Determination of the total charm cross section in 5TeV *pp* collisions in HonexComb project

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Quark-Gluon Plasma Characterisation with Heavy Flavour Probes
ECT* workshop

Istituto Nazionale di Fisica Nucleare

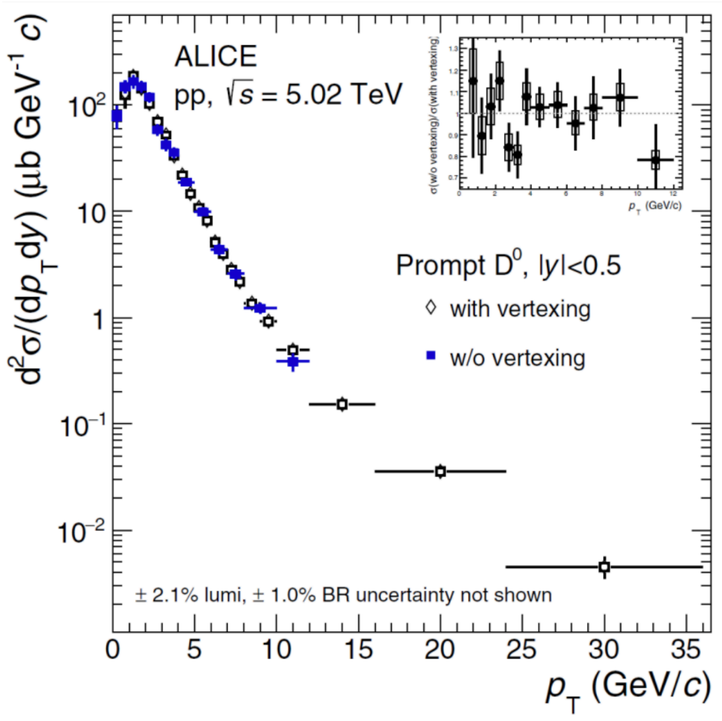
Total charm cross-section in *pp* collisions

- The measurement of the total charm cross-section emerged as one of the most promising area where combining measurements from different experiment could provide important benefits.
- All LHC experiments have competitive results for charmed hadrons that cover different regions of kinematic phase space ==> ingredients for the total charm cross-section
- A collection of open charm meson results from LHC:

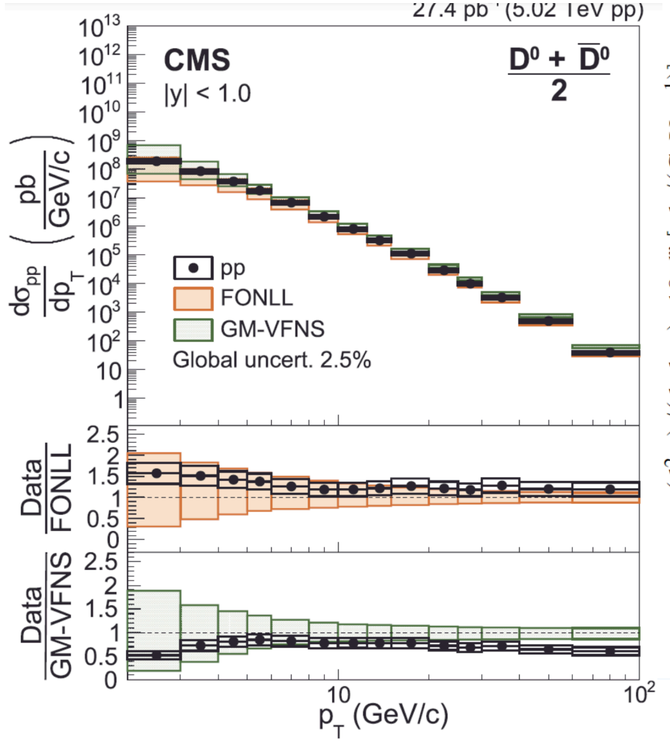
pp	ALICE	LHCb	CMS	ATLAS
5TeV	Eur. Phys. J. C79 (2019) 388 $D^0, D^{\pm}, D_s^{\pm}, D^{*\pm}$	JHEP 06 (2017) 147 $D^0, D^{\pm}, D_s^{\pm}, D^{*\pm}$	Phys. Lett. B 782 (2018) 474 D^0	
7TeV	Eur. Phys. J. C77 (2017) 550 $D^0, D^{\pm}, D_s^{\pm}, D^{*\pm}$	Nucl. Phys. B871 (2013) 1 $D^0, D^{\pm}, D_s^{\pm}, D^{*\pm}, \Lambda_c^+$		Nucl. Phys. B 907 (2016) 717 $D^{\pm}, D_s^{\pm}, D^{*\pm}$
13TeV		JHEP 05 (2017) 074, JHEP 09 (2016) 013 $D^0, D^{\pm}, D_s^{\pm}, D^{*\pm}$		

- 5TeV is a good starting point
  - New ALICE papers on prompt Λ_c^+ production in 5TeV (PRC 104, 054905, PRL 127, 202301)

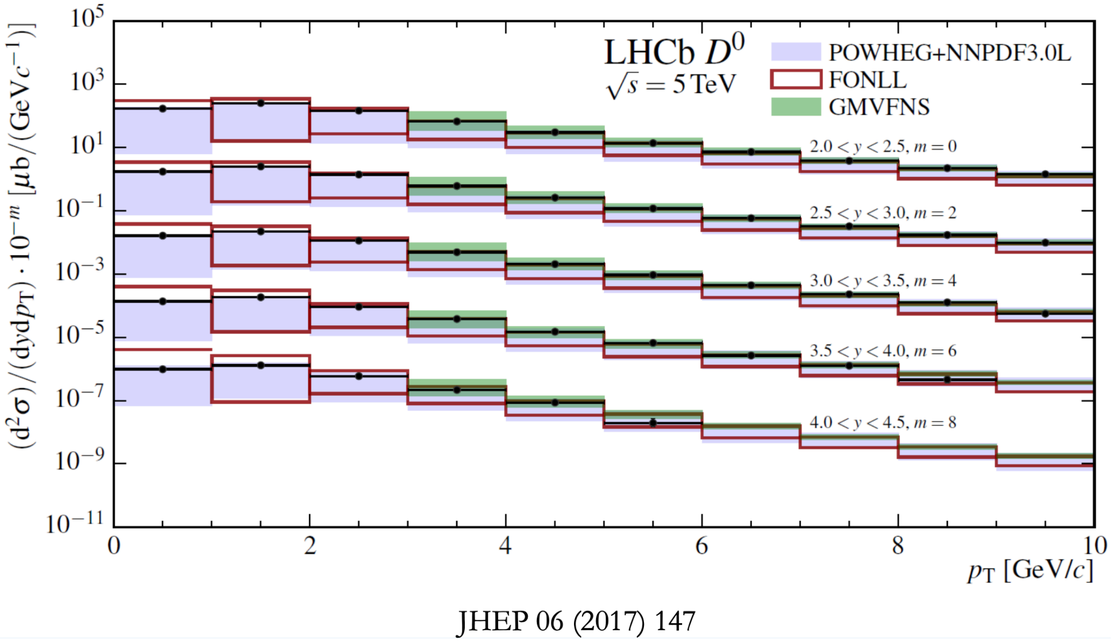
Available open charm results at 5TeV *pp* collisions
D mesons



Eur. Phys. J. C79 (2019) 388



Phys. Lett. B 782 (2018) 474

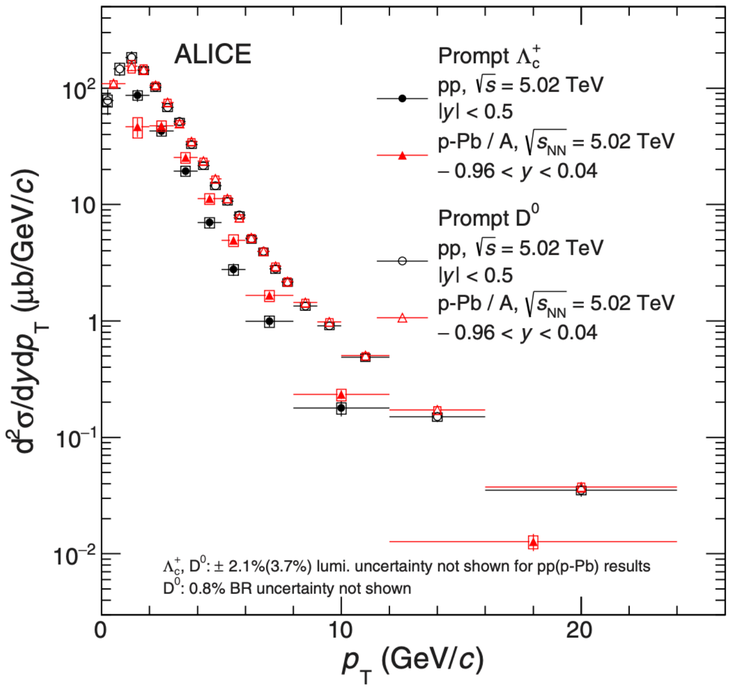


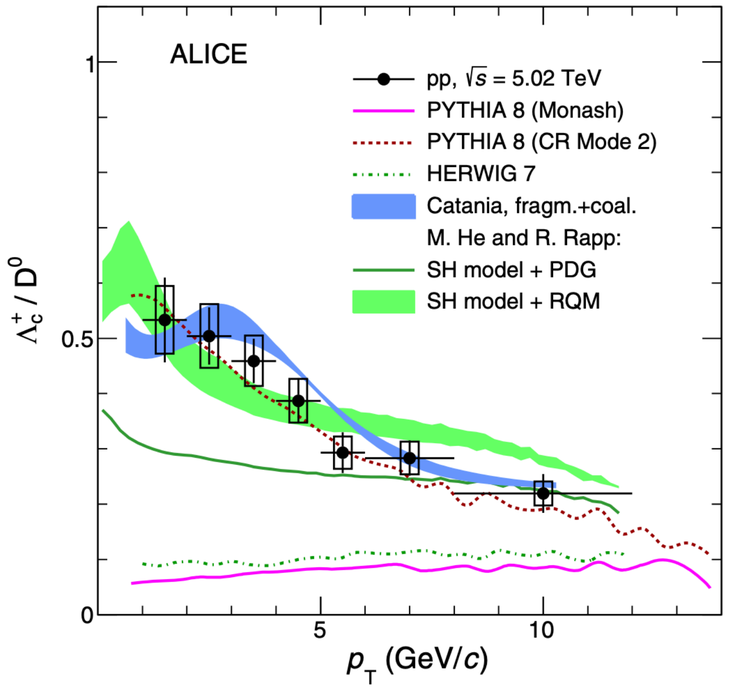
JHEP 06 (2017) 147

D^0 in 5TeV *pp*	ALICE	LHCb	CMS
p_T [GeV/c]	0 -- 36	0 -- 10	2 -- 100
Rapidity	|y| < 0.5	2.0 < y < 4.5	|y| < 1.0

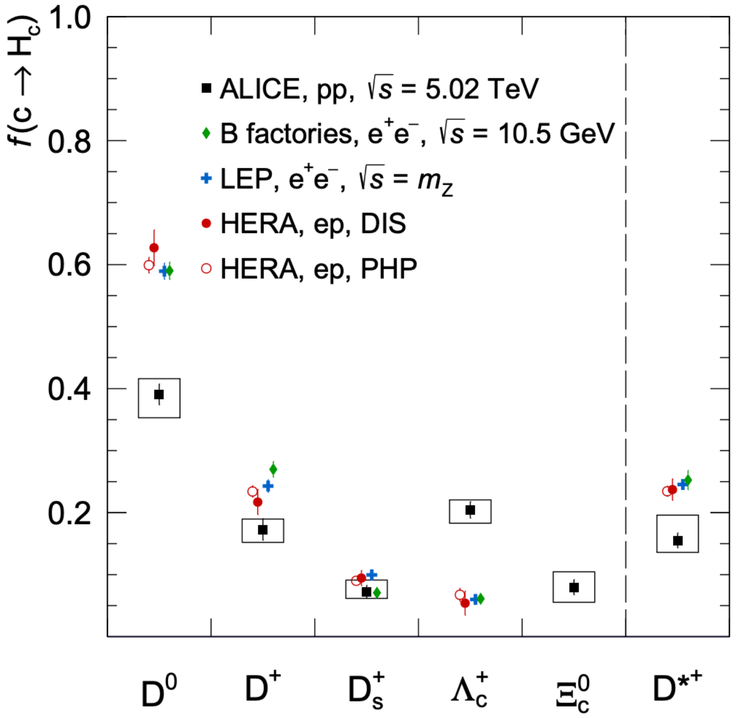
Available open charm results at 5TeV *pp* collisions
Charmed baryons

PRL 127, 202301





arXiv:2105.06335



- **The need of precisely measuring charmed baryon production has become relevant in presence of large enhancement in pp compared to e+e-**
- **Need to estimate the effect of different enhancement scenarios of these particles on the total cross section**

Objectives

- Objectives: obtain a combined measurement of $\sigma_{tot}(c\bar{c})$ and σ_{charm} vs. p_{T} and y using existing published measurements of ALICE, CMS and LHCb at 5 TeV.
  - Understand theory, find “best” description for total charm cross-section
  - Critical input for calculations in AA collisions

- Goals:
  - Collecting in a common database the relevant charm measurements in *pp* collisions in a consistent ROOT/txt format.
  - Providing summary plots to be used in review papers and summary talks
  - Providing comprehensive comparisons to theoretical calculations in the various rapidity and transverse momentum regions.
  - Encourage the development of dedicated tunes for theoretical calculations (e.g. Pythia) that consider the knowledge acquired after 10 years of charm measurements at the LHC
  - Common and unique inputs for charm differential cross-section vs. p_{T} and rapidity to be used as input for AA theoretical calculations
  - **Provide an estimation of the total charm cross-section, which incorporates the constraints coming from the various LHC experiments**

Charm results and combination

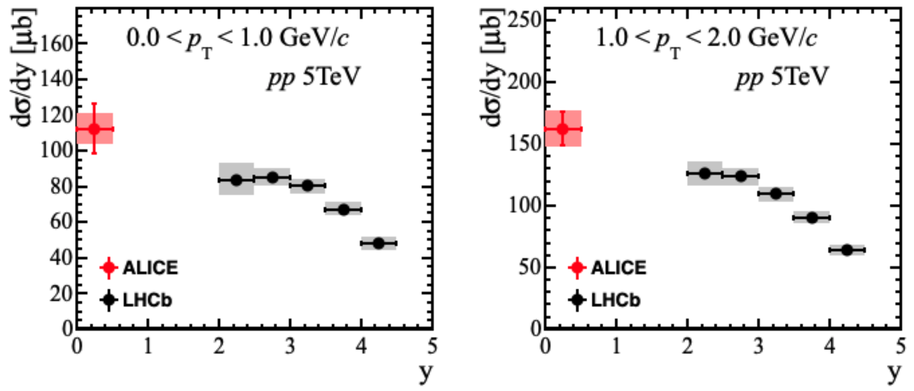
- Collection of open charm results in *pp* collisions at 5 TeV

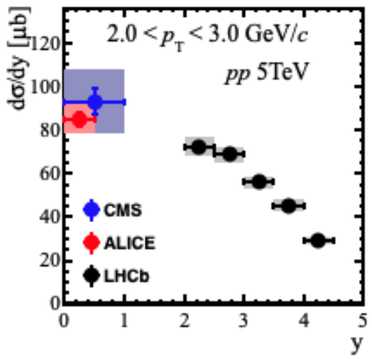
Experiment	Ref. code	Hadronic decays
ALICE	EPJC 79, 388 (2019)	$D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+$, $D^{*+} \to D^0\pi^+$ (+ c.c.)
ALICE	PRL 127, 202301	$\Lambda_c^+ \to pK^-\pi^+$, $\Lambda_c^+ \to pK_S^0$ (+ c.c.)
ALICE	PRC 104, 054905	$\Lambda_c^+ \to pK^-\pi^+$, $\Lambda_c^+ \to pK_S^0$ (+ c.c.)
CMS	PLB, v. 782, 2018, p 474-496	$D^0 \to K^-\pi^+$ (+ c.c.)
CMS	PLB, v. 803, 2020, 135328	$\Lambda_c^+ \to pK^-\pi^+$ (+ c.c.)
LHCb	JHEP, 147 (2017)	$D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+$, $D^{*+} \to D^0\pi^+$ (+ c.c.)

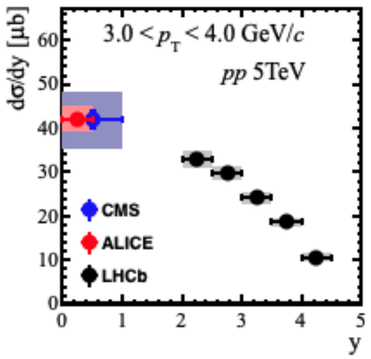
- Kinematic regions (D^0):
  - ALICE: $0 < p_T < 36$ GeV/c; $-0.5 < y < 0.5$
  - CMS: $2 < p_T < 100$ GeV/c; $-1.0 < y < 1.0$
  - LHCb: $0 < p_T < 10$ GeV/c; $2.0 < y < 4.5$ in $\Delta y = 0.5$ bins
- Produce compilation plots of σ_{charm} vs. p_T and y
- All information collected and accessible in twiki:
- https://twiki.cern.ch/twiki/bin/view/Honexcomb/HonexcombCharmSection

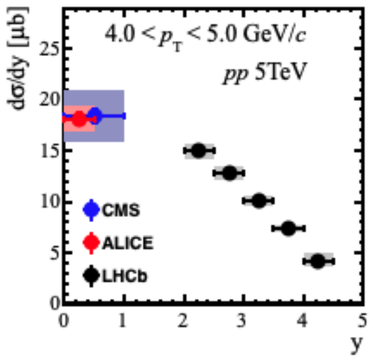
Decay	Branching ratio
$D^0 \to K^-\pi^+$	$3.950 \pm 0.031\%$
$D^+ \to K^-\pi^+\pi^+$	$9.38 \pm 0.16\%$
$D_s^+ \to \phi\pi^+ \to K^+K^-\pi^+$	$2.24 \pm 0.08\%$
$\Lambda_c \to pK^-\pi^+$	$6.28 \pm 0.32\%$
$\Lambda_c \to pK_s^0 \to p\pi^+\pi^-$	$1.10 \pm 0.06\%$

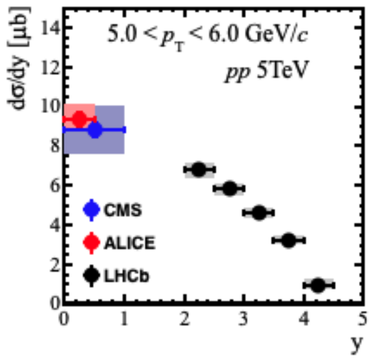
Combination plots for D^0

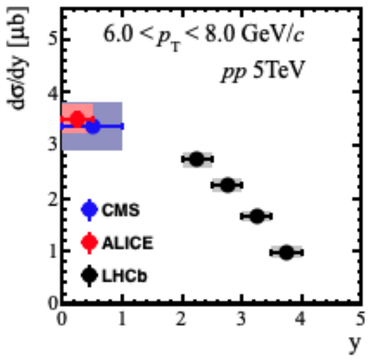


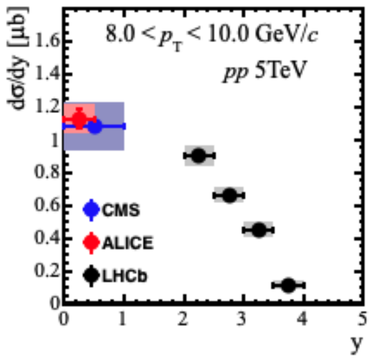


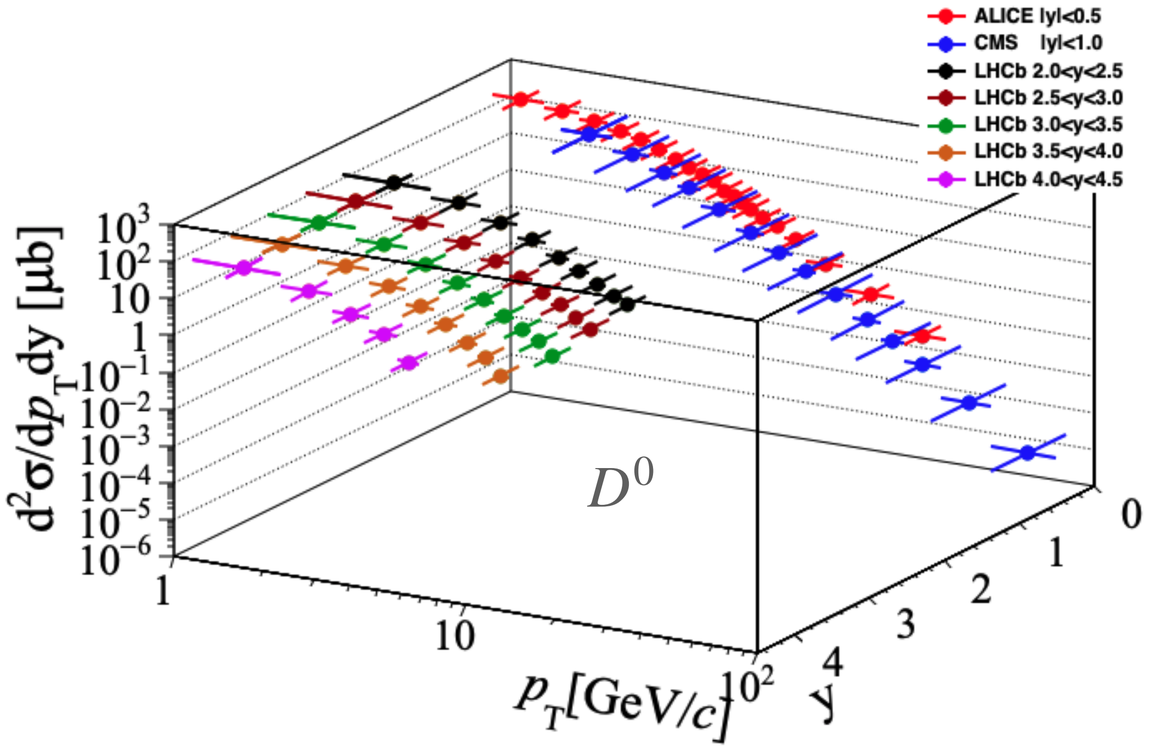












- Kinematic regions (D^0):
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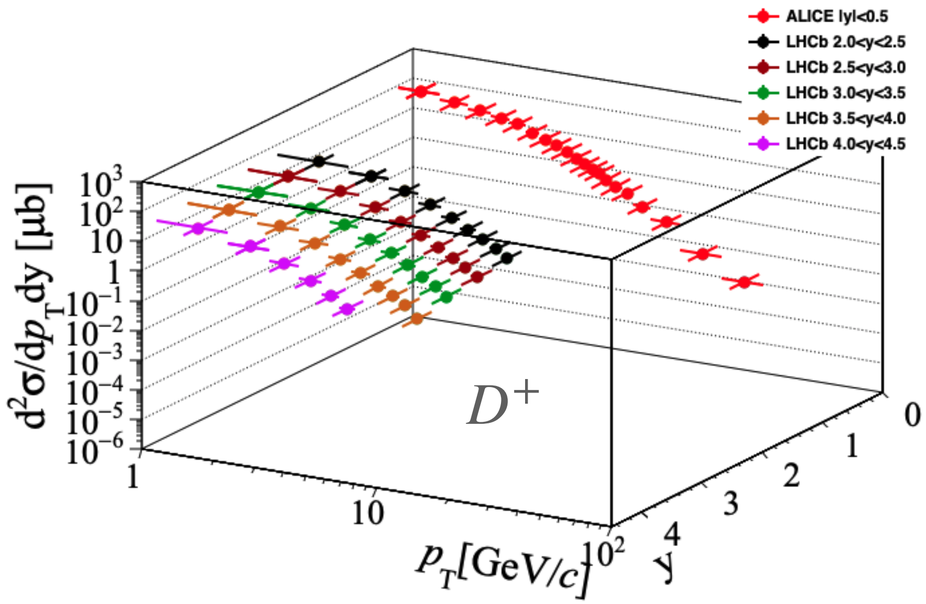
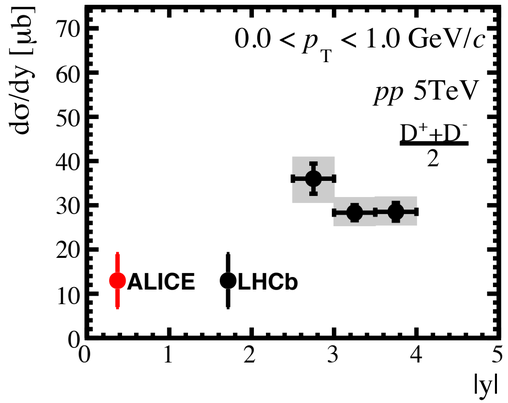
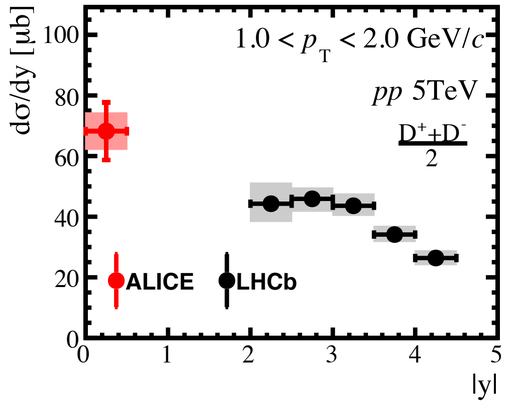
  - CMS: $2 < p_T < 100$ GeV/c; $-1.0 < y < 1.0$
  - LHCb: $0 < p_T < 10$ GeV/c; $2.0 < y < 4.5$

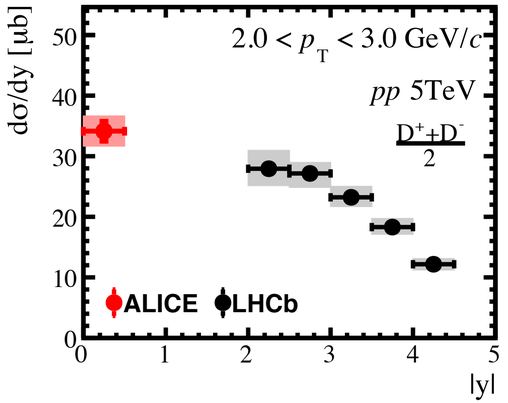
Combination plots for D^+

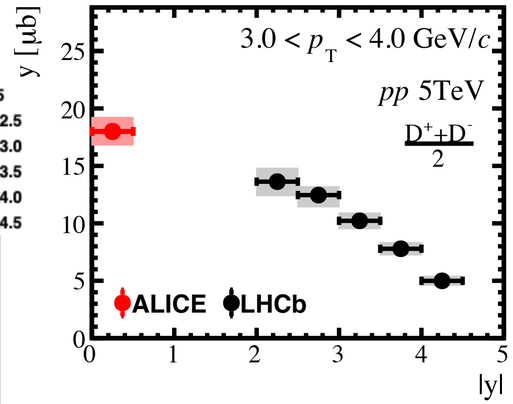
- D^+ cross-section in p_T and y
- D^+ cross-section vs. y in p_T slices

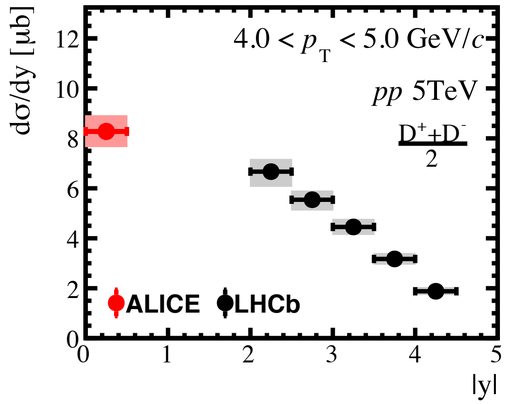


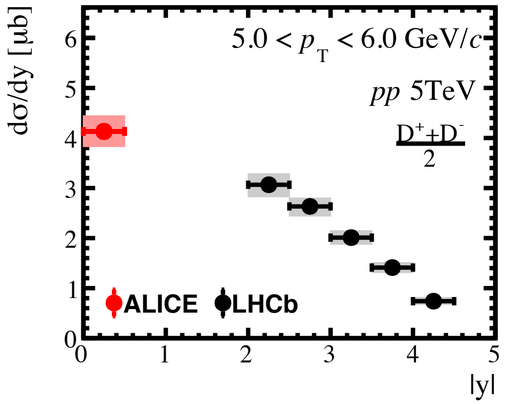


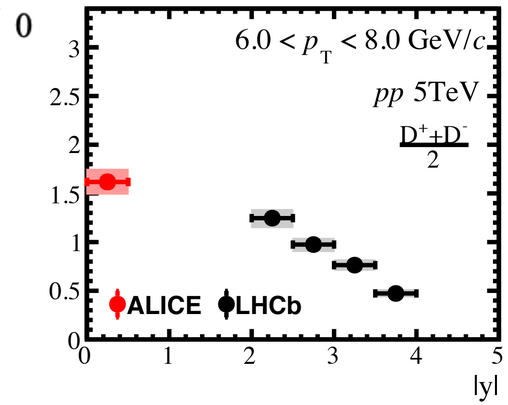


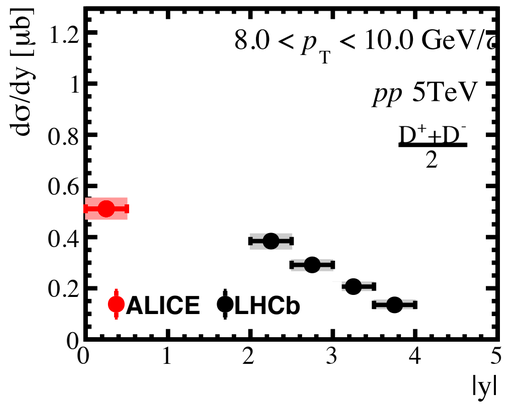






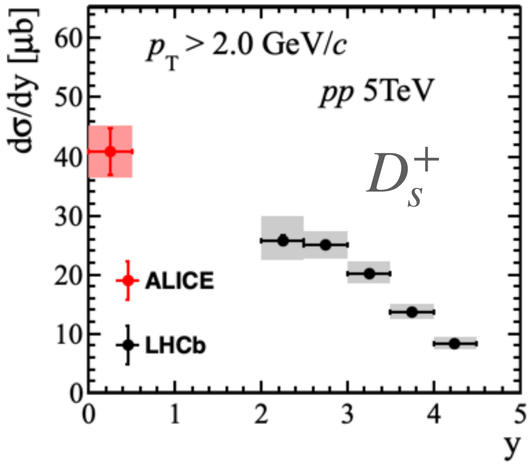


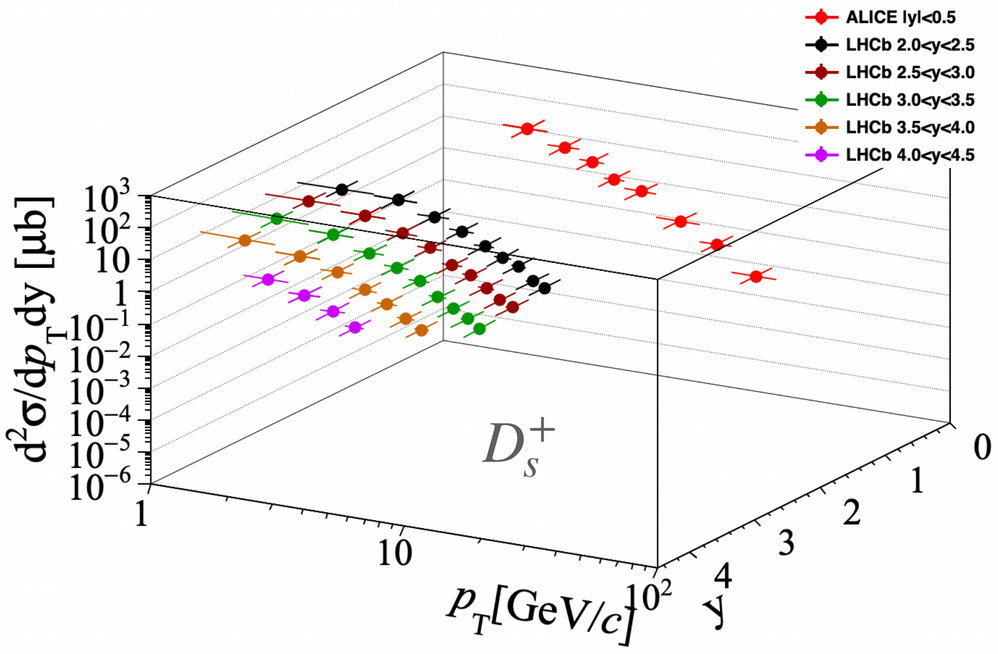


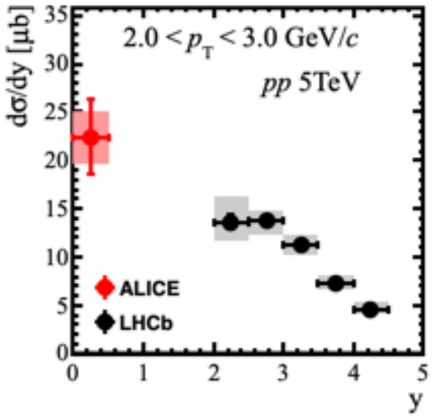


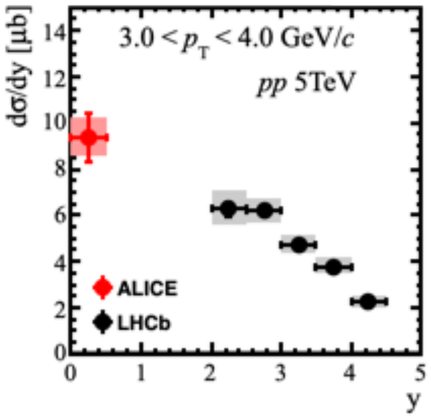
Combination plots for D_s^+

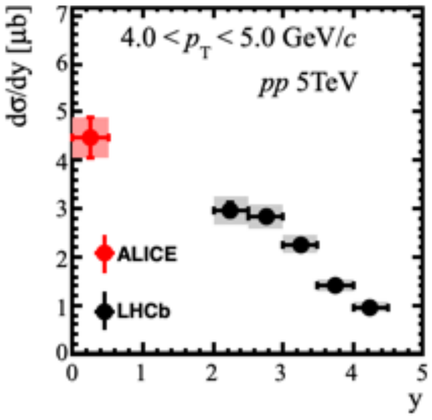
- D_s^+ cross-section in p_T and y
- D_s^+ cross-section vs. y in p_T slices

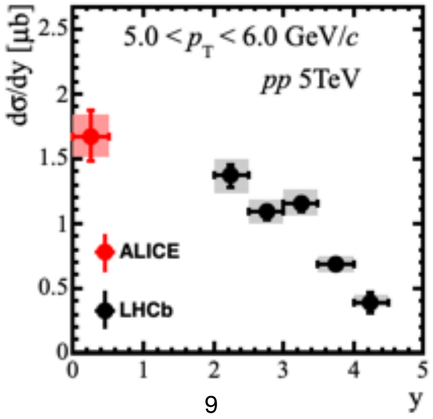


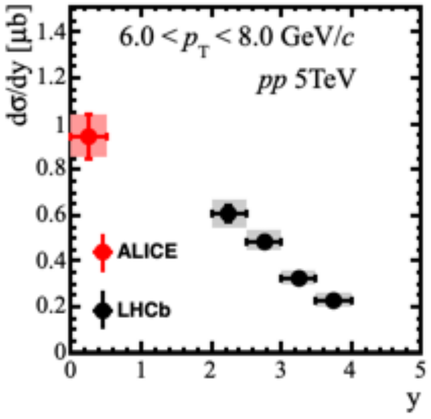






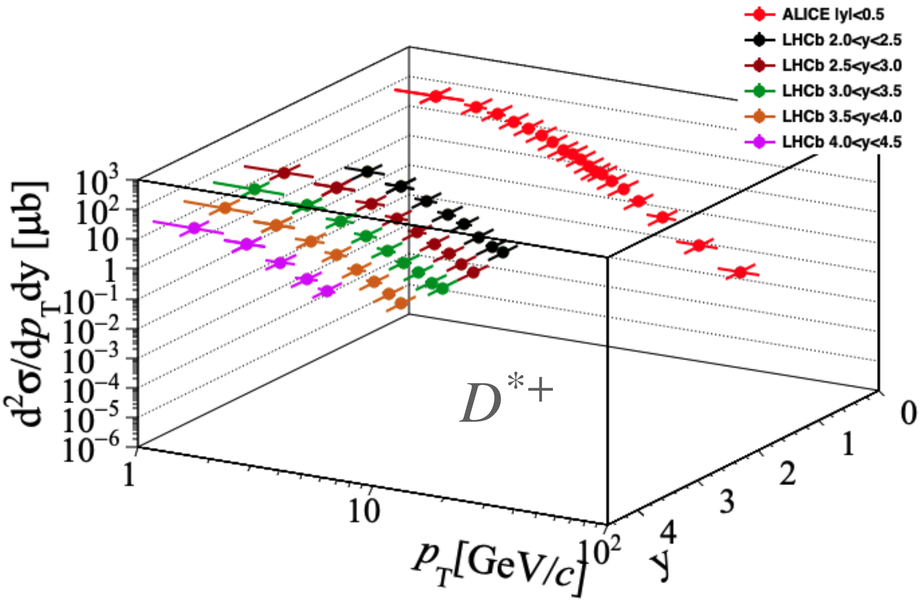


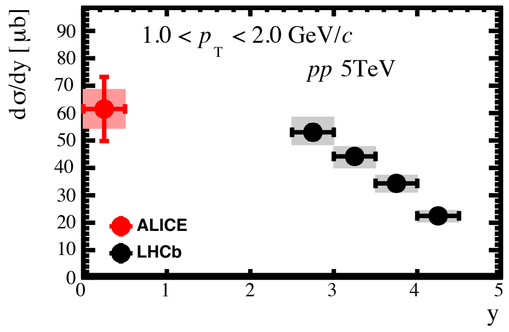


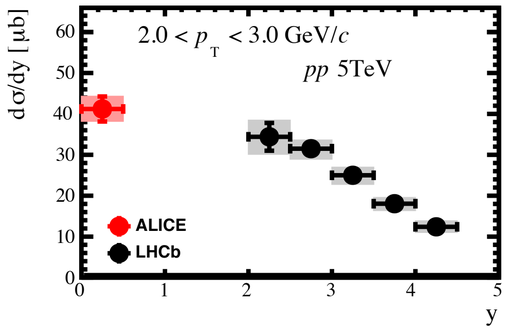


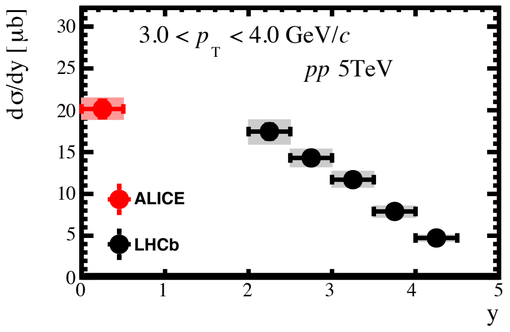
Combination plots for D^{*+}

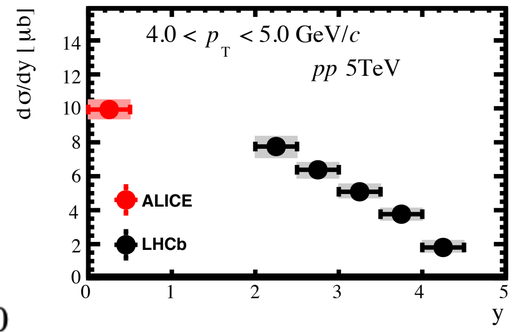
- D^* cross-section in p_T and y
- D^* cross-section vs. y in p_T slices

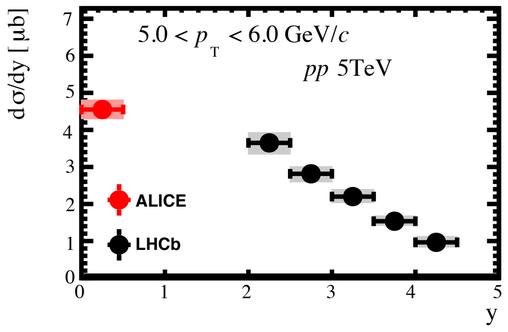


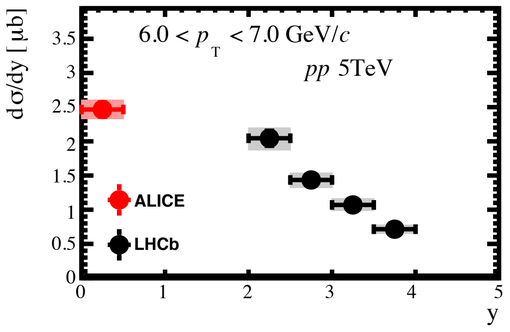


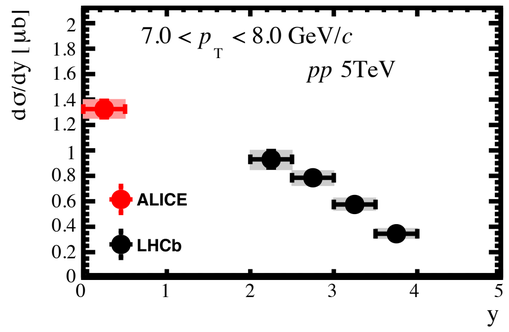


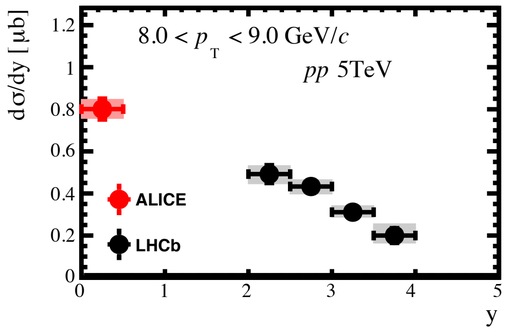


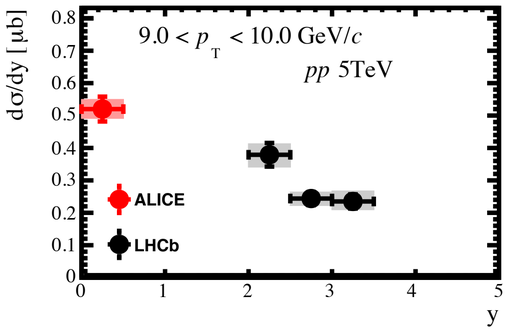










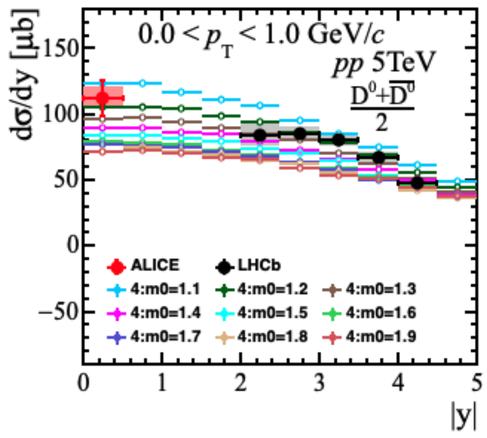


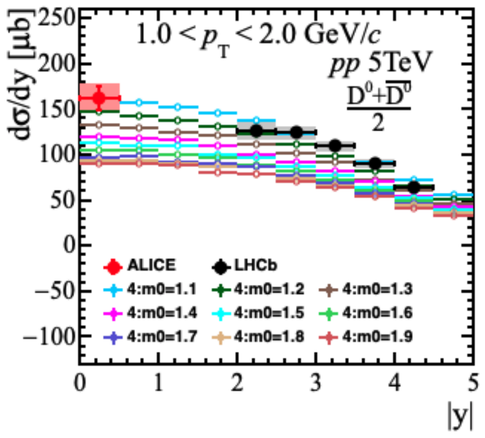
PYTHIA-data comparison

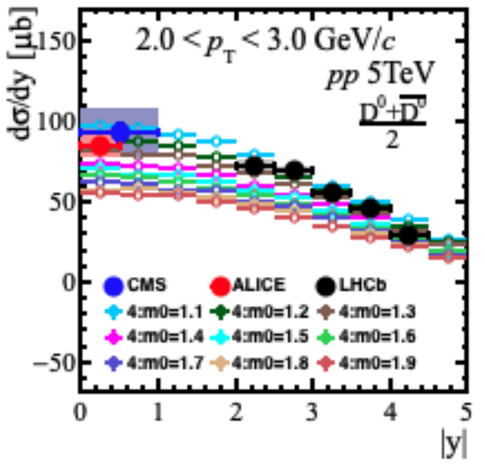
- Data from ALICE, CMS and LHCb do not cover the full rapidity range, interpolation and extrapolation must be performed to estimate the total charm cross section.
  - PYTHIA and FONLL event generators
- PYTHIA settings:
  - Parton-shower approach for charm production in very low p_{T}
  - For hard $2 \rightarrow 2$ process use the PYTHIA model for multiparton interactions [PRD 36 (1987) 2019]
  - The only remaining parameter to fix is the kinematic charm mass, default value in PYTHIA is 1.5 GeV
- Scan charm mass from 1.1 to 1.9 GeV, in 0.1 GeV step size. Produce 10M PYTHIA events for each charm mass value.
- Find the best charm mass value from simultaneous fit to measured charmed hadrons cross-section in (p_{T}, y) space.
- Currently, made comparisons for D^0, D^+, D_s^+ and D^* mesons.

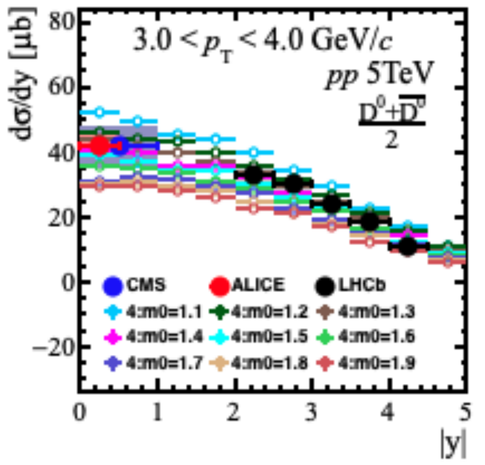
D^0 comparison to PYTHIA

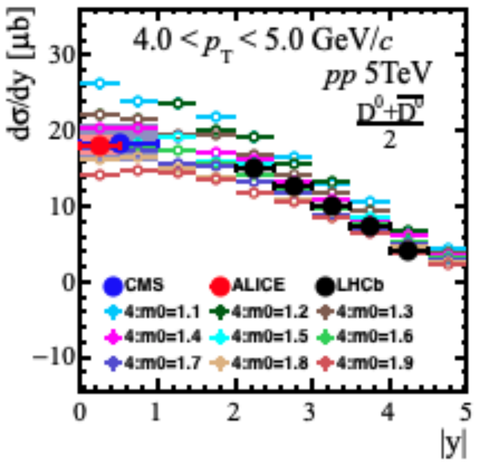
- 10M PYTHIA events for each charm mass value (m0) from 1.1 to 1.9 GeV, in 0.1GeV step.
- Cross-section vs. rapidity in p_T slices
- Using 5TeV *pp* data from ALICE, CMS and LHCb

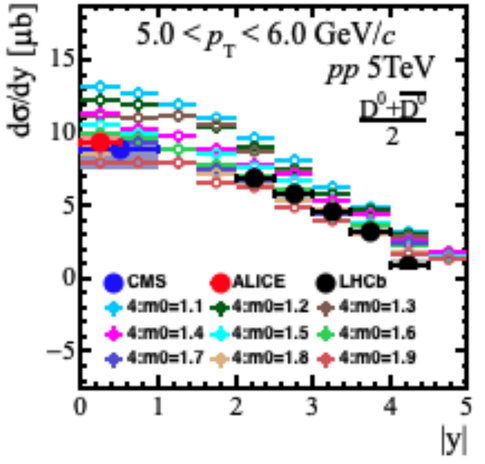


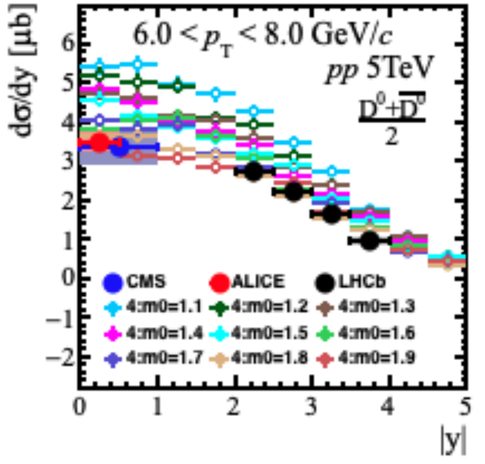


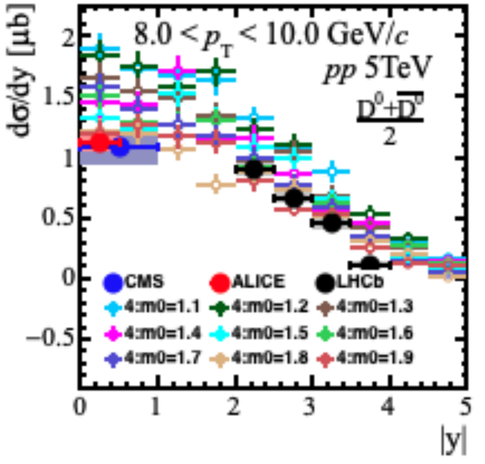






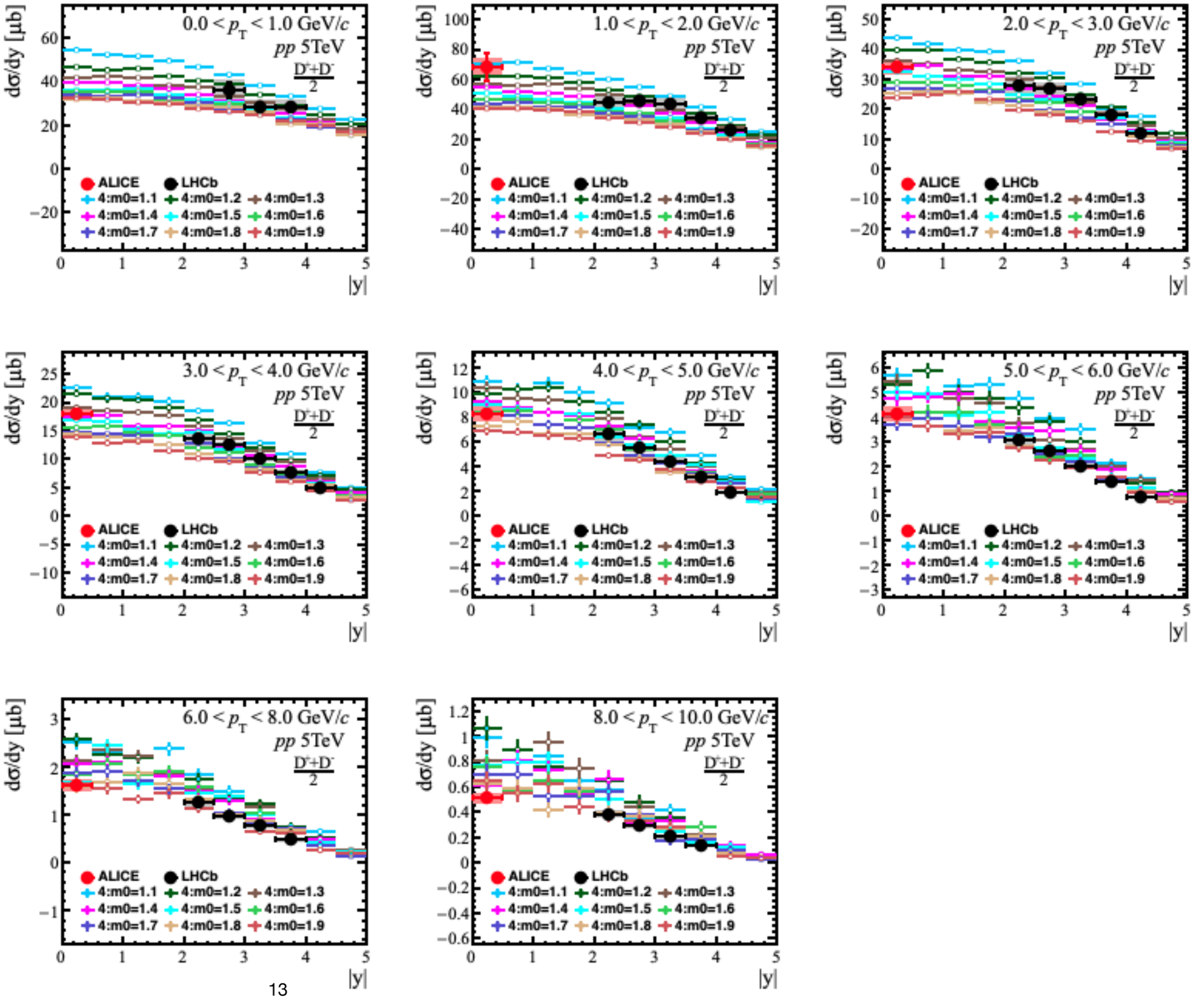






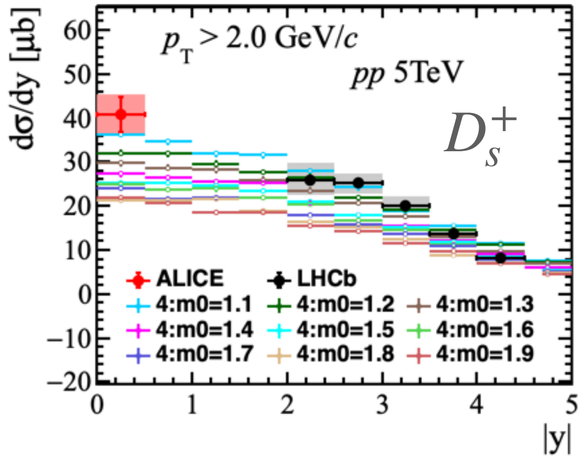
D^+ comparison to PYTHIA

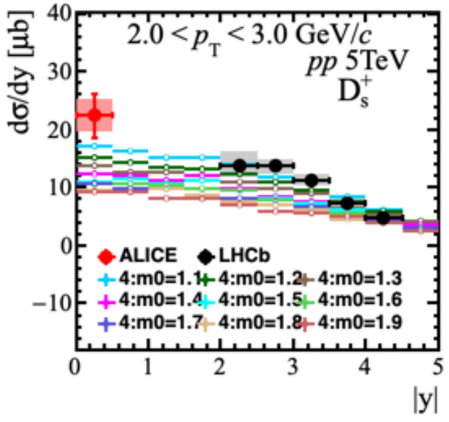
- 10M PYTHIA events for each charm mass value (m0) from 1.1 to 1.9 GeV, in 0.1GeV step.
- Cross-section vs. rapidity in p_T slices
- Using 5TeV *pp* data from ALICE and LHCb

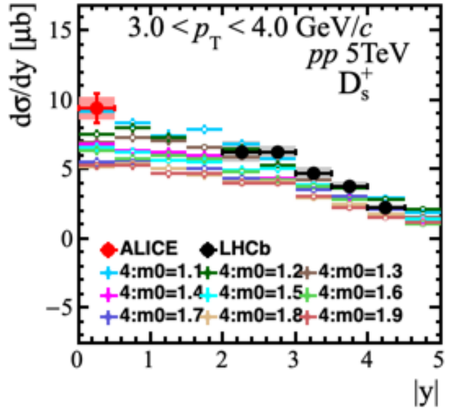


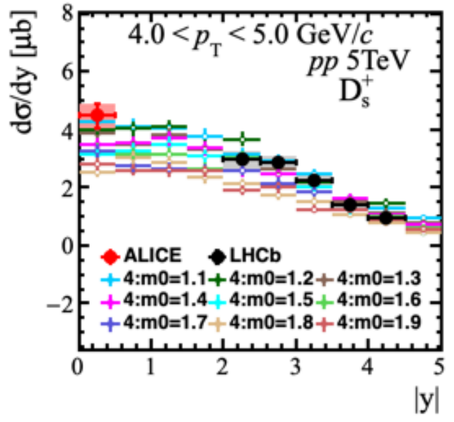
D_s^+ comparison to PYTHIA

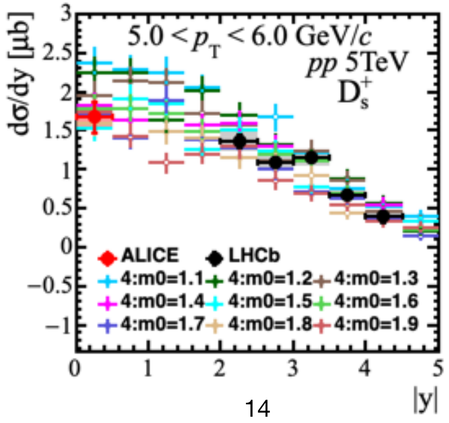
- 10M PYTHIA events for each charm mass value (m0) from 1.1 to 1.9 GeV, in 0.1GeV step.
- Cross-section vs. rapidity in p_T slices
- Using 5TeV *pp* data from ALICE and LHCb

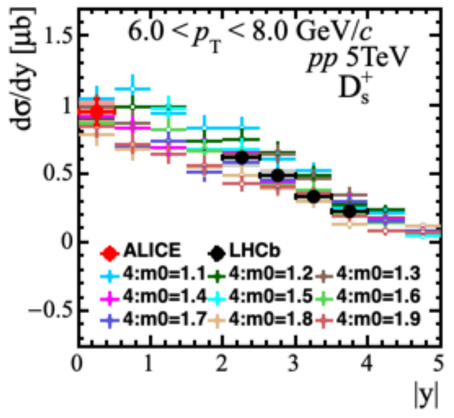






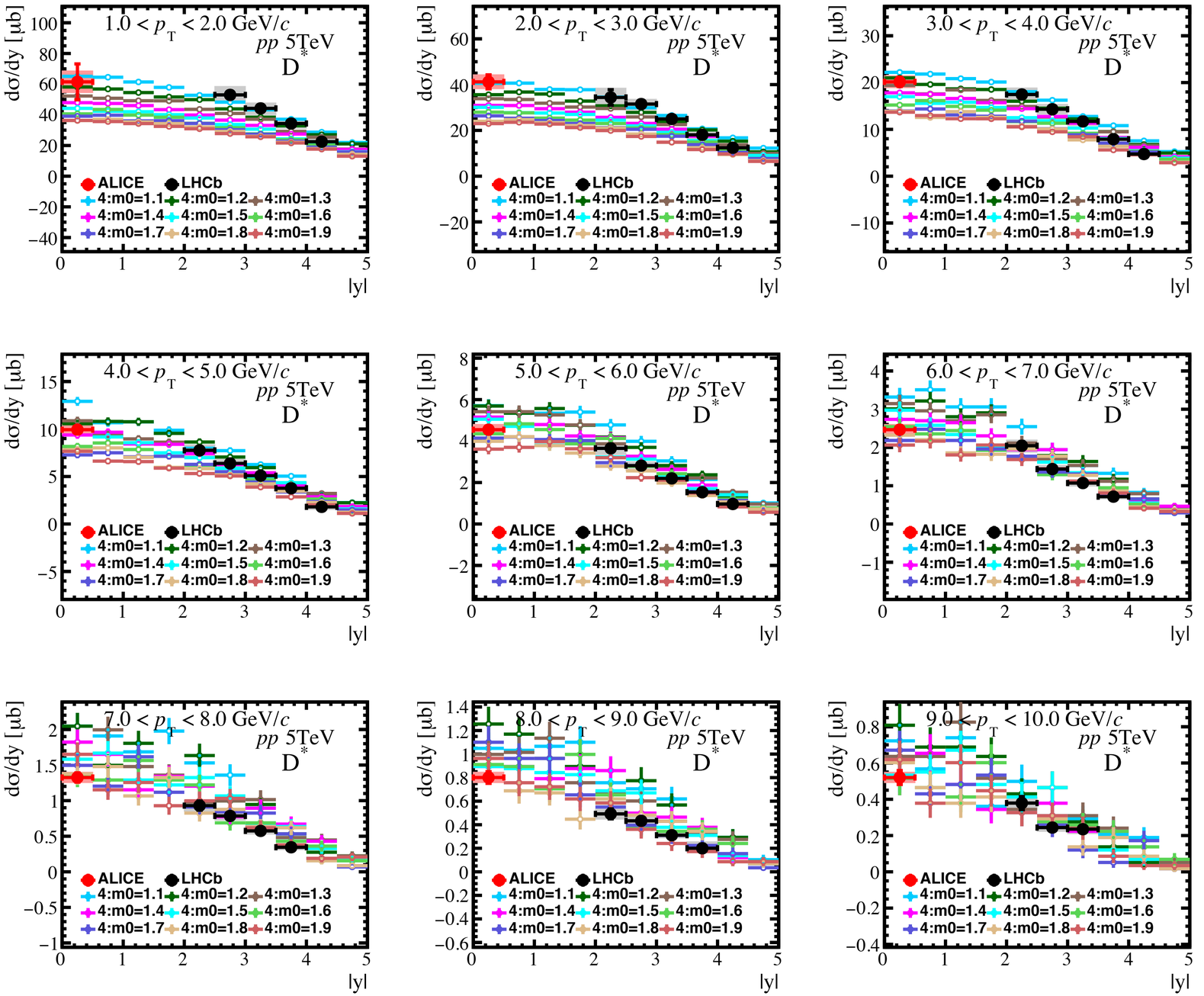






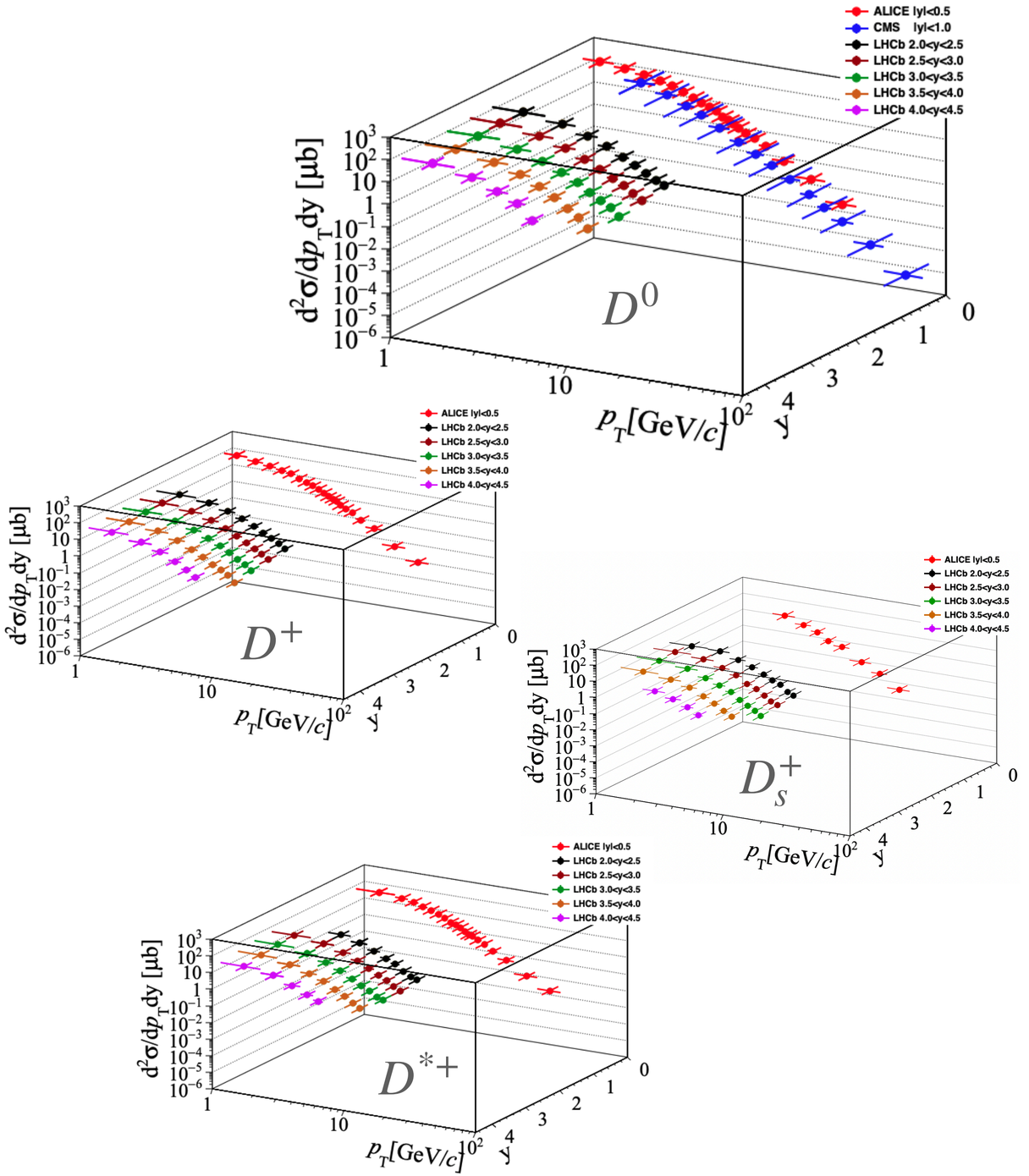
D^{*+} comparison to PYTHIA

- 10M PYTHIA events for each charm mass value (m0) rom 1.1 to 1.9 GeV, in 0.1GeV step.
- Cross-section vs. rapidity in p_T slices
- Using 5TeV *pp* data from ALICE and LHCb



Simultaneous fit

- Calculate χ^2 across D^0, D^+, D_s^+ and D^* from all experiments to find the charm mass value (m0) that describes data best.
- Compare each point between data and PYTHIA, calculate $\chi^2 = \Sigma \frac{(data - pythia)^2}{\sigma^2}$, summed over all data points.
- Consider correlation of systematic uncertainties
  - Common correlation between experiments
    - Branching ratio
  - Correlations within each experiment
    - between same meson species
    - between different meson species



Correlated systematics within experiments

- **Correlations in LHCb:**
  - Correlation matrices from HEPDATA for same and difference D meson species
- **Correlations in ALICE:**

	Uncertainties (%)				Correlations (%)	
	D^0	D^+	D_s^+	D^{*+}	Bins	Decay modes
Luminosity	3.8				100	100
Tracking	3–5	5–7	4–7	5–7	90–100	90–100
Branching fractions	1.2	2.1	5.8	1.5	100	0–95
Simulation sample size	0–10	0–10	2–9	1–10	0	0
Simulation modelling	0.3	0.7	0.6	2	0	0
PID sample size	0–1	0–1	0–2	0–2	0–100	0–100
PID binning	0–30	0–10	0–20	0–20	0	0
Fit model shapes	0–3	0–3	0–3	0.0–1.0	0	0

Systematic uncertainty	Same D mesons	Different D mesons
Luminosity	fully correlated	fully correlated
Raw yields		
Tracking	fully correlated	fully correlated
Cut efficiency	fully correlated	
PID	fully correlated	
MC p_T shape	fully correlated	
Feed-down	fully correlated	fully correlated

- **Correlations in CMS:**
  - Luminosity and BR are fully correlated

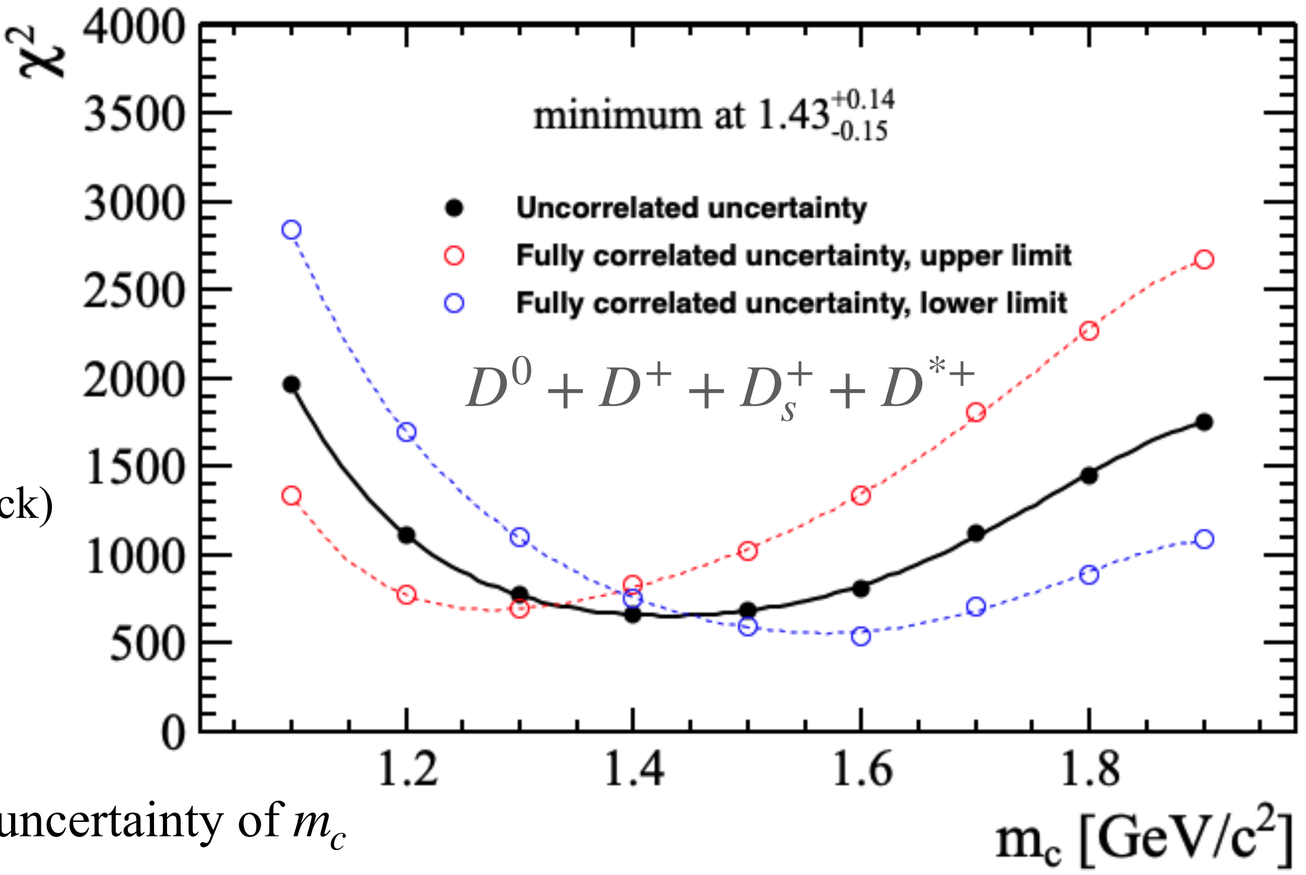
- Tested calculating χ^2 with correlated uncertainties:

$$\chi^2 = X^T V^{-1} X$$

- X = (measurement - expectation) = (data points - pythia)
  - X: an n-dimensional vector
  - n is the number of data points used in the calculation
- V = $n \times n$ covariance matrix
- V^{-1} = invert of covariance matrix

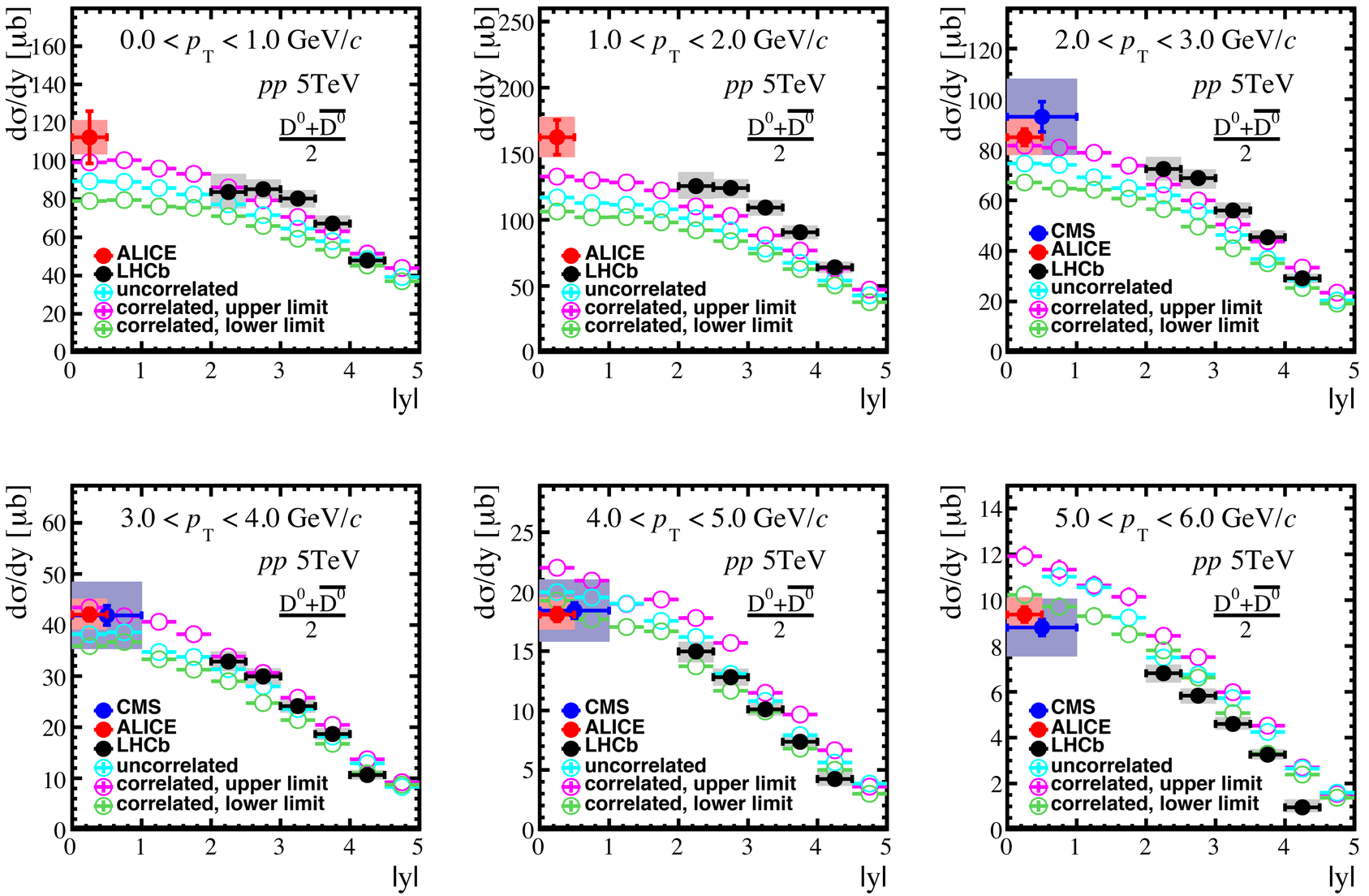
Simultaneous fit

- Calculate χ^2 across D^0, D^+, D_s^+ and D^{*+} from all experiments to find the best charm mass value (m0).
- Compare each point between data and PYTHIA, calculate $\chi^2 = \Sigma \frac{(data - pythia)^2}{\sigma^2}$, summed over all data points.
  - σ is the total uncertainty of a data point
- $p_T < 6$ GeV/c
- ALICE, LHCb and CMS points are used.
  - LHCb points provide most constraint.
- Assuming two extreme cases:
  - **Totally uncorrelated uncertainty** across data points (black)
  - **Totally correlated uncertainty**:
    - Shift all points up by 1 sigma (red)
    - Shift all points down by 1 sigma (blue)
- The variation of the minimum position can be used as uncertainty of m_c
  - Minimum position: $1.43^{+0.14}_{-0.15}$



Fit results: D^0 vs. Pythia

- Light blue:
  - Uncorrelated case
  - $m_c = 1.43\ GeV/c^2$
- Magenta:
  - Fully correlated, upper limit
  - $m_c = 1.28\ GeV/c^2$
- Green:
  - Fully correlated, lower limit
  - $m_c = 1.57\ GeV/c^2$
- Pythia band below data at low p_{T}
- Increase Δm_c to cover low p_{T} data poi
- Include Λ_c^+ into the fit.



Fit results: D^+ vs. Pythia

- Light blue:
  - Uncorrelated case
  - $m_c = 1.43\ GeV/c^2$
- Magenta:
  - Fully correlated, upper limit
  - $m_c = 1.28\ GeV/c^2$
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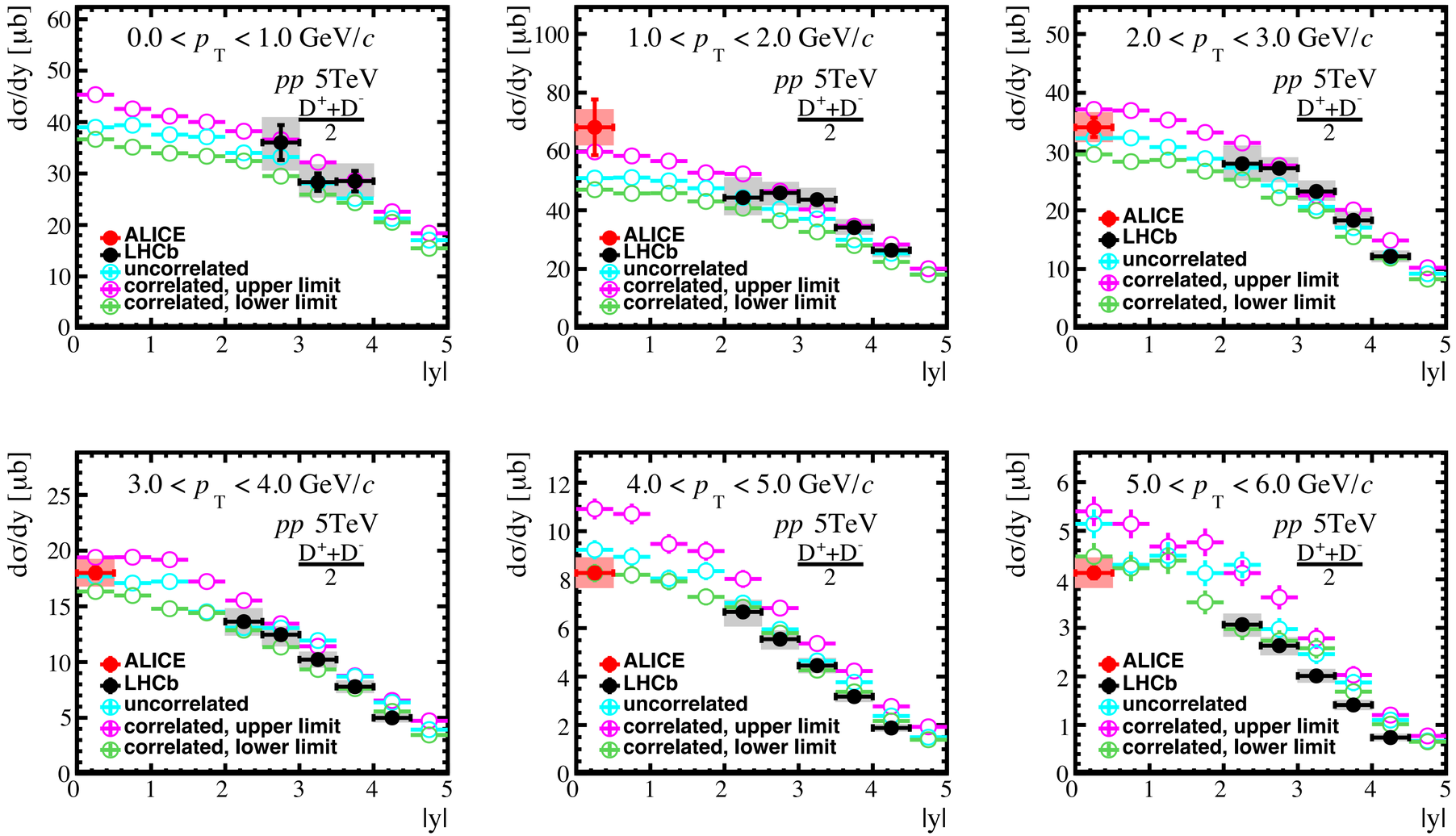

Fit results: D_s^+ vs. Pythia

- Light blue:
  - Uncorrelated case
  - $m_c = 1.43\ GeV/c^2$
- Magenta:
  - Fully correlated, upper limit
  - $m_c = 1.28\ GeV/c^2$
- Green:
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  - $m_c = 1.57\ GeV/c^2$
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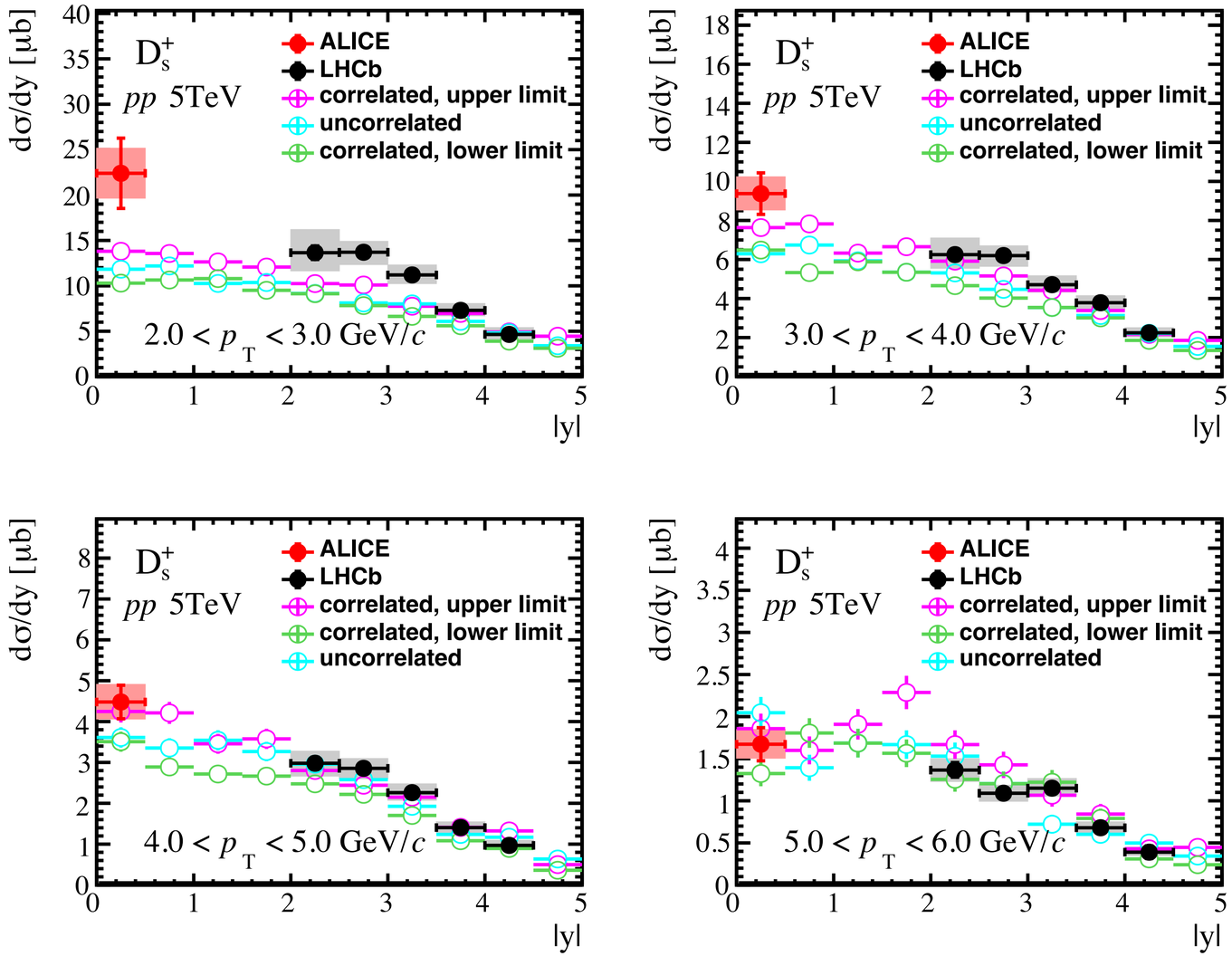

Fit results: D^{*+} vs. Pythia

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  - $m_c = 1.57\ GeV/c^2$
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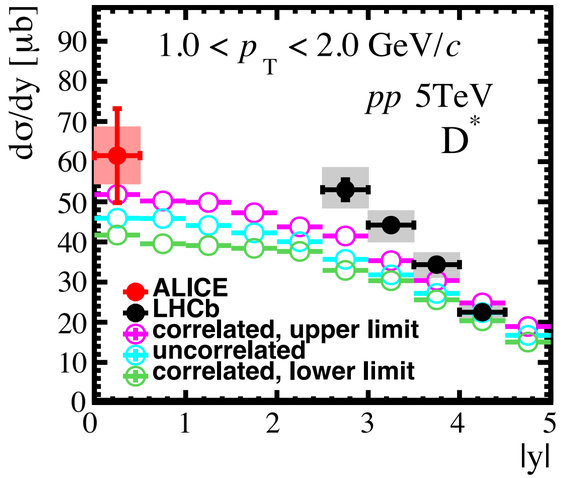
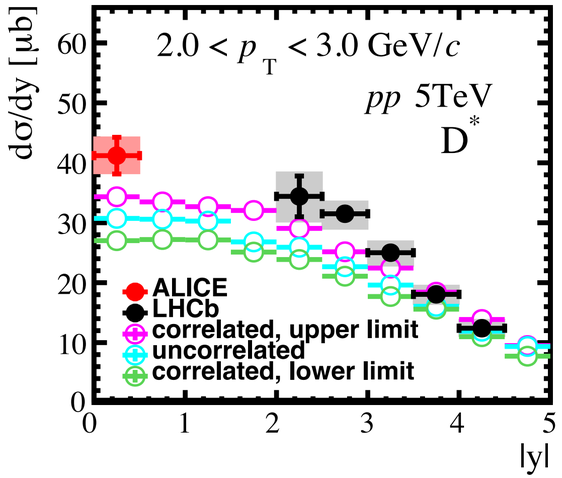
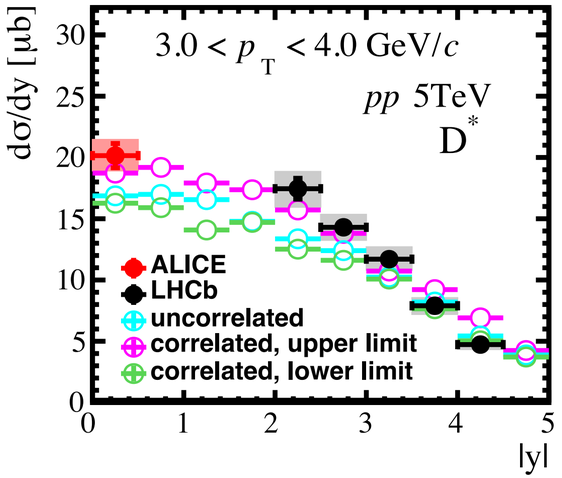
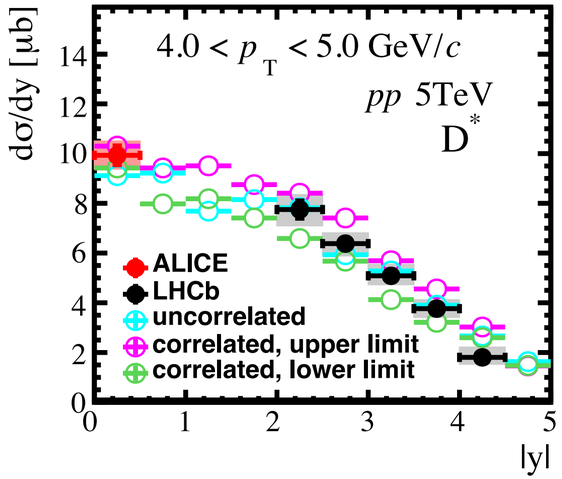
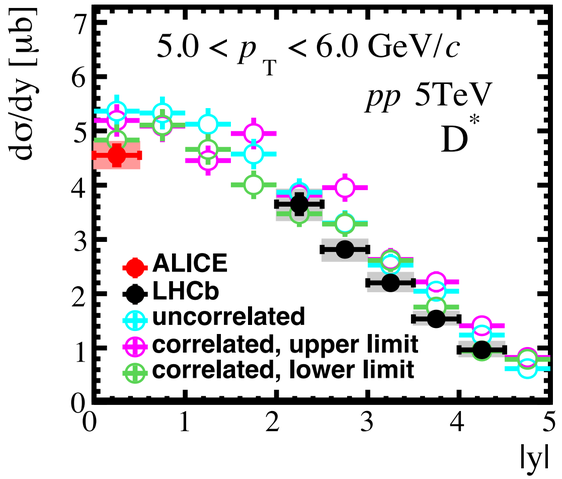
- Increase Δm_c to cover low p_{T} data points
- Include Λ_c^+ into the fit.











Summary

- The project of total charm cross-section from combining ALICE, CMS and LHCb measurements is making good progress.
- Compared with PYTHIA calculations, found parameters that describe data.
  - To-do: include ALICE Λ_c^+ data into the fitting.
- Working on extrapolation to obtain total cross-section.
- Preparing paper on data/theory comparisons and total charm cross-section in the coming months.