

Measurements of charm production and hadronization in pp collisions with ALICE

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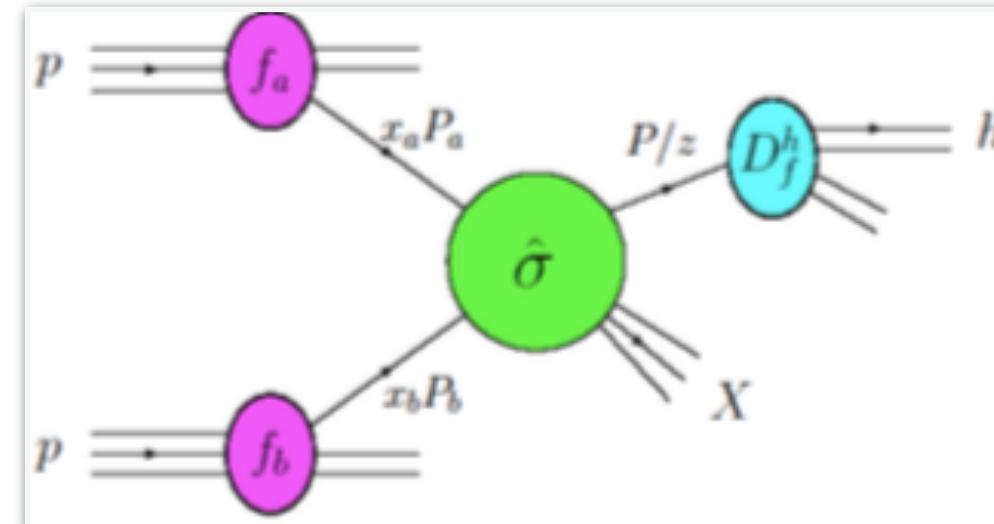
ISMD2021

50th International Symposium on
Multiparticle Dynamics (ISMD2021)

Heavy flavour production

$$\frac{d\sigma^D}{dp_T^D}(p_T; \mu_F; \mu_R) = \textcolor{magenta}{PDF(x_1, \mu_F) PDF(x_2, \mu_F)} \otimes \textcolor{green}{\frac{d\sigma^c}{dp_T^c}(x_1, x_2, \mu_R, \mu_F)} \otimes \textcolor{cyan}{D_{c \rightarrow D}(z = p_D/p_c, \mu_F)}$$

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



- pQCD models based on factorization approach use fragmentation functions measured in e^+e^- collisions considering them universal
- Charm baryons essential for total charm cross section and fragmentation fraction (FF) measurements
- Ratios of particle species: baryon-to-meson, baryon-to-baryon
 - Sensitive to HF quark hadronization

ALICE detector

V0 detector

- Event trigger

Time Projection Chamber(TPC)

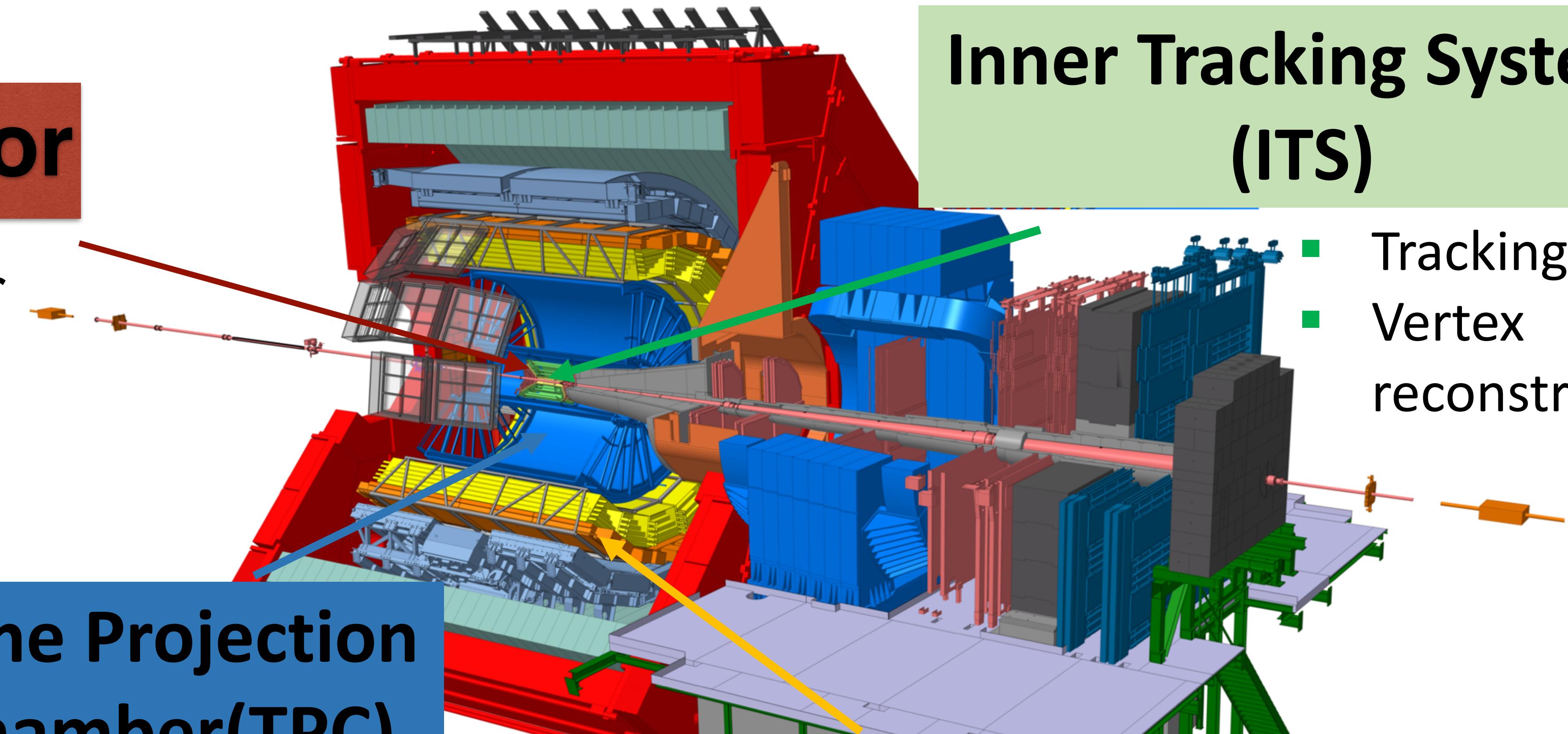
- Track reconstruction
- PID (dE/dx)

Inner Tracking System (ITS)

- Tracking
- Vertex reconstruction

Time of Flight (TOF)

- PID (time-of-flight)



Charm-hadron reconstruction

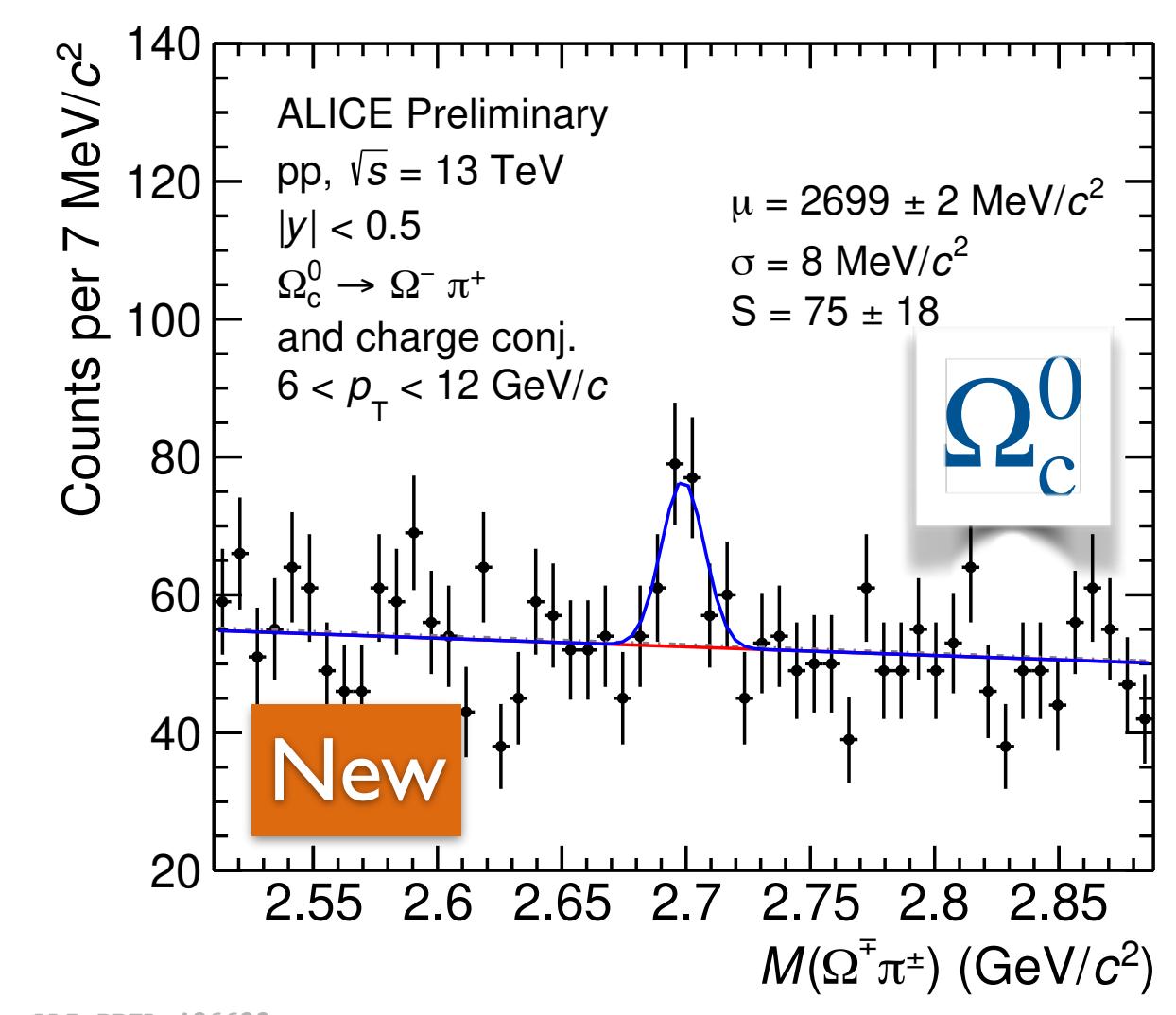
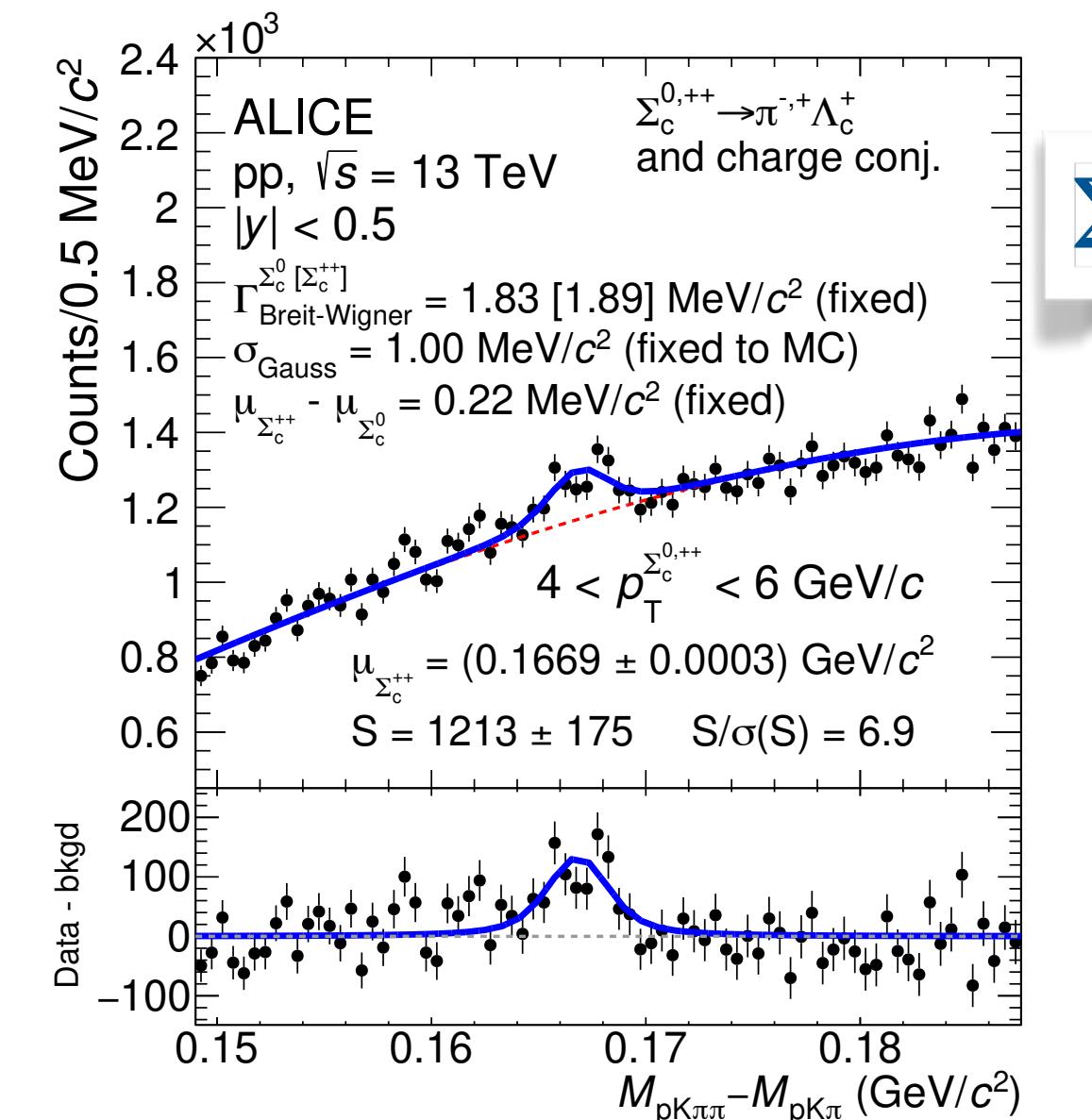
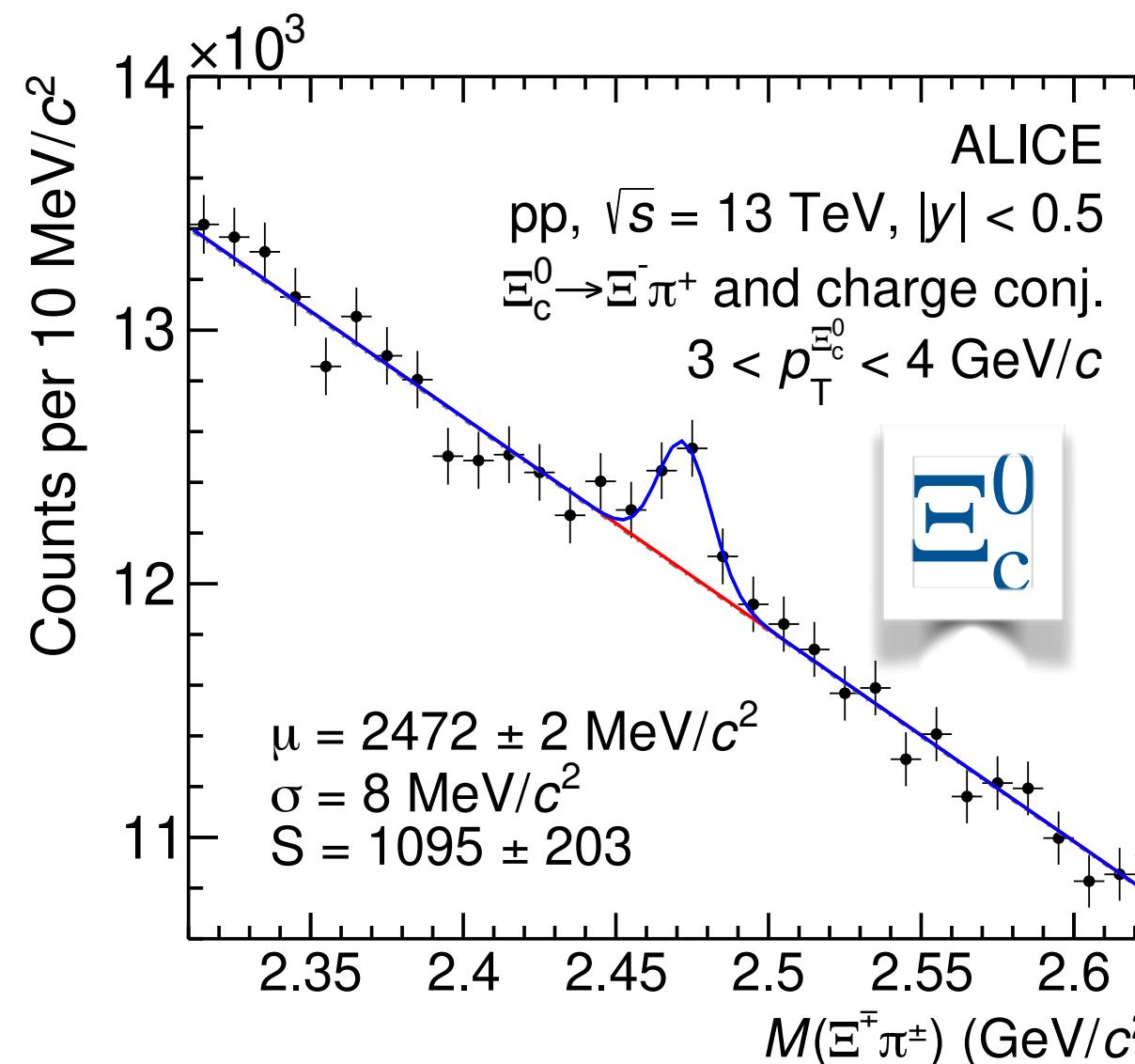
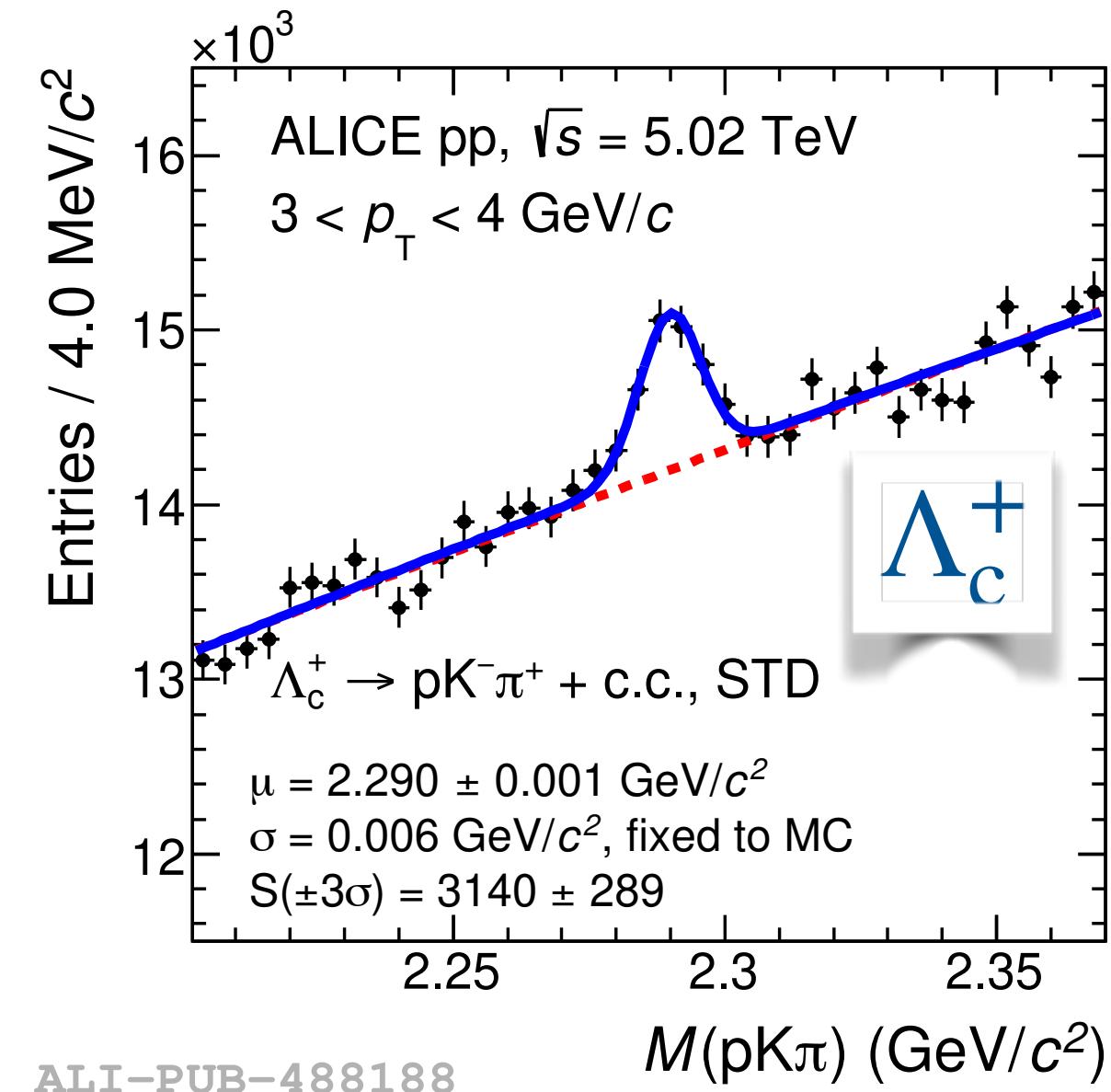
System	Year(s)	$\sqrt{S_{NN}}$ (TeV)	L_{int}
pp	2017	5.02	$\sim 20 \text{ nb}^{-1}$
p-Pb	2016-2018	13	$\sim 32 \text{ nb}^{-1}$
p-Pb	2016	5.02	$\sim 0.3 \text{ nb}^{-1}$

Hadronic decays:

- $D^0 \rightarrow K^- \pi^+$
- $D^+ \rightarrow K^- \pi^- \pi^+$
- $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$
- $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$
- $\Lambda_c^+ \rightarrow p K^- \pi^+ \text{ & } \Lambda_c \rightarrow p K_s^0$
- $\Sigma_c^0 \rightarrow \Lambda_c^+ \pi^- \text{ & } \Sigma_c^{++} \rightarrow \Lambda_c^+ \pi^+$
- $\Xi_c^0 \rightarrow \Xi^- \pi^+$
- $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$
- $\Omega_c^0 \rightarrow \Omega^- \pi^+$

Semileptonic decays:

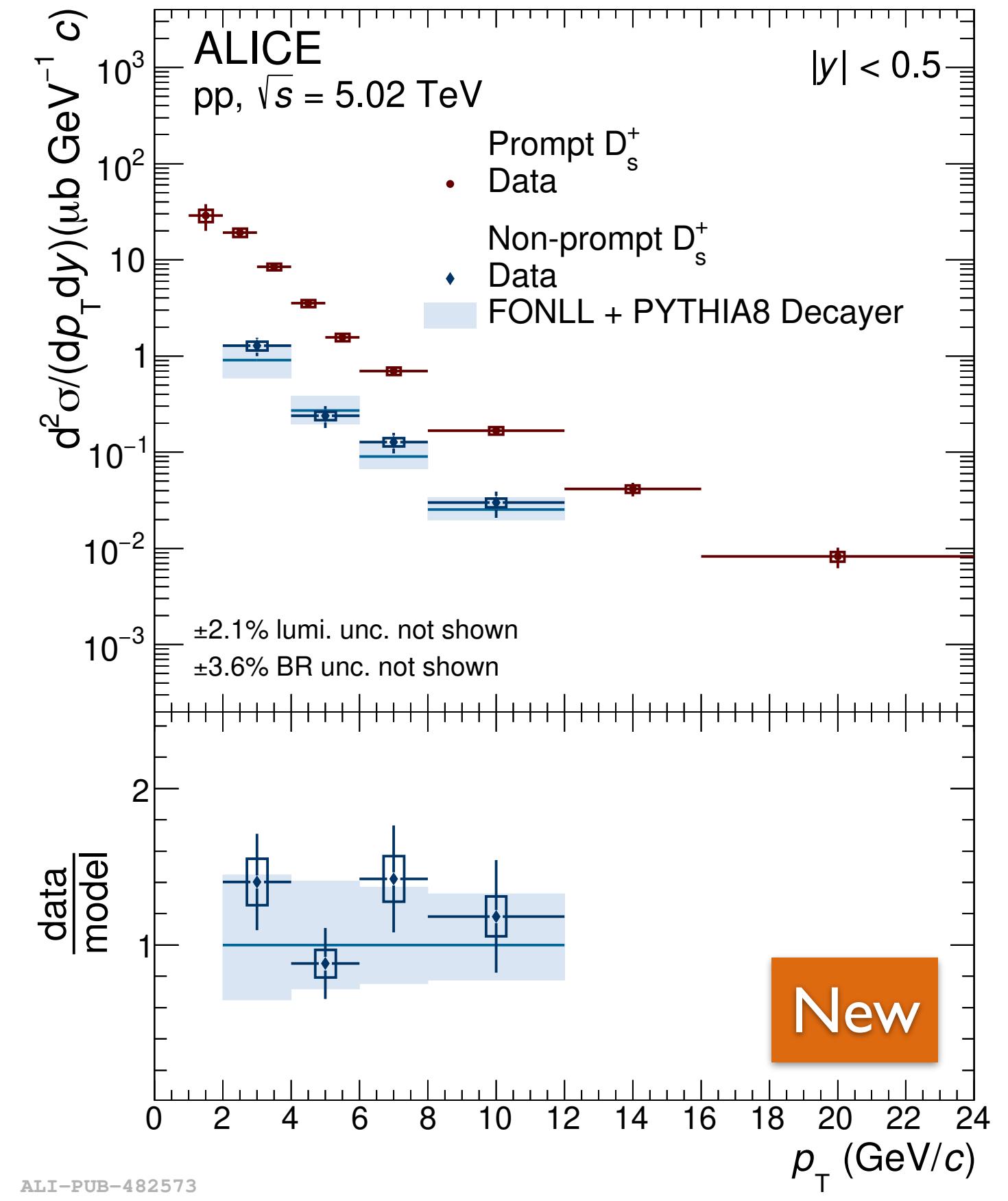
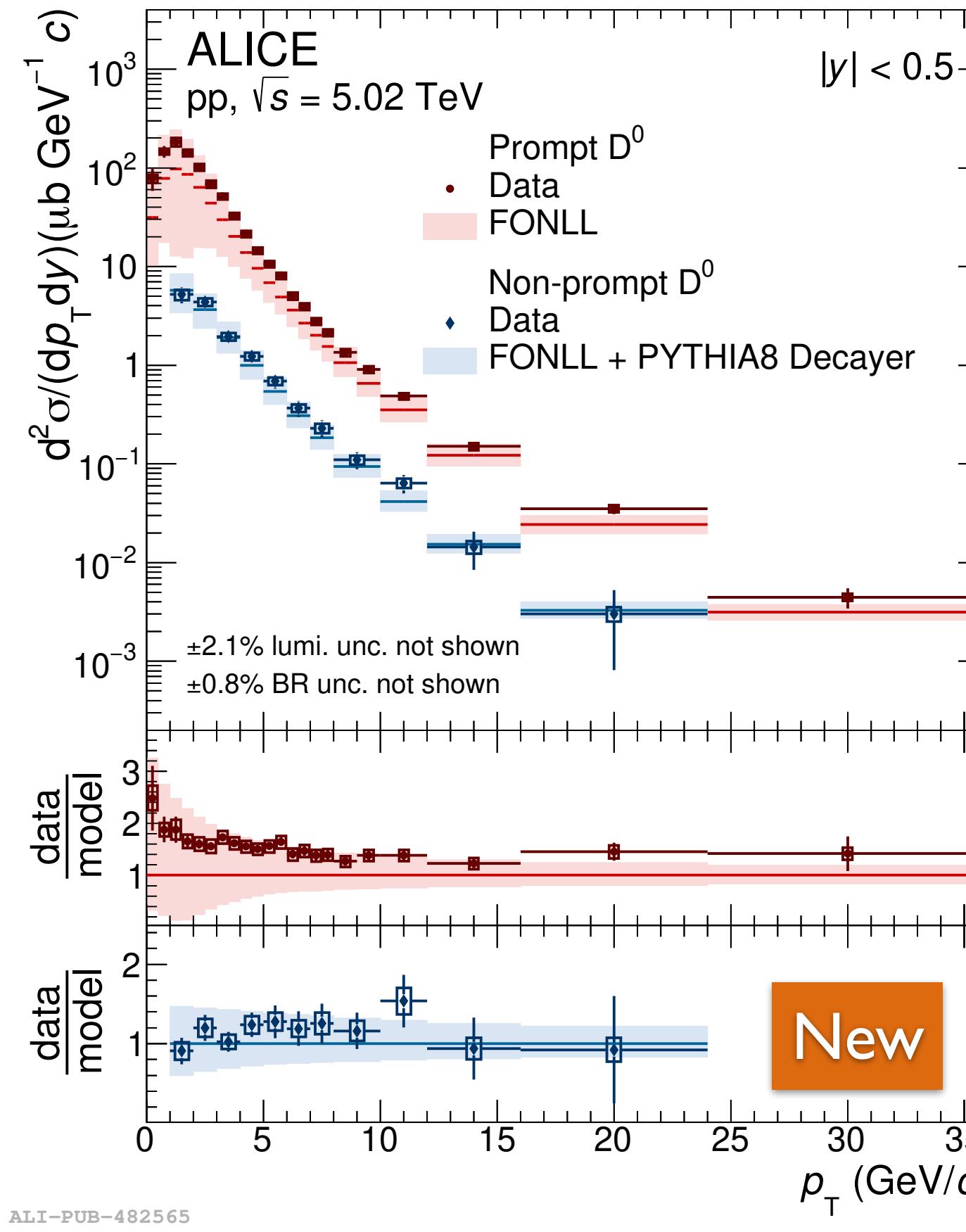
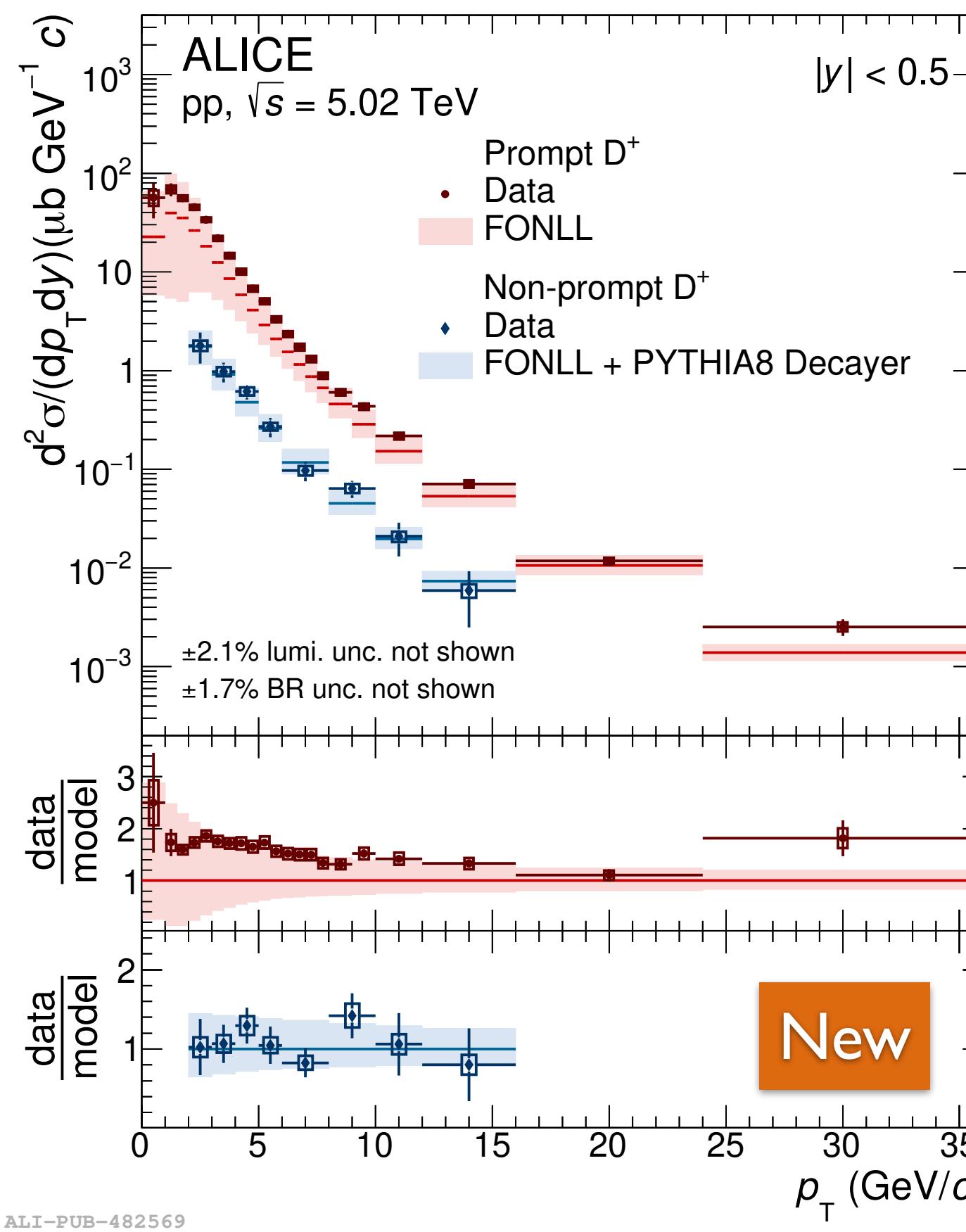
- $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$
- $\Xi_c^0 \rightarrow \Xi^- e^+ \nu_e$



D mesons

- The p_T -differential production cross sections of D mesons compared to model predictions
 - Prompt D mesons: on the upper edge of the FONLL uncertainty band
 - Non-prompt D mesons: agreement with the central value of FONLL + PYTHIA 8 Decayer

[arXiv: 2102.13601](#)

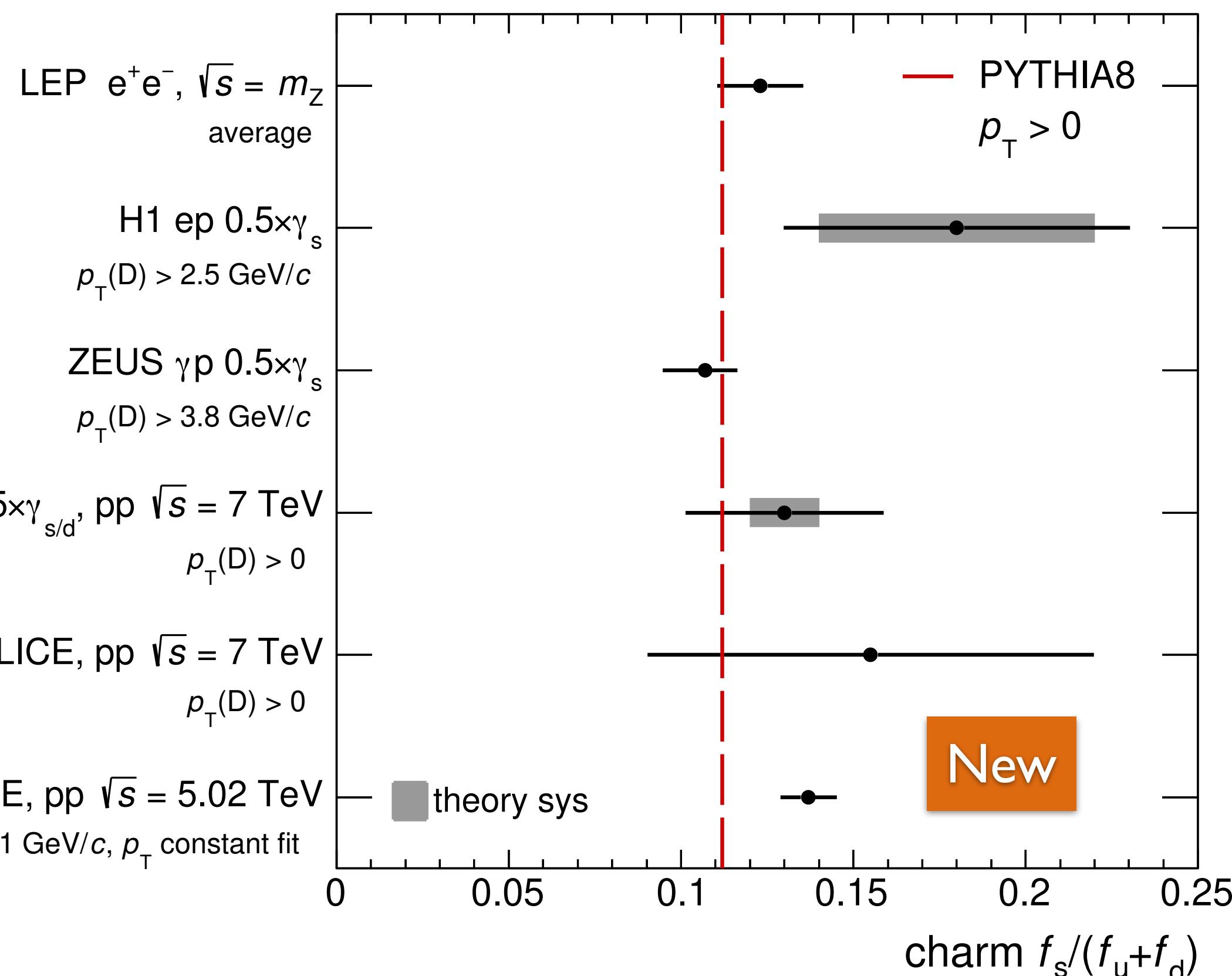


Charm and beauty fragmentation to meson

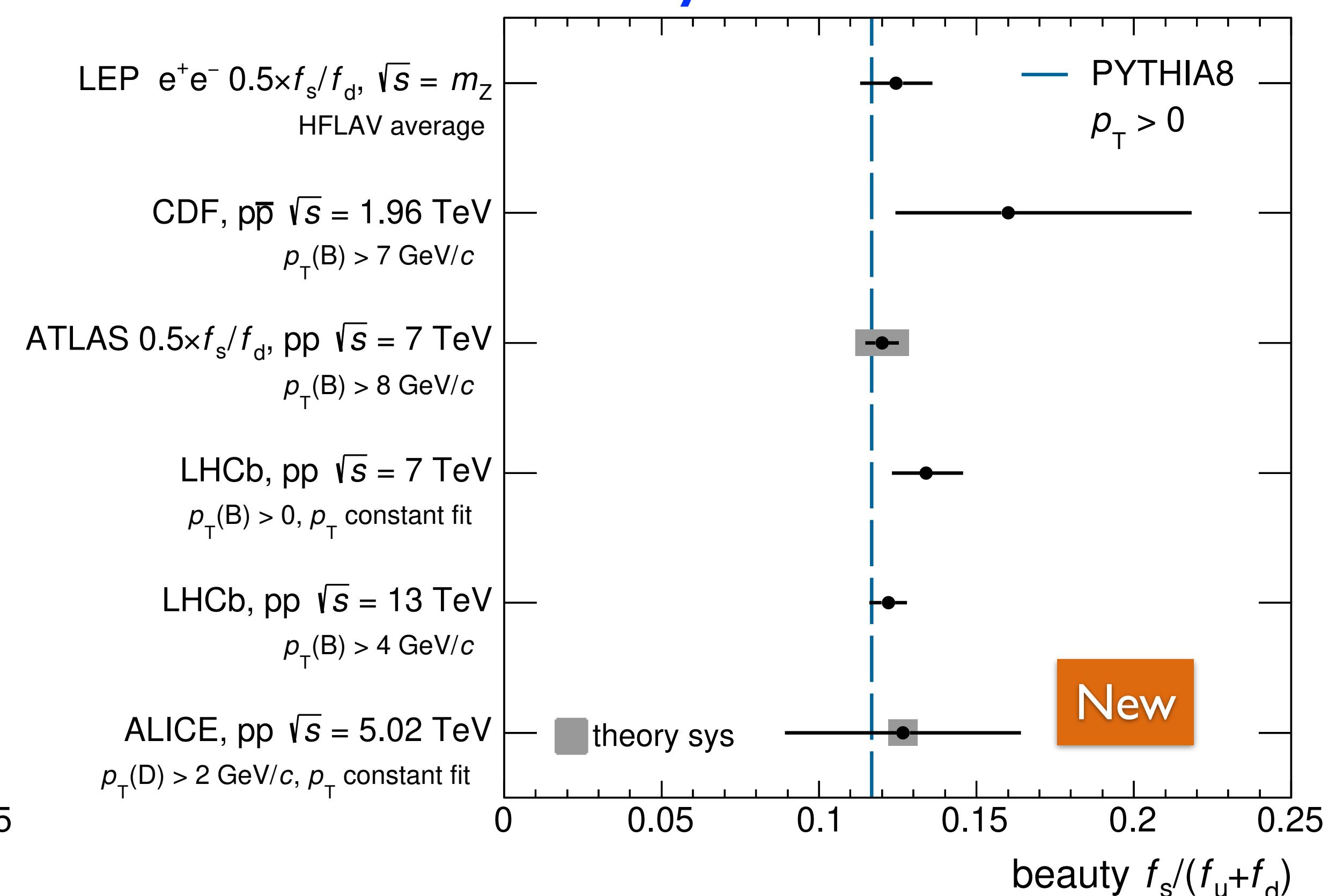
- Fragmentation fraction ratios for charm and beauty mesons compatible
- No significant dependence on energy and collision system

$D_s^+/(D^0 + D^+)$

Charm



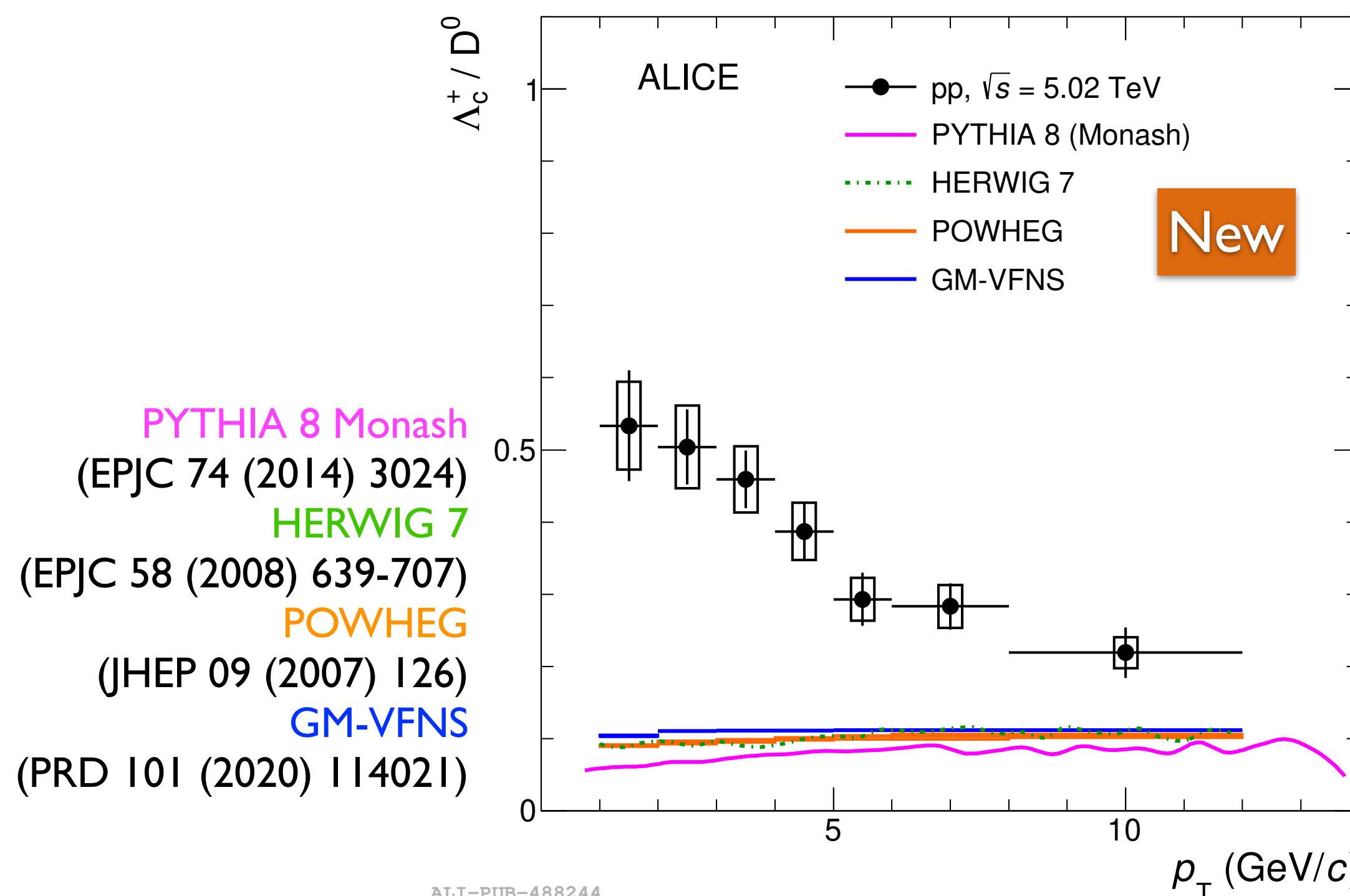
Beauty



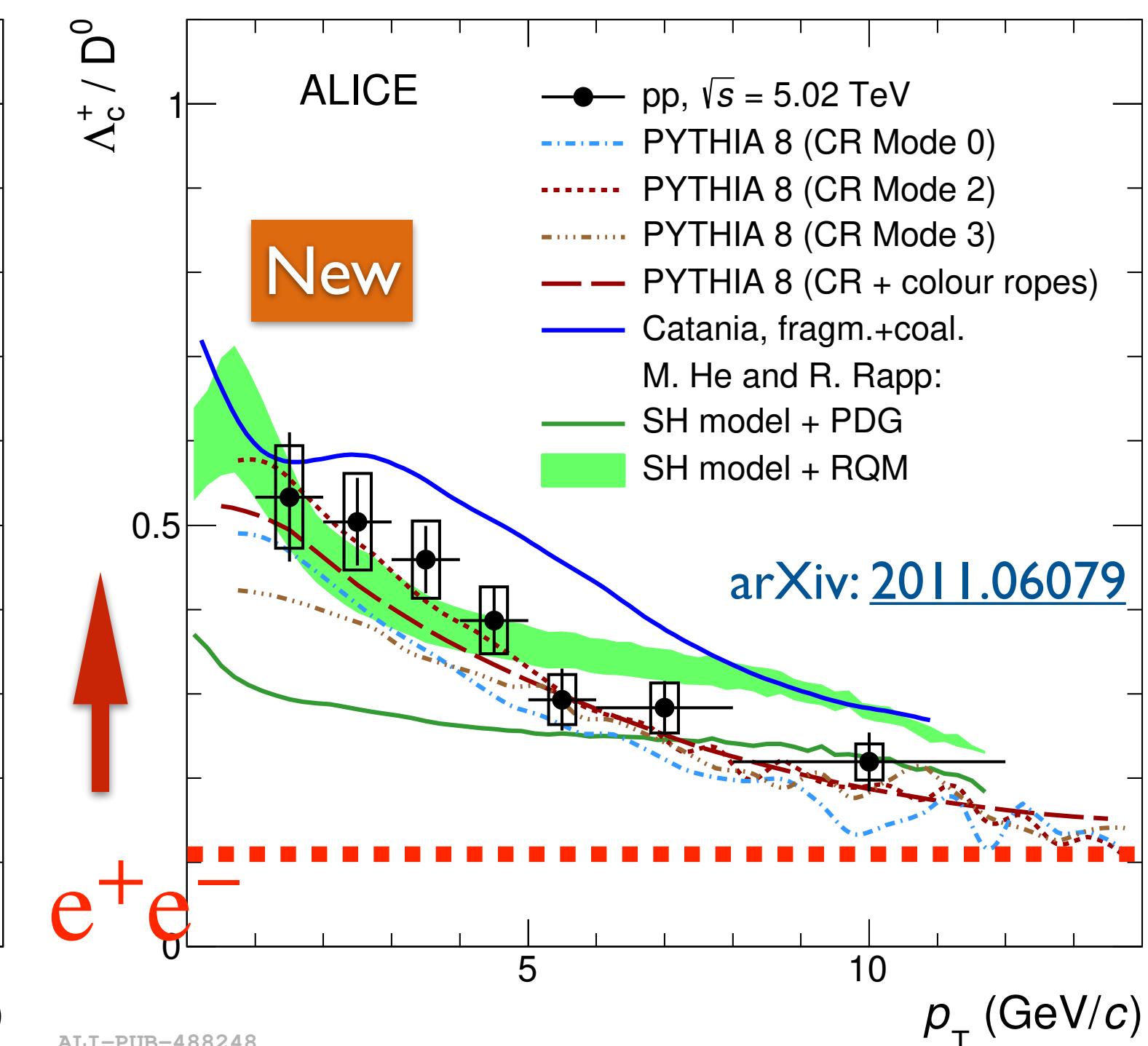
arXiv: 2102.13601

Charm-baryons: Λ_c^+

- Λ_c^+/\bar{D}^0 in pp collisions at 5.02 TeV compared with models that enhance the baryon formation
 - PYTHIA 8 with CR beyond leading color approximation (Mode 0, Mode 2, Mode3)
 - Catania with coalescence + fragmentation
 - M.He and R.Rapp+RQM: statistical hadronization model (SHM) approach



- HERWIG 7 with hadronization implemented via clusters
- POWHEG matched to PYTHIA 6 to generate parton shower
- GM-VFNS pQCD calculation: same choice of pQCD scales for Λ_c^+ and D^0

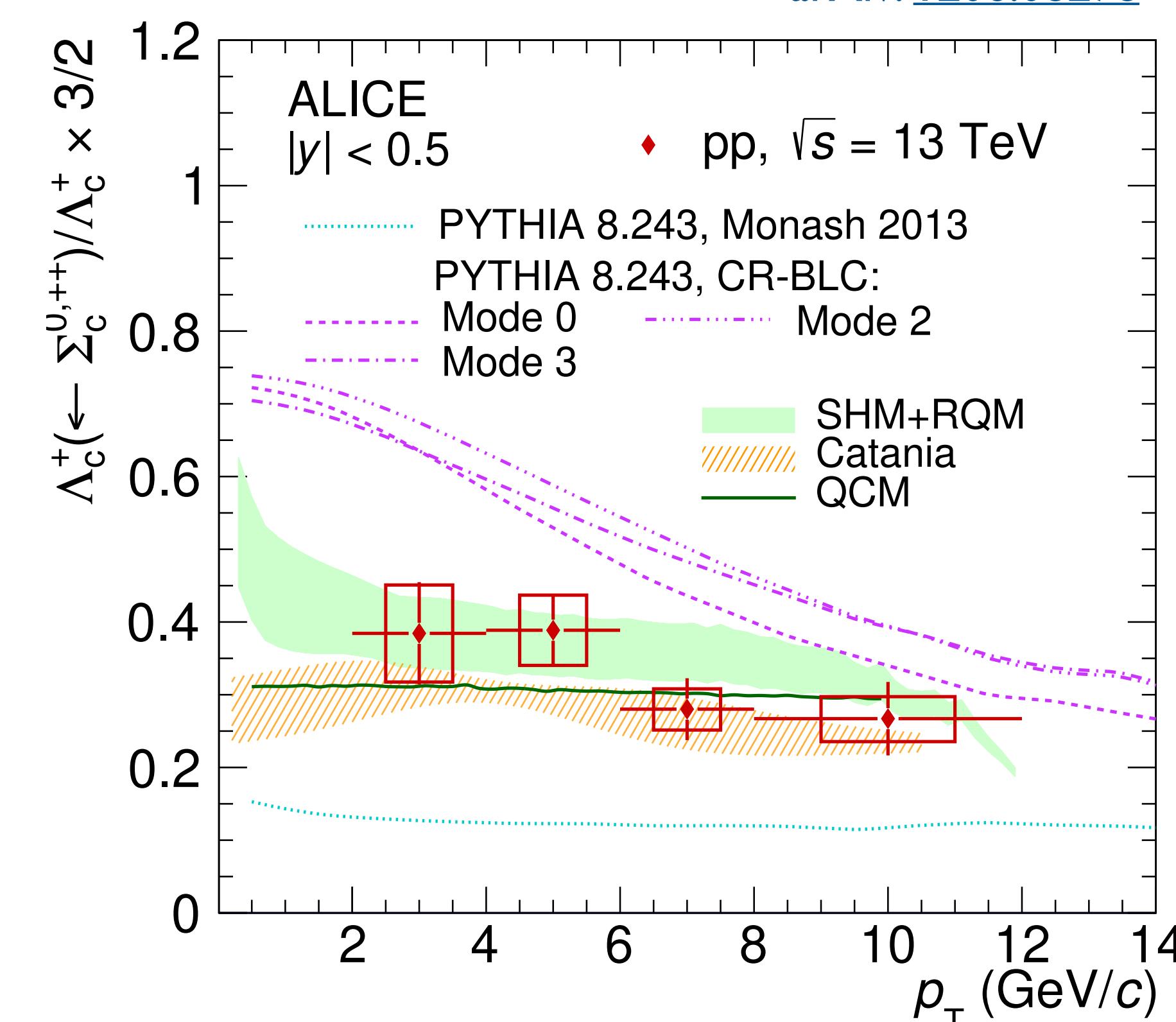
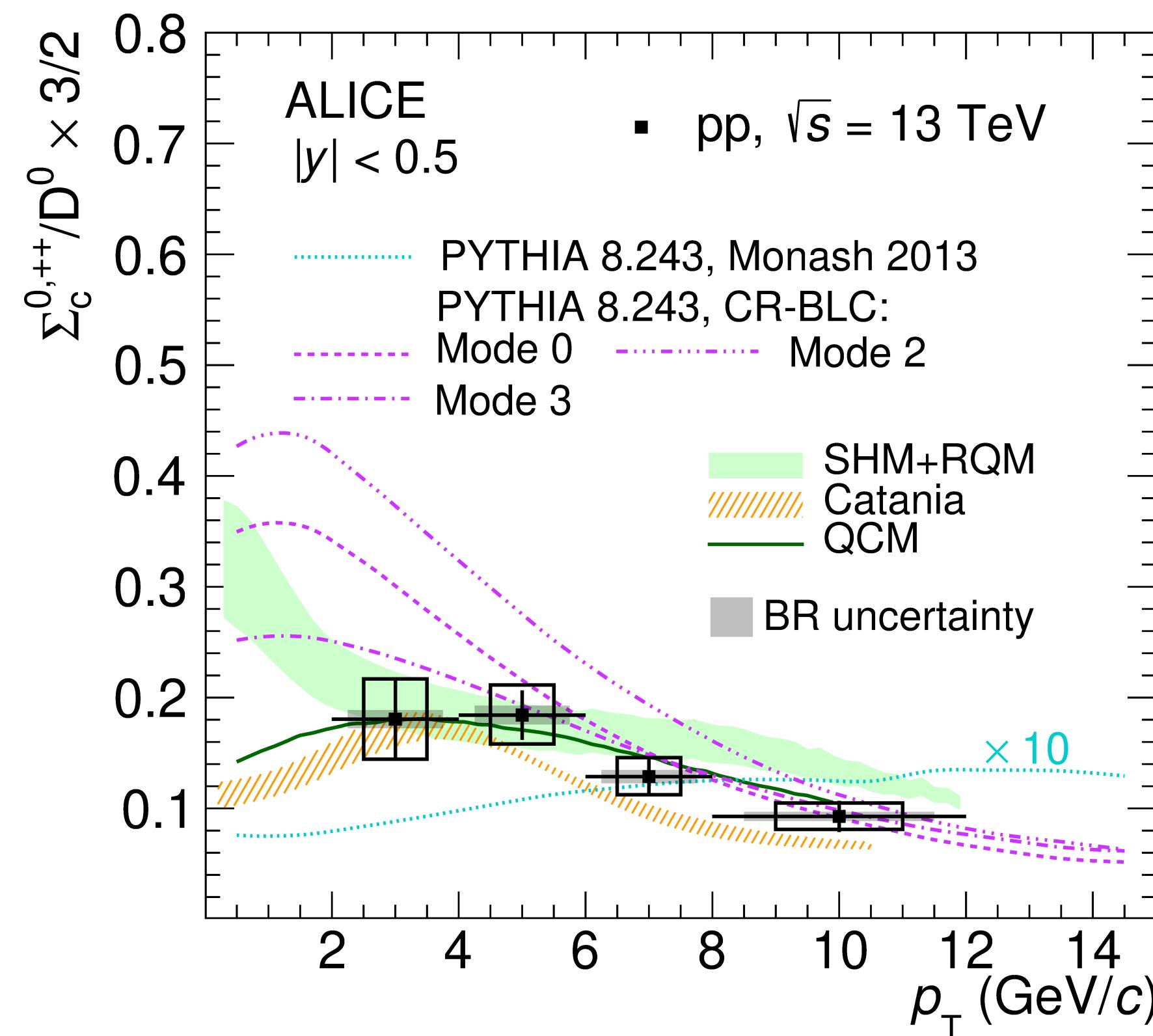


Charm baryon-to-meson ratio shows clear p_T dependence and is larger than e^+e^-

Charm-baryons: $\Sigma_c^{0,++}$

- $\Sigma_c^{0,++}/D^0$ and $\Lambda_c^+(\leftarrow \Sigma_c^{0,++})/\Lambda_c^+$ in pp collisions at 13 TeV
 - $\Sigma_c^{0,++}/D^0$ partially accounts for the Λ_c^0/D^0 enhancement in pp collisions
 - $\Sigma_c^{0,++}/D^0$ is well described by SHM+RQM and QCM
 - $\Lambda_c^+(\leftarrow \Sigma_c^{0,++})/\Lambda_c^+$ is overestimated by CR modes

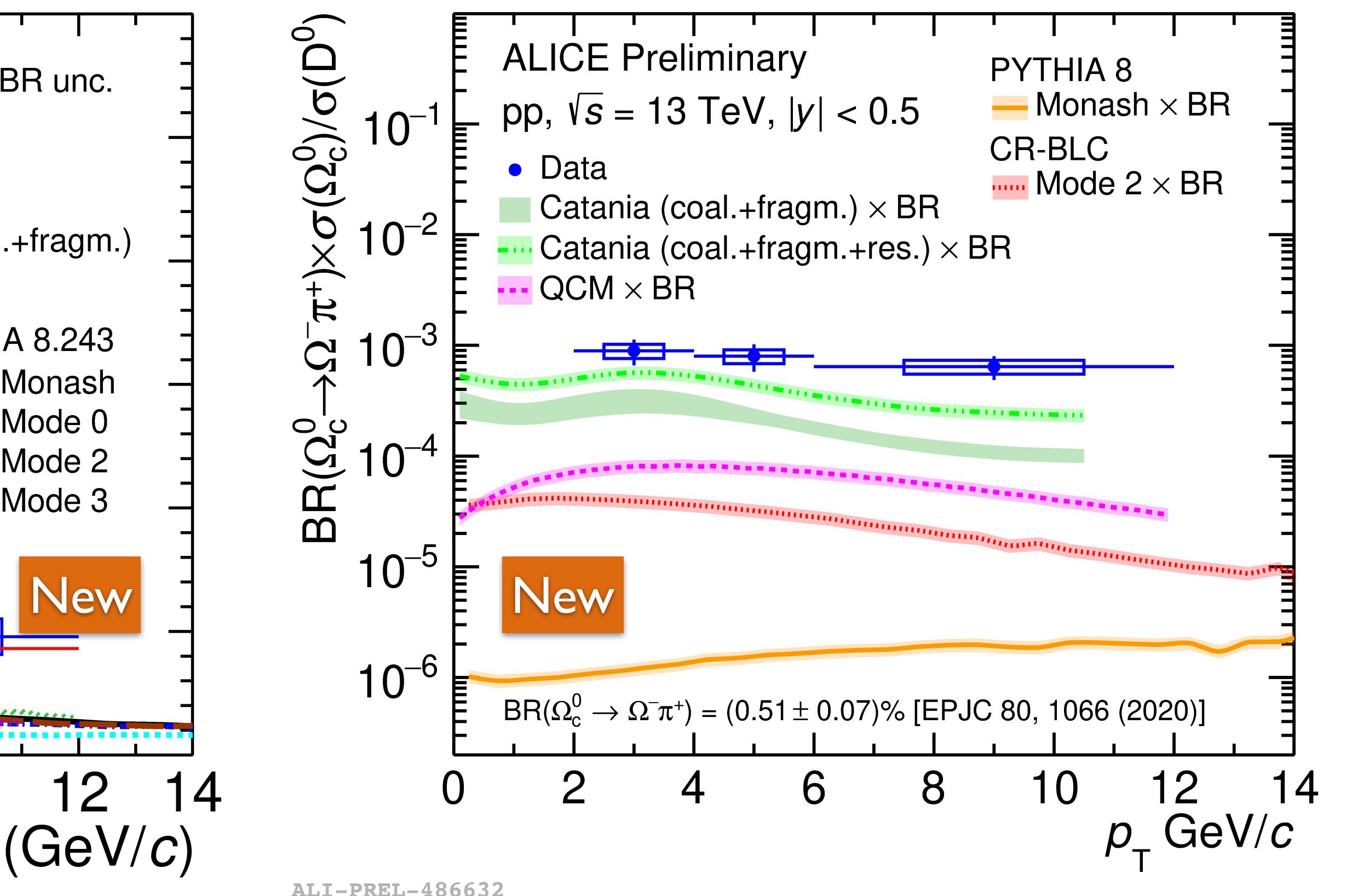
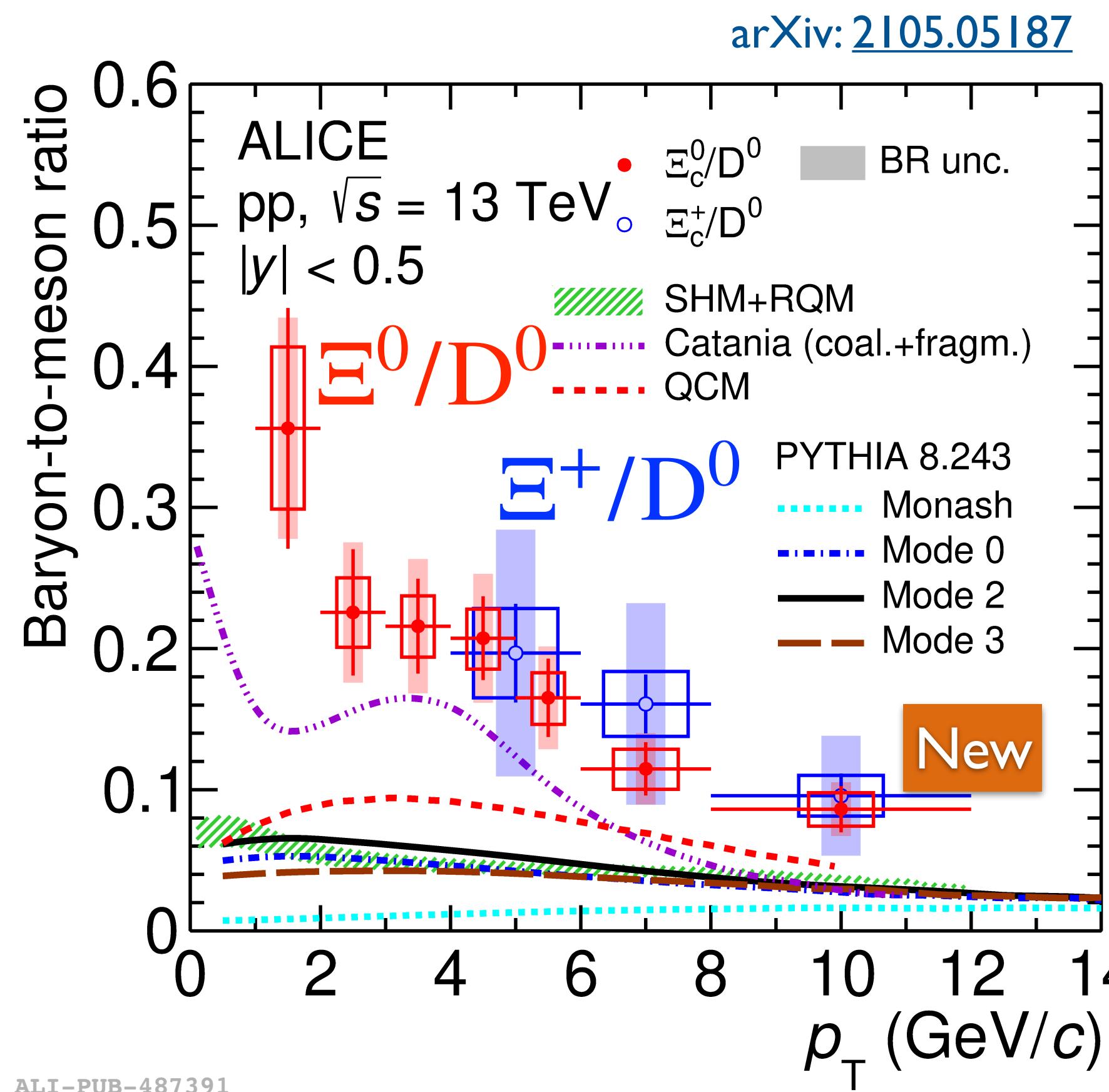
arXiv: [1206.08278](https://arxiv.org/abs/1206.08278)



PYTHIA 8 Monash
 (EPJC 74 (2014) 3024)
PYTHIA 8 CR Modes
 (JHEP 08 (2015) 003)
SHM+RQM
 (PLB 795 (2019) 117-121)
Catania
 (arXiv: 2012.12001)
QCM
 (EPJC 78 no.4, (2018) 344)

Charm-baryons: $\Xi_c^{0,+}$ & Ω_c^0

- $\Xi_c^{0,+}/D^0$, $(BR \times \Omega_c^0)/D^0$ in pp collisions at 13 TeV
 - PYTHIA 8: even with enhanced CR tunes, still underestimate the data
 - Coalescence models: largest Ω_c^0 enhancement

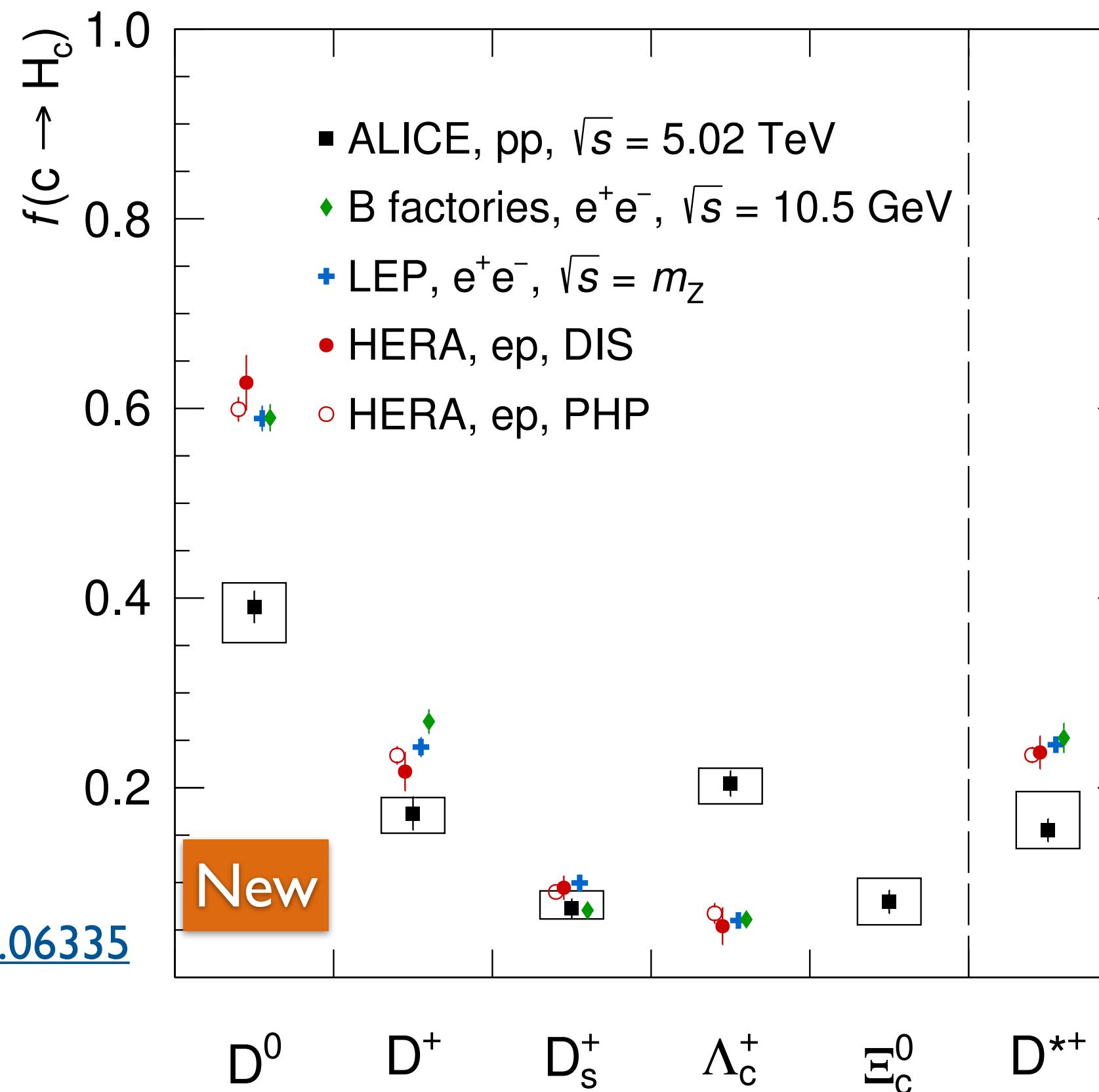


Charm fragmentation fractions

- Now enable to measure charm FF and charm total cross section

- D^0 and D^+ measured down to $p_T = 0$
- $\Xi_c^{0,+}$ included for the first time
- Consider twice Ξ_c^0 contribution to included Ξ_c^+

Fragmentation fraction $f(c \rightarrow H_c)$ NOT universal
 → Significant baryon enhancement in pp collisions

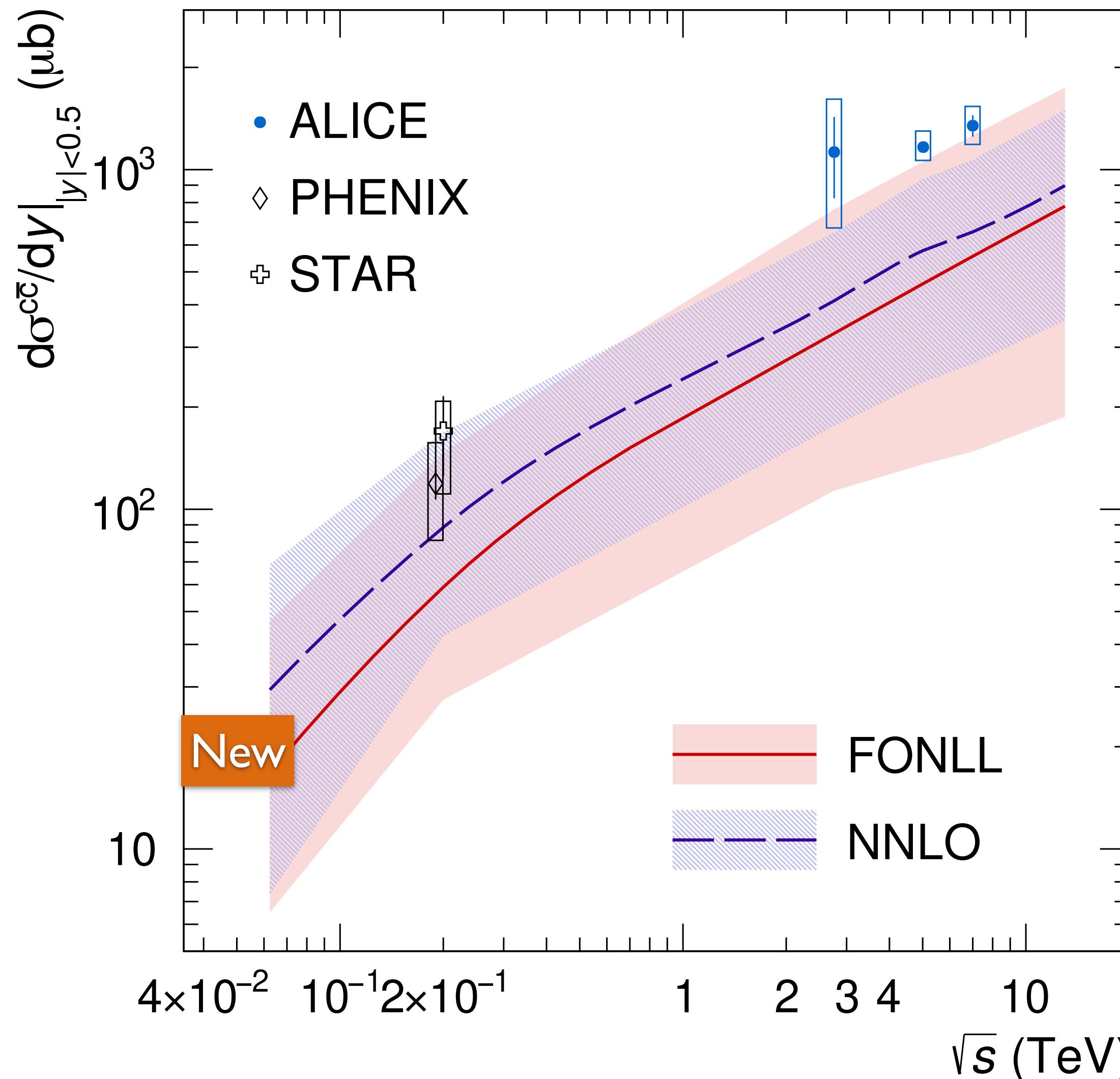


H_c	$f(c \rightarrow H_c)[\%]$
D^0	$39.1 \pm 1.7(\text{stat})^{+2.5}_{-3.7}(\text{syst})$
D^+	$17.3 \pm 1.8(\text{stat})^{+1.7}_{-2.1}(\text{syst})$
D_s^+	$7.3 \pm 1.0(\text{stat})^{+1.9}_{-1.1}(\text{syst})$
Λ_c^+	$20.4 \pm 1.3(\text{stat})^{+1.6}_{-2.2}(\text{syst})$
Ξ_c^0	$8.0 \pm 1.2(\text{stat})^{+2.5}_{-2.4}(\text{syst})$
D^{*+}	$15.5 \pm 1.2(\text{stat})^{+4.1}_{-1.9}(\text{syst})$

- Sum of FFs add up to unity, not counting here D^{*+} , which feeds into D^0 , D^+

Charm total production cross section

arXiv: 2105.06335



ALI-PUB-488622

Baryon-to-meson ratio in p-Pb and $\Lambda_c^+ R_{p\text{Pb}}$

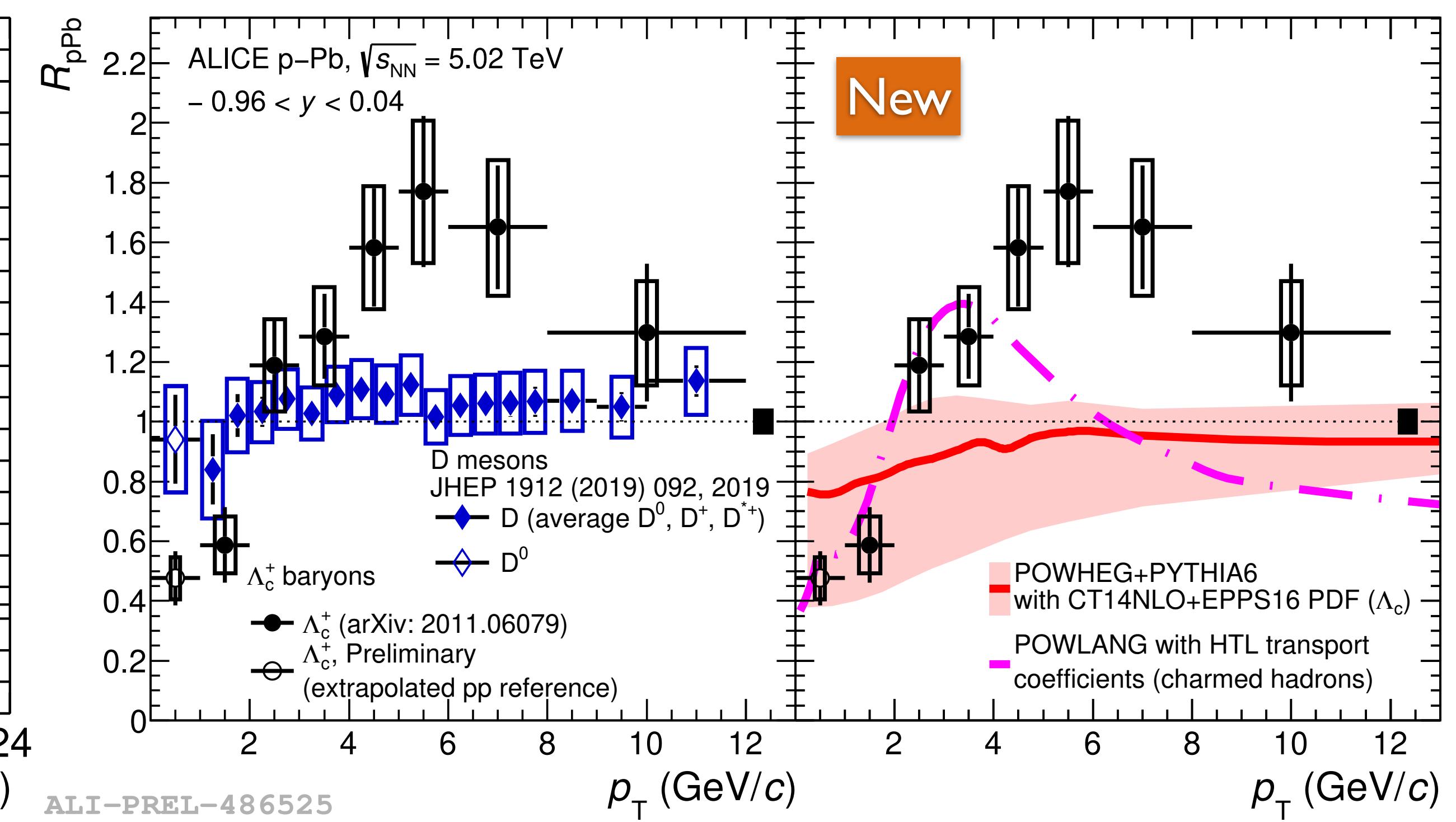
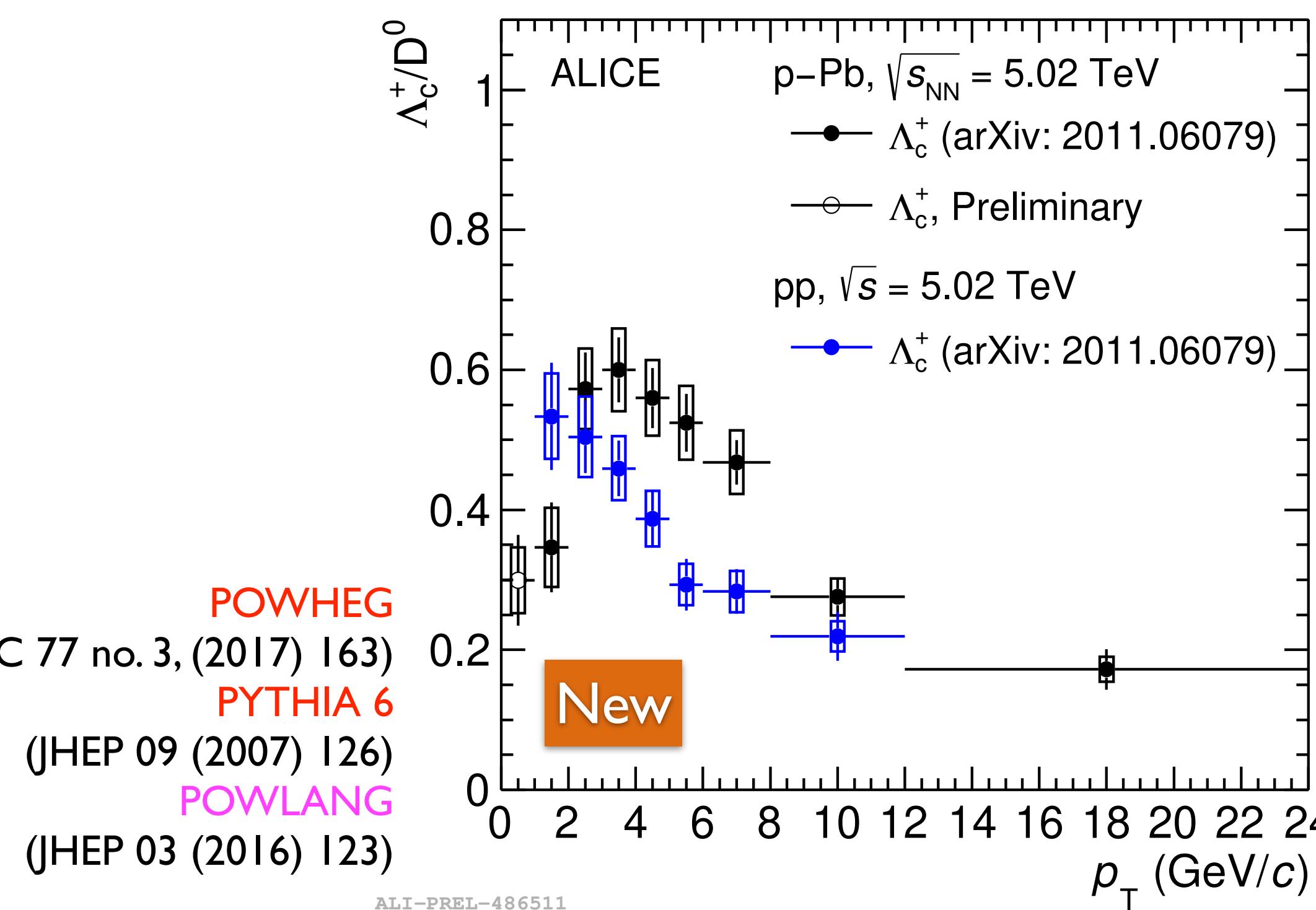


- First measurement of Λ_c^+ down to $p_T = 0$ in p-Pb collisions

- Λ_c^+/D^0 : larger in mid- p_T and lower in $p_T < 2 \text{ GeV}/c$ in p-Pb collisions w.r.t. pp collisions
- $R_{p\text{Pb}}(\Lambda_c^+)$: systematically above unity in $p_T > 2 \text{ GeV}/c$
but significant suppression in $p_T < 2 \text{ GeV}/c$

→ Possible modification due to radial flow or hadronization mechanism?

arXiv: 2011.06079

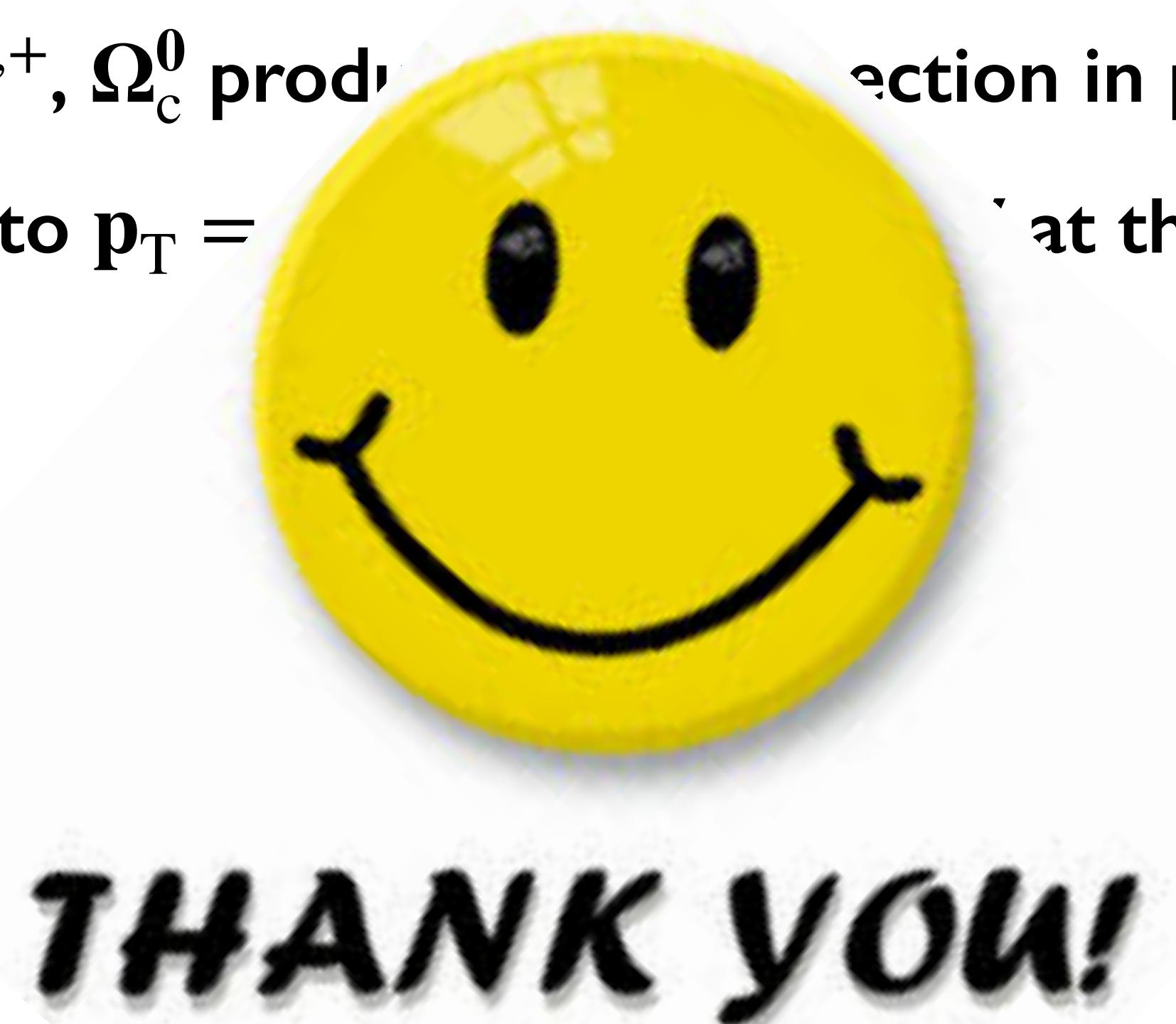


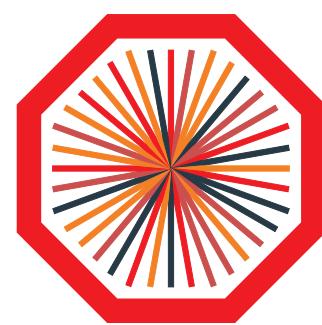
Summary

- First measurement of $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$, Ω_c^0 production cross section in pp at 13 TeV
- First measurement of Λ_c^+ down to $p_T = 0$ in p-Pb at 5.02 TeV at the LHC
- Large enhancement of all charm-baryon production in pp collisions than e^+e^- collisions
- Charm fragmentation fractions are NOT universal
- Total charm cross section in pp@ 5.02 TeV using all measured charm hadron states
- ALICE upgrade for Run3/4 will offer the opportunity to further investigate the charm-baryon production

Summary

- First measurement of $\Sigma_c^{0,++}$, $\Xi_c^{0,+}$, Ω_c^0 production in pp at 13 TeV
- First measurement of Λ_c^+ down to $p_T = 10$ GeV at the LHC
- Large enhancement of all charm cross sections in e^+e^- collisions
- Charm fragmentation fraction in hadron states
- Total charm cross section in hadron states
- ALICE upgrade for Run3/4 will offer improved capabilities to investigate the charm-baryon production



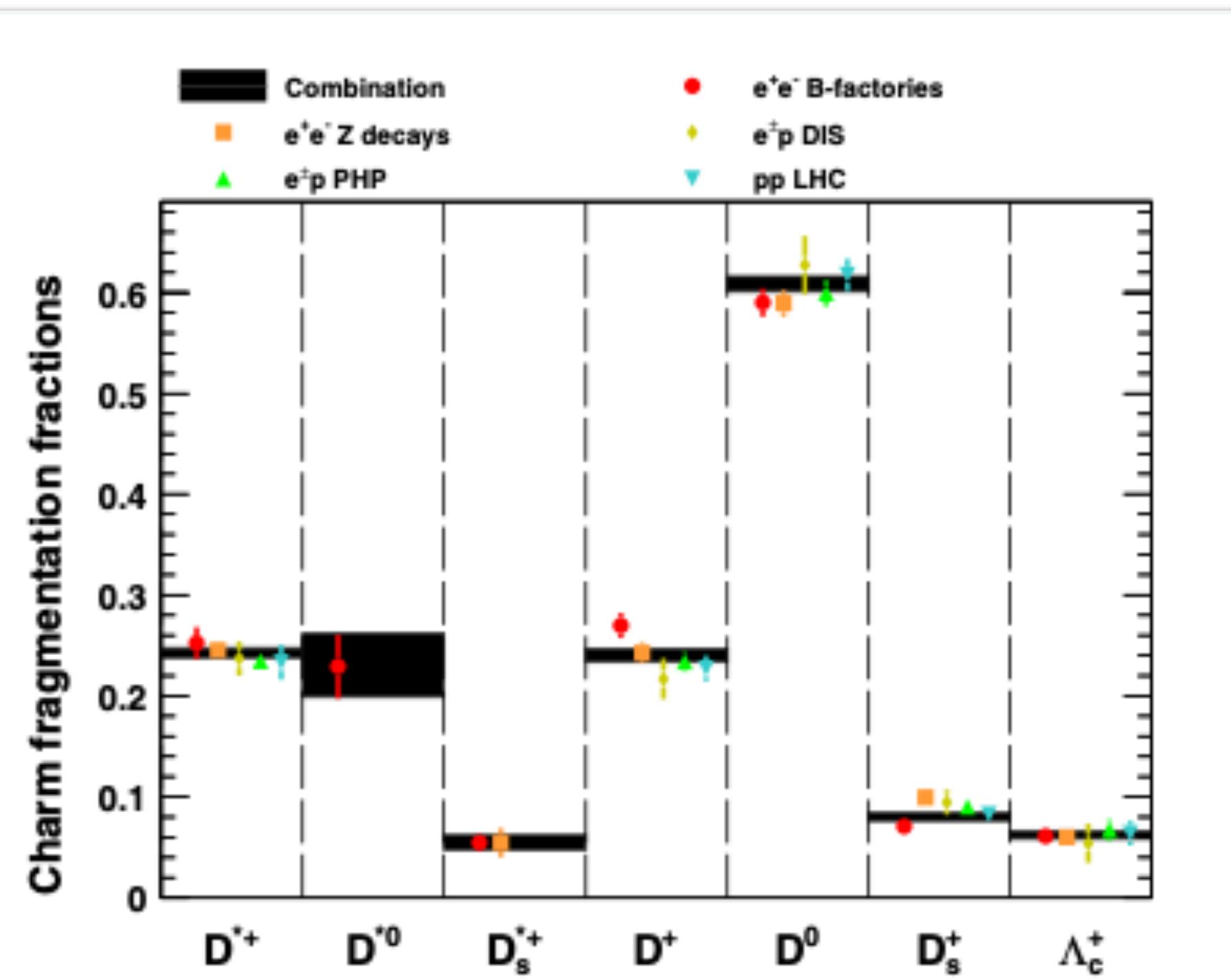


ALICE

Additional Slides

Charm FF in e^+e^- & ep

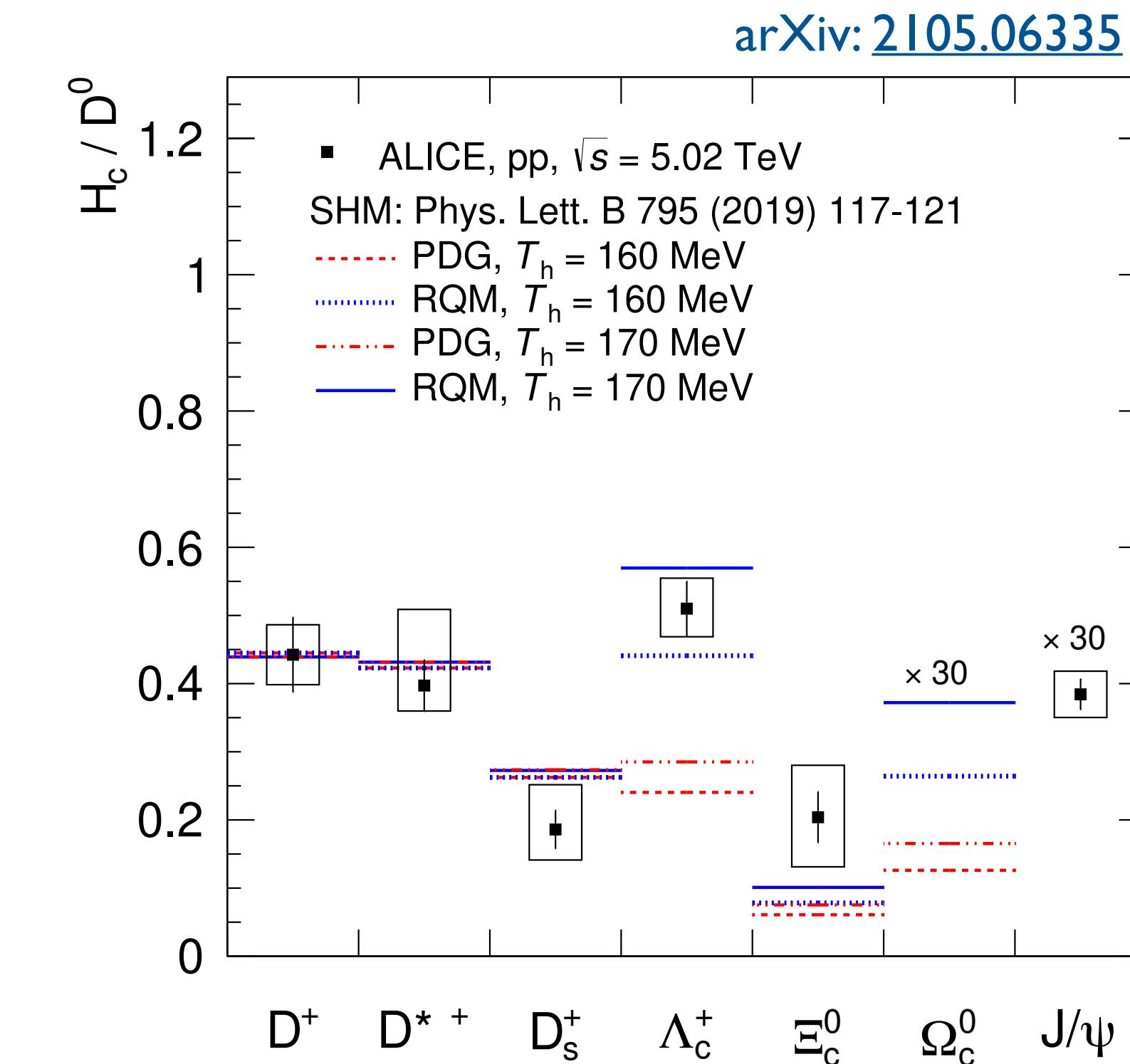
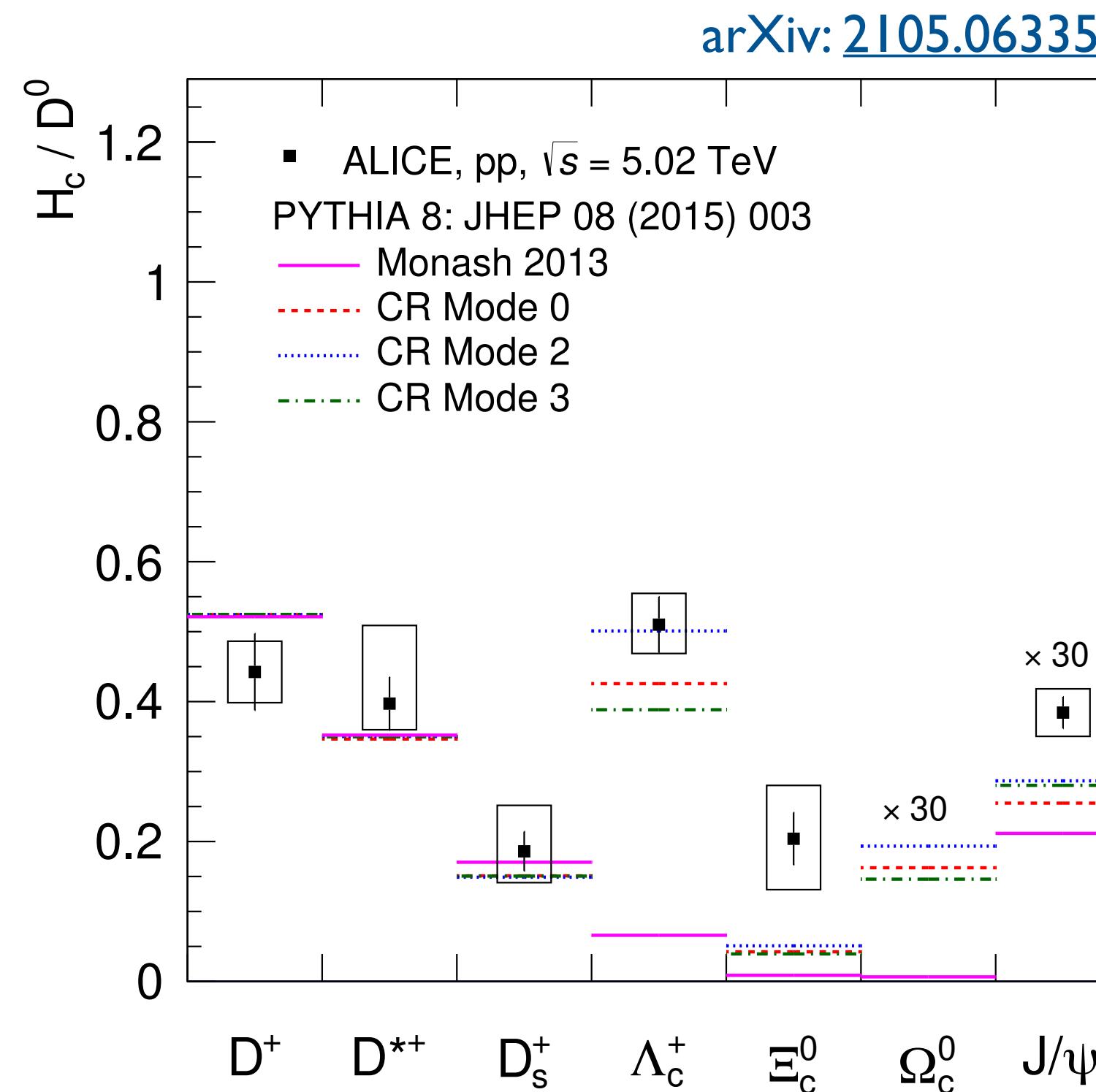
Eur. Phys. J. C76 (2016) no.7, 397



- In 2015, only LHCb Λ_c^+ measurement available at LHC for charm baryons
 - Consistent with e^+e^- - - - FF universal
- Caveat
 - No measurement of $\sigma(\Sigma_c)$, $\sigma(\Xi_c)$, and $\sigma(\Omega_c)$
- But now we have all of them in ALICE

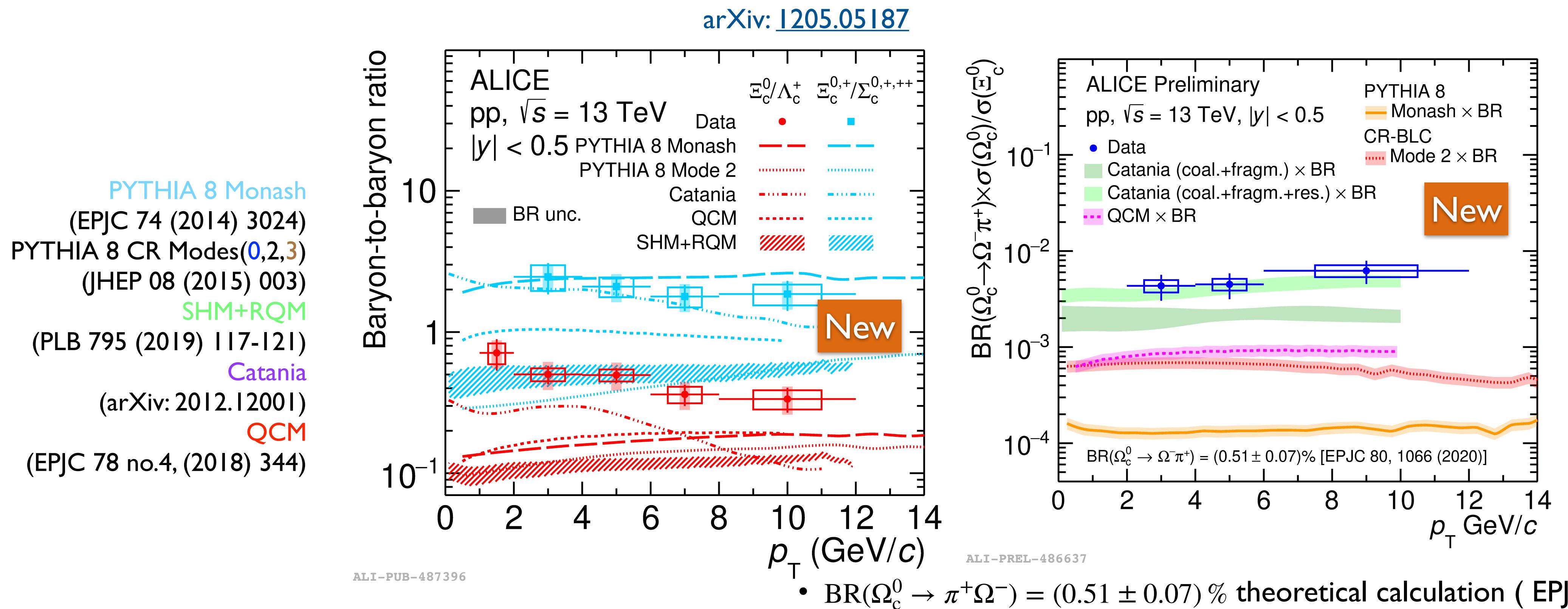
Charm H_c/D^0 ratios

- PYTHIA 8 with different tunes similar for D mesons and describe measurements within uncertainties
- Large effect found in PYTHIA 8 CR-BLC for charm baryons formation
- SHM for charm **mesons**: small variations with two T_c and consistent with measurements
- SHM for charm **baryons**: significant variations with two T_c and large variations with RQM



Charm-baryon $\Xi_c^{0,+}$ & Ω_c^0

- Ξ_c^0/Λ_c^+ , $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$, $(BR \times \Omega_c^0)/D^0$ in pp collisions at 13 TeV
 - $\Xi_c^{0,+}/\Sigma_c^{0,+,++}$: Catania and Monash describe the magnitude
- First measurement of charm baryon-to-baryon yield ratios at the LHC
- Similar enhancement for $\Xi_c^{0,+}$ and $\Sigma_c^{0,++}$, further enhancement for Ω_c^0 w.r.t e^+e^- collisions

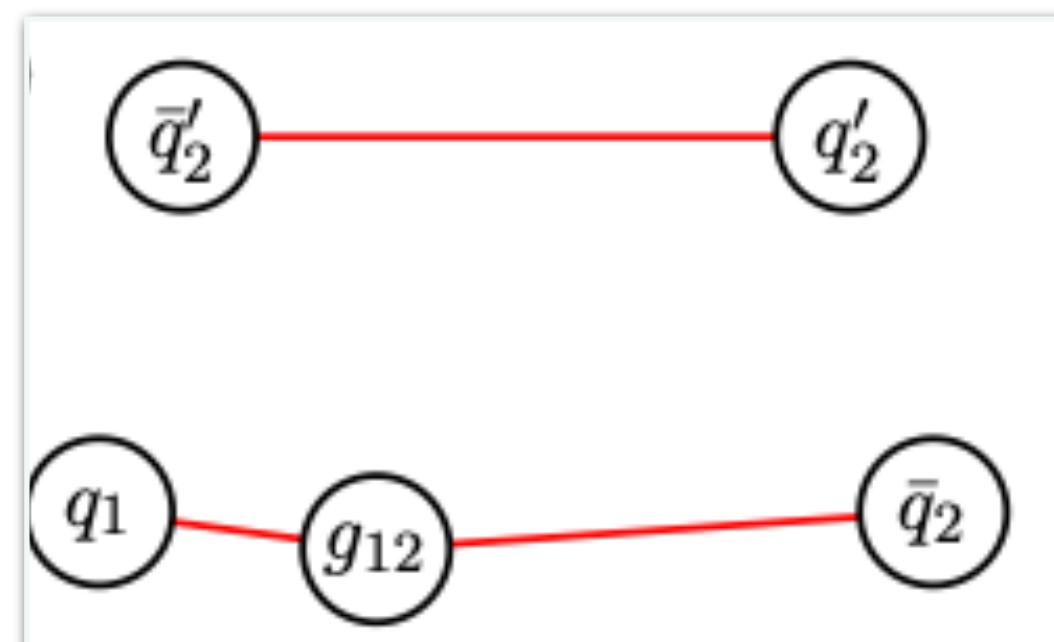


HF baryon enhancement mechanism

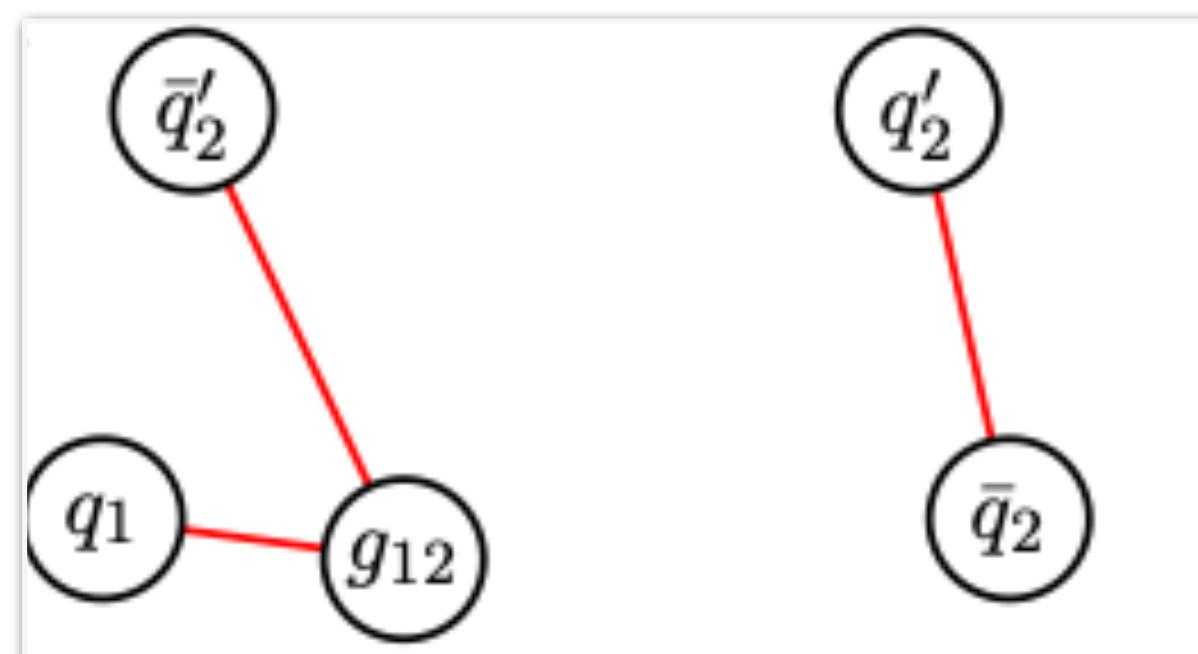
- PYTHIA 8 with Colour Reconnection (CR) tunes JHEP 08 (2015) 003

- Colour reconnection mode with QCD SU(3) topology weights + string-length minimization
- Junction connection topologies enhance baryon formation
- Mode parameters: string reconnection, connection causality of dipoles, time dilation

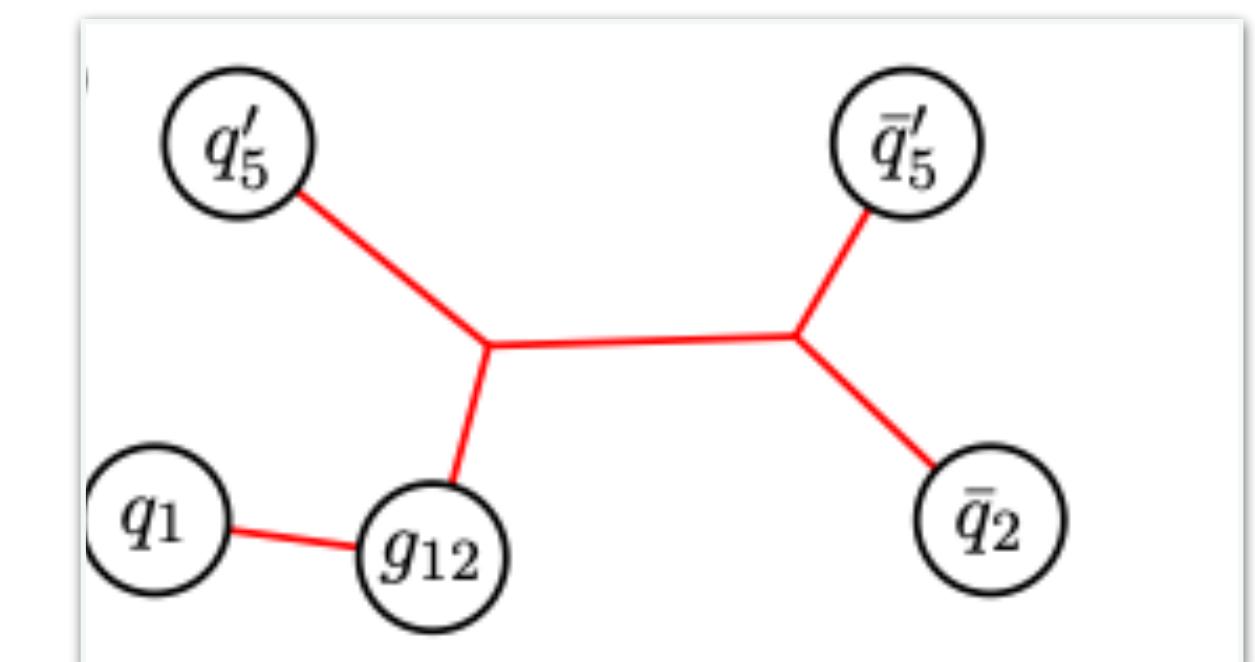
No CR



Old CR



New CR



- Partons created in different MPIs do not interact
- CR allowed between partons from different MPIs to minimize string length
- Used in Monash tune
- Minimization of the string length over all possible configuration
- Enhancement of hadrons
- Used in CR mode X tunes

HF baryon enhancement mechanism

- **Statistical Hadronization Model (SHM) + additional baryon states** PLB 795 (2019) 117-121
 - PDG: 5 $\Lambda_c(l=0)$, 3 $\Sigma_c(l=1)$, 8 $\Xi_c(l=l/2)$, 2 $\Omega_c(l=0)$
 - RQM (Relativistic Quark Model): Add 18 Λ_c , 42 Σ_c , 62 Ξ_c , 34 Ω_c PRD 84 (2011) 014025
- **Quark Recombination Mechanism (QCM)** EPJC 78 no. 4 (2018) 344
 - Combination of charm quarks with co-moving light quarks
- **Catania model** arXiv: 2012.12001
 - Coalescence process of heavy quarks with light quark based on the Wigner formalism + fragmentation process
 - Blast wave parametrization for light quarks spectra, FONLL calculation for heavy quarks spectra

Charmed baryons

Particle	Mass	Valence quarks
Λ_c^+	2.286	udc
$\Sigma_c^{0,++}$	2.455	ddc, uuc
Ξ_c^+	2.467	usc
Ξ_c^0	2.471	dsc
Ω_c^0	2.695	ssc
Ξ_c^{++}	3.621	ucc