function of momentum

Computing the source radius

Long standing idea of correlating the **source size** computed with **Hanbury-Brown Twiss** interferometry techniques to the **coalescence processes**

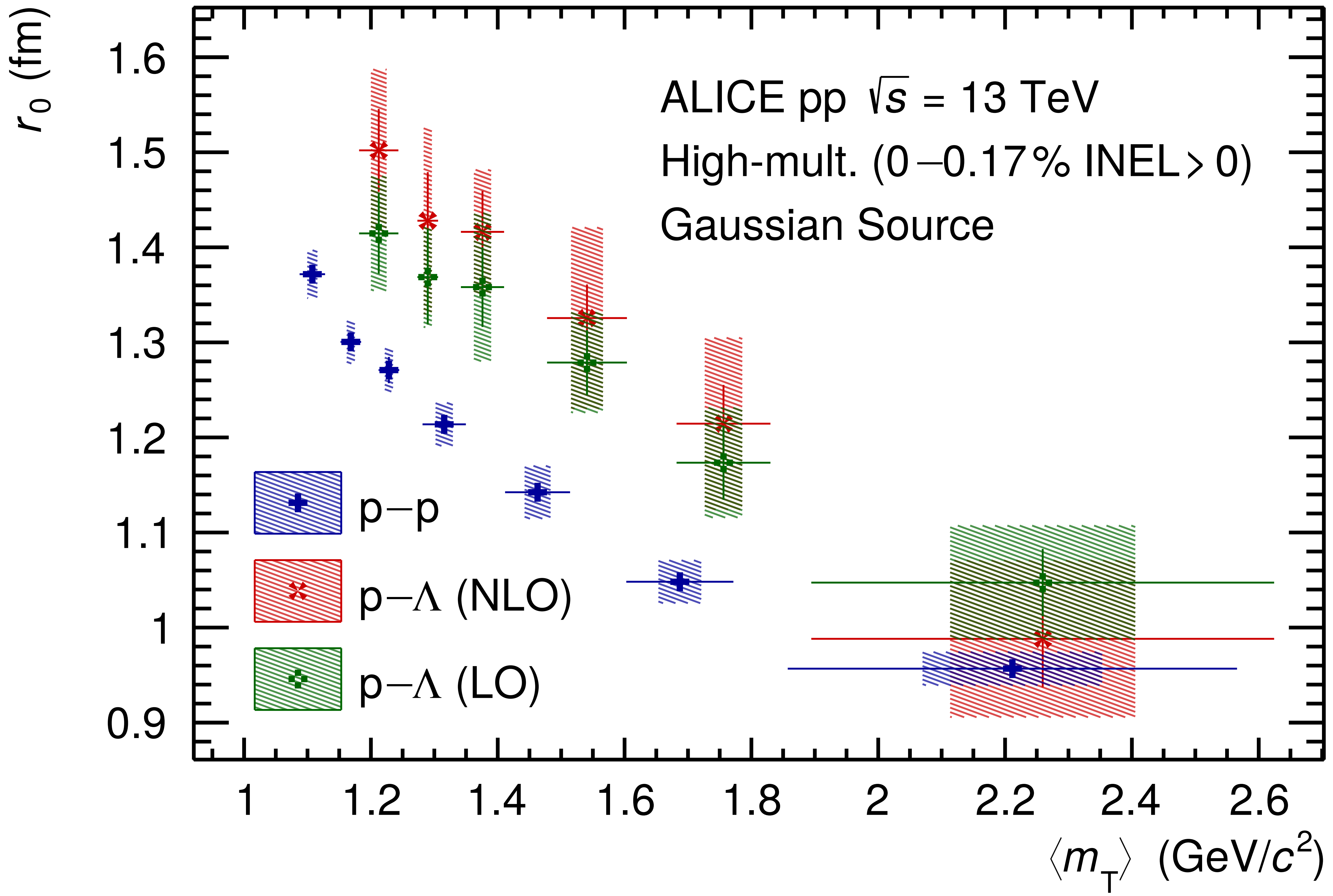
$$C(k^*) = \mathcal{N} \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)} = \int S(r)\ |\Psi(k^*, r)|^2\, d^3r$$

Study of two particle correlations to get information about the **source size** and the **interaction among particles**



Picture courtesy of A.Mathis

arxiv:2004.08018



Computing the source radius

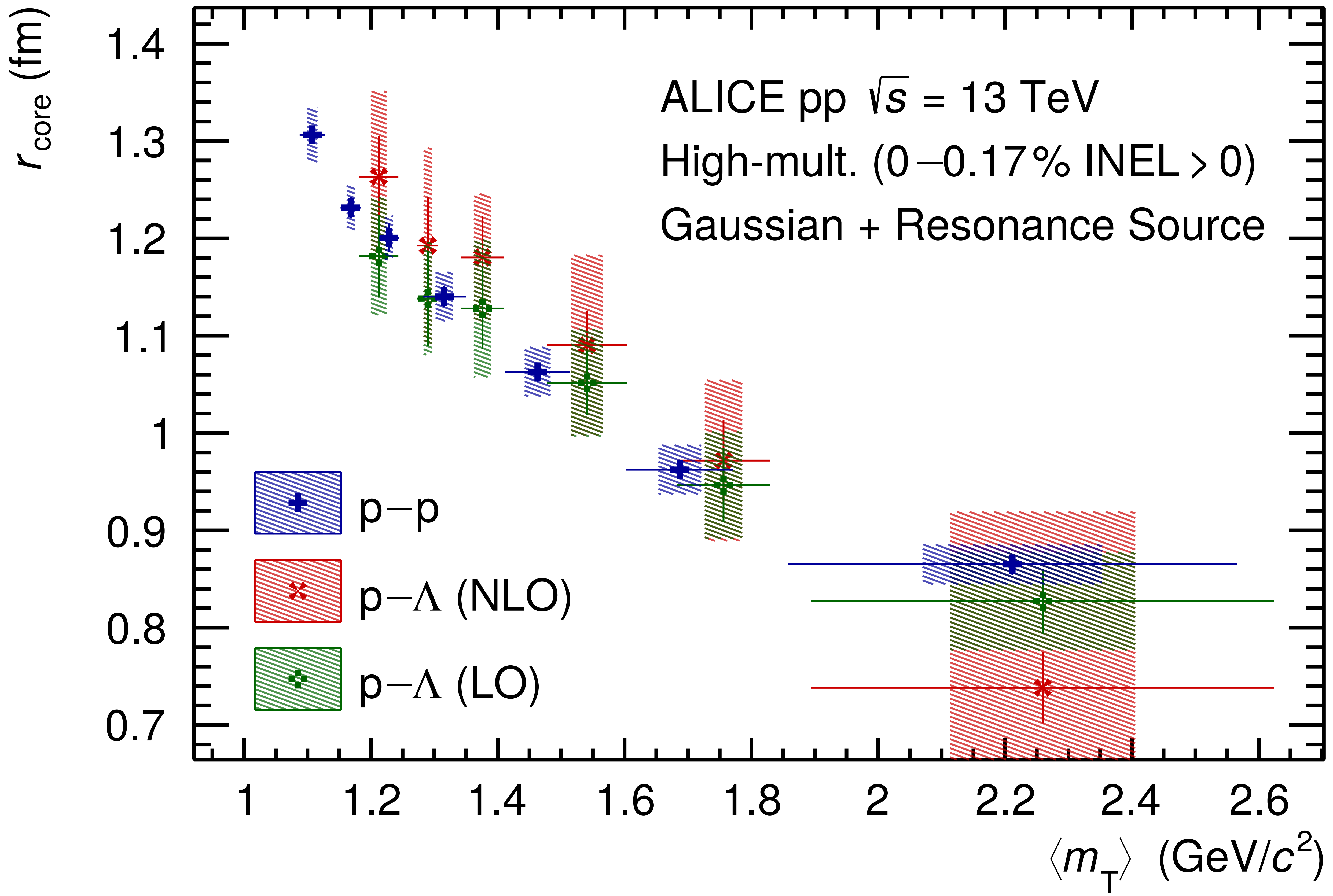
Long standing idea of correlating the **source size** computed with **Hanbury-Brown Twiss** interferometry techniques to the **coalescence processes**

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

arxiv:2004.08018

Study of two particle correlations to get information about the **source size** and the **interaction among particles**

- HBT correlations not enough to define a unique source radius!
  - Resonances affect the measurement
- First quantitative correction for this effect leads to the measurement of a universal baryon source



From the correlation to the coalescence parameter

A new development* that allows us to zoom into the production of nuclei through coalescence

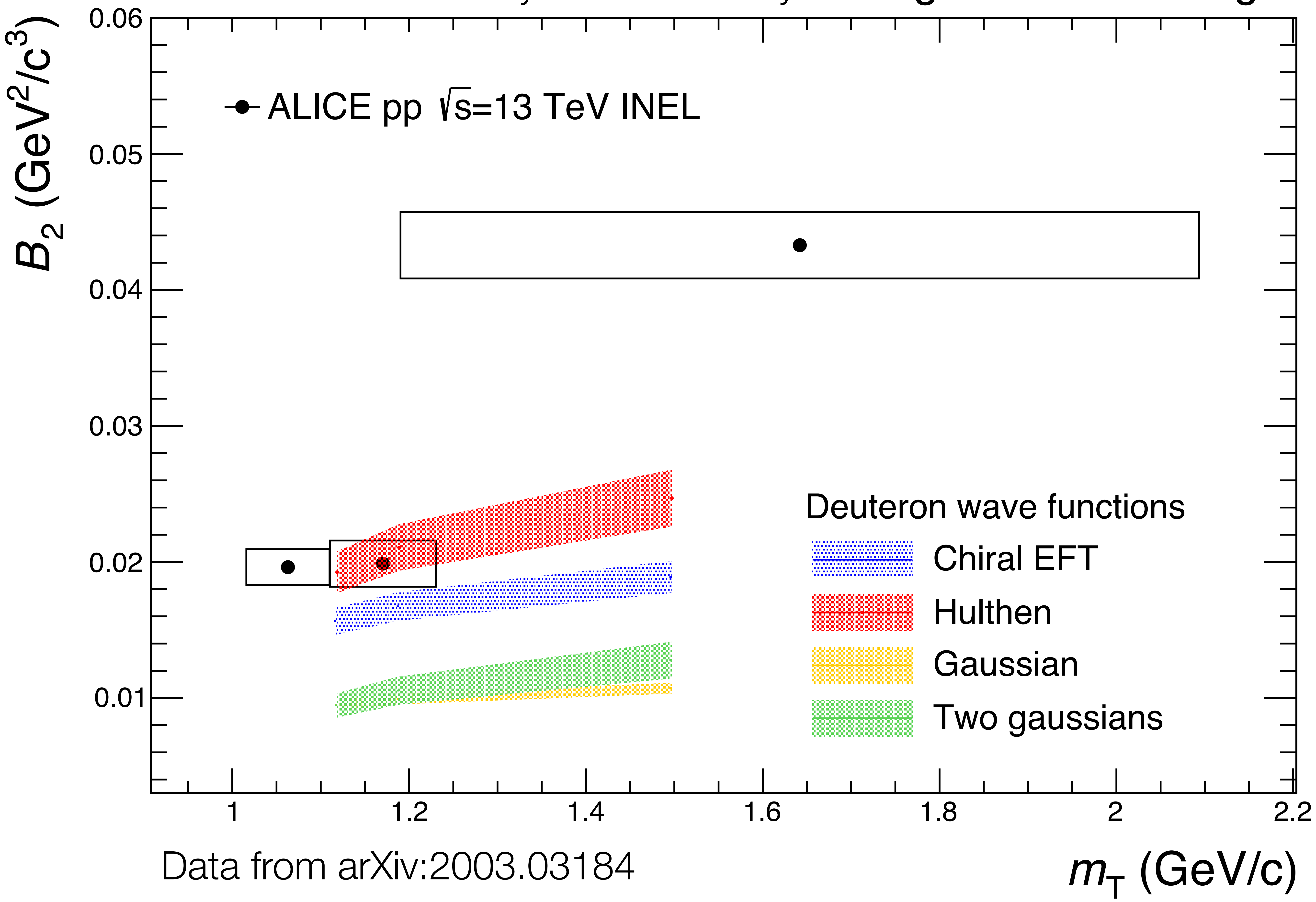
Correlation radius

$$B_2(p) \approx \frac{3}{2m} \int \mathrm{d}^3 q \, \mathscr{D}(\vec{q}) \, \mathscr{C}_2^{\mathrm{PRF}}(\vec{p}, \vec{q})$$

Wigner density

"Source Radius + Nucleus wave function -> B_2"

Preliminary calculations by **B. Singh and B. Hohlweger**



Data from arXiv:2003.03184

*K. Blum, M. Takimoto PRC99, 044913 (2019)

From the correlation to the coalescence parameter

A new development* that allows us to zoom into the production of nuclei through coalescence

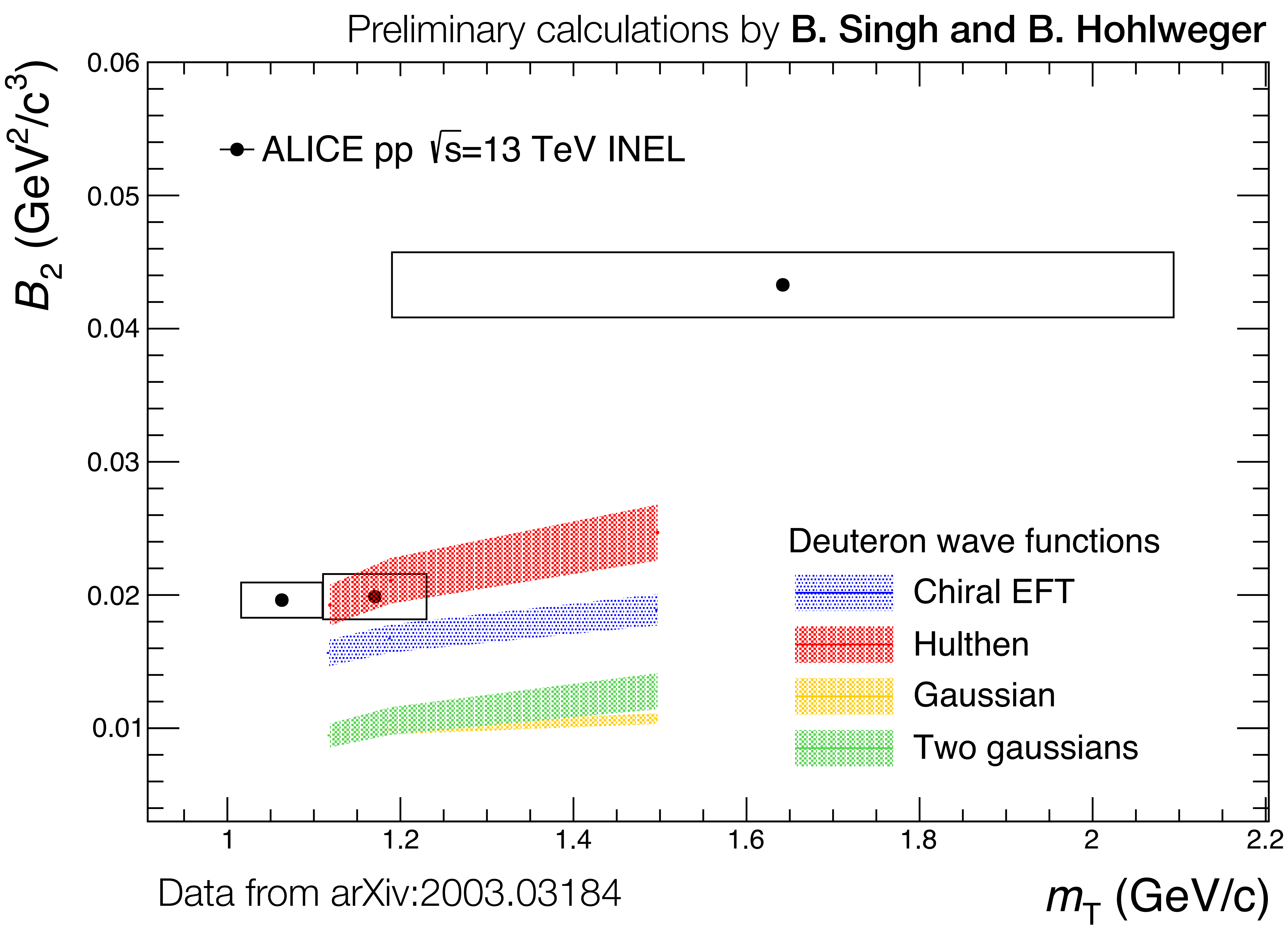
$$B_2(p) \approx \frac{3}{2m}\int \mathrm{d}^3q\,\mathscr{D}(\vec{q})\,\mathscr{C}_2^{\mathrm{PRF}}(\vec{p},\vec{q})$$

Correlation radius

Wigner density

"Source Radius + Nucleus wave function -> B_2"

- Different wave functions give very different expected coalescence parameter
  - Yet quantitative description of data is still far though

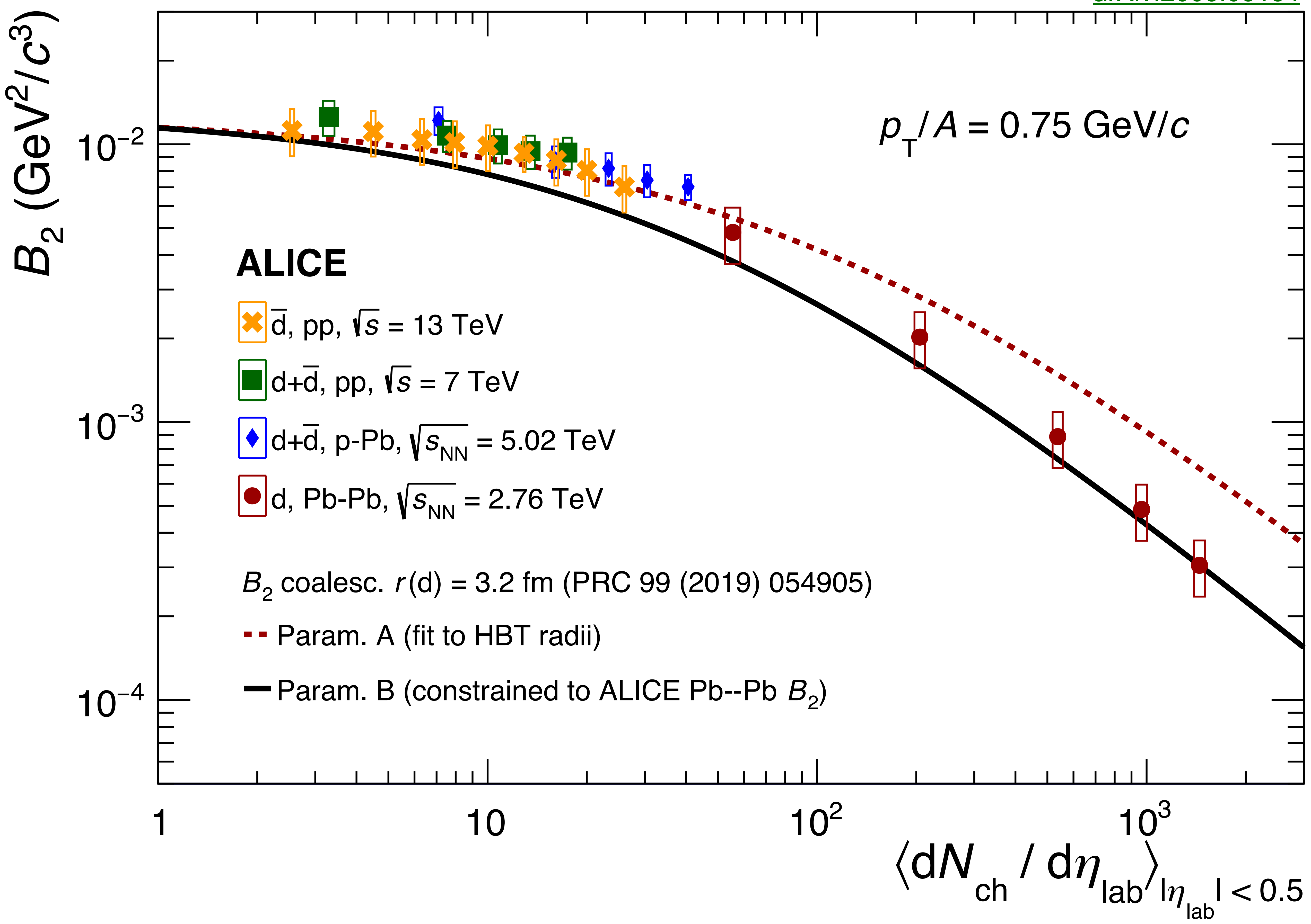


Data from arXiv:2003.03184

*K. Blum, M. Takimoto PRC99, 044913 (2019)

Unified description of nucleosynthesis at collider?

arXiv:2003.03184



Coalescence constrained to the HBT radii quantitatively describes the evolution of B_2 in small systems but fails in reproducing Pb-Pb results

The coalescence parameter evolves smoothly as a function of multiplicity

- Another hint of a system size aware production mechanism

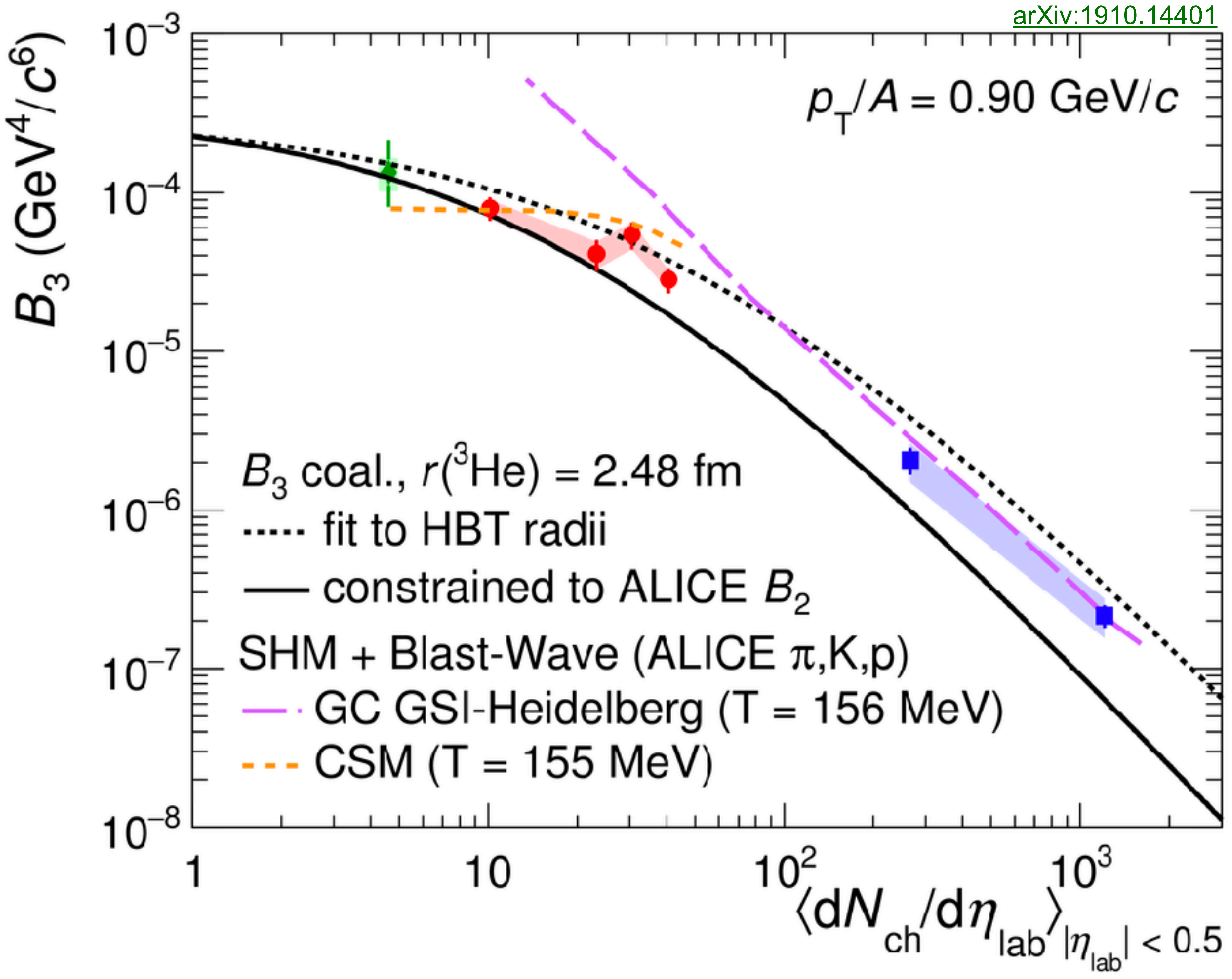
A possible parameterisation using the system HBT radius R:

$$^{*}\, B_A = \frac{2J_A + 1}{2^A} \frac{1}{\sqrt{A}} \frac{1}{m_T^{A-1}} \left(\frac{2\pi}{R^2 + r_A^2/4} \right)^{\frac{3}{2}(A-1)}$$

where the numerical factors come from approximations of the nucleus and nucleons sizes

*F. Bellini, A. Kalweit PRC.99.054905

Unified description of nucleosynthesis at collider?



Models struggle to quantitatively describe the measured B_3

The coalescence parameter evolves smoothly as a function of multiplicity

- Another hint of a system size aware production mechanism

A possible parameterisation using the system HBT radius R:

$$ {}^{*}\, B_A = \frac{2J_A+1}{2^A}\frac{1}{\sqrt{A}}\frac{1}{m_T^{A-1}}\left(\frac{2\pi}{R^2+r_A^2/4}\right)^{\frac{3}{2}(A-1)} $$

where the numerical factors come from approximations of the nucleus and nucleons sizes

*F. Bellini, A. Kalweit PRC.99.054905

Thermal vs coalescence in small systems

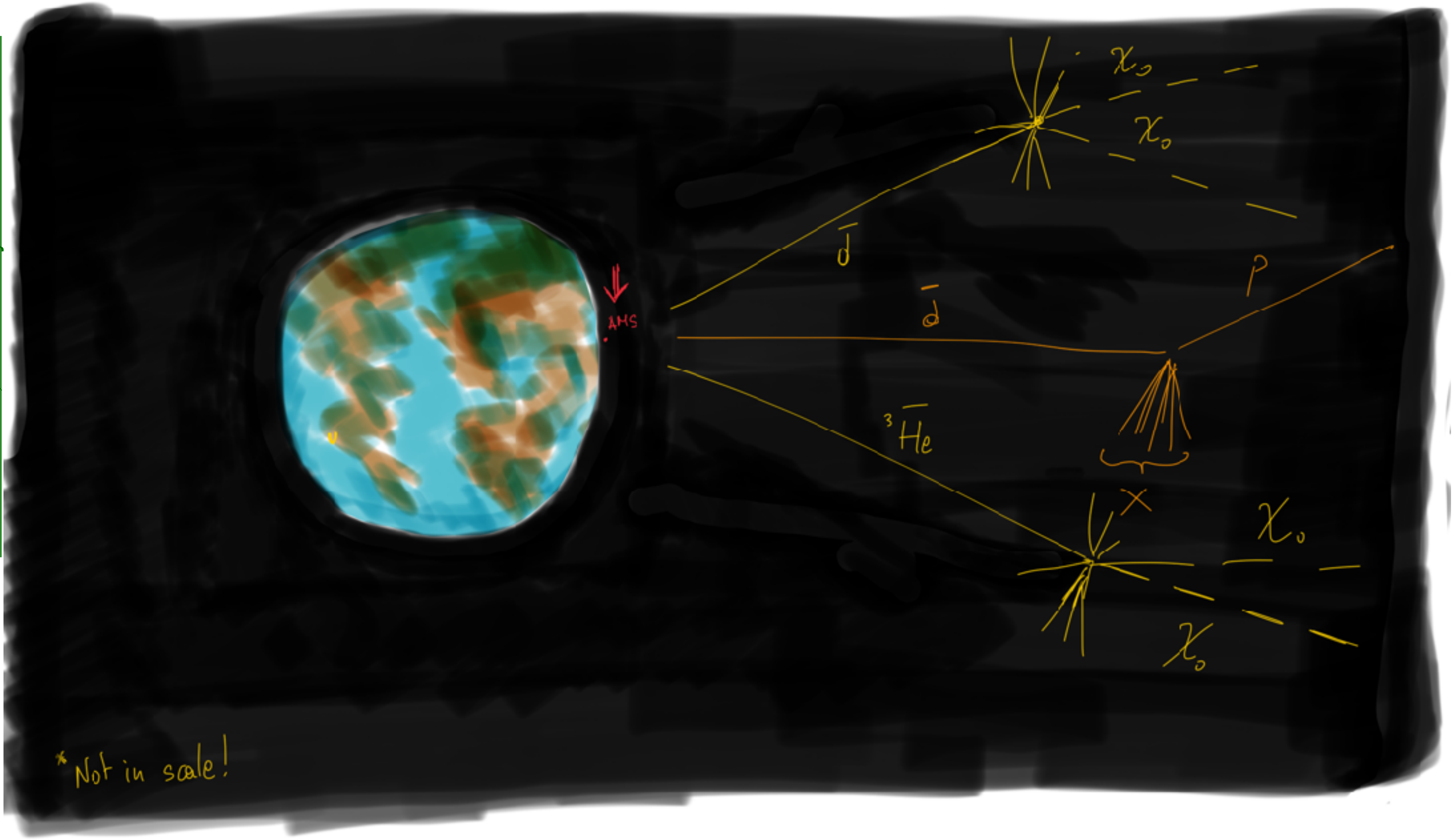
	Deuteron				^{3}He		
	B_2(p)	B_2 vs mult.	d/p vs mult.	p/π vs mult.	B_3(p)	B_3 vs mult.	^{3}He/p vs mult.
Coalescence	✓	✓	✓	NA	✗	✗	✗
Thermal model	NA	✗	✓	✗	NA	✗	✗

- Deuteron production in pp and p-Pb collisions is described by coalescence model
- Thermal model can describe d/p vs multiplicity, but at the same time fails in describing p/π
- A=3 nuclei are not described quantitatively by neither coalescence nor thermal models

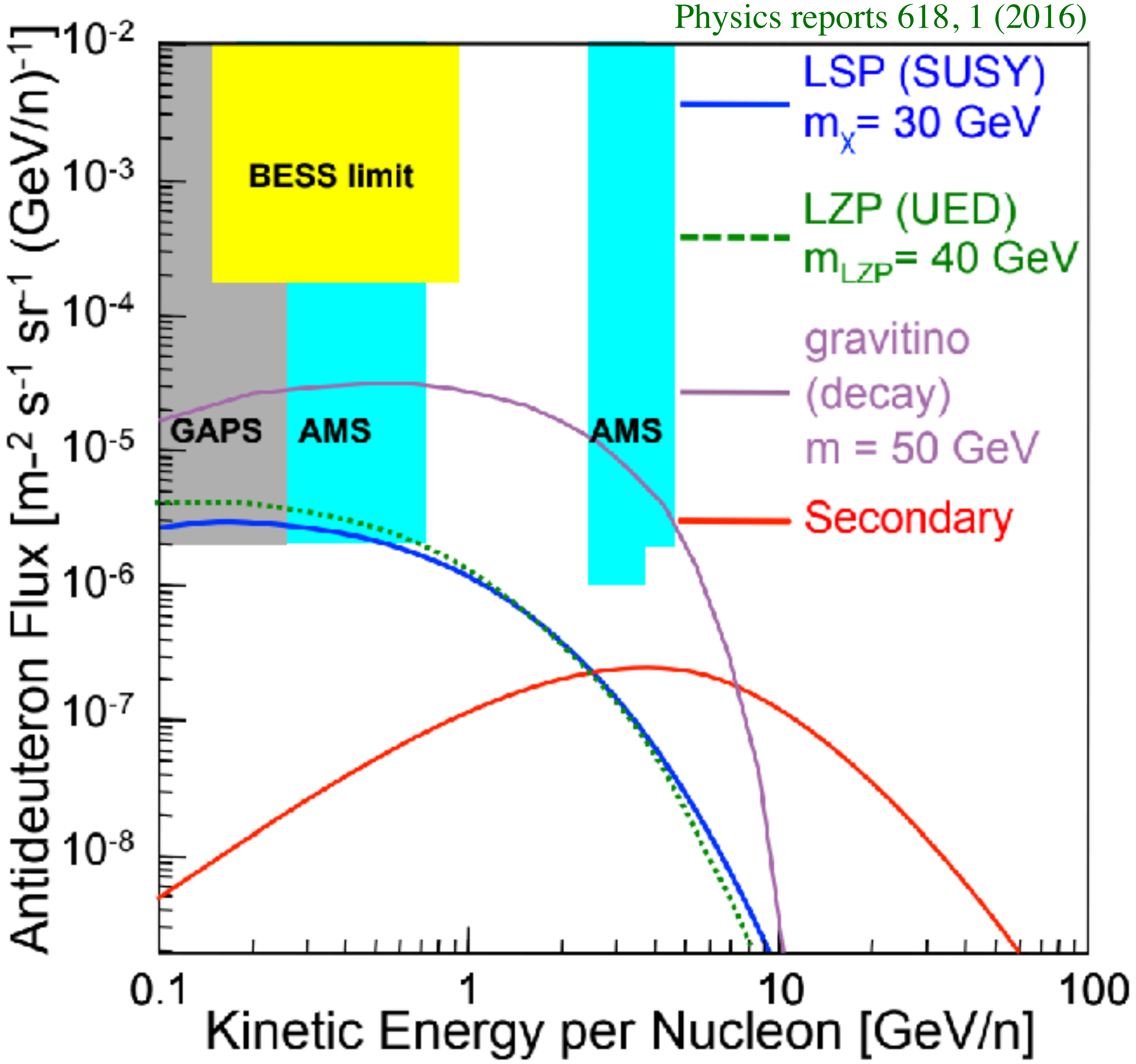
In space like in the laboratory

Understanding antinucleosynthesis at the LHC has important applications in other fields

K. Blum et al., 10.1103/PhysRevD.96.103021
F.Donato et al.,10.1103/PhysRevD.62.043003



Physics reports 618, 1 (2016)



- Long standing prediction: anti-nuclei as unambiguous probe of dark matter annihilation in the universe
- Only background: secondary production from ordinary matter collisions (mainly pp, p-A with small Z…)
  - Measure on Earth at collider the cross sections for this processes and constrain production models

The path of antinuclei to Earth

To understand the measurement of antinuclei in balloon and satellite experiments one has to understand their production and transport through the galaxy

$$\nabla \cdot (-K \nabla N_{\bar{d}} + V_c N_{\bar{d}}) + \partial_t (b_{tot} N_{\bar{d}} - K_{EE} \partial_t N_{\bar{d}}) + \Gamma_{ann} N_{\bar{d}} = q_{\bar{d}}$$

- **Propagation term**: Common to all the antiparticles

The path of antinuclei to Earth

To understand the measurement of antinuclei in balloon and satellite experiments one has to understand their production and transport through the galaxy

$$\nabla \cdot (-K \nabla N_{\bar{d}} + V_c N_{\bar{d}}) + \partial_t (b_{tot} N_{\bar{d}} - K_{EE} \partial_t N_{\bar{d}}) + \Gamma_{ann} N_{\bar{d}} = q_{\bar{d}}$$

- **Propagation term**: Common to all the antiparticles
- **Source term**: it can be constrained using the production measurements of ALICE

The path of antinuclei to Earth

To understand the measurement of antinuclei in balloon and satellite experiments one has to understand their production and transport through the galaxy

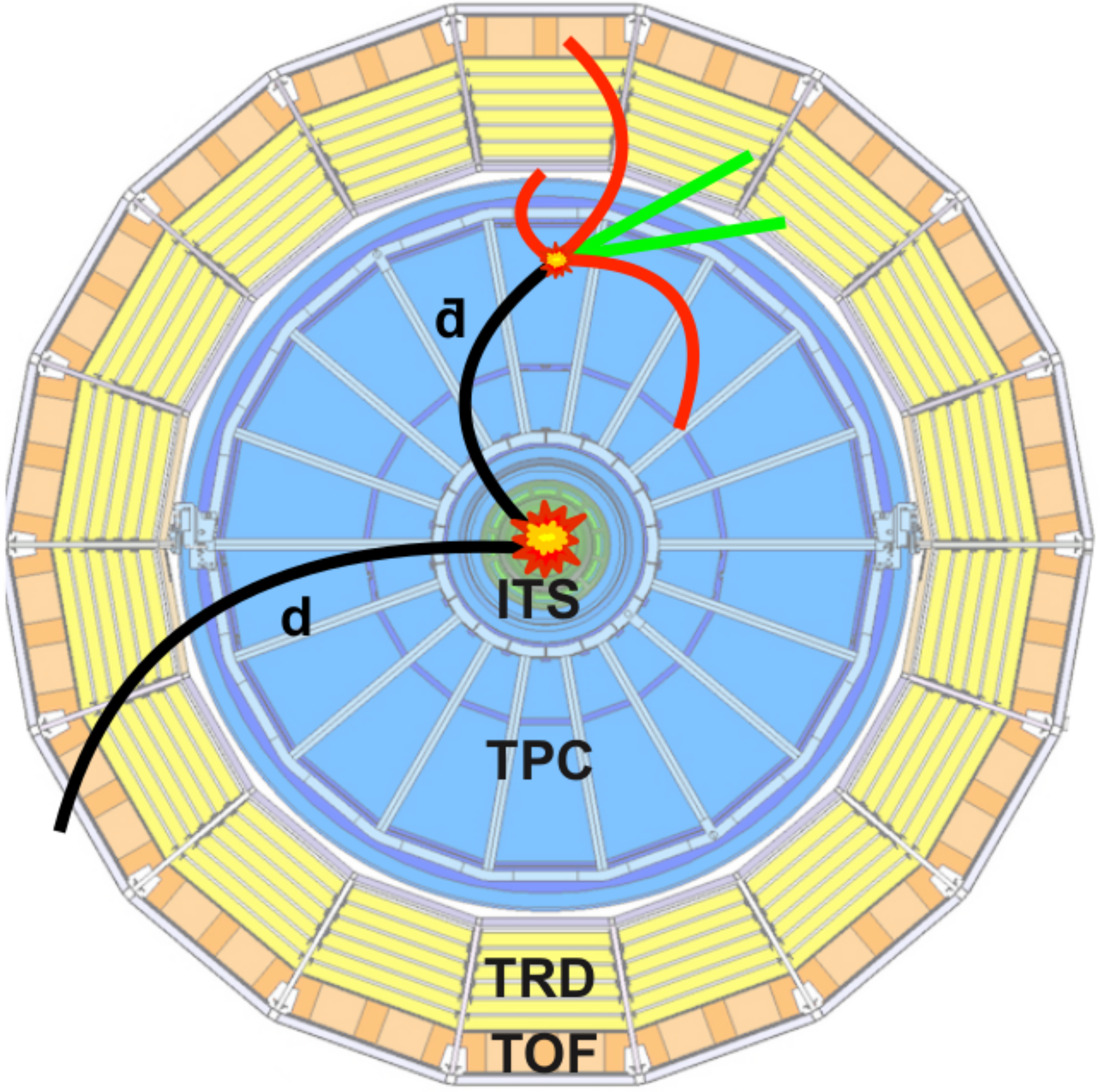
$$\nabla \cdot (-K \nabla N_{\bar{d}} + V_c N_{\bar{d}}) + \partial_t (b_{tot} N_{\bar{d}} - K_{EE} \partial_t N_{\bar{d}}) + \Gamma_{ann} N_{\bar{d}} = q_{\bar{d}}$$

- **Propagation term**: Common to all the antiparticles
- **Source term**: it can be constrained using the production measurements of ALICE
- **Annihilation term**: Known for antiprotons, mostly unknown for other antinuclei

The LHC, being an antimatter factory, is the perfect place to constrain this term!

The ALICE apparatus as annihilation target

- LHC produces equal amount of matter and antimatter at mid-rapidity
- Nuclei and antinuclei interact in a different way with the detector material
  - Larger inelastic component for antinuclei
    - ➡We detect fewer antinuclei than nuclei

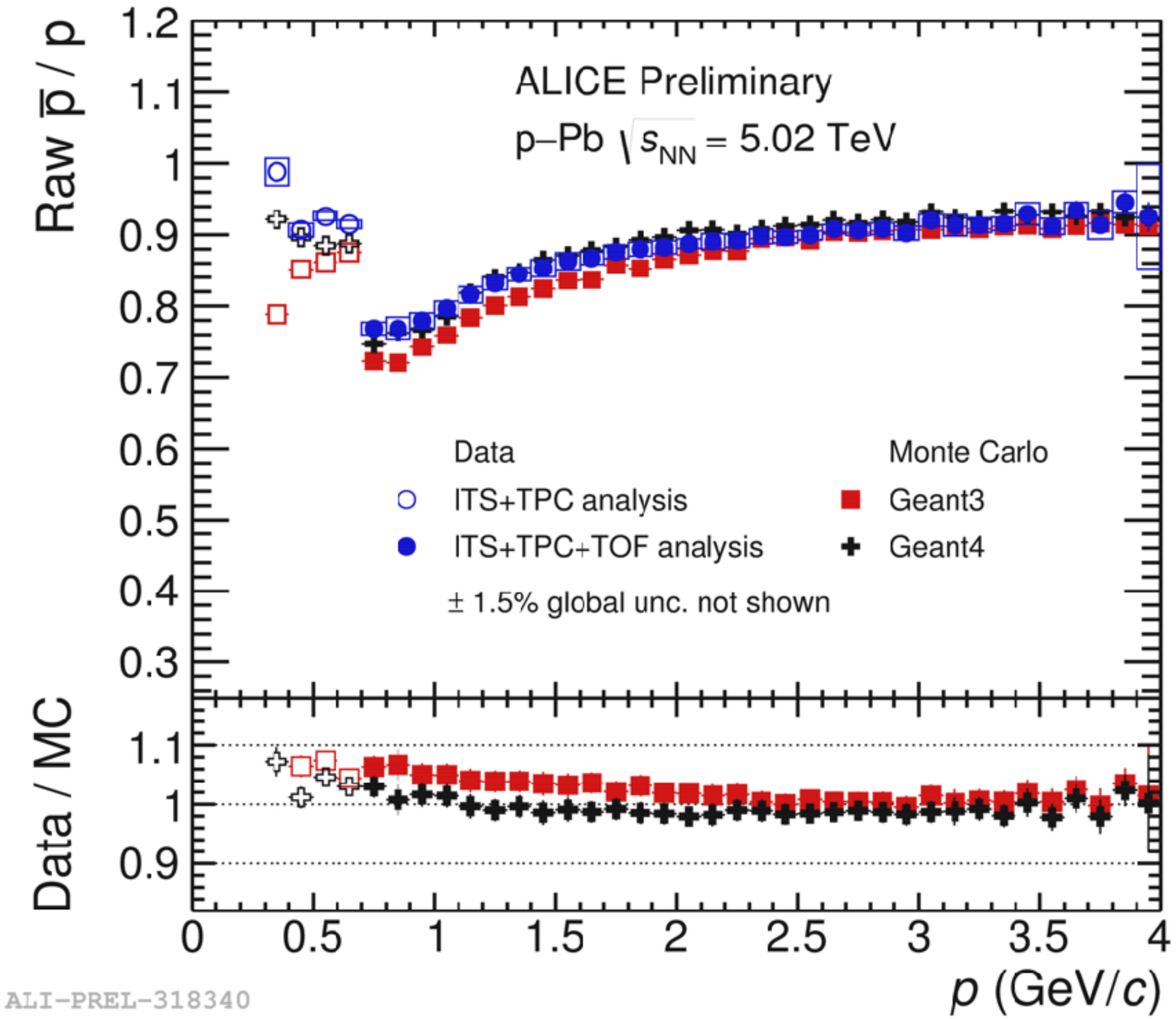


- Material budget at mid-rapidity:
  - Beam pipe (~0.3% X_0)
  - ITS (~8% X_0) and TPC (~4% X_0)
  - TRD (~25% X_0)
  - Space frame (~20% X_0 between TPC and TOF)

The antiproton case

- LHC produces equal amount of matter and antimatter at mid-rapidity
- Nuclei and antinuclei interact in a different way with the detector material
  - Larger inelastic component for antinuclei
    - ➡We detect less antinuclei than nuclei

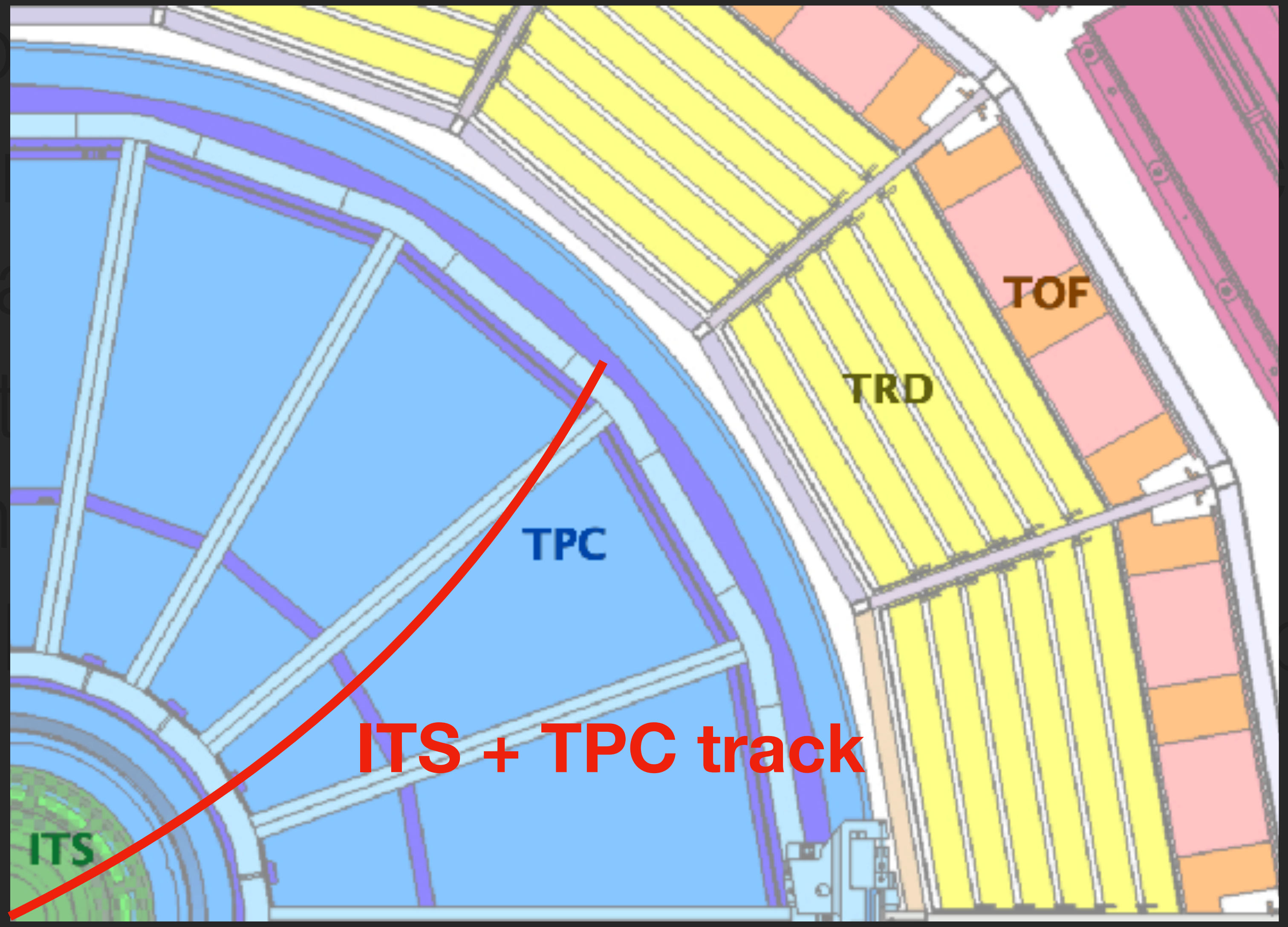
- This is evident in the raw ratio of detected antiprotons/protons
  - For antiprotons the annihilation cross section is well known
  - GEANT4 describes well the ratio

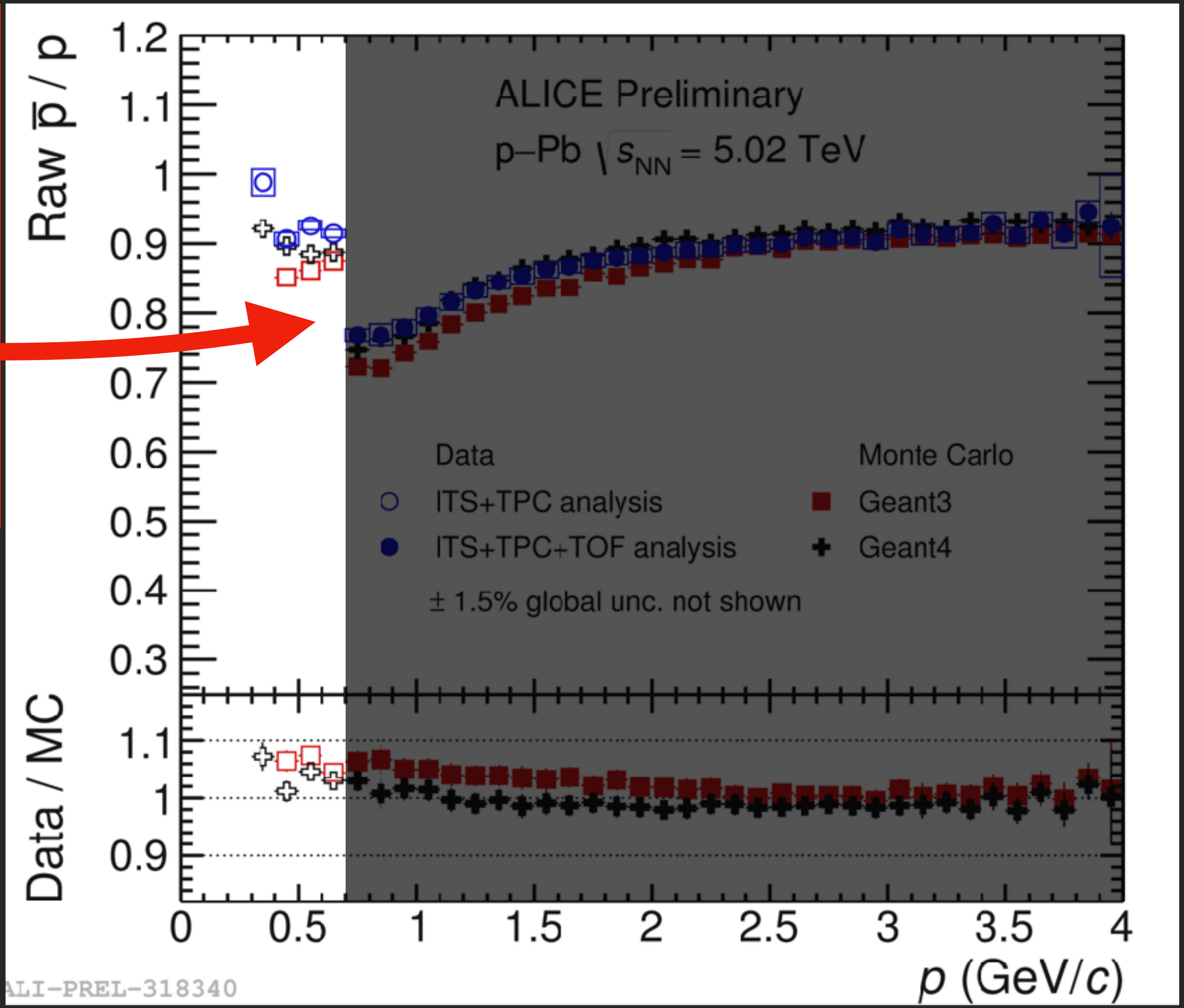


The antiproton case

The gap at 0.7 GeV/c marks the change of identification strategy (from TPC only to TOF)

- This change of strategy corresponds also to a change of amount of material crossed by the particles
- Well reproduced by GEANT4 for antiprotons!

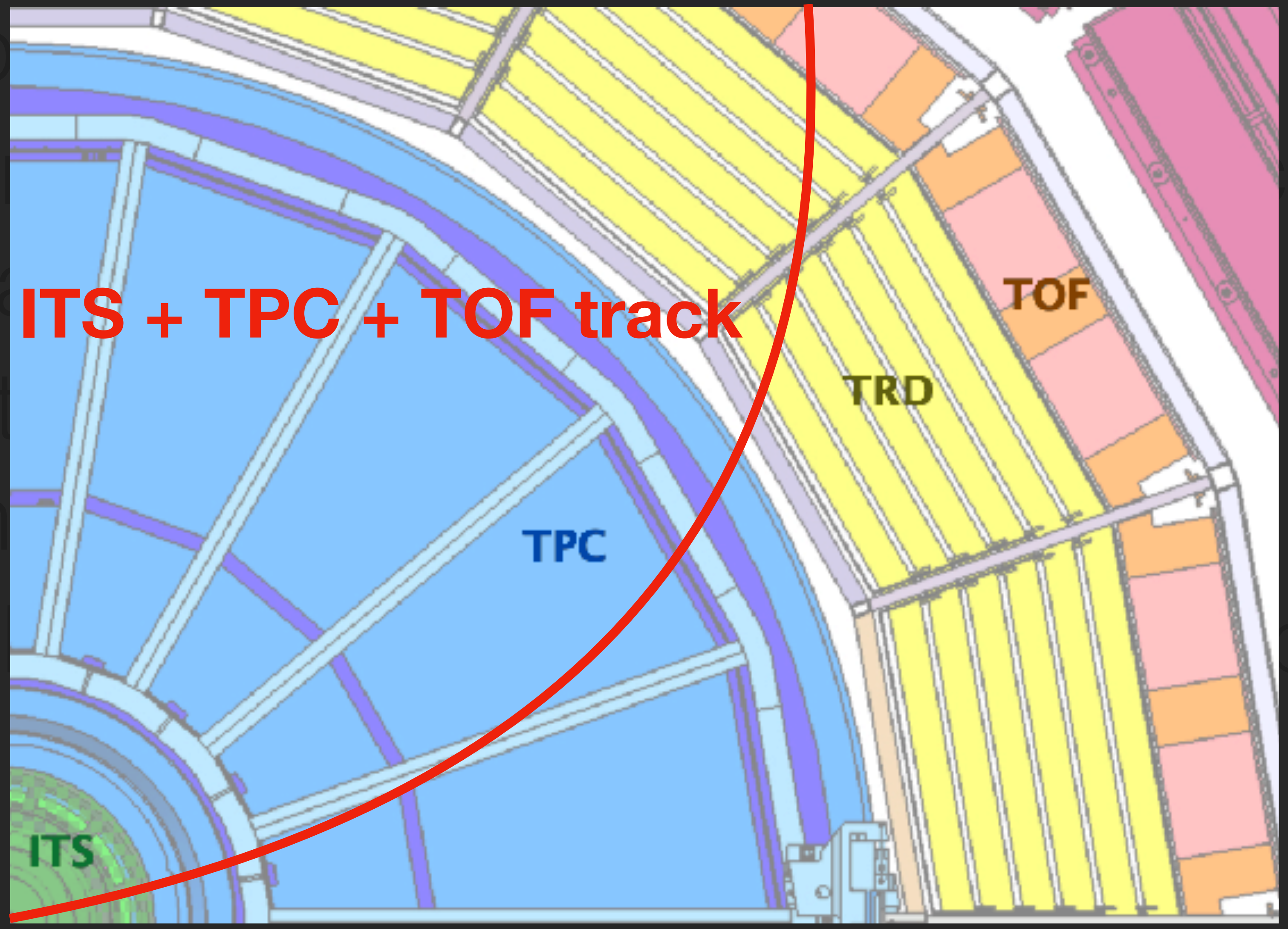


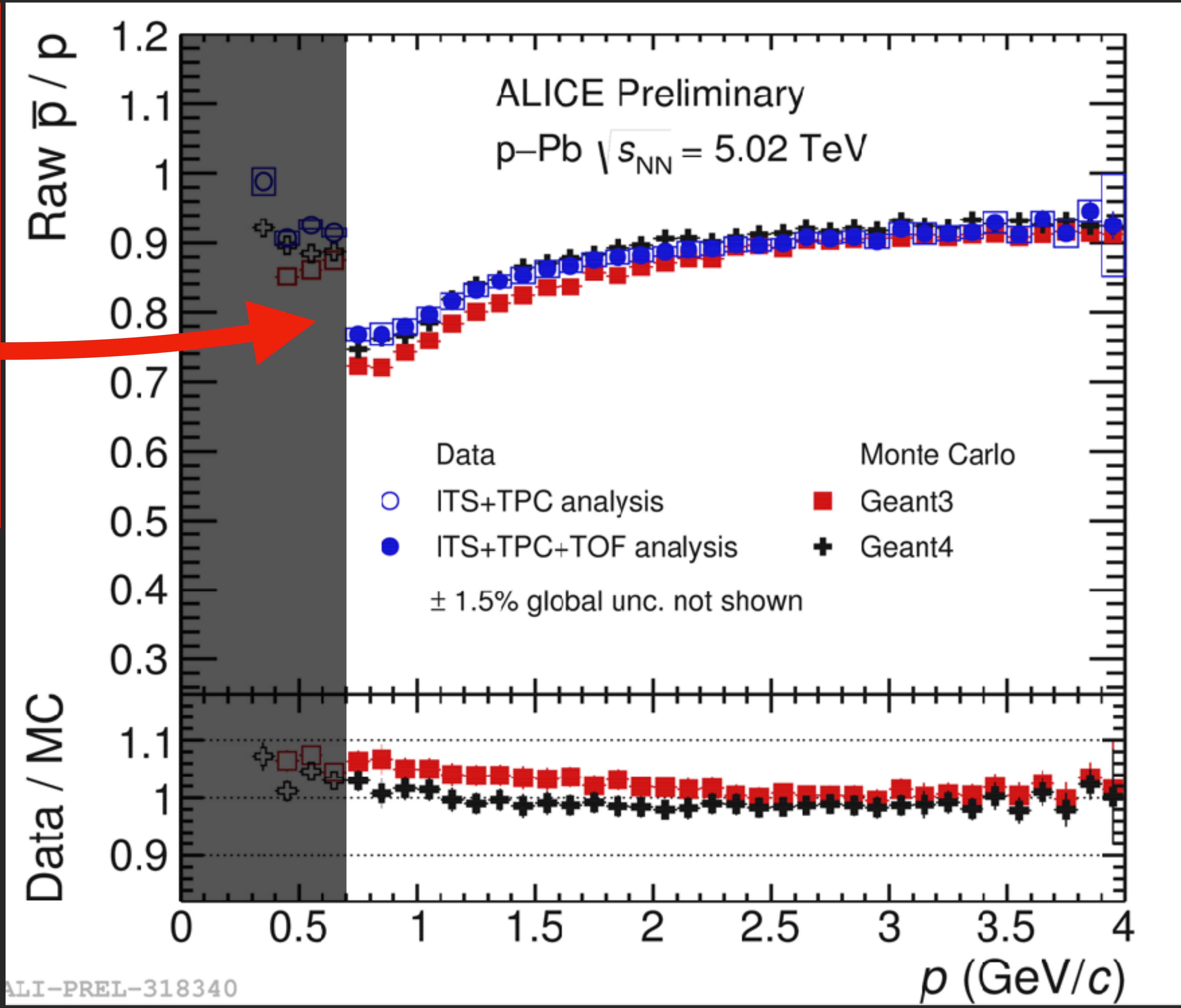


The antiproton case

The gap at 0.7 GeV/c marks the change of identification strategy (from TPC only to TOF)

- This change of strategy corresponds also to a change of amount of material crossed by the particles
- Well reproduced by GEANT4 for antiprotons!

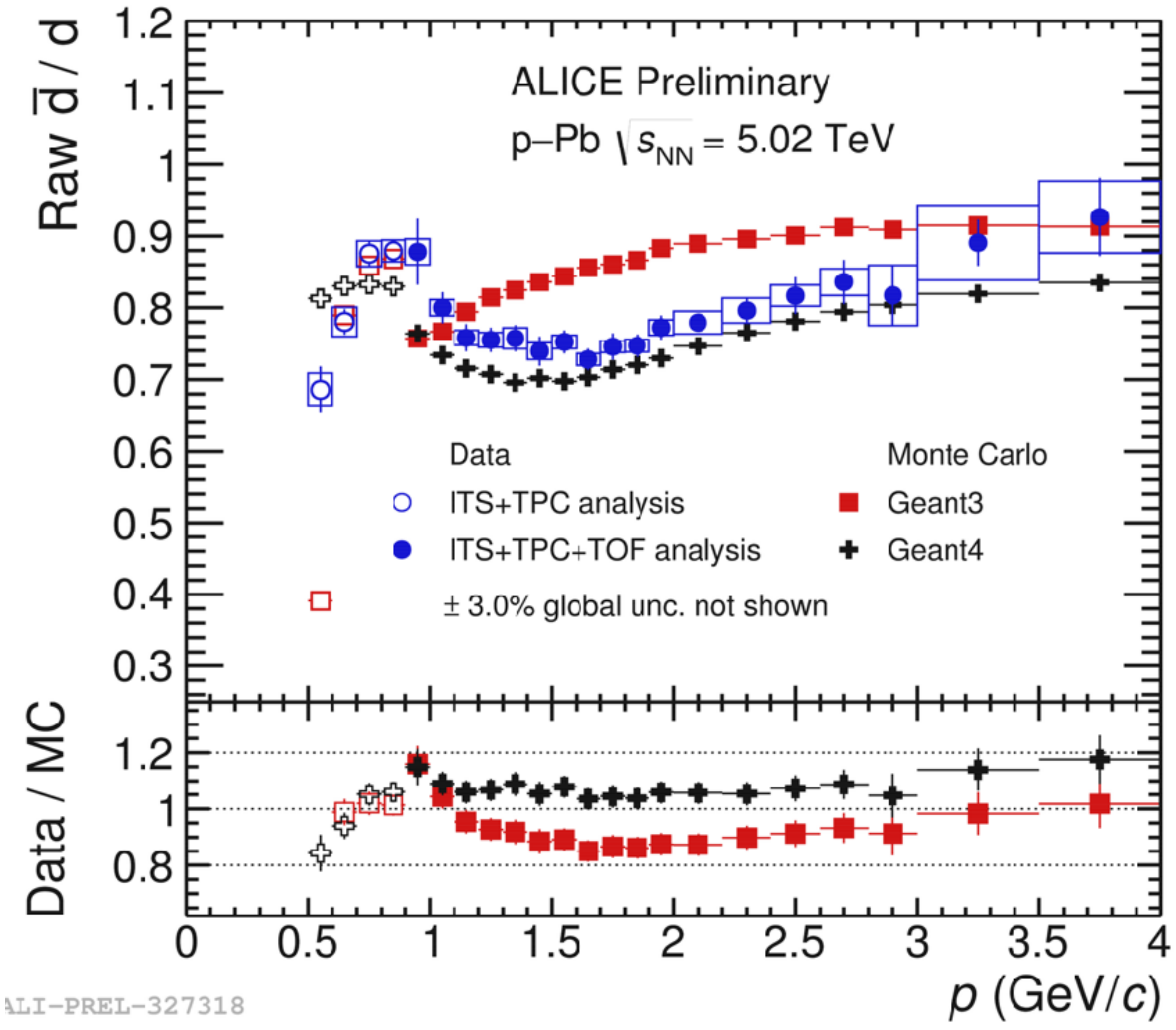




The antideuteron case

- LHC produces equal amount of matter and antimatter at mid rapidity
- Nuclei and antinuclei interact in a different way with the detector material
  - Larger inelastic component for antinuclei
    - ➡We detect less antinuclei than nuclei

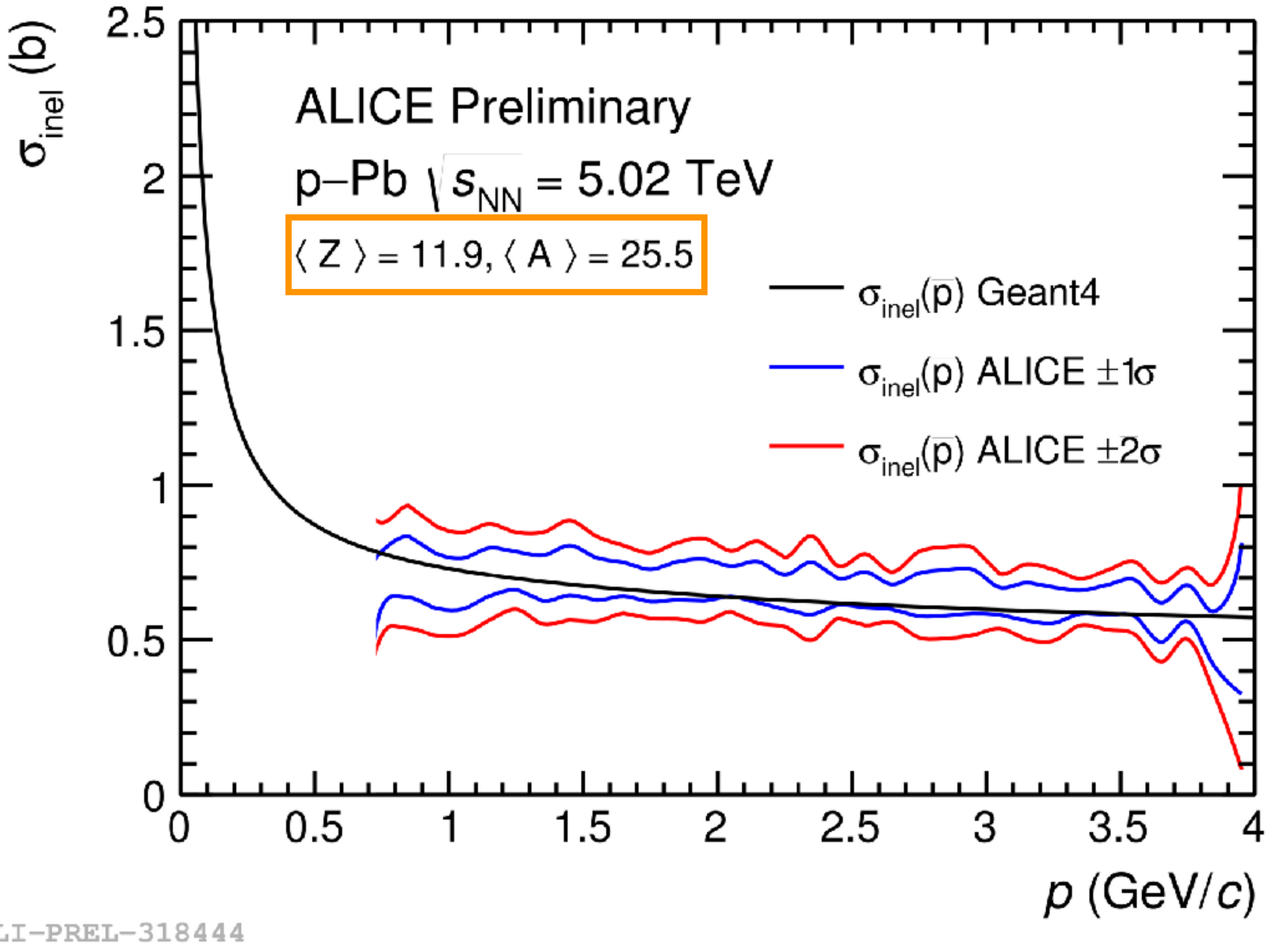
- Same measurement performed for $\bar{d}$ / d
- The antideuteron inelastic cross section was measured only at momentum >10 GeV/*c*
  - Transport models only can extrapolate the measurement at low momentum
  - Discrepancy between data and MC can be used to measure the inelastic cross section of antideuterons with the ALICE material



Antiproton inelastic cross section

By varying the cross section in the GEANT4 implementation it is possible to determine the cross section that best fits our data

- $\sigma_{inel}(\bar{p})$ has been estimated for an "averaged element" of ALICE detector material
- Good agreement with Geant4 parameterisations as expected
- Several measurements available for $\sigma_{inel}(\bar{p})$ on different materials, good description with Geant4 parameterisations

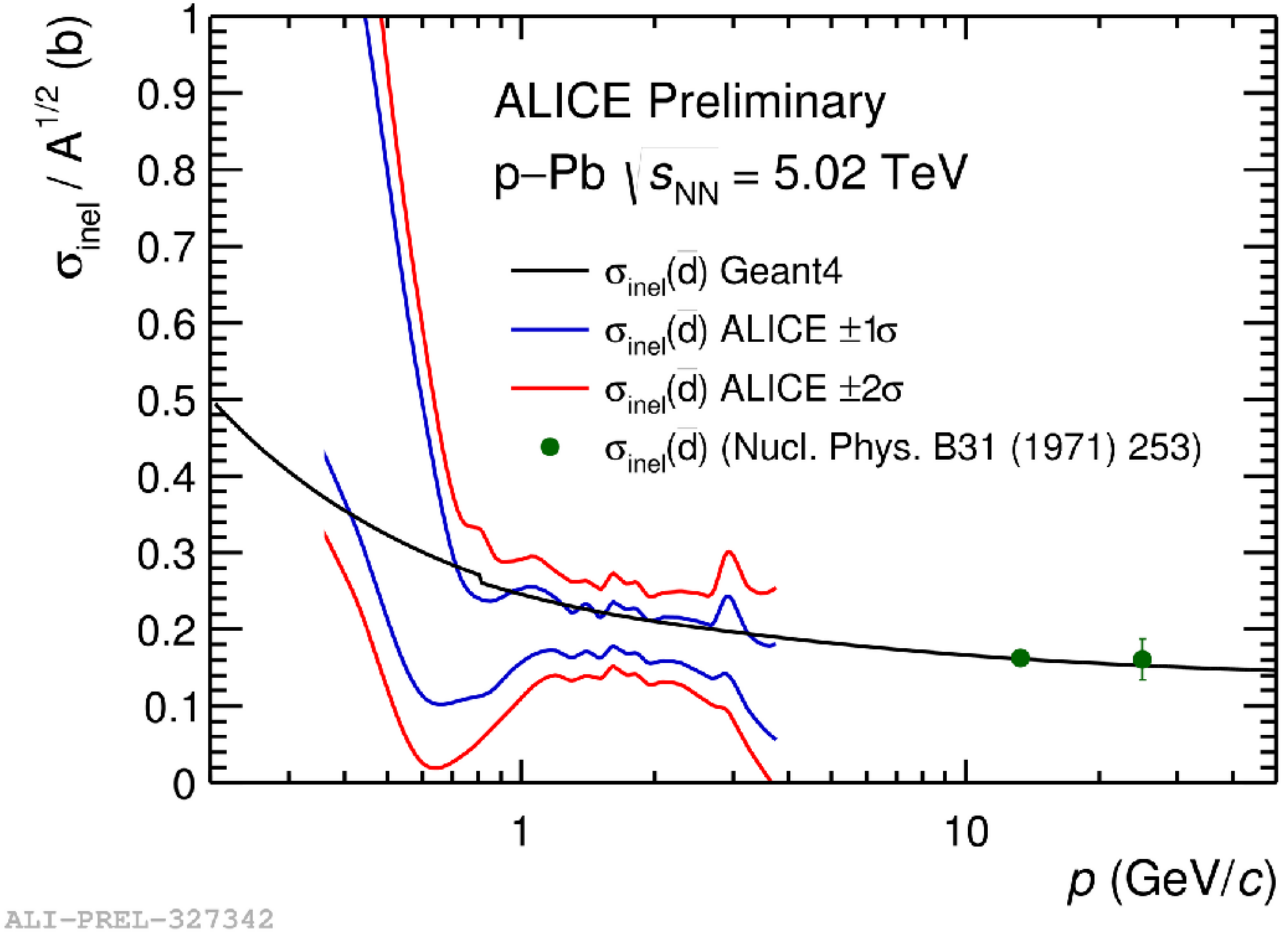


This validates the method and allows us to use it for other antinuclei

Antideuteron inelastic cross section

First measurement of the antideuteron inelastic cross section at low momentum

- Previous measurements only available at momenta larger than 10 GeV/*c*
  - *And performed almost 50 years ago*
- *Hint* of deviation from the GEANT4 Glauber parameterisation at low transverse momenta



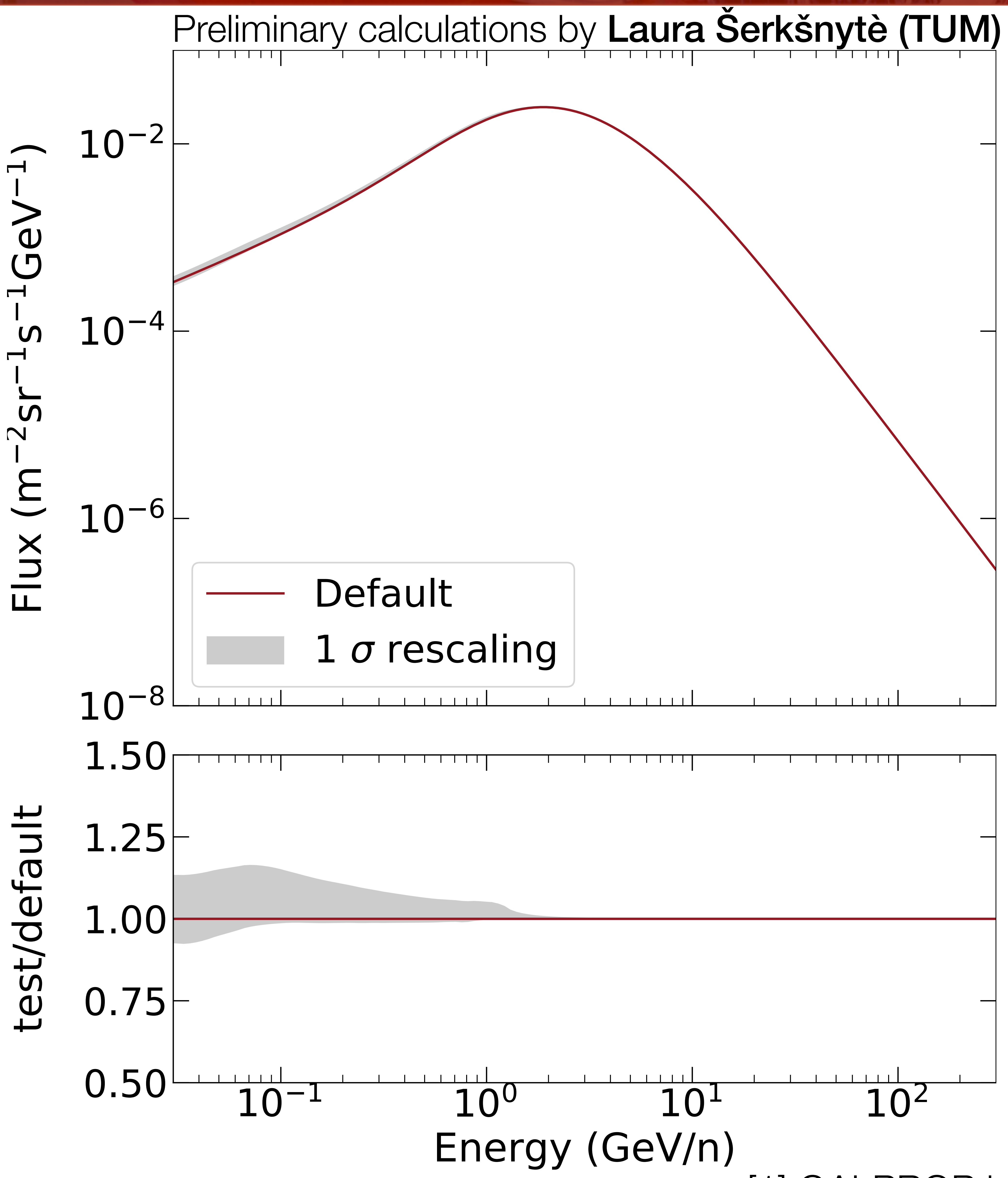
The effect on the expected fluxes of cosmic antinuclei

Exercise:

- Take a standard code for cosmic-ray transport [1]
- Modify the inelastic cross section of one of the hadrons currently implemented in the code (antiproton) by the difference between ALICE measurement for antideuteron inelastic cross section and GEANT4
- Check the impact on the expected flux before solar modulations

[1] GALPROP https://galprop.stanford.edu/

The effect on the expected fluxes of cosmic antinuclei



Exercise:

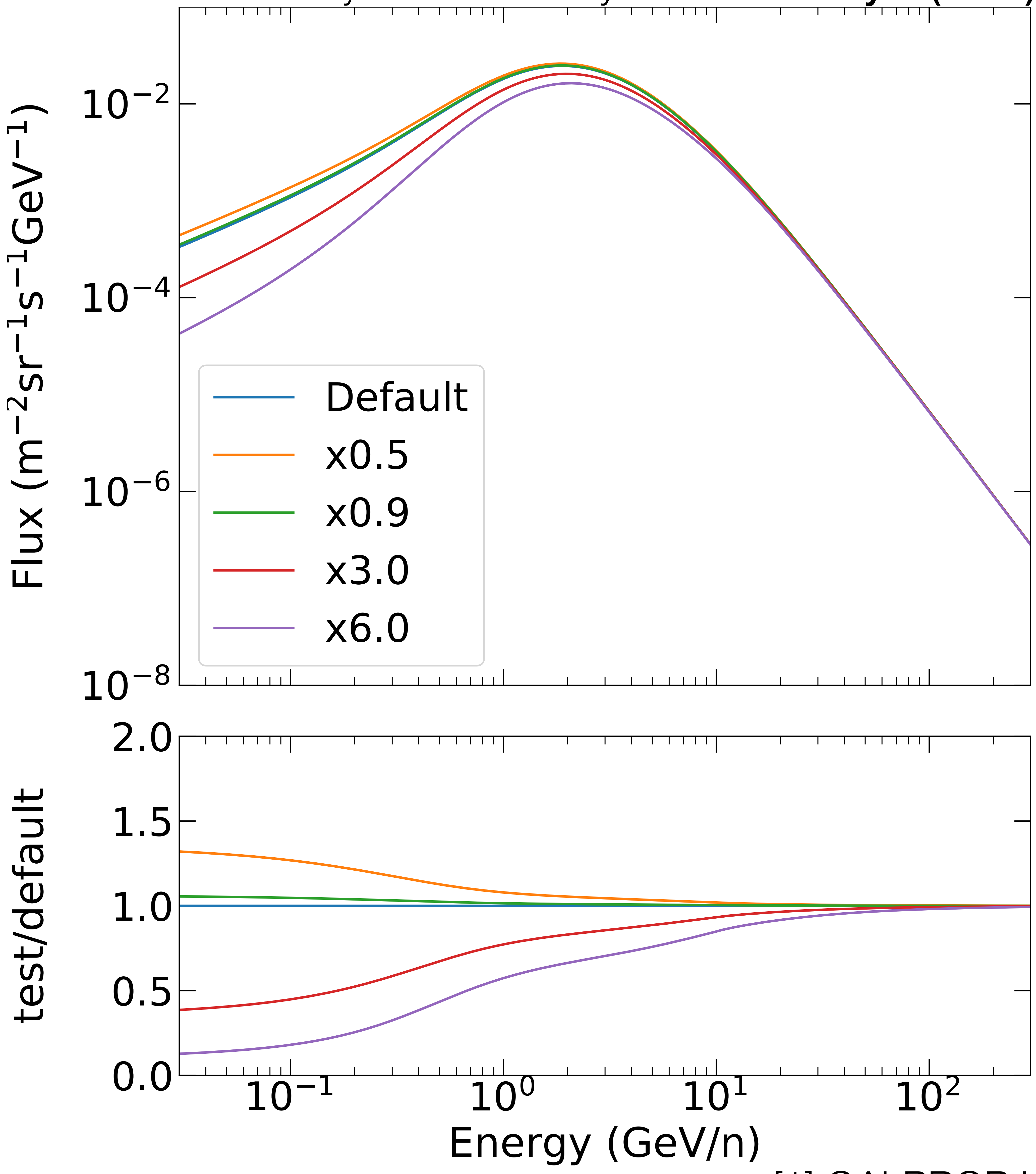
- Take a standard code for cosmic-ray transport [1]
- Modify the inelastic cross section of one of the hadrons currently implemented in the code (antiproton) by the difference between ALICE measurement for antideuteron inelastic cross section and GEANT4
- Check the impact on the expected flux before solar modulations

Result: Sizeable increase of the expected flux at low energy when scaling for the measured antideuteron modification of inelastic cross section

[1] GALPROP https://galprop.stanford.edu/

The effect on the expected fluxes of cosmic antinuclei

Preliminary calculations by **Laura Šerkšnytė (TUM)**



Exercise:

- Take a standard code for cosmic-ray transport [1]
- Modify the inelastic cross section of one of the hadrons currently implemented in the code (antiproton) by the difference between ALICE measurement for antideuteron inelastic cross section and GEANT4
- Check the impact on the expected flux before solar modulations

Result: Sizeable increase of the expected flux at low energy when scaling for the measured antideuteron modification of inelastic cross section

Outlook: For heavier antinuclei, like anti^{3}He, the difference to GEANT4 might even be larger and so would be the impact on the expected fluxes

[1] GALPROP https://galprop.stanford.edu/

Summary

Great progress of the field of (anti)nuclei in HEP in the recent years

- ALICE put tighter and tighter constraints on the models (arXiv:2003.03184)
  - Deuteron production in pp collision is reasonably well described by coalescence models

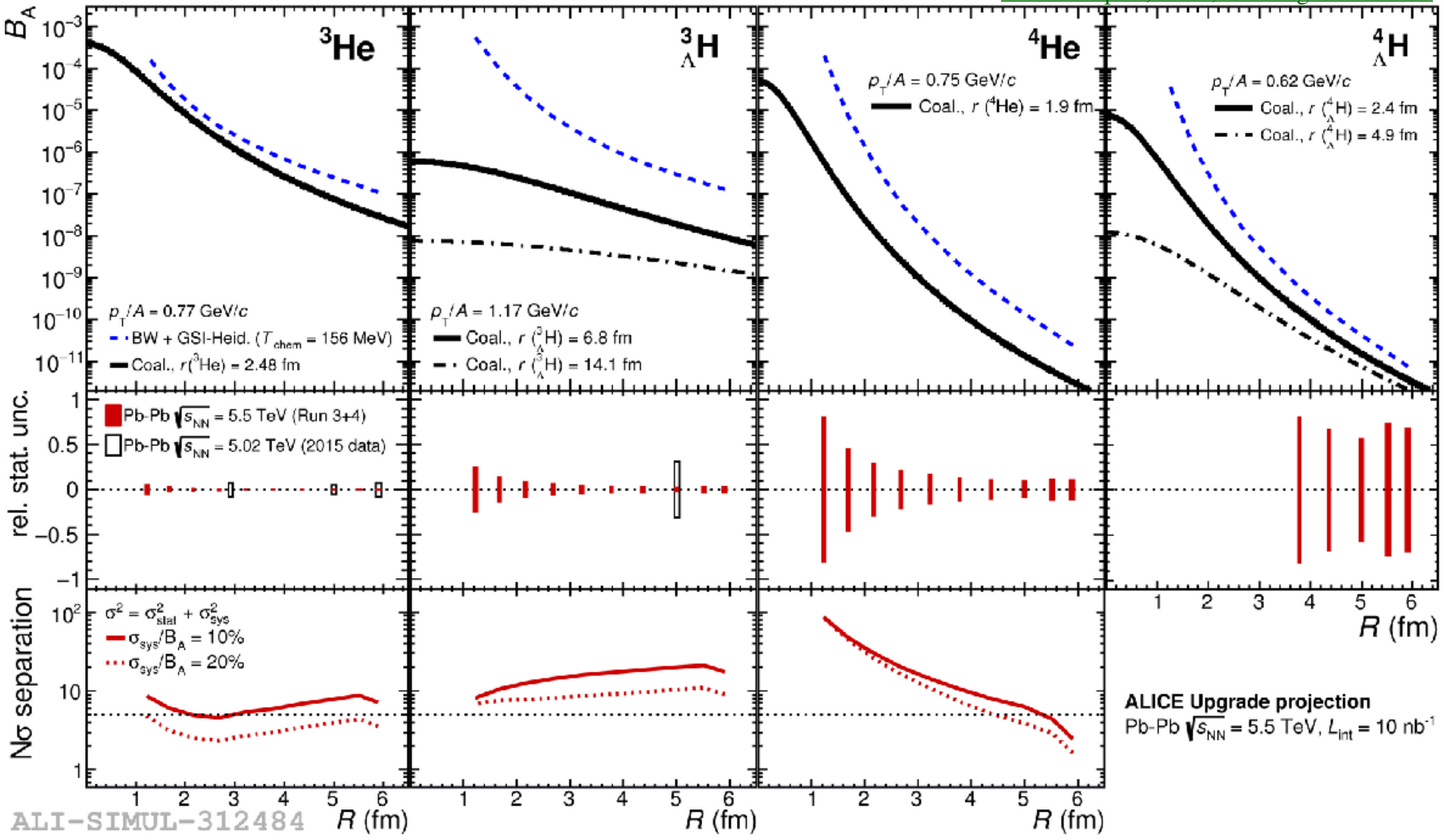
A>=3 nuclei are now the battleground for experiments/models

- ^{3}He/p as a function of multiplicity shows interesting deviations from models (arXiv:1910.14401)
- Having more precise measurement of ^{3}H and hypernuclei will give us valuable information about the A=3 nuclei production

Not only measurement of the production cross section!

- ALICE has provided the first measurement of antideuteron inelastic cross section with material
- Work ongoing to extend to this kind of measurement to other antinuclei

Yellow Report, WG5, arxiv.org:1812.06772

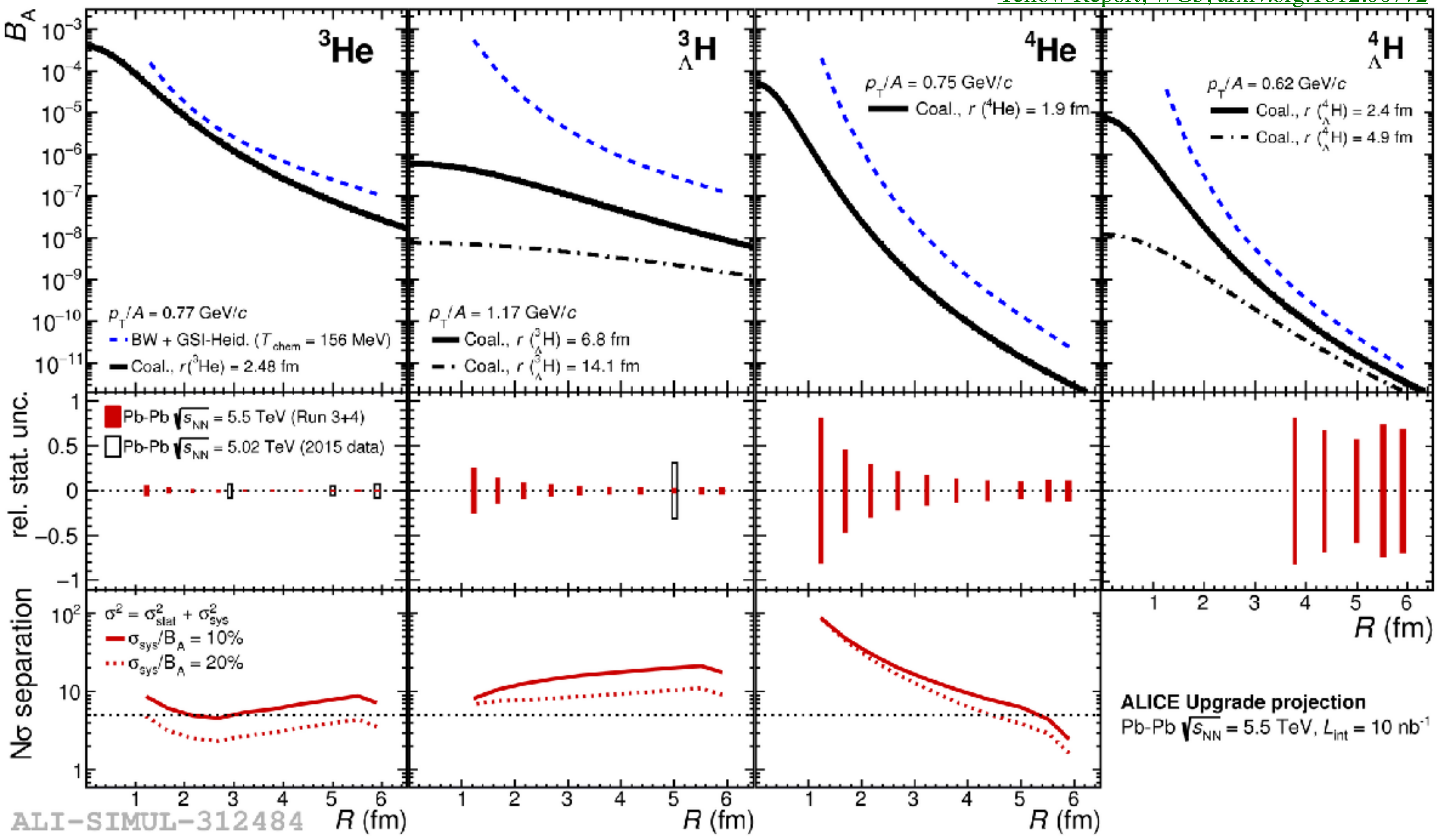


Projections for Pb-Pb collisions but similar results can be achieved in small systems

- Run 3 and Run 4 will allow us to measure in details the production of even 4He and hyper nuclei
  - Decisive test for probing the interplay between system size and (hyper)(anti)nucleus wave function

Outlook

Yellow Report, WG5, arxiv.org:1812.06772



Projections for Pb-Pb collisions but similar results can be achieved in small systems

- Run 3 and Run 4 will allow us to measure in details the production of even 4He and hyper nuclei
  - Decisive test for probing the interplay between system size and (hyper)(anti)nucleus wave function

But... Run 2 harvest is still not finished: new results are coming up for summer conferences

If you want to know more:

Origin of nuclear clusters in hadronic collisions

19-20 May 2020
CERN
Europe/Zurich timezone

Search...

- Overview
- Organizing committee
- Registration
- Participant List

The goal of this mini-workshop is to solve the question of the origin of loosely-bound nuclei formed in hadronic collisions. This is a well defined question, the solution of which could shed light on the puzzling feature of seemingly thermal statistics in the yields of different hadrons at the LHC and other experiments. The main discussion is theoretical, but there will be strong interplay with experimentalists working on relevant analyses.

The format consists of invited talks, geared towards an audience of experts in the field, as well as working group discussions structured around a number of currently on-going analyses.

VIDYO connection will be available.

Registration is open at https://indico.cern.ch/event/893621/