Open charm production cross section from combined LHC experiments

Jacek Otwinowski (IFJ PAN)

Various faces of QCD,
Wrocław, 26-28.04.2024

OUTLINE

- Heavy-flavour measurements
- Open charm hadrons at LHC
- Charm cross section
- Summary and Outlook

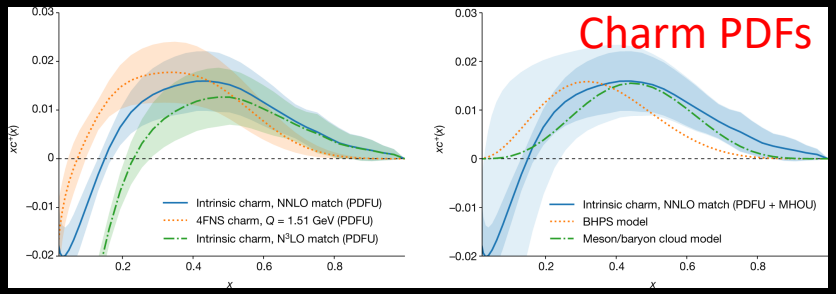
Focus on charm production in pp collisions!

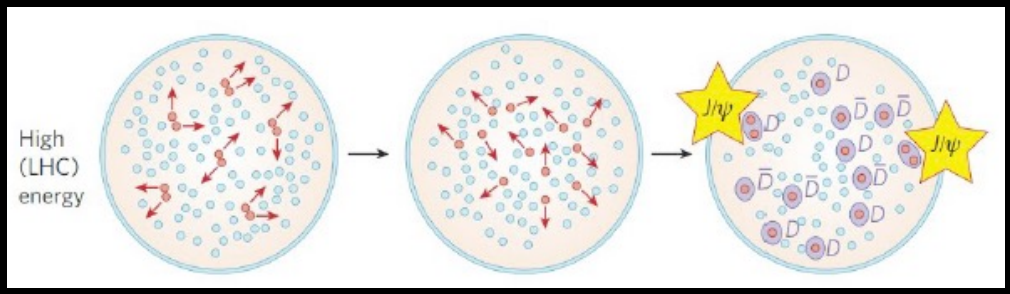
Heavy flavor measurements

- Ideal probes of initial- and final-state effects on particle production in pp, p-A and A-A
  - Parton Distribution Functions
  - Parton energy loss
  - Hadronization mechanisms (fragmentation/coalescence/dissociation/(re)generation)
- Important for testing perturbative QCD

→ Intrinsic charm in the proton, NNPDF Coll. *Nature* **608**, 483–487 (2022)
→ Dead-cone measurement for charm quark, ALICE Coll. *Nature* **605**, 440–446 (2022)
→ Baryon vs meson hadronization mechanism, ALICE Coll. Phys. Rev. Lett. 127 (2021) 202301

Transport and thermodynamic properties of the Quark-Gluon Plasma





Open charm hadrons at LHC

Measurements in pp collisions

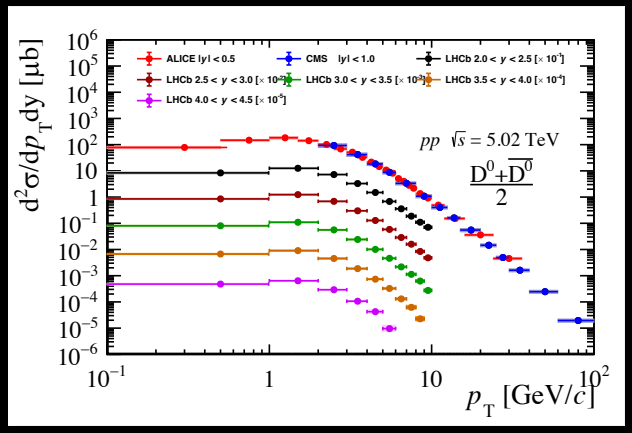
Experiment/ √s (TeV)	ALICE	ATLAS	CMS	LHCb
2.76	D^0, D^+, D^{*+}	-	-	-
5.02	D^0, D^+, D^{*+}, D_S^+, Λ_C^+, Ξ_C^0	-	D^0, Λ_C^+	D^0, D^+, D^{*+}, D_S^+
7	D^0, D^+, D^{*+}, D_S^+, Λ_C^+	D^+, D^{*+}, D_S^+	D^0, D^+, D^{*+}	D^0, D^+, D^{*+}, D_S^+, Λ_C^+
13	D^0, D^+, D^{*+}, D_S^+, Λ_C^+, $\Xi_C^{0,+}$, $\Sigma_C^{0,++}$, Ω_C^0	-	D^0, D^+, D^{*+}	D^0, D^+, D^{*+}, D_S^+

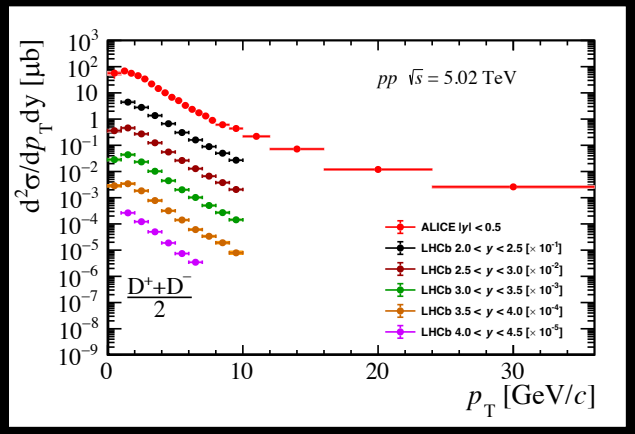
- Prompt open charm mesons and baryons (and their charge conjugates) are measured at central and forward rapidity and over wide p_T range

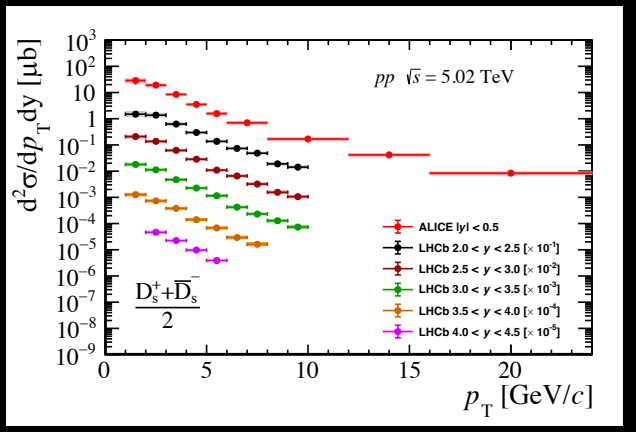
→ Total charm cross section determination using combined results from LHC experiments

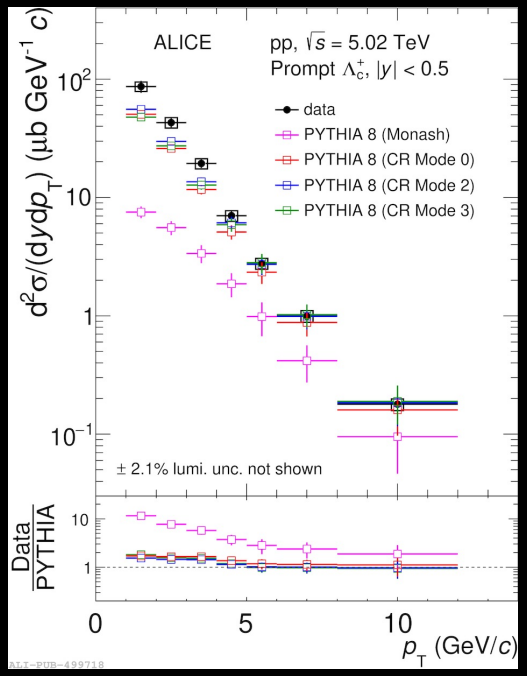
Open charm hadrons in pp at 5 TeV

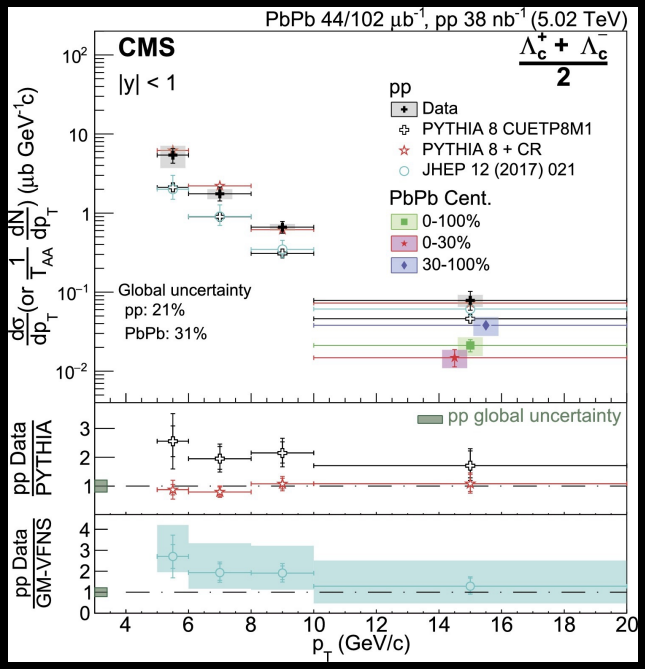
ALICE Eur.Phys.J. C79 (2019) no.5, 388, JHEP 05 (2021) 220, CMS Phys. Lett. B782 (2018) 474-493 LHCb JHEP06 (2017) 147

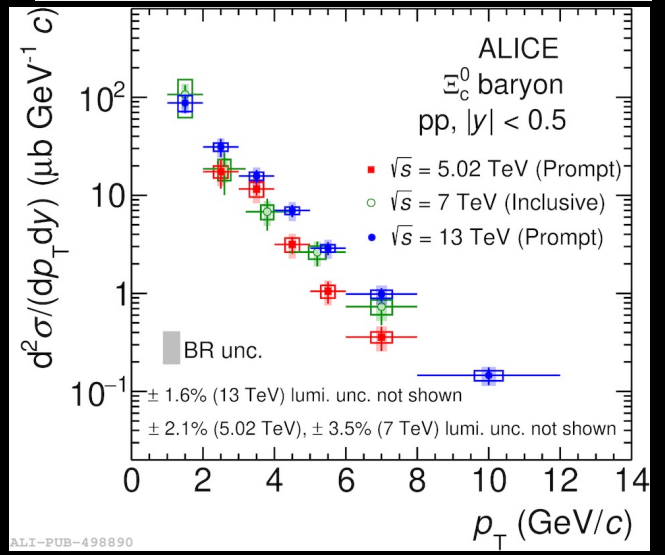








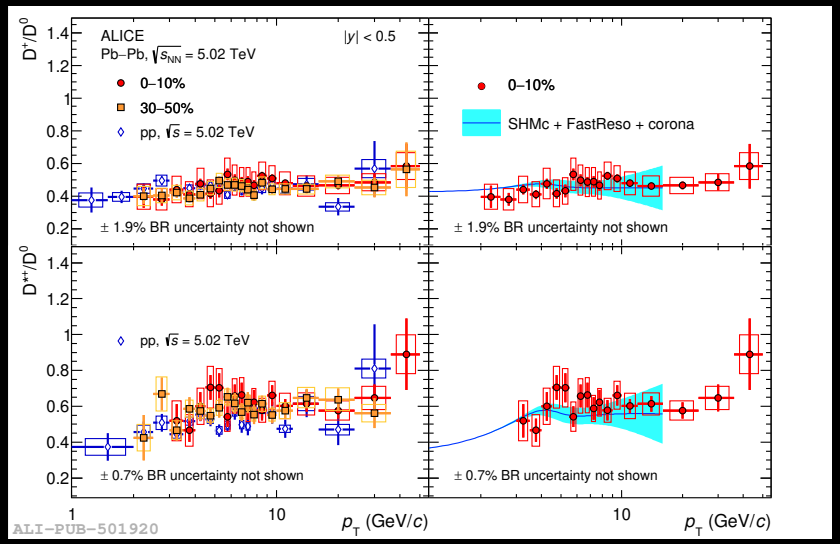




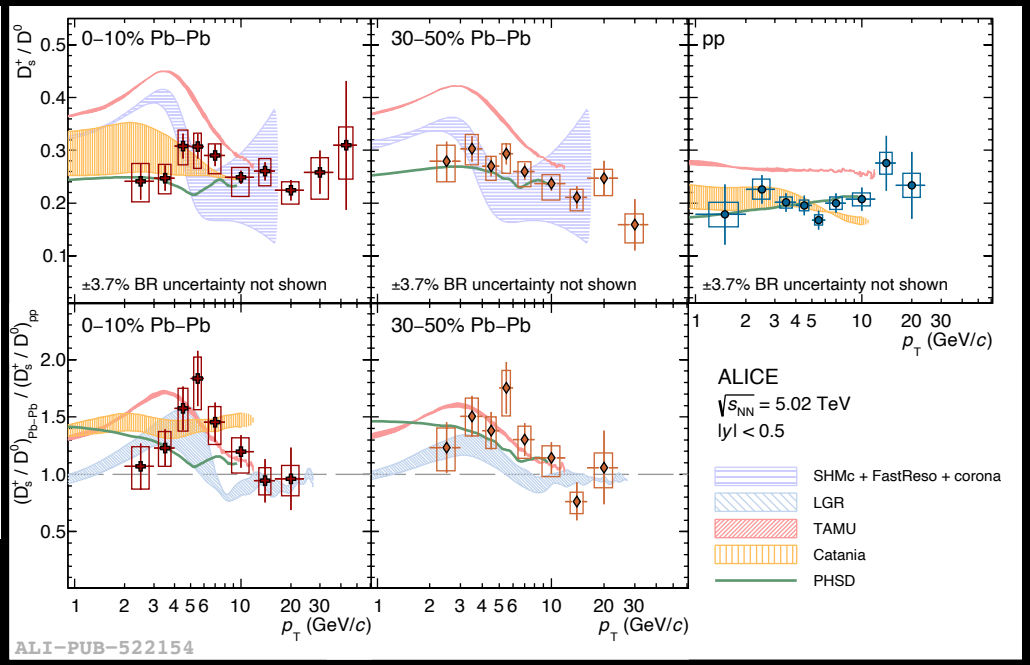
ALICE Phys. Rev. C 104 (2021) 054905
JHEP 10 (2021) 159
CMS Phys. Lett. B 803 (2020) 135328

D meson ratios in pp and Pb-Pb

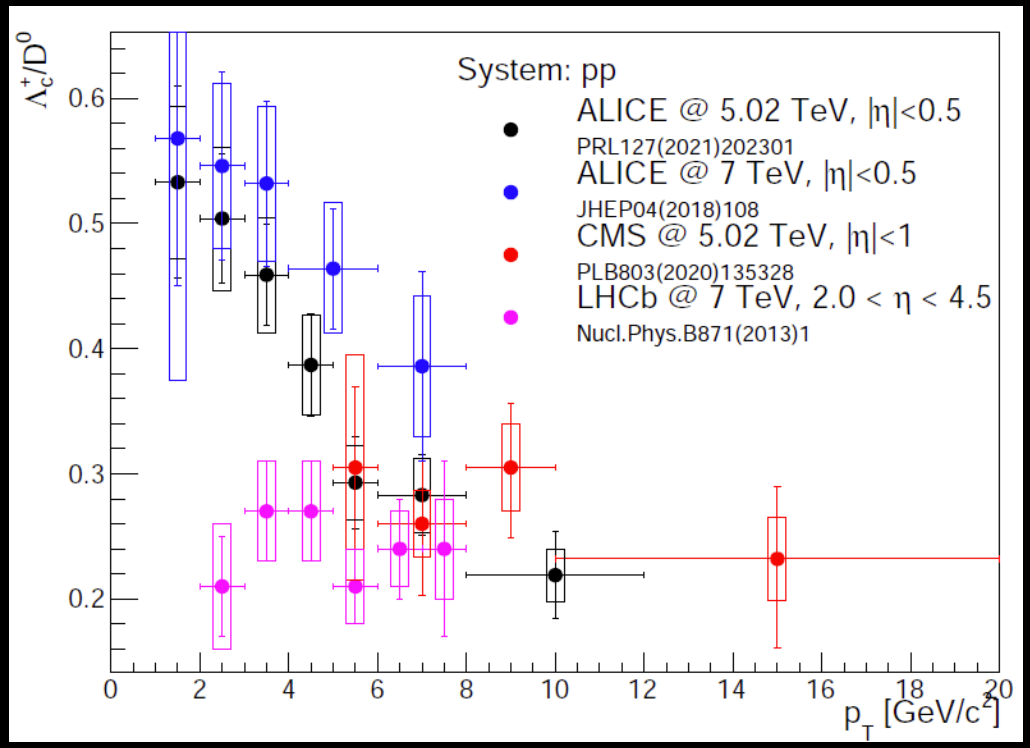
ALICE JHEP 2022, 174 (2022)



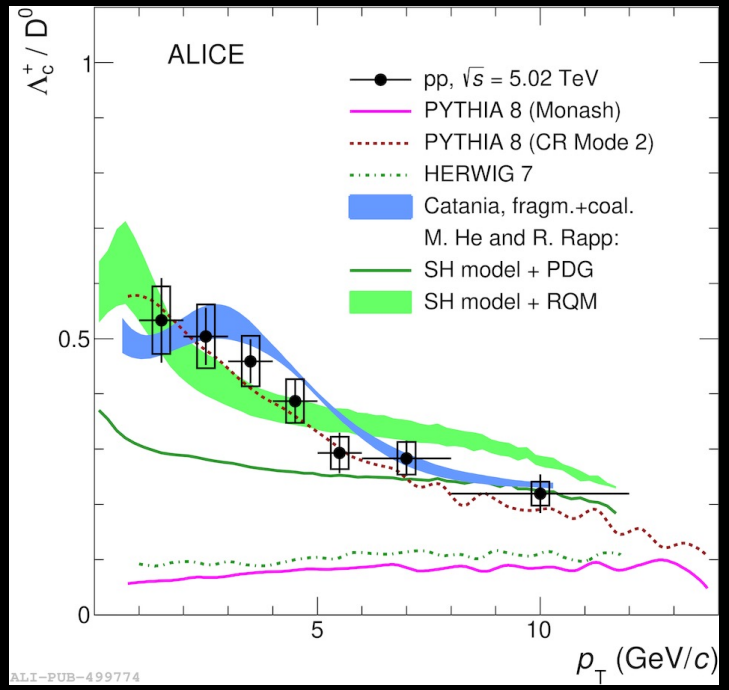
ALICE Phys. Lett. B 827 (2022) 136986



Λ_c vs D^0 hadronization mechanism



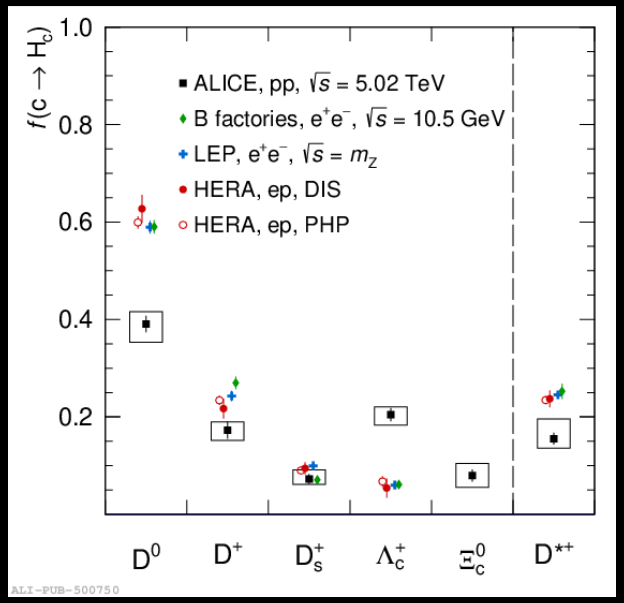
ALICE, Phys. Rev. Lett. 127 (2021) 202301

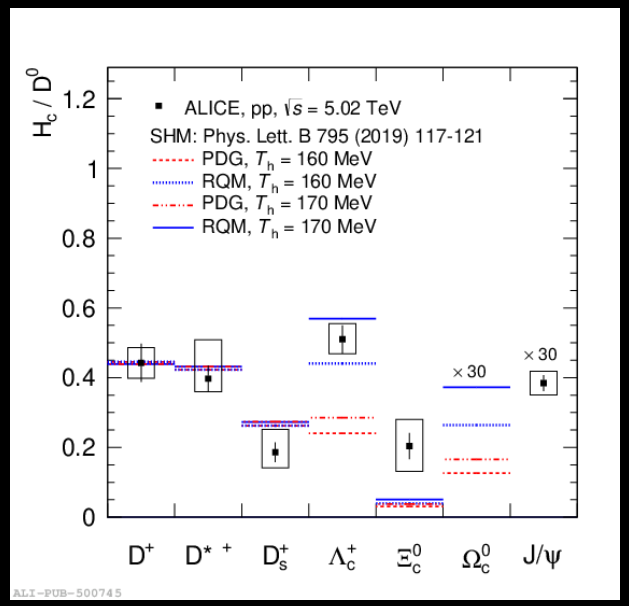


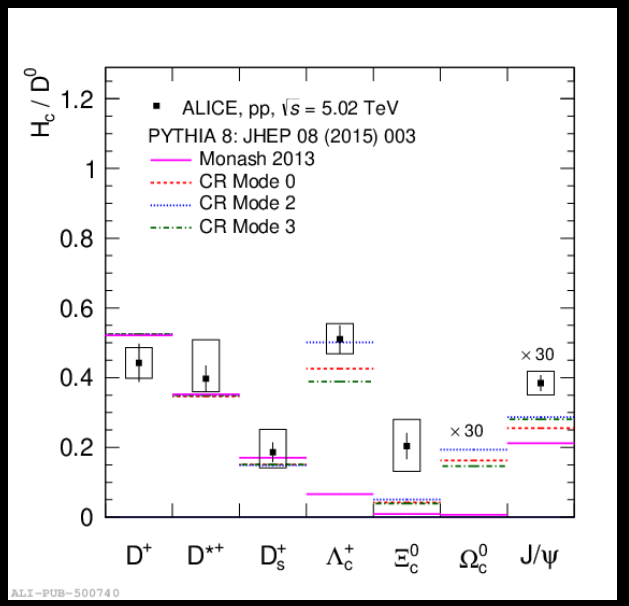
- Different Λ_c vs D^0 production mechanism at central and forward rapidity?
- Pythia 8 with CR consistent with data at central rapidity

Charm fragmentation

ALICE Phys. Rev. D 105 (2022) L011103



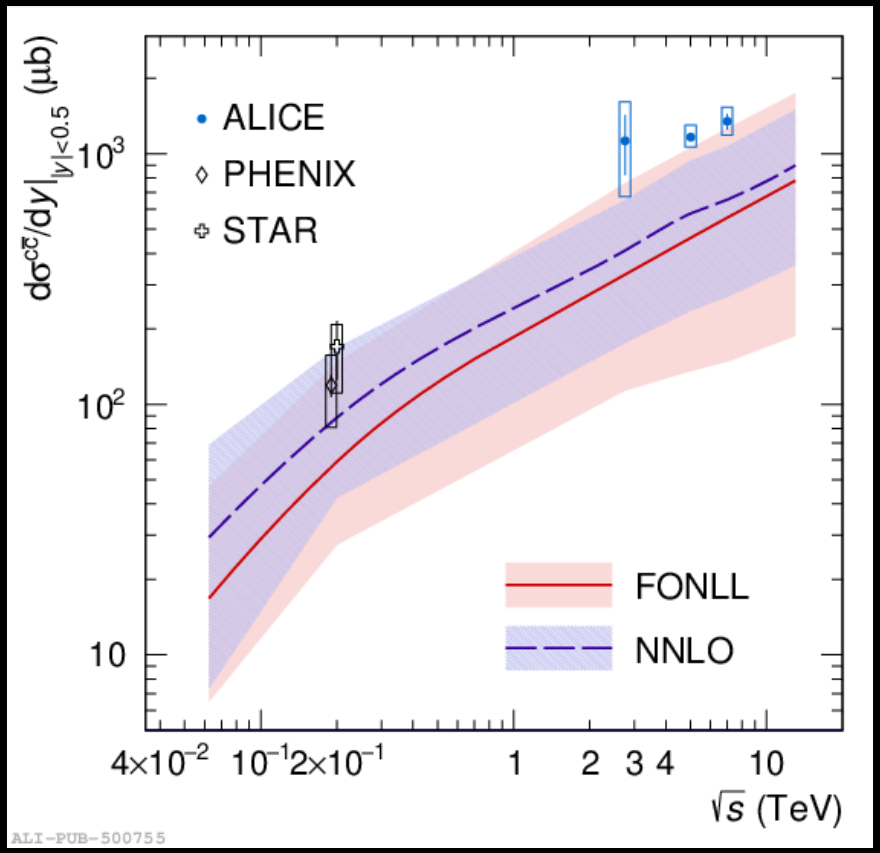




Charm fragmentation depends on collision system (broken universality)

Total charm cross section in pp at 5 TeV (ALICE data)

ALICE, Phys. Rev. D 105 (2022) L011103



- Total charm cross section at $|y|<0.5$

$\sigma_{cc} = \sigma(D^0) + \sigma(D^+) + \sigma(D^+_S) + \sigma(\Lambda_C^+) + 2*\sigma(\Xi_C^0)$

  - $\sigma(\Xi_C^+) \sim \sigma(\Xi_C^0)$ from 13 TeV ALICE measurement
  - $\sigma(\Omega_C^0) \sim \sigma(\Xi_C^0)$ from Catania model (included in syst. uncert.)
  - J/ψ contribution neglected

- Measurements at the upper edge of pQCD calculations

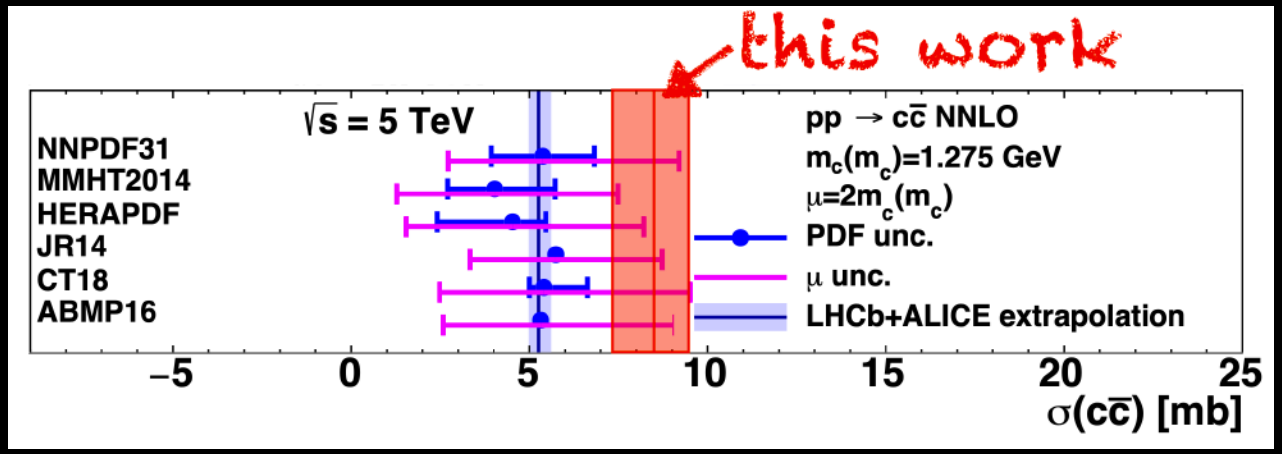
Total charm cross section in pp at 5 TeV (ALICE and LHCb data)

Y. Yang and A. Geiser arXiv:2311.07523

- Total charm cross section determination using D^0 mesons
- Extrapolation to the full phase space based on FONLL with non-universal charm fragmentation

$$\tilde{f}_{H_c}(p_T) \equiv \frac{d\sigma_{H_c}}{\Sigma_{wd} d\sigma_{H_c}} \equiv f_{H_c}^{uni} F(p_T)$$

$$d\sigma_{H_c}^{\text{FONLL with } \tilde{f}} = \tilde{f}_{H_c}(p_T) \cdot \left(d\sigma_{pp\to c\bar{c}}^{\text{FONLL}} \otimes D_{c\to H_c}^{\text{NP}} \right)$$



$$\sigma_{c\bar{c}} = 8.43^{+0.25}_{-0.25}(\text{data})^{+0.40}_{-0.42}(\tilde{f})^{+0.67}_{-0.56}(\text{PDF})^{+0.13}_{-0.12}(\mu_f, \mu_r, m_c, \alpha_K)^{+0.65}_{-0.88}(f^{pp})[\text{mb}]$$

Open charm cross section measurement from combined LHC experiments (Strong2020/HonexComb)

C. Bierlich (Pythia), J. Wilkinson (ALICE), J.Sun (LHCb), G. Manca (LHCb),
R. Granier de Cassagnac (CMS), and JO (ALICE) arXiv:2311.11426

Total charm cross section determination in pp at 5 TeV

Goal: Combine LHC results to determine total charm cross section, extrapolated to the full phase space ($|y|<8$, $p_T < 36$ GeV/c)

Experiment	ALICE	CMS	LHCb
Luminosity (pb^{-1})	$(19.3\pm0.4)\times10^{-3}$	27.4 ± 0.6	8.60 ± 0.33
Hadrons	D^0,$D^\pm$,$D^{*\pm}$, $D_s^\pm$,Λ_c,Ξ_c^0	D^0,Λ_c	D^0,$D^\pm$, $D^{*\pm}$, $D_s^\pm$
p_T range (GeV/c)	0–36	2–100	0–10
y range	$\lvert y\rvert$ <0.5	$\lvert y\rvert$ <1.0	2.0< y <4.5

- Different p_T range depending on particle species
- CMS data used only for estimation of systematic uncertainties
- Extrapolation to a full phase space requires a good parametrization

Extrapolation procedure with PYTHIA

A dedicated PYTHIA tune (CR2) used for the kinematic charm quark mass estimation and extrapolation

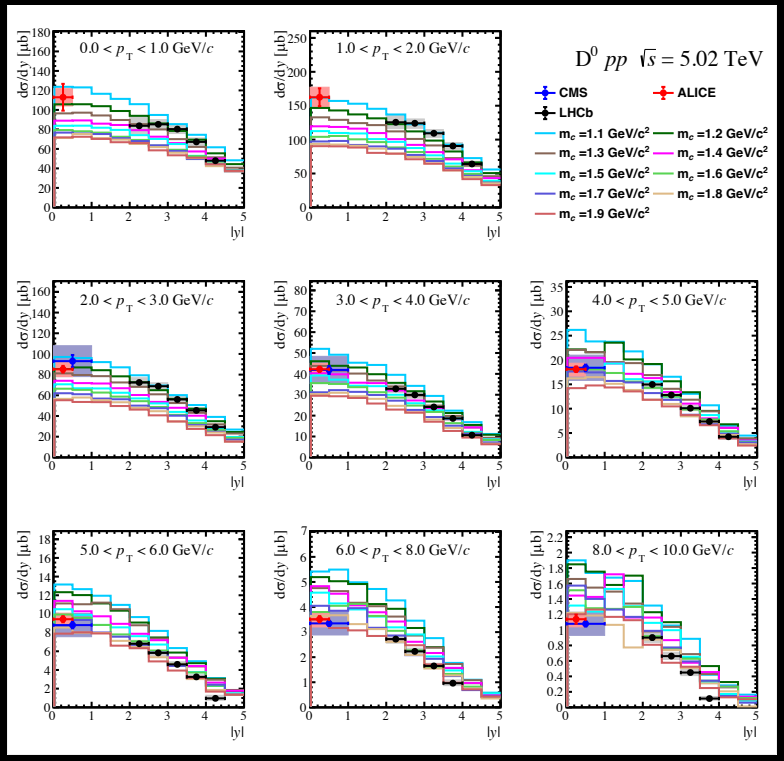
- Charm hadron production in PYTHIA down to low p_T
  - At LO (qq→cc, gg→cc)
  - Parton shower (g→cc)
  - Multiparton interactions
  - Lund string model for fragmentation
  - Colour reconnection + rope model

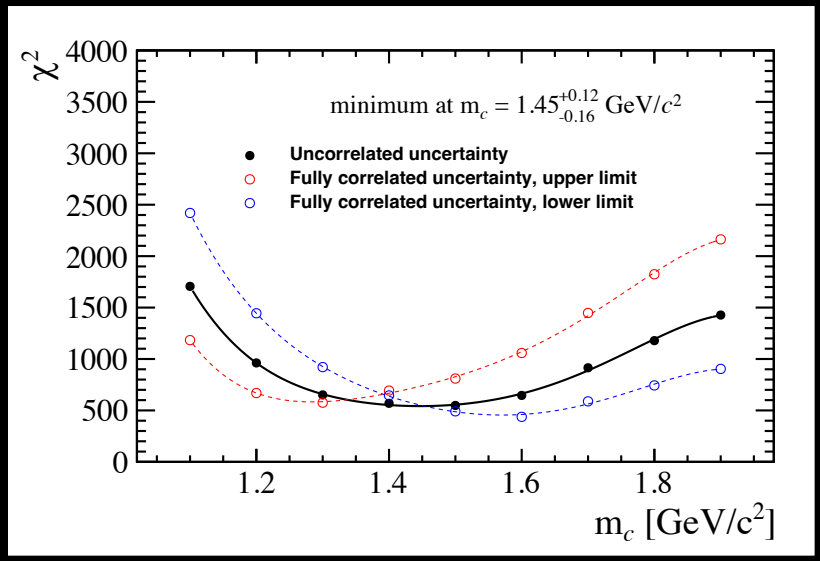
Parameter name	Monash 2013 [43]	Used value [30,31]
ColourReconnection:mode	–	1
ColourReconnection:allowDoubleJunRem	–	off
BeamRemnants:remnantMode	0	1
Ropewalk:ropeHadronization	–	on
Ropewalk:doFlavour	–	on
Ropewalk:doShoving	–	on
PartonVertex:setVertex	–	on
StringFlav:probStoUD	0.217	0.2
StringFlav:probQQtoQ	0.081	0.078
StringZ:aLund	0.68	0.36
StringZ:bLund	0.98	0.56
StringFlav:mesonCvector	0.88	1.35
StringFlav:probQQ1toQQ0join	0.5,0.7	0.0275,0.0275
	0.9,1.0	0.0275,0.0275
MultipartonInteractions:pT0Ref	2.28	2.15
Ropewalk:beta	–	0.2
Ropewalk:deltat	–	0.05
Ropewalk:gAmplitude	–	0.0
Ropewalk:tShove	–	0.1

Kinematic charm quark mass estimation

Kinematic charm mass is the only free parameter to be fixed for the cross-section calculations in PYTHIA

- The value of m_C ~ 1.5 GeV/c^2 was previously used based on the results from WA82, E769 and E791 experiments
- Large sample of data from LHC on D^0 mesons is used for this estimation

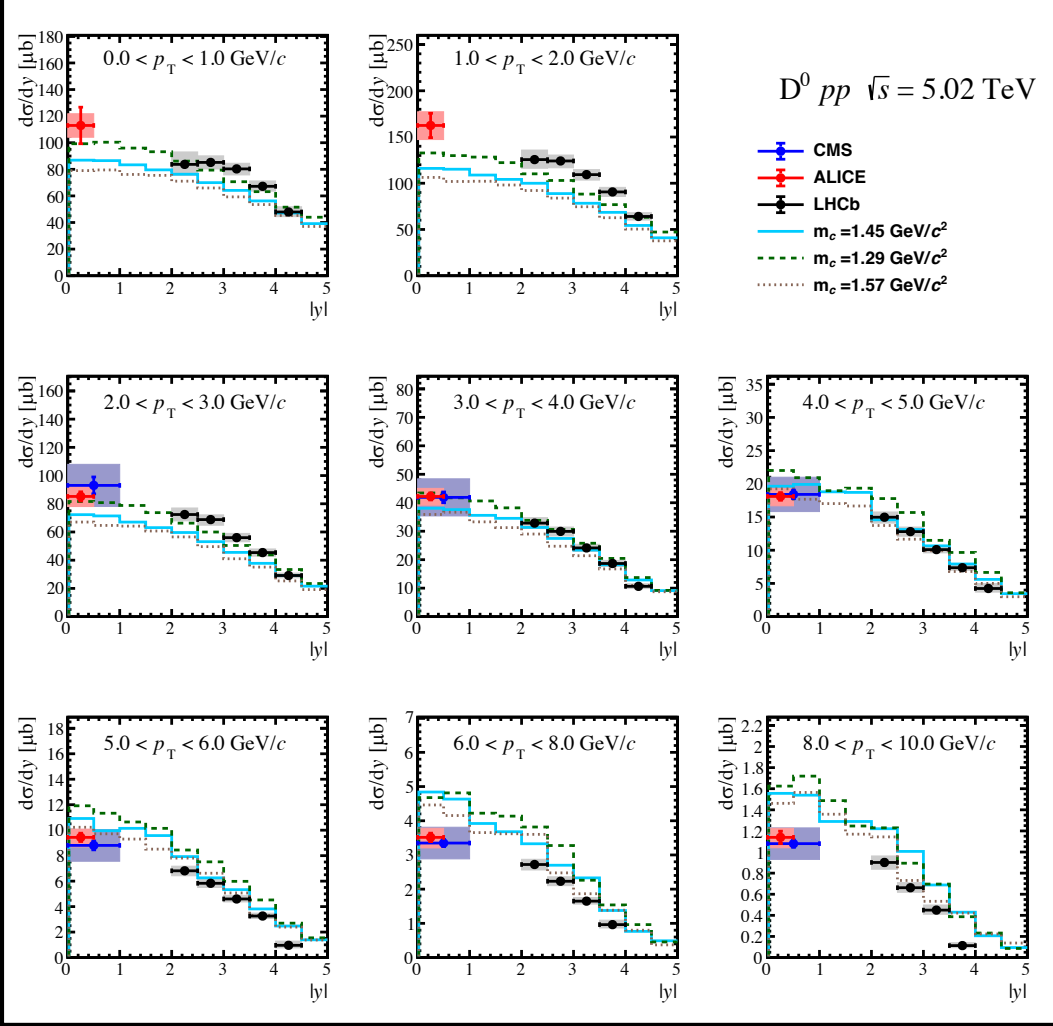




- χ^2 calculated between data points and PYTHIA
- Minimum from the 5th order polynomial fit

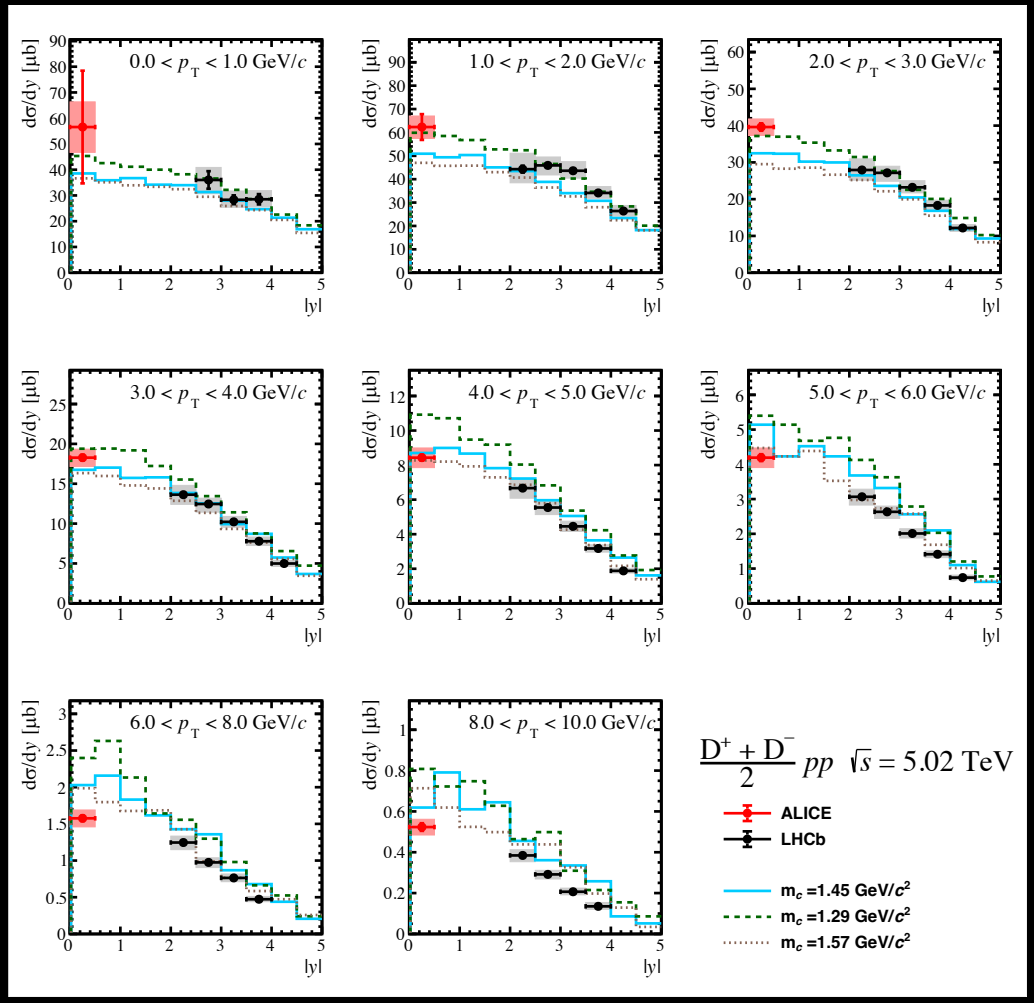
PYTHIA tune for D^0 extrapolation

Results shown for the ±1**σ** variation around m_c = 1.45 GeV/c^2



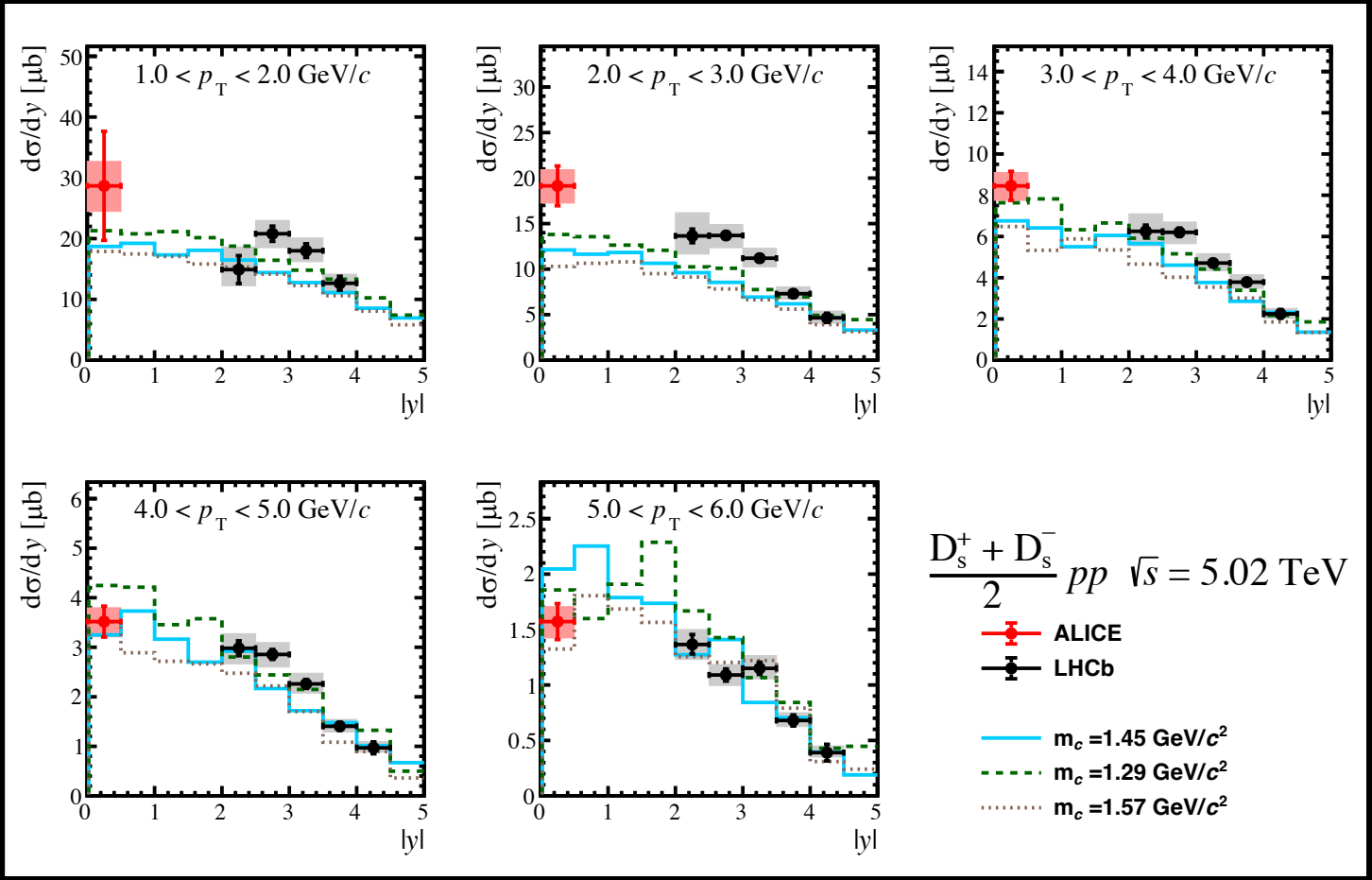
PYTHIA tune for D^+ extrapolation

Results shown for the ±1**σ** variation around m_c = 1.45 GeV/c^2



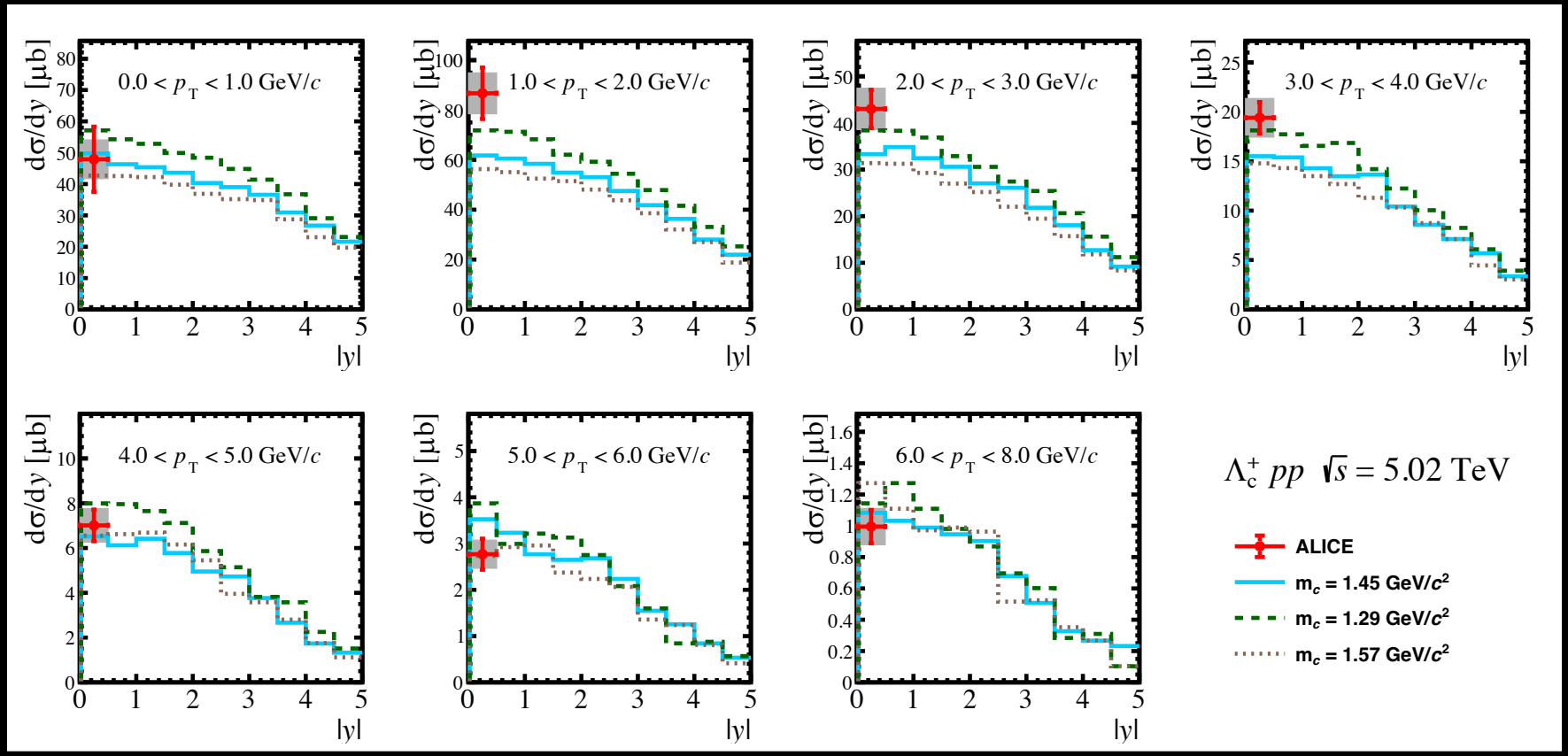
PYTHIA tune for D_s^+ extrapolation

Results shown for the ±1**σ** variation around m_c = 1.45 GeV/c^2



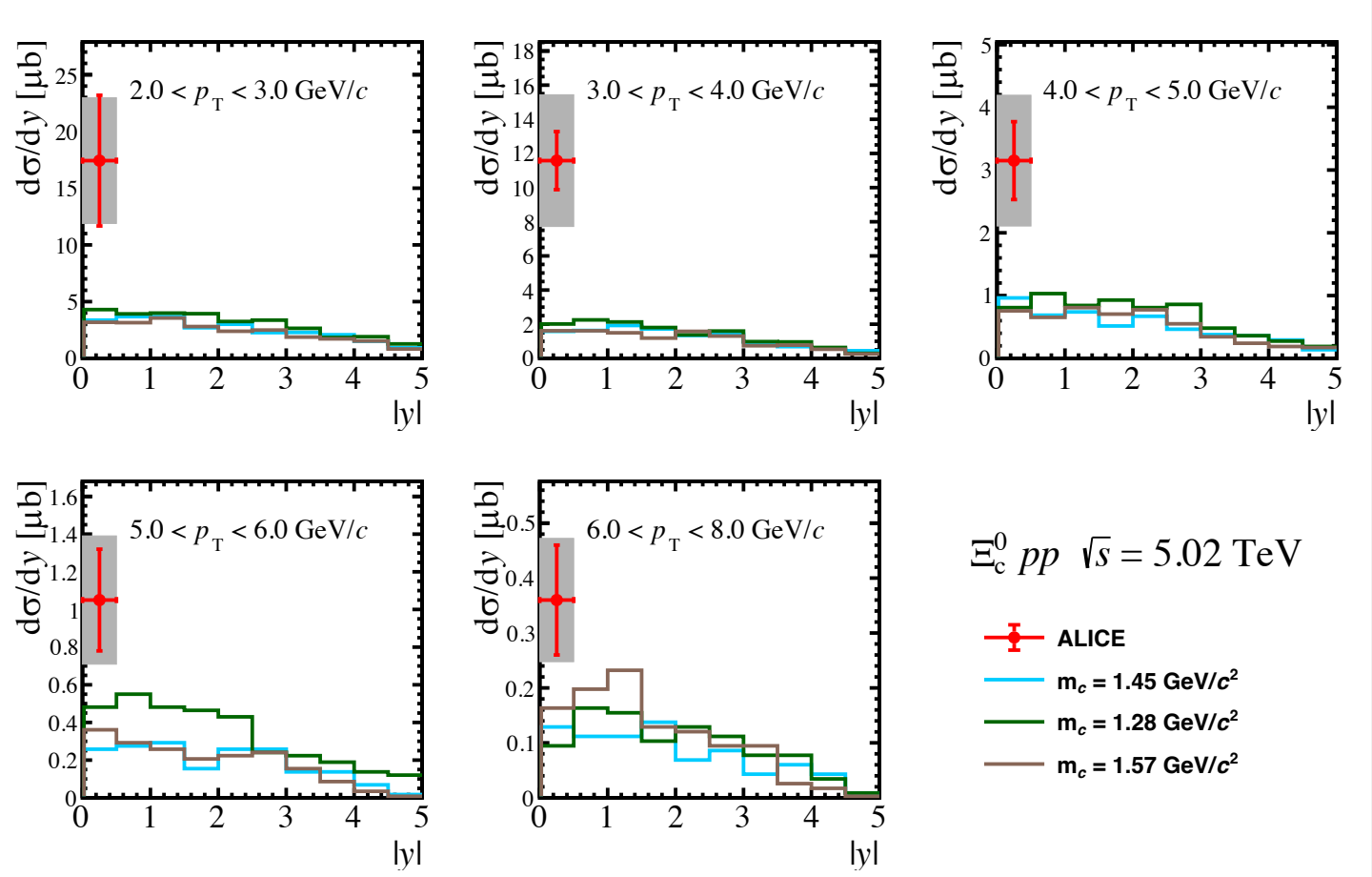
PYTHIA tune for Λ_C^+ extrapolation

Results shown for the ±1**σ** variation around m_c = 1.45 GeV/c^2



PYTHIA tune for Ξ_c^0 extrapolation

Results shown for the ±1**σ** variation around m_c = 1.45 GeV/c^2



Total charm cross section in pp at 5 TeV

- $\sigma_{c\bar{c}} = \sigma(D^0) + \sigma(D^+) + \sigma(D+_S) + \sigma(\Lambda_C^+) + 2*\sigma(\Xi_C^0)$
  - $\sigma(\Xi_C^+) \sim \sigma(\Xi_C^0)$ from 13 TeV ALICE measurement
  - $\sigma(\Omega_C^0) \sim \sigma(\Xi_C^0)$ from Catania model (included in syst. uncert.)
  - J/ψ contribution neglected

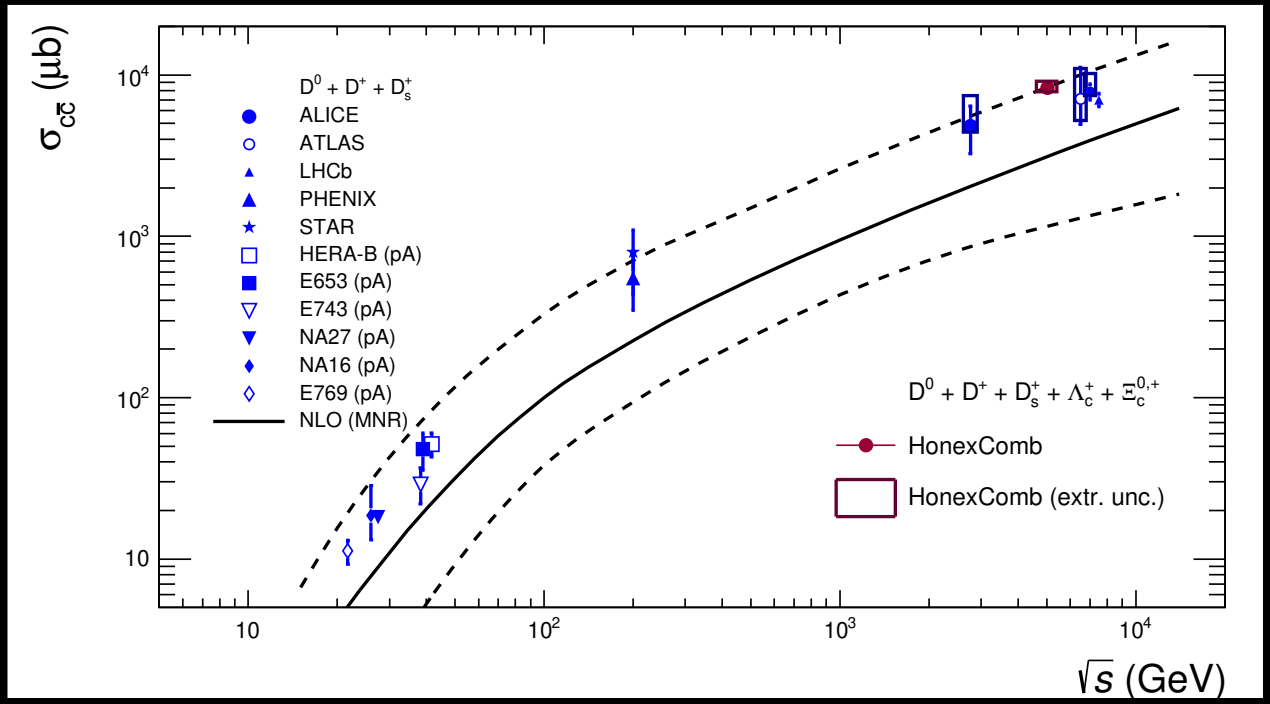
- Extrapolation to full phase space ($|y|<8$, $p_T < 36$ GeV/c) using Pythia tune with $m_c = 1.45$ GeV/c^2
  - Fractions extracted using exclusively Pythia spectra

- Systematic uncertainties include
  - $\pm 1\sigma$ variation around minimum $m_c = 1.45$ GeV/c^2
  - Correlated and uncorrelated contributions propagated from measurements
  - Monash2013 tune used for Ξ_C^0 extrapolation (rapidity dependence not measured) – lower limit
  - $\sigma(\Omega_C^0) \sim \sigma(\Xi_C^0)$ – upper limit
  - Alternative extrapolation with Tsallis (in p_T) and Gaussian (in y) parametrizations

Total charm cross section in pp at 5 TeV

arXiv:2311.11426

- Total charm cross section, extrapolated to the full phase space ($|y|<8$, $p_T < 36$ GeV/c)
- Measurements at the upper edge of pQCD calculations ($m_c = 1.5$ GeV/c^2)



$$\sigma_{c\bar{c}}(\mathrm{pp}, 5.02\,\mathrm{TeV}) = 8.34 \pm 0.22(\mathrm{stat.})^{+0.37}_{-0.37}(\mathrm{syst.})^{+0.36}_{-0.46}(\mathrm{extr.})^{+0.68}_{-0}(\Omega_c)\,\mathrm{mb}$$

Summary

- Non-universal charm fragmentation in pp and ep/ee collisions
- Total charm cross section estimation, extrapolated to the full phase space

FONLL based data driven approach (D^0 mesons from ALICE and LHCb) arXiv:2311.07523

$$\sigma_{c\bar{c}} = 8.43^{+0.25}_{-0.25}(\text{data})^{+0.40}_{-0.42}(\tilde{f})^{+0.67}_{-0.56}(\text{PDF})^{+0.13}_{-0.12}(\mu_f, \mu_r, m_c, \alpha_K)^{+0.65}_{-0.88}(f^{PP})[\text{mb}]$$

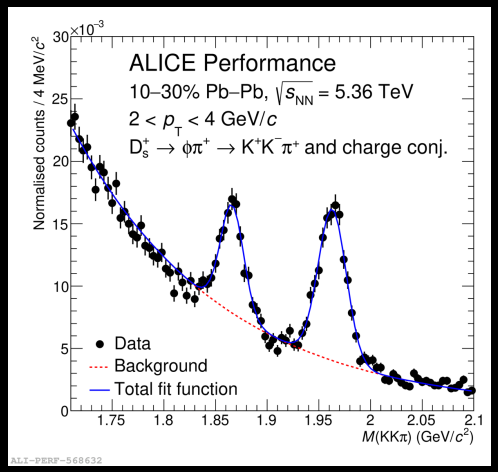
Pythia 8 tune (CR + rope model, m_c=1.45 GeV/c^2) based extrapolation using open charm mesons and baryons from ALICE, CMS and LHCb) arXiv:2311.11426

$$\sigma_{c\bar{c}}(\text{pp}, 5.02\,\text{TeV}) = 8.34 \pm 0.22(\text{stat.})^{+0.37}_{-0.37}(\text{syst.})^{+0.36}_{-0.46}(\text{extr.})^{+0.68}_{-0}(\Omega_c)\,\text{mb}$$

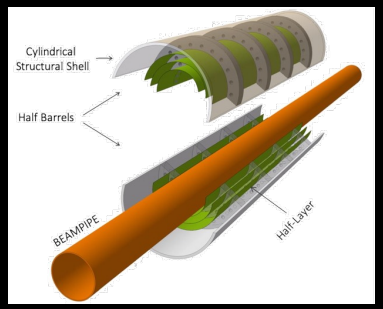
More data on charm baryons from LHC experiment would be beneficial!

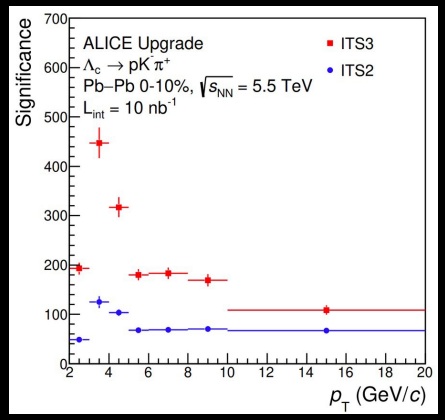
Outlook

Run 3: performance

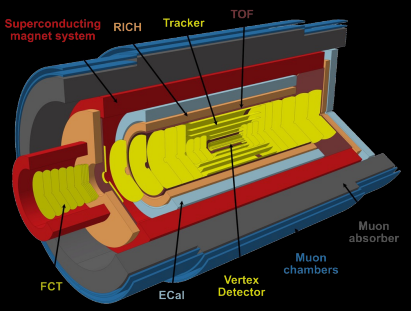


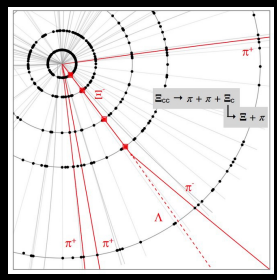
LS3 upgrade: ITS3





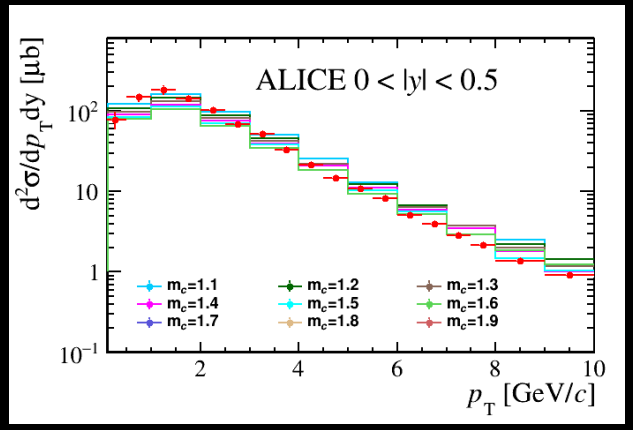
LS4: Future heavy-ion detector (ALICE 3)

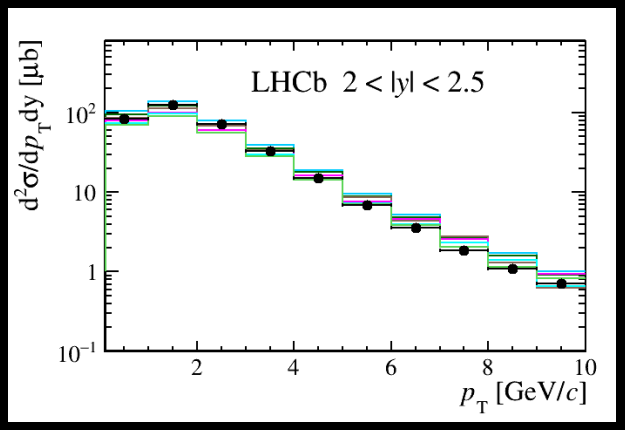


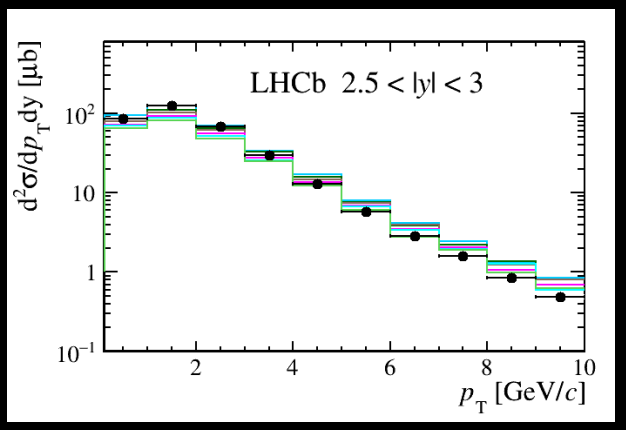


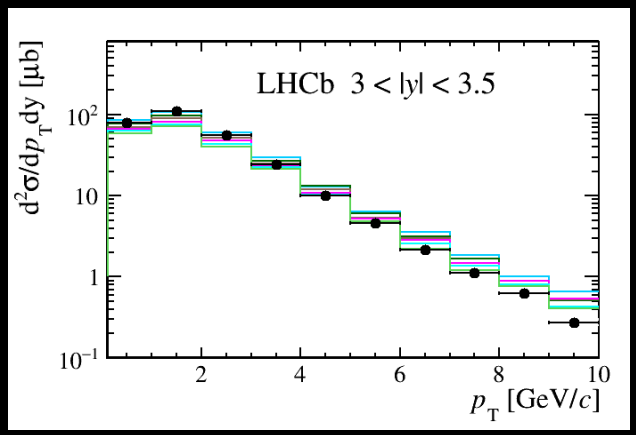
Backup

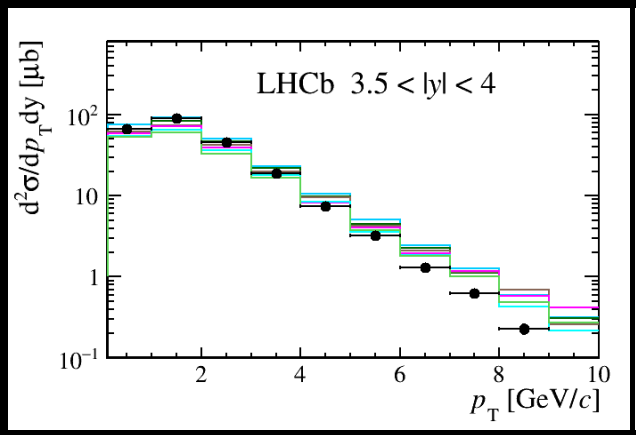
PYTHIA tune for D^0 extrapolation (HonexComb)

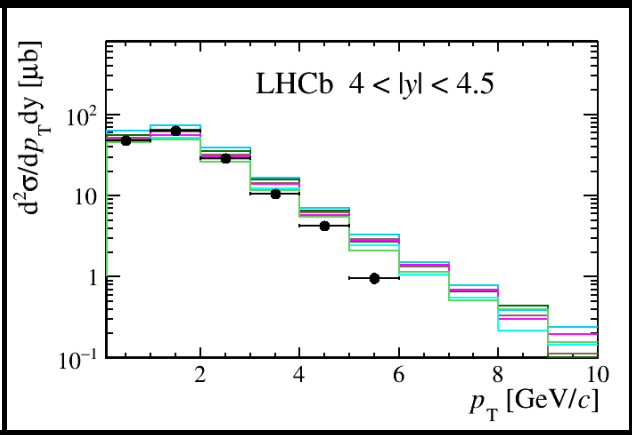




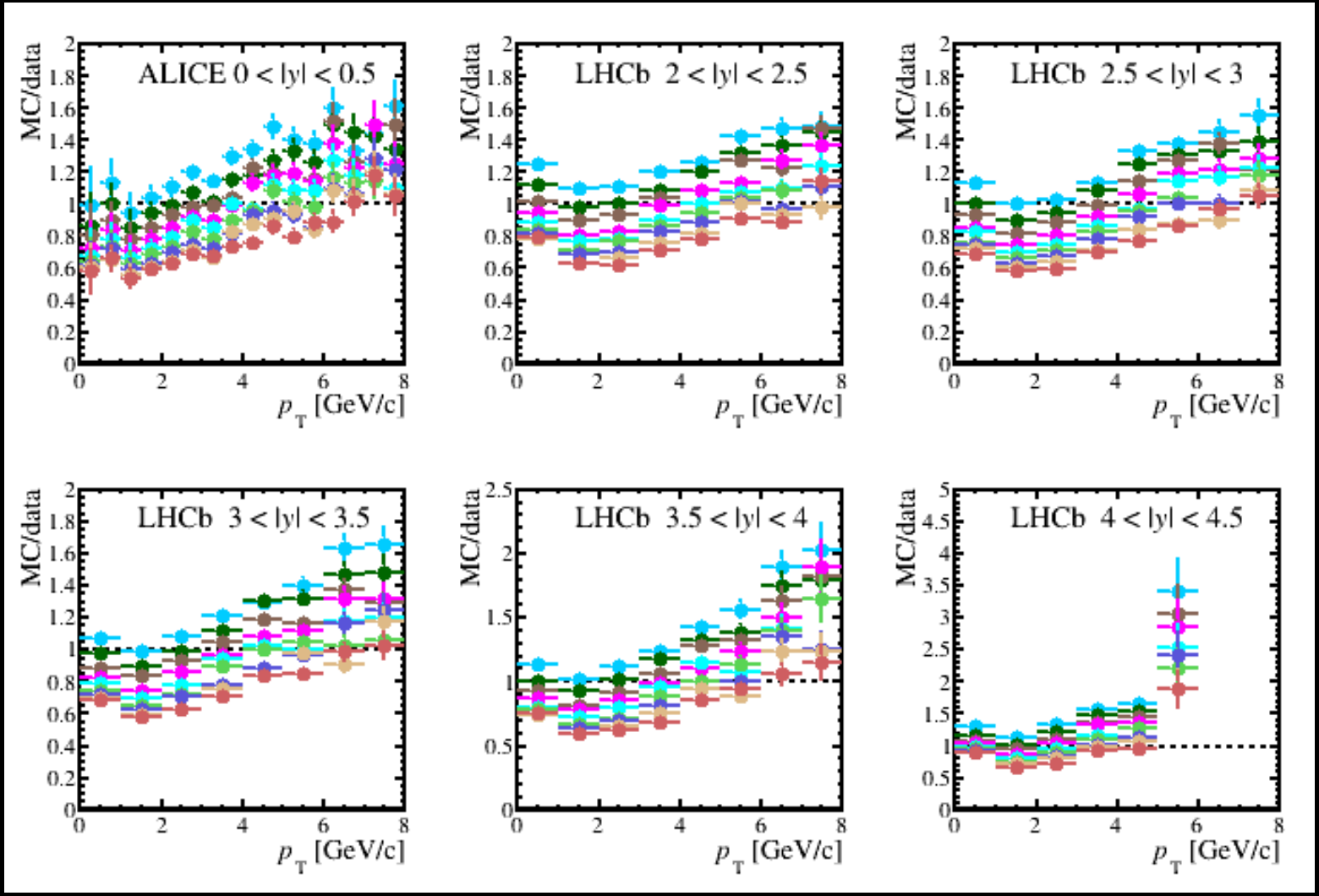






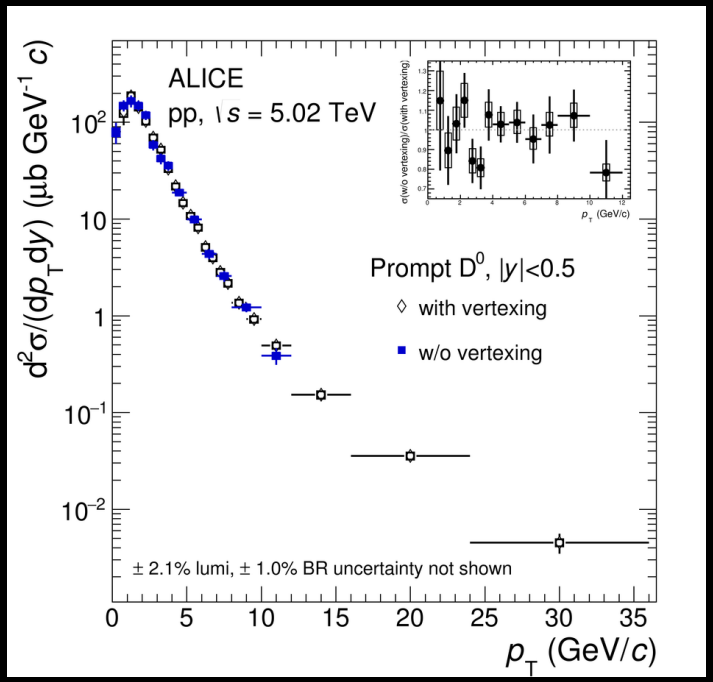


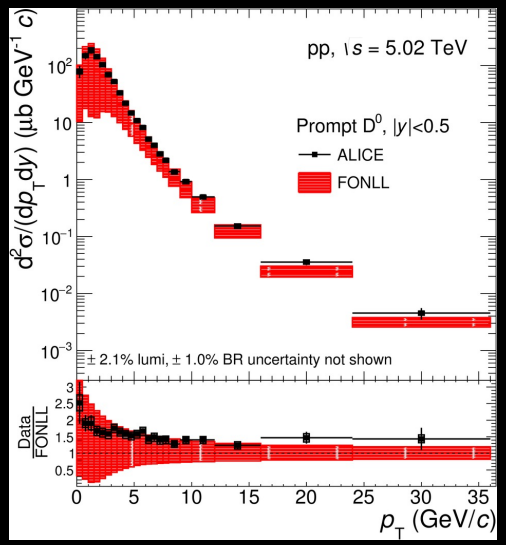
PYTHIA tune for D^0 extrapolation (HonexComb)

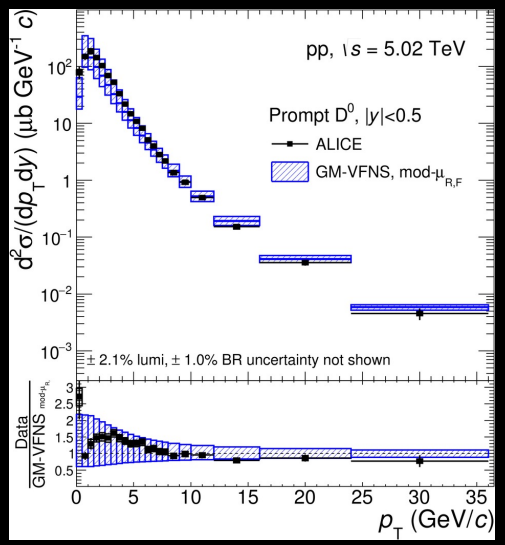


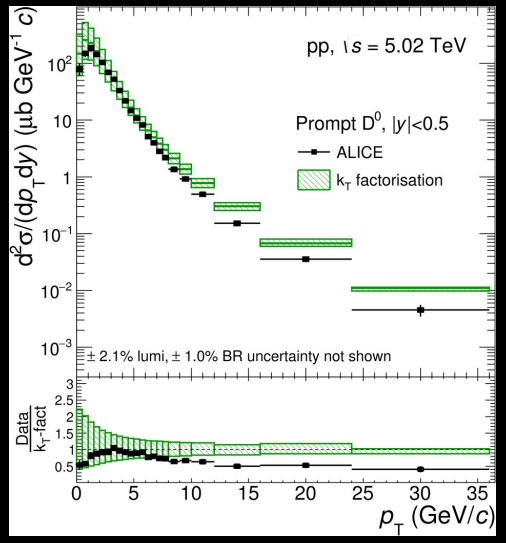
Open charm hadrons at LHC

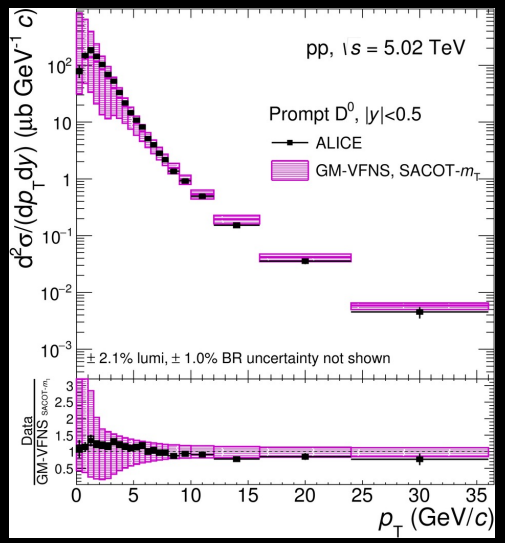
Eur.Phys.J. C79 (2019) no.5, 388











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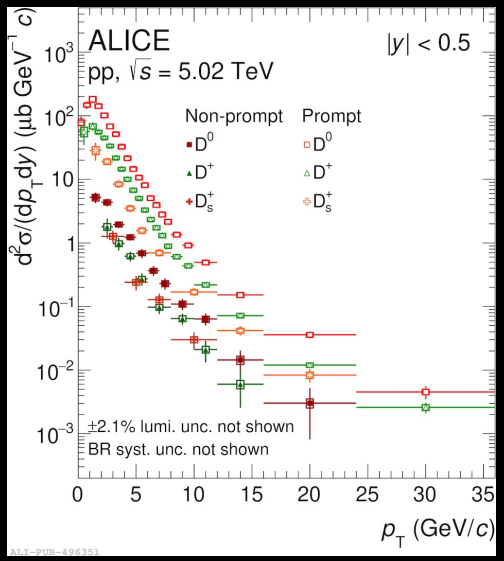

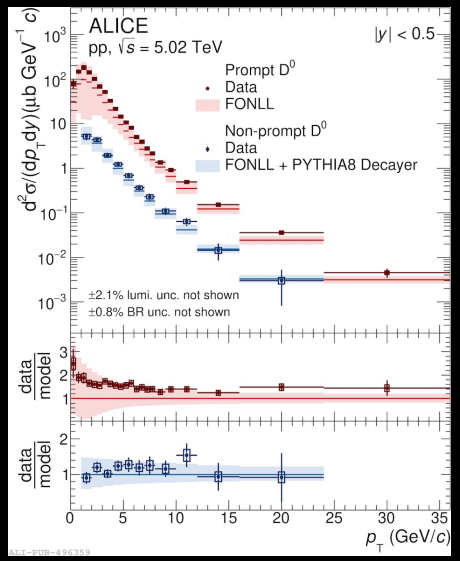

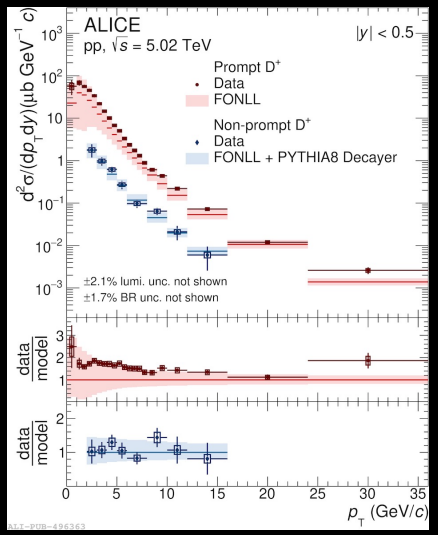

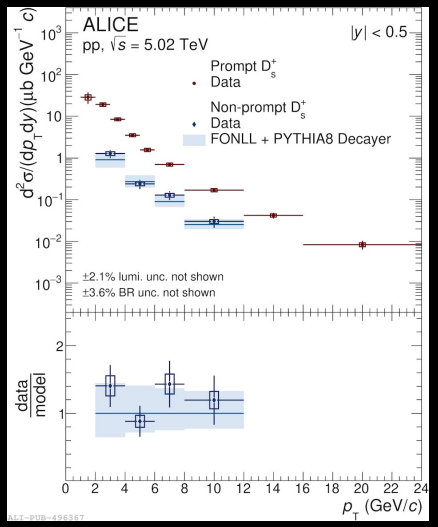

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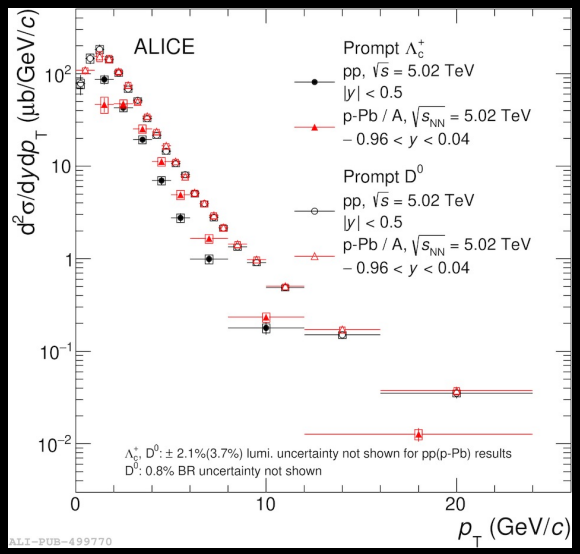
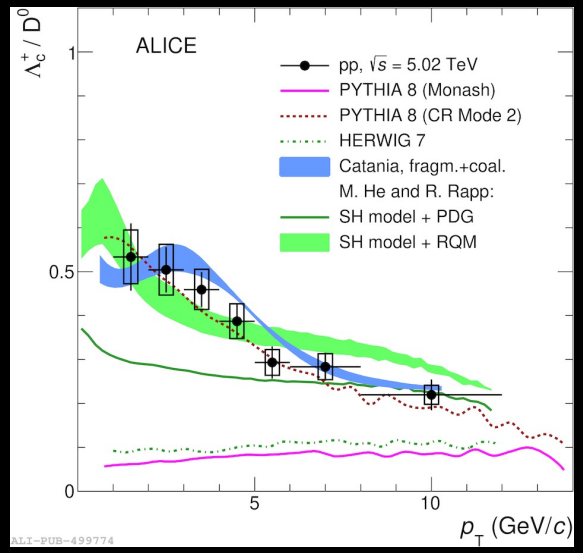
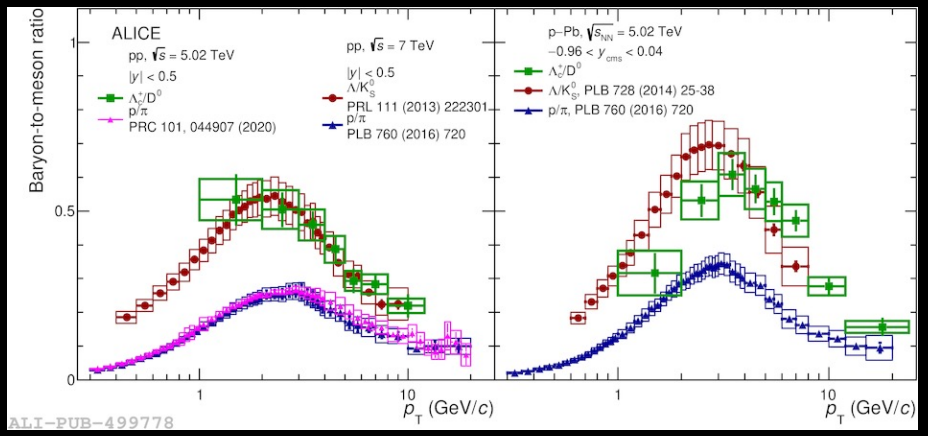
Phys. Rev. Lett. 127 (2021) 202301

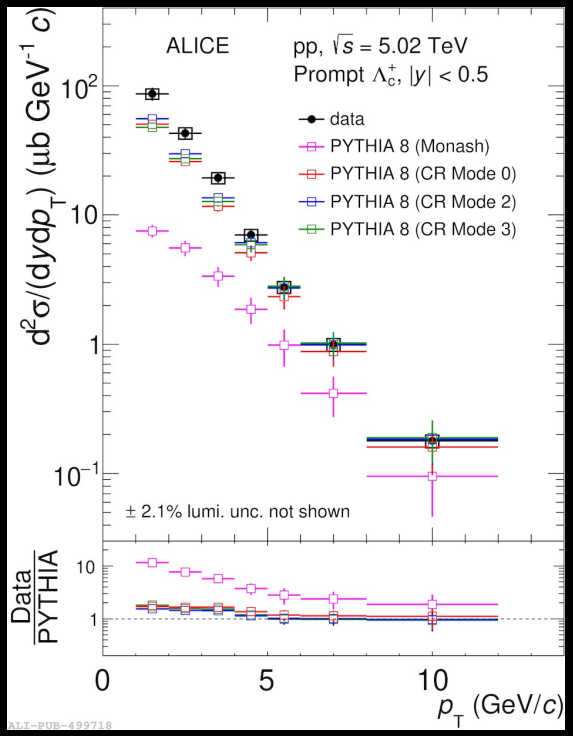


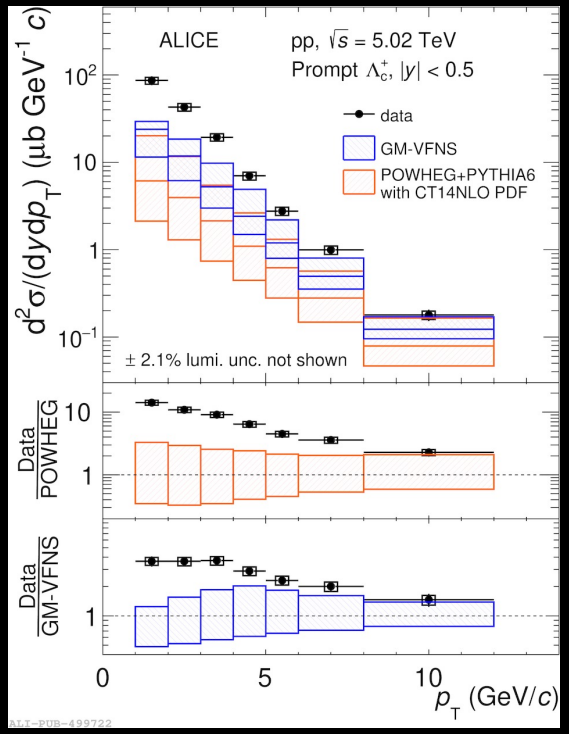


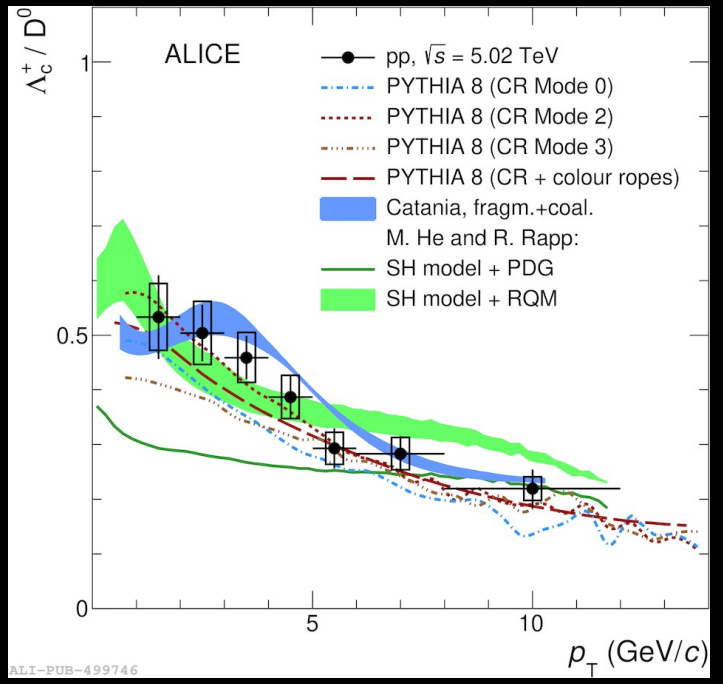


Open charm hadrons at LHC

Phys. Rev. C 104 (2021) 054905







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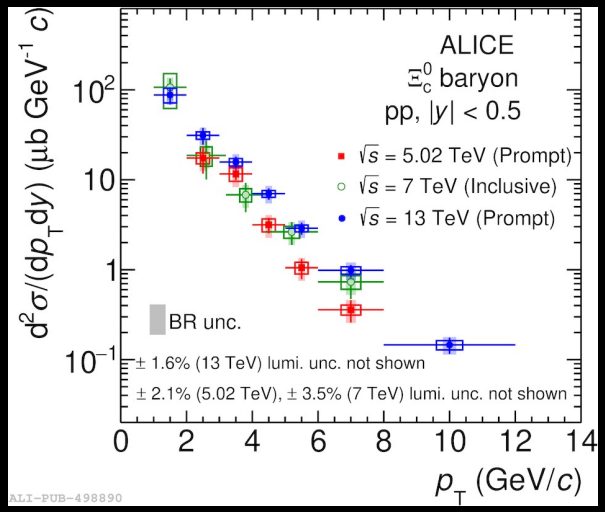
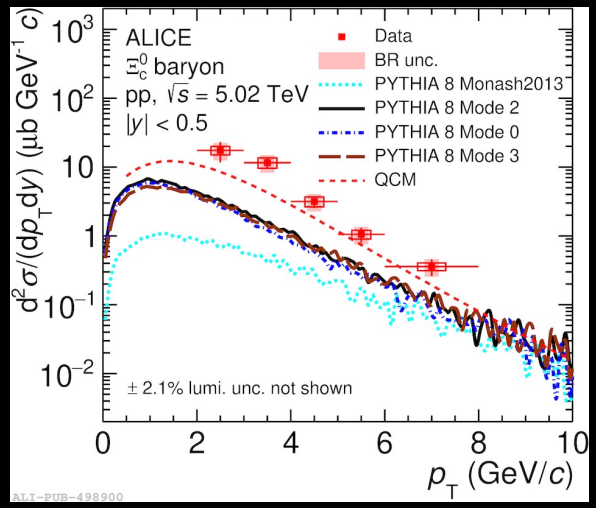
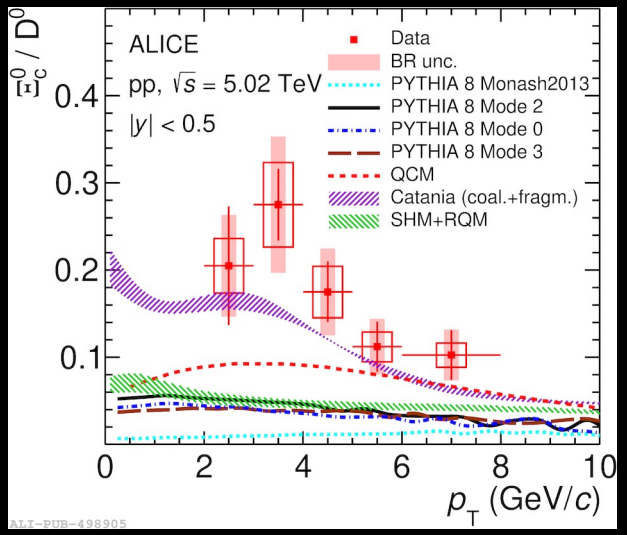
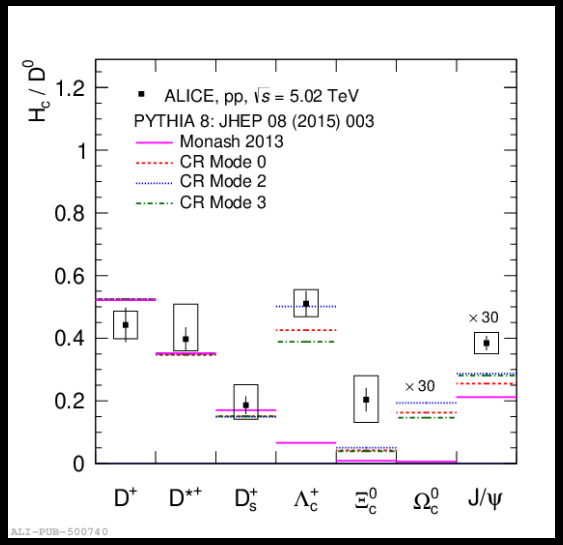


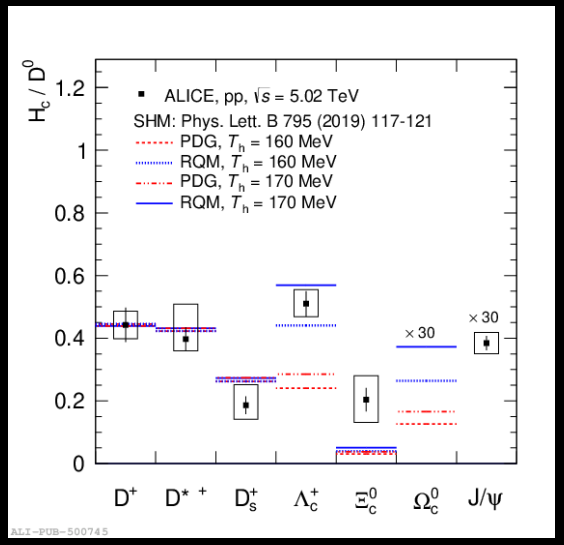


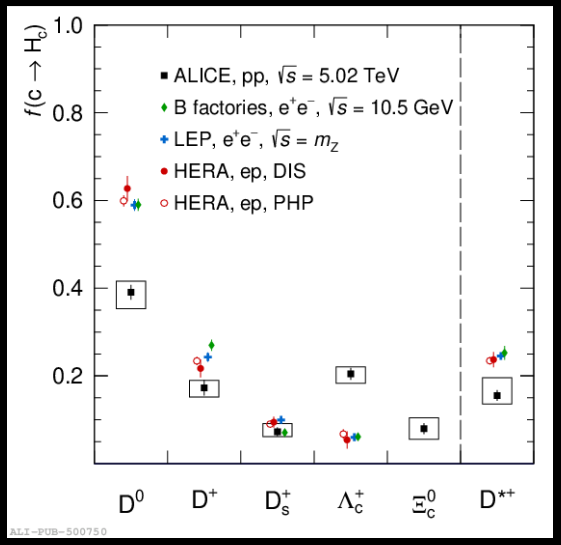


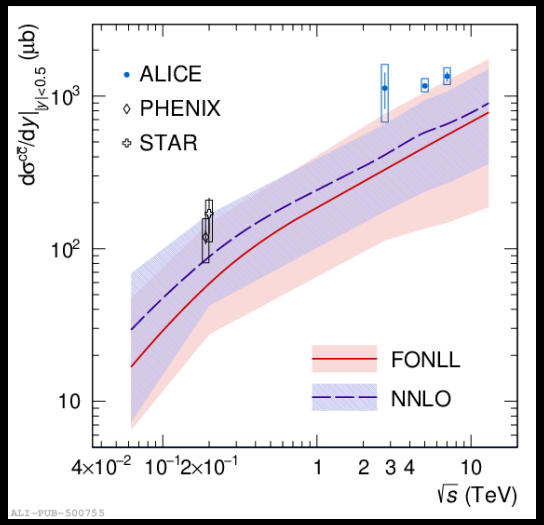
Open charm hadrons at LHC

Phys. Rev. D 105 (2022) L011103



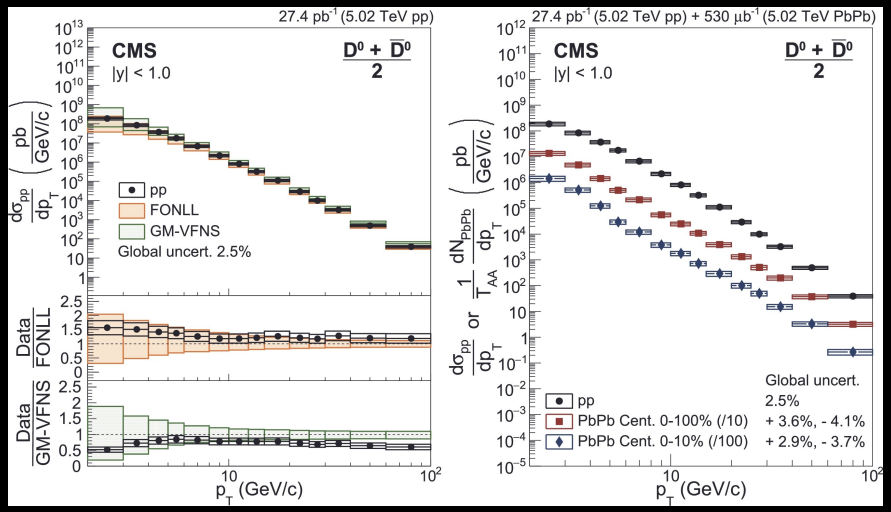




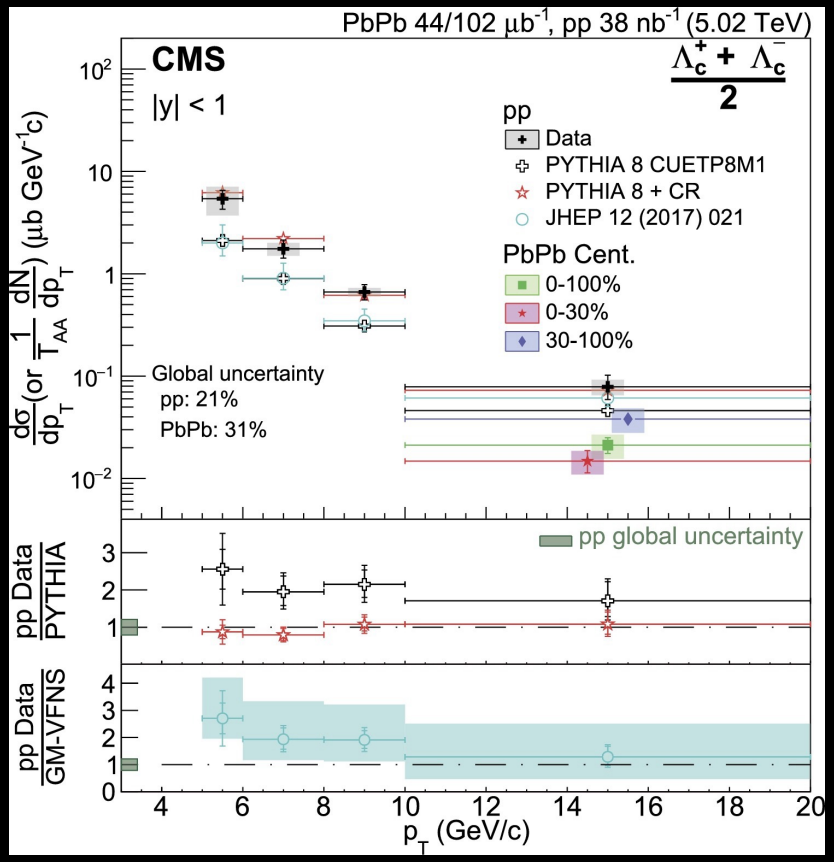


Open charm hadrons at LHC

CMS, Phys. Lett. B782 (2018) 474-493



CMS, Phys. Lett. B 803 (2020) 135328



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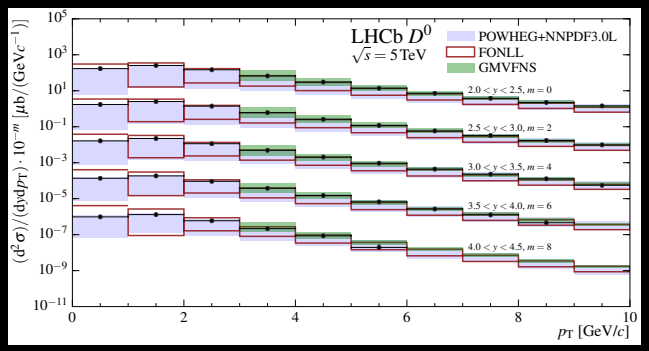
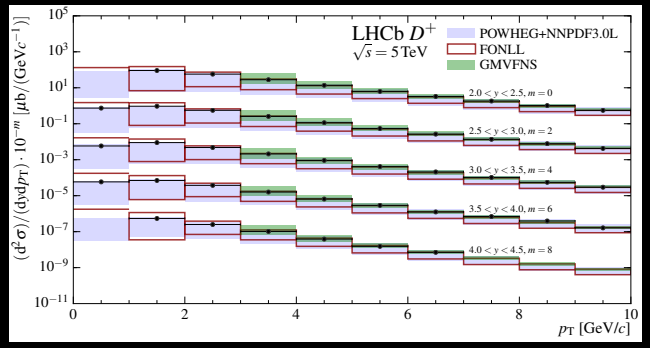
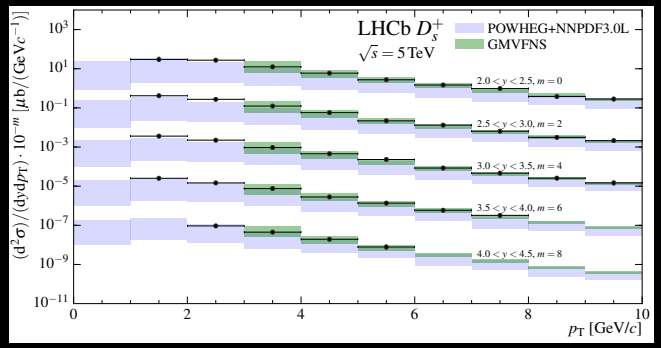
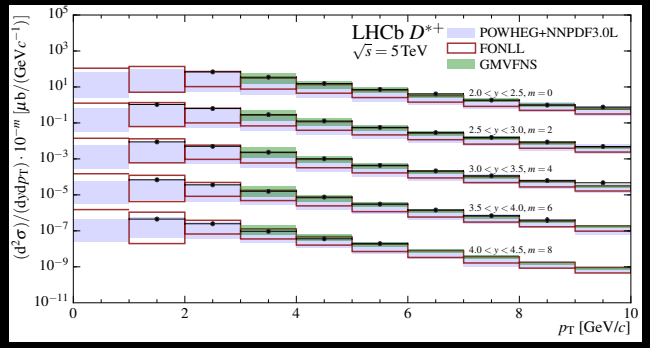
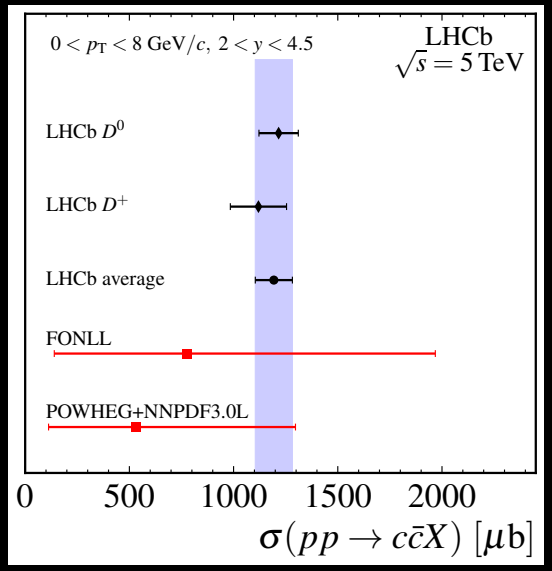
LHCb Coll, JHEP06 (2017) 147

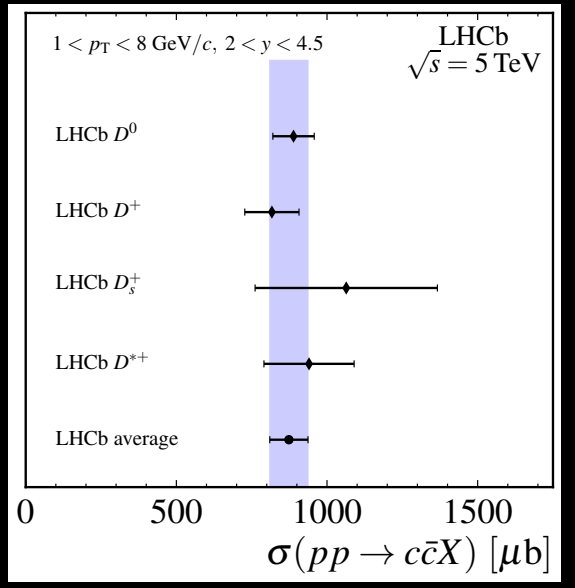








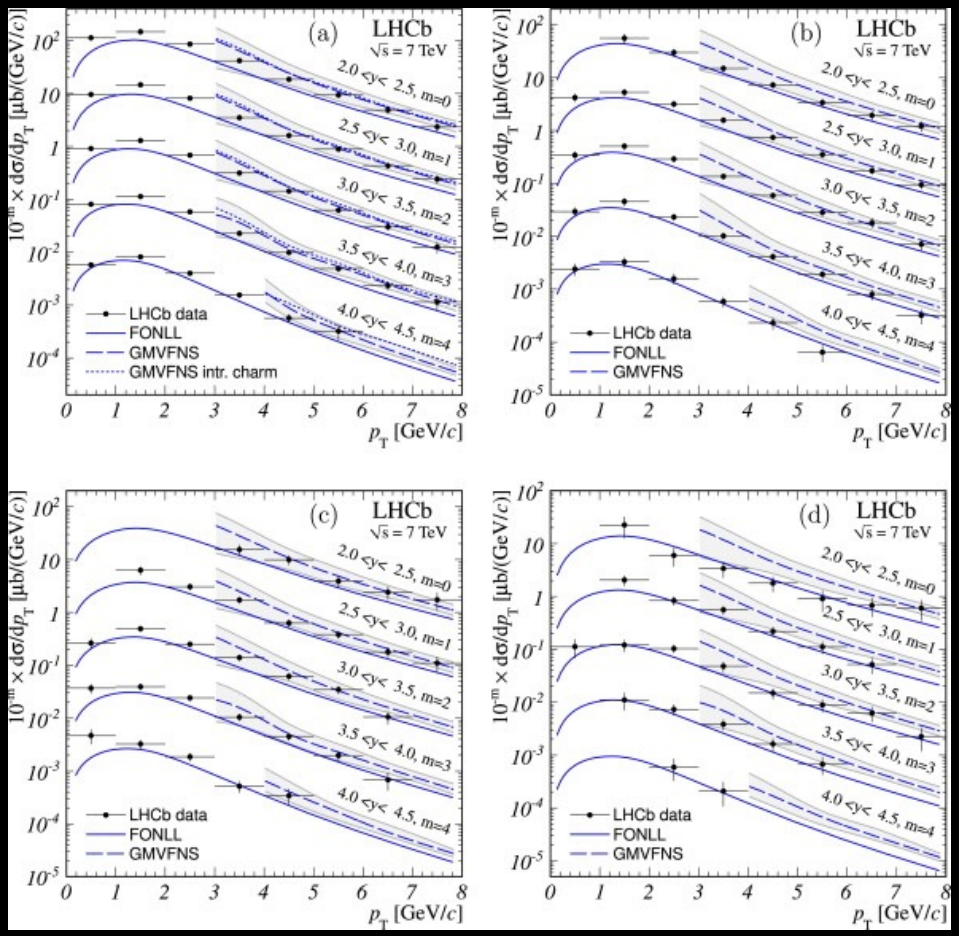




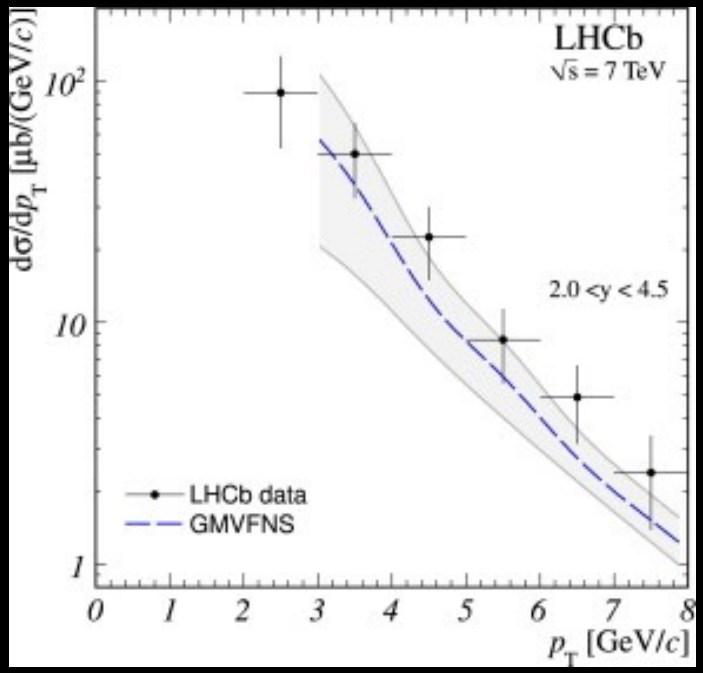
Open charm hadrons at LHC

LHCb Coll., Nucl. Phys. B 871 (2013) 1-20

D^0, D^+, D^{*+}, D_S^+



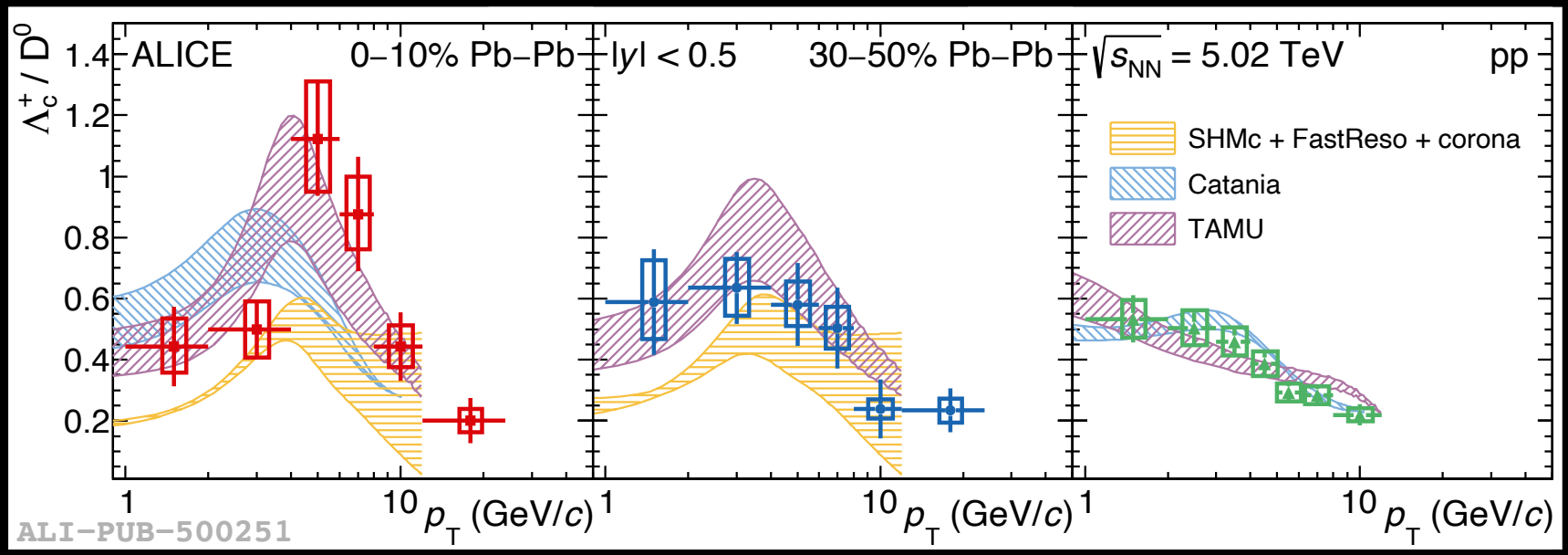
Λ_C^+



Prompt Λ_c baryon production in pp and Pb-Pb

Constraining hadronization mechanisms

Phys. Lett. B 839 (2023) 137796



- Prompt Λ_C / D meson ratio in pp and Pb-Pb compared to model predictions
- Λ_C / D ratio increases from pp to central Pb-Pb collisions at intermediate p_T → enhanced production via coalescence
- All models include hadronization mechanisms via coalescence and fragmentation (at high p_T)