(Recent measurements on)
Open charm and beauty production

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Disclaimer: only a selection of the results could be shown (time limit)

Strange Quark Matter 2024, Strasbourg (France)

Why heavy flavours?

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- Heavy quarks are produced in initial hard scatterings with **large Q^2 → calculable with pQCD.**
- Large masses $m_b > m_c \gg \Lambda_{QCD}$ → short formation time (<QGP lifetime) → **experience whole medium evolution**
- Interactions with the medium don't change the flavour, but can modify the phase-space distribution.
  Thermal production rate in the QGP is expected to be 'small'.
  → **destruction or creation in the medium is difficult**

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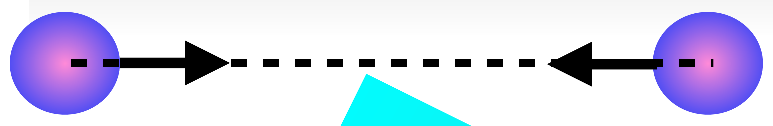
- Factorization approach:

$$\frac{d^2\sigma}{dp_T dy}(AB \to CX) \propto \sum_{abcd} \int_0^1 dx_a \int_0^1 dx_b\, f_A^a(x_a, Q^2) f_B^b(x_b, Q^2) \frac{d\sigma}{dt}(ab \to cd)\, D_c^C(z_c, Q^2)$$

Parton distribution functions — Partonic cross section — Fragmentation function

- **Fragmentation functions assumed to be universal** across collision systems.
- For the quarkonium case, the binding of the quark pair involves soft scales, non-perturbative nature.

What can we learn?

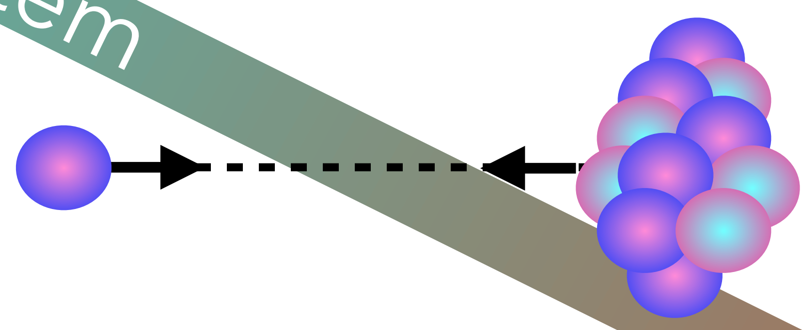


- Test **pQCD calculations**
  - PDFs
  - μ_R μ_F scales

- Sensitive to **fragmentation / hadronisation**
  - Fragmentation fraction universality being questioned by recent LHC data
  - Scrutinize hadron formation / nature

system

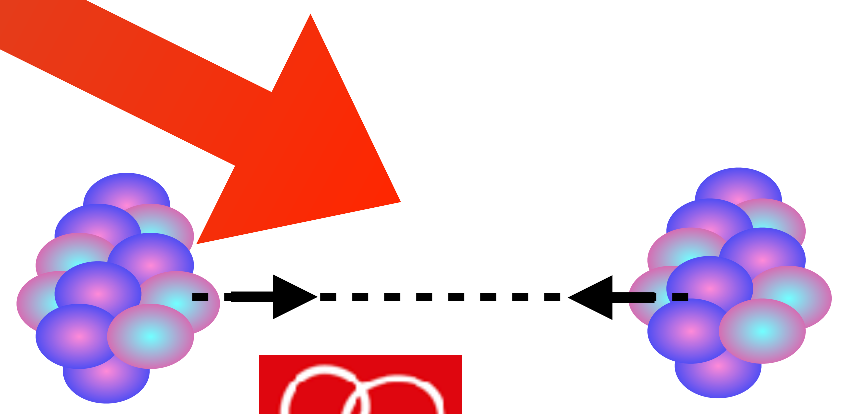
- **Initial state effects**
  - saturation /
    modification of PDFs in nuclei
  - …



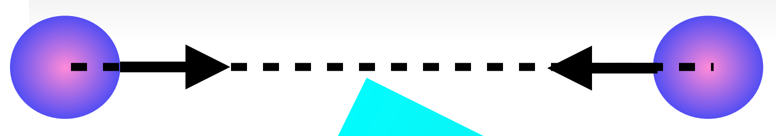
- **Underlying event / multiple parton interactions**
  - Interplay between soft/hard processes
  - Multiple parton interaction (MPI) contribution

- **Final state effects**
  - energy loss
  - transport
  - thermalisation
  - …

- Early **magnetic field**



What can we learn?



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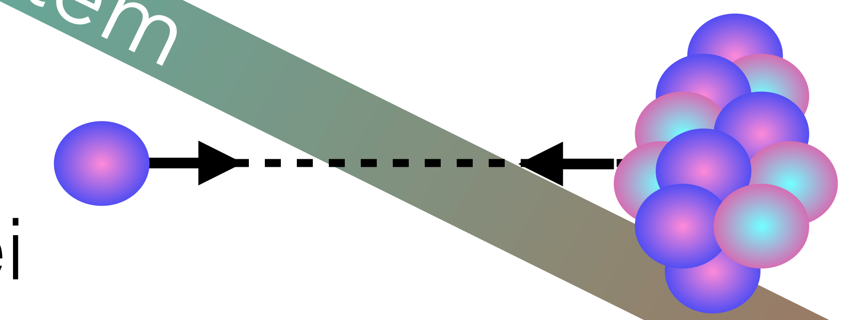

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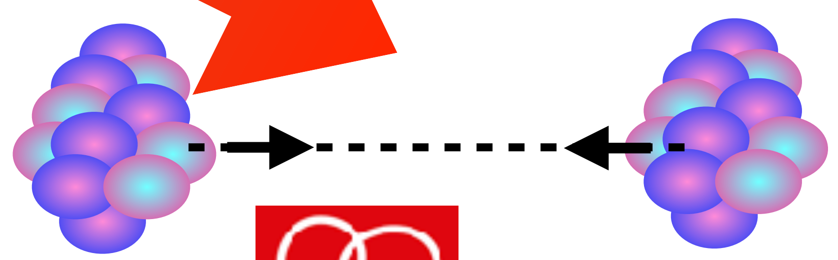
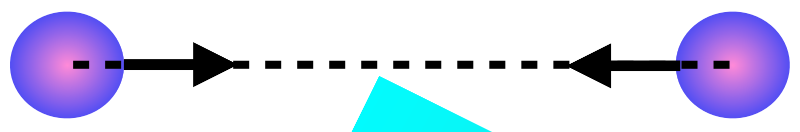


- **Understand particle production across collision system size.**
- **Investigate the source of collective effects.**
- **Characterize heavy quark interaction with the medium.**

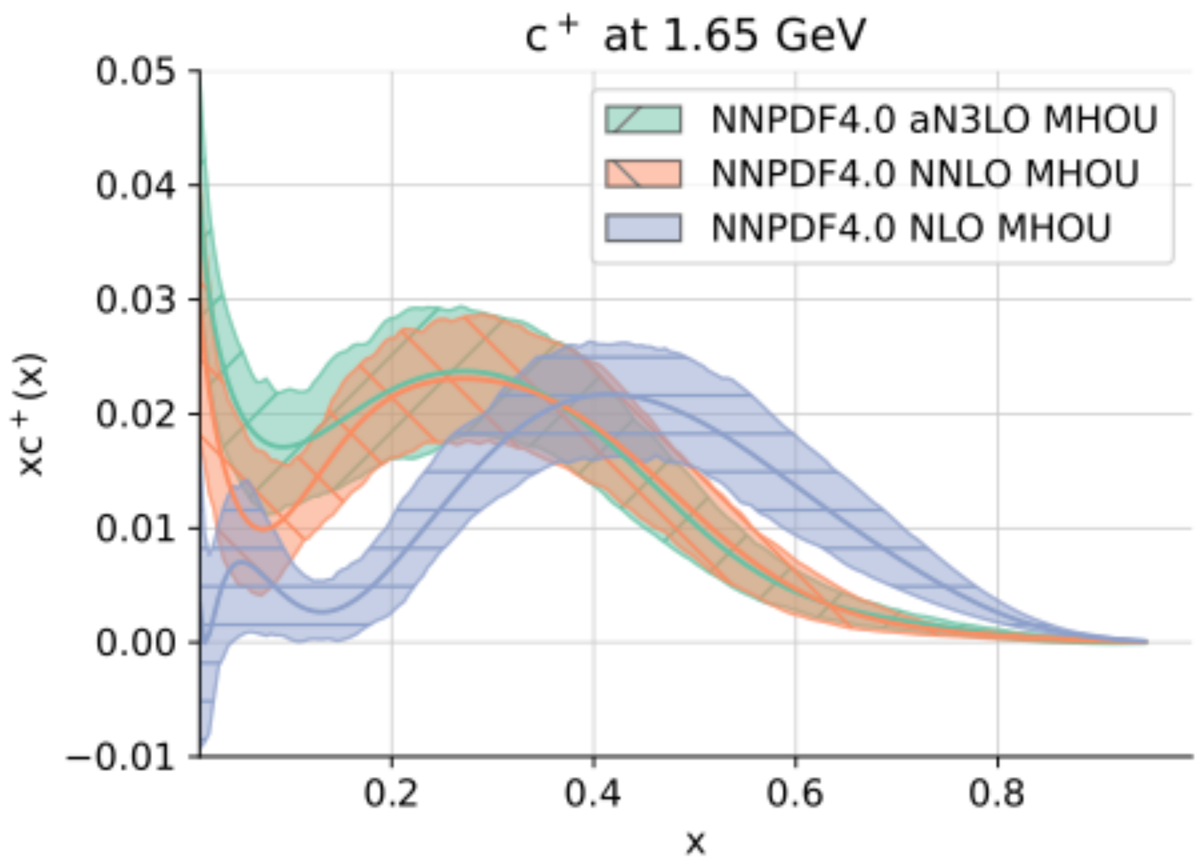


Talk. J. Wang

Talk. M. Faggin

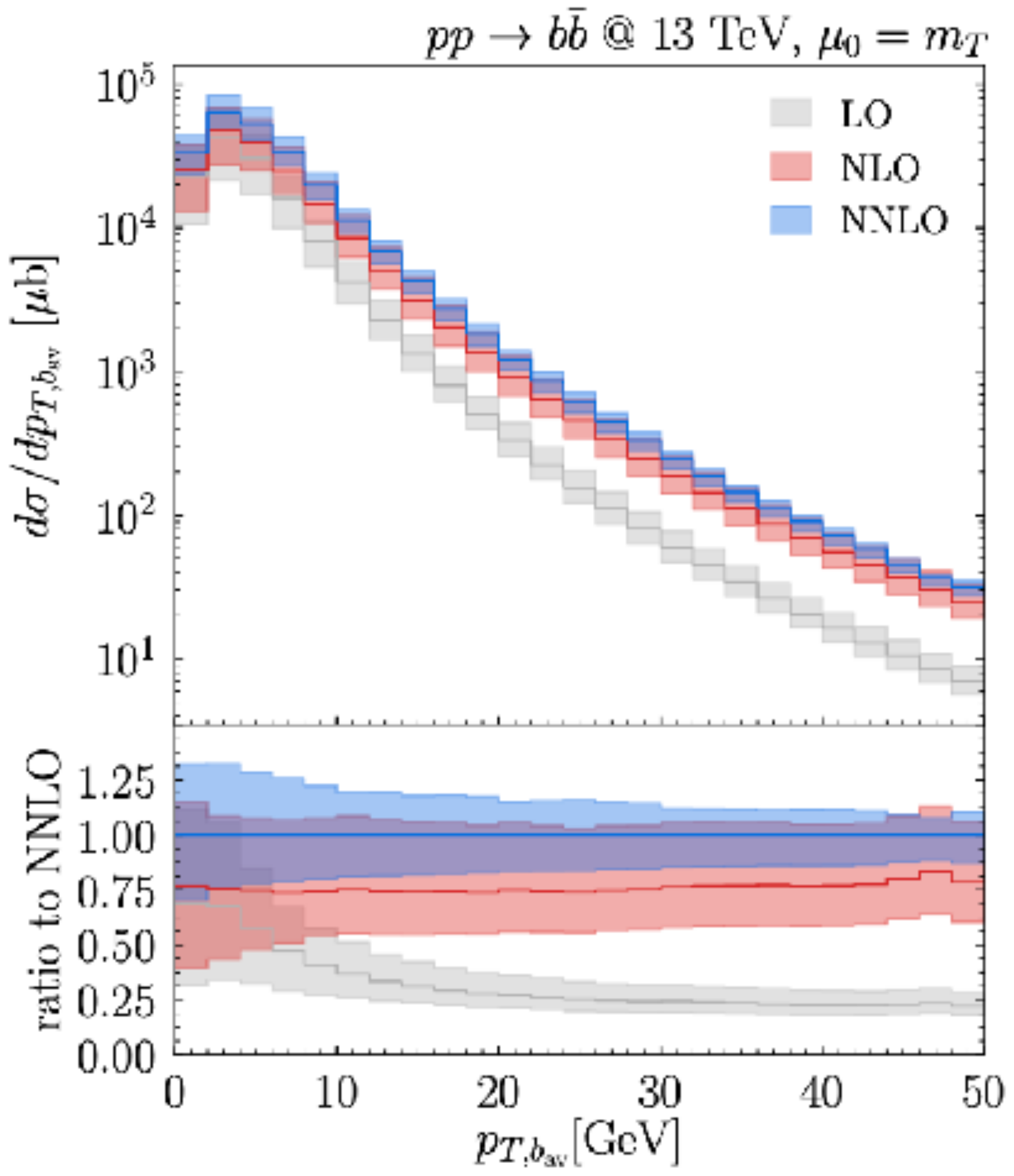
Talk. A. Baty

Talk. J. Cho

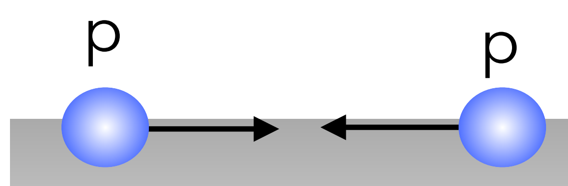


N3LO PDF, NNPDF Coll.; arXiv:2402.18635

Testing pQCD
(on yields)

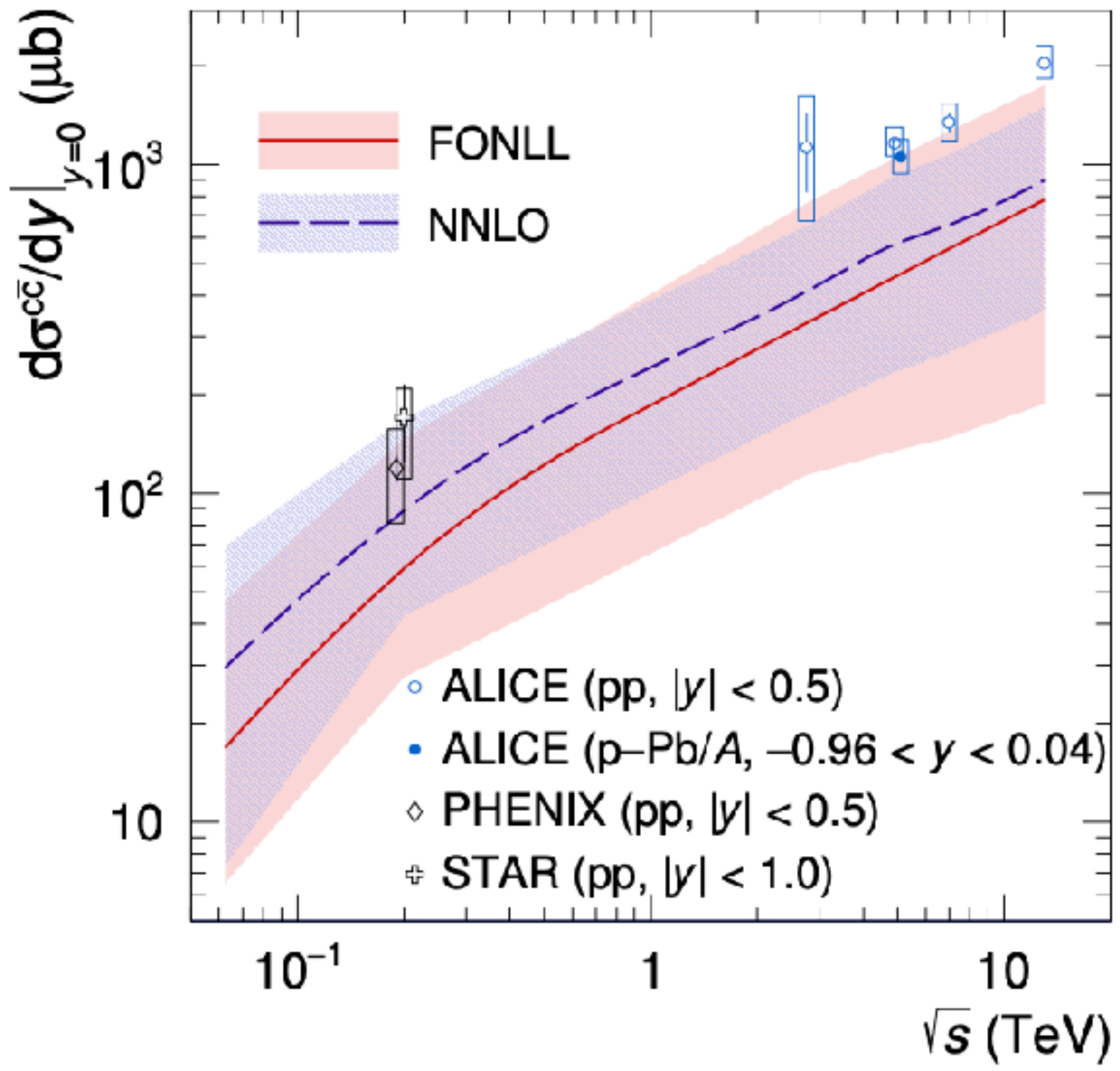


NNLO, Catani et al. JHEP 03 (2021) 029

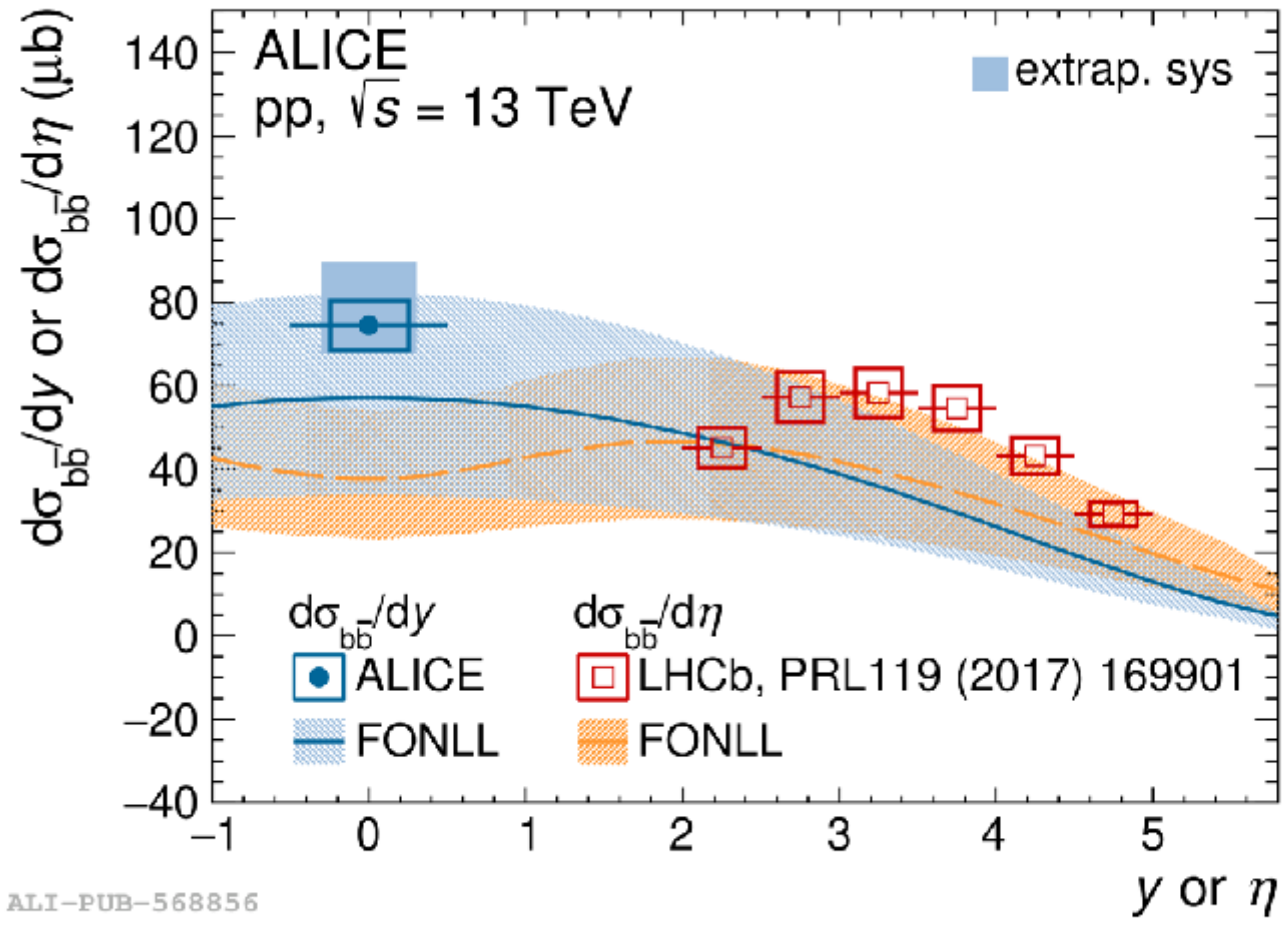


Recent cross section measurements in pp

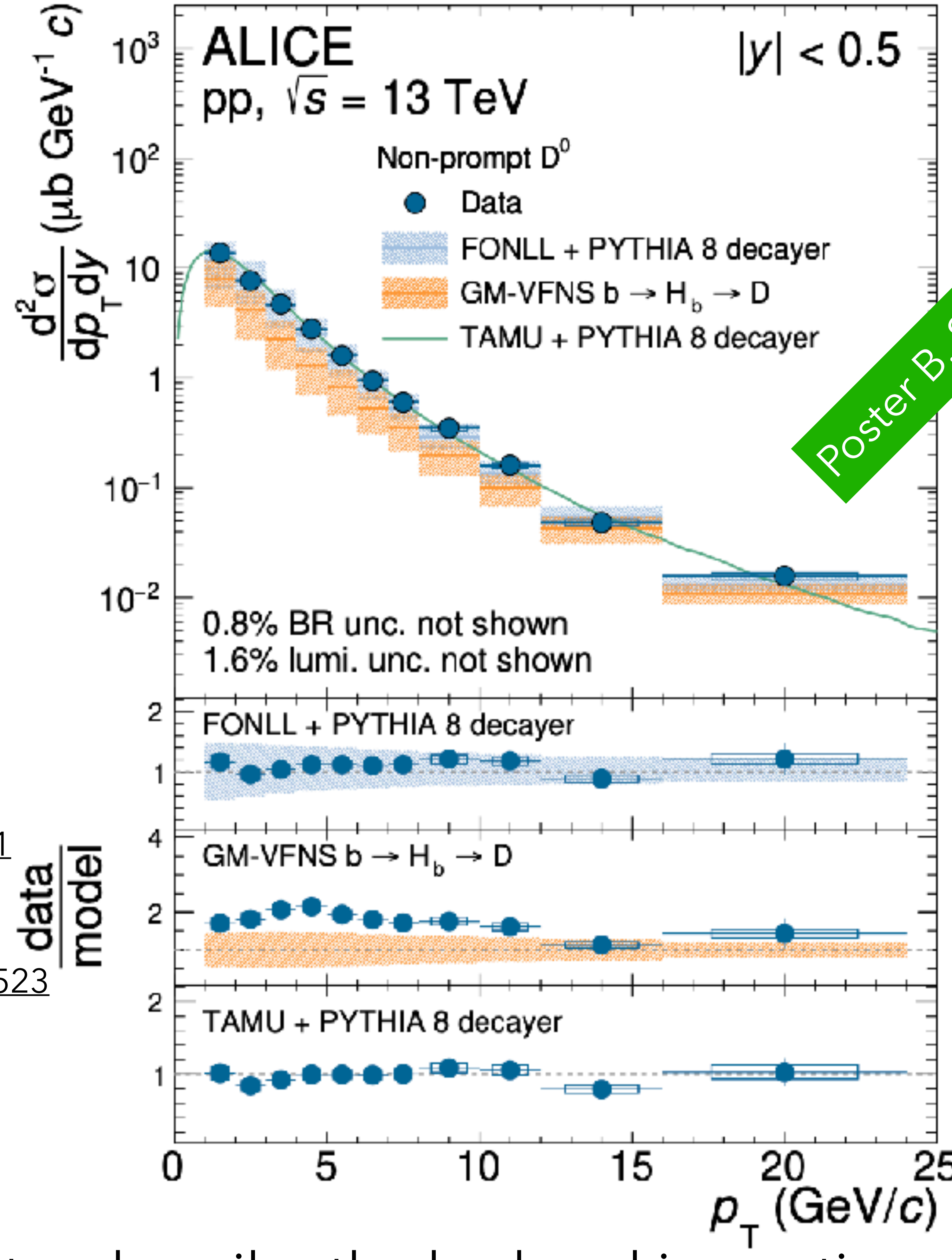
Charm cross section vs. √s



Beauty cross section vs. η or y



Non-prompt D^0 cross section vs p_T



Poster B. Sharma

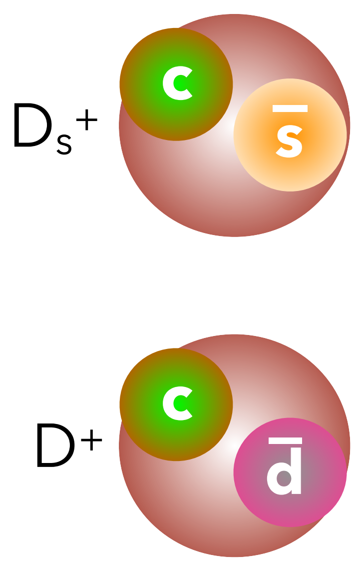
ALICE, arXiv:2405.14571
ALICE, Phys. Rev. D 105 (2022) L011103
FONLL, Cacciari et al. JHEP 03 (2001) 006
NNLO, Catani et al. JHEP 03 (2021) 029
NNLO+NNLL, Gemeret, arXiv:2405.10772

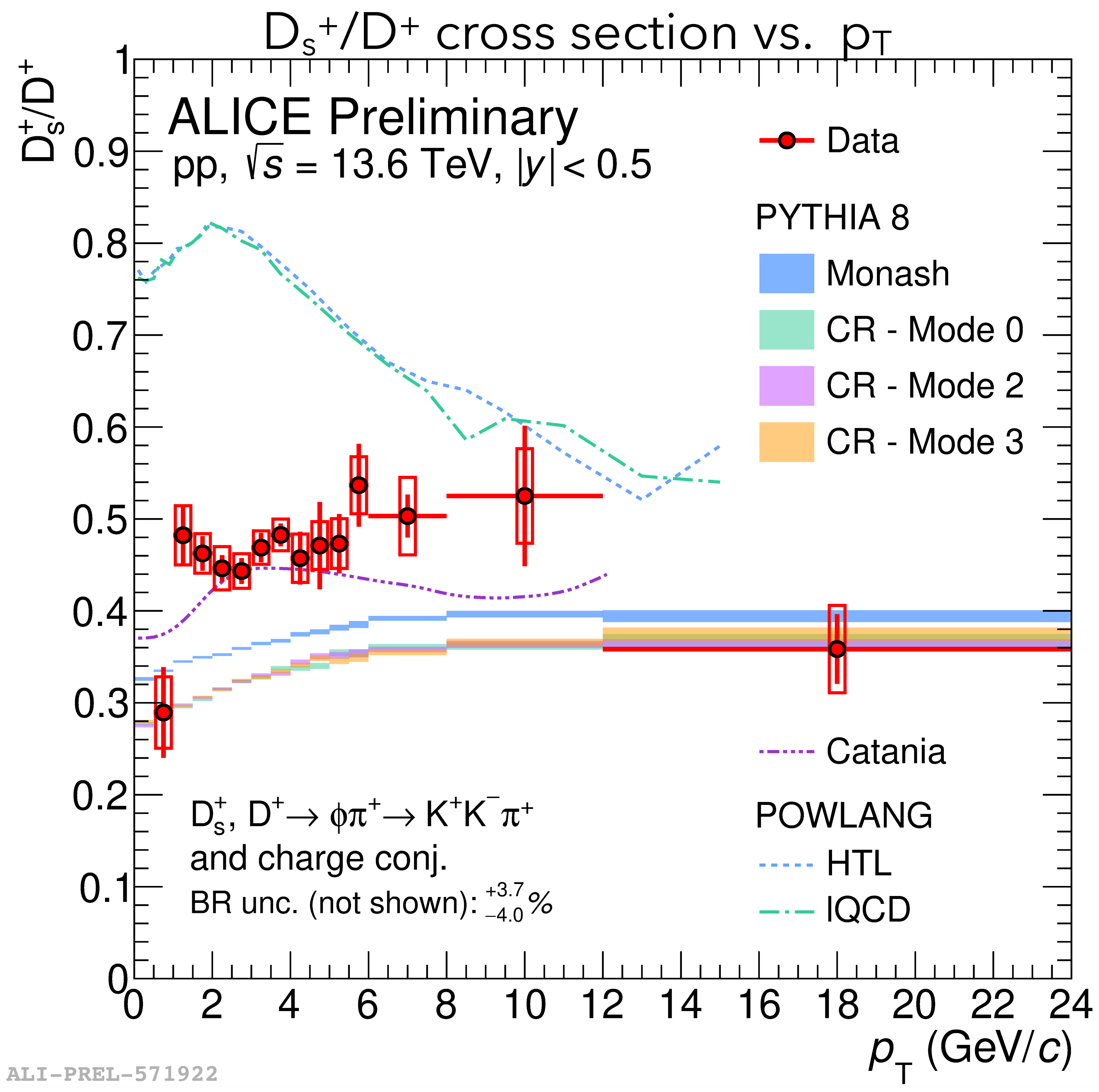
ALICE, arXiv:2402.16417
LHCb, PRL 119 (2017) 169901

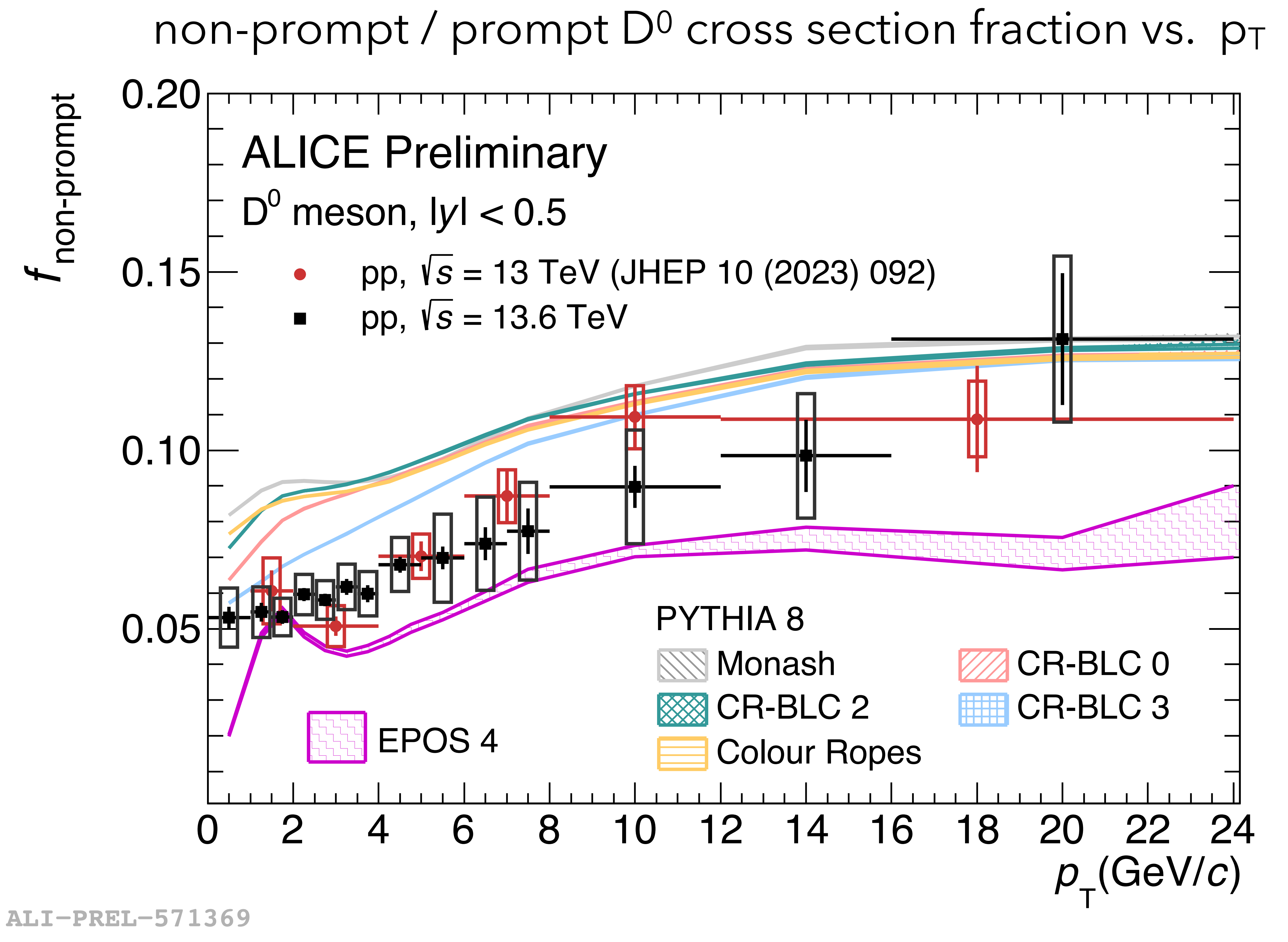
Yang, Geiser, arXiv:2311.07523

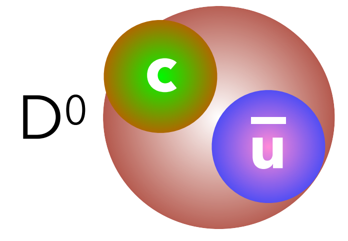
- Significant experimental progress:
  improved precision and more differential measurements → **precision era**
- Time to move to NNLO or NNLO+NNLL calculation accuracy?
  Refinement of the non-perturbative hadronisation model would help to better describe the hadron kinematics.

Glimpse on particle ratios from pp $\sqrt{s}$ =13.6 TeV data









Talk. M. Faggin

Poster M. Zhang

- Particle ratios and non-prompt fraction present **no significant energy dependence**
- Promising more differential and precise measurements with Run3 data
- Both models including initial or final state effects have difficulties to reproduce data. Possible influence of the under prediction of charm cross section, PDFs, hadronisation,…?

ALICE Preliminary
ALICE, arXiv:2402.16417

PYTHIA 8: JHEP 08 (2015) 003
POWLANG: arXiv:2306.02152
EPOS3: NPA 967 (2017) 672-675
EPOS4: PRC 108 (2023) 034904

Talk. A. Merzlaya

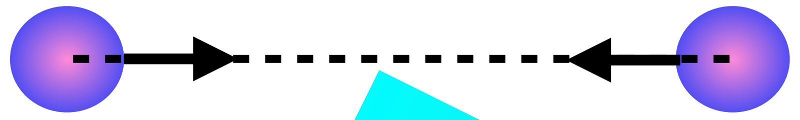
Talk. J. Wang

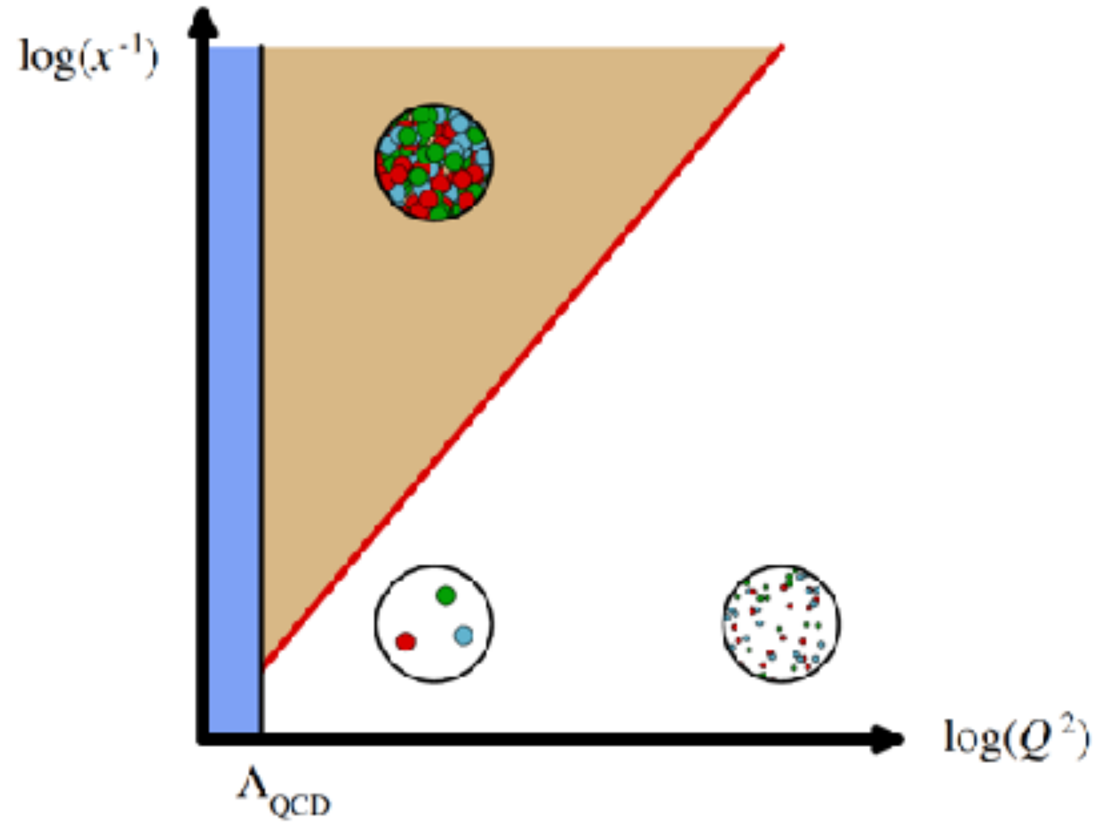
Talk. M. Faggin

Talk. C. Landesa

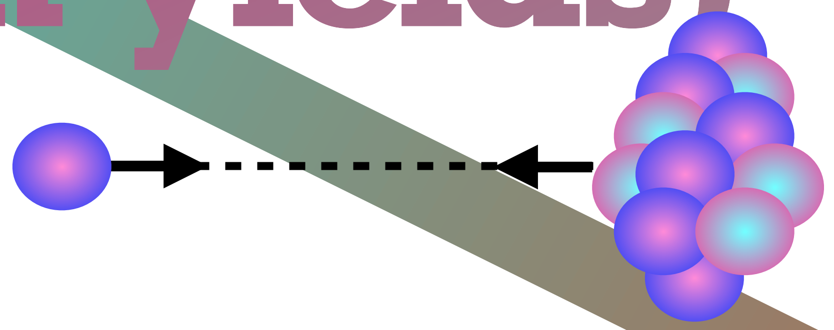
Talk. A. Baty

Talk. J. Cho

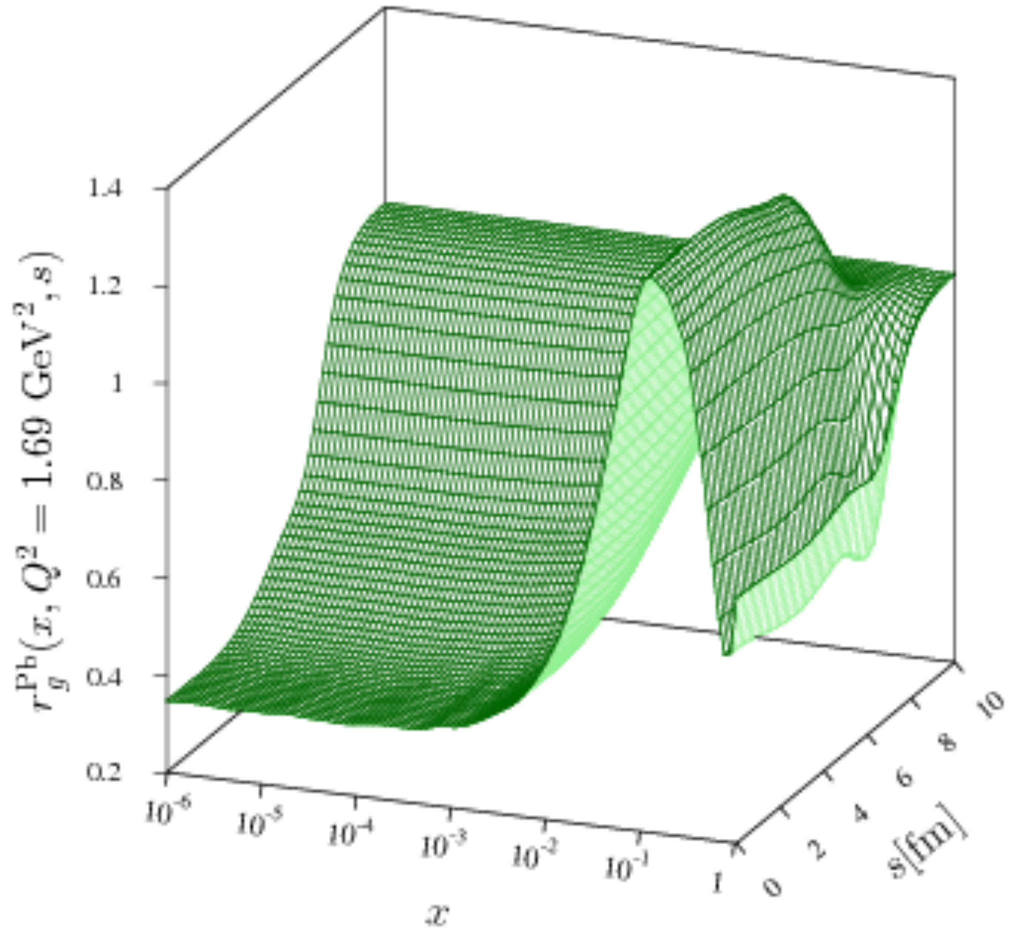




Initial state effects
(on yields)



Saturation,
Modification of PDFs in nuclei

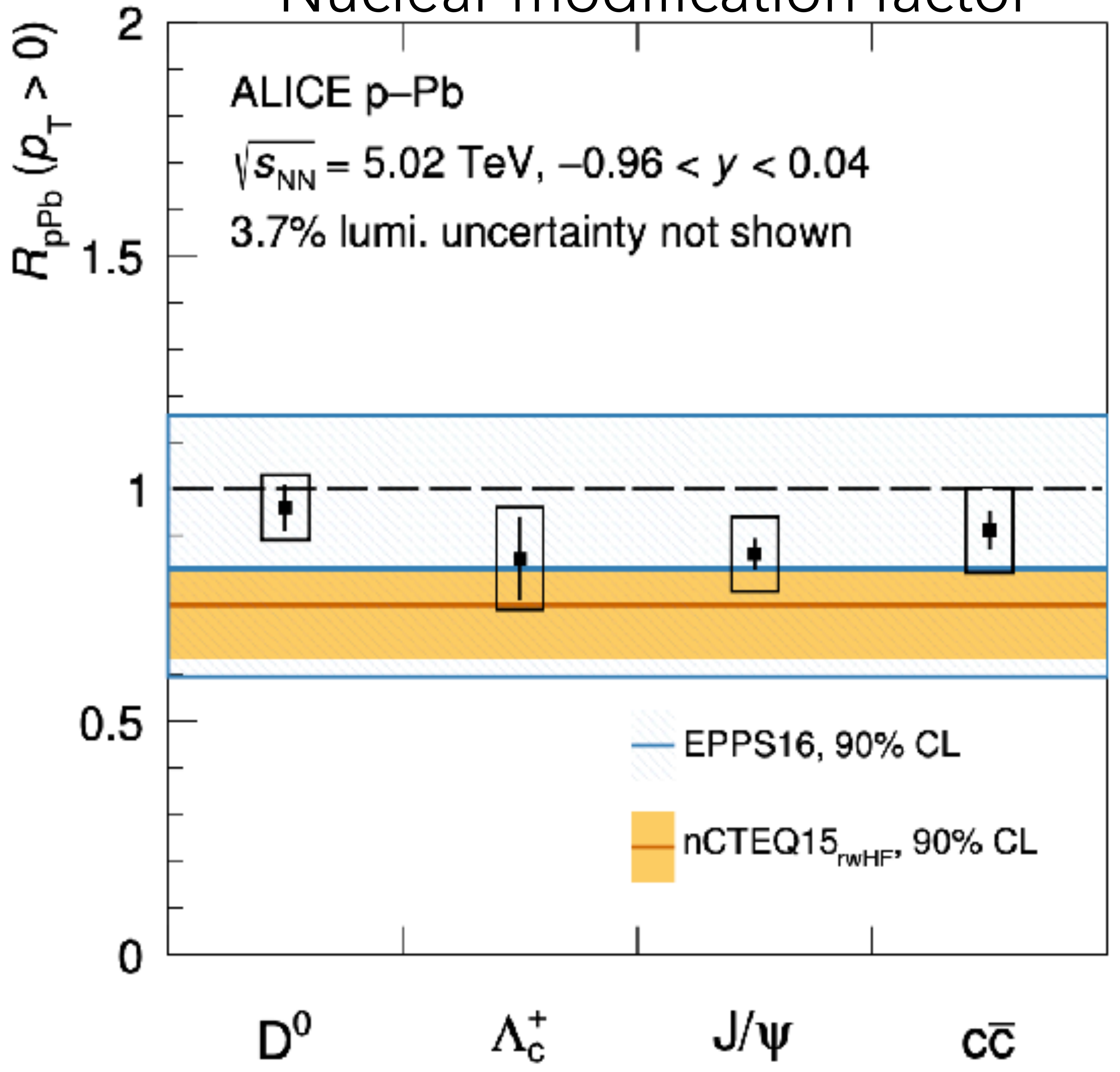


I. Helenius et al., Nucl.Phys.A 904-905 (2013) 999

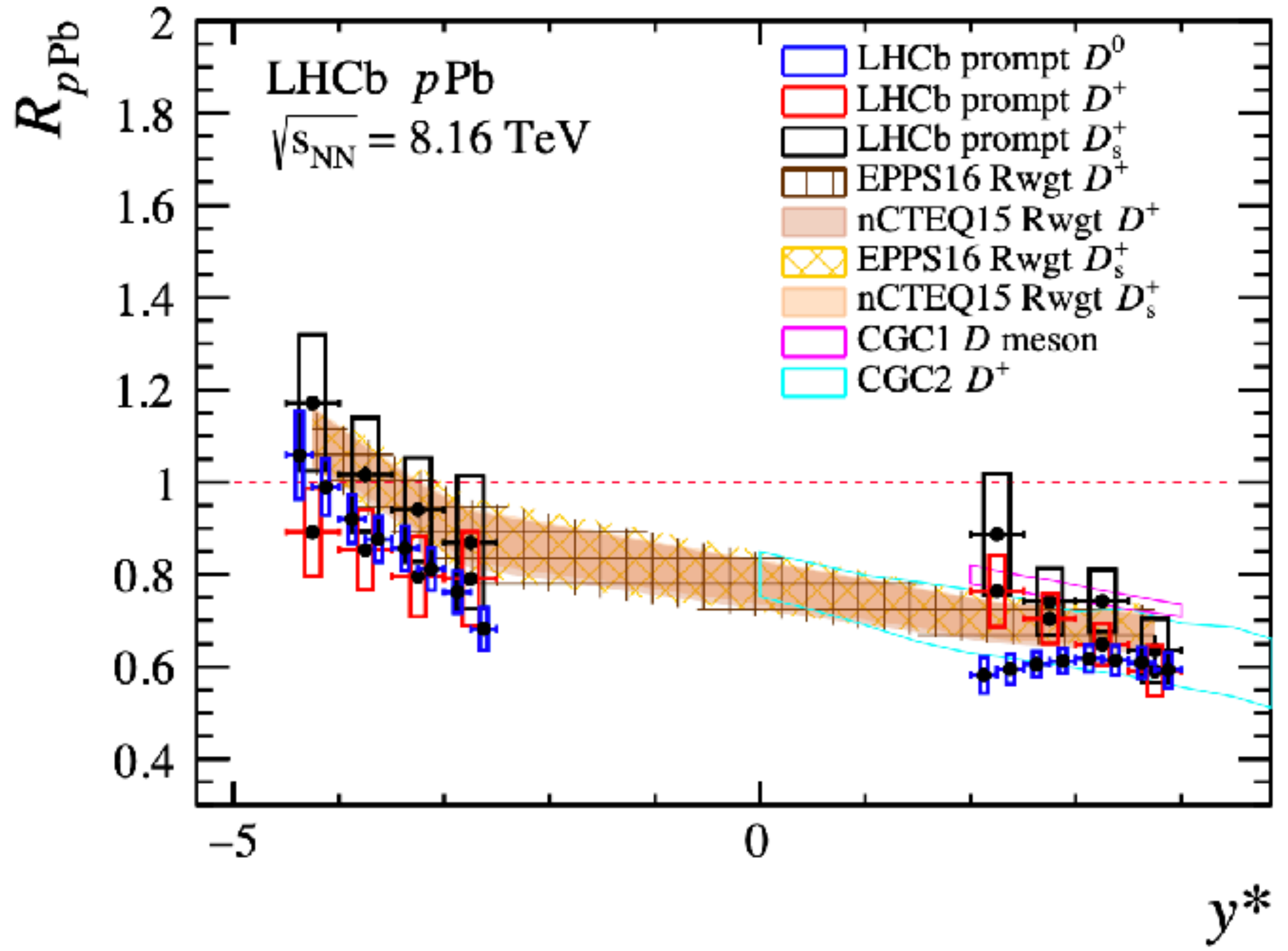
$$R_{\mathrm{pA}}^{\mathrm{probe,CC}} = \frac{\mathrm{d}N_{\mathrm{pA}}^{\mathrm{probe,CC}}}{\langle N_{\mathrm{coll}}\rangle^{\mathrm{CC}} \cdot \mathrm{d}N_{\mathrm{NN}}^{\mathrm{probe}}} \xrightarrow{\int b} R_{\mathrm{pA}}^{\mathrm{probe}} = \frac{\sigma_{\mathrm{pA}}^{\mathrm{probe}}}{\mathrm{A} \cdot \sigma_{\mathrm{NN}}^{\mathrm{probe}}}$$

Constraining the initial state with pPb data

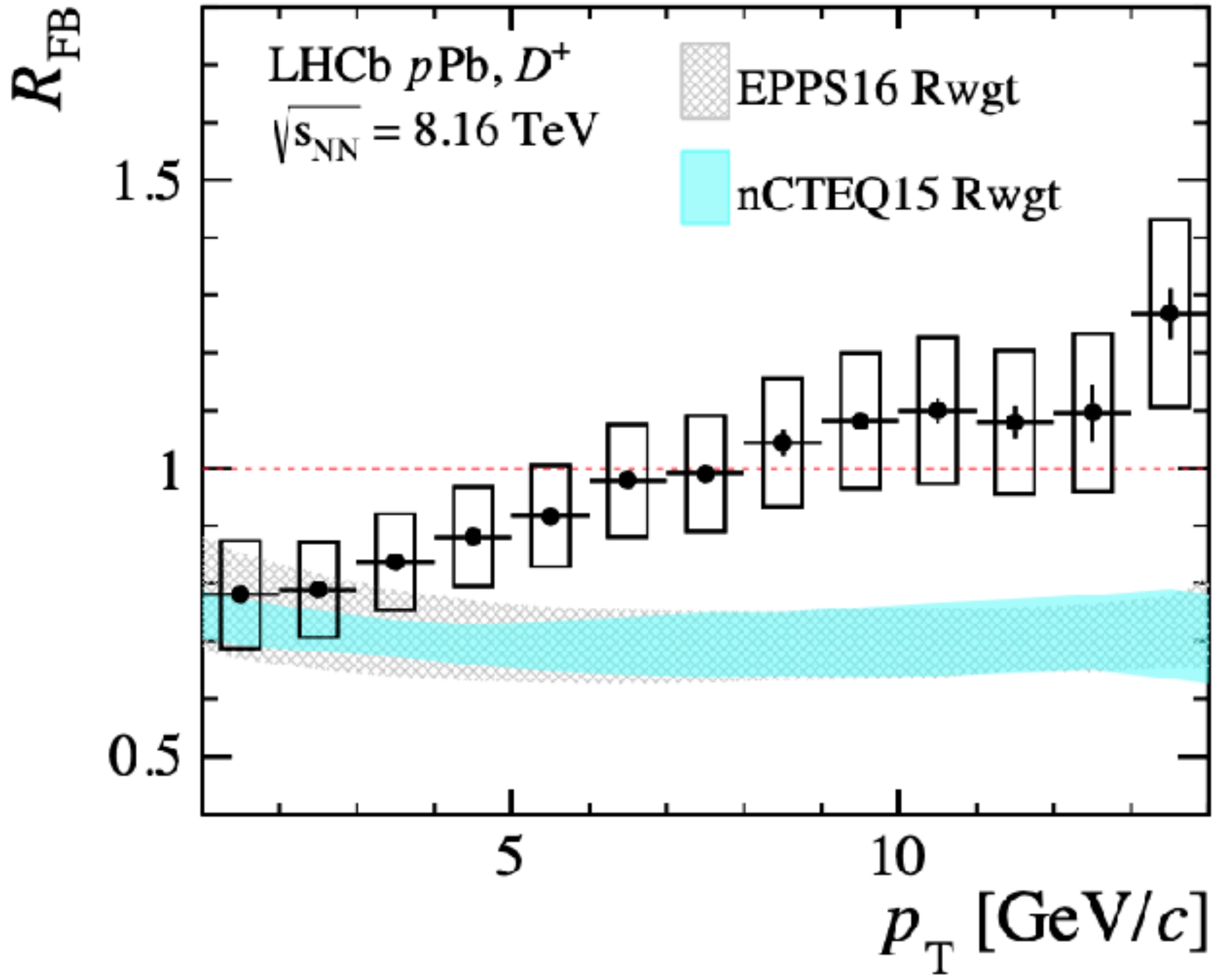
Nuclear modification factor



Nuclear modification factor vs. y



D^+ Forward to backward ratio vs. p_T



- p_T-integrated quantities show a suppression at forward rapidity
  Effects consistent with model (CGC, nPDF) calculations
- D^+, D_s^+ y and p_T differential measurements present **deviations from nPDF** calculations
- Weaker anti-shadowing or final state effects at play?

Talk. J. Wang
Talk. C. Landesa

ALICE, arXiv:2405.14571
LHCb, arXiv:2311.08490

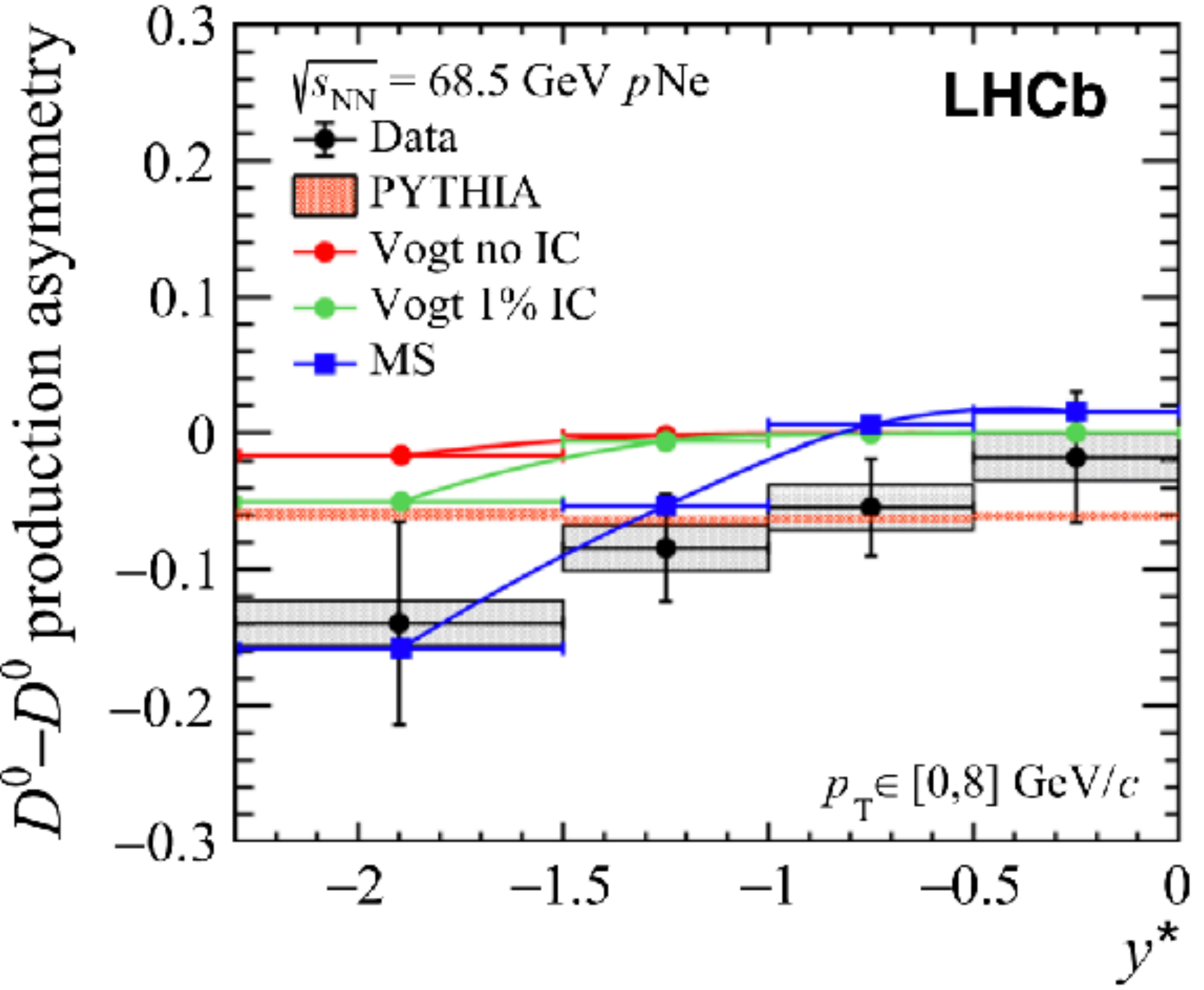
CGC1: Ducloué et al., PRD 91 (2015) 114005
CGC2: Ma et al,, PRD 98 (2018) 074025

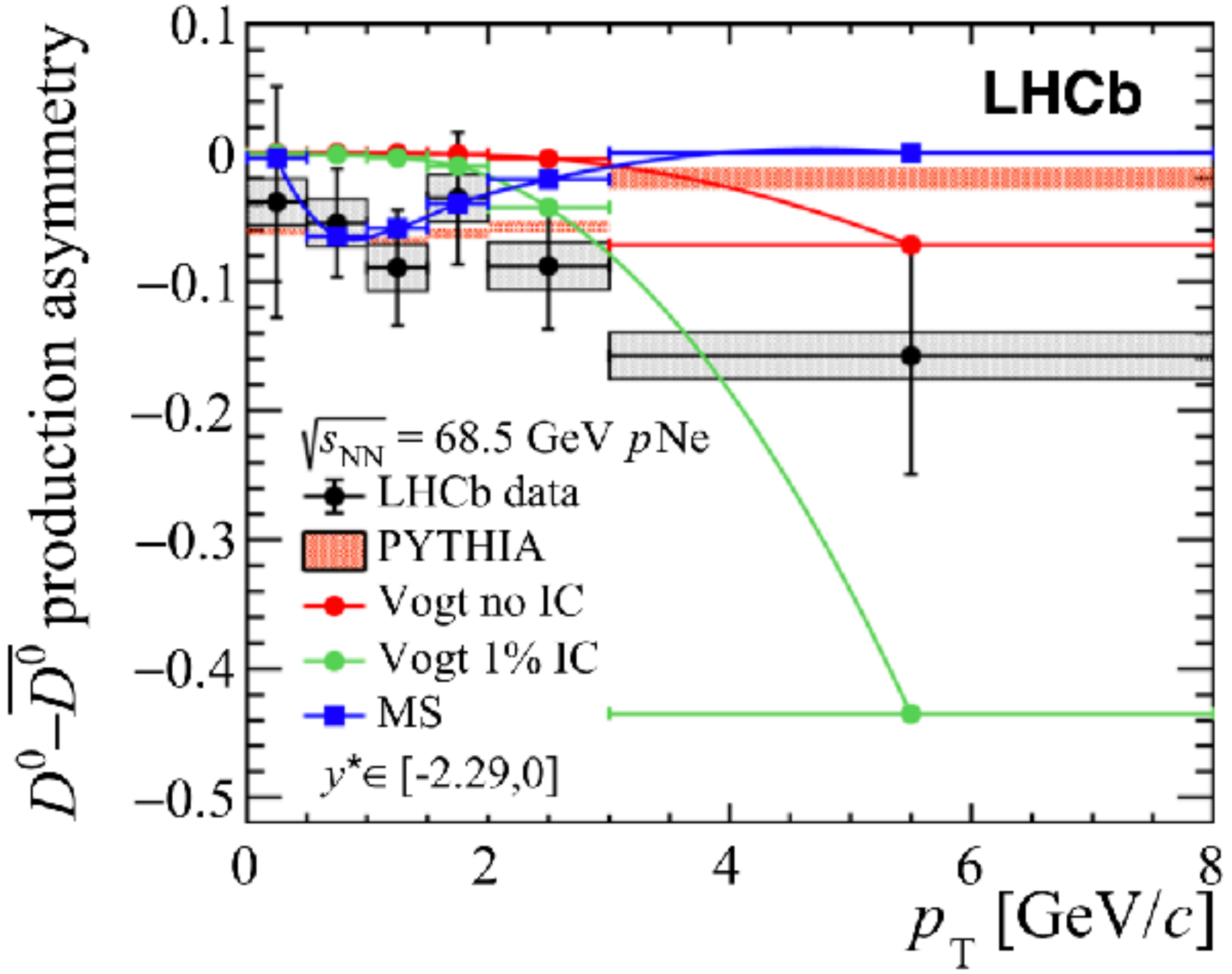
HELAC-Onia: Shao et al., CPC 184 (2013) 2562
EPPS16: Eskola et al., EPJC 77 (2017) 163
nCTEQ15: Kovaric et al., PRD 93 (2016) 085037

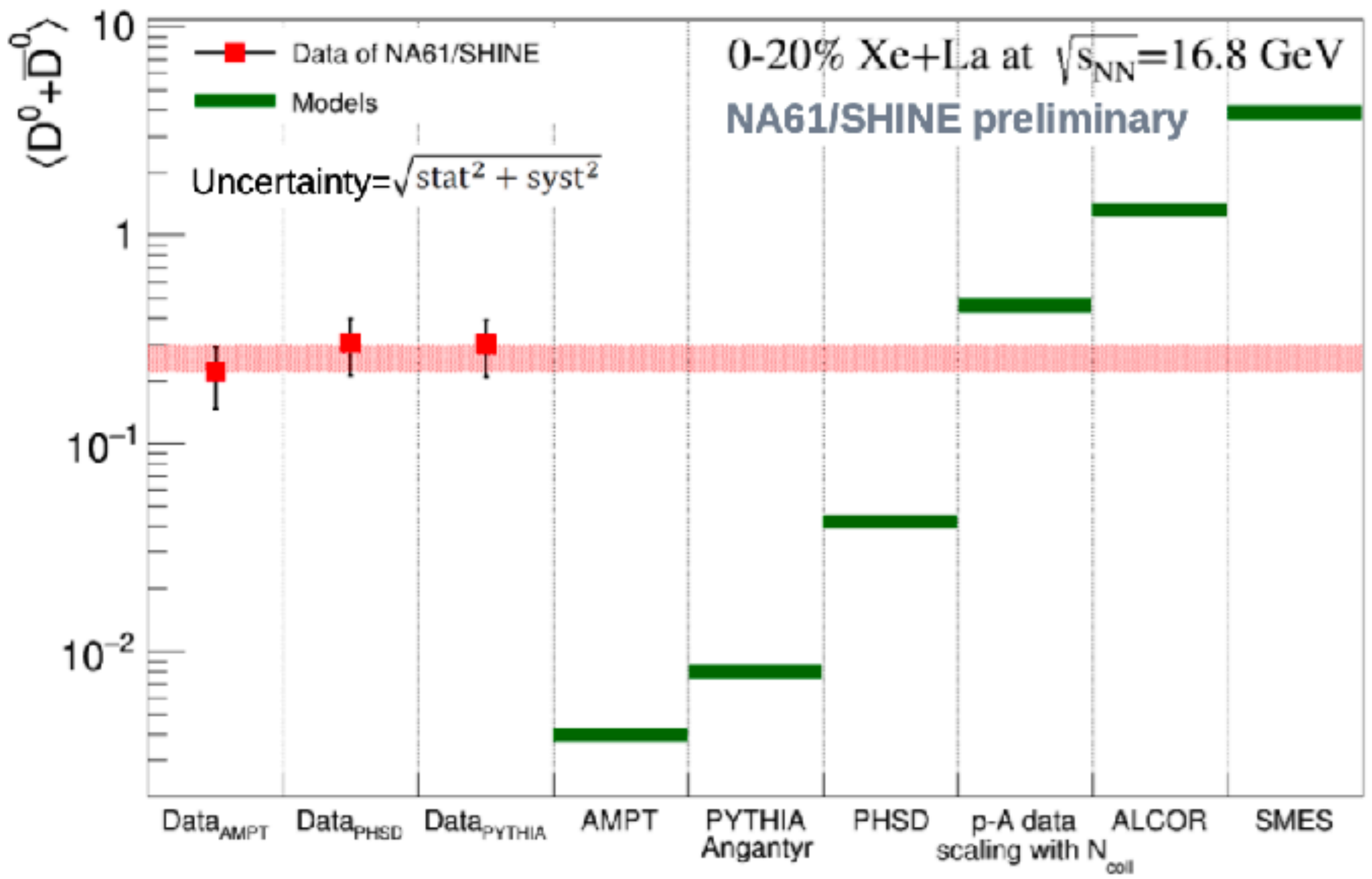
Constraining the initial state with pNe & XeLa data

(D^0 – D^0bar)/(D^0 + D^0bar) as a function of y and p_T in pNe

(D^0 + D^0bar) yield, 0.2 < p_T < 2.0 GeV in XeLa







- D^0–D^0bar production asymmetry y and p_T dependence in pNe data (LHCb) might hint at effects not included in PYTHIA. Contribution of intrinsic charm and/or recombination?
- Promising first measurements of D^0 mesons in XeLa data by NA61/SHINE

Talk. A. Merzlaya

Talk. J. Wang

LHCb, EPJC83 (2023) 541
Vogt, PRC103, 035204 (2021).
Maciula, PLB835, 137530 (2022).

Talk. Chowdhury

Talk. WJ. Xing

Talk. M. Zhang

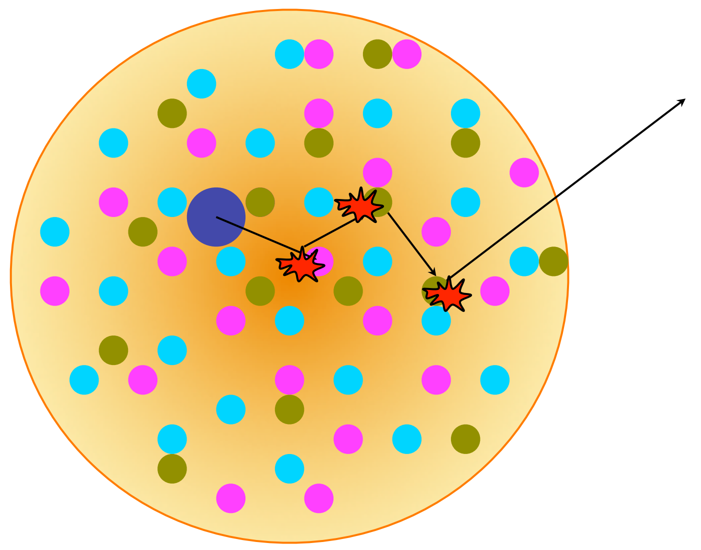
Talk. S. Chandra

Talk. S. Floerchinger

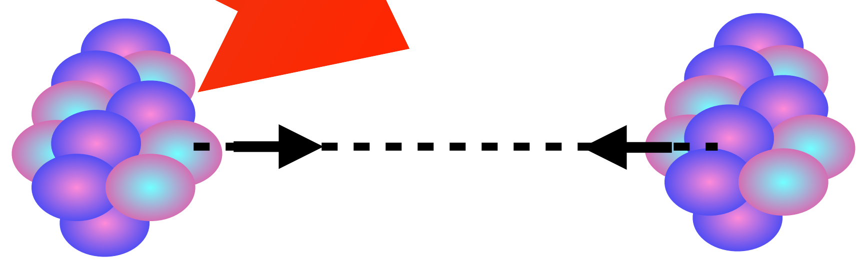
Talk. O. Lomicky

Energy loss

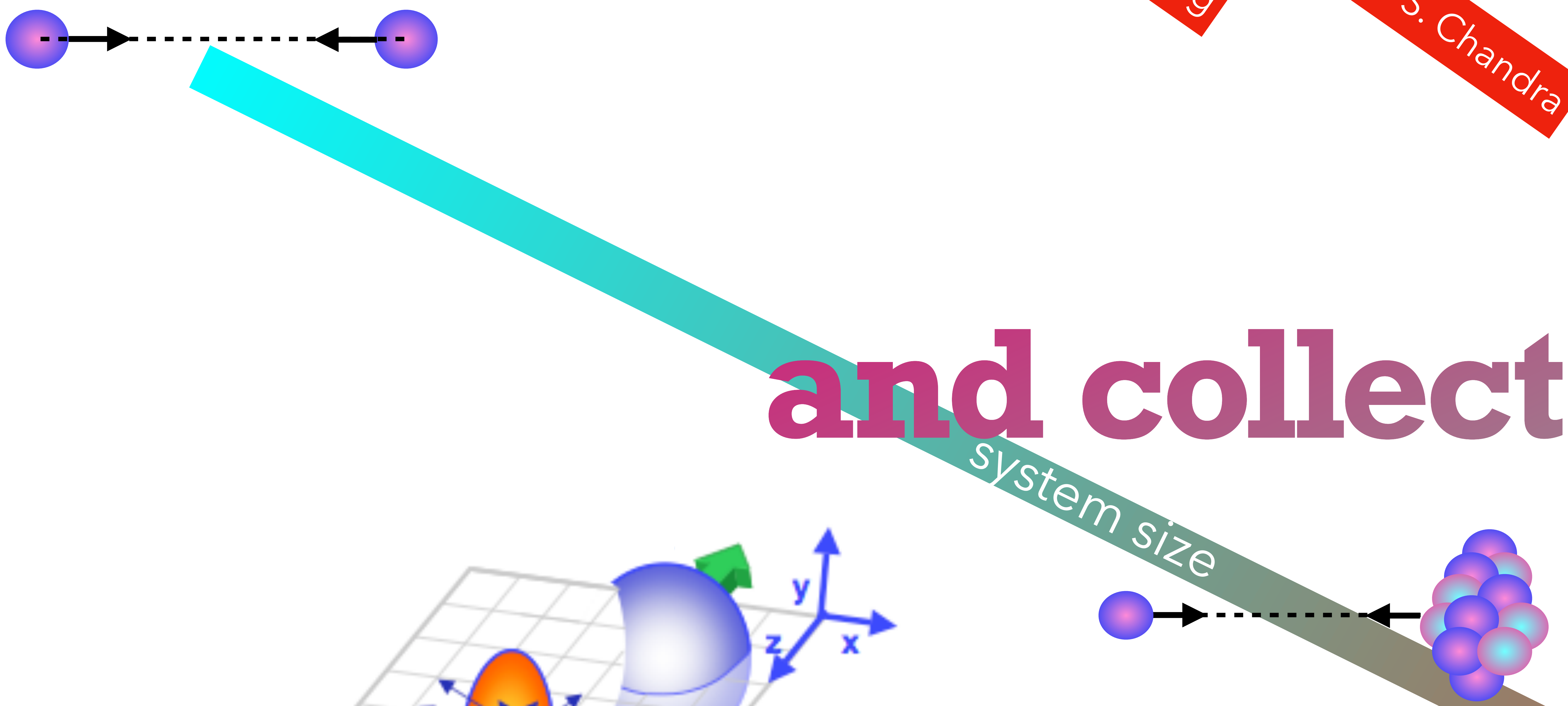
Energy loss: R_{AA}
Interaction of heavy quarks with the medium
Colour charge and parton mass dependence.



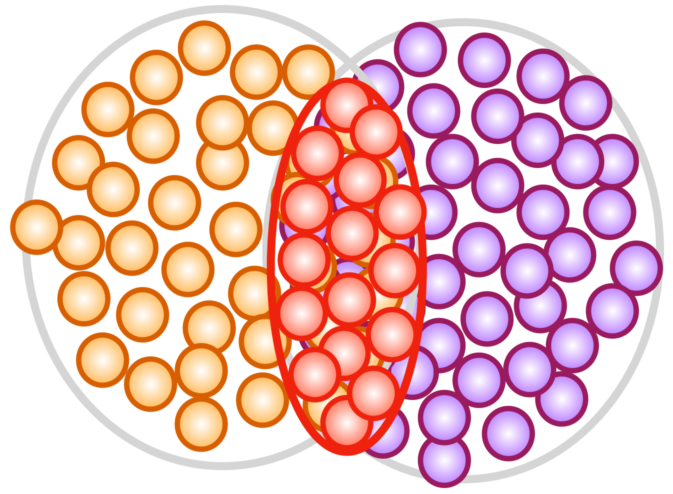
$$R_{AB}^{\text{probe,CC}} = \frac{dN_{AB}^{\text{probe,CC}}}{\langle N_{\text{coll}}\rangle^{\text{CC}} \cdot dN_{NN}^{\text{probe}}} \xrightarrow{\int b} R_{AB}^{\text{probe}} = \frac{\sigma_{AB}^{\text{probe}}}{AB \cdot \sigma_{NN}^{\text{probe}}}$$



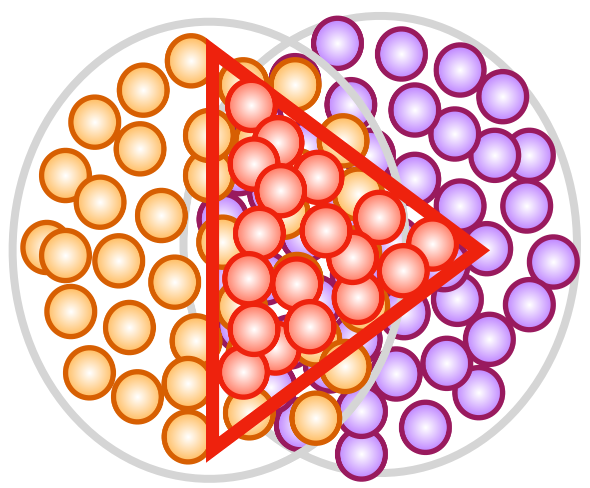
and collectivity

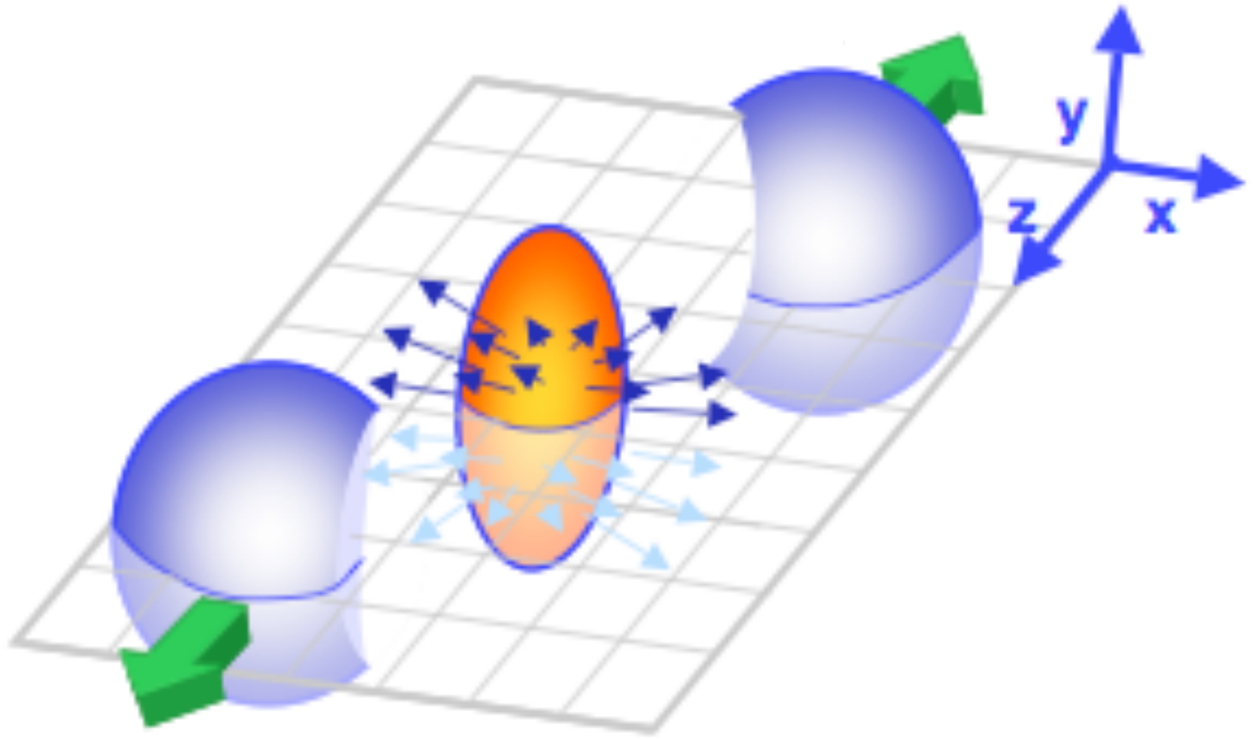


Elliptic flow v_2
Initial spatial anisotropy
and re-interactions



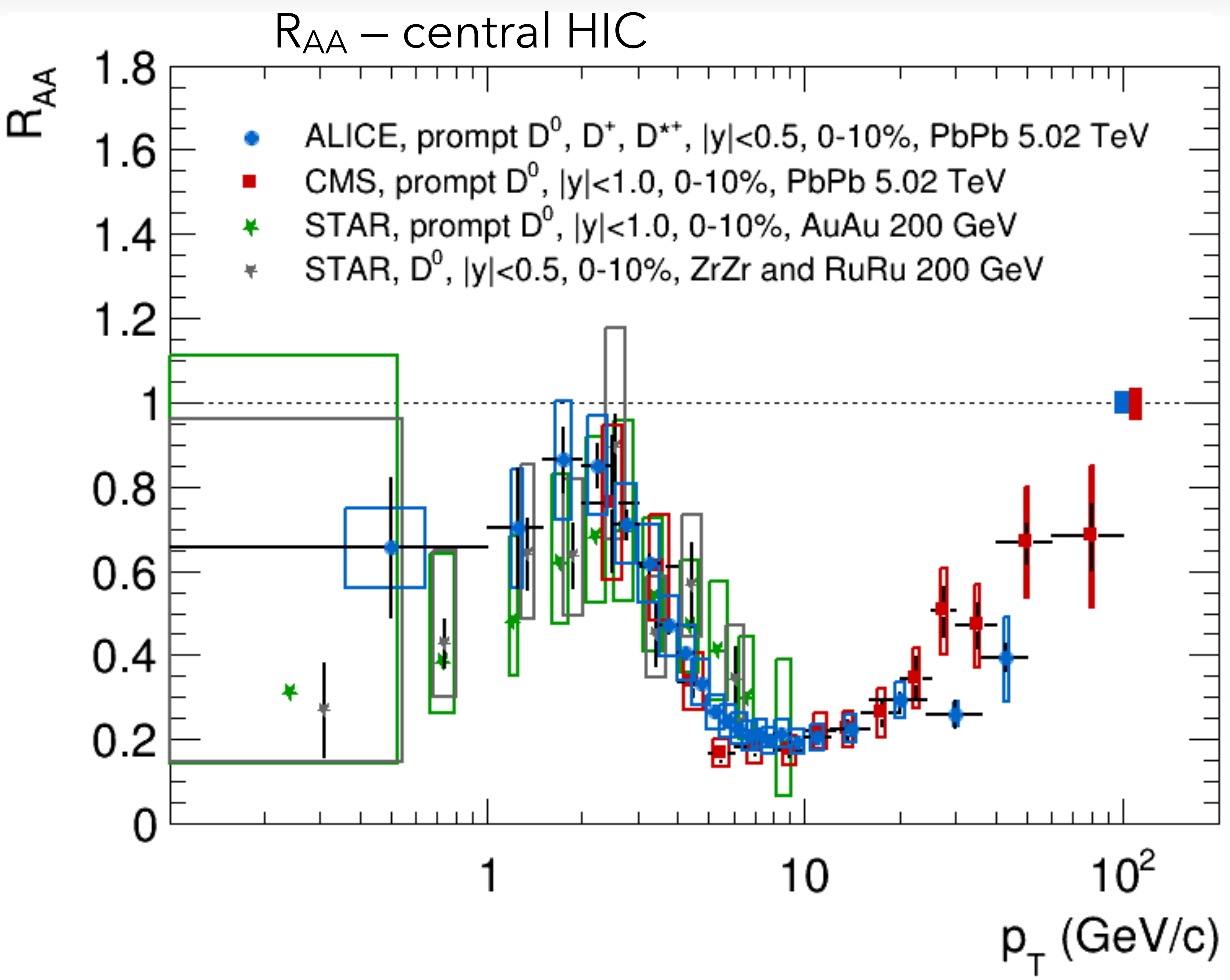
Triangular flow v_3
Fluctuations in the
initial state

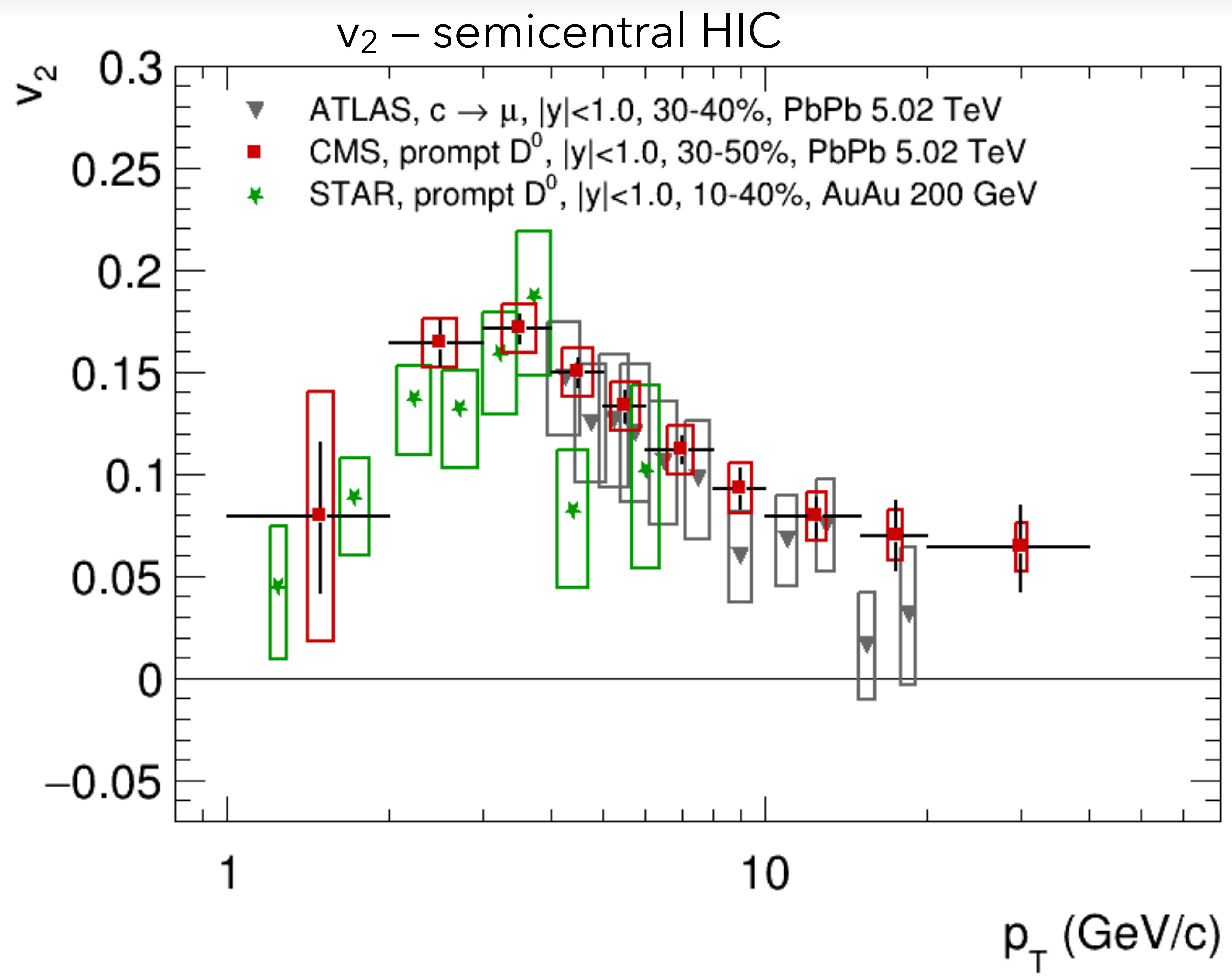




$$\frac{d^3N}{d^3\vec{p}} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n(\phi - \Psi_R)\right)\right]$$

Charm hadrons in medium

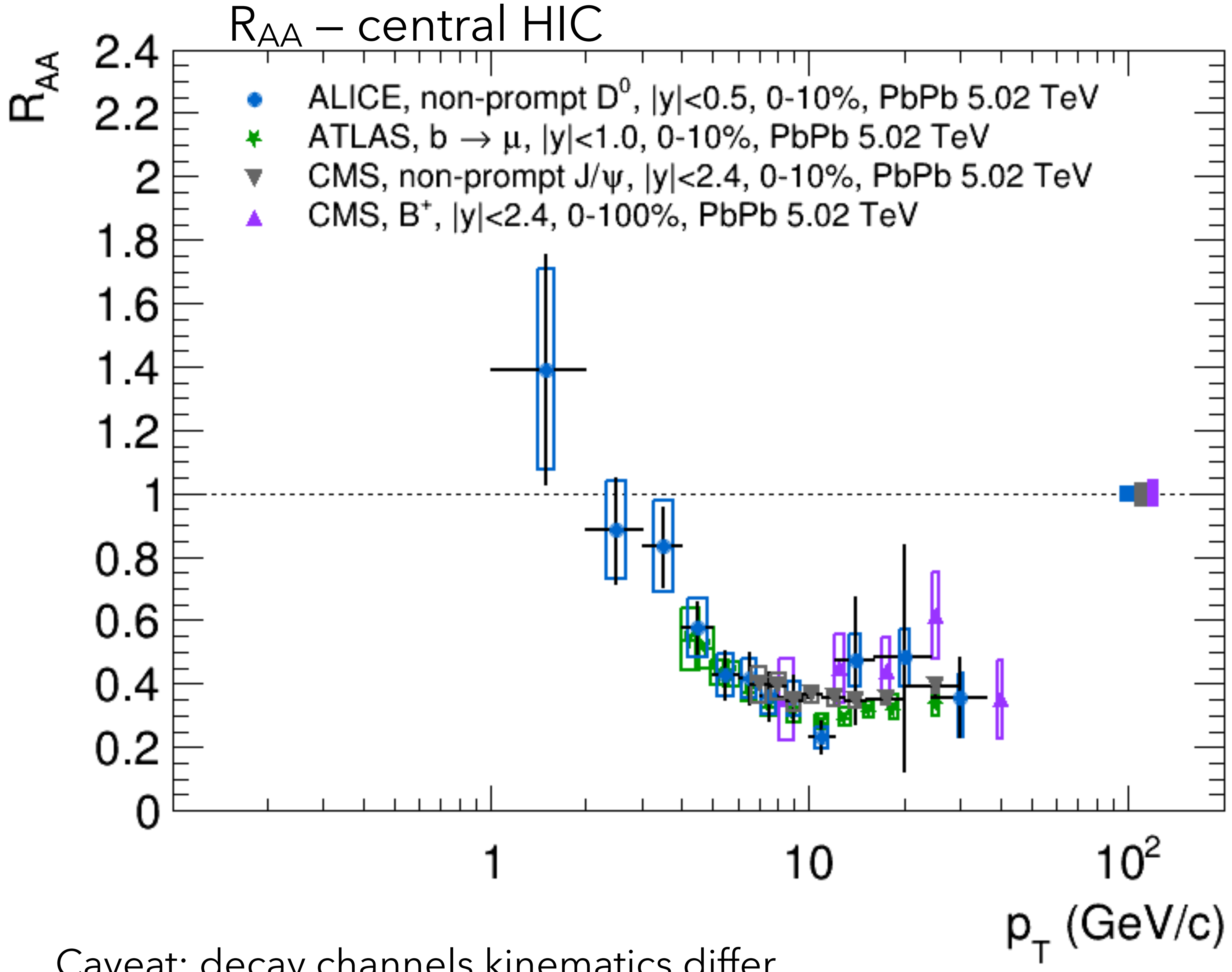




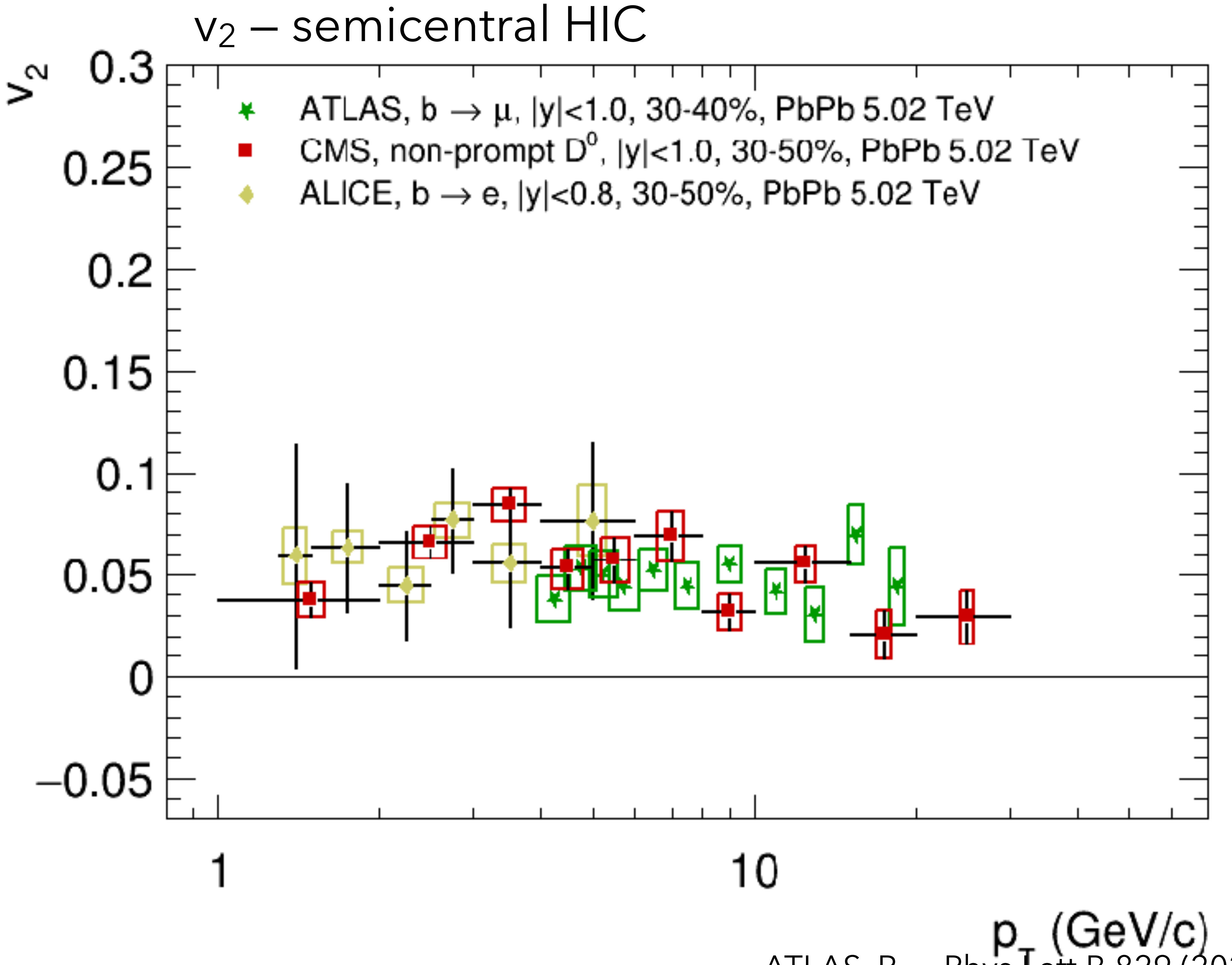
- Precise measurements of R_{AA} and v_2 in a wide p_T interval
- Similar results at RHIC and at the LHC despite different kinematics
- **Significant energy loss** of charm in medium
- **Positive v_2**: participation to the collective motion

ALICE, R_{AA}, JHEP 01 (2022) 174
CMS, R_{AA}, , PLB 782 (2018) 474
STAR, R_{AA}, Phys.Rev.C 99 (2019) 3, 034908
STAR Preliminary
ALICE, v_2, PLB 813 (2021) 136054
CMS, v_2, PRL 120 (2018) 202301
ATLAS, v_2, Phys.Lett.B 807 (2020) 135595
STAR, v_2, PRL 118 (2017) 21

Beauty hadrons in medium



Caveat: decay channels kinematics differ

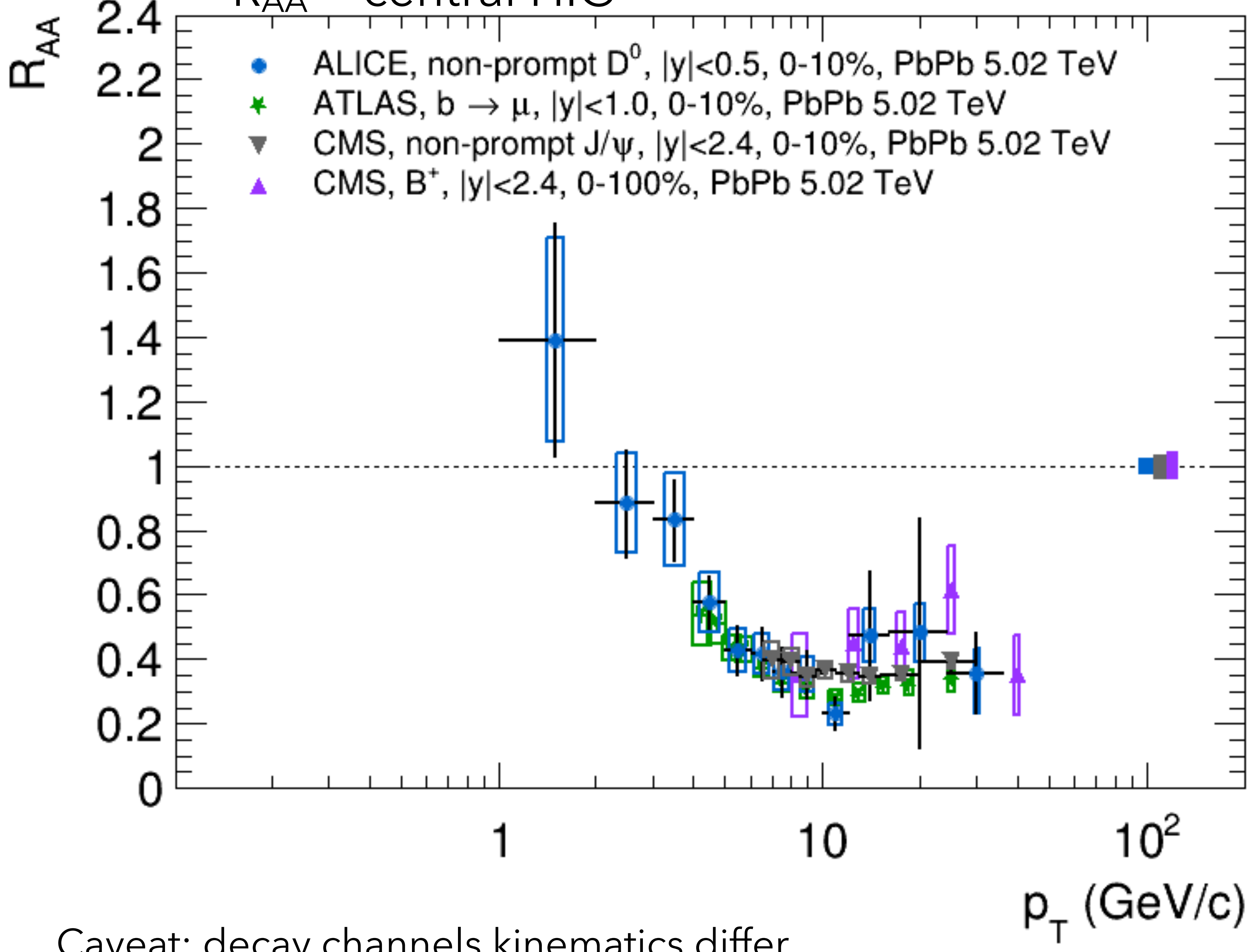


ATLAS, R_{AA}, Phys.Lett.B 829 (2022) 137077
ALICE, R_{AA}, non-prompt D^0, JHEP 12 (2022) 126
ALICE, R_{AA}, b to e, arXiv: 2211.13985
CMS, R_{AA}, B+, PRL 119 (2017) 15, 152301
CMS, R_{AA}, non-prompt D^0, PRL 123 (2019) 022001
ATLAS, v_2, b to mu, Phys.Lett.B 807 (2020) 135595
ALICE, non-prompt D v2, EPJ.C 83 (2023) 1123
ALICE, v_2, b to e, Phys.Rev.Lett. 126 (2021) 16, 16200
CMS, v_2, non-prompt D^0, arXiv: 2212.01636

- Plenty of decay channels being investigated, increasing reach and precision
- **Significant energy loss** of beauty in medium
- **Positive v_2** for p_T > 2-3 GeV, **lower values for beauty than for charm hadrons**

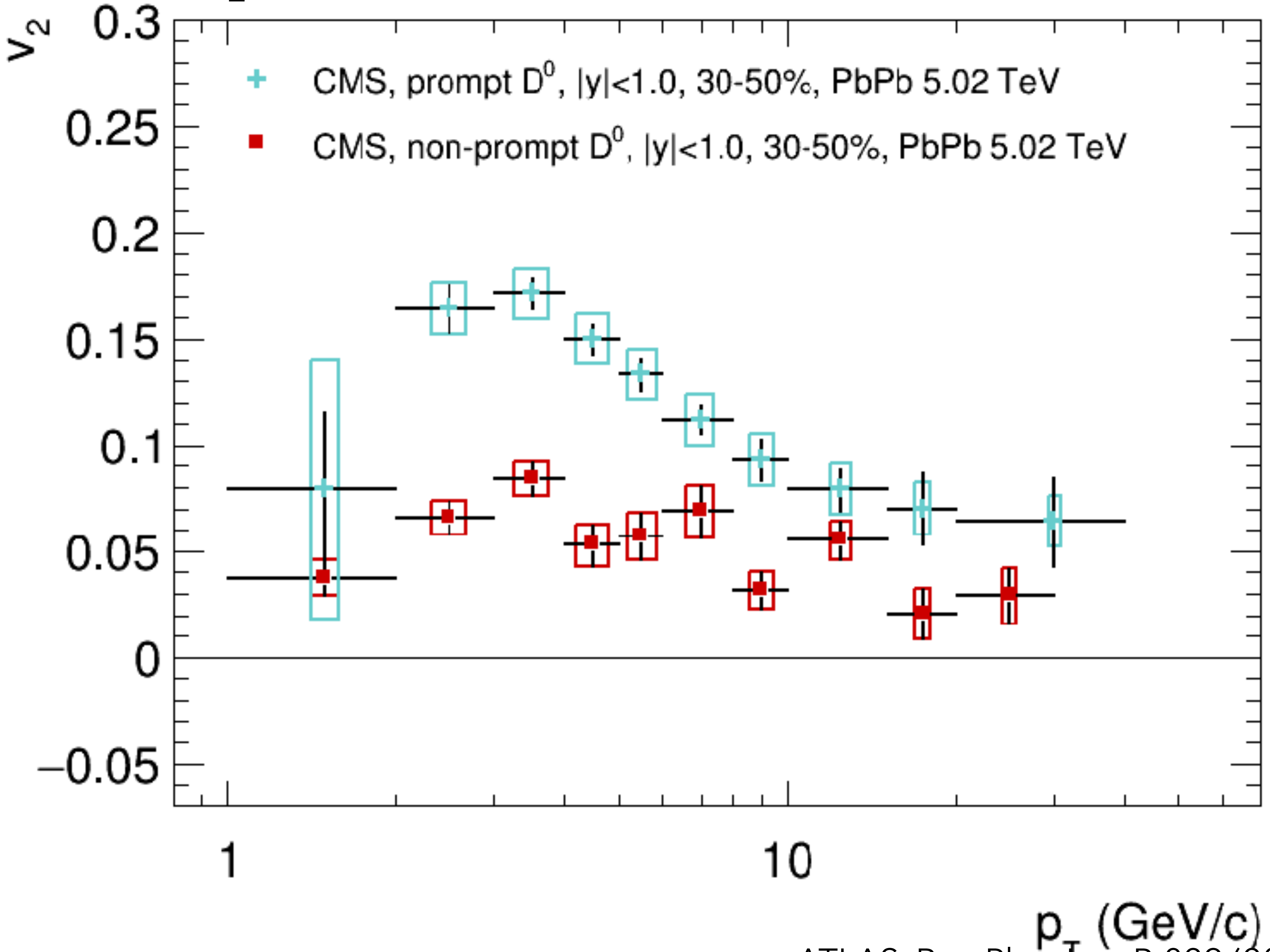
Beauty hadrons in medium

R_{AA} – central HIC



Caveat: decay channels kinematics differ

v_2 – semicentral HIC



ATLAS, R_{AA}, Phys.Lett.B 829 (2022) 137077
ALICE, R_{AA}, non-prompt D^0, JHEP 12 (2022) 126
ALICE, R_{AA}, b to e, arXiv: 2211.13985
CMS, R_{AA}, B+, PRL 119 (2017) 15, 152301
CMS, R_{AA}, non-prompt D^0, PRL 123 (2019) 022001
ATLAS, v_2, b to mu, Phys.Lett.B 807 (2020) 135595
ALICE, non-prompt D v2, EPJ.C 83 (2023) 1123
ALICE, v_2, b to e, Phys.Rev.Lett. 126 (2021) 16, 16200
CMS, v_2, non-prompt D^0, arXiv: 2212.01636

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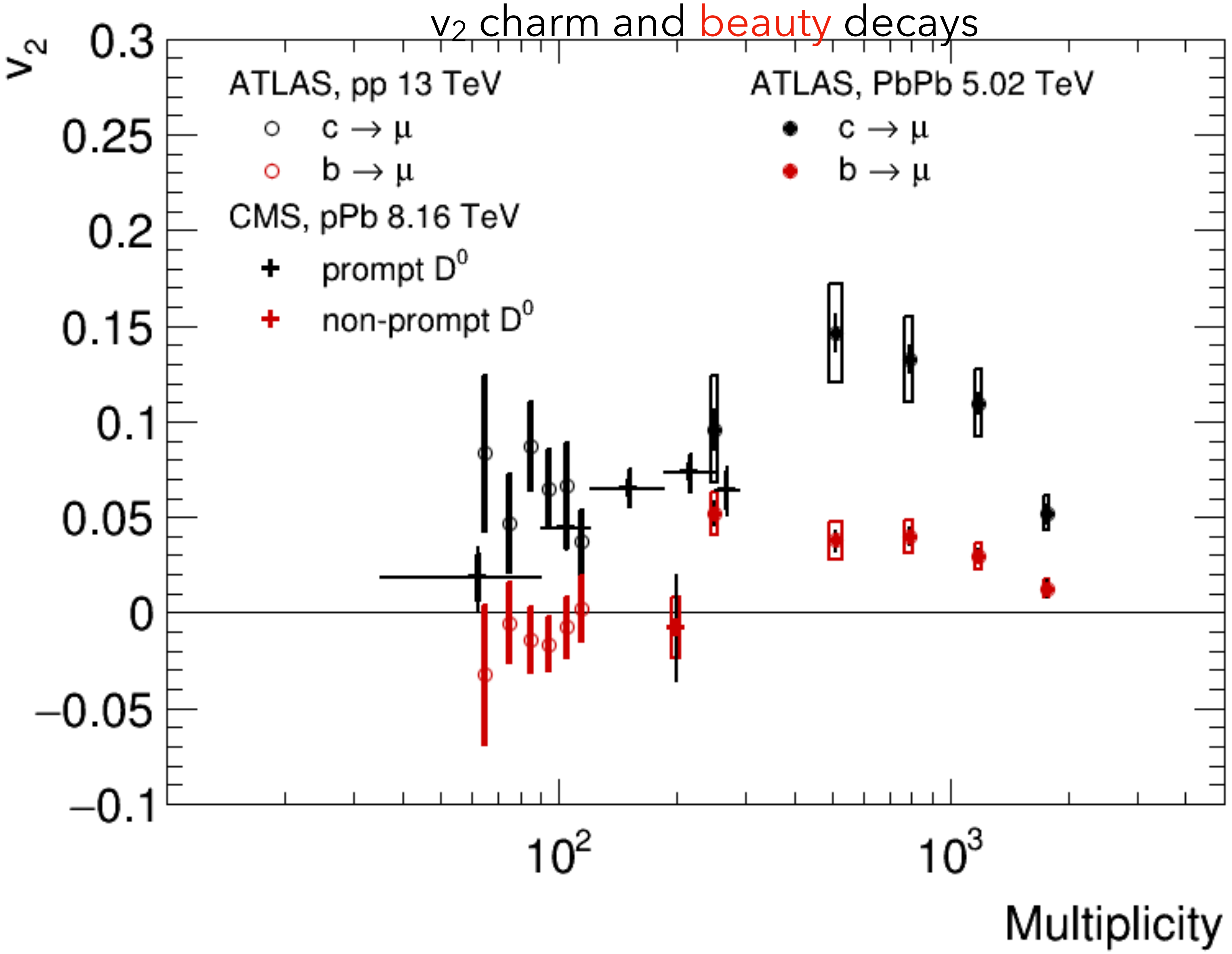
Zooming on v_2 across system size

v_2 charm and beauty decays

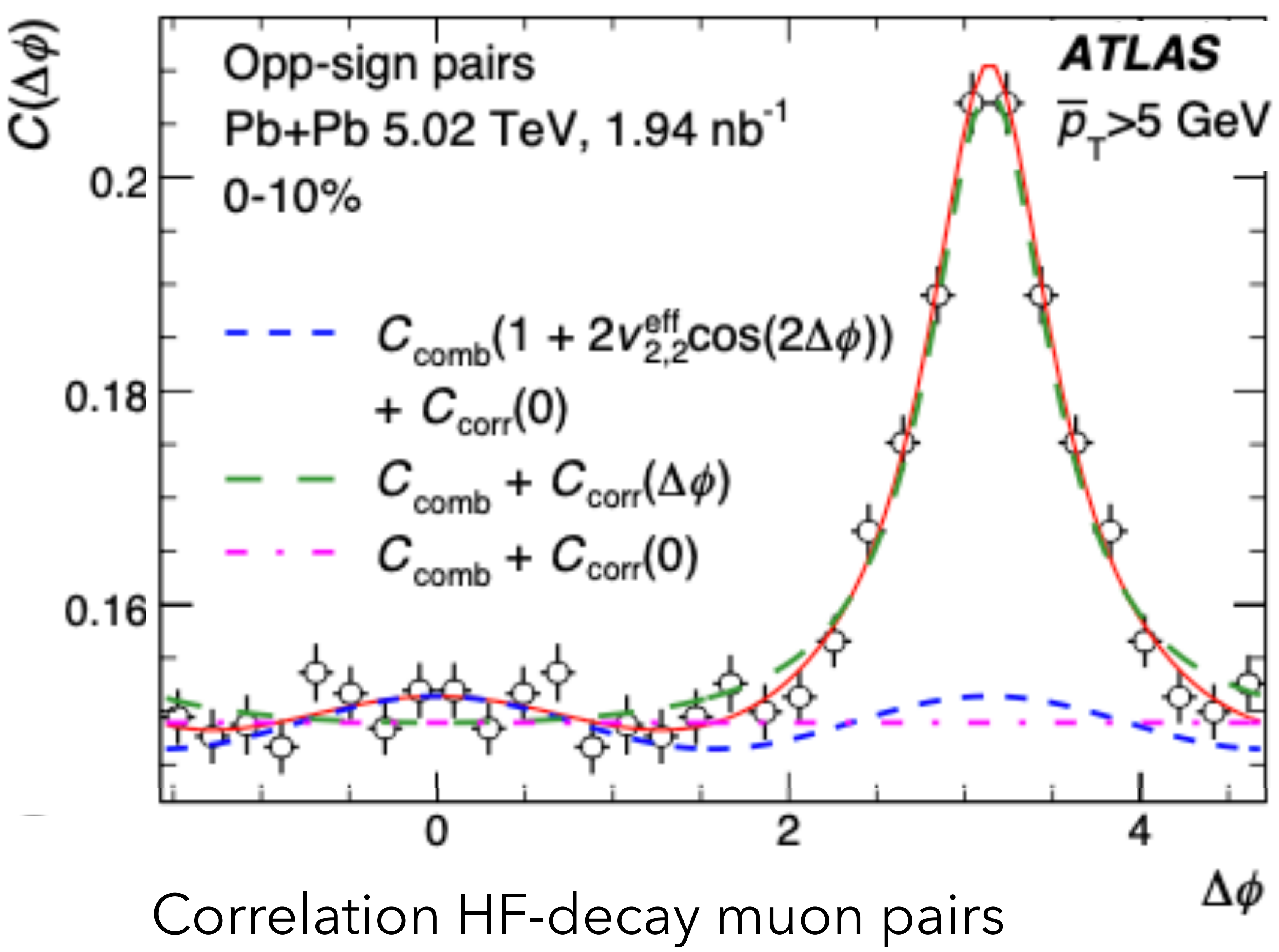


STAR, PLB 844 (2023) 138071
ATLAS, pp, PRL 124 (2020) 082301
ATLAS, PbPb, PLB 807 (2020) 135595
CMS, pPb, prompt D^0, PRL 121 (2018) 8, 082301
CMS, pPb, non-prompt D^0, PRL 813 (2021) 136036
ALICE, pPb, JHEP 2019 (2019) 92
LHCb, D^0, arXiv:2205.03936

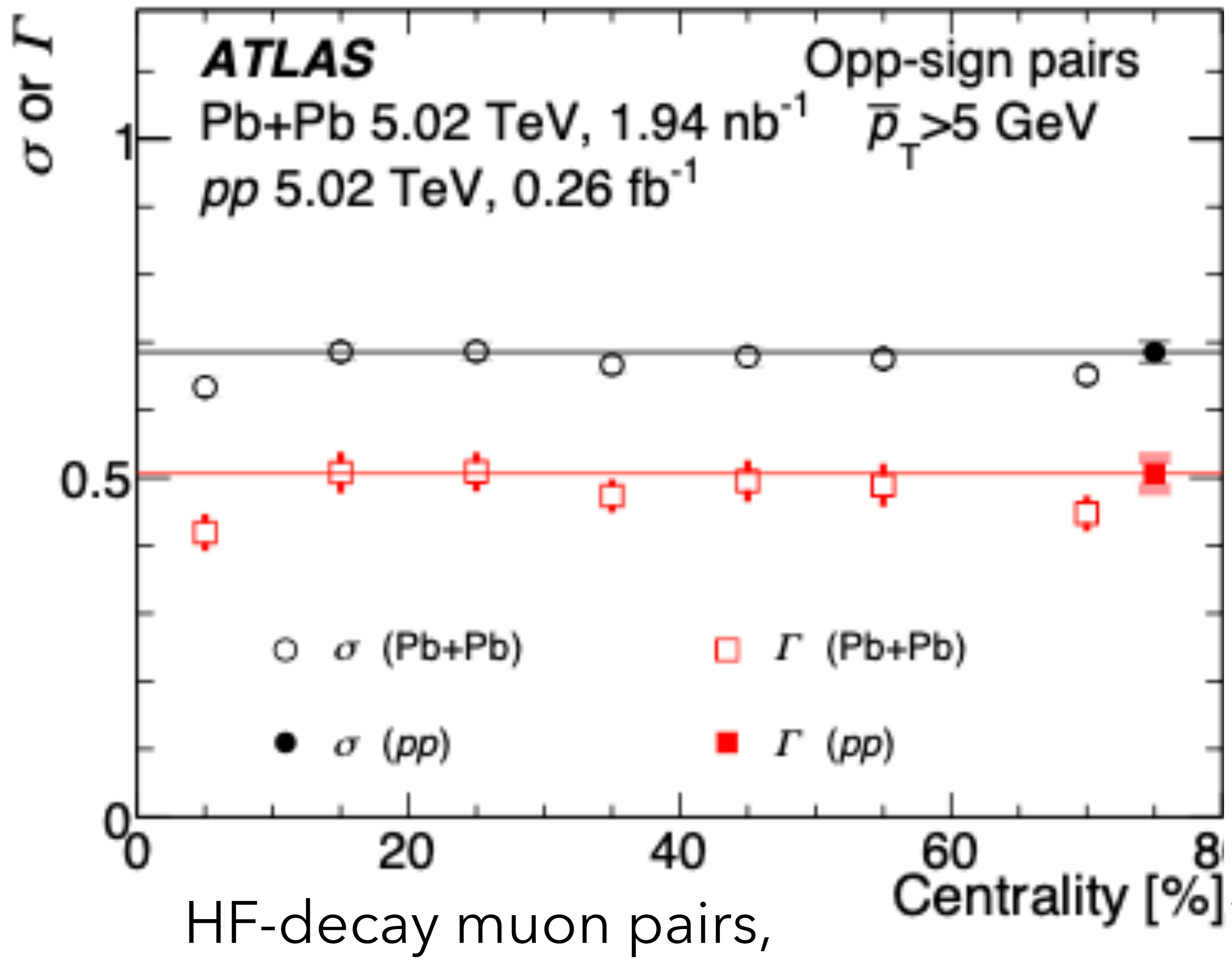
- Heavy flavour **v_2 follows a smooth evolution with charged-particle multiplicity**
  - non-zero values for charm in pp and pPb collisions
  - important role of initial state effects and/or influence of final state effects?
- Crucial to quantify beauty v_2 in small systems

Talk. M. Zhang
Talk. L. Bichon III

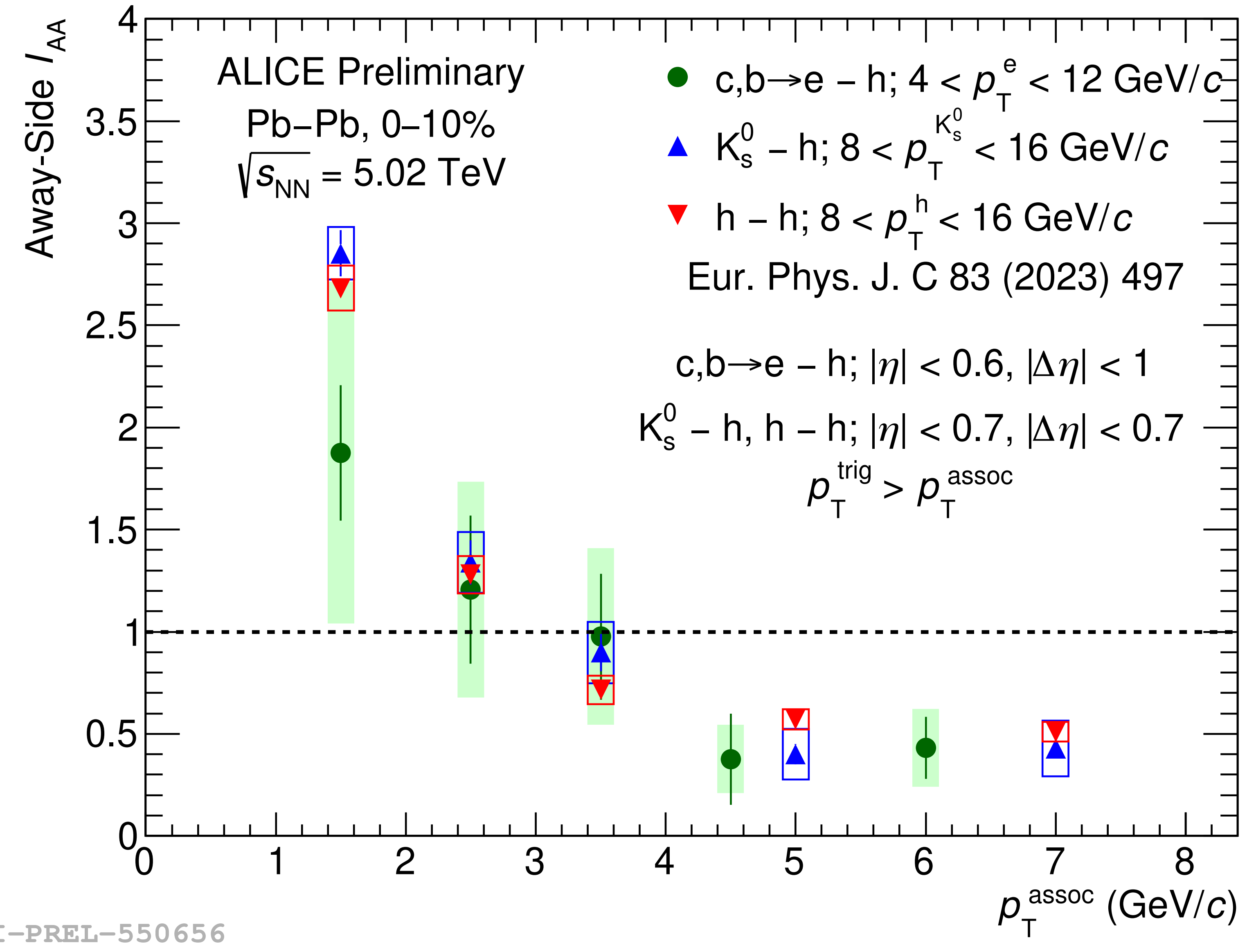
Study of jet-quenching via angular correlations



Correlation HF-decay muon pairs



HF-decay muon pairs,
width (σ) and peak (Γ) vs. centrality



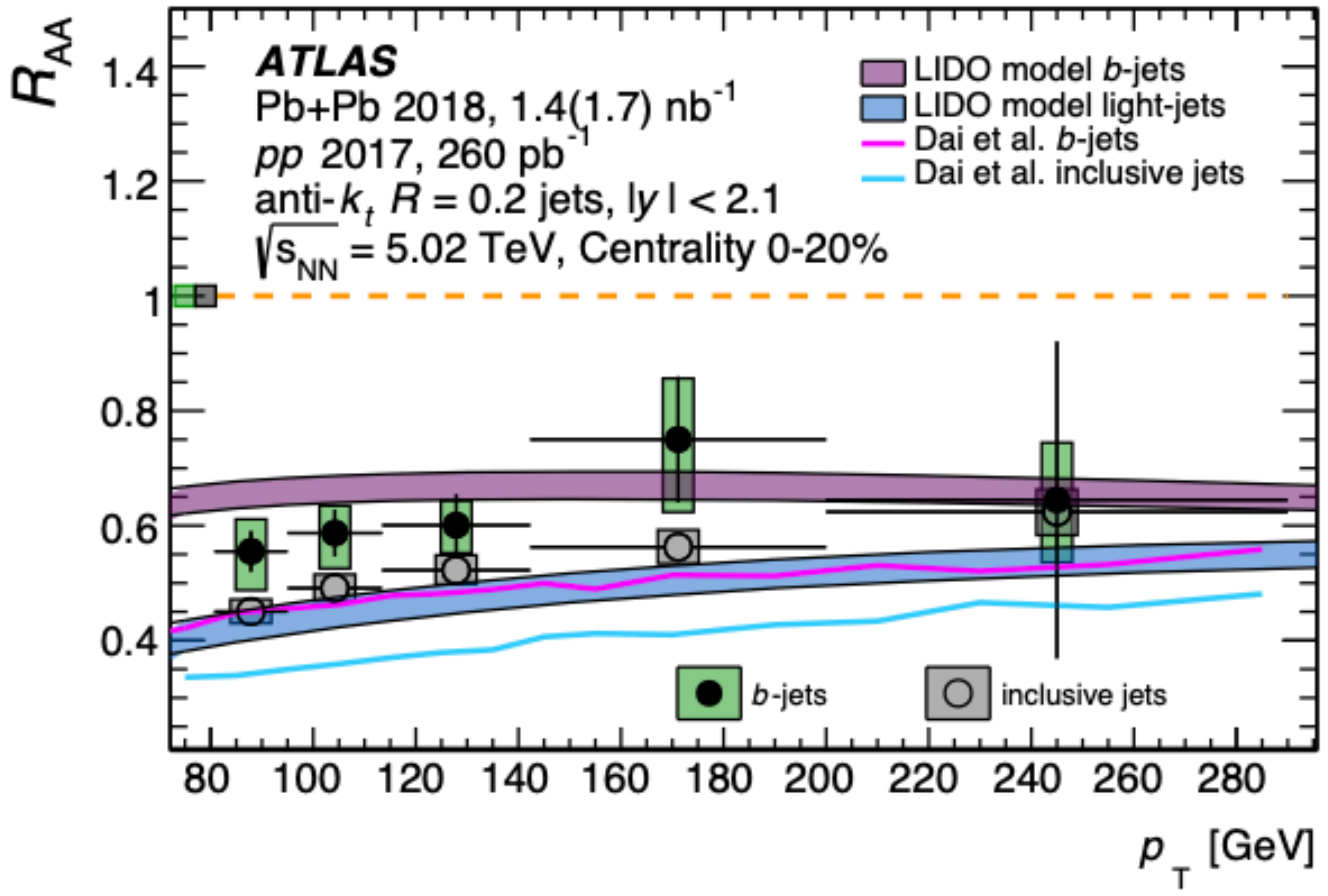
$I_{AA} = Y_{AA}/Y_{pp}$ HF-decay electrons vs. p_T

ALICE Preliminary
ATLAS, PRL 132 (2024) 202301
M. Nahrgang et al., PRC 90 (2014) 024907

- Heavy-flavour angular correlations at low p_T are expected to be sensitive to the relative importance of collisional and radiative scatterings
- **No significant modification (broadening) of the away-side peak width** vs. centrality, apart from a narrowing in the 0-10% interval (2σ)
- Suppression of the associated-particle yield at high p_T suggestive of jet quenching

Poster J. Wright

Moving to higher p_T? b-jets in medium



R_{AA} central collisions

ATLAS, EPJC (2023) 83:438
CMS, PLB 844 (2023) 137849
LIDO: W. Ke et al, Phys. Rev. C 98, 064901 (2018)
Phys. Rev. C 100, 064911 (2019),
Dai et al: Chinese Phys. C 2020, 44:104105

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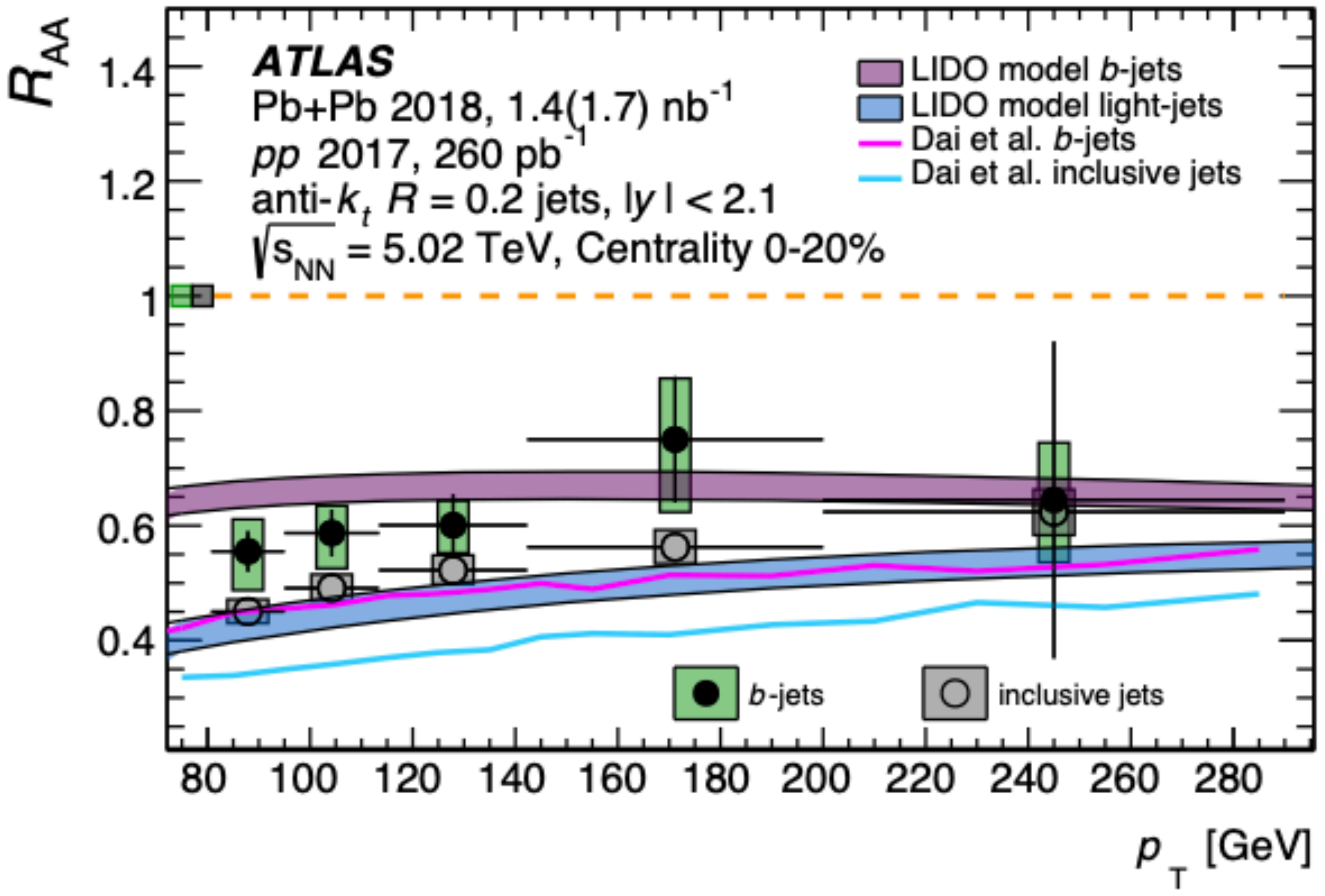

R_{AA} central collisions

- Suggest R_{AA} values for **b-jets higher than for inclusive jets** in central collisions

ATLAS, EPJC (2023) 83:438
CMS, PLB 844 (2023) 137849
LIDO: W. Ke et al, Phys. Rev. C 98, 064901 (2018)
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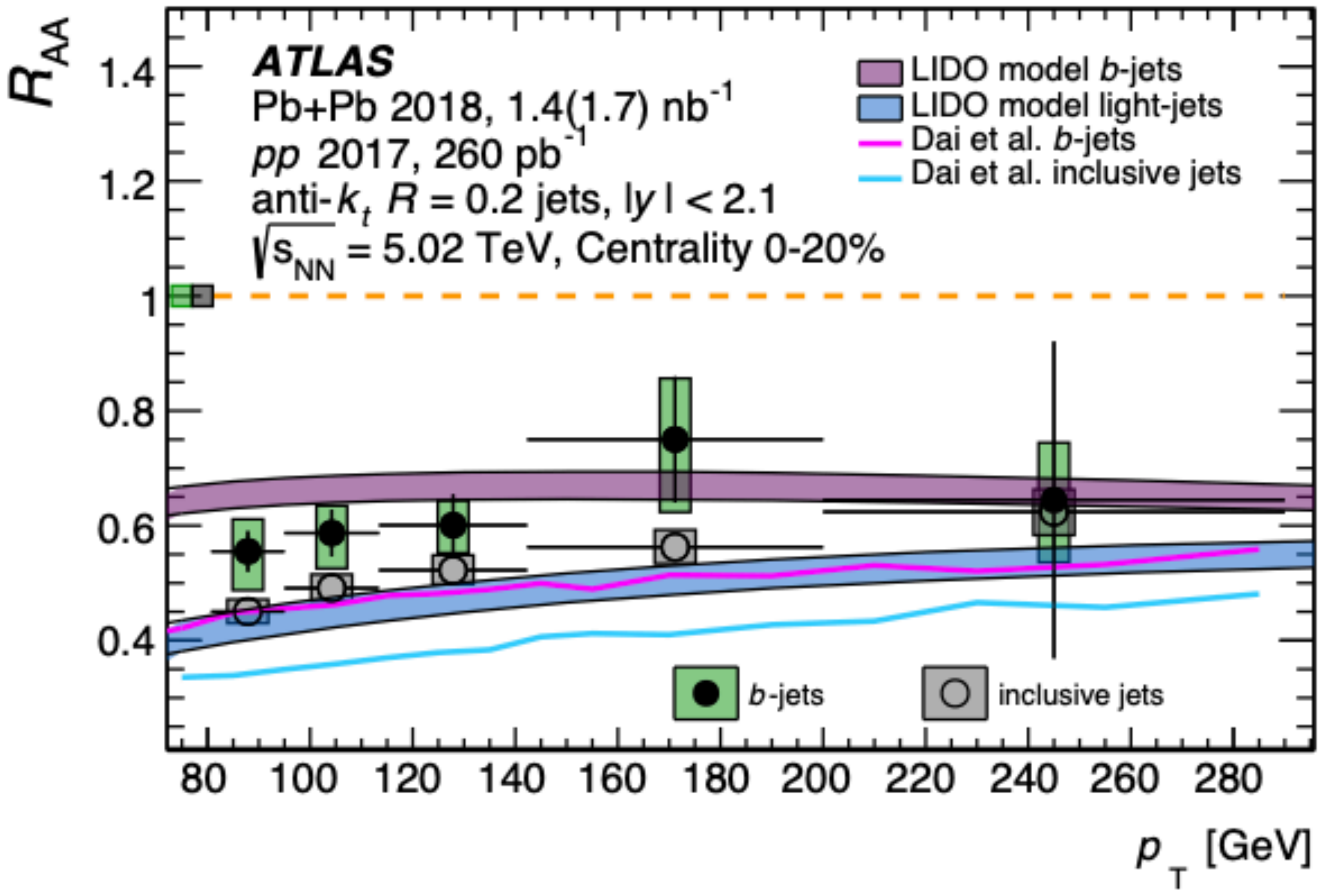
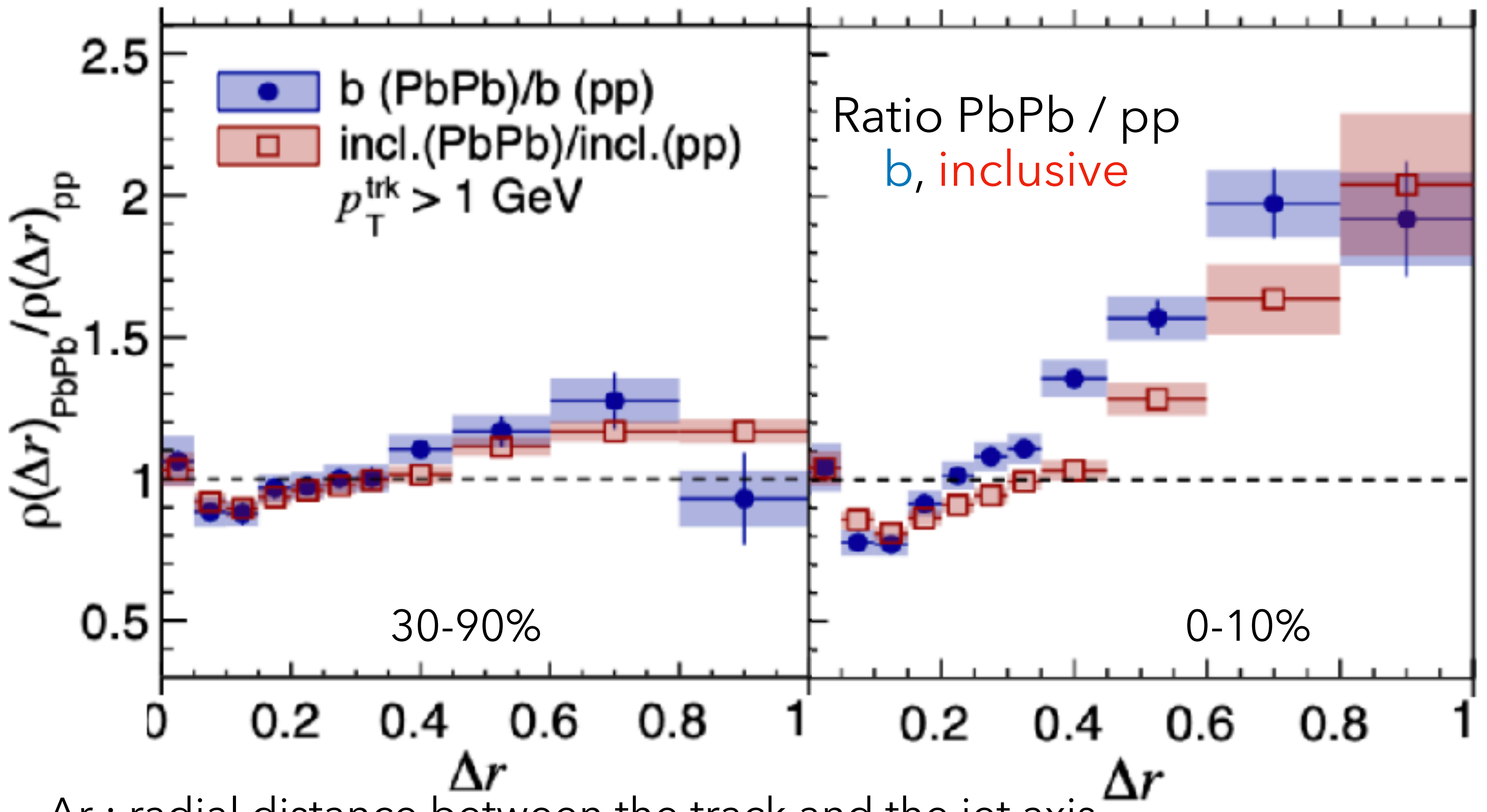
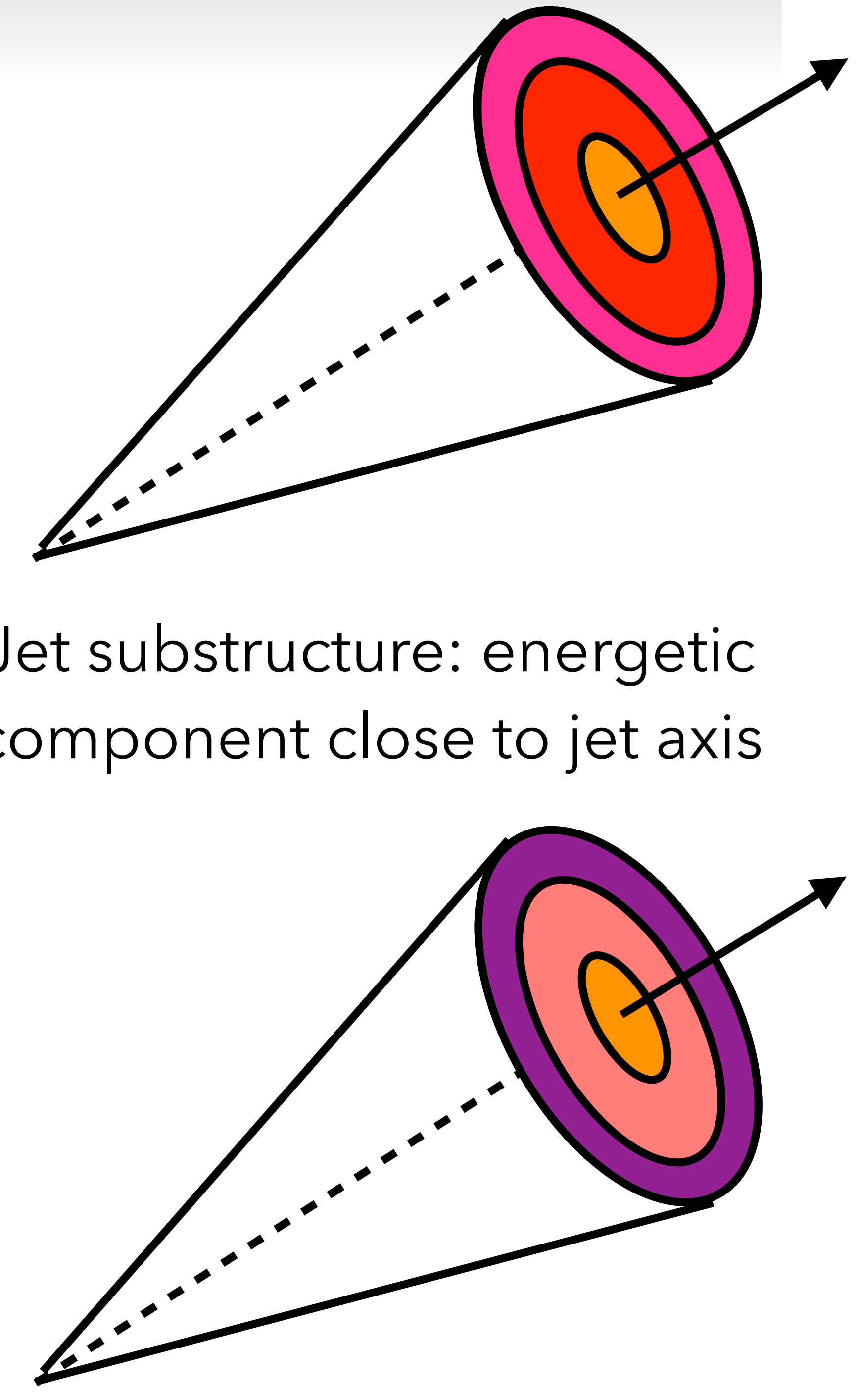


R_{AA} central collisions



Δr : radial distance between the track and the jet axis
ρ : normalised profile of charged particles in jets
Jet-track correlation p_T jet > 120 GeV, p_T track > 1 GeV



Jet substructure: energetic component close to jet axis

Jet substructure modified: core stays intact, intermediate part is reduced, larger activity in the border and far away

- Suggest R_{AA} values for **b-jets higher than for inclusive jets** in central collisions
- Energetic core (close to jet axis) stays intact, intermediate part is reduced, and enhancement of the activity on the surface/edges and far away from the jet.

ATLAS, EPJC (2023) 83:438
CMS, PLB 844 (2023) 137849
LIDO: W. Ke et al, Phys. Rev. C 98, 064901 (2018), Phys. Rev. C 100, 064911 (2019),
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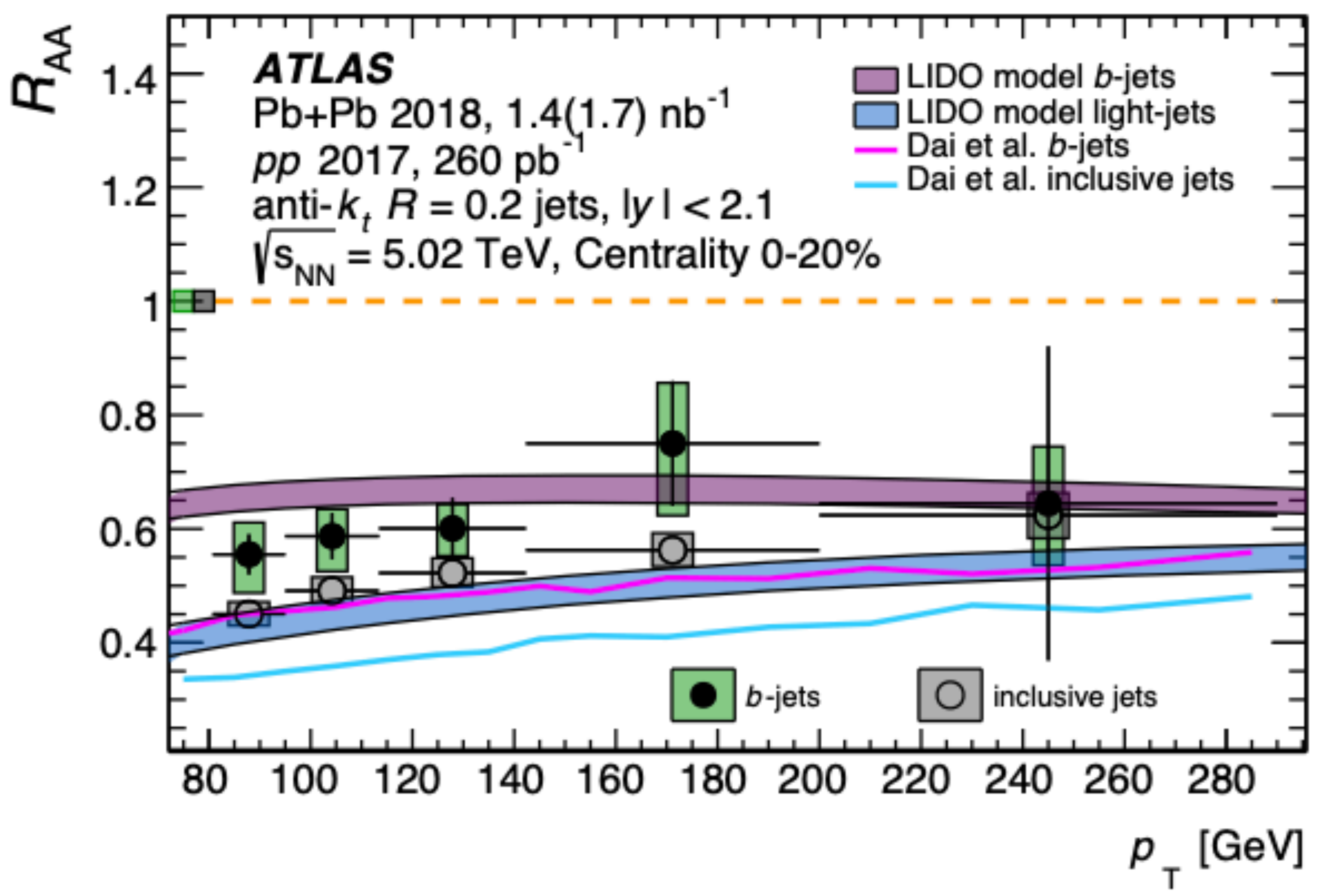
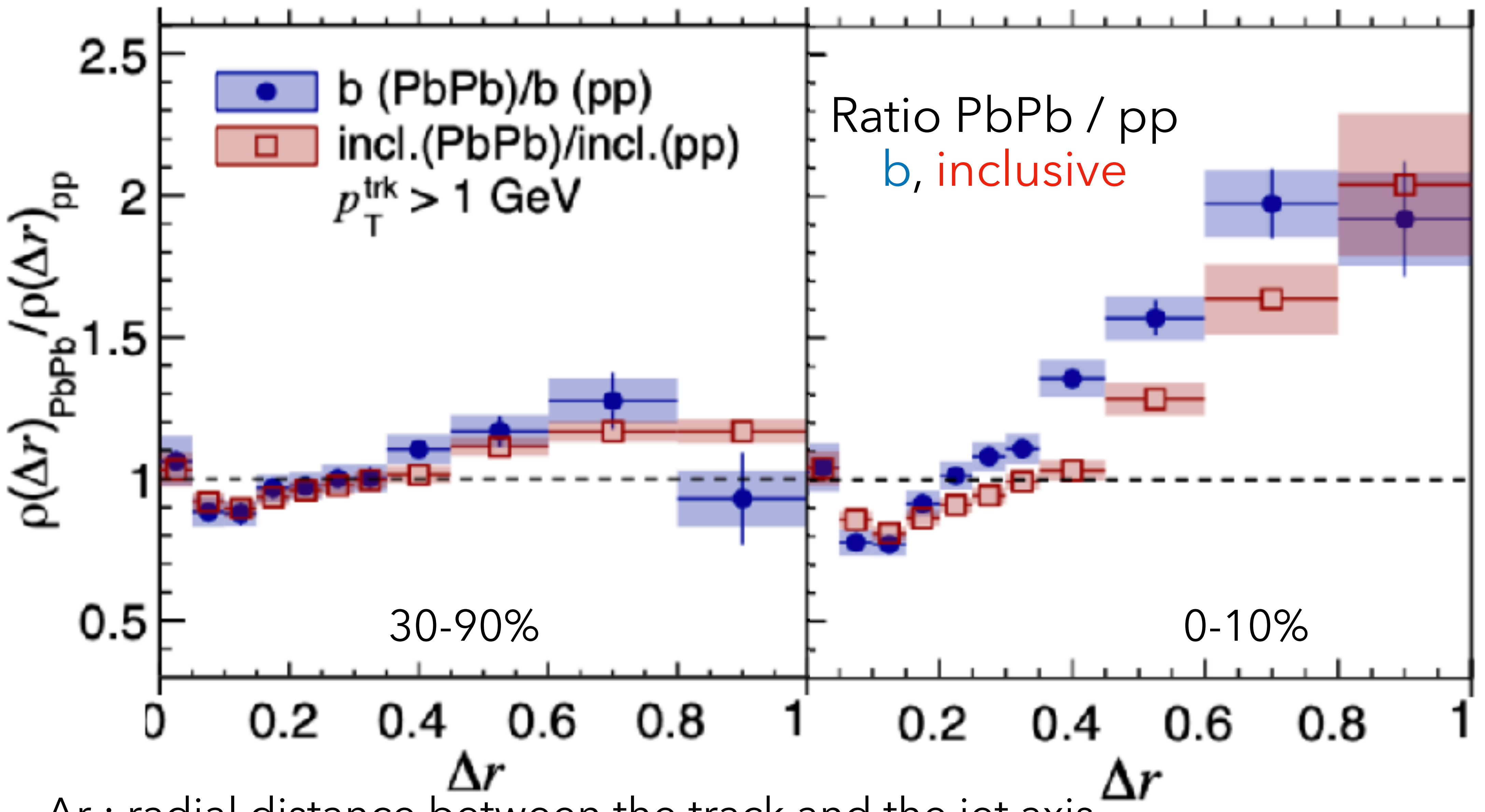


R_{AA} central collisions



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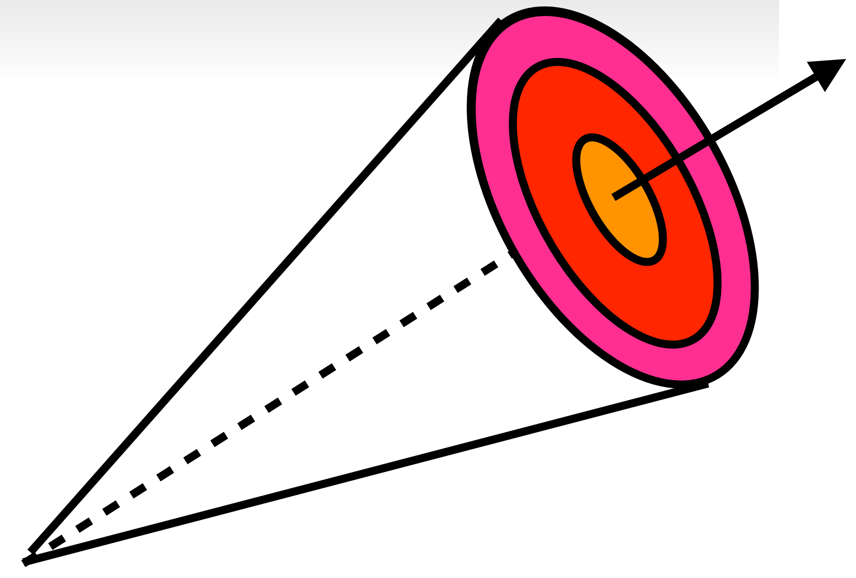
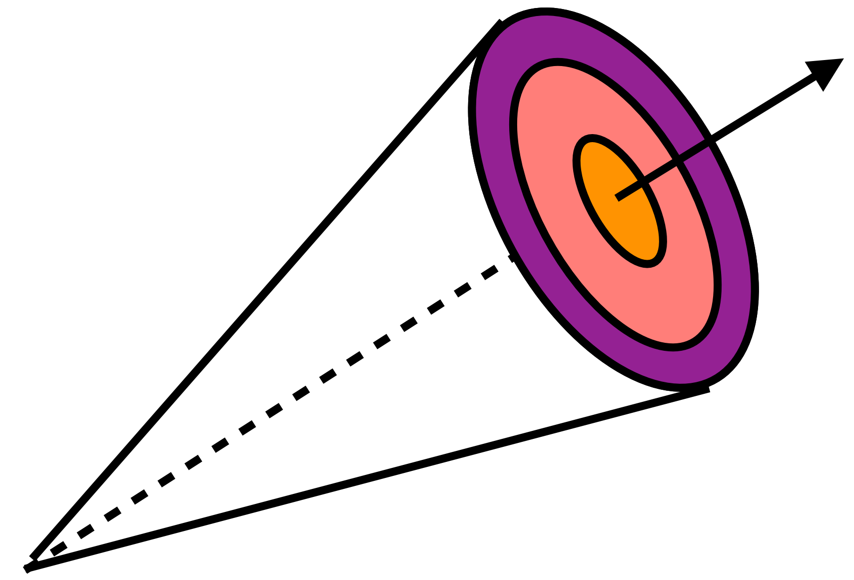


Jet substructure: energetic component close to jet axis



Jet substructure modified:
core stays intact,
intermediate part is reduced,
larger activity in the border and far away

- Suggest R_{AA} values for **b-jets higher than for inclusive jets** in central collisions
- Energetic core (close to jet axis) stays intact, intermediate part is reduced, and enhancement of the activity on the surface/edges and far away from the jet.
- The **modification is more pronounced for b-jets** than for inclusive jets, and is already present in pp.
- Possible influence of b-jet fragmentation, mass effect and/or color (b/g) charge of parton energy loss?

ATLAS, EPJC (2023) 83:438
CMS, PLB 844 (2023) 137849
LIDO: W. Ke et al, Phys. Rev. C 98, 064901 (2018)
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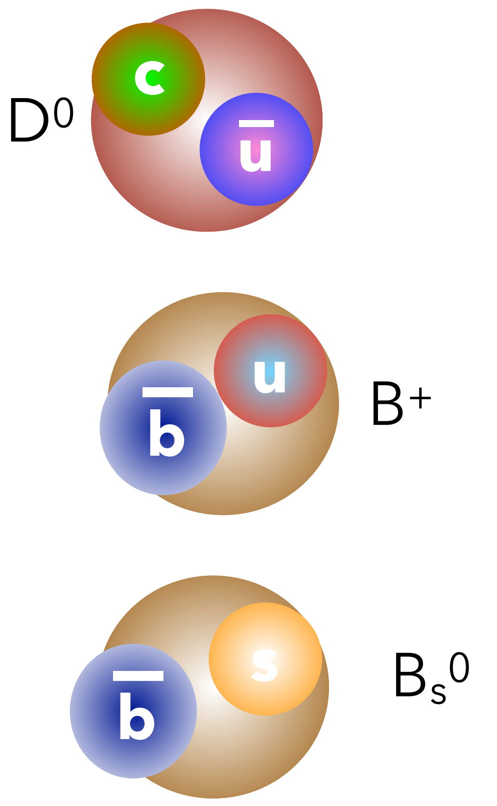
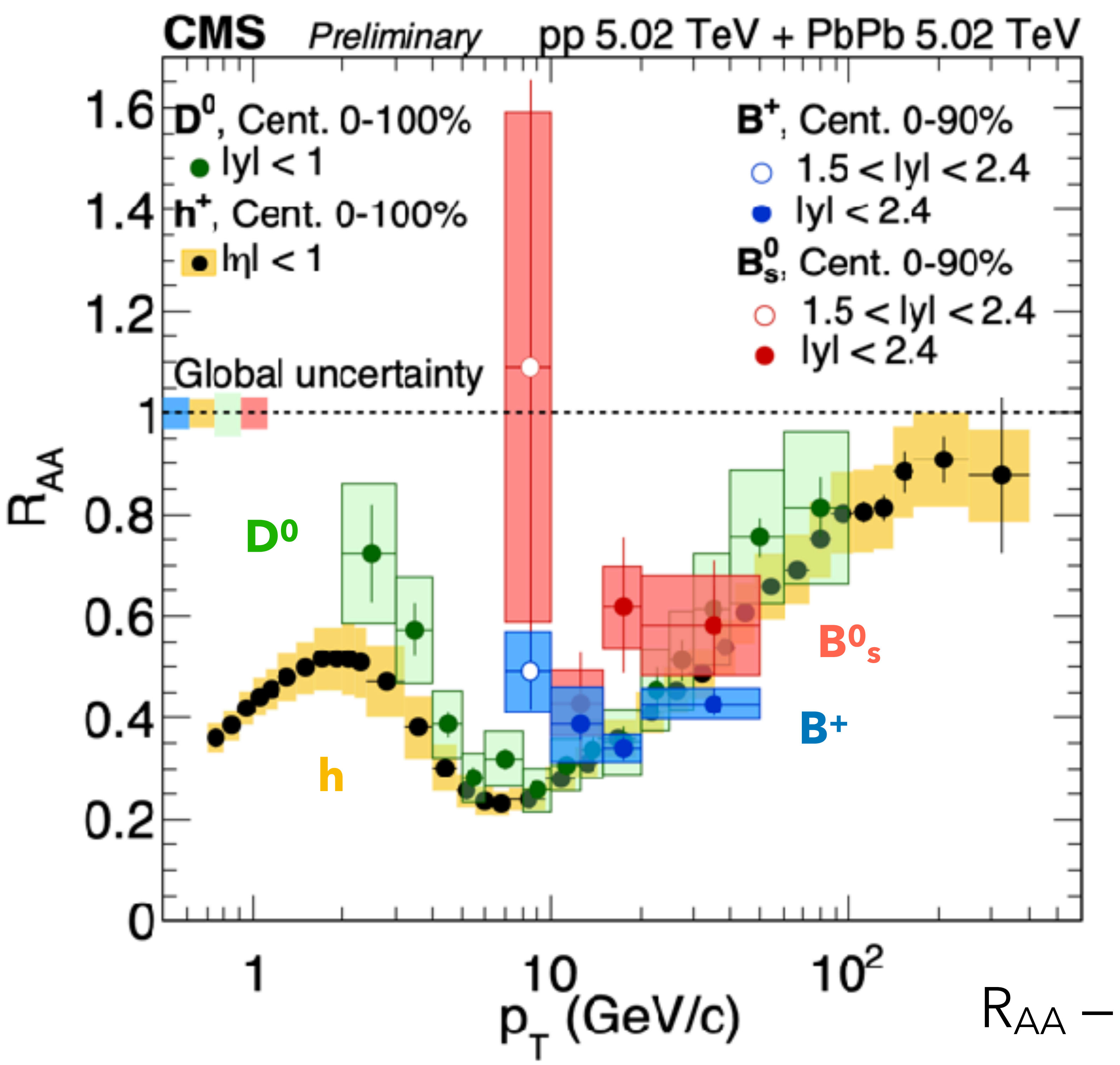
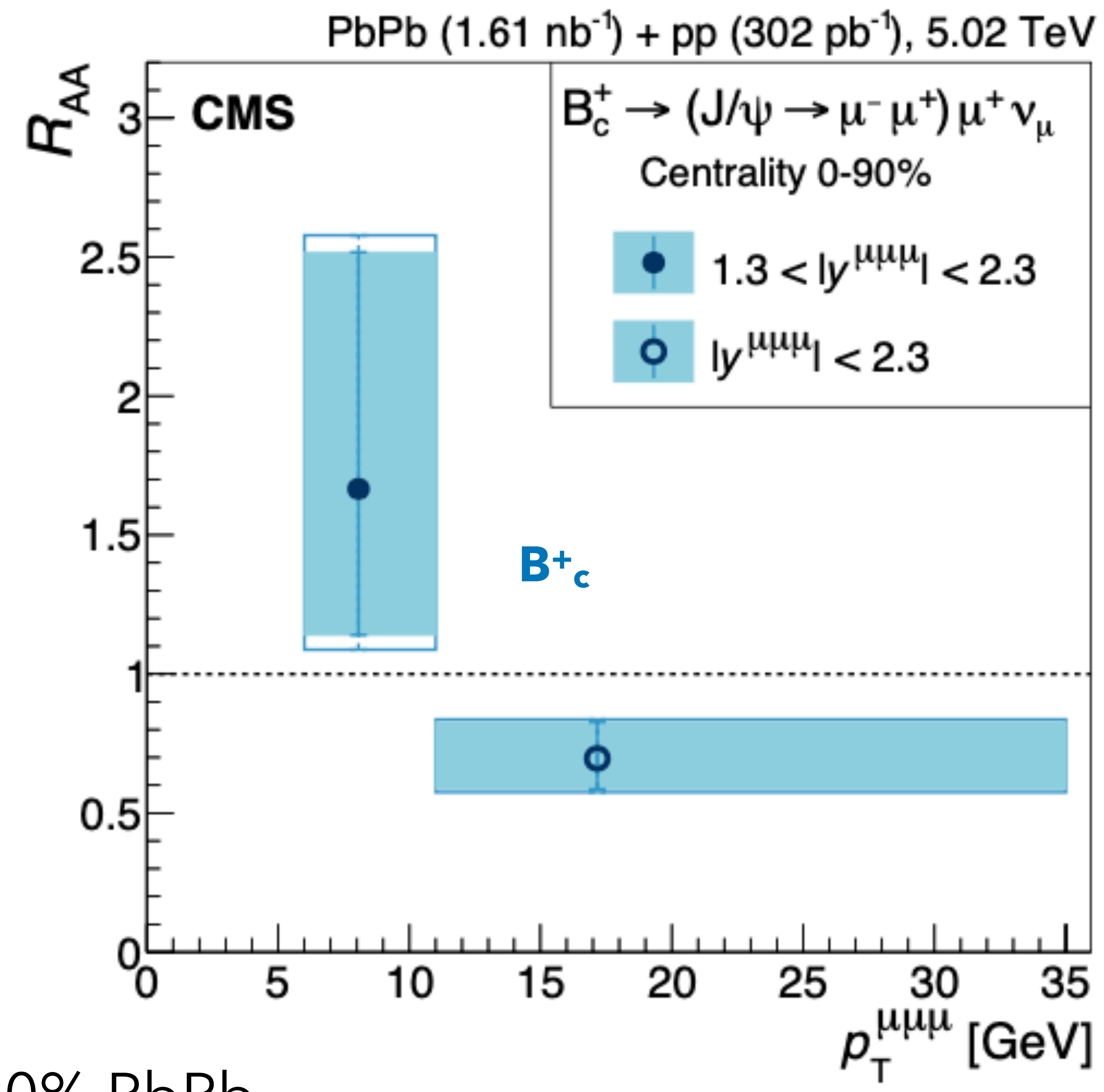
Dai et al: Chinese Phys. C 2020, 44:104105

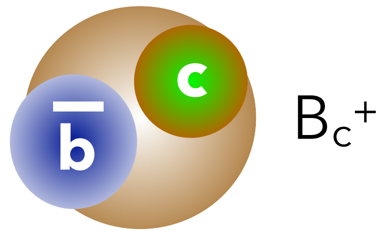
Going rarer? B_s^0 and B_c^+ in PbPb

Talk. JA Mejia Guisao







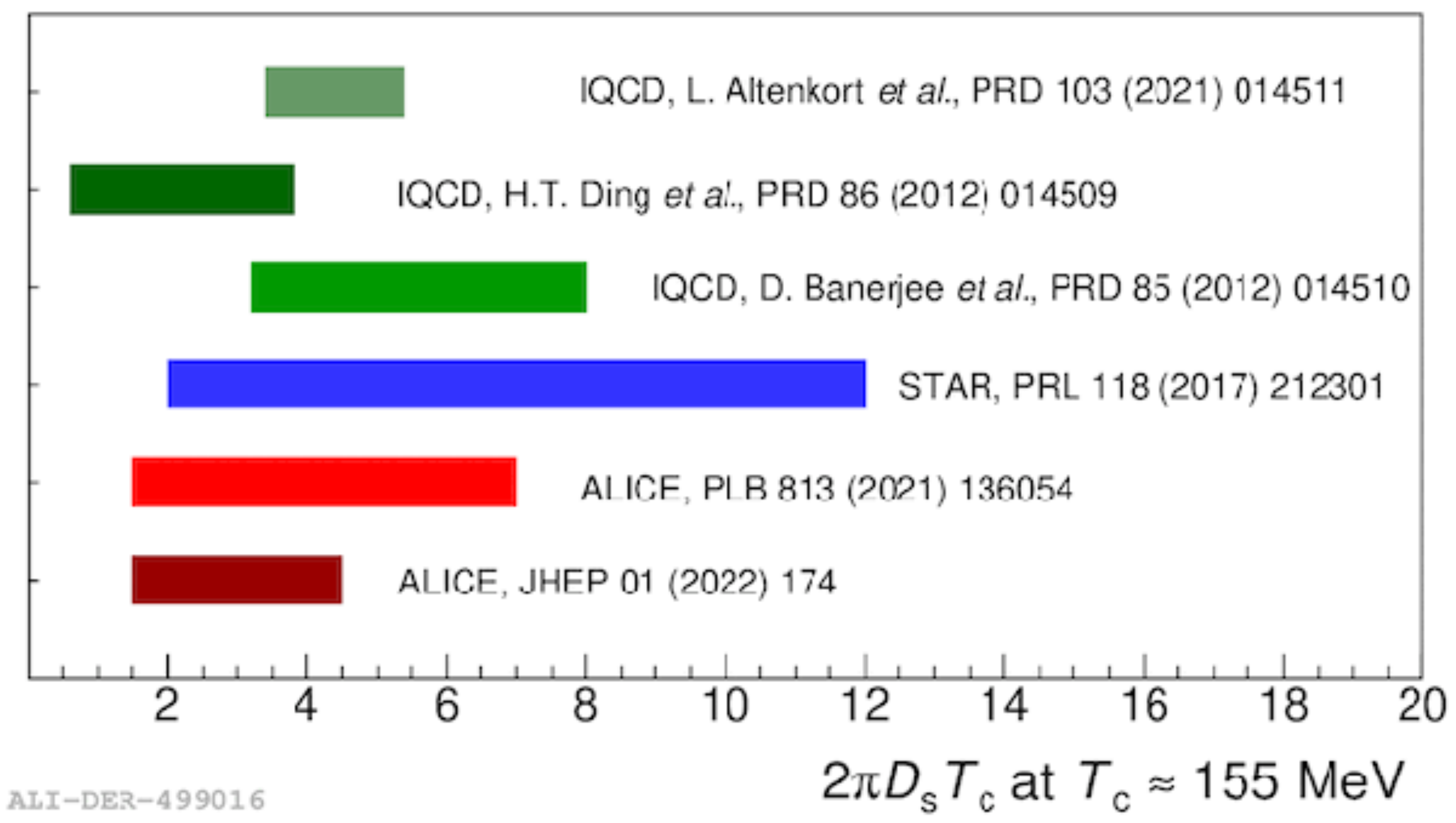


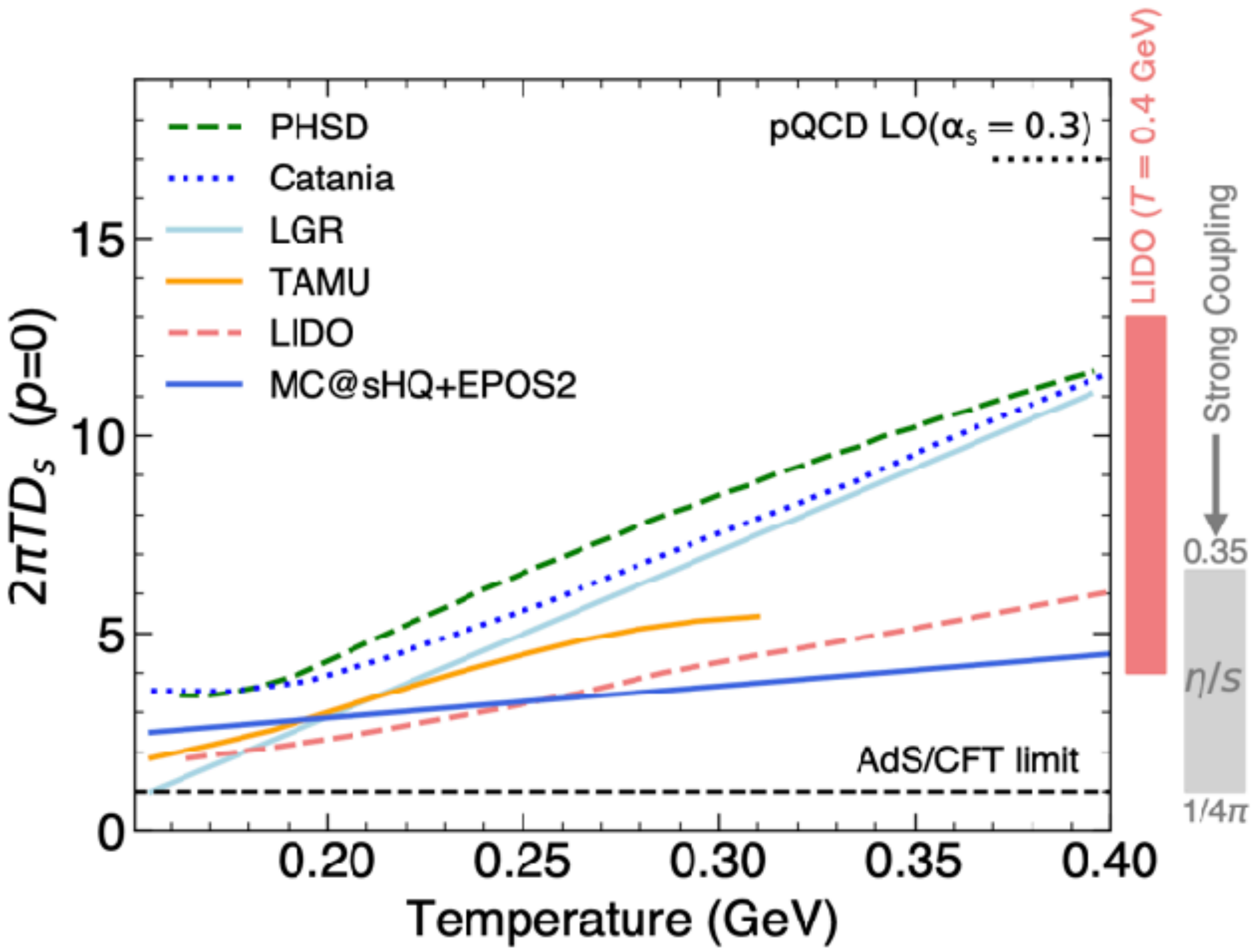
R_{AA} – 0-90% PbPb

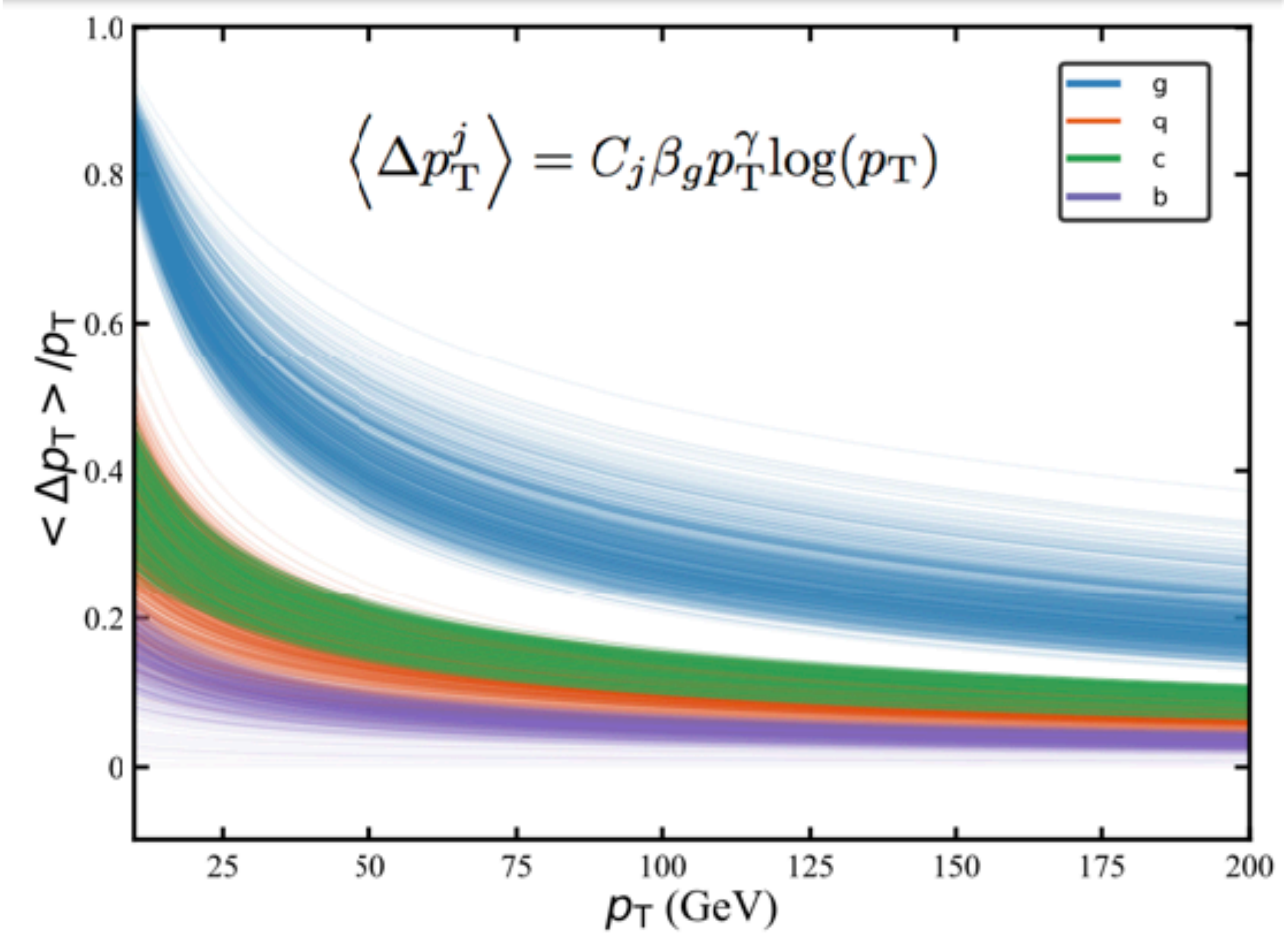
- Similar suppression of beauty hadrons (B^+, B_s^+) for $p_T \gtrsim 10$ GeV
- B_c^+ is a unique charm-bottom state
  → sensitive to both energy loss (suppression) and recombination
  Moderate suppression at high p_T.

CMS Preliminary
CMS, PRL 128, 252301 (2022)
CMS, CMS-PAS-HIN-21-014 (2023)

Wrapping all these up? Model comparison







- Data-model comparison of prompt D^0 R_{AA} and v_2 set **constraints on heavy quark spatial diffusion** coefficient $1.5 < 2\pi D_s T_c < 4.5$ at $T_{pc} = 155$ MeV
  → $\tau_{charm} = (m_{charm}/T) D_s(T) \approx 3\text{-}9$ fm/c for $m_c = 1.5$ GeV
  Values consistent with a **strongly-coupled QGP**!
- D, B hadron & b-jet results consistent with expectations based on energy loss parton **flavour hierarchy**

Talk. WJ. Xing

ALICE, arXiv: 2211.04384
ALICE prompt D^0, JHEP 01 (2022) 174
CMS, PRL 128, 252301 (2022)
CMS, CMS-PAS-HIN-21-014 (2023)
WJ, Xing et al., Phys.Lett.B 850 (2024) 138523
TAMU, He et al., PLB 735 (2014) 445
CUJET3.0, Xu et al, JHEP 02 (2016) 169
DREENA-A, Zigic et al., PRC 106 (2022) 044909
AdS/CFT, Horowitz, PRD 91 (2015) 085019

Talk. V. Greco

Talk. J Cho

Talk. O. Lomicky

Talk. S. Chandra

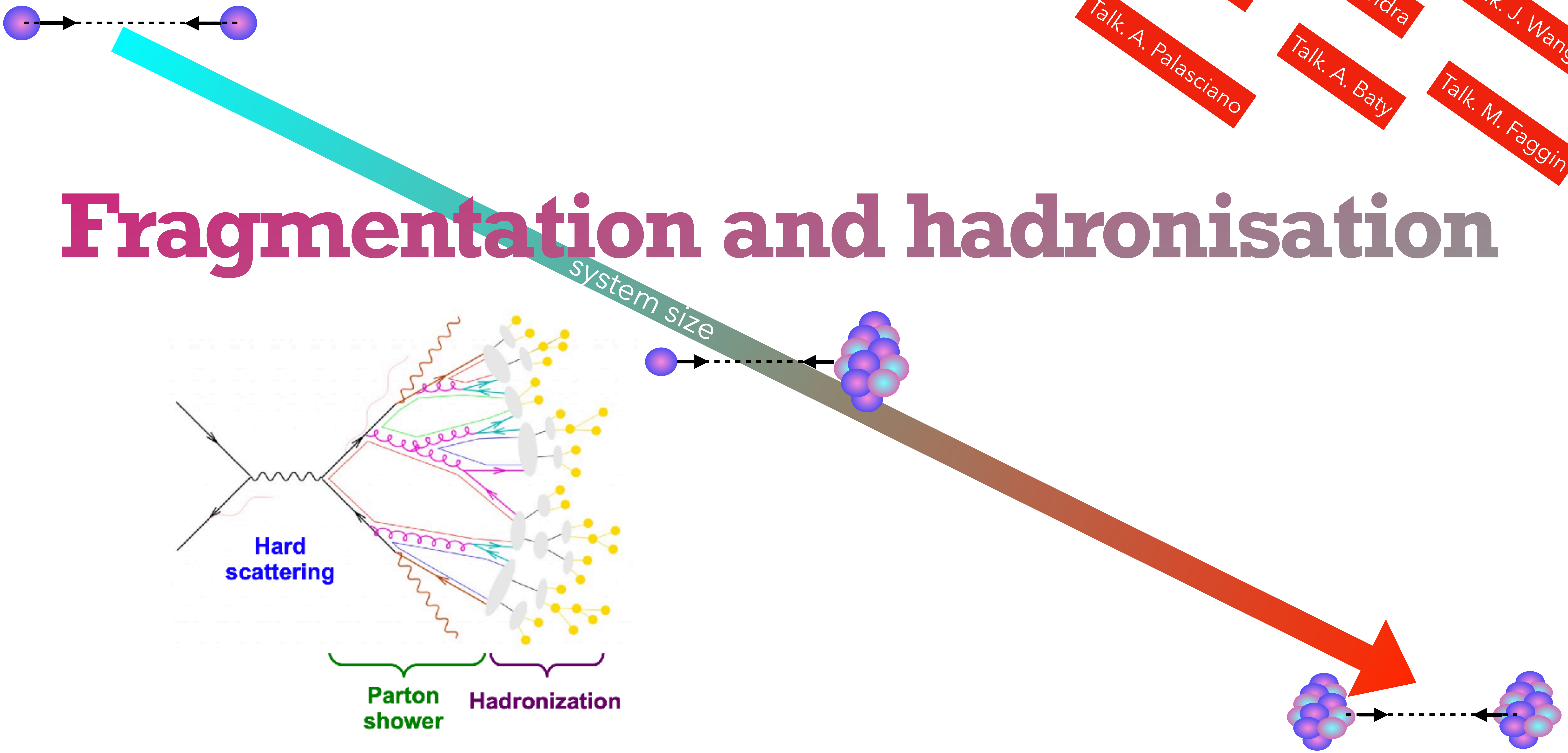
Talk. J. Wang

Talk. A. Palasciano

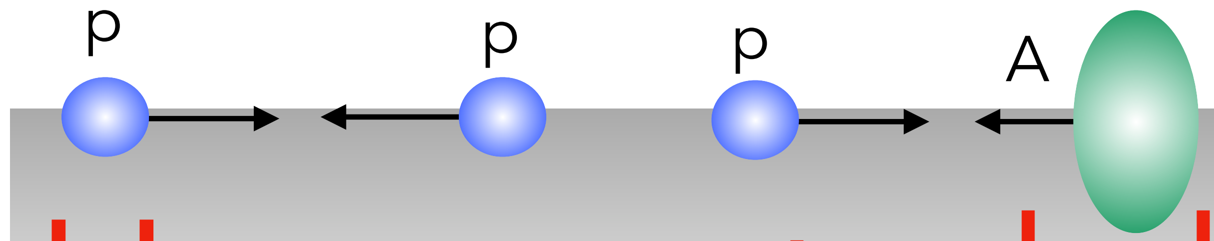
Talk. A. Baty

Talk. M. Faggin

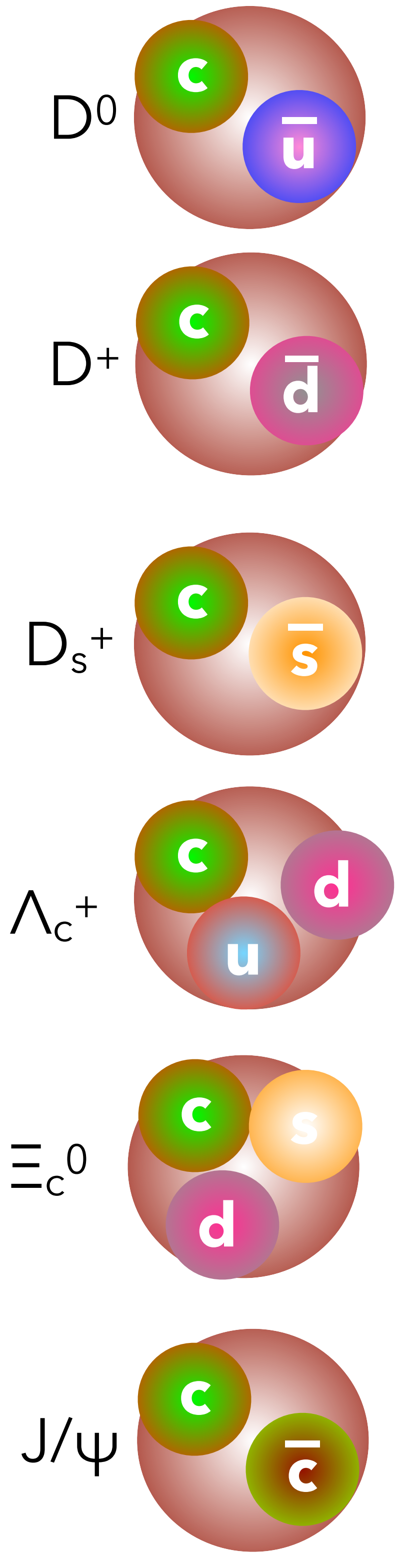
Fragmentation and hadronisation

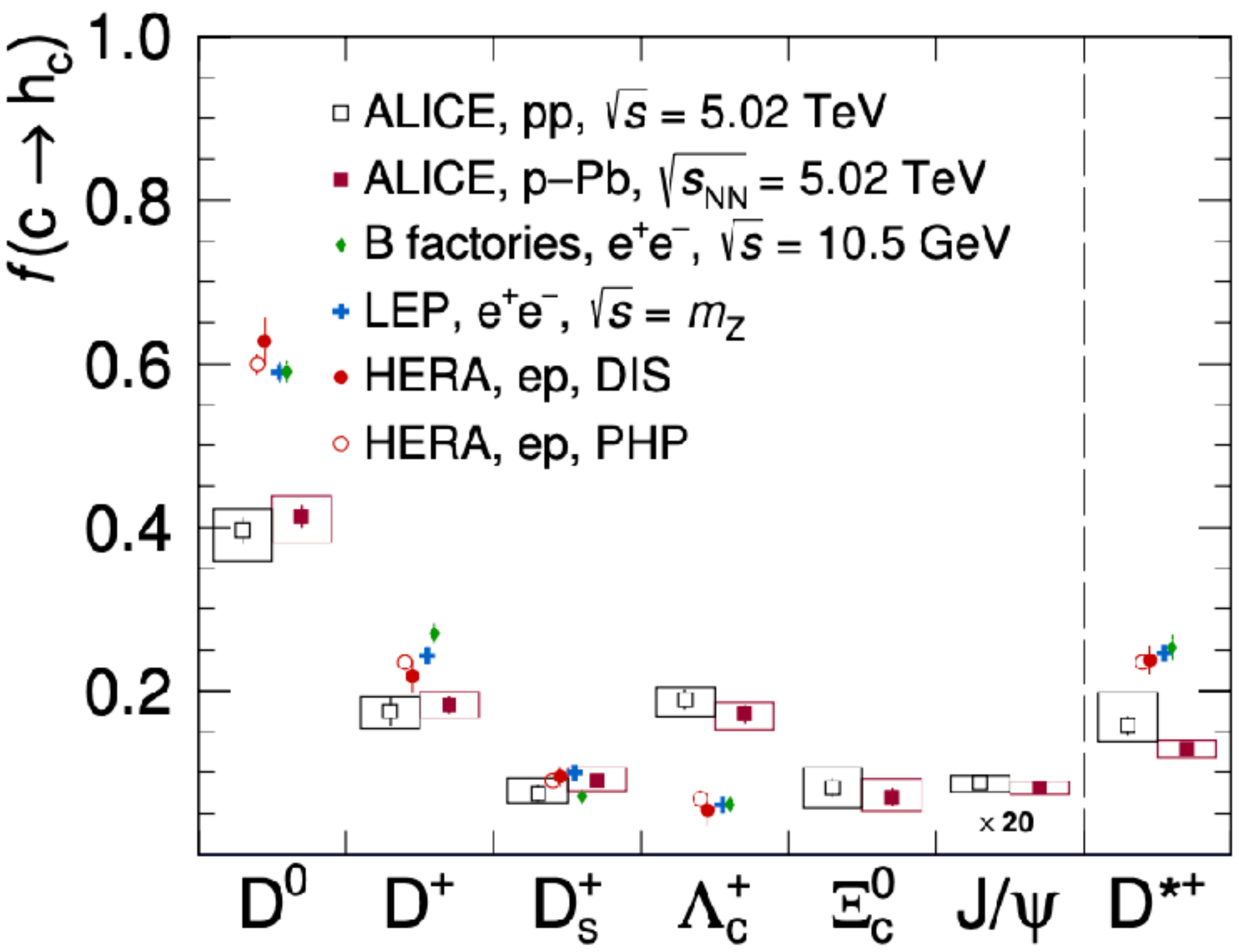


Unexpected charm fragmentation fractions in pp & pPb



Talk. J Cho



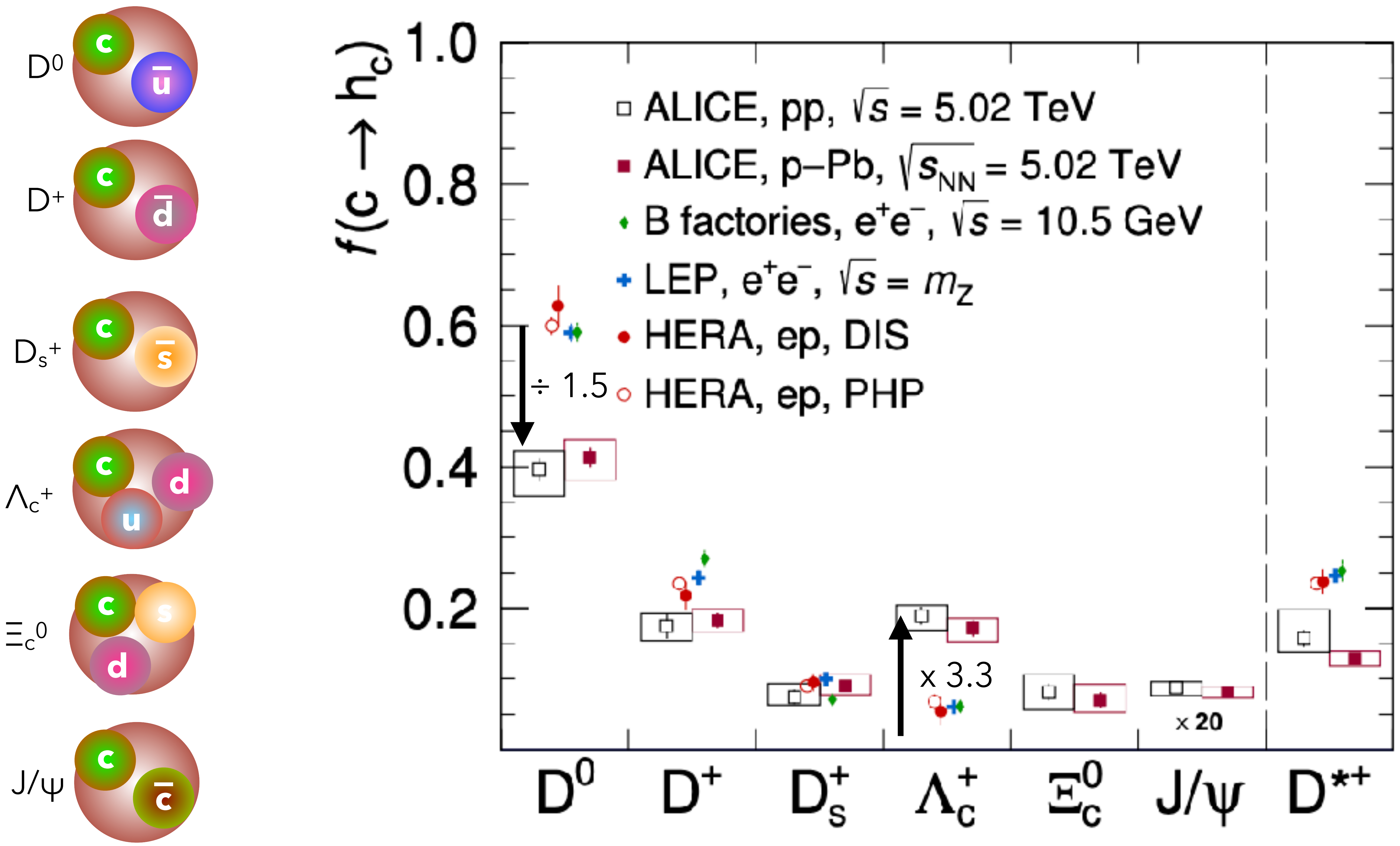


ALICE, arXiv: 2405.14571
ALICE, Phys. Rev. D 105 (2022) L011103

- **Significant difference of the charm fragmentation fractions in pp vs. e+e- and ep collisions.**
  Evidence of the dependence of the parton-to-hadron fragmentation fractions on the collision system. Universality?
- Similar results in pp and pPb collisions.
  No significant modification of charm fragmentation fractions due to the system size.

Unexpected charm fragmentation fractions in pp & pPb

Talk. J Cho



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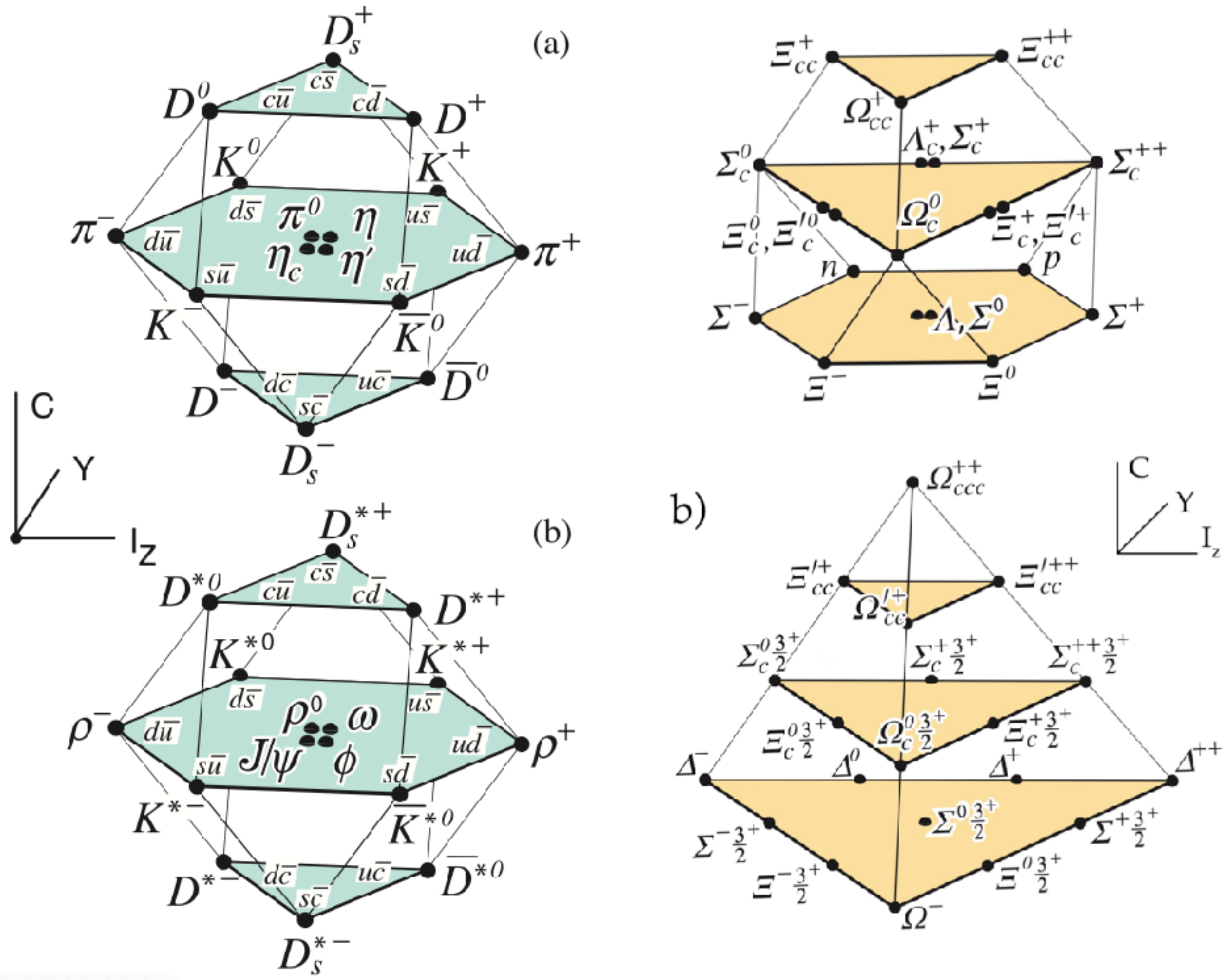
How to study fragmentation and hadronisation?



PDG quark model multiplets of charm hadrons
C (charm content), Y (hypercharge), I_z (isospin)

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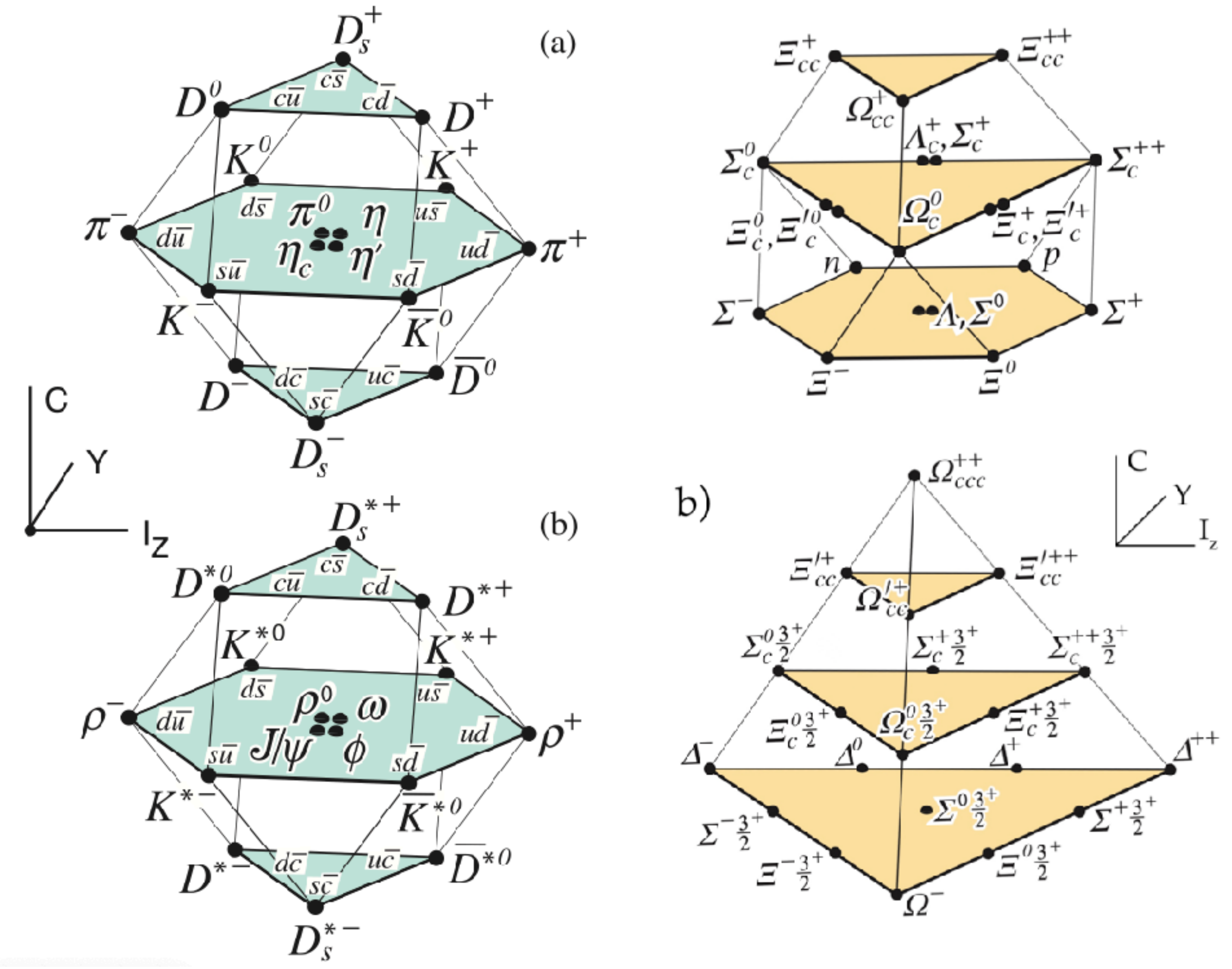

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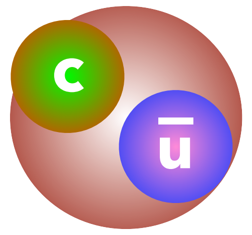
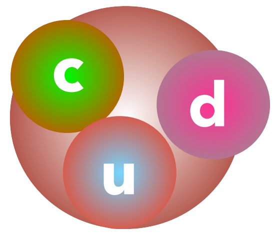
- Similar process for **mesons and baryons**?

e.g. D^0  vs. Λ_c^+  ?

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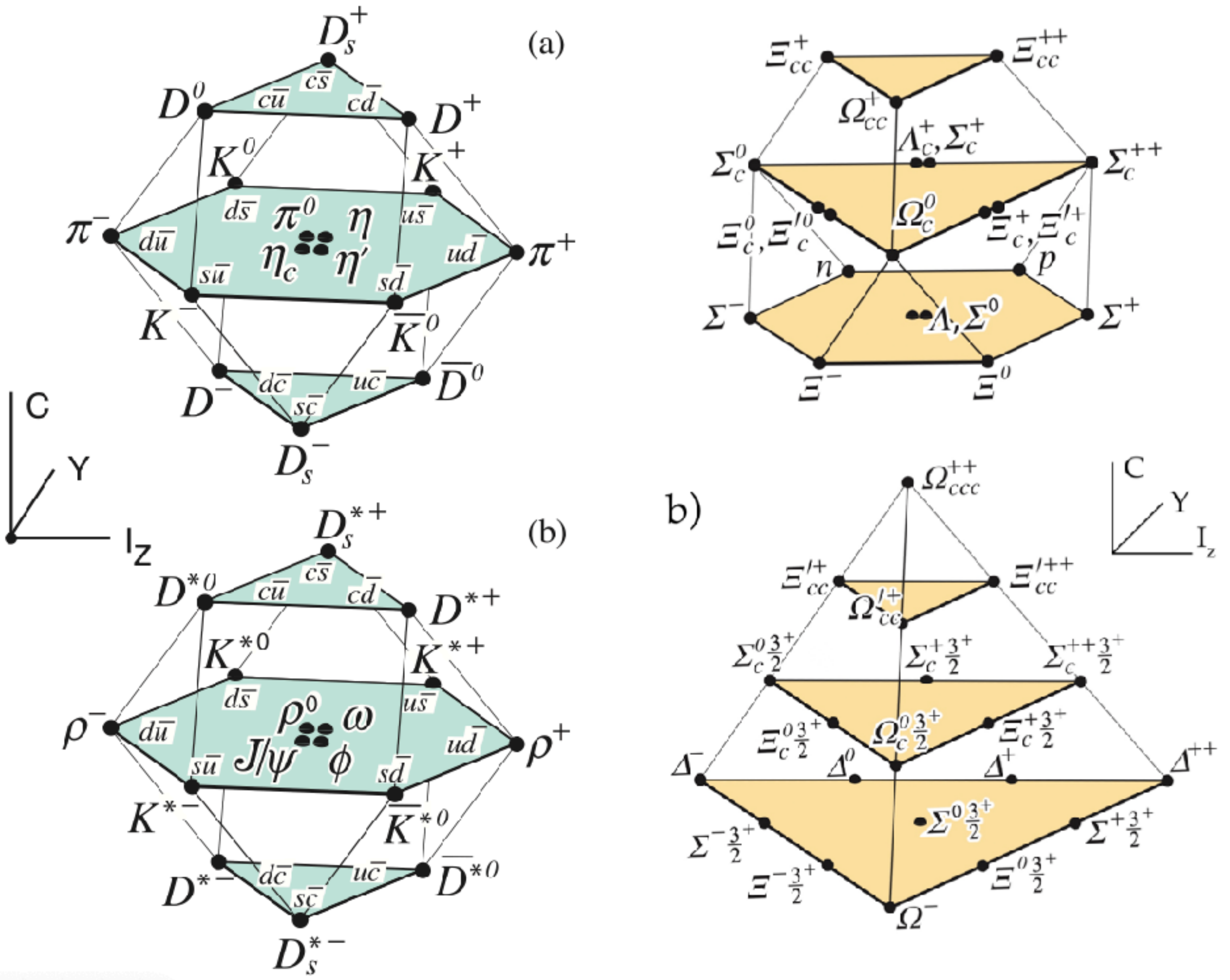

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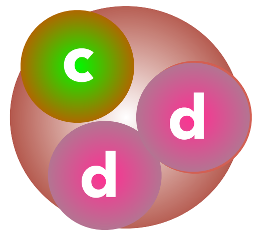
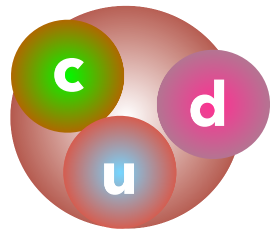
e.g. Σ_c^0 

vs. Λ_c^+ 

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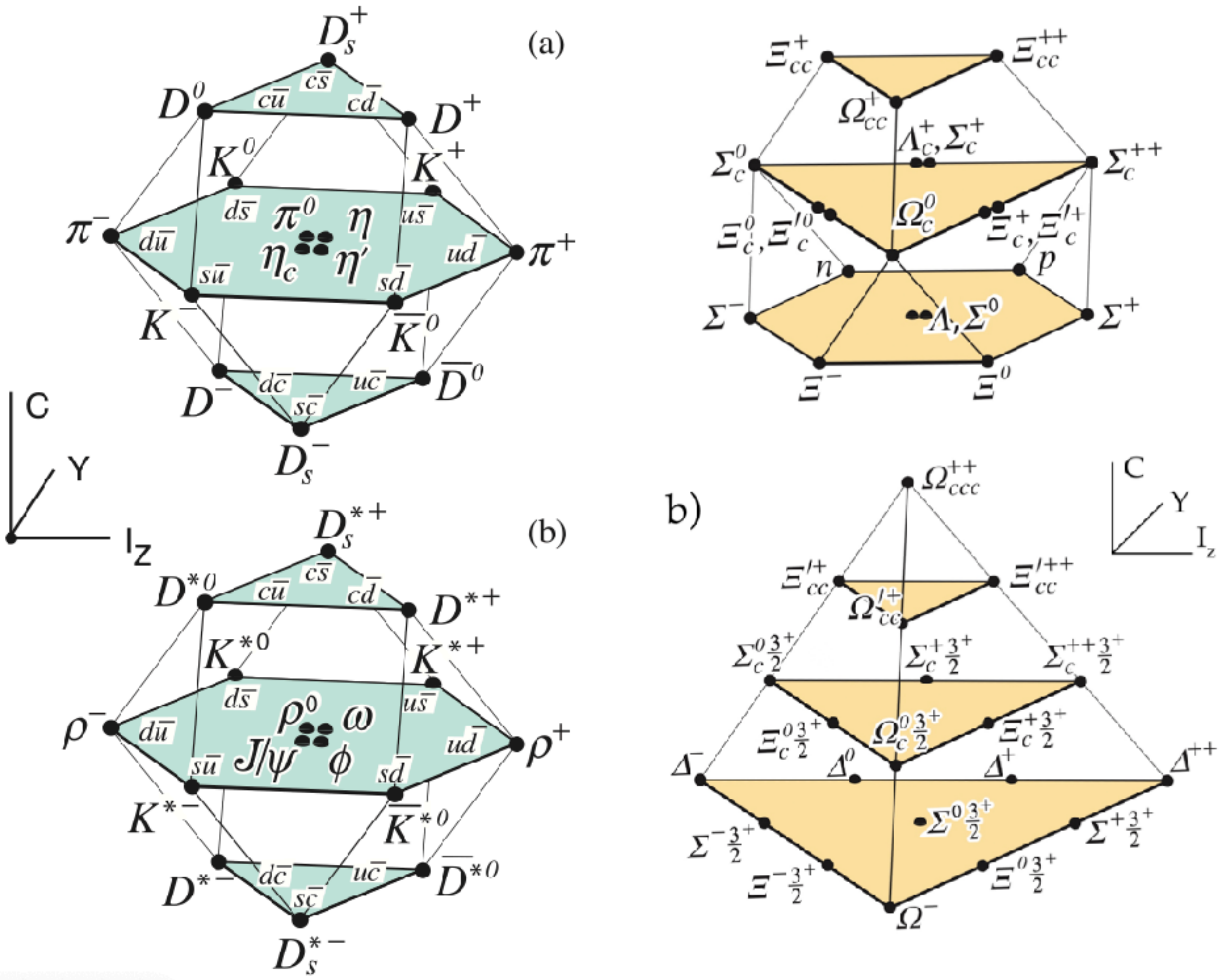

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C (charm content), Y (hypercharge), I_z (isospin)

- Similar process for **mesons and baryons**?
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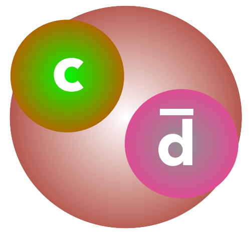
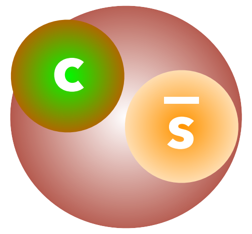
- **Strange** quark content influence?

e.g. D^+ 

vs. D_s^+ 

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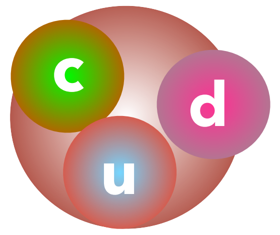
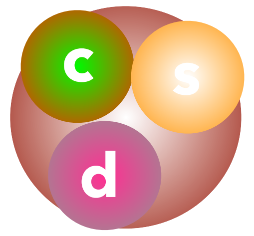
e.g. Λ_c^+ 

vs. Ξ_c^0 

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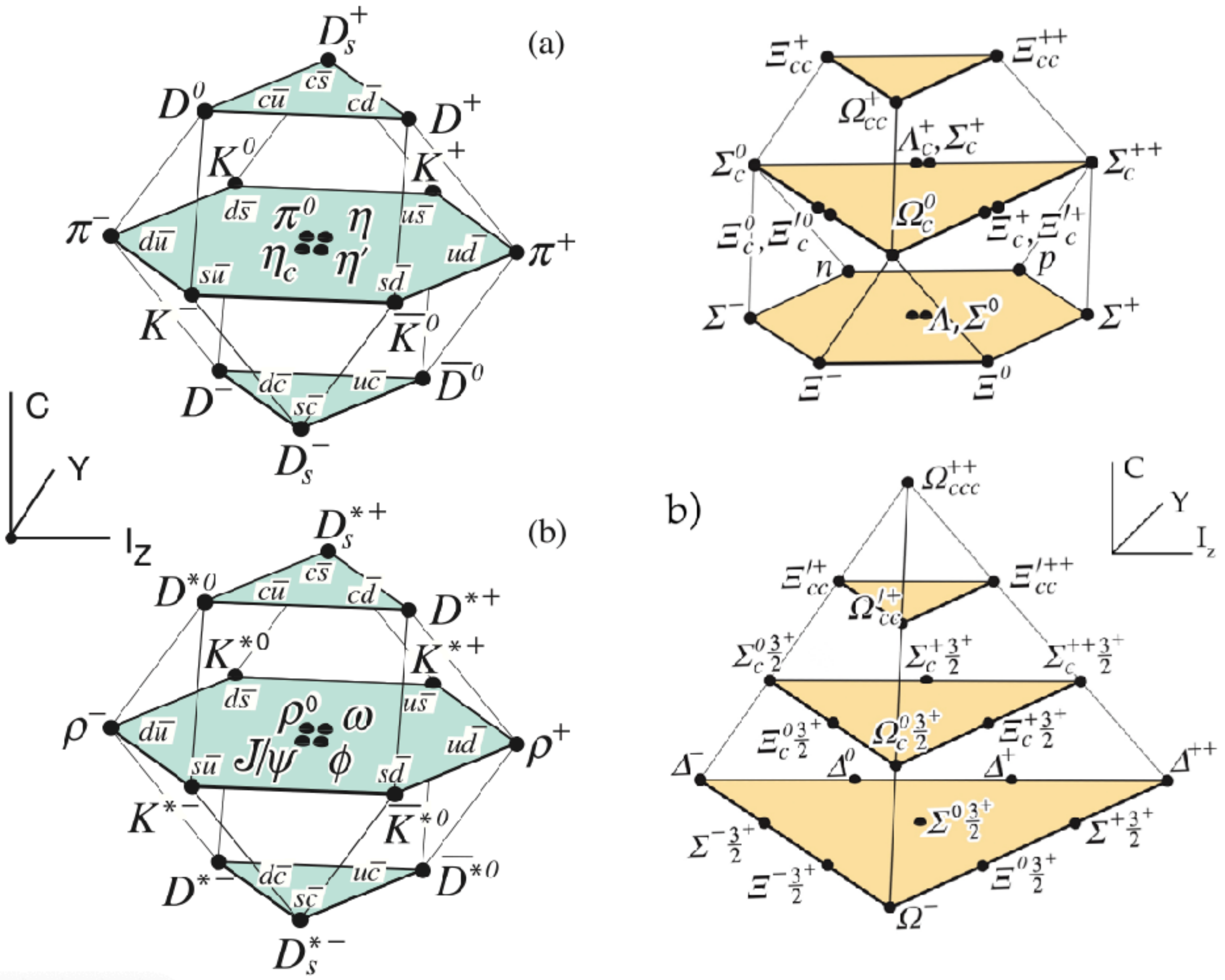

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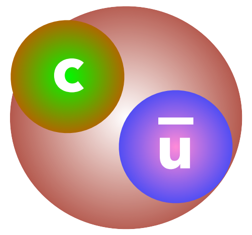
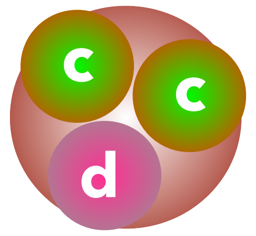
- Measure **states with two or more heavy quarks**?

e.g. D^0 

vs. Ξ_{cc}^+ 

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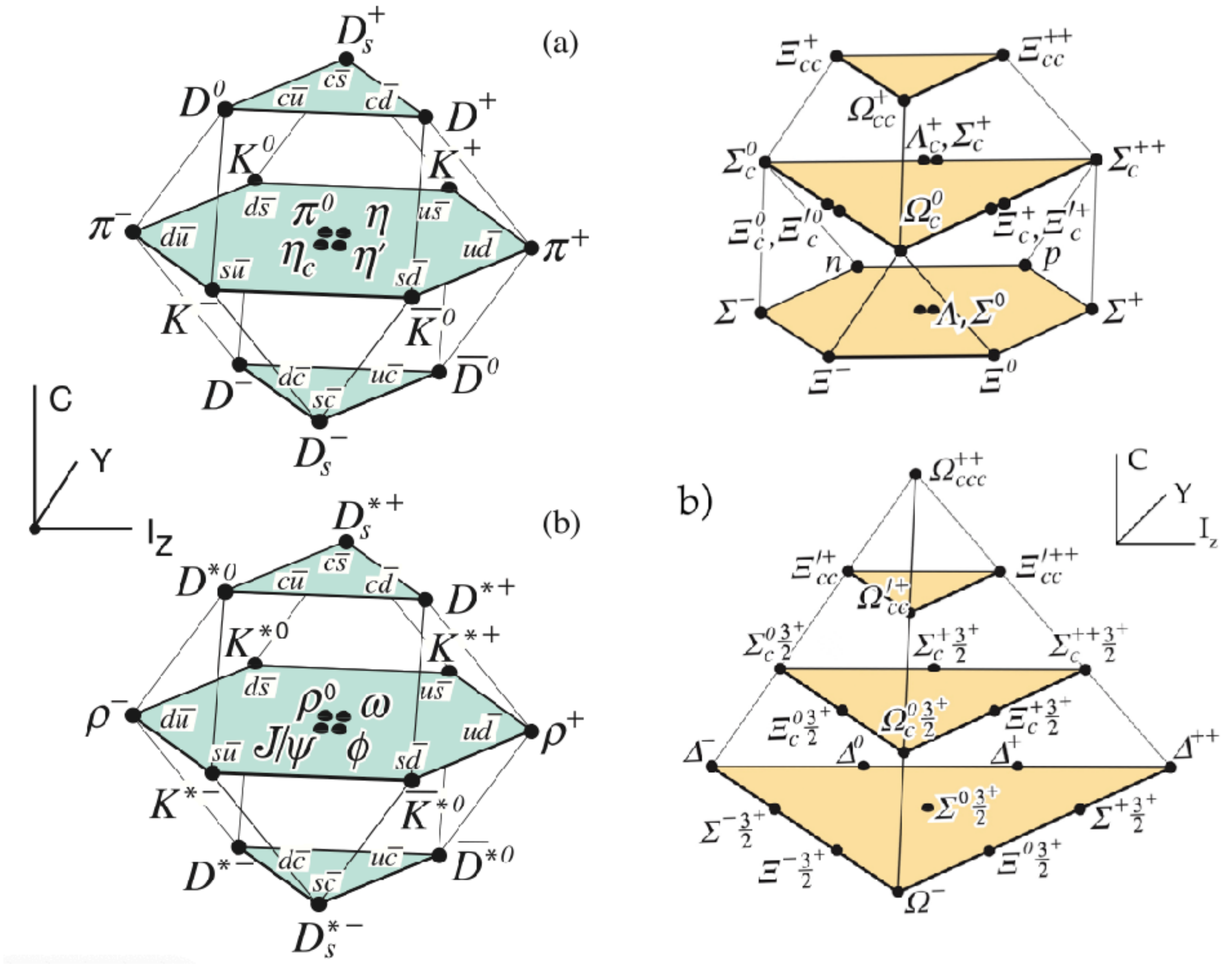
How to study fragmentation and hadronisation?



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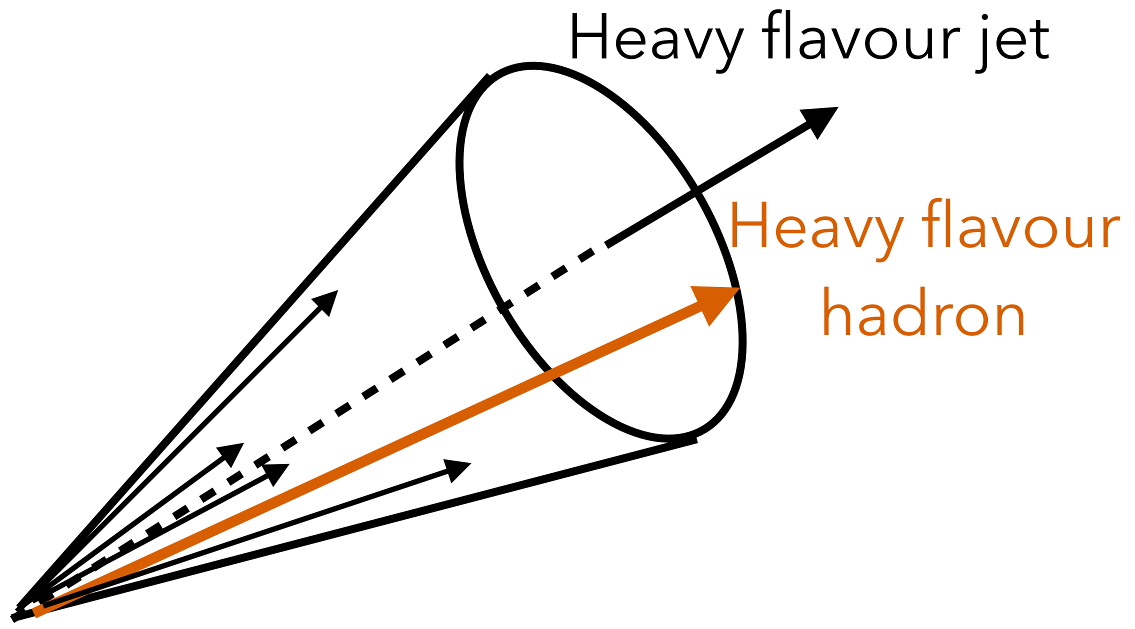

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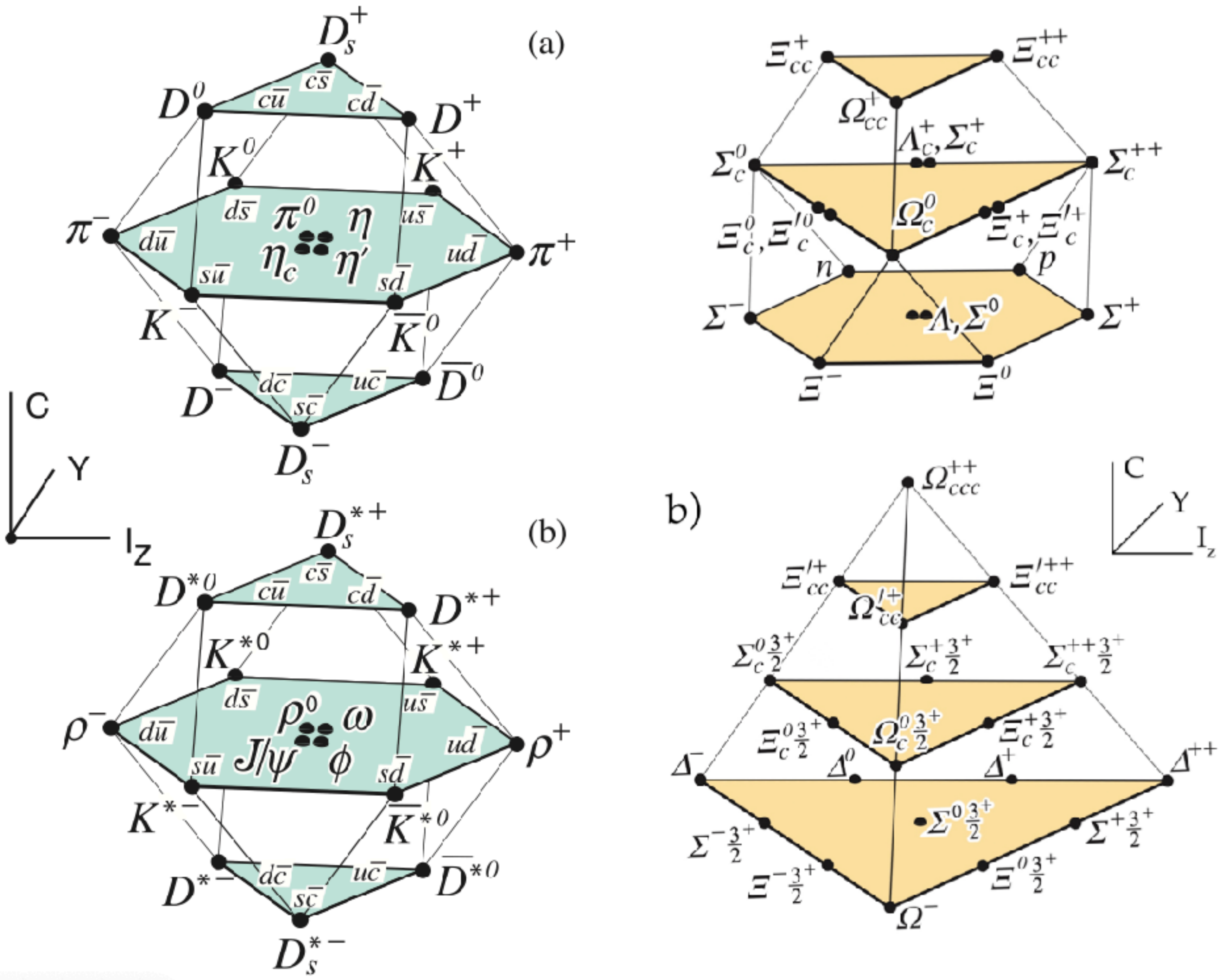

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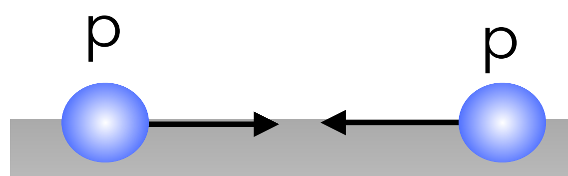
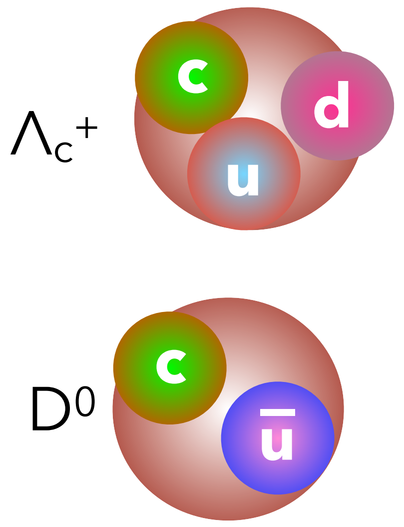
- Measure **states with two or more heavy quarks**?
- Angular **correlations** and heavy-flavour–**jet** studies?
- Perform such studies as a function of the **system size** (from pp to pA and AA) and the charged-particle **multiplicity** (collision centrality) as differentially as possible (y, p_T)

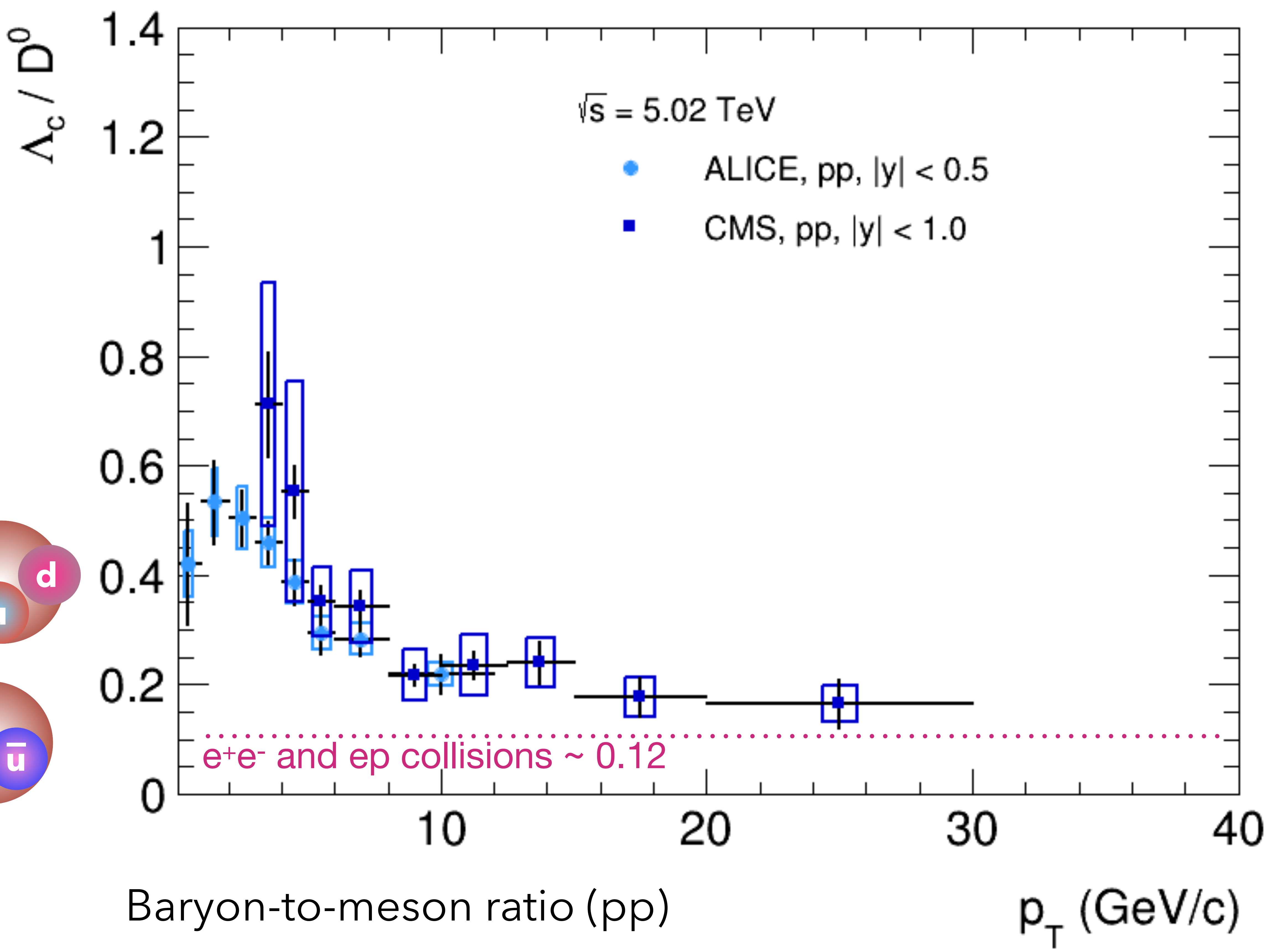


Baryons vs. mesons: charm hadron results (pp)?

Talk. J Cho

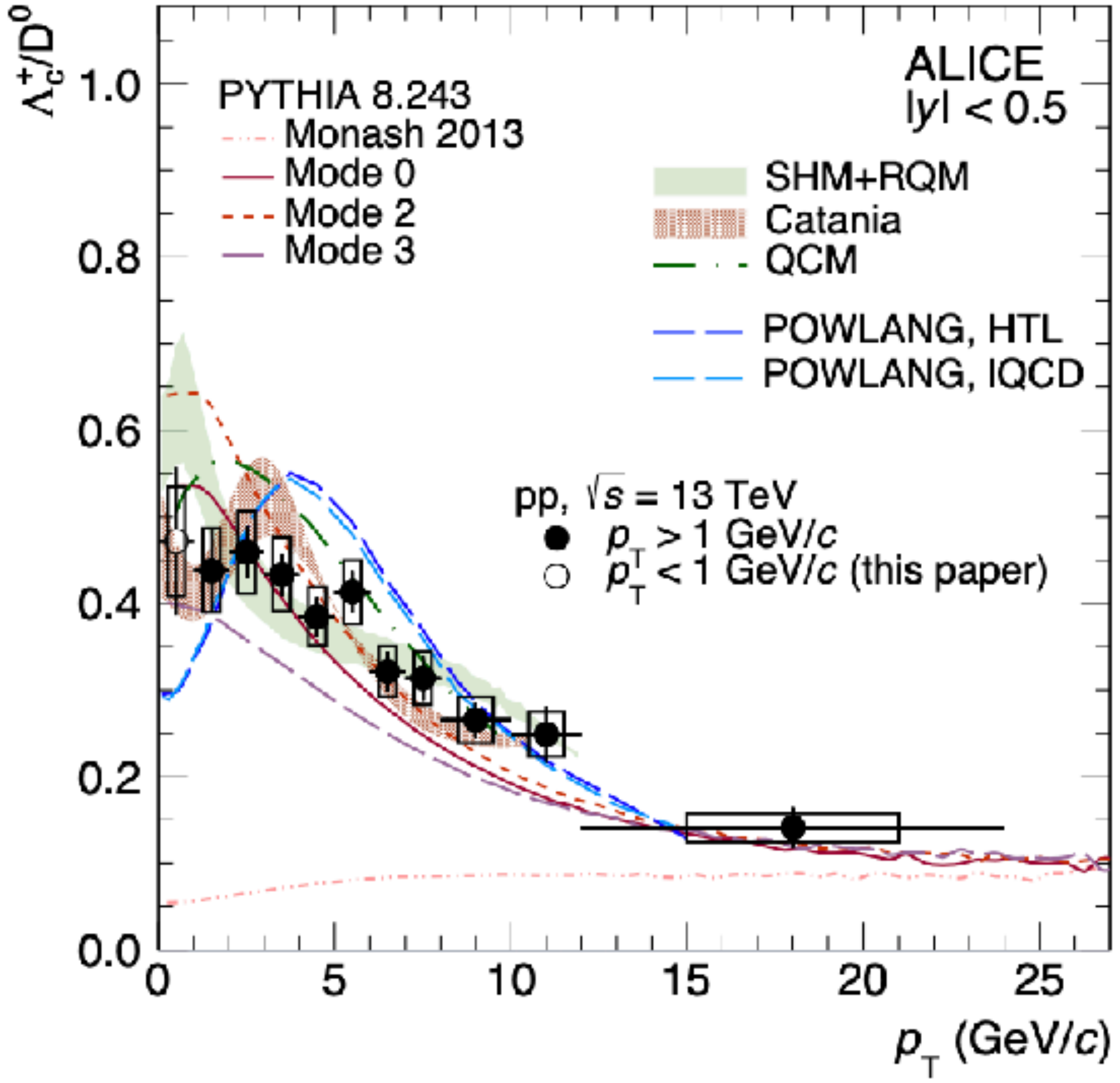
Talk. S. Chandra





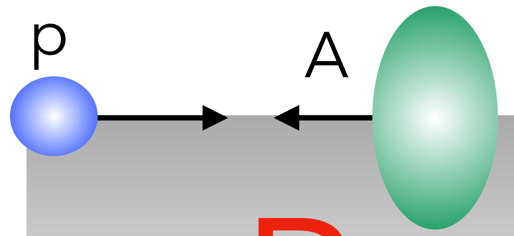
Baryon-to-meson ratio (pp)

- Observed a **strong p_T dependence** of the baryon-to-meson ratios in the charm sector, similar to that observed in the light-flavour sector.
- Described by models considering **additional mechanisms/ interactions at play in a high-density environment wrt the independent fragmentation picture**:
  - **colour reconnection** beyond leading colour,
  - quark **coalescence**,
  - statistical hadronisation model (**SHM**)

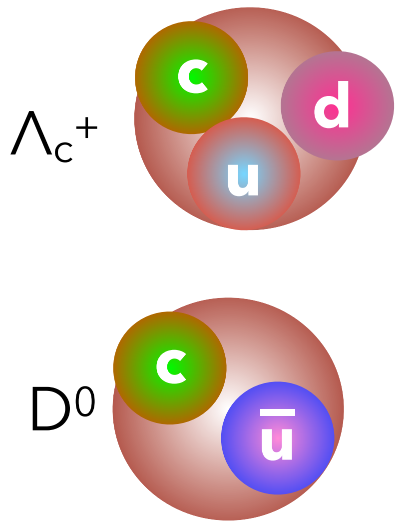


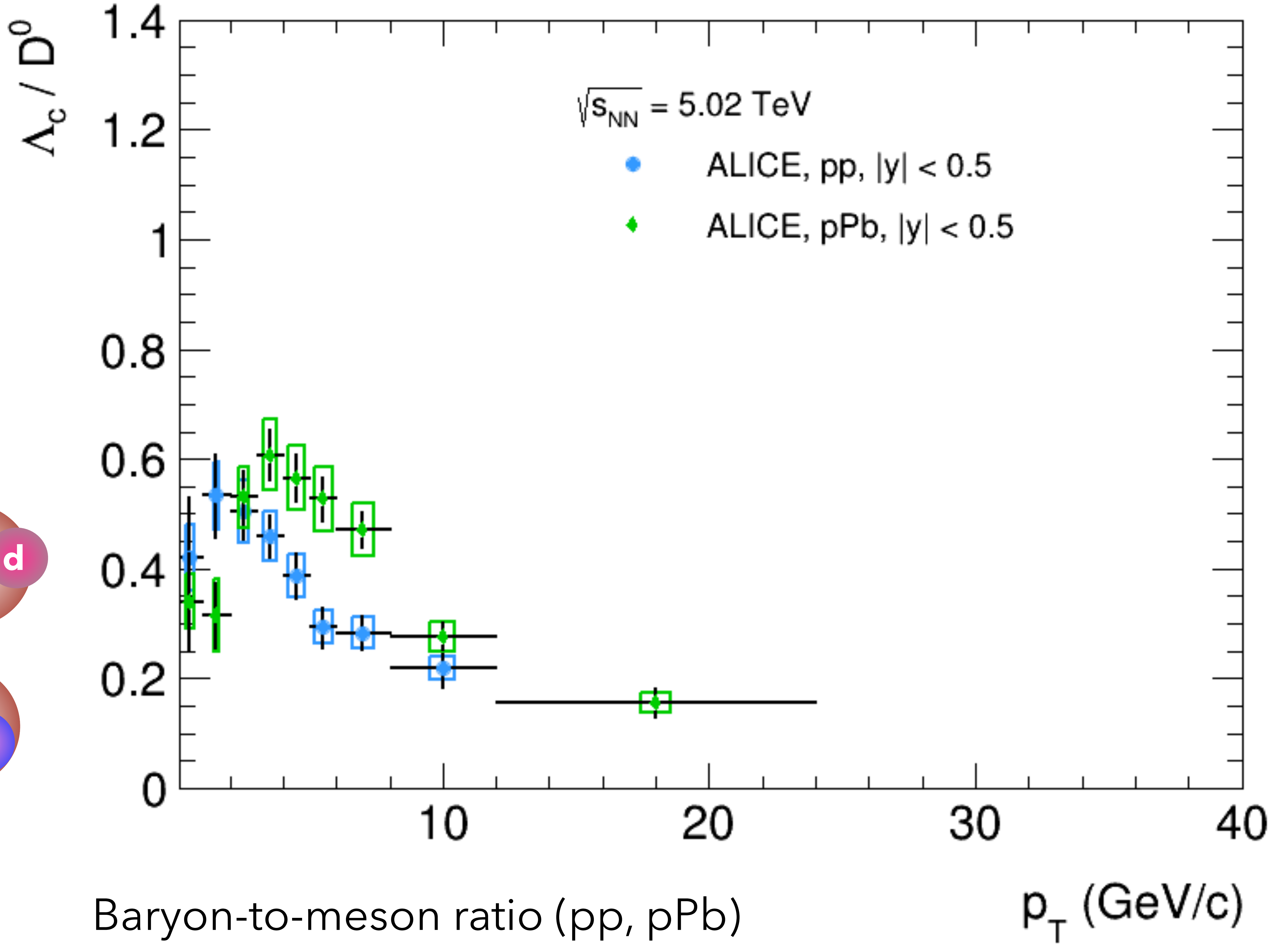
ALICE, pp, pPb, PRC 107 (2023) 064901
ALICE, pp, JHEP 12 (2023) 086
CMS, pp, PbPb, JHEP 01 (2024) 128

PYTHIA8: Skands et al., EPJC 74 (2014) 3024
POWLANG: Beraudo et al., arXiv:2306.02152
SHM+RQM: He et al., PLB 795 (2019) 117-121
QCM: Song et al., EPJC 78 (2018) 344
Catania: Scardina et al, PRC96 (2017) 044905, PLB 821 (2021) 136622



Baryons vs. mesons: charm hadron results (pPb)?



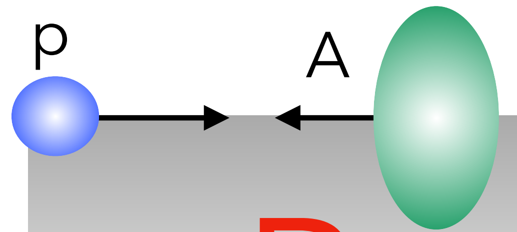


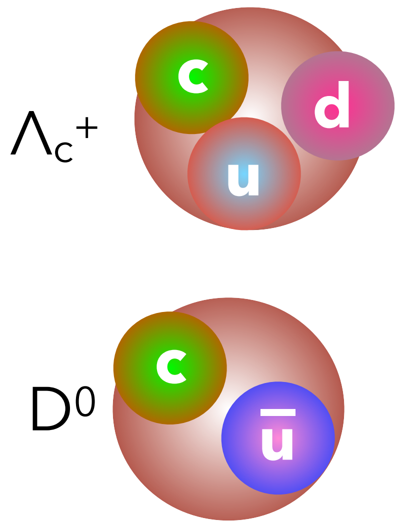
Baryon-to-meson ratio (pp, pPb)

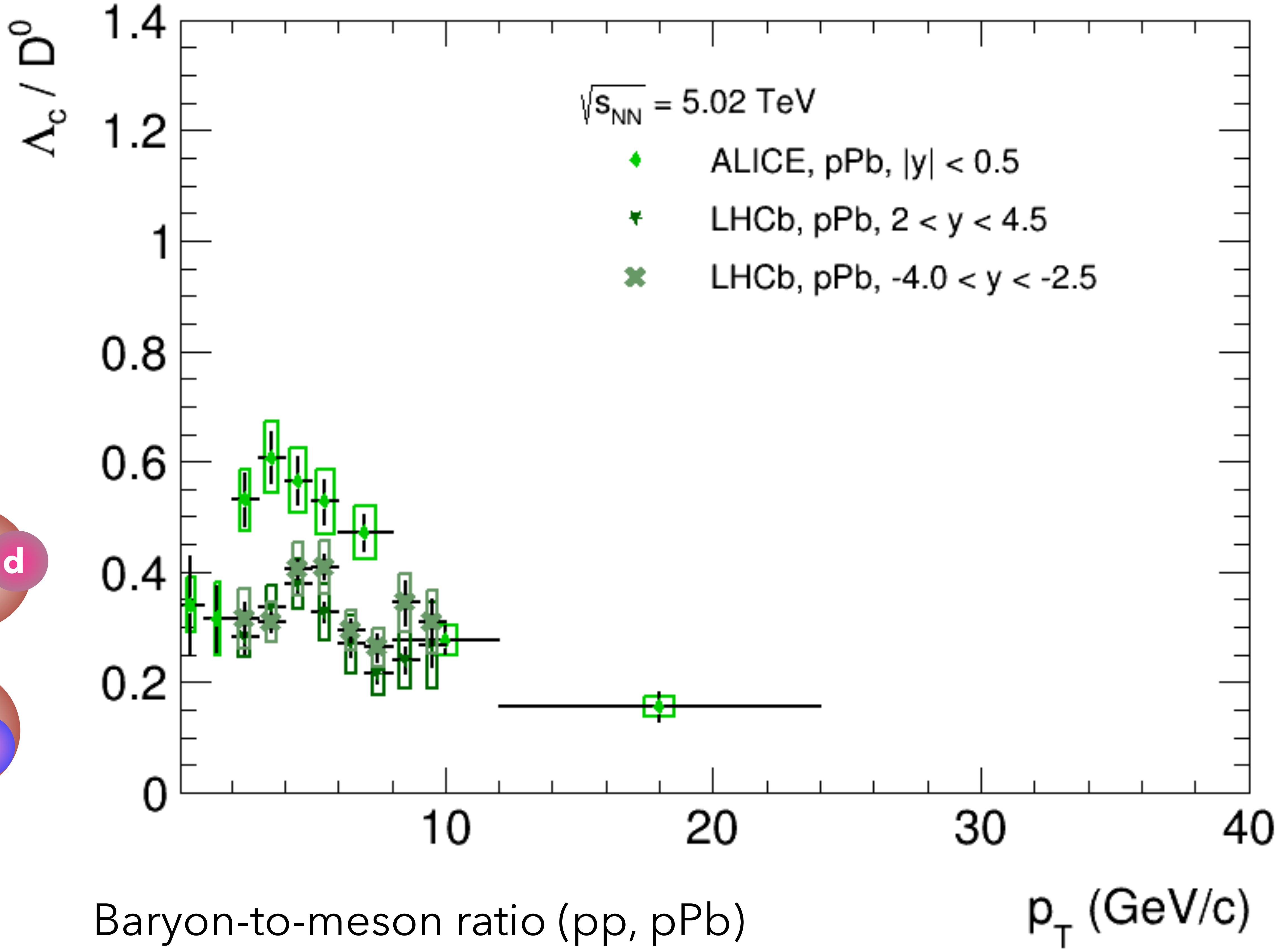
ALICE, pp, pPb, PRC 107 (2023) 064901
CMS, pp, PbPb, JHEP 01 (2024) 128
LHCb, pPb, JHEP 02 (2019) 102
LHCb, PbPb, JHEP06 (2023) 132

- Observed a **strong p_T dependence of the baryon-to-meson ratios in the charm sector**, similar to that observed in the light-flavour sector.
- Ratio **modified in pPb** w.r.t. pp (intermediate p_T). Possible influence of recombination or radial flow?
- No significant p_T dependence observed at large rapidity in pPb.
  Possible **rapidity dependence**?

Baryons vs. mesons: charm hadron results (pPb)?







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ALICE, pp, pPb, PRC 107 (2023) 064901
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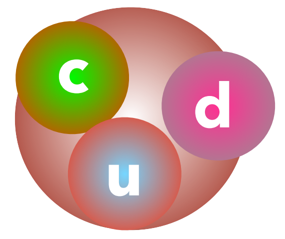
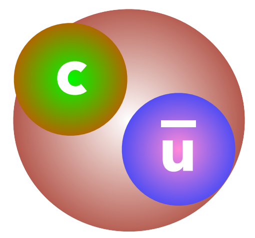
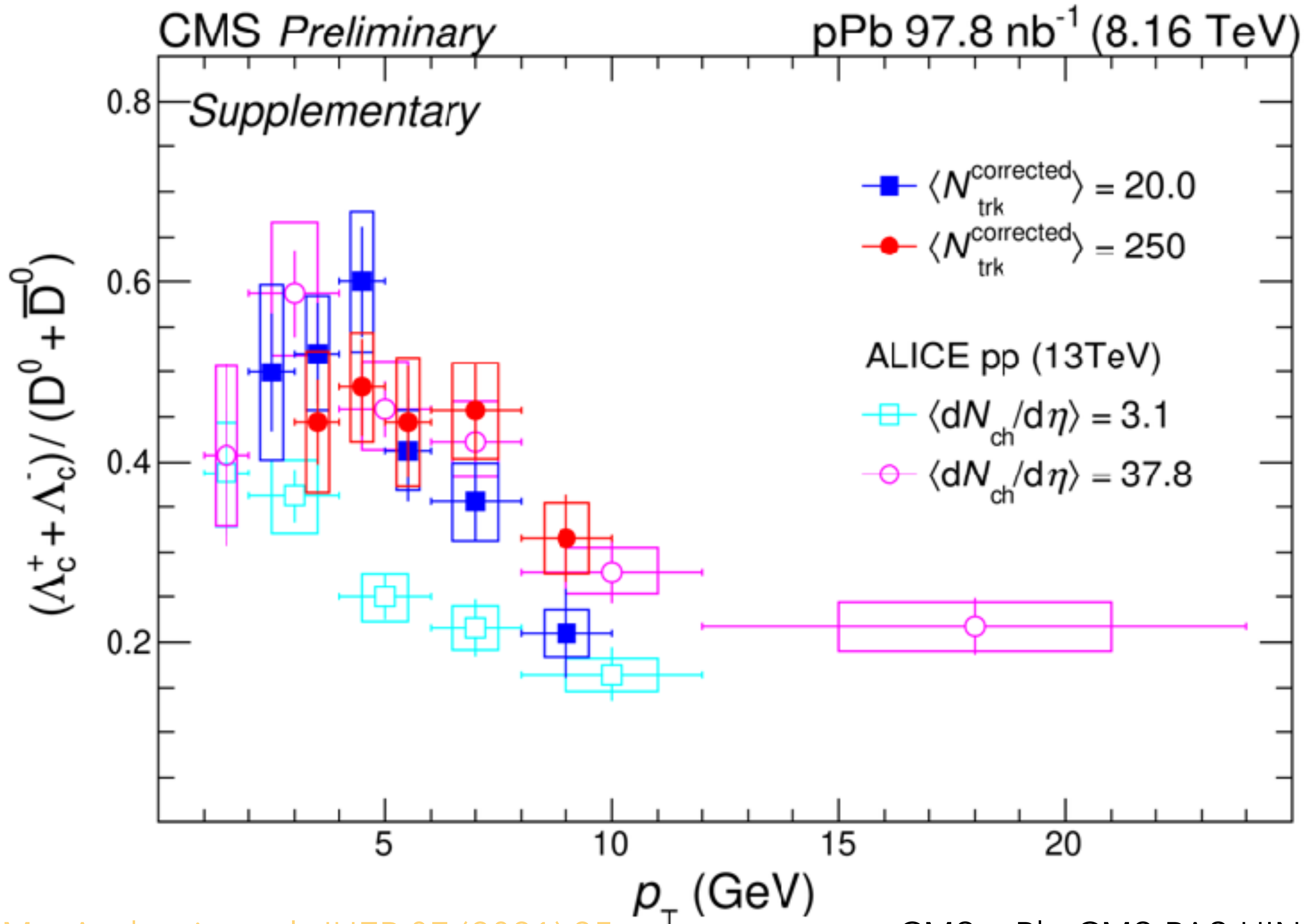
Baryons vs. mesons: charm hadrons vs. multiplicity?

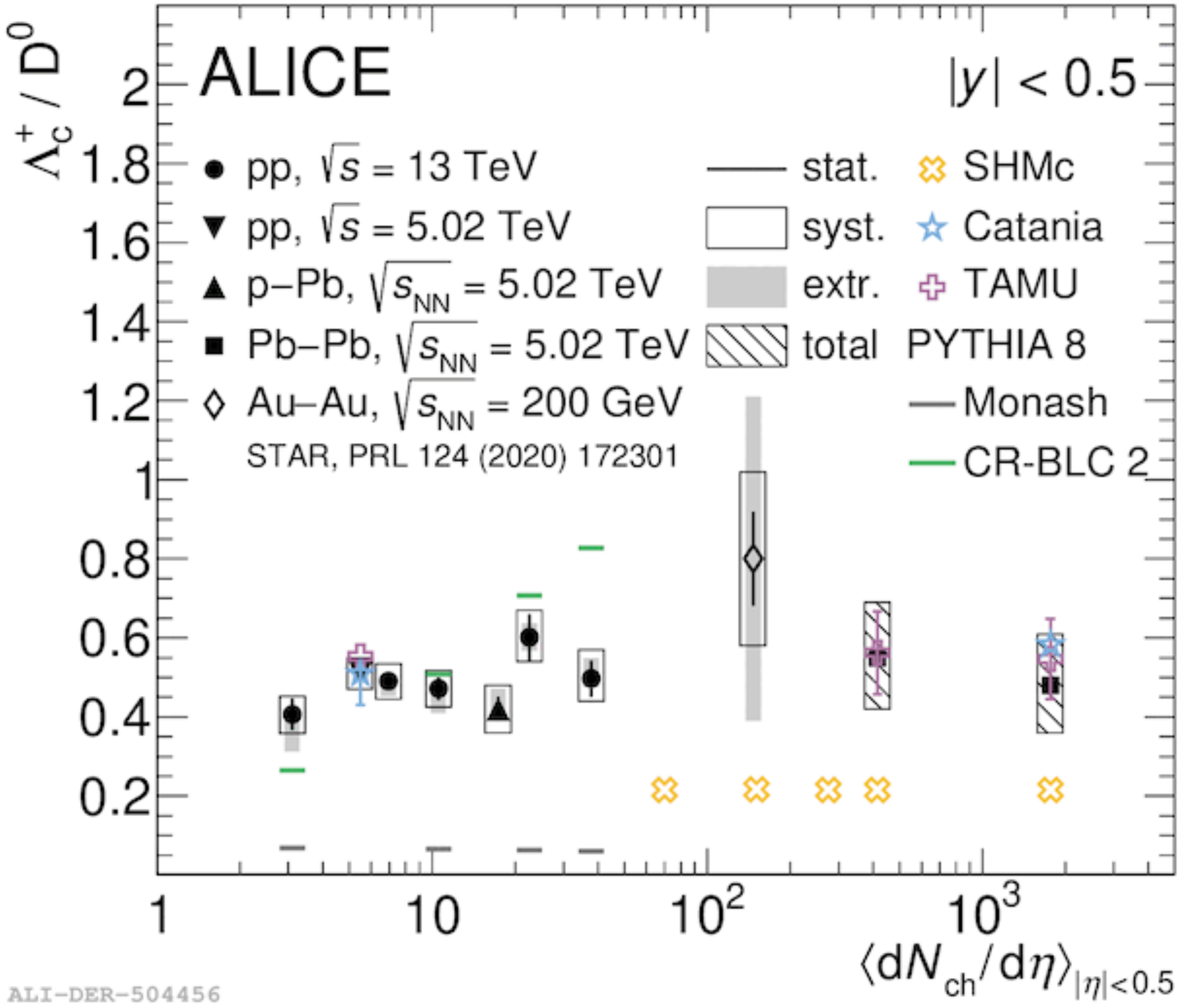
Λ_c^+



D^0





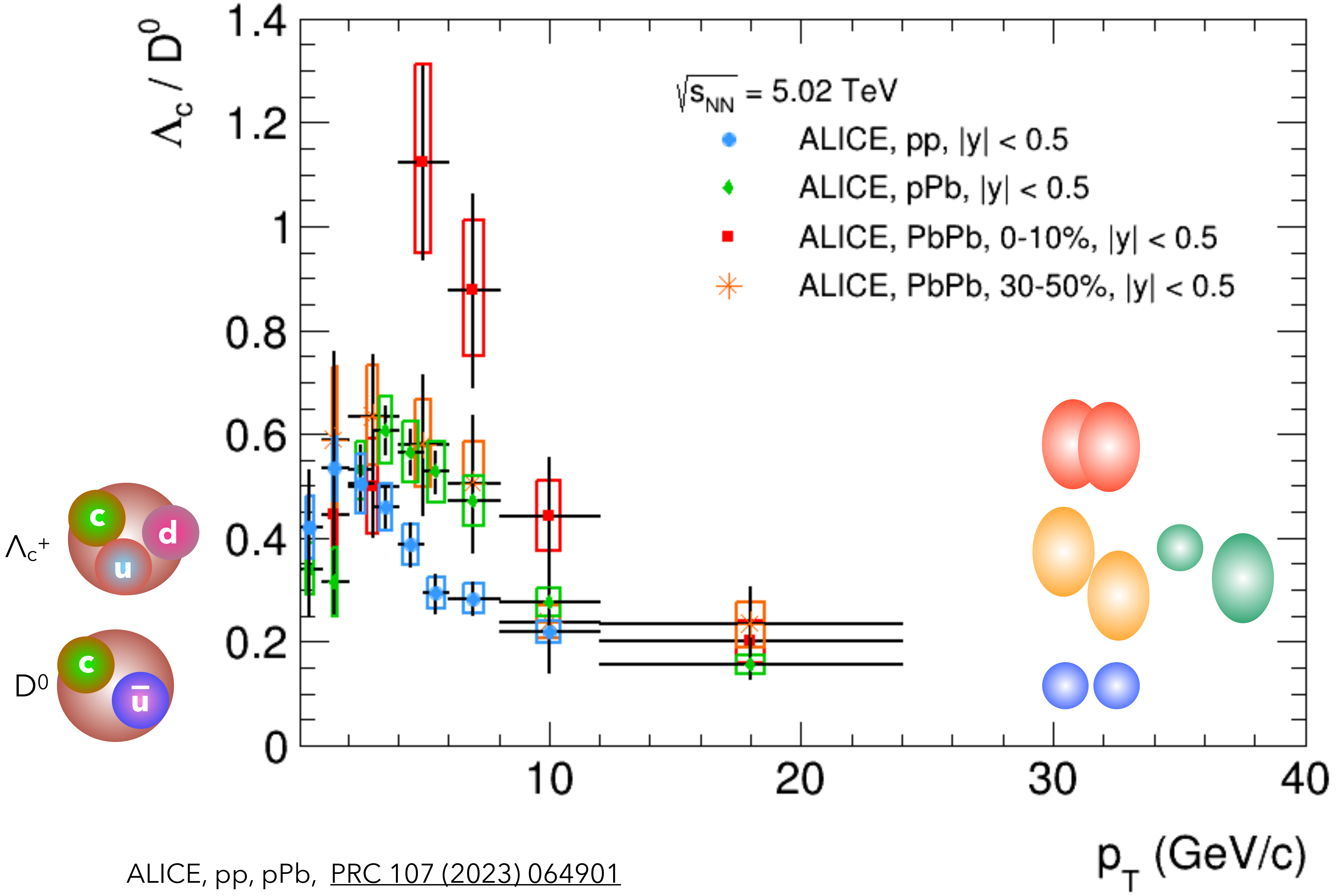


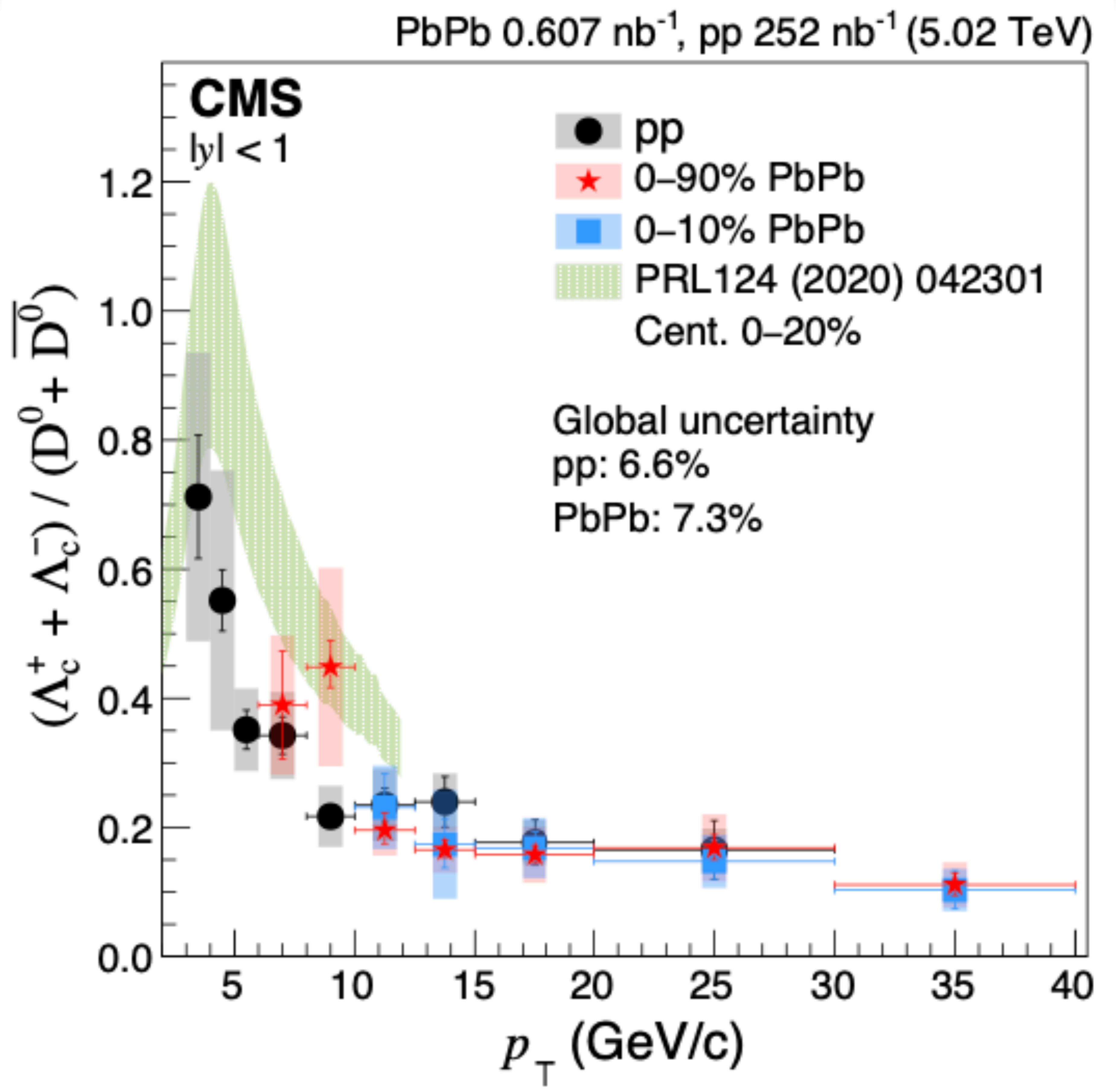
SHMc: Andronic et al. JHEP 07 (2021) 35
Catania: Scardina et al, PRC96 (2017) 044905
TAMU: He et al, PRL 124 (2020) 042301
Monash; P. Skands, et al, Eur.Phys.J.C74 n.8 (2014) 3024
CR-BLC; JR Christiansen, et al, JHEP 08 (2015) 003

CMS, pPb, CMS-PAS-HIN-21-016 (2023)
ALICE, pp, PLB 829 (2022) 137065
STAR, AuAu, PRL 124 (2020) 172301
ALICE pp pPb 5 TeV, PRC 104 (2021) 054905
ALICE, PbPb, PLB 839 (2023) 137796

- Observed **evolution of the p_T distribution** with charged-particle multiplicity
- **No significant effect for the p_T-integrated ratio** vs. charged-particle multiplicity
- **Likely due to a redistribution of momentum**, rather than to an overall enhancement of baryon yield.

Baryons vs. mesons: charm hadron results (PbPb)?



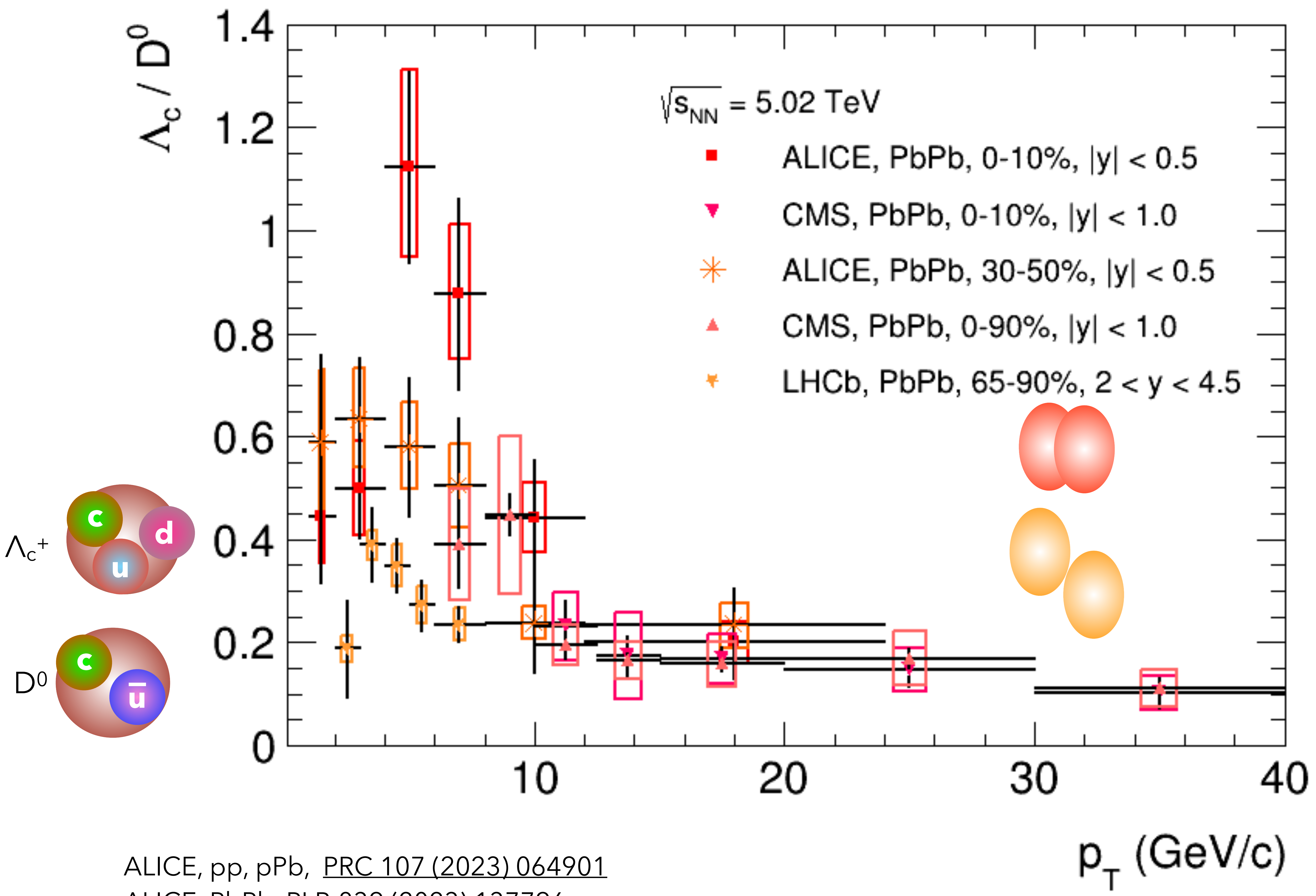


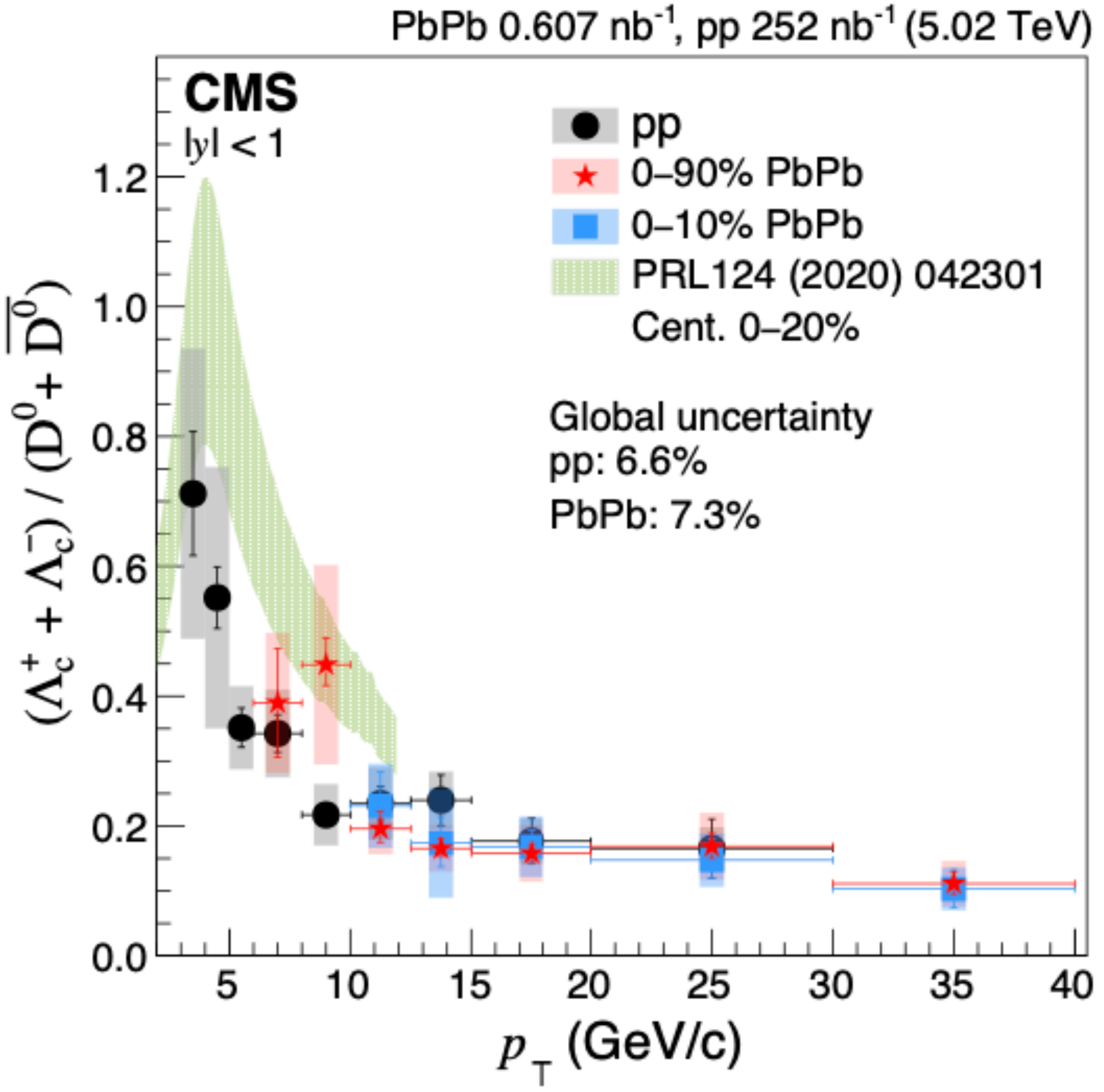
ALICE, pp, pPb, PRC 107 (2023) 064901
ALICE, PbPb, PLB 839 (2023) 137796
CMS, pp, PbPb, JHEP 01 (2024) 128
LHCb, pPb, JHEP 02 (2019) 102
LHCb, PbPb, JHEP06 (2023) 132

TAMU: He et al, PRL 124 (2020) 042301

- **Larger modification** of the p_T distribution for the **most central** collisions
- Qualitative agreement with model calculation

Baryons vs. mesons: charm hadron results (PbPb)?





ALICE, pp, pPb, PRC 107 (2023) 064901
ALICE, PbPb, PLB 839 (2023) 137796
CMS, pp, PbPb, JHEP 01 (2024) 128
LHCb, pPb, JHEP 02 (2019) 102
LHCb, PbPb, JHEP06 (2023) 132

TAMU: He et al, PRL 124 (2020) 042301

- **Larger modification** of the p_T distribution for the **most central** collisions
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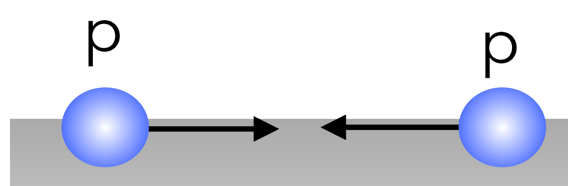
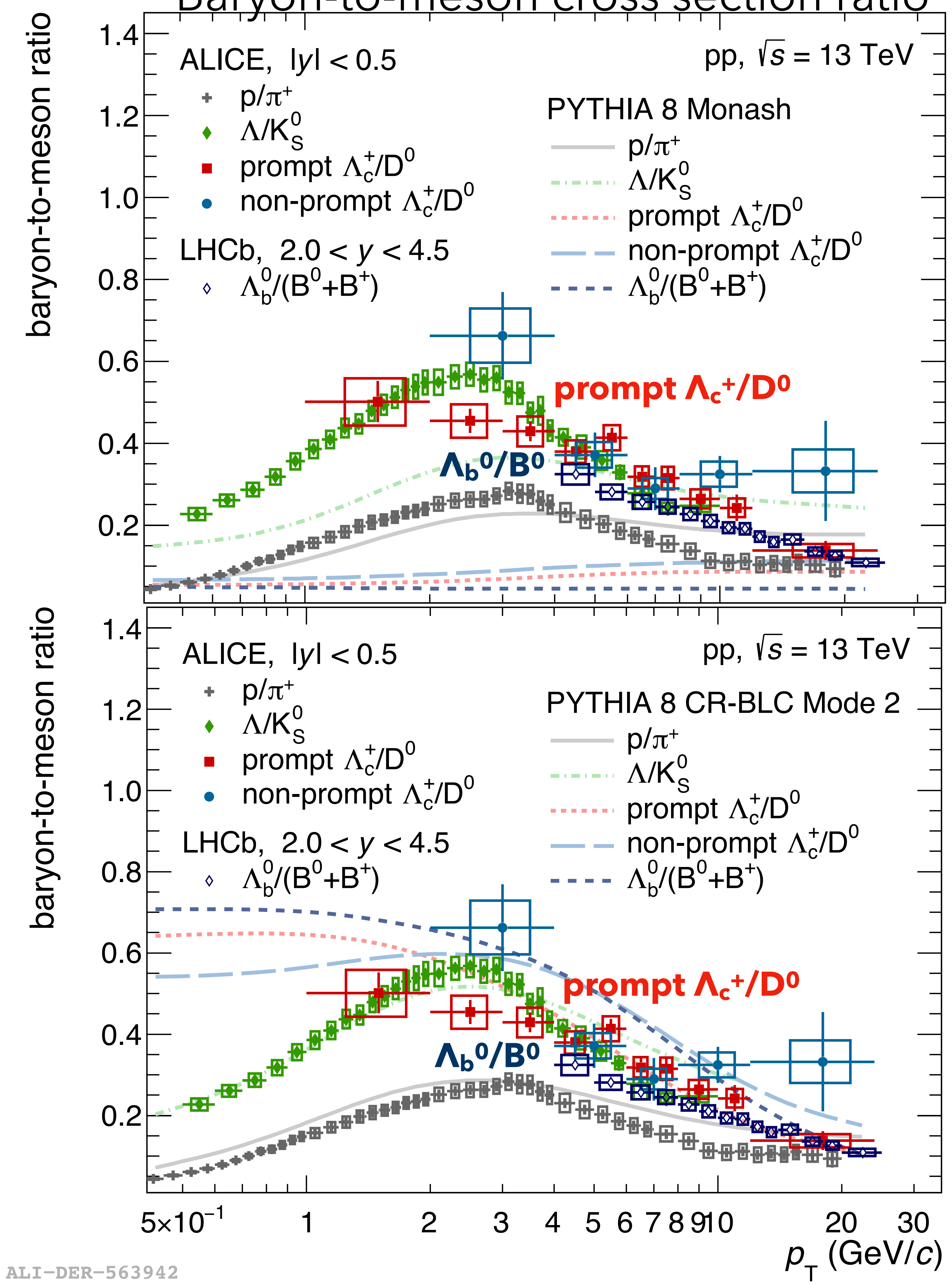
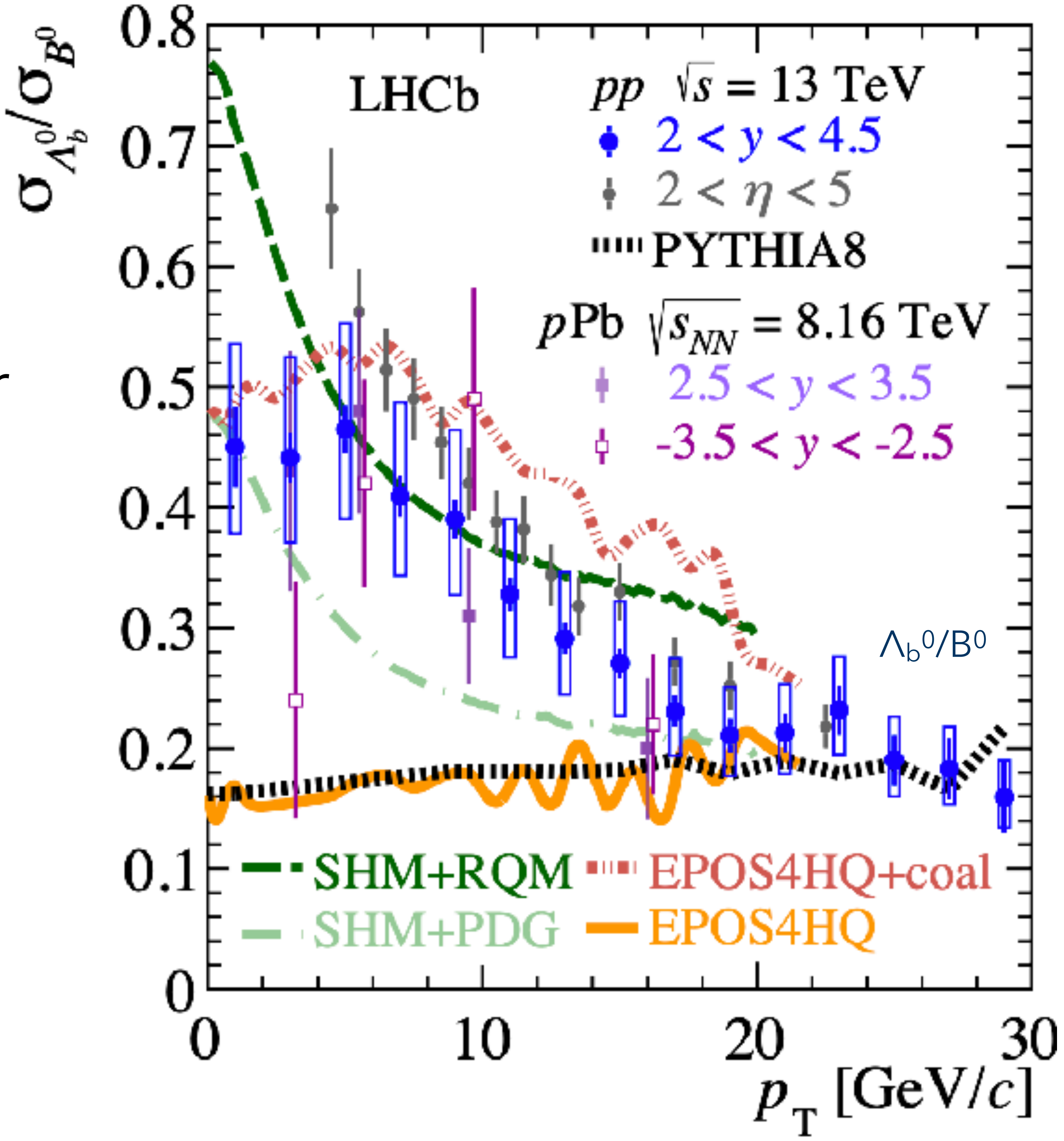


Baryons vs. mesons in the beauty sector (pp)

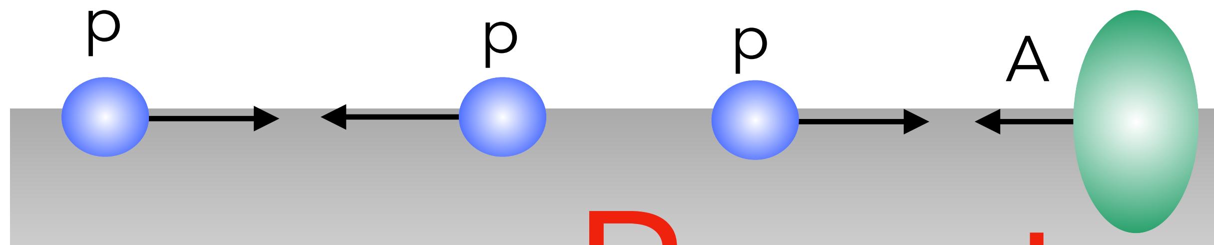
Baryon-to-meson cross section ratio



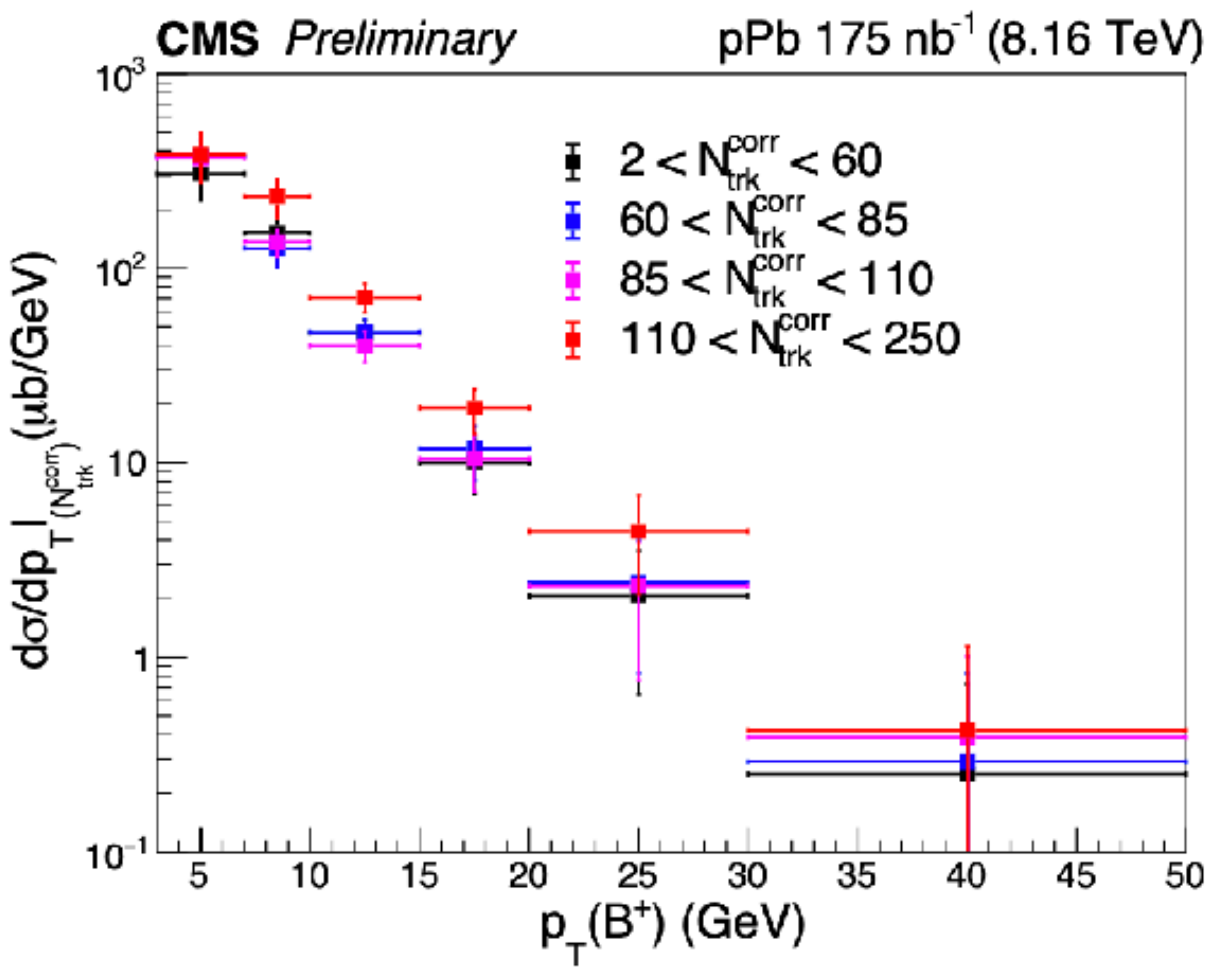
- **Similar findings observed in the beauty sector** (Λ_b^0/B^0 and non-prompt Λ_c^0/D^0)
- Strong p_T dependence of the beauty baryon-to-meson ratios
- Results described by models considering additional effects to the independent fragmentation picture, e.g. **coalescence** or **colour-reconnection** mechanisms



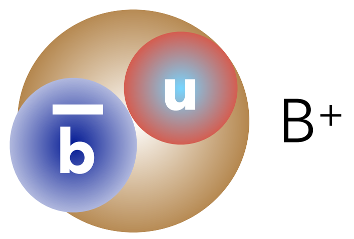
ALICE, PRD 108 (2023) 112003
LHCb, PRD 100 (2019) 031102
ALICE, PRL 128 (2022) 012001
ALICE, EPJC 81 (2021) 256
CDF, Phys.Rev.D77:072003,2008

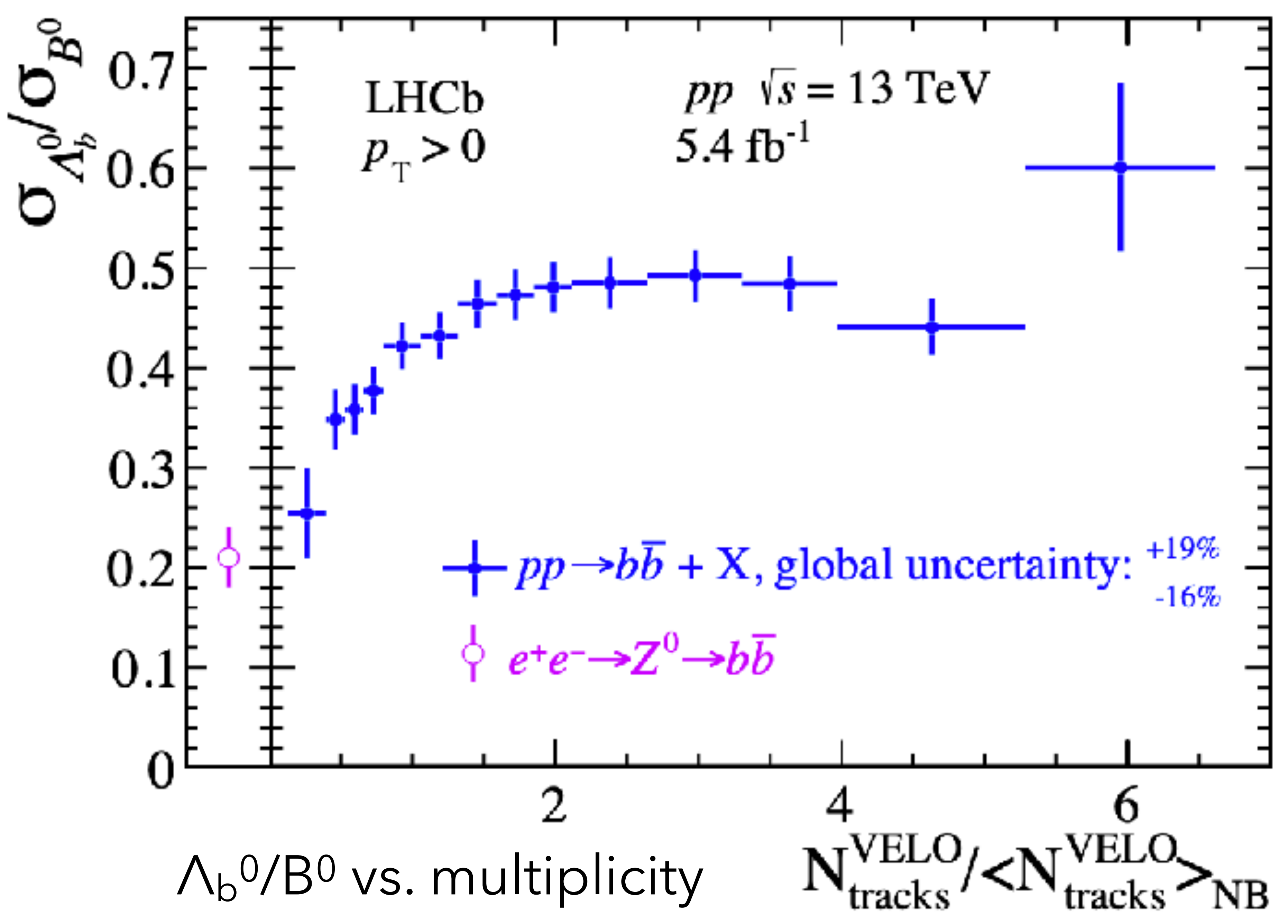


Beauty hadrons multiplicity dependence

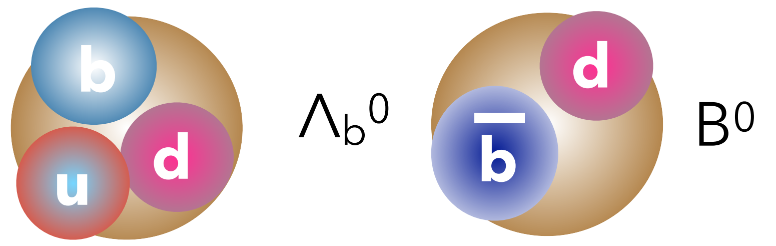


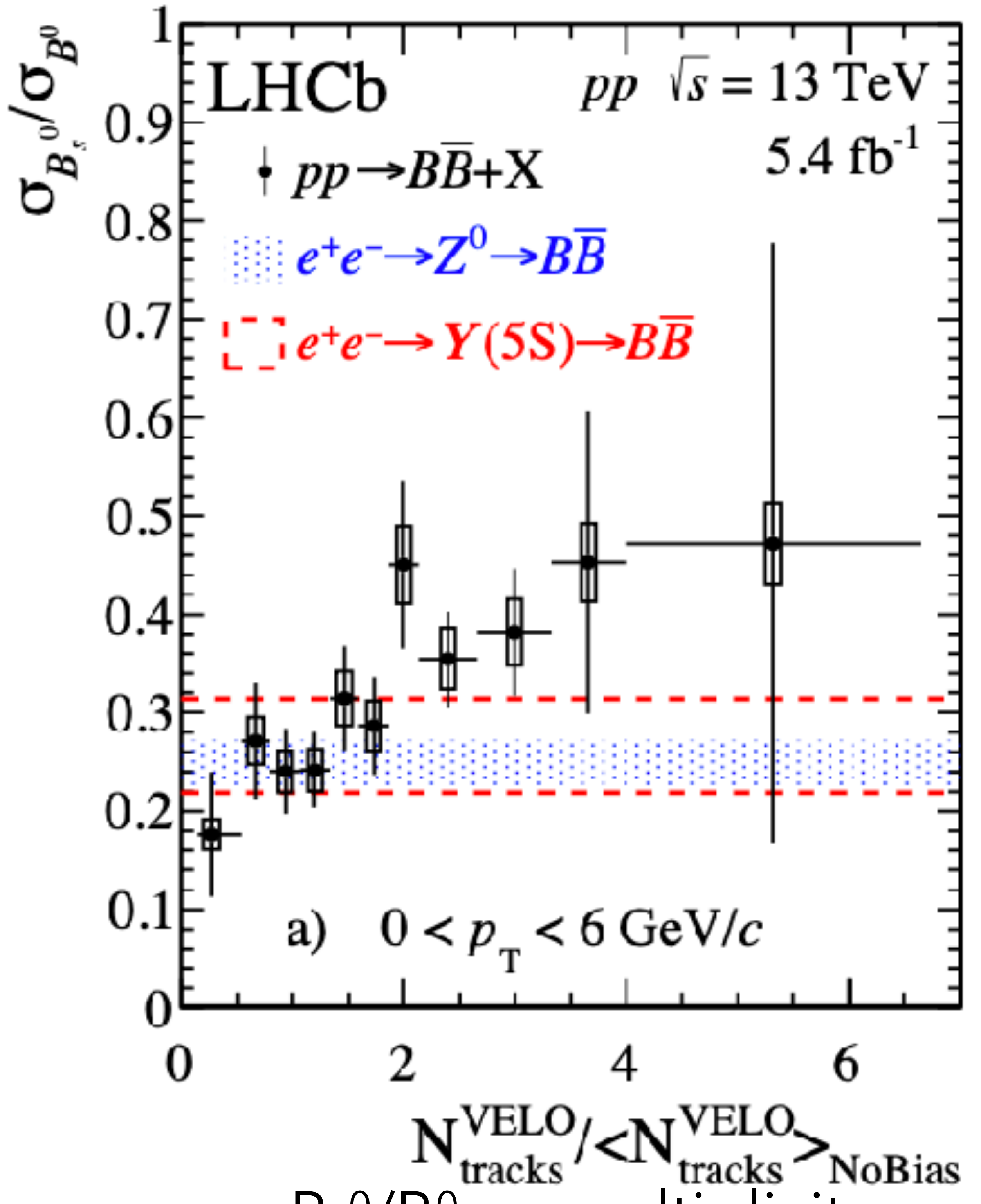
B^+ cross section (pp)



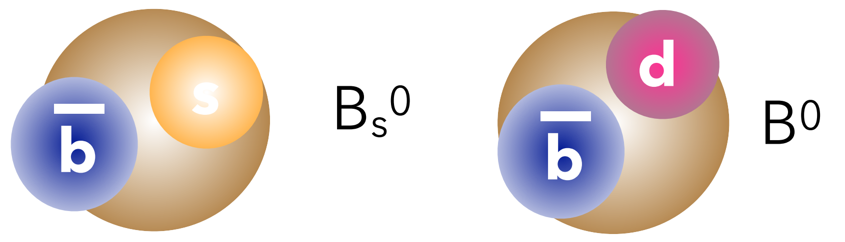


Λ_b^0/B^0 vs. multiplicity





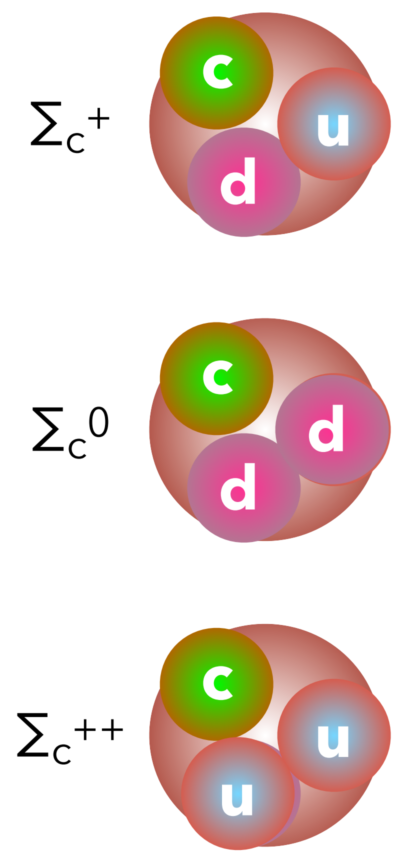
B_s^0/B^0 vs. multiplicity



LHCb, arXiv:2310.12278
LHCB-PAPER-2022-001, arXiv: 2204.13042
CMS, CMS-PAS-HIN-22-001

- **Evolution of the ratios with charged-particle multiplicity**
- Interplay of **coalescence** (dominant at low p_T) and vacuum **fragmentation** (dominant at high p_T)?
- Complementary studies introducing a y-gap between the observable and the multiplicity?

Excited states: charm baryons from pp √s =13.6 TeV data

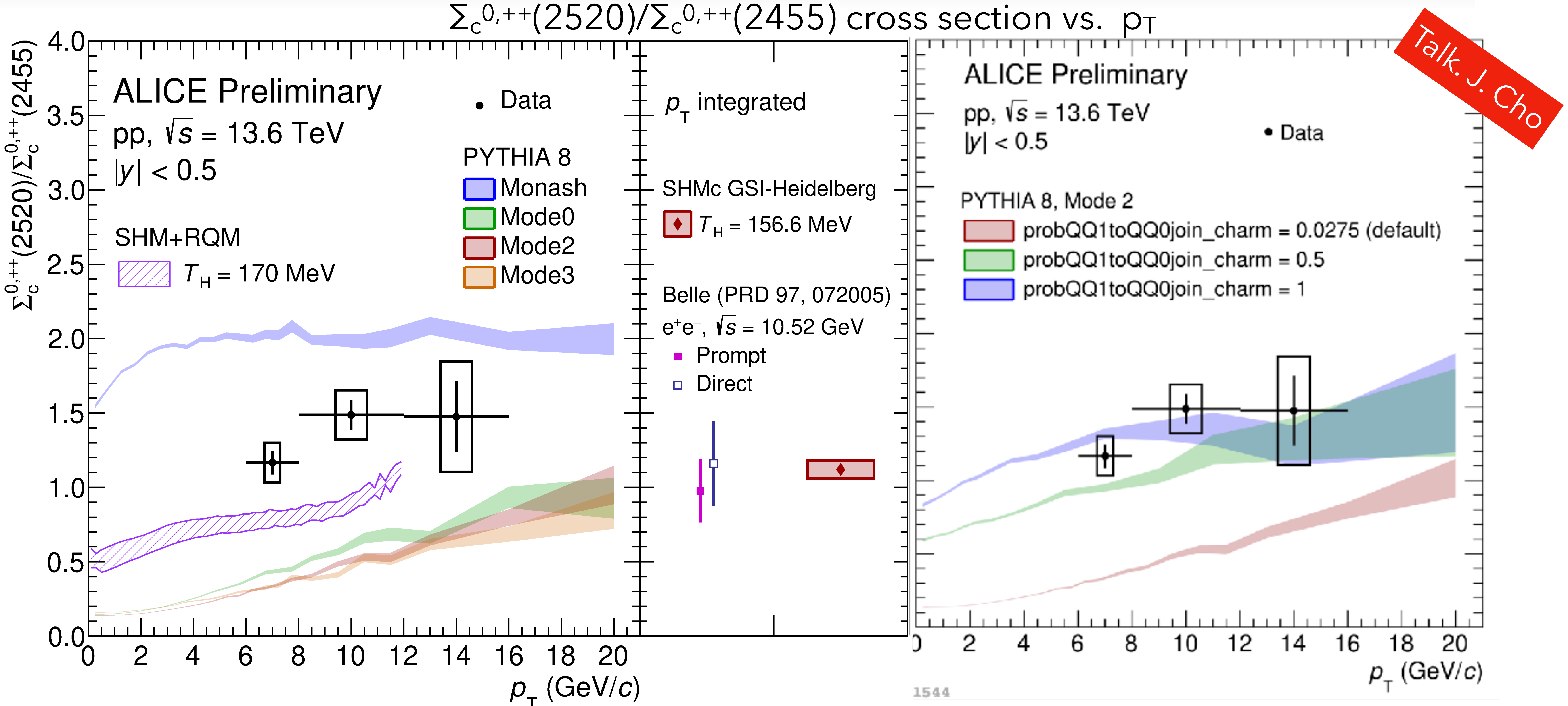


Belle, PRD 97, 072005 (2018)
ALICE Preliminary

$\Sigma_c^{0,++} \rightarrow \Lambda_c^+ \pi^{-,+}$

State	J^P
$\Sigma_c^+(2520)$	$3/2^+$
$\Sigma_c^+(2455)$	$1/2^+$

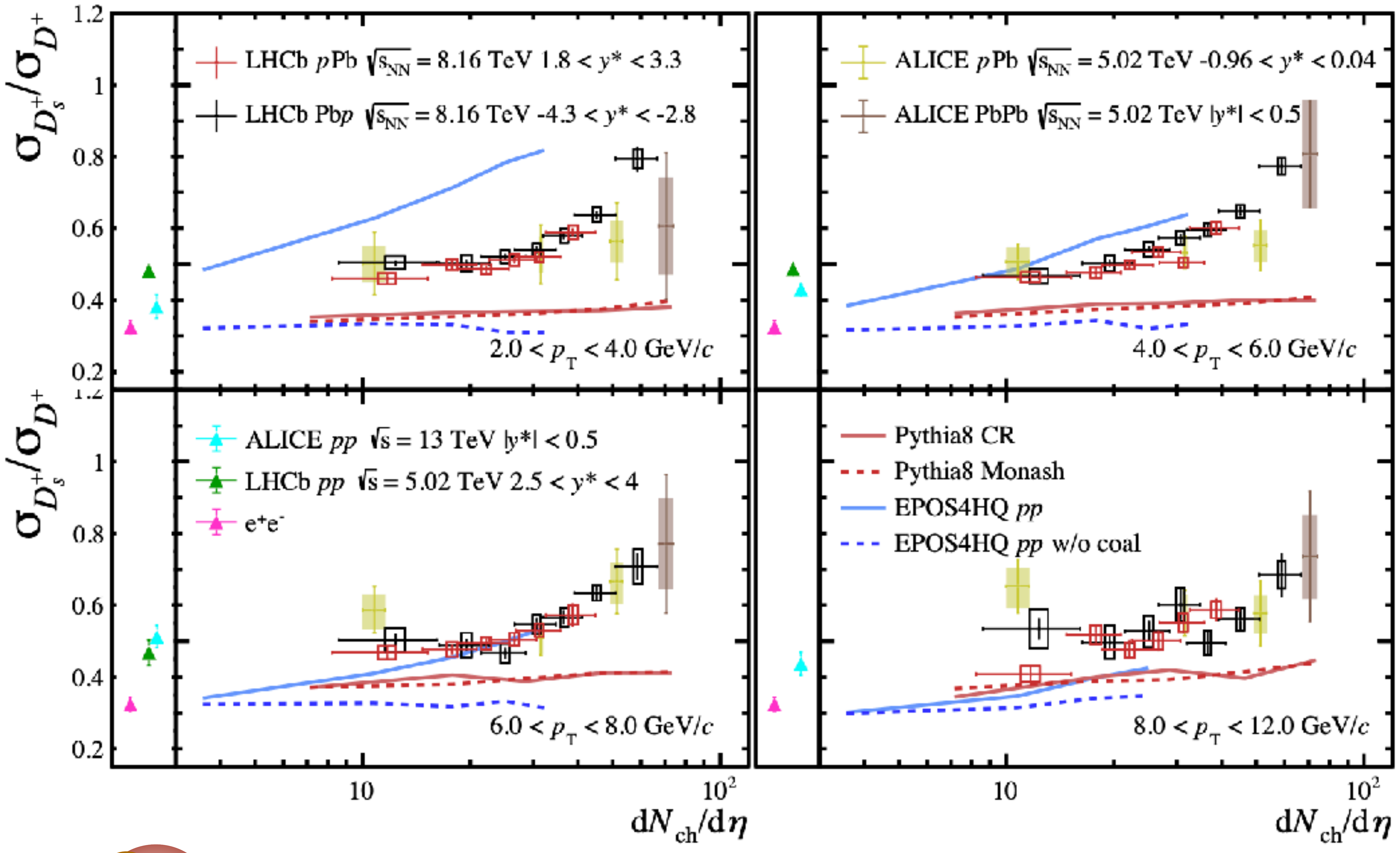
PYTHIA 8: JHEP 08 (2015) 003
SHMc: JHEP 07 (2021) 035
Altman et al: arXiv: 2405.19137



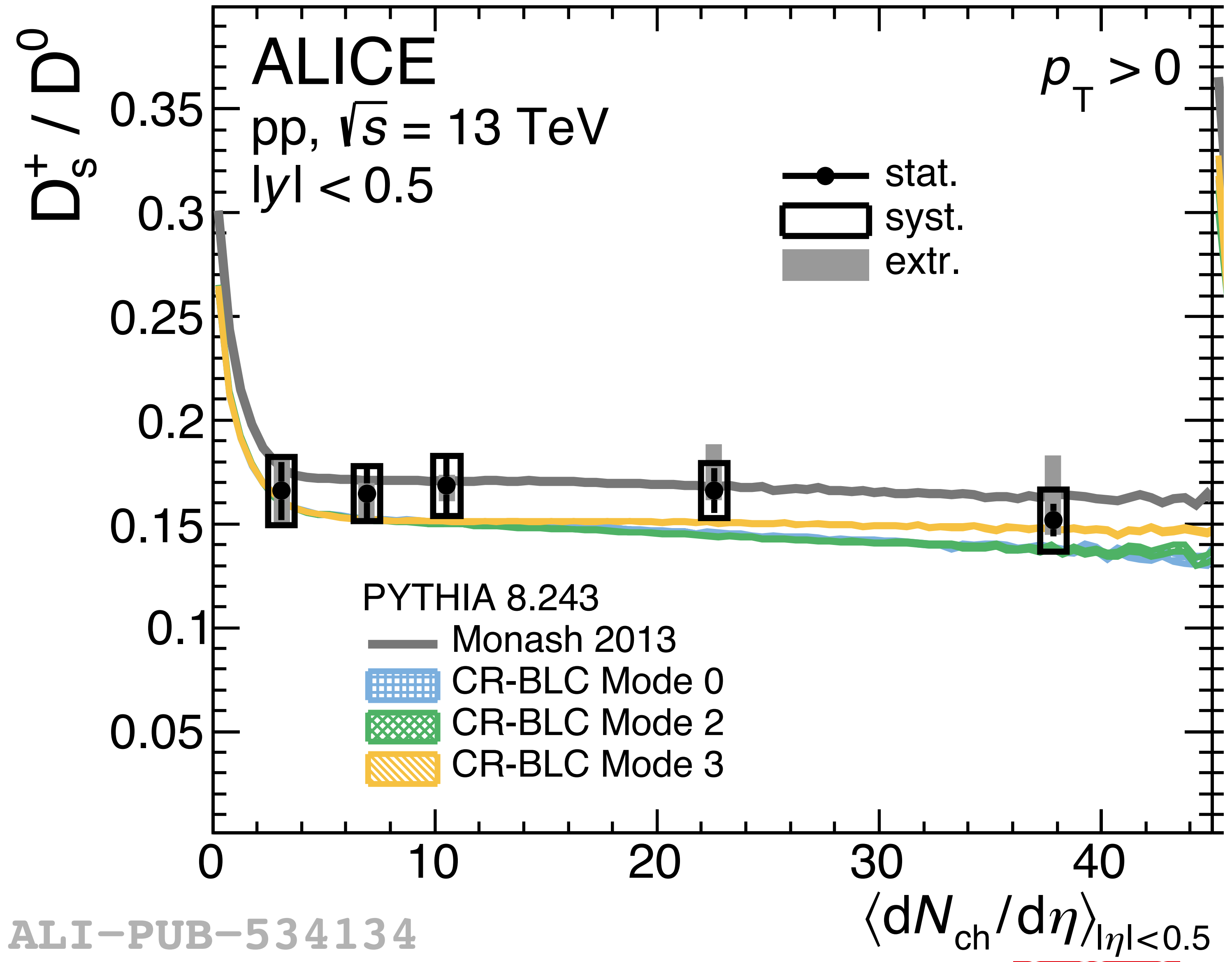
probQQ1toQQ0join regulates the probability that junction diquarks containing charm have spin=1 or spin=0

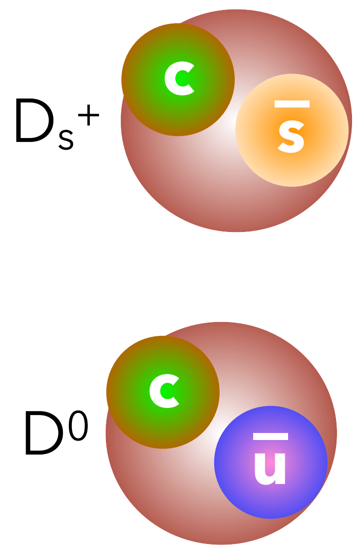
- Ratio (pp) larger than unity and of similar magnitude than Belle's (e^+e^-) results
- Comparison to models:
  - PYTHIA 8 CR (Monash) tunes under-(over-)estimate data, CR-BLC tune (on $\Lambda_{c\leftarrow}\Sigma_c/\Lambda_c$ data) performs better
  - SHM (T_H=156.6 MeV) reproduces data
- Role of diquarks in hadronisation modelling. **Data constrains hadronisation models!**

Strangeness: What about mesons with s-quark content?



- Observation of an **increase of the D_s^+/D^+ ratio as a function of charged-particle multiplicity in pPb** collisions at large rapidity.
- Qualitatively consistent with the quark coalescence picture?



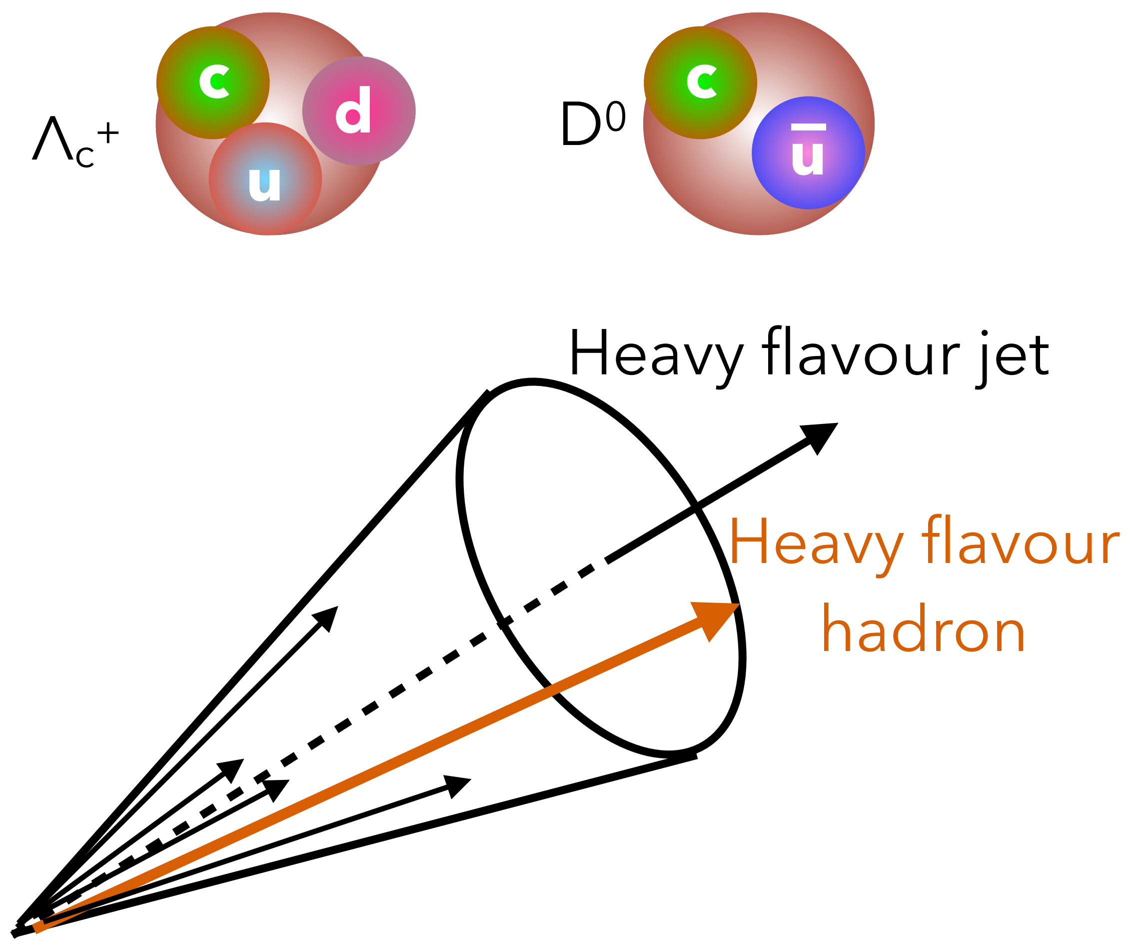


LHCb, arXiv:2311.08490
ALICE, JHEP 12 (2019) 092
ALICE, PLB 829 (2022) 137065
STAR, PRL 127 (2021) 092301

Talk. C. Landesa

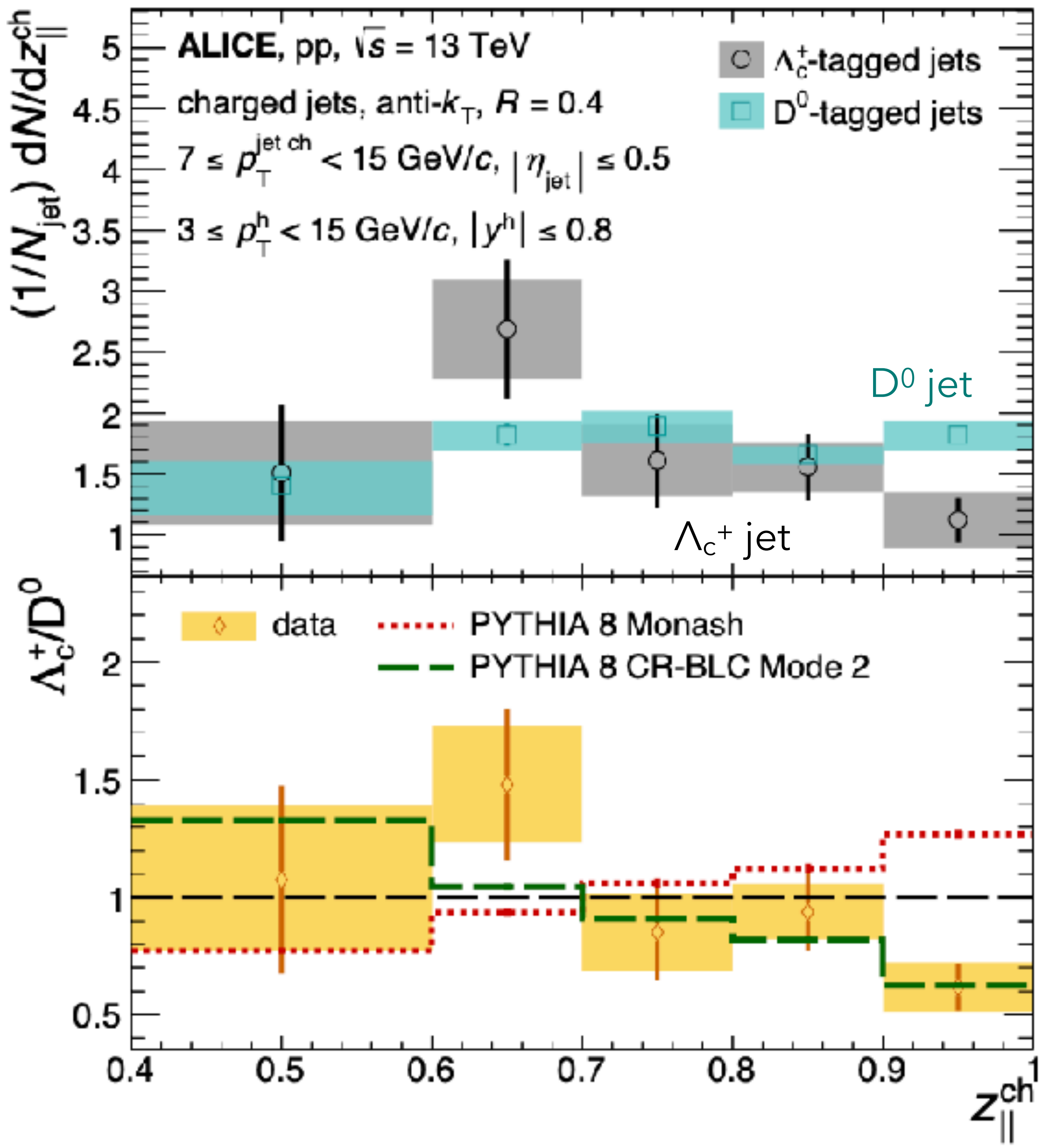
Talk. M. Faggin

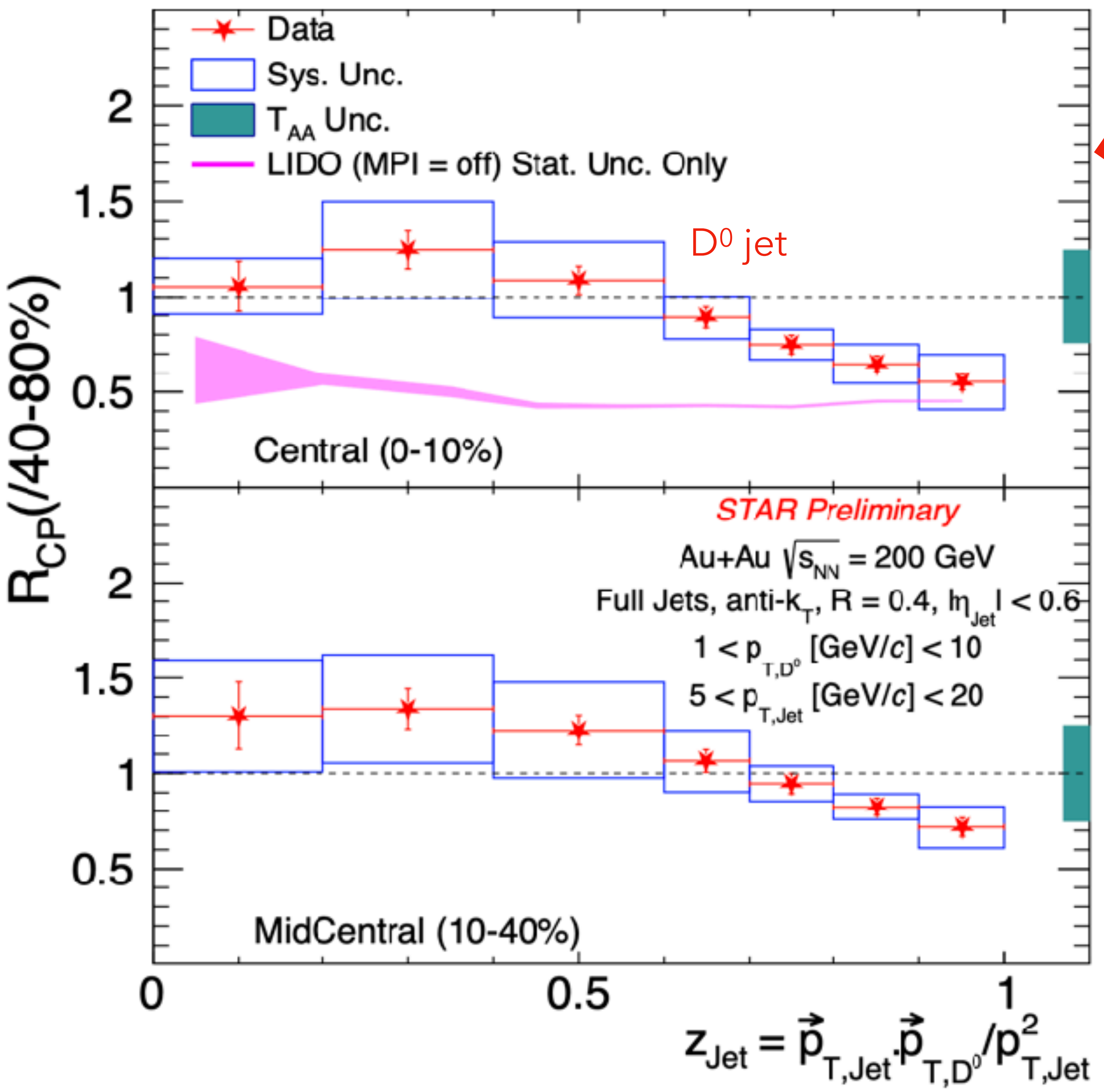
Jets: Charm-jet studies to constrain hadronisation?



$$z_{||}^{ch} = \frac{\mathbf{p}_{jet} \cdot \mathbf{p}_{HF}}{\mathbf{p}_{jet} \cdot \mathbf{p}_{jet}}$$

ALICE, arXiv: 2301.13798
ALICE, arXiv: 2204.10167
STAR Preliminary





Talk. A. Palasciano
Talk. O. Lomicky

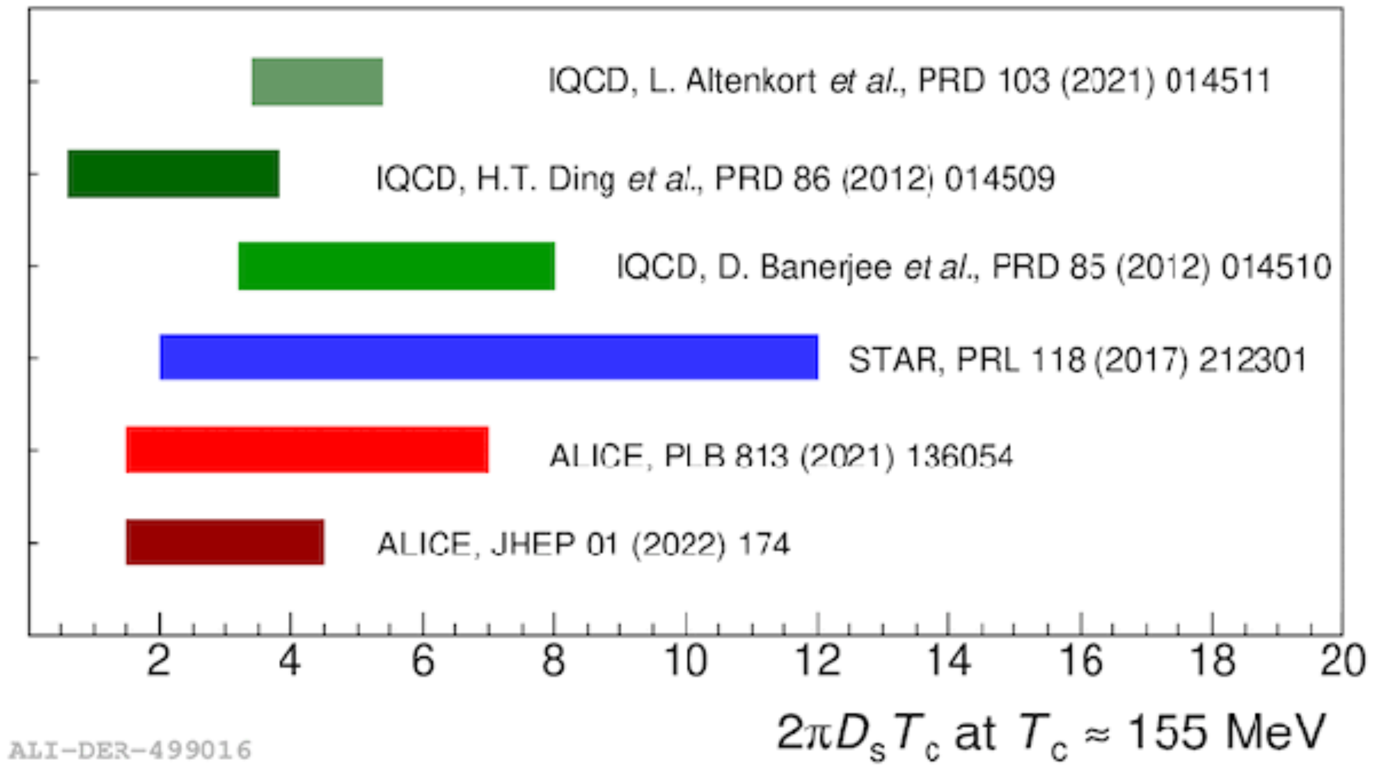
Fraction of the jet momentum carried by the particle along the direction of the jet axis

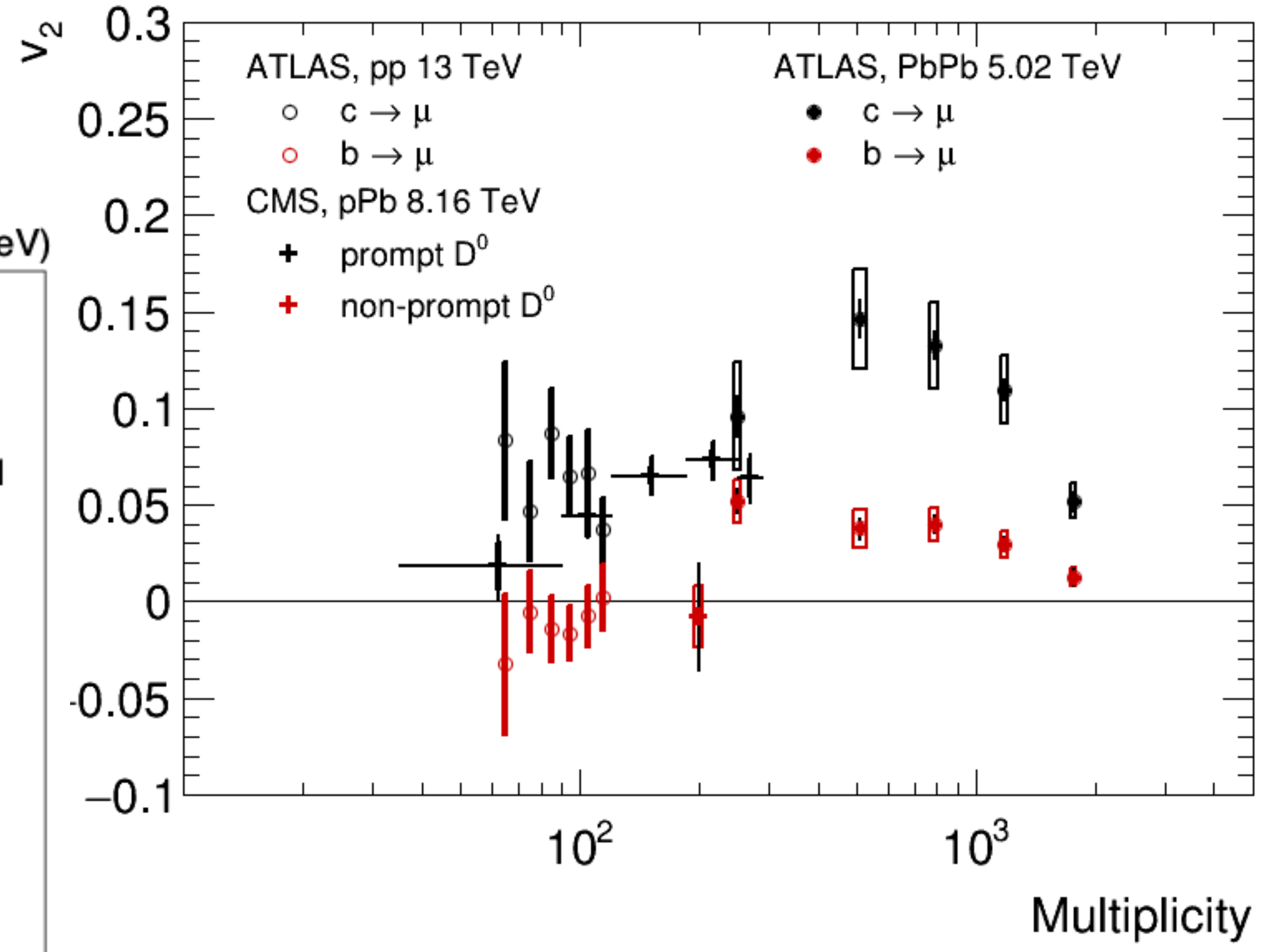
- Hint of different (softer) fragmentation for Λ_c than D^0 in pp.
  PYTHIA 8 calculation with colour-reconnection seems to describe the trend.
- Hint of larger suppression for D^0-jets carrying a larger jet momentum fraction in AuAu

Monash; P. Skands, et al, Eur.Phys.J.C74 n.8 (2014) 3024
CR-BLC; JR Christiansen, et al, JHEP 08 (2015) 003
LIDO, PRC 98 (2018) 064901

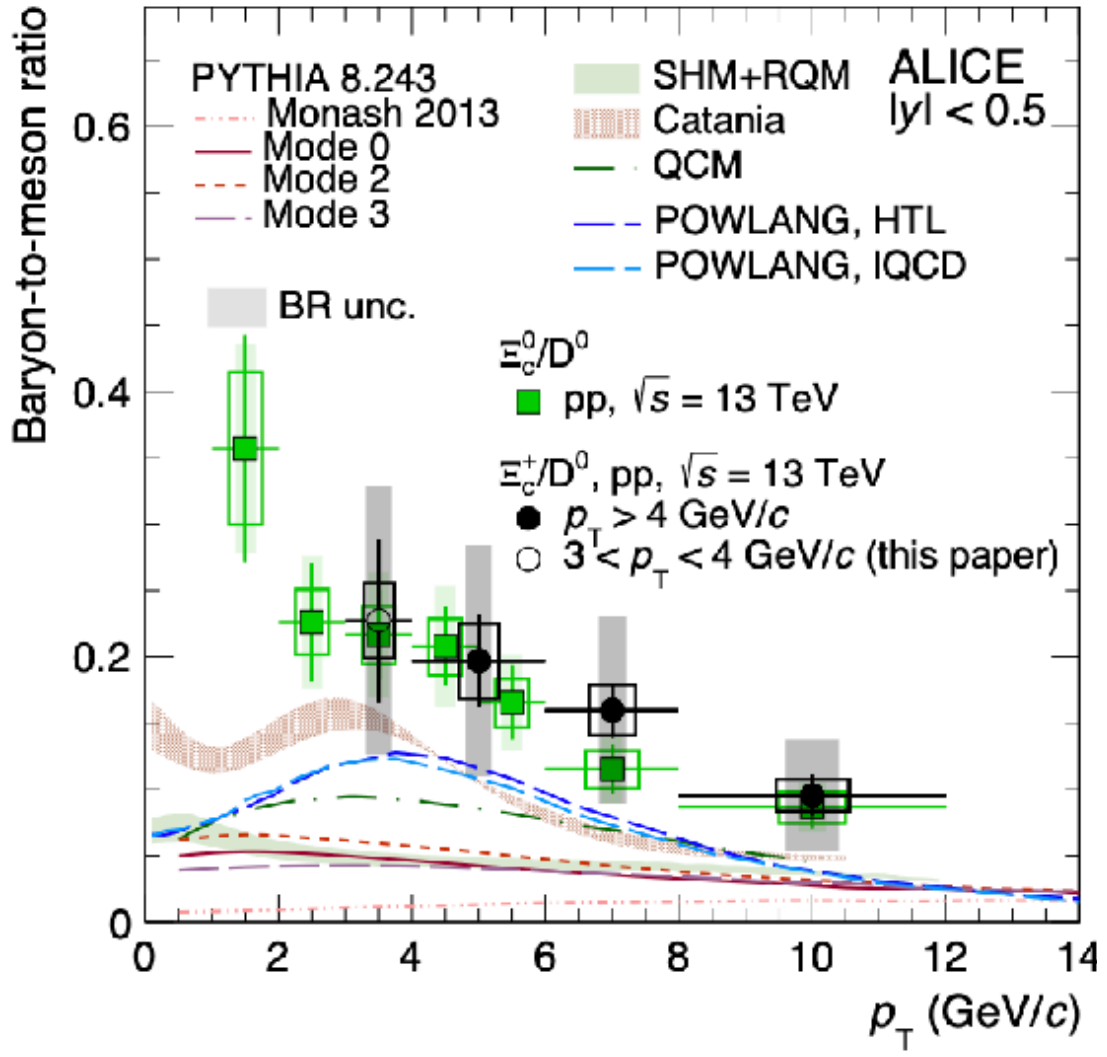
Executive summary

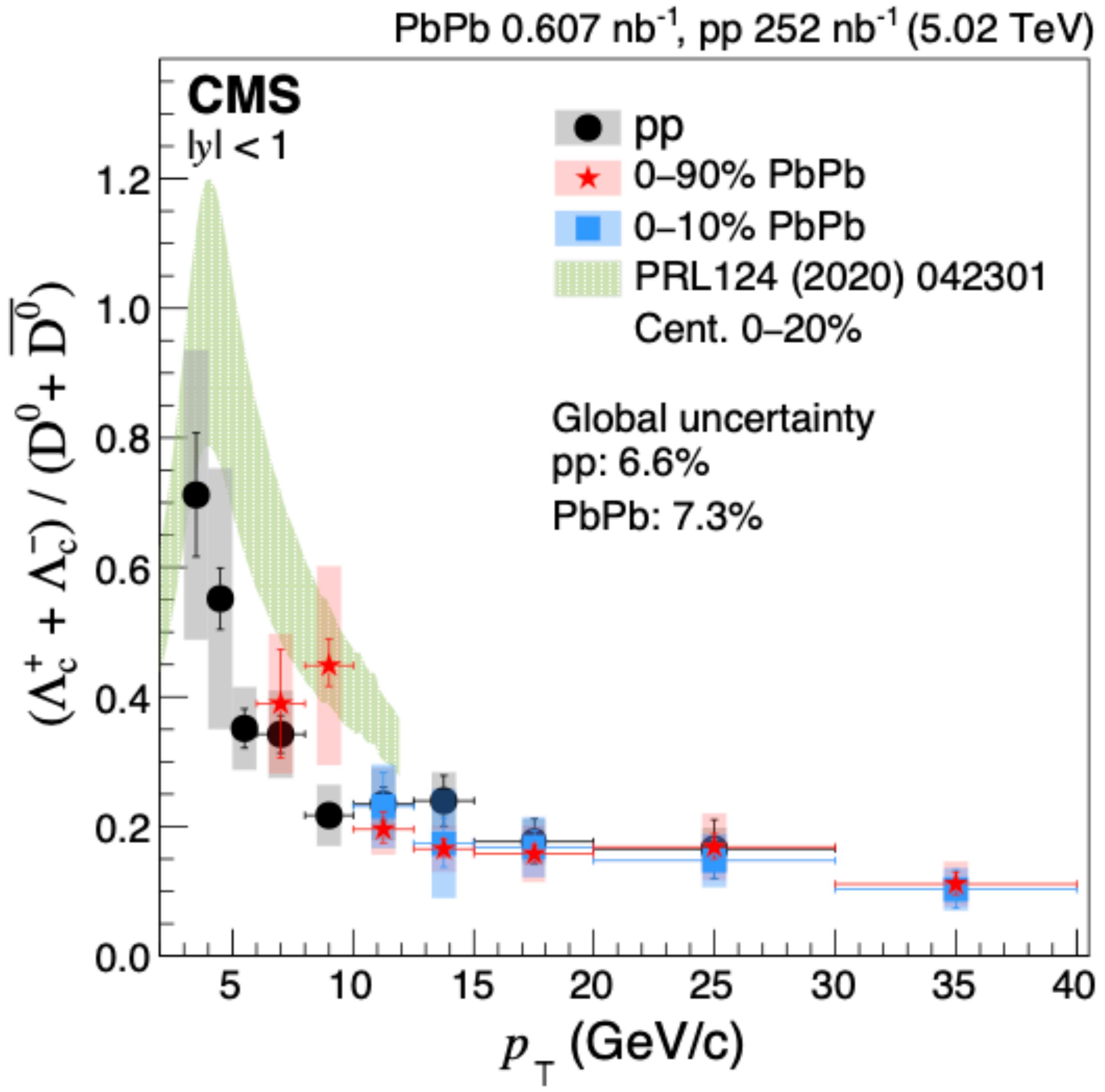
- Entering the heavy flavour precision era
  - Simultaneous comparison of (R_{AA}, v_n, jet shapes…) measurements with model calculations improves our understanding of heavy quark interaction with the medium.
  - The origin of the collective motion in small systems is still under debate. Important role of initial state effects and/or influence of final state effects ?
  - Role of fragmentation and hadronisation is under scrutiny, both in medium and in vacuum.
  - Data provides constraints to model calculations.





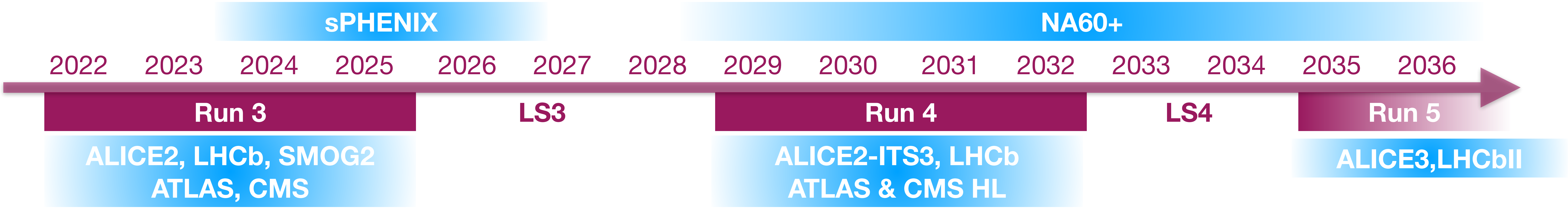
Apologies for all those results
I could not present, e.g. spin alignment, non-prompt/prompt D^0 vs mult, correlations, femtoscopy,….





Executive summary: wish list

- Precise measurements in a wide p_T interval in all colliding systems (from pp to pA and AA):
  - charm and beauty hadron measurements down to p_T=0
  - heavy-flavour jet and angular correlations differential measurements in a wide p_T interval
- Coming soon or just appearing!
  - D+D, B+B or D(B)+J/ψ(ϒ) correlations ➞ constrain the role of multiparton interactions
  - Excited states, e.g. D^{+}_{s1}, $\Sigma_c^{0,++}$… ➞ constrain feed-down to ground states
  - Λ_b, Ξ_b, Ω_b ➞ constrain beauty feed-down
  - …
- In the future also doubly or multiple heavy quark states to further test recombination/coalescence



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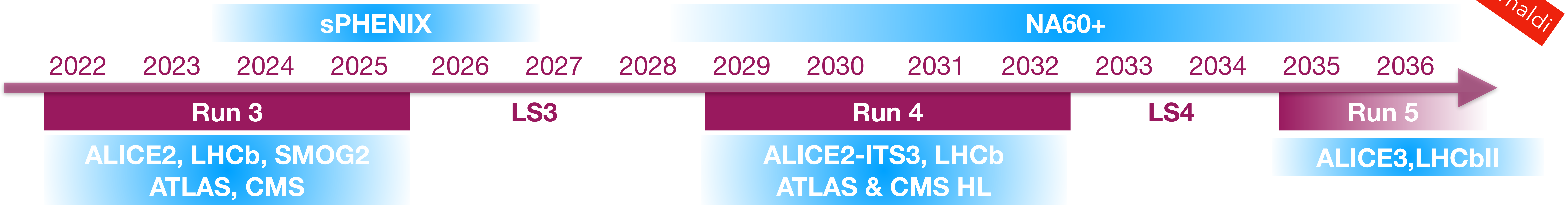
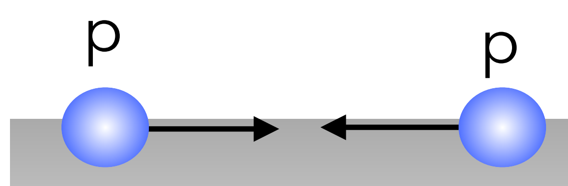
Talk Z. Chen
Talk J. Klein
Talk S. Siddhanta
Talk G. Volpe
Talk. H. Huang
Talk. R. Arnaldi



Big thank you to the organisers!

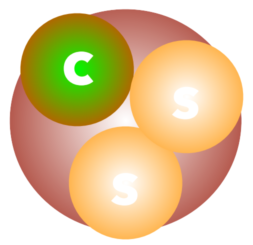
Special thanks to F. Colamaria, A. Dainese, F. Grosa,
F. Prino, A. Rossi for fruitful discussions and suggestions

Additional material



Constraining charm strange baryon measurements in pp

Talk. J. Cho

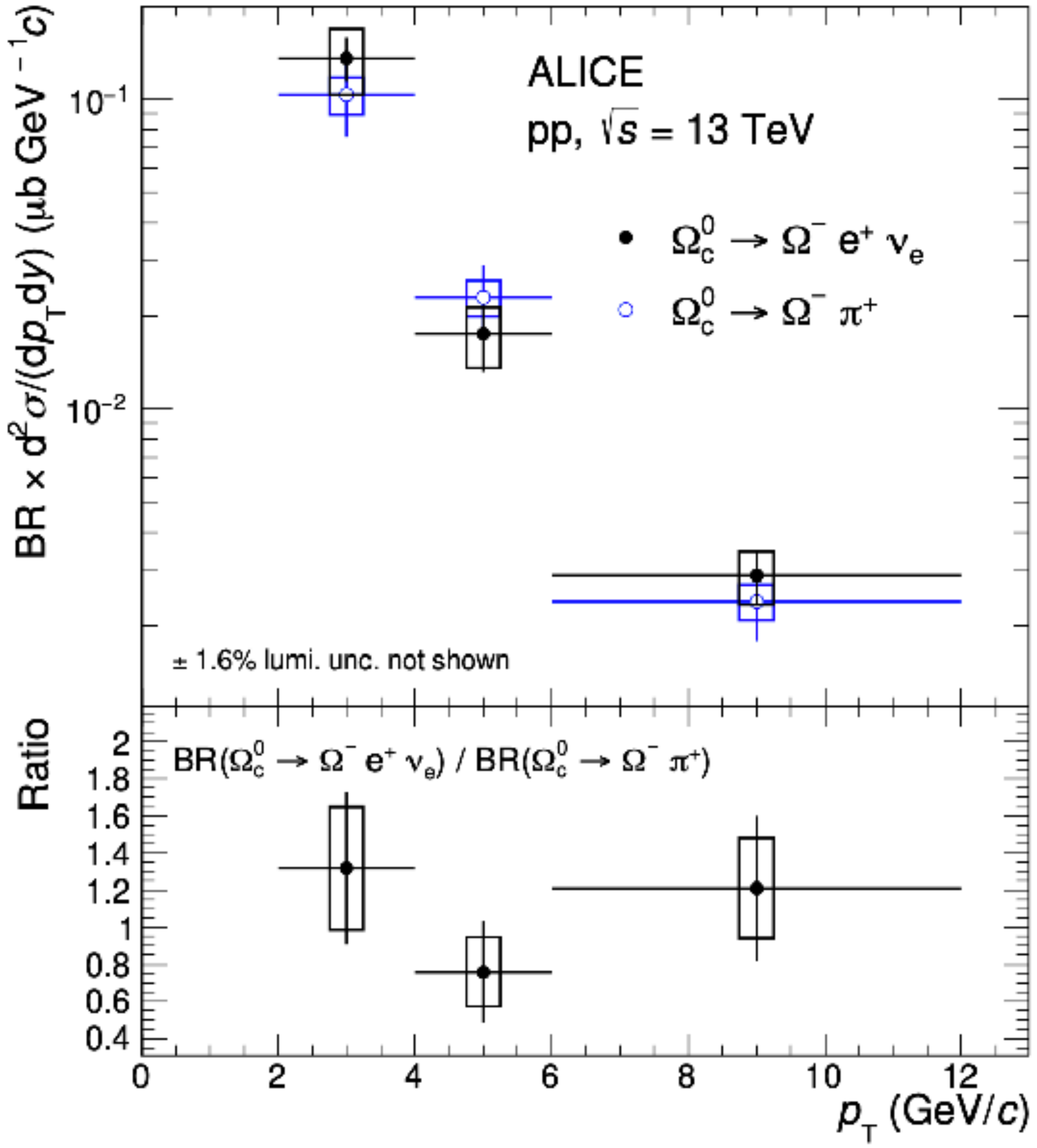


Ω_c^0

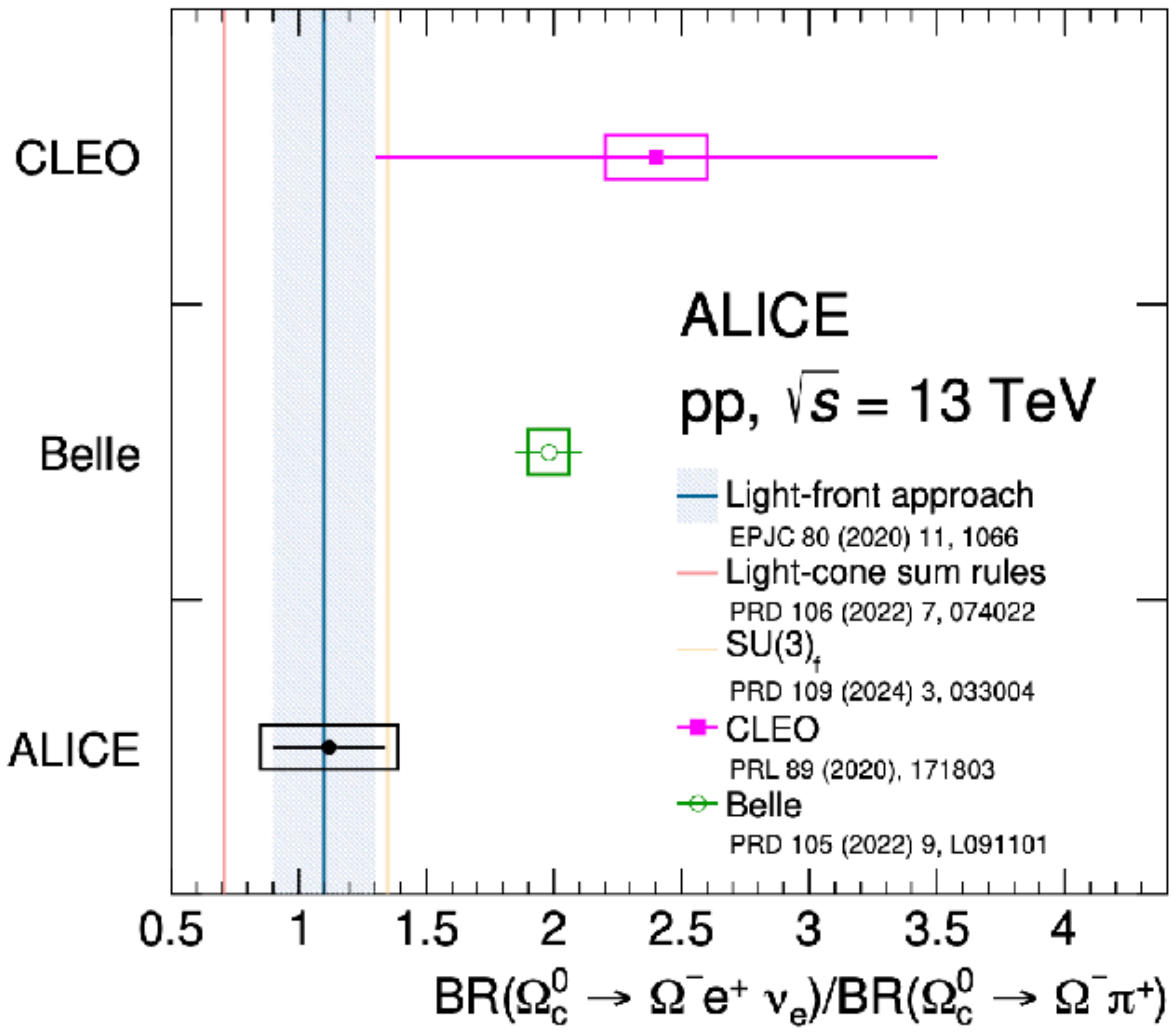
$\Omega_c^0 \rightarrow \Omega^- e^+ \nu_e$

$\Omega_c^0 \rightarrow \Omega^- \pi^+$

Ω_c^0 cross section vs. p_T



Ω_c^0 branching-fraction ratio

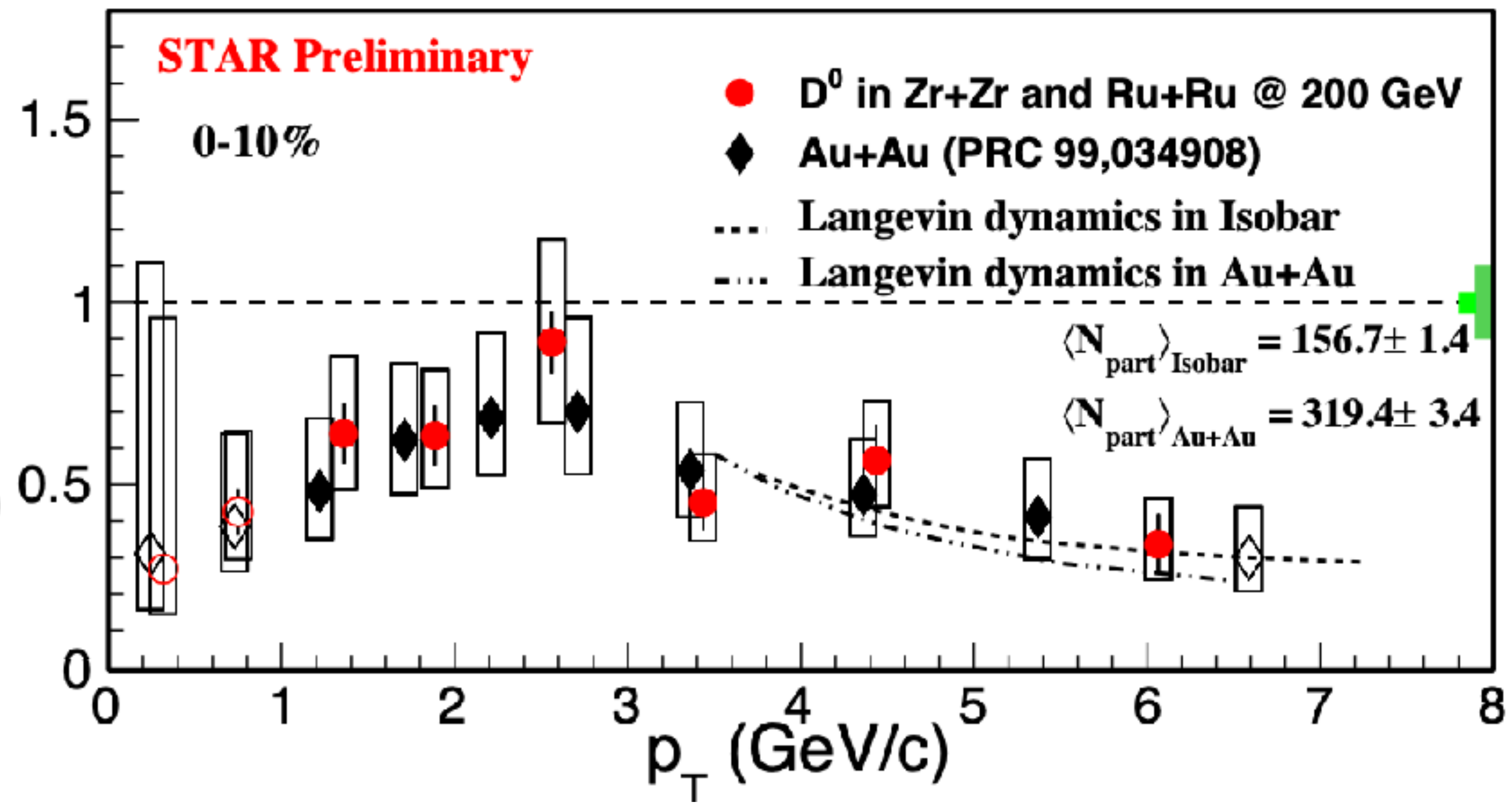


ALICE, arXiv:2404.17272
Belle, PRD 105 (2022) L091101
CLEO, PRL 89 (2020) 171803
LFA: EPJC 80 (2020) 11, 1066
LCS: PRD 106 (2022) 7, 074022
SU(3)f: PRD 109 (2024) 3, 033004

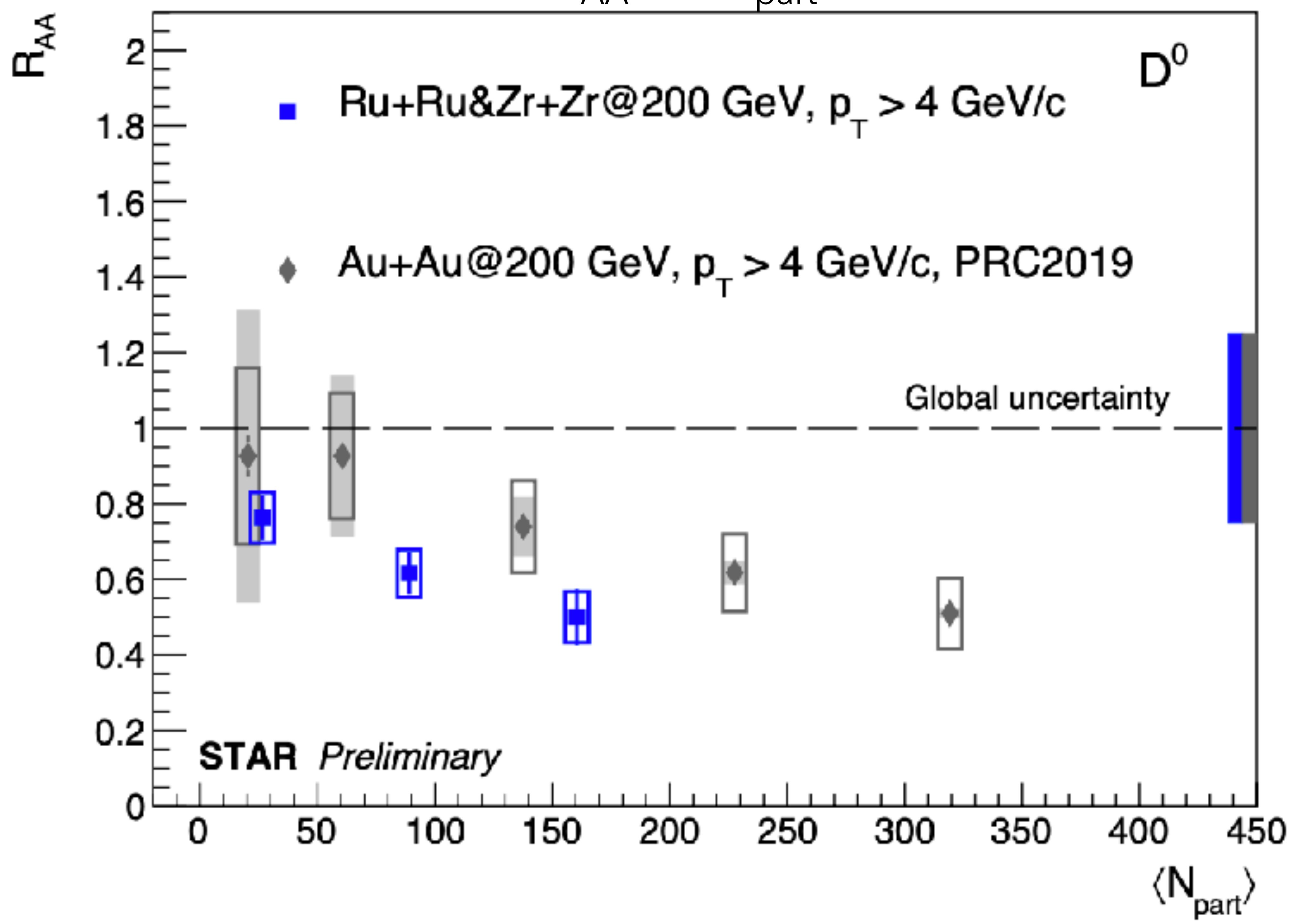
- Results interpretation limited by the **absence of precise branching ratio measurements**.
- ALICE branching-fraction ratio value consistent with model calculations and 2.3σ lower than Belle's
- More charm states are becoming accessible. Future studies of hadronisation in PbPb?

Recent studies of charm hadrons vs. system size

D^0 R_{AA} – central HIC – vs. p_T



D^0 R_{AA} vs. N_{part}

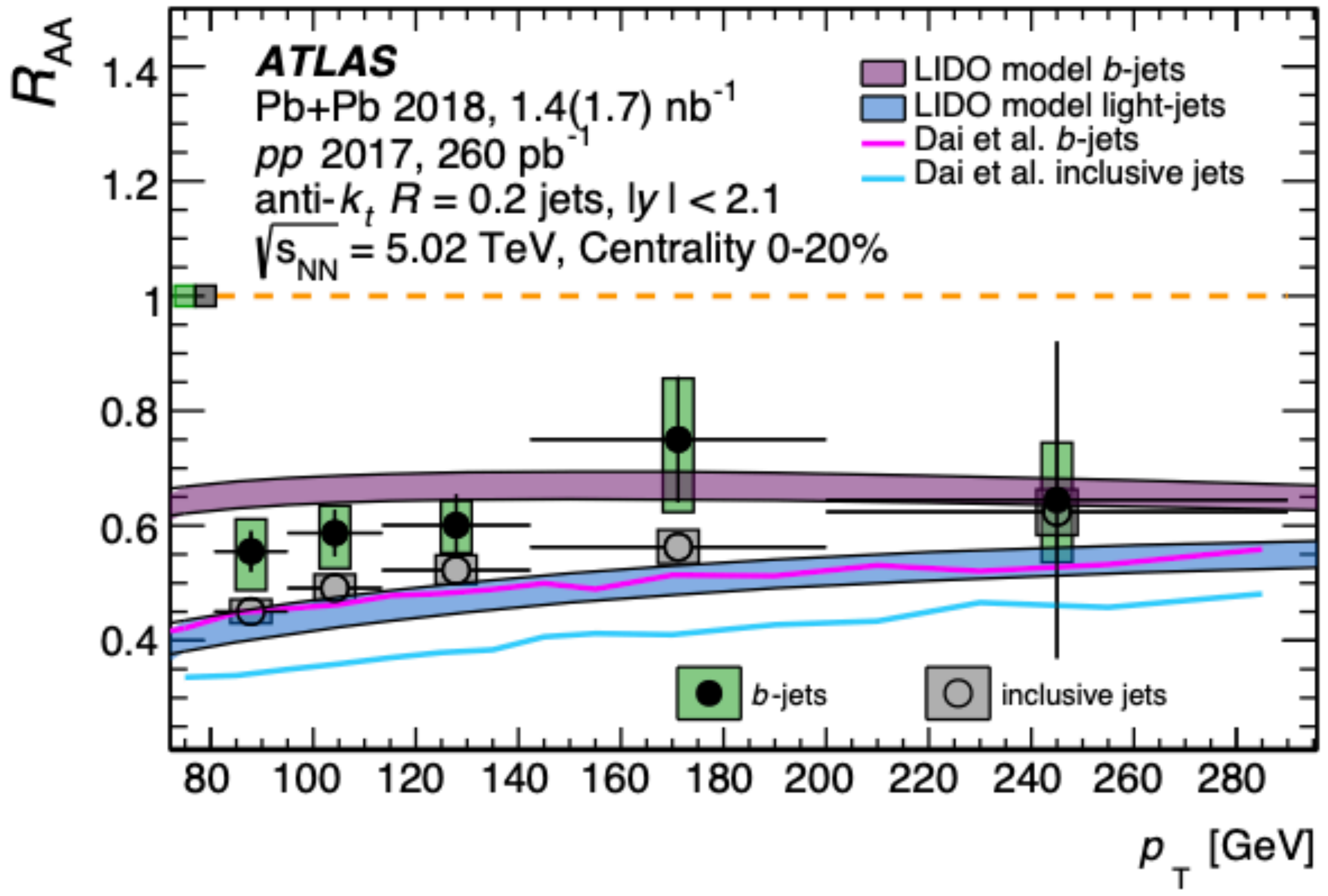


STAR Preliminary
STAR, PRC 99 034908

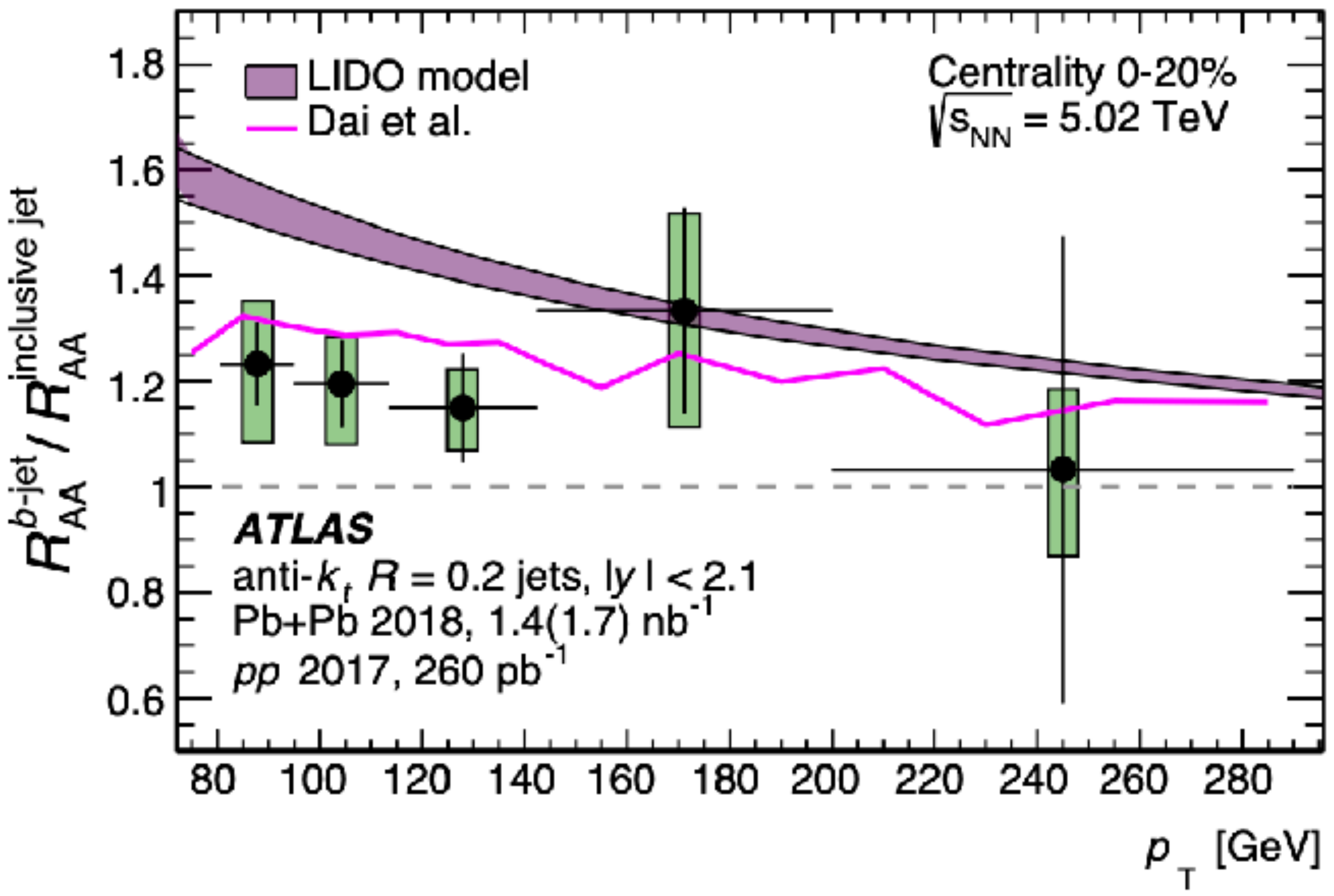
- Similar D^0 R_{AA} in isobar (moderate system size) collisions
- **Similar behaviour of charm in moderate collision's system size**

Poster V. Dmitrijevna

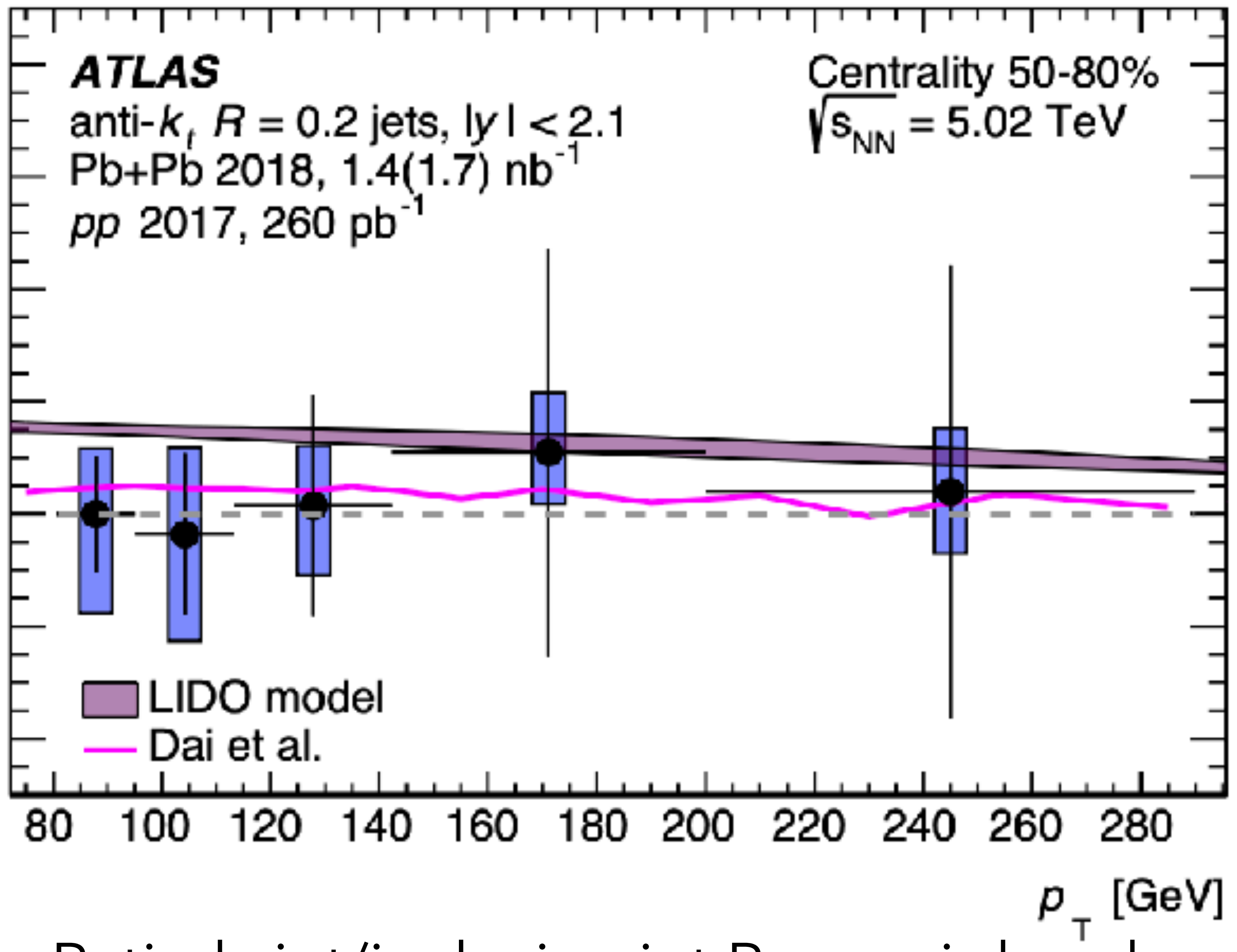
Moving to higher p_T? b-jets in medium



R_{AA} central collisions



Ratio b-jet/inclusive-jet R_{AA} central



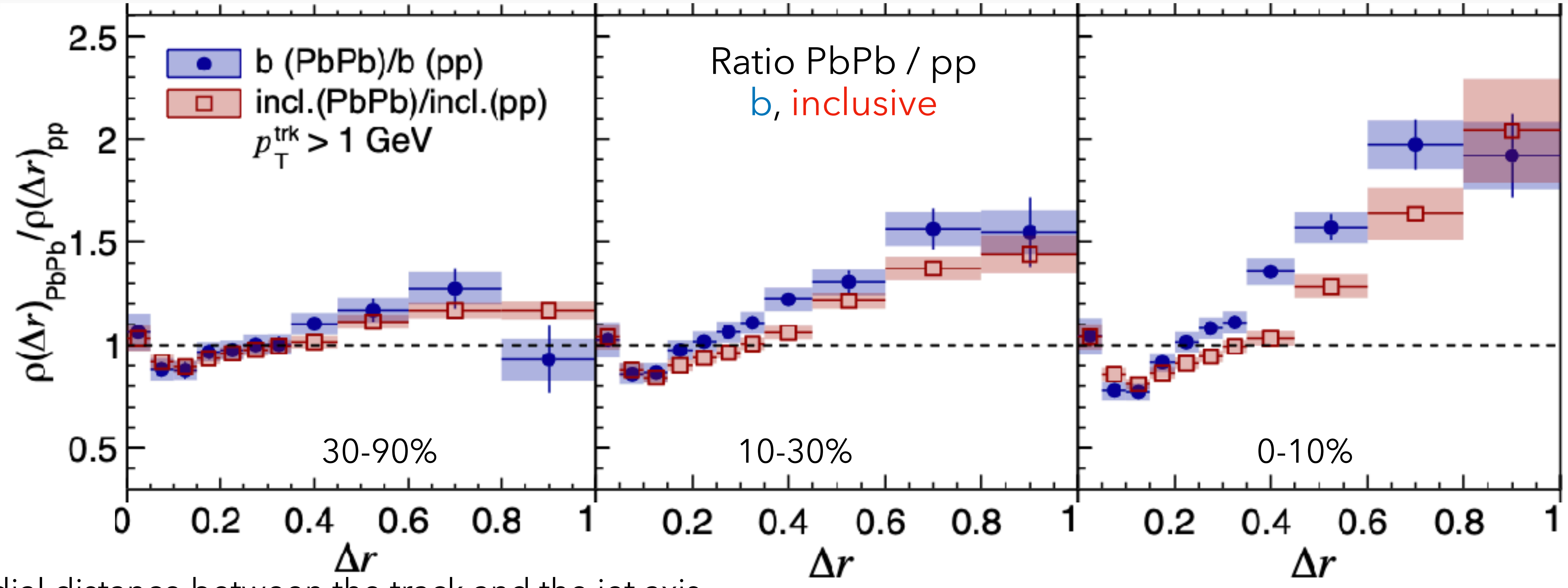
Ratio b-jet/inclusive-jet R_{AA} peripheral

- Suggest R_{AA} values for **b-jets higher than for inclusive jets** in central collisions
- Similar trend for peripheral collisions.
- Possible influence of b-jet fragmentation and/or
  mass effect on parton energy loss (expected to be small at large p_T)?
  color (b/g) charge of parton energy loss?

LIDO: W. Ke et al, Phys. Rev. C 98, 064901 (2018), Phys. Rev. C 100, 064911 (2019),
Dai et al: Chinese. Phys. C 2020, 44:104105

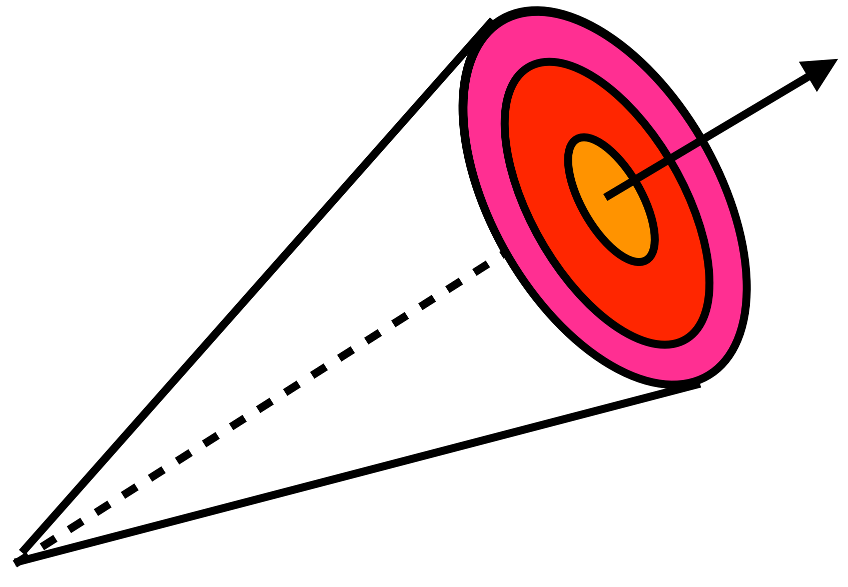
ATLAS, EPJC (2023) 83:438

Looking at the energy distribution? b-jet shape

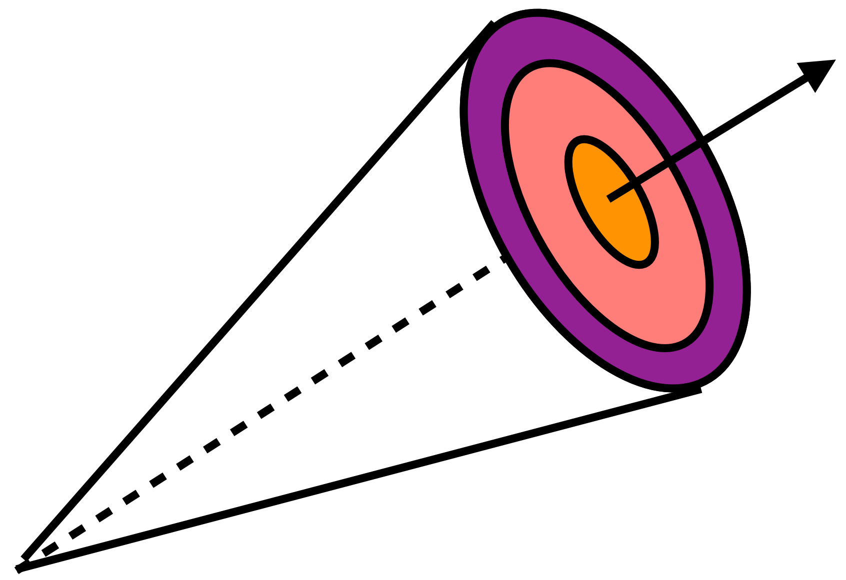


Δr : radial distance between the track and the jet axis
ρ : normalised profile of charged particles in jets
Jet-track correlation p_T jet > 120 GeV, p_T track > 1 GeV

CMS, PLB 844 (2023) 137849



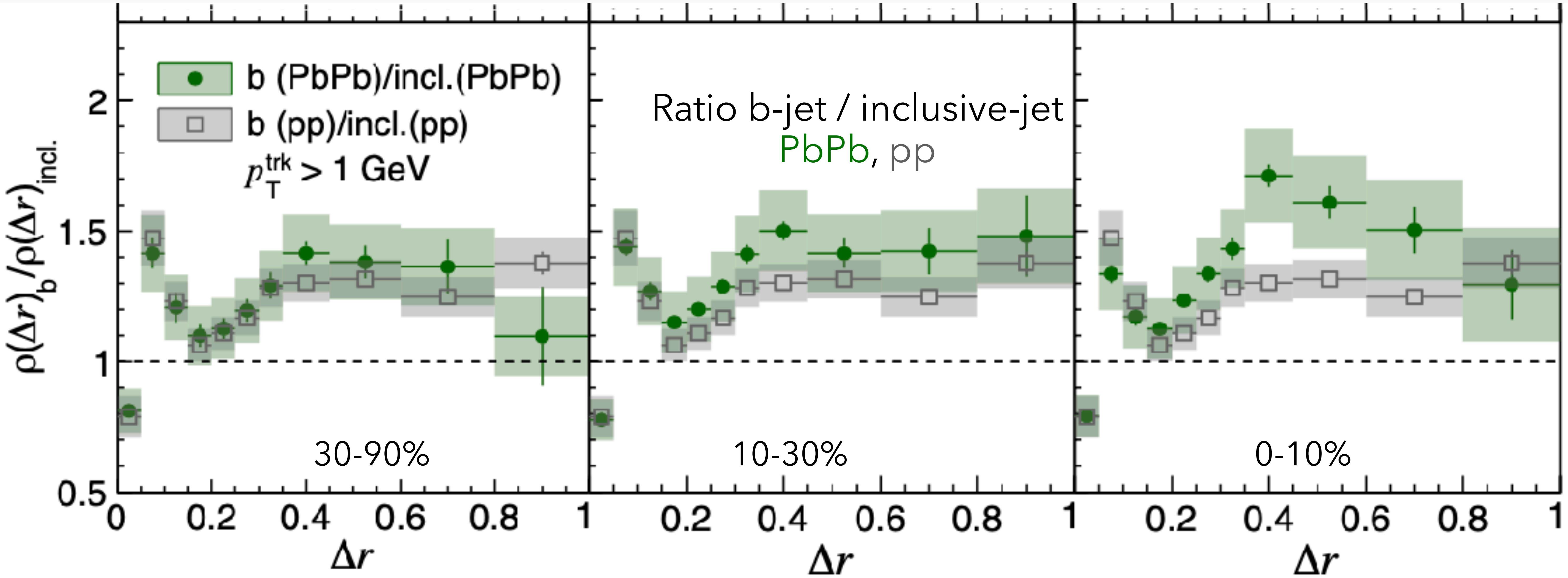
Jet substructure: energetic component close to jet axis



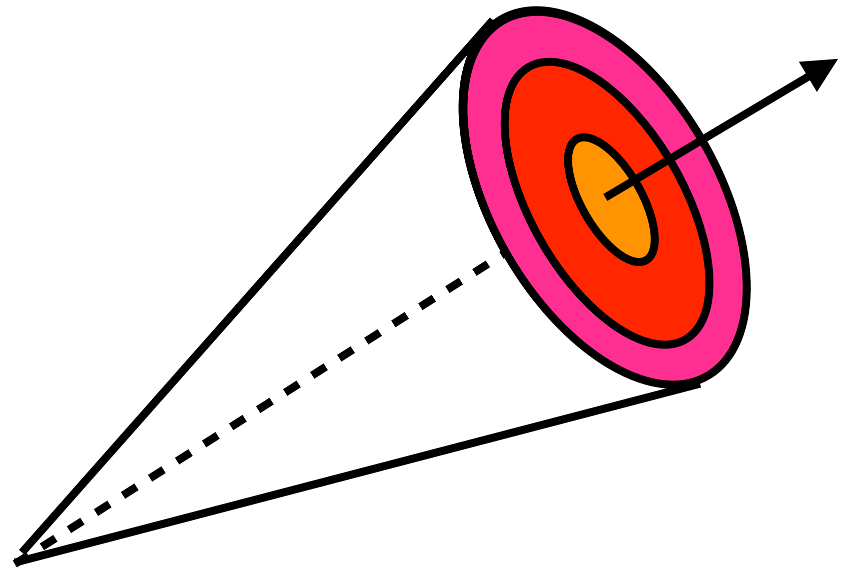
Jet substructure modified:
core stays intact,
intermediate part is reduced,
larger activity in the border and far away

- Energetic core (close to jet axis) stays intact, intermediate part is reduced, and enhancement of the activity on the surface/edges and far away from the jet.
- The **modification is more pronounced for b-jets** than for inclusive jets, and is already present in pp.
  b-jet fragmentation?
  Dead-cone effect (mass effect expected to be small at large pT)?
  Increased medium response to heavy quark propagation?

Looking at the energy distribution? b-jet shape



CMS, PLB 844 (2023) 137849



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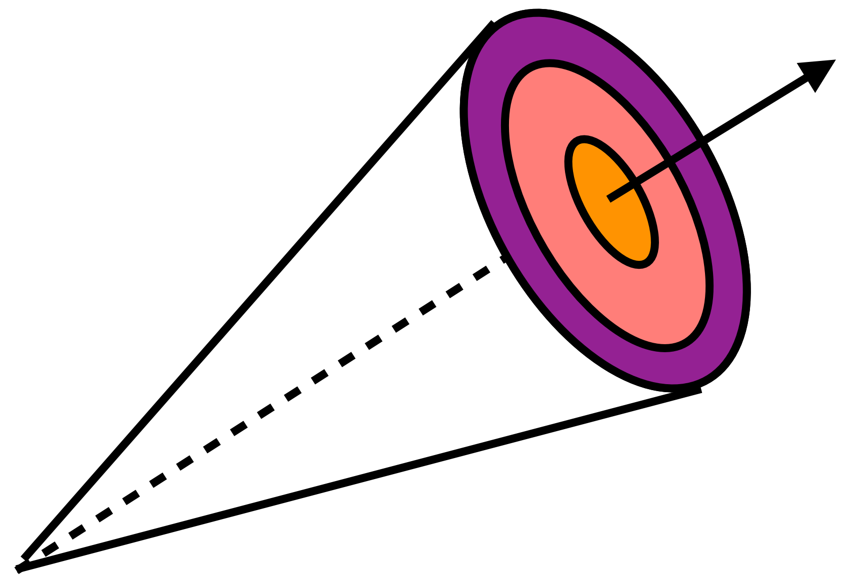

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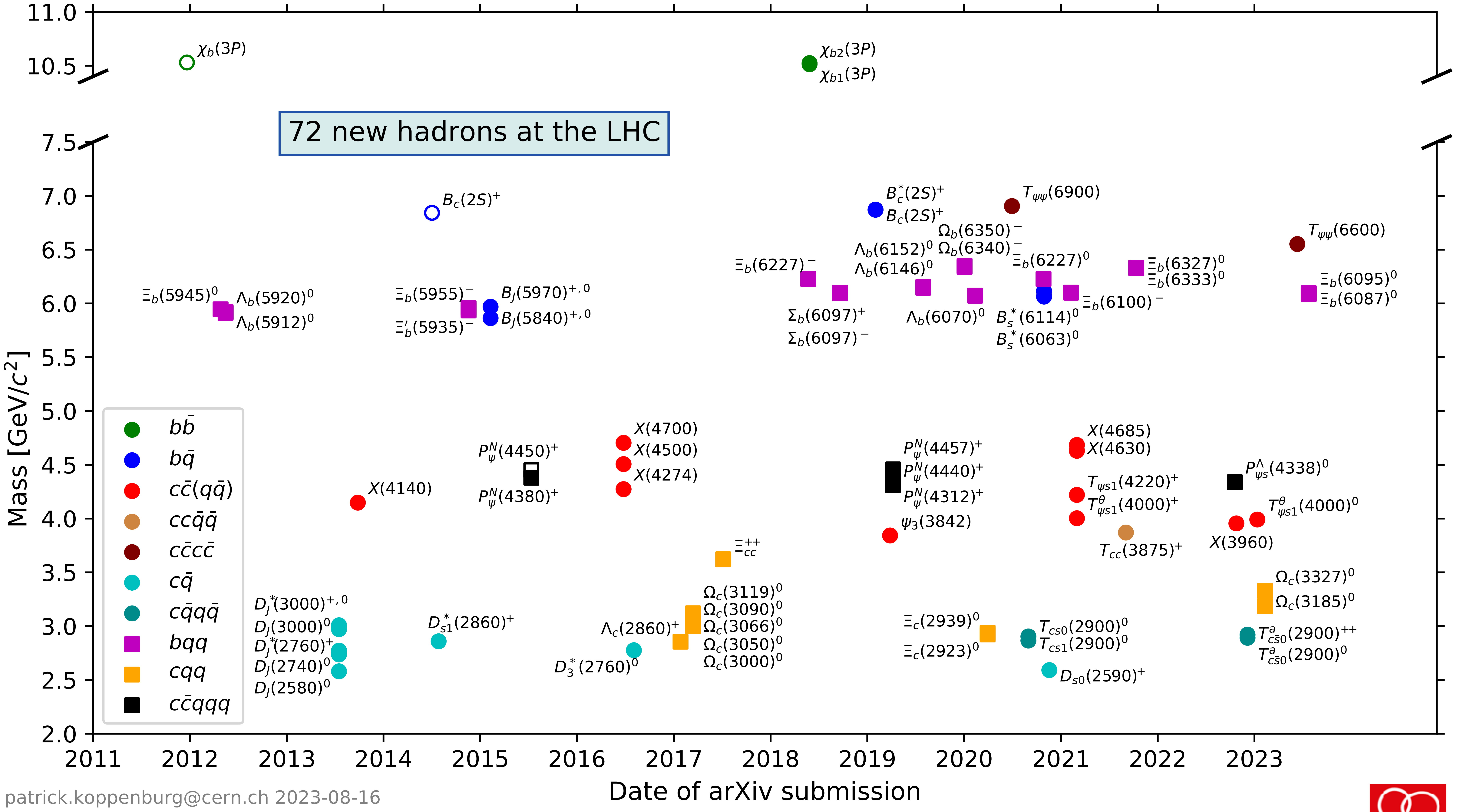
- The **modification is more pronounced for b-jets** than for inclusive jets, and is already present in pp.
  b-jet fragmentation?
  Dead-cone effect (mass effect expected to be small at large pT)?
  Increased medium response to heavy quark propagation?

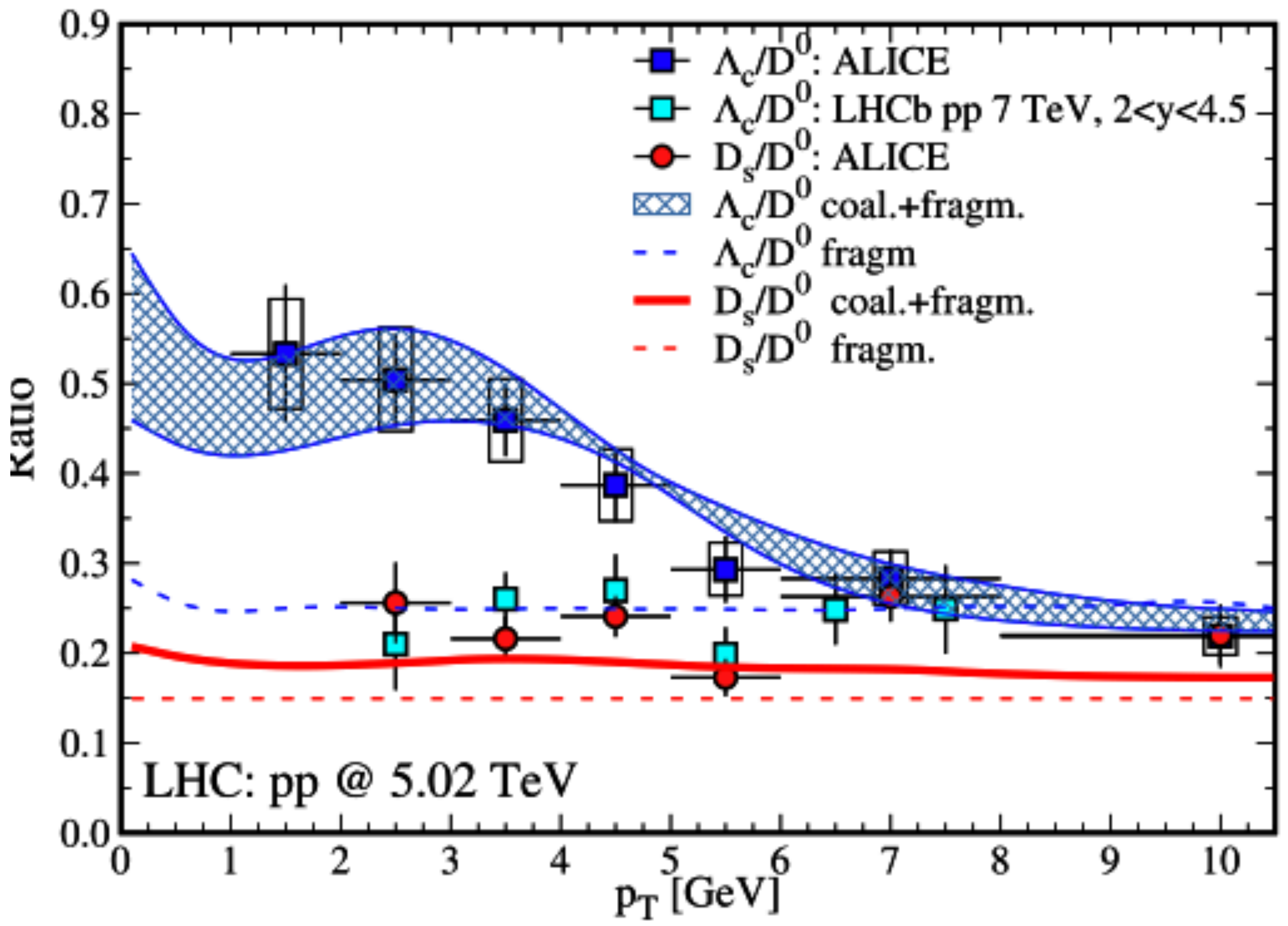
Masses and discovery date for states observed at the LHC

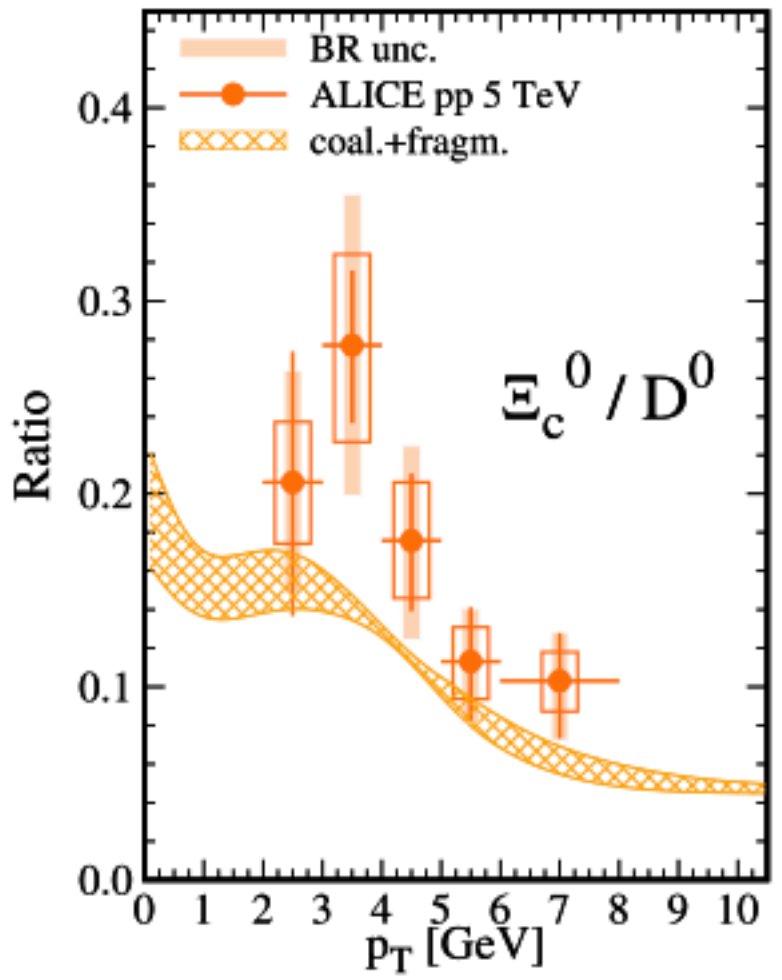


Charm hadrons in coalescence+fragmentation model

Table 2
Ground states of charmed mesons and baryons as well as their first excited states including their decay modes with their corresponding branching ratios as given in Particle Data Group [34,54].

Meson	Mass(MeV)	I (J)	Decay modes	B.R.
$D^+ = \bar{d}c$	1869	$\frac{1}{2}$ (0)		
$D^0 = \bar{u}c$	1865	$\frac{1}{2}$ (0)		
$D_s^+ = \bar{s}c$	2011	0 (0)		
Resonances				
D^{*+}	2010	$\frac{1}{2}$ (1)	$D^0\pi^+$; D^+X	68%,32%
D^{*0}	2007	$\frac{1}{2}$ (1)	$D^0\pi^0$; $D^0\gamma$	62%,38%
D_s^{*+}	2112	0 (1)	D_s^+X	100%
Baryon				
$\Lambda_c^+ = udc$	2286	$0(\frac{1}{2})$		
$\Xi_c^+ = usc$	2467	$\frac{1}{2}(\frac{1}{2})$		
$\Xi_c^0 = dsc$	2470	$\frac{1}{2}(\frac{1}{2})$		
$\Omega_c^0 = ssc$	2695	$0(\frac{1}{2})$		
Resonances				
Λ_c^+	2595	$0(\frac{1}{2})$	$\Lambda_c^+\pi^+\pi^-$	100%
Λ_c^+	2625	$0(\frac{3}{2})$	$\Lambda_c^+\pi^+\pi^-$	100%
Σ_c^+	2455	$1(\frac{1}{2})$	$\Lambda_c^+\pi$	100%
Σ_c^+	2520	$1(\frac{3}{2})$	$\Lambda_c^+\pi$	100%
$\Xi_c^{\prime +,0}$	2578	$\frac{1}{2}(\frac{1}{2})$	$\Xi_c^{+,0}\gamma$	100%
Ξ_c^+	2645	$\frac{1}{2}(\frac{3}{2})$	$\Xi_c^+\pi^-$,	100%
Ξ_c^+	2790	$\frac{1}{2}(\frac{1}{2})$	$\Xi_c^{\prime}\pi$,	100%
Ξ_c^+	2815	$\frac{1}{2}(\frac{3}{2})$	$\Xi_c^{\prime}\pi$,	100%
Ω_c^0	2770	$0(\frac{3}{2})$	$\Omega_c^0\gamma$,	100%





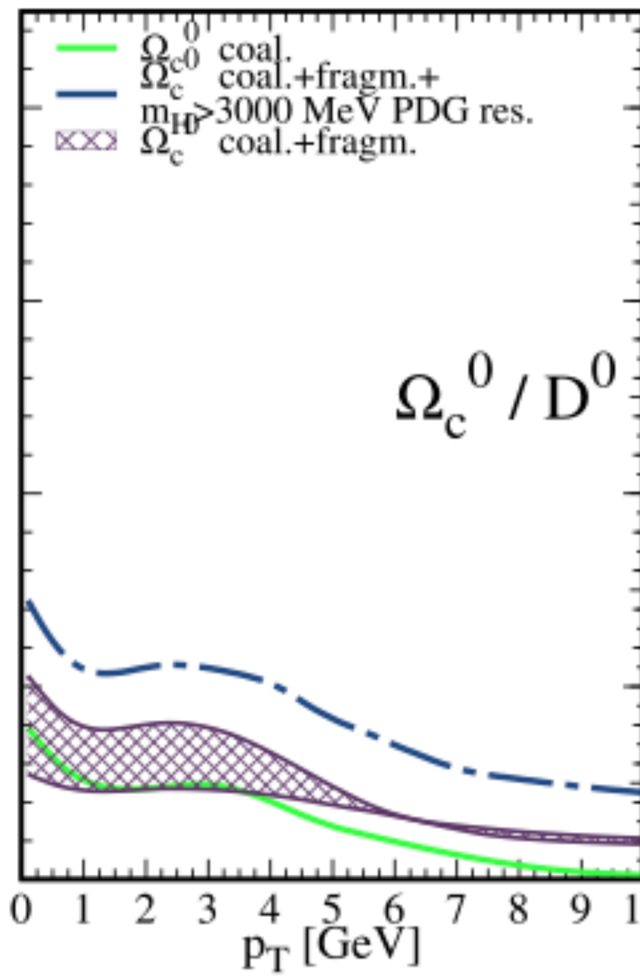
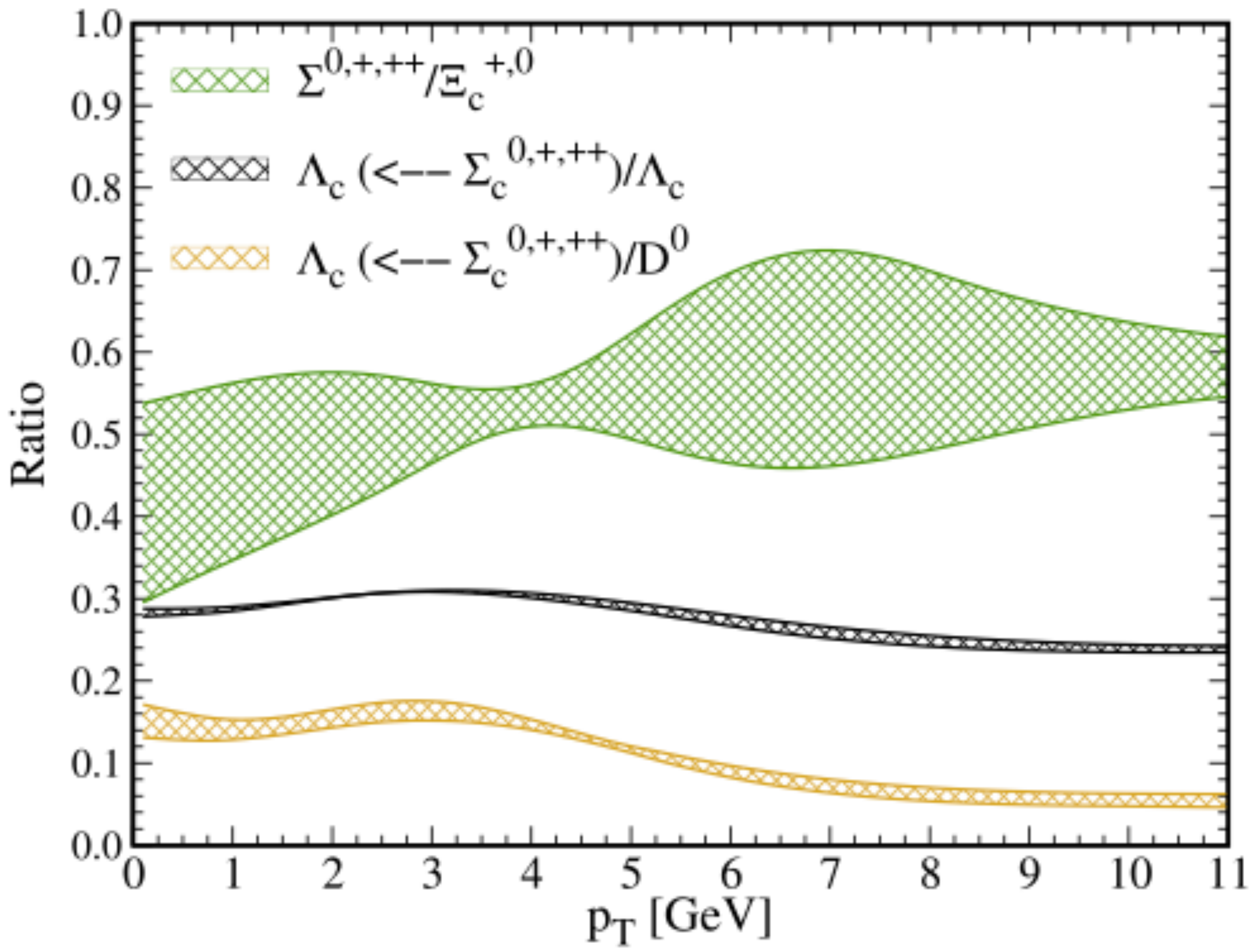
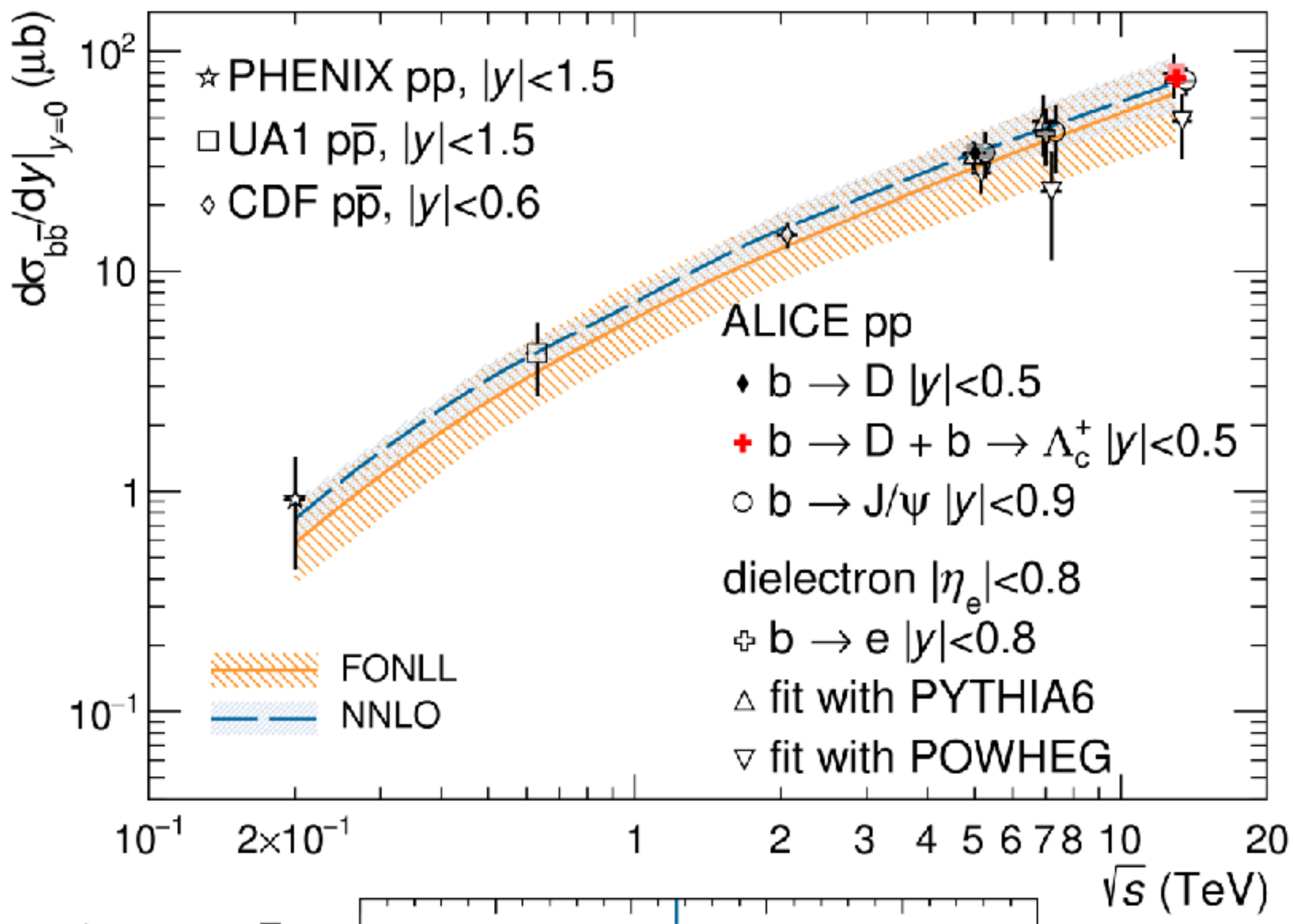


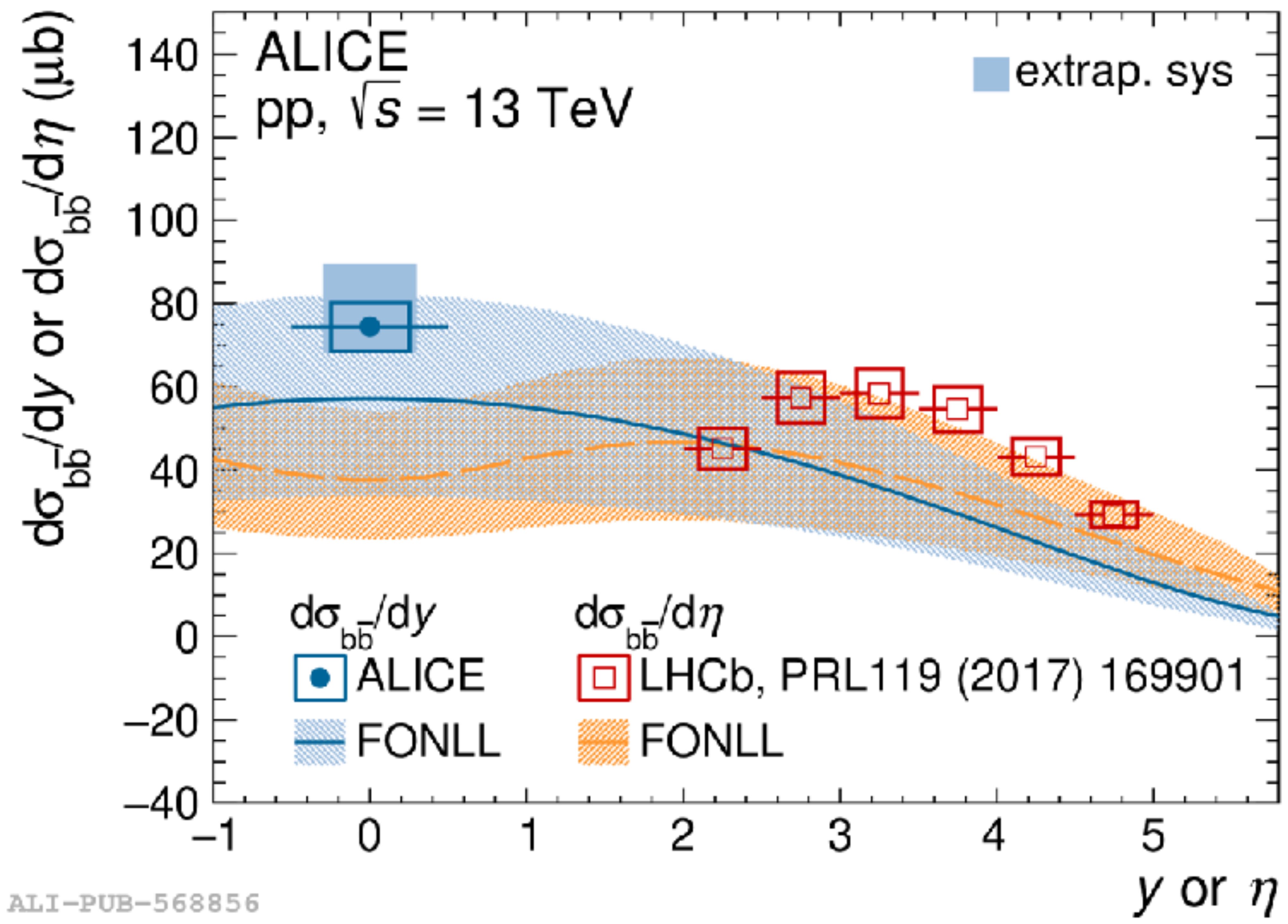
Table 1
Mean square charge radius $\langle r^2 \rangle_{ch}$ in fm^2 and the widths parameters σ_{pi} in GeV. The mean square charge radius is taken quark model [46,47].

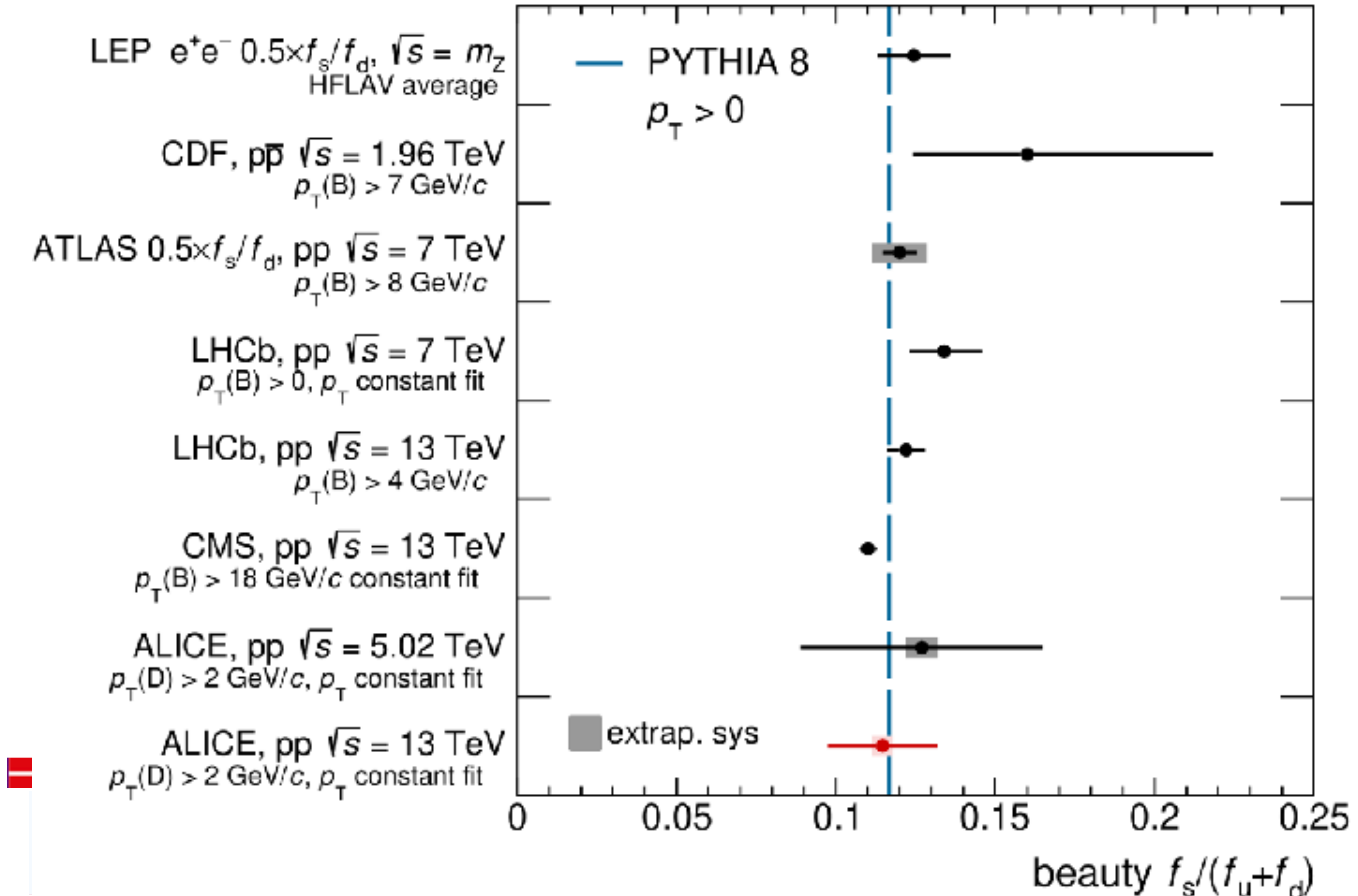
Meson	$\langle r^2 \rangle_{ch}$	σ_{p1}	σ_{p2}
$D^+ = [c\bar{d}]$	0.184	0.282	–
$D_s^+ = [\bar{s}c]$	0.083	0.404	–
Baryon	$\langle r^2 \rangle_{ch}$	σ_{p1}	σ_{p2}
$\Lambda_c^+ = [udc]$	0.15	0.251	0.424
$\Xi_c^+ = [usc]$	0.2	0.242	0.406
$\Omega_c^0 = [ssc]$	-0.12	0.337	0.53



Minissale et al., PLB 821 (2021) 136622

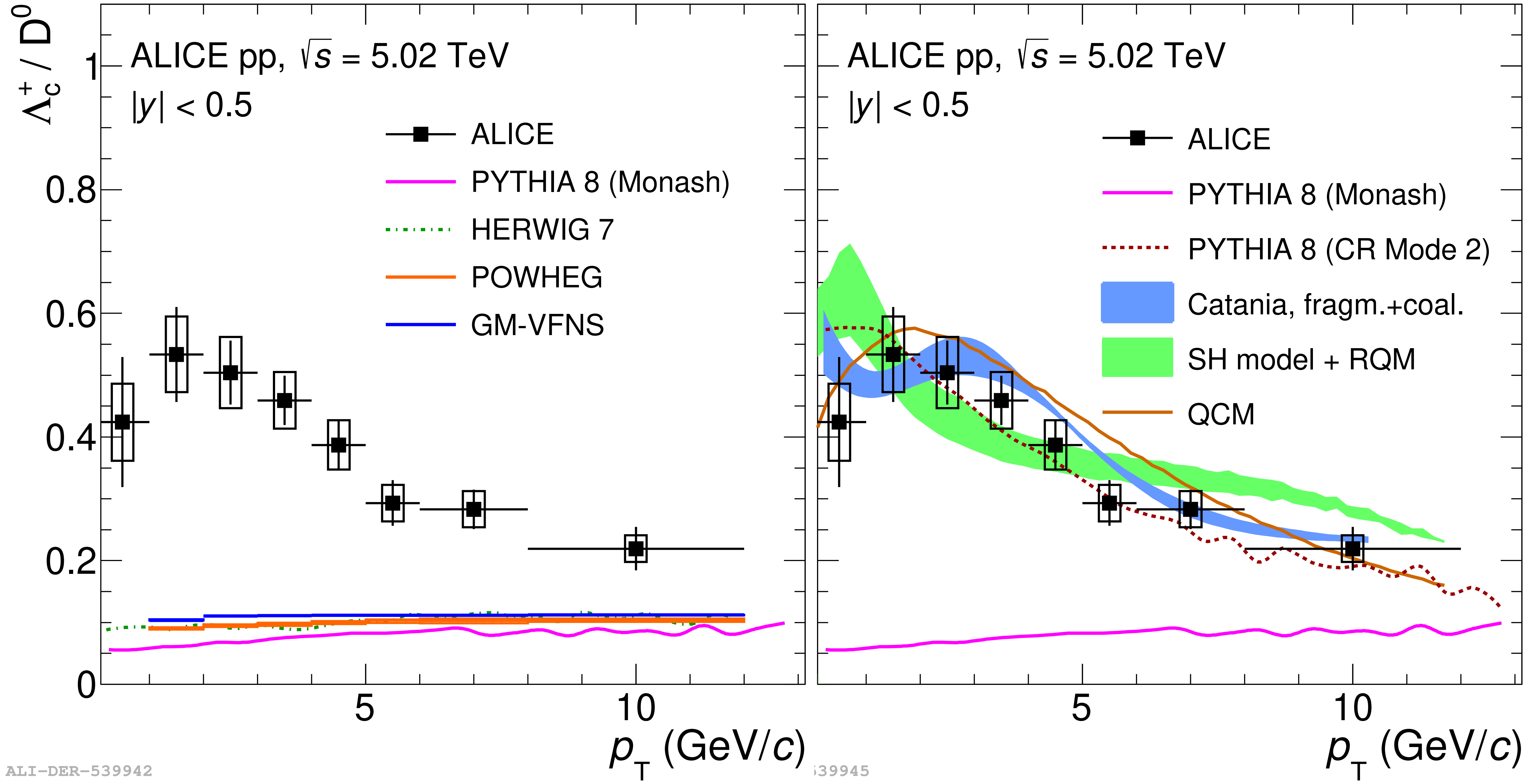






ALICE, arXiv:2402.16417

Λ_c^+/D^0 ratio in pp vs. models

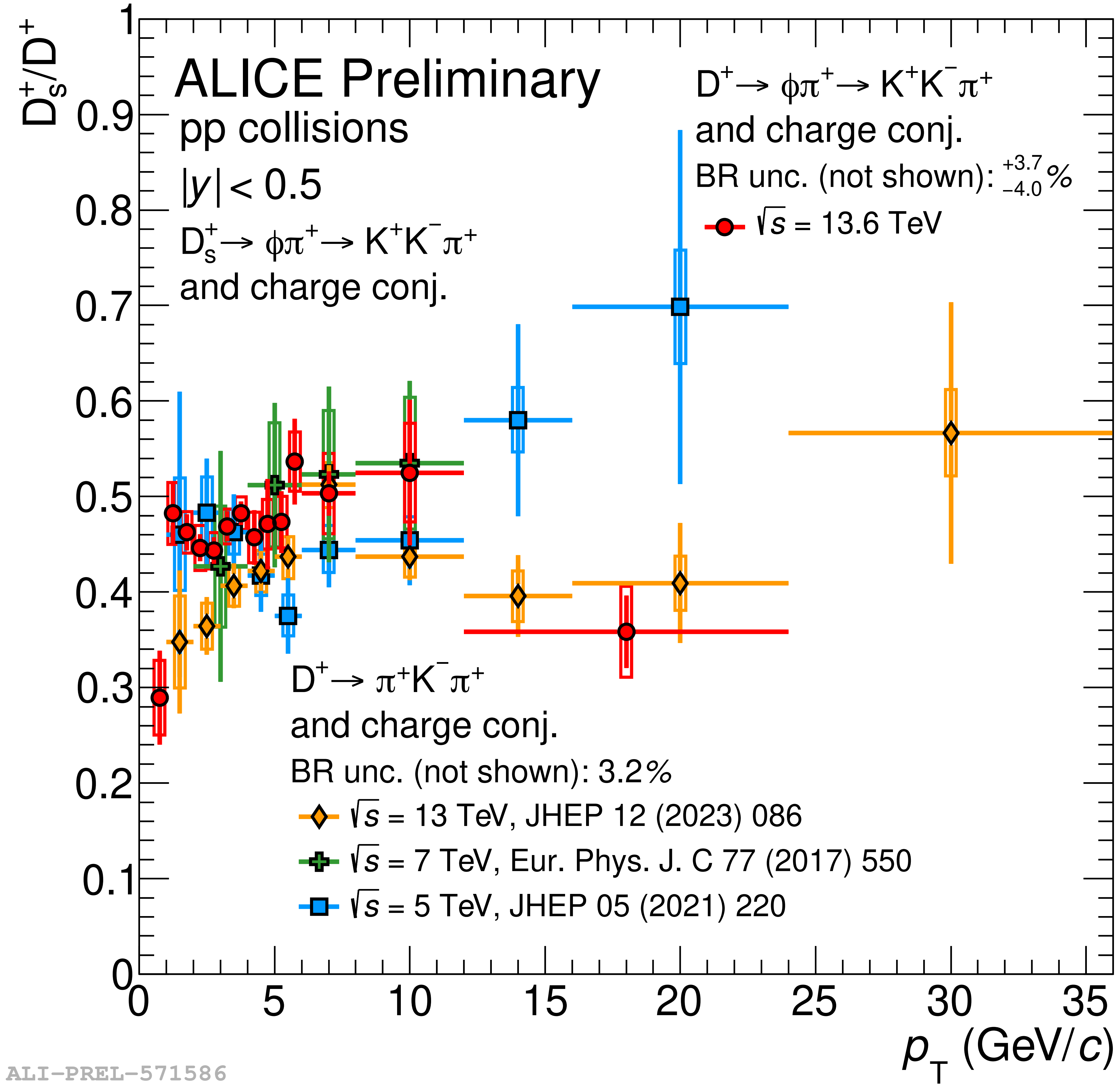


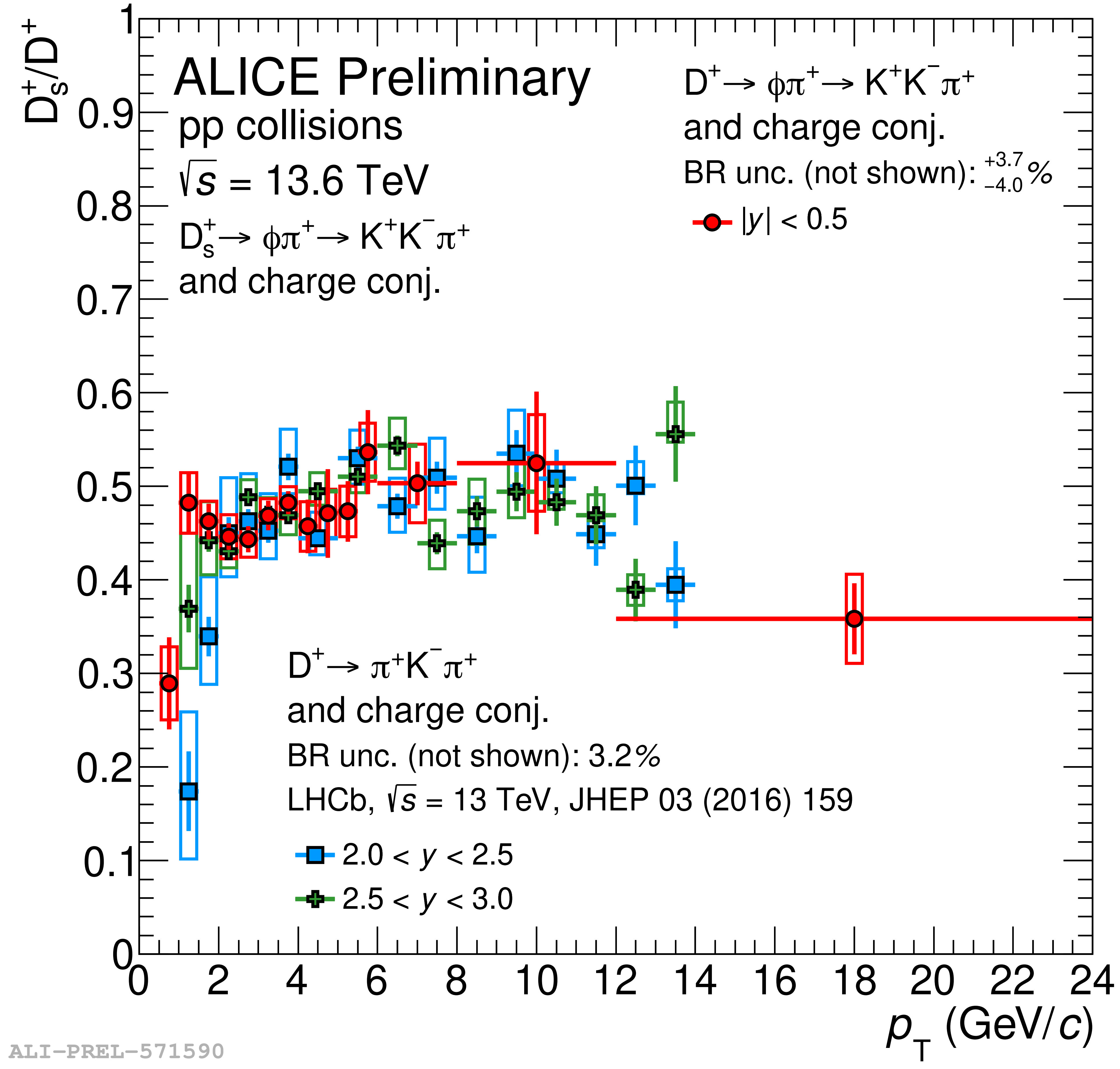
- GM-VFNS: pQCD calculation based on factorisation approach
- PYTHIA8 (Monash): standard Lund string fragmentation. Independent hadronisation of different MPI products
- HERWIG7: cluster hadronisation
- POWHEG:

- PYTHIA8 (CR mode 2): with string formation beyond leading colour (colour reconnection). Including junction reconnection topologies that enhance baryons.
- Catania: coalescence + vacuum fragmentation
  Expanding system of thermalised partons followed by coalescence at a fixed temperature
- QCM: recombination model based on statistical weights
- SH+RQM: statistical hadronisation model with increased feed down from charm-baryon states

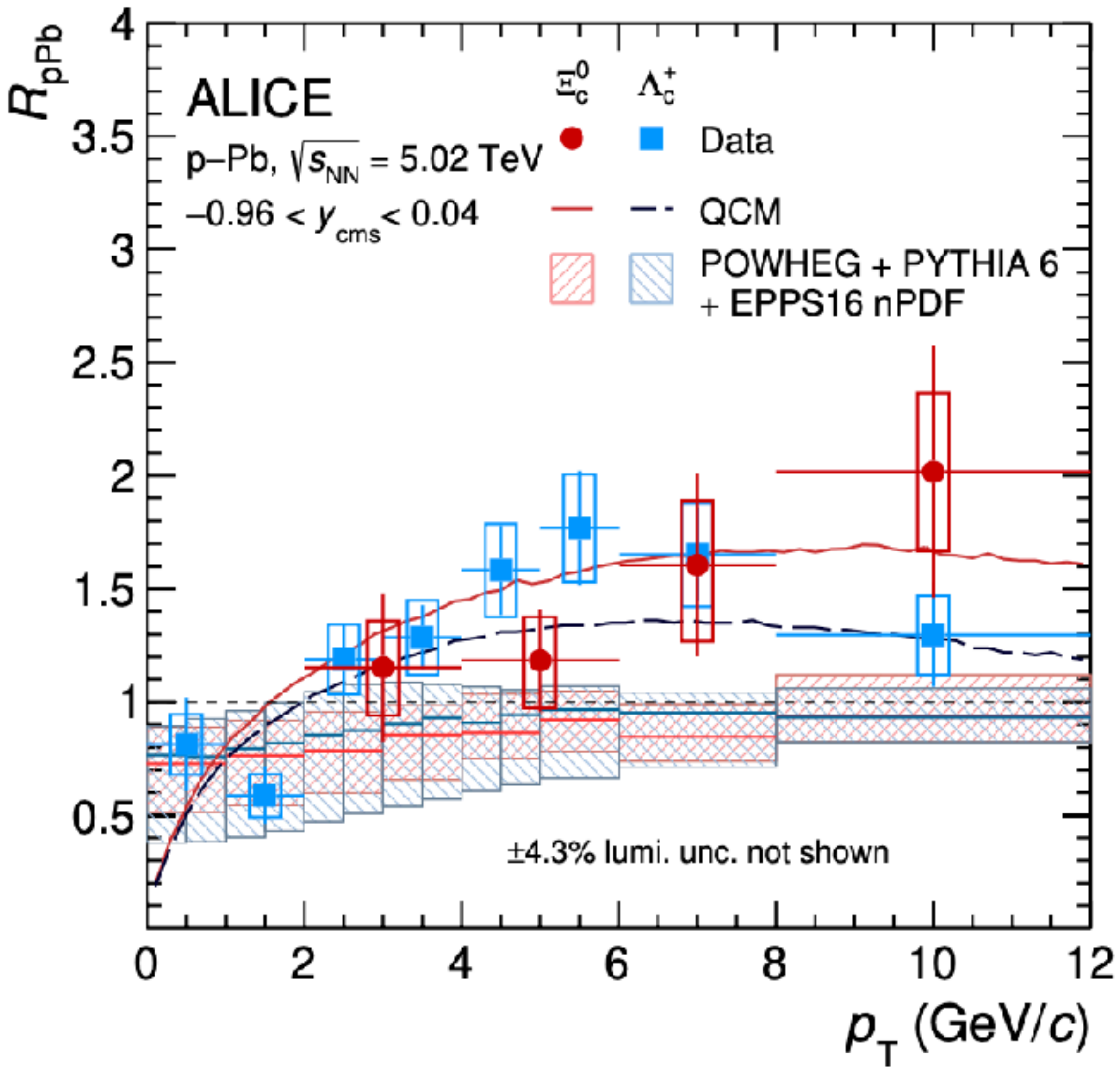
ALICE & LHCb D_s^+/D^+ in pp

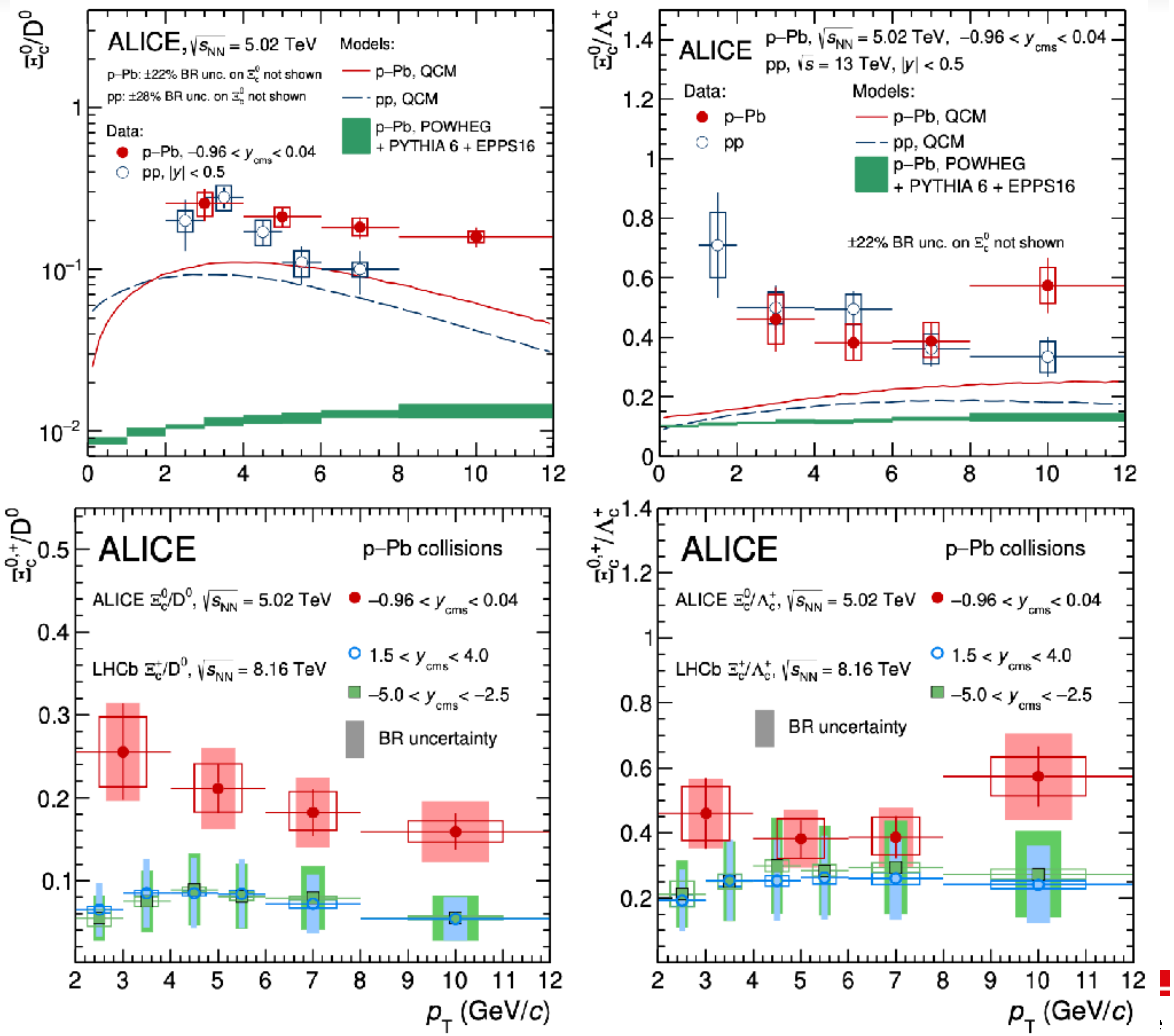
- No rapidity nor energy dependence observed





$\Xi_c^{0,+}/D^0$, $\Xi_c^{0,+}/\Lambda_c^+$ in pPb collisions



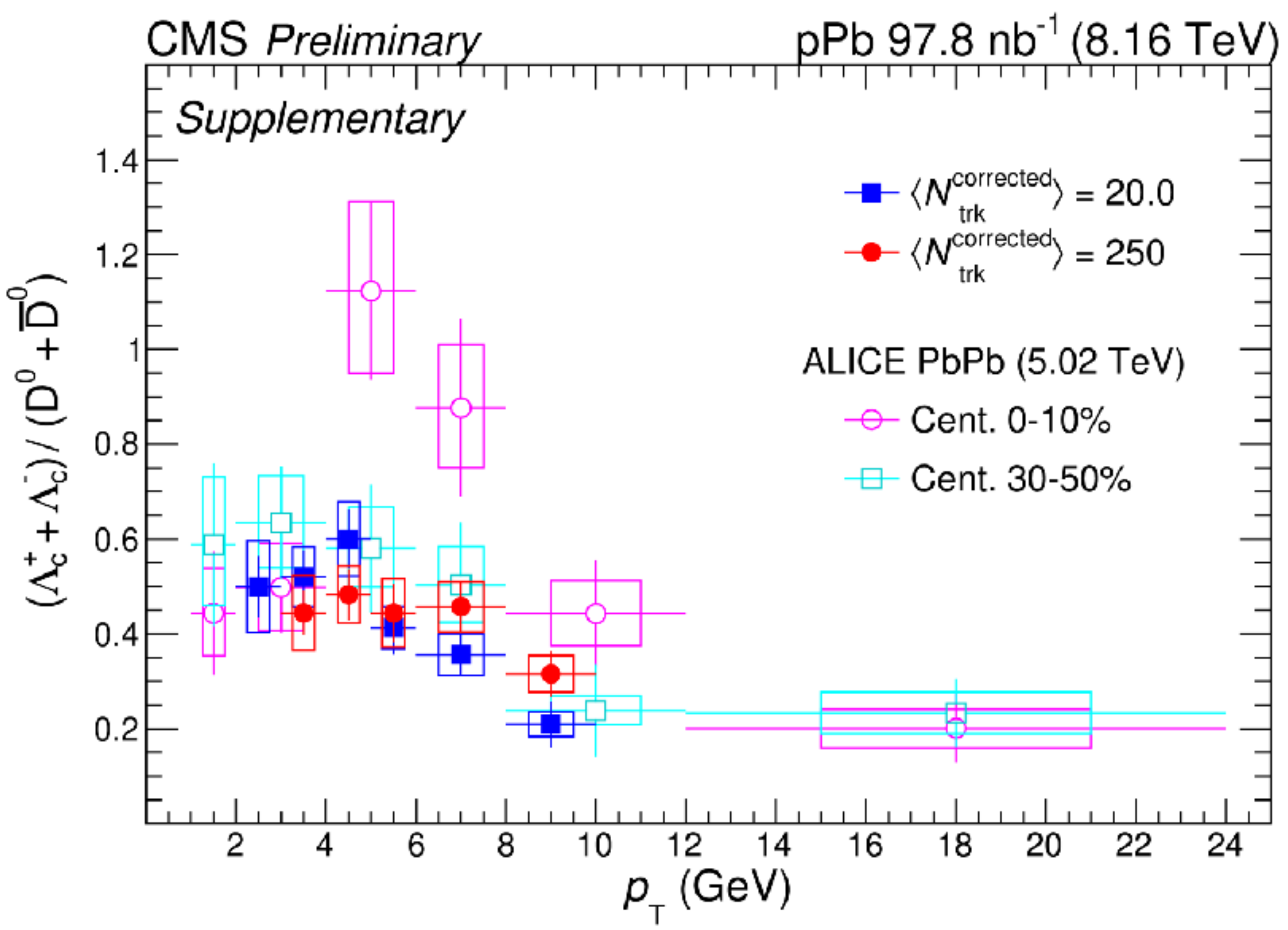


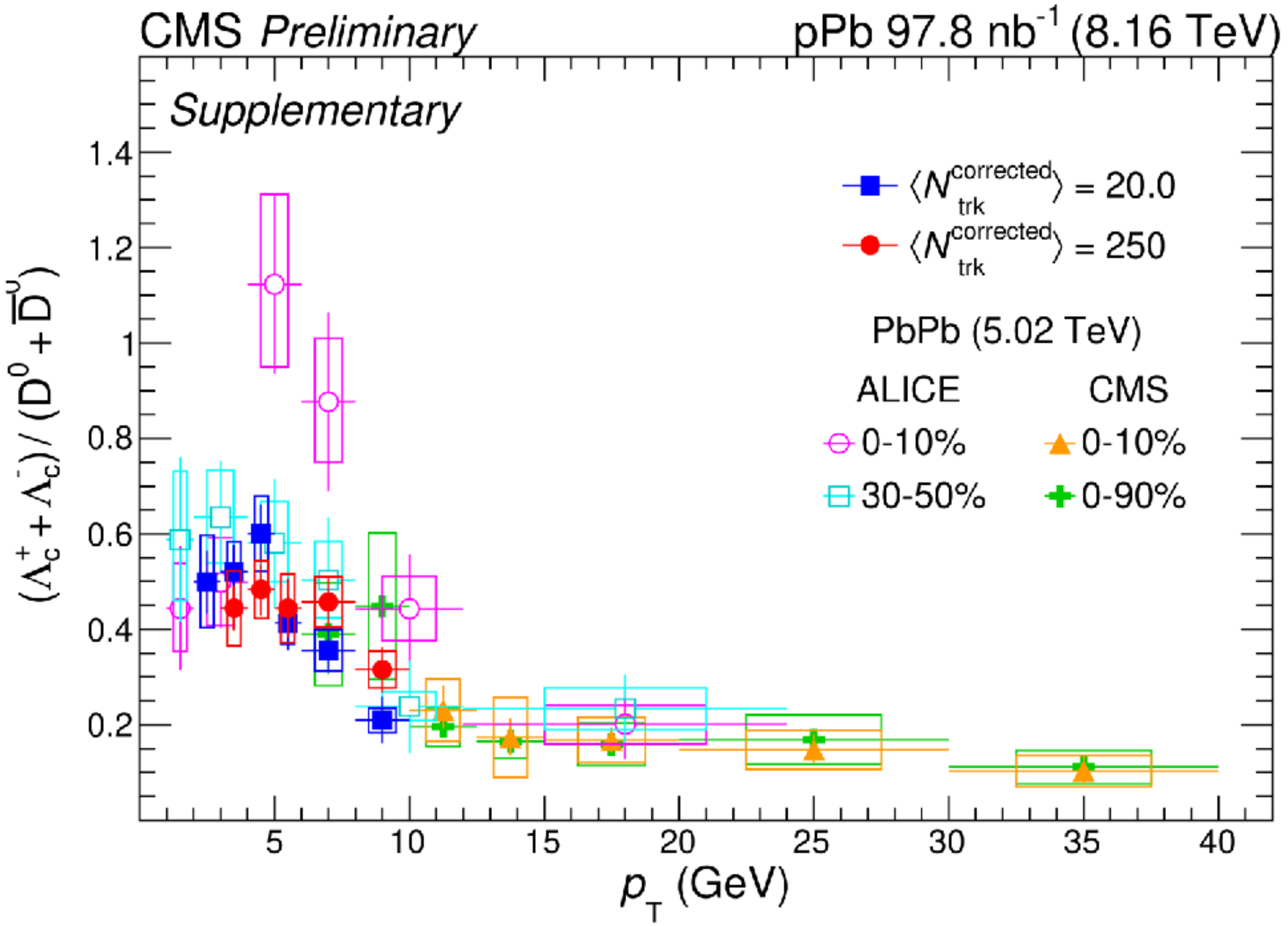
ALICE, arXiv: XXX

$\Xi_c^{0,+}/D^0$, $\Xi_c^{0,+}/\Lambda_c^+$ in pPb collisions

LHCb; arXiv:2305.06711
LHCb, arXiv:2012.11462

ALICE, pp, pPb, PRC 107 (2023) 064901
ALICE, PbPb, PLB 839 (2023) 137796
CMS, pp, PbPb, JHEP 01 (2024) 128
LHCb, pPb, JHEP 02 (2019) 102
LHCb, PbPb, JHEP06 (2023) 132

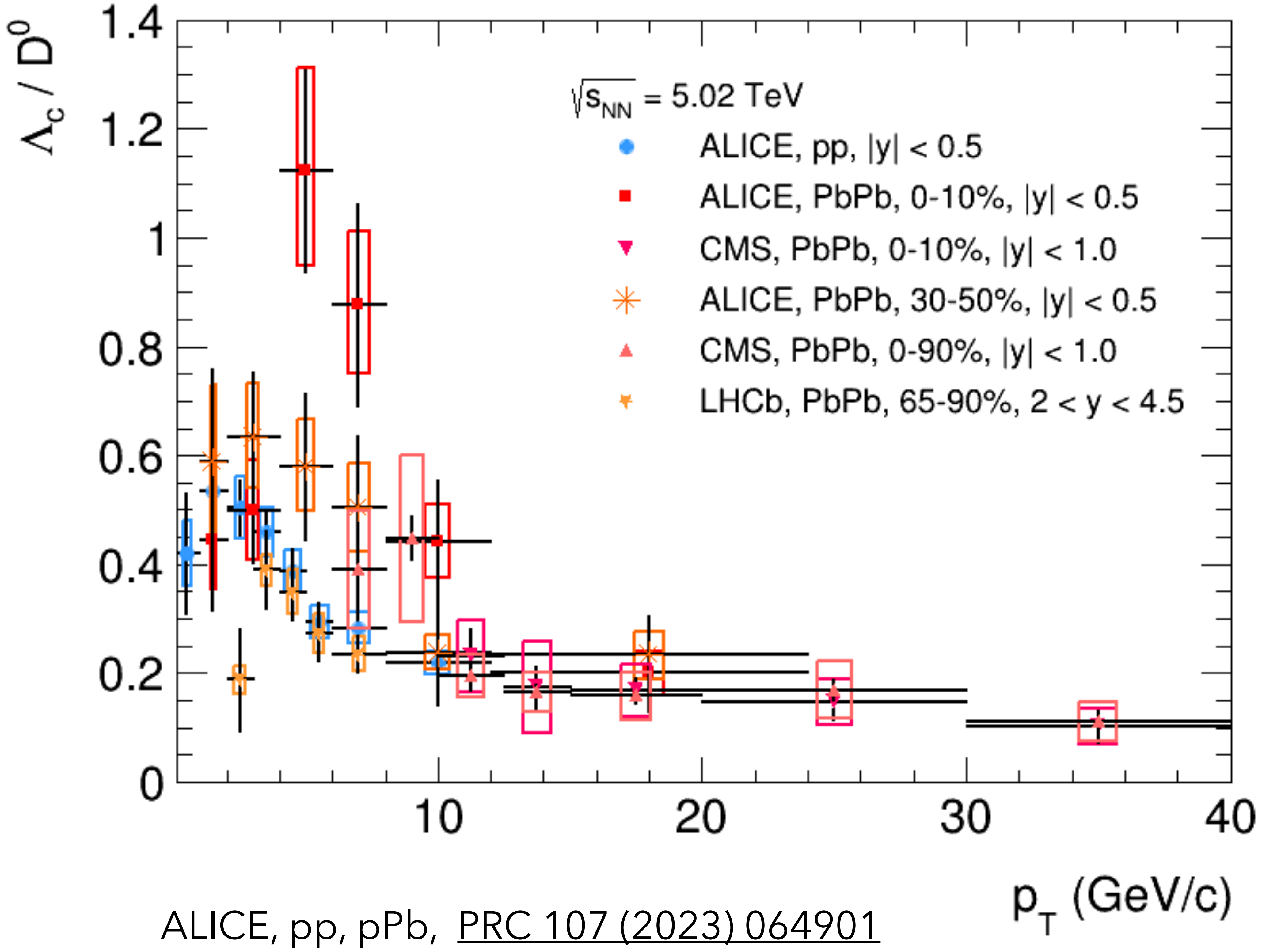




CMS, pPb, CMS-PAS-HIN-21-016 (2023)

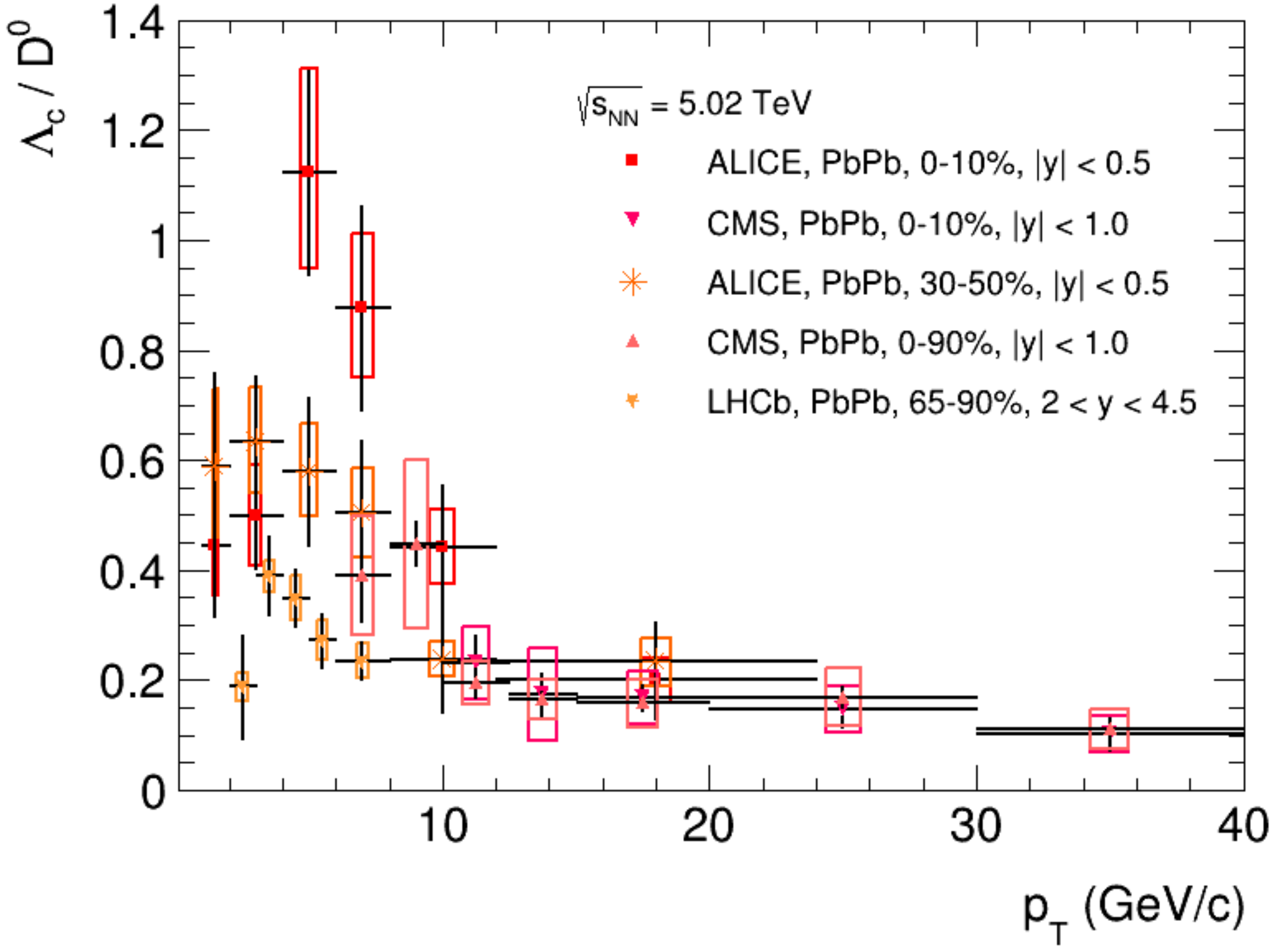
ALICE, pp, PLB 829 (2022) 137065

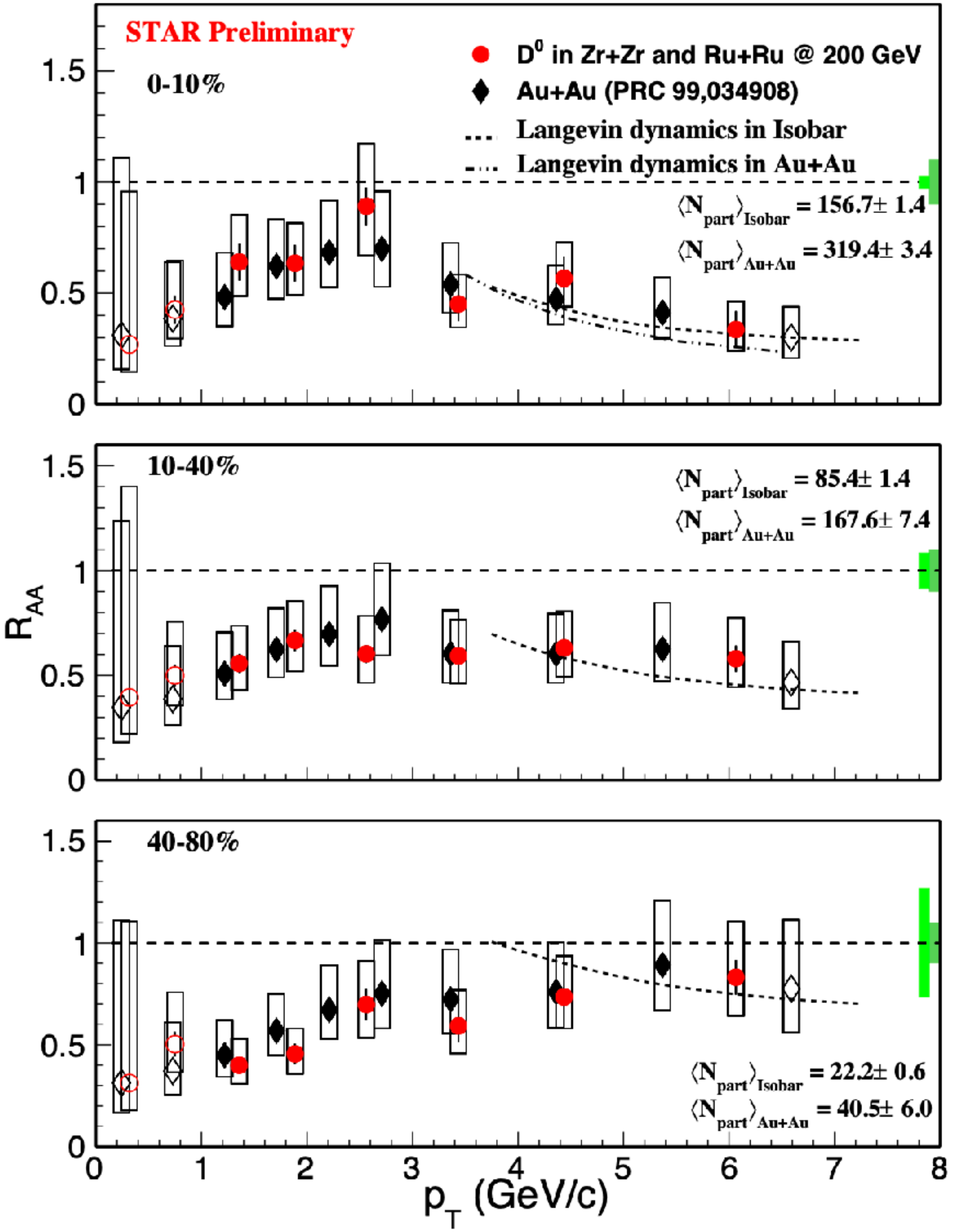
Charm baryon-to-meson ratio in PbPb

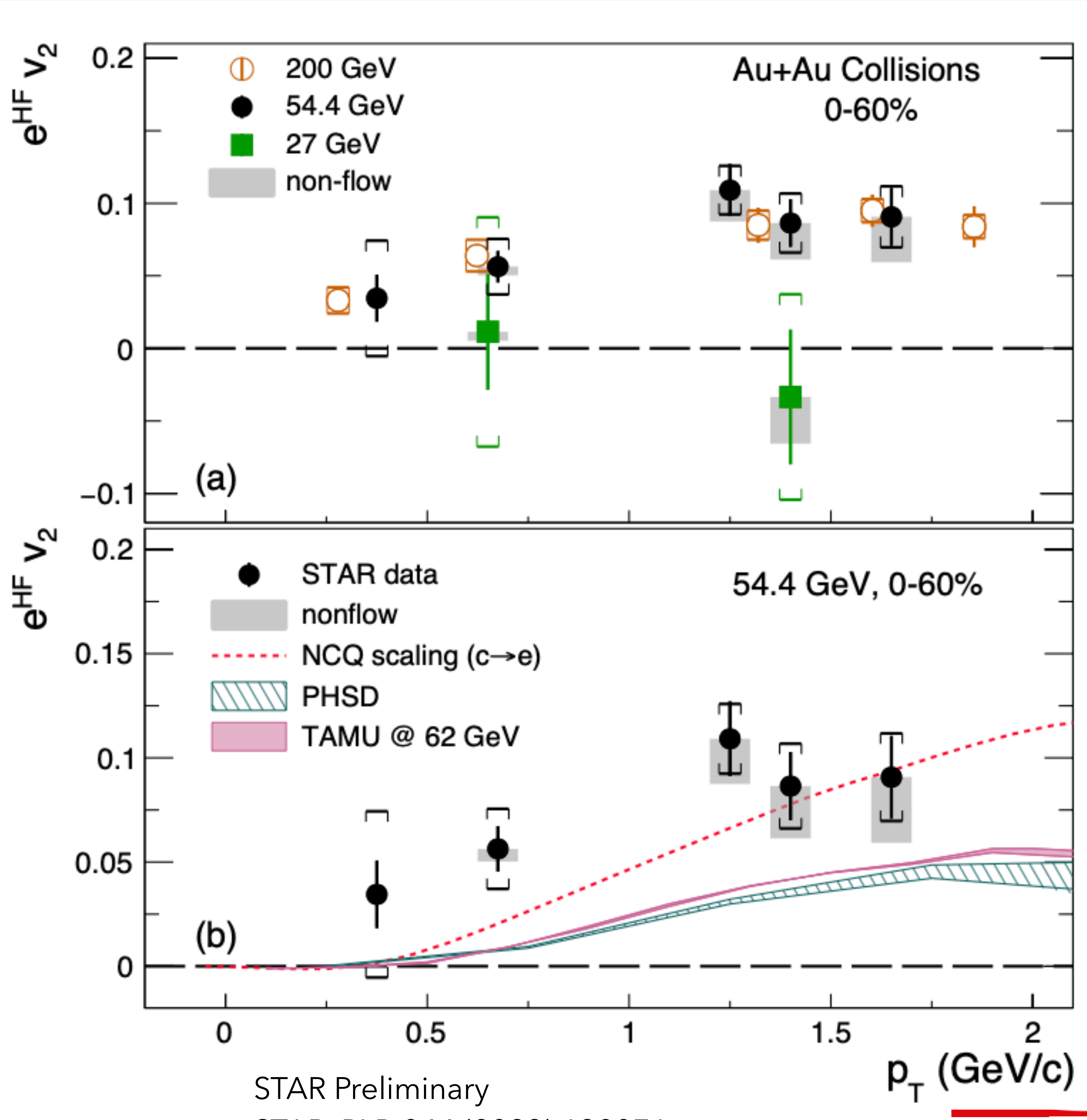


ALICE, pp, pPb, PRC 107 (2023) 064901
ALICE, PbPb, PLB 839 (2023) 137796
CMS, pp, PbPb, JHEP 01 (2024) 128
LHCb, pPb, JHEP 02 (2019) 102
LHCb, PbPb, JHEP06 (2023) 132

kPin

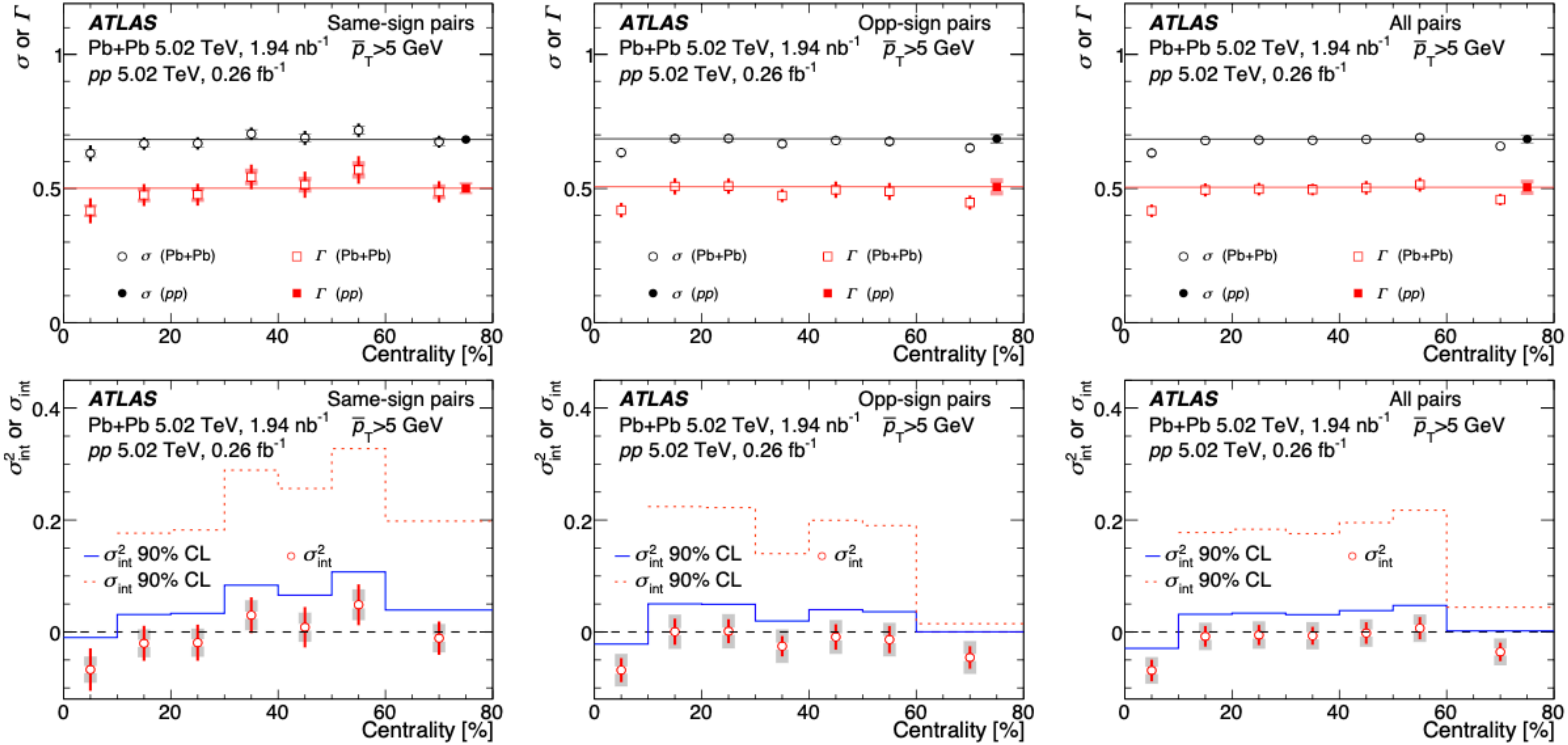




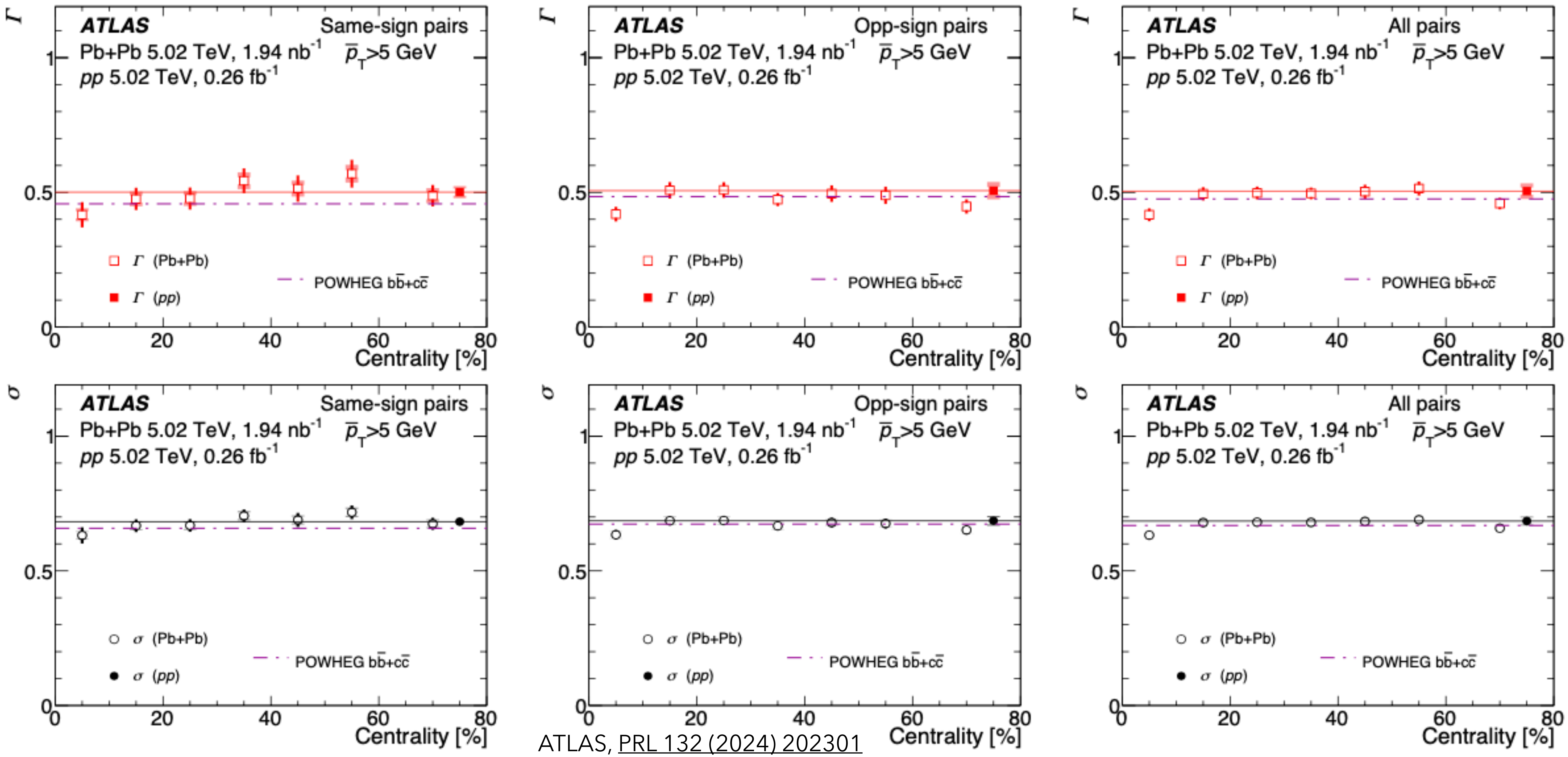


STAR Preliminary

STAR, PLB 844 (2023) 138071

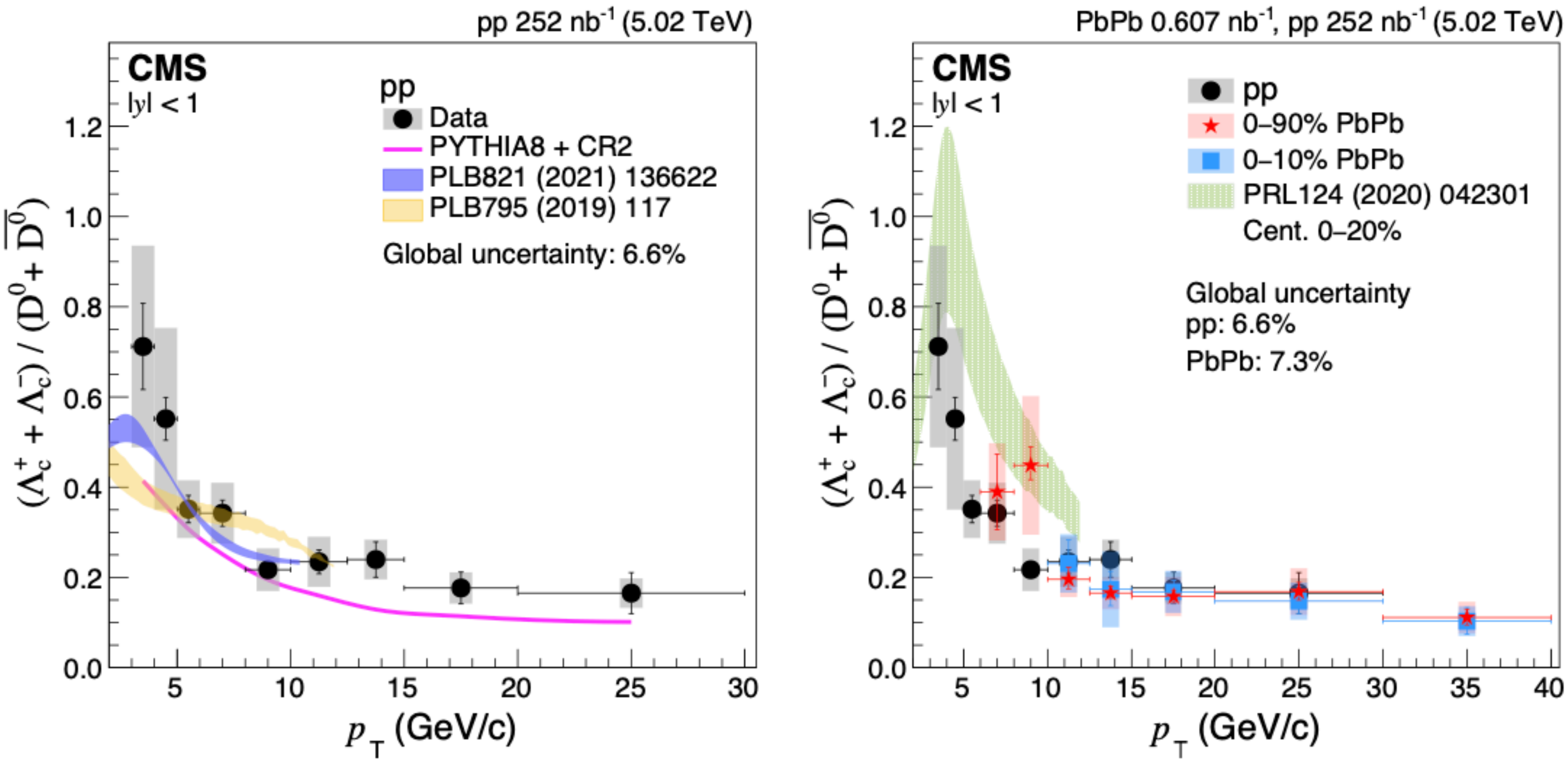


ATLAS, PRL 132 (2024) 202301



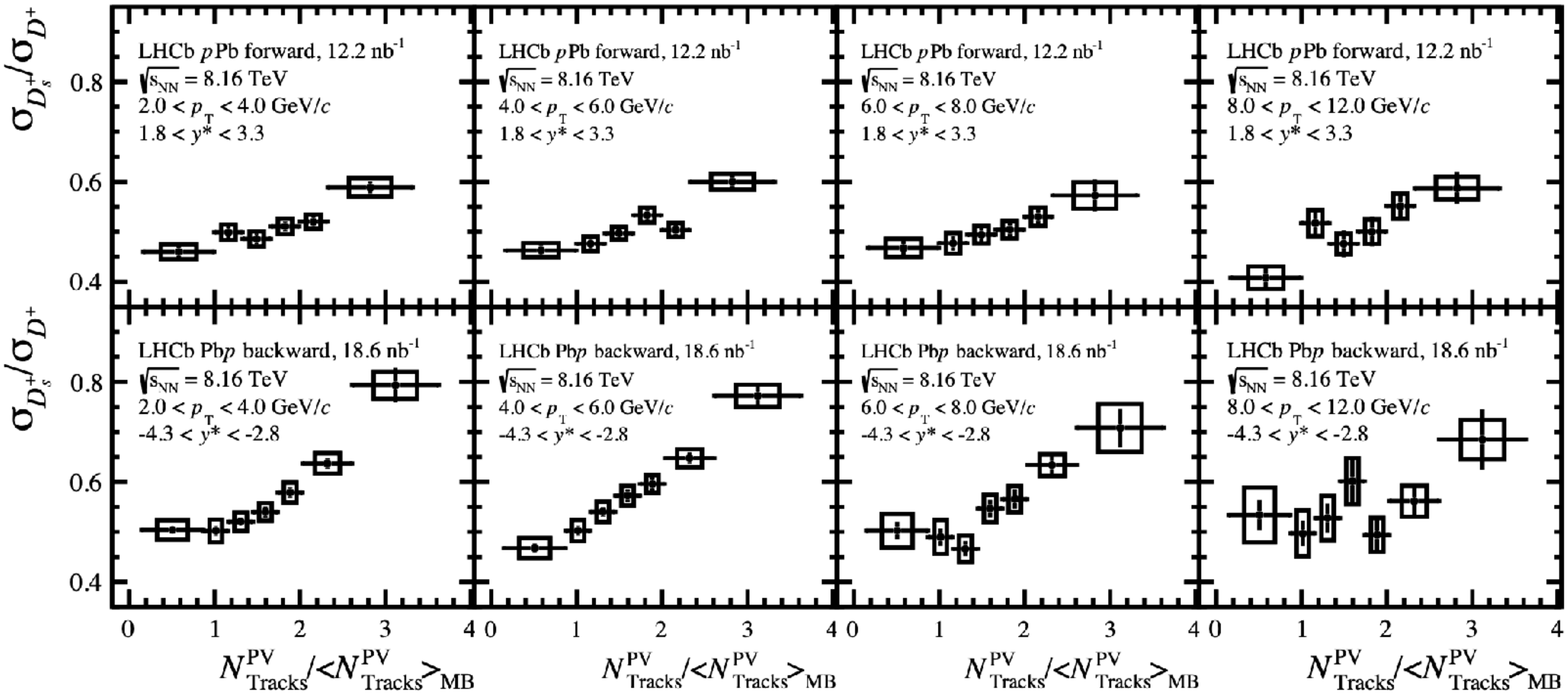
ATLAS, PRL 132 (2024) 202301

Charm baryon-to-meson ratio vs. models



CMS, JHEP 01 (2024) 128

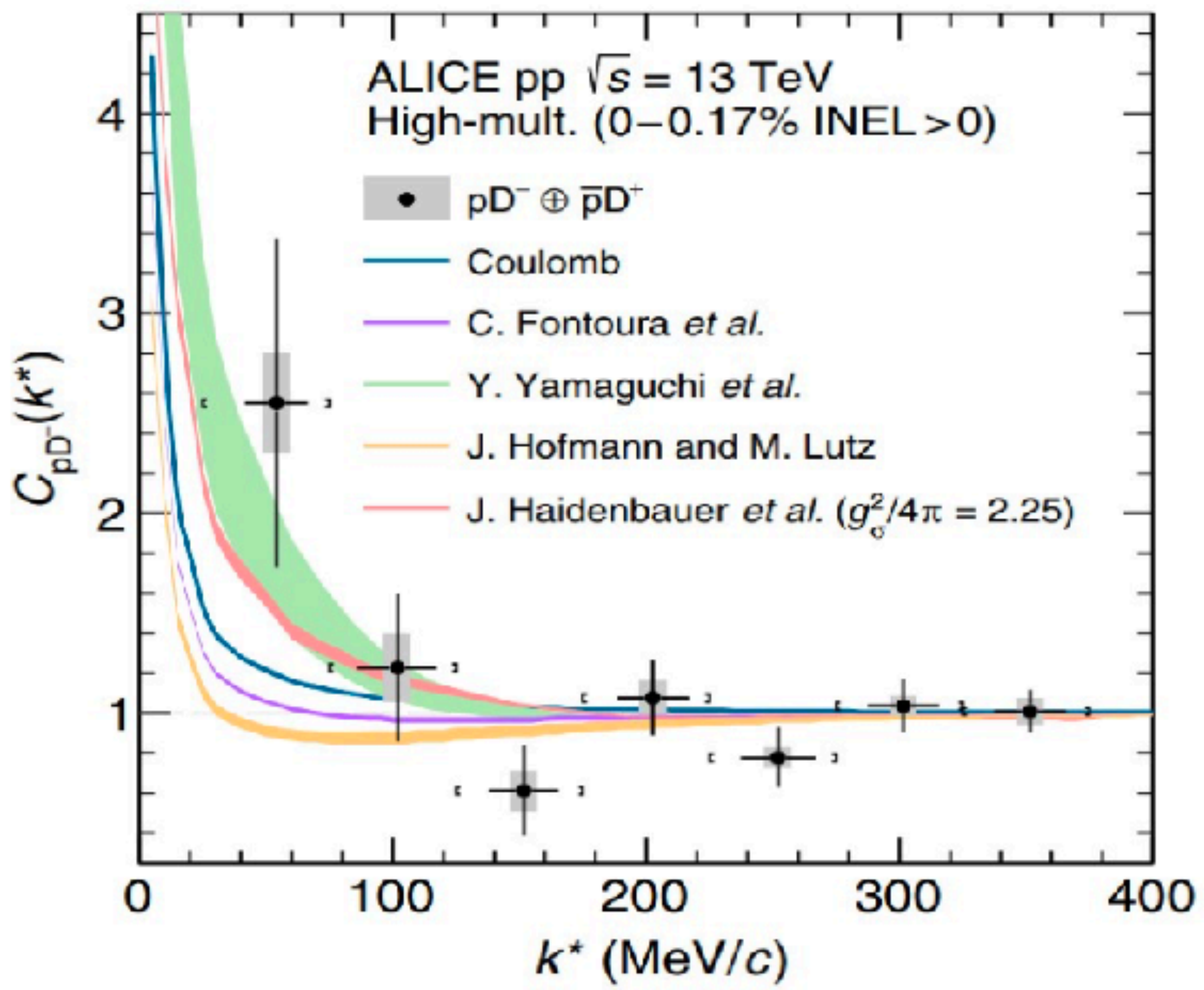
Charm strange hadrons: D_s^+/D^+ ratio vs. multiplicity



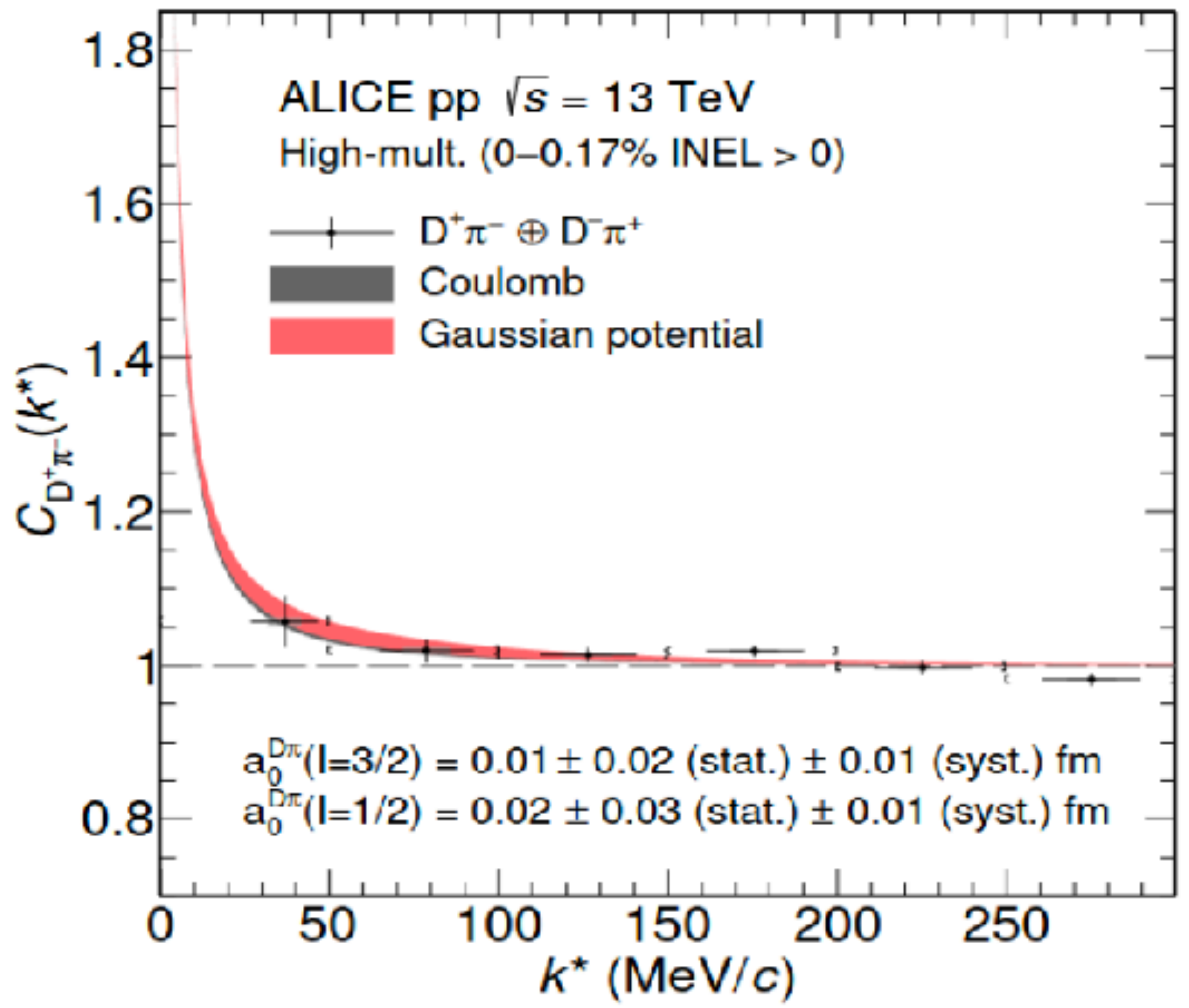
LHCb, arXiv:2311.08490

D-h femtoscopy at the LHC

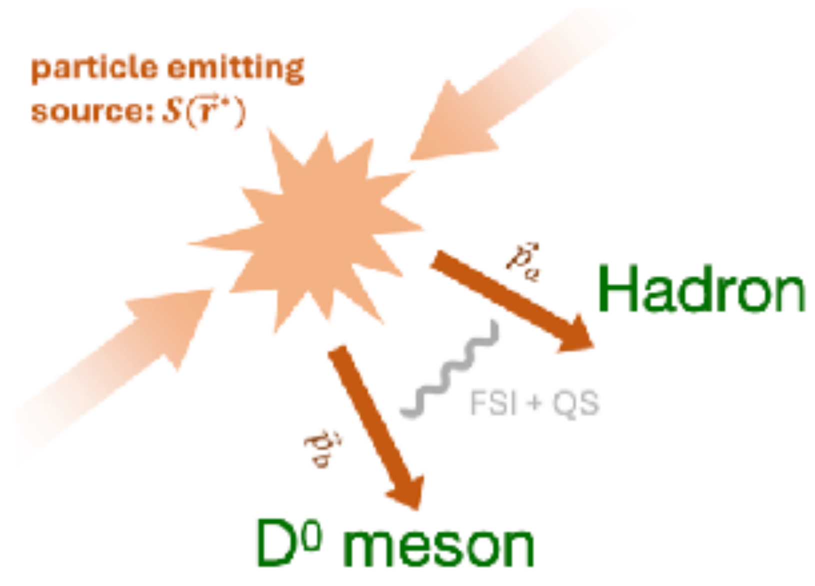
ALICE, Phys. Rev. D 106, 052010



ALICE, https://doi.org/10.48550/arXiv.2401.13541



D-h femtoscopy at RHIC



- Only strong interaction contribution to $D^0/\bar{D}^0 - h^{\pm}$ femtoscopy

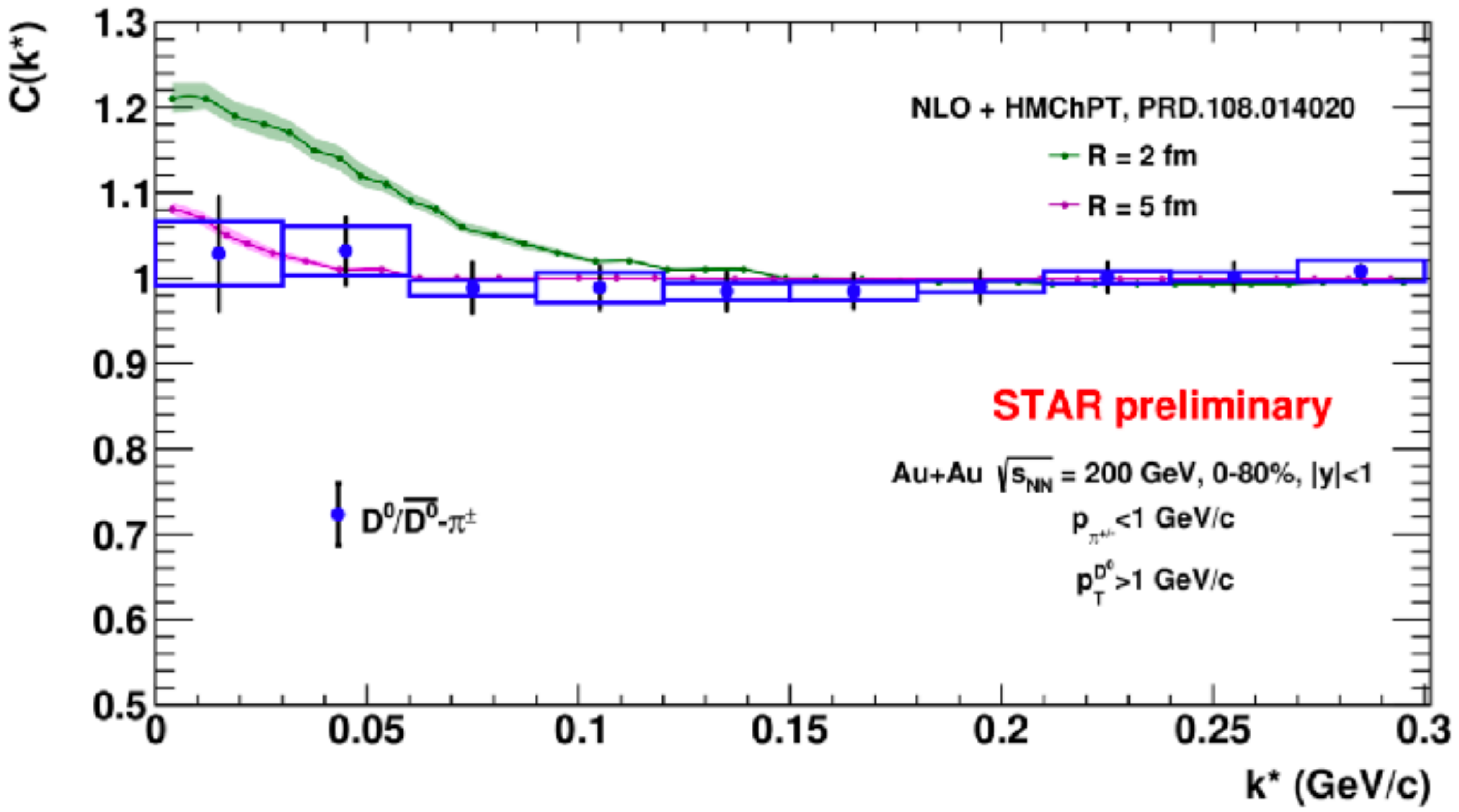


Figure 11: C(k*) for D⁰-π pairs with systematic uncertainties (boxes). Green and pink bands are theory predictions of C(k*) for D-π channel using source radii of 2 fm and 5 fm respectively

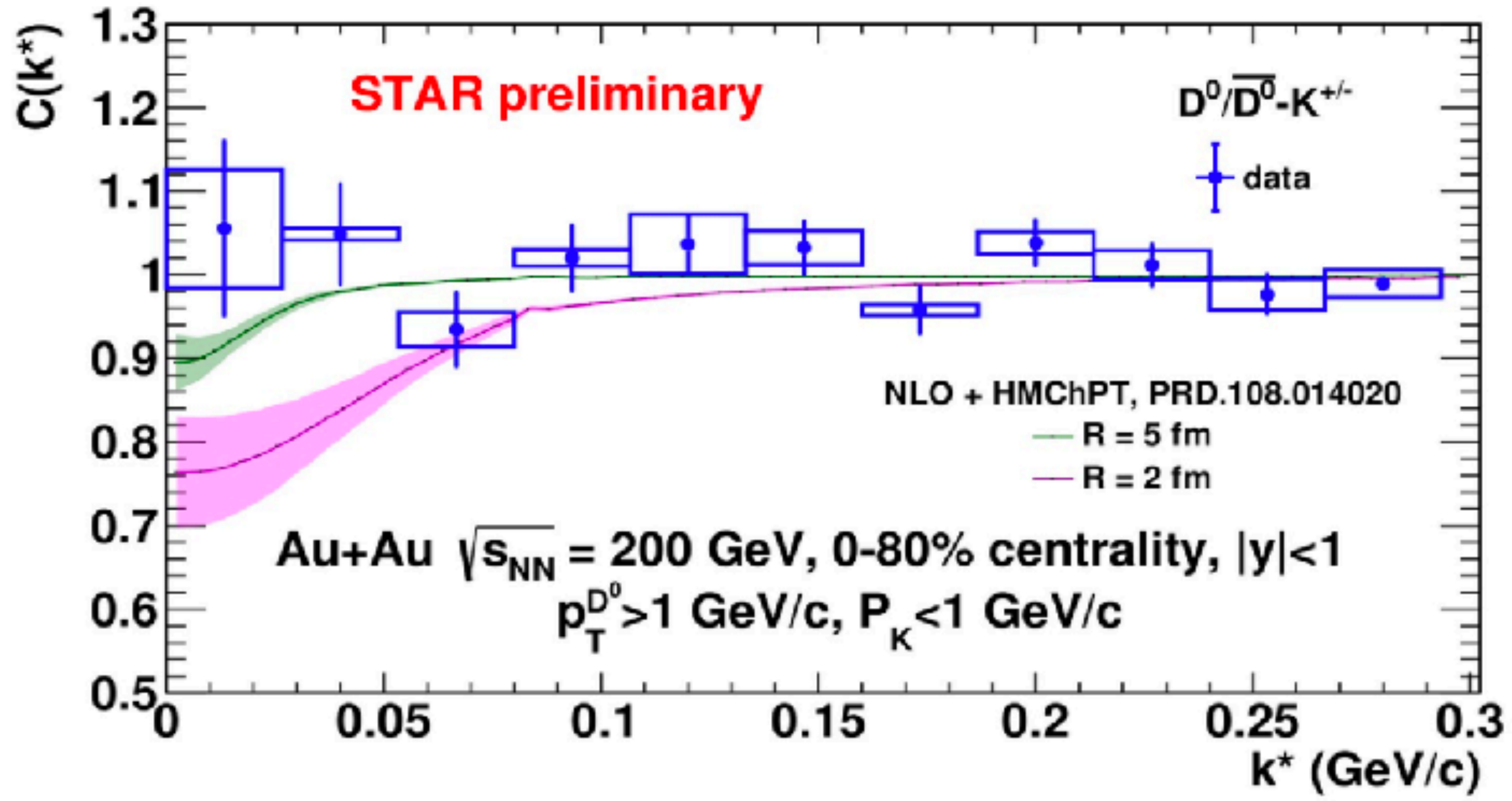


Figure 10: C(k*) for D⁰-K pairs with systematic uncertainties (boxes). Green and pink bands are theory predictions of C(k*) for D⁰-K⁺ channel using source radii of 5 fm and 2 fm respectively

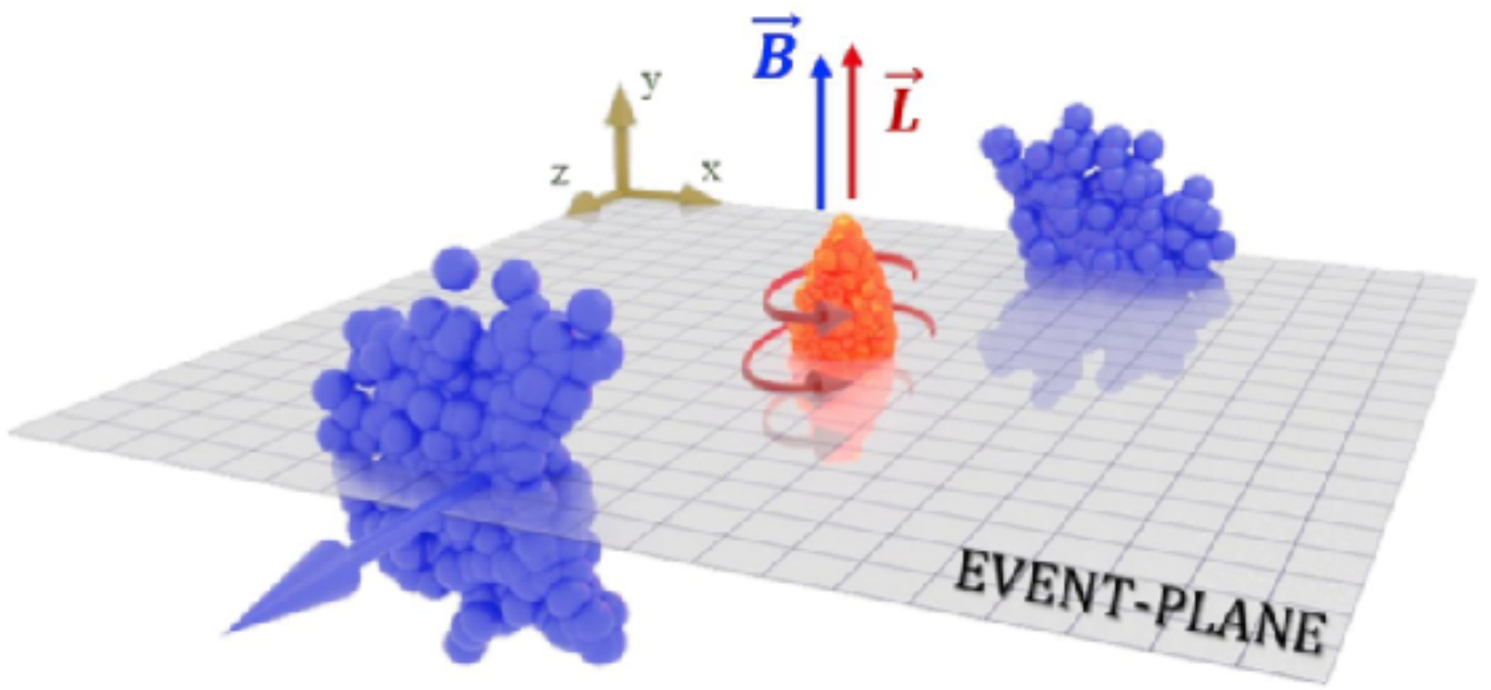
- STAR data does not observe significant correlations. It is consistent with theoretical model predictions with emission source size of 5 fm or large

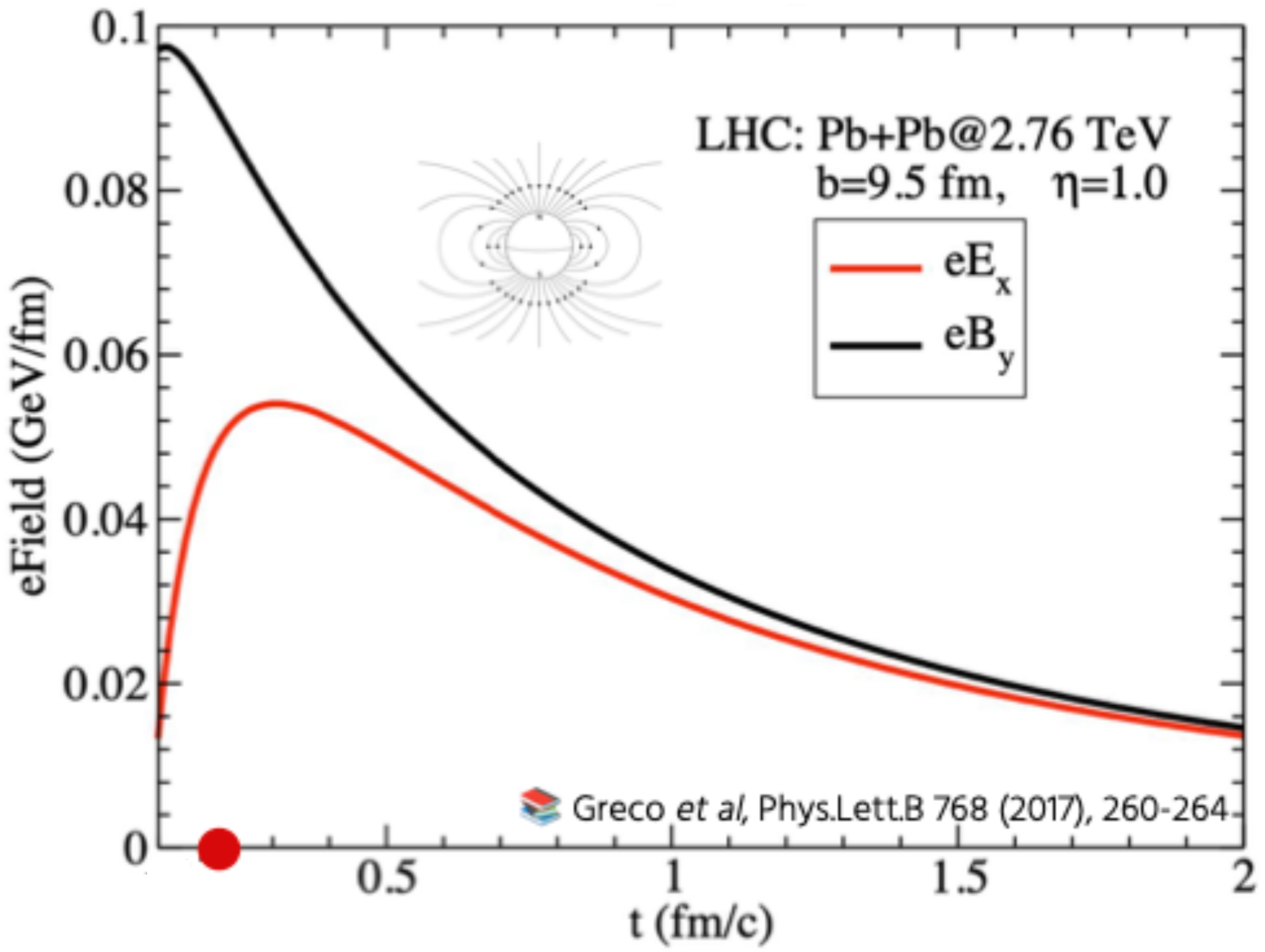
.

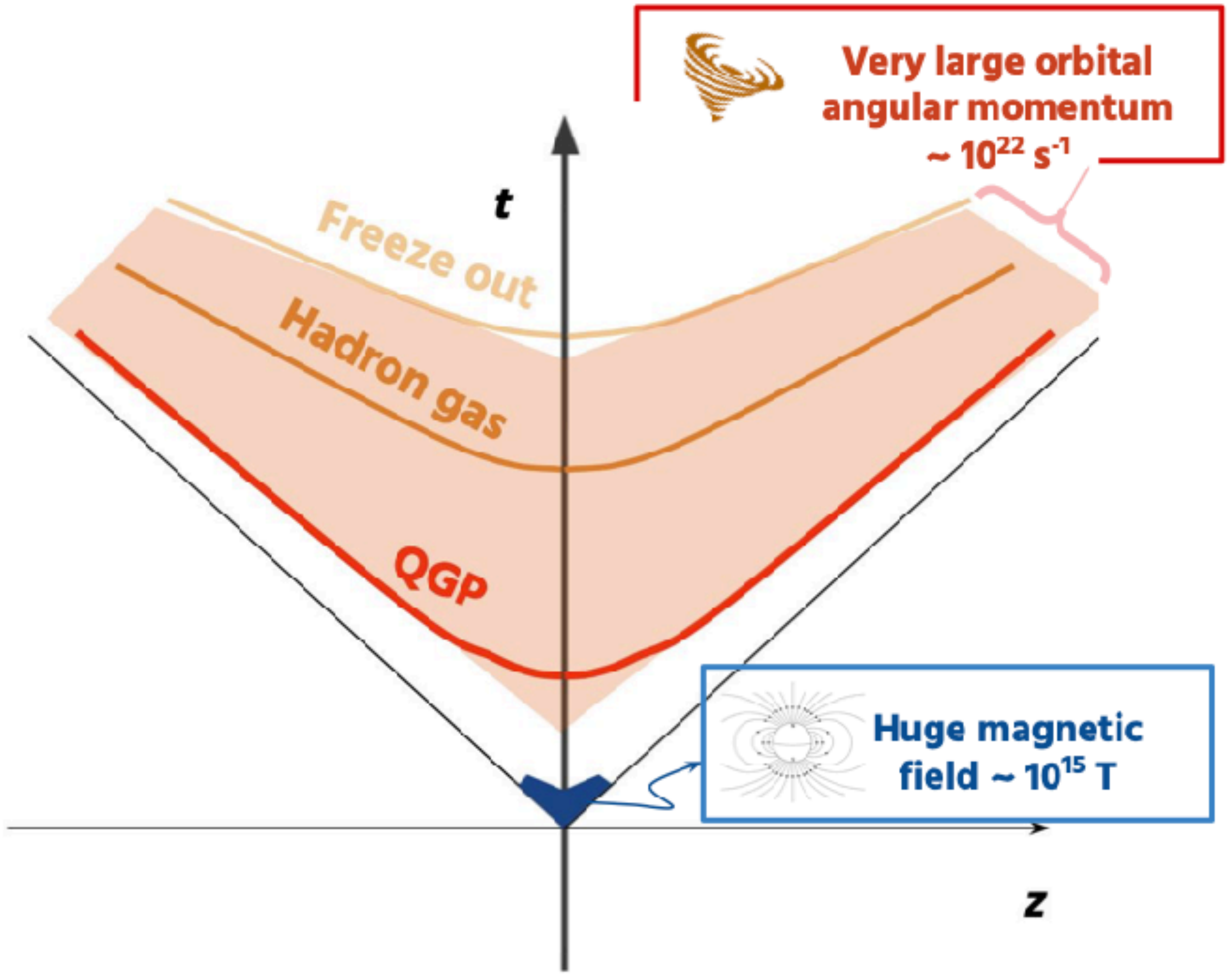
Early magnetic field and angular momentum

Talk. H. Sharma

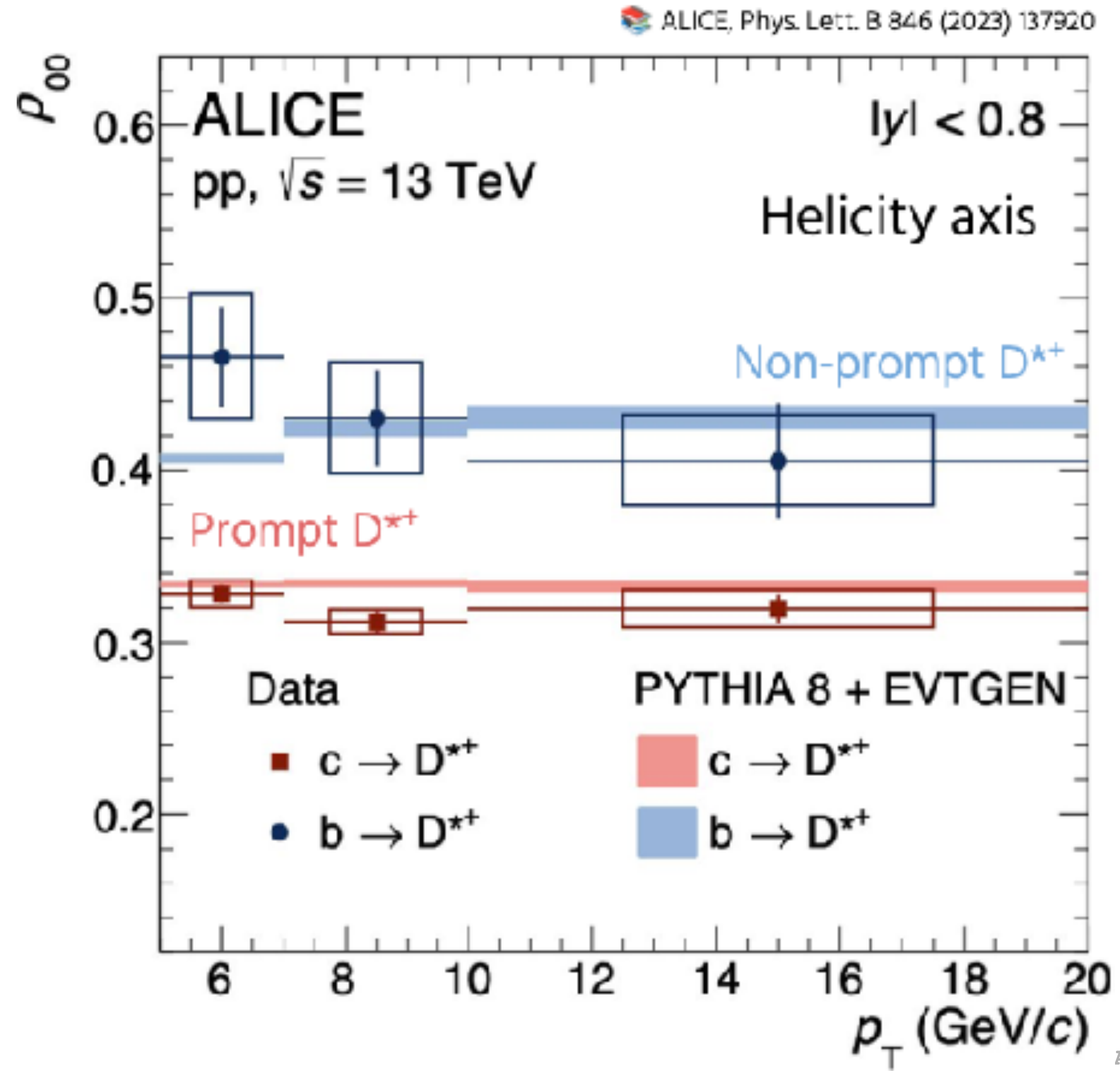
- In non-central collisions:
  - Charged spectator motion produces magnetic field (B) ~ 10^{15} T that decreases with time
  - A highly vortical system with orbital angular momentum (L) ~ 10^{22} s^{-1}
- L can align a particle's spin projection along the spin quantization axis through spin-orbit coupling
- Charm quark being produced in the early stages (t~1/m~0.1 fm/c) is more sensitive than light quarks to the EM field

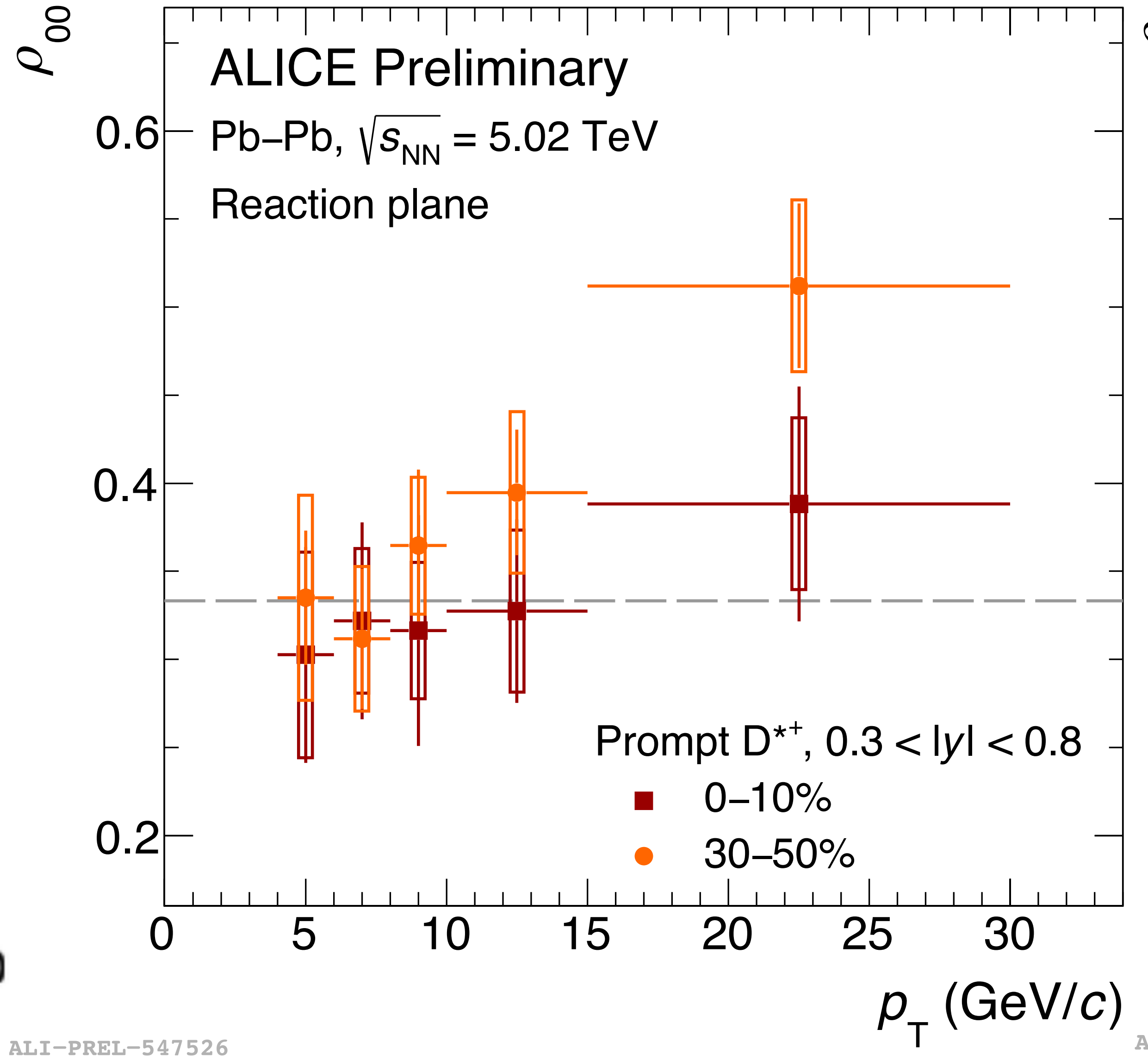


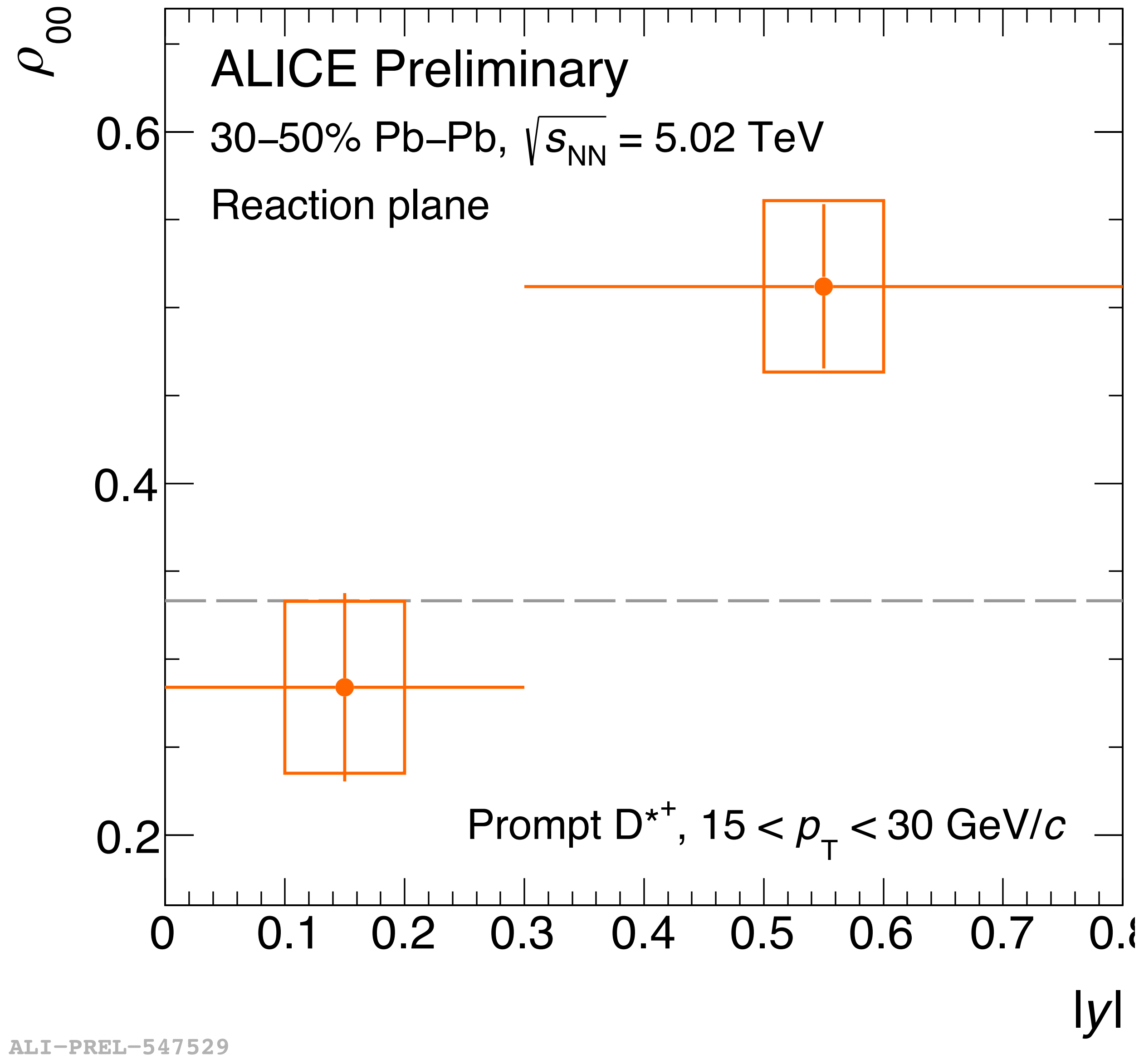


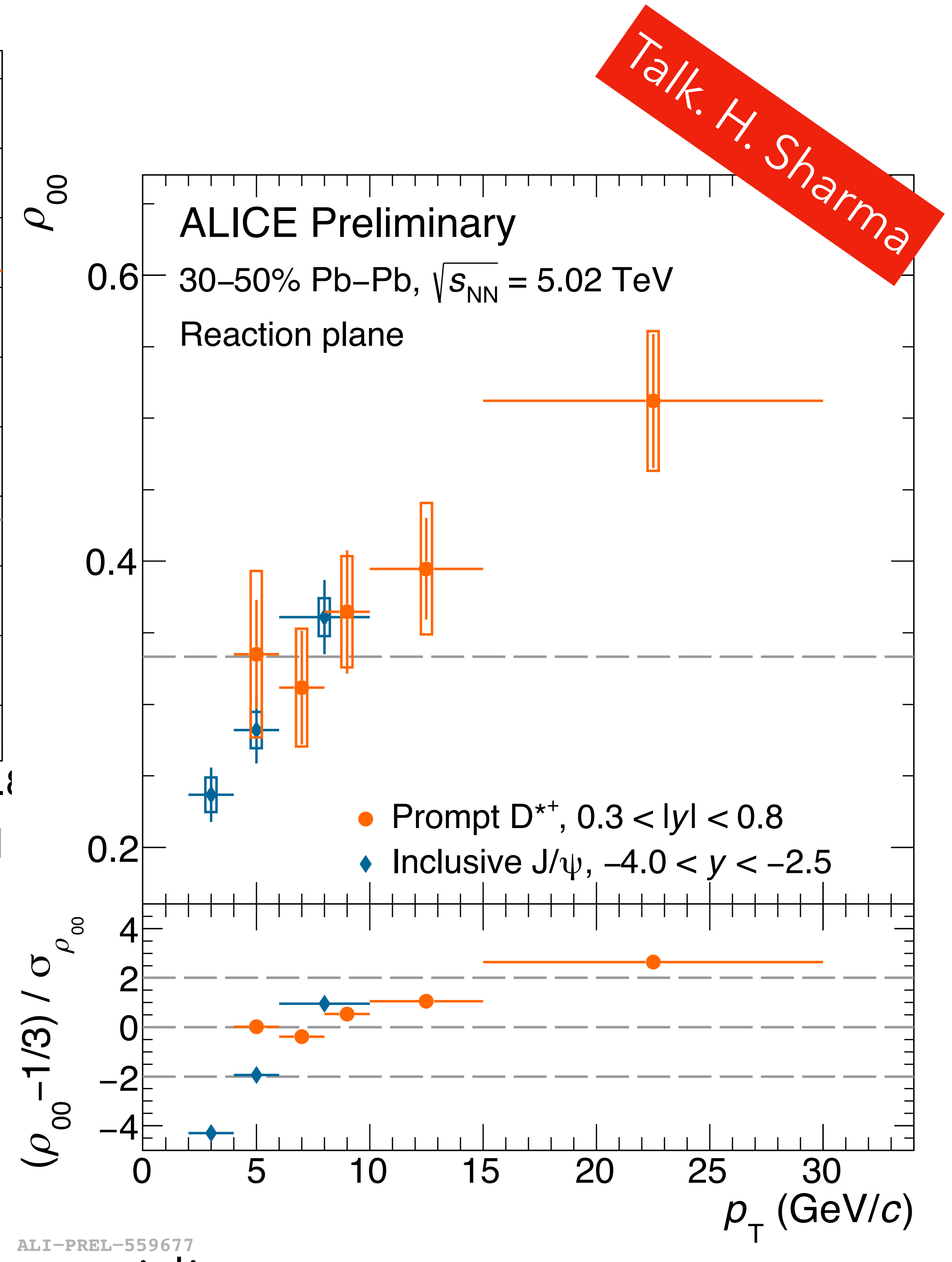


Spin alignment measurements in pp and PbPb collisions

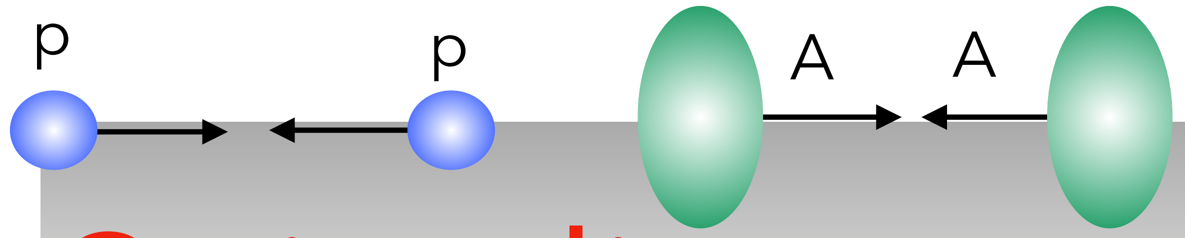




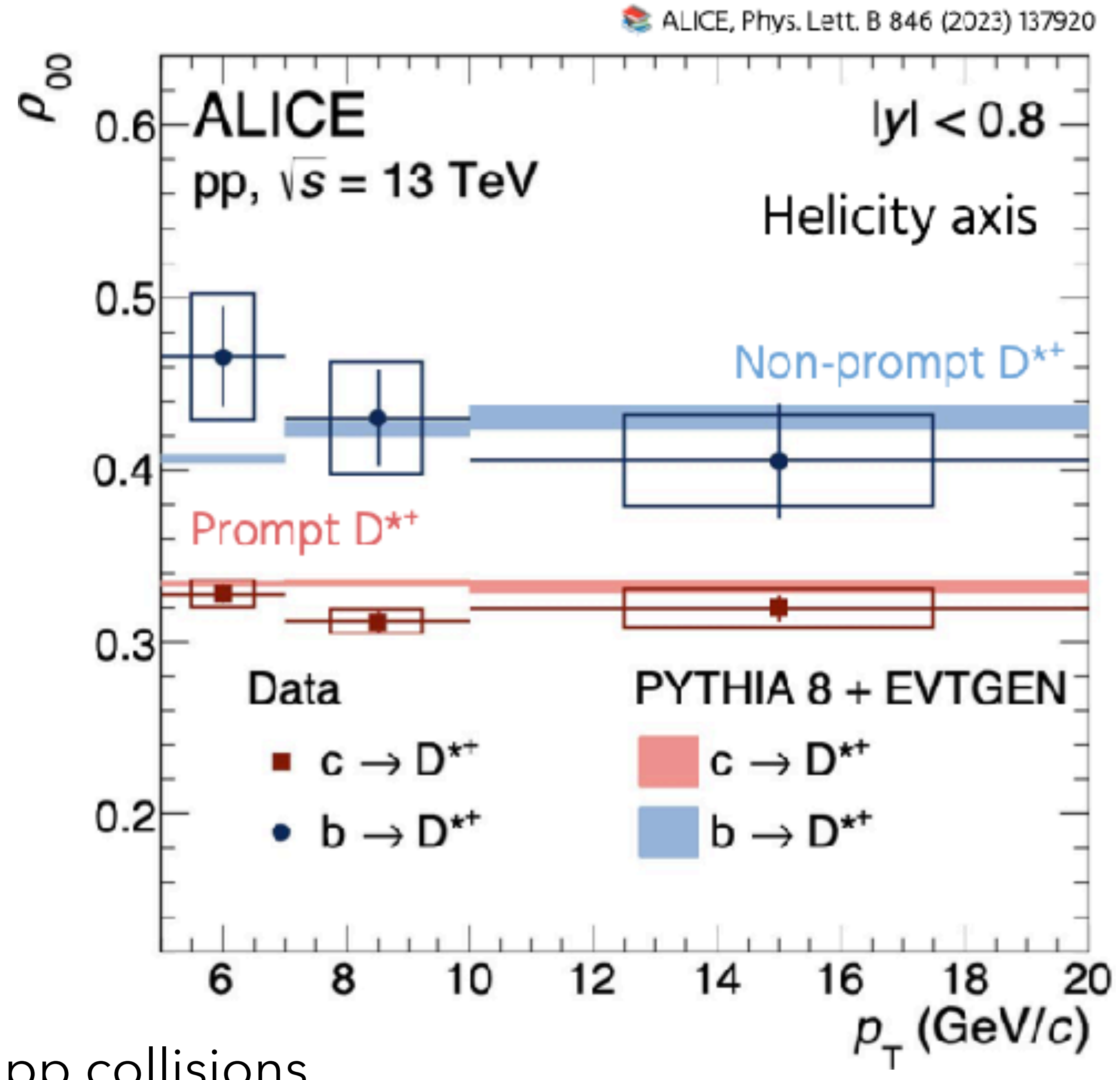




- Spin alignment ($\rho_{00} > 1/3$) observed for non-prompt D^{*+} in pp collisions.
  Consistent with PYTHIA+EVTGEN calculations.
- Hint of spin alignment ($\rho_{00} > 1/3$) at high p_T in 30-50% PbPb collisions, more pronounced at larger rapidity.
  Consistent with picture that B field decreases slowly at large rapidity.
- Similar results observed for J/ψ and D^{*+}.
  Low p_T J/ψ production affected by recombination. Interplay of recombination and fragmentation?

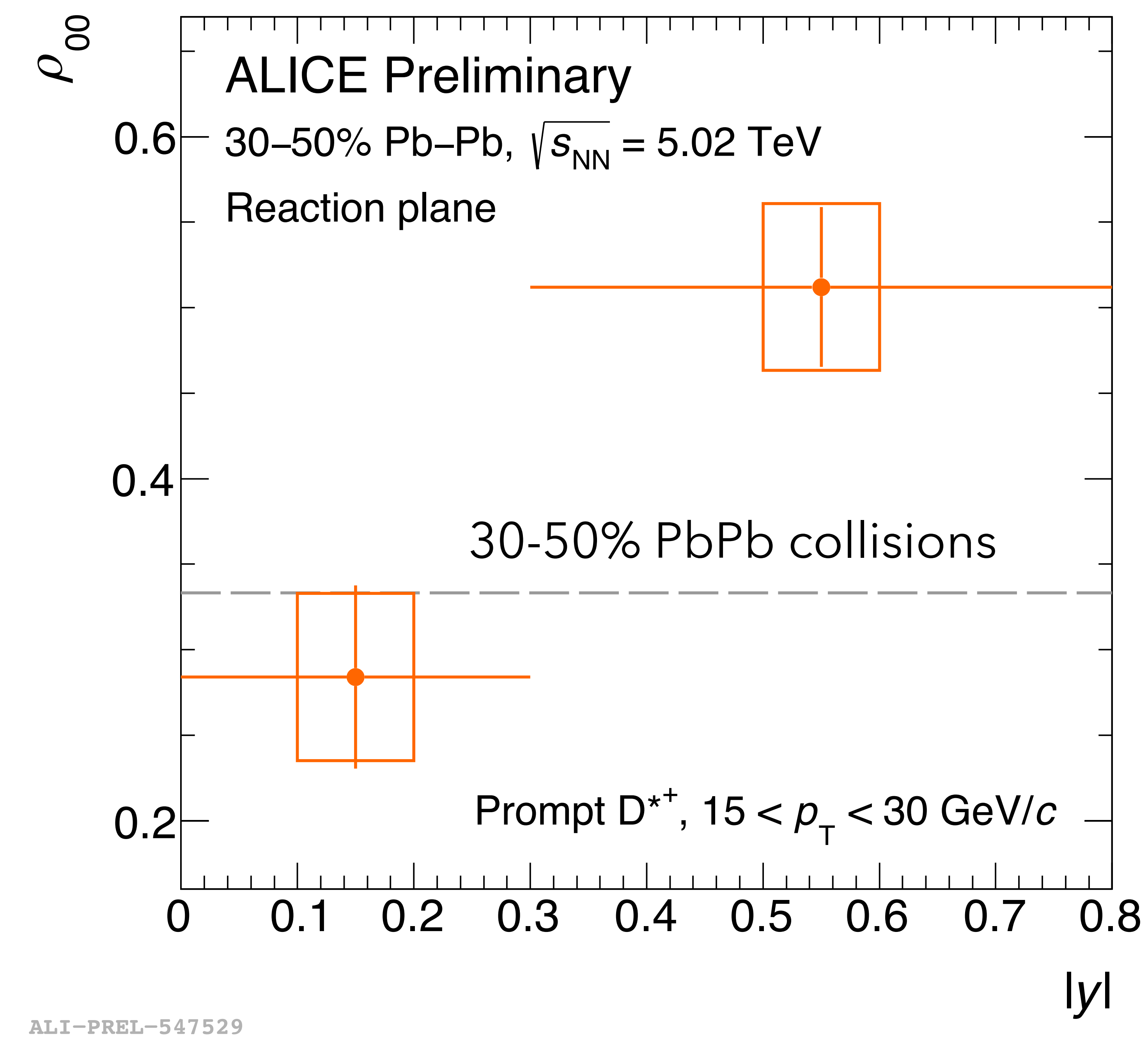


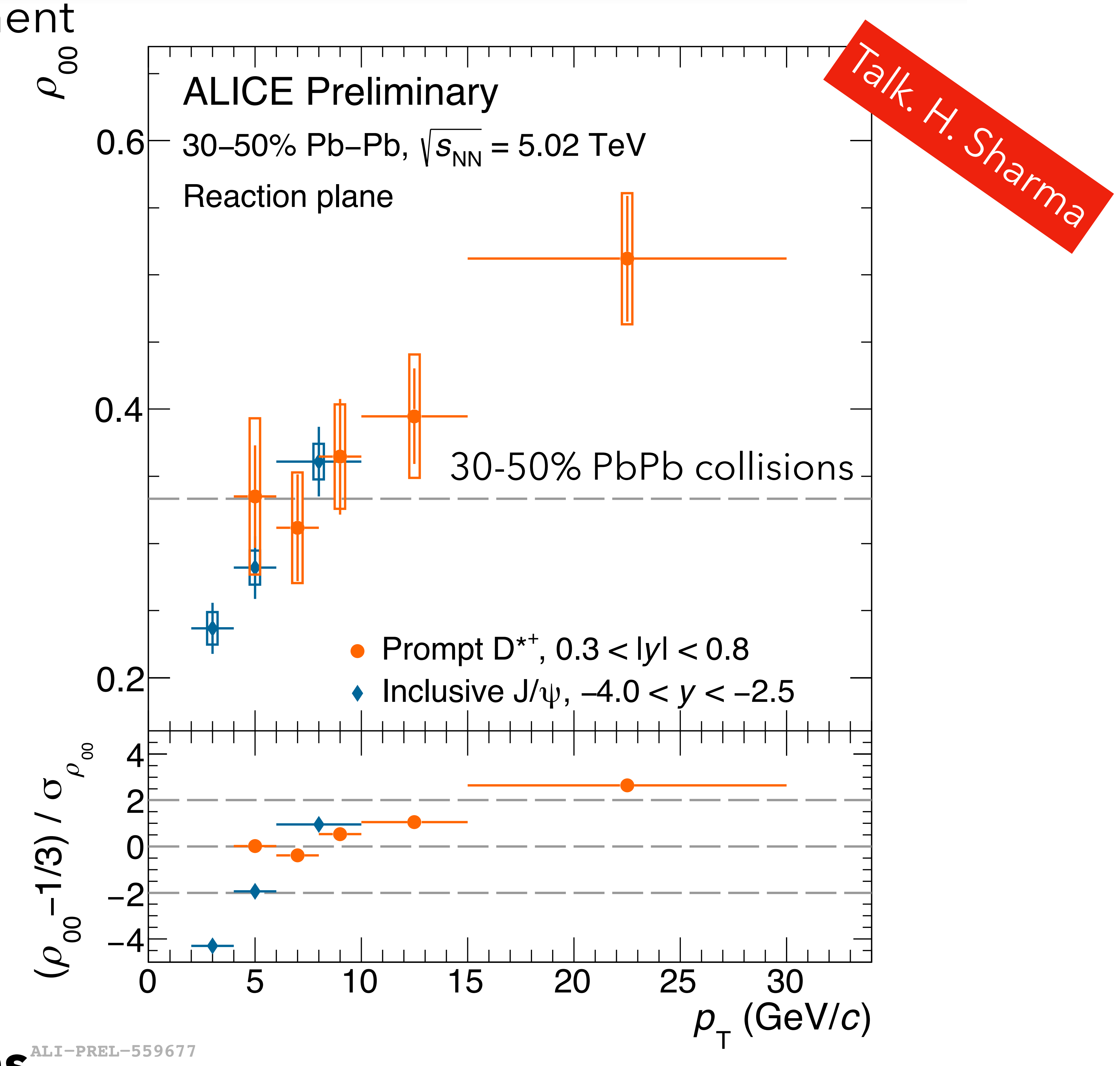
Spin alignment measurements in pp and PbPb collisions



pp collisions

Prompt and non-prompt D*+ spin alignment

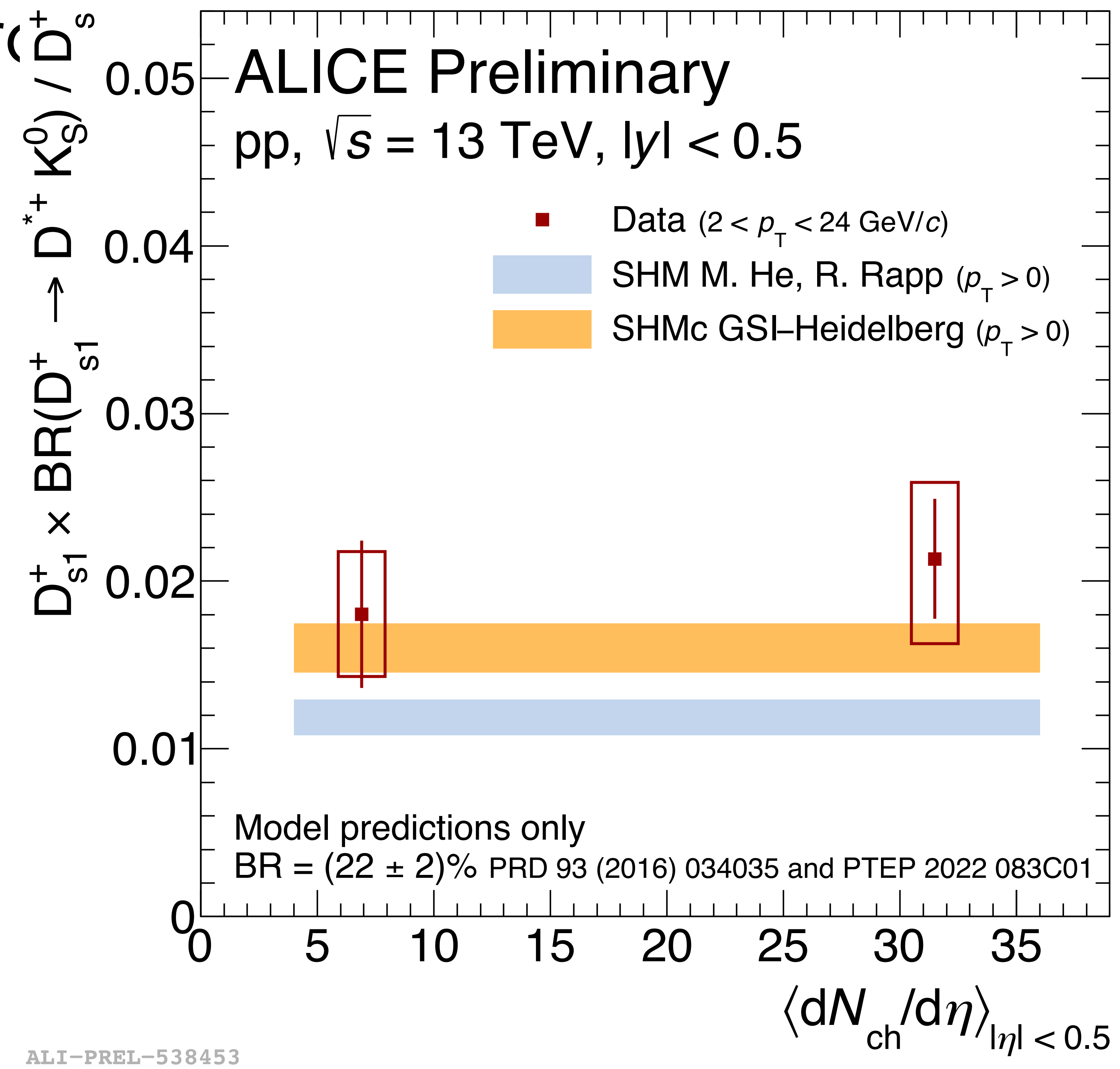


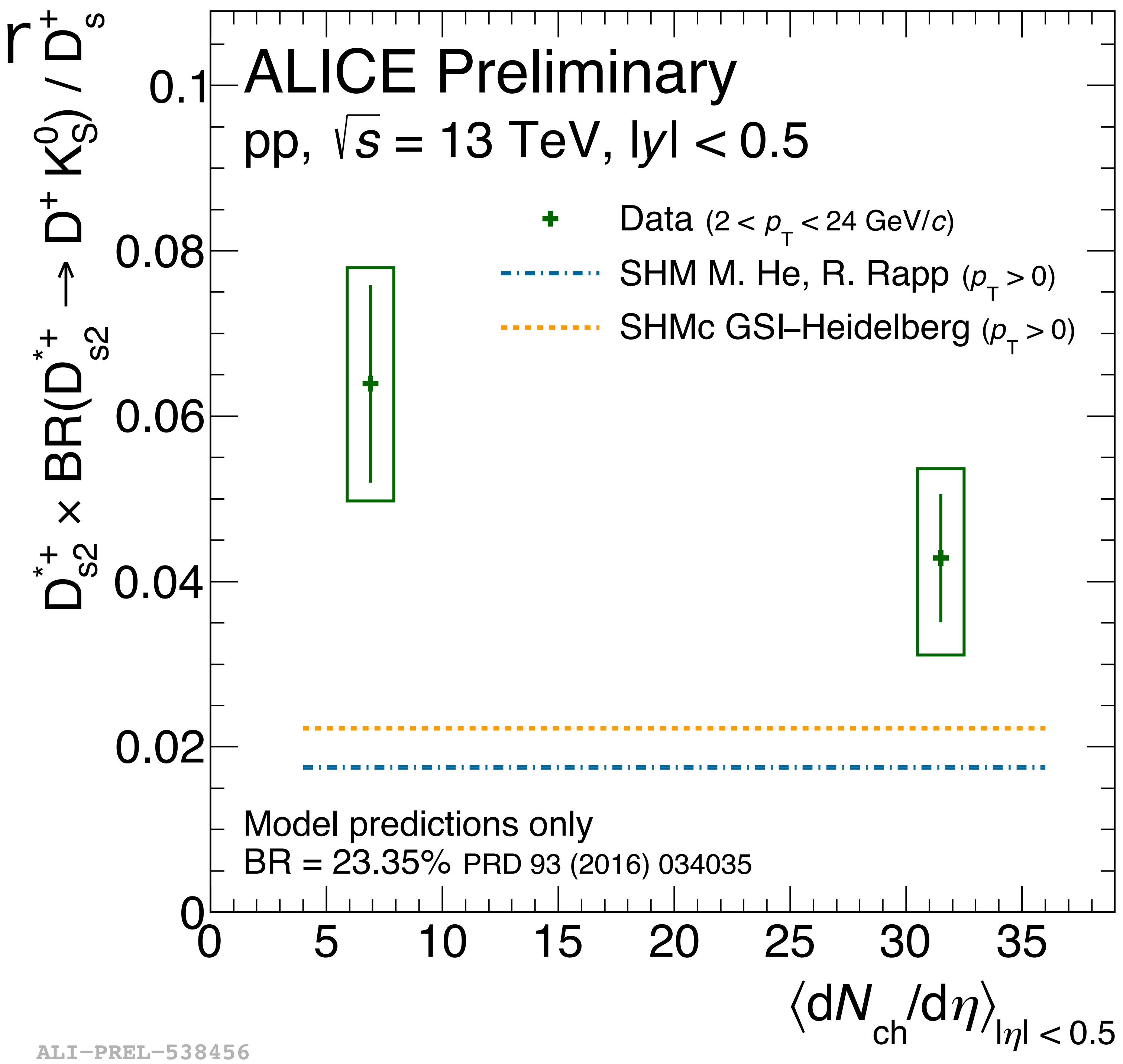


- Spin alignment ($\rho_{00} > 1/3$) observed for non-prompt D*+ in pp collisions. Consistent with PYTHIA+EVTGEN calculations.
- **Hint of spin alignment ($\rho_{00} > 1/3$) at high p_T in 30-50% PbPb collisions.**
- Similar results observed for J/ψ and D*+. Low p_T J/ψ production affected by recombination. Interplay of recombination and fragmentation?
- **Sensitive to the early magnetic field?**

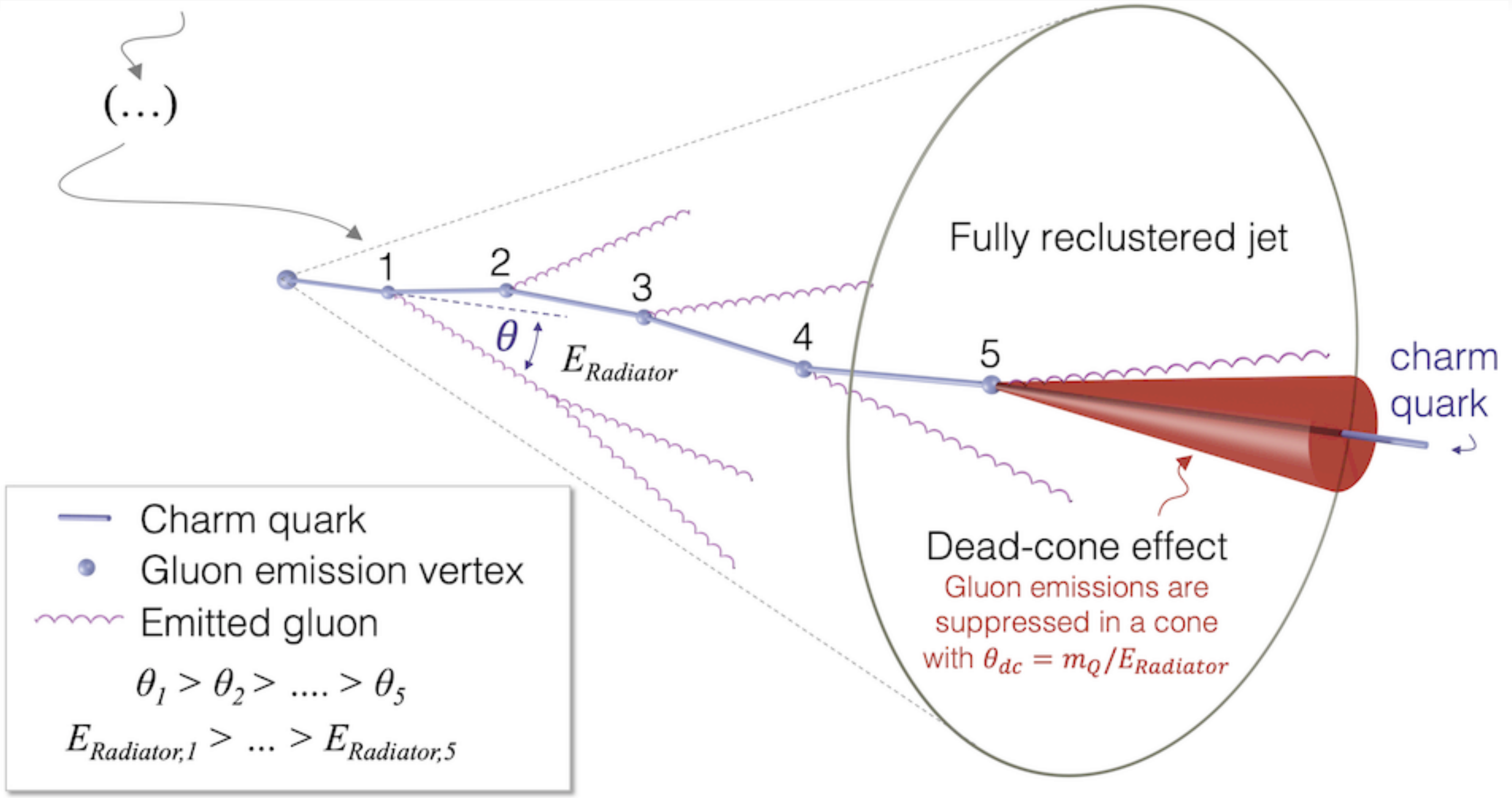
Ds excited states

- Excited to gr… v a r…





Gluon radiation in vacuum



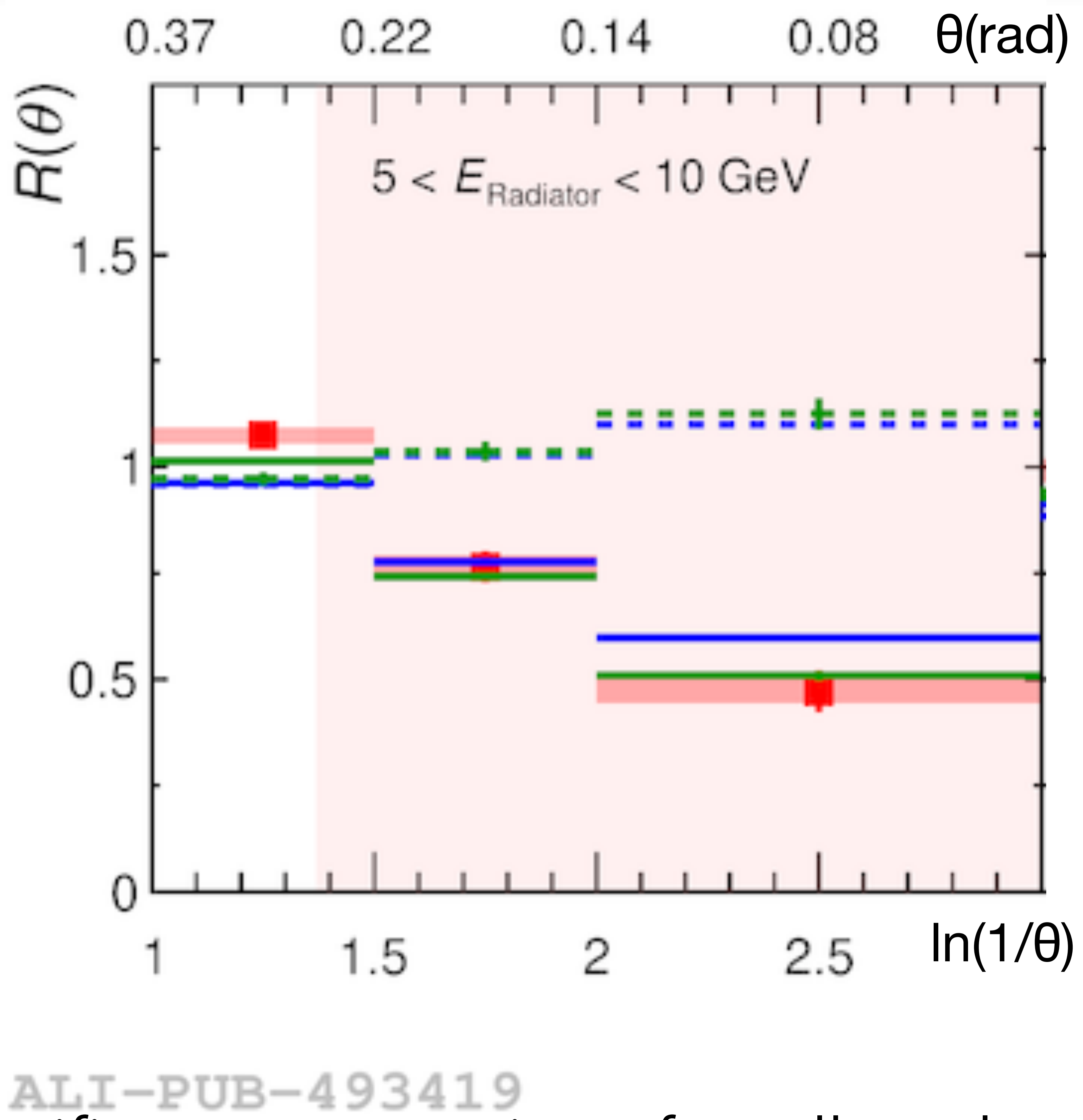
Sketch detailing the reconstruction of the showering charm quark, using iterative declustering.

- In vacuum, gluon radiation from heavy quarks is suppressed at small angles < $m_Q/E_{radiator}$ (pQCD).
- Reconstruction of parton shower of charm quarks possible via iterative declustering techniques according to the Cambridge-Aachen algorithm (based on angular distance).

L. Cunqueiro, M. Ploskon, Phys. Rev. D 99, 074027 (2019)
Y. Dokshitzer et al, JHEP 08 (1997) 001

ALICE, arXiv:2106.05713

Gluon radiation from heavy quarks in pp collisions



$$R(\theta) = \frac{1}{N^{D^0\,\text{jets}}}\frac{dn^{D^0\,\text{jets}}}{d\ln(1/\theta)} \Bigg/ \frac{1}{N^{\text{inclusive jets}}}\frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)}\Bigg|_{k_T, E_{\text{radiator}}}$$

- ALICE Data
- PYTHIA 8
- SHERPA
- PYTHIA 8 LQ / inclusive no dead-cone limit
- SHERPA LQ / inclusive no dead-cone limit

pp $\sqrt{s}$ = 13 TeV

charged jets, anti-k_T, R=0.4

C/A reclustering

$p_{T,\text{inclusive jet}}^{\text{ch,leading track}} \geq 2.8$ GeV/c

$k_T > \Lambda_{QCD}$, Λ_{QCD} = 200 MeV/c

$|\eta_{lab}| < 0.5$

$\theta_{\text{dead-cone}} < m_c/E_{\text{radiator}}$

ALICE, arXiv:2106.05713

- Significant suppression of small-angle splittings for D^0-tagged jets.
- **Direct observation of dead-cone effect in QCD.**
  - insight into the influence of mass effects on jet properties and constraints for MC.
  - possibility to constrain quark masses experimentally ?