Theoretical aspects of charm and bottom production at the LHC, in view of the most recent results

XII Franco-Italian B physics Workshop:
Tensions in flavour measurements
Napoli, May 22-24 2017

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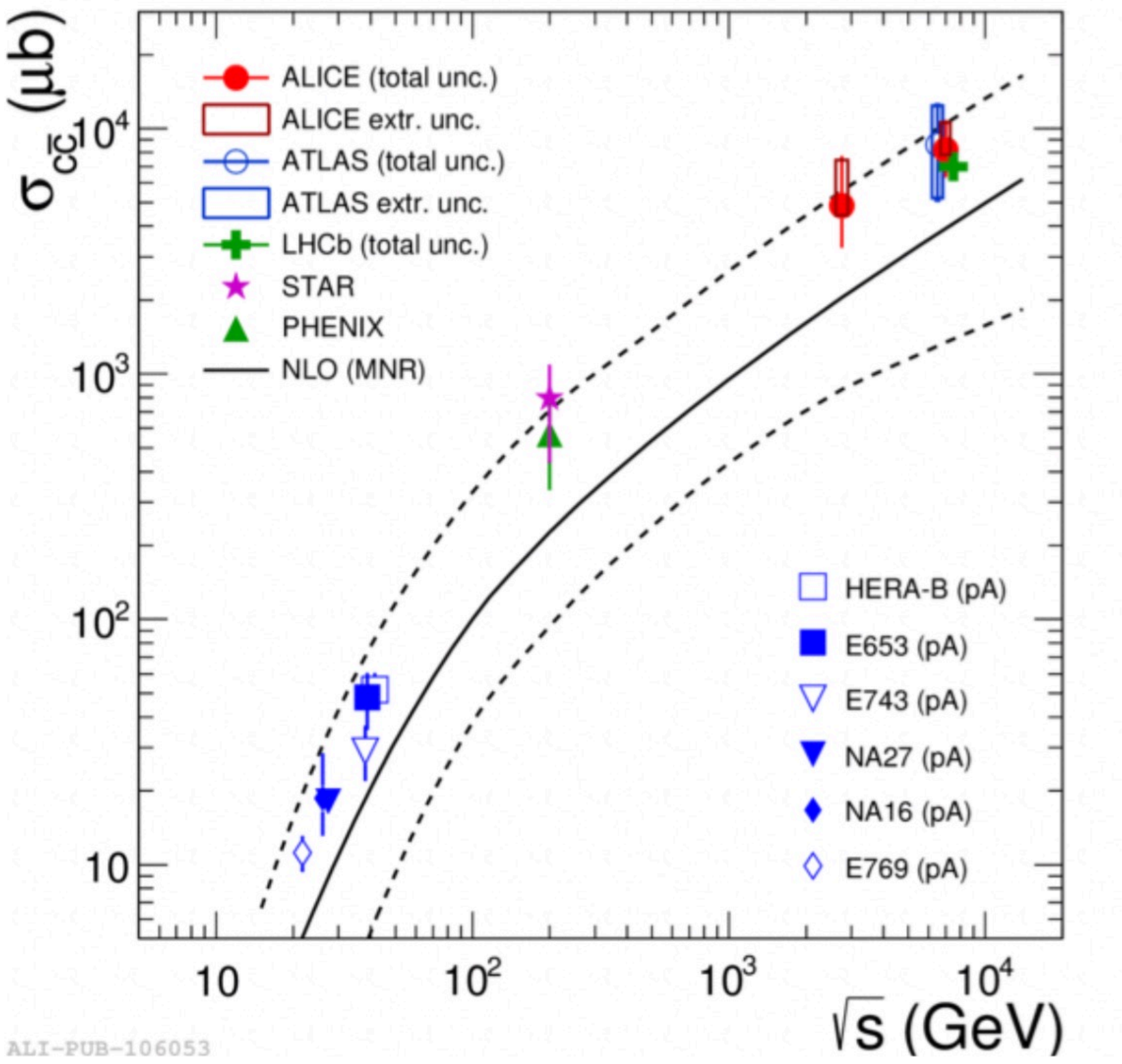
Charm-pair production from fixed target to LHC

[Phys. Rev. C 94 (2016) 054908]



- why should we even bother discussing a “theory” that has a factor of 10 uncertainty??
- why should experiments even bother doing these measurements? what are they testing? what are we learning?

obvious answer to 2nd bullet (“why measure”):

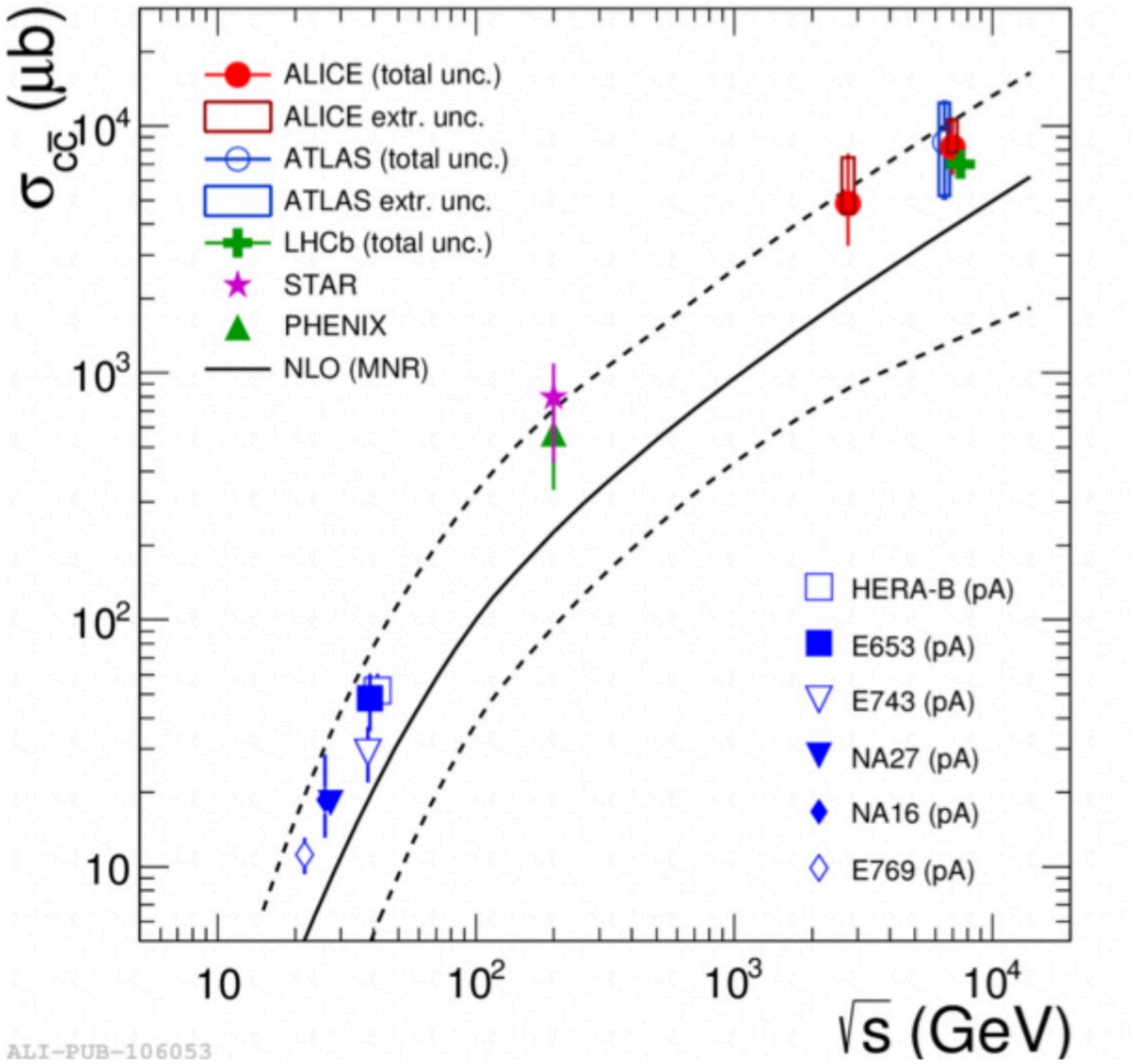
- expt’s don’t need theorists, they shouldn’t care if there is a theory, they must explore how Nature works, and tell us!
- hvq production plays a key role in addressing a series of fundamental questions, which the LHC was built to address
  - studies of the Higgs properties (H identification through its **bb** final state is hostage to large QCD **bb** bg’s)
  - QGP (comparison of hvq production in pp vs pA vs AA)
  - CPV ($pp \to B^- \neq pp \to B^+$ pollutes CP asymmetries)
- but also relevant in other fields, e.g. cosmic rays ($c \to \nu$ major source of HE νs in ICEcube)

TH is not needed here, the expt’s can figure things out themselves, but it helps (eg export bg estimates from control samples to signal samples)!

As for the first issue (ie, is there a “theory” worth discussing?):

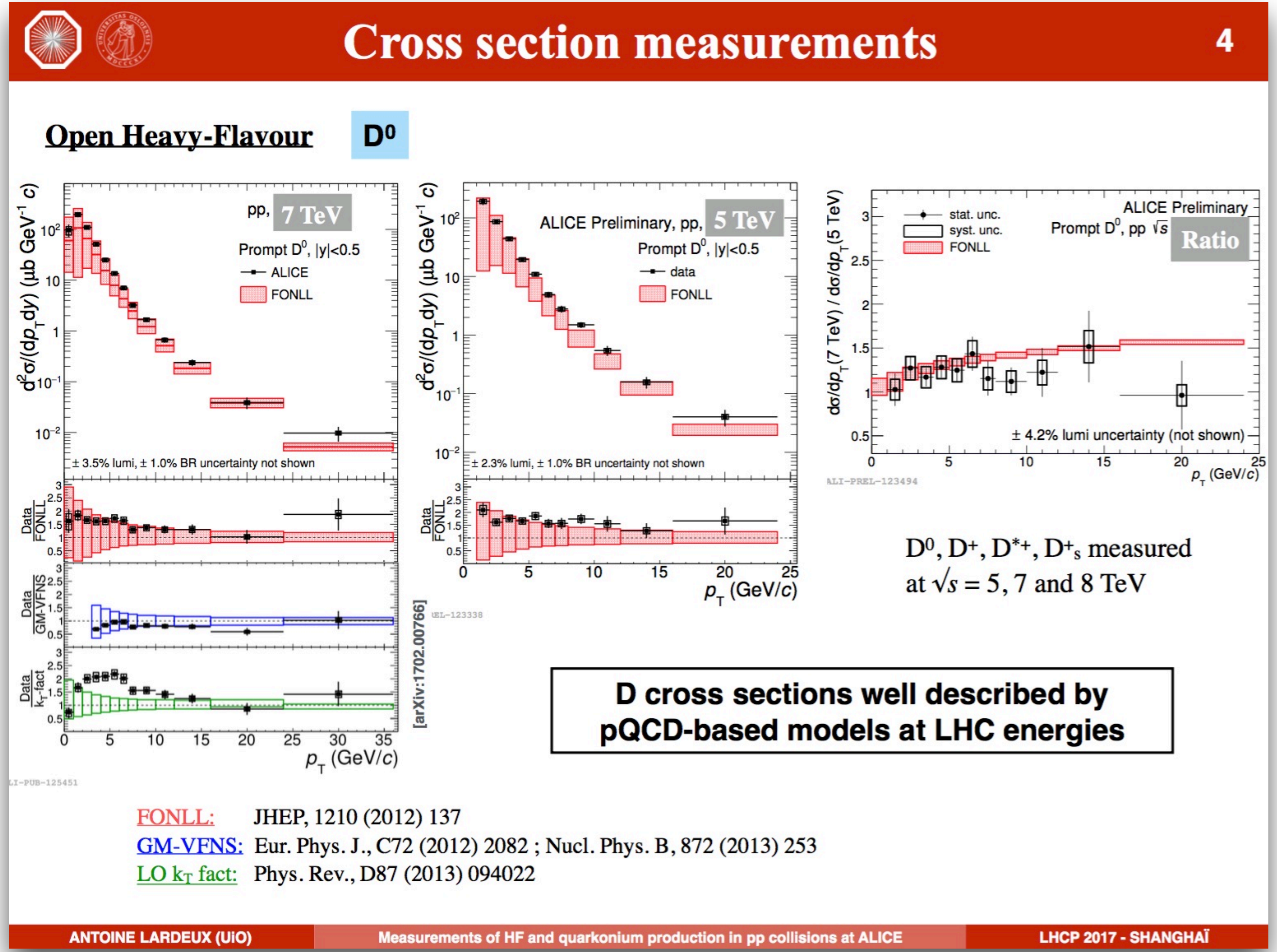
- **hint: strong correlation and consistency in σ_{exp}/σ_{TH} , over 3 orders of magnitude in $\sqrt{S}$**

[Phys. Rev. C 94 (2016) 054908]



and, in general, there is a reasonable agreement between data and theory that goes beyond total rates

Exclusive D^0 decays



Cross section measurements

4

Open Heavy-Flavour D^0

D^0, D^+, D^{*+}, D^+_s measured at $\sqrt{s}$ = 5, 7 and 8 TeV

D cross sections well described by pQCD-based models at LHC energies

FONLL: JHEP, 1210 (2012) 137
GM-VFNS: Eur. Phys. J., C72 (2012) 2082 ; Nucl. Phys. B, 872 (2013) 253
LO k_T fact: Phys. Rev., D87 (2013) 094022

ANTOINE LARDEUX (UiO) Measurements of HF and quarkonium production in pp collisions at ALICE LHCP 2017 - SHANGHAÏ

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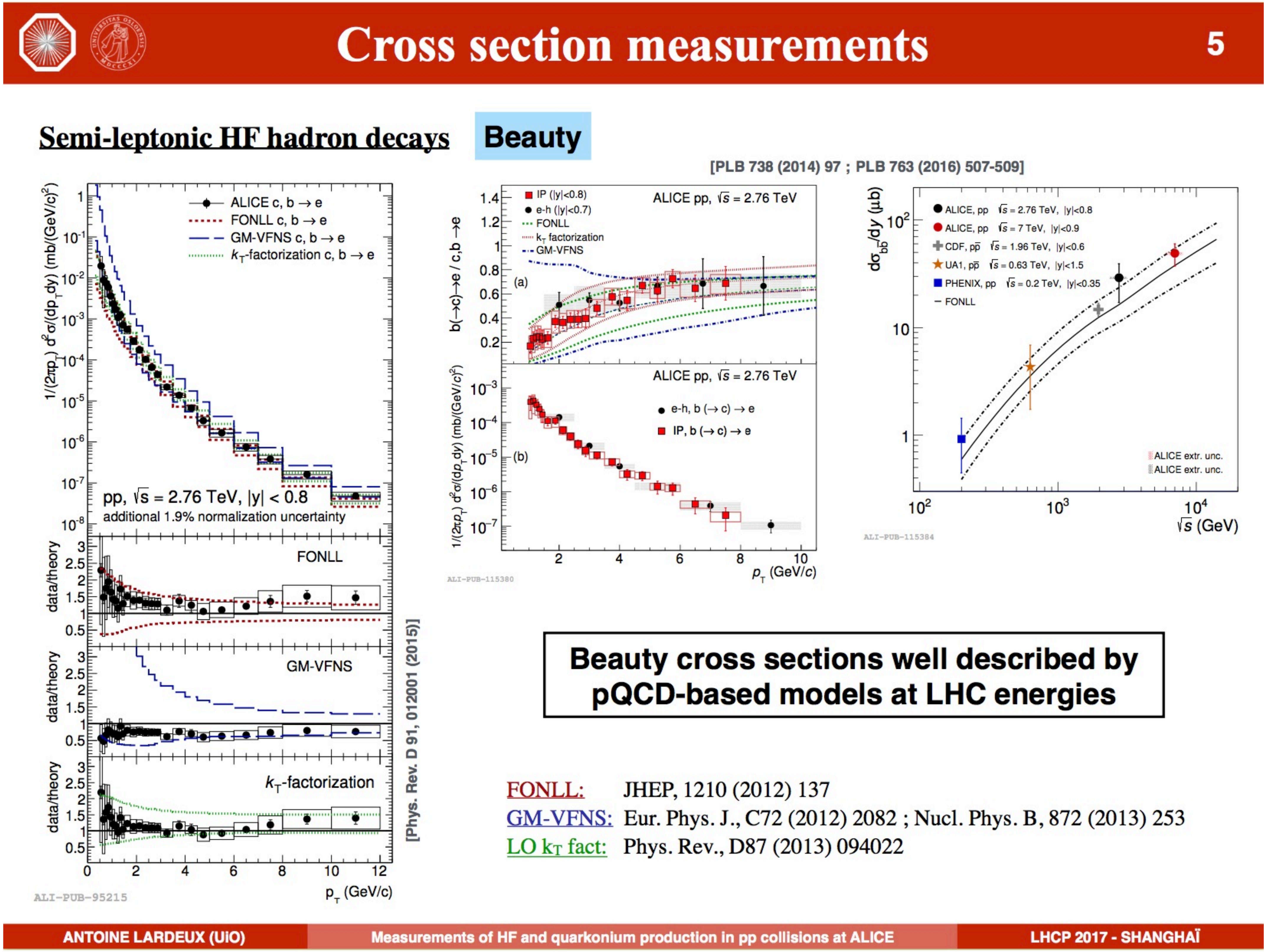
Semileptonic B decays



Cross section measurements

5

Semi-leptonic HF hadron decays

Beauty

[PLB 738 (2014) 97 ; PLB 763 (2016) 507-509]

[Phys. Rev. D 91, 012001 (2015)]

Beauty cross sections well described by pQCD-based models at LHC energies

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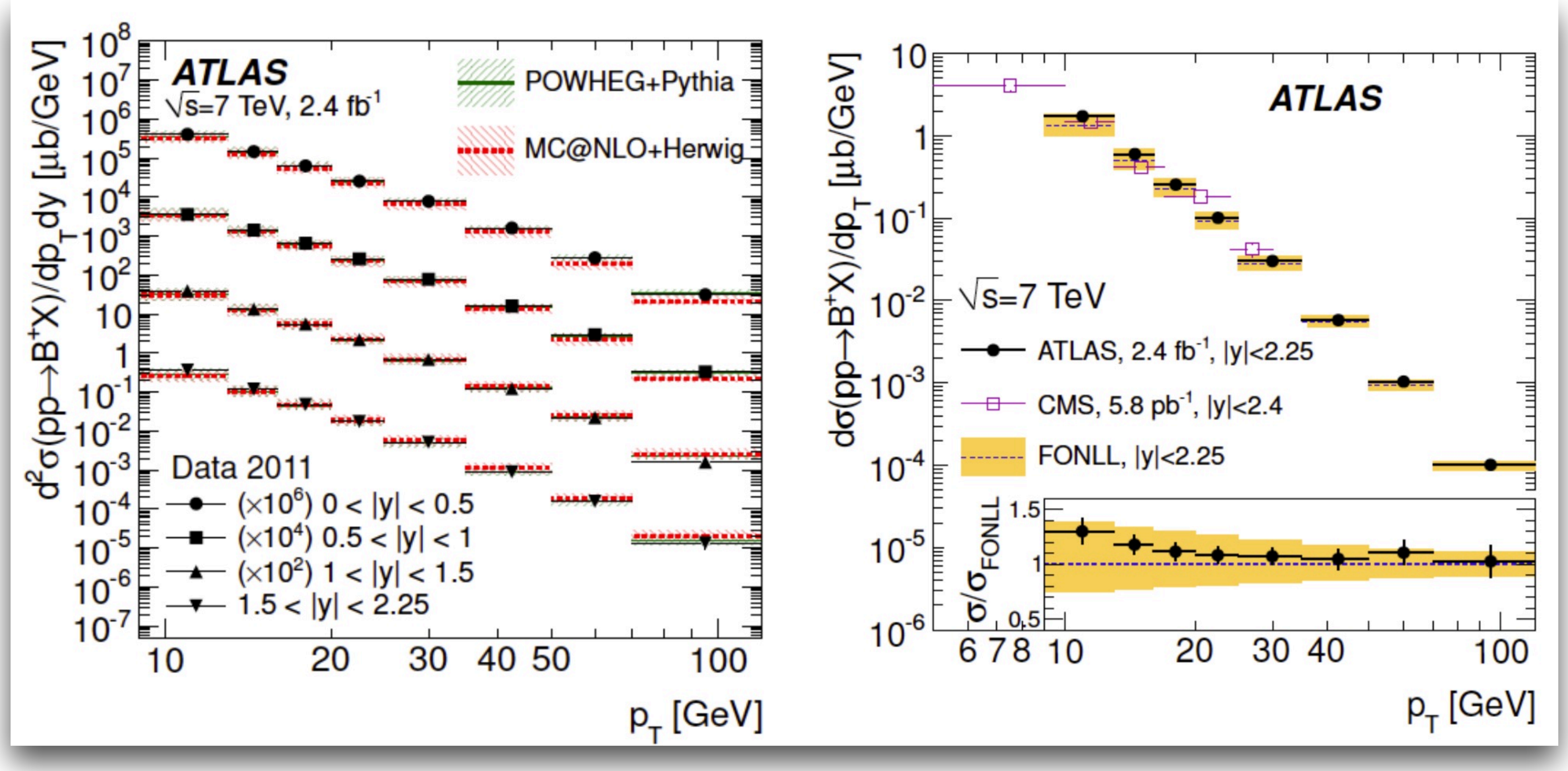
Exclusive $B^+ \to J/\psi\ K^+$ decays



ATLAS, JHEP 10(2013)042

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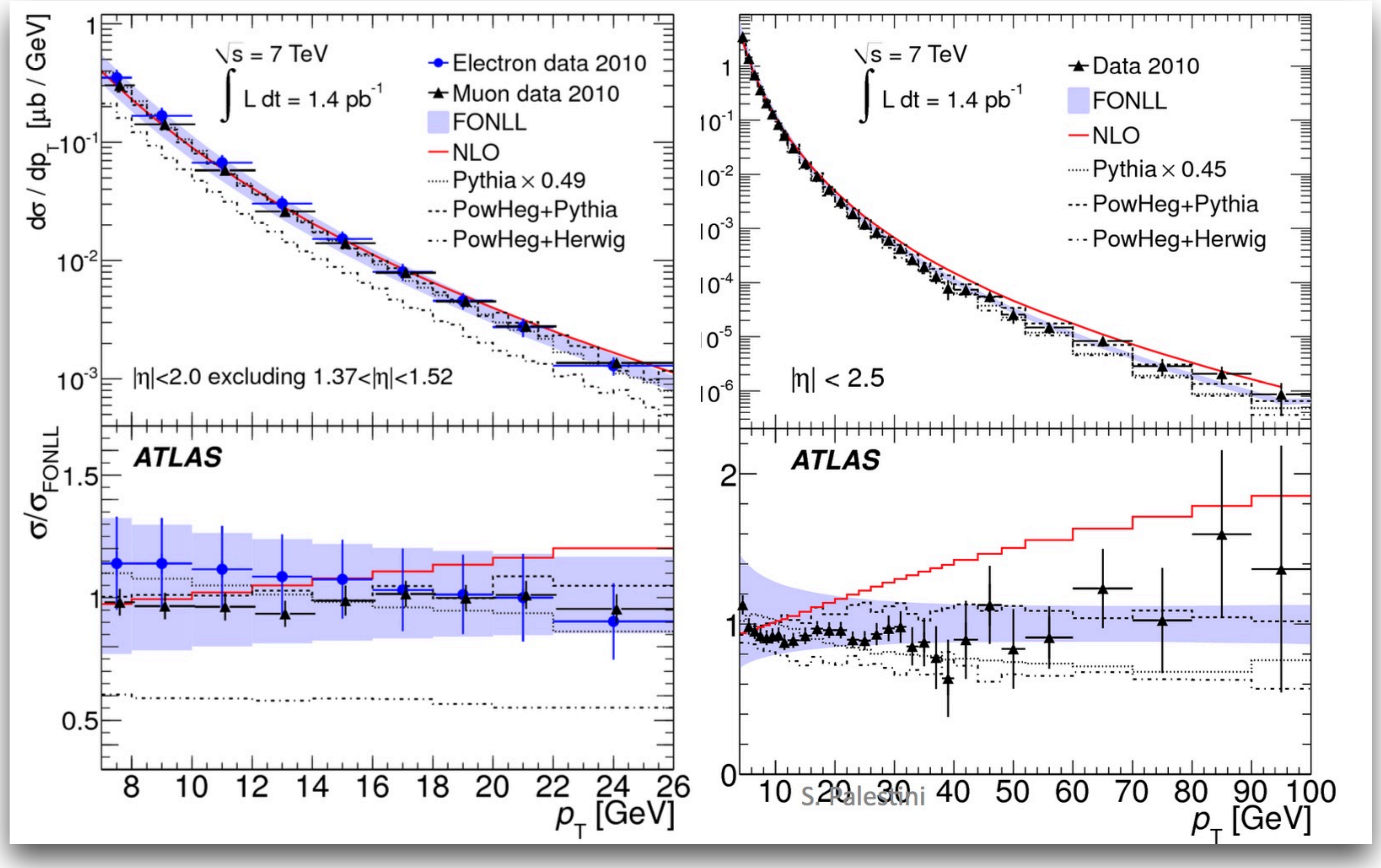
Inclusive SL b decays



ATLAS, Phys.Lett.B797(2012)438

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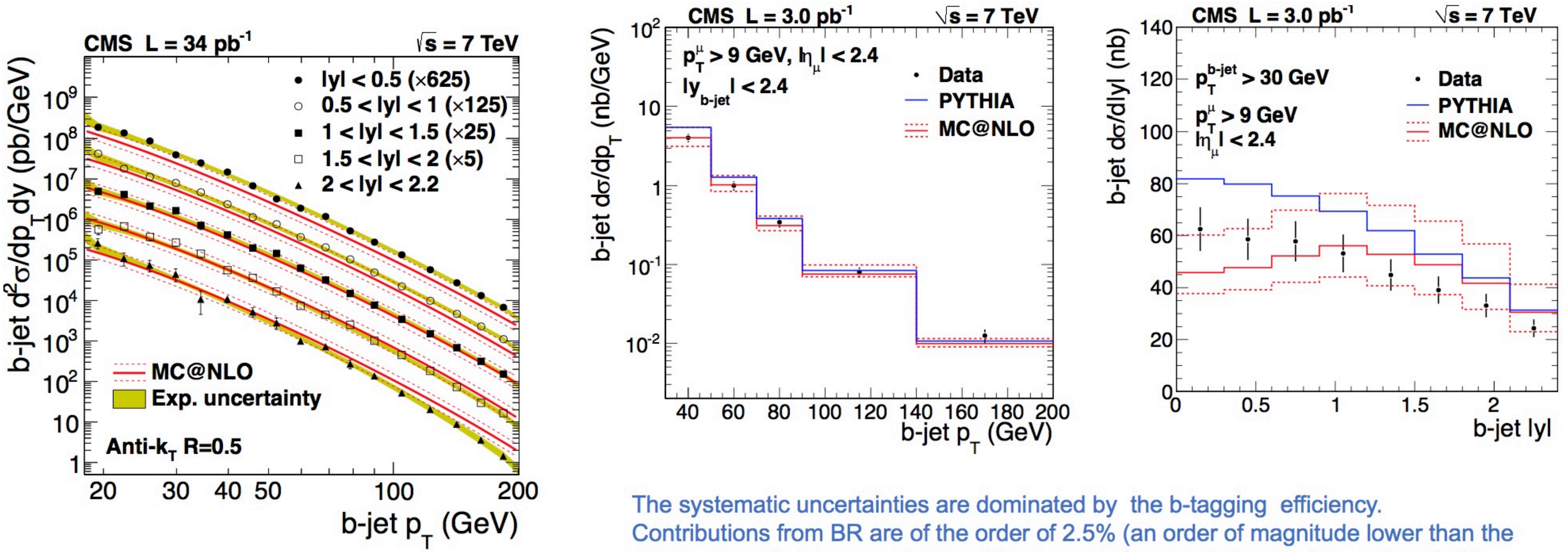
b-jets



The systematic uncertainties are dominated by the b-tagging efficiency. Contributions from BR are of the order of 2.5% (an order of magnitude lower than the dominant one). The uncertainty of the b-quark fragmentation is of the order of 4%

CMS, J. High Energy Phys. 04 (2012) 084

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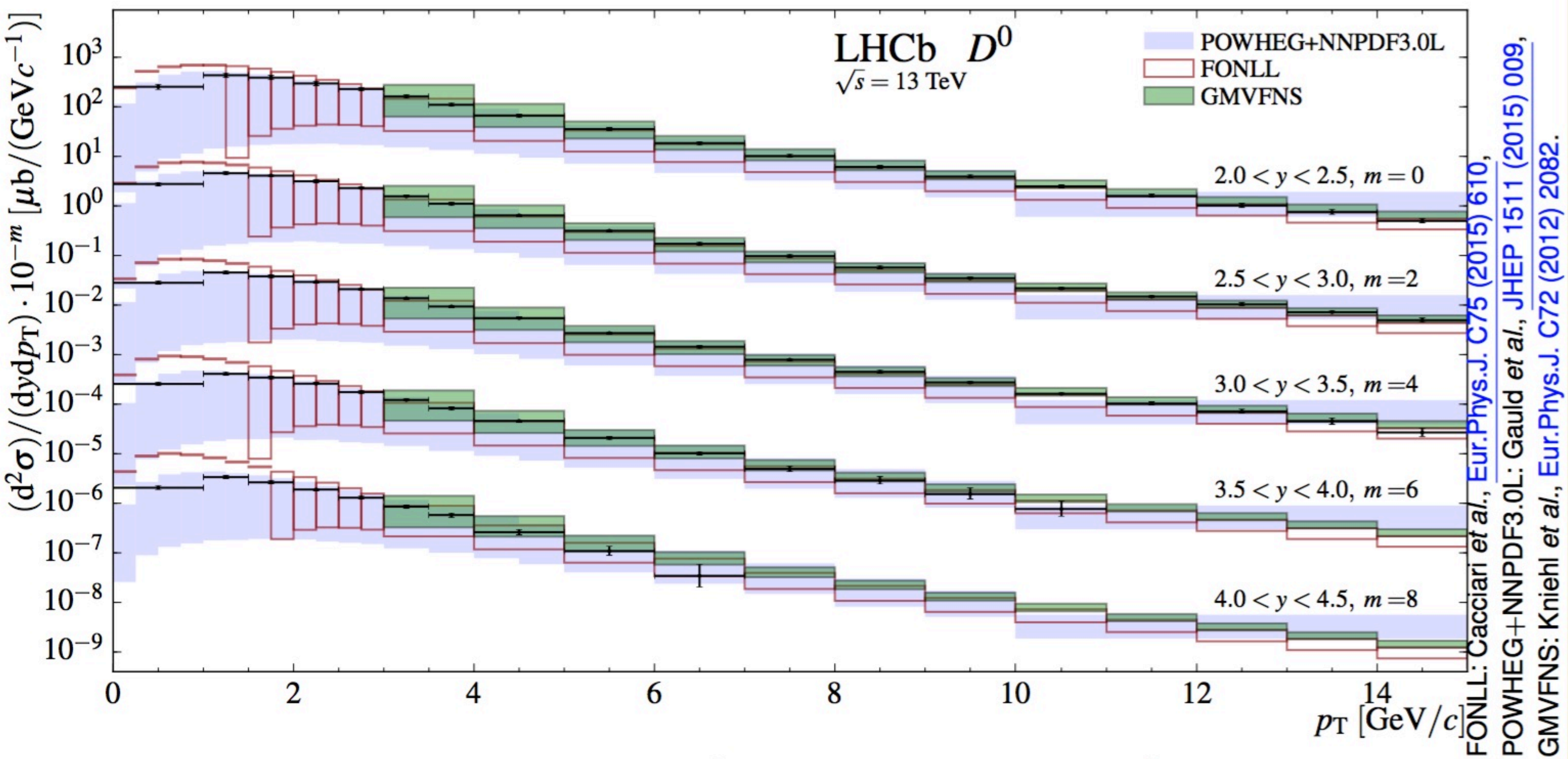
D^0 production at foward rapidity



Double differential cross-sections, $d^2\sigma_i/dp_T dy$, of prompt D^0 vs. p_T.

LHCb, JHEP 1603 159, JHEP 1609 013

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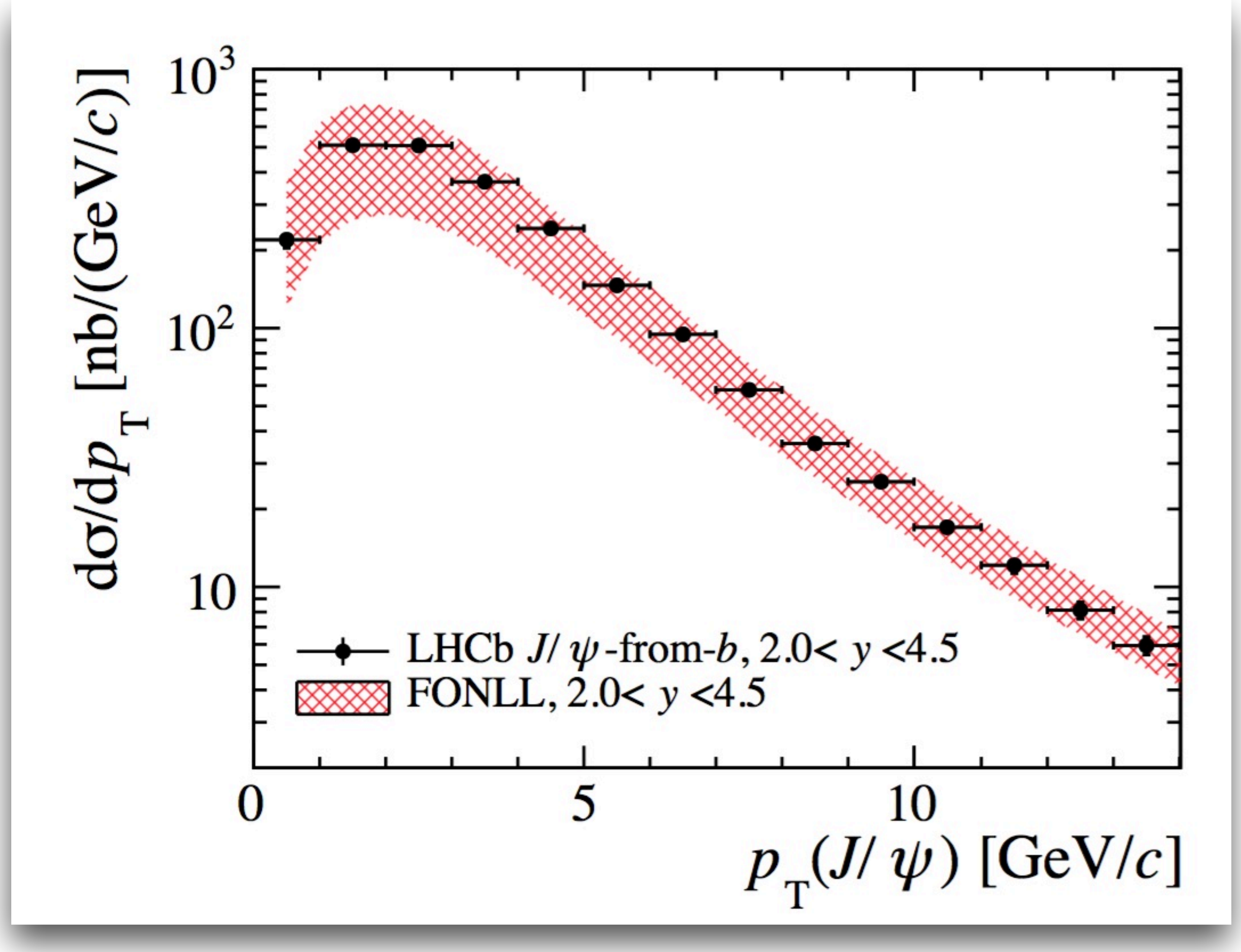
Inclusive B→J/ψ X decays at forward rapidity



FONLL: Cacciari et al., EPJ C75 (2015) 12, 610

LHCb, JHEP 1510 (2015) 172

the TH challenges

- identify observables that can be reliably predicted, pushing precision to the % level
- identify important measurements that can benefit from increased precision
- contribute to the reduction of systematics, related to production uncertainties, which may influence the precision of flavour-physics measurements
- …. and continue investing in trying to improve !!

ultimately, there is also the pleasure of cracking difficult dynamical problems, at the border between perturbative and non-perturbative QCD, and learning more about the complex underlying mechanisms at play in hadron collisions ….

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- NNLO for hvq pair hadroproduction available, also for b and c total rates, but still unsuitable for differential distributions

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- Key ingredient is the **correlation** between theoretical systematics at different beam energies and across the rapidity range:
  - m_Q is obviously fully correlated
  - QCD scale variations: correlated at any given p_T value
  - PDFs: fully correlated, but probing different x at different $\sqrt{S}$
  - BRs, fragmentation fractions and frag functions fully correlated

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  - BRs, fragmentation fractions and frag functions fully correlated
- At this time, we need to build confidence that our assumptions about theoretical systematics are robust

Key references to recent TH work exploring these ideas

- Charm production in the forward region: constraints on the small-x gluon and backgrounds for neutrino astronomy. R.Gauld et al. arXiv:1506.08025
- [CMN] Gluon PDF constraints from the ratio of forward heavy-quark production at the LHC at root(S)=7 and 13 TeV, M.Cacciari M.Mangano and P.Nason, arXiv:1507.06197
- Impact of heavy-flavour production cross sections measured by the LHCb experiment on parton distribution functions at low x, PROSA Collaboration (Zenaiev et al.), arXiv:1503.04581
- Prompt neutrino fluxes in the atmosphere with PROSA parton distribution functions (Garzelli et al), arXiv:1611.03815
- [GR] Precision determination of the small-x gluon from charm production at LHCb, R.Gauld and J.Rojo, arXiv:1610.09373
- [GMS] Lepton fluxes from atmospheric charm revisited, Grazielli, Moch, Stigl, arxiv:1507.01570
- [G] Understanding forward B-hadron production, R.Gauld, arxiv:1703.03636

Sources of TH syst's for charm XS's at 13 TeV

[CMN]

$10^8 \rightarrow 12\text{x}10^8$

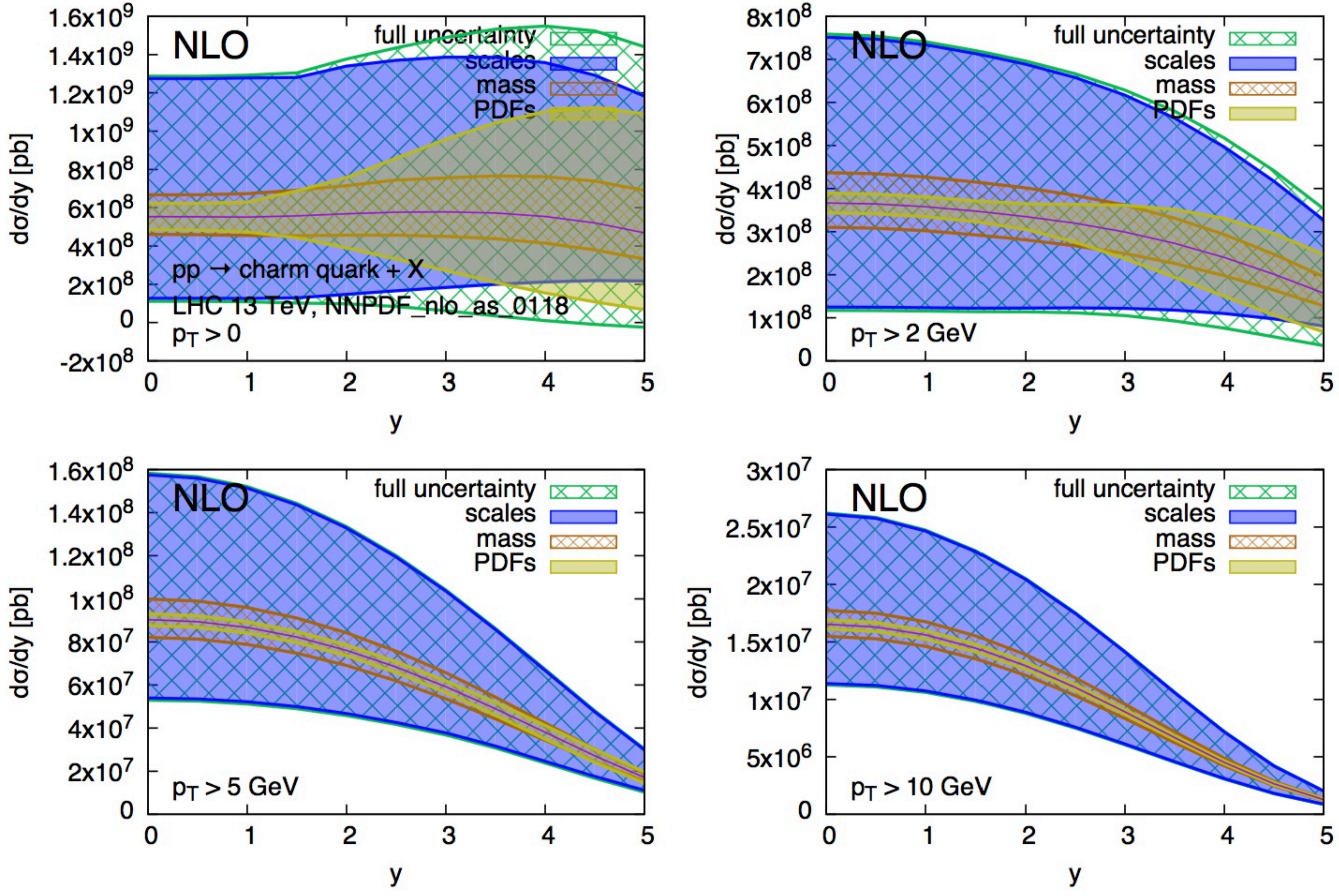


Figure 2: Charm quark rapidity distributions at $\sqrt{S} = 13$ TeV.

Rates normalized to central value

[CMN]

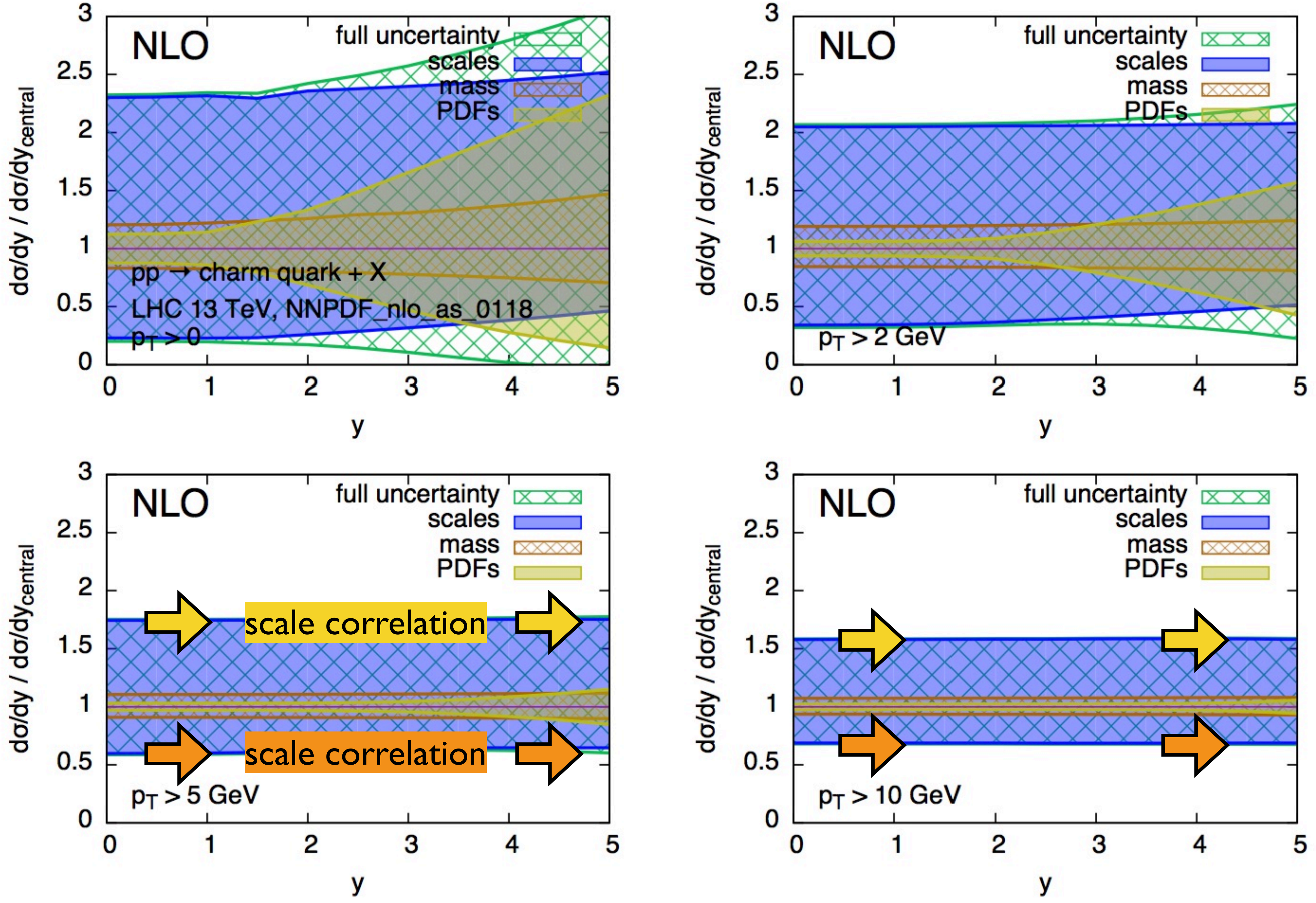
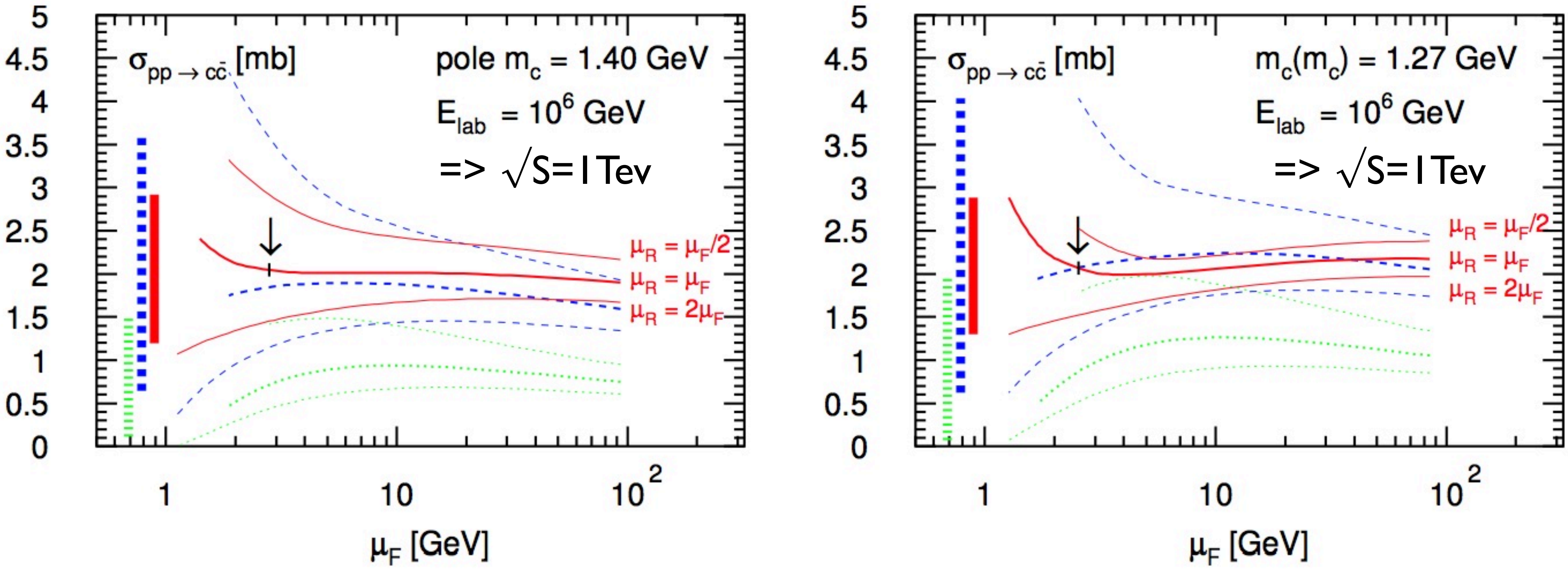


Figure 4: Charm quark rapidity distributions at $\sqrt{S} = 13$ TeV, normalised to the central theoretical prediction.

LO vs NLO vs NNLO scale dependence

[GMS]

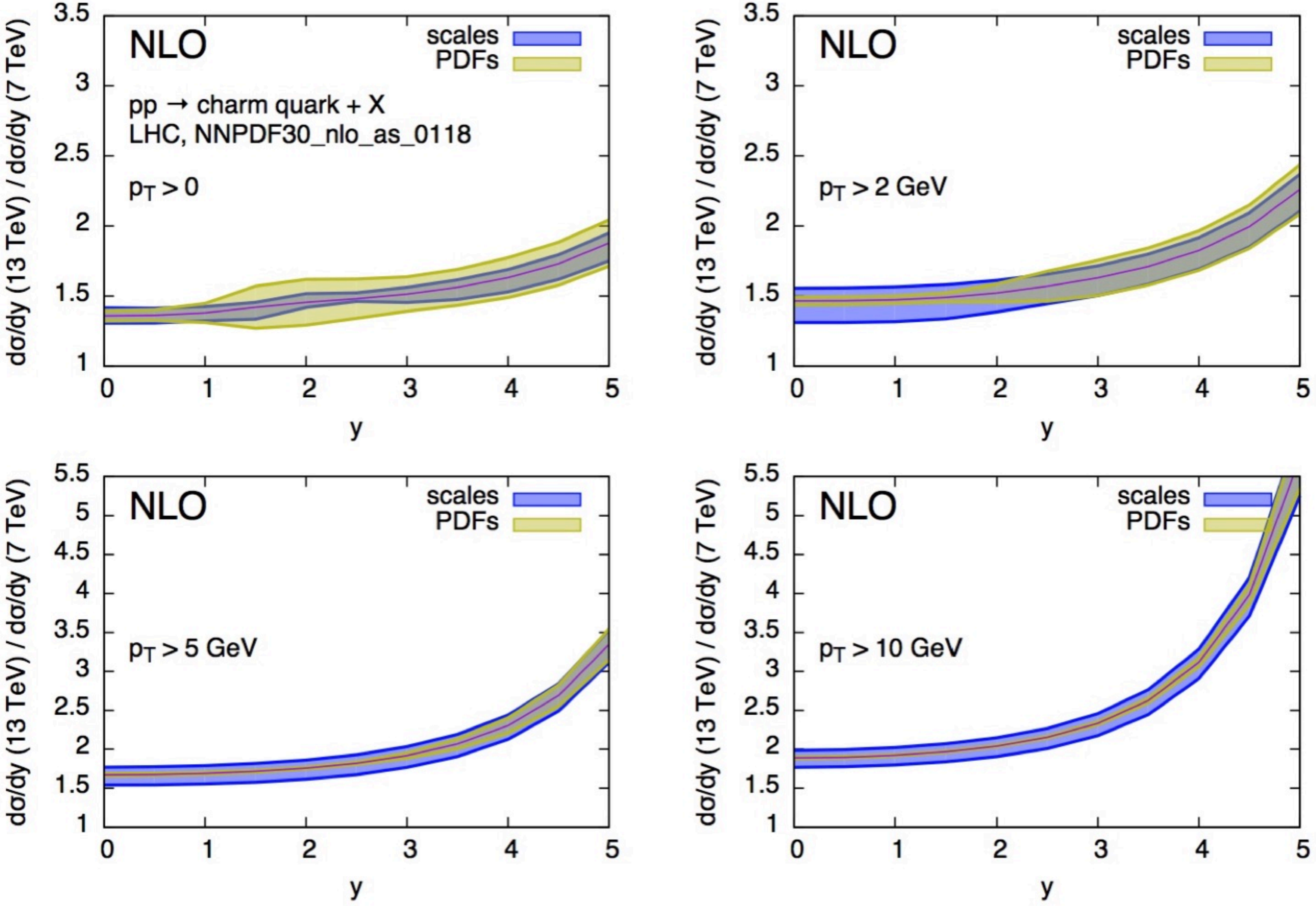


=> $\sqrt{S}$=1Tev

=> $\sqrt{S}$=1Tev

NNLO scale syst reduction important, but still insufficient for high precision **absolute** predictions

Systematics of ratio of charm XS's at 13/7 TeV [CMN]

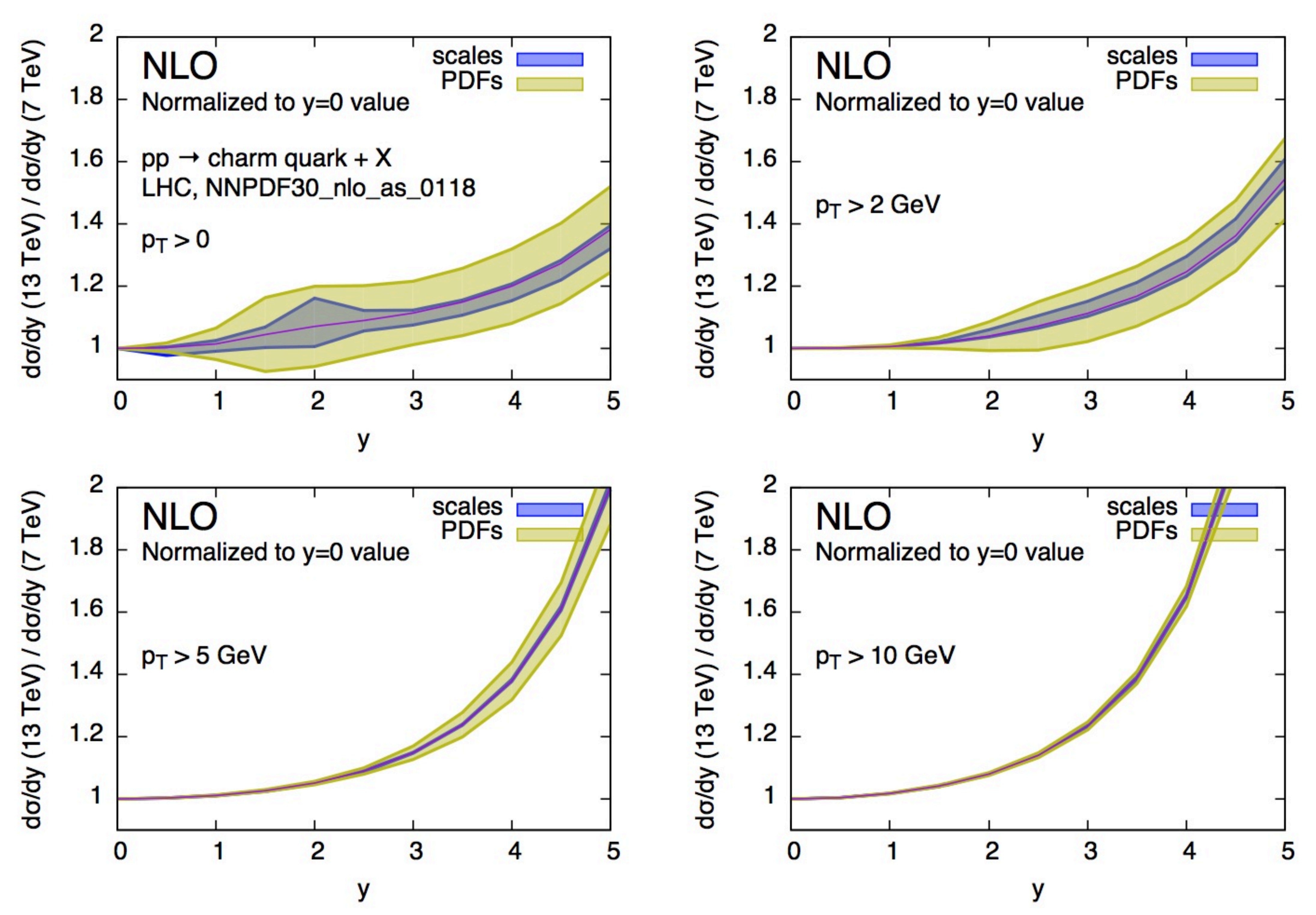


Immense reduction of scale systematics !!

x 10 => ±10%

Systematics of ratio of charm XS's at 13/7 TeV, scaled to ratio at y=0

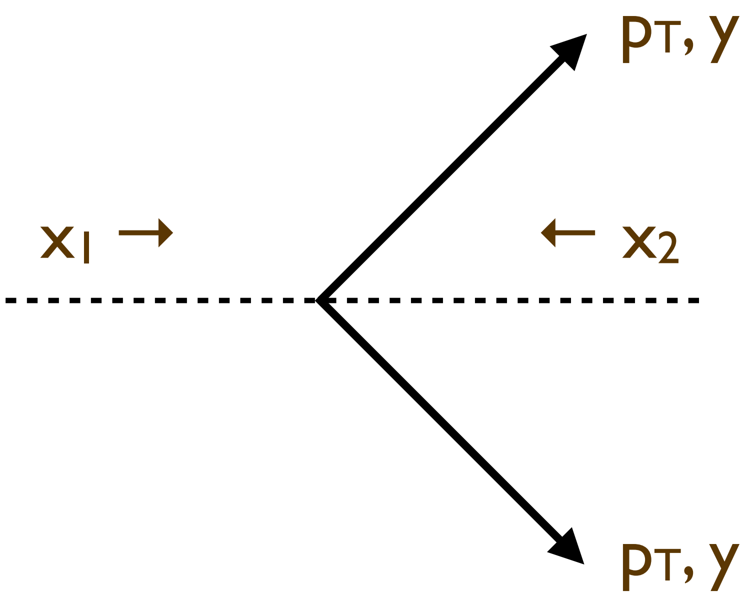
[CMN]



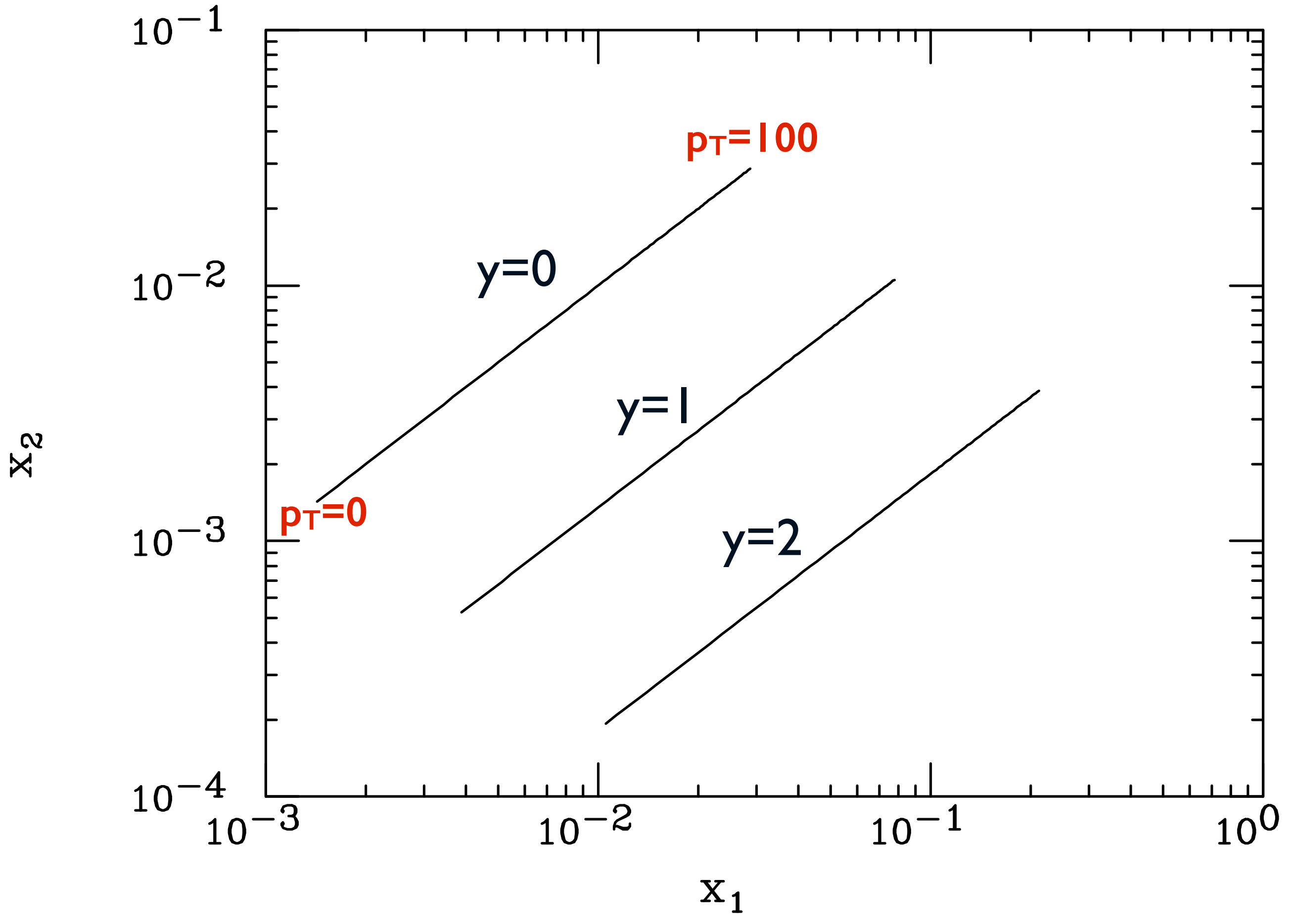
=> all that's left is the PDF systematics!

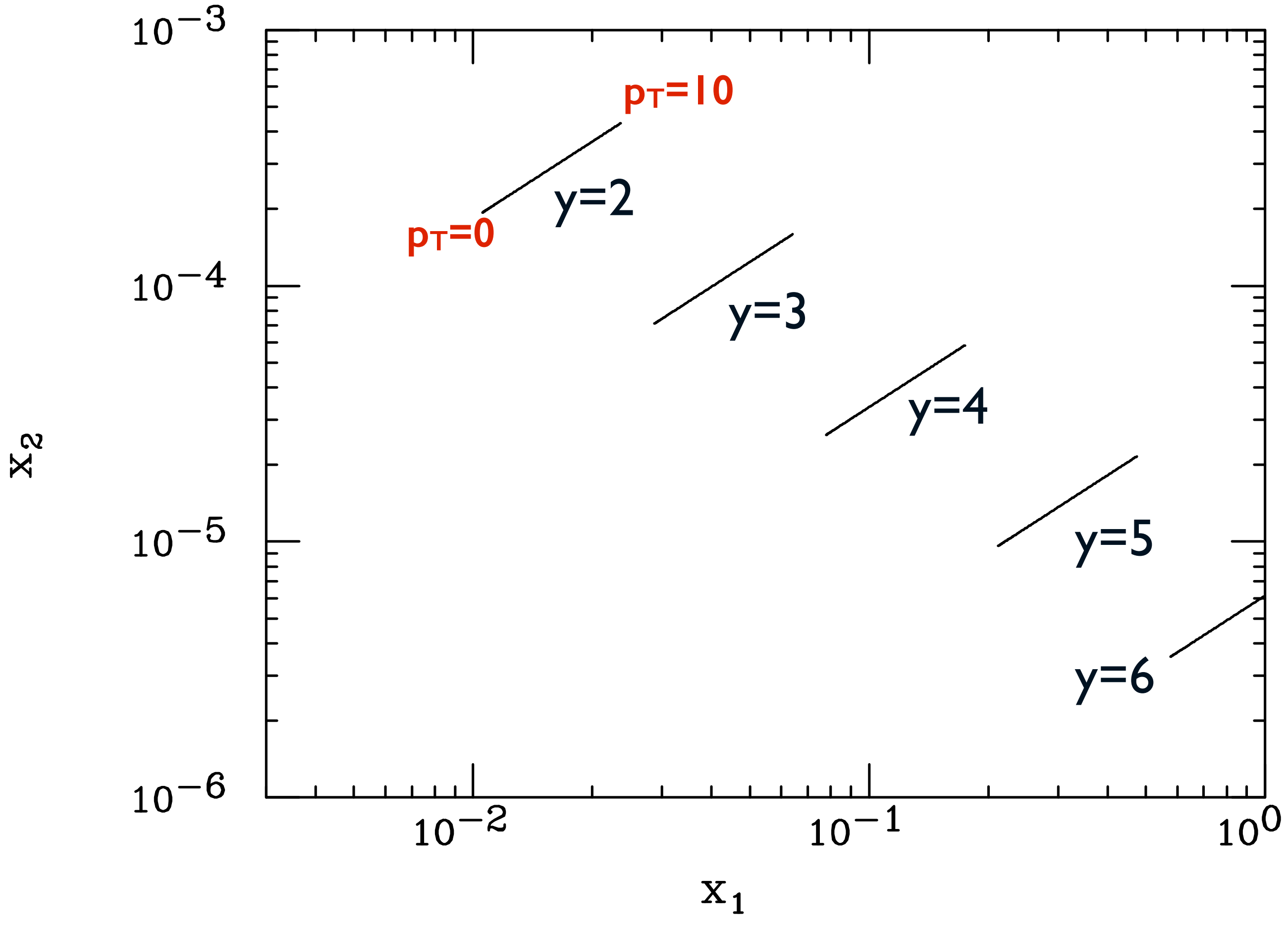
=> useful probe of PDF behaviour!

Event kinematics



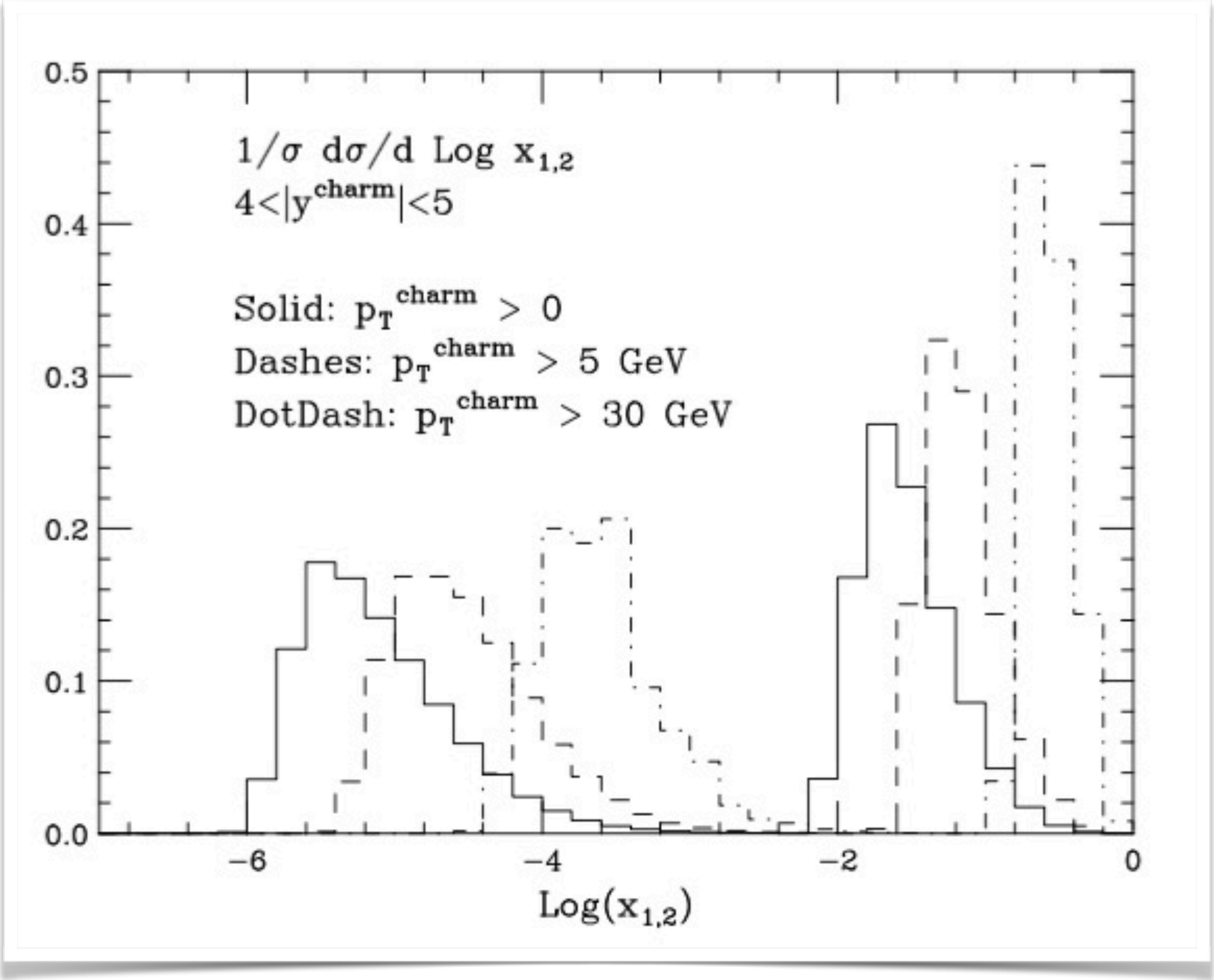
$$x_{1,2} = \frac{m_T}{E_b}\, e^{\pm y}$$





x range covered by gluon PDF

[CMN]



Bottom syst's for rate normalized to central value

[CMN]

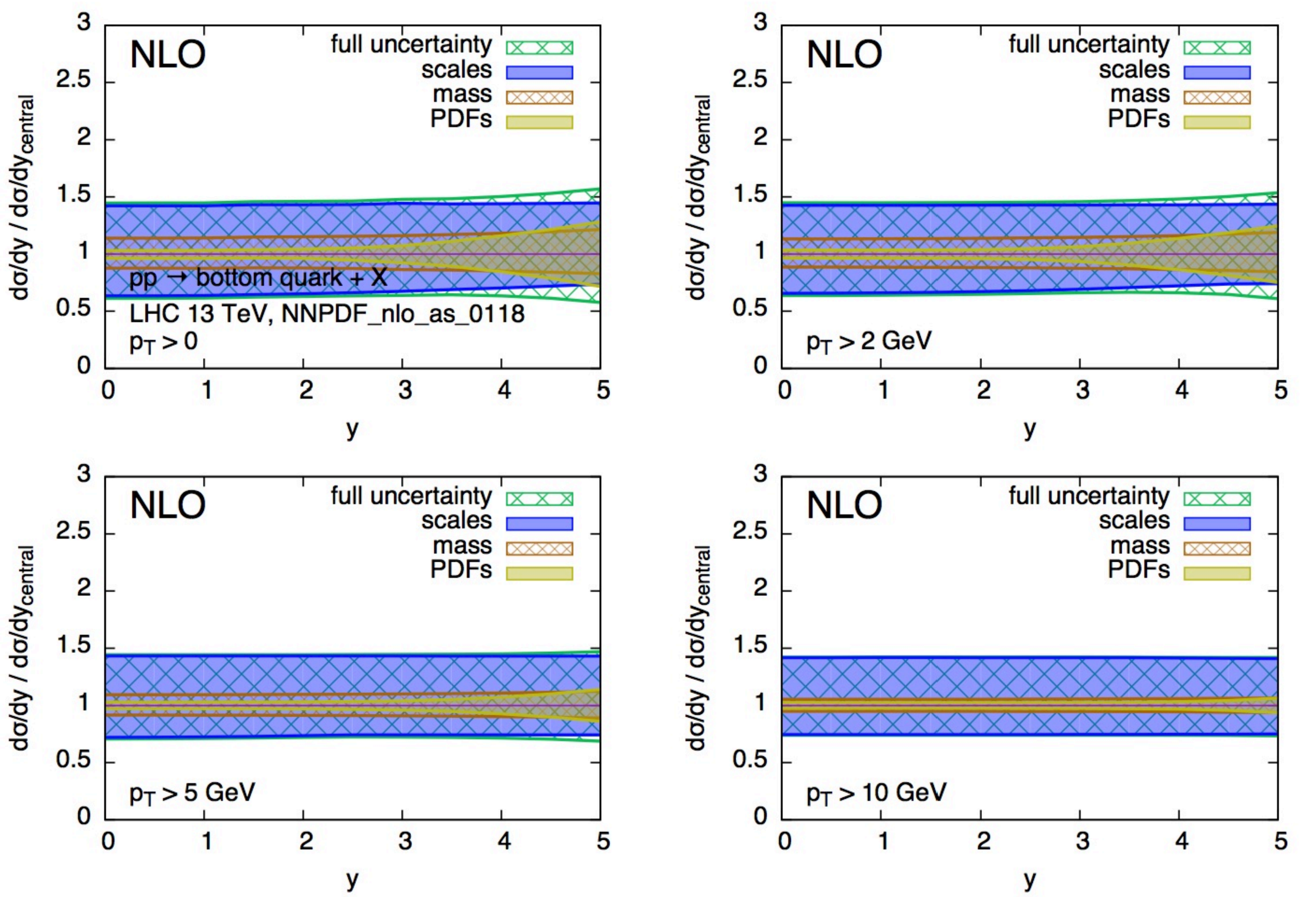
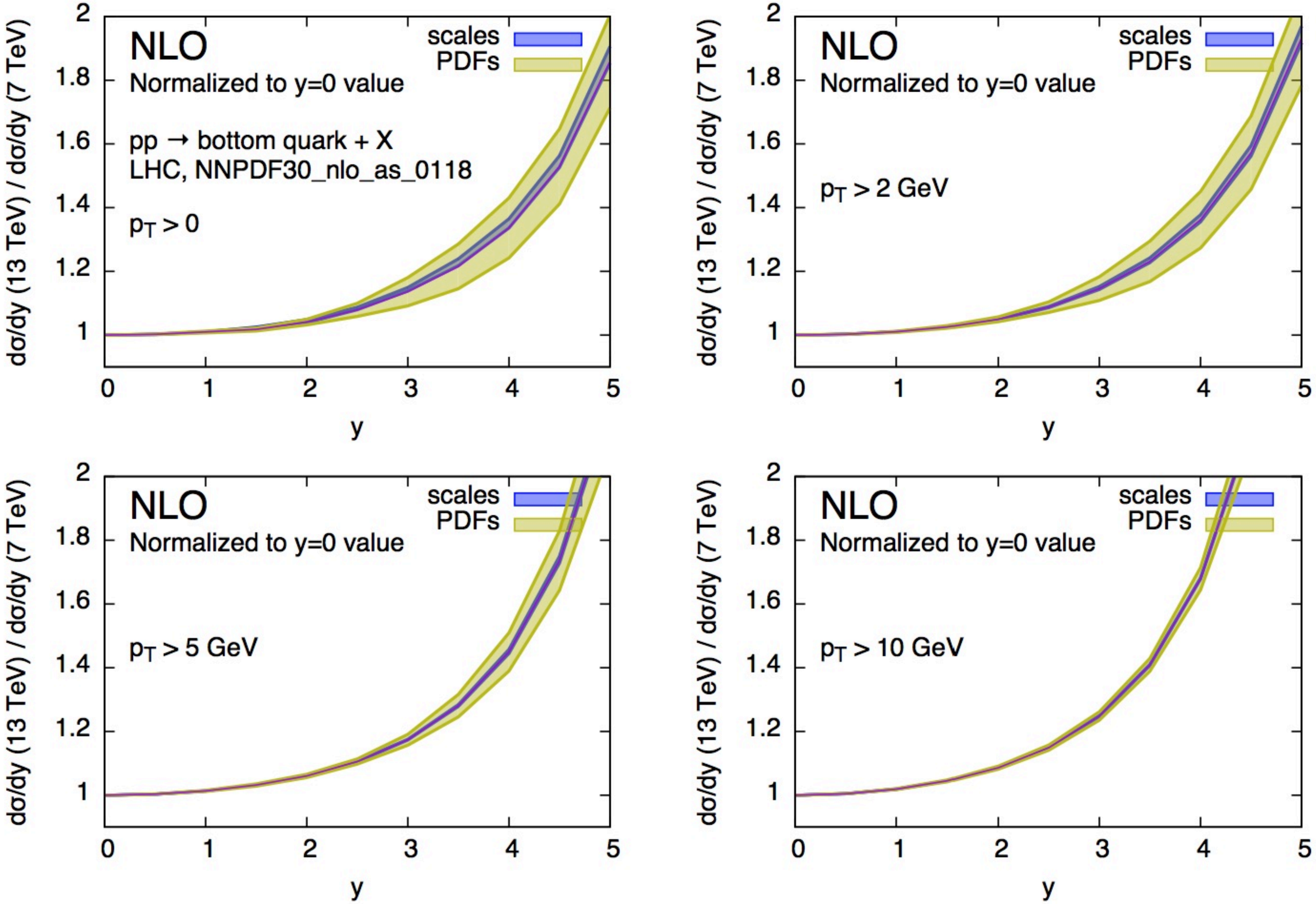
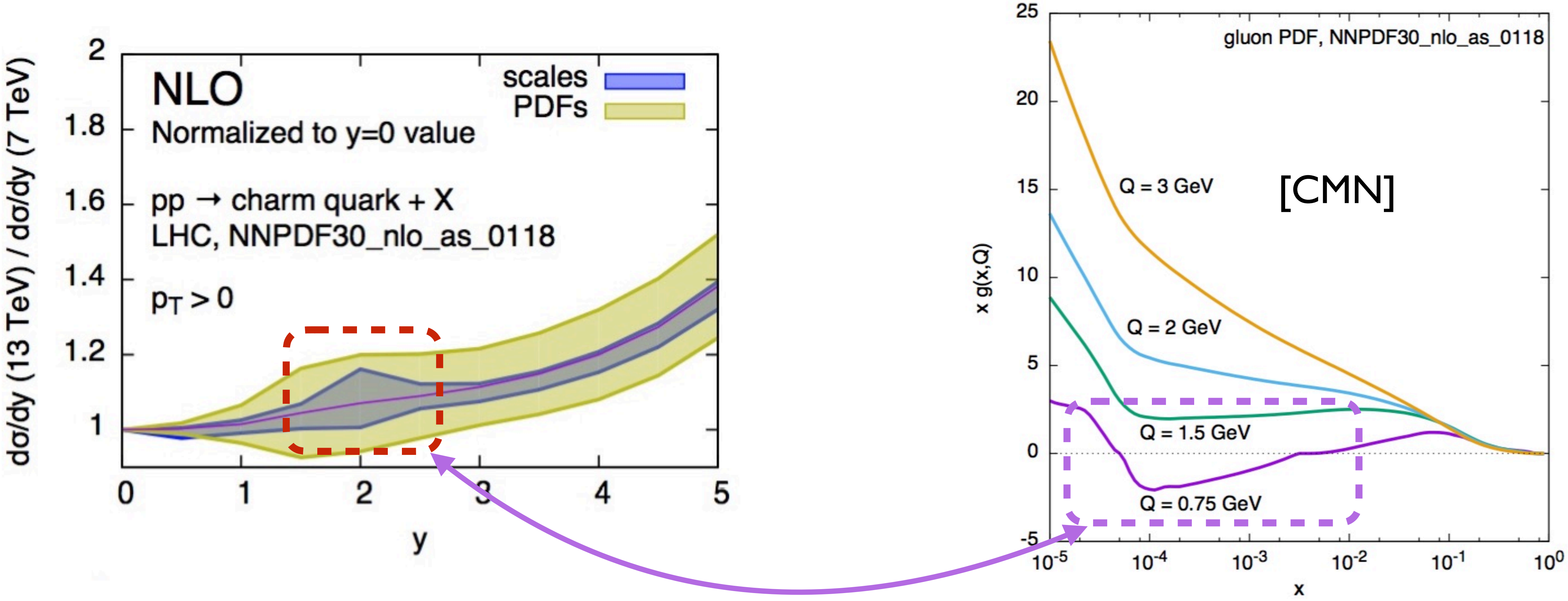


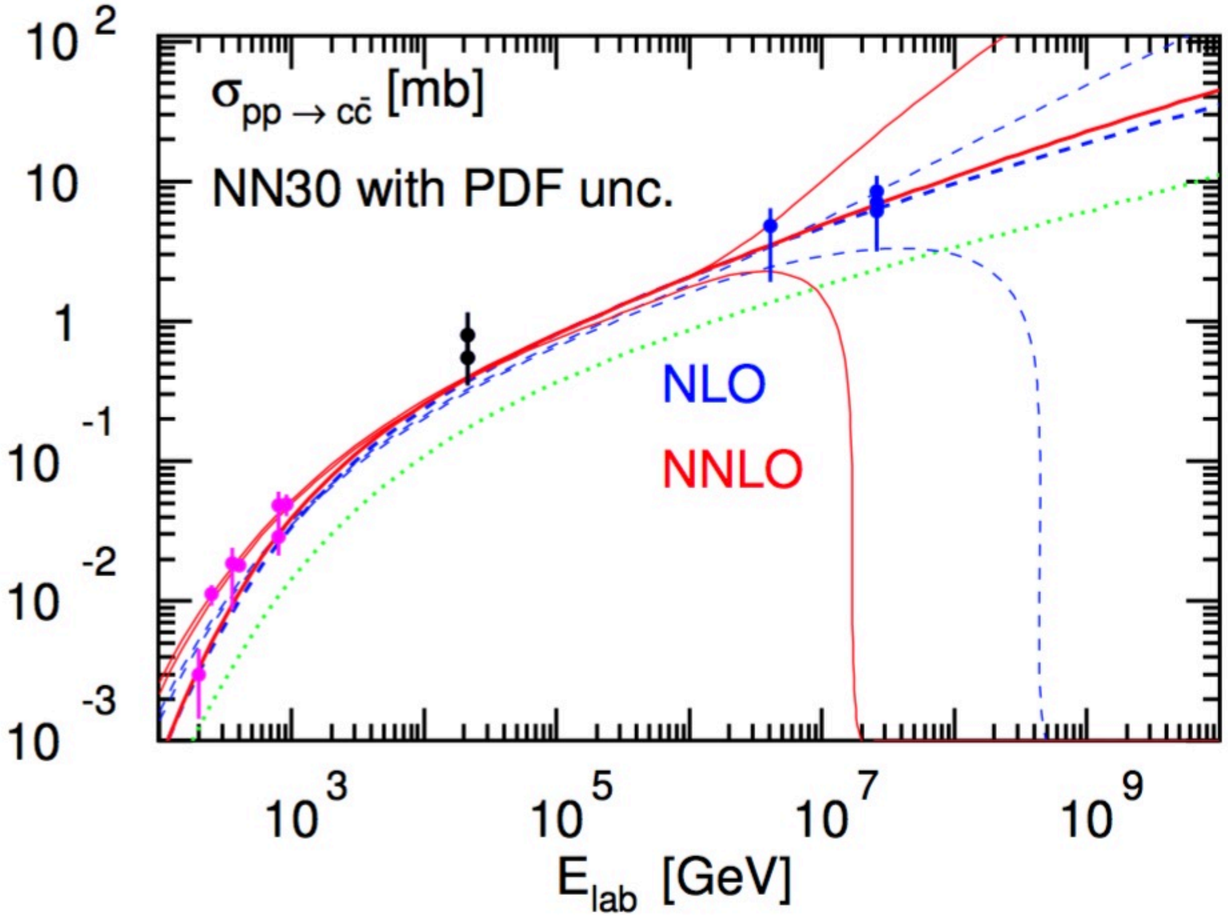
Figure 5: Bottom quark rapidity distributions at $\sqrt{S} = 13$ TeV, normalised to the central theoretical prediction.

Systematics of **ratio** of **bottom** XS's at 13/7 TeV, [CMN] scaled to ratio at y=0



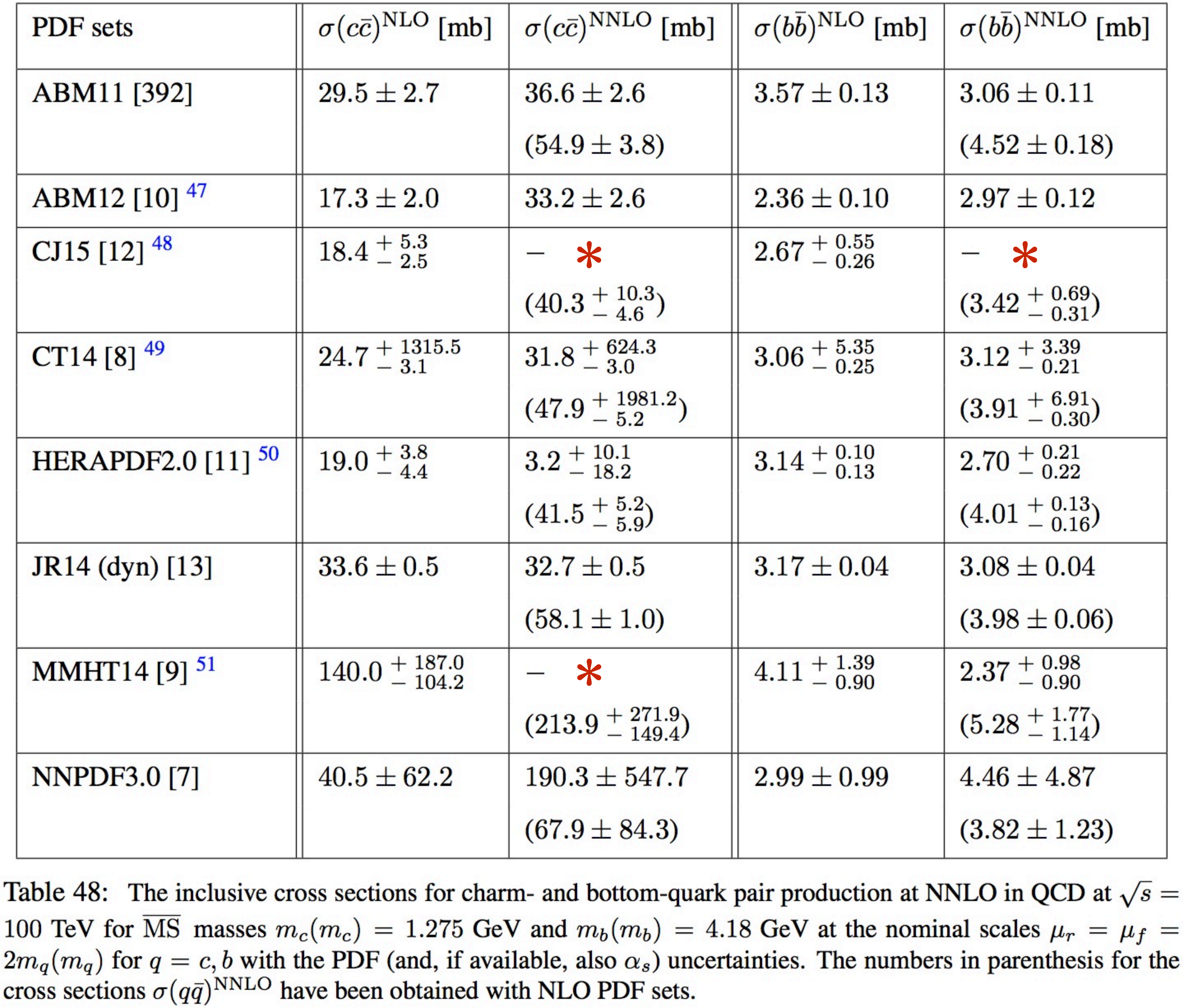
PDF issues





Some PDF sets lead to negative gluons at small x => negative rates at small scales for energies beyond LHC

The issue shows up dramatically at 100 TeV ….



PDF sets	$\sigma(c\bar{c})^{\rm NLO}$ [mb]	$\sigma(c\bar{c})^{\rm NNLO}$ [mb]	$\sigma(b\bar{b})^{\rm NLO}$ [mb]	$\sigma(b\bar{b})^{\rm NNLO}$ [mb]
ABM11 [392]	29.5 ± 2.7	36.6 ± 2.6 (54.9 ± 3.8)	3.57 ± 0.13	3.06 ± 0.11 (4.52 ± 0.18)
ABM12 [10] [47]	17.3 ± 2.0	33.2 ± 2.6	2.36 ± 0.10	2.97 ± 0.12
CJ15 [12] [48]	$18.4 {}^{+\,5.3}_{-\,2.5}$	– * $(40.3 {}^{+\,10.3}_{-\,4.6})$	$2.67 {}^{+\,0.55}_{-\,0.26}$	– * $(3.42 {}^{+\,0.69}_{-\,0.31})$
CT14 [8] [49]	$24.7 {}^{+\,1315.5}_{-\,3.1}$	$31.8 {}^{+\,624.3}_{-\,3.0}$ $(47.9 {}^{+\,1981.2}_{-\,5.2})$	$3.06 {}^{+\,5.35}_{-\,0.25}$	$3.12 {}^{+\,3.39}_{-\,0.21}$ $(3.91 {}^{+\,6.91}_{-\,0.30})$
HERAPDF2.0 [11] [50]	$19.0 {}^{+\,3.8}_{-\,4.4}$	$3.2 {}^{+\,10.1}_{-\,18.2}$ $(41.5 {}^{+\,5.2}_{-\,5.9})$	$3.14 {}^{+\,0.10}_{-\,0.13}$	$2.70 {}^{+\,0.21}_{-\,0.22}$ $(4.01 {}^{+\,0.13}_{-\,0.16})$
JR14 (dyn) [13]	33.6 ± 0.5	32.7 ± 0.5 (58.1 ± 1.0)	3.17 ± 0.04	3.08 ± 0.04 (3.98 ± 0.06)
MMHT14 [9] [51]	$140.0 {}^{+\,187.0}_{-\,104.2}$	– * $(213.9 {}^{+\,271.9}_{-\,149.4})$	$4.11 {}^{+\,1.39}_{-\,0.90}$	$2.37 {}^{+\,0.98}_{-\,0.90}$ $(5.28 {}^{+\,1.77}_{-\,1.14})$
NNPDF3.0 [7]	40.5 ± 62.2	190.3 ± 547.7 (67.9 ± 84.3)	2.99 ± 0.99	4.46 ± 4.87 (3.82 ± 1.23)

Table 48: The inclusive cross sections for charm- and bottom-quark pair production at NNLO in QCD at $\sqrt{s}$ = 100 TeV for $\overline{\rm MS}$ masses $m_c(m_c) = 1.275$ GeV and $m_b(m_b) = 4.18$ GeV at the nominal scales $\mu_r = \mu_f = 2m_q(m_q)$ for $q = c, b$ with the PDF (and, if available, also α_s) uncertainties. The numbers in parenthesis for the cross sections $\sigma(q\bar{q})^{\rm NNLO}$ have been obtained with NLO PDF sets.

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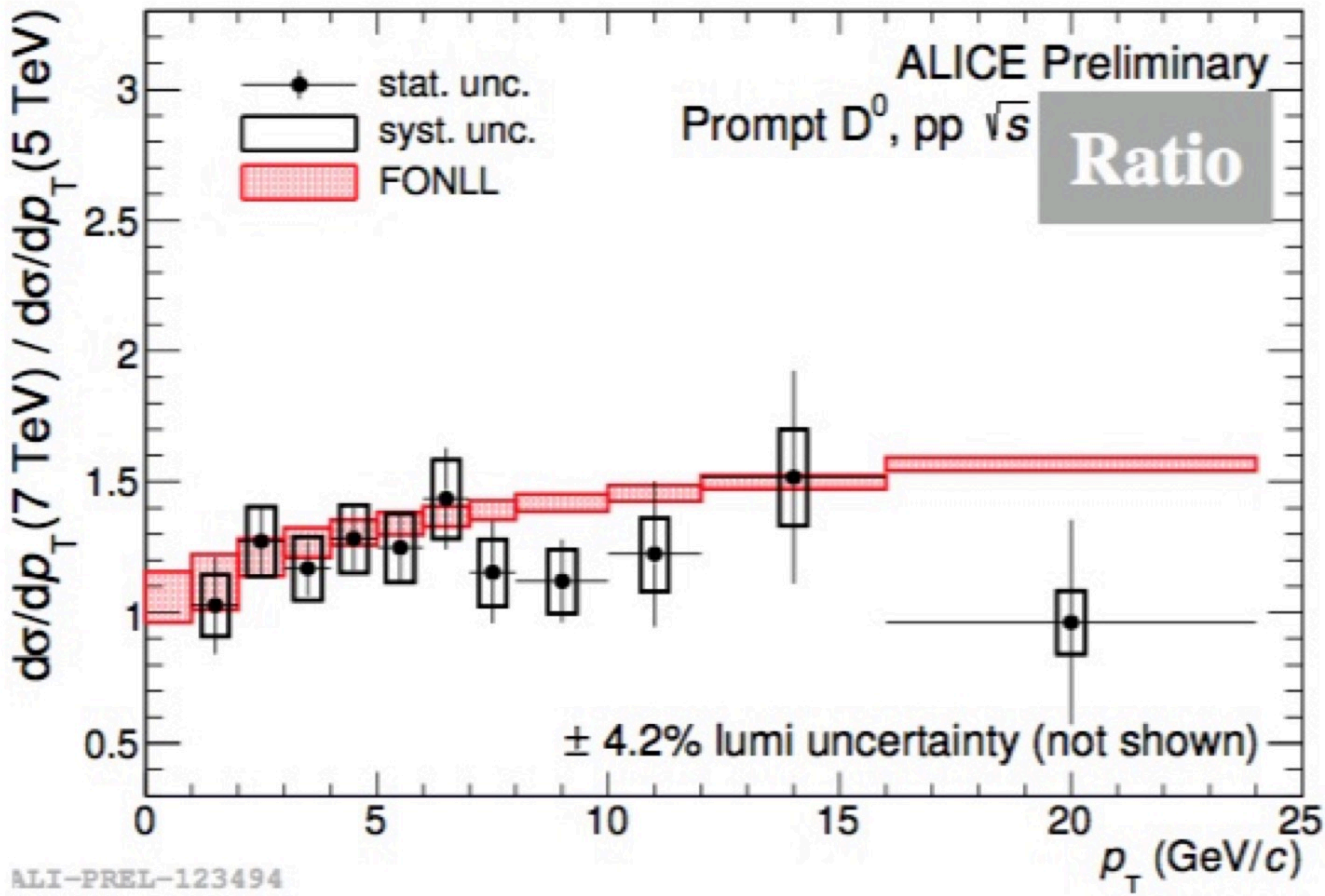
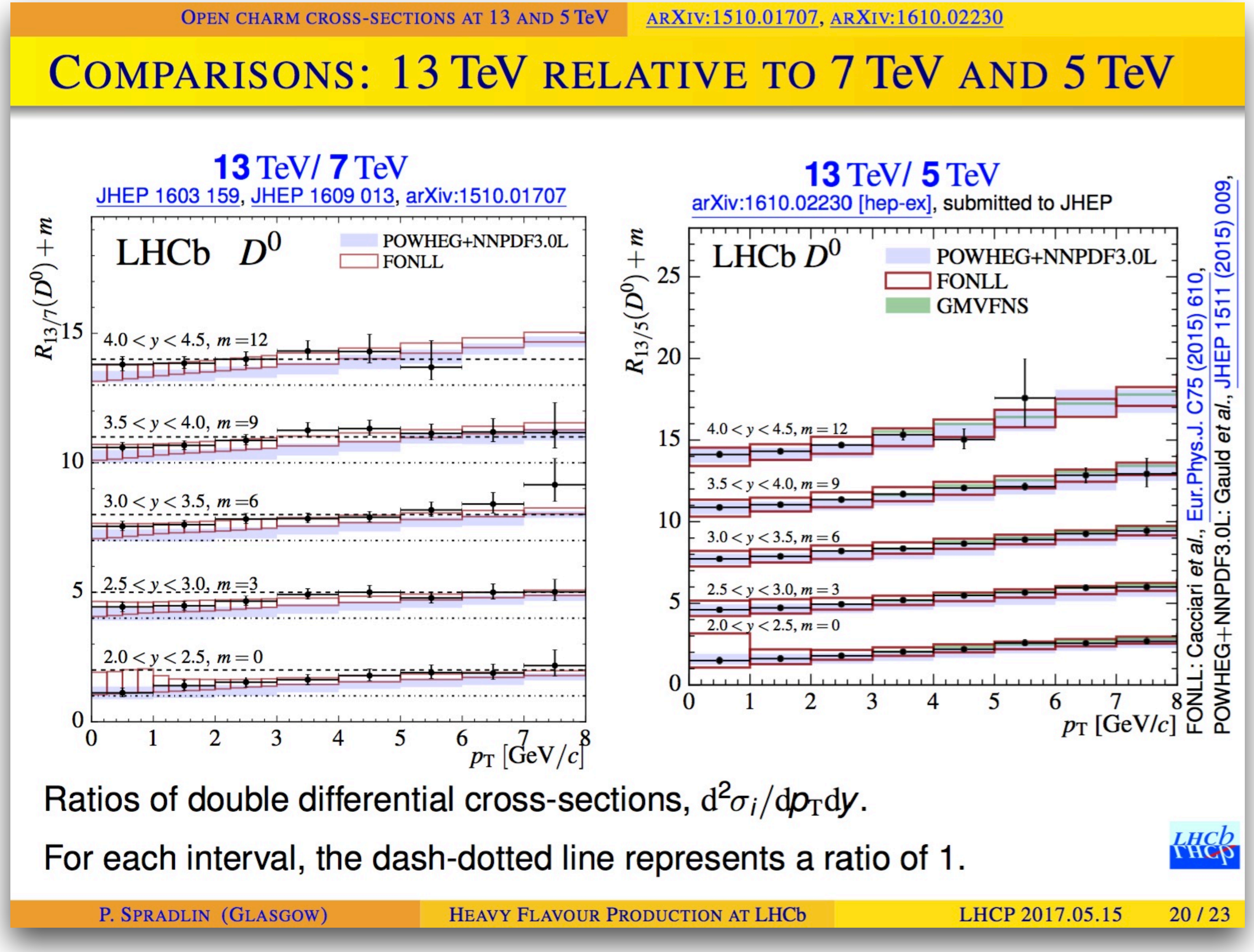
— => $\sigma<0$

The impact of LHC data


ALICE Preliminary
Prompt D^0, pp $\sqrt{s}$
Ratio
stat. unc.
syst. unc.
FONLL
± 4.2% lumi uncertainty (not shown)
$d\sigma/dp_T$(7 TeV) / $d\sigma/dp_T$(5 TeV)
p_T (GeV/c)
0
5
10
15
20
25
0.5
1
1.5
2
2.5
3
ALI-PREL-123494



OPEN CHARM CROSS-SECTIONS AT 13 AND 5 TeV   arXiv:1510.01707, arXiv:1610.02230

COMPARISONS: 13 TeV RELATIVE TO 7 TeV AND 5 TeV

13 TeV/ 7 TeV

JHEP 1603 159, JHEP 1609 013, arXiv:1510.01707

13 TeV/ 5 TeV

arXiv:1610.02230 [hep-ex], submitted to JHEP

FONLL: Cacciari *et al.*, Eur.Phys.J. C75 (2015) 610,
POWHEG+NNPDF3.0L: Gauld *et al.*, JHEP 1511 (2015) 009,

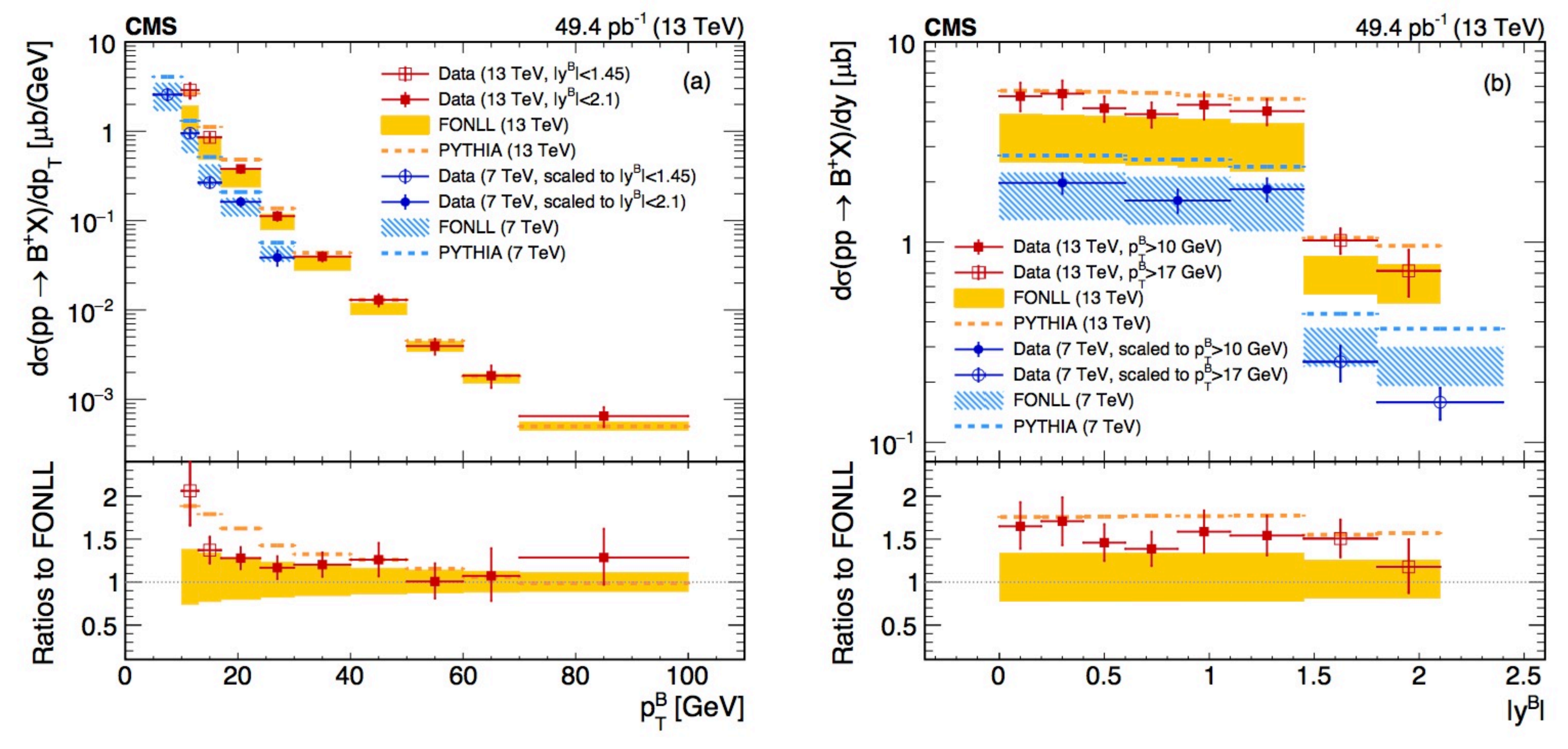
Ratios of double differential cross-sections, $\mathrm{d}^2\sigma_i/\mathrm{d}p_\mathrm{T}\mathrm{d}y$.

For each interval, the dash-dotted line represents a ratio of 1.

P. SPRADLIN (GLASGOW)   HEAVY FLAVOUR PRODUCTION AT LHCb   LHCP 2017.05.15   20 / 23

The pedestal subtraction hides that fact that the slope is much bigger at large y.
E.g. for pt=8 R~3 @y=2-2.5, and R=6 @y=4-4.5
This is the result of the greater sensitivity to small-x and large-x PDFs at large pt and large y

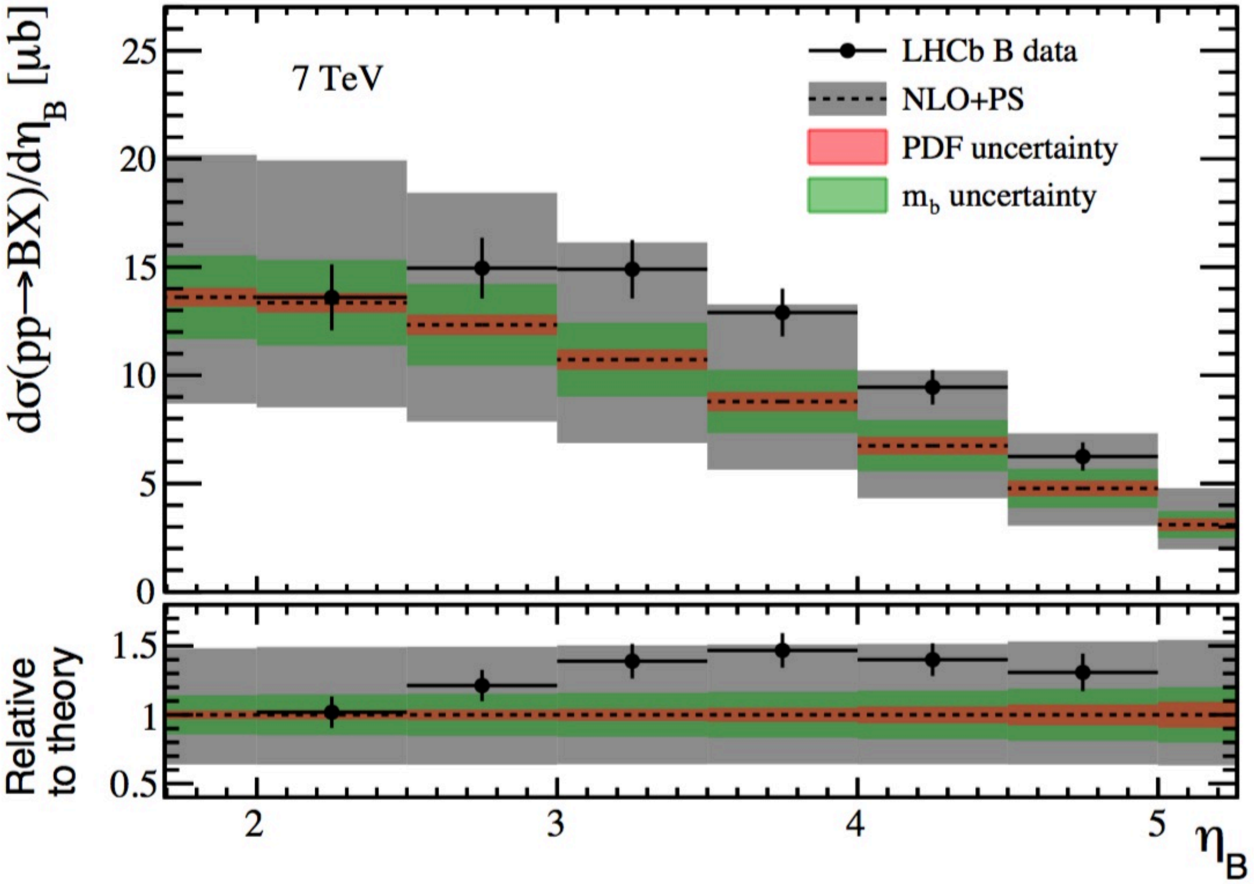
CMS bottom XS's at 13 and 7 TeV

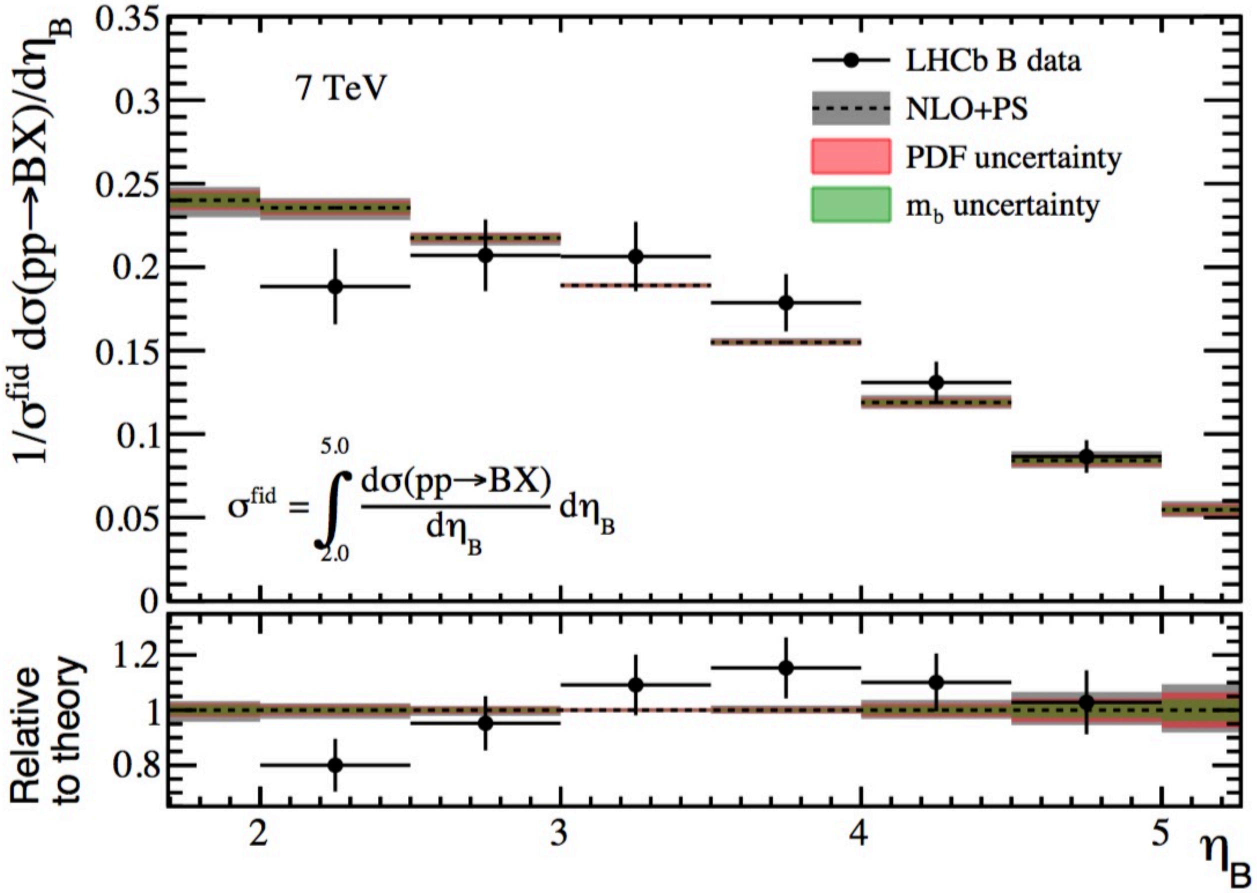


CMS, arXiv:1609.00873

Some disturbing issues:

[G]





Data: LHCb arXiv:1009.2731

The difference in shape at small-η is a bit worrysome, given the rather sharp TH predictions ….

Nevethreless, the data are sufficient to set new remarkable constraints on the gluon PDF at small-x

Impact of LHCb charm XS measurements at 5, 7 and 13 TeV on gluon PDF [GR]

LHCb arXiv:1610.02230

[GR]

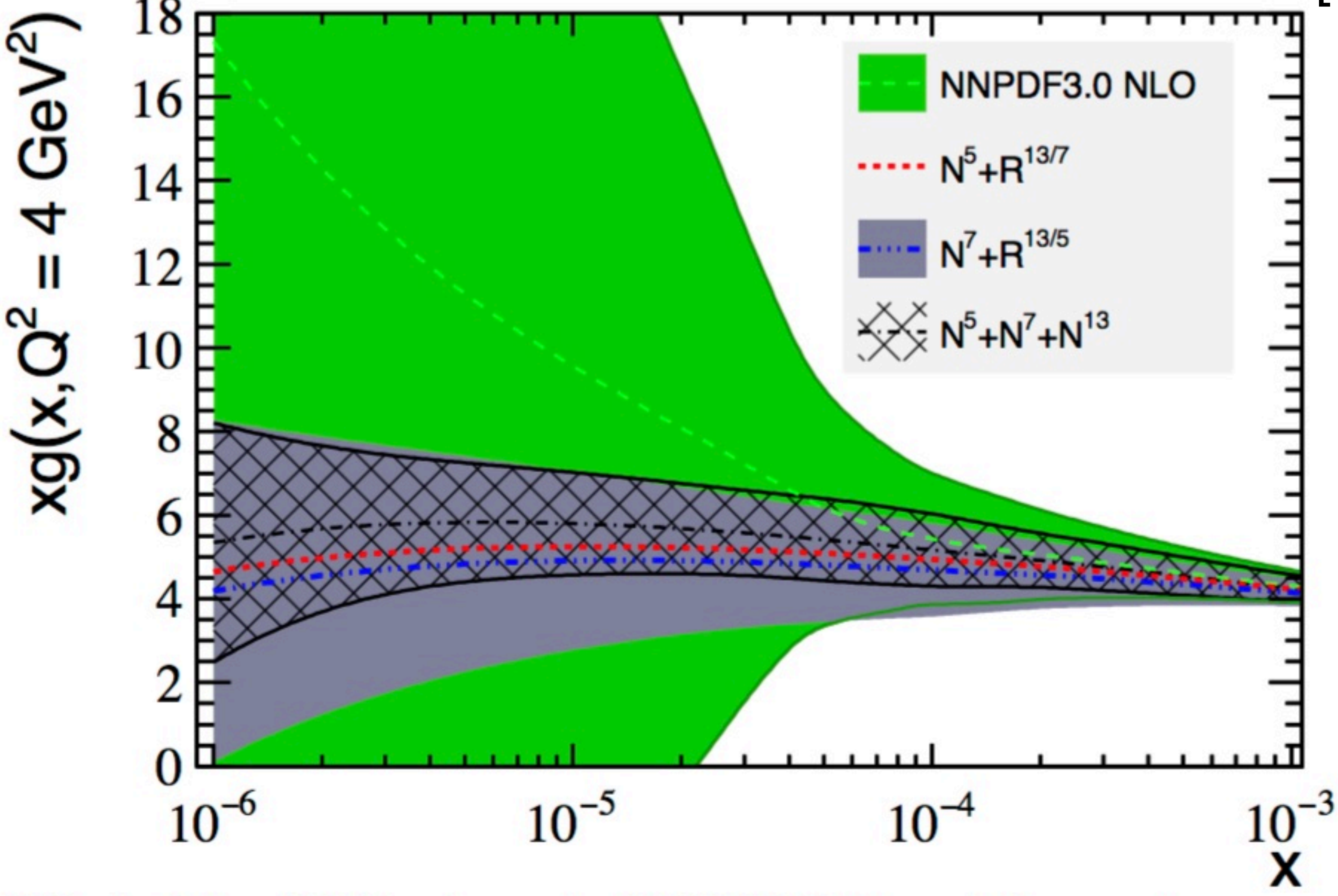
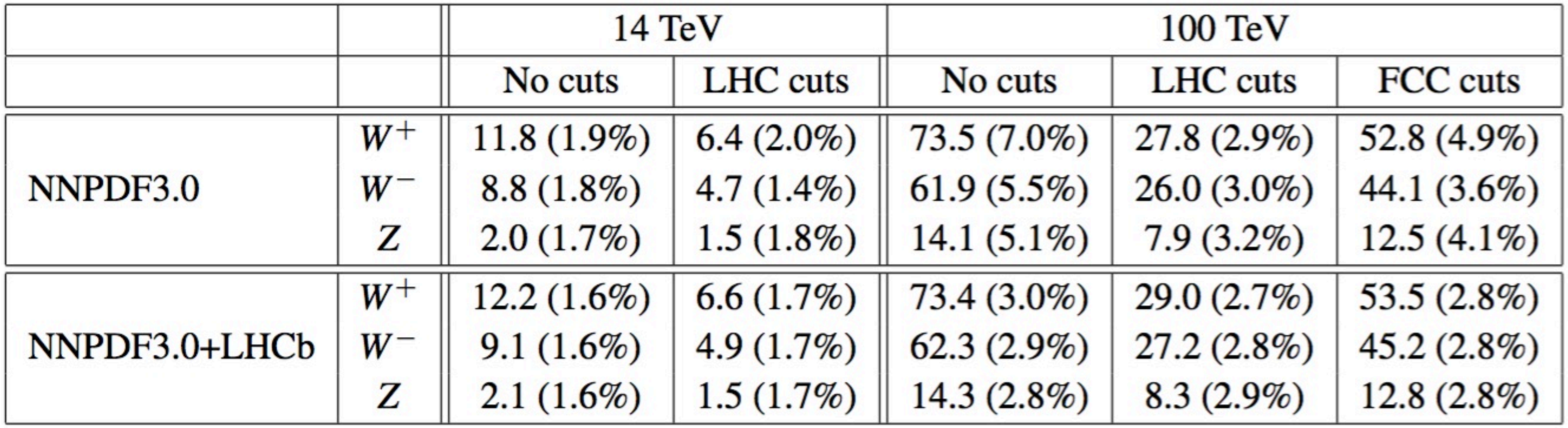


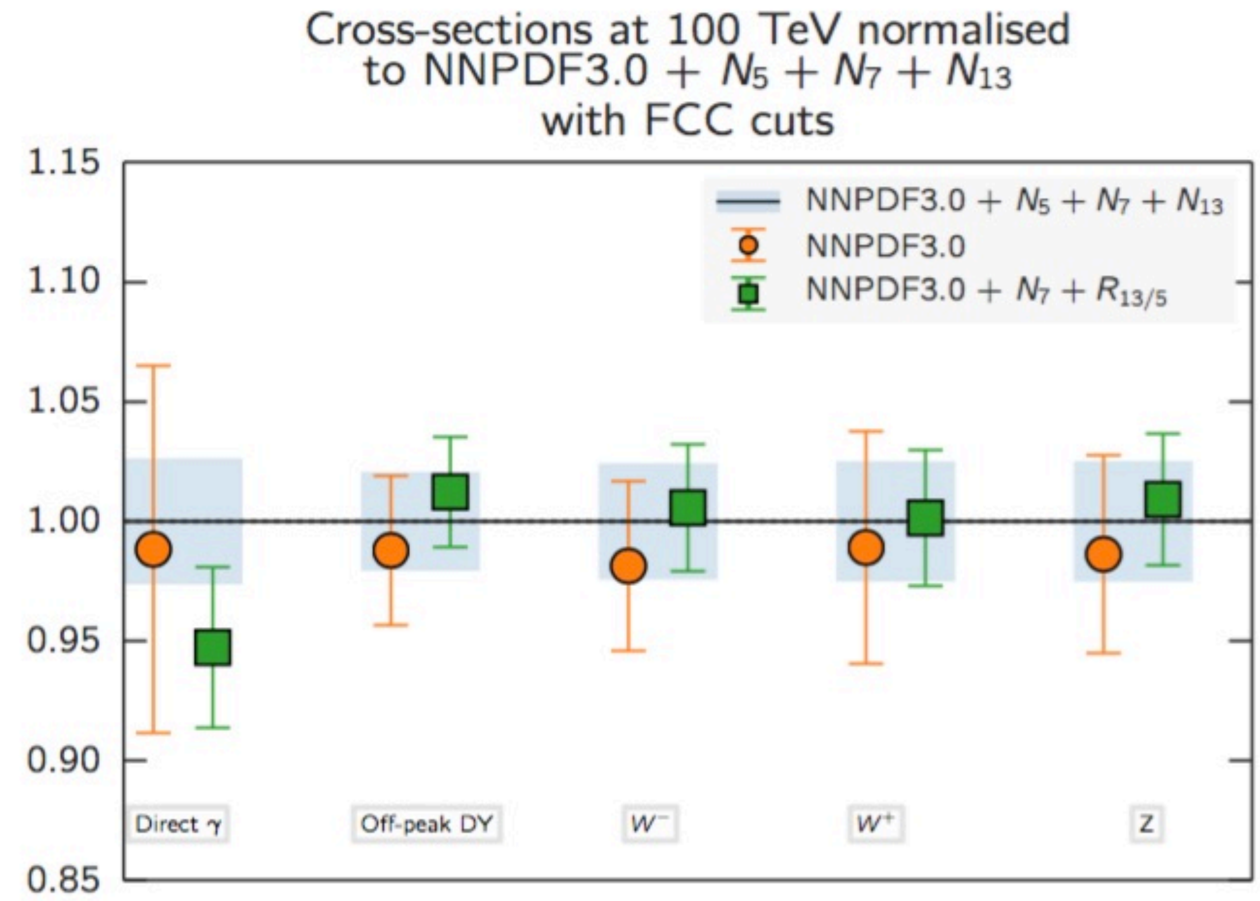
FIG. 2: The NLO gluon in NNPDF3.0 and for various combinations of LHCb data included, at $Q^2 = 4\ \text{GeV}^2$.

Impact on XS predictions for 100 TeV pp collider

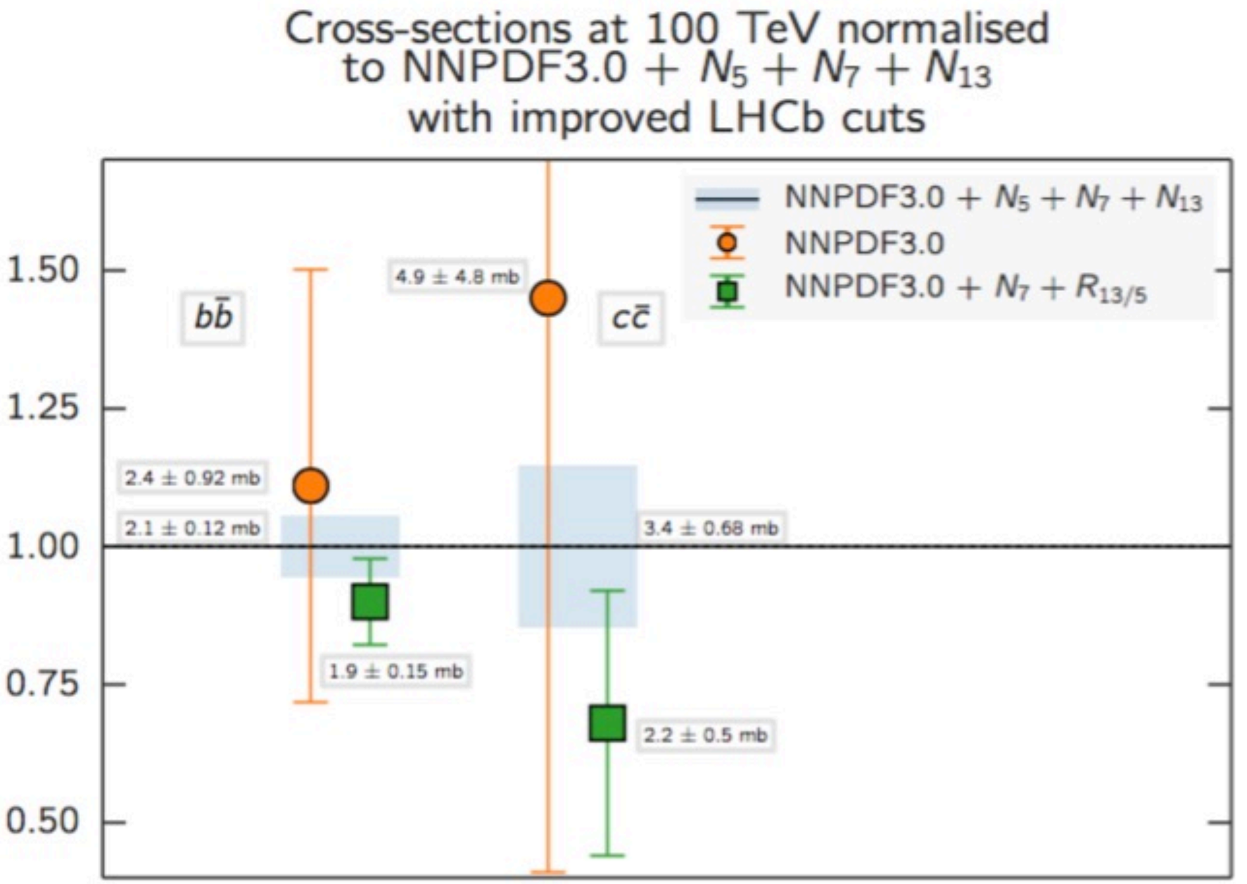
Gauld, Rojo, Slade, arXiv:1705.04217



		14 TeV		100 TeV		
		No cuts	LHC cuts	No cuts	LHC cuts	FCC cuts
NNPDF3.0	W^+	11.8 (1.9%)	6.4 (2.0%)	73.5 (7.0%)	27.8 (2.9%)	52.8 (4.9%)
	W^-	8.8 (1.8%)	4.7 (1.4%)	61.9 (5.5%)	26.0 (3.0%)	44.1 (3.6%)
	Z	2.0 (1.7%)	1.5 (1.8%)	14.1 (5.1%)	7.9 (3.2%)	12.5 (4.1%)
NNPDF3.0+LHCb	W^+	12.2 (1.6%)	6.6 (1.7%)	73.4 (3.0%)	29.0 (2.7%)	53.5 (2.8%)
	W^-	9.1 (1.6%)	4.9 (1.7%)	62.3 (2.9%)	27.2 (2.8%)	45.2 (2.8%)
	Z	2.1 (1.6%)	1.5 (1.7%)	14.3 (2.8%)	8.3 (2.9%)	12.8 (2.8%)



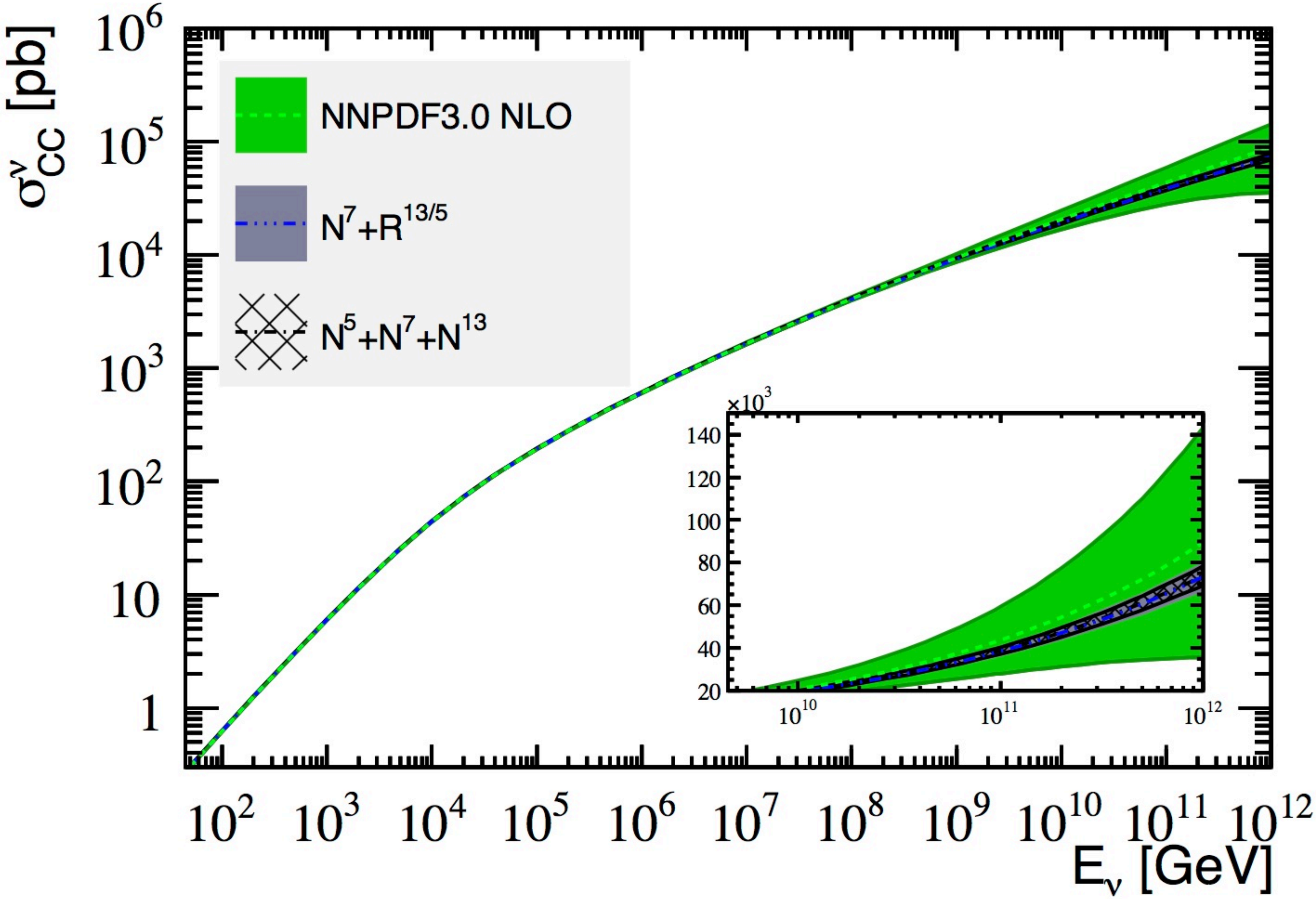
Cross-sections at 100 TeV normalised to NNPDF3.0 + $N_5 + N_7 + N_{13}$ with FCC cuts



Cross-sections at 100 TeV normalised to NNPDF3.0 + $N_5 + N_7 + N_{13}$ with improved LHCb cuts

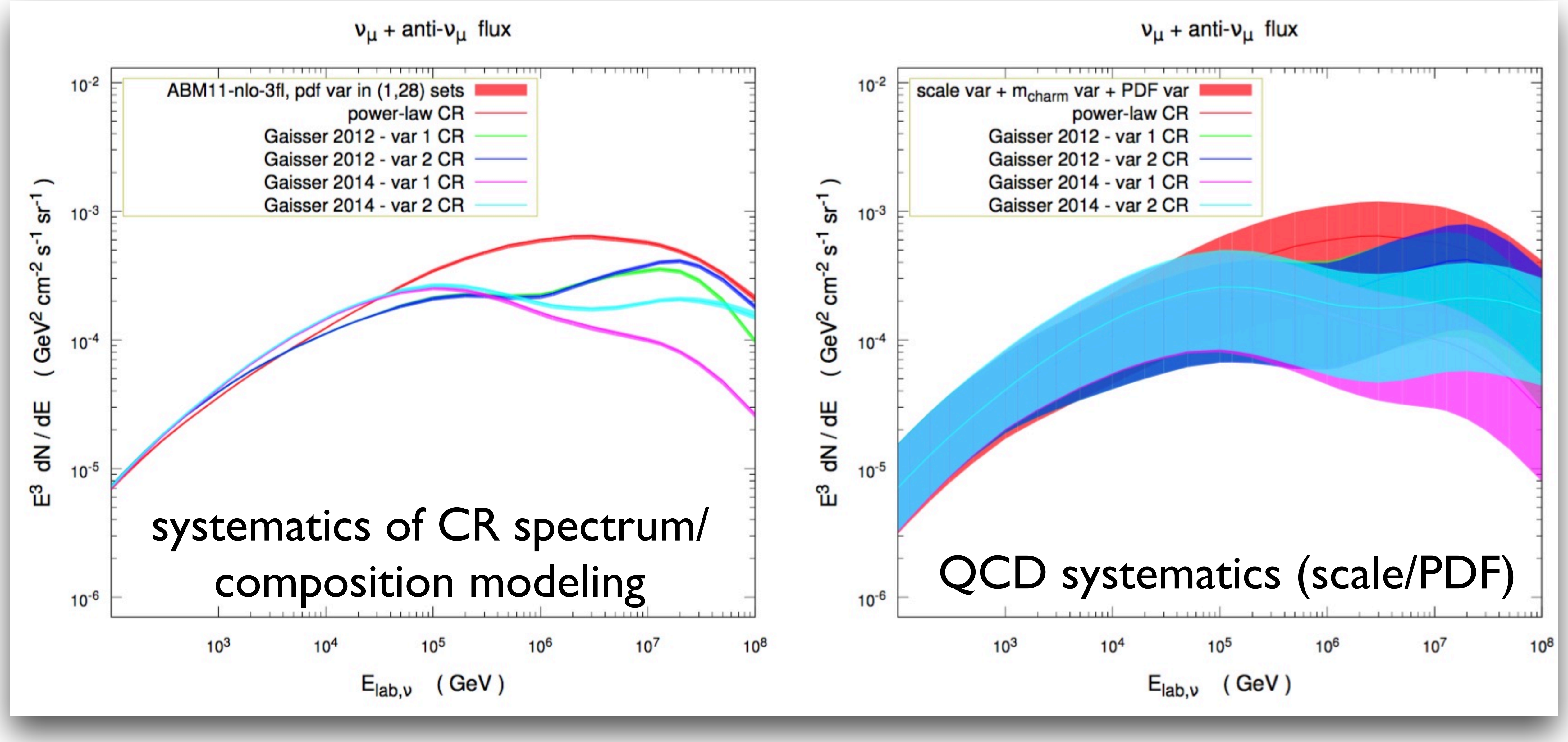
Impact of “charm-XS-improved” gluon PDF on $\sigma_{\nu N}$ at high energy

[GR]



Bgs to cosmogenic ν's: HE ν's from decays of charm produced in cosmic ray showers

[GMS]



systematics of CR spectrum/composition modeling

QCD systematics (scale/PDF)

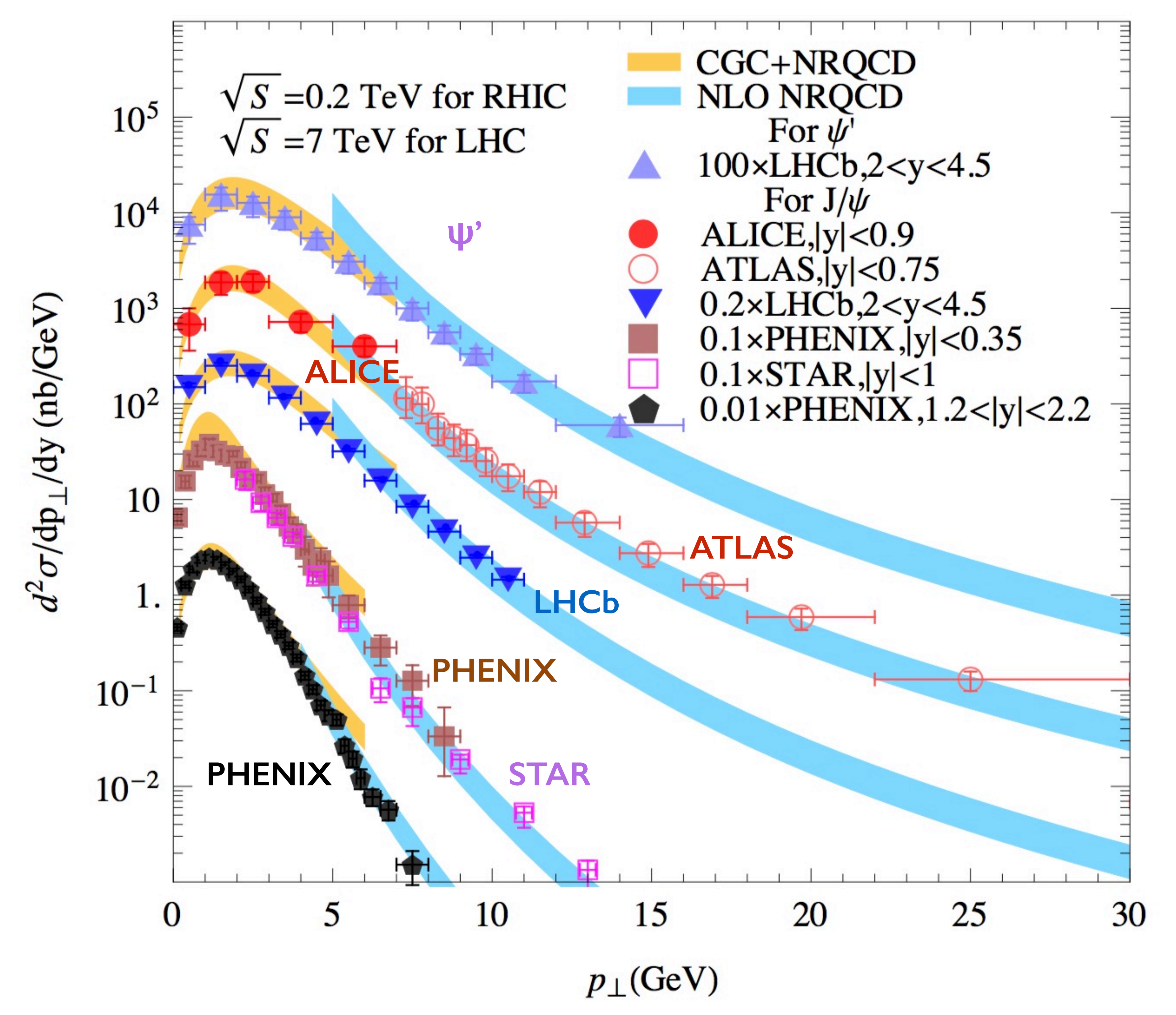
Reduction in QCD systematics is needed to properly assess bgs, and possibly learn about CR syst's

Next steps

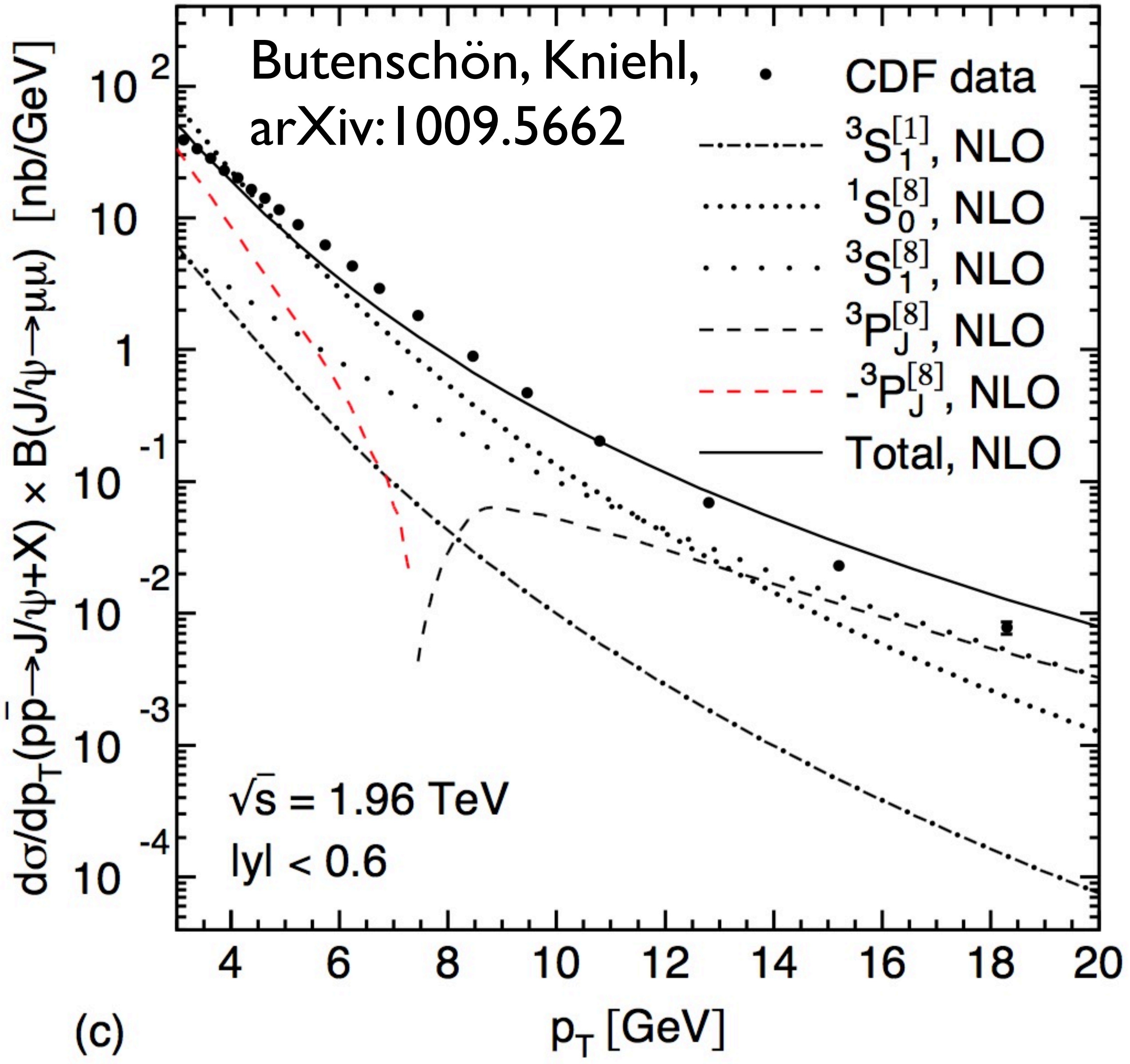
- Wait for a final round of measurements of c and b production at 13 TeV, and updated XS ratio measurements
- Assess global consistency of interpretation of both c and b data (e.g. do they lead to the same gluon PDF constraints?)
- Important deviations from the precise predictions of XS ratios could point to onset of new dynamical effects (eg role of small-x resummation) … but this is not true of **<u>any</u>** deviation, for a large kinematic range these TH predictions are robust
- Match xs's at the ATLAS/CMS-LHCb boundary, η~2-2.5, to give further robustness to the overall picture
- Push the kinematic reach of measurements (eg high-E_T b's and b-jets)
- Test fragmentation function universality in the hadronic environment
- Look forward to availability of full NNLO differential distributions

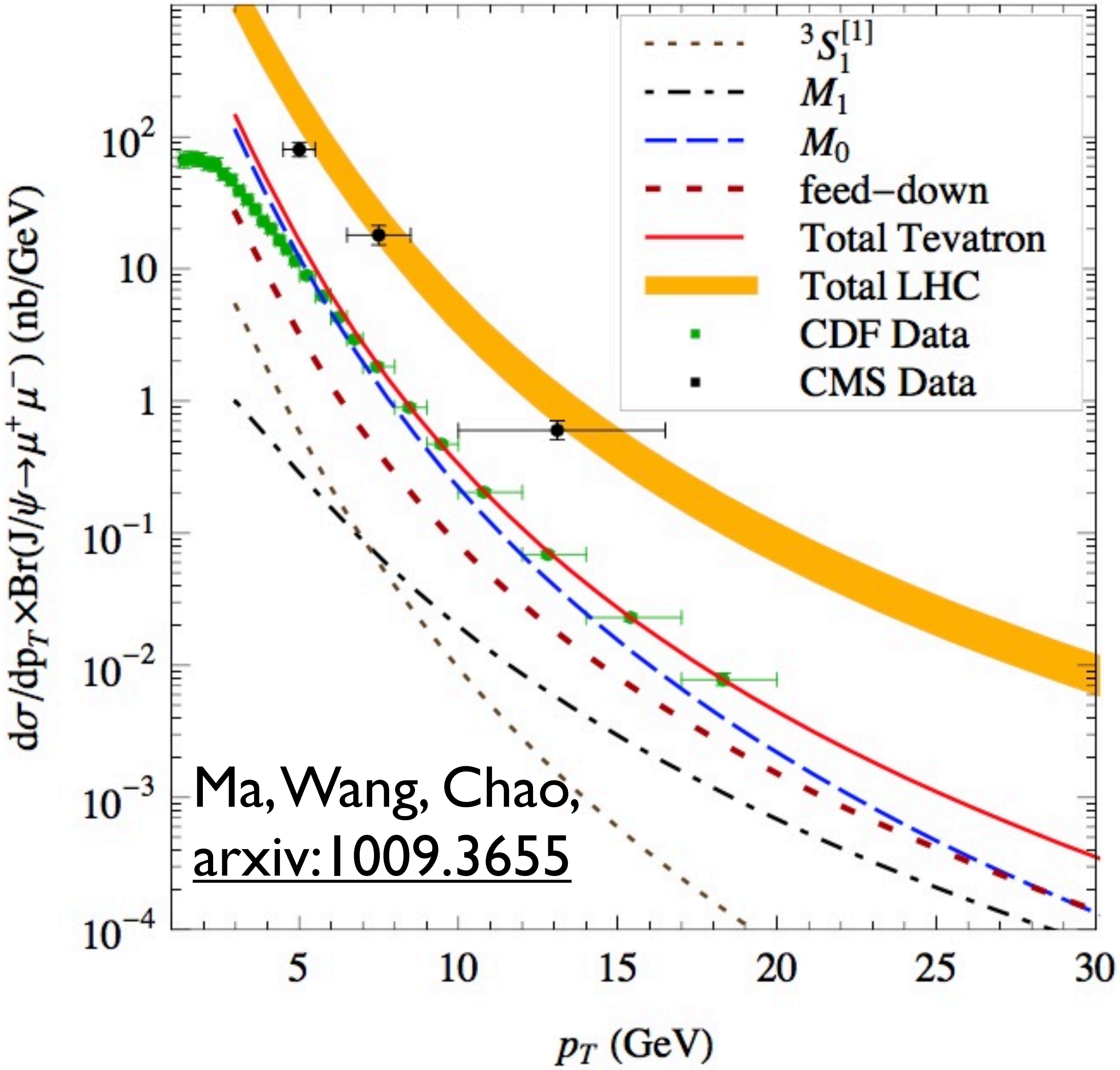
ψ & ψ' production, pt spectra

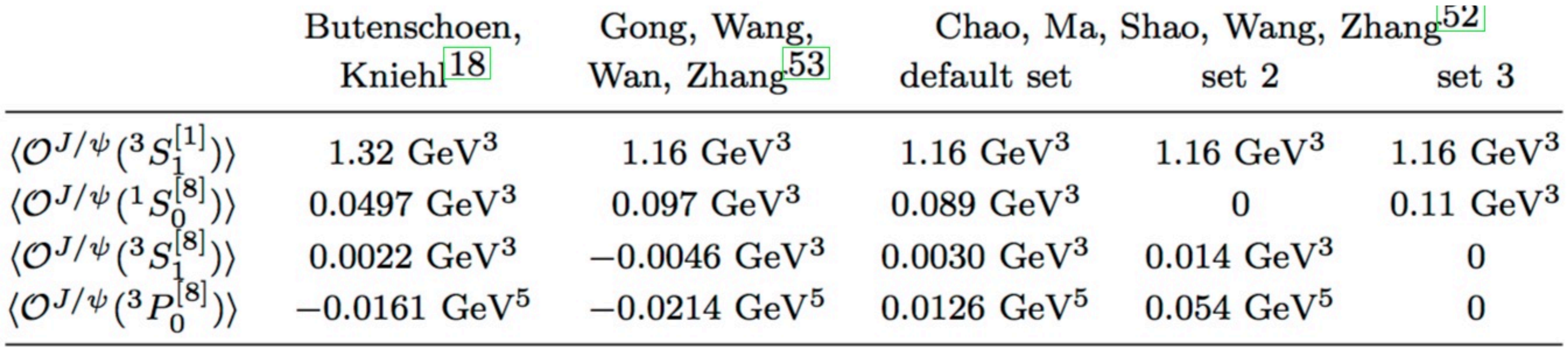
Data vs NLO NRQCD



Significant dependence on fits NRQCD long distance matrix elements (LDME), arising from set of ops considered, pert order, and pt range used in the fits







	Butenschoen, Kniehl[18]	Gong, Wang, Wan, Zhang[53]	Chao, Ma, Shao, Wang, Zhang[52] default set	set 2	set 3
$\langle\mathcal{O}^{J/\psi}(^3S_1^{[1]})\rangle$	1.32 GeV^3	1.16 GeV^3	1.16 GeV^3	1.16 GeV^3	1.16 GeV^3
$\langle\mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle$	0.0497 GeV^3	0.097 GeV^3	0.089 GeV^3	0	0.11 GeV^3
$\langle\mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle$	0.0022 GeV^3	−0.0046 GeV^3	0.0030 GeV^3	0.014 GeV^3	0
$\langle\mathcal{O}^{J/\psi}(^3P_0^{[8]})\rangle$	−0.0161 GeV^5	−0.0214 GeV^5	0.0126 GeV^5	0.054 GeV^5	0

Upsilon production, pt spectra

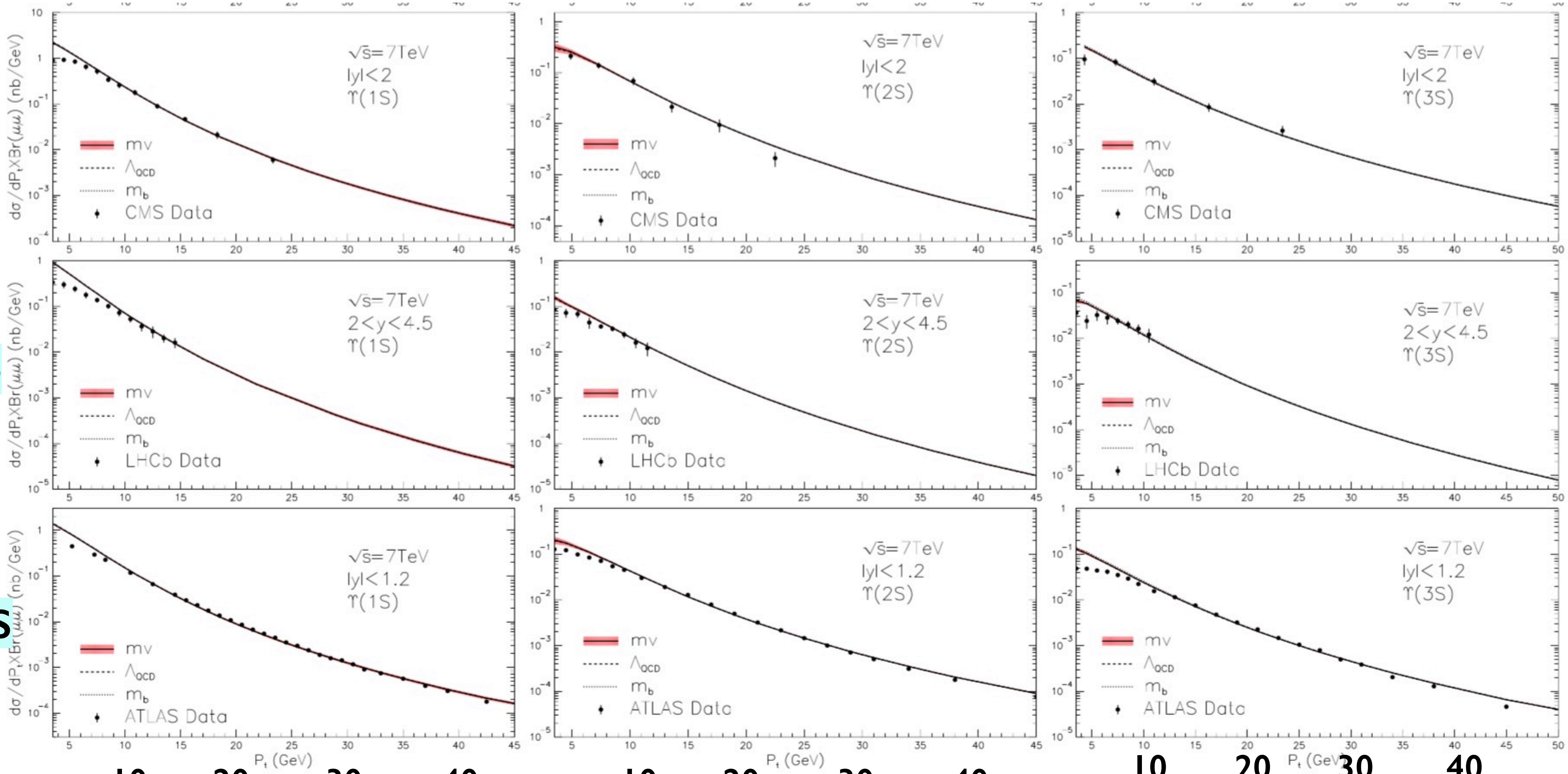
Data vs NLO NRQCD

Υ(1S) Υ(2S) Υ(3S)

CMS

LHCb

ATLAS



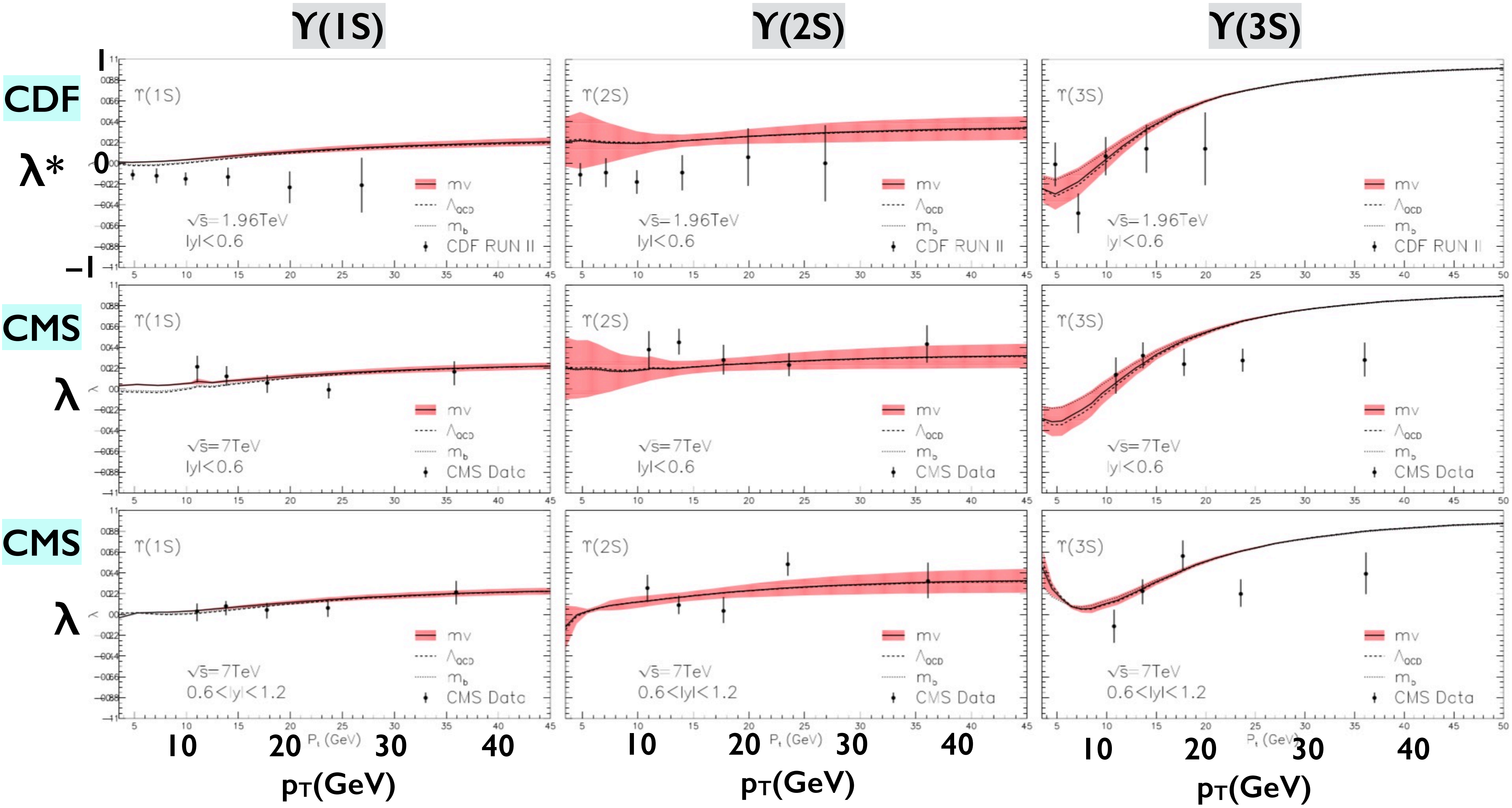
10 20 30 40

p$_T$(GeV)

Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang, arxiv:1305.0748

Upsilon production, polarization

Data vs NLO NRQCD



Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang, arxiv:1305.0748

* $\lambda = 0, +1, -1$ => nopol, ⊥ pol, // pol

ψ production inside jets

LHCb, arXiv:1701.05116

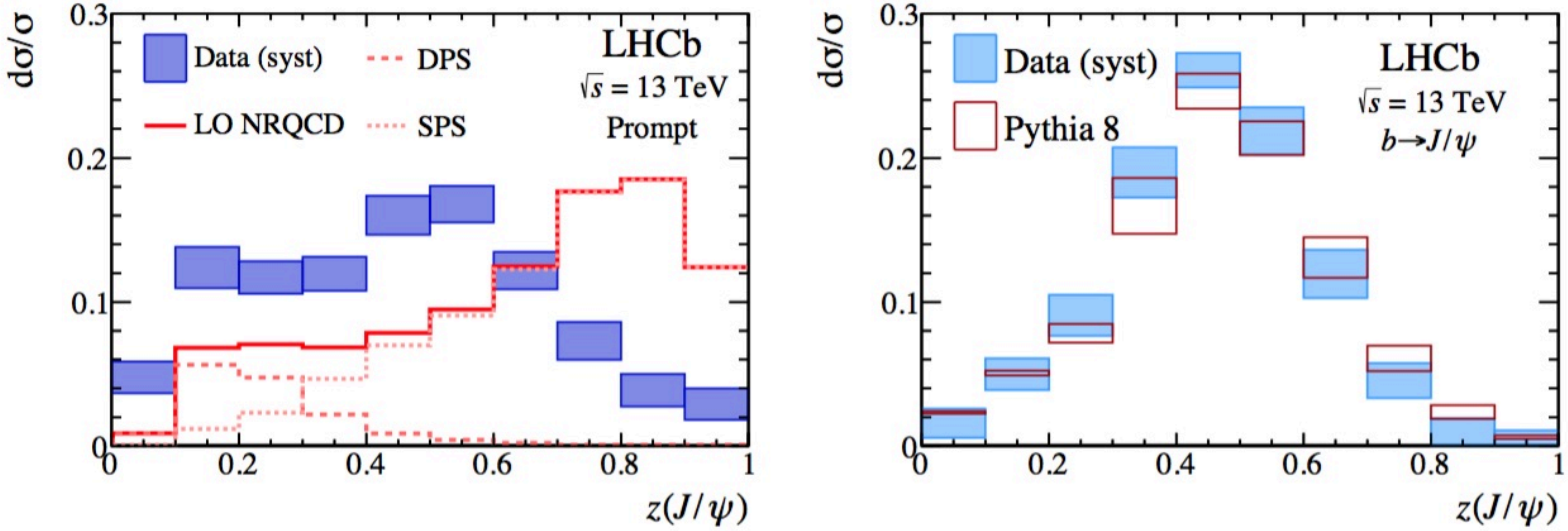
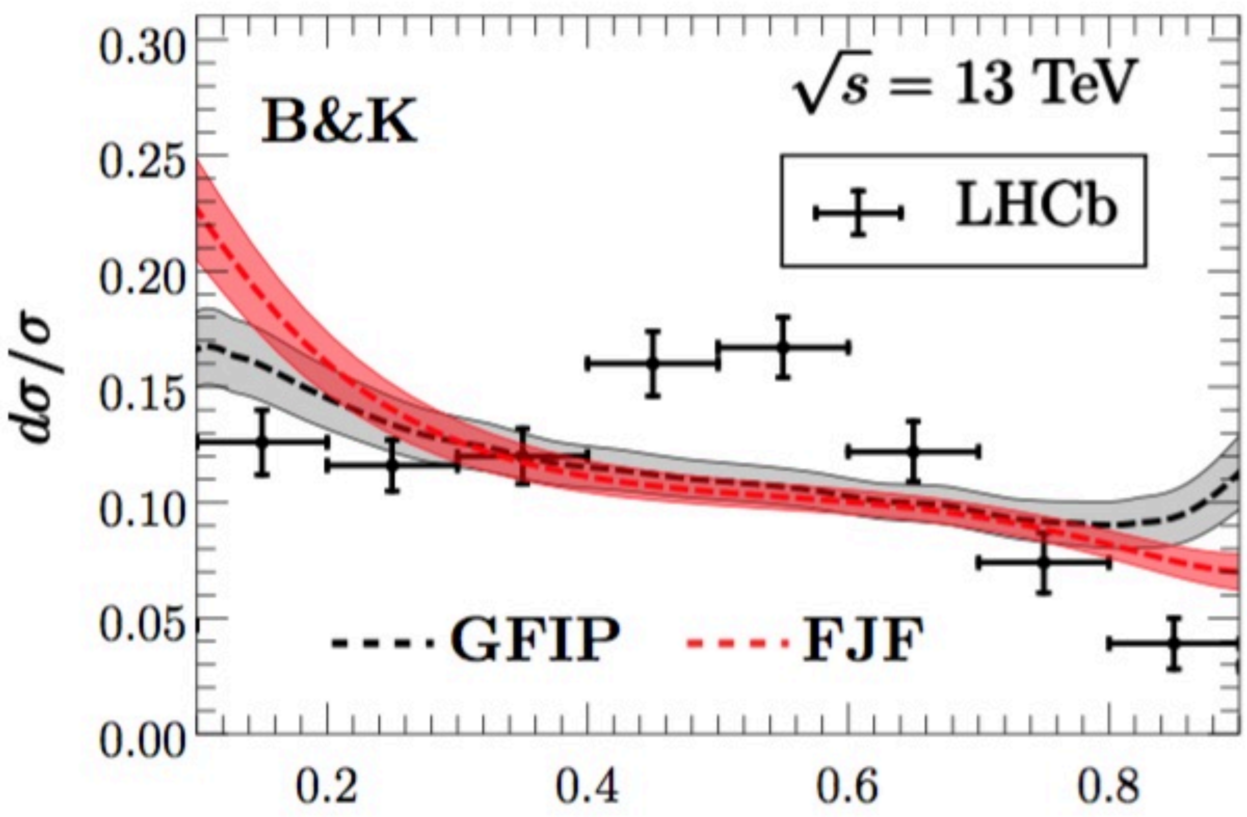
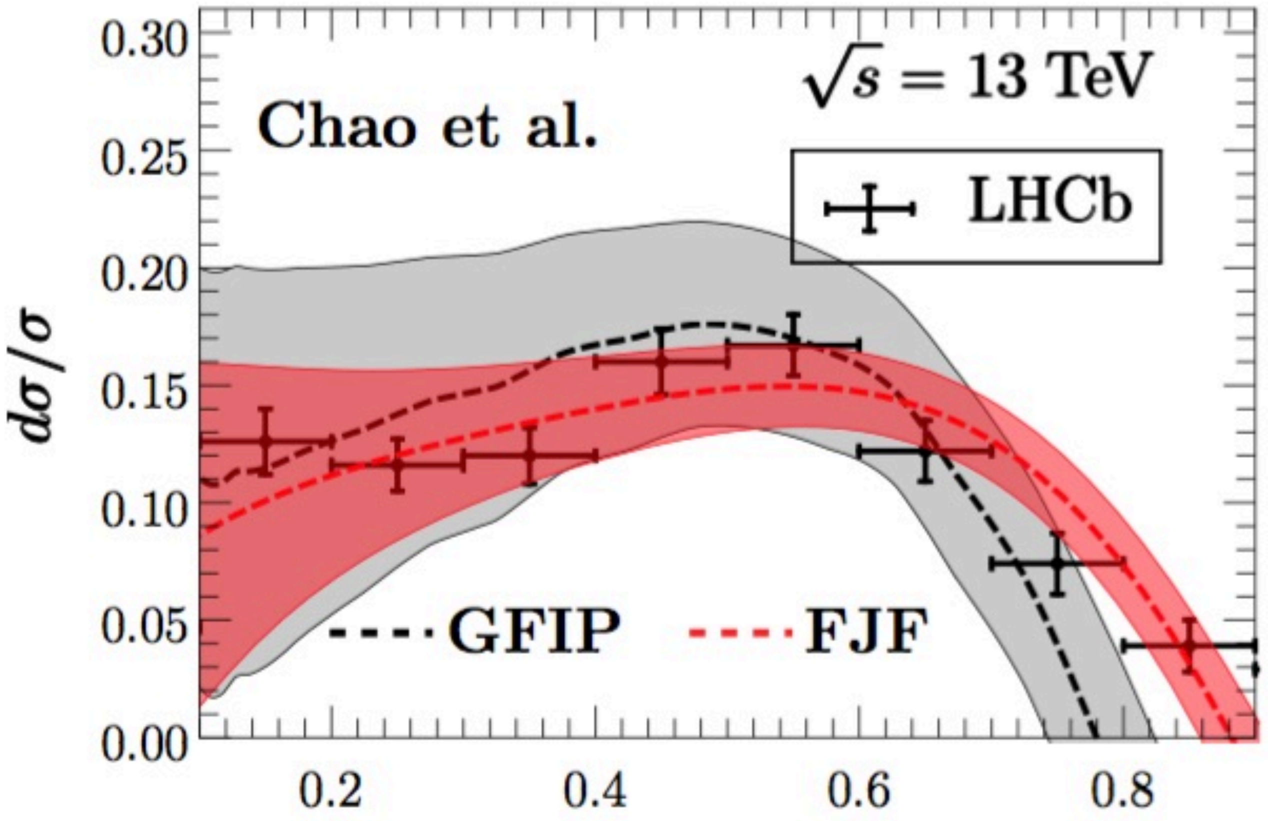


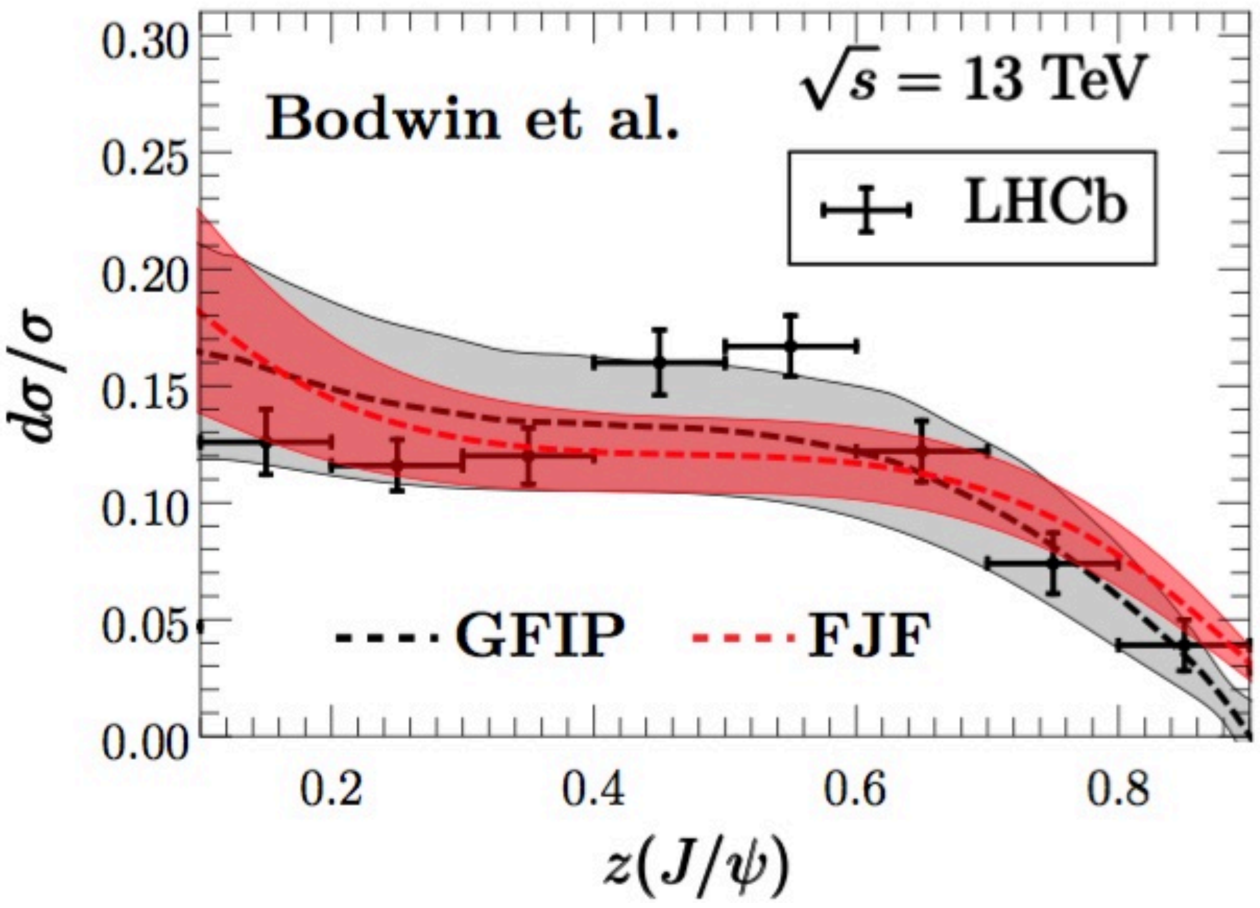
Figure 4: Measured normalized $z(J/\psi)$ distributions for J/ψ mesons produced (left) promptly and (right) in b-hadron decays, compared to predictions obtained from PYTHIA 8. The statistical uncertainties are negligible. The (DPS) double and (SPS) single parton scattering contributions to the prompt prediction are also shown (the DPS effective cross section in PYTHIA 8 is 31 mb).

Remark: NRQCD-based production description in default Pythia is rather naive, and a discrepancy with a thoeretically more robust calculation was first noticed in Bain et al, arXiv:1603.06981
So this comparison is not very compelling in terms of assessing the reliability of NRQCD

First-principle NRQCD predictions







Bain et al, arxiv:1702.05525
See also
Baumgart et al, arXiv:1406.2295
Bain et al, arXiv:1603.06981

FJF: fragmenting jet functions
GFIP: gluon-fragmentation improved Pythia

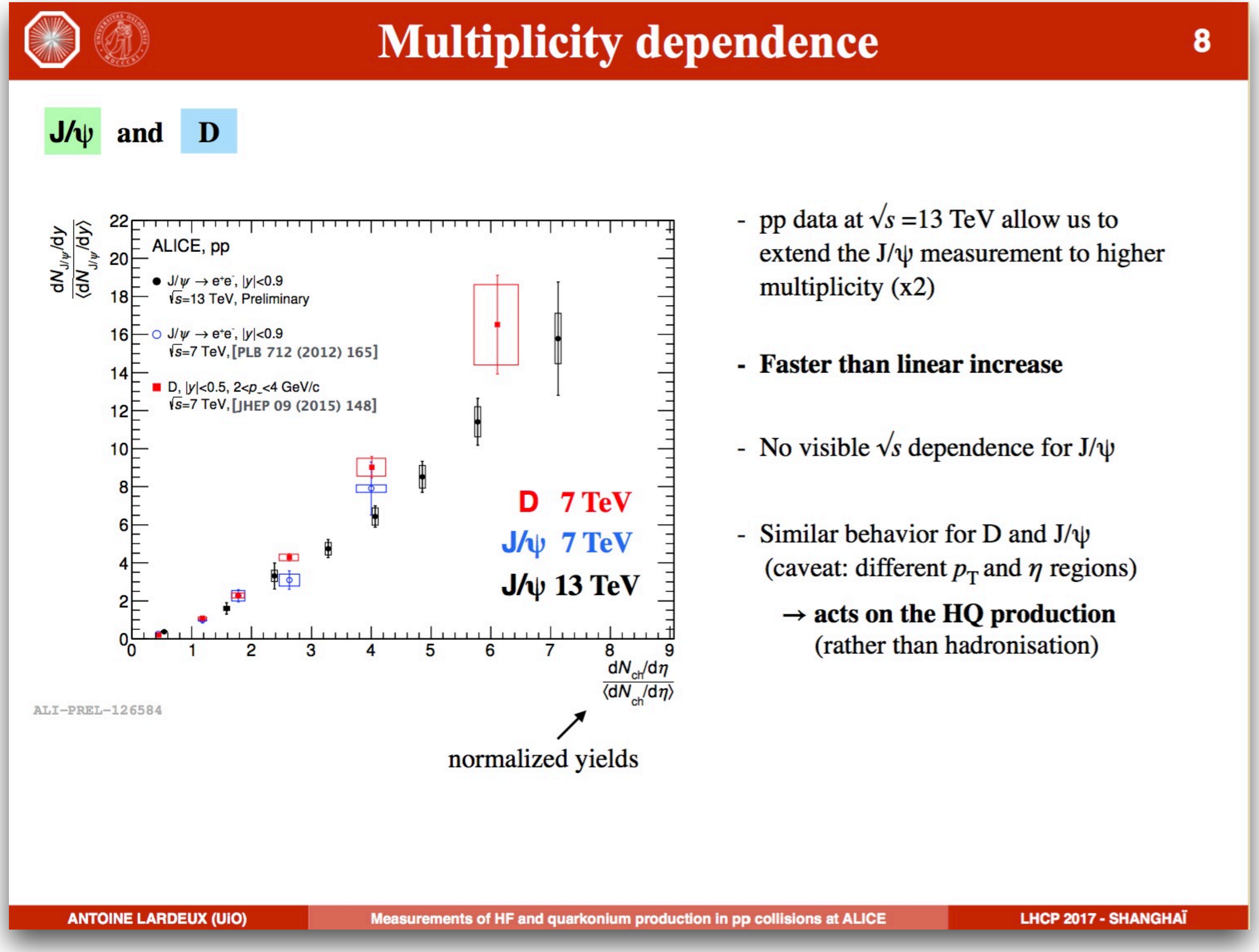
BK, Chao et al, Bodwin et al: different fits of NRQCD LDME

Personal assessment

- Given the complexity of the problem of describing onium production, I believe NRQCD is in good shape
- p_T spectra, across multitude production environments (HERA, Tevatron, LHC) are rather well accounted for
- The situation of polarization is complicated by exisiting internal discrepancies between various measurements at Tevatron and LHC, as well as by the role of feeddown and of different contributions by various states
- Fragmentation function is ok, in my view ….

More avenues

Collective effects in pp collisions?



Multiplicity dependence

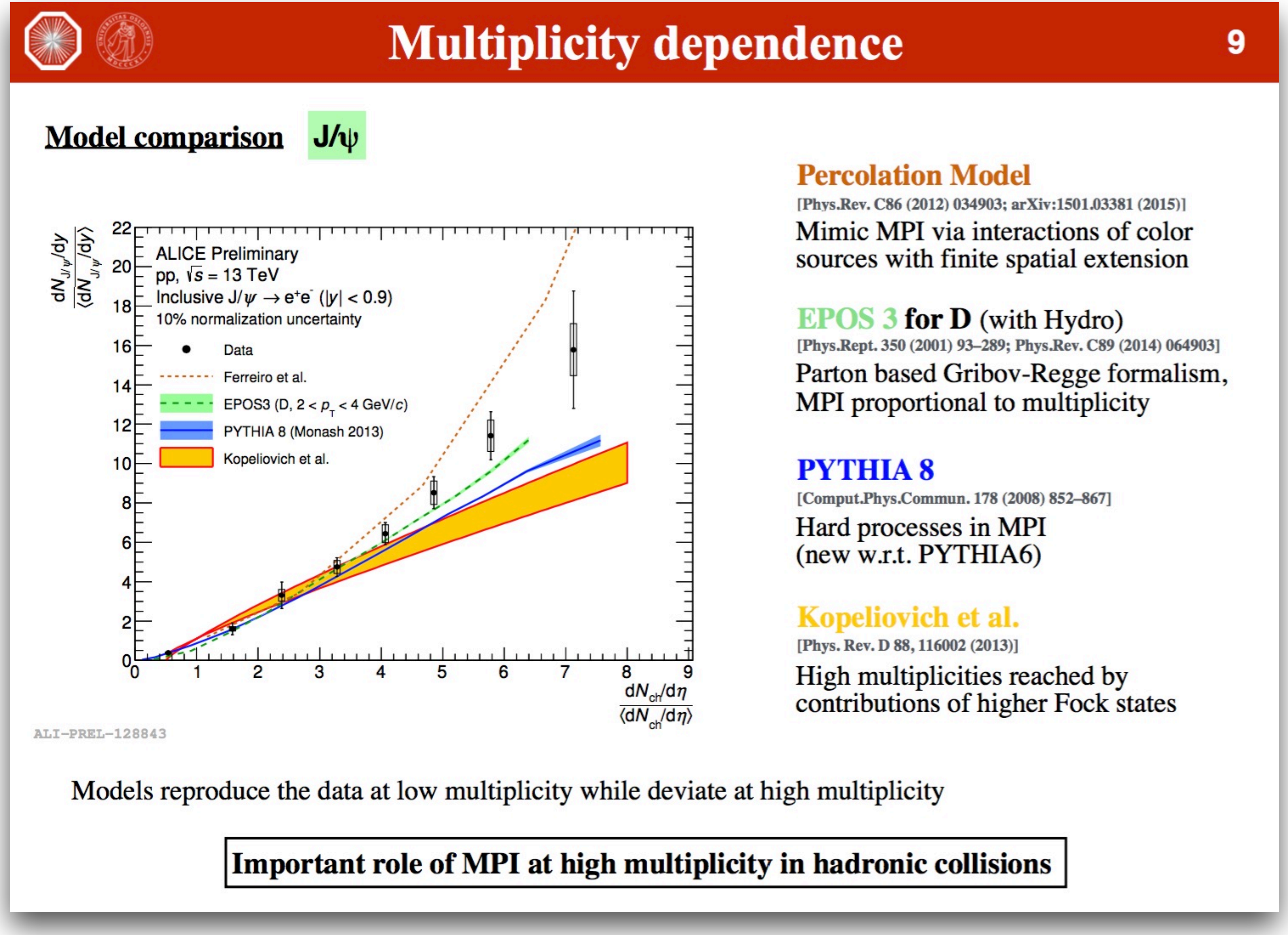
J/ψ and **D**

normalized yields

- pp data at $\sqrt{s}$ =13 TeV allow us to extend the J/ψ measurement to higher multiplicity (x2)
- **Faster than linear increase**
- No visible $\sqrt{s}$ dependence for J/ψ
- Similar behavior for D and J/ψ (caveat: different p_T and η regions)

  → **acts on the HQ production** (rather than hadronisation)

N$_{track}$ dependence not explained by standard MCs



Multiplicity dependence

Model comparison **J/ψ**

Percolation Model

[Phys.Rev. C86 (2012) 034903; arXiv:1501.03381 (2015)]

Mimic MPI via interactions of color sources with finite spatial extension

EPOS 3 for D (with Hydro)

[Phys.Rept. 350 (2001) 93–289; Phys.Rev. C89 (2014) 064903]

Parton based Gribov-Regge formalism, MPI proportional to multiplicity

PYTHIA 8

[Comput.Phys.Commun. 178 (2008) 852–867]

Hard processes in MPI (new w.r.t. PYTHIA6)

Kopeliovich et al.

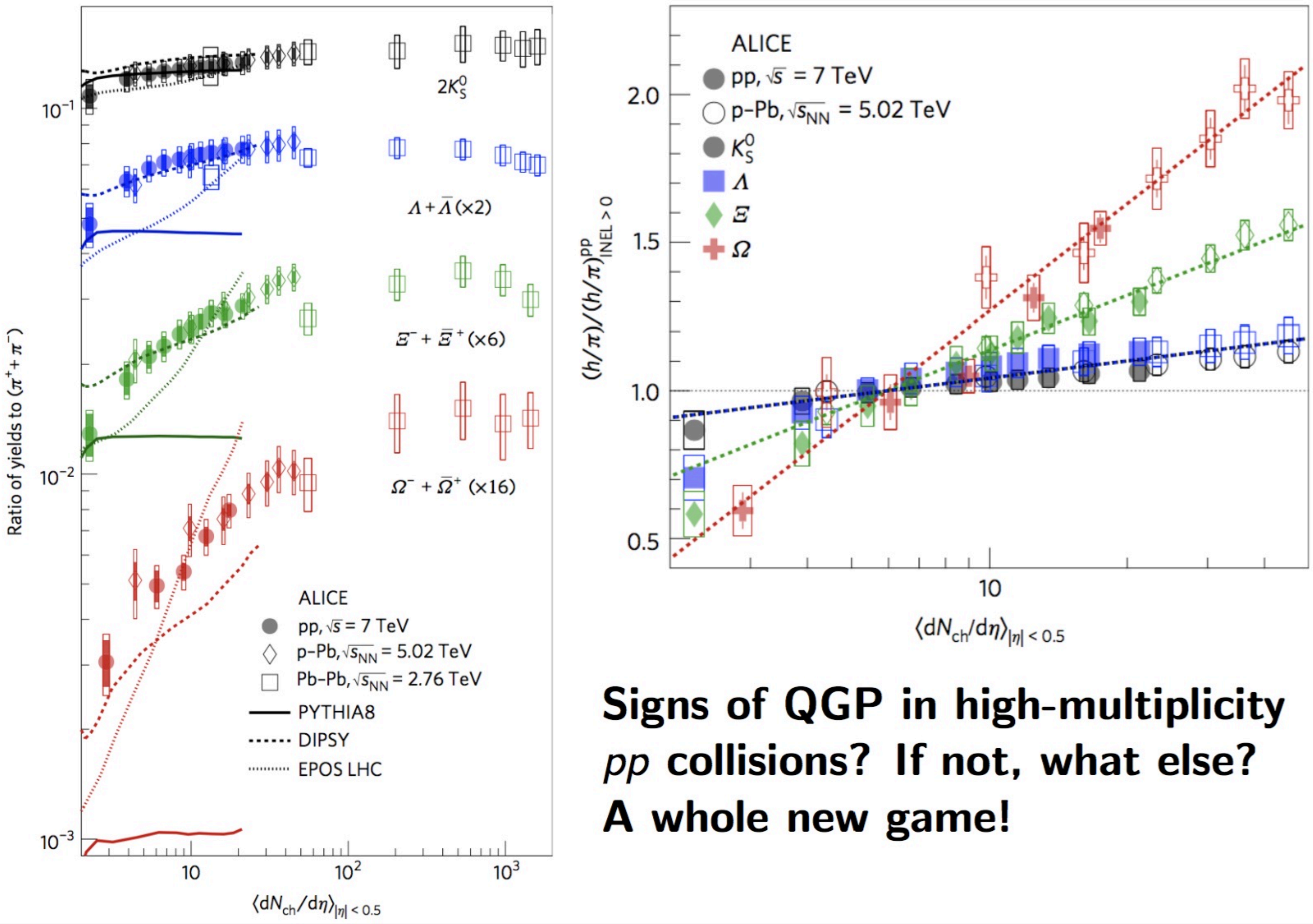
[Phys. Rev. D 88, 116002 (2013)]

High multiplicities reached by contributions of higher Fock states

Models reproduce the data at low multiplicity while deviate at high multiplicity

Important role of MPI at high multiplicity in hadronic collisions

NB



Signs of QGP in high-multiplicity *pp* collisions? If not, what else? A whole new game!

Recent ALICE data on the relative production rate of strange hadrons show an increase with final-state event multiplicity. This is not predicted by standard QCD MCs. It would be interesting to search for a similar effect in f_s/f_d vs $dN_{ch}/d\eta$

Overall conclusions

- HVQ production at LHC remains a highly interesting topic
- Flexibility of LHC operations (different E_{beam}) and of detectors (η range, p_T range, production modes, etc) opens new opportunities for incisive measurements
- TH is slowly but steadily improving, and a set of precise predictions (eg for XS ratios) is available
- The outcome of these measurements has important consequences for a wide array of applications, from PDF fits, low-x gluons, extrapolations to the highest energies, better bg estimates for the study of Higgs properties, new physics searches, CR physics, collective phenomena …