HF@LHC
IPPP Durham
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Prompt heavy flavour production

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Total cross sections

NLO total cross sections @ LHC 13

Charm	Bottom	Top
6.7 mb $^{+150\%}_{-75\%}$	400 μb $^{+47\%}_{-36\%}$	710 pb $^{+12\%}_{-12\%}$
An opinion	A prediction	A test of pQCD

NNPDF 3.0, 7-point scale variation within factor of 2, mass range for charm and bottom, no PDF uncertainty

An exercise in scale uncertainty

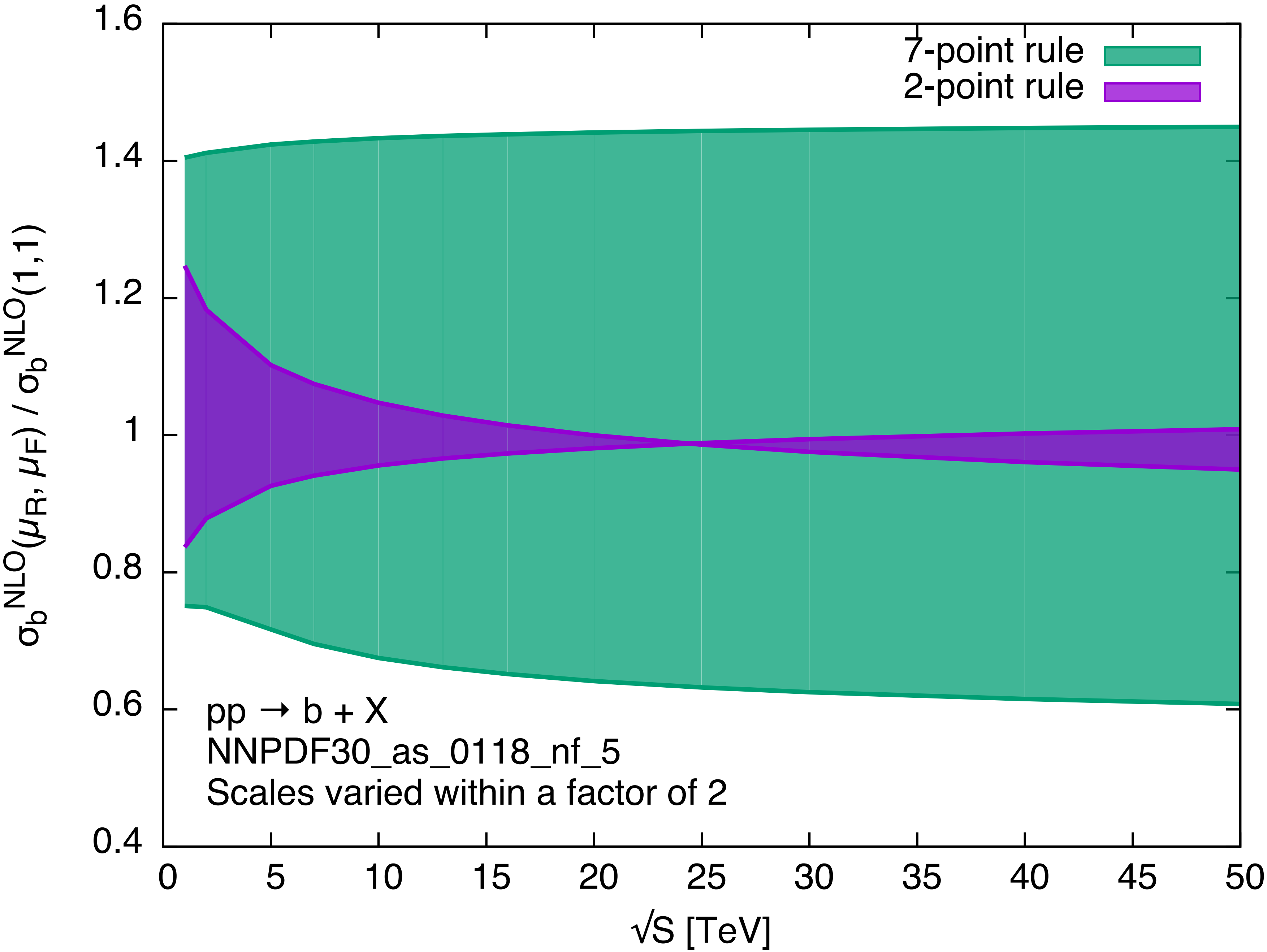
NLO bottom total cross section at LHC 13:

$400\ \mu b\ ^{+44\%}_{-33\%}$ 7-point rule, scales only

$400\ \mu b\ ^{+3\%}_{-3\%}$ 2-point rule, scales only

This behaviour is peculiar to LHC energy. It does not appear at Tevatron energy.

An exercise in scale uncertainty



Central scale choice

An argument I (too) often see:

"the main criterion is to optimize the perturbative convergence"

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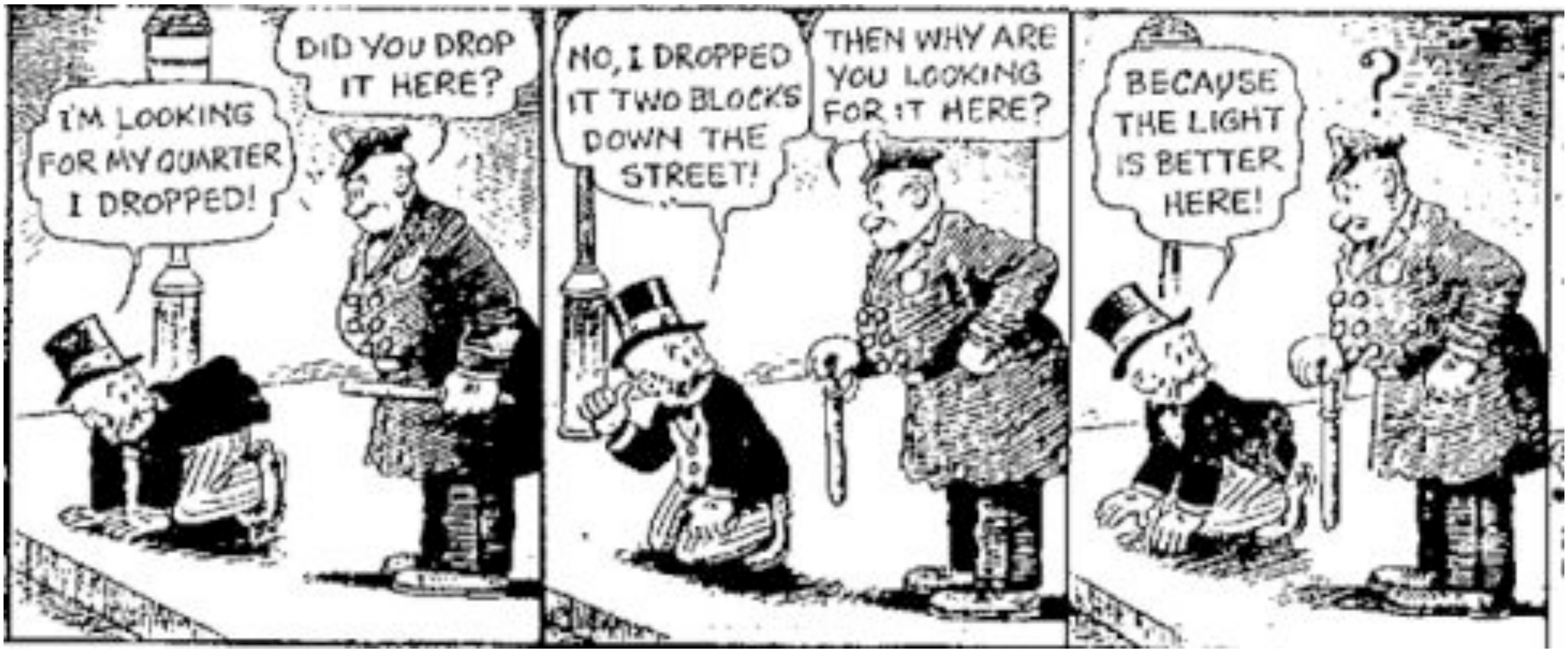
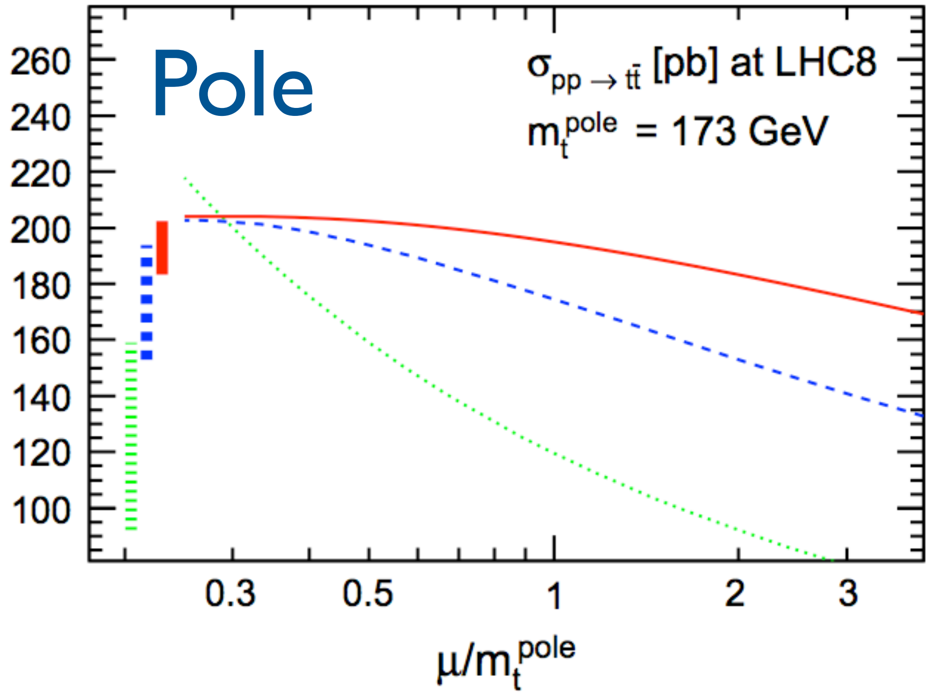
Its logical equivalent:

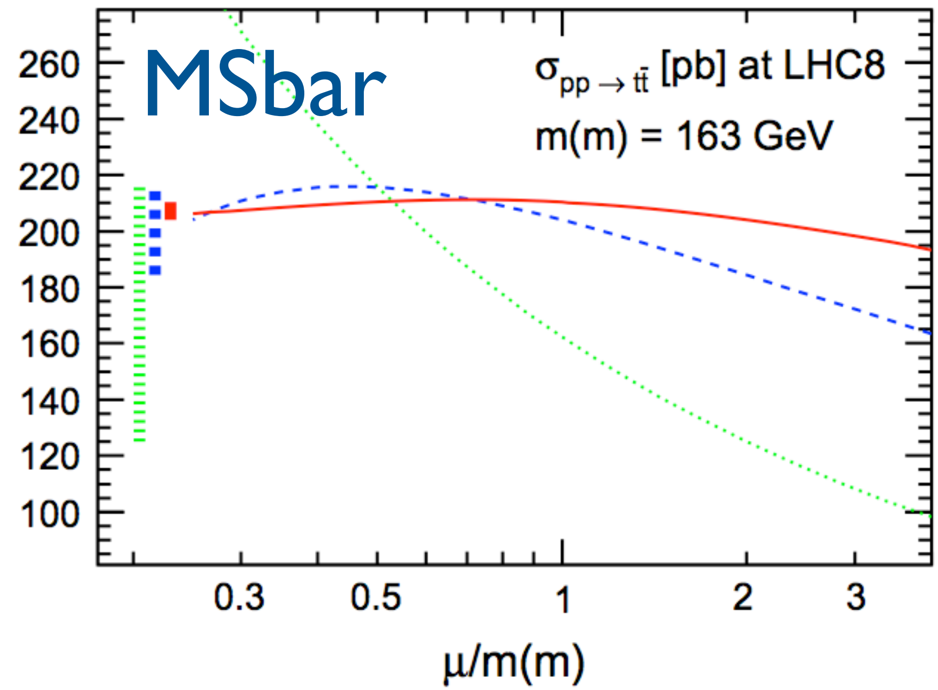


Mass scheme

Moch et al. have advocated the use of the MSbar mass instead of the pole mass, arguing that it leads better convergence and to a reduced scale dependence of the cross section

arXiv:1305.6422





Cross section in MSbar mass scheme obtained replacing in pole mass scheme calculation using

$$\frac{M}{\overline{m}(\overline{m})} = 1 + \frac{4}{3}\left(\frac{\bar{\alpha}_s}{\pi}\right) + \left(\frac{\bar{\alpha}_s}{\pi}\right)^2 (-1.0414\ N_L + 13.4434)$$

and then expanding and truncating at desired order.

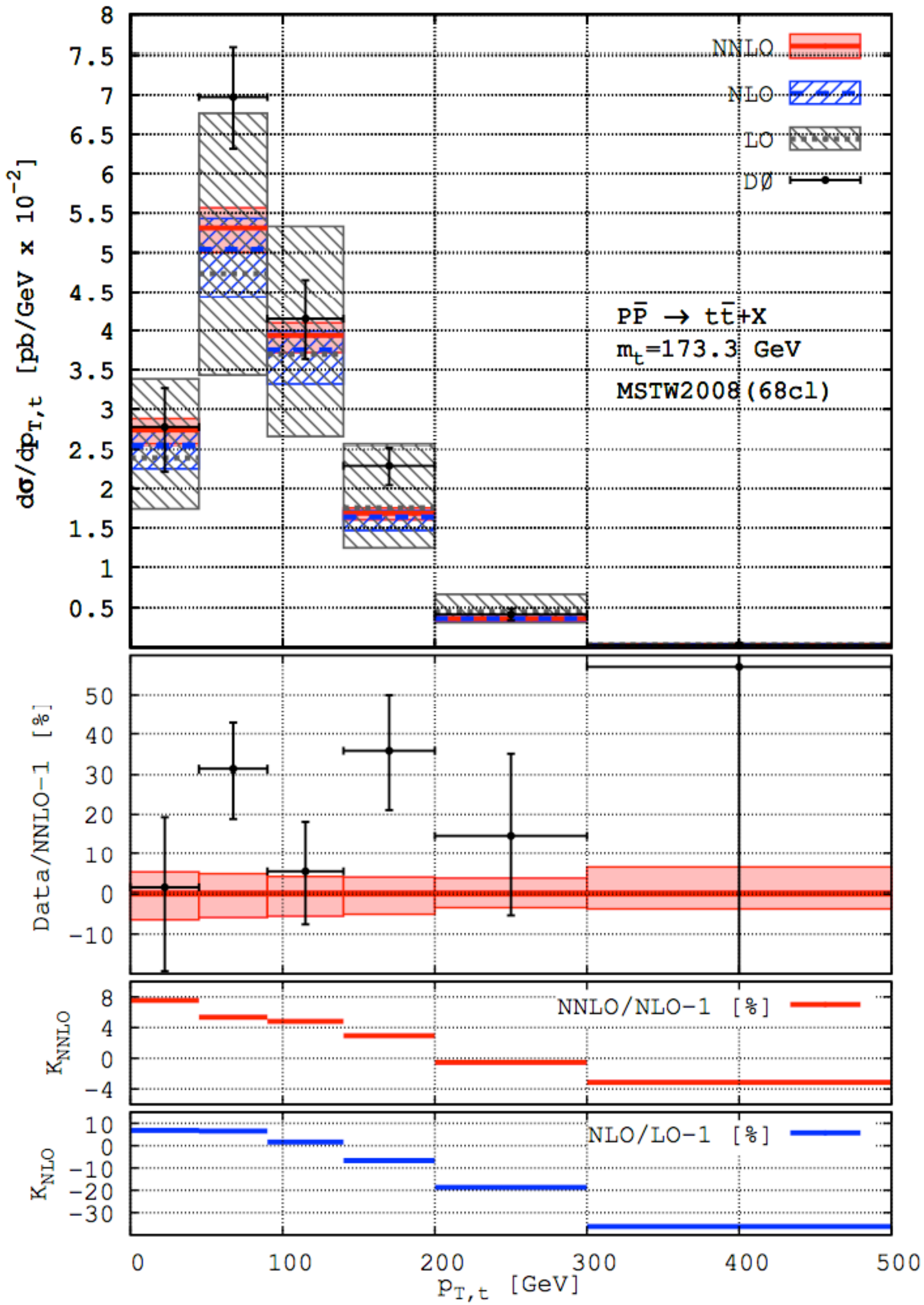
Part of the uncertainty reduction disappears when varying also the scale in the MSbar mass.

Differential cross sections

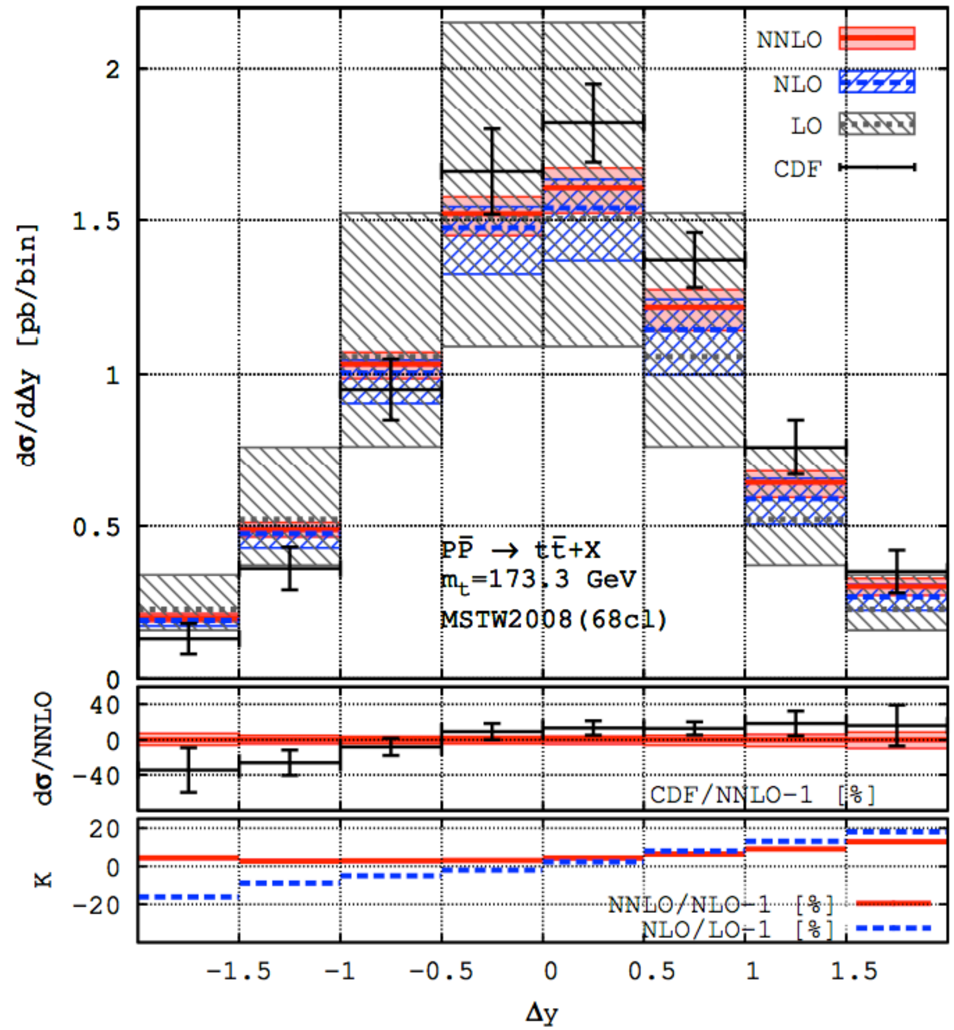
- NNLO distributions
- Large pt resummation
- Forward production, 13/7 ratios

MC, Mangano, Nason 1507.06197

NNLO top differential distributions



Czakon, Fiedler, Heymes, Mitov, 1601.05375



Large-p_t theoretical issues

For $p_t \gg m$ enhanced quasi-collinear gluon radiation is possible, even from top quarks

$\Rightarrow \alpha^n \log^{n-k}(p_t/m)$ terms in series

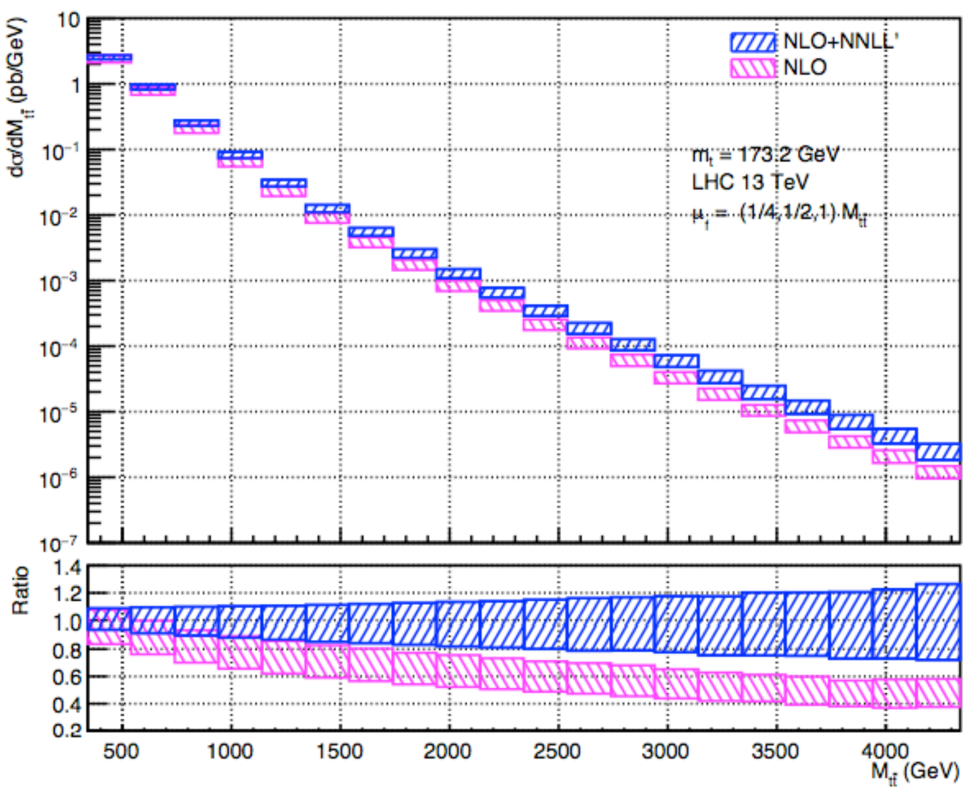
How big are they?
How do we deal with them?

NLO+NNLL' m_{ttbar} and p_t top distr.

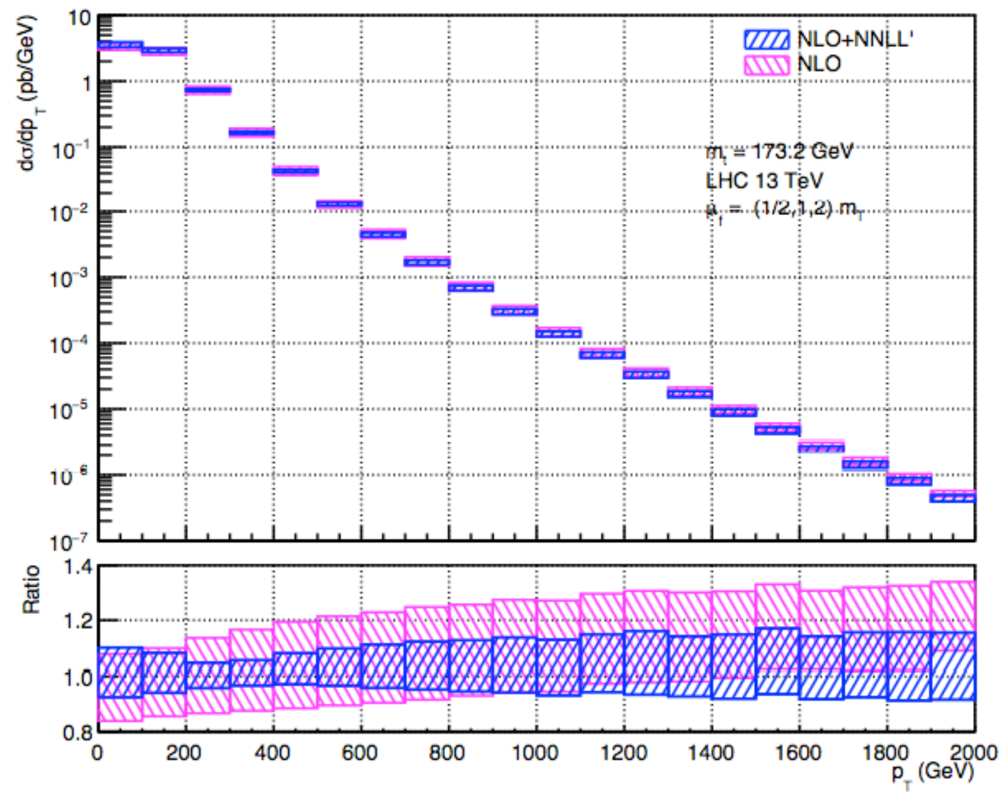
Resummation of soft and collinear gluons,
affecting both the small invariant mass of the pair and the large-p_t regions

Pecjak, Scott, Wang, Yang, 1601.07020

M_{ttbar}



p_t



Quasi-collinear logs from gluon emission off heavy quarks have been resummed in FONLL for charm and bottom

Ingredients: a massive fixed order calculation, a 'massless' resummed calculation, a proper matching:

FONLL = FO + RS - double counting

Orders and logs

A matched calculation can be written as

fixed order resummed

$$N^kLO.N^mLL = N^kLO + N^mLL - \text{double counting}$$

What is known for $d\sigma/dp_t$?

$N^kLO.N^mLL$ for $d\sigma/dp_t$

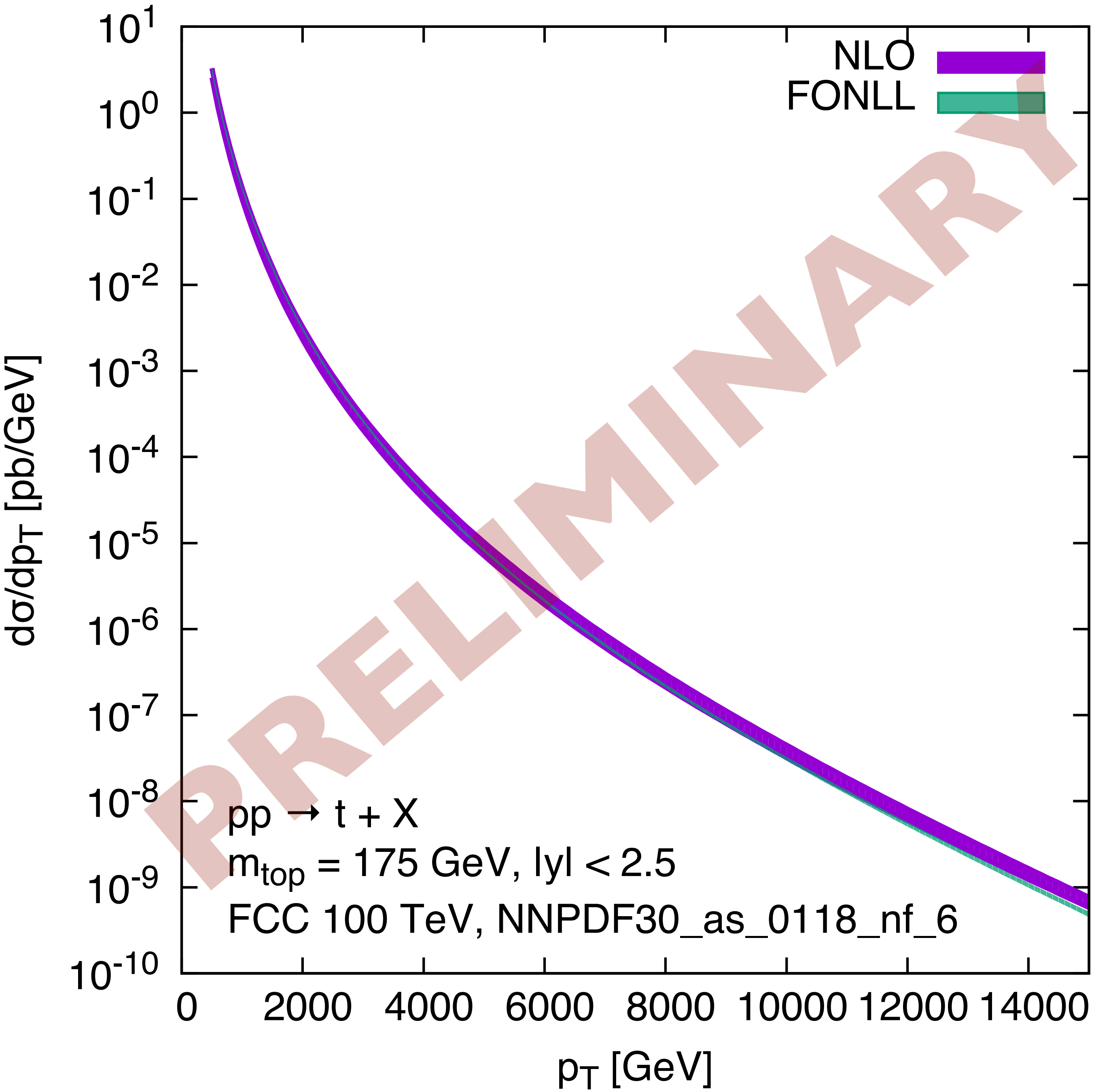
k	m	Label	Known since
0	-	LO	1978/79 multiple authors
1	-	NLO	1989 Nason, Dawson, Ellis
1	1	NLO.NLL	1998 MC, Greco, Nason (this is 'FONLL')
1	2	NLO.NNLL	Awaiting the NNLO jet production calc.
2	-	NNLO	2015 Czakon,Fiedler, Heymes,Mitov
2	1	NNLO.NLL	Ingredients exist. Doable in principle
2	2	NNLO.NNLL	Awaiting the NNLO jet production calc.

FONLL for top at FCC

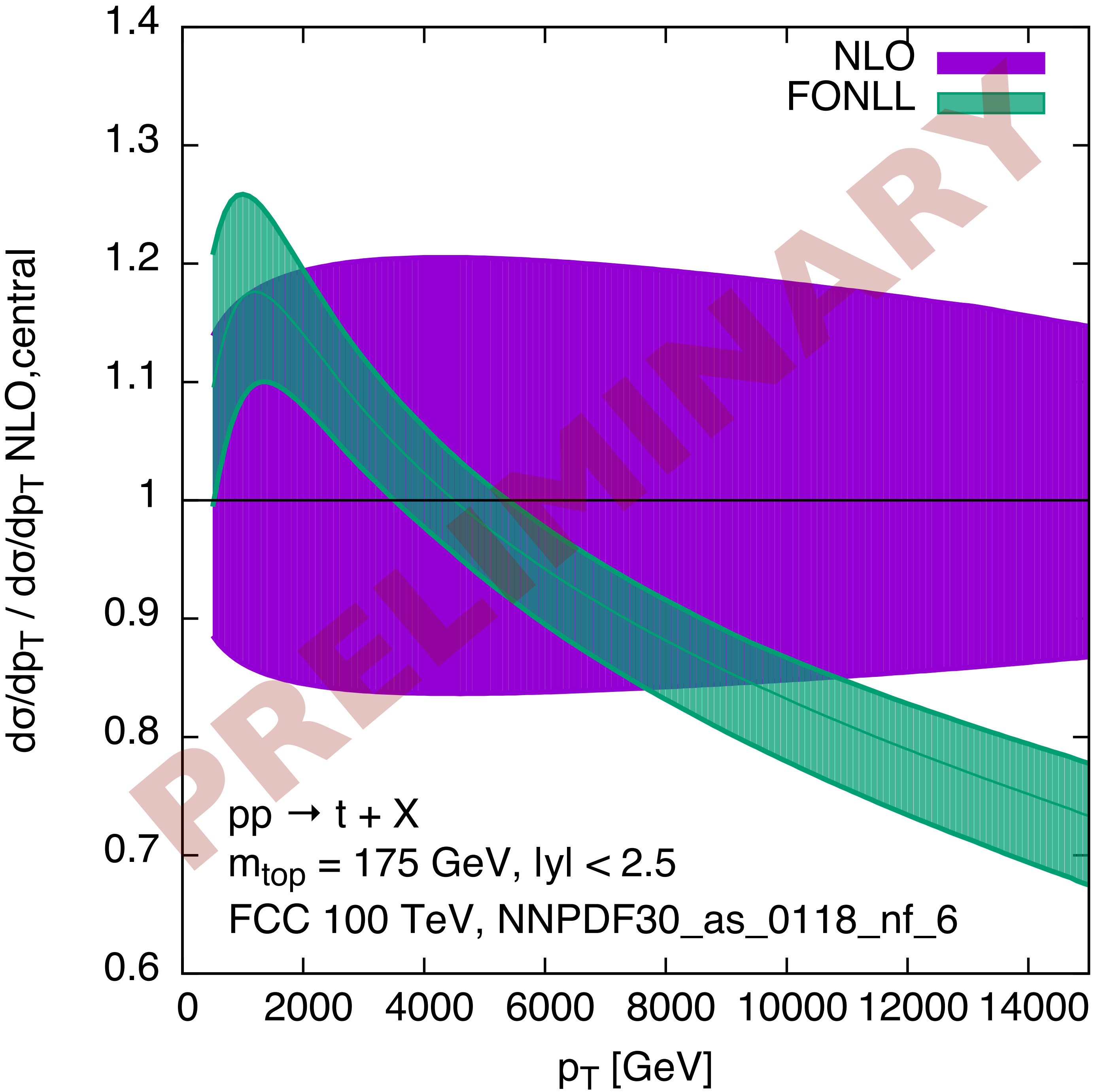
Upgrade of FONLL to v1.4 (not yet released)

Ingredients needed for top quark production:

- 6 light flavours running in α_s
- PDFs with 6 flavours (top quark perturbatively generated)
  - NNPDF30_as_0118_nf_6
  - CT14nlo_NF6
  - others?



Uncertainty band: 7-points rule for fact. and ren. scales

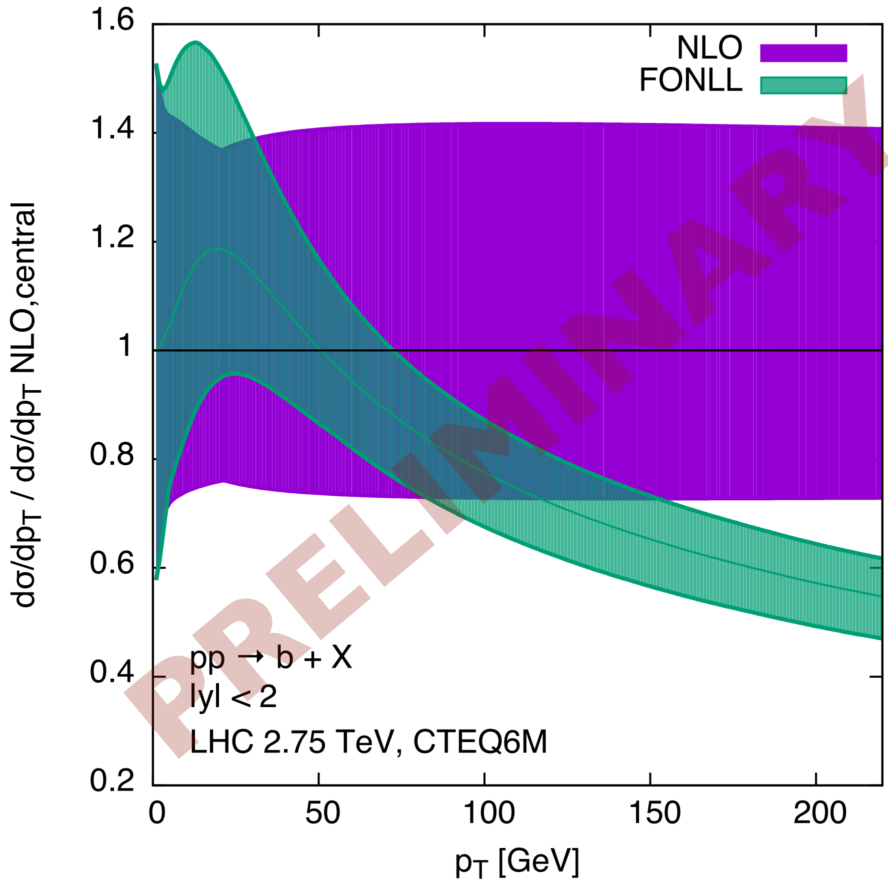


Factor of 2 reduction in rate w.r.t. NLO for p_t > 2 TeV

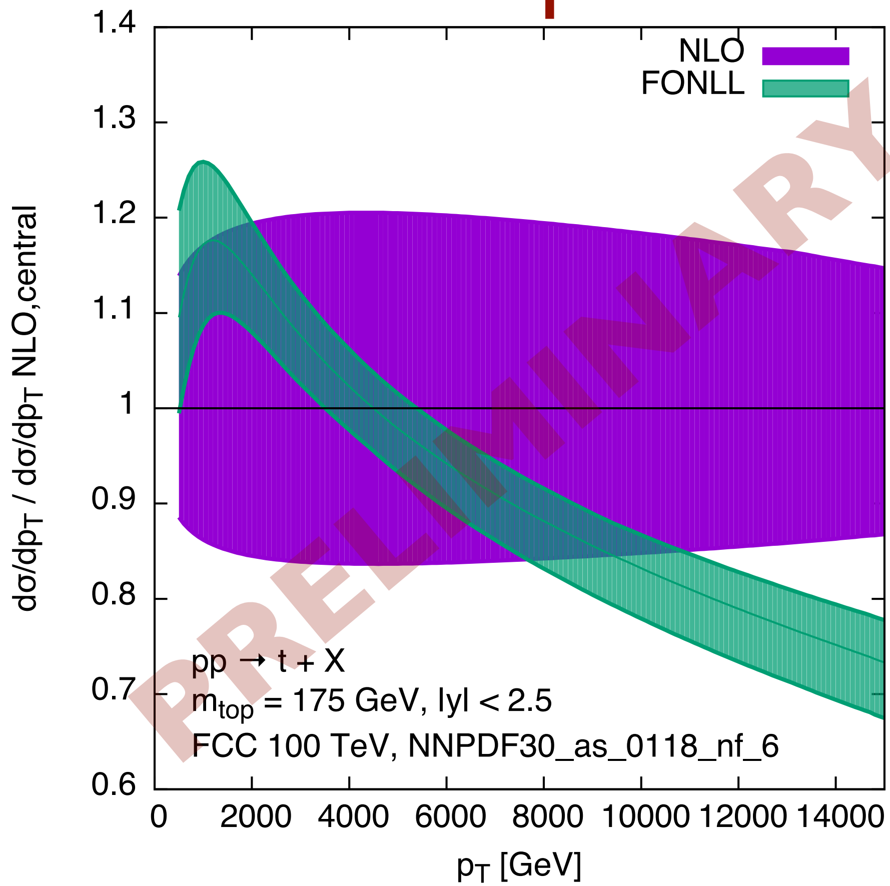
Check

Compare to bottom quarks at 2.75 TeV CM energy and p_t up to 200 GeV

bottom



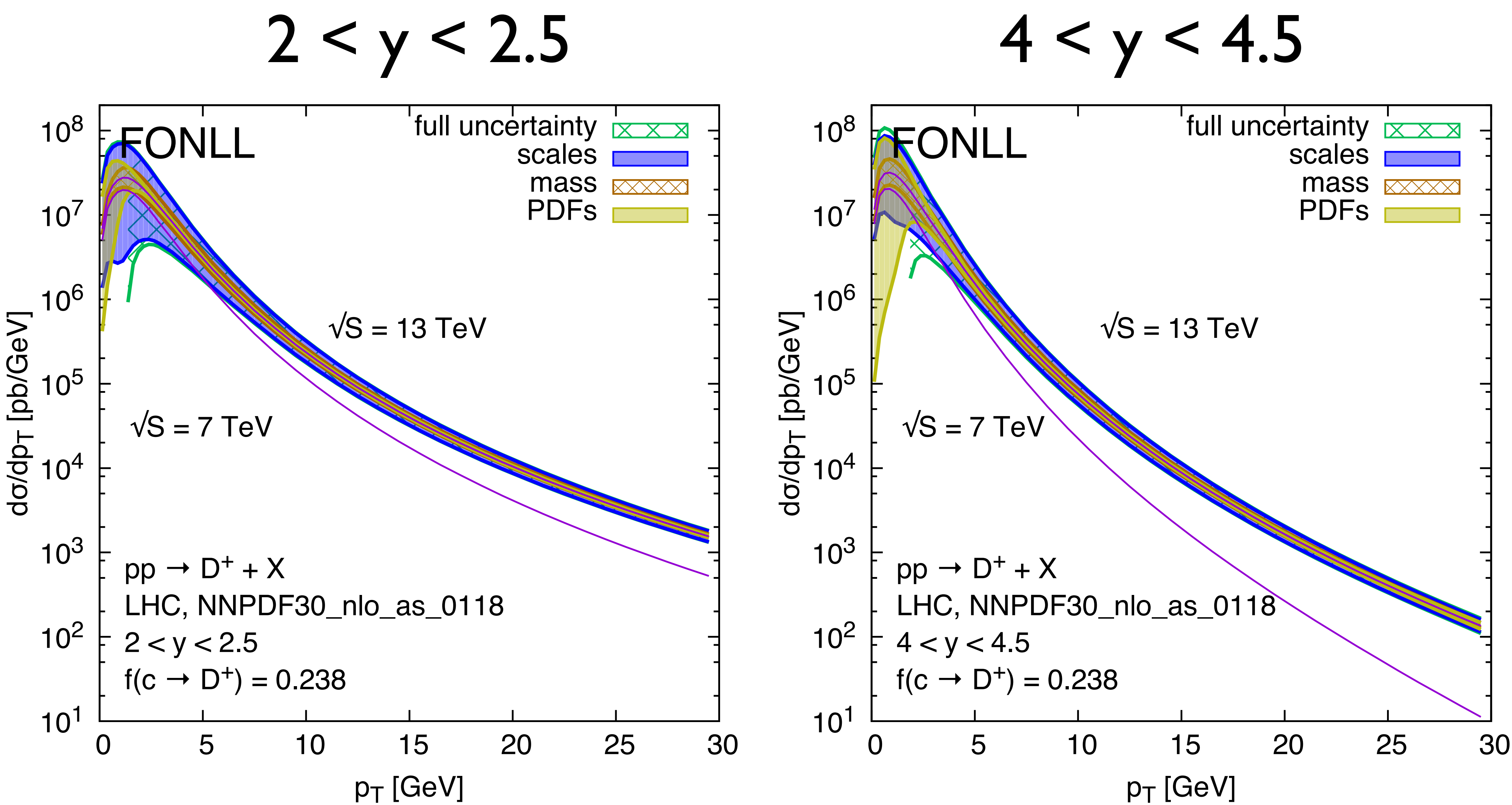
top



Effects of quasi-collinear logs seem to scale consistently

Charm production at 7 and 13 TeV

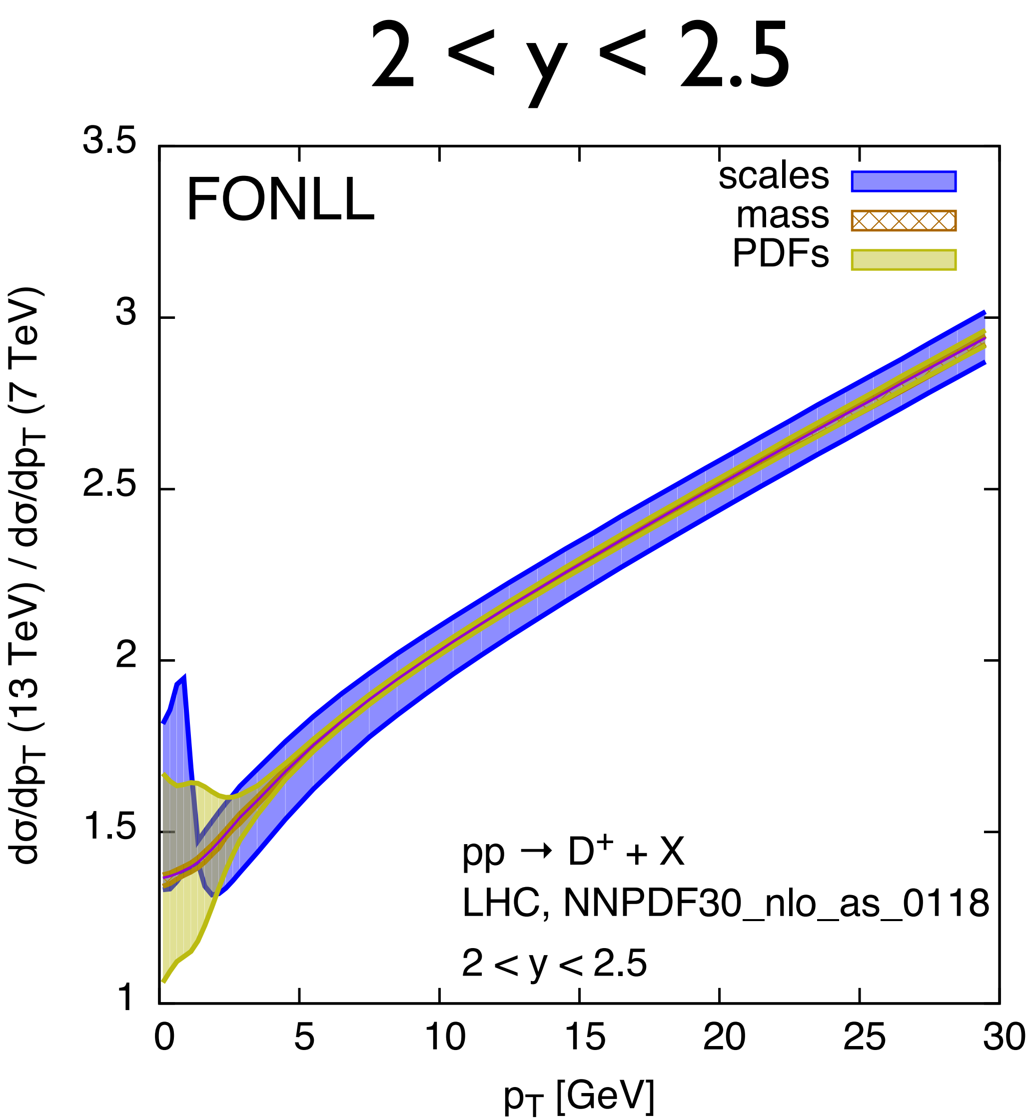
MC, Mangano, Nason 1507.06197

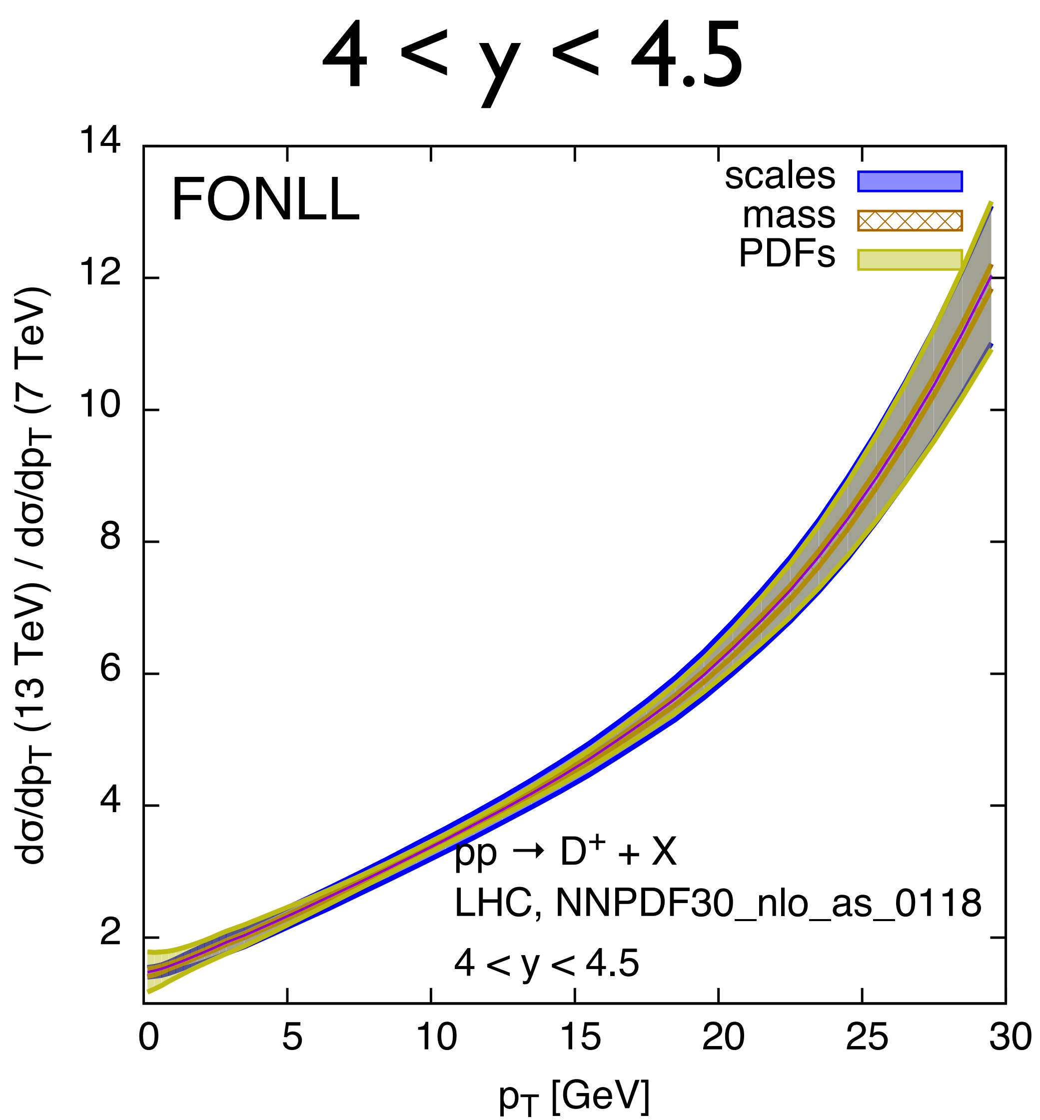


Uncertainty dominated by scale dependence

Charm production at 7 and 13 TeV

MC, Mangano, Nason 1507.06197

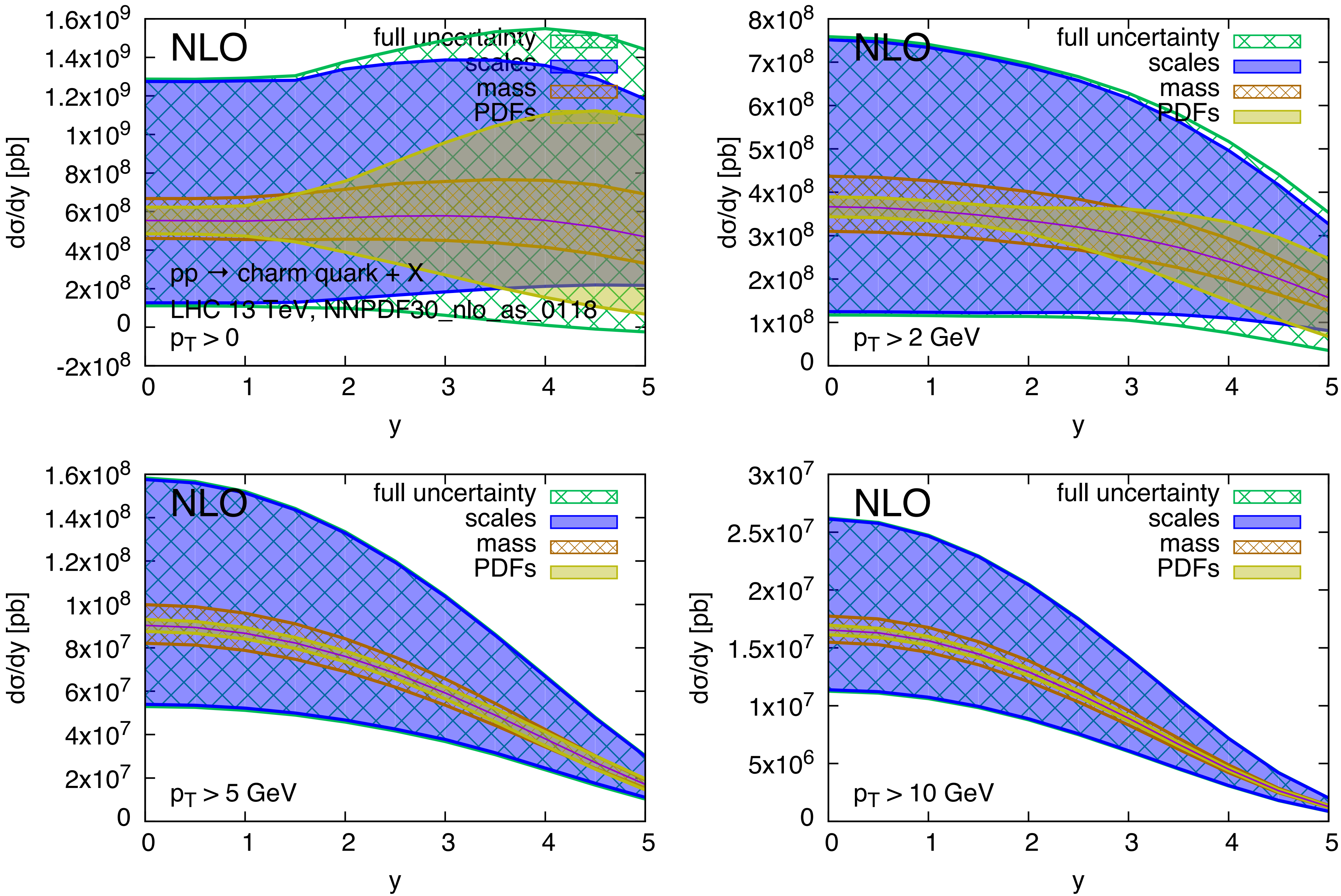




Uncertainty largely dominated by scale dependence,
except forward at very small and quite large transverse momentm

Charm rapidity distribution

MC, Mangano, Nason 1507.06197



Charm rapidity distribution

Charm rapidity distribution largely dominated by scale uncertainties.

Strategies to reduce these systematics:

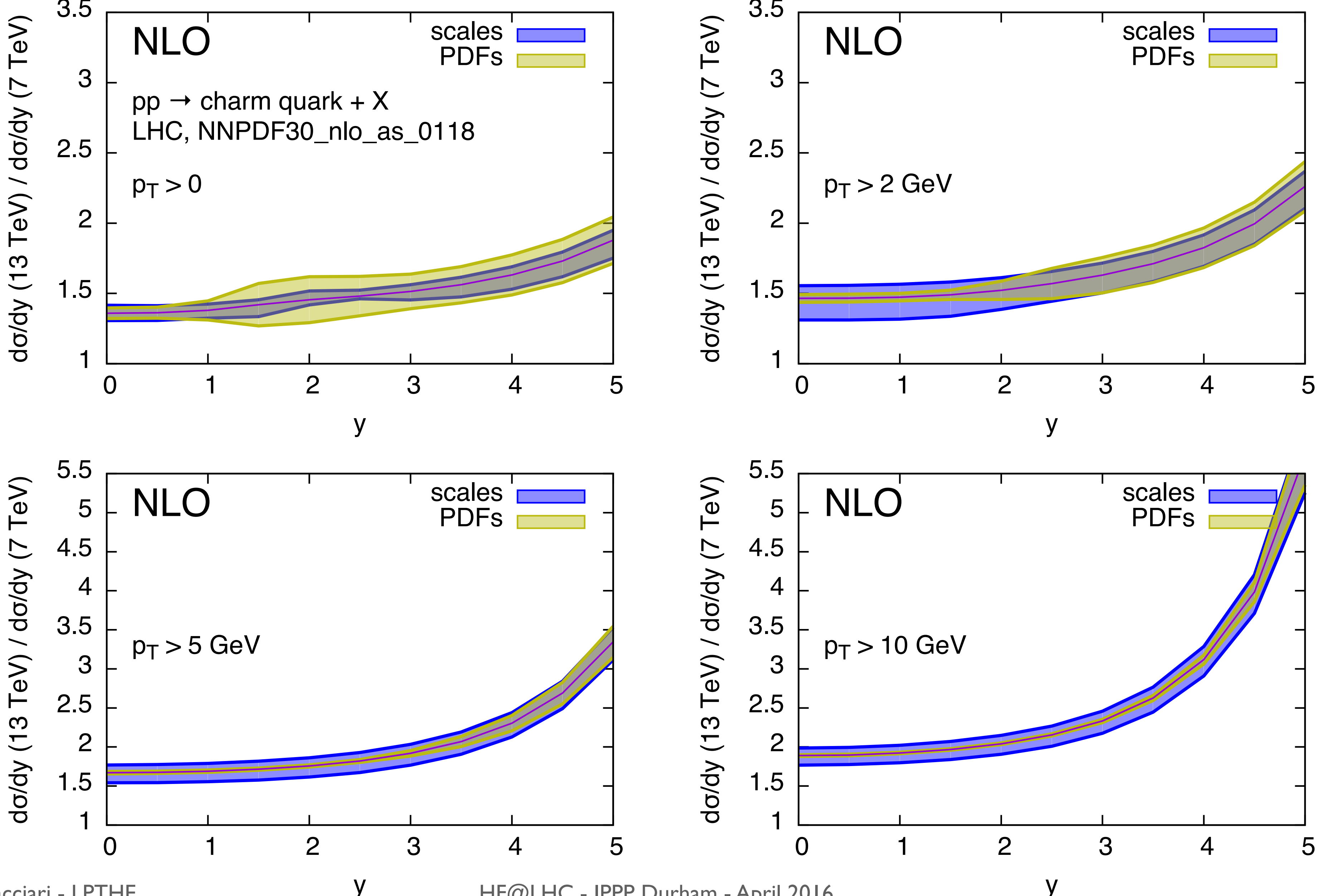
assume scale dependence correlated, normalize to a given rapidity bin and/or take ratios of different centre of mass energies (e.g. 13 TeV / 7 TeV)

(see also PROSA Collab. 1503.04581 and Gauld et al. 1506.08025)

Charm rapidity ratios

MC, Mangano, Nason 1507.06197

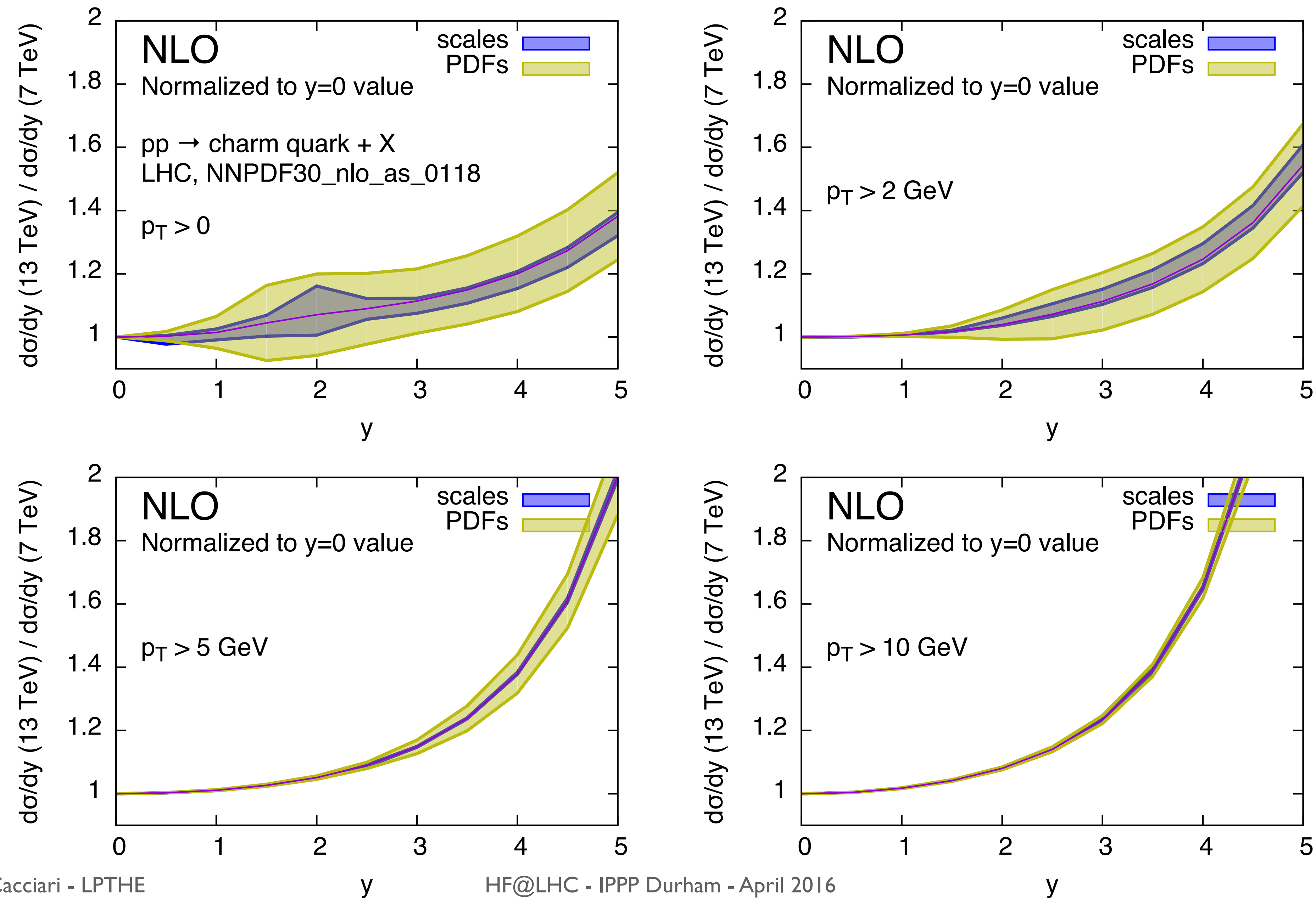
dσ/dy (13 TeV) / dσ/dy (7 TeV)



Normalized charm rapidity ratios

MC, Mangano, Nason 1507.06197

[dσ/dy (13 TeV) / dσ/dy (7 TeV)] normalized to y=0



Conclusions

- Most ingredients in place to go to NNLO+NNLL accuracy for total cross sections and relevant distribution. NNLO+NLL should be sufficient for most purposes though.

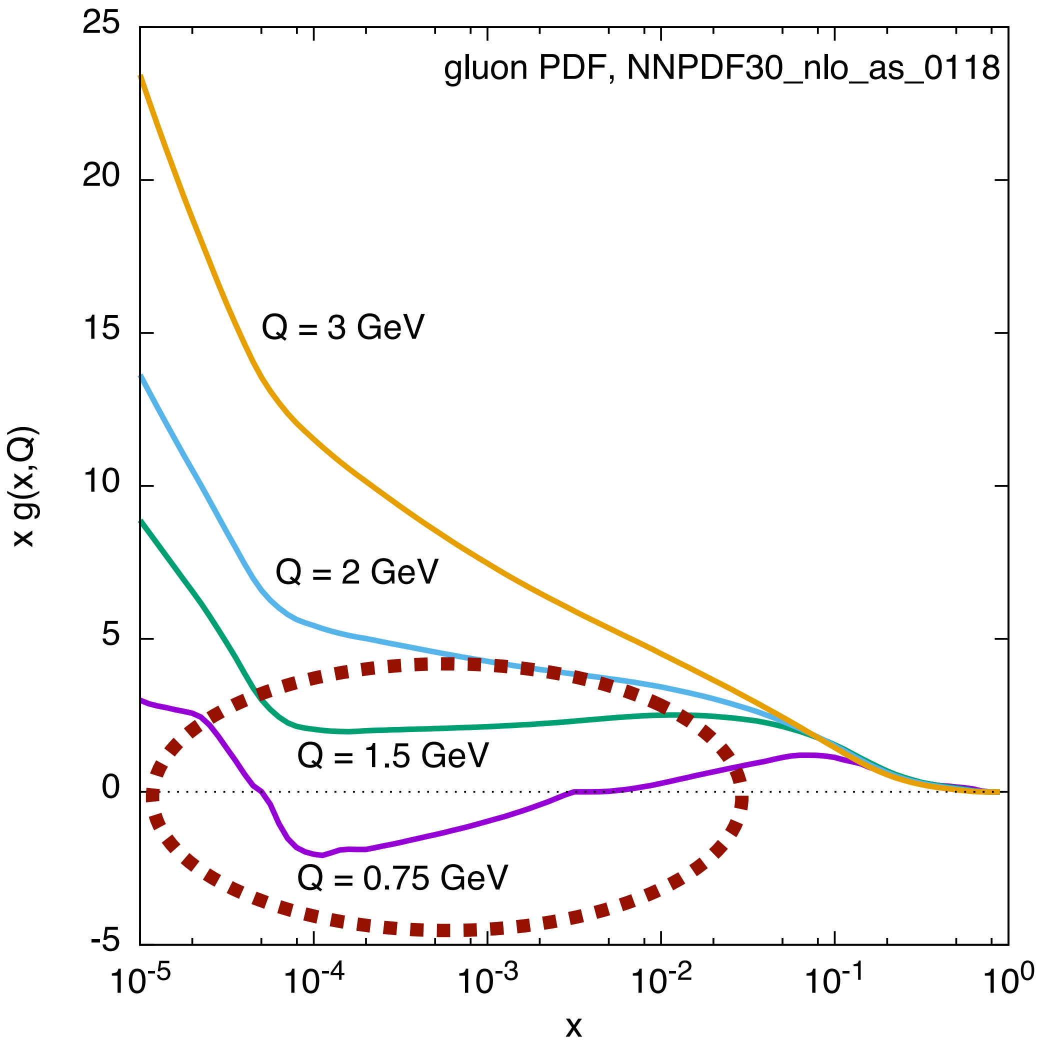
- A major step forward will be fast and reliable codes for NNLO distributions

- Charm and bottom production at large rapidity, suitably normalized, may be used to constrain PDFs

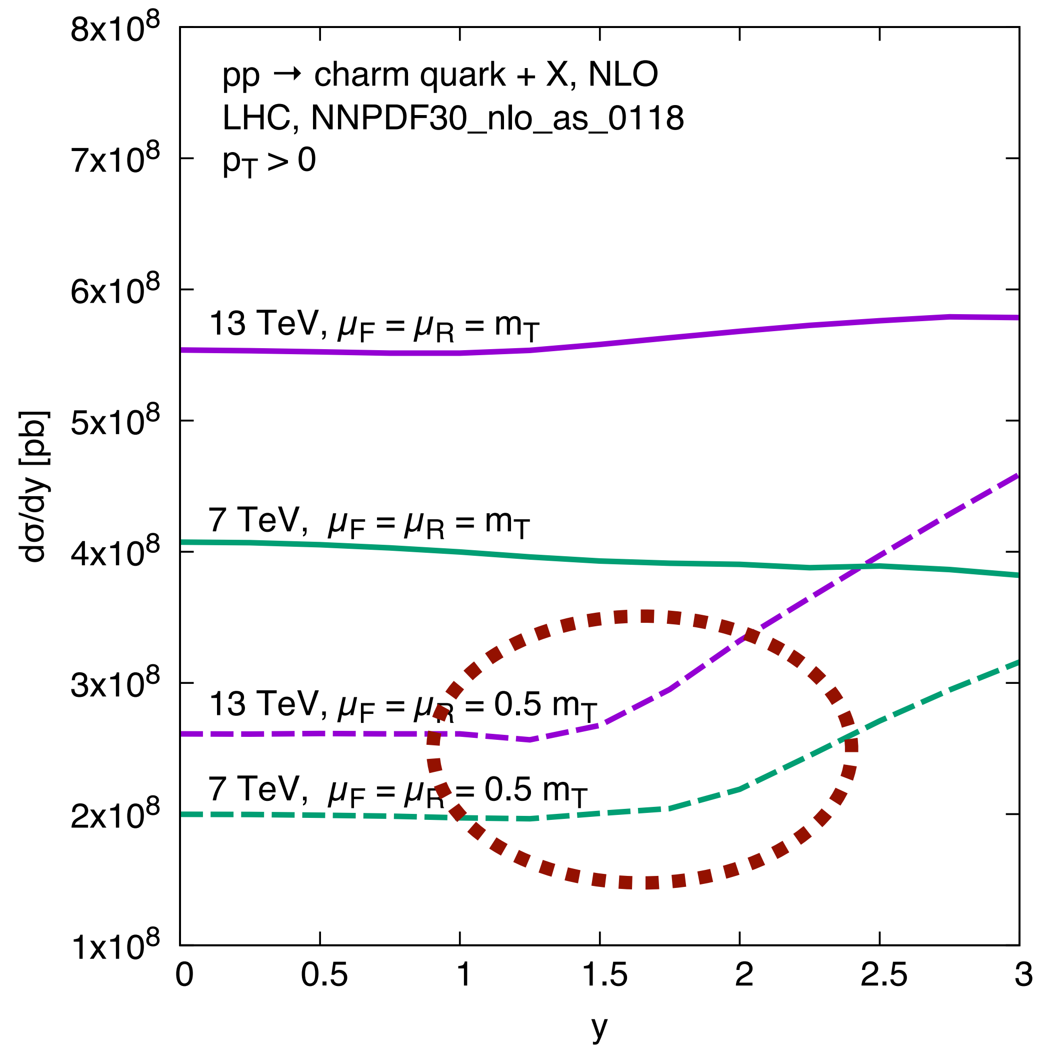
Backup

Mismatch at y ~ 2

Gluon PDF at small Q and smallish x

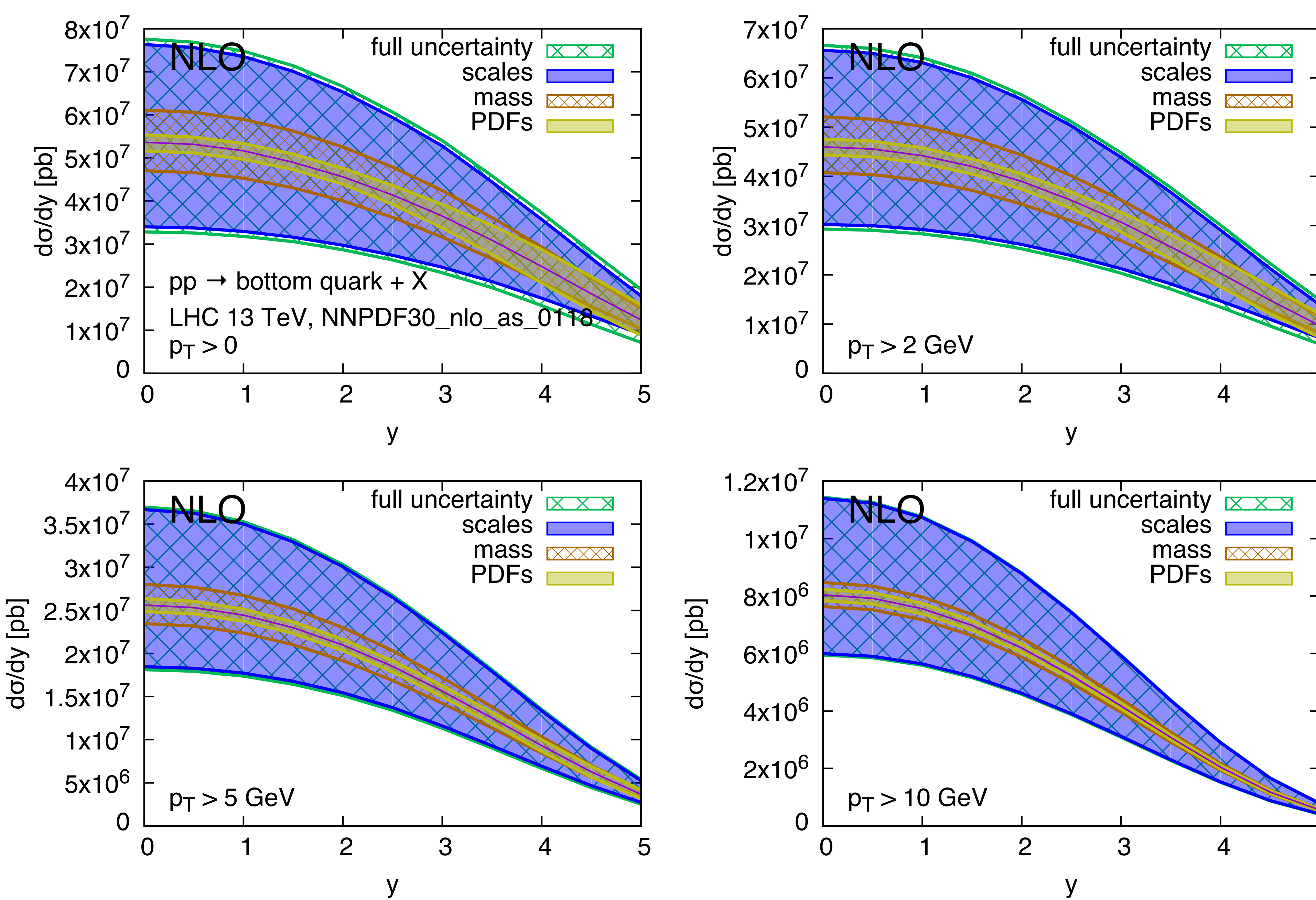


Charm dσ/dy



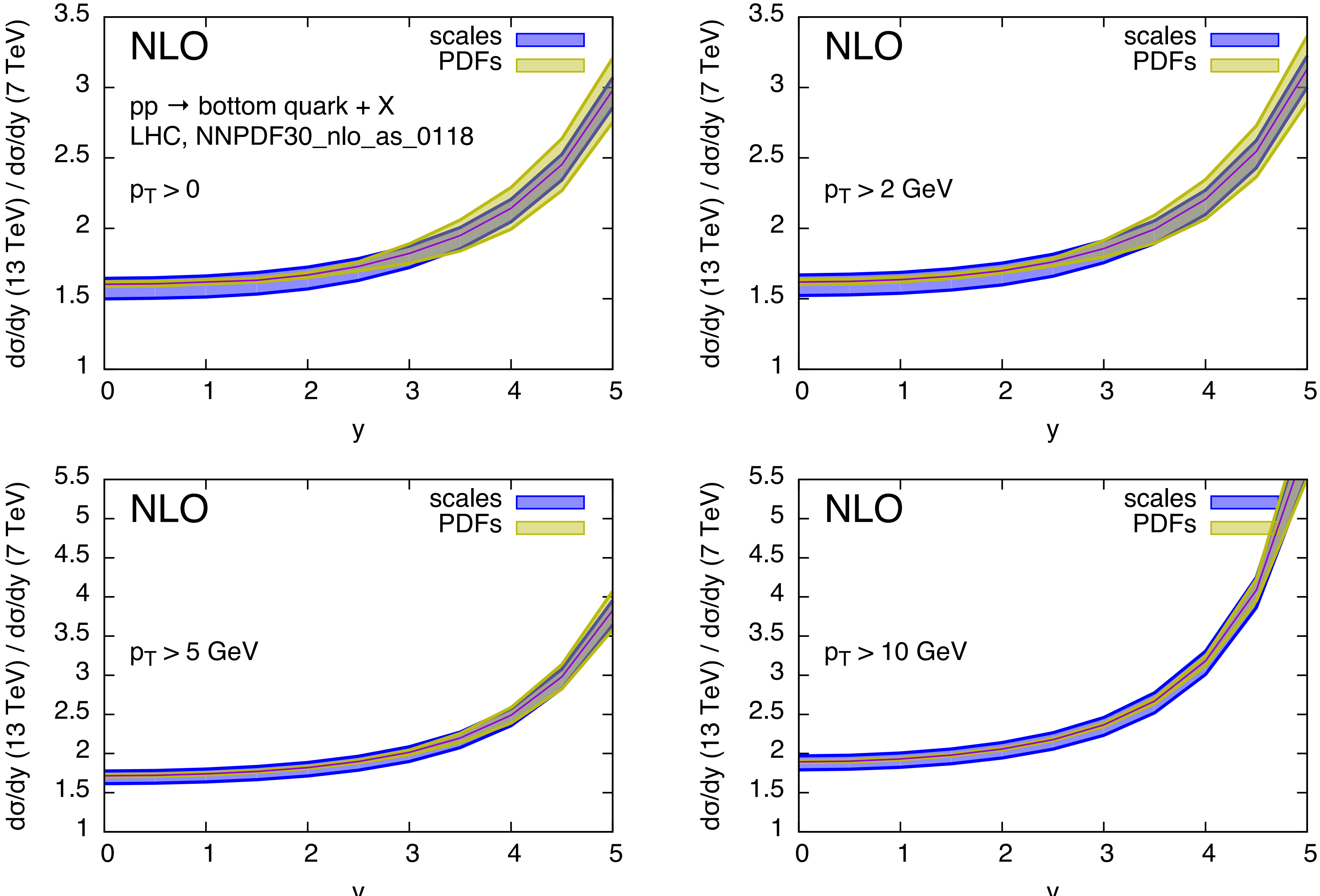
Bottom rapidity distribution

MC, Mangano, Nason 1507.06197



Bottom rapidity ratios

MC, Mangano, Nason 1507.06197



Normalized bottom rapidity ratios

MC, Mangano, Nason 1507.06197