Update on top-pair production

and

new ideas for treating heavy-flavors in the proton

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fastNLO tables with top-pair differential distributions

Czakon, Heymes, Mitov 2017

fastNLO tables for top @ NNLO

- ✓ All distributions computed by us so far are available as files.
- ✓ But they are
  - ✓ Not as convenient
  - ✓ Computed for specific PDF sets and α_S.
- ✓ Recomputing for different parameters is not practical; the full calculation takes 10^4 - 10^5 CPU hours!
- ✓ We have produced differential distribution in the form of fastNLO tables

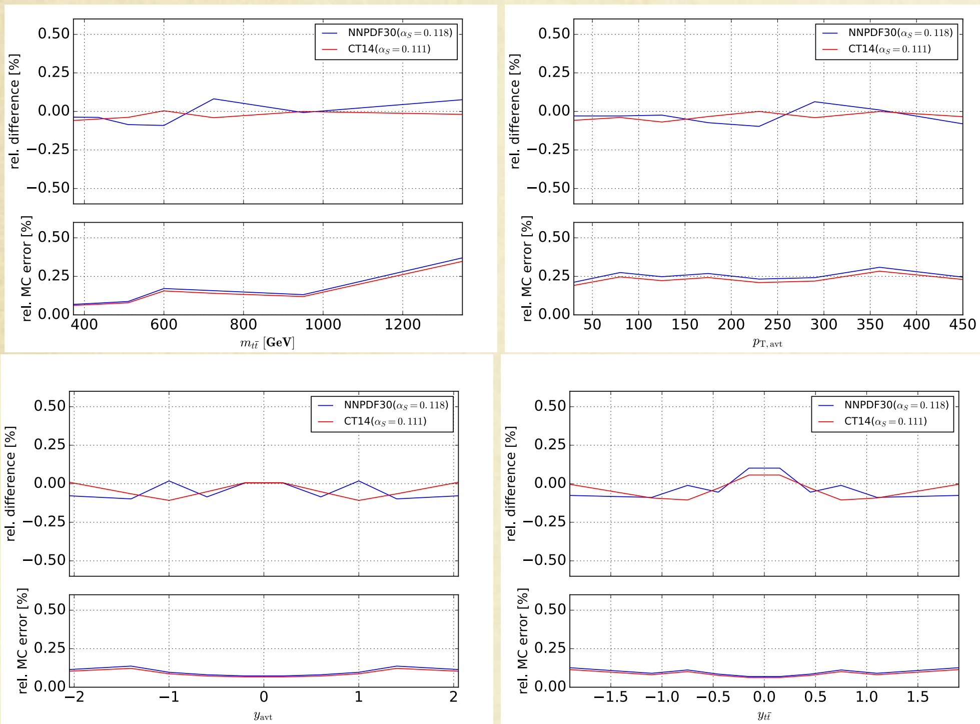
Kluge, Rabbertz, Wobisch, hep-ph/0609285
D. Britzger et al. [fastNLO Collaboration], arXiv:1208.3641

- ✓ Basically, the tables are interpolations of partonic cross-sections (for a fixed distribution and bins).
- ✓ Therefore, it is super fast to recompute the cross-section ~ O(sec's) with new PDF set.
- ✓ This can be used by anybody: PDF fits, experimental and theory studies.
- ✓ One could also include EW effects by rescaling with K-factor (also computed by us – see later)
- ✓ Planning to extend to all future calculations, to 2dim distributions, etc.

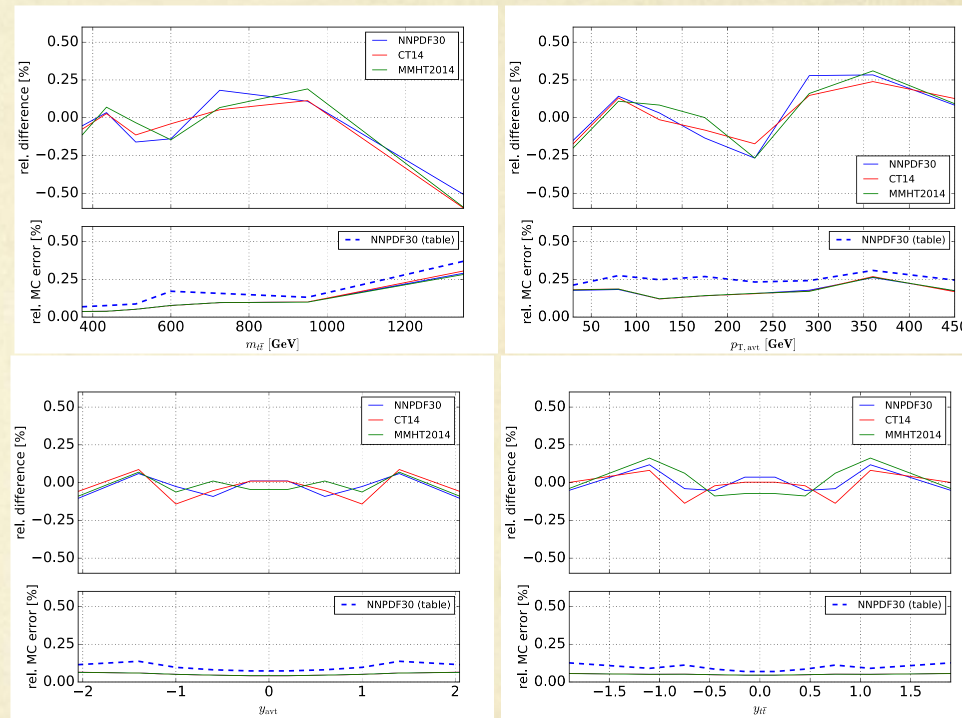
Making the results easy to use

Czakon, Heymes, Mitov 2017

- ✓ fastNLO does not have a utility for estimating MC error
- ✓ We estimate the interpolation error to be very small (permil). The overall quality is similar to previous calculations we have made public



Interpolation error



Absolute error relative to an old calculation for 3 pdf sets

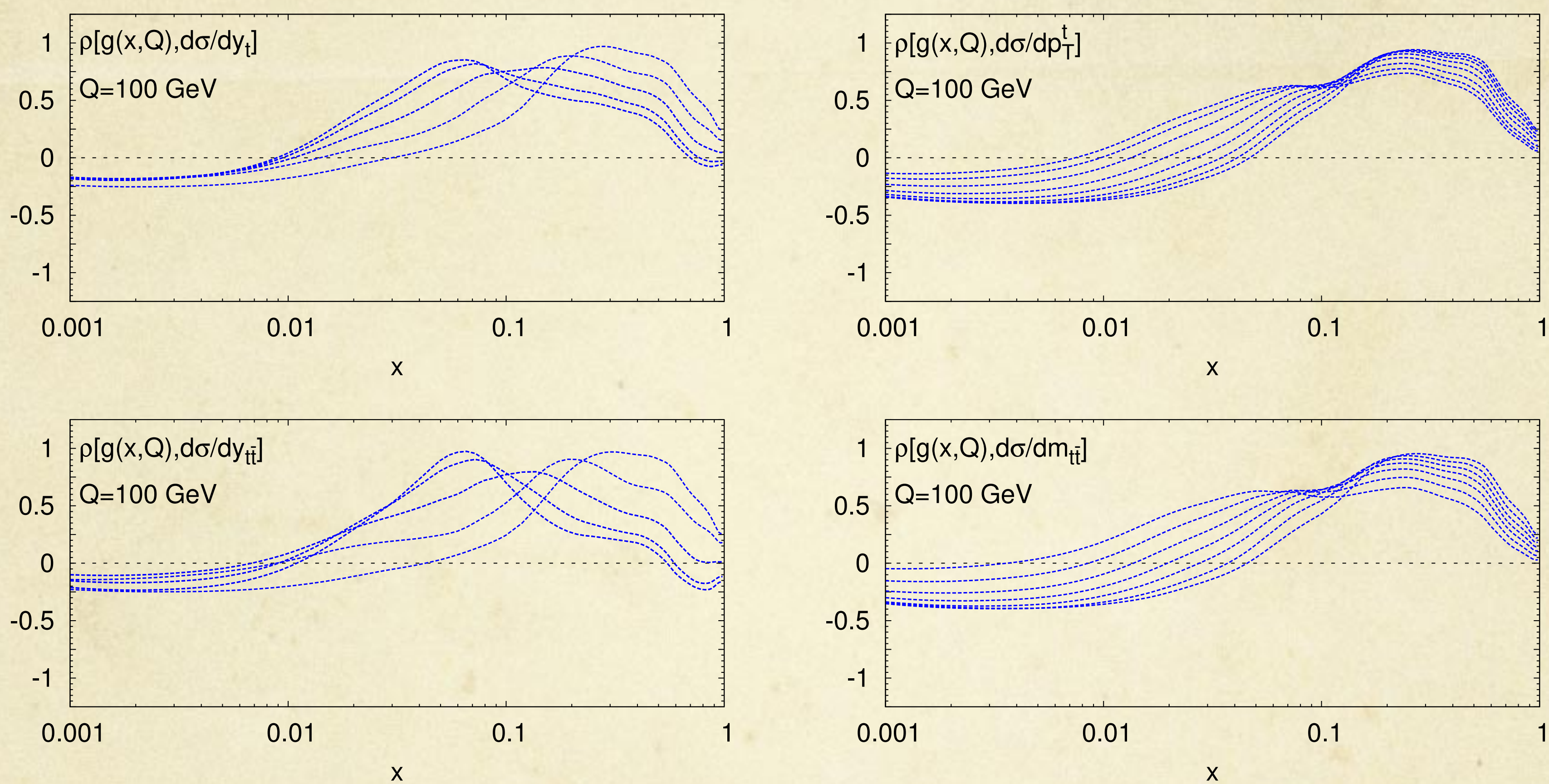
Project website: http://www.precision.hep.phy.cam.ac.uk/results/ttbar-fastnlo/

Fitting PDF from top-pair data

Czakon, Hartland, Mitov, Nocera, Rojo 2016

PDF from LHC data

✓ Top production is very sensitive to the gluon PDF



Czakon, Hartland, Mitov, Nocera, Rojo 2016

✓ No other process offers such access to the gluon PDF at large x!

✓ New study from Z P_T at NNLO has similar sensitivity but not at large x. The two are consistent.

Boughezal, Gufanti, Petriello, Ubiali 2017

PDF from LHC data

Czakon, Hartland, Mitov, Nocera, Rojo 2016

✓ We fit:

- the normalized y_t distribution from ATLAS at $\sqrt{s} = 8$ TeV (lepton+jets channel),
- the normalized $y_{t\bar{t}}$ distribution from CMS at $\sqrt{s} = 8$ TeV (lepton+jets channel),
- total inclusive cross-sections at $\sqrt{s} = 7$, 8 and 13 TeV (all available data).

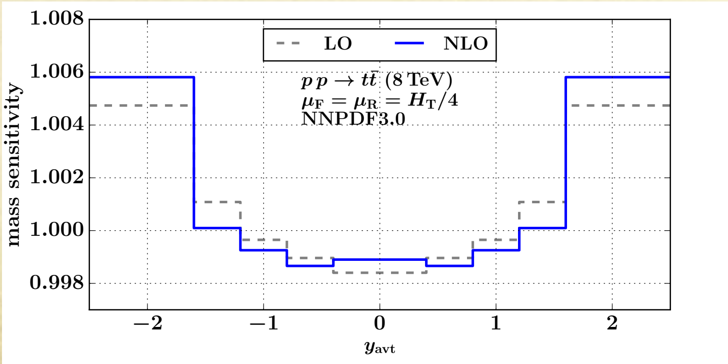
✓ Our benchmark PDF set is NNPDF3.0

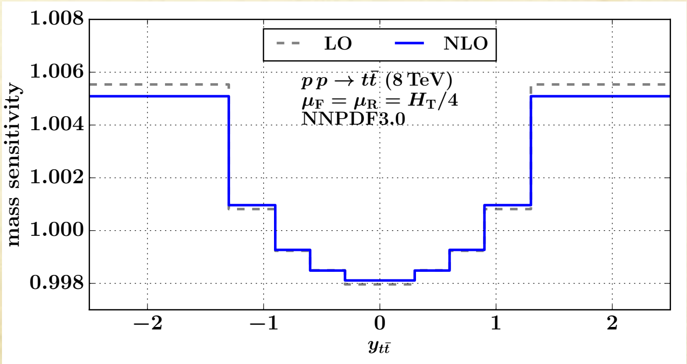
✓ Our fit is global

✓ We find:

✓ It is not easy to fit ATLAS and CMS simultaneously (but each one can be fit individually)

✓ The distributions chosen minimize the impact of
  - ✓ EW corrections (not included)
  - ✓ m_{top} uncertainty (the y_t and y_{tt} distributions are least sensitive to m_{top})

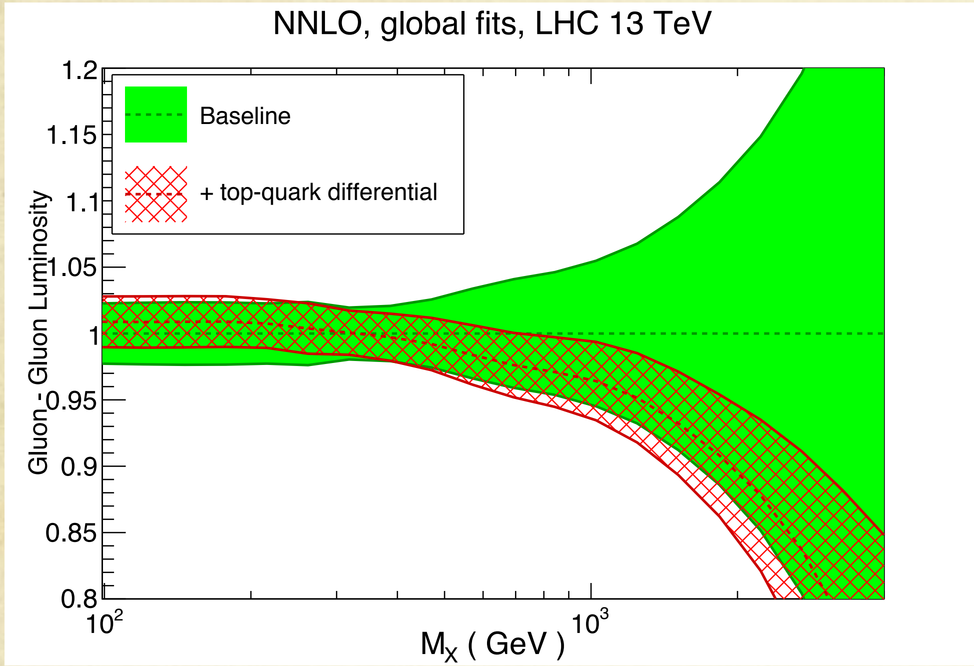


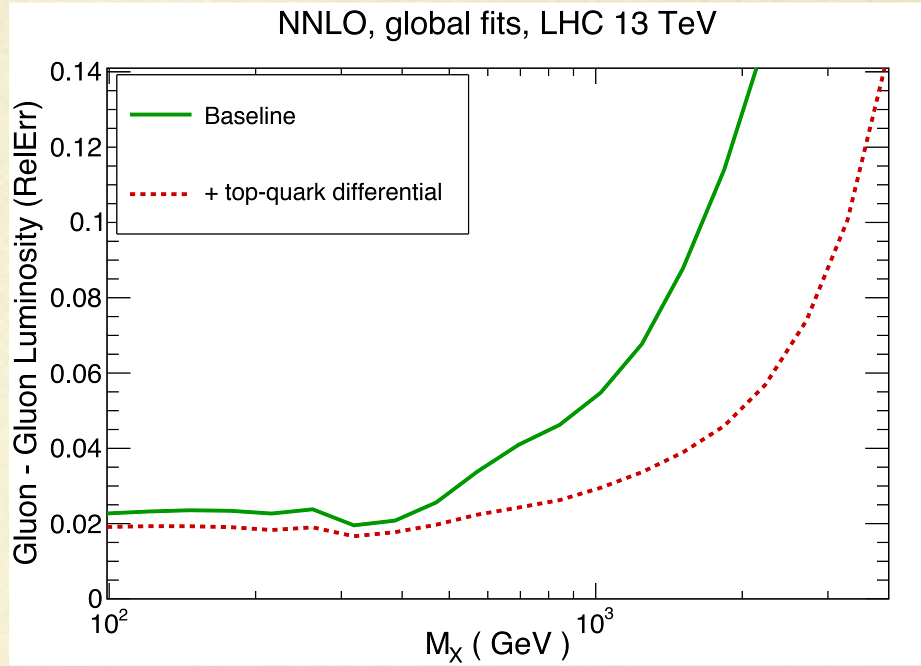


PDF from LHC data

Czakon, Hartland, Mitov, Nocera, Rojo 2016

✓ Improvement in the gluon PDF after top data is included





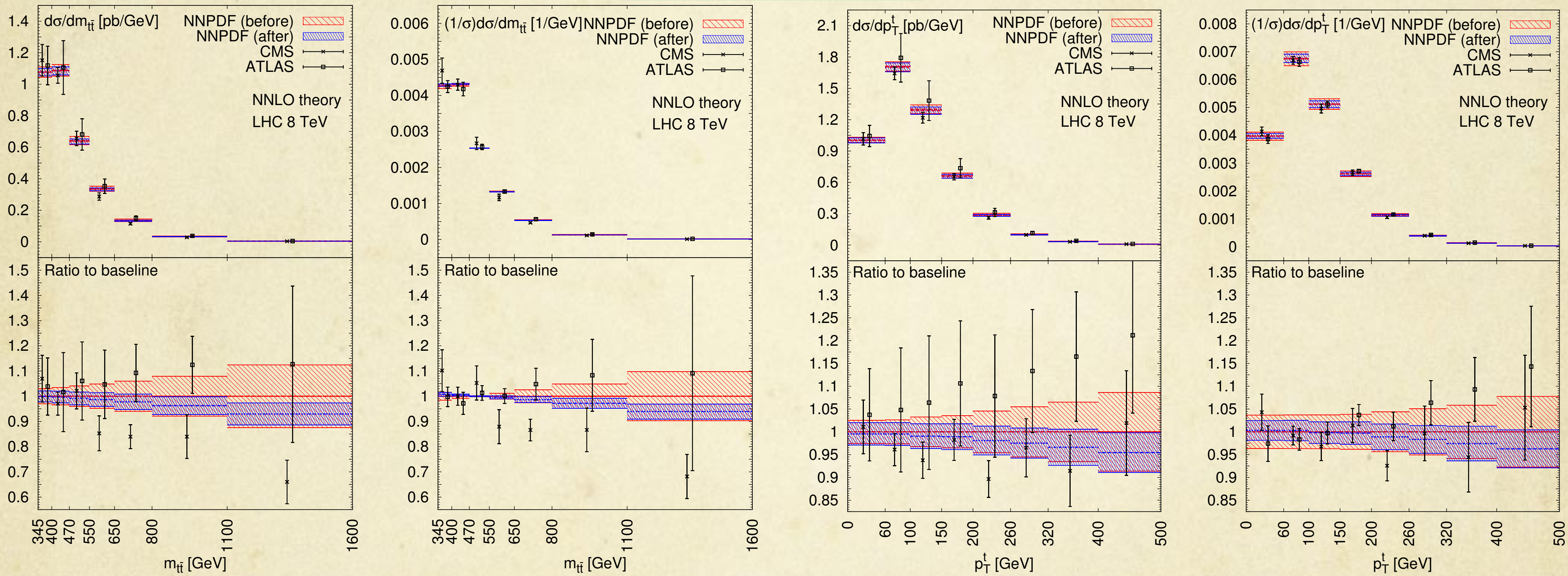
✓ Even jets may not have more constraining power.

PDF from LHC data

Czakon, Hartland, Mitov, Nocera, Rojo 2016

✓ Before the fit / after the fit comparison for the effect on the two distributions that have not been fitted:

PDF error only shown!



✓ Very significant reduction of PDF error!

Combining NNLO QCD with NLO EW

Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro 2017

NNLO QCD + NLO EW

Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro 2017

- ✓ NLO EW corrections were computed 20+ years ago
  - ✓ Tiny for total cross-section (1% or less)
  - ✓ Could be significant differentially, especially for large M_{tt} and P_T.
  - ✓ NLO EW corrections are now automated (several groups). We use aMC@NLO.

See talk by S. Frixione

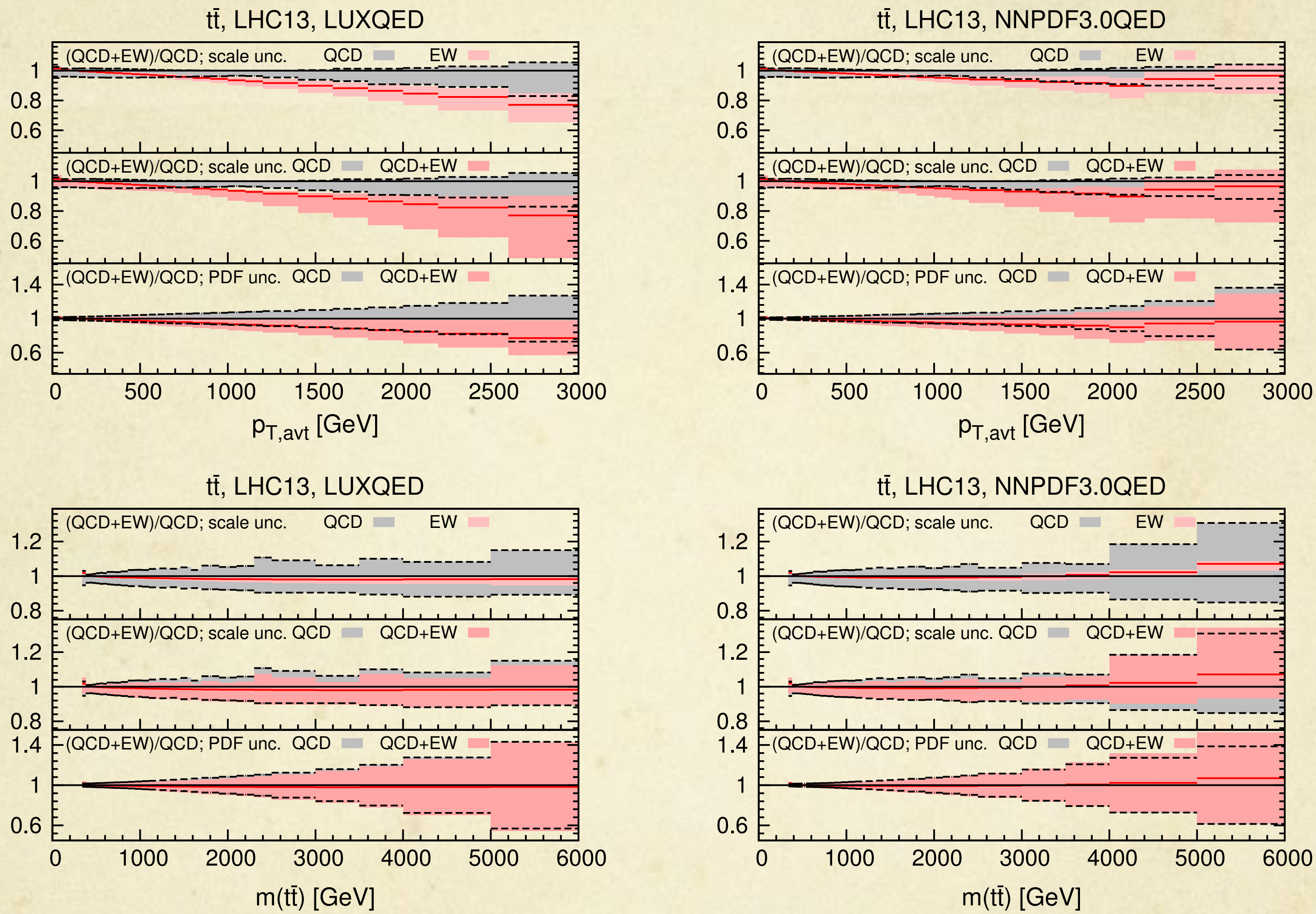
- ✓ We present pheno predictions for both 8 and 13 TeV. We also tackle 3 issues:
  - ✓ The effect of the photon PDF (could be very significant – see next)
  - ✓ The difference between additive and multiplicative approaches for combining QCD+EW (not large – except for very large M_{tt} and P_T)
  - ✓ Heavy boson radiation (tiny)

Project website: http://www.precision.hep.phy.cam.ac.uk/results/ttbar-nnloqcd-nloew/

NNLO QCD + NLO EW

Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro 2017

- ✓ Effect of photon PDF can be very significant



- ✓ The two PDF sets above (LUXqed and NNPDF3.0qed) have very different photon PDF's (but compatible within PDF errors)

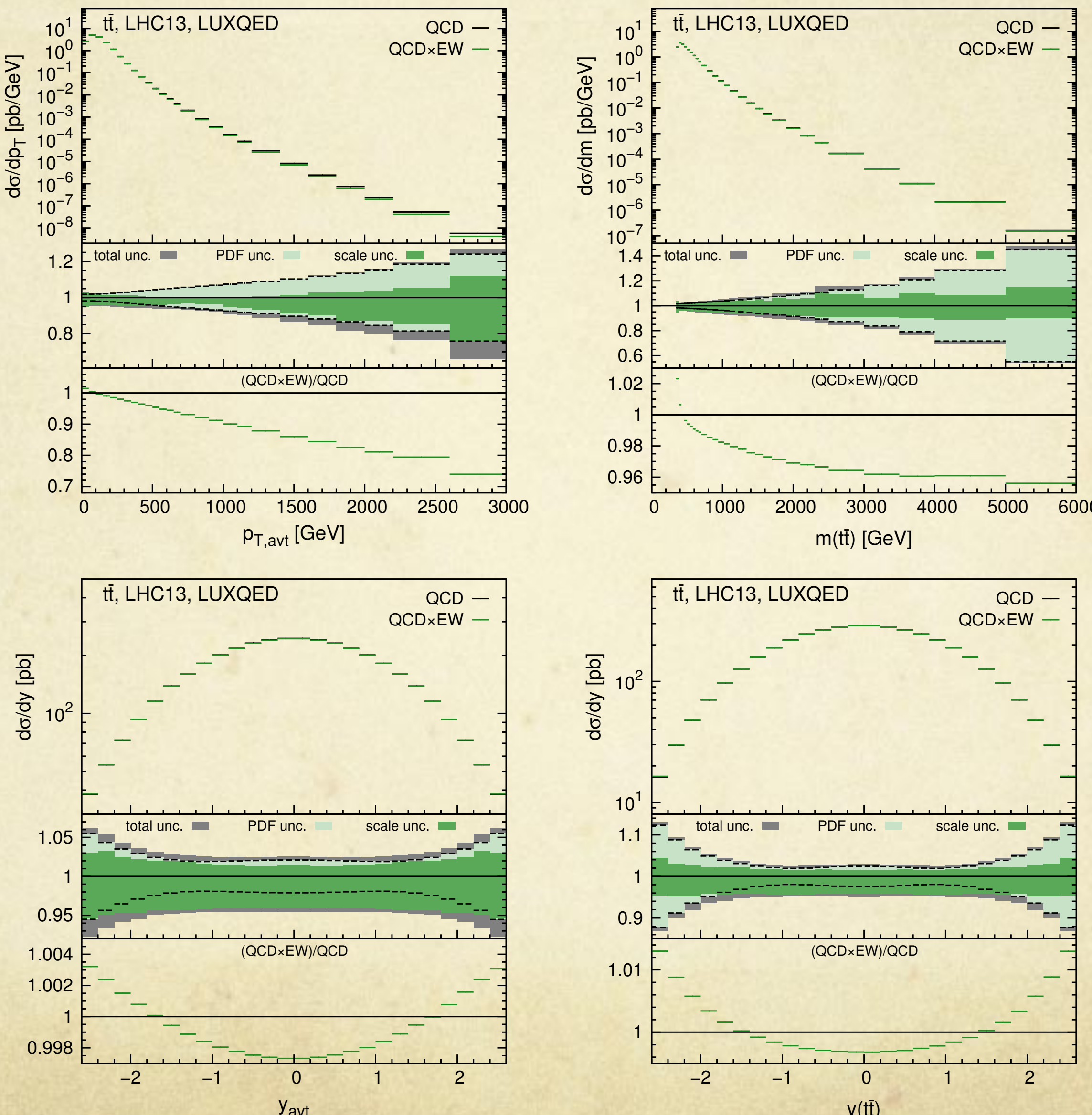
LUXqed = Manohar, Nason, Salam, Zanderighi 2016

- ✓ Much better understanding of the photon PDF in the last 1 year; will impact future PDF sets

NNLO QCD + NLO EW

Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro 2017

✓ Pheno predictions (based on LUXqed pdf set and multiplicative approach)



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All that follows is PRELIMINARY

Part II:

New ideas for treating heavy-flavors in the proton

V. Bertone, Glazov, Mitov, A. Papanastasiou, M. Ubiali , to appear

All in a nutshell

- ✓ Consider bottom as the only heavy flavor (for simplicity)
- ✓ A Variable Flavor Number Scheme (FNS) is better than a fixed FNS
- ✓ How to construct it? Here are the solid basics:
  - ✓ Can't have massive initial partons (dictated by factorization)
  - ✓ When quarks are very heavy they decouple
  - ✓ When very light – should be taken massless
- ✓ However: the intermediate region -- where the theory provides no guidance -- is large
- ✓ In the literature the threshold is taken to be equal to the mass of the heavy quark
  - ✓ Threshold (with/out mass) variation interpreted as uncertainty has been studied in:

Stirling et al '11
Bonvini, Papanastasiou, Tackmann '15

- ✓ We question the wisdom for such a choice and propose a rather different one

On the treatment of heavy flavors in the proton

- ✓ Why in the past the threshold has been taken equal to the mass of the heavy quark?
- ✓ Short answer: a pure accident! Based on:
- ✓ Many years ago, when NLO was something to dream about, people wanted:
  - ✓ Continuity: it was feared that a discontinuity in the pdf at threshold may induce discontinuities in observables.
  - ✓ Of course, we still want continuity: we observe that at higher orders continuity in observables is restored for a range of thresholds! In other words the discontinuity in PDFs need not be feared.
  - ✓ At LO in QCD, the matching is continuous for any value of the threshold
  - ✓ At NLO the continuity of PDFs is only present if the threshold is chosen to be at the heavy quark mass
  - ✓ The mass m is a “natural” scale
- ✓ However, this continuity at NLO is just an accident and is not a feature that persists
  - ✓ In the space-like at higher orders (NNLO and N^3LO)
  - ✓ In the time-like
  - ✓ For α_S.

Our proposal

- ✓ It is all very simple:
  - ✓ Take the threshold to be significantly higher than the mass (x5 – x10)
  - ✓ Assume the functional form of μ_F and μ_R has been chosen. For simplicity we take $\mu_F=\mu_R$.
  - ✓ Below threshold (i.e. $\mu_F < \mu_{THR}$) we work in 4FS, as usual
  - ✓ Above threshold (i.e. $\mu_F > \mu_{THR}$) we work in 5FS with a massless heavy flavor
- ✓ Massless calculations account for all terms $\sim \ln^n(m)$ and m^0. They only miss terms of $O(m^2)$
- ✓ Our approach involves an approximation; however, unlike the standard case we have a parameter that controls the error: $O(m^2/\mu^2_{THR})$
- ✓ If $\mu_{THR} = (5–10) \times m$, then missing power corrections are completely negligible (1%-4%)
- ✓ Benefits:
  - ✓ No need for complicated and sometimes cumbersome prescriptions
  - ✓ Use ‘plain’ calculations that are always used in their region of validity
  - ✓ Control over $O(m^2)$ type terms
  - ✓ Threshold should not be taken too high (more than around x10) in order not to spoil collinear resummation.

Effect on PDFs

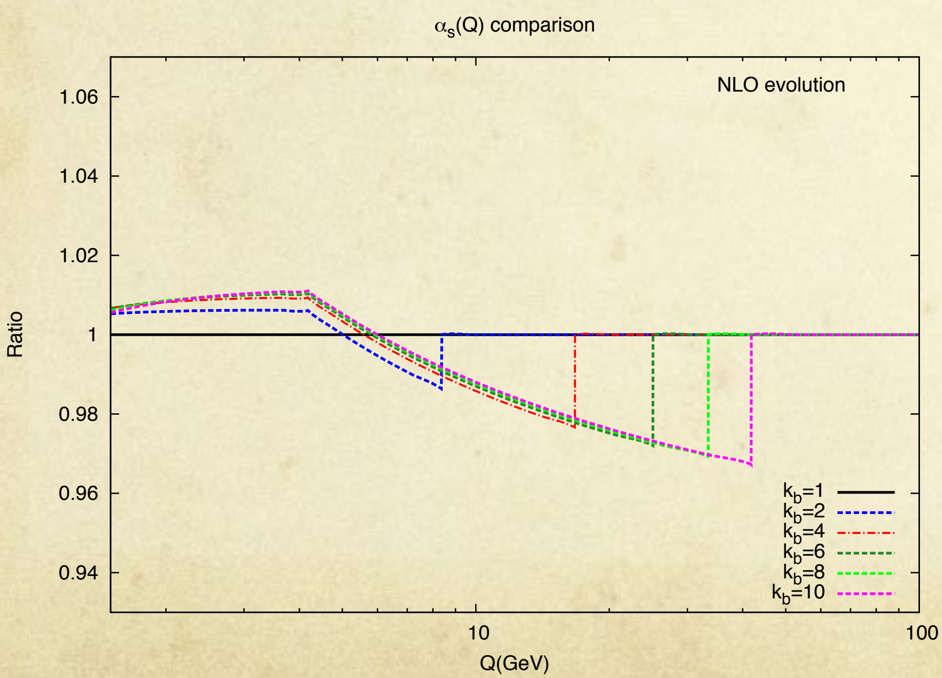
✓ The first thing to consider is the effect on α_S and PDFs

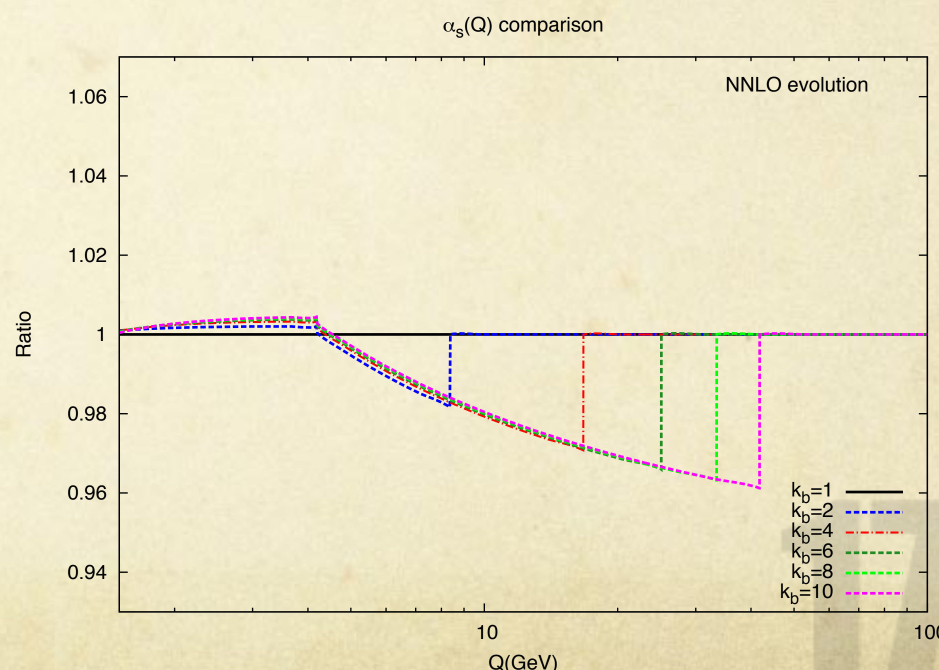
✓ To this end we have generate a family of PDFs, based on NNPDF3.0, with various thresholds spanning the range [1 – 10] x m.

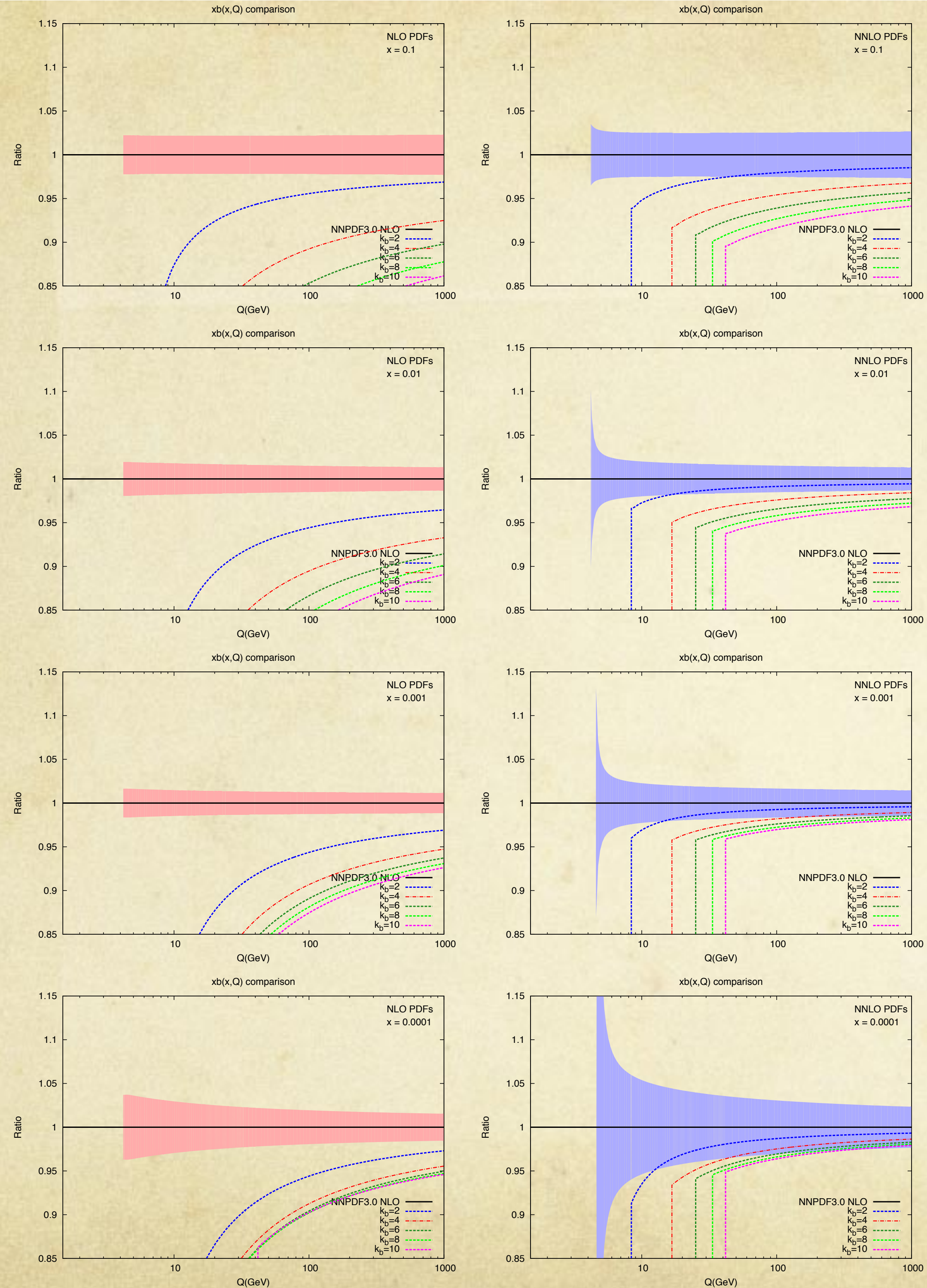
✓ Evolution for each set is done consistently, at LO, NLO and NNLO.

✓ Charm and top are considered here as usual. In principle their thresholds should be increased.

✓ The scale dependence of α_S , shown relative to the standard case, looks like:







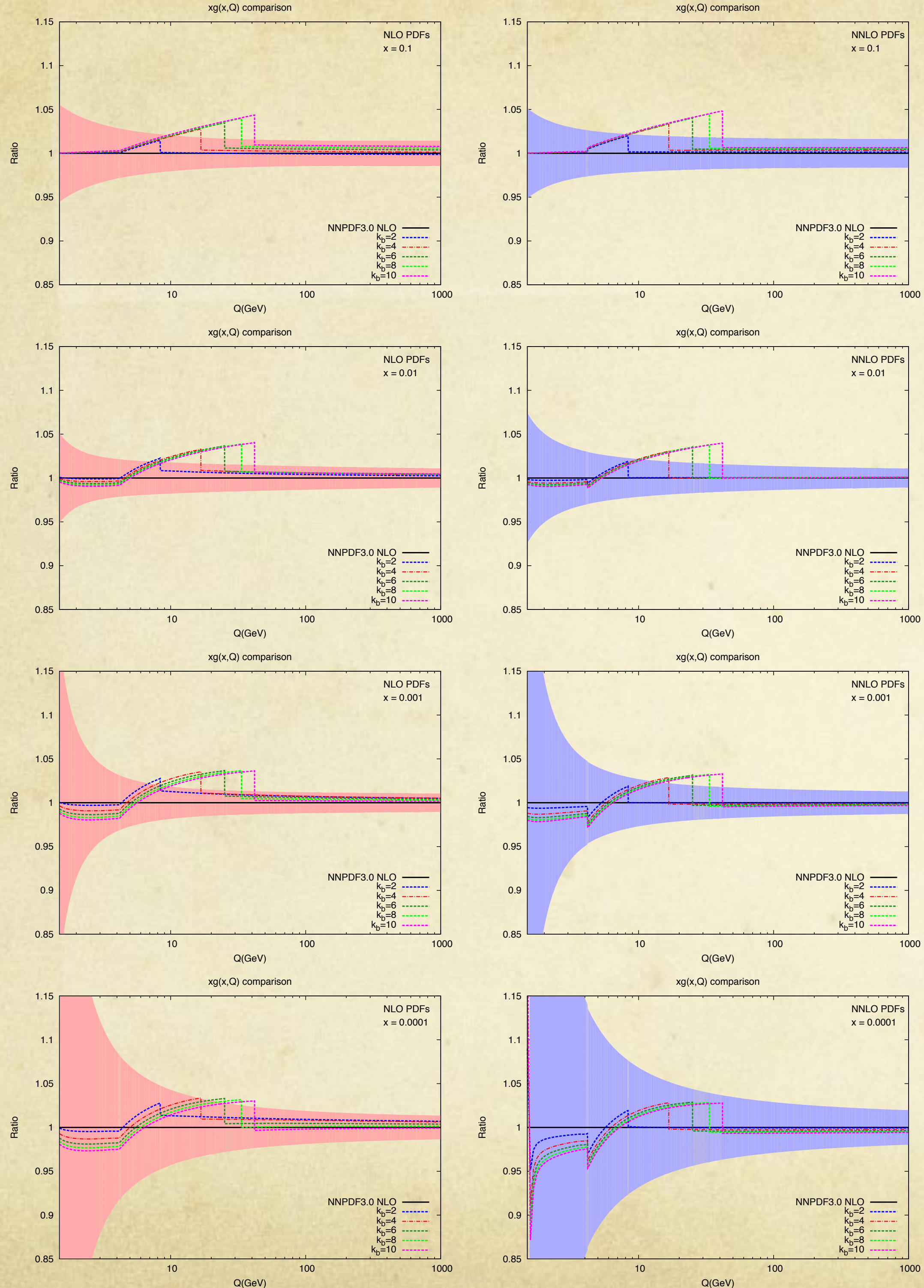
b - PDF

NLO (left) and NNLO (right)

for four values of x

Note the drastic improvement at NNLO

“Discontinuities are good”



g - PDF

NLO (left) and NNLO (right)

for four values of x

Note the agreement between all sets at large Q (as desired).

NNLO an improvement over NLO

"Discontinuities are good"

Similar story for all other PDFs

Effect on observables

- ✓ The discontinuities in α_S and PDFs are clearly visible. What happens with observables?

- ✓ We study the effect on:

  1. Standard precision LHC candles (tt, single top, Higgs, Z)
  2. Processes sensitive to b-PDF (single top, bbZ, b-jet P_T in b+Z)
  3. Discontinuities in 2) and in tt-like and Z-like processes that can be computed through NNLO in both 4FS and 5FS (Z-like means Z production but with modified m_Z; same for top)

- ✓ We observe the amazing self-consistency of the theory:

  - ✓ The large discontinuities in α_S and PDFs are nowhere to be found in observables.

  - ✓ In other words, an apparent cancellation takes place

    - ✓ A hint of a possible non-minimal formulation of the theory?

- ✓ It is absolutely essential to not only look at LO but always at NLO and whenever possible at NNLO.

- ✓ Huge improvement from the inclusion of higher orders which brings about continuity in observables.

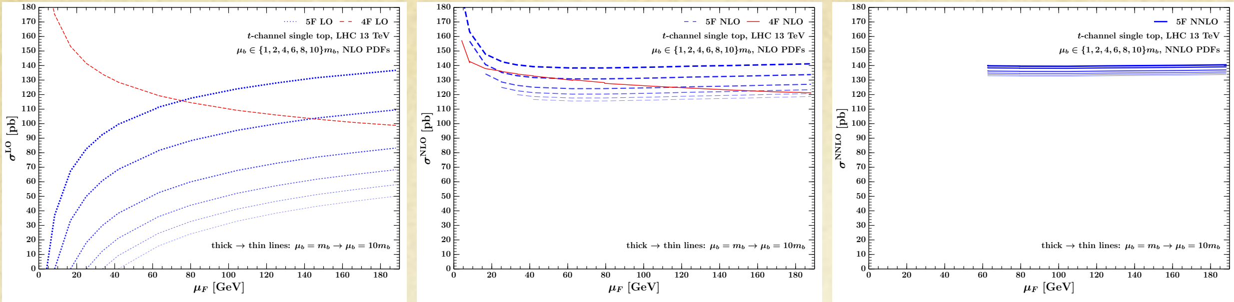


Figure 1. Single top t-channel cross-section at LHC 13 TeV at LO (left), NLO (center) and NNLO (right) as a function of μ_F for several values of μ_b.

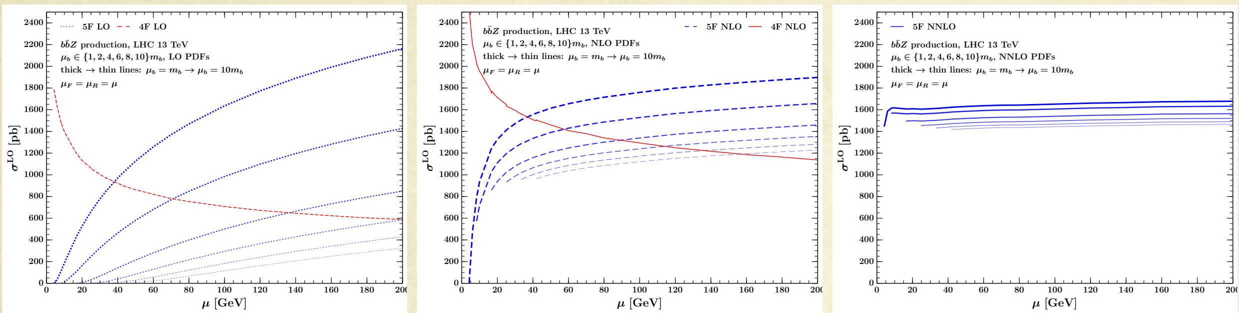


Figure 2. As in fig. 1 but for the total $b\bar{b}Z$ production cross-section at LHC 13 TeV.

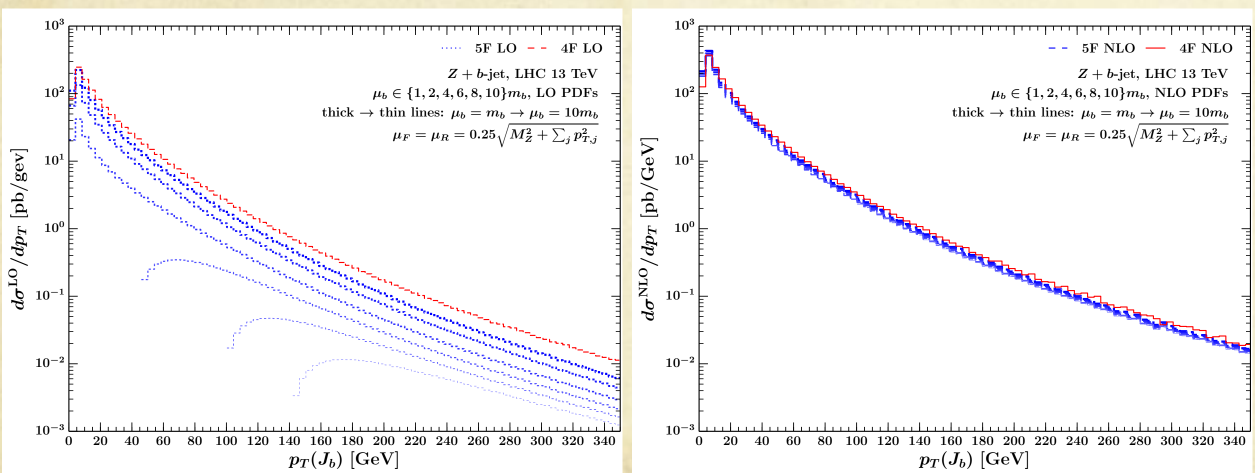


Figure 3. The differential cross-section of $Z + b$-jet at LHC 13 TeV as a function of $p_T(J_b)$ at LO (left) and NLO (right) for several values of μ_b.

Effect on observables

Drastic improvement from inclusion of higher orders

Discontinuities in observables

$$\text{Discontinuity} = 1 - \frac{\sigma^{5\text{F}}(m \text{ fixed}, \mu_{F,R} = \mu_b + \epsilon)}{\sigma^{4\text{F}}(m \text{ fixed}, \mu_{F,R} = \mu_b - \epsilon)}\,,$$

- ✓ Drastic improvement from inclusion of higher orders
- ✓ Improvement with larger thresholds

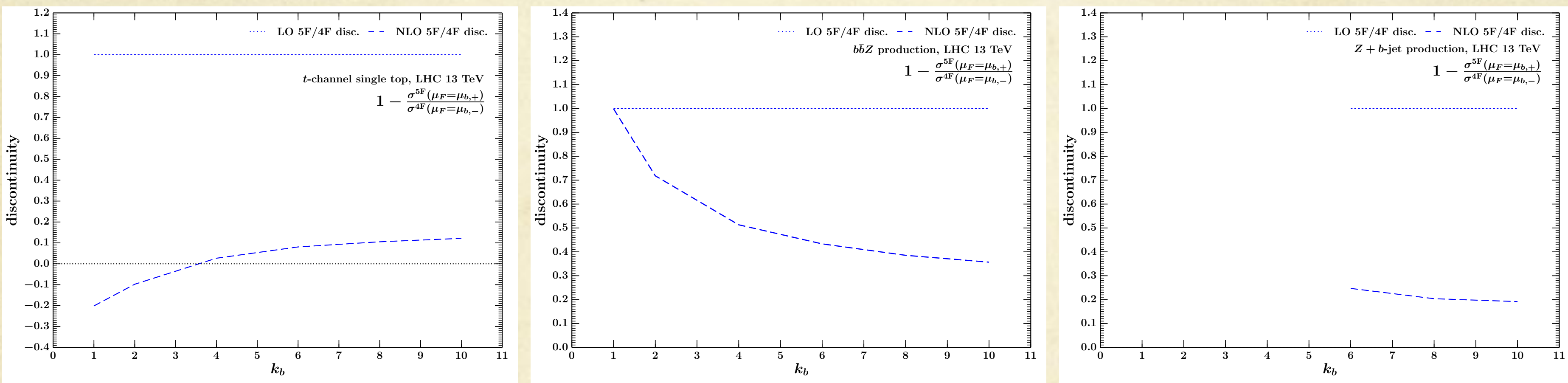


Figure 7. Discontinuity between 5F cross-section above threshold and 4F cross-section below threshold for LO (dotted) and NLO (dashed) for t-channel single top cross-section (left), $b\bar{b}Z$ production cross-section (center) and the $p_T(J_b)$ differential distribution in $Z+b$ (right). All are for LHC at 13 TeV as a function of k_b. The discontinuity is defined in eq. 3.3.

Standard LHC candles (Z and tt)

k_{μ_b}	σ_{LO} [pb]	σ_{NLO} [pb]	σ_{NNLO} [pb]
1	4.42964E+04	5.42333E+04	5.64074E+04
2	4.46018E+04 (+0.7%)	5.43158E+04 (+0.1%)	5.62619E+04 (-0.3%)
4	4.51340E+04 (+1.9%)	5.40903E+04 (-0.3%)	5.60047E+04 (-0.7%)
6	4.55424E+04 (+2.8%)	5.38918E+04 (-0.6%)	5.58349E+04 (-1.0%)
8	4.58731E+04 (+3.6%)	5.37355E+04 (-0.9%)	5.57117E+04 (-1.2%)
10	4.61520E+04 (+4.2%)	5.36088E+04 (-1.2%)	5.56158E+04 (-1.4%)

Table 3. Dependence of the total Z cross section at LHC 13 TeV on the threshold scale $\mu_b = k_{\mu_b} m_b$ (recall that $k_{\mu_b} = 1$ represents the standard choice in all publicly available PDF sets). Shown is the 5FS cross-section predicted at LO, NLO and NNLO for $m_Z = \mu_R = \mu_F = 91.1876$ GeV.

k_{μ_b}	σ_{LO} [pb]	σ_{NLO} [pb]	σ_{NNLO} [pb]
1	560.86	735.21	806.15
2	566.28 (+1.0%)	736.49 (+0.2%)	807.50 (+0.2%)
4	570.59 (+1.7%)	739.52 (+0.6%)	809.22 (+0.4%)
6	572.63 (+2.1%)	741.78 (+0.9%)	810.33 (+0.5%)
8	573.86 (+2.3%)	743.53 (+1.1%)	811.14 (+0.6%)
10	574.70 (+2.5%)	744.95 (+1.3%)	811.78 (+0.7%)

Table 4. Dependence of the $t\bar{t}$ total cross section at LHC 13 TeV on the threshold scale $\mu_b = k_{\mu_b} m_b$ (recall that $k_{\mu_b} = 1$ represents the standard choice in all publicly available PDF sets). Shown is the 5FS cross-section predicted at LO, NLO and NNLO for $m_t = \mu_R = \mu_F = 173.3$ GeV.

Standard LHC candles (ggH and t-ch top)

k_{μ_b}	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]	$\sigma_{\rm NNLO}$ [pb]
1	18.375	35.055	44.423
2	18.836 (+2.5%)	35.327 (+0.8%)	44.466 (+0.1%)
4	19.332 (+5.2%)	35.442 (+1.1%)	44.480 (+0.1%)
6	19.635 (+6.7%)	35.466 (+1.2%)	44.481 (+0.1%)
8	19.855 (+8.1%)	35.469 (+1.2%)	44.478 (+0.1%)
10	20.028 (+9.0%)	35.465 (+1.2%)	44.475 (+0.1%)

Table 5. Dependence of the ggH total cross section at LHC 13 TeV on the threshold scale $\mu_b = k_{\mu_b} m_b$ (recall that $k_{\mu_b} = 1$ represents the standard choice in all publicly available PDF sets). Shown is the 5FS cross-section predicted at LO, NLO and NNLO for $m_H = 2\mu_R = 2\mu_F = 125.0$ GeV.

k_{μ_b}	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]	$\sigma_{\rm NNLO}$ [pb]
1	119.19	138.28	139.90
2	90.26 (-24.2%)	130.78 (-5.4%)	138.48 (-1.0%)
4	62.22 (-47.8%)	124.10 (-10.2%)	136.30 (-2.6%)
6	46.30 (-61.2%)	120.34 (-13.0%)	134.90 (-3.6%)
8	35.23 (-70.4%)	117.69 (-14.9%)	133.86 (-4.3%)
10	26.78 (-77.5%)	115.63 (-16.4%)	133.03 (-4.9%)

Table 6. Dependence of the single-top total cross section at LHC 13 TeV on the threshold scale $\mu_b = k_{\mu_b} m_b$ (recall that $k_{\mu_b} = 1$ represents the standard choice in all publicly available PDF sets). Shown is the 5FS cross-section predicted at LO, NLO and NNLO. We set $m_t = 173.3$ GeV and $\mu_{F,R} = m_t/2$.

$R_{t/\bar{t}}$ is unaffected

Conclusions

- ✓ Update on new results in precision top-pair production at LHC
    - ✓ Results in new format: first NNLO calculation using fastNLO tables
    - ✓ Merged with EW corrections
    - ✓ Applications: PDF extraction: best tool for gluon
- ✓ New take on how to treat heavy-flavors in proton PDF
- ✓ Idea very simple: significantly increase the threshold
    - ✓ This is the only parameter which the theory does not specify; has not been explored.
- ✓ Discontinuities in coupling and PDFs do not lead to as large discontinuities in observables!
- ✓ The largest effect we could find is in single top: total x-section lowered by almost 5% compared to standard case. This is large compared to NNLO scale error but comparable to (future) experimental error.
- ✓ Standard candles have small changes.
- ✓ Approach would be very appropriate for top. So far all top calculations done in 5FS, not 6FS, despite kinematics is in the TeV range.