Highlights of ALICE recent results

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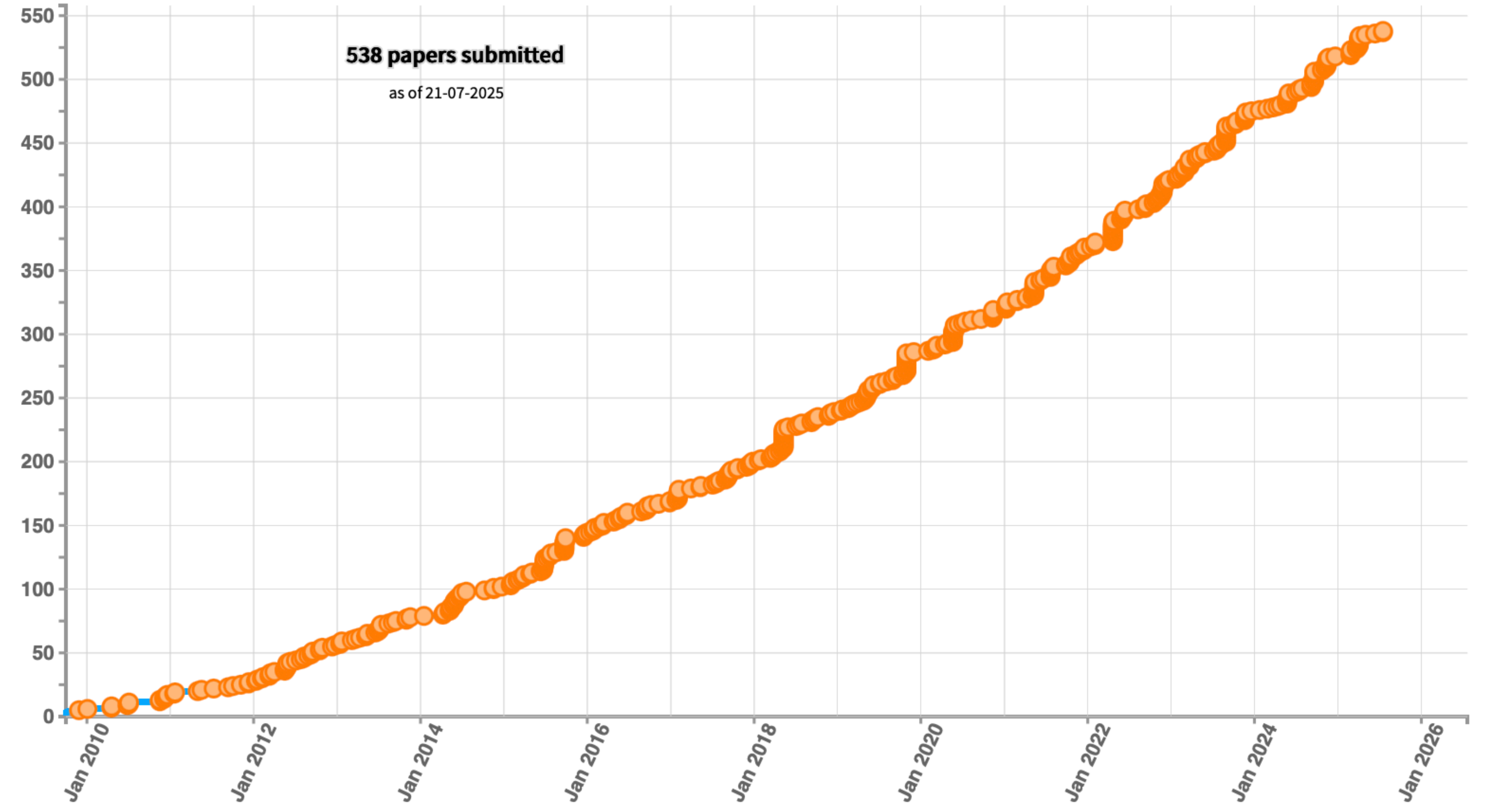
The ALICE Collaboration

- 40 countries
- 169 institutes
- 2004 members

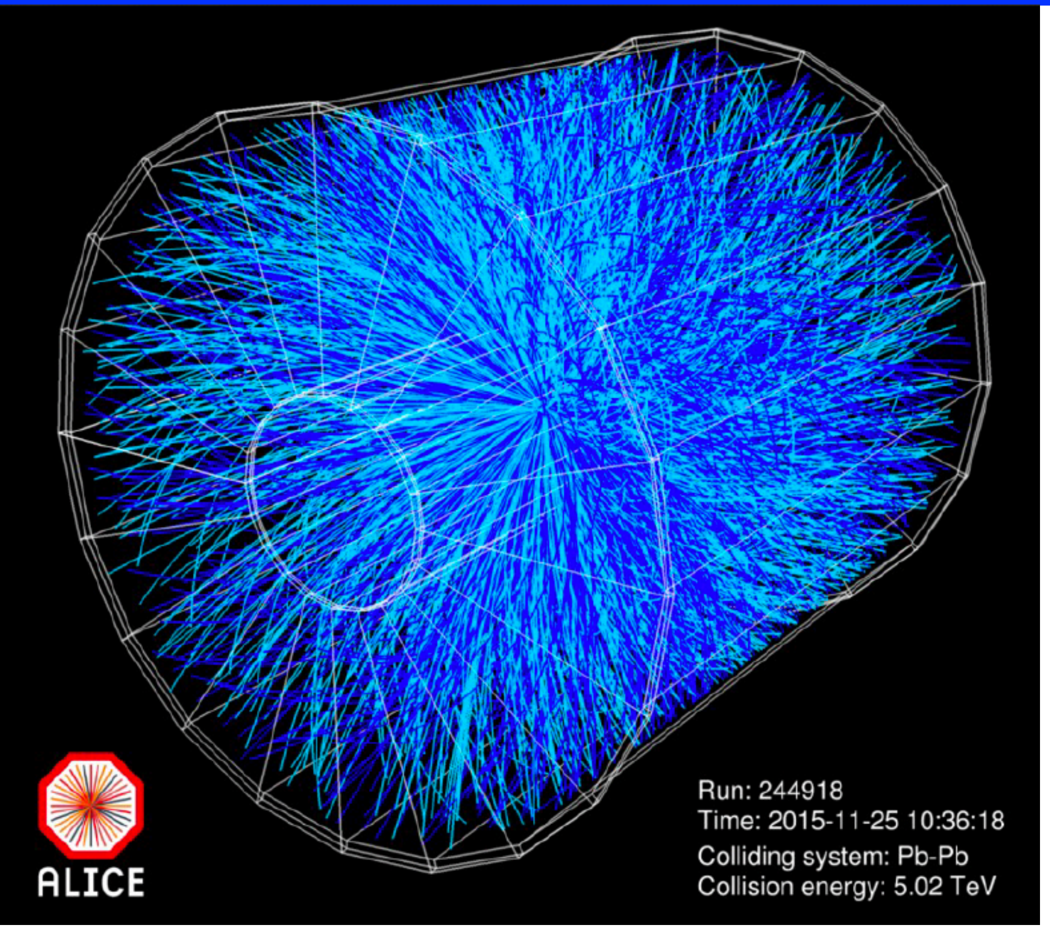
- Goal:
  - Properties of QCD matter at extreme conditions
  - Characterization of Quark-Gluon Plasma (QGP)
  - Influence of initial- and final-state effects on particle production

ALICE Physics Papers Timeline

https://alice-publications.web.cern.ch/node/4

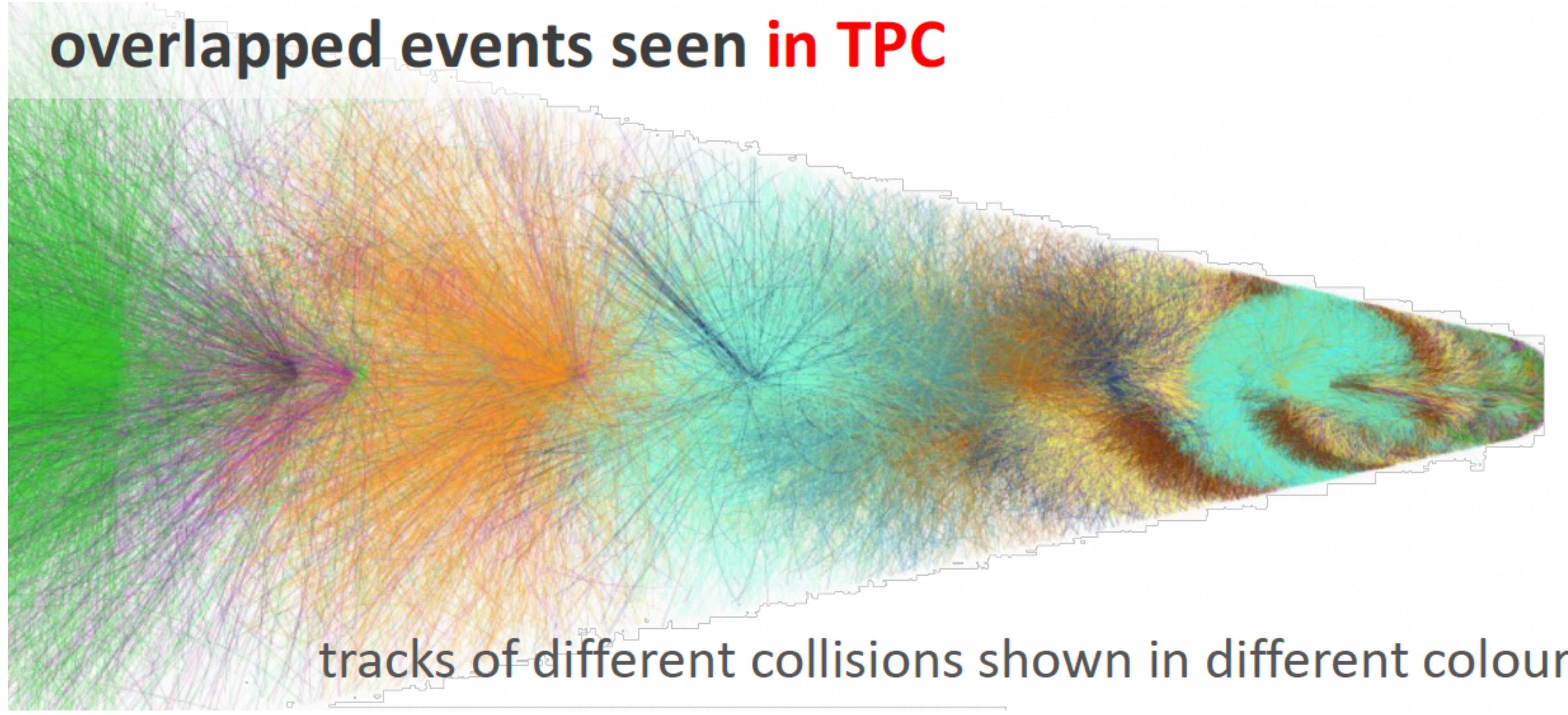


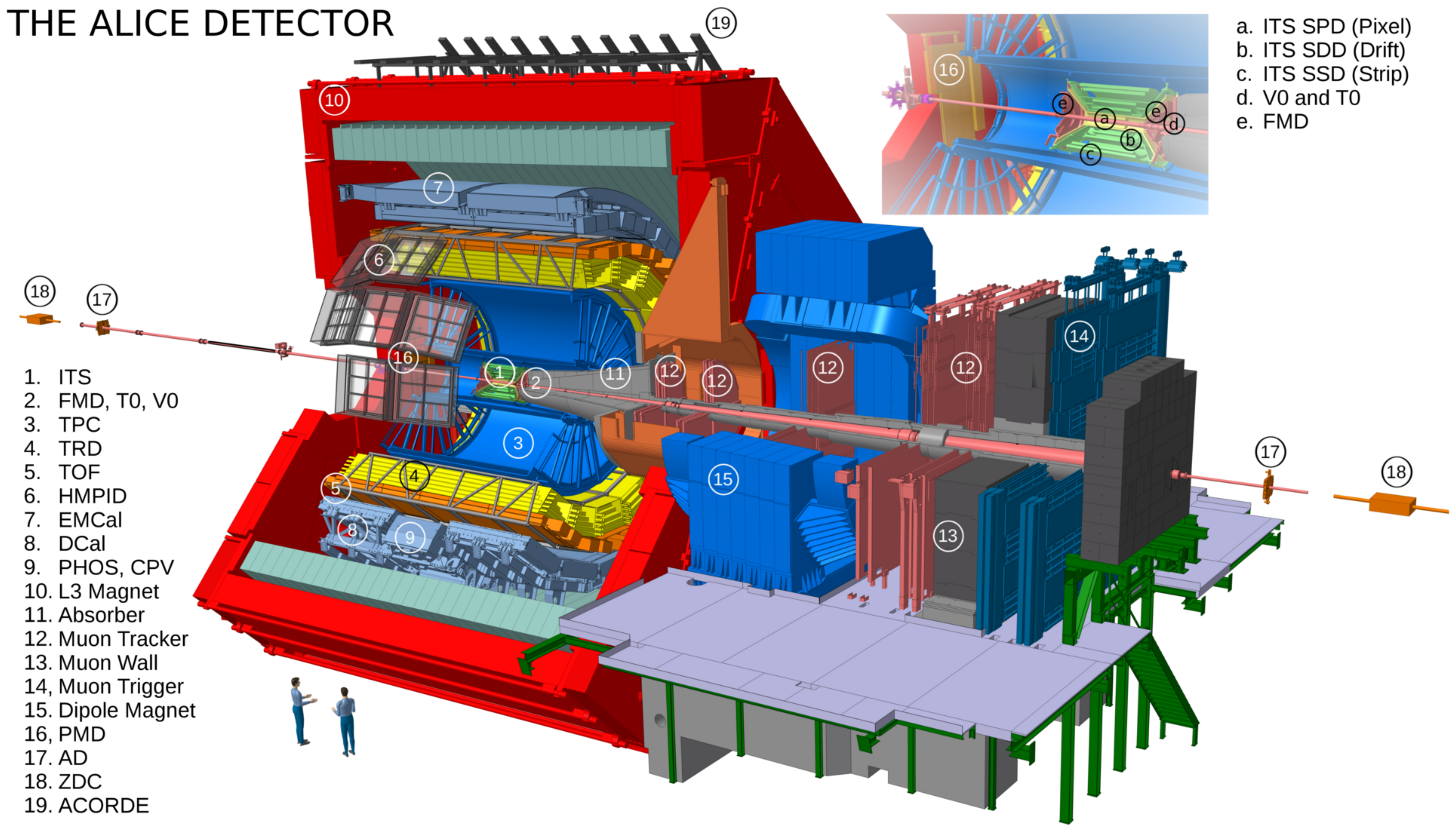
A Large Ion Collider Experiment (ALICE)



ALICE upgrade during LS2 (2019-2021)

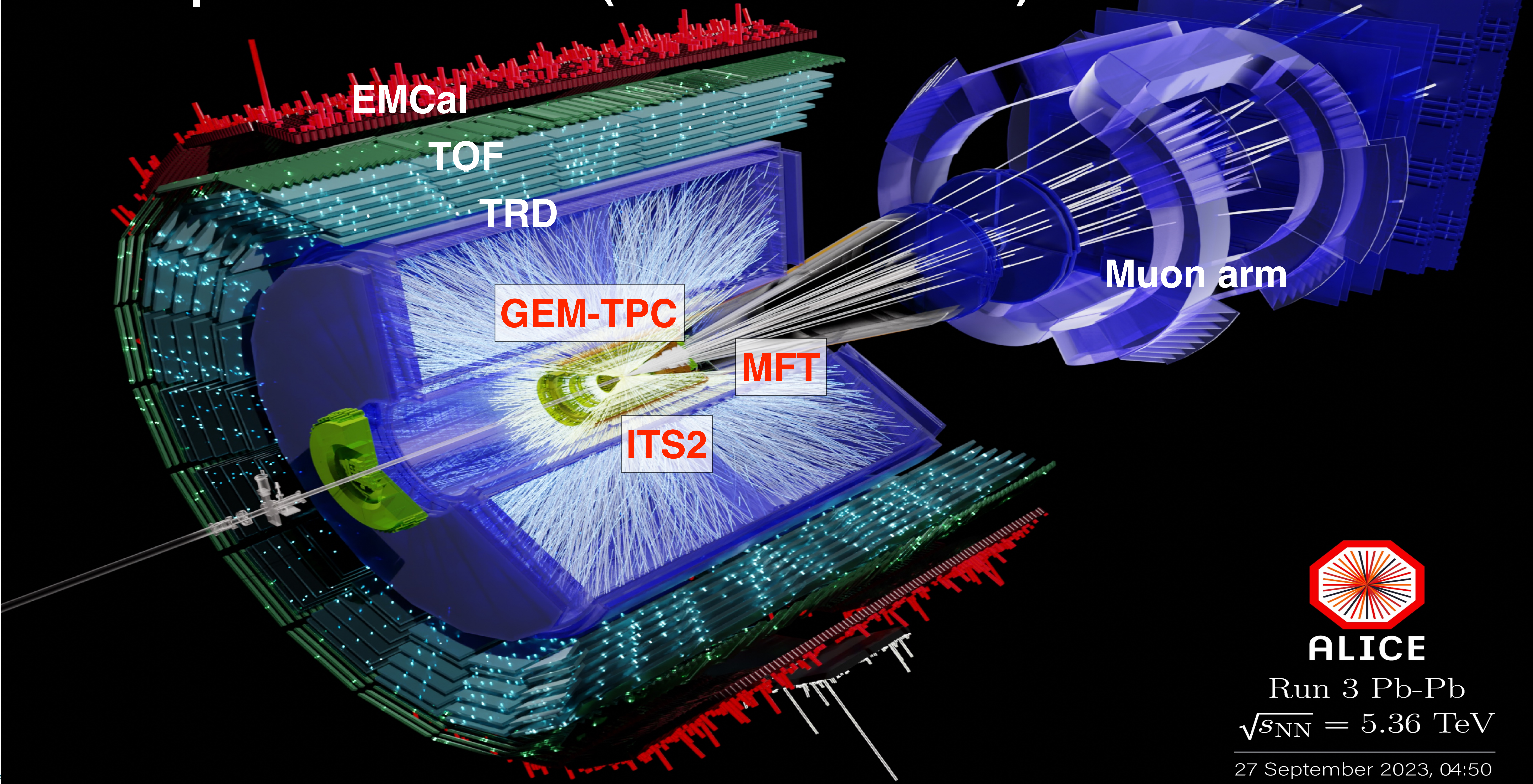
- Continuous readout → more statistics
- Better vertexing + high efficiency at low p_T with ITS2
- Online reconstruction and data compression



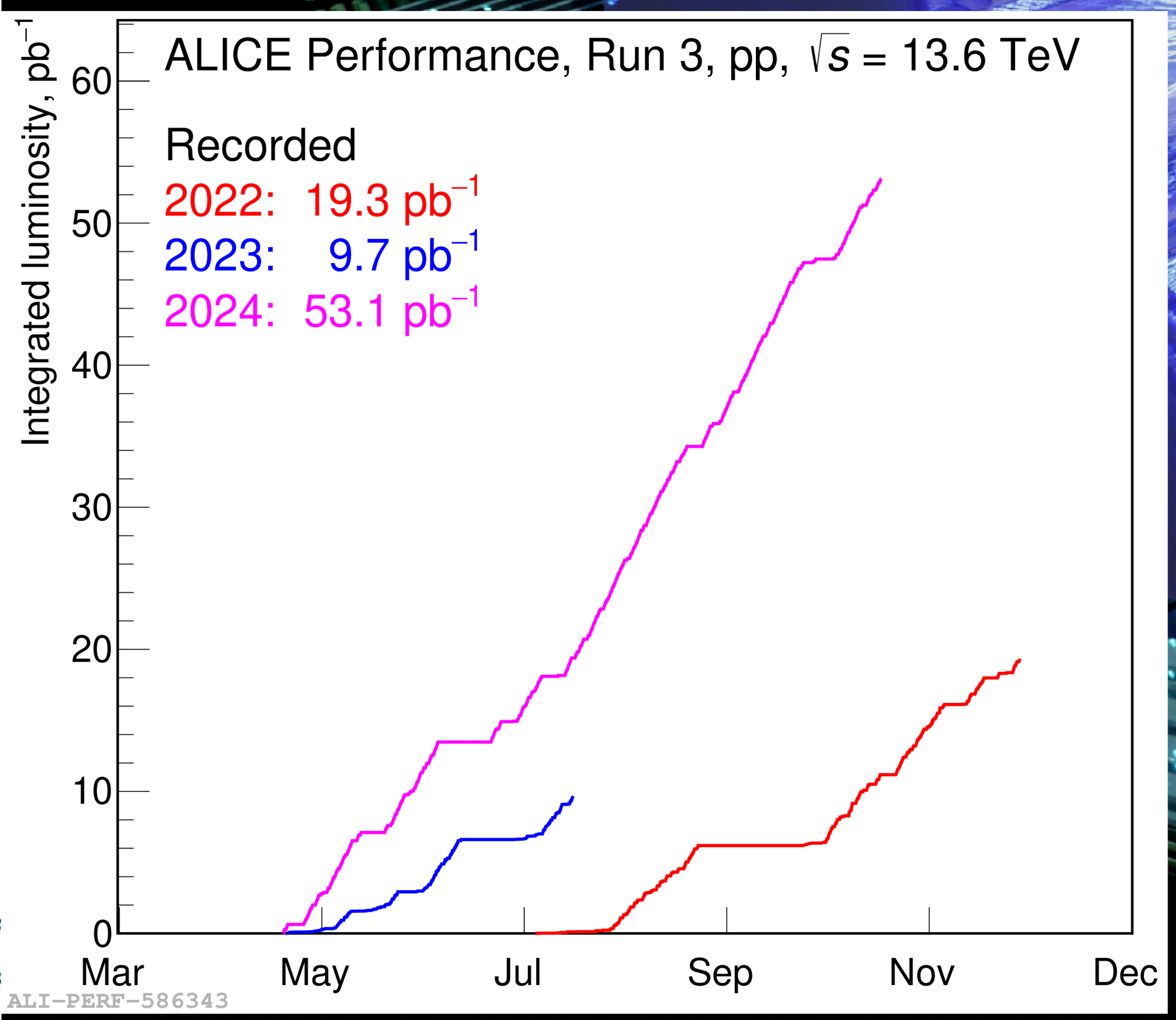


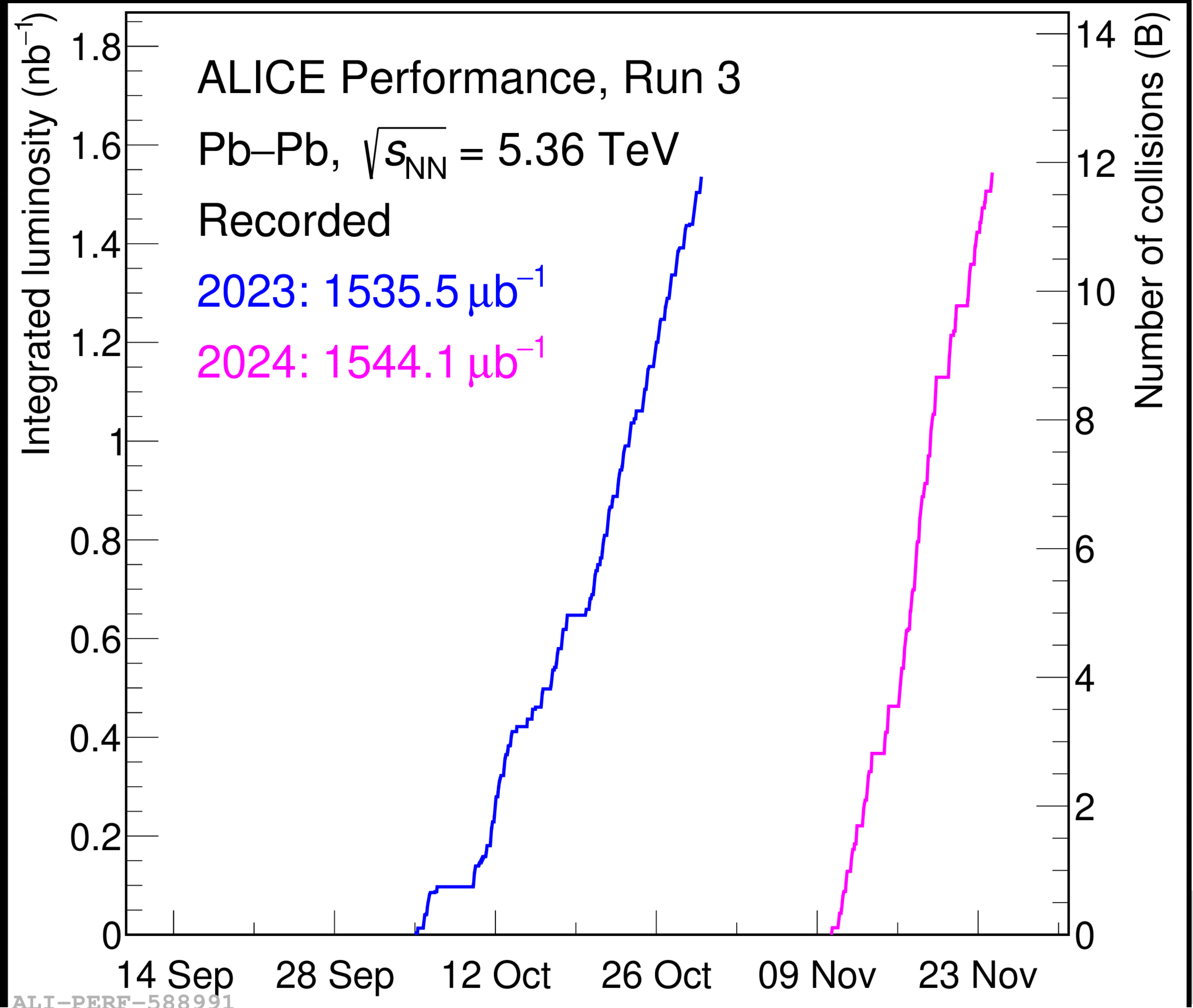
- ALICE capabilities:
  - Extensive PID and low-p_T tracking down to 150 MeV/c
  - GEM-based TPC: 50 kHz Pb-Pb, continuous readout
  - ITS 2: pointing resolution of 35 μm at 1 GeV/c
  - MFT: forward tracking and vertexing

Setup in Run 3 (2022-2026)

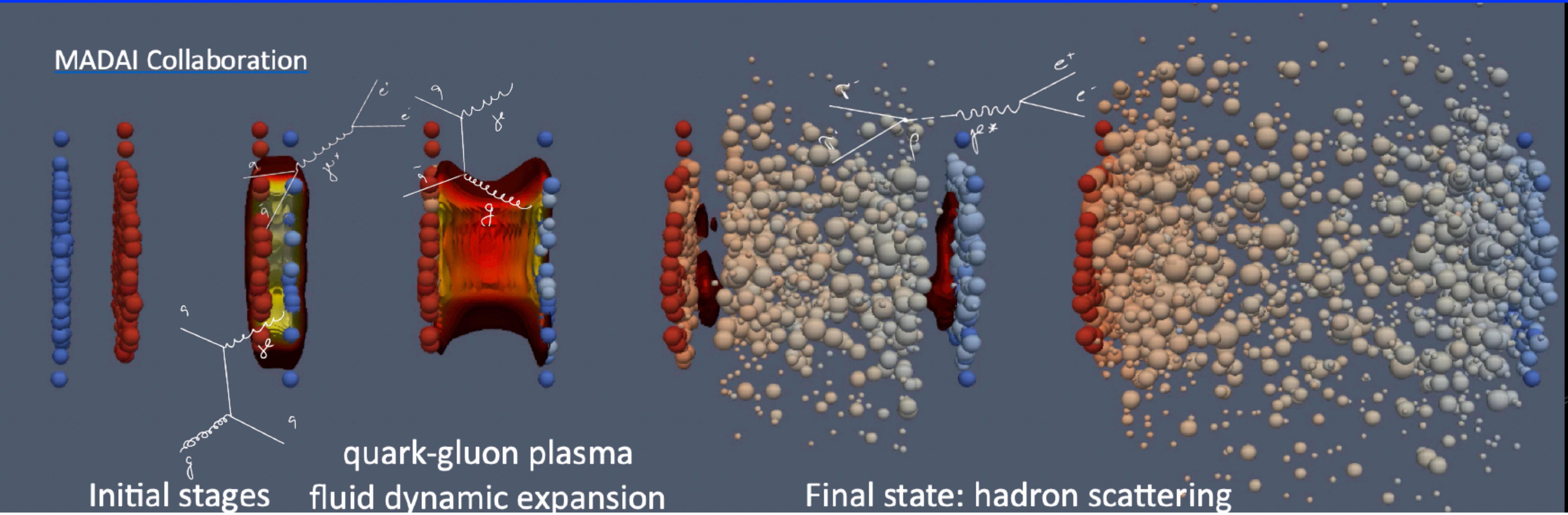


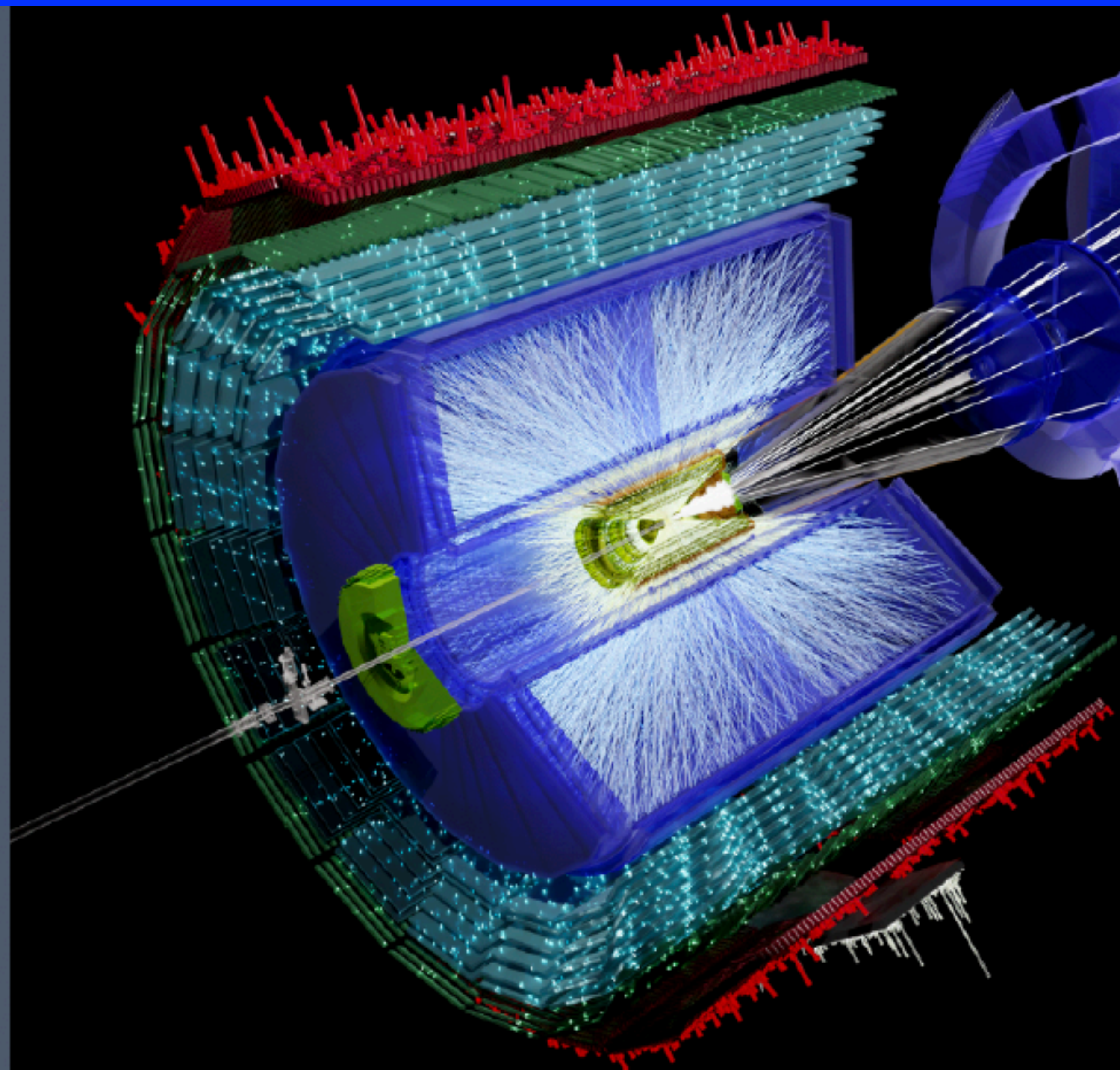
Setup in Run 3 (2022-2026)



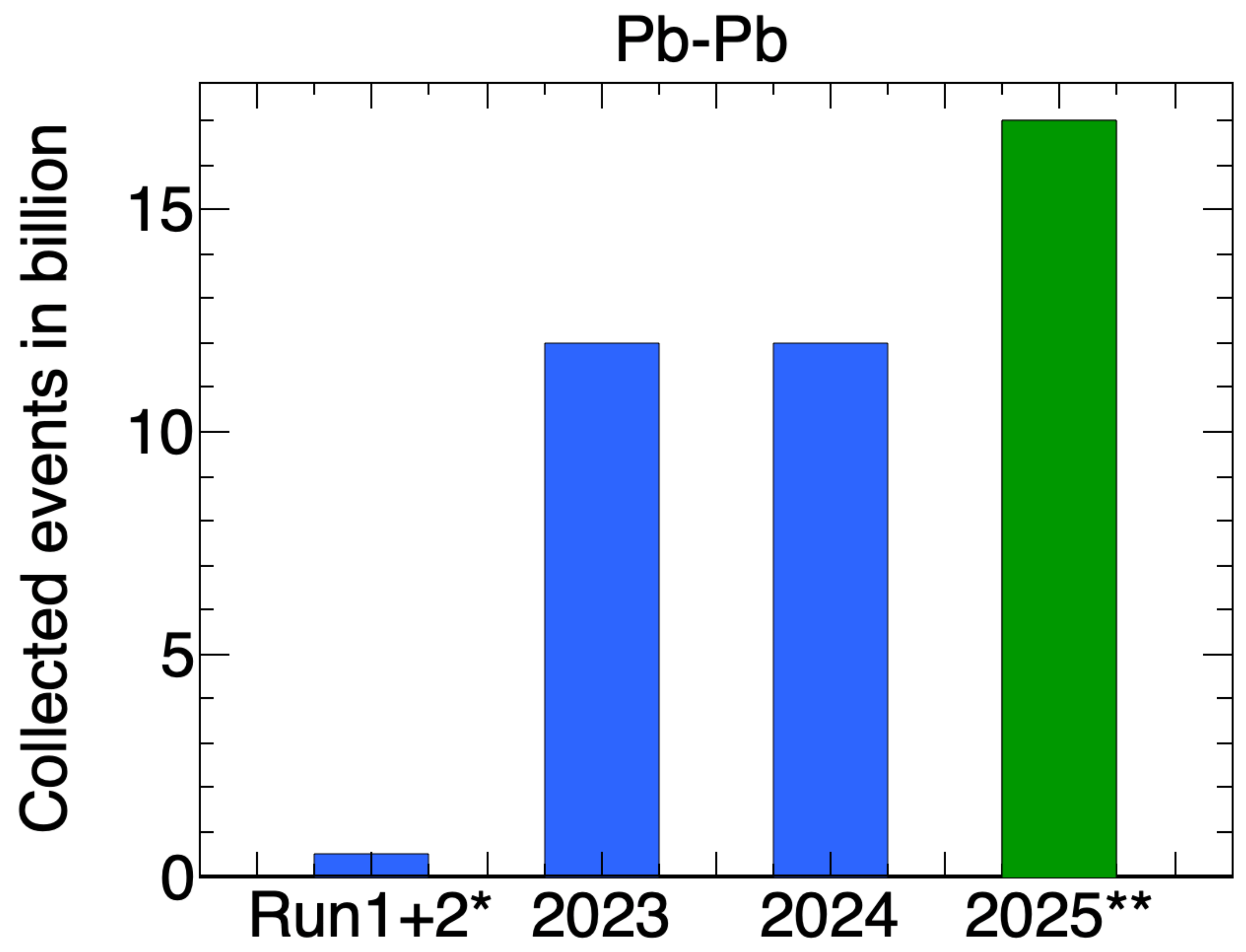


QCD matter at its extreme





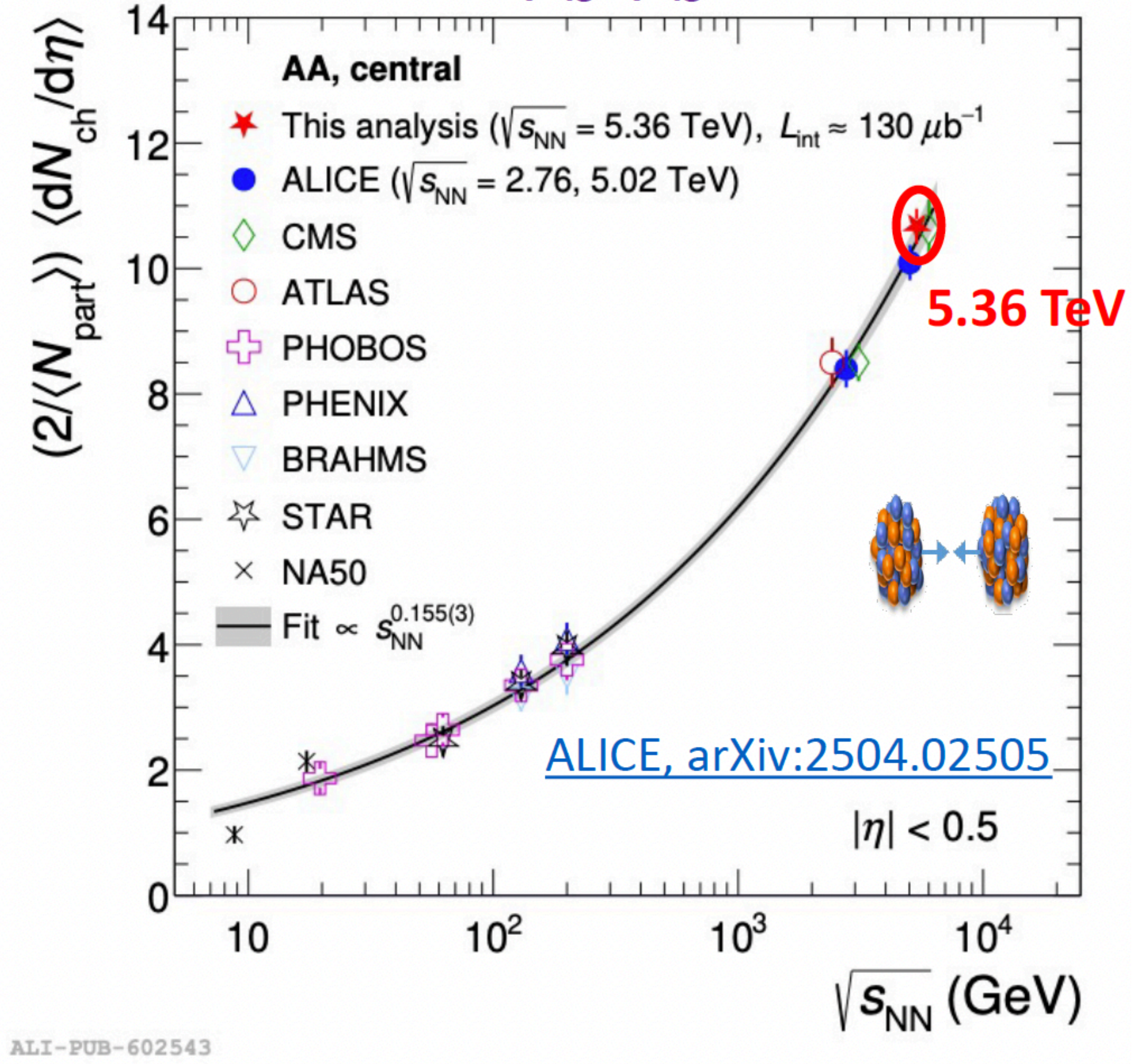
- By colliding different ion species
  - pp & p-Pb & Pb - Pb
  - Xe - Xe (Run 2)
  - p-O & O - O & Ne - Ne (finished in 2025)



*for central barrel only (MB)
**expected in 2025

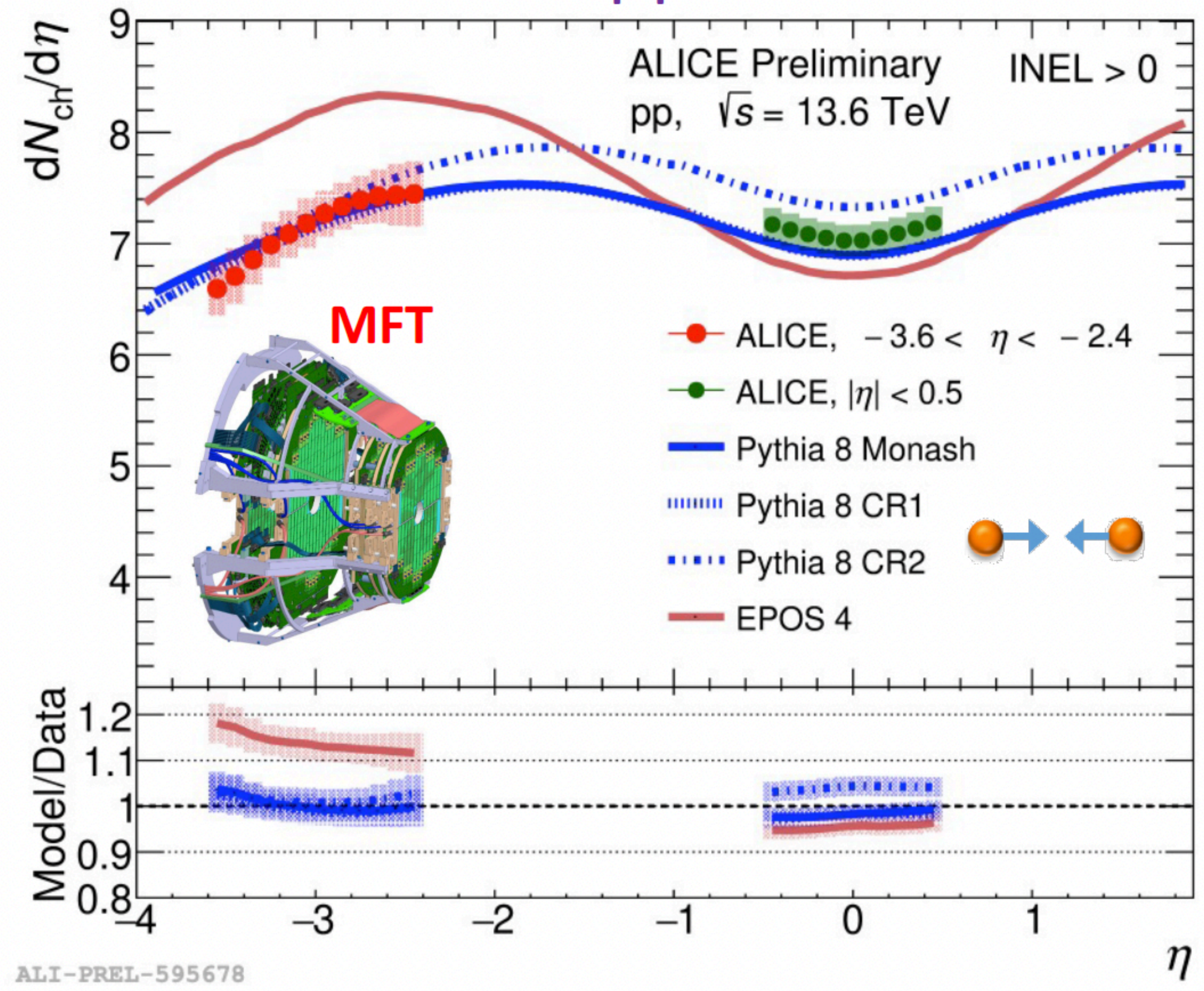
Final state: charged-particle density dN/dη

Pb-Pb



Energy density
$\varepsilon \propto dN_{ch}/d\eta$

pp



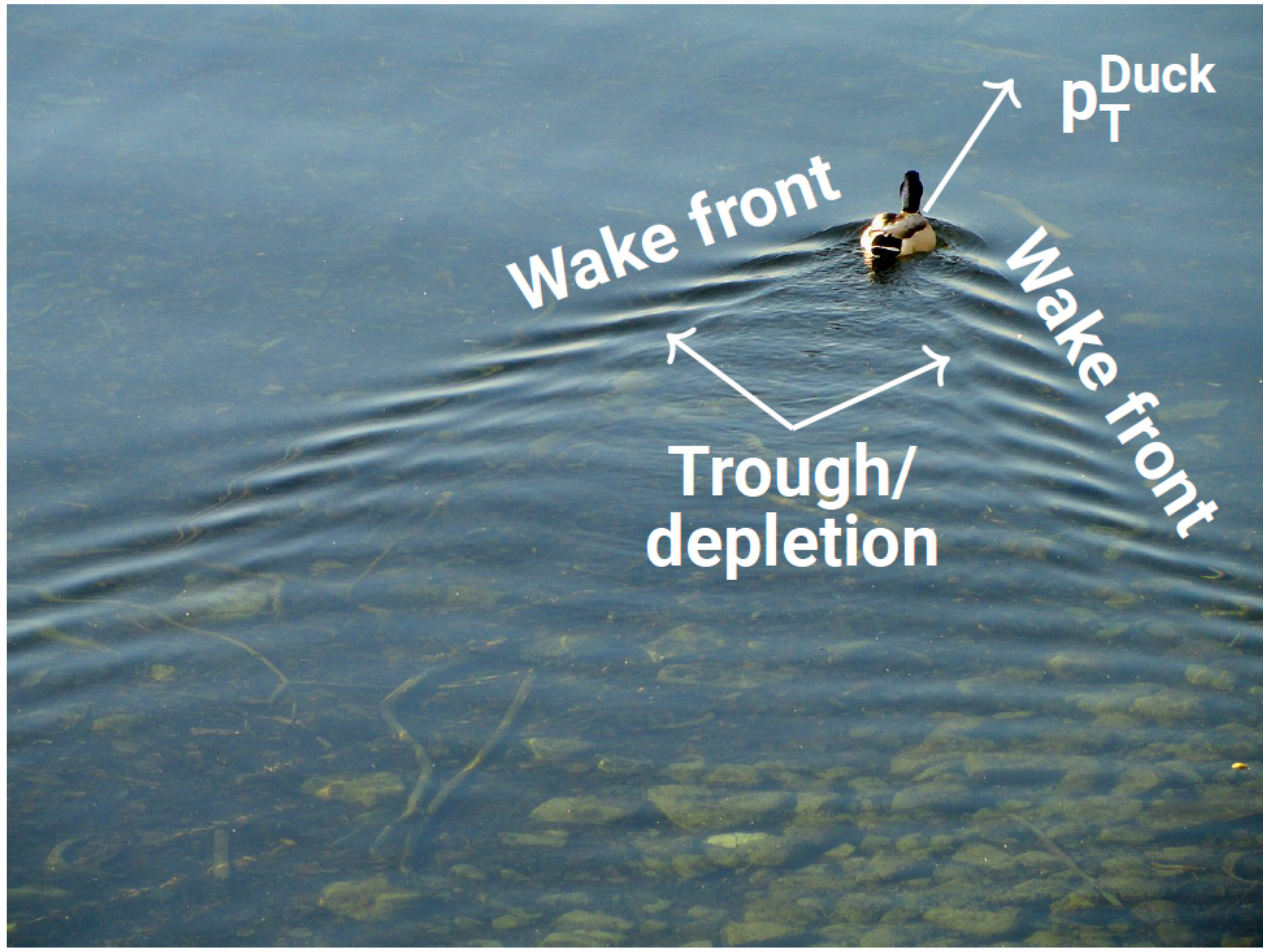
- Multiplicity measured with charged tracks at mid- and forward- rapidities
  - ➡ First paper with Run 3 results: in line with extrapolation from lower energies
  - ➡ First measurement using new MFT detector: trend at forward rapidity compatible with PYTHIA 8

Hard parton interactions with QGP

Jet energy loss and medium response

- Energetic objects traversing a medium induce excitations (a ‘response’)

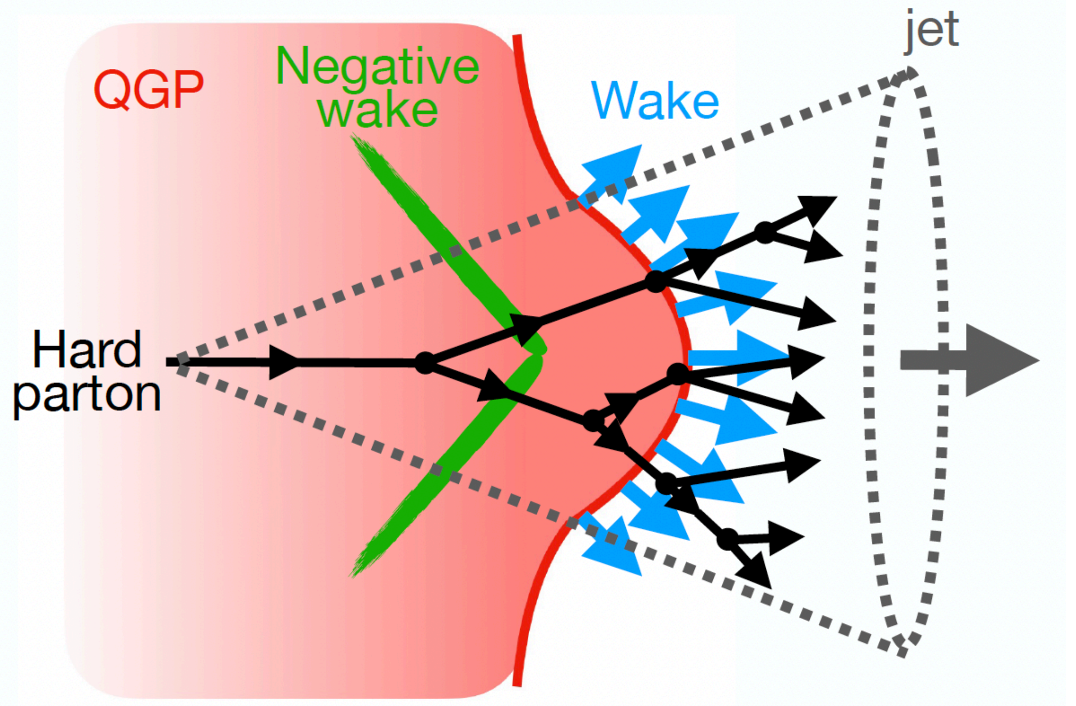
Duck via Wikimedia



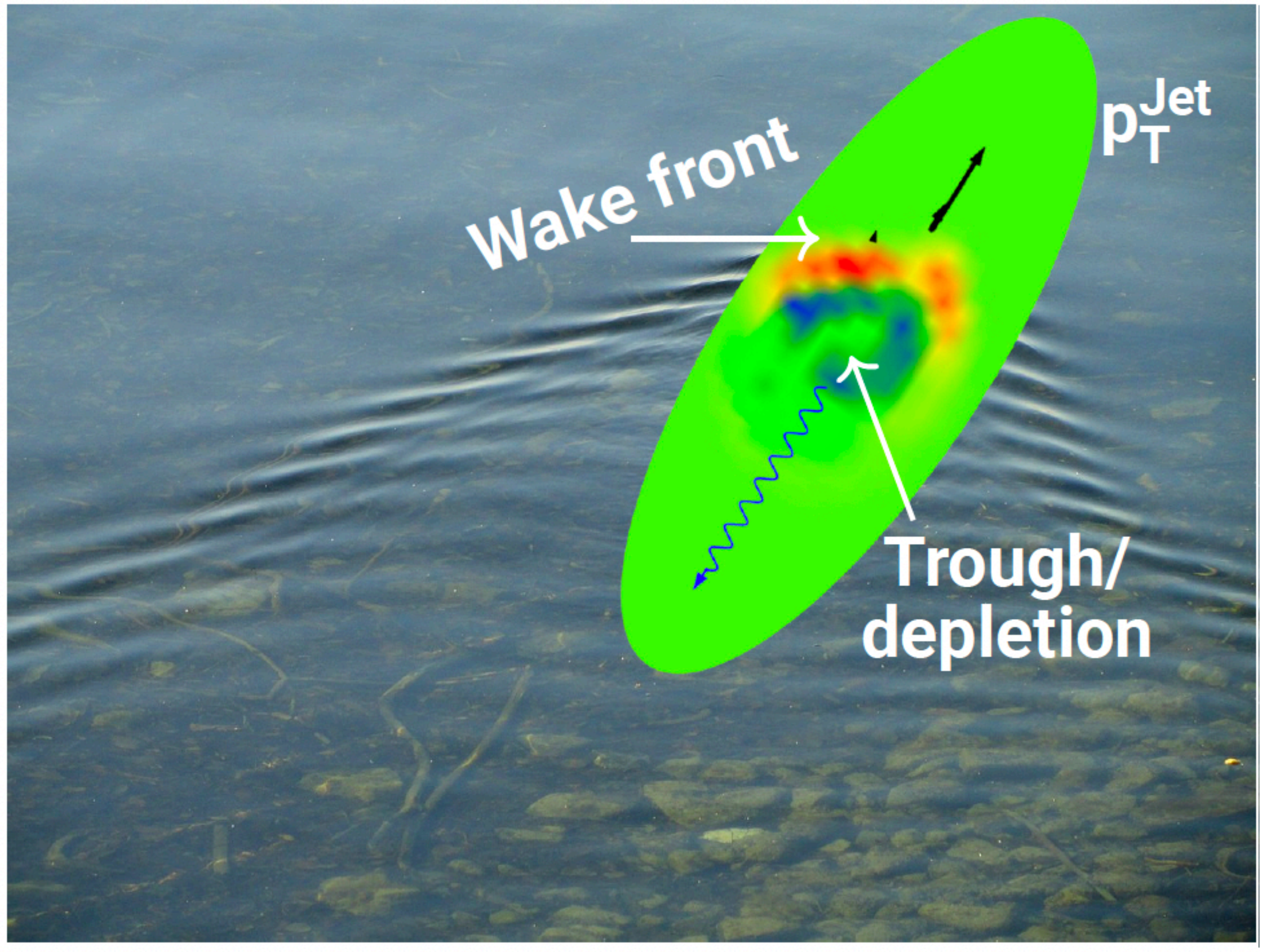
A duck in water induces a wake

Jet energy loss and medium response

- Energetic objects traversing a medium induce excitations (a 'response')



Duck via Wikimedia, jet wake via PLB 777 (2018) 86



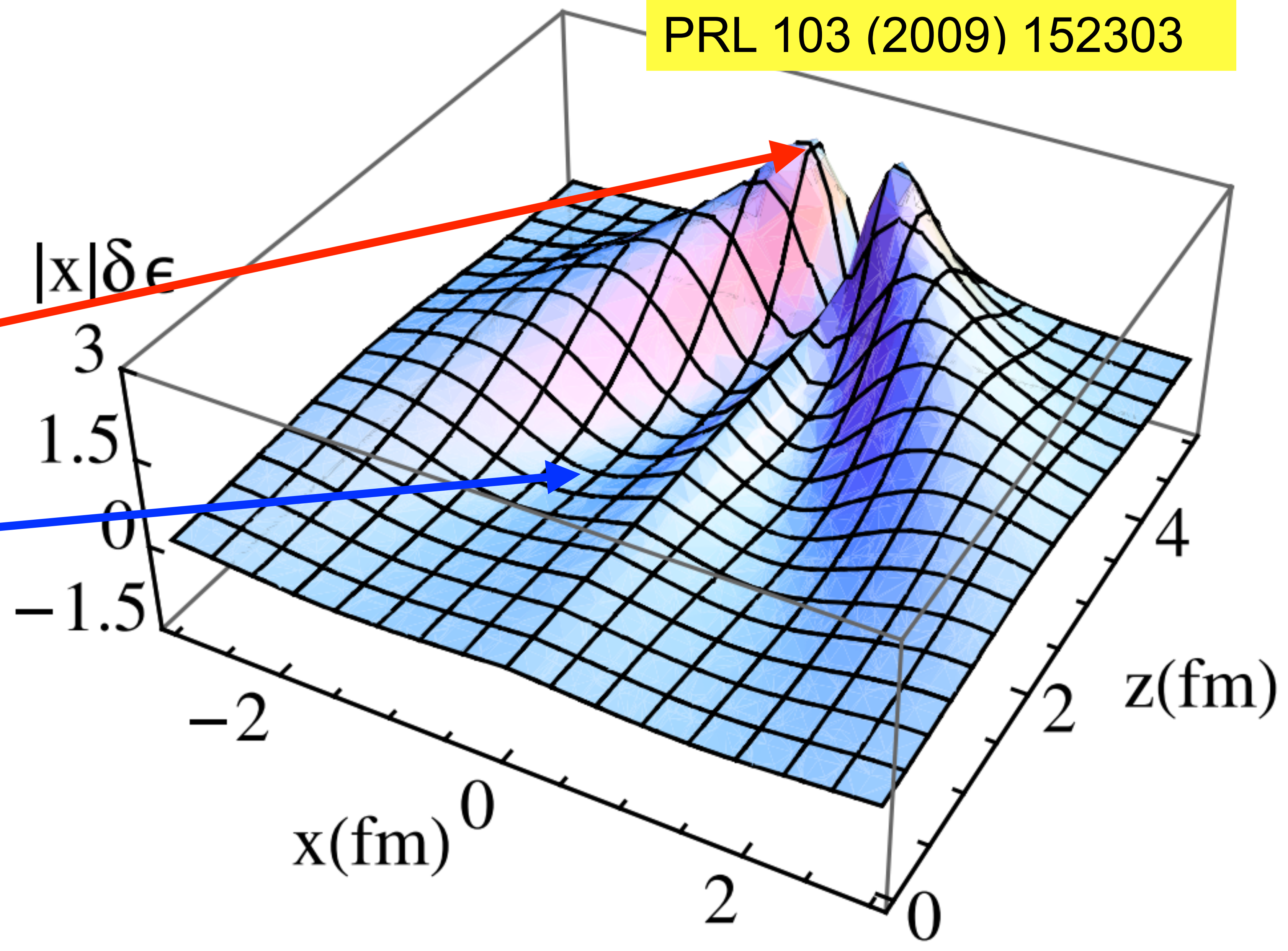
A jet in QGP induces a wake

- Jet lose energy due to interaction with medium
  - ➡ jet fragmentation pattern changes
  - ➡ medium also modified by jets

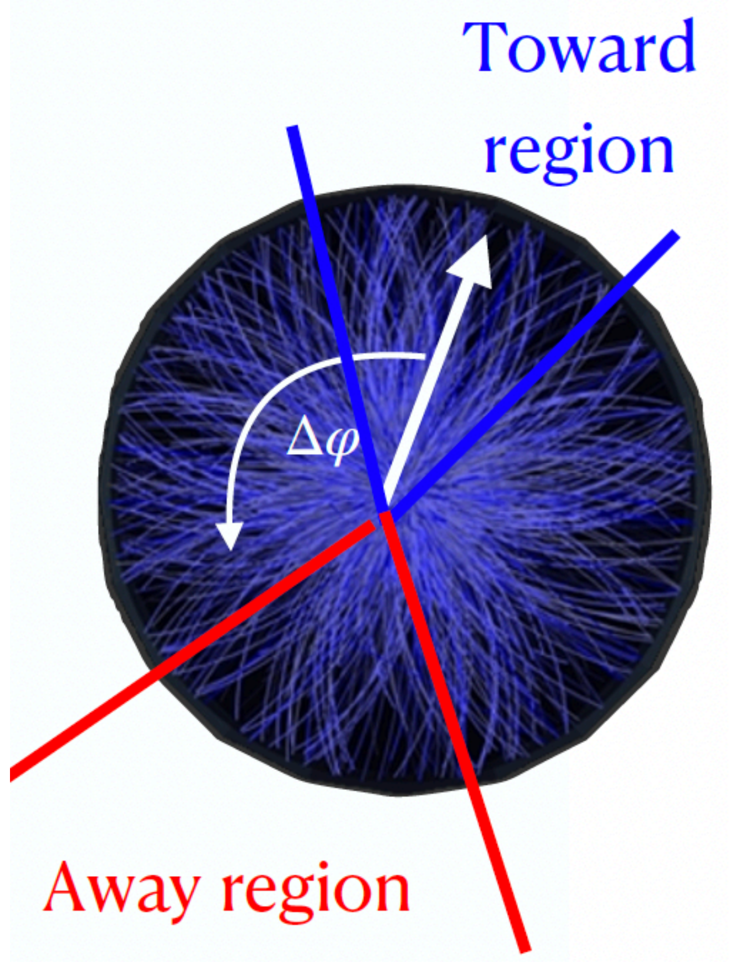
Expectations: "wake effects"

Enhancement around jet

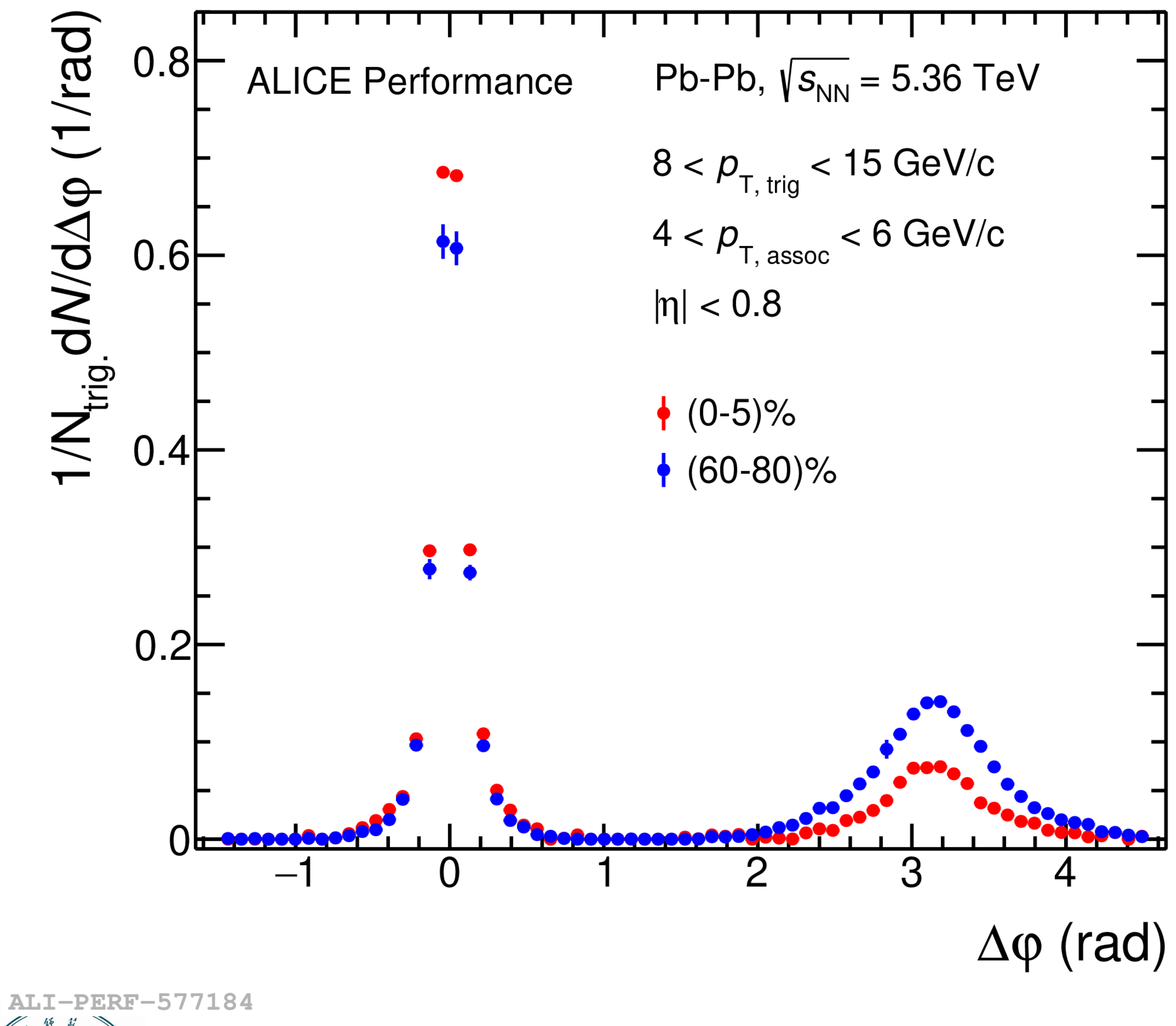
Depletion opposite jet

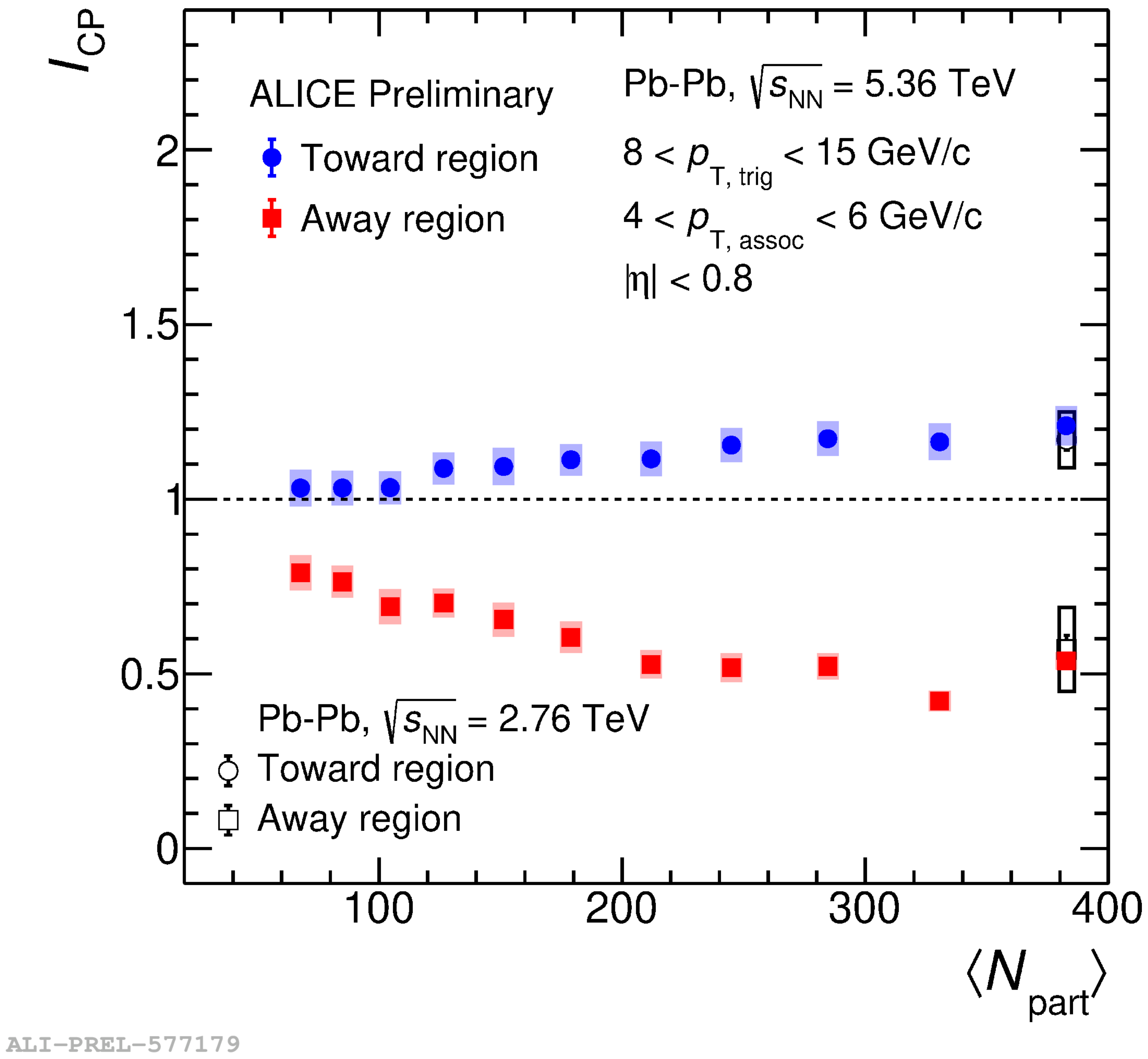


Jet quenching via di hadron correlations

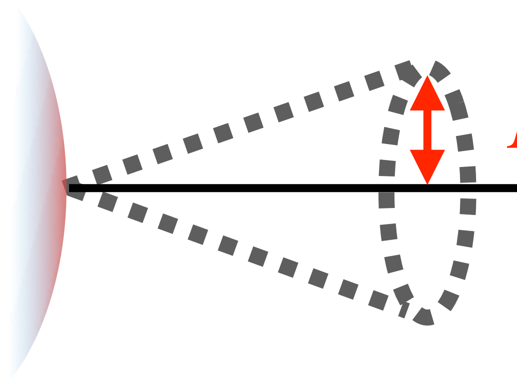


- High p_T trigger track used as a jet proxy
- Comparison between central and peripheral collisions - medium modification (I_{cp}):
  - **Suppression** of the away-side peak
    - **Stronger** towards central collisions - more medium
  - **Enhancement** of the near-side peak





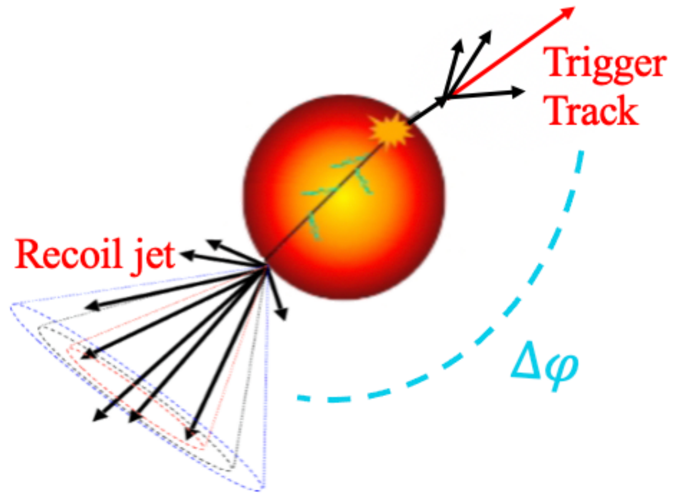
Semi-inclusive jet energy redistribution

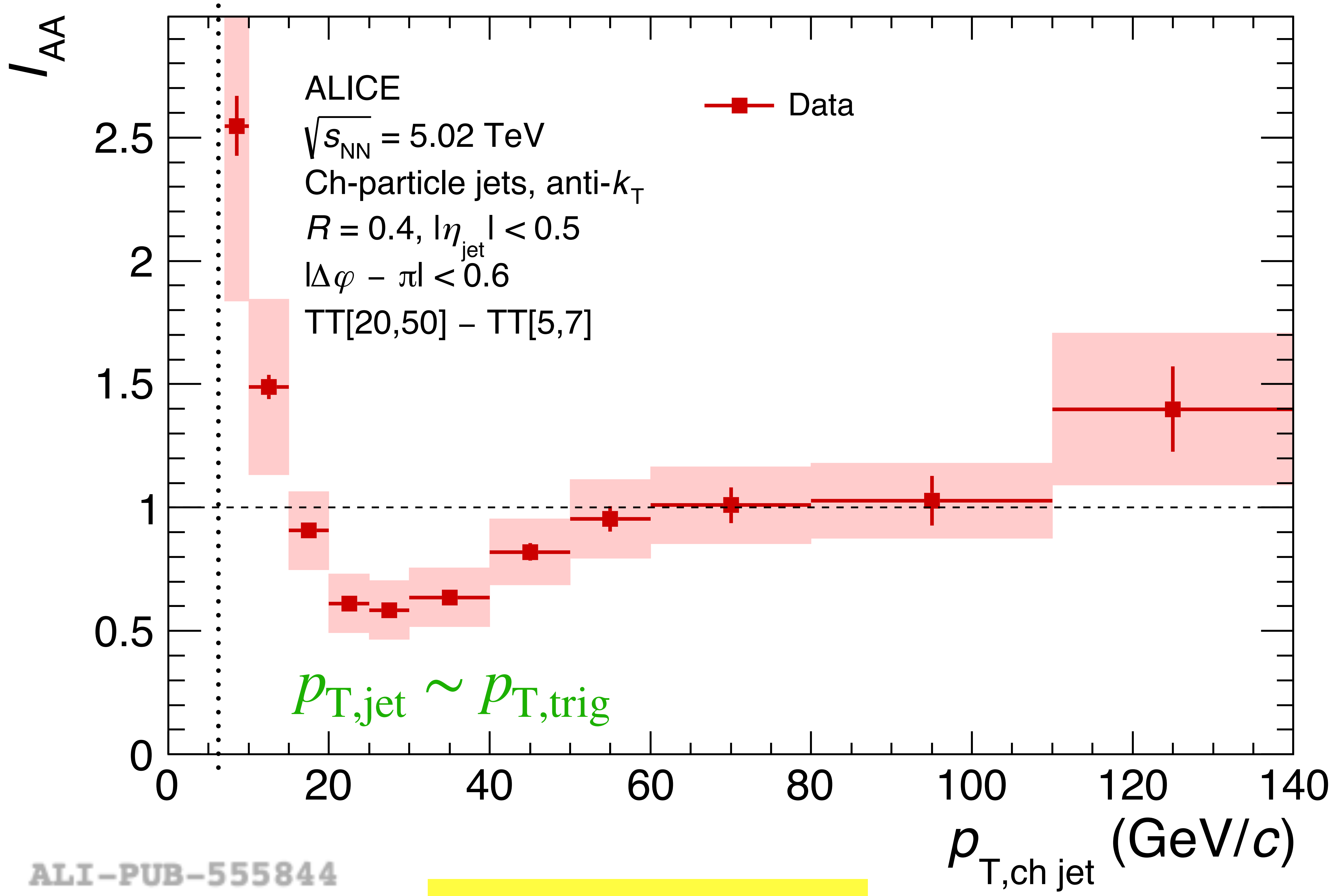


0–10%

R = 0.4

$$I_{AA} \equiv \frac{\Delta_{\mathrm{recoil}}\,(p_{\mathrm{T}})_{\mathrm{AA}}}{\Delta_{\mathrm{recoil}}\,(p_{\mathrm{T}})_{\mathrm{pp}}}$$

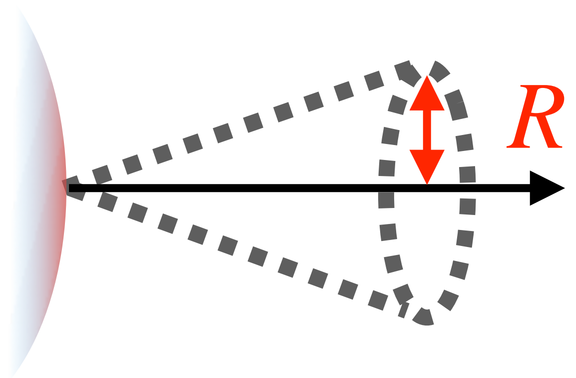




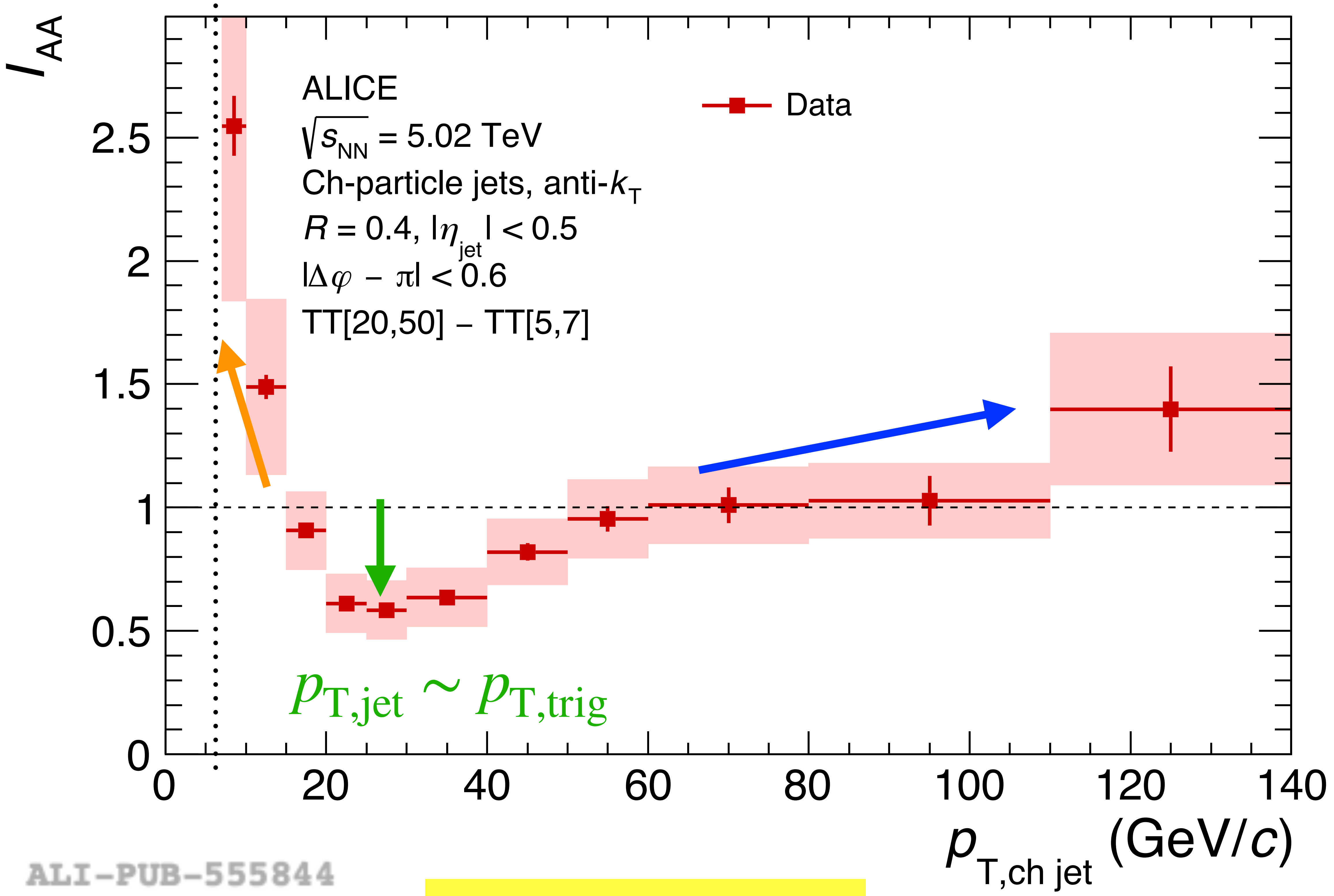
PRC 110 (2024) 014906

- First measurements of semi-inclusive recoil jet yields down to very low p_T (7 GeV/c) with ALICE

Semi-inclusive jet energy redistribution



0–10%   ***R* = 0.4**



ALI-PUB-555844

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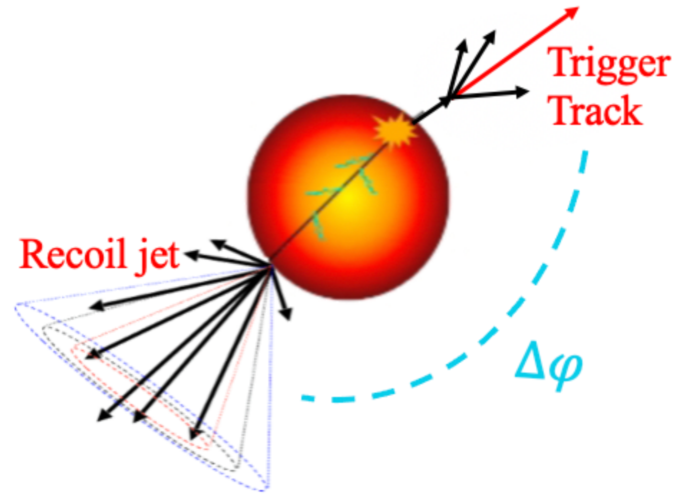
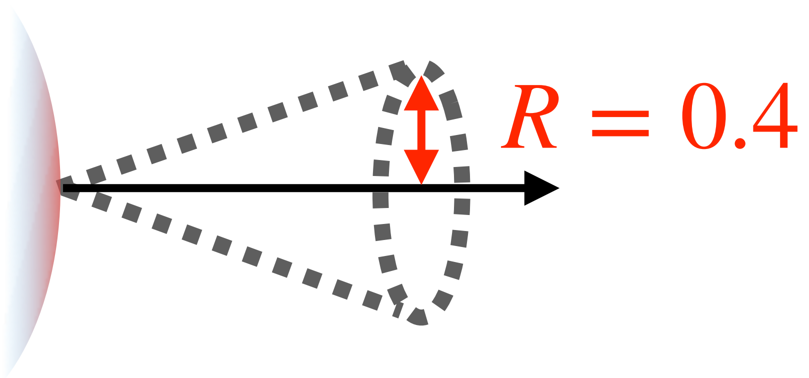
$$I_{AA} \equiv \frac{\Delta_{recoil}(p_T)_{AA}}{\Delta_{recoil}(p_T)_{pp}}$$



- First measurements of semi-inclusive recoil jet yields down to very low p_T (7 GeV/c) with ALICE
- Jet yield enhancement at low p_T → hint of energy recovery in low p_T jets?
- Jet yield suppression at $20 < p_{T,jet} < 60$ GeV/c → Jet energy loss
- Rising trend with increasing jet p_T → Interplay of jet quenching and jet production

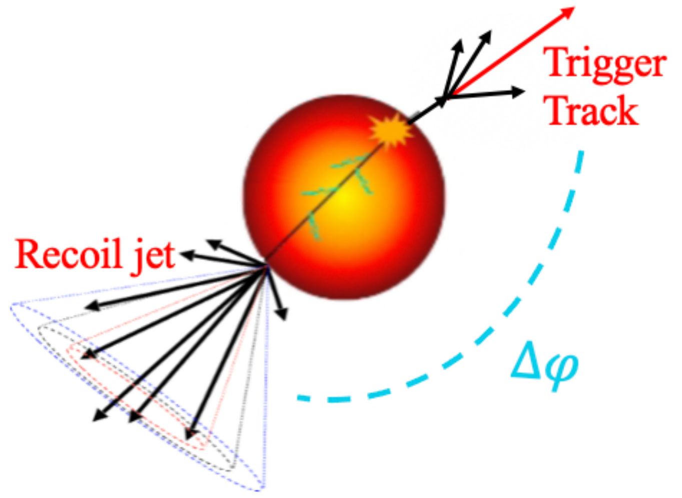
Semi-inclusive jet energy redistribution

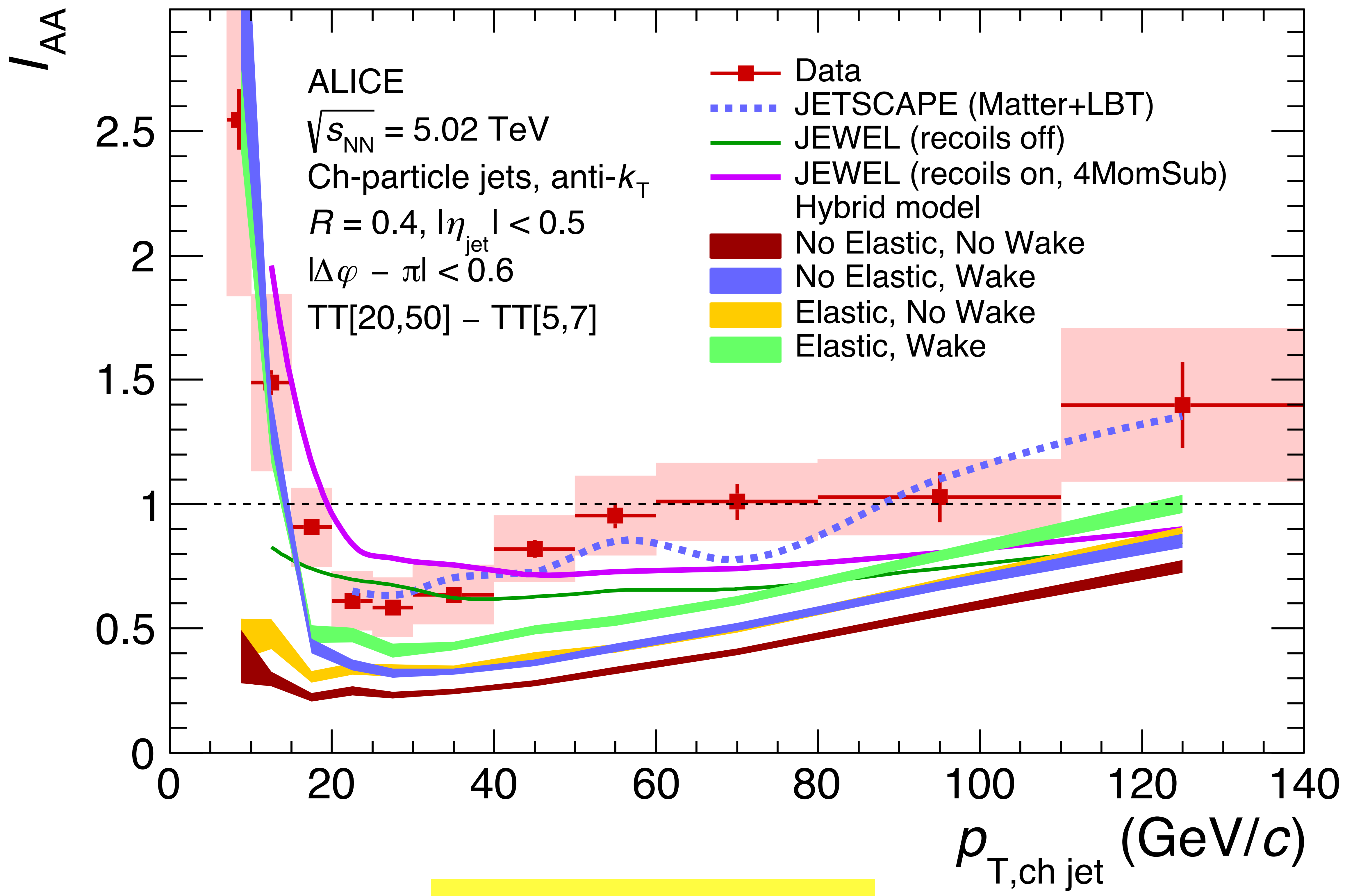


0–10%

R = 0.4

$$I_{AA} \equiv \frac{\Delta_{\rm recoil}\,(p_{\rm T})_{\rm AA}}{\Delta_{\rm recoil}\,(p_{\rm T})_{\rm pp}}$$

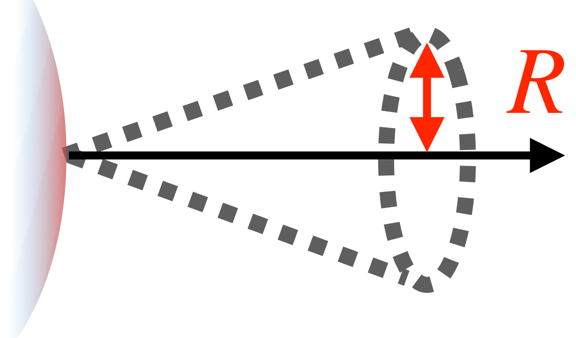




PRC 110 (2024) 014906

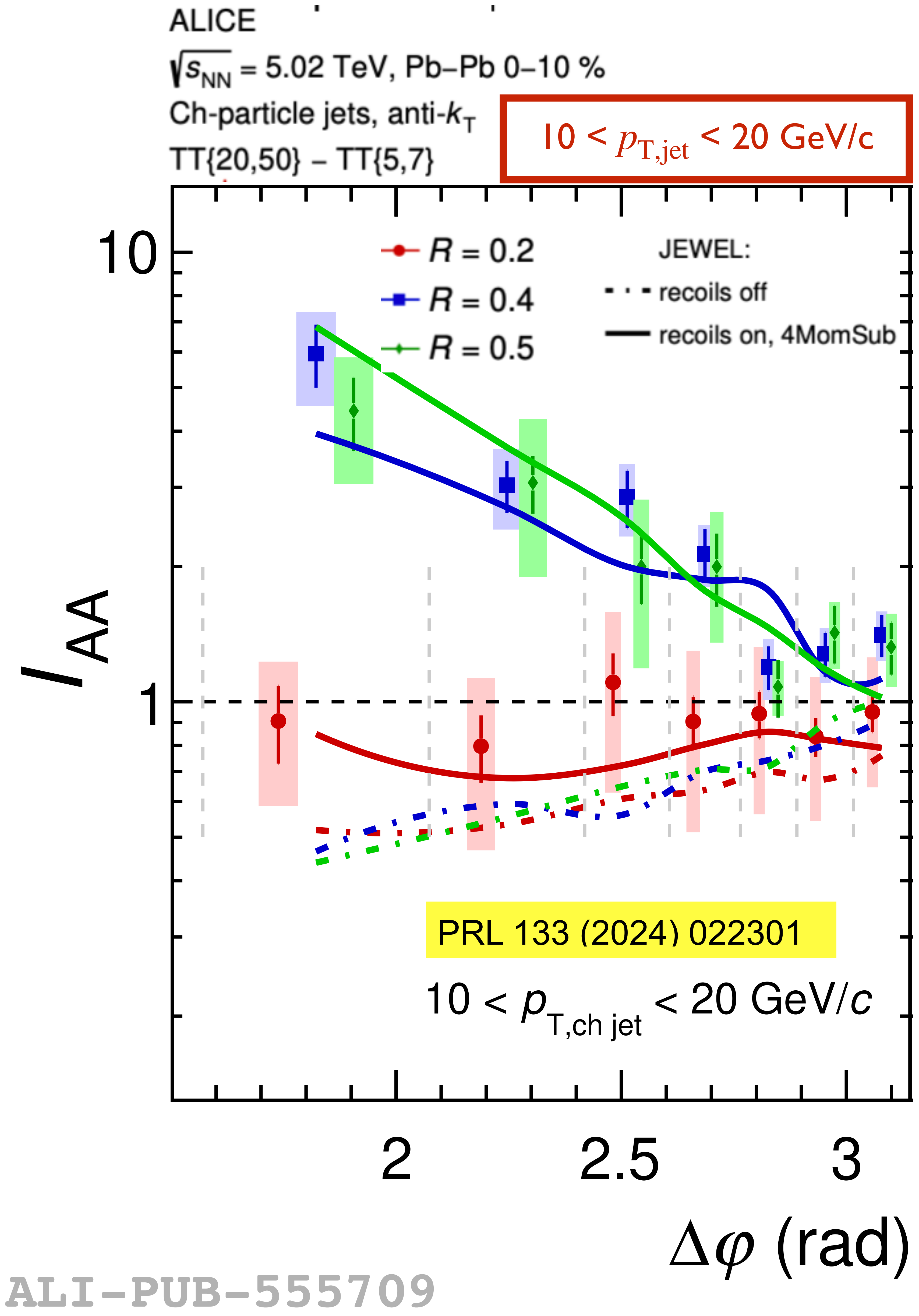
- First measurements of semi-inclusive recoil jet yields down to very low $p_{\rm T}$ (7 GeV/c) with ALICE
- The rising trend is qualitatively described by all predications
- Hybrid model and JEWEL predictions overestimate the suppression at high $p_{\rm T}$
- Hybrid model with wake effect and JEWEL with recoils on capture the yield enhancement at low $p_{\rm T}$
  → Medium response could be responsible for enhancement

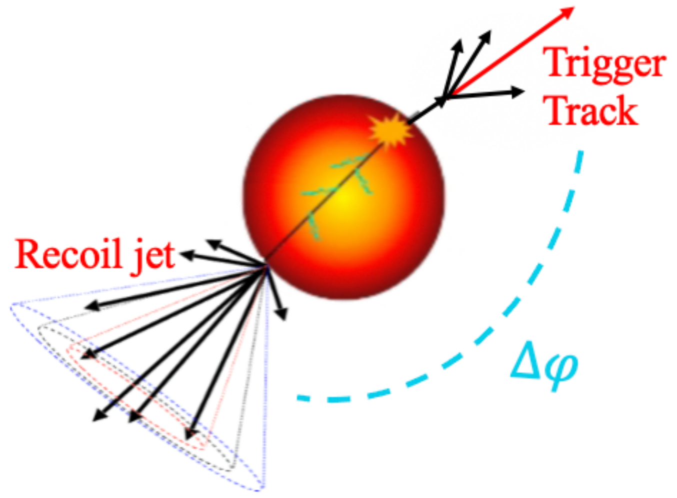
Recoil jet azimuthal modification



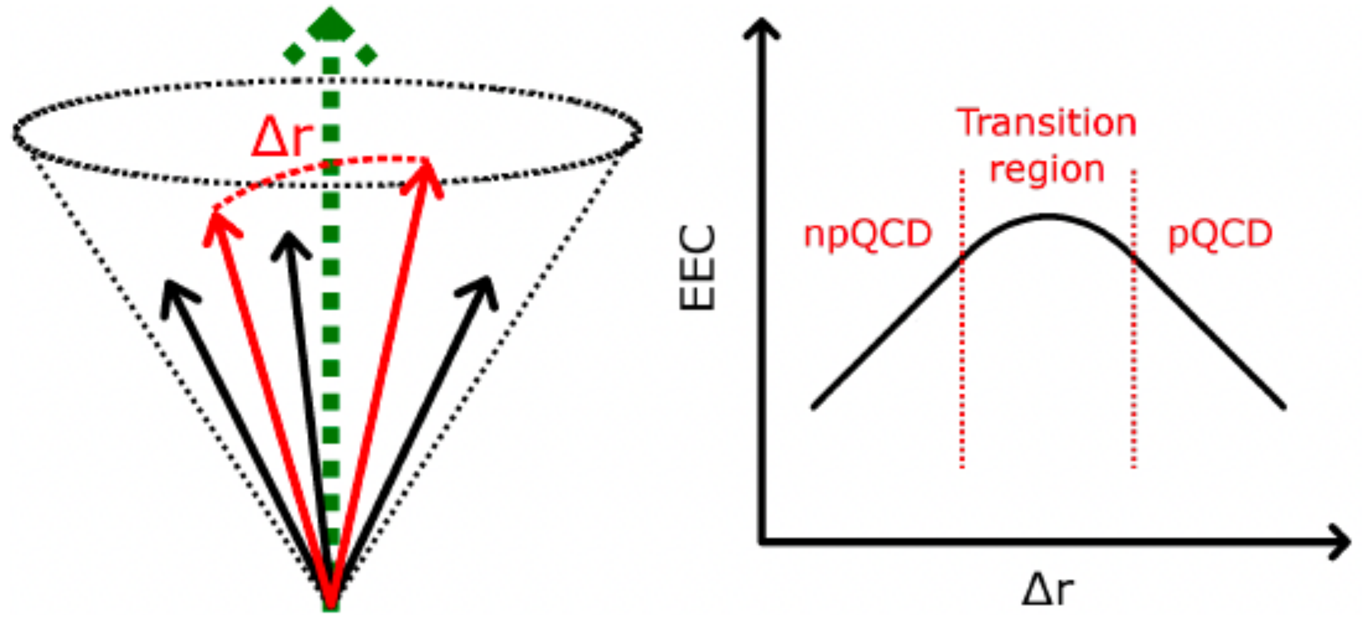
$$I_{\mathrm{AA}} \equiv \frac{\Delta_{\mathrm{recoil}}\,(p_{\mathrm{T}})_{\mathrm{AA}}}{\Delta_{\mathrm{recoil}}\,(p_{\mathrm{T}})_{\mathrm{pp}}}$$

- Broadening of recoil jets from R = 0.2 to R = 0.4 for 10 < $p_{\mathrm{T,ch\,jet}}$ < 20 GeV/c
  - Characteristic of medium response
  - Soft radiation is recovered partially with increasing radius
- All features of distribution reproduced by JEWEL with recoils on …
  - ➡ Observed broadening consistent with medium response

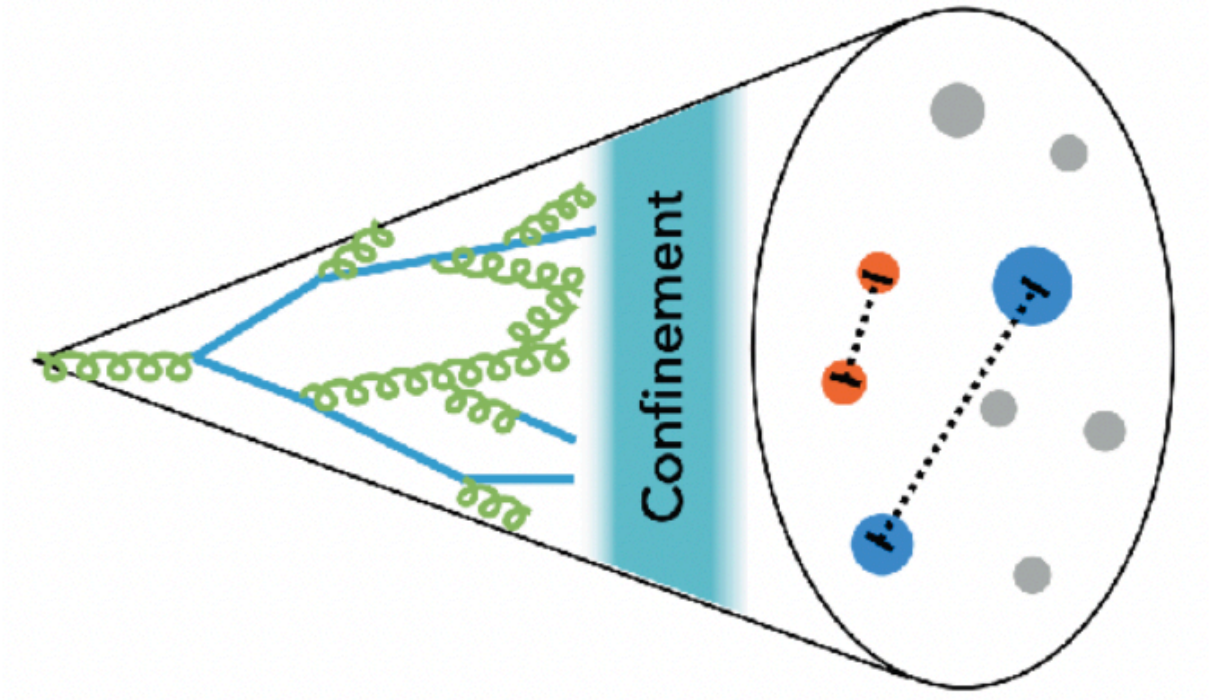


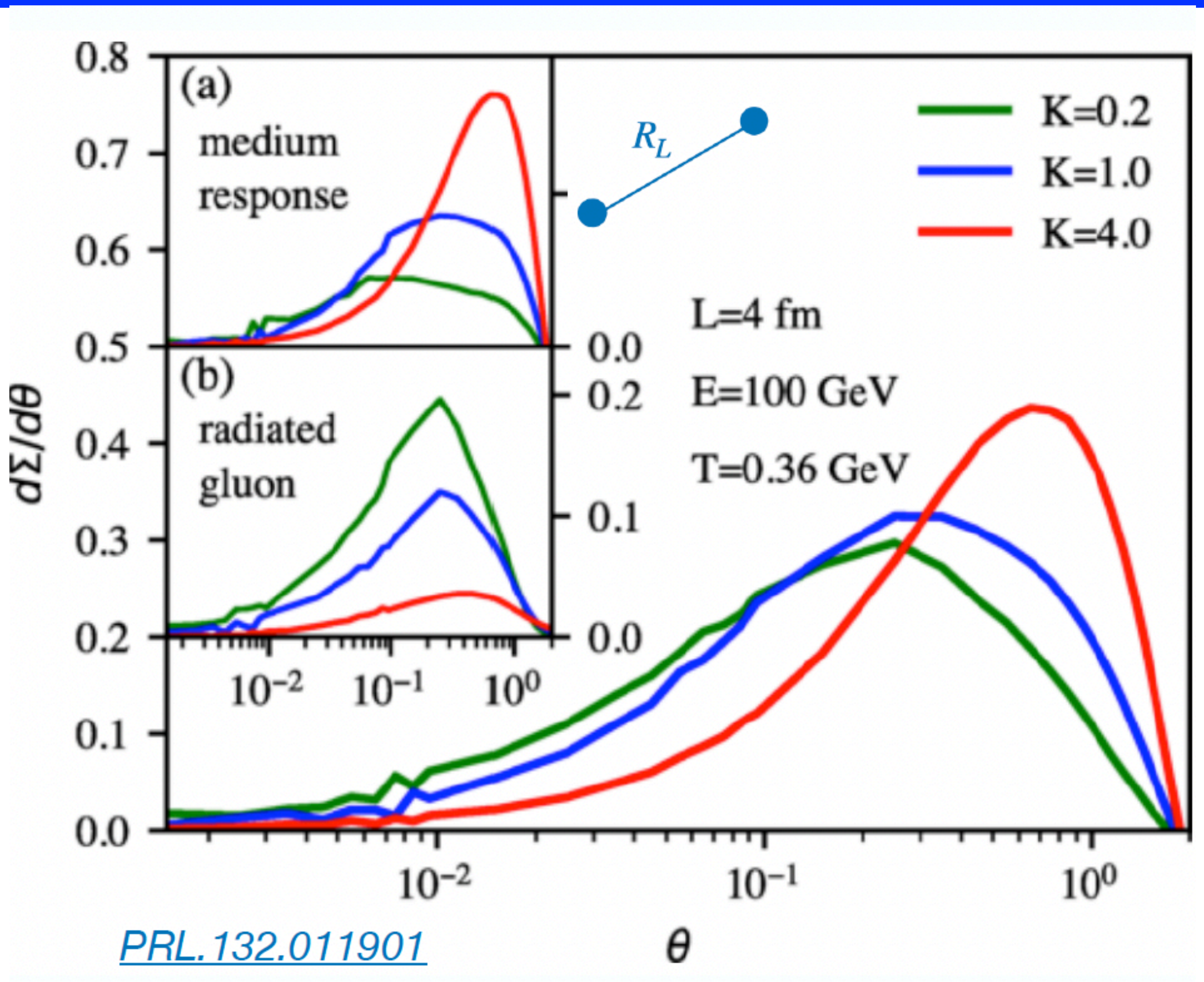


Energy-energy correlator and medium response



EEC (2-point energy correlator)

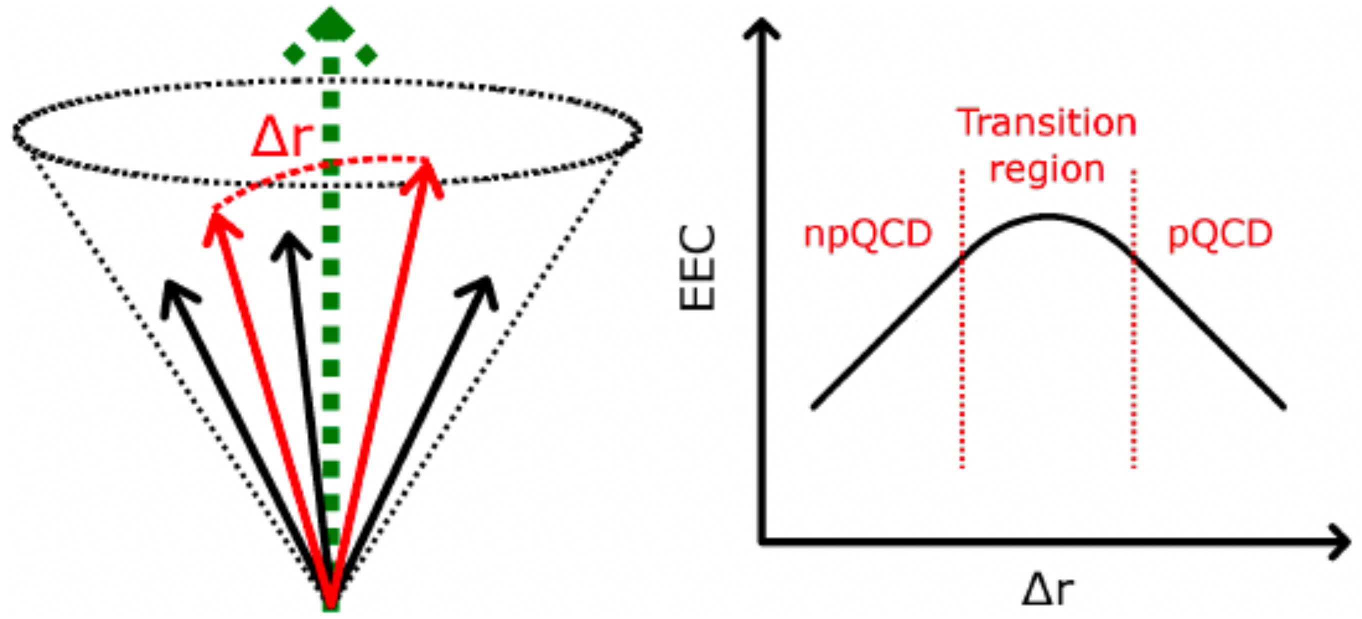




PRL.132.011901

- Jet-wake effects expected to change the EEC shape at larger angles

Energy-energy correlator and medium response



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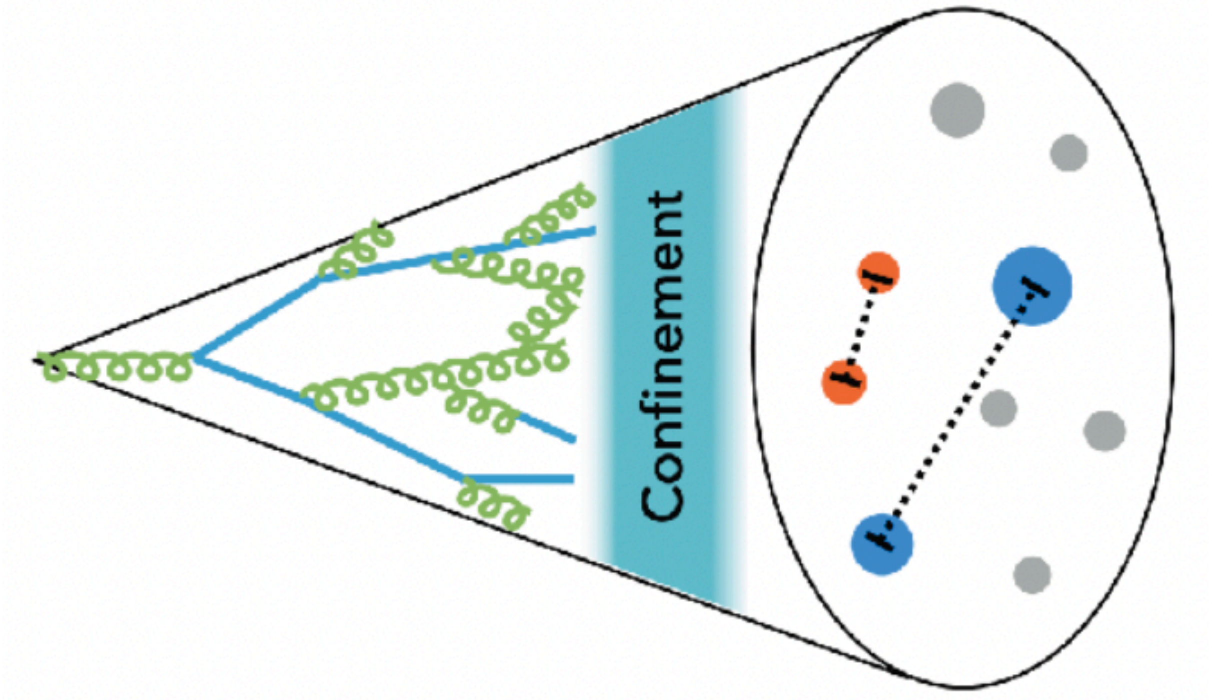

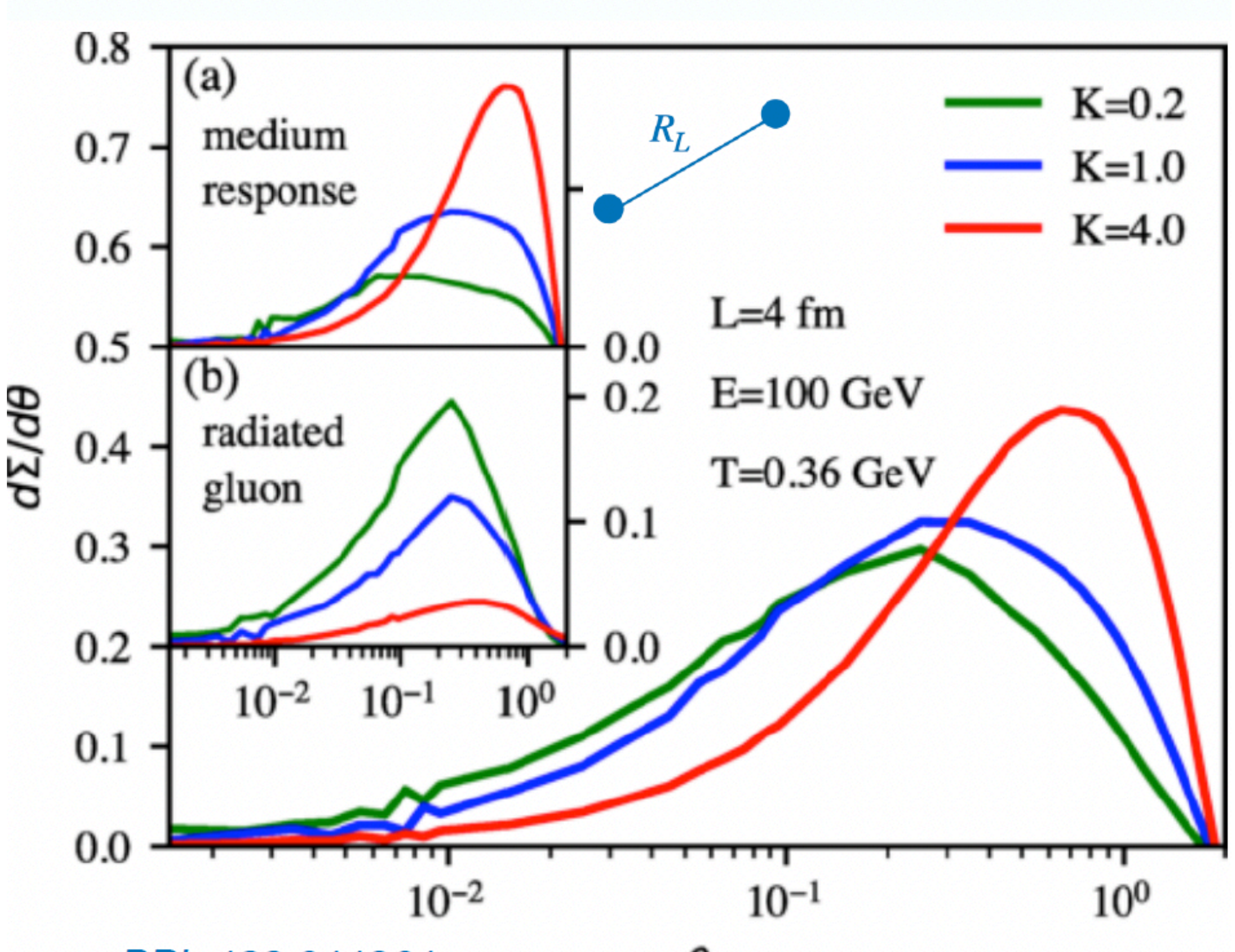

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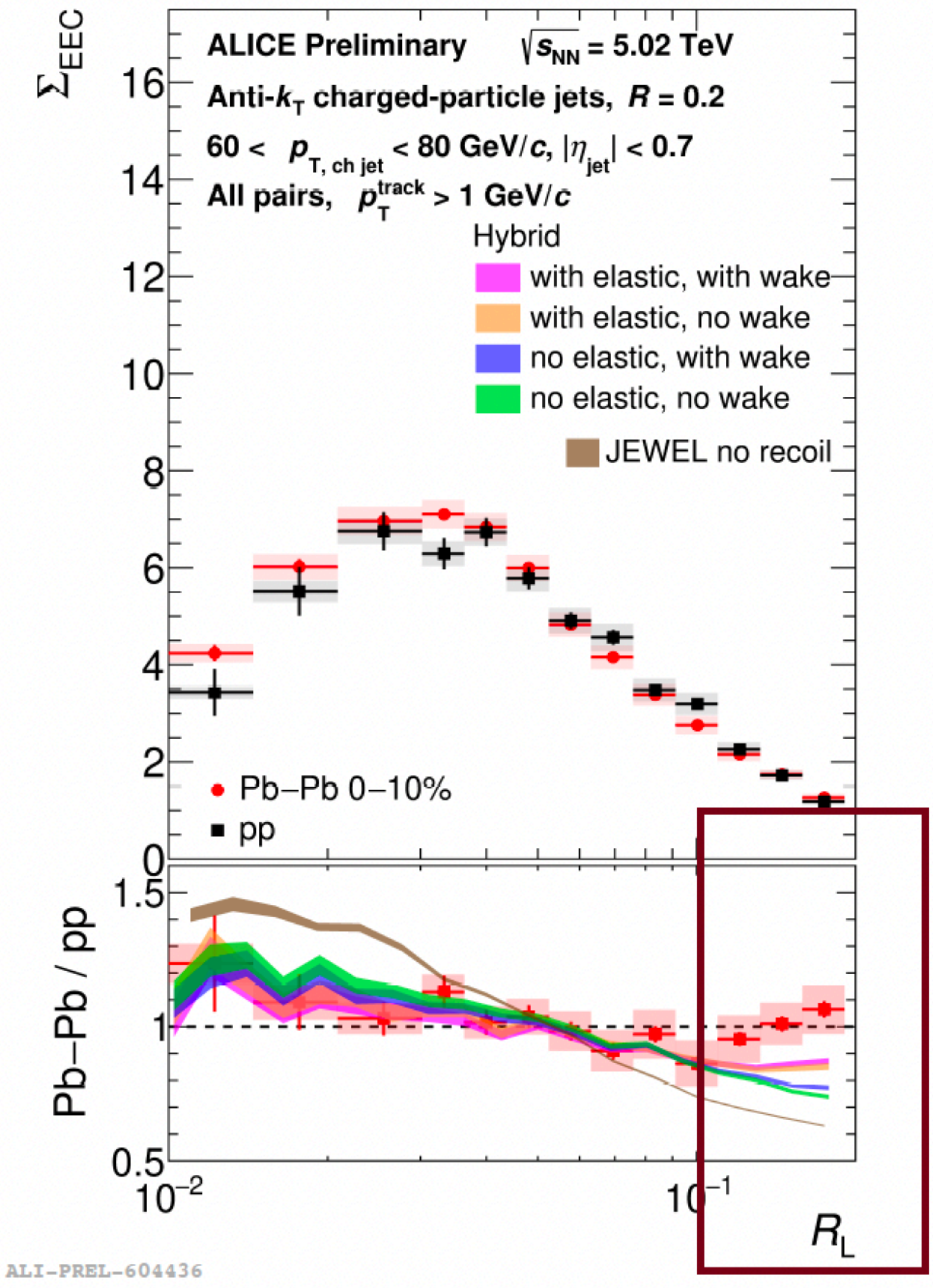
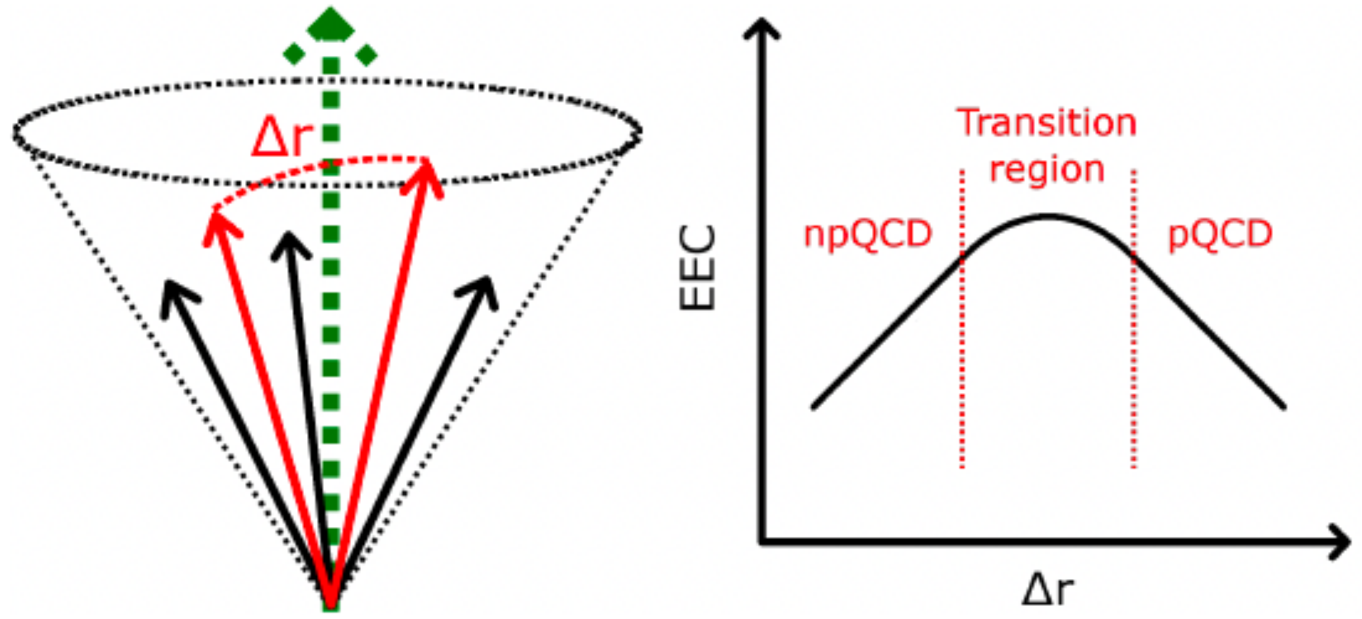


- Jet-wake effects expected to change the EEC shape at larger angles
- Hints of enhancement at low R_L and suppression at high R_L

Energy-energy correlator and medium response



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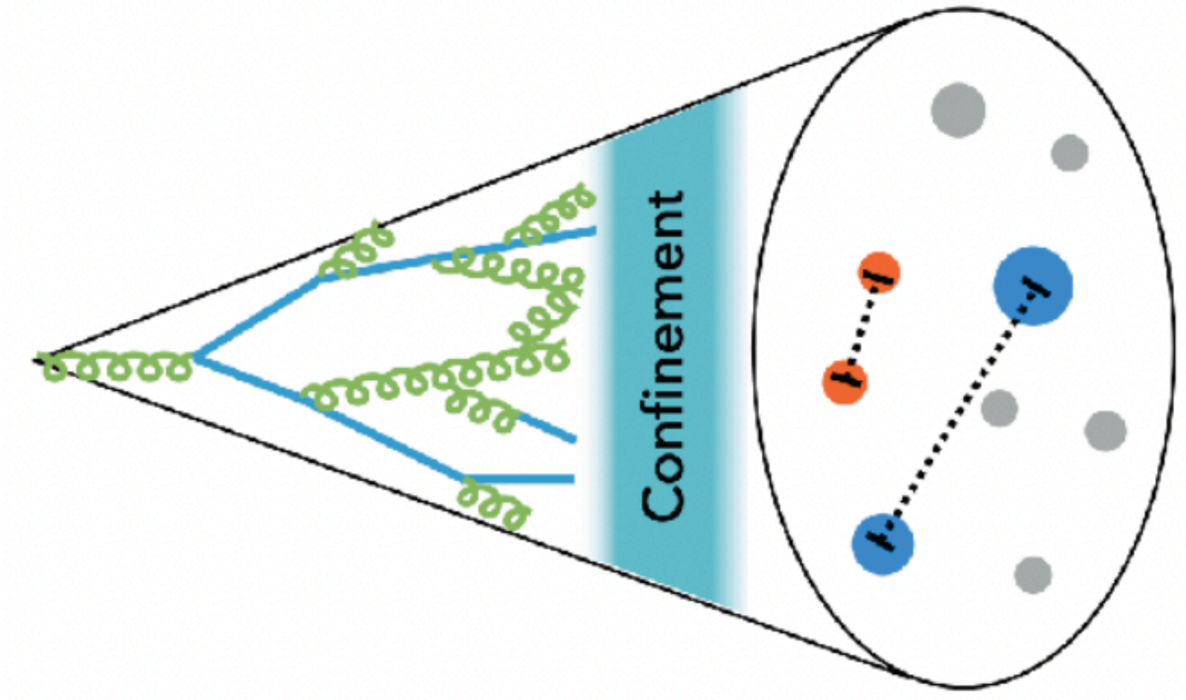
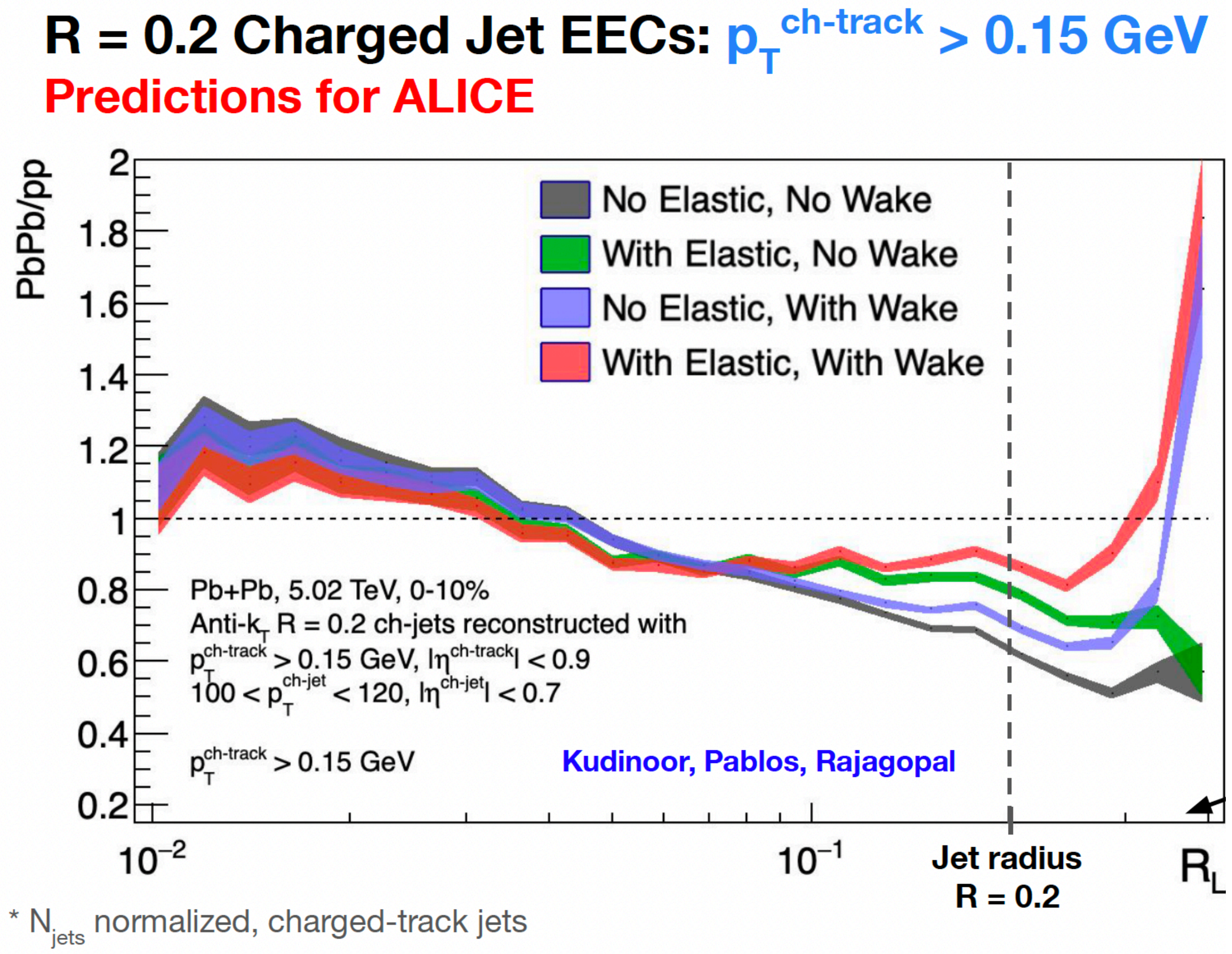
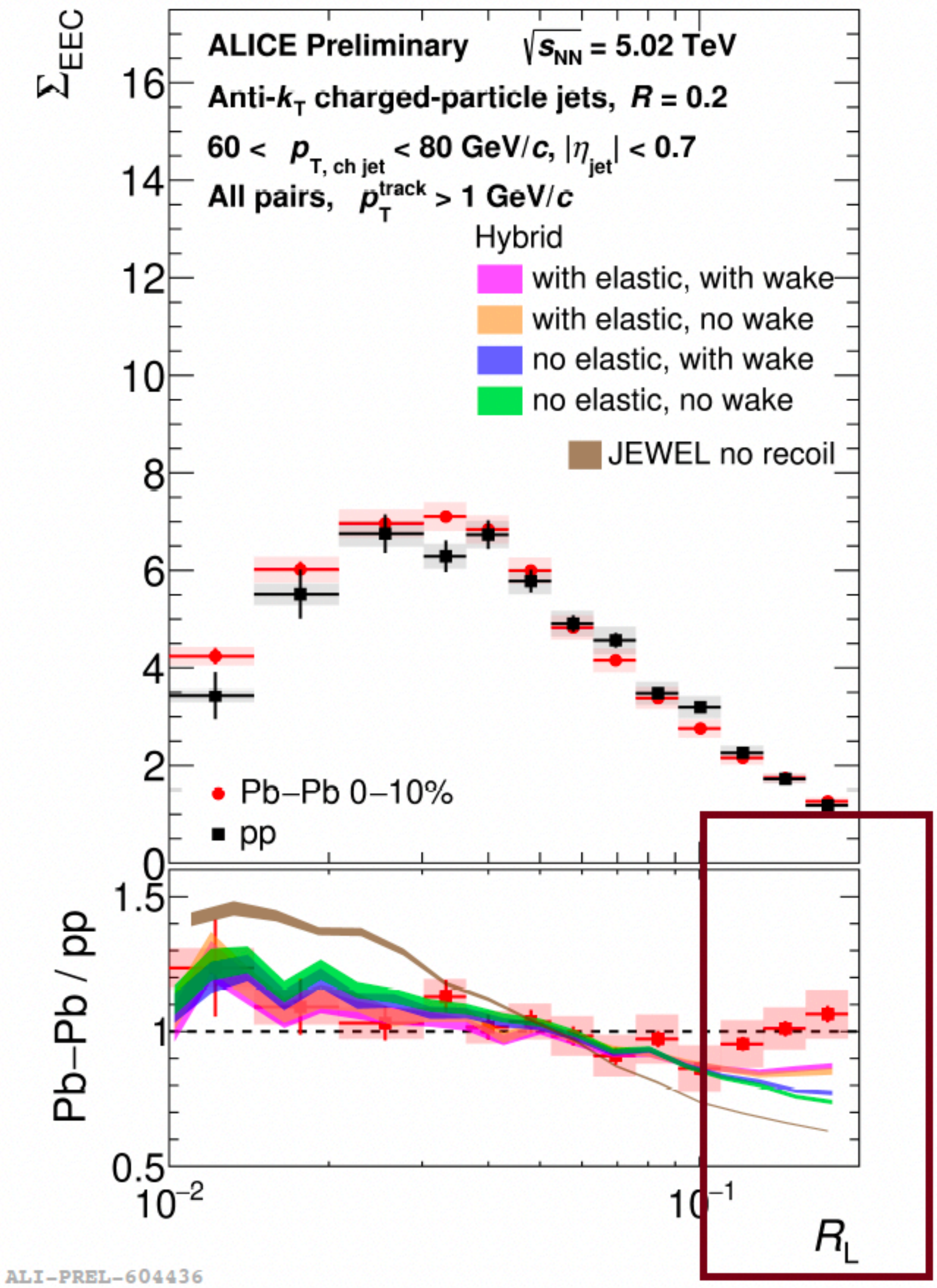


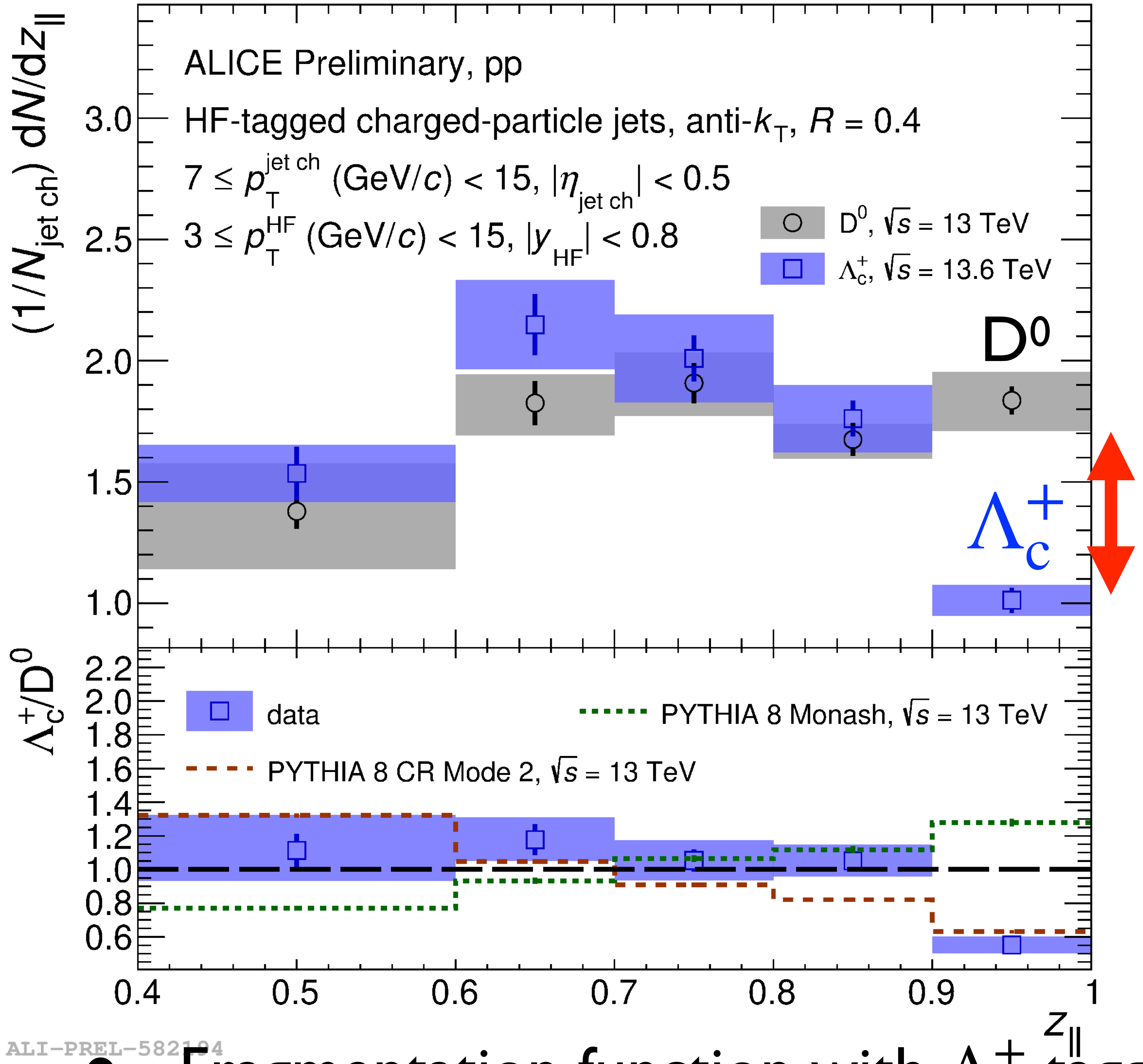


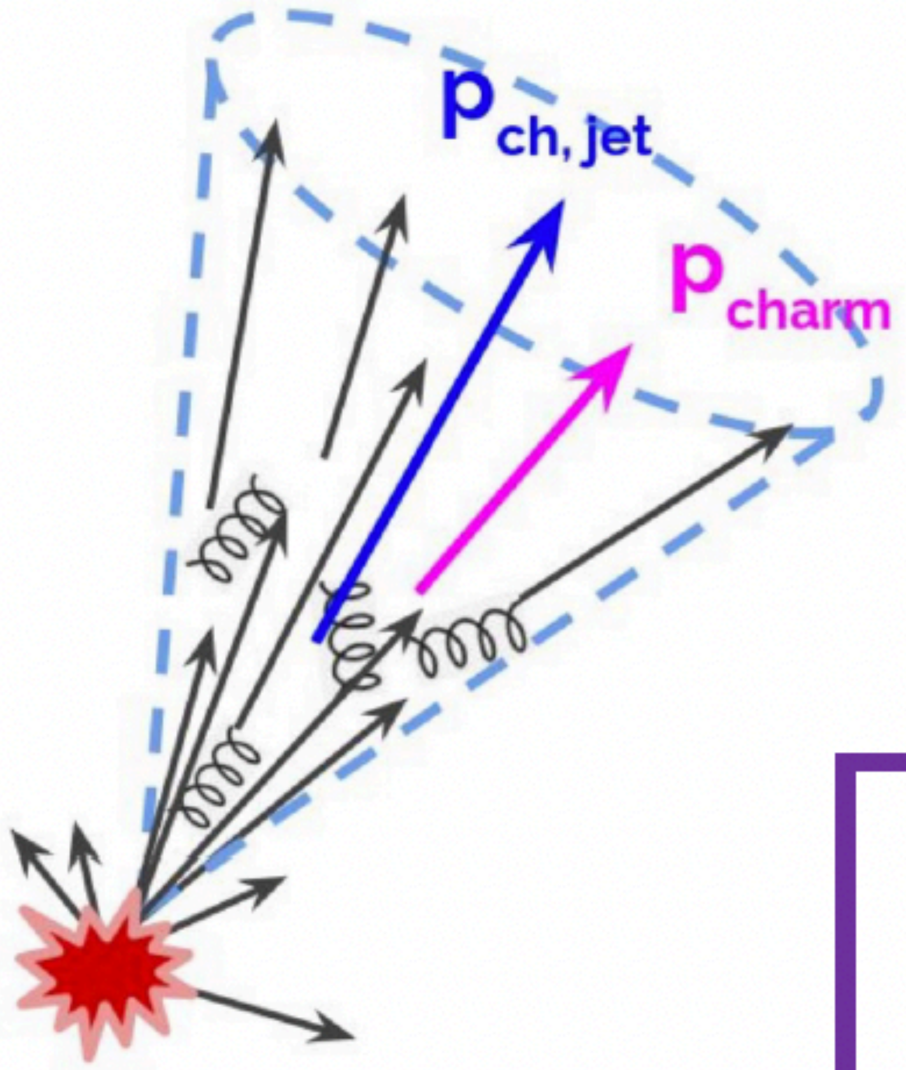


- Jet-wake effects expected to change the EEC shape at larger angles
- Hints of enhancement at low R_L and suppression at high R_L
- Predictions by theorists suggest to enlarge jet-radius and lower p_T in order to search wake effects → accessible with Run 3 data

Improvements of jet analysis with Run 3 data

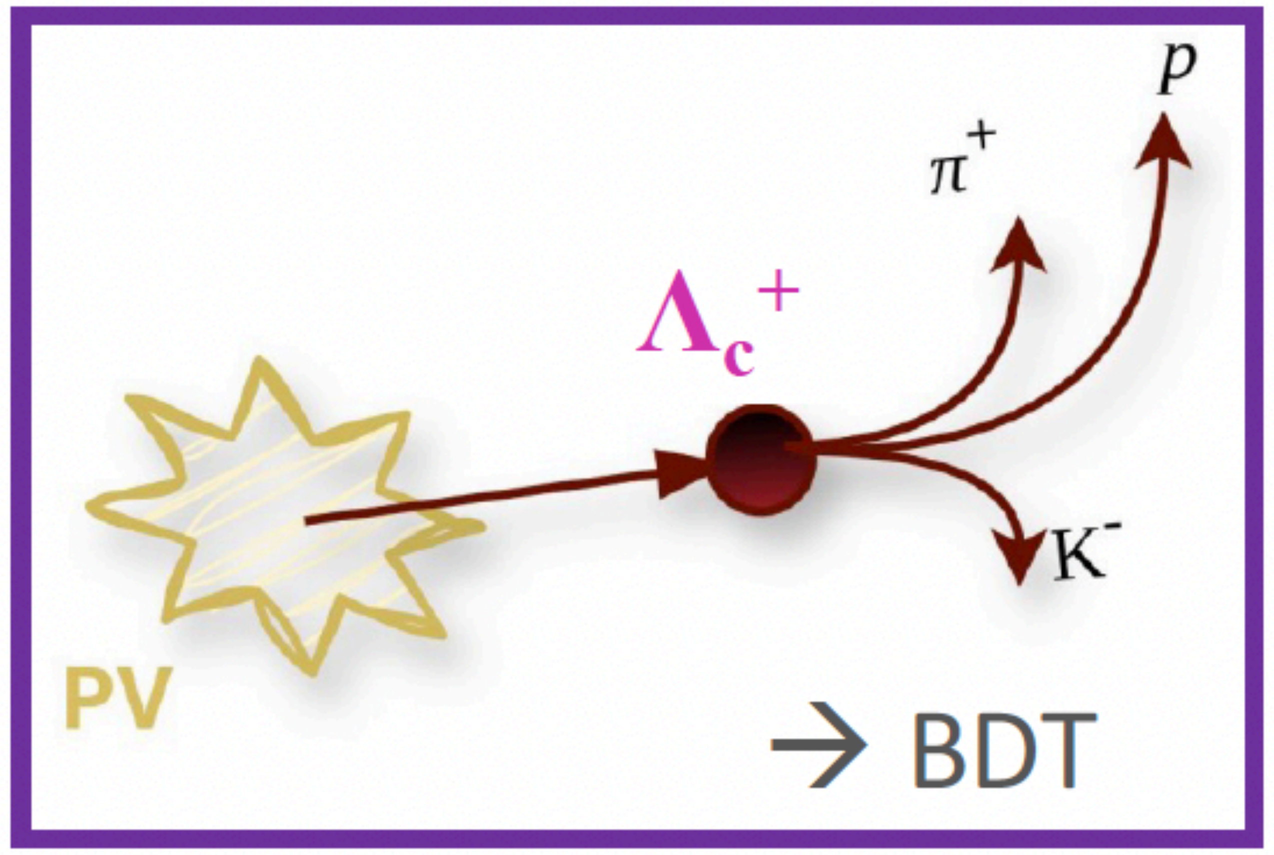
Fragmentation function with Λ_c^+ -tagged jets





longitudinal momentum fraction

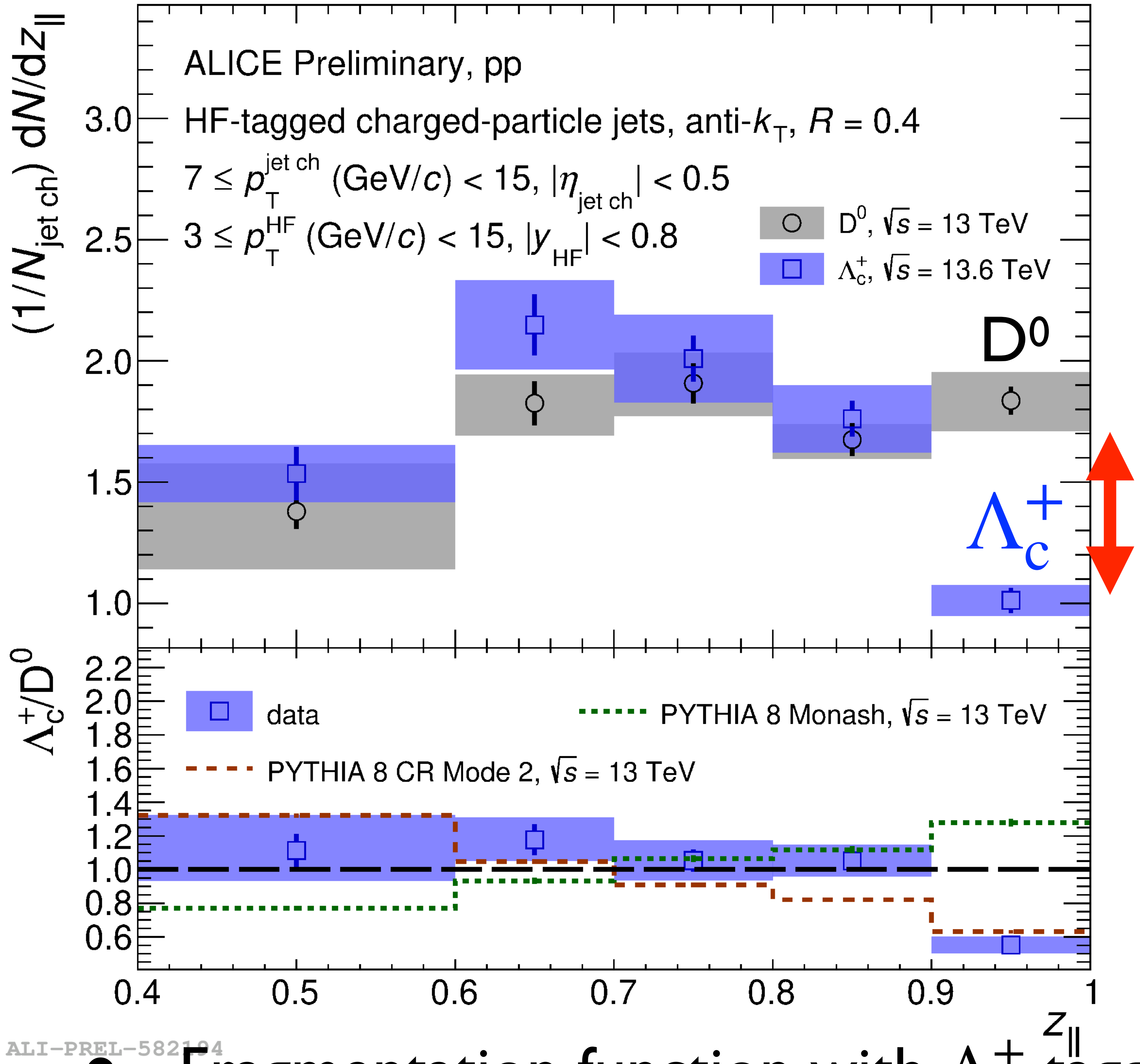
$$z_{||} = \frac{\vec{p}_{\text{ch, jet}} \cdot \vec{p}_{\text{HF}}}{\vec{p}_{\text{ch, jet}} \cdot \vec{p}_{\text{ch, jet}}}$$



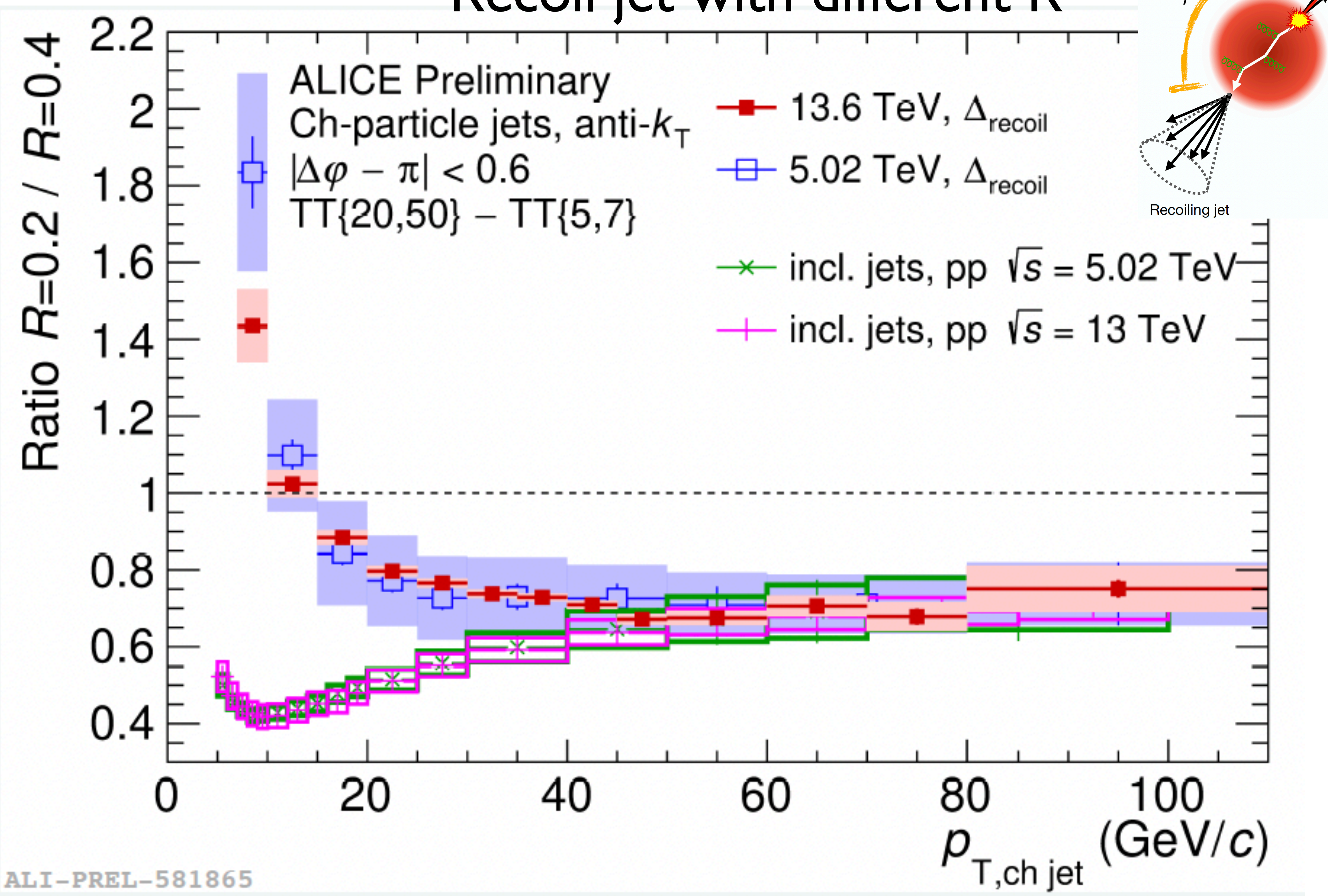
- Fragmentation function with Λ_c^+ tagged jets shows much improved sensitivity to hadronisation mechanisms → hints of softer fragmentation of charm into Λ_c^+ than D^0

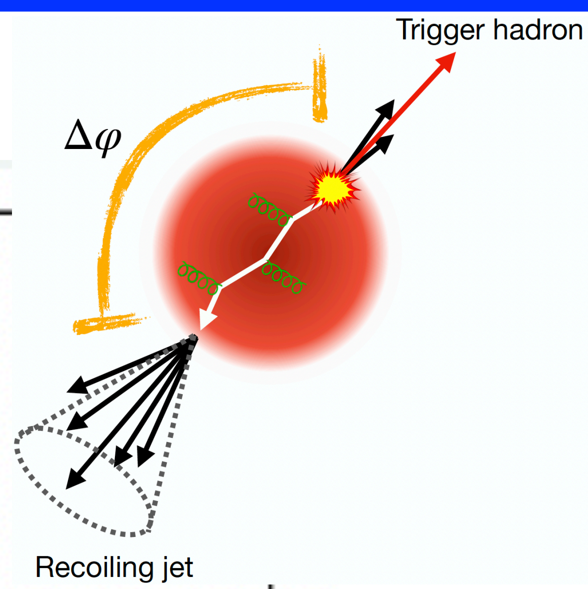
Improvements of jet analysis with Run 3 data

Fragmentation function with Λ_c^+ -tagged jets



Recoil jet with different R

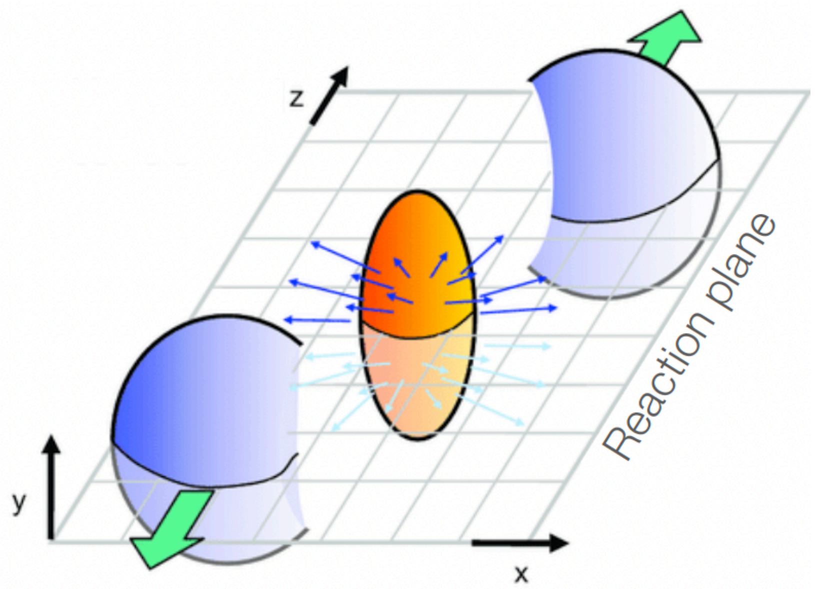


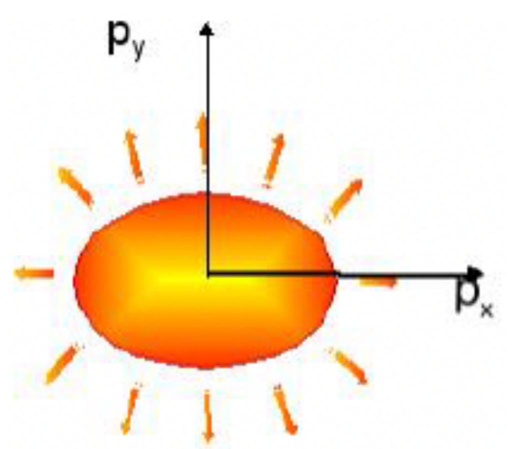


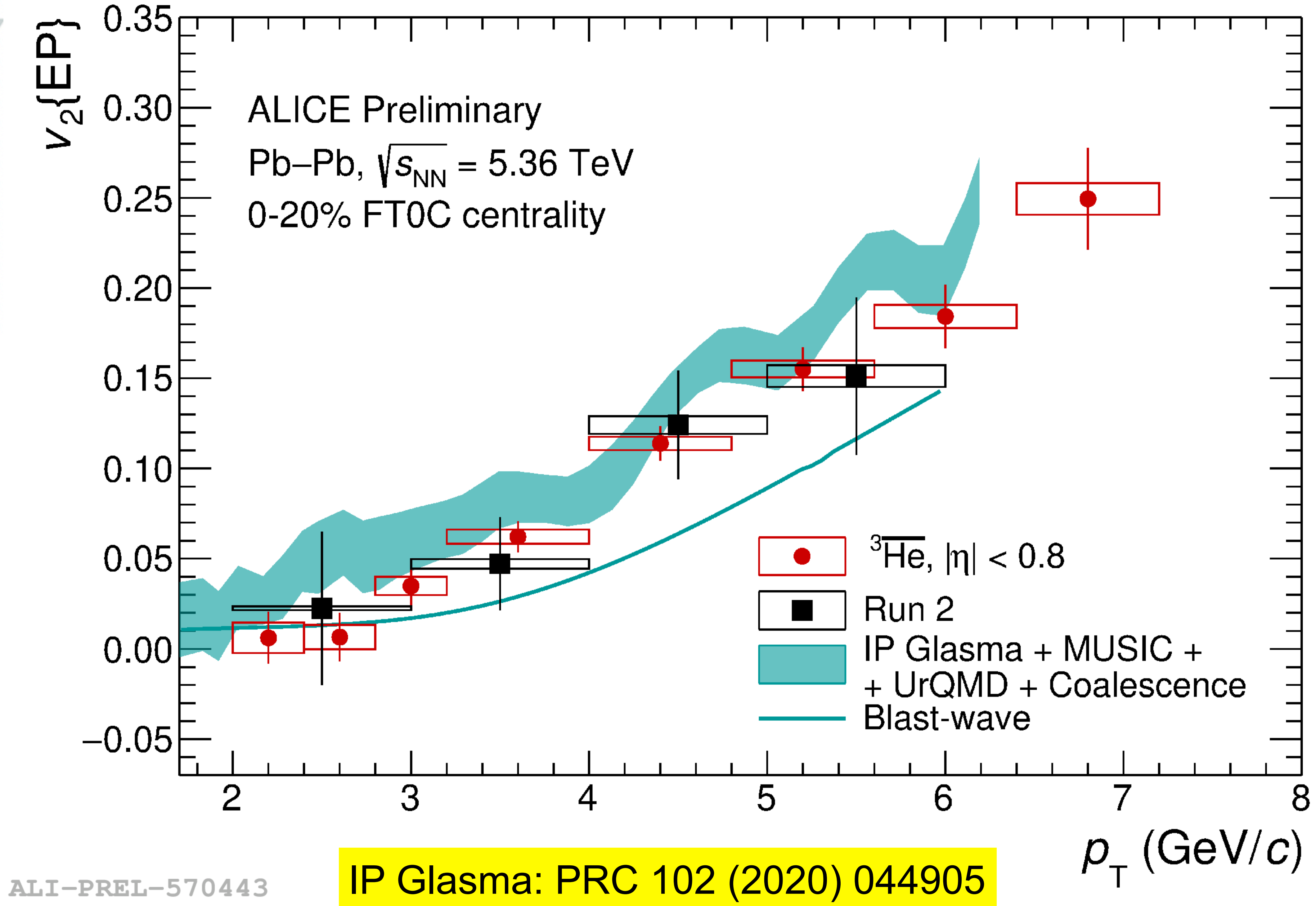
- Fragmentation function with Λ_c^+ tagged jets shows much improved sensitivity to hadronisation mechanisms → hints of softer fragmentation of charm into Λ_c^+ than D^0
- Recoil jet measurements show much better precision with respect to Run 2

QGP (hydrodynamic) expansion

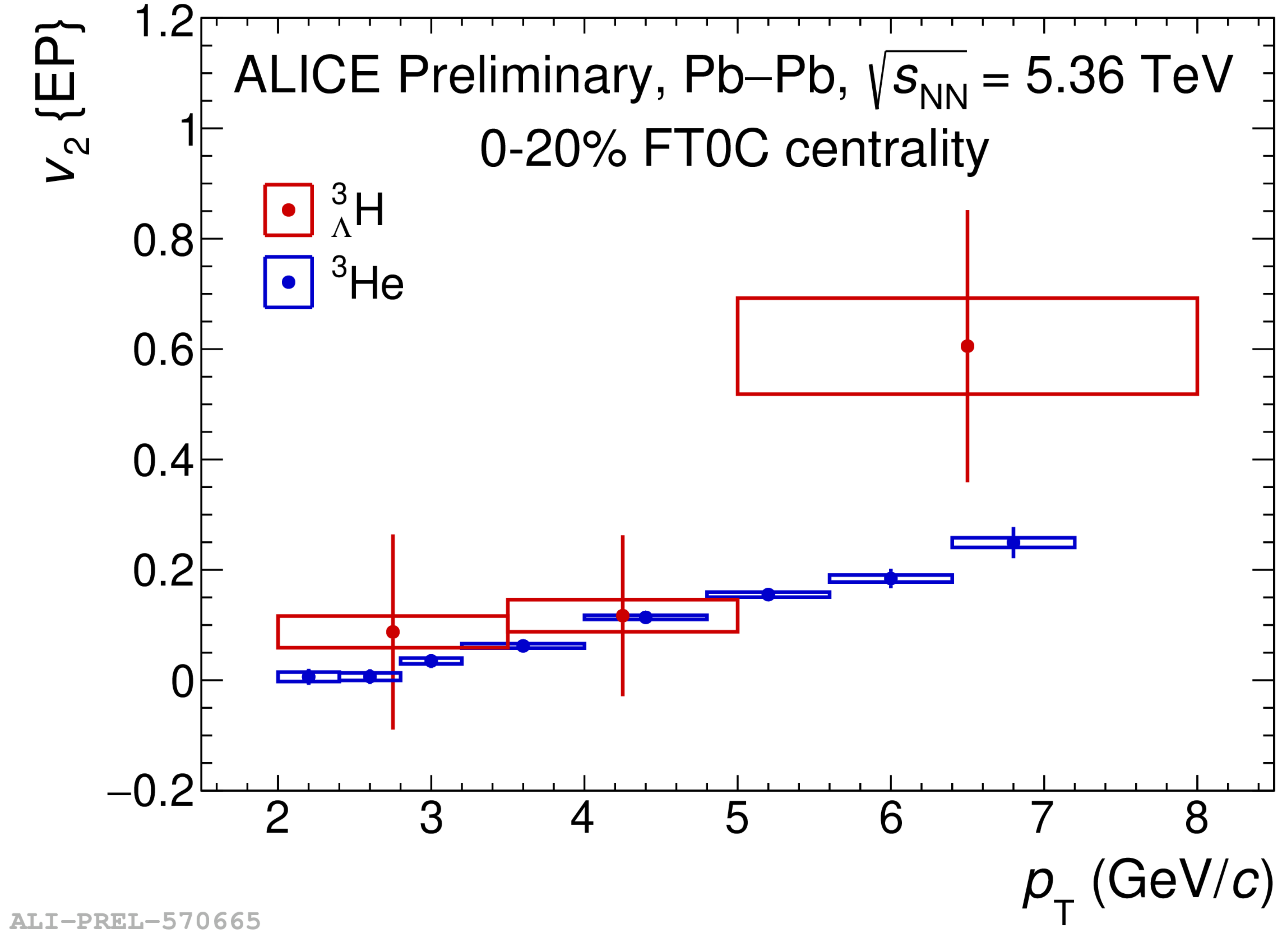
Elliptical flow of light nuclei





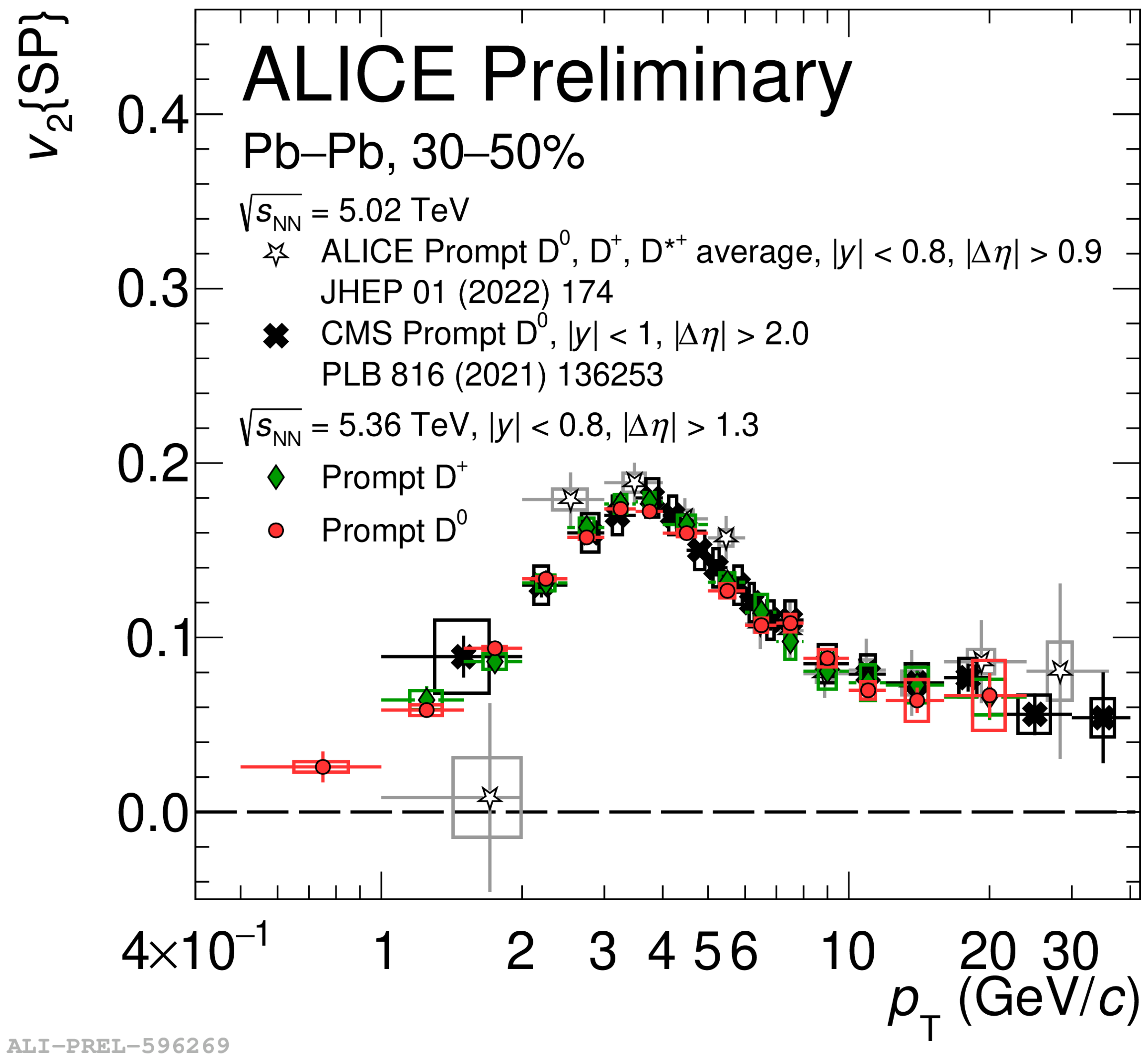


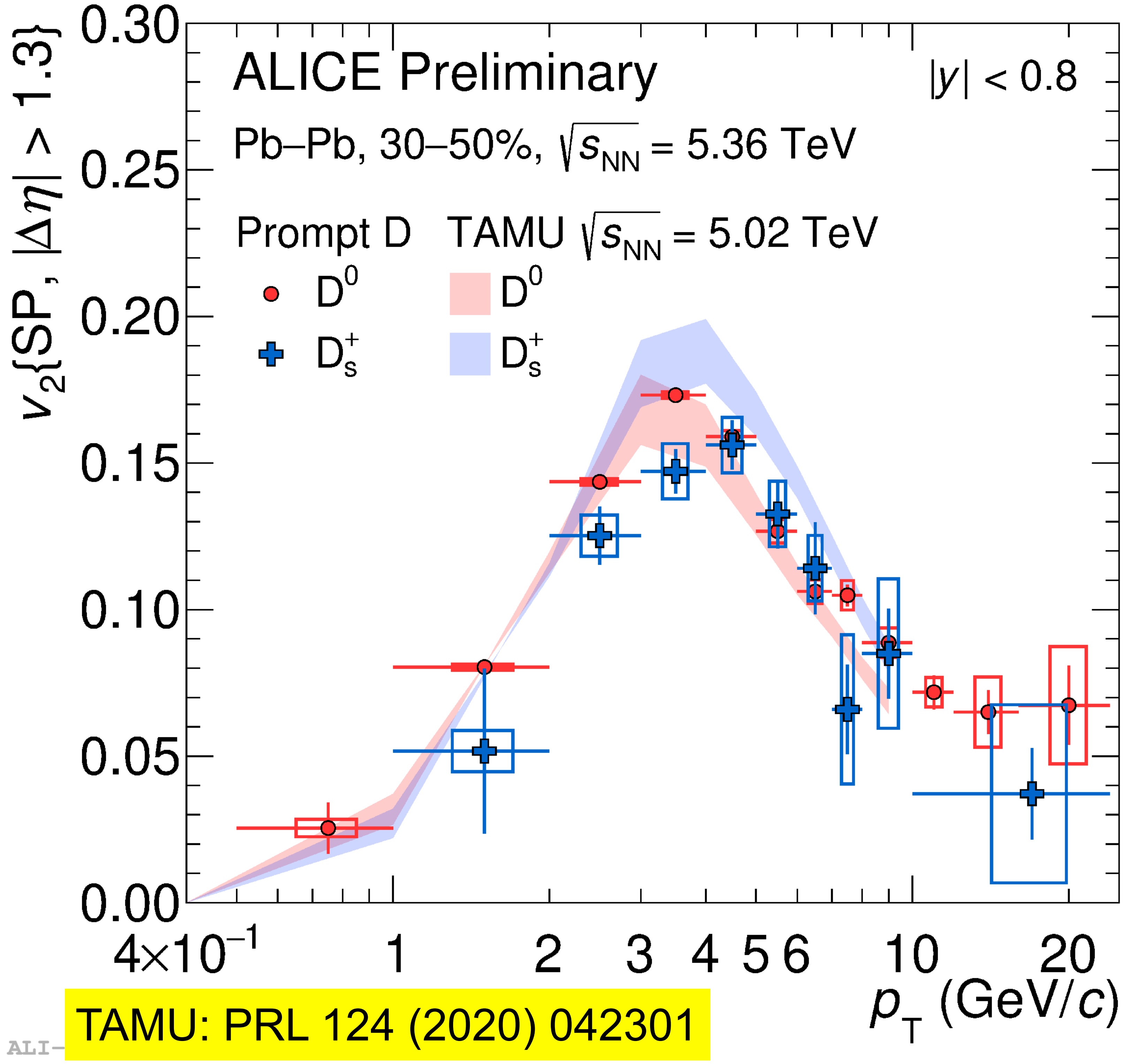
IP Glasma: PRC 102 (2020) 044905
Blastwave, PRC 48 (1993) 2462

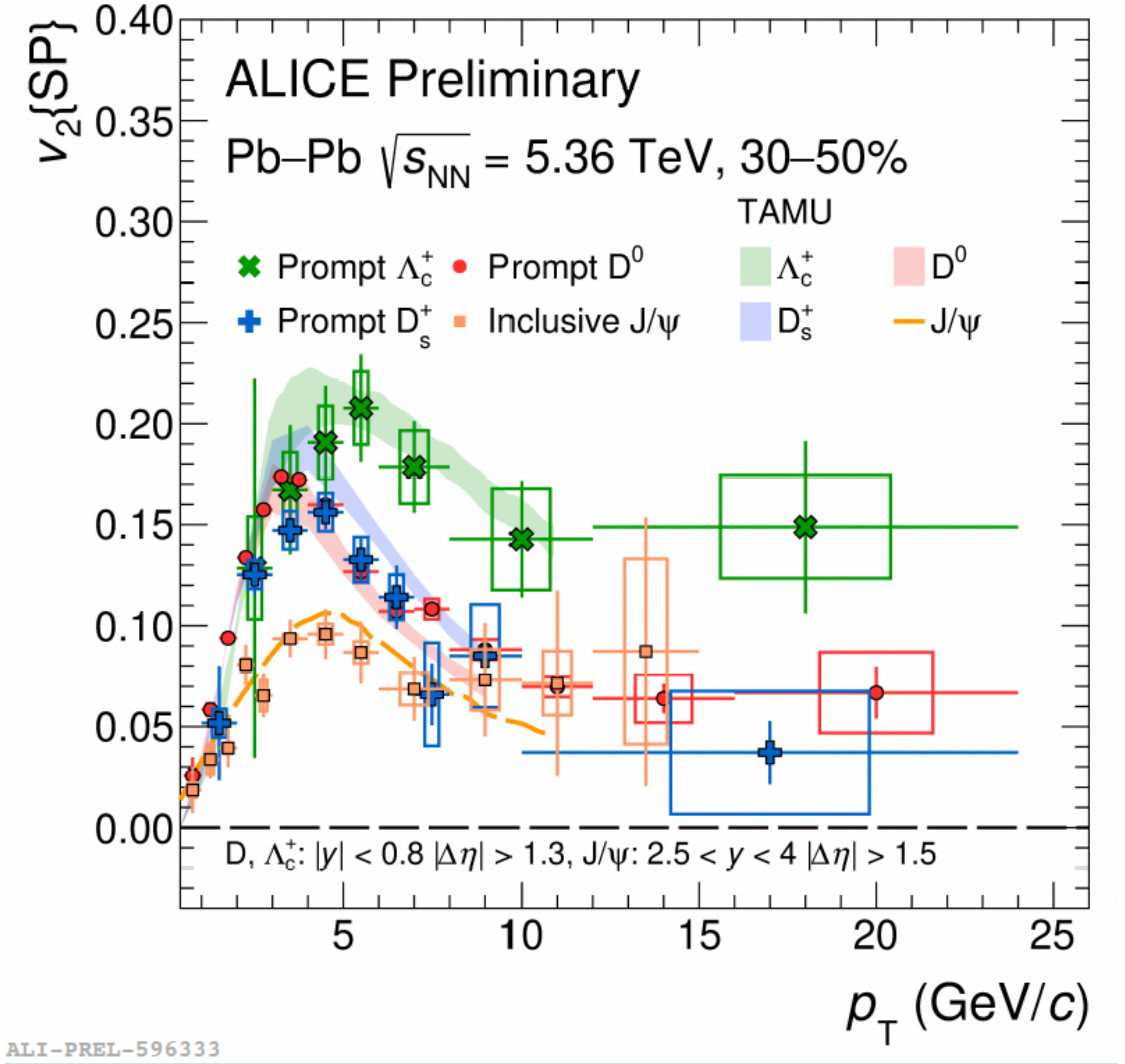


- v_2 of anti-^{3}He in Run3 - better precision
  - Discriminating power between coalescence and Blast-wave (fit to π/k/p)
- Flow of hypertriton measured for the first time
  - Compatible with ^{3}He but with large uncertainties

Elliptical flow of heavy flavor



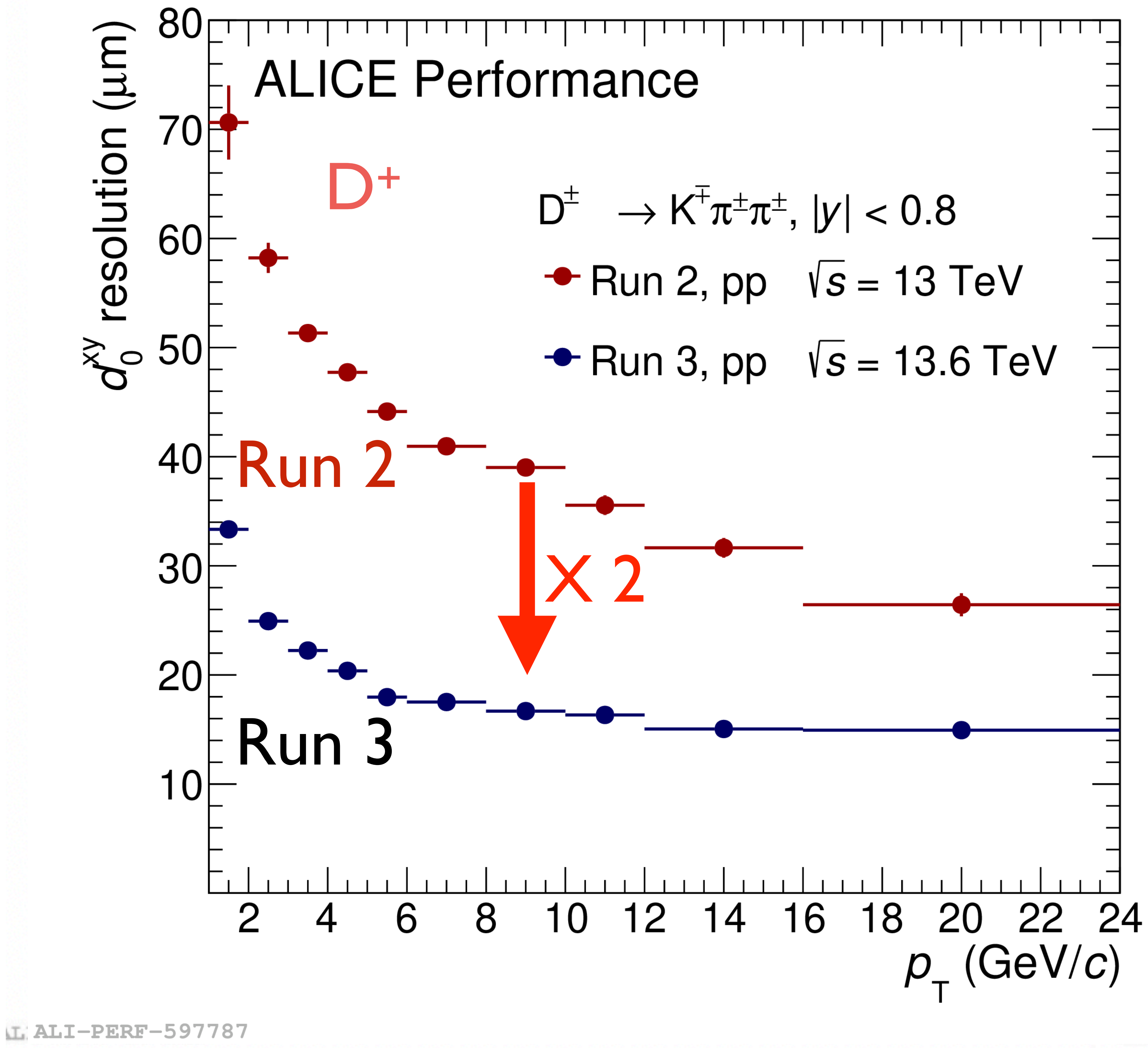


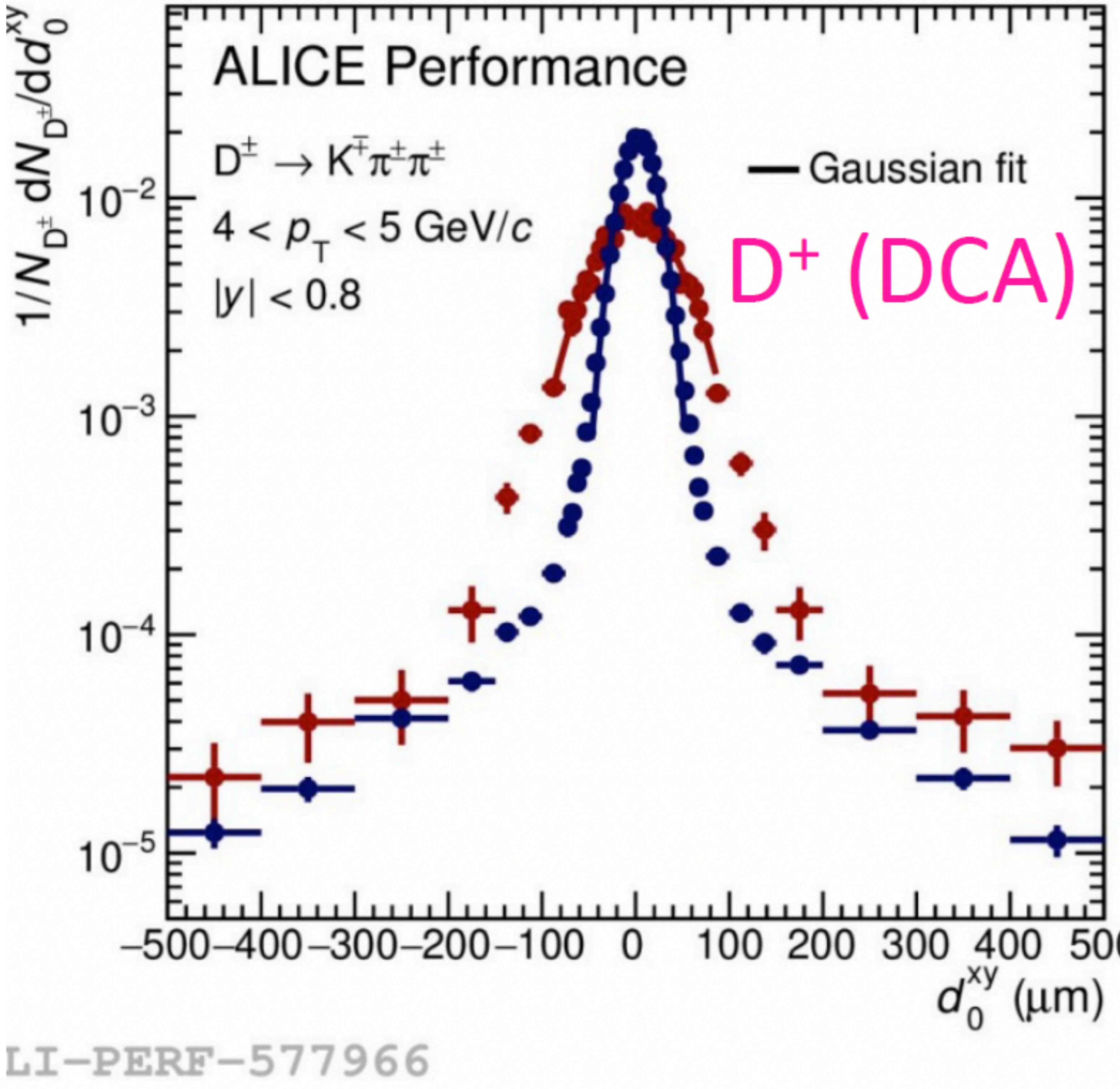


- Prompt D-meson v_2 measured using Run 3 Pb–Pb data sample → more precise and differential
  - no significant difference between strange and non-strange D mesons
  - D meson elliptic flow reproduced by the transport(TAMU) model
- Significant different Λ_c^+ v_2 compared to D-meson → baryon/meson effect?
- A significant J/ψ v_2 is observed at forward rapidity - consistent with the charm quark thermalization

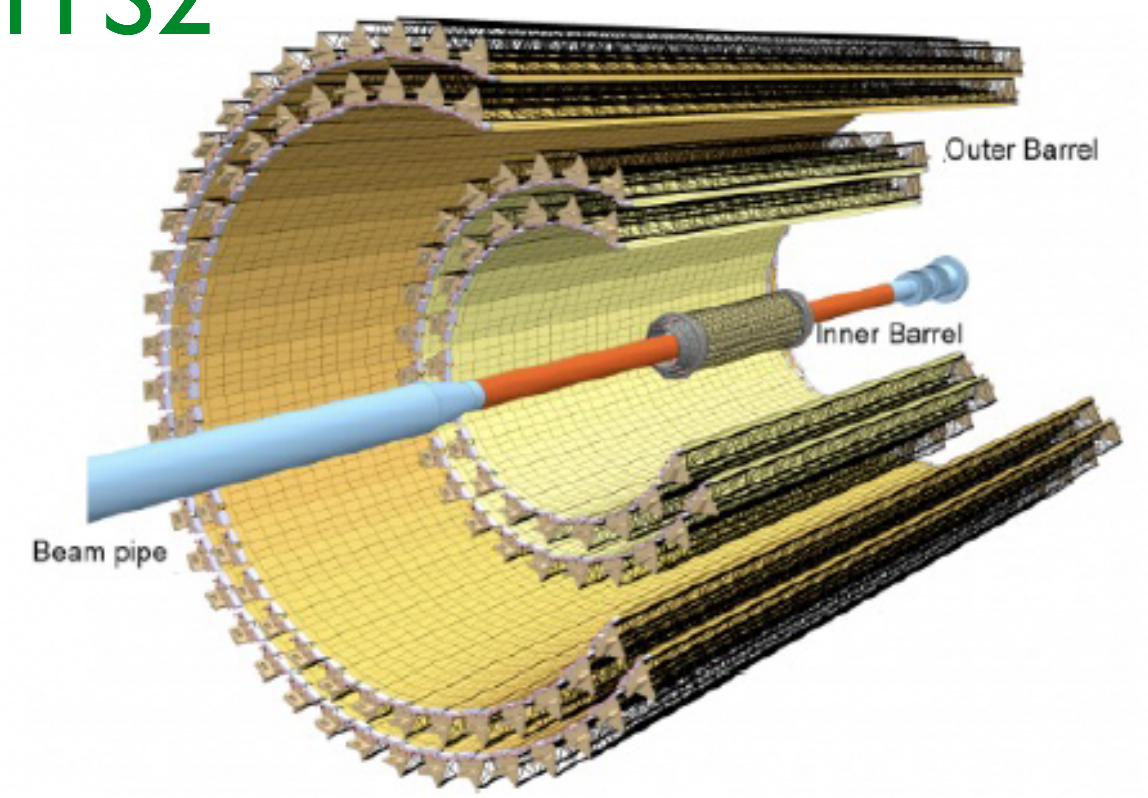
Hadronization

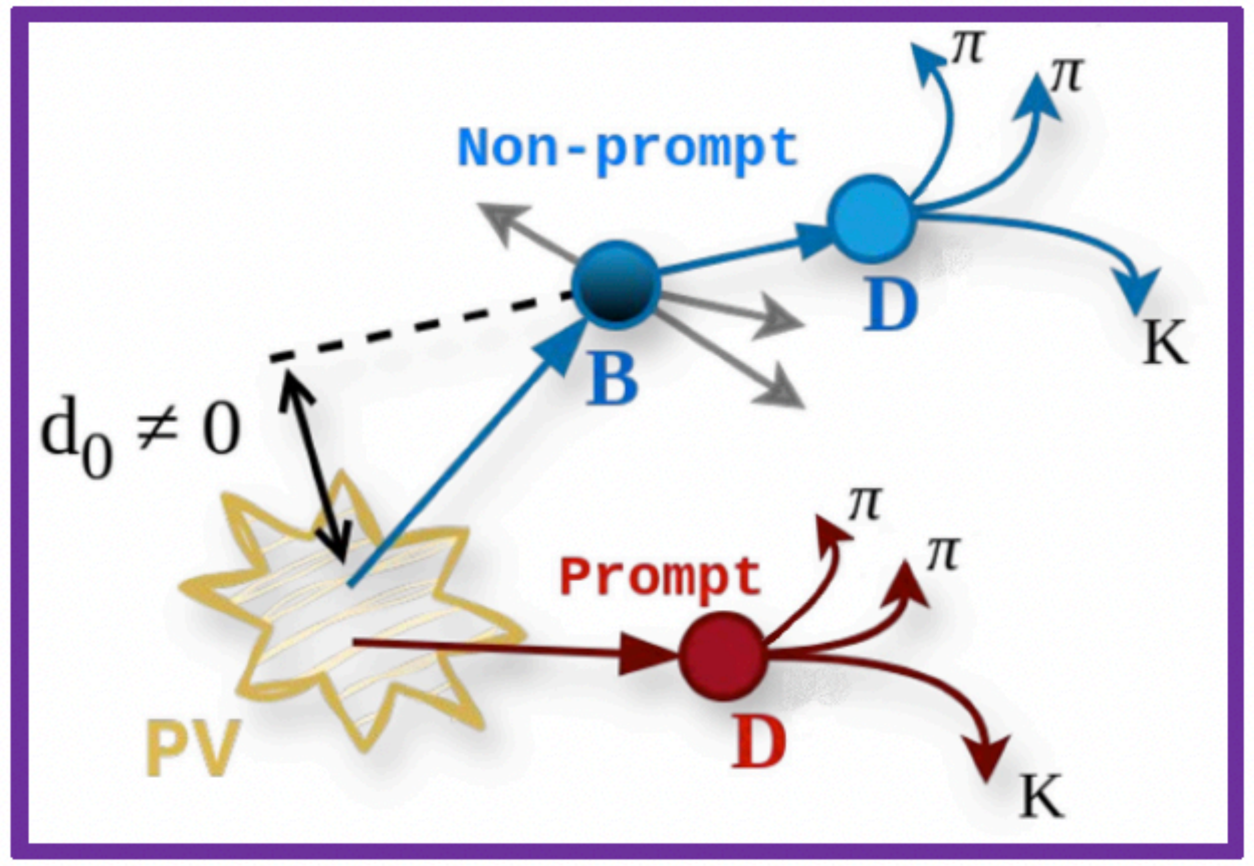
Improved performance for HF particles





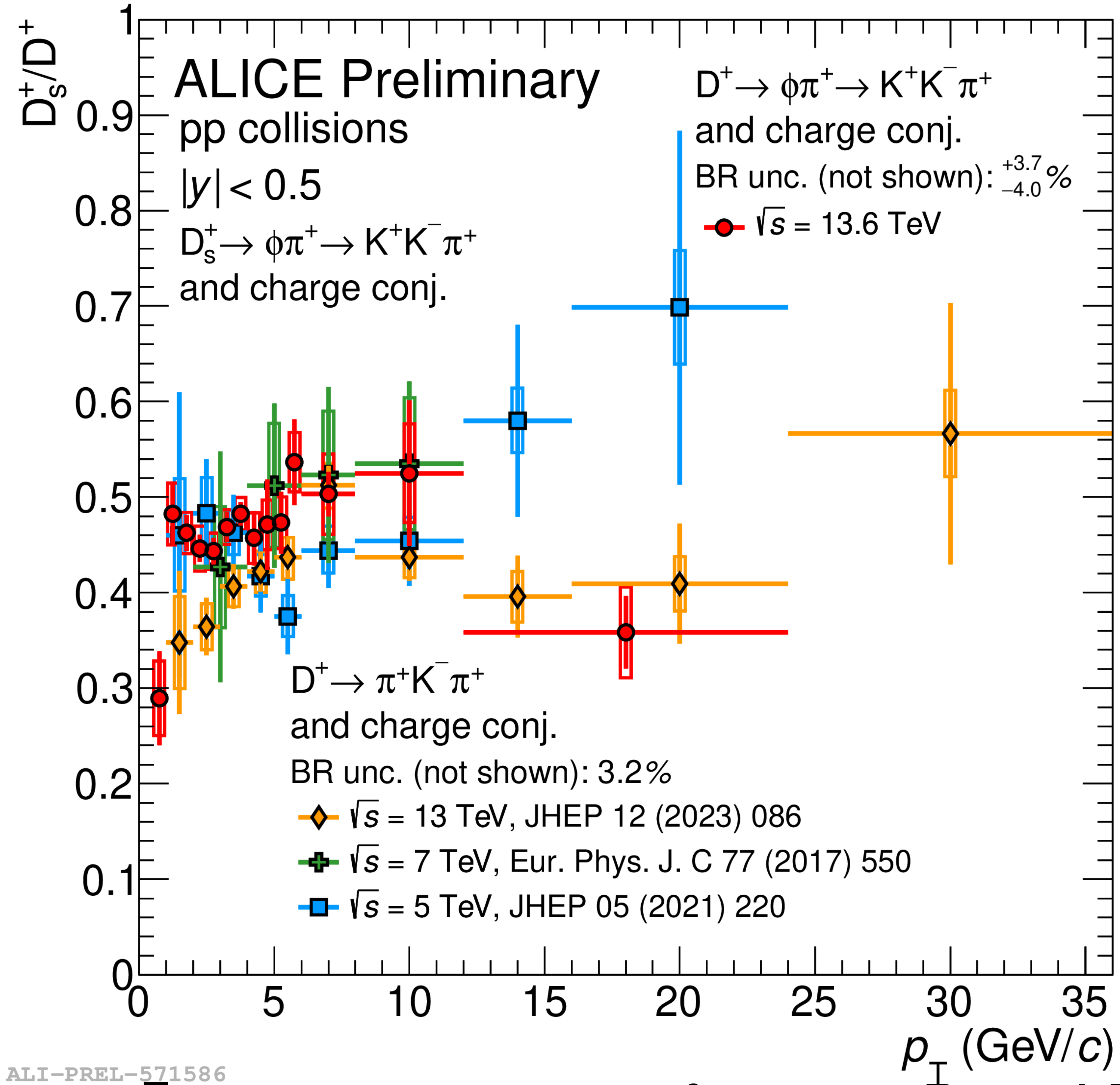
ITS2

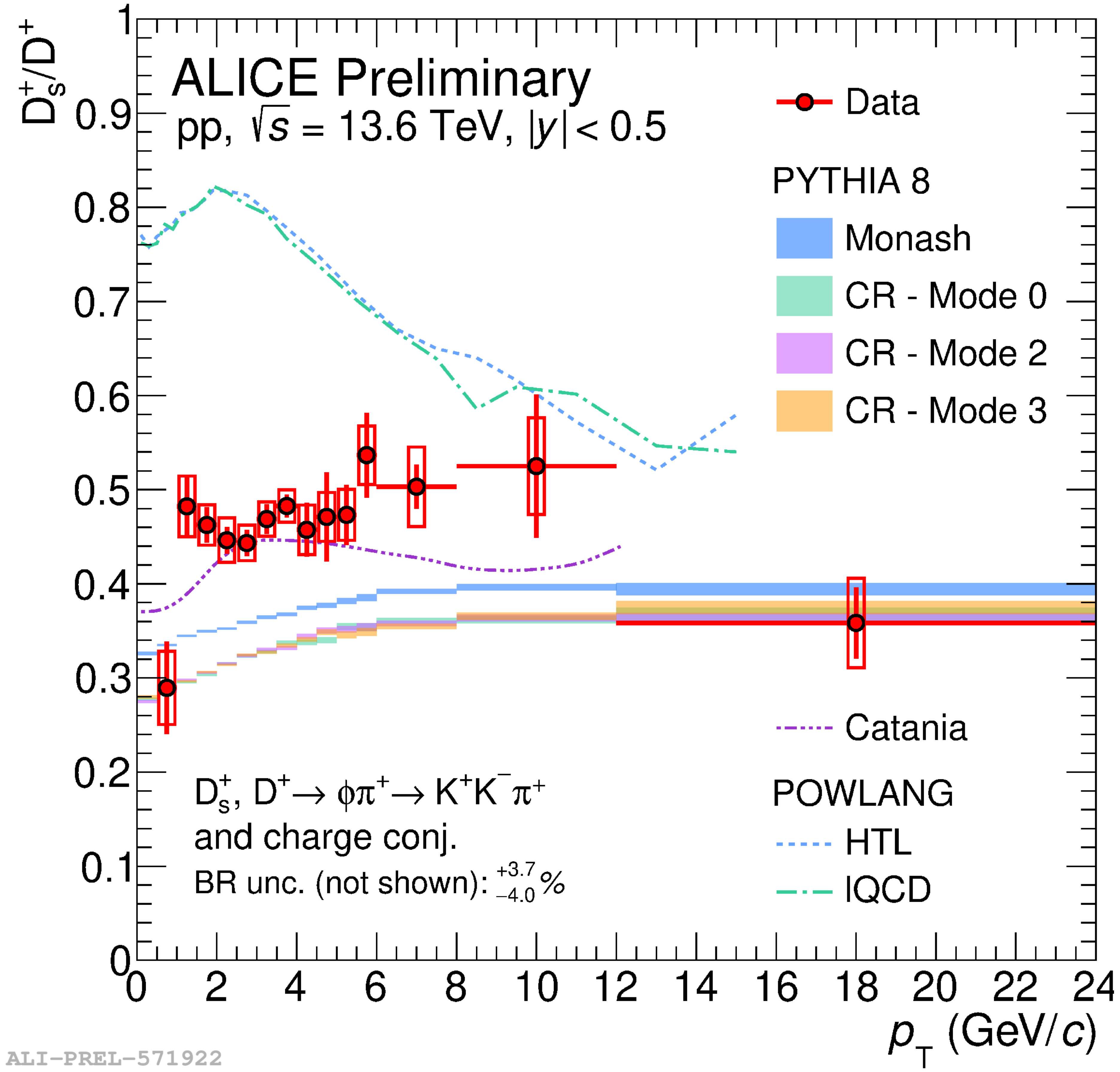




- ITS2 pointing resolution in Run 3 is x2 better than in Run 2
  - ➡ Important for heavy-flavor prompt/non-prompt separation

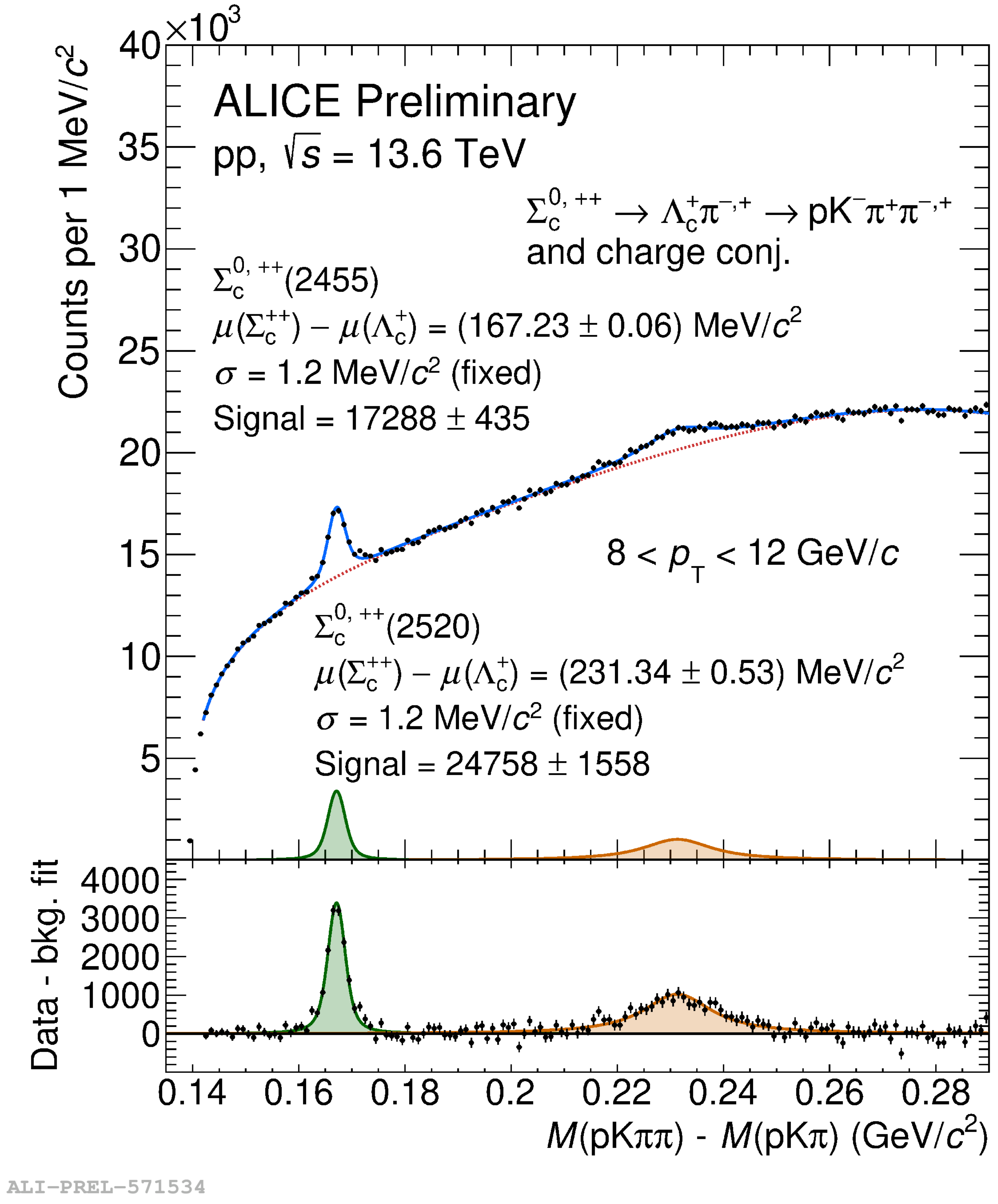
Charm production: D mesons

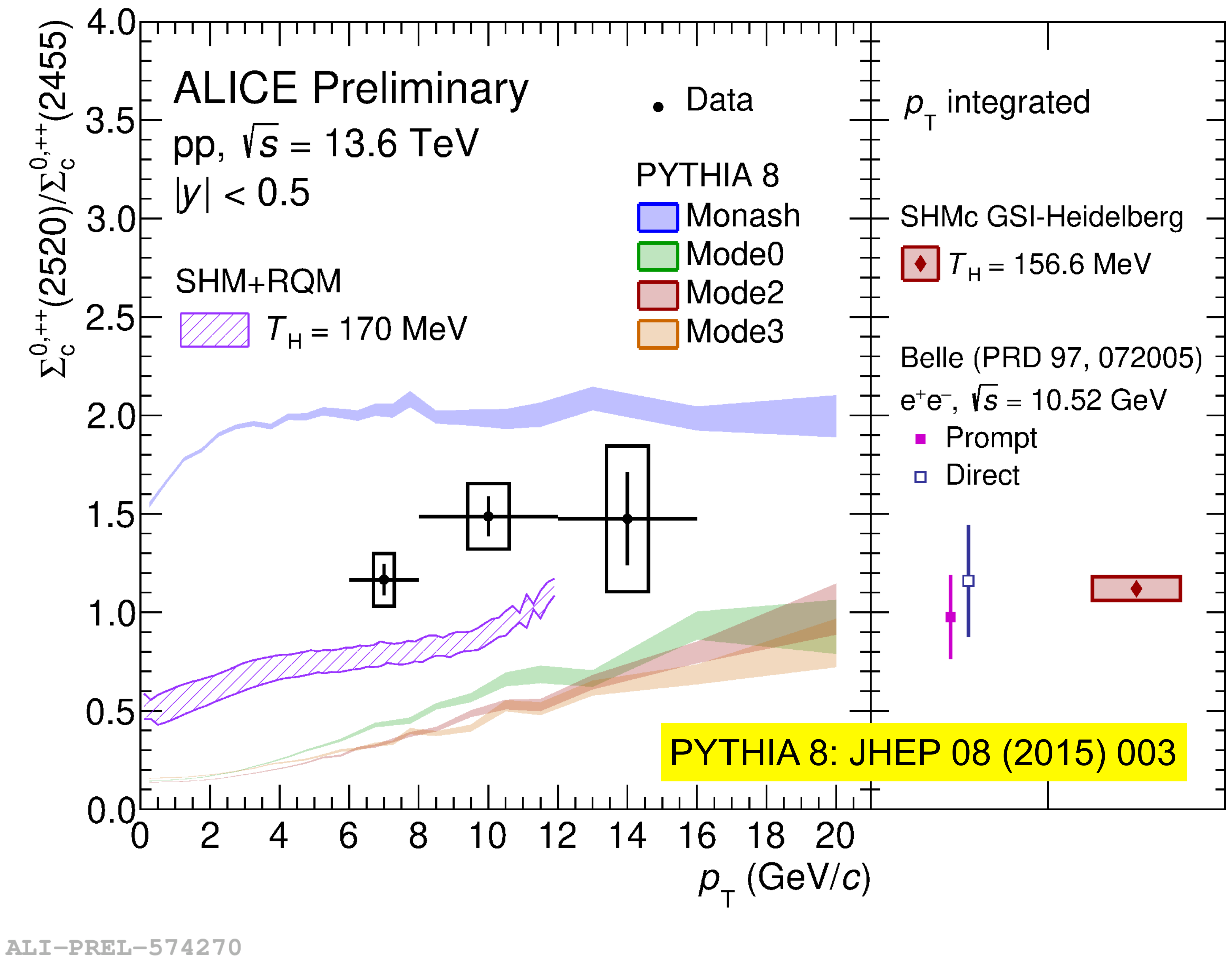


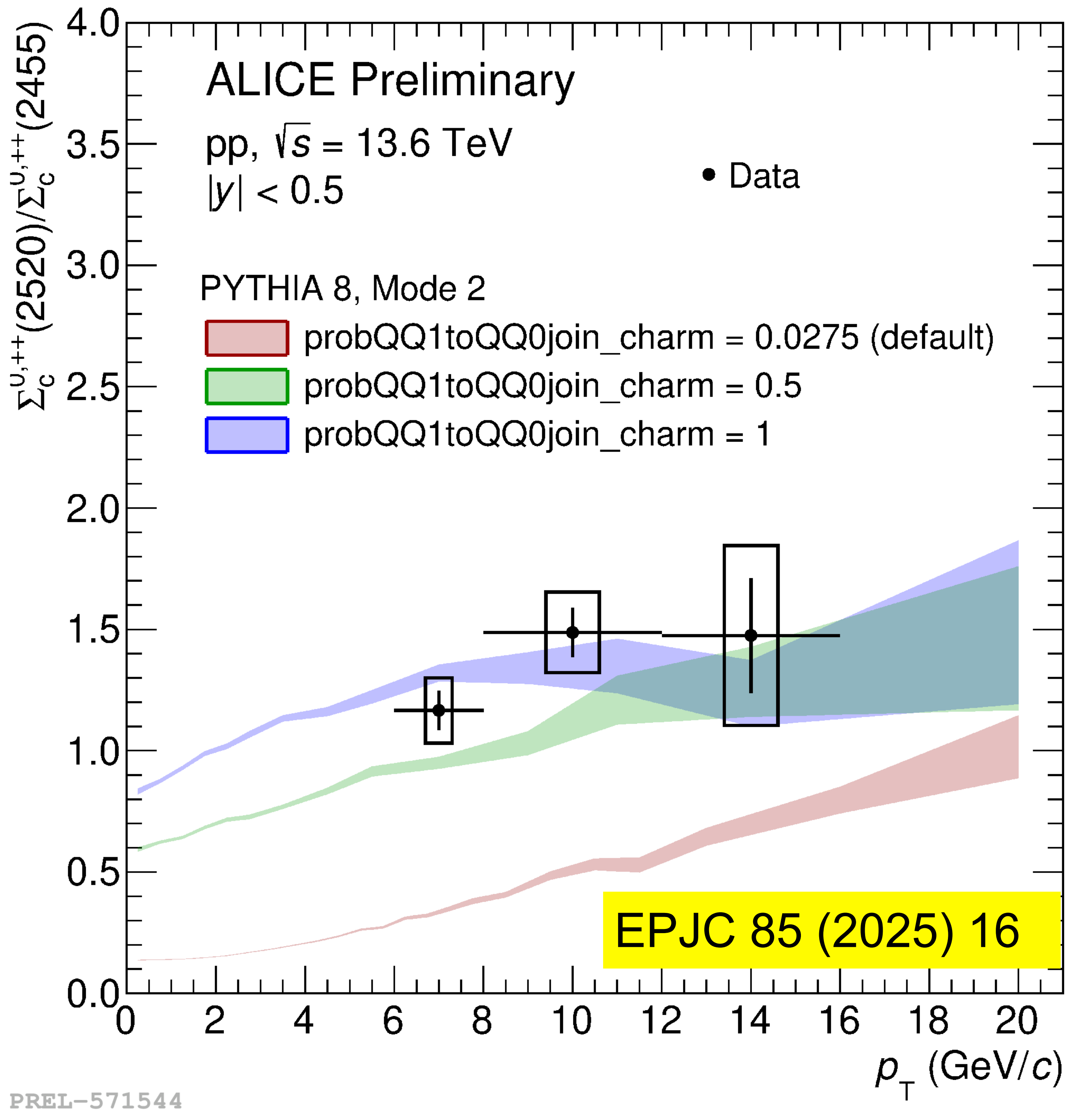


- First measurement of prompt D_s and D^+ ratio with finer granularity and down zero p_T
  - provide a better baseline for Pb–Pb measurements, tools to investigate the strangeness enhancement in charm sector
  - coalescence model (Catania) gives best description, while others can not describe the data

Charm production: baryons

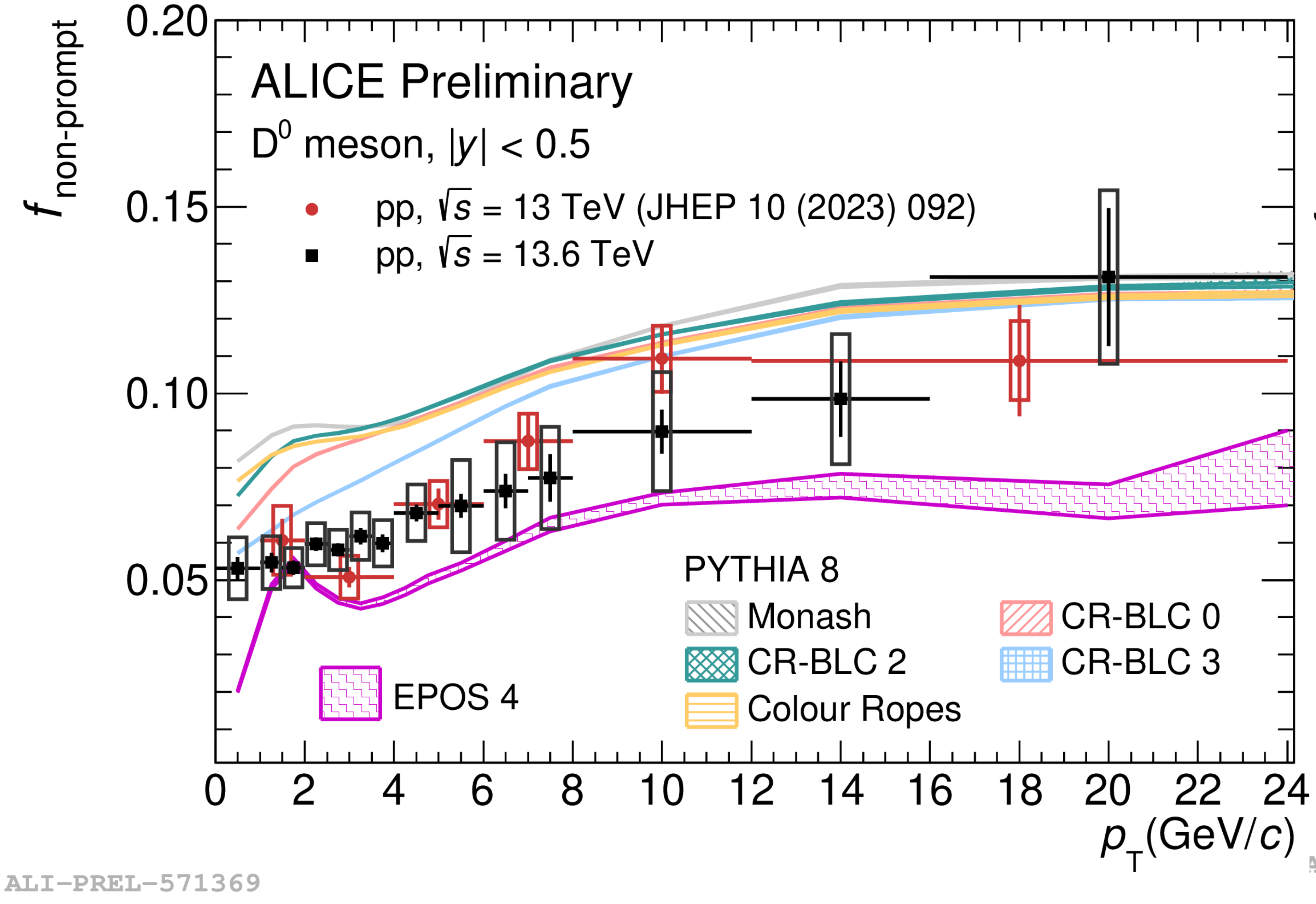


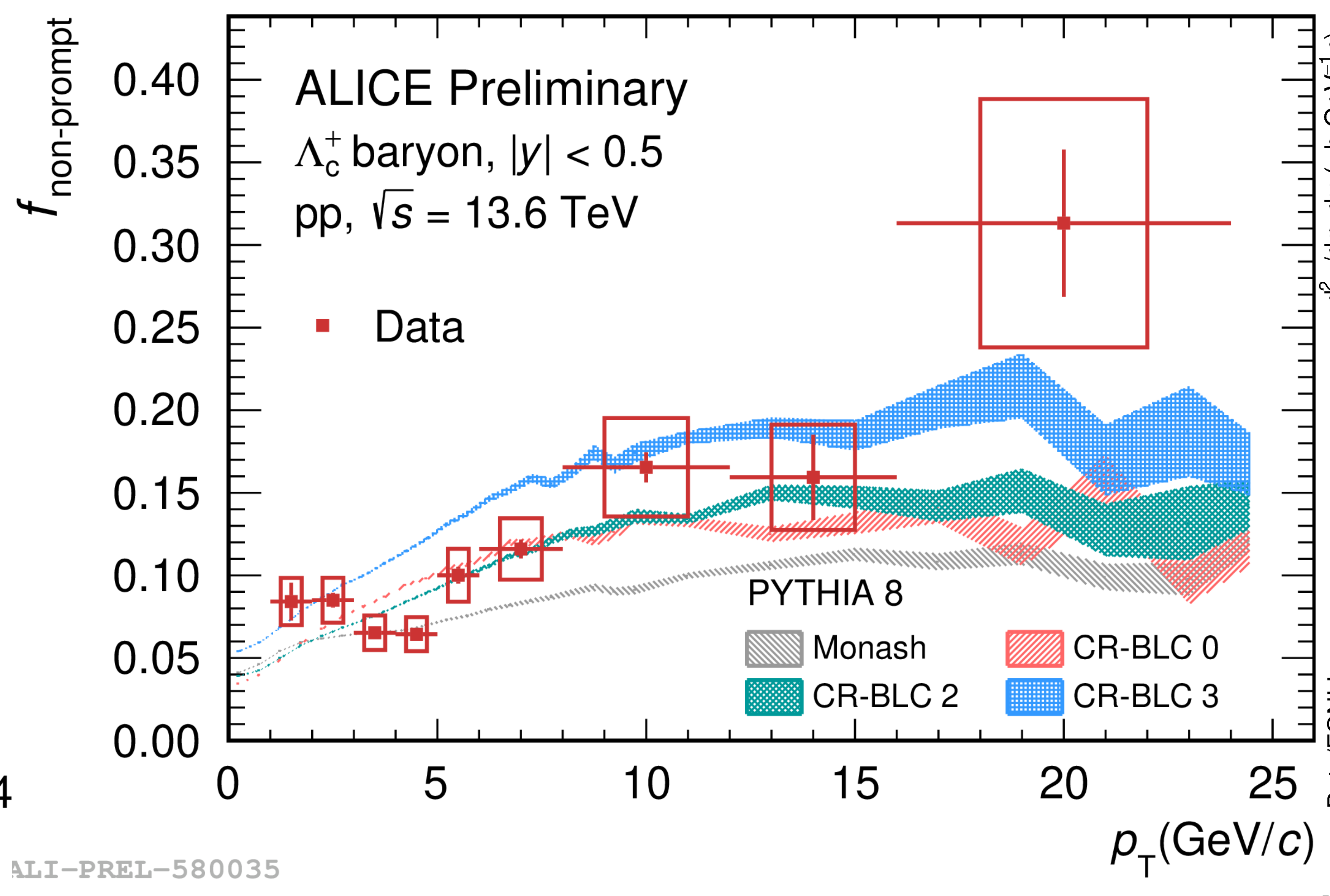


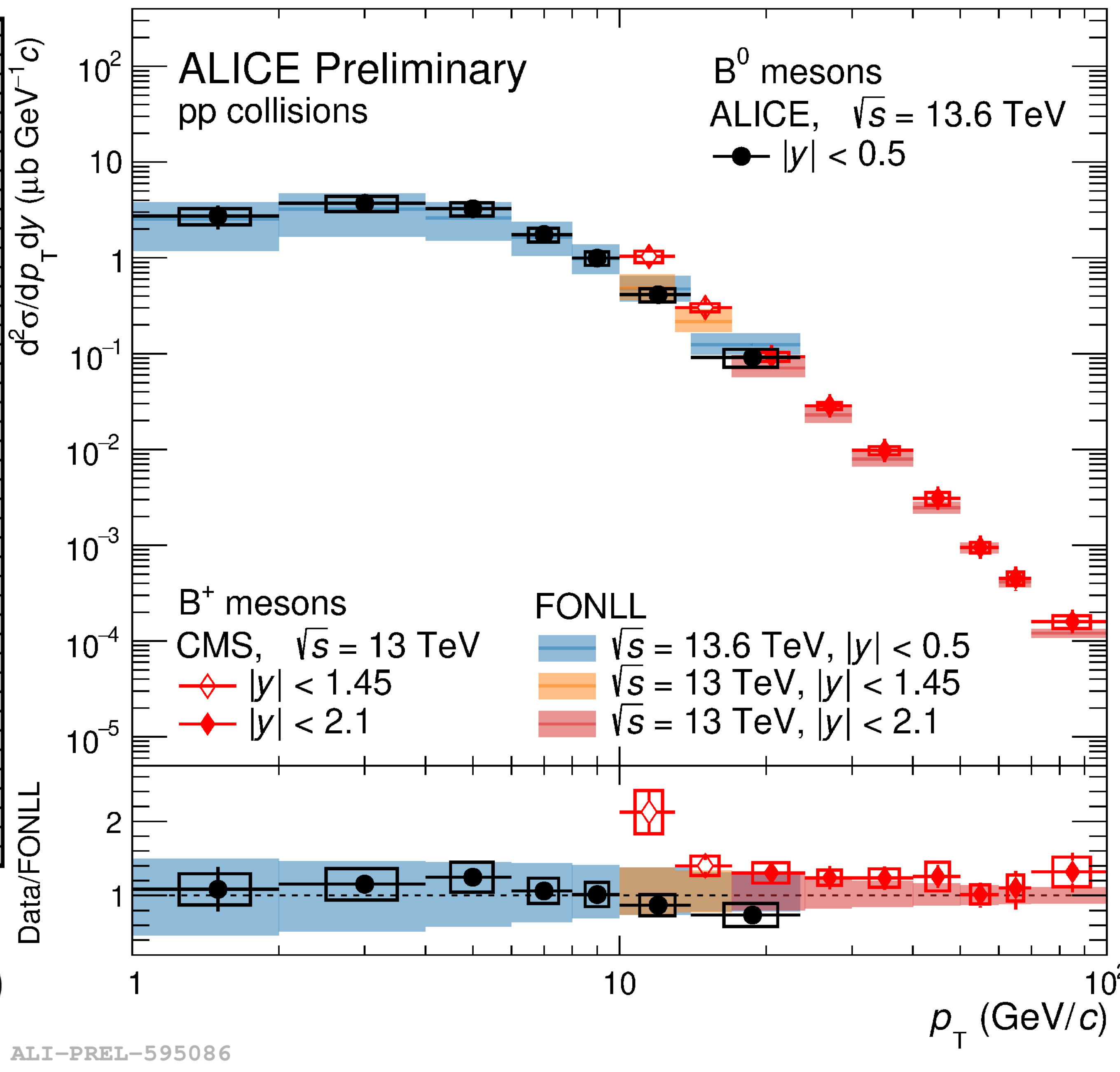


- First measurement of the production of Σc (2520) relative to Σc (2455) in pp at √s = 13.6 TeV
  - comparable yields for both resonances
  - not described by default PYTHIA → running of parameters improve the description

Open beauty production







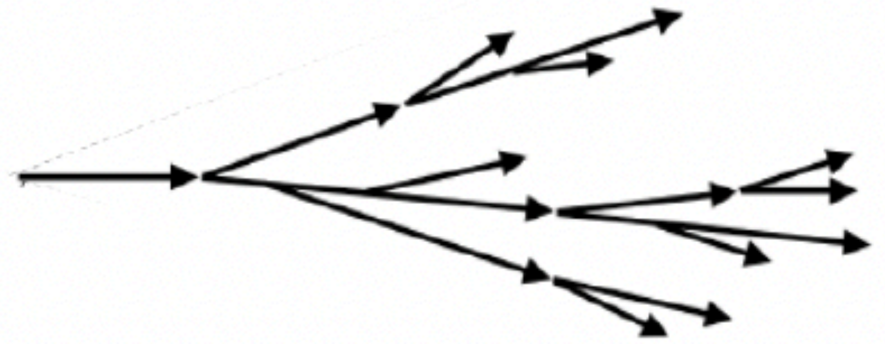
- Non-prompt D^0 fraction measured in Run 3: improved precision compared to Run 2 results and extended down to $p_T = 0$
- Non-prompt Λ_c fraction measured p_T down to 1 GeV/c
- First direct observation of B^0 meson in ALICE, measured down to p_T = 1 GeV/c

➡ better constraint of the open beauty production

Flavour dependence of QCD showers

Gluon-initiated shower

Broader shower profile
Higher number of emissions



$$P_{g\to gg} = 2C_A \frac{(1-z(1-z))^2}{z(1-z)}$$

Quark-initiated shower

Narrower shower profile
Fewer emissions in the shower

$$P_{q\to qg} = C_F \frac{1+(1-z)^2}{z}$$

Casimir Colour factors

Different emission properties due to the different amount of colour charge carried by quarks and gluons

$$\frac{C_{\rm A}}{C_{\rm F}} = \frac{9}{4}$$

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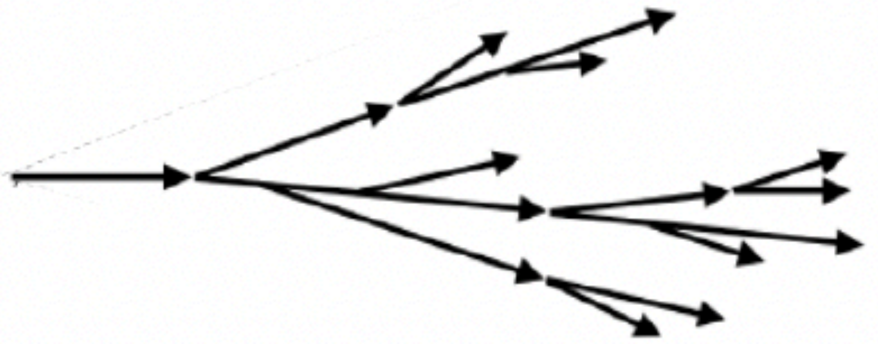

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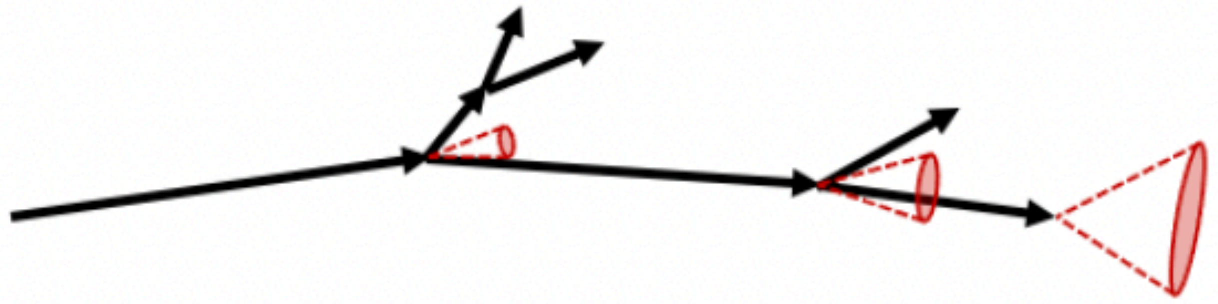
Fewer emissions in the shower

$$P_{q\to qg} = C_F \frac{1+(1-z)^2}{z}$$

Heavy-quark-initiated shower

Suppression of small angle emissions
Harder fragmentation



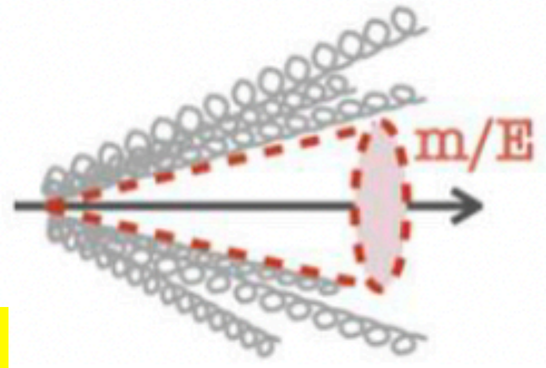
$$P_{Q\to Qg} = C_F[\frac{1}{z} - 1 + \frac{z}{2} - \frac{z(1-z)m^2}{k_\perp^2 + z^2m^2}]$$

The dead-cone effect

A suppression of emissions in a cone of size θ = m/E around the direction of the emitter

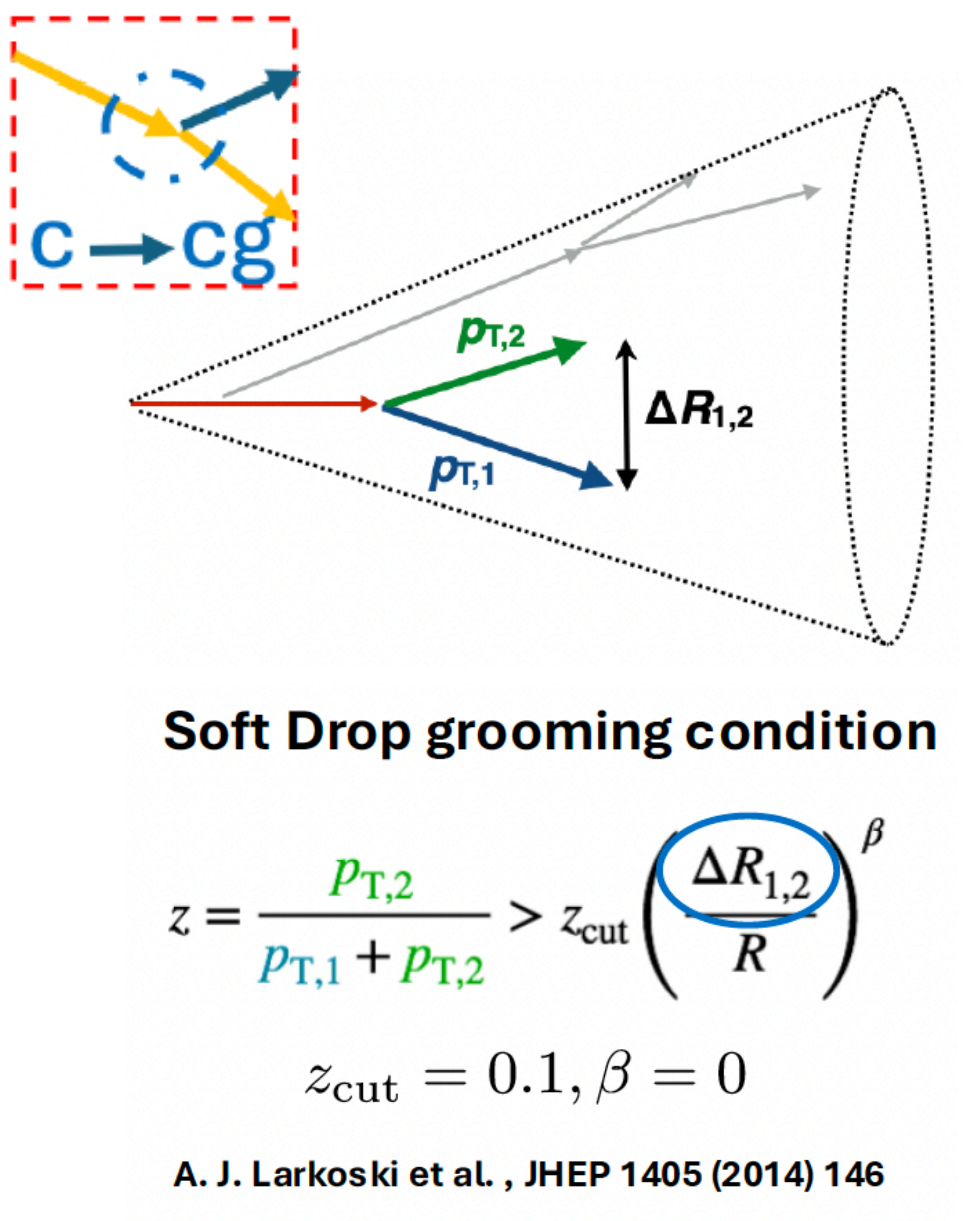
Sizeable effect for low energy heavy quarks

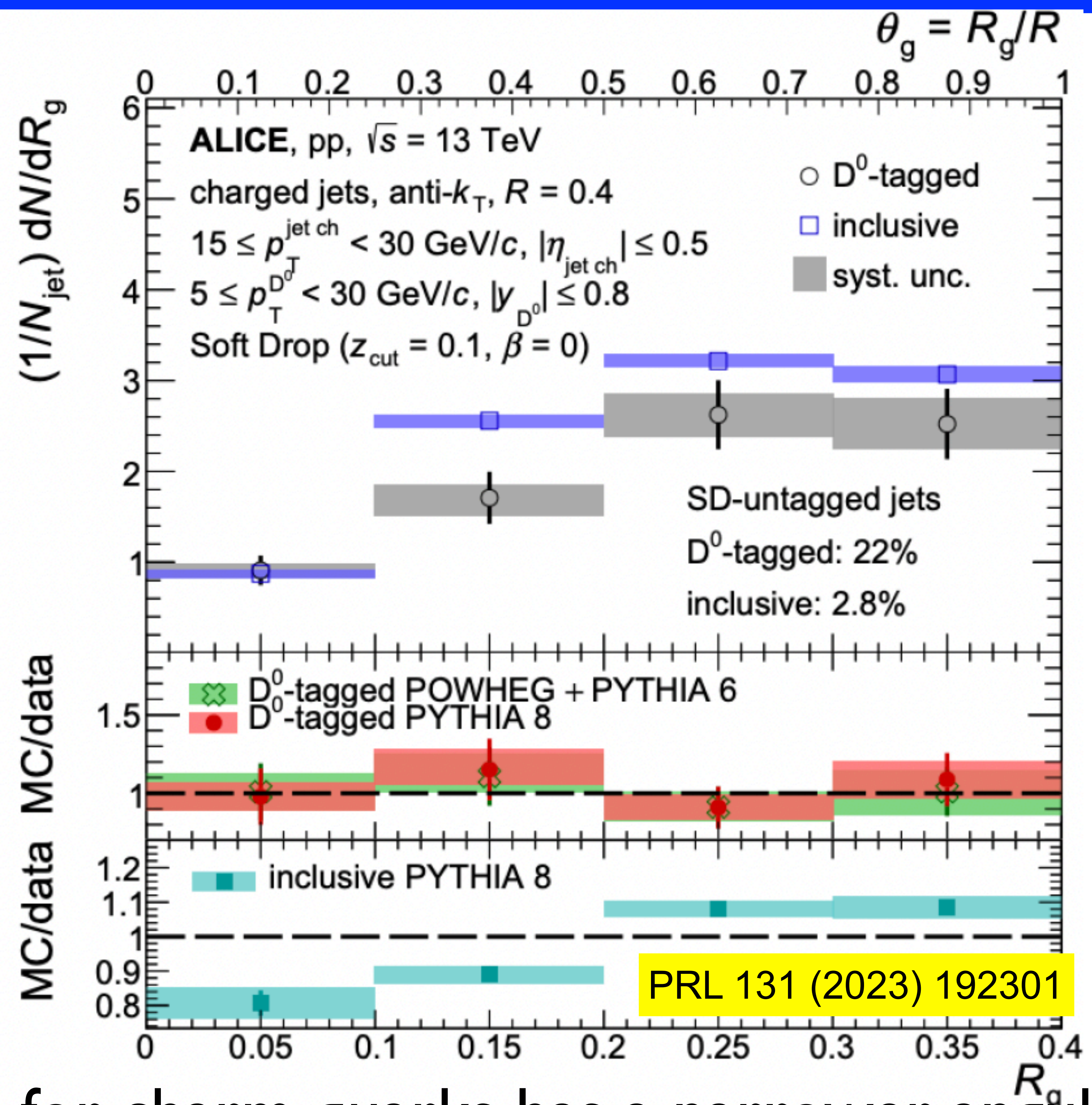
➡ Low energy heavy-flavour jets can maximize sensitivity to mass effects

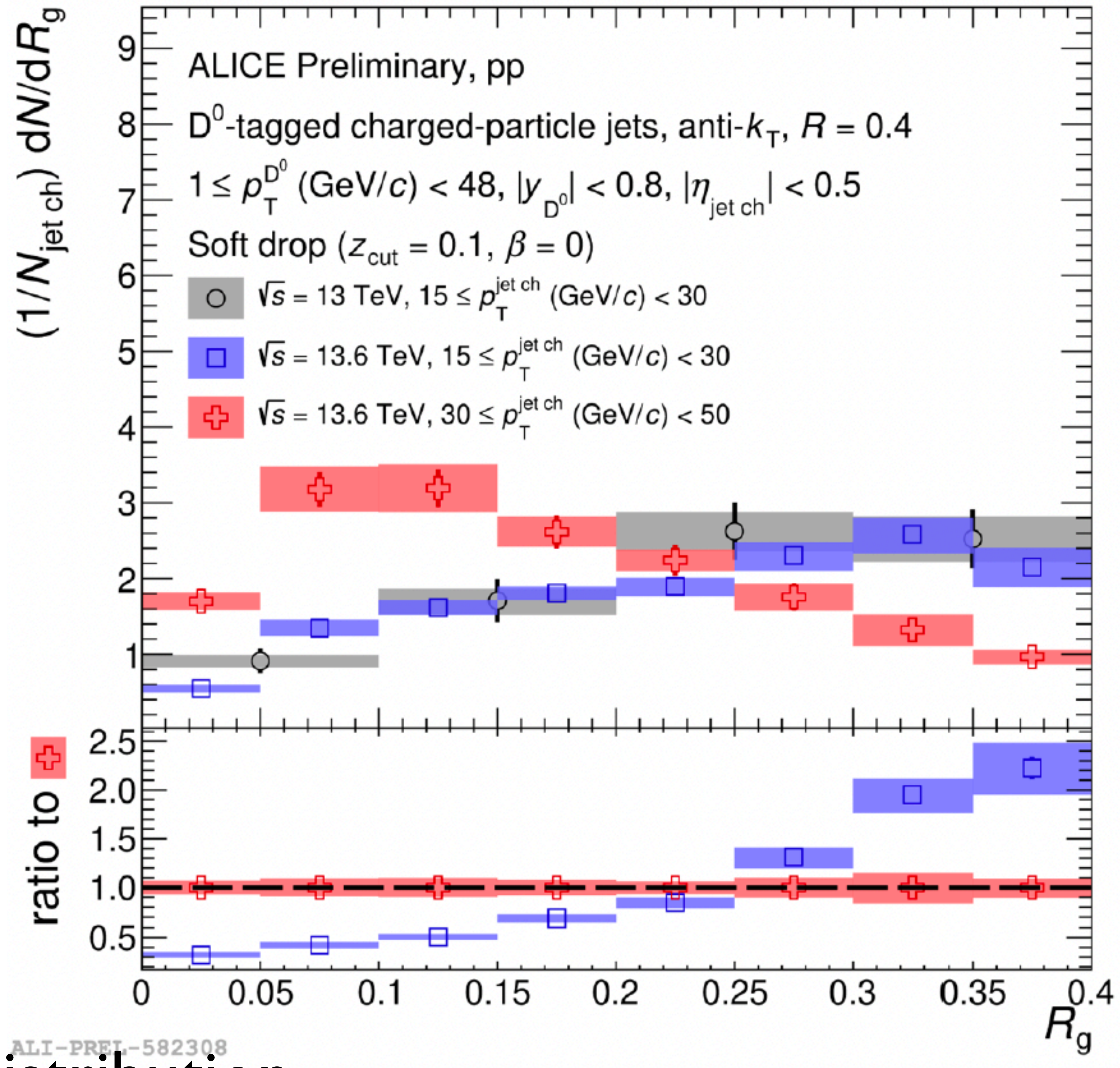


J. Phys. G17 (1991) 1602

Accessing charm splitting function

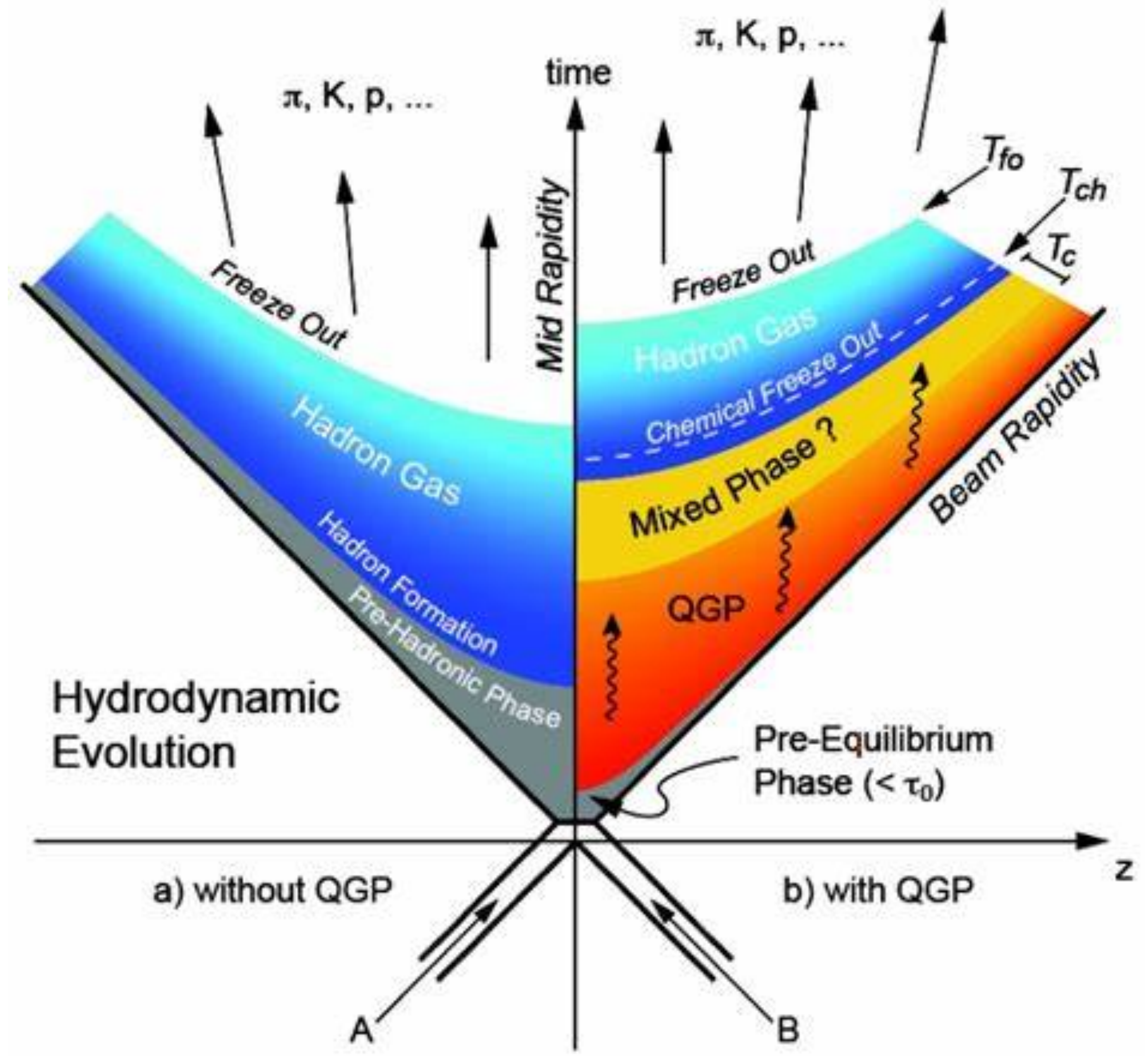


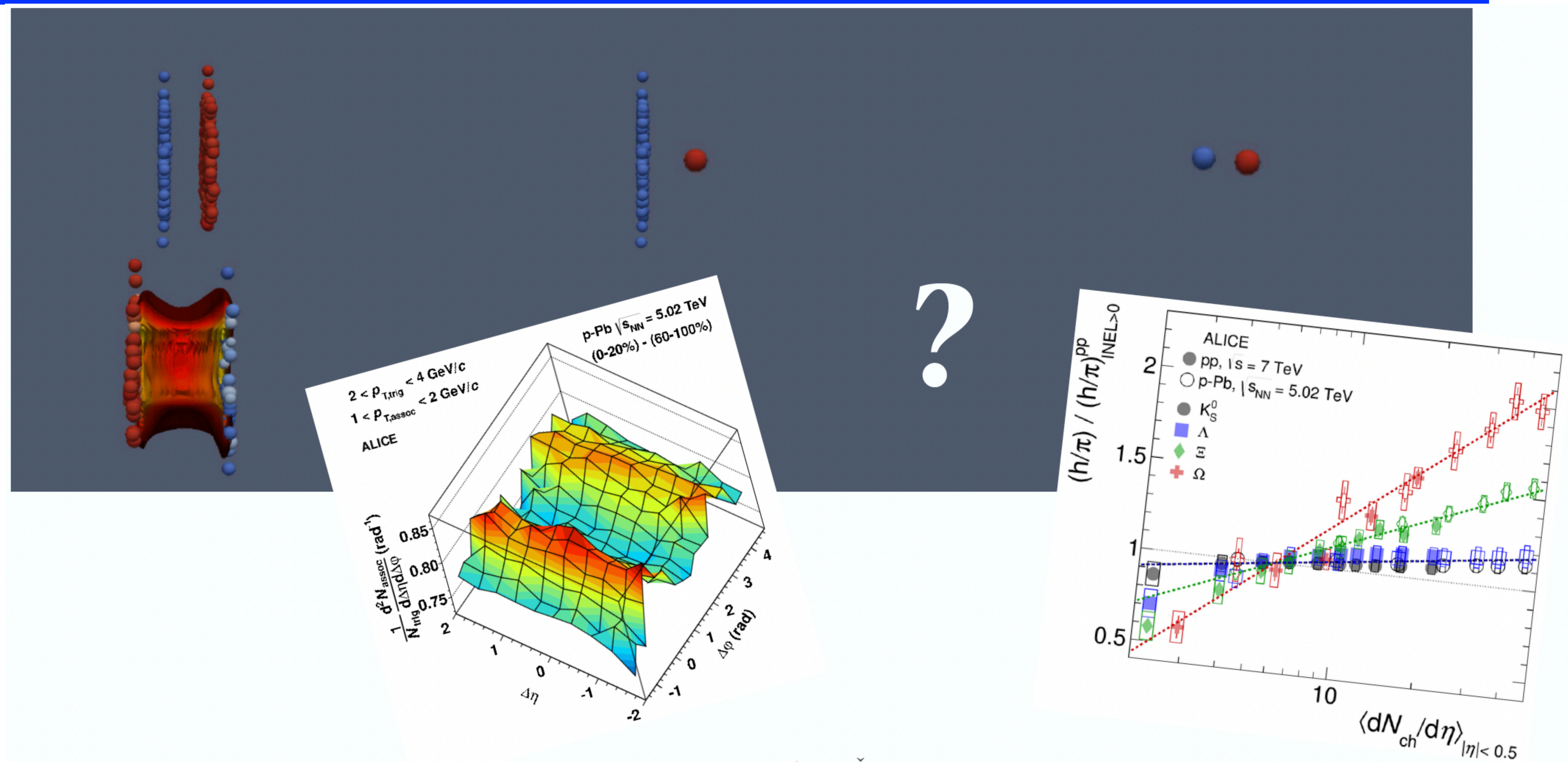




- The splitting function for charm quarks has a narrower angular distribution
  - At large angles dominated by Casimir colour effects
  - At small angles a competition between the dead cone and Casimir effects is observed
- Run 3 allows for the investigation of the different evolutions of mass and Casimir effects

Search for QGP limits

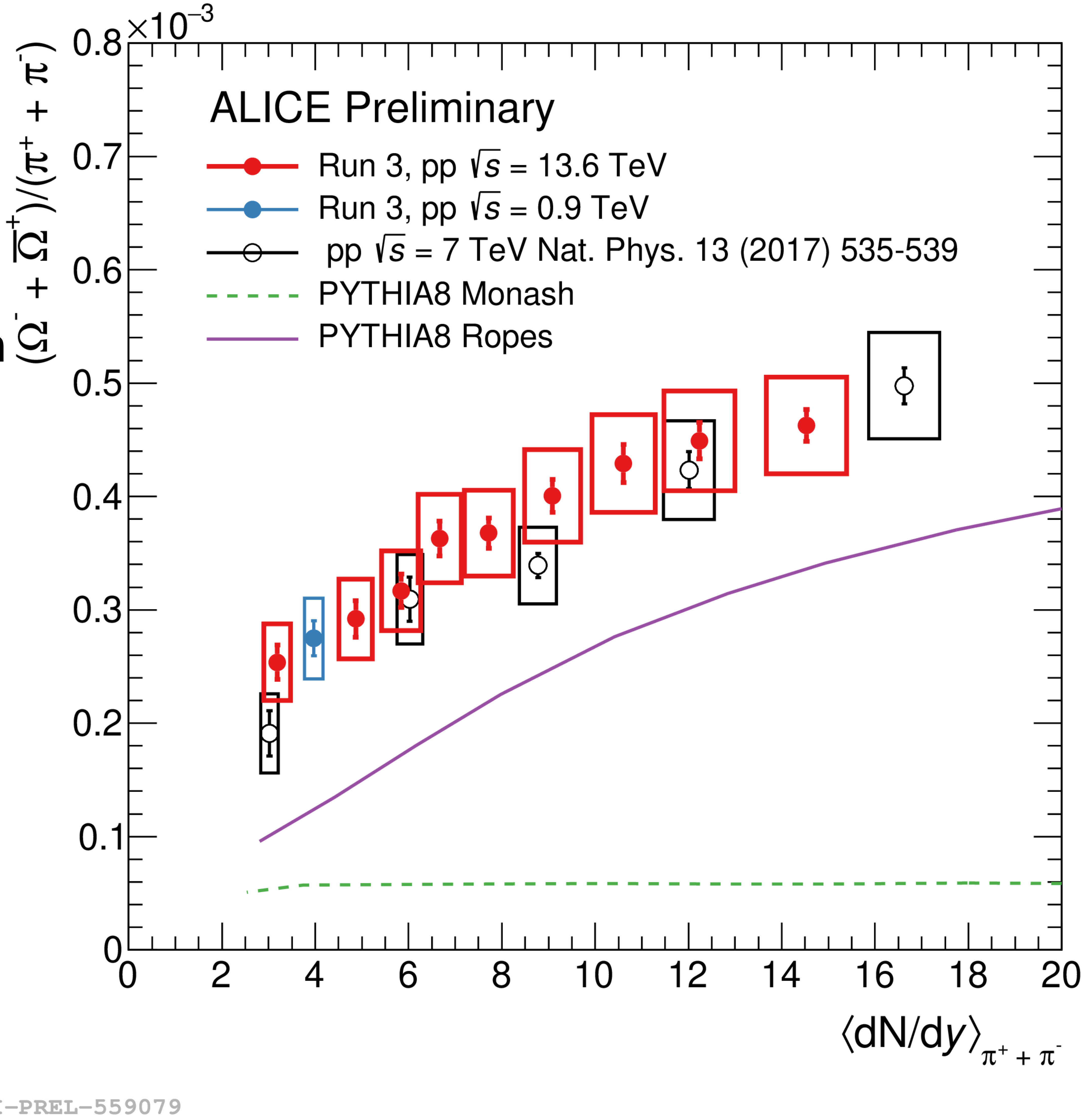




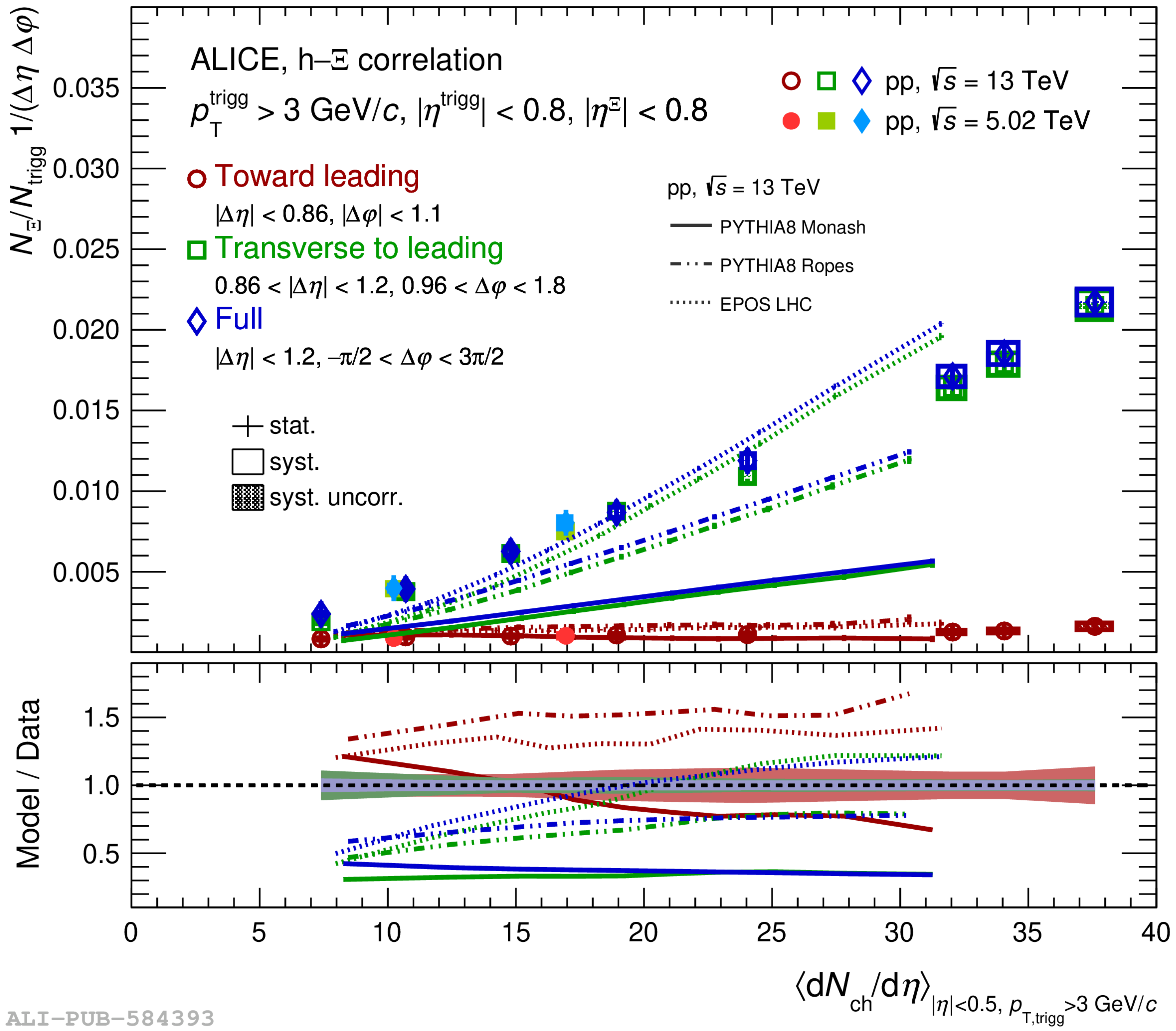
Strange hadron production

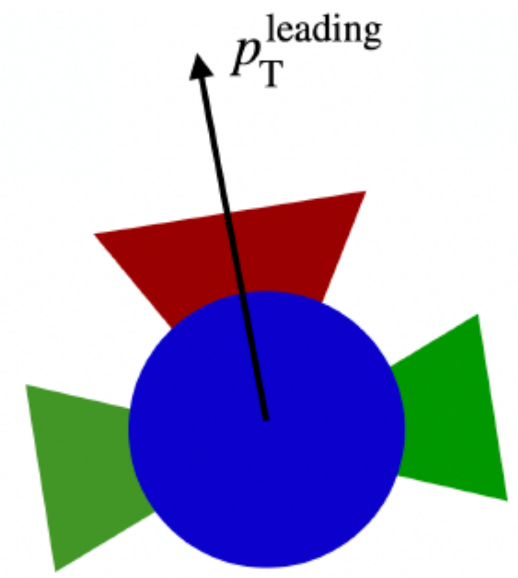
- Strangeness increases with multiplicity, from pp to Pb-Pb collisions:
  - hierarchy of increasing trend with strangeness content
- Several approaches try to describe strangeness hadronization in small systems
  - pQCD inspired models need extra mechanisms
- First Ω yield measured in pp collisions at √s= 900 GeV at the LHC
  - comparison with measurements at different collision energies for pp collisions √s= 900, 7, 13.6 GeV
  - unprecedented multiplicity differential study with Run 3 data

➡ full sample will allow to extend the multiplicity reach

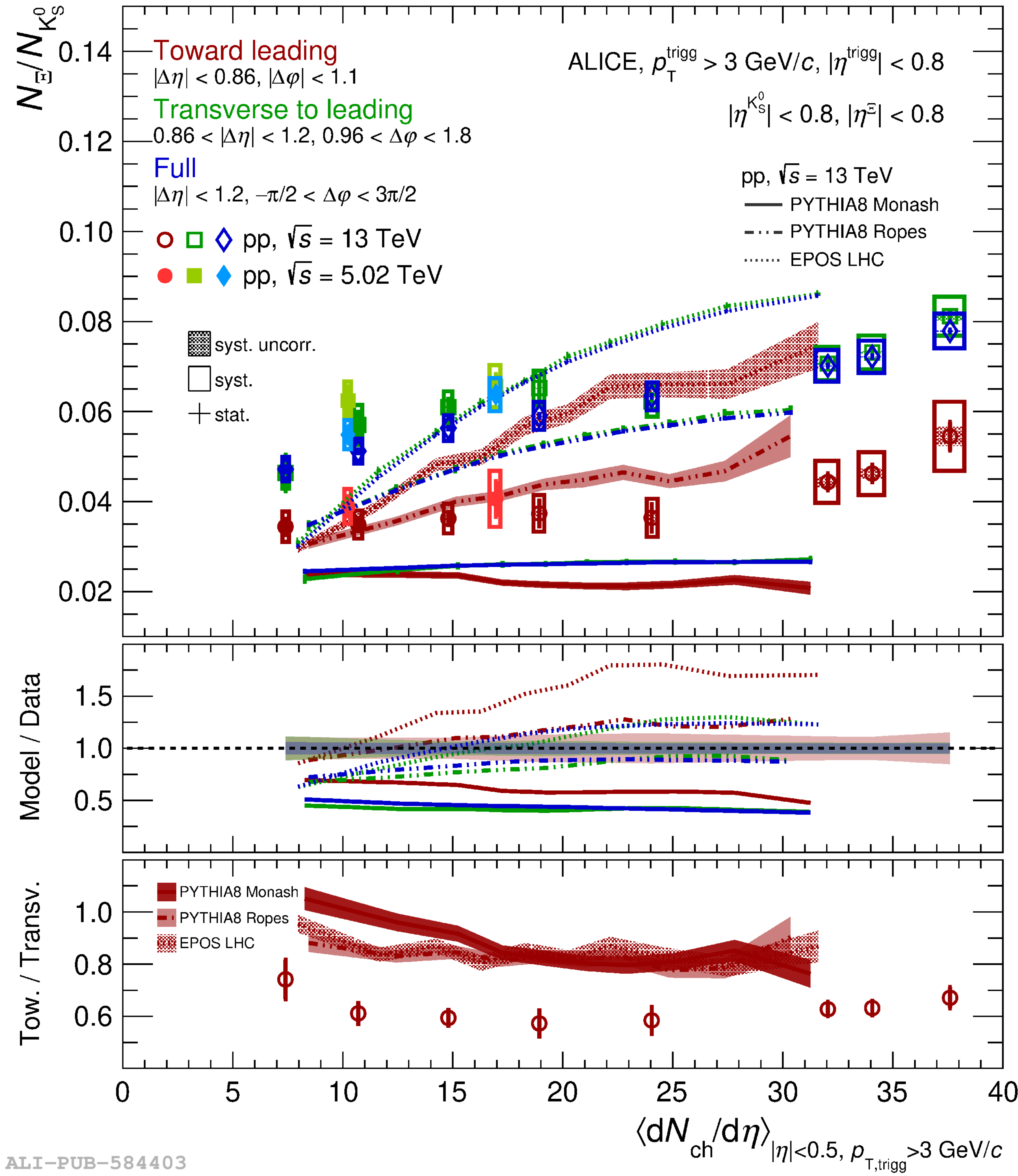


Strangeness enhancement origin search



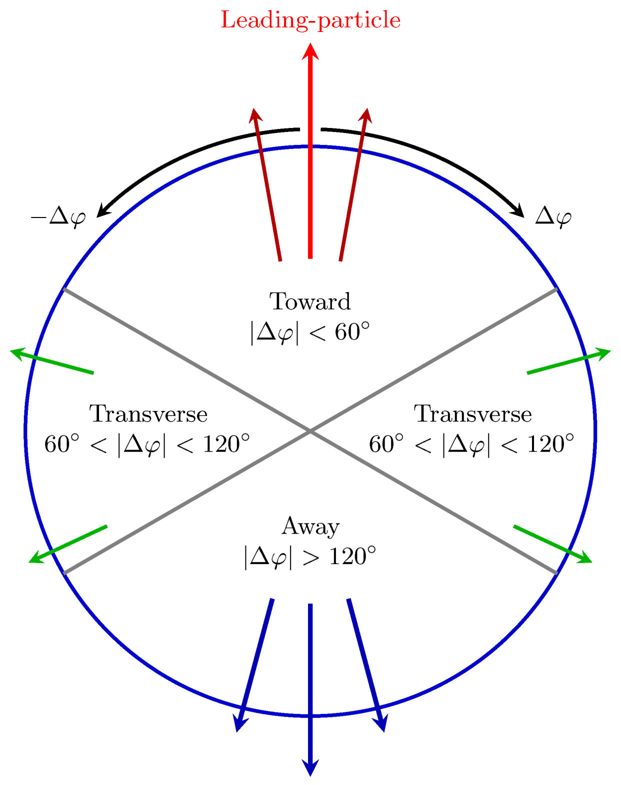


JHEP 09 (2024) 204

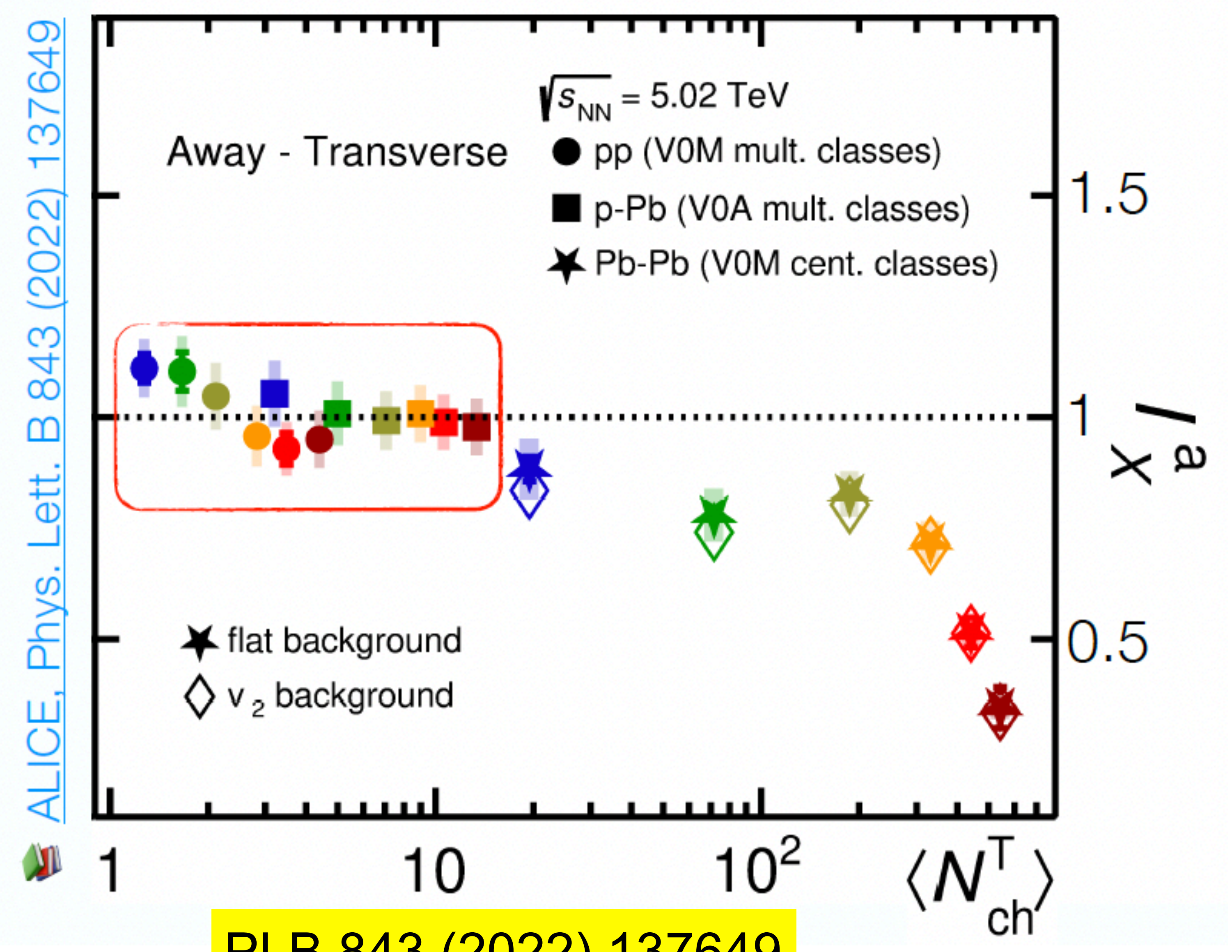


- Majority of the total production is from UE contribution
- Steepness of the strangeness increase is quite similar between jets and UE
  - Models can't reproduce data well

Search for jet quenching in small systems



$$I_X^a = \frac{(dN_{ch}^{AS-TS}/dp_T)_{V0M}}{(dN_{ch}^{AS-TS}/dp_T)_{MB}}$$



PLB 843 (2022) 137649

- Using particle correlation methods to study associated particles behavior as a function of (transverse) multiplicity
  - No enhancement (suppression) observed for Near (Away) side in pp and p-Pb collisions

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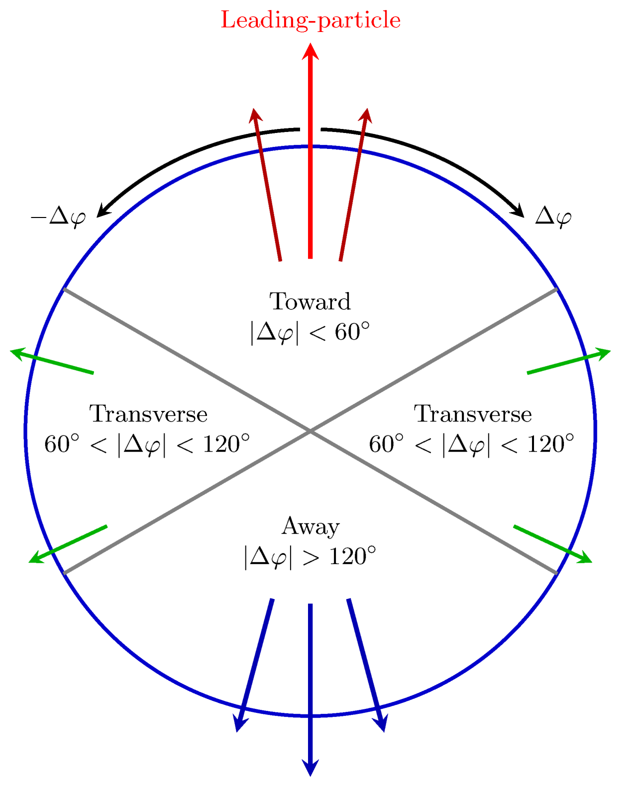

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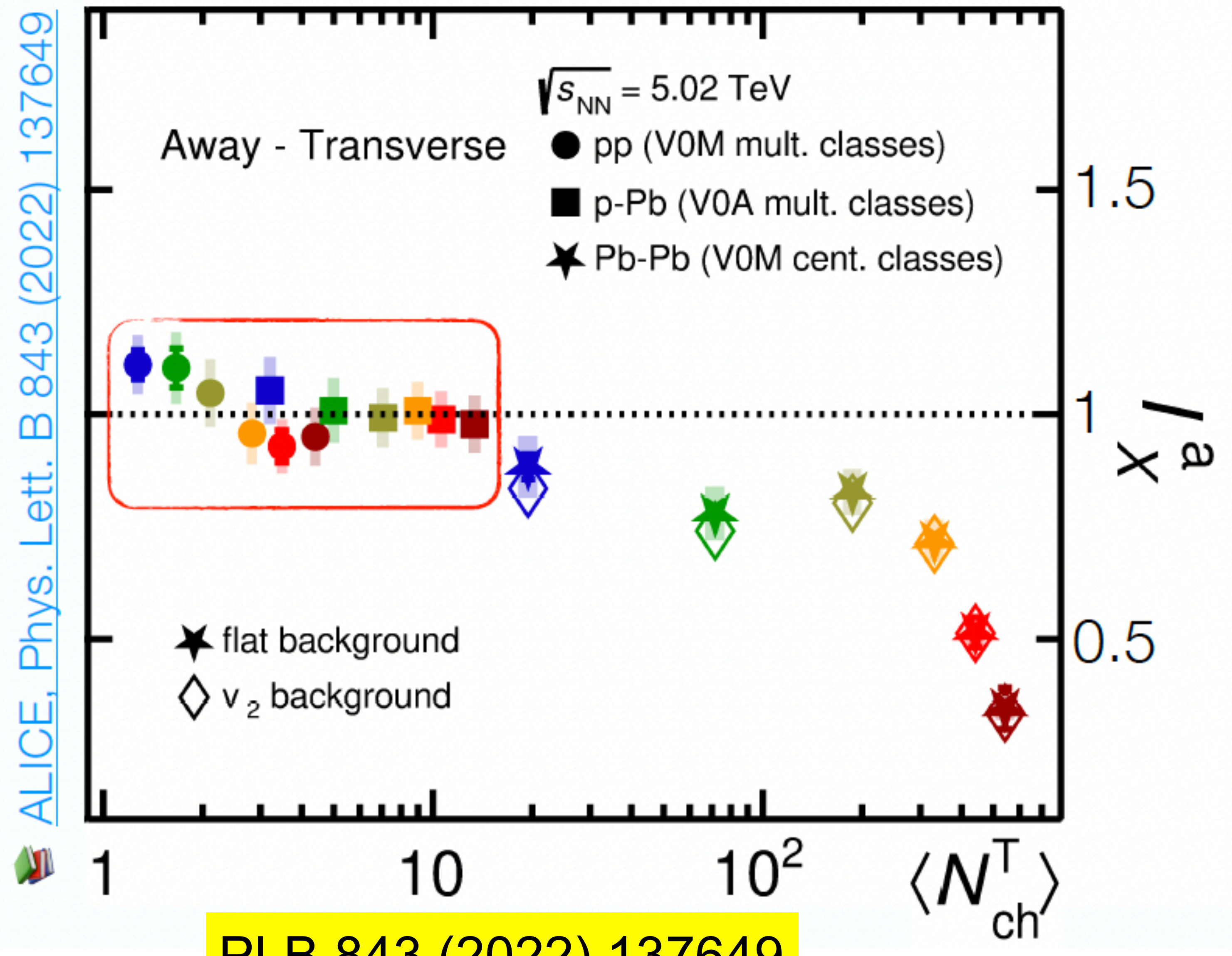
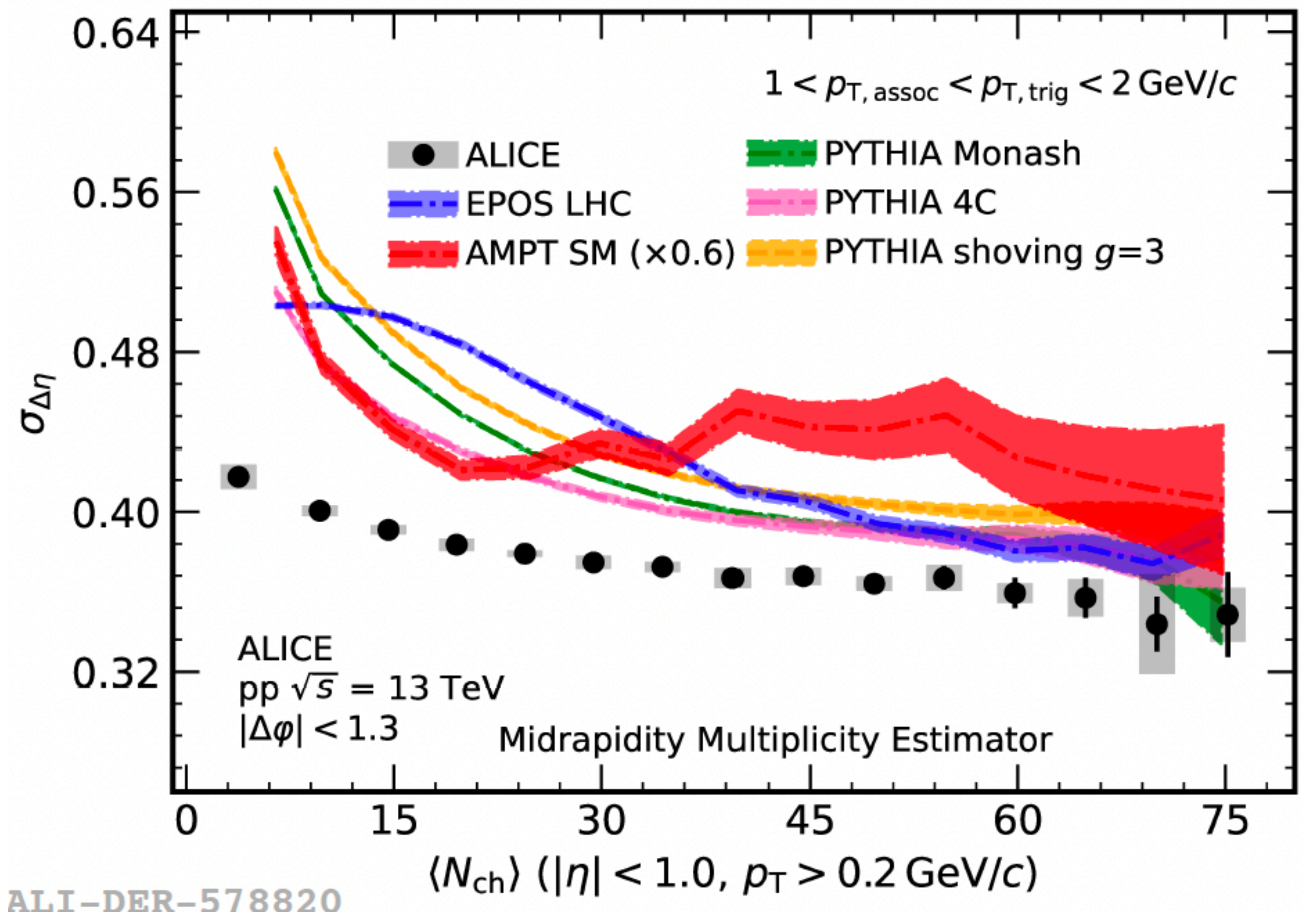


PLB 843 (2022) 137649



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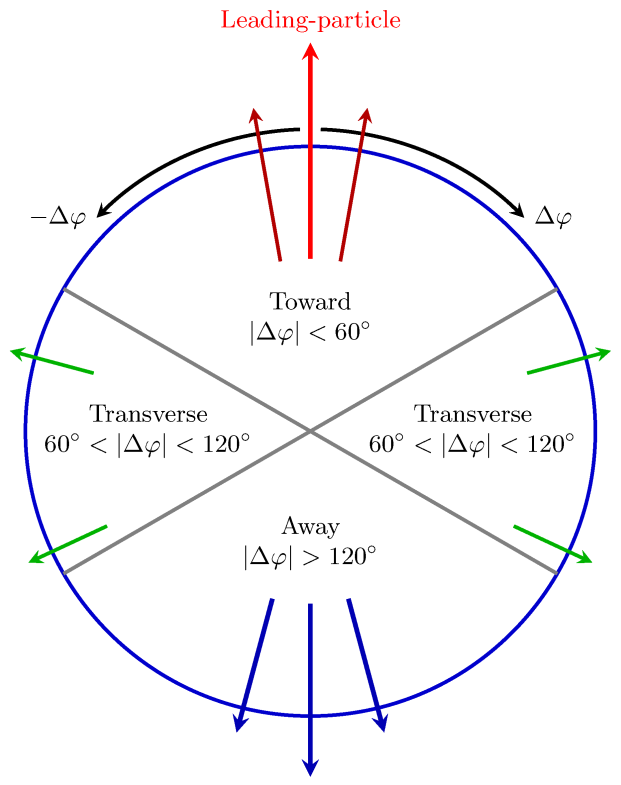

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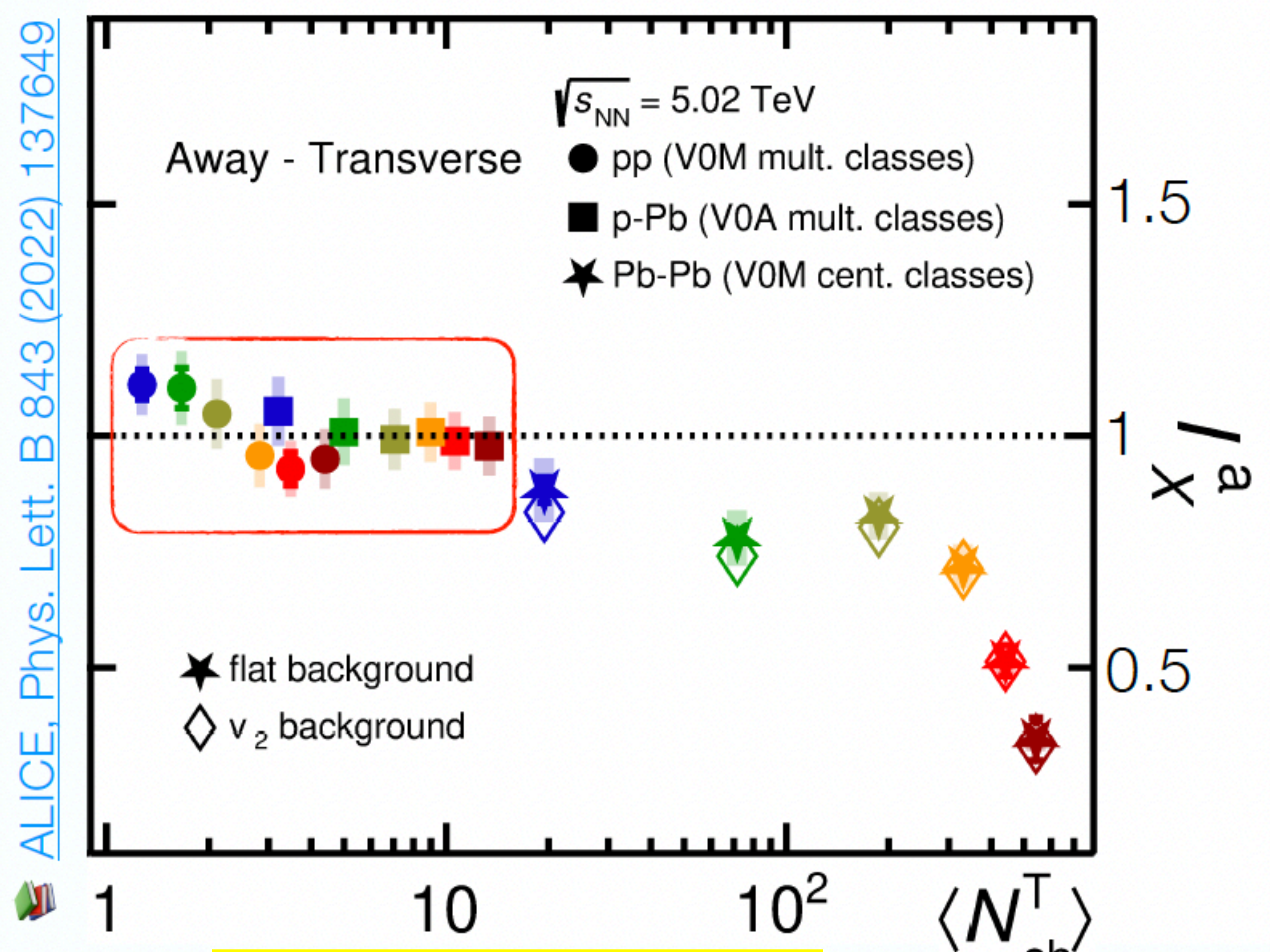

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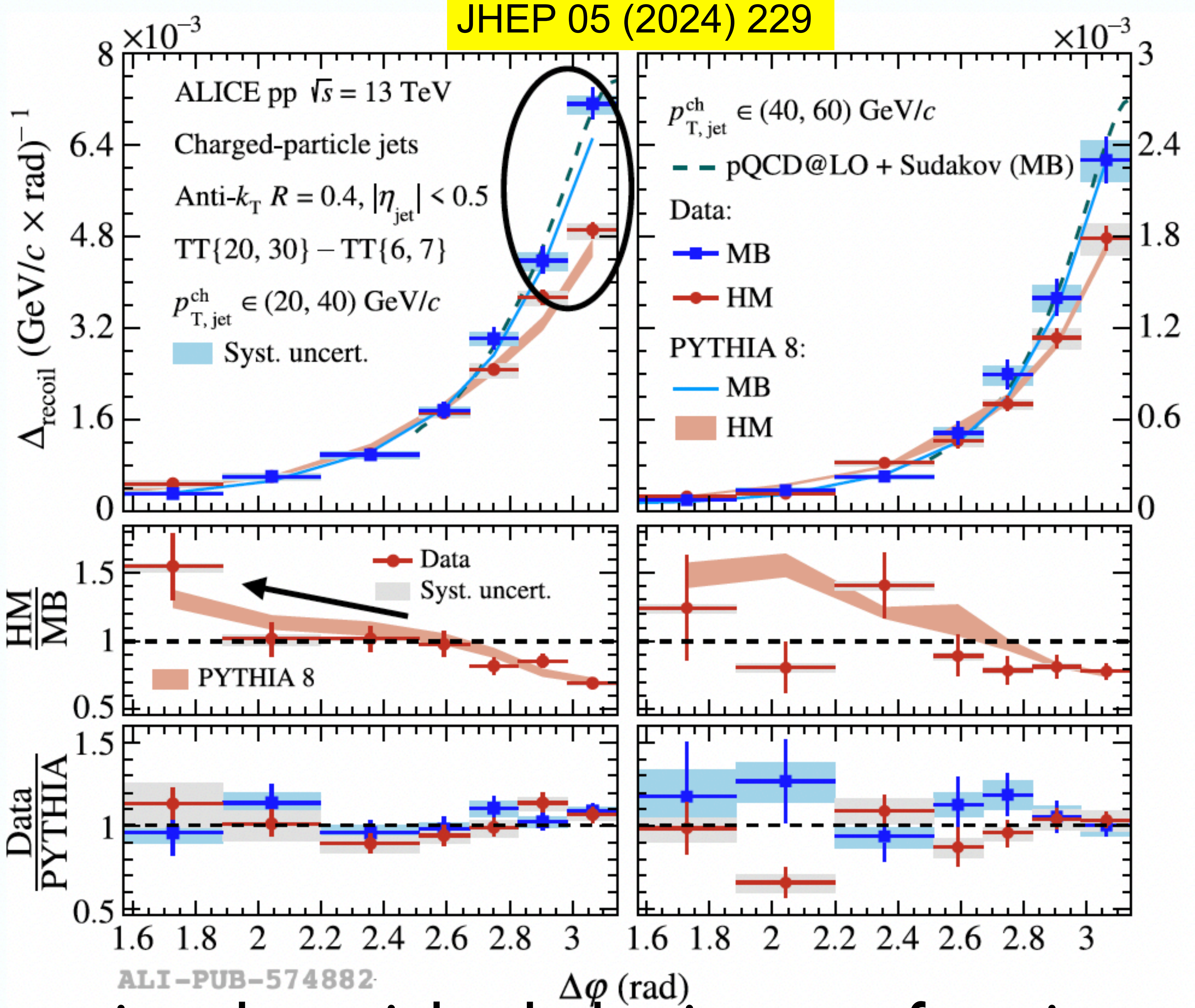
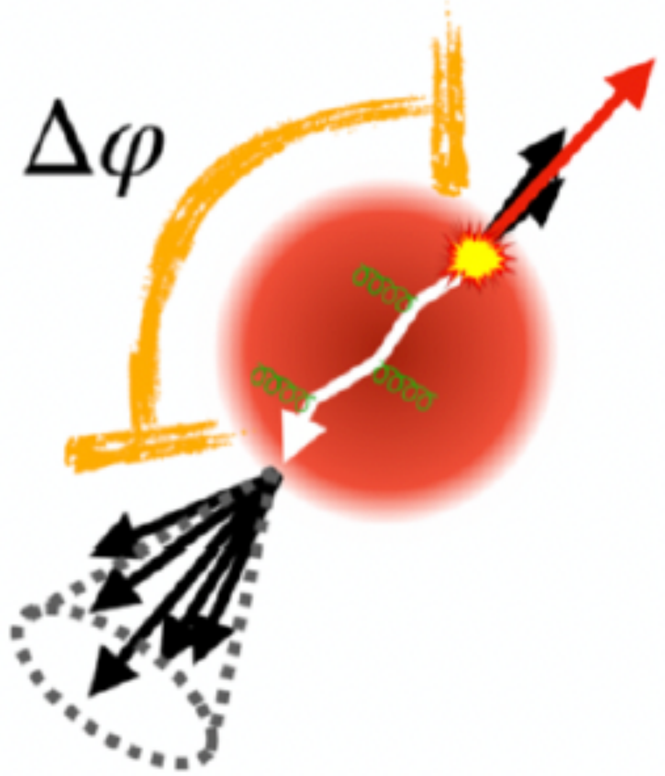
JHEP 05 (2024) 229





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  - No enhancement (suppression) observed for Near (Away) side in pp and p-Pb collisions
  - Peak width become narrower in HM events for low p_T associated particles
  - Azimuthal broadening in HM events observed for recoiling jets with high p_T trigger particles

Fresh news: chasing the small size-limit of QGP

- Collective-like effects present in high multiplicity pp and p-Pb collisions
- But: No jet quenching observed in p-Pb (d-Au) at high multiplicity
- Open questions:
  - ➡ How plasma-like properties emerge in QCD?
  - ➡ What is the smallest droplet of QGP?

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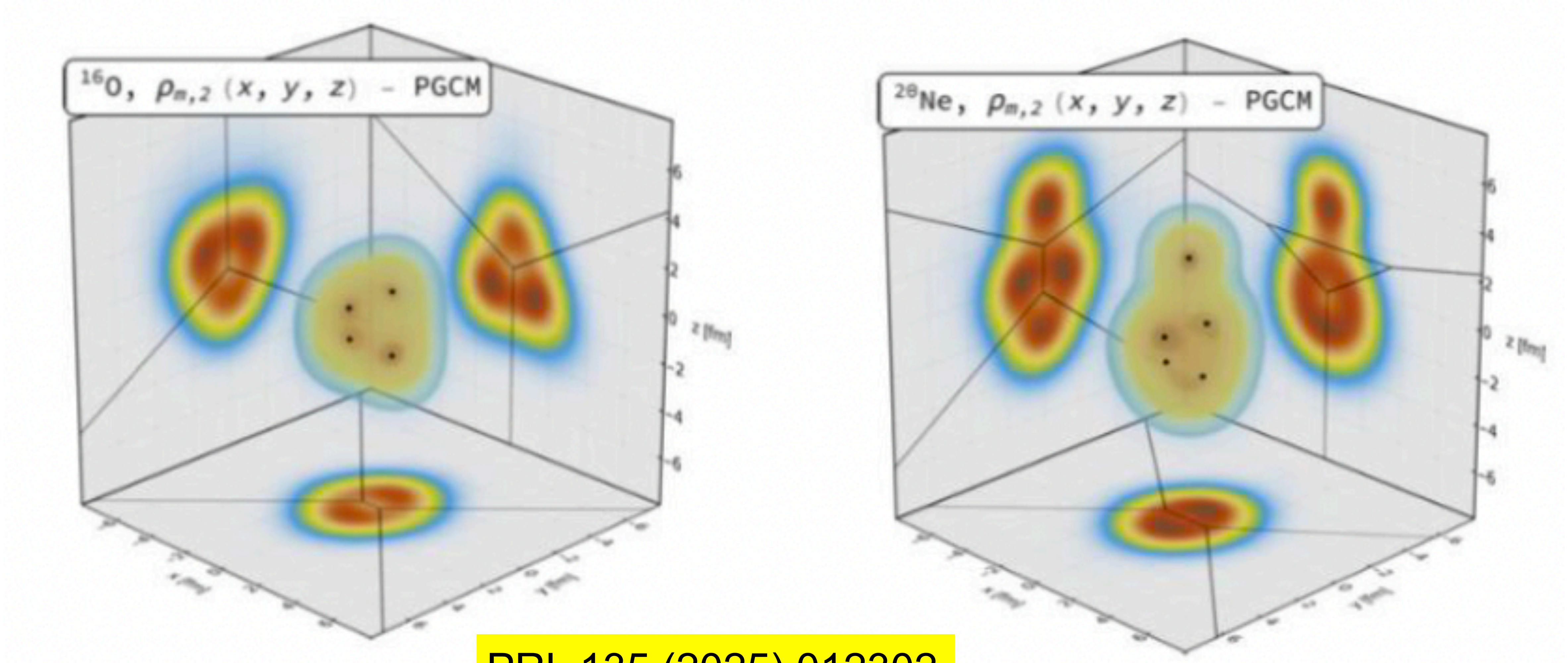
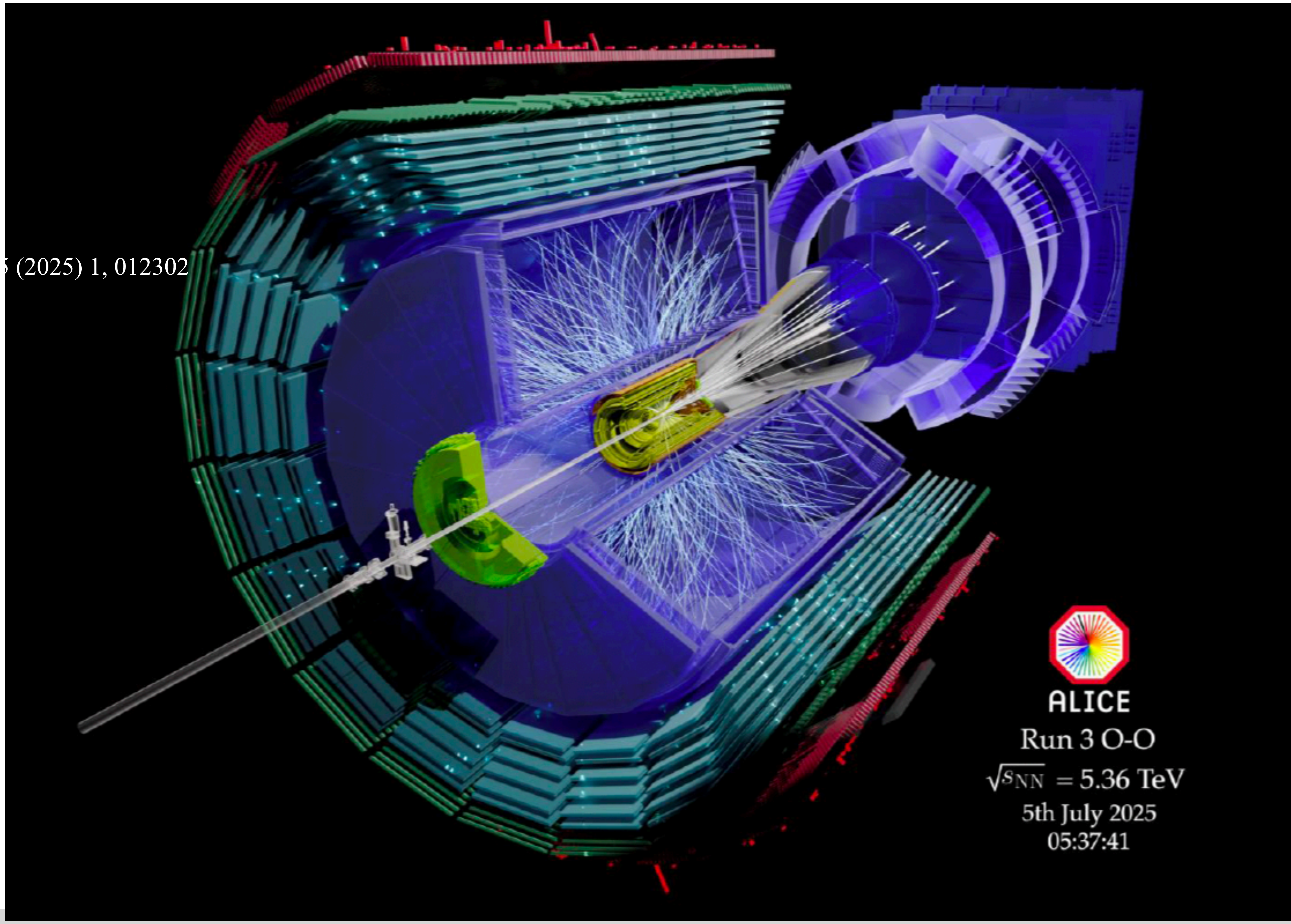
July 2025:

O-O, Ne-Ne, p-O data taking



PRL 135 (2025) 012302



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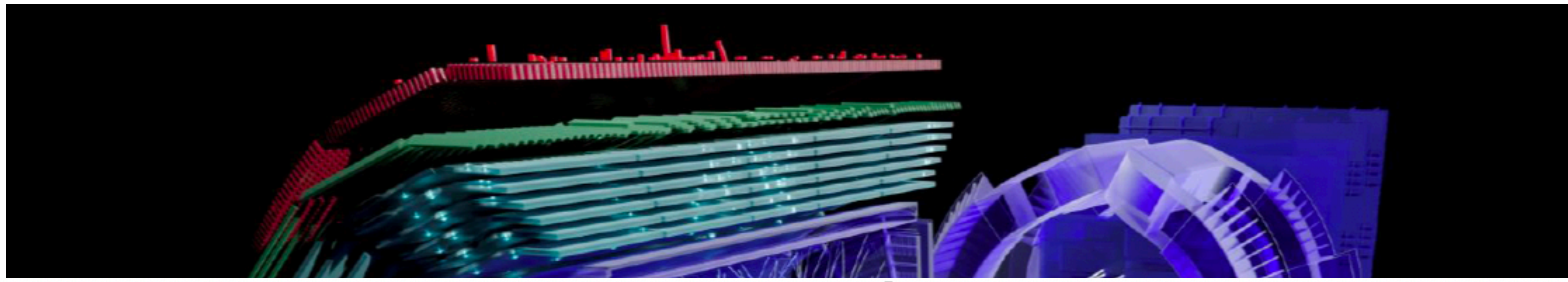
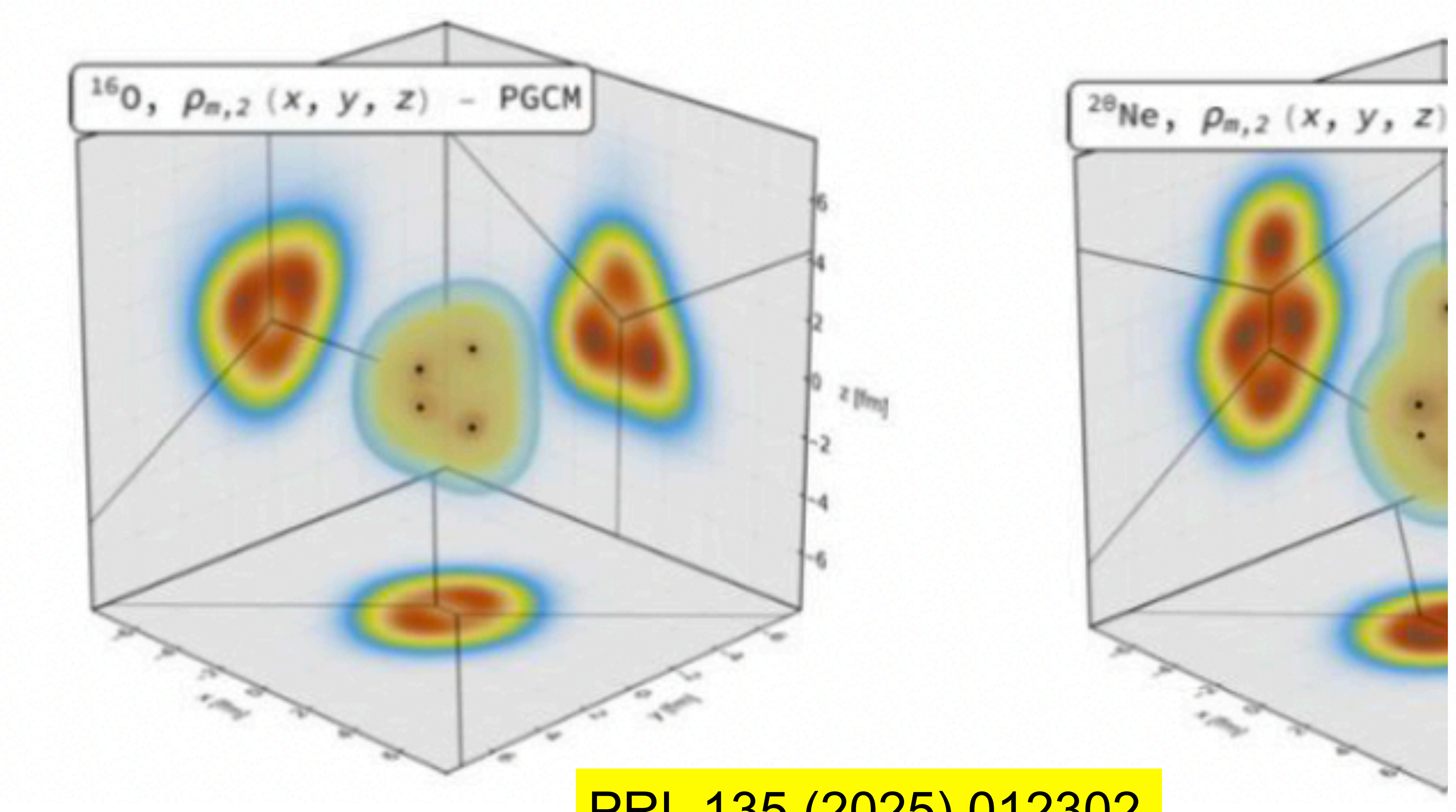
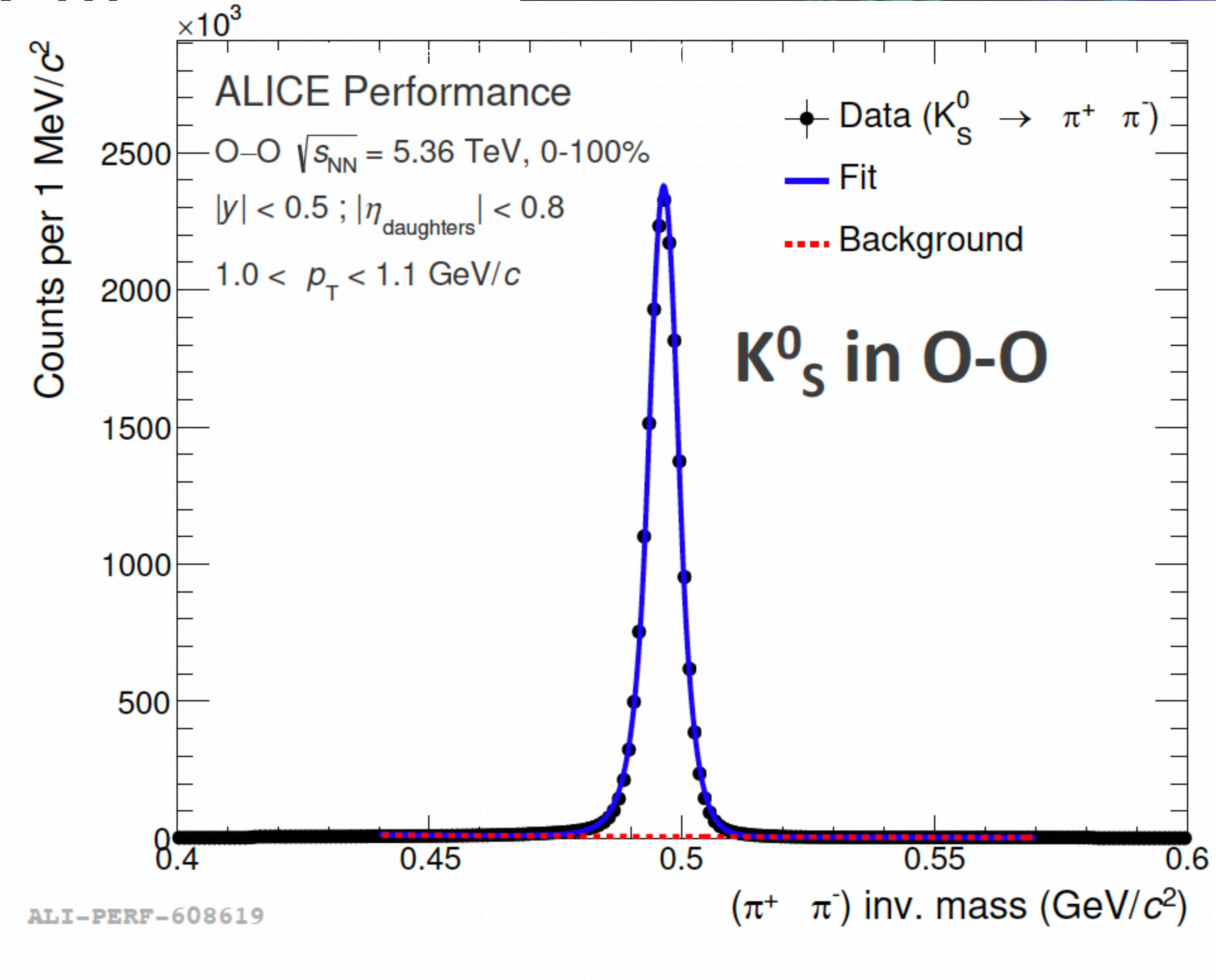
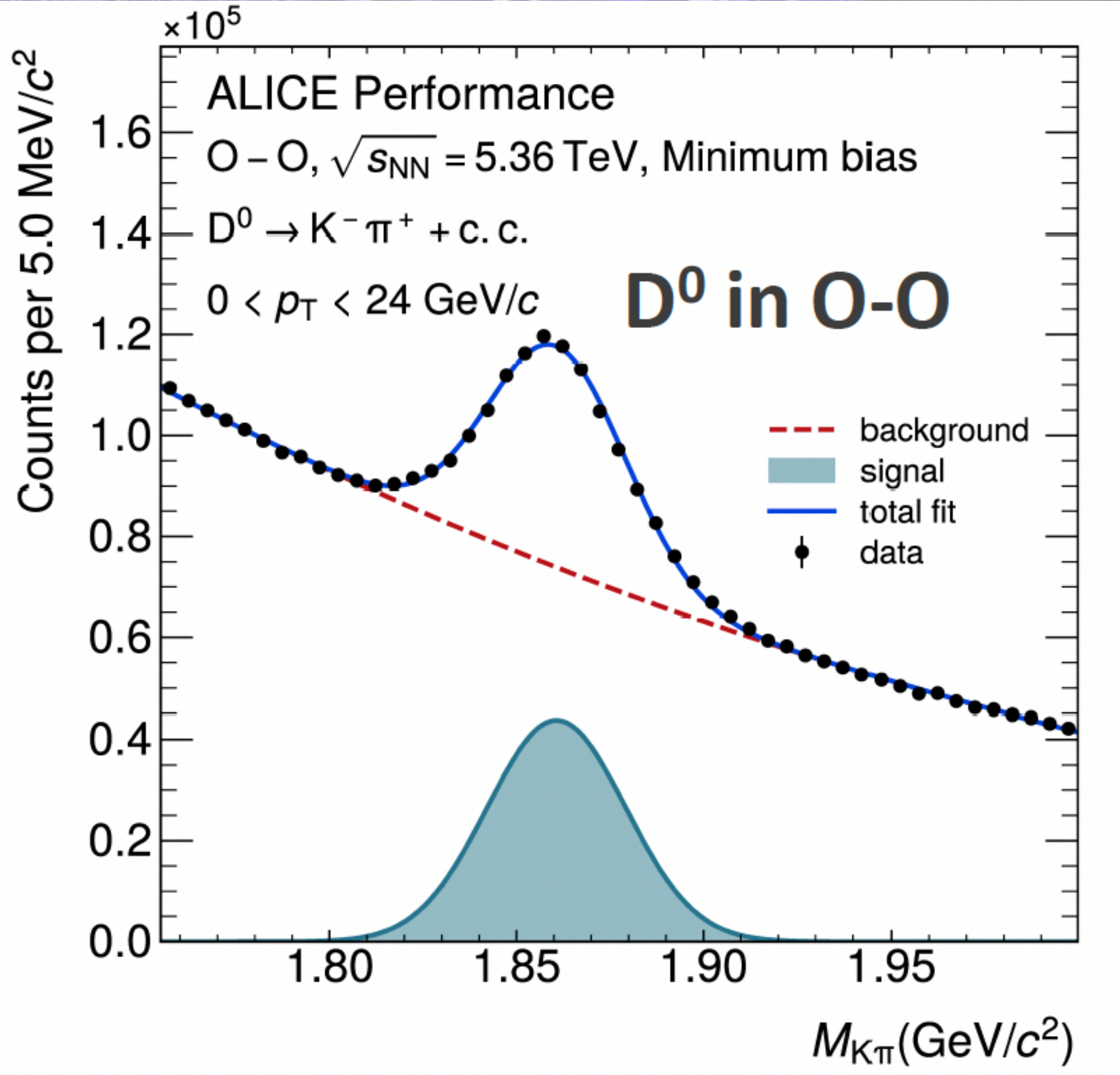




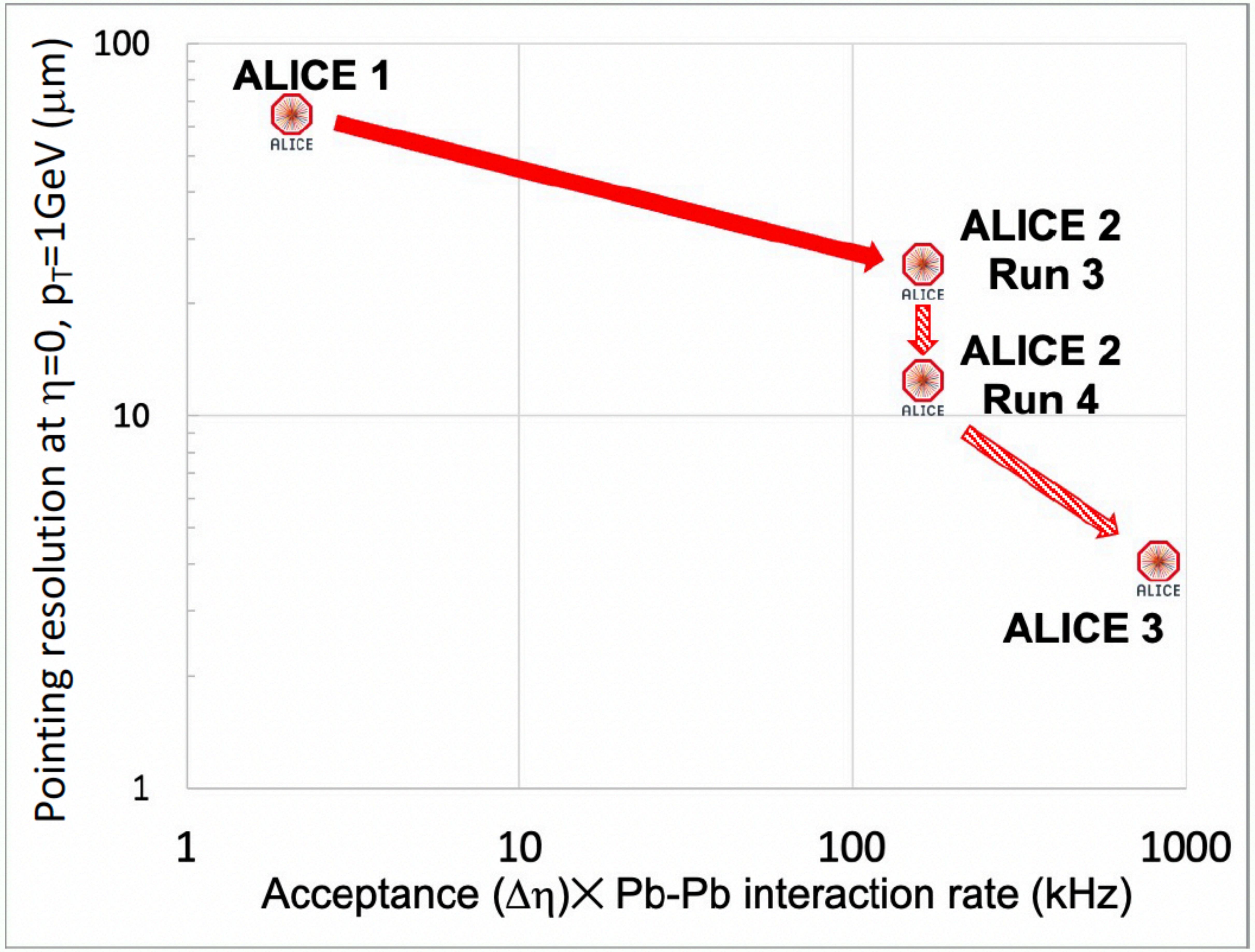
PRL 135 (2025) 012302



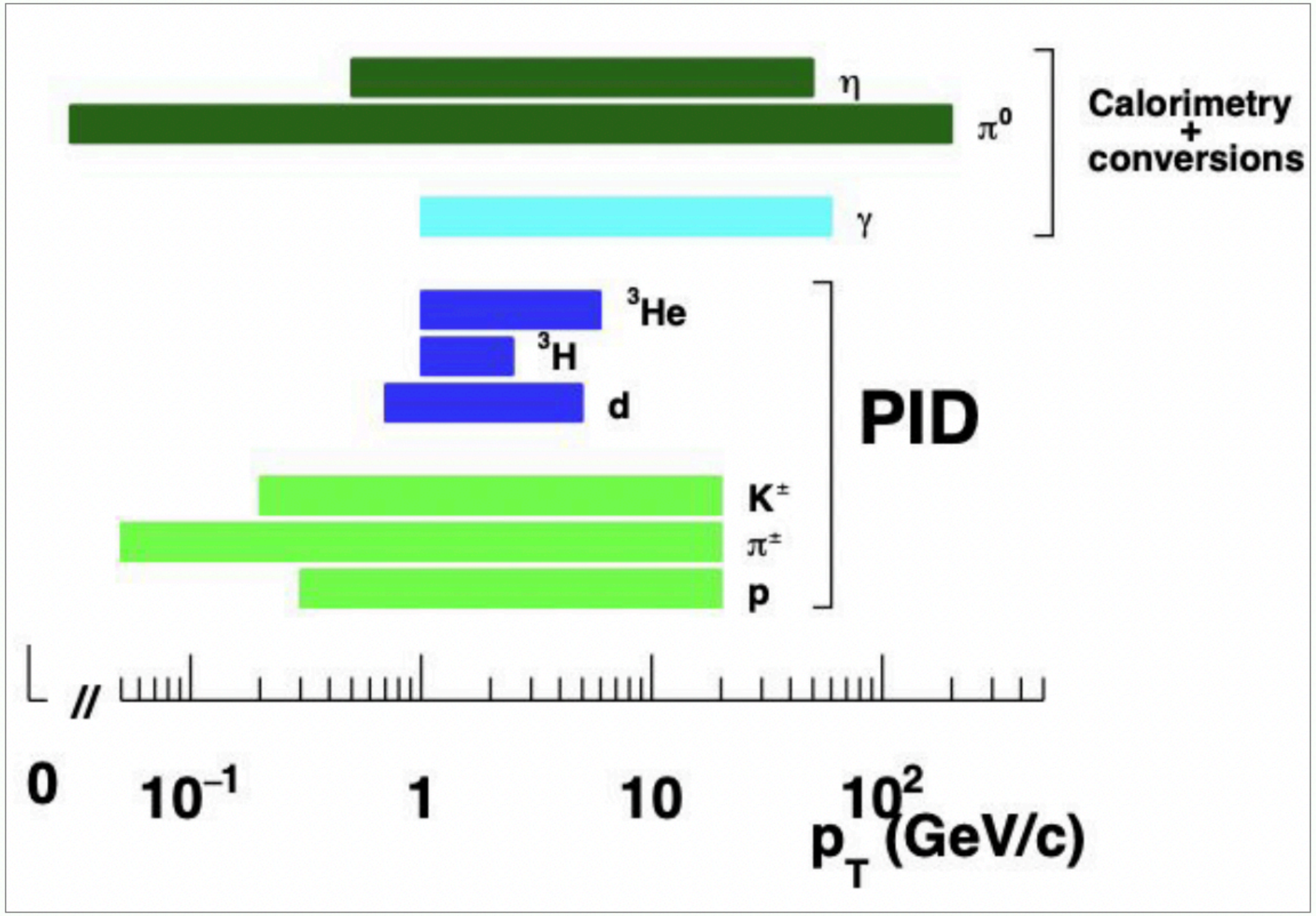


ALICE: what's next?

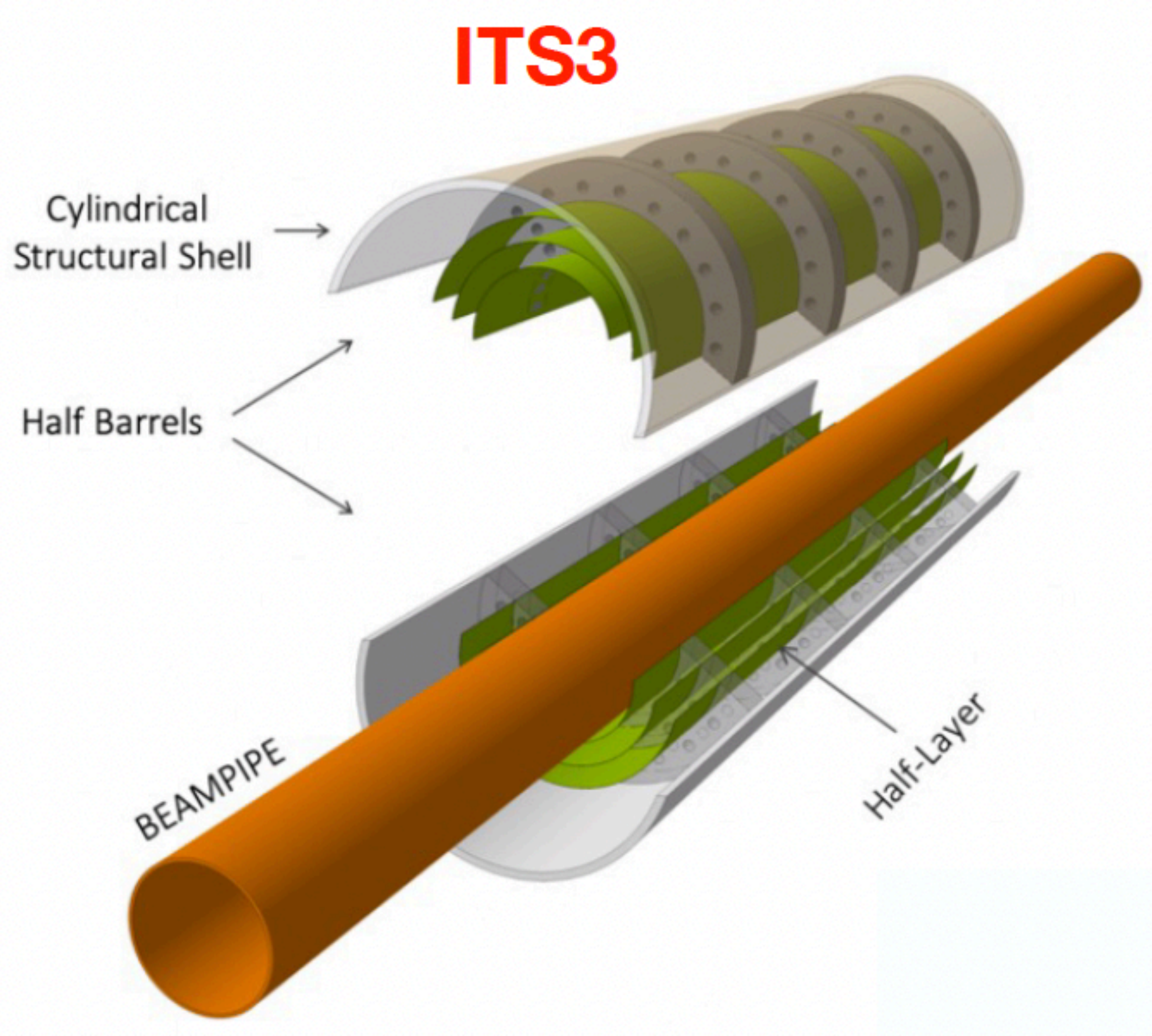
Evolution towards higher pointing resolution and larger effective acceptance

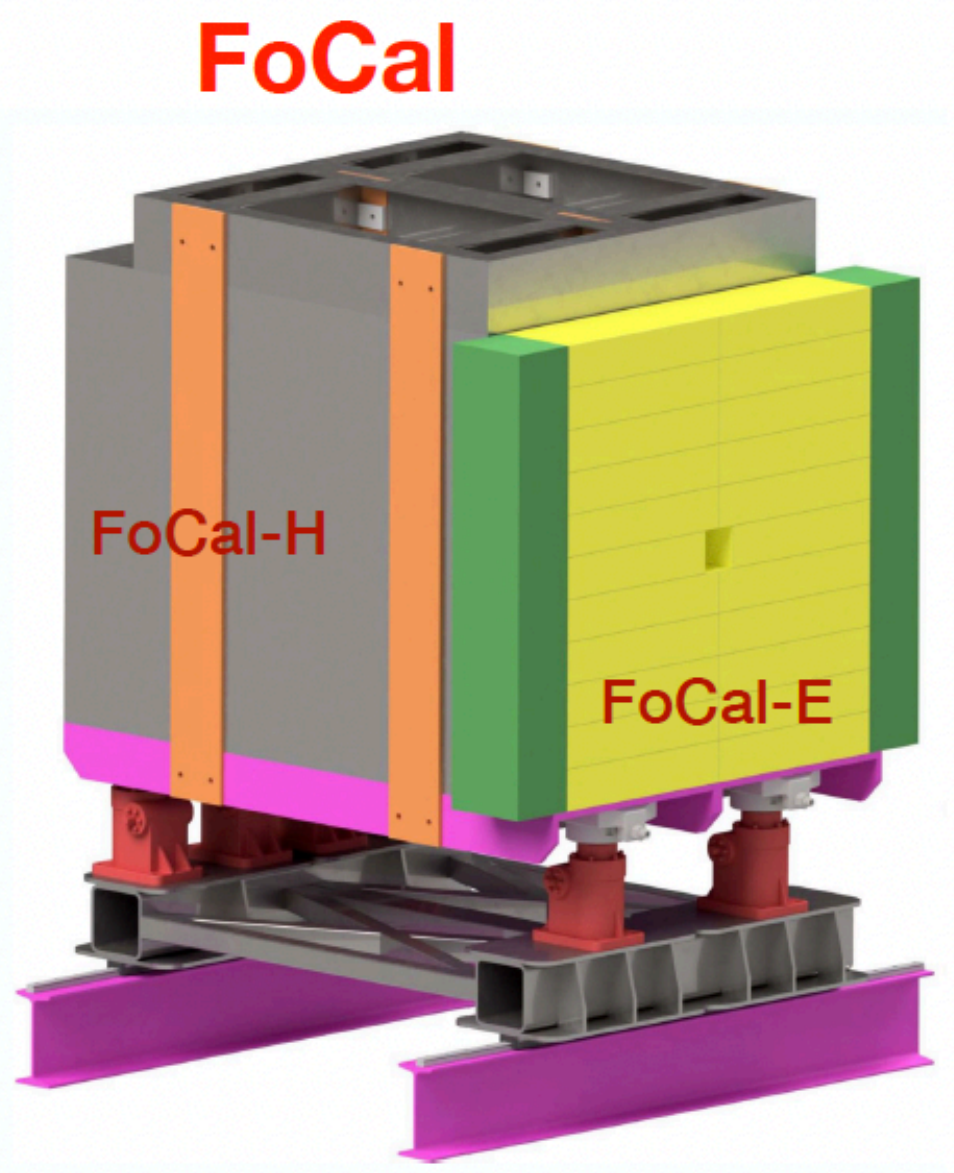


Maintain and enhance ALICE's unique capabilities in particle identification



Towards future: ALICE 2 (beyond Run 3)





ITS3 & FoCal

- Specific upgrades in LS3 (2026-29)
- TDRs approved in March 2024
- Moving towards "production" phase

ITS3 TDR: CERN-LHCC-2024-003

FoCal TDR: CERN-LHCC-2024-004

Towards future: ALICE 3 (beyond Run 4)

Run 3	LS3				Run 4				LS4		Run 5
2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037

ALICE 3: **Major upgrade in LS4 (2034-35)**

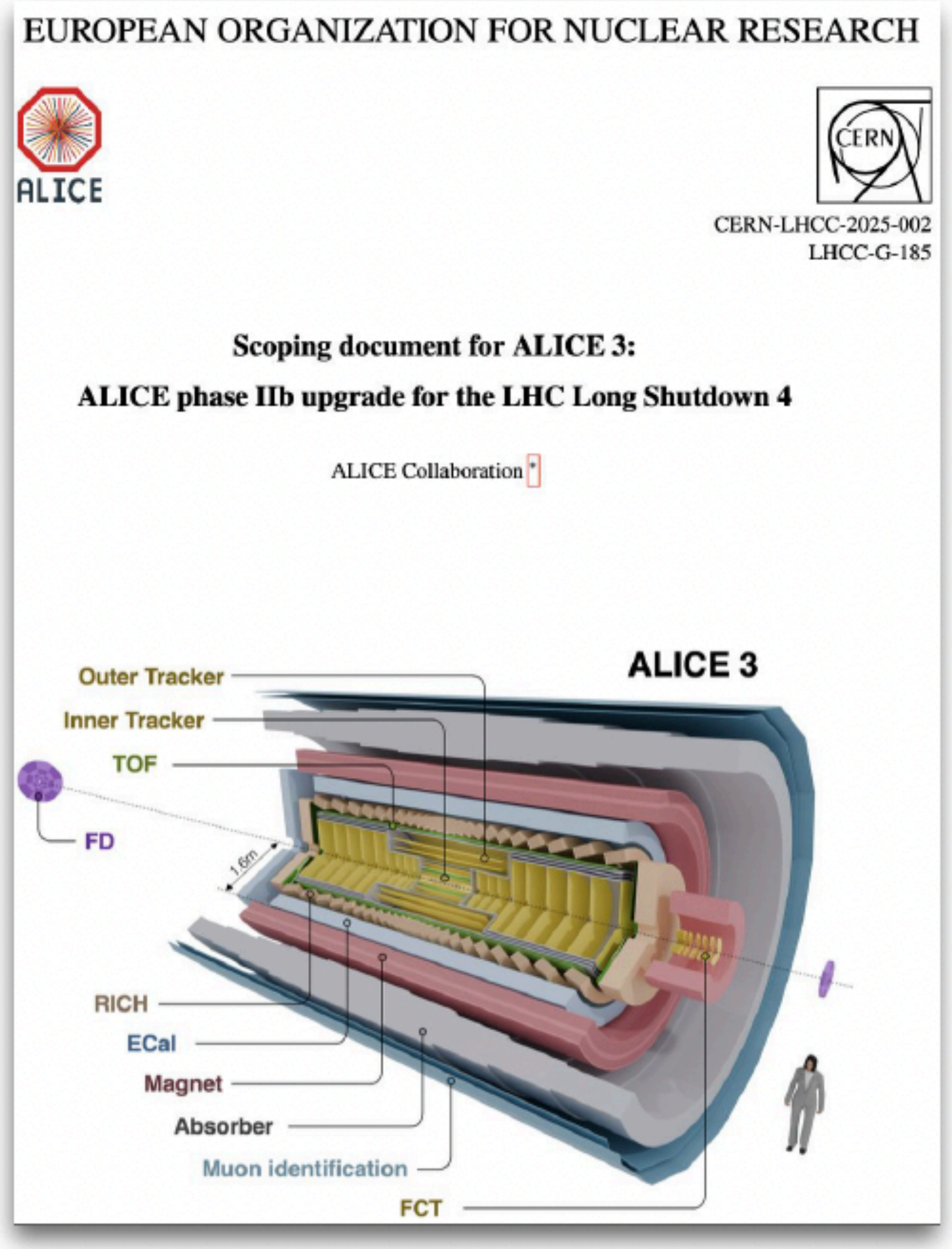
→ **Next-generation heavy-ion experiment** - **First ideas at Heavy-Ion town meeting in 2018 (arXiv:1902.01211)**

→ **Letter of Intent:**
Review by the LHCC in March 2022 (arXiv:2211.02491)

→ **Scoping Document:**
Review just completed (CERN-LHCC-2025-002)


CERN-LHCC-2022-009
(LHCC-I-038)
11 March 2022
ALICE

Letter of intent for
ALICE 3
VERSION 1


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
ALICE
CERN
CERN-LHCC-2025-002
LHCC-G-185

Scoping document for ALICE 3:
ALICE phase IIb upgrade for the LHC Long Shutdown 4

ALICE Collaboration

● **Moving towards "comprehensive R&D" phase**

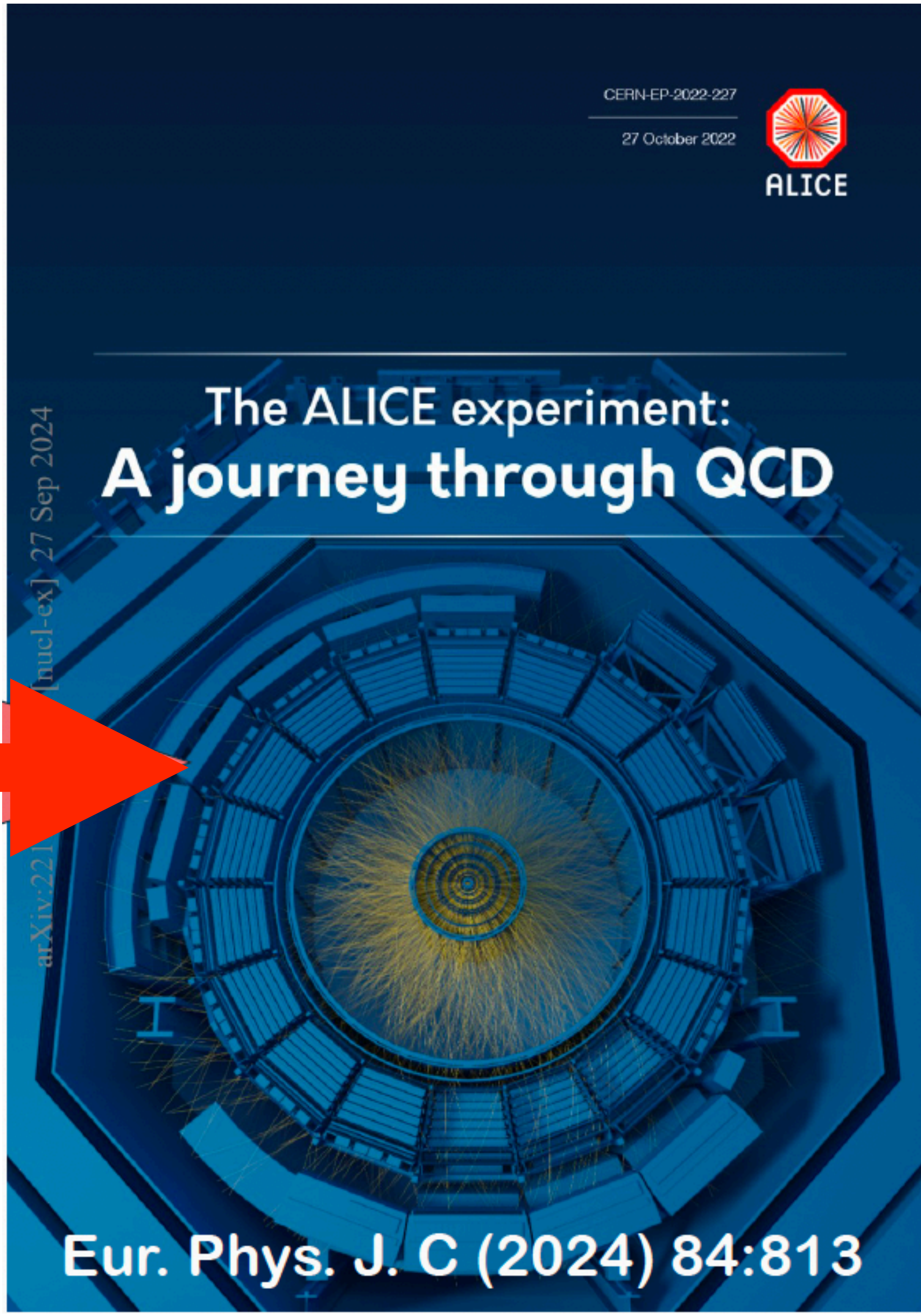
Summary

- The ALICE experiment is specifically designed to study every phase of heavy-ion collisions

- This presentation provides an overview of selected recent results from the ALICE experiments. The results showcased do not represent the full scope of measurements!

- The complete data and detailed studies from Run 1 and Run 2 (2009–2018) are documented in…

- The journey continues with ongoing research in Run 3 and beyond…



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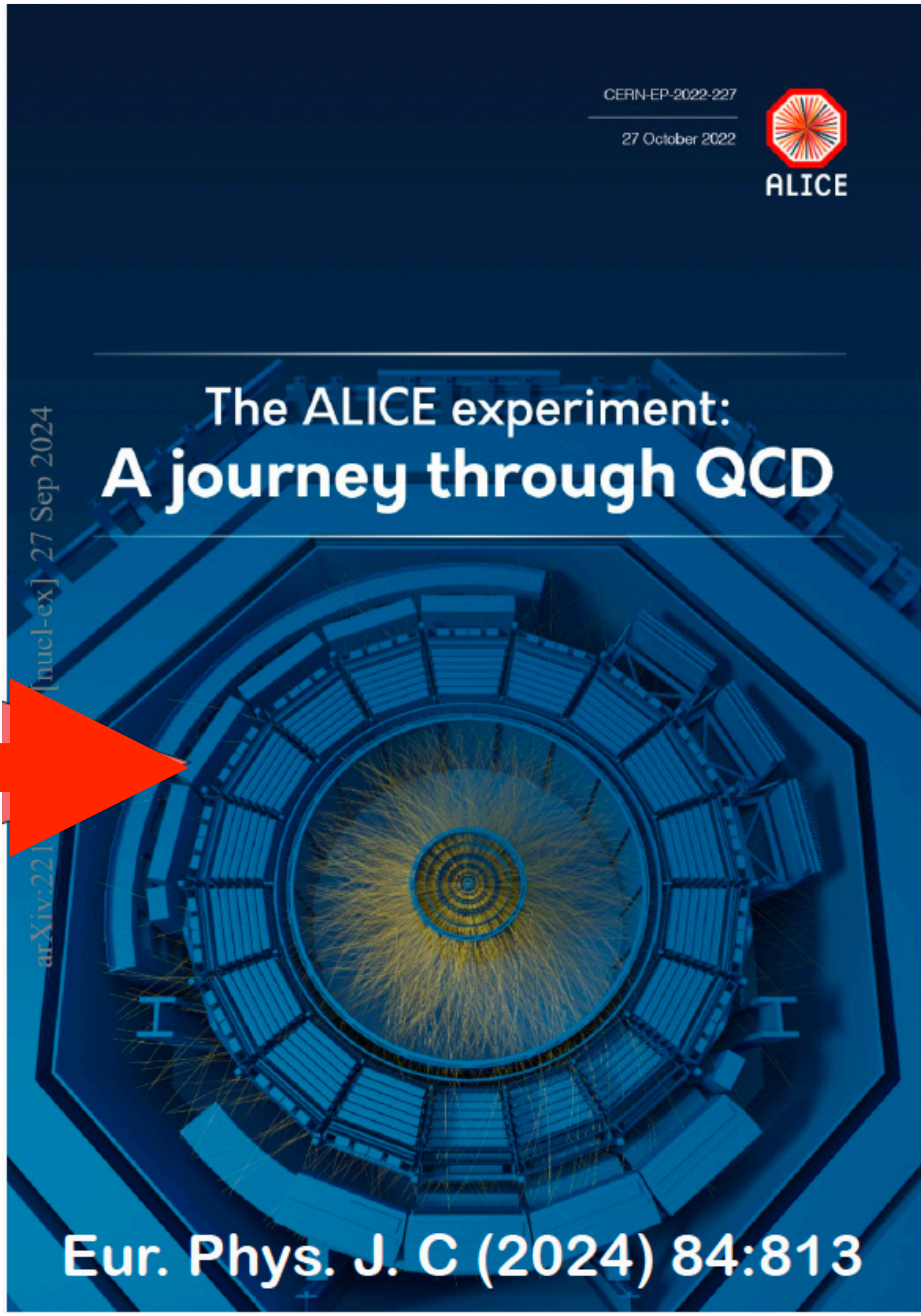

Stay tuned! Thanks for your attention!

Backup