Recent developments in precision top-pair production at hadron colliders

Alexander Mitov

Cavendish Laboratory

UNIVERSITY OF CAMBRIDGE

Work with Michael Czakon, David Heymes and others

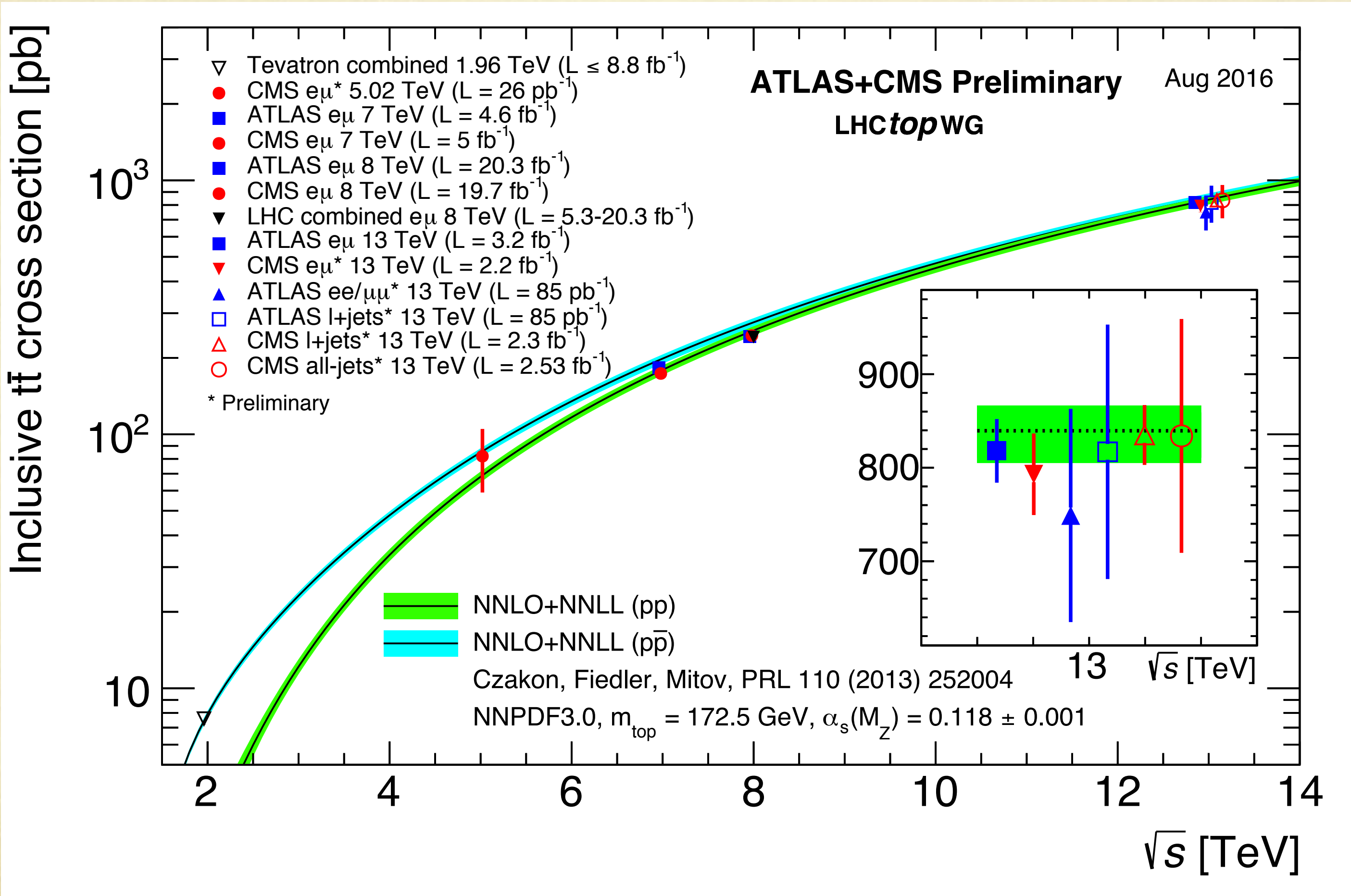
Content of the talk

- Introduction
- Precision top-pair production status report
  - differential tt production
  - Applications
    - PDF extraction
    - Combined NNLO QCD + NLO EW
    - Usability: fastNLO tables
  - Bump searches
- Top mass extraction at the LHC: *the real issues*
- Summary and Outlook
- (will not present anything on single top or top decay)

Introduction

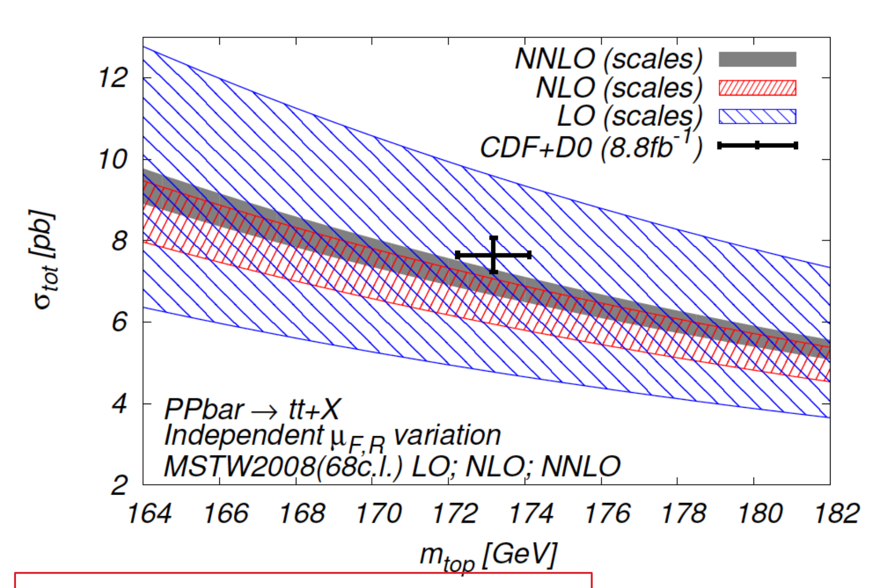
✓ The cross-section agrees well for all measured collider energies:

Tevatron + ATLAS + CMS combination 2016

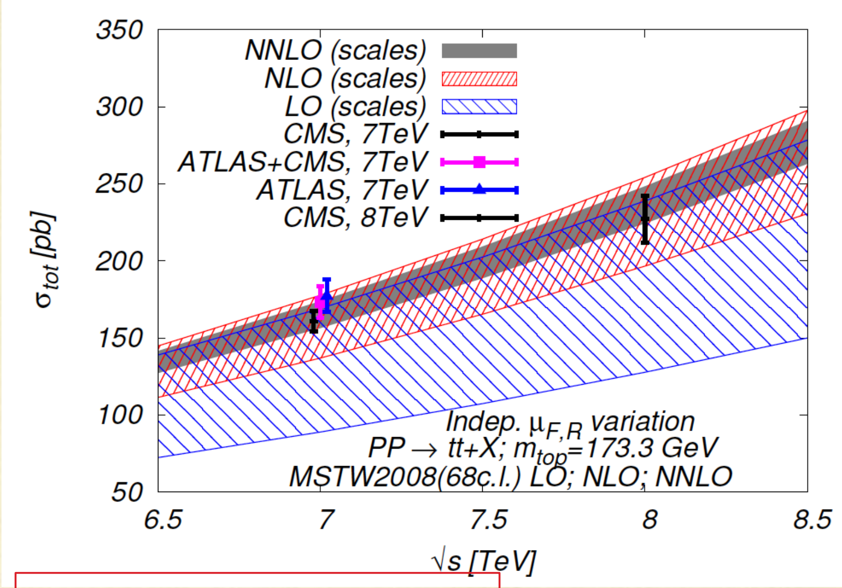


Good perturbative convergence

✓ Independent F/R scales variation



Scale variation @ Tevatron



Scale variation @ LHC

✓ Good overlap of various orders (LO, NLO, NNLO).

✓ Suggests the (restricted) independent scale variation is a good estimate of missing higher order terms!

This is very important: good control over the perturbative corrections justifies less-conservative overall error estimate, i.e. more predictive theory.

For more detailed comparison, including soft-gluon resummation, see arXiv 1305.3892

LHC: general features at NNLO+NNLL

Czakon, Fiedler, Mitov ‘13

Czakon, Mangano, Mitov, Rojo ‘13

✓ We have reached a point of saturation: uncertainties due to

- ✓ scales (i.e. missing yet-higher order corrections) ~ 3%
- ✓ pdf (at 68%cl) ~ 2-3%
- ✓ $alpha_S$ (parametric) ~ 1.5%
- ✓ m_{top} (parametric) ~ 3%

→ All are of similar size!

✓ Soft gluon resummation makes a difference: scale uncertainty 5% → 3%

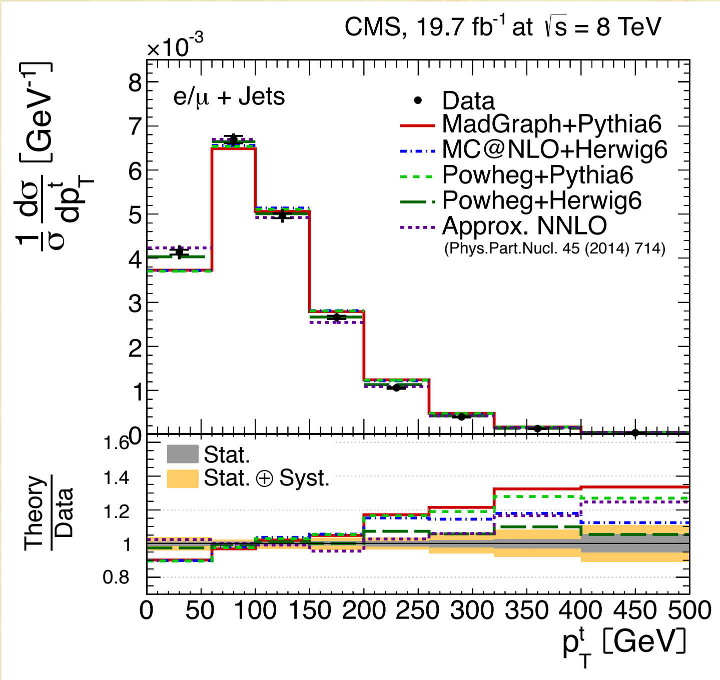
✓ The total uncertainty tends to decrease when increasing the LHC energy

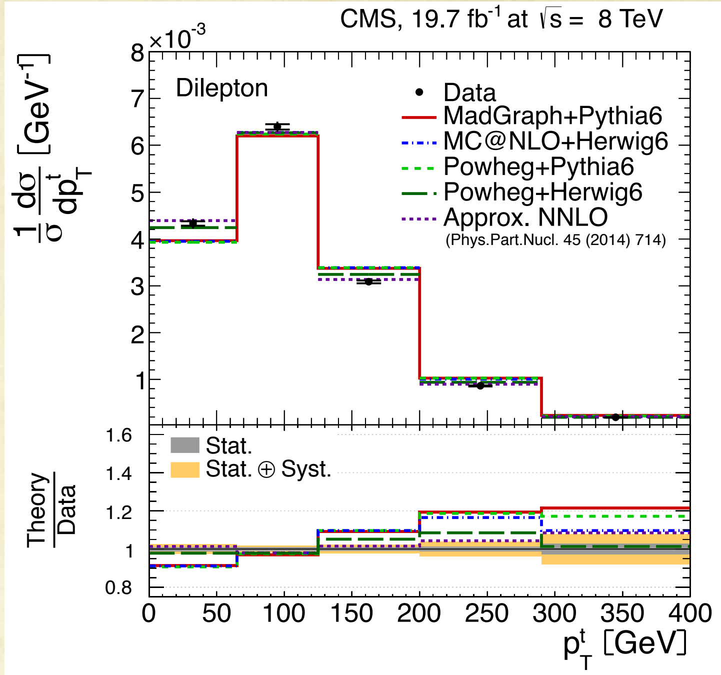
Fully differential tt production at hadron colliders

6

The LHC top P_T discrepancy

✓ Since 2012 there has been a consistent discrepancy between top quark measurements and SM



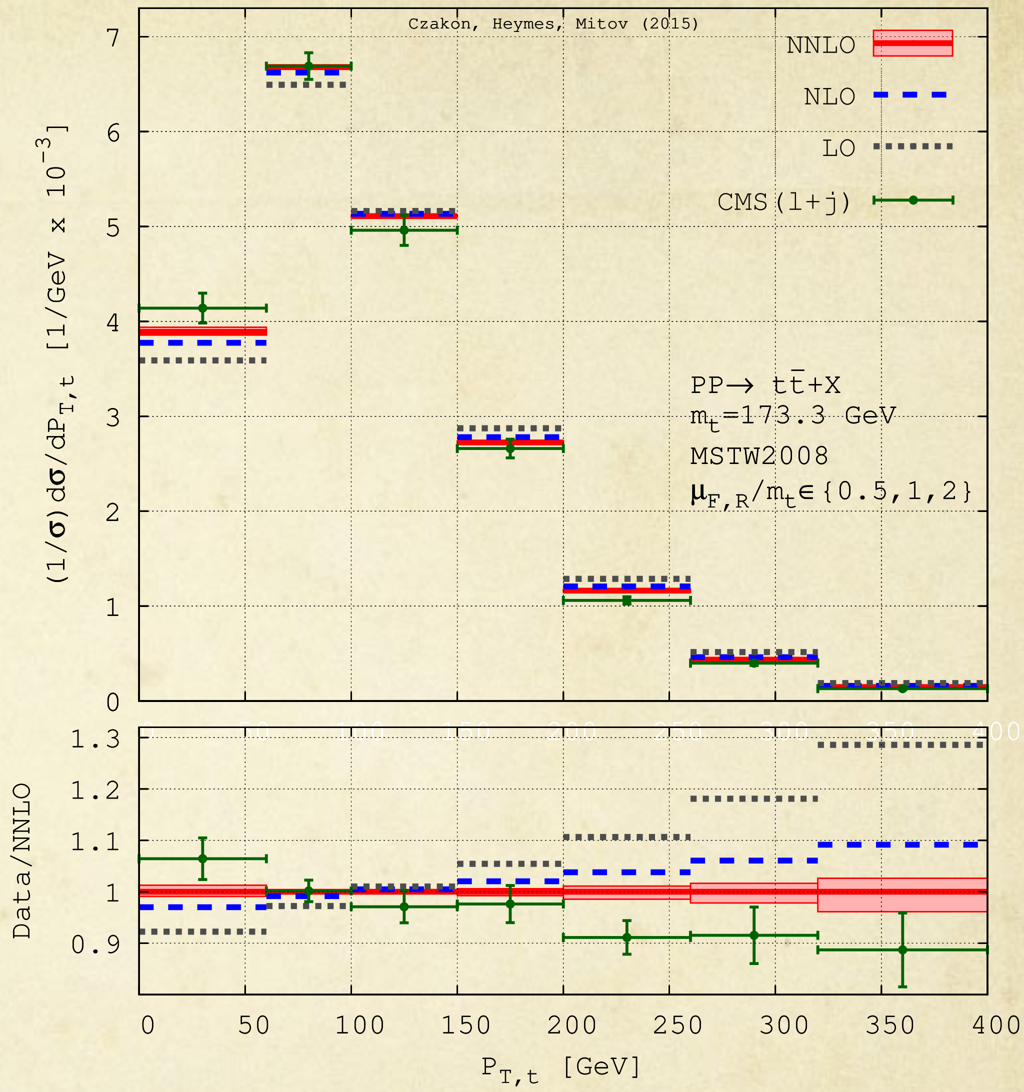


✓ Several qualifications:

- ✓ Lepton- and jet-based observable appear to be fine.
- ✓ Top quark-level ones – no so much.
- ✓ But tops are not measured; they are "inferred" from data using MC's.
- ✓ Therefore, any discrepancy between SM top quark predictions and 'measurements' are testing how well current MC's describe top production.
- ✓ Implications are very broad and go much beyond top physics: Higgs, BSM.

The LHC top P_T discrepancy

- ✓ There are two obvious theory sources:
  - Higher order corrections that we know are not inside MC's (NNLO QCD for example)
  - Possible deficiencies in MC's: treatment of color, recoil, hadronization, etc.
- ✓ Goal: clarify the role of NNLO QCD (before we start adjusting MC's!)
- ✓ NNLO QCD corrections systematically improve the agreement with CMS data.
- ✓ Let's review some features of the calculation

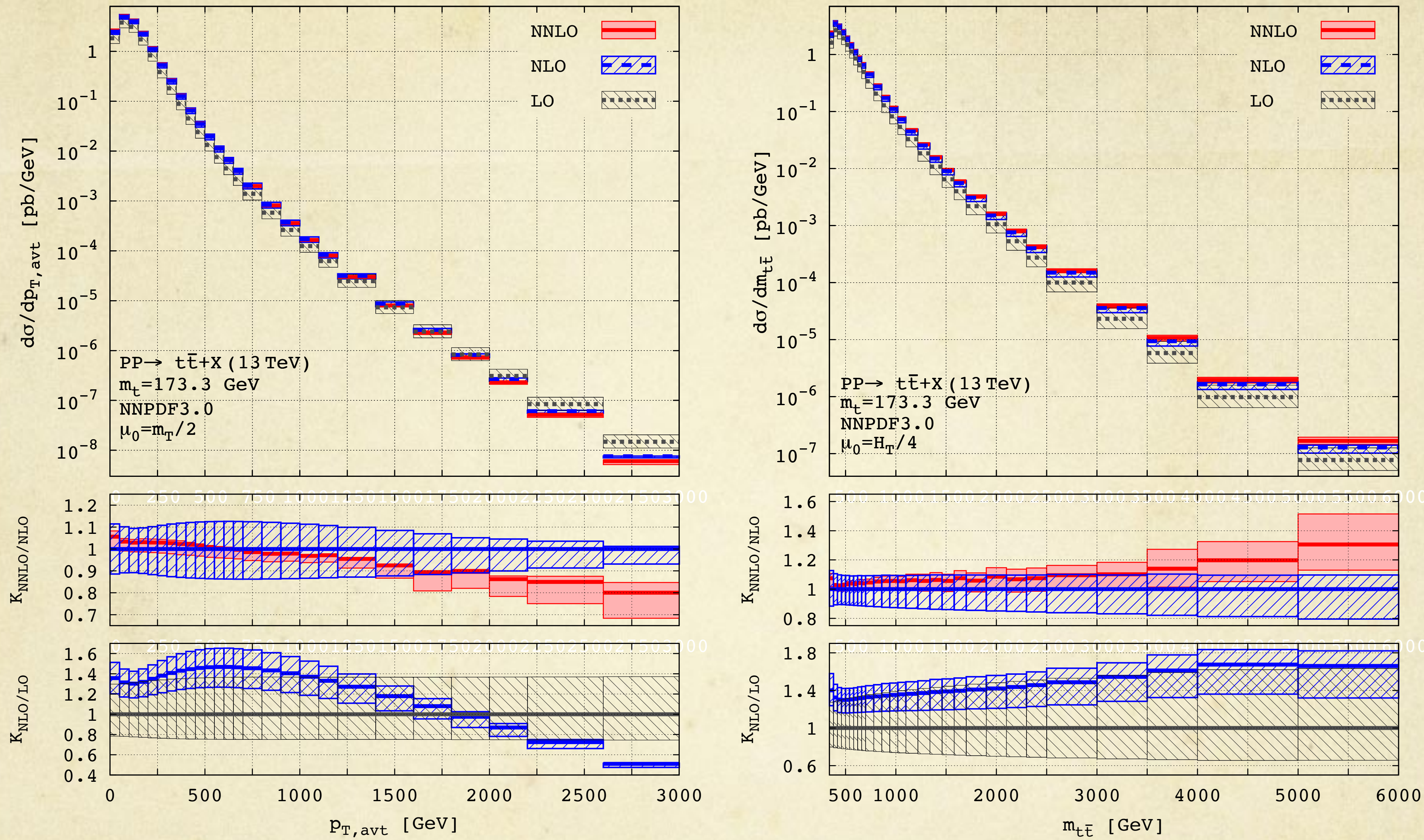


Czakon, Heymes, Mitov 2015

(this calculation with fixed scales)

8

Differential calculations with dynamic scales



- ✓ The quality of the calculation is very high.
- ✓ Note also the extended range.

Czakon, Heymes, Mitov 2016

On scale setting

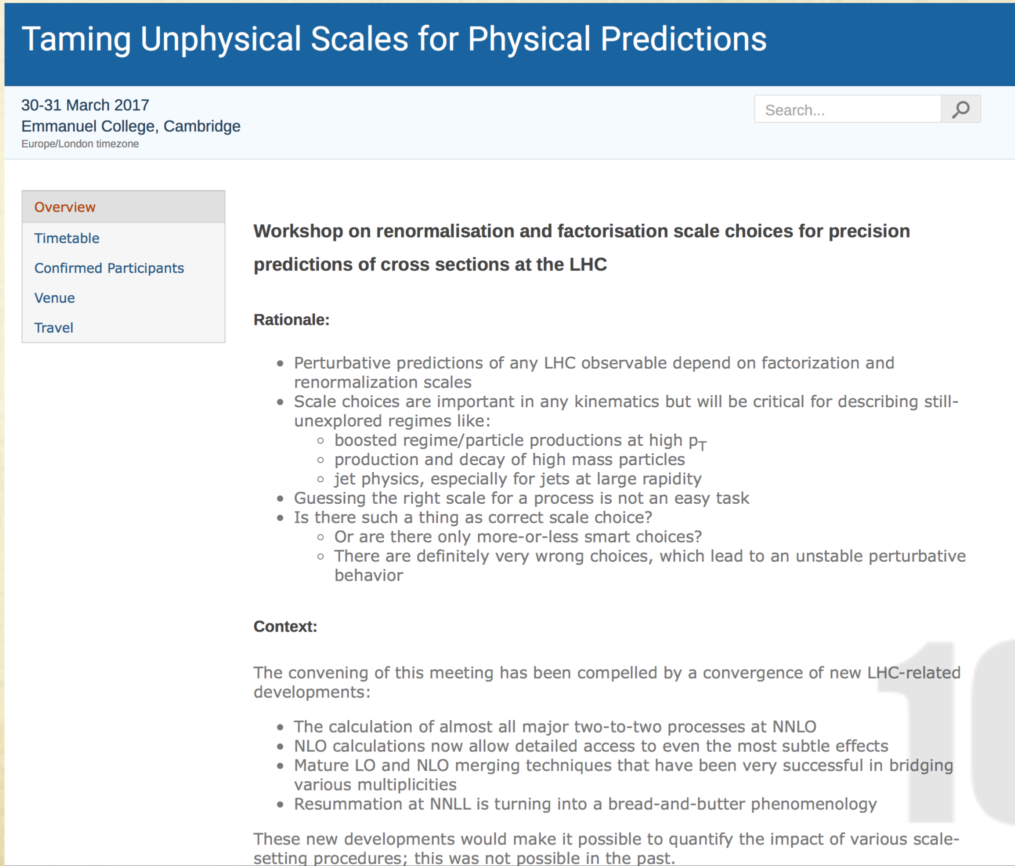
- ✓ Choice of scales is an open – perhaps underappreciated – problem which affects all collider processes.
- ✓ It is hard to give a definite prediction for an unphysical scale; still, some solid approaches could be followed.
- ✓ A first Workshop on scales and scale-setting took place 30-31 March 2017 in Cambridge

Please visit

https://indico.cern.ch/e/scales

to see the many very interesting talks.

Possible follow-up at Les Houches.


Taming Unphysical Scales for Physical Predictions

30-31 March 2017
Emmanuel College, Cambridge
Europe/London timezone

Search...

Overview
Timetable
Confirmed Participants
Venue
Travel

Workshop on renormalisation and factorisation scale choices for precision predictions of cross sections at the LHC

Rationale:

- Perturbative predictions of any LHC observable depend on factorization and renormalization scales
- Scale choices are important in any kinematics but will be critical for describing still-unexplored regimes like:
  - boosted regime/particle productions at high p_T
  - production and decay of high mass particles
  - jet physics, especially for jets at large rapidity
- Guessing the right scale for a process is not an easy task
- Is there such a thing as correct scale choice?
  - Or are there only more-or-less smart choices?
  - There are definitely very wrong choices, which lead to an unstable perturbative behavior

Context:

The convening of this meeting has been compelled by a convergence of new LHC-related developments:

- The calculation of almost all major two-to-two processes at NNLO
- NLO calculations now allow detailed access to even the most subtle effects
- Mature LO and NLO merging techniques that have been very successful in bridging various multiplicities
- Resummation at NNLL is turning into a bread-and-butter phenomenology

These new developments would make it possible to quantify the impact of various scale-setting procedures; this was not possible in the past.

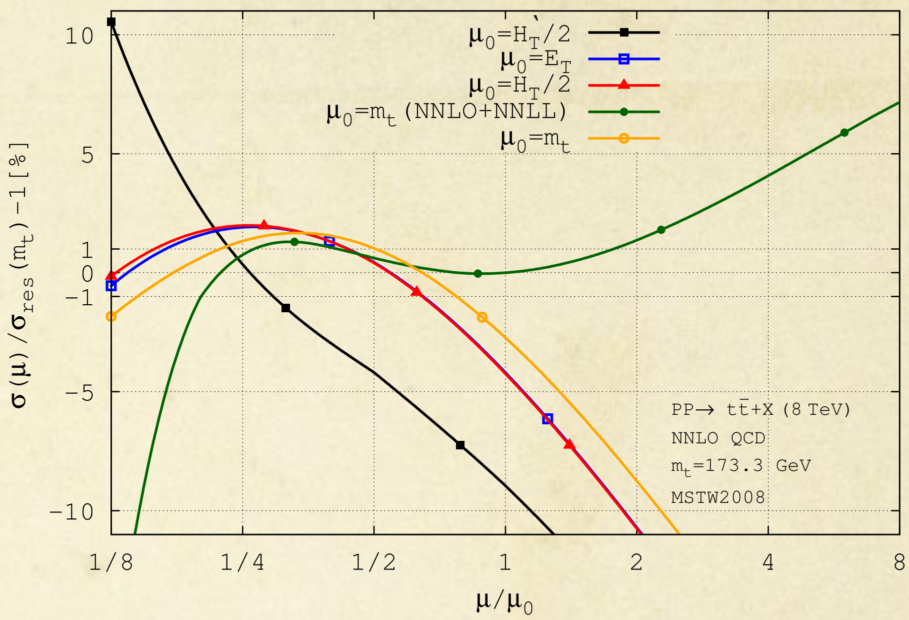
Organizers:
Czakon, Huston, Mitov, Worek, Webber

Choice of dynamic scales in top production

Czakon, Heymes, Mitov 2016

- Several tried and tested choices:

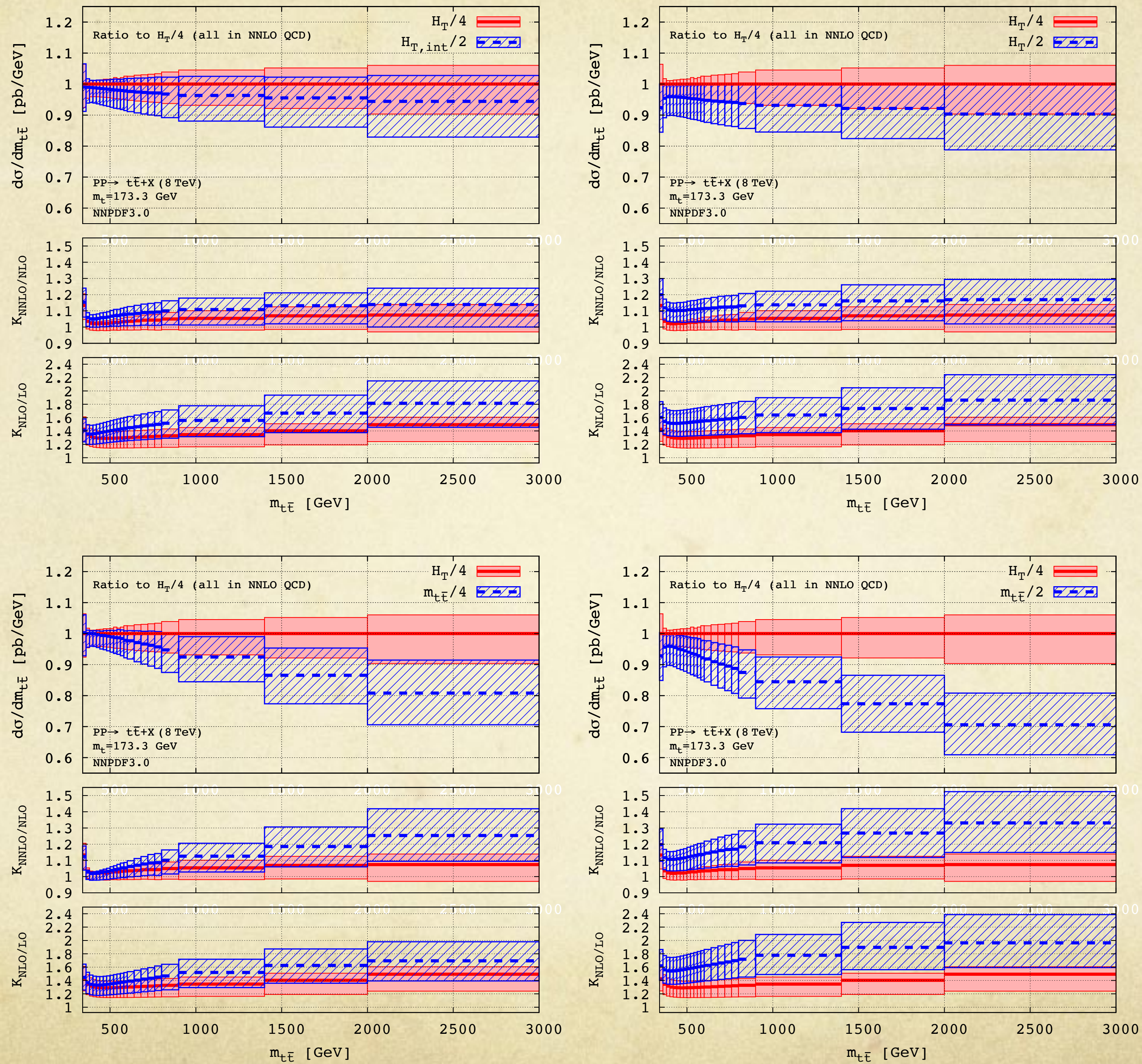
$$\mu_0 \sim m_t \,,$$
$$\mu_0 \sim m_T = \sqrt{m_t^2 + p_T^2} \,,$$
$$\mu_0 \sim H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} \,,$$
$$\mu_0 \sim H_T' = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} + \sum_i p_{T,i} \,,$$
$$\mu_0 \sim E_T = \sqrt{\sqrt{m_t^2 + p_{T,t}^2}\sqrt{m_t^2 + p_{T,\bar{t}}^2}} \,,$$
$$\mu_0 \sim H_{T,\text{int}} = \sqrt{(m_t/2)^2 + p_{T,t}^2} + \sqrt{(m_t/2)^2 + p_{T,\bar{t}}^2} \,,$$
$$\mu_0 \sim m_{t\bar{t}} \,,$$



- What are we looking for here?
  - A scale that ensures fastest perturbative convergence (and agreement with data at low P_T, where lots of data is available and well understood)

$$\mu_0 = \begin{cases} \frac{m_T}{2} & \text{for :} \quad p_{T,t},\; p_{T,\bar{t}} \text{ and } p_{T,t/\bar{t}}\,, \\ \frac{H_T}{4} & \text{for :} \quad \text{all other distributions}\,. \end{cases}$$

NNLO differential with various dynamic scales (M_{tt} @ 8 TeV)



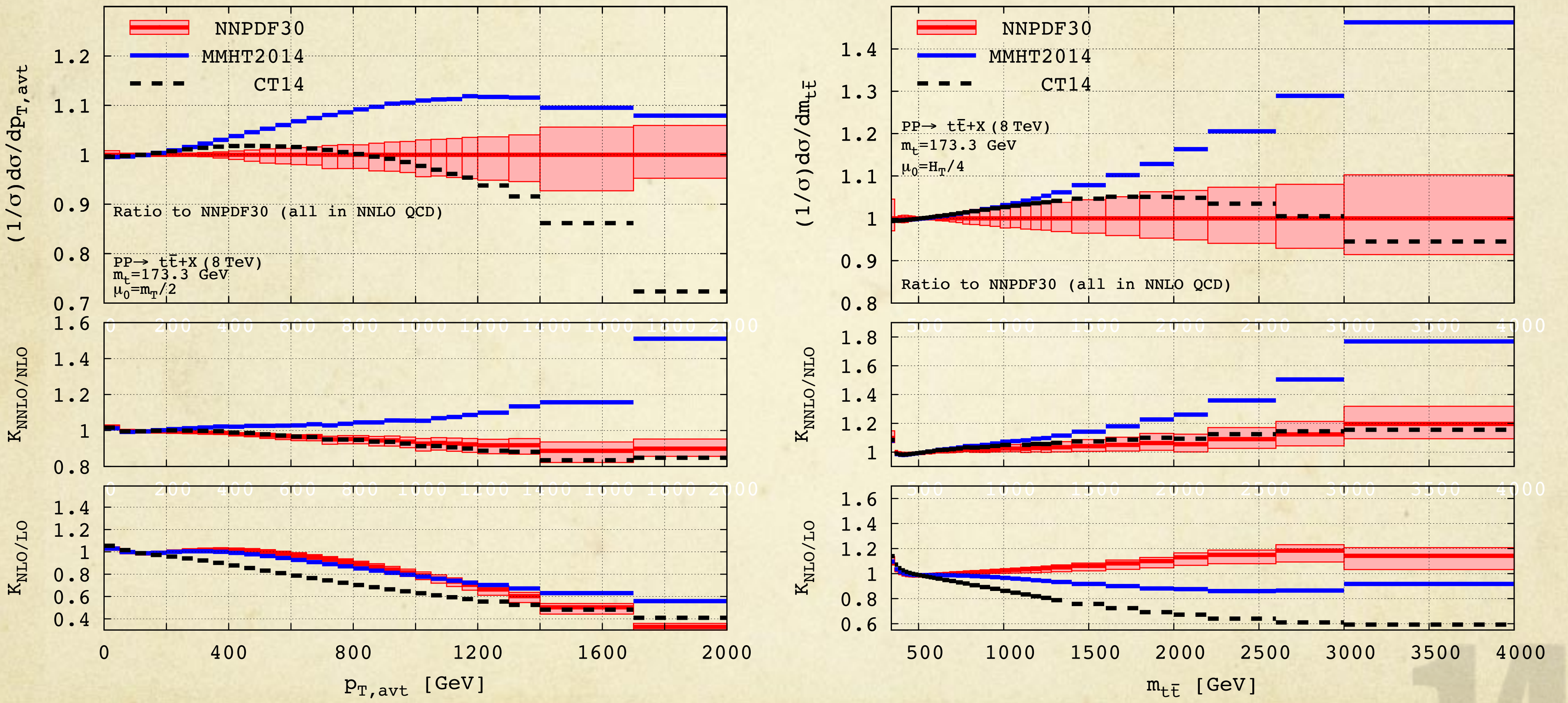
Czakon, Heymes, Mitov 2016

Agreement with data and PDF’s

PDF dependence

✓ Clearly, the predictions significantly depend on the choice of PDF set

LHC at 8 TeV:



✓ For moderate M_{tt}/P_T the PDF error starts to overcome the one from scales

Tevatron distributions: absolute normalization

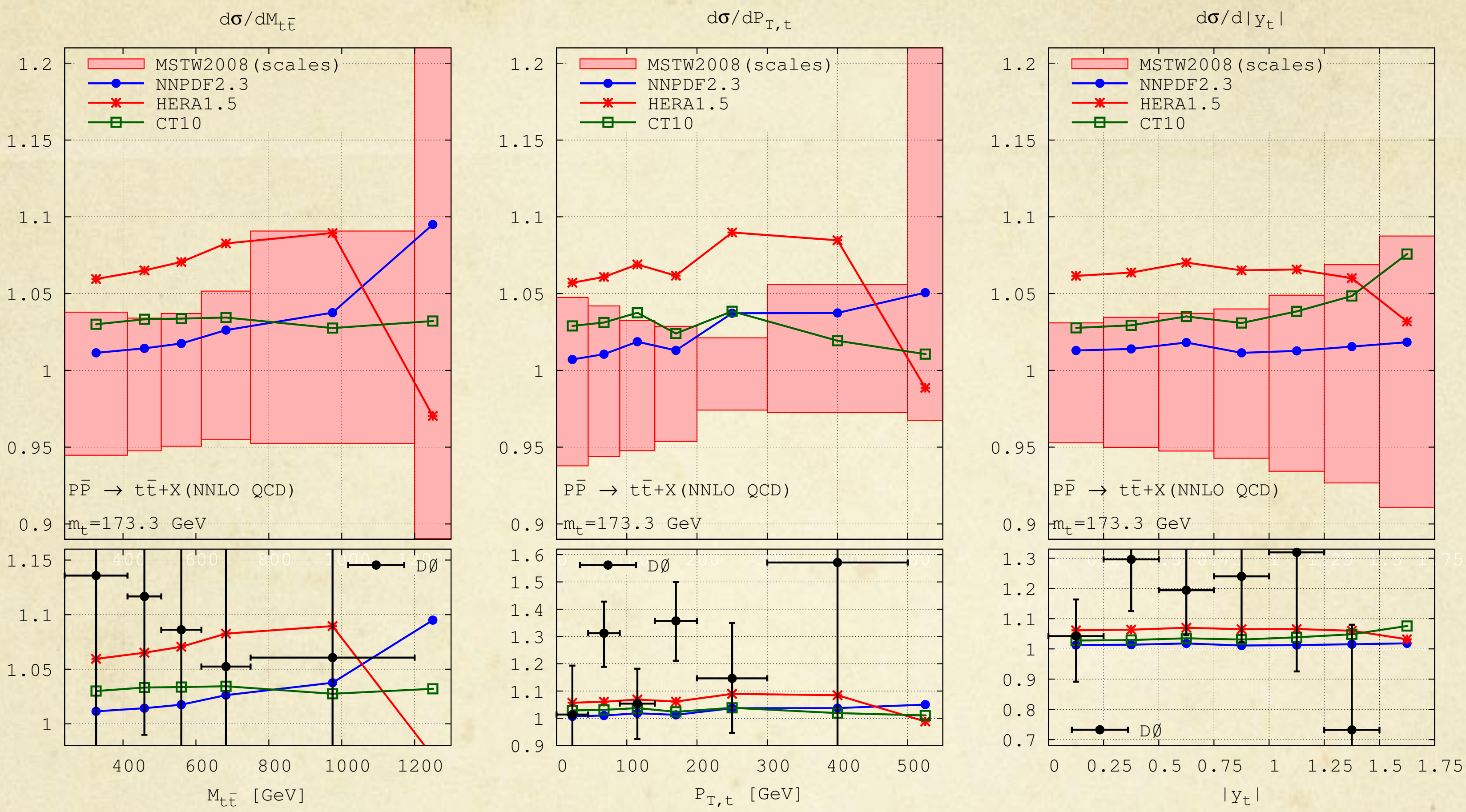


Figure 10. NNLO QCD prediction for three differential distributions (in $M_{t\bar{t}}$, $P_{T,t}$ and $|y_t|$) with four pdf sets. Given are the ratios of the CT10, HERA 1.5 and NNPDF 2.3 based predictions with respect to MSTW2008. For reference also the scale dependence of the MSTW2008 prediction is shown (red band). For improved visibility, in the lower plots we compare the same predictions with the available data from the DØ Collaboration [15].

Comparison of theory with LHC data

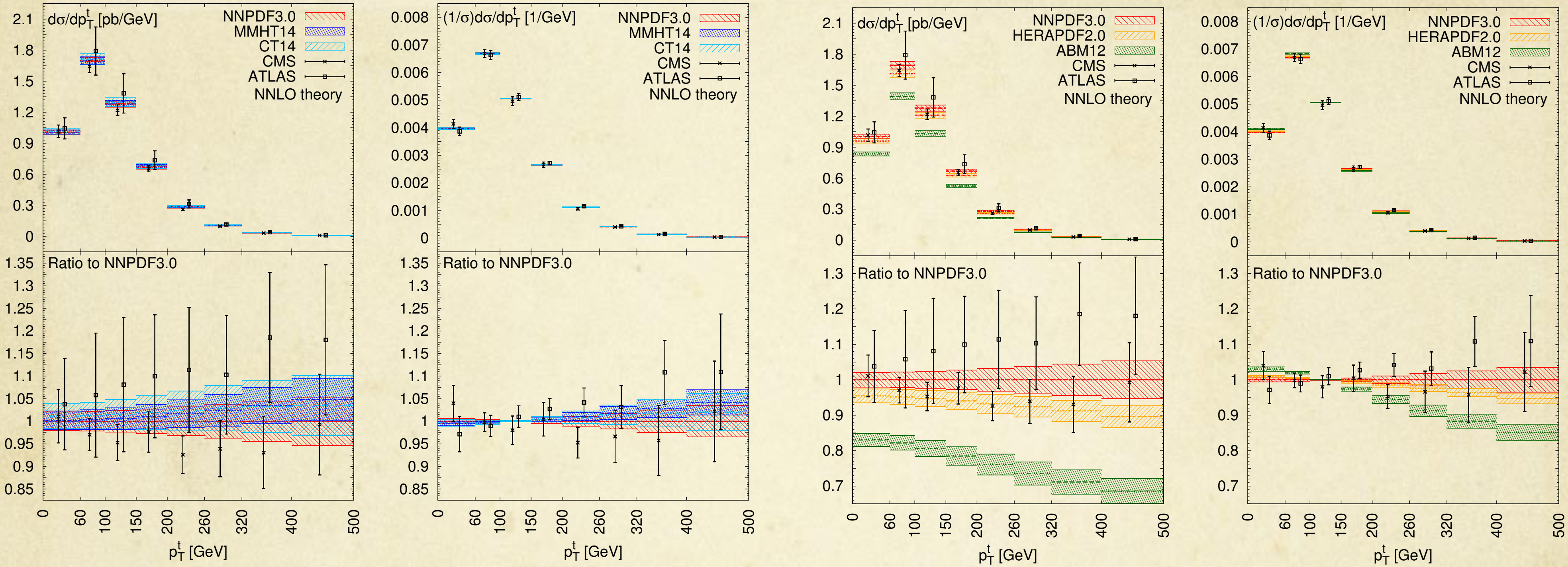
- ✓ Comprehensive study of th/data agreement for many pdf sets

Czakon, Hartland, Mitov, Nocera, Rojo 2016

- ✓ State of the art NNLO QCD versus ATLAS & CMS with 5 PDF sets
  - ✓ Dynamic scales (that ensure fastest convergence, at least through NNLO)
  - ✓ NNPDF3.0, CT14, MMHT2014, HERA2.0 , ABM12
- ✓ Compared separately absolute normalizations and normalized distributions
- ✓ Conclude that the differences between ATLAS and CMS data are as significant as the error of the theory prediction!

Comparison of theory with LHC data

Czakon, Hartland, Mitov, Nocera, Rojo 2016

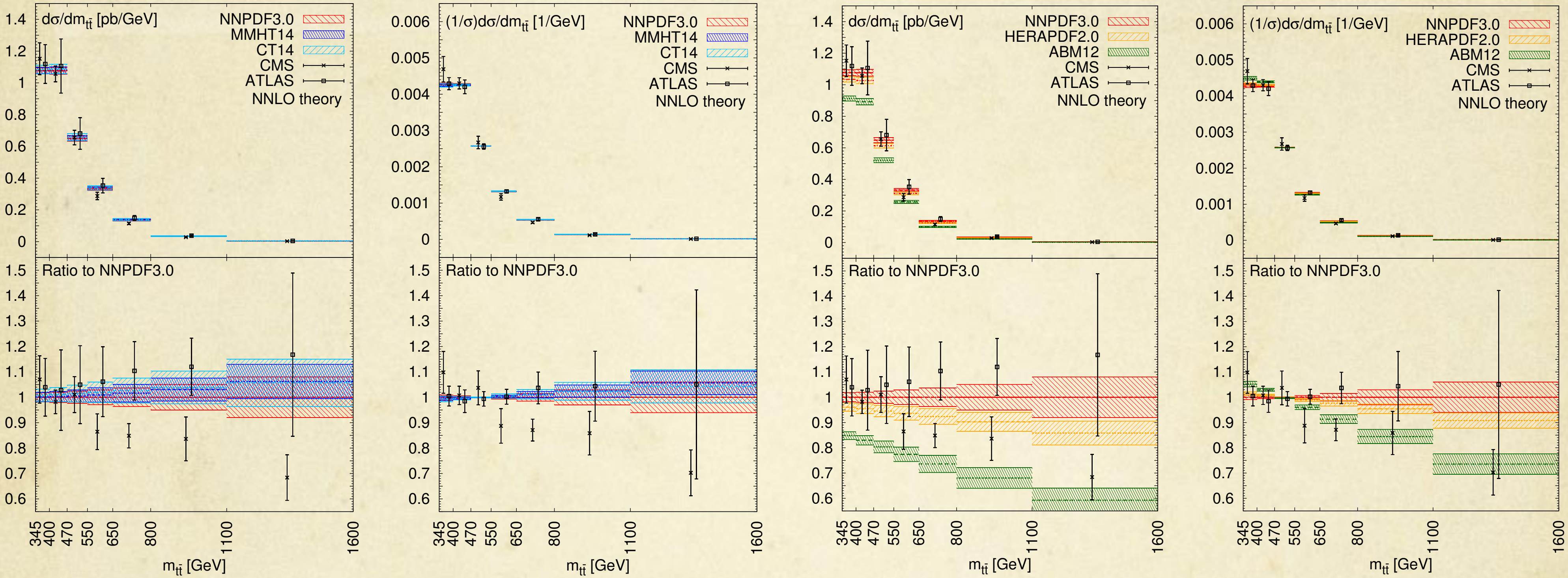


PDF error only shown!

- ✓ Top P_T distribution at LHC 8 TeV
- ✓ NNLO QCD versus ATLAS & CMS with 5 PDF sets
- ✓ Compared separately absolute normalizations and normalized distributions

Comparison of theory with LHC data

Czakon, Hartland, Mitov, Nocera, Rojo 2016

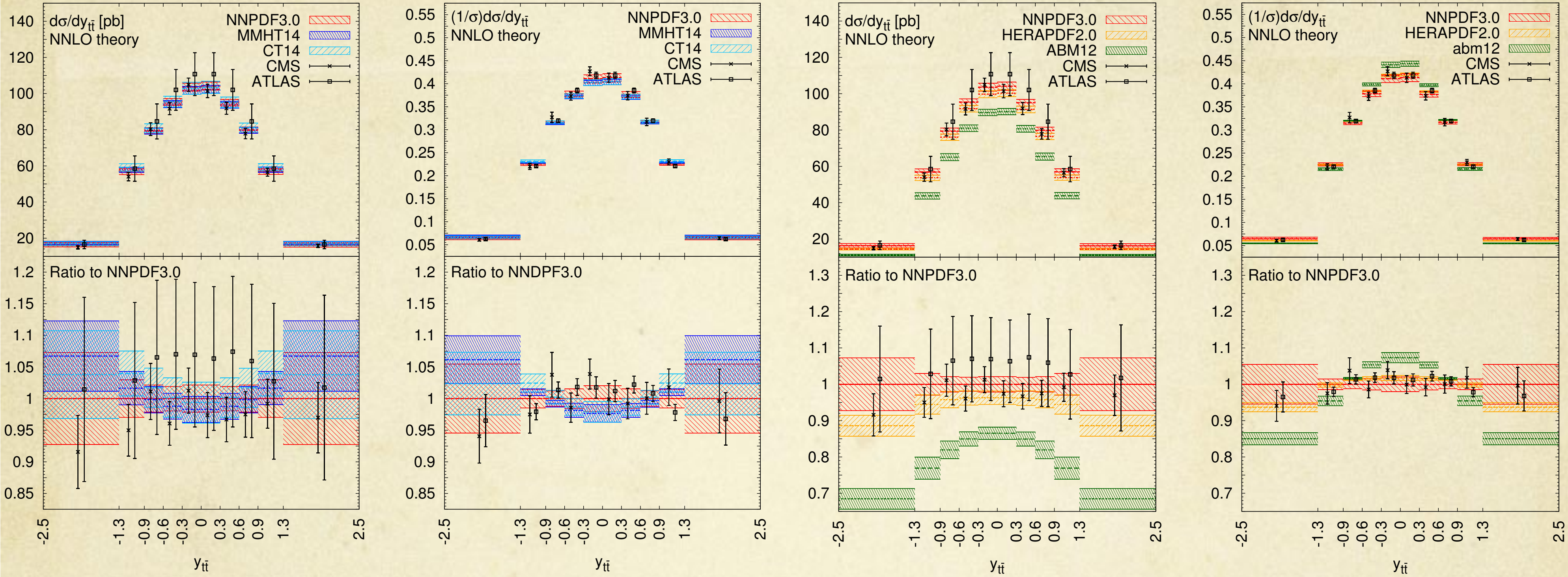


PDF error only shown!

- ✓ Top M_{tt} distribution at LHC 8 TeV
- ✓ NNLO QCD versus ATLAS & CMS with 5 PDF sets
- ✓ Compared separately absolute normalizations and normalized distributions

Comparison of theory with LHC data

Czakon, Hartland, Mitov, Nocera, Rojo 2016

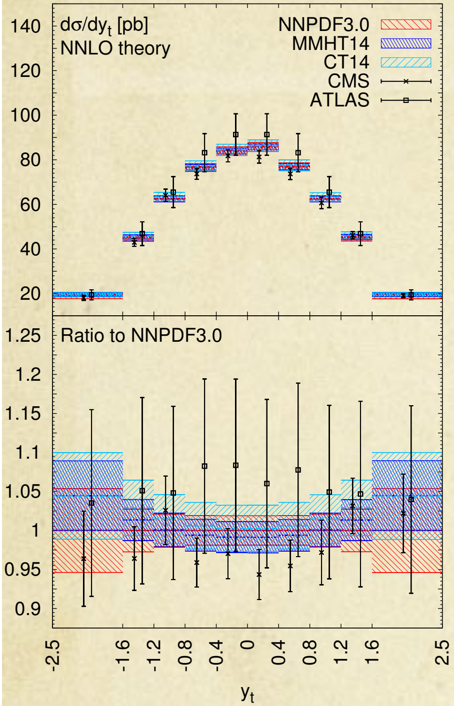


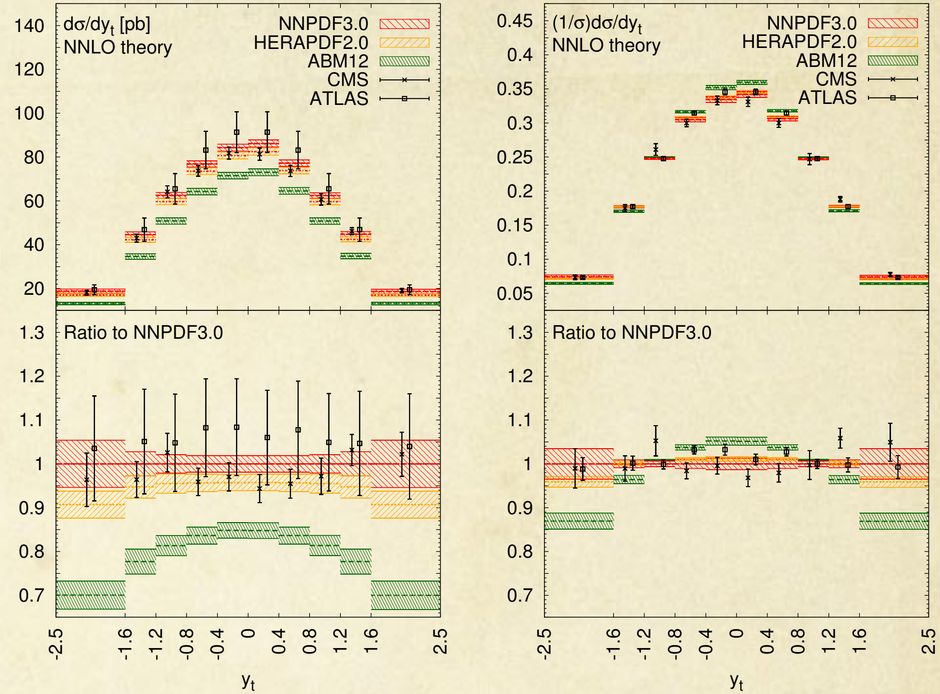
PDF error only shown!

- ✓ Top y_{tt} distribution at LHC 8 TeV
- ✓ NNLO QCD versus ATLAS & CMS with 5 PDF sets
- ✓ Compared separately absolute normalizations and normalized distributions

Comparison of theory with LHC data

Czakon, Hartland, Mitov, Nocera, Rojo 2016





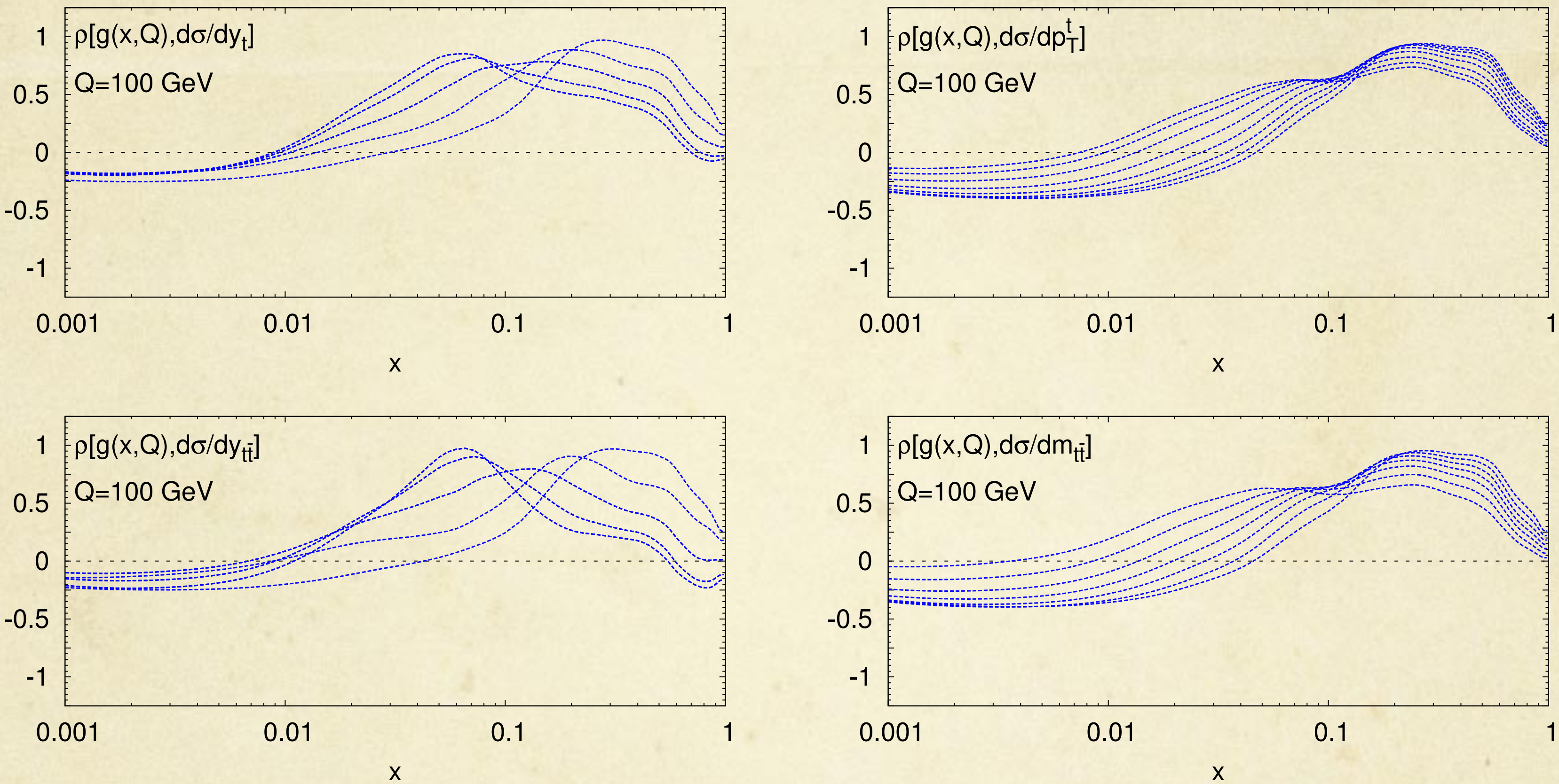
PDF error only shown!

- ✓ Top y_t distribution at LHC 8 TeV
- ✓ NNLO QCD versus ATLAS & CMS with 5 PDF sets
- ✓ Compared separately absolute normalizations and normalized distributions

Fitting PDF from top-pair data

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).

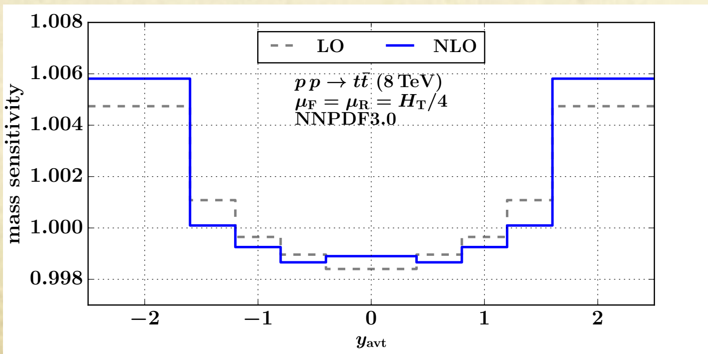
  ✓ Our benchmark PDF set is NNPDF3.0

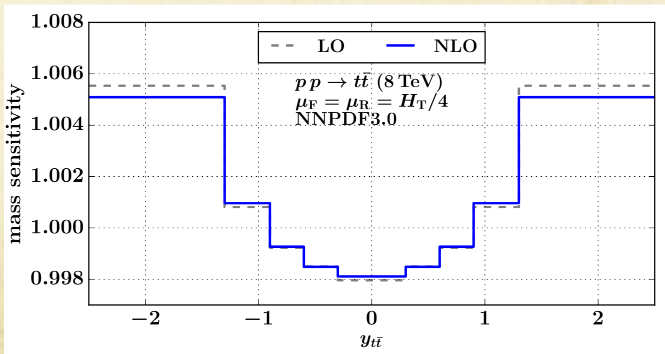
  ✓ Our fit is global

✓ We find:

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

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

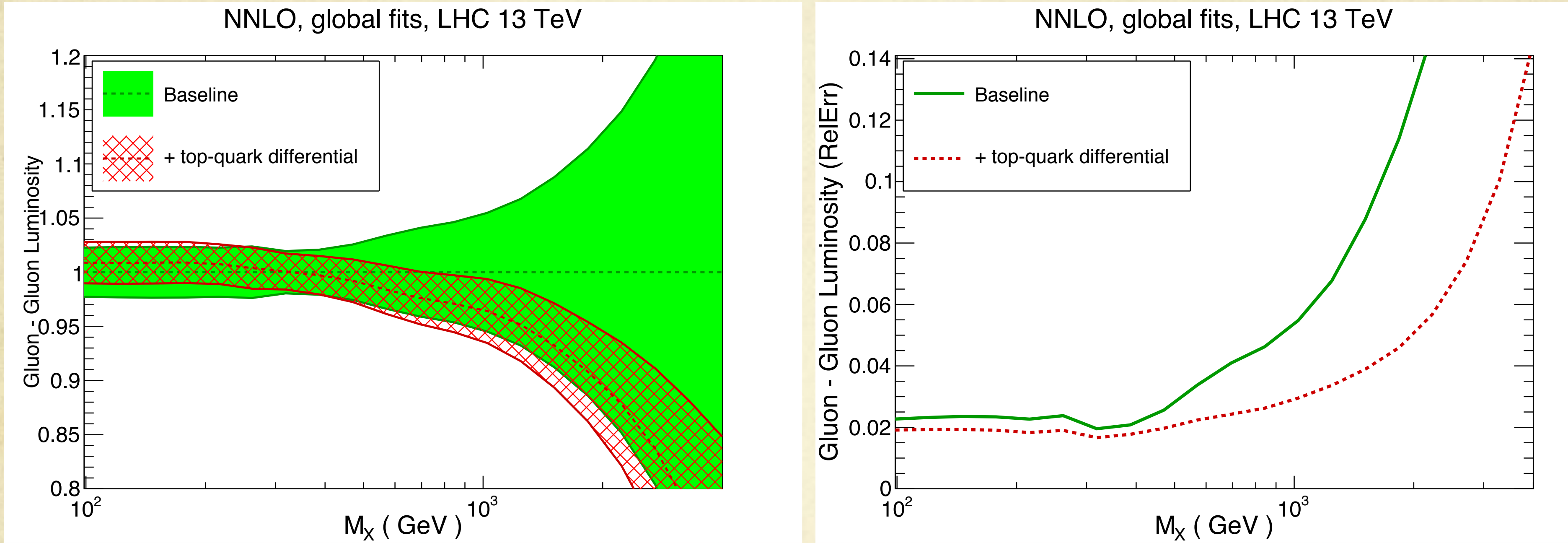




PDF from LHC data

Czakon, Hartland, Mitov, Nocera, Rojo 2016

✓ Improvement in the gluon PDF after top data is included



✓ Even jets would, likely, not have more constraining power.

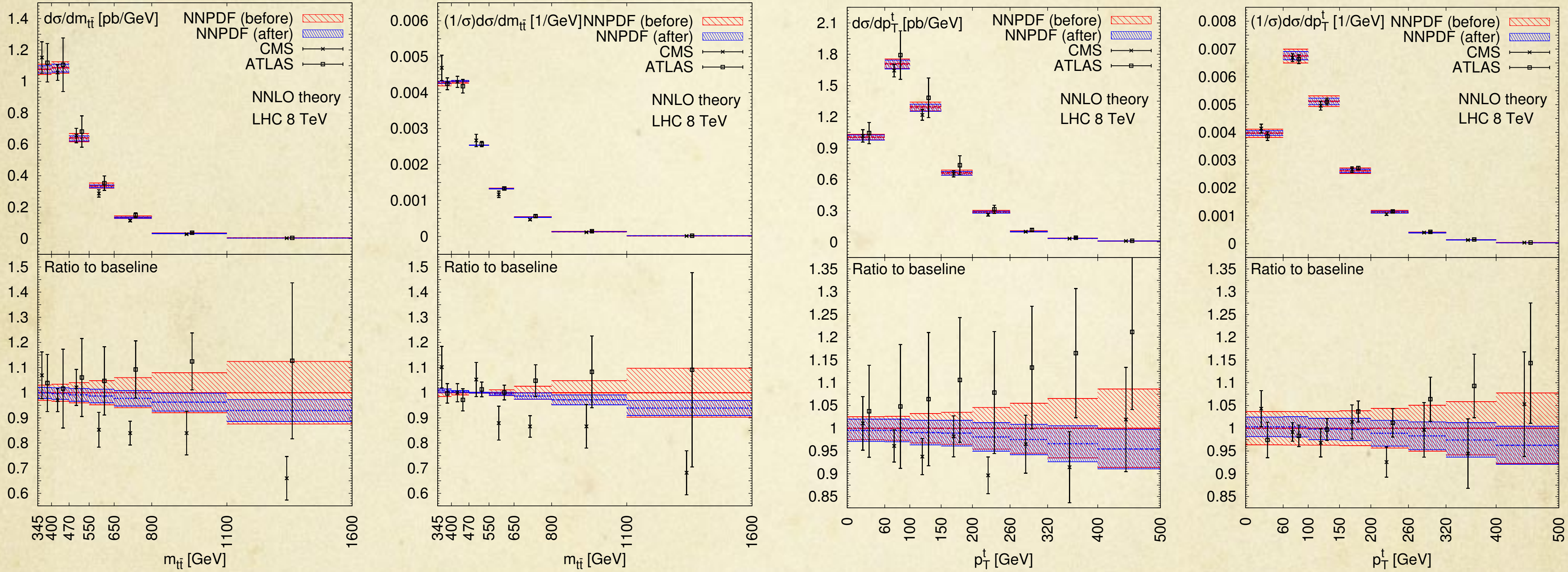
24

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

NNLO QCD + NLO EW

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

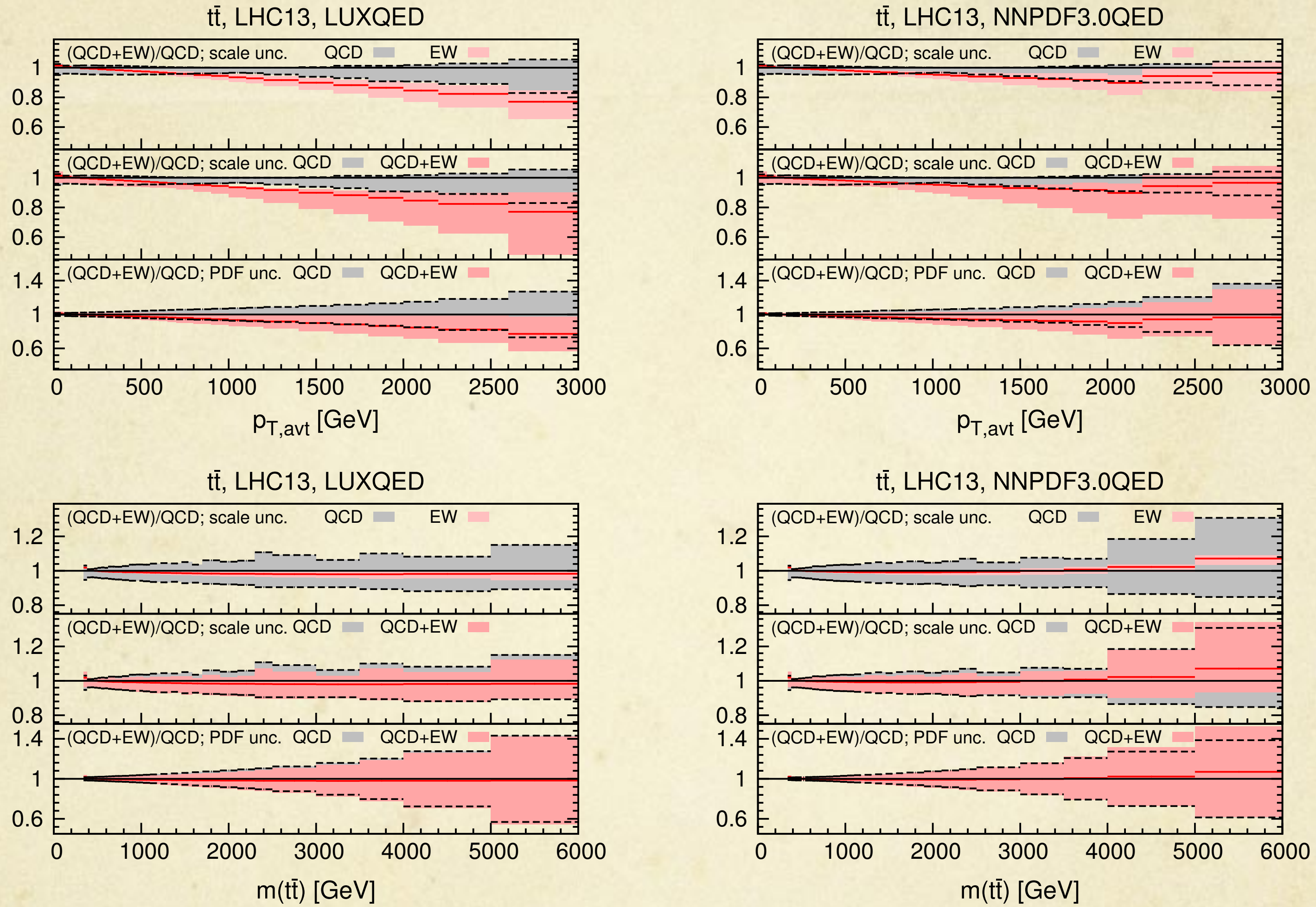
- ✓ NLO EW corrections were computed 20+ years ago
  - ✓ Tiny for total cross-section (1% or less)
  - ✓ Could be significant differentially, especially for large M_{tt} and P_T.
  - ✓ NLO EW corrections are now automated (several groups). We use aMC@NLO.
- ✓ We present pheno predictions for both 8 and 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)

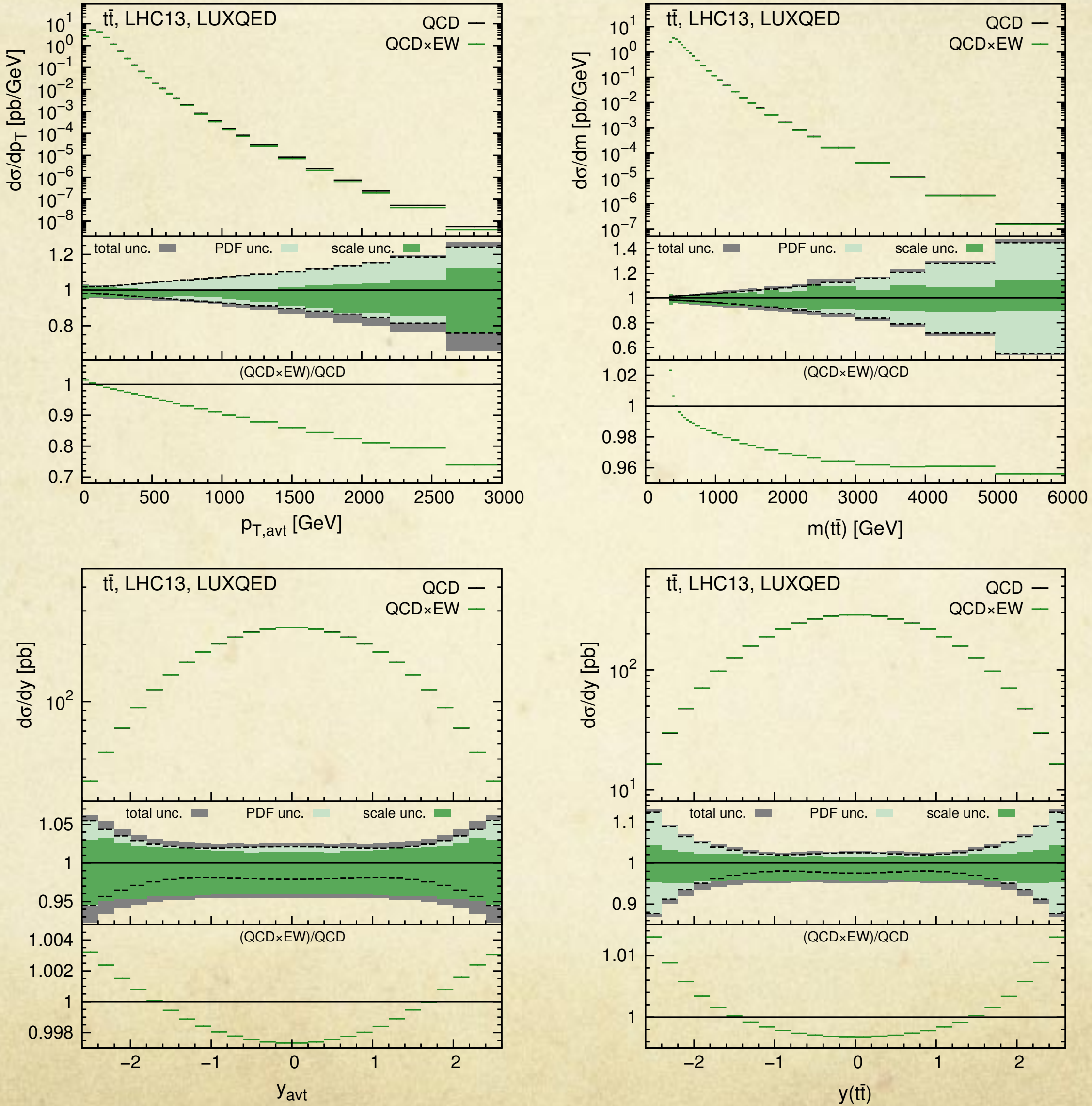
LUXqed = Manohar, Nason, Salam, Zanderighi 2016

✓ 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)



Making the results easy to use

Making the results easy to use

Czakon, Heymes, Mitov 2017

- ✓ All distributions computed by us 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

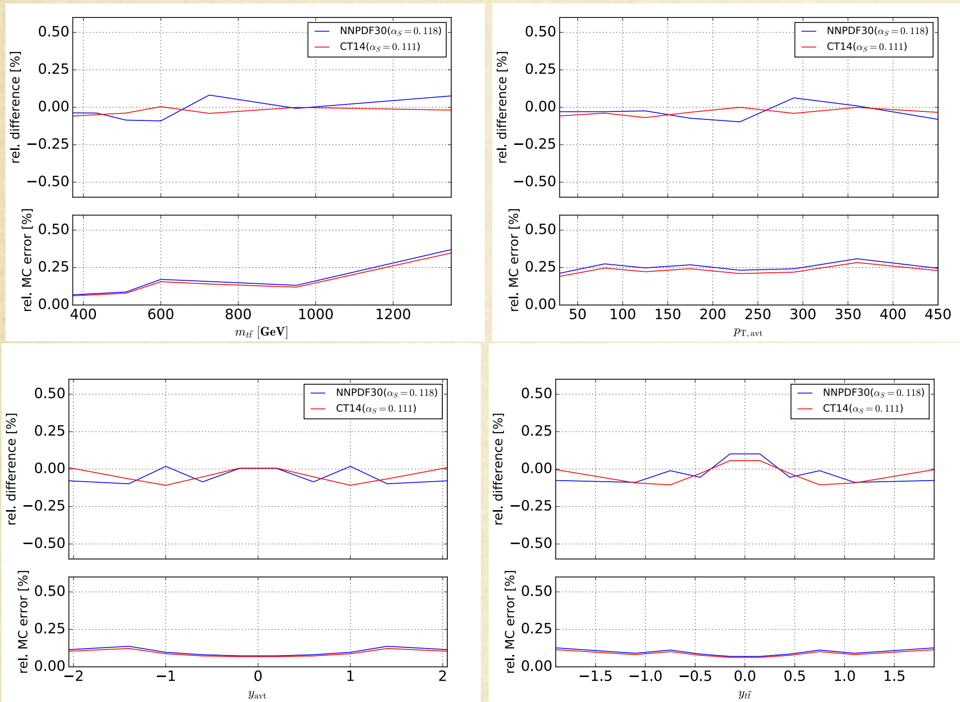
Kluge, Rabbertz, Wobisch, hep-ph/0609285
D. Britzger et al. [fastNLO Collaboration], arXiv:1208.3641

- ✓ Basically, the tables are interpolation of the partonic cross-section (for a given 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, exerimental and theory studies.
- ✓ One could also include EW effects by rescaling with the K-factor computed by us (see previous slides)
- ✓ Planning to extend to all future calculations and also to 2dim distributions.

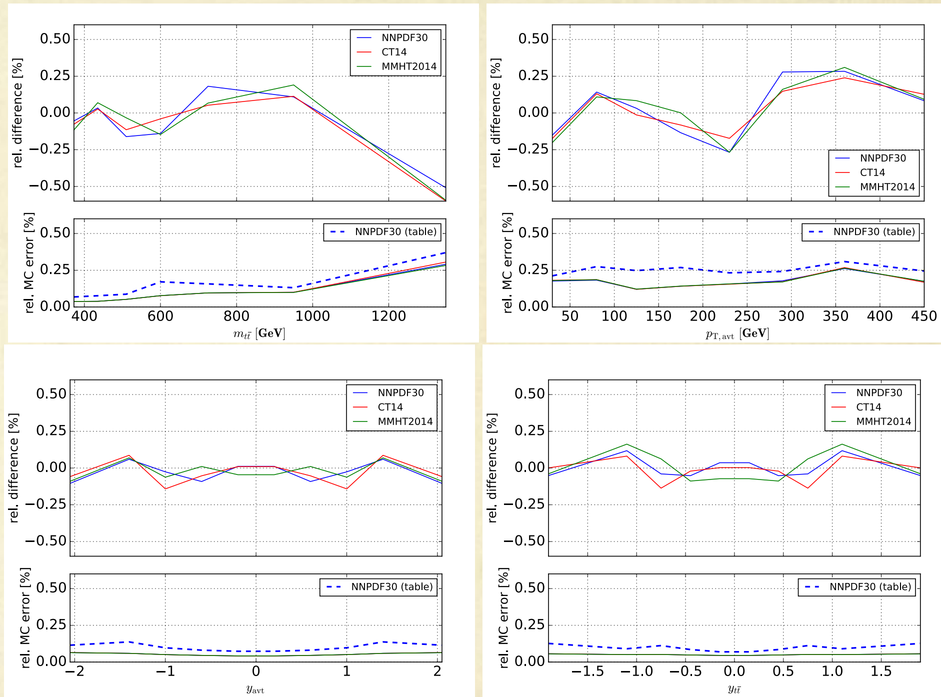
Making the results easy to use

Czakon, Heymes, Mitov 2017

✓ The interpolation error is very small (permil) and the quality is similar to previous calculations we have made public



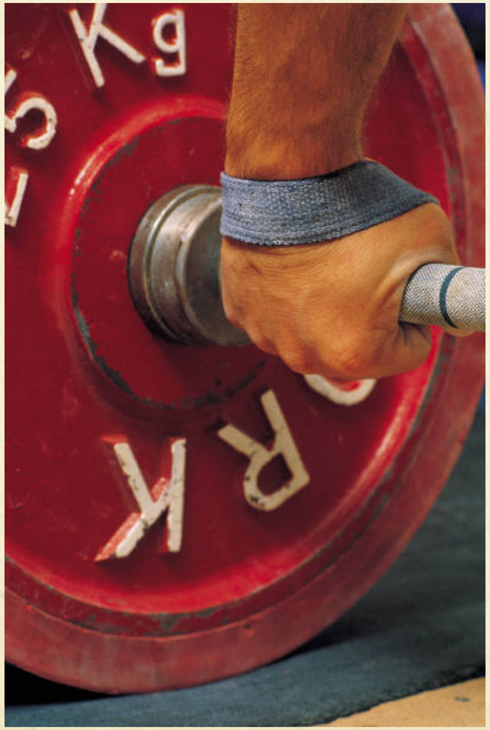
Interpolation error



Absolute error relative to an old calculation for 3 pdf sets

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

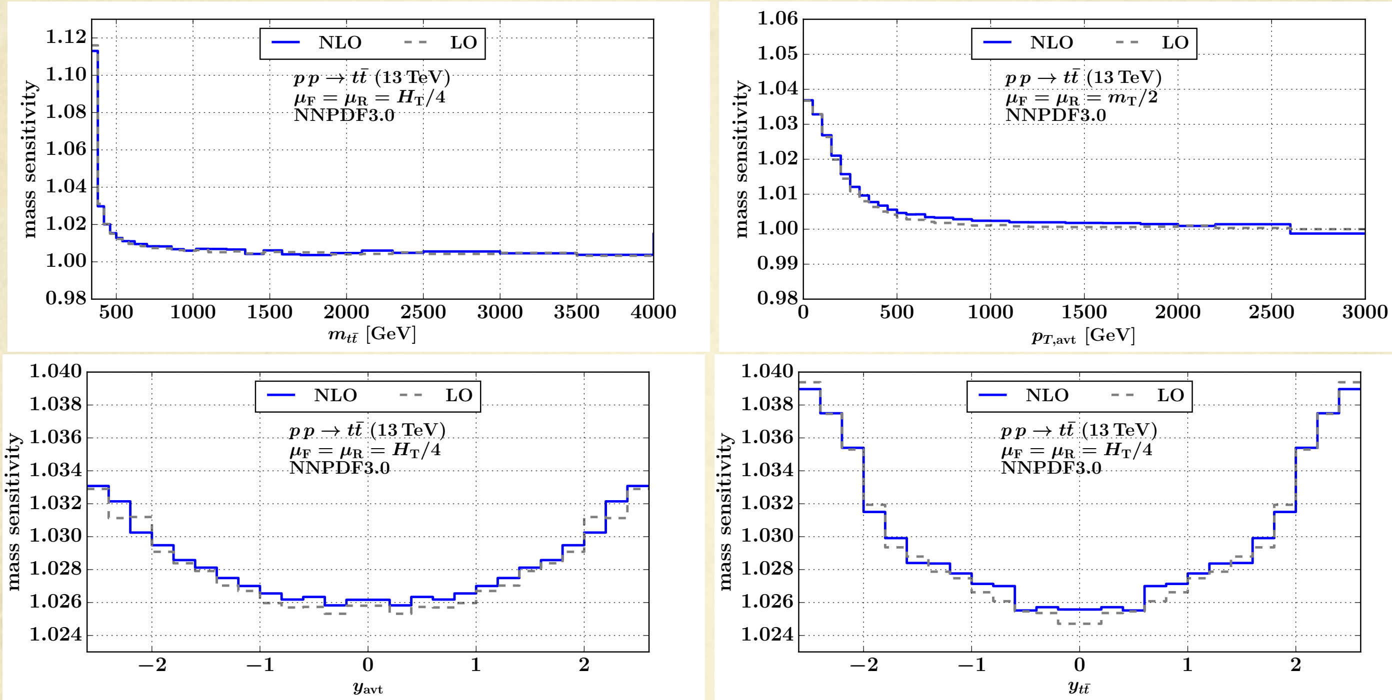
Top quark mass



Why worry about the value of m_{top}?

✓ In the PDF study we emphasized extraction from distributions that are not very sensitive to m_{top}.

From arXiv:1608.00765



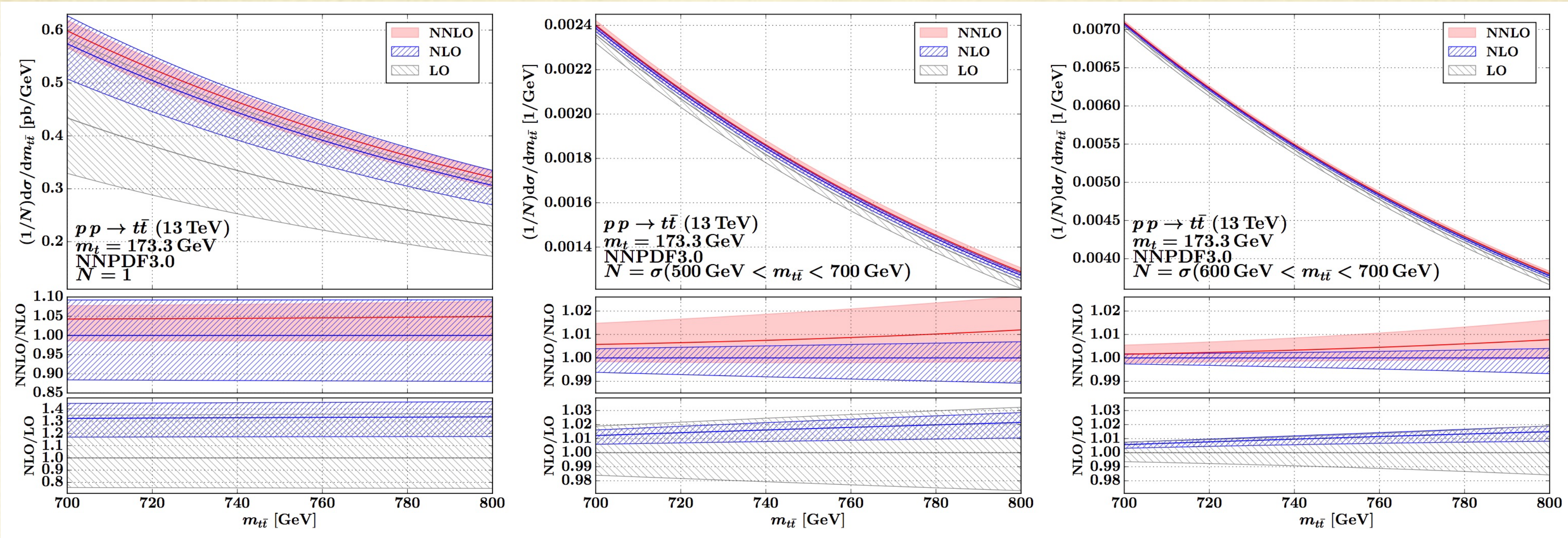
✓ The above sensitivities are defined per 1 GeV change in m_{top}.

Why worry about the value of m_{top}?

- ✓ Another place where m_{top} sensitivity plays on outsized role is bump-hunting in ttbar events
- ✓ This was studied by us in the context of the 750 GeV diphoton excess

arXiv:1608.00765

- ✓ One can make the SM background more predictive (by reducing scale and PDF errors) if one normalizes the spectrum:



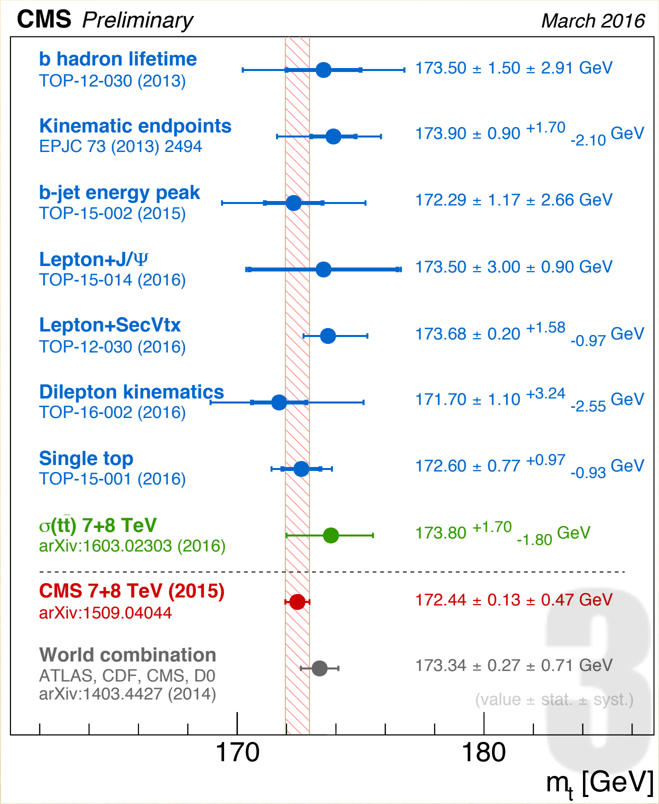
- ✓ As can be concluded from the plots on the previous slide the m_{top} sensitivity in the 750 range is small. However, if one normalizes to the inclusive cross-section then this will introduce large (about 2%) m_{top} sensitivity, while the scale and pdf errors will get strongly reduced.

- ✓ Basically, this way the m_{top} sensitivity may become leading uncertainty!

Why worry about the value of m_{top}?

- ✓ Recall, that the sensitivity was defined for change in m_{top} of 1 GeV
- ✓ If the actual error on m_{top} is less than that (current world average implies 0.7 GeV) then this is no big deal.
- ✓ However, can the top mass be off by (much) more than that?
- ✓ If the 3 GeV spread among independent precise measurements is any indication then, yes, this is a possibility!

$$m_t = 173.34 \pm 0.76\,\text{GeV} \quad \text{[World Average]}$$
$$m_t = 172.04 \pm 0.77\,\text{GeV} \quad \text{[CMS Collaboration]}\,,$$
$$m_t = 174.98 \pm 0.76\,\text{GeV} \quad \text{[D0 Collaboration]}\,.$$



Why worry about the value of m_{top}?

✓ Knowing the top mass has important implications beyond immediate collider physics

- ✓ Higgs inflation
- ✓ Vacuum stability in SM and beyond

That point to a lower value of m_{top} around 171 GeV.

✓ Clearly, we need to address the question: how well do we really know the top mass?

✓ This is not an academic question!

- ➢ m_{top} is not an observable; cannot be measured directly.
- ➢ It is extracted indirectly, through the sensitivity of observables to m_{top}

$$\sigma^{\rm exp}(\{Q\}) = \sigma^{\rm th}(m_t, \{Q\})$$

✓ The implication: the "determined" value of m_{top} is as sensitive to theoretical modeling as it is to the measurement itself

✓ The measured mass is close to the pole mass (top decays …)

✓ Lots of activity (past and ongoing).

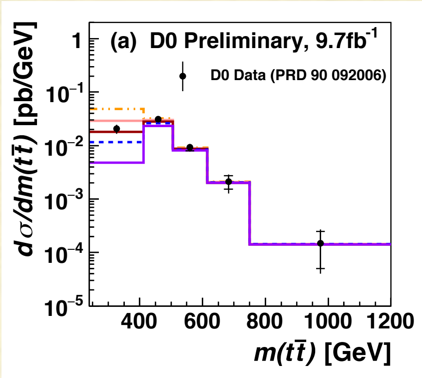
Why worry about the value of m_{top}?

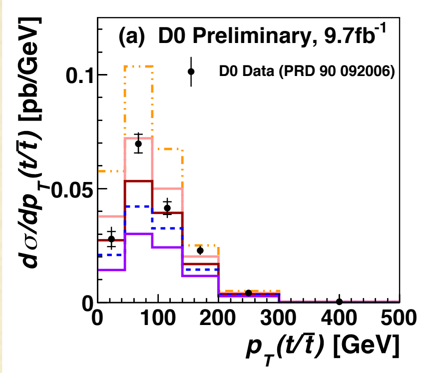
✓ Large spread among measurements is possible in the context of different theory systematics

> To me, the problem of m_{top} extraction should turn from "more precise determination" to better understanding of the theory systematics and their size.

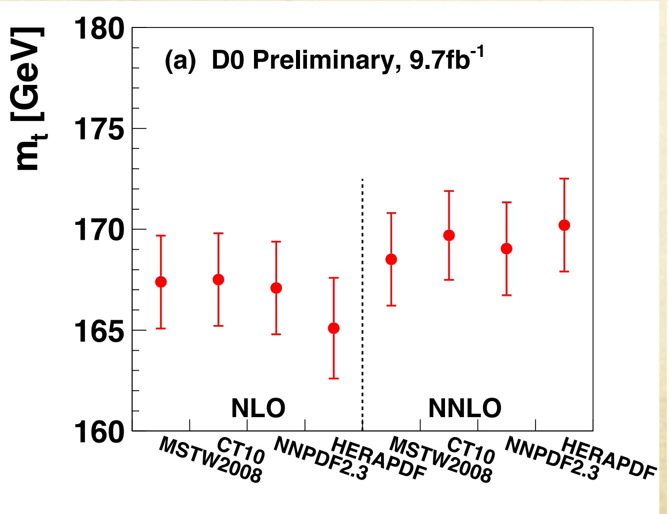
✓ Another example: m_{top} from differential measurements at D0

D0 Note 6473-CONF





Extracted mass at NLO and NNLO



From NNLO extraction

$$m_{top} = 169.1 \pm 2.5 \text{ (tot.) GeV}$$

✓ Significantly lower than the other measurements!

In order to properly understand and estimate the theory systematics we propose a particular observable

Frixione, Mitov '14

$$pp \to t\bar{t} + X$$
$$t \to W + b + X$$
$$W \to \ell + \nu_\ell$$

These are ttbar dilepton events, subject to standard cuts:

$$|\eta_\ell| \leq 2.4 \ , \ \ |\eta_b| \leq 2.4 \ ,$$
$$p_{T,\ell} \geq 20 \text{ GeV} \ , \ \ p_{T,b} \geq 30 \text{ GeV}$$

- Construct the distributions from leptons only
- Require b-jets [anti-k_T, R=0.5] within the detector (i.e. integrate over the b's)

The definition of the observable possesses several important properties:

- It is inclusive of hadronic radiation, which makes it well-defined to all perturbative orders in the strong coupling,
- It does not require the reconstruction of the t and/or $\bar{t}$ quarks (indeed we do not even speak of t quark),
- Due to its inclusiveness, the observable is as little sensitive as possible to modelling of hadronic radiation. This feature increases the reliability of the theoretical calculations.

✓ The top mass is extracted from the ***shapes, not normalizations***, of the following distributions:

kinematic distribution
$p_T(\ell^+)$
$p_T(\ell^+\ell^-)$
$M(\ell^+\ell^-)$
$E(\ell^+) + E(\ell^-)$ ← Studied before by: Biswas, Melnikov, Schulze '10
$p_T(\ell^+) + p_T(\ell^-)$

✓ Working with distributions directly is cumbersome.

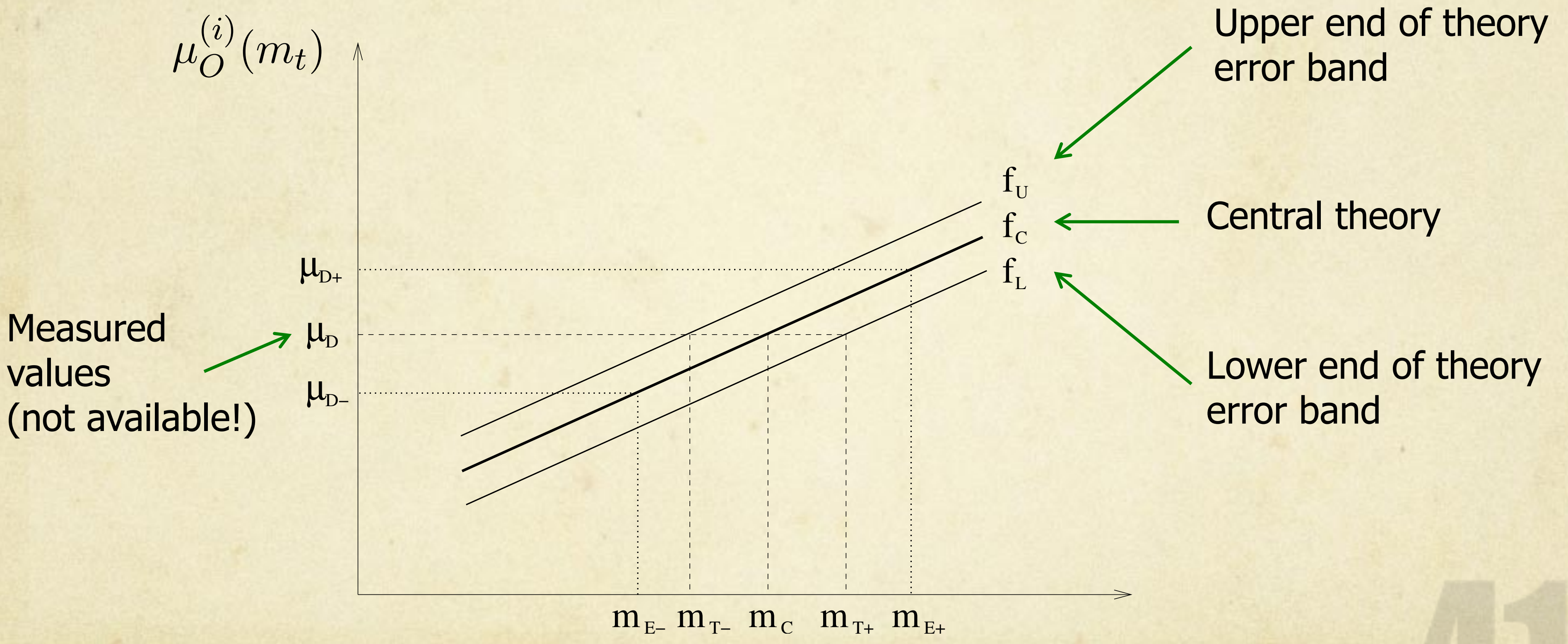
✓ Instead, utilize the first 4 moments of each distribution

$$\sigma = \int d\sigma \qquad \mu_O^{(i)} = \frac{1}{\sigma}\int d\sigma\, O^{\,i} \qquad \mu_O^{(0)} = 1\,, \qquad \mu_O^{(1)} = \langle O \rangle$$

Note: both are subject to cuts (or no cuts); we tried both.

- Here is how it all works:

1) Compute the dependence of the moments $\mu_O^{(i)}(m_t)$ on the top mass
2) Measure the moment
3) Invert 1) and 2) to get the top mass (would be the pole mass, since this is what we use)



41

Theory systematics: Predictions

observable; setup	$i=1$	$i=1\oplus 2$	$i=1\oplus 2\oplus 3$
all; LO+PS	$187.90^{+0.6}_{-0.6}[428.3]$	$187.71^{+0.60}_{-0.60}[424.2]$	$187.83^{+0.58}_{-0.60}[442.8]$
all; LO+PS+MS	$175.98^{+0.63}_{-0.69}[16.9]$	$176.05^{+0.63}_{-0.68}[17.8]$	$176.12^{+0.61}_{-0.68}[18.9]$
all; NLO+PS	$175.43^{+0.74}_{-0.80}[29.2]$	$176.20^{+0.73}_{-0.79}[30.1]$	$175.67^{+0.73}_{-0.76}[31.2]$
all; $\mathrm{NLO_{FO}}$	$174.41^{+0.72}_{-0.73}[96.6]$	$174.82^{+0.71}_{-0.73}[93.1]$	$175.44^{+0.70}_{-0.68}[94.8]$
all; $\mathrm{LO_{FO}}$	$197.31^{+0.42}_{-0.35}[2496.1]$	$197.19^{+0.42}_{-0.35}[2505.6]$	$197.48^{+0.36}_{-0.35}[3005.6]$
1,4,5; LO+PS	$173.68^{+1.08}_{-1.31}[0.8]$	$173.68^{+1.08}_{-1.31}[0.9]$	$173.75^{+1.08}_{-1.31}[0.9]$
1,4,5; LO+PS+MS	$173.61^{+1.10}_{-1.34}[1.0]$	$173.63^{+1.10}_{-1.34}[1.0]$	$173.62^{+1.10}_{-1.34}[1.0]$
1,4,5; NLO+PS	$174.40^{+0.75}_{-0.81}[3.5]$	$174.43^{+0.75}_{-0.81}[3.5]$	$174.60^{+0.75}_{-0.79}[3.2]$
1,4,5; $\mathrm{NLO_{FO}}$	$174.73^{+0.72}_{-0.74}[5.5]$	$174.72^{+0.71}_{-0.74}[5.6]$	$175.18^{+0.64}_{-0.71}[4.6]$
1,4,5; $\mathrm{LO_{FO}}$	$175.84^{+0.90}_{-1.05}[1.2]$	$175.75^{+0.89}_{-1.05}[1.2]$	$175.82^{+0.89}_{-1.04}[1.2]$

$$m_t^{\mathrm{pd}} = 174.32 \text{ GeV}$$

[...] = χ^2 per d.o.f.

label	kinematic distribution
1	$p_T(\ell^+)$
2	$p_T(\ell^+\ell^-)$
3	$M(\ell^+\ell^-)$
4	$E(\ell^+)+E(\ell^-)$
5	$p_T(\ell^+)+p_T(\ell^-)$

Conclusions on top mass

✓ New developments have resurrected the interest in knowing m_{top} precisely

- ✓ Vacuum Stability in SM
- ✓ Higgs Inflation

✓ There are many dedicated hadron collider measurements.
They return consistent values around m_{top} = 173 GeV
and uncertainty (mostly on the measurement!) of below 1 GeV.

✓ Questions remain: can there be a significant additional theoretical systematics O(1 GeV) ?

✓ This is not an abstract problem: m_{top} is not an observable and so is a theoretically defined concept.

✓ New developments (notably ongoing work in Powheg) and more precise NNLO+decay calculations will help improve our understanding of the correct value of mtop from LHC data

✓ This is unrelated to the idea about the so-called MC mass (which is a non-issue!).

✓ Moreover, often quoted non-perturbative uncertainty on the top mass was recently shown to be below 100MeV.

Beneke, Marquard, Nason, Steinhauser 2016

✓ This is completely negligible not only now but for the future LHC!

Summary and Conclusions

- Clearly, top physics is in precision phase

- High quality agreement between SM and Tevatron/LHC measurements at all collider energies.

- Total and differential x-section for tT production now known in full NNLO.

  - So far all is for stable tops.
  - Decay in NWA is feasible.

- Important phenomenology

  - Constrain and improve PDF's

  - Searches for new physics

  - Very high-precision test of SM (given exp is already at 5% !). Good agreement.

Future directions

- Top decay
- Understand properly the TeV P_T region (large collinear logs, etc.)
- NNLO predictions for LHC A_C forthcoming
- NNLO 2dim differential distributions

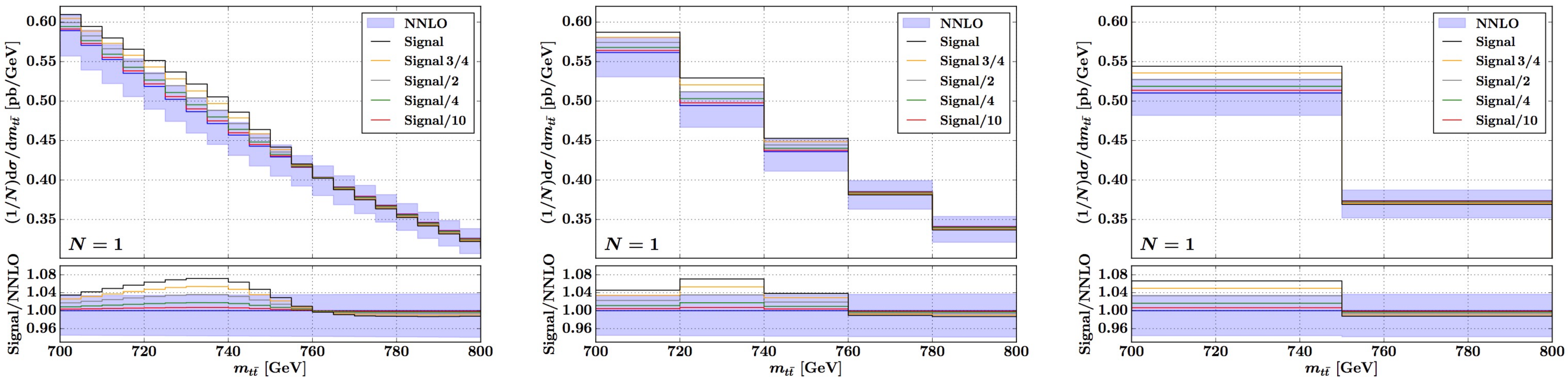
Backup slides

Bump-hunting around M_{tt}=750 GeV

$$\sigma(N) = \frac{1}{N}\frac{d\sigma}{dm_{t\bar{t}}}\,.$$

$$\begin{aligned} N &= 1 \quad \text{(i.e. the unnormalised distribution)}\,,\\ N_{\rm tot} &= \sigma_{\rm tot}\,,\\ N_{100} &= \sigma(600\,\text{GeV} < m_{t\bar{t}} < 700\,\text{GeV})\,,\\ N_{200} &= \sigma(500\,\text{GeV} < m_{t\bar{t}} < 700\,\text{GeV})\,. \end{aligned}$$

✓ Bump-hunting in the un-normalized spectrum



Signal taken from the following paper

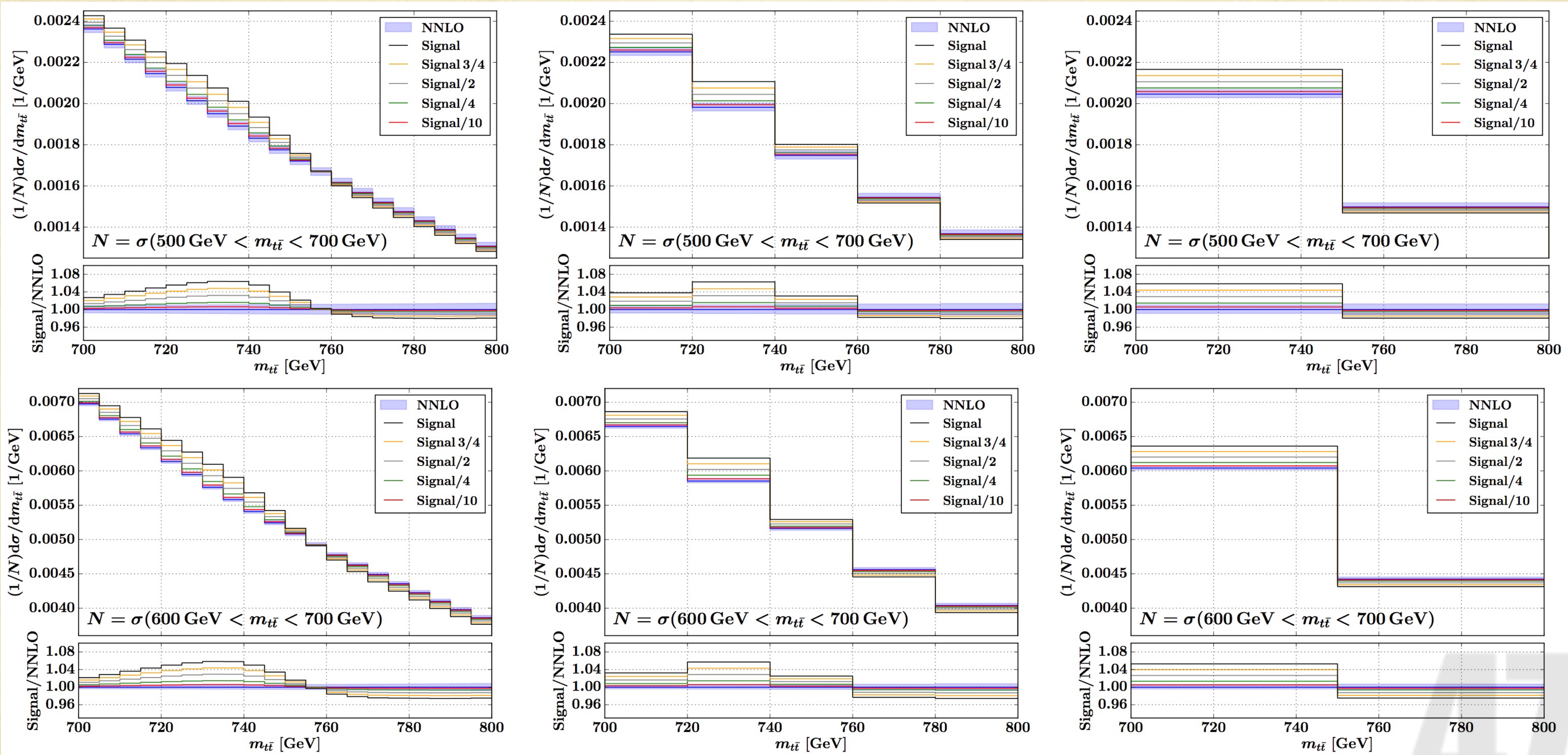
Hespel, Maltoni, Vryonidou arXiv:1606.04149

Bump-hunting around M_{tt}=750 GeV

$$\sigma(N) = \frac{1}{N}\frac{d\sigma}{dm_{t\bar{t}}}\,.$$

$$\begin{aligned} N &= 1 \quad \text{(i.e. the unnormalised distribution)}\,, \\ N_{\rm tot} &= \sigma_{\rm tot}\,, \\ N_{100} &= \sigma(600\,\text{GeV} < m_{t\bar{t}} < 700\,\text{GeV})\,, \\ N_{200} &= \sigma(500\,\text{GeV} < m_{t\bar{t}} < 700\,\text{GeV})\,. \end{aligned}$$

✓ Bump-hunting in the normalized spectrum



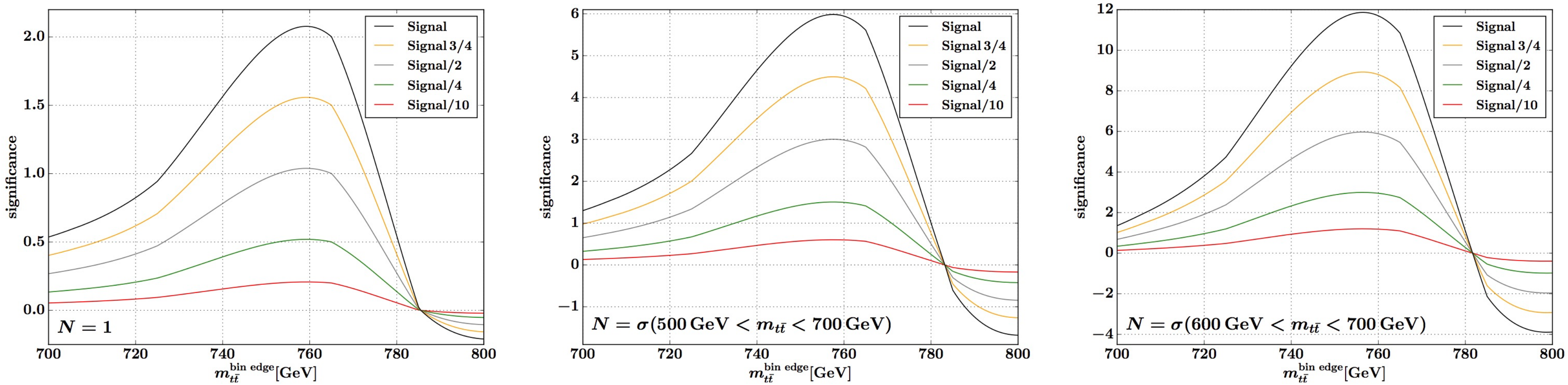
Signal taken from the following paper Hespel, Maltoni, Vryonidou arXiv:1606.04149

Bump-hunting around M_{tt}=750 GeV

$$\sigma(N) = \frac{1}{N}\frac{d\sigma}{dm_{t\bar{t}}}\,.$$

$$\begin{aligned} N &= 1 \quad \text{(i.e. the unnormalised distribution)}\,, \\ N_{\rm tot} &= \sigma_{\rm tot}\,, \\ N_{100} &= \sigma(600\,\text{GeV} < m_{t\bar{t}} < 700\,\text{GeV})\,, \\ N_{200} &= \sigma(500\,\text{GeV} < m_{t\bar{t}} < 700\,\text{GeV})\,. \end{aligned}$$

✓ Bump-hunting with a sliding bin-window of width 50 GeV (plotted is position of high bin edge)



where: $\text{significance} = \frac{(\text{SM}+\text{BSM})_{\text{central}} - (\text{pure SM})_{\text{central}}}{(\text{pure SM})_{\text{error}}}$

Signal taken from the following paper Hespel, Maltoni, Vryonidou arXiv:1606.04149