Characterisation of heavy-quark propagation and thermalisation in QGP with ALICE

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on behalf of the ALICE Collaboration
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HP2024 NAGASAKI

ALICE

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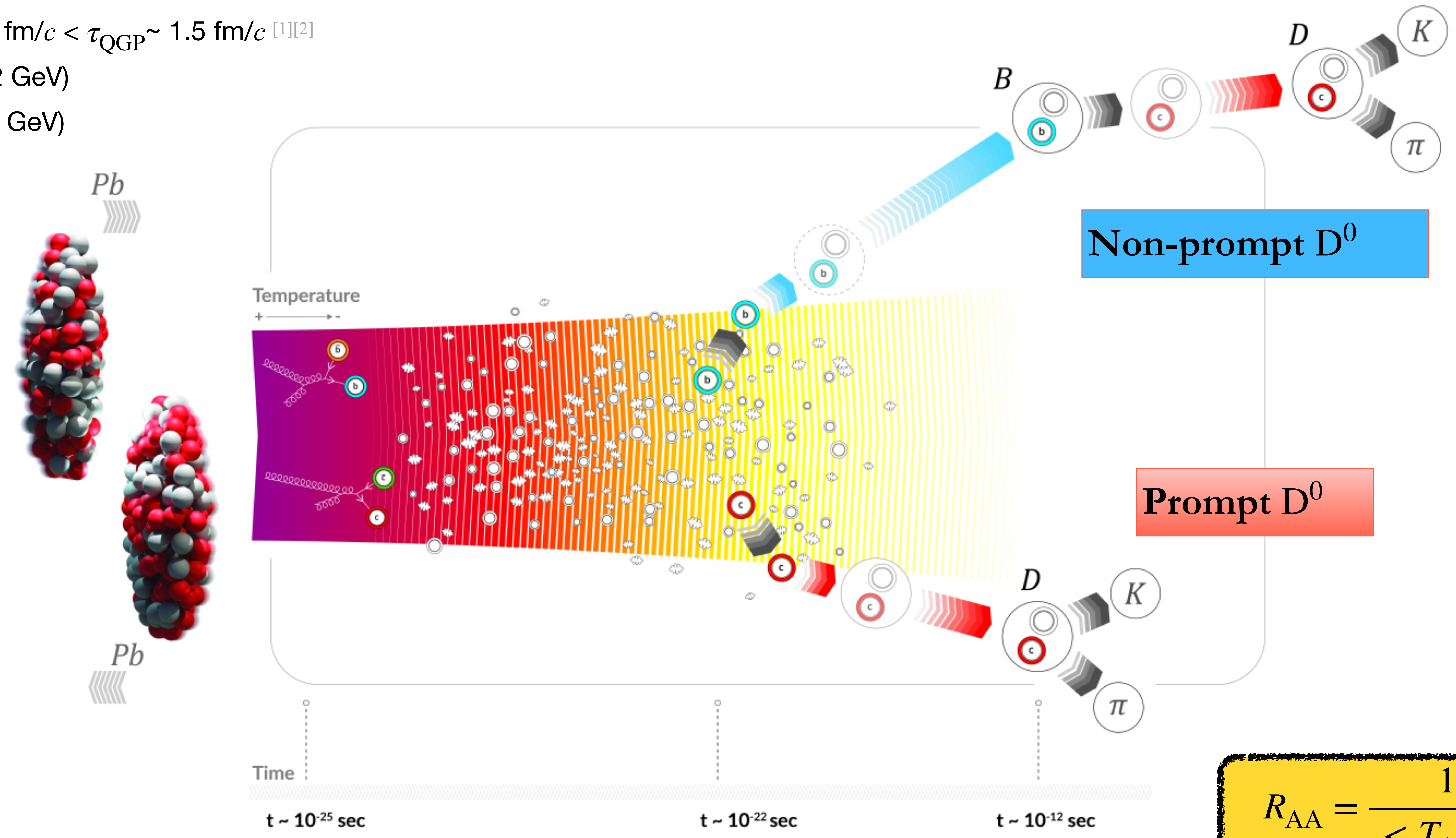
Heavy quarks produced via hard-scattering in initial stages of heavy-ion collisions due to their large mass :

- τ_b~0.12 fm/c < τ_c ~0.394 fm/c < τ_{QGP}~ 1.5 fm/c [1][2]
- $m_b > m_c \gg \Lambda_{QCD}$ (~ 0.2 GeV)
- $m_b > m_c \gg T_{QGP}$ (~ 0.6 GeV)



$$R_{AA} = \frac{1}{< T_{AA} >} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

Excellent probes to study the QGP properties:

- Parton energy loss: collisional or radiative, influenced by dead-cone effect

[1] Ann.Rev.Nucl.Part.Sci. 69 (2019) 417-445
[2] F.M Liu et al., PRC 89, 034906 (2014)

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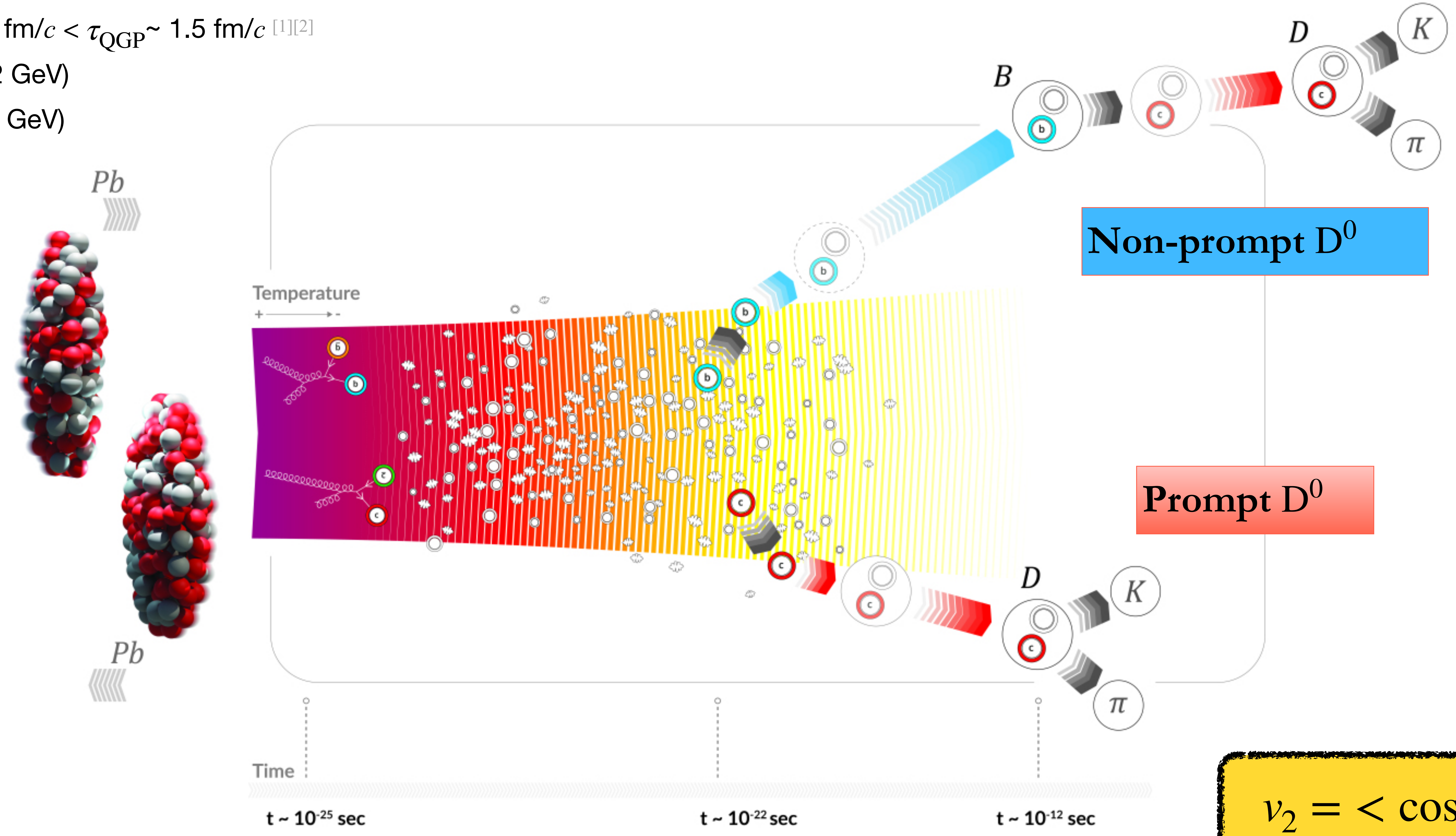

$$v_2 = < \cos[2(\varphi - \psi_2)] >$$

Excellent probes to study the QGP properties:

- Parton energy loss: collisional or radiative, influenced by dead-cone effect
- Collective motion: test degree of thermalization, path-length dependence

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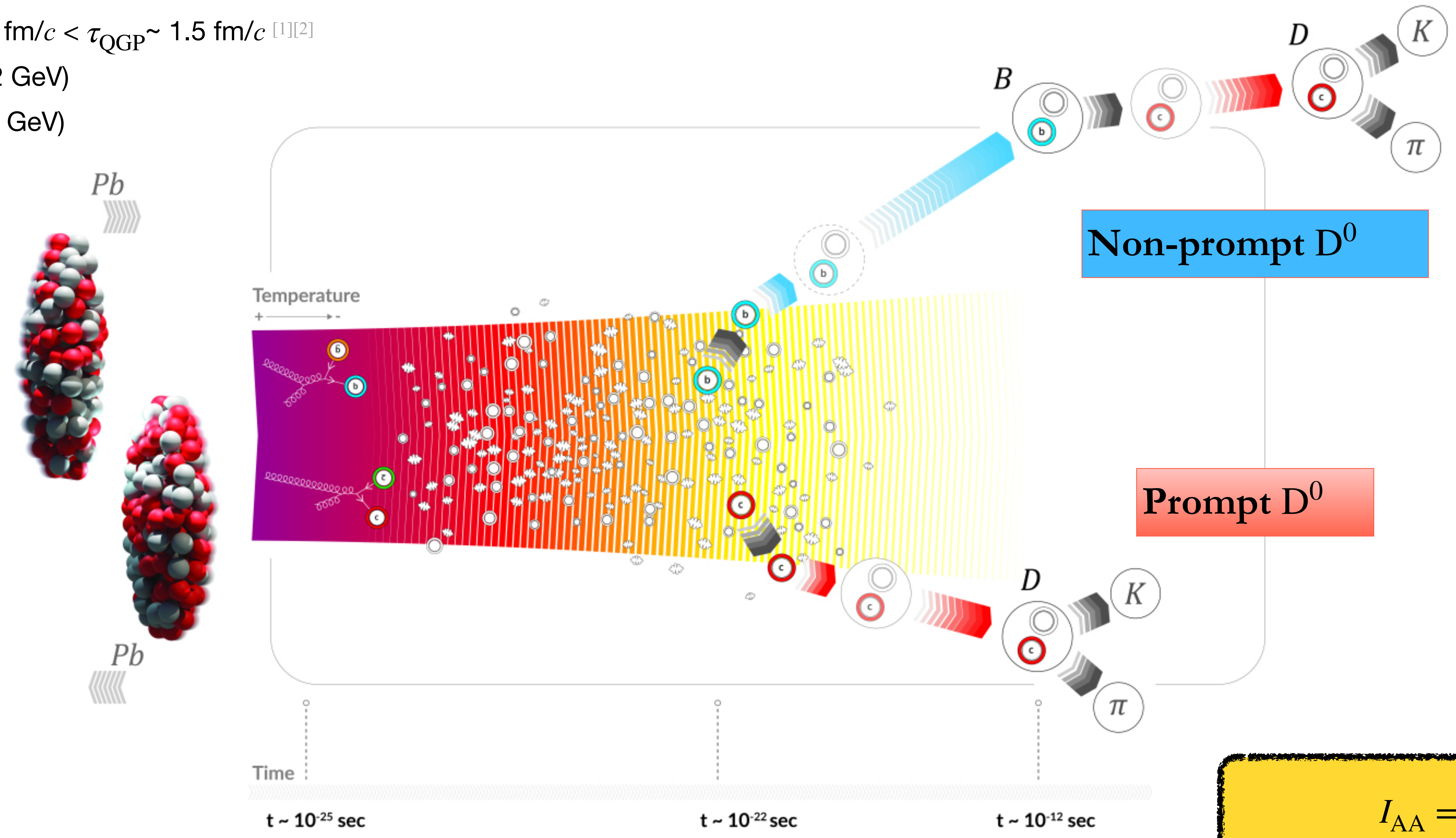

$$I_{AA} = \frac{Y^{Pb-Pb}_{\Delta\varphi}}{Y^{pp}_{\Delta\varphi}}$$

Excellent probes to study the QGP properties:

- Parton energy loss: collisional or radiative, influenced by dead-cone effect
- Collective motion: test degree of thermalization, path-length dependence
- HF correlations and jets: sensitive to medium-induced jet-fragmentation modification and energy loss

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ALICE detector for Run 1 and 2

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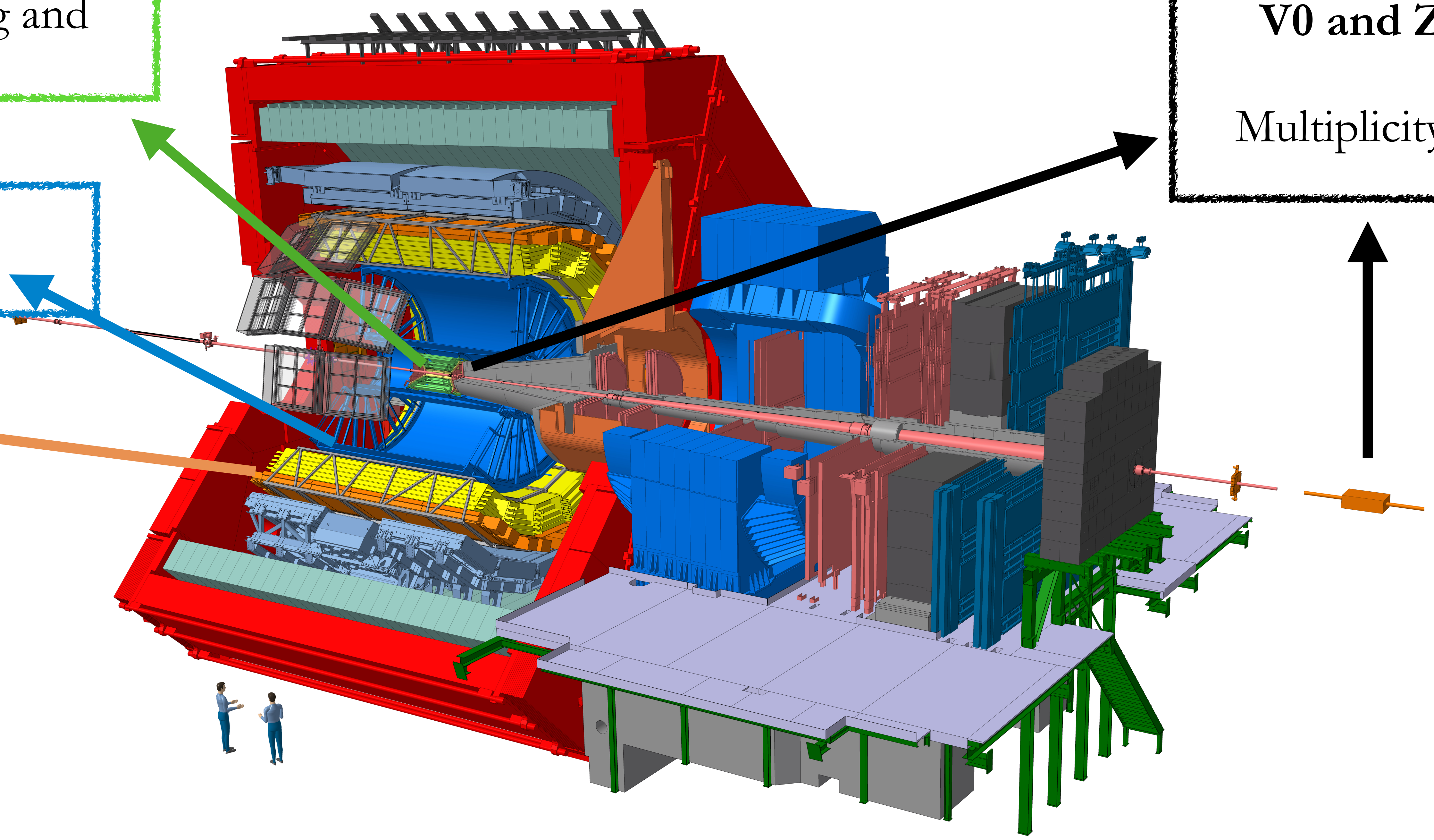
Inner Tracking System : Vertexing and tracking

Time Projection Chamber: Vertexing , Tracking and PID

Time-of-flight detector: PID



V0 and Zero-Degree Calorimeter: Trigger, Multiplicity or Centrality determination

Hadronic decay channel reconstructed:

- $D^0 \rightarrow K^-\pi^+$ (**c**, **b**)
- $D_s^+ \rightarrow K^-K^+\pi^+$ (**c**, **b**)
- $D^+ \rightarrow K^-\pi^+\pi^+$ (**c**, **b**)
- $D^{*+} \rightarrow D^0\pi^+$
- $D_{s1}^+ \rightarrow D^*K_s^0$
- $D_{s2}^{*+} \rightarrow D^+K_s^0$

- $\Lambda_c^+ \rightarrow pK_s^0$ (**c**, **b**)
- $\Lambda_c^+ \rightarrow pK^-\pi^+$ (**c**, **b**)
- $\Xi_c^0 \rightarrow \Xi^-\pi^+$
- $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$
- $\Sigma_c^{0,++} \rightarrow \Lambda_c^+\pi^{-,+}$
- $\Omega_c^0 \rightarrow \Omega^-\pi^+$

Prompt: $c \rightarrow H_c$ $(D^{0,+}, D_s^+, D^{*+}, \Lambda_c^+, \Xi_c^{0,+}, \Omega_c)$

Non-prompt: $b \rightarrow H_b \rightarrow H_c$ $(D^{0,+}, D_s^+, \Lambda_c^+)$

$c \rightarrow e$ / $b (\rightarrow c) \rightarrow e$

- pp collisions: $\sqrt{s}$ = 5.02 TeV ($\mathcal{L}_{int}$ ~ 19 nb^{-1}, MB), $\sqrt{s}$ = 13 TeV ($\mathcal{L}_{int}$ ~ 32 nb^{-1}, MB)
- p–Pb collisions: $\sqrt{s_{NN}}$ = 5.02 TeV ($\mathcal{L}$int ~ 287 ub-1, MB)
- **Pb–Pb collisions: $\sqrt{s_{NN}}$ = 5.02 TeV (0-10% $\mathcal{L}_{int}$ ~130 ub^{-1}, 30-50% $\mathcal{L}_{int}$ ~ 56 ub^{-1})**

ALICE detector for Run 3

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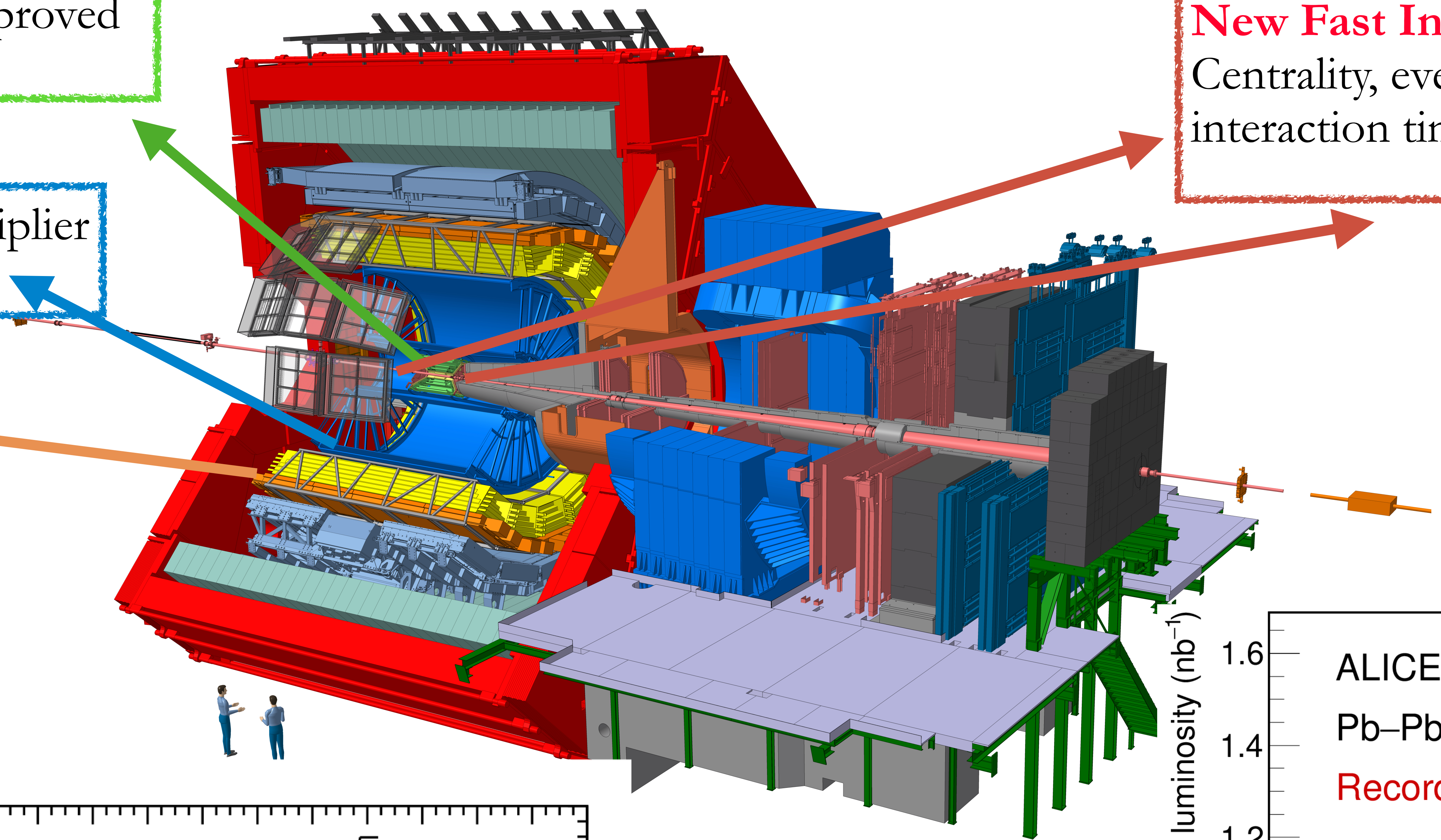
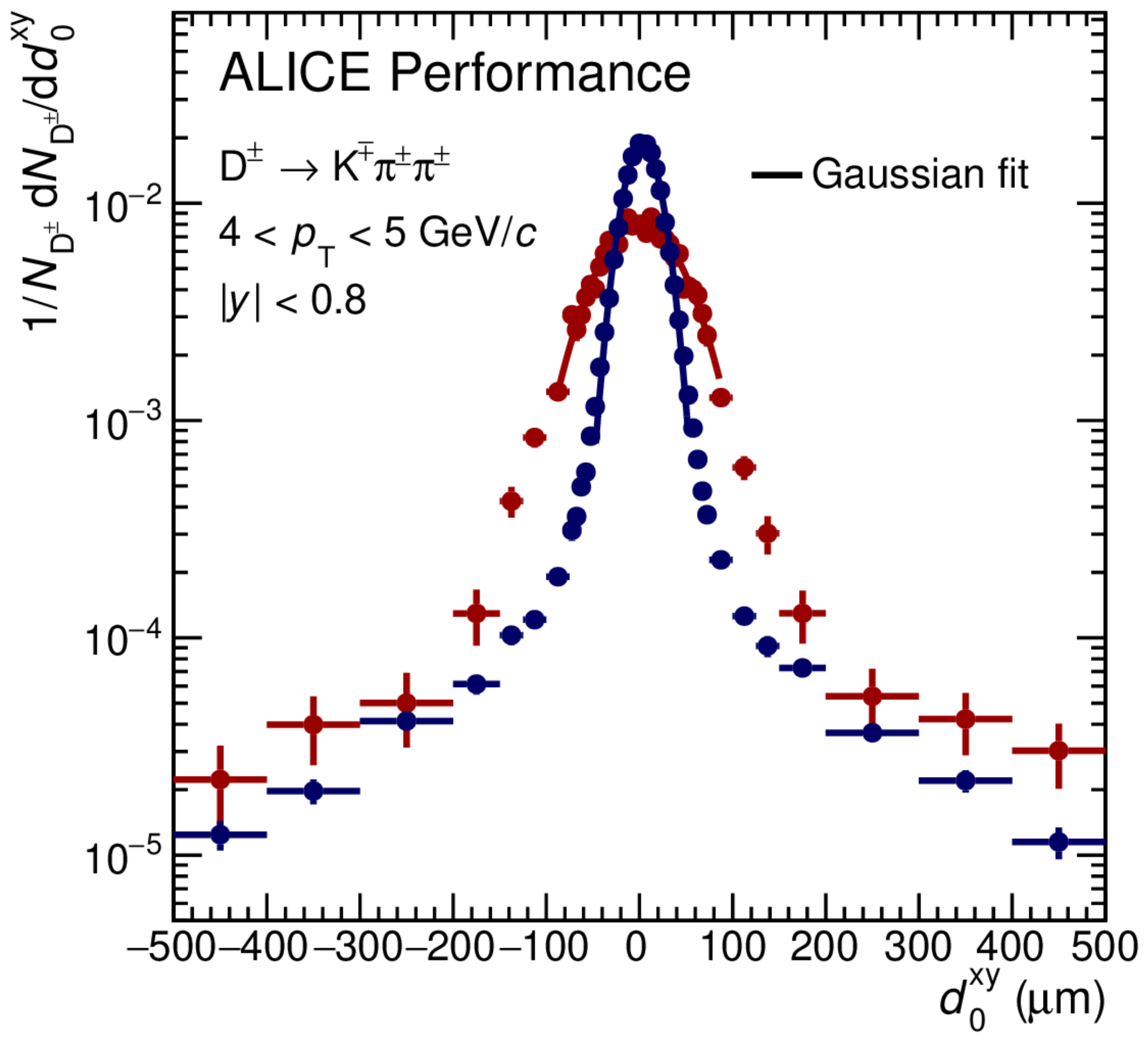
New ITS : CMOS Pixel, MAPS improved resolution and fast readout

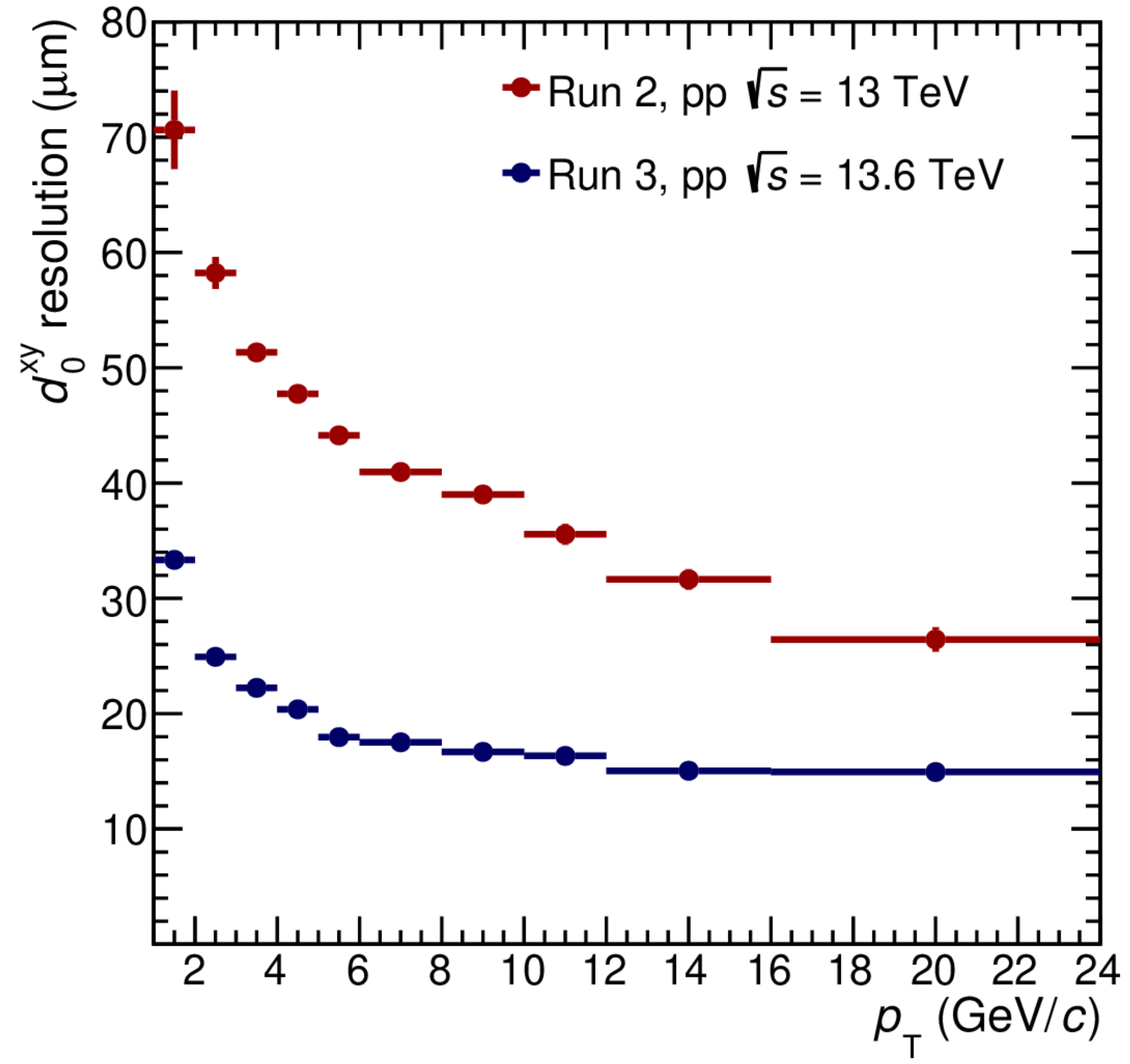
Upgrade TPC: Gas Electron Multiplier
Faster and continuous readout

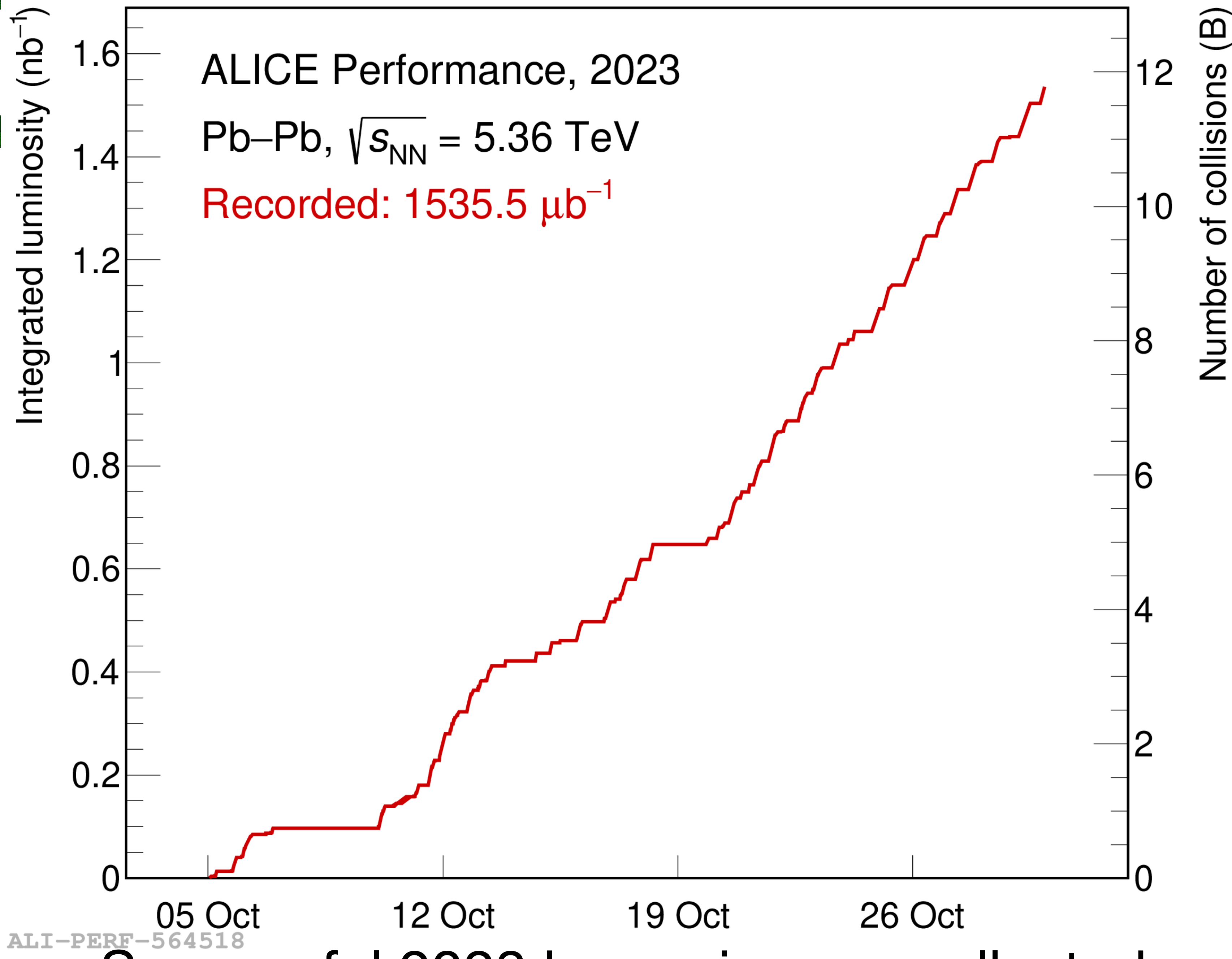
Time-of-flight detector: PID

New Fast Interaction Trigger (FIT): Centrality, event plane, luminosity and interaction time









Successful 2023 heavy-ion run collected 1.6 nb^{-1}, approx. 11.5 G min. bias events

Prompt and Non-prompt D^0 R_{AA} (Run 2)

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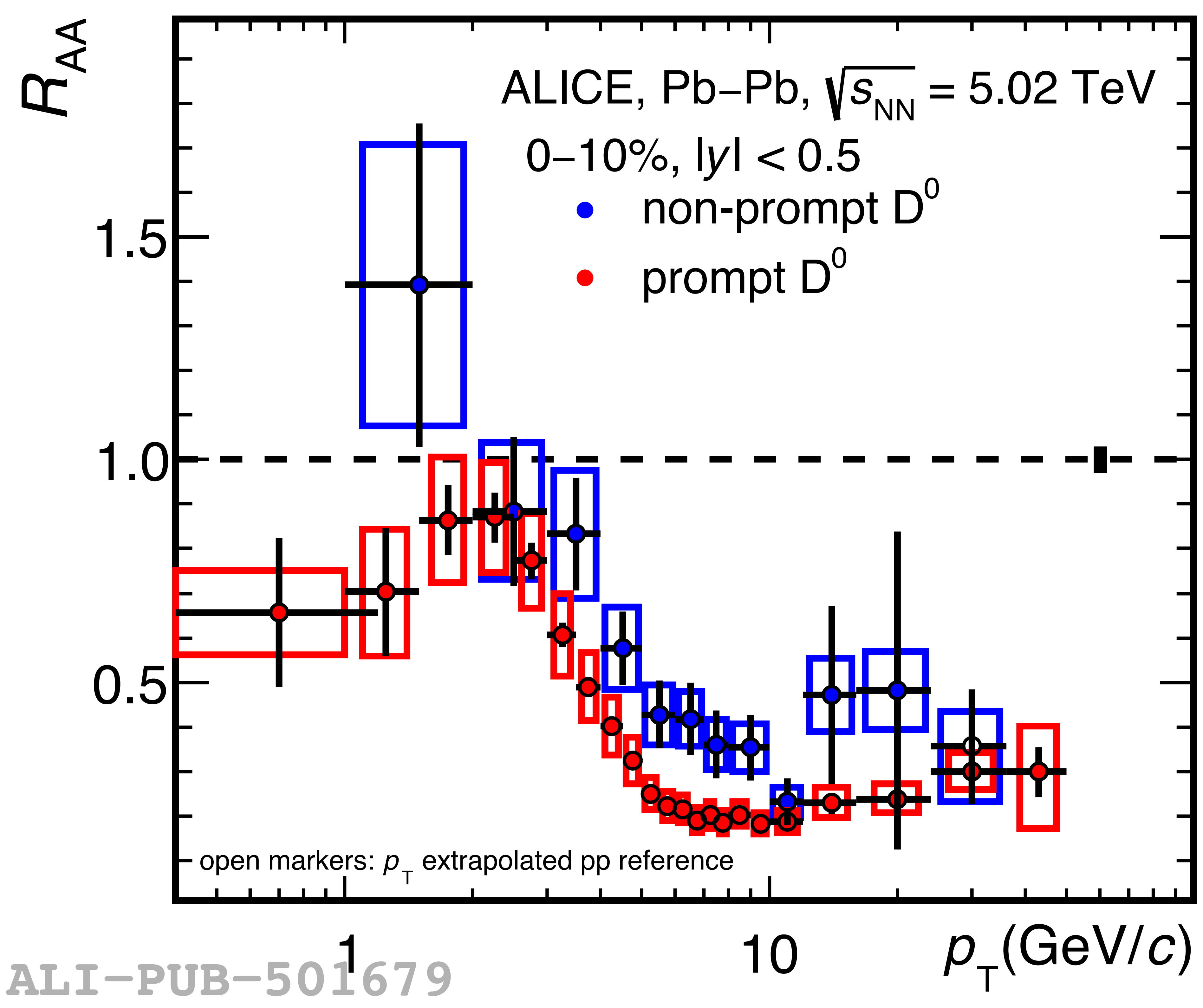
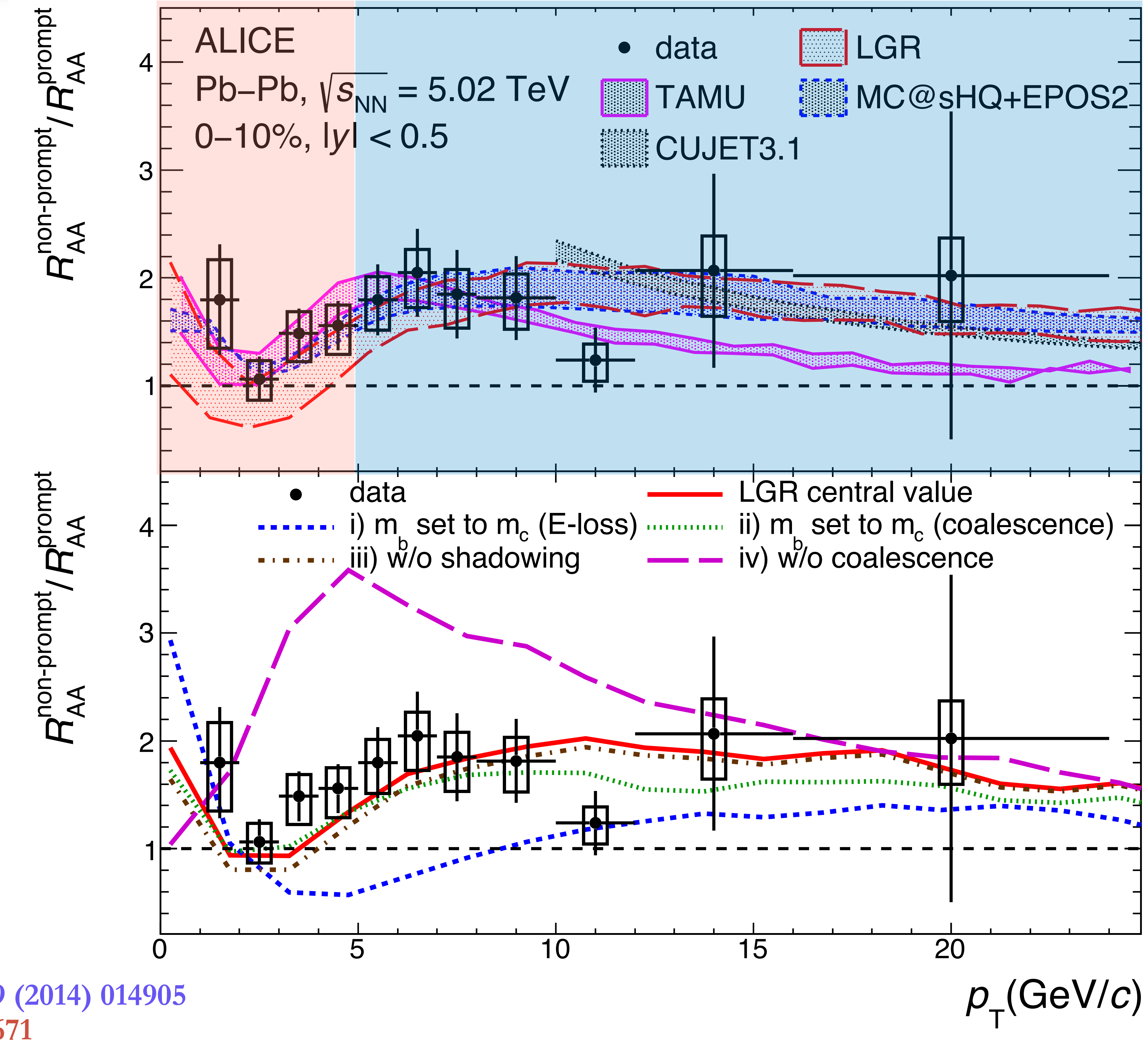
JHEP 12 (2022) 126





TAMU: PLB 735 (2014) 445
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: EPJC 80, no.7, (2020) 671
CUJET3: CPC 43, no.4, (2019) 044101

Beauty quark R_{AA} suppression:

➡ Hint of R_{AA}(charm) < R_{AA}(beauty) at p_T < 10 GeV/c

➡ R_{AA}(beauty) / R_{AA}(charm) ratio comparison with models:

- p_T < 5 GeV/c : sensitive to shadowing / flow / hadronisation / decay kinematics for charm and beauty
- p_T > 5 GeV/c : 3.9 σ above unity → beauty quarks show less energy loss than charm quarks

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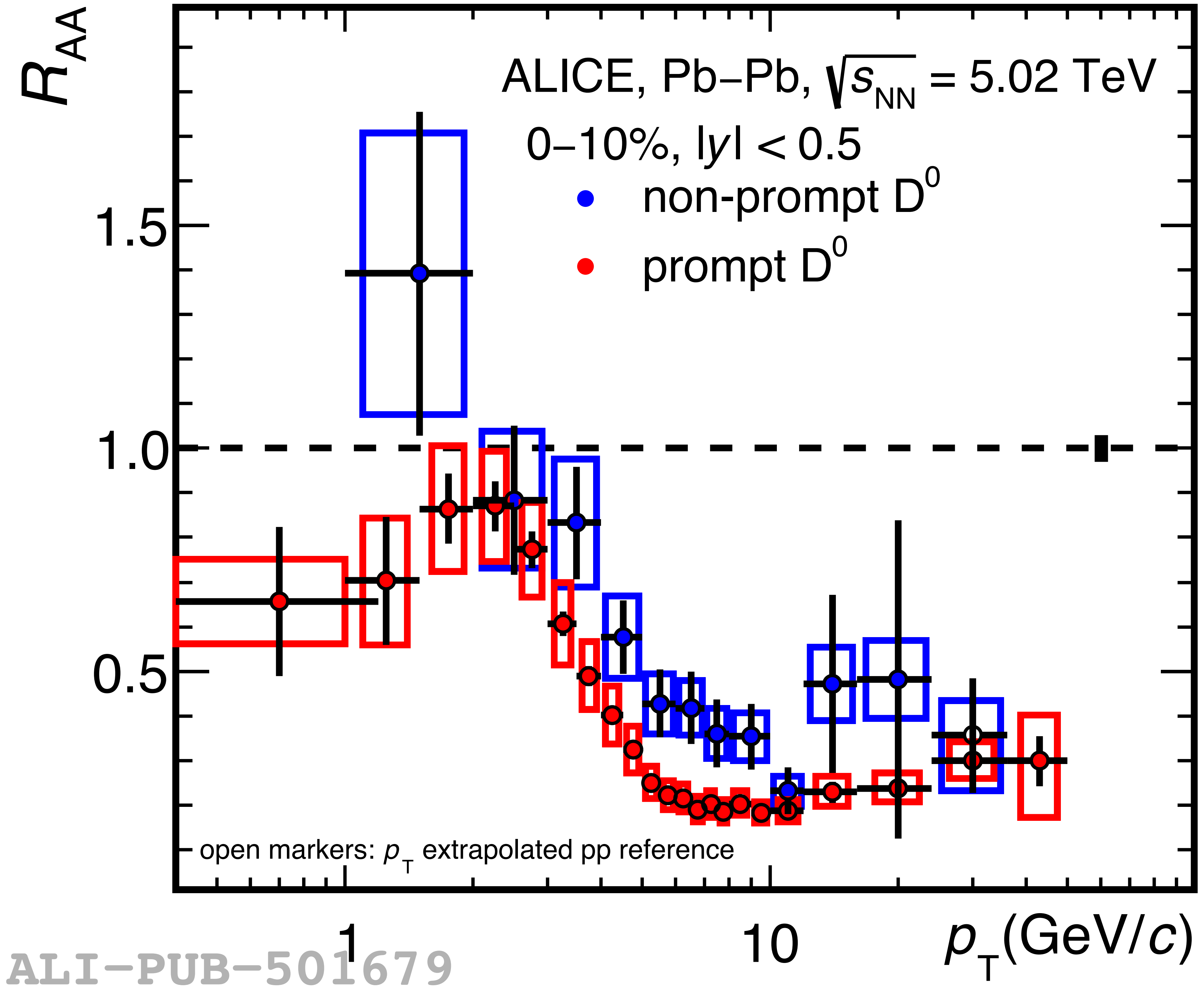

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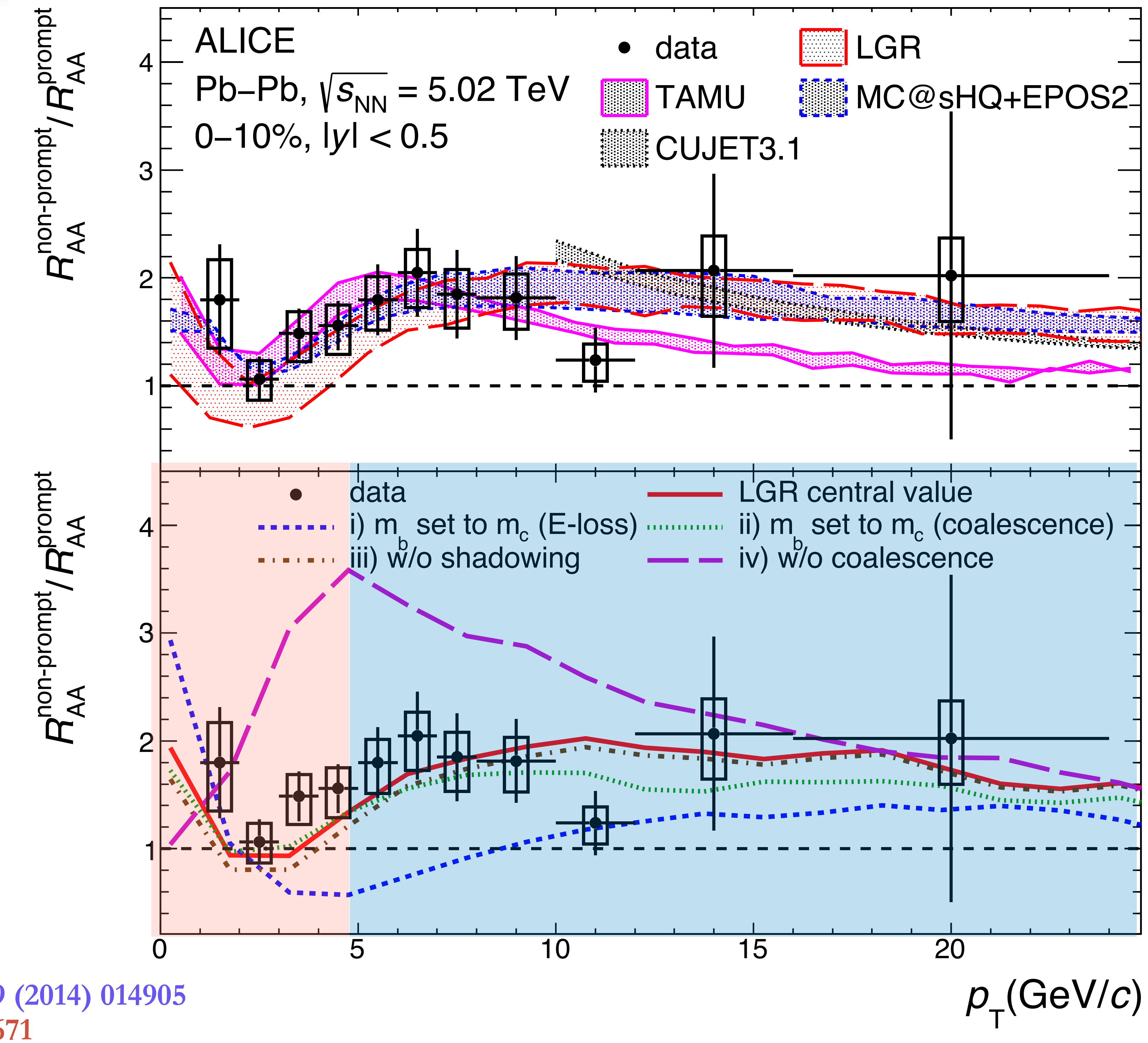

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CUJET3: CPC 43, no.4, (2019) 044101

ALI-PUB-501659

Beauty quark R_{AA} suppression:

➡ Hint of R_{AA}(charm) < R_{AA}(beauty) at p_T < 10 GeV/c

➡ Testing effect of LGR ingredients:

- p_T < 5 GeV/c : The "valley" structure —> the formation of prompt D-mesons via charm-quark coalescence (iv)
- p_T > 5 GeV/c : The significant enhancement of double ratio at high p_T is related to the mass dependent quark in-medium energy loss effect(i)

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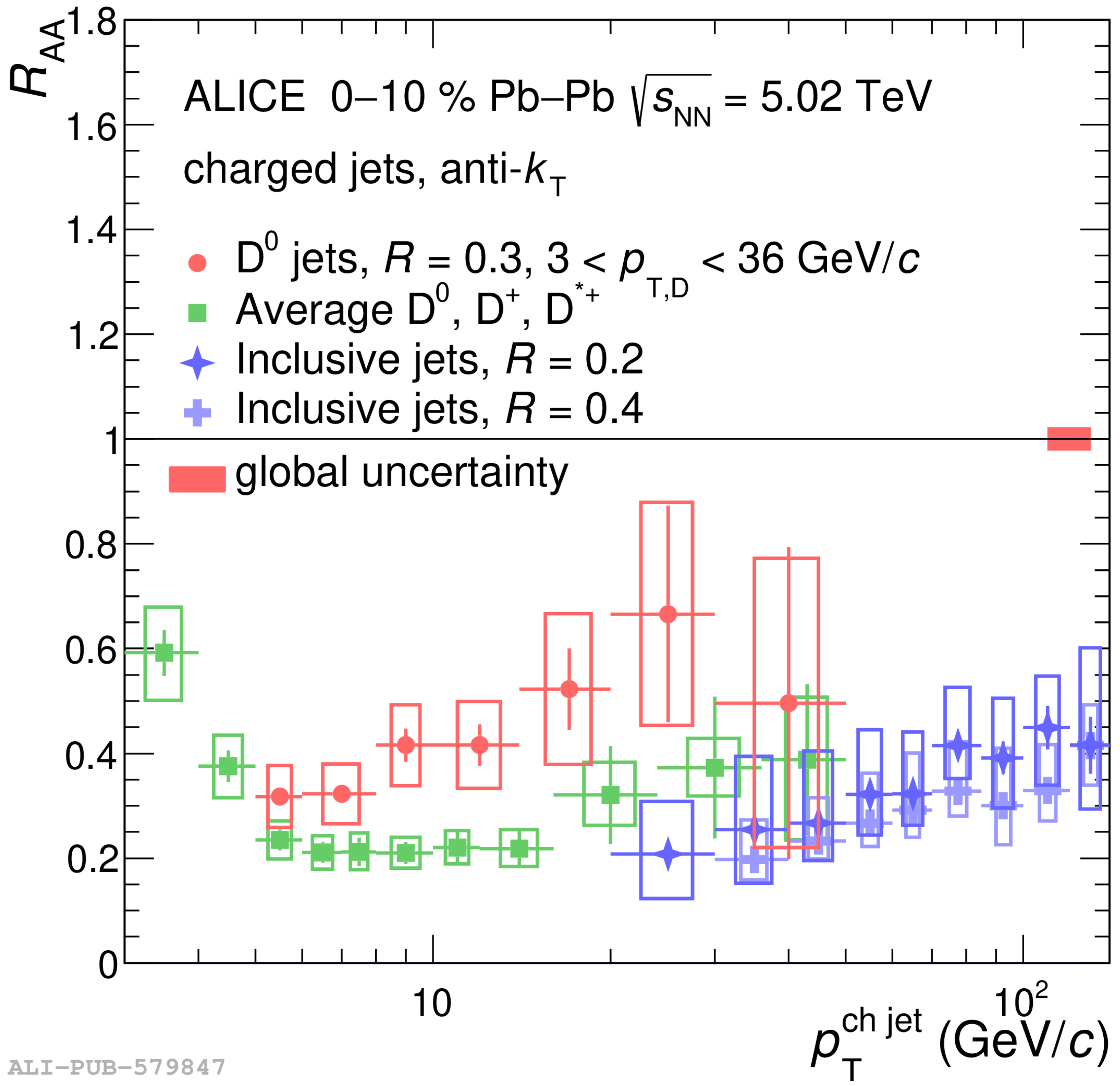
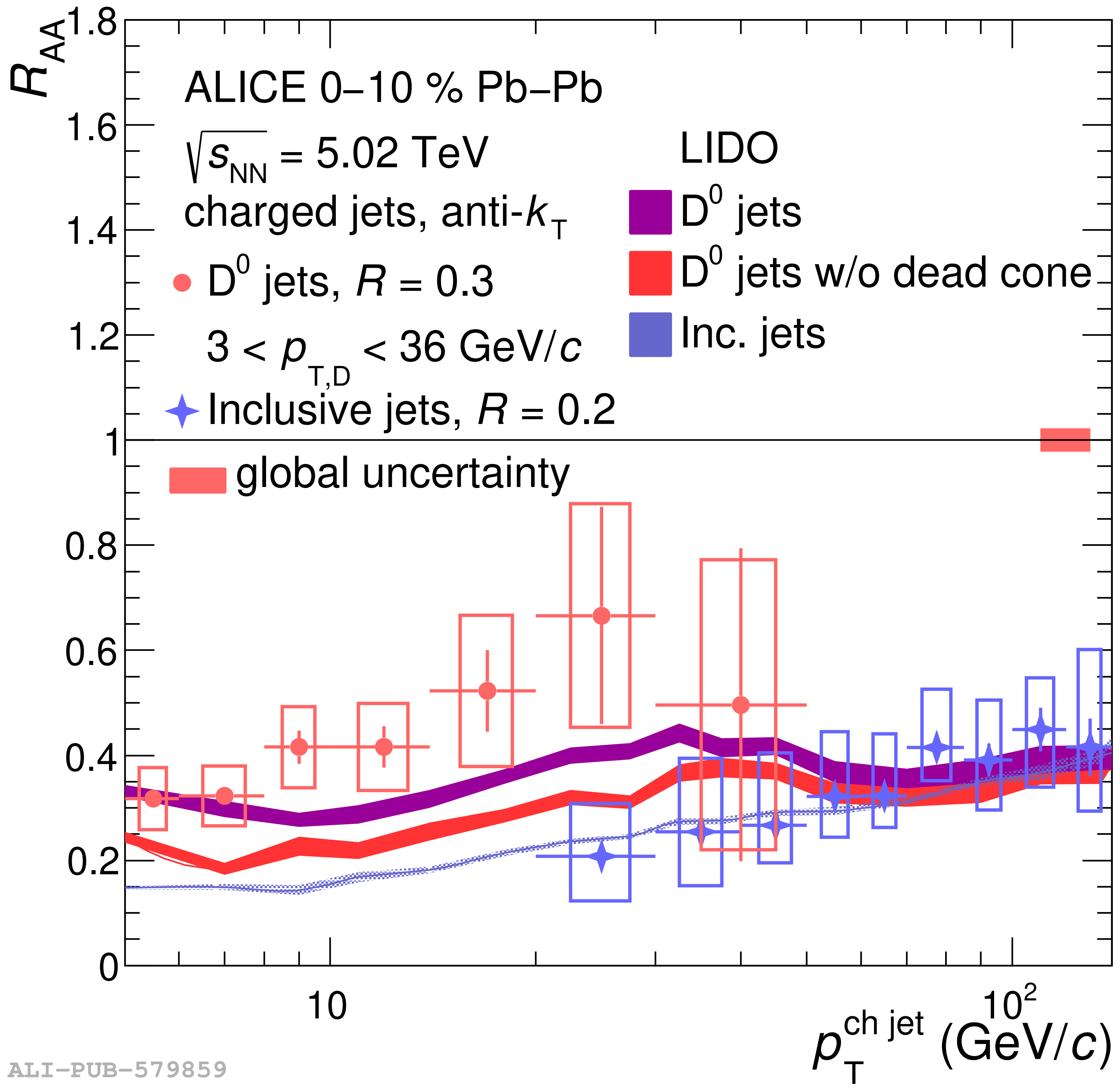
arXiv:2409.11939

NEW Paper



NEW Paper



Gain further direct access to the initial parton kinematics through D^0-mesons tagged jets

➡ R_{AA}(D^0-jet) > R_{AA}(Inclusive jet)? Comparison is sensitive to Casimir colour factor and dead-cone effect

- Described by heavy quark transport model (**LIDO**) including collisions and radiation processes as well as the dead-cone effect

  ➡ Mass-hierarchy energy loss is more relevant at lower p_T ($p_T < 50$ GeV/c) compared to high p_T

LIDO: Phys. Rev. C **100**, 064911, Phys. Rev. C **98**, 064901

D^0-jet R_{AA} (Run 2)

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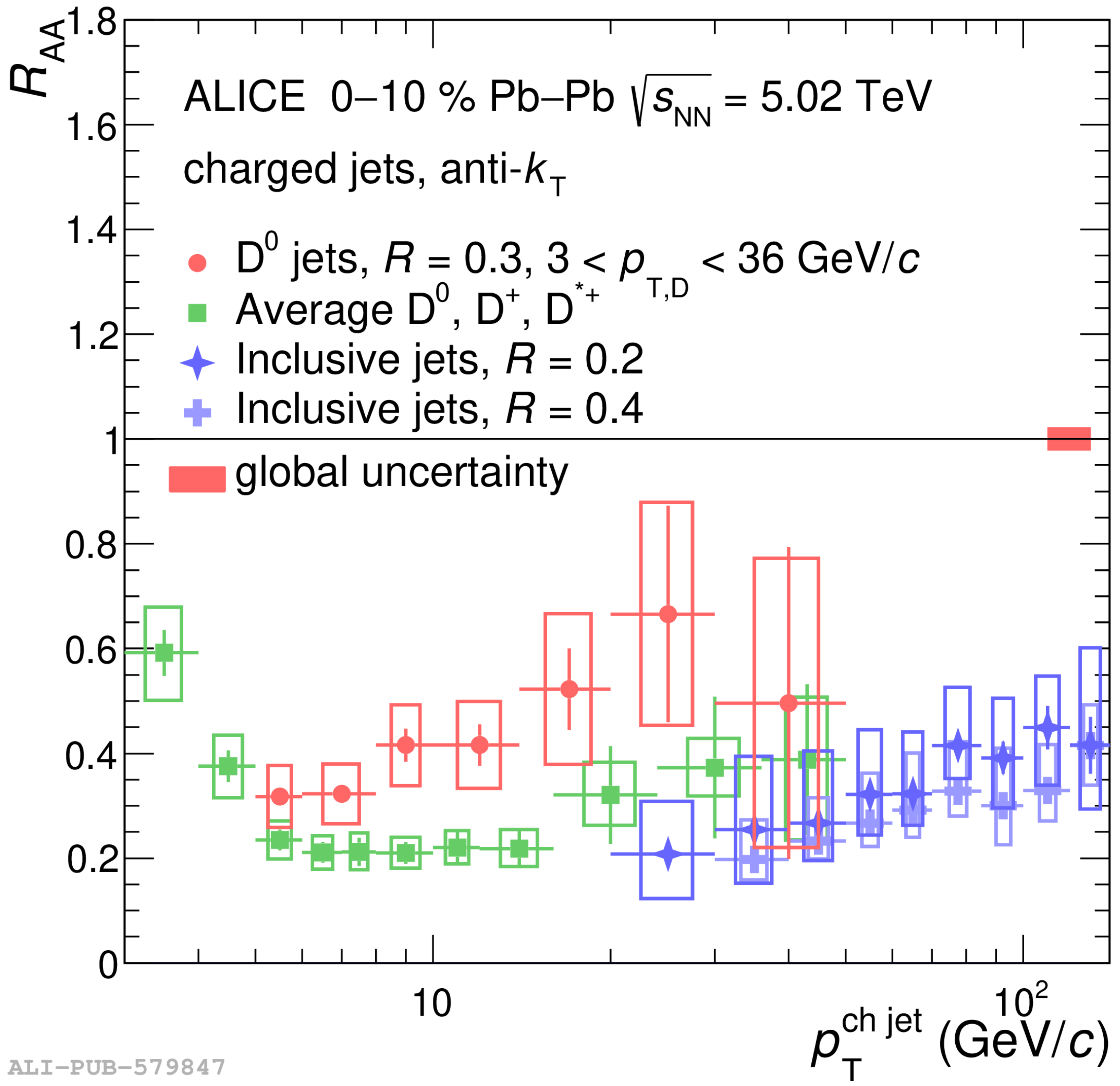
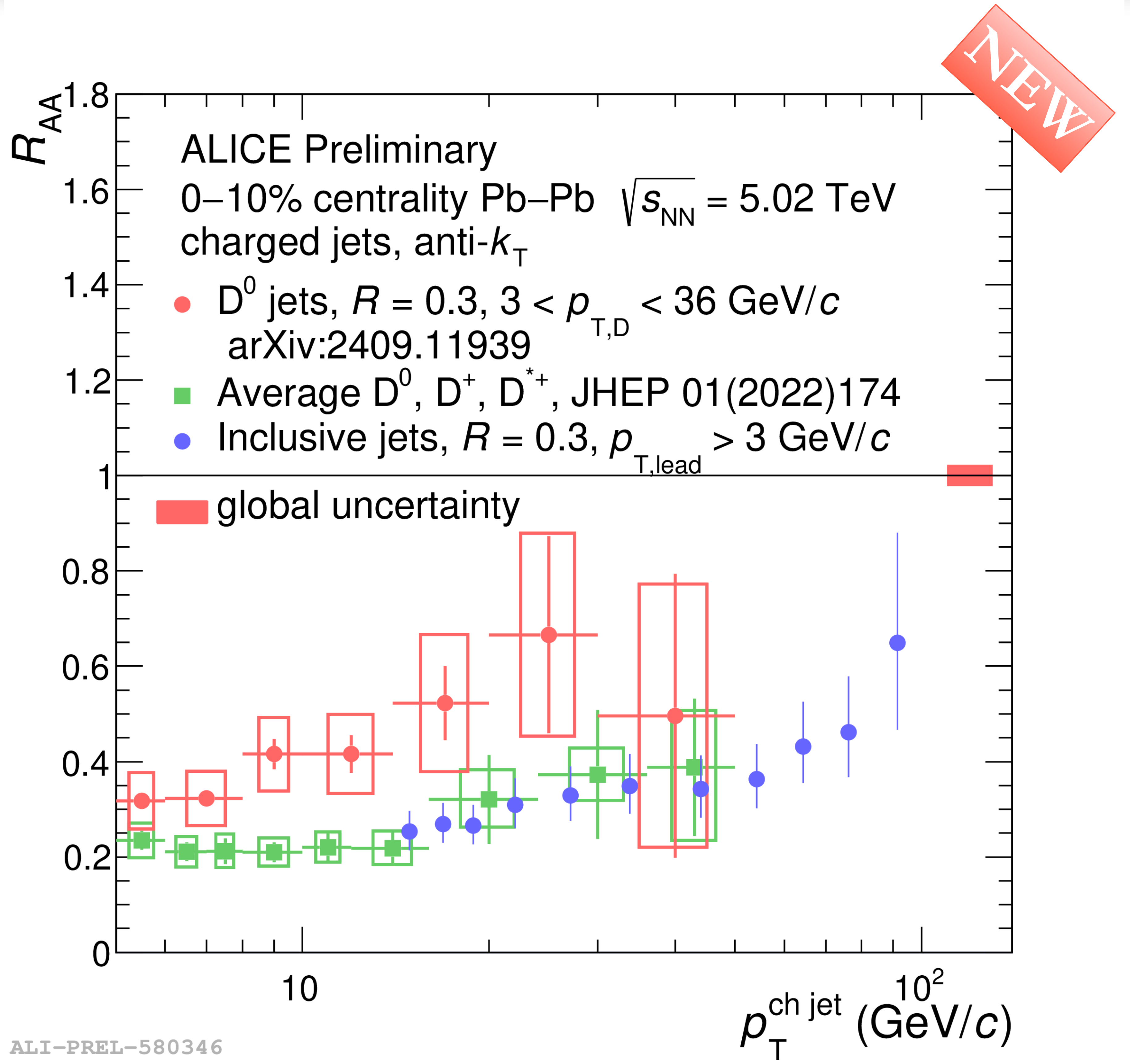
NEW Paper

arXiv:2409.11939





Gain further direct access to the initial parton kinematics through D^0-mesons tagged jets

➡R_{AA}(D^0-jet) > R_{AA}(Inclusive jet)? Comparison is sensitive to Casimir colour factor and dead-cone effect

•Confirmed by the new preliminary result of inclusive jet based on the mixed-event approach (more precise and lower p_T)

Prompt and Non-prompt D^0 v_2 (Run 2)

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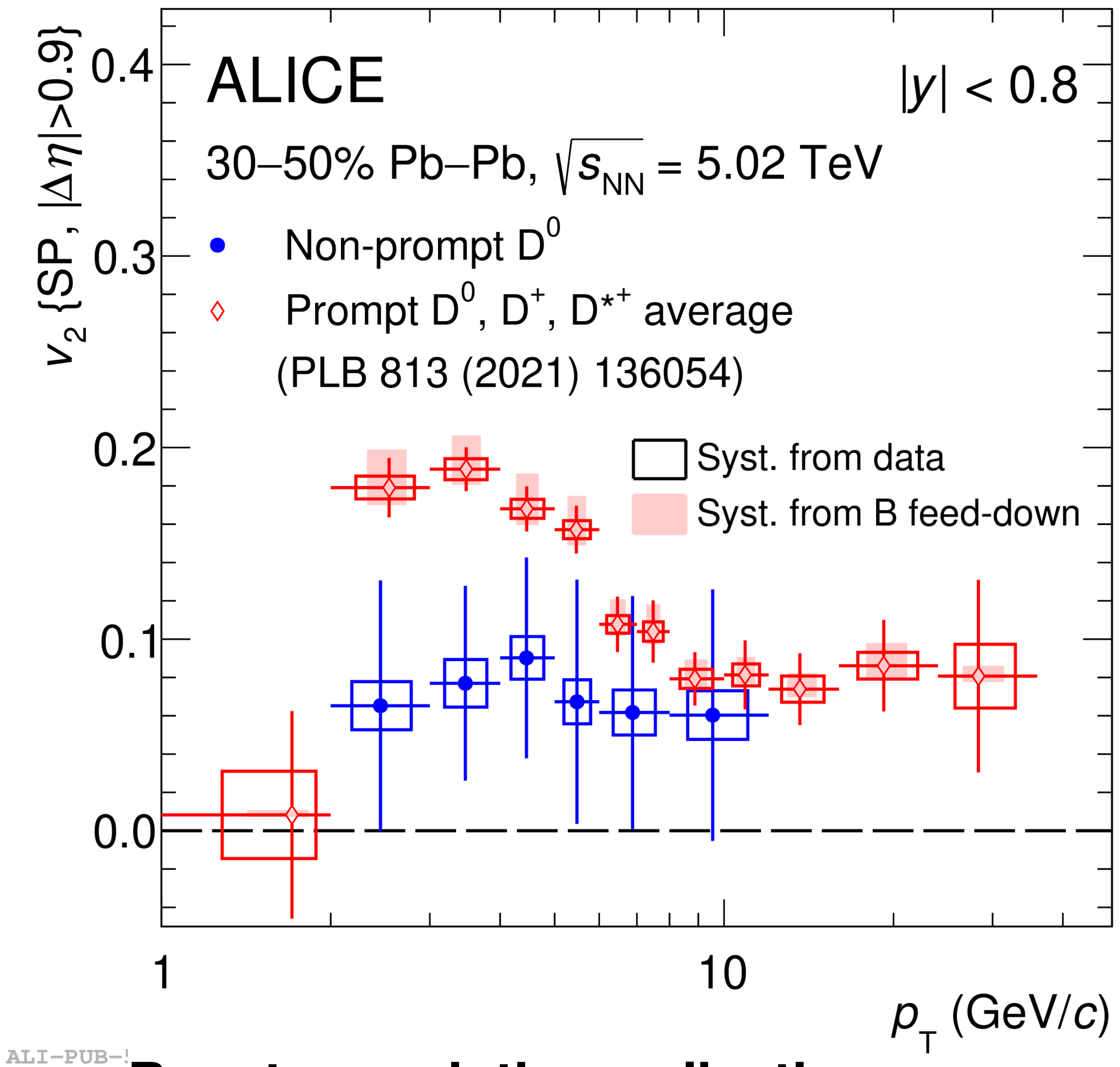
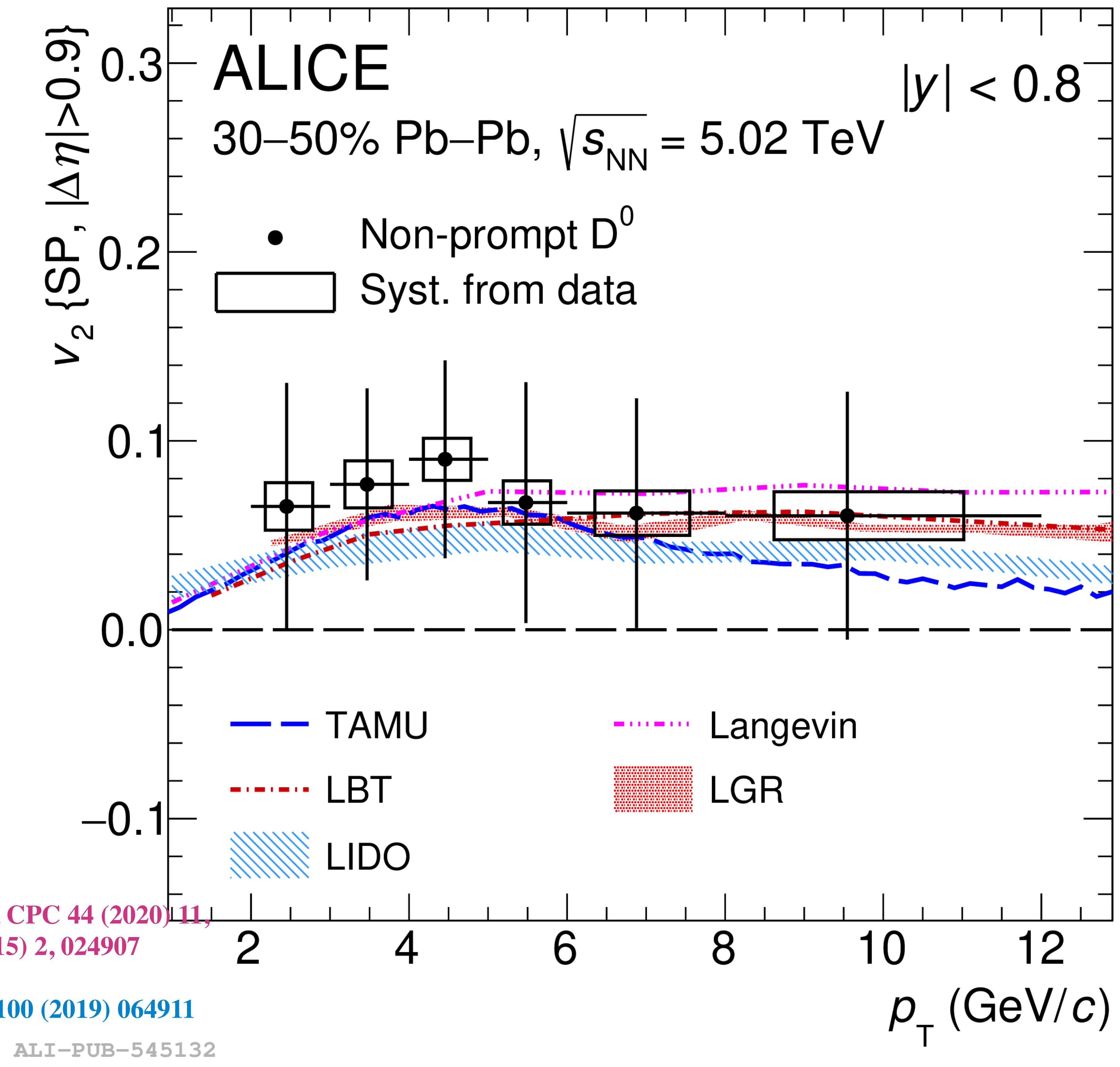
Eur. Phys. J. C 83 (2023) 1123





Langevin: *EPJC* 81 (2021) 11, 1035, CPC 44 (2020) 11,
PRC 88 (2013) 044907, PRC 92 (2015) 2, 024907
TAMU: PLB 813 (2021) 136054
LIDO: PRC98 (2018) 064901, PRC100 (2019) 064911
LGR: EPJC 80 (2020) 12, 1113

Beauty quark thermalisation:

➡ v_2 (charm) > v_2 (beauty) at low p_T

➡ Non-zero non-prompt D^0 v_2 with 2.7 σ significance

- Beauty quarks flow or beauty-hadron flow from recombination of beauty with flowing light quarks?
- Described by beauty transport models include **collisional** energy loss and hadronisation through **coalescence**

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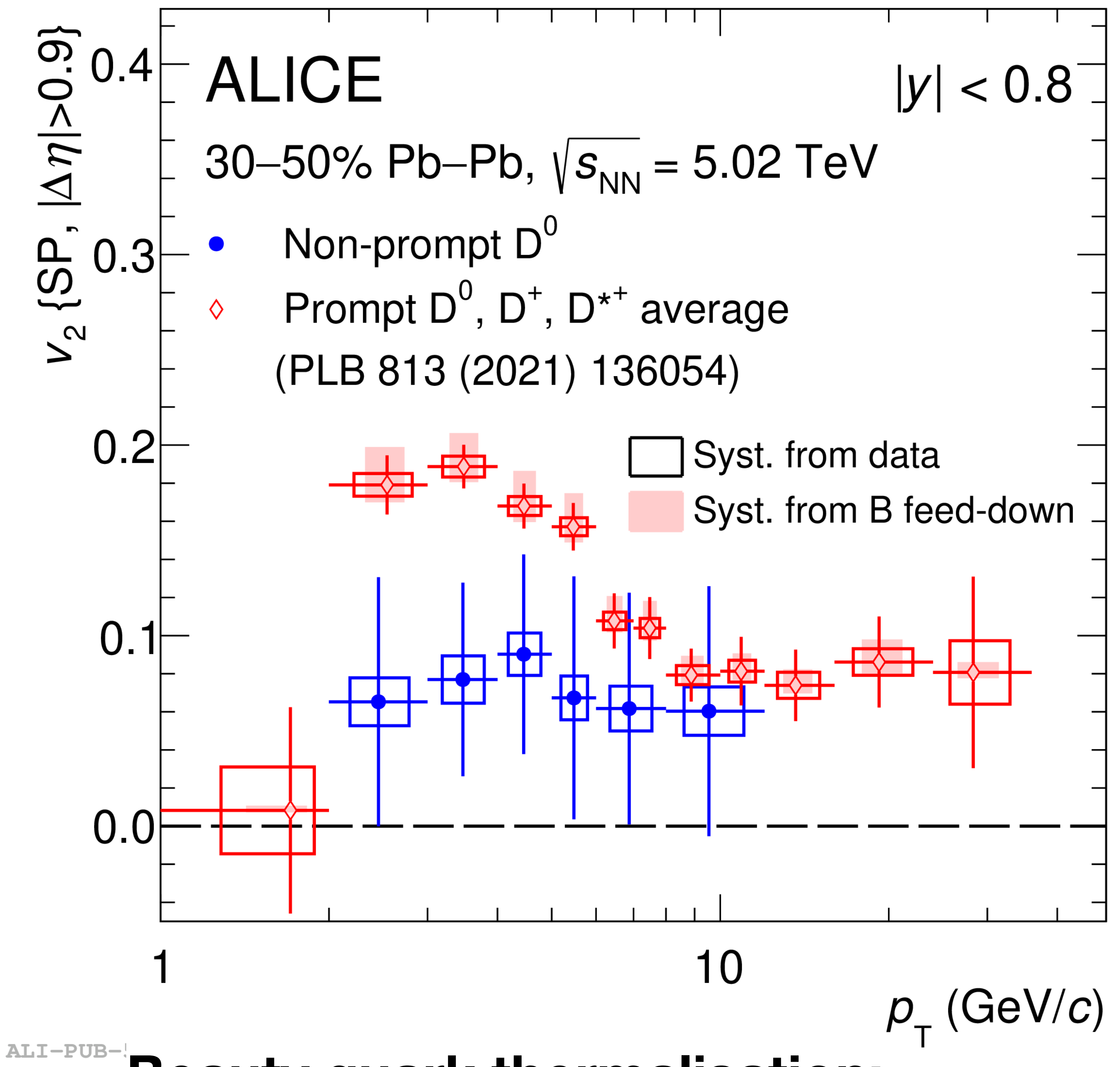
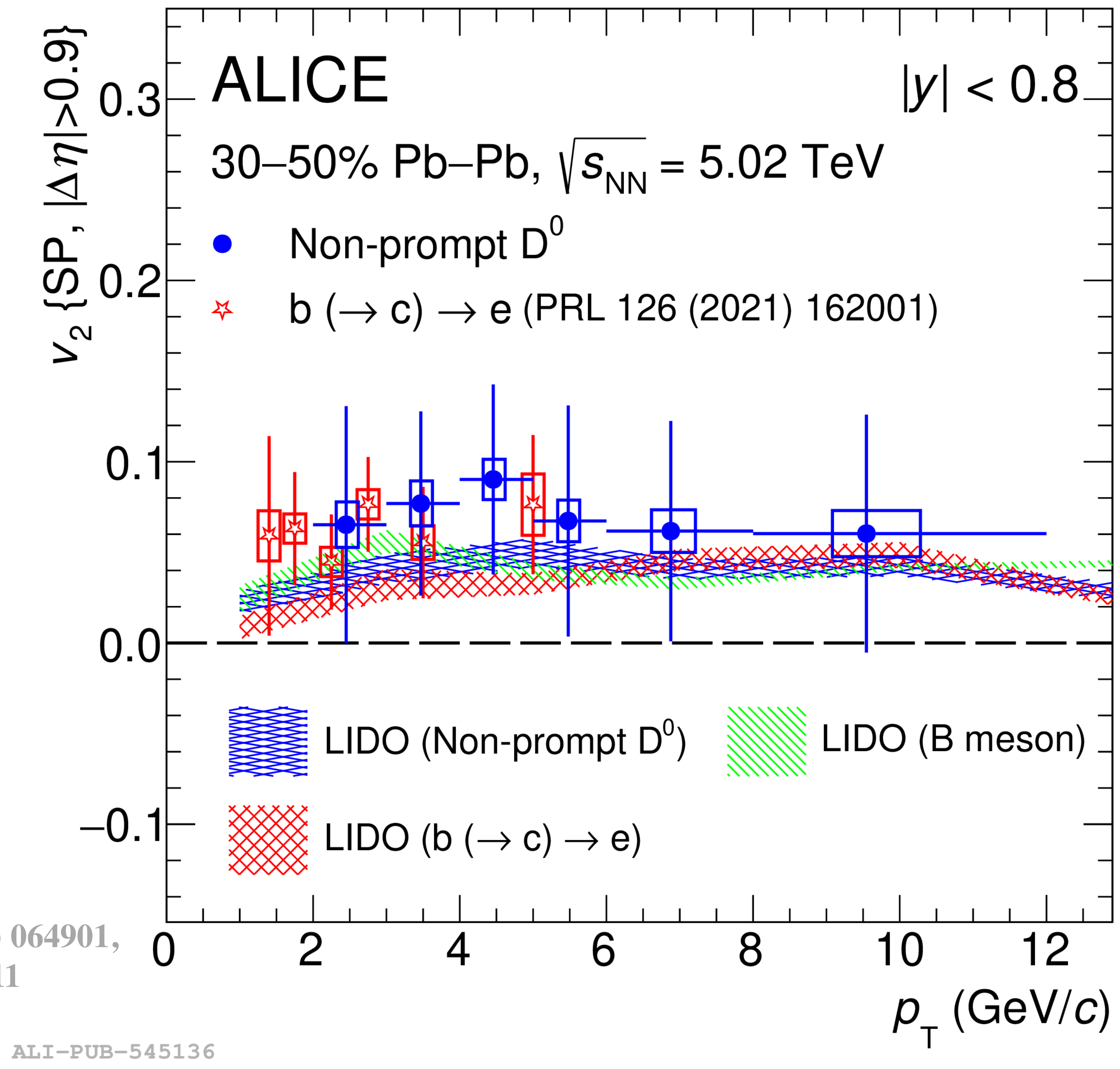
Eur. Phys. J. C 83 (2023) 1123





LIDO: PRC 98 (2018) 064901, PRC 100 (2019) 064911

Beauty quark thermalisation:

➡ v_2 (charm) > v_2 (beauty) at low p_T

➡ Non-zero non-prompt D^0 v_2 with 2.7 σ significance and compatible with b (→c) → e v_2 within uncertainties

- No differences for the LIDO model for v_2 of different beauty probes
- Decay kinematics does not play a significant role?

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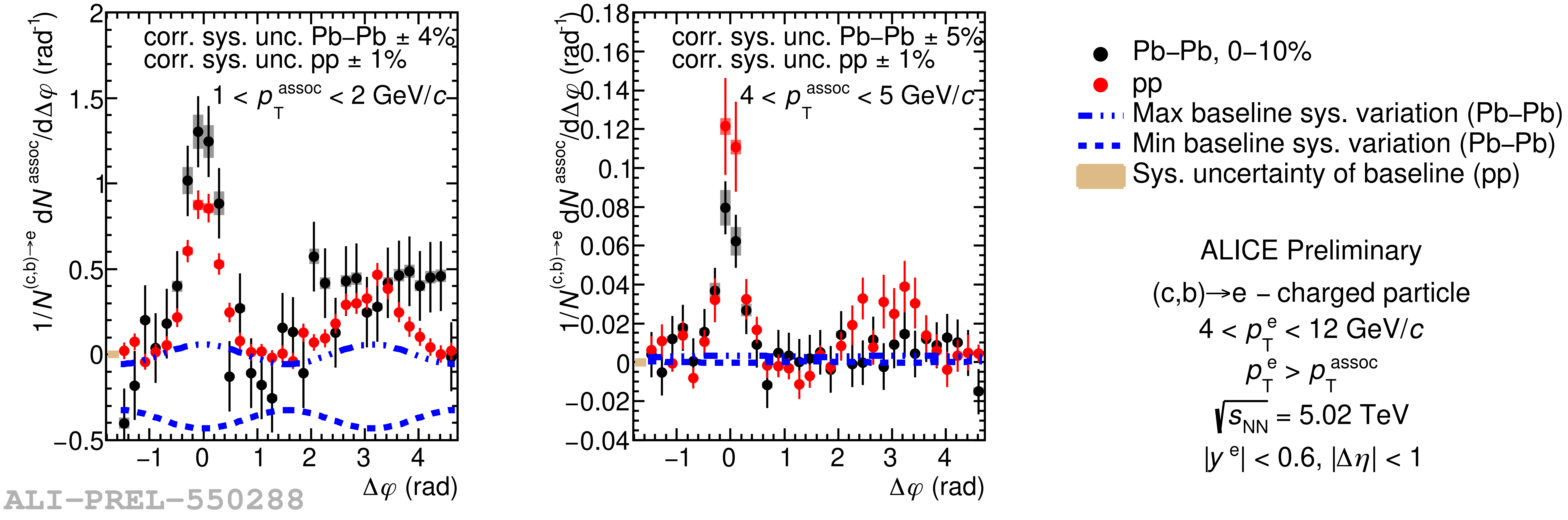


Azimuthal correlation distributions of heavy-flavor decay electrons (HFe) with charged particles:

$$\Delta\varphi(\mathrm{HFe-h}) = \varphi^{\mathrm{HF}}_{\mathrm{Trigger}} - \varphi^{\mathrm{h}}_{\mathrm{Assoc}}$$

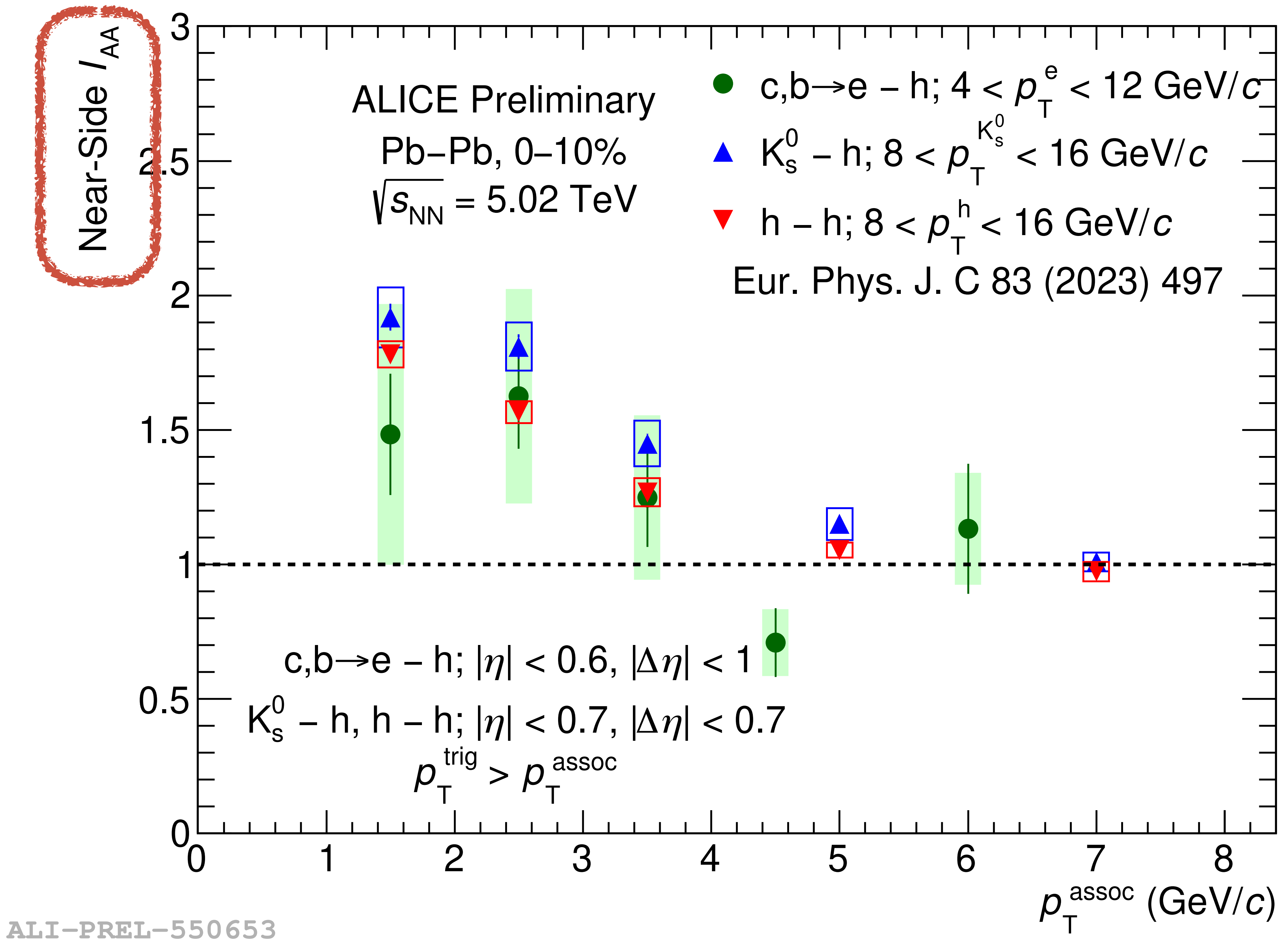
- Associated yield from near-side and away-side peaks in both pp and Pb–Pb collisions

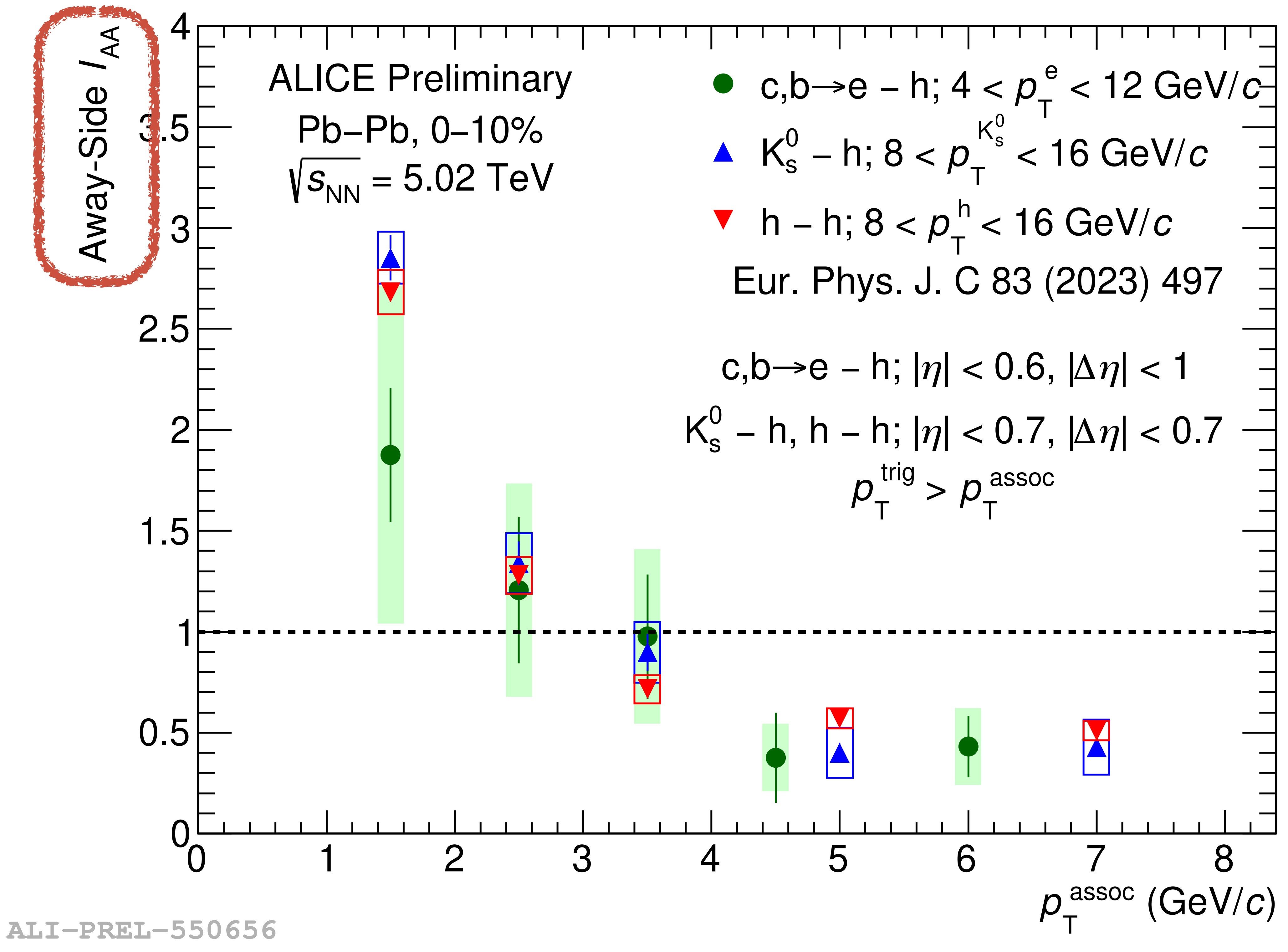
➡ Interplay between the parton production spectrum and the energy loss in the medium by:

$$I_{AA} = \frac{Y^{\mathrm{Pb-Pb}}_{\Delta\varphi}}{Y^{\mathrm{pp}}_{\Delta\varphi}}$$

HF decay electron I_{AA} compared to light-flavor I_{AA} (Run 2)

LF: Eur. Phys. J. C 83 (2023) 497





HFe-hadron azimuthal correlations compared to di-hadron correlations: HFe I_{AA} in agreement with light flavor I_{AA} within uncertainties

Near-side I_{AA}: High p_T^{assoc}**:** consistent with unity. Low p_T^{assoc}**:** Hint of enhancement → potential medium excitation? modified HQ fragmentation?

Away-side I_{AA}: Jet quenching dominant at high-p_T^{assoc} (p_T^{assoc}> 4 GeV/c)

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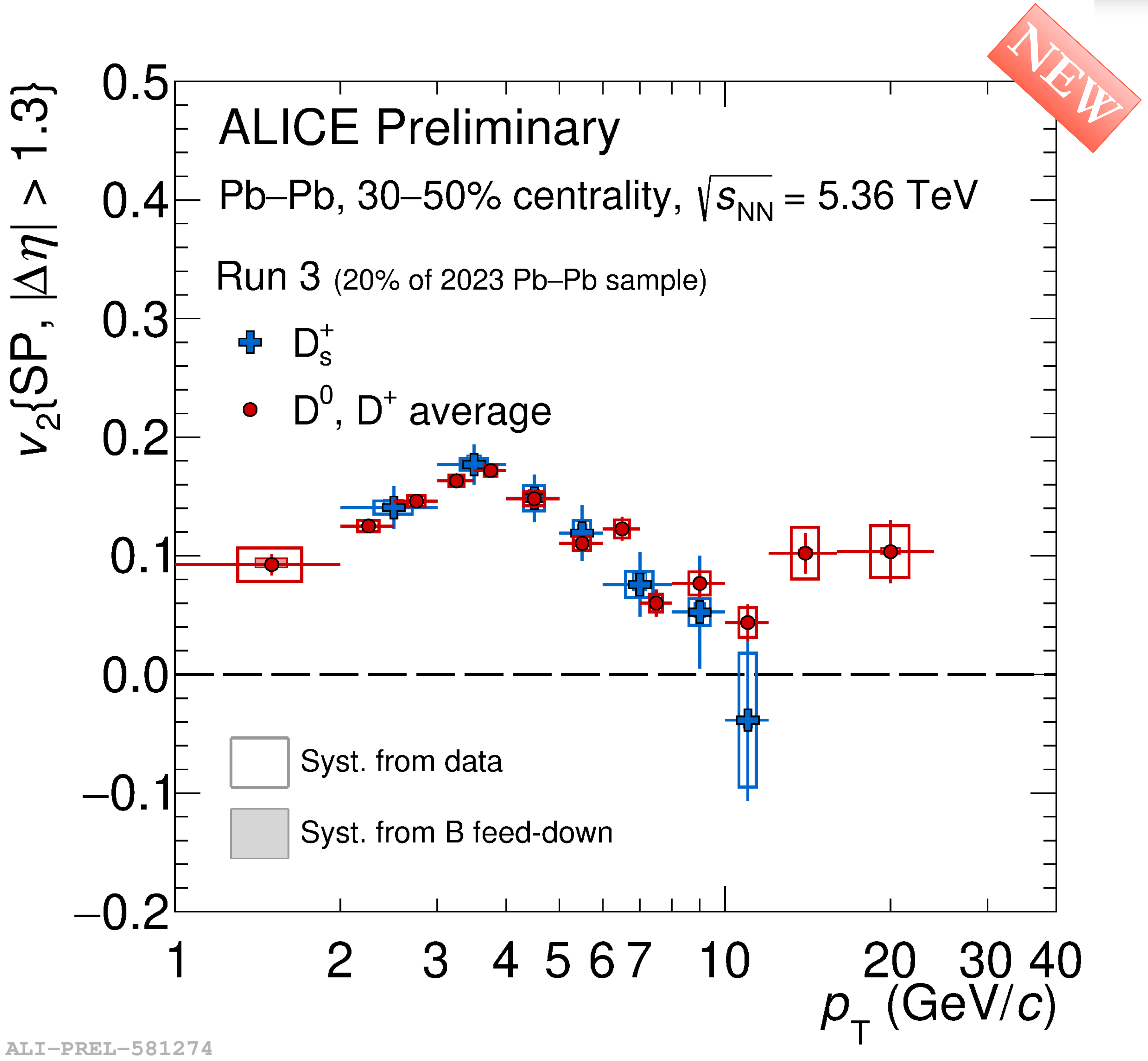

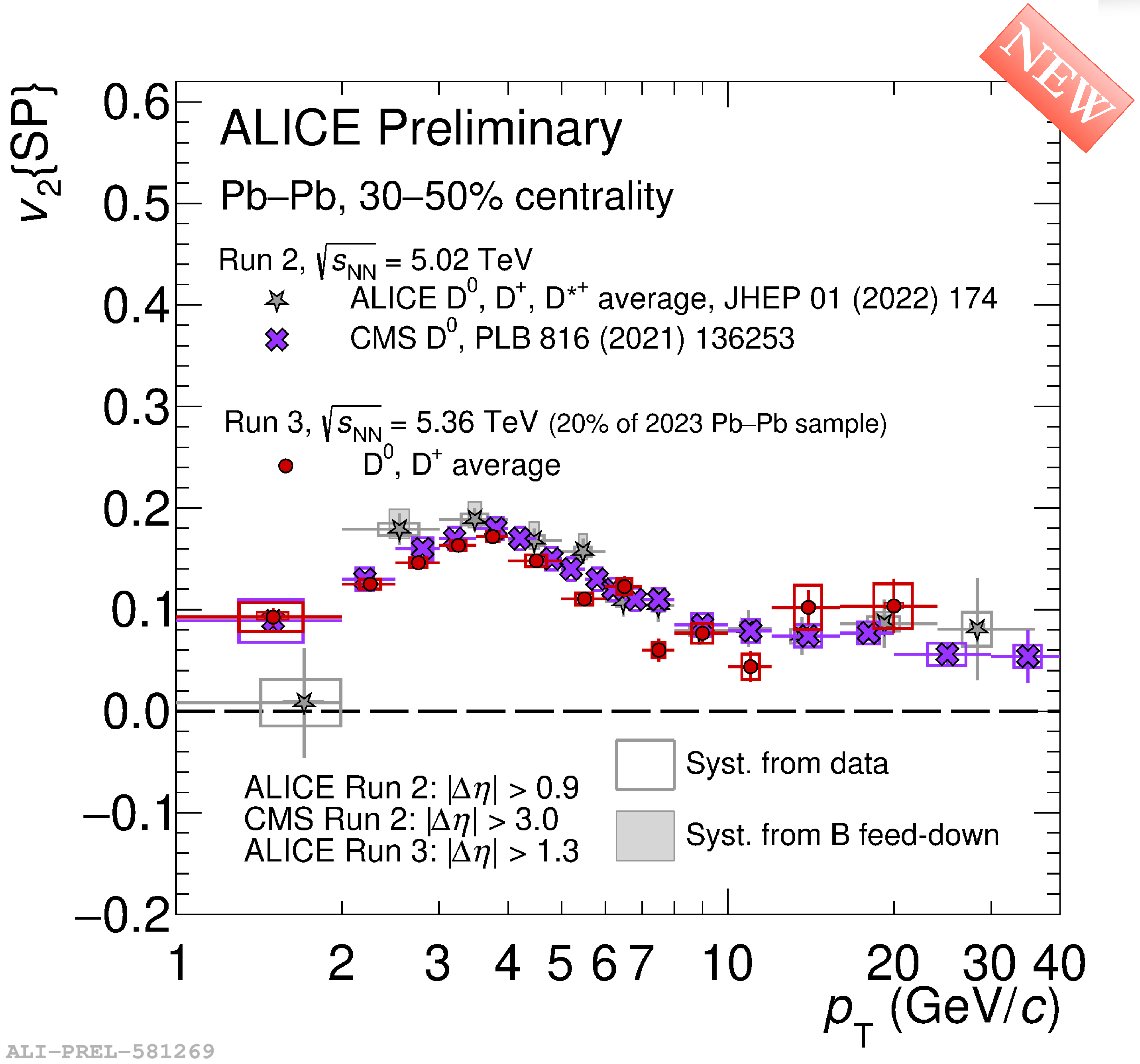

First measurement of prompt $D^{0,+}$ and D_s^+ meson v_2 in ALICE Run 3 (x 4 larger data sample w.r.t Run 2) :

- Compatible $D^{0,+}$ v_2 (non-strange) with D_s^+ v_2 (strange)
- Compatible $D^{0,+}$ v_2 (ALICE) with D^0 v_2 (CMS)
- Run 3 results are more precise of the $D^{0,+,*+}$ average from Run 2 and x 2 more granular at intermediate p_T

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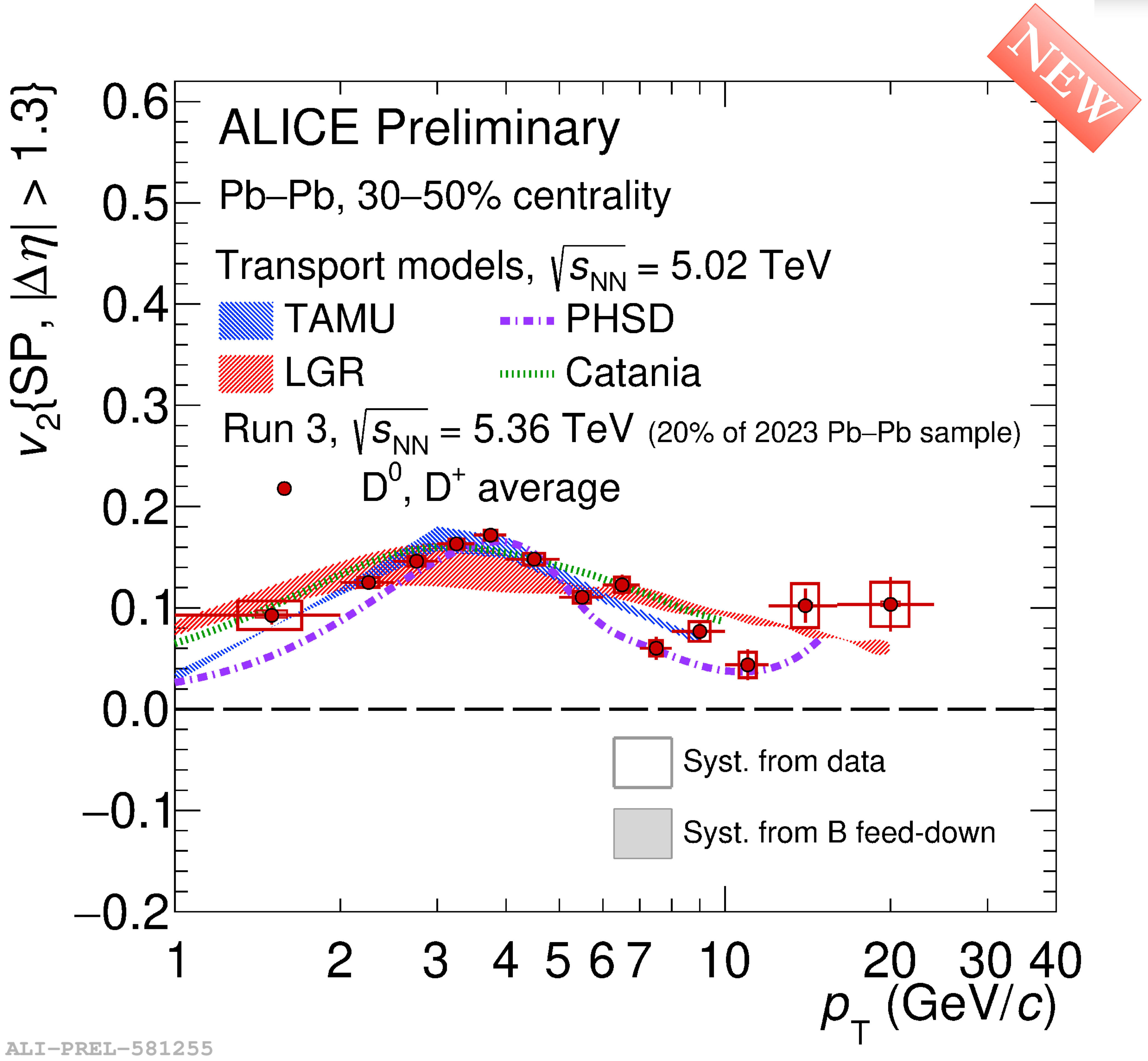

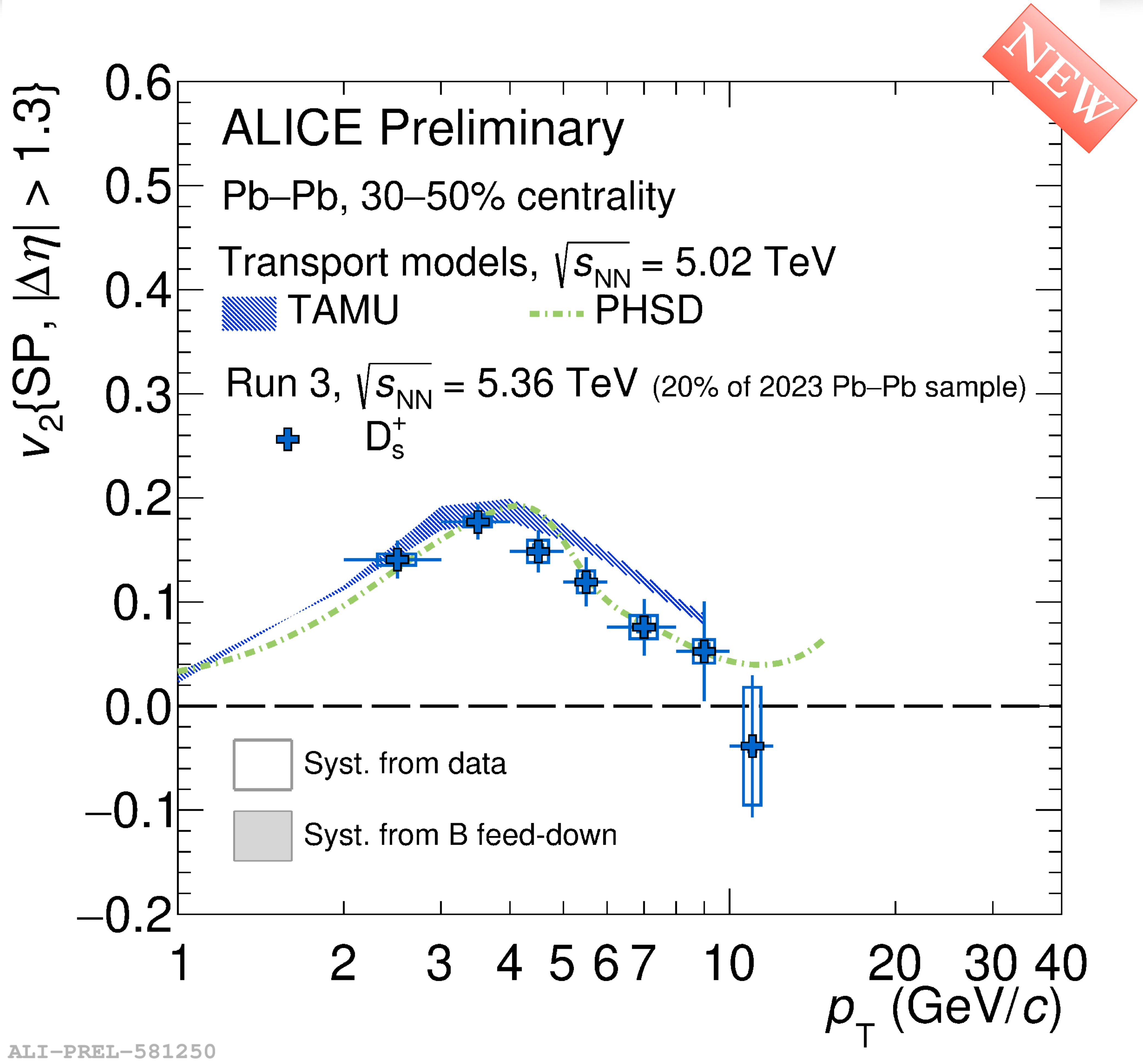

TAMU: PLB 735 (2014) 445, PRL 124 (2020) 042301
PHSD: PRC 92 (2015) 014910
LGR: EPJC 80, no.7, (2020) 671
CATANIA: PRC 96, 044905 (2017)

➡ Described by charm transport models that include **collisional** energy loss and hadronisation through **coalescence**

Prompt Λ_c^+ v_2 in Pb–Pb collisions at 5.36 TeV (Run 3)

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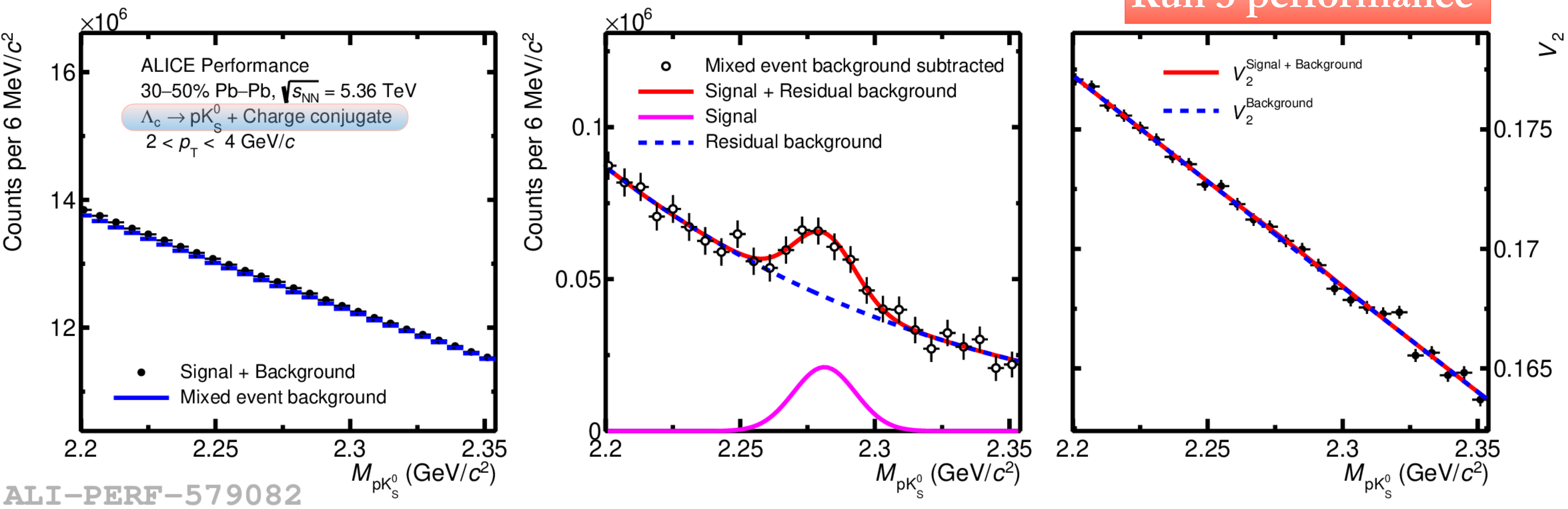
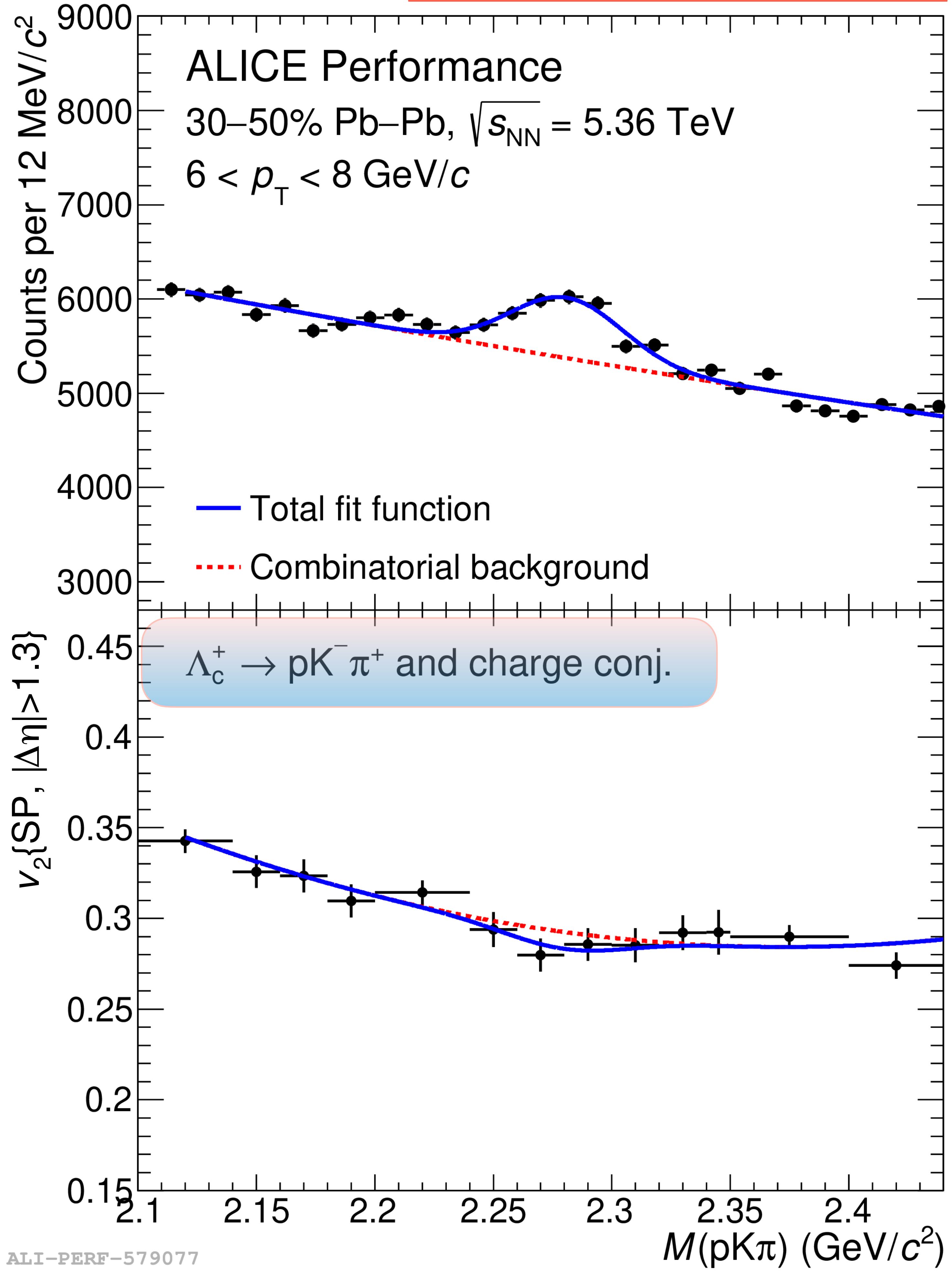
Run 3 performance



Run 3 performance



HF v_2 measurements extended to the charm baryon sector

➡ **The analysis of prompt charm baryon Λ_c^+ v_2 in two decay channels are ongoing**

- $\Lambda_c^+ \to pK^0_S$ and charge conjugates
- $\Lambda_c^+ \to pK^-\pi^+$ and charge conjugates

Summary and outlook

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The complete measurements from ALICE Run 2 provide valuable insights into:

- mass dependence in energy loss (R_{AA})
- different degrees of participation in collective motion and hadronization between charm and beauty quarks (v_2)
- HFe correlation measurements indicate the significant jet-quenching effects at high-p_T^{assoc} ($p_T^{assoc} > 4$ GeV/c)

New Inner Tracking System (ITS 2) detector and increased integrated luminosity for LHC Run 3

- The first prompt D meson v_2 measurements in ALICE Run 3 show results consistent with those from Run 2

➡ A factor 5 larger data sample will be analysed in the immediate future

➡ Extend the v_2 analysis including first measurement of charm-baryon v_2

Summary and outlook

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Thanks for you attention!

Backup slides

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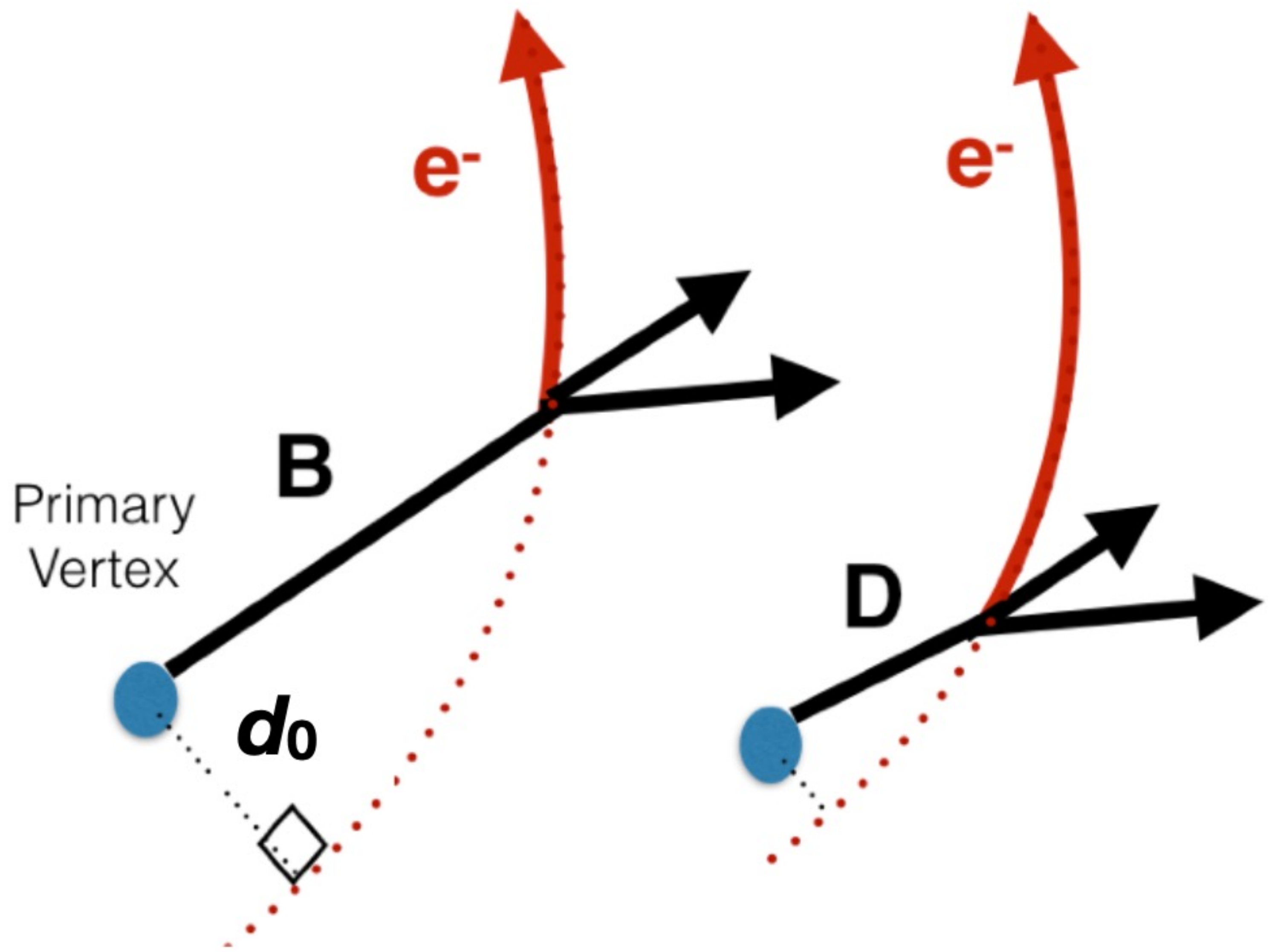

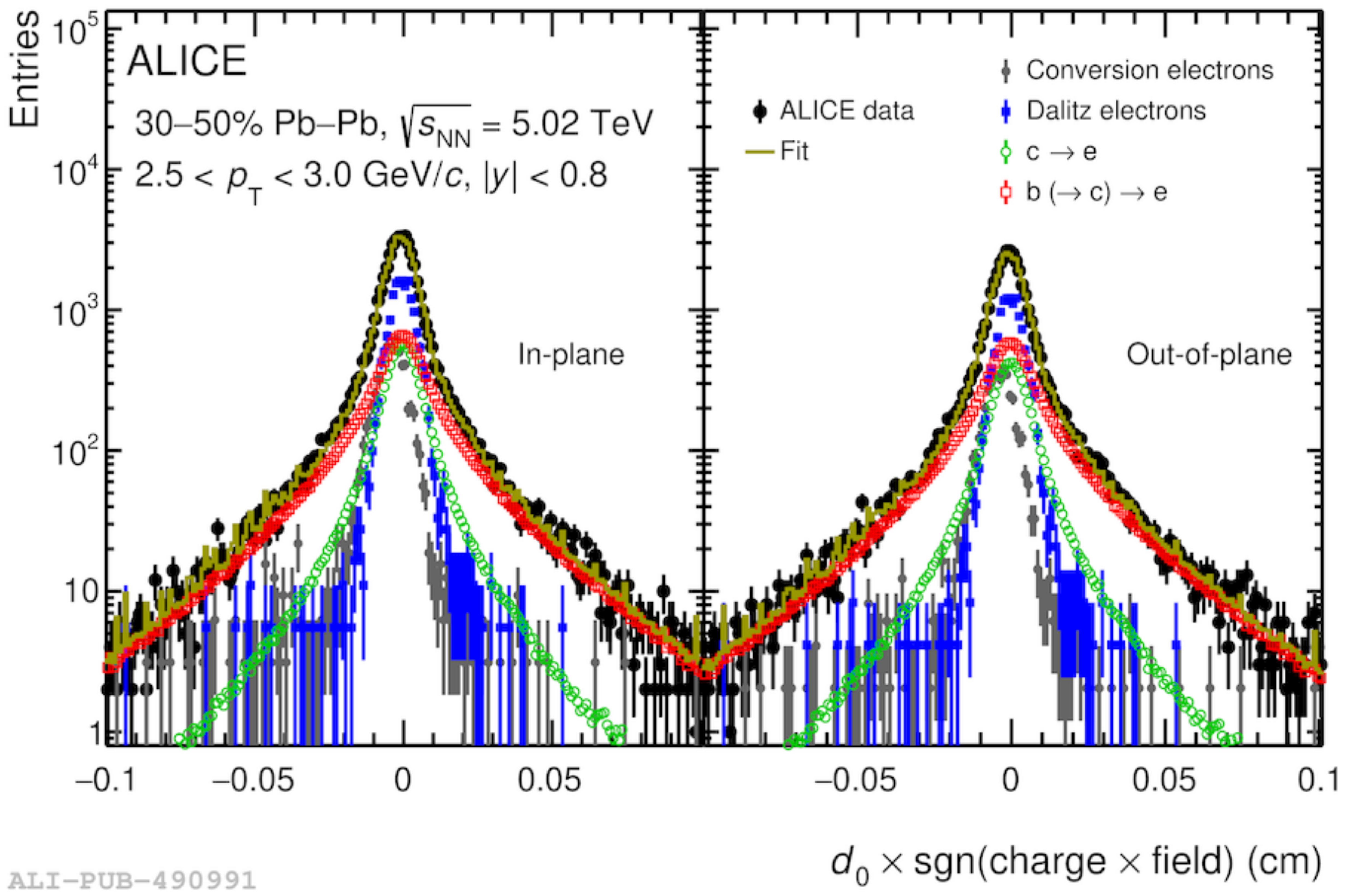

- Large branching ratios via semileptonic decays: b → e + X (~10%) , b → c → e + X (~10%)
- Longer lifetime than c-quark and other electron sources: τ_b ~ 500 μm/c; τ_c ~ 60-300 μm/c

  ➡ larger impact parameter (d_0) w.r.t primary vertex
- b → e yield obtained with template fit on impact parameter distributions

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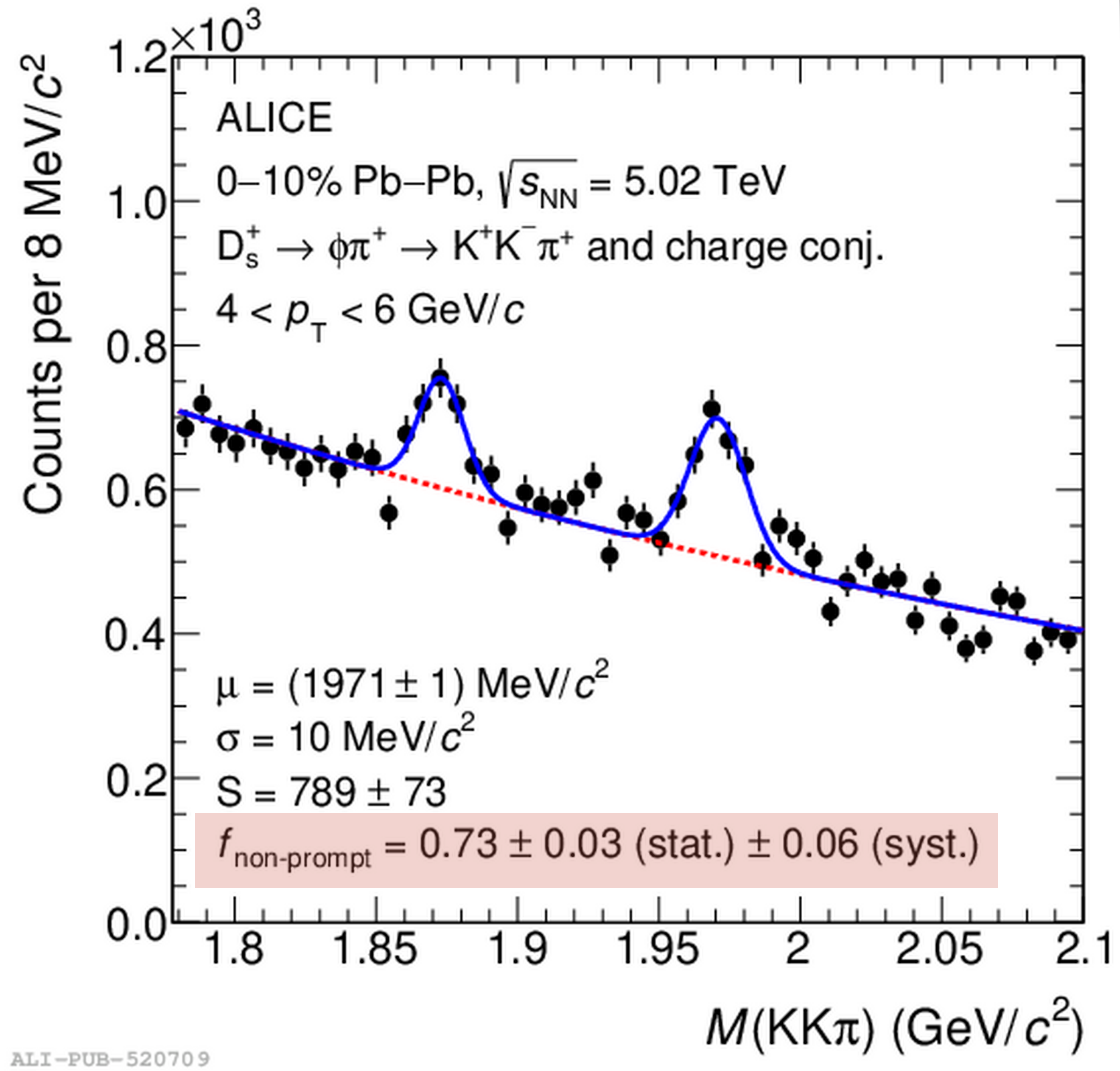
- Use Machine Learning method with a multi-classification by BDT to select candidates, separating prompt D and non-prompt D mesons and combinatorial background[1]
- Signal was extracted from invariant mass fit



- Prompt and non-prompt D mesons contributions extracted from χ^2 minimization of the system of n sets of selections with different prompt and non-prompt D-meson contributions