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ON BEHALF OF ALICE

CHARMED BARYONS MEASUREMENTS FROM pp TO Pb-Pb

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GSI

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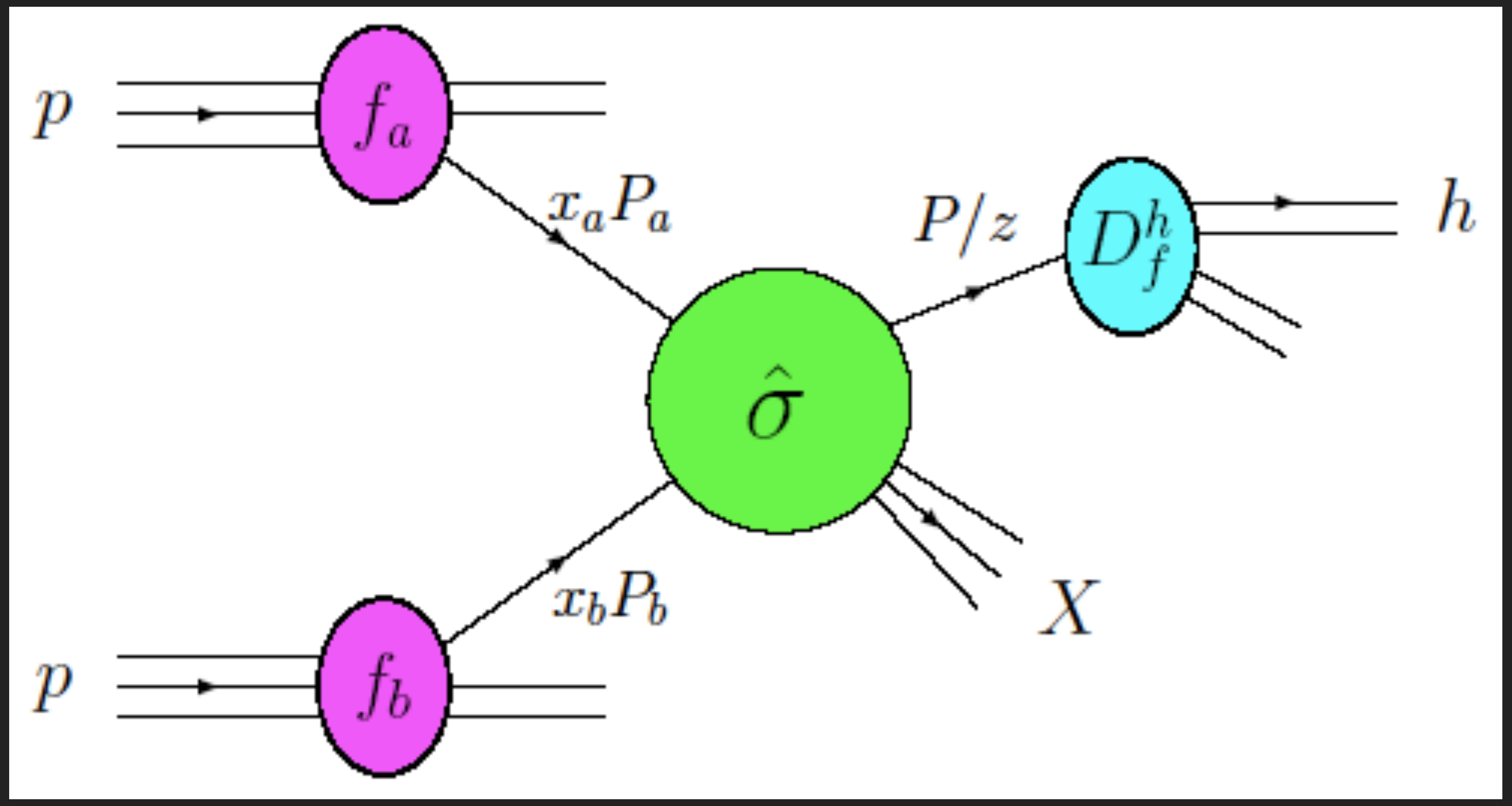
Motivation

- Charm & beauty meson production well described by factorisation theorem:

$$\frac{d\sigma^{D}}{dp_{T}^{D}}(p_T;\mu_F;\mu_R) = PDF(x_1,\mu_F)PDF(x_2,\mu_F) \otimes \frac{d\sigma^{c}}{dp_{T}^{c}}(x_1,x_2,\mu_R,\mu_F) \otimes D_{c\to D}(z=p_D/p_c,\mu_F)$$

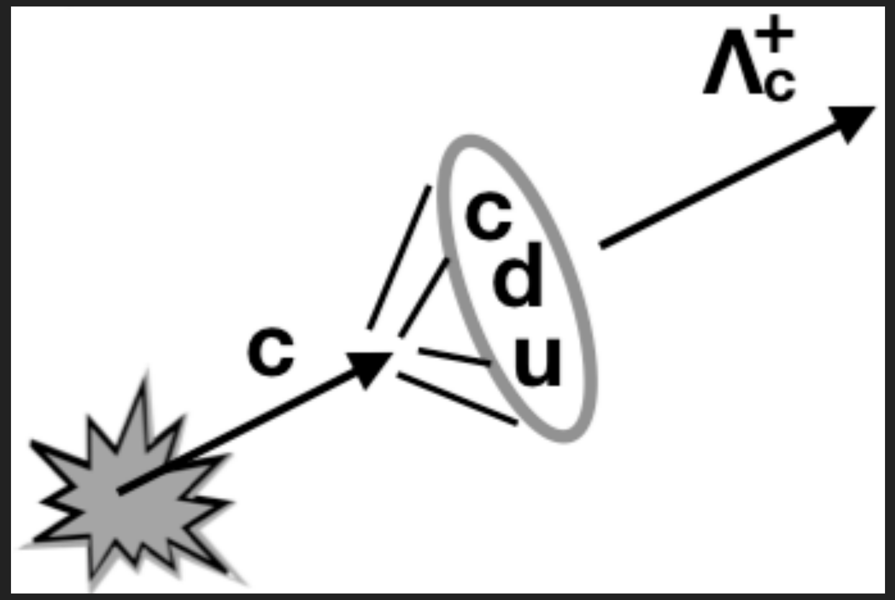
initial state parton distribution function | pQCD partonic cross section | hadronization by fragmentation



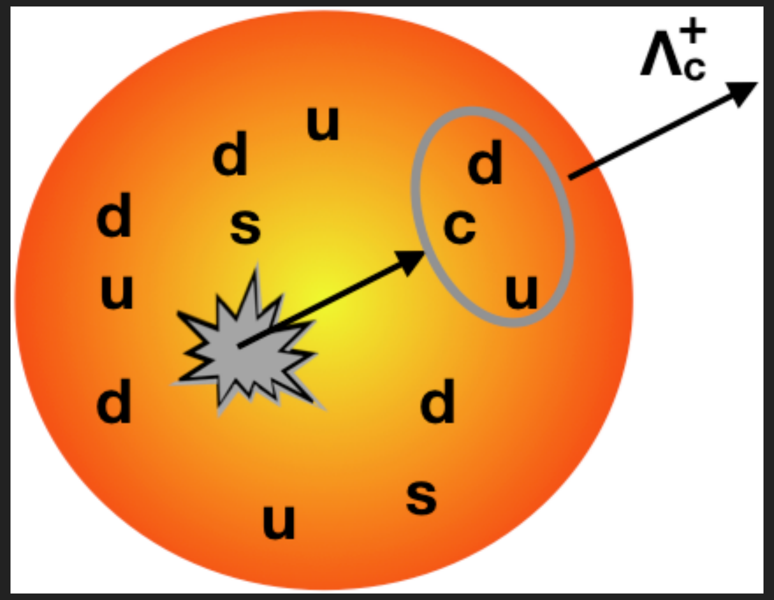
- Charm baryon-to-meson ratio sensitive to hadronization mechanism

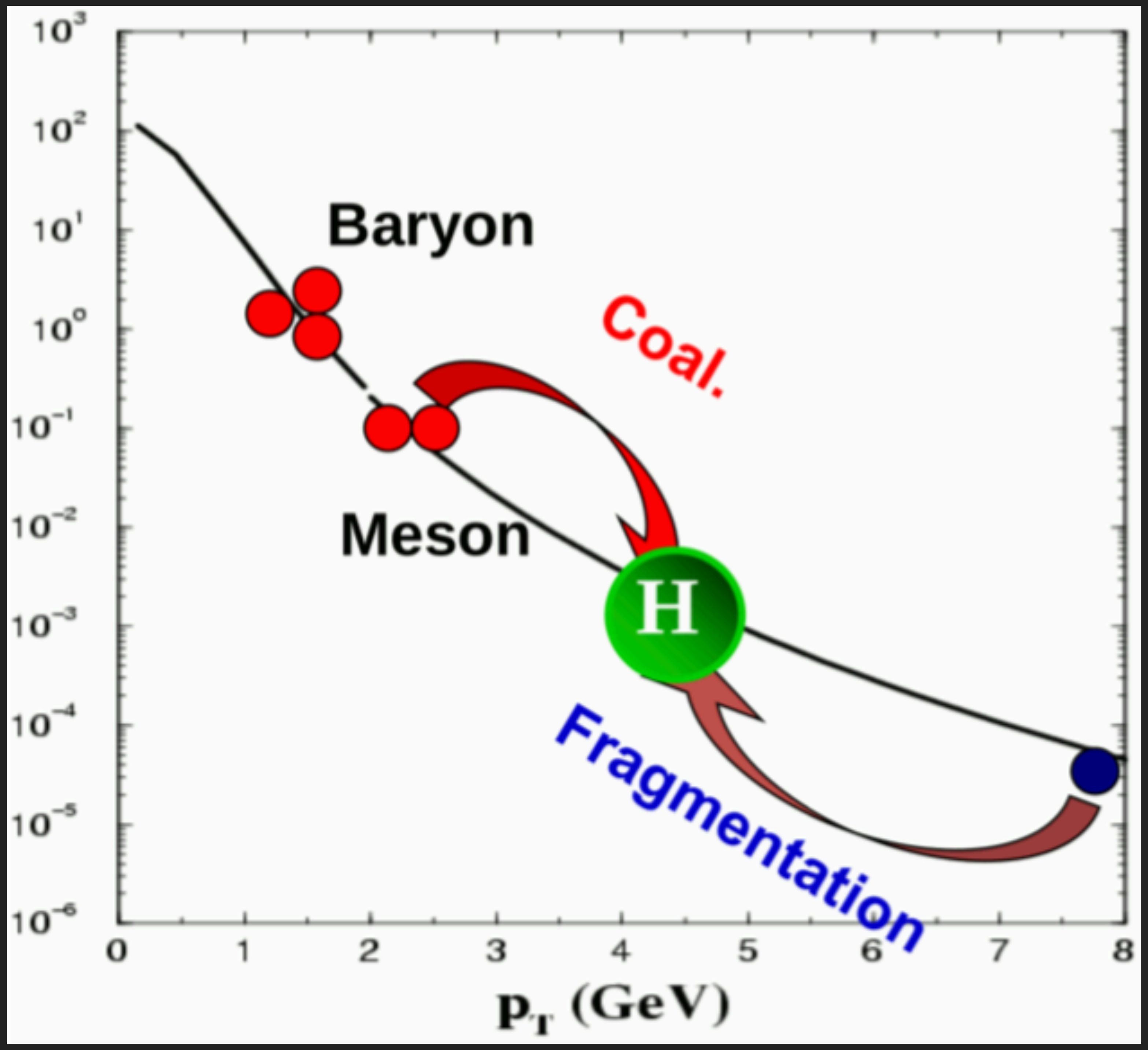
- Role of charm measurements in all collision systems
  - pp: test of perturbative QCD calculations
  - p-Pb : cold nuclear matter effects
  - Pb-Pb: modification of hadronization mechanism in the medium

Fragmentation:



Coalescence:





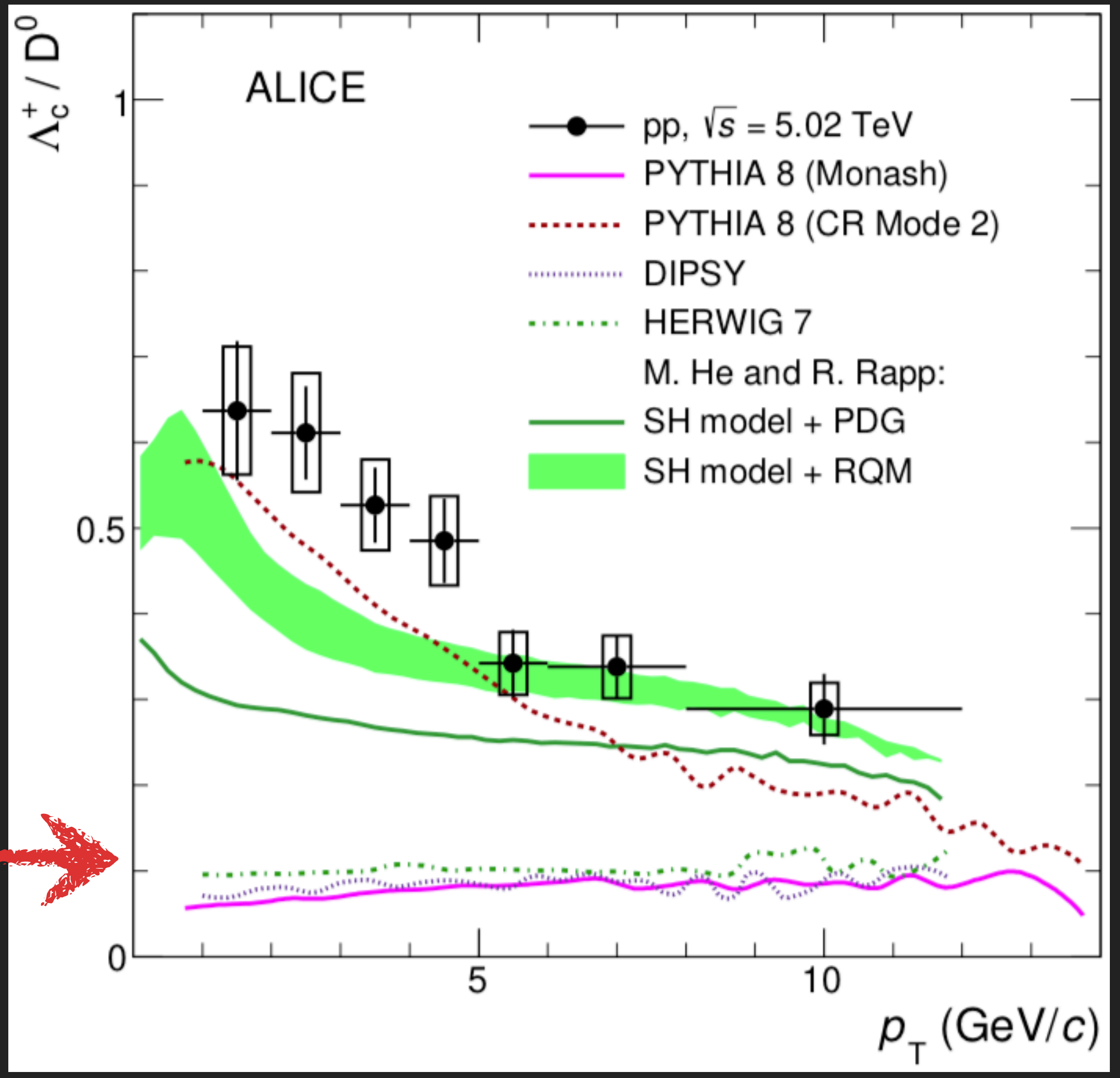
Motivation

- Λ_c^+/D^0 enhanced in pp w.r.t. e+e-
  - Fragmentation not universal?
  - Colour reconnection?
  - Unobserved charm-baryon states?

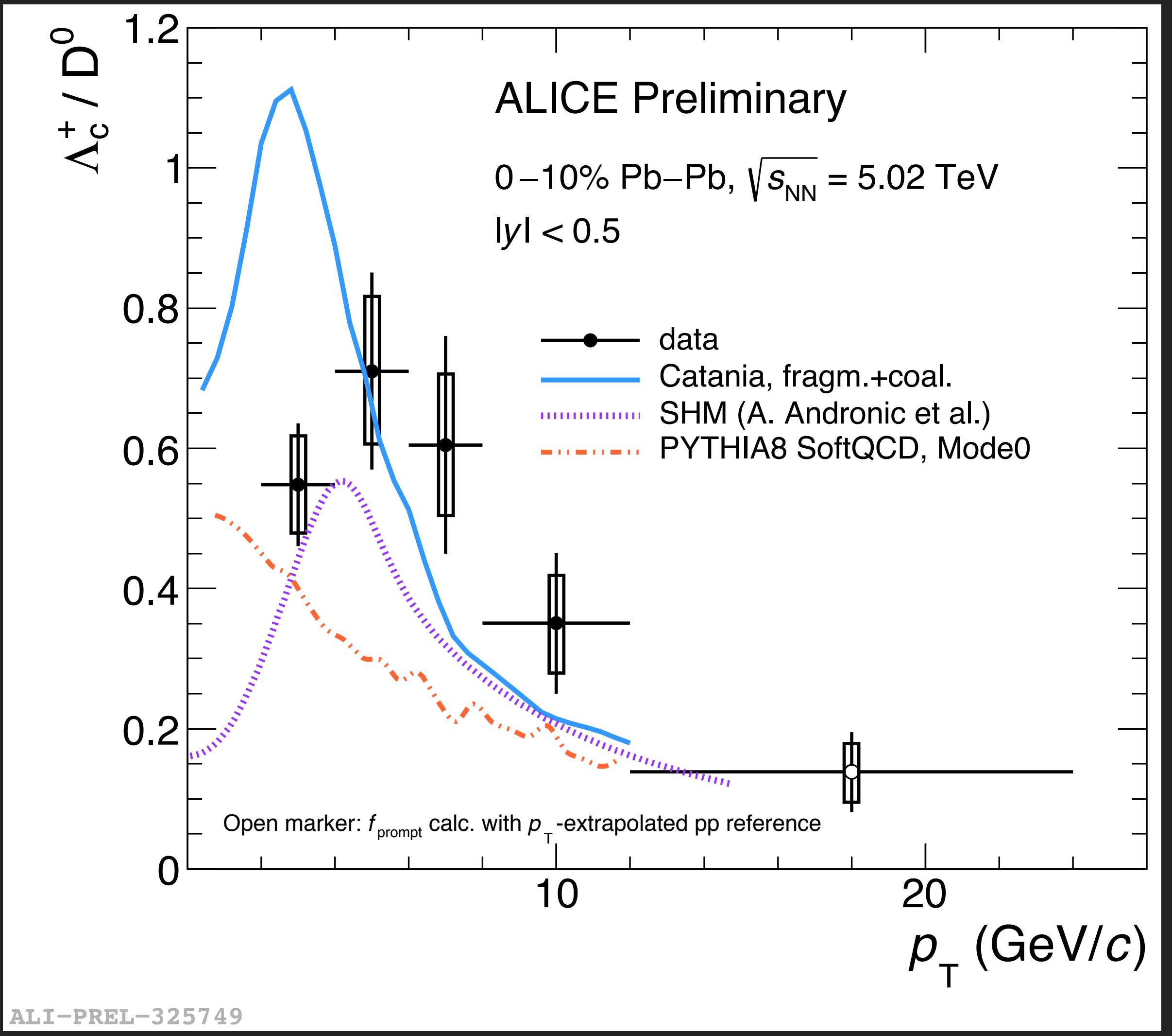
	$\Lambda_c^+/D^0 \pm$ stat. $\pm$ syst.	System	$\sqrt{s}$ (GeV)
CLEO [43]	$0.119 \pm 0.021 \pm 0.019$	ee	10.55
ARGUS [42,98]	0.127 ± 0.031	ee	10.55
LEP average [80]	$0.113 \pm 0.013 \pm 0.006$	ee	91.2
ZEUS DIS [51]	$0.124 \pm 0.034^{+0.025}_{-0.022}$	ep	320
ZEUS γp, HERA I [49]	$0.220 \pm 0.035^{+0.027}_{-0.037}$	ep	320
ZEUS γp, HERA II [50]	$0.107 \pm 0.018^{+0.009}_{-0.014}$	ep	320

[JHEP 1804 (2018) 108]

e+e-



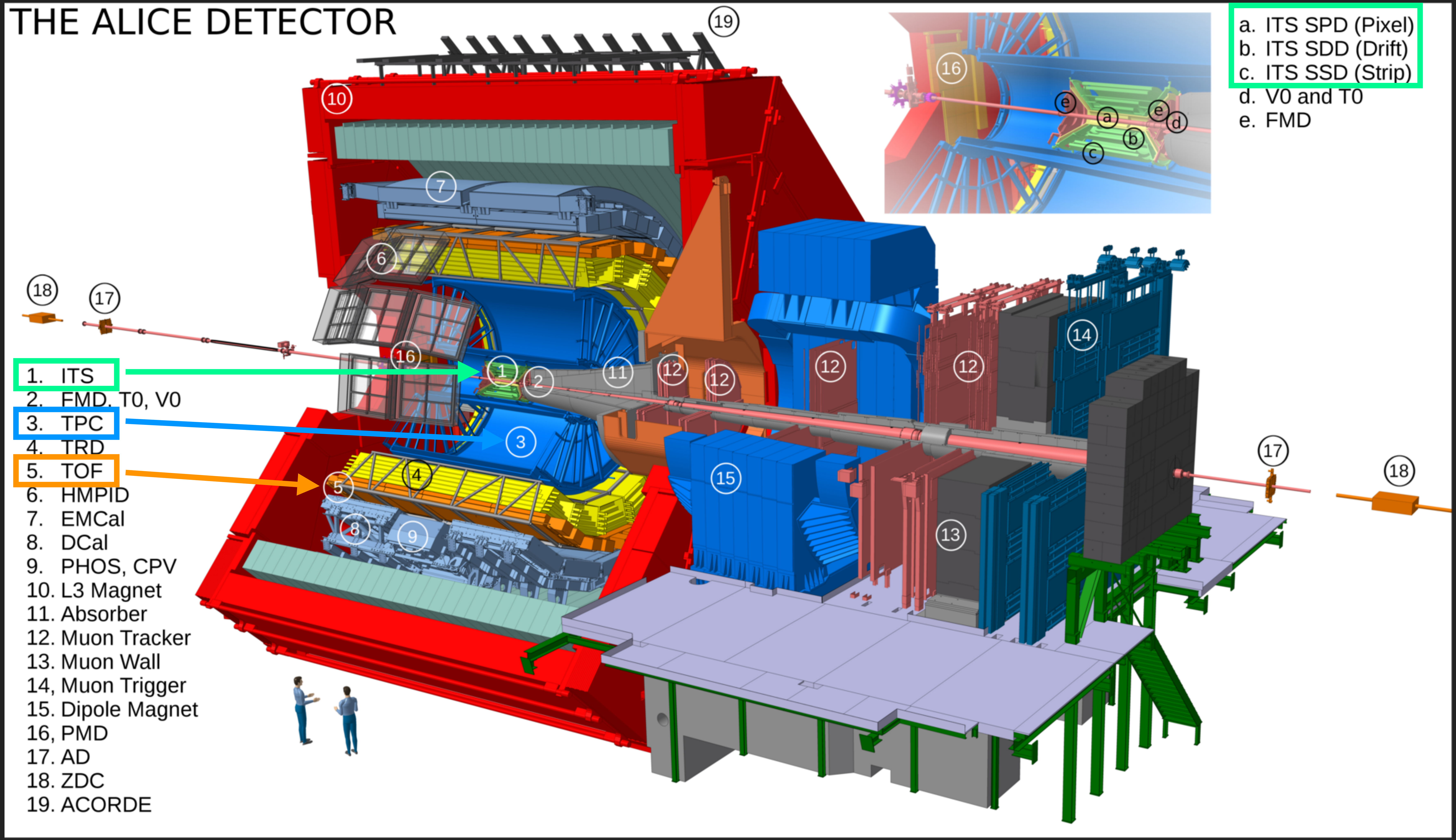
- Λ_c^+/D^0 enhanced in Pb-Pb w.r.t. pp and p-Pb
  - Models including coalescence and fragmentation describe the enhancement in Pb-Pb
  - Radial-flow push in Pb-Pb?



- Heavier charmed-baryon measurement (Σ_c, Ξ_c, Ω_c)
  - Further possible enhancement due to strange component
  - Needed for total charm cross section
  - Ξ_c: see Tiantian's talk (Heavy Flavor/Heavy Ion, 17:32 Nov. 6)
  - Ω_c: under investigation, will be ready next year

ALICE detector

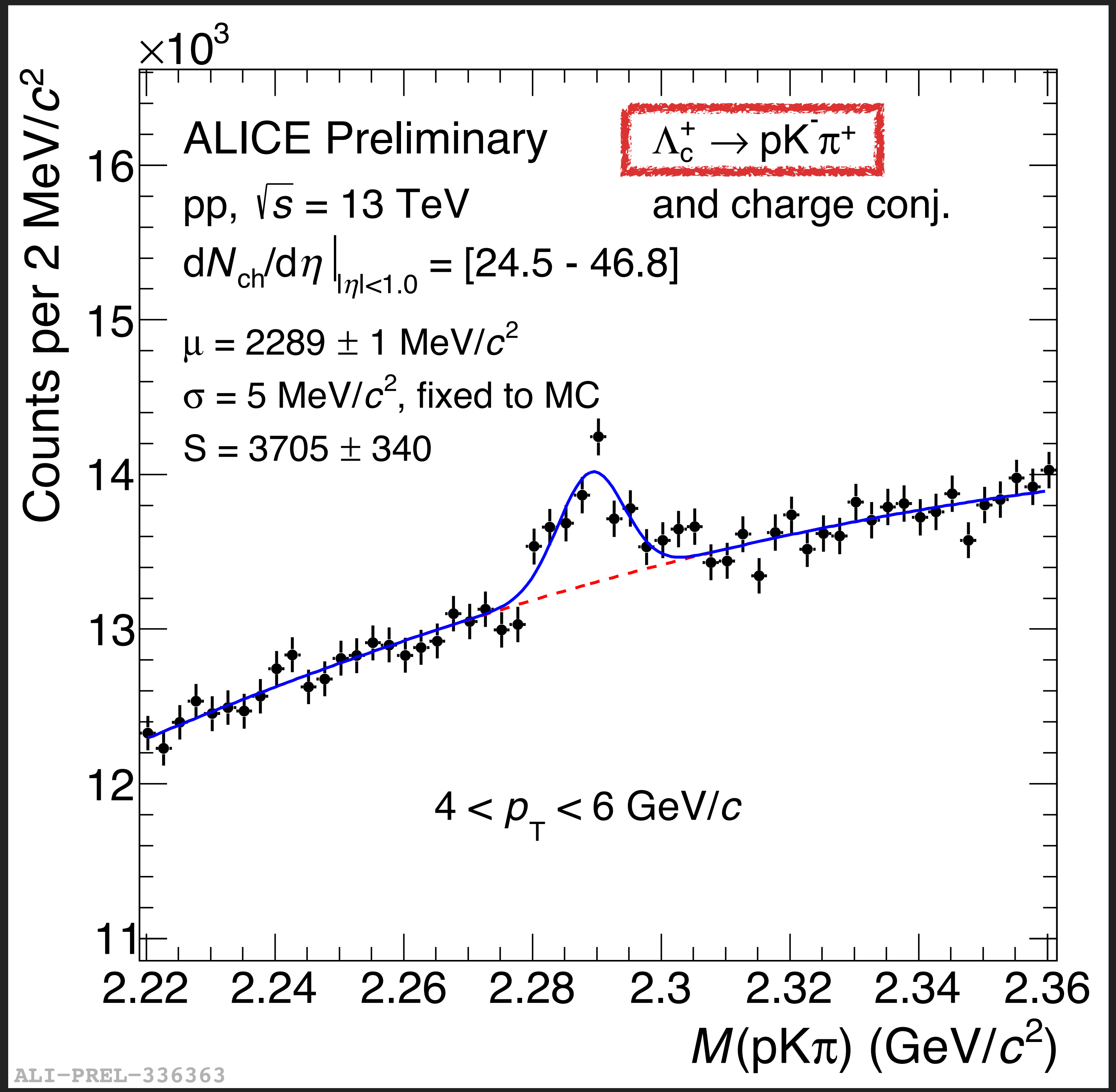
- Inner Tracking System (ITS)
  - $|\eta| < 0.9$
  - Tracking, vertex, particle identification (PID), multiplicity
- Time Projection Chamber (TPC)
  - $|\eta| < 0.9$
  - Tracking, PID
- Time-Of-Flight (TOF)
  - $|\eta| < 0.9$
  - Tracking, PID

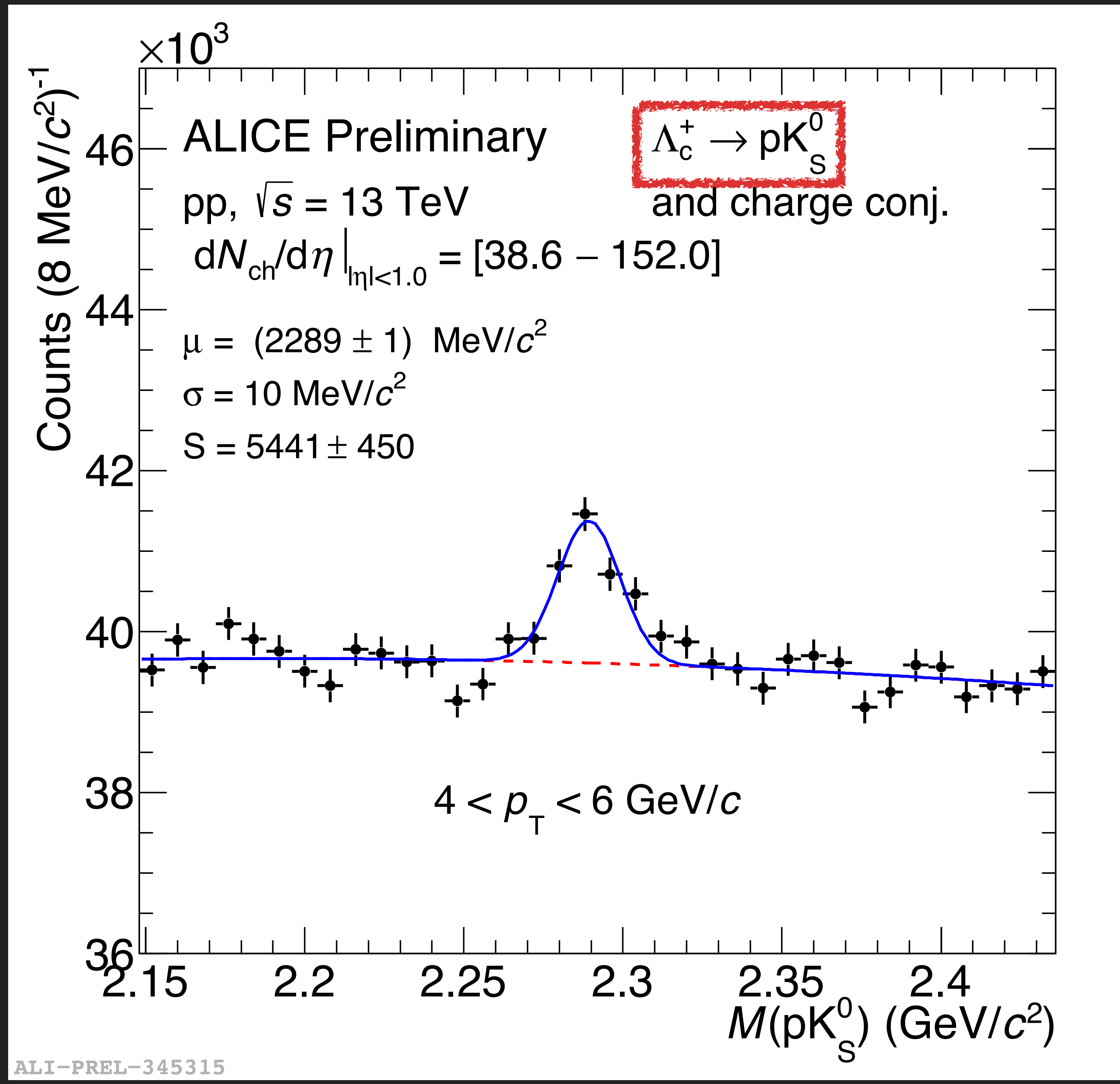


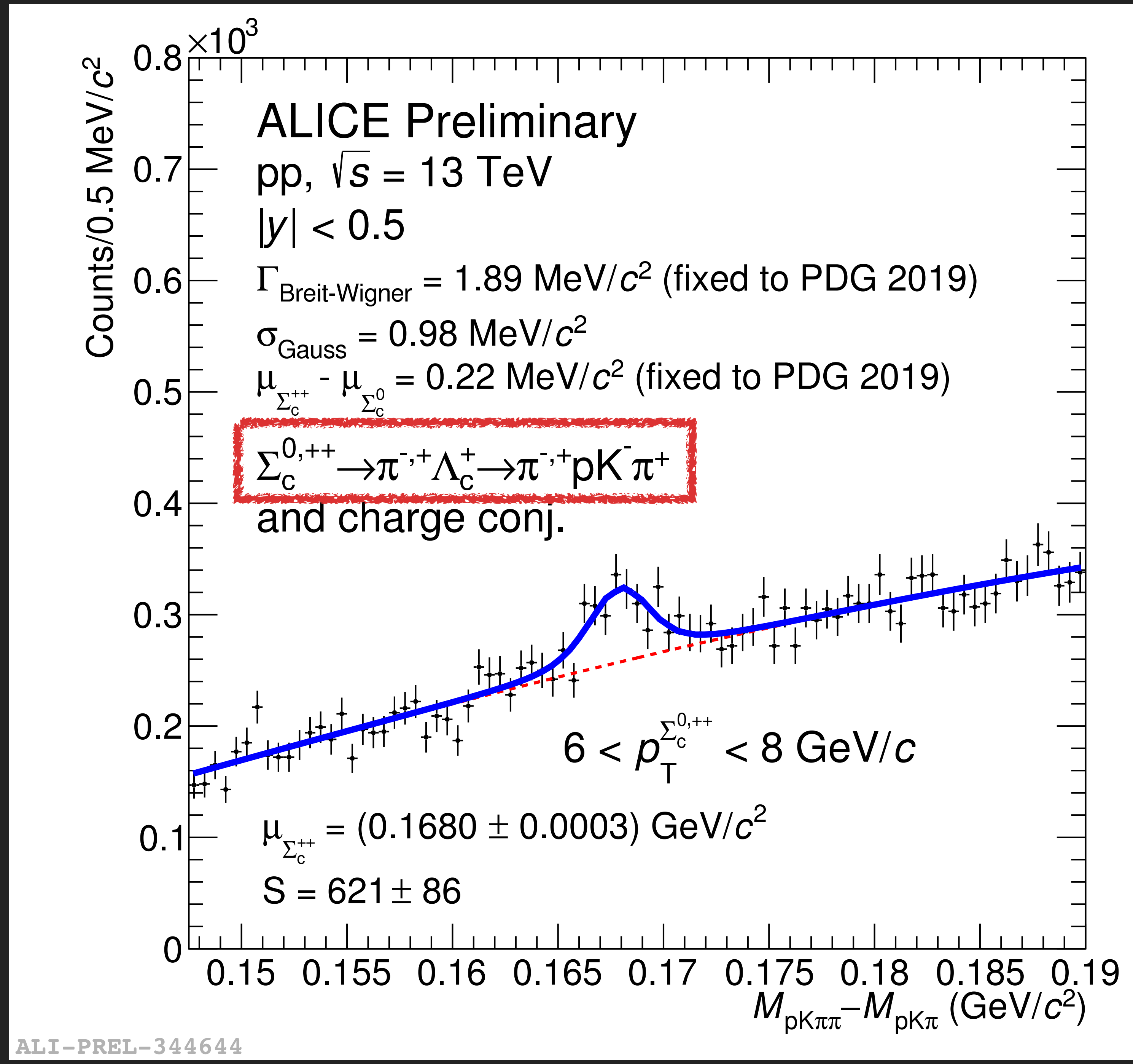
Charm-baryon analysis

- Hadronic decays:
  - $\Lambda_c^+ : \Lambda_c^+ \rightarrow pK^-\pi^+, \Lambda_c^+ \rightarrow pK_s^0$
  - $\Sigma_c^{0,++} : \Sigma_c^0 \rightarrow \Lambda_c^+\pi^-, \Sigma_c^{++} \rightarrow \Lambda_c^+\pi^+$

- PID and topological selections
- Signal extraction via invariant mass analysis
- Acceptance x efficiency correction
- B feed-down subtraction

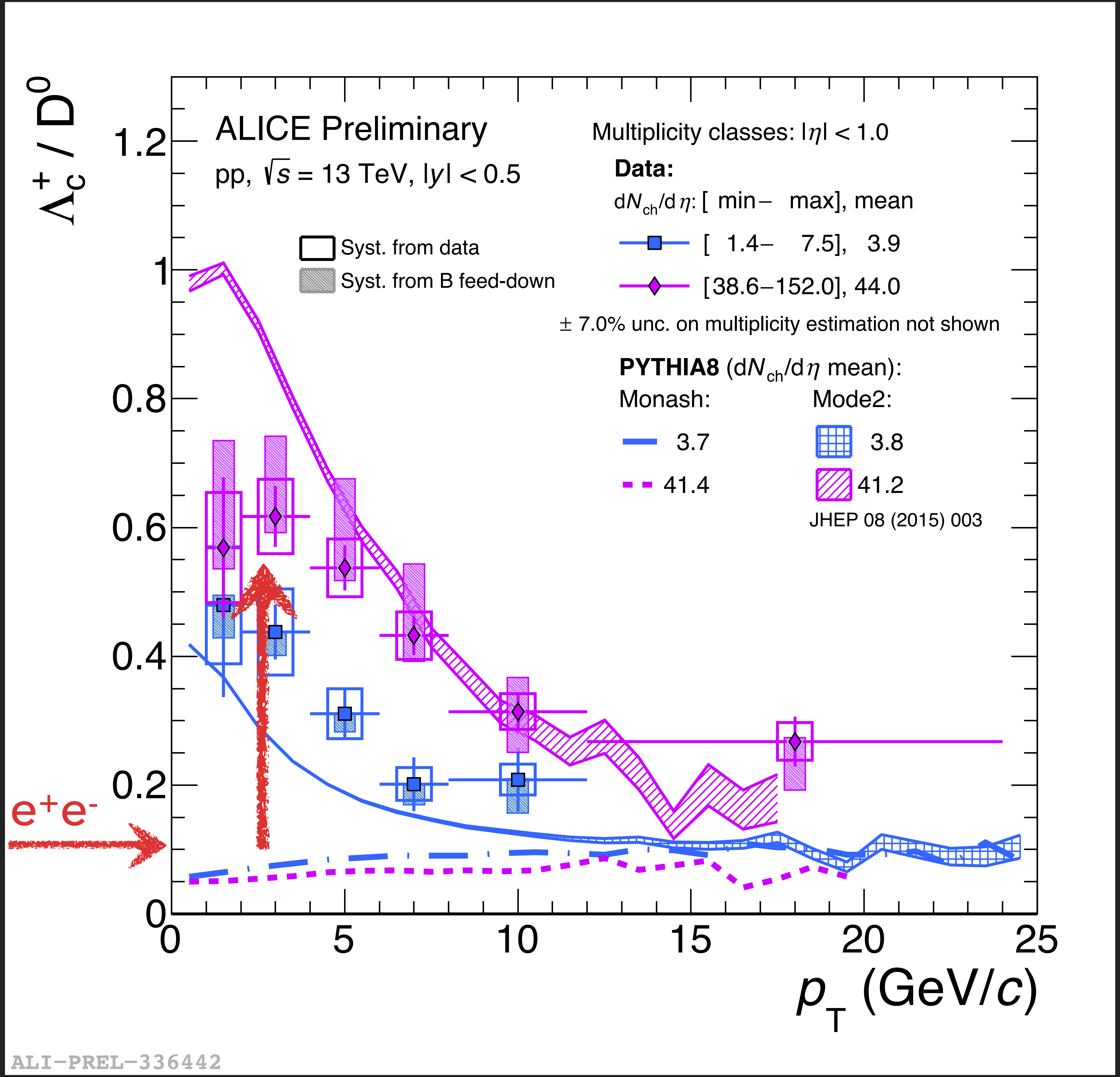






pp collision

Λ_c^+/D^0 in pp collision with different multiplicity at 13 TeV



- Λ_c^+/D^0 largely enhanced in pp w.r.t. e^+e^-
- Significant enhancement with increasing multiplicity in pp collision
- PYTHIA8:
  - Monash (tuned on e^+e^-) NOT reproduce enhancement and multiplicity dependence
  - CR with string formation beyond leading colour approximation describes multiplicity dependence
    - Reconnections among junctions
    - Multi-parton interactions

PYTHIA8
[Comput. Phys. Commun. 178 (2008) 852]
PYTHIA8 Monash
[Eur. Phys. J. C 74 (2014) 3024]
PYTHIA8 (Mode2)
[JHEP 08 (2015) 003]

$\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/D^0$ in pp collision at 13 TeV

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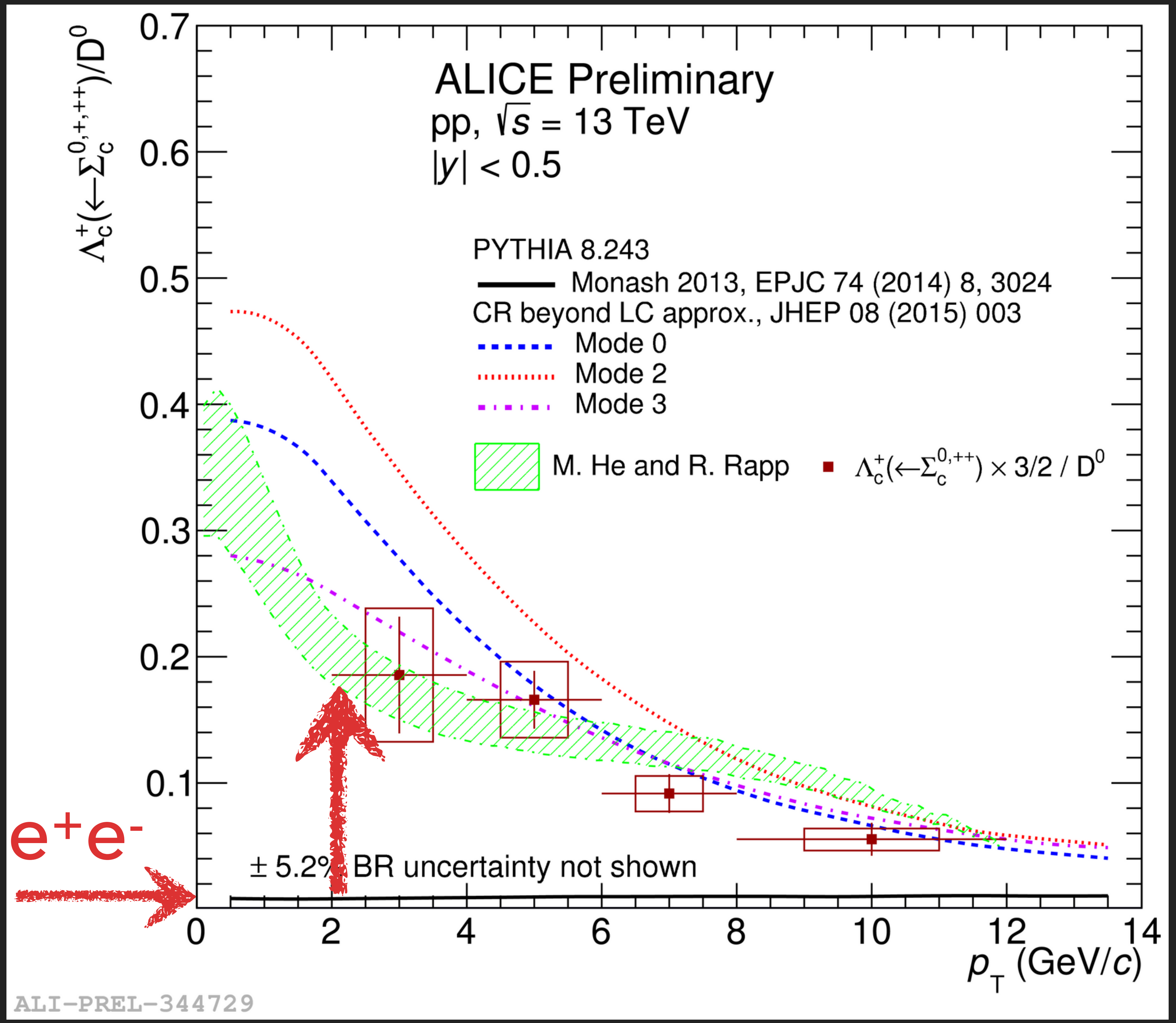
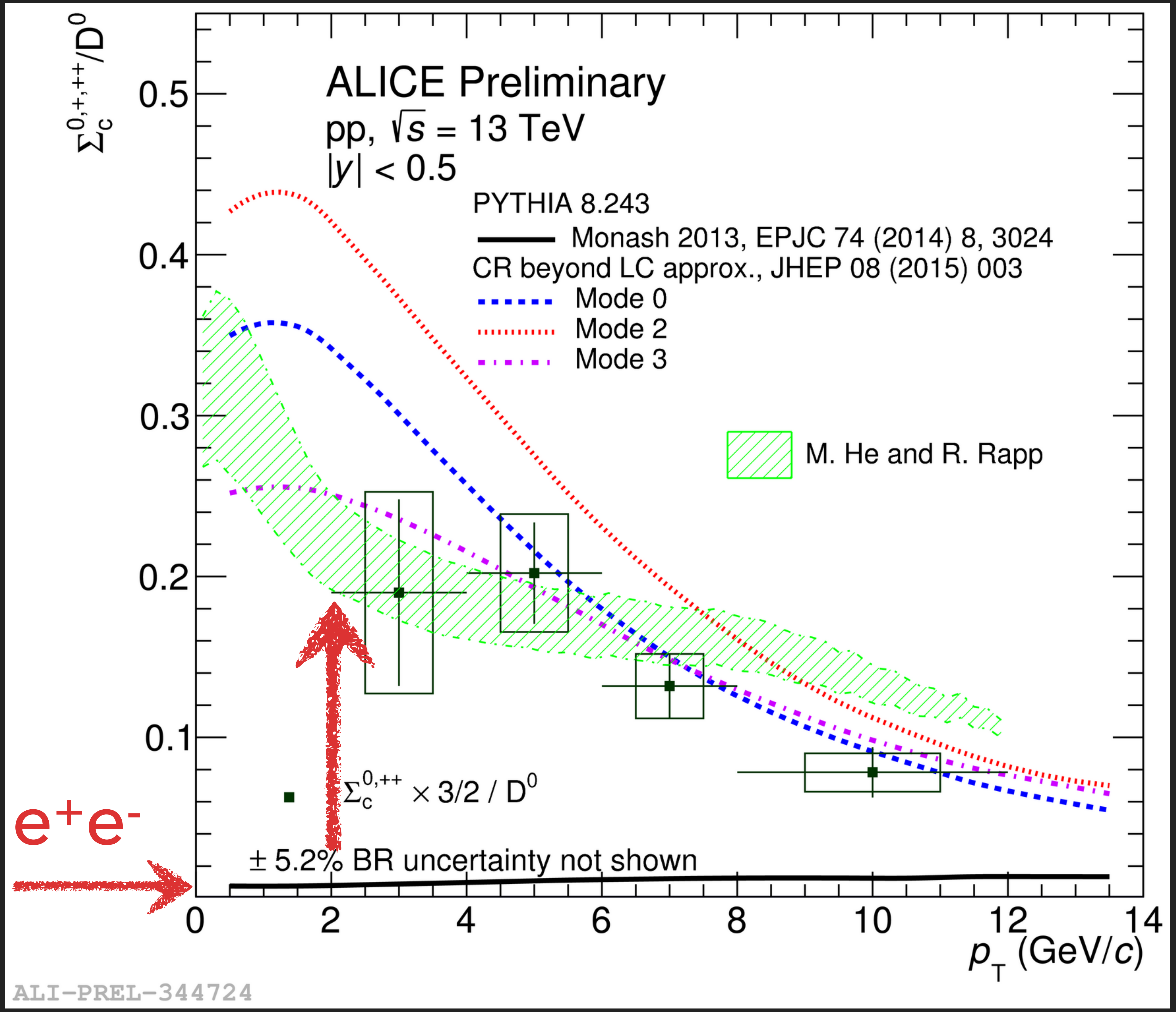
- Largely underestimated by PYTHIA8 default tune (Monash)
- PYTHIA8 with CR & M. He and R. Rapp describe data
  - PYTHIA8 with junction, both Λ_c^+ and $\Sigma_c^{0,+,++}$ yields increased a lot
  - SHM with increased set of charm-baryon states
    - SHM not affected by internal structure of particle or by hadronization mechanisms, but just take into account their masses
- $\Lambda_c^+(\leftarrow \Sigma_c^{0,+,++})/D^0$ has similar p_T-dependency as Λ_c^+/D^0
  - Λ_c^+/D^0 enhancement in pp collision can be only partially explained by $\Sigma_c^{0,+,++}$ feed-down



M. He and R. Rapp
[PLB 795 (2019) 117-121]

$\Sigma_c^{0,+,++}/D^0$ in pp collision at 13 TeV



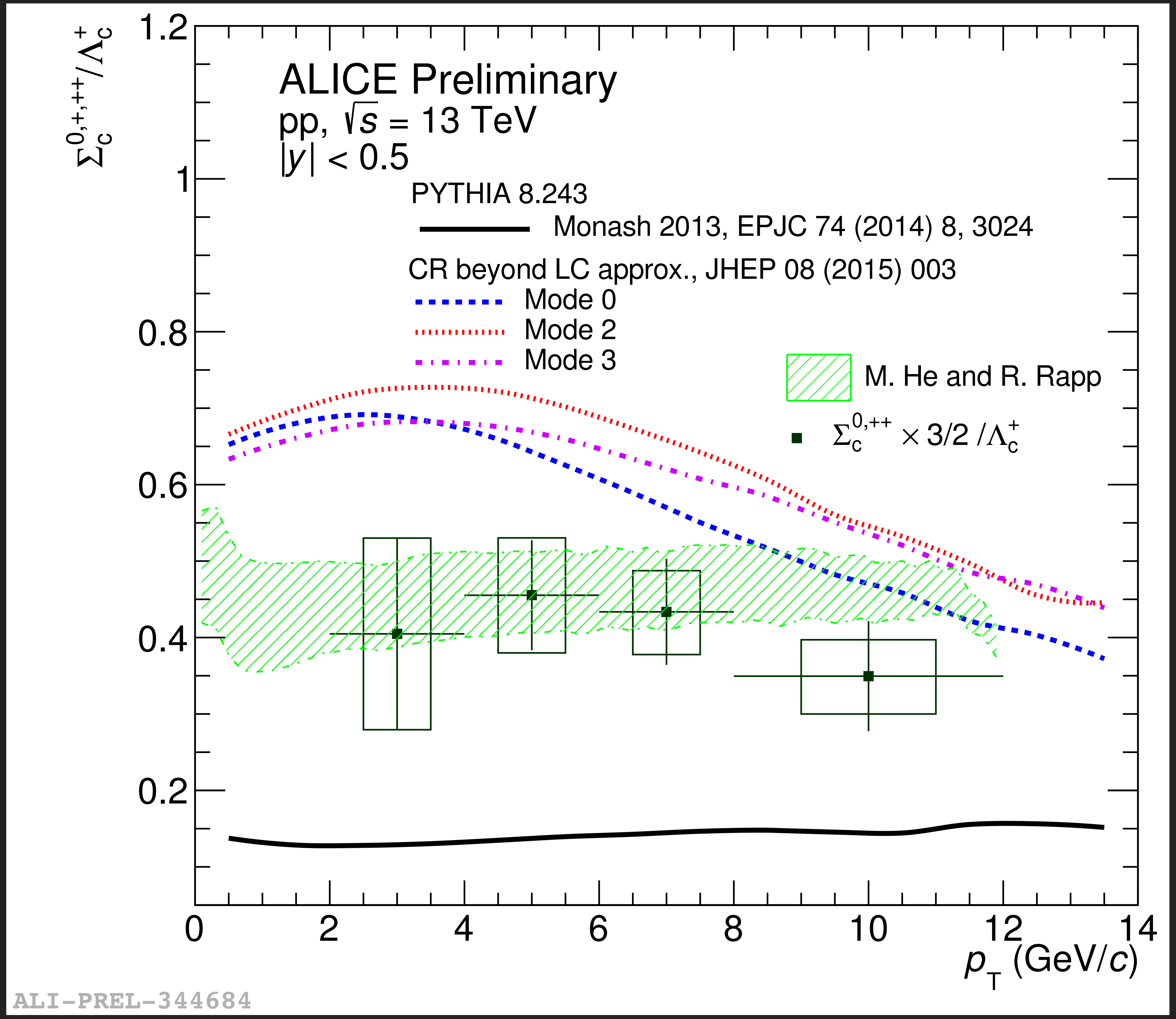
M. He and R. Rapp
[PLB 795 (2019) 117-121]

Particle	New CR model (N_{par}/N_{events}) string	junction	all	Old CR model N_{par}/N_{events} (all)
D^+	$5.3 \cdot 10^{-2}$	0	$5.3 \cdot 10^{-2}$	$6.5 \cdot 10^{-2}$
Λ_c^+	$4.0 \cdot 10^{-3}$	$7.9 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	$6.6 \cdot 10^{-3}$
Σ_c^{++}	$2.7 \cdot 10^{-4}$	$1.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$5.4 \cdot 10^{-4}$
Σ_c^{+}	$2.5 \cdot 10^{-4}$	$1.5 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$5.2 \cdot 10^{-4}$
Σ_c^{0}	$2.5 \cdot 10^{-4}$	$1.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$5.1 \cdot 10^{-4}$

- Largely underestimated by PYTHIA8 default tune (Monash)
  - Production of Σ_c via a combination of c with spin-1 diquark formed in string fragmentation process
  - Suppression due to high spin-1 diquark mass
- PYTHIA8 with CR & M. He and R. Rapp describe data
  - PYTHIA8 with junction, Σ_c formed directly and yield increased a lot
    - about same ud and uu(dd) production (up to combinatorics factors)
  - SHM with RQM expected more Σ_c states
  - Similar Σ_c yield predicted by CR and SHM with RQM

$\Sigma_c^{0,+,++}/\Lambda_c^+$ in pp collision at 13 TeV

- Underestimated by PYTHIA8 Monash and overestimated by PYTHIA8 with CR
- Described by M. He and R. Rapp with augmented set of charm-baryon states



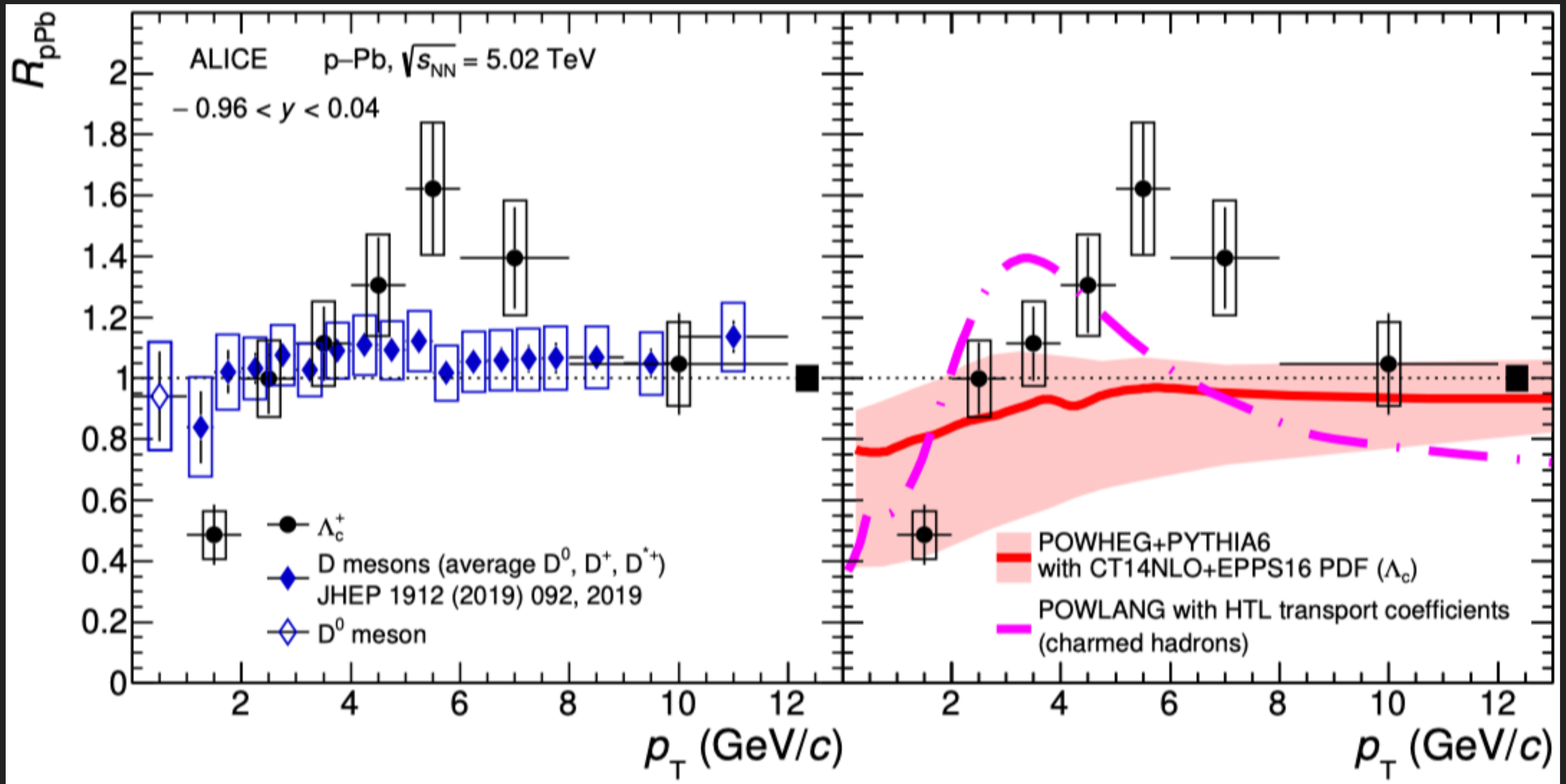
M. He and R. Rapp [PLB 795 (2019) 117-121]

Model	Λ_c / D^0	Σ_c
PYTHIA8 Monash	underestimate	underestimate
PYTHIA8 CR	describe	describe Σ_c/D^0 overestimate Σ_c/Λ_c
M. He and R. Rapp	describe	describe

p-Pb collisions

$R_{\mathrm{pPb}}(\Lambda_c^+)$ in p-Pb collisions at 5.02 TeV

- Compatible with unity except $1 < p_{\mathrm{T}} < 2\ \mathrm{GeV}/c$ $\rightarrow$ Suppression in low p_{T}
- Consistent with $R_{\mathrm{pPb}}(\mathrm{D})$ within uncertainties
- Models cannot quantitatively reproduce data
  - POWHEG+PYTHIA6 with CT14NLO+EPPS16 PDF
    - POWHEG event generator with PYTHIA6 parton shower and EPPS16 parameterisation of the nuclear modification of the PDFs
    - The uncertainty band includes the uncertainties on the nuclear PDFs and on the choice of the pQCD scales
  - POWLANG with HTL transport coefficients
    - Assume that a hot deconfined medium is formed in p-Pb collisions
    - Not implement specific differences in hadronisation mechanisms for baryons and mesons



POWHEG
[JHEP 09 (2007) 126]
EPPS16
[EPJC 77 no. 3, (2017) 163]
POWLANG
[JHEP 02 (2019) 102]

Λ_c^+/D^0 in p-Pb collisions at 5.02 TeV

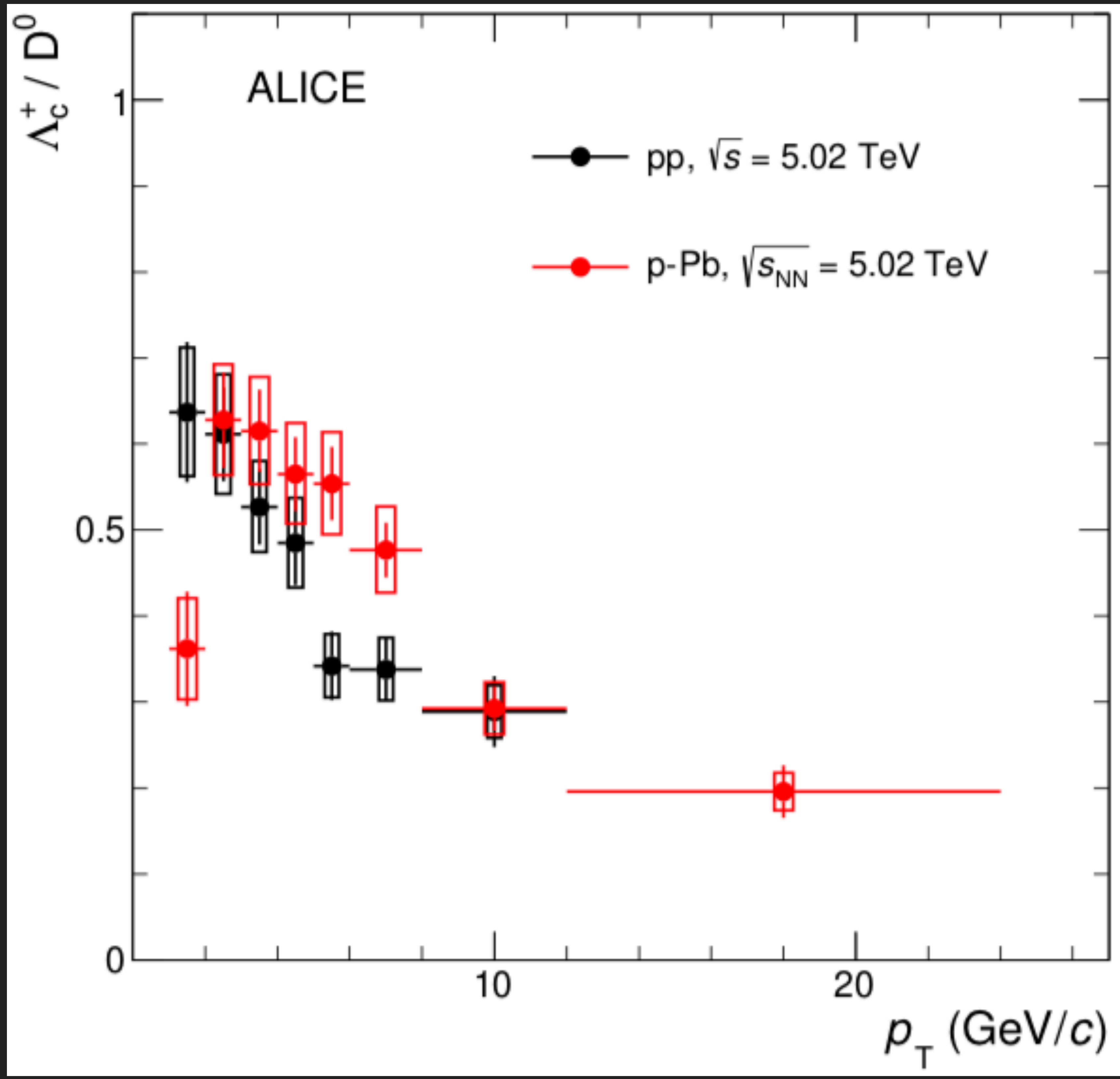
Λ_c^+/D^0 vs. p_T:

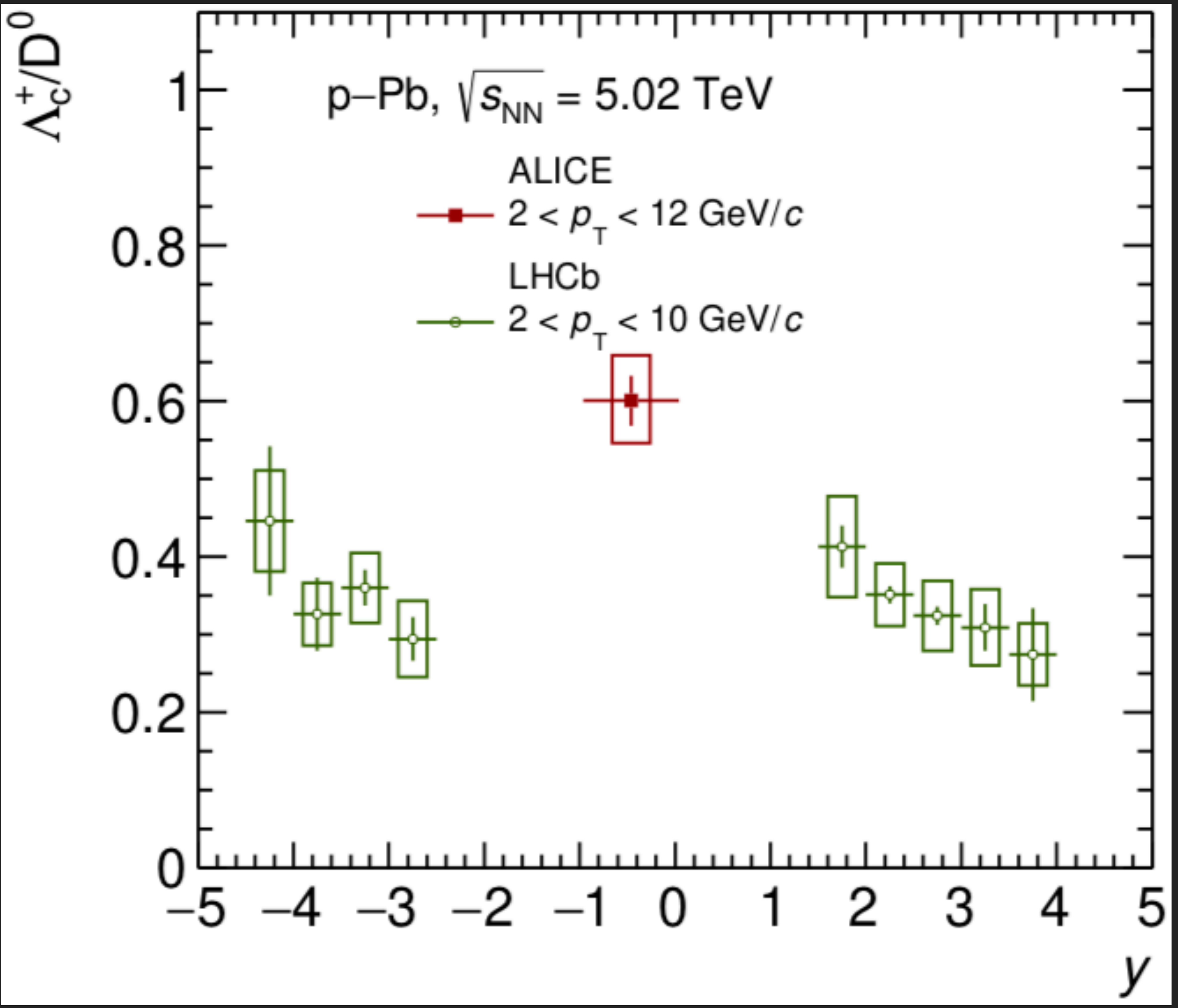
- Decrease with increasing p_T in both pp and p-Pb
- Qualitatively consistent in pp and p-Pb

Λ_c^+/D^0 vs. y:

- Enhancement at midrapidity w.r.t. forward and backward rapidities

LHCb [JHEP 02 (2019) 102]





Pb–Pb collisions

$R_{AA}(\Lambda_c^+)$ in Pb-Pb collisions at 5.02 TeV

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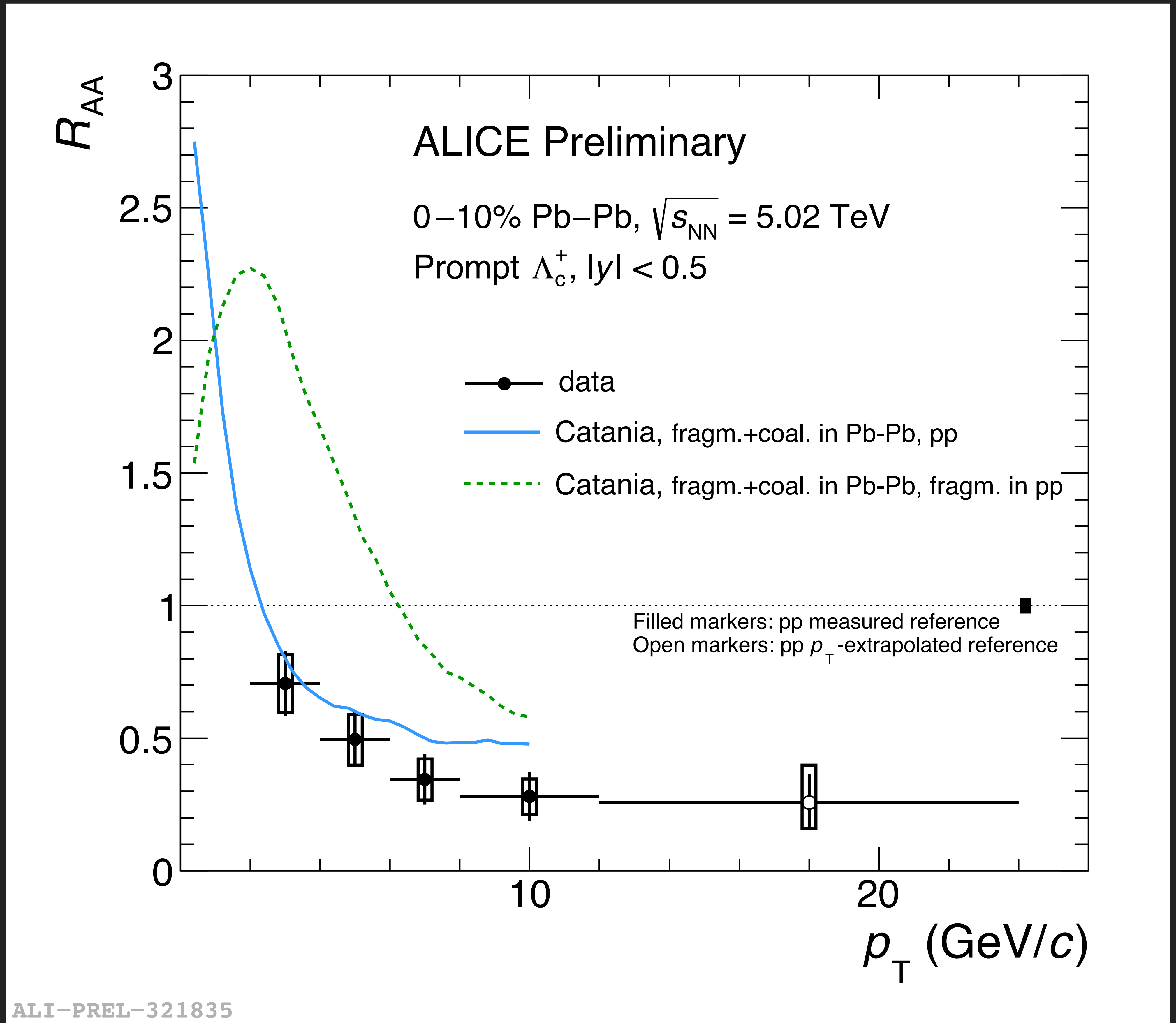
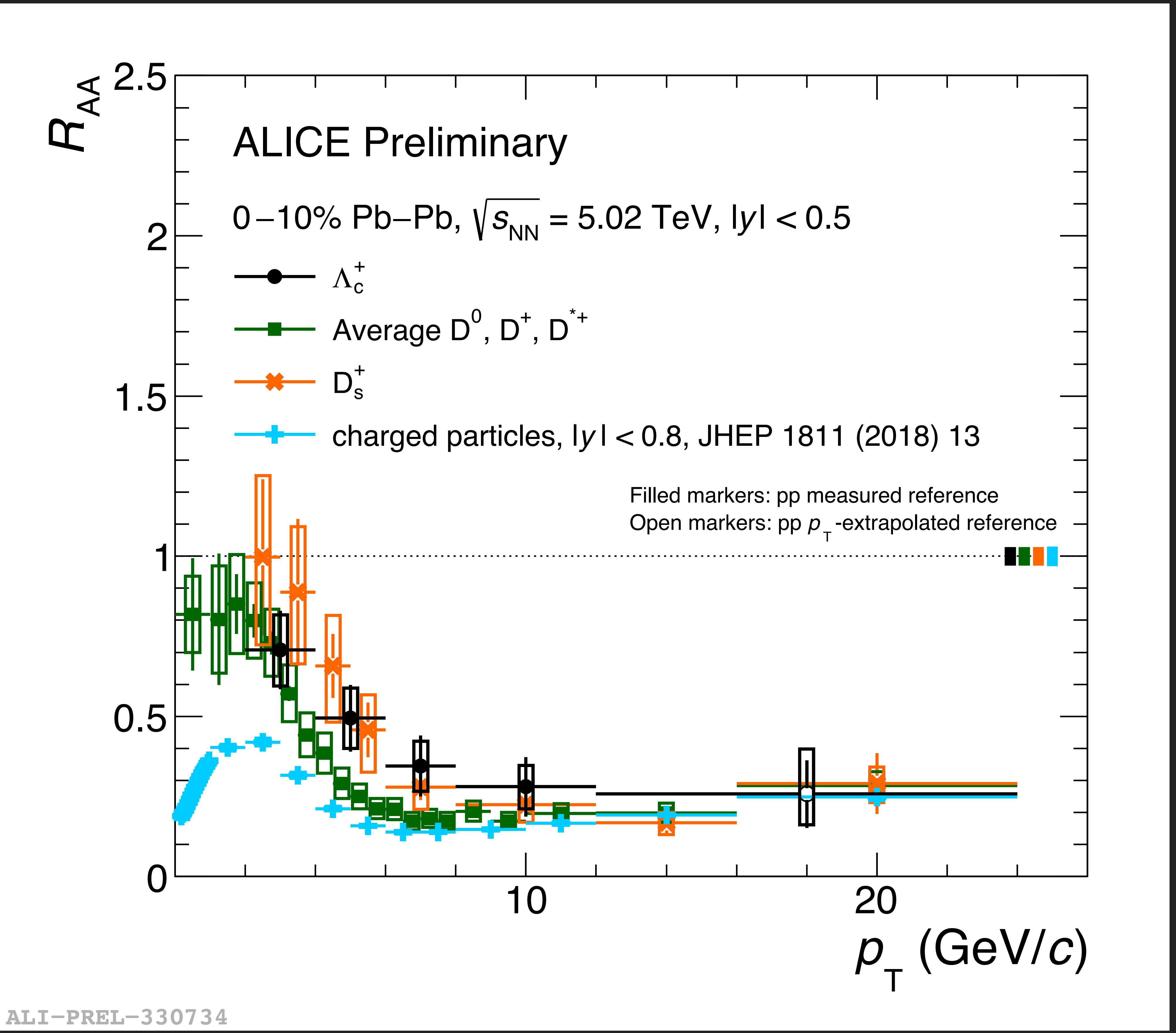
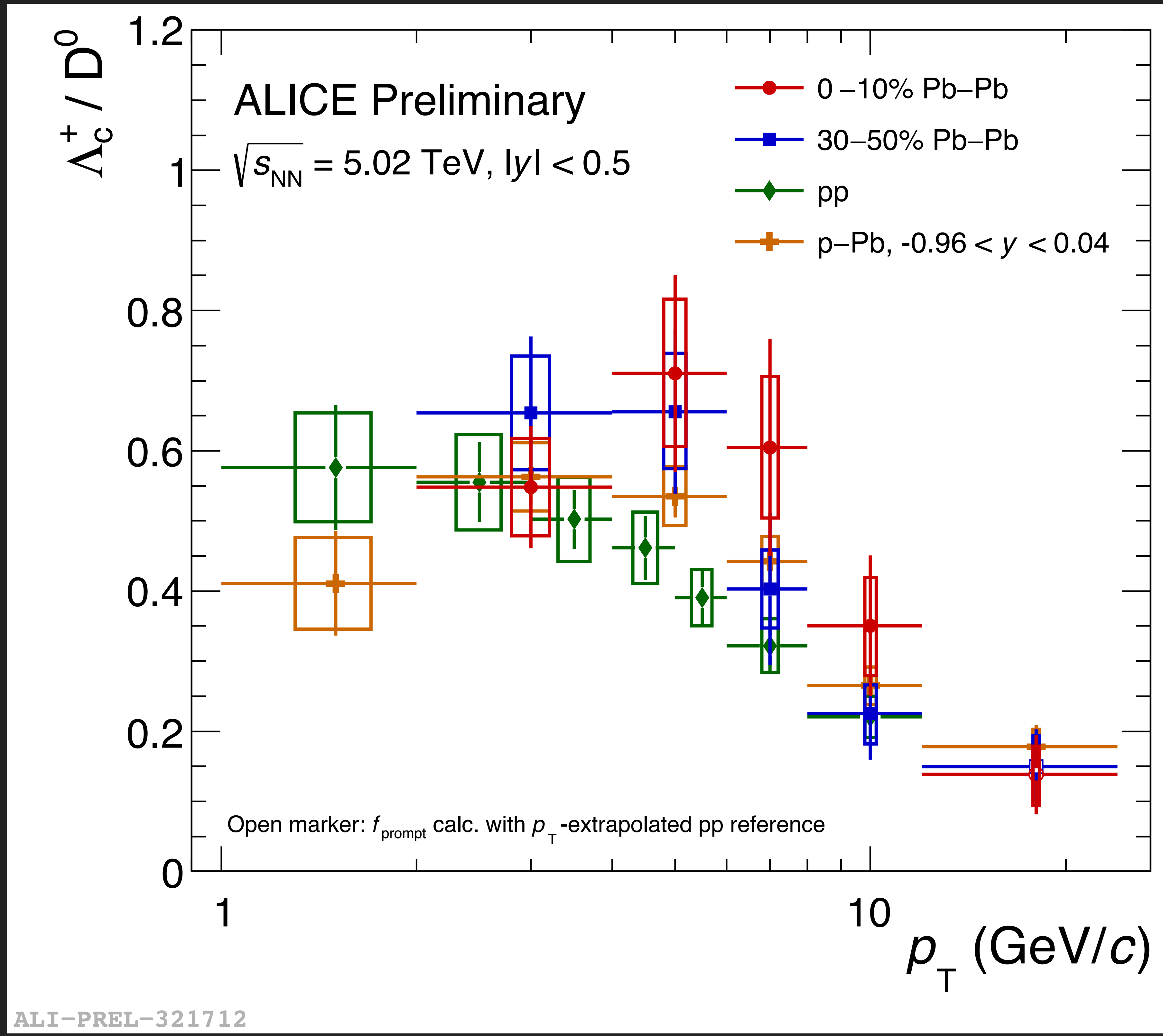


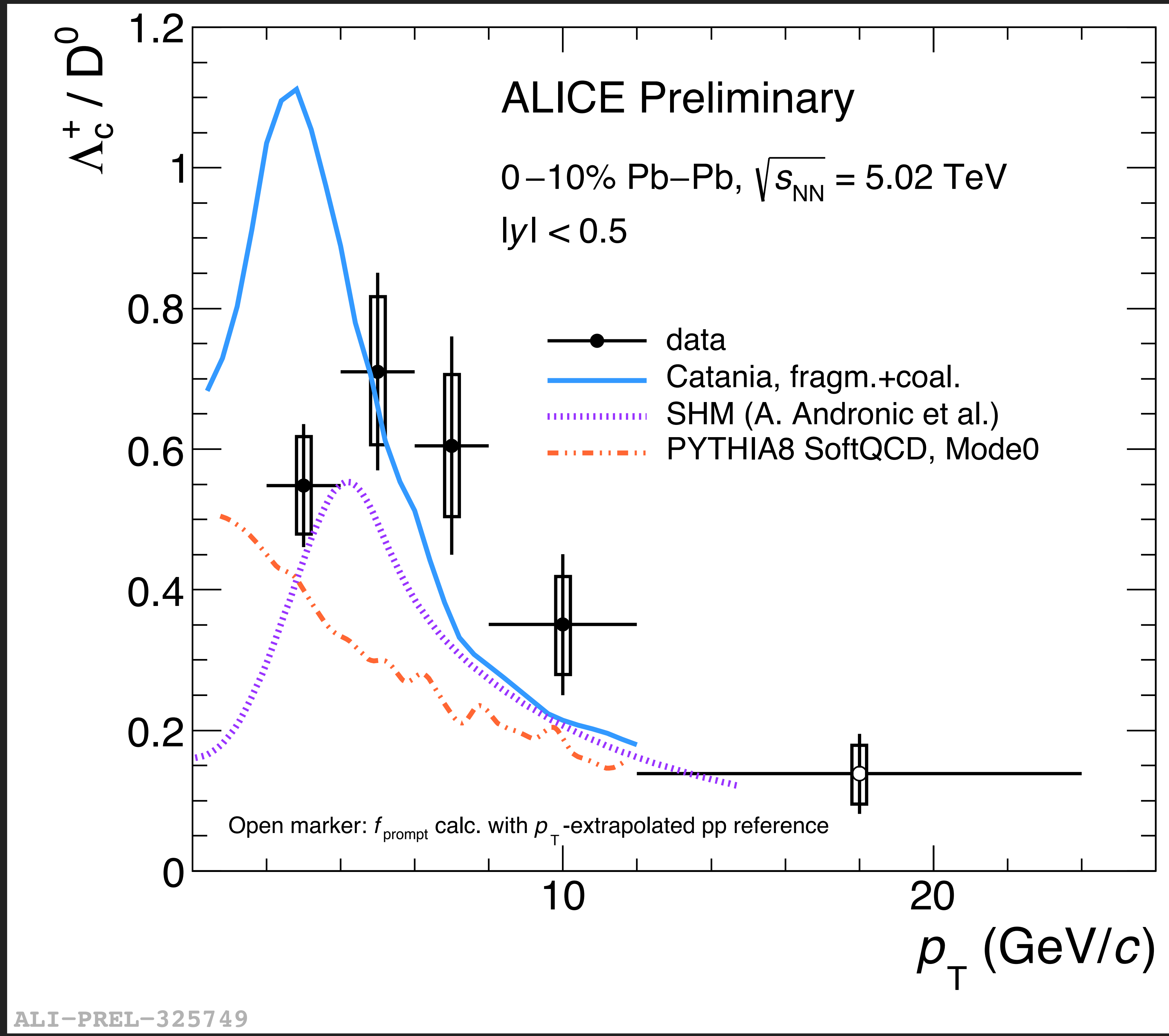


Catania
[Eur.Phys.J.C (2018) 78:348]

- Λ_c^+ suppressed in Pb-Pb → by a factor ~ 1.5 up to $p_T = 12$ GeV/c
- Data described by model with both fragmentation and coalescence presented in Pb-Pb and pp
- Nuclear suppression hierarchy: $R_{AA}(\Lambda_c^+) \sim R_{AA}(D_s^+) > R_{AA}(D) > R_{AA}(h^\pm)$

Λ_c^+/D^0 in Pb–Pb collisions at 5.02 TeV

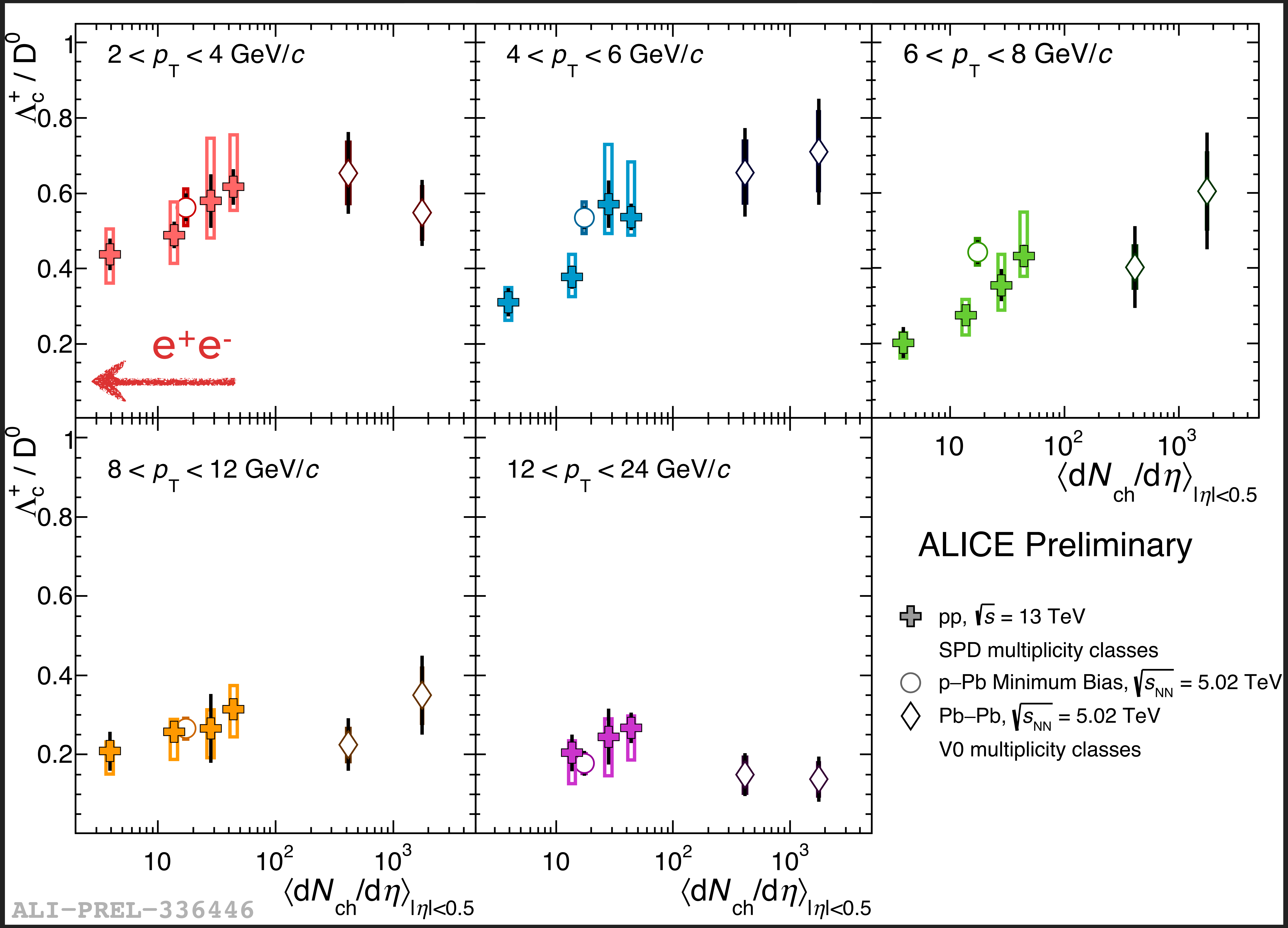




Catania
[Eur.Phys.J.C (2018) 78:348]
Statistical hadronization model (SHM)
[J.Phys.G37:094014,2010]
[Phys.Lett.B659:149-155,2008]
[Eur.Phys.J.C51:113-133,2007]
PYTHIA8
[Comput. Phys. Commun. 178 (2008) 852]
PYTHIA8 (SoftQCD, Mode0)
[JHEP 08 (2015) 003]

- Hint of Λ_c^+/D^0 enhancement in intermediate p_T from pp to Pb-Pb
  - Radial-flow push in Pb-Pb?
  - Coalescence effect?
- Data described by model with fragmentation+coalescence in $p_T > 4$ GeV/c
- Data slightly underestimated by SHM

Λ_c^+/D^0 vs. Multiplicity in pp, p-Pb and Pb-Pb collisions



- Increase smoothly from low multiplicity pp to Pb-Pb
  - Low pp multiplicity > e^+e^-
  - High pp multiplicity ~ Pb-Pb
    - Saturate already at high multiplicity in pp ?

Summary

In pp collision:

- Hadronization in pp very different than e+e- and depends on multiplicity
- PYTHIA8 with CR beyond LC describes Λ_c^+/D^0 and $\Sigma_c^{0,+,++}/D^0$, but overestimate $\Sigma_c^{0,+,++}/\Lambda_c^+$
- SHM with augmented set of charm-baryon states describes Λ_c^+/D^0, $\Sigma_c^{0,+,++}/D^0$ and $\Sigma_c^{0,+,++}/\Lambda_c^+$

In p-Pb collisions:

- $R_{\mathrm{pPb}}(\Lambda_c^+)$ compatible with unity and consistent with $R_{\mathrm{pPb}}(\mathrm{D})$ within uncertainties
- Models cannot quantitatively reproduce $R_{\mathrm{pPb}}(\Lambda_c^+)$
- Λ_c^+/D^0 qualitatively consistent with pp collision, enhanced at midrapidity w.r.t. forward and backward rapidity

In Pb-Pb collisions:

- Λ_c^+ production consistent with fragmentation+coalescence and SHM
- Hint of possible Λ_c^+/D^0 enhanced at mid p_T

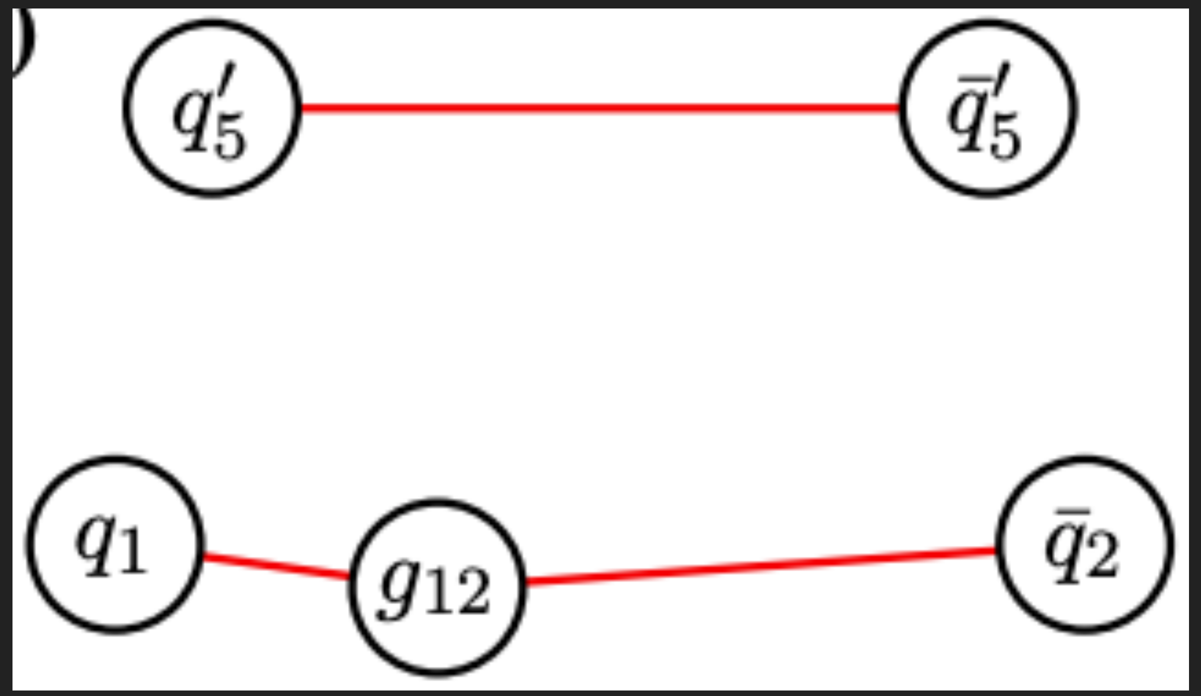
BACKUP

Overview of theoretical calculations (I)

- PYTHIA8 [JHEP 08 (2015) 003]
  - Primordial Λ_c^+ enhanced by factor ~2 with new CR model
  - Extra contribution from feed-down of Σ_c states (x20~30 more)
  - The junction topology favours baryon formation

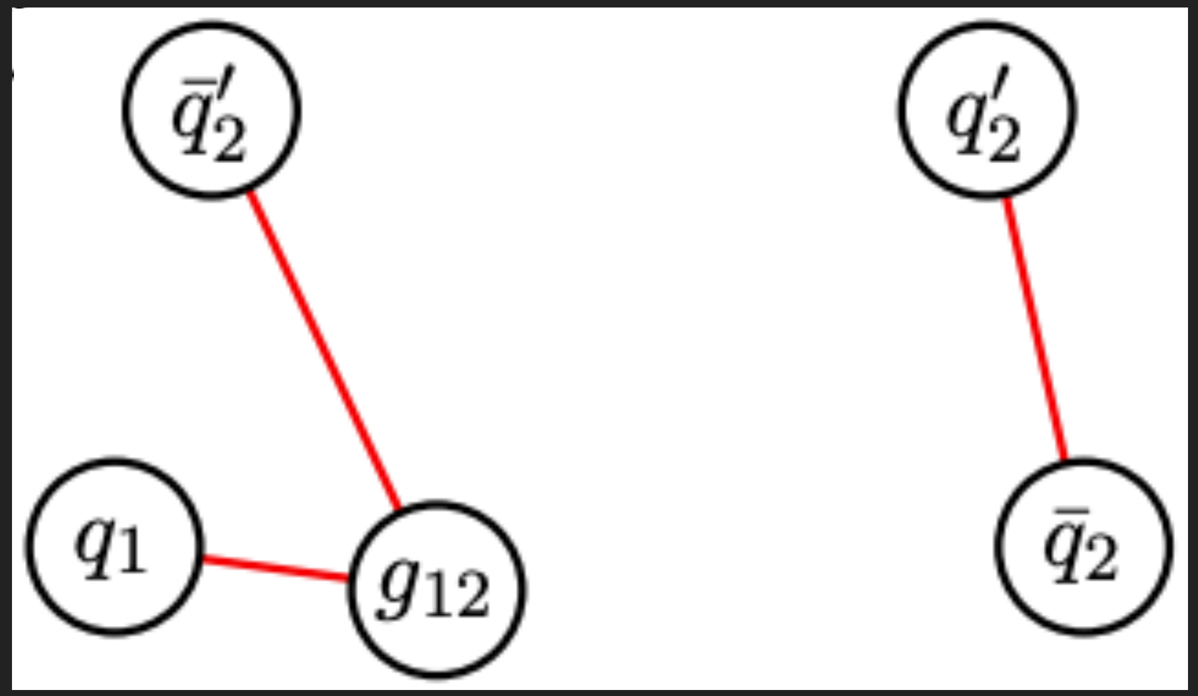
Particle	New CR model (N_{par}/N_{events}) string	junction	all	Old CR model N_{par}/N_{events} (all)
D^+	$5.3 \cdot 10^{-2}$	0	$5.3 \cdot 10^{-2}$	$6.5 \cdot 10^{-2}$
Λ_c^+	$4.0 \cdot 10^{-3}$	$7.9 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	$6.6 \cdot 10^{-3}$
Σ_c^{++}	$2.7 \cdot 10^{-4}$	$1.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$5.4 \cdot 10^{-4}$
Σ_c^+	$2.5 \cdot 10^{-4}$	$1.5 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$5.2 \cdot 10^{-4}$
Σ_c^0	$2.5 \cdot 10^{-4}$	$1.3 \cdot 10^{-2}$	$1.3 \cdot 10^{-2}$	$5.1 \cdot 10^{-4}$

No CR



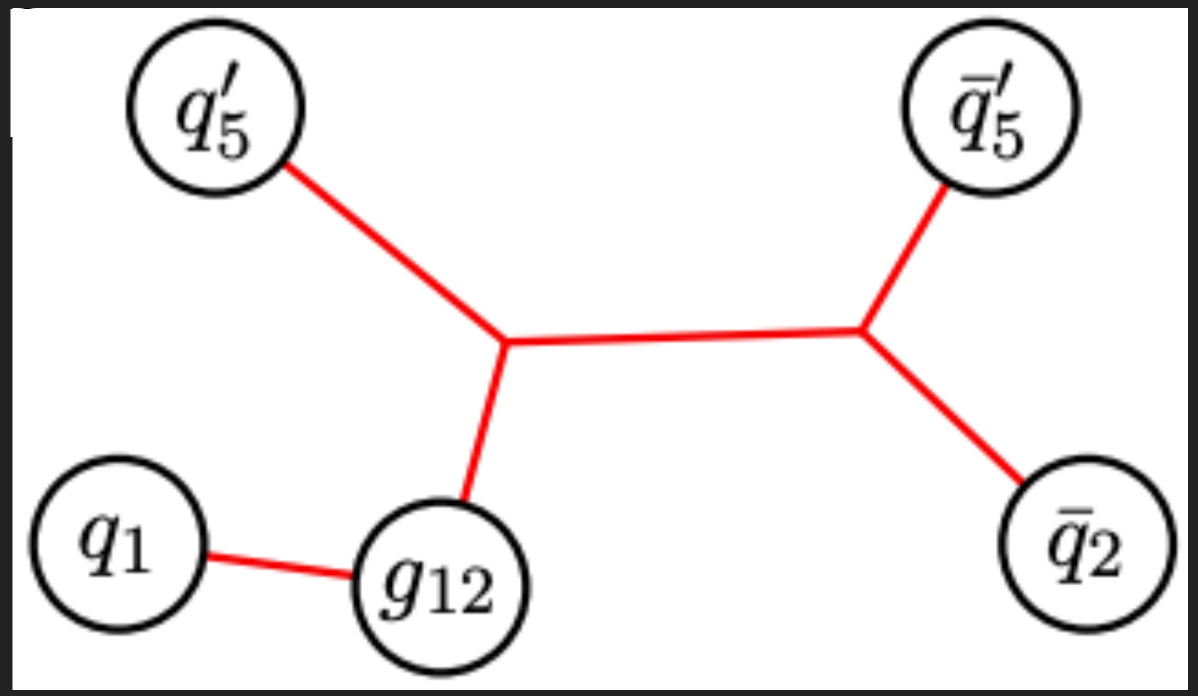
- ✳ Partons created in different MPIs do not interact

MPI-based CR (old CR model)



- ✳ CR allowed between partons from different MPIs to minimize string length
- ✳ As implemented in Monash

More-QCD CR (new CR model)



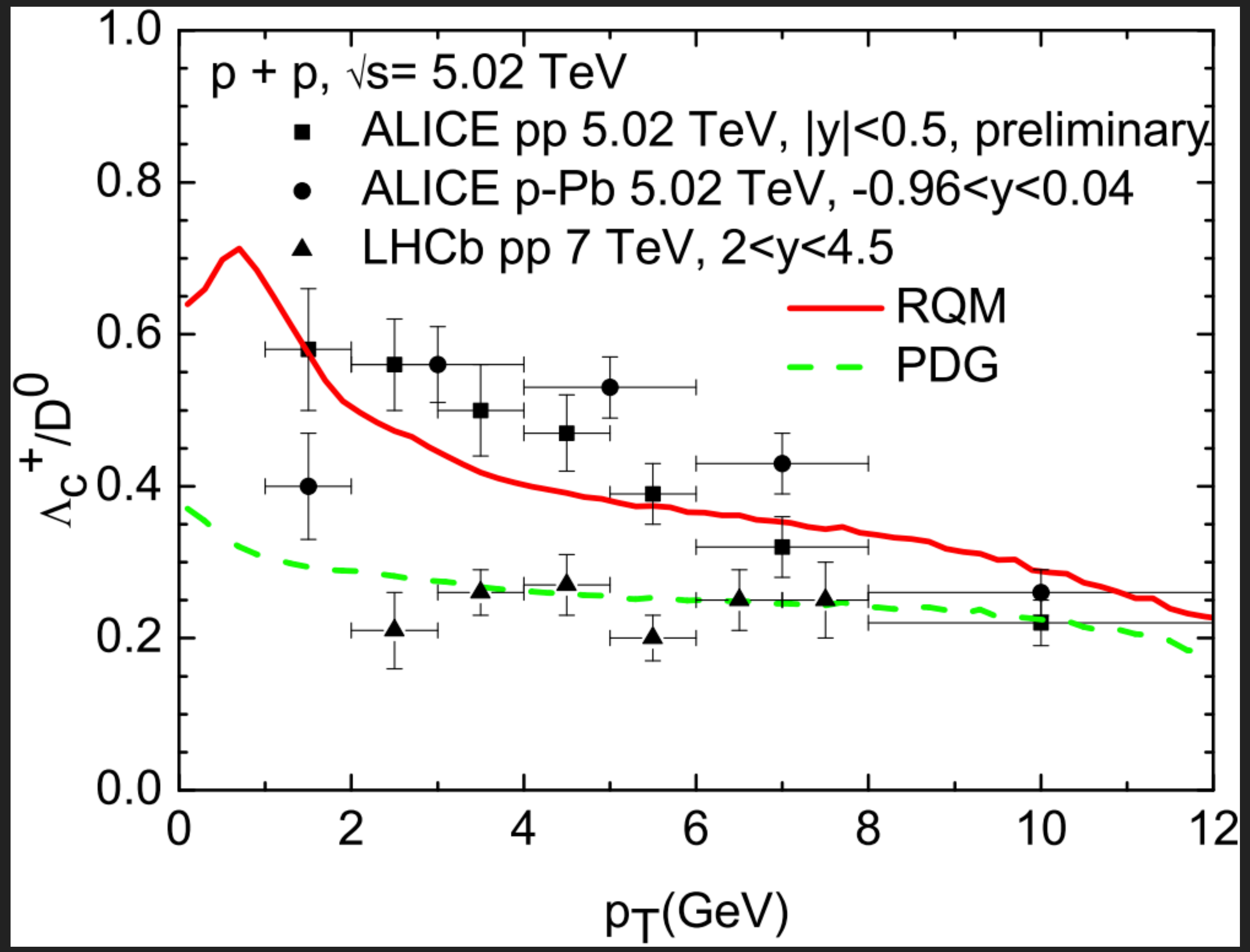
- ✳ Uses a simple model of the colour rules of QCD to determine the formation of strings and introduce junctions
- ✳ Minimization of the string length over all possible configurations
- ✳ Include CR with MPIs and with beam remnants

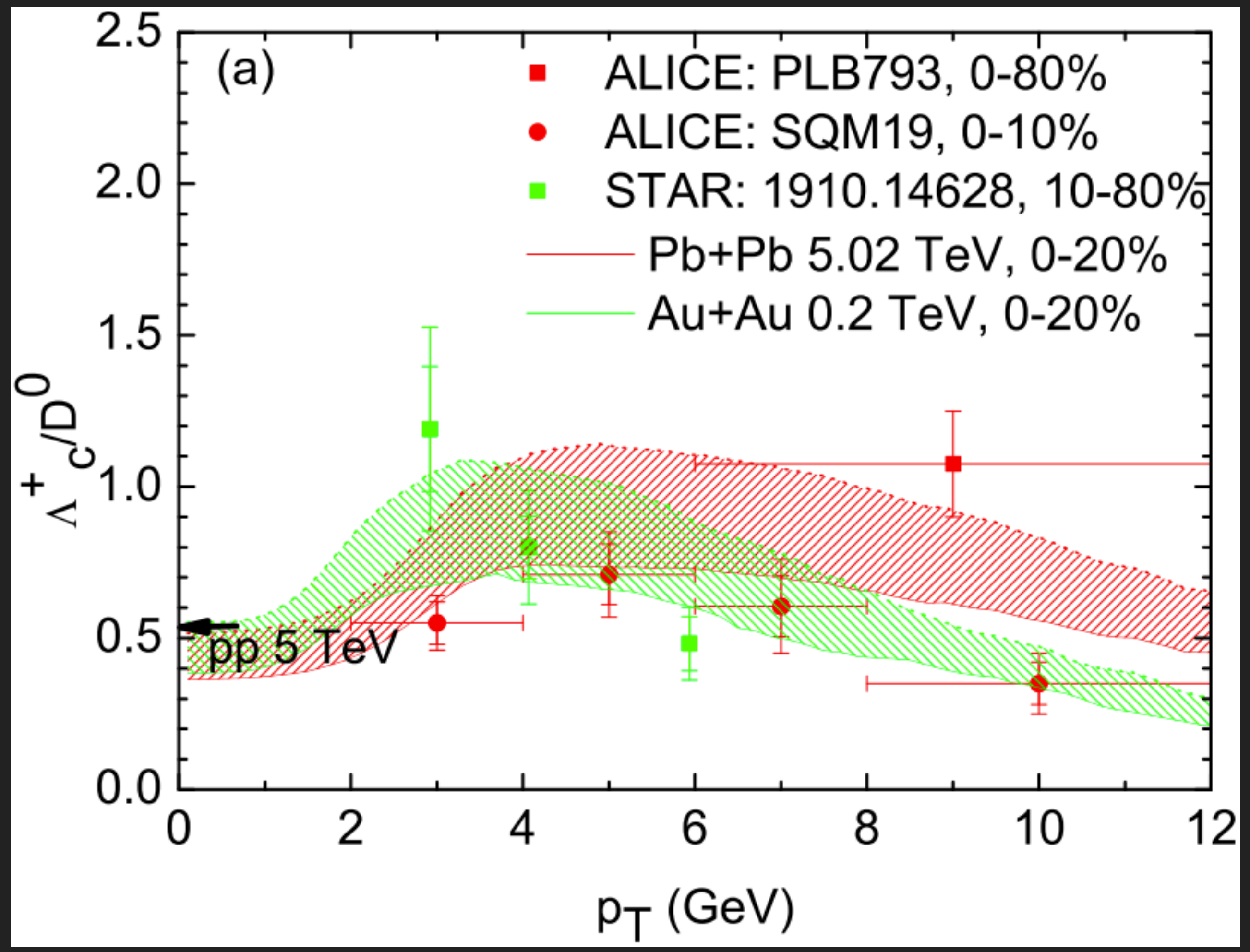
Overview of theoretical calculations (II)

- Min He and Ralf Rapp [PLB 795 (2019) 117-121] [PRL 124, 042301 (2020)]
  - SHM with increased set of charm-baryon states
    - Estimate missing states from RQM (relativistic quark model) [PRD 84:014025,2011] and PDG
    - RQM describes Λ_c^+/D^0 better than PDG $\rightarrow$ RQM: extra 18 Λ_c, 42 Σ_c, 62 Ξ_c, 34 Ω_c
  - Describe Λ_c^+/D^0 measurement well in pp, p-Pb and Pb-Pb collisions with RQM

r_i	D^+/D^0	D^{*+}/D^0	D_s^+/D^0	Λ_c^+/D^0
PDG(170)	0.4391	0.4315	0.2736	0.2851
PDG(160)	0.4450	0.4229	0.2624	0.2404
RQM(170)	0.4391	0.4315	0.2726	0.5696
RQM(160)	0.4450	0.4229	0.2624	0.4409

[PLB 795 (2019) 117-121]



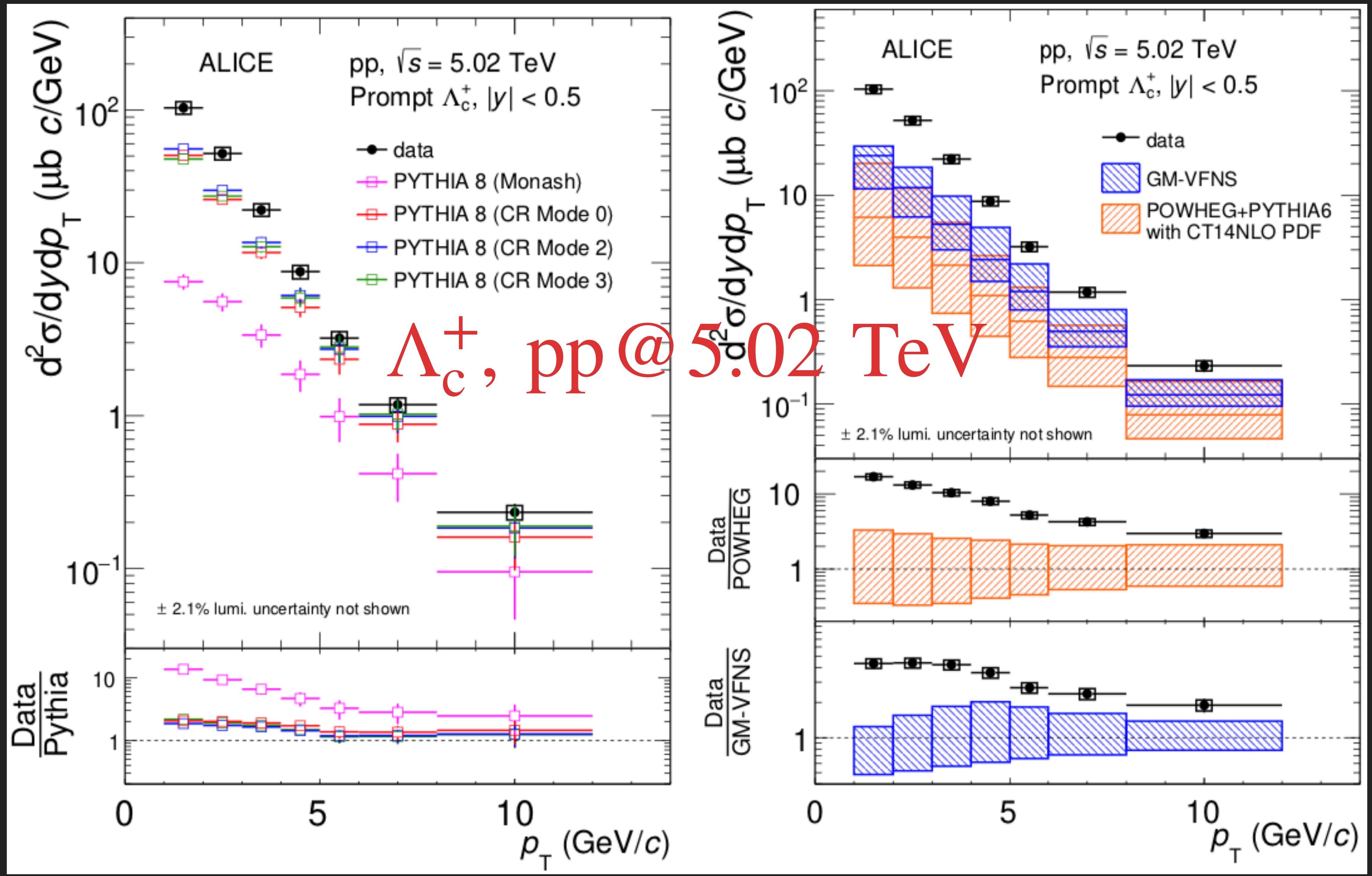


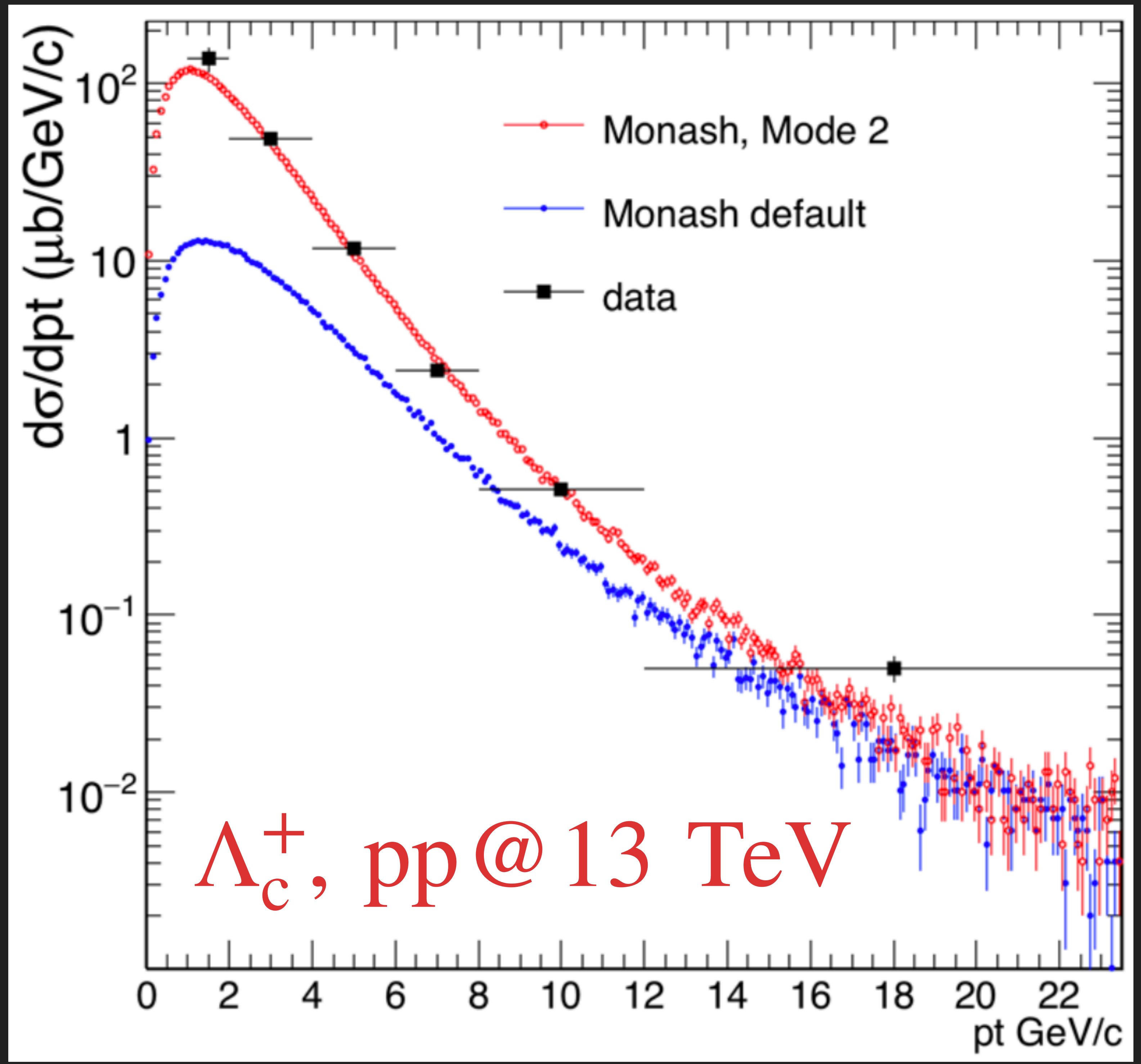
[PRL 124, 042301 (2020)]

- SHMC (SHM for charmed hadrons) [PLB 797 (2019) 134836]
  - Assume (anti-)charm quark number conserved during the QGP phase, i.e., thermal production or annihilation negligible
  - Quarks thermalized in QGP before hadronization and rapidly freeze-out at phase boundary at $T = 156.5$ MeV
- Catania [Eur.Phys.J.C (2018) 78:348]
  - Transport model with hadronization via coalescence+fragmentation

Λ_c^+ cross section in pp collision at 5.02 and 13 TeV

PYTHIA8 Monash
[Eur. Phys. J. C 74 (2014) 3024]
PYTHIA8 (Mode0, 2, 3)
[JHEP 08 (2015) 003]
GM-VFNS
[Phys. Rev. D 101, 114021 (2020)]
POWHEG
[JHEP 09 (2007) 126]





pp@5.02 TeV

- All models **underestimate** the measured p_{T}-differential prompt Λ_c^+ cross section
  - PYTHIA 8 Monash tune and PYTHIA 8 Mode0, 2, 3 with colour reconnection (CR) beyond leading-colour approximation
  - GM-VFNS: parton model with quark masses, a new fragmentation function for Λ_c^+ (combining e^+e^- from OPAL and Belle) has been used
  - POWHEG: next-to-leading-order (NLO) generator

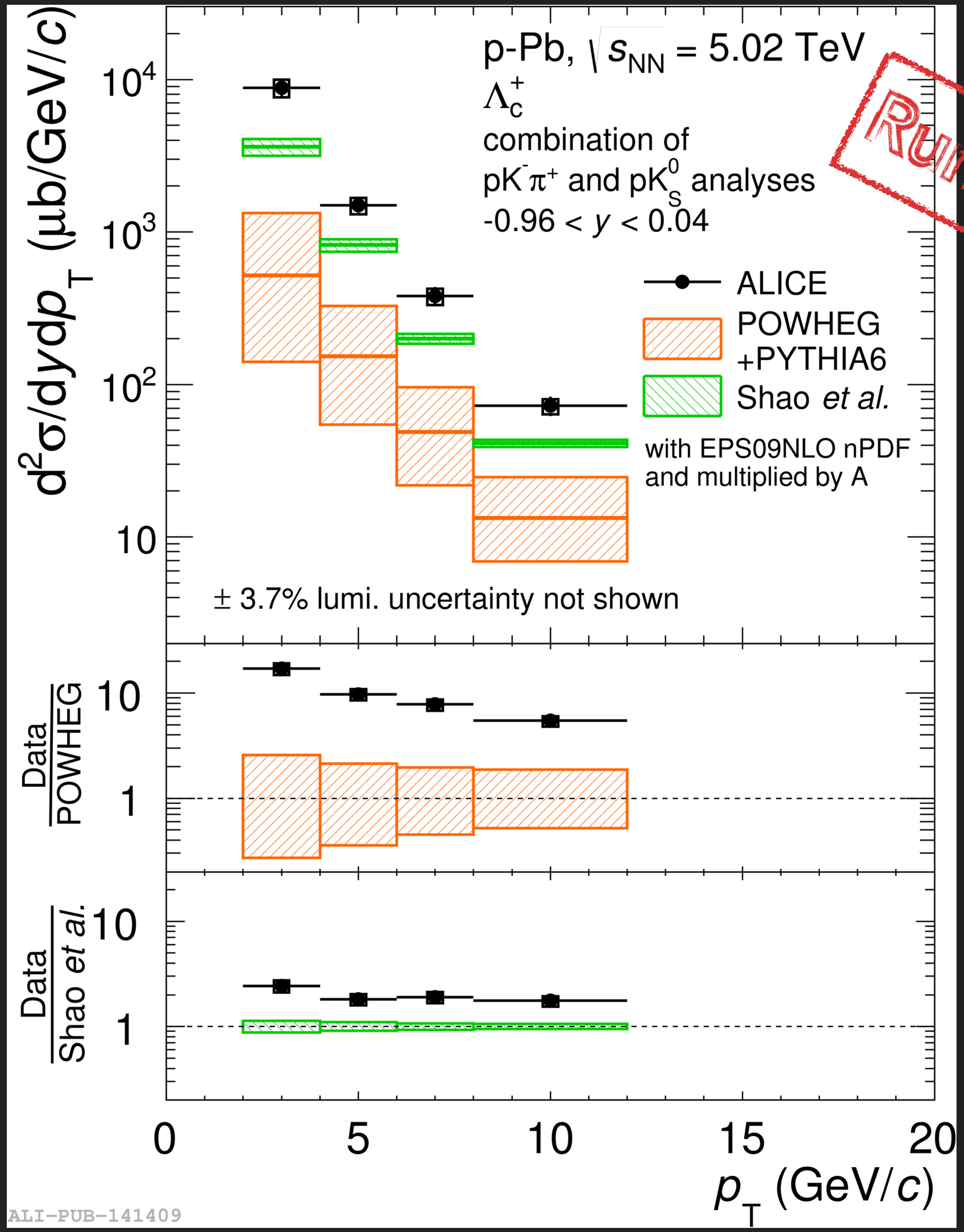
pp@13 TeV

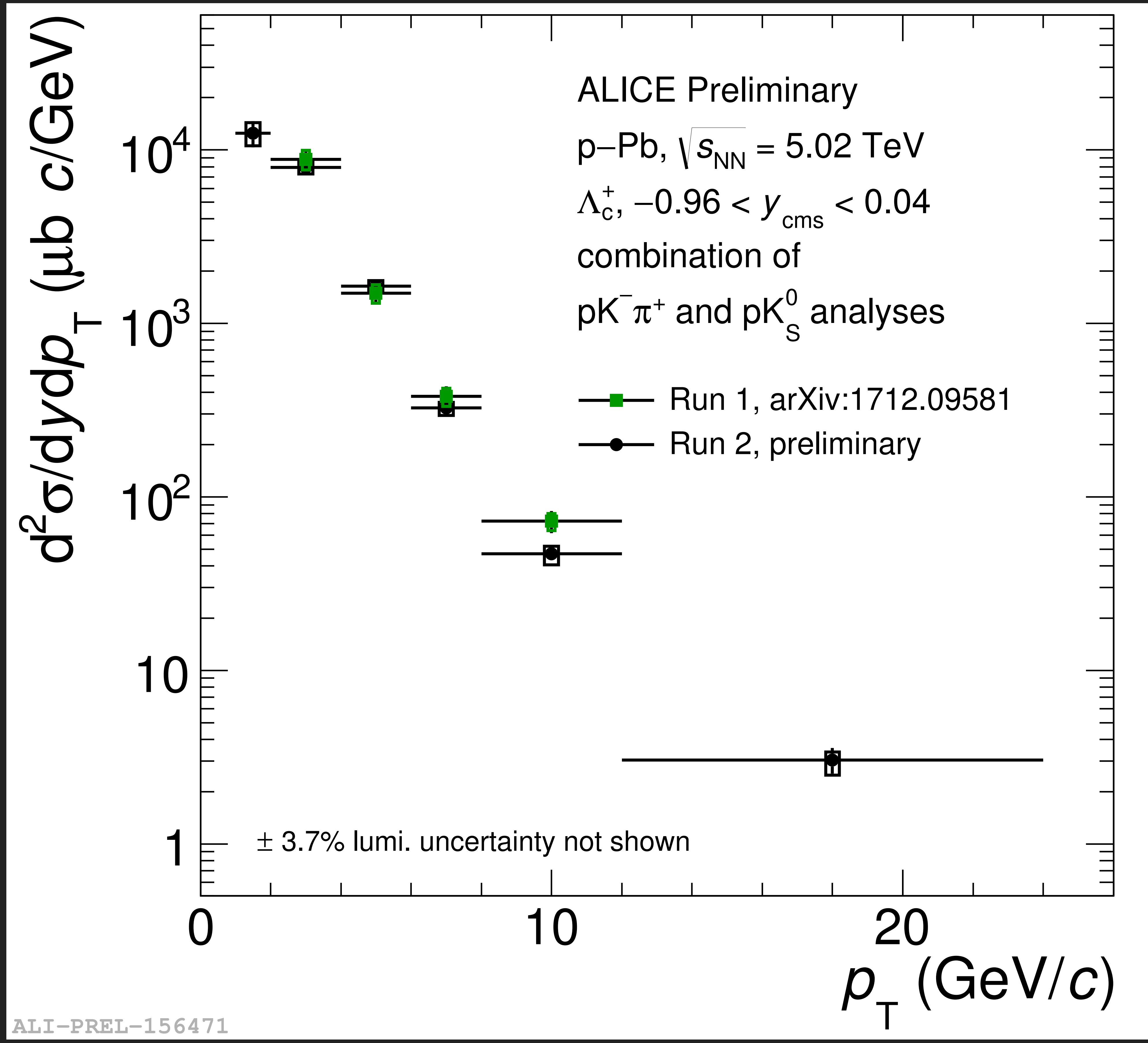
- PYTHIA 8 Mode 2 describe the measured p_{T}-differential prompt Λ_c^+ cross section

- Agreement of PYTHIA 8 Mode2 with data depends on collision energy
- Large difference observed for Λ_c^+ in pp w.r.t. ee and ep, indicates a limit to the universality of usage of Fragmentation Fractions from LEP

Λ_c^+ cross section in p–Pb collisions at 5.02 TeV

[JHEP 04 (2018) 108]



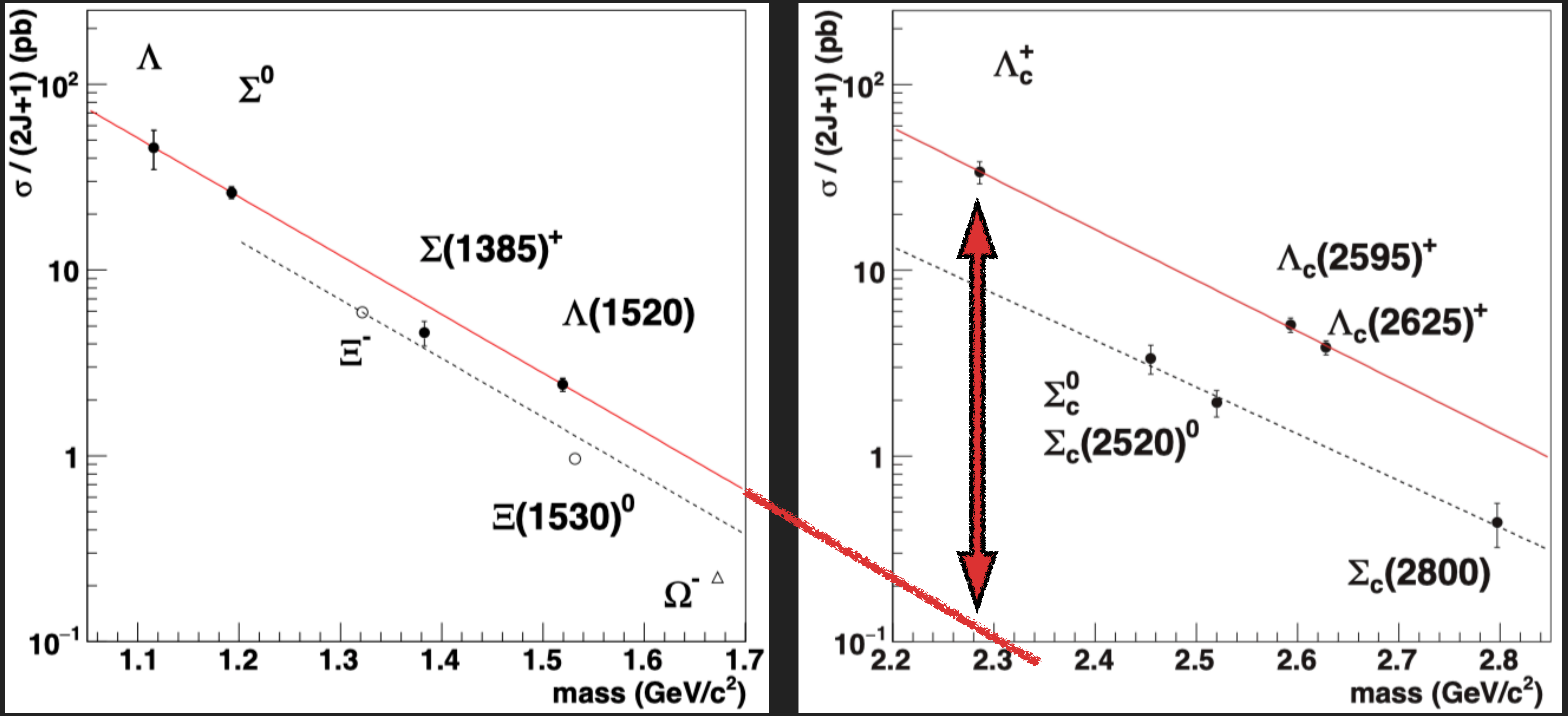


- The p_T-differential cross section significantly underestimated by models (from comparison to Run-1 predictions)
  - POWHEG: non-perturbative fragmentation functions $f(c \to \Lambda_c^+)$ estimated from e^+e^- data. Non-universality?
  - Shao: data-driven model based on pp LHCb data with EPS09NLO nPDF

Σ_c suppression from spin-1 diquark suppression in e+e-

ALICE

Belle [PRD 97, 072005 (2018)]



- Λ_c production rate higher than extrapolation of hyperon curve to charm mass window
  - ➡ Different production mechanism, points to important role of diquark production for charm baryons
- Λ_c and Σ_c cross-section difference support charm baryon production from diquark degrees of freedom and a spin-0 diquark component for Λ_c