Charm total cross sections and extraction of QCD parameters

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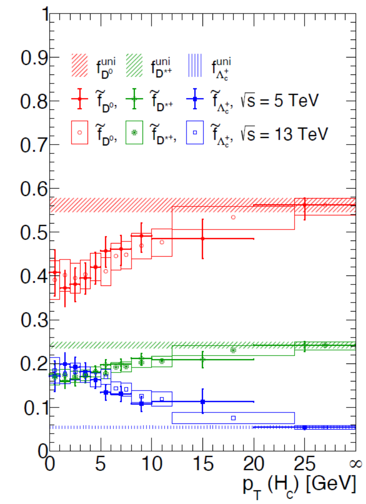


Phenomenology study based on published data

Model-independent treatment of charm fragmentation nonuniversality

for measurement of total charm pair production cross sections

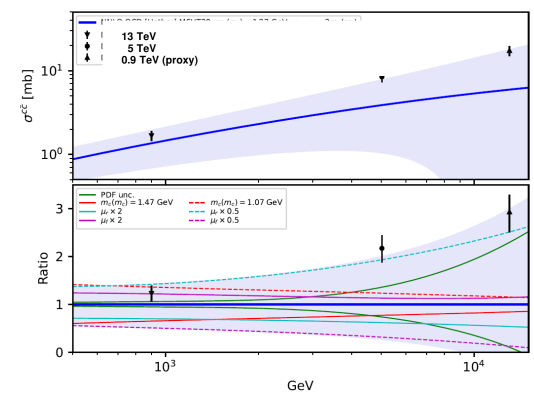
Relying on perturbative QCD + constraints from data only

(no a priori assumptions on non-perturbative QCD effects)

Fully consistent with all previous e^+e^- and ep data and theory predictions

Started on 5 TeV LHC charm data, see contribution Y. Yang to EPS 2023, arXiv:2311.07523

Complementary to and consistent with study with similar purpose based on MC model tuning for 5TeV LHC data only, arXiv:2311.11426 (not discussed further here).



This talk (preliminary):

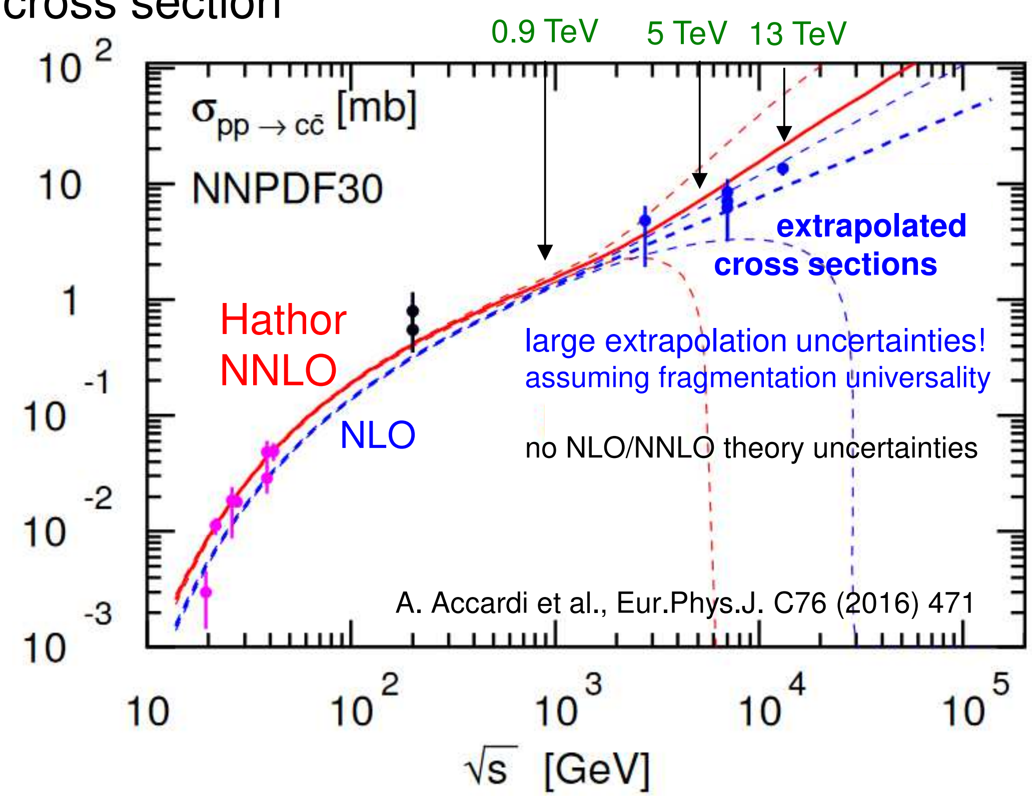
- **Extend phenomenological application to 13 TeV LHC data**
- **First glimpse at sensitivity for the extraction of charm quark mass and/or low-x constraints on PDFs at NNLO from LHC charm data**

Why measure the total ccbar cross section?

- **Total cross section** has **smallest theoretical pQCD uncertainty**
- **NNLO predictions** available for total charm cross section
  (differential cross sections: still only NLO+NLL)
- **No theory dependence on fragmentation**
  (or other nonperturbative effects)

(see also D. d'Enterria, Moriond 2017)

treated in this contribution:



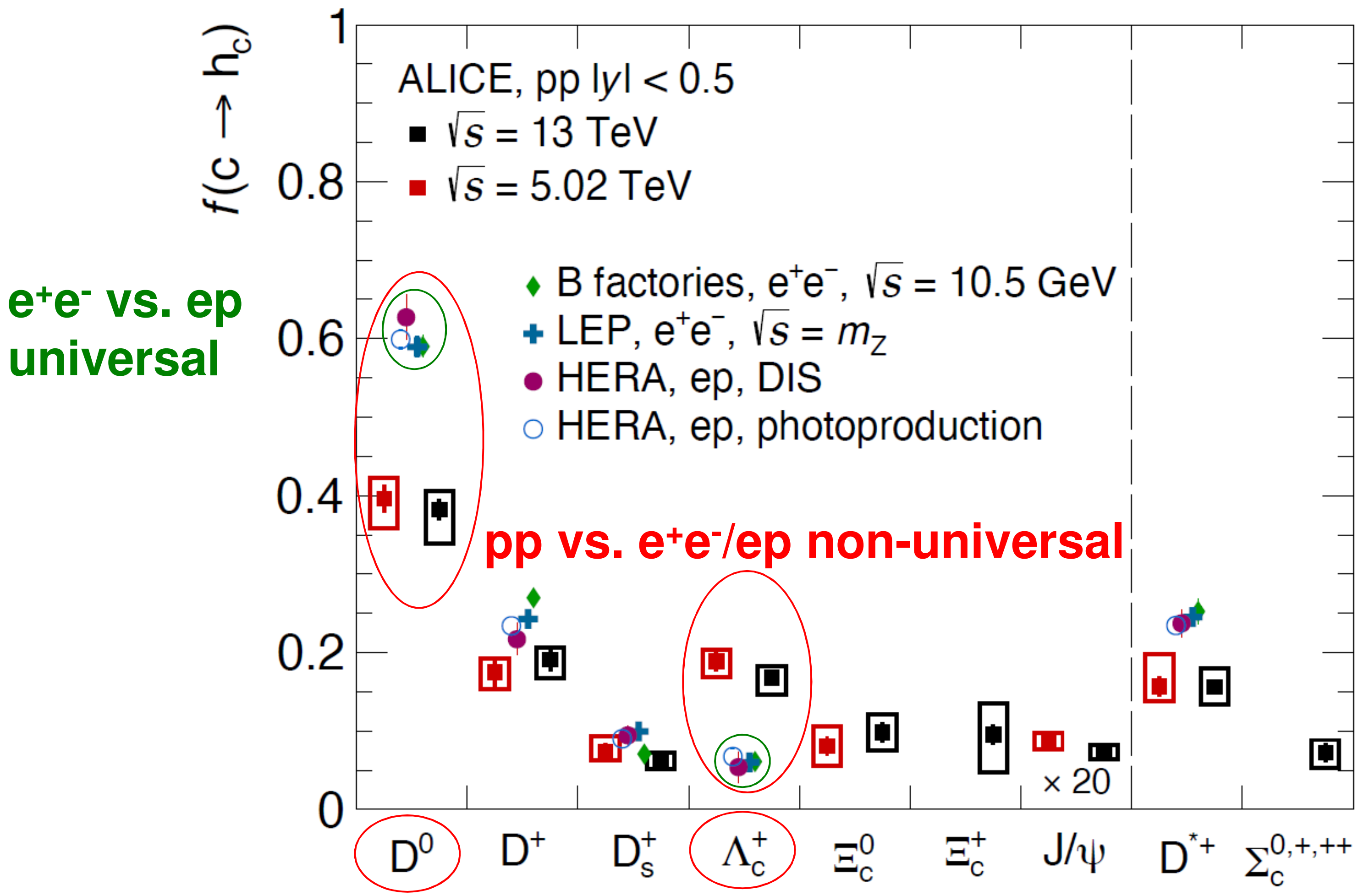
-> use **measured double differential (p_T and y) single charm cross sections** over **largest possible phase space** and

extrapolate/interpolate to total cross section,

accounting for charm fragmentation nonuniversality (new)

Non-universality of charm fragmentation

Charm fragmentation fractions (p_T-integrated production fractions) **in e^+e^-, ep, and pp**



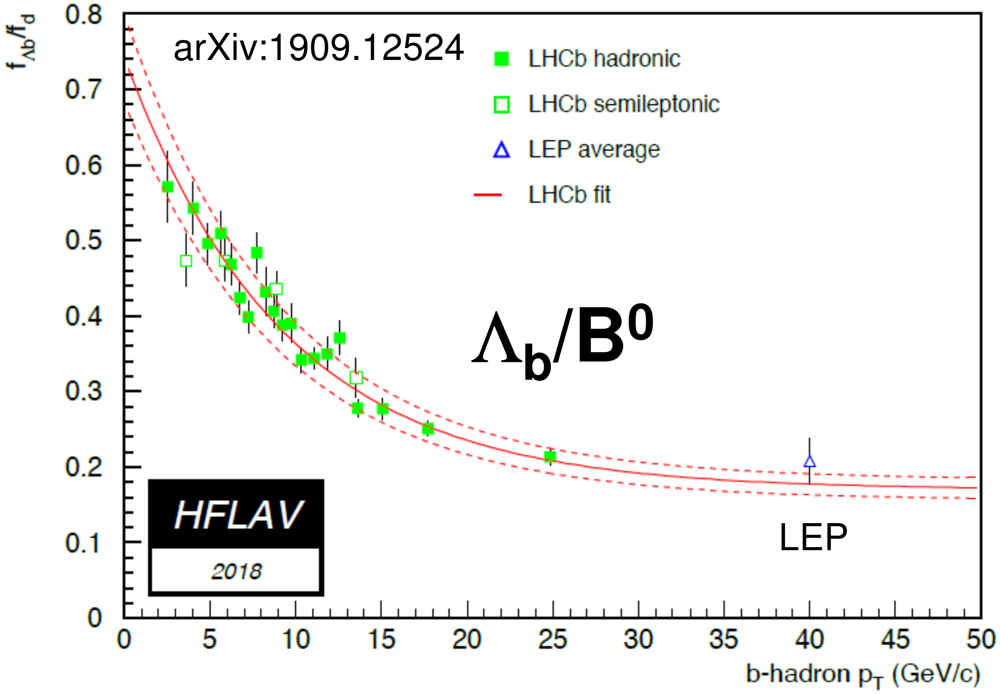
arXiv:2308.04877

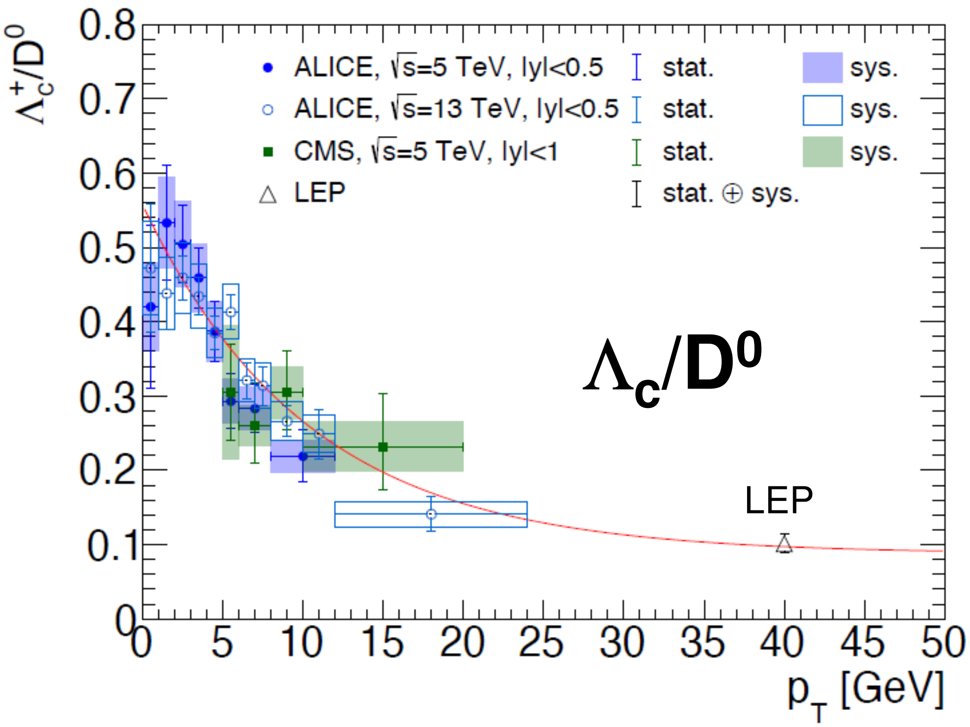
can not be cured by using different fragmentation functions

what about p_T and y dependence of production fractions?

Non-universality of charm fragmentation

Both beauty and charm baryon to meson production ratios in pp collisions exhibit strong p_T dependence,
asymptotically approaching `universal' LEP e^+e^- values at high p_T





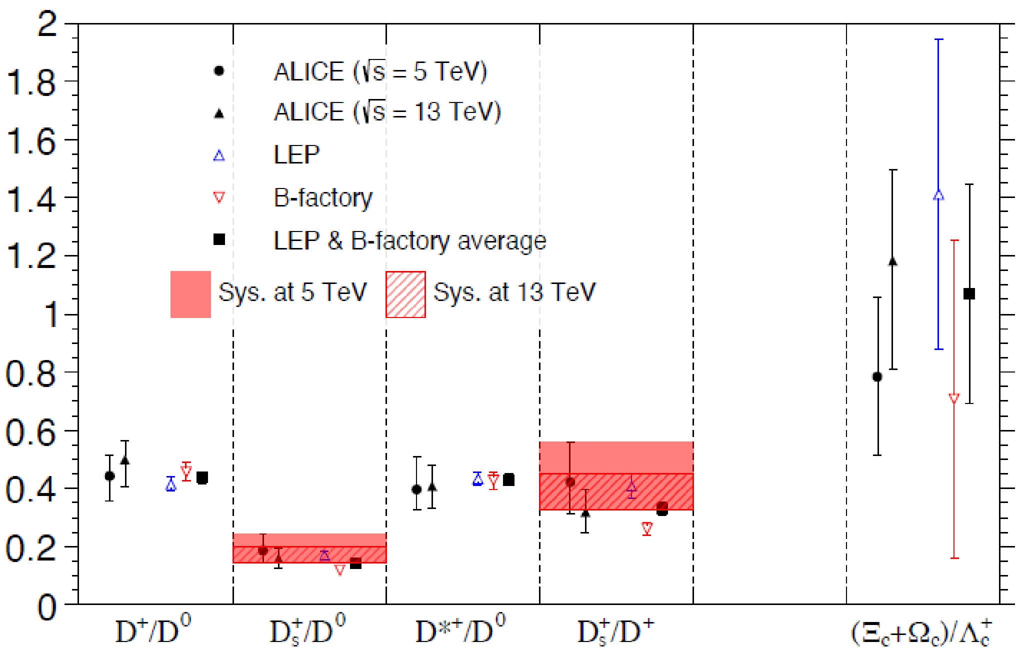
-> strategy (data driven! directly use measurements):

treat baryon to meson production fractions vs p_T as non-universal

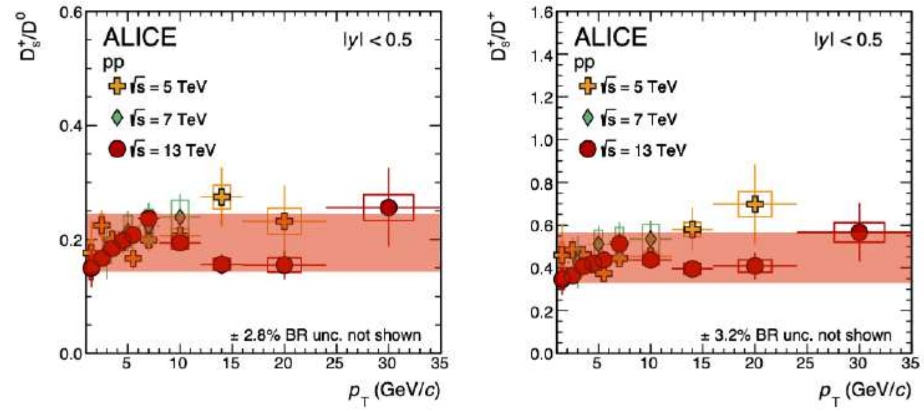
treat asymptotic high p_T limit as universal

Non-universality of charm fragmentation

Study meson/meson and baryon/baryon ratios



arXiv:2308.04877



no significant p_T dependence!

assign systematic uncertainties for potential small deviations, as e.g. known for B_s/B^0

no significant initial state dependence!

-> strategy (data driven!):

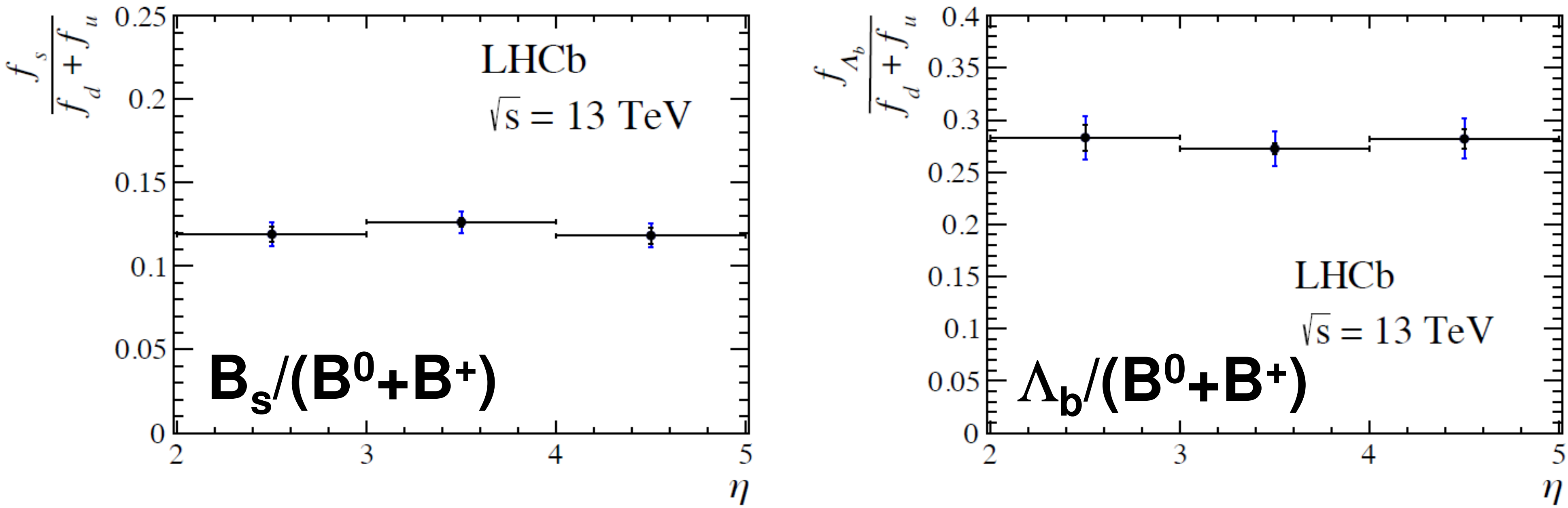
treat meson-to-meson and baryon-to-baryon production ratios as universal

(both integrated and as function of p_T, within uncertainties)

Non-universality of charm fragmentation

Neither beauty meson-to-meson nor baryon-to-meson production ratios in pp collisions exhibit noticeable rapidity (y) dependence

arXiv:1902.06794



-> strategy (data driven!):

treat charm production fractions as universal in rapidity (within unc.)

-> can use ALICE measurements of p_T dependence at all rapidities

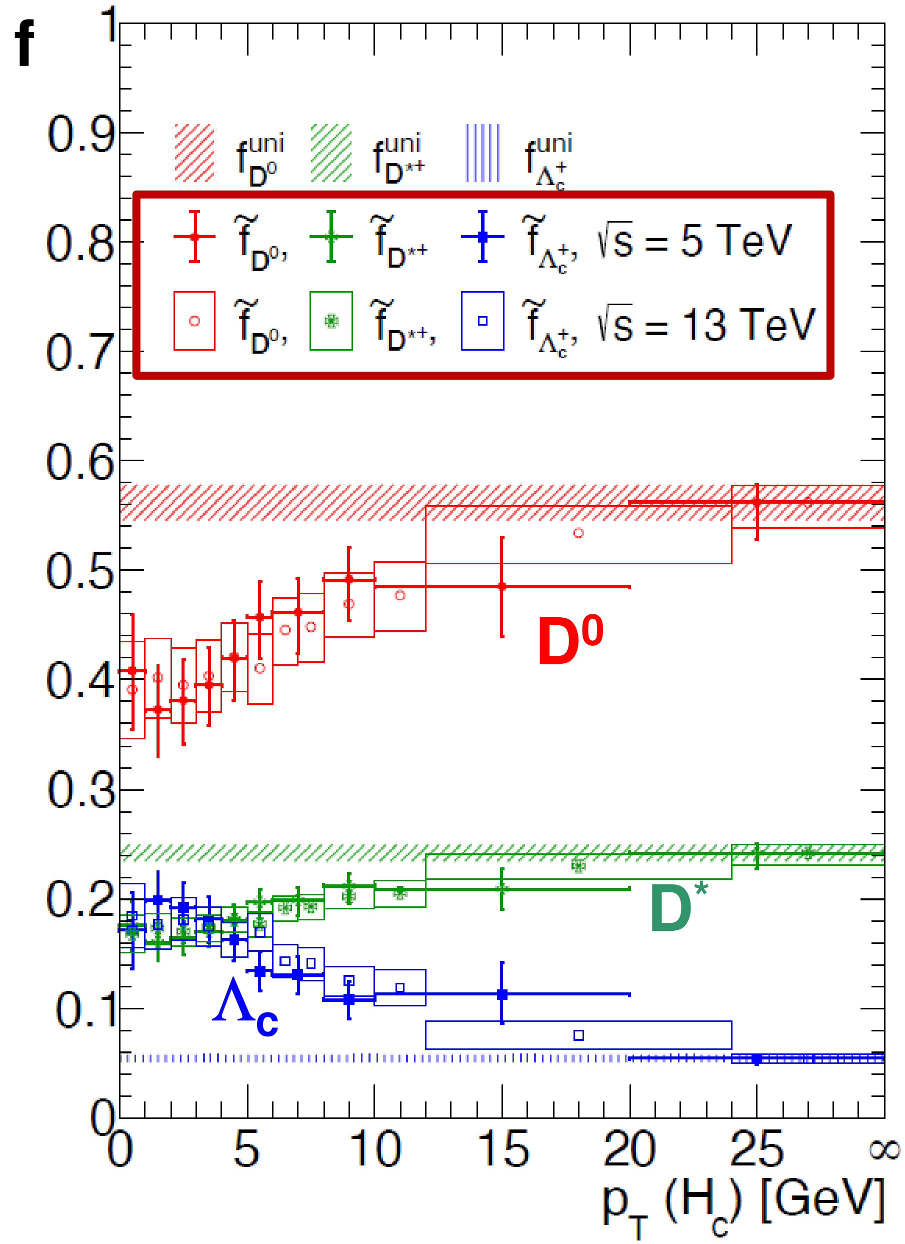
Will be consistency-checked with charm data later

Non-universality of charm fragmentation

represent nonuniversality in terms of p_T-dependent charm hadron production fractions taken directly from data
(no functional parametrization)

So far, treat 5 and 13 TeV measurements separately.
Consistent, so possibly combine in the future.

Reminder:
meson/meson ratios remain universal
baryon/baryon ratios remain universal
rapidity dependence remains universal



FONLL (NLO+NLL) QCD theory predictions vs. data driven FONLL (ddFONLL)

standard FONLL theory:

arXiv:1205.6344

charm quark level

$$d\sigma^{\text{FONLL}}_{pp\to c\bar{c}} = f_i f_j \otimes d\hat{\sigma}_{ij\to c\bar{c}}$$

PDFs — $f_i f_j$

massive NLO + massless NLL matrix elements — $d\hat{\sigma}_{ij\to c\bar{c}}$

perturbative QCD parameters: μ_f μ_r m_c

(`seven point variation')

charm hadron level

$$d\sigma^{\text{FONLL}}_{H_c} = \boxed{f^{uni}_{H_c}} \cdot (d\sigma^{\text{FONLL}}_{pp\to c\bar{c}} \otimes D^{NP}_{c\to H_c})$$

universal fragmentation fraction, a number, e.g. **from e^+e^-, ep**

universal fragmentation function e.g. Kartvelishvili, **from LEP**

single parameter: α_K

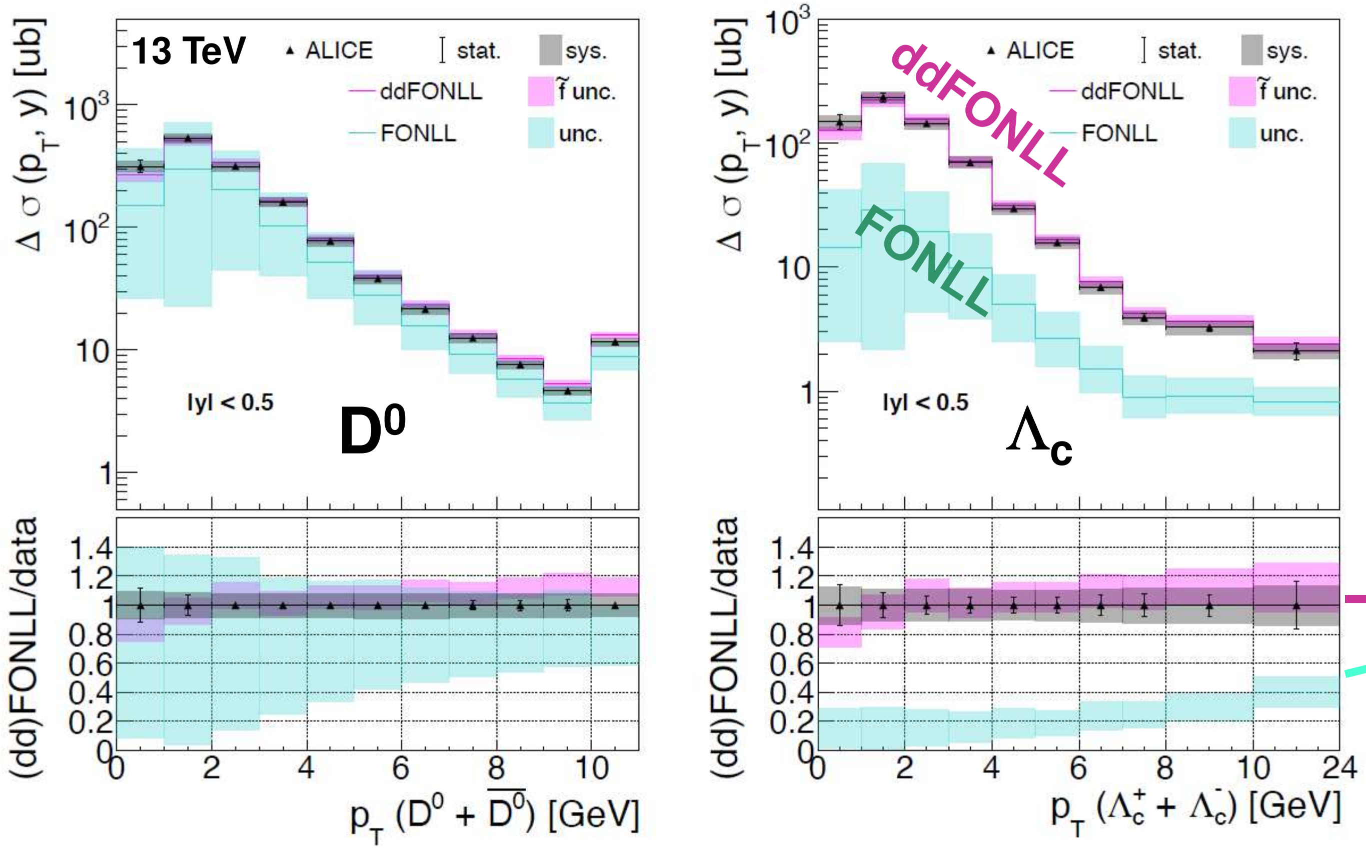
data driven FONLL (ddFONLL): arxiv:2311.07523

for treatment of PDFs, see backup

$$d\sigma^{\text{ddFONLL}}_{H_c} = \boxed{\tilde{f}_{H_c}(p_T)} \cdot (d\sigma^{\text{FONLL}}_{pp\to c\bar{c}} \otimes D^{NP}_{c\to H_c})$$

all parameters, including QCD scales, (re)fitted to data (χ^2 minimization)

Performance illustration on 13 TeV ALICE data



5 TeV in backup

Cascade_c in backup

will converge at high p_T

FONLL: a priori prediction with full uncertainty, with `classical' universality assumption, PDF unc. and 7-point scale variation

ddFONLL: fit to ALICE+LHCb D^0 data (next slide), here $\tilde{f}_{D^0}(p_T)$ unc. only (w/o fitted $\mu_f, \mu_r, m_c, \alpha_K$ uncertainties and PDF uncertainties),

+ `postdiction' for Λ_c data (full uncertainty ~50% larger, mainly PDFs)

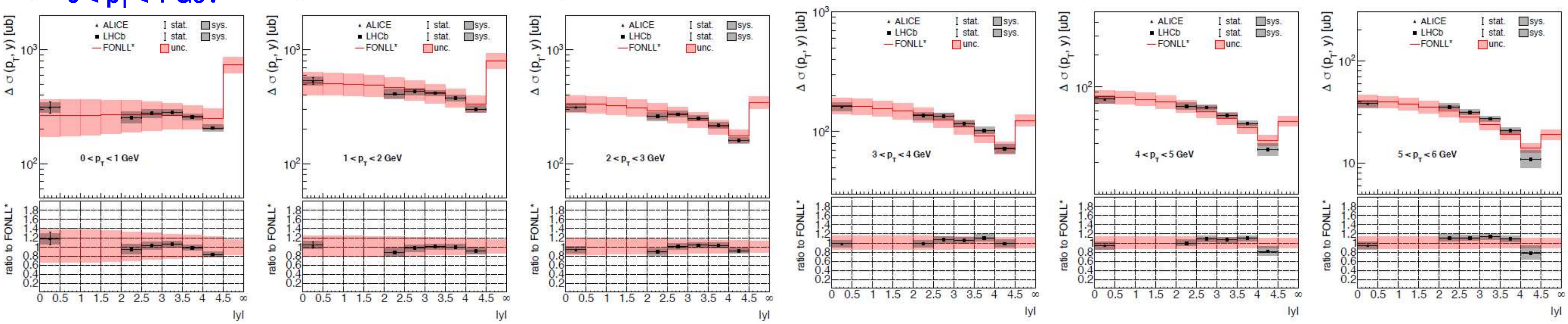
Application to published 13 TeV ALICE+LHCb D^0 data

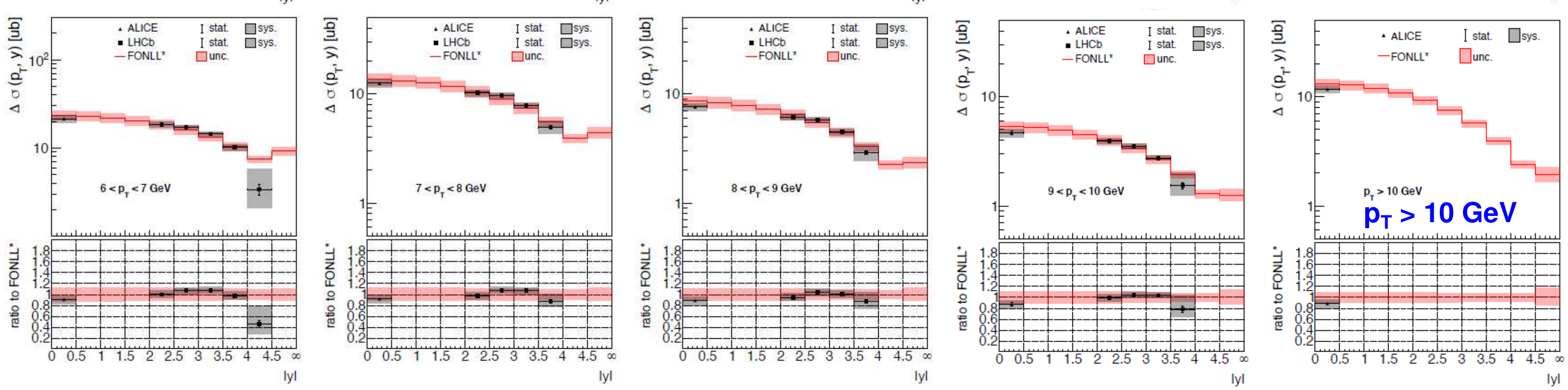
5 TeV
in backup

D^0 CROSS SECTION IN FULL KINEMATIC RANGE

✔ *Data constrained FONLL* with total uncertainty (CTEQ6.6 PDF $\oplus\ \tilde{f} \oplus (\mu_f, \mu_r, m_c, \alpha_K)$) gives good descriptions for D^0 measurements in the full kinematic range

$0 < p_T < 1$ GeV





good description of rapidity spectra in all p_T bins

-> strategy for extrapolation to total charm cross section:
use data whenever available, otherwise ddFONLL data constrained band

Extrapolate to total charm pair cross section

-> **fit parameters in backup**

13 TeV:

$$\sigma_{tot}(\text{ccbar}) = 17.43^{+0.56}_{-0.53}(\text{data})^{+0.69}_{-0.78}(\tilde{f})^{+1.47}_{-1.22}(\text{PDF})^{+0.24}_{-0.18}(\mu_f, \mu_r, m_c, \alpha_K)^{+1.19}_{-2.05}(f^{pp}) \text{ mb}$$

phase space extrapolation factor ~1.9

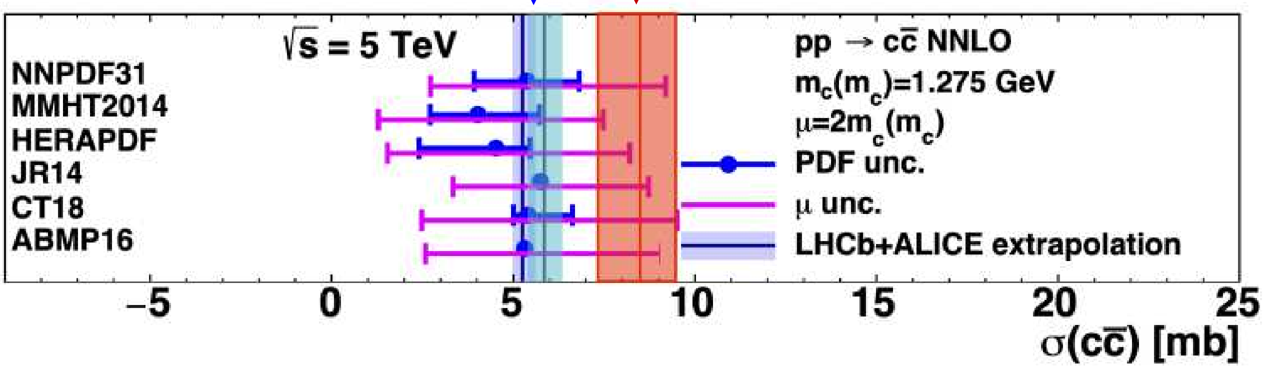
5 TeV: (arXiv:2311.07523)

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

phase space extrapolation factor ~1.8

this work (~50% increase)

assuming universality



M. Garzelli et al., arXiv:2009.07763, JHEP 04 (2021) 043)

-> treatment of charm fragmentation nonuniversality has significant impact on total cross section result!

ddFONLL "QCD" fit parameters

4-dimensional "fit" of ALICE + LHCb double differential D^0 data (χ^2 scan)

Reminder: now phenomenological parameters (no longer a priori pQCD)

$$\mu_0 = \mathrm{sqrt}(m_c^2 + p_{Tc}^2)$$

		5 TeV	13 TeV
factorization scale	μ_f	1.0-2.0 μ_0 (1.68)	1.19-1.52 μ_0 (1.41)
renormalization scale	μ_r	0.34-0.87 μ_0 (0.48)	0.29-0.48 μ_0 (0.37)
charm `pole' mass	m_c	1.3-1.9 GeV (1.7)	1.7-2.1 GeV (1.9)
Kartvelishvili fragm. par.	α_K	6-25 (9)	5-9 (6)

… but all in `reasonable' QCD parameter range.

factorization scale prefers to be on the higher side

renormalization scale prefers to be on the low side

(compare arXiv:1506.07519 and arXiv:0711.1983 for **theoretical** arguments)

mass is on the higher side (but still consistent with pole mass obtained from running mass)

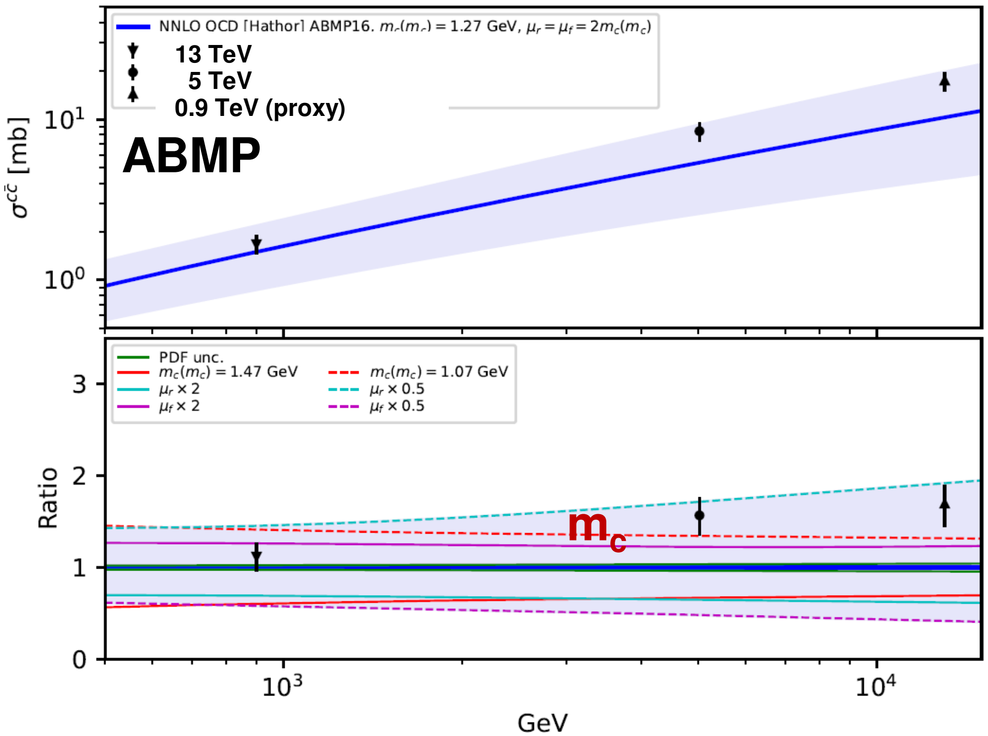
`average' fragmentation parameter comes out consistent with LEP value of 6.1

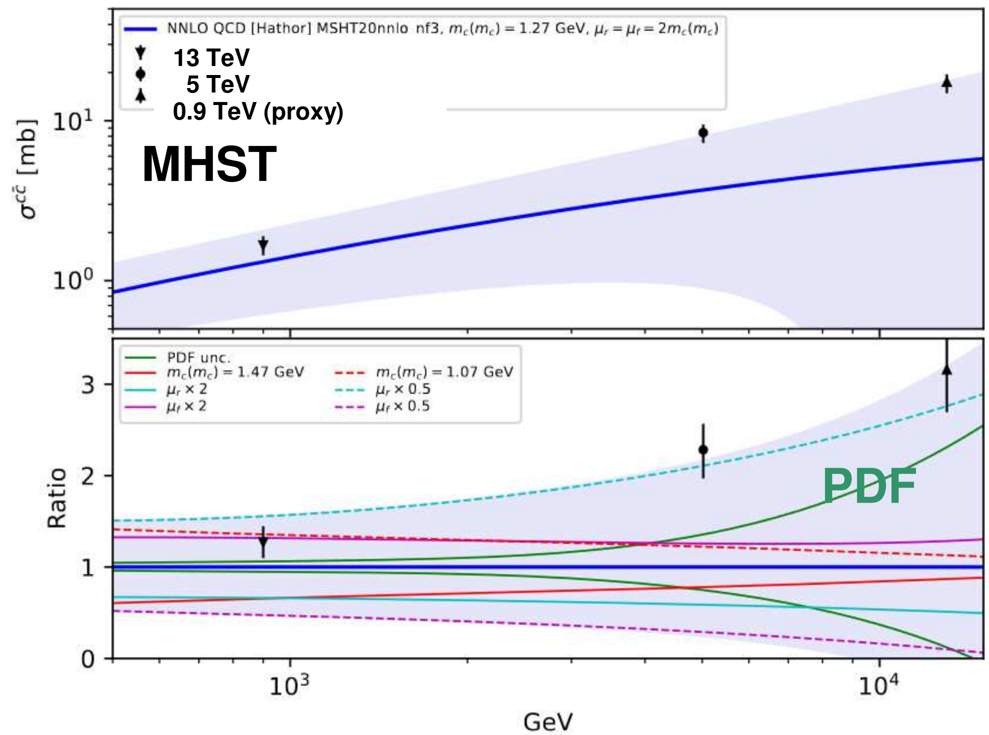
use 5 TeV fit parameters to `estimate' 0.9 TeV cross section: (*not* a measurement, but use as proxy)

σ_{tot}(ccbar, 0.9 TeV) = $1.7^{+0.24}_{-0.24}(\mathrm{total})\mathrm{mb}.$

Total charm pair cross section vs. sqrt(s), NNLO

Hathor, full NNLO, 3 flavour, running mass, $\mu_0 = 2m_c(m_c)$ very preliminary, e.g.





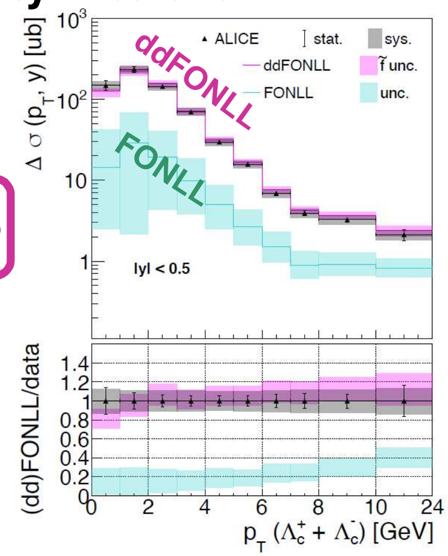
Same theory setup as arXiv:2009.07763

Sensitivity to NNLO PDFs at low x (~10^{-5}), in particular at 13 TeV
Sensitivity to $m_c(m_c)$: ~50 MeV experimental, ≤ 200 MeV including QCD scale

First such direct constraint estimates from hadronic collisions at NNLO

Summary, conclusions and outlook

A novel data-based phenomenological approach has been worked out to integrate the established nonuniversality of charm fragmentation and its uncertainty into the extrapolation of total charm pair cross sections at LHC.



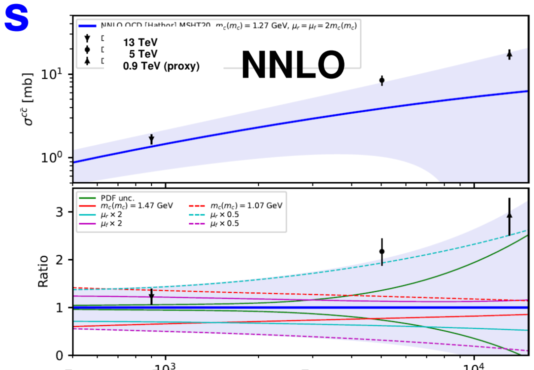
applied to 5 TeV and 13 TeV measurements by ALICE and LHCb:

$\sigma_{c\bar{c}} = 8.43^{+1.05}_{-1.16}(\text{total})$ **mb** $\sigma_{c\bar{c}} = 17.43^{+2.10}_{-2.57}(\text{total})$ **mb**

To our knowledge, the first such results ever.

Supersedes previous results not accounting for fragmentation universality violation (**substantial difference, O(50%)**).

Results are in reasonable agreement with NNLO QCD expectations (near upper edge)



Comparison of sqrt(s) dependence with NNLO QCD theory gives insights on pQCD (multi-scale problem), constraints on PDFs, and charm quark mass, from hadronic collisions at NNLO.

Outlook:

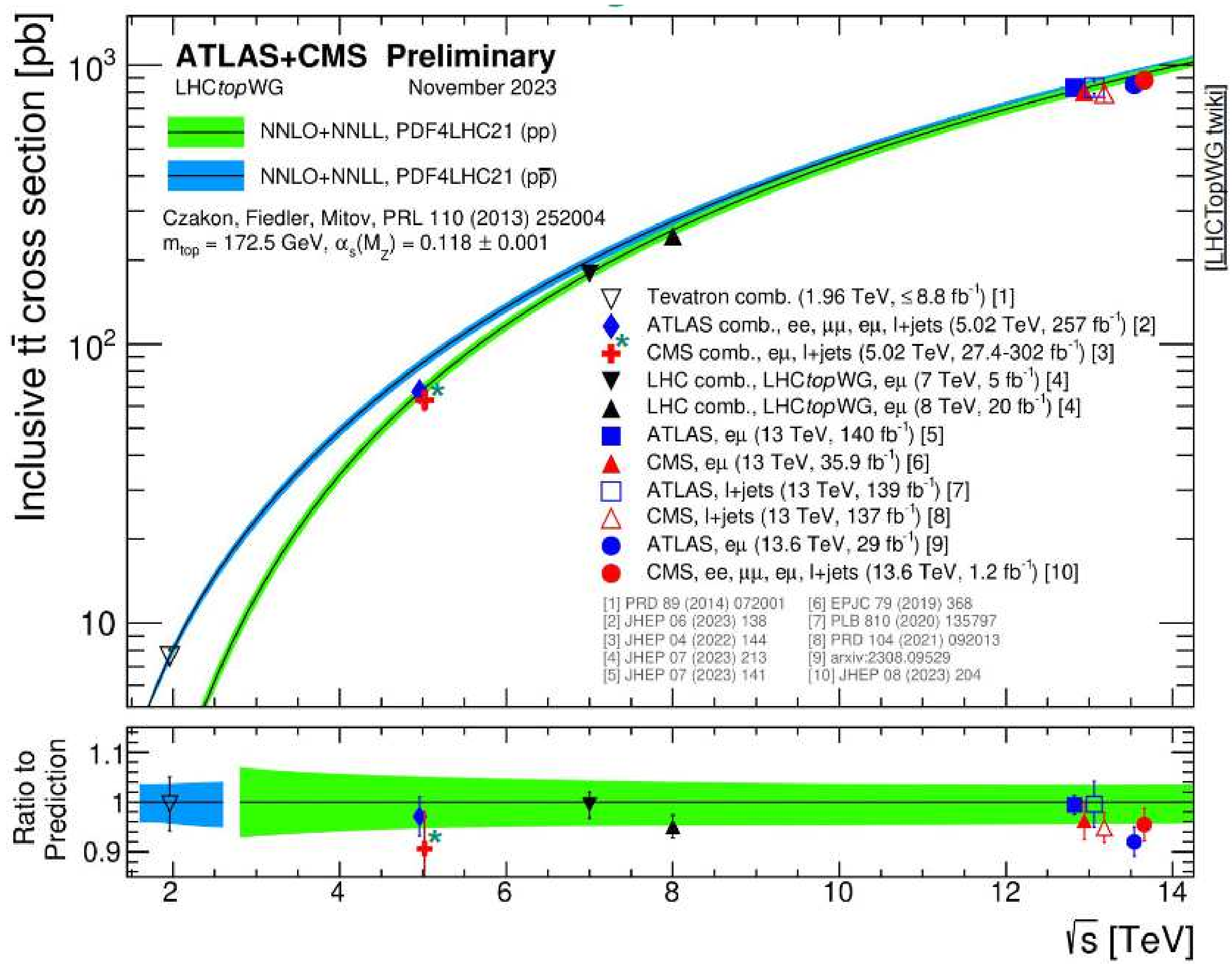
ddFONLL method can be directly extended to beauty production and/or heavy ion collisions, while remaining fully consistent with FONLL treatment of past or future charm/beauty results in e^+e^- or ep collisions by construction.

Can also be extended to NNLO+NNLL (talk T. Generet this morning).

Backup

Teaser: measurements of total ttbar cross section

plethora of
LHC results
on total
top cross section
(see e.g. talk
K. Mazumdar
on monday)



produce the same
for charm

(so far `unmeasured' at LHC; only strong extrapolations available, relying on (disproven) charm fragmentation universality assumption)

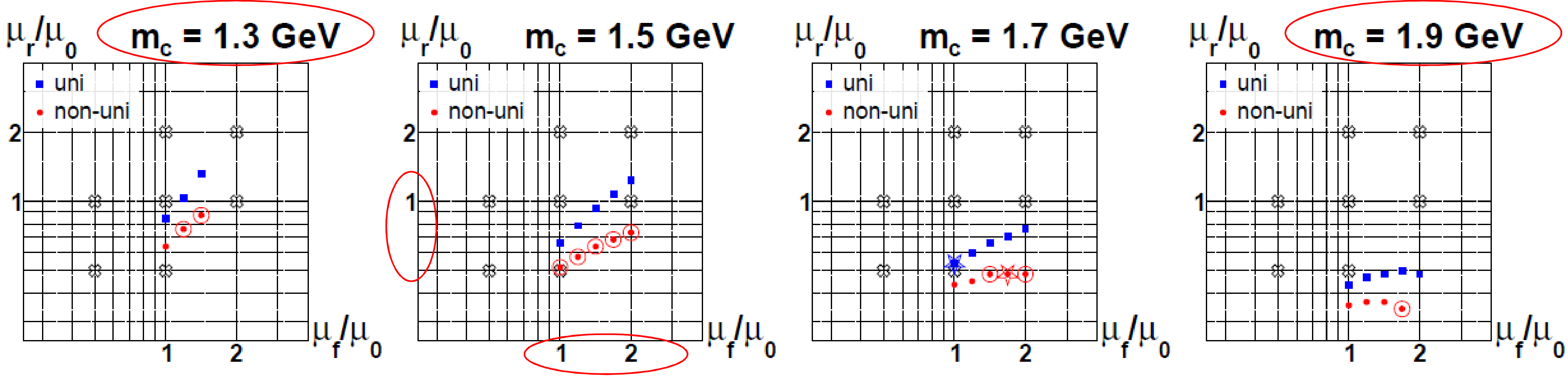
Application to published 5 TeV ALICE+LHCb charm data

From slides Y.Yang at EPS 2023

PHENOMENOLOGICAL RESULTS

✔ μ_f^b, μ_r^b, m_c^b and α_K^b from fit of input data with uncertainties by $\Delta\chi^2$ (4D) applying S factor of 1.46:

☆: the best parameters
o: the uncertainty parameters



with $6 < \alpha_K < 25$ (cf. $\alpha_K \sim 6$ with LEP data)

fitted parameter ranges reasonable

→ strong correlations observed between theory scales at lower m_c

✔ derived so-called *data constrained FONLL*: $d\sigma_{H_c}^{\text{FONLL with } \tilde{f}}(\mu_f^b, \mu_r^b, m_c^b, \alpha_K^b)$ with assigned uncertainties

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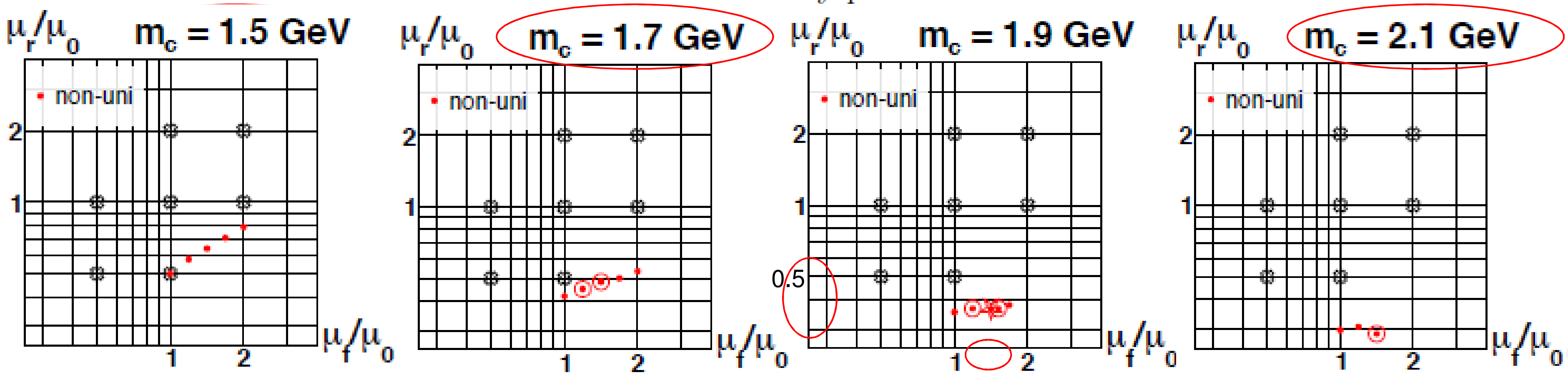
§ $\mu_0 = \sqrt{m_c^2 + p_T^2}$

Application to published 13 TeV ALICE+LHCb charm data

Phenomenological results

✔ μ_f^b, μ_r^b, m_c^b and α_K^b from fit of input data with uncertainties by $\Delta\chi^2$ (4D) applying S factor of 1.16

☆: the best parameters
o: the uncertainty parameters



with $5 < \alpha_K < 9$ (cf. $\alpha_K \sim 6$ with LEP data)

fitted parameter ranges reasonable

→ strong correlations observed between theory scales at lower m_c

✔ derived so-called *data constrained FONLL*: $d\sigma_{H_c}^{\text{FONLL with } \tilde{f}}(\mu_f^b, \mu_r^b, m_c^b, \alpha_K^b)$ with assigned uncertainties

§ $\mu_0 = \sqrt{m_c^2 + p_T^2}$

13 TeV total charm pair cross section

		[GeV]	$\Delta\sigma_{D^0+\overline{D^0}}$ [mb]
ALICE	$0.0 < \lvert y\rvert < 0.5$	$0 < p_T < 50$	$1.50^{+0.14}_{-0.14}$
LHCb	$2.0 < \lvert y\rvert < 2.5$	$0 < p_T < 15$	$1.20^{+0.12}_{-0.11}$
	$2.5 < \lvert y\rvert < 3.0$	$0 < p_T < 15$	$1.25^{+0.09}_{-0.09}$
	$3.0 < \lvert y\rvert < 3.5$	$0 < p_T < 15$	$1.18^{+0.07}_{-0.07}$
	$3.5 < \lvert y\rvert < 4.0$	$0 < p_T < 11$	$1.04^{+0.07}_{-0.06}$
	$4.0 < \lvert y\rvert < 4.5$	$0 < p_T < 7$	$0.78^{+0.06}_{-0.06}$
	Σ	Σ	$5.44^{+0.40}_{-0.38}$
ALICE+LHCb			$6.94^{+0.43}_{-0.41}$
ddFONLL (region not covered by data)			$6.38^{+0.52}_{-0.60}(\tilde{f})^{+1.12}_{-0.93}(\text{PDF})$
$\sigma_{c\bar{c}}$ [mb]	$17.43^{+0.56}_{-0.53}(\text{data})^{+0.69}_{-0.78}(\tilde{f})^{+1.47}_{-1.22}(\text{PDF})^{+0.24}_{-0.18}(\mu_f, \mu_r, m_c, \alpha_K)^{+1.19}_{-2.05}(f^{pp})$ $17.43^{+2.10}_{-2.57}(\text{total})$		

Table 6.9: $\sigma_{c\bar{c}}$ at 13 TeV with $f^{pp}_{D^0} = 0.382^{+0.026}_{-0.045}$. The uncertainties of the measurements are the summed uncertainties of statistical and systematic uncertainties in a quadrature.

FONLL (NLO+NLL) QCD theory predictions and PROSA/CTEQ PDFs

From slides Y.Yang at EPS 2023

Charm hadron production in *pp* collisions

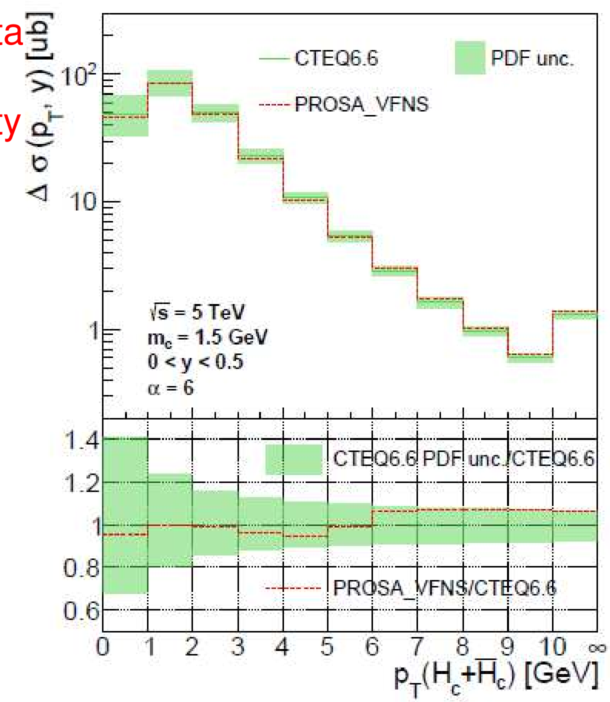
Hadron cross section ($d\sigma_{H_c}$) given by convolutions of perturbative cross section ($d\hat{\sigma}_{ij\to c\bar{c}}$) and non-perturbative functions (f_i, f_j, $D^{\mathrm{NP}}_{c\to H_c}$):

$$d\sigma_{H_c} \propto d\sigma_{pp\to c\bar{c}} \otimes D^{\mathrm{NP}}_{c\to H_c}, \quad d\sigma_{pp\to c\bar{c}} = f_i f_j \otimes d\hat{\sigma}_{ij\to c\bar{c}}$$

- ✔ $d\hat{\sigma}_{ij\to c\bar{c}}$ given at NLO+NLL (FONLL) in QCD
  - → has scales (μ_f and μ_r) and pole mass (m_c) uncertainties
- ✔ PDFs f_i and f_j of initial states determined from measurements
  - → used CTEQ6.6 as a proxy of PROSA_VFNS (arXiv:1911.13164)
- ✔ fragmentation function ($D^{\mathrm{NP}}_{c\to H_c}$) for final states also from measurements
  - → used Kartvelishvili function having a single parameter α_K, roughly constrained not to be too far off the one extracted from LEP
- ✔ normalization given by a fragmentation fraction from e^+e^-/ep ($f^{uni}_{H_c}$) in universality assumption
  - → original FONLL theory (arXiv:1205.6344):

$$d\sigma^{\mathrm{FONLL}}_{H_c} = f^{uni}_{H_c} \cdot (d\sigma^{\mathrm{FONLL}}_{pp\to c\bar{c}} \otimes D^{NP}_{c\to H_c})$$

constrained by low-x charm data **w/o** assuming charm unversality



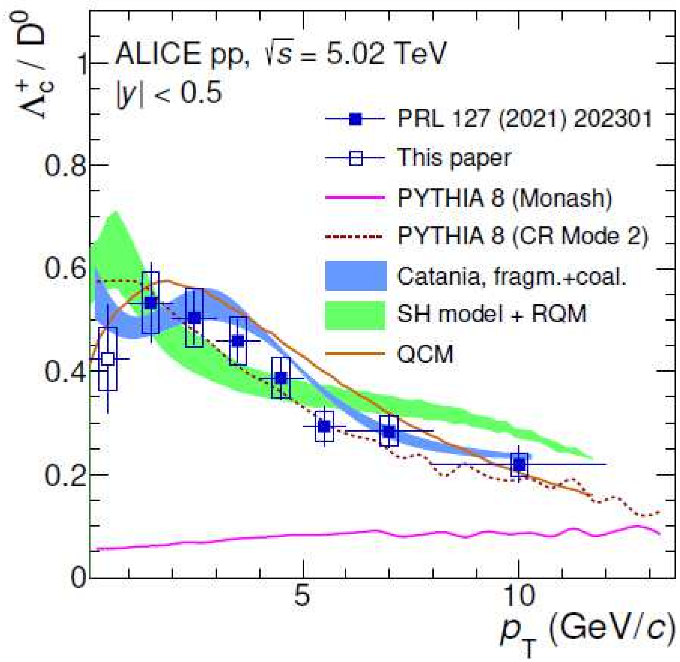
-> strategy (data driven "theory"):

modify phenomenologically to include nonunversality and fit to data (within uncertainties)

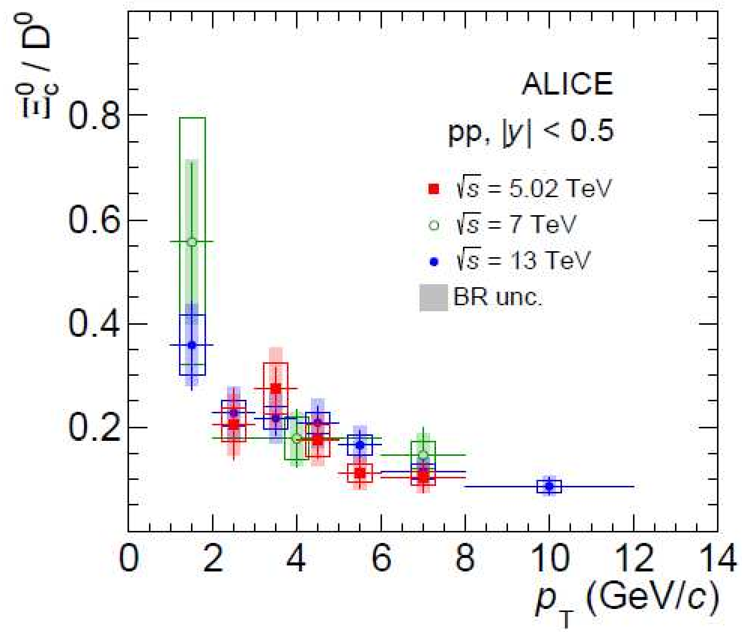
Baryon to baryon ratio

From slides Y.Yang at EPS 2023

Λ_c^+/D^0 AND Ξ_c^0/D^0 MEASUREMENT



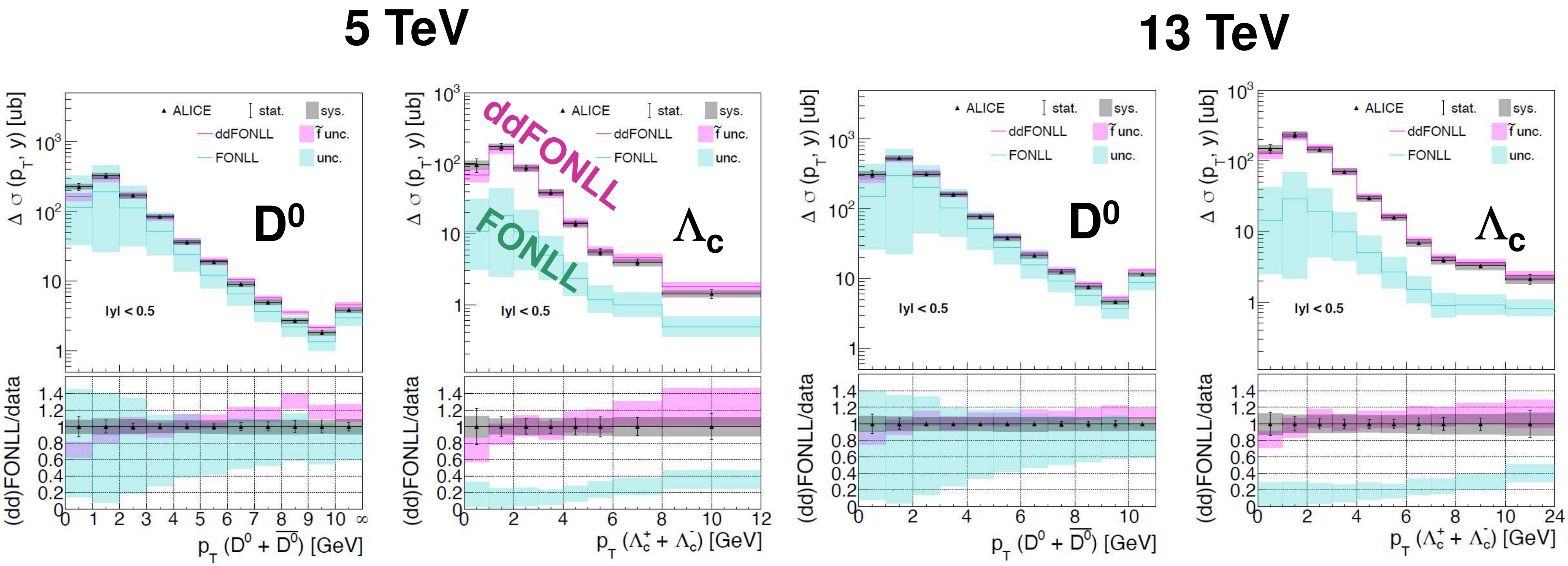
arXiv:2211.14032



arXiv:2105.05616

✔ no significant p_T dependence observed for baryon-to-baryon

Performance illustration on 5 + 13 TeV ALICE data



FONLL: full uncertainty, with `classical' universality assumption

ddFONLL: f̃ uncertainty only (for cross check)

Cascade_c at 5 TeV

plot adapted from arXiv:2311.11426

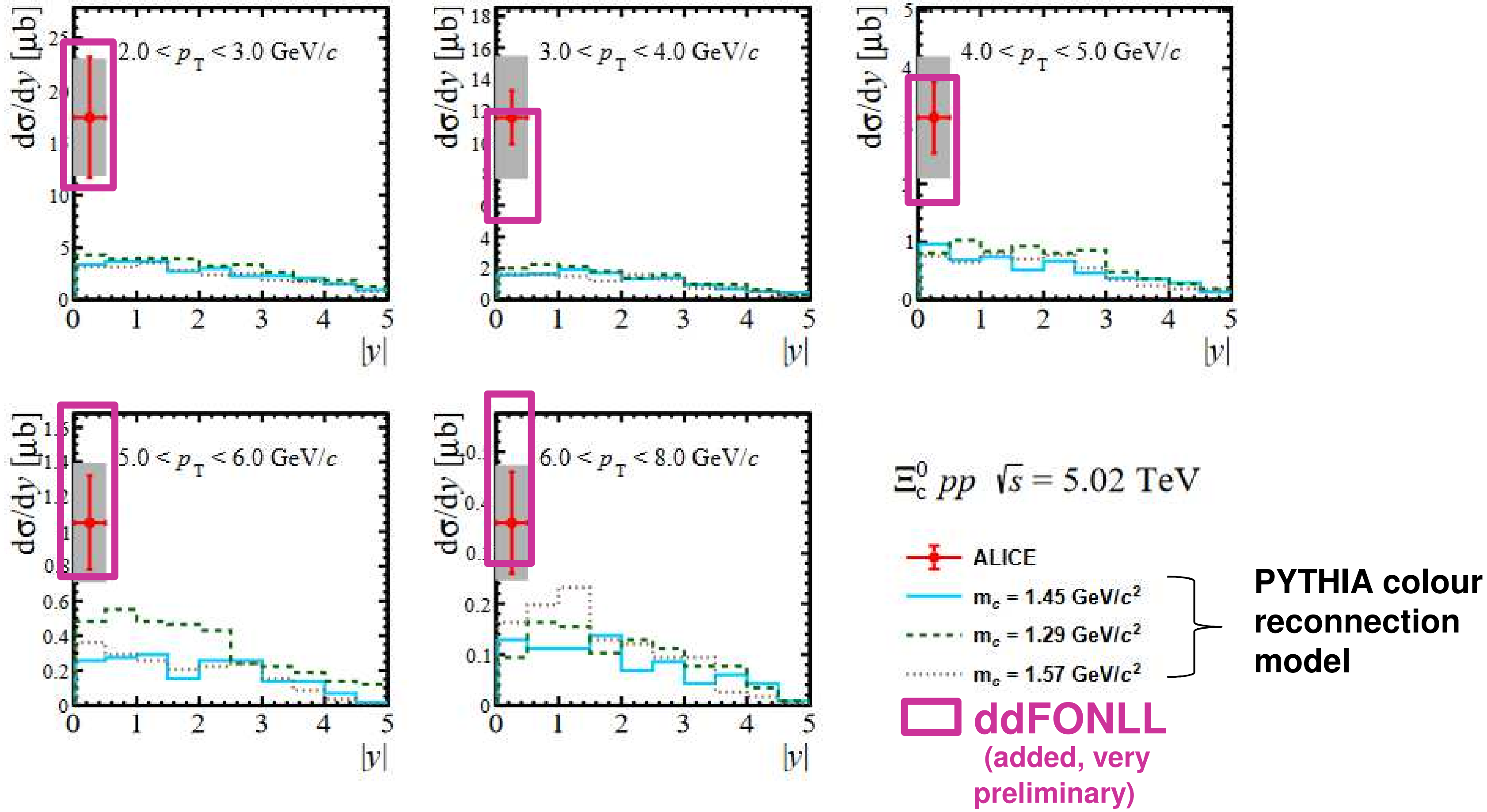


Figure 11: Measured Ξ_c^0 cross section as a function of rapidity compared with PYTHIA simulations with the bands corresponding to a 1σ variation around the optimum.

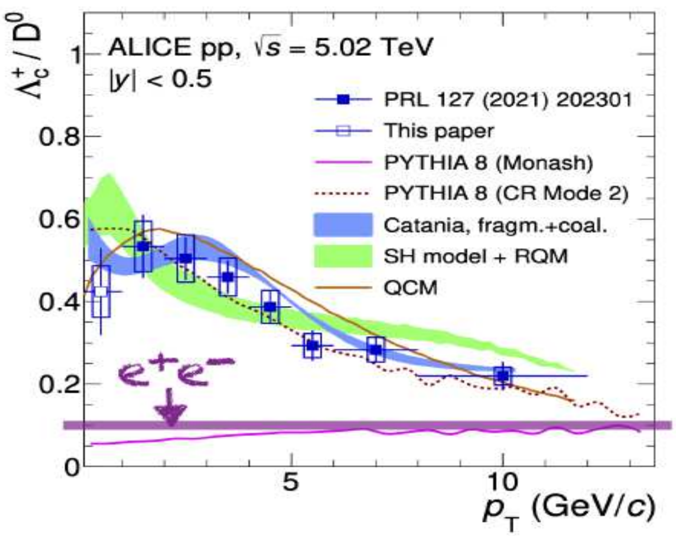
ddFONNL also works for Cascade_c!

Non-universality of charm fragmentation

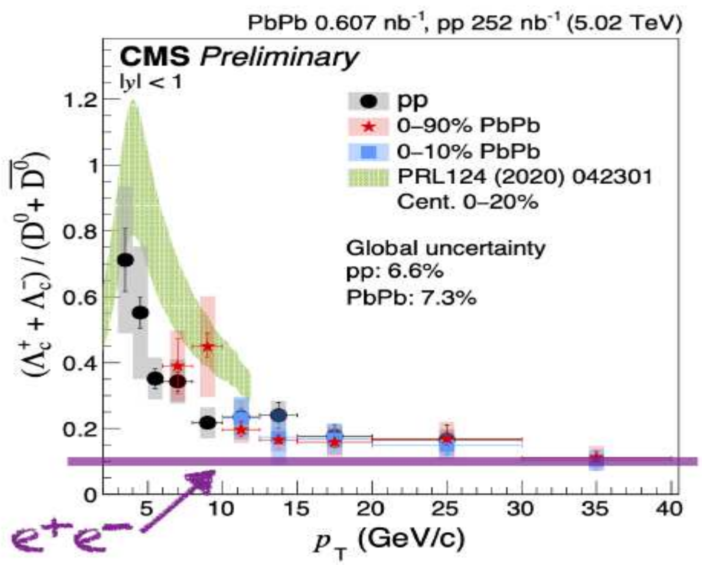
From slides Y.Yang at EPS 2023

p_T DEPENDENT Λ_c^+/D^0 MEASUREMENTS

pp non-universal!



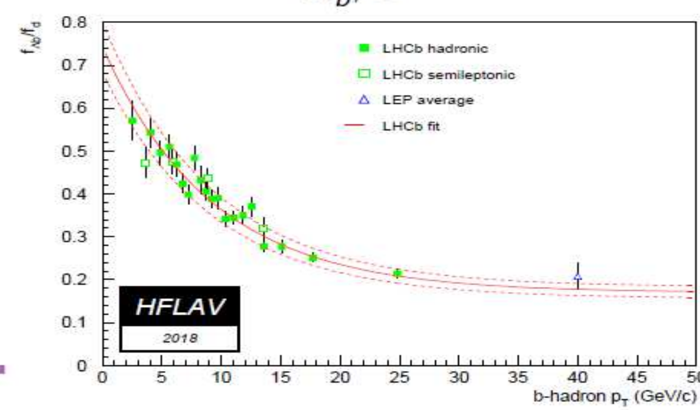
arXiv:2211.14032



CMS-PAS-HIN-21-004

for comparison:

Λ_b^0/B^0



arXiv:1909.12524

✔ clear p_T dependence observed on Λ_c^+/D^0 measurements from pp

→ asymptotically close to e^+e^- value, $0.10^{+0.01}_{-0.01}$ (as like observed on Λ_b^0/B^0)

-> strategy (data driven!):

treat baryon to meson production fractions vs p_T as non-universal

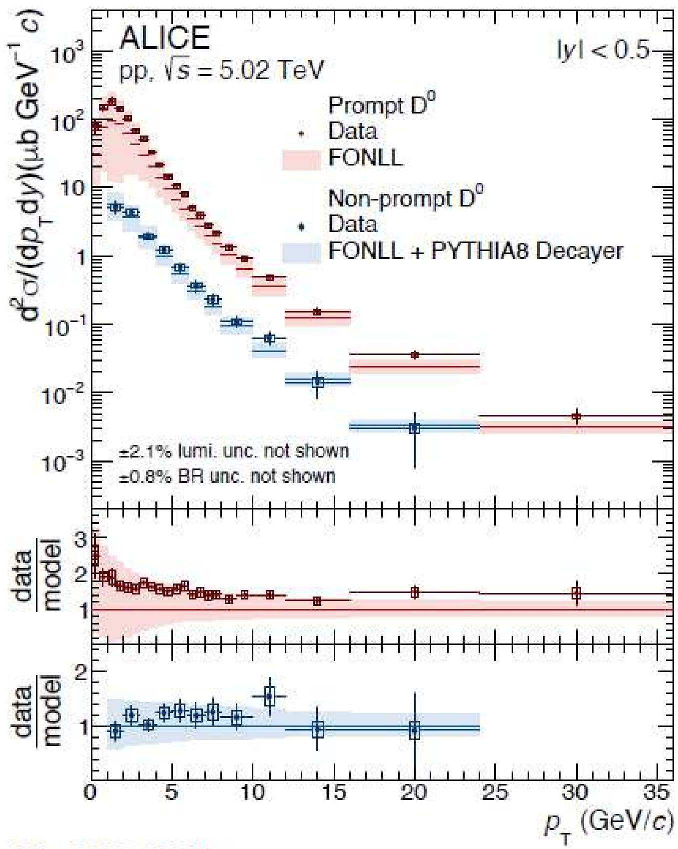
treat asymptotic high p_T limit as universal

Application to published 5 TeV ALICE+LHCb charm data

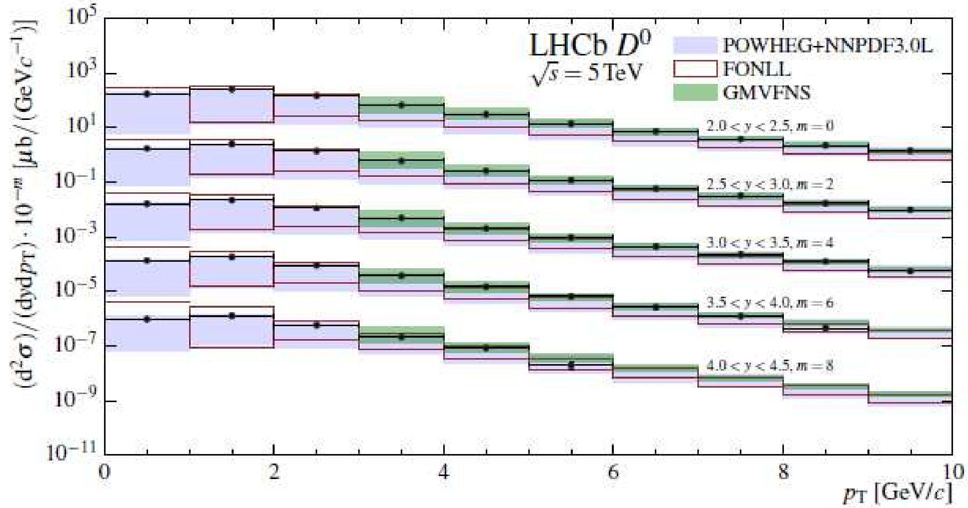
From slides Y.Yang at EPS 2023

EXTRAPOLATING D^0 MEASUREMENTS AT 5 TEV

Input measurements:



arXiv:2102.13601



arXiv:1610.02230

✔ applied χ^2 fit for both $d\sigma_{H_c}$ phenomenol. modified and $d\sigma^{FONLL}_{H_c}$ with $\tilde{f}$ to find best description of data with 4 free parameters (μ_f, μ_r, m_c and α_K):

$$\chi^2 = \sum_{\text{data bins}} \frac{(\text{FONLL} - \text{data})^2}{\text{statistical unc.}^2 + \text{systematic unc.}^2}$$

→ i.e., finding μ_f^b, μ_r^b, m_c^b and α_K^b of the least χ^2

✔ use to extrapolate D^0 **measurements at 5 TeV from LHC**

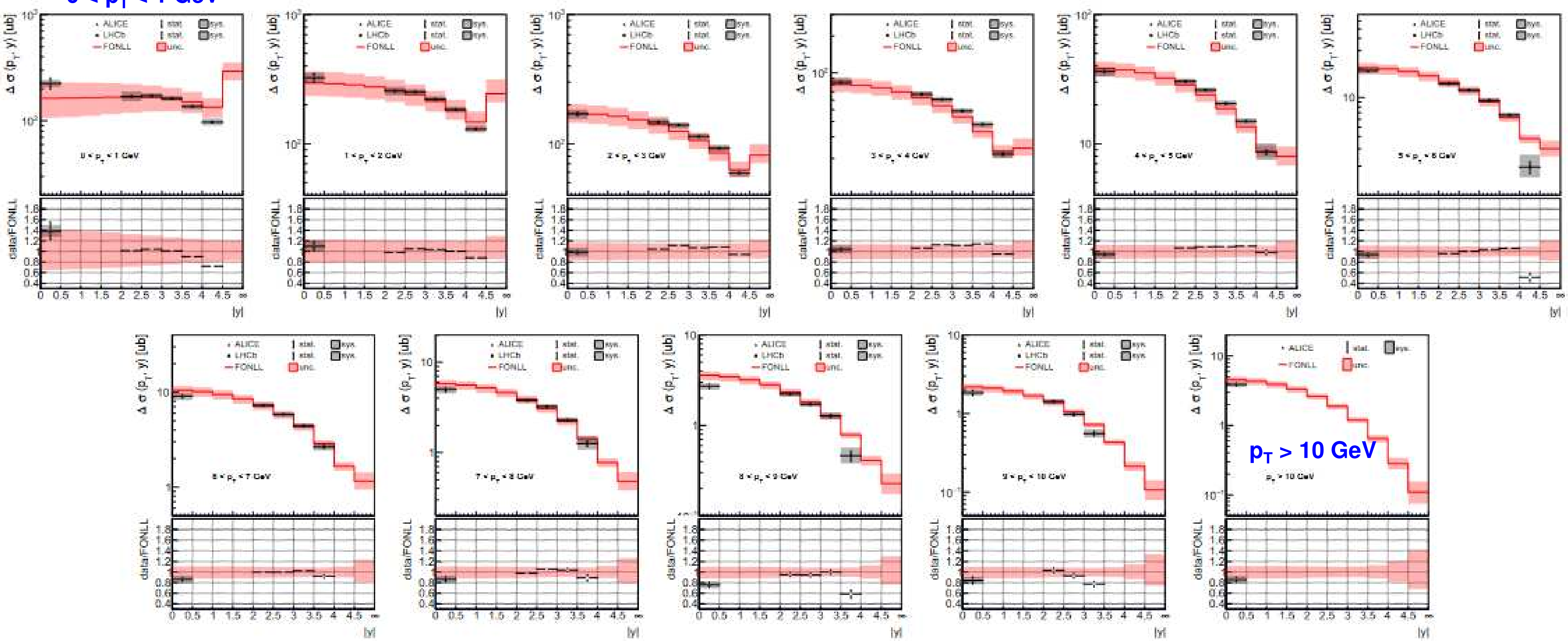
Application to published 5 TeV ALICE+LHCb charm data

From slides Y.Yang at EPS 2023

D^0 CROSS SECTION IN FULL KINEMATIC RANGE

✔ *Data constrained FONLL* with total uncertainty (CTEQ6.6 PDF $\oplus\ \tilde{f}\ \oplus\ (\mu_f,\ \mu_r,\ m_c,\ \alpha_K)$) gives good descriptions for D^0 measurements in the full kinematic range (as a function of p_T in backup)

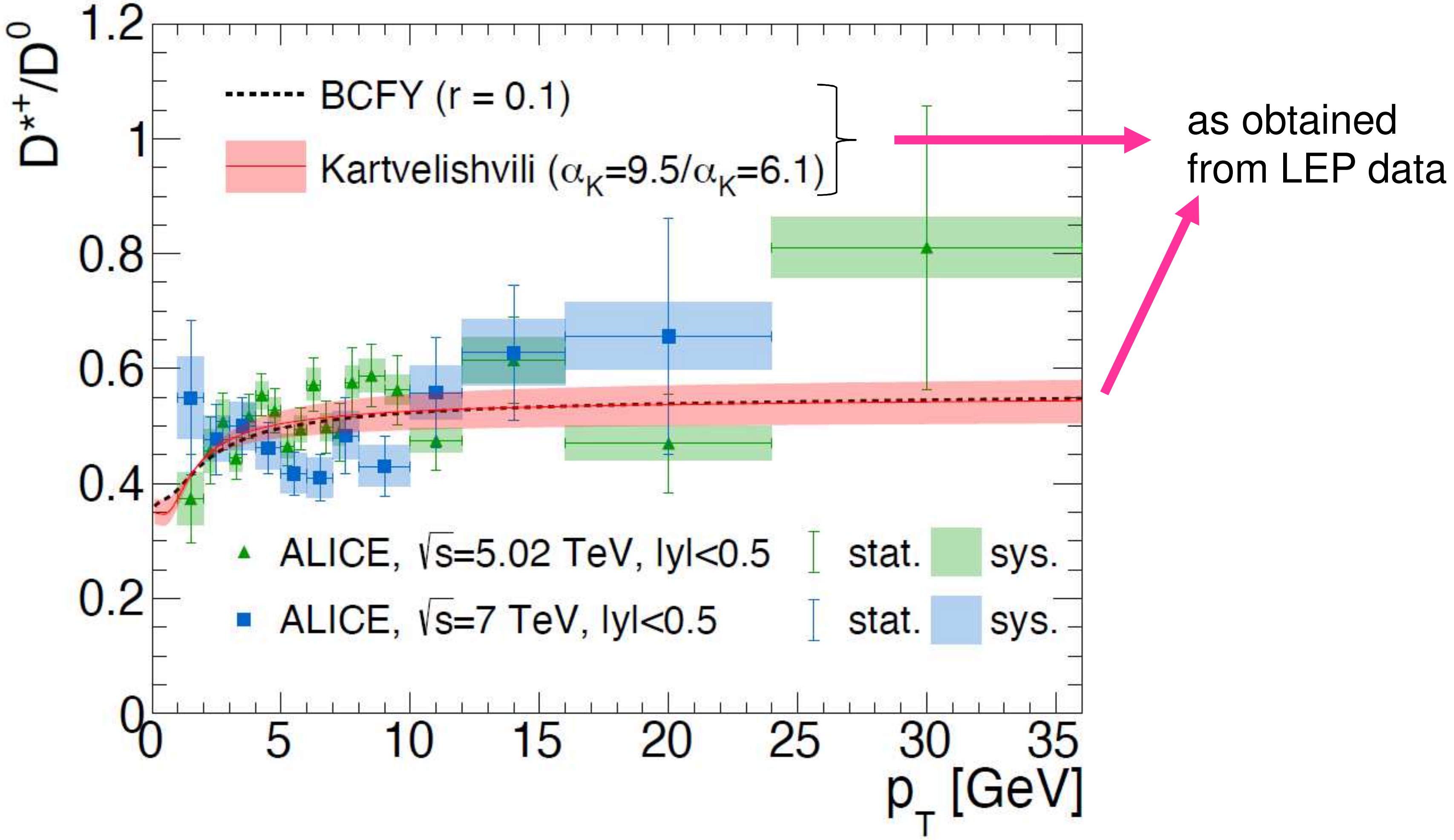
$0 < p_T < 1$ GeV



-> strategy:

use data whenever available, otherwise data constrained theory

D* vs. D^0 fragmentation



LHC data consistent with LEP -> universality holds for D*/D

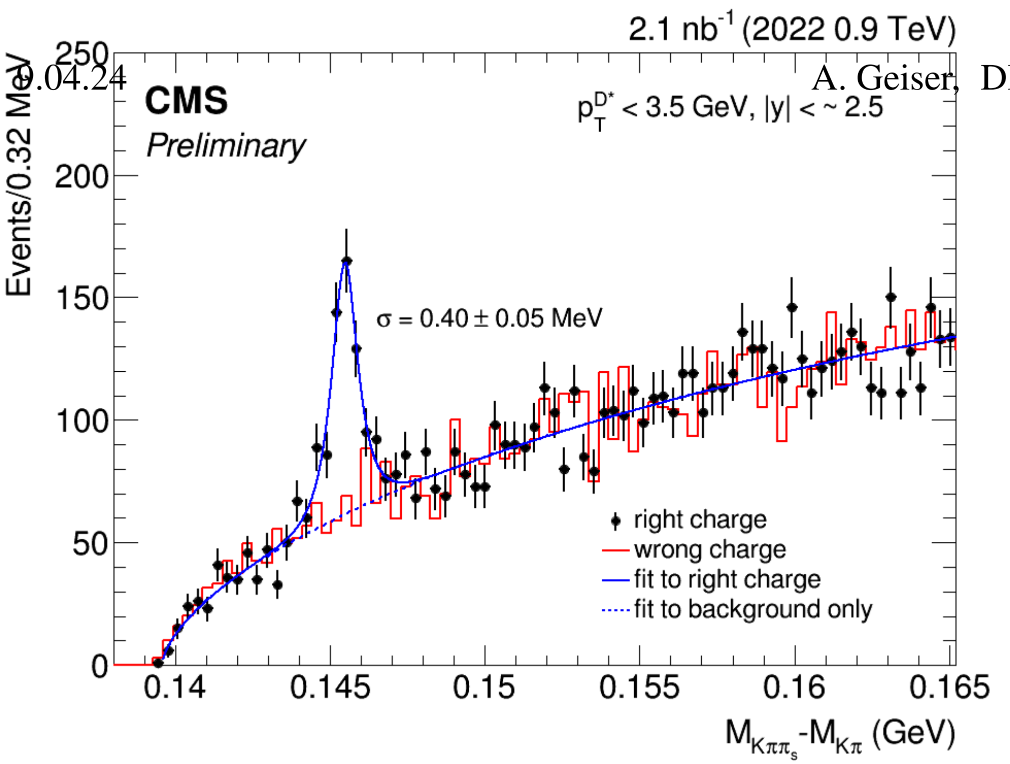
-> ddFONLL for D^0 can be translated into ddFONLL for D*

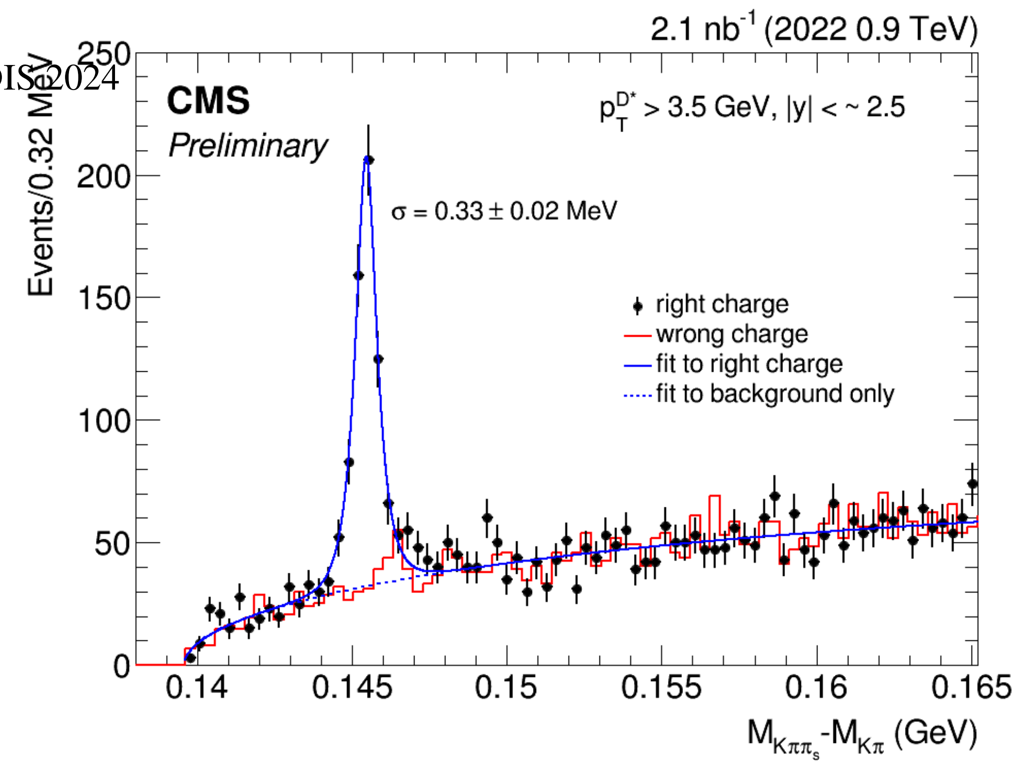
(e.g. future 0.9 TeV measurements)

Charm cross sections at 0.9 TeV?

CMS-DP-2022-024

D* $p_T < 3.5$ GeV D* $|y| < \sim 2.5$ D* $p_T > 3.5$ GeV





no cross sections available so far, but would like to have proxy for QCD studies
-> use plain ddFONLL applied to 0.9 TeV FONLL with 5 TeV fit parameters, expect:

σ_{tot}(ccbar) = $1.7^{+0.24}_{-0.24}(\mathrm{total})\mathrm{mb.}$ **not a measurement!**