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High p_T/m_{tt} predictions for $t\bar{t}$ including QCD and EW corrections

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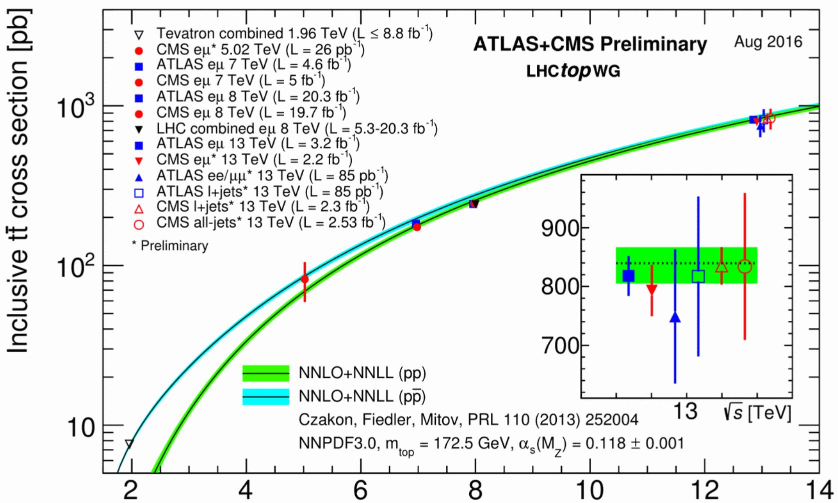
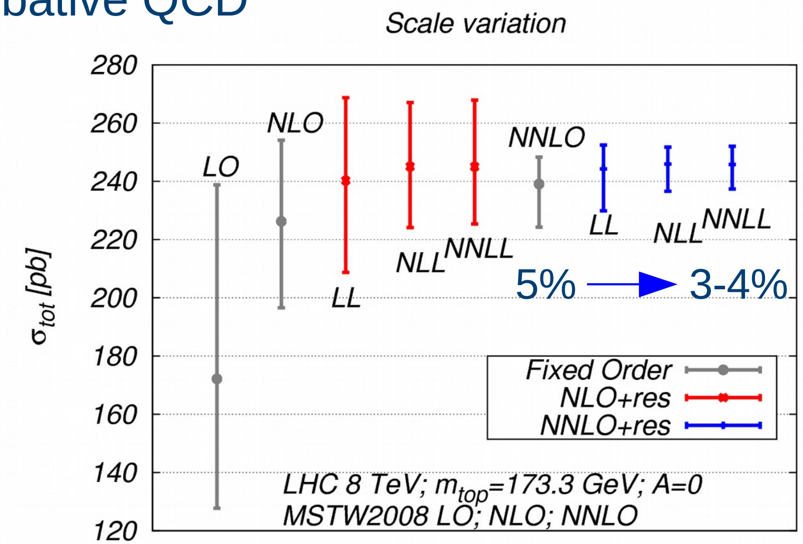
Precision theory for the LHC 2016, Quy-Nhon

Cavendish Laboratory - HEP Group

Top-Quark pairs at the LHC (total cross section)

- Precision for the top-quark pair cross section?
- Total cross section prediction in perturbative QCD





Czakon, Fielder, Mitov 2013

- Uncertainties:

Scales	~ 3-4%
pdf	~ 2-3%
α_S	~ 1.5%
m_{top}	~ 3%

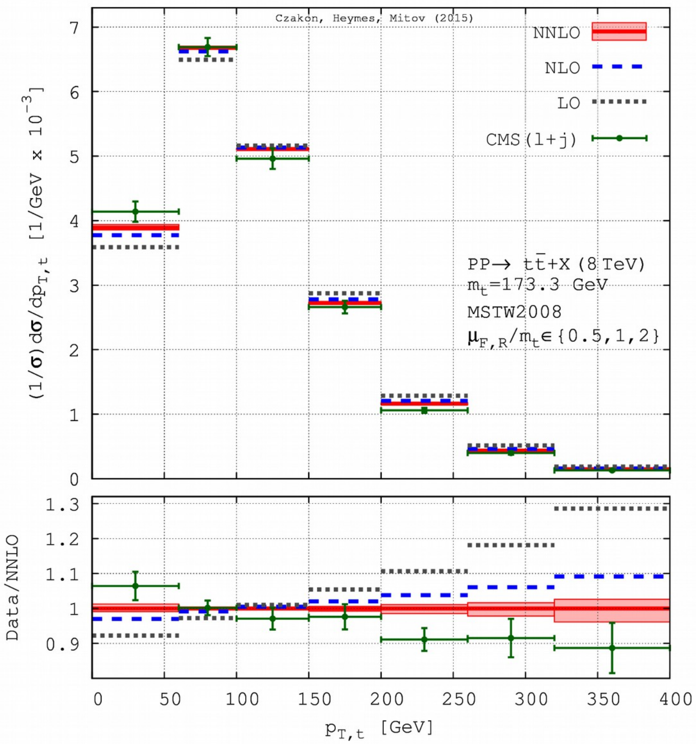
→ NNLO needed (at least)

Talk by Yvonne Peters

Measurement < 4% expected

Top-Quark pairs at the LHC (differential)

- Precision (NNLO) for differential distributions → better description of data
- Example: transverse momentum distribution at 8 TeV



Czakon, DH, Mitov 2015

- Discrepancy between data and prediction is alleviated at NNLO
- Calculation with fixed scales (here: m_{top}) is limited to low pT and invariant mass region
- Dynamical scales in extended kinematical regime required (→ probed at the LHC)

→ Precision predictons

Dynamical scales for top-quark pair production (1)

- Fixed order perturbative QCD
  - Only ambiguity is the choice of renormalization and factorization scale

$$\sigma_{h_1 h_2}(P_1, P_2) = \sum_{ab} \iint_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \, f_{a/h_1}(x_1, \mu_F^2) \, f_{b/h_2}(x_2, \mu_F^2) \, \hat{\sigma}_{ab}(x_1 P_1, x_2 P_2; \, \alpha_s(\mu_R^2), \, \mu_R^2, \, \mu_F^2)$$

- Choose dynamical scale in order to maintain/improve perturbative convergence

$$\mu_0 \sim m_t \,,$$

$$\mu_0 \sim m_T = \sqrt{m_t^2 + p_T^2} \,,$$

$$\mu_0 \sim H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} \,,$$

$$\mu_0 \sim H_T' = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} + \sum_i p_{T,i} \,,$$

$$\mu_0 \sim E_T = \sqrt{\sqrt{m_t^2 + p_{T,t}^2}\sqrt{m_t^2 + p_{T,\bar{t}}^2}} \,,$$

$$\mu_0 \sim H_{T,\mathrm{int}} = \sqrt{(m_t/2)^2 + p_{T,t}^2} + \sqrt{(m_t/2)^2 + p_{T,\bar{t}}^2} \,,$$

$$\mu_0 \sim m_{t\bar{t}} \,,$$

½ ← Recommendation for p_T of the top ($\mu_0 \sim m_T$)

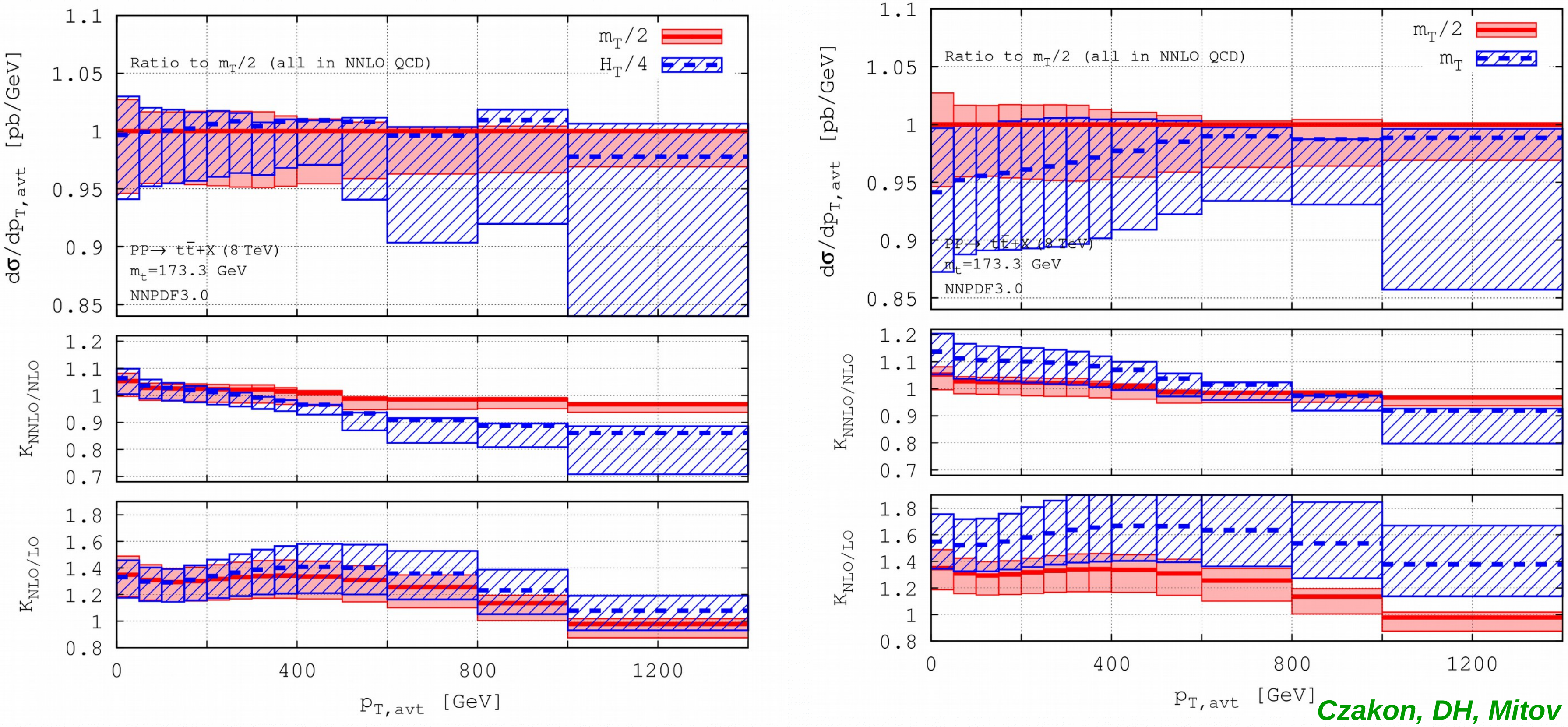
¼ ← Recommendation for $m_{t\bar{t}}$ (and others) ($\mu_0 \sim H_T$)

Czakon, DH, Mitov 2016

Remark: Different observables/different processes require different scales.

Dynamical scales for top-quark pair production (2)

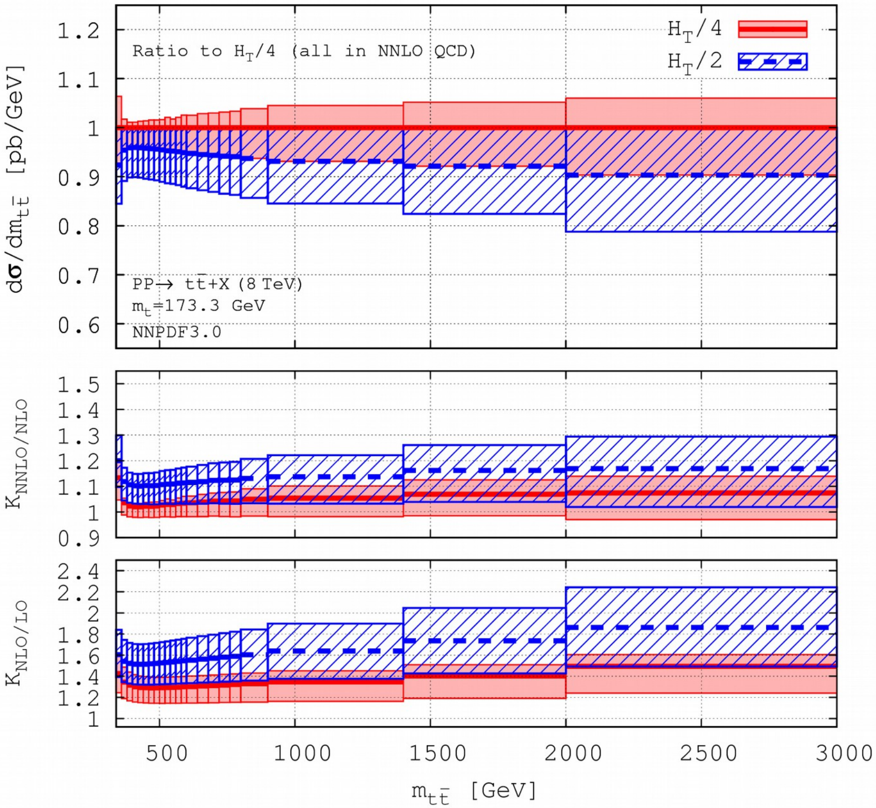
- Comparison of different scales (average top/antitop p_T) at 8 TeV
  - Main differences in k-factors and scale uncertainties

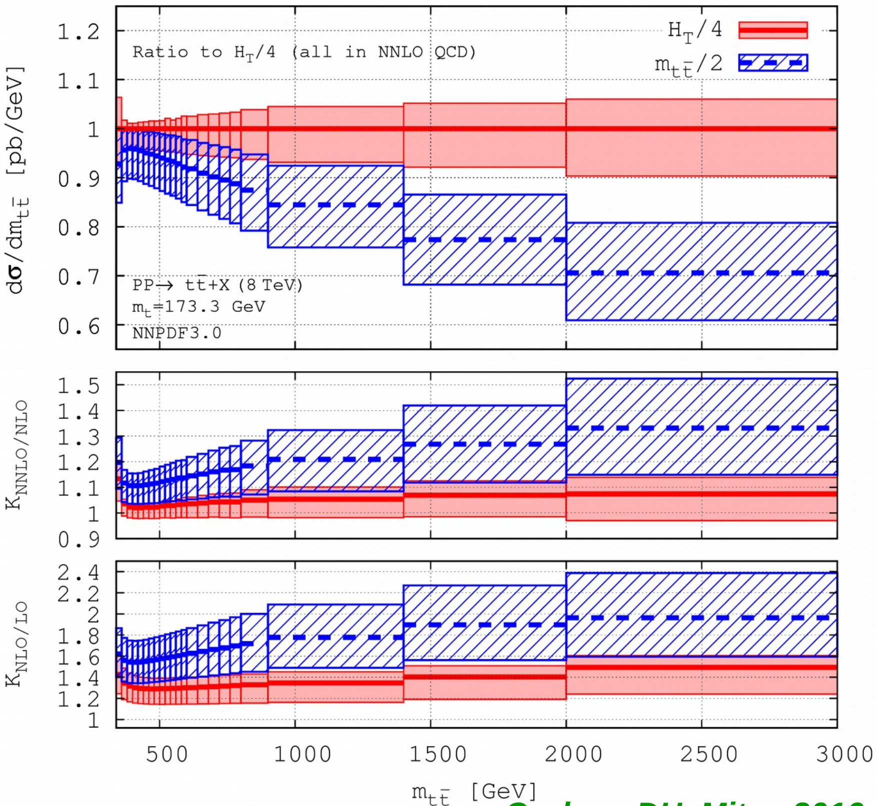


Czakon, DH, Mitov 2016

Dynamical scales for top-quark pair production (3)

- Comparison of different scales ($m_{t\bar{t}}$ – distribution) at 8 TeV
  - Scales based on invariant mass itself seem to behave worse

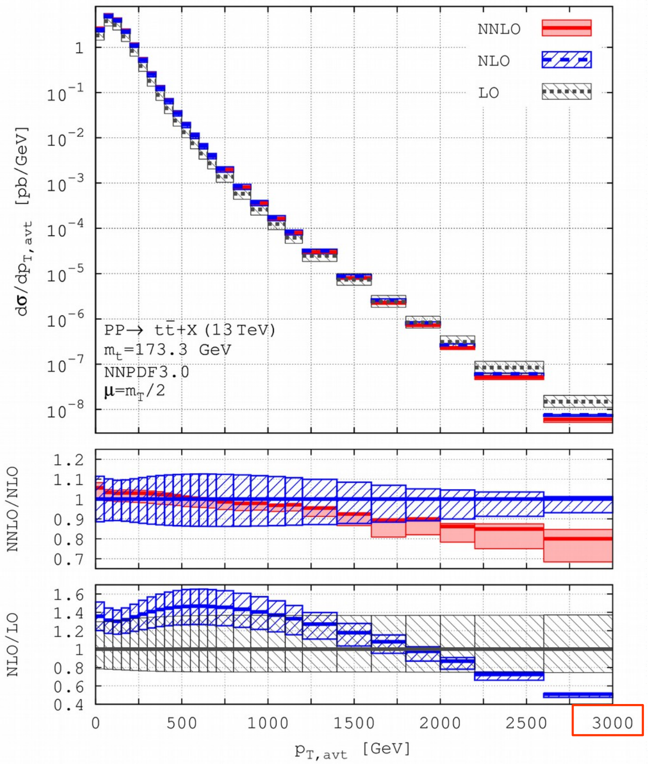




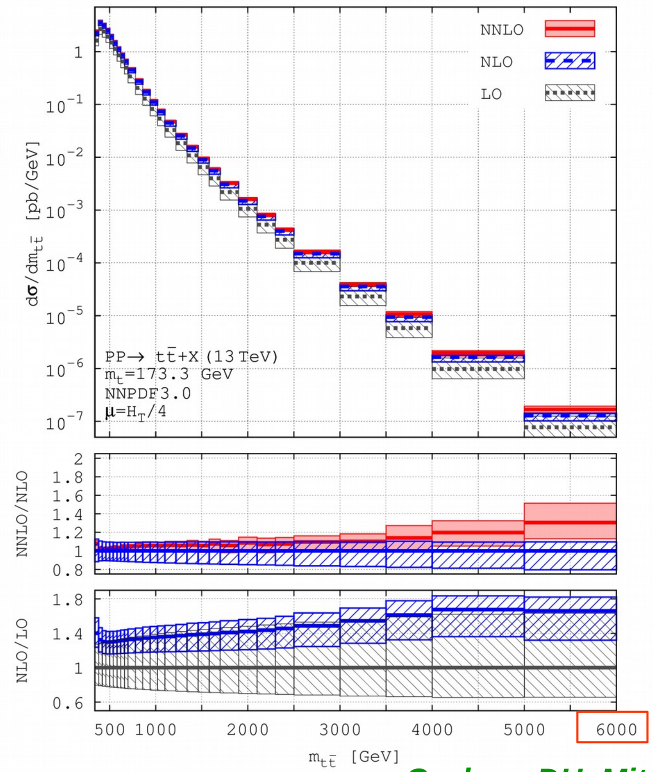
Czakon, DH, Mitov 2016

Differential NNLO QCD predictions for the LHC (1)

- LHC at 13 TeV
- Good perturbative convergence in a wide kinematical regime
- Scale choice is independent of the PDF set used



How far can we go at the LHC?

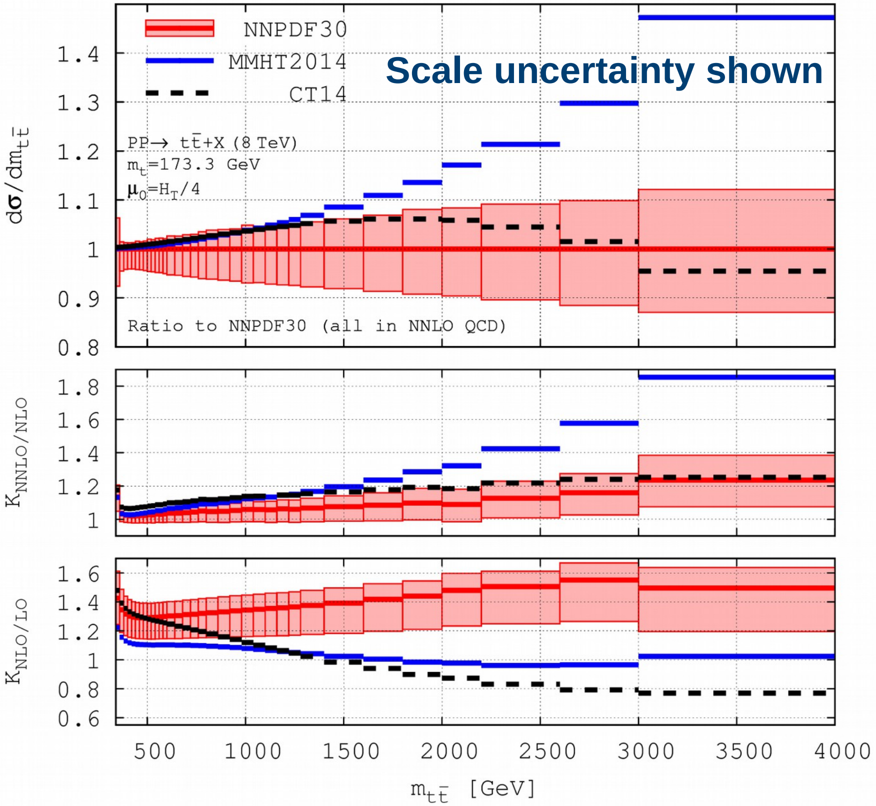


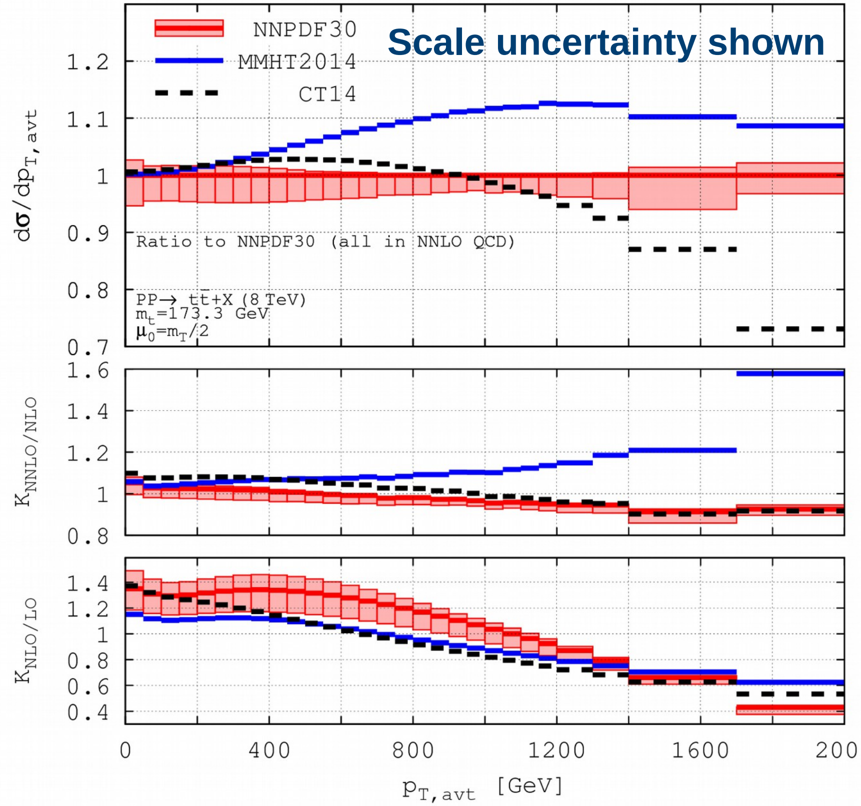
Czakon, DH, Mitov 2016

Differential NNLO QCD predictions for the LHC (2)

- Above a certain threshold (m_{tt} and p_T) PDF sets have large uncertainties
- Main source of uncertainty at (very) large p_T/m_{tt}
- Use $t\bar{t}$ -distributions to constrain pdf sets?

Czakon, DH, Mitov 2016





EW corrections to $t\bar{t}$

EW correction for tt production (1)

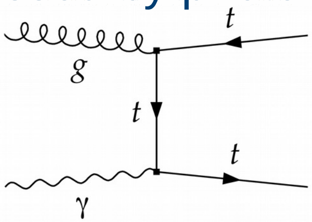
- Naive power counting suggests that one should consider EW corrections at this level of accuracy (α_s~ 0.1, α ~ 0.01)

		naive	reality(σ_{tot})
LO QCD	α_s^2	100%	100%
NLO QCD	α_s^3	10%	50%
NNLO QCD	α_s^4	1%	15%

Talk by Hua-Sheng Shao

		naive
LO EW	$\alpha_s\alpha$	10%
	α^2	1%
NLO EW	$\alpha_s^2\alpha$	1%
	...	subleading

Suppressed by photon PDF



Sudakov enhanced negative corrections at regions $M_w << p_{T,}, m_{tt}$

EW correction for $t\bar{t}$ production (2)

- History of EW corrections for on-shell $t\bar{t}$
  - Purely weak ***Beenakker et al. 1994; Kühn et al. 2006-2013; Bernreuther et al. 2006; Campbell et al. 2016***
  - QED ***Hollik, Kollar 2008***
  - Asymmetry A_{FB} ***Hollik, Pagani 2011; Kühn, Rodrigo 2012; Manohar, Trott 2012; Bernreuther, Si 2012***
  - NLO+EW+decay(NWA) ***Bernreuther, Si 2010***

- NLO QCD + EW (MadGraph5_aMC@NLO framework) ***Pagani, Tsinikos, Zaro 2016***
  - Thorough study of photon induced contributions $\alpha_s\alpha$, $\alpha_s^2\,\alpha$, … (subleading)
  - Pdf sets including photon pdf

MRSTW2004QED	***Martin et al. 2004***
CT14QED	***Schmidt et al. 2016***
NNPDF2.3QED, NNPDF3.0QED	***Ball et al. 2013; Bertone Carraza 2016***
LUXqed	***Manohar et al. 2016 (Talk by Giulia Zanderighi)***

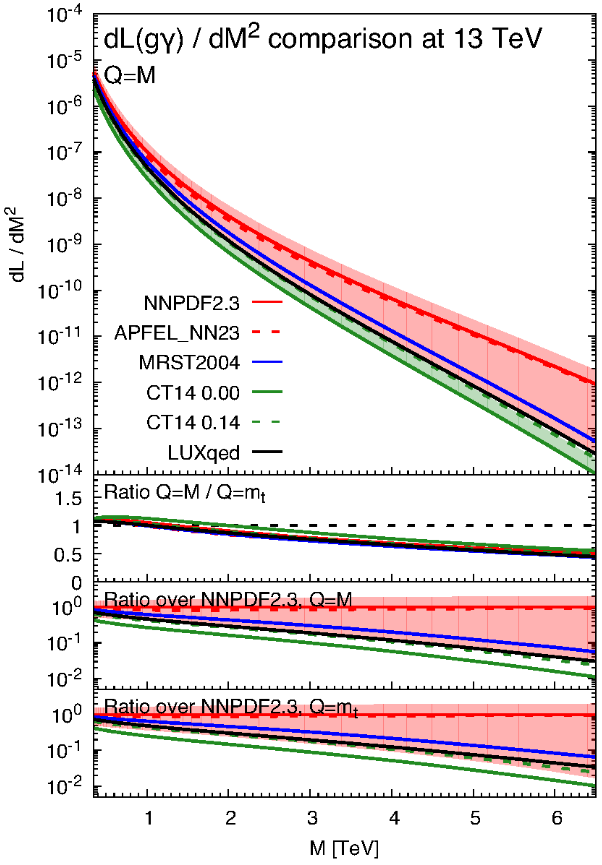
Talk by Lucian Harland-Lang (PDF session)

EW correction for tt production

Pagani, Tsinikos, Zaro 2016

- Different treatment of the photon in different PDF sets
  - relevant at large x
  - NNPDF23(30) large uncertainty due to agnostic treatment
  - Other PDF sets have smaller uncertainty and are at the lower edge of the NNPDF uncertainty band
  - Very small uncertainties in LUXqed

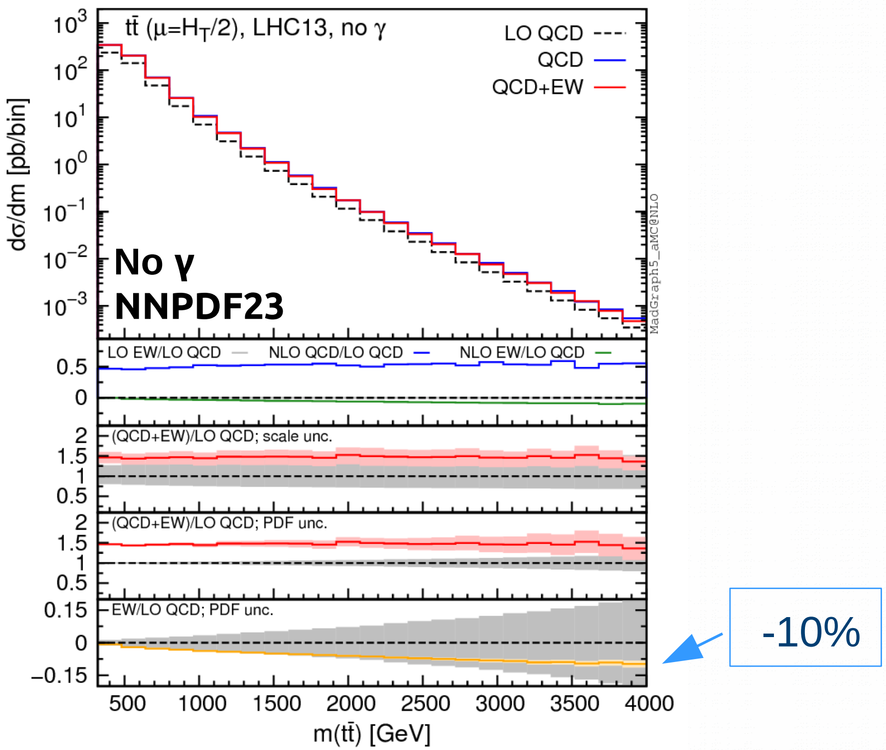
    Precision DIS data used *Talks by Giulia Zanderighi, Lucian Harland-Lang*

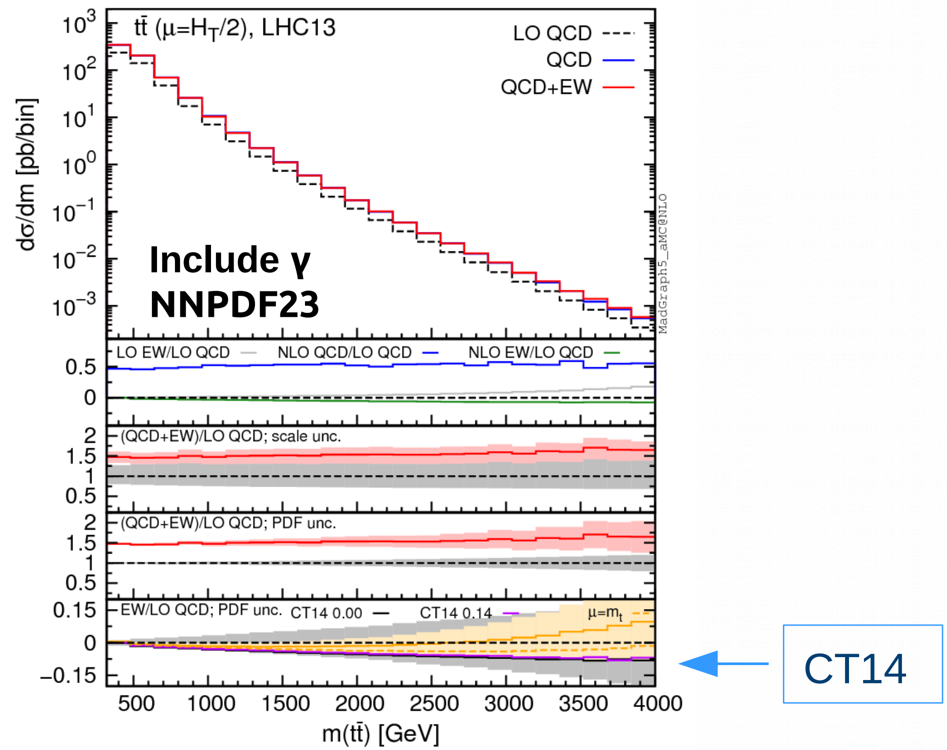


NLO QCD + EW (13 TeV)

Pagani, Tsinikos, Zaro 2016

- Moderate Sudakov behaviour at large m_{tt} (4000 GeV)
- Compensated by photon induced contributions (NNPDF23), large uncertainties
- Photon induced contributions negligible for CT14QED

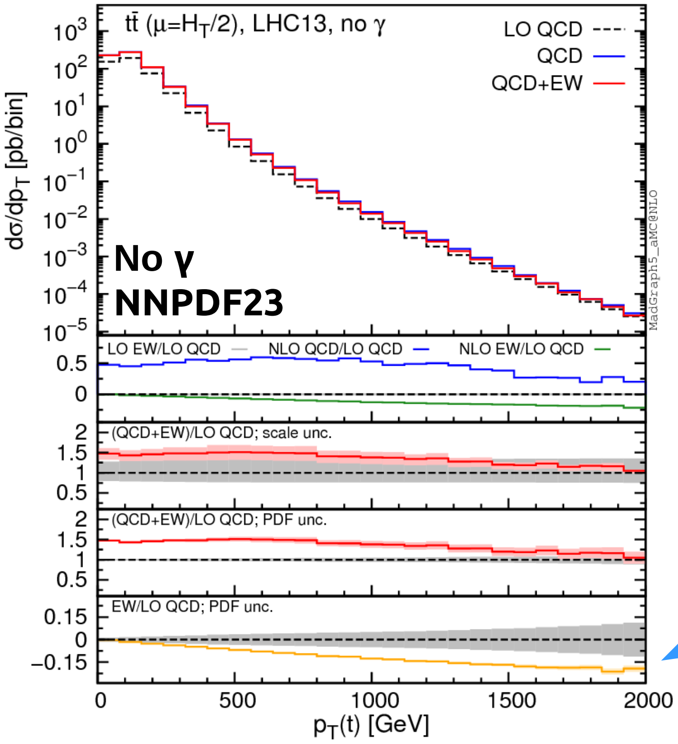




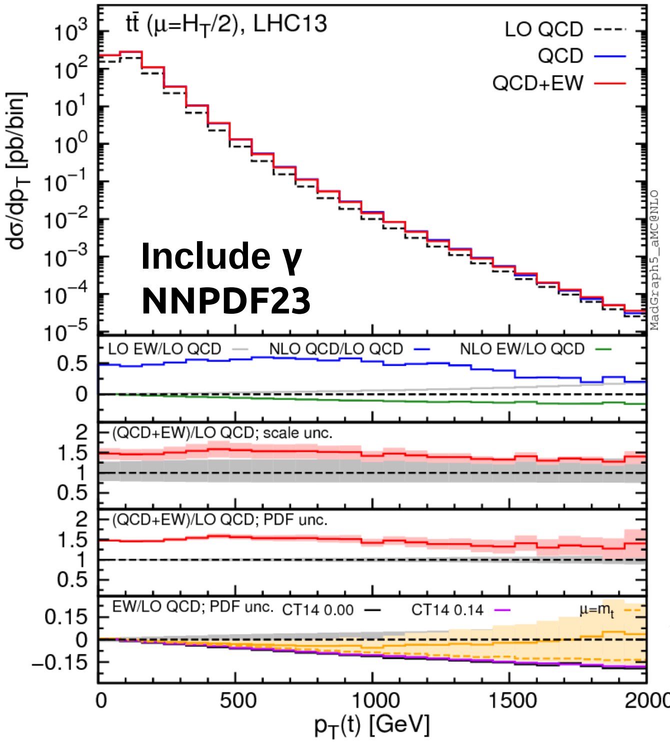
NLO QCD + EW (13 TeV)

Pagani, Tsinikos, Zaro 2016

- Moderate Sudakov behaviour at large p_T (2000 GeV)
- Compensated by photon induced contributions (NNPDF23), large uncertainties
- Photon induced contributions negligible for CT14QED



-20%



CT14

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Czakon, DH, Mitov, Pagani, Tsinikos, Zaro (in progress)

Can we do better?

Combining NNLO QCD + EW corrections

Combining NNLO QCD and EW corrections

Czakon, DH, Mitov, Pagani, Tsinikos, Zaro (in progress)

- New PDF sets became available: NNPDF30QED (shown here)
- LUXqed (fastNLO tables is work in progress)
- Scale choice based on recommendation for top-pair distributions

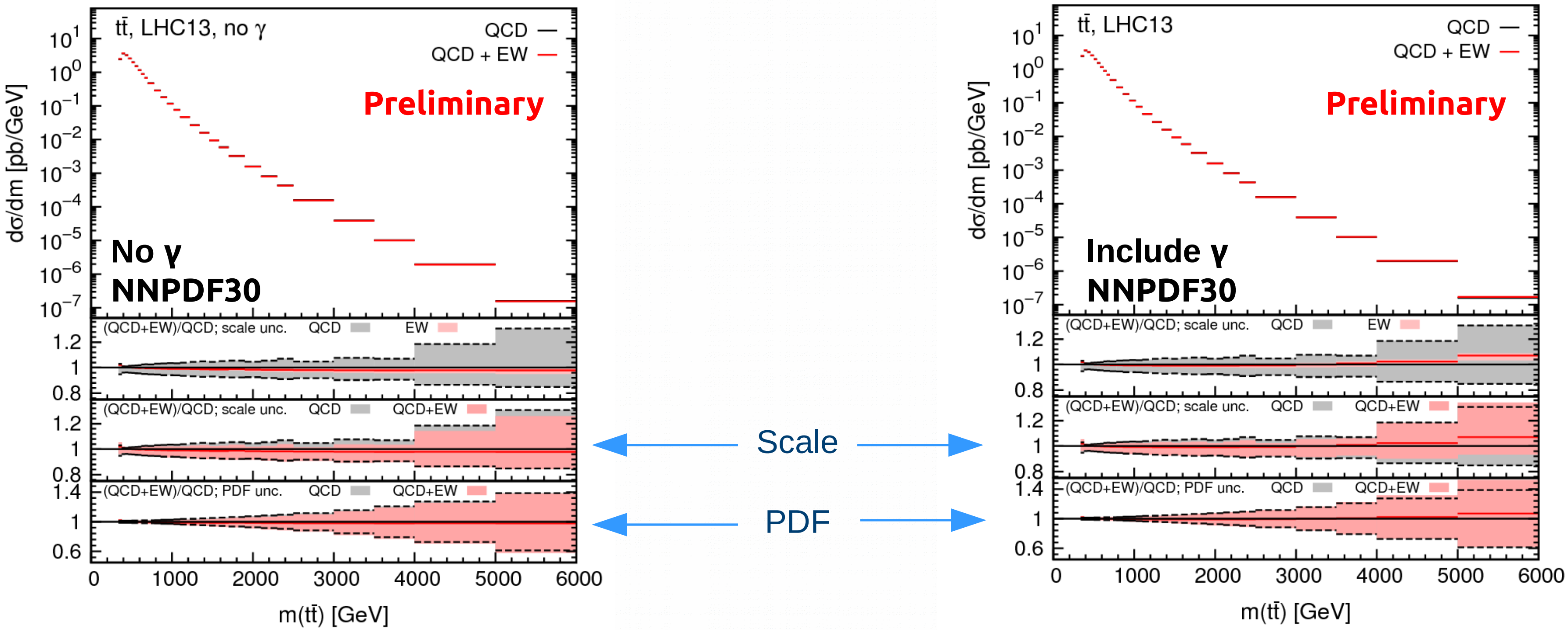
$$\mu = \begin{cases} m_T/2 \text{ for } p_{T,avt} \\ H_T/4 \text{ for } m(t\bar{t}), y_{avt}, y(t\bar{t}) \end{cases}$$

- Approximate PDF uncertainty at NNLO by rescaling with NLO
- QCD = NNLO QCD, EW = (LO EW, NLO EW, subleading terms)
- EW corrections calculated with MadGraph5_aMC@NLO
  - Setup as in *Pagani, Tsinikos, Zaro 2016*

Combining NNLO QCD and EW for the invariant mass

Czakon, DH, Mitov, Pagani, Tsinikos, Zaro (in progress)

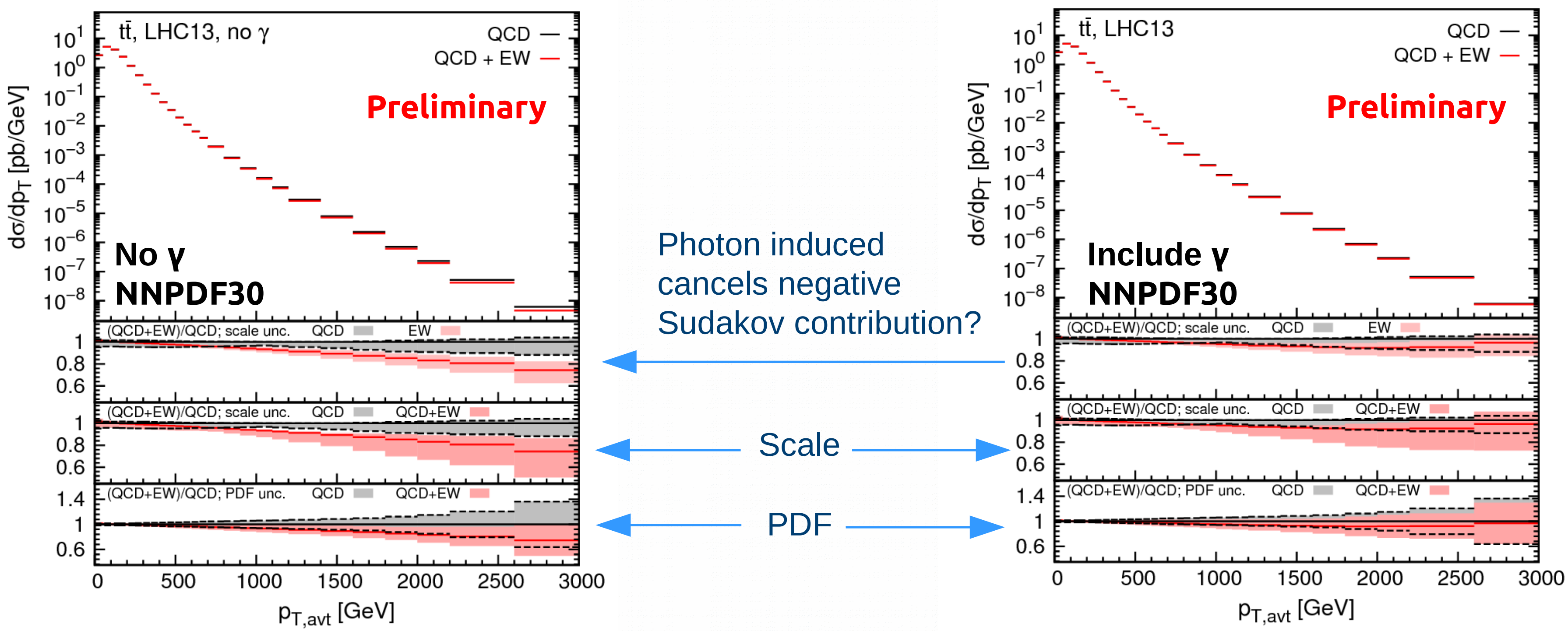
- Very small EW corrections in the whole energy range (1%)
- Large PDF uncertainties in the high energy range ($m_{tt} > \sim 3$ TeV)
- Use NNLO for new physics searches (bump-hunting) *Czakon, DH, Mitov 2016*



Combining NNLO QCD and EW for the p_T of the top

Czakon, DH, Mitov, Pagani, Tsinikos, Zaro (in progress)

- Negative Sudakov contributions are sizeable (up to 20%) at very large p_T (> 2 TeV)
- They are outside the QCD scale uncertainty band, but inside the PDF uncertainty
- Photonic contributions are at the same order, but positive (Cancellation ?)
- PDF uncertainty is large at high p_T

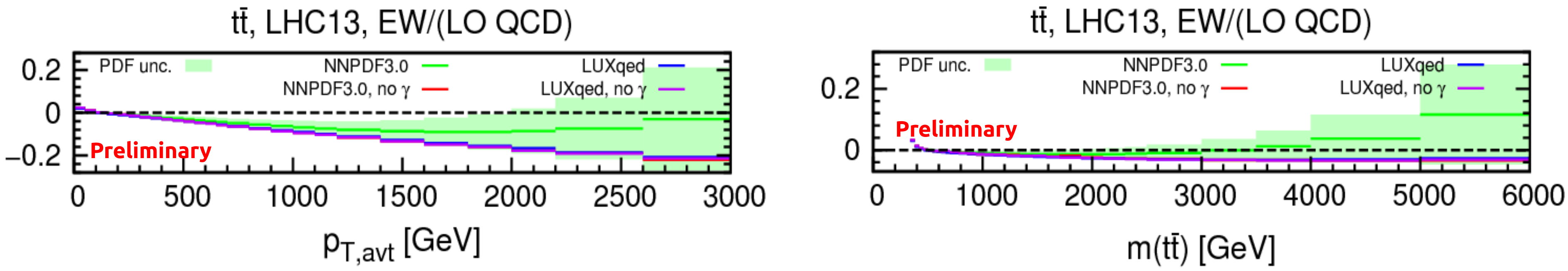


Dependence on the Photon PDF

NNPDF30 and LUXqed

Czakon, DH, Mitov, Pagani, Tsinikos, Zaro (in progress)

- Large differences for photon PDFs
- Photon contribution is much smaller in LUXqed
- LUXqed at the lower edge of NNPDF30 uncertainty band
- NNPDF30 (no γ) at the same order as LUXqed
  - → EW corrections at high pT can be sizeable (only Sudakov)
  - → no compensation from photon induced channels expected



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Czakon, DH, Mitov 2016

Application:

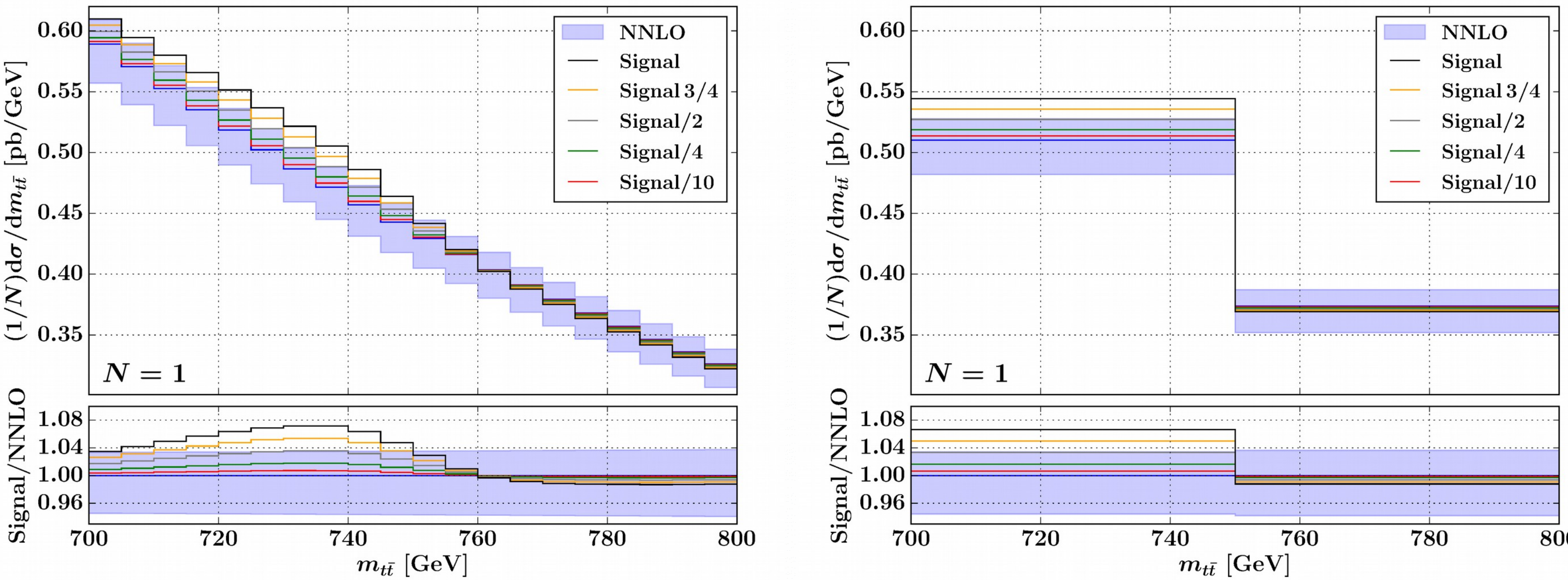
Bump-hunting using m_{tt} – distribution at NNLO

Bump Hunting using m_{tt} – distribution at NNLO

- Minimize uncertainties → choose appropriate normalization
- Discriminate a possible BSM signal from background for different possible binnings

NNLO scale + (approx.) PDF uncertainty added in quadrature

Czakon, DH, Mitov 2016



Signal from: Hespel, Maltoni, Vryonidou 2016

- Significance depends on bin-width and position of the bin

Bump Hunting using m_{tt} – distribution at NNLO

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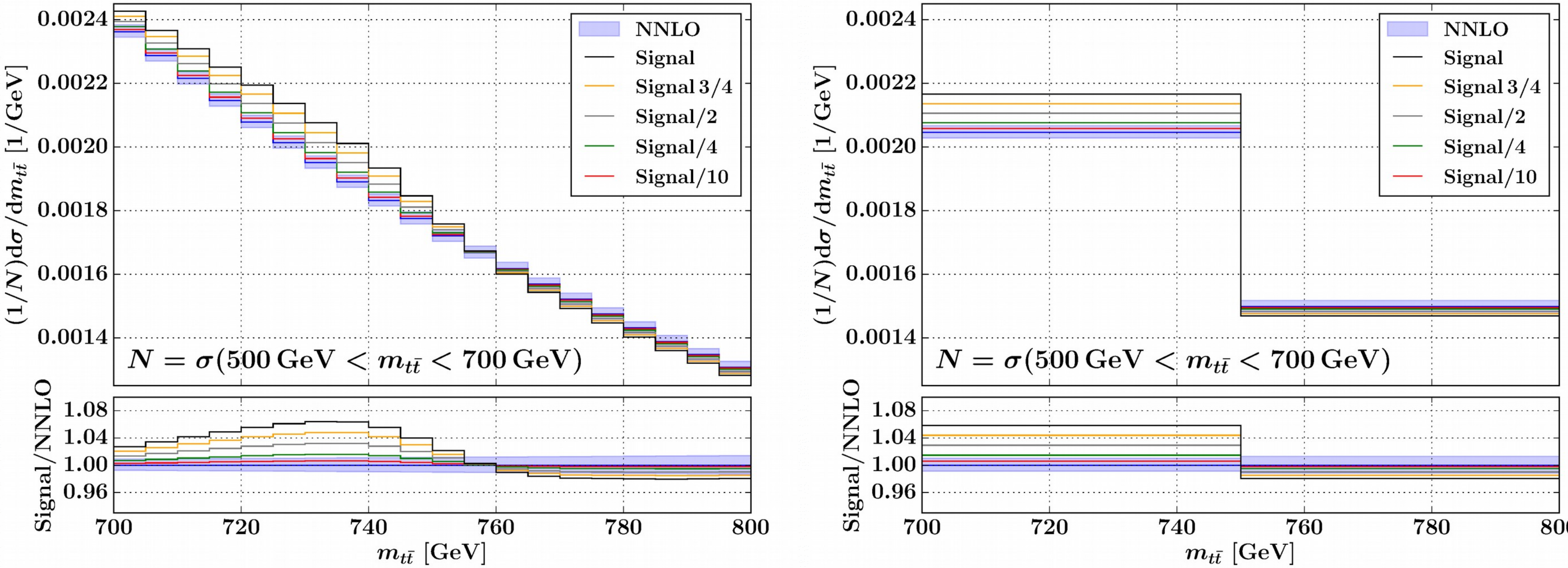
Czakon, DH, Mitov 2016



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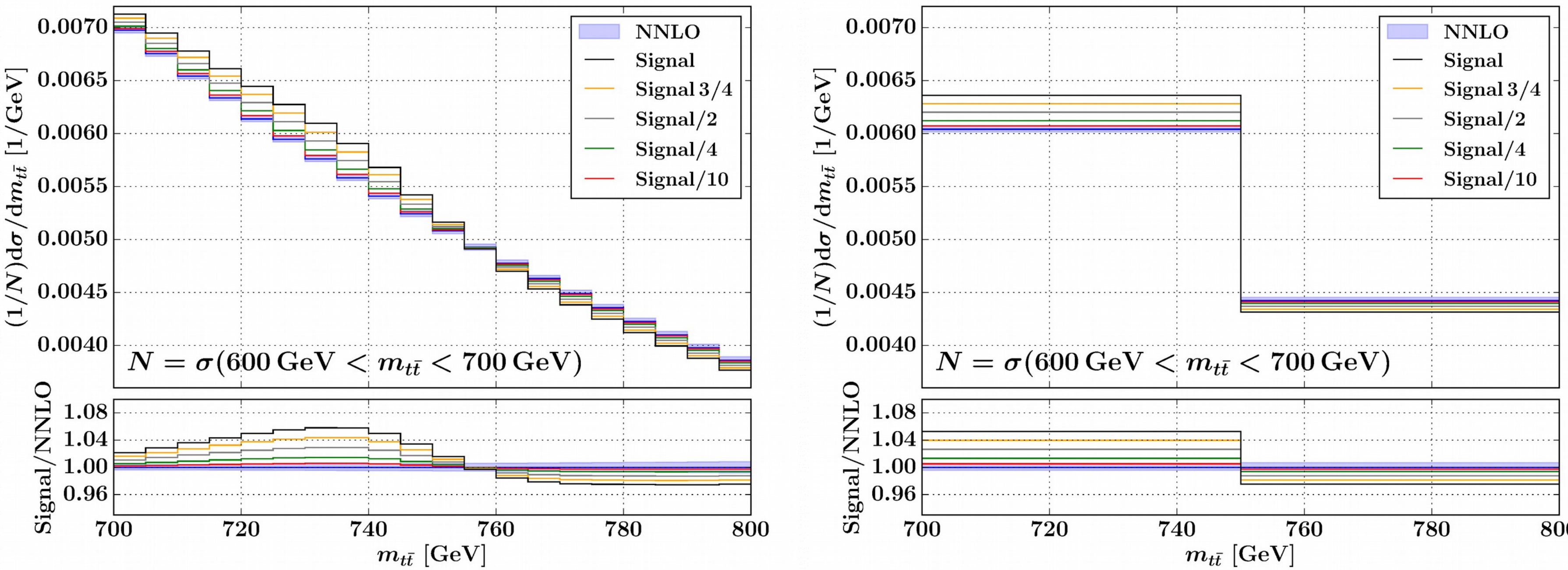

Signal from: Hespel, Maltoni, Vryonidou 2016

- Significance depends on bin-width and position of the bin

Conclusion

NNLO QCD

- High precision predictions ↔ fixed order results for top-quark pair production at NNLO QCD
- Precision at high p_T/m_{tt} currently limited by pdf uncertainty
- Use NNLO $t\bar{t}$ predicitons to constrain PDF sets in these regions

Combined NNLO QCD + EW

- EW corrections could be sizeable at large p_T (13 TeV)
  - Negative Sudakov contribution up to -20 % (still inside QCD PDF uncertainty)
  - Positive photon induced contributions of the same order for NNPDF30 with large uncertainties
  - Photon induced contributions expected to be small for other (photon) PDF sets (LUXqed, future pdf sets: MMHT)
- EW corrections are generally small for the m_{tt} distribution (13 TeV)
  - Use precision for new physics searches

- Here: focus on p_T and m_{tt}, but other distributions available (rapidity, …, 8TeV)
- Outlook
  - provide NNLO QCD results as fastNLO tables → different PDF sets
  - Study of effects of Vector Boson Radiation
  - Include top decays at NNLO in the NWA

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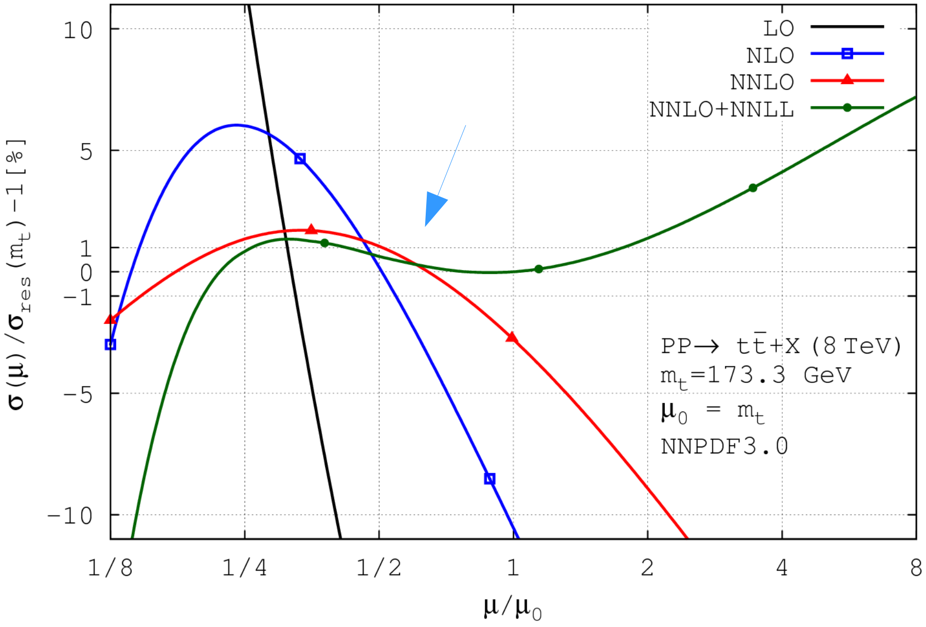
Back Up

Scale dependance of the total cross section

- Look for convergence
  - Scale value which minimizes difference
    - NLO → NNLO → (NNLO + NNLL)
  - Best convergence: $\mu_0 < m_{top}$
  - Little dependence on PDFset at NNLO



- Value of NNLO cross section at point of best convergence equals the NNLO+NNLL at the usual canonical scale $\mu_0 = m_{top}$

  → Therefore: Resummation has negligible impact on the total cross section at the point of fastest convergence

Czakon, DH, Mitov 2016

Related results

- This talk is about on-shell top-quark pair production only, with focus on p_T and m_{tt} differential distributions
- LO, NLO, NNLO → fixed order perturbative QCD
  - Here (residue subtraction): ***Czakon, Fiedler, DH, Mitov 2012-2016***
  - Partial results with different approaches exist

    Antenna subtraction: ***Abelof, Gehrmann-DeRidder, Maierhofer, Pozzorini 2014***

    q_T-subtraction/slicing: ***Catani, Grazzini, Torre 2014, 2015***

- Potentially large logs in the boosted regime (Resummation) ***Pecjak et al. 2016***
  - Not discussed here

- For recent studies of off-shell effects see, e.g.
  - QCD : pp → tt + j (complete off-shell) at NLO ***Bevilacqua, Hartanto, Kraus, Worek 2016***
  - NLO EW : pp → (tt) → leptons (complete off-shell) ***Denner, Pellen 2016***