Charm total cross section measurements at the LHC and beyond

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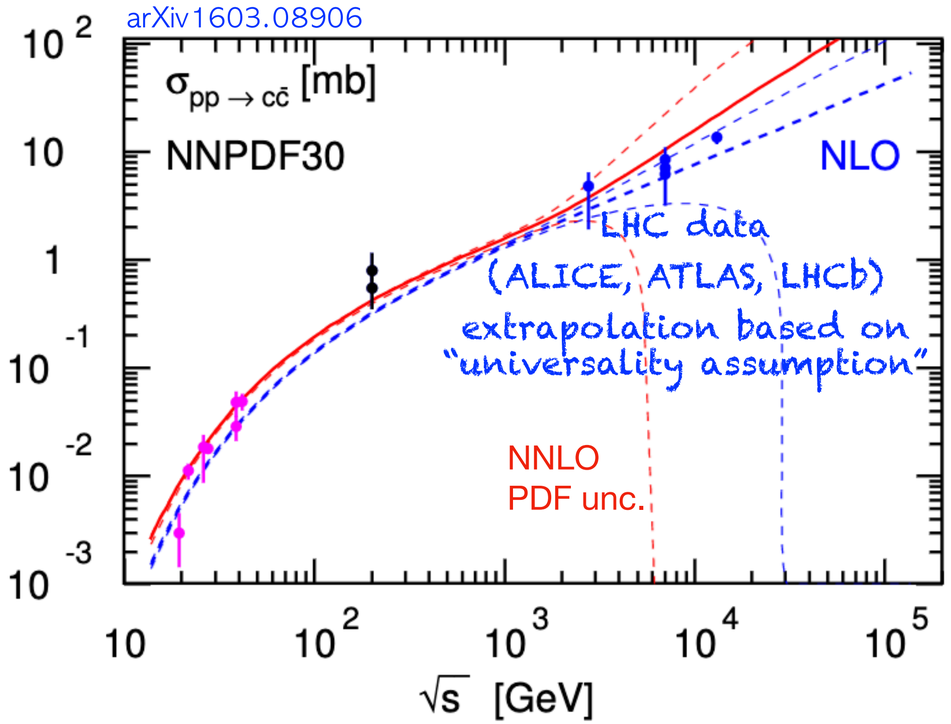
ICHEP, Prague, July 19th, 2024

Analysis Motivation

the highest order for charm today

✓ Total charm cross section measurements can be compared with **NNLO** QCD theory
- measured fiducial cross section should be extrapolated using a theory/model
  - so far based on *fragmentation universality assumption*
  - recent LHC data: **charm fragmentation non-universal!**



- a theory-inspired extrapolation function derived for *pp* data (arXiv:2311.07523 & arXiv:2406.03581)
  - used to extrapolate CMS+LHCb data at 7 TeV (refer to CMS talk, Y.Yang)
- can be used to constrain e.g., m_c and low x of PDFs
  - refer to an example today

28 July 2021, CERN COURIER

STRONG INTERACTIONS | NEWS

Charm breaks fragmentation universality

28 July 2021

A report from the ALICE experiment

The study of heavy-flavour hadron production in proton–proton (pp) collisions provides an important test for quantum chromodynamics (QCD) calculations. Heavy-flavour hadron production is usually computed with perturbative–QCD (pQCD) calculations as the convolution of the parton distribution functions (PDFs) of the incoming protons, the partonic cross section and the fragmentation functions that describe the transition from charm quarks into charm hadrons. The latter are typically parametrised from measurements performed in e^+e^- or ep collisions, under the assumption that the hadronisation of charm quarks into charm hadrons is a universal process that is independent of the colliding systems.

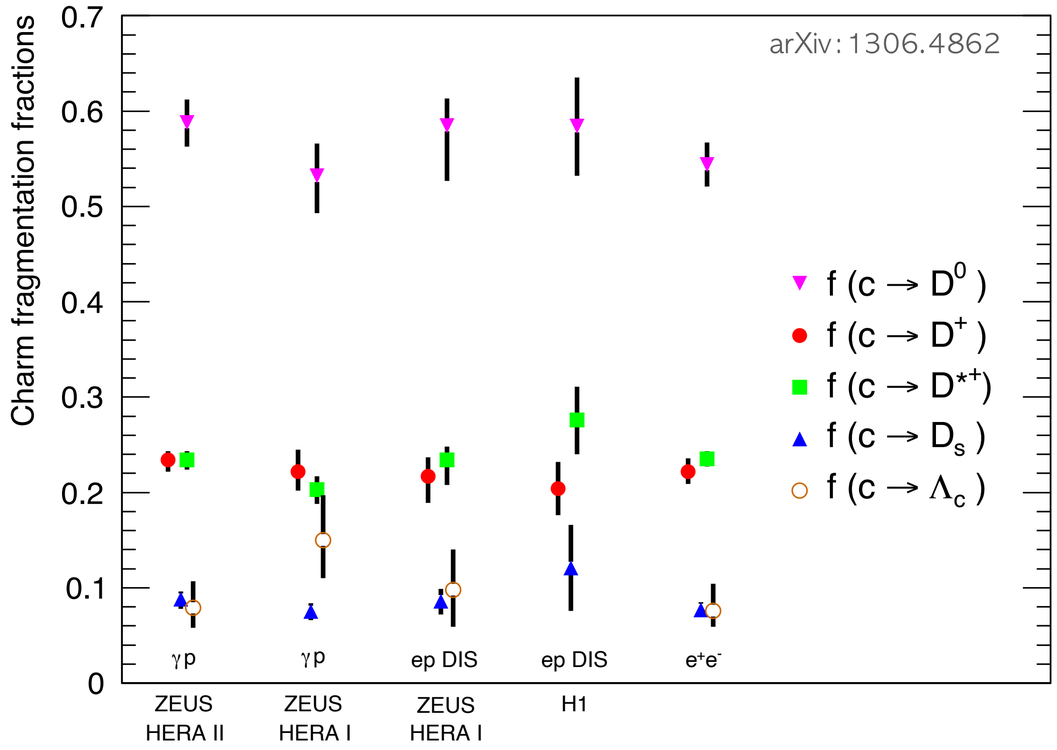
The assumption that charm-to-hadron fragmentation is universal is not valid

The large data samples collected during Run 2 of the LHC at $\sqrt{s}$ = 5.02 TeV allowed the ALICE collaboration measure the vast majority of charm quarks produced in the pp collisions by reconstructing the decays of the ground-state charm hadrons, measuring all the charm-meson species and the most abundant charm baryons (Λ_c^+, and $\Xi_c^{0,+}$) down to very low transverse momenta. The result was presented today at the European Physical Society conference on high-energy physics (EPS-HEP 2021).

Universality Assumption of Charm Fragmentation

✓ To extrapolate measured fiducial cross sections, experimental inputs required for *fragmentation*

- **charm fragmentation fraction**: probability of charm to fragment into a hadron state *in full phase space*
  - i.e., fraction of *total* hadronic cross section to *total* charm cross section
  - measurements from e^+e^-/ep collisions ($f_{H_c}^{uni}$) showed no significant differences

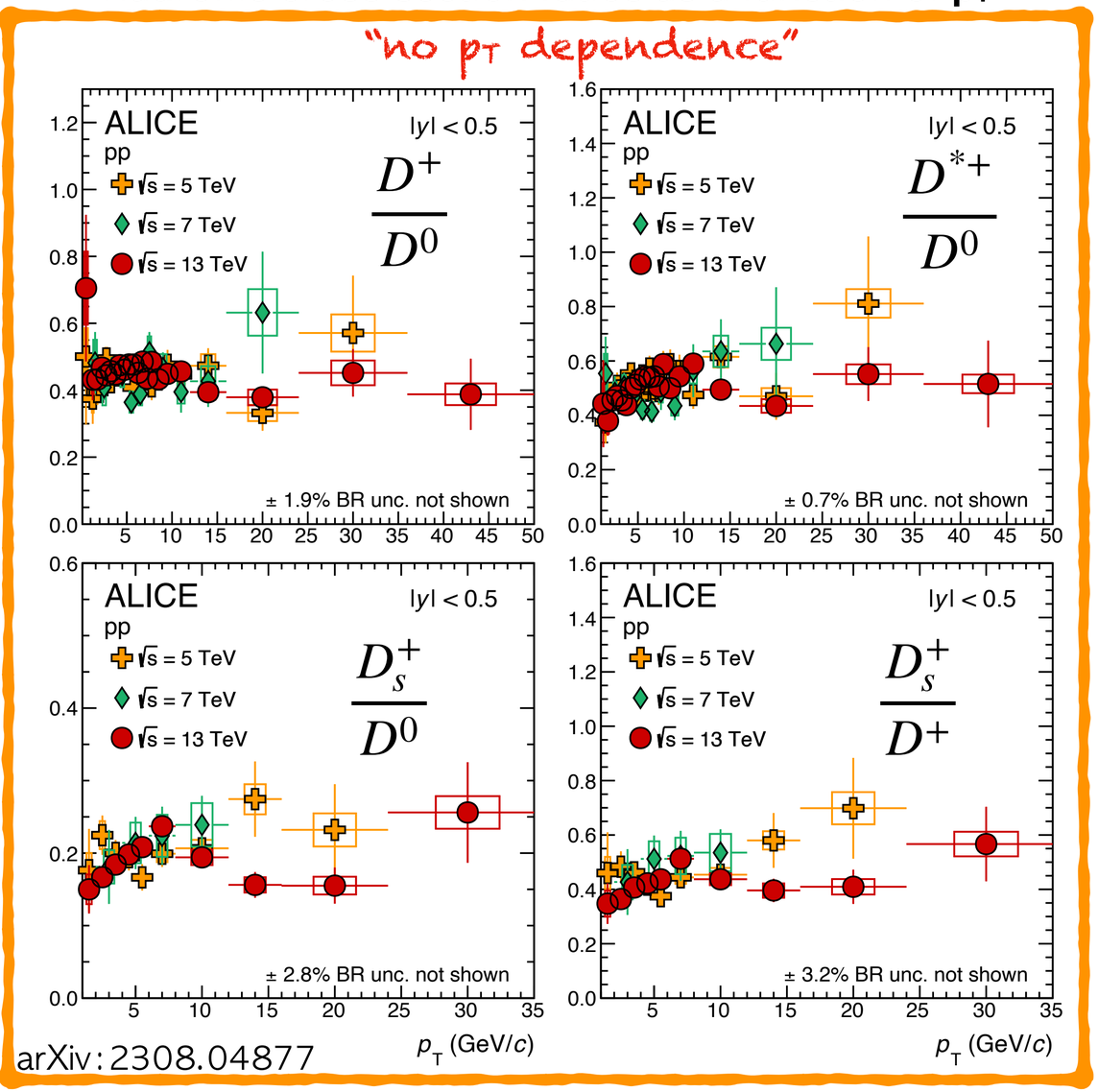


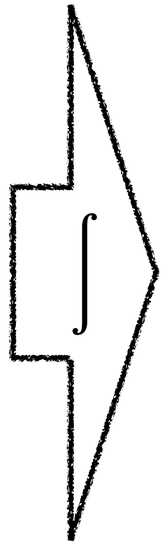
- charm fragmentation assumed so far to be universal, i.e., independent of collision systems and kinematic space

Meson-to-meson and Baryon-to-baryon

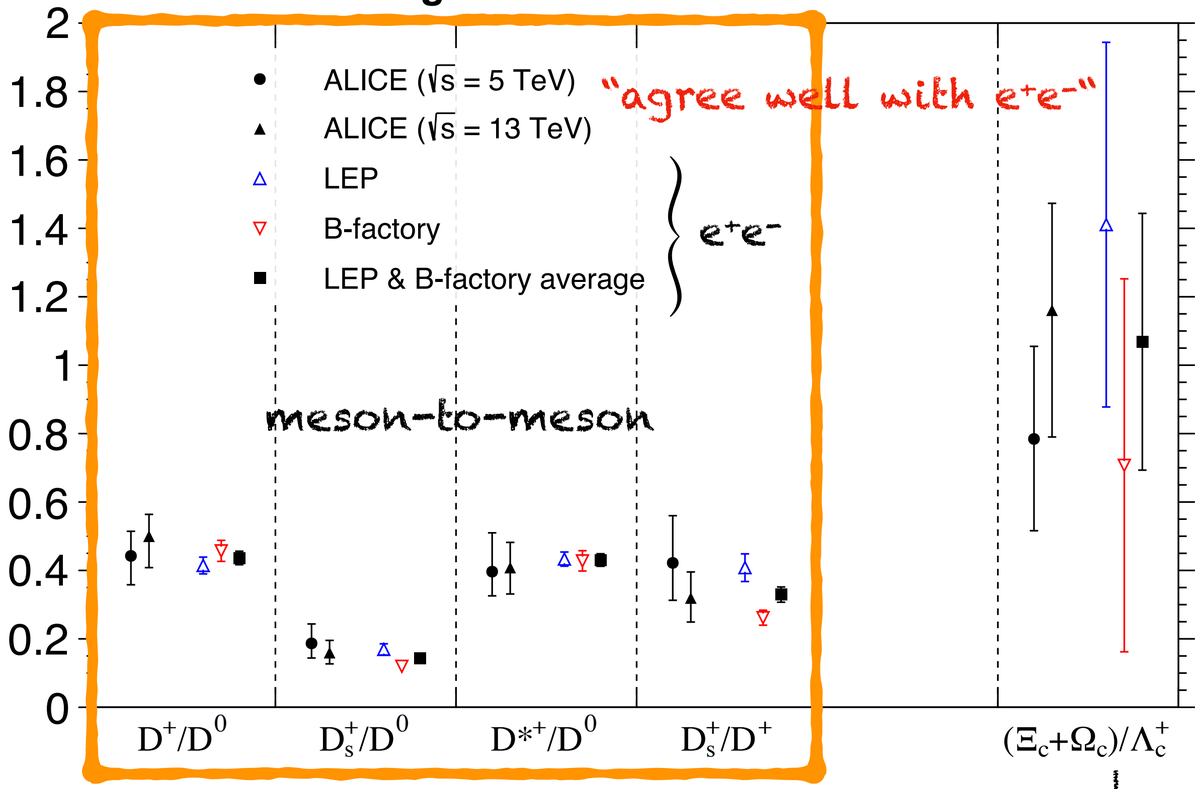
✓ Recent LHC data: “no significant dependence on collision systems and kinematic space”

Hadronic cross section ratios as a function of p_T





Fragmentation fraction ratios

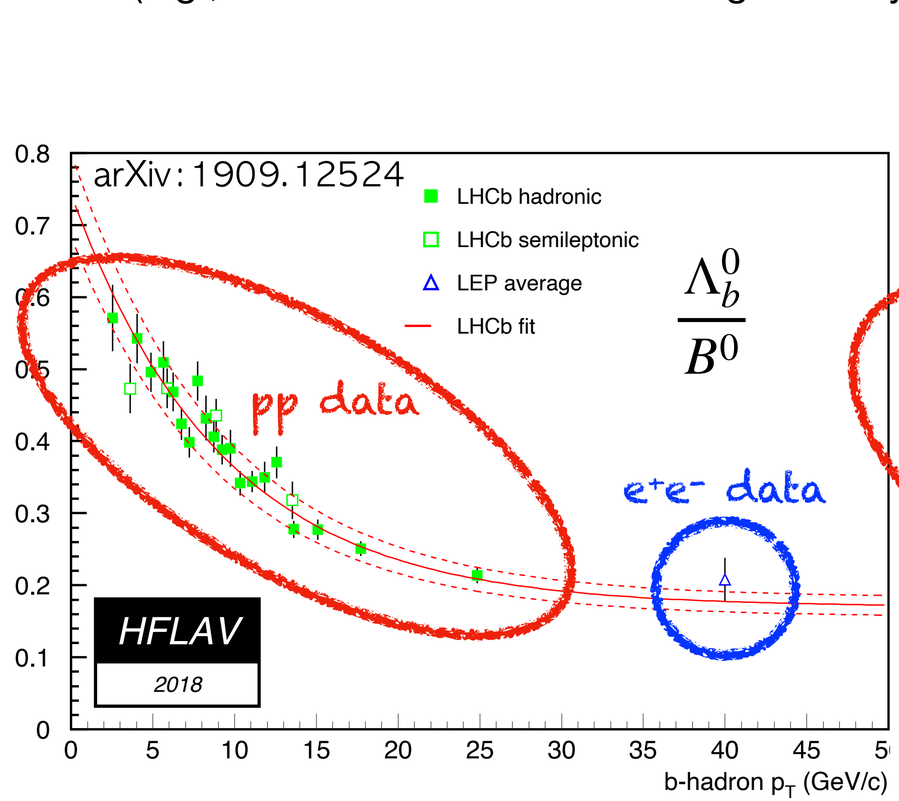


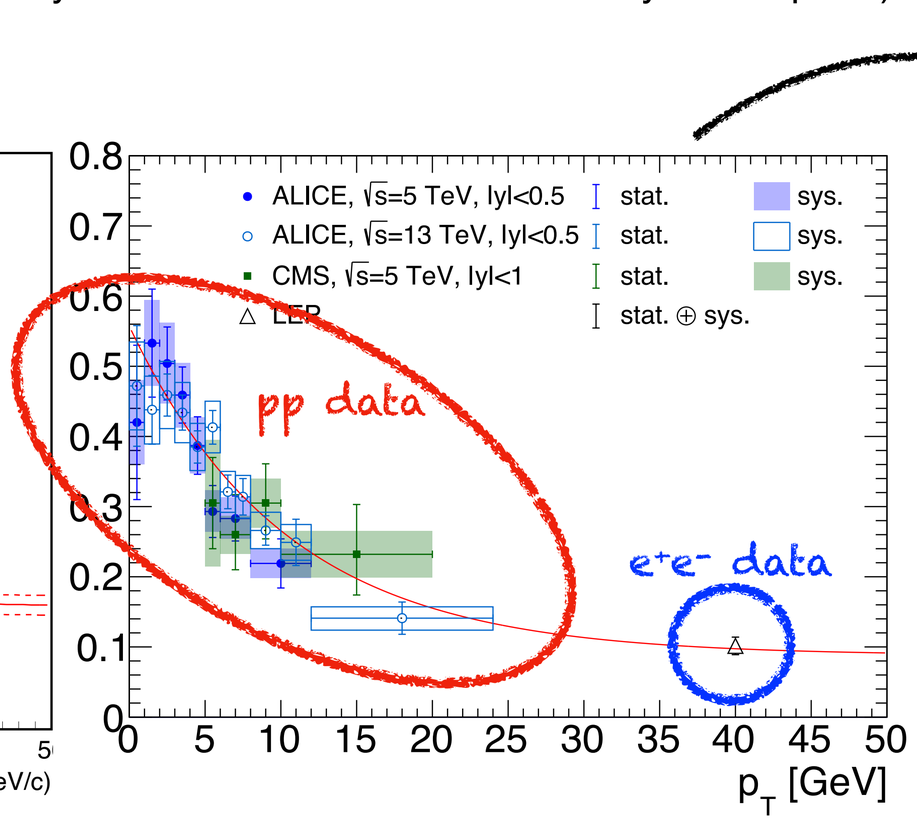
refer to BackUp slide

baryon-to-baryon

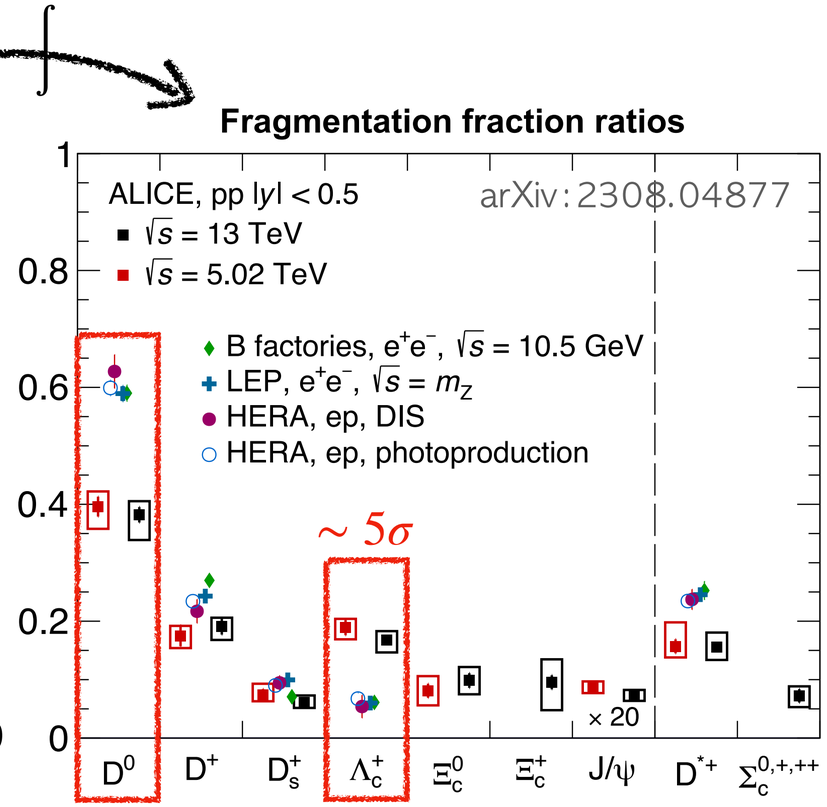
Fragmentation Non-universality

- ✓ pp data of **baryon-to-meson** shows clear p_T dependence
  - much larger at low p_T and asymptotically close at high p_T to e.g., e^+e^- data
  - results $\sim 5\sigma$ difference on fragmentation fraction compared to e^+e^-/ep collisions
- ✓ **Charm fragmentation non-universal** for different collision systems
  - should be treated properly for pp data!
    (e.g., total charm cross section significantly underestimated with universality assumption)





Fragmentation fraction ratios



Data-driven FONLL

the highest order prediction of differential cross section for charm

✓ **FONLL** modified to extrapolate pp data

FONLL (NLO+NLL QCD theory)

based on *fragmentation universality assumption*

fragmentation fraction from e^+e^-/ep

non-perturbative fragmentation function parametrised with e^+e^-/ep

$$d\sigma_{H_c} = f_{H_c}^{uni} \cdot (d\sigma_c \otimes D_{c\to H_c}^{\mathrm{NP}})$$

perturbative $c\bar{c}$ cross section up to NLO+NLL (μ_f, μ_r, m_c)

$$;\ d\sigma_c = f_i f_j \otimes d\hat{\sigma}_{ij}$$

PDF

partonic cross section

Data-driven FONLL (ddFONLL)

without the need to assume any particular non-universal fragmentation model

"p_T dependent production fraction" for weakly decaying ground states including D* (See next)

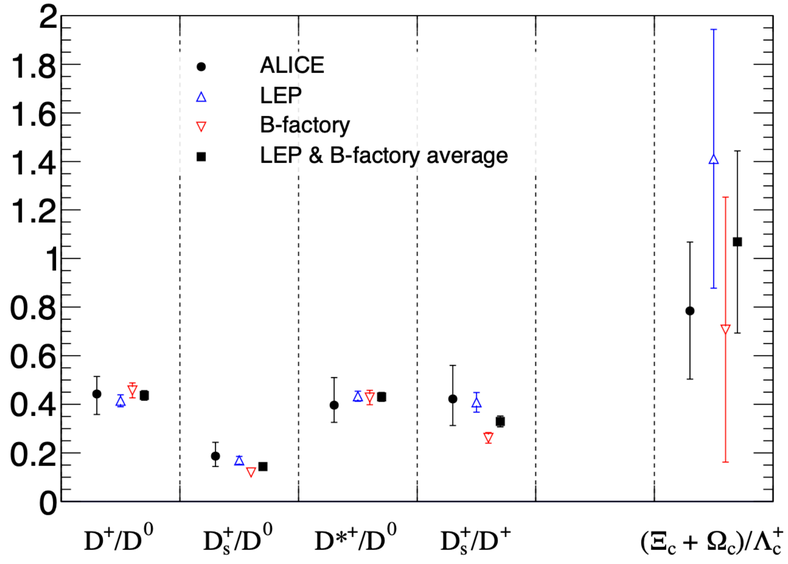
$$\Delta\sigma_{H_c}^{\mathrm{FONLL\ with\ \tilde{f}}} = \tilde{f}_{H_c} \cdot (\Delta\sigma_c \otimes D_{c\to H_c}^{\mathrm{NP}})$$

Kartvelishvili function used (α_K)

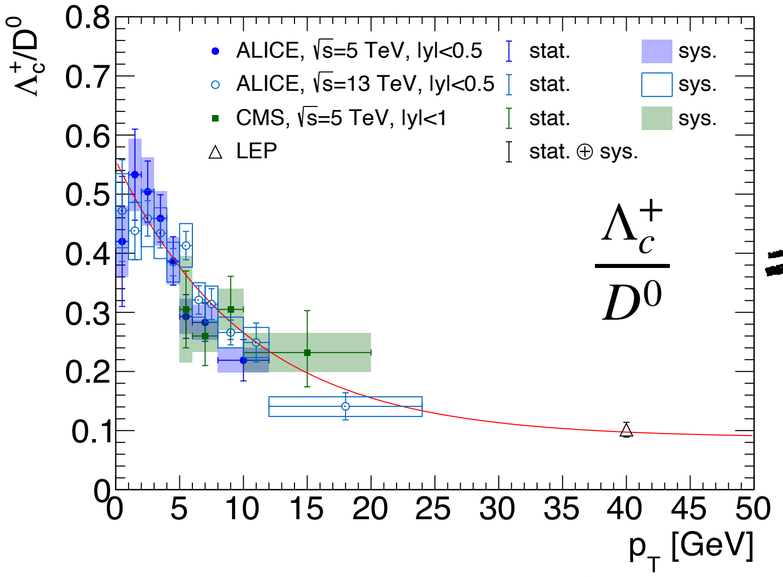
χ^2 fit with 4 free parameters $(\mu_f, \mu_r, m_c, \alpha_K)$ introduced to reduce large FONLL uncertainty

$\tilde{f}$ Defined for Data-driven FONLL

✓ p_T dependent production fraction ($\tilde{f}_{H_c}$) introduced to account for charm fragmentation non-universality, totally based on data

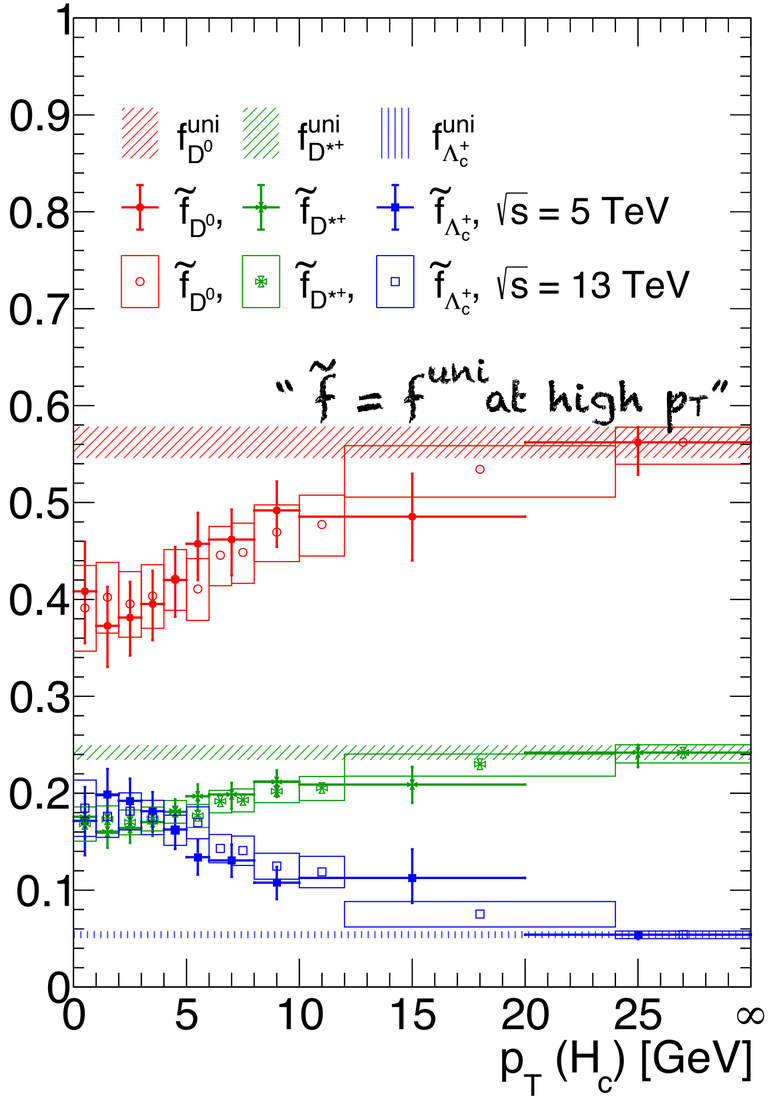


(Assumption1)
meson-to-meson and baryon-to-baryon ratios are universal



(Assumption2)
baryon-to-meson ratios are dependent on p_T, while independent of y

$$= \frac{\tilde{f}_{\Lambda_c^+}}{\tilde{f}_{D^0}}$$



refer to BackUp slide for systematic unc.

refer to D*/D0 ratio in BackUp slide

✓ $\tilde{f}$ ratios of meson-to-meson (including D*) and baryon-to-baryon are p_T independent
- normalisation determined by f^{uni}

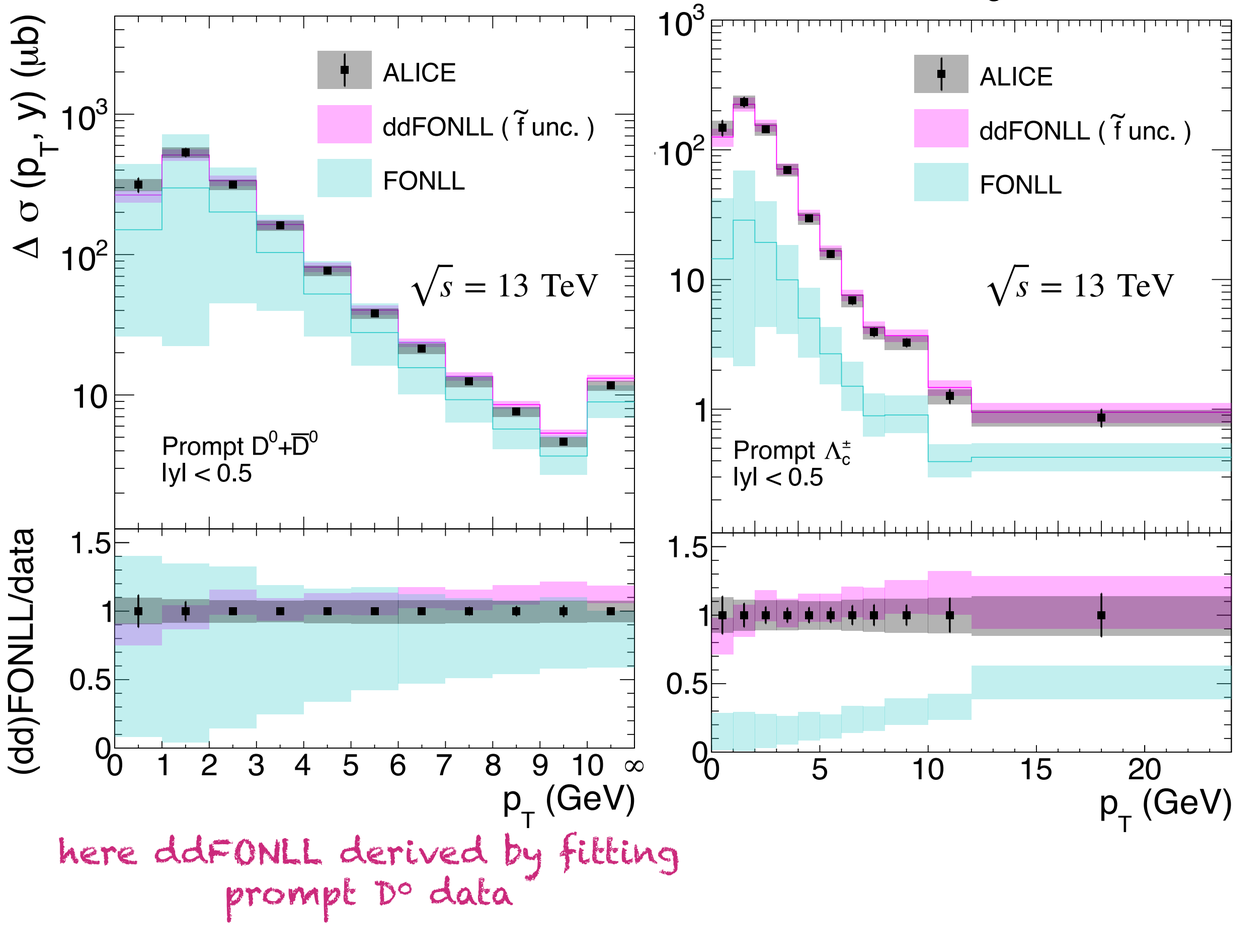
✓ $\tilde{f}$ ratios of baryon-to-meson are p_T dependent
- determined by the most precise measurement of baryon-to-meson ratio (Λ_c^+/D^0)

Parametrisation for *pp* Data

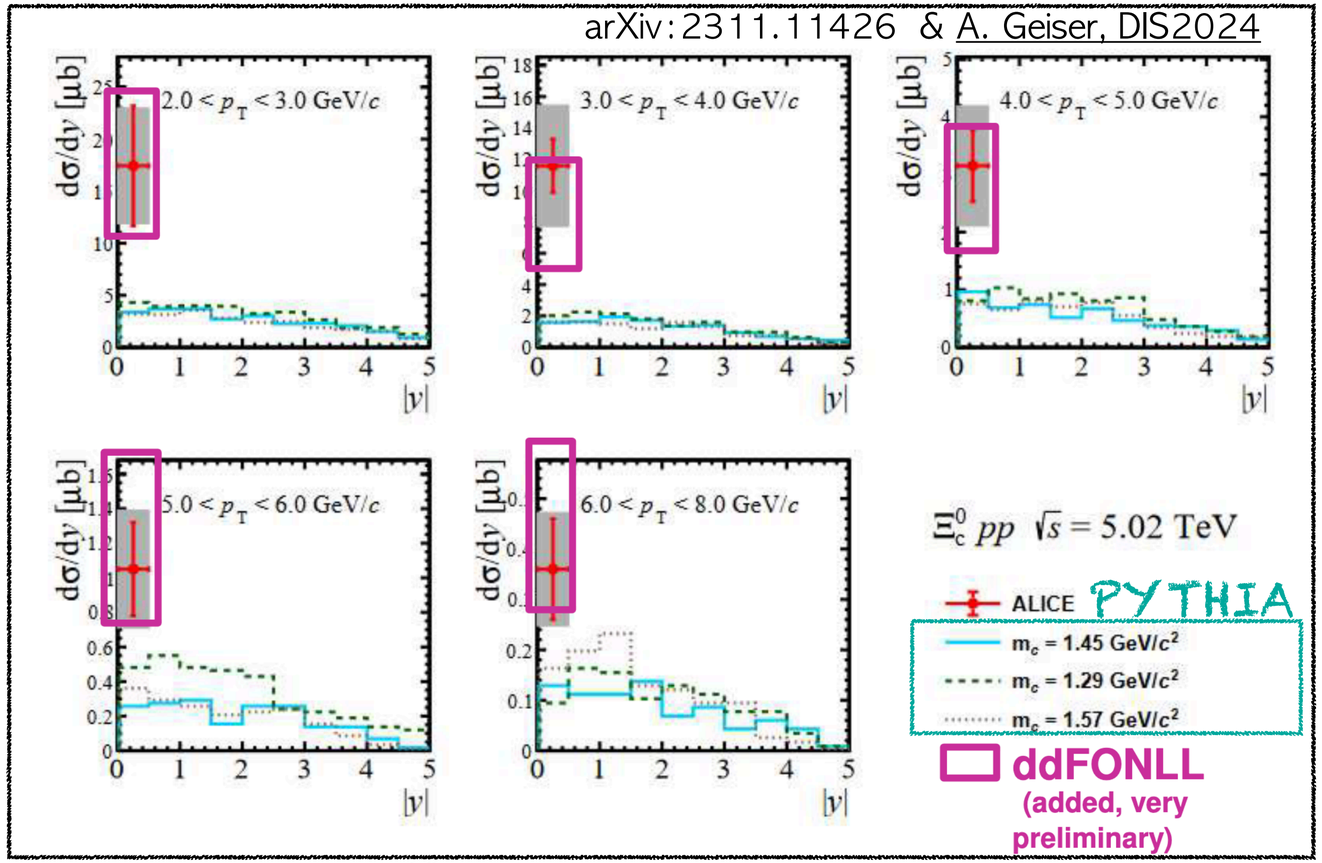
✓ ddFONLL introduced for all weakly decaying ground states including D^{*+} produced in *pp* collisions

- **ddFONLL with a part of uncertainties** gives reasonable description for both meson and baryon data
  - e.g., all baryon states cannot be described by any other theory/model yet

D^0 Λ_c^+ Ξ_c^0



here ddFONLL derived by fitting prompt D° data

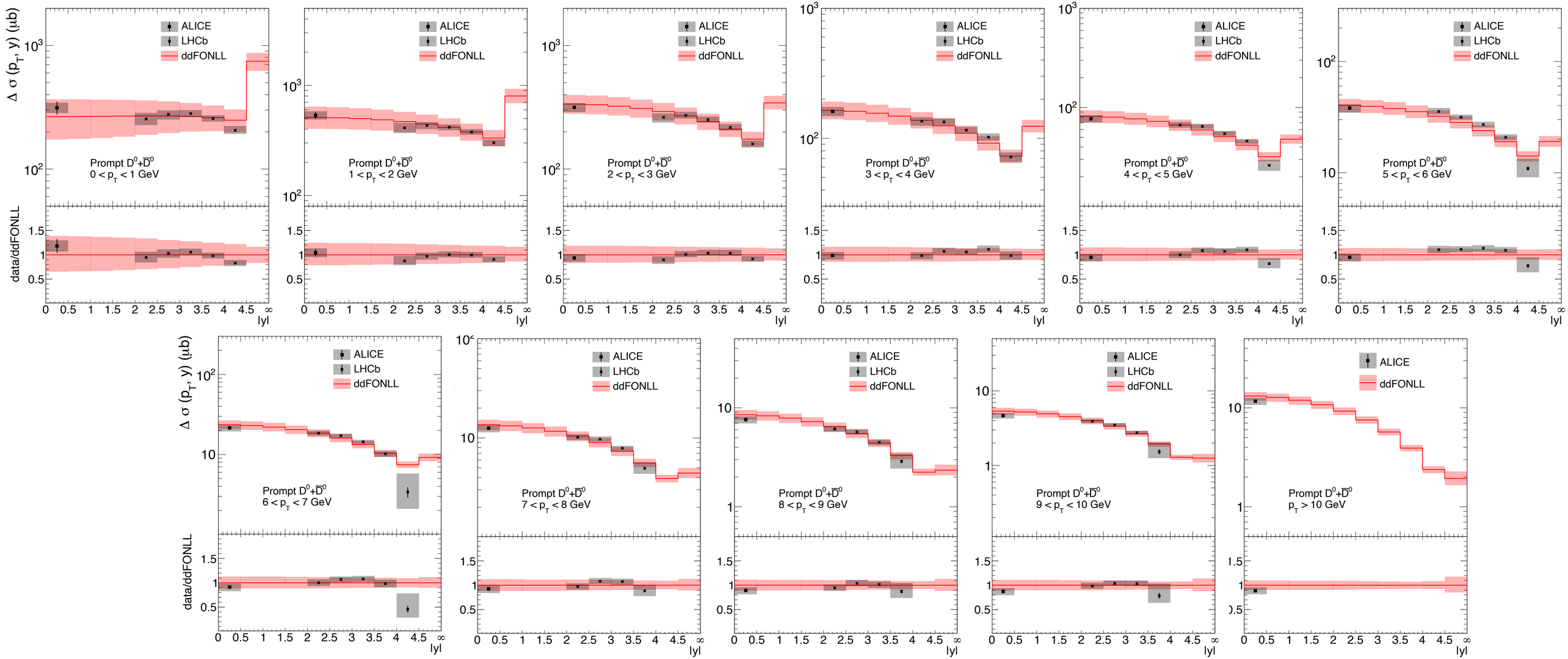


Total D^0 Cross Section

arXiv:2308.04877 & arXiv:1510.01707

refer to BackUp slide for 5 TeV results

✓ 13 TeV prompt D^0 **data from ALICE and LHCb** extrapolated using **ddFONLL**



- **ddFONLL** gives good descriptions for **data** overall in full kinematic range (consistent with assumption of rapidity independence)

✓ $\sigma_{D^0} = \Delta\sigma_{D^0}^{\text{data}}(\text{measured phase space}) + \Delta\sigma_{\text{D}^0}^{\text{ddFONLL}}(\text{unmeasured phase space})$

Total Charm Cross Section

$$\checkmark\ \sigma_{c\bar{c}} = \frac{\sigma_{D^0}}{f^{pp}_{D^0}} = \frac{\Delta\sigma^{\text{data}}_{D^0}(\text{measured phase space}) + \Delta\sigma^{\text{ddFONLL}}_{D^0}(\text{unmeasured phase space})}{f^{pp}_{D^0}}$$

$f^{pp}_{D^0}$ → fragmentation fraction for pp collisions

"data with non-universal fragmentation"

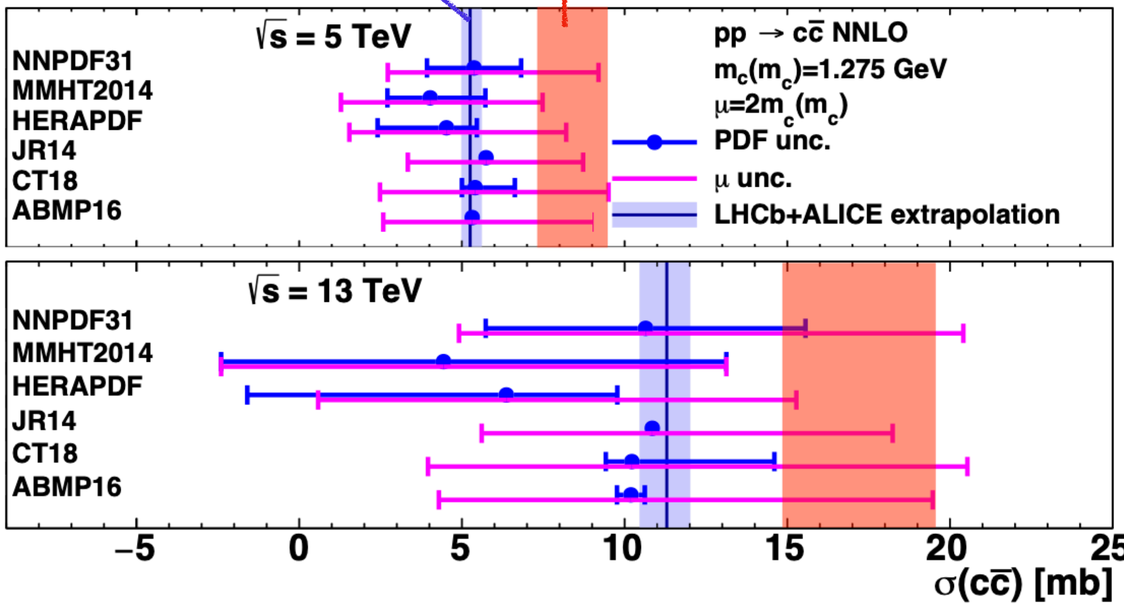
"data with universality assumption"

$$\cdot\ \sigma_{c\bar{c}} = \frac{3.64^{+0.19}_{-0.19}(\text{data}) + 2.95^{+0.31}_{-0.33}(\tilde{f})^{+0.52}_{-0.44}(\text{PDF})^{+0.10}_{-0.09}(\mu_f, \mu_r, m_c, \alpha_K)}{0.391^{+0.030}_{-0.041}}$$

"EF = 1.8"

$$\cdot\ \sigma_{c\bar{c}} = \frac{6.94^{+0.43}_{-0.41}(\text{data}) + 6.38^{+0.52}_{-0.60}(\tilde{f})^{+1.12}_{-0.93}(\text{PDF})^{+0.18}_{-0.14}(\mu_f, \mu_r, m_c, \alpha_K)}{0.382^{+0.026}_{-0.045}}$$

"EF = 1.9"



- consistent with upper edge of uncertainty band of NNLO theory
- significantly increased total charm cross sections with non-universal fragmentation

"Extrapolation Factor"

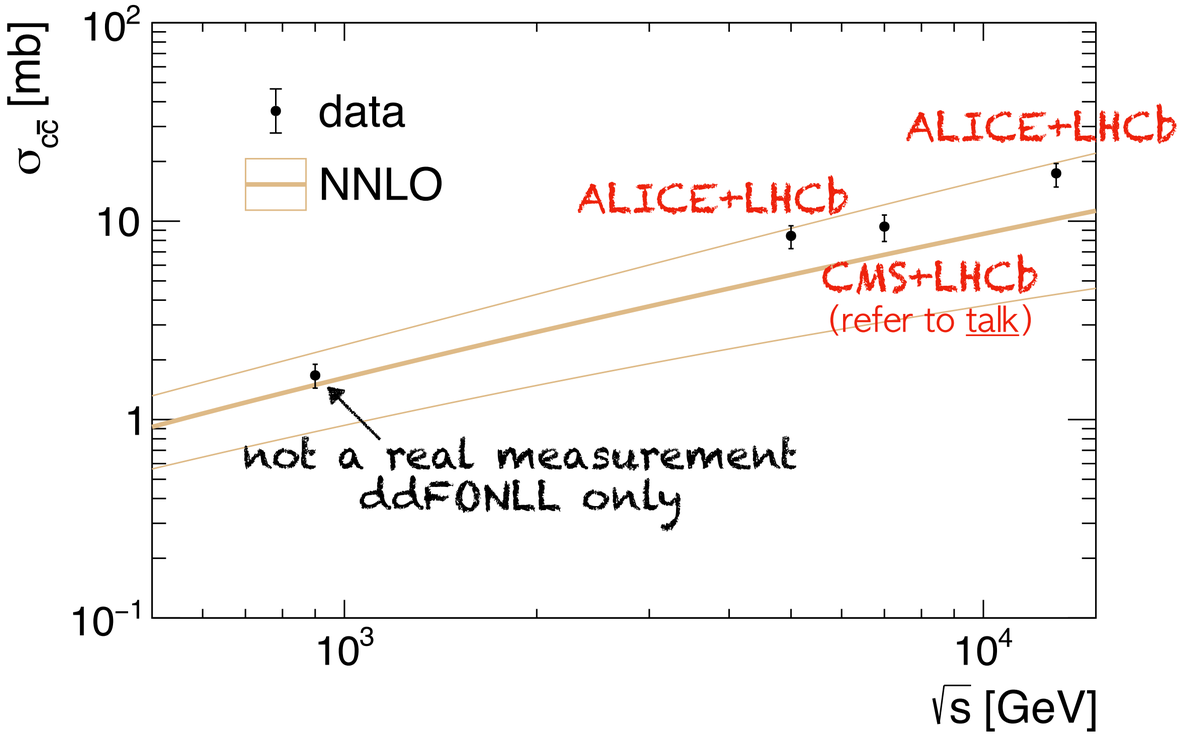
$$\text{EF} = \frac{\Delta\sigma^{\text{data}}_{H_c} + \Delta\sigma^{\text{ddFONLL}}_{H_c}}{\Delta\sigma^{\text{data}}_{H_c}}$$

Total Charm Cross Section Measurement as a Function of p_T and Beyond

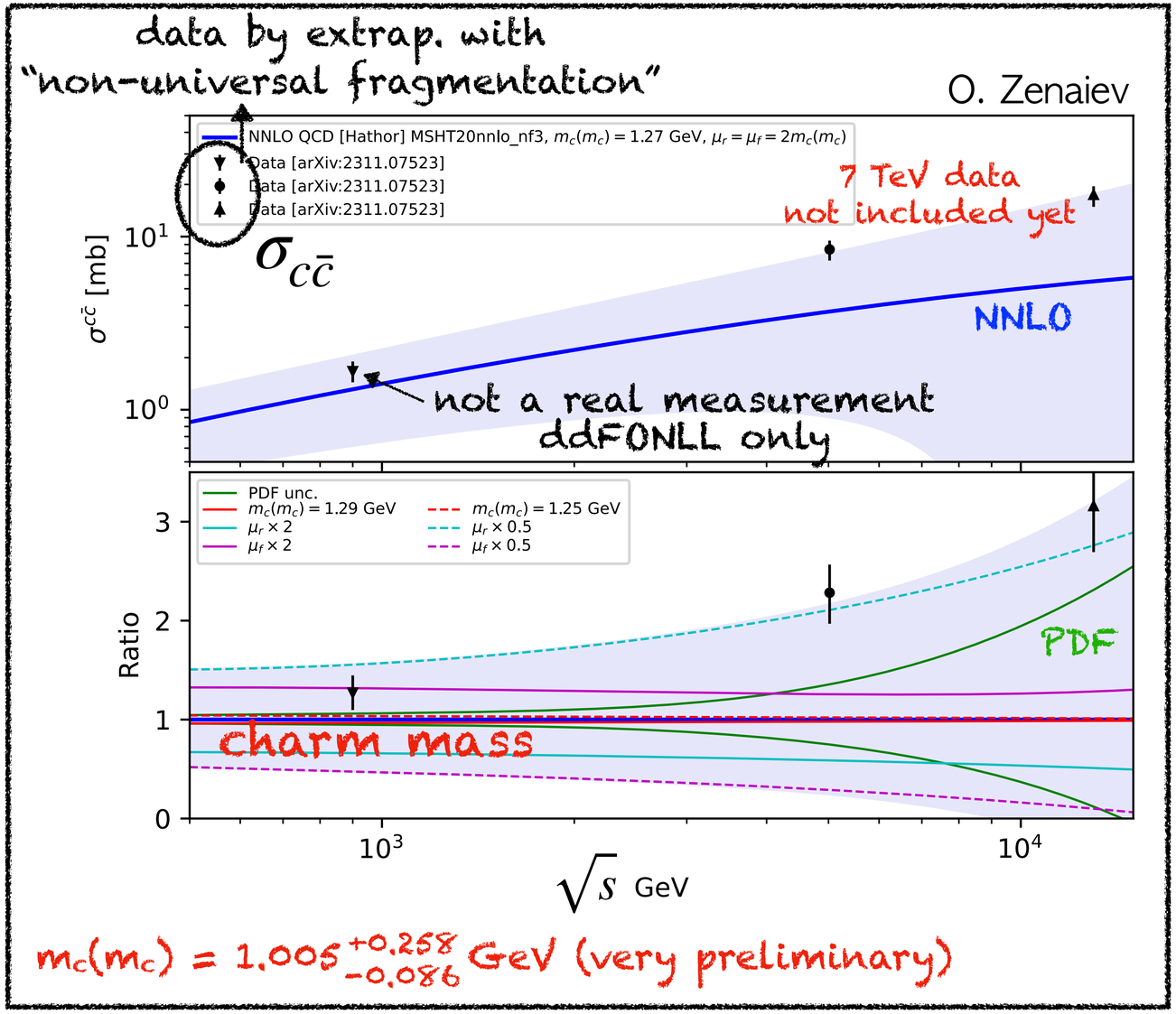
Very preliminary

✓ Total charm cross section measured as a function of $\sqrt{s}$ for the first time with non-universal fragmentation

- part of data points used to constrain e.g., m_c



✓ Future 0.9 TeV measurement from LHC can give significant contribution for this kind of study



Summary

✓ Data-driven FONLL (ddFONLL) was introduced to extrapolate pp data
- based on LHC data without the need to assume any particular non-universal fragmentation model
- by construction, can describe all weakly decaying ground states including D^{*+}

✓ Total charm cross section measured as a function of p_T for the first time with non-universal fragmentation
- covered from 5 to 13 TeV with prompt D^0 and D^{*+} data from ALICE, CMS and LHCb
- measurements show good agreement with NNLO QCD theory
- preliminary result of constraint on e.g., m_c was shown using part of data
  - can be improved further with additional data including measurement at 0.9 TeV

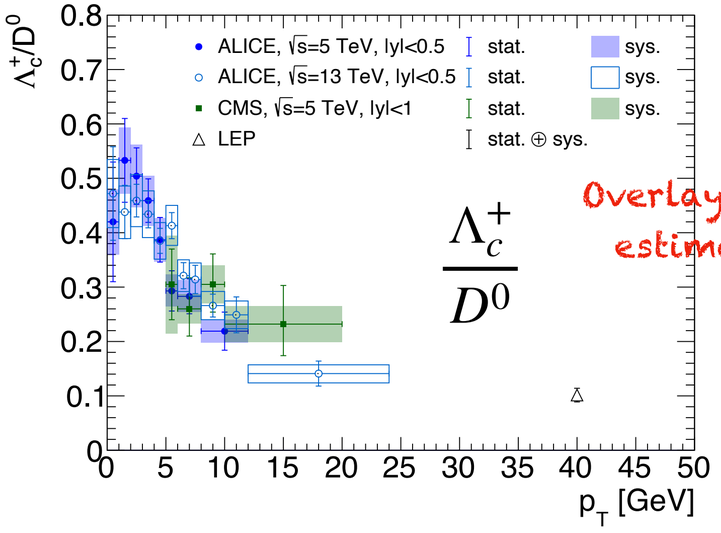
Thanks for your attention!

BackUp

Baryon-to-baryon Ratio as a Function of p_T

arXiv:2308.04877

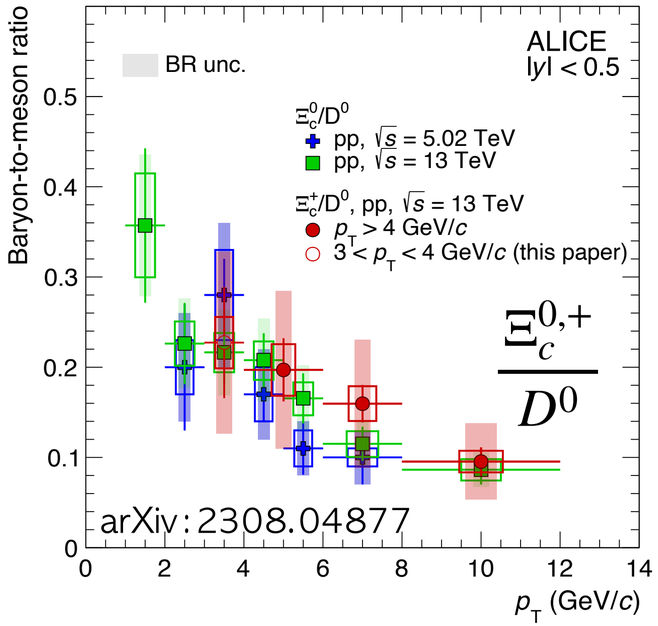
✓ No direct measurement of baryon-to-baryon

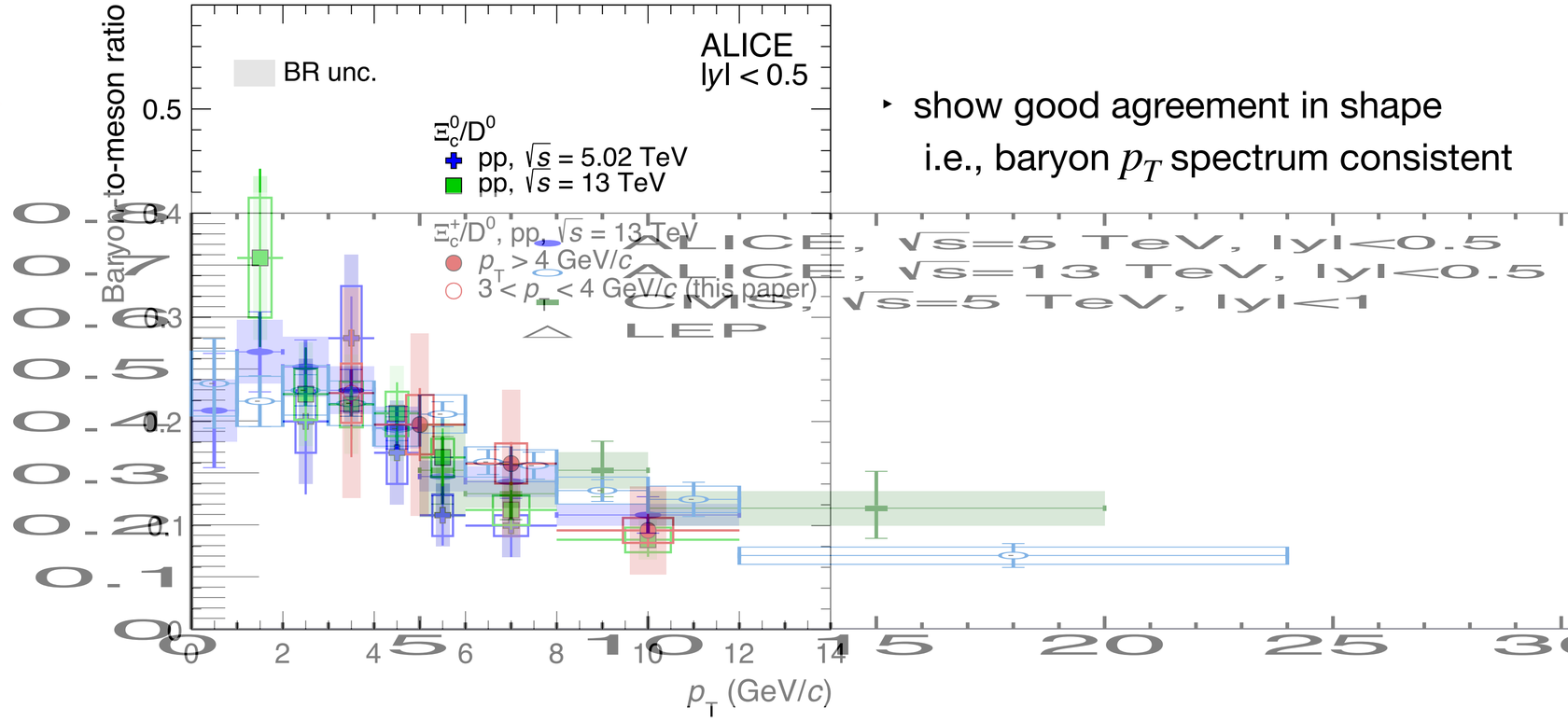


Overlaying with normalisation roughly estimated, based on fragmentation fraction measurements

~0.51

$f(c \to h_c)$	pp, $\sqrt{s} = 5.02$ TeV (%)	pp, $\sqrt{s} = 13$ TeV (%)
D^0	39.6 ± 1.7 (stat.) $^{+2.6}_{-3.8}$ (syst.)	38.2 ± 1.3 (stat.) $^{+2.3}_{-4.3}$ (syst.)
D^+	17.5 ± 1.8 (stat.) $^{+1.7}_{-2.1}$ (syst.)	19.1 ± 1.4 (stat.) $^{+1.5}_{-2.3}$ (syst.)
D_s^+	7.4 ± 1.0 (stat.) $^{+1.9}_{-1.1}$ (syst.)	6.1 ± 0.5 (stat.) $^{+1.2}_{-0.9}$ (syst.)
Λ_c^+	18.9 ± 1.3 (stat.) $^{+1.5}_{-2.0}$ (syst.)	16.8 ± 0.8 (stat.) $^{+1.5}_{-2.1}$ (syst.)
Ξ_c^0	8.1 ± 1.2 (stat.) $^{+2.5}_{-2.5}$ (syst.)	9.9 ± 1.3 (stat.) $^{+2.3}_{-2.4}$ (syst.)
Ξ_c^+	Assumed to be the same as Ξ_c^0	9.6 ± 1.2 (stat.) $^{+3.9}_{-4.8}$ (syst.)
J/ψ	0.44 ± 0.03 (stat.) $^{+0.04}_{-0.06}$ (syst.)	0.37 ± 0.02 (stat.) $^{+0.04}_{-0.05}$ (syst.)

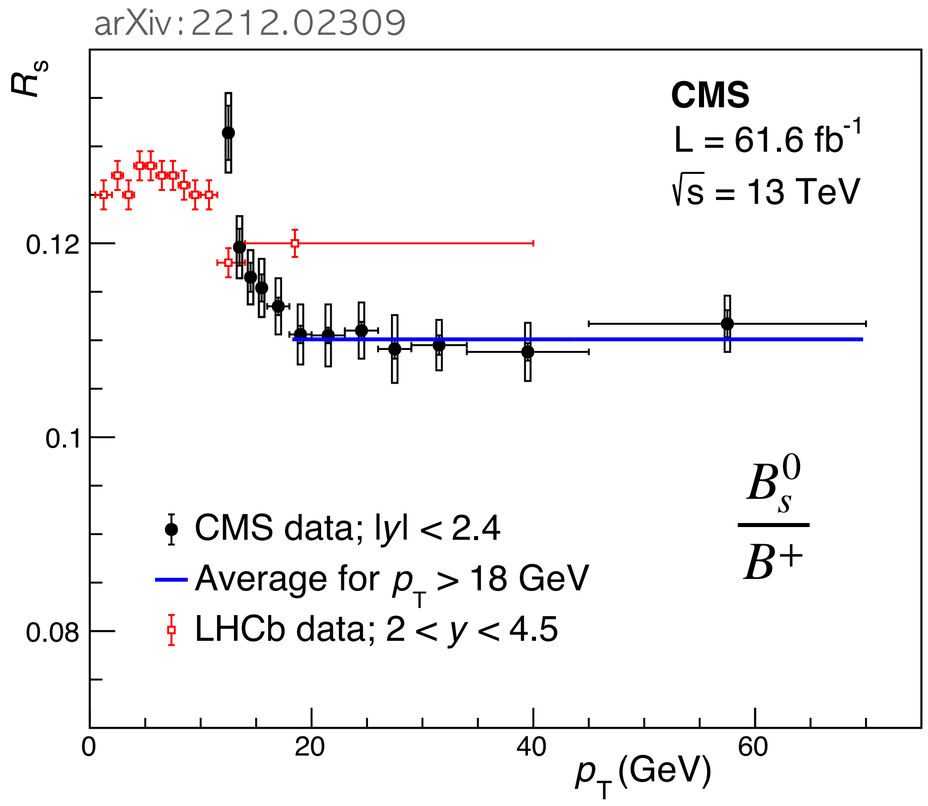




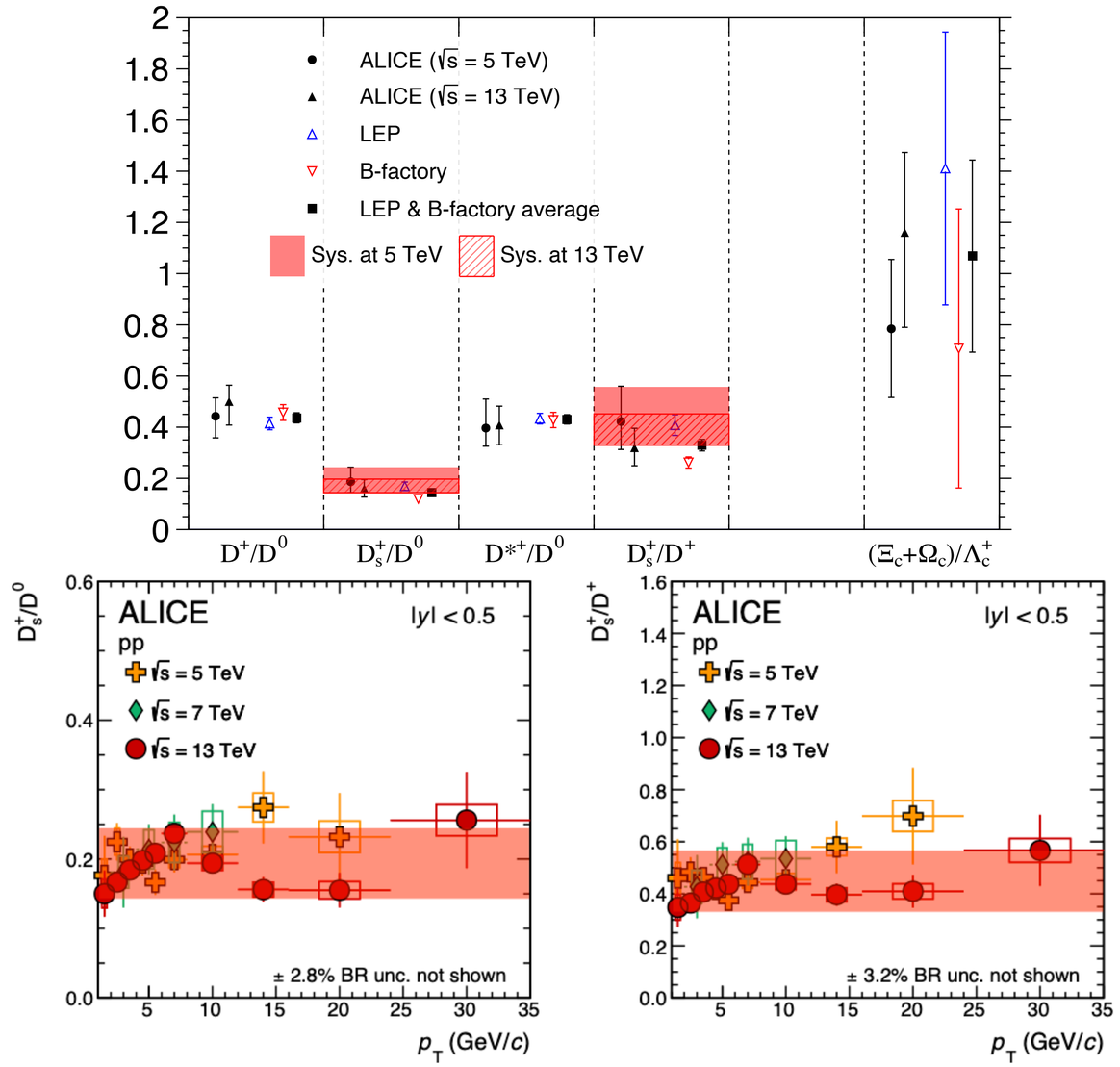
- show good agreement in shape
  i.e., baryon p_T spectrum consistent

Systematic Uncertainty for Assumption 1

✓ With much better precision, significant p_T dependence observed meson-to-meson ratios in beauty production



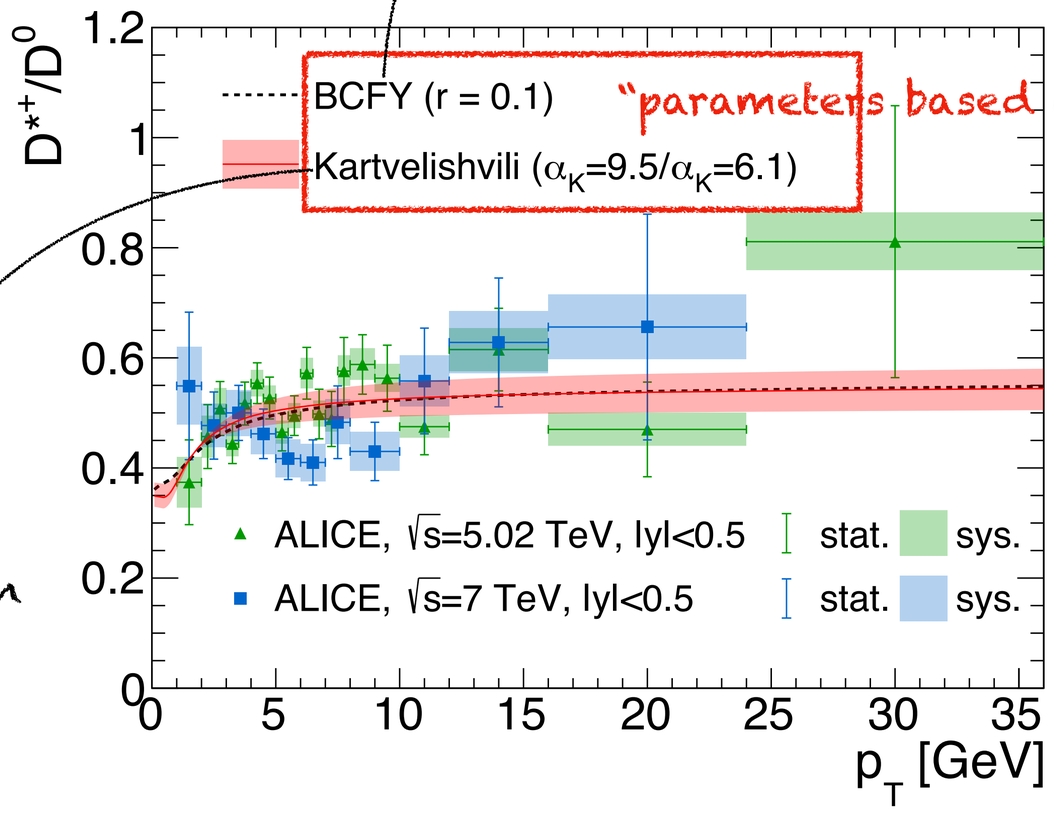
✓ One-sided uncertainty assigned to account for possible p_T dependent ratios of D_s^+ to other mesons



D^{*+} to D^0 Ratio

✓ pp data and FONLL predictions (based on fragmentation universality assumption) show agreement in D^{*+}/D^0

dedicated fragmentation function for D meson



general fragmentation function

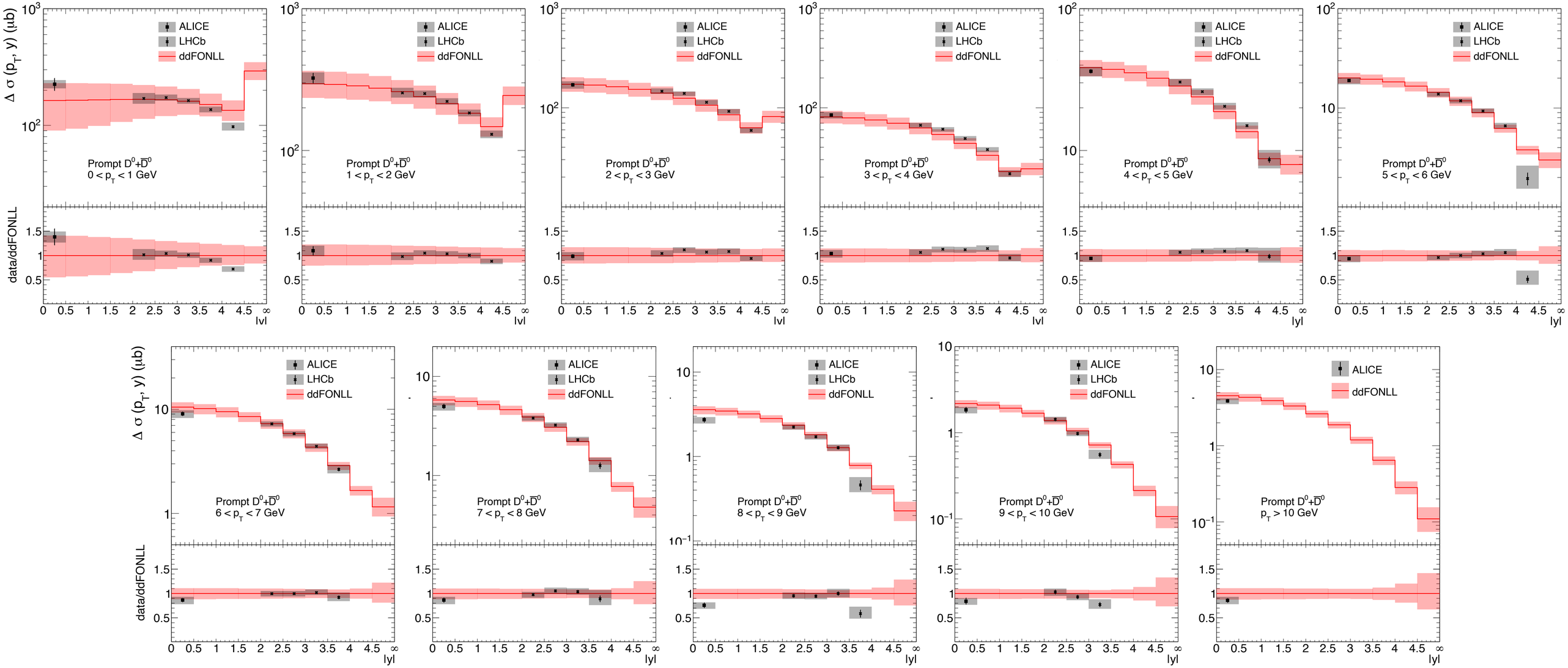
$$D^{\mathrm{NP}}(x) = (\alpha_K + 1)(\alpha_K + 2)x^{\alpha_K}(1 - x)$$

- no need of p_T correction relative to universality assumption
- possible p_T dependence taken care of by using free α_K in χ^2 fit

Total D^0 Cross Section

arXiv:2102.13601 & arXiv:1610.02230

✓ 5 TeV prompt D^0 **data from ALICE and LHCb** extrapolated using **ddFONLL**



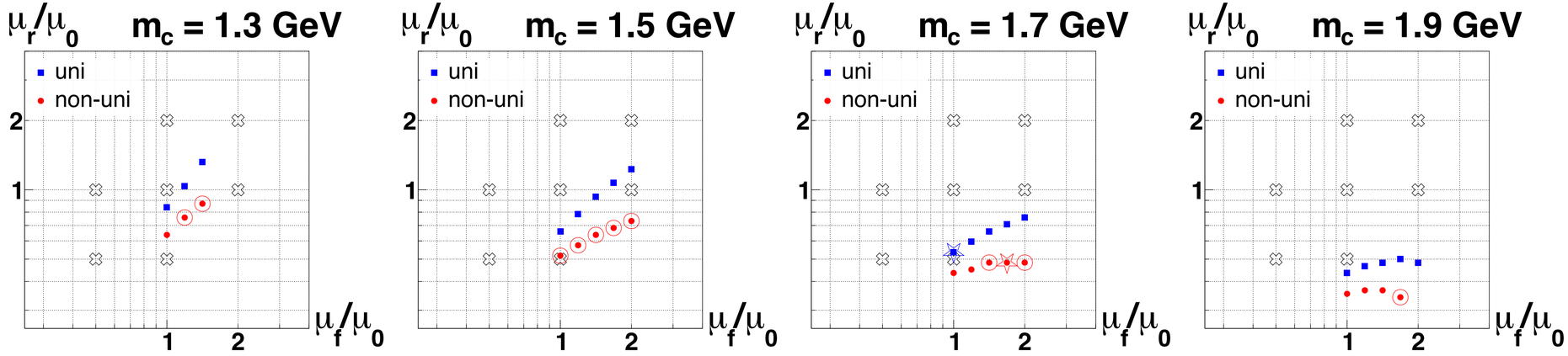
Fitted Parameters

☆ The best parameters

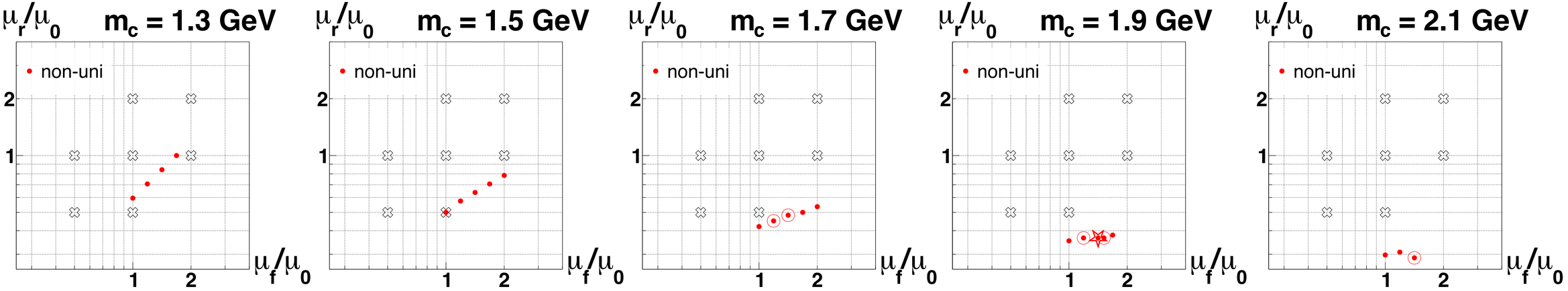
◯ The uncertainty parameters

● Local least χ^2 results (projection of 3D (μ_f, μ_r, α_K) into 2D (μ_f, μ_r) for fixed m_c)

5 TeV



13 TeV

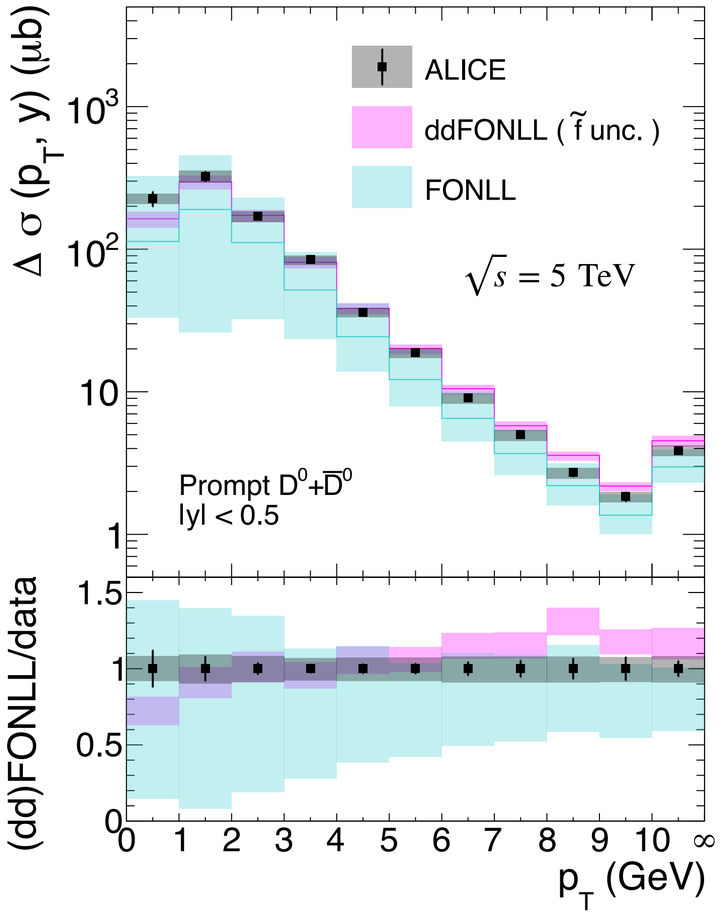


✓ Consistent with conventional parameters for theory; $0.5 < \mu_f/\mu_0 < 2$, $0.5 < \mu_r/\mu_0 < 2$, $1.3 < m_c < 1.7$ GeV, $\alpha_K \sim 6(9)$ for $D^0(D^{*+})$

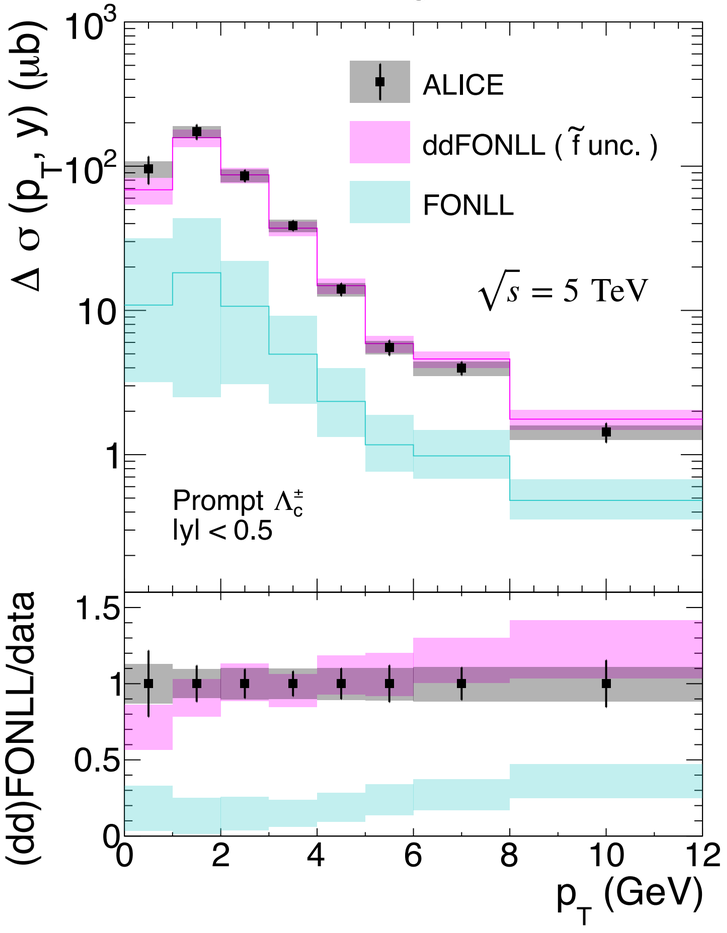
- parameters consistent with universality assumption

p_T Spectrum for D^0 and Λ_c^+ at 5 TeV

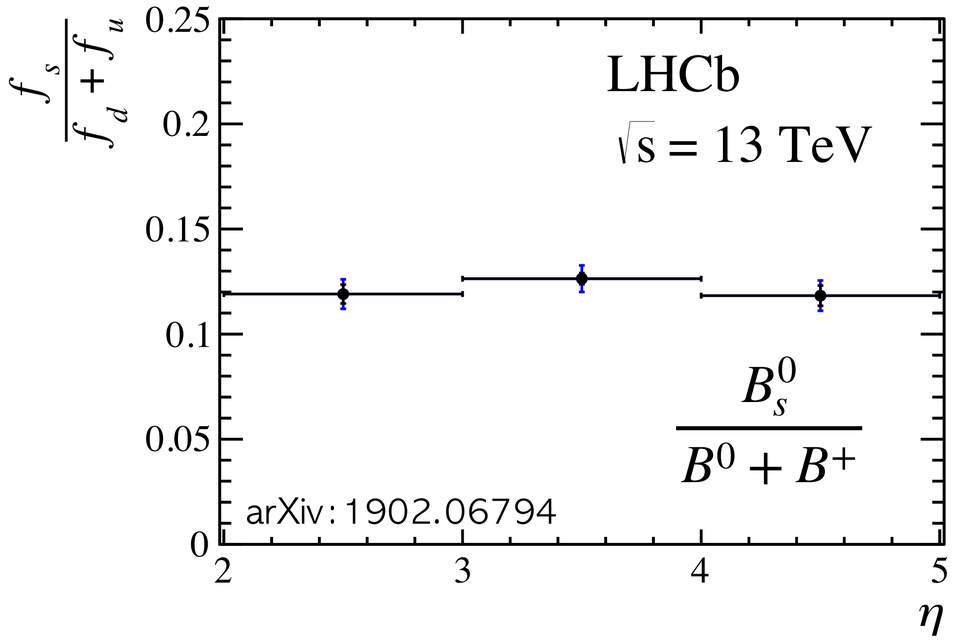
D^0

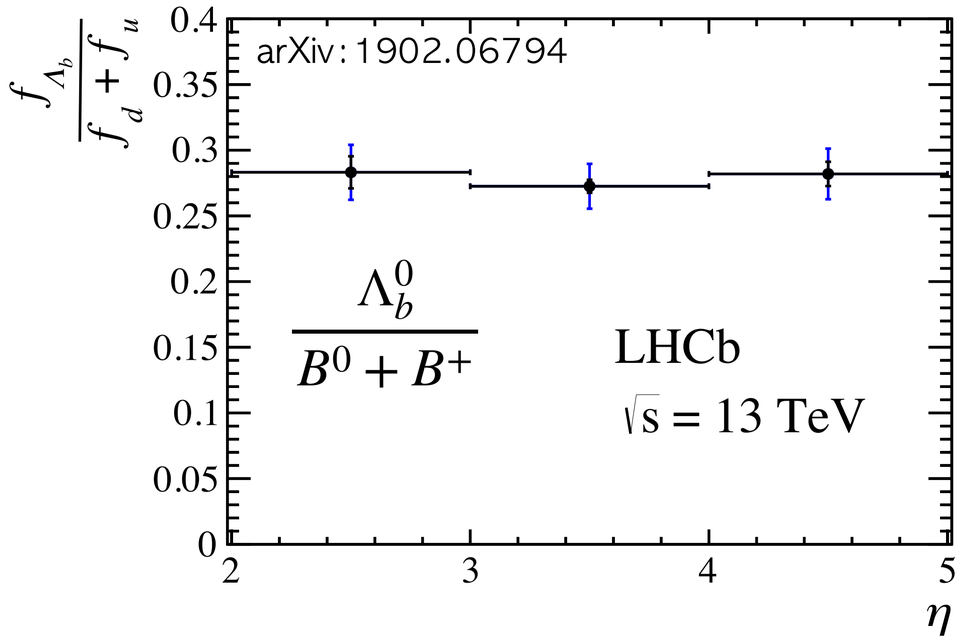


Λ_c^+



Production Ratio Measurements as a Function of Rapidity





D^{*+} Reconstructed on CMS Run 3 Data

CMS-DP-2022-024