Status of higher-order electroweak calculations

Doreen Wackeroth
University at Buffalo, SUNY

QCD Tools for LHC Physics: From 8 to 14 TeV
"What's needed and why?"

Fermilab

November, 14-15, 2013

Electroweak corrections for LHC physics

For a recent review see, e.g., talk by S.Dittmaier at Les Houches 2013 at

https://phystev.in2p3.fr/wiki/_media/:groups:lh13_ew.pdf

This talk: a selection of recent results with emphasize on open issues:

- Combination of QCD and EW corrections
- Beyond 1-loop
- Photon PDFs
- Assessment of theory uncertainties

Motivation: see Snowmass report of the QCD working group, including an updated *wishlist*.

Anderson et al, 1310.5189

Excerpt of Snowmass *wishlist*

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
H + j	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(gg) @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

Anderson et al, 1310.5189

Characteristics of EW corrections

$\frac{\alpha(M_Z)}{\pi} \approx 0.0025$ vs. $\frac{\alpha_s(M_Z)}{\pi} \approx 0.037$

Possible enhancements:

QED: $\frac{\alpha(0)}{\pi} \log(\frac{m_f^2}{Q^2}) \approx -0.024$ for $Q = M_W, f = \mu$

Origin: Soft/collinear FS photon radiation
In sufficiently inclusive observables these mass singularities completely cancel. Kinoshita, Lee, Nauenberg (1962,1964)

Weak at LL: $-\frac{\alpha}{\pi s_w^2} \log^2(\frac{M_V^2}{Q^2}) \approx -0.052$ for Q=2 TeV

Origin: Remnants of UV singularities after renormalization and soft/collinear IS and FS emission of virtual and real W and Z bosons.
In contrast to QED and QCD, also in inclusive observables these corrections do not completely cancel. Ciafaloni, Ciafaloni, Comelli (2000)

NLO EW calculations are available for
$pp, p\bar{p} \to W; Z \to l\nu; l^+l^-; VV; Wj; Zj \to \nu lj; l^+l^-j; t\bar{t}$; single top, and $b\bar{b}, jj$ (weak); and for dominant Higgs production processes ($gg \to H; W/ZH; VBF$, for a review see, e.g., Higgs cross section WG report, arXiv:1101.0593)

Weak Sudakov logs: $\alpha_W^l \ln^n(\frac{Q^2}{M_W^2})$; $n \leq 2l$

In the high-energy limit, $\frac{Q}{M_{W,Z}} \to \infty$, EW Sudakov logarithms have been studied in analogy to soft/collinear logarithms in QED,QCD.

- 1-loop: LL and NLL are universal and factorize Denner, Pozzorini (2001)
- Beyond 1-loop: Resummation techniques based on IR evolution equations (IREE) or SCET yield results up to NNLL ($ln^n(\frac{s}{M_W^2}), n = 2, 3, 4$).
  - IREE: EW theory splits into symmetric $SU(2) \times U(1)$ ($M_W = M_Z = M_\gamma = M$ for $\mu > M$) and QED regime and effect of EW symmetry breaking neglected. Fadin, Lipatov, Martin, Melles (2000)
  - SCET: At $\mu = Q$ match full theory to SCET($M = 0$), evolve to $\mu = M$ SCET($M \neq 0$), match to SCET with no gauge bosons.
  - SCET and IREE Sudakov form factors are equivalent. Chiu, Golf, Kelley, Manohar (2008); Chiu, Fuhrer, Hoang, Kelley, Manohar (2009); Chiu, Fuhrer, Kelley, Manohar (2010), Fuhrer et al (2011)

Resummation results at LL and NLL confirmed by explicit diagramatic one-loop and two-loop calculations.

Melles (2000), Hori et al (2000), Beenakker, Werthenbach (2000,2002), Pozzorini (2004); Feucht et al (2003,2004); Jantzen et al (2005,2006); Denner et al (2003,2008)

Higgs production via gluon fusion

'Best' prediction of the total cross section for Higgs production in gluon fusion (in pb):

NNLO+NNLL+EW

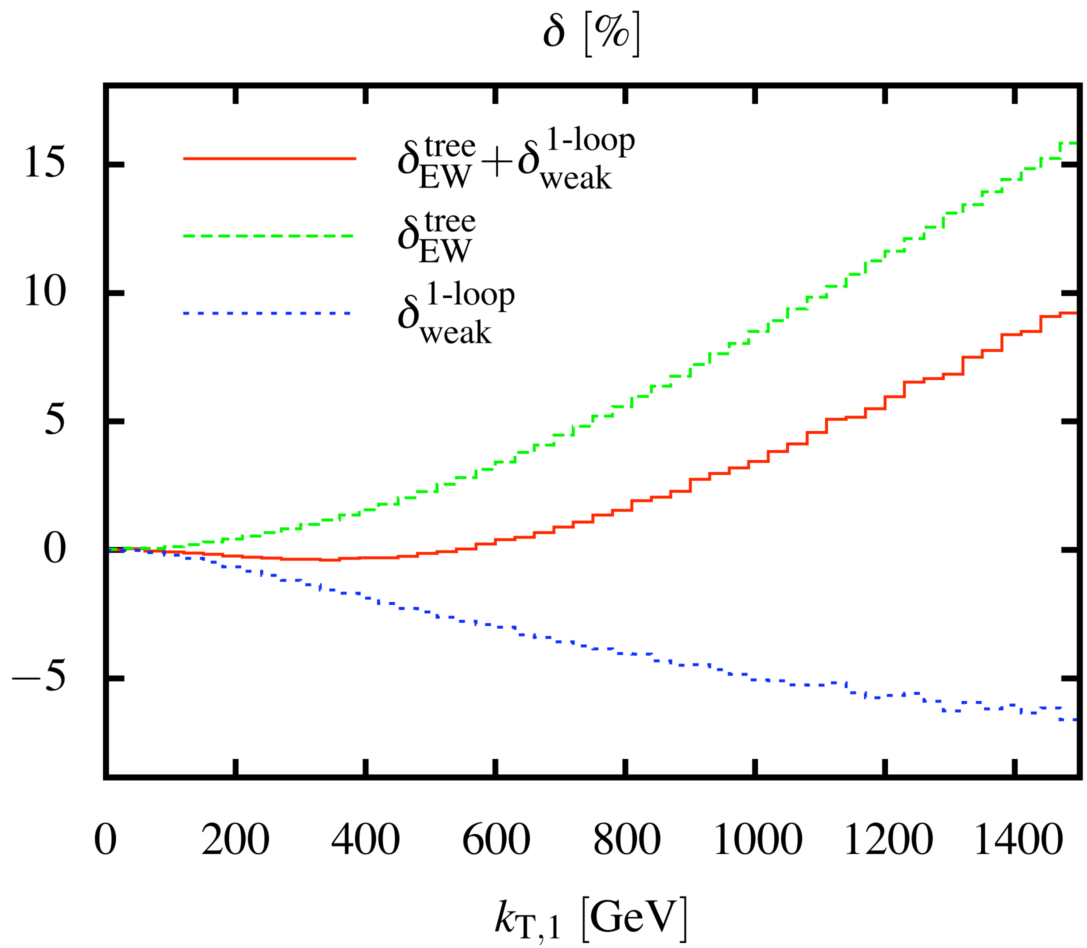
$$\sigma = 19.31^{+7.2\%}_{-7.8\%}(\text{scale})^{+7.5\%}_{-6.9\%}(\text{PDF}+\alpha_S)$$

N^3LO QCD work in progress!   Grazzini, de Florian, 1206.4133

NLO EW corrections shift the NNLO QCD result by about +5% (complete factorization) and by +1% (partial factorization).   Actis et al, 0809.1301

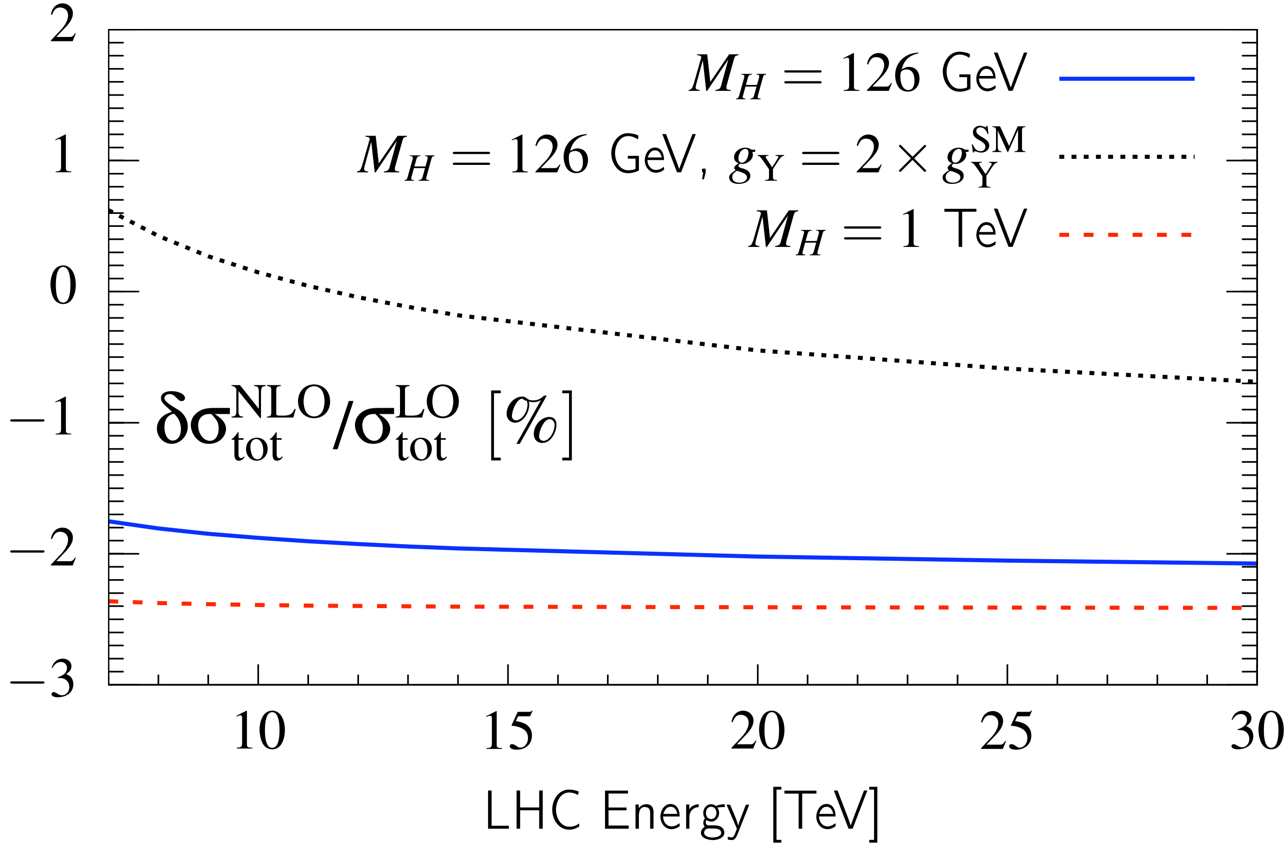
Explicit calculation of mixed EW-QCD corrections is close to result obtained with complete factorization.   Anastasiou *et al*, 0811.3458

Relative weak corrections to leading jet k_T distribution to pp->jj+X at the 8 TeV LHC



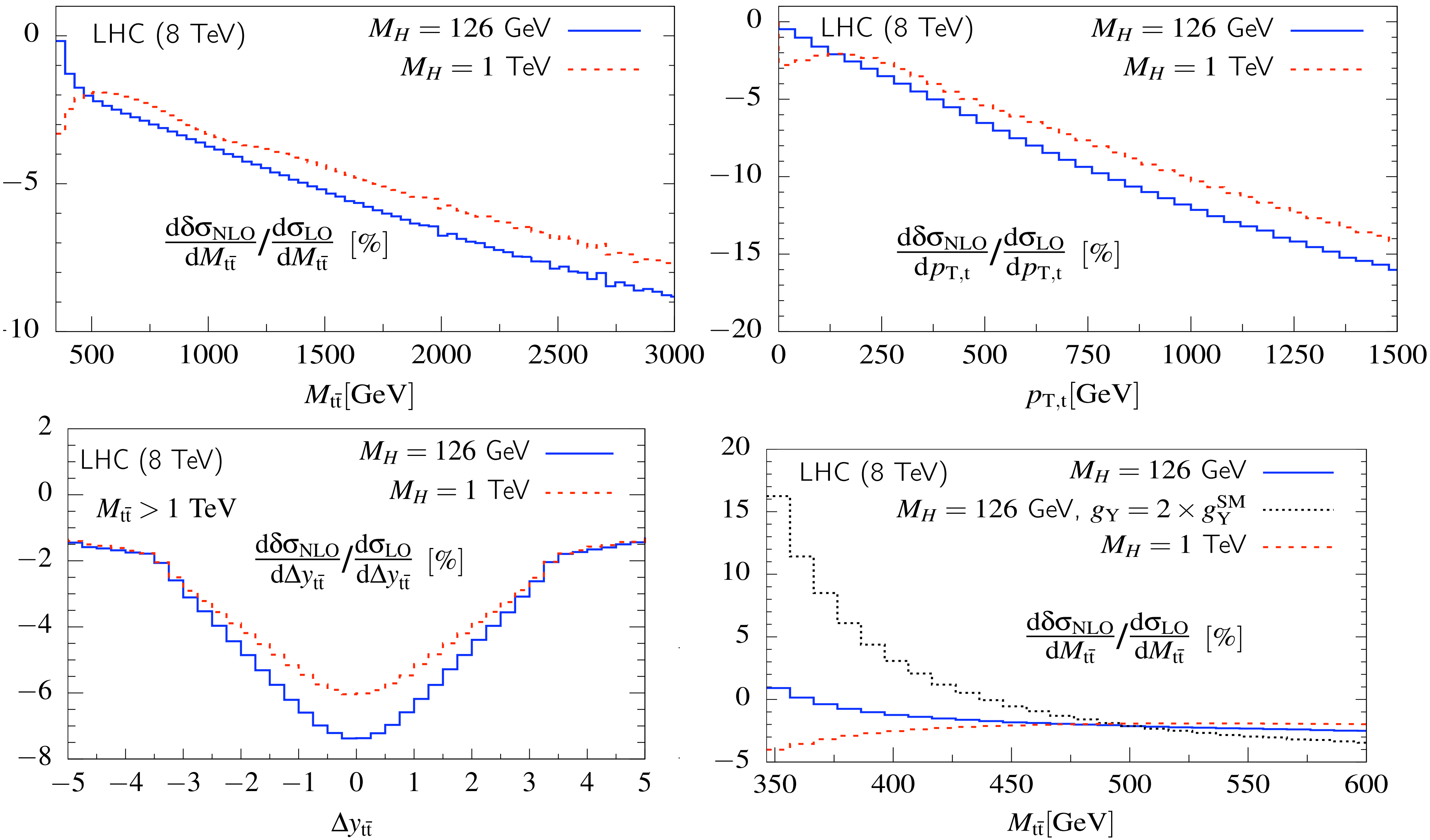
S.Dittmaier, A.Huss, C.Speckner, arXiv:1306.6298

Impact of weak 1-loop corrections in top-pair production at the 8 TeV LHC



H.Kühn, A. Scharf and P. Uwer, arXiv:1305.5773

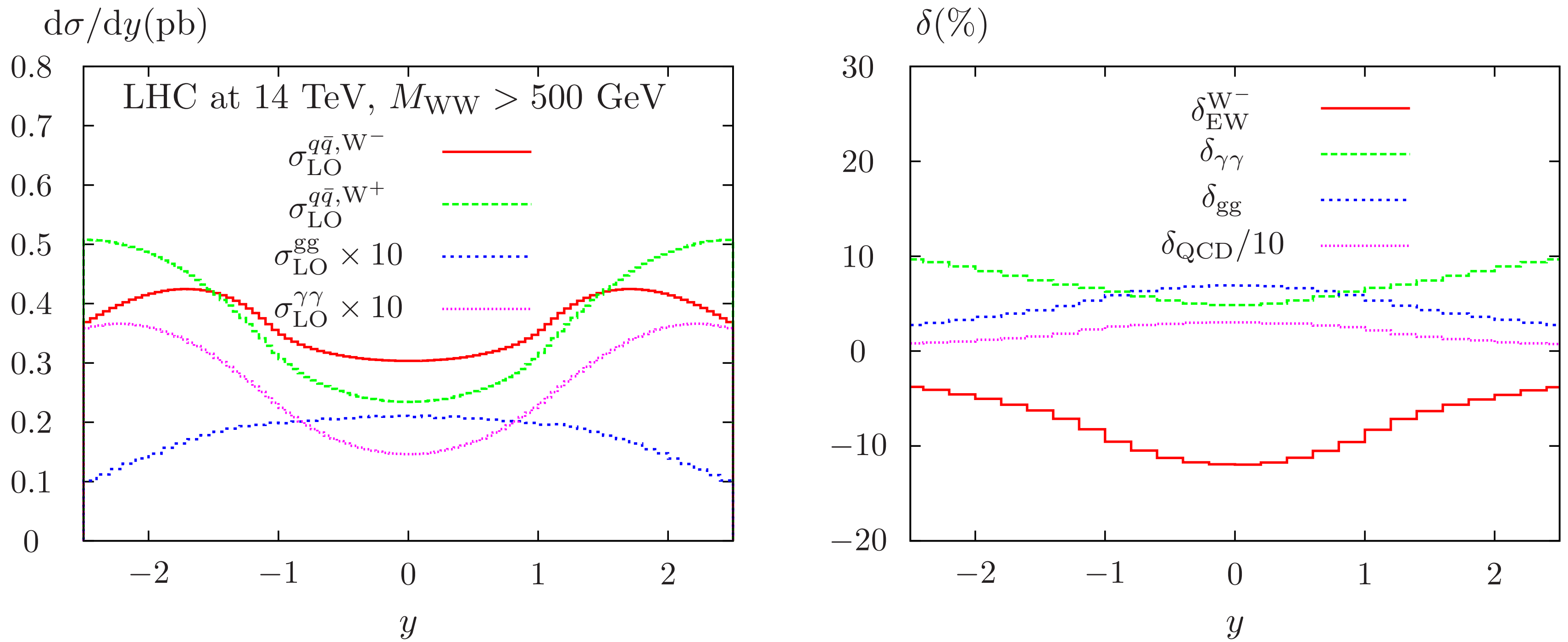
Impact of weak 1-loop corrections in top-pair production at the 8 TeV LHC



H.Kühn, A. Scharf and P. Uwer, arXiv:1305.5773

pp→W^+W^- at NLO EW at the LHC

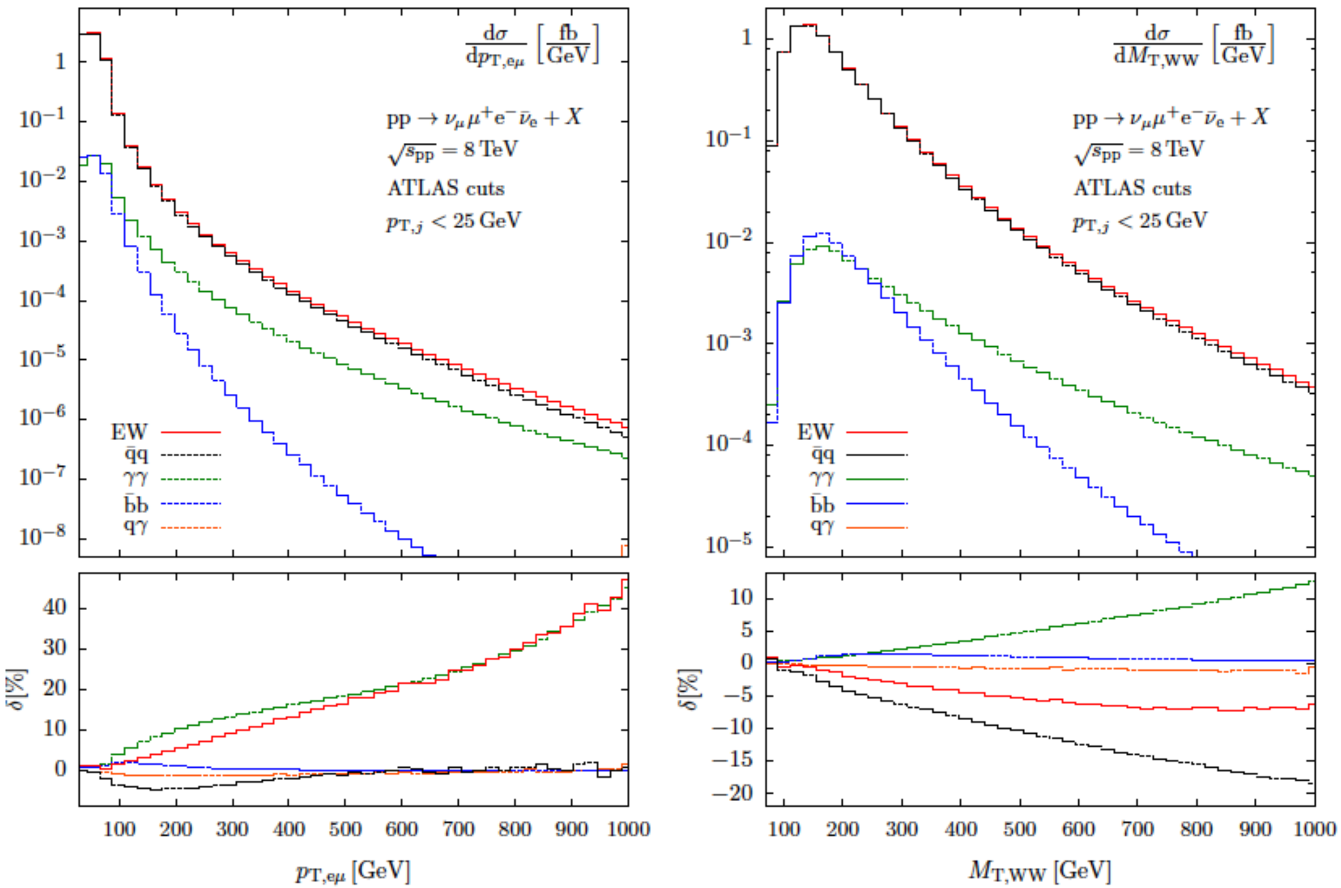
W rapidity distributions at LO and relative NLO EW corrections for different initial states:



Bierweiler *et al*, 1208.3147; WZ,ZZ: 1305.5402

$$pp \to WW \to \nu_\mu \mu^+ e^- \bar{\nu}_e$$

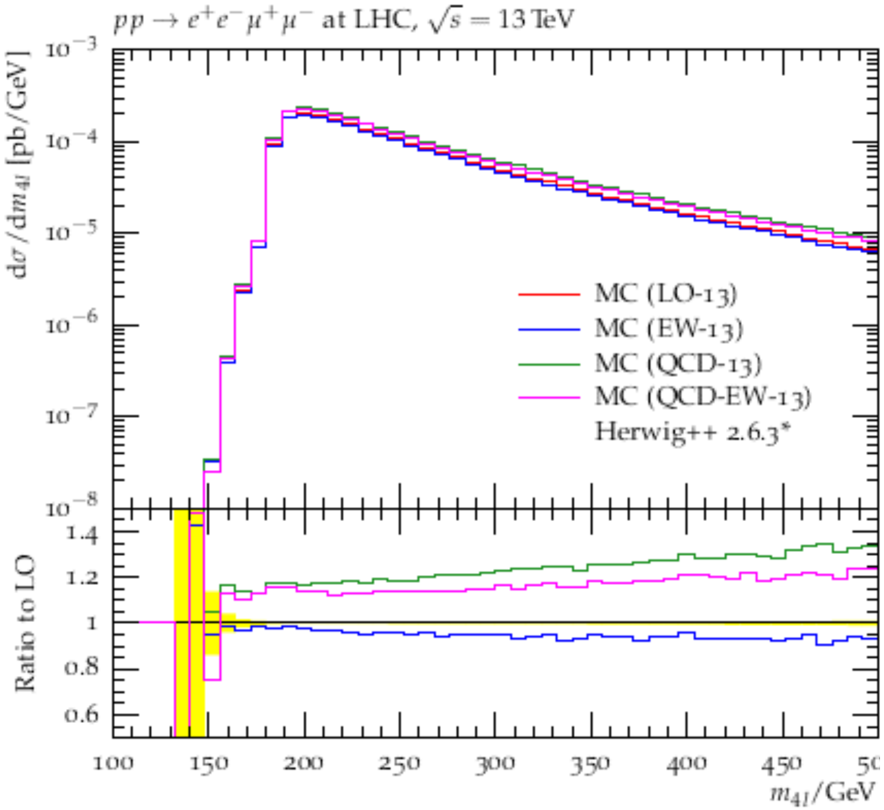
at NLO EW in DPA

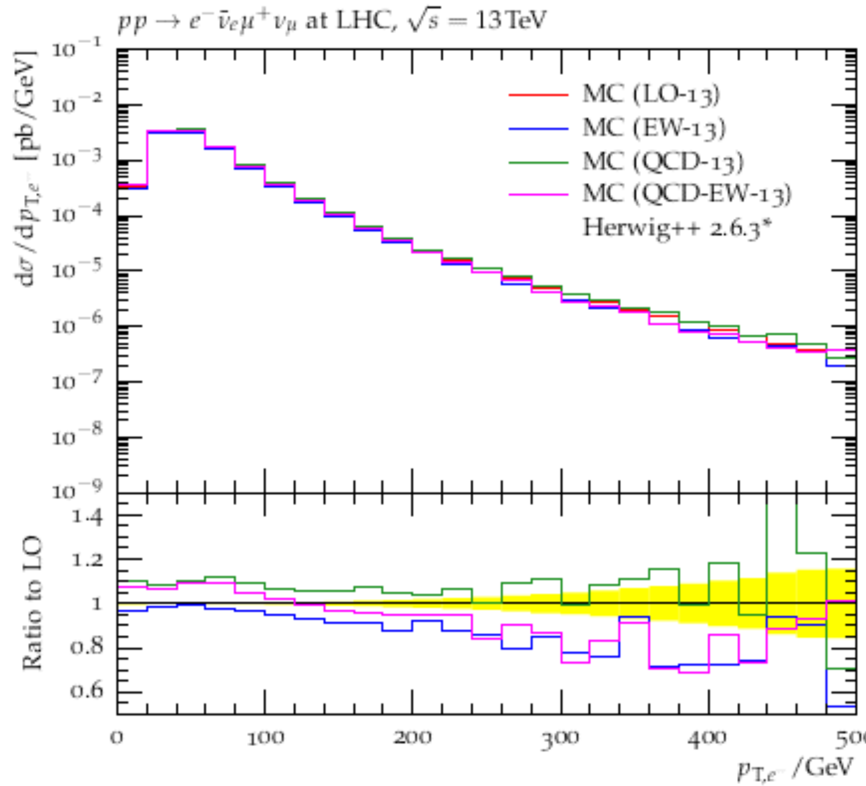


Biloni *et al*, 1310.1564

NLO EW correction to WW,ZZ,WZ in HERWIG

$$\mathrm{d}\hat{\sigma}_{\mathrm{EW}\times\mathrm{QCD}} = K^{V_1V_2}_{q\bar{q}'}(\hat{s},\hat{t}) \times \mathrm{d}\hat{\sigma}_{\mathrm{QCD}}$$



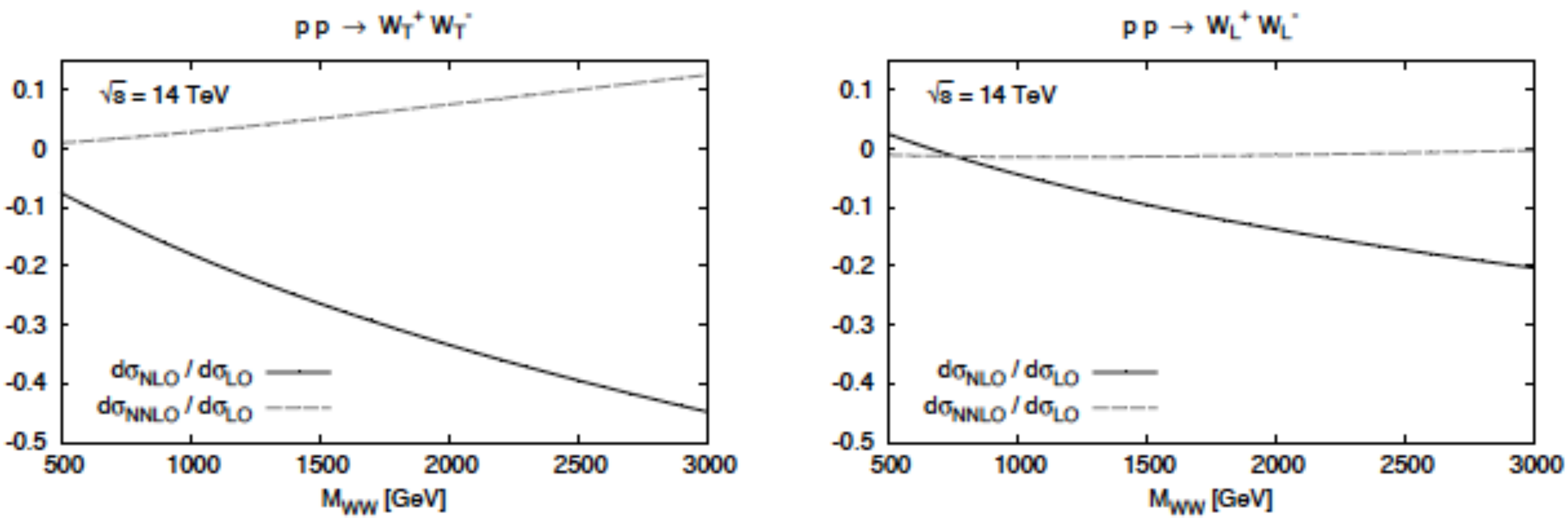


Gieseke *et al*, 1310.2843

$$\left|\sum_i \mathbf{p}^i_{\mathrm{T},l}\right| < 0.3 \sum_i \left|\mathbf{p}^i_{\mathrm{T},l}\right|$$

WW production at EW NLL and NNLL in the high energy limit

J.H.Kuhn et al, 1101.2563



Large cancellations between NLL and NNLL in transverse case (LL dominated) and between LL,NLL, and NNLL in the $W_L W_L$ production process.

See also results obtained in the EFT approach by Chiu et al. (2008)

QED in NNPDF

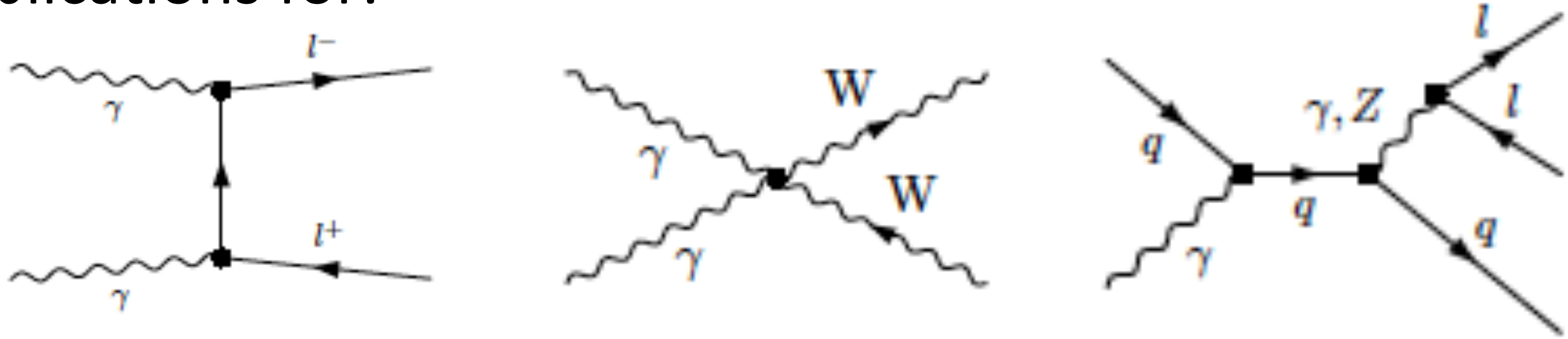
Combined QED-QCD evolution equation:

$$Q^2 \frac{\partial}{\partial Q^2} f(x, Q^2) = \left[\frac{\alpha(Q^2)}{2\pi} P^{\rm QED} + \frac{\alpha_s(Q^2)}{2\pi} P^{\rm QCD} \right] \otimes f(x, Q^2)$$

Photon PDF:

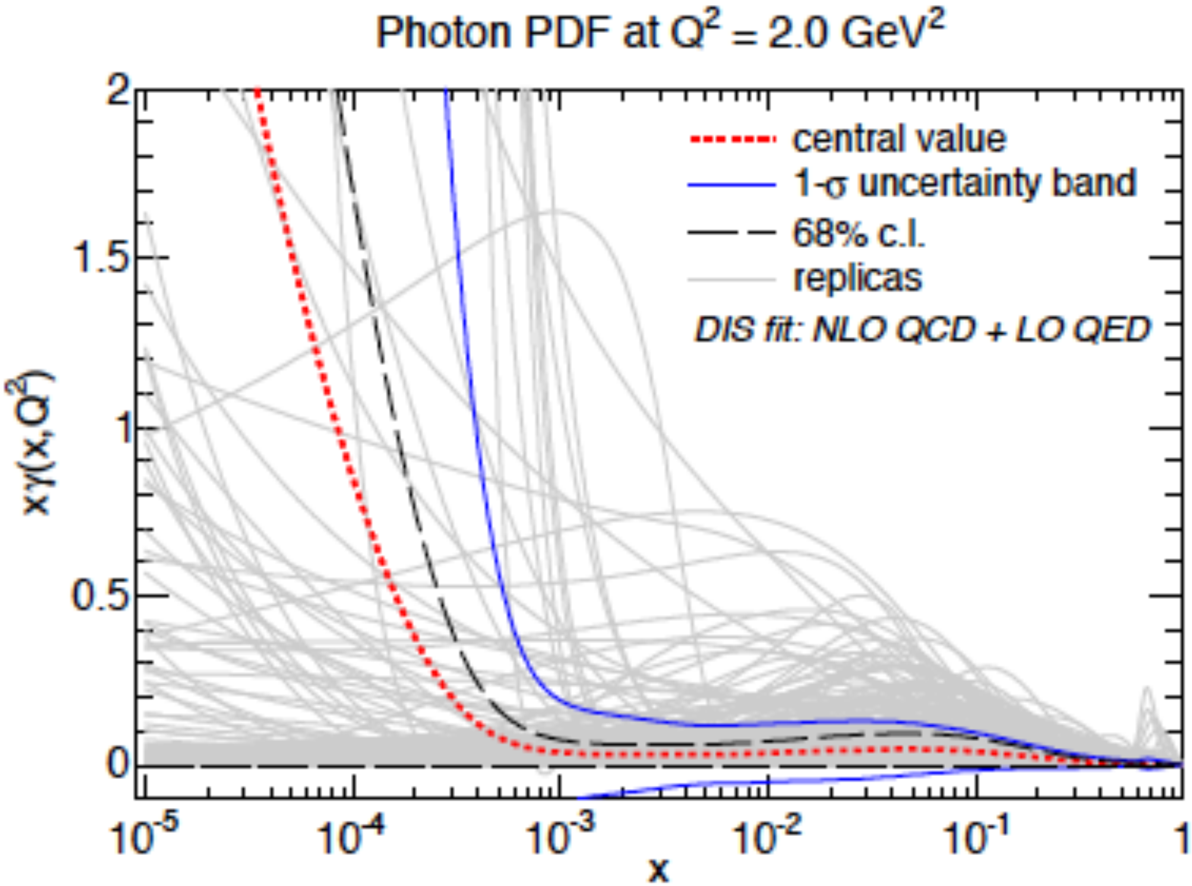
$$\gamma(x, Q_0^2) = (1-x)^{m_\gamma} \, x^{-n_\gamma} \mathrm{NN}_\gamma(x)$$

Implications for:



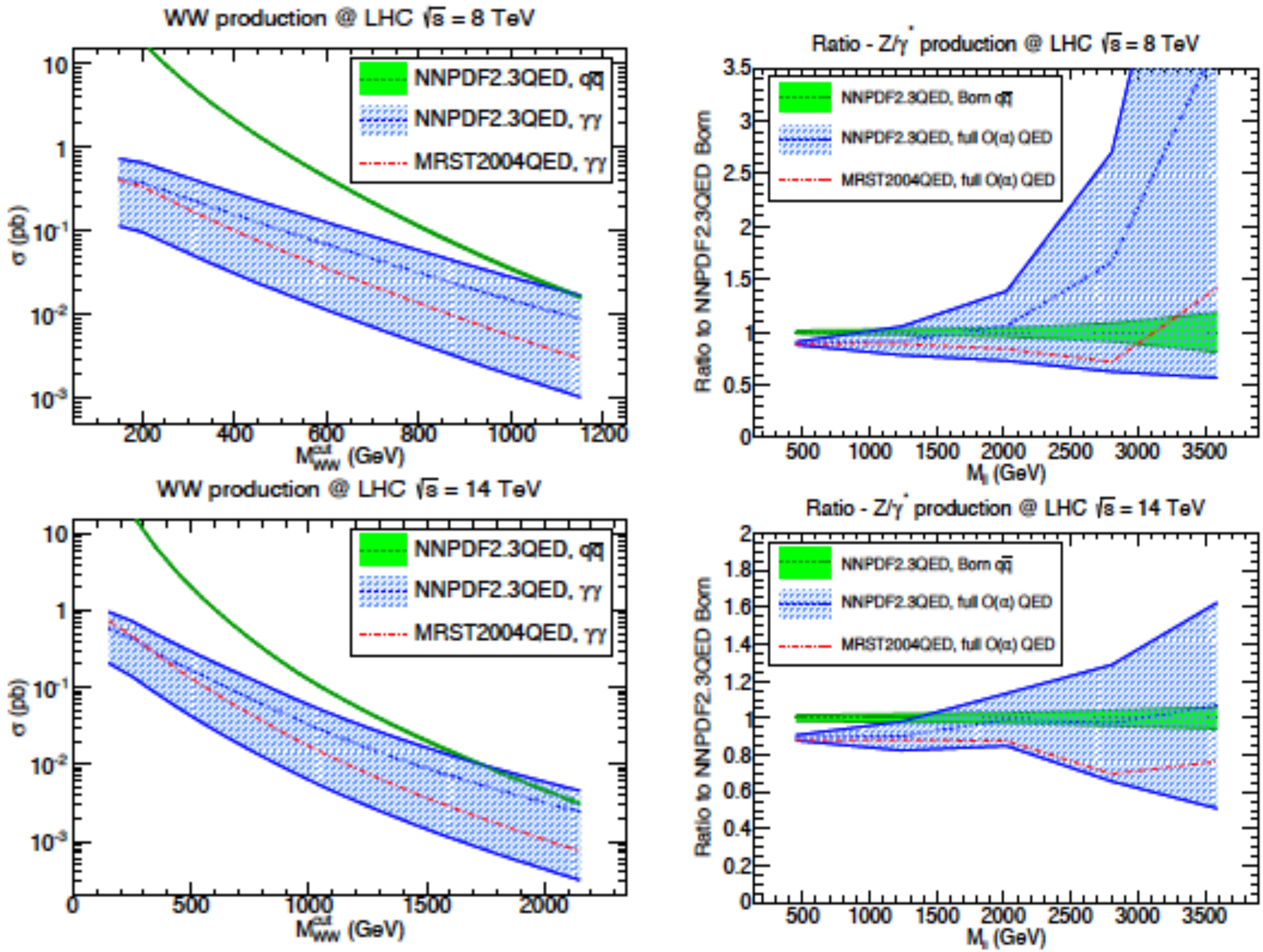
Ball et al, 1308.0598

NNPDF Photon PDF from DIS data



LHC data constrain shape and normalization.

Ball et al, 1308.0598



Ball et al, 1308.0598

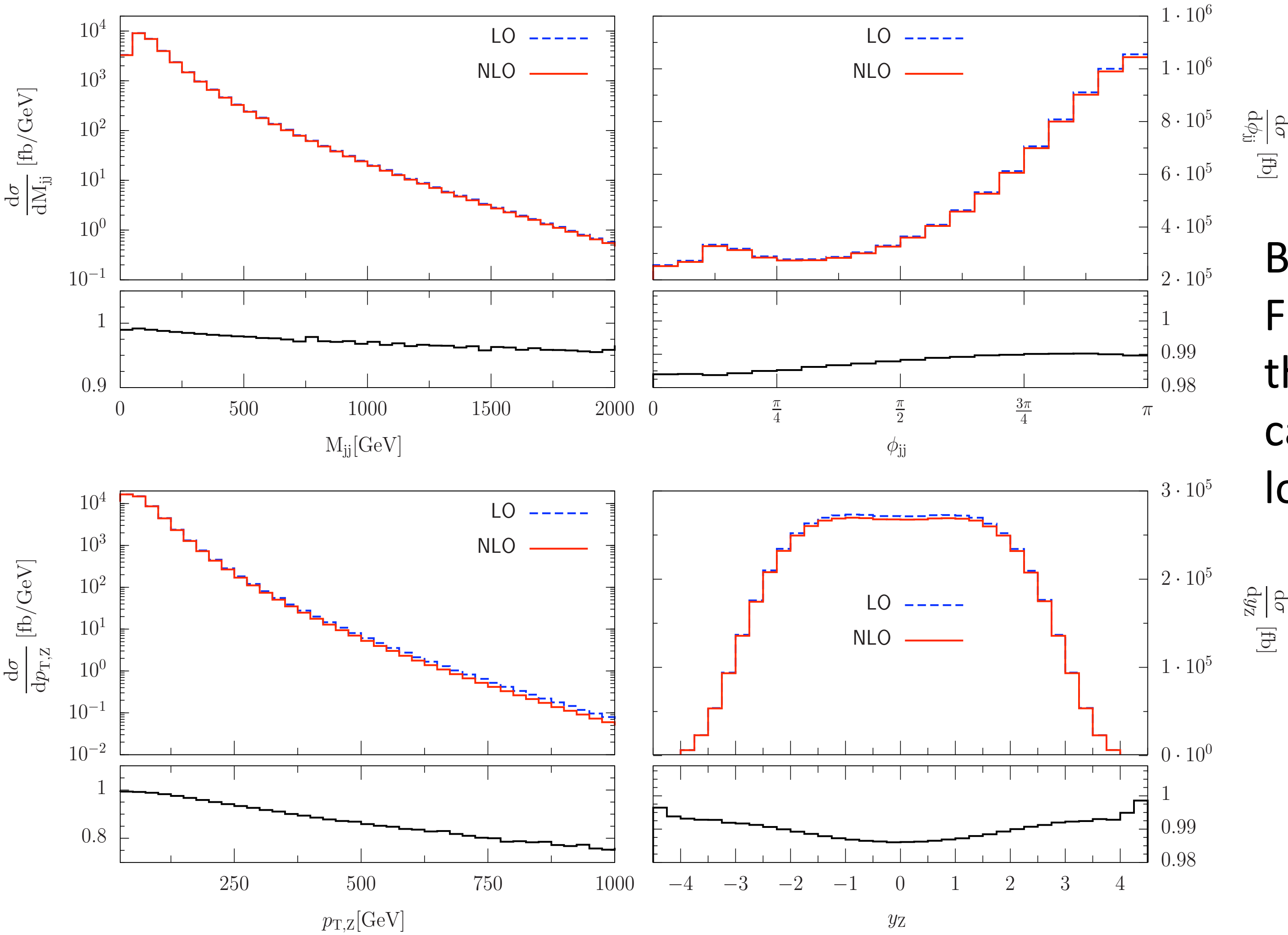
Electroweak 1-loop corrections to Z/W+n jets

- Exact 1-loop EW corrections are known for W/Z+1 jet Kuhn et al, hep-ph/057178, 0708.0476; Denner et al, 1211.507,0906.1656
- and for Z+2 jet (only gluonic contributions, 4-quark contributions in progress) Actis et al, arXiv:1211.6316
- At energy scales above the electroweak scale EW corrections are dominated by weak Sudakov logarithms

for a review see, e.g., H.Kuhn, Acta Physica Polonia B39(2008); talk by S.Dittmaier at Les Houches 2013

- Weak 1-loop Sudakov corrections to Z+1,2,3 jets production are now implemented in Alpgen 1.4.1.2, Chiesa *et al*. arXiv:1305.6837

Z+2j @ NLO EW at the 8 TeV LHC

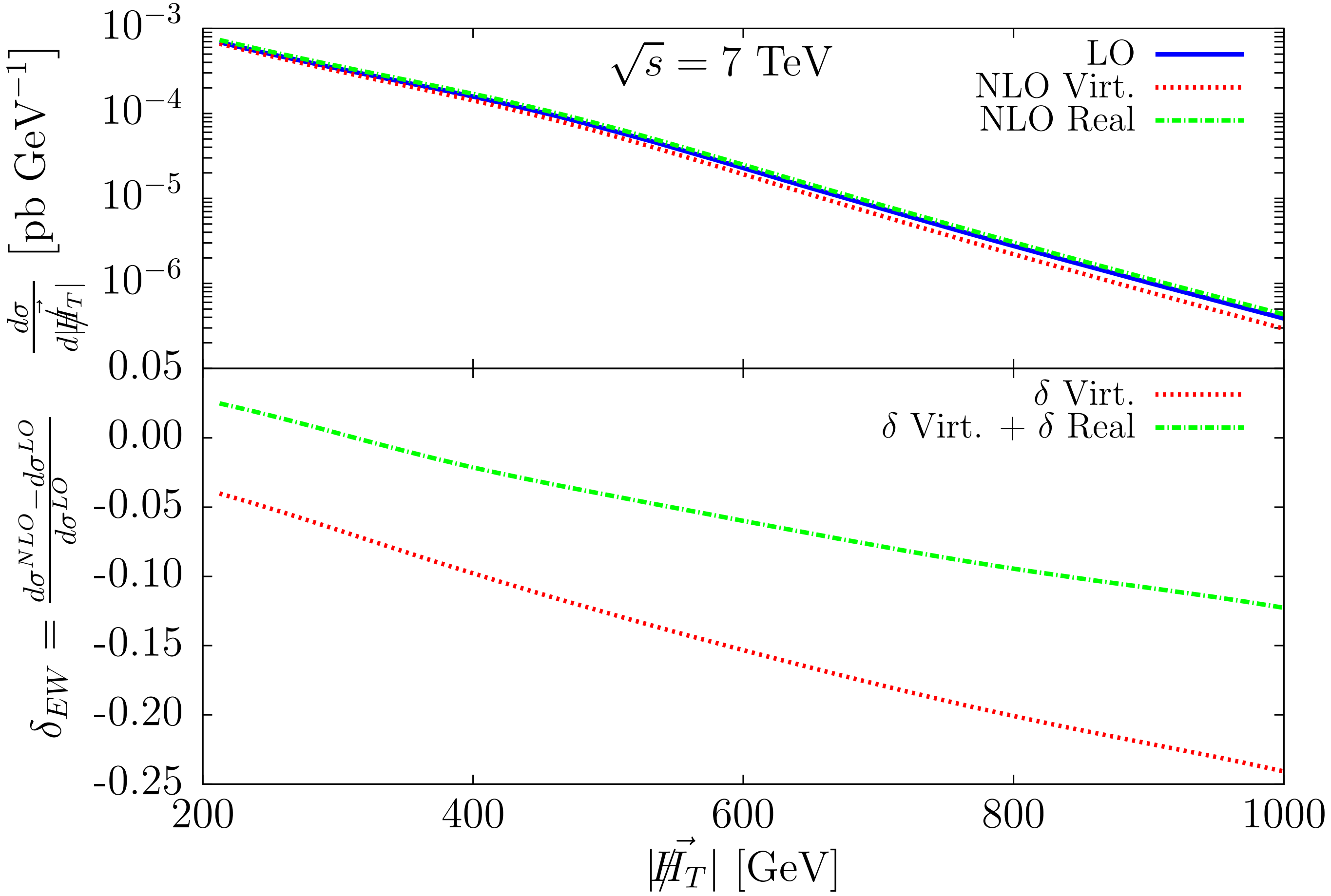


Based on REcola: Fortran90 code for the recursive calculation of one-loop amplitudes

Actis et al, arXiv:1211.6316

$$p_{T,\mathrm{jet}} > 25\,\mathrm{GeV}, \qquad |y_{\mathrm{jet}}| < 4.5$$

Z+3j: Weak 1-loop Sudakov corrections in Alpgen



$H_T > 500$ GeV $\quad |\vec{\not{H}}_T| > 200$ GeV $\quad \vec{\not{H}}_T = -\sum_i \vec{p}_{t\,i},$

$p_T^j > 50$ GeV $\quad |\eta_j| < 2.5 \quad \Delta R_{(j_i, j_k)} > 0.5$

$\Delta\phi(\vec{p}_T^{\,j_1, j_2}, \vec{\not{H}}_T) > 0.5 \quad \Delta\phi(\vec{p}_T^{\,j_3}, \vec{\not{H}}_T) > 0.3$

Chiesa *et al*. arXiv:1305.6837

NLO EW×QCD to W and Z production in POWHEG

- Implementation in POWHEG-W by Bernaciak et al 1201.4804 and Barze et al. 1202.0465
- Implementation in POWHEG-Z by Barze et al, 1302.4606
- Implementation by Barze et al: NLO QCD and EW both interfaced to QCD and QED shower MCs.

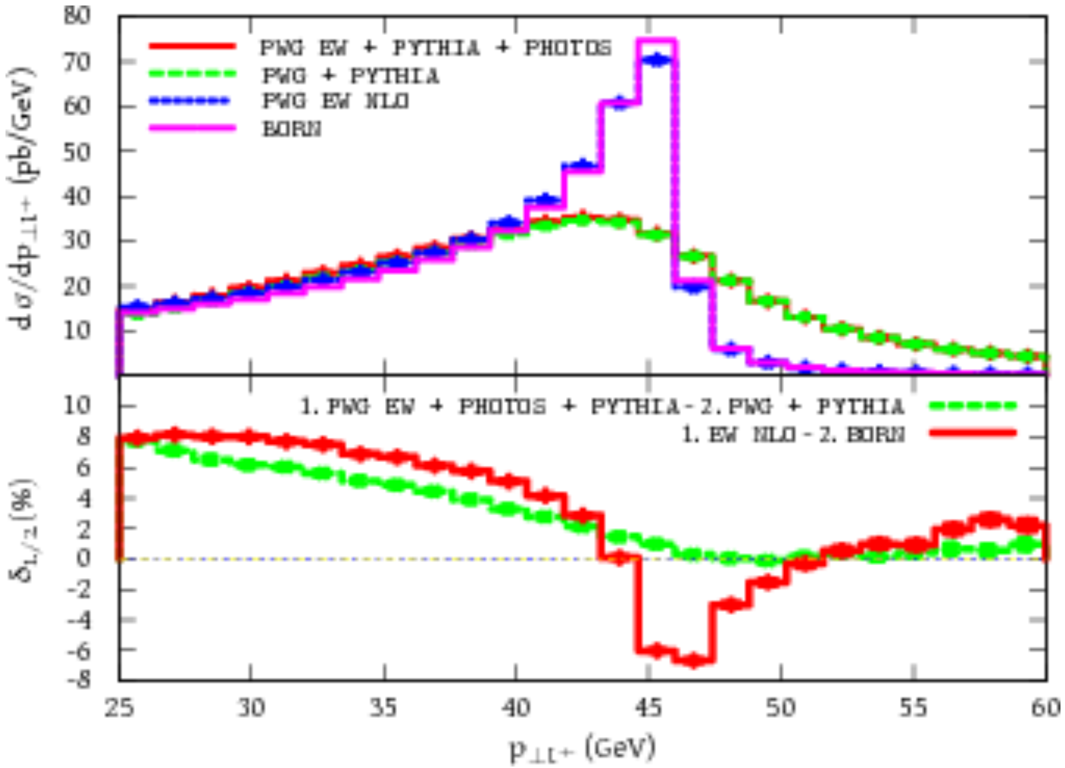
Implementation by Bernaciak et al:

$$d\sigma = \sum_{\text{flavors}} \bar{B}(\Phi_n) d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\text{min}}) + \sum_{\alpha_r} \frac{\left[d\Phi_{\text{rad}} \Delta(\Phi_n, k_T > p_T^{\text{min}}) R(\Phi_{n+1}) \right]}{B(\Phi_n)} \right\}$$

$$\bar{B}(\Phi_2) = B(\Phi_2) + V_{\text{QCD}}(\Phi_2) + V_{\text{EW}}(\Phi_2) + \int_{\oplus} \frac{dz}{z} \left[G_{\oplus,\text{QCD}}(\Phi_{2,\oplus}) + G_{\oplus,\text{EW}}(\Phi_{2,\oplus}) \right]$$

$$+ \int_{\ominus} \frac{dz}{z} \left[G_{\ominus,\text{QCD}}(\Phi_{2,\ominus}) + G_{\ominus,\text{EW}}(\Phi_{2,\ominus}) \right] + \sum_{\alpha_r \in \text{IS}} \int d\Phi_{\text{rad},IS} \left[\hat{R}(\Phi_3) + R_{\text{EW}}(\Phi_3) \right]$$

Impact of NLO EW in presence of QCD corrections on P_T(lepton) in pp->γ,Z->l^+l^-



Barze *et al,* 1302.4606

Calculation of mixed 2-loop QCD-EW corrections is work in progress. See talk by S.Dittmaier at Radcor 2013.

Getting ready for the 14 TeV Run

- The community has identified what is needed.
- The calculational tools needed to achieve the necessary precision in LHC predictions are in place.
- Impressive progress has been made already.
- But (much) more work is ahead of us and hopefully this important *bread and butter* physics will find continued support.