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Precision predictions for $t\bar{t}$ production. Status and prospects.

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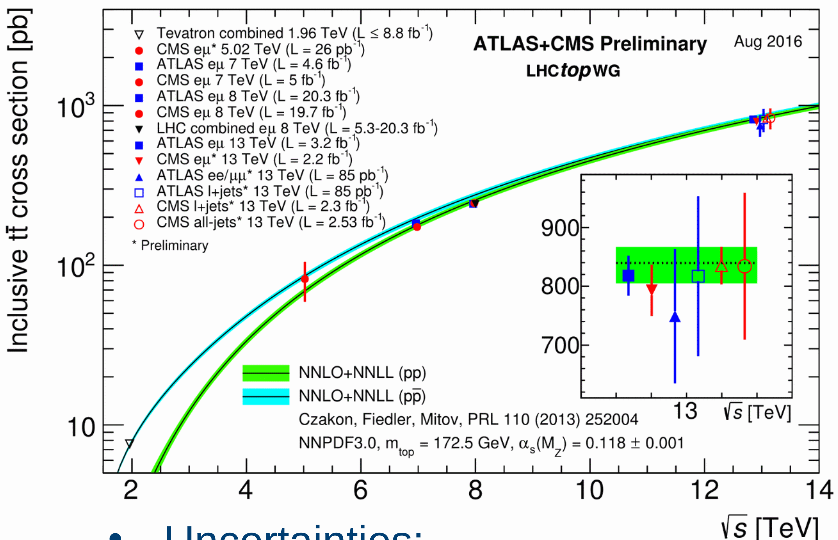
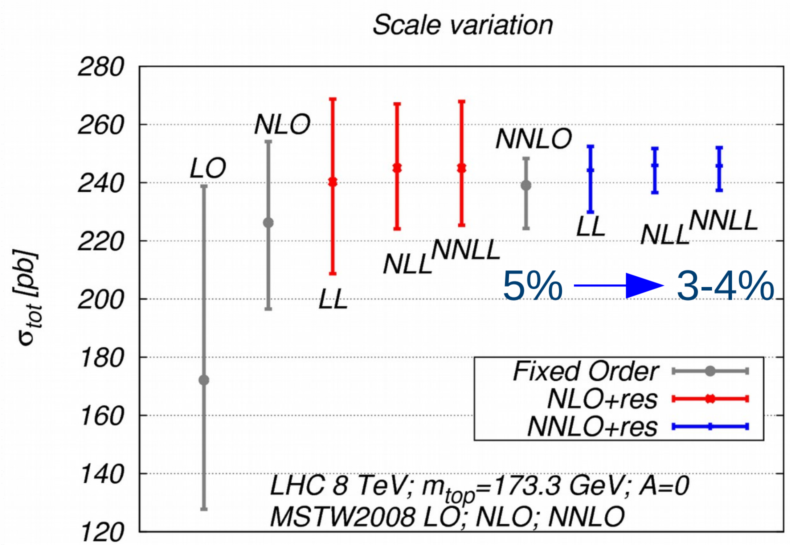
Future challenges for precision QCD 2016, Durham

Cavendish Laboratory - HEP Group

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

- Precision QCD predictions for the top-quark pair production cross section





Czakon, Fielder, Mitov 2013

- Uncertainties:

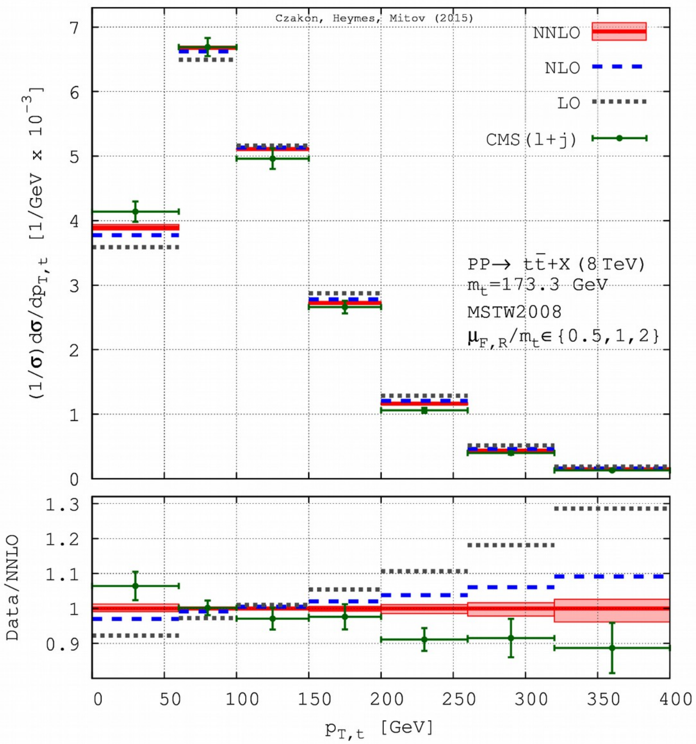
Scales	~ 3-4%
pdf	~ 2-3%
α_S	~ 1.5%
m_{top}	~ 3%

NNLO needed (at least)

Single measurements: < 4%

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 p_T and invariant mass region
- Dynamical scales in extended kinematical regime required (→ probed at the LHC)

→ Precision predictions in a wide regime

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 (applies to $\mu_0 \sim m_T$)

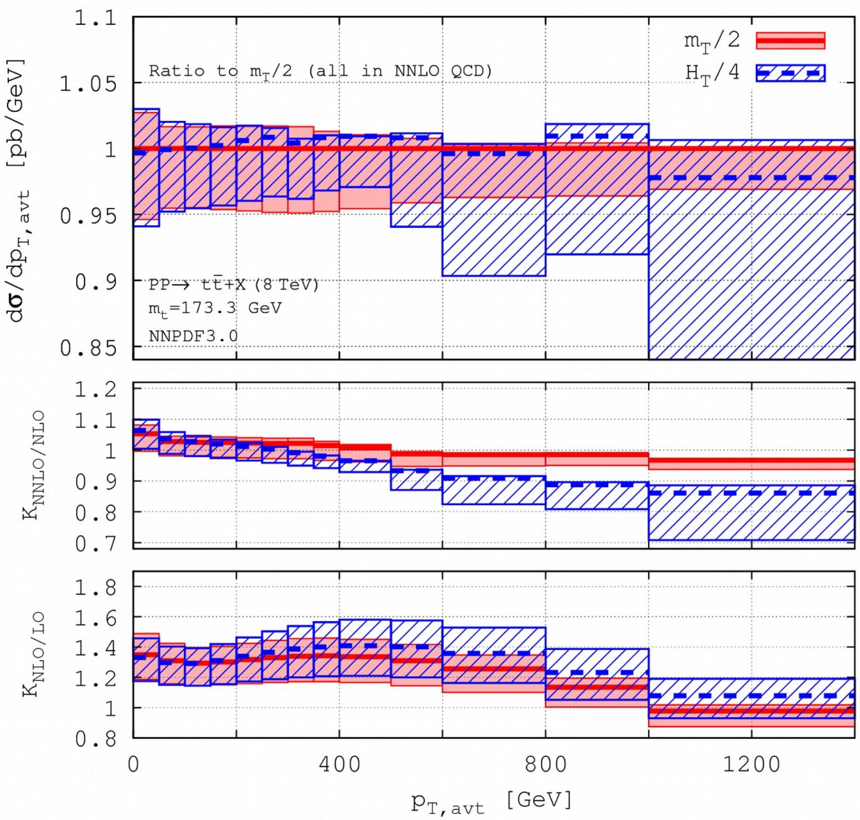
¼ ← Recommendation for $m_{t\bar{t}}$ (and others) (applies to $\mu_0 \sim H_T$)

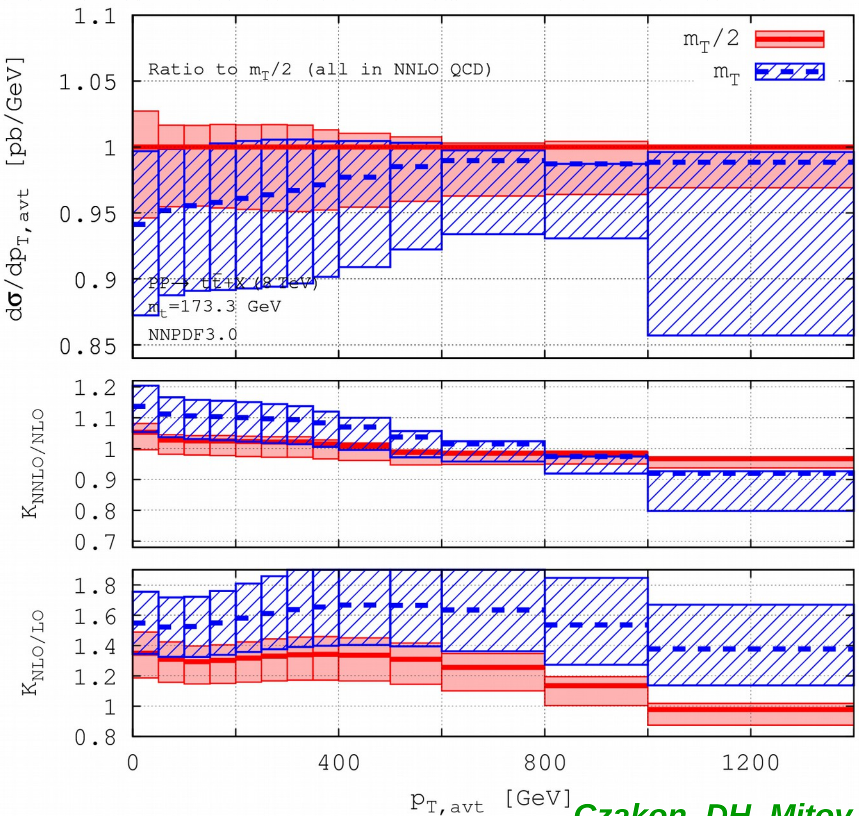
Czakon, DH, Mitov 2016

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

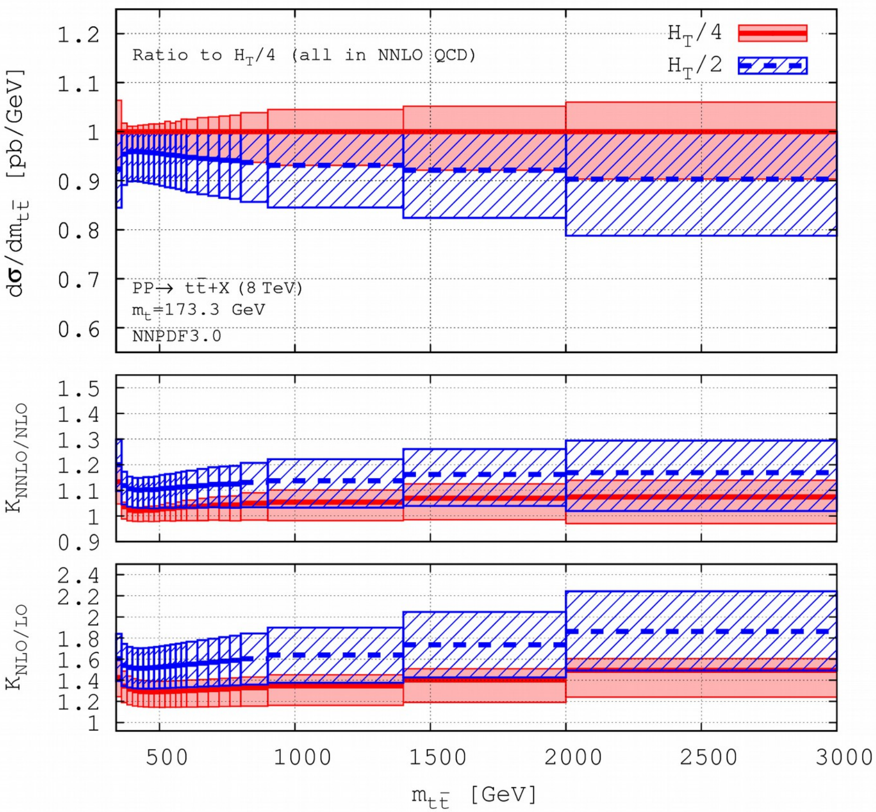


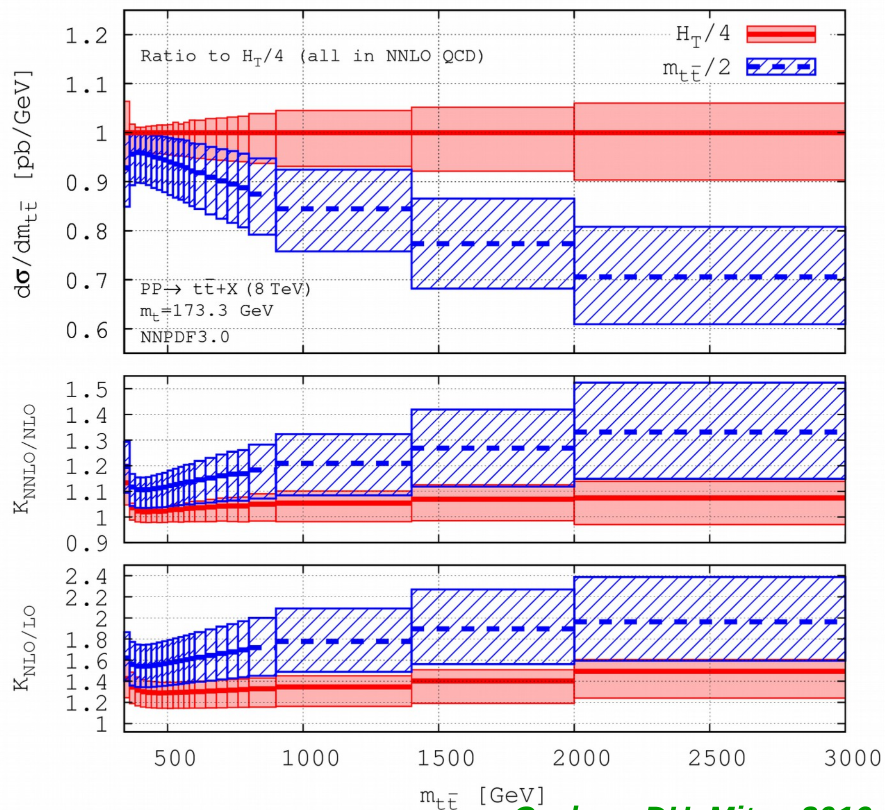


Czakon, DH, Mitov 2016

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

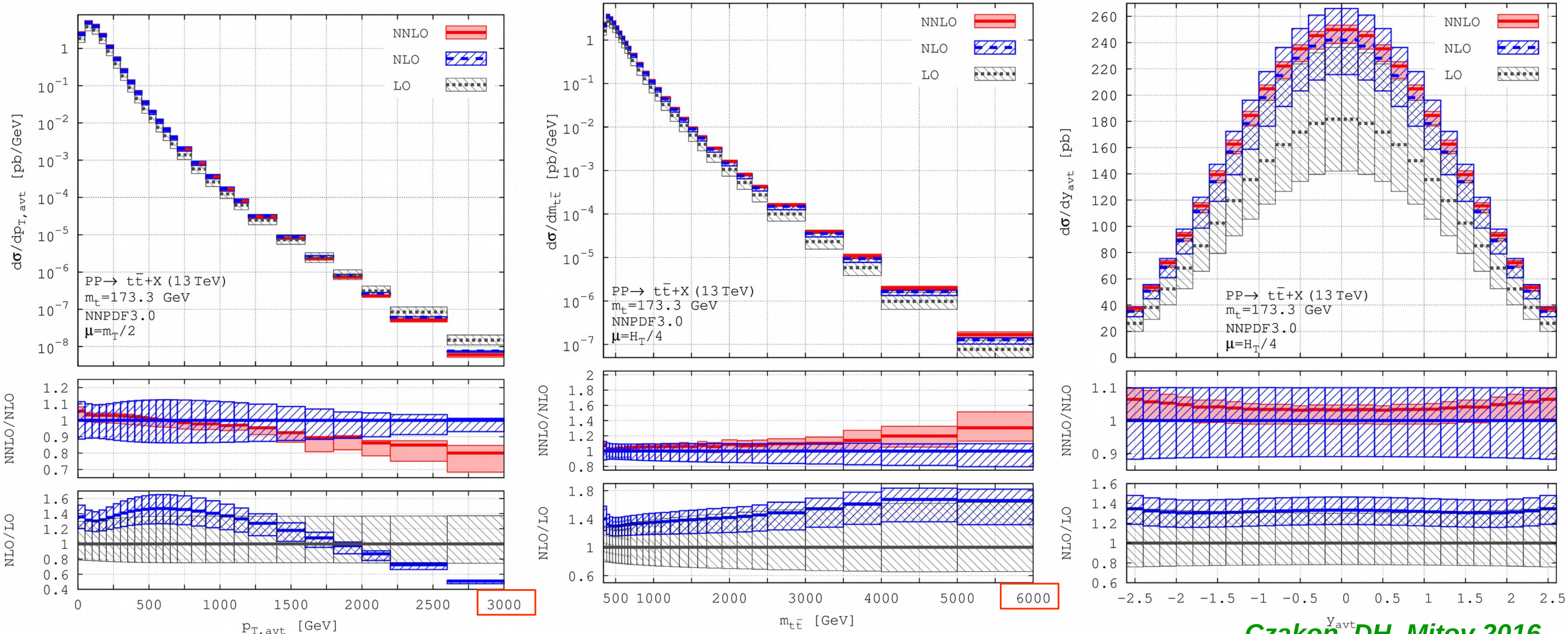




Czakon, DH, Mitov 2016

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

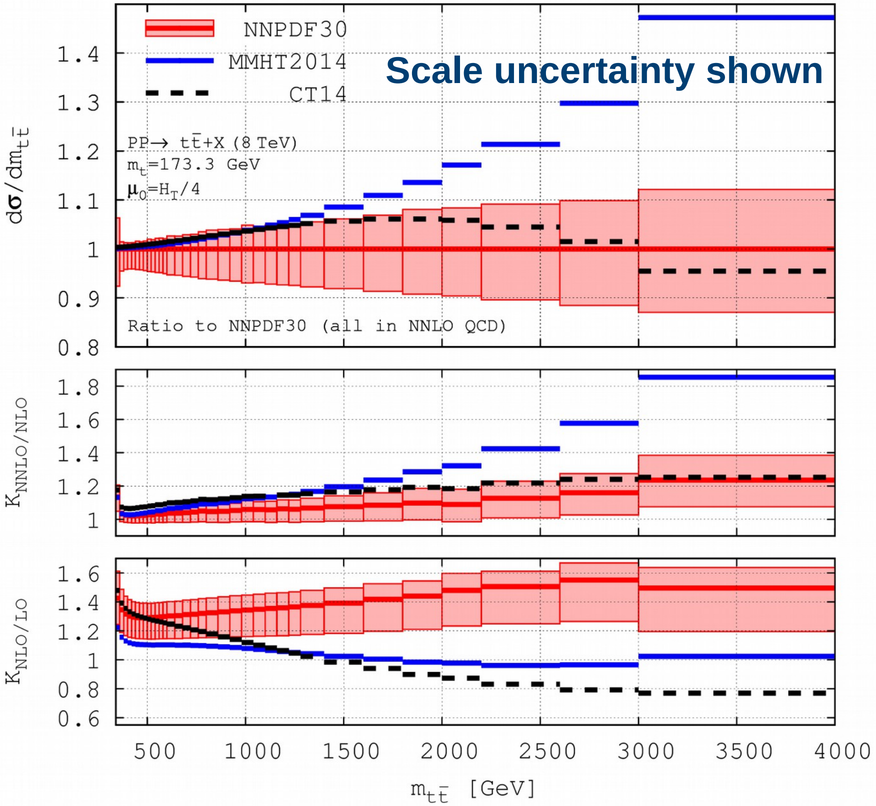


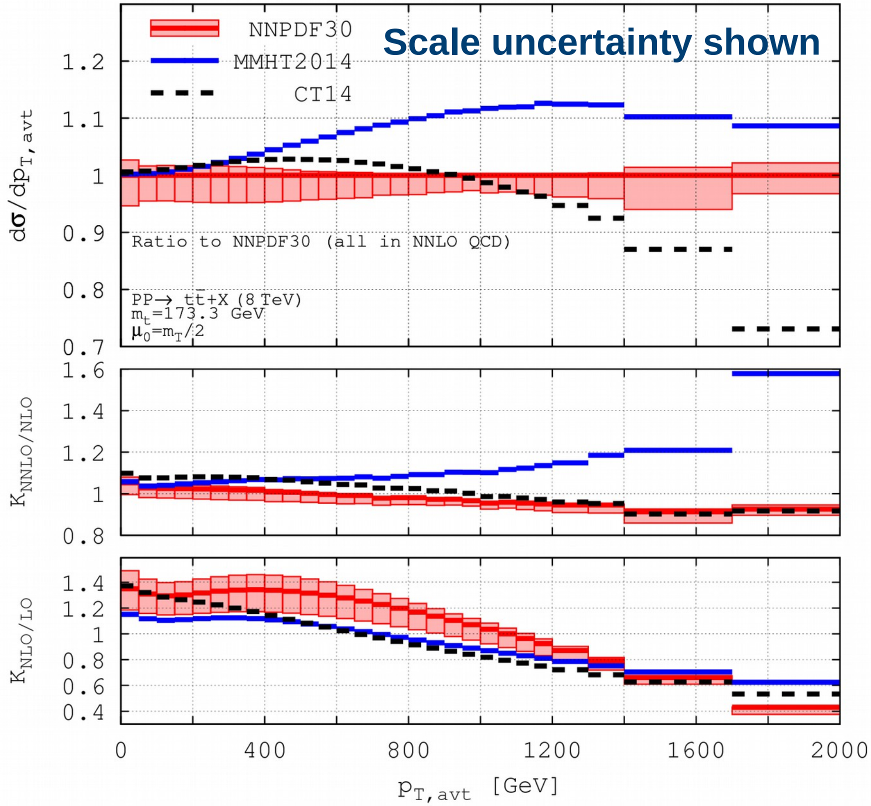
Czakon, DH, Mitov 2016

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





Impact of differential distributions on gluon PDF

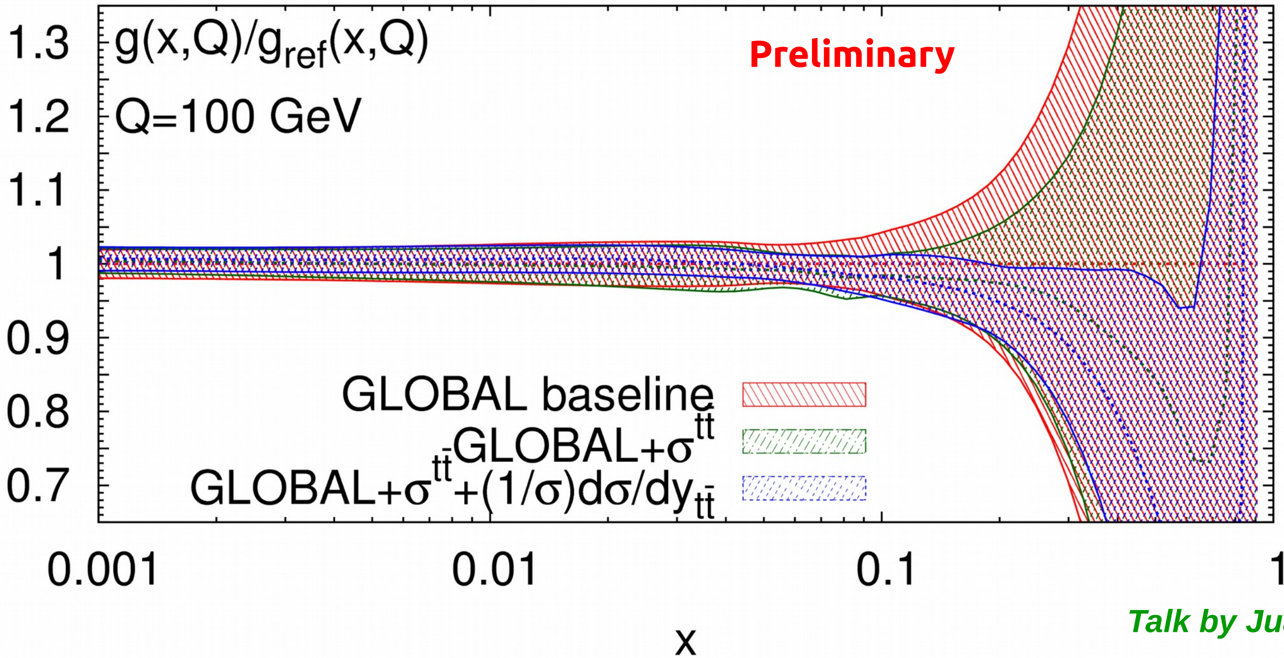
- Inclusion of total cross section already reduces gluon PDF uncertainty at x > 0.1 using Tevatron and LHC measurements (NNPDF30, MMHT14, ...)

  Czakon, Mangano, Mitov, Rojo 2013

  → Reduction of uncertainties of gluon initiated processes

- Include tt top quark differential distributions at 8TeV (ATLAS, CMS) into NNPDF

  Czakon, Hartland, Mitov, Nocera, Rojo in preparation



Talk by Juan Rojo at PDF4LHC meeting 2016

Adding NLO EW corrections

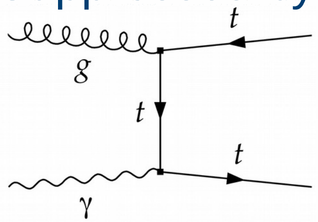
EW correction for tt production

- Naive power counting suggests that one should consider EW corrections at this level of accuracy ($\alpha_s \sim 0.1$, $\alpha \sim 0.01$)

		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%

		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

- 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 P. Nason***

  - Conclusion: Treatment of the photon pdf as in LUXqed (small photonic contribution)

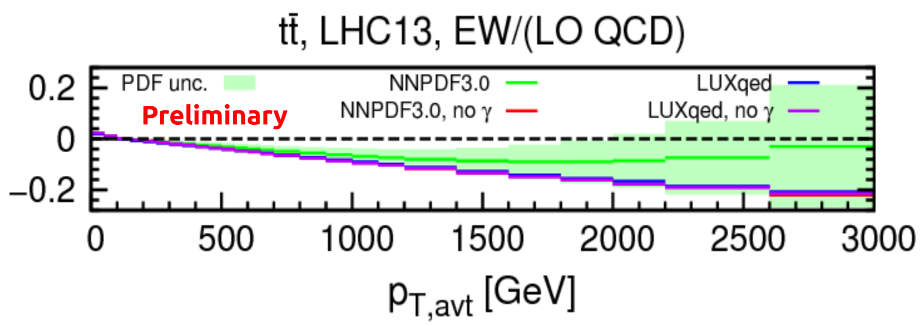
Dependence on the Photon PDF

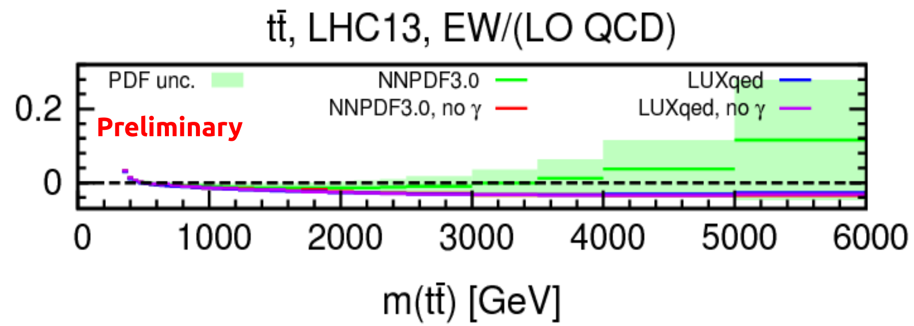
NNPDF30 vs. LUXqed

Czakon, DH, Mitov, Pagani, Tsinikos, Zaro in preparation

- Large differences for photon PDFs
- Photon contribution is much smaller in LUXqed (negligible ?)
- LUXqed at the lower edge of NNPDF30 uncertainty band
- NNPDF30 (no γ) at the same order as LUXqed

  → no compensation from photon induced channels expected

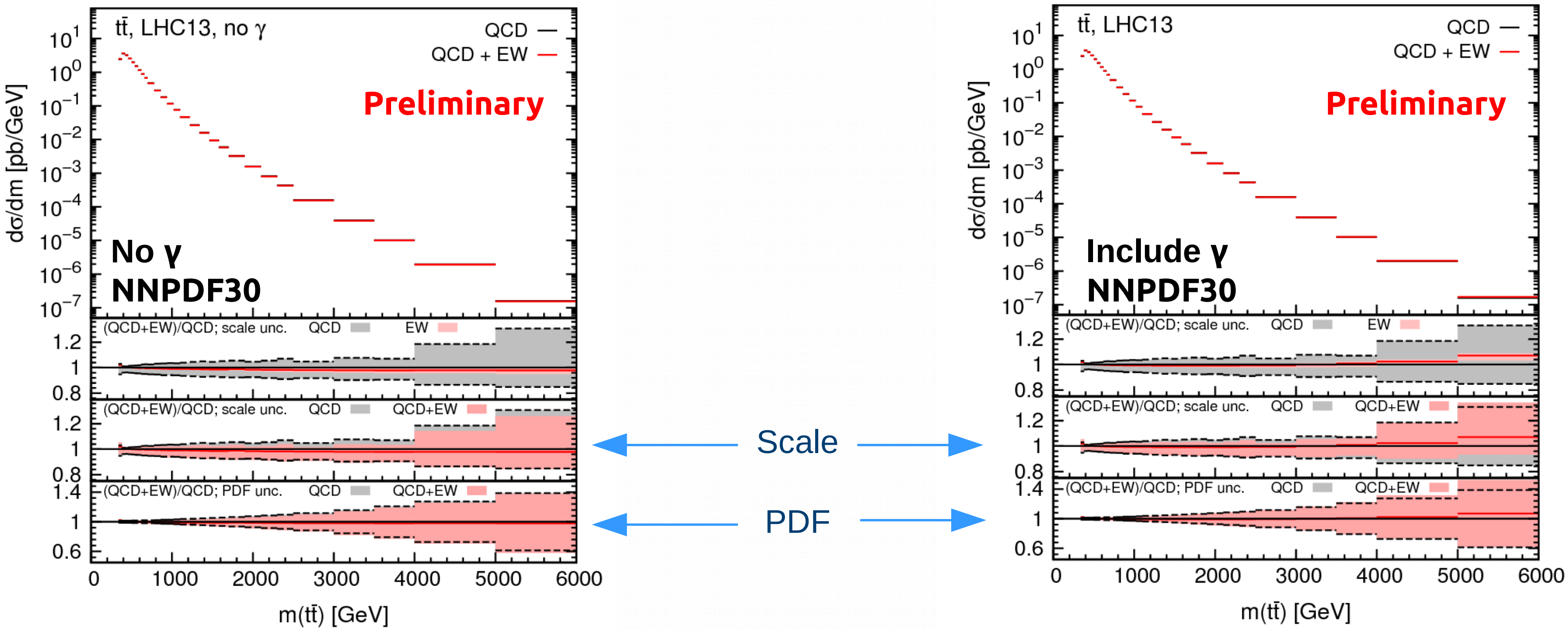




Combining NNLO QCD and EW for the invariant mass

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

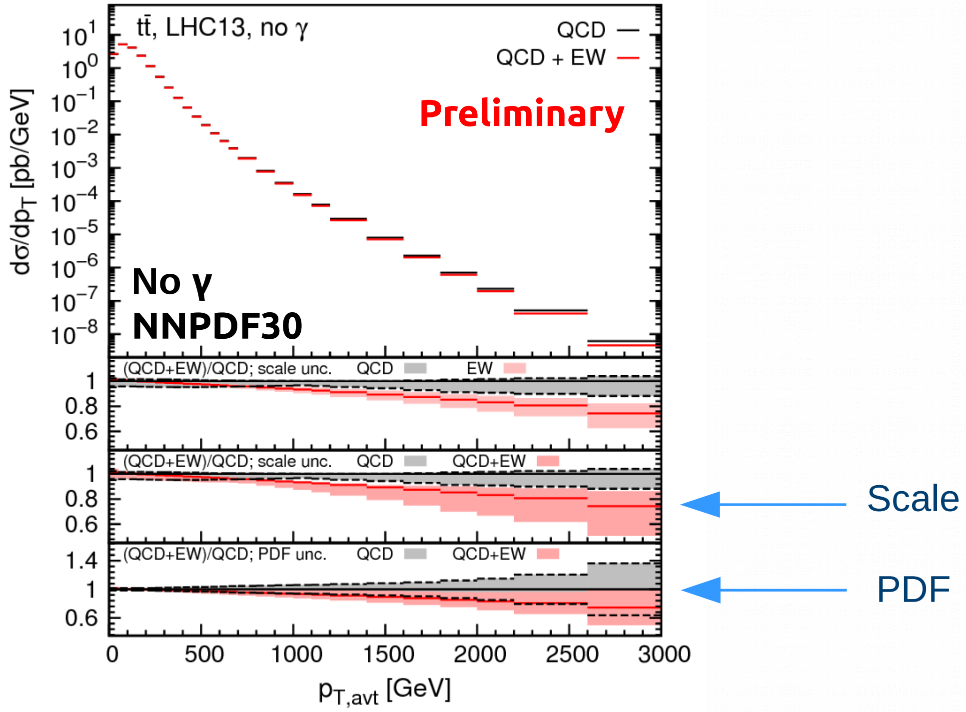
- Very small EW corrections in the whole energy range (1%)
- Large PDF uncertainties in the high energy range (m_{tt} > ~ 3 TeV)
- Use NNLO for new physics searches (bump-hunting) *Czakon, DH, Mitov 2016*



Combining NNLO QCD and EW for the p_T of the top

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

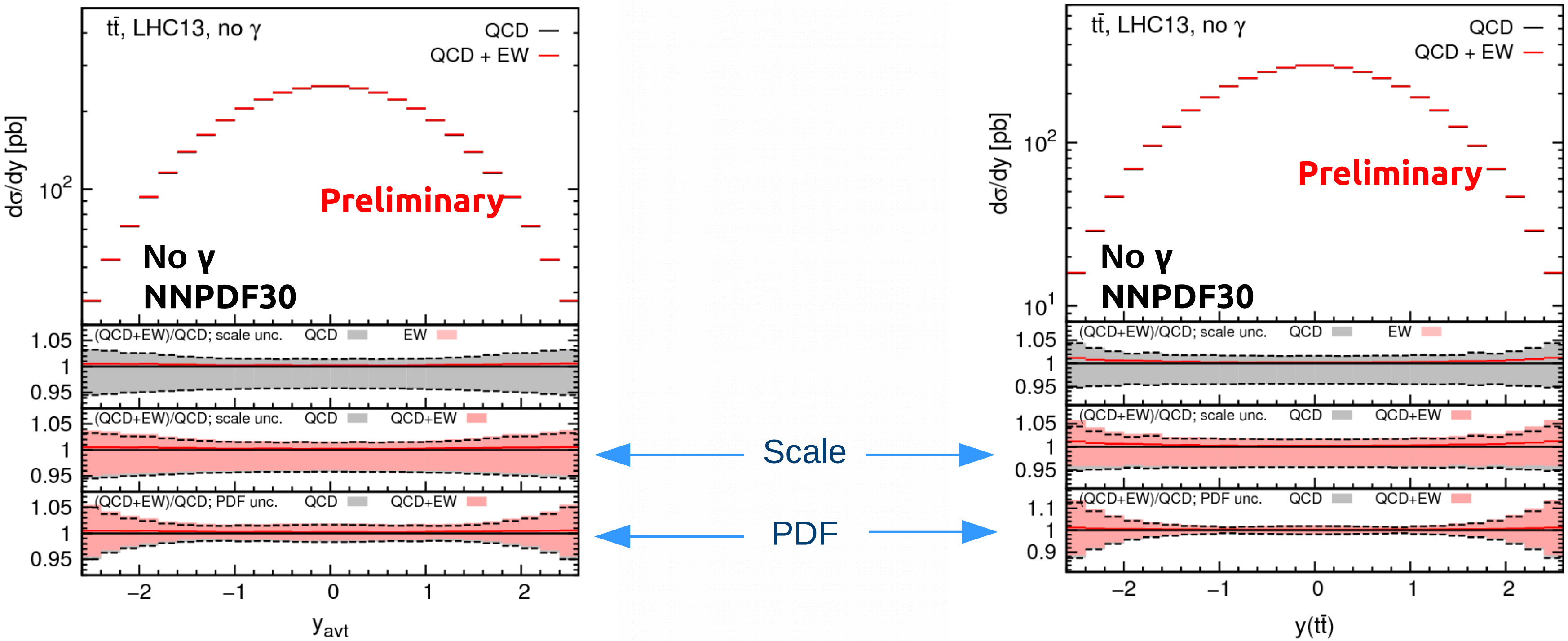
- Negative Sudakov contributions are sizeable (up to 20%) at very large p_T (> 2 TeV)
- They are outside the QCD scale uncertainty band, but inside the PDF uncertainty
- PDF uncertainty is large at high p_T



Combining NNLO QCD and EW for the rapidity

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

- Very small EW corrections in the whole range (1%)
- PDF uncertainties large at at high ytt



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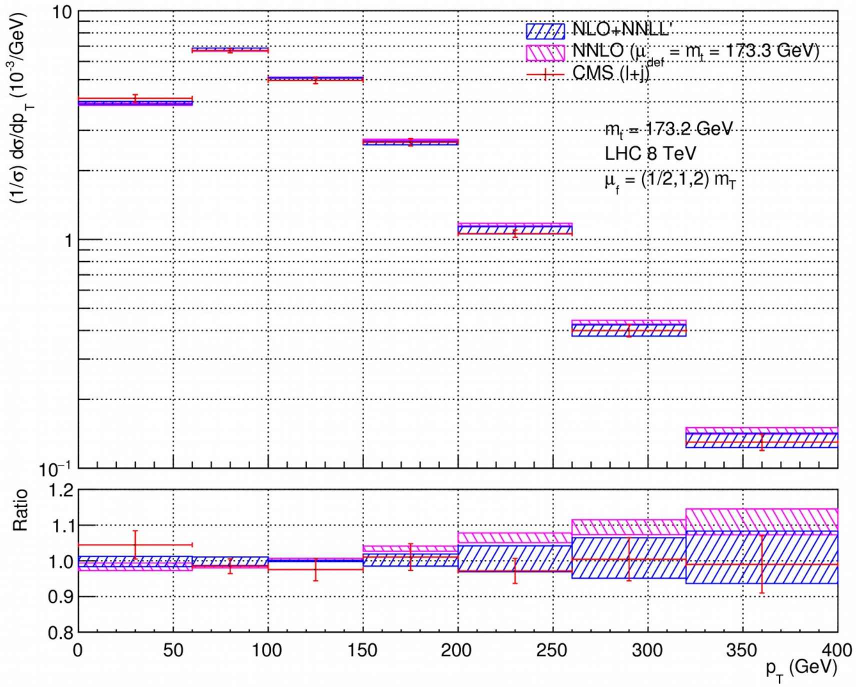
Large logarithms in the boosted regime

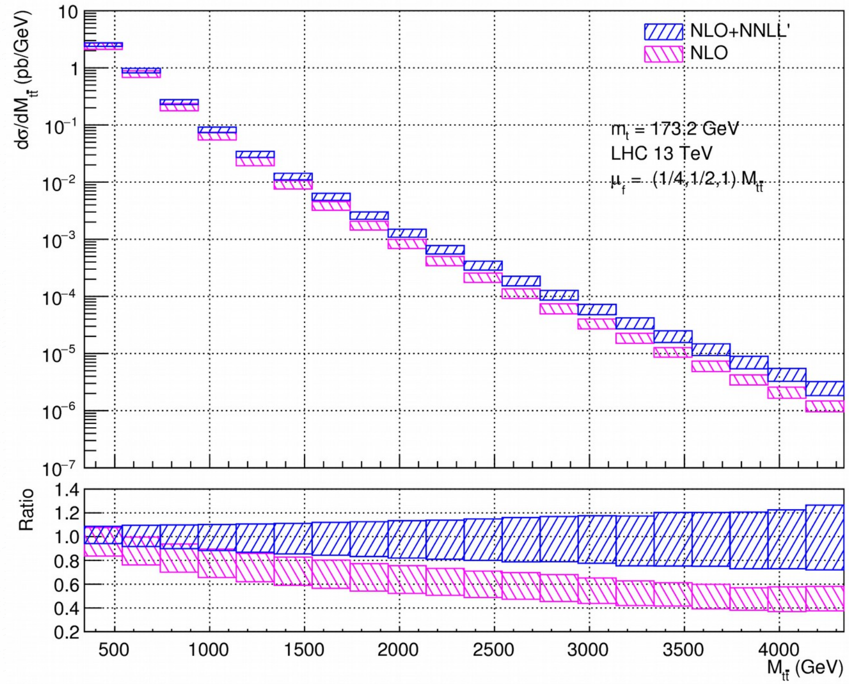
Large QCD logarithms in the boosted regime

Ferroglia, Pecjak, Scott, Wang, Yang 2015-2016

- Large logarithms at $s > m_t$

  e.g. : $\ln^n(m_t/m_T)$, where $m_T = \sqrt{m_t^2 + p_T^2}$
- Not captured by fixed order perturbation theory → Resummation NNLL'





- At which scale do these contributions become important? ***Work in progress at NNLO***

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Czakon, DH, Mitov 2016

Application:

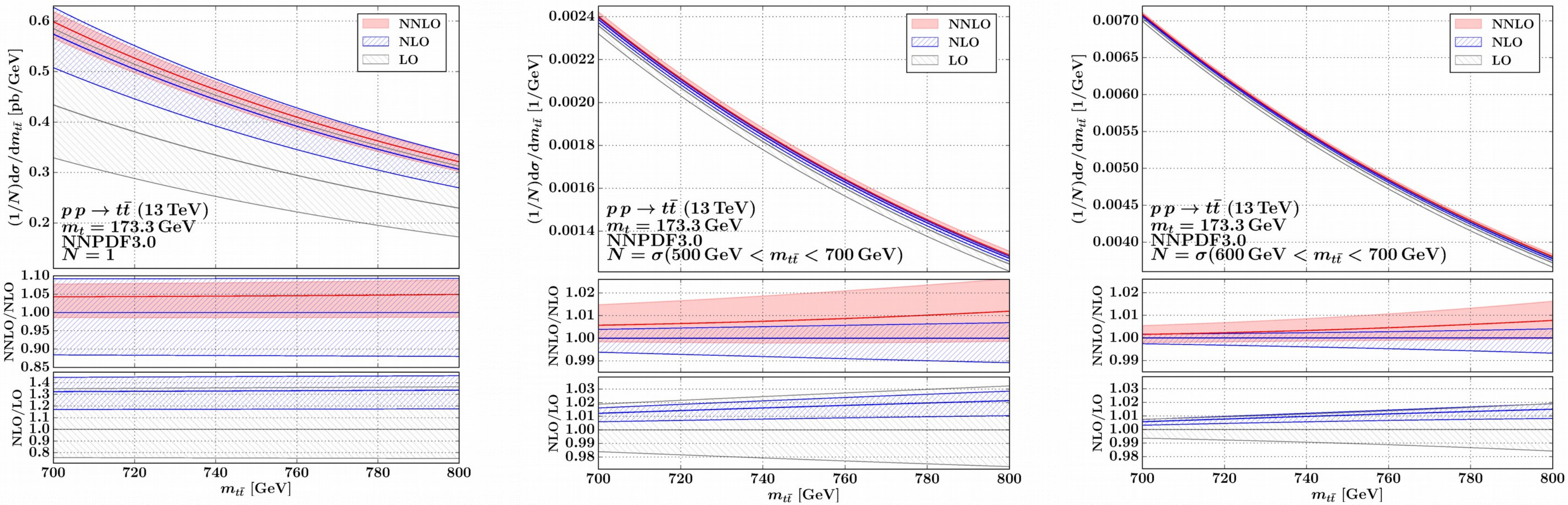
Bump-hunting using m_{tt} – distribution at NNLO

Bumps in top-pair invariant mass distribution

- Minimize theory uncertainty → choose appropriate normalization

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

Czakon, DH, Mitov 2016



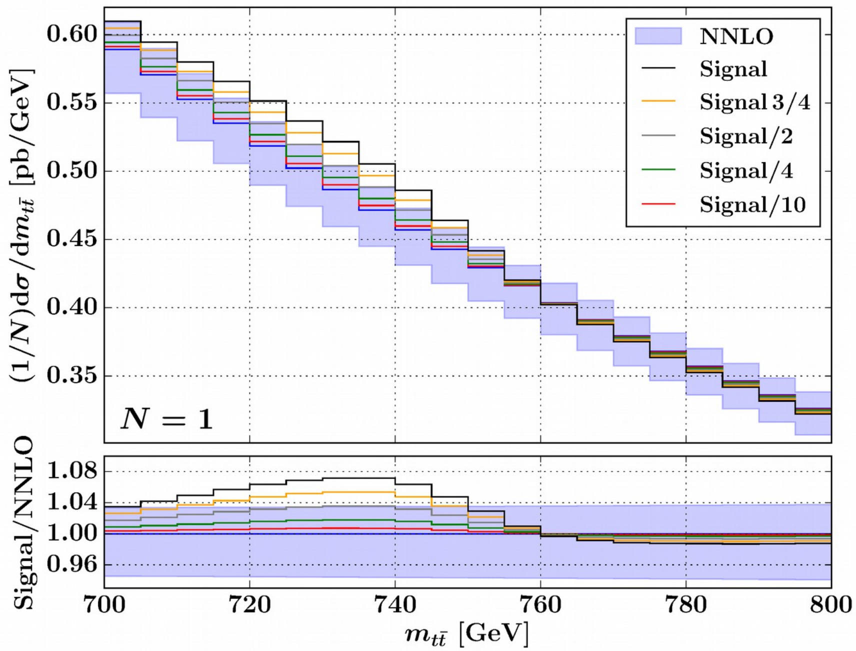
- Trade off between experimental uncertainty and theory uncertainty to choose N
  - Minimize dependence on the top-mass << 1%, checked at NLO
- Analytic fit of the distribution allows flexible rebinning

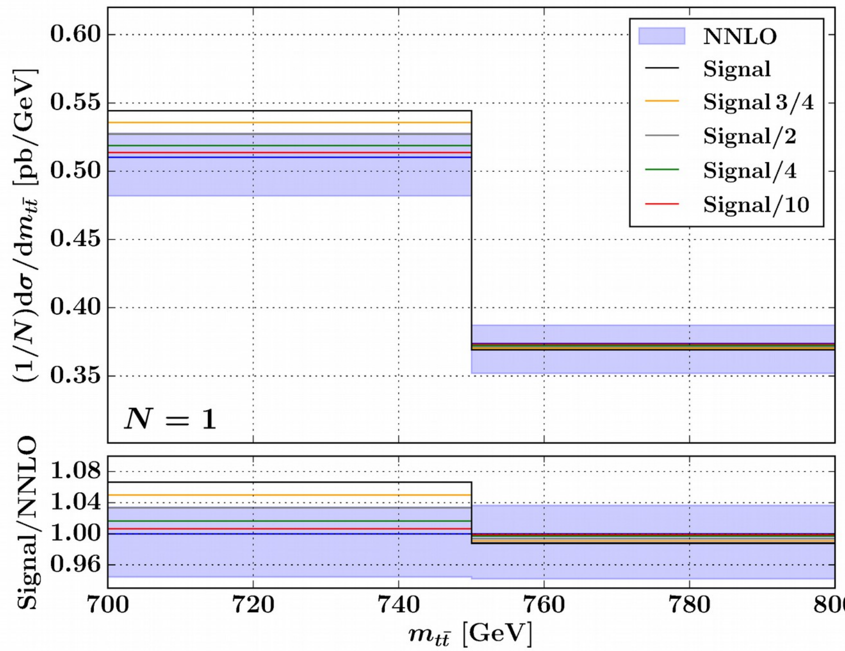
Bump Hunting using m_{tt} – distribution at NNLO

- 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

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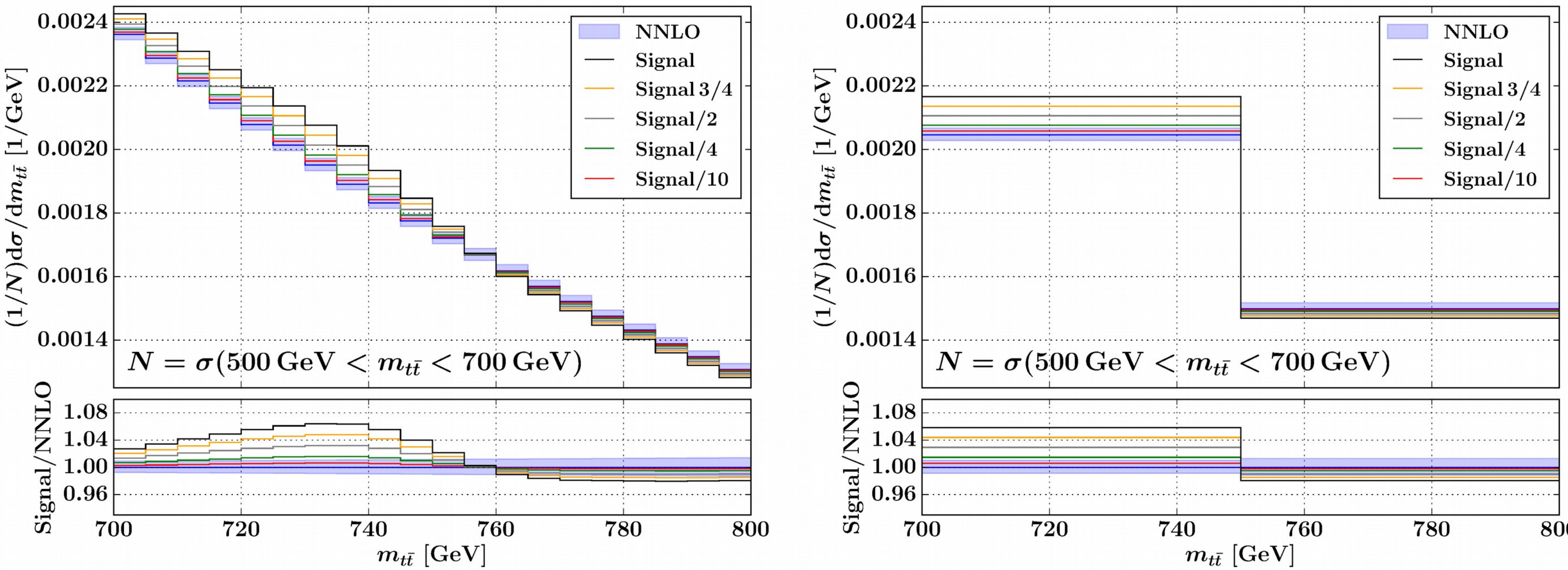

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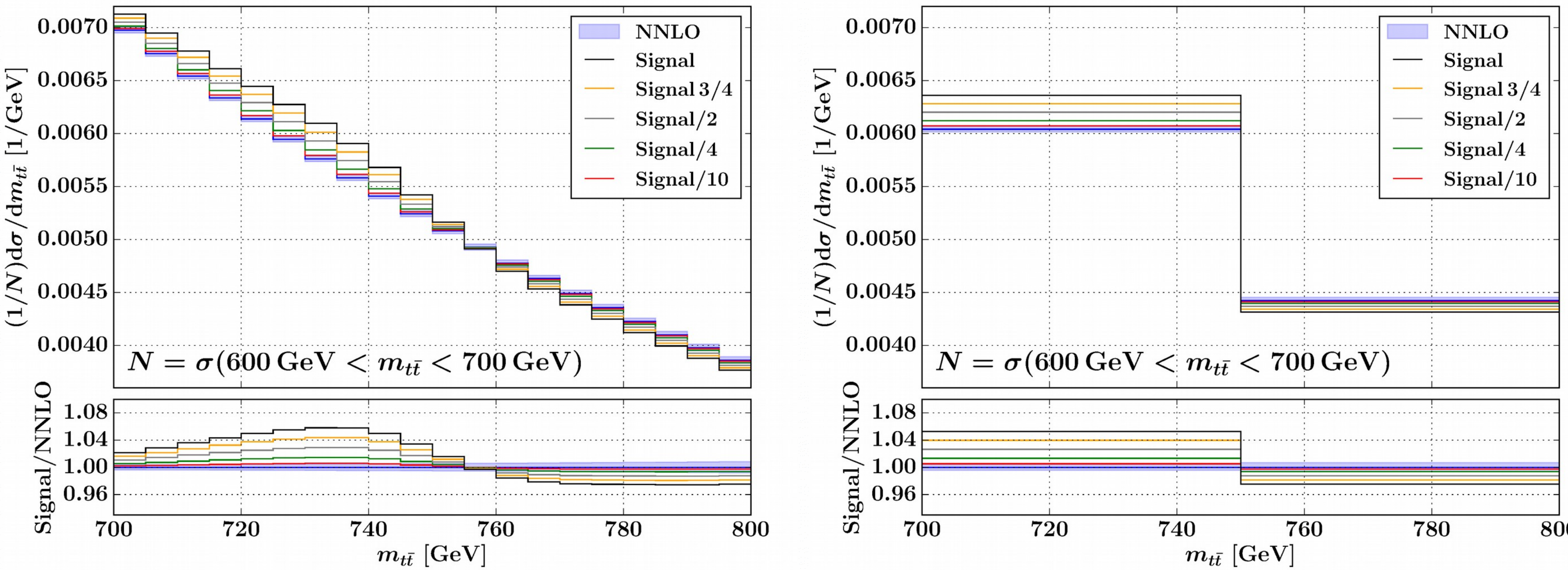

Signal from: Hespel, Maltoni, Vryonidou 2016

- 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} /y currently limited by pdf uncertainty
- Use NNLO $t\bar{t}$ predictions to constrain PDF sets using LHC data
- FastNLO tables in preparation

Britzger, Rabbertz, Stober, Wobisch: fastNLO

Combined NNLO QCD + EW

- EW corrections could be sizeable at large p_T
  - Negative Sudakov contribution up to -20 % (but: inside QCD PDF uncertainty)
  - Photon induced contributions are small (LUXqed, future pdf sets: MMHT)
- EW corrections are generally small for other distribution
  - Use precision for new physics searches
- **Outlook**
- Resummation effects
- Including top-decays in the NWA at NNLO in progress
- Top mass extraction using differential distributions at the LHC

Brucherseifer, Caola, Melnikov 2013
Gao, Li, Zhu 2012

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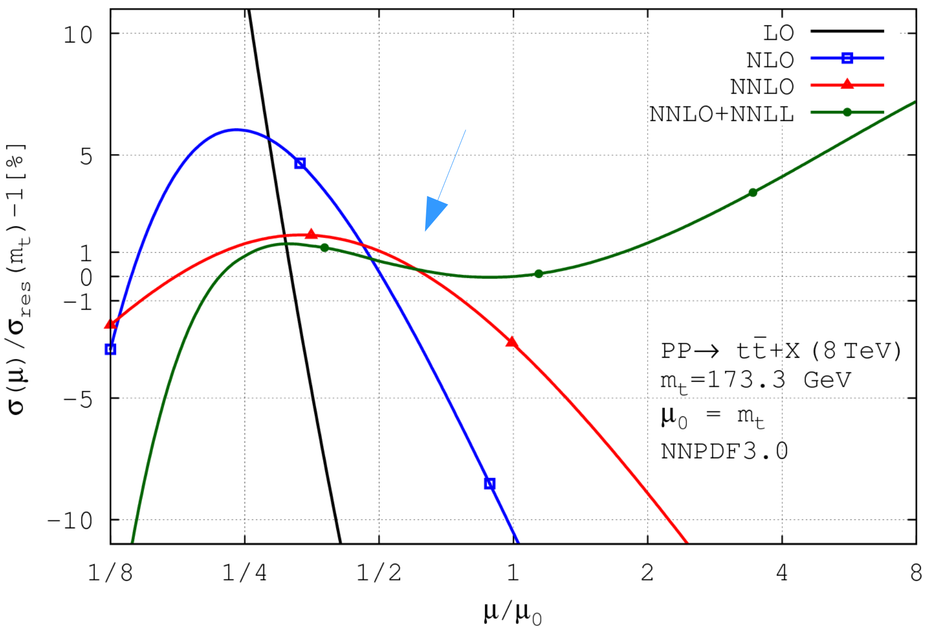
Back Up

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