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Heavy-flavour hadronisation in small and large systems

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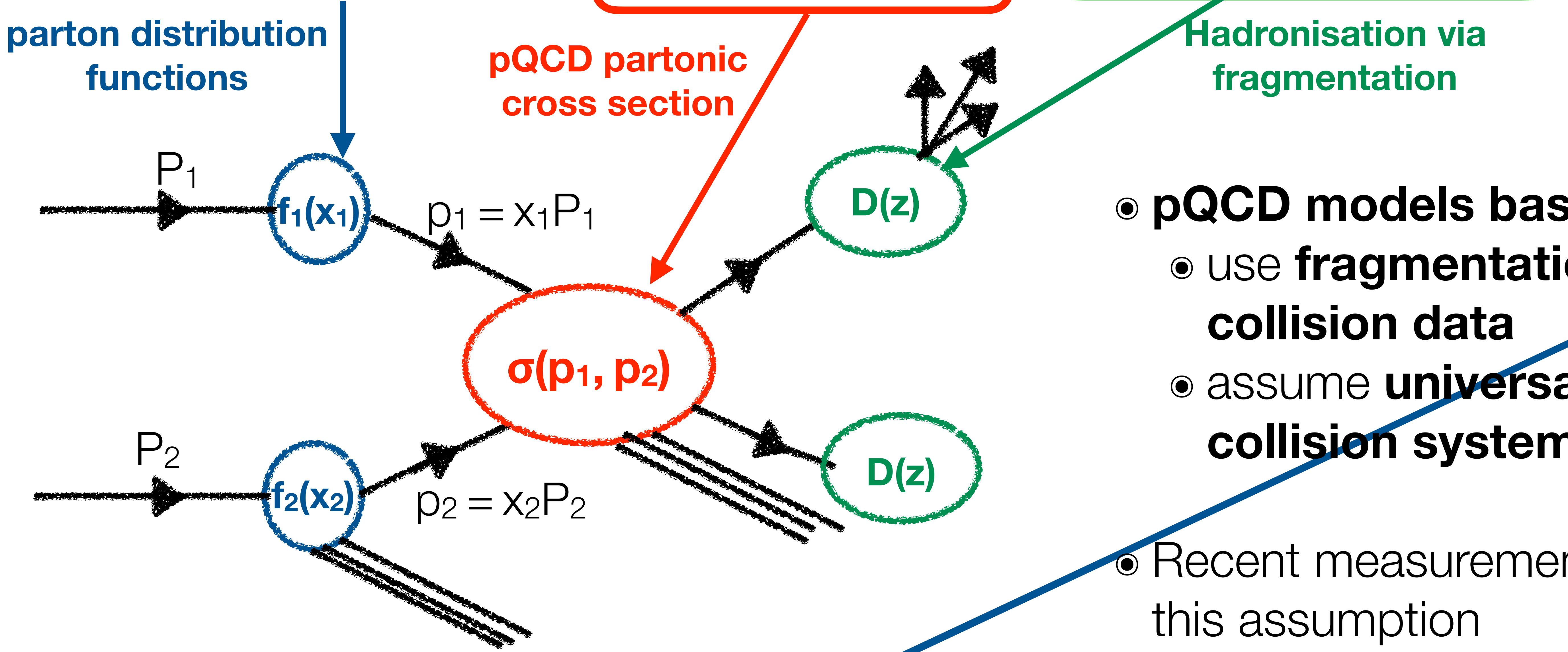
Heavy-flavour hadronisation in small systems

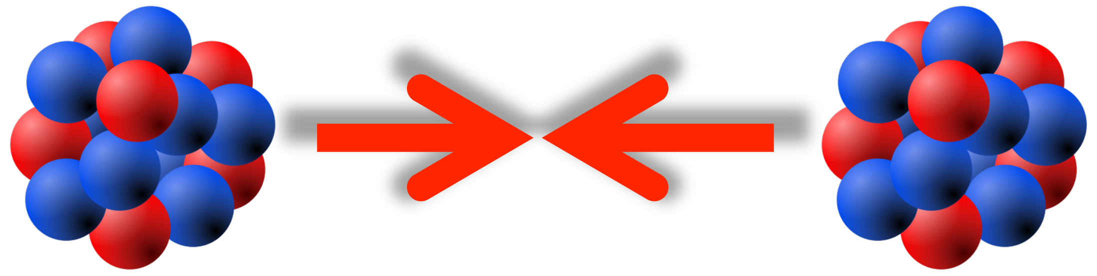
- The **standard picture** based on **the factorisation approach:**

$$\frac{d\sigma^{H_c}}{dp_T} = PDF(x_1\mu_F)PDF(x_2\mu_F) \otimes \frac{d\sigma^c}{dp_T^c}(x_1, x_2, \mu_R, \mu_F) \otimes D_{c\to H_c}(z = p_{H_c}/p_c, \mu_F)$$



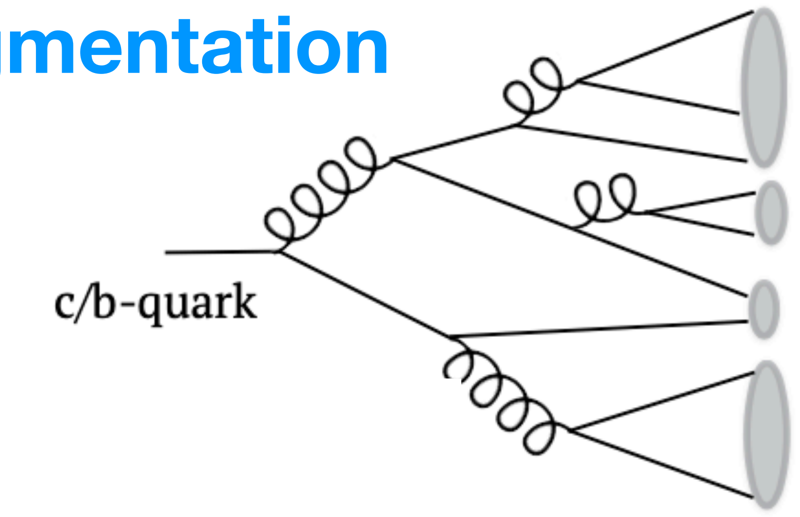
- **pQCD models based on the factorisation appoach:**
  - use **fragmentation fractions parametrised on e$^+$e$^-$ and ep collision data**
  - assume **universality of fragmentation fractions** versus **collision systems** and **energies**
- Recent measurements of heavy-flavour baryon production challenge this assumption
- Additional mechanisms at play in pp collisions beyond simple string fragmentation?

Heavy-flavour hadronisation in large systems

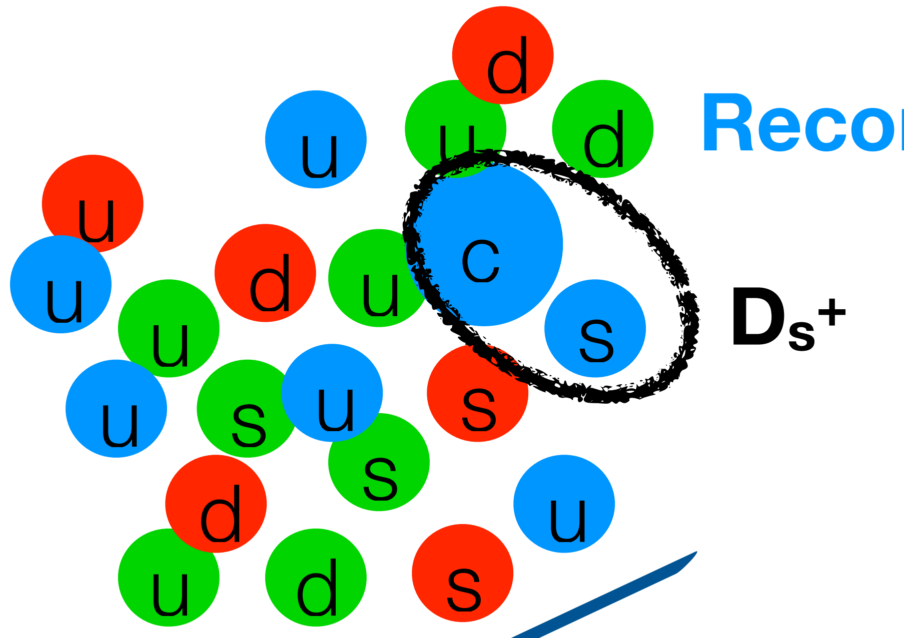


- **Phase space at the hadronisation is filled with partons**
  - partons which are close to each other in phase space (position and momentum) can recombine into hadrons
- Competing mechanisms for hadronisation in QGP: **fragmentation vs recombination**

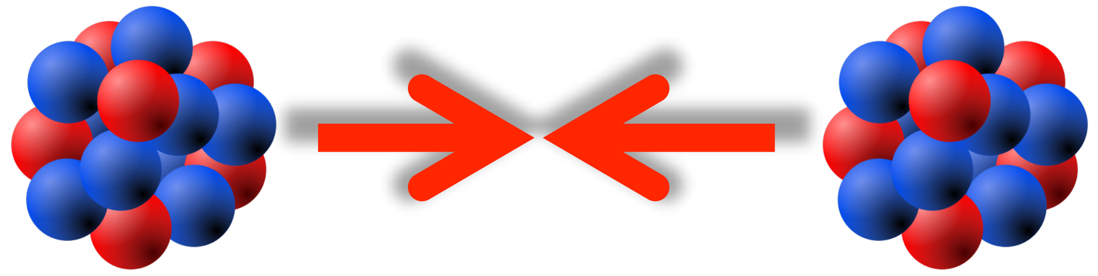
Fragmentation



Recombination/coalescence



Heavy-flavour hadronisation in large systems



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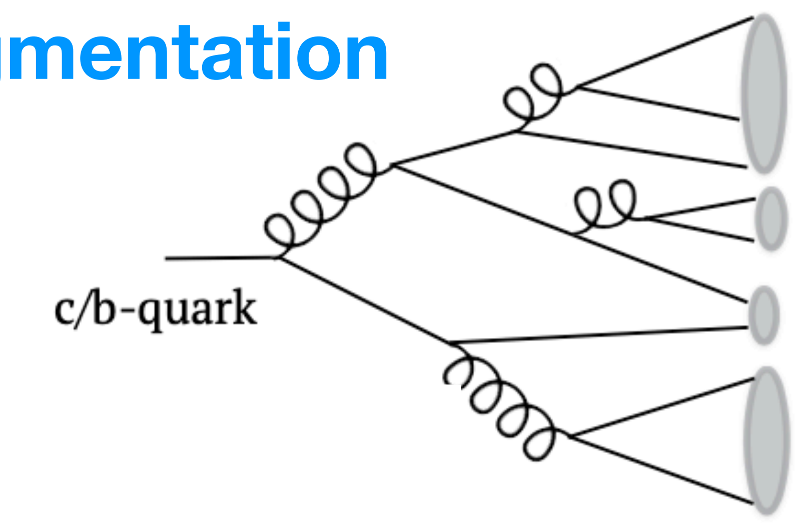

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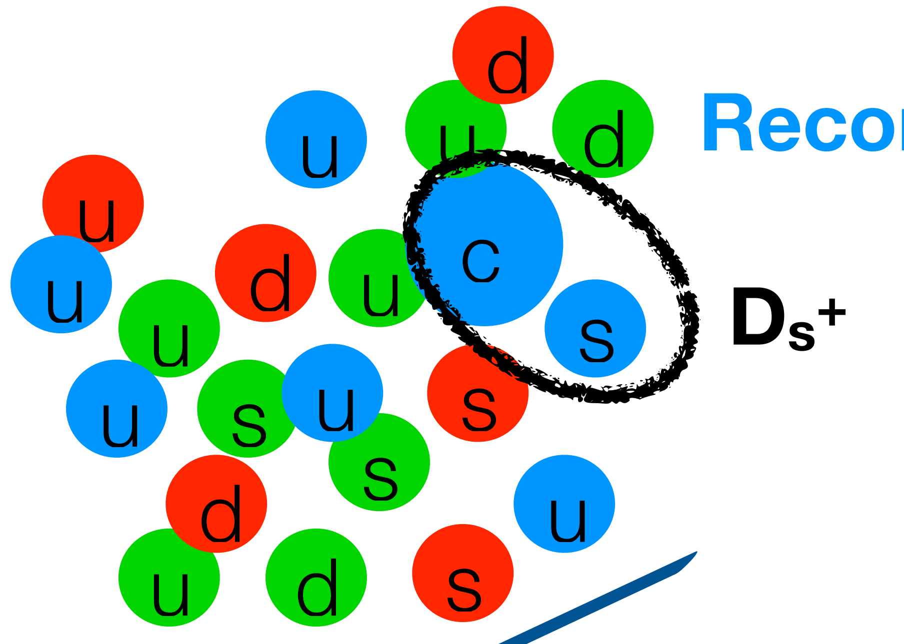
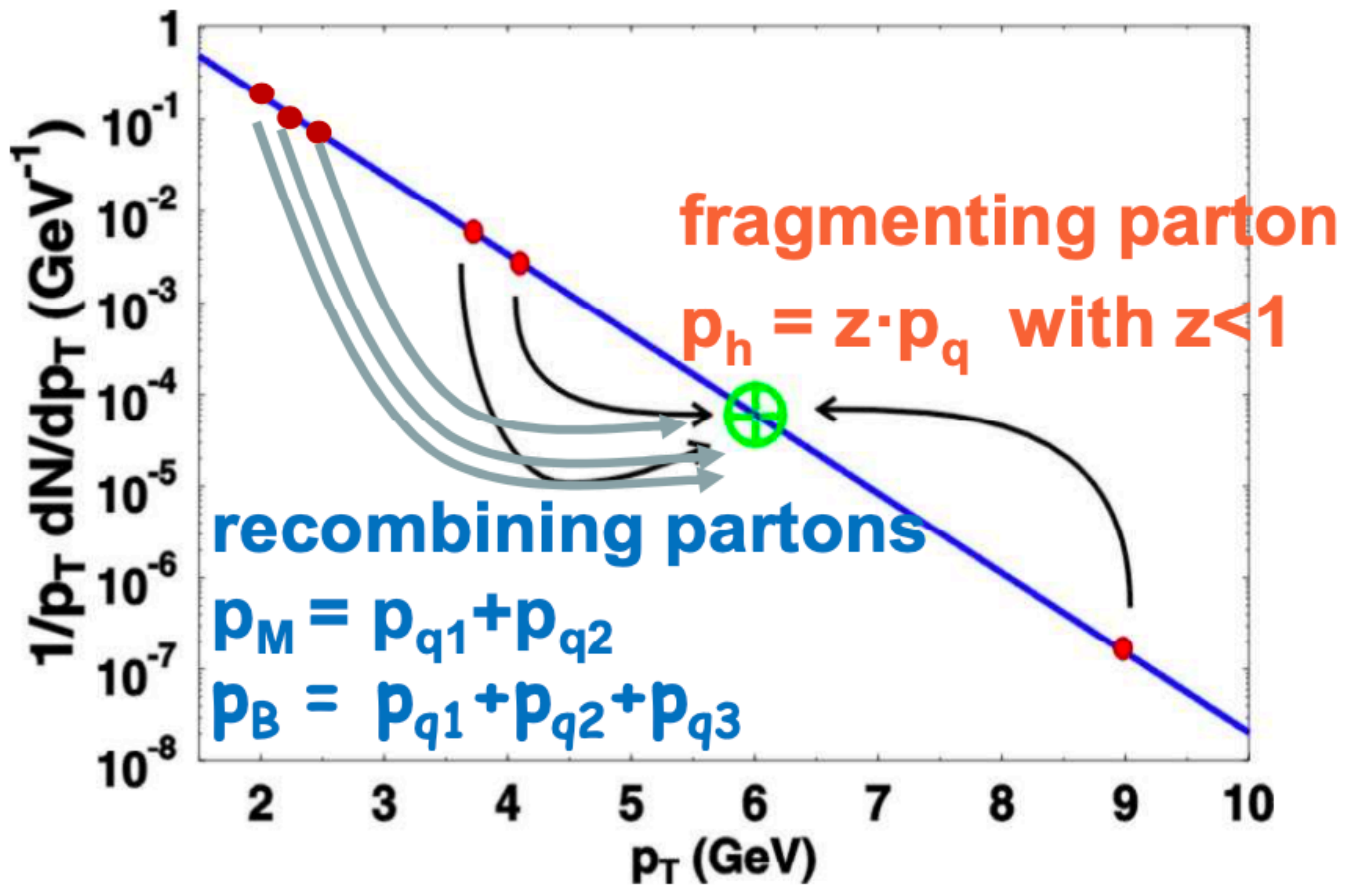


- **Modification of the p_T distribution of produced hadrons:**
  - **Enhancement of baryon-to-meson ratio at intermediate p_T**
  - Strange quarks abundant in the QGP
    -> Enhancement of heavy-flavour mesons with strange quarks relative to non-strange heavy-flavour mesons



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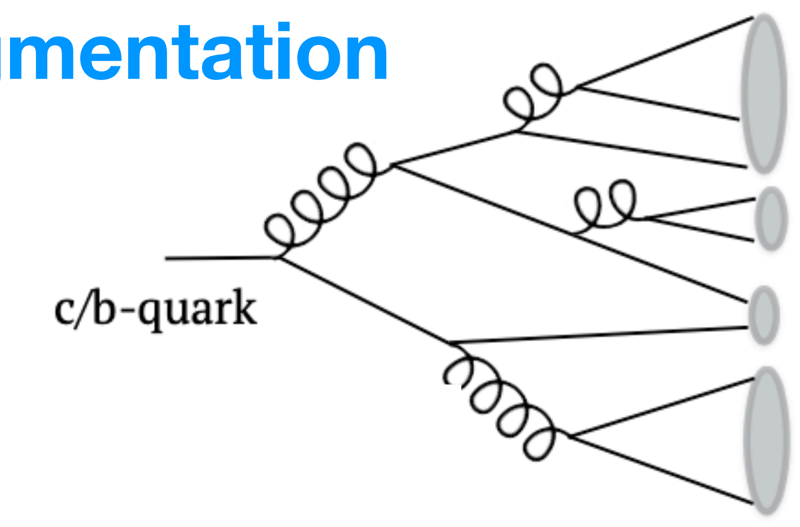

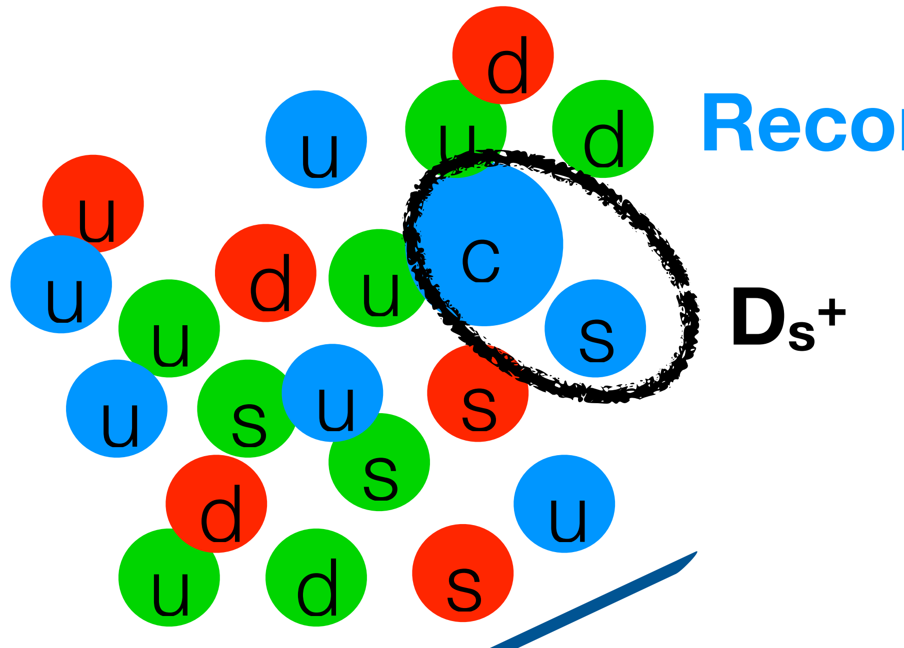

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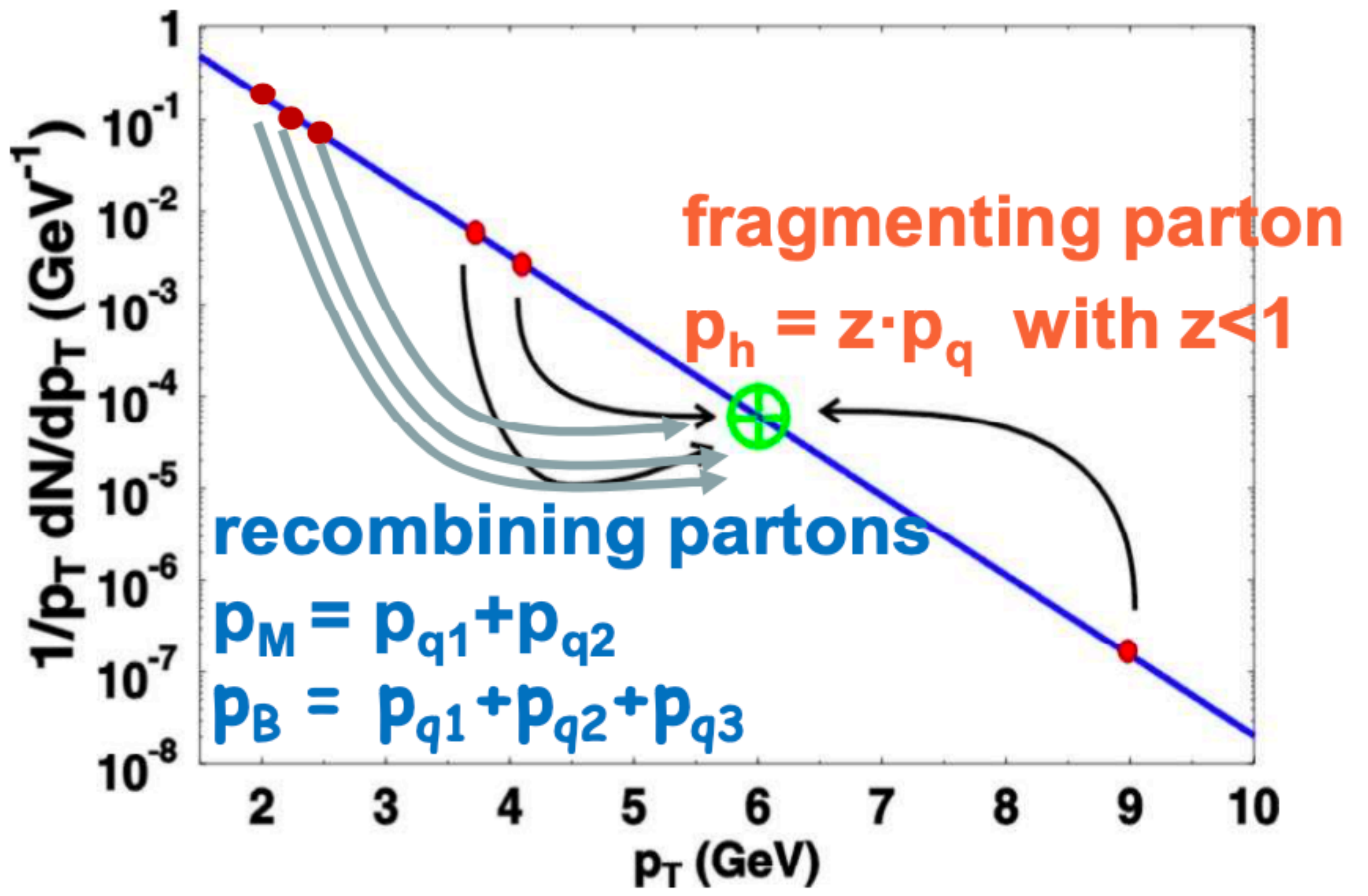
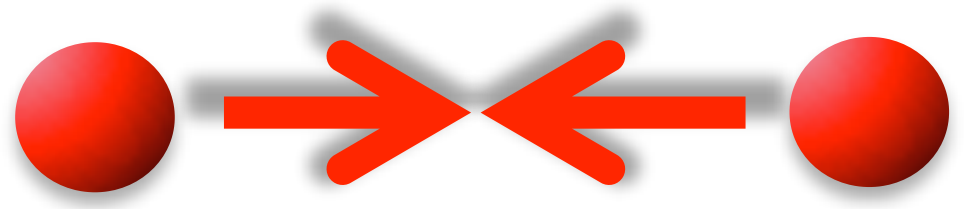


Ratio of the production yields of different hadron species are sensitive to modification of the hadronisation process

Heavy-flavour hadronisation in small systems

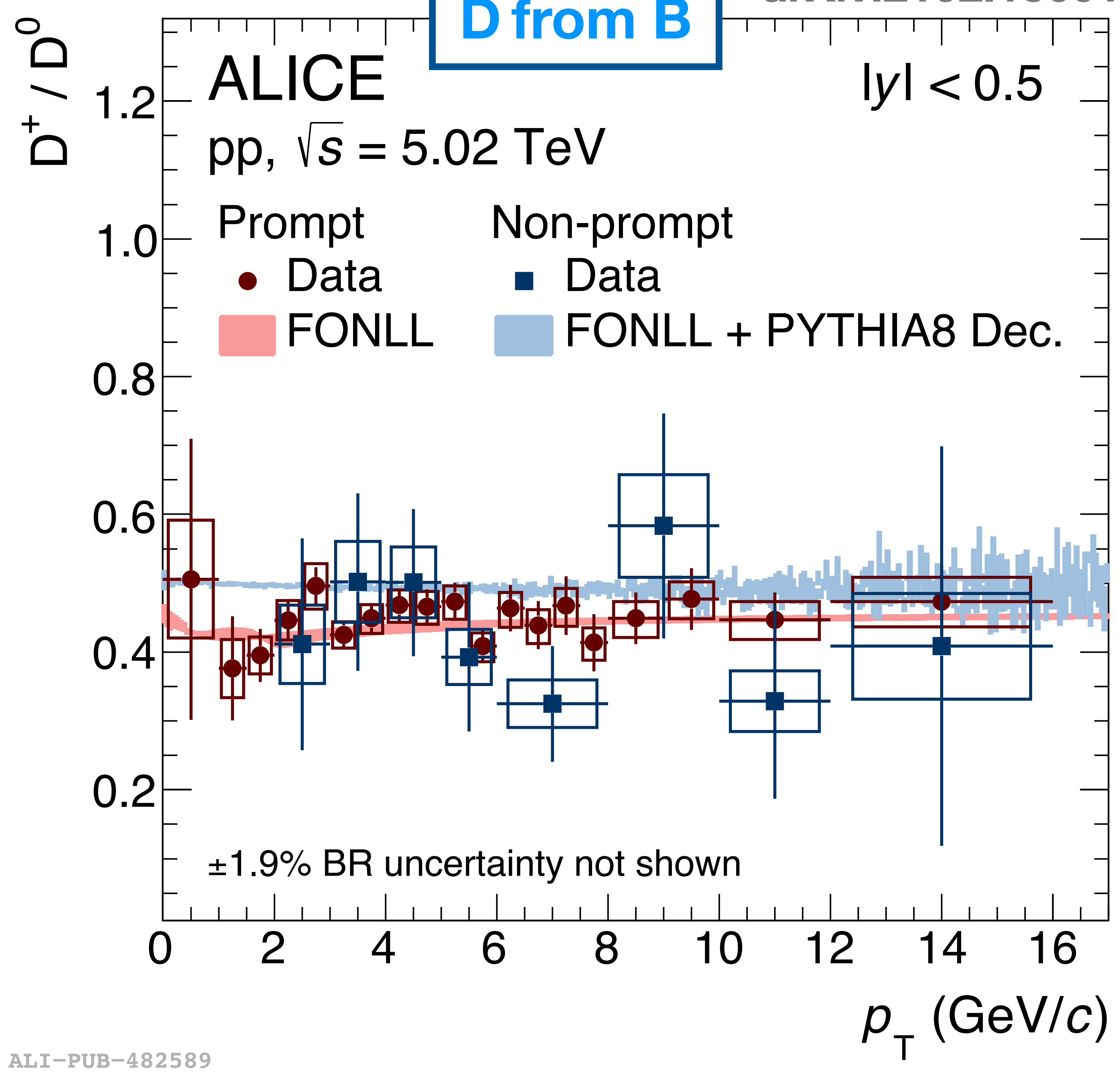


Charm meson-over-meson production ratios

- Charm-hadron-species relative abundances sensitive to fragmentation fractions

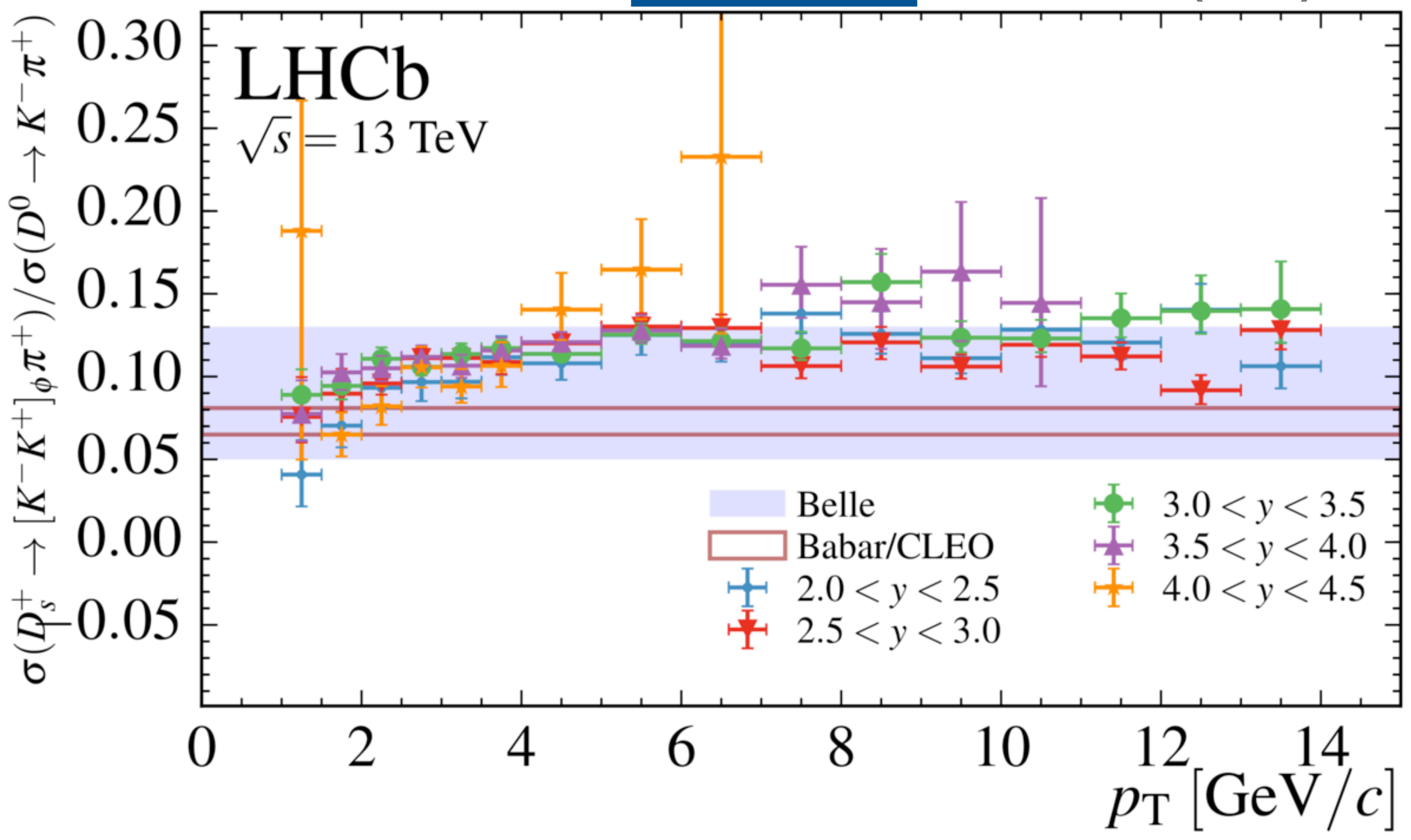
prompt D
D from B

arXiv:2102.13601



D_s^+ / D^0

JHEP 05 (2017) 074



- Almost **flat p_T trend**
- In agreement within uncertainties with models and with measurements at e^+e^- colliders

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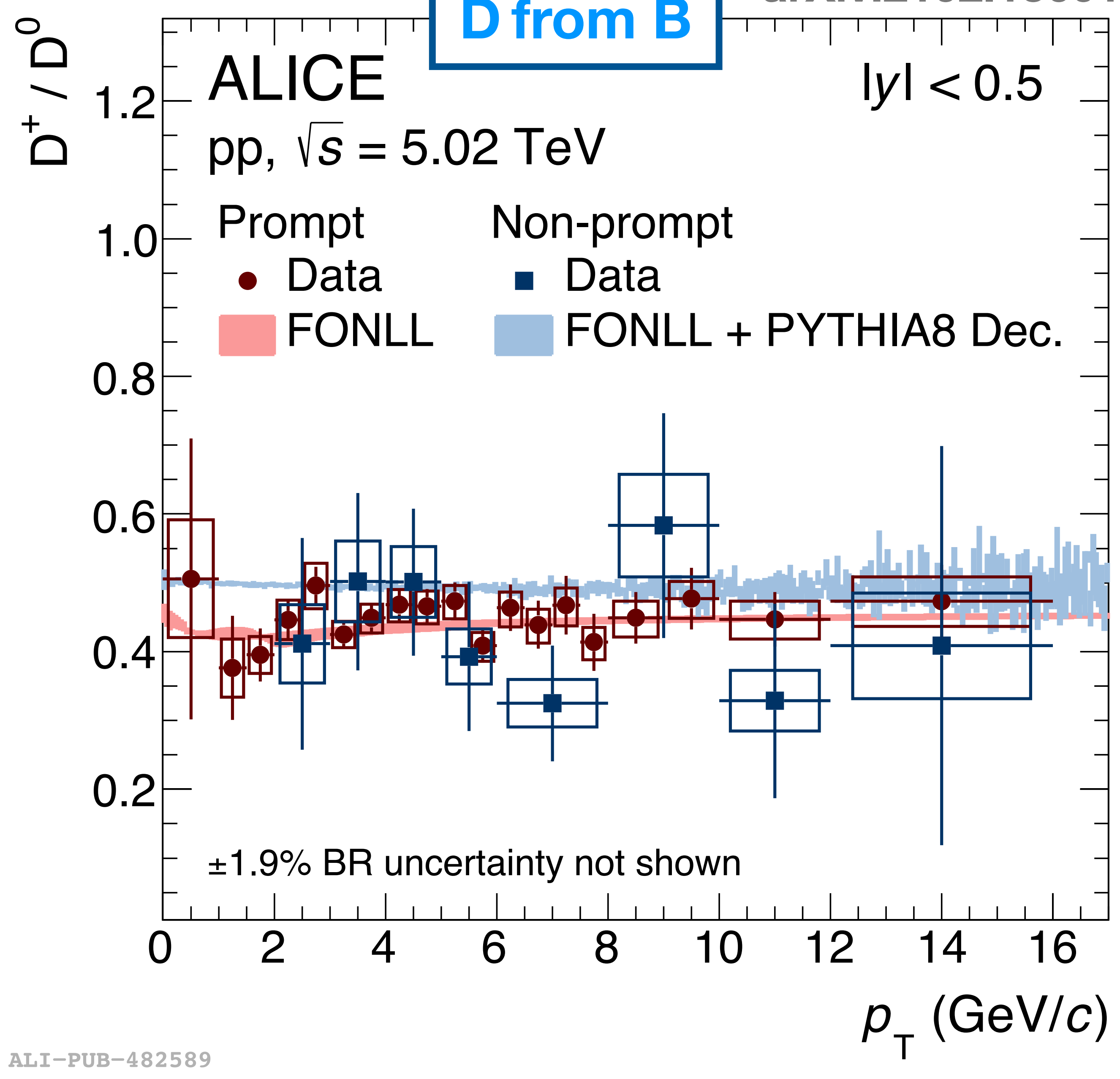

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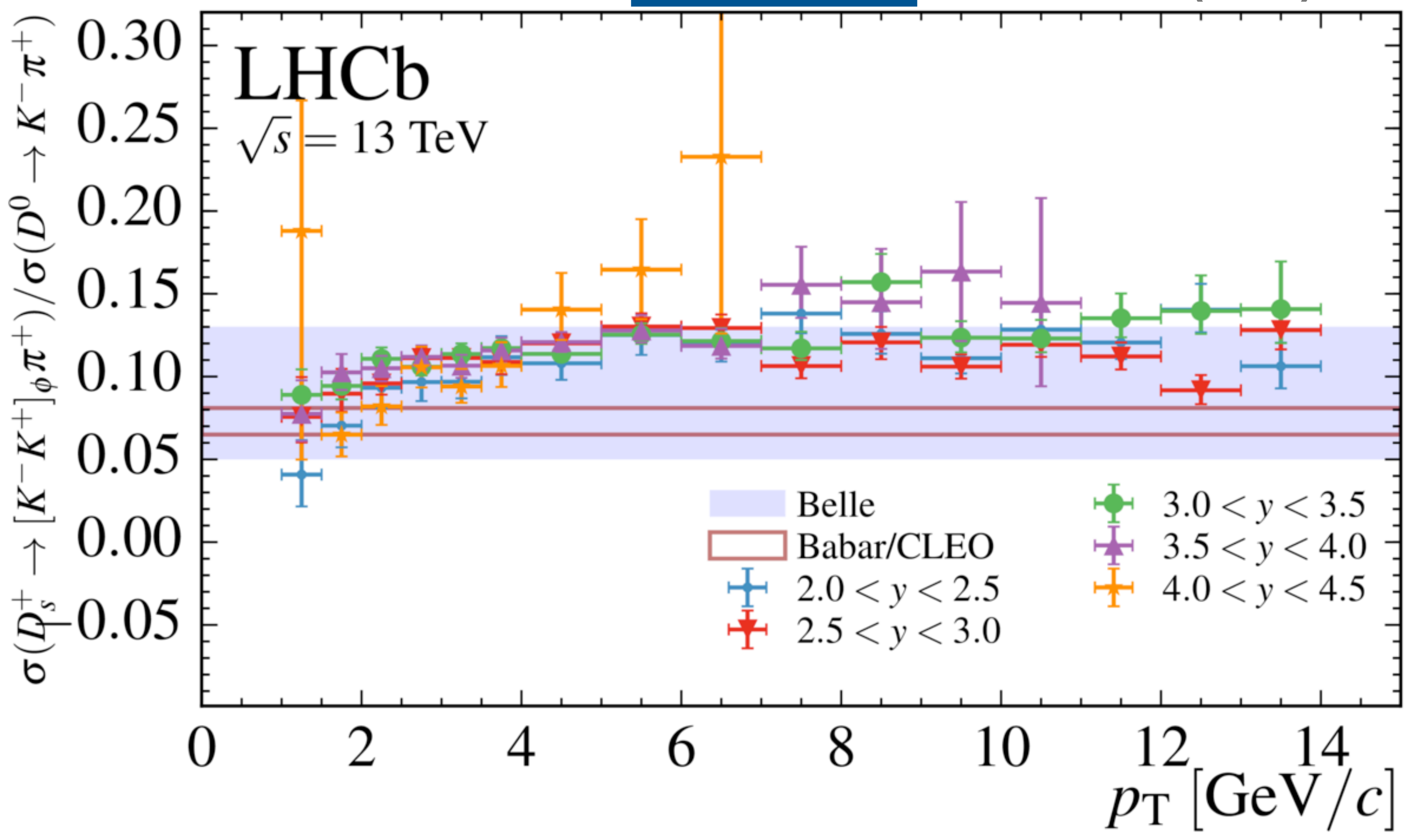
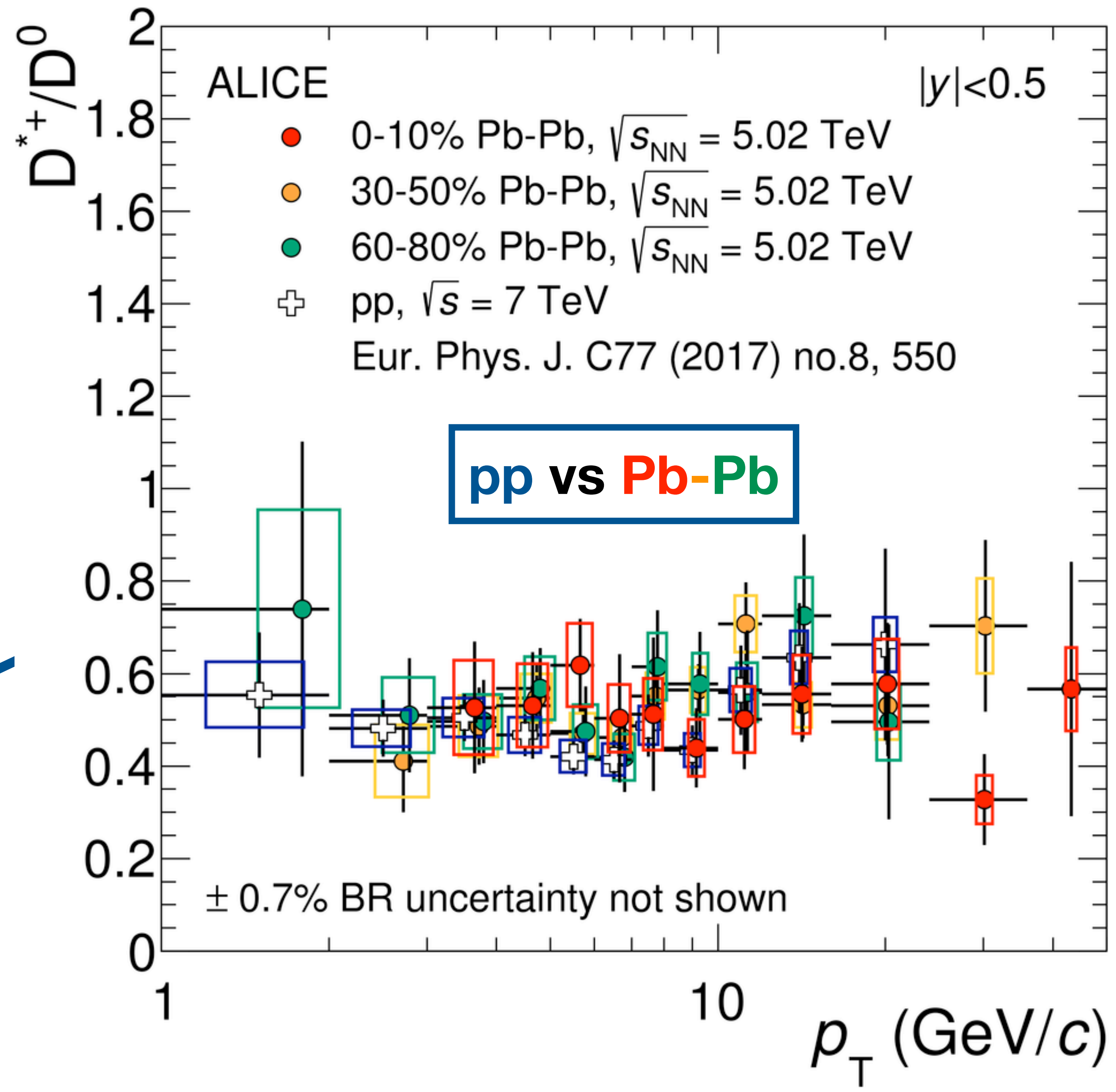


JHEP 1810 (2018) 174



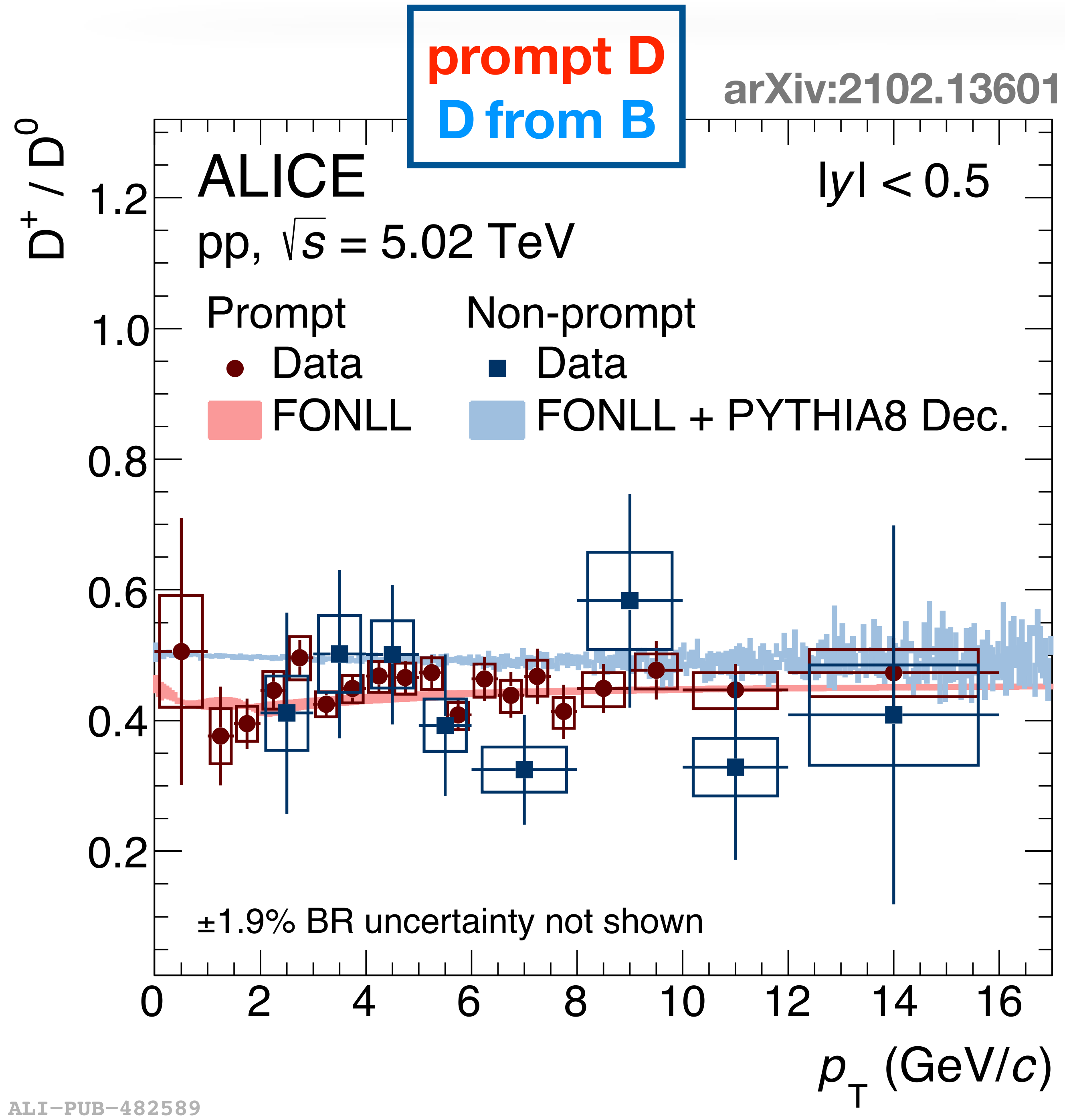
pp vs Pb-Pb

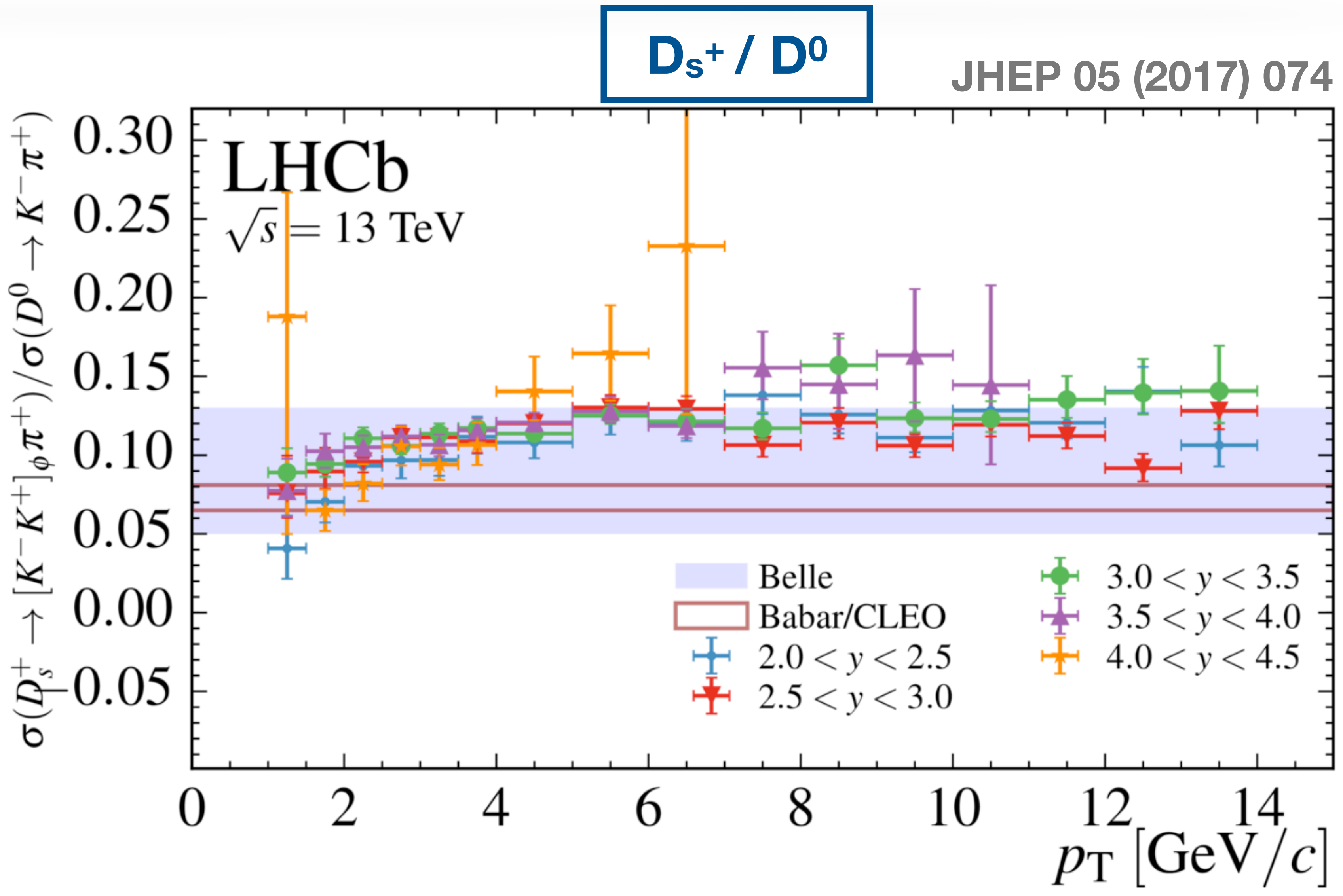
- Almost **flat p_T trend**
- In agreement within uncertainties with models and with measurements at e^+e^- colliders

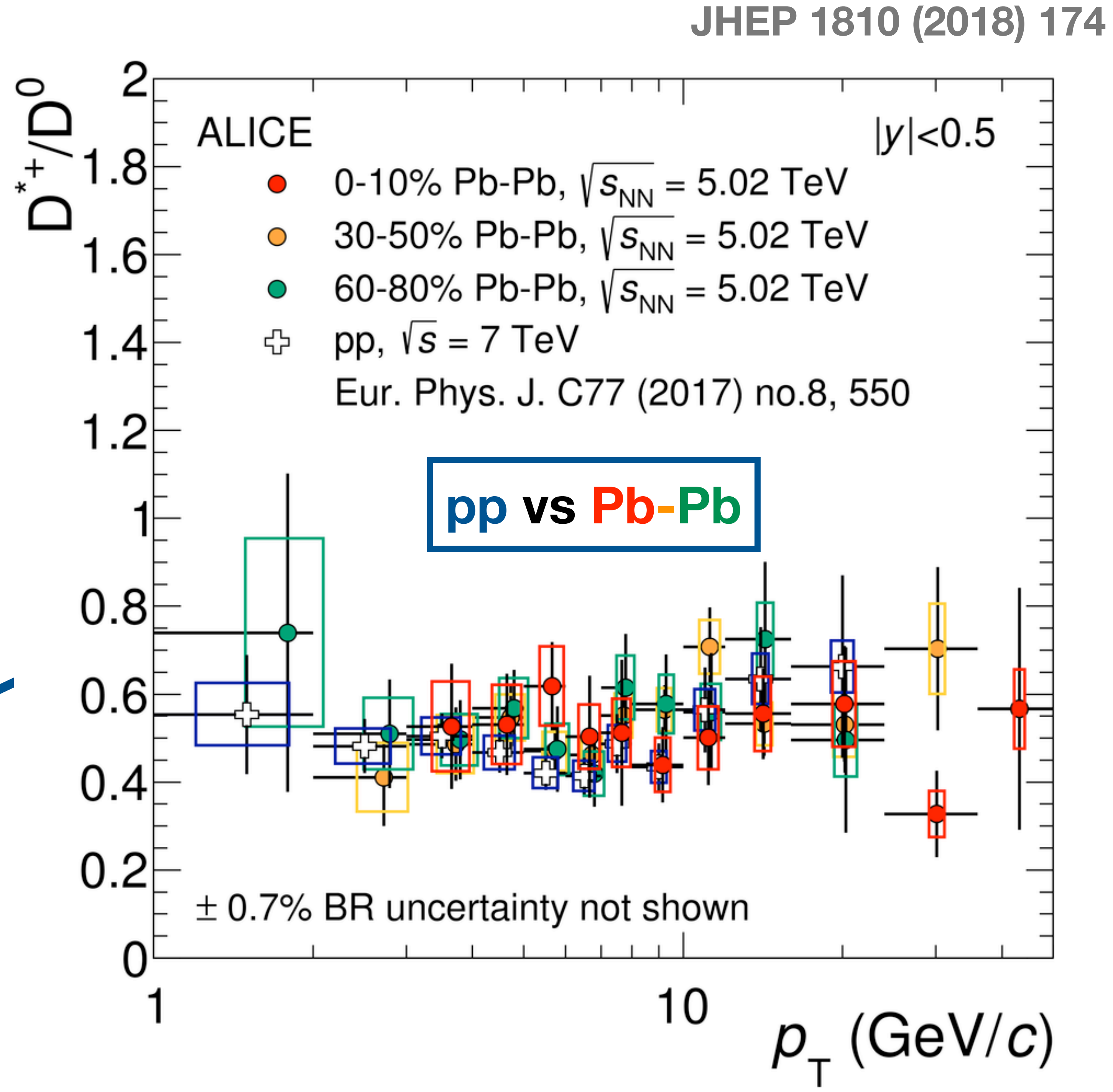
- No dependence on the collision system observed for non-strange D mesons

Charm meson-over-meson production ratios

- Charm-hadron-species relative abundances sensitive to fragmentation fractions







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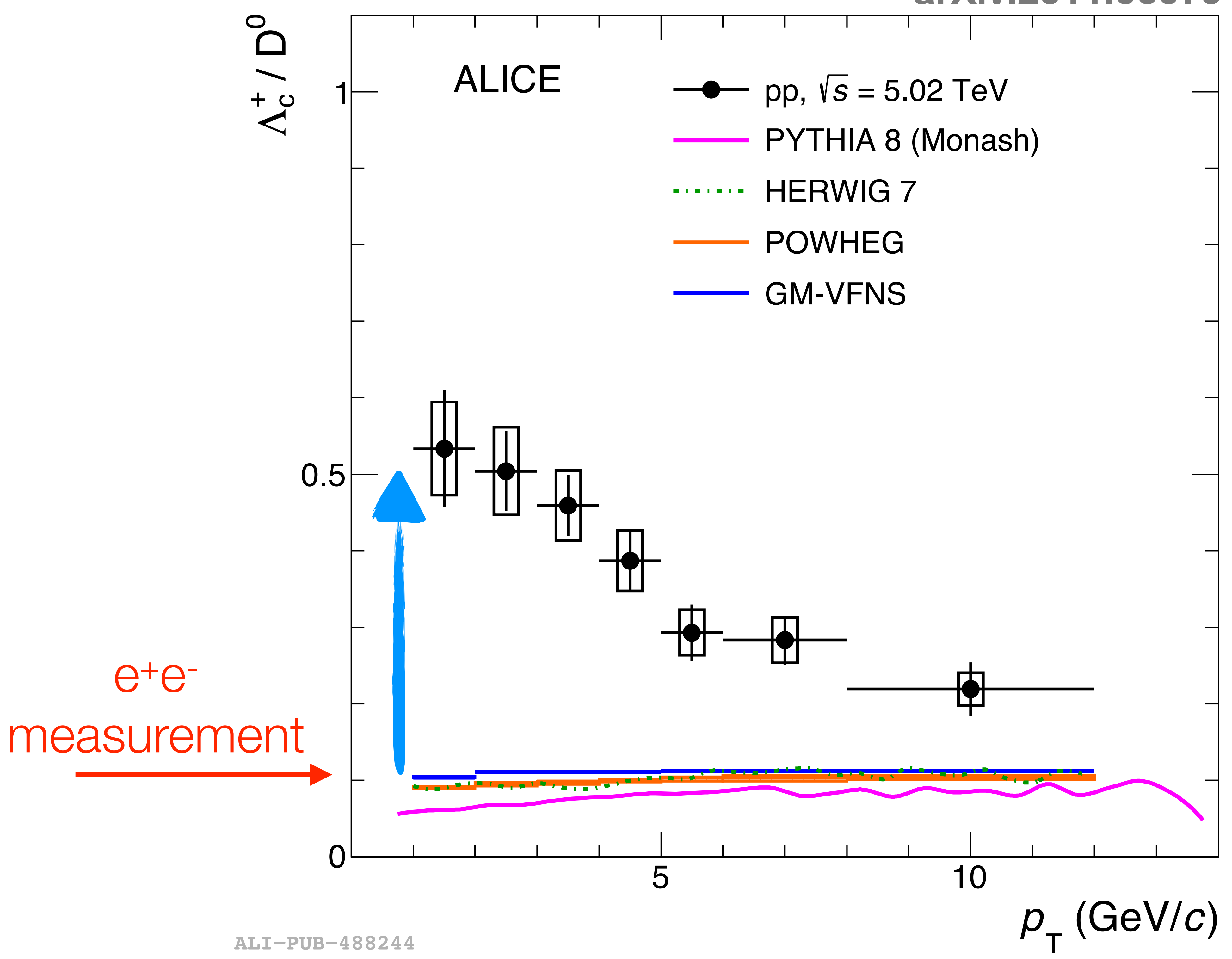
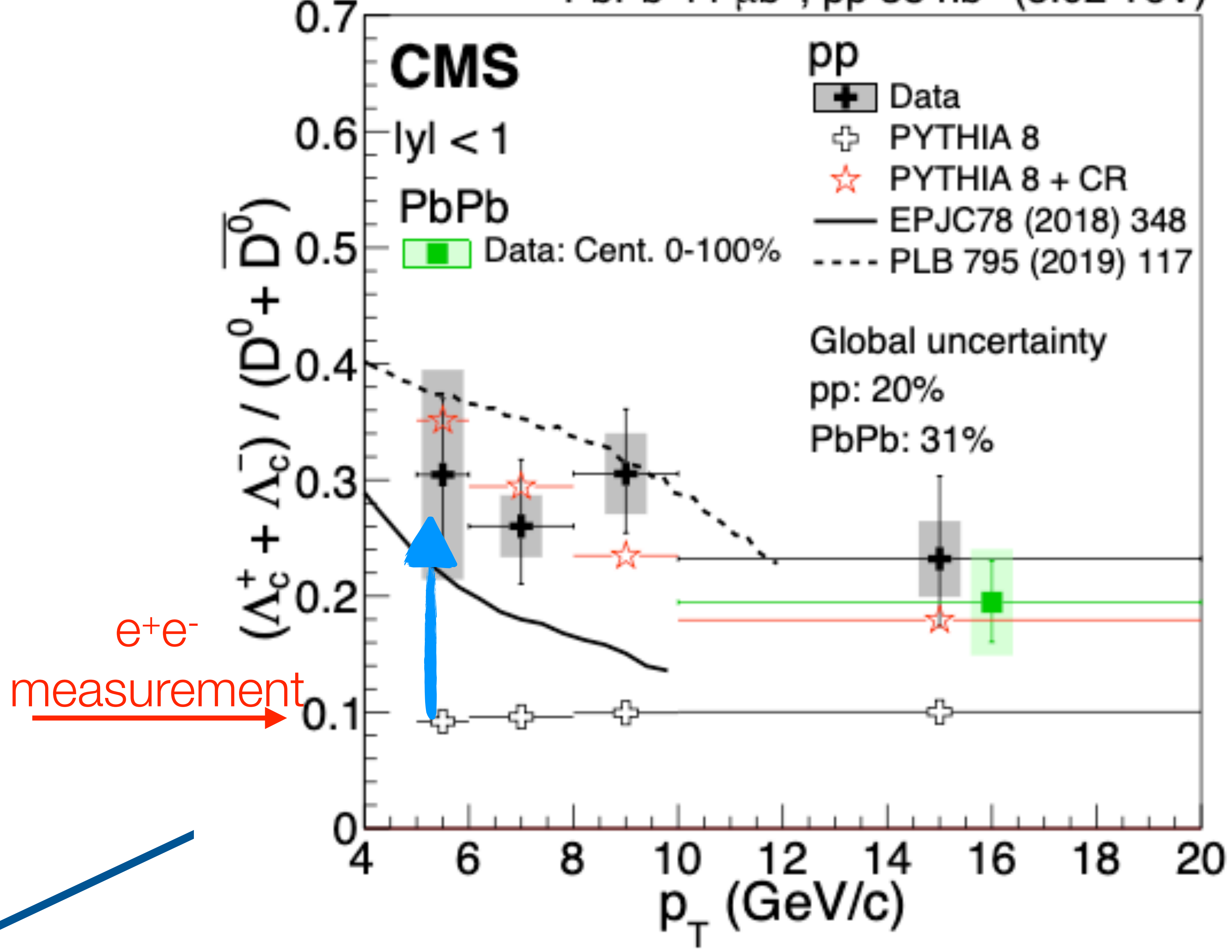
Λ_c^+/D^0 ratio

arXiv:2011.06078
arXiv:2011.06079



PLB 803 (2020) 135328



- **Strong p_T trend observed**
- **Larger than measurements in e^+e^- and ep collisions**
- Compatible results at mid-rapidity between ALICE and CMS
- **PYTHIA 8 Monash**, **HERWIG**, **POWHEG** and **GM-VFNS** do not reproduce the p_T dependence

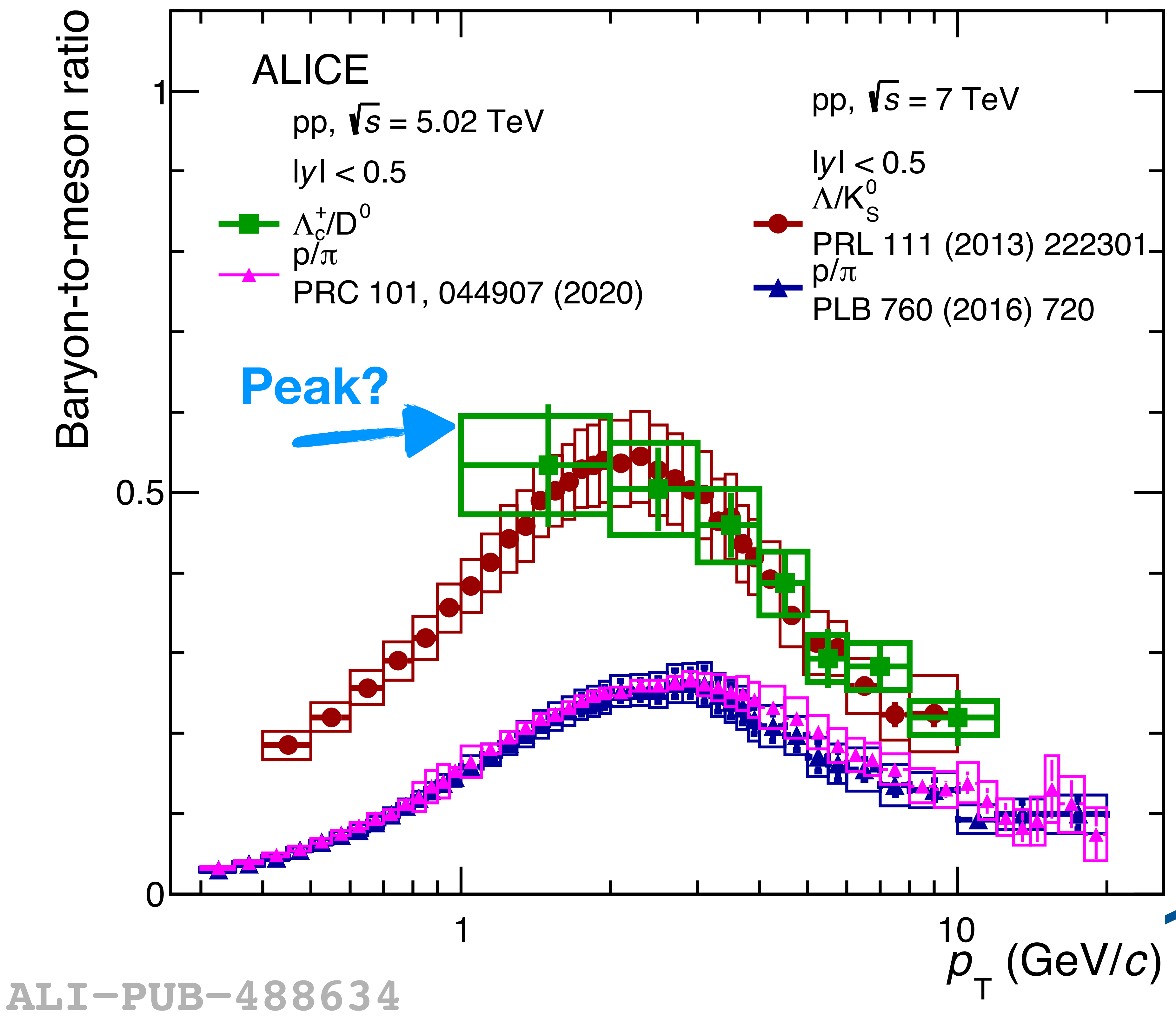
PYTHIA 8 Monash: EPJ C74 (2014) 3024
HERWIG 7: EPJ C58 (2008) 639
POWHEG: JHEP 09 (2007) 126
GM-VFNS: PRD 101 (2020) 114021

Non universality of the fragmentation fractions for charm baryons

Which is the origin of the modification of the Λ_c^+/D^0 ratio?

Λ_c^+/D^0 vs light flavours ratios

arXiv:2011.06078
arXiv:2011.06079



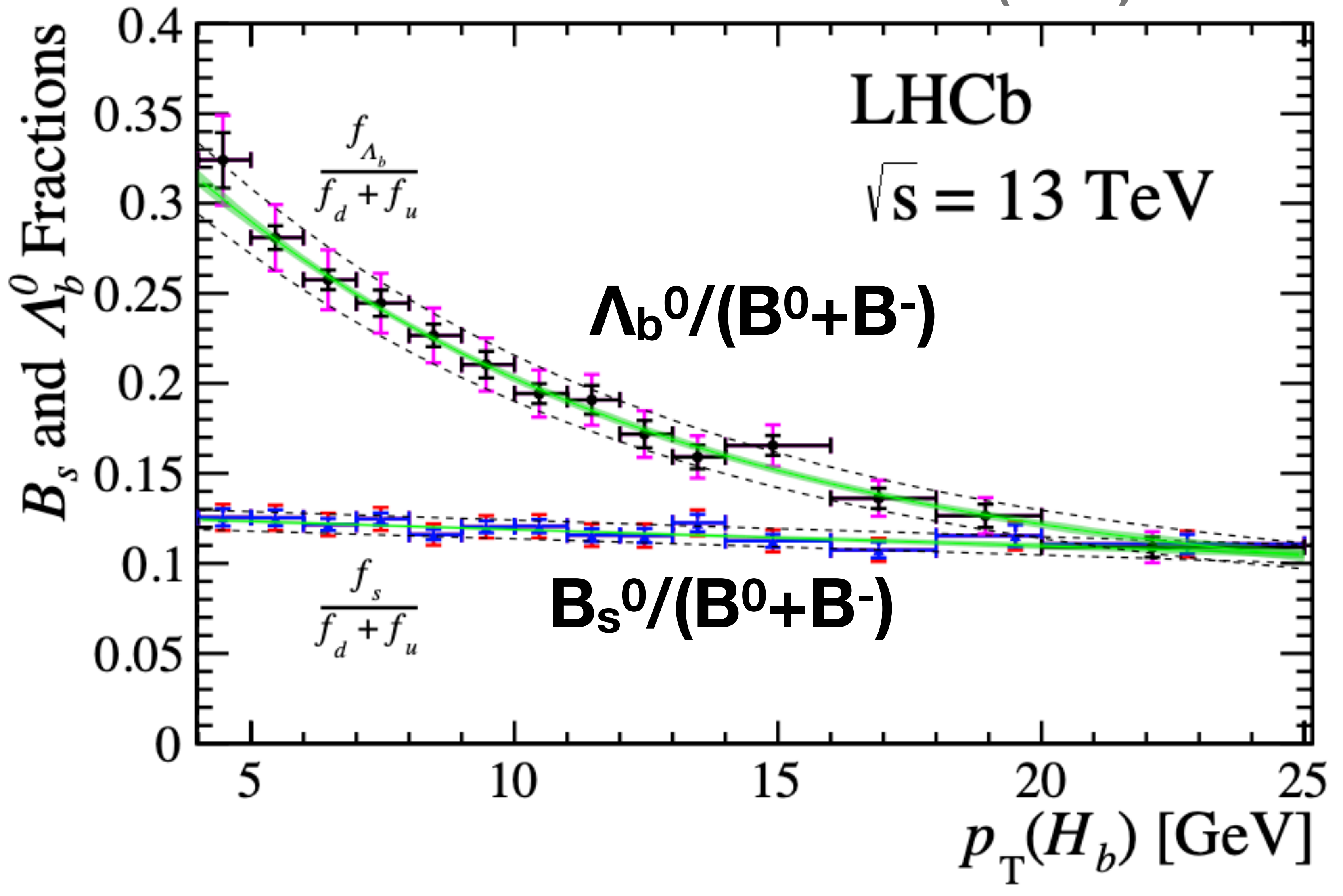
- Similar features for Λ_c^+/D^0 and light-flavour ratios

Common mechanism for light and charm baryon formation?

- Caveat:
  - Light-flavour hadrons have a significant contribution from gluon fragmentation
  - Low p_T light-flavour hadrons mainly originate from soft scattering process involving small momentum transfers

Ratio of fragmentation fractions through beauty hadrons

PRD 100 (2019) 031102

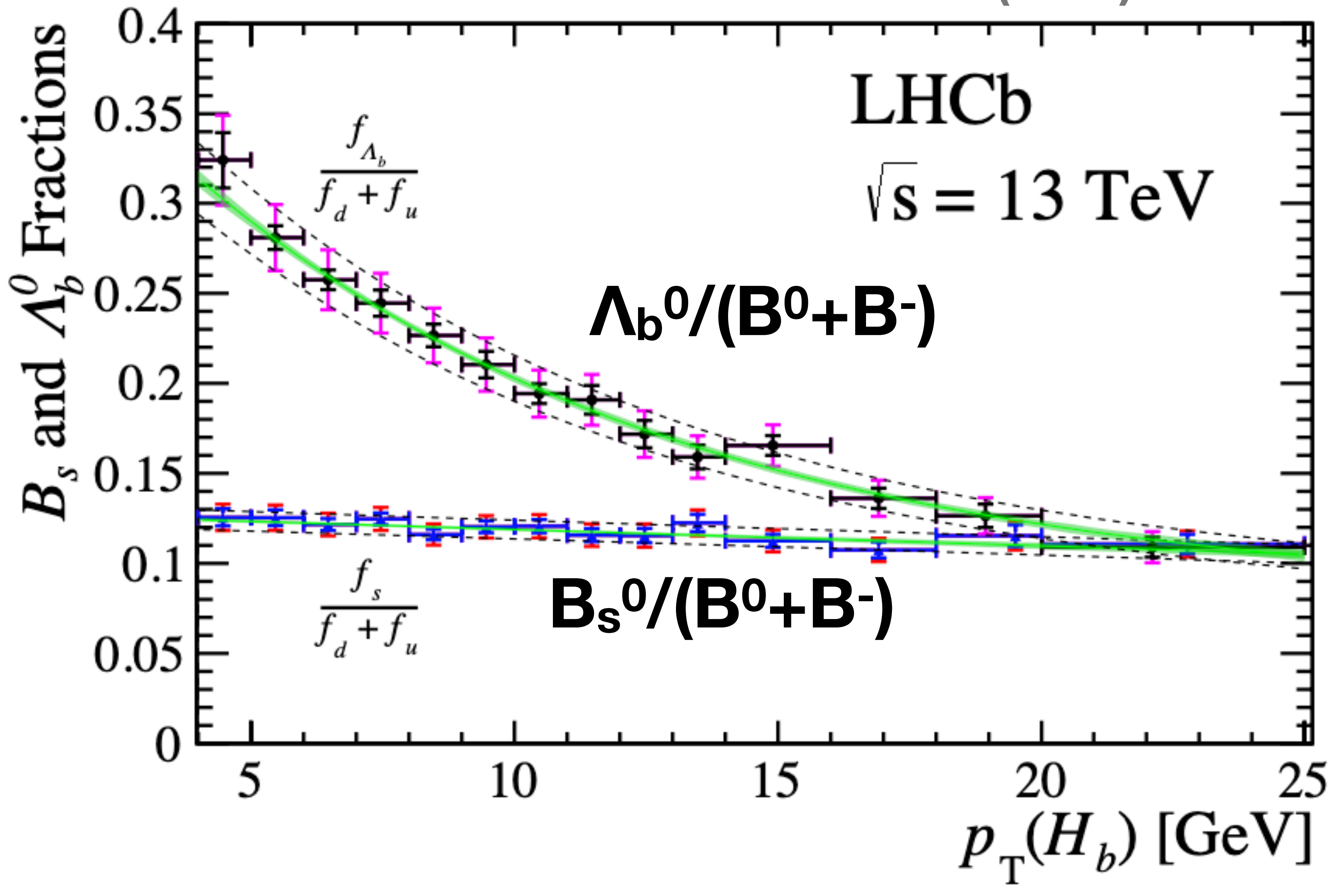


- $f_{\Lambda b}/(f_d+f_u)$ strongly depends on p_T

Is the decreasing trend of the baryon-to-meson ratio a baryon/meson effect or a mass effect?

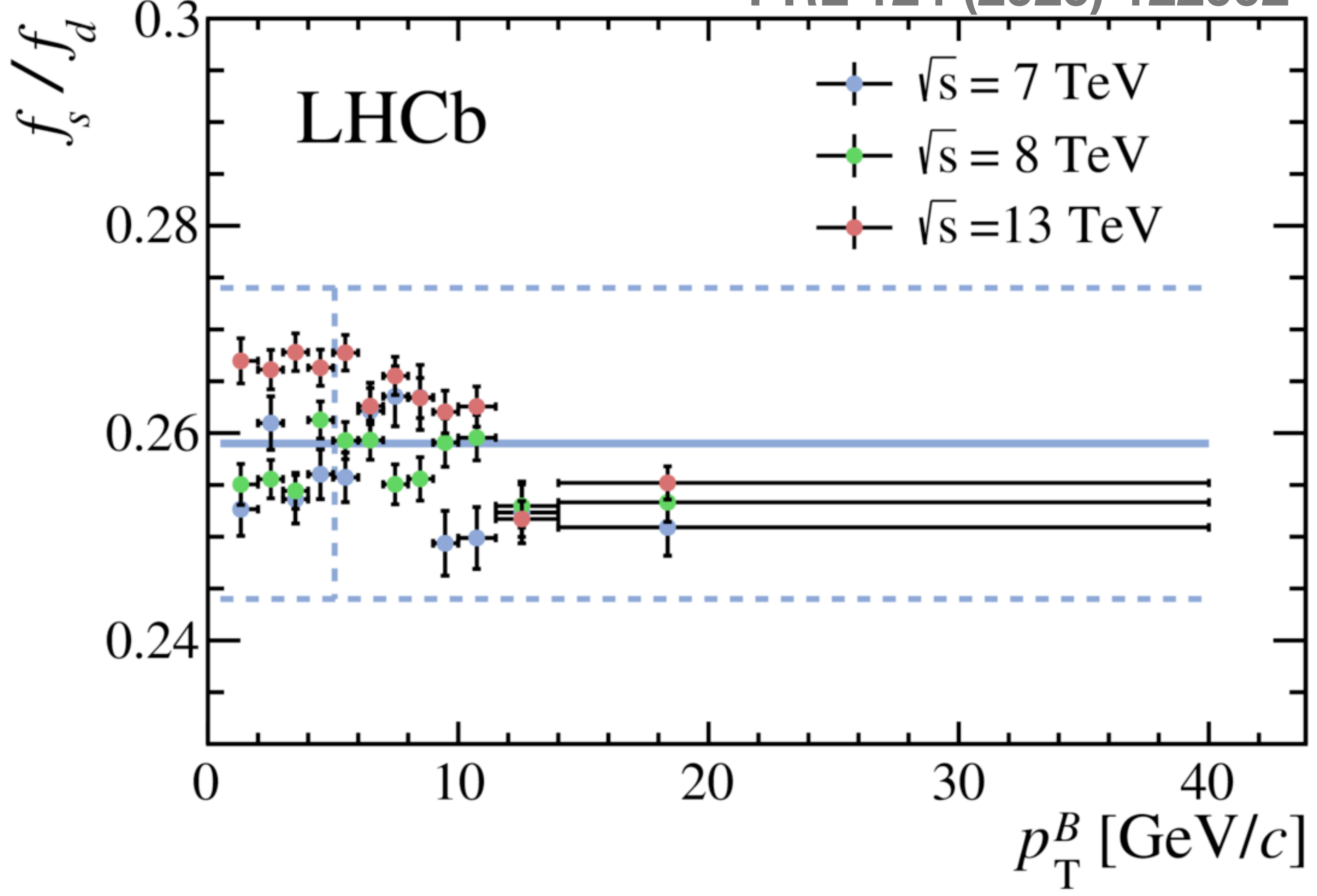
Ratio of fragmentation fractions through beauty hadrons

PRD 100 (2019) 031102

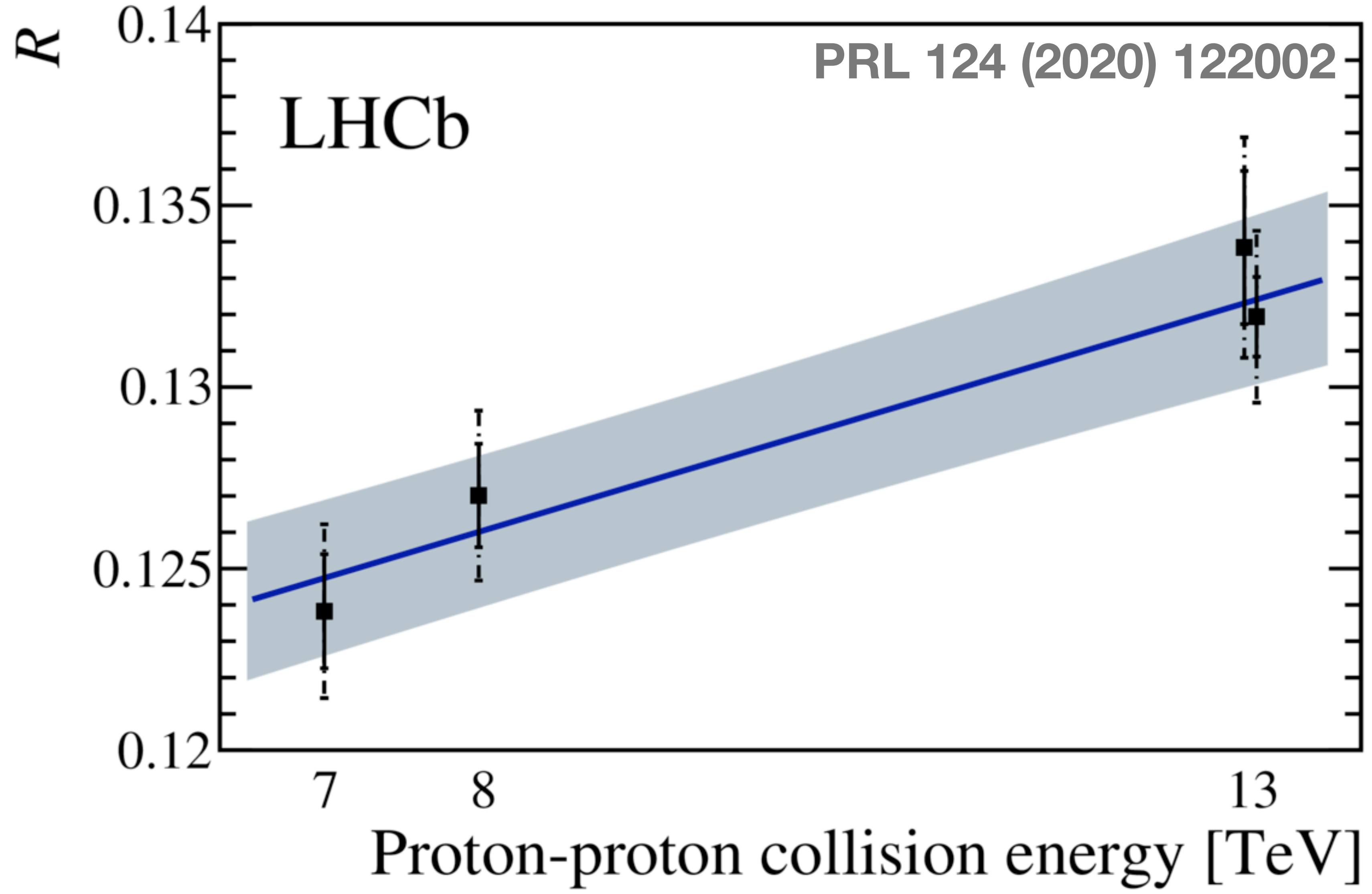


$$\frac{f_s}{f_d} \propto \frac{n_{corr}(B_s^0 \to D_s^- \pi^+)}{n_{corr}(B^0 \to (D^- K^+ | D^- \pi^+)}$$

PRL 124 (2020) 122002



$$R \propto \frac{f_s}{f_u} \propto \frac{n_{corr}(B_s^0 \to J/\psi \phi)}{n_{corr}(B^+ \to J/\psi K^+)}$$



- $f_{\Lambda b}/(f_d+f_u)$ **strongly depends on** p_T

Is the decreasing trend of the baryon-to-meson ratio a baryon/meson effect or a mass effect?

- **f_s/f_d depends linearly on p_T (significance 6σ)**
- dependency driven by the 13 TeV sample (significance 8.3σ)
- other energies not significant when considered separately

- **depends linearly on energy (significance 4.8σ)**

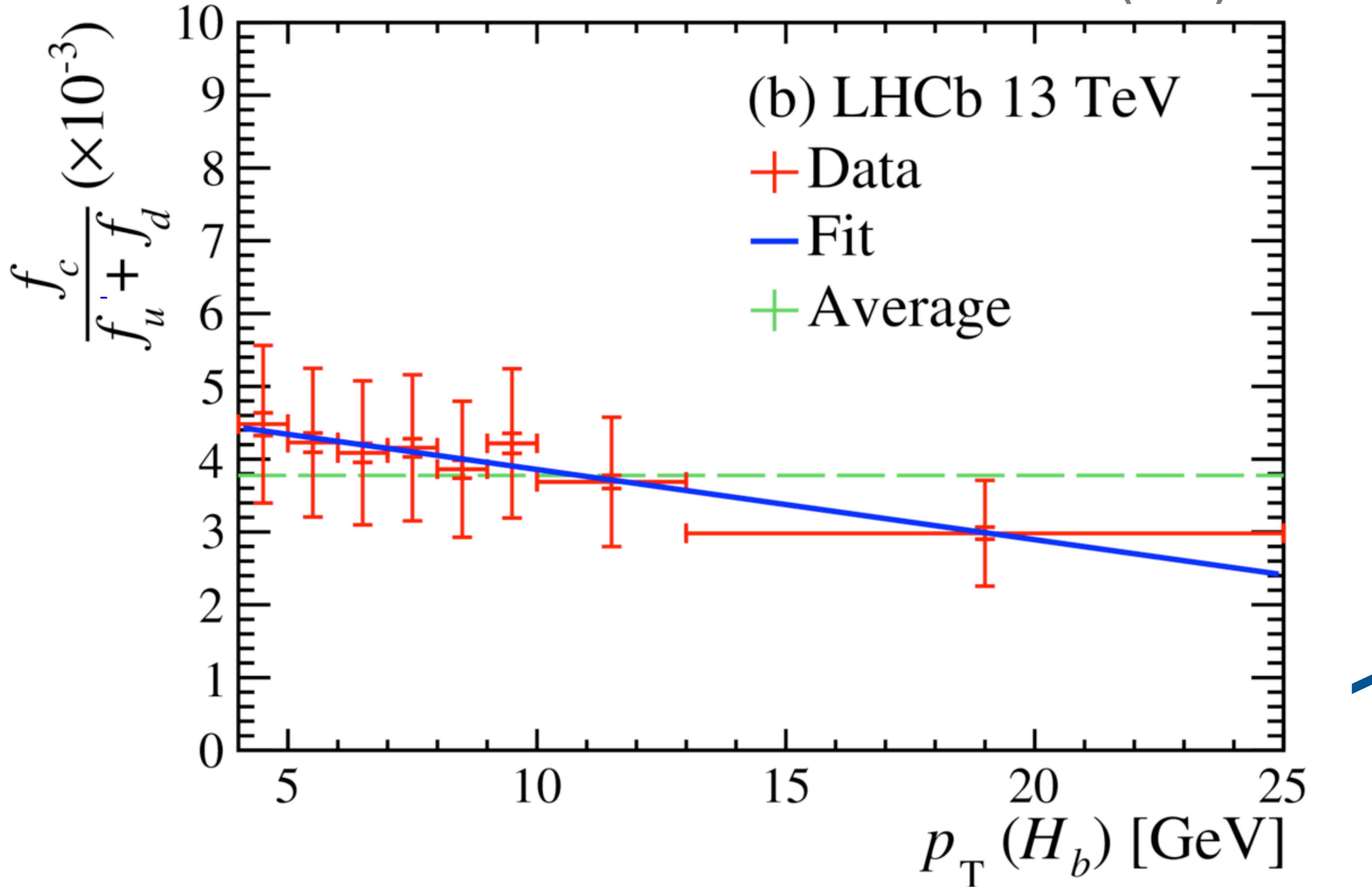
New measurements with larger statistics will allow further investigation of the p_T dependence of f_s/f_d

B_c-meson measurements

- **Ground state of two different heavy-flavour quarks (c+b)** with a mass of ~6.4 GeV/c²

$$\frac{f_c}{f_u+f_d} \propto \frac{n_{corr}(B_c^- \to J/\psi\mu^-\bar{\nu})}{n_{corr}(B_0 \to D^0 X\mu^-\bar{\nu}) + n_{corr}(B^+ \to D^+ X\mu^-\bar{\nu})}$$

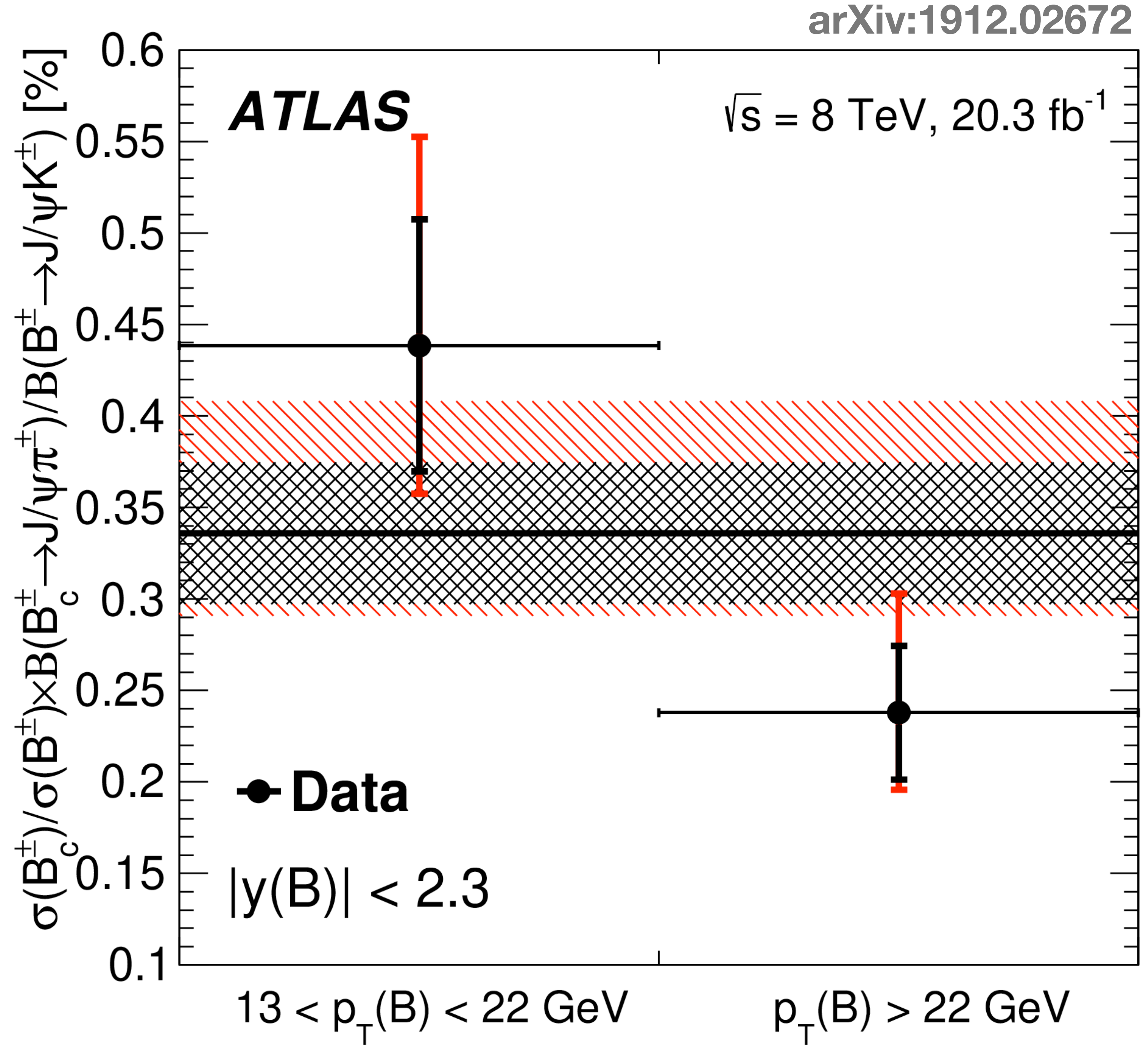
PRD 100 (2019) 112006



$$\frac{f_c}{f_u+f_d}(p_T) = A\left[p_1 + p_2\left(p_T(H_b) - \langle p_T\rangle\right)\right]$$

Energy	p_1	$p_2 \cdot 10^{-2}$ (GeV^{-1})
7 TeV	$3.82 \pm 0.09 \pm 0.05$	$-6.2 \pm 1.7 \pm 1.1$
13 TeV	$4.13 \pm 0.05 \pm 0.04$	$-9.7 \pm 0.8 \pm 1.0$

arXiv:1912.02672



Hint of not-flat p_T trend, but not as pronounced as $\Lambda_b^0/(B^0+B^+)$

Which mechanisms could enhance HF baryon production?

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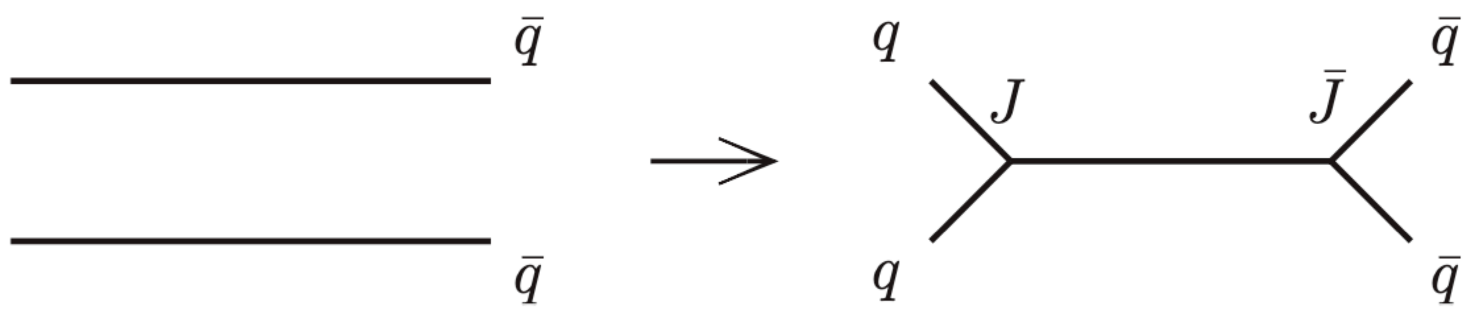
Christiansen, Skands, JHEP 1508 (2015) 003

- **PYTHIA 8 with enhanced Colour Reconnection (CR) effects**
  - allows string formation beyond leading colour approximation
  - junction connection topologies enhance baryon formation



(b) Type II: junction-style reconnection

Which mechanisms could enhance HF baryon production?

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- **Statistical Hadronization Model (SHM) including additional excited baryon states predicted by the Relativistic Quark Model (RQM)**
  - **PDG**: 5 Λ_c (I=0), 3 Σ_c (I=1), 8 Ξ_c (I=1/2), 2 Ω_c (I=0)
  - **RQM**: add 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c

SHM: He, Rapp, PLB 795 (2019) 117-121
RQM: Ebert, Faustov, Galkin, PRD 84 (2013) 014025

n_i $(\cdot 10^{-4}$ fm$^{-3})$	D^0	D^+	D^{*+}	D_s^+	Λ_c^+	$\Xi_c^{+,0}$	Ω_c^0
PDG(170)	1.161	0.5098	0.5010	0.3165	0.3310	0.0874	0.0064
RQM(170)	1.161	0.5098	0.5010	0.3165	0.6613	0.1173	0.0144

Which mechanisms could enhance HF baryon production?

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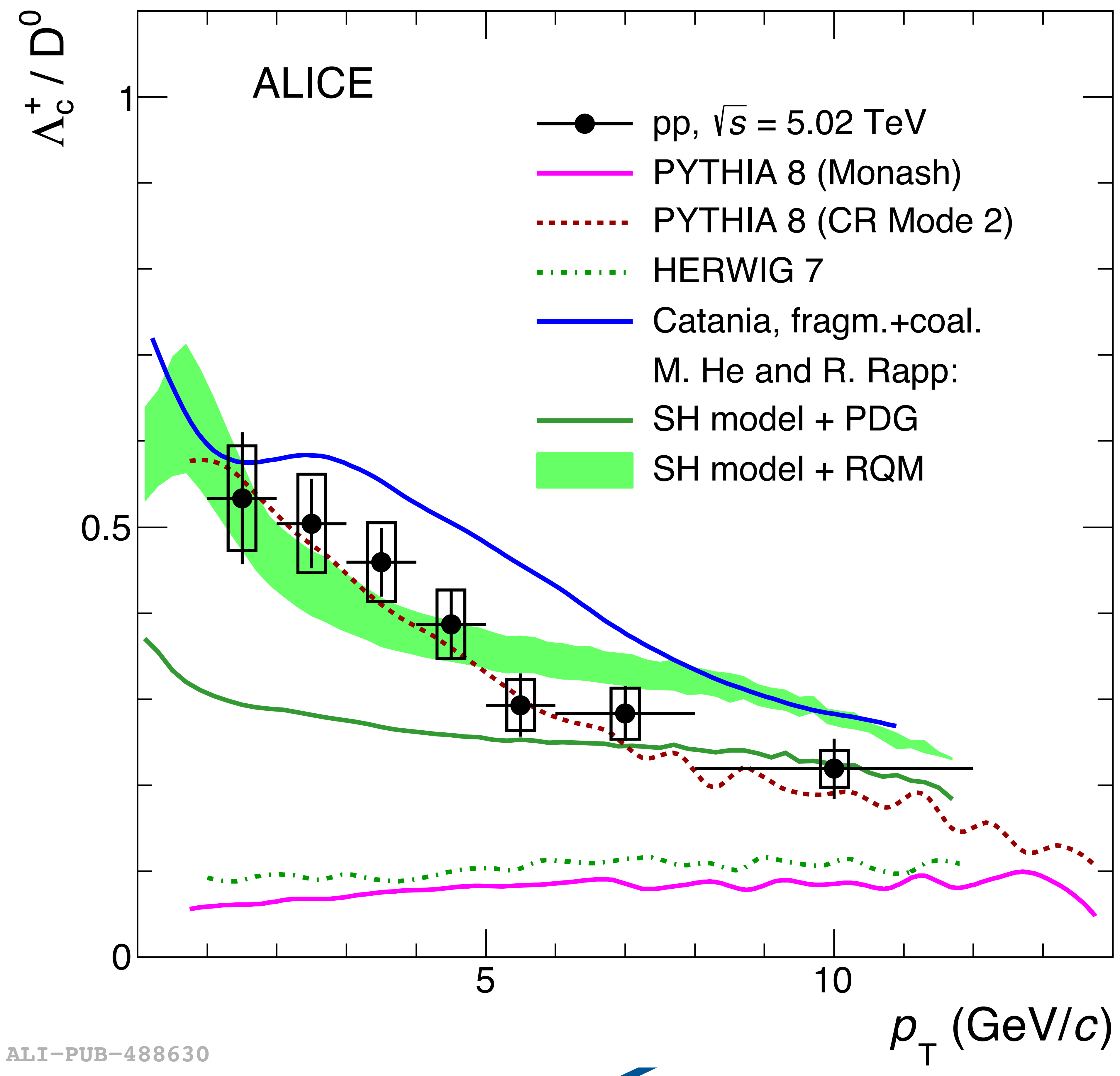
- **Quark Recombination Mechanism (QCM)** — **Song, Li, Shao, EPJ C78 no. 4 (2018) 344**
  - combination of charm quarks with light quarks with equal velocity
  - relative abundances of the different baryon species fixed by thermal weights

Λ_c^+/D^0 ratio: comparison with models

arXiv:2011.06078
arXiv:2011.06079



- **PYTHIA 8 with enhanced CR** enhances the baryon production with respect to **PYTHIA 8 Monash**
- **SHM+RQM** enhances the baryon yield with respect to SHM+PDG
- **Catania** is the model that most enhances the baryon yield and slightly overestimates the data

Λ_c^+/D^0 in low and high multiplicity events

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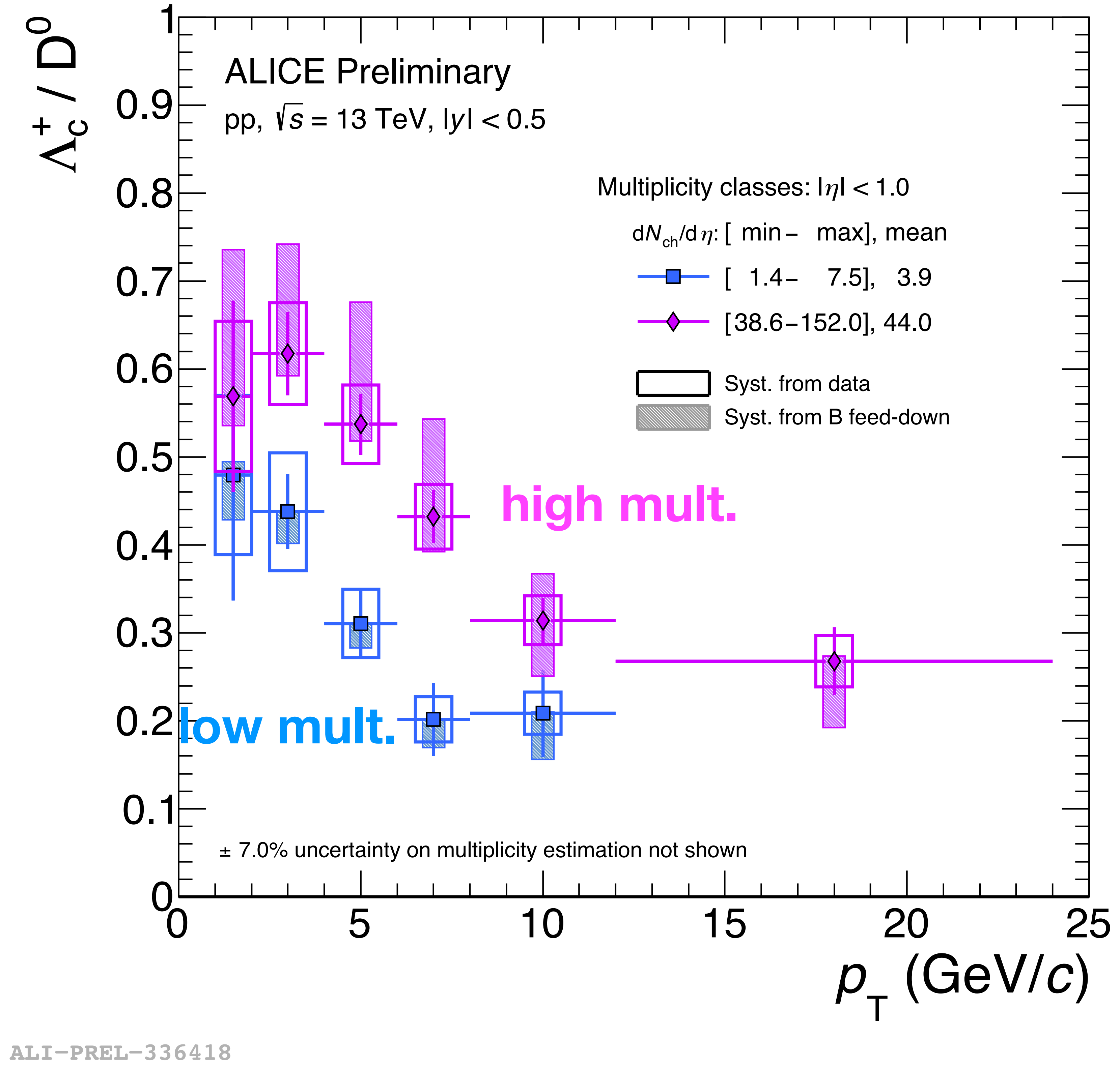
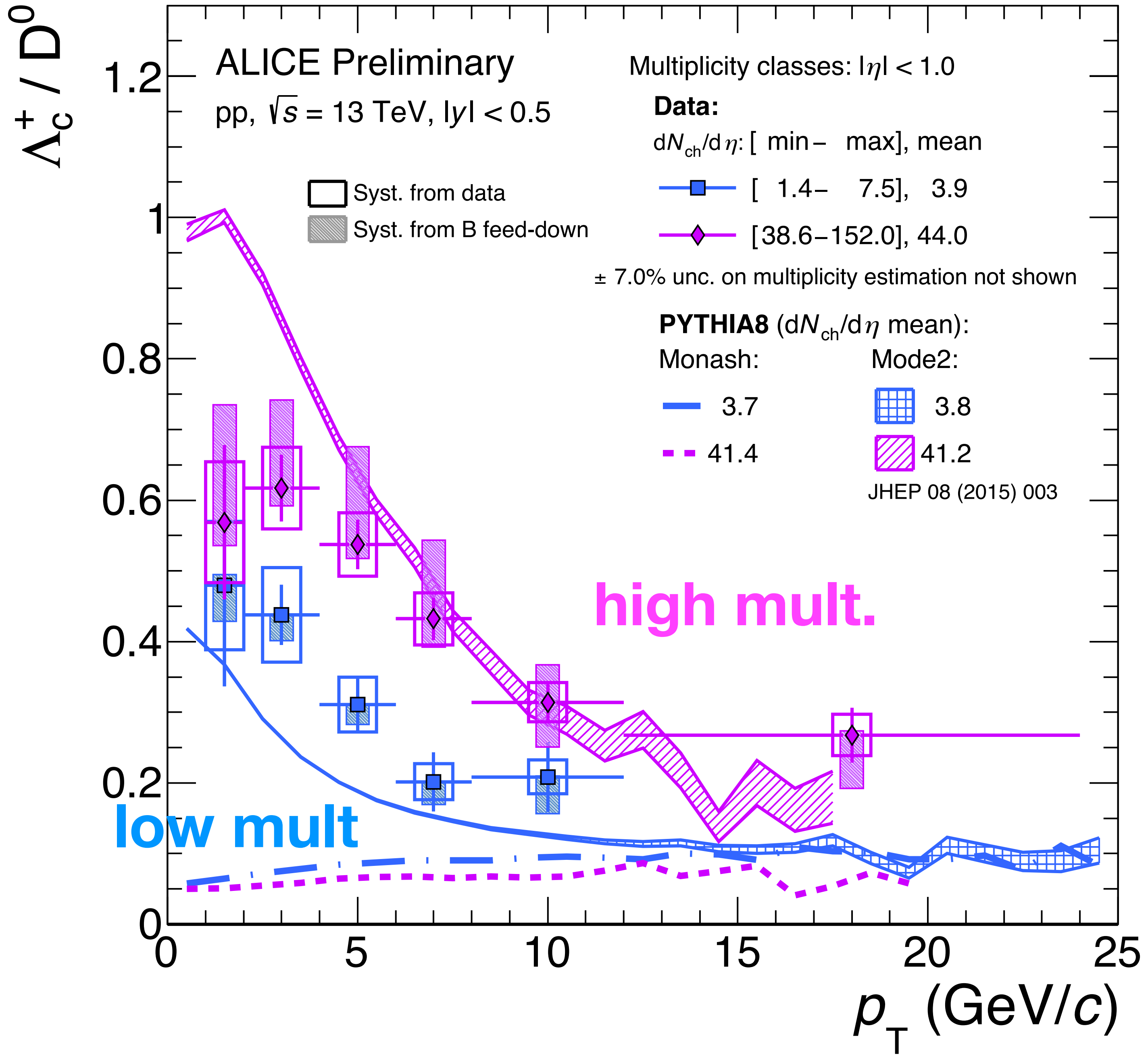
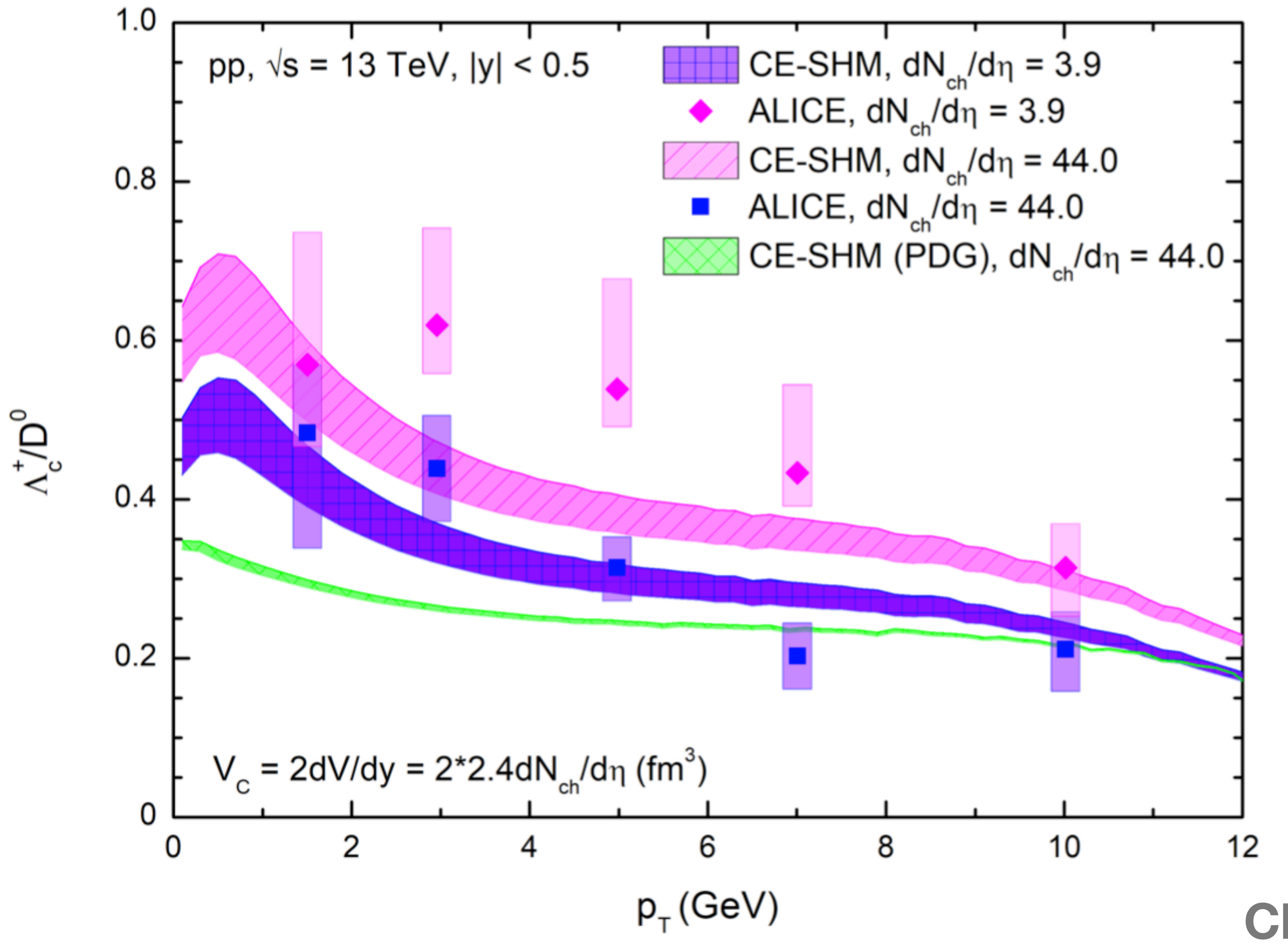


- **Evident dependence on multiplicity of Λ_c^+/D^0**
- Also in the **lowest multiplicity** the Λ_c^+/D^0 ratio is larger than measurement in e^+e^- and ep collisions

Chen, He, PLB (2021) 136144

Λ_c^+/D^0 in low and high multiplicity events





Chen, He, PLB (2021) 136144

- **Evident dependence on multiplicity of Λ_c^+/D^0**
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- **PYTHIA 8 Monash:**
  - does not reproduce the p_T trend

- **PYTHIA 8 with enhanced CR:**
  - describes the p_T trend
  - describes the magnitude of the Λ_c^+/D^0 ratio

- **SHM+RQM:**
  - shows a multiplicity dependence
  - compatible for the low multiplicity events but understimates the ratio in high multiplicity events

Heavier charmed baryon states: $\Sigma_c^{0,+,++}$

	mass (MeV/c^2)	Quark Content
Λ_c^+	2286	udc
Σ_c^{++}, Σ_c^0	2455	uuc, ddc
Ξ_c^+	2467	usc
Ξ_c^0	2471	dsc
Ω_c^0	2699	ssc

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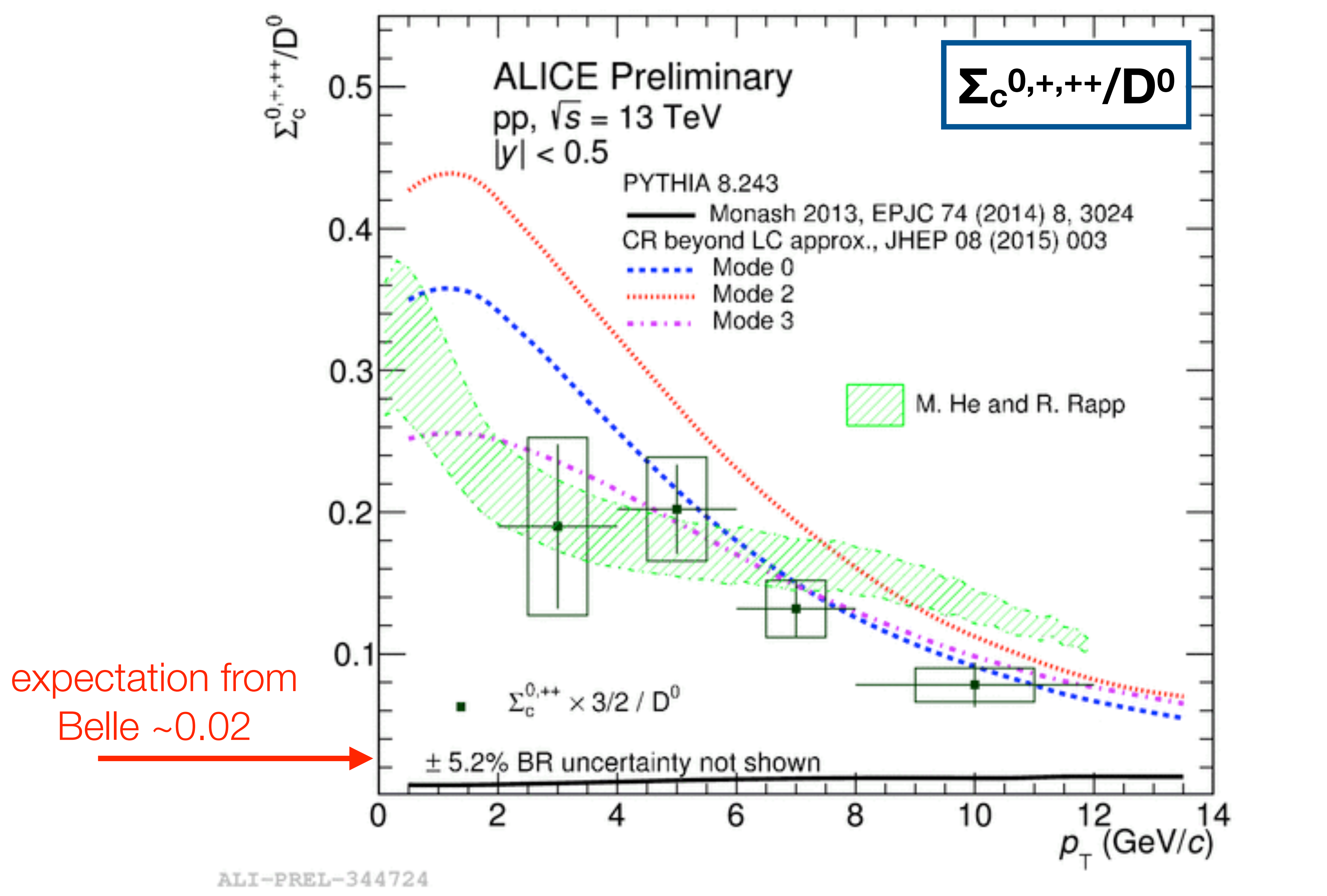

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- **$\Sigma_c^{0,+,++}/D^0$** largely enhanced with respect to **Pythia 8 Monash** and e^+e^- measurements

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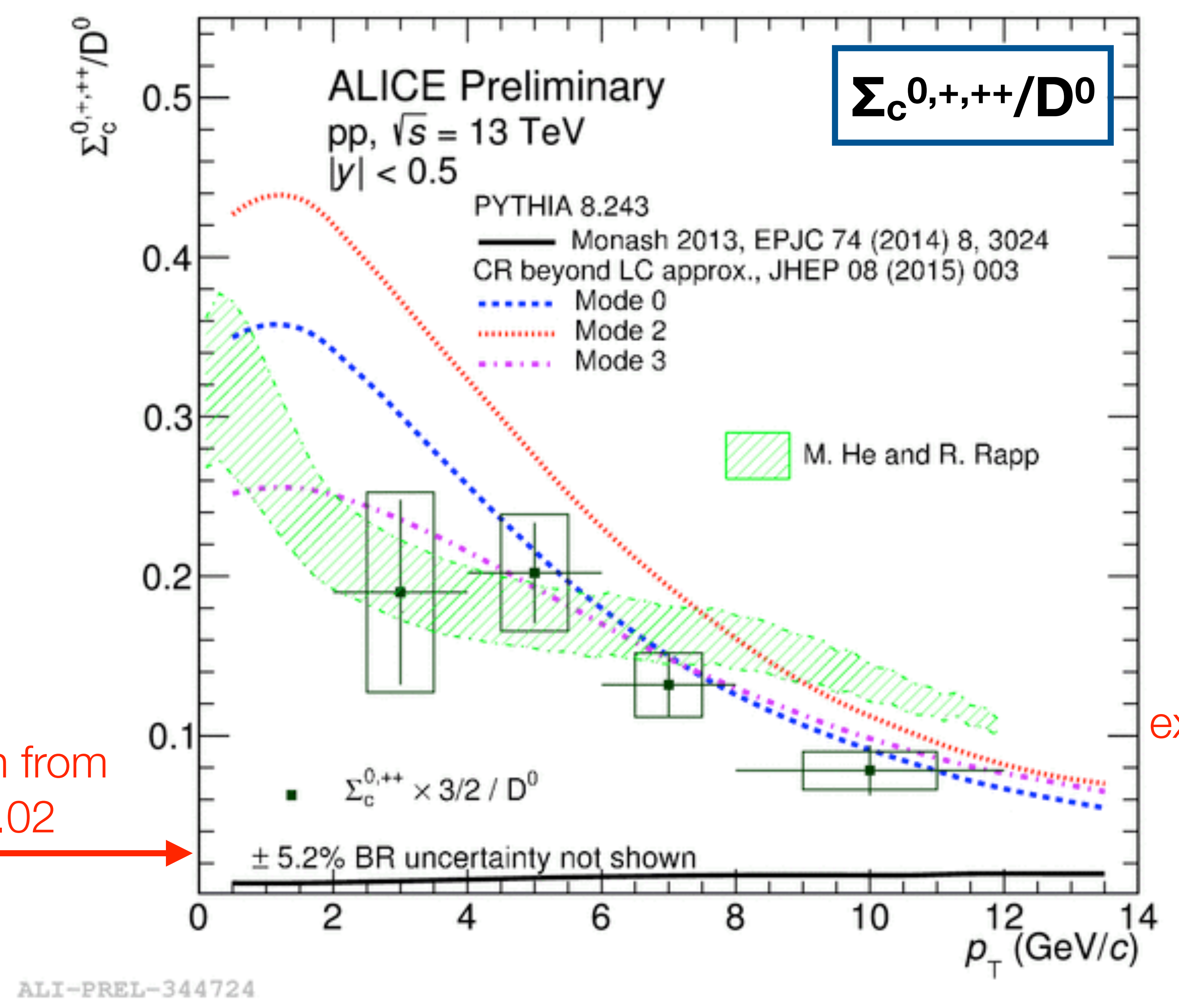
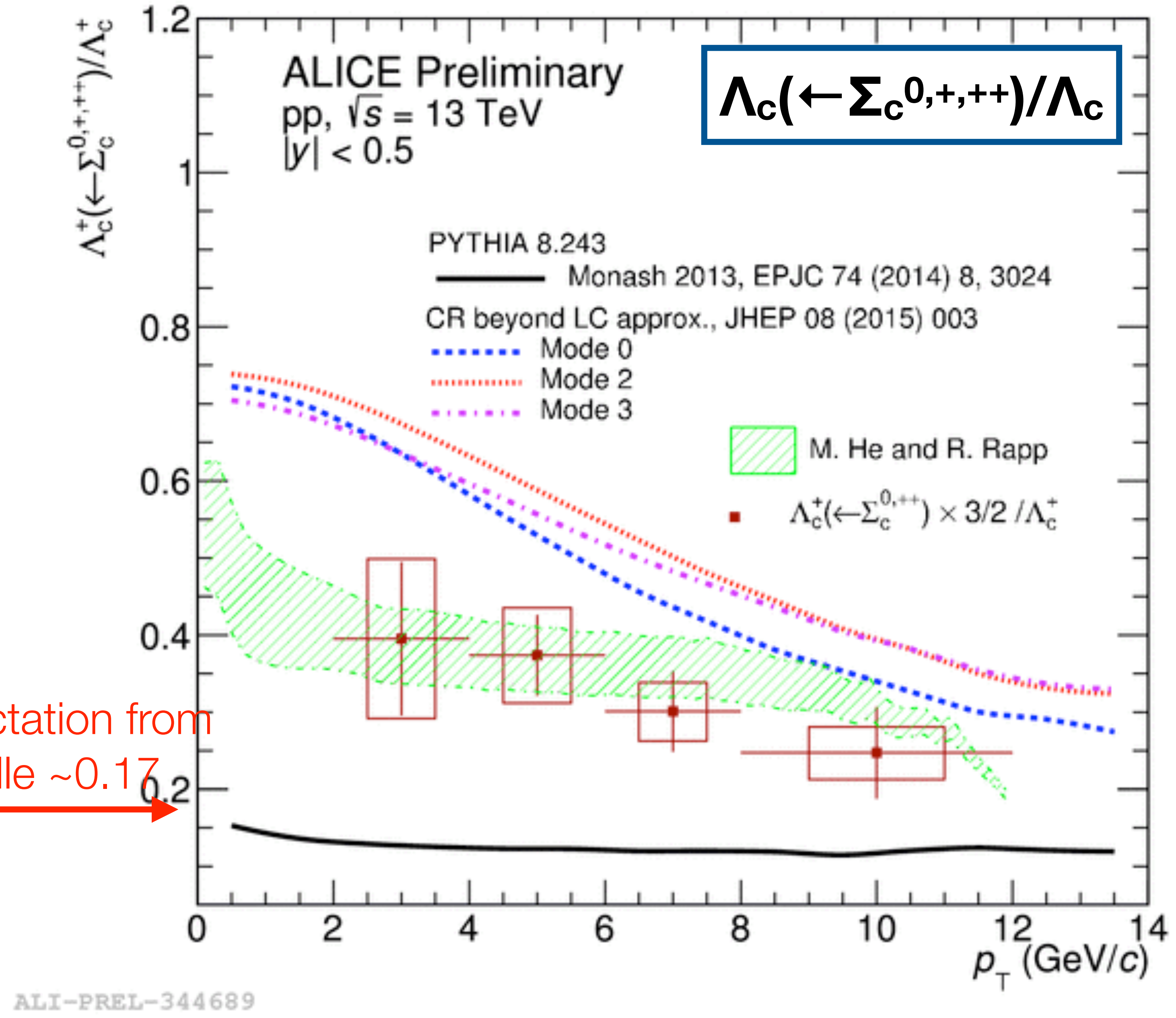


expectation from Belle ~0.02



expectation from Belle ~0.17

- **$\Sigma_c^{0,+,++}/D^0$** largely enhanced with respect to **Pythia 8 Monash** and e^+e^- measurements
- ~40% of feed-down Λ_c^+ from $\Sigma_c^{0,+,++}$
  - only partially accounts for the larger Λ_c^+/D^0 ratio in pp wrt e^+e^- measurements

- PYTHIA 8 with CR describes $\Sigma_c^{0,+,++}/D^0$ but overestimates the $\Lambda_c^+(\leftarrow\Sigma_c^{0,+,++})/\Lambda_c^+$ ratio
- SHM+RQM describes both measurements

Heavier charmed baryon states: Ξ_c^0 and Ξ_c^+

	mass (MeV/c²)	Quark Content
Λ_c^+	2286	udc
$\Sigma_c^{++}, \Sigma_c^0$	2455	uuc, ddc
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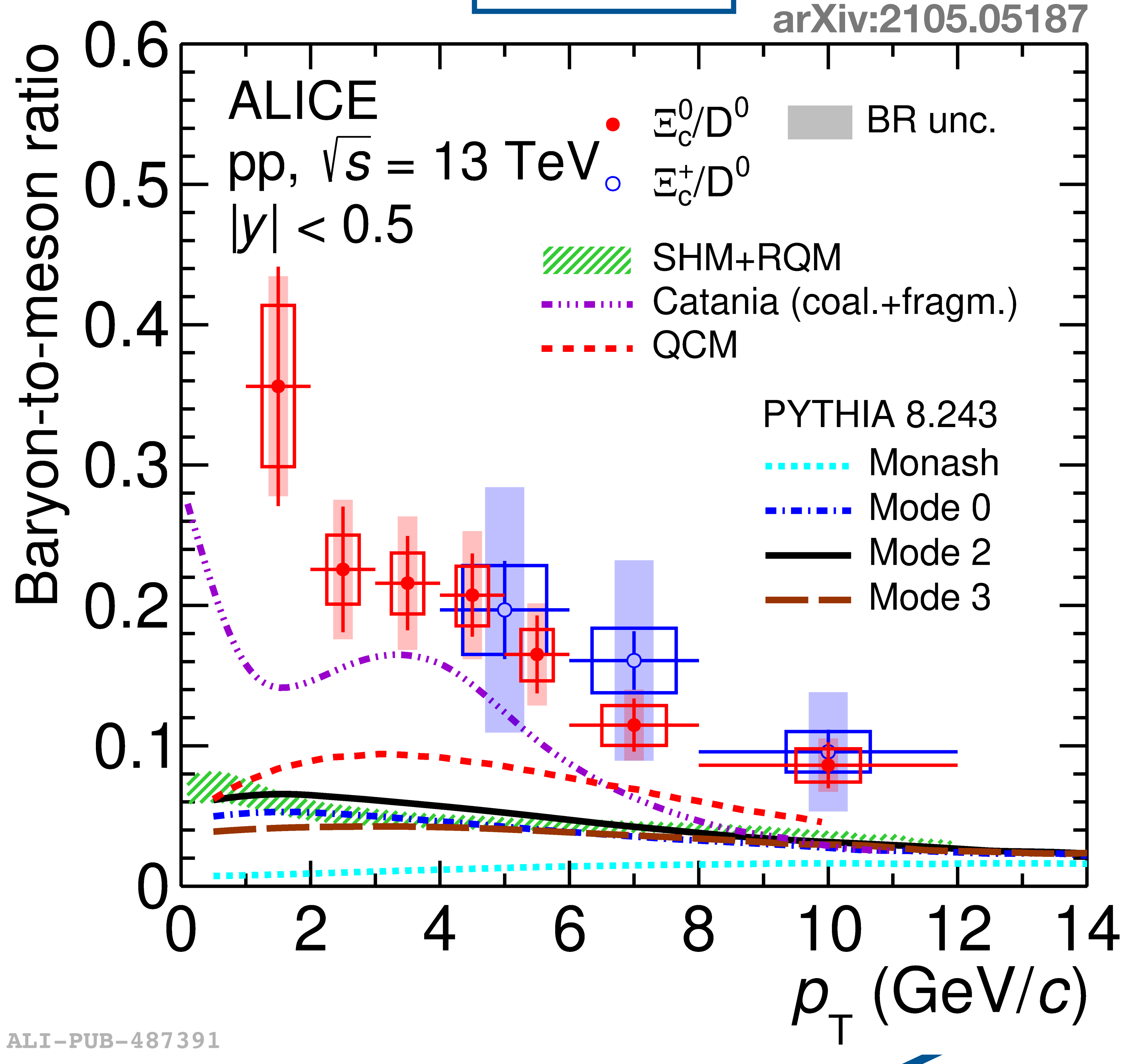
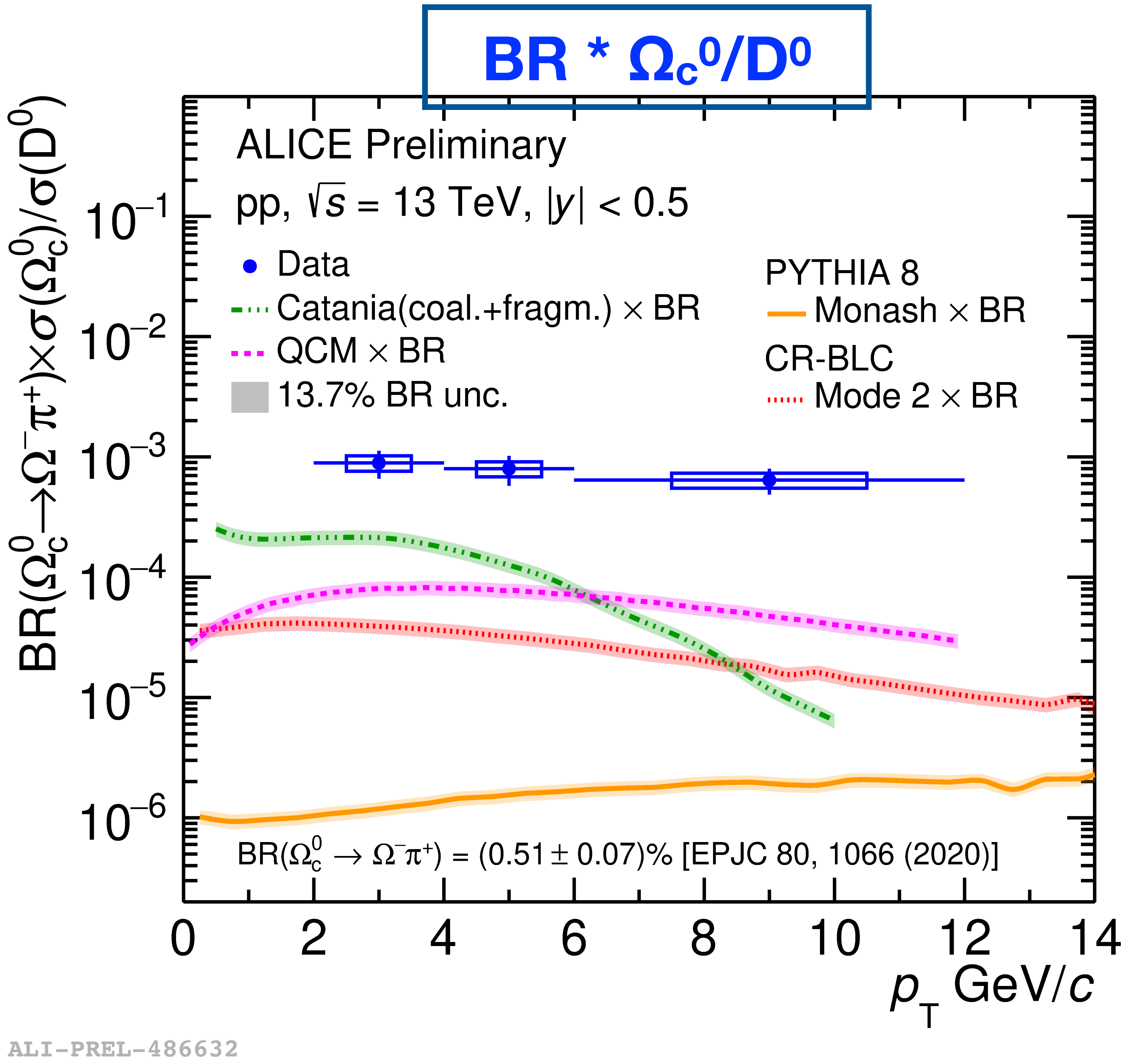
$\Xi_c^{0,+}/D^0$

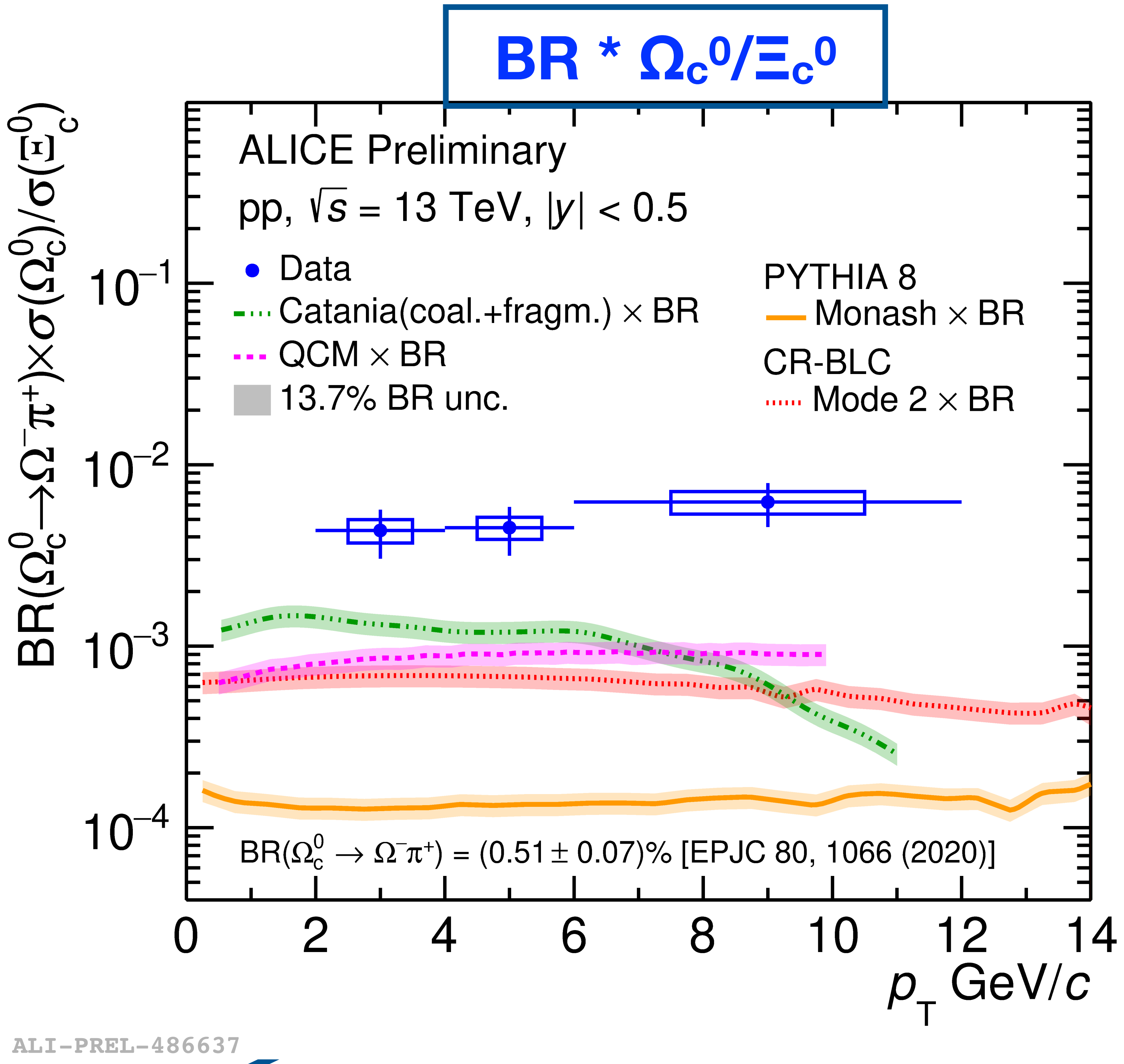


- **p_T dependence of the $\Xi_c^{0,+}/D^0$ ratio** not described by models
- **PYTHIA 8 with enhanced CR**
  -> additional strange-quark production needed?
- **SHM+RQM**
  -> not enough resonances for charm-strange baryons?
- **QCM**
  ->simple coalescence is not enough?
- **Catania** model closest to the data
  -> both fragmentation and coalescence needed?

Heavier charmed baryon states: Ω_c^0

	mass (MeV/c²)	Quark Content
Λ_c^+	2286	udc
$\Sigma_c^{++}, \Sigma_c^0$	2455	uuc, ddc
Ξ_c^+	2467	usc
Ξ_c^0	2471	dsc
Ω_c^0	2699	ssc



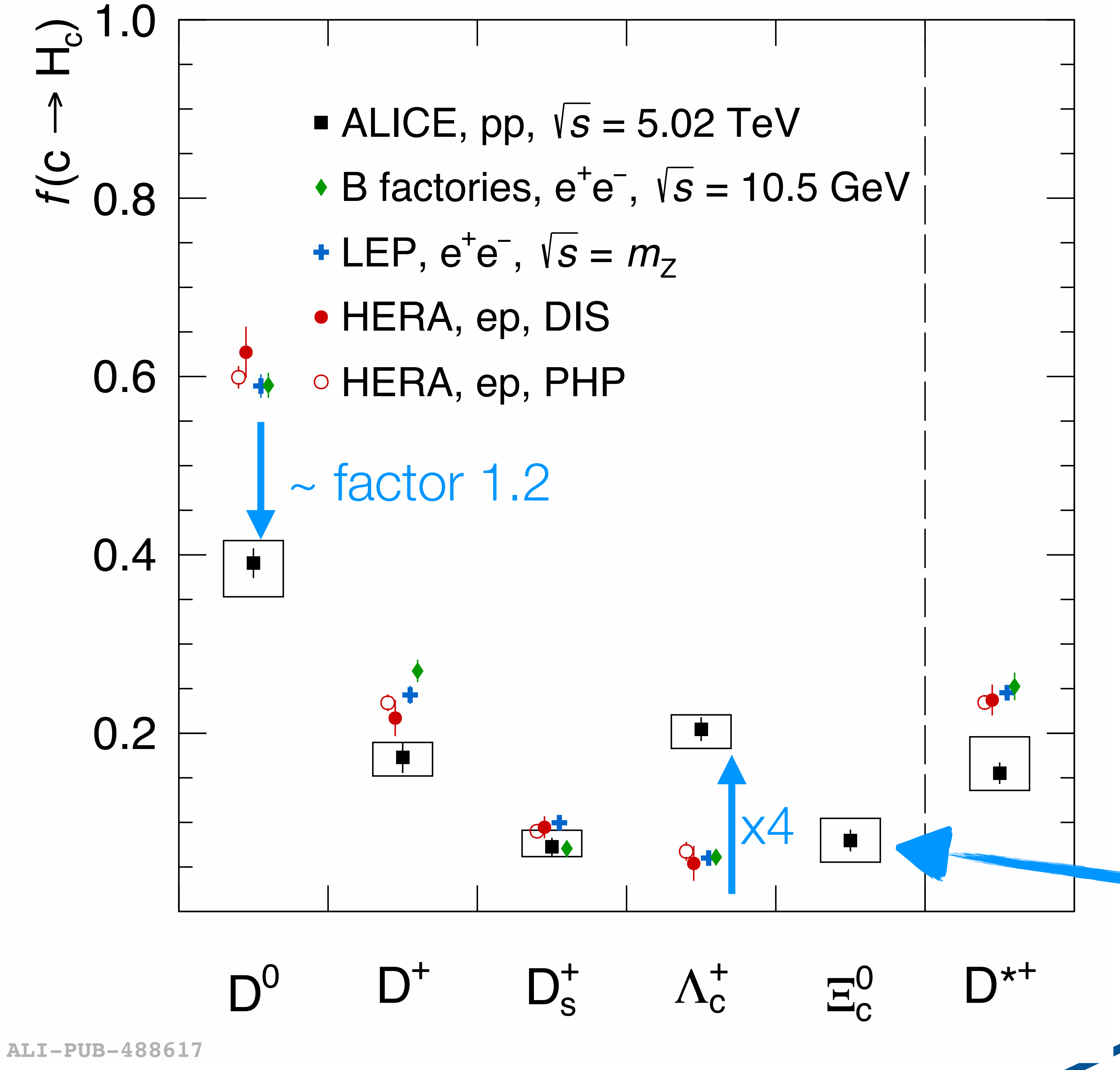


$BR(\Omega_c^0 \rightarrow \pi^+\Omega^-) = (0.51 \pm 0.07)\%$ from theory calculations   Yu-Kuo Hsiao et al., EPJC 80 (2020) 1066

- BR* Ω_c^0/D^0 ratio shows no p_T dependence
- All the models underestimate the BR* Ω_c^0/D^0 and BR* Ω_c^0/Ξ^0

Charm fragmentation fractions in pp collisions

arXiv:2105.06335



B factories: EPJC 76 no. 7 (2016) 397
LEP: EPJC 75 no. 1 (2015) 19
HERA: EPJC 76 no. 7 (2016) 397

Calculated as the ratio of the p_T-integrated cross section of each measured hadron specie by the sum of the cross sections of the different ground-states charm hadrons

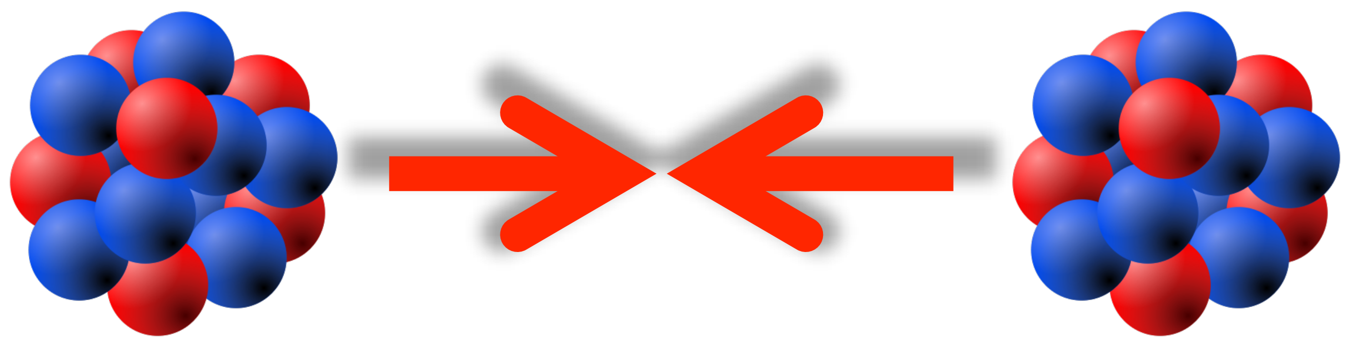
H_c	$f(c \to H_c)[\%]$
D^0	$37.5 \pm 1.6(\text{stat})^{+2.3}_{-3.5}(\text{syst})$
D^+	$16.6 \pm 1.7(\text{stat})^{+1.5}_{-1.9}(\text{syst})$
D_s^+	$7.0 \pm 1.0(\text{stat})^{+1.8}_{-1.1}(\text{syst})$
Λ_c^+	$23.7 \pm 1.3(\text{stat})^{+1.4}_{-2.1}(\text{syst})$
Ξ_c^0	$7.6 \pm 1.2(\text{stat})^{+2.4}_{-2.3}(\text{syst})$
D^{*+}	$14.9 \pm 1.1(\text{stat})^{+3.9}_{-1.8}(\text{syst})$

$f(c \to H_c)$ different in pp and e^+e^- and ep collisions

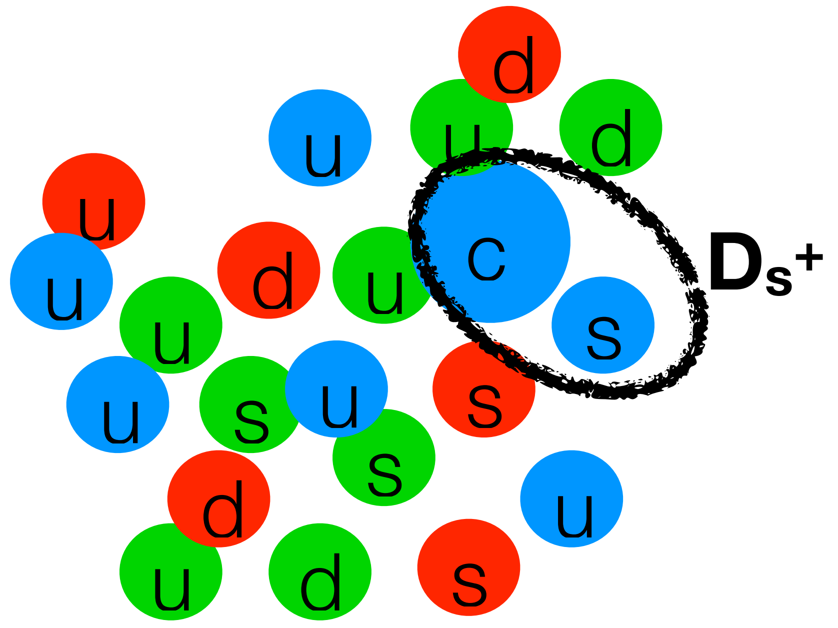
First measurement of $f(c \to \Xi_c^0)$

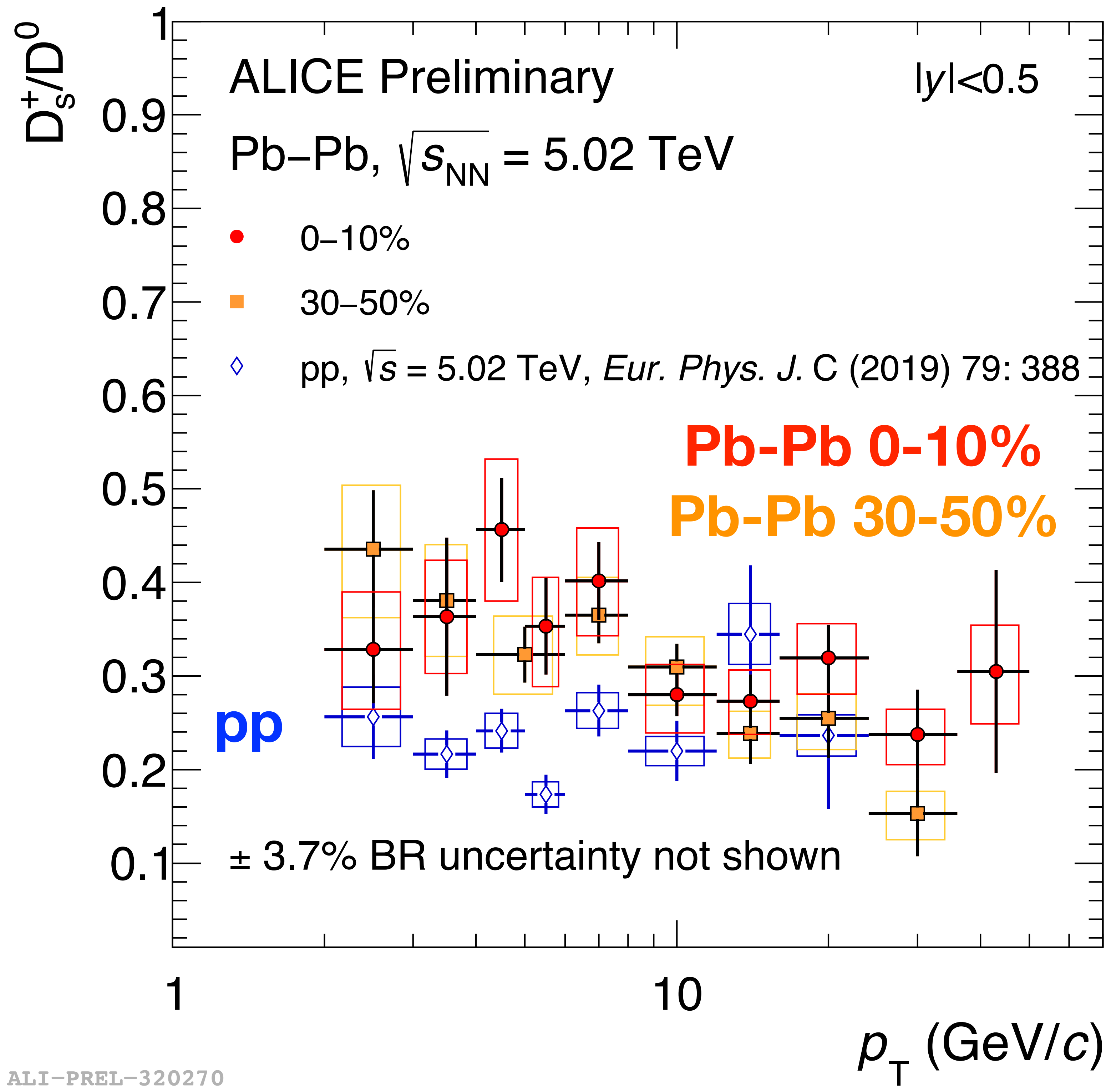
Important for the calculation of the total charm cross section

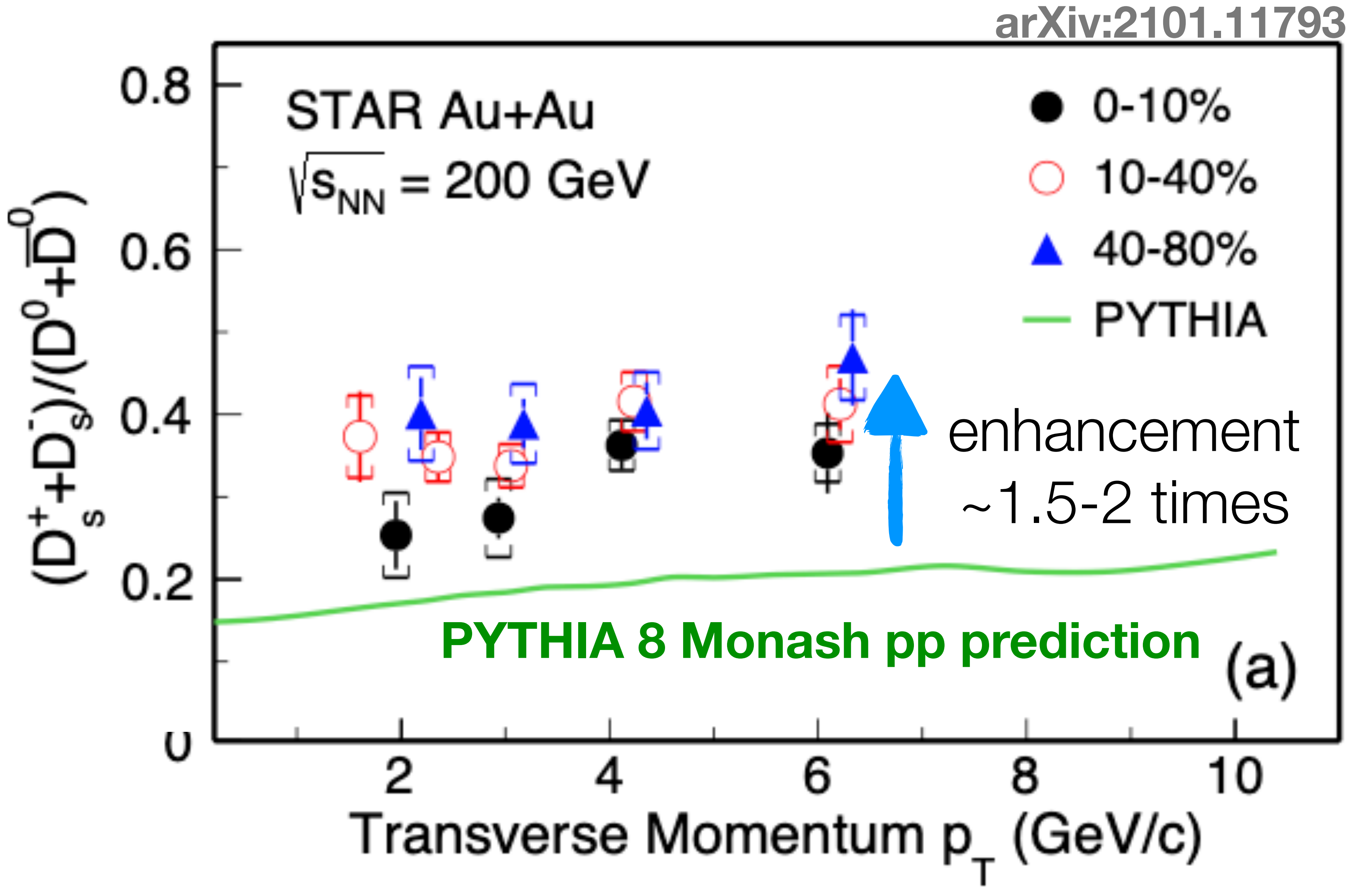
Heavy-flavour hadronisation in large systems



D_s^+/D^0 in nucleus-nucleus collisions

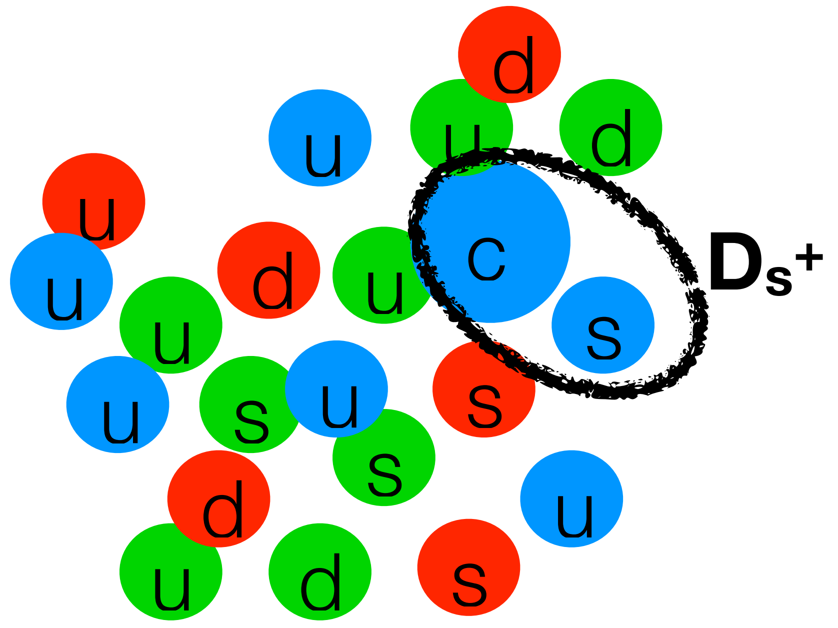


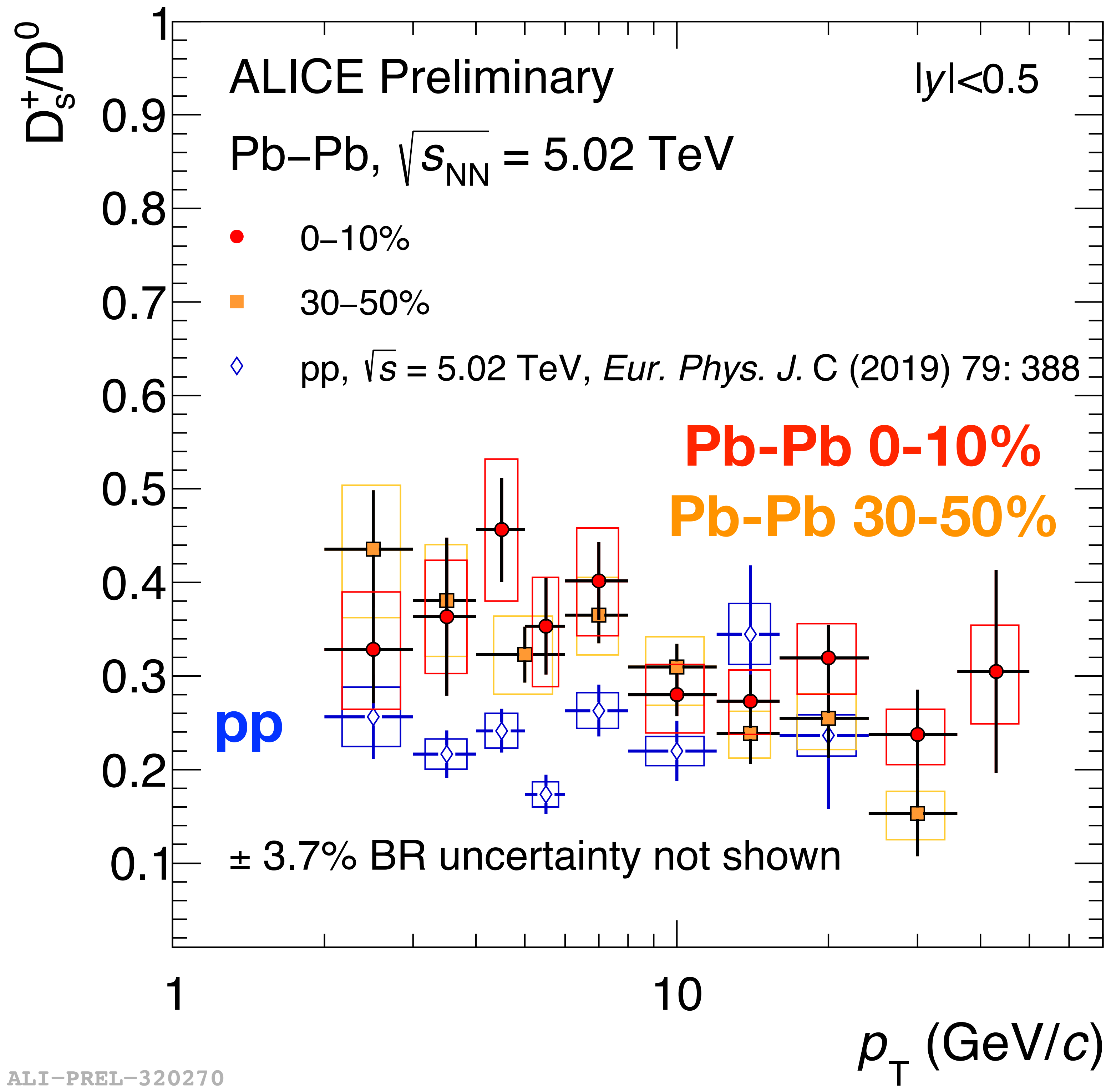


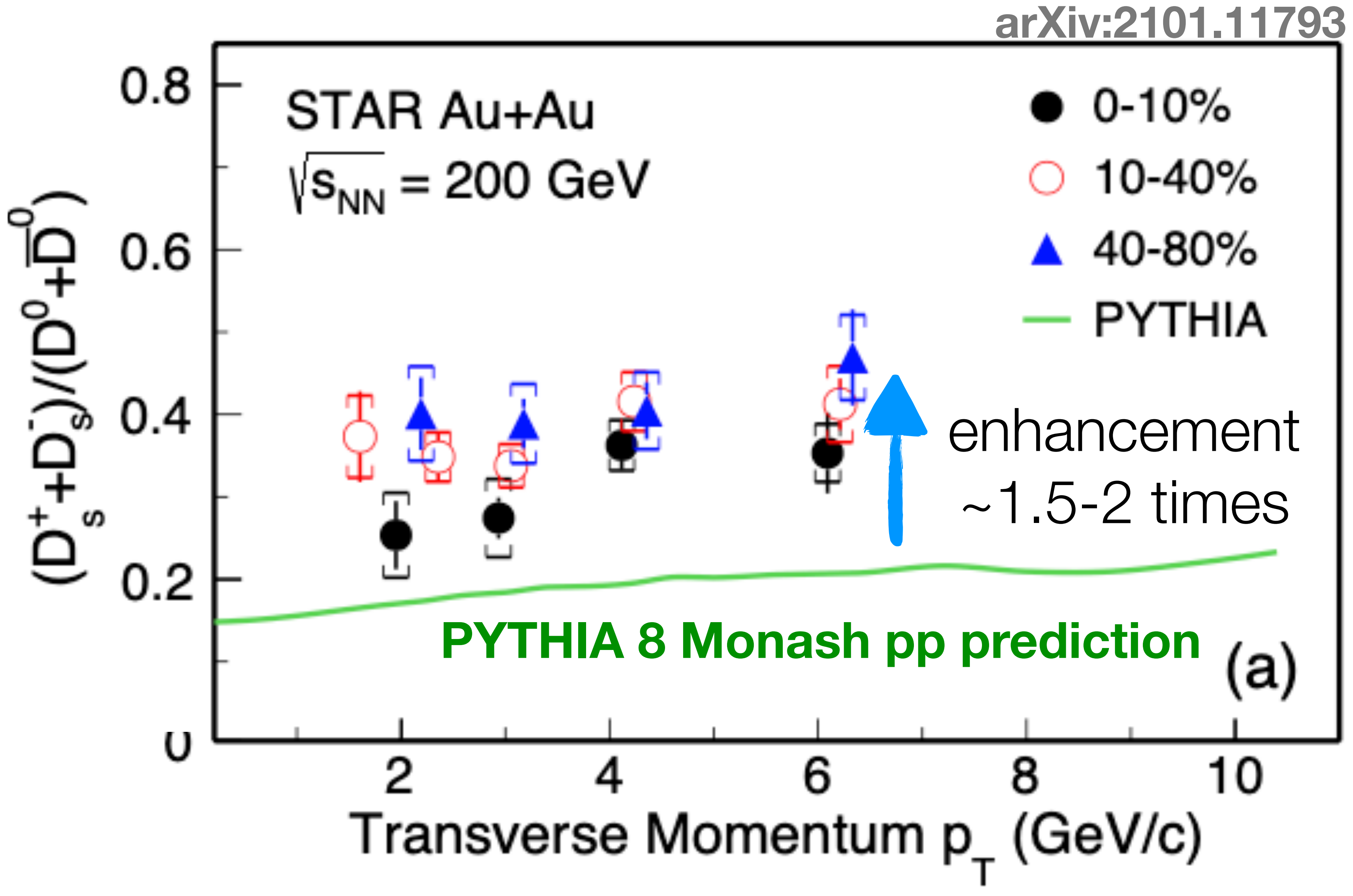


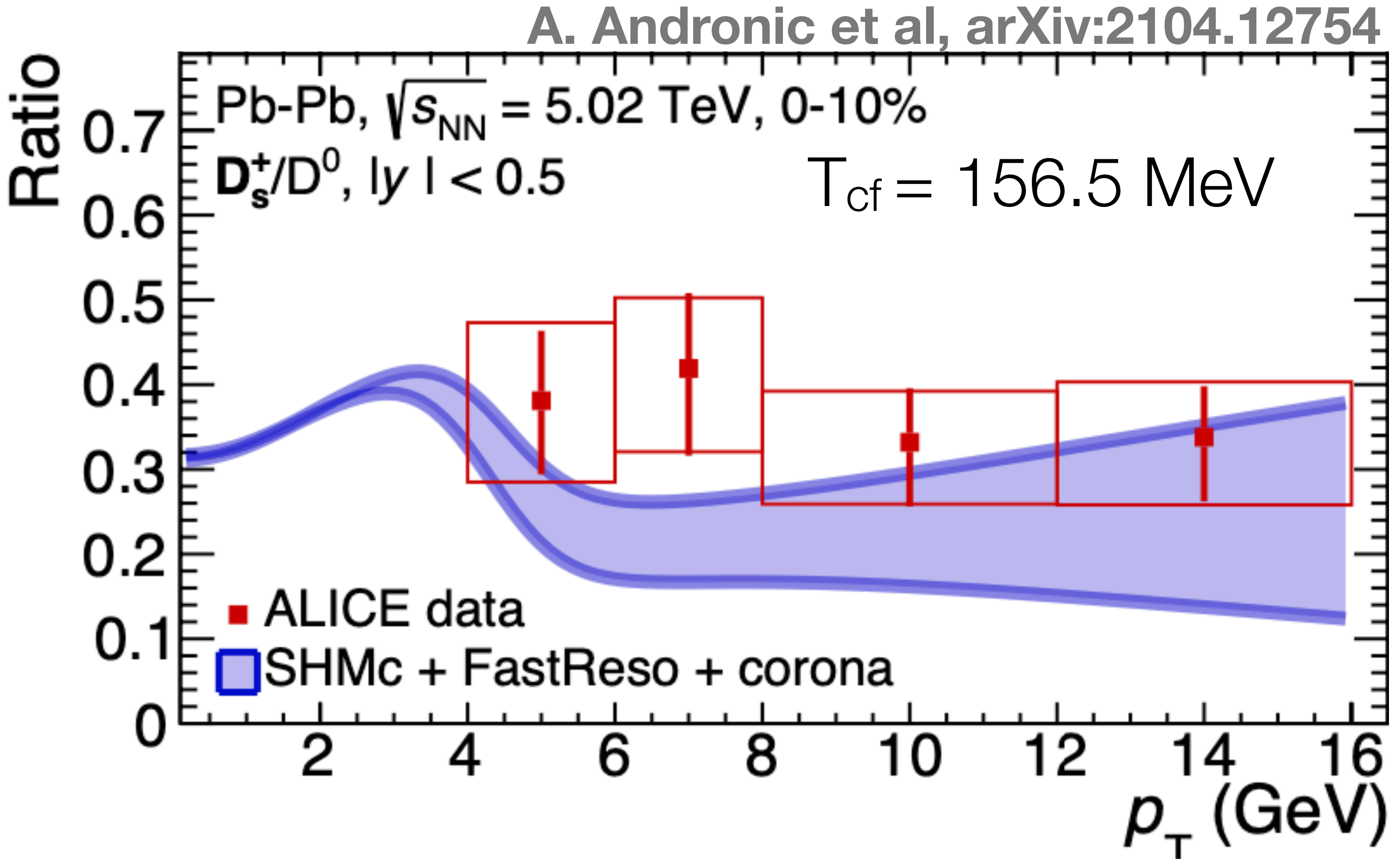
- **Hint of enhanced D_s^+/D^0** ratio in nucleus-nucleus collisions compared to pp collisions for p_T< 8-10 GeV/c at both RHIC and LHC energies
- Similar magnitude in central and semi-central collisions

D_s^+/D^0 in nucleus-nucleus collisions





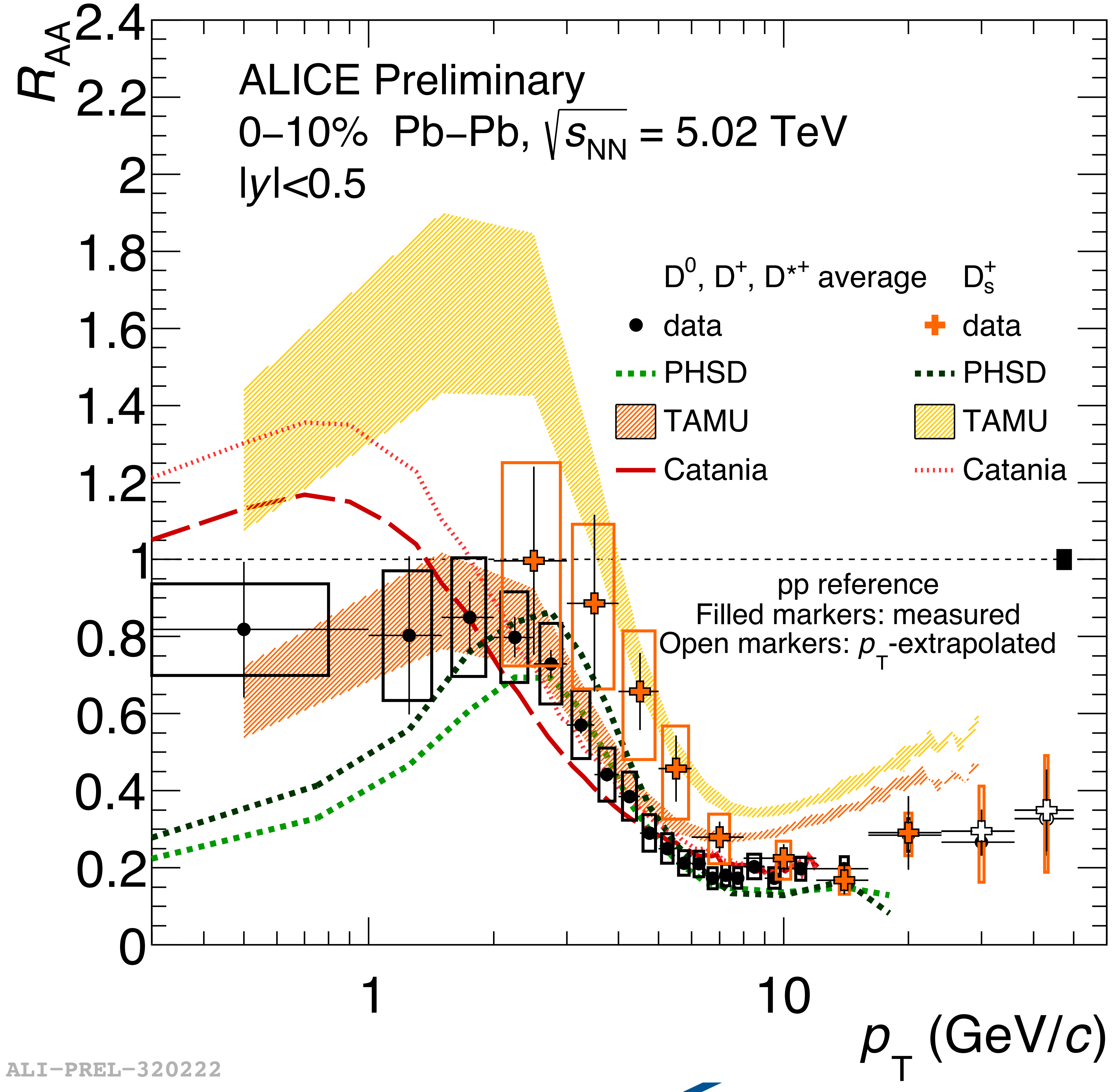




- **Hint of enhanced D_s^+/D^0** ratio in nucleus-nucleus collisions compared to pp collisions for p_T< 8-10 GeV/c at both RHIC and LHC energies
- Similar magnitude in central and semi-central collisions

- D_s^+/D^0 ratio at low p_T in Pb-Pb collisions compatible within uncertainties with the **Statistical Hadronisation Model (SHM)**

D_s^+ nuclear modification factor

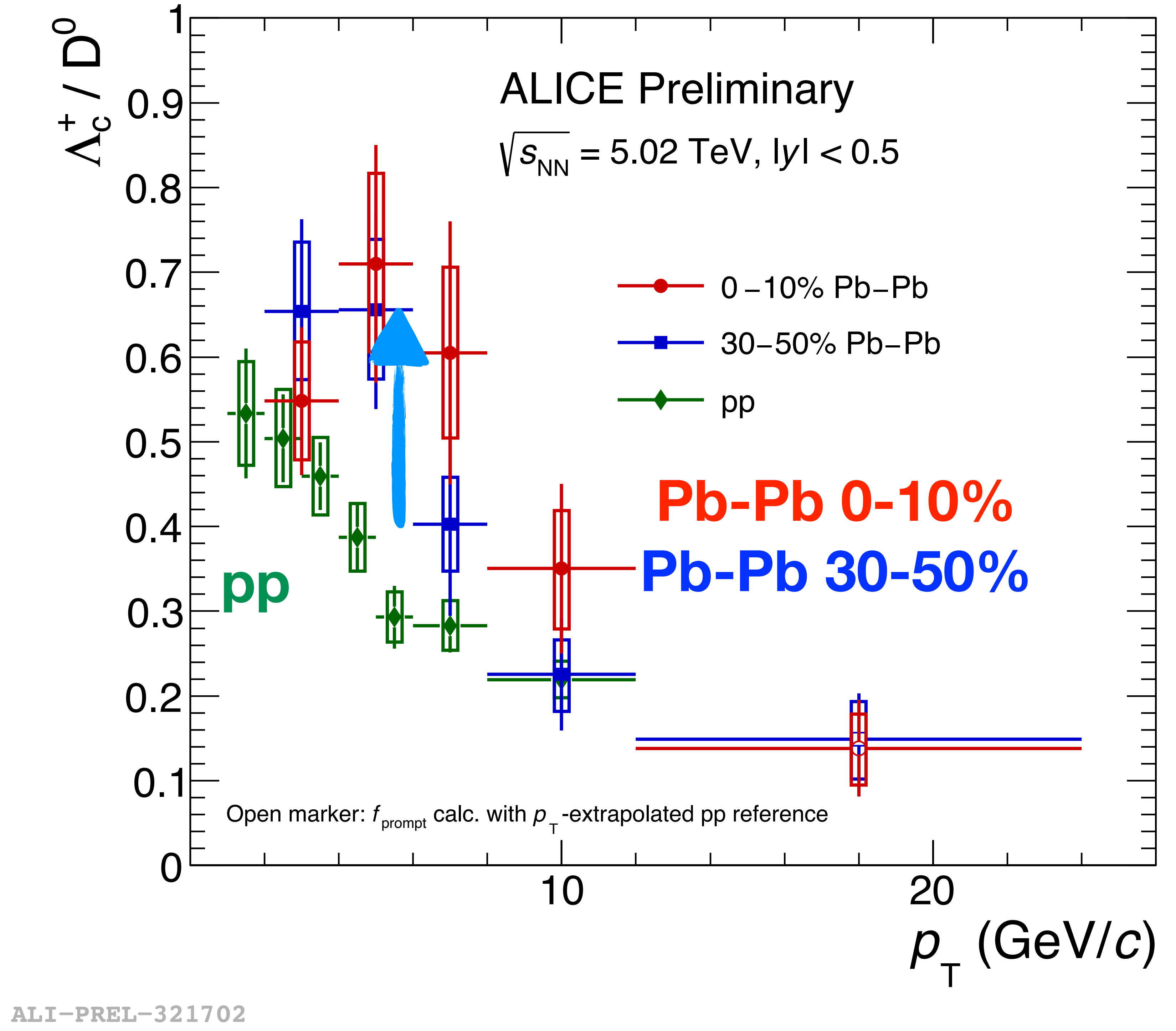


TAMU: PLB 735 (2014) 445-450
PHSD: PRC 92, 014910 (2015)
Catania: EPJC 78, 348 (2018)

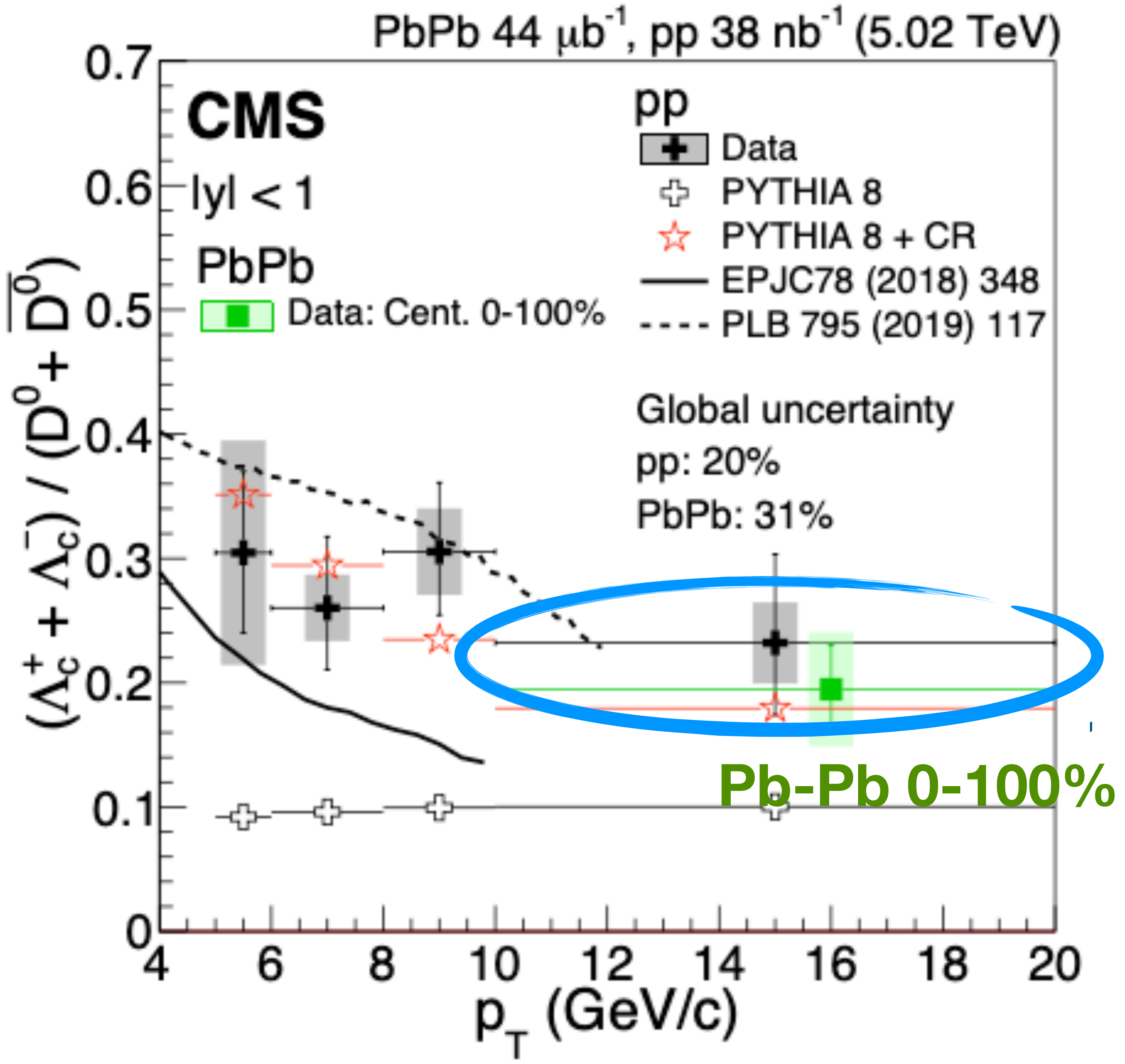
- **Smaller D_s^+ R_{AA}** with respect to **non-strange D-meson R_{AA}**
- **D_s^+ enhancement** qualitatively **reproduced by models including charm-quark coalescence in a strangeness rich environment**

- **Charm-quark coalescence** is an important ingredient of the models to **describe the measurement at intermediate p_T**

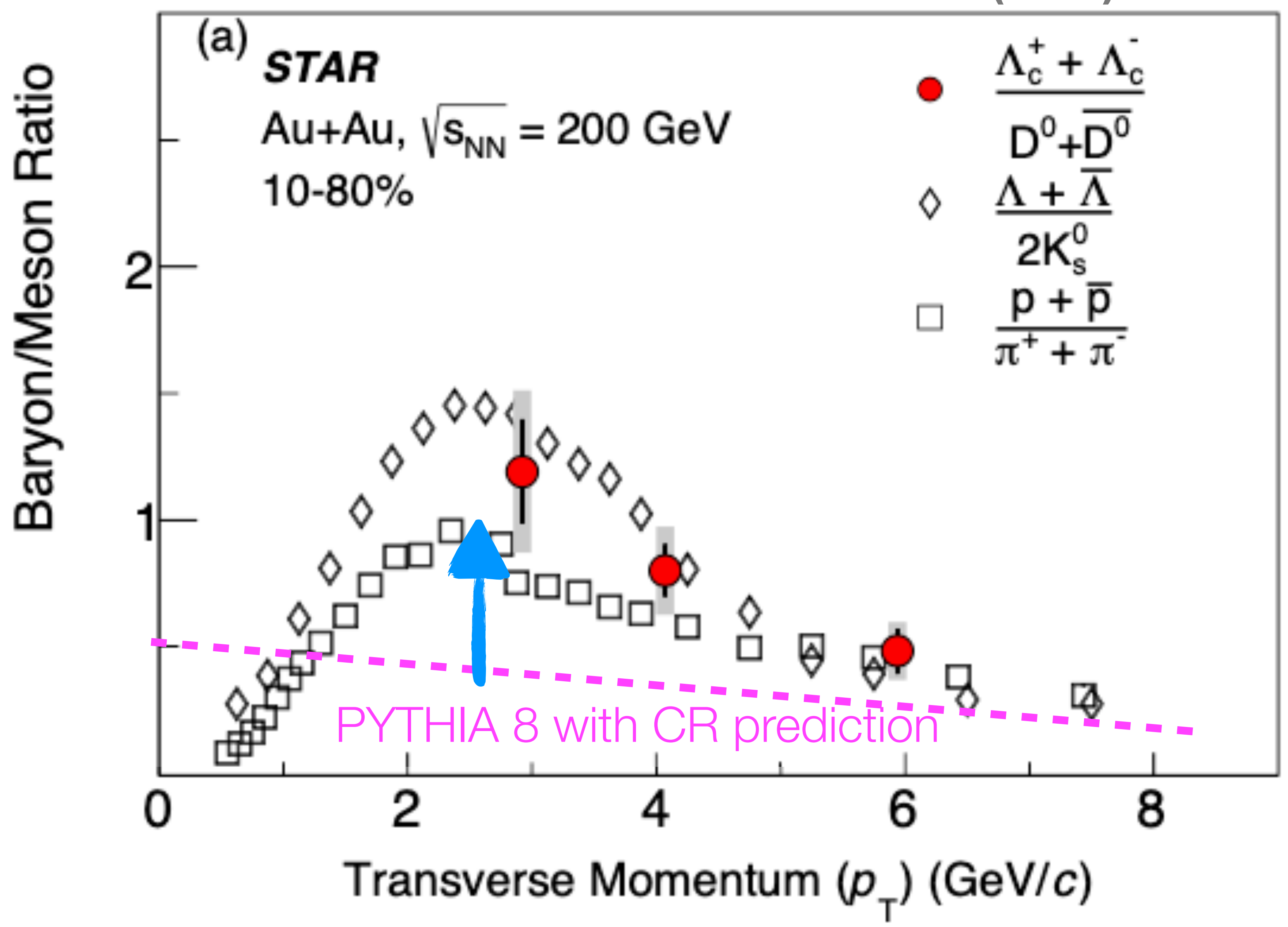
Λ_c^+/D^0 in nucleus-nucleus collisions



PLB 803 (2020) 135328

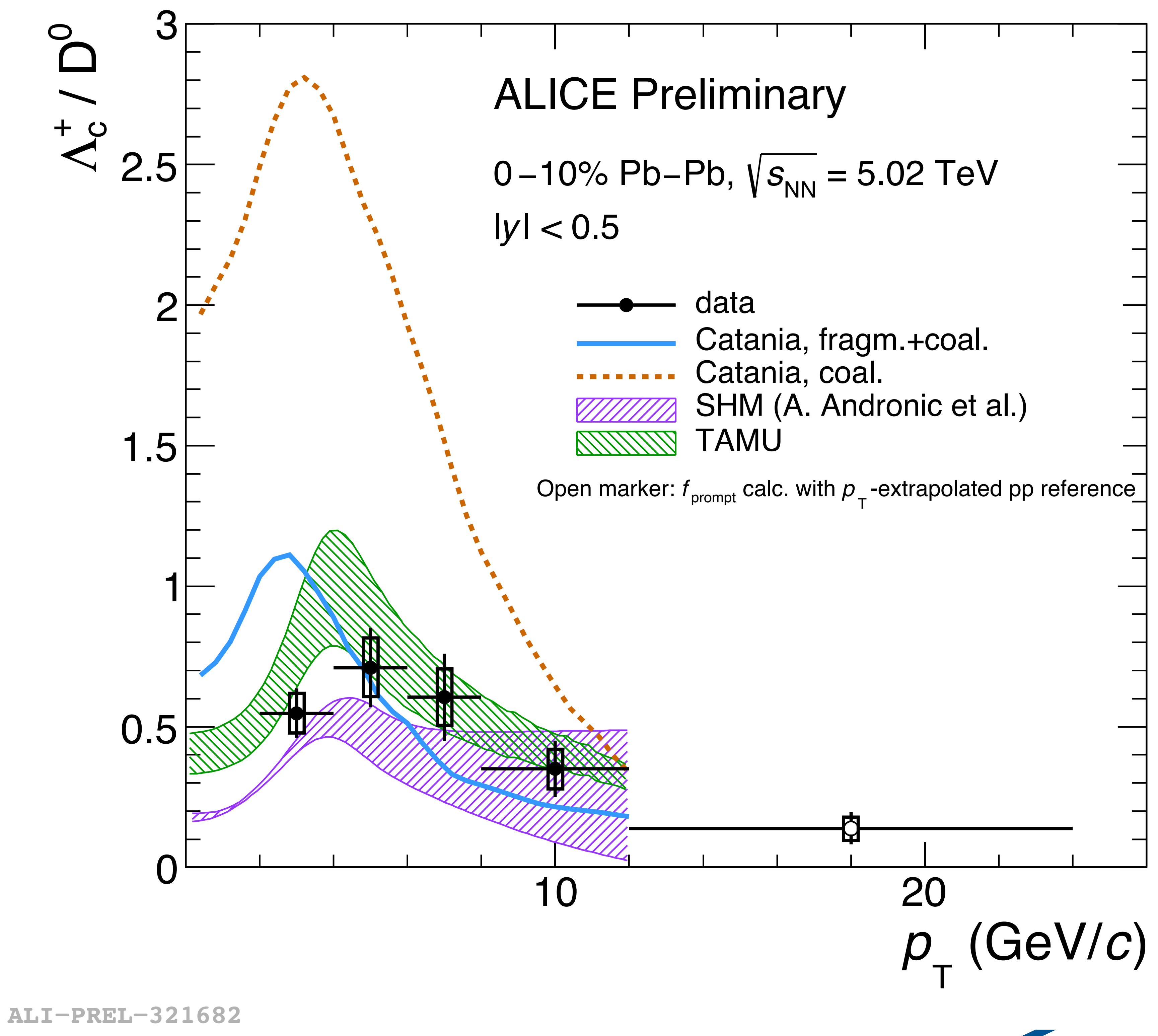


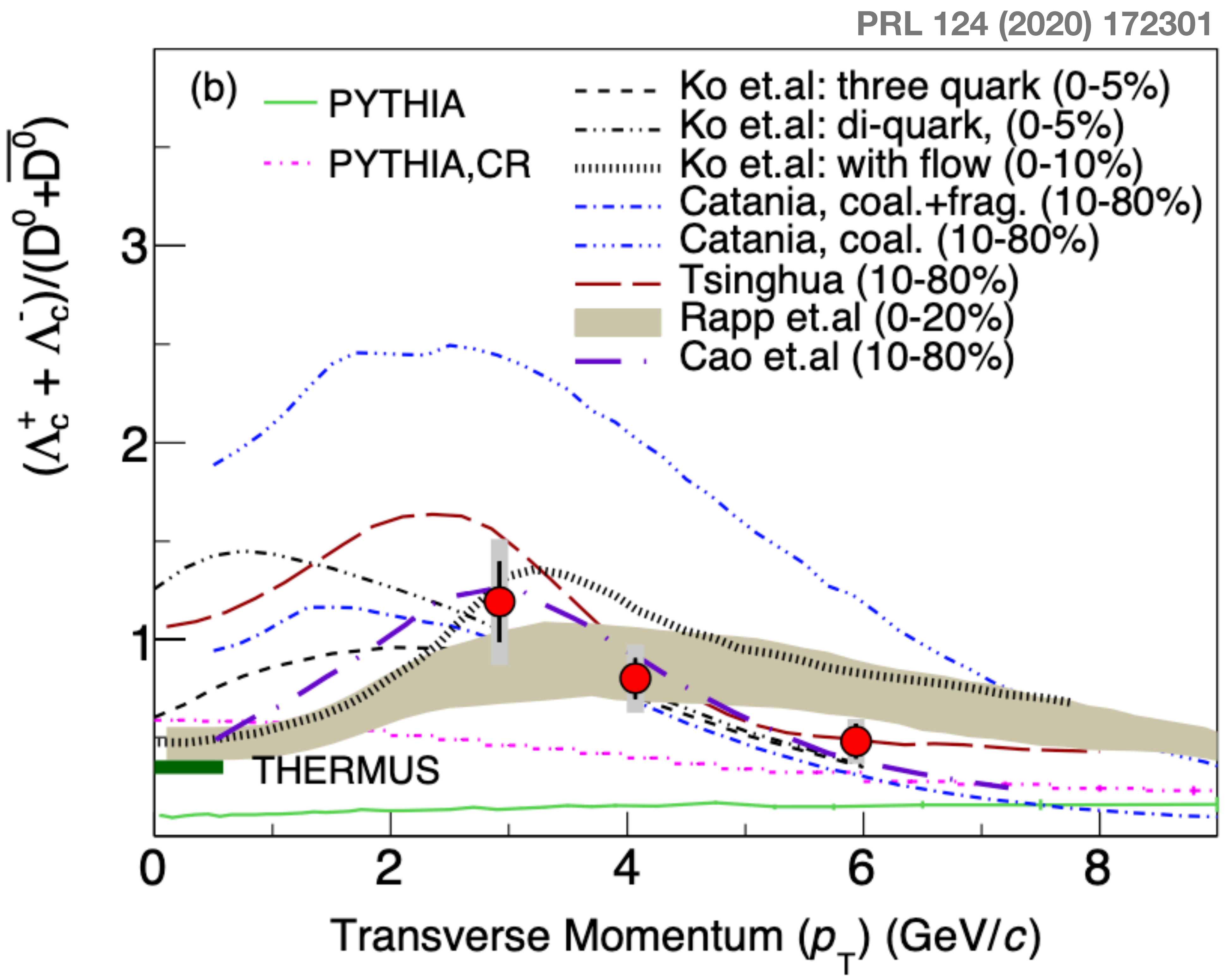
PRL 124 (2020) 172301



- **Hint of enhancement of Λ_c^+/D^0** in Pb-Pb collisions wrt pp collision at intermediate p_T at both RHIC and LHC energies
  - hadronisation mechanism? Radial-flow push in Pb-Pb collisions?
- **Λ_c^+/D^0** compatible with pp at high p_T (>10 GeV/c)

Λ_c^+/D^0 ratio compared with models

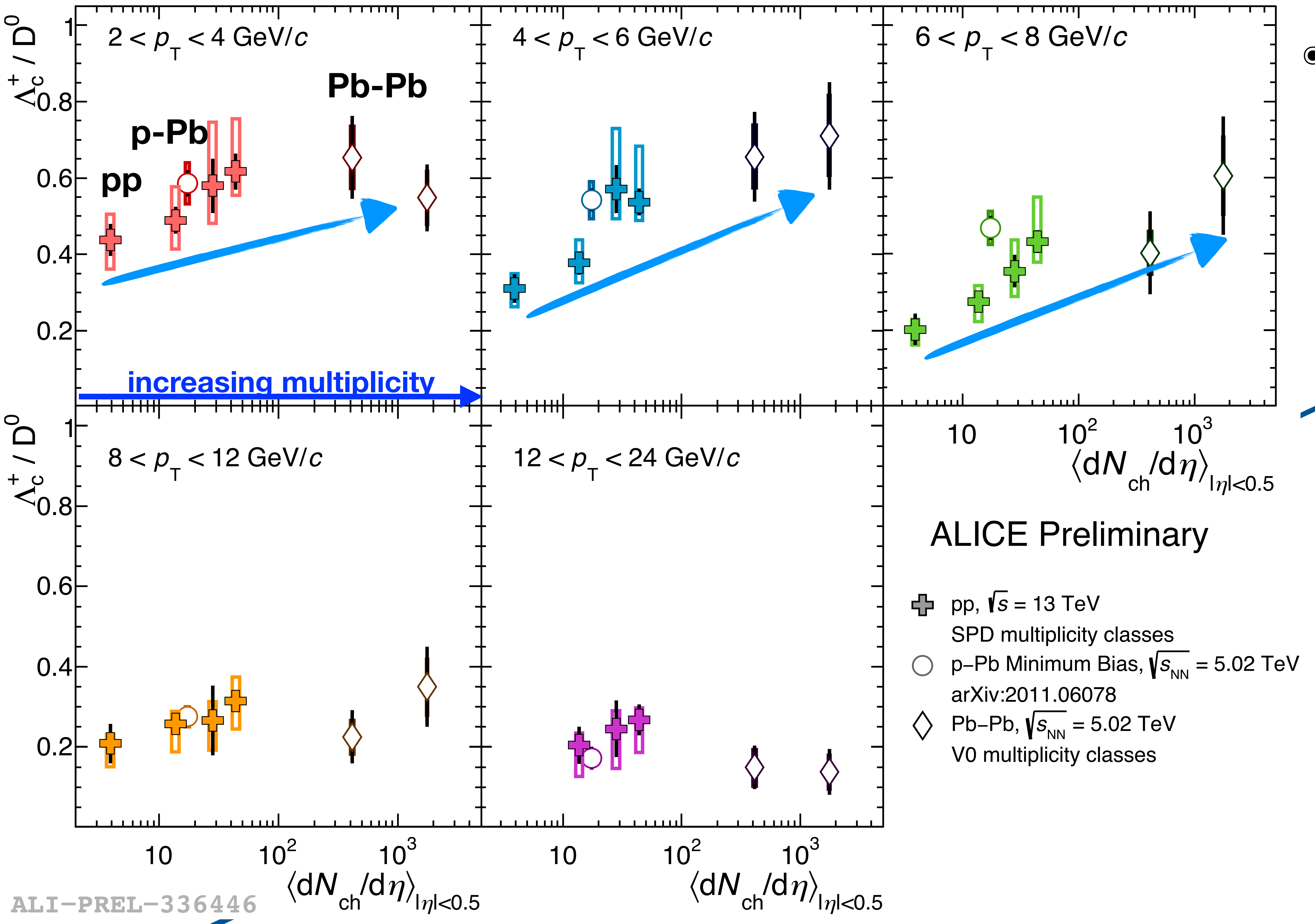




- **Λ_c^+/D^0 ratio** described by models implementing **heavy-quark hadronisation via recombination and fragmentation** and by the **statistical hadronisation model**
- Pure coalescence models clearly overestimate the data

Catania: EPJ C78 (2018) 348
TAMU: PRL 124 (2020) 042301
SHM: A. Andronic et al, arXiv:2104.12754
Ko et al. three quark: PRC 79 (2009) 044905
Ko et al. with flow: PRC 101 (2020) 024909
Tsinghua: arXiv:1805.10858
Cao et al.: PLB 807 (2020) 135561

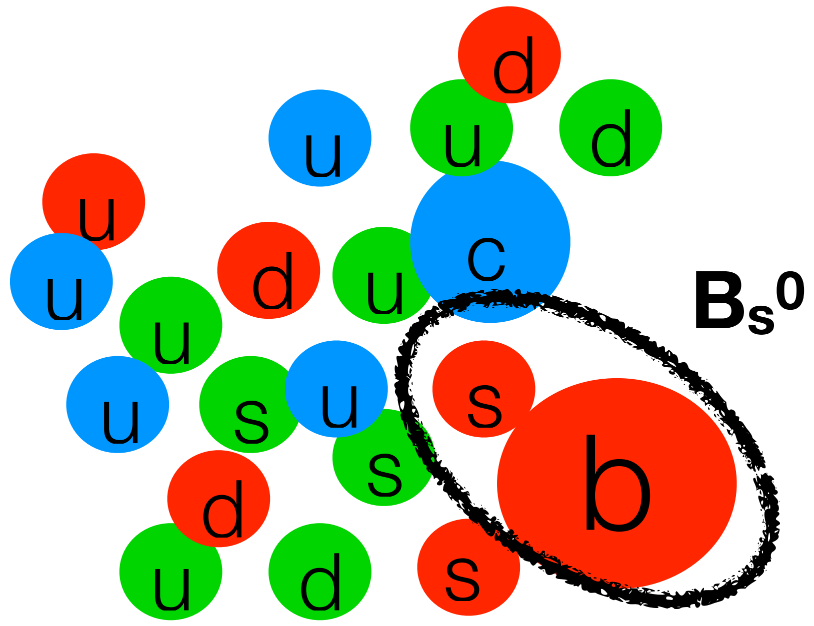
Λ_c^+/D^0 from pp to Pb-Pb

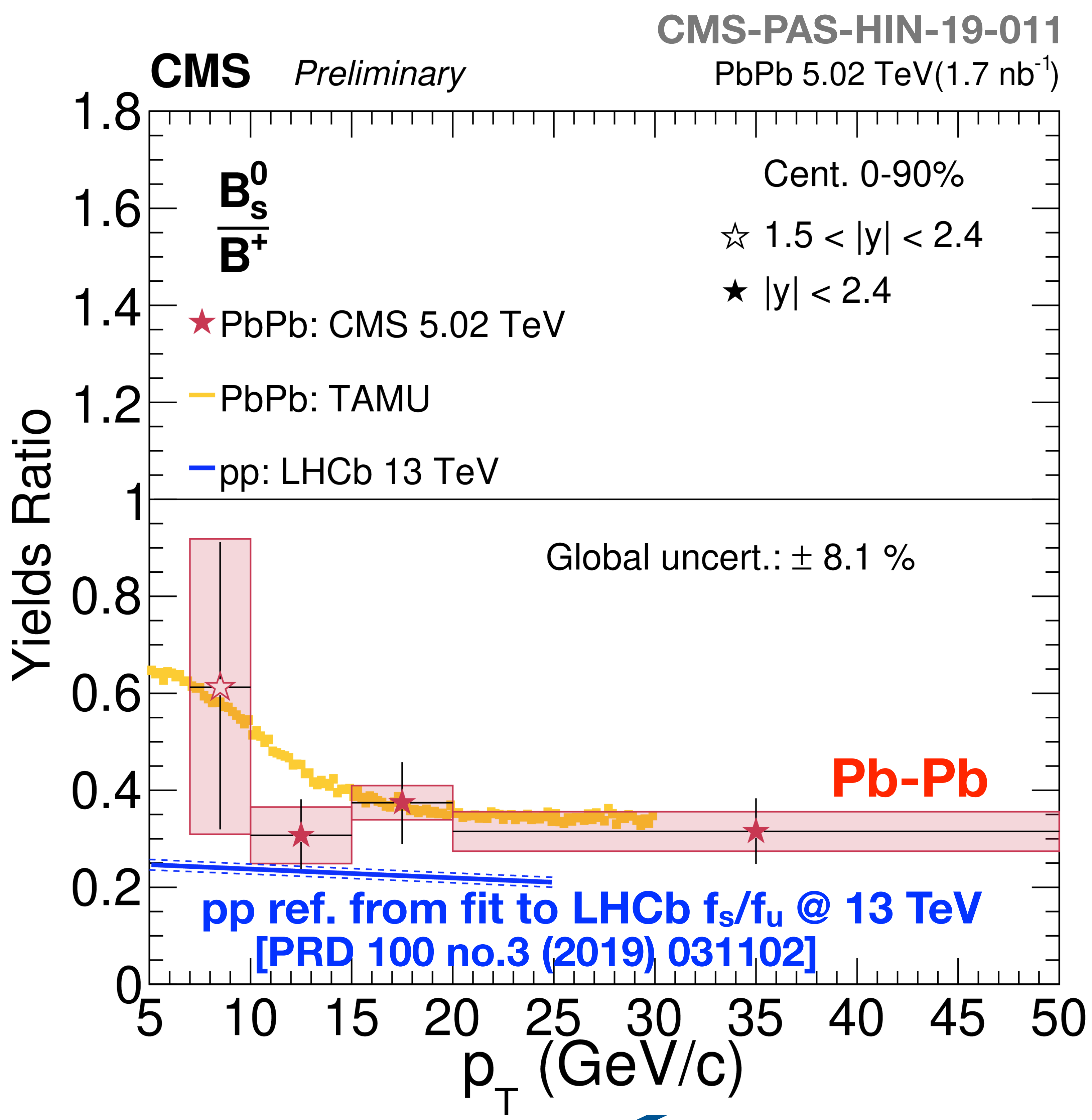


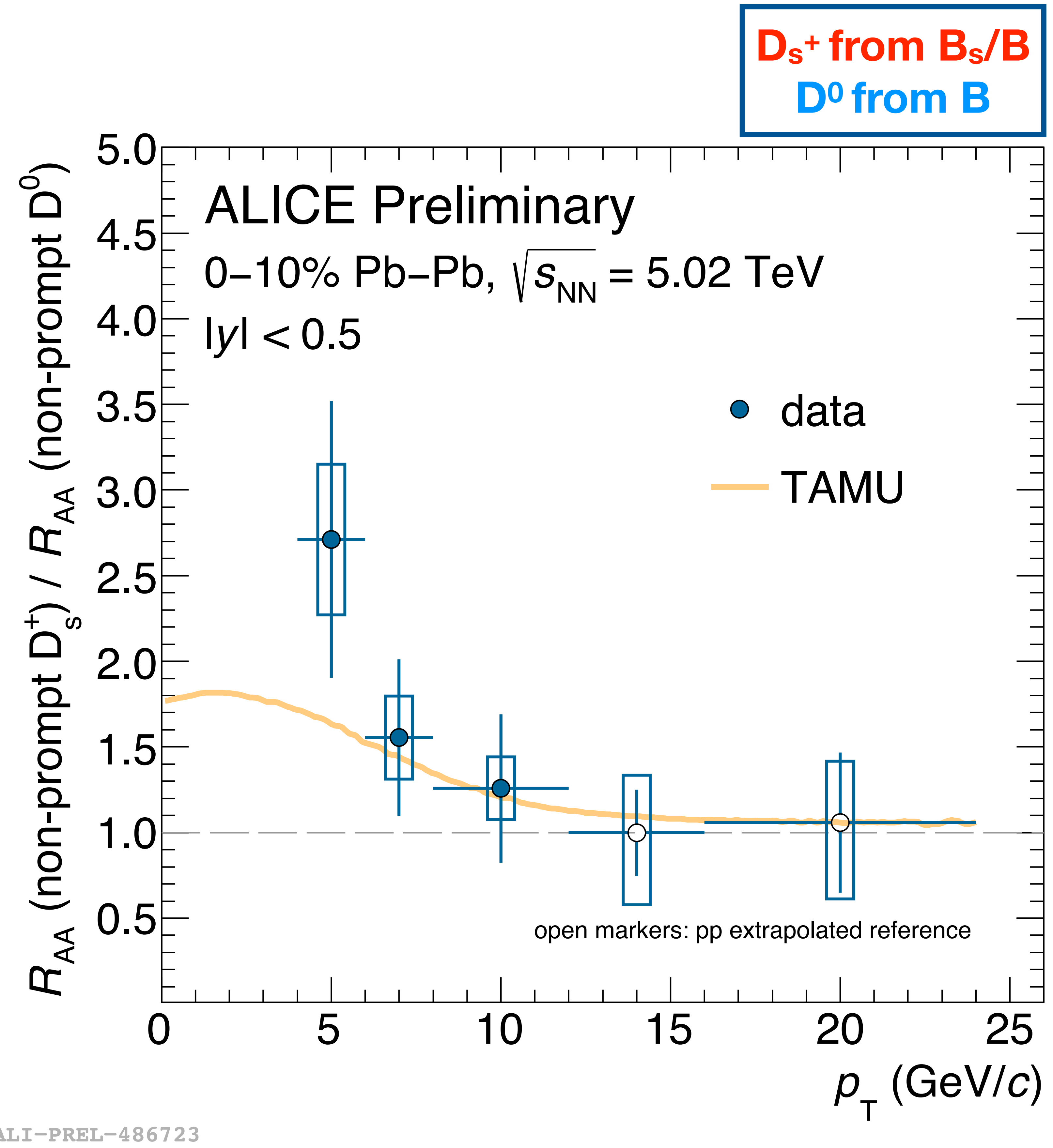
- **Smooth trend vs multiplicity** from pp to Pb-Pb collisions at low and intermediate p_T?

Caveat: a trend in a given p_T range could be also be due to a modification of the p_T shape

Coalescence of beauty quarks?





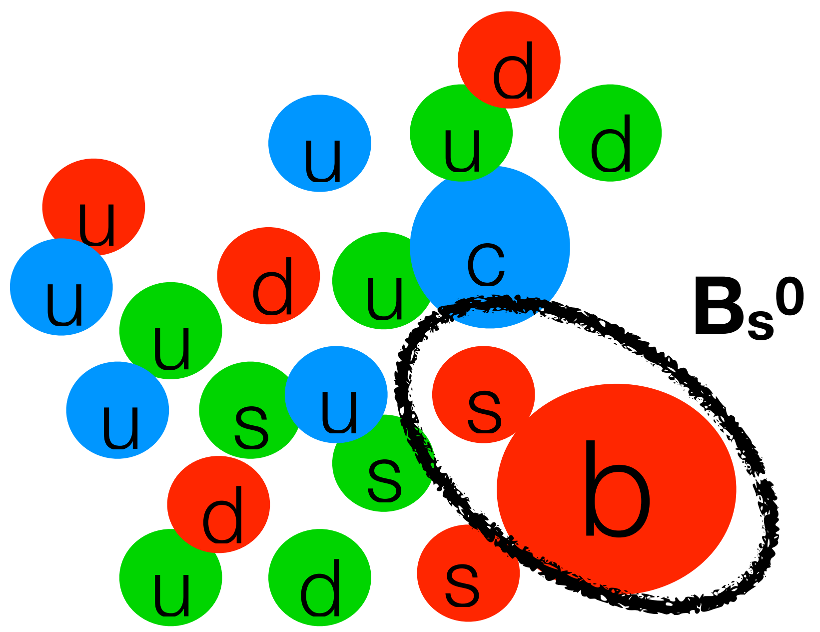


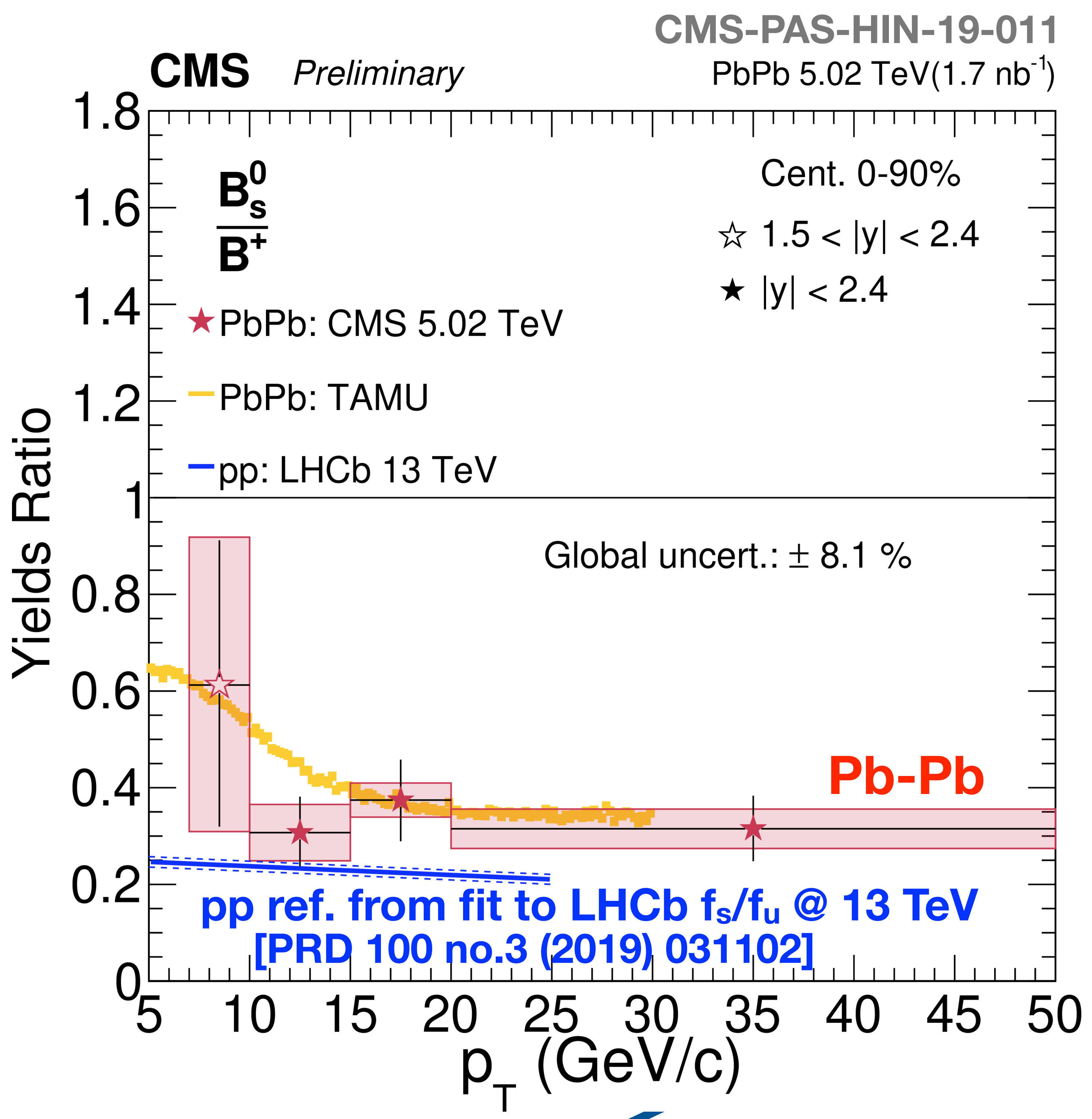
~ 50% of D_s^+ from B_s

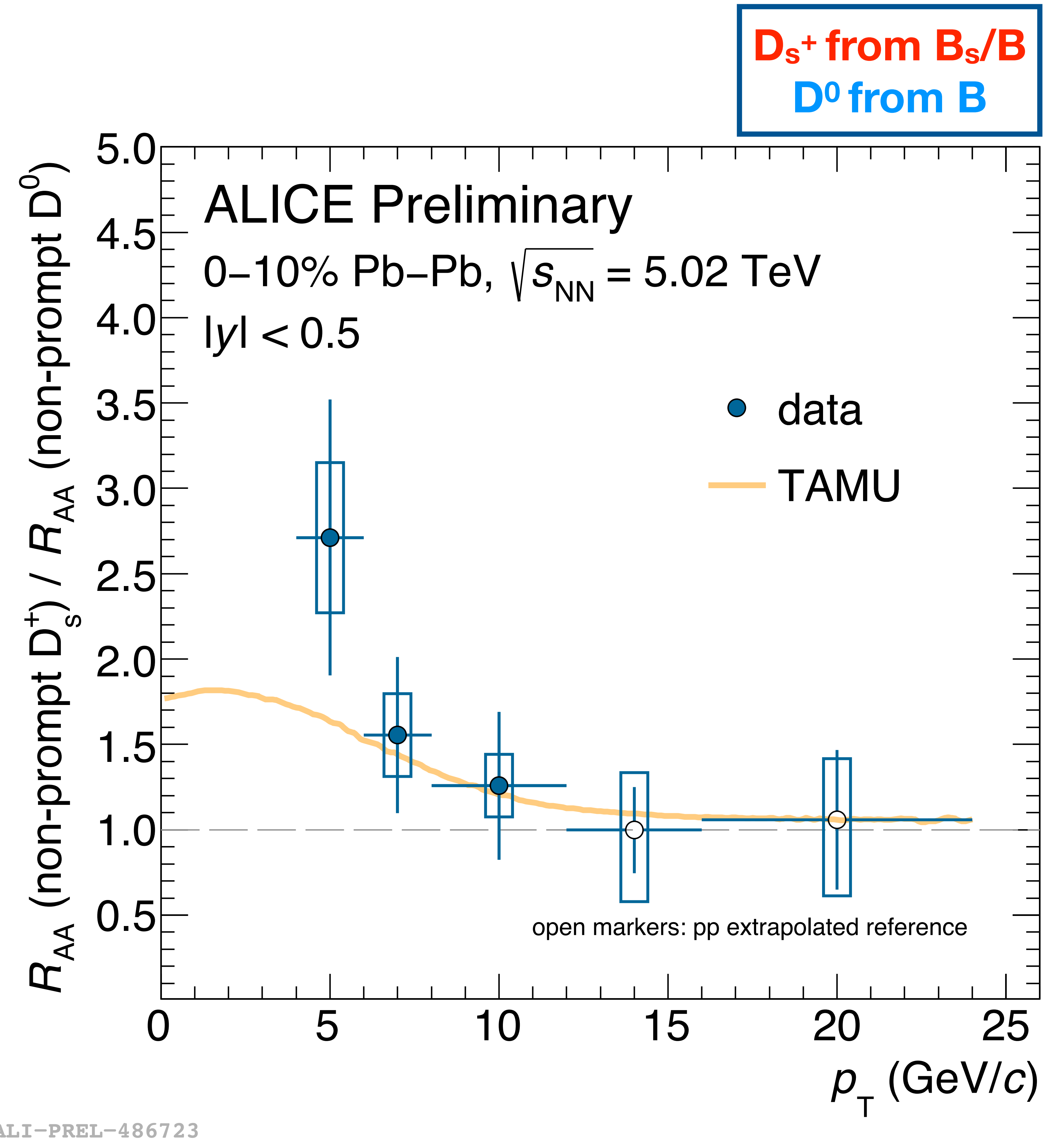
- **B_s^0/B^+ ratio** compatible with both **TAMU predictions** for Pb-Pb collisions and **pp reference** results
- **R_{AA} (non-prompt D_s^+)/R_{AA} (non-prompt D^0)** above unity at low p_T
  - **TAMU** describes the observed trend
- **Enhanced production of B_s^0 mesons** at low p_T from **beauty-quark hadronisation via coalescence**

TAMU: PLB 735 (2014) 445

Coalescence of beauty quarks?







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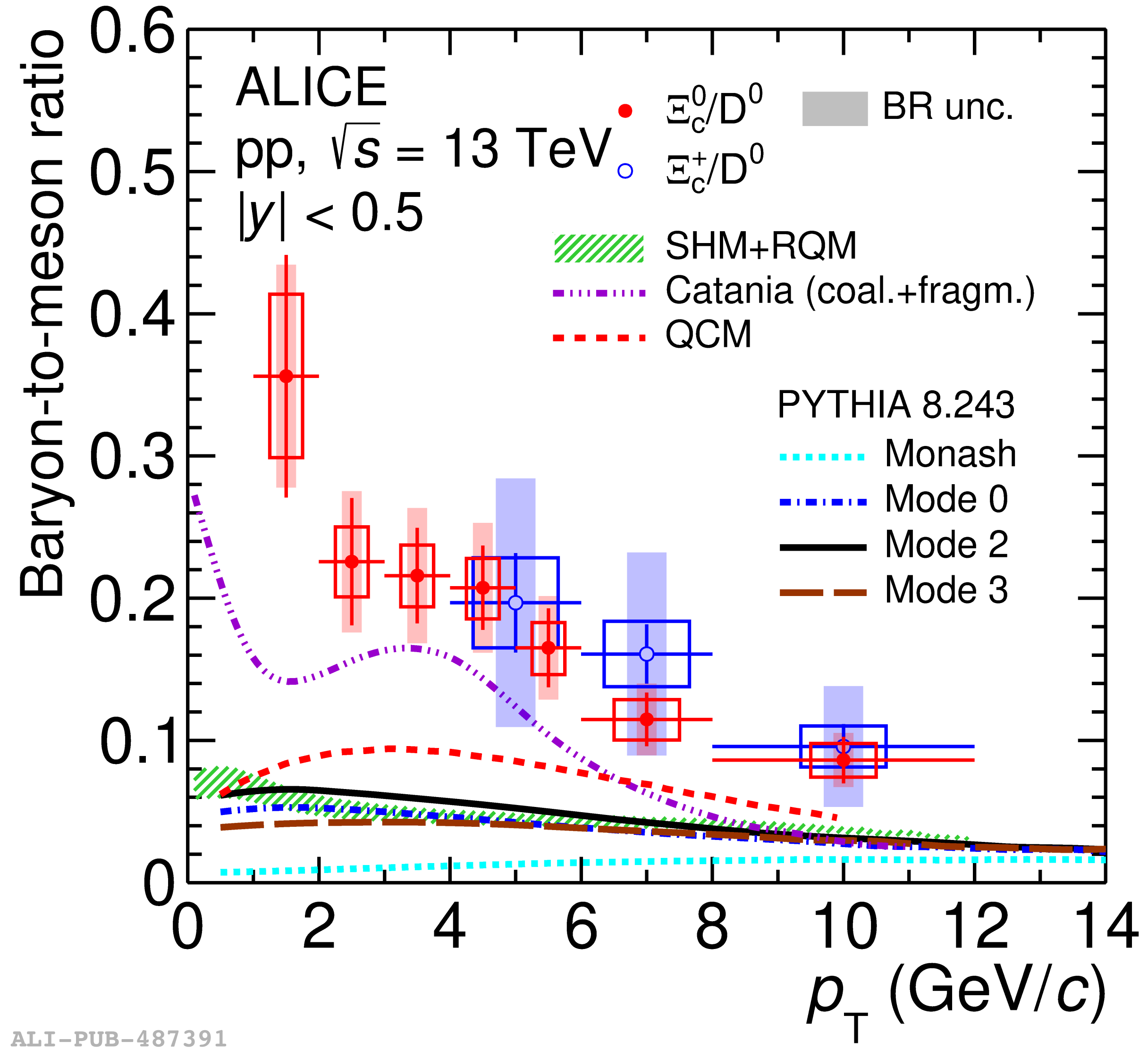
TAMU: PLB 735 (2014) 445

Interesting to see the results on B_c production in Pb-Pb collisions from CMS

Conclusions and outlook

- **Several measurements of single heavy-flavour hadrons available -> indicate non universality of the fragmentation fractions**

- **Various models** proposed to explain the enhancement of the charm baryon-to-meson ratio observed in pp collisions
  - Further comparison between data and models useful to understand the picture



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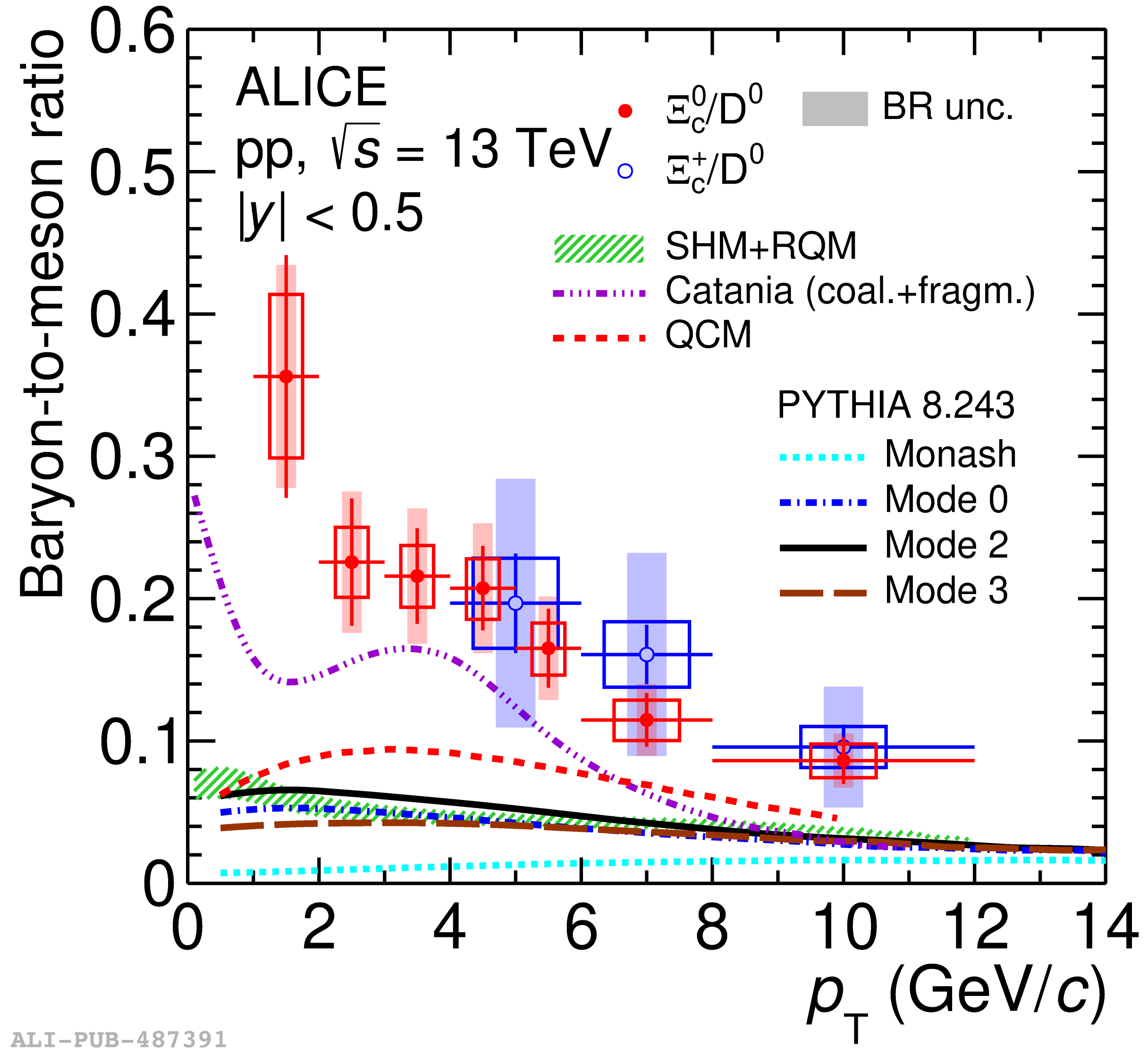
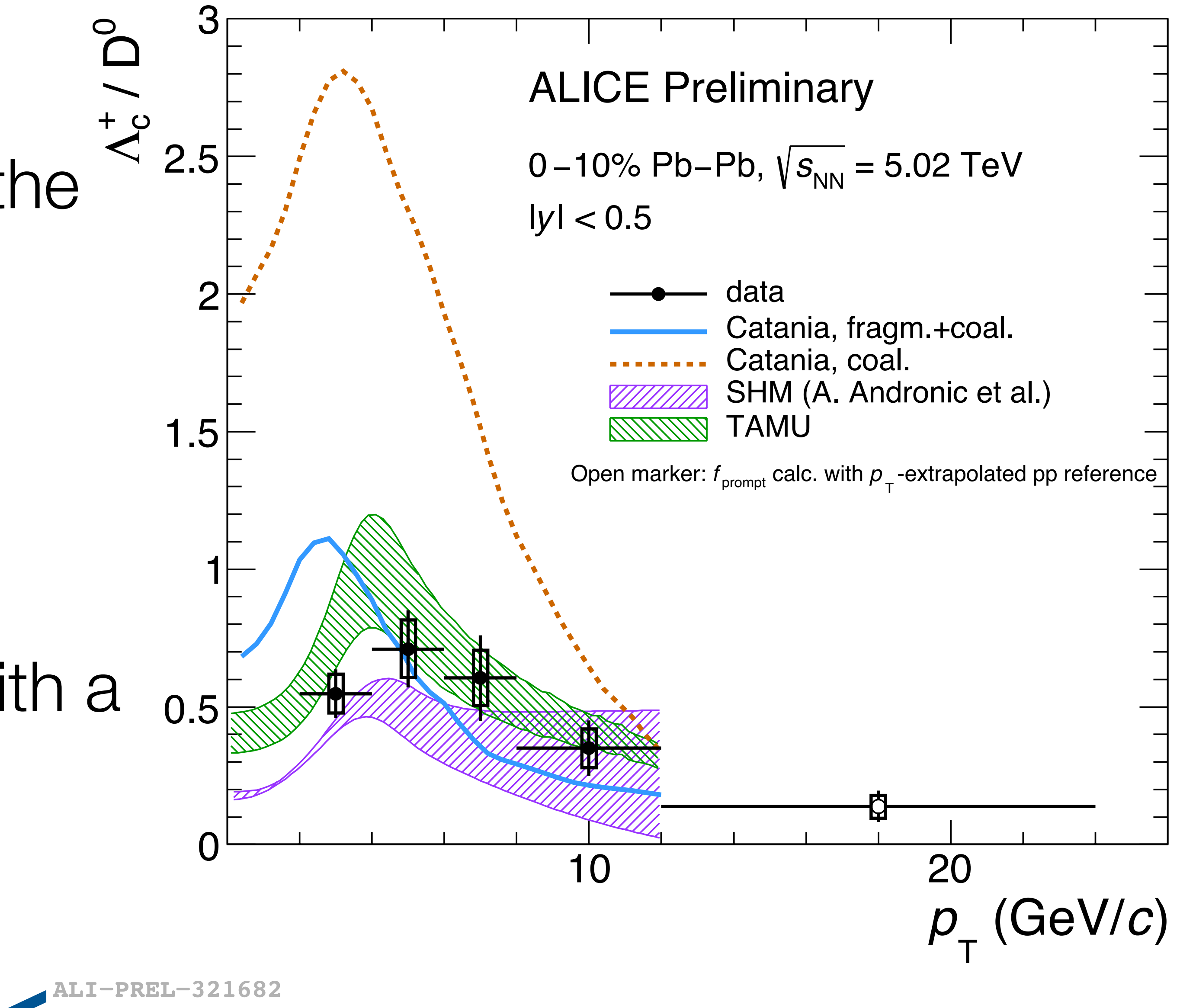




- **D_s^+/D^0 and Λ_c^+/D^0 ratios** in Pb-Pb collisions compatible with a scenario of hadronisation via **coalescence at low p_T** and **fragmentation at high p_T** and **calculations from the statistical hadronisation model**

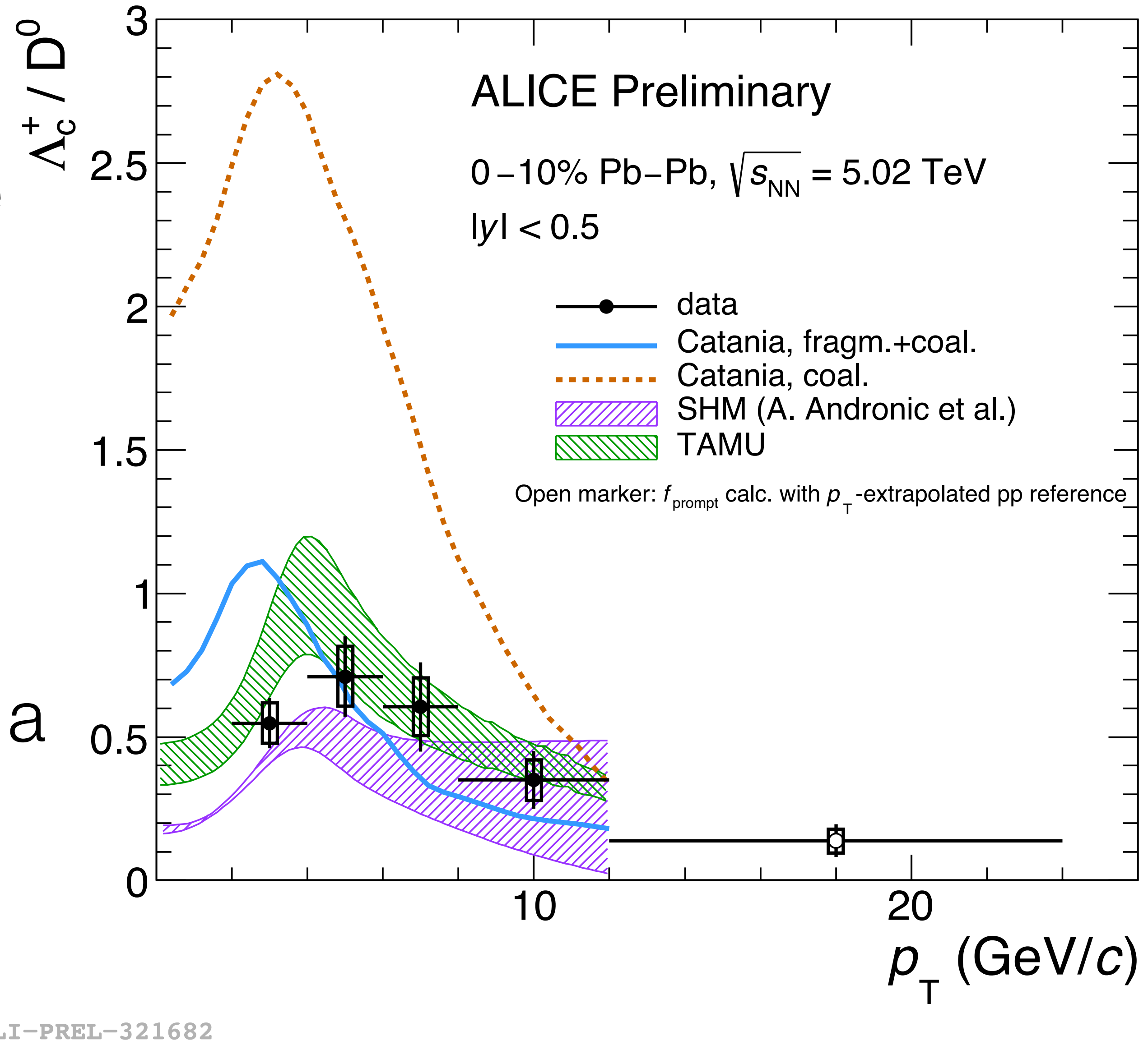
- Understanding of heavy-flavour hadronisation interesting to **extract heavy quark transport parameters of the QGP**

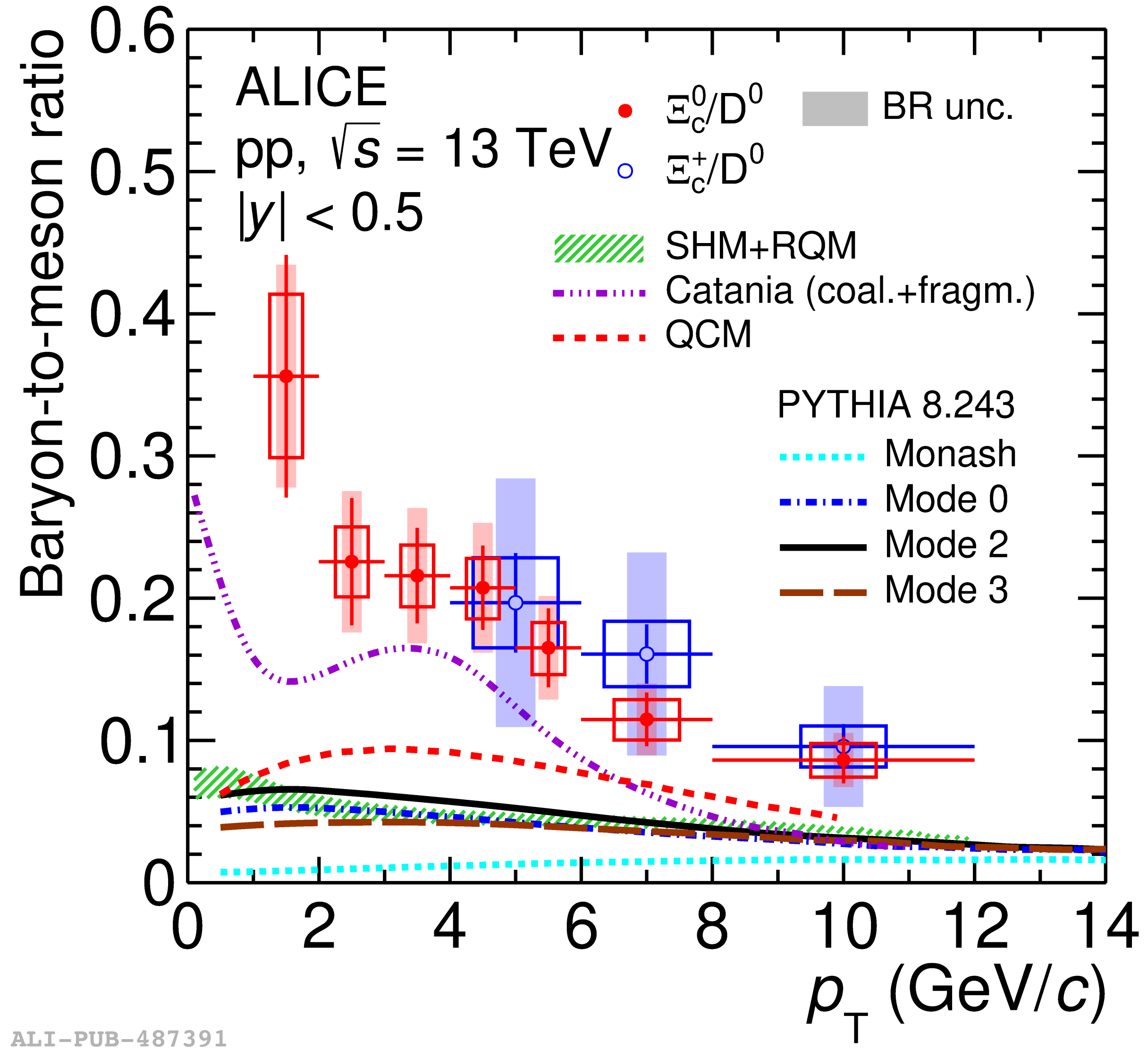
- **Common trend for heavy-flavour hadron production with multiplicity** going from small (pp and p-Pb) to large (Pb-Pb) systems?

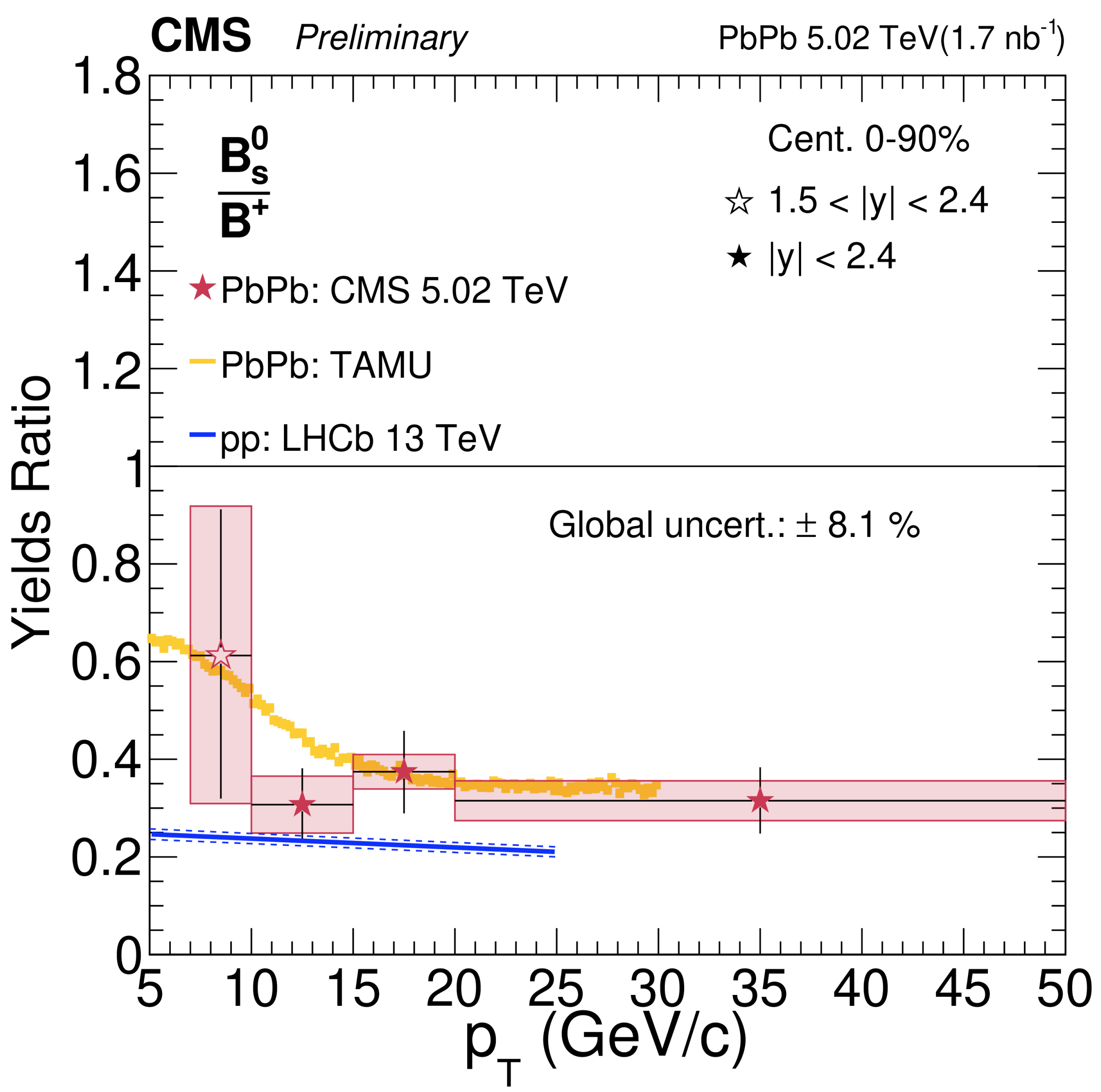
Conclusions and outlook

- **Several measurements of single heavy-flavour hadrons available -> indicate non universality of the fragmentation fractions**

- **Various models** proposed to explain the enhancement of the charm baryon-to-meson ratio observed in pp collisions
    - Further comparison between data and models useful to understand the picture







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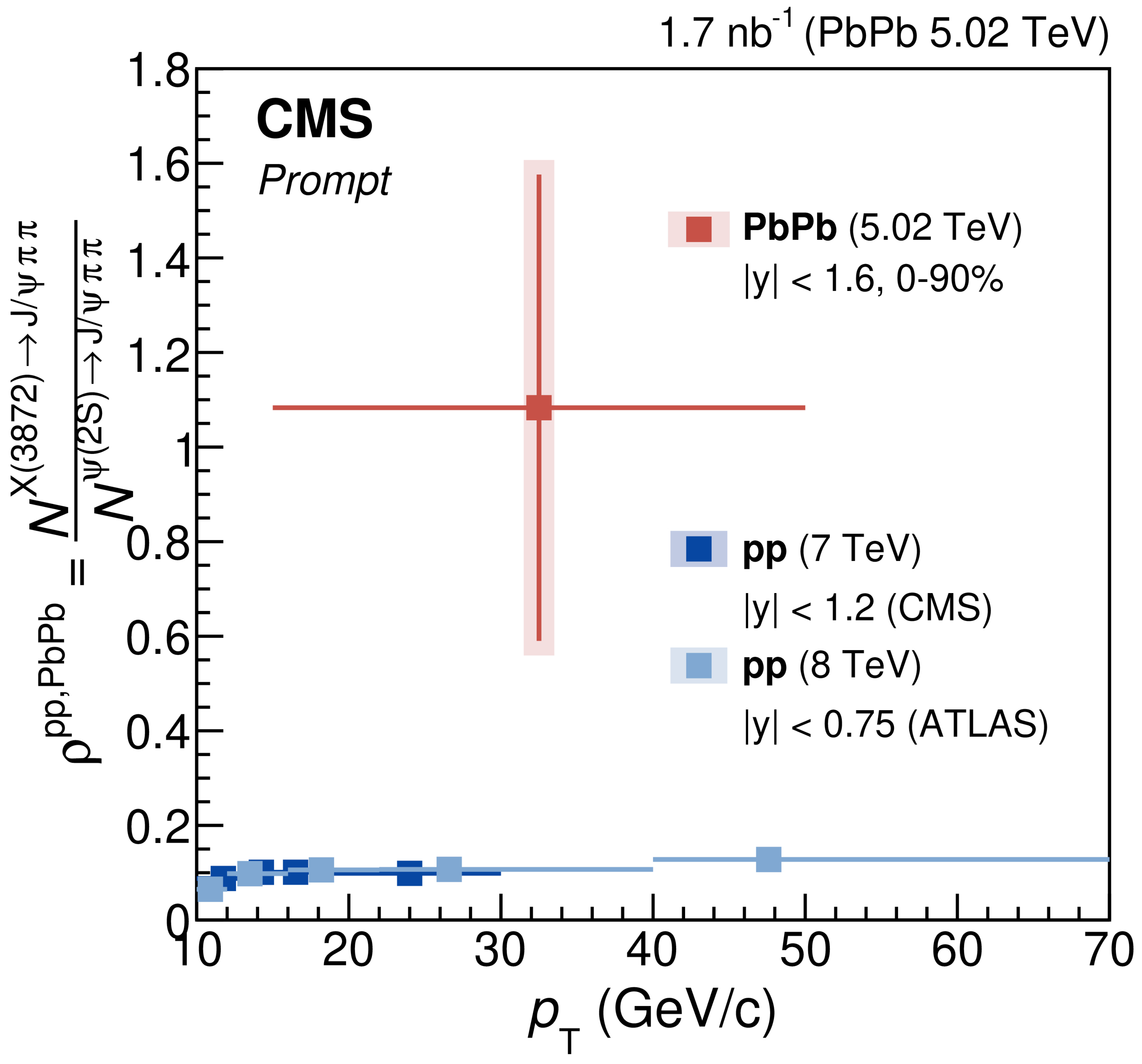
- Understanding of heavy-flavour hadronisation interesting to **extract heavy quark transport parameters of the QGP**

Future measurements of multi-charm baryons, beauty baryons and mesons, and exotic states will be fundamental to investigate the hadronisation process in both small and large systems

Back up slides

X(3872)

- **Exotic state** whose nature is unknown:
  - compact tetraquark object ($c\bar{c}u\bar{u}$), loosely bound hadronic molecule ($D\bar{D}^{0*}$) or something else?
- Production **enhanced** or **suppressed** in QGP depending on its internal structure



- **$R_{AA}(\Upsilon(2S))$ = 0.142 ± 0.061 (stat) ± 0.020 (syst)** in 15< p_T< 20 GeV/c
  => **R_{AA} (X(3872))>1**
  but compatible with unity within 1σ and with $R_{AA}(\Upsilon(2S))$ within 2σ

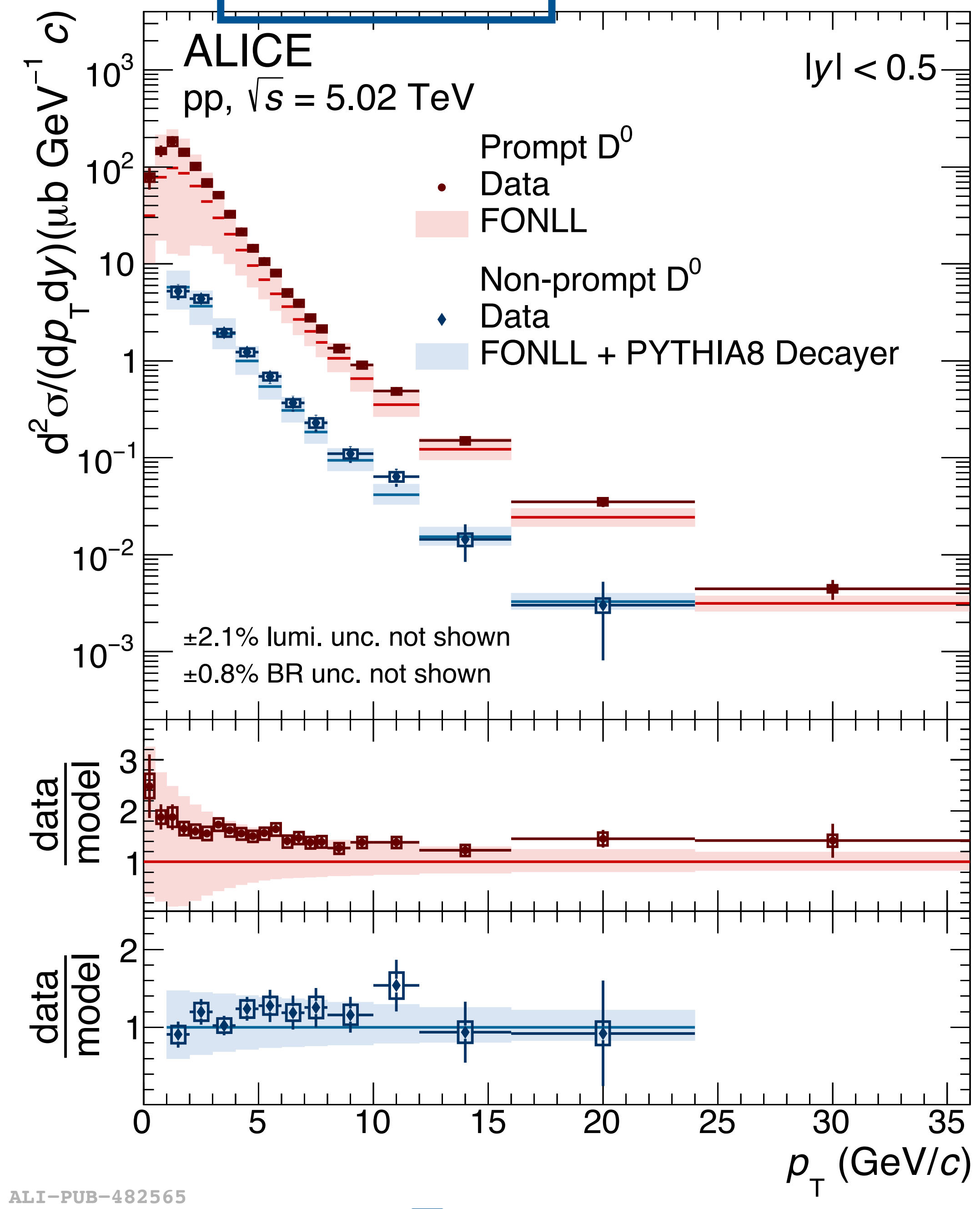
Heavy-flavour meson production in pp collisions

- **Theory calculations based on the factorisation theorem** describe **heavy-flavour meson production within uncertainties**
  - use **fragmentation fractions parametrised on e^+e^- and ep collision data**
  - include NLO calculations with NLL resummation

➡**Describe D and B meson production within uncertainties**

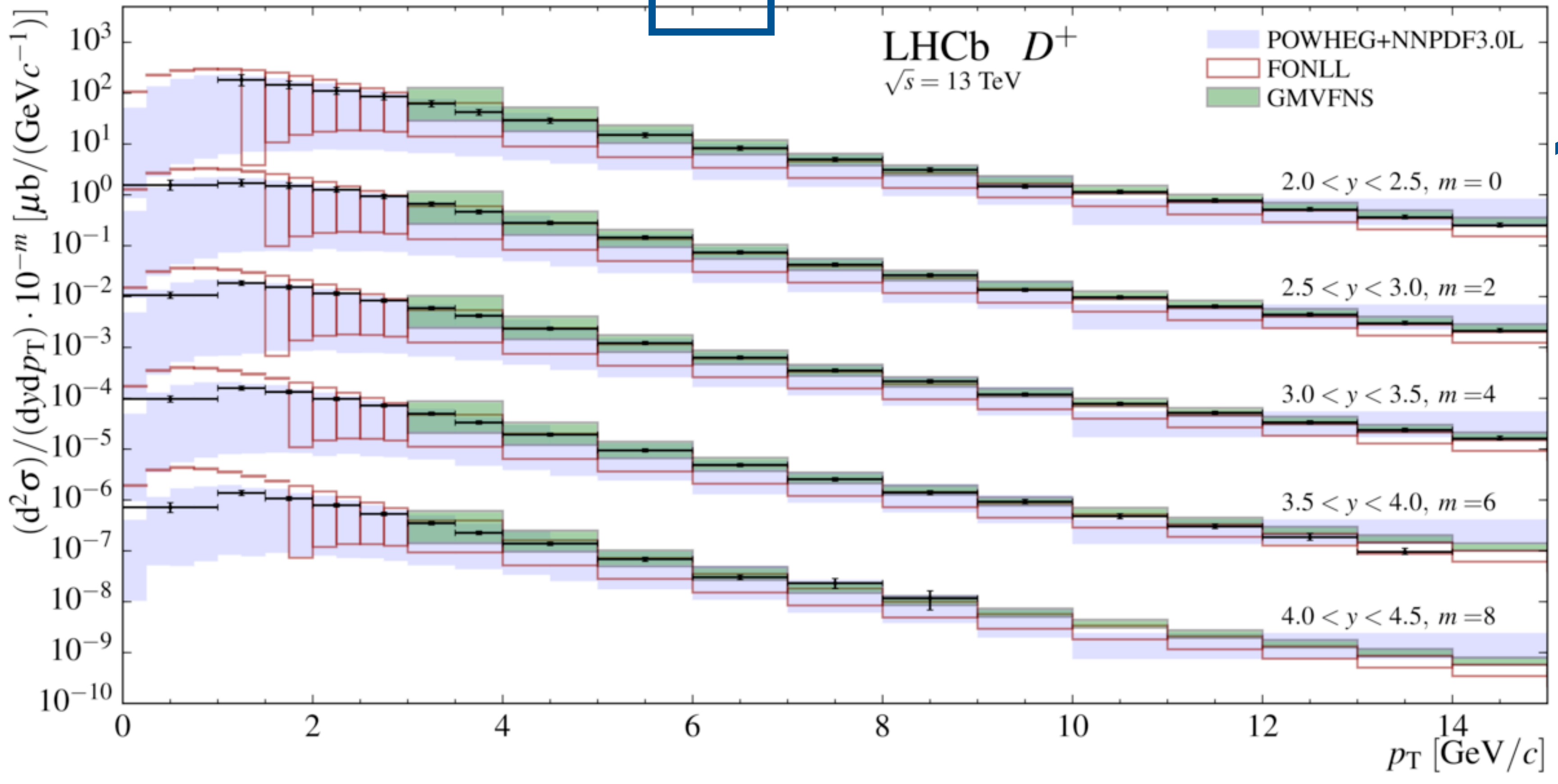
prompt D^0
D^0 from B

arXiv:2102.13601
EPJ C79 no. 5 (2019) 388



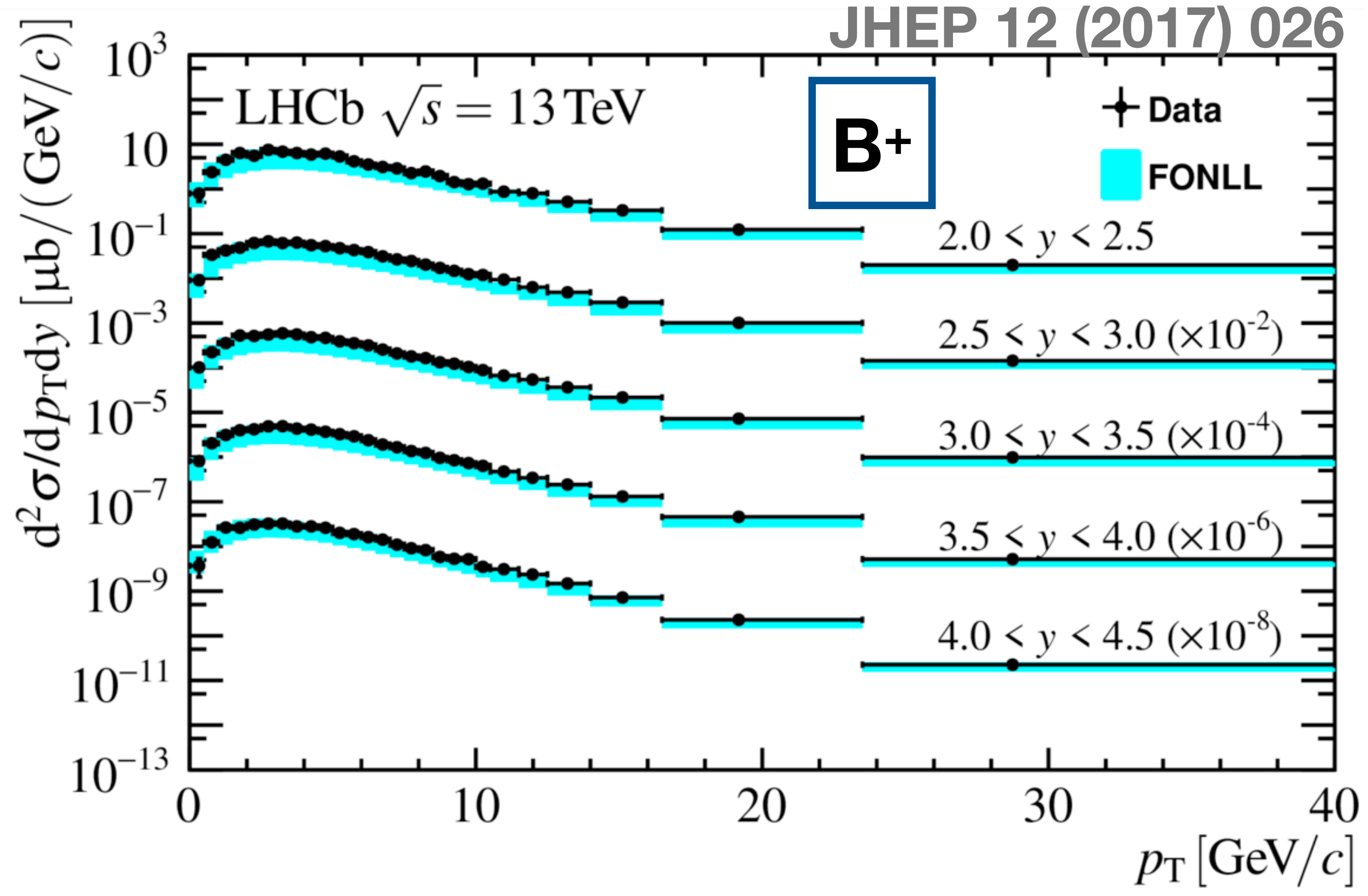
D+

JHEP 05 (2017) 074

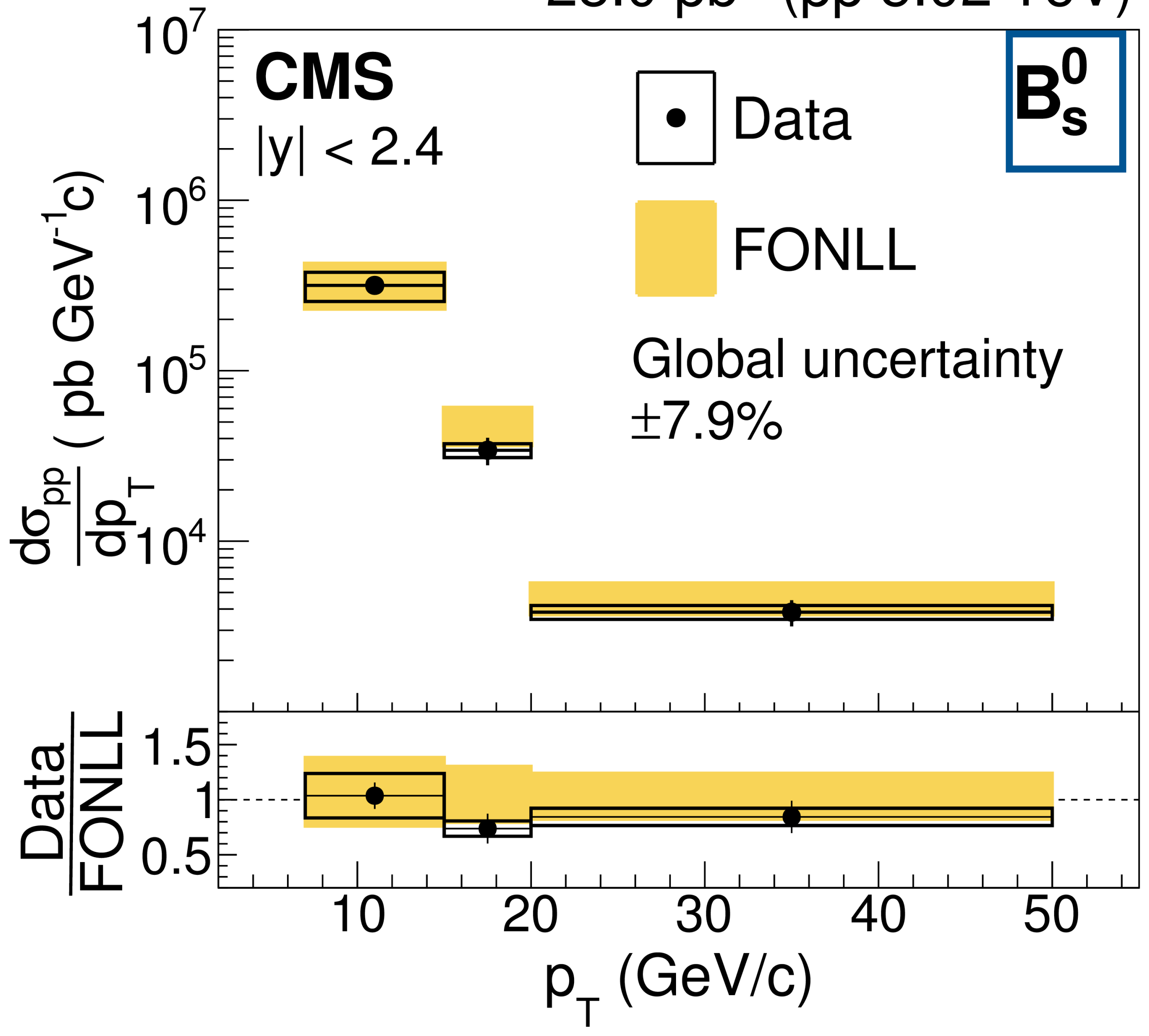


FONLL: JHEP 1210 (2012) 137
GM-VFNS: EPJ C72 (2012) 2082
POWHEG: JHEP 06 (2010) 043

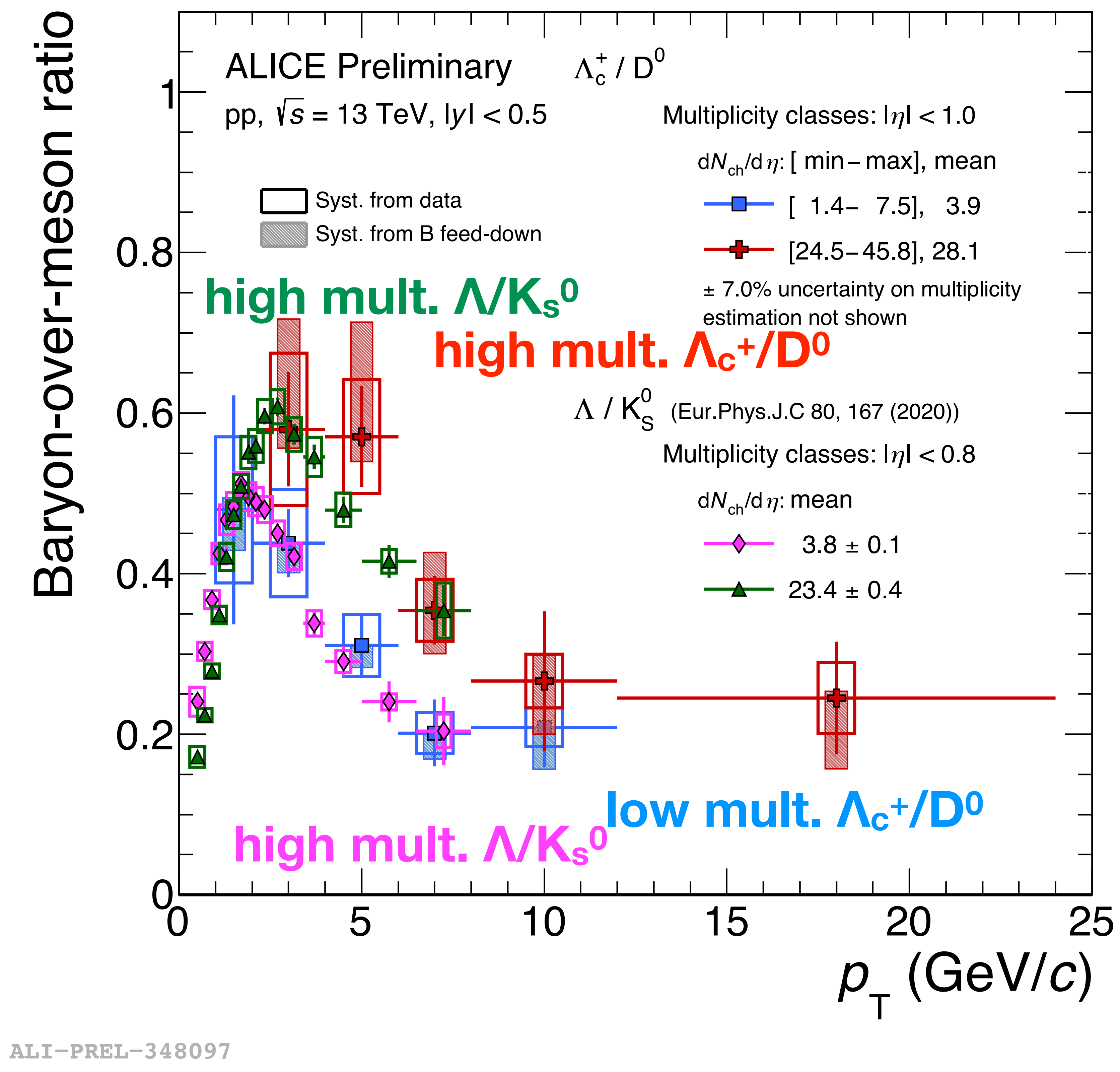
JHEP 12 (2017) 026



PLB 796 (2019) 168



Λ_c^+/D^0 in low and high multiplicity events

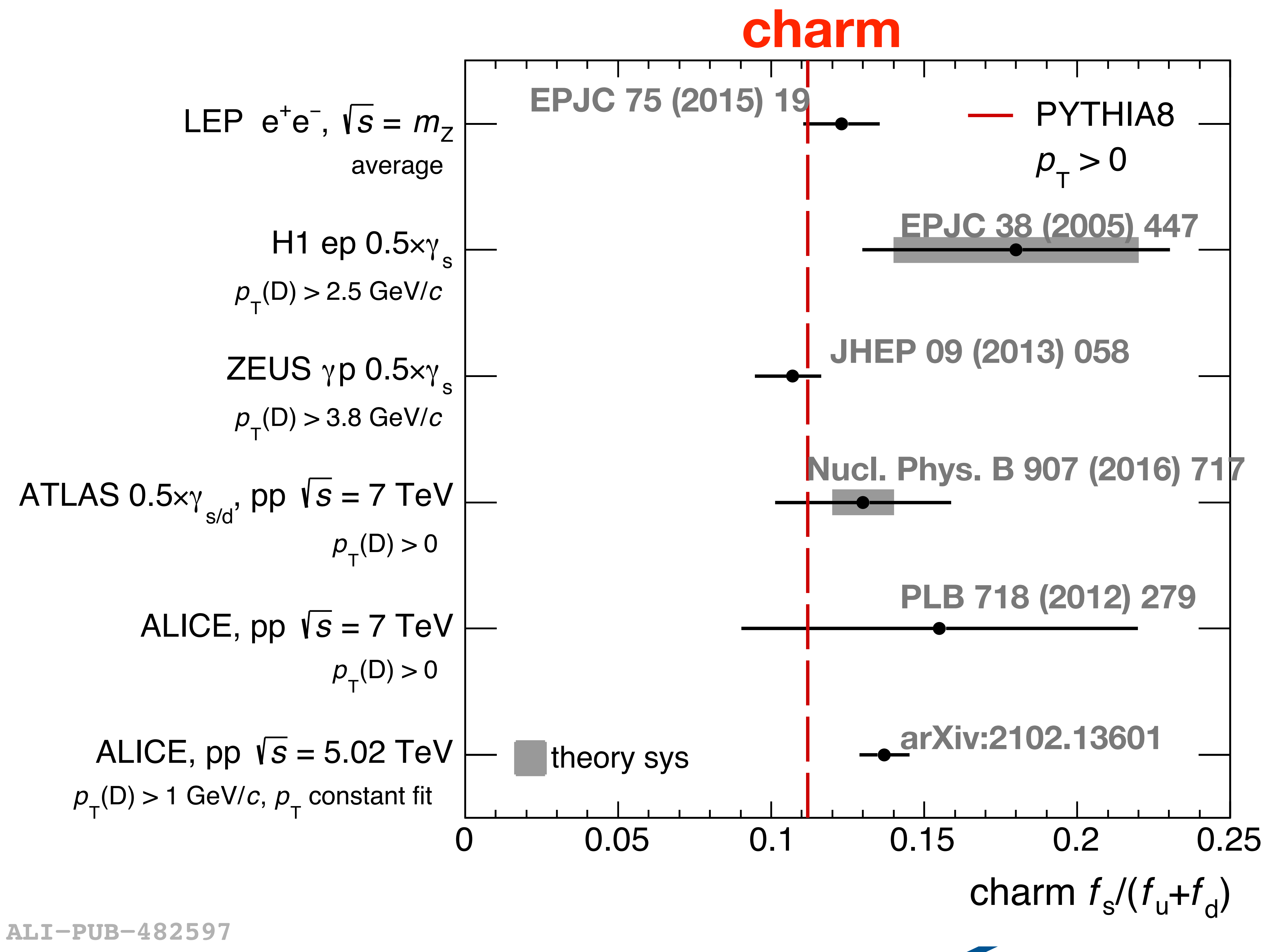


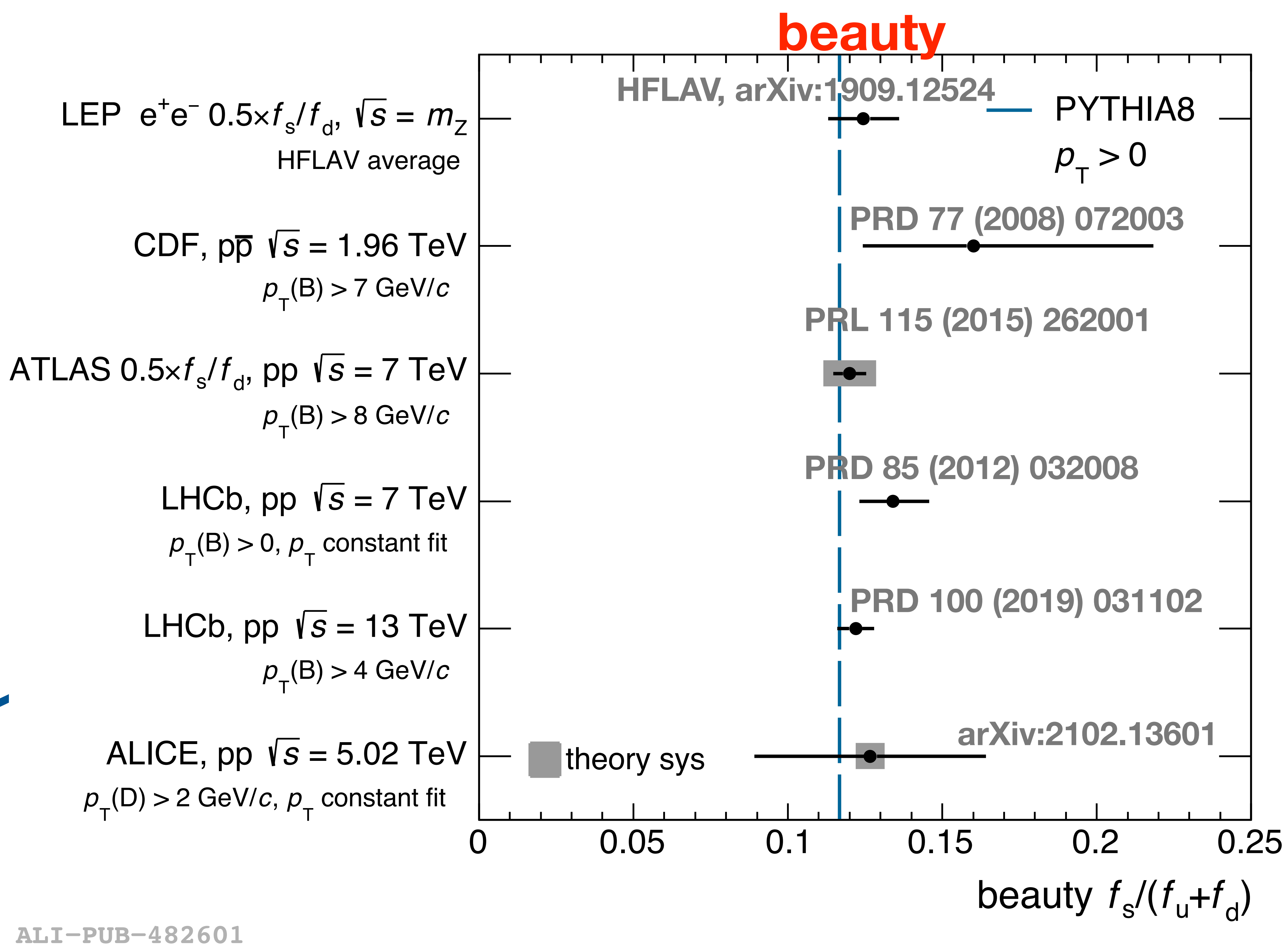
- **Evident dependence on multiplicity of Λ_c^+/D^0**
- Also in the **lowest multiplicity** the Λ_c^+/D^0 ratio larger than measurement in e^+e^- and ep collisions

- **Similar trend in the heavy-flavour and light-flavour sector**

Ratio of fragmentation fractions: $f_s/(f_u+f_d)$

- Based on measurements of the **heavy-strange mesons over heavy-non-strange mesons**

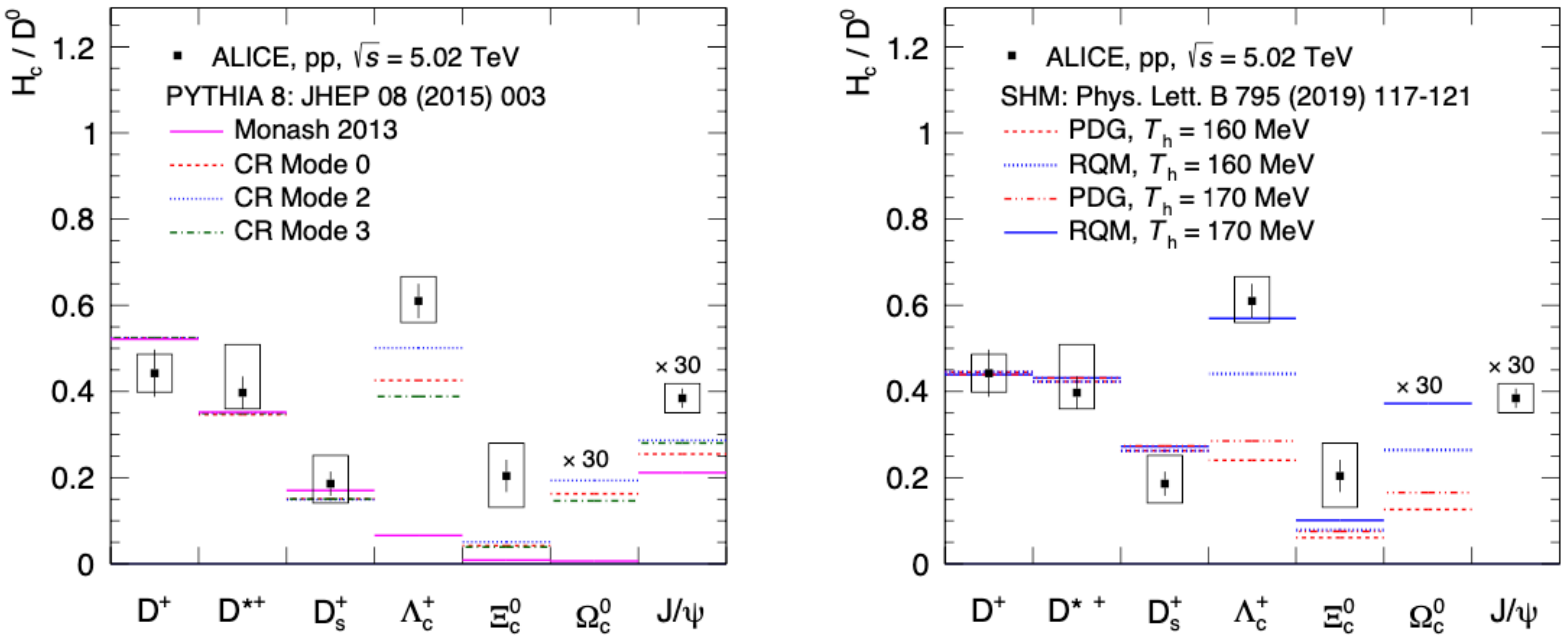




- All the measurements are in agreement within uncertainties and with **PYTHIA 8 Monash** predictions
- Similar results between charm and beauty

P. Skands et al., EPJC 74 (2014) 3024

H_c/D^0 ratio: comparison with PYTHIA 8, Monash, SHM



Baryon-to-meson ratio: comparison with e^+e^- results

	$\Lambda_c^+/D^0 \pm$ stat. $\pm$ syst.	System	$\sqrt{s}$ (GeV)	Notes
ALICE	$0.62 \pm 0.05 \pm 0.05\,^{+0.01}_{-0.03}$	pp	5020	$p_T > 0, \lvert y \rvert < 0.5$
ALICE	$0.45 \pm 0.03 \pm 0.06^{+0.06}_{-0.04}$	p–Pb	5020	$p_T > 0, -0.96 < y < 0.04$
CLEO [7]	$0.119 \pm 0.021 \pm 0.019$	e^+e^-	10.55	
ARGUS [6, 8]	0.127 ± 0.031	e^+e^-	10.55	
LEP average [9]	$0.113 \pm 0.013 \pm 0.006$	e^+e^-	91.2	
ZEUS DIS [12]	$0.124 \pm 0.034^{+0.025}_{-0.022}$	e^-p	320	$1 < Q^2 < 1000$ GeV^2, $0 < p_T < 10$ GeV/c, $0.02 < y < 0.7$
ZEUS γp, HERA I [10]	$0.220 \pm 0.035^{+0.027}_{-0.037}$	e^-p	320	$130 < W < 300$ GeV, $Q^2 < 1$ GeV^2, $p_T > 3.8$ GeV/c, $\lvert \eta \rvert < 1.6$
ZEUS γp, HERA II [11]	$0.107 \pm 0.018^{+0.009}_{-0.014}$	e^-p	320	$130 < W < 300$ GeV, $Q^2 < 1$ GeV^2, $p_T > 3.8$ GeV/c, $\lvert \eta \rvert < 1.6$

arXiv:2011.06078
arXiv:2011.06079

Heavier charmed baryon states: Ξ_c^0 and Ξ_c^+

	mass (MeV/c²)	Quark Content
Λ_c^+	2286	udc
$\Sigma_c^{++}, \Sigma_c^0$	2455	uuc, ddc
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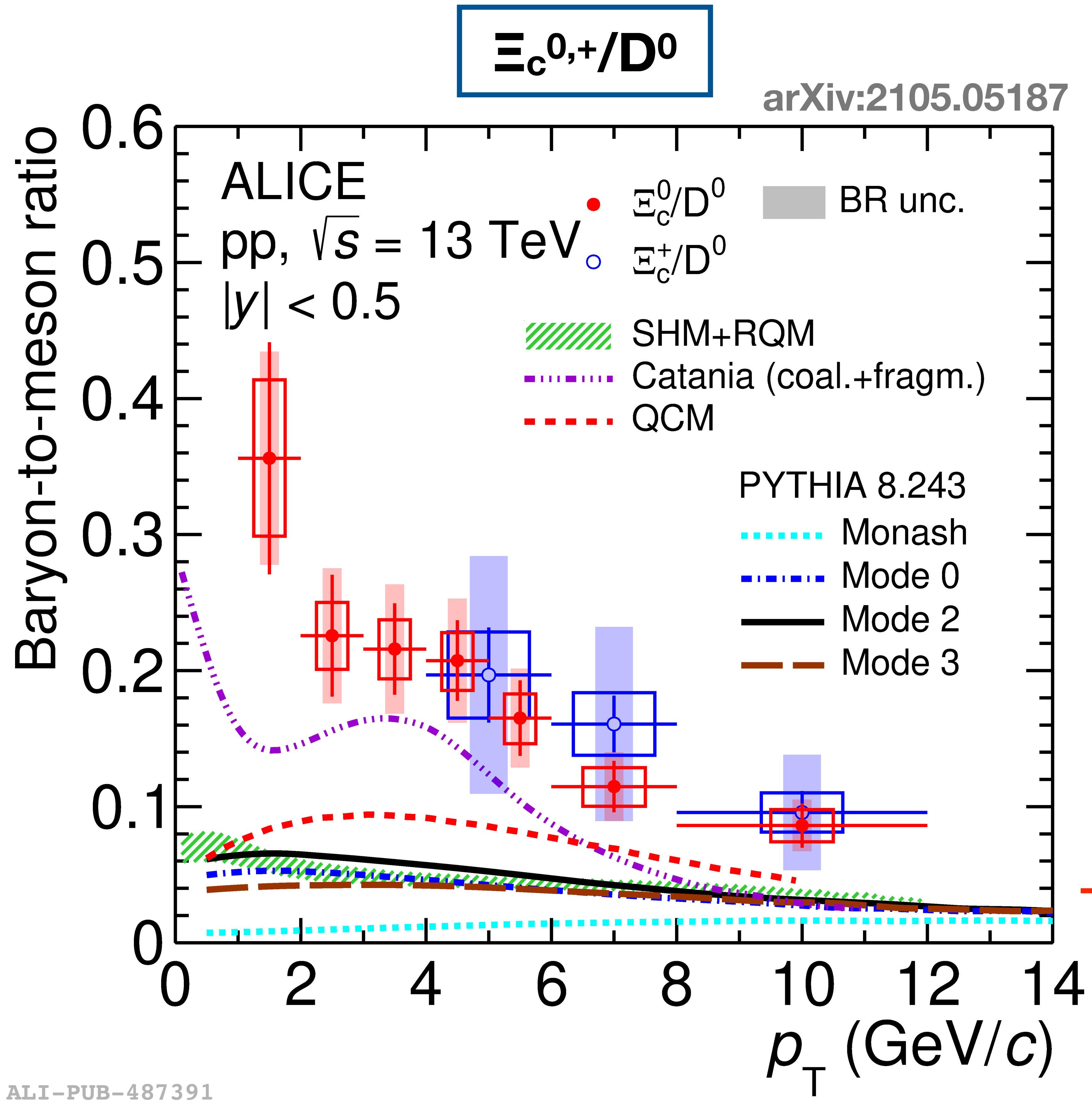
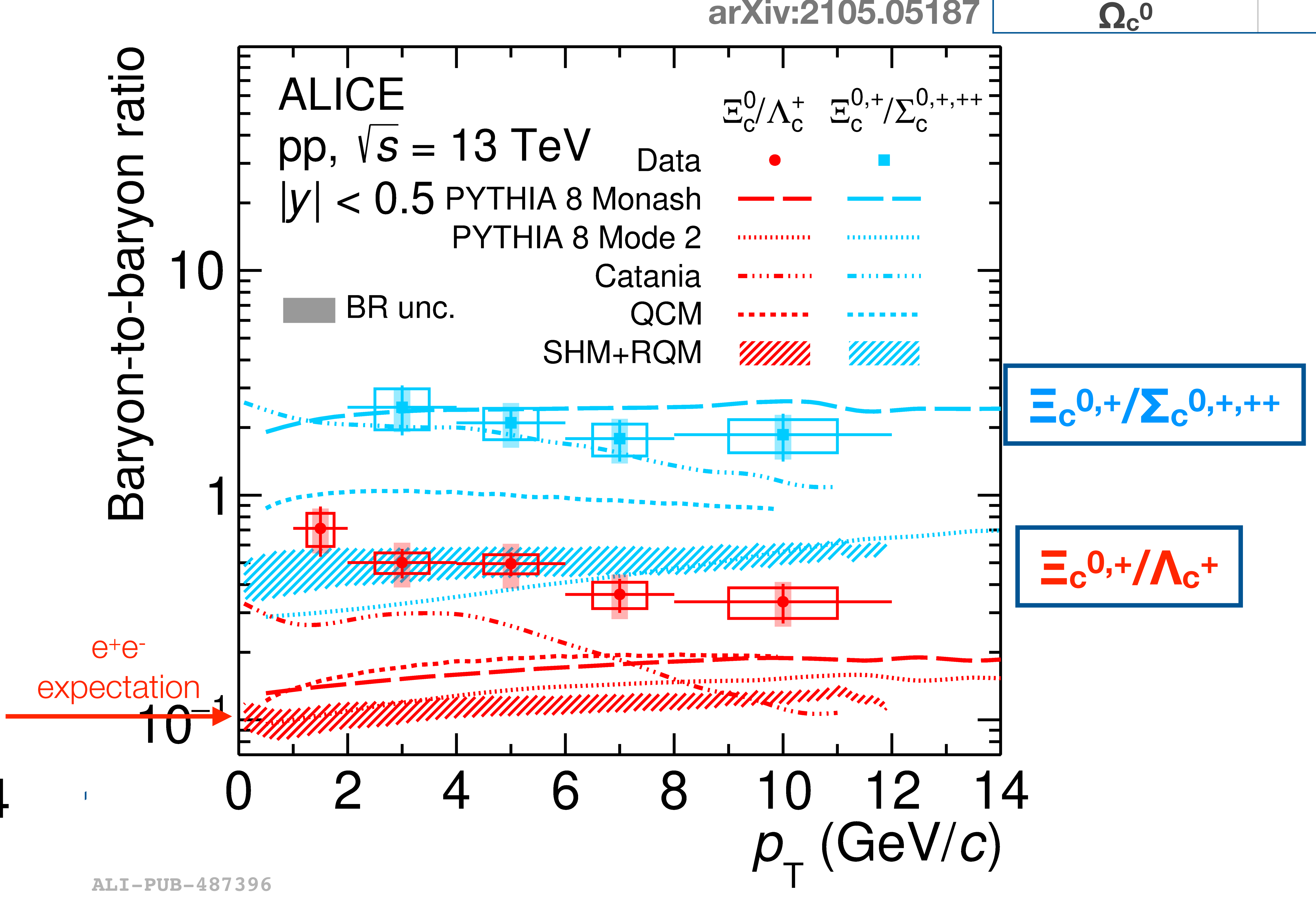


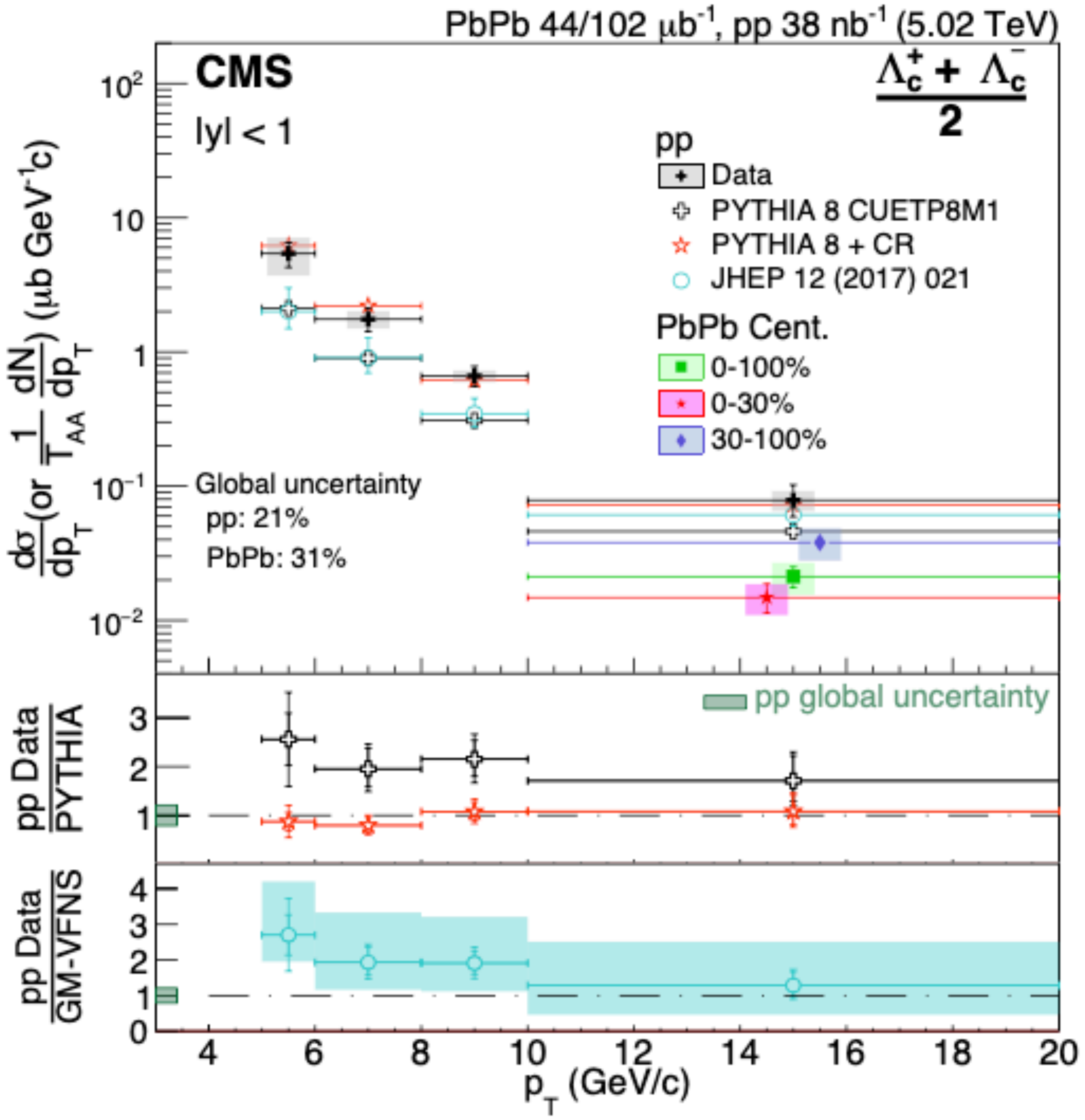


- Ξ_c^0/Λ_c^+ larger than expectations and models calculations
- $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$ described within uncertainties by Pythia Monash and by Catania
  - Different quark content but very similar mass

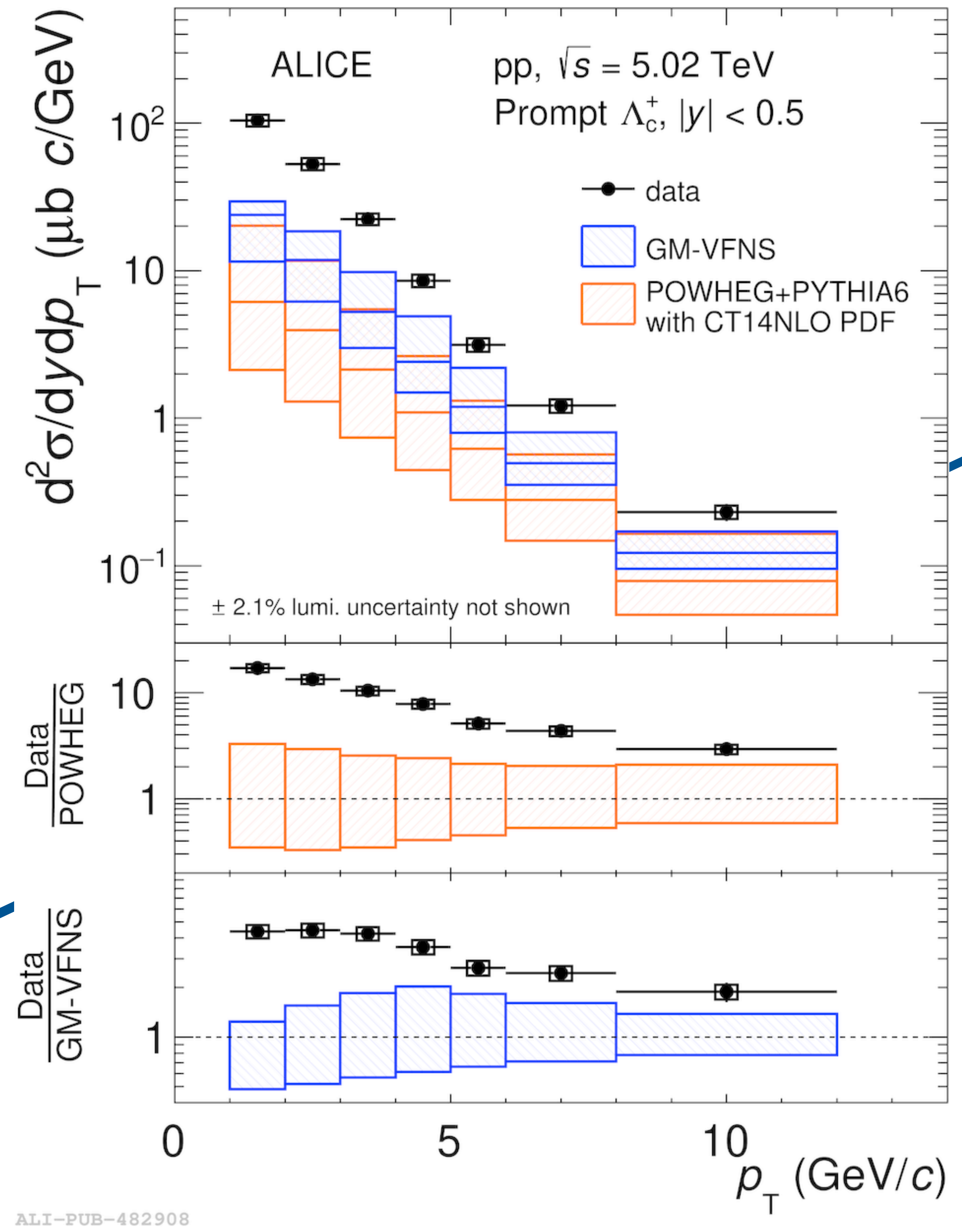
Λ_c^+ baryon cross sections in pp collisions

- Λ_c^+ baryon production cross section measured at mid and forward rapidity
- Theory calculations based on the factorisation theorem **underestimate** the data ad mid-rapidity

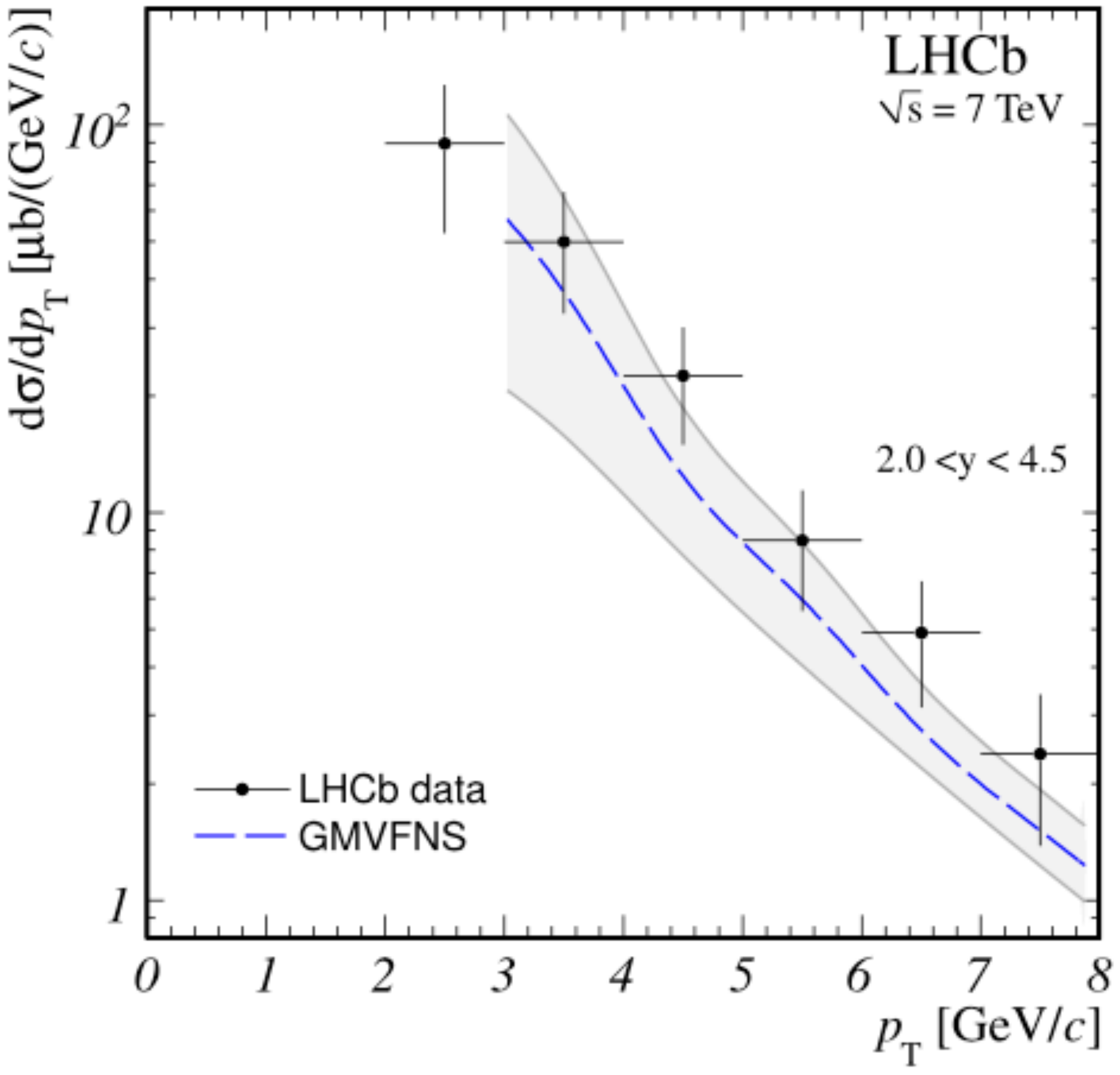
PLB 803 (2020) 135328



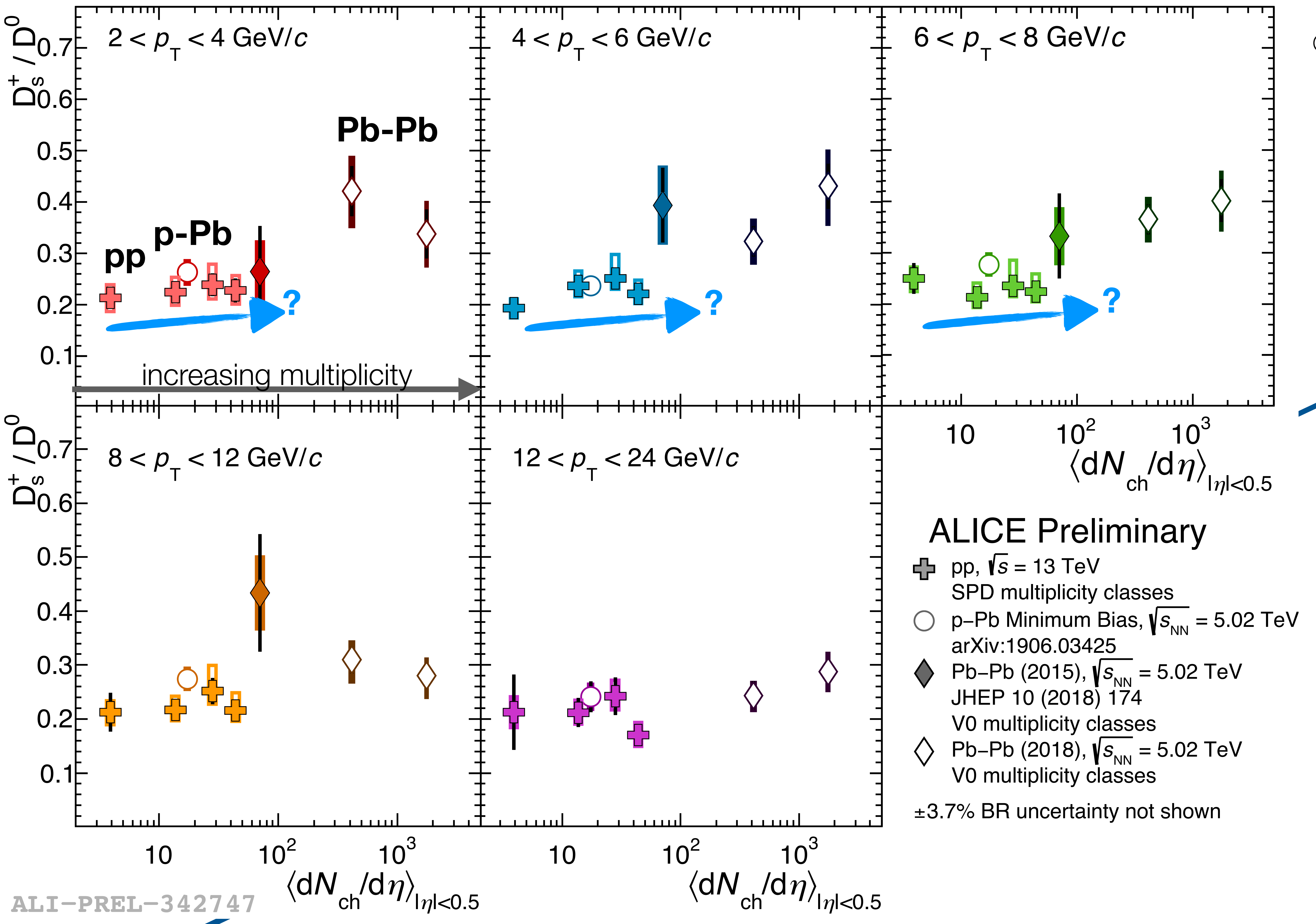
arXiv:2011.06078
arXiv:2011.06079



Nucl. Phys. B 871 (2013) 1-20

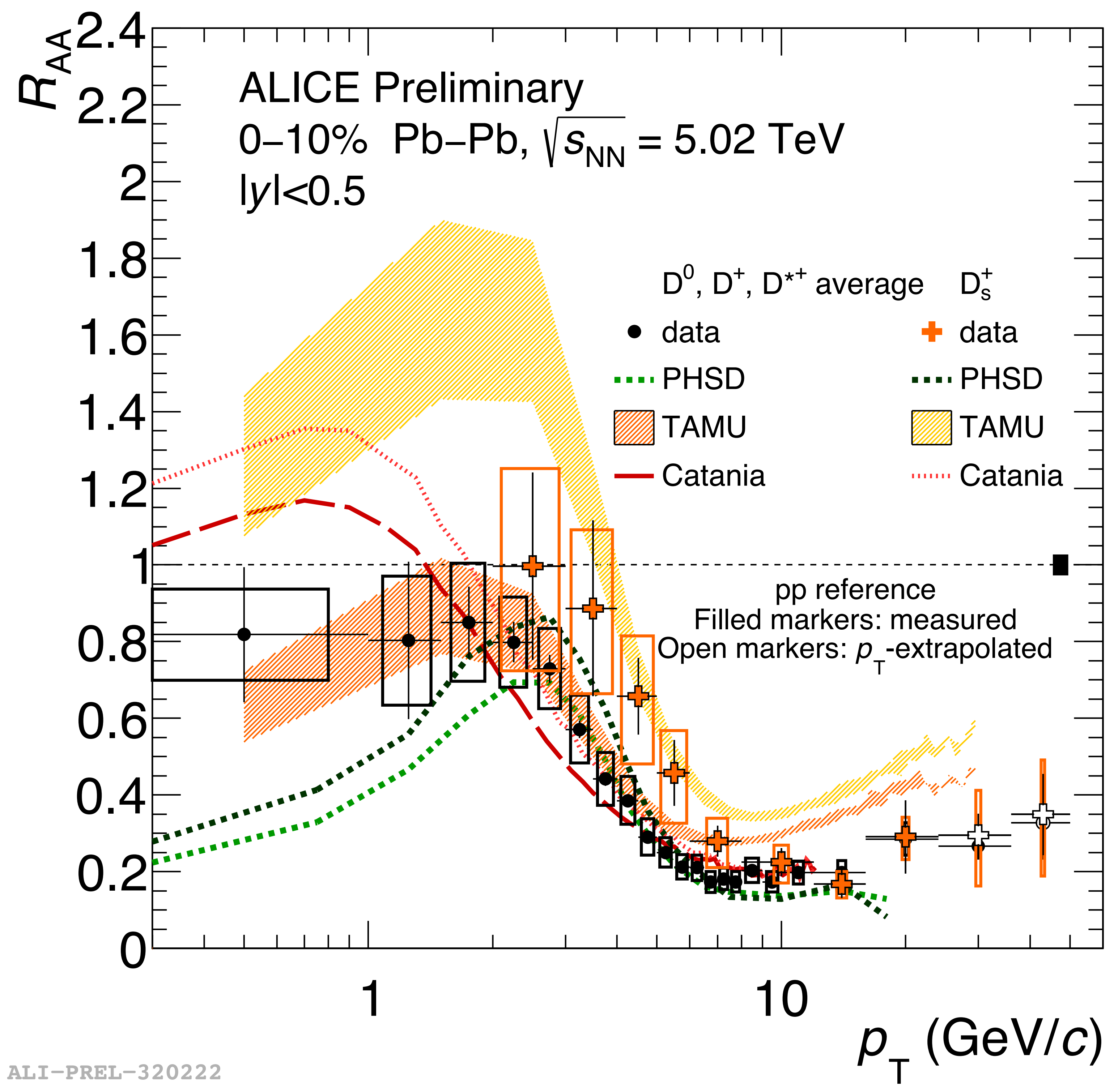


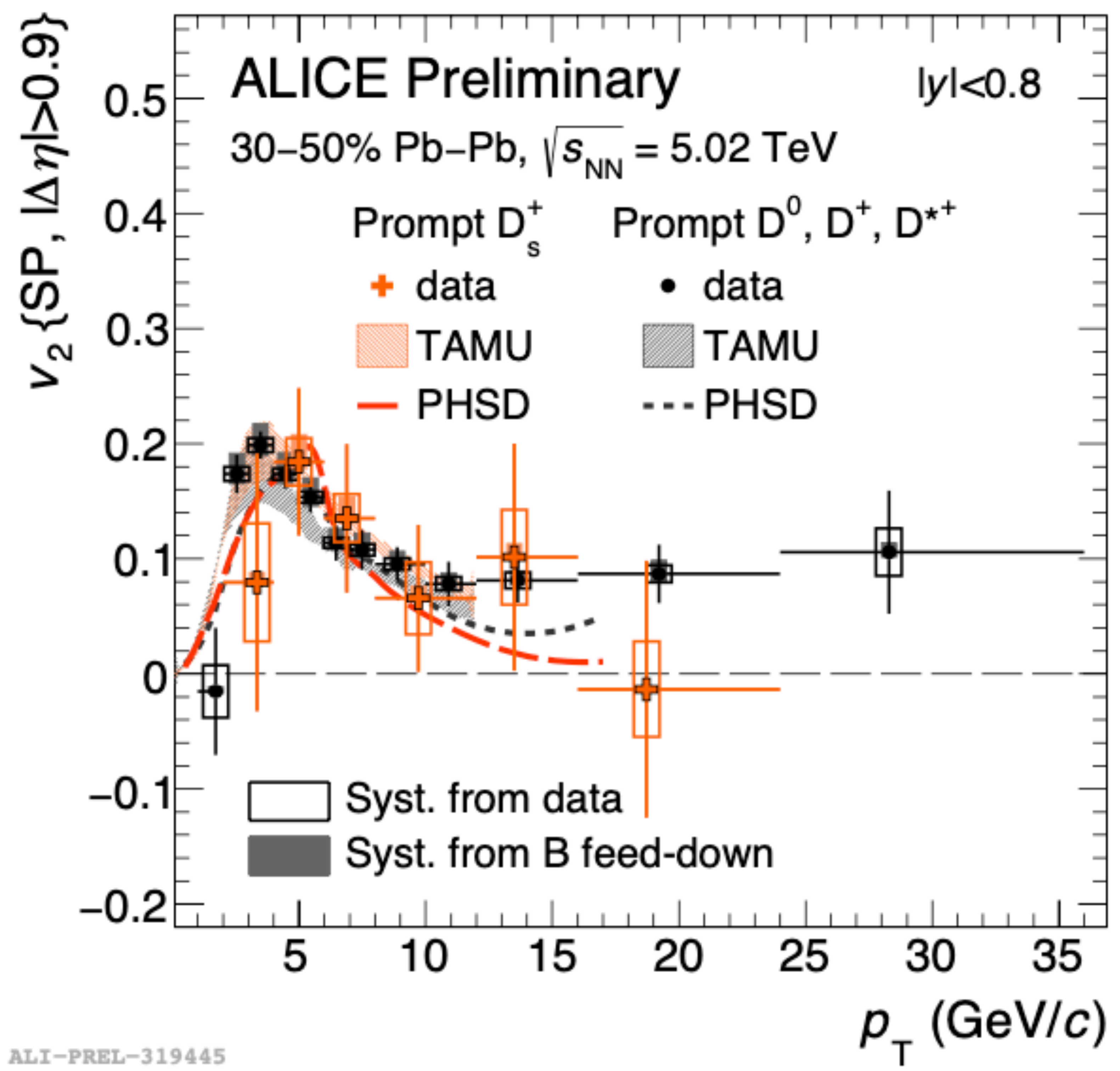
D_s^+/D^0 from pp to Pb-Pb



- Smooth trend vs multiplicity from pp to Pb-Pb collisions?

D_s^+ nuclear modification factor and v_2





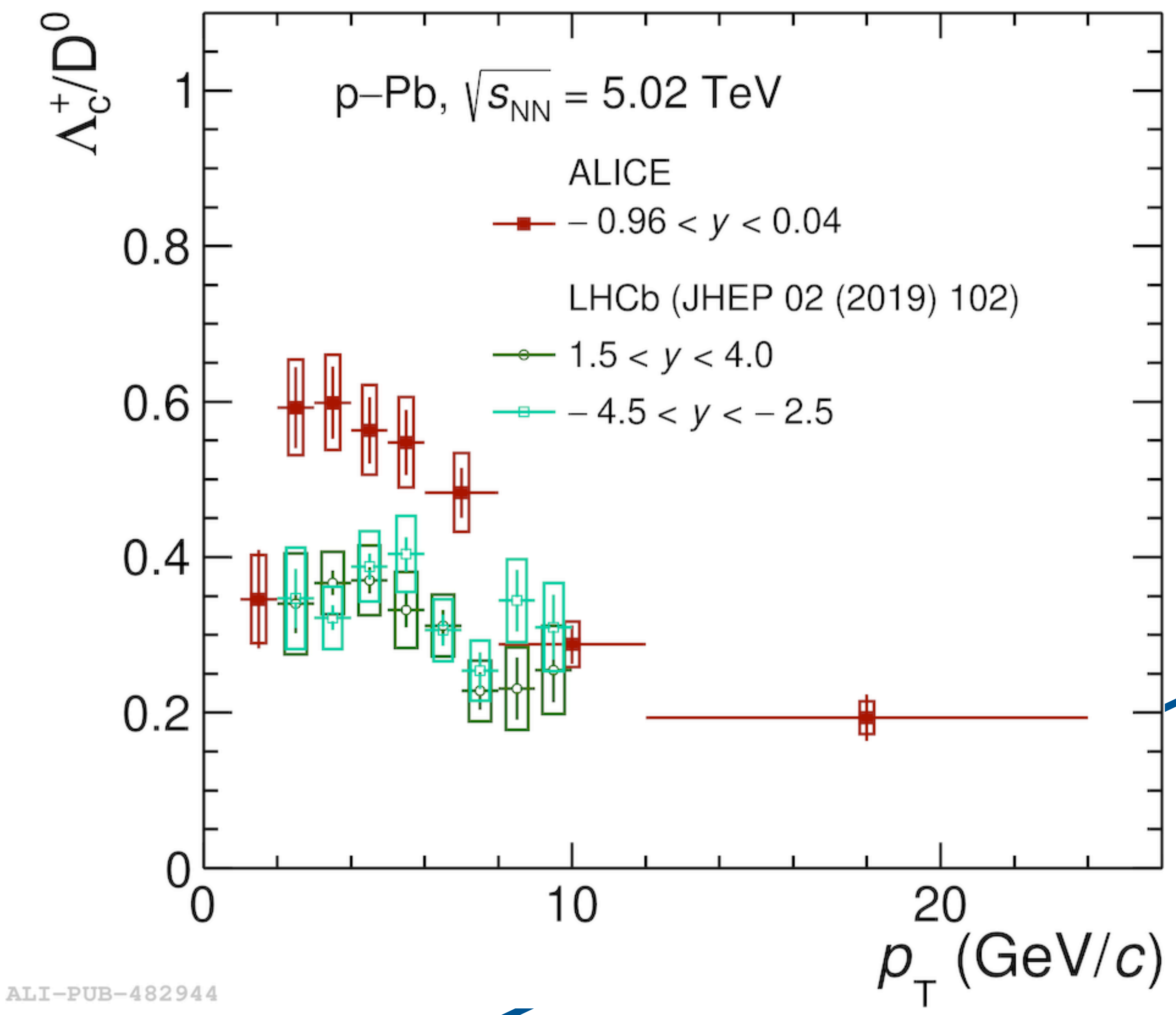
- **Smaller D_s^+ R_{AA}** with respect to **non-strange D-meson R_{AA}**
- **D_s^+ enhancement** qualitatively **reproduced by models including charm-quark coalescence in a strangeness rich environment**

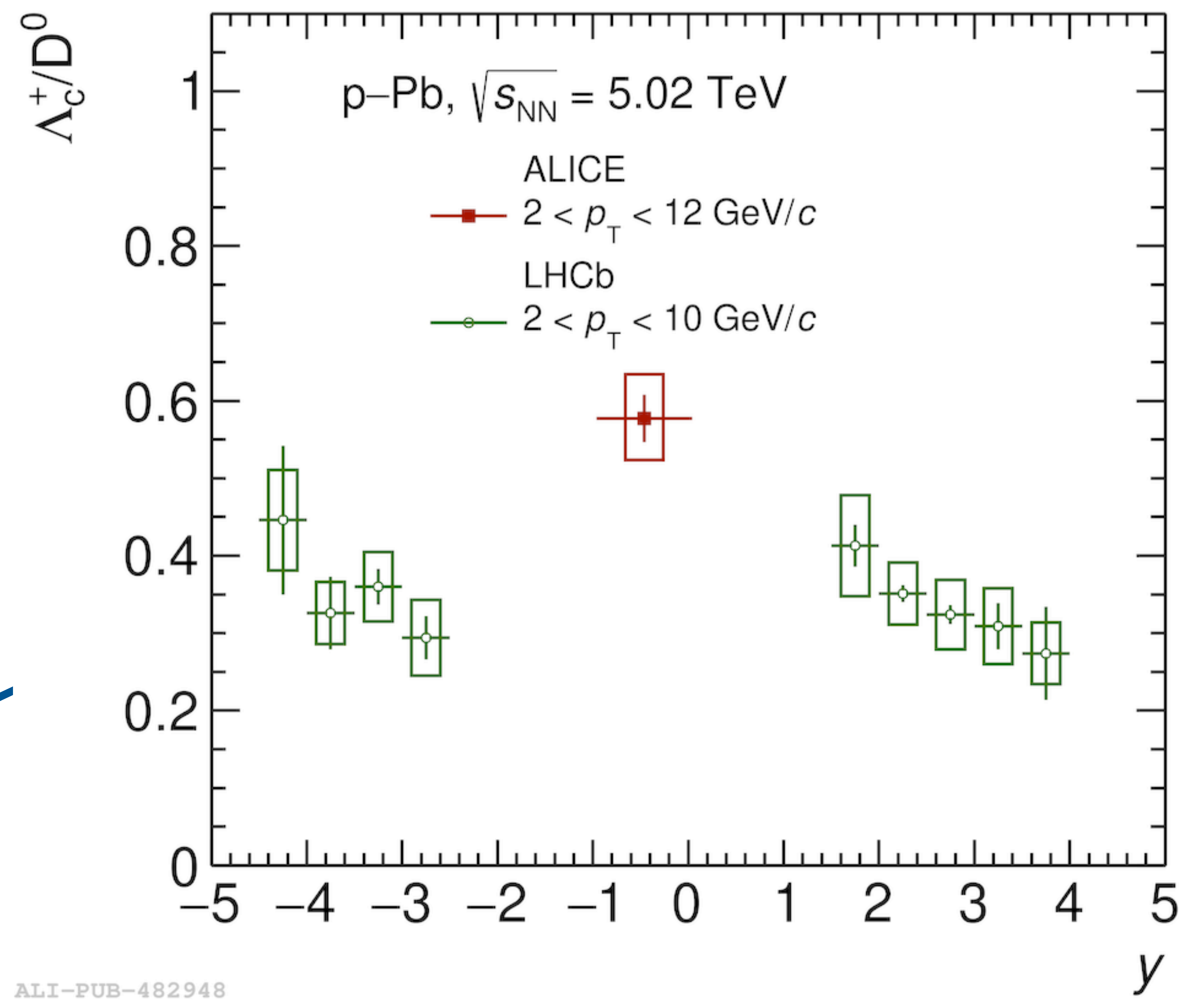
TAMU: PLB 735 (2014) 445-450
PHSD: PRC 92, 014910 (2015)
Catania: EPJC 78, 348 (2018)

- **Positive v_2** for **D_s^+** and **non-strange D mesons** reproduced by theoretical models based on charm-quark transport
- **Charm-quark coalescence** is an important ingredient of the models to **describe the measurement at intermediate p_T**

Λ_c^+/D^0 in p-Pb collisions

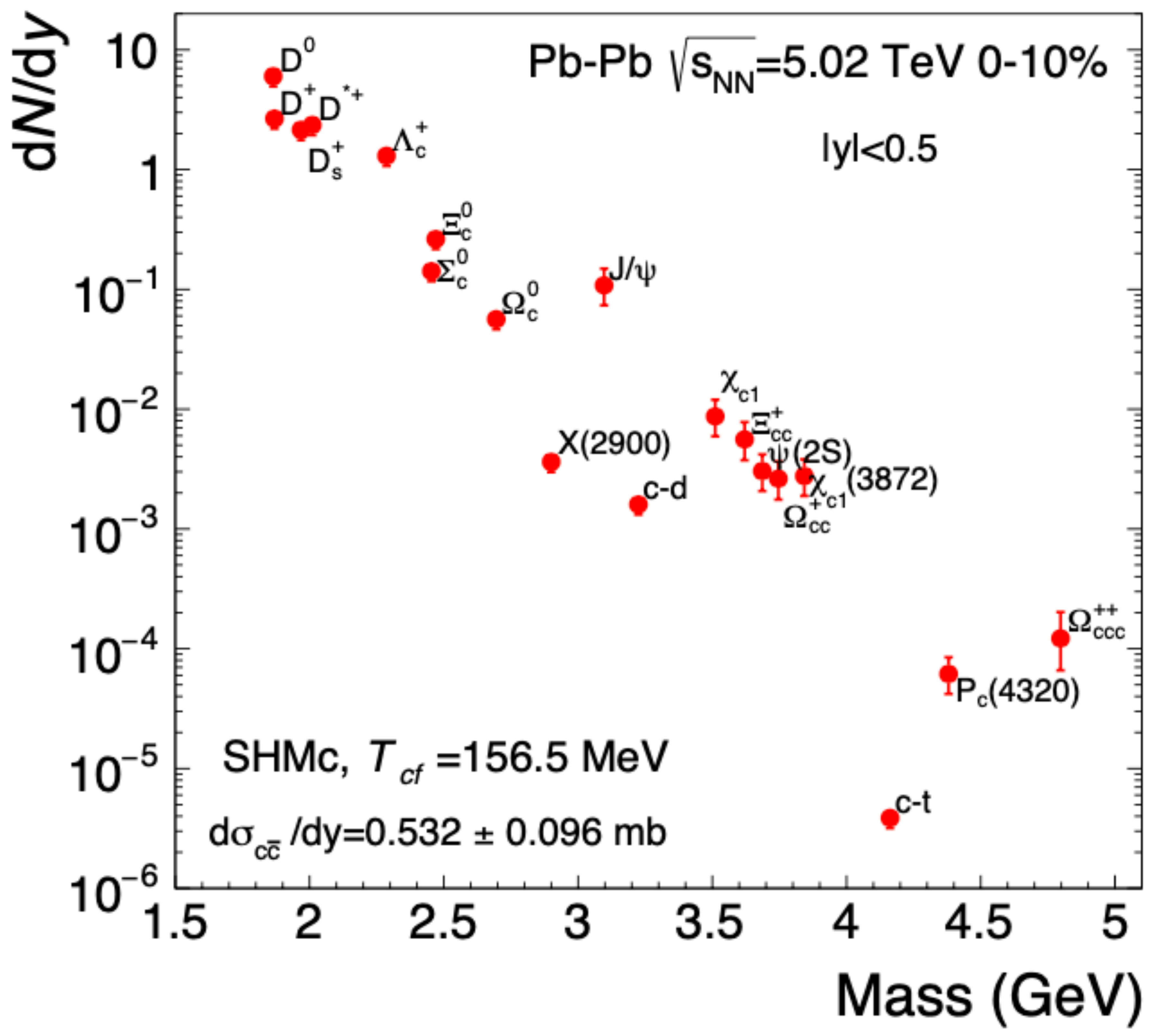
arXiv:2011.06078
arXiv:2011.06079





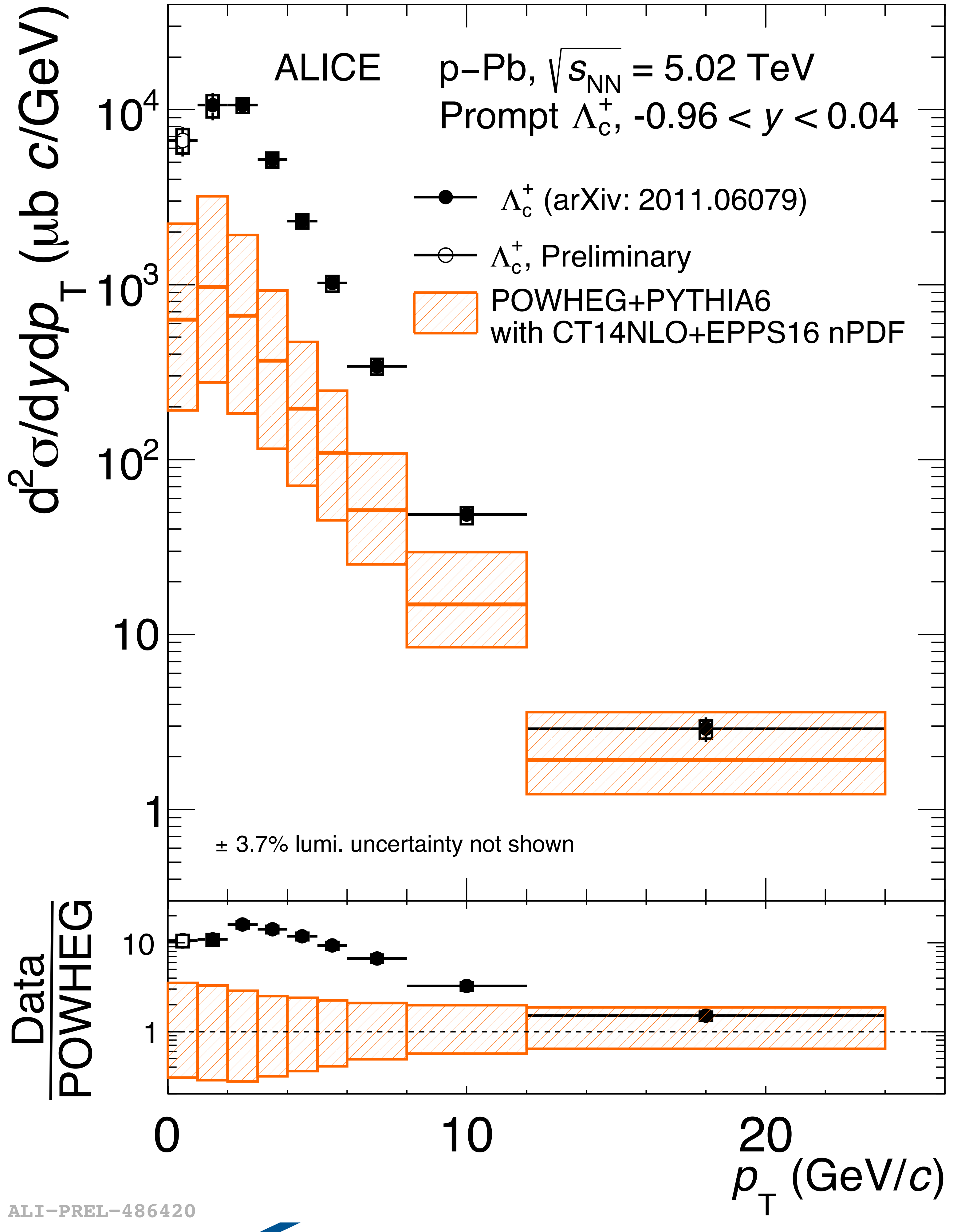
Measurement of multi-charm hadrons?

A. Andronic et al, arXiv:2104.12754

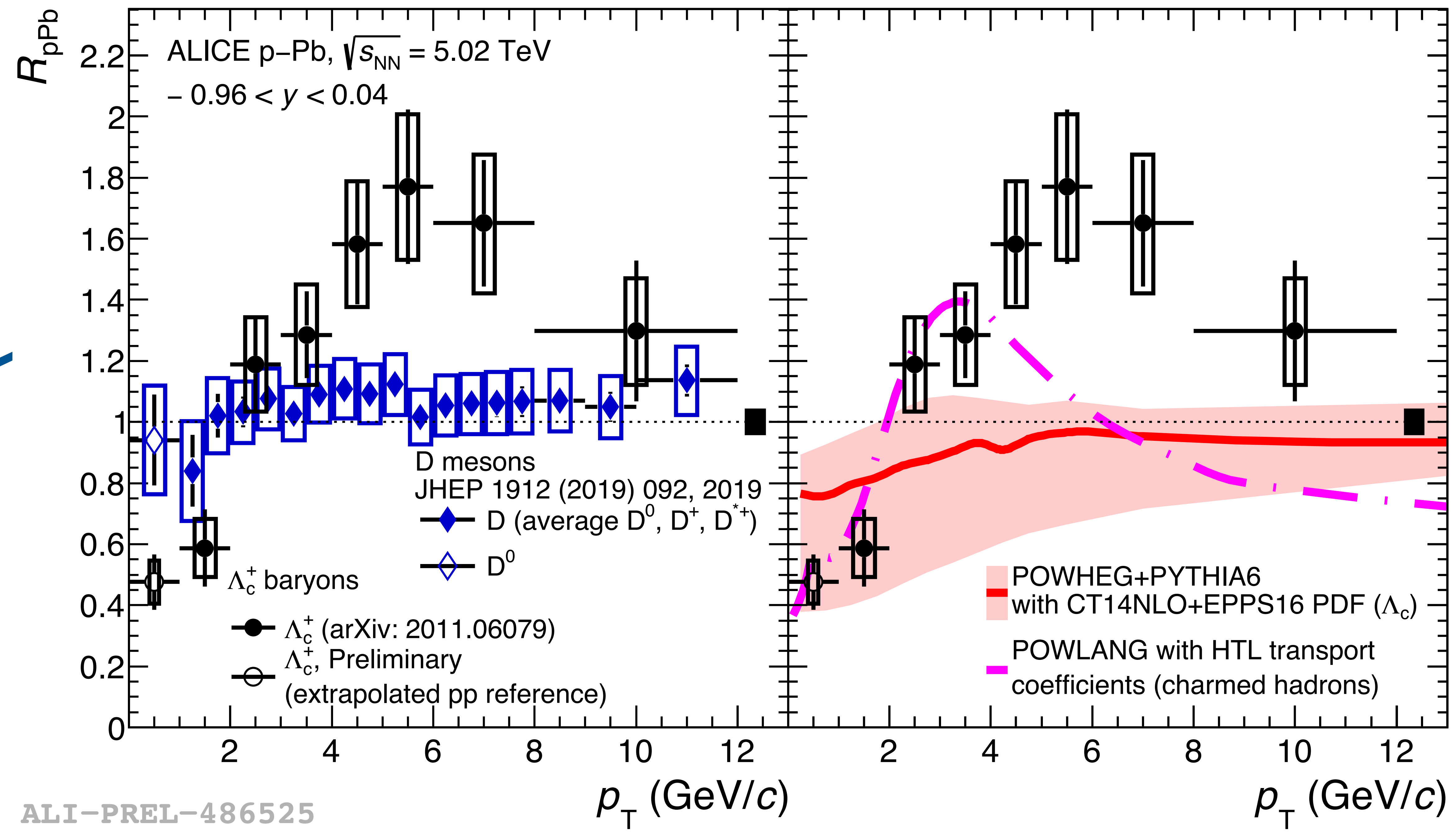


- **SHMc predicts very large enhancements for hadrons with 2 or 3 charm quarks** with respect to pure thermal production
- As a consequence of the enhancement, a *charm hadron hierarchy* appears

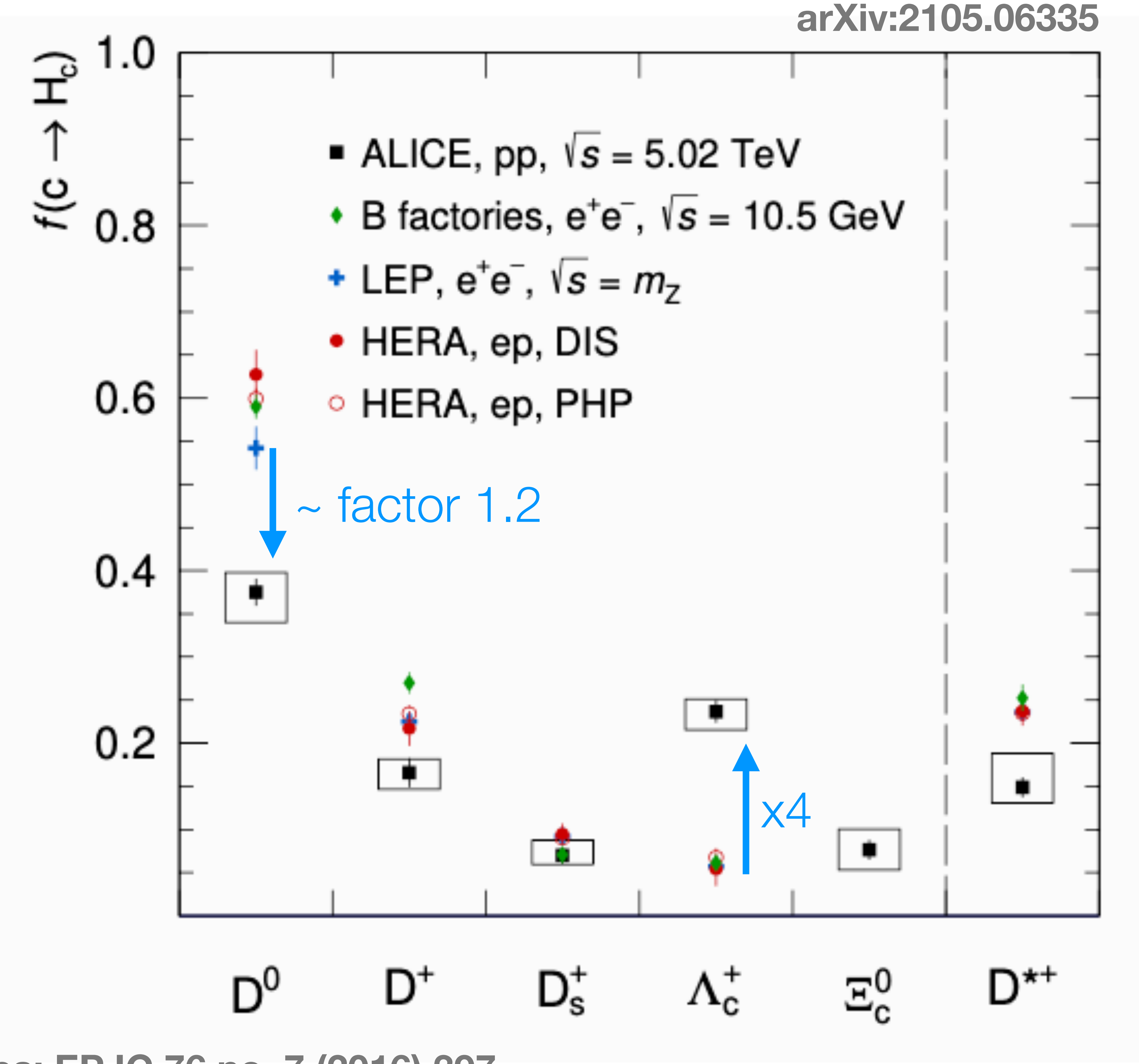
Λ_c^+/D^0 in p-Pb collisions



- Λ_c^+ R_{pPb} consistent with D meson R_{pPb}
- Consistent with unity for $p_T > 2$ GeV/c
- In $1 < p_T < 2$ GeV/c $R_{pPb} < 1$ with 4.1σ significance
- POWHEG+PYTHIA6 and POWLANG do not describe the data quantitatively



Charm fragmentation fractions in pp collisions

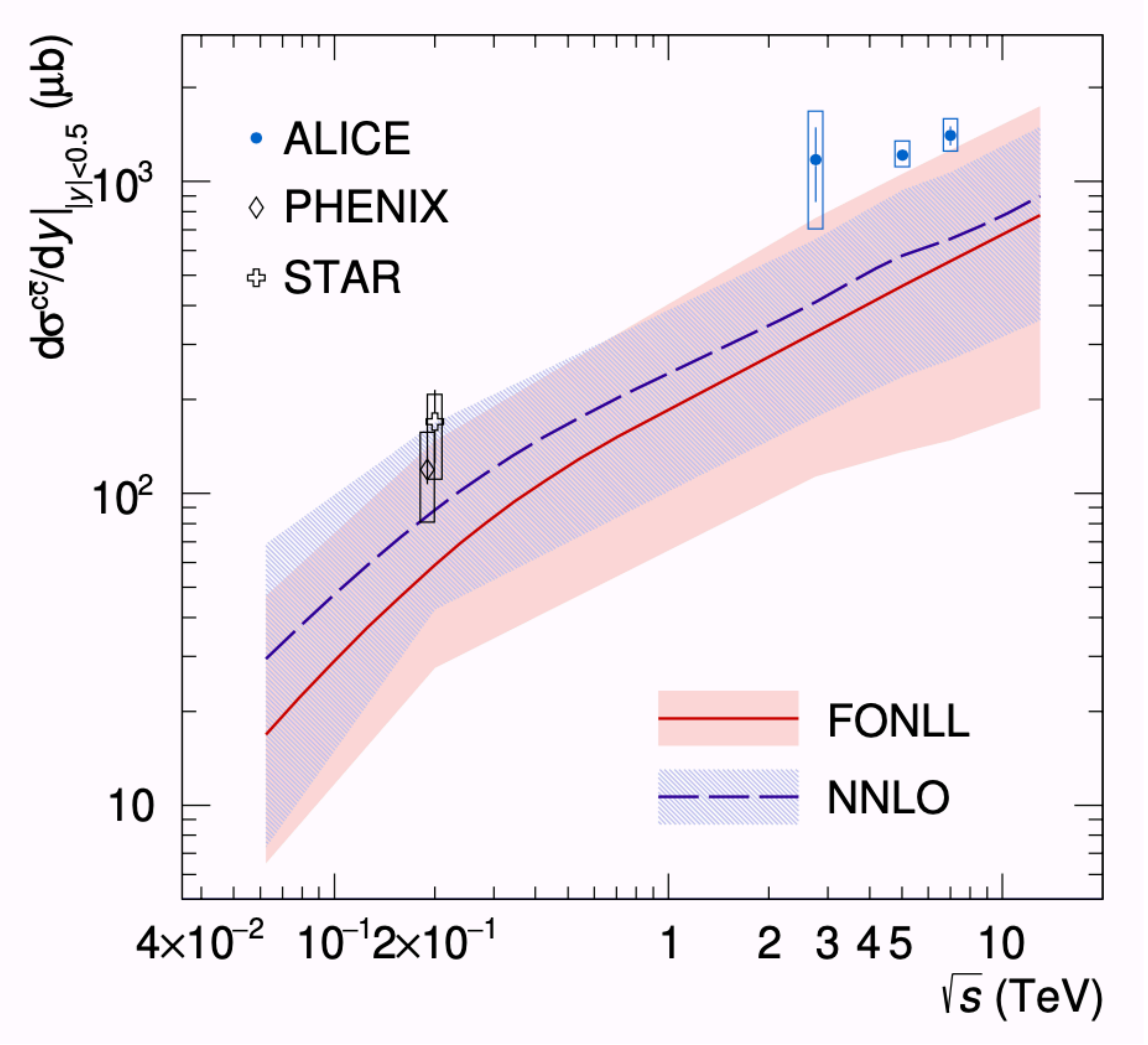


B factories: EPJC 76 no. 7 (2016) 397
LEP: EPJC 75 no. 1 (2015) 19
HERA: EPJC 76 no. 7 (2016) 397

Calculated as the ratio of the p_T-integrated cross section of each measured hadron specie by the sum of the cross sections of the different ground-states charm hadrons

H_c	$f(c \to H_c)[\%]$
D^0	$37.5 \pm 1.6(\text{stat})^{+2.3}_{-3.5}(\text{syst})$
D^+	$16.6 \pm 1.7(\text{stat})^{+1.5}_{-1.9}(\text{syst})$
D_s^+	$7.0 \pm 1.0(\text{stat})^{+1.8}_{-1.1}(\text{syst})$
Λ_c^+	$23.7 \pm 1.3(\text{stat})^{+1.4}_{-2.1}(\text{syst})$
Ξ_c^0	$7.6 \pm 1.2(\text{stat})^{+2.4}_{-2.3}(\text{syst})$
D^{*+}	$14.9 \pm 1.1(\text{stat})^{+3.9}_{-1.8}(\text{syst})$

f(c->H_c) different in pp and e^+e^- and ep collisions



- **Total cc cross section at $\sqrt{s}$=5.02 calculated with the new fragmentation fractions**
  - Updated values at $\sqrt{s}$=2.76 and 7 TeV are ~40% larger than previous measurements