Hadronisation of heavy quarks in pp collisions with ALICE at the LHC

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ALICE

Physics Motivations

- **Charm** and **beauty** quarks: $\mathbf{m_c} \sim 1.3$ GeV / c^2, $\mathbf{m_b} \sim 4.2$ GeV / c^2
- Produced in hard-scattering processes
- The production of heavy-flavour hadrons in hadronic collisions can be described by the factorisation approach

$$\frac{d\sigma^{\mathrm{D}}}{dp_{\mathrm{T}}^{\mathrm{D}}}\left(p_{\mathrm{T}};\mu_{\mathrm{F}};\mu_{\mathrm{R}}\right) = PDF\left(x_1,\mu_{\mathrm{F}}\right) PDF\left(x_2,\mu_{\mathrm{F}}\right) \otimes \frac{d\sigma^{\mathrm{c}}}{dp_{\mathrm{T}}^{\mathrm{c}}}\left(x_1,x_2,\mu_{\mathrm{R}},\mu_{\mathrm{F}}\right) \otimes D_{\mathrm{c}\to\mathrm{D}}\left(z=p_{\mathrm{D}}/p_{\mathrm{c}},\mu_{\mathrm{F}}\right)$$

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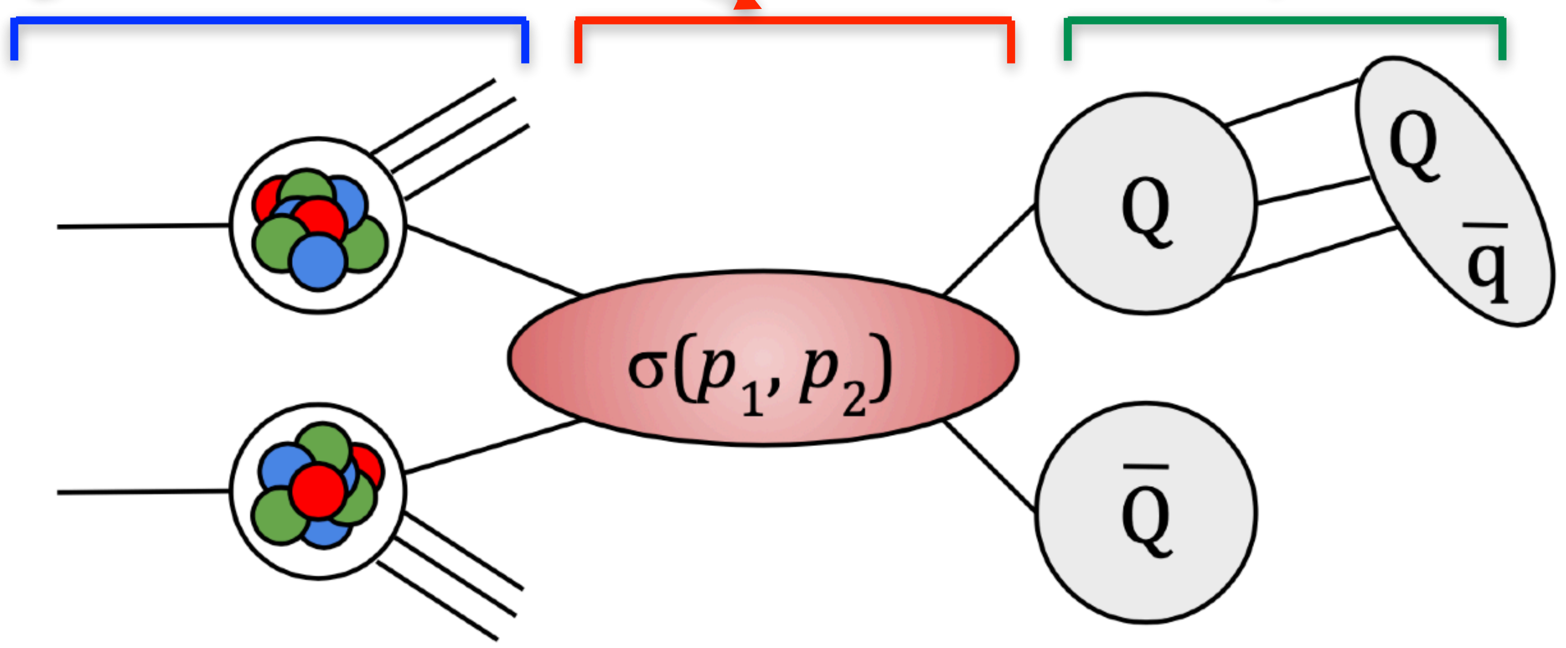
Parton distribution functions (PDFs)

Hard scattering cross section (pQCD)

Fragmentation function (hadronisation)

- Test of perturbative QCD calculations



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Parton distribution functions (PDFs)

Hard scattering cross section (pQCD)

Fragmentation function (hadronisation)

- The yield ratios of hadrons are sensitive to the heavy-flavour hadronisation process
- Measurement of fragmentation fractions (FF)

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Parton distribution functions (PDFs)

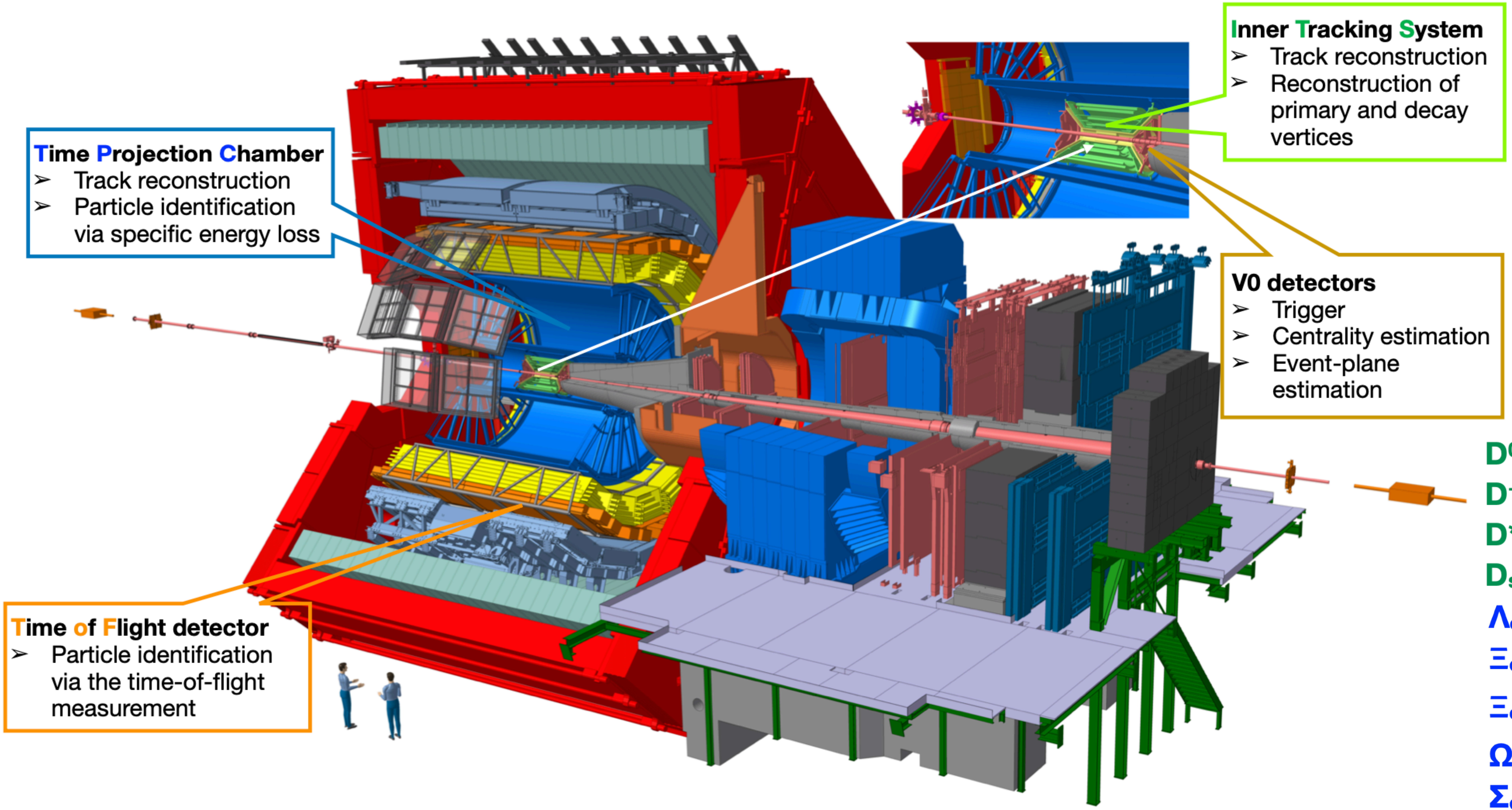
Hard scattering cross section (pQCD)

Fragmentation function (hadronisation)

pp collisions

- Reference for p-Pb and Pb-Pb collisions
- Test of pQCD calculations
- Study hadronisation

ALICE Detector

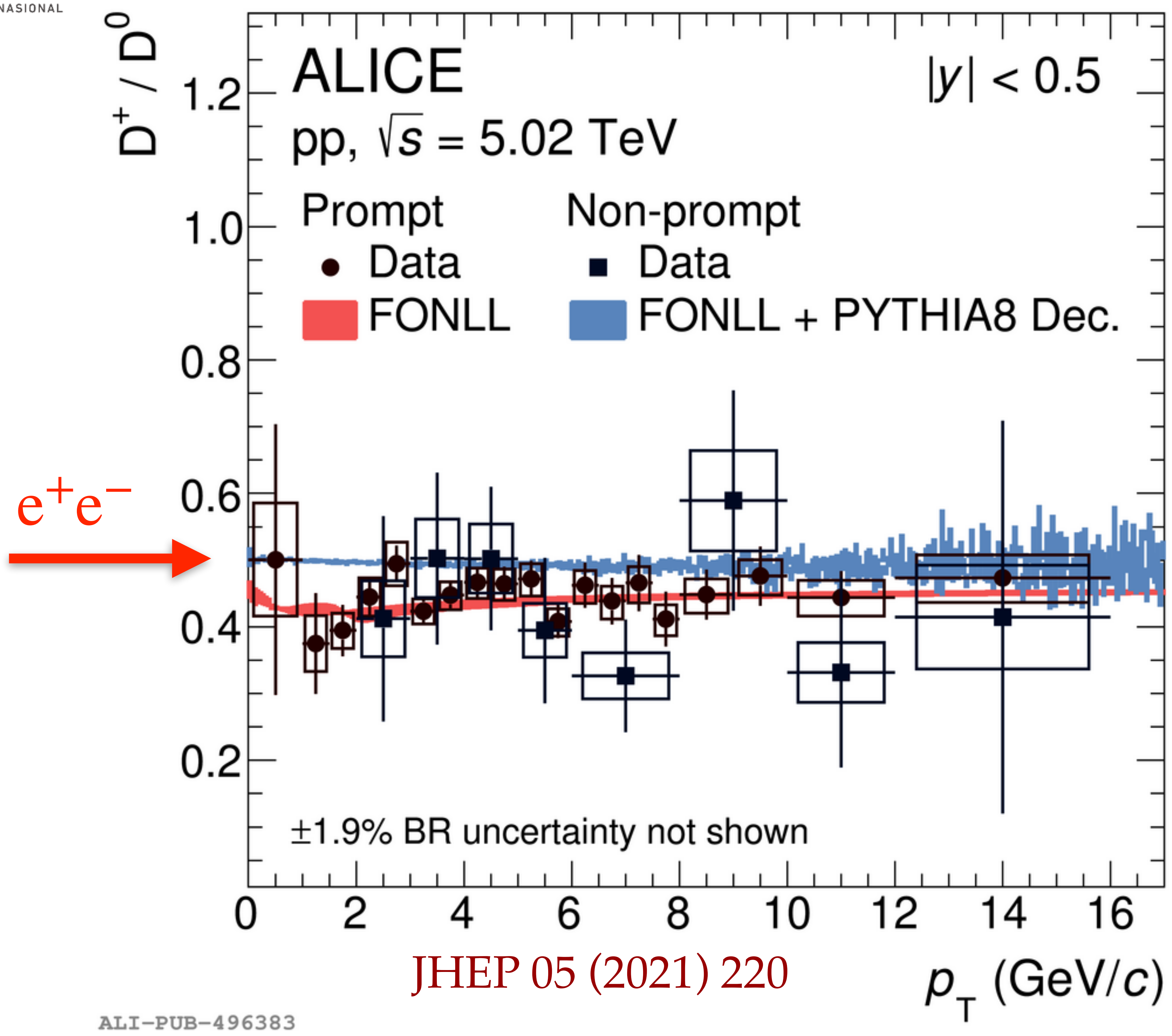


Mesons
- $D^0 \rightarrow K^-\pi^+$,
- $D^+ \rightarrow K^-\pi^+\pi^+$,
- $D^{*+} \rightarrow D^0\pi^+$
- $D_s^+ \rightarrow \Phi\ \pi^+ \rightarrow K^-K^+\pi^+$

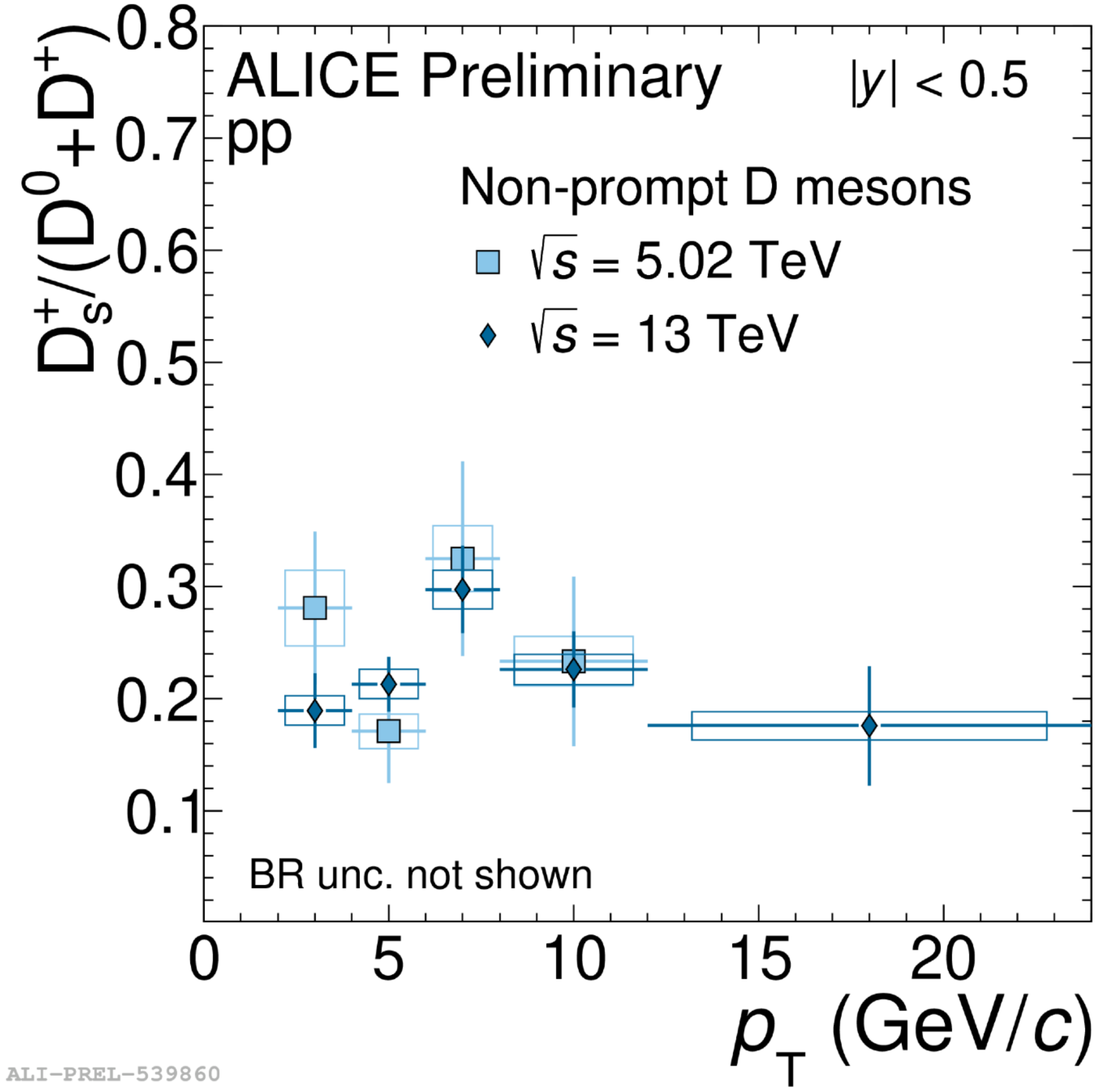
Baryons
- $\Lambda_c^+ \rightarrow \pi^+K^-p$, $\Lambda_c^+ \rightarrow K_0^s\ p$
- $\Xi_c^+ \rightarrow \pi^+\pi^+\Xi^-$
- $\Xi_c^0 \rightarrow \pi^+\Xi^-$
- $\Omega_c^0 \rightarrow \pi^+\Omega^-$
- $\Sigma_c^{0,++} \rightarrow \Lambda_c^+\pi^{-,+}$

- Prompt: $c \rightarrow D^0, \Lambda_c^+, \ldots$
- Non-prompt: $B_H \rightarrow D^0, \Lambda_c^+, \ldots$

Charm and beauty mesons

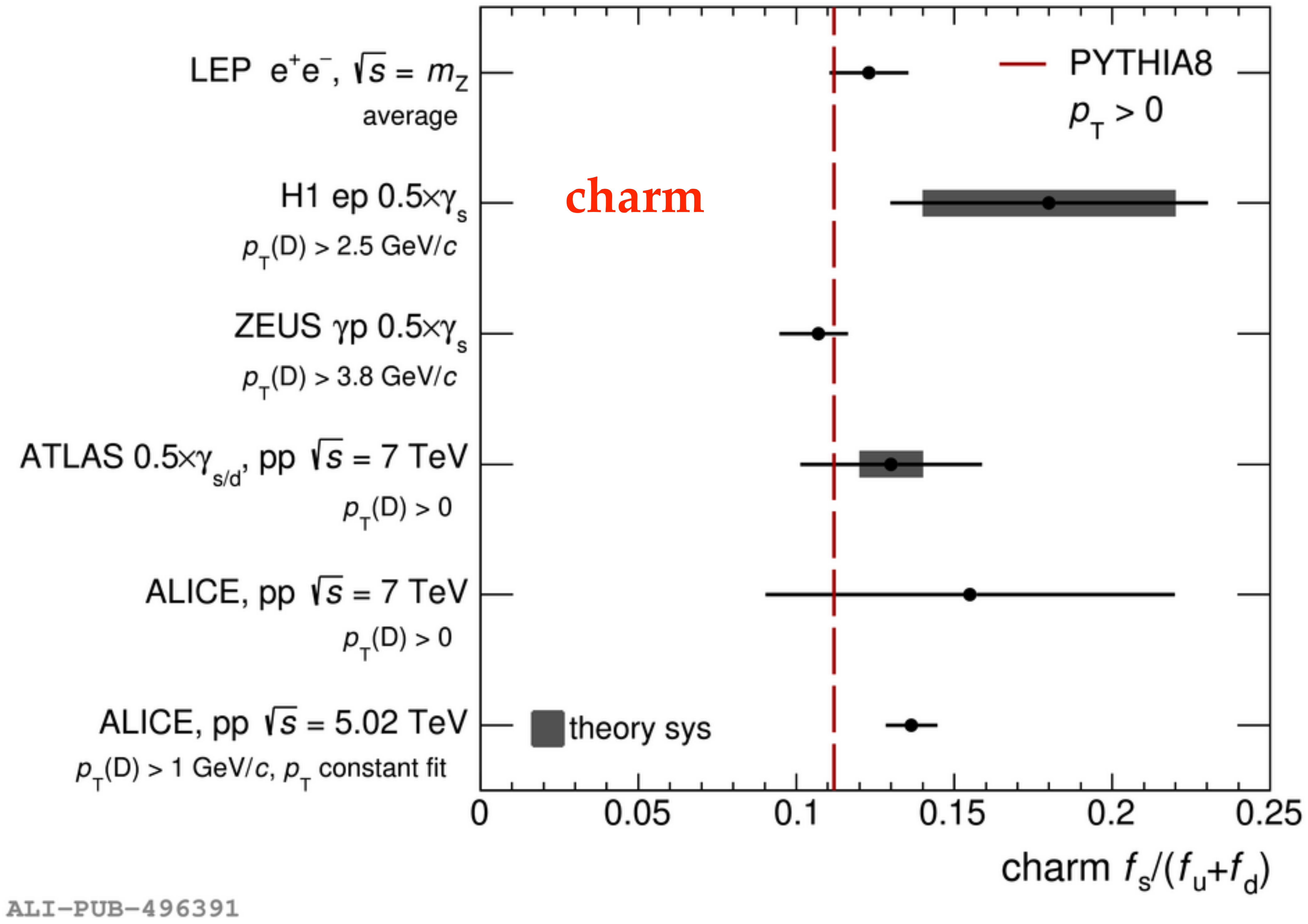


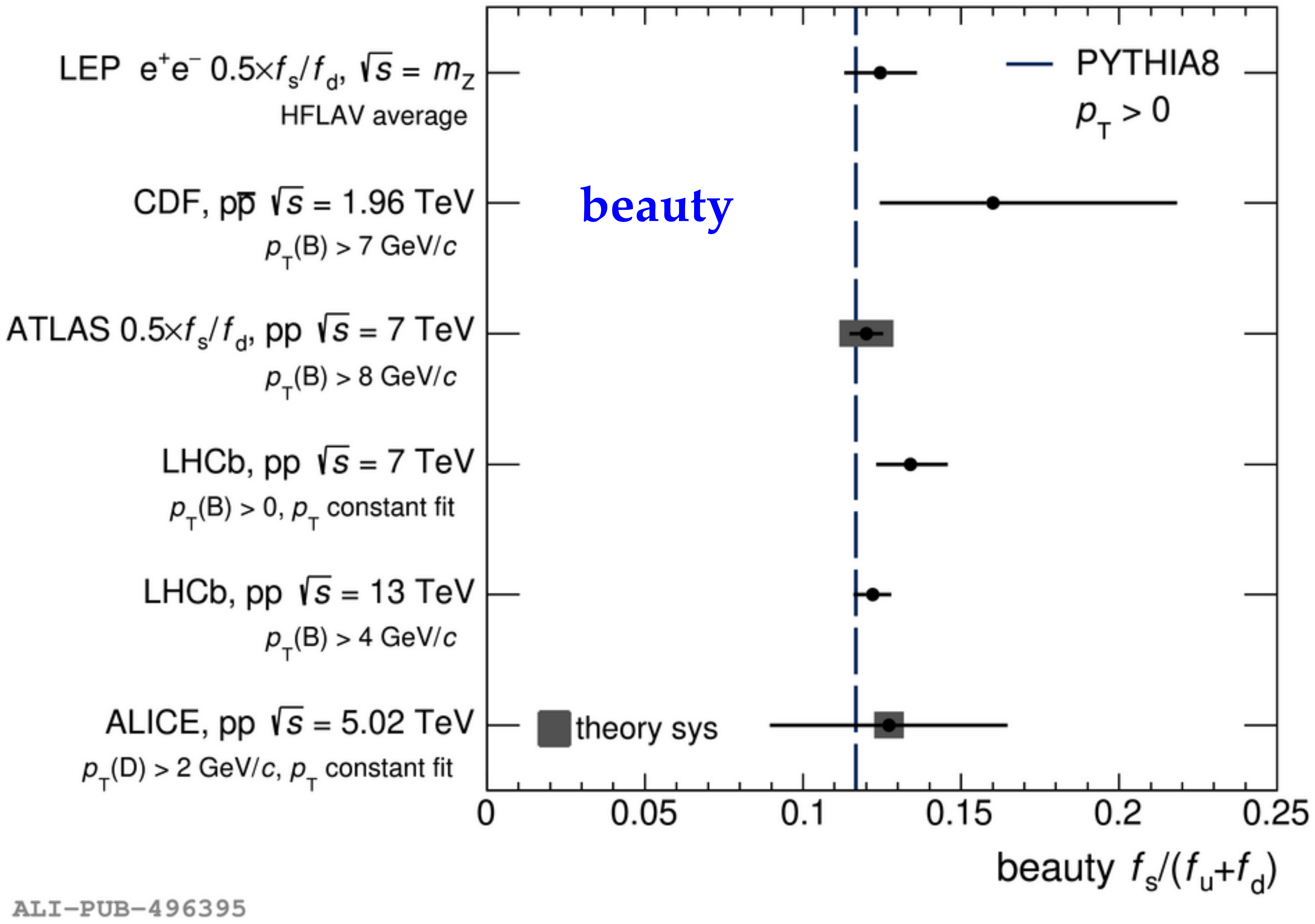
JHEP 05 (2021) 220



- No significant p_T-dependence
- Good agreement with models that use FF tuned on leptonic collisions and with measurements at e^+e^- colliders
- Meson-to-meson yield ratios independent of p_T and collisions energies
- Non-prompt D-meson production measured down to low p_T (D_s^+ down to $p_T = 2$ GeV/c) -> access to beauty-meson production mechanisms

Charm and beauty fragmentation to mesons

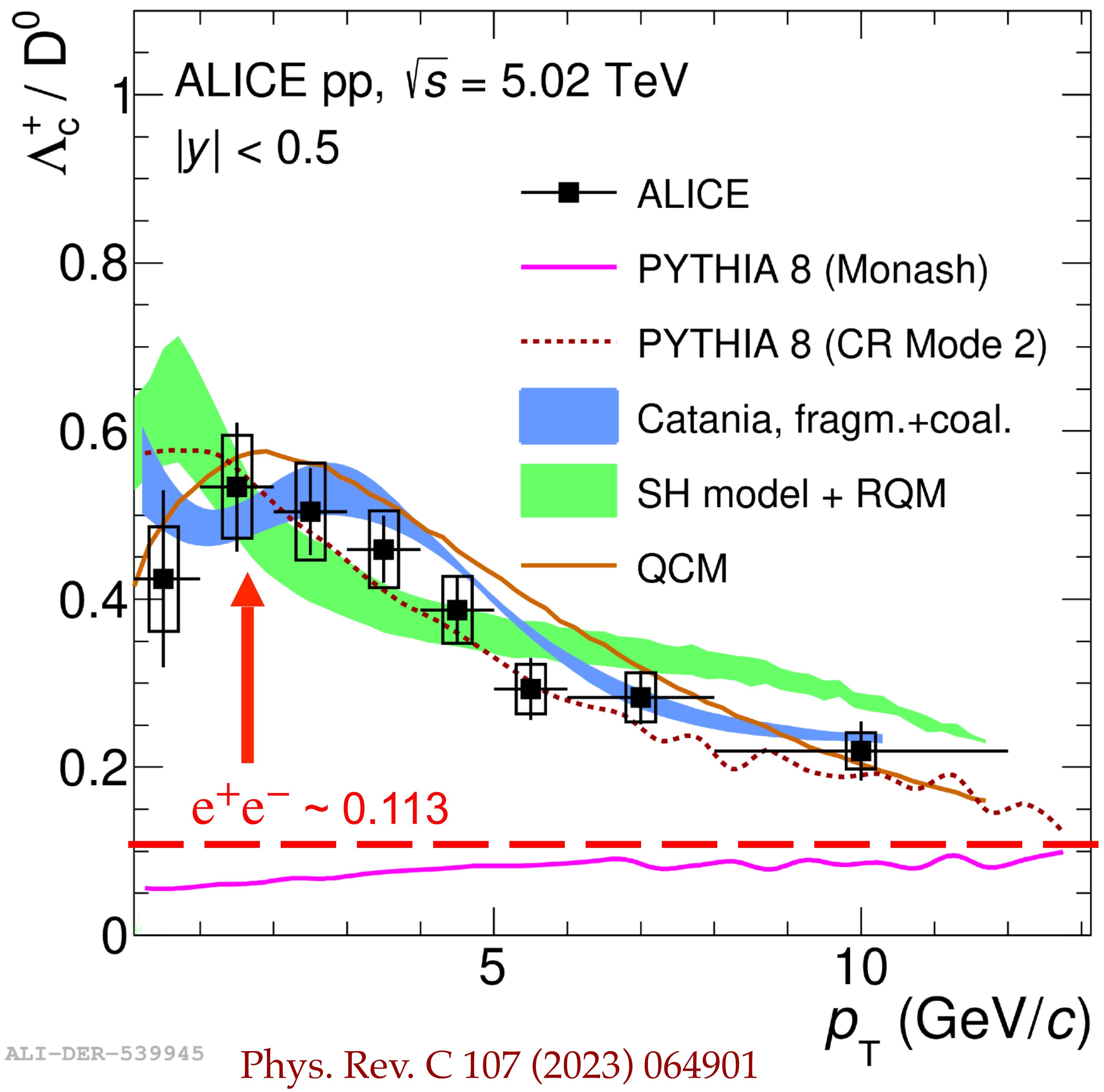




JHEP 05 (2021) 220

- Fragmentation fraction ratios for charm and beauty mesons are well described by PYTHIA8 predictions (with FF tuned on e^+e^-)
- No significant dependence on energy and collision systems
  - From $e^+e^-$and ep to hadronic collisions

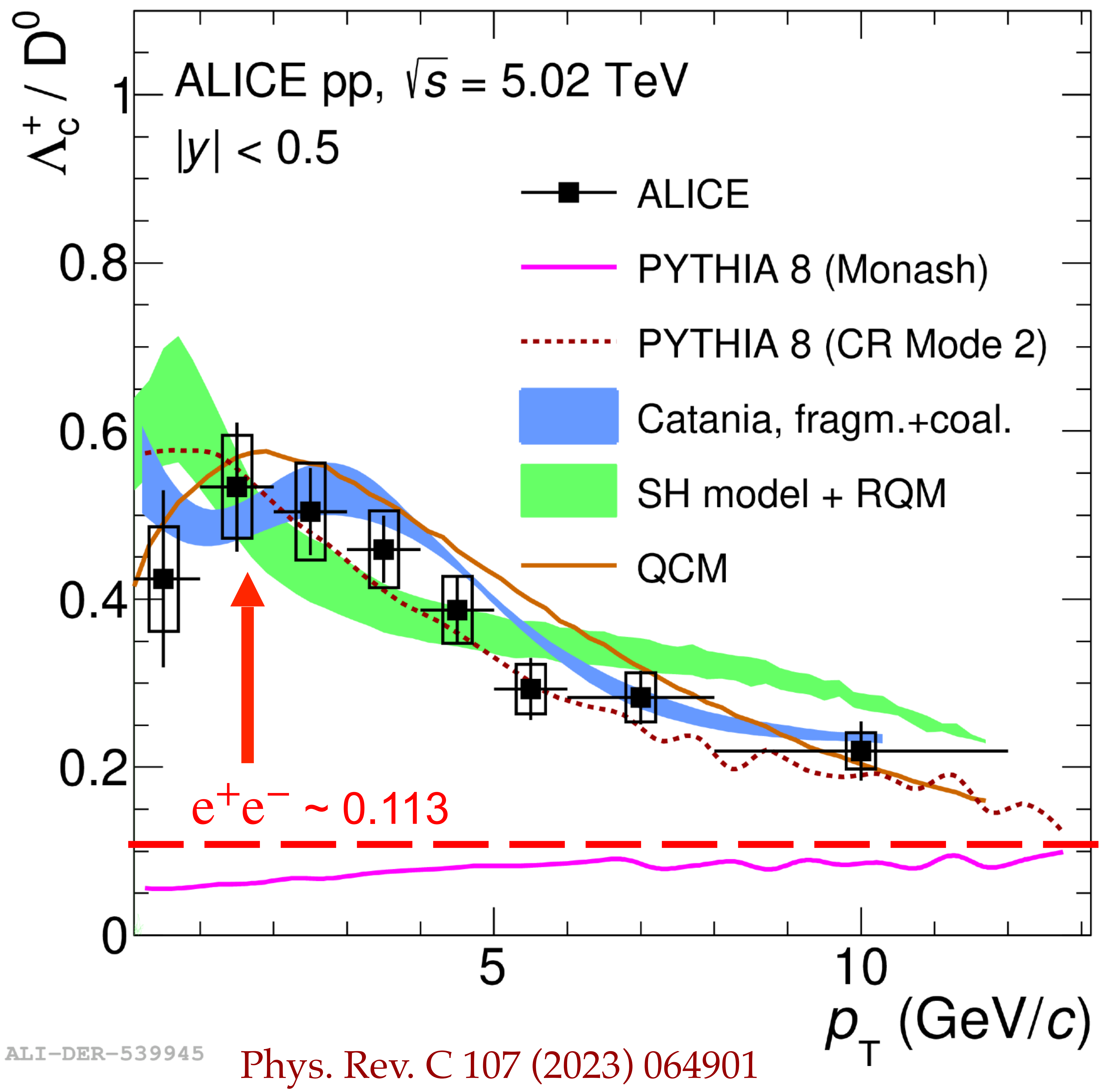
Charm baryon-to-meson ratios



Phys. Rev. C 107 (2023) 064901

- Λ_c^+/D^0 ratios significantly higher than e^+e^- results (LEP average: 0.113 ± 0.013 ± 0.006) EPJC 75 (2015) 19
- p_T dependence observed, not present in e^+e^- results
- PYTHIA8 Monash
  Λ_c^+/D^0 ratio at low p_T larger than what predicted by string fragmentation models tuned on e^+e^- data
- Models which introduce a modified hadronisation with respect to in-vacuum fragmentation describe instead the data: PYTHIA8 (CR Mode 2), Catania, SHM+RQM, and QCM
- PYTHIA8 (CR Mode 2)
  Colour reconnection mechanisms beyond leading colour (BLC) approximation with new junction topologies that favour baryon formation JHEP 1508 (2015) 003
- Catania
  - thermalised system of u,d,s and gluons PLB 821 (2021) 136622
  - hadronisation via interplay of fragmentation and coalescence

Charm baryon-to-meson ratios



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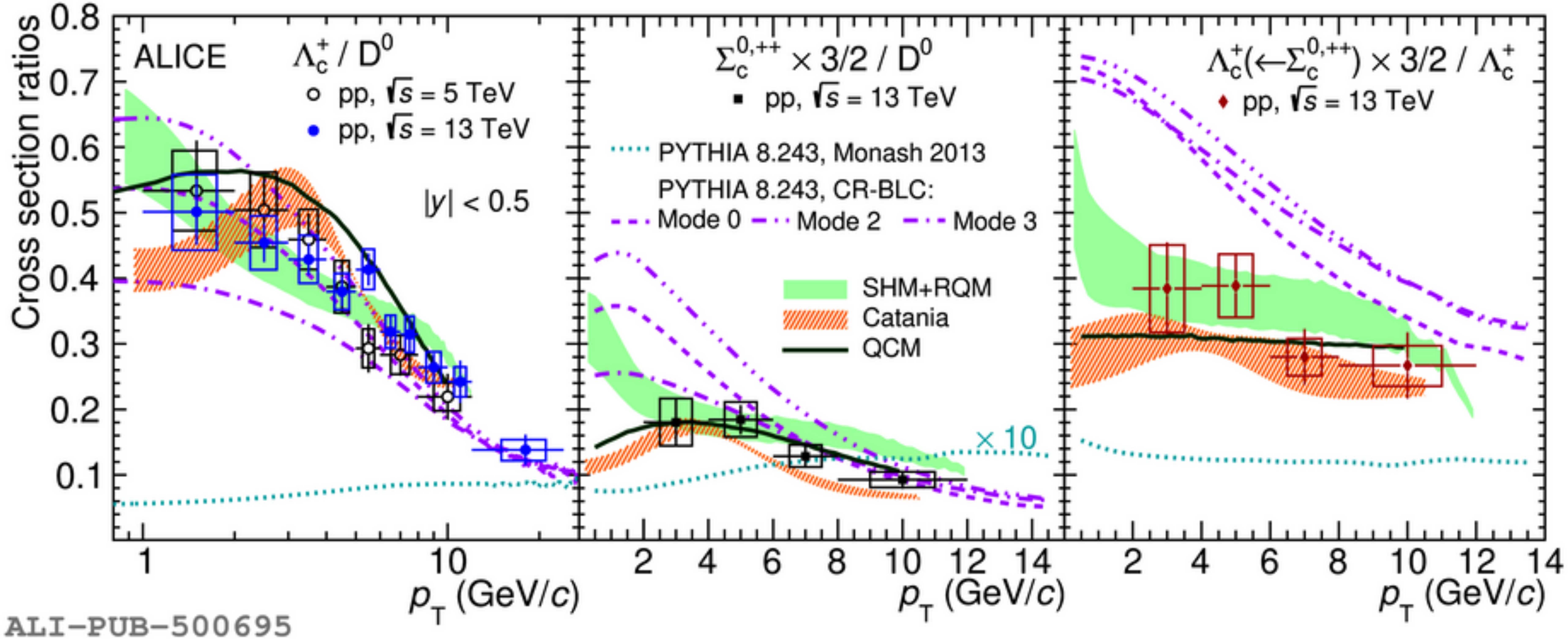
- Λ_c^+/D^0 ratios significantly higher than e^+e^- results (LEP average: $0.113 \pm 0.013 \pm 0.006$) EPJC 75 (2015) 19
- p_T dependence observed, not present in e^+e^- results

- SH model + RQM
  - Quark hadronisation driven by statistical weights govern by hadron masses
  - Feed down from excited baryon states predicted by the Relativistic Quark Model (RQM) PLB 795 (2019) 117-121
- QCM
  - Pure coalescence model
  - Charm is combined with co-moving light antiquark or two quarks EPJC 78 (2018) 344

- Λ_c^+/D^0 ratios qualitatively described by PYTHIA8 (CR Mode 2), Catania, SHM+RQM, and QCM

Charm baryon-to-meson ratios

Phys. Rev. Lett. 128 (2022) 012001

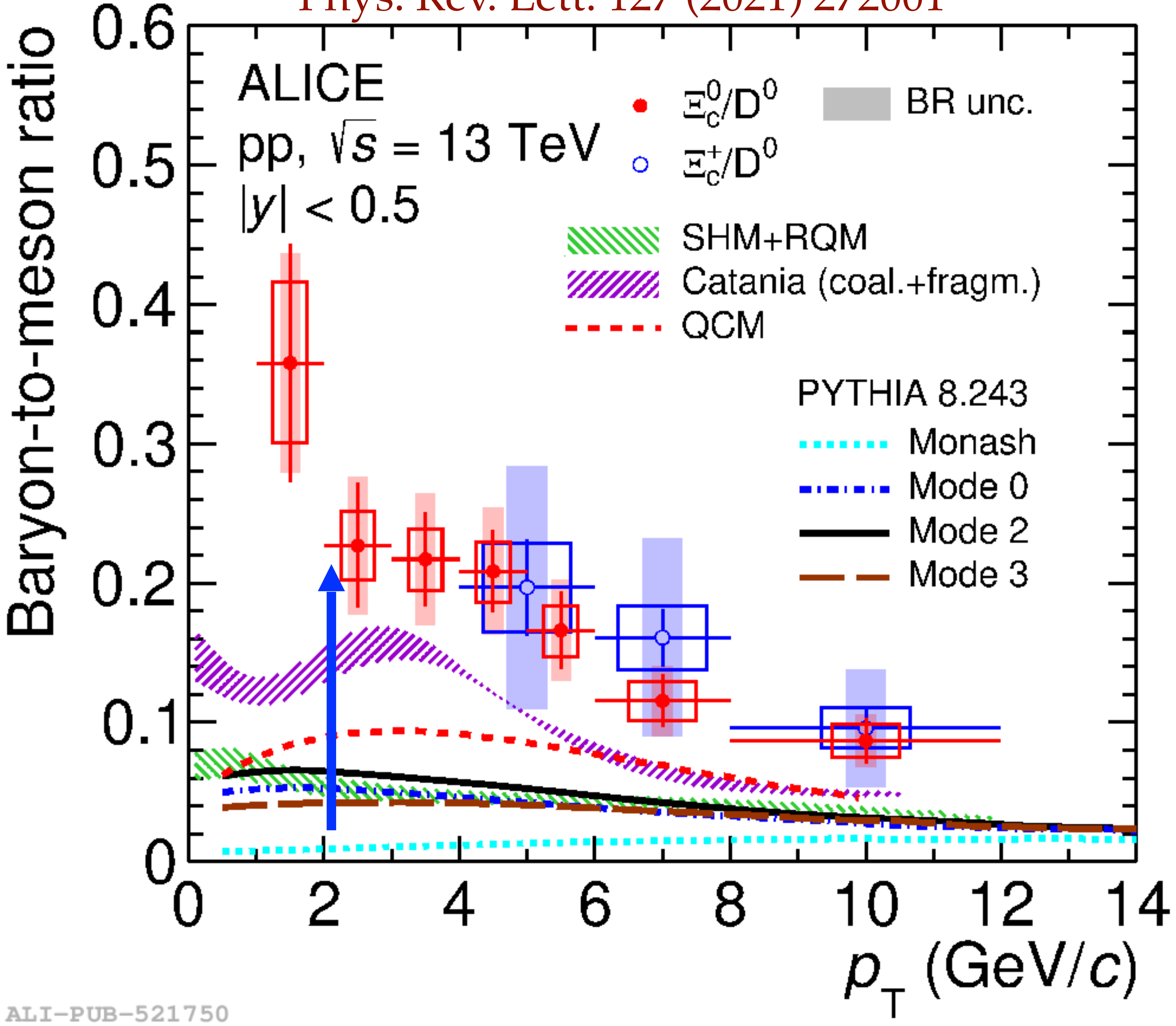


- Enhancement observed for heavier charm baryons
- $\Sigma_c^{0,++}/D^0$ largely enhanced with respect to e^+e^- measurements (~0.02 from Belle, PRD 97 (2005) 07)
- PYTHIA8 with CR-BLC, SHM+RQM, Catania, and QCM describe the $\Sigma_c^{0,++}/D^0$ ratio
- SHM+RQM, Catania, and QCM describe the $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/\Lambda_c^+$ ratio while PYTHIA8 with CR-BLC overestimates the data

Charm baryon-to-meson ratios

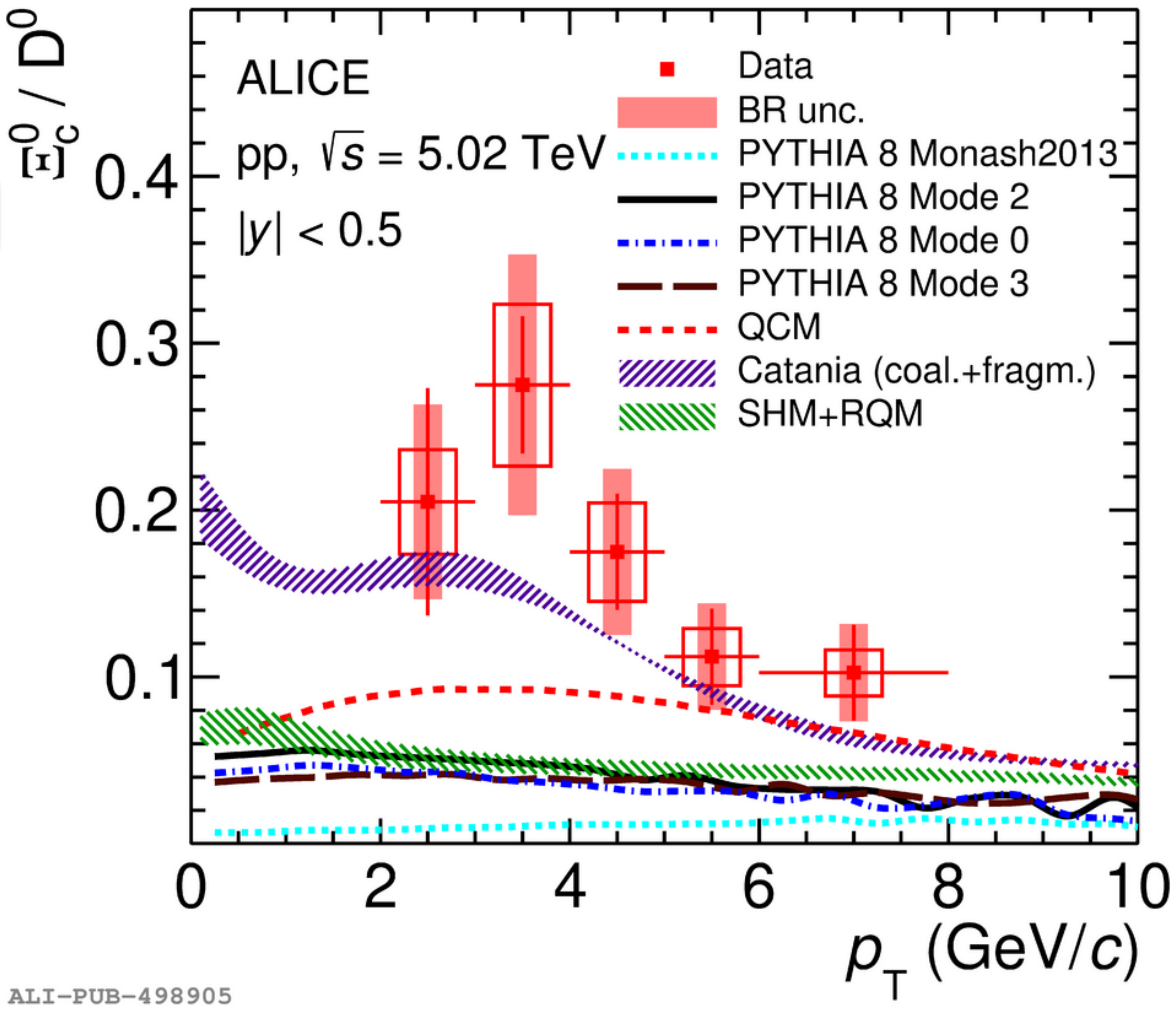
13 TeV

Phys. Rev. Lett. 127 (2021) 272001



5 TeV

JHEP 10 (2021) 159

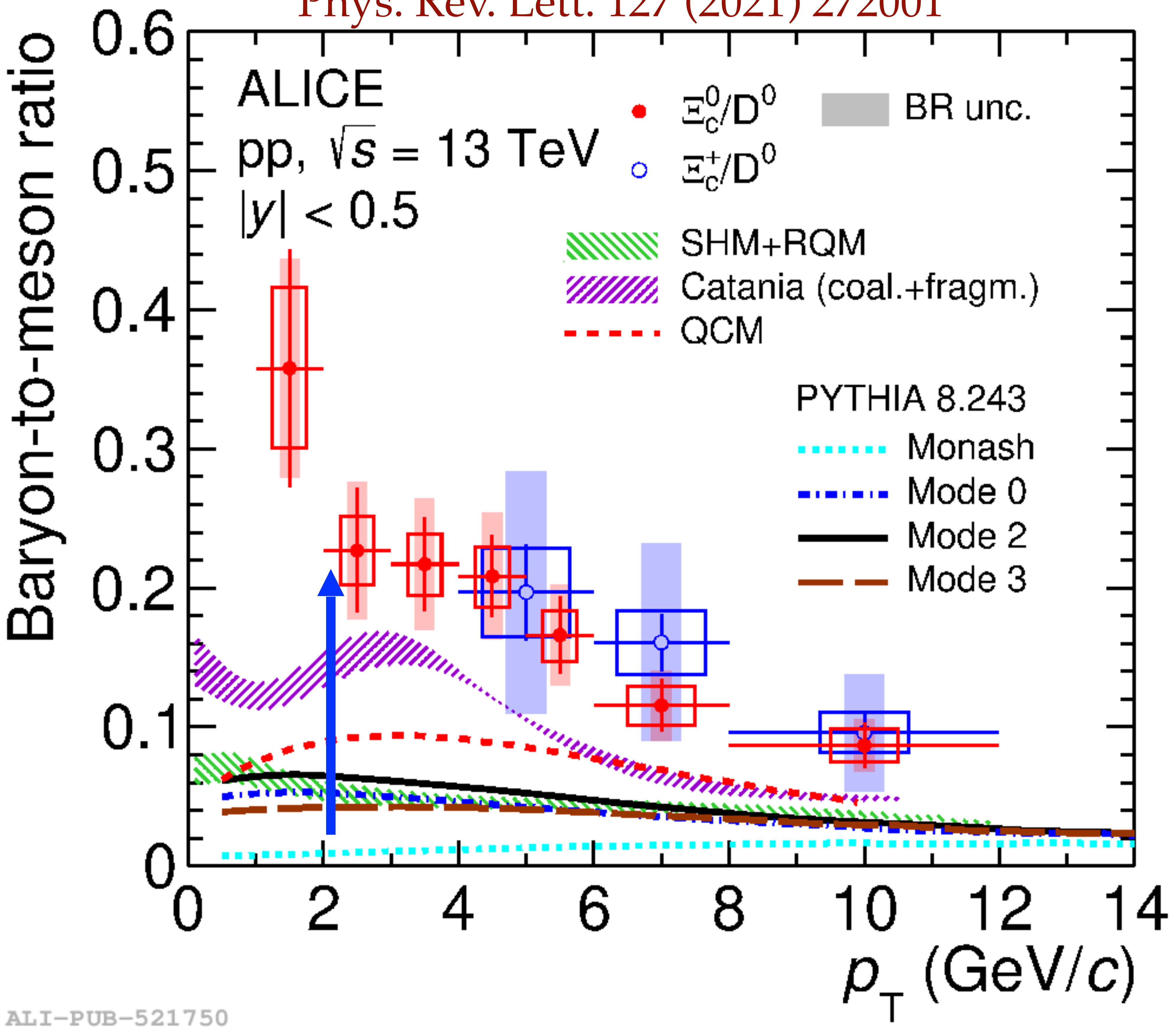


- $\Xi_c^{0,+}/D^0$ higher than PYTHIA8 Monash, tuned to reproduced e^+e^- results
- Catania model (including hadronisation via coalescence) describes better the shape of the measured $\Xi_c^{0,+}/D^0$

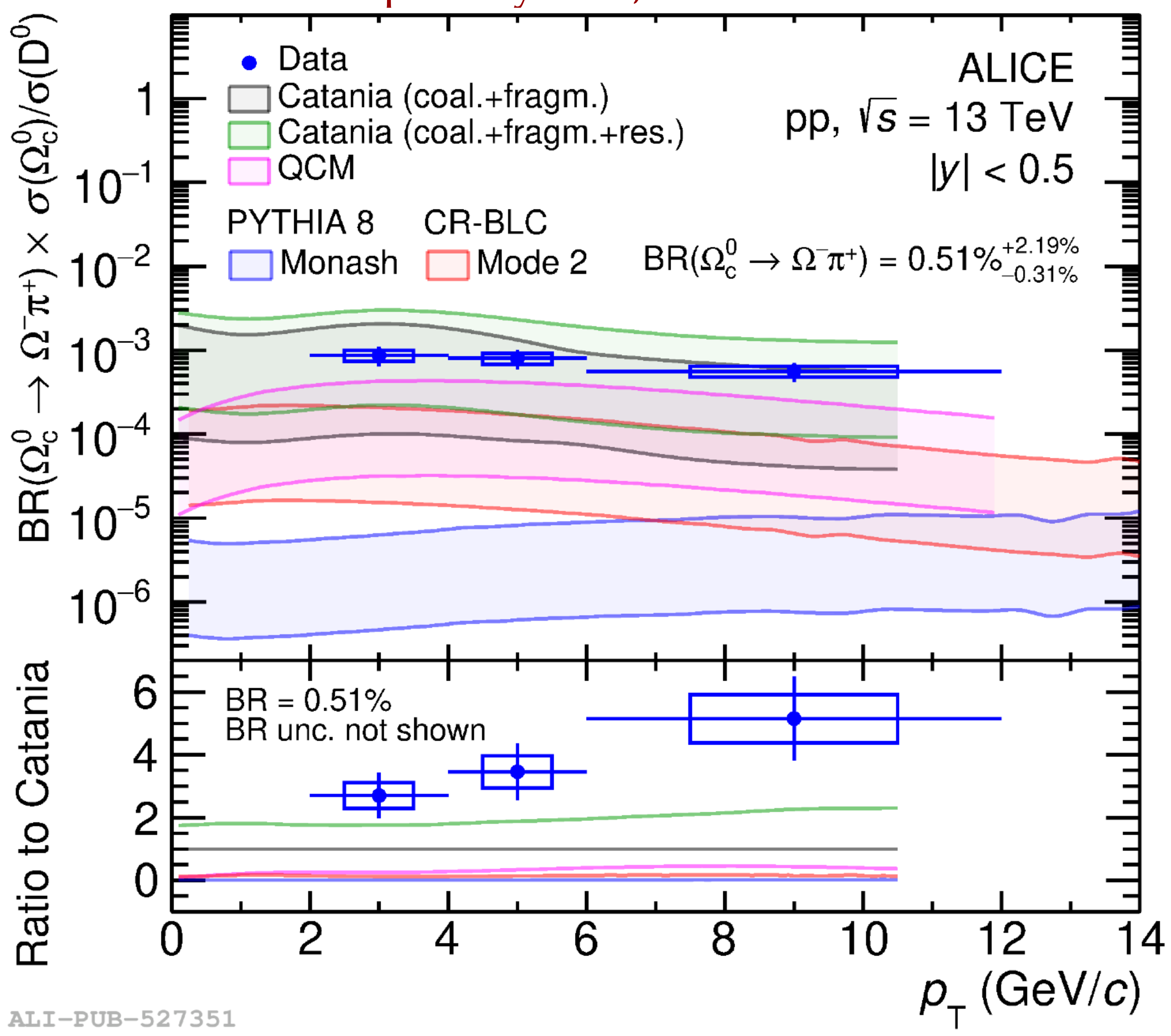
Charm baryon-to-meson ratios

13 TeV

Phys. Rev. Lett. 127 (2021) 272001



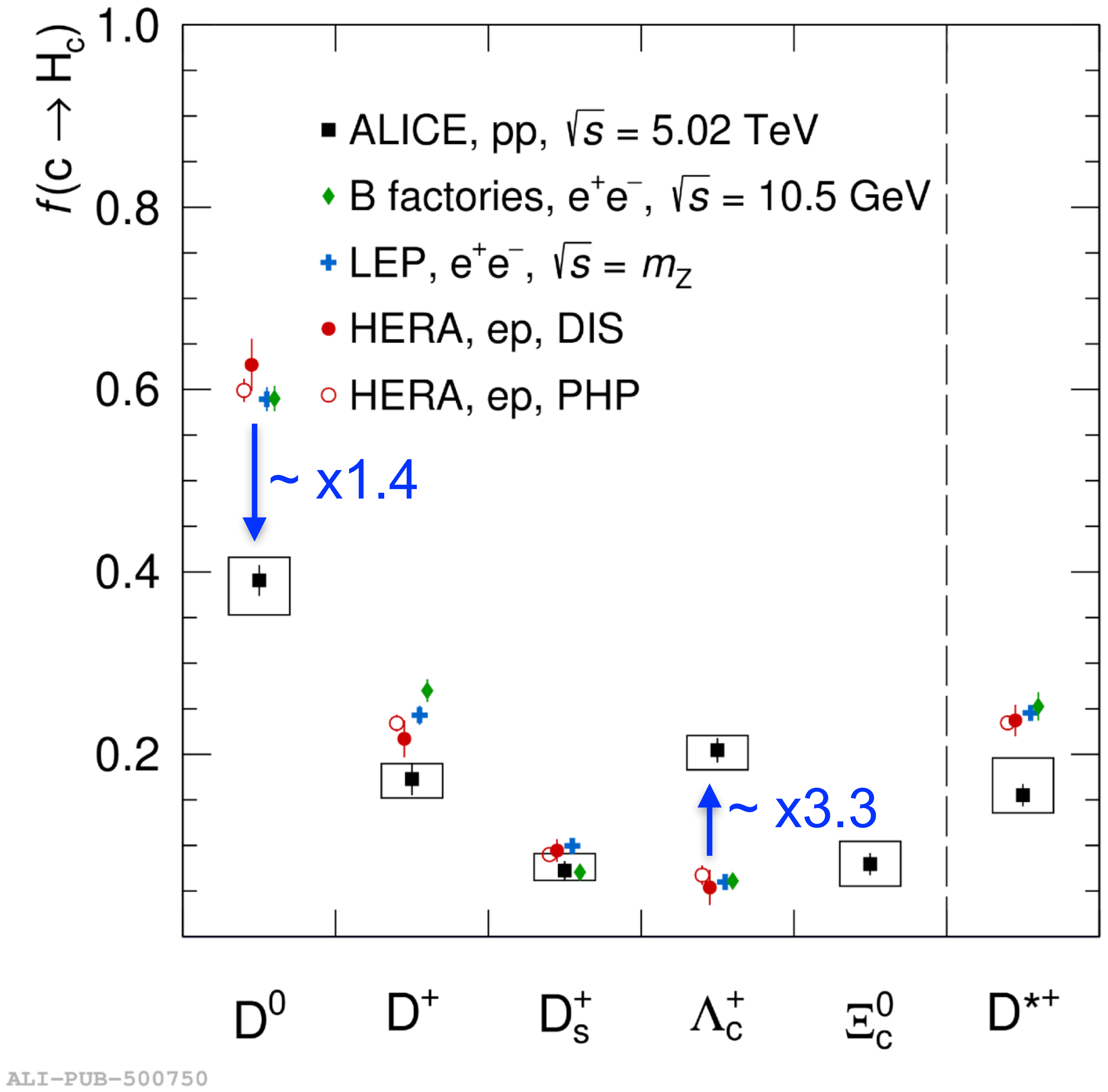
Accepted by PLB, arxiv:2205.13993



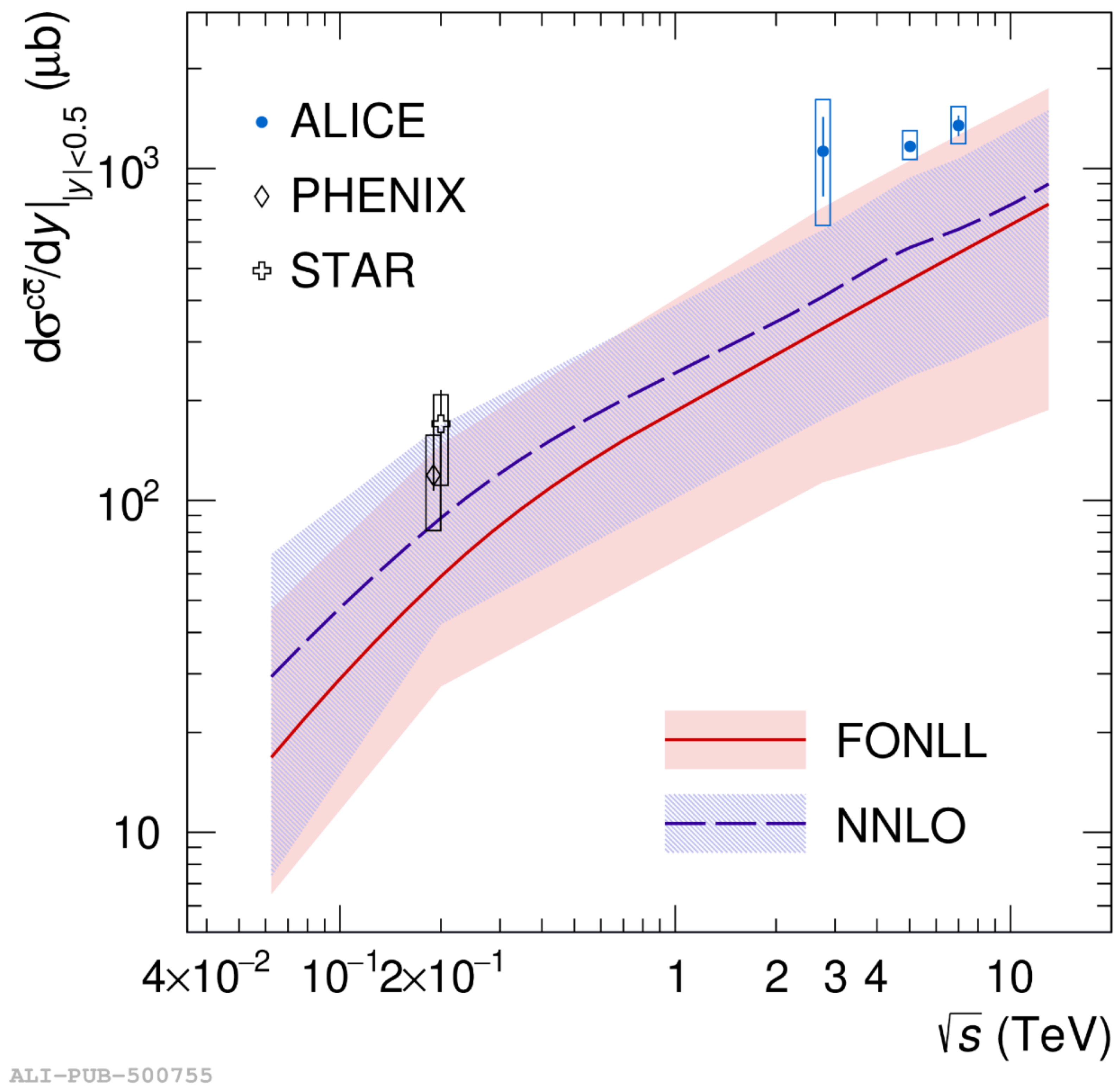
BR ($\Omega_c^0 \to \Omega^-\pi^+$) = (0.51 ± 0.07)% from theory calculations
Yu-Kuo Hsiao et al., EPJC 80 (2020) 1066)

- $\Xi_c^{0,+}/D^0$ higher than PYTHIA8 Monash, tuned to reproduced e^+e^- results
- Catania model (including hadronisation via coalescence) describes better the shape of the measured $\Xi_c^{0,+}/D^0$
- BR ($\Omega_c^0 \to \Omega^-\pi^+$) * Ω_c^0/D^0 ratios show no p_T dependence
- Catania model closer to the measurement when decays from additional higher-mass resonances are considered

Charm fragmentation fractions and total charm cross section



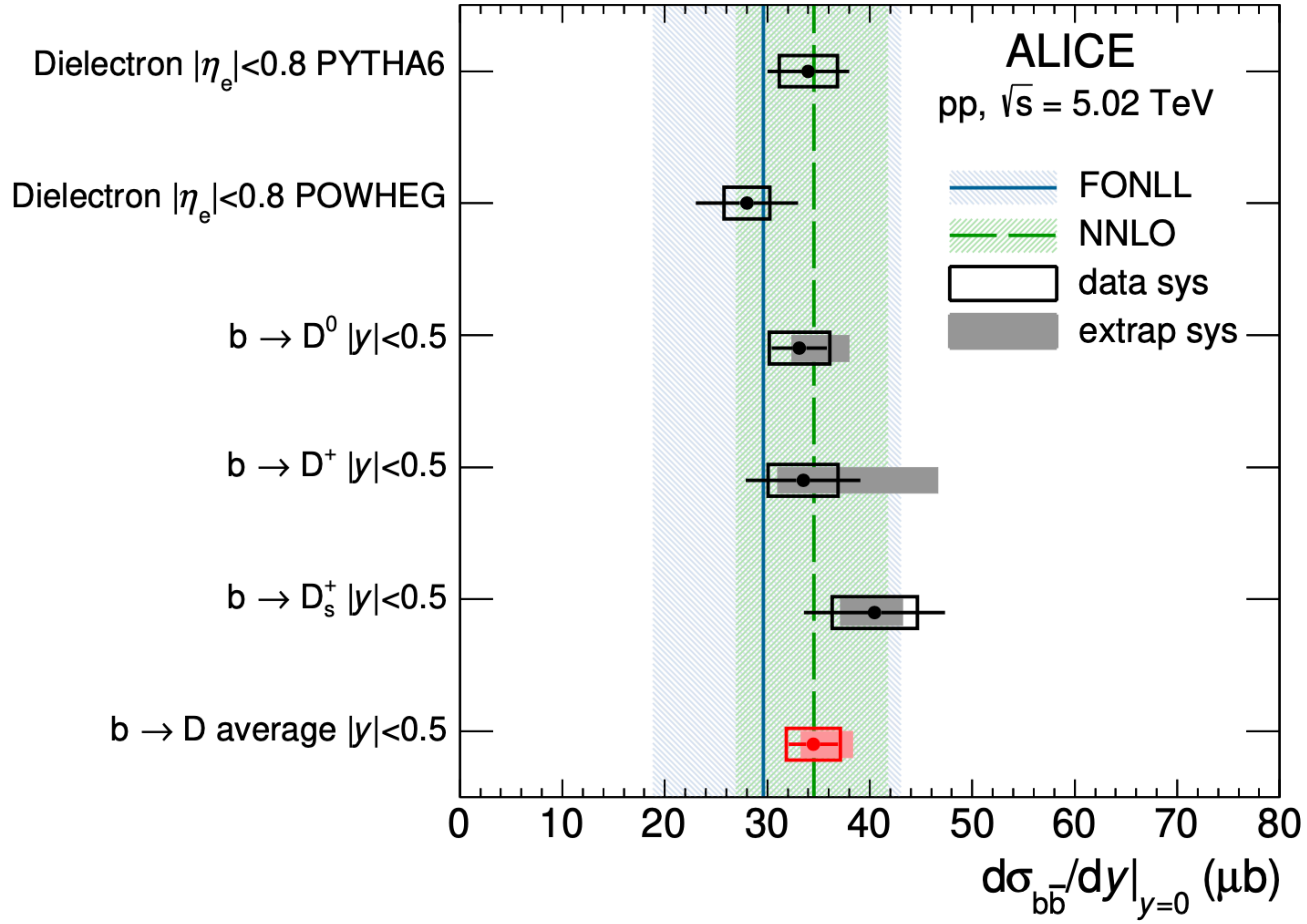
Phys. Rev. D 105, L011103 (2022)

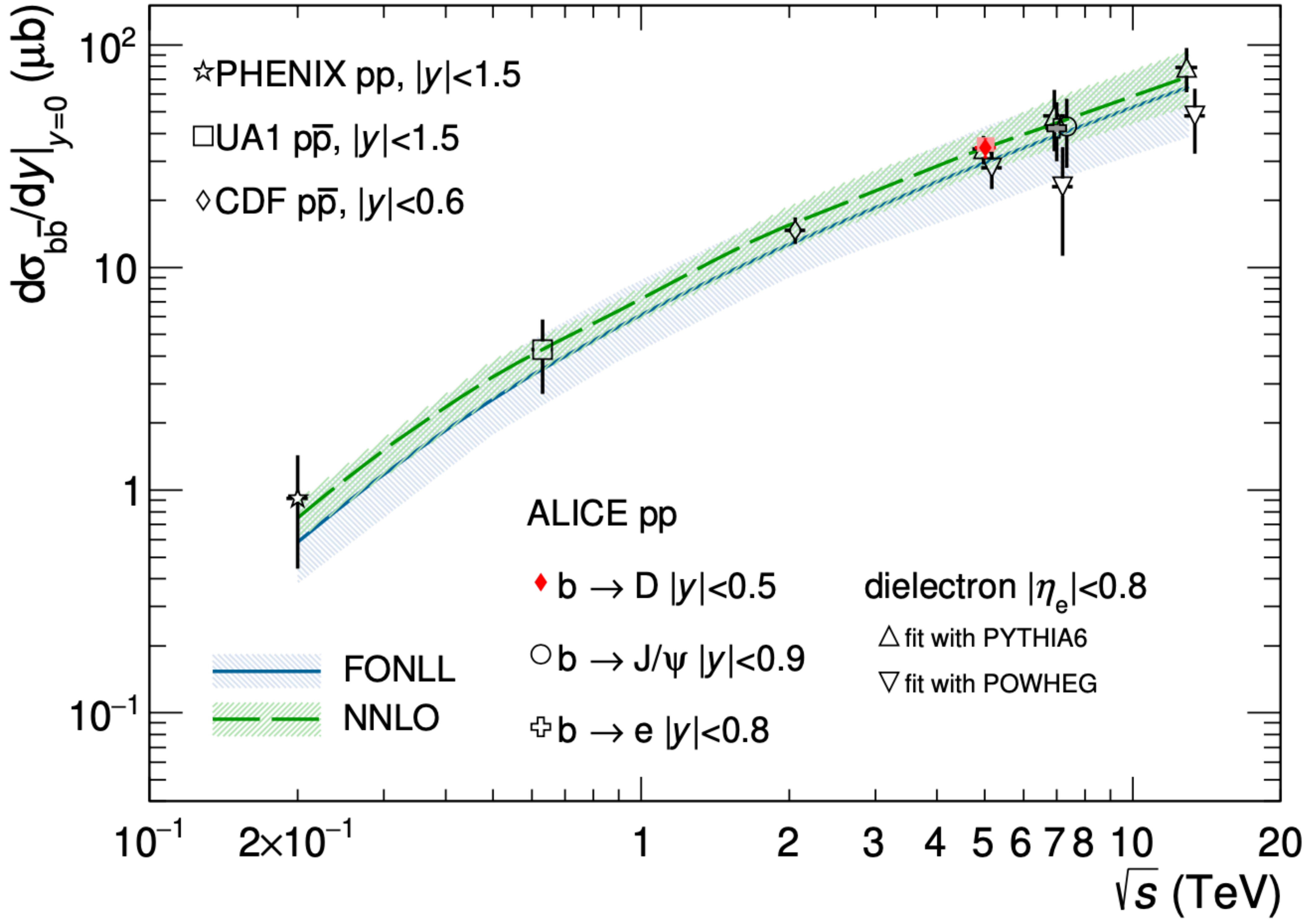


- Significant baryon enhancement with respect to e^+e^- and ep collisions
  - Enhancement of a factor of ~3.3 for Λ_c^+
- $f(c \to H_c)$ different in pp and e^+e^- and ep collisions: **fragmentation fractions are not universal across the collisions systems**
- $c\bar{c}$ production cross section measured at midrapidity lie on the upper edge of the FONLL and NNLO calculation uncertainty bands

Total beauty cross section

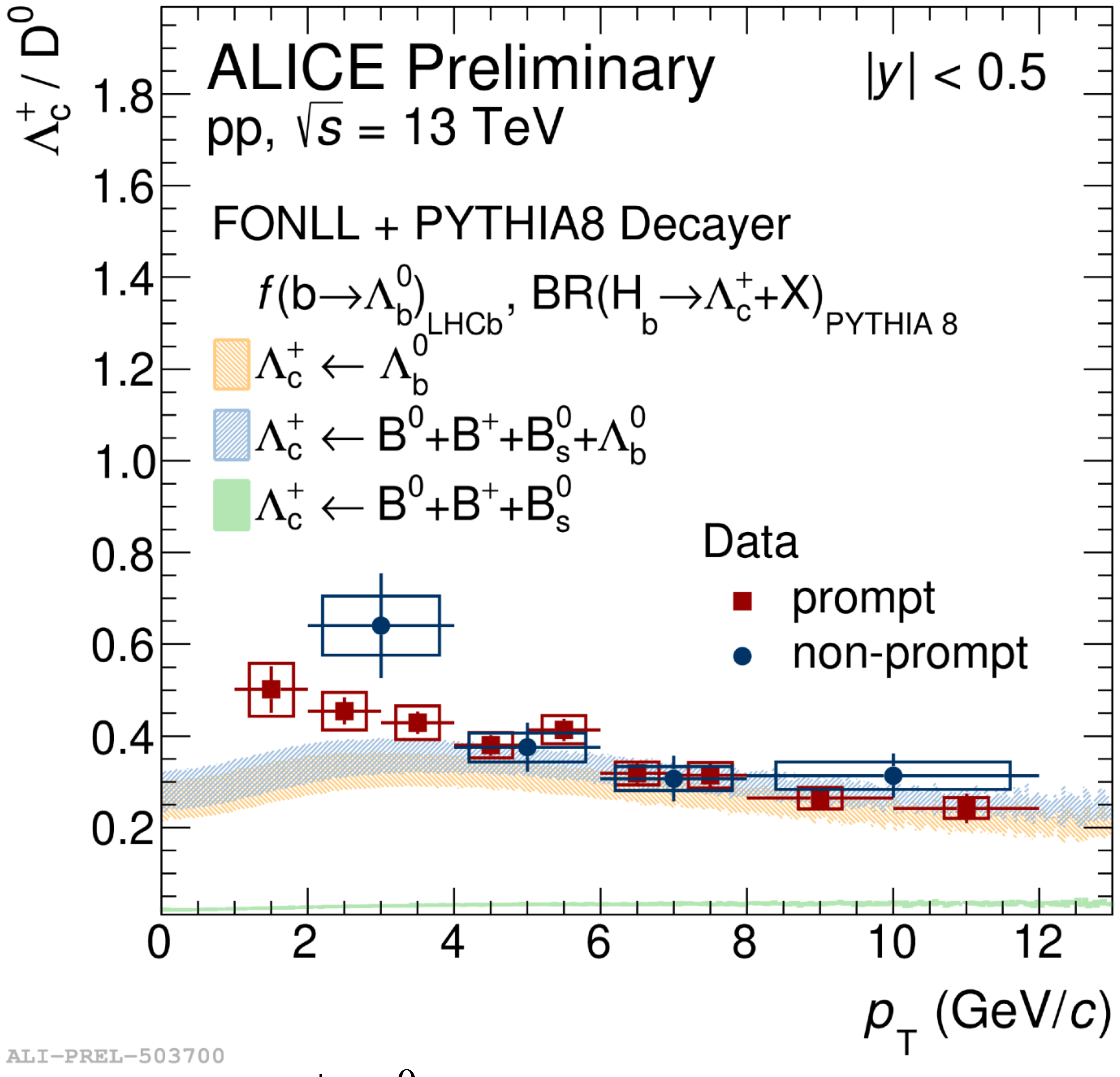
JHEP 05 (2021) 220





- The results from D-meson species are compatible within uncertainties among each other and with those obtained from dielectron, as well as with pQCD predictions (FONLL and NNLO)
- $b\bar{b}$ production cross section measured at midrapidity is found to be compatible with FONLL and NNLO calculations

Beauty baryon-to-meson ratios

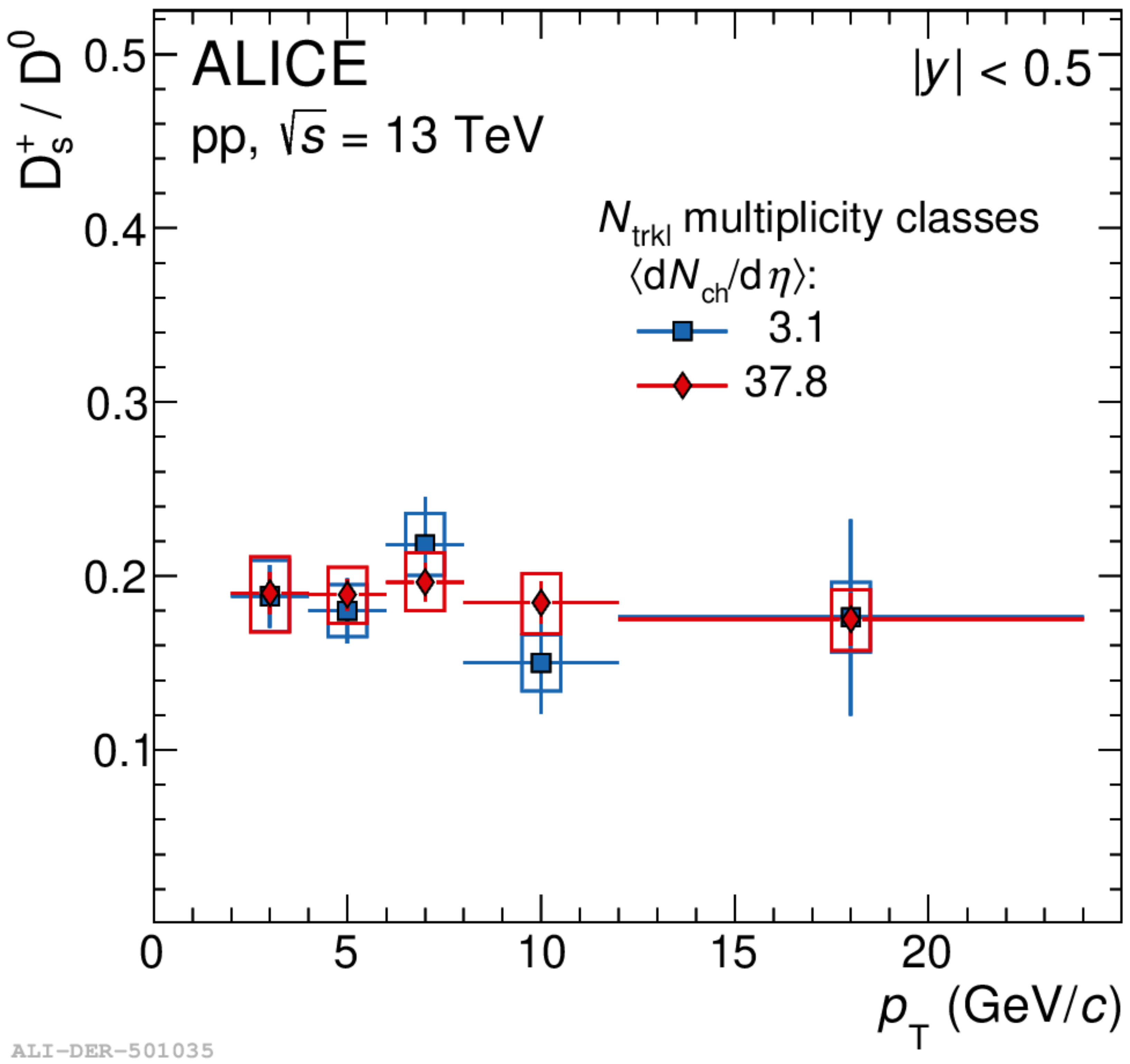


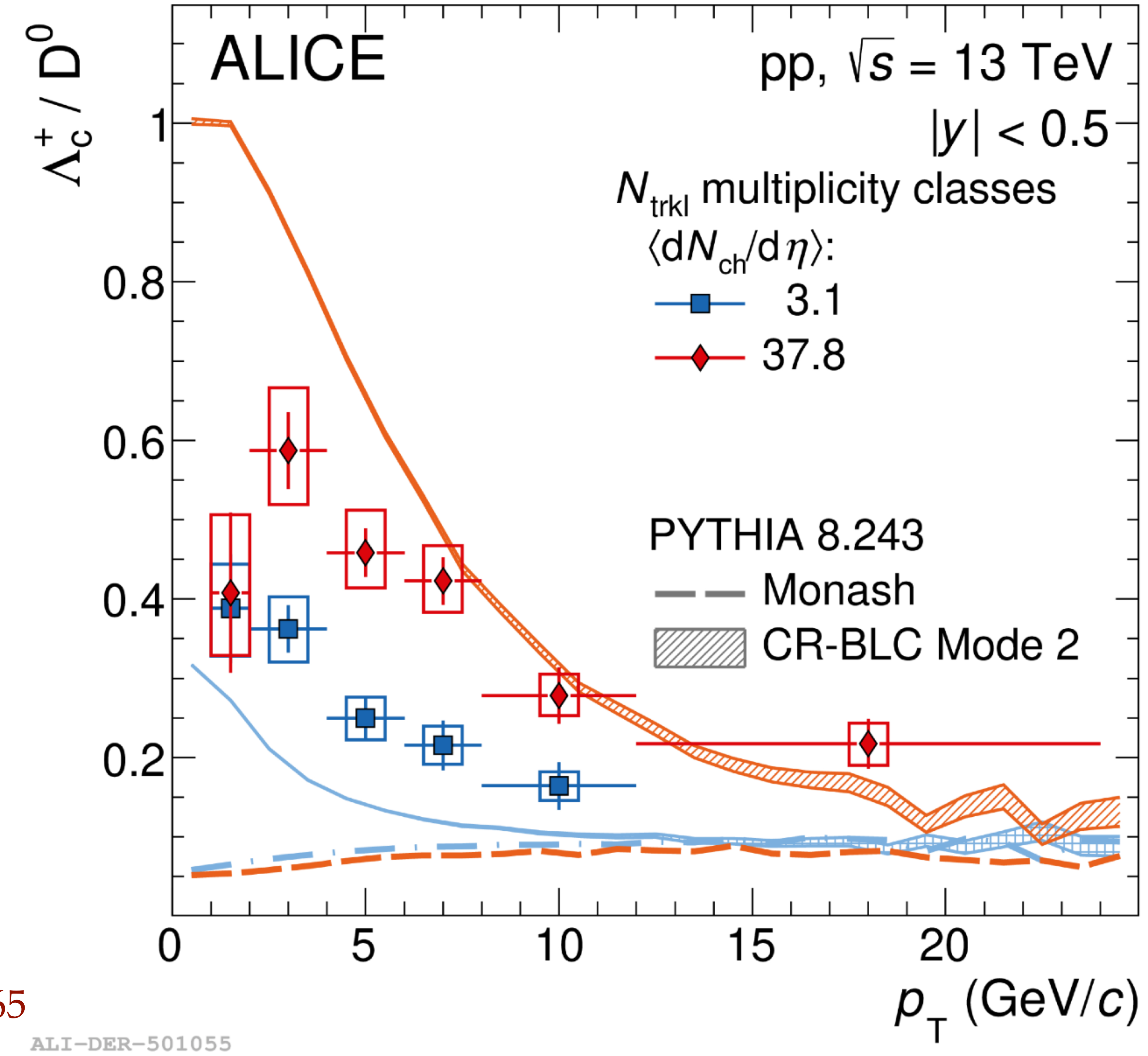
- Good agreement between prompt and non-prompt Λ_c^+/D^0 ratios
- Similar baryon-to-meson enhancement compared to e^+e^- measurements
- Non-prompt Λ_c^+/D^0 ratios are well described by FONLL + PYTHIA8 model (when fragmentation fractions measured by LHCb are employed)

  -> access to beauty-baryon production mechanisms!

Prompt D mesons and Λ_c^+ vs. event multiplicity

D_s^+/D^0 and Λ_c^+/D^0 ratios measured in pp collisions at $\sqrt{s}$ = 13 TeV in MB collisions and for different multiplicity classes





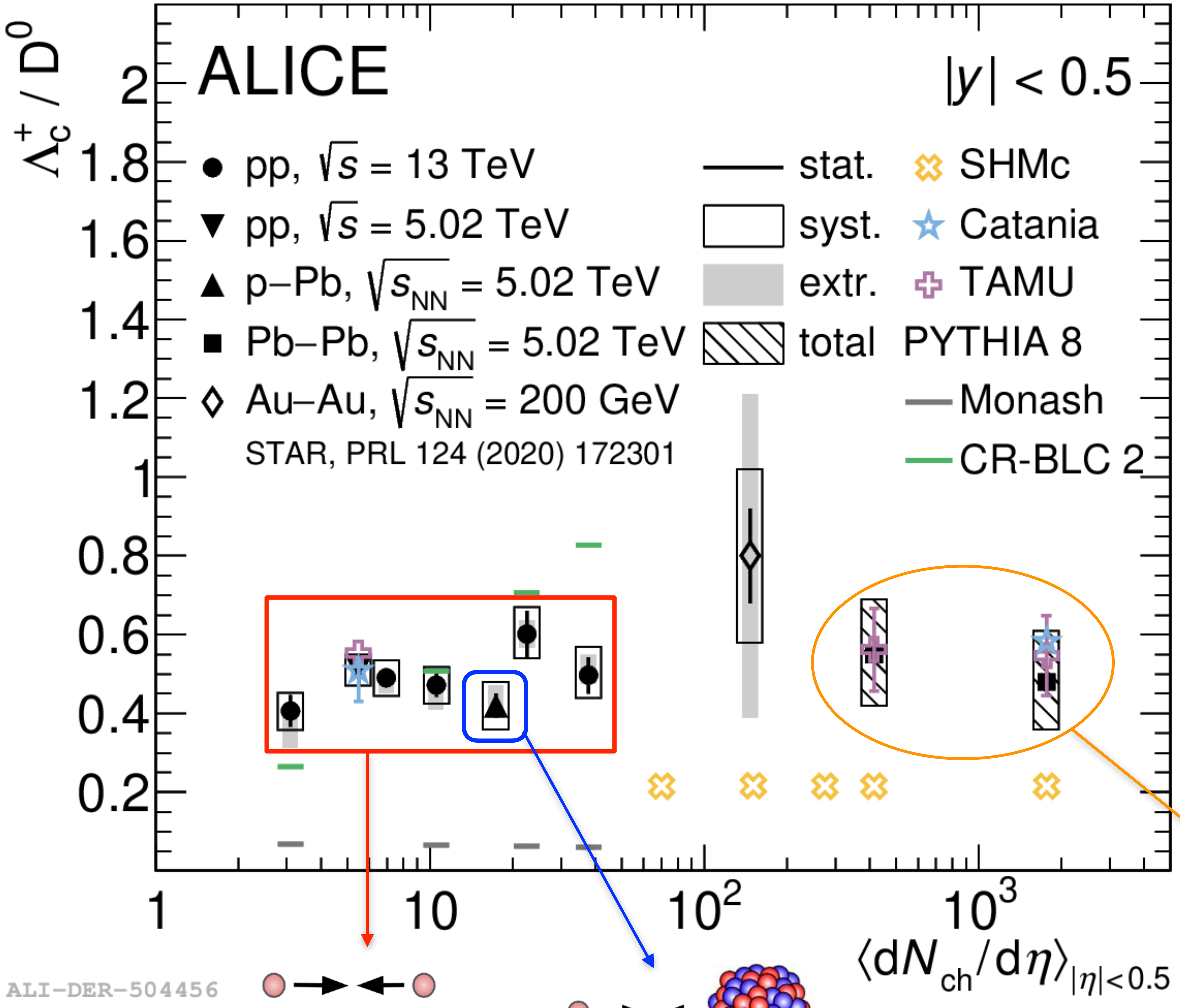
Phys. Lett. B 829 (2022) 137065

- D_s^+/D^0 ratios do not show any p_T dependence and event multiplicity
- For $1 < p_T < 12$ GeV/c, clear hierarchy of the Λ_c^+/D^0 ratios from high to low multiplicity events (5.3 σ significance)
- PYTHIA8 Monash does not reproduce the p_T trend of the Λ_c^+/D^0 across different event multiplicities while PYTHIA8 CR-CLB describes the magnitude and the p_T trend of the Λ_c^+/D^0

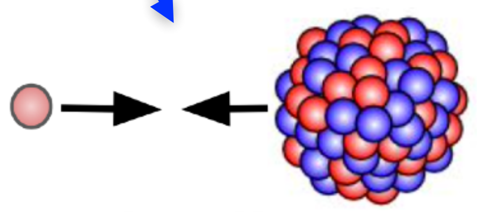
Prompt Λ_c^+/D^0 vs. event multiplicity

- ALICE, pp at 13 TeV: Phys.Lett.B 829 (2022) 137065
- ALICE, pp and p-Pb at 5.02 TeV: Phys. Rev. Lett. 127, 202301
  Phys. Rev. C 104, 054905
- ALICE, Pb-Pb at 5.02 TeV: https://arxiv.org/abs/2112.08156
- STAR, Au-Au at 200 GeV: Phys. Rev. Lett. 124, 172301

Phys. Lett. B 829 (2022) 137065

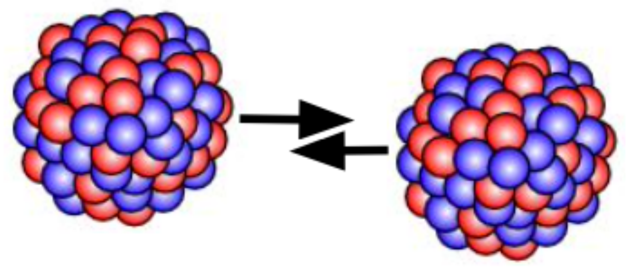


pp collisions



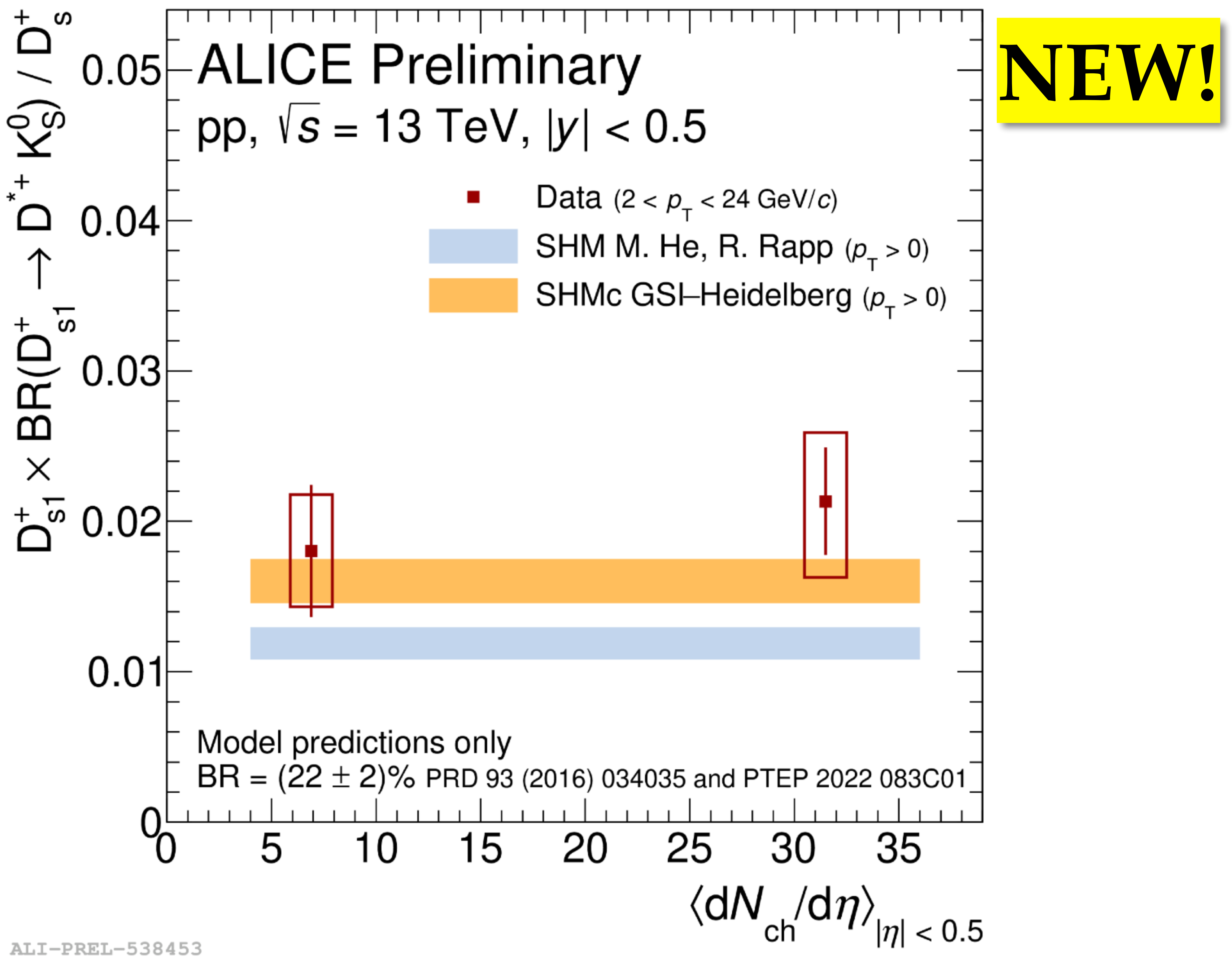
p-Pb collisions

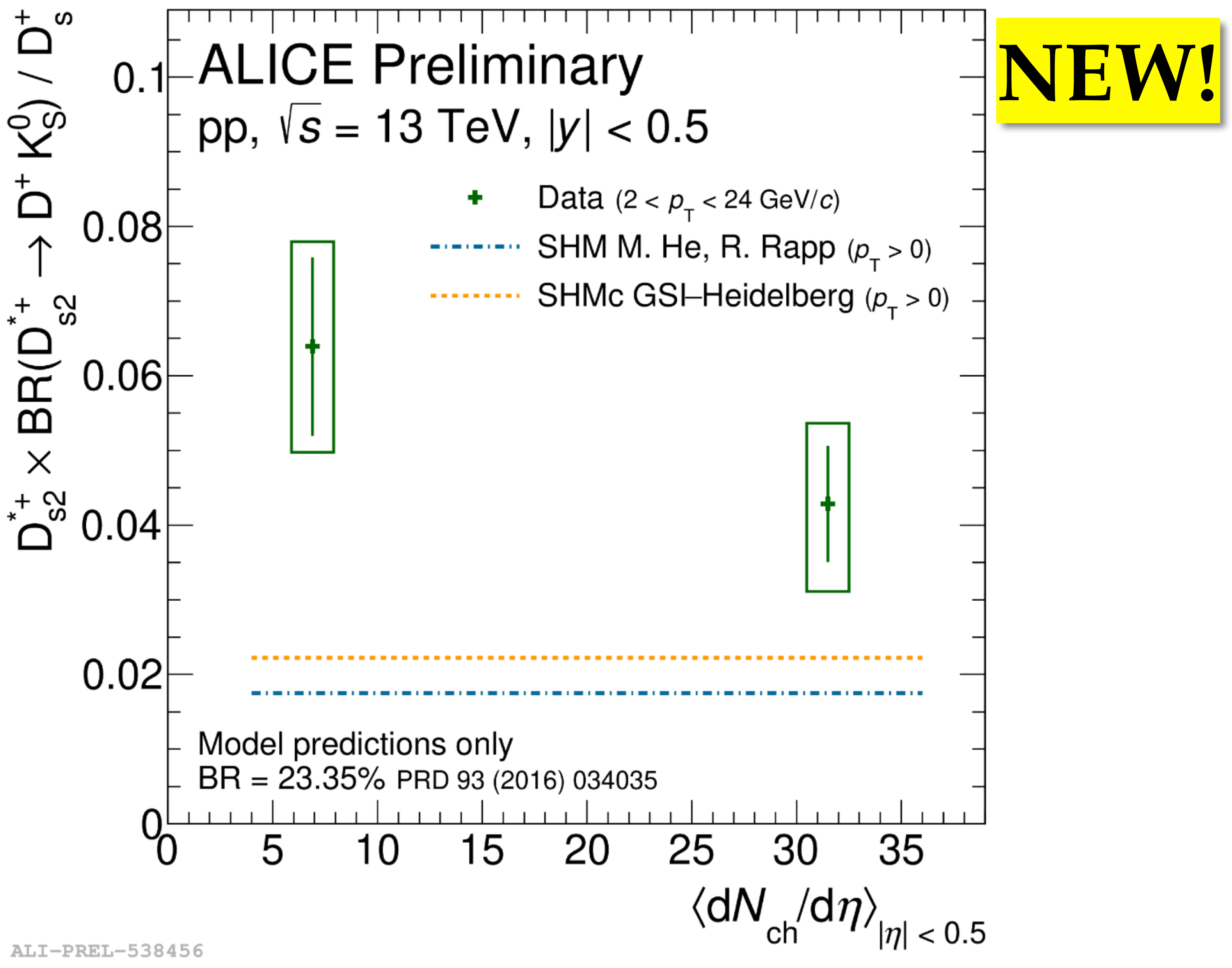
- pp, p-Pb, Pb-Pb shown together as a function of event multiplicity
- p_T-integrated, extrapolated down to $p_T = 0$, Λ_c^+/D^0 ratios do not dependent on **multiplicity**, **collision system** and **energy** within uncertainties
- Re-distribution of p_T that acts differently for baryons and mesons
  -> No modification of overall p_T-integrated yield ratios
- Same mechanism in all collision systems? Modified hadronisation? Radial flow?
- Flat trend reproduced by models with hadronisation via **fragmentation** + **recombination** (Catania, TAMU)



Pb-Pb collisions

A few more hints: D_{s1}^{+} and D_{s2}^{*+} production

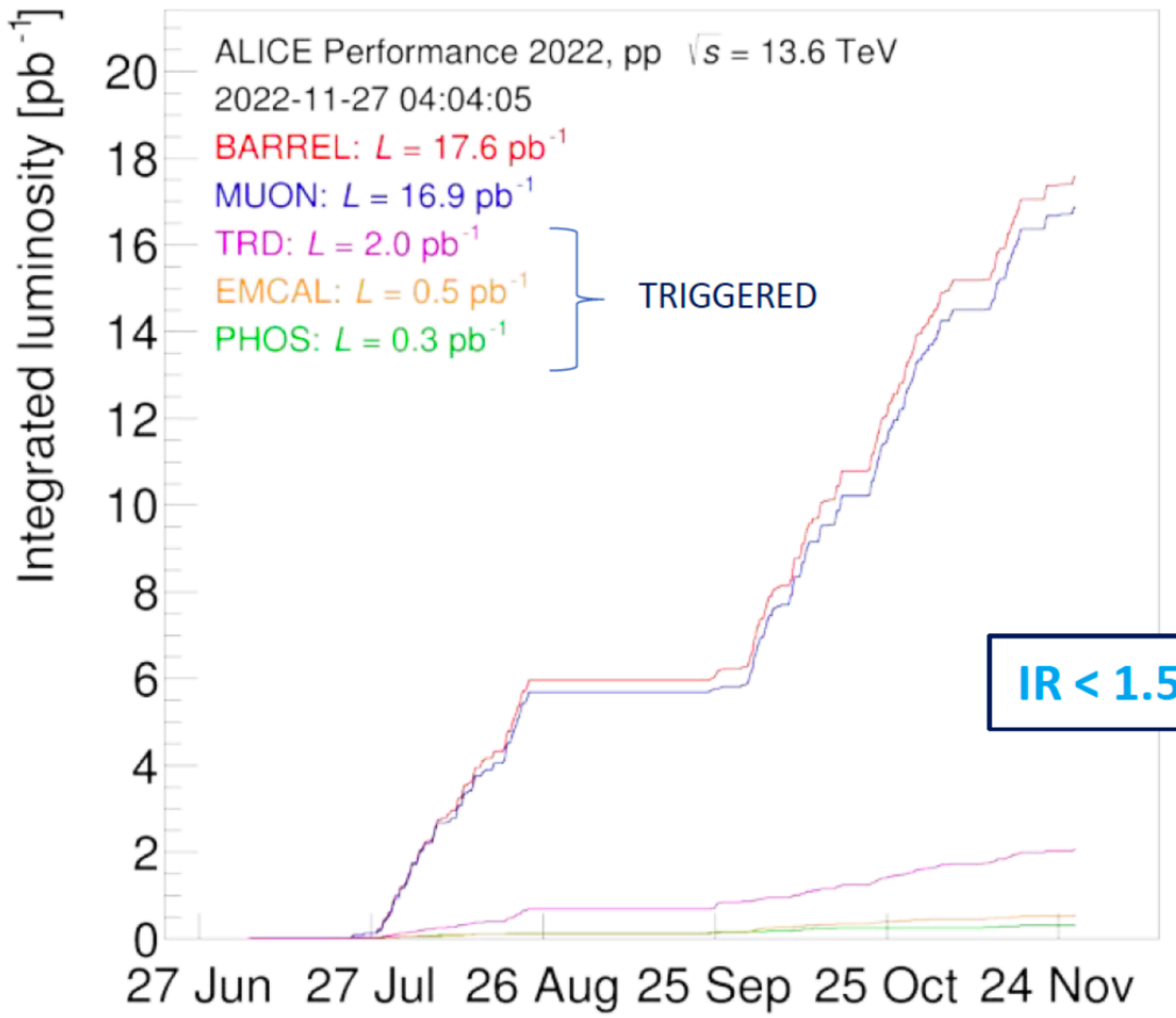




- First measurement of D_s^+-resonance production in pp collisions at $\sqrt{s} = 13$ TeV
- No multiplicity dependence on D_{s1}^{+}/D_s^+ ratio
  - Reproduced by the statistical hadronisation model (SHM)
- Hint of decreasing trend of D_{s2}^{*+}/D_s^+ ratio with event multiplicity?
  - Interplay between hadron lifetime and hadronic rescattering?
  - Hint of tension with SHM predictions
  - Total uncertainties too large to conclude

Outlook: LHC Run 3 data taking

- Larger interaction rate and upgrade of ALICE apparatus during LS 2
  -> Larger data samples in Run 3 than Run 2 (x10-100 depending on the collision system)
  -> Improved impact parameter resolution
  -> Lead to more precise measurements, and with an extended p_T reach, of the observables studied in Run 2
- Direct reconstruction of beauty mesons and baryons
- Better constraints to theoretical models of the strongly interacting medium and hadronisation



IR < 1.5 MHz

➡Target samples of ALICE high-energy pp programme
- L_{int} = 200 pb^{-1}, B = 0.5 T
- L_{int} = 3 pb^{-1}, B = 0.2 T

➡Target samples of ALICE high-energy PbPb programme
- L_{int} = 13 nb^{-1}, $\sqrt{s_{NN}}$ = 5.3 TeV

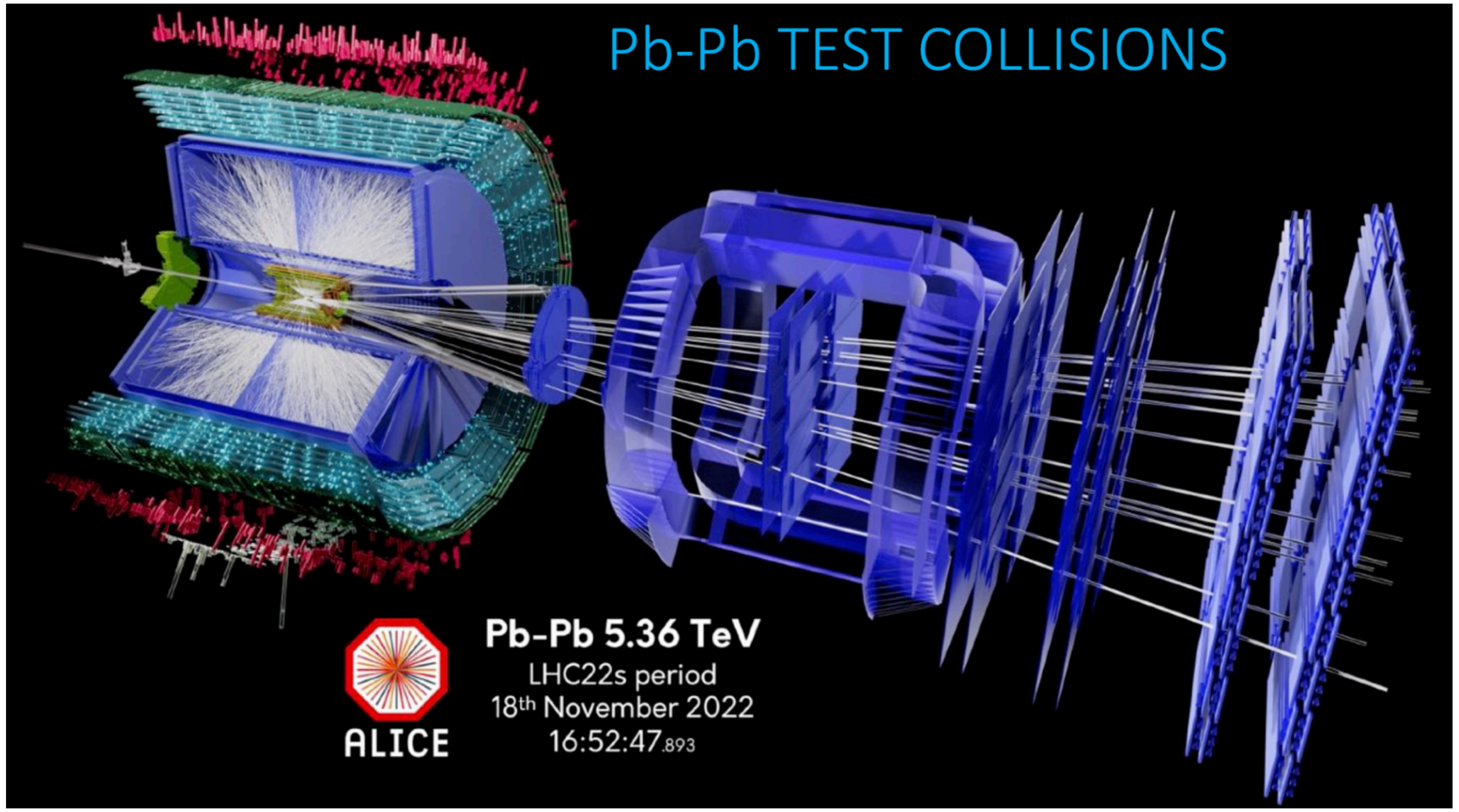
	ITS 1	ITS 2	
Distance to interaction point (mm)	39	22	→ Closer to interaction point
X_0 (innermost layer) (%)	~1.14	~0.35	→ Lower material budget
Pixel pitch (μm^2)	50 × 425	27 × 29	→ Improved granularity
Readout rate (kHz)	1	100	→ Faster readout
Spatial resolution ($r\varphi \times z$) (μm^2)	11 × 100	5 × 5	→ Improved resolution

Summary

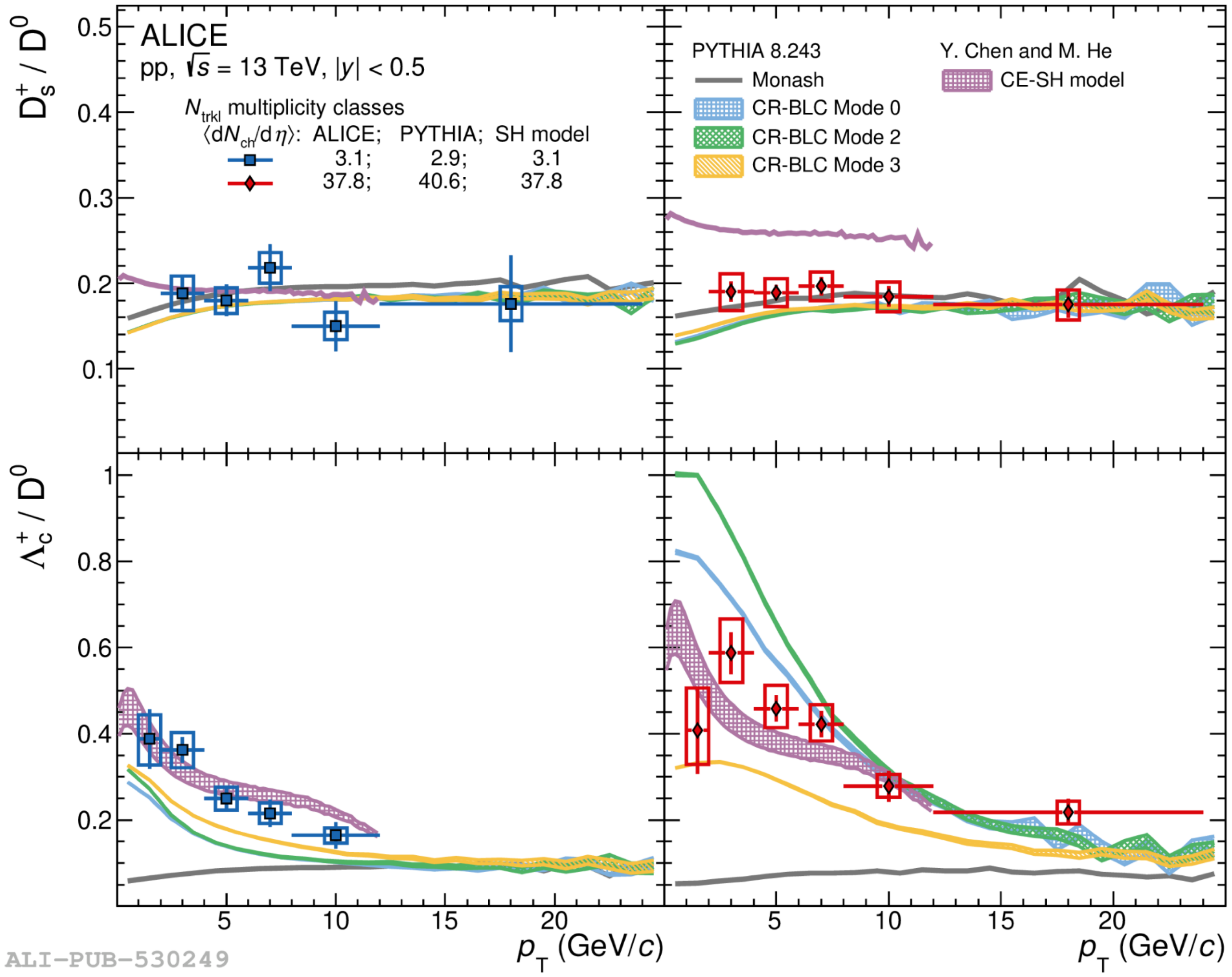
- D-meson production well described using the fragmentation fraction from e^+e^- measurements
- Large enhancement of all charm-baryon production in pp collisions w.r.t. e^+e^- collisions
- In addition to simple fragmentation, other hadronisation mechanisms are needed to describe the measurements in pp collisions
- Dependence of the fragmentation fractions on collisions system is firmly established
- First measurement of D_s^+-resonance production in pp collisions at $\sqrt{s} = 13$ TeV

ALICE Collaboration ready to analyse Run 3 data to investigate the currently open questions

Thank you for your attention!



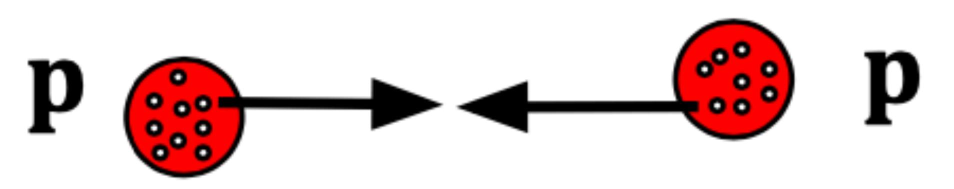
BACKUP SLIDES



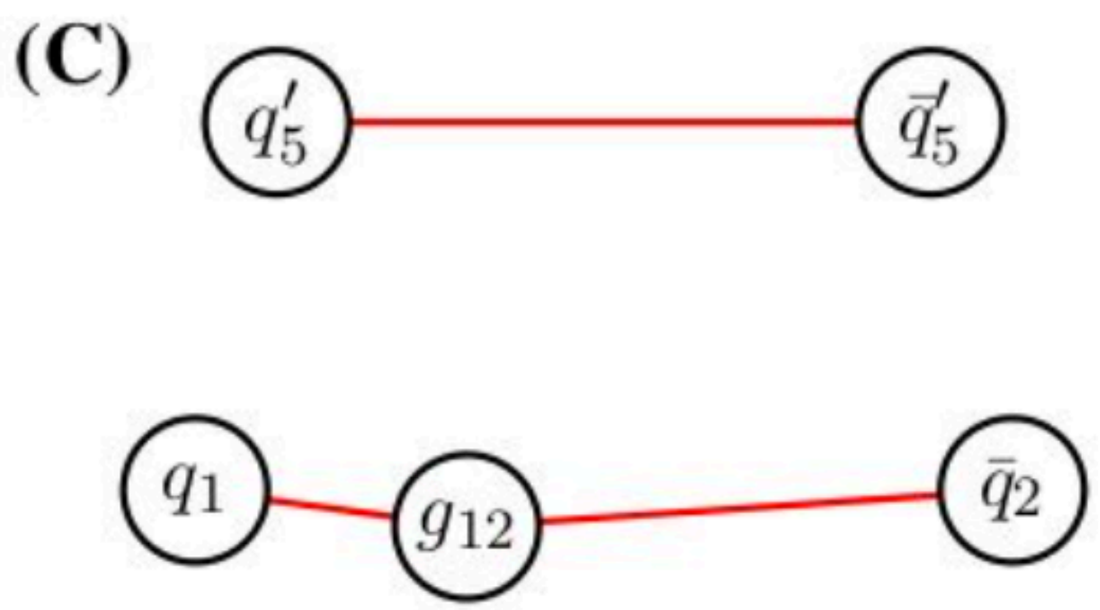
[Phys. Lett. B 829 (2022) 137065]

CR beyond leading colour

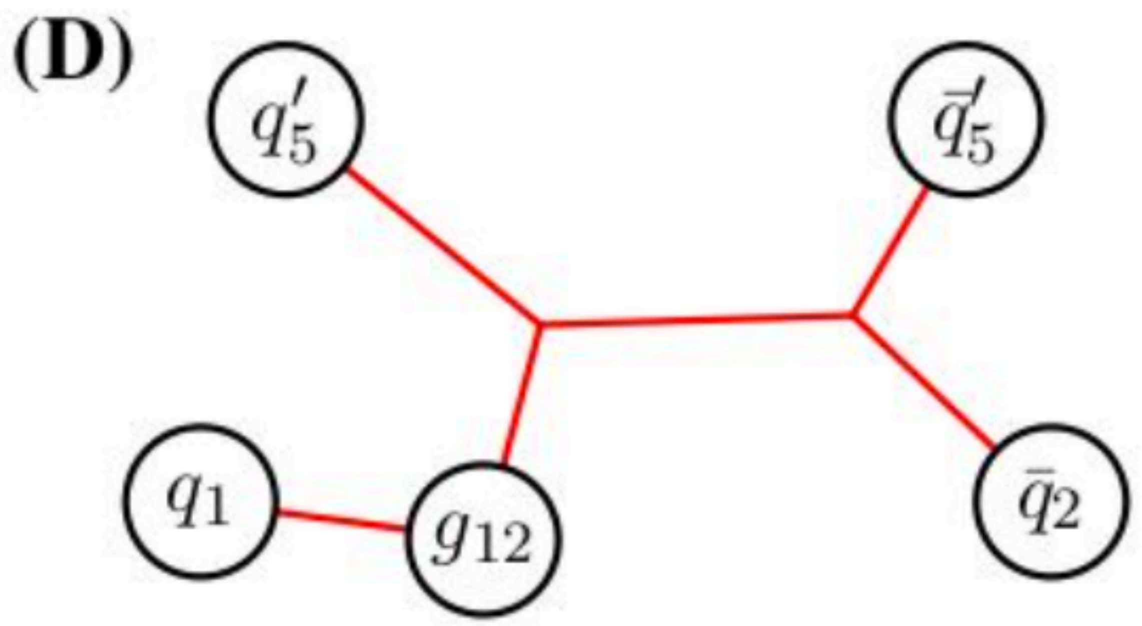
- Initial state not insensitive to strong force (coloured partons, beam remnants)
- MPI → crucial to explain underlying event



No CR



CR-BLC: junctions

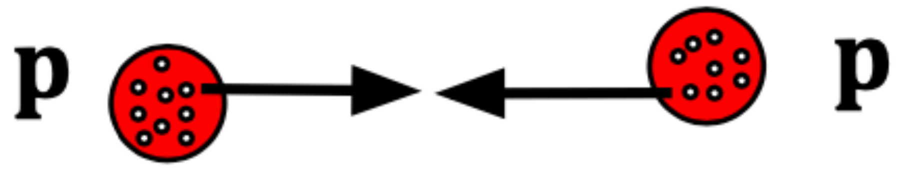


CR beyond Leading Color approximation (CR-BLC)

- "Simplified QCD" with 9 color indices to determine the string formation
- String length minimization over all possible configurations, even those beyond the Leading Color topology
  → Monash: only CR among LC
- Enhanced leading color among MPIs and beam remnants
- Conditions for color reconnections:
  - Invariant mass of string *j*-th must overcome a threshold m_0
    $C = m_{0j}/m_0 > 1$: enhanced reconnections
  - Causality: two strings must resolve each other between formation and hadronization, according to the time dilation due to the relative boost
    →Mode 0, 2, 3: different "severity" on this condition

JHEP 08 (2015) 003

Statistical approaches and coalescence



SHM+RQM PLB 795 (2019) 117-121

- Hadron formation driven by the mass at a hadronization temperature $T_H \rightarrow$ stat. weights $n_i \sim m_i^2 T_H K^2(m_i/T_H)$
- Strong feed-down from an augmented set of excited charm baryon states
  - PDG: 5 Λ_c, 3 Σ_c, 8 Ξ_c, 2 Ω_c
  - RQM: additional (not yet measured) 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c

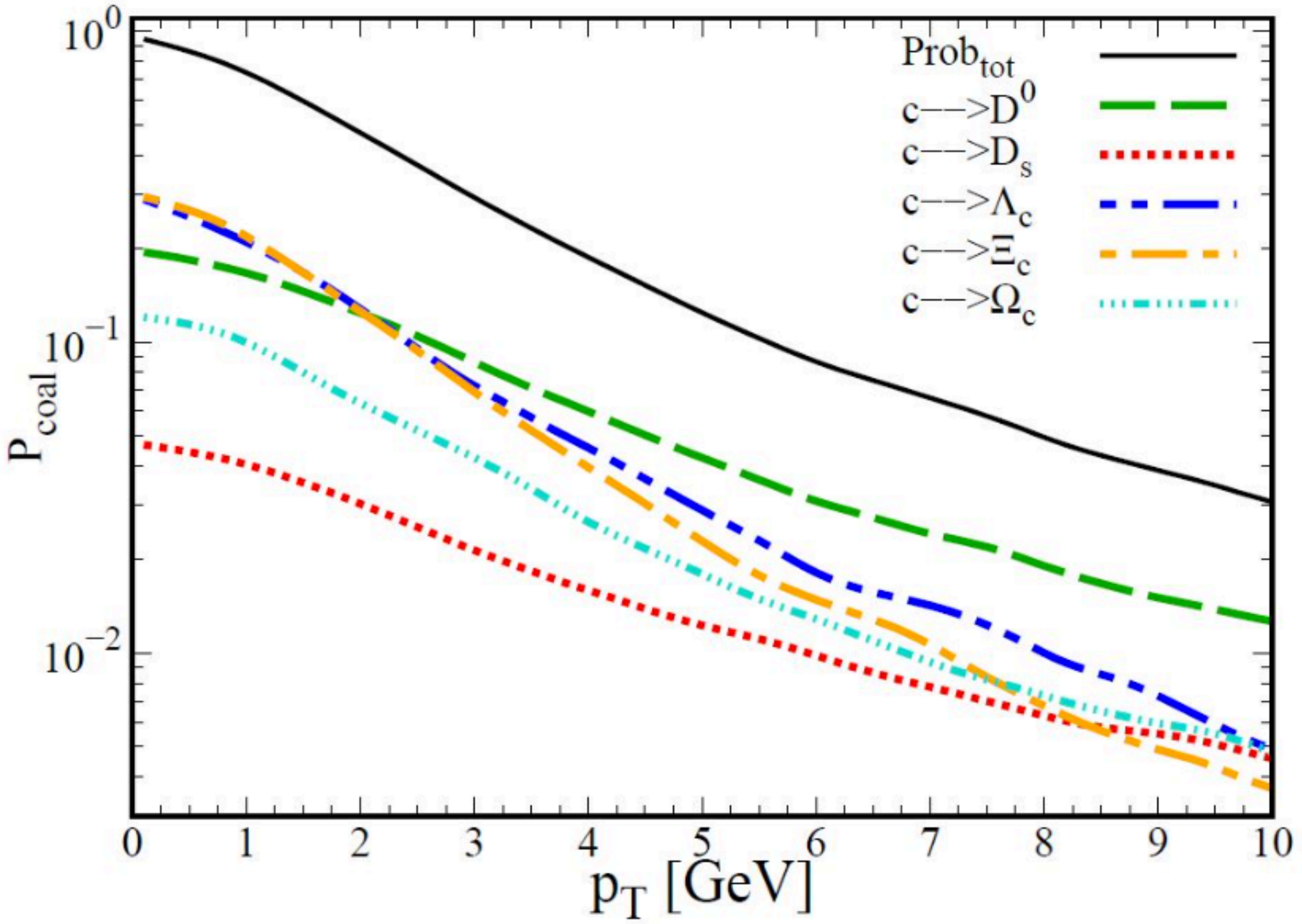
n_i [$\times 10^{-4}$ fm^{-3}] (T_H [MeV])	Λ_c^+	$\Xi_c^{0,+}$	Ω_c^0
PDG (170)	0.3310	0.0874	0.0064
RQM (170)	0.6613	0.1173	0.0144

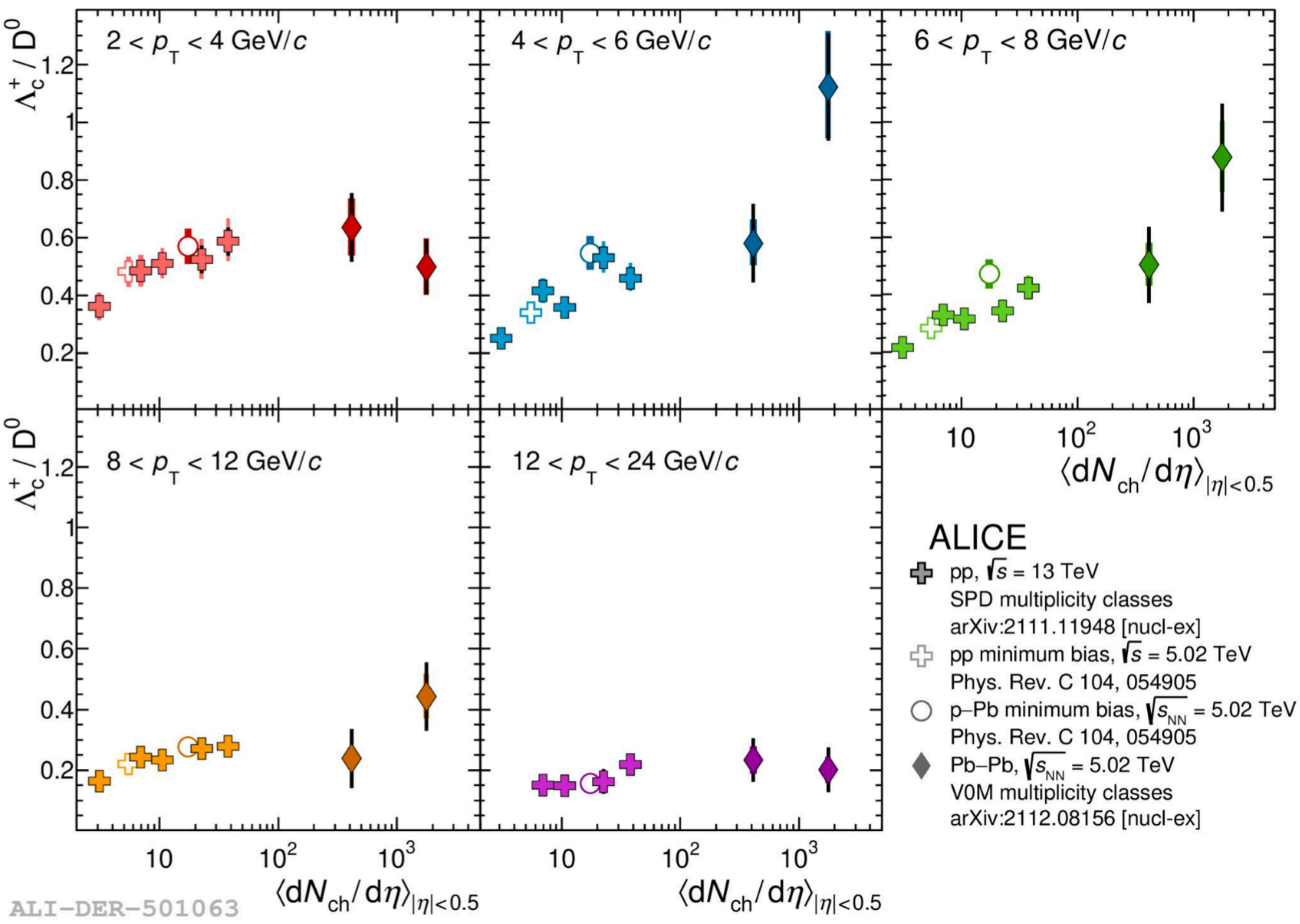
Quark Coalescence Mechanism (QCM) Eur. Phys. J. C (2018) 78: 344

- Thermal weights to account for relative production of scalar and vector mesons
- Hadron p_T- spectrum from recombination of charm quarks from the hard scattering with equal-velocity light quarks in the nearby in phase-space

Catania coalescence model PLB 821, 136622

- Thermalised system of u, d, s and gluons
- Charm quark can hadronize either via fragmentation or coalescence
- Charm hadronization into ground and (PDG) excited states
  - The latter ones increase the abundance of the former ones
  - Statistical "penalty" weight $[m_{H*}/m_H]^{3/2} \times \exp(-\Delta E/T)$





Λ_c^+ / D^0
$2 < p_T < 4$ GeV/c
$4 < p_T < 6$ GeV/c
$6 < p_T < 8$ GeV/c
$8 < p_T < 12$ GeV/c
$12 < p_T < 24$ GeV/c
$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$
ALICE
pp, $\sqrt{s}$ = 13 TeV
SPD multiplicity classes
arXiv:2111.11948 [nucl-ex]
pp minimum bias, $\sqrt{s}$ = 5.02 TeV
Phys. Rev. C 104, 054905
p–Pb minimum bias, $\sqrt{s_{NN}}$ = 5.02 TeV
Phys. Rev. C 104, 054905
Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
V0M multiplicity classes
arXiv:2112.08156 [nucl-ex]
ALI-DER-501063