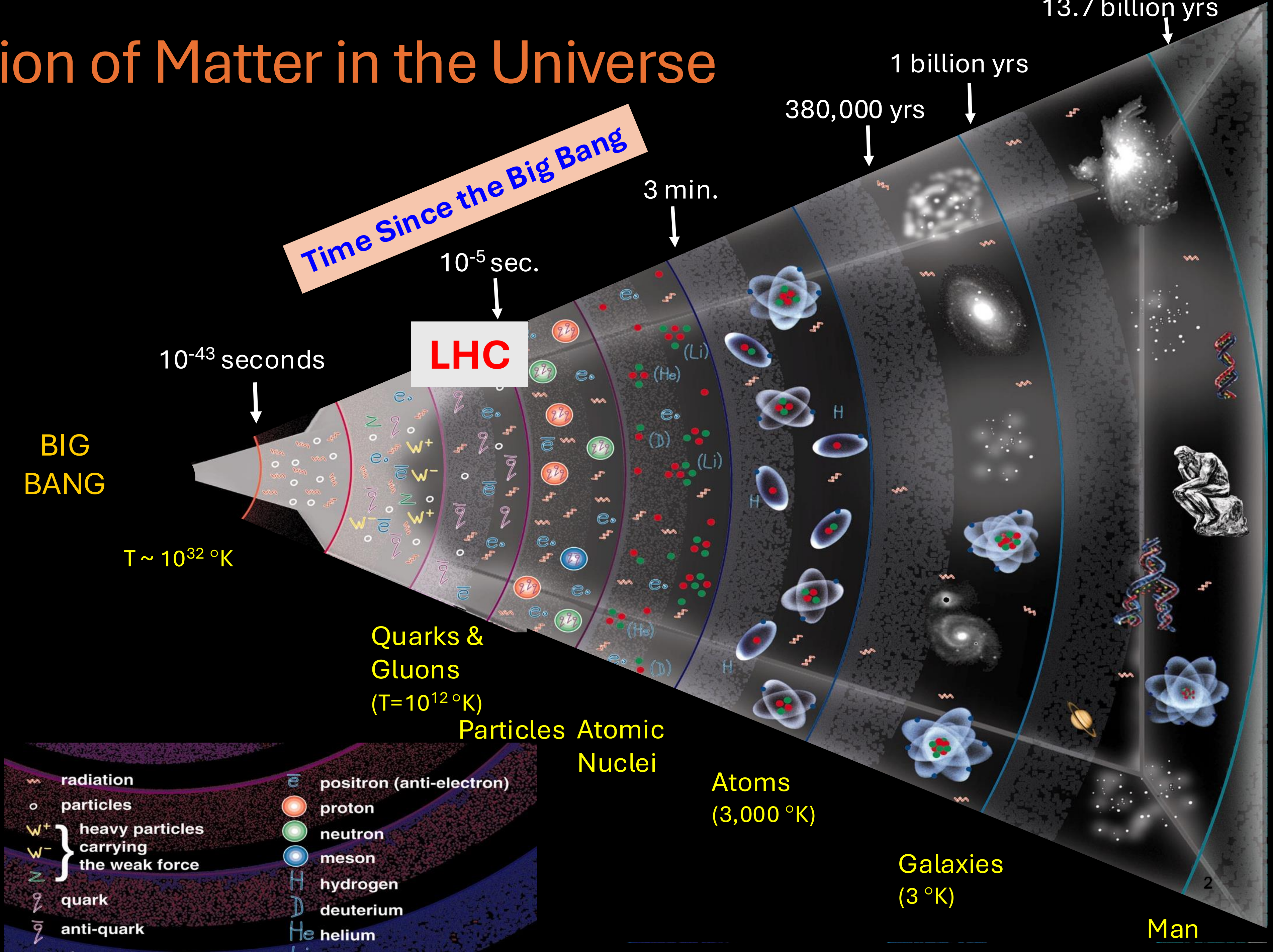
Understanding the interaction between hadrons: latest news from ALICE

$^{4}_{\bar{\Lambda}}\overline{\mathrm{He}}$

Stefania Bufalino
Politecnico and INFN, Torino (Italy)

*ALICE, Phys.Rev.Lett.*134(2025)16,162301

Evolution of Matter in the Universe



Time Since the Big Bang

BIG
BANG

T ~ 10^{32} °K

10^{-43} seconds

LHC

10^{-5} sec.

3 min.

380,000 yrs

1 billion yrs

13.7 billion yrs

Quarks &
Gluons
(T=10^{12} °K)

Particles

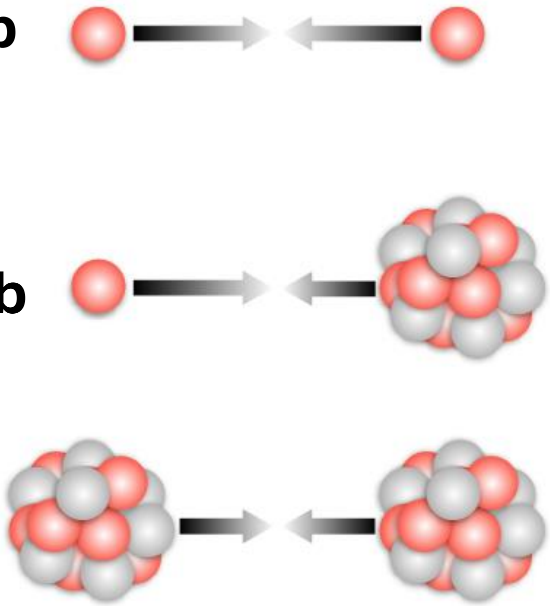
Atomic
Nuclei

Atoms
(3,000 °K)

Galaxies
(3 °K)

Man

Evolution of Matter in Laboratory



pp

p-Pb

Pb-Pb

Reference for measurements in other systems

pp

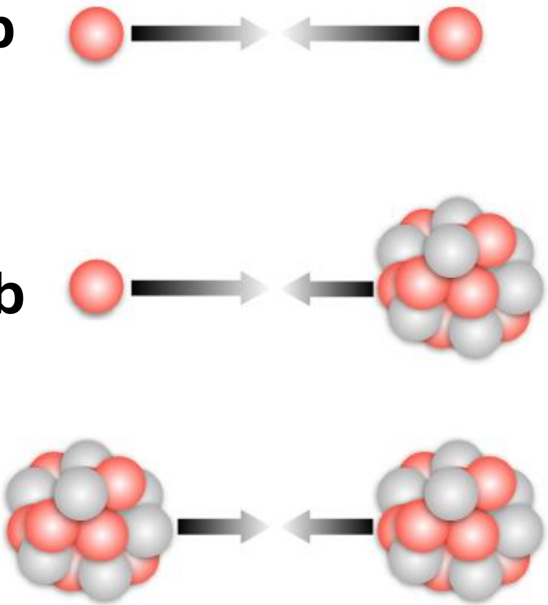
Study of cold nuclear matter effects

p-Pb

Study of QCD matter at high T and energy density

Pb-Pb

Evolution of Matter in Laboratory



pp

p-Pb

Pb-Pb

Run 2

pp, $\sqrt{s_{NN}}$ = 13 TeV

p–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

Run 3

pp, $\sqrt{s_{NN}}$ = 13.6 TeV

(Pb –Pb, $\sqrt{s_{NN}}$ = 5.36 TeV)
→ analyses ongoing!

Reference for measurements in other systems

pp

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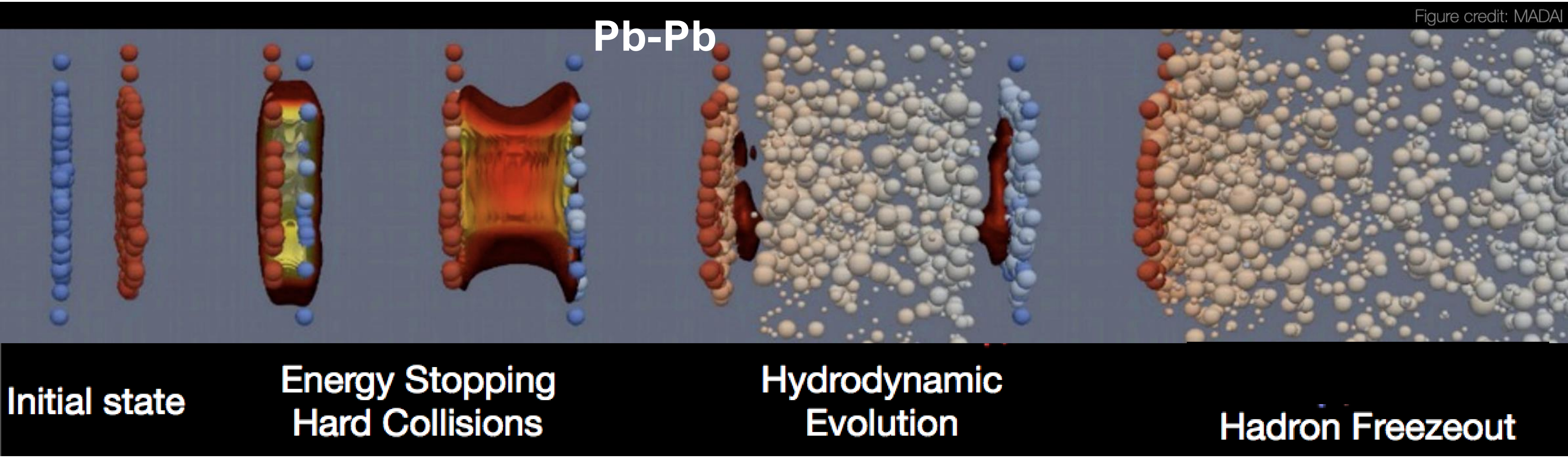


Pb–Pb collisions at LHC energies

- Hot and dense QGP with high T and ~zero μ_B

→ Matter and anti-matter are produced with the same abundance

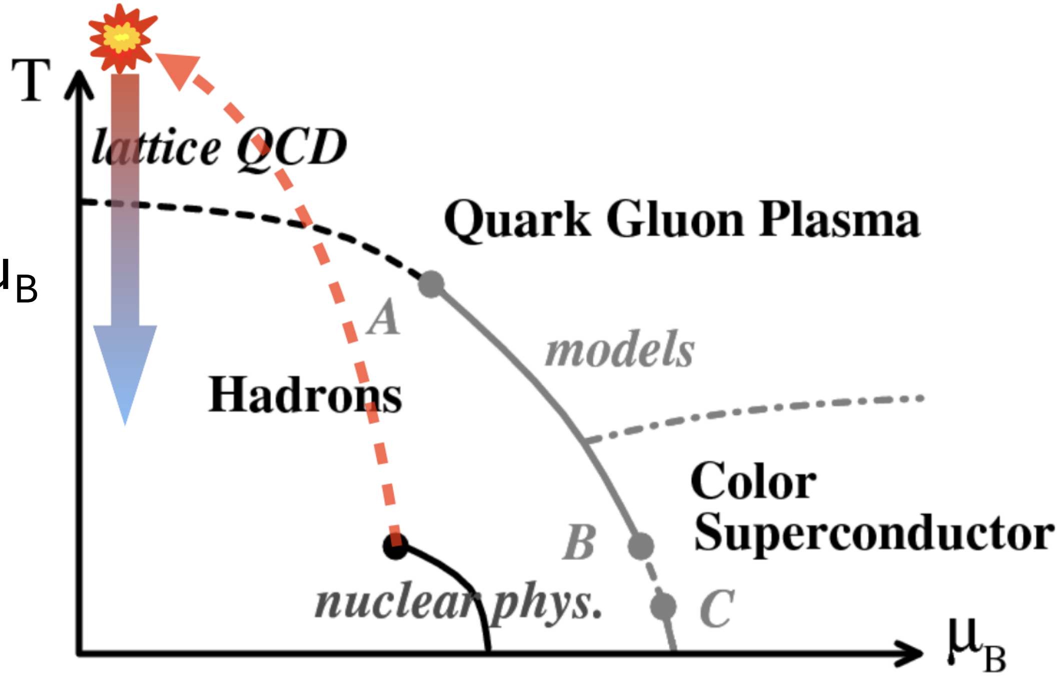
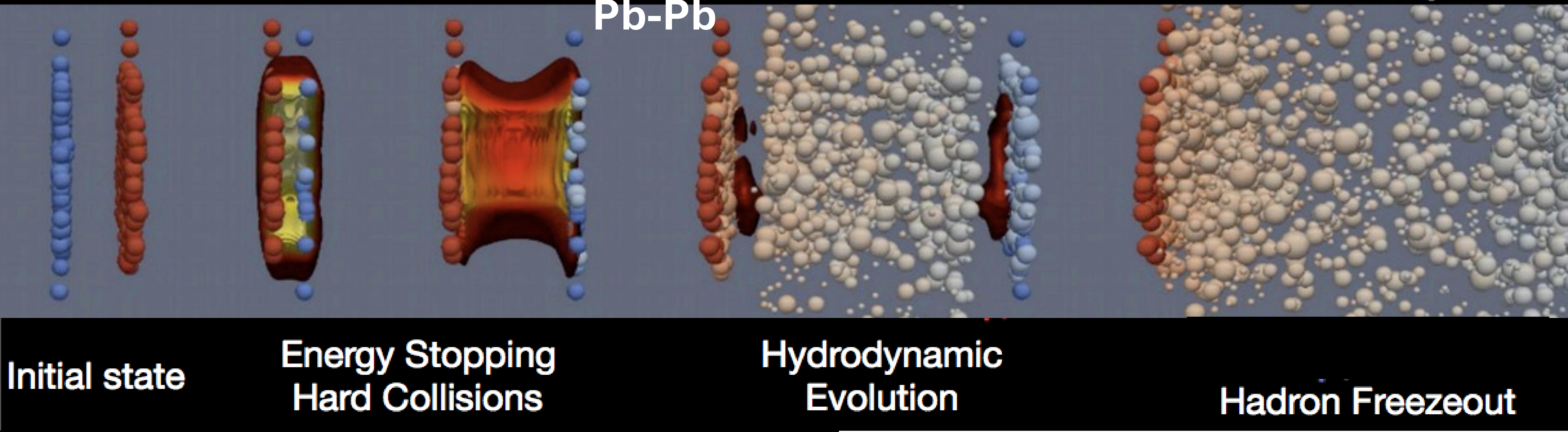
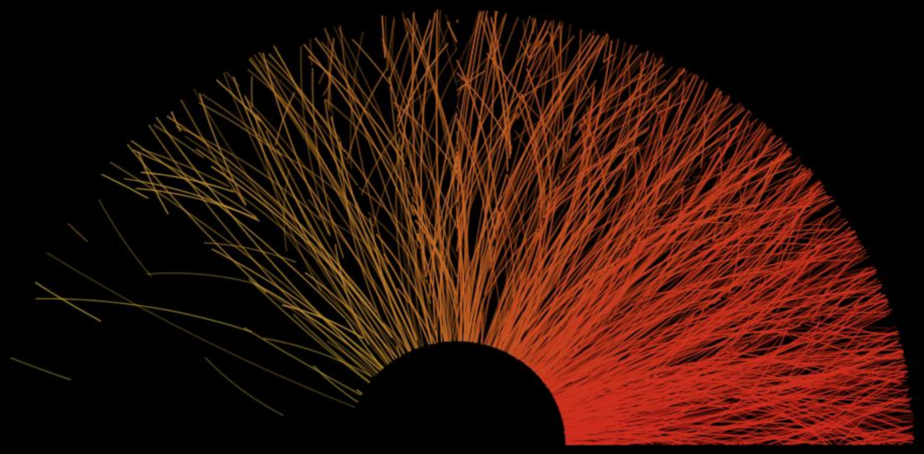


Figure credit: MADAI

Pb-Pb



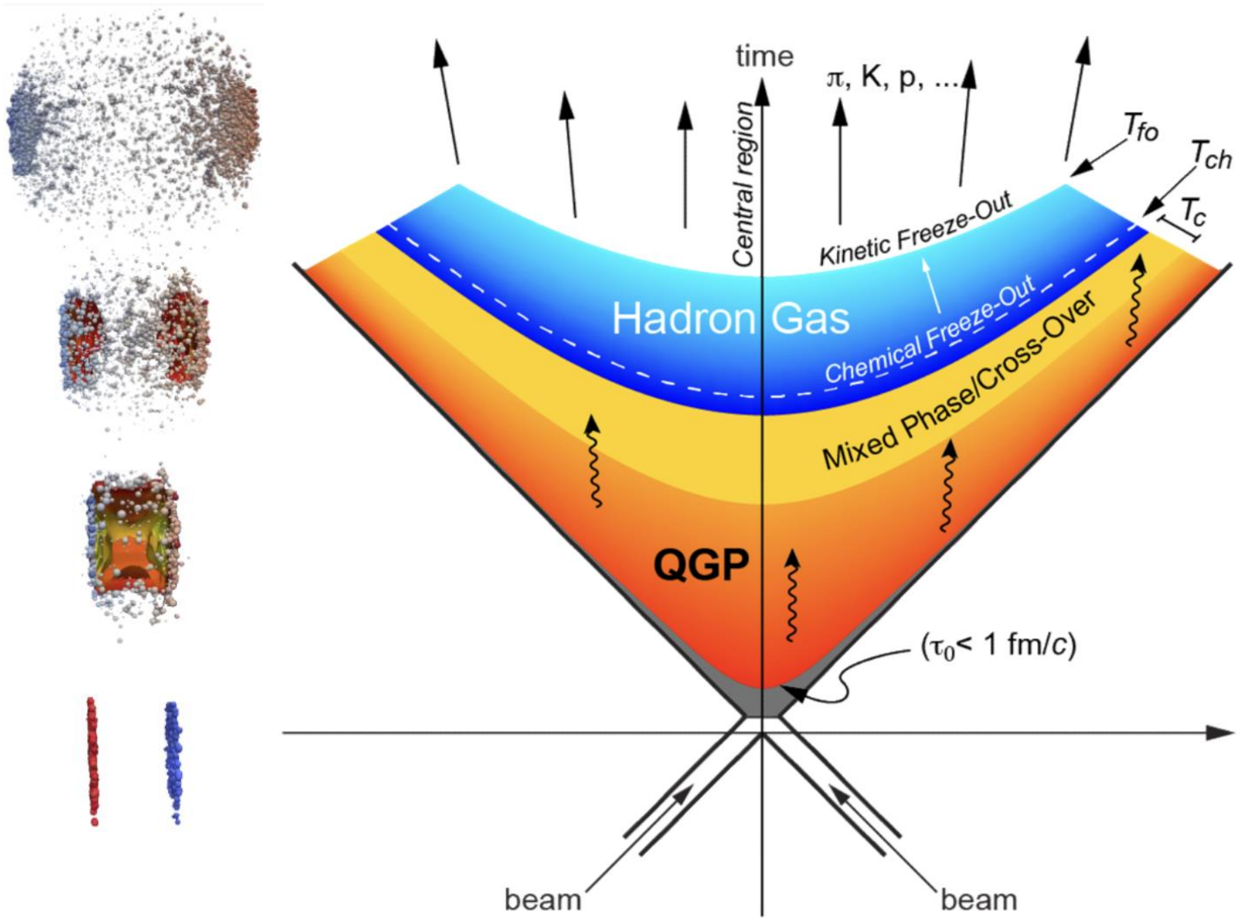


Small systems and hadronisation

pp

Traces of QGP? (events with high multiplicities)

Heavy ion collision: space-time evolution

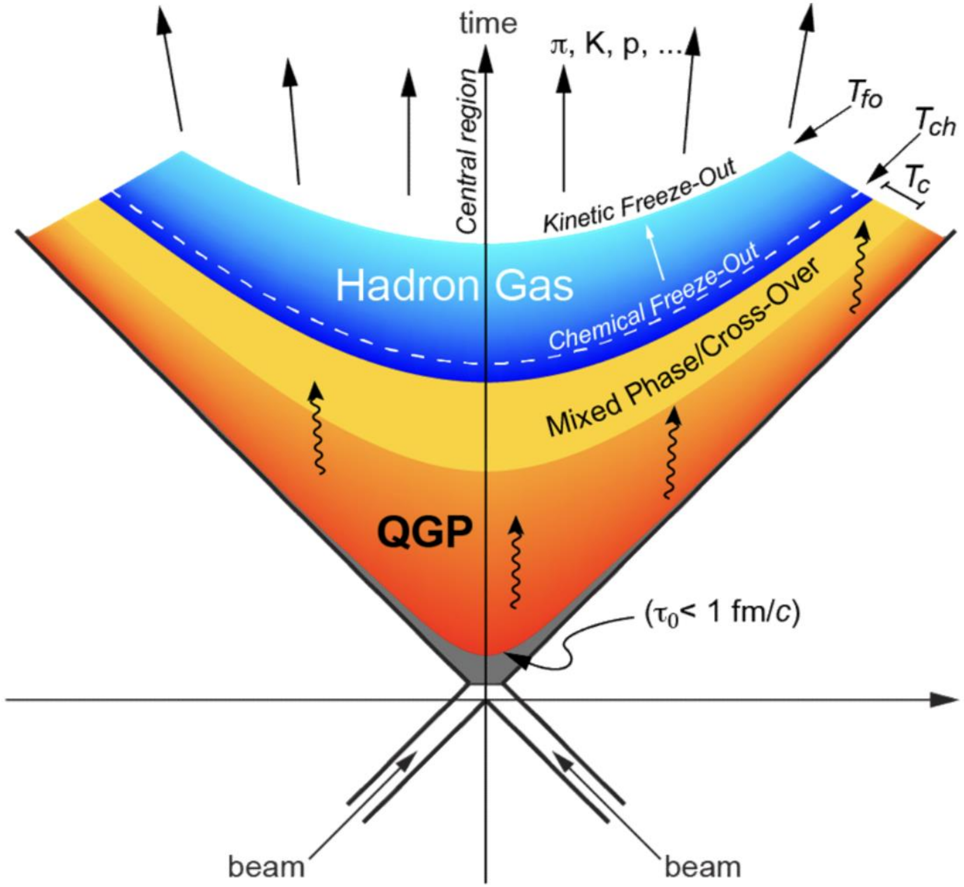


Heavy ion collision: space-time evolution

- Thermalization time

  ⇨System reaches local equilibrium

  $t_{eq} \sim 0.6$ fm/c



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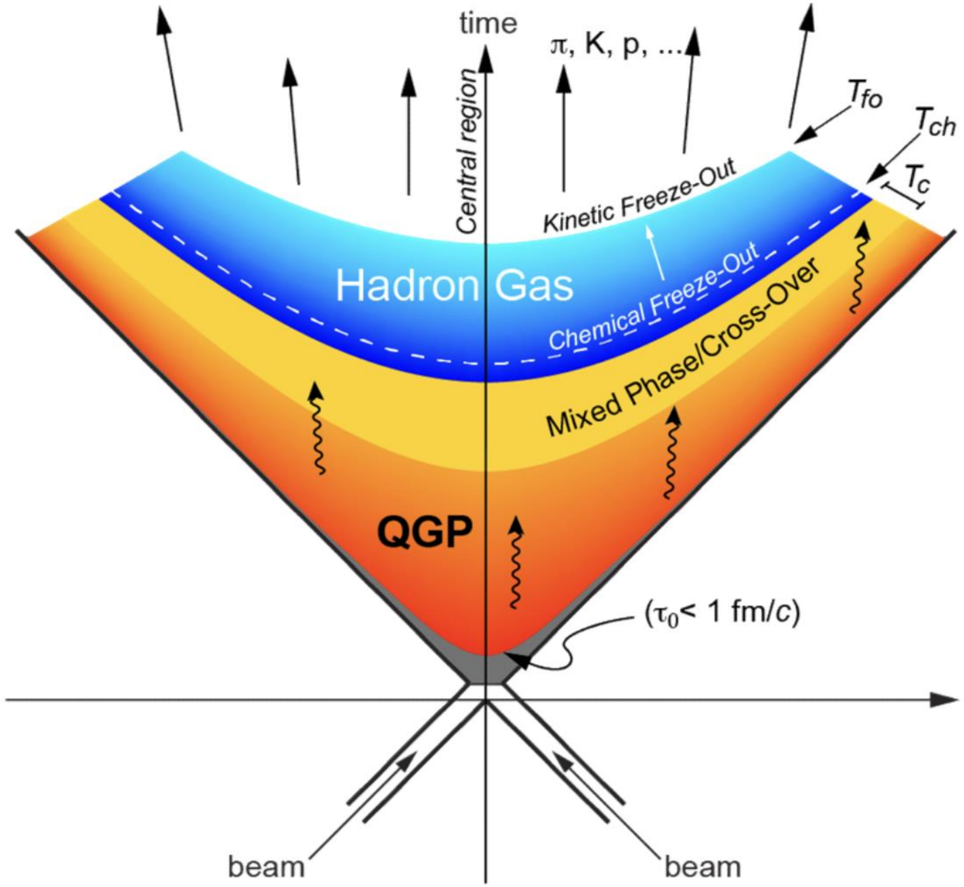
  - ⇨Inelastic interactions cease
  - ⇨Particle abundances (“chemical composition”) are fixed (except maybe resonances)

  $T_{ch} \sim 170$ MeV



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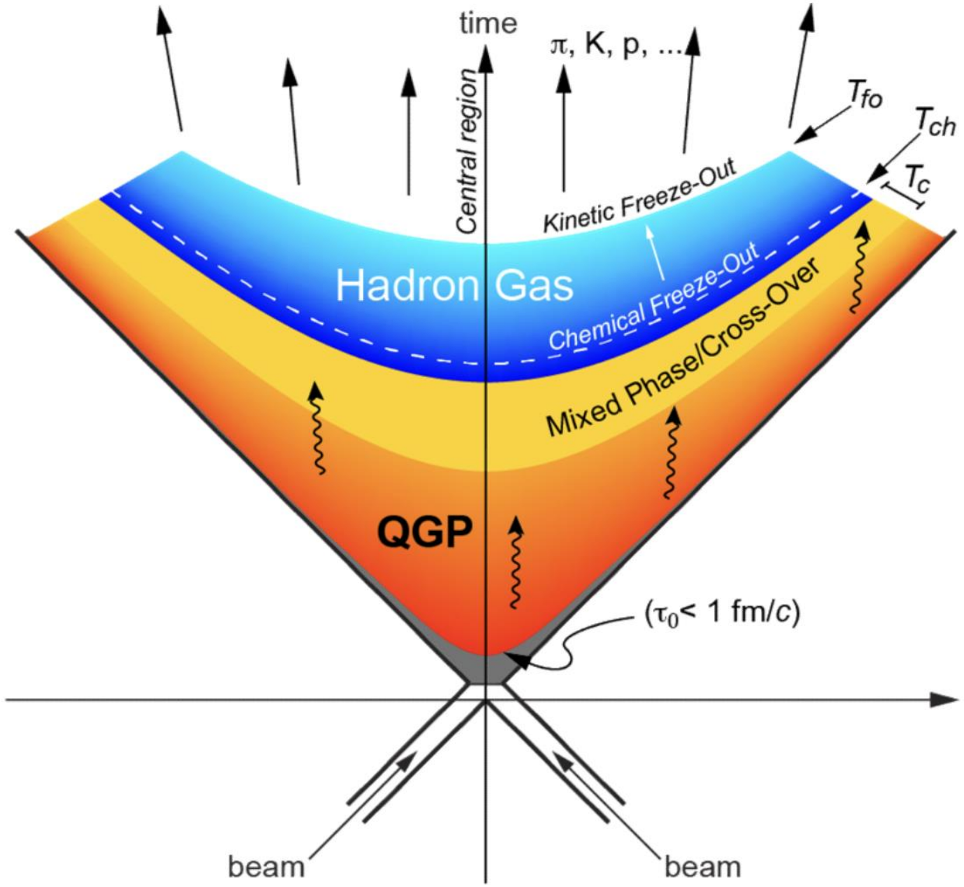
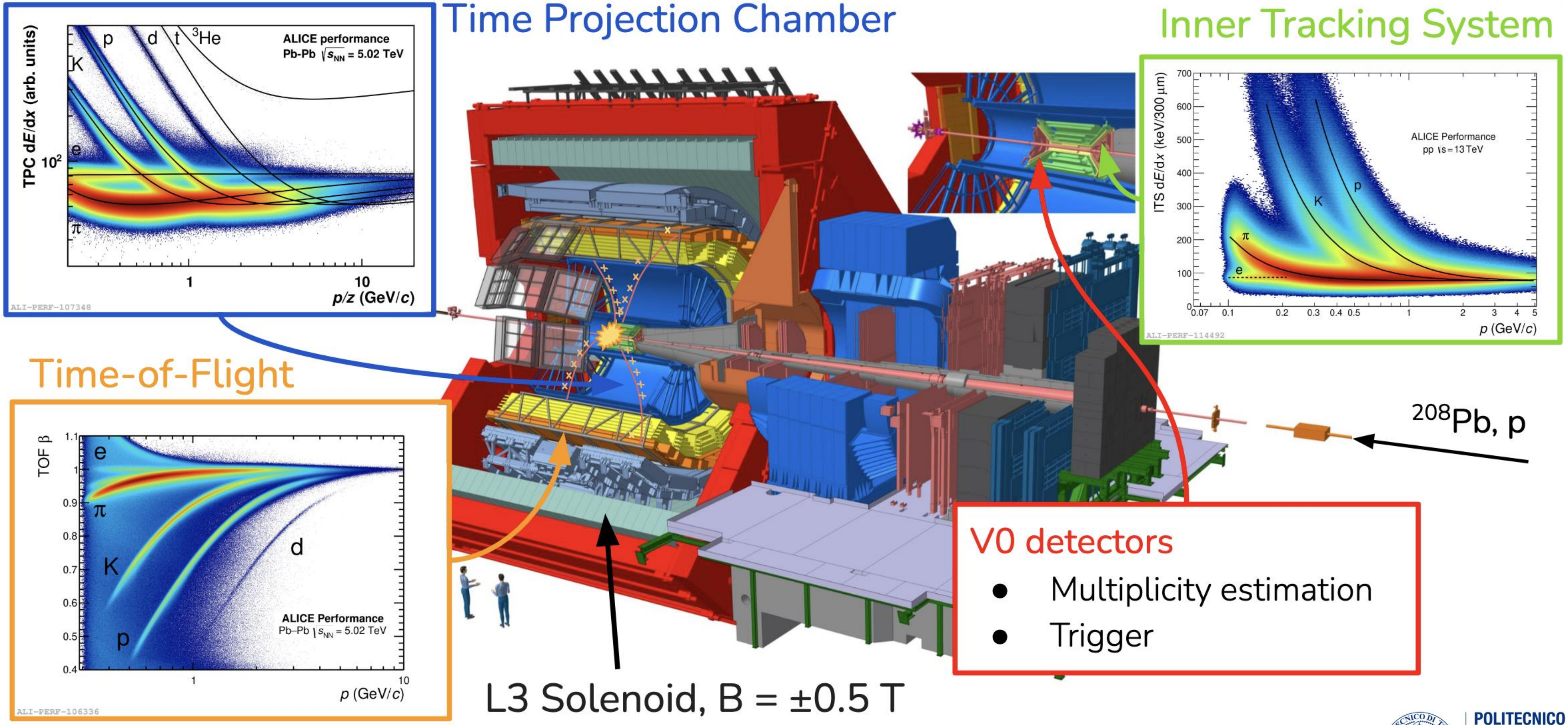
- Thermal freeze-out
  - ⇨Elastic interactions cease
  - ⇨Particle dynamics (“momentum spectra”) fixed

  $T_{fo} \sim 110$-130 MeV



The ALICE detector in the LHC Run 2



Time Projection Chamber

Inner Tracking System

Time-of-Flight

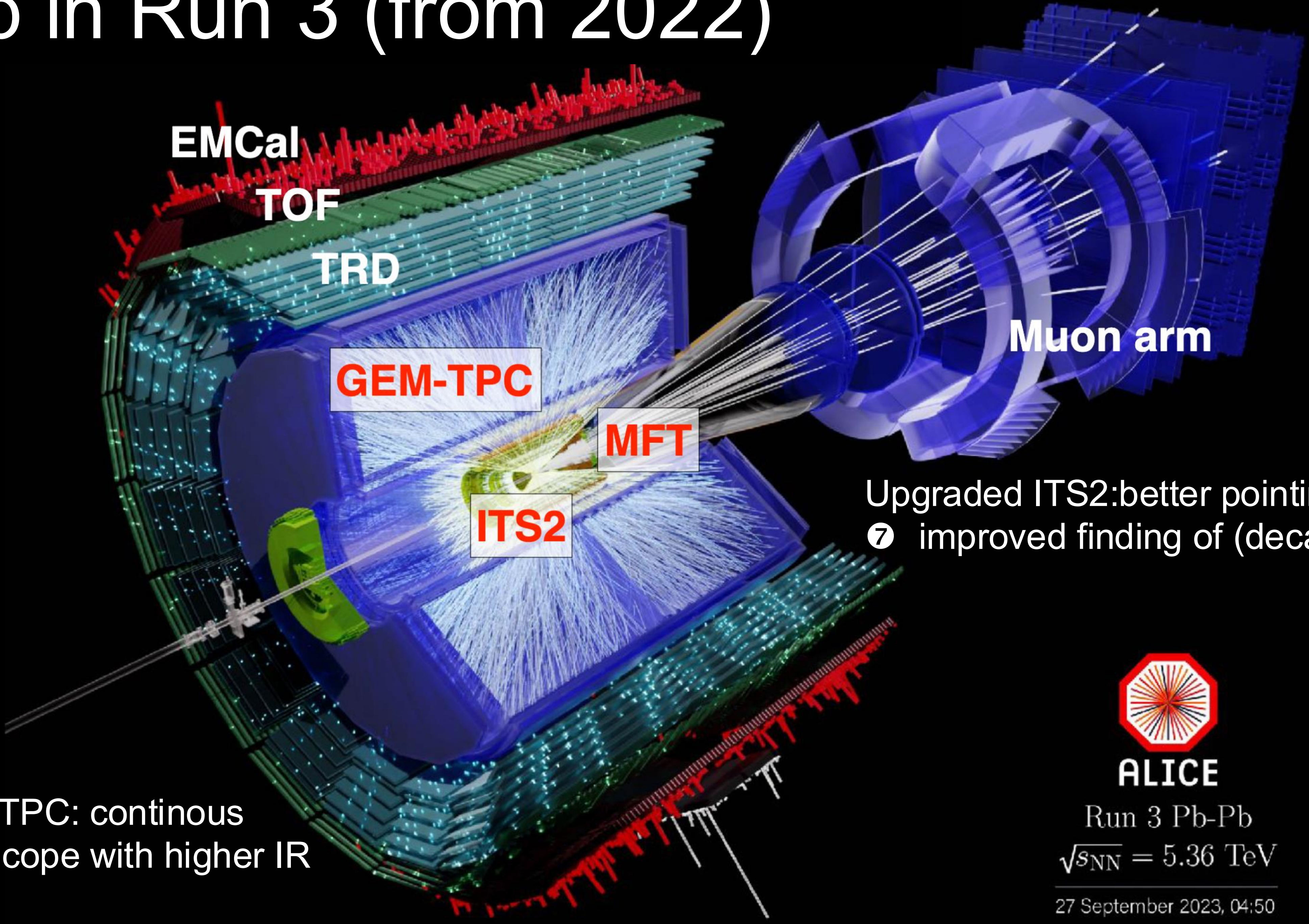
^{208}Pb, p

V0 detectors

- Multiplicity estimation
- Trigger

L3 Solenoid, B = ±0.5 T

Setup in Run 3 (from 2022)



Upgraded ITS2:better pointing resolution
❼ improved finding of (decay) vertices

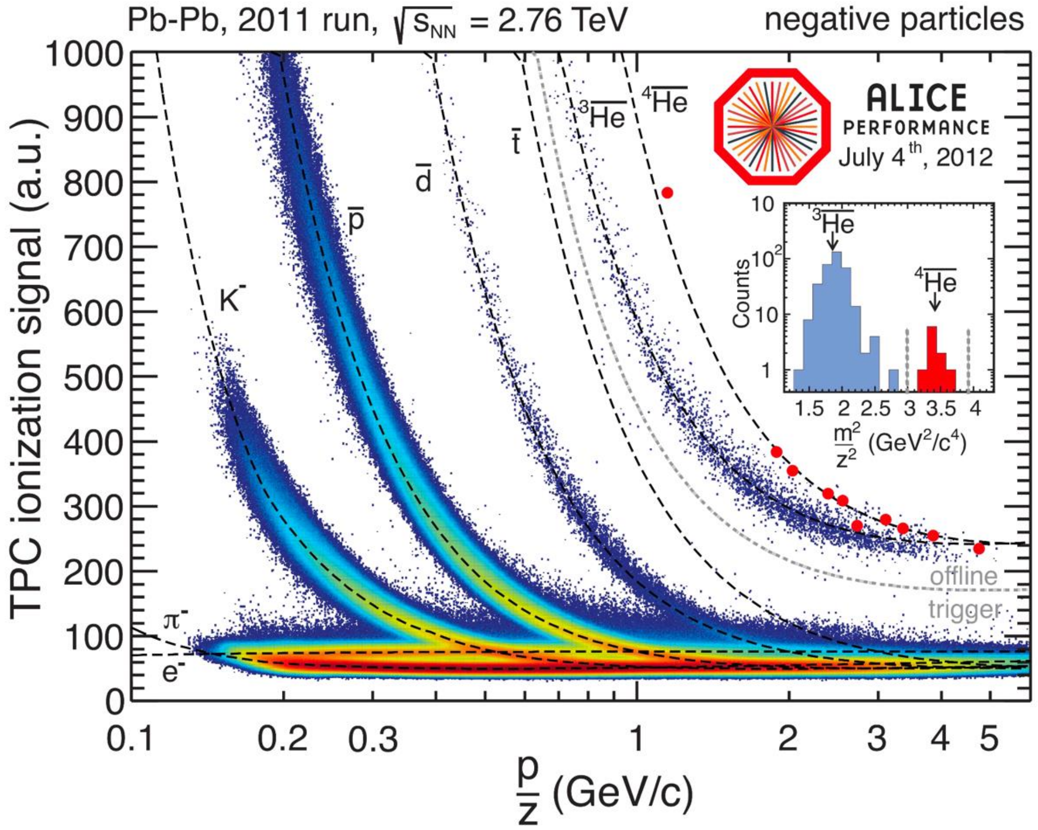
Upgraded TPC: continous
readout to cope with higher IR

Matter and anti-matter production

Light anti-nuclei in high energy collisions

Light nuclei are observed in high-energy heavy-ion collision experiments

- Hot and dense medium, T = O(100 MeV)
- Binding energies O(1-10 MeV)
- How can loosely-bound states emerge from such extreme conditions?



ALI-PERF-36713

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ALICE

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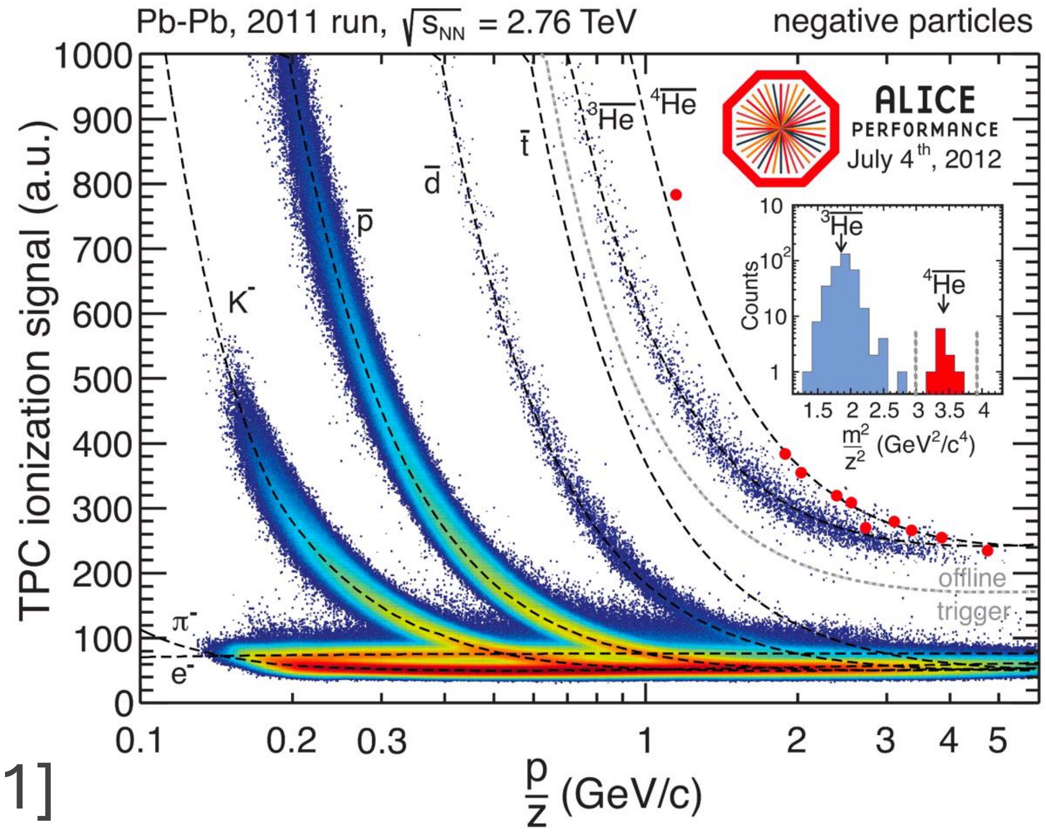

Light (anti)(hyper)nuclei at the collider as a doorway to the Cosmos

- Constraining models of astrophysical backgrounds in indirect dark-matter searches [1]
- Hypernuclei properties → hyperon-nucleon interactions → input to model neutron-star matter [2]

[1] Donato et al, Phys.Rev.D 62 (2000) 043003
[2] Logoteta et al, *Eur.Phys.J.A* 55 (2019) 11, 207

INFN
TORINO

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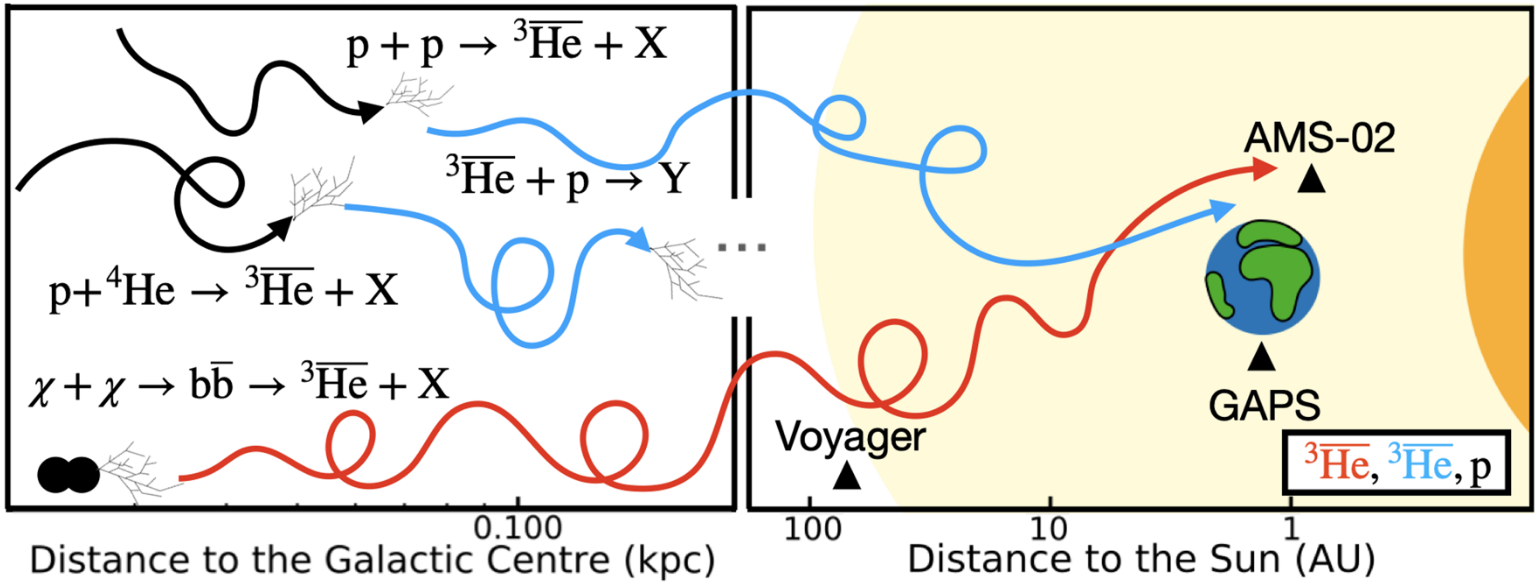
DI TORINO
Dipartimento
di Scienza Applicata
e Tecnologia

The dark side of ALICE

Antinuclei: antimatter counterpart of our matter world

- Extremely rare objects in nature, low background from “ordinary” processes
- Unique probe for new exotic physics! Dark matter, antistars, …

$^3\overline{\text{He}}$ production and propagation in the Galaxy [1]



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

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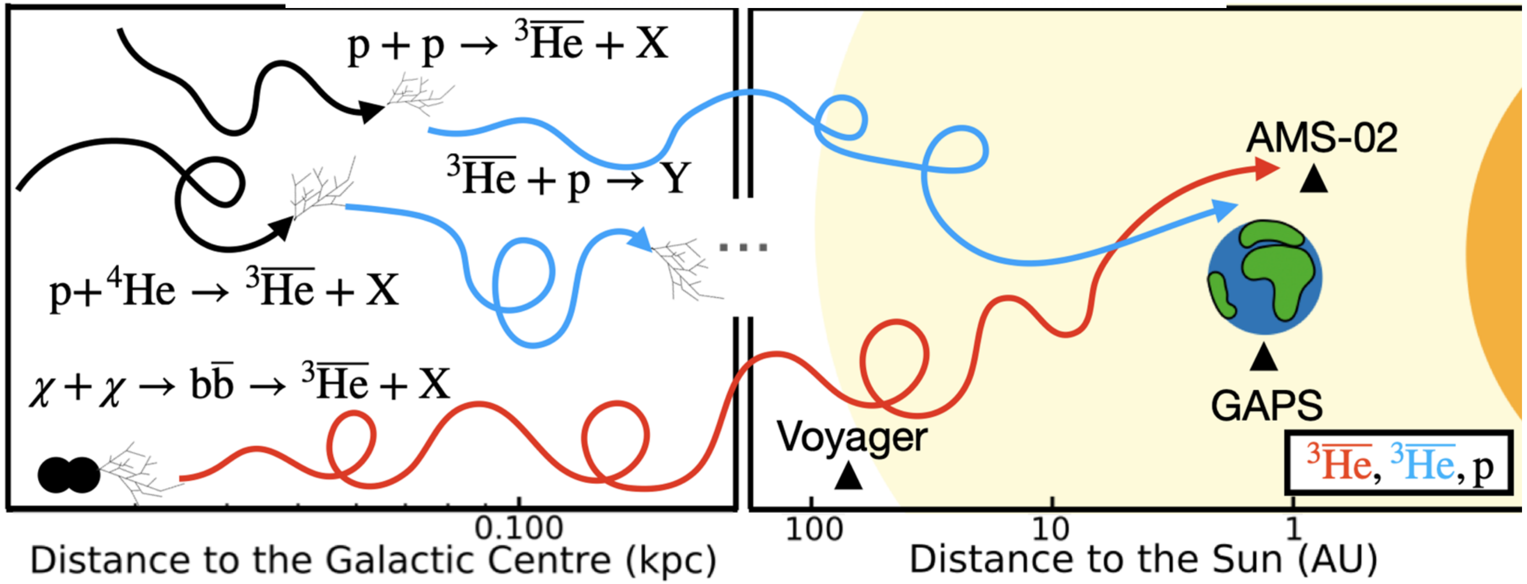

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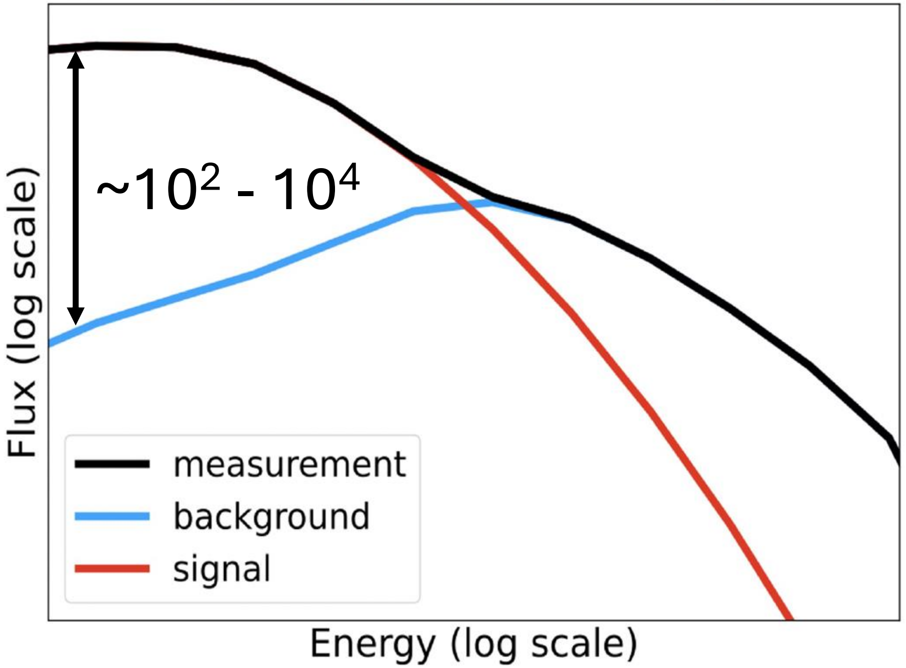


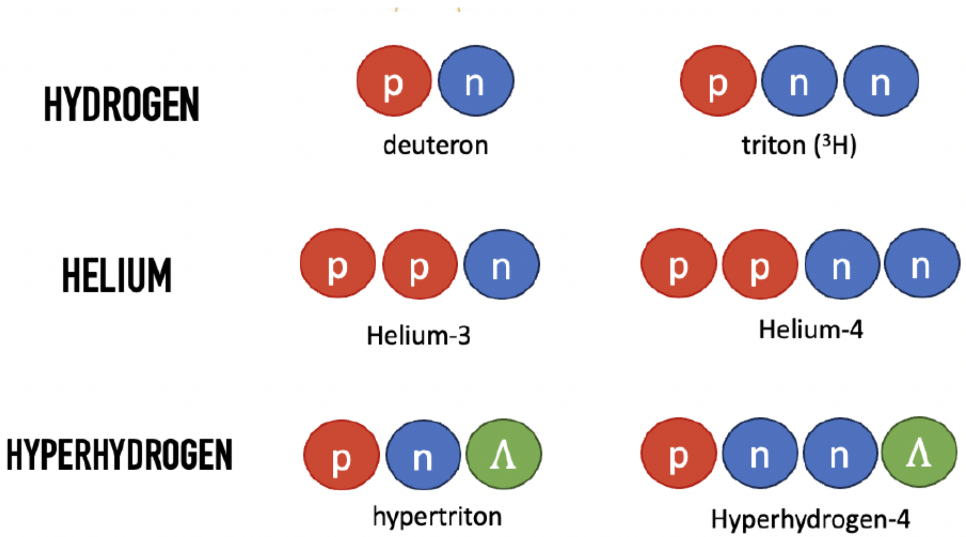
Flux of antinuclei from cosmic rays

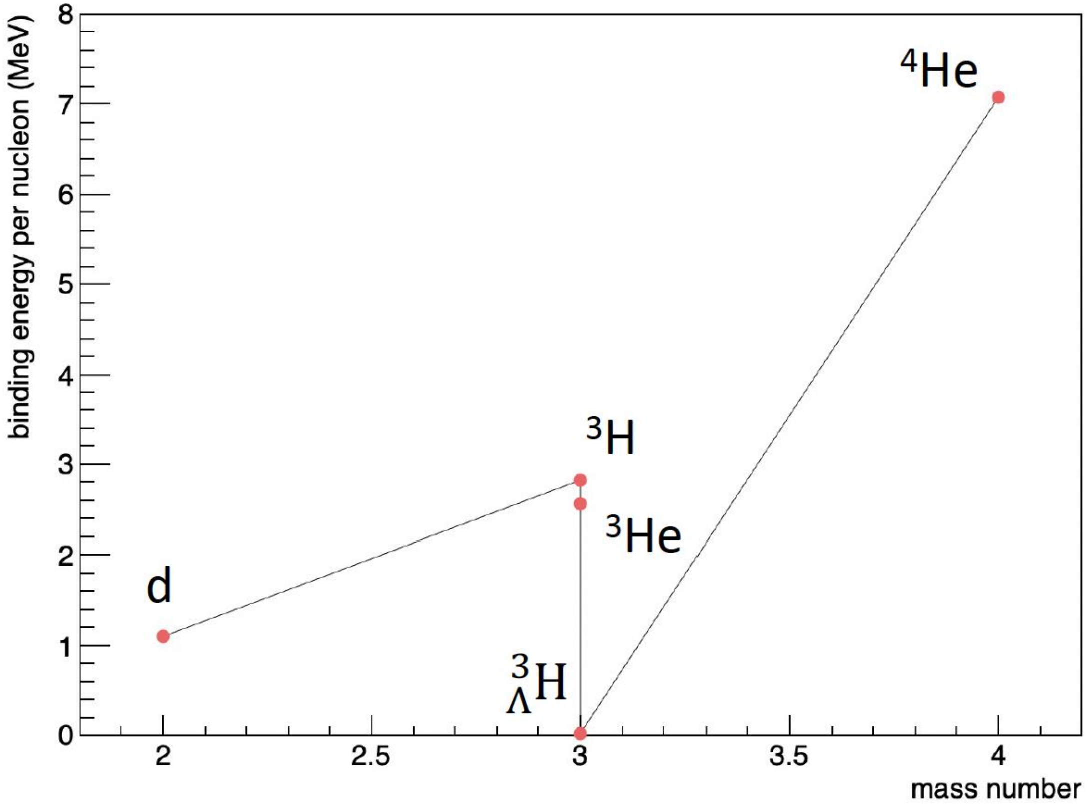
Measurements of light antinuclei production is of the utmost importance for astrophysics!

How can loosely-bound states survive?

In ultra-relativistic heavy-ion collisions at the LHC

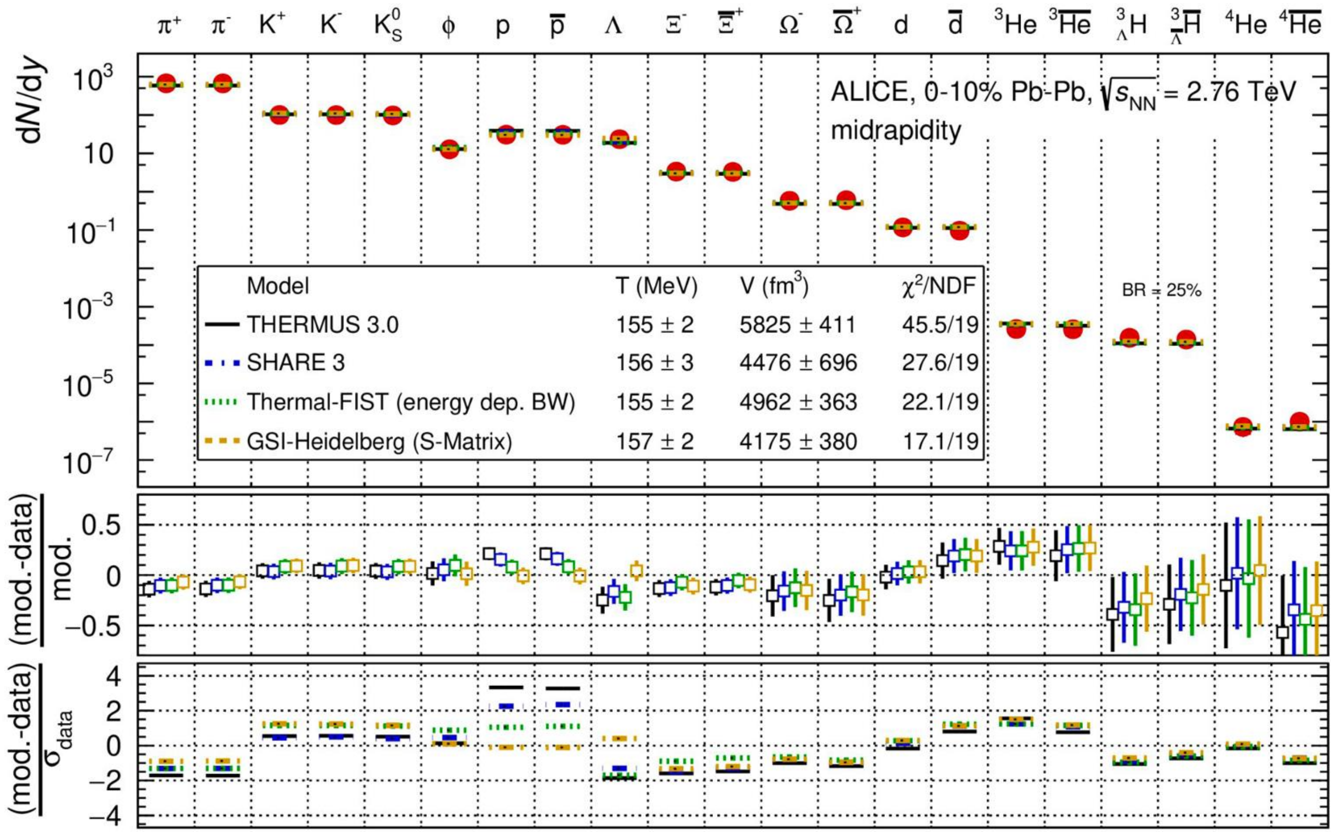
- Temperature of the system is T ~ 155 MeV
- Light (hyper)nuclei are produced among other particles
- (Hyper)nuclei have very small binding energies per nucleon compared to T





Nucleosyntesis models

- Statistical hadronisation
  - Yields of light-flavour hadrons including light (hyper)nuclei are instantly fixed at the freeze-out of inelastic interactions
  - Yields only depend on the mass and common thermal parameters *T* and *V*



ALI-PUB-583697

Eur. Phys. J. C 84 (2024) 8, 813

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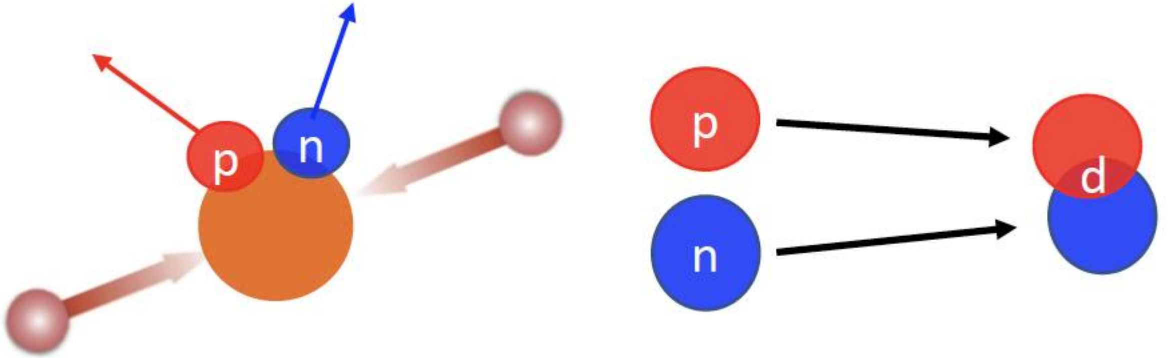
- Coalescence
  - (Anti)nuclei arise from the overlap of the (anti)nucleons phase-space distributions with the Wigner density of the bound state
  - Microscopic description



Coalescence parameter B_A connected to coalescence probability

$$B_A(p_T^p) = E_A \frac{d^3 N_A}{d p_A^3} \Big/ \left(E_p \frac{d^3 N_p}{d p_p^3} \right)^A \Bigg|_{p_T^p = p_T^A / A}$$

Butler et al., Phys. Rev. 129 (1963) 836
Mahlein et al., arxiv:2302.12696

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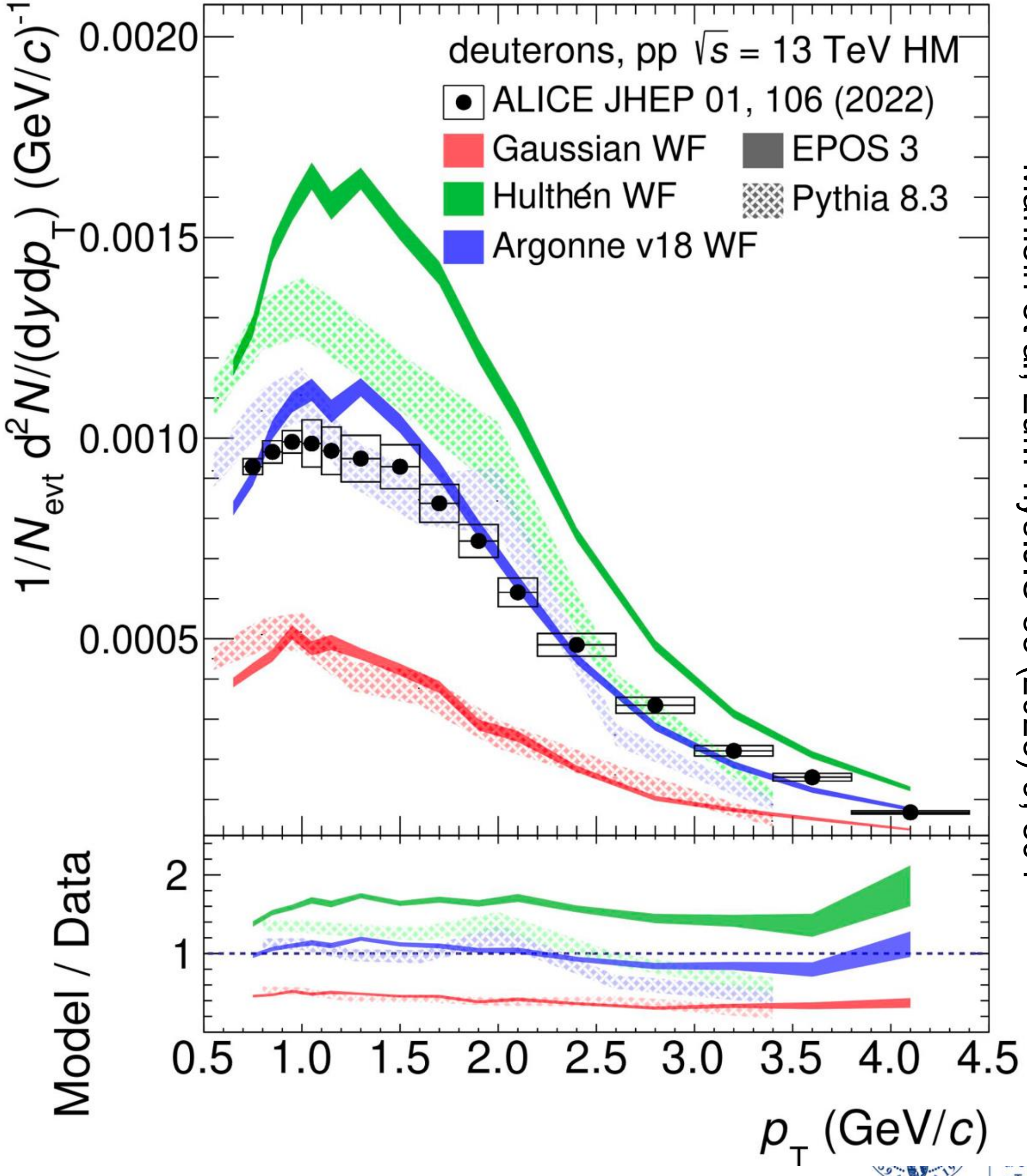
  - Light (hyper)nuclei are formed by pre-existing nucleons overlapping in phase space
  - State-of-the-art models rely on Wigner function formulation



Mahlein et al, Eur.Phys.J.C 83 (2023) 9, 804

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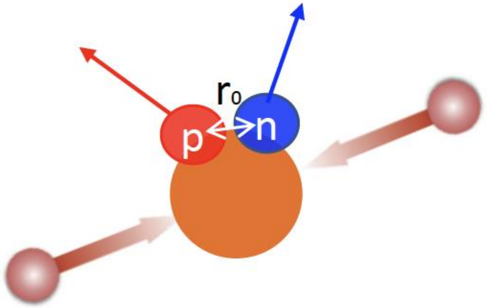
Main difference:
for coalescence **size** matters,
for SHM only **mass** matters

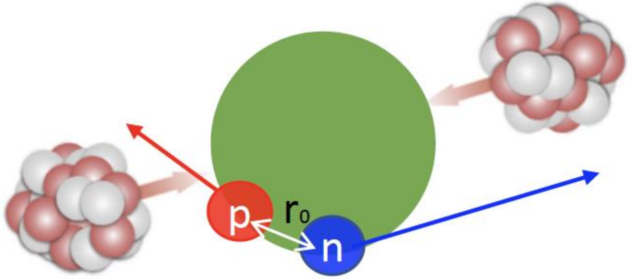
Size of nuclei vs. size of system



pp[1], p—Pb[2]: r_0= 1–1.5 fm

Small collision systems

[1] PRC 99 (2019) 024001
[2] PRL 123 (2019) 112002



Pb—Pb[3]: r_0= 3–6 fm

Heavy-ions

[3] PRC 96 (2017) 064613

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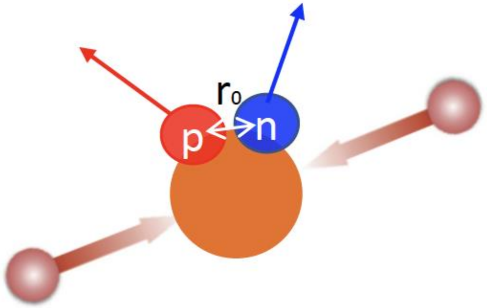

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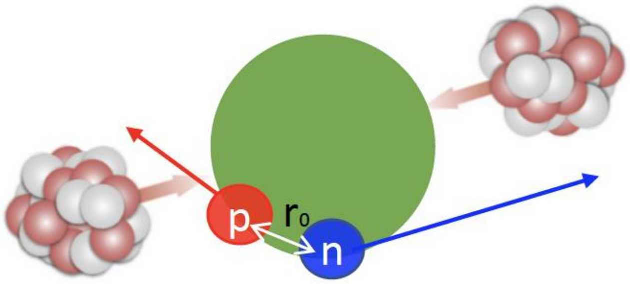

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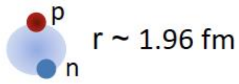
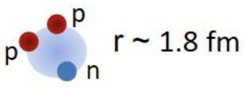
charged-particle multiplicity

$\langle dN_{ch} / d\eta \rangle_{|\eta|<0.5}$

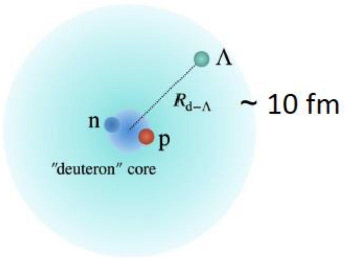
d



^{3}He

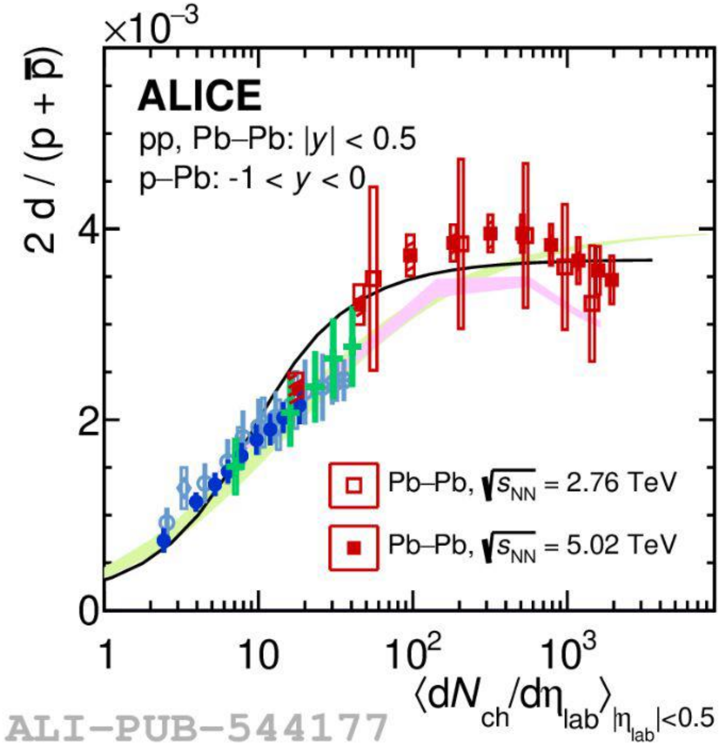


$^{3}_{\Lambda}$H



Nuclei production in Run 1 and Run 2

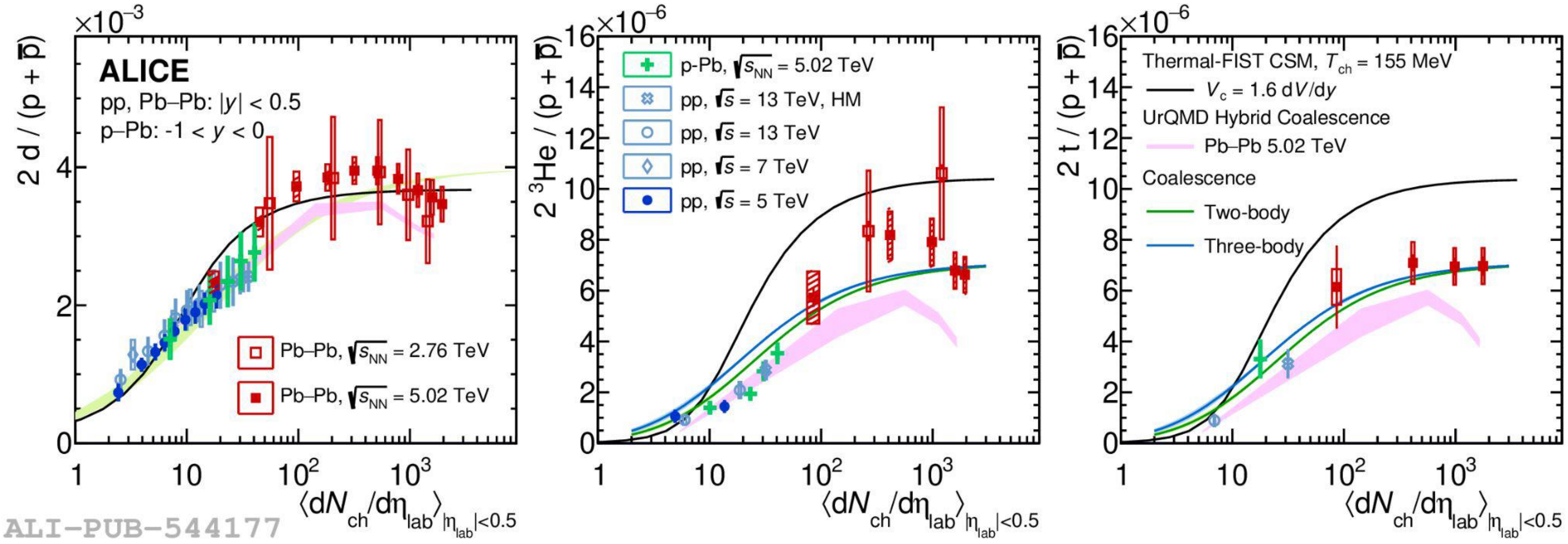
- Extensive studies of (anti)nuclei production across different colliding systems
  - A=2 → less separation power for different models within experimental uncertainties



Phys. Rev. C 107 (2023) 6, 064904

Nuclei production in Run 1 and Run 2

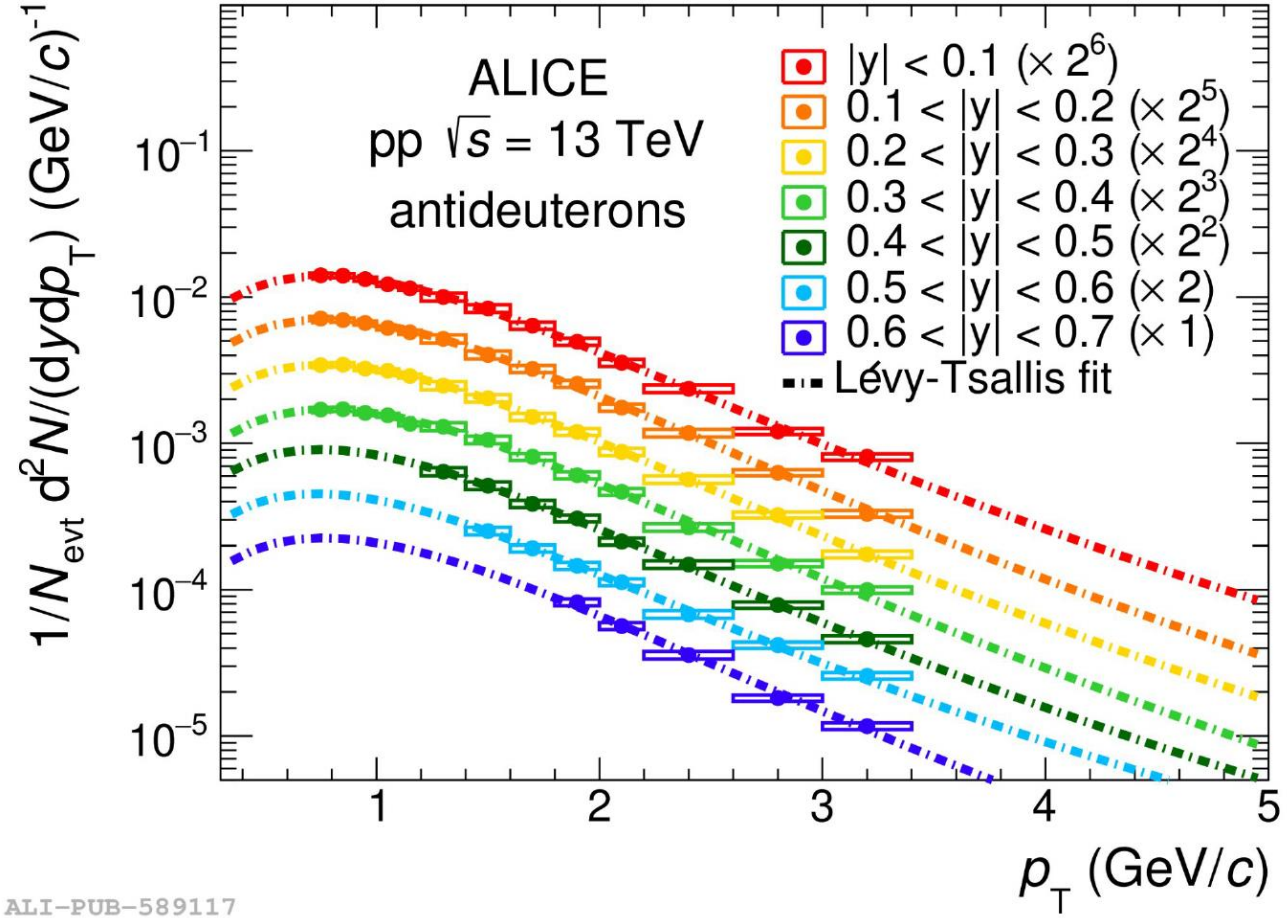
- Extensive studies of (anti)nuclei production across different colliding systems
  - A=2 → less separation power for different models within experimental uncertainties
  - A=3 → slight preference for coalescence with respect to statistical hadronization



Phys. Rev. C 107 (2023) 6, 064904

Nuclei production vs rapidity

- First measurement of the rapidity dependence of antideuteron production in pp collisions up to $|y| = 0.7$
- $0.5 < |y| < 1.5 \rightarrow$ crucial input to model the flux of cosmic rays produced in interactions with the interstellar medium [2]



ALI-PUB-589117

[1] Phys. Lett. B 860 (2025) 139191

[2] Blum, *Phys.Rev.C* 109 (2024) 3, L031904

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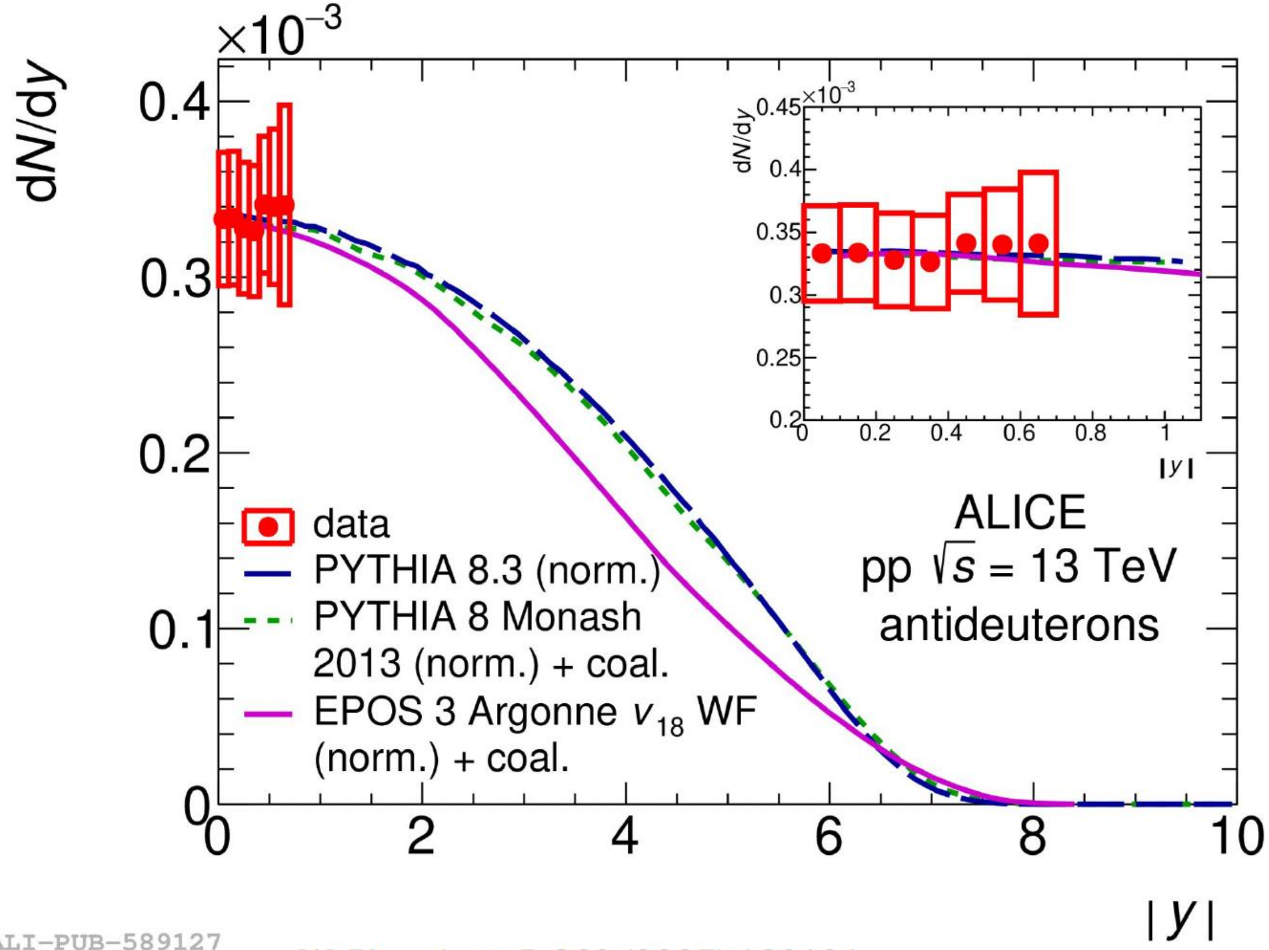
- 0.5 < |*y*| < 1.5 → crucial input to model the flux of cosmic rays produced in interactions with the interstellar medium [2]
- The antideuteron yield is independent of rapidity within uncertainties
  - Limited sensitivity to different models (with/without coalescence)
- Tighter constraints on models will require more forward measurements → LHCb and ALICE 3

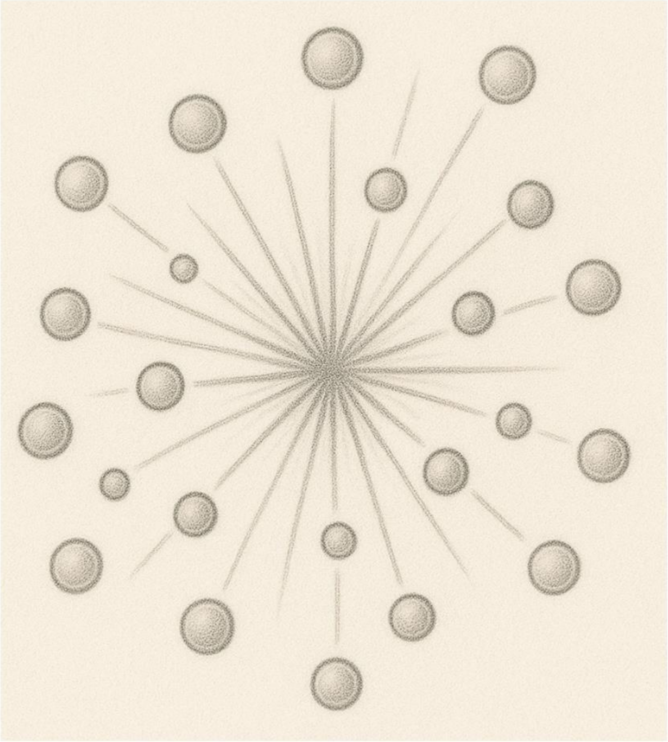


ALI-PUB-589127

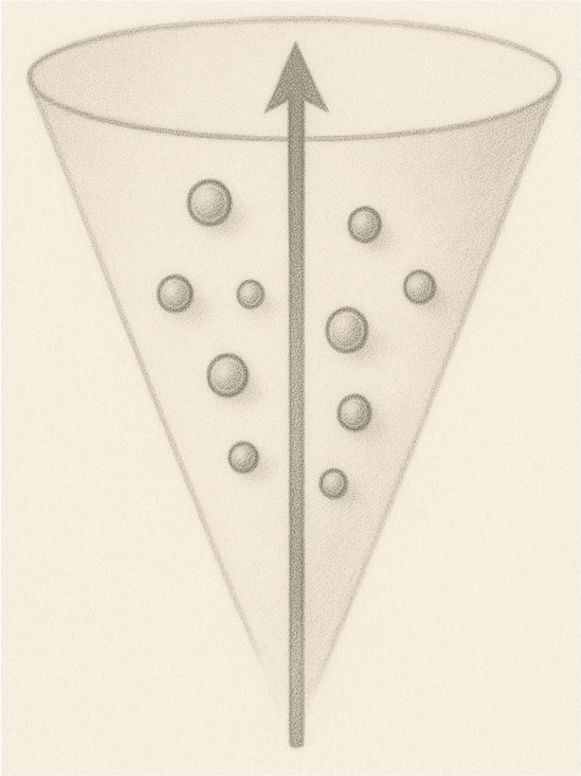
[1] Phys. Lett. B 860 (2025) 139191
[2] Blum, *Phys.Rev.C* 109 (2024) 3, L031904

Test of the coalescence model

One way to investigate the coalescence mechanism is by focusing in a small phase-space region (jet cone) and comparing the production of nuclei by coalescence there wrt the minimum bias production (UE)



Underlying Event: particle production from MPIs



Jets: particle production from single parton shower

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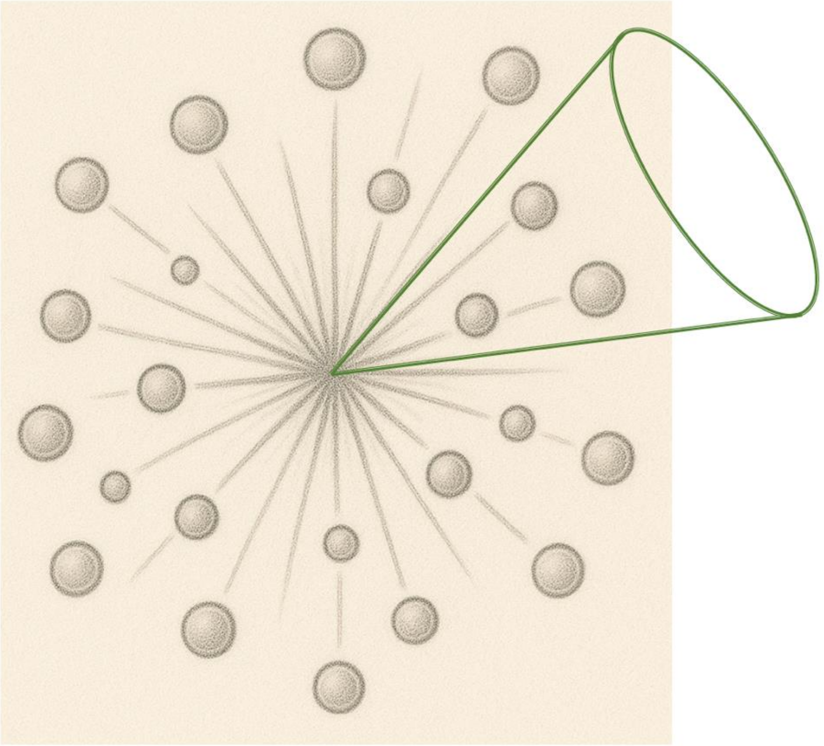

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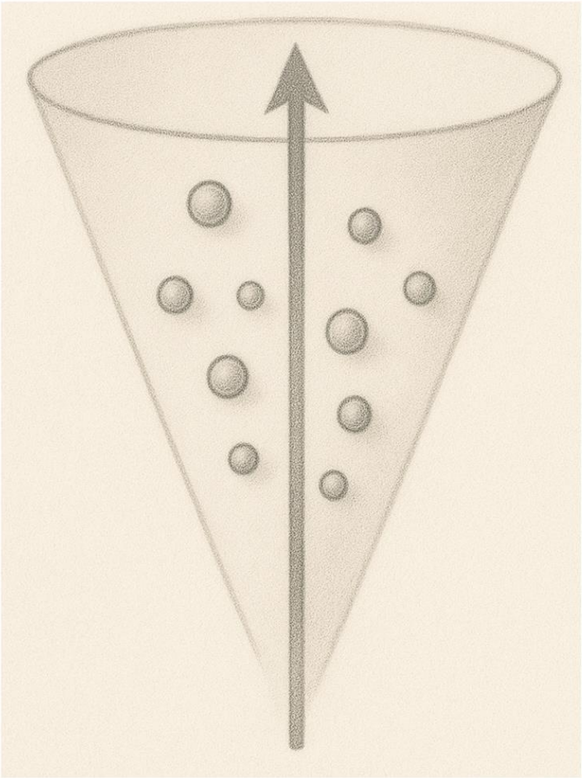

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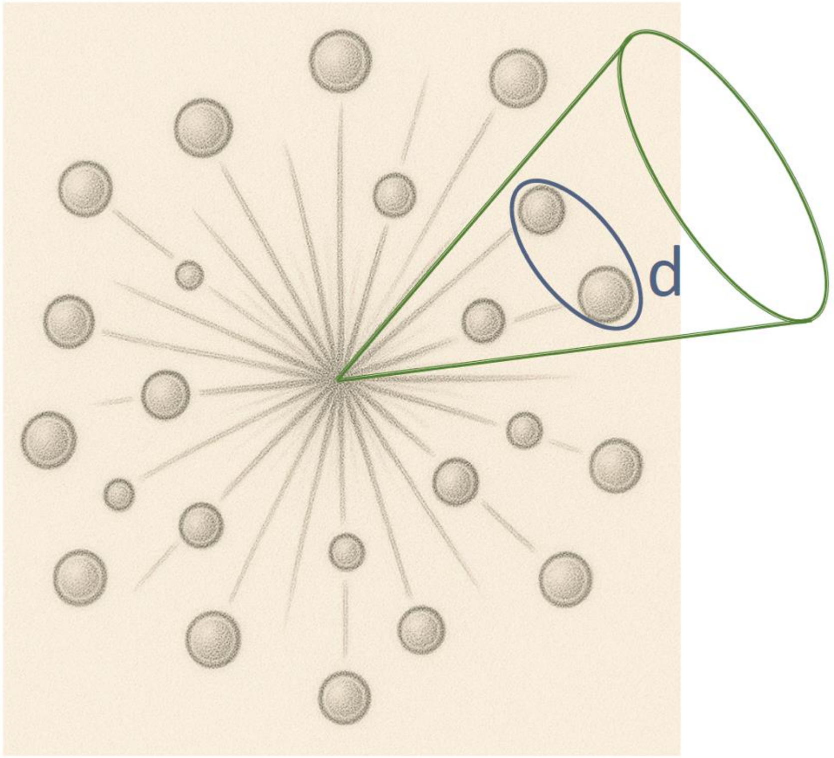

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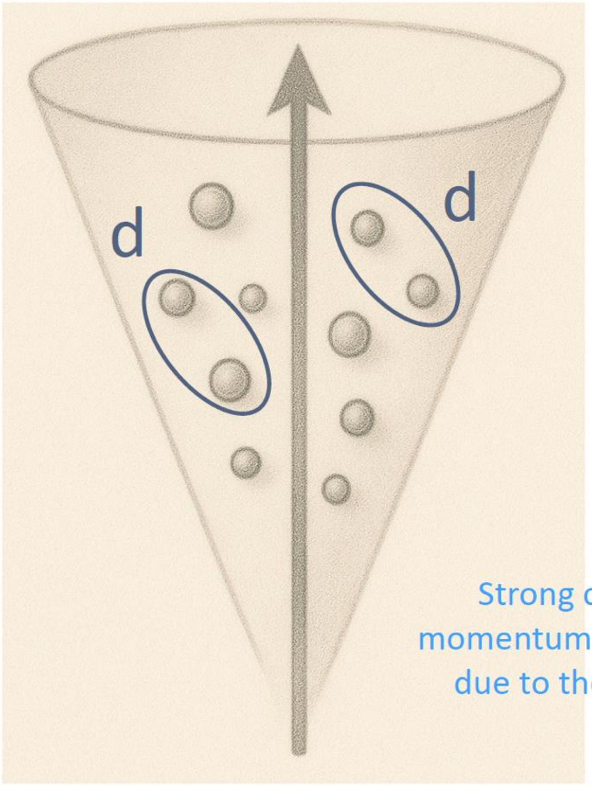
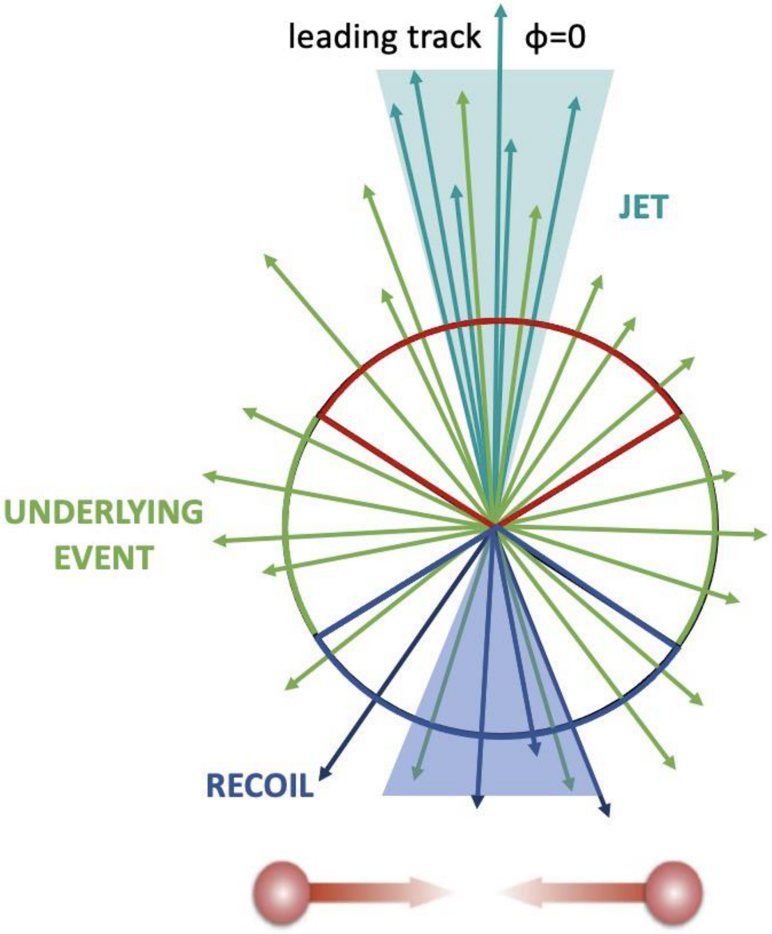


Strong constraints on space-momentum correlations of nucleons due to the same parton shower

Jets: particle production from single parton shower

Nuclei production in and out of jet

- Powerful tool to investigate coalescence mechanism is the study of nuclear production in and out of jets
- In jets nucleons are created close to each other in phase-space



Toward: |Δϕ| < 60°

Transverse: 60° < |Δϕ| < 120°

Away: |Δϕ| > 120°

T. Martin et al., Eur. Phys. J. C (2016) 76: 299

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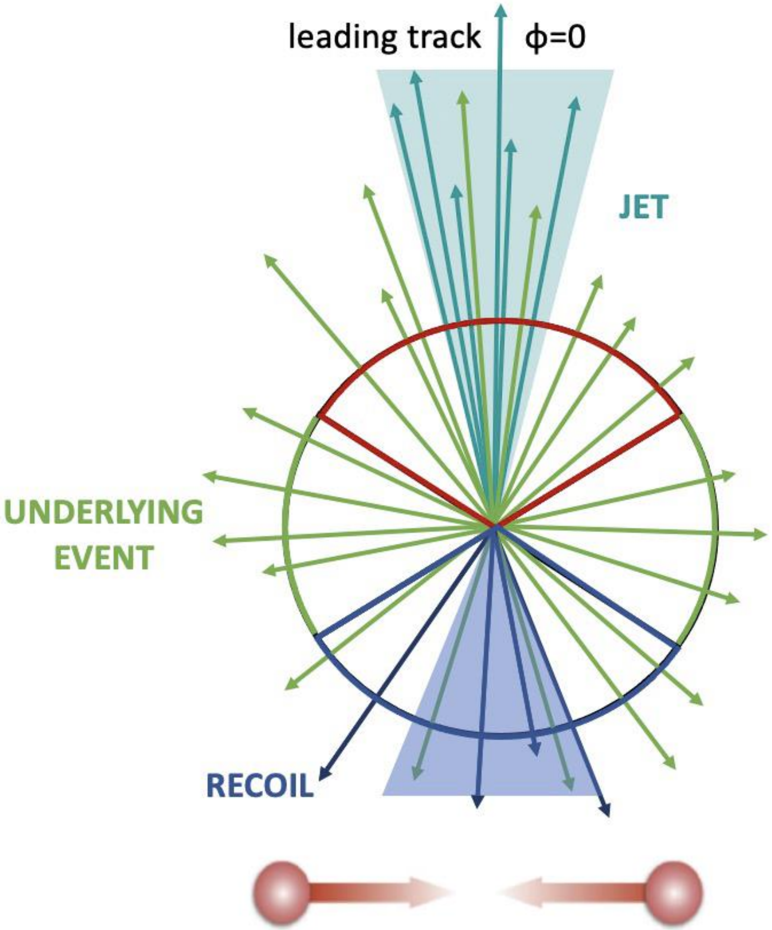
→ **Study B_2 in and out of jets**: jets obtained simply by subtracting the UE from the Toward region (Jet + UE)



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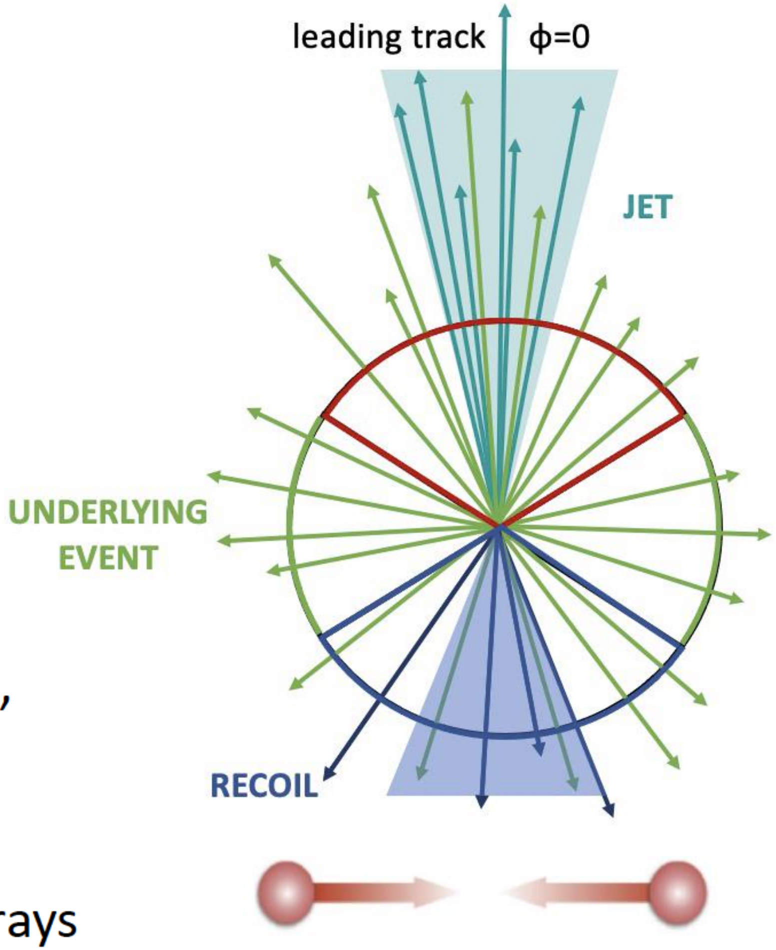
- Studying the antideuteron production in jets in small systems (pp, pA) is important to understand and model nuclear production
- Production models are crucial to study cosmic rays
- Antideuteron in the Galaxy is produced in interactions of cosmic rays (p, ^{4}He) with kinetic energies of ~300 GeV



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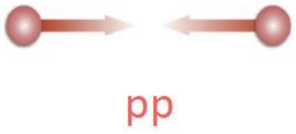
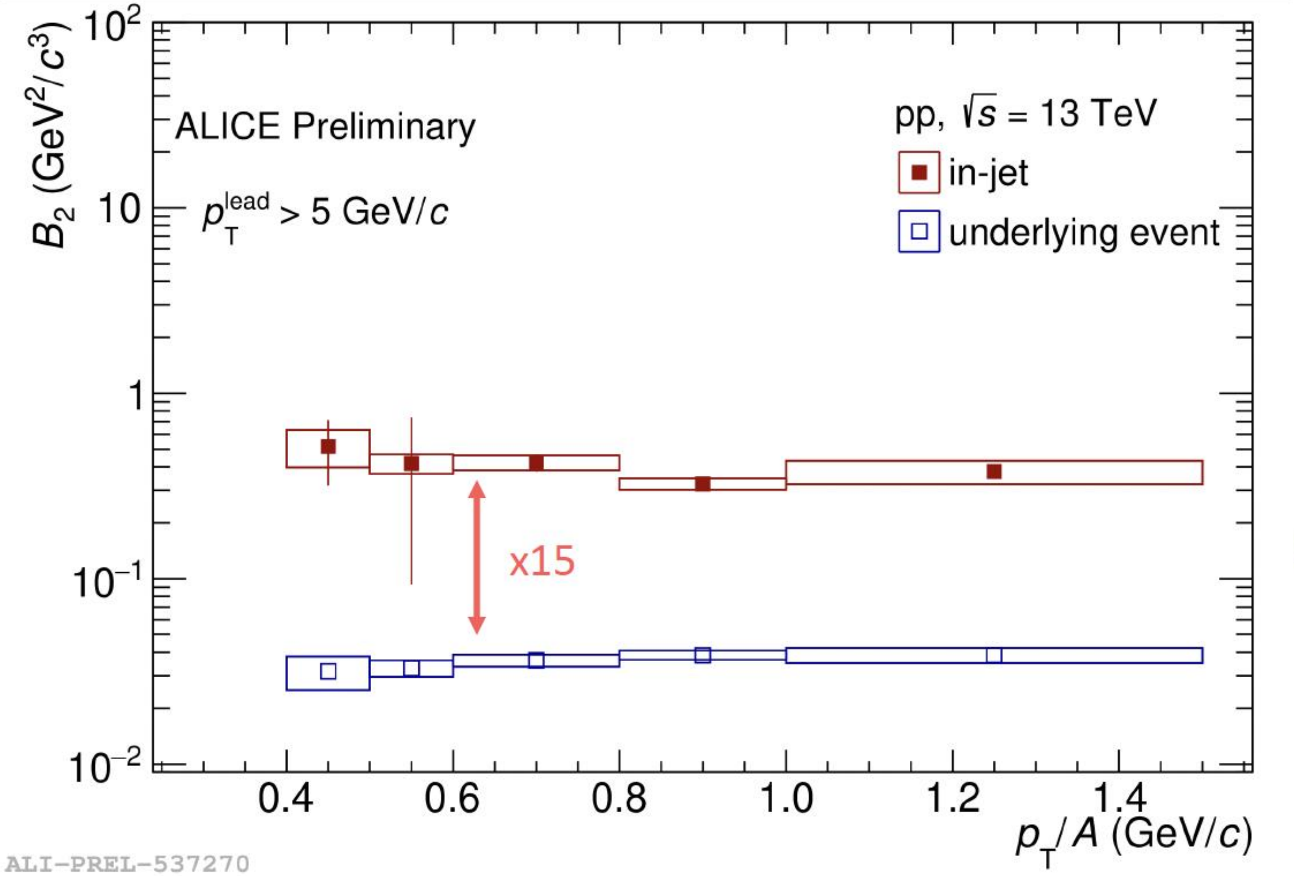
T. Martin et al., Eur. Phys. J. C (2016) 76: 299

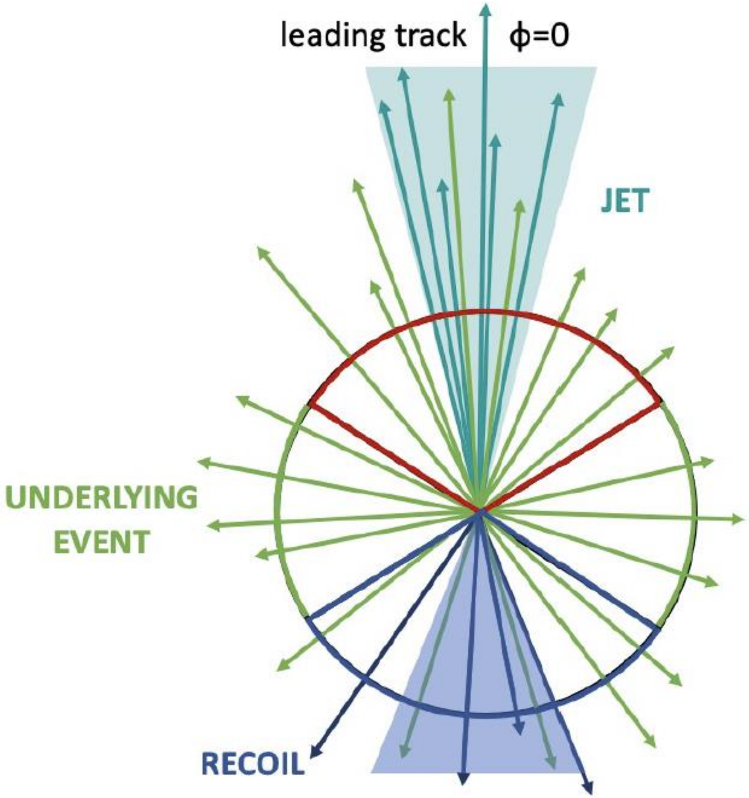
Serksnyte et al., Phys. Rev. D 105 (2022) 8, 083021

Coalescence parameters





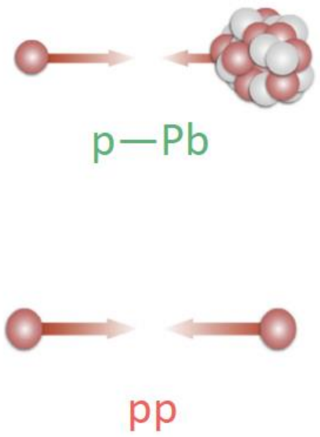
Phys.Rev.Lett. 131 (2023) 4, 042301

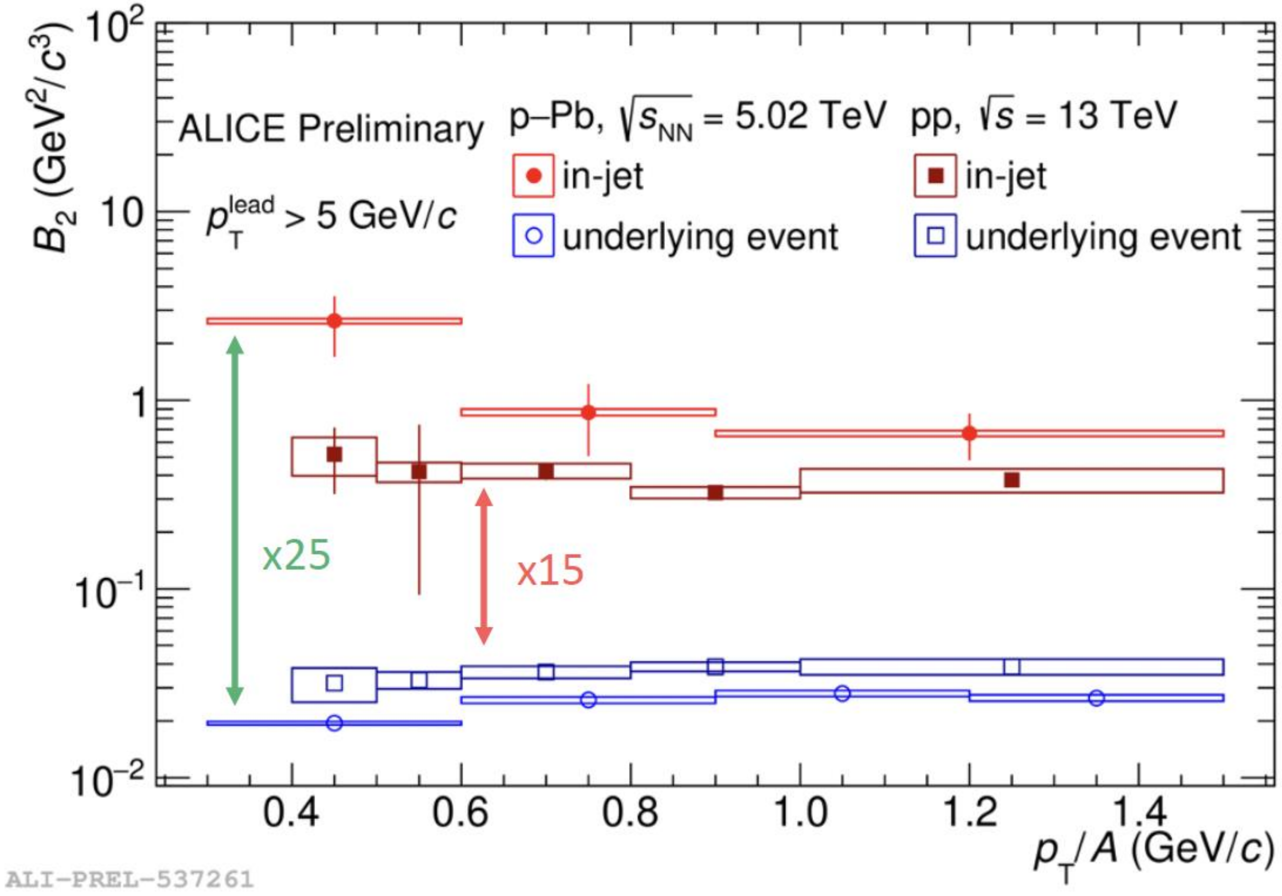


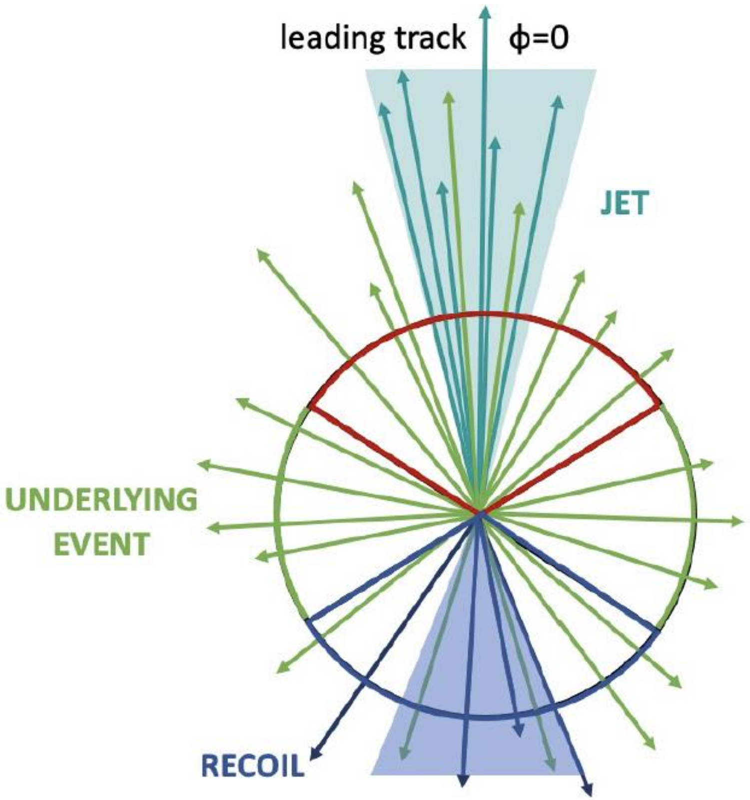
Enhanced deuteron coalescence probability in jets wrt UE is observed for the first time in pp collisions → *coalescence picture*

Coalescence parameters

Phys.Rev.C 99 (2019) 024001
Phys.Rev.Lett. 123 (2019) 112002
Phys.Rev.Lett. 131 (2023) 4, 042301





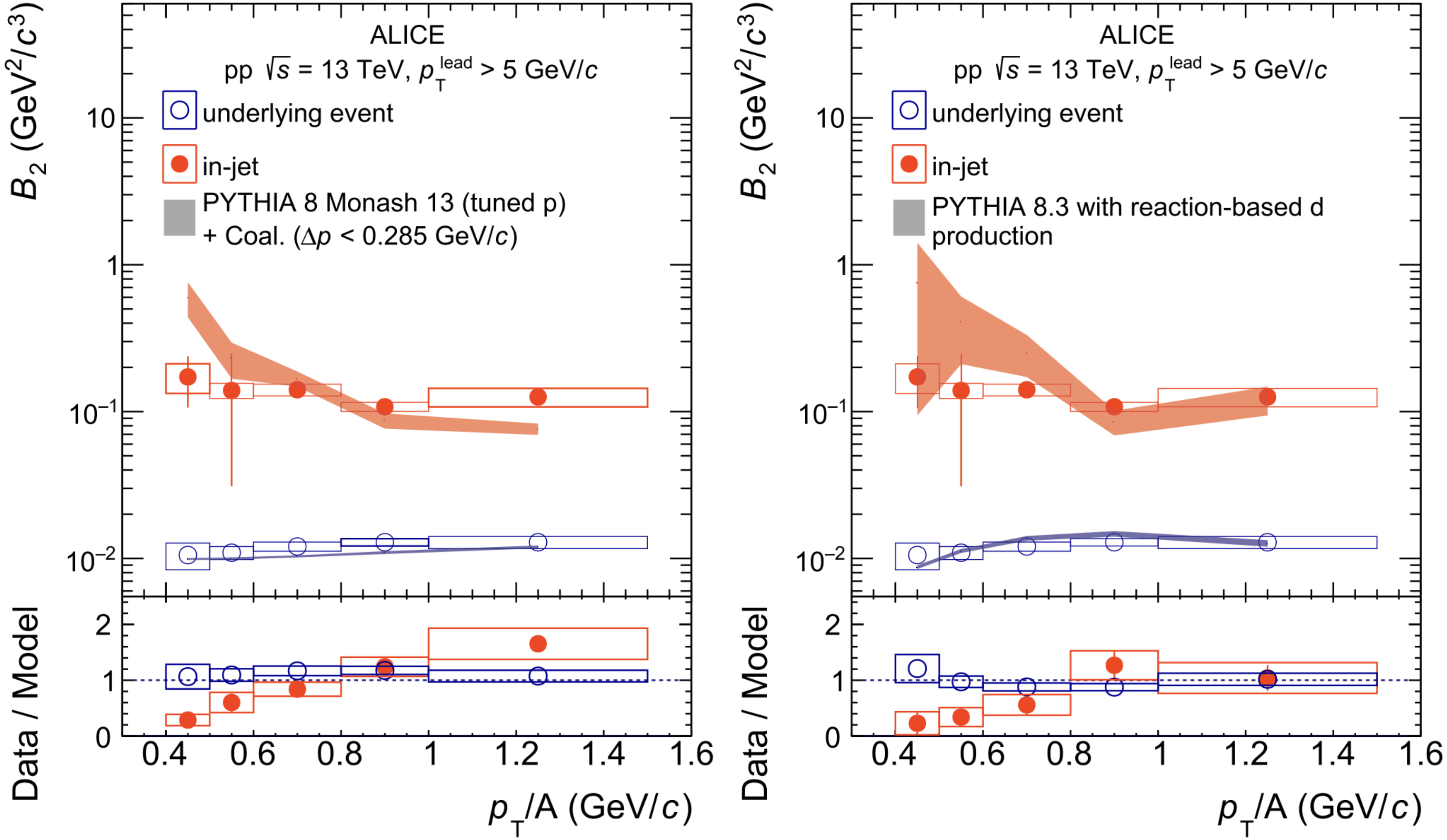


- ○ B_2 in-jet in p-Pb is larger than B_2 in-jet in pp

→ could be related to the different particle composition of jets in pp and p-Pb

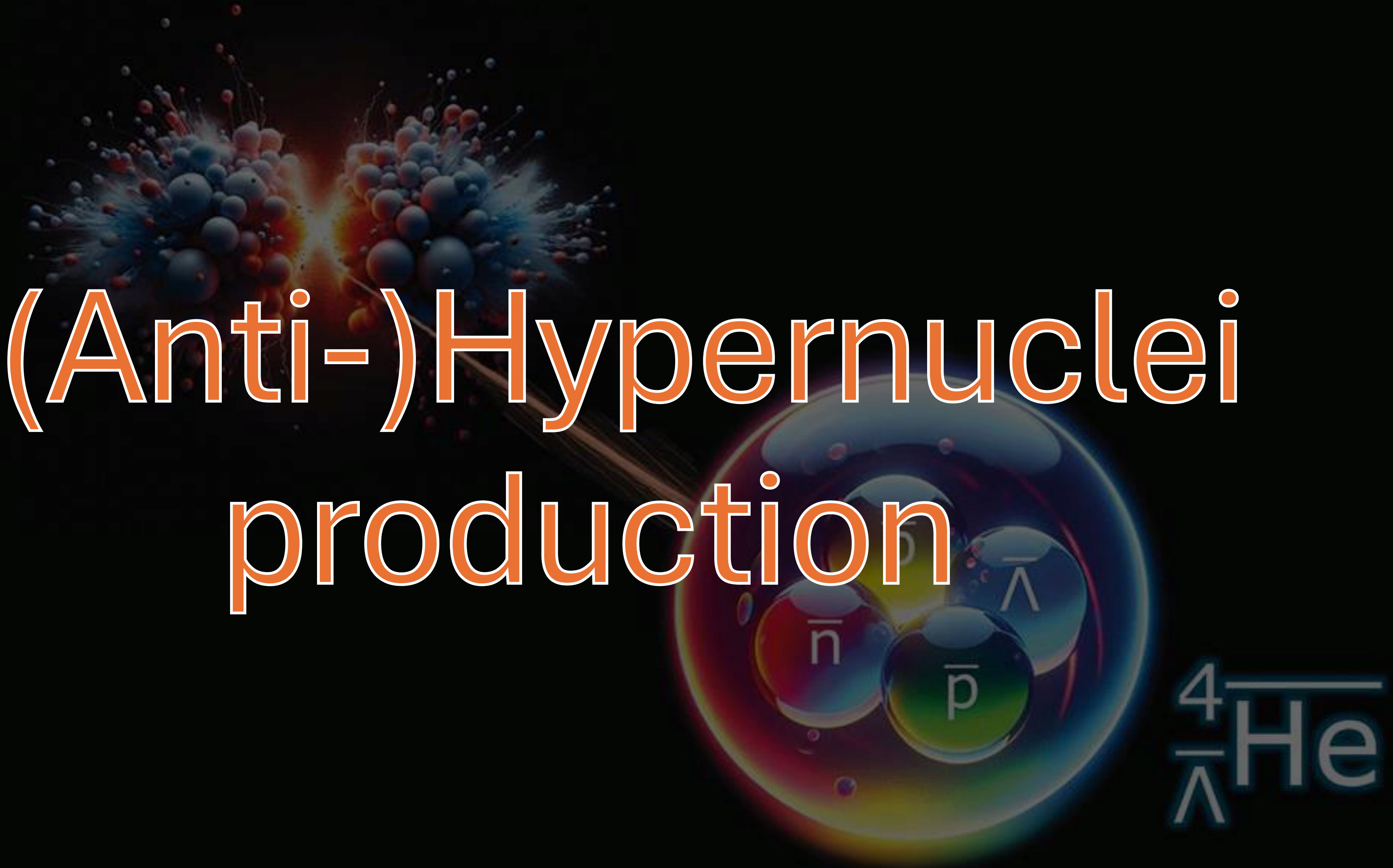
- ○ B_2 in UE in p-Pb is smaller than B_2 in UE in pp due to the larger source size in p-Pb

Coalescence parameters: data vs model



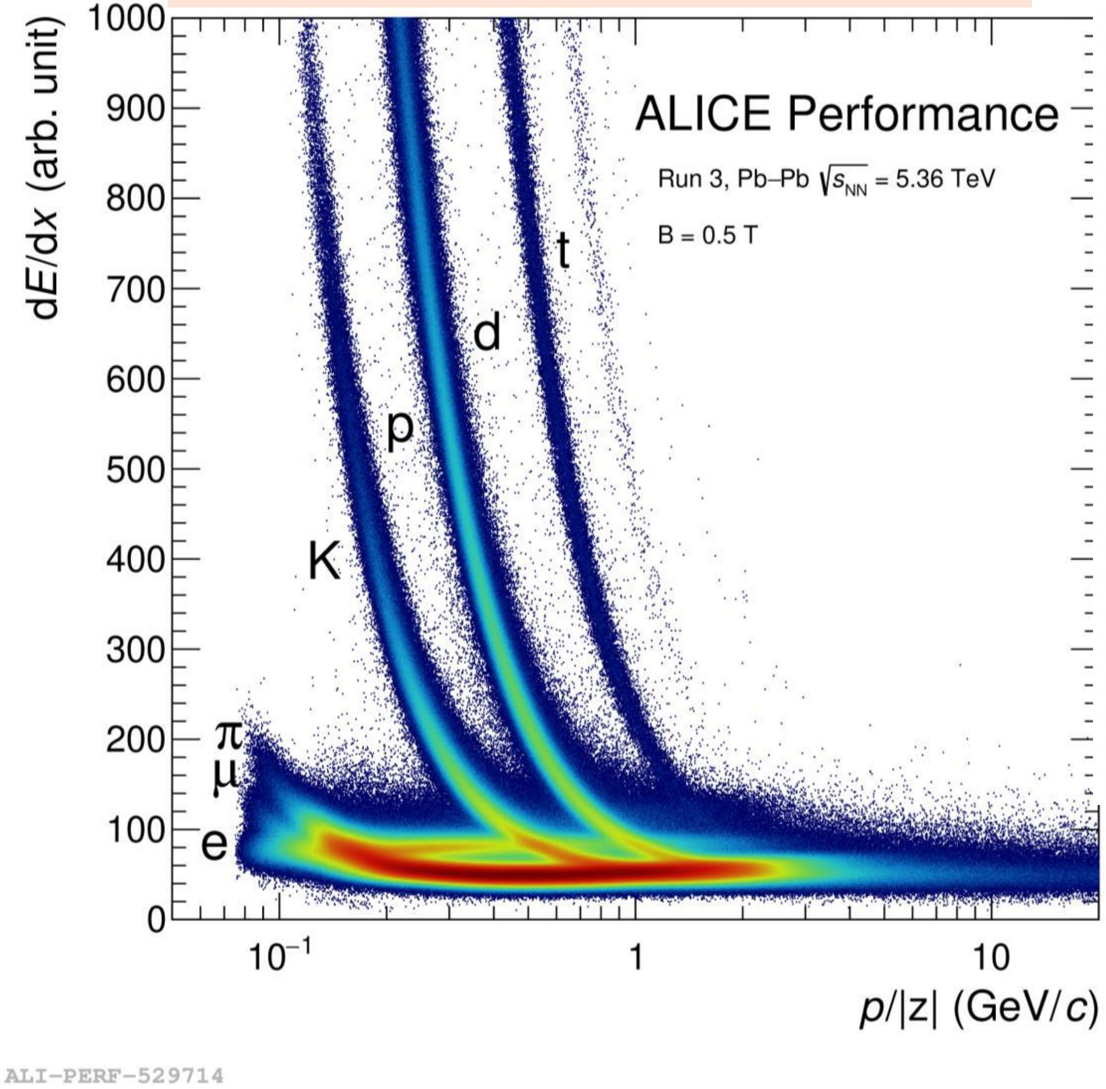
- B_2 UE PYTHIA describes the trend of data
- B_2 in-jet PYTHIA reproduces difference between UE and jet but shows a decreasing trend not observed in data → p_T trend to be further investigated

(Anti-)Hypernuclei production



Hypernuclei in high energy collisions

Identification daugther tracks



- Using TPC PID via the specific energy loss
- Excellent separation of different particle species

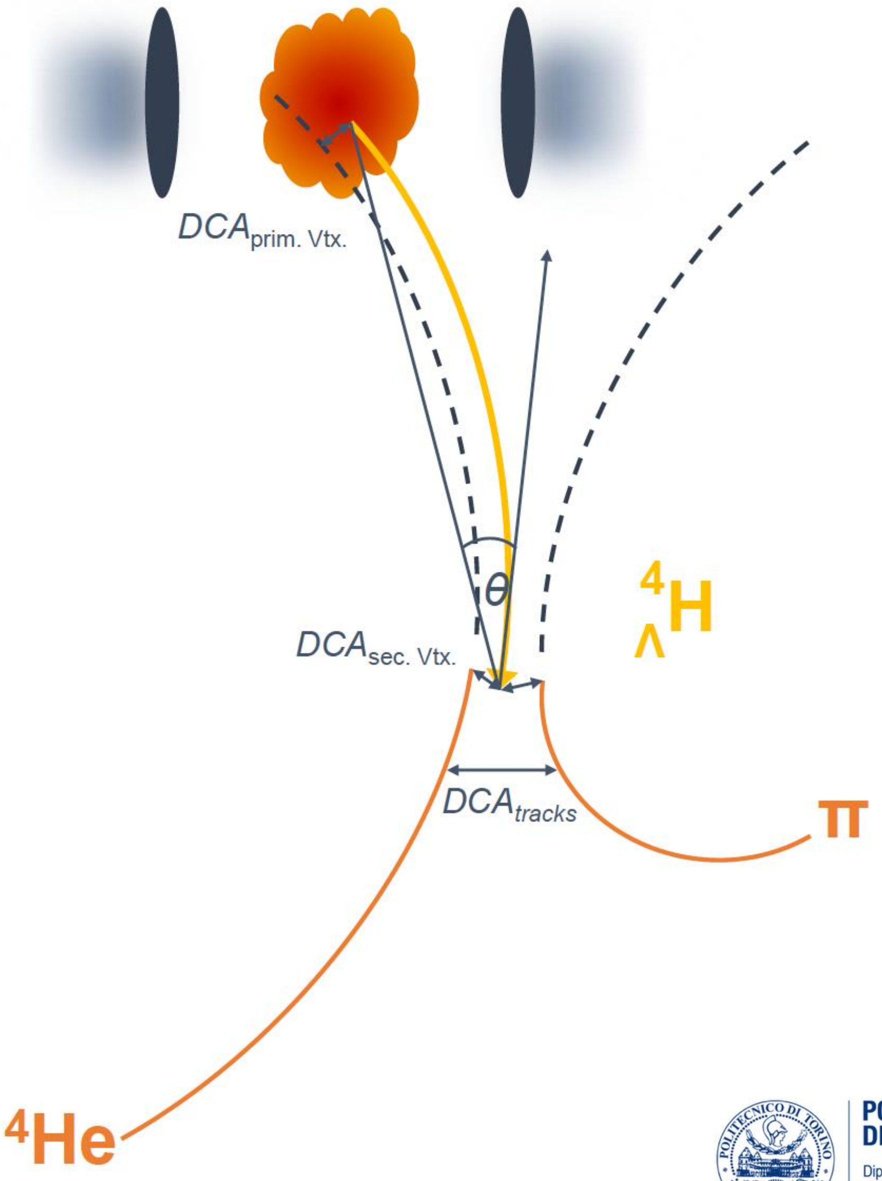
Particle	Decay mode	Branching Ratio
$^{3}_{\Lambda}H$	$^{3}He + \pi^{-}$ + c.c. d + p + π^{-} + c.c.	~25% ~40%
$^{4}_{\Lambda}H$	$^{4}He + \pi^{-}$ + c.c.	~50%
$^{4}_{\Lambda}He$	^{3}He + p + π^{-} + c.c.	~29%

Hypernuclei in high energy collisions

Recontruction and invariant mass technique

- The identified daughters are assumed to come from a common vertex
- Their tracks are matched by algorithms to find the best possible decay vertex

- Challenge: huge combinatorial background
- Solution: topological and kinematical cuts

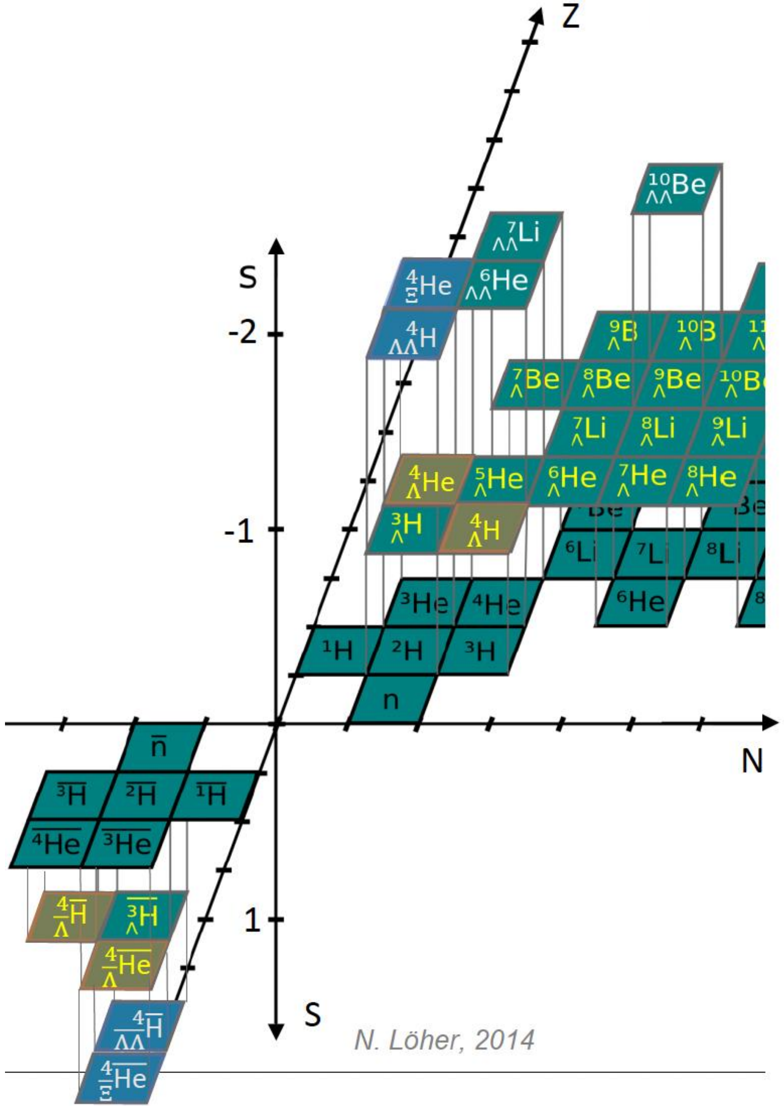


Hypernuclei in high energy collisions

- Hypernuclei consist of nucleons and hyperons
- Decay weakly after a few centimeters ($c\tau \approx$ 5-7 cm) into two or more daughters
- Lightest known hypernucleus hypertriton:

$$B_\Lambda \approx 100 \text{ keV} \rightarrow r_{d\Lambda} \approx 10 \text{ fm}$$

Hildenbrand et. al., Phys. Rev. C 100, 034002 (2020)



N. Löher, 2014

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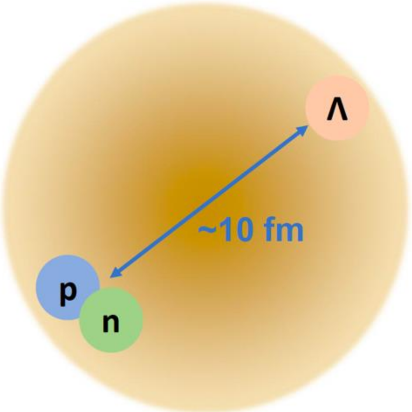
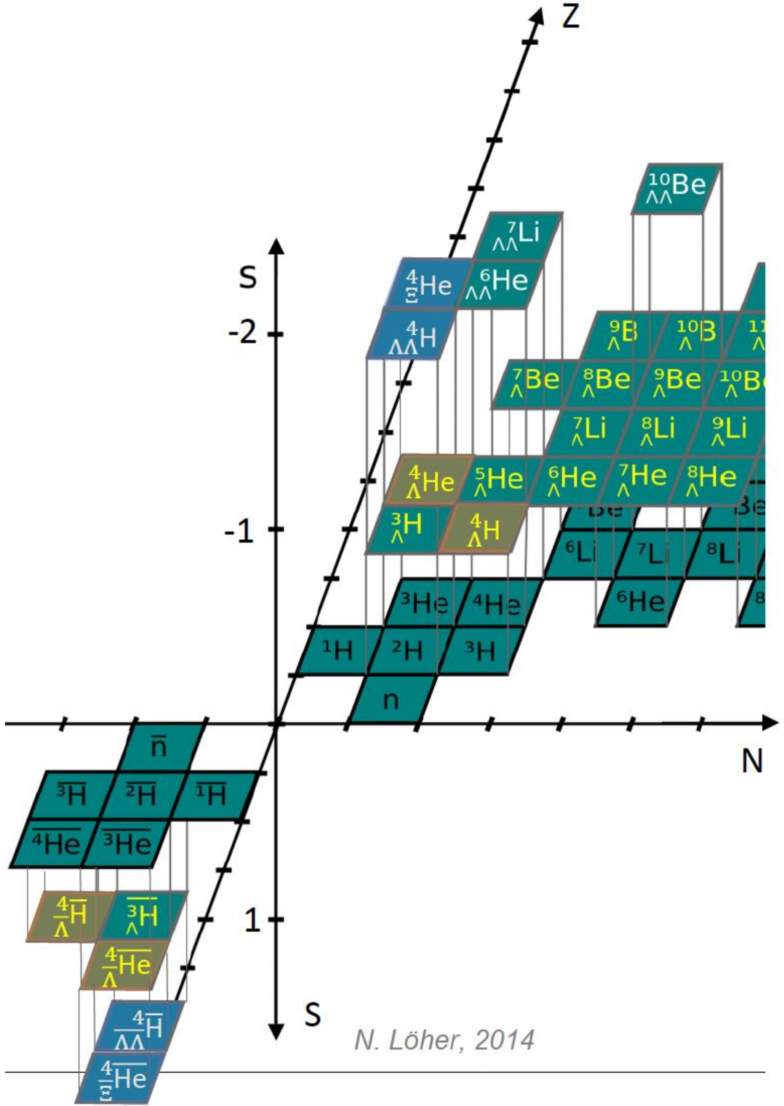
${}^{3}_{\Lambda}\mathrm{H}$

$B_{\Lambda} \approx$ O(keV)



Recently measured by ALICE!

ALICE, Phys. Rev. Lett. 131, 102302 (2023)



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Hildenbrand et. al., Phys. Rev. C 100, 034002 (2020)

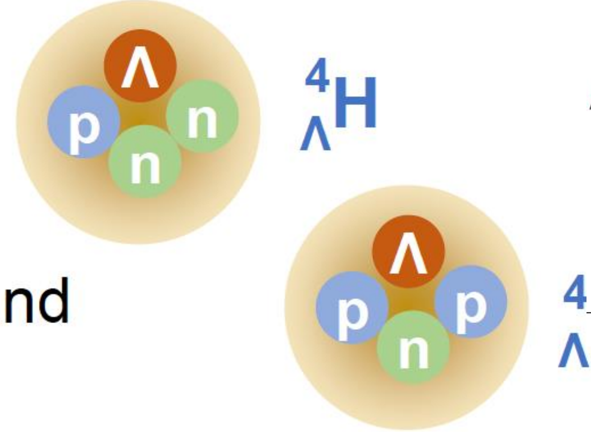
- Heavier hypernuclei at the LHC:

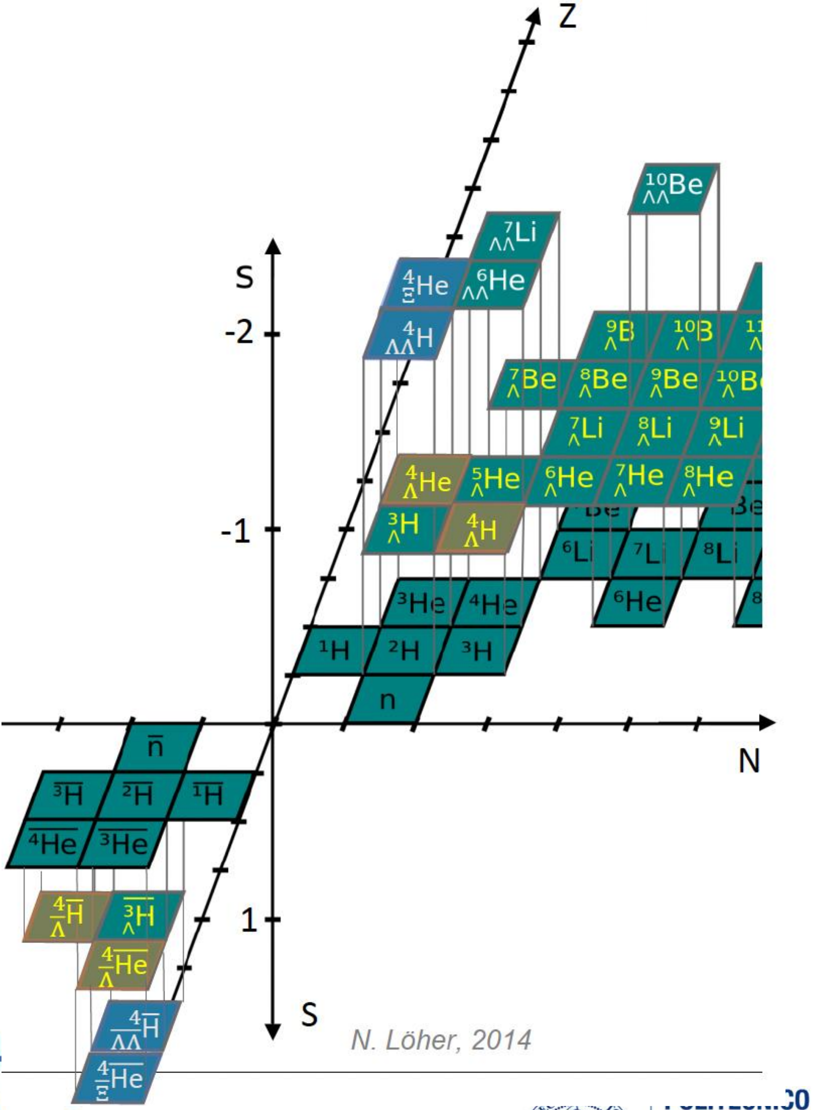
$$B_\Lambda \approx 2\ \text{MeV} \rightarrow r \approx 2\ \text{fm}$$

Yamamoto et. al., Phys. Rev. Lett. 115, 222501 (2015)

A = 4 hypernuclei are more bound and each has an excited state

Schäfer et. al., Phys. Rev. C 106, L031001 (2022)



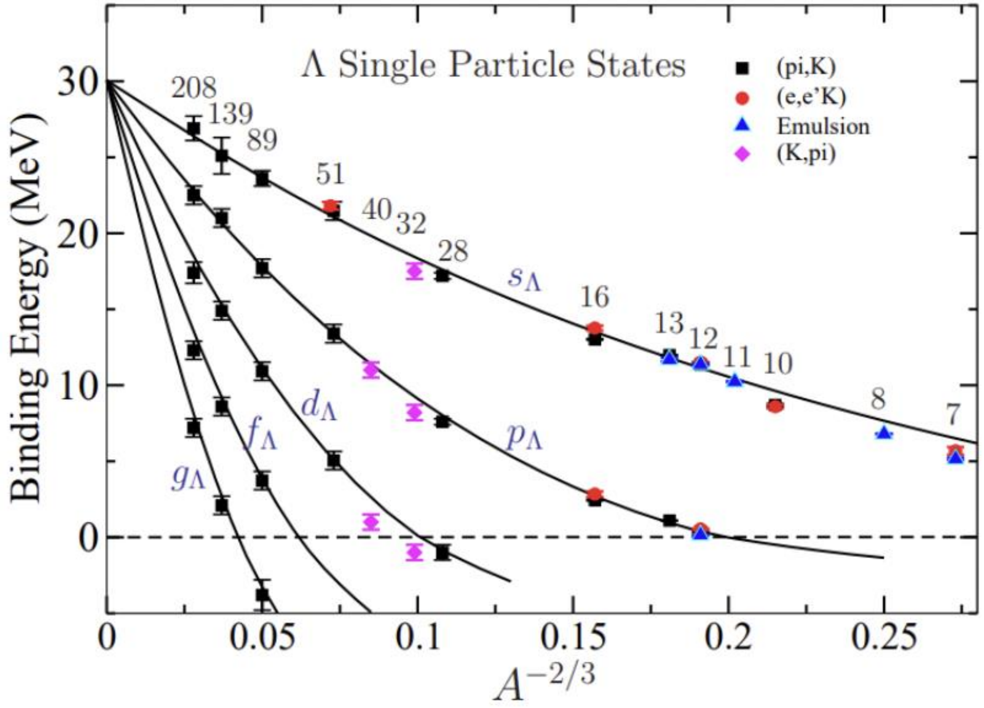


N. Löher, 2014

Anti-hypernuclei with ALICE

Hypernuclei: bound states of nucleons and hyperons

- Formation of interesting states (hypertriton, hyperhelium, ...), testing the nuclear shell model [1]



[1] Gal et al., Rev.Mod.Phys. 88 (2016) 3, 035004

Anti-hypernuclei with ALICE

Hypernuclei: bound states of nucleons and hyperons

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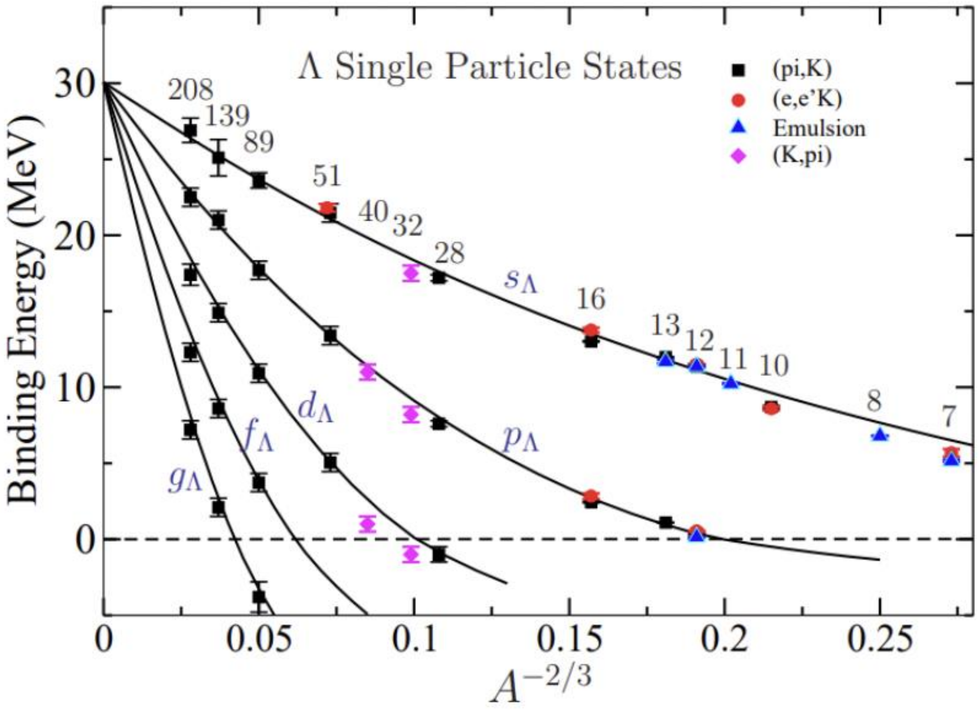
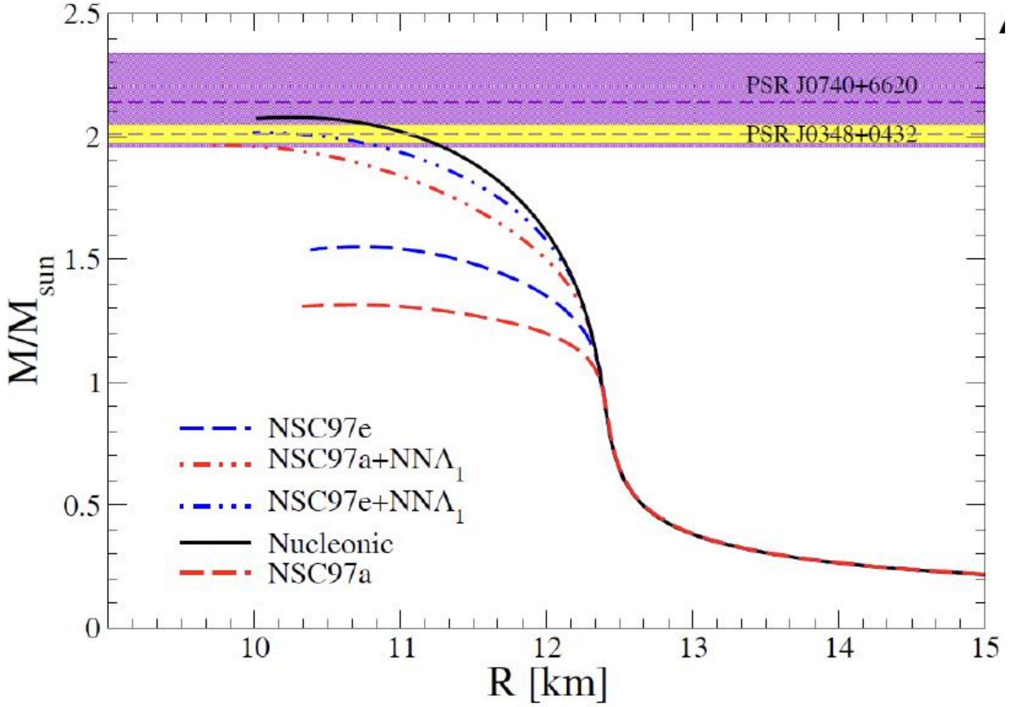
- Neutron stars' EOS [2] (understanding of Λ−N and Λ−Λ interaction!)





[1] Gal et al., Rev.Mod.Phys. 88 (2016) 3, 035004
[2] Logoteta et al., Eur.Phys.J.A 55 (2019) 11, 207

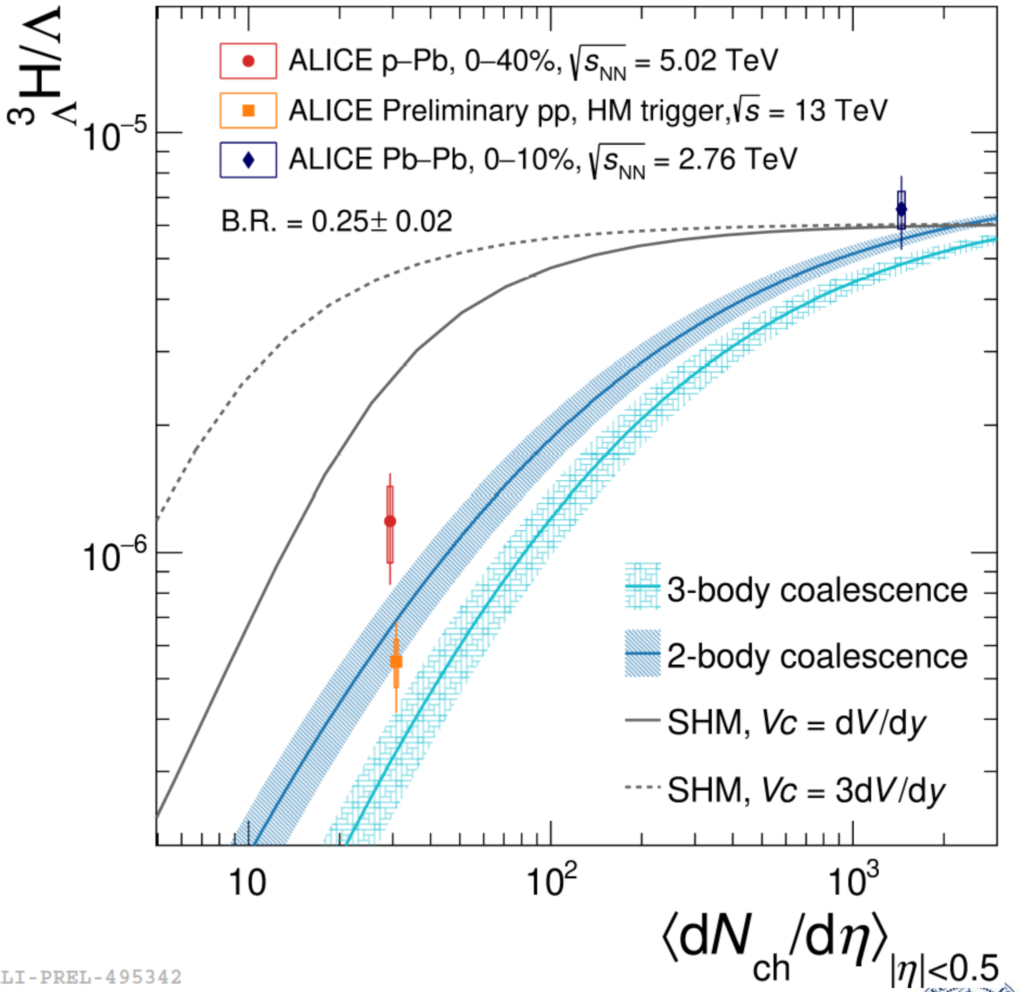
Hypertriton production in Run 2

For statistical hadronization models (SHM) the object size is not relevant →suppression due to canonical conservation of quantum numbers

In a coalescence picture large suppression of the production in small systems expected due to the large object size

Measurements in Run 2 pp and p–Pb collisions favor the coalescence approach

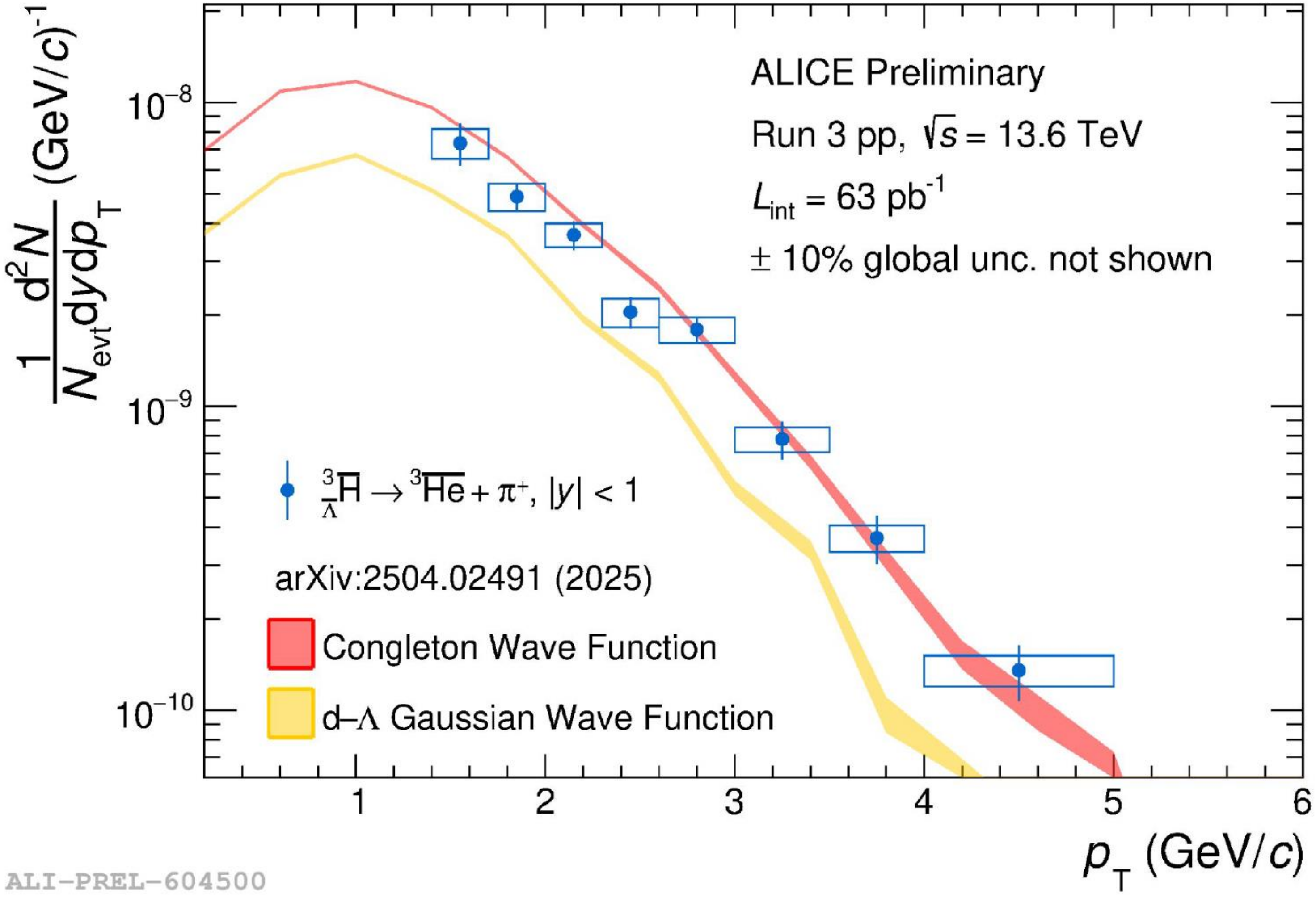
ALICE, Phys. Rev. Lett. 128 25, 252003 (2022)



ALI-PREL-495342

Hypertriton production in small systems

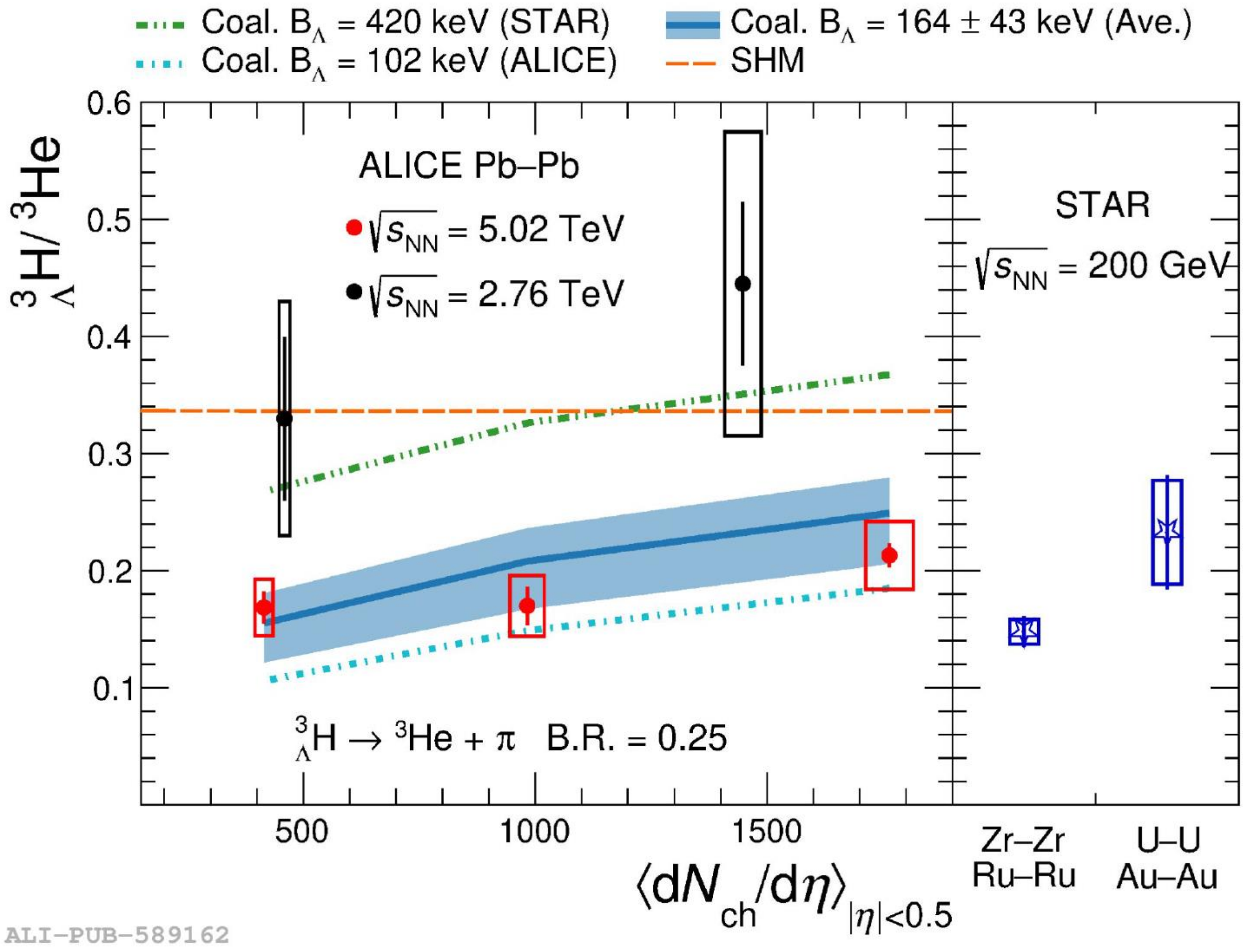
- First precise measurement of the p_T spectrum of ${}^{3}_{\Lambda}$H in pp
- Constraints on the wave function using realistic coalescence afterburner code [1]
  - ${}^{3}_{\Lambda}$H as a d-Λ system
  - Congleton wave function favoured by the data with respect to Gaussian



[1] Mahlein et al, Eur.Phys.J.C 84 (2024) 11, 1136

Hypertriton production in Pb-Pb

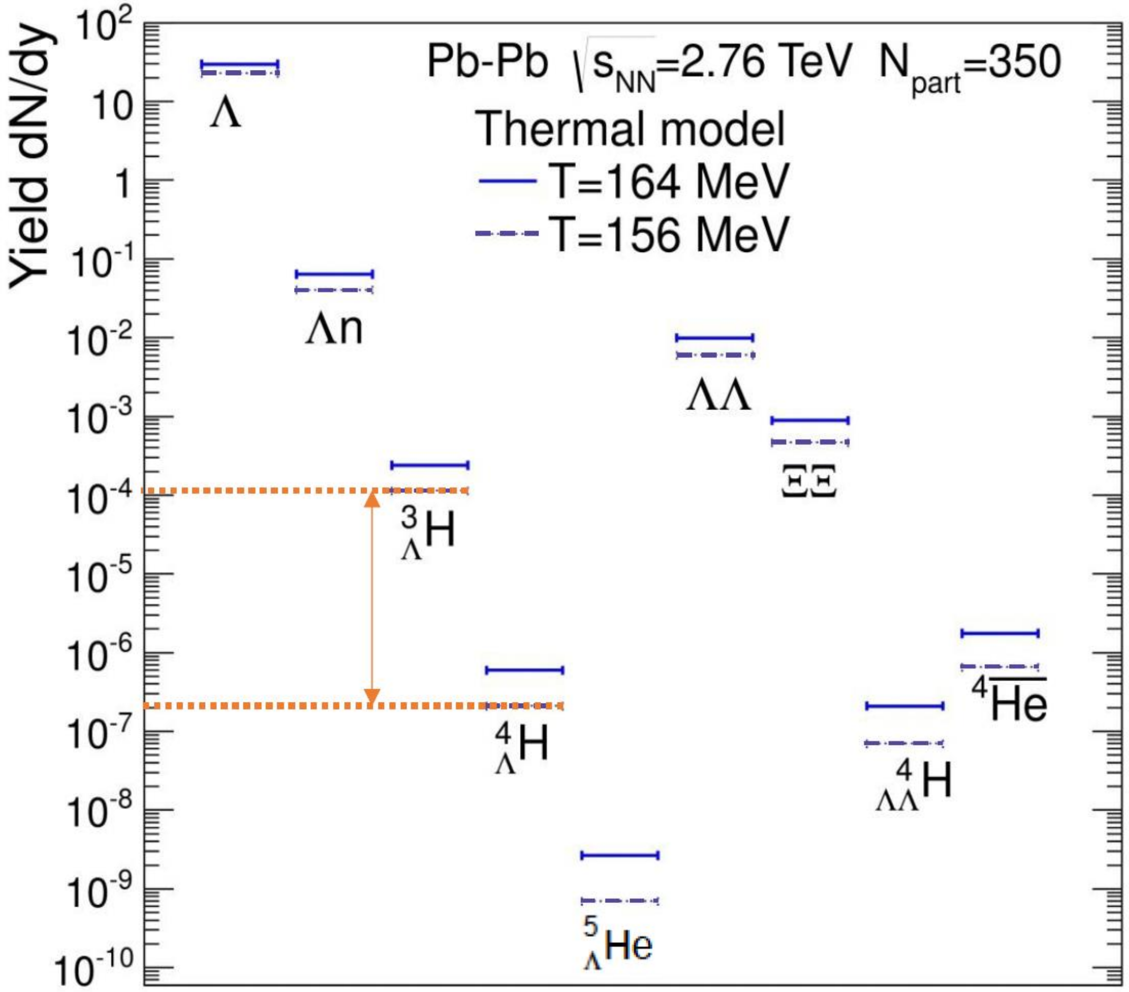
- The uncertainty on the ${}^{3}_{\Lambda}$H/^{3}He ratio is reduced by a factor > 4 compared to the LHC Run 1
    - Coalescence predictions with world-average B_Λ input agree with the data
    - ALICE measurements are in agreement with STAR data in other ion-ion systems at lower centre-of-mass energy



[1] Phys. Lett. B 860 (2025) 139066

A=4 hypernuclei in ALICE

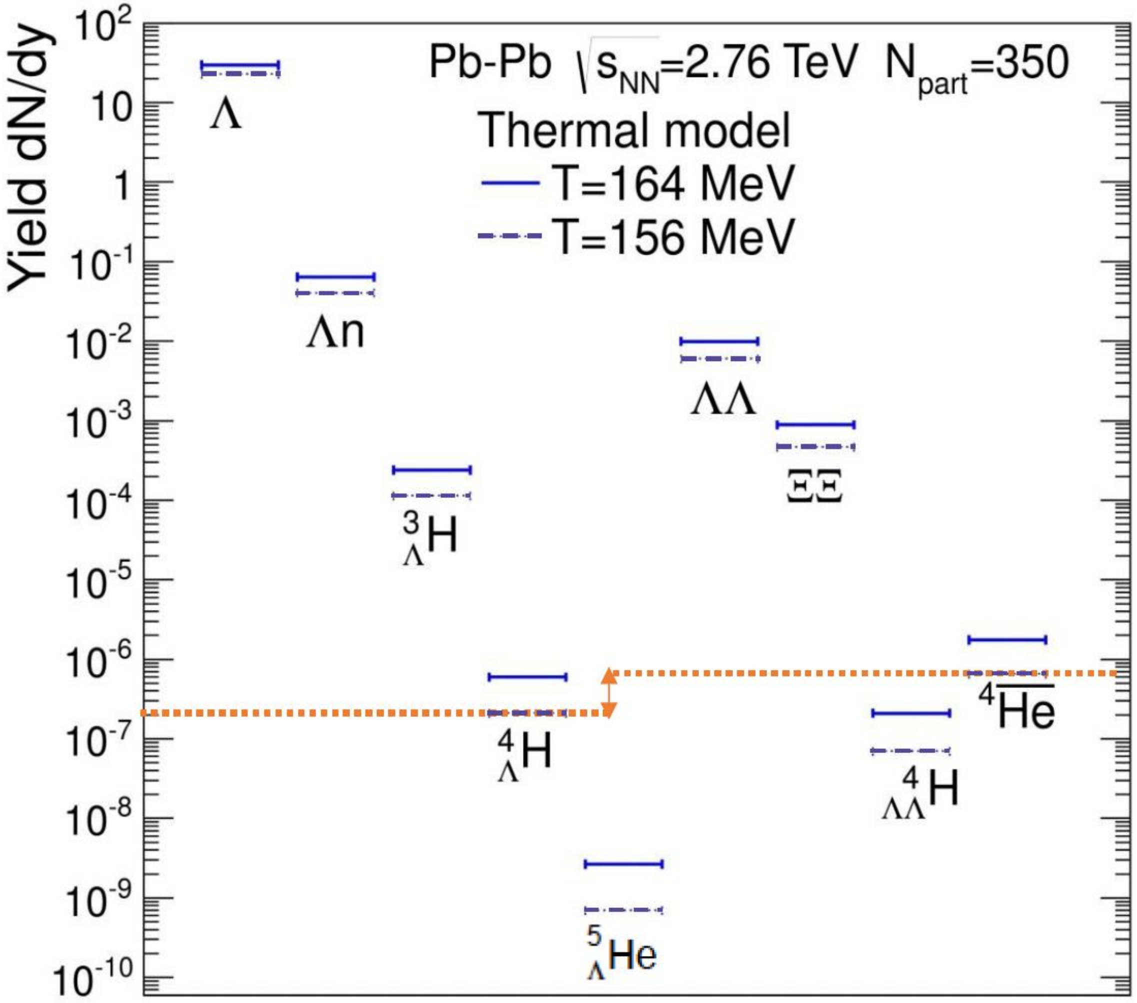
- Expectations for hypernuclei from the statistical hadronization model at T_{ch} = 156 MeV
- Penalty factor by adding one nucleon to a particle ≈ 300 in Pb–Pb collisions



A. Andronic, private communication
model from A. Andronic et al., Phys. Lett. B 697, 203 (2011)

A=4 hypernuclei in ALICE

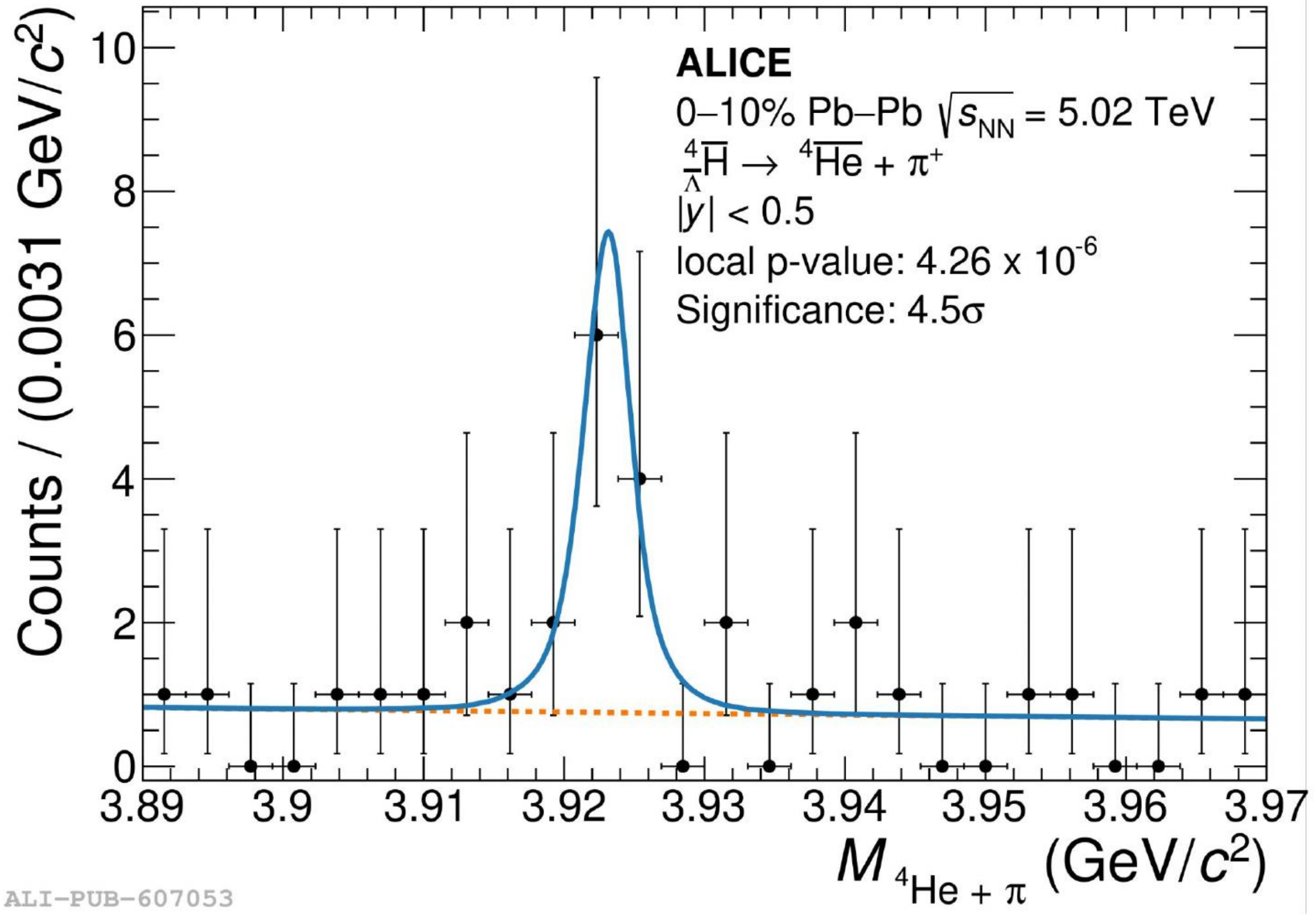
- Expectations for hypernuclei from the statistical hadronization model at T_{ch} = 156 MeV
- Penalty factor by adding one nucleon to a particle ≈ 300 in Pb—Pb collisions
- Further suppression due to strangeness content
- Large statistics needed



A. Andronic, private communication
model from A. Andronic et al., Phys. Lett. B 697, 203 (2011)

A=4 hypernuclei production in Pb–Pb

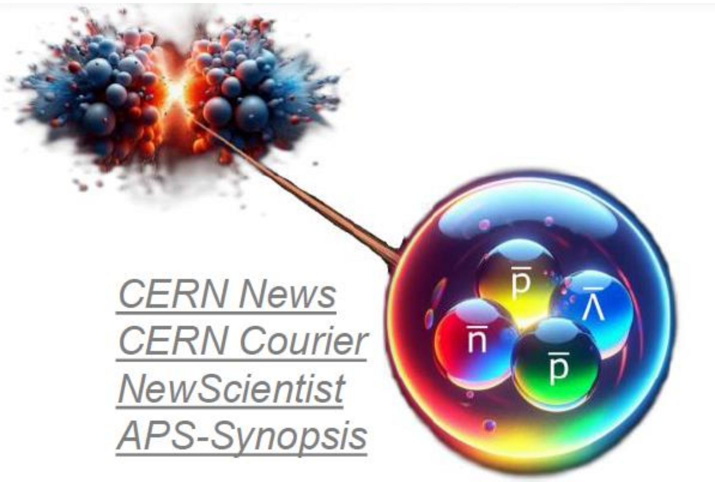
- (Anti)$^{4}_{\Lambda}$H and (anti)$^{4}_{\Lambda}$He reconstructed in Pb–Pb through charged 2-body and 3-body decay channels
    - Identification of the candidates relying on machine learning



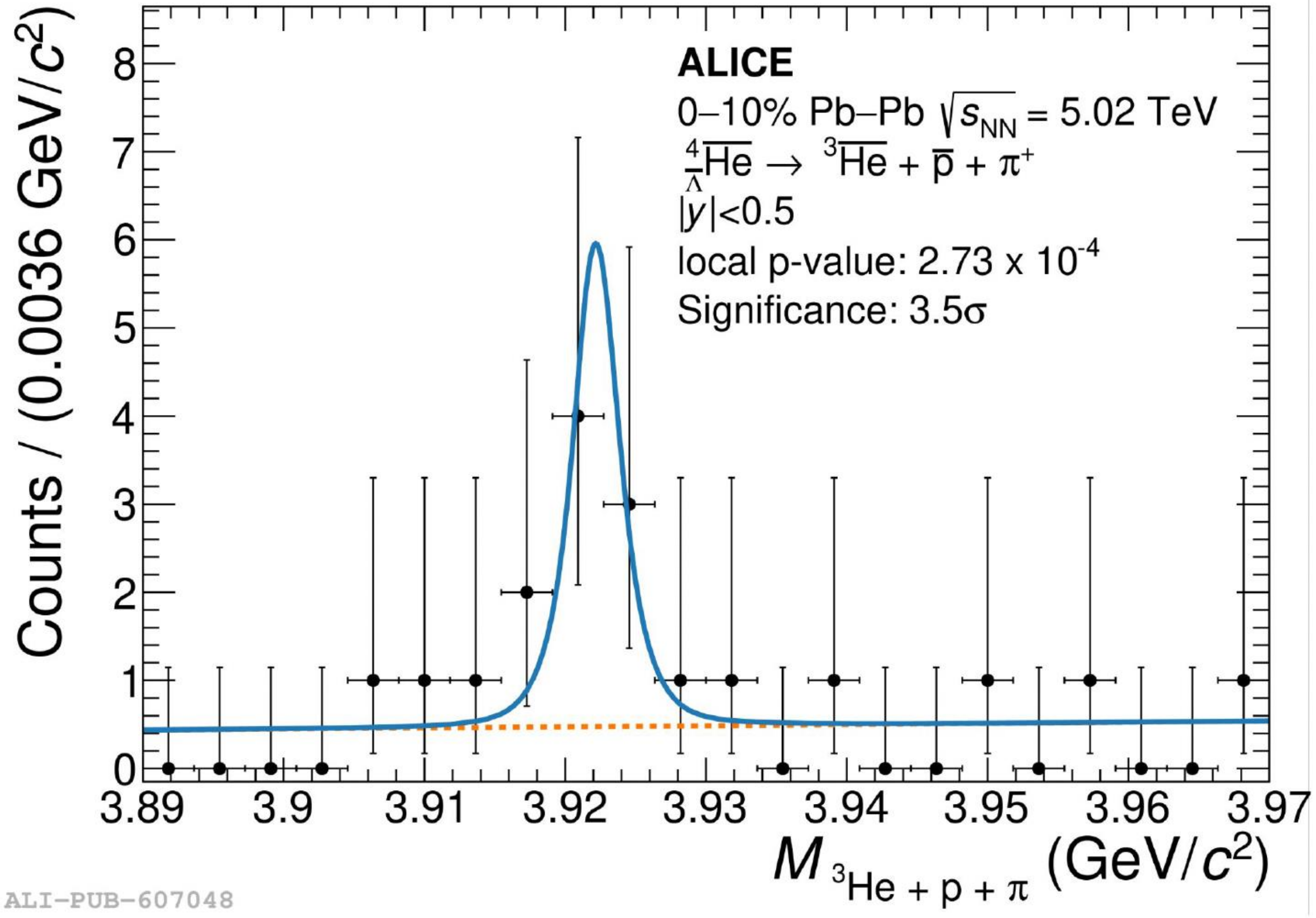
[1] Phys. Rev. Lett. 134 (2025) 162301

A=4 hypernuclei production in Pb–Pb

- (Anti)$^{4}_{\Lambda}$H and (anti)$^{4}_{\Lambda}$He reconstructed in Pb–Pb through charged 2-body and 3-body decay channels
  - Identification of the candidates relying on machine learning
  - Anti$^{4}_{\Lambda}$He → first evidence of this antimatter state



CERN News
CERN Courier
NewScientist
APS-Synopsis

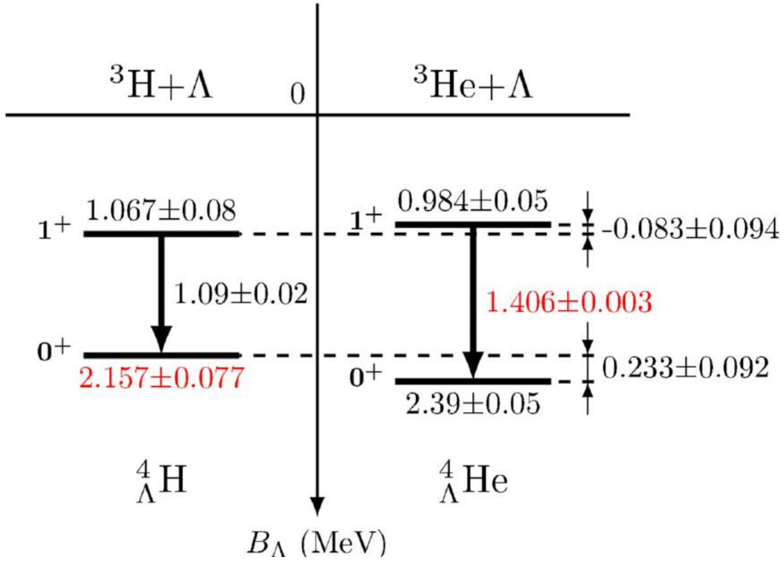


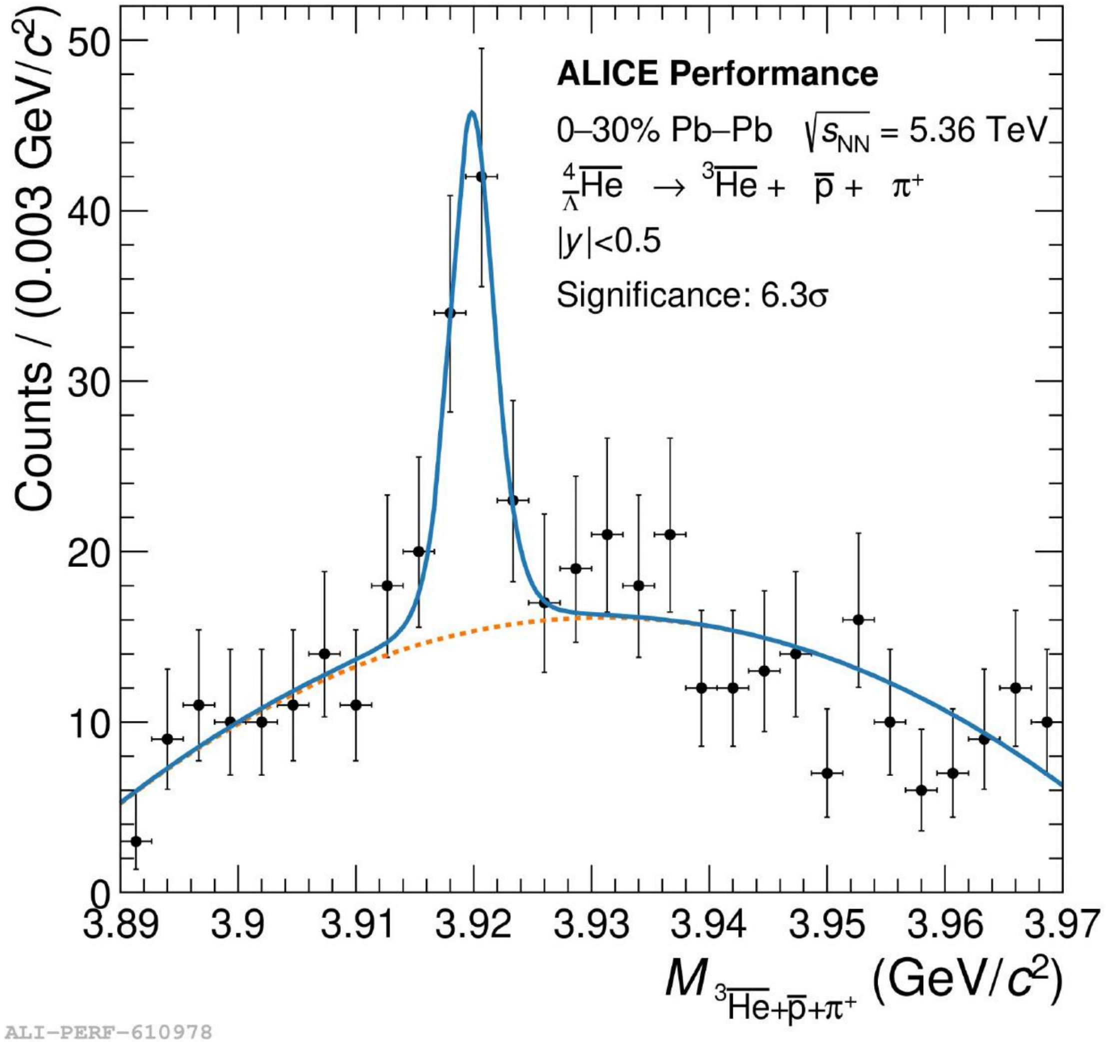
ALI-PUB-607048

[1] Phys. Rev. Lett. 134 (2025) 162301

A=4 hypernuclei production in Run 3

- Larger integrated luminosity in Run 3 → observation of anti$^{4}_{\Lambda}$He with > 5σ significance
- Enabling precision study of strong interaction properties, e.g., charge symmetry breaking of Λ-nucleon interaction [1]





ALI-PERF-610978

[1] Gal et al, J. Phys. Conf. Series 966 (2018) 012

Summary

- *Production of antinuclei measured at accelerators are crucial input in astrophysical searches for dark matter*
- *Antinuclear production measurements in and out of jets in pp and p-Pb collisions helps to further constrain the coalescence model*
- *Measurements of antinuclear production vs. rapidity used to extrapolate B_2 at forward rapidity → predict antinuclear flux from cosmic rays*
- *A wealth of new precision measurements is becoming available to the community also for A=4*
- *The upgraded ALICE apparatus plays a central role in (hyper)nuclear physics at the LHC*

Thank you!

stefania.bufalino@polito.it