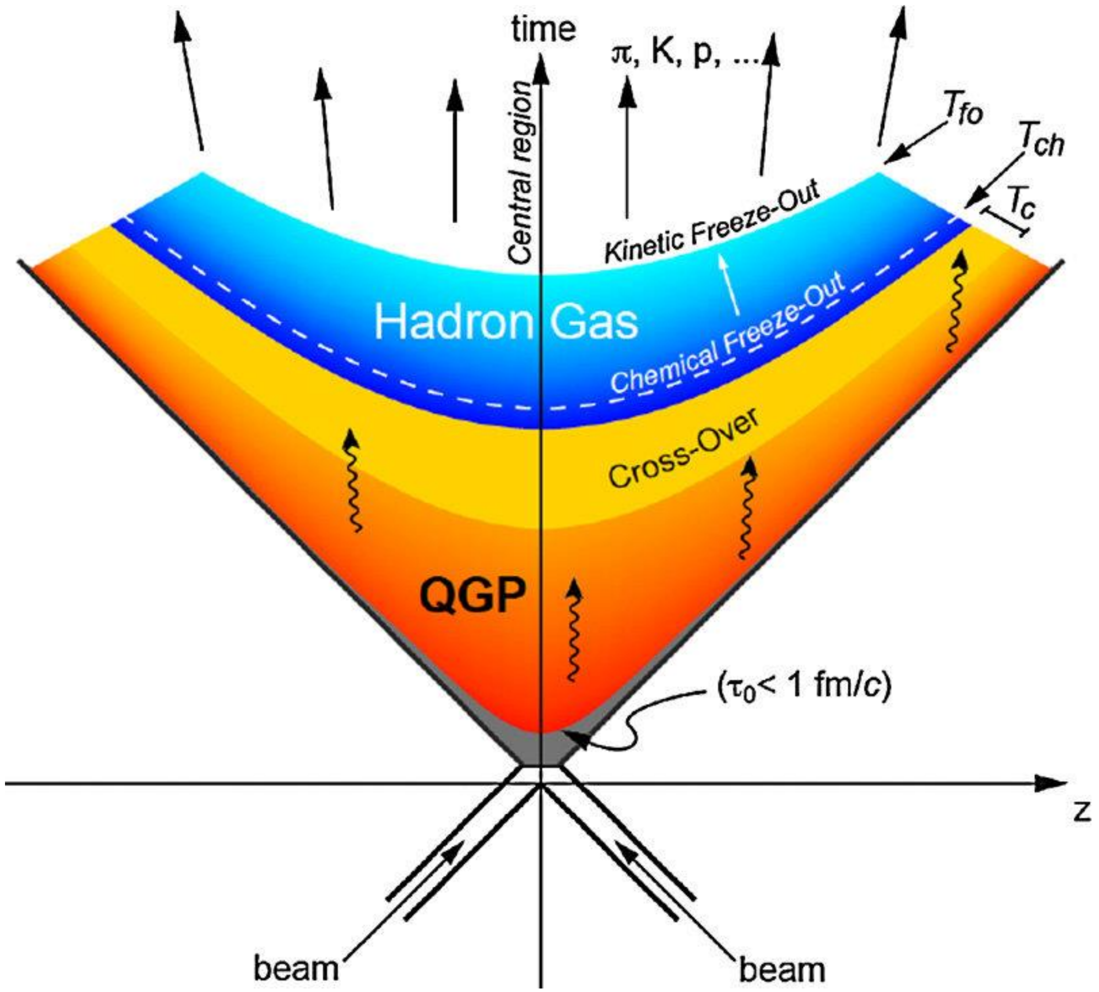
Measurement of the deuteron coalescence probability in jets with ALICE

Marika Rasà*
On behalf of the ALICE Collaboration

*University and INFN of Catania

Physics motivation



- Light (anti)nuclei are produced in high-energy hadronic collisions at the LHC
- Matter and antimatter are produced in (almost) the same amount at midrapidity
- Their production mechanism is still not understood
- Two phenomenological models:
  - Statistical hadronization
  - Coalescence

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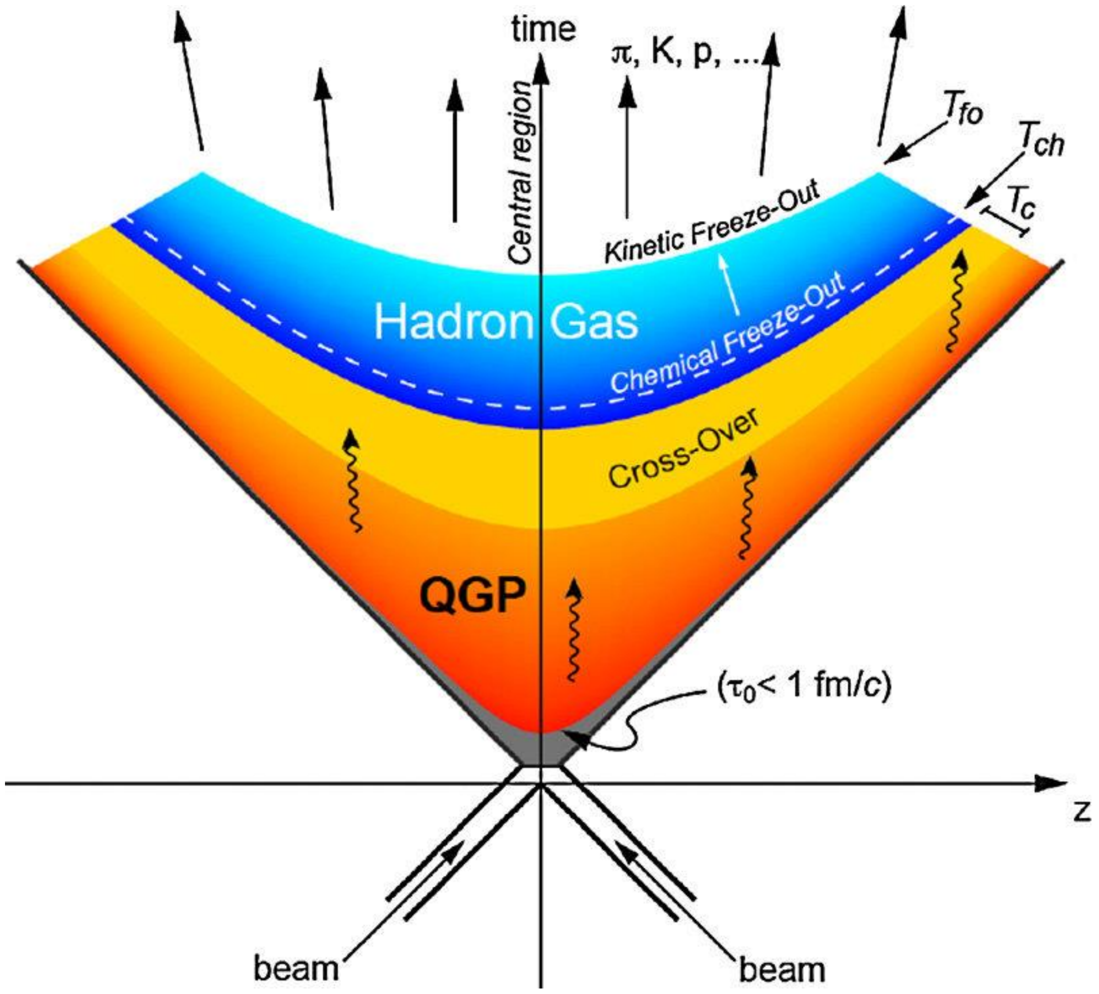

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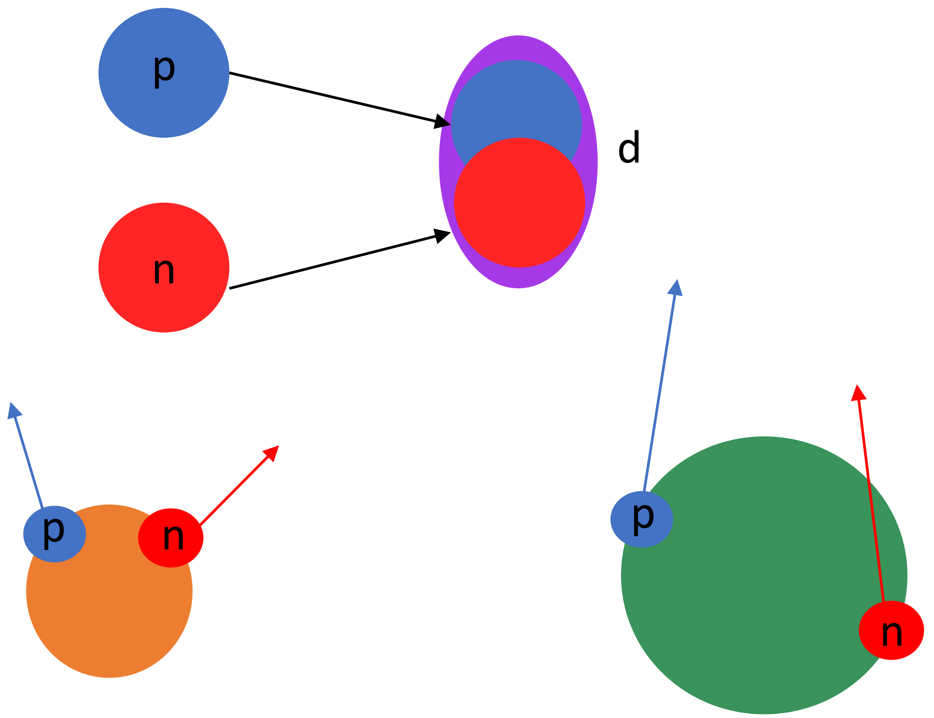
- Two phenomenological models:
  - Statistical hadronization
  - Coalescence *Focus on it*

Coalescence model

S. T. Butler et al., Phys. Rev. 129 (1963) 836



Small source size → Large B_A

pp ~ 1 fm

p–Pb ~ 1.5 fm

Large source size → Small B_A

Pb–Pb ~ 3-6 fm

- If (anti)nucleons are close in phase space and match the spin state, they can form an (anti)nucleus

- Coalescence parameter B_A is the key observable:

$$E_{\mathrm{A}} \frac{\mathrm{d}^3 N_{\mathrm{A}}}{\mathrm{d}p_{\mathrm{A}}^3} = B_{\mathrm{A}} \cdot \left(E_{\mathrm{p}} \frac{\mathrm{d}^3 N_{\mathrm{p}}}{\mathrm{d}p_{\mathrm{p}}^3} \right)^{\mathrm{A}} \qquad p_{\mathrm{p}} = p_{\mathrm{A}}/\mathrm{A}$$

Invariant yield of nucleus | Coalescence parameter | Invariant yield of protons

- Coalescence parameter depends on both the source size and radial extension of the nucleus wave function:

In-jet and underlying event

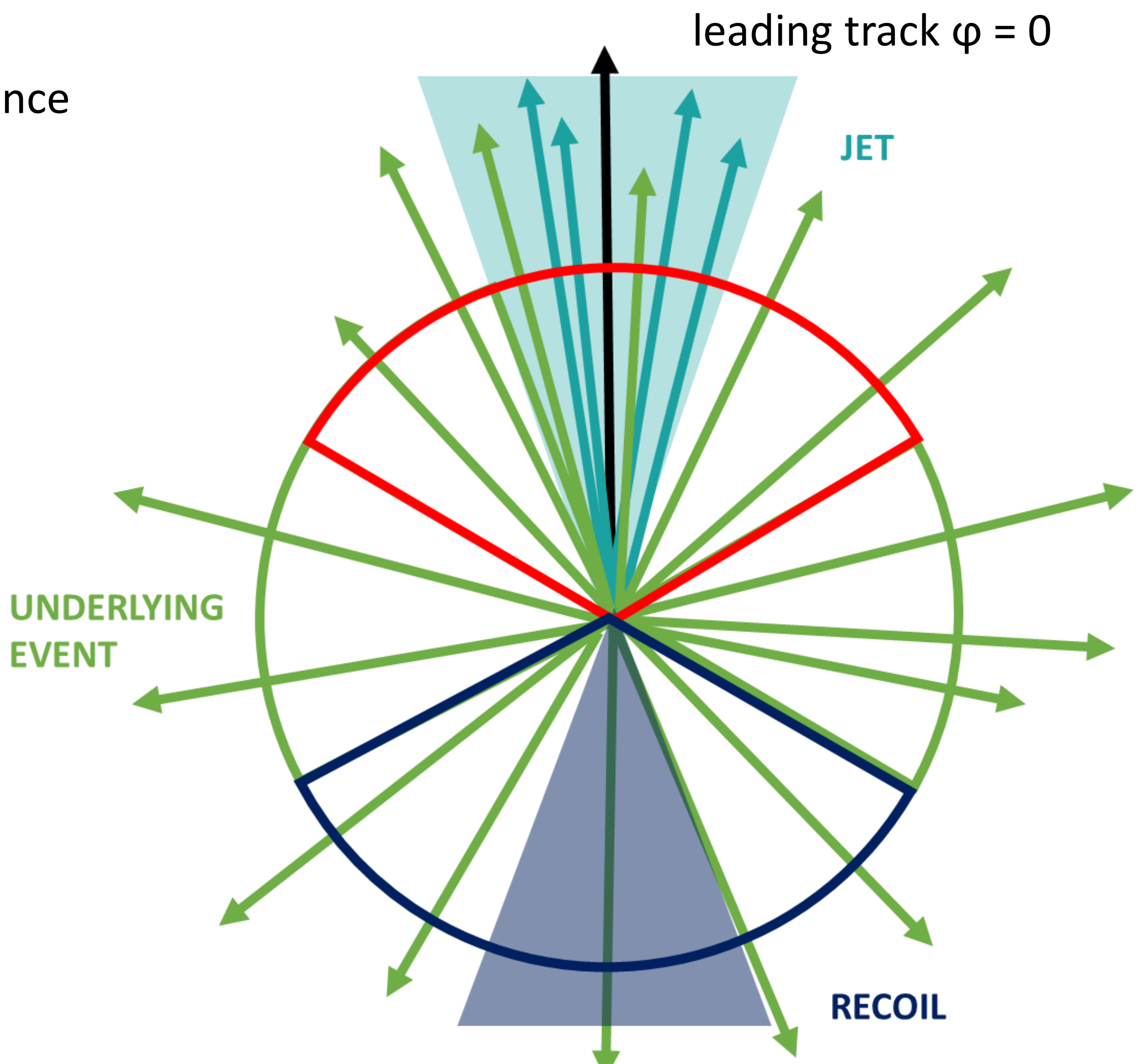
- The study in small systems, such as pp and p–Pb, is interesting since the nucleons are closer in phase space wrt Pb–Pb

- Leading particle (highest p_T and $p_T > 5$ GeV/c) used as a proxy for the jet axis

- CDF technique used to find the three azimuthal regions

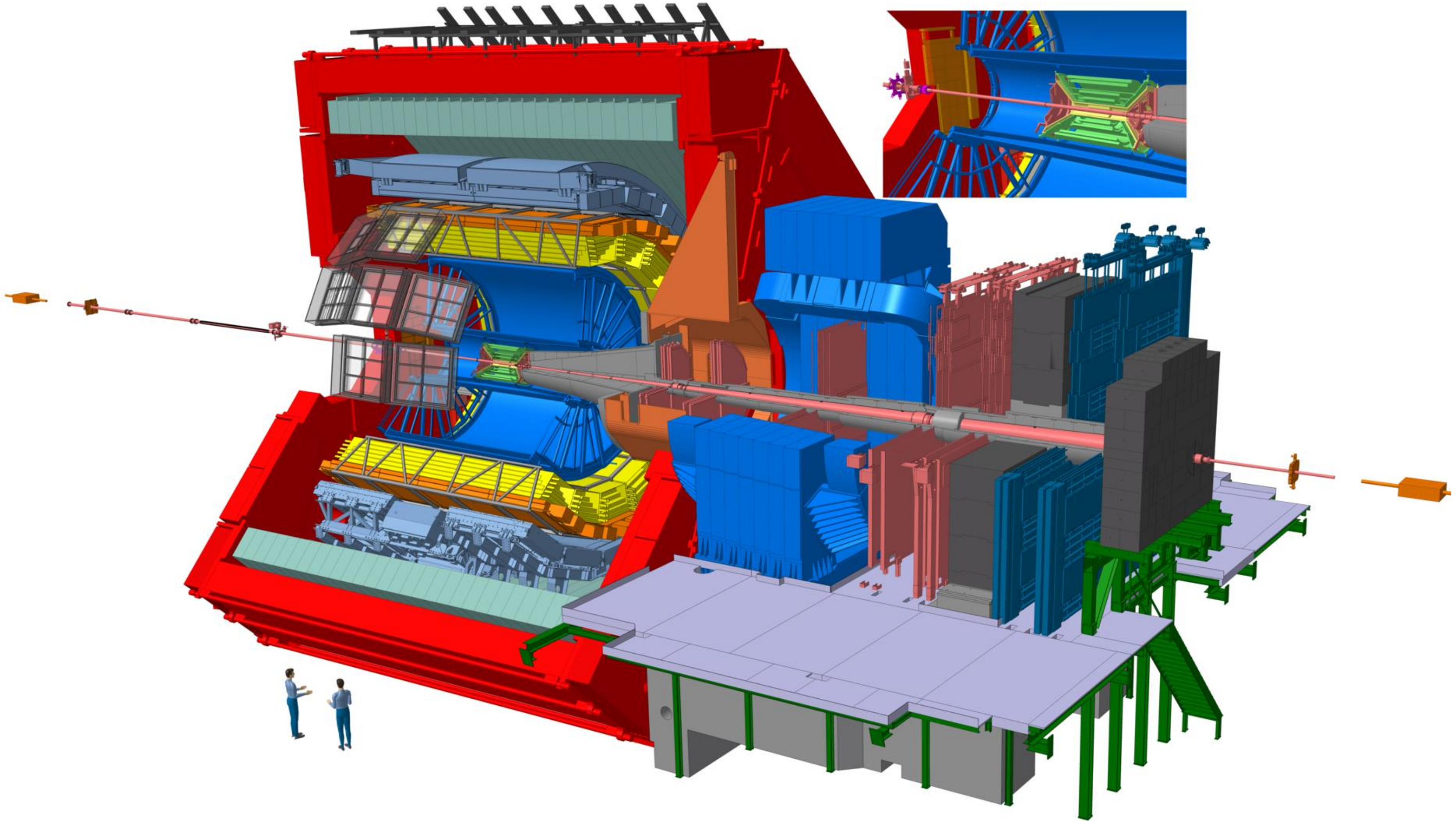
  - **Toward** ($|\Delta\varphi| < 60°$) : contains JET and UE
  - **Transverse** ($60° < |\Delta\varphi| < 120°$) : dominated by the Underlying Event (UE)
  - **Away** ($|\Delta\varphi| > 120°$): contains recoil jet and UE

- **Jet**: **Toward** – **Transverse**



Martin, T., Skands, P. & Farrington, S. *Eur. Phys. J. C* **76**, 299 (2016)

The ALICE detector in Run 2



- Most suited LHC experiment to study light (anti)nuclei production
- Excellent PID capabilities

JINST 3 (2008) S08002
Int. J. Mod. Phys. A 29 (2014) 1430044

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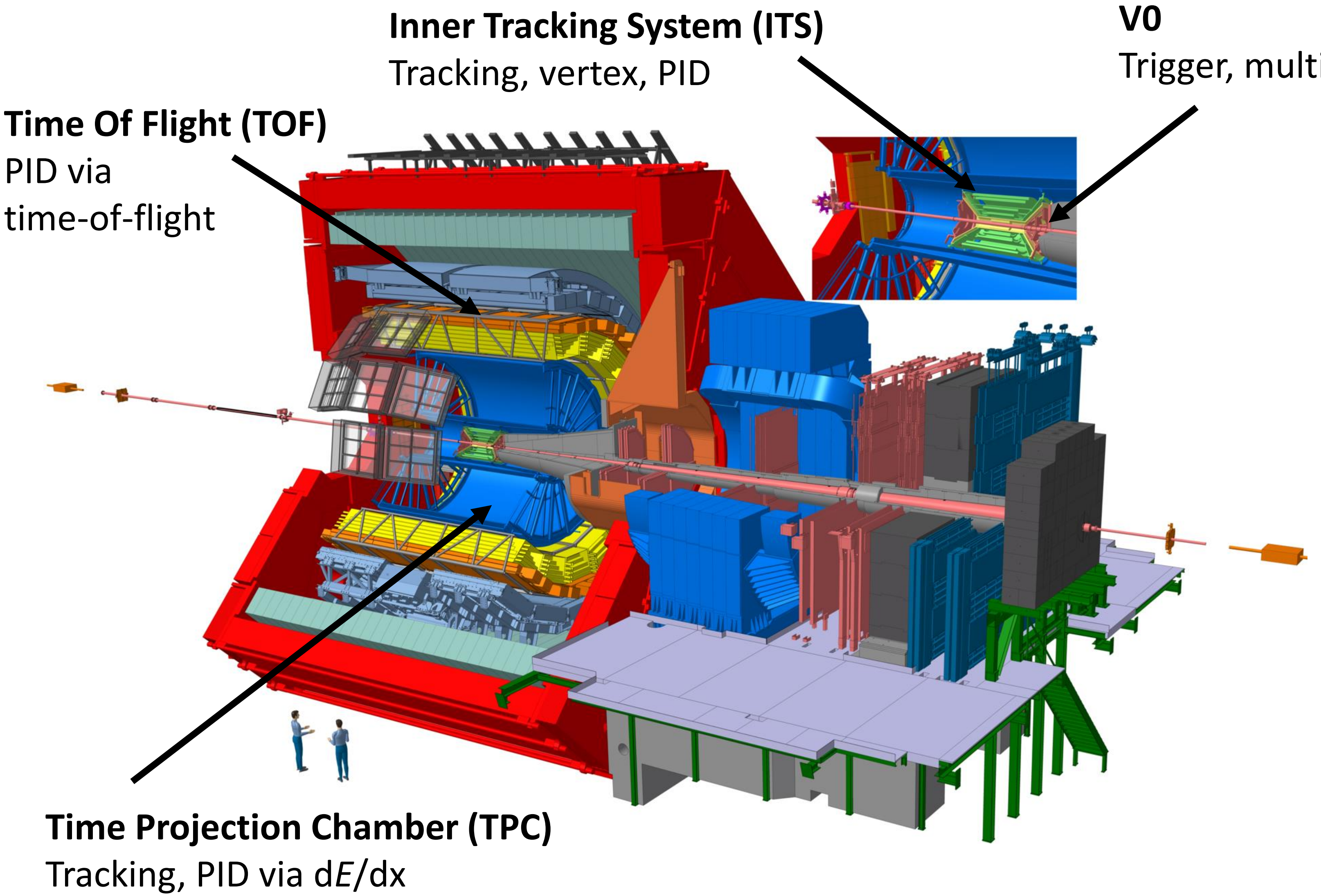

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- Excellent PID capabilities

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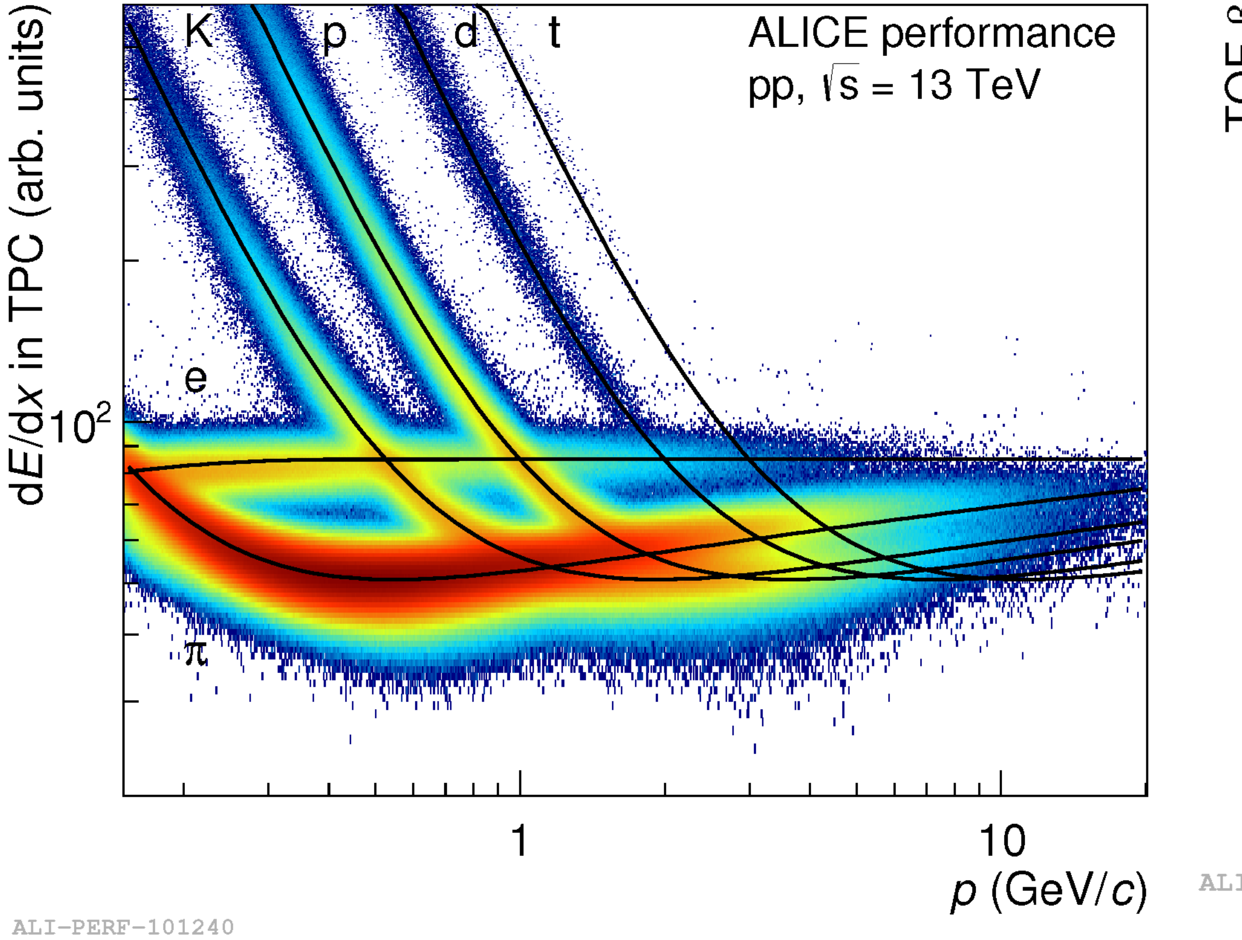
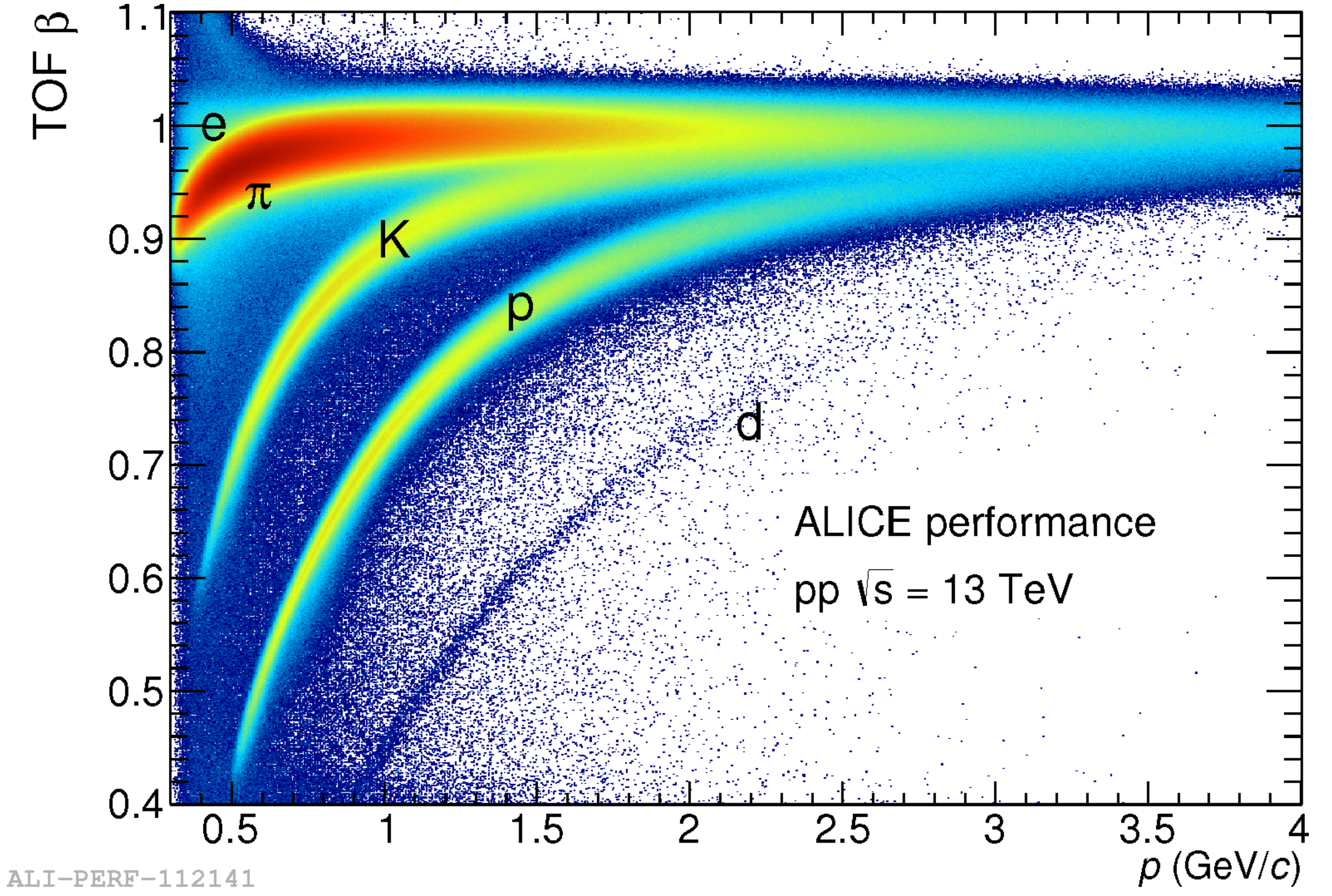
Deuteron identification

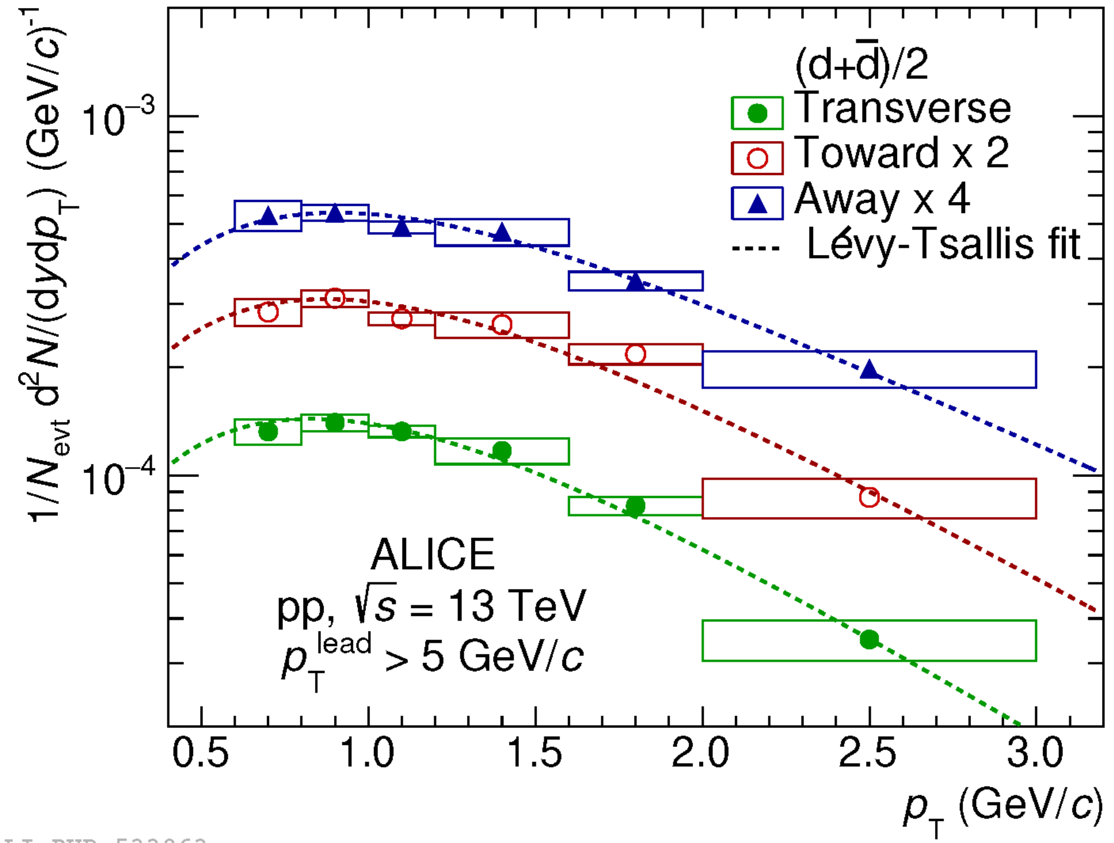


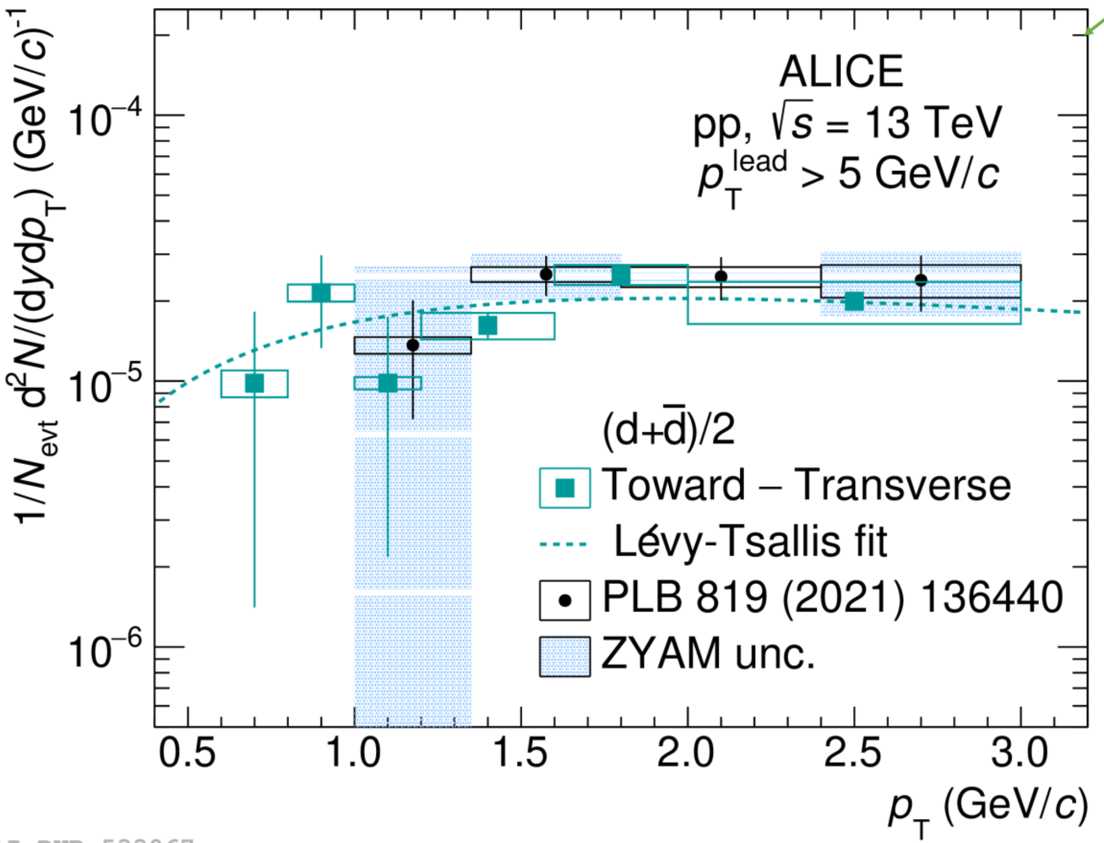


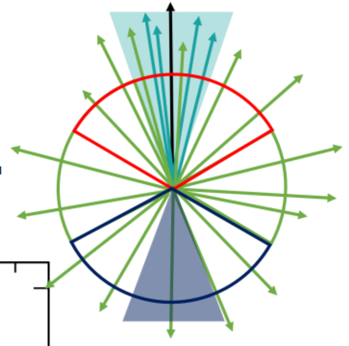
Low p_T region (below 1 GeV/c): PID via dE/dx
$\sigma_{dE/dx}$ ~ 5.5% in pp, ~ 7% in Pb–Pb

High p_T region (over 1 GeV/c): PID via time-of-flight
σ_{PID} ~ 70 ps for pp, ~ 60 ps for Pb–Pb

(Anti)deuteron spectra: pp @ 13 TeV







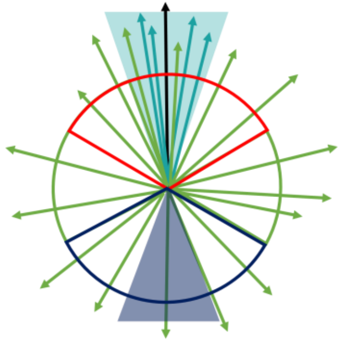
Jet = Toward – Transverse

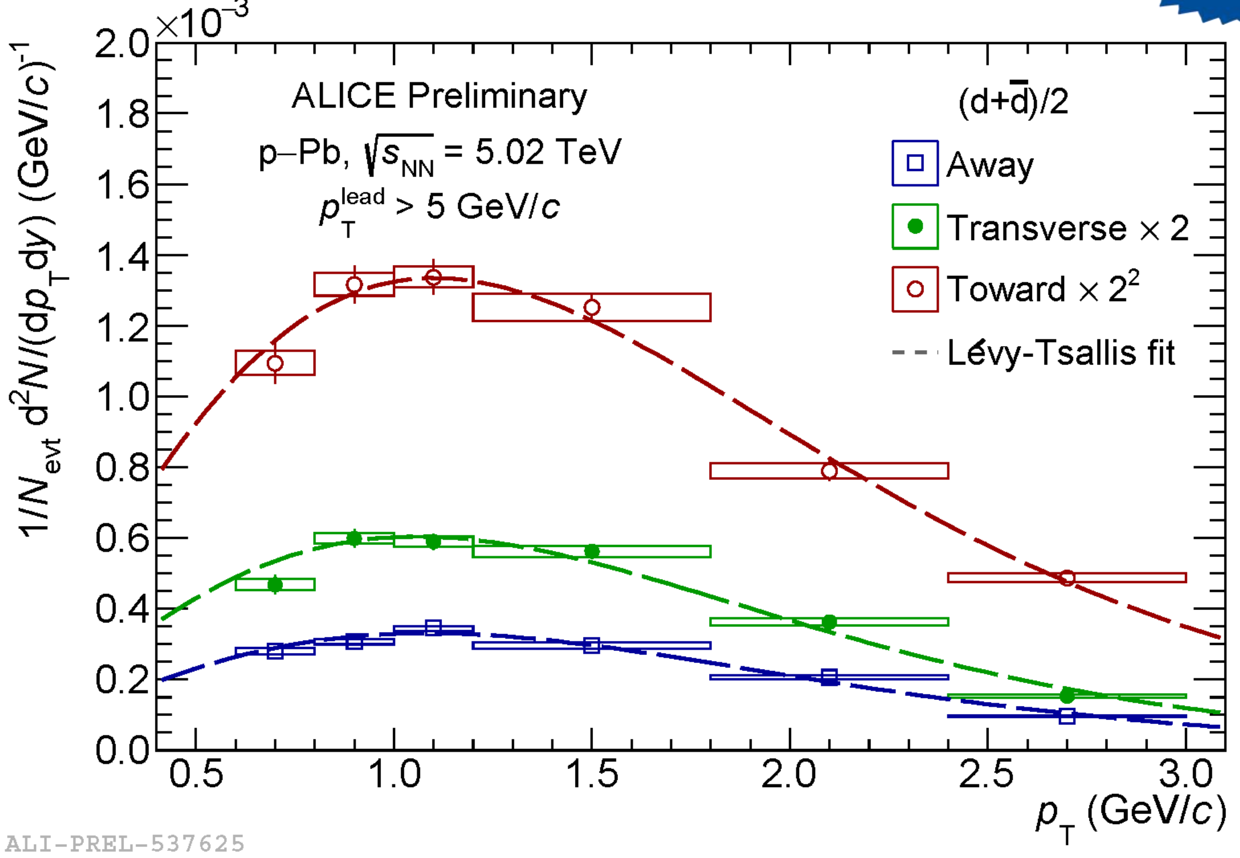
arXiv:2211.15204v1

Deuteron production in events with p_T^{lead} > 5 GeV/c

The results are consistent with those obtained using the two-particle correlation method

(Anti)deuteron spectra: p–Pb @ 5.02 TeV





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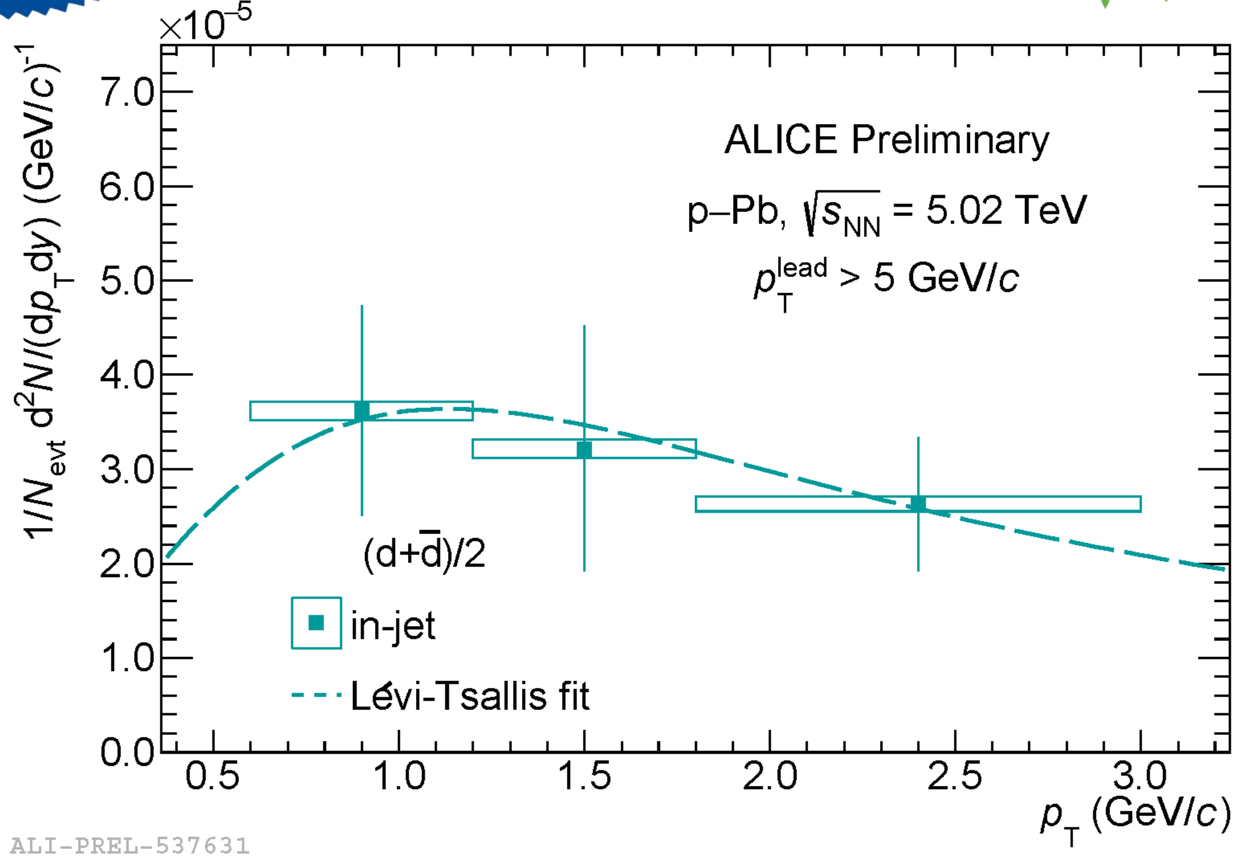
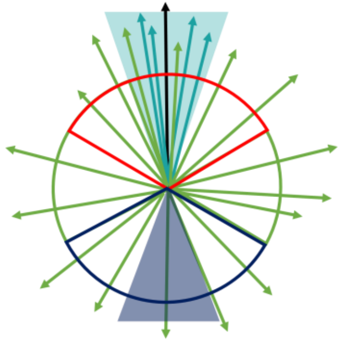
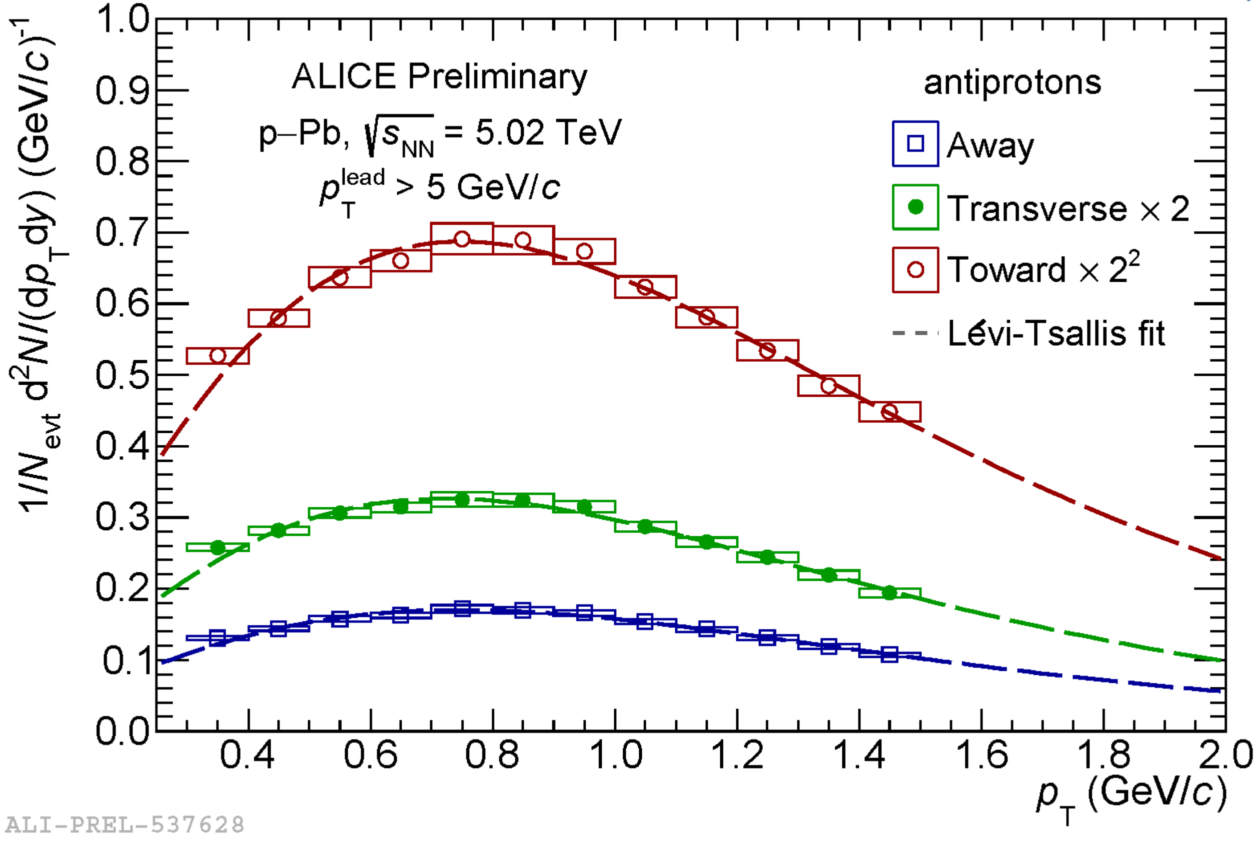


Jet = Toward - Transverse

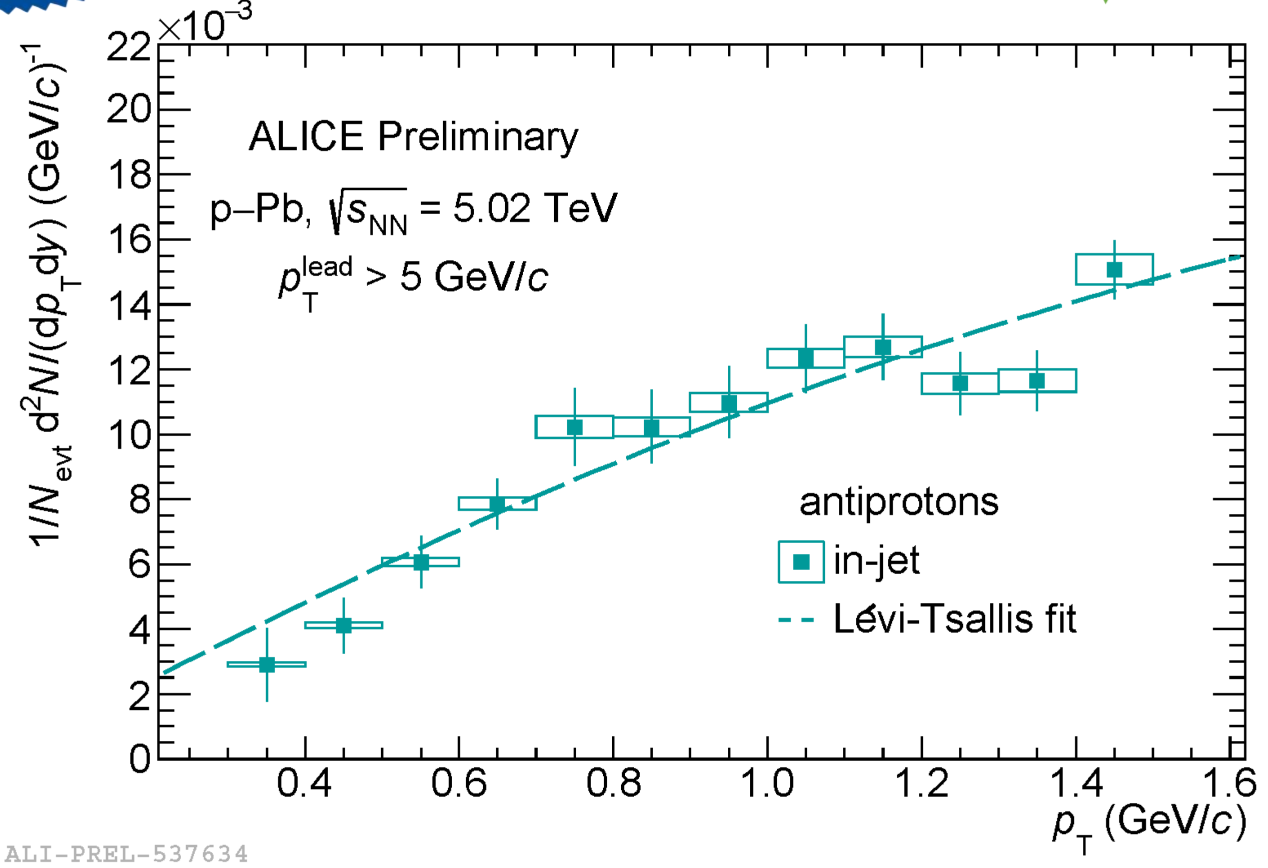
Antiproton spectra: p–Pb @ 5.02 TeV



NEW!

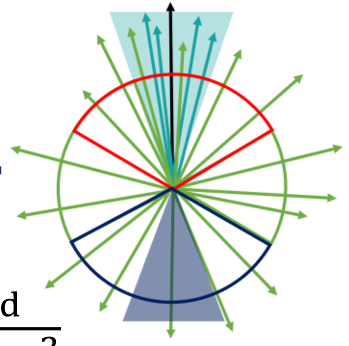


Antiproton production in events with p_T^{lead} > 5 GeV/c

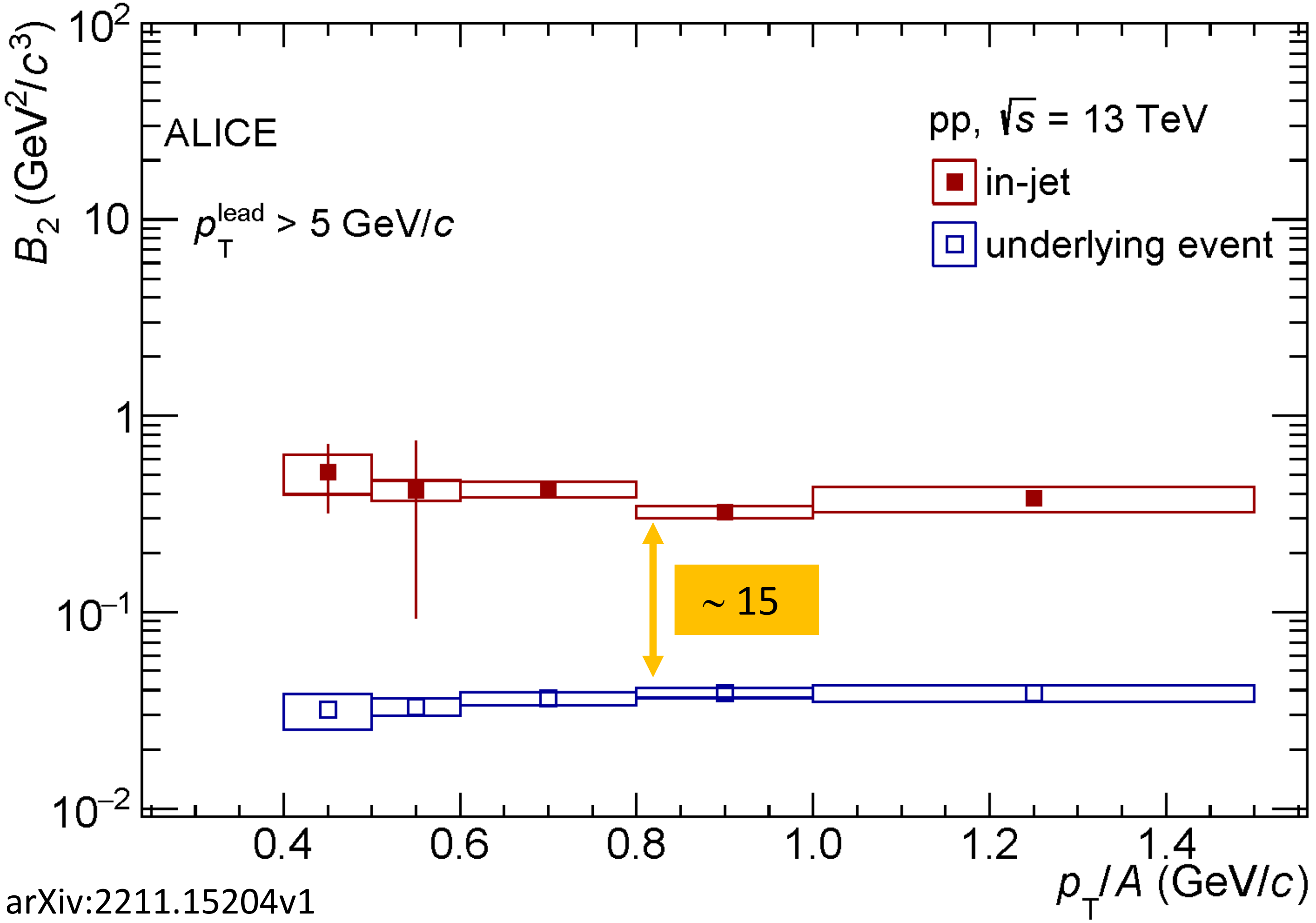


Jet = Toward - Transverse

B_2 in jet and UE



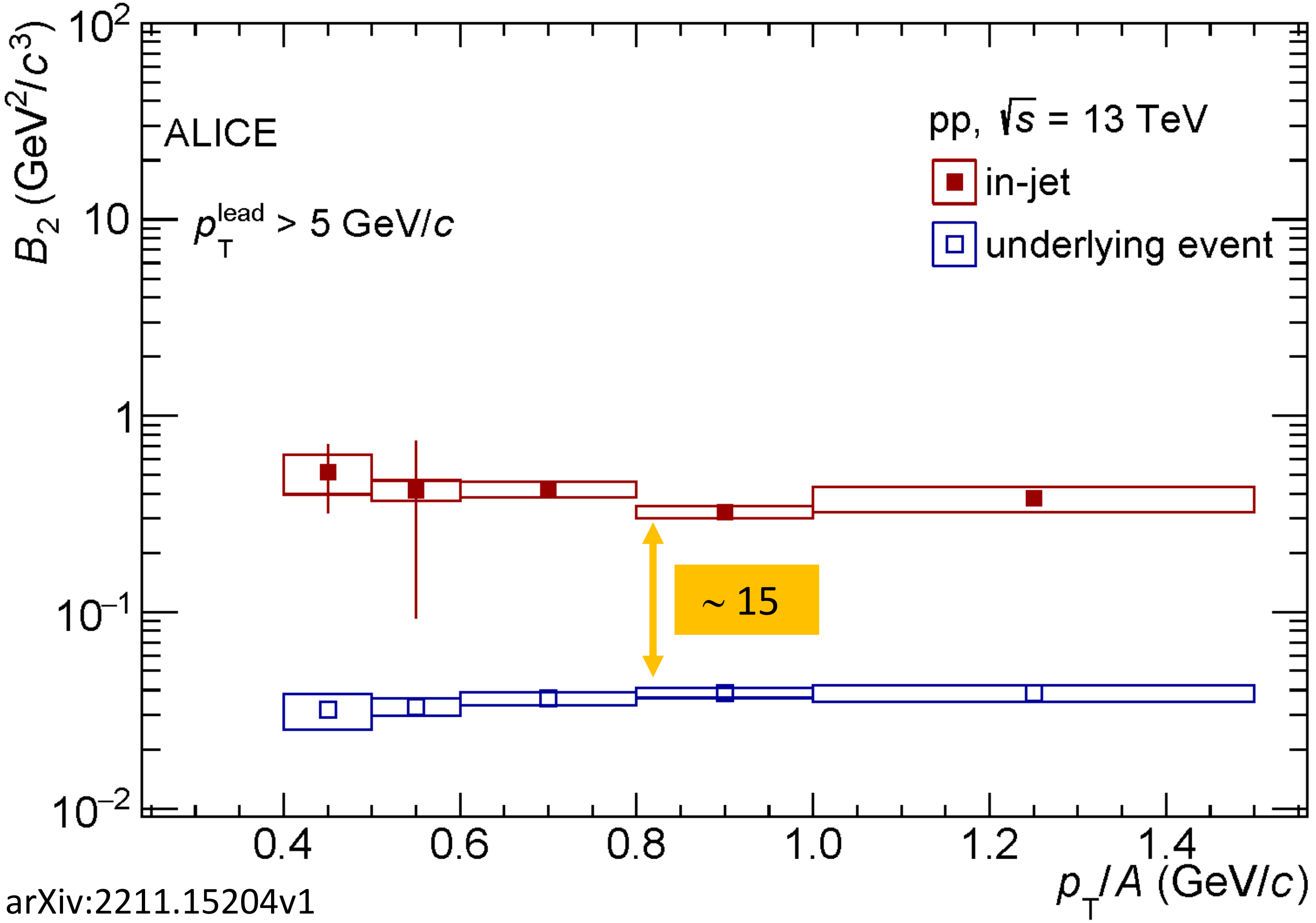
$$B_2 = \frac{\frac{1}{(2\pi/3)p_T^d}\left(\frac{d^2N}{dydp_T}\right)_d}{\left(\frac{1}{(2\pi/3)p_T^p}\left(\frac{d^2N}{dydp_T}\right)_p\right)^2}$$



arXiv:2211.15204v1

- Enhancement of B_2^{jet} wrt B_2^{UE} in pp collisions

B_2 in jet and UE



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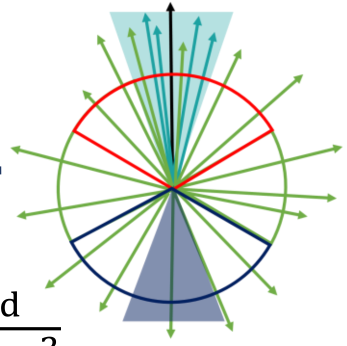

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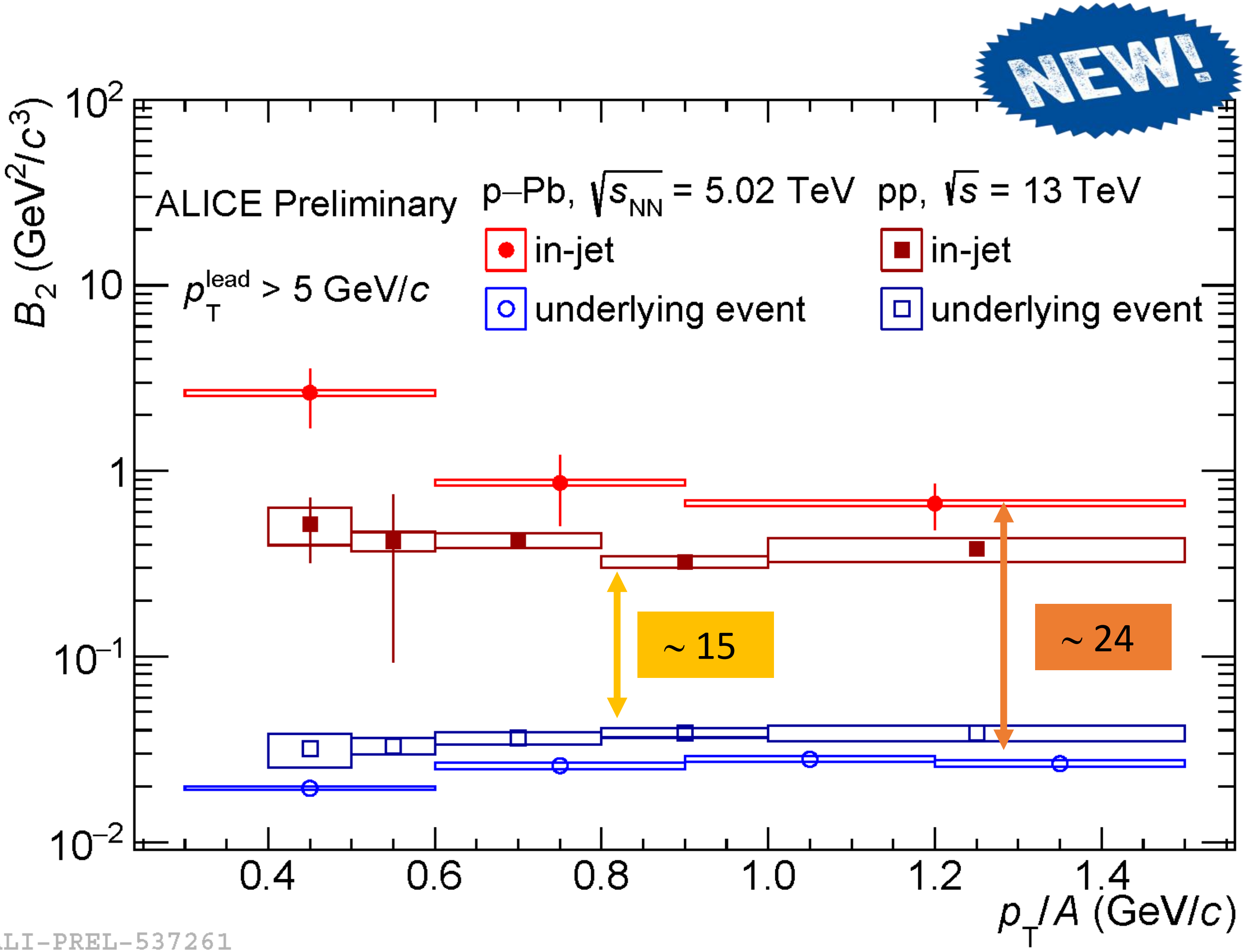
- What happens in p–Pb collisions?

B_2 in jet and UE



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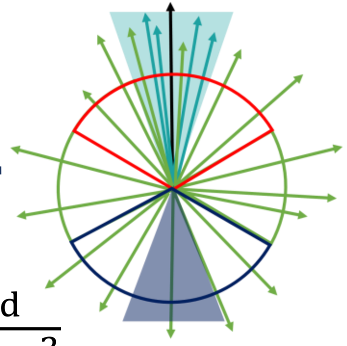

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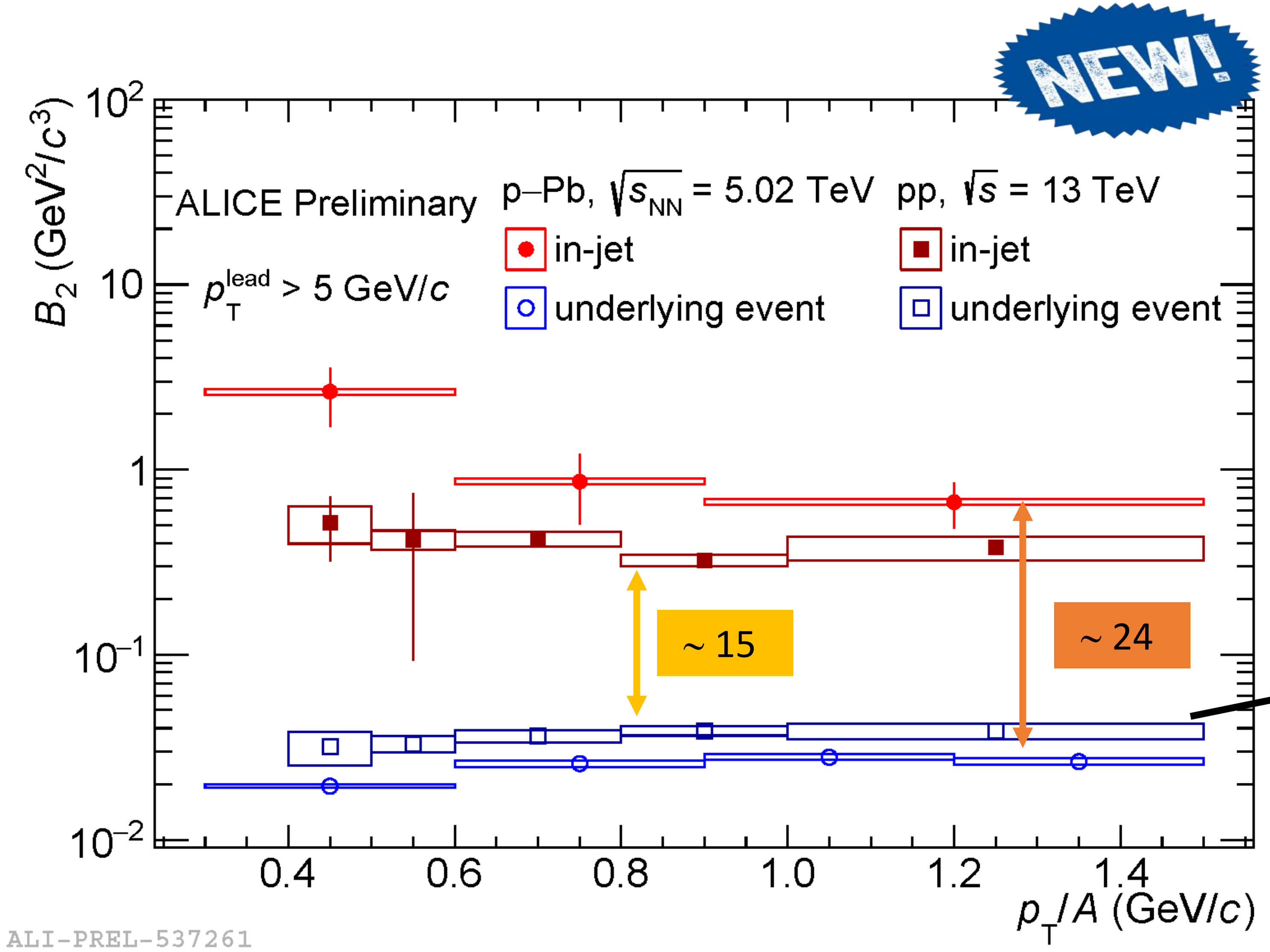

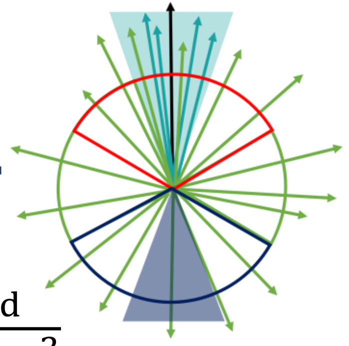

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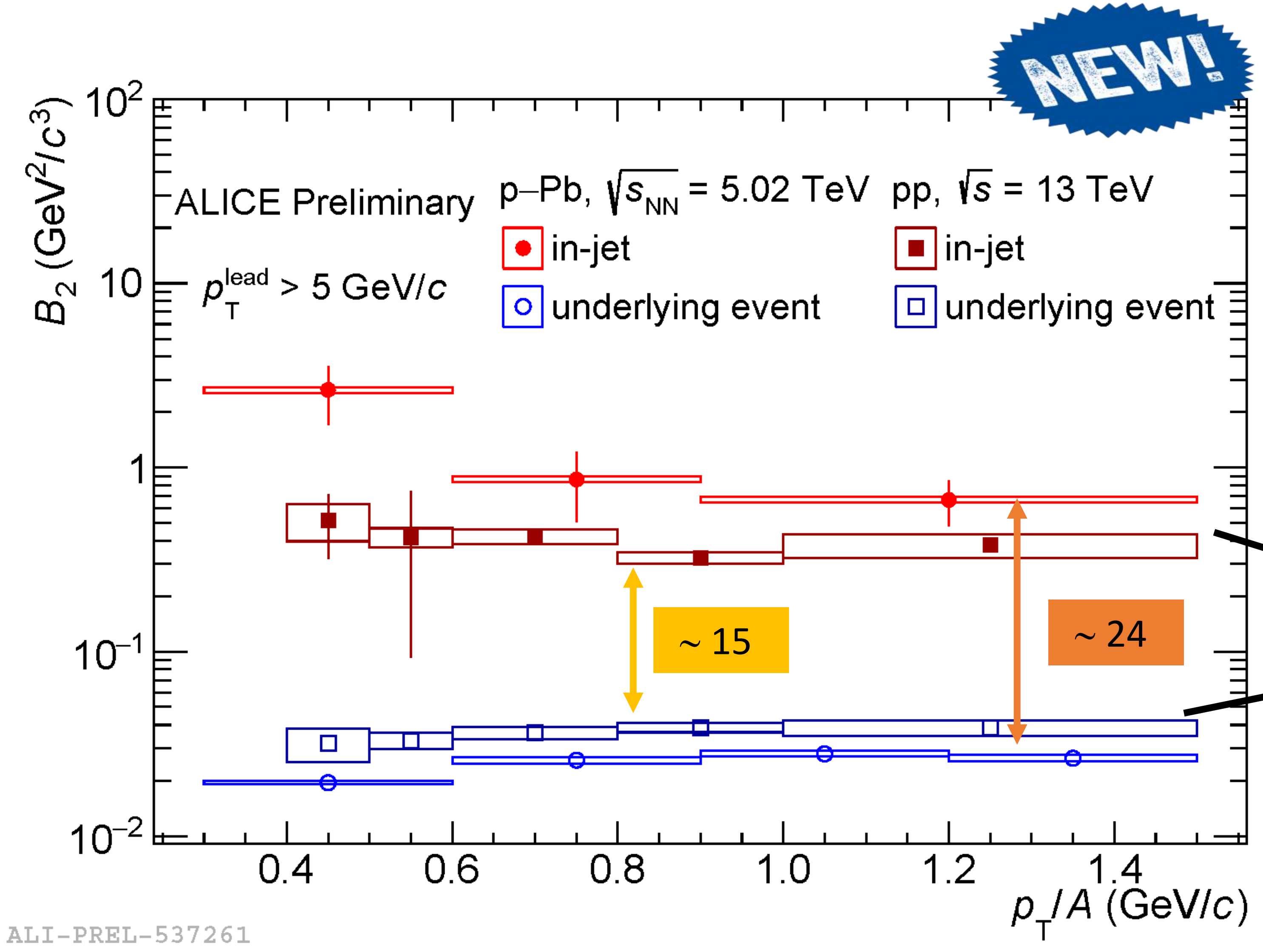
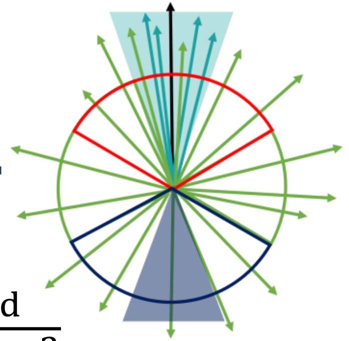
B_2^{UE}(p–Pb) < B_2^{UE}(pp) since p–Pb source size is larger than pp source size

B_2 in jet and UE





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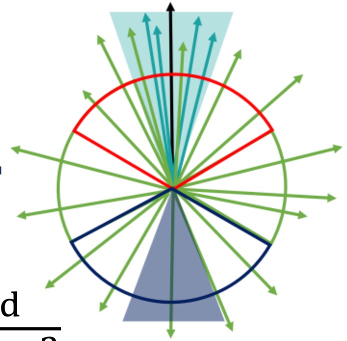
- Enhancement of B_2^{jet} wrt B_2^{UE} in pp collisions
- What happens in p–Pb collisions?
- Enhancement factor is larger wrt pp collisions

B_2^{jet} (p–Pb) > B_2^{jet} (pp)

B_2^{UE} (p–Pb) < B_2^{UE}(pp) since p–Pb source size is larger than pp source size

Assuming the same source size for nucleons in jet, nucleons are probably closer in momentum space in p–Pb wrt pp

B_2 in jet and UE



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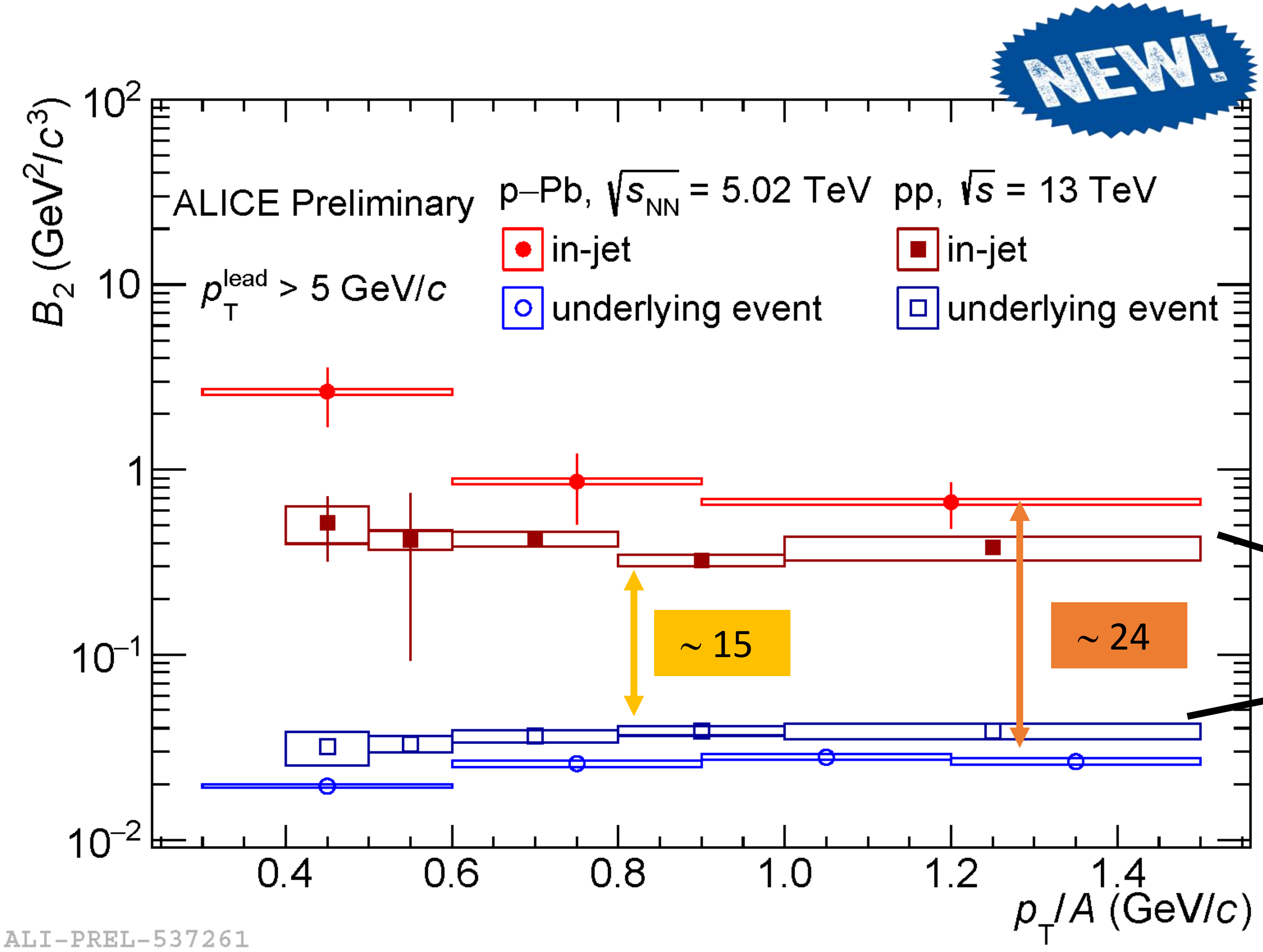

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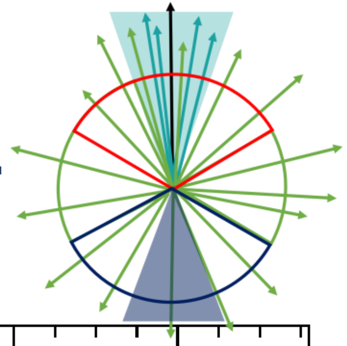
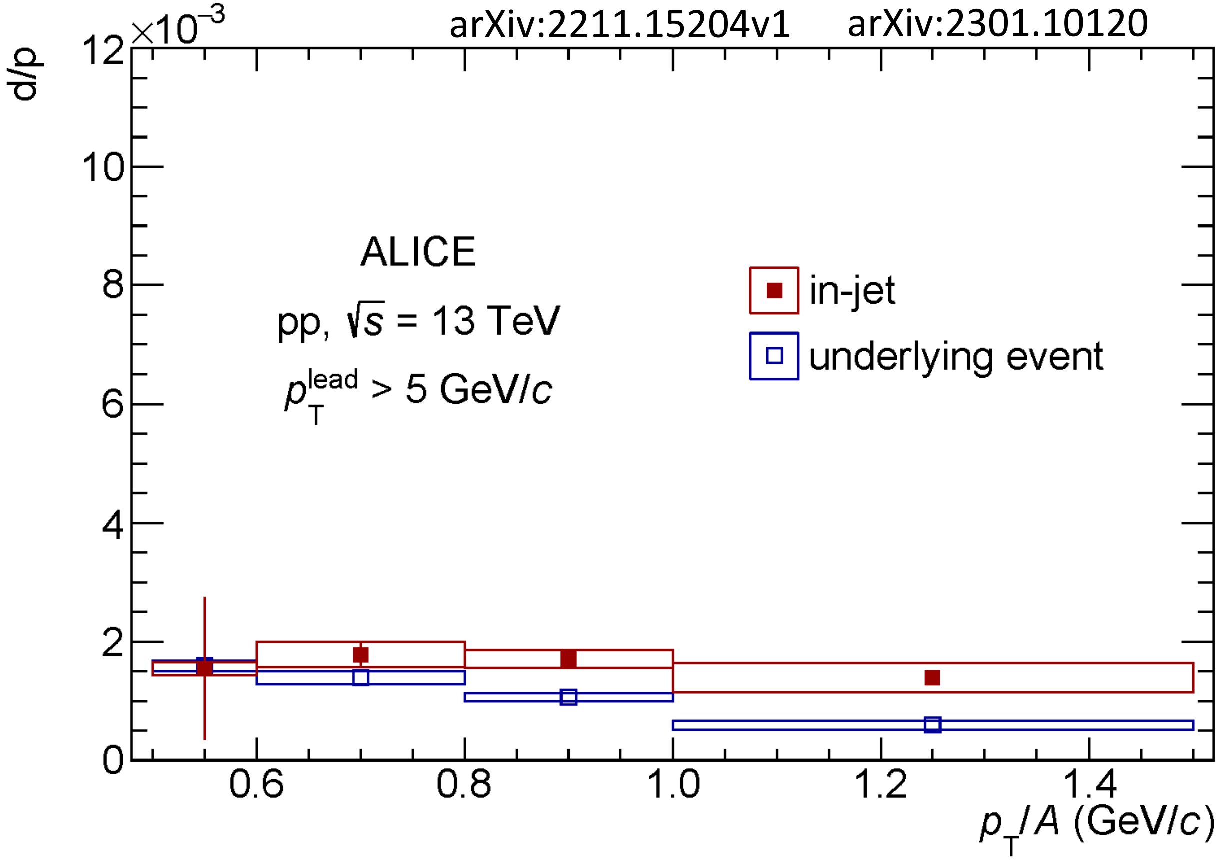
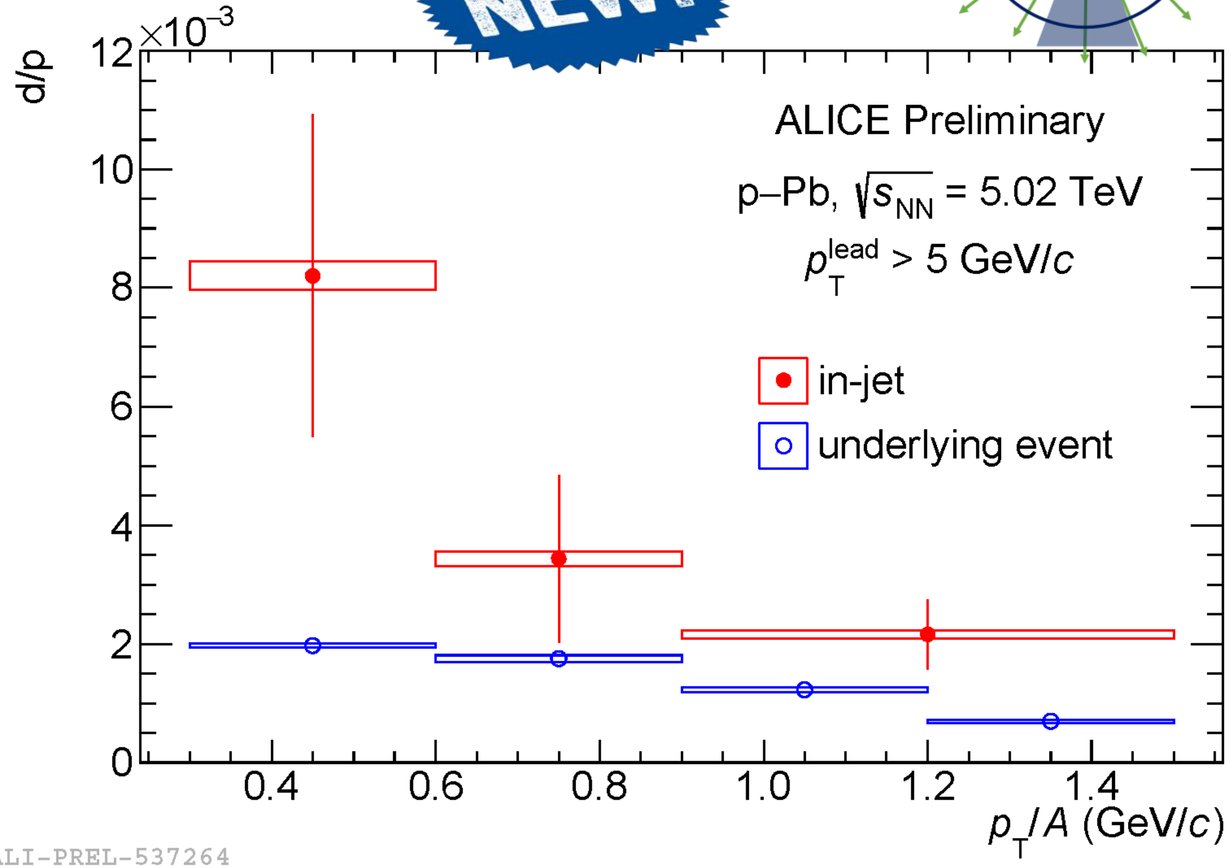
For the first time, we see some differences between jets in pp and p–Pb collisions

Difference related to particle composition?

d/p in jet and UE



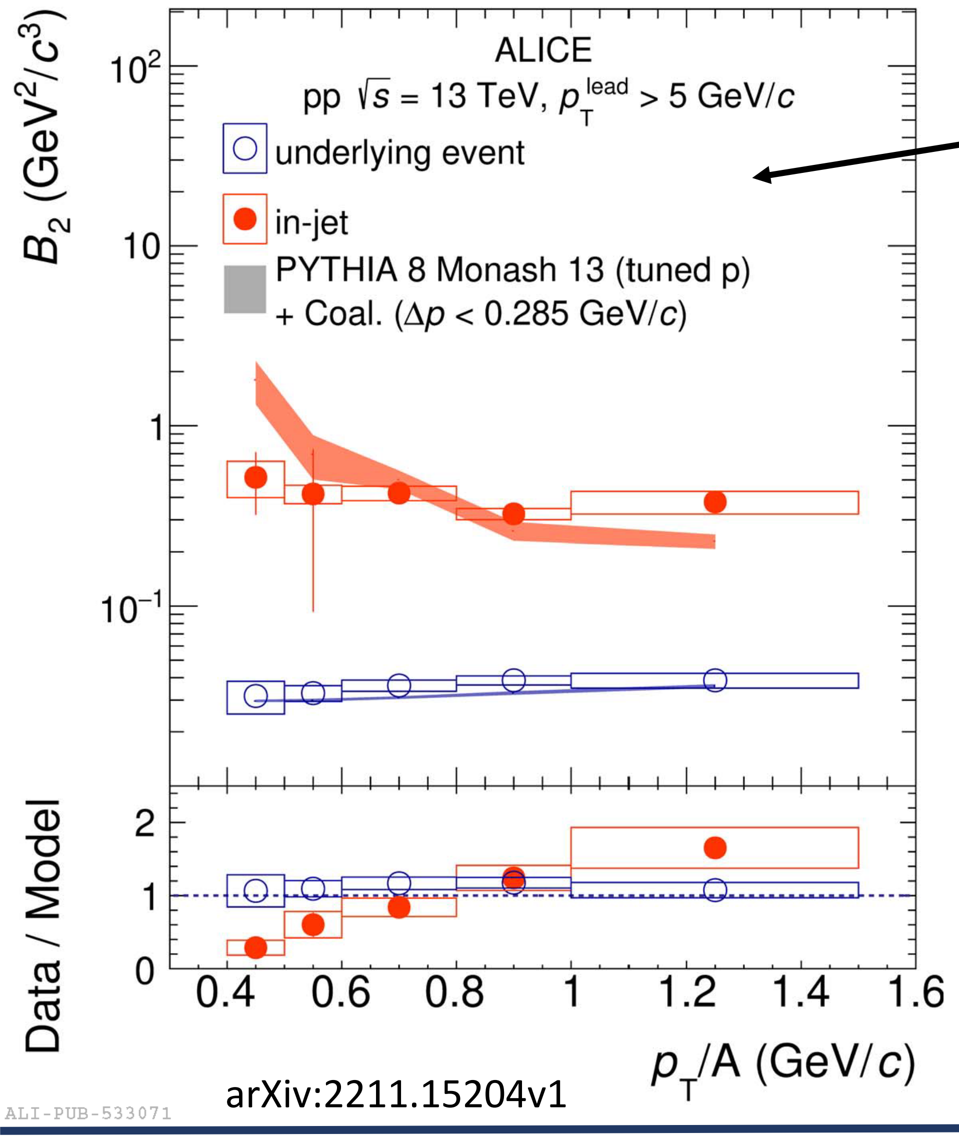




- d/p calculated as ratio of normalized spectra
- d/p ^{jet} is higher than d/p ^{UE}

- **Higher d/p ^{jet} in p–Pb collisions wrt pp collisions**
- Different particle composition → could affect the coalescence probability

B_2 in jet and UE – model comparison



arXiv:2211.15204v1

- Two different models:
  - PYTHIA 8 Monash 13 + simple coalescence

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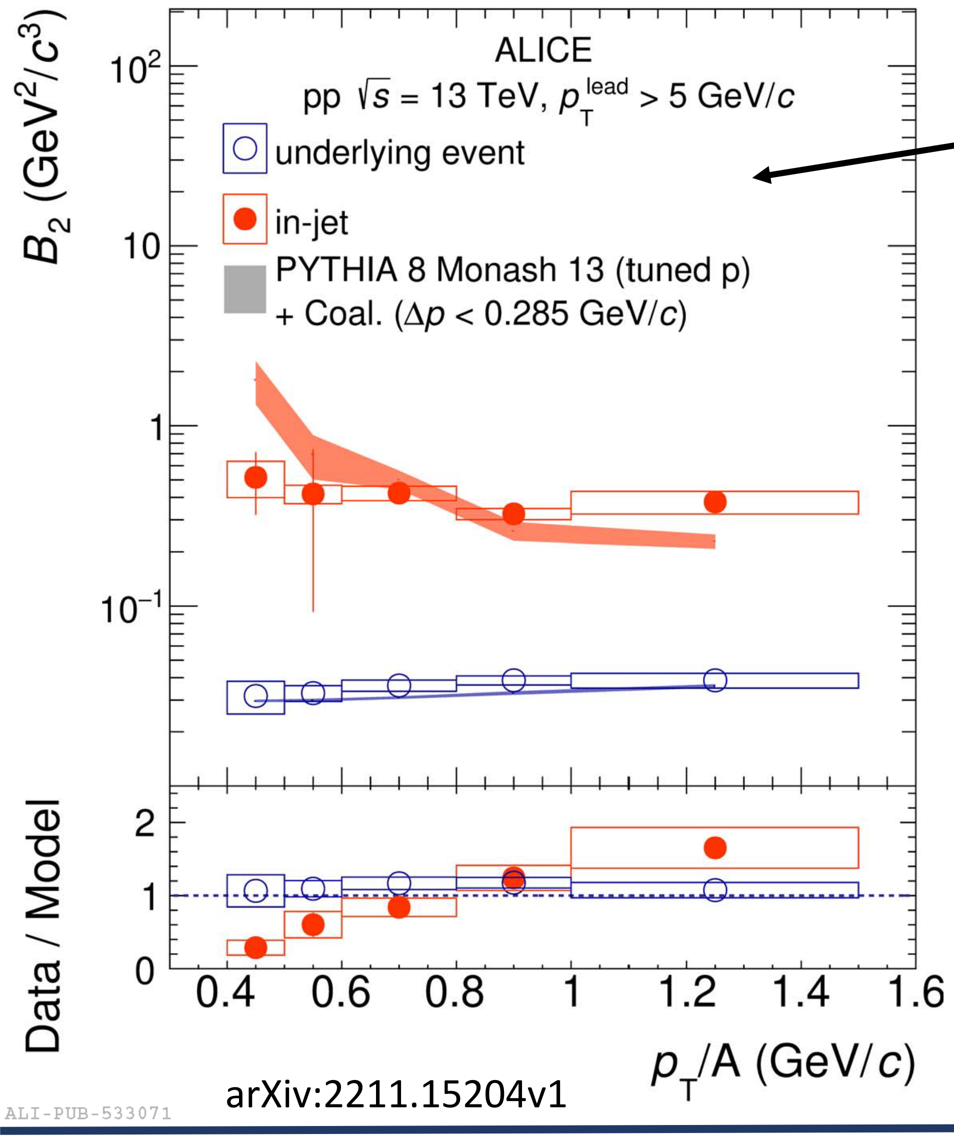

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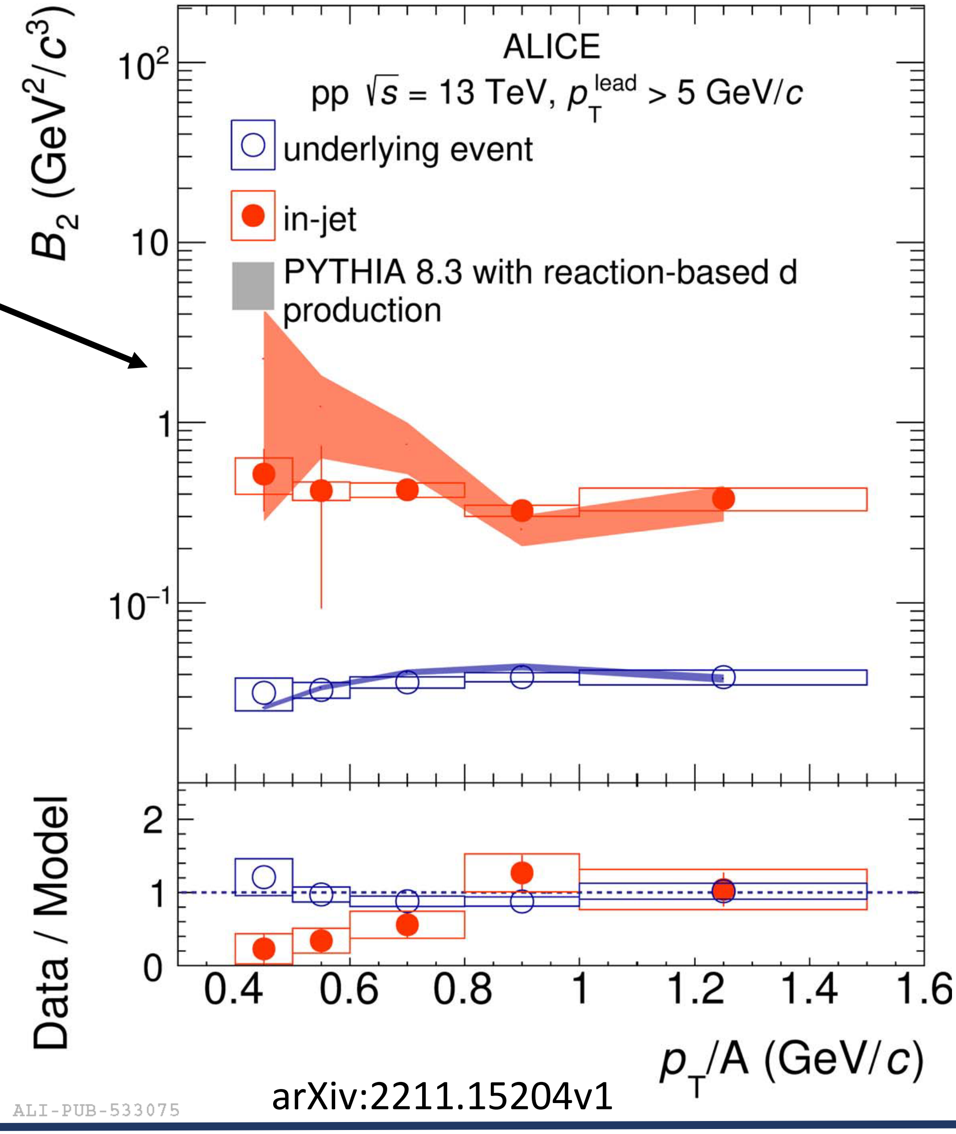

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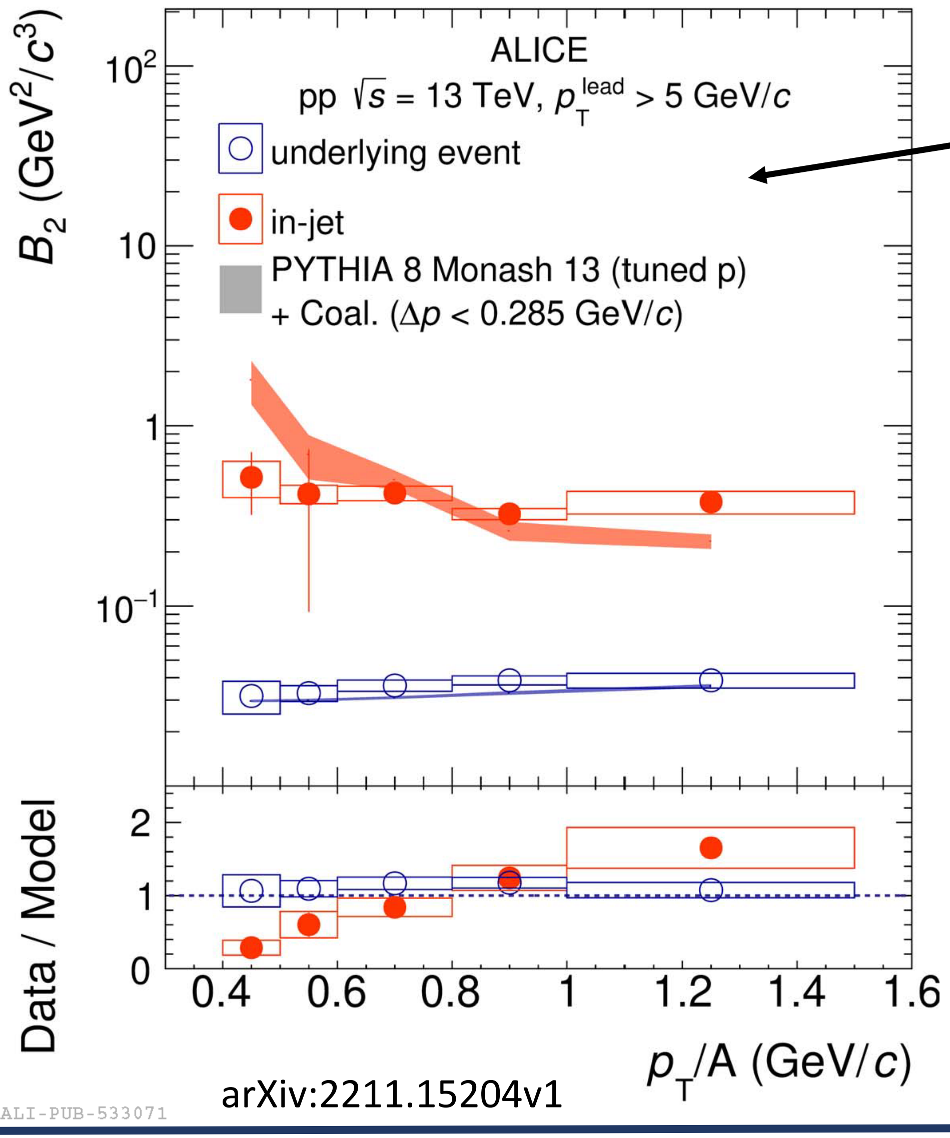

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- Two different models:
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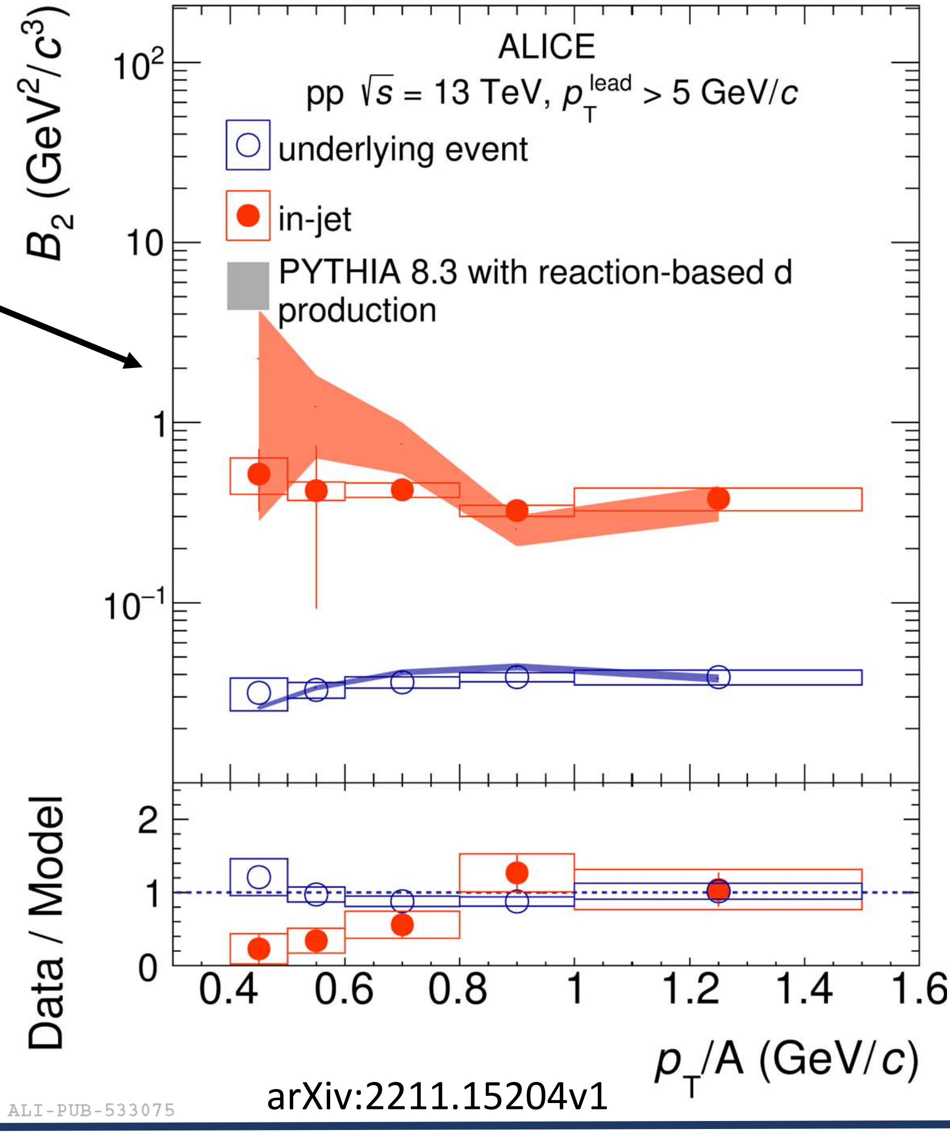
  - PYTHIA 8.3 with reaction-based deuteron production (Bierlich et al., arXiv:2203.11601)
- Both models qualitatively reproduce the data and the large difference between B_2^{jet} and B_2^{UE}



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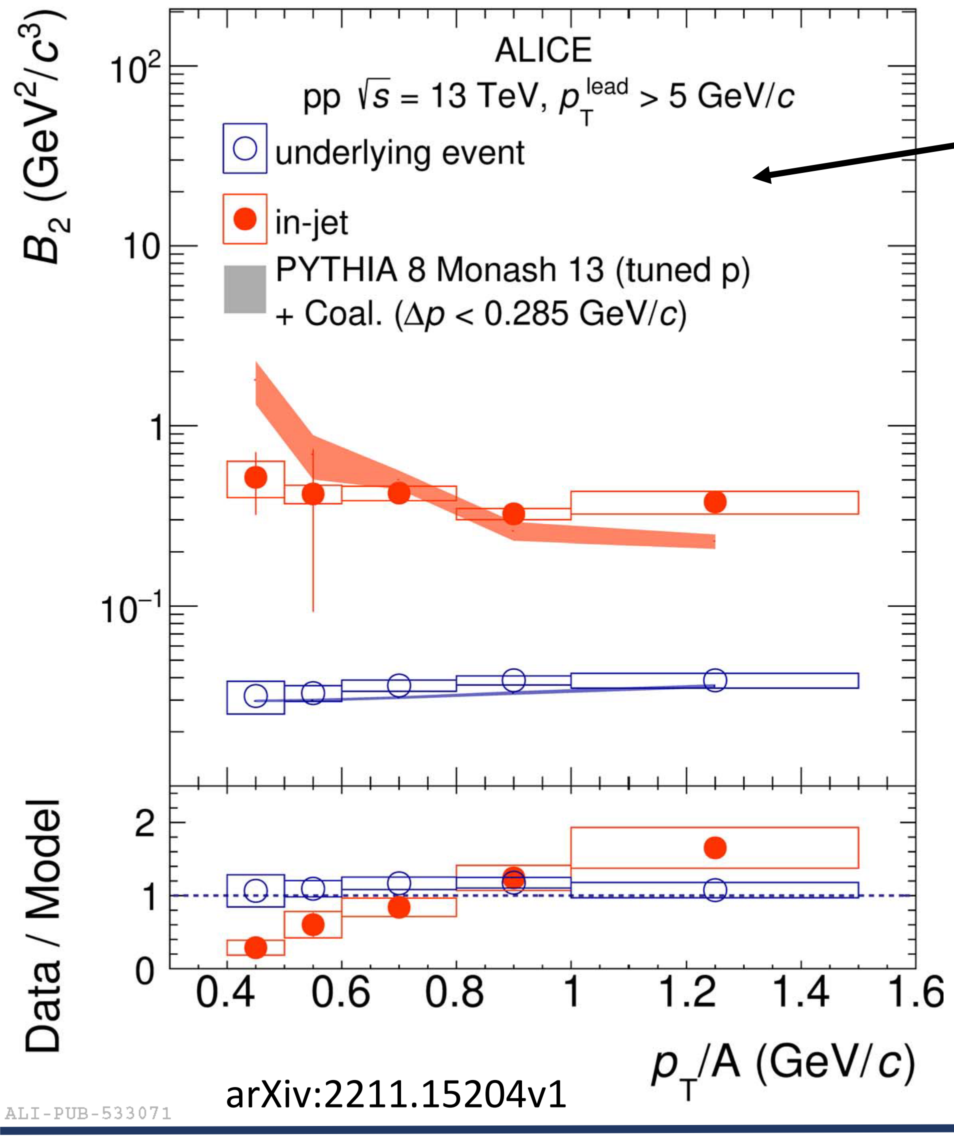
B_2 in jet and UE – model comparison



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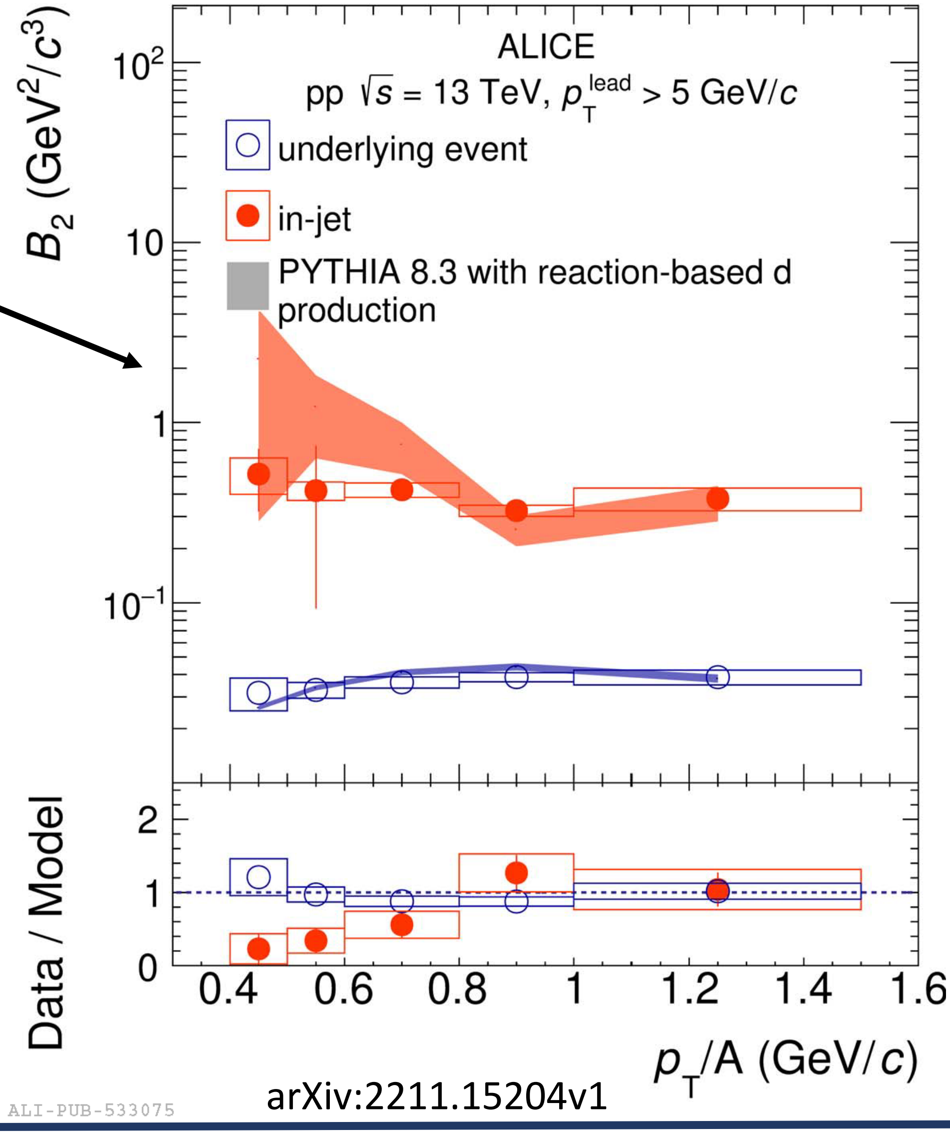
- Both models qualitatively reproduce the data and the large difference between $B_2^{\,jet}$ and $B_2^{\,UE}$
- Further comparison with models



arXiv:2211.15204v1

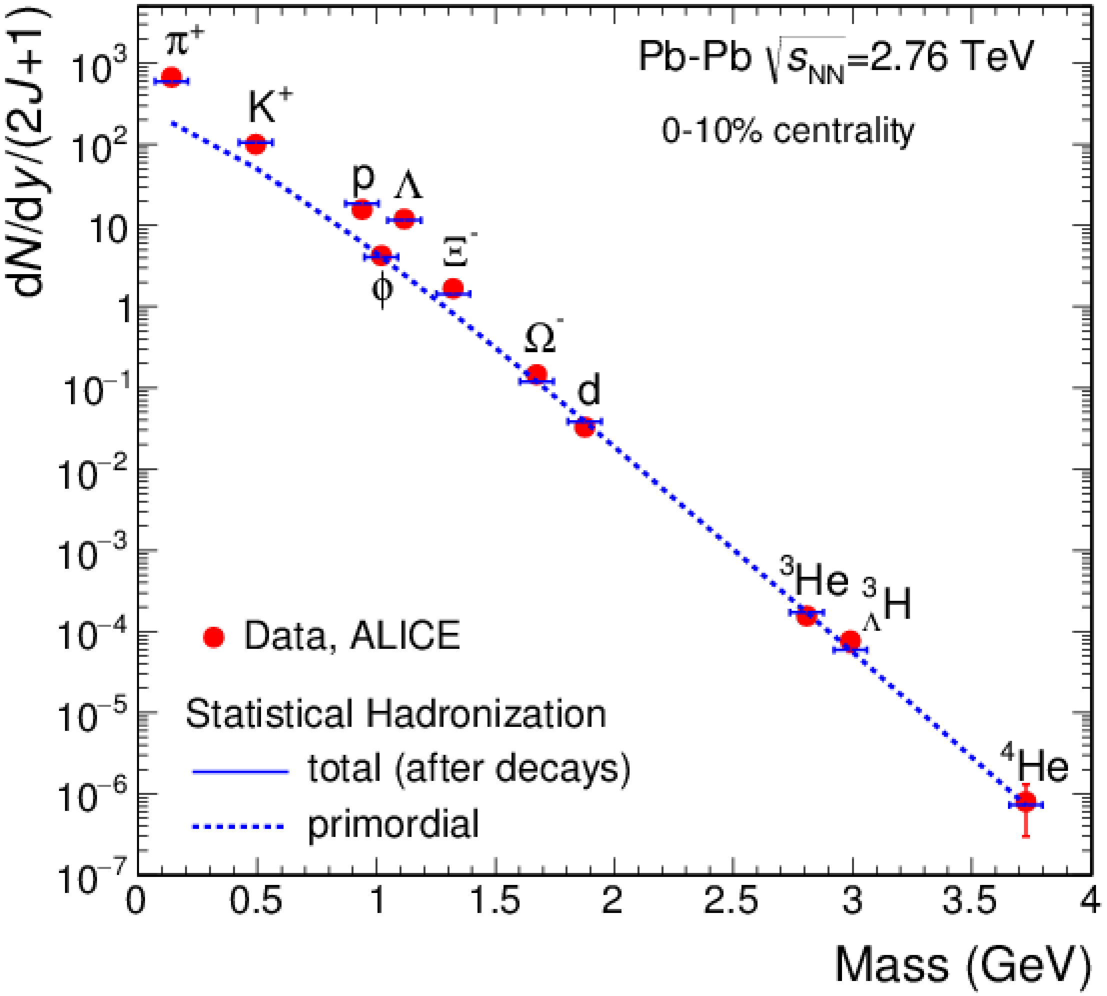
Summary

- Light (anti)deuteron production in three azimuthal regions in pp and p–Pb collisions
- Coalescence parameter in-jet and underlying event
  - Enhancement of B_2^{jet} wrt B_2^{UE} of a factor 15 (24) in pp (p–Pb) collisions
- **Higher B_2^{jet} in p–Pb collisions wrt pp collisions**
  - **Nucleons are probably closer in momentum space in p–Pb wrt pp**
- **Higher d/p ratio in p–Pb collisions wrt pp collisions for jets**
- Good agreement with model comparison in pp collisions
- New investigation in Run 3 data

Thank you for the attention!

Backup

Statistical models



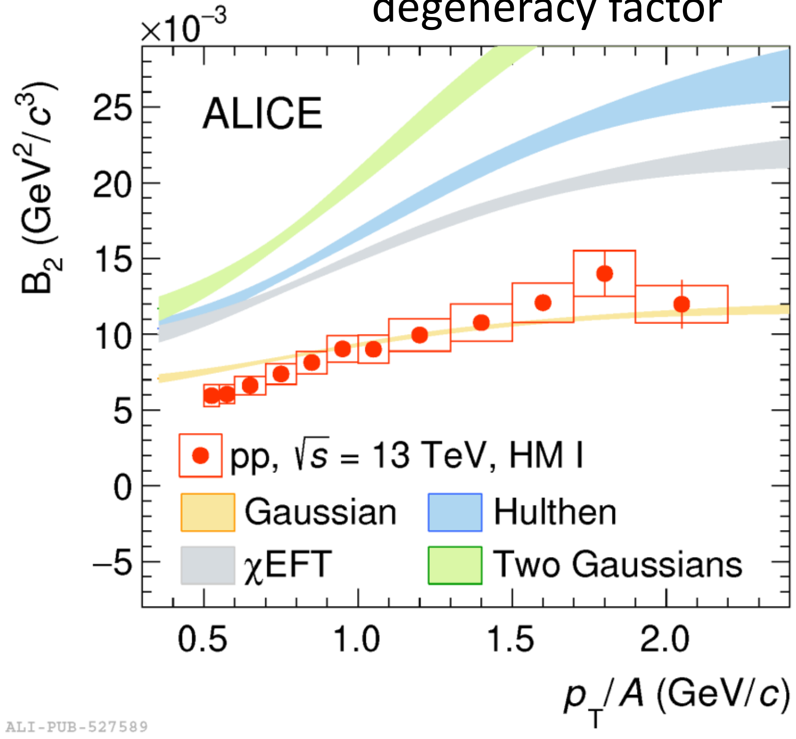
- Hadrons emitted from a system in statistical and chemical equilibrium
- T_{chem} is the key parameter
- $dN/dy \propto \exp(-m/T_{chem})$
- Nuclei binding energy ~ few MeV → how they can survive?
- Particle yield well described with a common T_{chem} of ~ 156 MeV

Andronic et al, Nature vol. 561, 321-330 (2018)

(Advanced) coalescence model

- Wigner function formalism

$$N_A = \underbrace{g_a}_{\text{spin-isospin degeneracy factor}} \cdot \int d^3x_1 \ldots d^3x_A \cdot d^3k_1 d^3k_A \cdot \underbrace{f_1(x_1,k_1) \cdot f_A(x_A,k_A)}_{\text{phase space distributions of nucleons}} \cdot \underbrace{W_A(x_1,\ldots,x_A,k_1,\ldots,k_A)}_{\text{Wigner density of nucleons}}$$

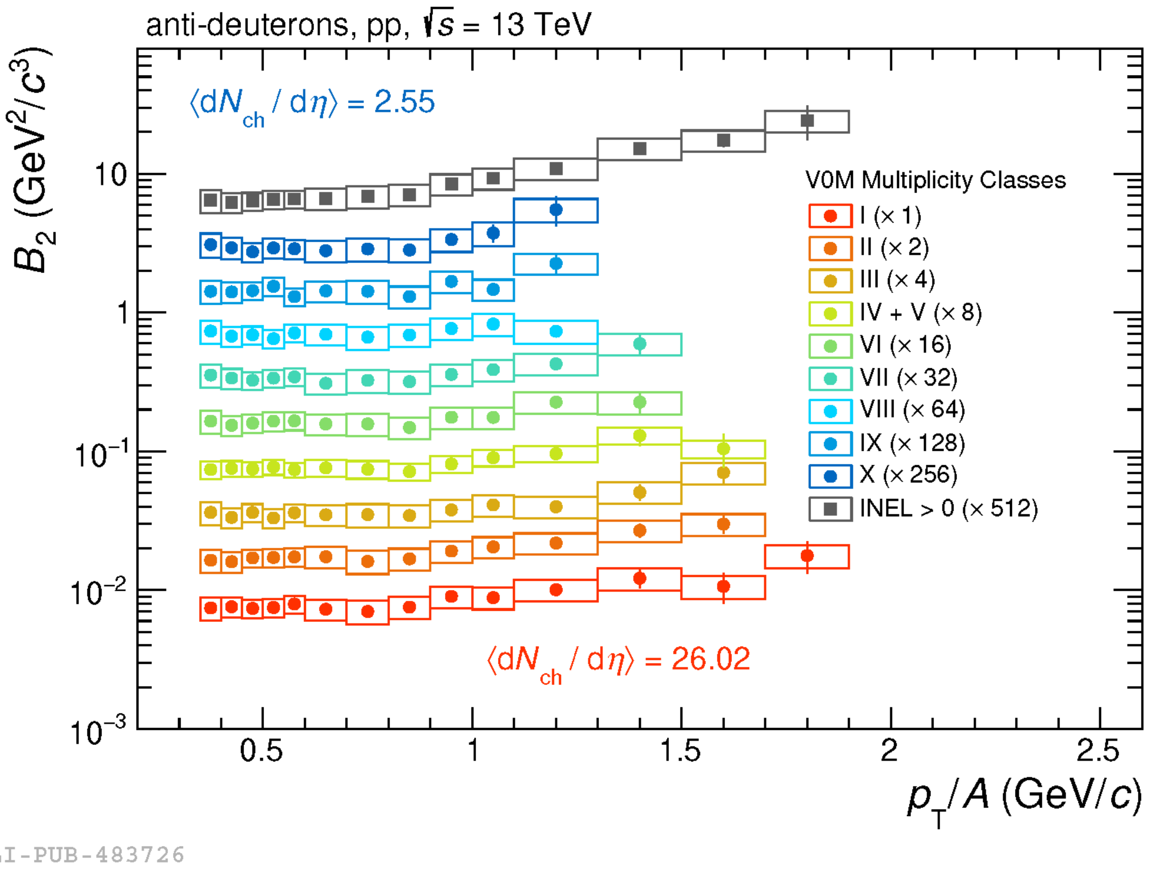


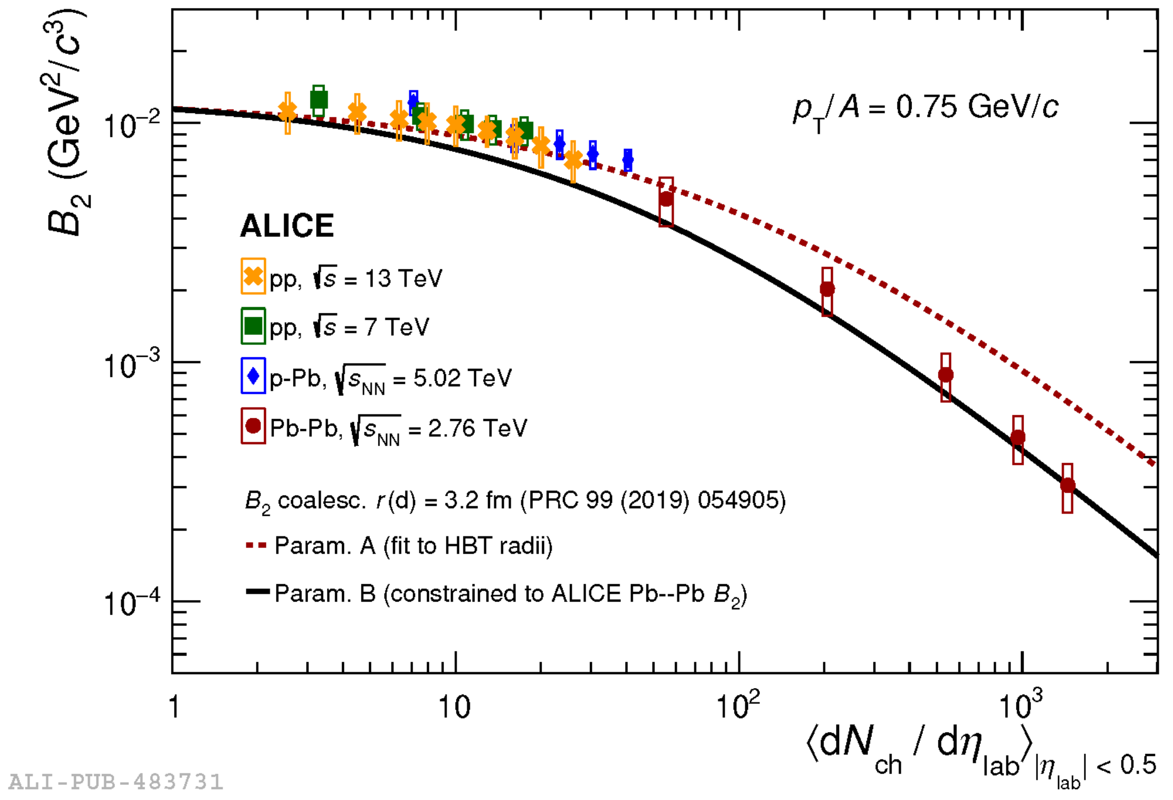
- Different Wigner density functions available:
  - Gaussian: standard one
  - Double gaussian
  - Hulthén: Yukawa-like potential
  - χEFT: Chiral effective field theory

JHEP 01 (2022) 106

Coalescence parameter

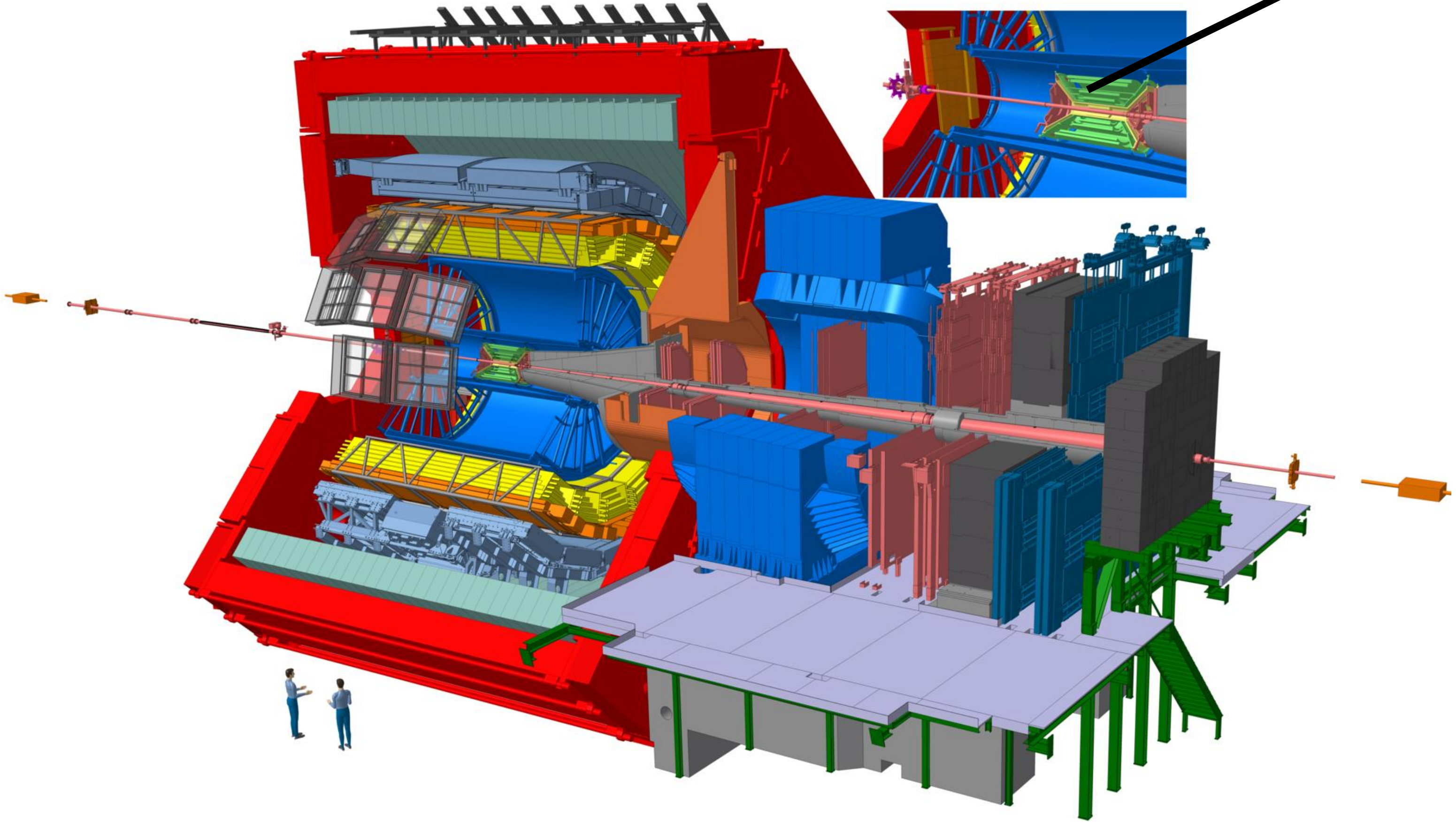
Eur. Phys. J. C 80 (2020) 889





- B_A is rather flat in all multiplicity classes, but increase at high p_T/A in the MB class
- Smooth evolution from small to large source size

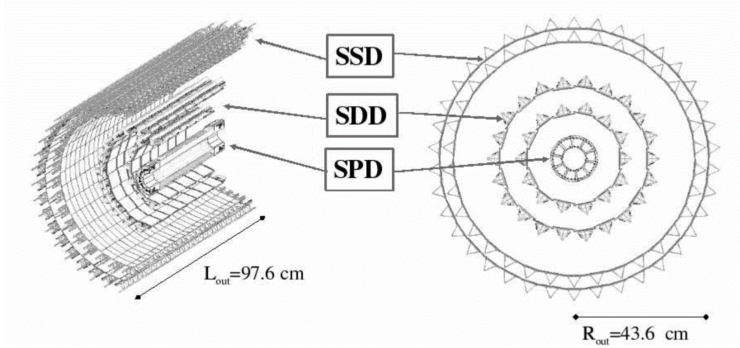
The ALICE detector in Run 2



Inner Tracking System (ITS)

Six concentrical layer of silicon sensors:

- 2 layers of Silicon Pixel Detectors (SPD);
- 2 layers of Silicon Drift Detectors (SDD);
- 2 layers of Silicon micro-Strip Detectors (SSD).



JINST 3 (2008) S08002
Int. J. Mod. Phys. A 29 (2014) 1430044

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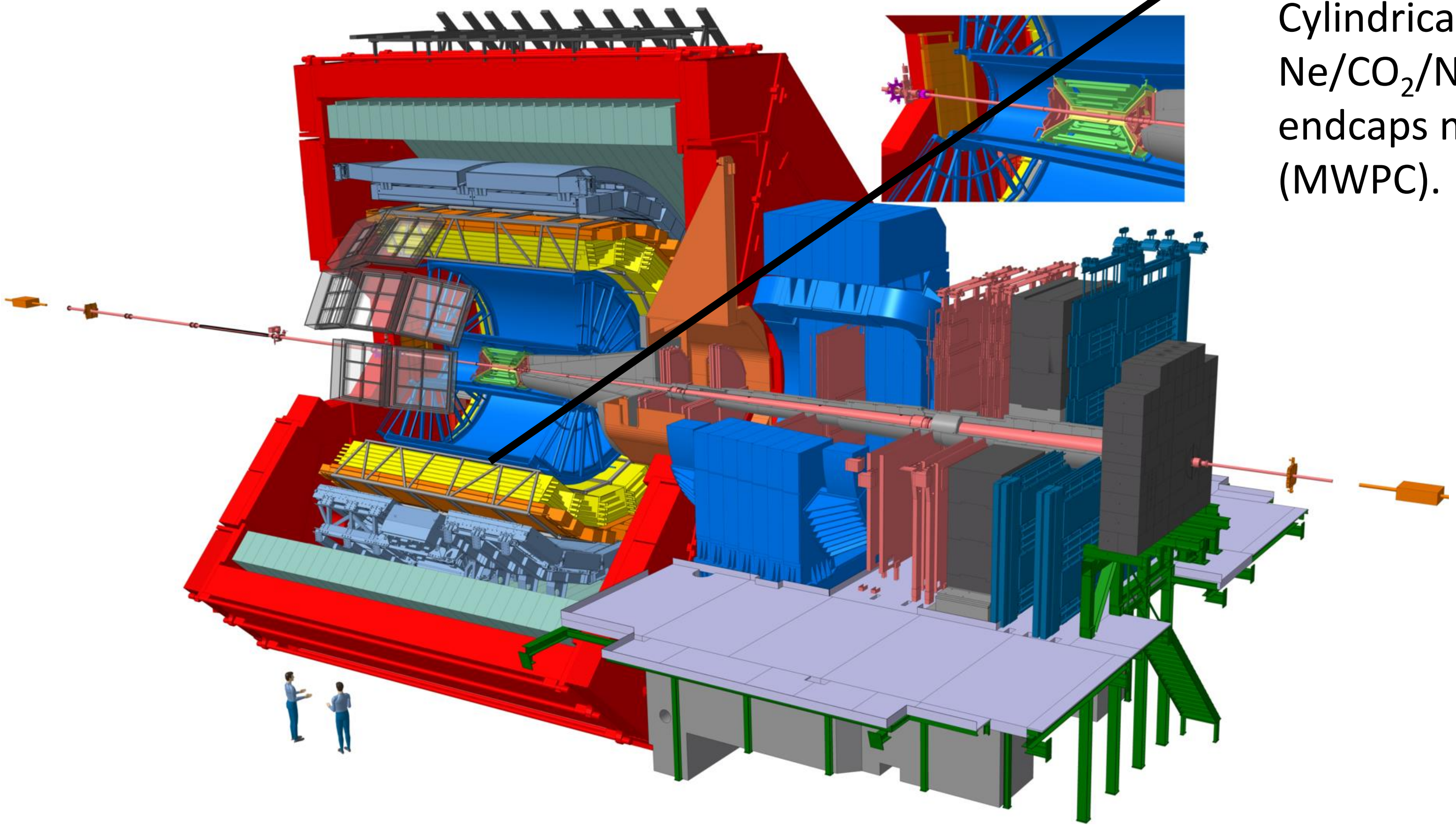
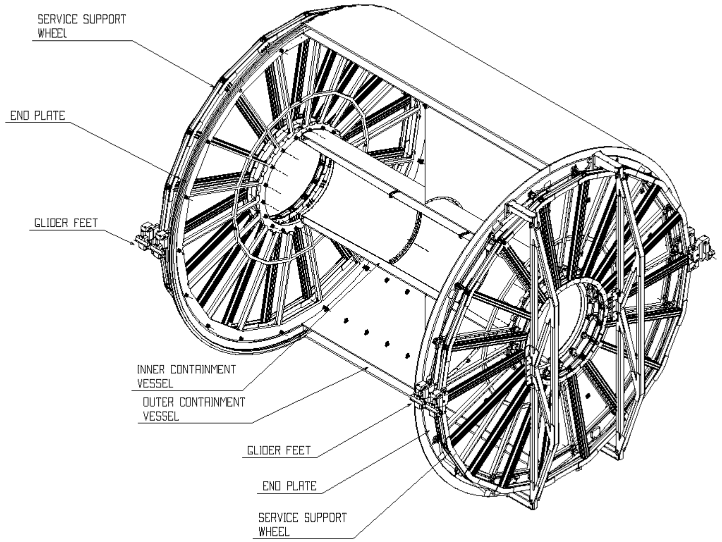


Time Projection Chamber (TPC)

Cylindrical gas detector, made by a field cage filled with $Ne/CO_2/N_2$ (90/10/5). The cage is closed with two endcaps made of Multi-Wire Proportional Chambers (MWPC).



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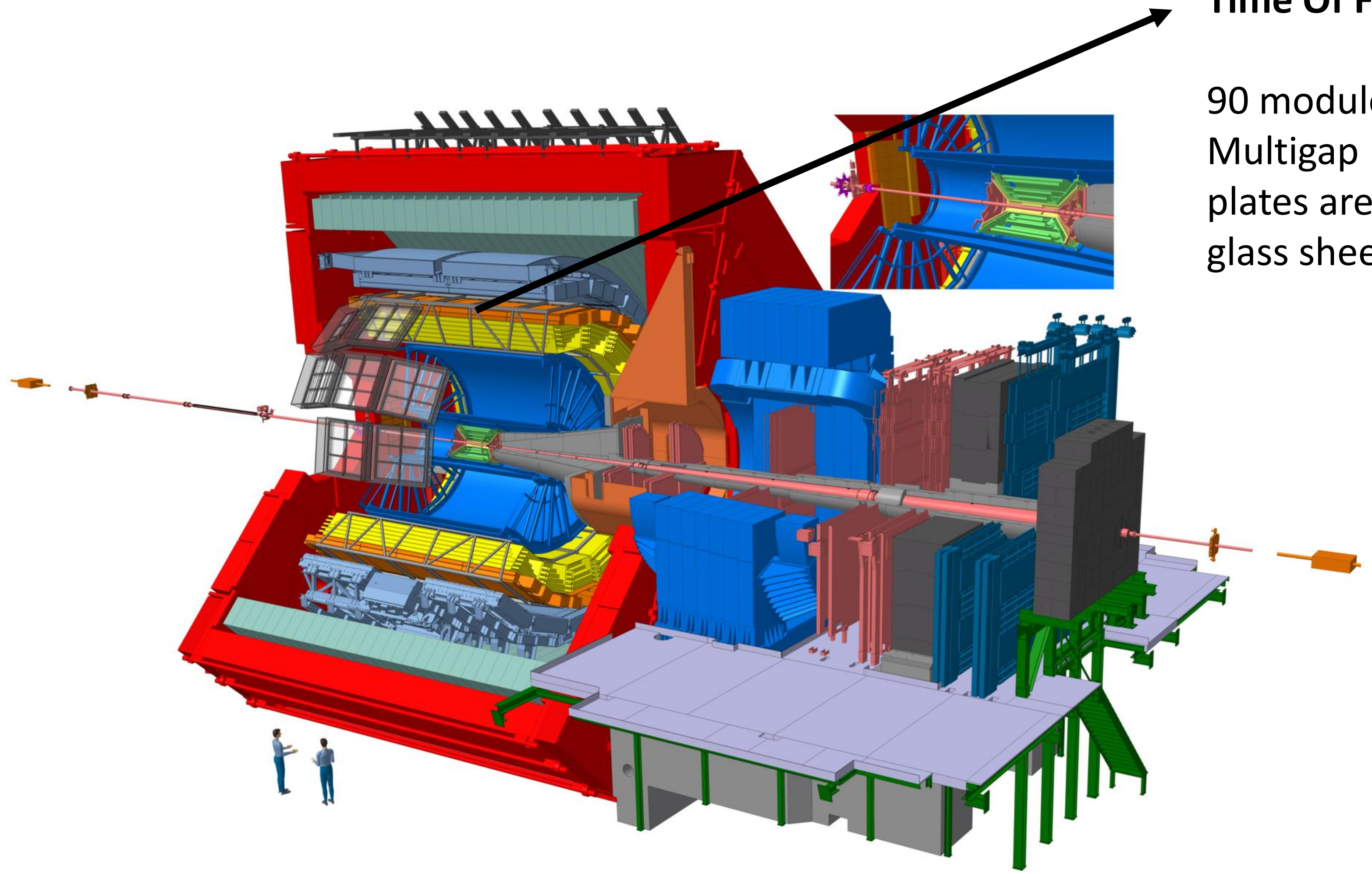
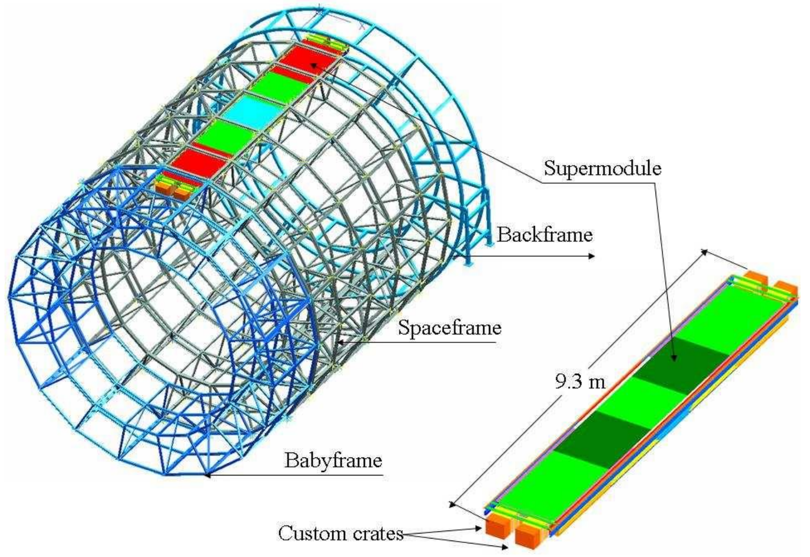
The ALICE detector in Run 2



Time Of Flight (TOF)

90 modules formed by a system of 10 gaps double stack Multigap Resistive Plate Chambers (MRPC). The resistive plates are made with commercially available soda-lime glass sheets with a gap of 250 µm.



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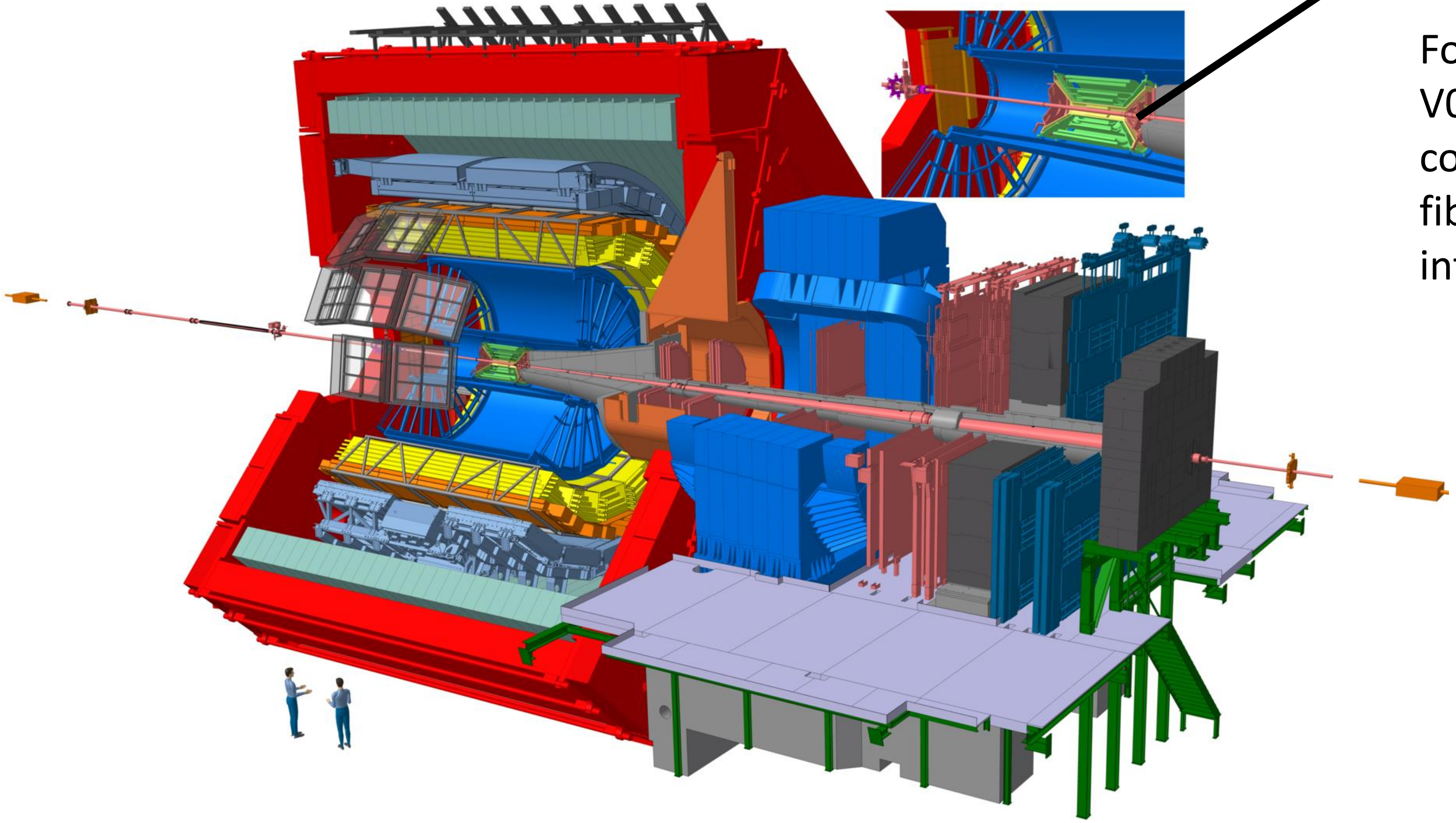
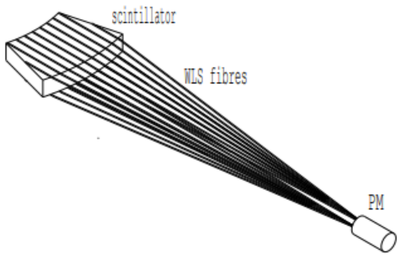
The ALICE detector in Run 2

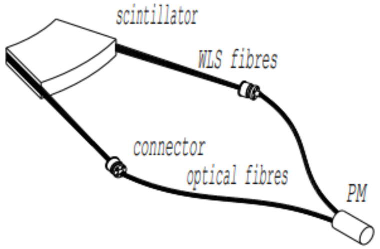


V0

Formed by two different modules, V0A and V0C, consisting of two arrays of scintillator counters and Wave-Length Shifting (WLS) fibres installed on either sides of the interaction point.



V0A



V0C

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Pythia simulation

- PYTHIA 8.3:
  - d production via ordinary reactions
  - Energy dependent cross sections parametrized based on data
  - Reactions:

    $p + n \rightarrow \gamma + d$

    $p + n \rightarrow \pi^0 + d$

    $p + n \rightarrow \pi^0 + \pi^0 + d$

    $p + n \rightarrow \pi^+ + \pi^- + d$

    $p + p \rightarrow \pi^+ + d$

    $p + p \rightarrow \pi^+ + \pi^0 + d$

    $n + n \rightarrow \pi^- + d$

    $n + n \rightarrow \pi^- + \pi^0 + d$

- PYTHIA 8 Monash:
  - Simple coalescence
  - d is formed if $\Delta p < p_0$, with p_0 = 285 MeV/c