Recent results on open heavy-flavour production from small to large collision systems with ALICE

ALICE

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Istituto Nazionale di Fisica Nucleare

EP-LHC seminar
CERN@HOME | 30th June 2020

Outline

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- Proton-proton collisions: heavy flavours as test of perturbative QCD
  - ➡ Prompt and non-prompt D mesons in proton-proton collisions
  - ➡ Charm and beauty production via dielectron measurements (arXiv:2005.11995)

- Heavy-ion collisions: heavy flavours as probes of the quark-gluon plasma
  - ➡ Prompt and non-prompt D mesons
  - ➡ Azimuthal anisotropy of heavy flavour particles (arXiv:2005.11130, arXiv:2005.11131)

- Proton-proton + heavy-ion collisions: studies of charm-quark hadronisation
  - ➡ Strange charm mesons and charm baryon production in heavy-ion collisions
  - ➡ Charm-baryon production in proton-proton collisions

Based on recent results presented in LHCP 2020 and HP 2020

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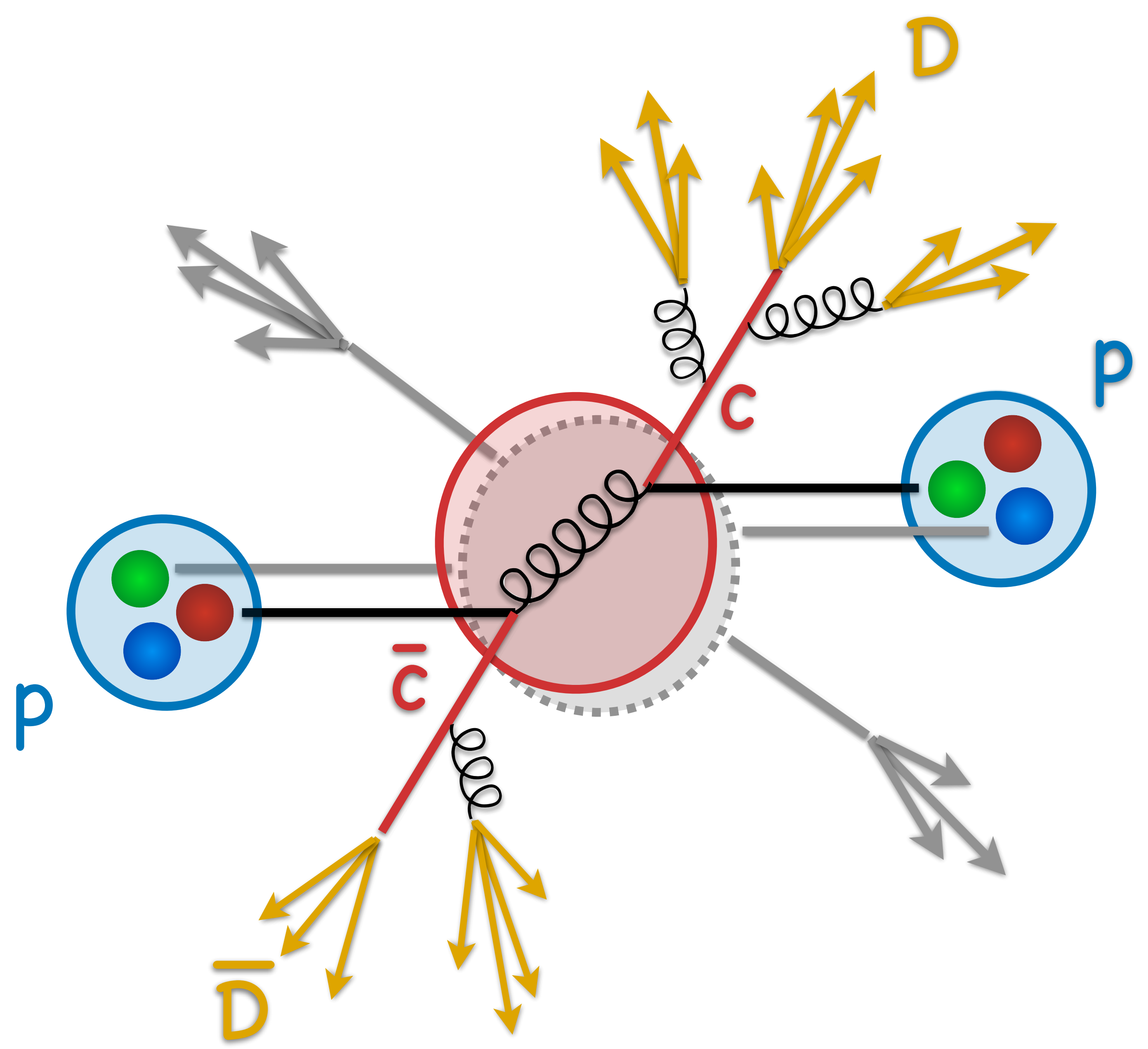

- Heavy flavours (charm and beauty quarks) are produced in hard-scattering processes
- Described with perturbative QCD calculations based on the factorisation theorem

$$\sigma_{\mathrm{hh}\to\mathrm{Hh}} = \mathrm{PDF}(x_{\mathrm{a}}, Q^2)\ \mathrm{PDF}(x_{\mathrm{b}}, Q^2) \otimes \sigma_{\mathrm{ab}\to\mathrm{q\bar{q}}} \otimes D_{\mathrm{q}\to\mathrm{h}}(z_q, Q^2)$$

Parton distribution functions (non perturbative)

Partonic cross section (perturbative)

Fragmentation functions (non perturbative)

Heavy-flavour production in pp collisions

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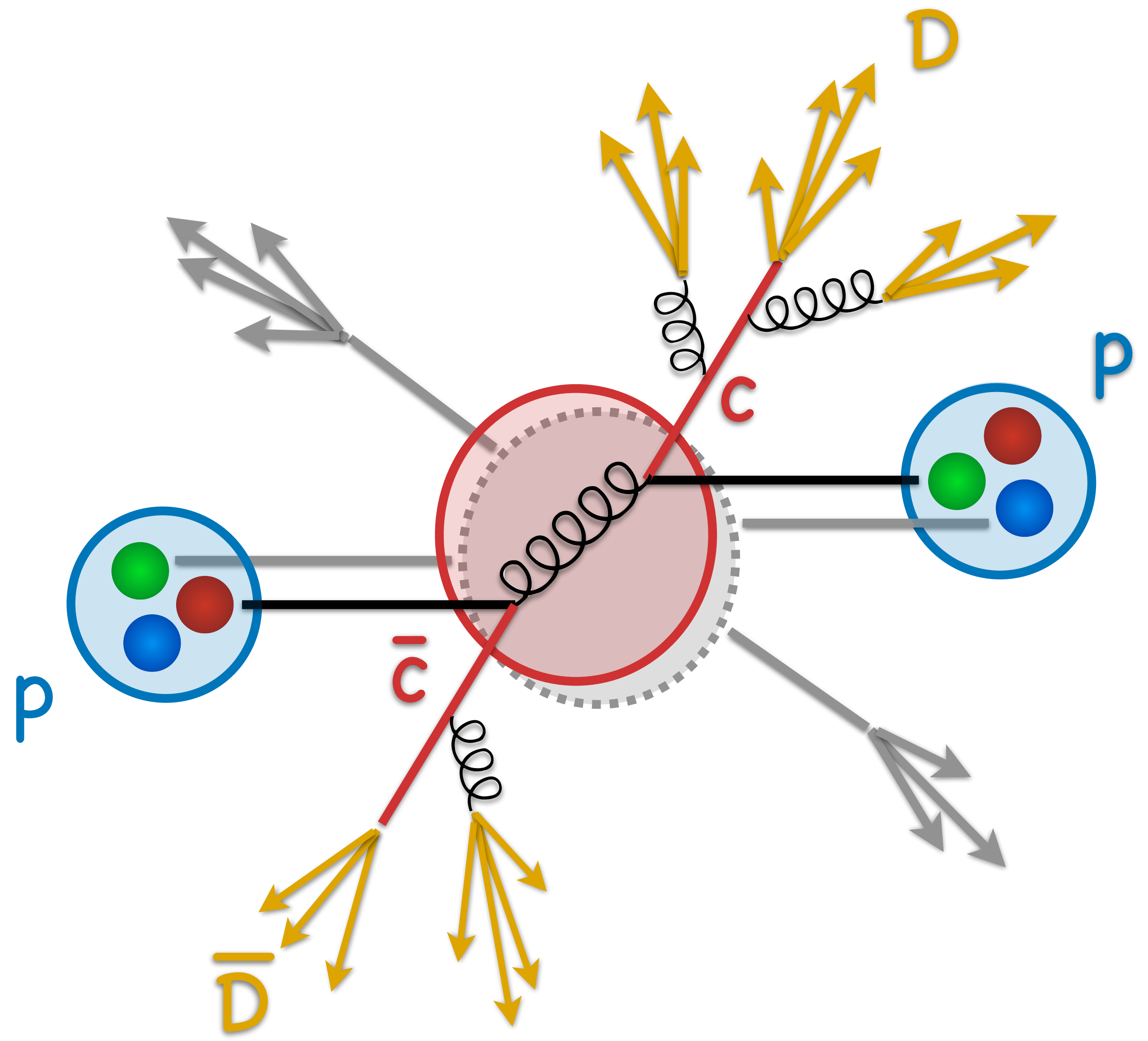

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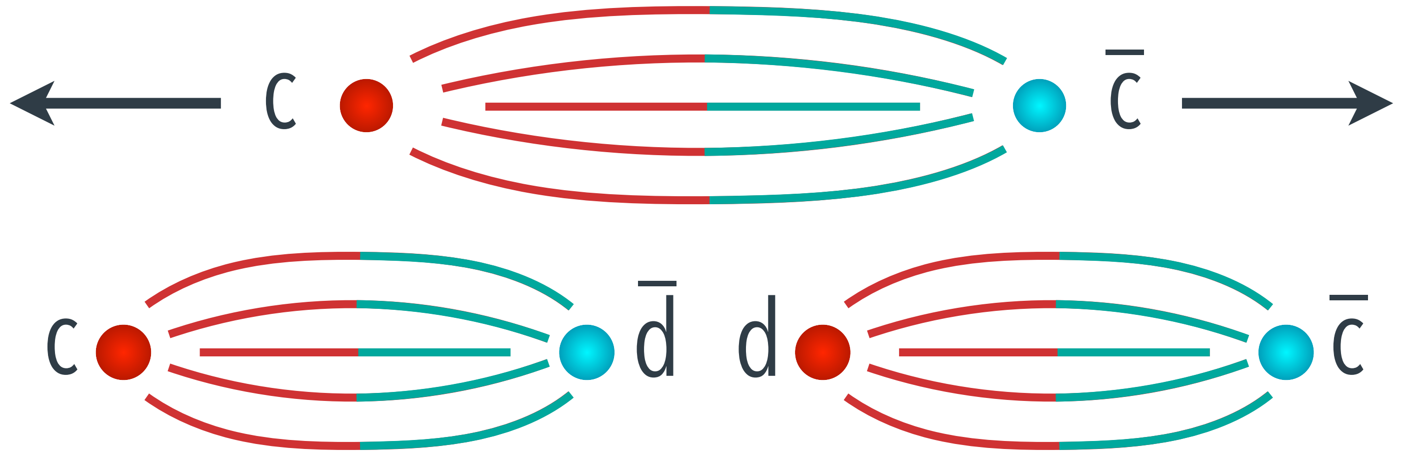
$$\sigma_{\mathrm{hh}\to\mathrm{Hh}} = \mathrm{PDF}(x_\mathrm{a}, Q^2)\ \mathrm{PDF}(x_\mathrm{b}, Q^2) \otimes \sigma_{\mathrm{ab}\to\mathrm{q\bar{q}}} \otimes D_{\mathrm{q}\to\mathrm{h}}(z_q, Q^2)$$

Parton distribution functions (non perturbative)

Partonic cross section (perturbative)

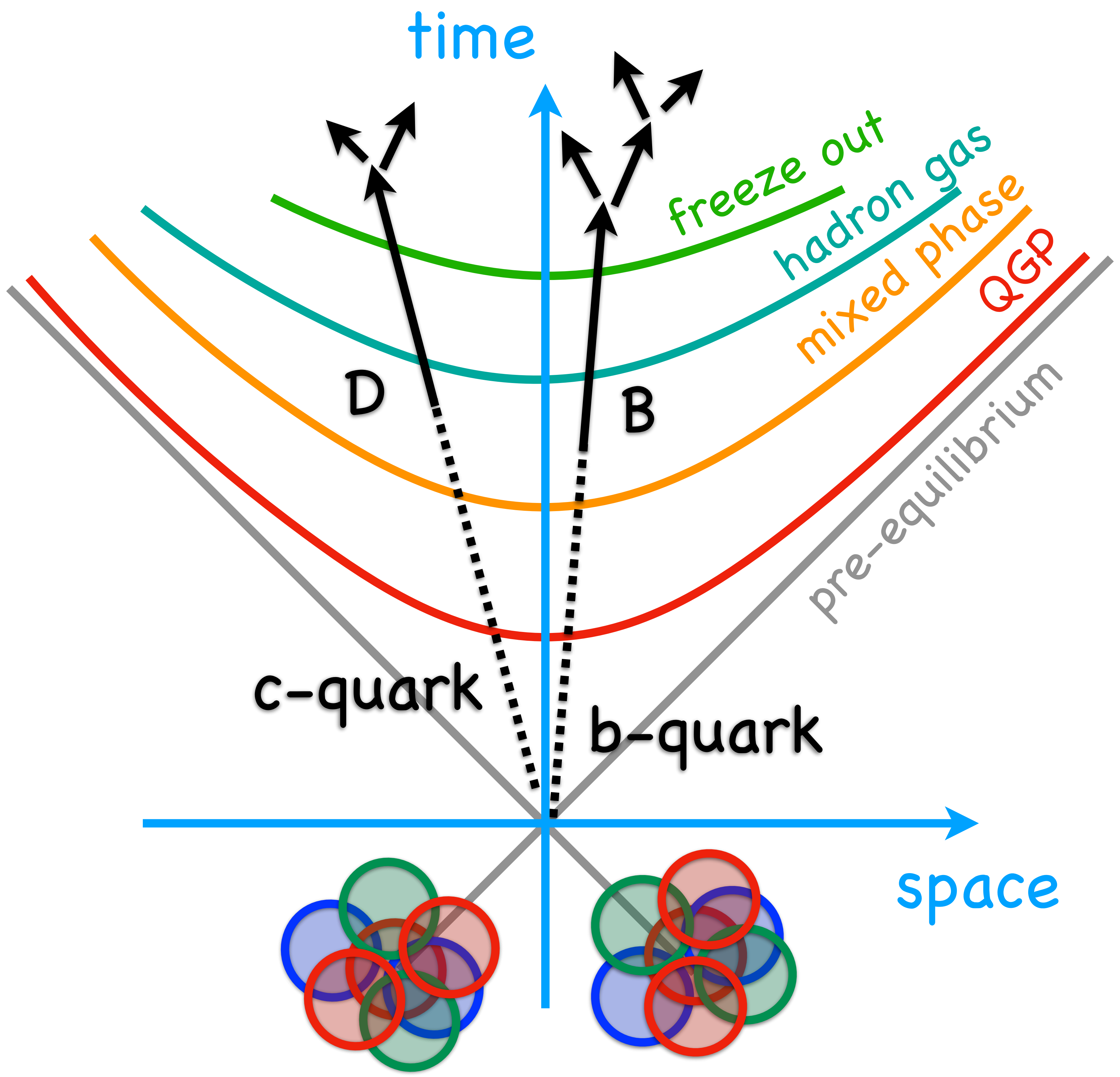
Fragmentation functions (non perturbative)

- Is the hadronisation different in pp and e^+e^- collisions?
  1. String fragmentation (e.g. PYTHIA)
     - ➡ strings: color-flux tubes between $q\bar{q}$ endpoints, hadronisation via string breaking
  2. Statistical hadronisation model
     - ➡ Hadronisation governed by the masses of available hadron states at a universal hadronisation "temperature" T_H
       - abundances of species ∝ $\exp(-m/T_\mathrm{H})$
  3. Other models not discussed today (e.g. cluster decay in HERWIG)



Z. Phys. C1 (1979) 105

PLB 795 (2019) 117-121

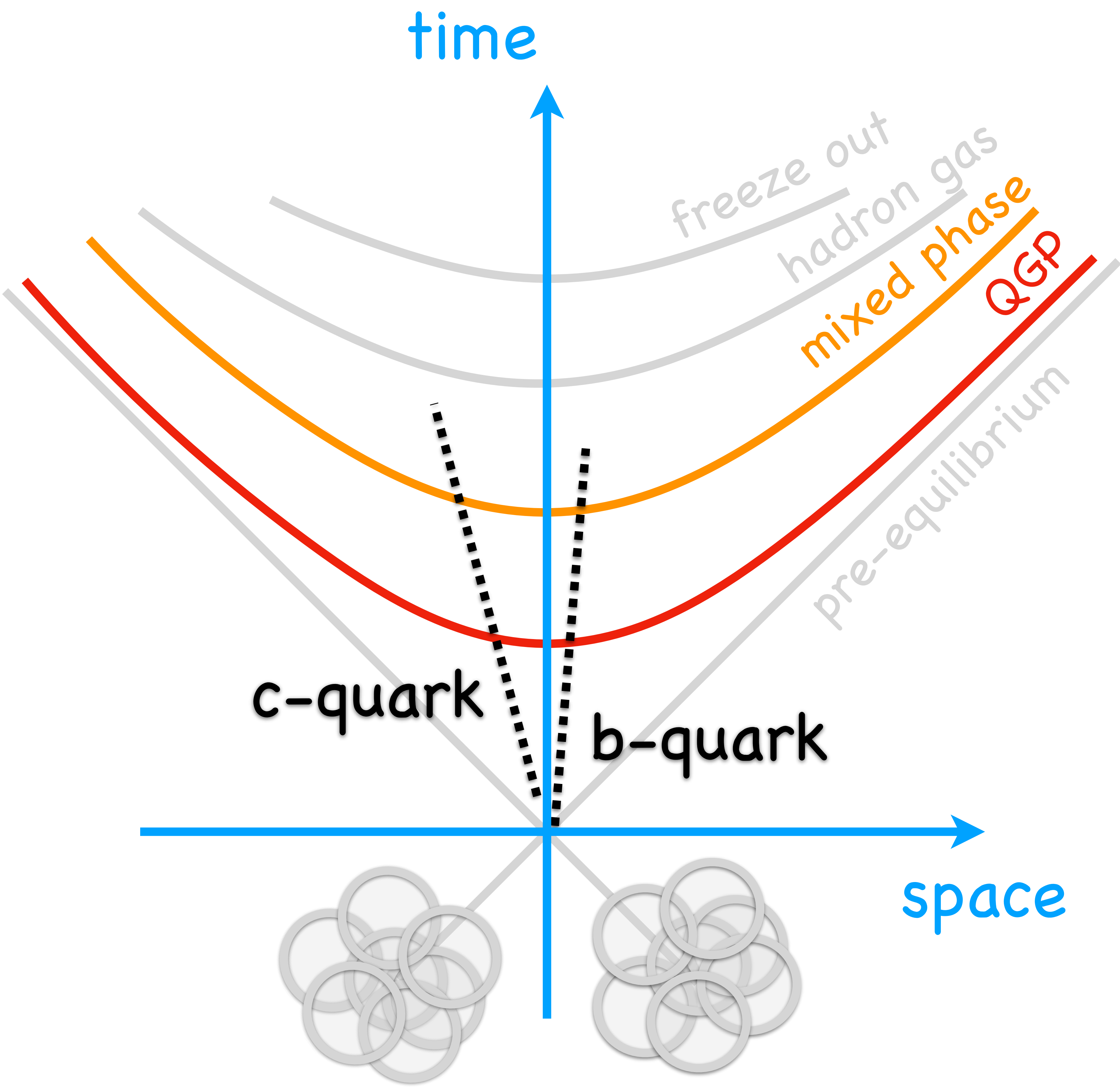


- QCD calculations on lattice predict a phase transition from the ordinary nuclear matter to a colour-deconfined medium, called *quark–gluon plasma* (QGP)
  - ➡ created in ultra-relativistic heavy-ion collisions
  - ➡ very high energy density $\varepsilon > 15$ GeV/fm^3
  - ➡ after a pre-equilibrium phase expands hydrodynamically

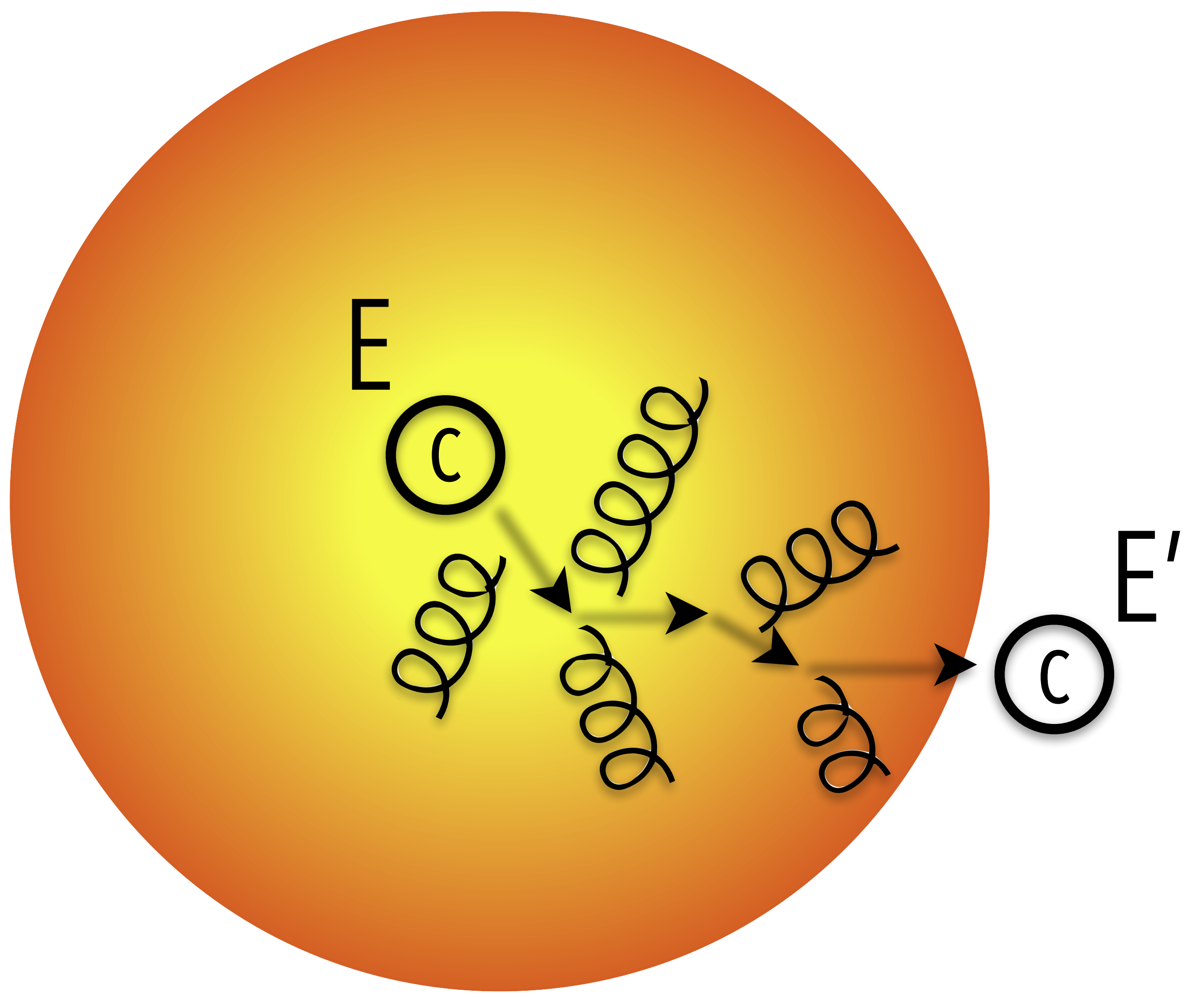
- Heavy flavours: produced in shorter time scales than QGP formation time
  - ➡ $\tau_{\mathrm{HF}} \lesssim \hbar/m \approx 0.05\text{-}0.1$ fm/c depending on p_{T}
  - ➡ $\tau_{\mathrm{QGP\ form}}$ (LHC) ≈ 0.3 fm/c

  } HF experience the full system evolution

PRC 89 (2014) 034906



- HF propagate in the QGP with a Brownian motion
  - ➡ interact with medium constituents
  - ➡ loose energy via elastic collisions and radiative processes
  - ➡ heavy-quark thermalisation in the QGP?



- ➡ $\tau_{\mathrm{HF}} \lesssim \hbar/m \approx$ 0.05-0.1 fm/c depending on p_{T}
- ➡ $\tau_{\mathrm{QGP\ form}}$ (LHC) $\approx$ 0.3 fm/c
  - PRC 89 (2014) 034906
- ➡ $\tau_{\mathrm{QGP\ lifetime}} \approx$ 10 fm/c
  - PLB 696 (2011) 328-337

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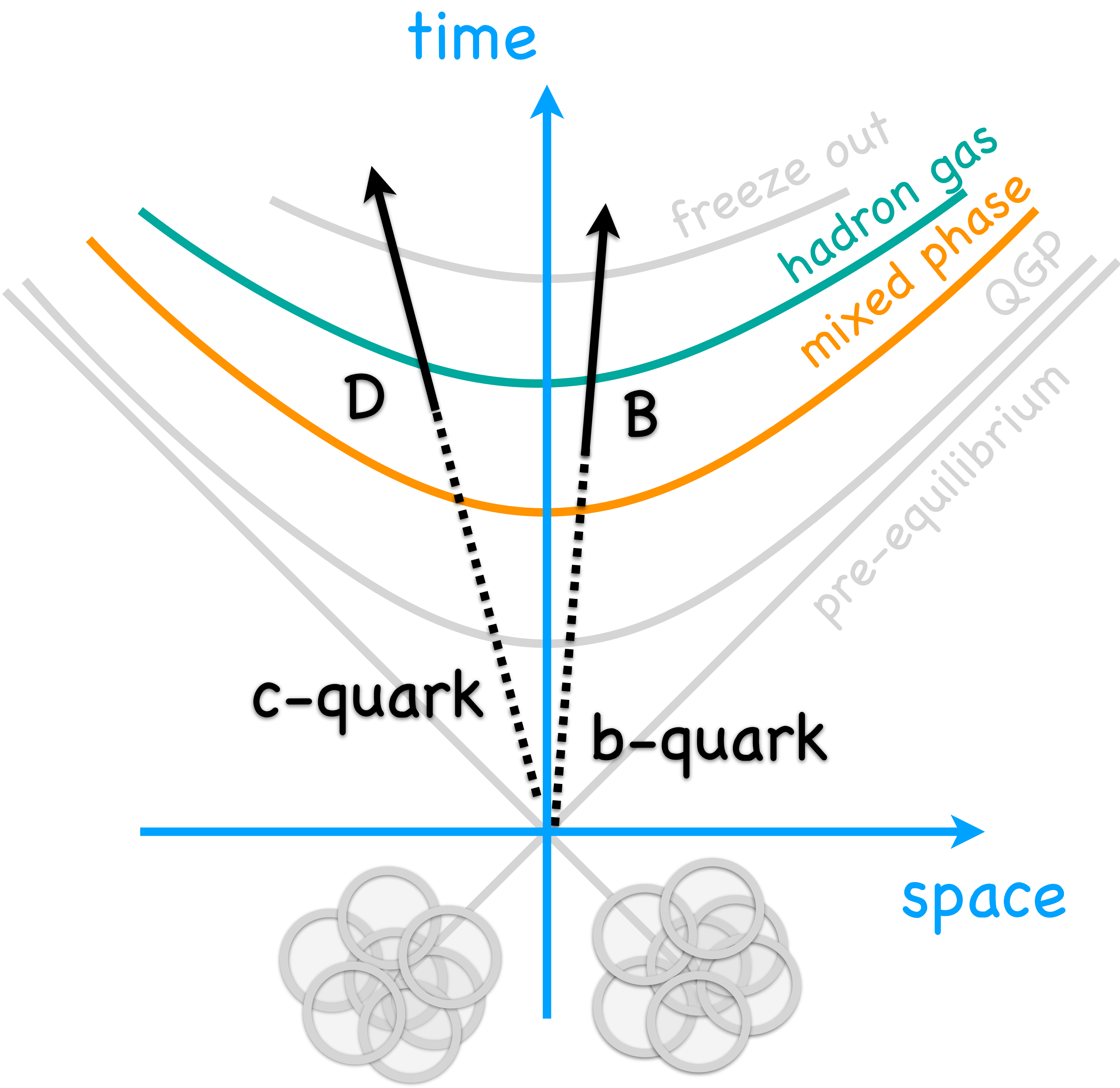
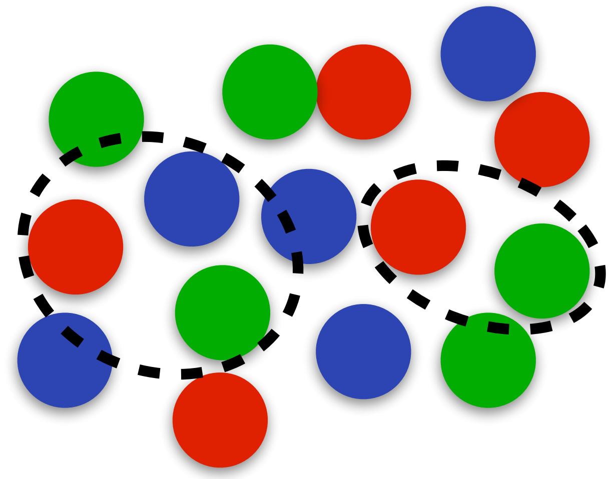


- Competing mechanisms for the HF hadronisation in the QGP

  1. Fragmentation $D_{q\rightarrow h}(z_q, Q^2)$
     - ➡ energy-loss of partons while traversing the QGP modifies fraction of the parton momentum z_q taken by the hadron
       - equal for all hadron species
  2. Coalescence
     - ➡ partons close in phase space can recombine into hadrons
     - ➡ quarks with different mass coalesce if have similar velocities



PRL 90 (2003) 202302
PRL 90 (2003) 202303
PRC 67 (2003) 064902
PLB 595 (2004) 202-208

- Statistical hadronisation model
  - ➡ Hadrons emitted from the interaction region in statistical equilibrium at the QGP phase boundary

PLB (2008) 659:149-155

A Large Ion Collider Experiment

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Time Projection Chamber

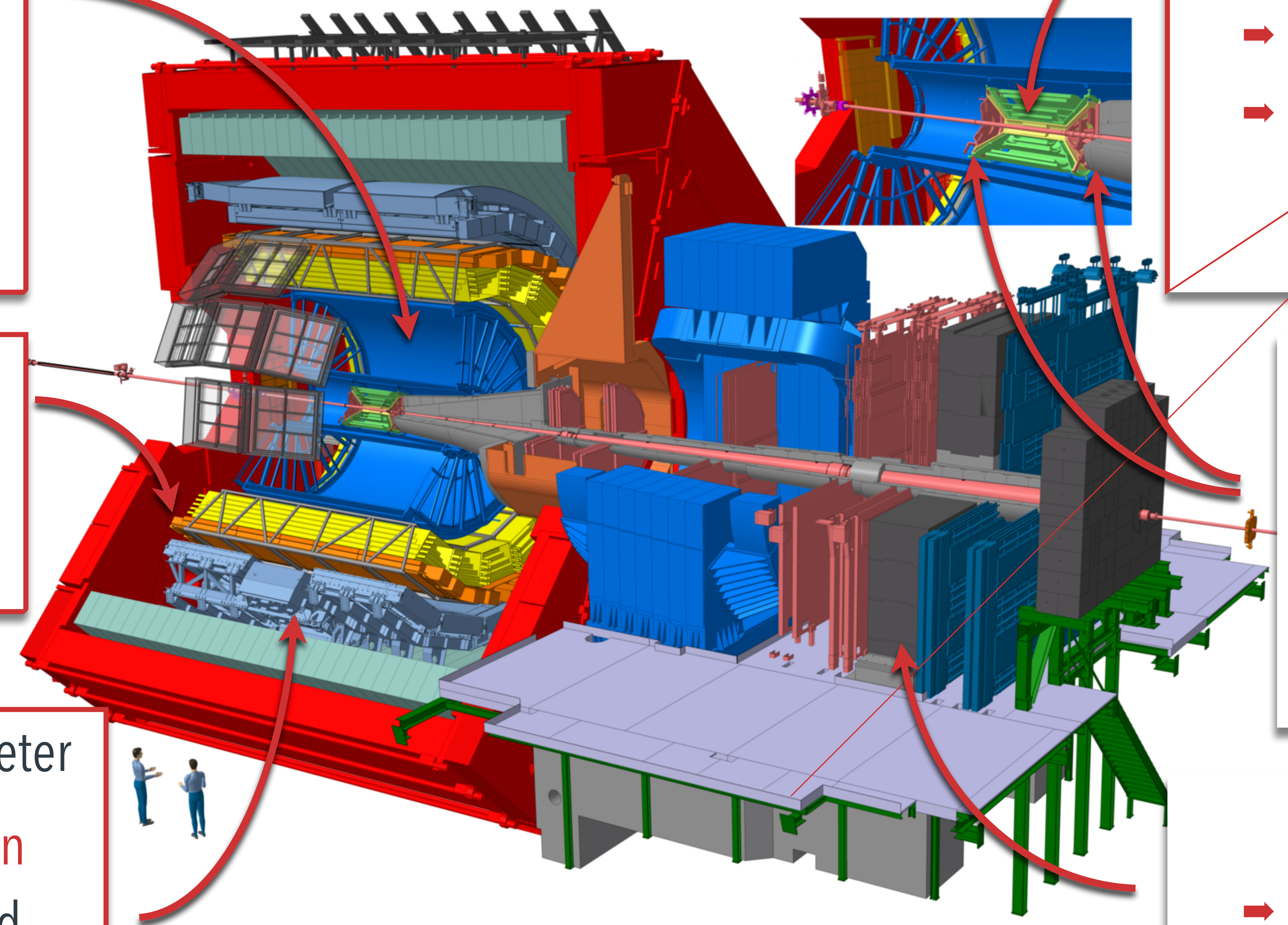
- ➡ Track reconstruction
- ➡ Particle identification via specific energy loss

Time-of-Flight detector

- ➡ Particle identification via time-of-flight

Electromagnetic Calorimeter

- ➡ Particle identification via energy deposited
- ➡ Trigger



Inner Tracking System

- ➡ Track reconstruction
- ➡ Primary and decay vertices reconstruction

V0 detectors

- ➡ Trigger
- ➡ Centrality determination
- ➡ Event-plane estimation

Muon Spectrometer

- ➡ Muon identification and trigger
- ➡ Track reconstruction

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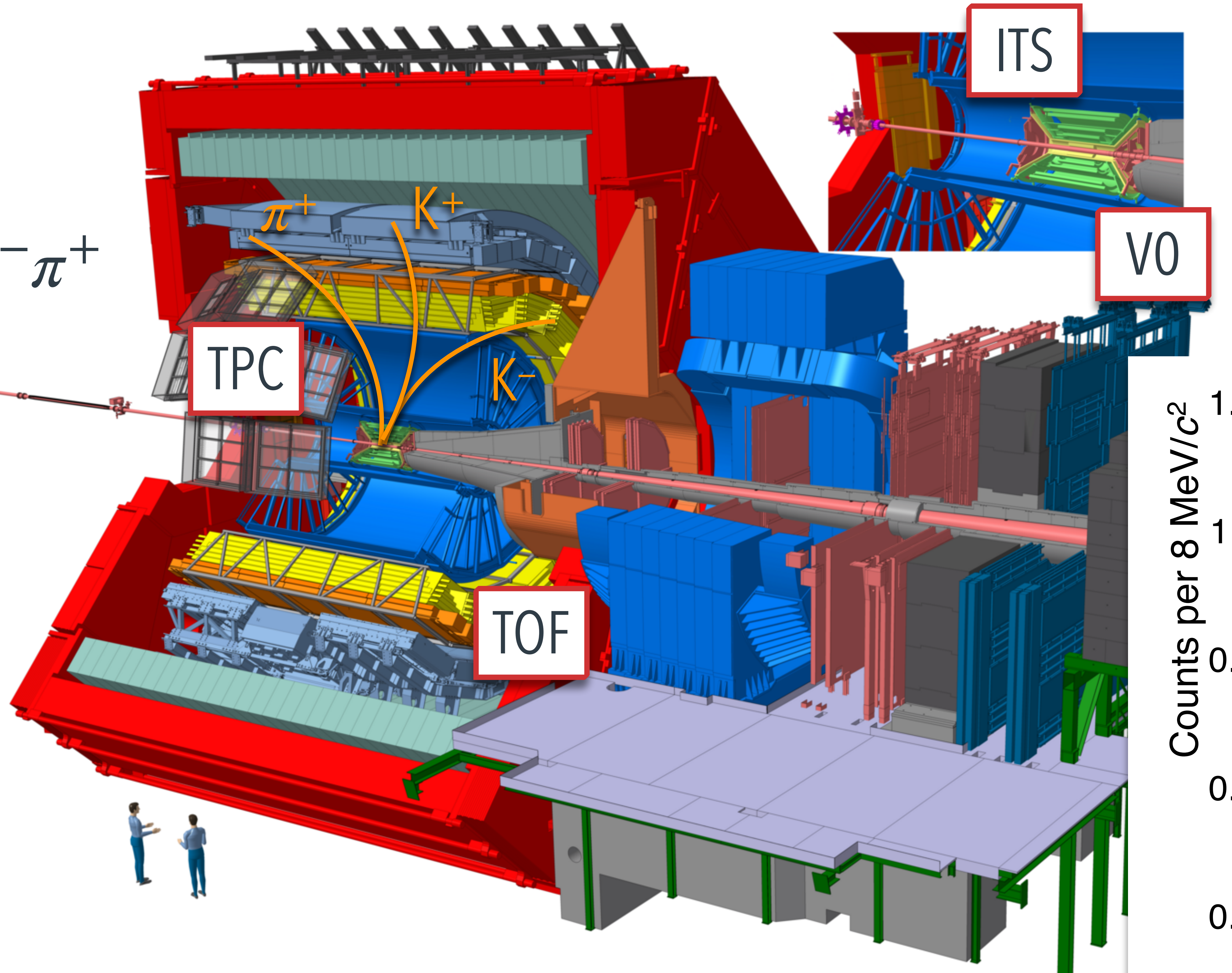
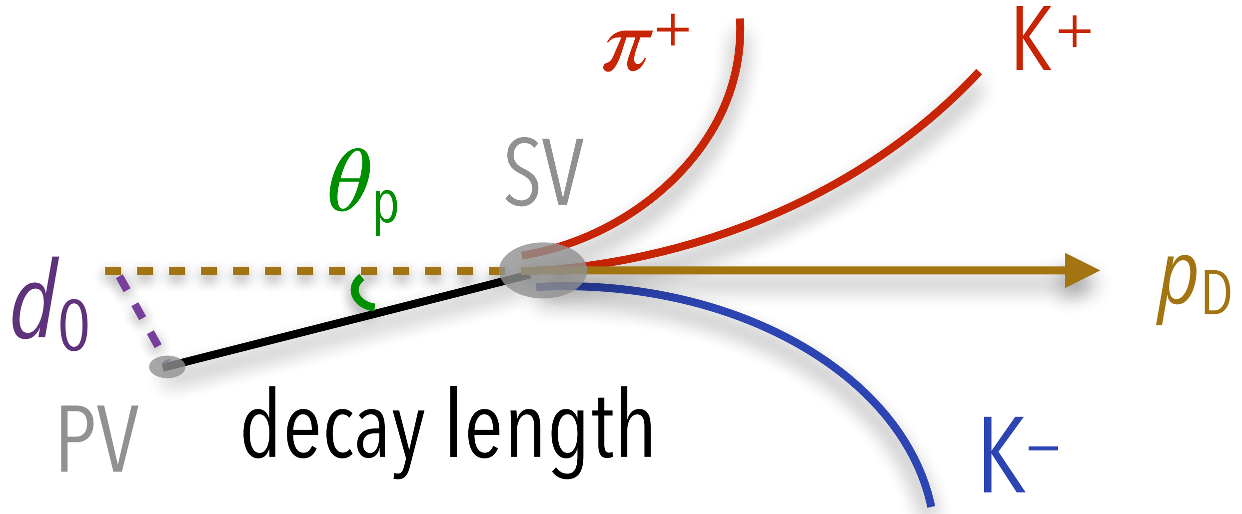
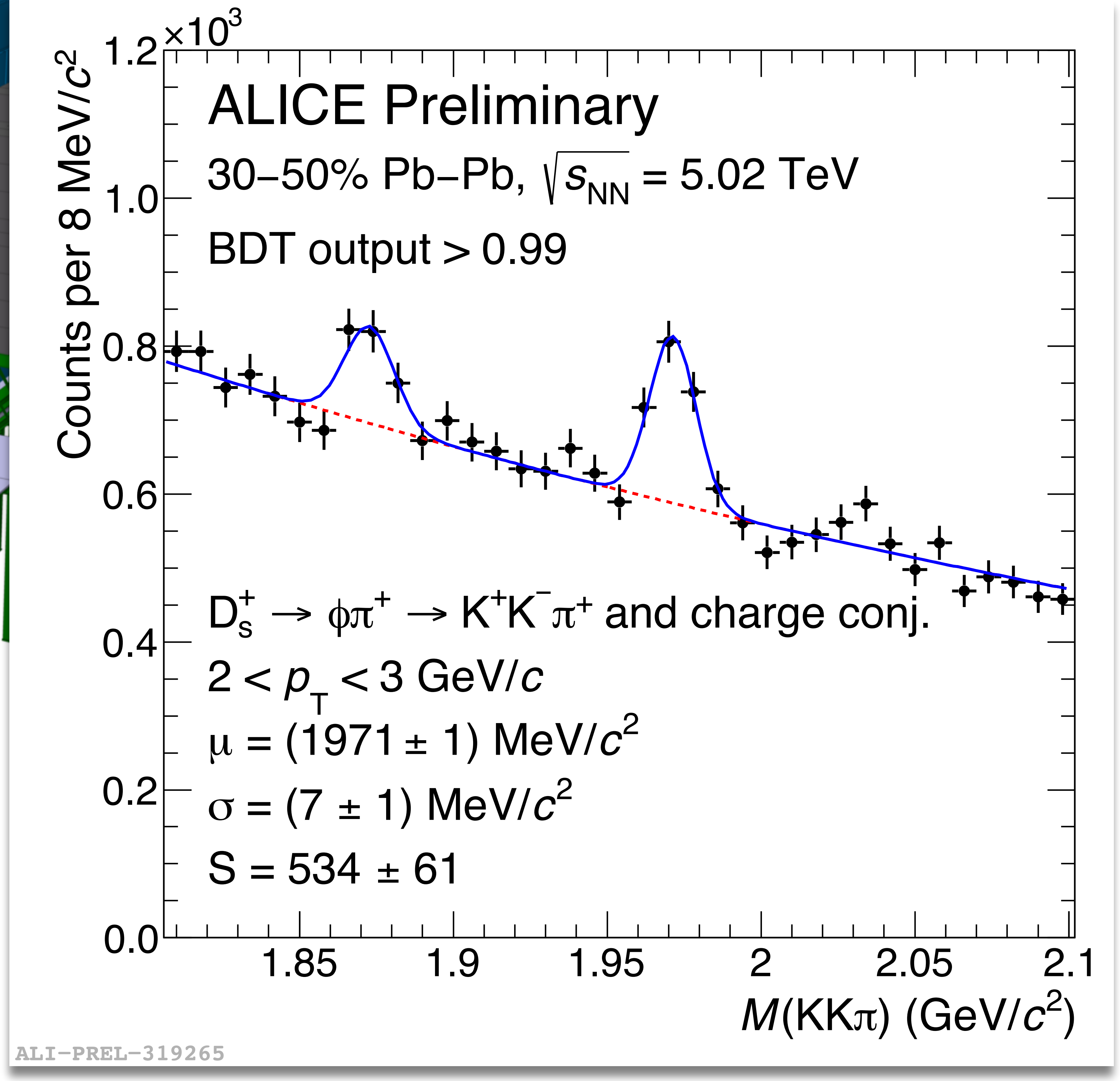
- Open HF hadrons fully reconstructed via hadronic decays:
  - ➡ $D^0 \rightarrow K^-\pi^+$
  - ➡ $D^+ \rightarrow K^-\pi^+\pi^+$
  - ➡ $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$
  - ➡ $D^{*+} \rightarrow D^0\pi^+$
  - ➡ $\Lambda_c^+ \rightarrow pK^-\pi^+$
  - ➡ $\Lambda_c^+ \rightarrow pK_s^0$
  - ➡ $\Sigma_c^{0,++} \rightarrow \Lambda_c^+\pi^{-,+}$
  - ➡ $\Xi_c^0 \rightarrow \Xi^-\pi^+$
  - ➡ $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$



  - ➡ Displaced decay-vertex topology selection
  - ➡ Particle identification of decay tracks
  - ➡ Signal extracted via invariant-mass analysis





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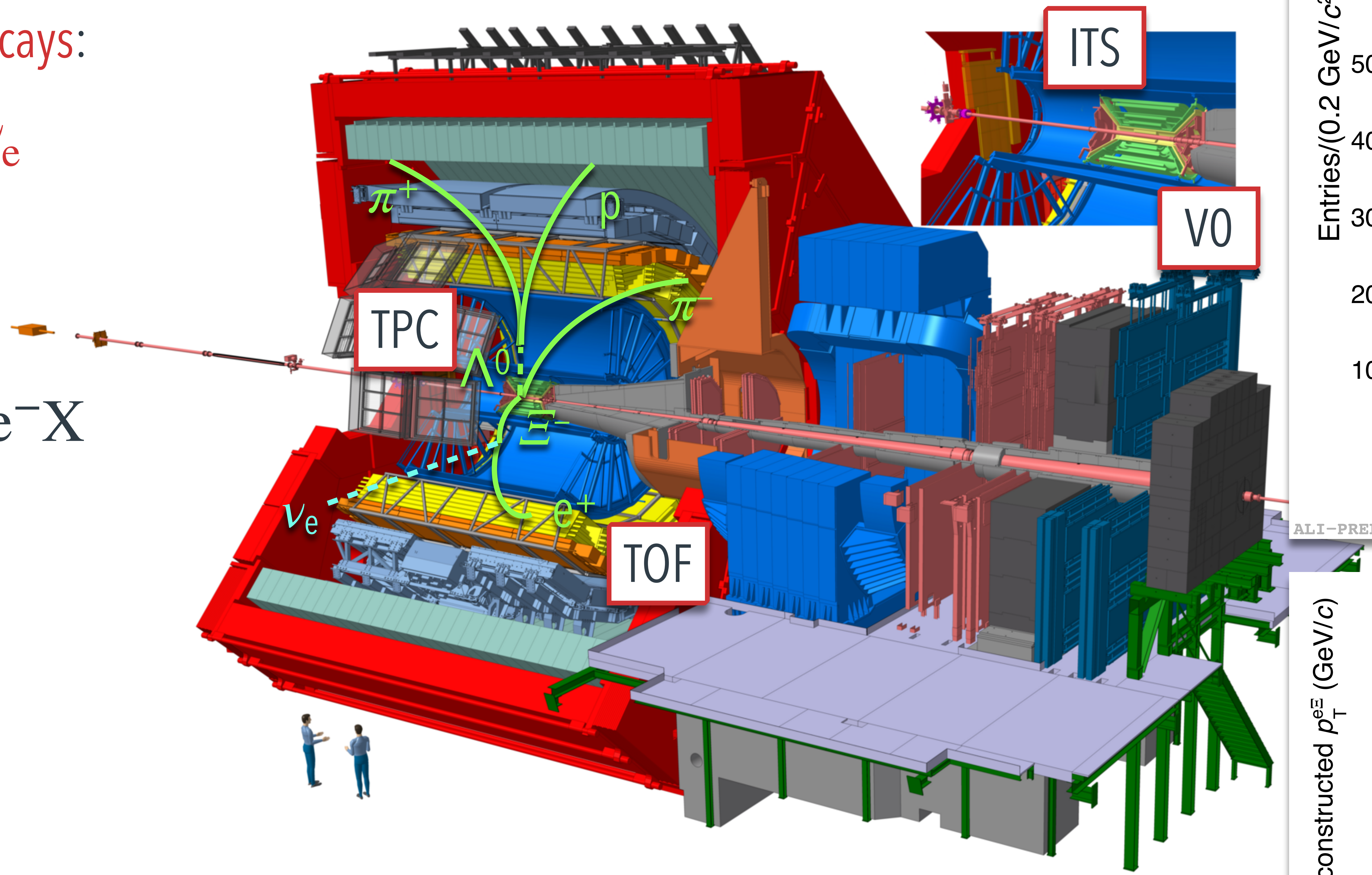
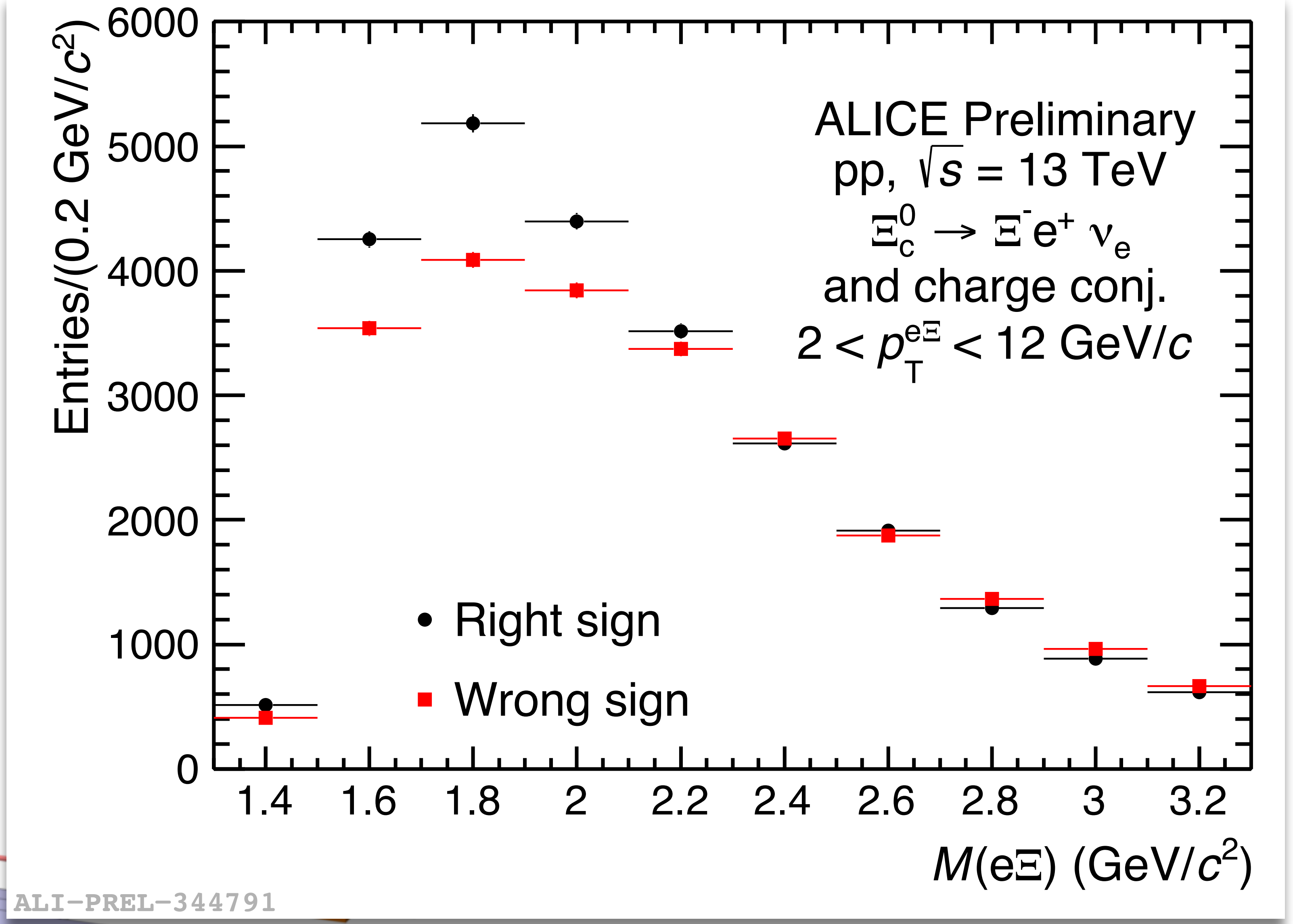
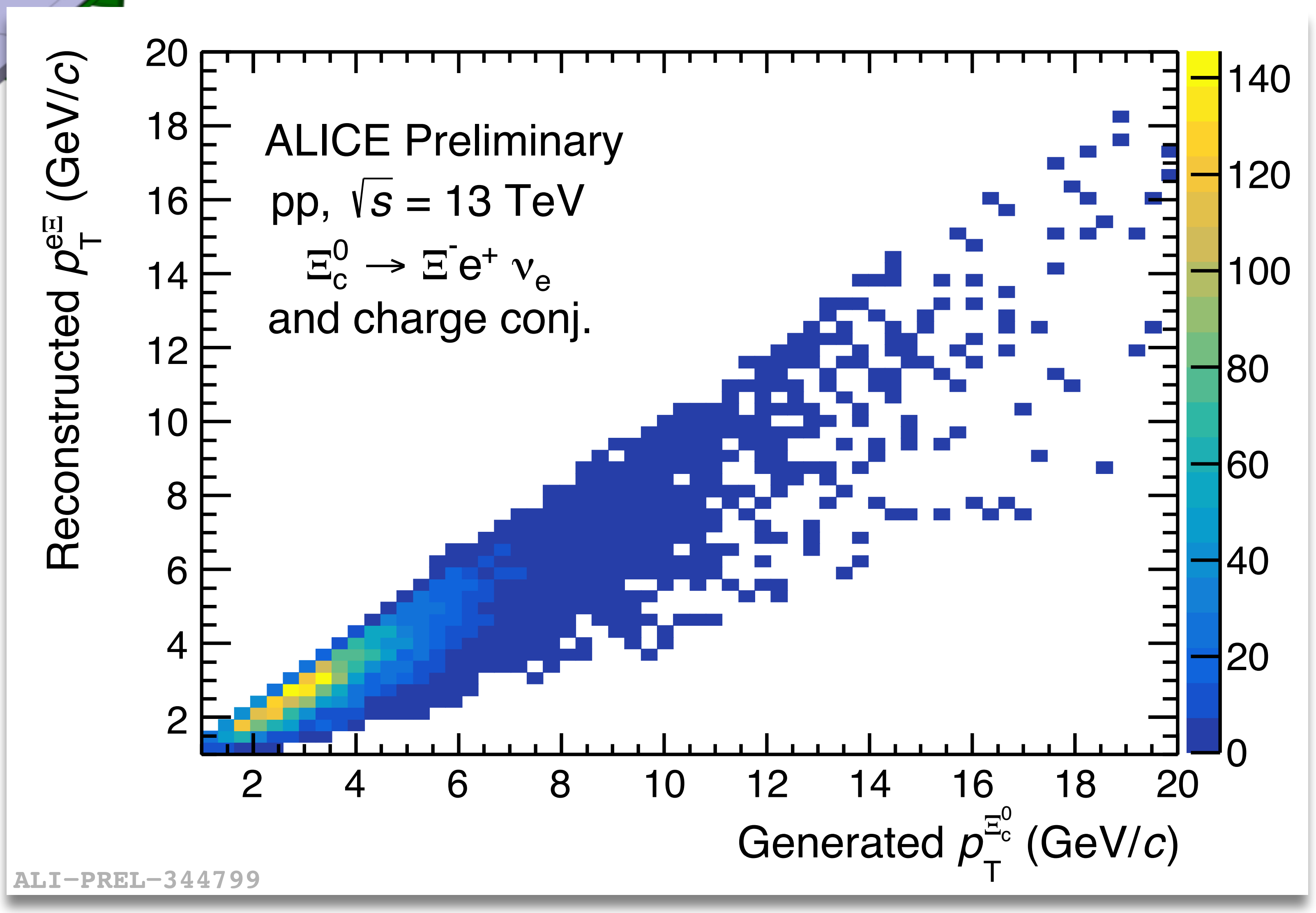
- Open HF hadrons partially reconstructed via semileptonic decays:
  - ➡ $\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e$
  - ➡ $c, b \rightarrow e^{\pm}X$
  - ➡ $c, b \rightarrow \mu^{\pm}X$
  - ➡ $c\bar{c}, b\bar{b} \rightarrow e^+e^-X$







- ➡ Yield subtracting wrong-sign from right-sign Ξe pairs
- ➡ Correction for neutrino missing energy

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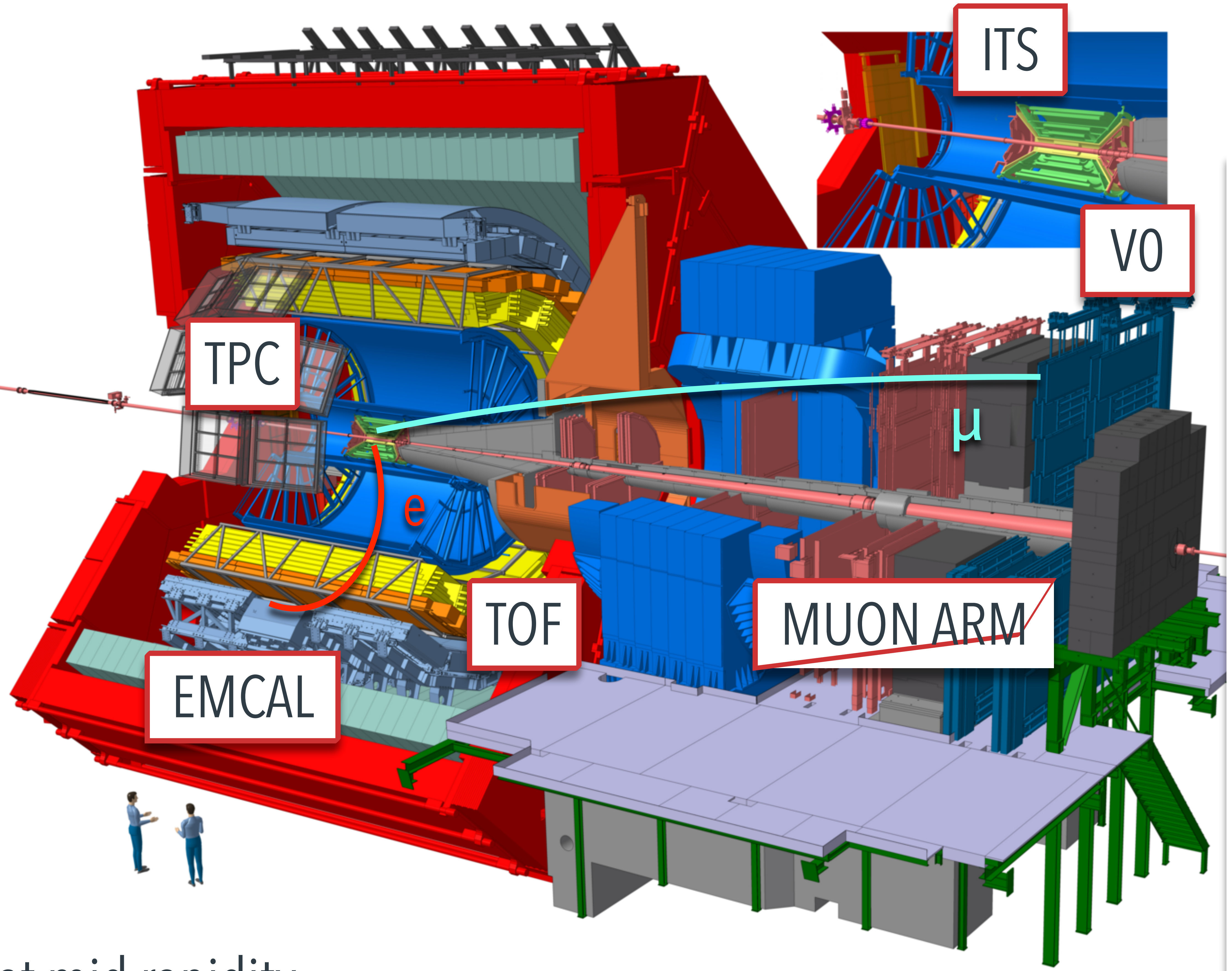
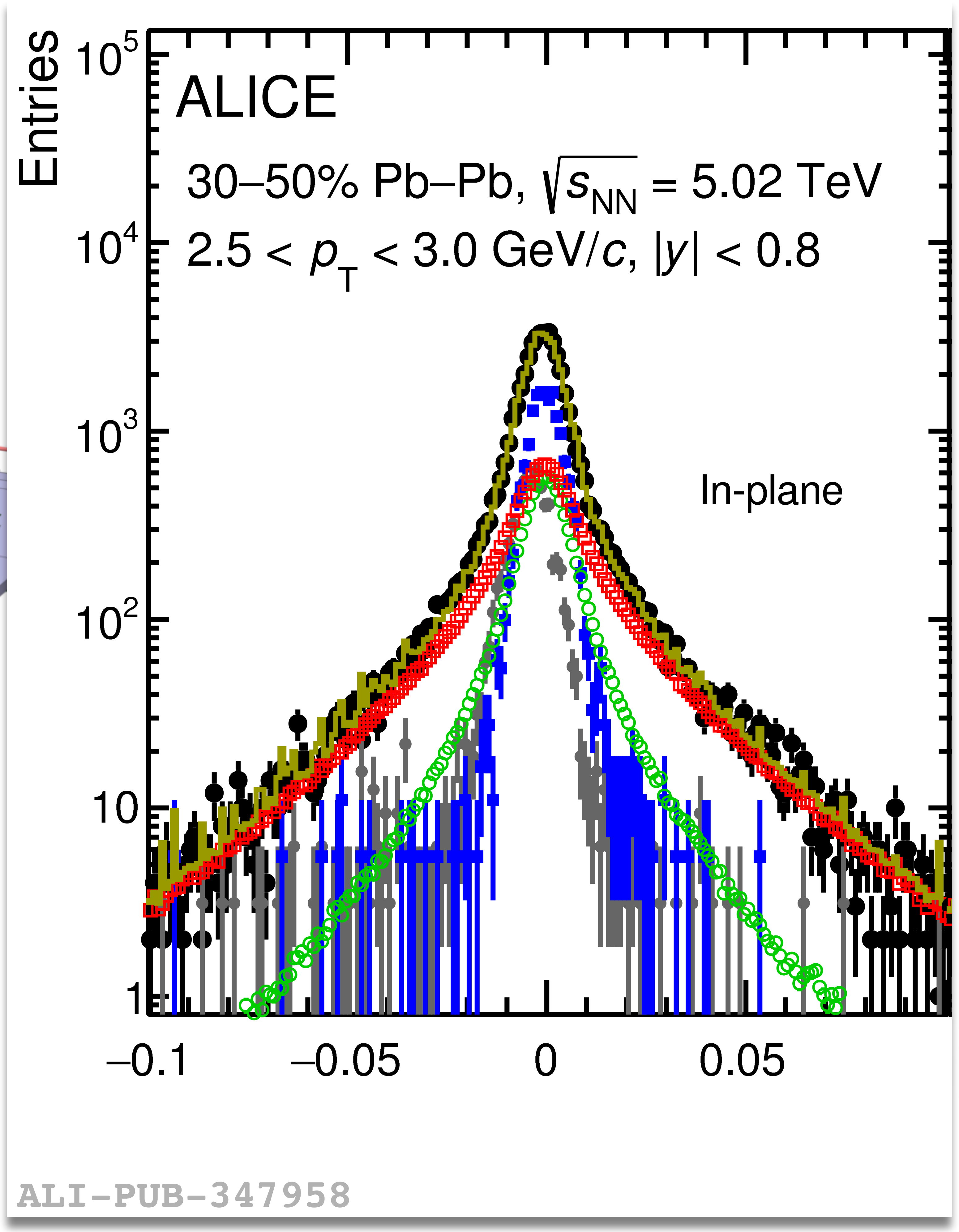
  - ➡ $c\bar{c}, b\bar{b} \to e^+ e^- X$

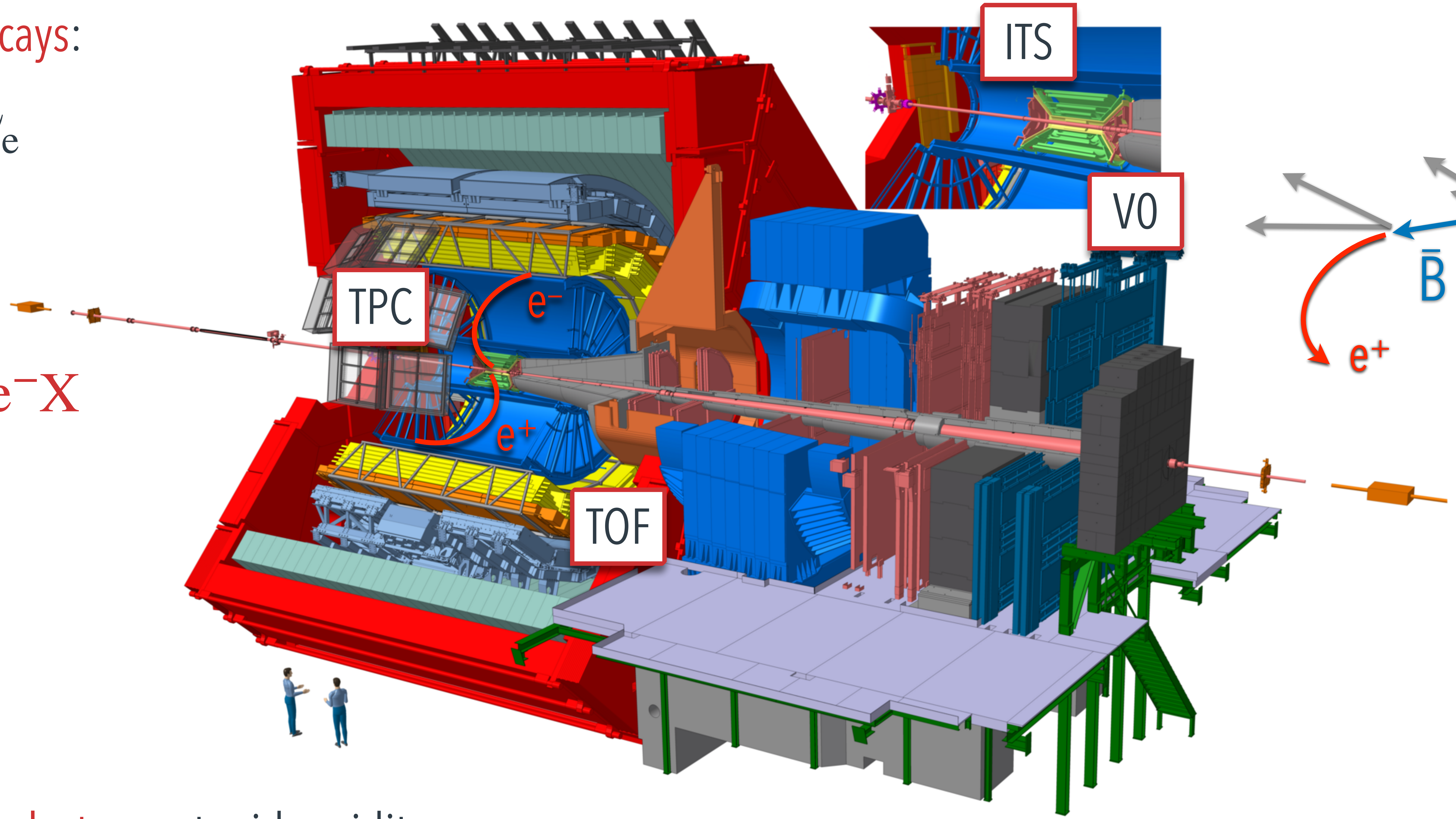


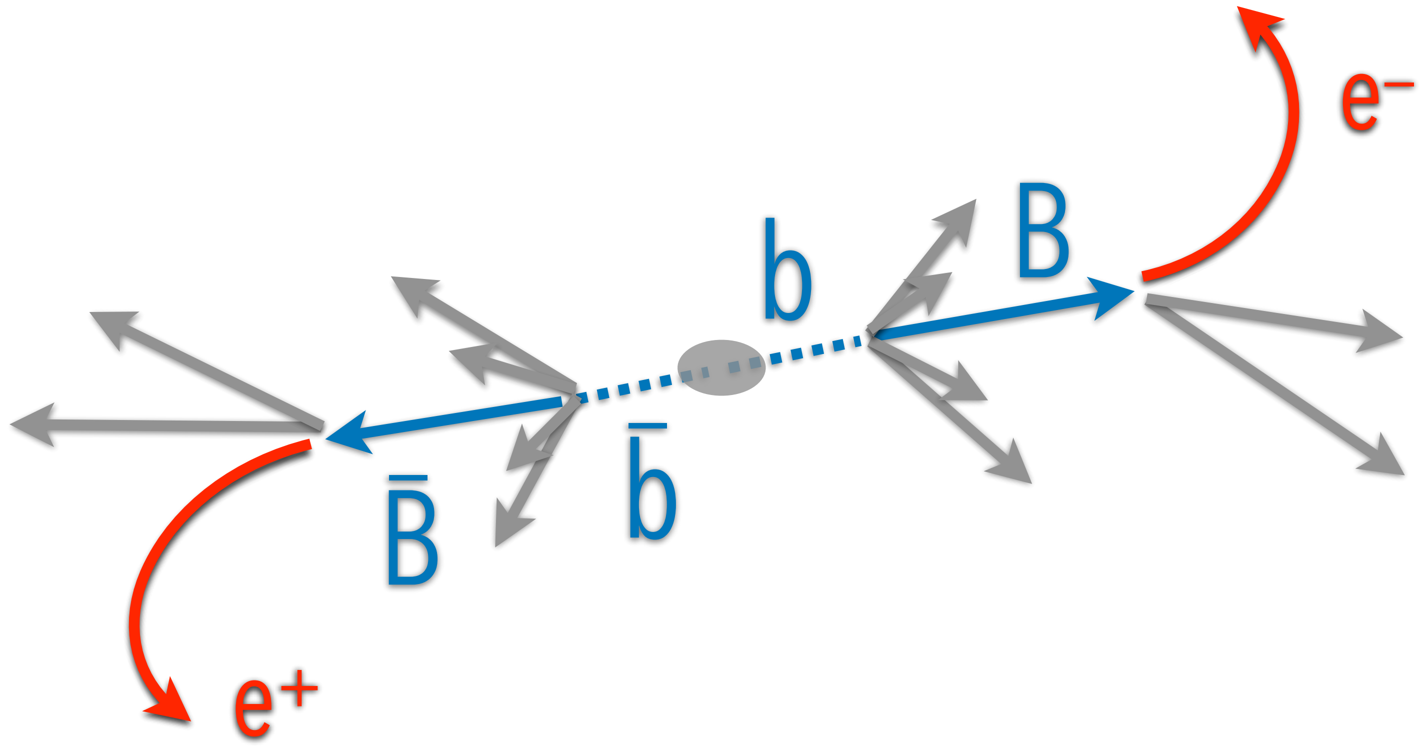
arXiv:2005.11130



- ➡ Identification of electrons at mid rapidity
- ➡ Identification of muons at forward rapidity
- ➡ Subtraction of hadron contamination and $e^{\pm}$ and $\mu^{\pm}$ from non-HF sources

- Open HF hadrons partially reconstructed via semileptonic decays:
  - ➡ $\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e$
  - ➡ $c, b \rightarrow e^{\pm} X$
  - ➡ $c, b \rightarrow \mu^{\pm} X$
  - ➡ $c\bar{c}, b\bar{b} \rightarrow e^+ e^- X$





- ➡ Identification of electrons at mid rapidity
- ➡ Measurement of dielectron production cross section as a function of e^+e^- invariant mass and transverse momentum
- ➡ Charm and beauty contribution extracted with multi-component fit

Charm and beauty cross sections from dielectron measurements

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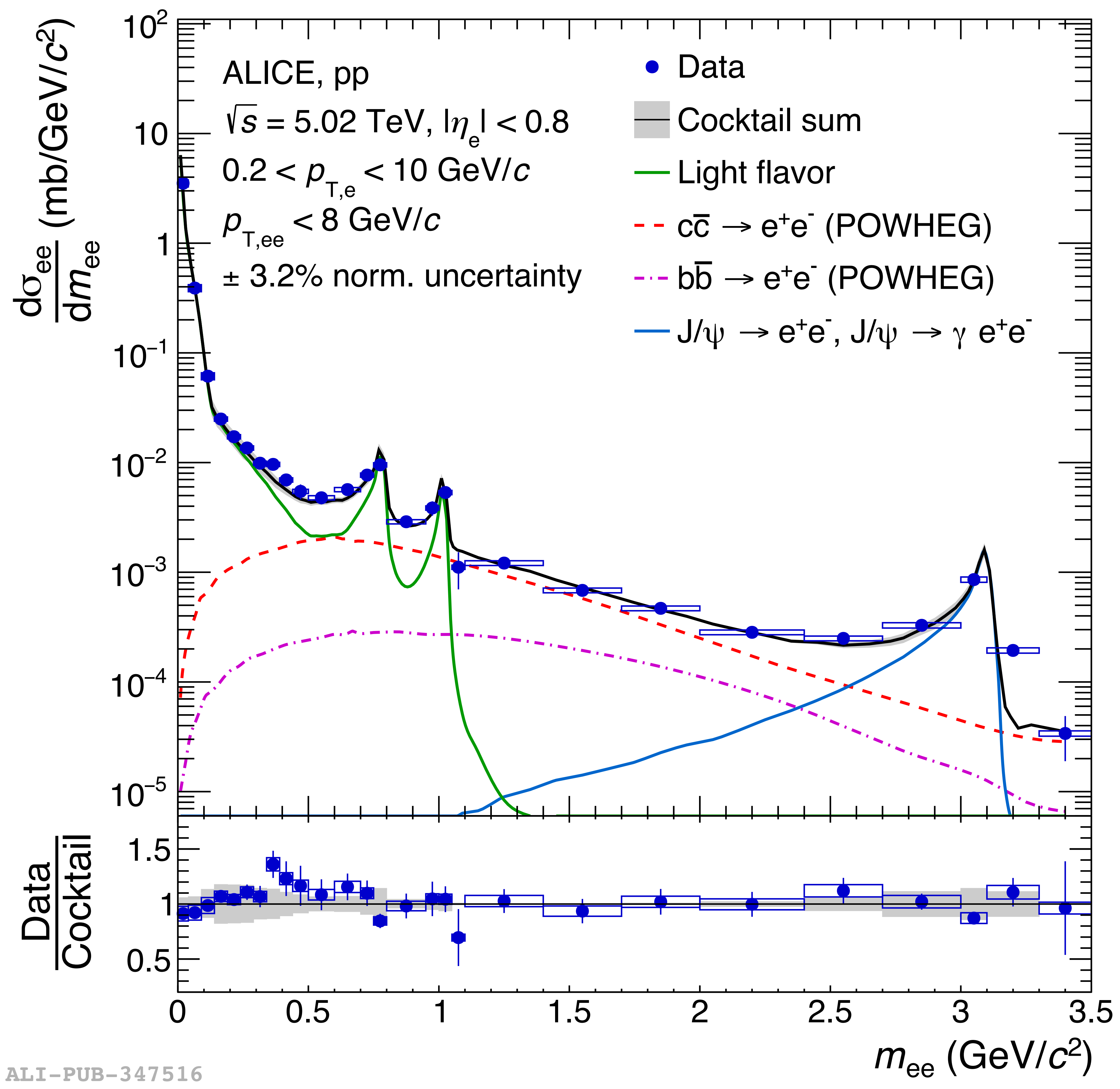

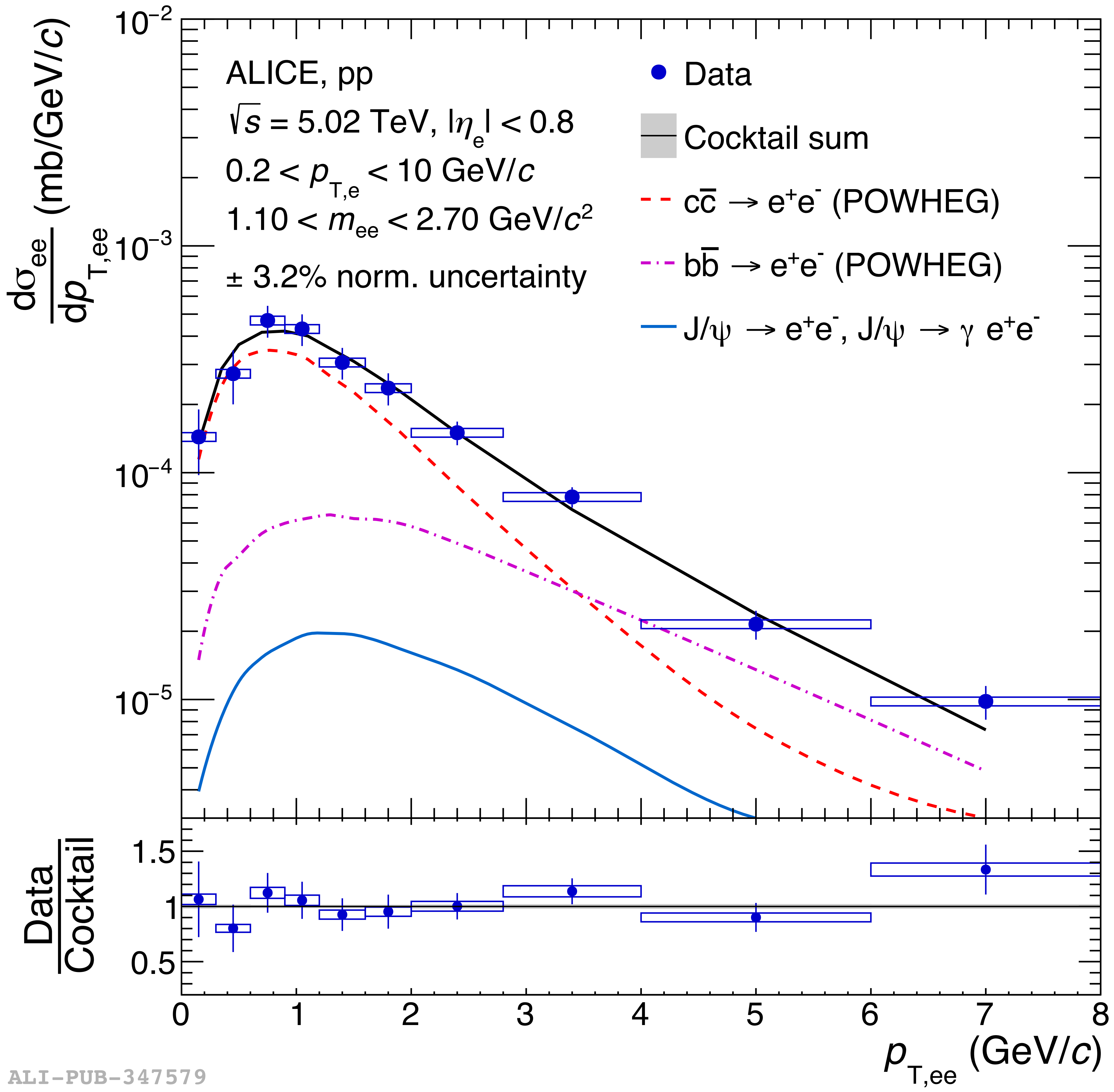

- Open charm and beauty contribution obtained from simultaneous fit of e^+e^- invariant-mass and transverse momentum differential cross section with POWHEG or PYTHIA templates

Dielectrons: arXiv:2005.11995
PYTHIA6: JHEP 05 (2006) 026
POWHEG: JHEP 11 (2007) 070

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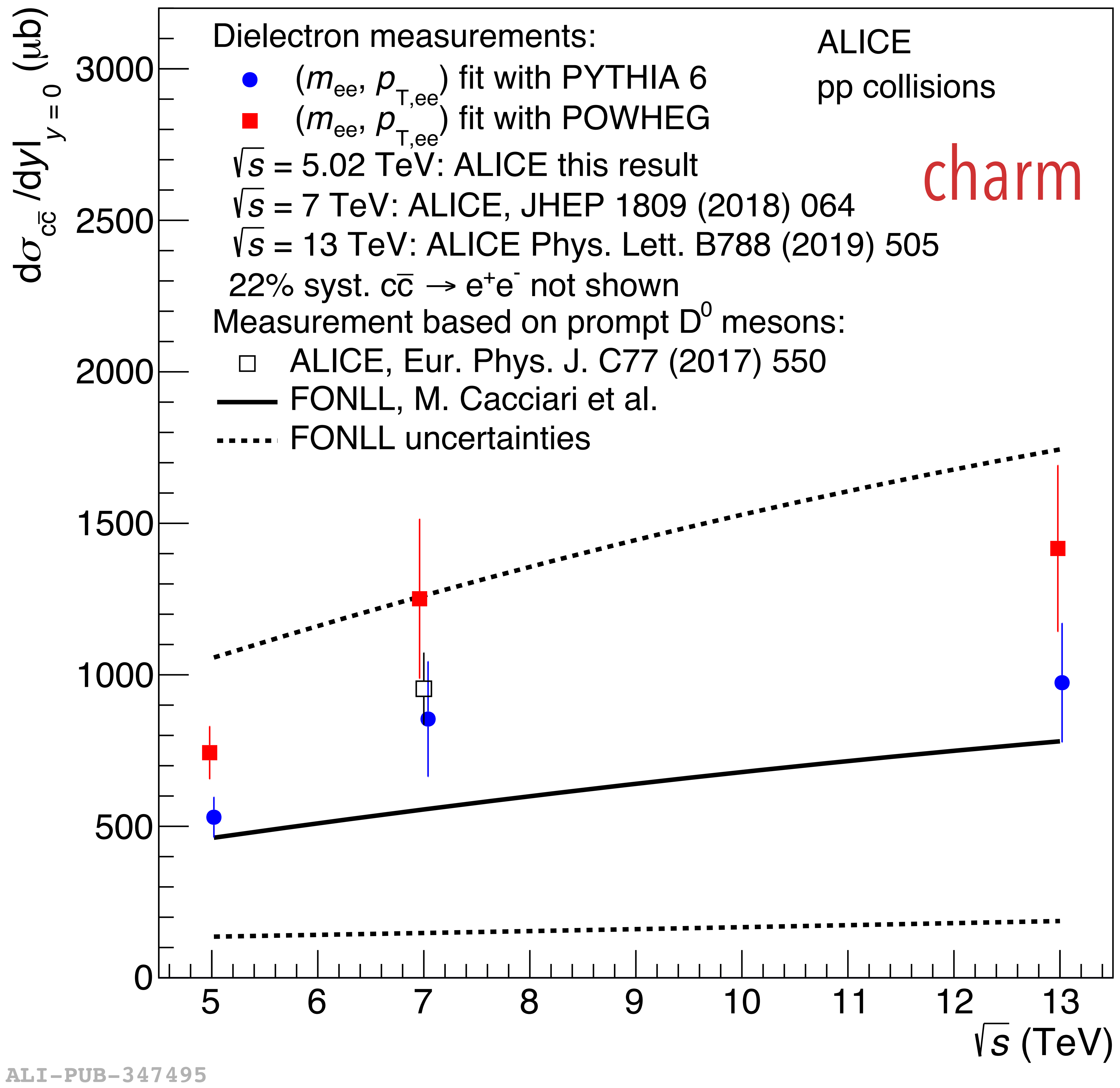

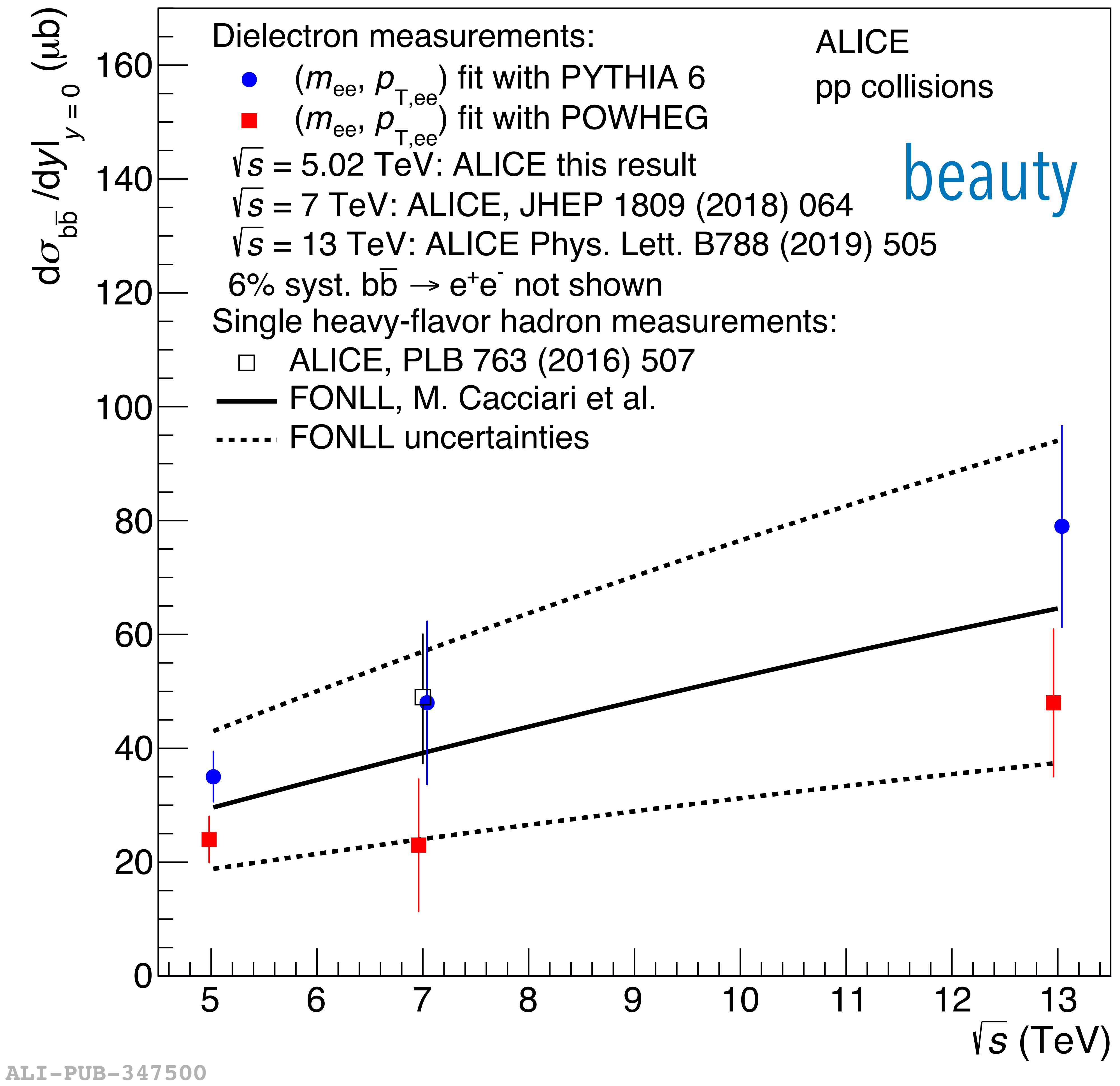

- Measurements of $c\bar{c}$ and $b\bar{b}$ production cross sections at mid rapidity obtained with POWHEG and PYTHIA fits compatible with pQCD (FONLL) predictions
- Compatible with extrapolations from full reconstructed decays for charm and displaced e± for beauty

Dielectrons: arXiv:2005.11995
PYTHIA6: JHEP 05 (2006) 026
POWHEG: JHEP 11 (2007) 070
FONLL: JHEP 1210 (2012) 137

D mesons in pp collisions vs. pQCD calculations

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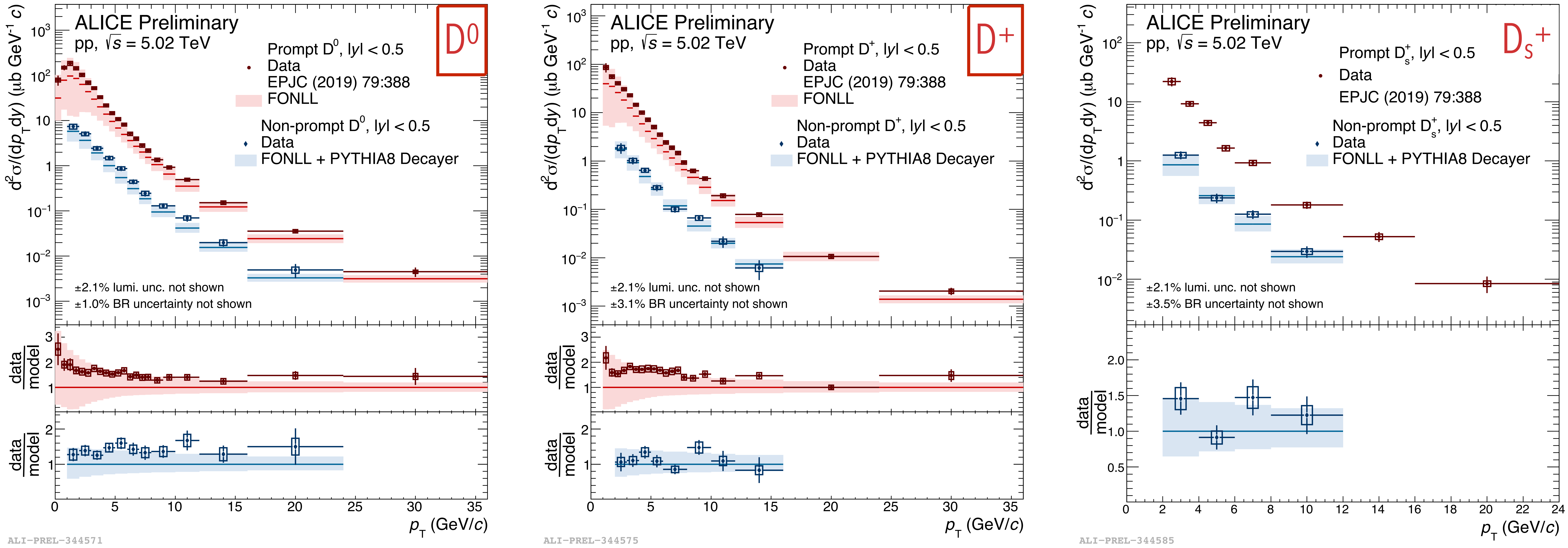
prompt: c → D   non-prompt: b → B → D



- p_T-differential cross section of prompt and non-prompt D mesons described by pQCD (FONLL) calculations down to low p_T
  - ➡ FONLL predictions include fragmentation functions from e⁺e⁻ measurements

Prompt D mesons: EPJC (2019) 79:378
FONLL: JHEP 1210 (2012) 137

In-medium energy loss: D meson nuclear modification factor

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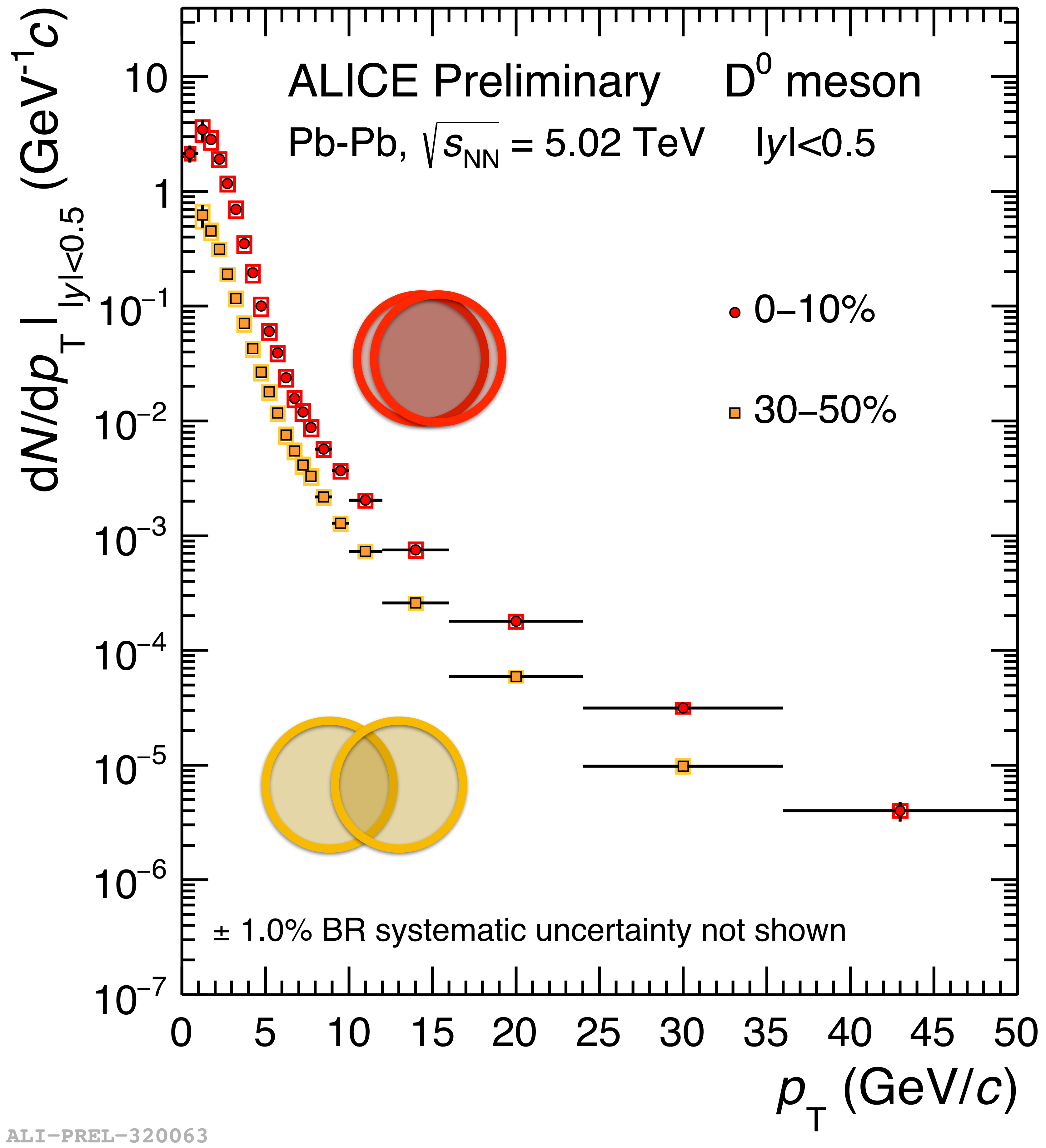
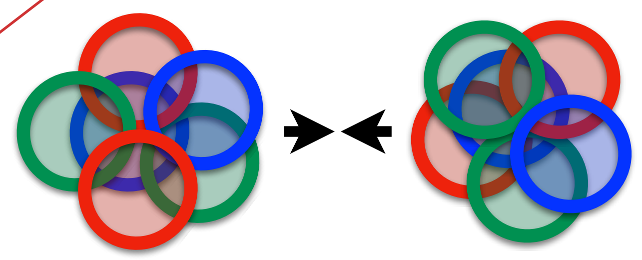
production yield in heavy-ion collisions



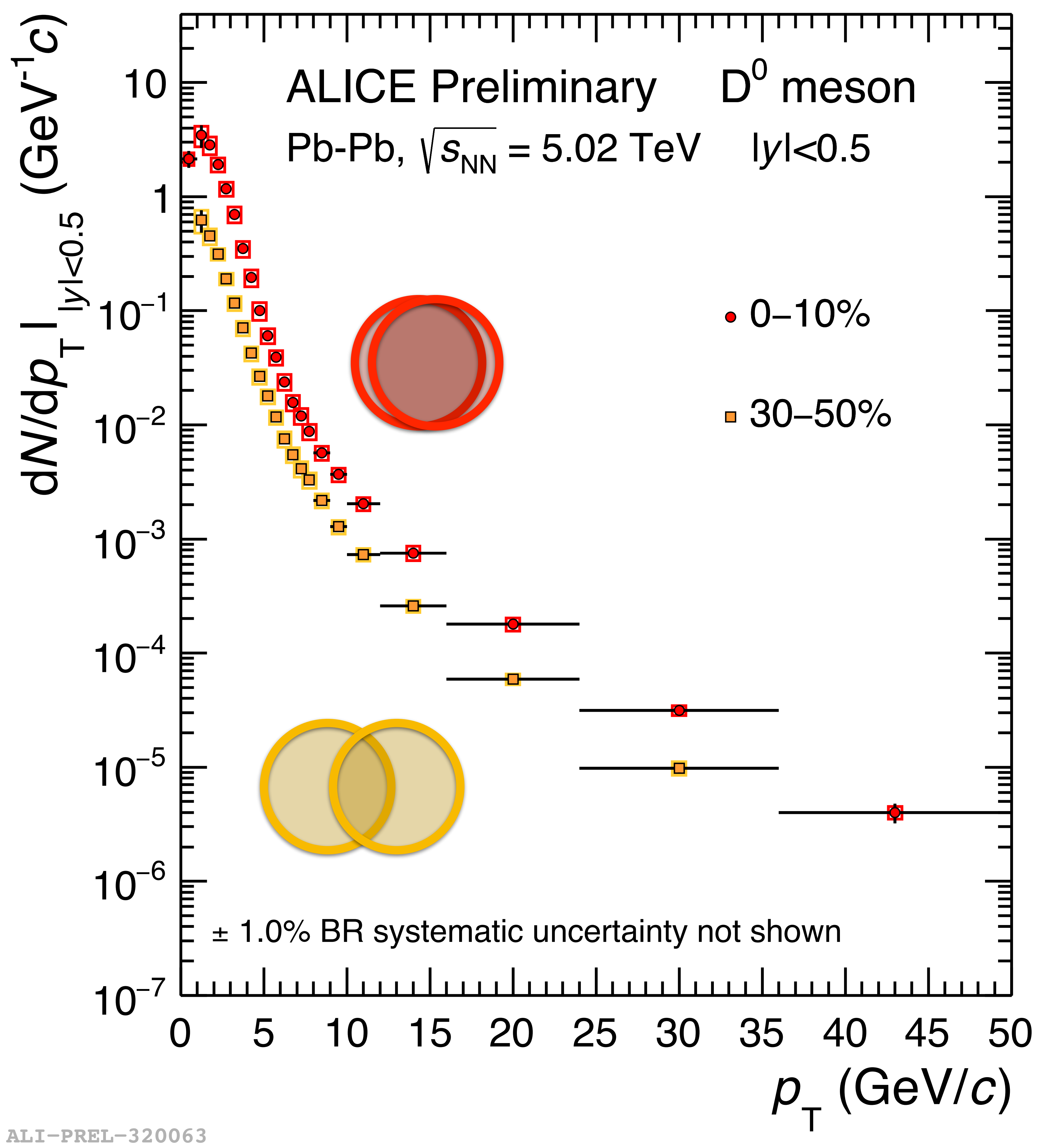


$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

production yield in pp collisions

binary nucleon-nucleon collisions

- For hard processes expected equal unity if no modifications induced by the nuclear environment (N_{coll} *scaling*) production yield in heavy-ion collisions



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production yield in pp collisions

binary nucleon-nucleon collisions

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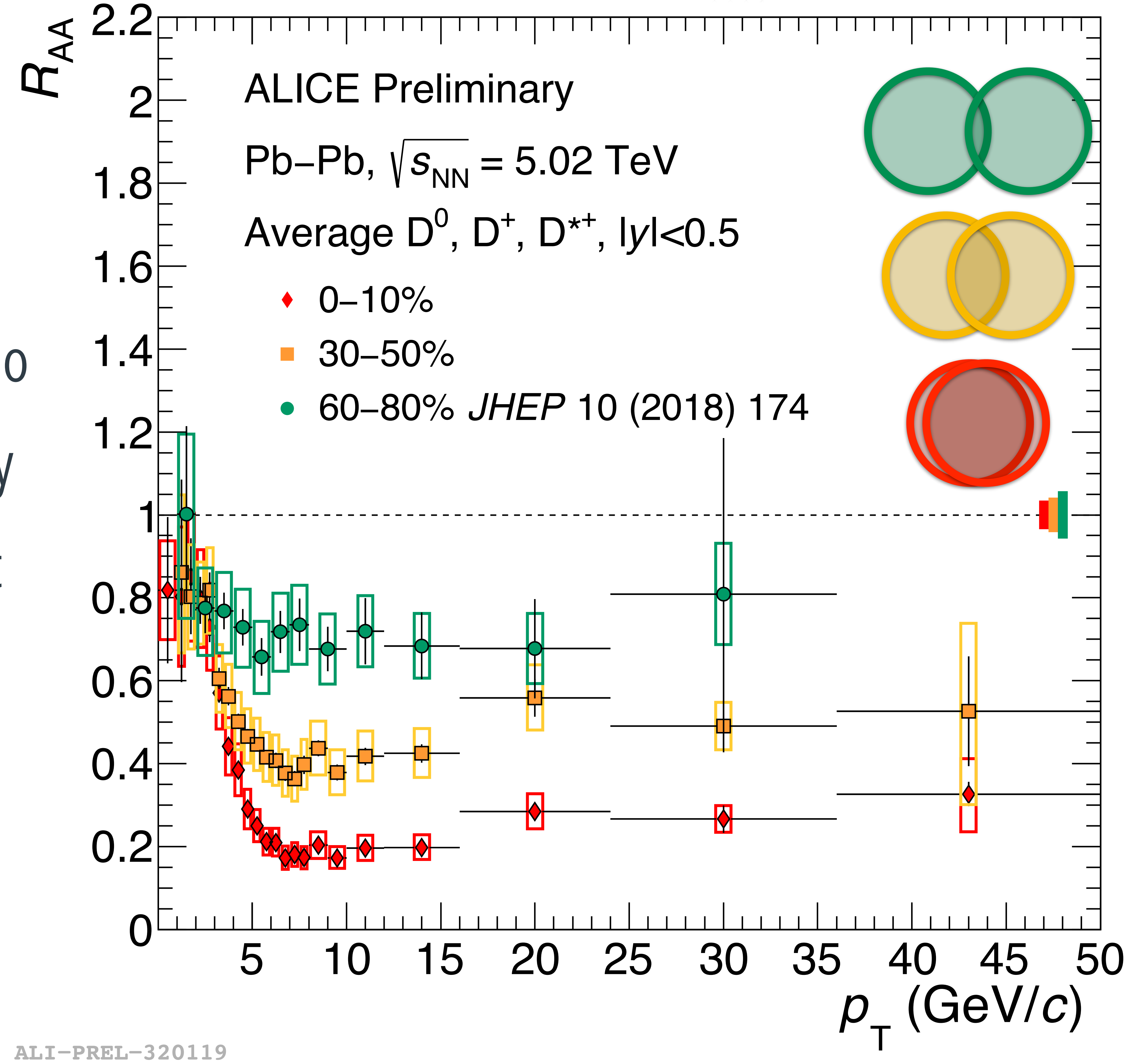
JHEP 10 (2018) 174



- Increasing suppression of D yields for $p_T > 3$ GeV/c in more central collisions
  - ➡ in-medium energy loss shifts p_T distribution to lower p_T

In-medium energy loss: D meson nuclear modification factor

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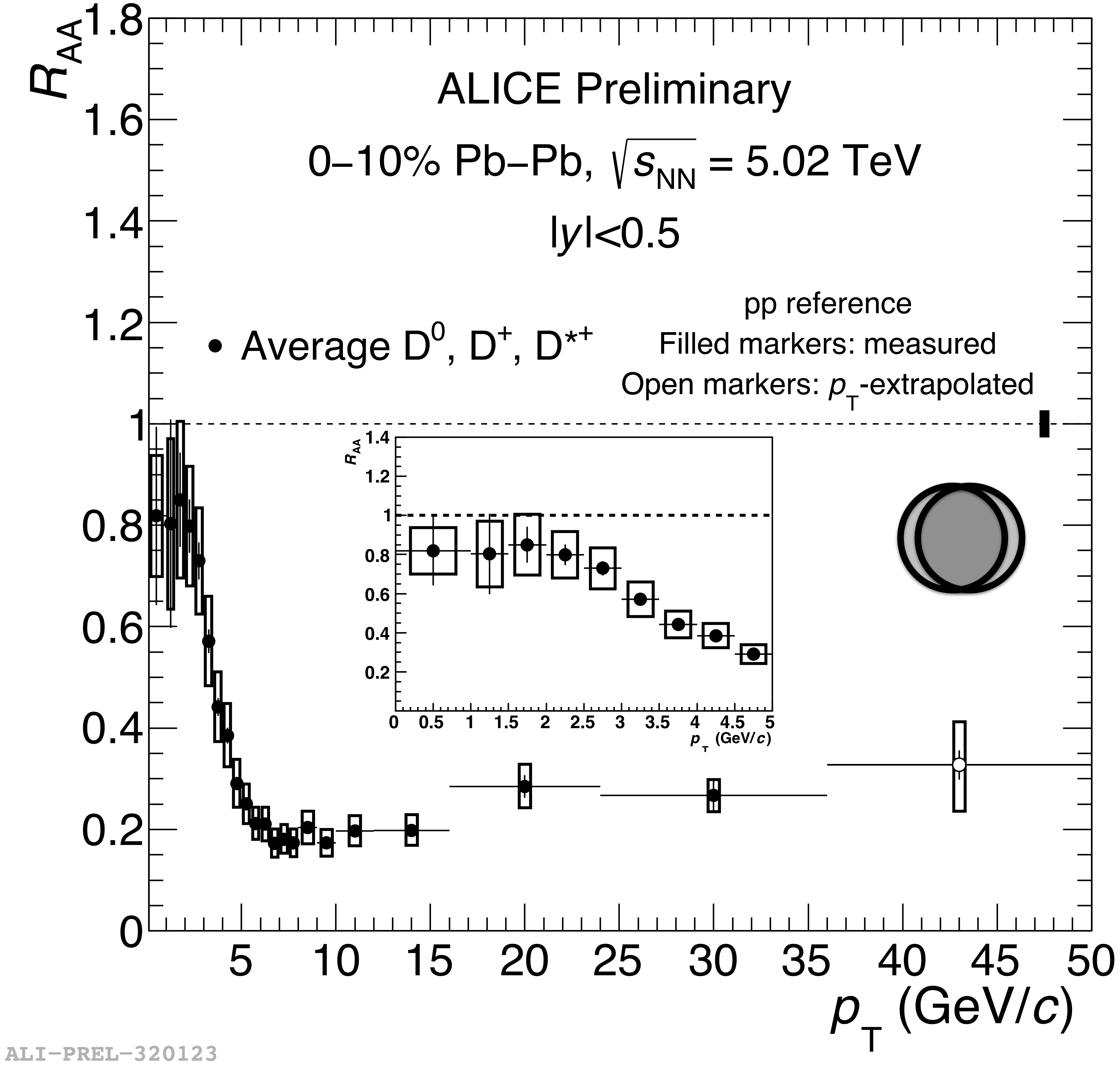
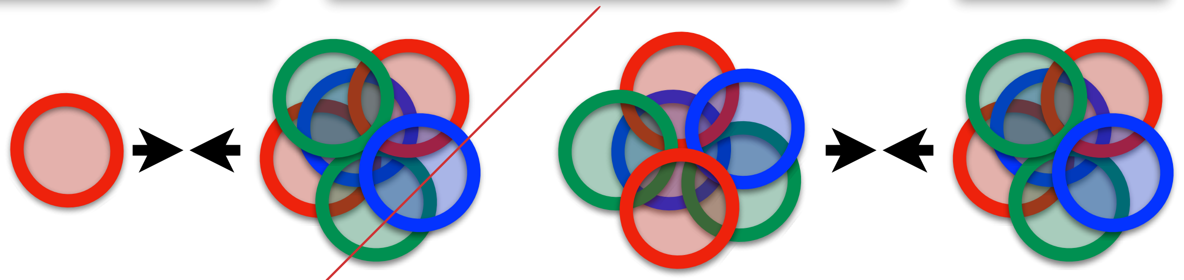
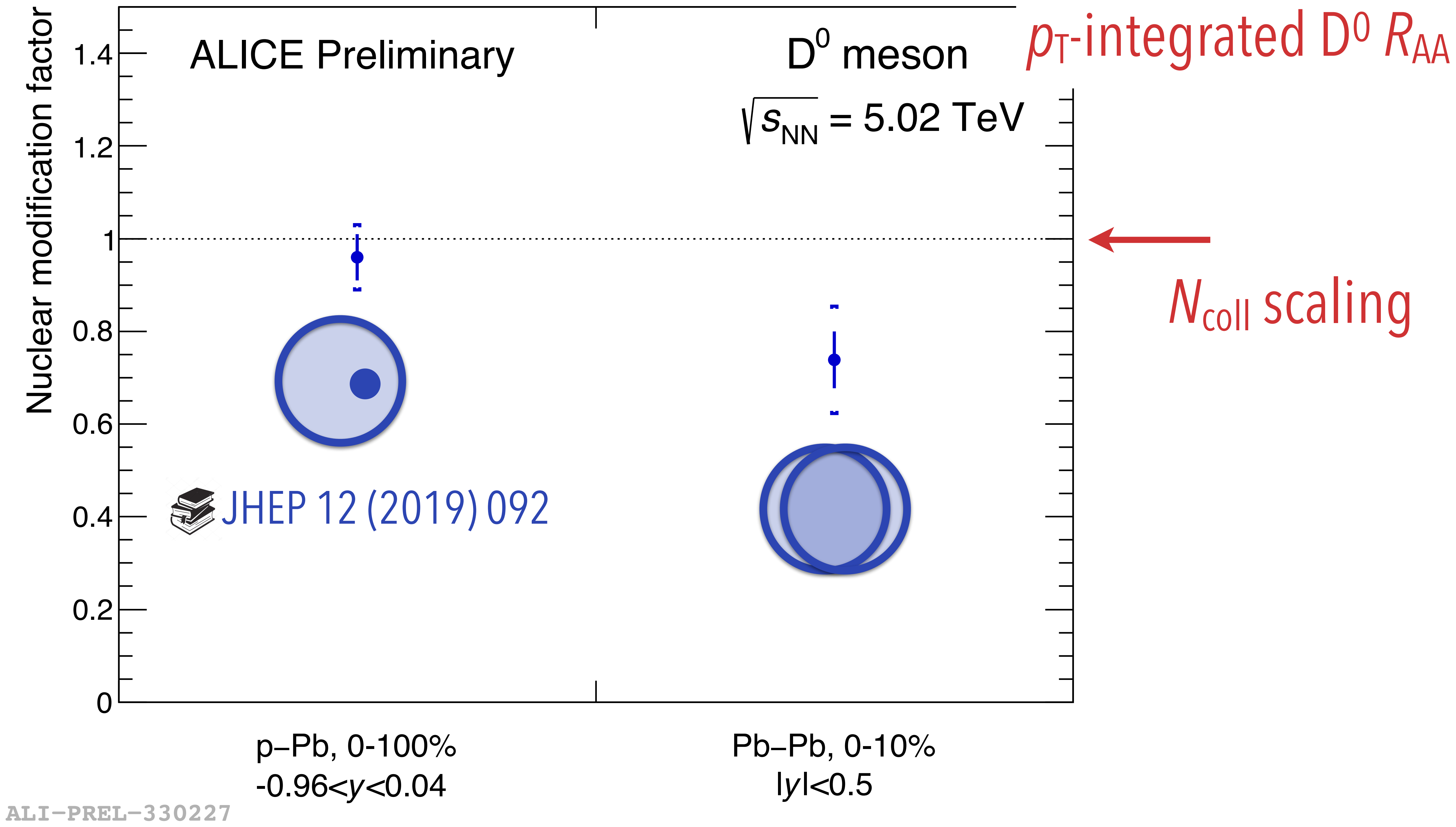
- D^0 R_{AA} measured down to $p_T = 0$



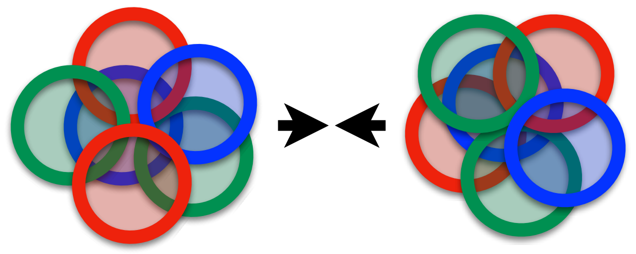
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

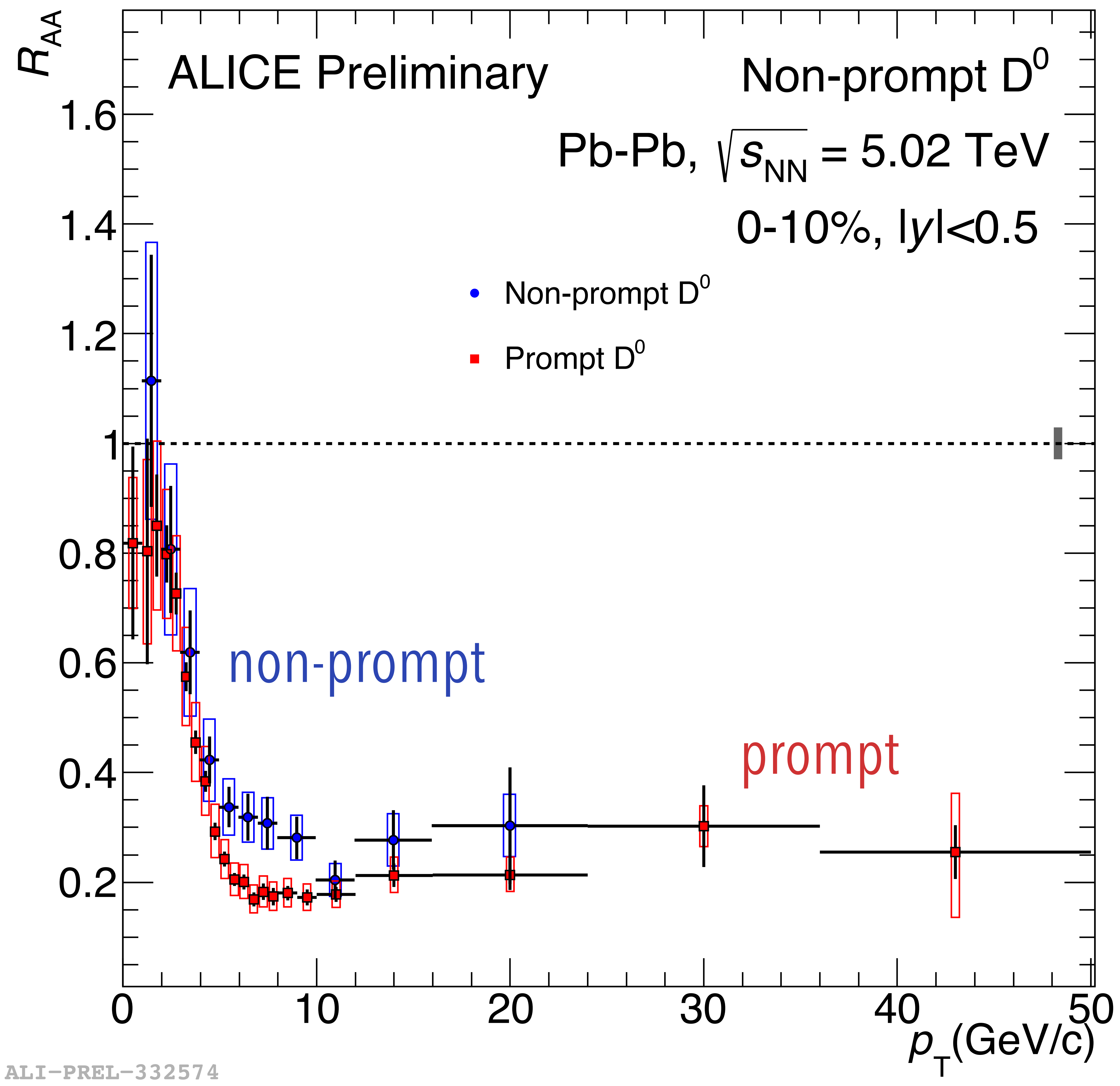




- Hint of p_T-integrated D^0 R_{AA} in central Pb-Pb collisions < 1 and < R_{pPb}
  - ➡ modification of charm hadronisation in the QGP?

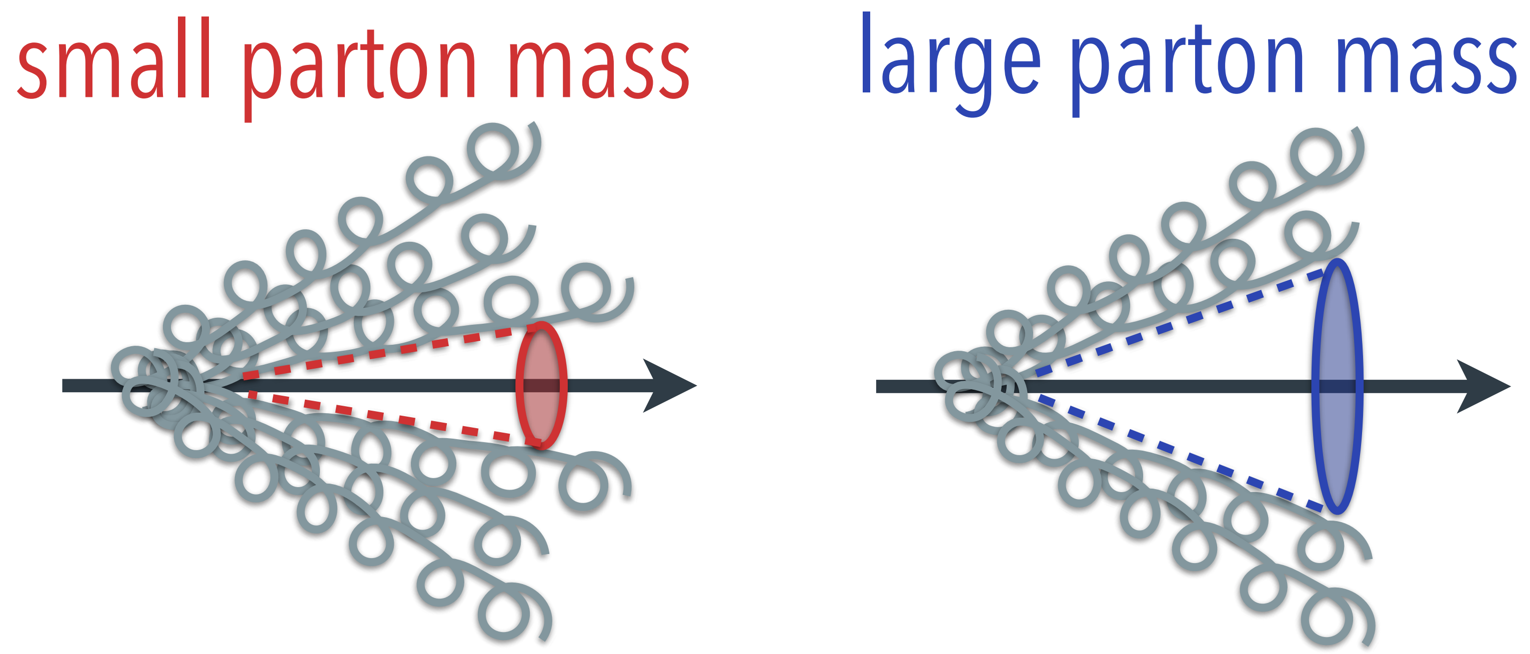
In-medium energy loss: charm vs. beauty



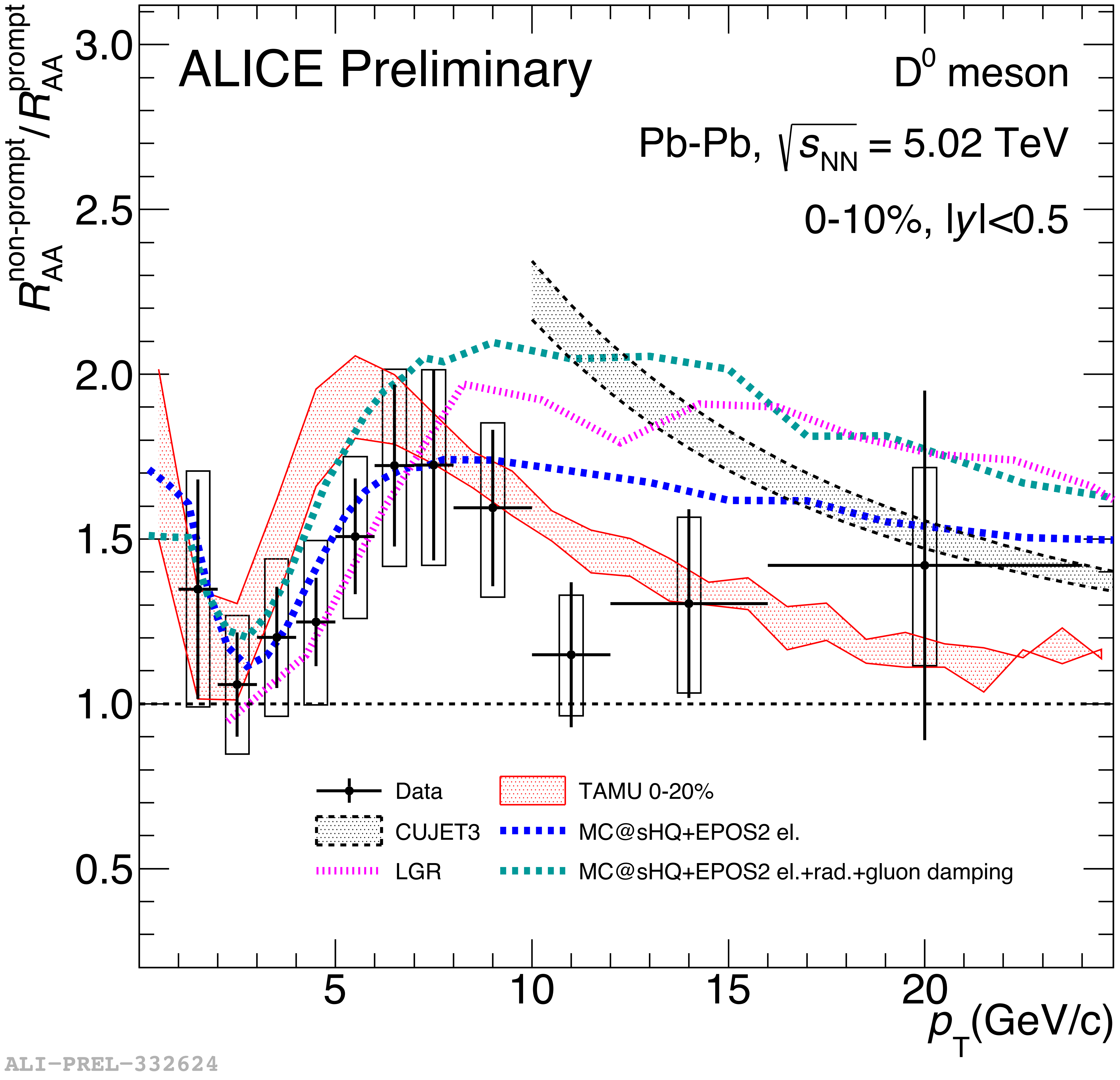


$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

- R_{AA} (prompt D) < R_{AA} (non-prompt D)
  - ➡ parton-mass dependence of energy loss
    - dead cone effect: gluon radiation suppressed for small angles (ϑ < m/E)
    - direct observation of dead cone effect with D^0-tagged jets → Laura Havener CERN-EP seminar today 11h30

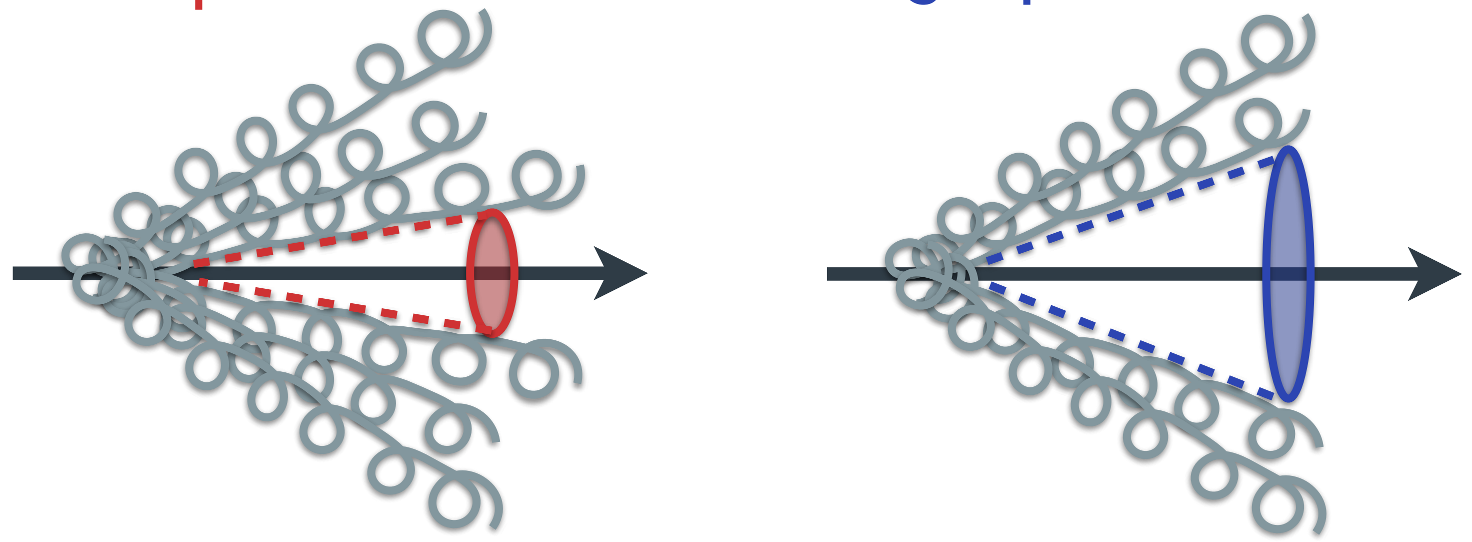


In-medium energy loss: charm vs. beauty



- CUJET3.0: JHEP02(2016)169
- LGR: arXiv:1912.08965
- TAMU: PLB 735 (2014) 445-450
- MC@sHQ+EPOS2: PRC 89 (2014) 014905

- R_{AA} (prompt D) < R_{AA} (non-prompt D)
  - ➡ p_T < 5 GeV/c: different decay kinematics / radial flow
  - ➡ p_T > 5 GeV/c: smaller energy loss for beauty than charm
  - ➡ described by models including collisional and radiative energy loss



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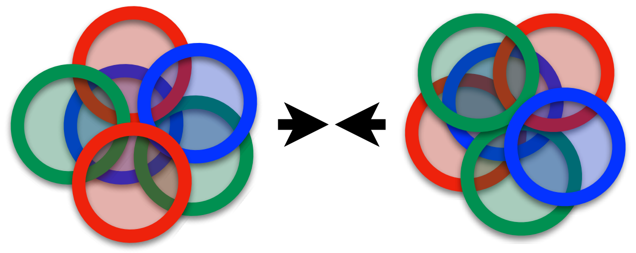


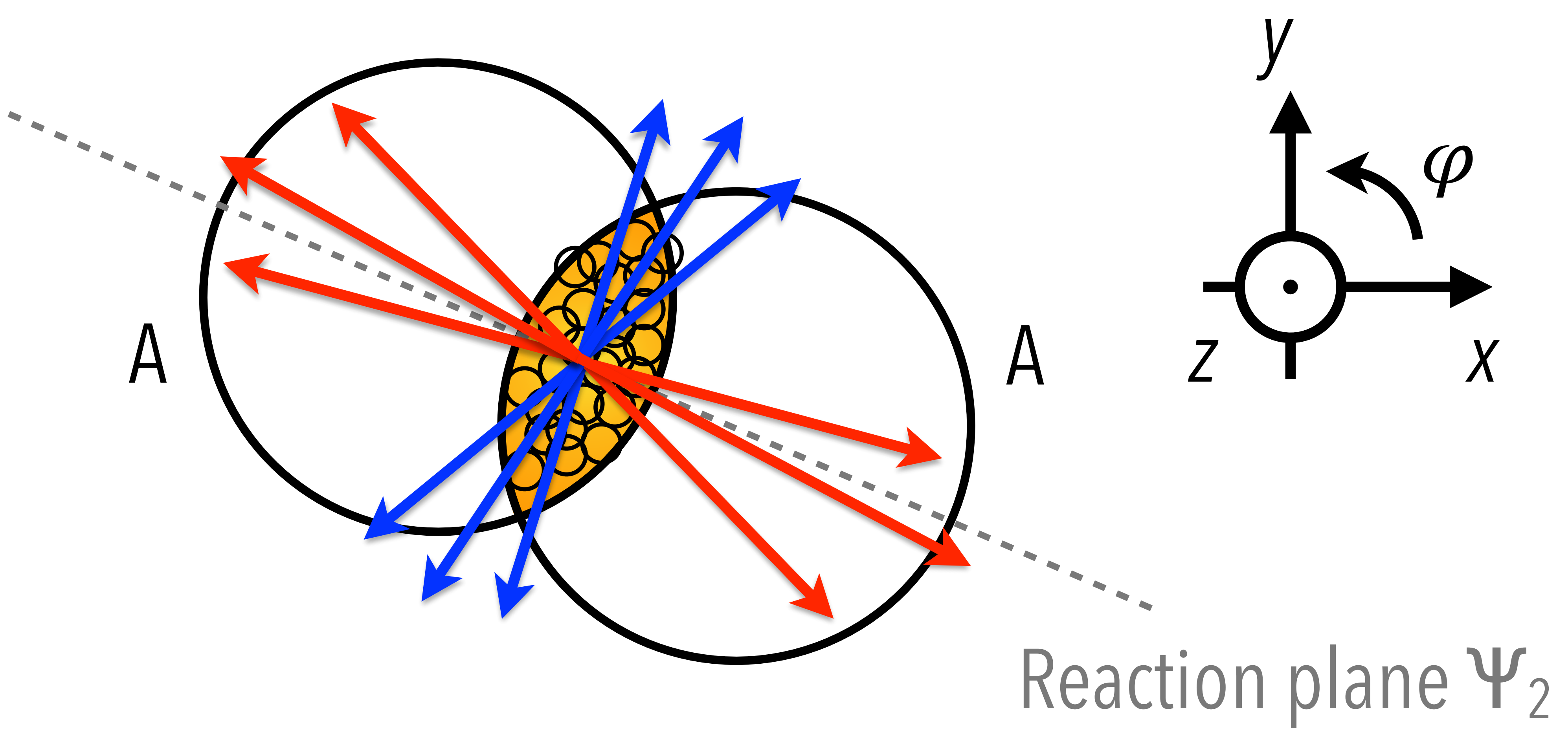
- The interaction region exhibits a geometrical anisotropy
- The initial geometrical anisotropy is transferred to a momentum anisotropy by the pressure gradients

Z.Phys.C 70 (1996) 665-672
NPA 590 (1995) 561c-564c
PRC 58 (1998) 1671–1678

$$E\frac{d^3N}{dp_T} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left\{1 + \sum_{i=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]\right\}$$

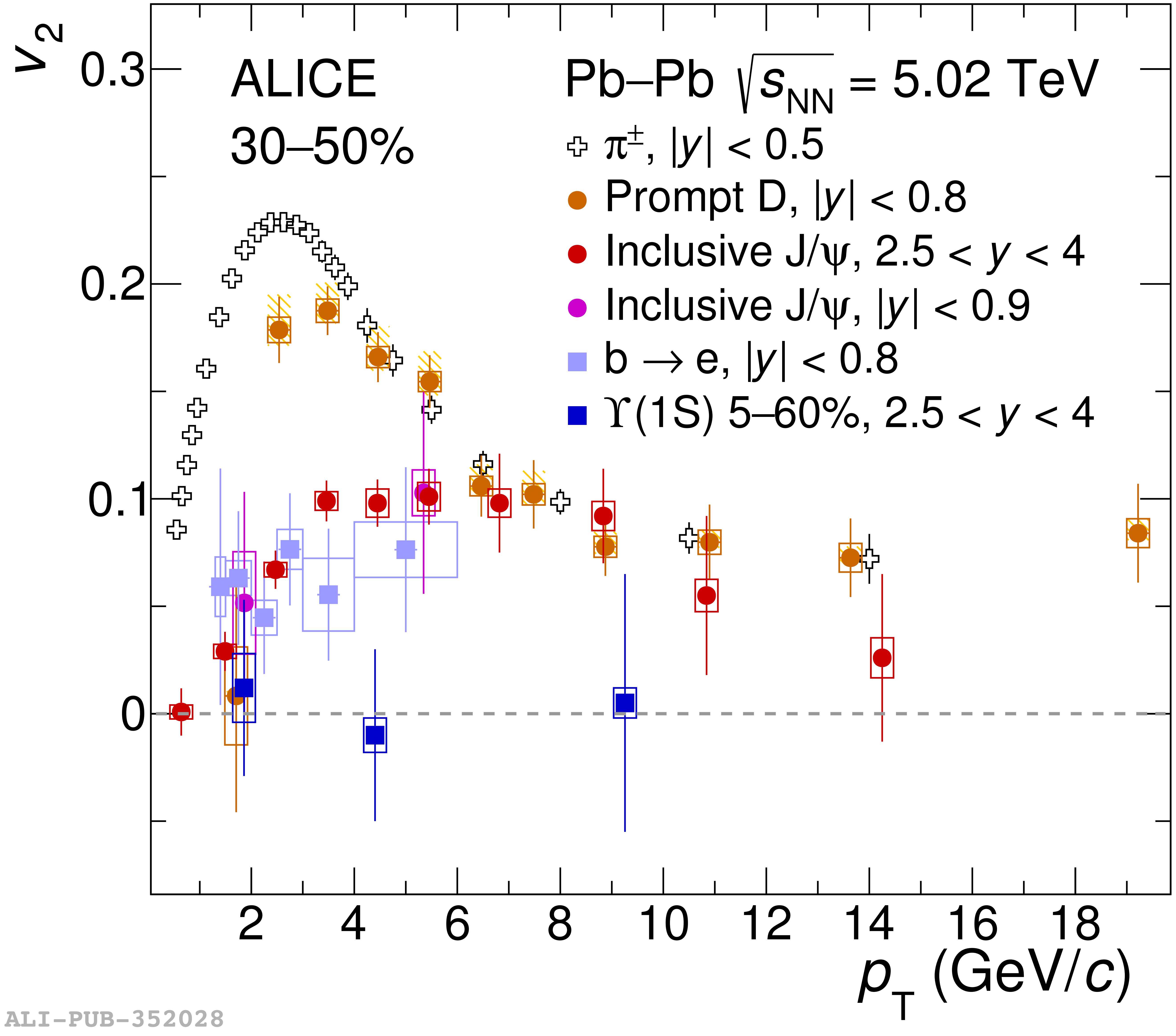
$$v_2 = \langle\cos[2(\varphi - \Psi_2)]\rangle$$

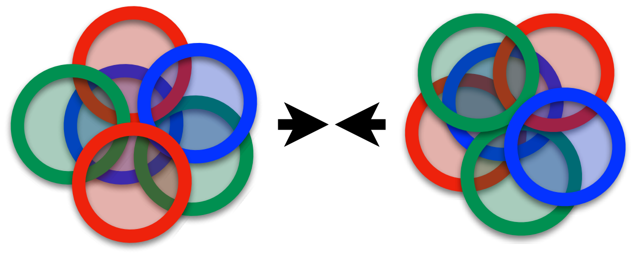
second harmonic coefficient, elliptic flow



- Asymmetry of particle production between in-plane and out-of-plane directions
  - ➡ low p_T: participation of the heavy quarks to the collective motion of the system and their possible thermalisation
  - ➡ high p_T: path-length dependence of in-medium parton energy loss

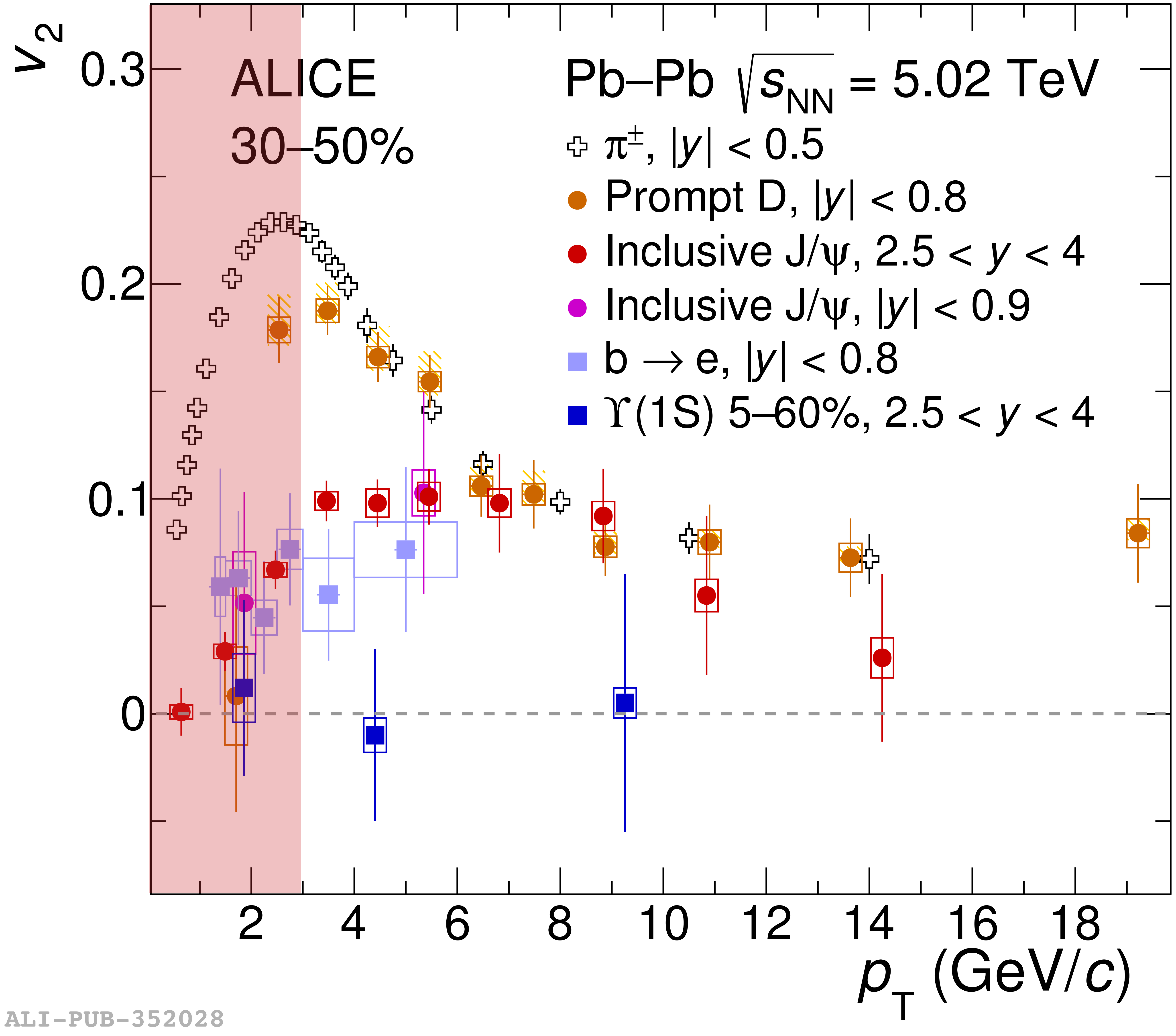
Elliptic flow of HF particles

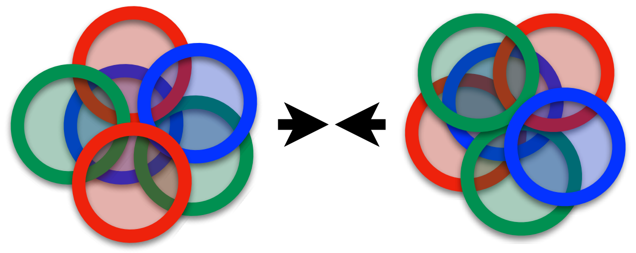




- Positive v_2 for open HF particles
- Positive v_2 for J/ψ, compatible with zero for ϒ(1S)

D: arXiv:2005.11131
e←b: arXiv:2005.11130
π: JHEP 09 (2018) 006
J/ψ: arXiv:2005.14518
ϒ(1S): PRL 123 (2019)192301





- Positive v_2 for open HF particles
- Positive v_2 for J/ψ, compatible with zero for ϒ(1S)

- p_T < 3 GeV/c: ordering with mass

  $v_2(\Upsilon) \lesssim v_2(e \leftarrow b) \approx v_2(J/\psi) < v_2(D) < v_2(\pi^{\pm})$

D: arXiv:2005.11131
e←b: arXiv:2005.11130
π: JHEP 09 (2018) 006
J/ψ: arXiv:2005.14518
ϒ(1S): PRL 123 (2019)192301

Elliptic flow of HF particles

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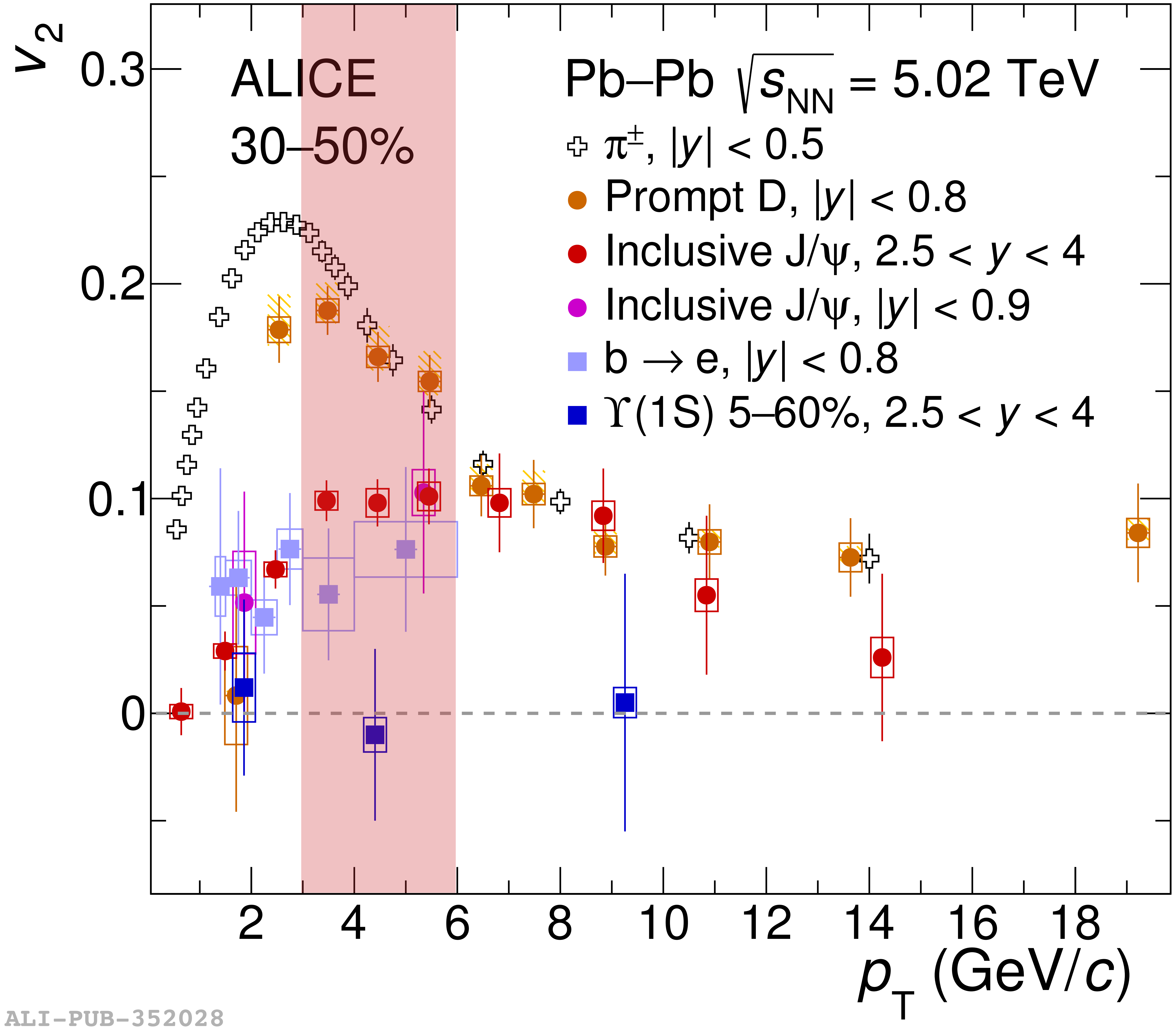

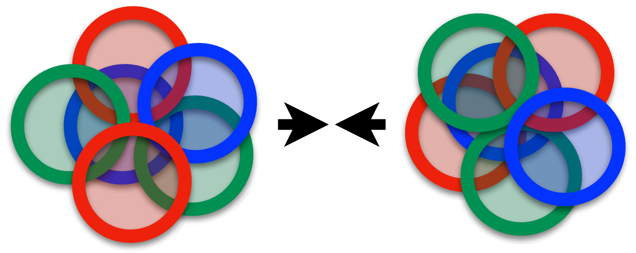

- Positive v_2 for open HF particles
- Positive v_2 for J/ψ, compatible with zero for ϒ(1S)
- p_T < 3 GeV/c: ordering with mass
  v_2(ϒ) ≲ v_2(e←b) ≈ v_2(J/ψ) < v_2(D) < v_2($\pi^\pm$)
- 3 < p_T < 6 GeV/c: heavy-quark hadronisation via coalescence with flowing light quarks
  - ➡ v_2(J/ψ) < v_2(D) ≈ v_2($\pi^\pm$)
  - ➡ v_2(ϒ) < v_2(e←b)

D: arXiv:2005.11131
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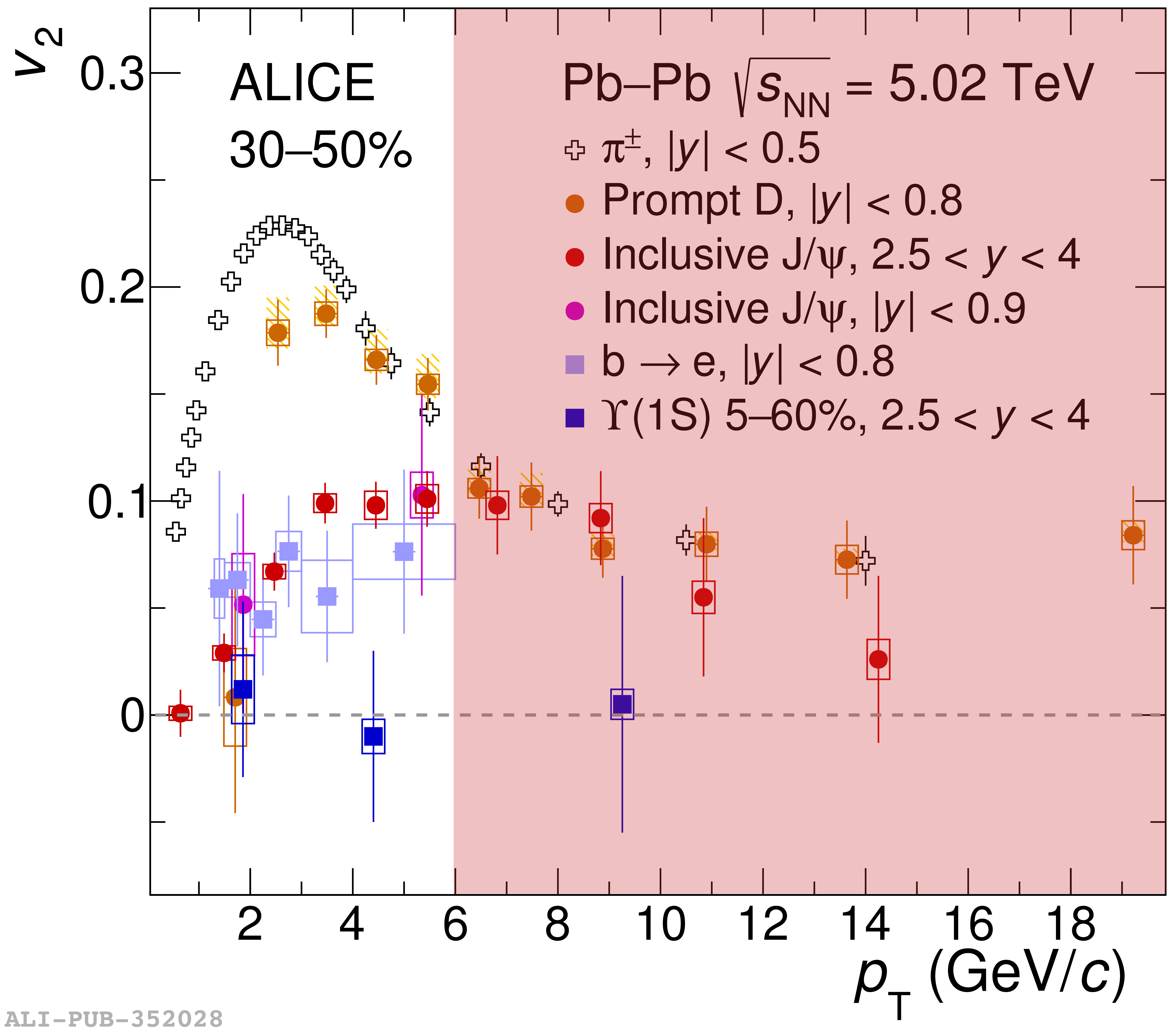

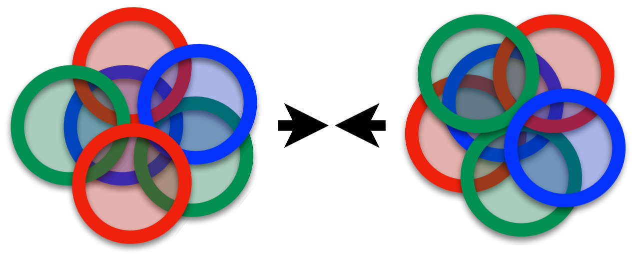

- Positive v_2 for open HF particles
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- p_T < 3 GeV/c: ordering with mass
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  - ➡ $v_2(J/\psi) < v_2(D) \approx v_2(\pi^{\pm})$
  - ➡ $v_2(\Upsilon) < v_2(e \leftarrow b)$
- p_T > 6 GeV/c: similar path-length dependence of energy loss for heavy and light partons
  - ➡ $v_2(J/\psi) \approx v_2(D) \approx v_2(\pi^{\pm})$

D: arXiv:2005.11131
e←b: arXiv:2005.11130
π: JHEP 09 (2018) 006
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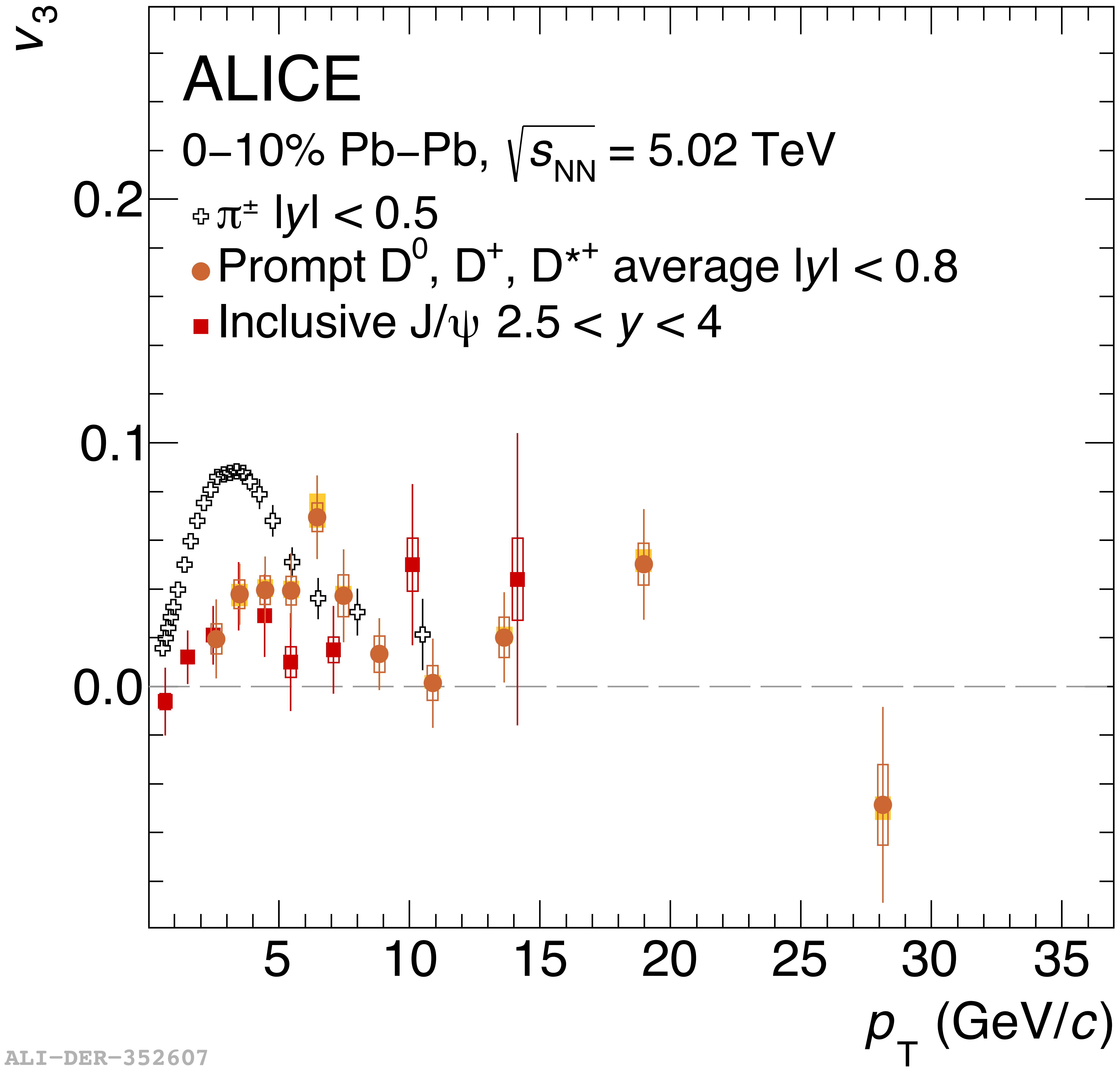
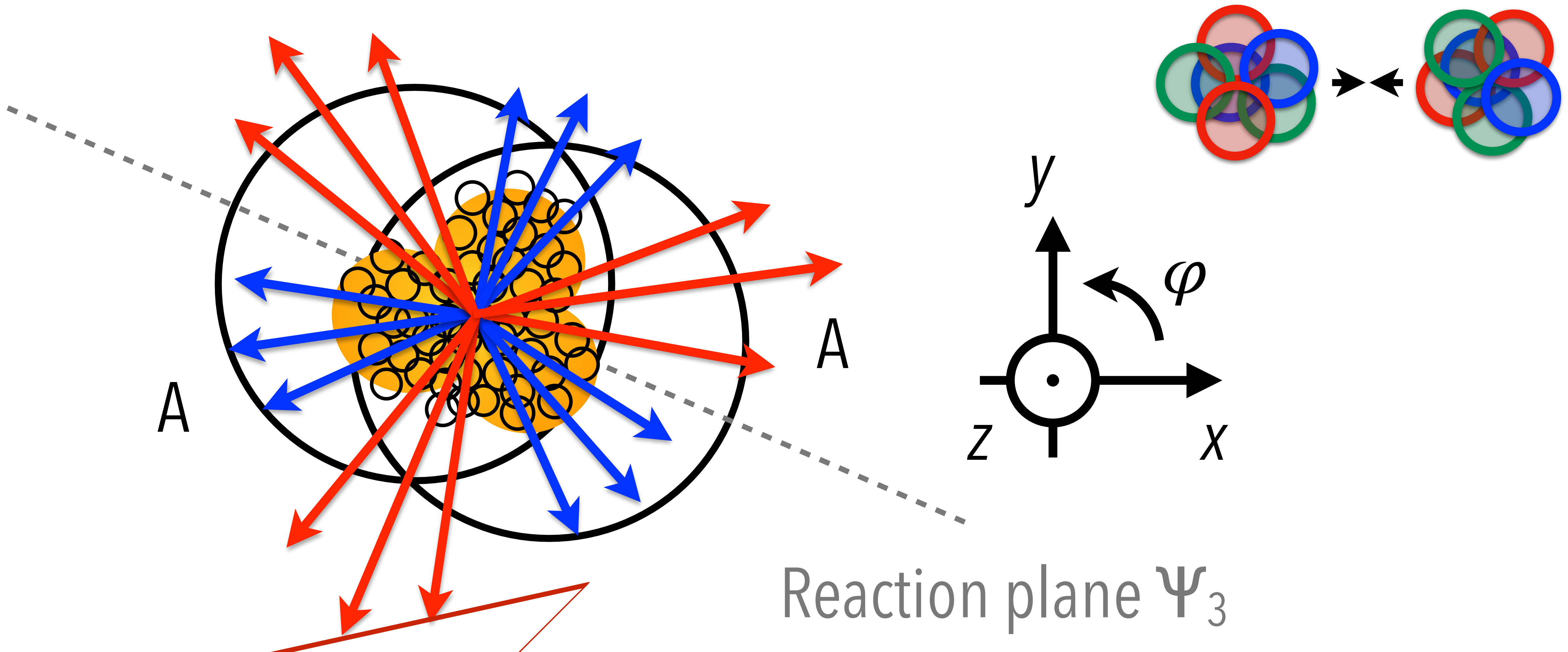


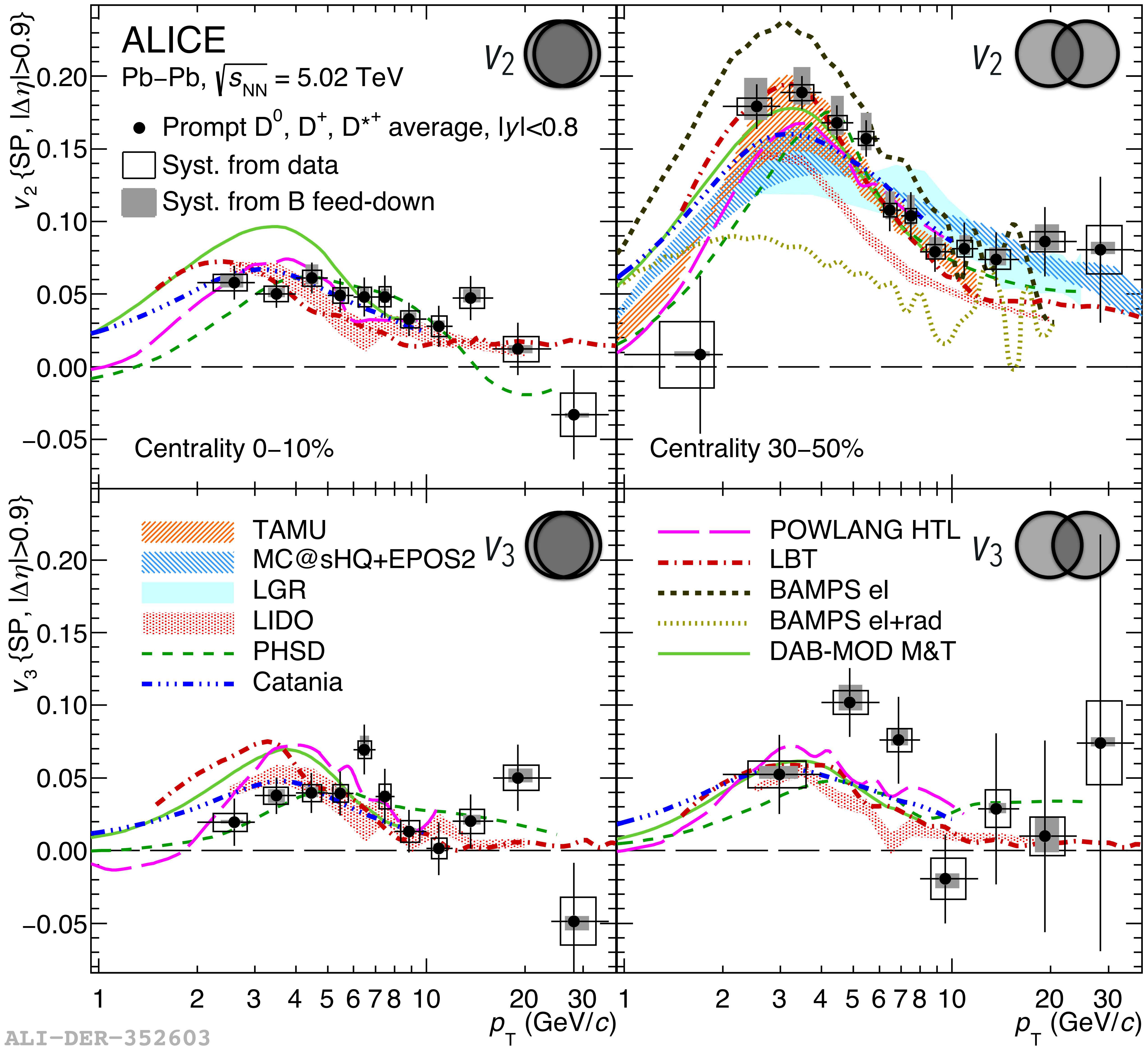


$v_3 = \langle \cos[3(\varphi - \Psi_3)] \rangle$

third harmonic coefficient, triangular flow

- Originated from event-by-event fluctuations in the initial distributions of participant nucleons in the overlap region
- $p_T < 5$ GeV/c: $0 < v_3(J/\psi) \approx v_3(D) < v_3(\pi)$
  - ➡ charm quark sensitive to initial state fluctuations

π: JHEP 09 (2018) 006 D: arXiv:2005.11131 J/ψ: arXiv:2005.14518 arXiv:2005.11131



- Model ingredients:
  - transport of charm quarks in an hydrodynamically expanding medium via Boltzmann or Langevin equations
    - diffusion coefficient D_s related to thermalisation time of charm quark

$$1.5 < 2\pi D_s T_c < 7$$

for models that describe data with χ^2/ndf < 2

$$\tau_{\mathrm{charm}} = (m_{\mathrm{charm}}/T) \cdot D_s = 3 - 14\ \mathrm{fm}/c \approx \tau_{\mathrm{QGP}}$$

  - charm-quark energy loss (elastic and/or inelastic collisions)
  - charm-quark hadronisation via coalescence

TAMU: PRL 124 (2020) 042301
MC@sHQ+EPOS2: PRC 89 (2014) 014905
LGR: arXiv:1912.08965
LIDO: PRC 98 (2018) 064901
PHSD: PRC 93 (2016) 034906
Catania: PLB 805 (2020) 135460
POWLANG: EPJC (2019) 79:494
LBT: PRC 94 (2016) 014909
BAMPS: JPG 42 (2015) 11, 115106
DAB-MOD: arXiv:1906.10768

In-medium hadronisation: strange D mesons

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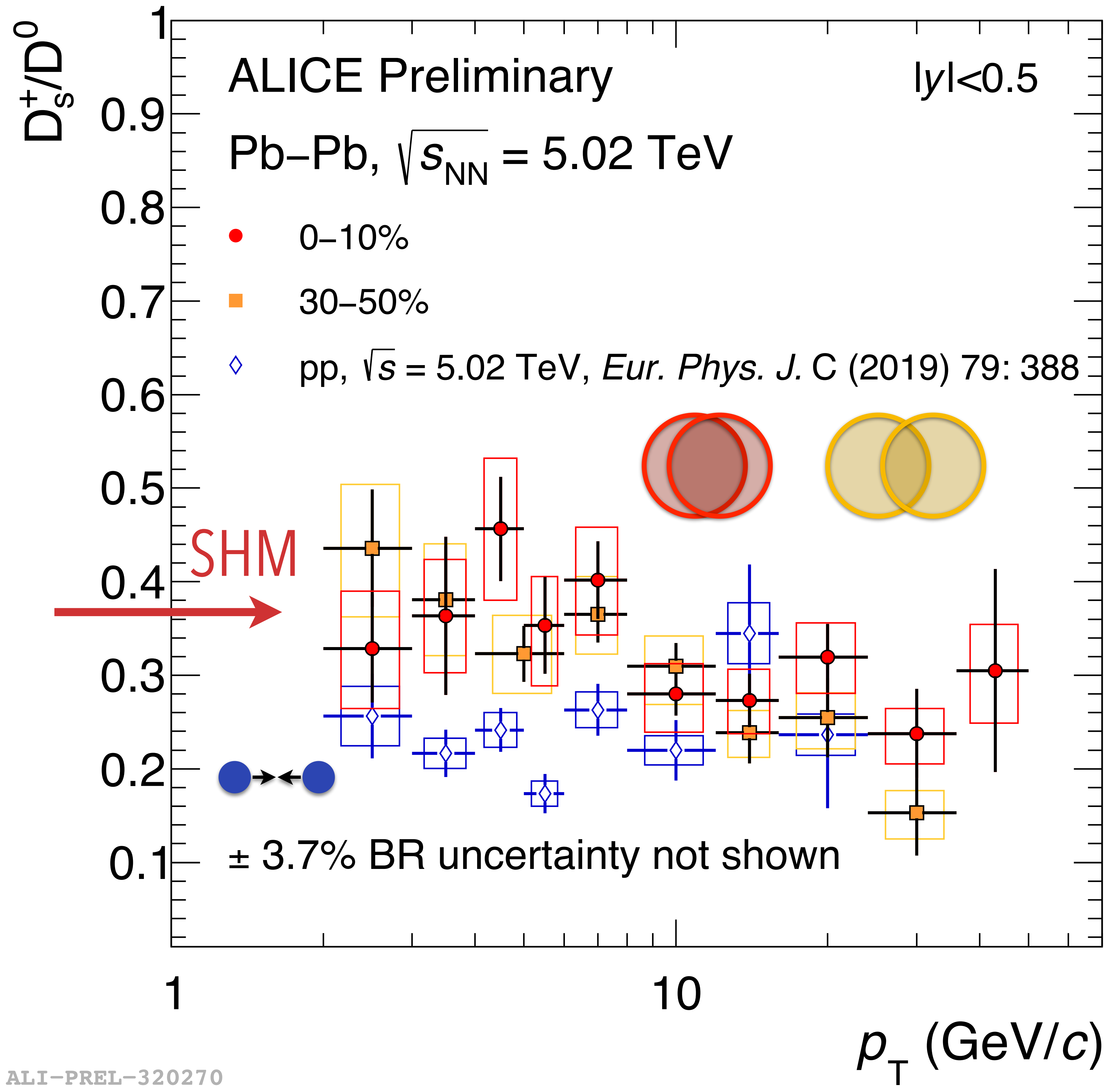
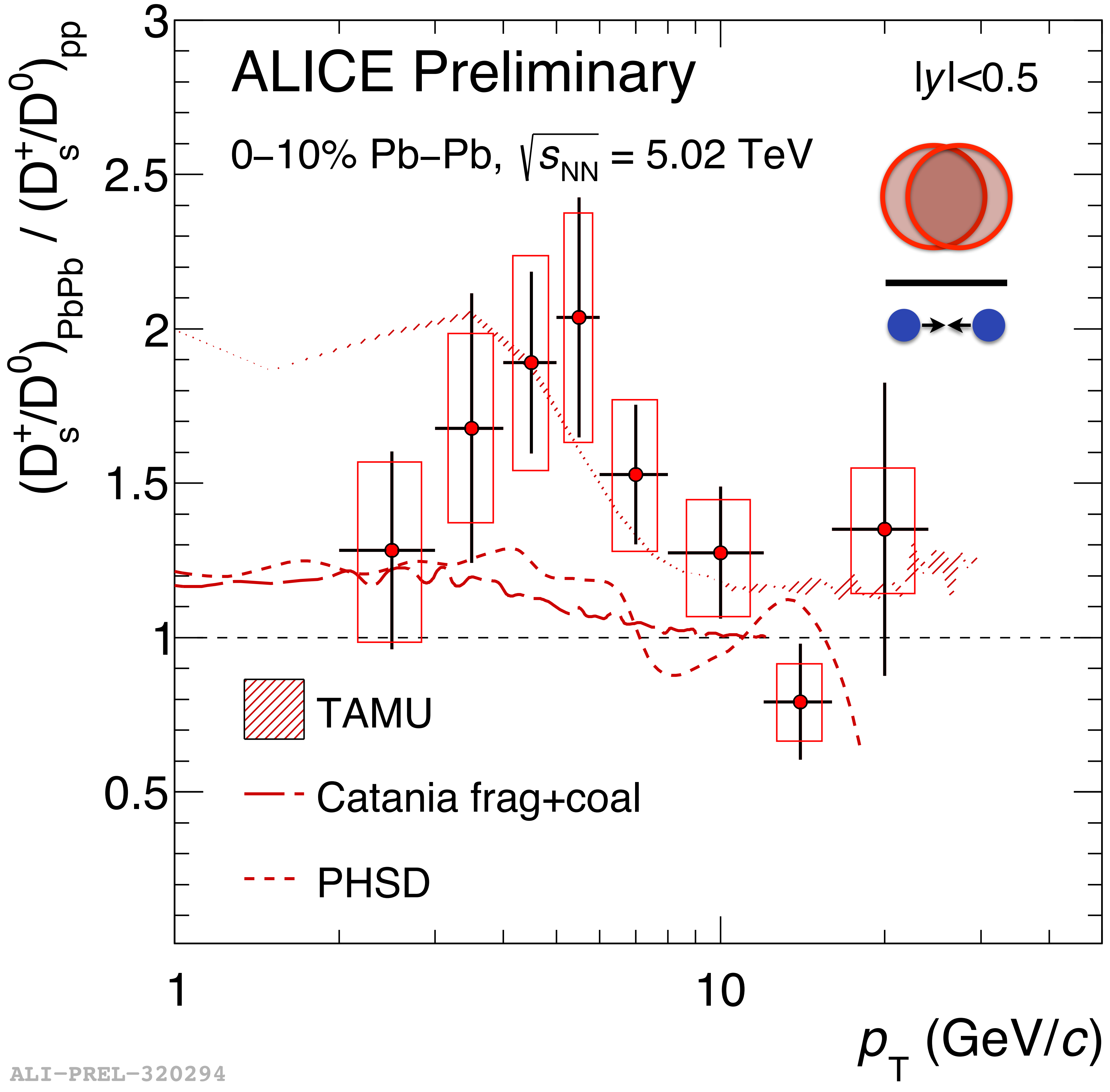
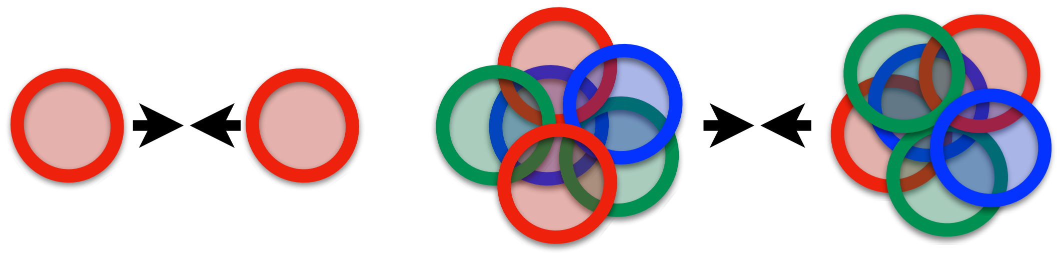
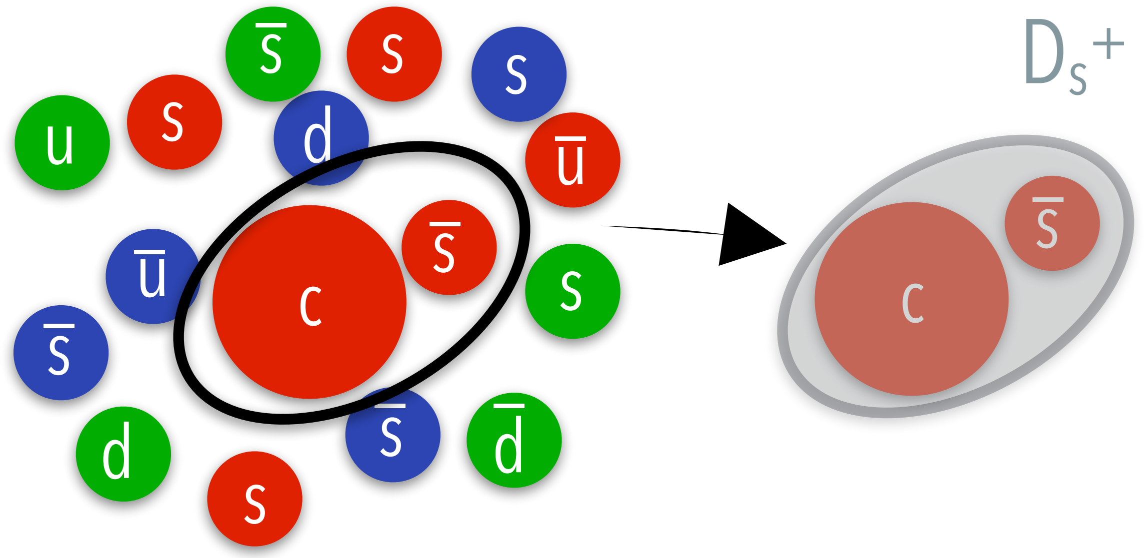




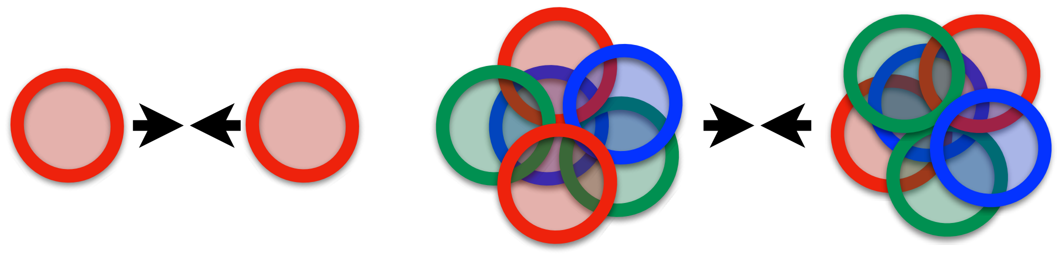


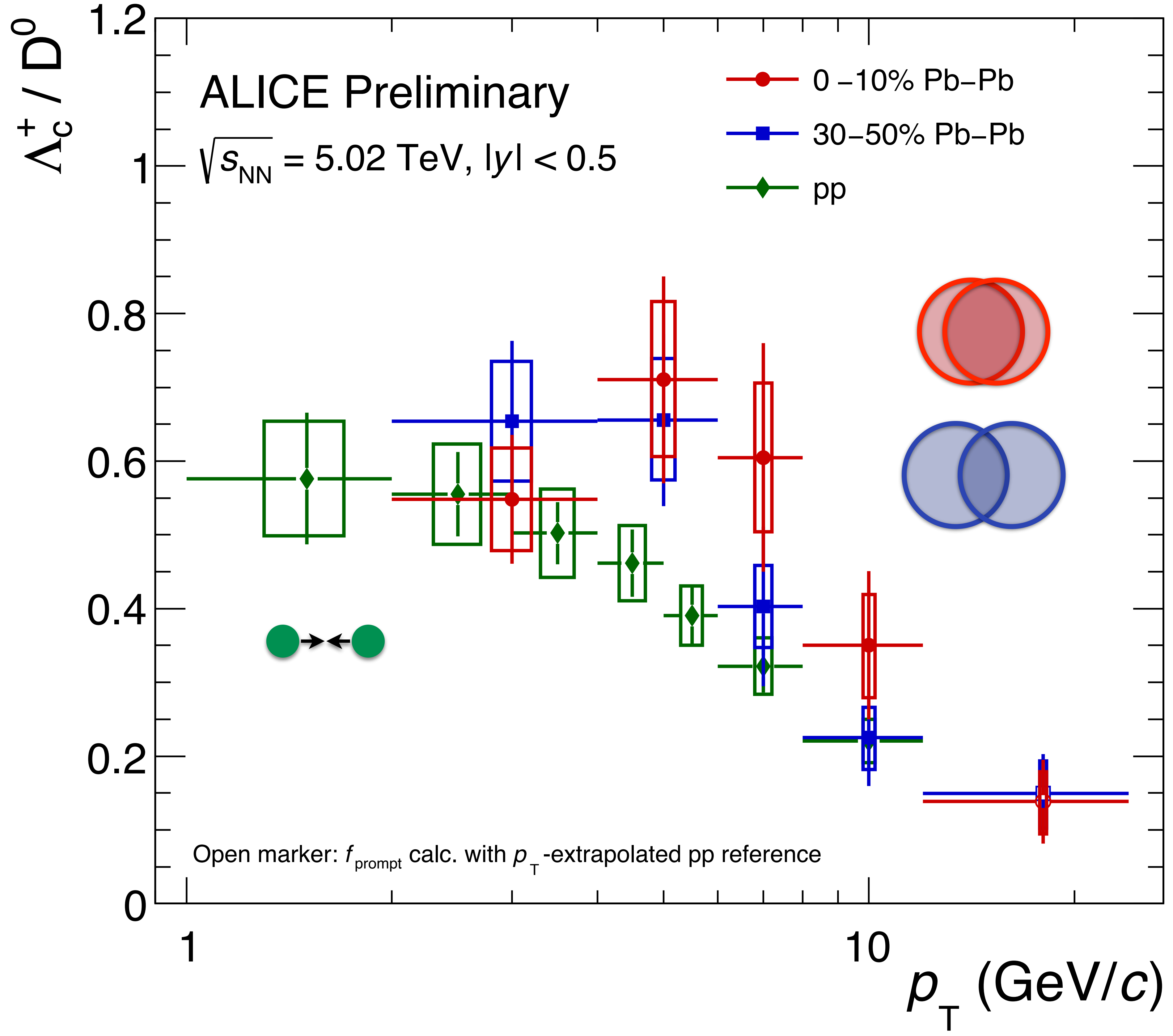
pp: EPJC (2019) 79:378
TAMU: PLB 735 (2014) 445-450
Catania: EPJC 78 (2018) 348
PHSD: PRC 93 (2016) 034906



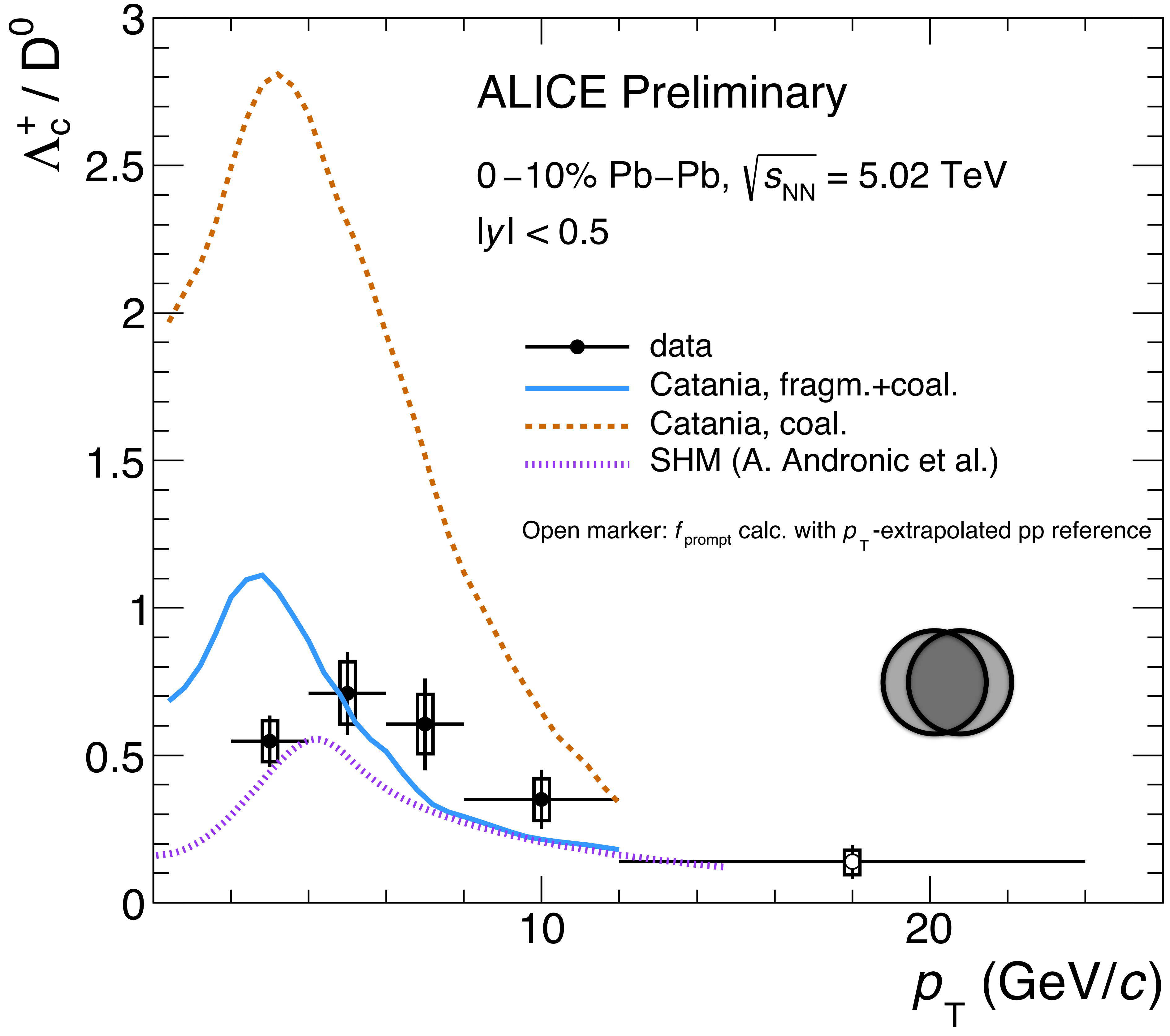
- Enhanced production of strange and multi-strange hadrons observed in heavy-ion collisions
- Hint of enhanced D_s^+/D^0 in Pb-Pb compared to pp collisions for $p_T < 8$ GeV/c
- Qualitatively described by models implementing charm-quark hadronisation via fragmentation+coalescence in a strangeness rich QGP
- D_s^+/D^0 at low p_T consistent with prediction from statistical hadronisation model (SHM) PLB (2008) 659:149-155

In-medium hadronisation: charm baryons





ALI-PREL-323761



ALI-PREL-321682

Catania: EPJC 78 (2018) 348
SHM: arXiv:1901.09200

- Hint of enhanced Λ_c^+/D^0 in Pb-Pb compared to pp collisions for $p_T < 6$ GeV/c

- Measurement described for $p_T > 4$ GeV/c by model with charm hadronisation via fragmentation+coalescence
- Measurement slightly underestimated by SHM

In-medium hadronisation: charm baryons

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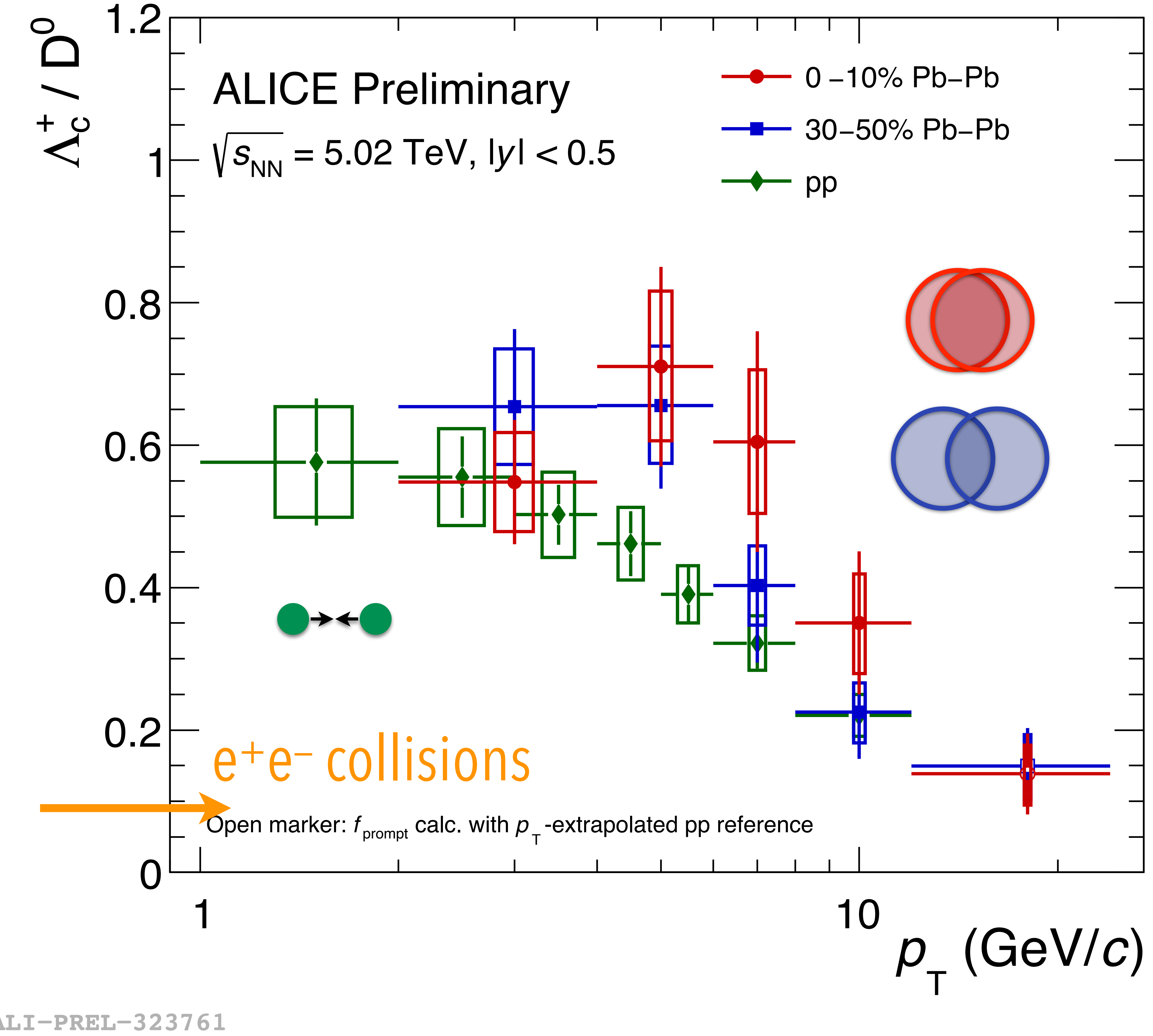
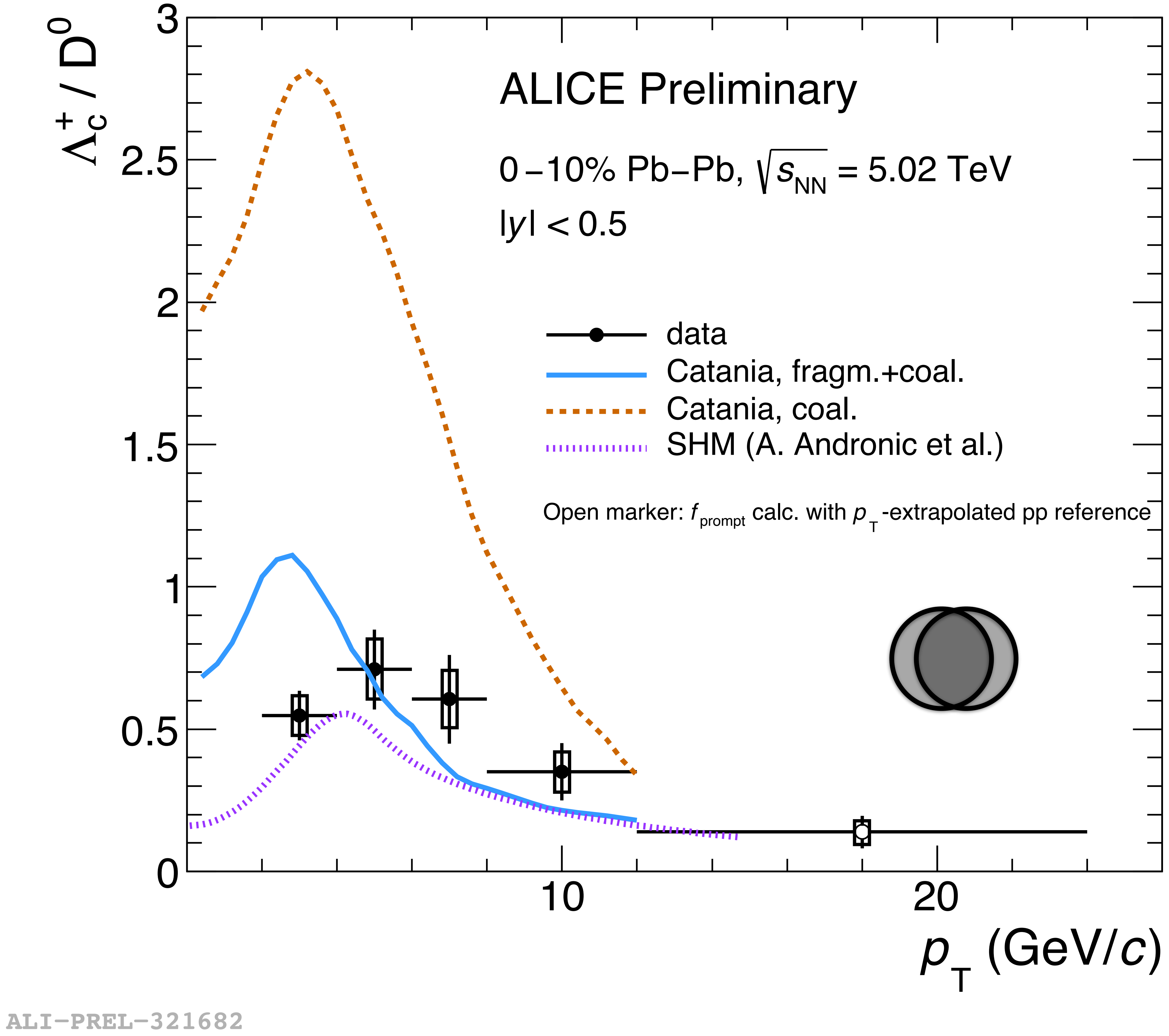
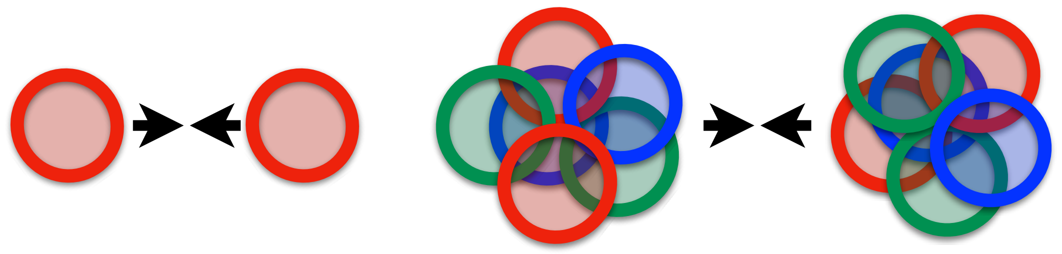




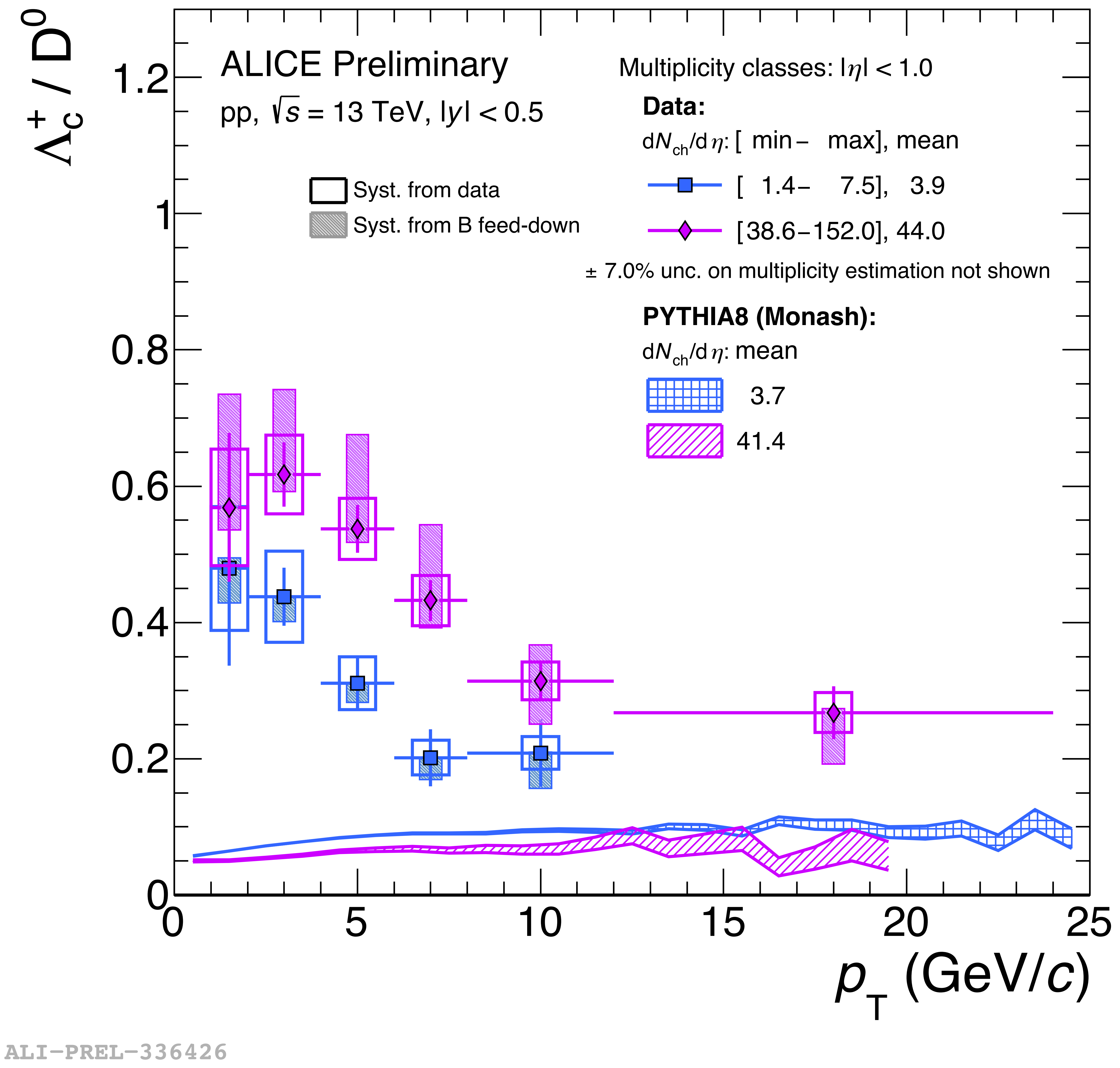


Catania: EPJC 78 (2018) 348
SHM: arXiv:1901.09200

- Hint of enhanced Λ_c^+/D^0 in Pb-Pb compared to pp collisions for $p_T < 6$ GeV/c

- Measurement described for $p_T > 4$ GeV/c by model with charm hadronisation via fragmentation+coalescence
- Measurement slightly underestimated by SHM
- Λ_c^+/D^0 in pp collisions largely enhanced compared to e^+e^- collisions

Charm-baryon production in pp collisions: Λ_c



- Λ_c^+/D^0 shows an increase from low-multiplicity to high-multiplicity pp collisions
- PYTHIA8
  - ➡ Monash (tuned on e^+e^-) does not reproduce the observed enhancement and multiplicity dependence

Monash: EPJC 74 (2014) 8, 3024

Charm-baryon production in pp collisions: Λ_c

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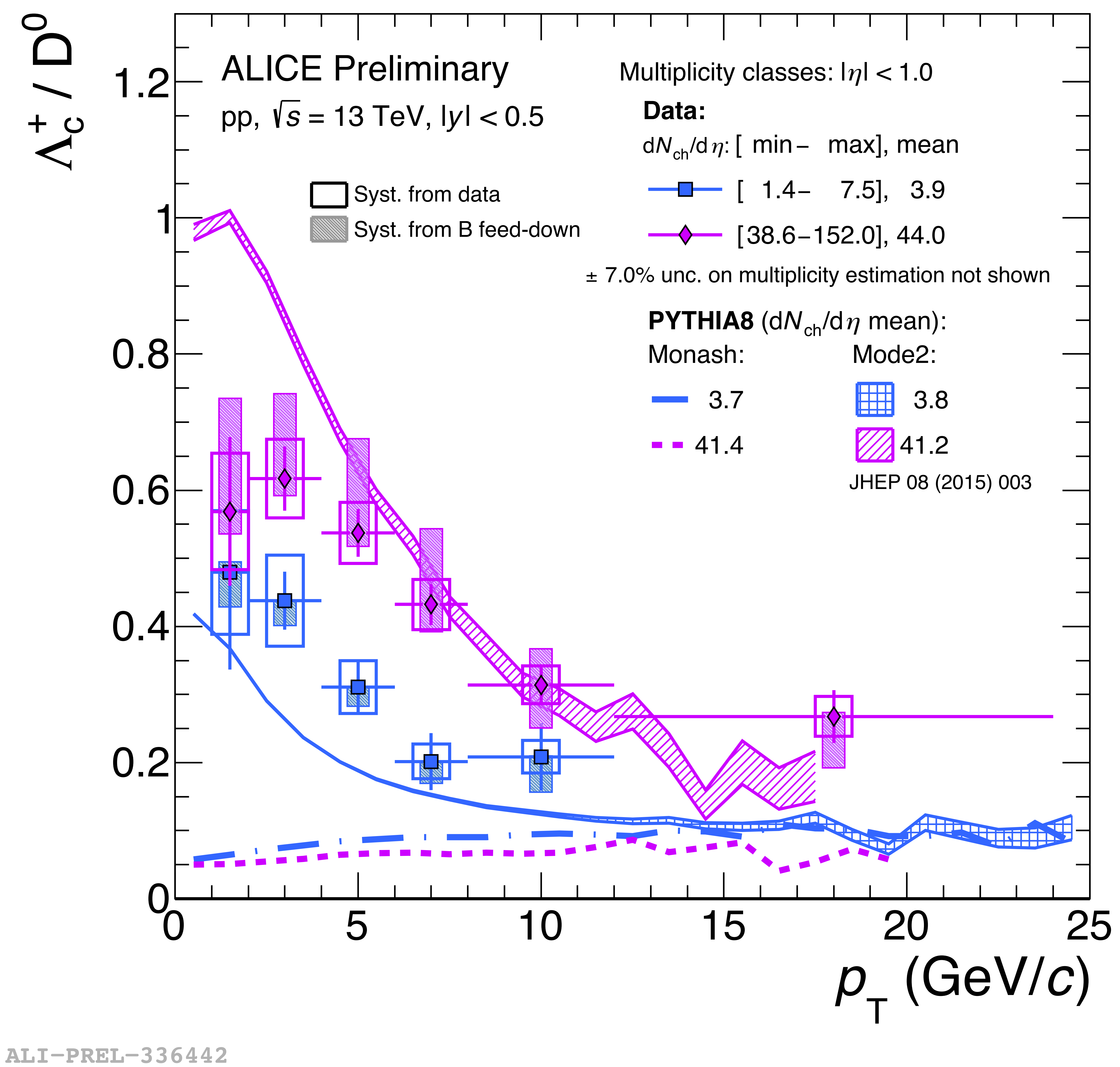
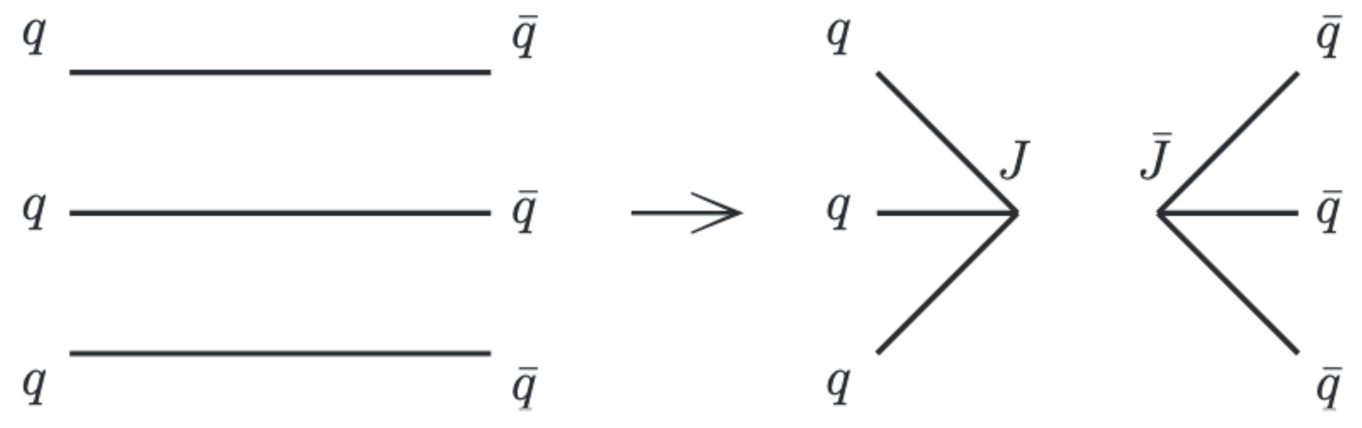
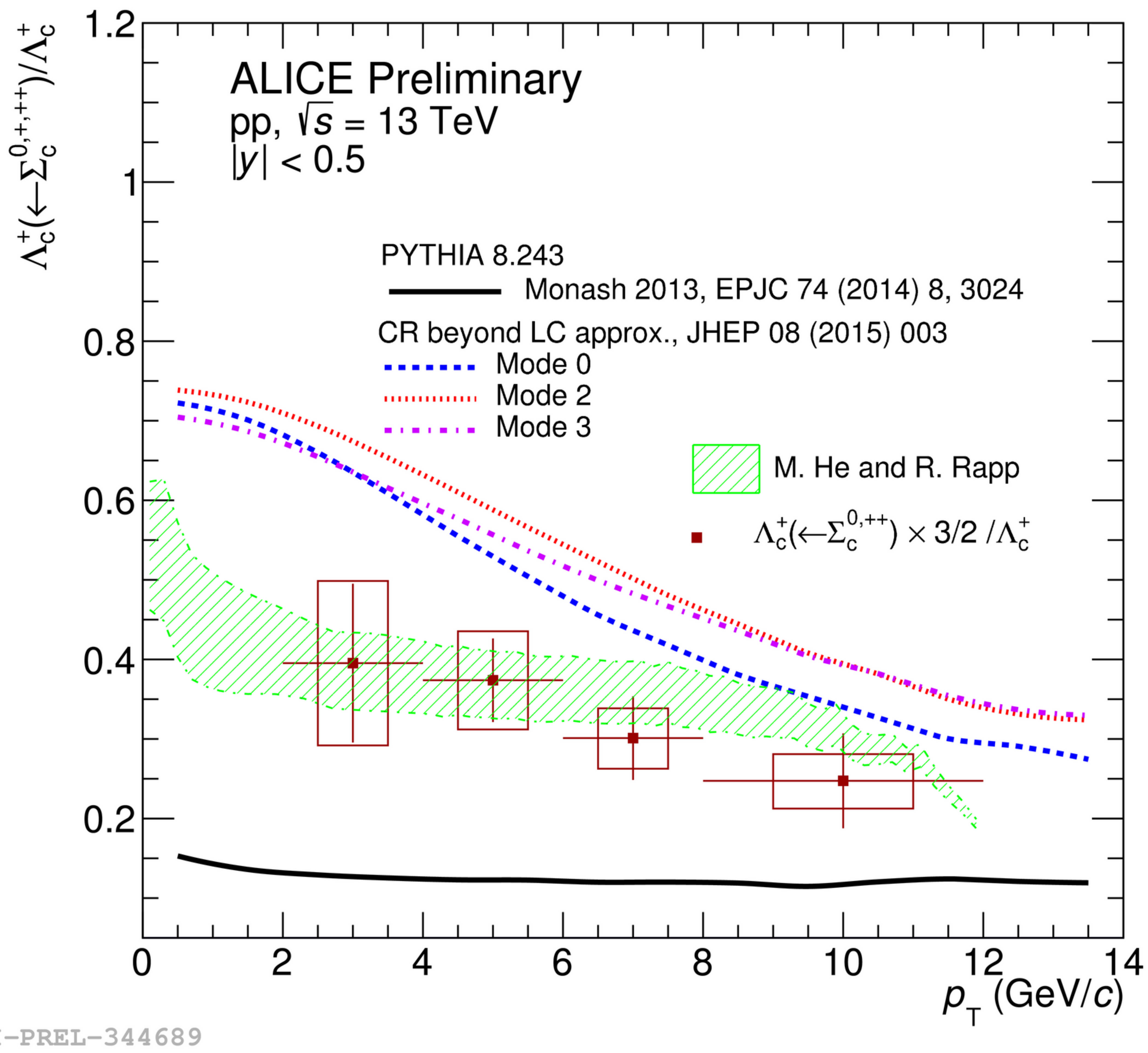


- Λ_c^+/D^0 shows an increase from low-multiplicity to high-multiplicity pp collisions
- PYTHIA8
  - ➡ Monash (tuned on e^+e^-) does not reproduce the observed enhancement and multiplicity dependence
  - ➡ CR with string formation beyond LC approximation describes the multiplicity dependence
    - allows reconnections among junctions
    - relevant for pp collisions (multi-parton interactions)
    - relevant for baryon formation



(c) Type III: baryon-style junction reconnection

Monash: EPJC 74 (2014) 8, 3024
CR: JHEP 08 (2015) 003



- Observed enhanced $\Sigma_c^{0,+,++}$ production in pp collisions
  - ➡ contributes to Λ_c^+ enhancement but not sufficient to describe the total observed Λ_c^+ enhancement
- Λ_c^+ from $\Sigma_c^{0,+,++}$ decays underestimated by PYTHIA8 Monash and overestimated by PYTHIA8 with CR

Monash: EPJC 74 (2014) 8, 3024
CR: JHEP 08 (2015) 003

- Described by statistical hadronisation model with augmented set of charm-baryon states predicted by QCD calculations on the lattice

PLB 795 (2019) 117-121

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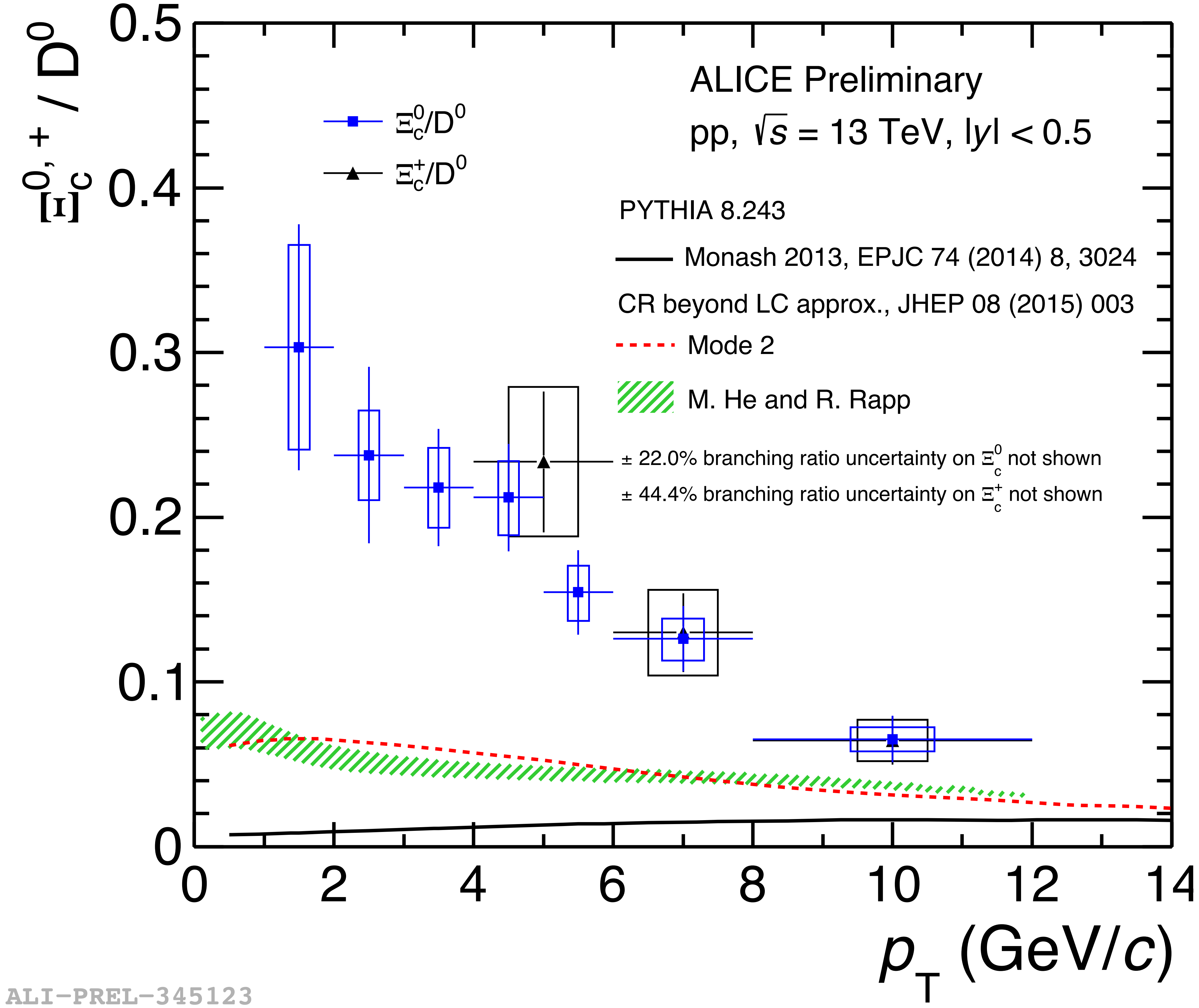
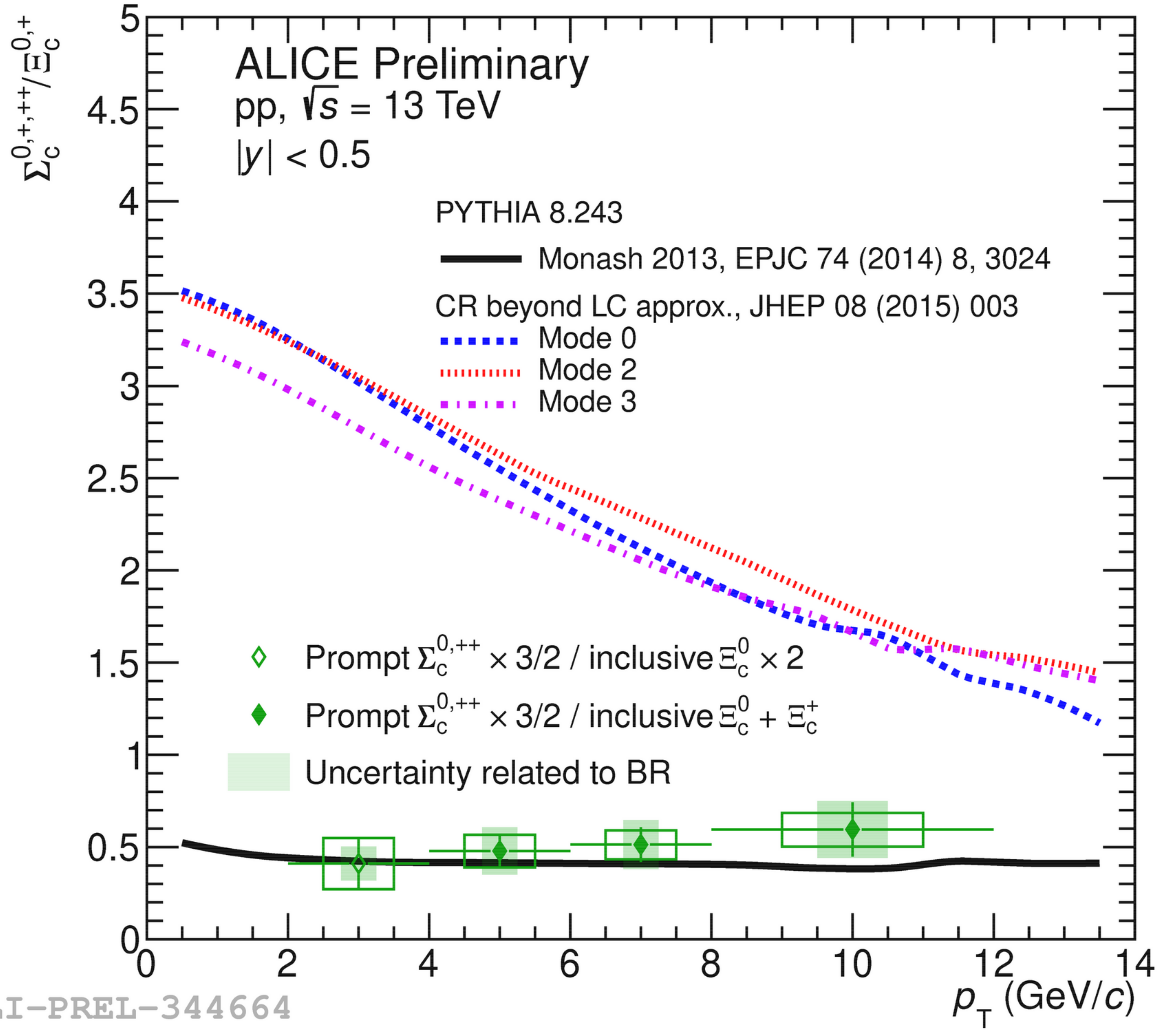


ALI-PREL-345123

- Observed enhanced $\Xi_c^{0,+}$ production in pp collisions
- $\Xi_c^{0,+}$ / D^0 underestimated by PYTHIA8 with CR and SHM with augmented set of charm-baryon states



ALI-PREL-344664

- $\Sigma_c^{0,+,++}$ / $\Xi_c^{0,+}$
  - ➡ overestimated by PYTHIA8 with CR
  - ➡ described by PYTHIA8 Monash

PYTHIA8 Monash: EPJC 74 (2014) 8, 3024
PYTHIA8 CR: JHEP 08 (2015) 003
SHM+baryon states: PLB 795 (2019) 117-121

Conclusions

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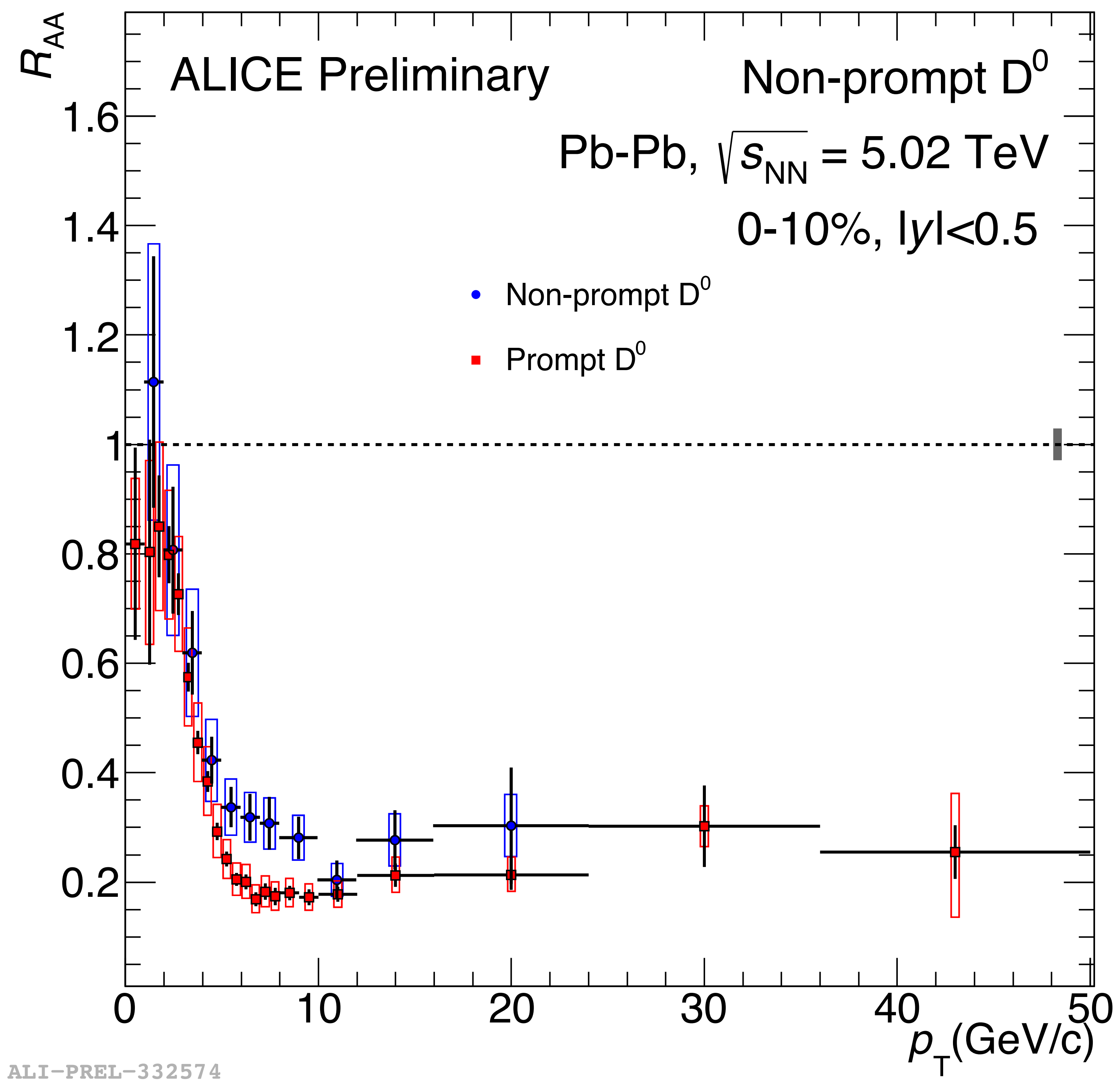
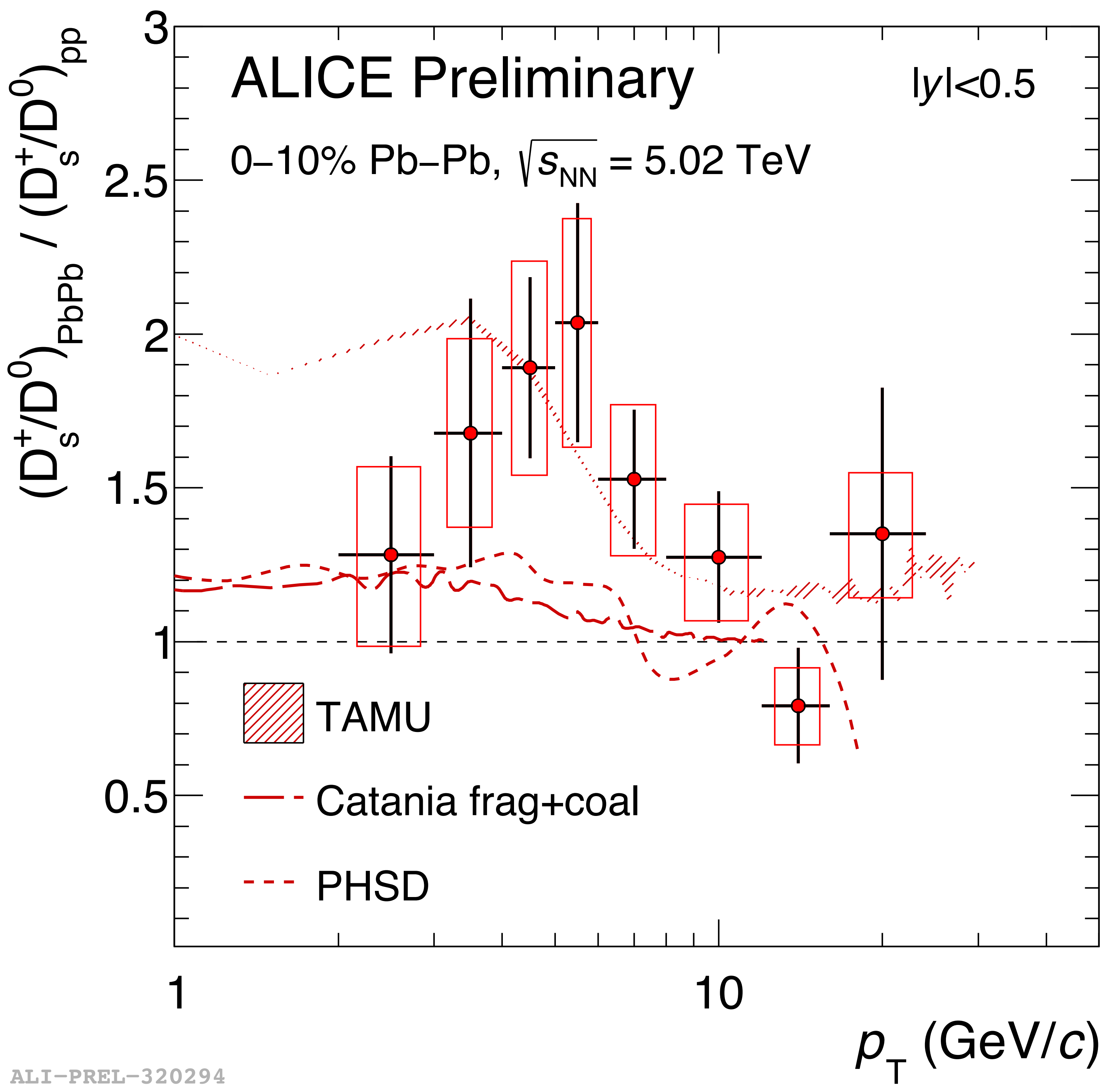
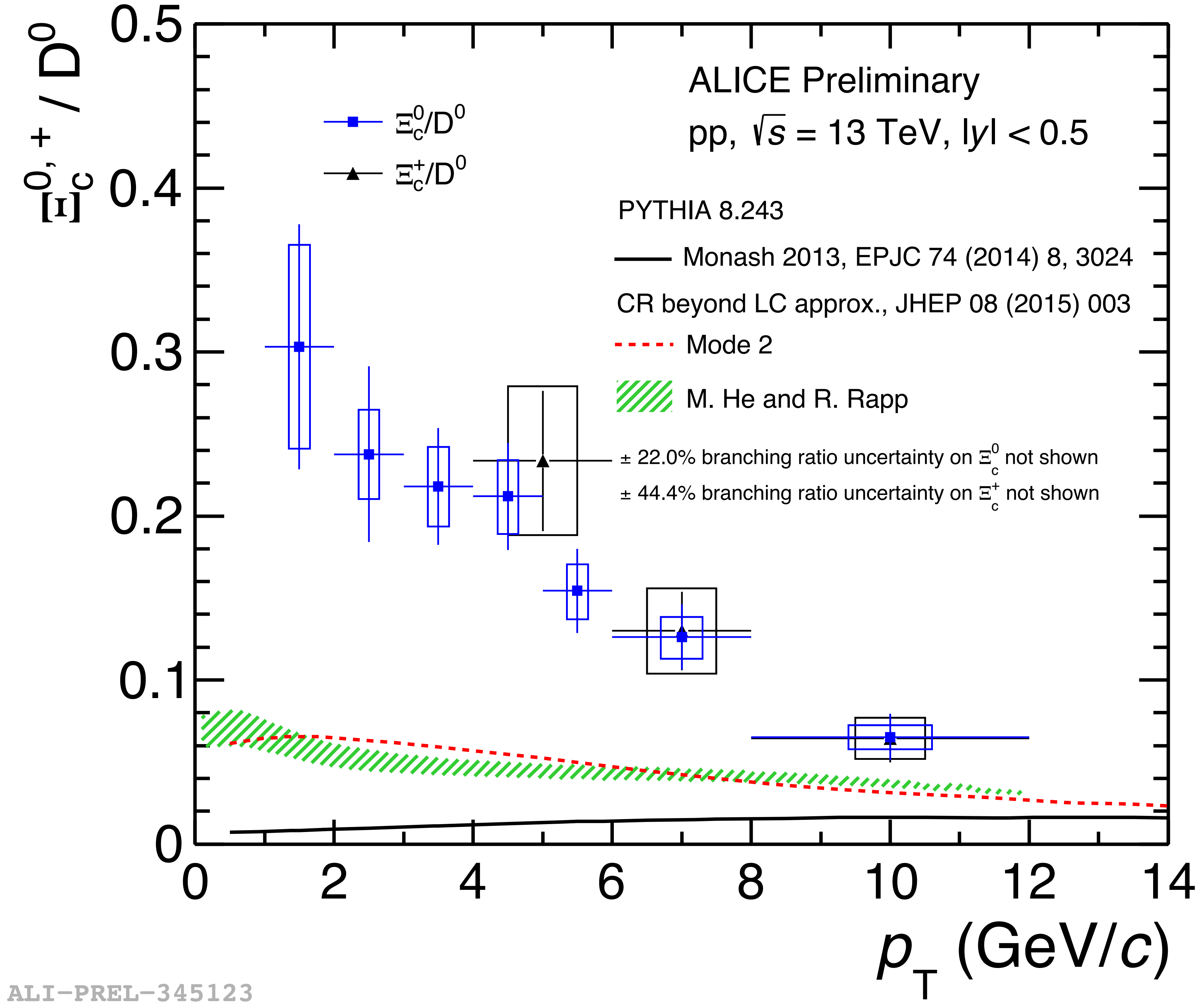
- ALICE unique vertexing and PID capabilities allowed crucial HF measurements with Run 2 data:
  - ➡ Charm mesons measured down to $p_T = 0$ in pp and Pb–Pb collisions
  - ➡ Beauty hadrons measured in different collisions systems
  - ➡ Charm-strange mesons and charm baryons in Pb-Pb collisions down to low p_T
  - ➡ Higher-mass charm baryons in small systems







Conclusions

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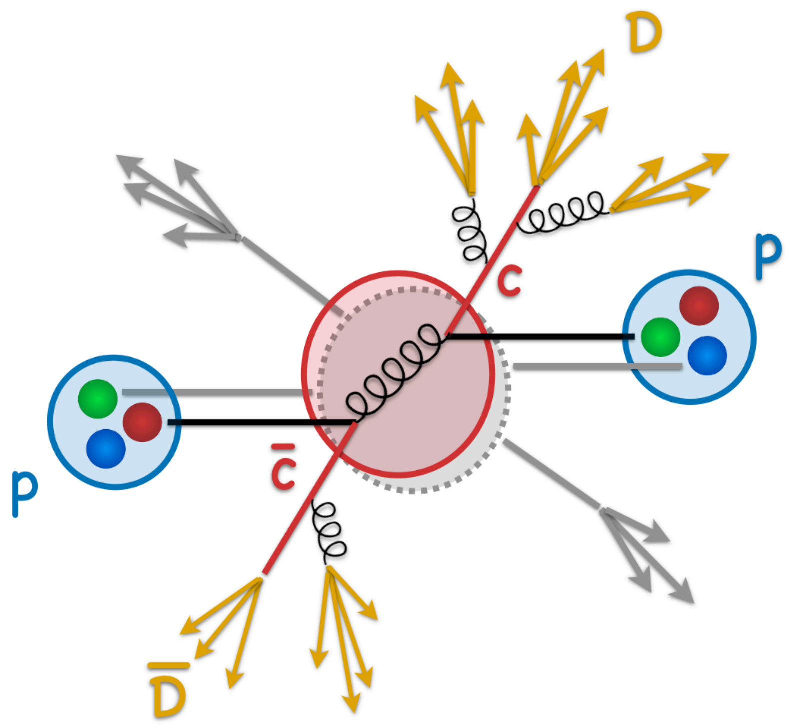
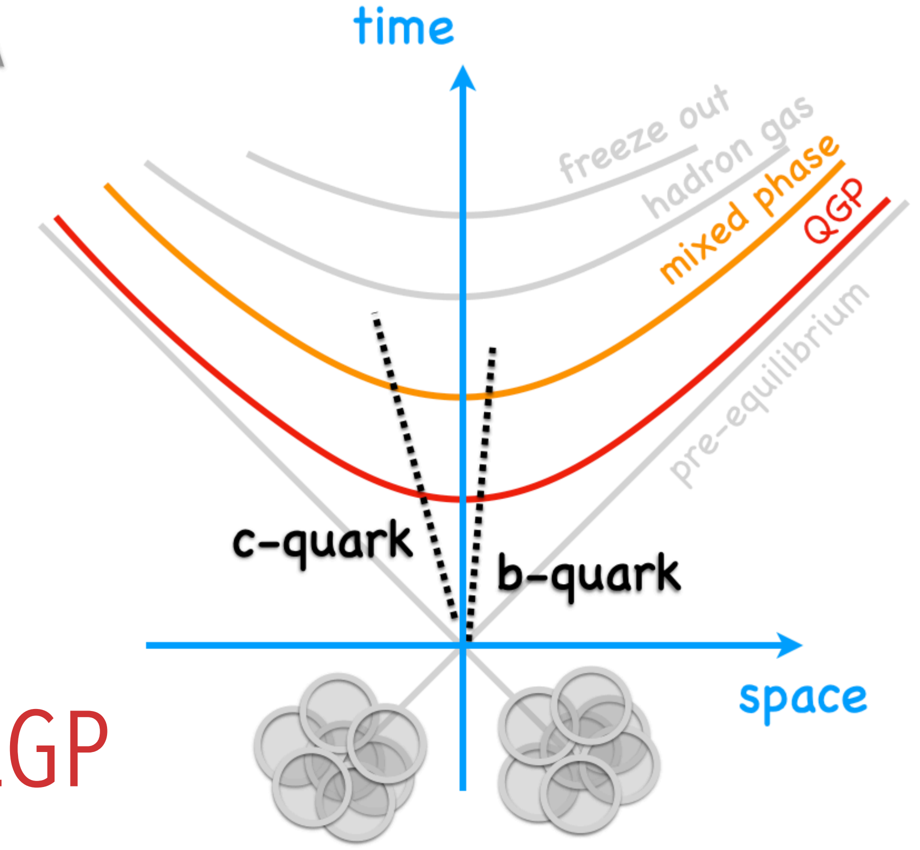
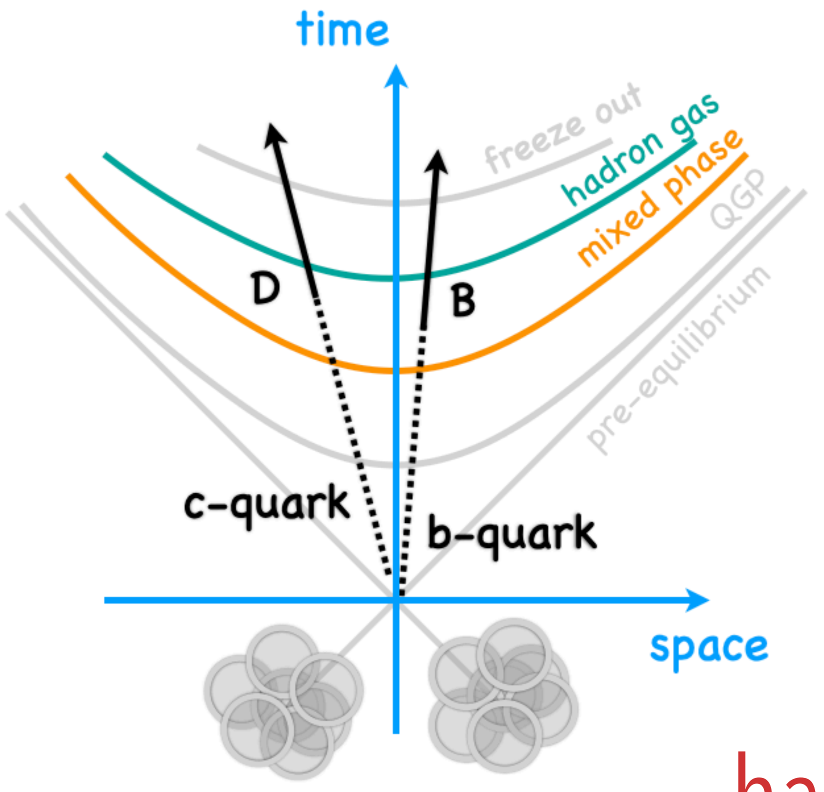
- Learnt so far:
  - ➡ HF production cross-sections down to low p_{T} in pp collisions are compatible with pQCD calculations
  - ➡ D-meson p_{T} spectra strongly suppressed in central Pb–Pb collisions
    - energy loss hierarchy E_{loss} (beauty) < E_{loss} (charm) → dead cone effect
  - ➡ Heavy flavour particles participate in collective motion of the system
    - charm-quark thermalisation time ~ QGP lifetime
  - ➡ Charm-hadron production in Pb–Pb collisions consistent with coalescence and SHM
  - ➡ Charm hadronisation modified also in pp collisions
    - String fragmentation with colour reconnection
    - SHM with augmented charm-baryon states



production



interactions in QGP



hadronisation

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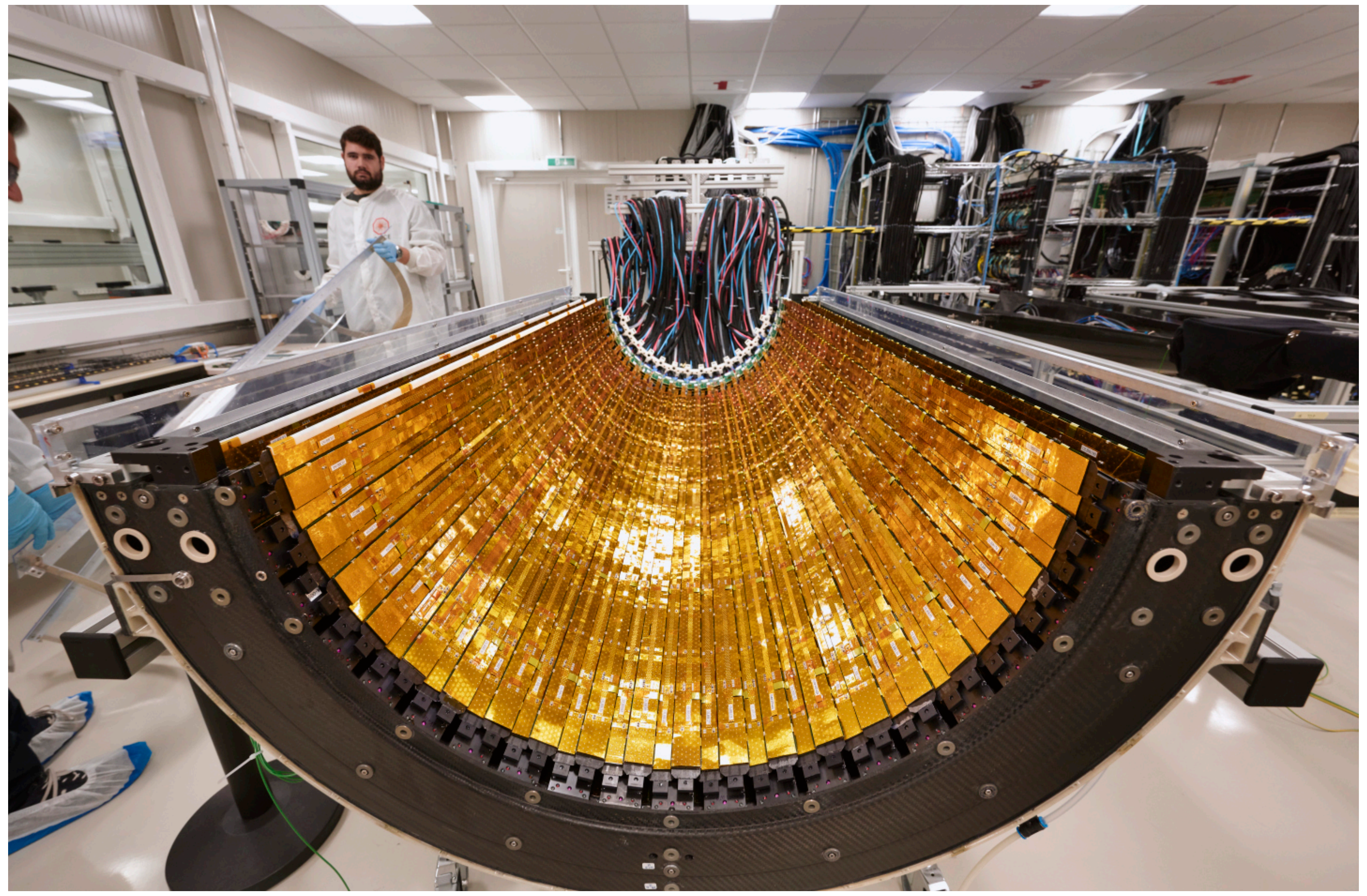
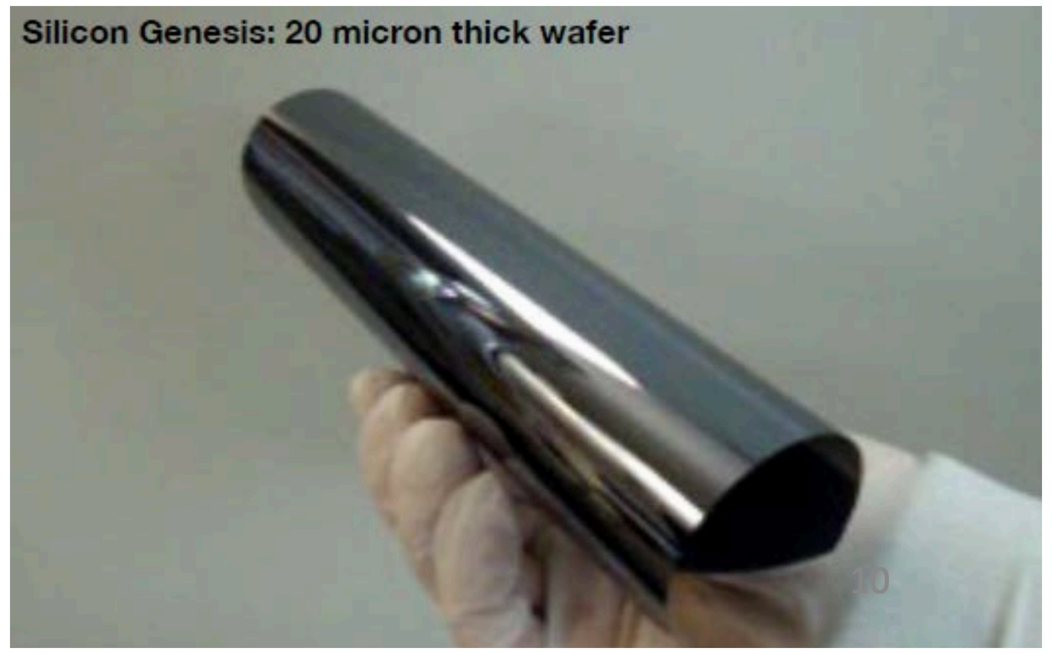
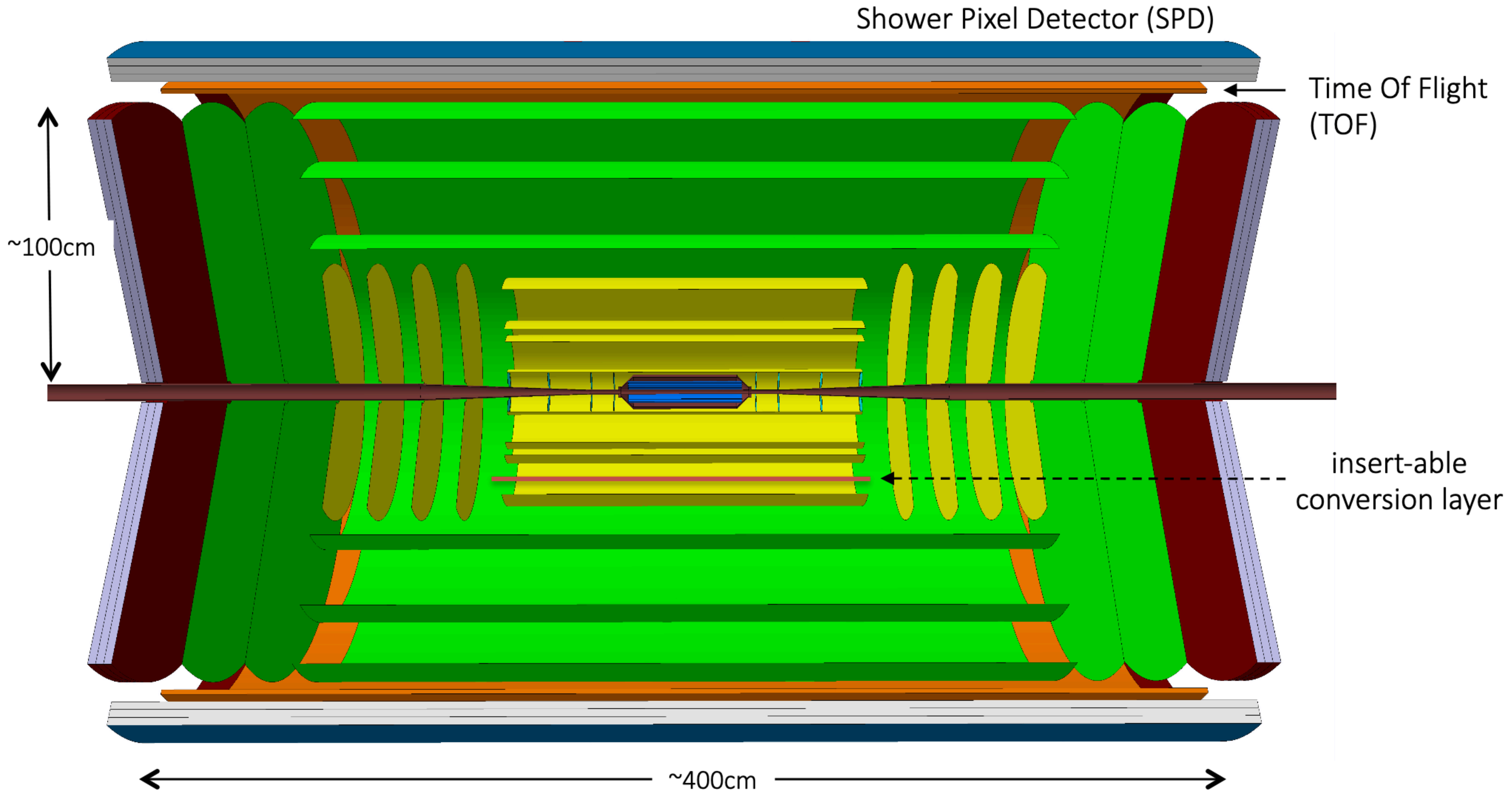


- Wide ALICE upgrade program for LHC Run 3 and 4 crucial for HF
  - ➡ increase collected Pb-Pb luminosity by more than one order of magnitude
  - ➡ new silicon Inner Tracking System
    - Run 3: ITS2 TDR: CERN-LHCC-2013-024
    - Run 4: ITS3 LOI: CERN-LHCC-2019-018
  - ➡ Run5: all silicon ultra-light detector



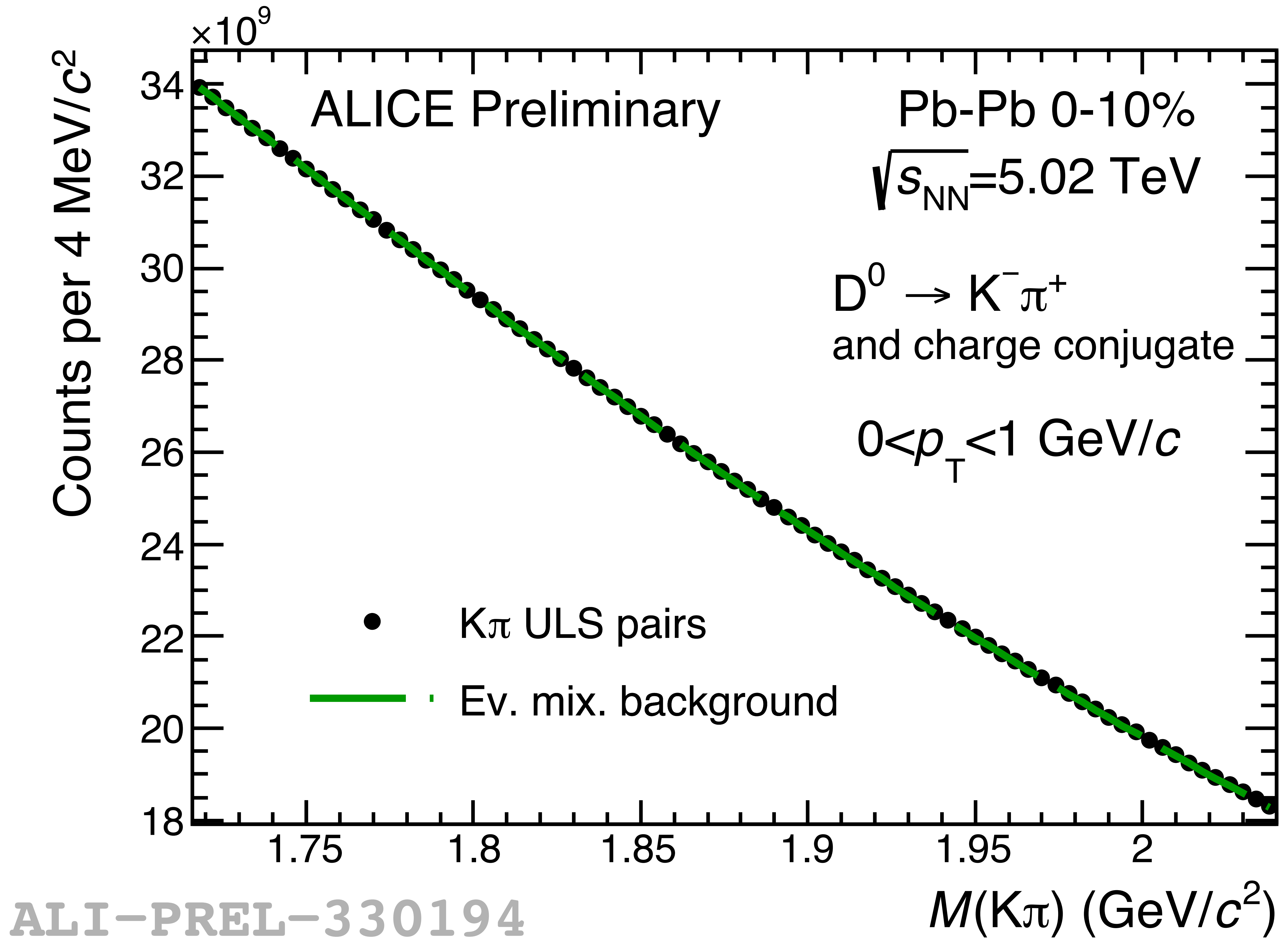
arXiv:1902.01211

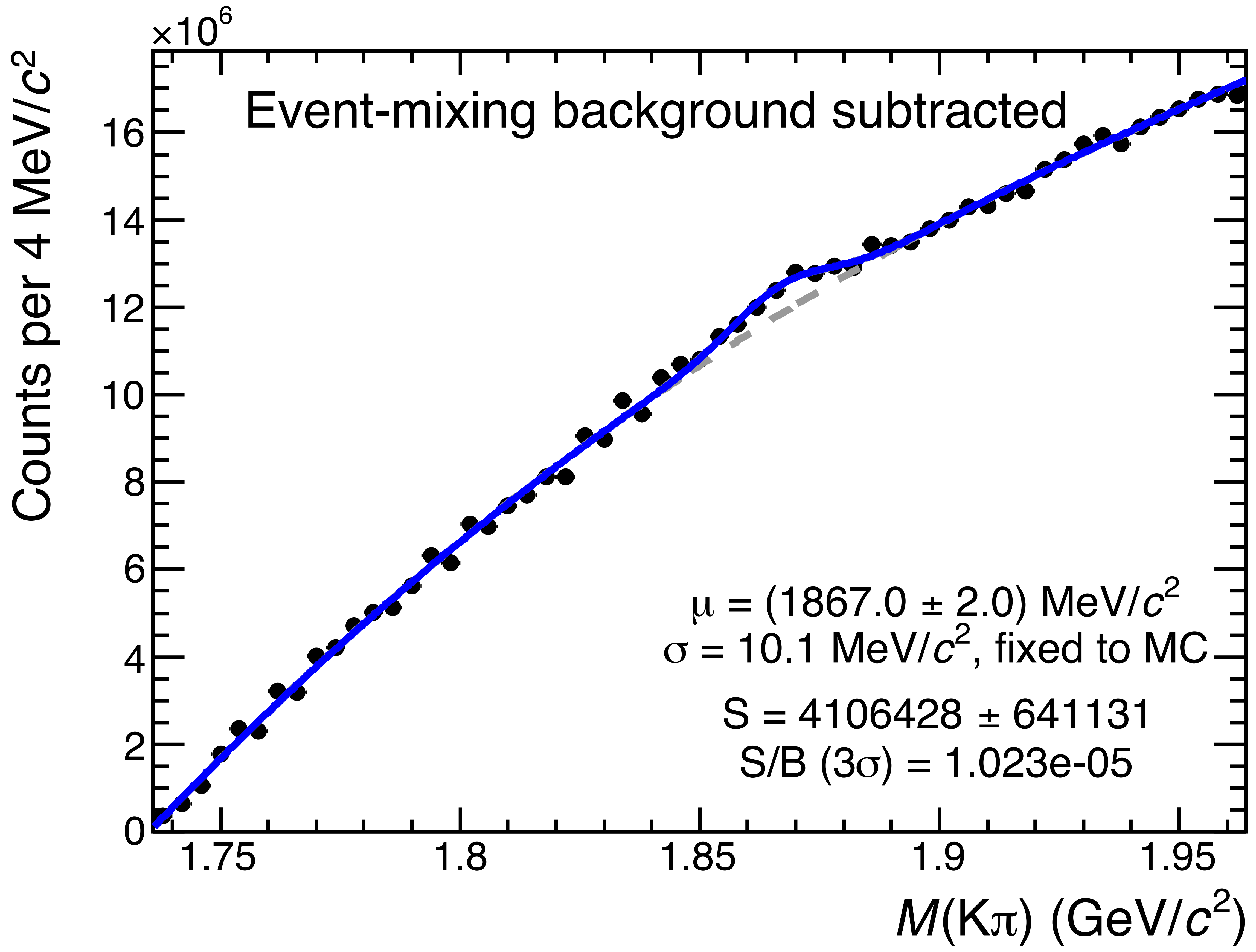


- New / more precise HF measurements down to low p_T
  - ➡ Precise measurements of charm mesons and baryons
  - ➡ Access to measurements of beauty-strange meson and beauty-baryon production and azimuthal anisotropy
  - ➡ Run 5: multi-charm baryon production in heavy-ion collisions

ADDITIONAL SLIDES

Measurement of D^0 mesons at very low p_T



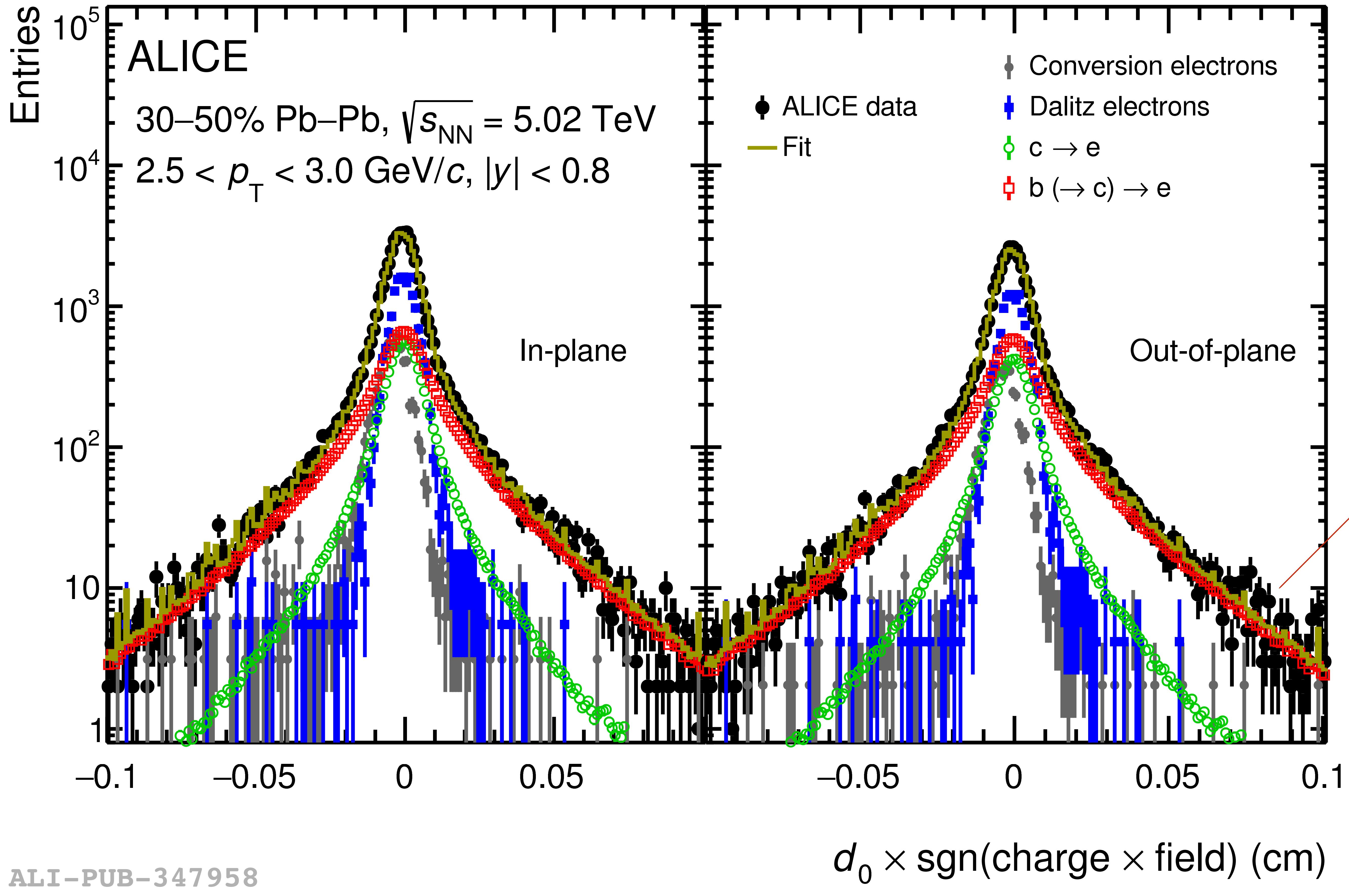


- Particle identification of decay tracks
- No selections on decay-vertex topology
- Background distribution subtracted with event-mixing template

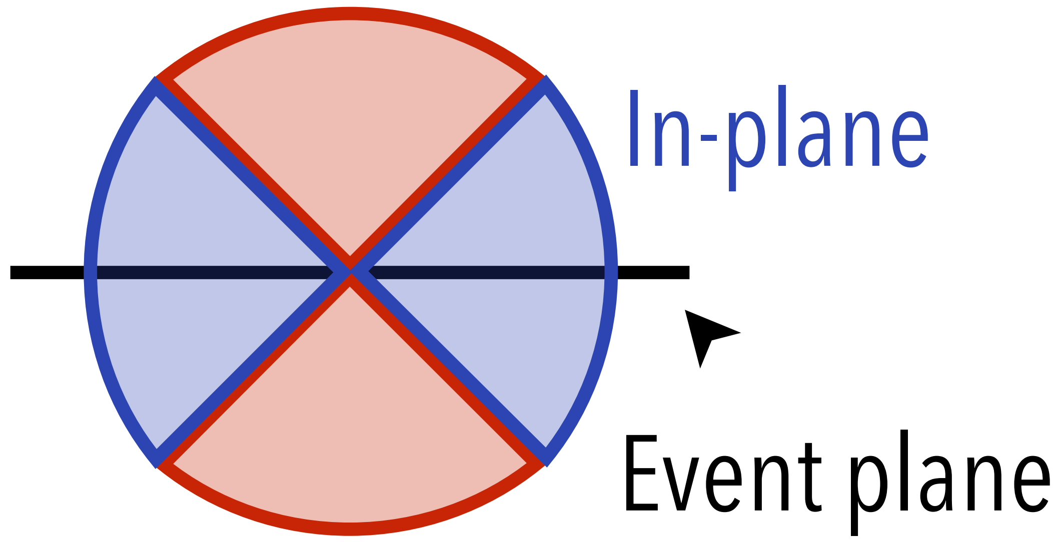
Measurement of HFe elliptic flow – event-plane method

- v_2 measured with the Event-Plane (EP) method
  - ➡ computation of event-plane angle

$$\psi_n = \frac{1}{n}\tan^{-1}\left(\frac{Q_{n,y}}{Q_{n,x}}\right) \quad \text{where} \quad \mathbf{Q}_n = \left(\sum_{k=0}^{N_{tracks}} \cos(n\varphi_k), \sum_{k=0}^{N_{tracks}} \sin(n\varphi_k)\right)$$



- Yield extracted in-plane and out-of-plane
  - ➡ (7π/4, π/4] U (3π/4,5π/4]
  - ➡ (π/4, 3 π/4] U (5π/4, 7π/4]



- v_2 computed as

$$v_2 = \frac{\pi}{4R_2}\frac{N_{in-plane} - N_{out-of-plane}}{N_{in-plane} + N_{out-of-plane}}$$

Measurement of D-meson elliptic flow – scalar-product method

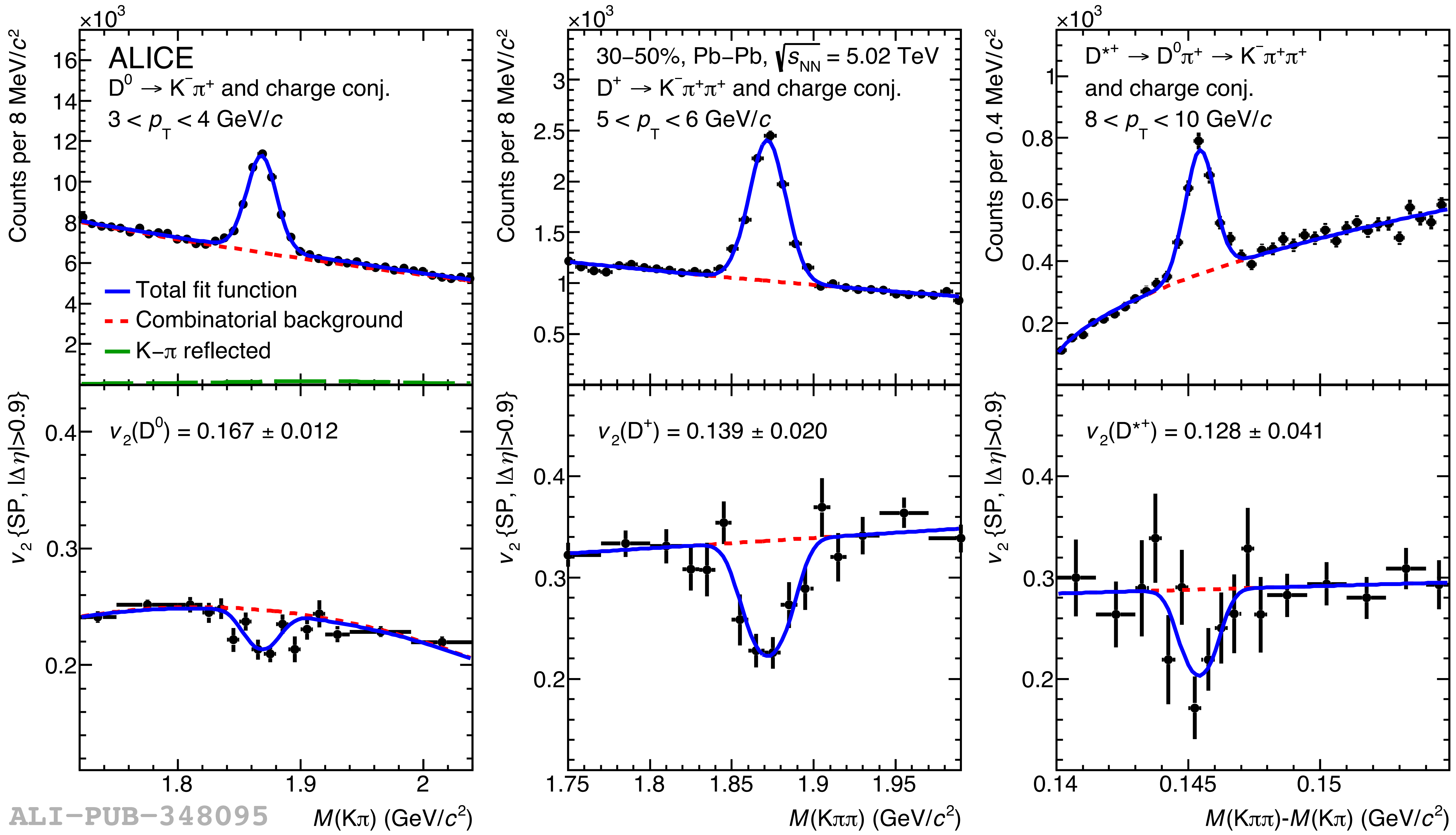
- v_n measured with the Scalar-Product (SP) method

$$v_n\{SP\} = \langle\langle \mathbf{u}_n \cdot \mathbf{Q}_n^{A*}\rangle\rangle \Bigg/ \sqrt{\frac{\langle \mathbf{Q}_n^A \cdot \mathbf{Q}_n^{B*}\rangle\langle \mathbf{Q}_n^A \cdot \mathbf{Q}_n^{C*}\rangle}{\langle \mathbf{Q}_n^B \cdot \mathbf{Q}_n^{C*}\rangle}}$$

where

$$\mathbf{Q}_n = \left(\sum_{k=0}^{N_{\text{tracks}}} \cos(n\varphi_k), \sum_{k=0}^{N_{\text{tracks}}} \sin(n\varphi_k)\right)$$

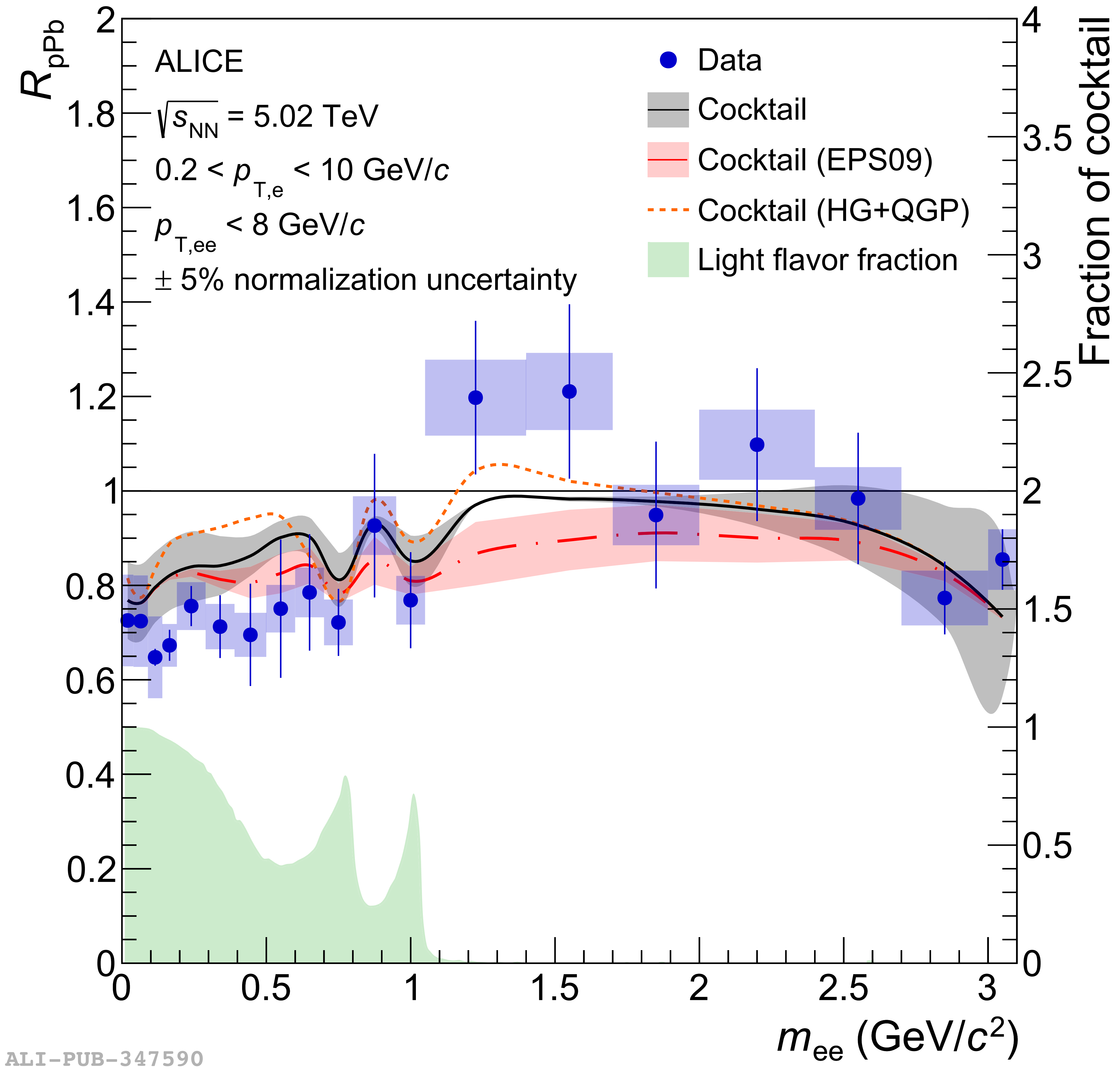
$$\mathbf{u}_n = \left(\cos(n\varphi_D), \sin(n\varphi_D)\right)$$



- Since per-particle identification of D mesons not possible, two component (signal, background) fit of v_n vs. invariant mass performed:

$$v_n^{\text{tot}}(M) = \frac{S}{S+B}(M) \cdot v_n^{\text{signal}} + \frac{B}{S+B}(M) \cdot v_n^{\text{bkg}}(M)$$

Nuclear modification factor of charm and beauty from dielectrons



$$R_{pPb}(m_{ee}) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pPb}/dm_{ee}}{dN_{pp}/dm_{ee}}$$

binary nucleon-nucleon collisions

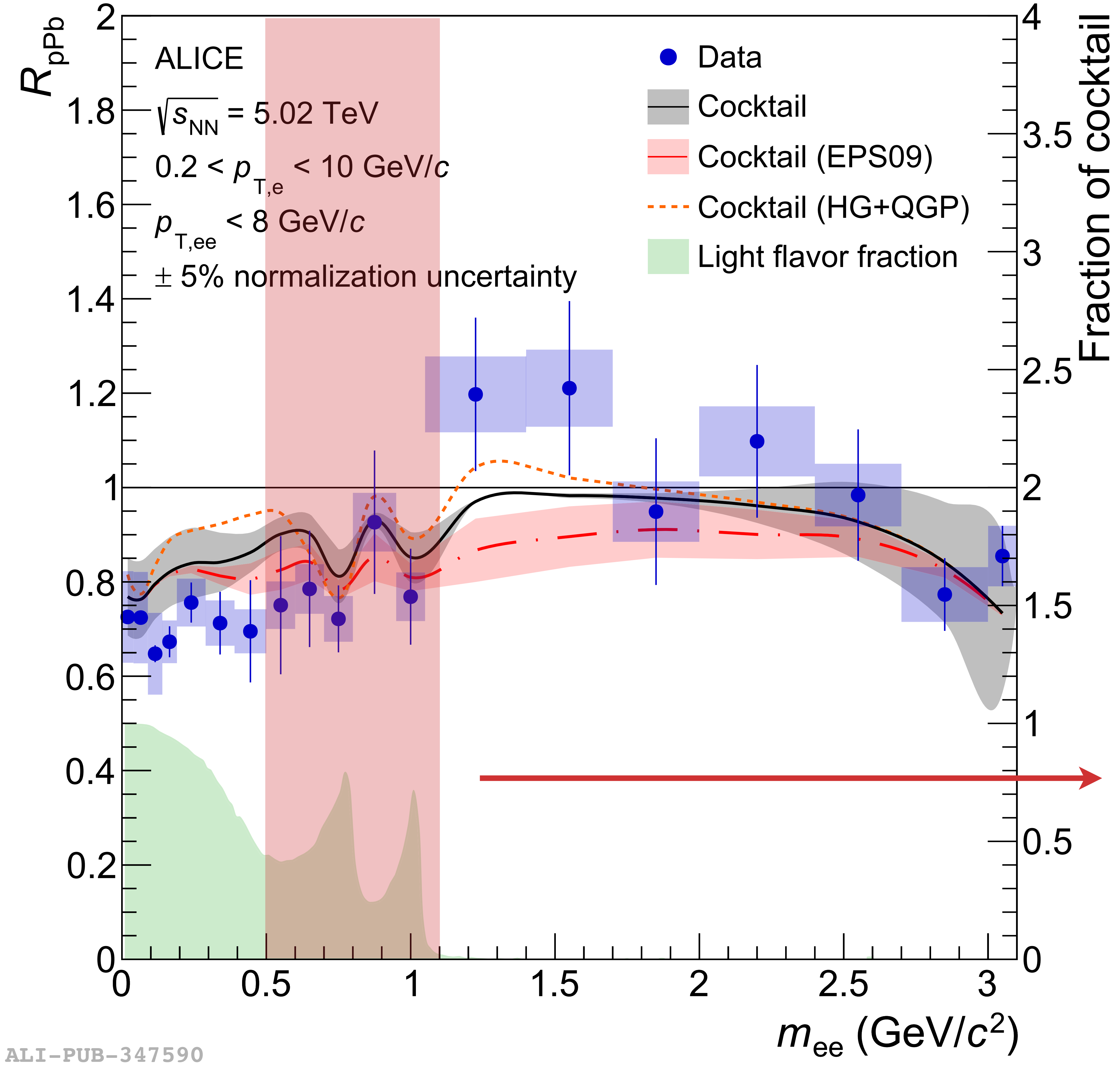
production yield in p–Pb collisions

production yield in pp collisions

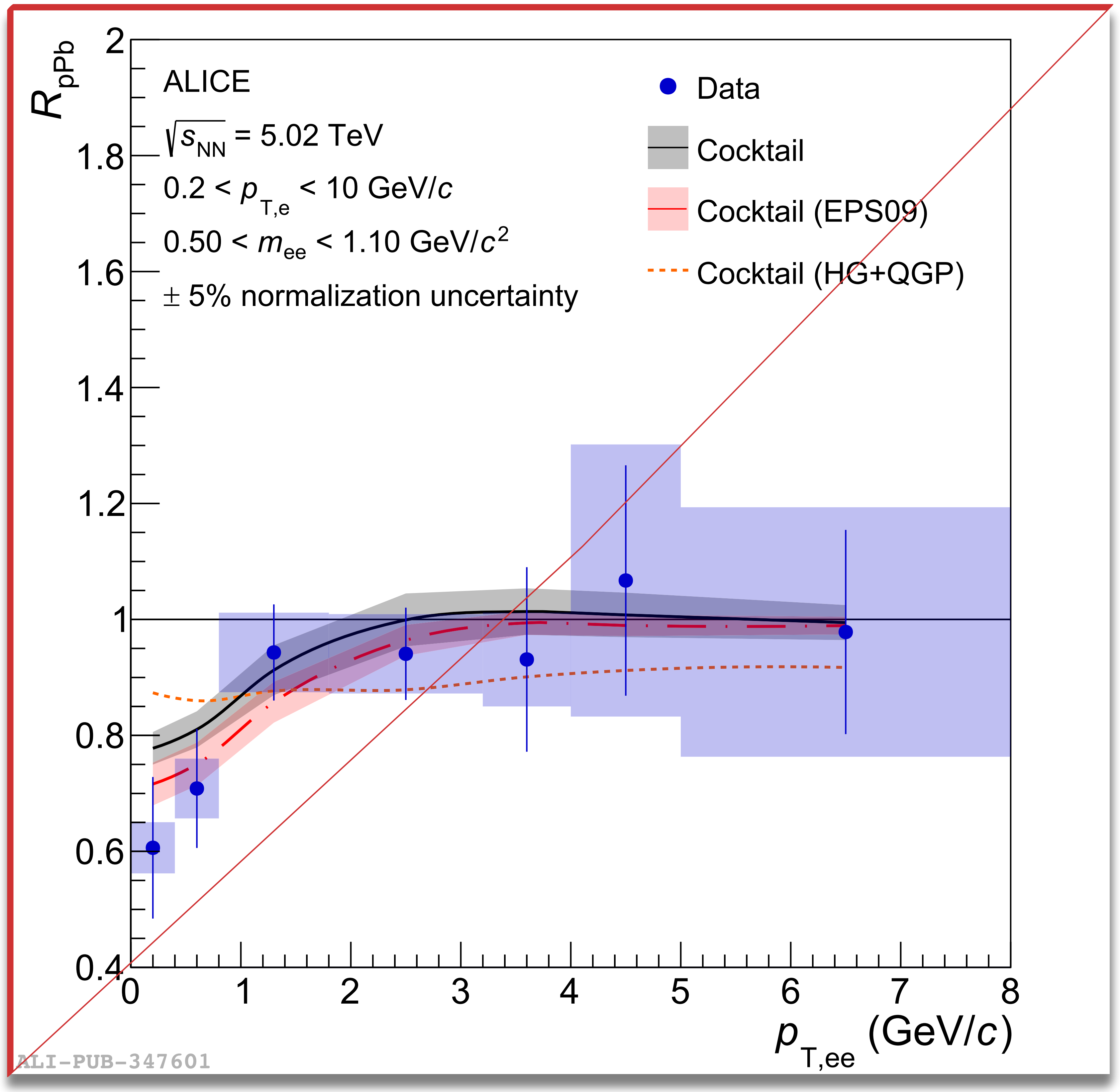
- Hard processes
  - ➡ expected equal unity if no modifications induced by the nuclear environment (N_{coll} *scaling*)
- Soft processes:
  - ➡ expected lower than unity (scaling with number of participant nucleons)

Dielectrons: arXiv:2005.11995 EPS09: JHEP 04 (2009) 065 HG+QGP: arXiv:2005.11995

Nuclear modification factor of charm and beauty from dielectrons



$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

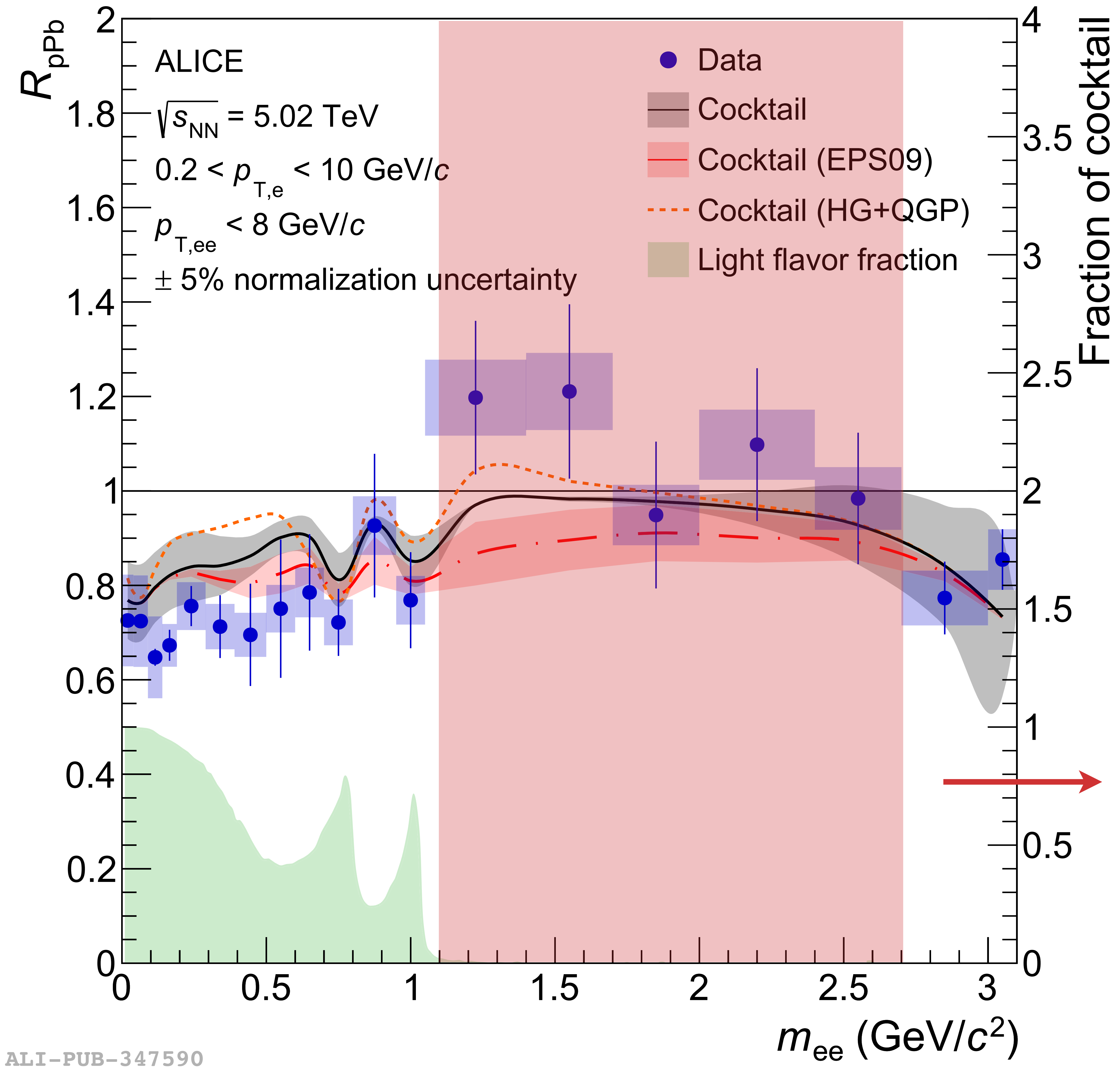


$0.5 < m_{ee} < 1.1$ GeV/c^2

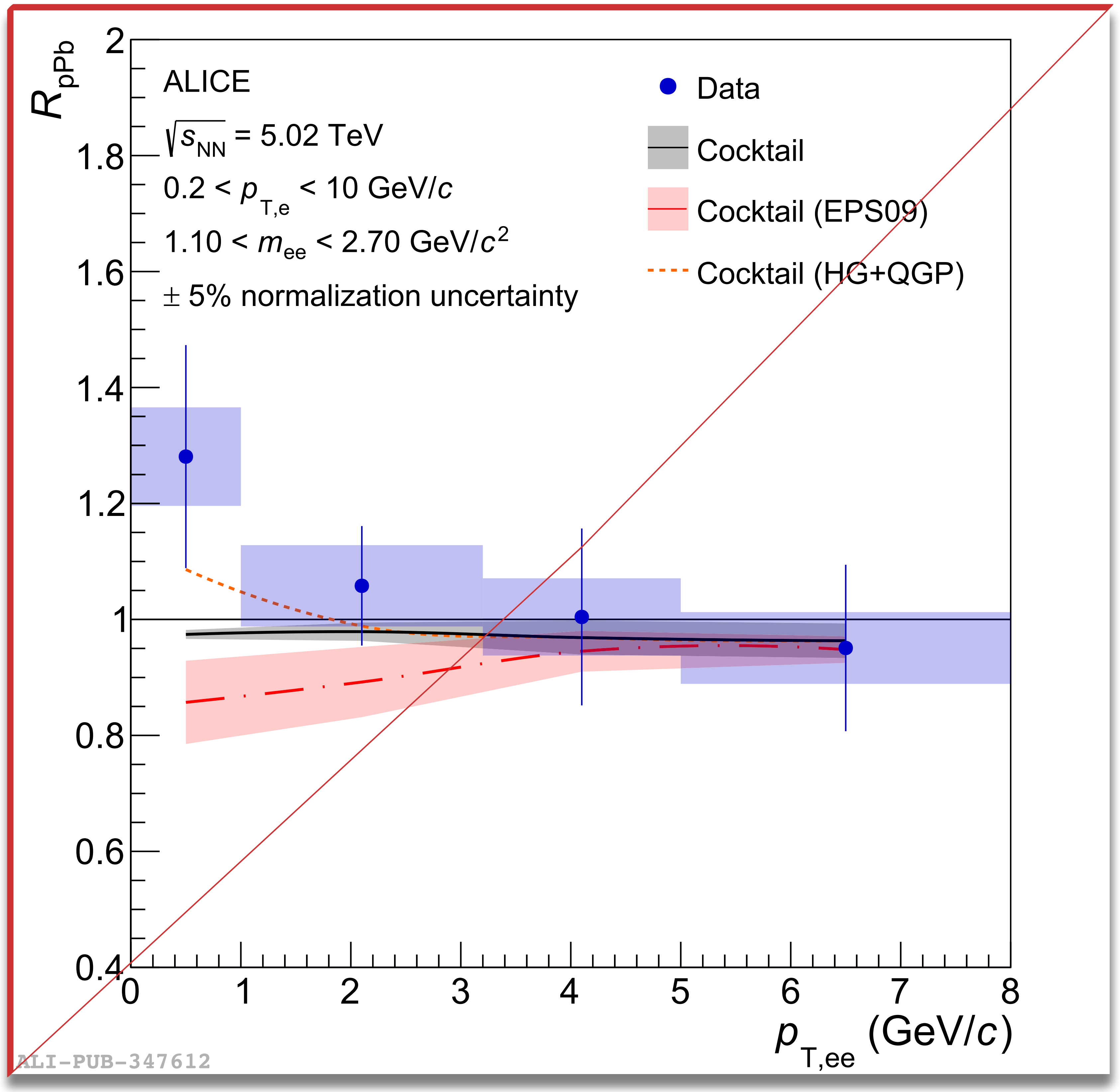
- Low $p_T \rightarrow R_{pPb} < 1$
  - ➡ contribution from light-flavoured soft particle production
  - ➡ modification of PDFs (*shadowing*)
- High $p_T \rightarrow R_{pPb} \approx 1$
  - ➡ only hard processes contribution (both light and heavy flavours)

Dielectrons: arXiv:2005.11995 EPS09: JHEP 04 (2009) 065 HG+QGP: arXiv:2005.11995

Nuclear modification factor of charm and beauty from dielectrons



$$R_{pPb}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pPb}/dp_T}{dN_{pp}/dp_T}$$

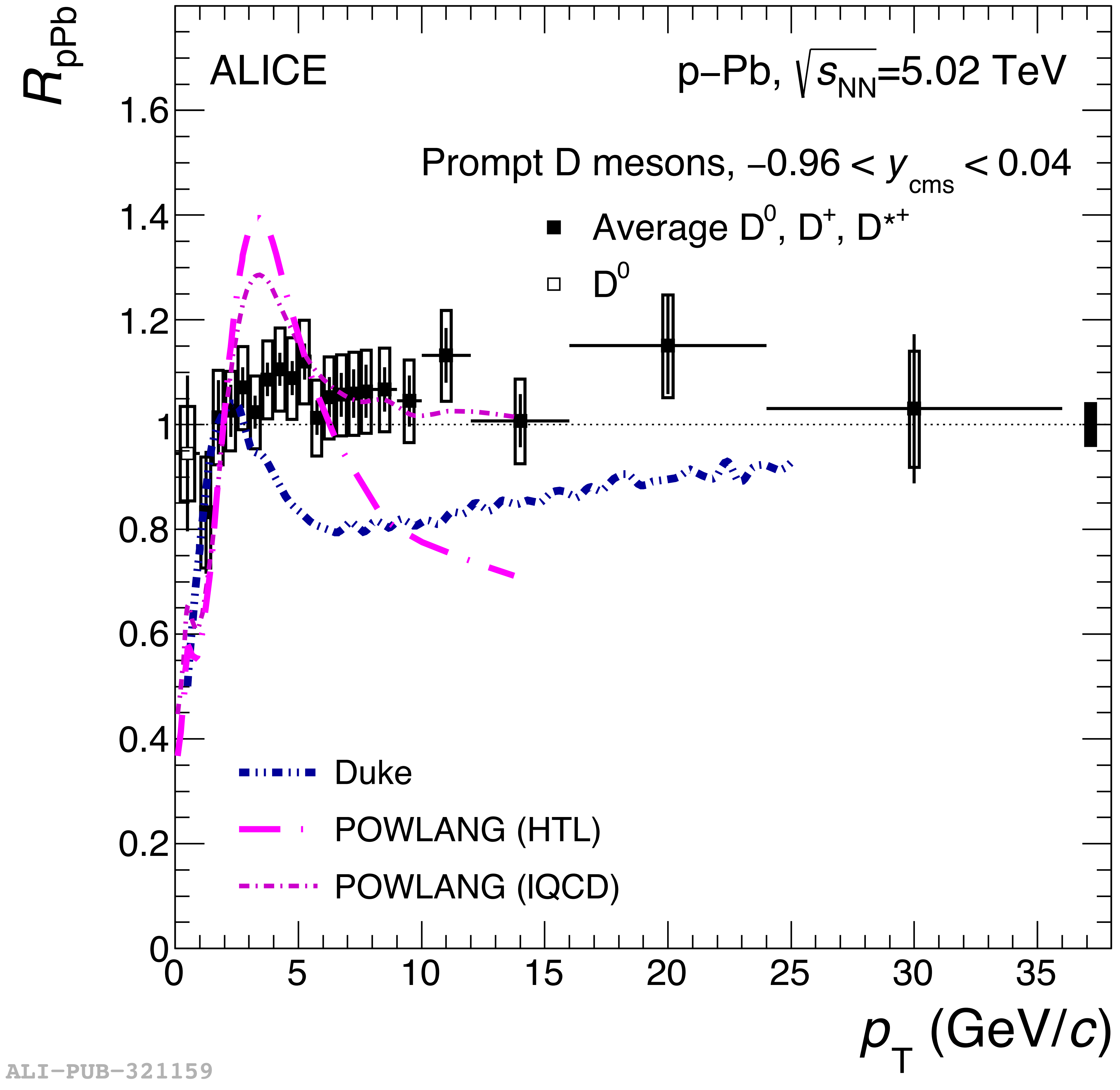


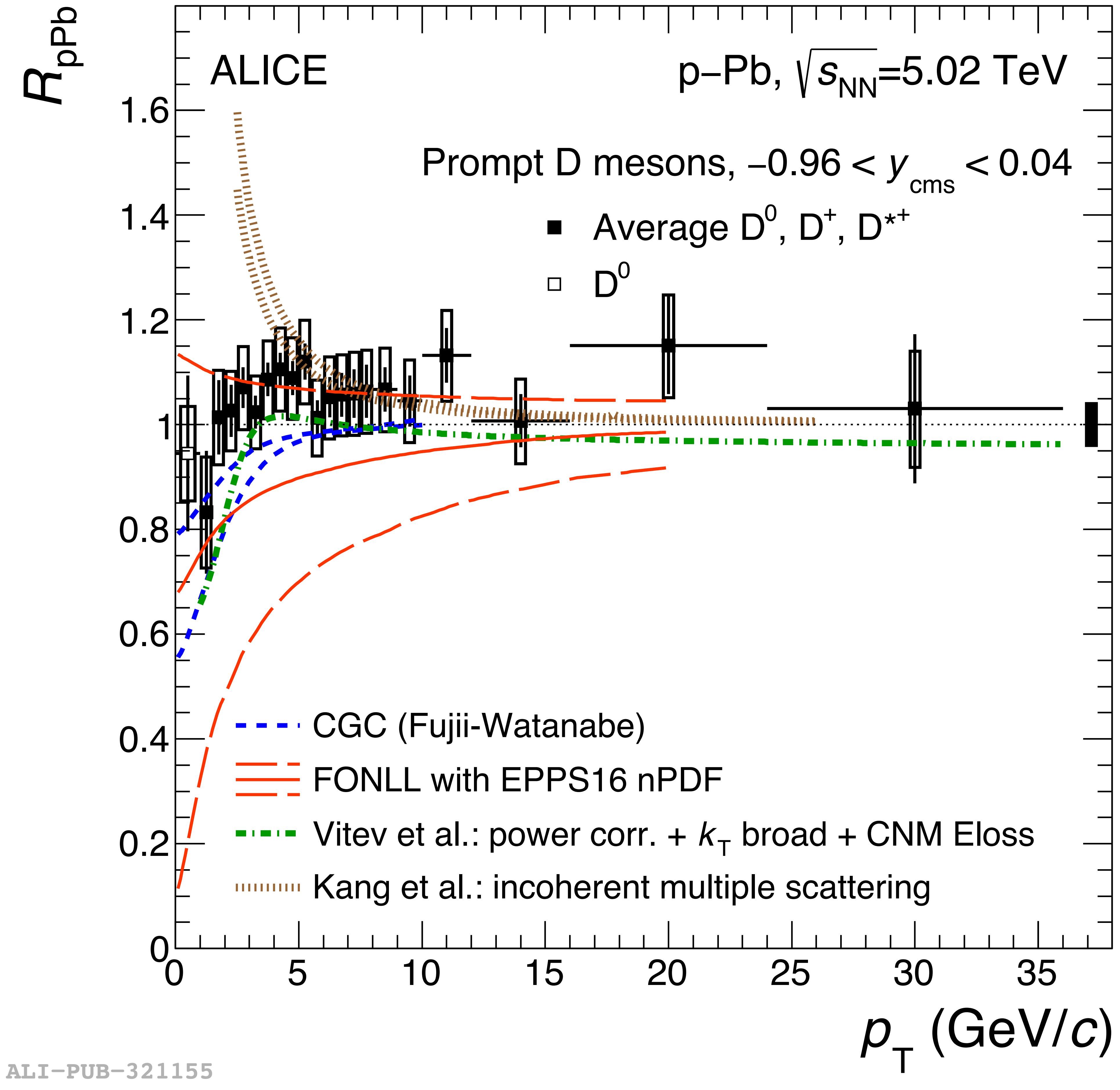
$1.1 < m_{ee} < 2.7$ GeV/c^2

- Dominant HF contribution
  - ➡ $R_{pPb} \approx 1$ also at low p_T
  - ➡ only nuclear PDFs (EPS09) effect disfavoured
  - ➡ data favour additional contribution from thermal radiation
  - ➡ effect of nuclear PDFs (EPS09) and thermal radiation (HG+QGP) in opposite directions

Dielectrons: arXiv:2005.11995
EPS09: JHEP 04 (2009) 065
HG+QGP: arXiv:2005.11995

D-meson R_{pPb}





Duke: NPPP 276–278 (2016) 225
POWLANG: JHEP 03 (2016) 123
CGC: NPA 920 (2013) 78
FONLL: JHEP 1210 (2012) 137
EPPS16: EPJC 77 (2017) 3, 163
Vitev: PRC 75 (2007) 064906
Kang: PLB 737 (2015) 23

Centrality evolution of D-meson elliptic and triangular flows

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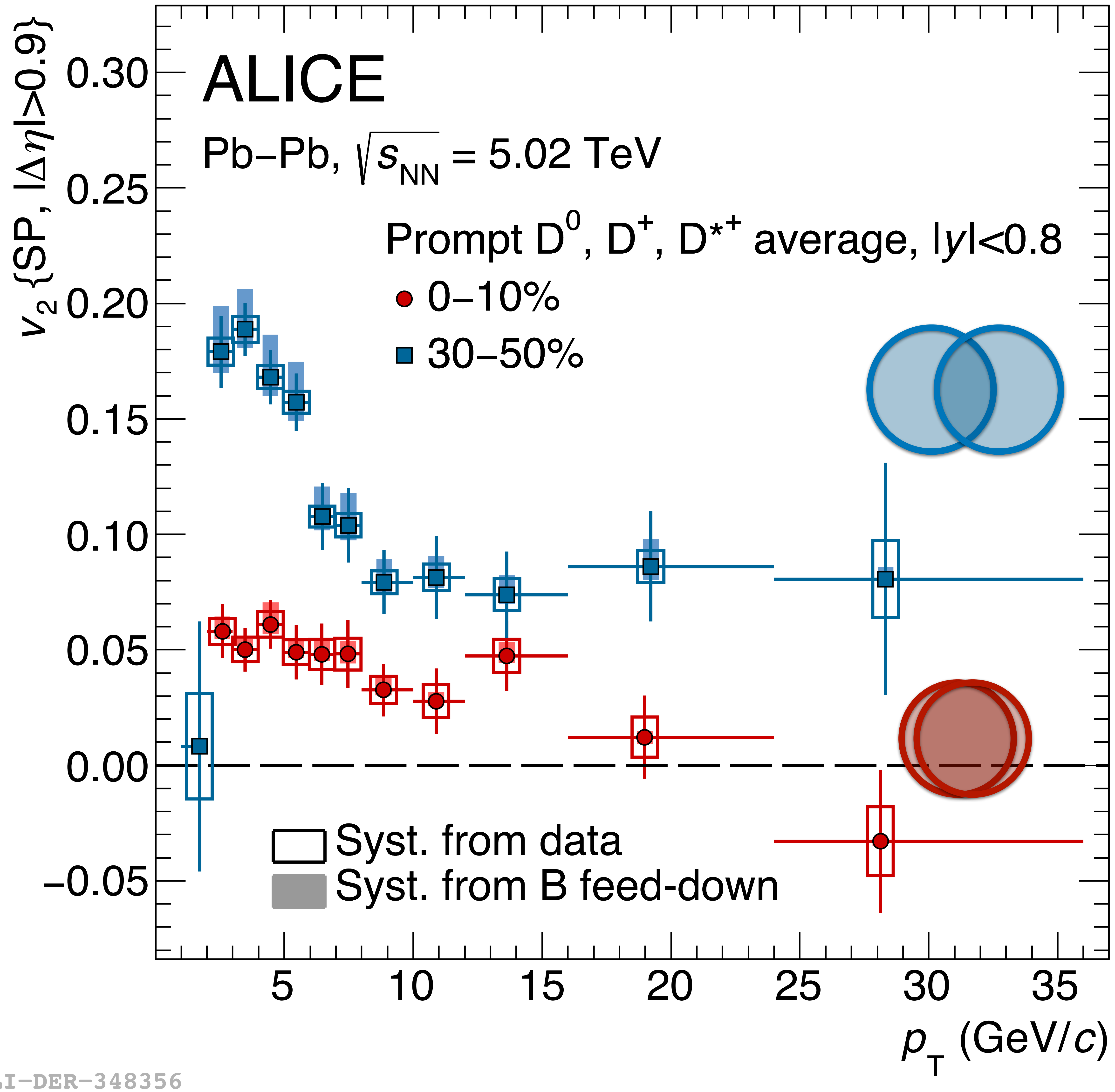
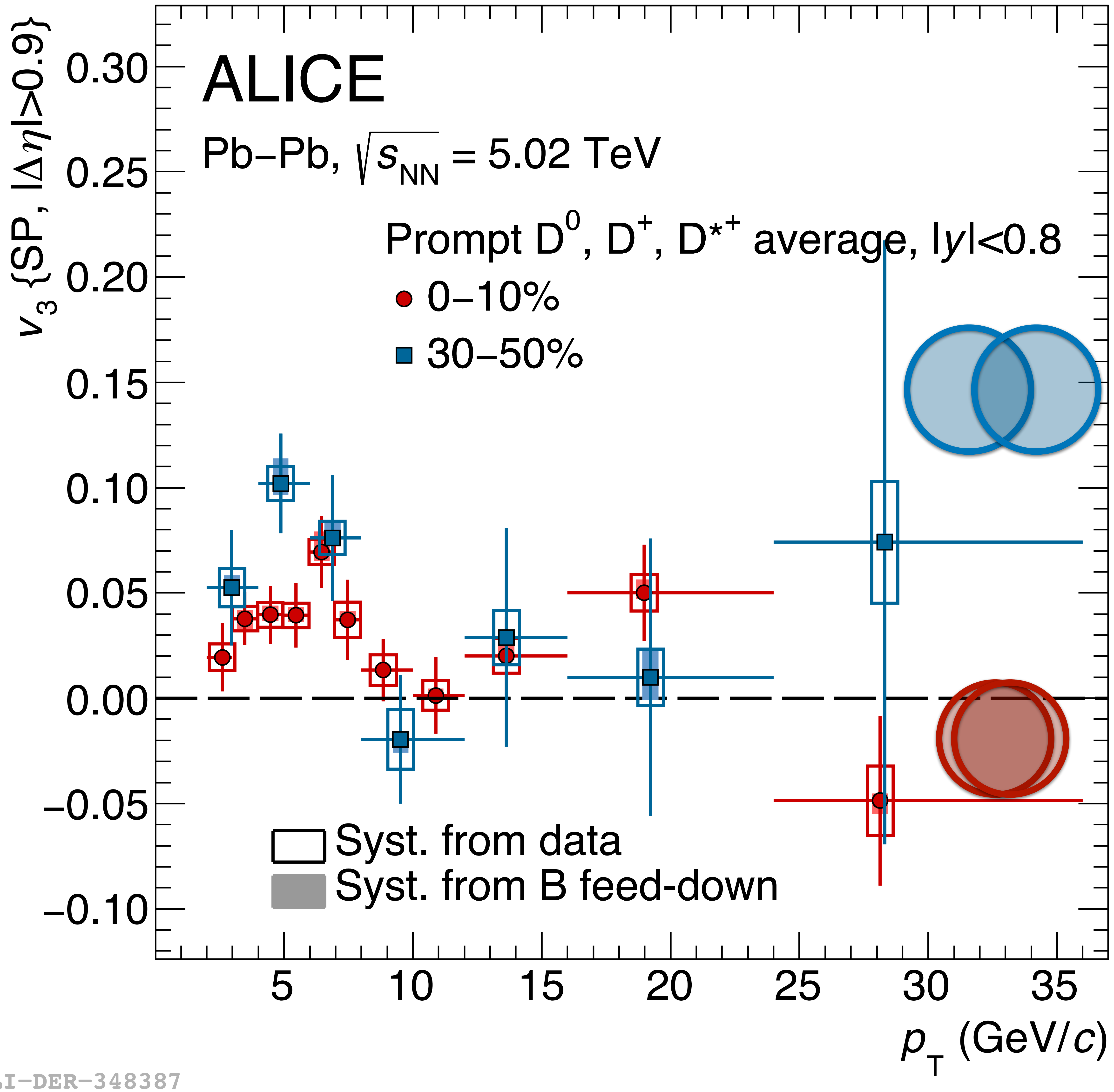


ALI-DER-348356



ALI-DER-348387

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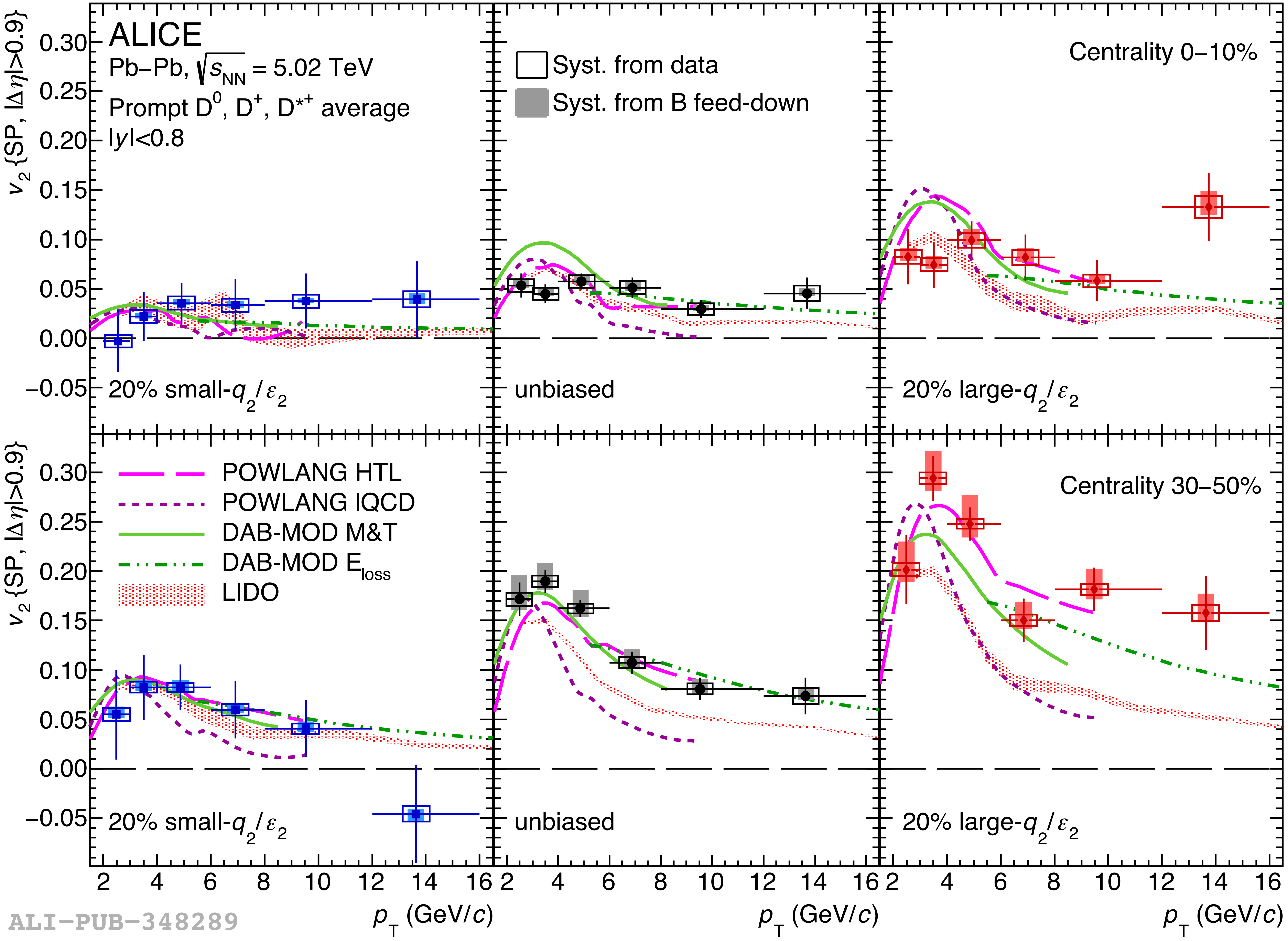
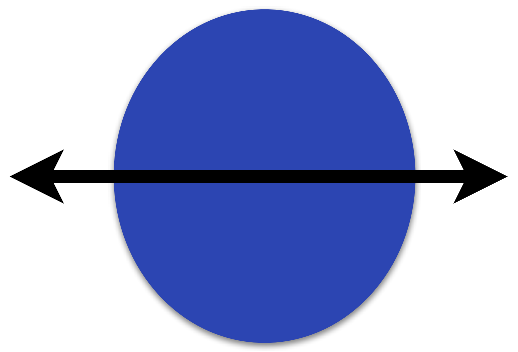


- The Event-shape engineering (ESE) technique relies on the classification of events at a certain centrality according to the magnitude of the second-harmonic reduced flow vector:

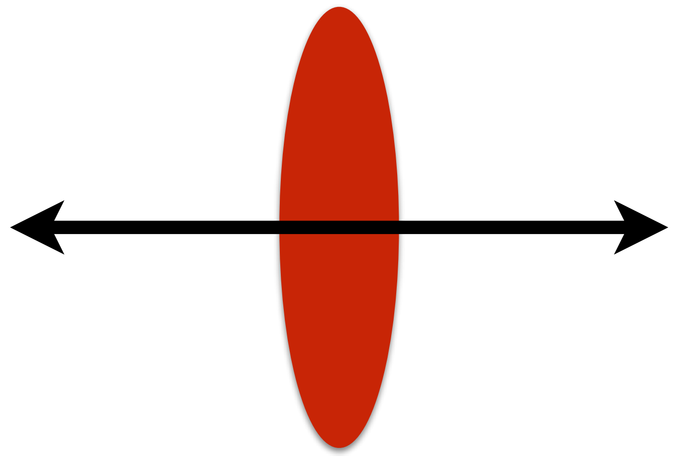
$$q_2 = |\vec{Q}_2| / \sqrt{M}$$

$$\vec{Q}_2 = \sum_{j=1}^{M} e^{i2\varphi_j}$$



20% smallest q_2^{TPC}

$\langle v_2 \rangle_{small-q_2} < \langle v_2 \rangle_{unb}$

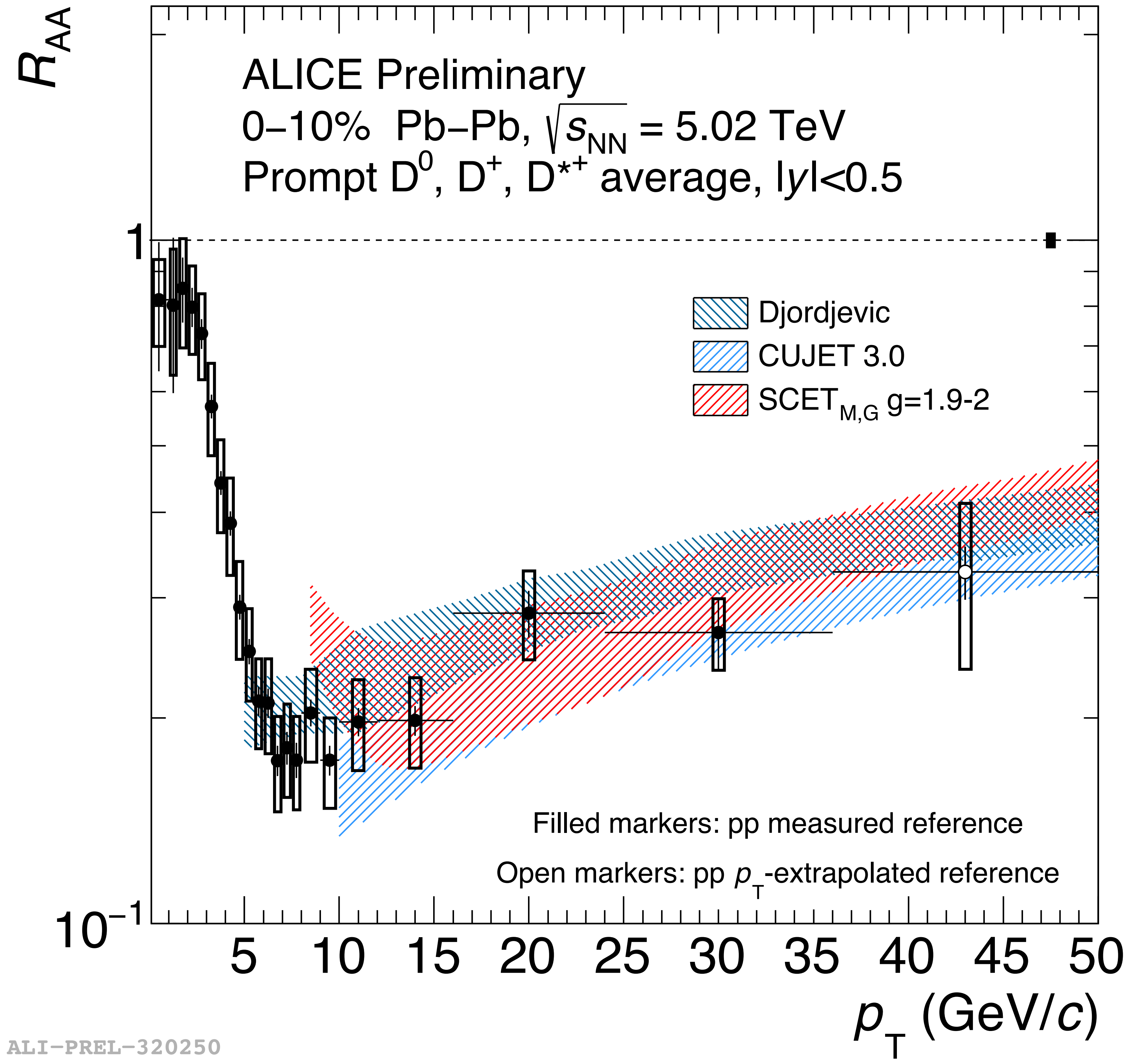


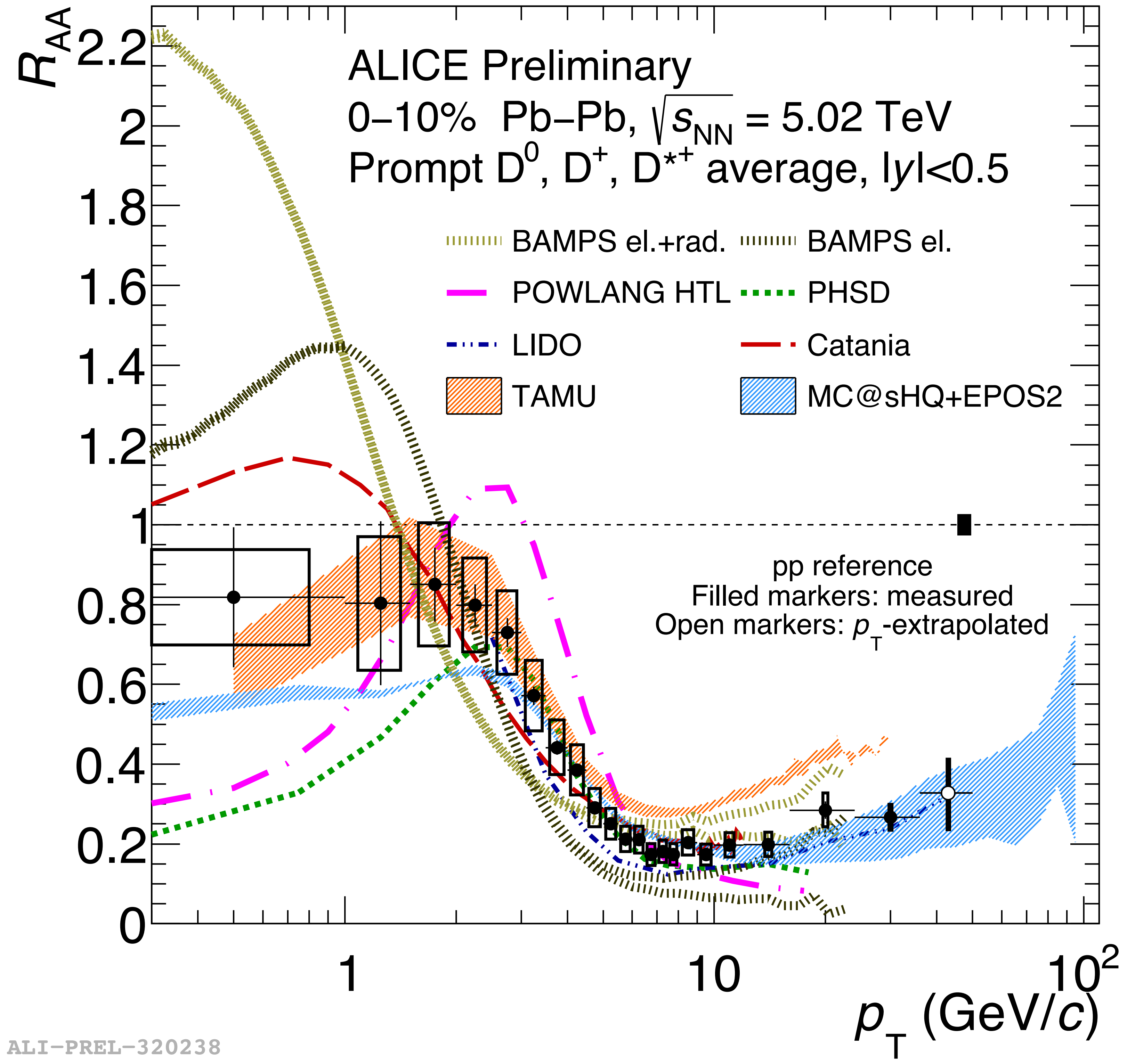
20% largest q_2^{TPC}

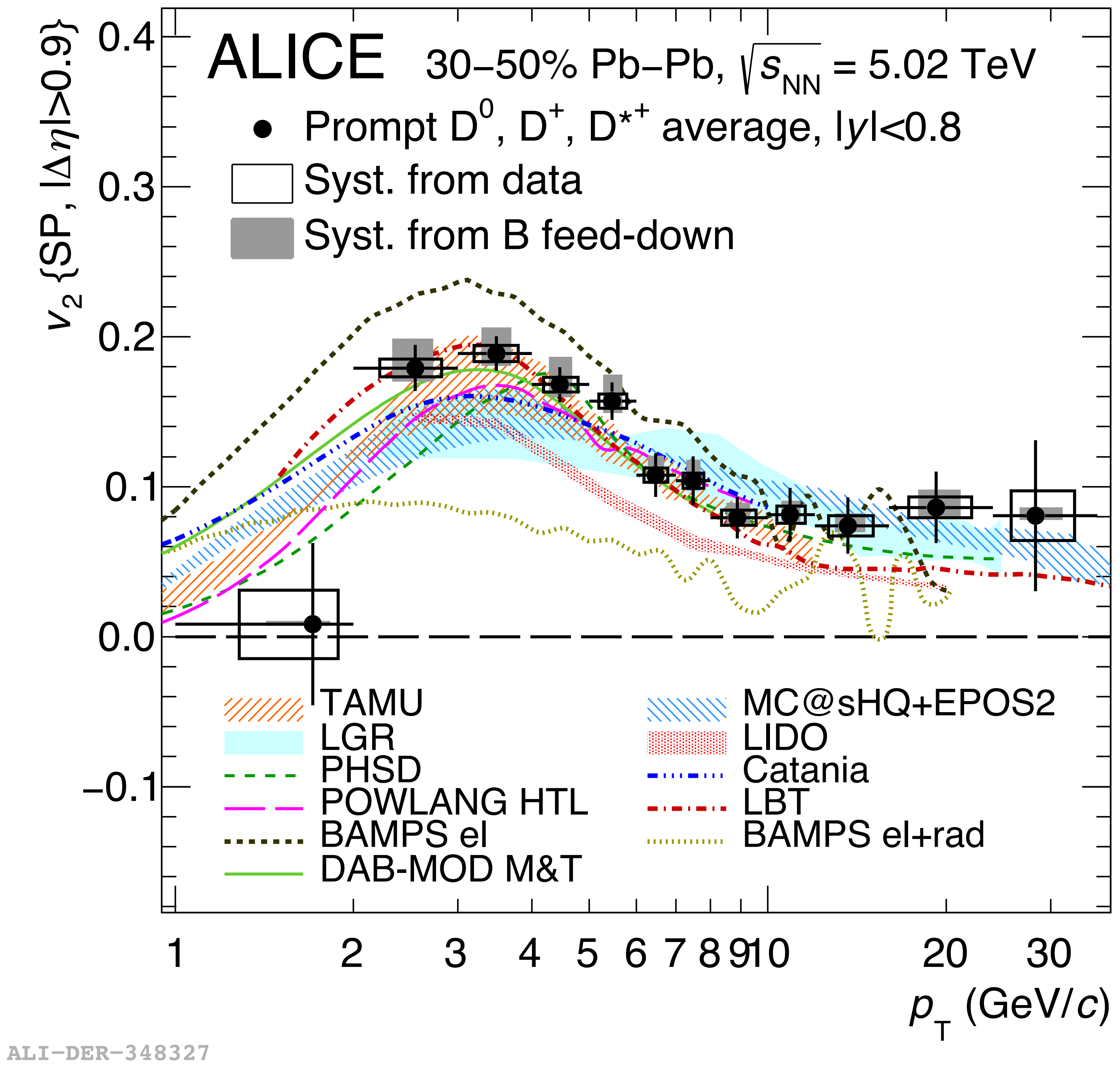
$\langle v_2 \rangle_{large-q_2} > \langle v_2 \rangle_{unb}$

Towards a simultaneous description of R_{AA} and v_2

arXiv:2005.11131

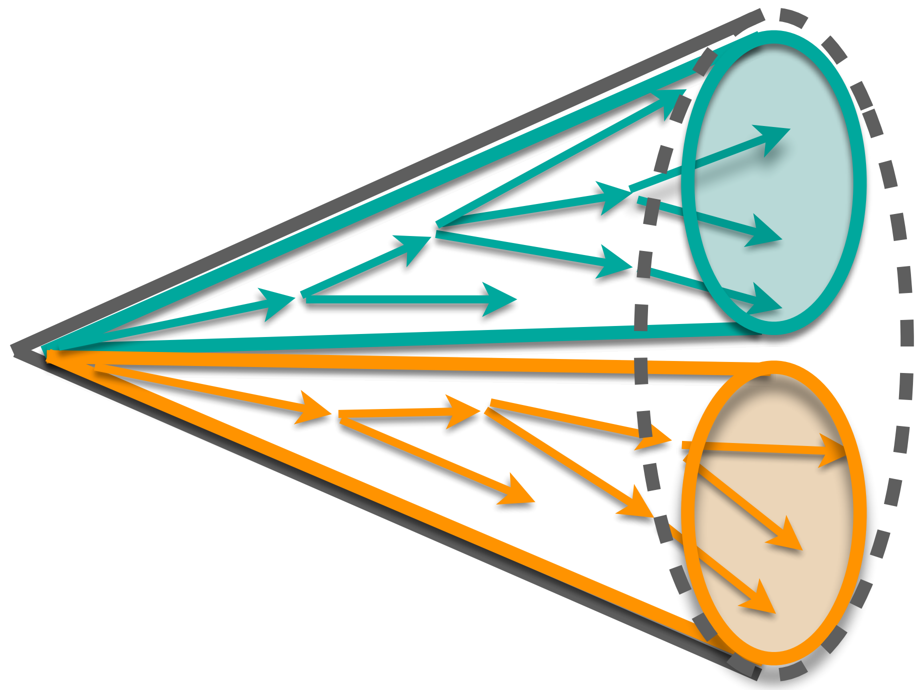






- Djordjevic: PRC 92, 024918 (2015)
- CUJET3.0: JHEP 02 (2016) 169
- SCET: JHEP 03 (2017) 146
- TAMU: PRL 124 (2020) 042301
- MC@sHQ+EPOS2: PRC 89 (2014) 014905
- LGR: arXiv:1912.08965
- LIDO: PRC 98 (2018) 064901
- PHSD: PRC 93 (2016) 034906
- Catania: PLB 805 (2020) 135460
- POWLANG: EPJC (2019) 79:494
- LBT: PRC 94 (2016) 014909
- BAMPS: JPG 42 (2015) 11, 115106
- DAB-MOD: arXiv:1906.10768

Lund plane

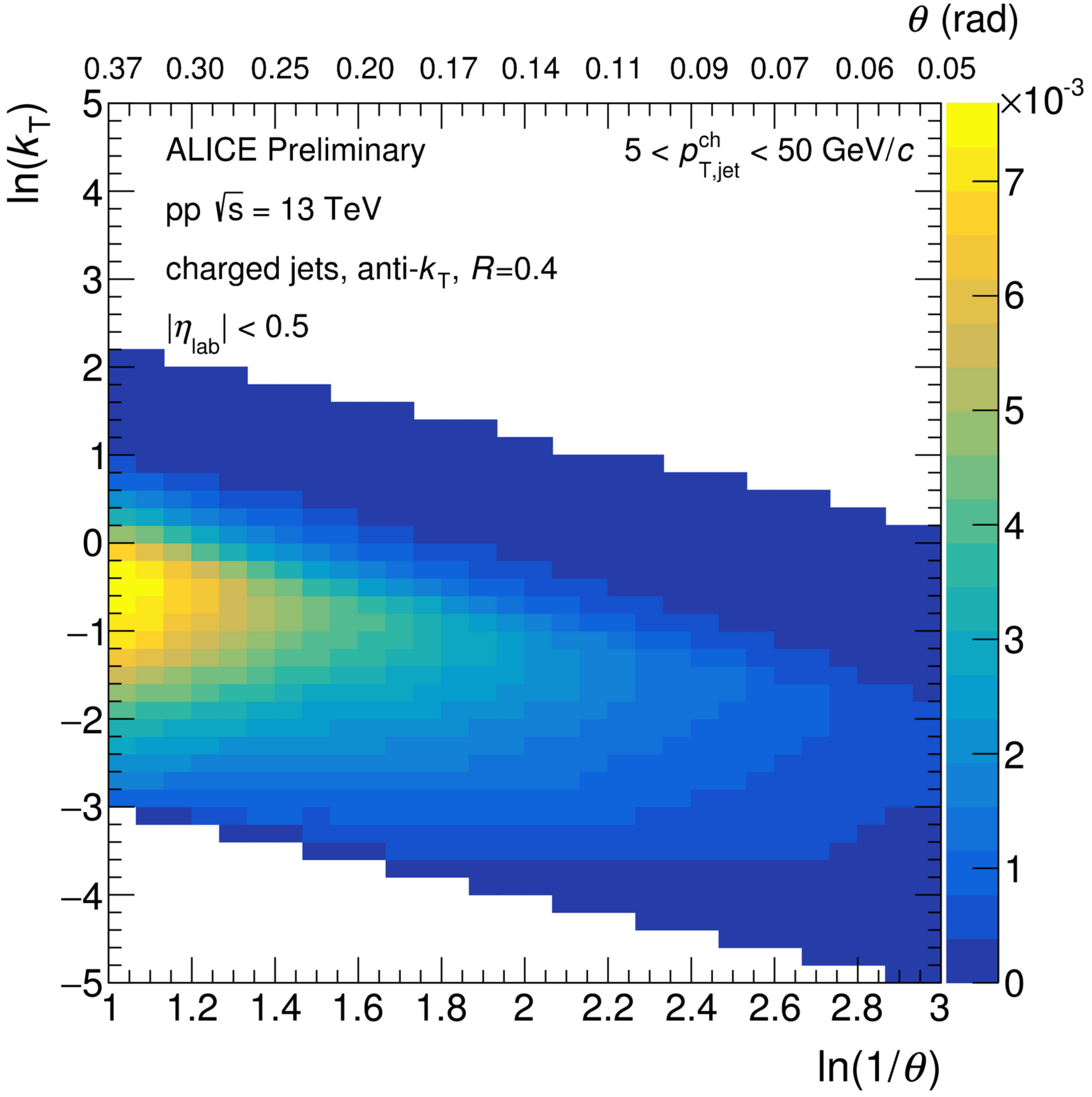


$\theta = \Delta R$

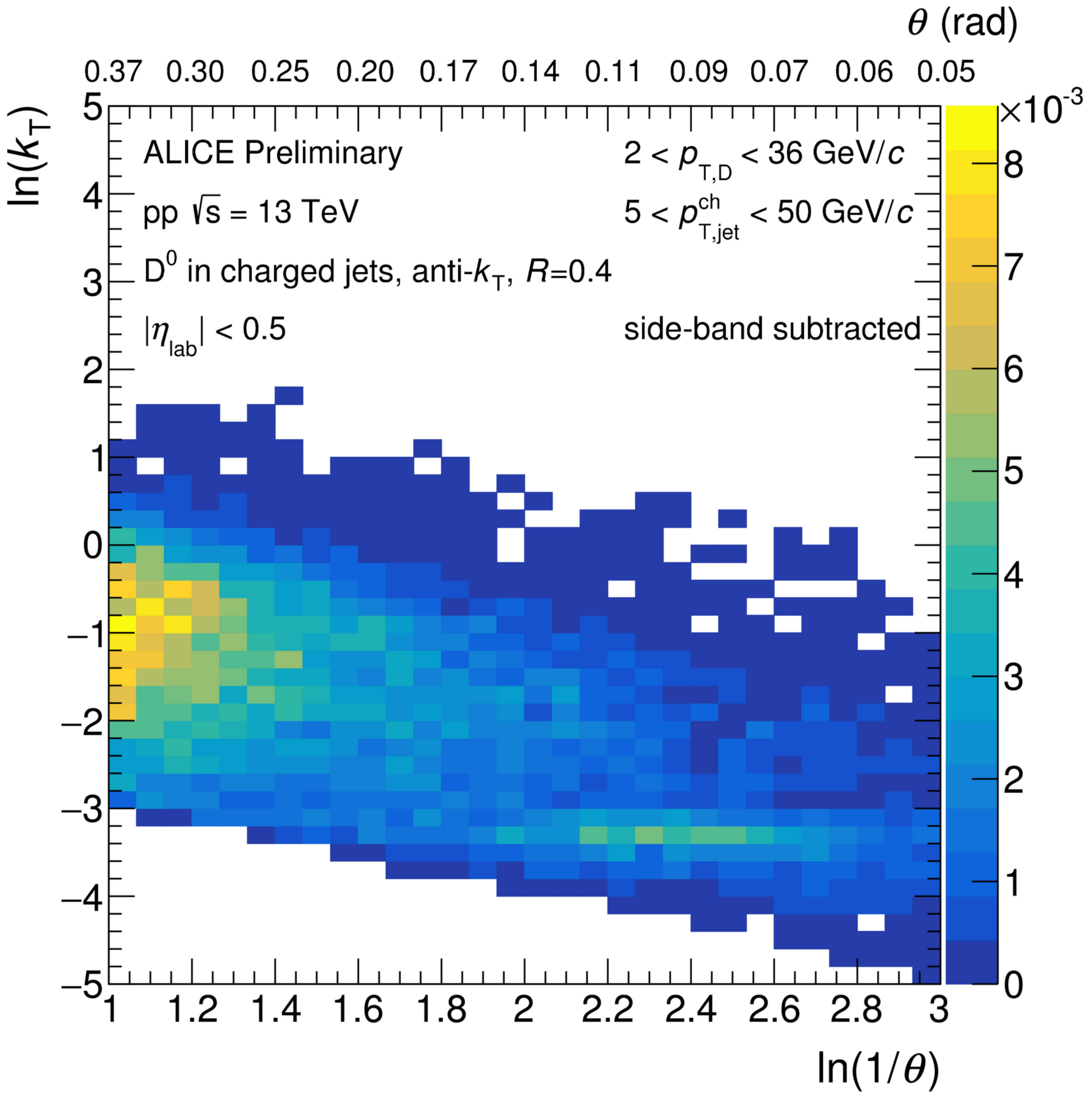
opening angle between subjets

$k_{\mathrm{T}} = z p_{\mathrm{T}} \sin(\Delta R)$

relative transverse momentum of subjets

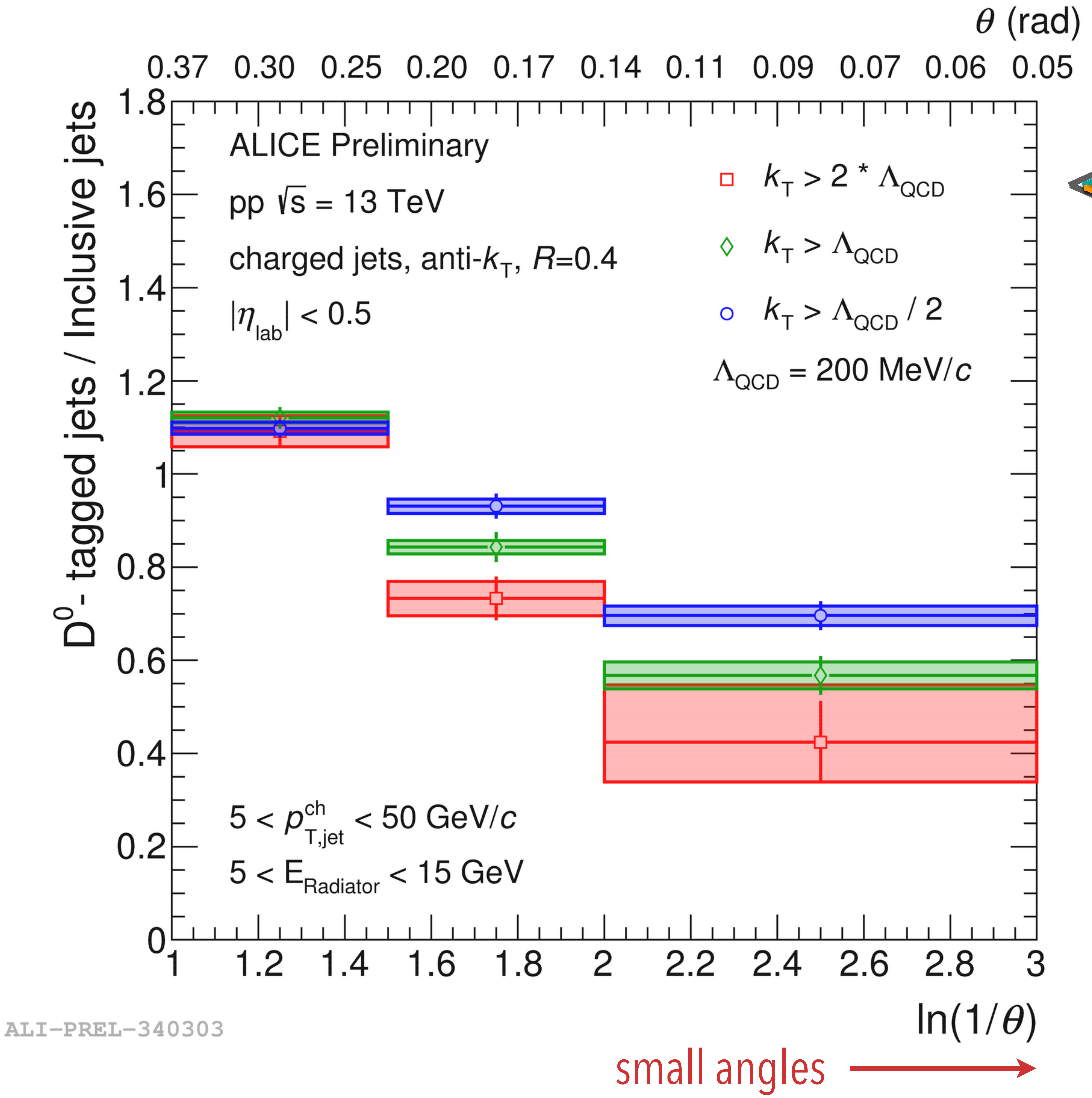


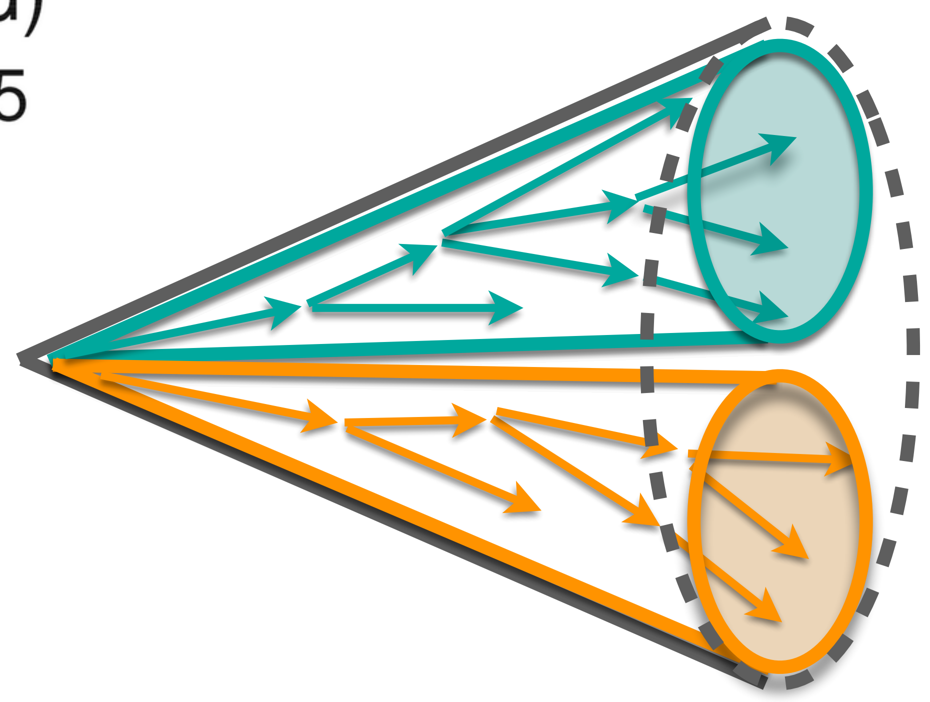
ALI-PREL-339786



ALI-PREL-339746

Direct observation of dead cone effect





$\theta = \Delta R$ opening angle between subjets

$k_T = z p_T \sin(\Delta R)$ relative transverse momentum of subjets

- Suppression of splittings at small angles in D^0-tagged jets compared to inclusive jets
  - ➡ dead cone effect
- More results on jets in Laura Havener CERN-EP seminar