HARD SCATTERING AND ELECTROWEAK CORRECTIONS AT THE LHC

J.H. Kühn

I. Introduction

II. Z, W and Photon Production (brief reminder)
J.H.K., Kulesza, Pozzorini, Schulze

III. W-Pair Production
Bierweiler, Kasprzik, J.H.K, Uccirati

IV. Conclusions

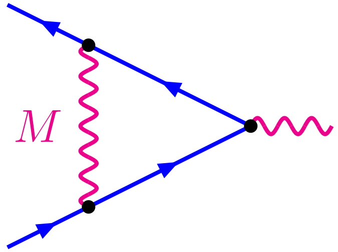
I. Introduction

"Typical" size of electroweak corrections: $\frac{\alpha_{\text{weak}}}{\pi} \approx 10^{-2}$

new aspects at LHC: $\sqrt{\hat{s}} \approx$ 1-2TeV $\gg M_{W,Z}$

strong enhancement of negative corrections

one-loop example: massive U(1)



$$\Rightarrow \quad \text{Born} * \left[1 + \frac{\alpha}{4\pi} \left(-\ln^2 \frac{s}{M^2} + 3 \ln \frac{s}{M^2} - \frac{7}{2} + \frac{\pi^2}{3} \right) \right]$$

$\frac{s}{M^2}$	$-\ln^2 \frac{s}{M^2}$	$+3\ln \frac{s}{M^2}$	$-\frac{7}{2} + \frac{\pi^2}{3}$	Σ	$* \, 4 \, \frac{\alpha_{\text{weak}}}{4\pi}$
$\left(\frac{1000}{80}\right)^2$	-25.52	$+15.15$	-0.21	-10.6	-13%
$\left(\frac{2000}{80}\right)^2$	-41.44	$+19.31$	-0.21	-22.3	-27%

(four-fermion cross section $\Rightarrow$ factor 4)

- leading $\log^2$ multiplied by (charge)$^2 = I(I+1) = \begin{cases} 3/4 & I = 1/2 \\ 2 & I = 1 \end{cases}$

  $\Rightarrow$ further enhancement for W-pairs by nearly factor 2.

- important subleading logarithms (NLL+...)

- two-loop terms may be relevant

- interplay between electroweak and QCD corrections

- important differences between fermions and electroweak gauge bosons

II. Z, W and Photon Production at LHC

(Reminder: J.H.K., Kulesza, Pozzorini, Schulze 2005-2008)

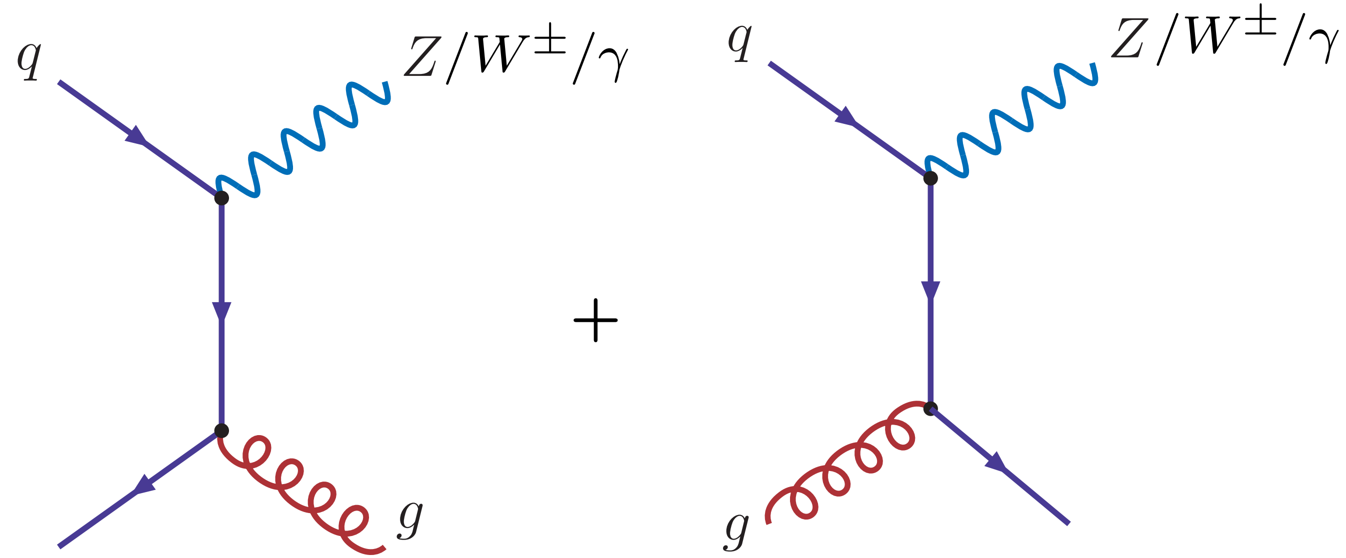
Phys. Lett. B609(2005) 277, Nucl. Phys. B727(2005) 368,

JHEP 0603:059,2006, Phys.Lett. B651(2007), NPB797 (2008) 27

Related work: Dittmaier, Kasprzik, ...

sizable rate at large p_{T} (1-2 TeV)

Large electroweak corrections ($\hat{s} \gg M_{W,Z}^2$)



Complete NLO corrections available

High energy limit

consider $q\bar{q} \to Zg$

NLL $\widehat{=}$ double + single logarithmic terms

$H_0 \widehat{=}$ Born, H_1^{A}, $H_1^{\mathrm{N}} \widehat{=}$ abelian and nonabelian corrections

$$H_1^{\mathrm{A}} \overset{\mathrm{NLL}}{\sim} -\left[\log^2\left(\frac{|\hat{s}|}{M_W^2}\right) - 3\log\left(\frac{|\hat{s}|}{M_W^2}\right)\right] H_0,$$

$$H_1^{\mathrm{N}} \overset{\mathrm{NLL}}{\sim} -\left[\log^2\left(\frac{|\hat{t}|}{M_W^2}\right) + \log^2\left(\frac{|\hat{u}|}{M_W^2}\right) - \log^2\left(\frac{|\hat{s}|}{M_W^2}\right)\right] H_0$$

- remaining subleading terms $\leq 2.5\%$
- NNLL includes non-enhanced terms (angular dependent)
- compact formulae for NNLL result.

size of the correction:

$$\sqrt{\hat{s}} = 200 \text{ GeV}: \quad \frac{\delta\sigma}{\sigma} \leq 0.3\%$$

$$\sqrt{\hat{s}} = 4000 \text{ GeV}: \quad \frac{\delta\sigma}{\sigma} \approx 20 - 30\%$$

Full NLO result checked against NLL based on general considerations

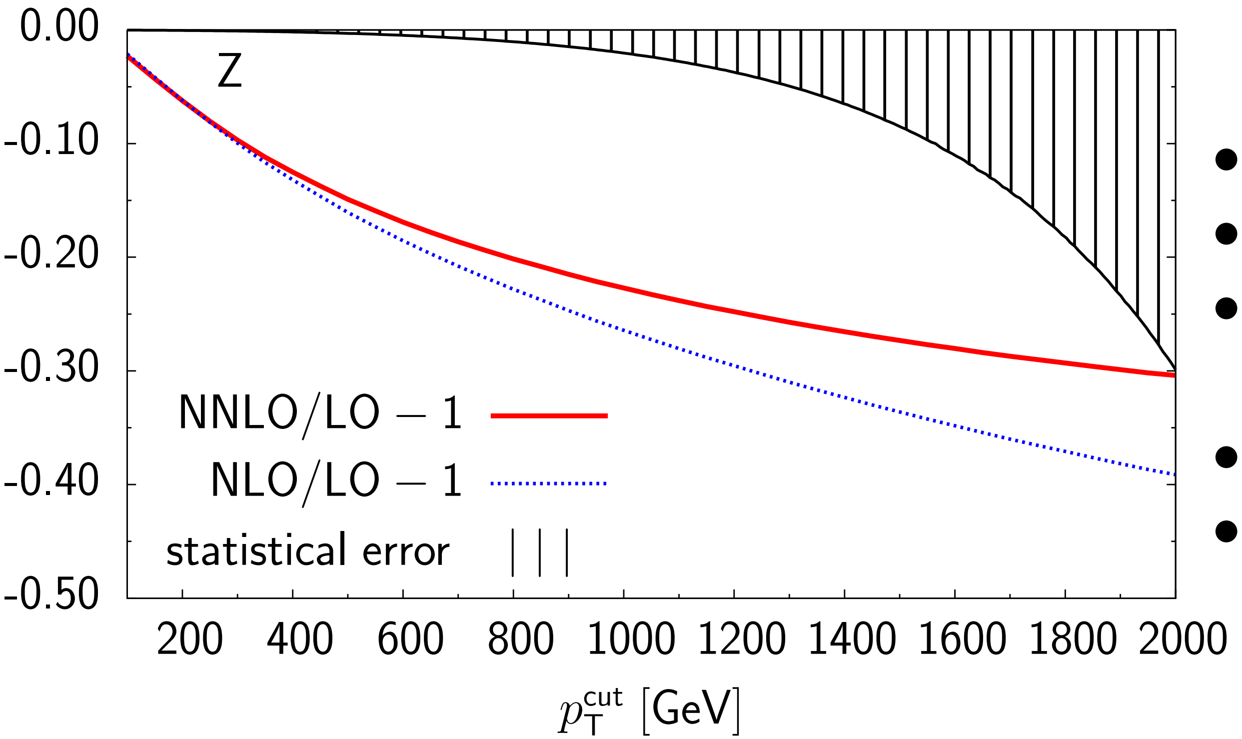
Predict dominant **two-loop** term (NLL):

$$
\begin{aligned}
A^{(2)} \;=\; \sum_{\lambda=\mathrm{L,R}} \Bigg\{ & \frac{1}{2}\left(I^{Z}_{q_\lambda} C^{\mathrm{ew}}_{q_\lambda} + \frac{c_{\mathrm{W}}}{s^3_{\mathrm{W}}} T^3_{q_\lambda}\right) \Bigg[I^{Z}_{q_\lambda} C^{\mathrm{ew}}_{q_\lambda} \left(\mathrm{L}^4_{\hat{s}} - 6\mathrm{L}^3_{\hat{s}}\right) \\
& + \frac{c_{\mathrm{W}}}{s^3_{\mathrm{W}}} T^3_{q_\lambda} \left(\mathrm{L}^4_{\hat{t}} + \mathrm{L}^4_{\hat{u}} - \mathrm{L}^4_{\hat{s}}\right) \Bigg] - \frac{T^3_{q_\lambda} Y_{q_\lambda}}{8 s^4_{\mathrm{W}}} \left(\mathrm{L}^4_{\hat{t}} + \mathrm{L}^4_{\hat{u}} - \mathrm{L}^4_{\hat{s}}\right) \\
& + \frac{1}{6} I^{Z}_{q_\lambda} \left[I^{Z}_{q_\lambda} \left(\frac{b_1}{c^2_{\mathrm{W}}} \left(\frac{Y_{q_\lambda}}{2}\right)^2 + \frac{b_2}{s^2_{\mathrm{W}}} C_{q_\lambda} \right) + \frac{c_{\mathrm{W}}}{s^3_{\mathrm{W}}} T^3_{q_\lambda} b_2 \right] \mathrm{L}^3_{\hat{s}} \Bigg\}
\end{aligned}
$$

with $\mathrm{L}^n_{\hat{r}} = \log^n\left(\frac{|\hat{r}|}{M^2_W}\right)$, $b_1 = -41/(6c^2_{\mathrm{W}})$ and $b_2 = 19/(6s^2_{\mathrm{W}})$, $I^Z_{q\lambda} = \frac{c_{\mathrm{W}}}{s_{\mathrm{W}}} T^3_{q\lambda} - \frac{s_{\mathrm{W}}}{c_{\mathrm{W}}} \frac{Y_{q\lambda}}{2}$

valid for $\hat{s}/M^2_W \gg 1$ and $|\hat{s}/\hat{t}| = \mathcal{O}(1)$, $|\hat{s}/\hat{u}| = \mathcal{O}(1)$.

Complete one loop calculation
NLL approximation at two loops



- one-loop $\sim$ 30% at $p_T \sim 1$TeV
- two-loop relevant above 1 TeV
- important angular-dependent logarithmic terms
- experiment: p_T up to 2 TeV
- idealized stat. error for 300 fb^{-1}

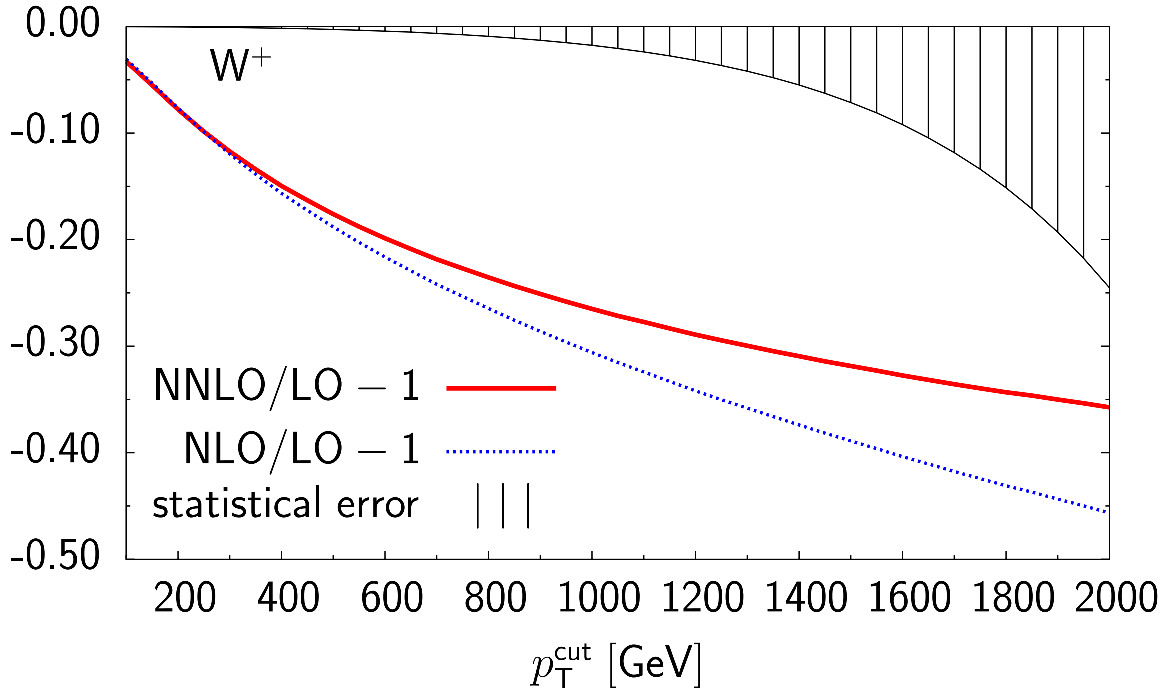
Relative **NLO** and **NNLO** corrections w.r.t. the **LO** and statistical error for the unpolarized integrated cross section for $pp \to Zj$ at $\sqrt{s} = 14$ TeV.

(Similarly, but smaller by a factor 2 for jet+γ)

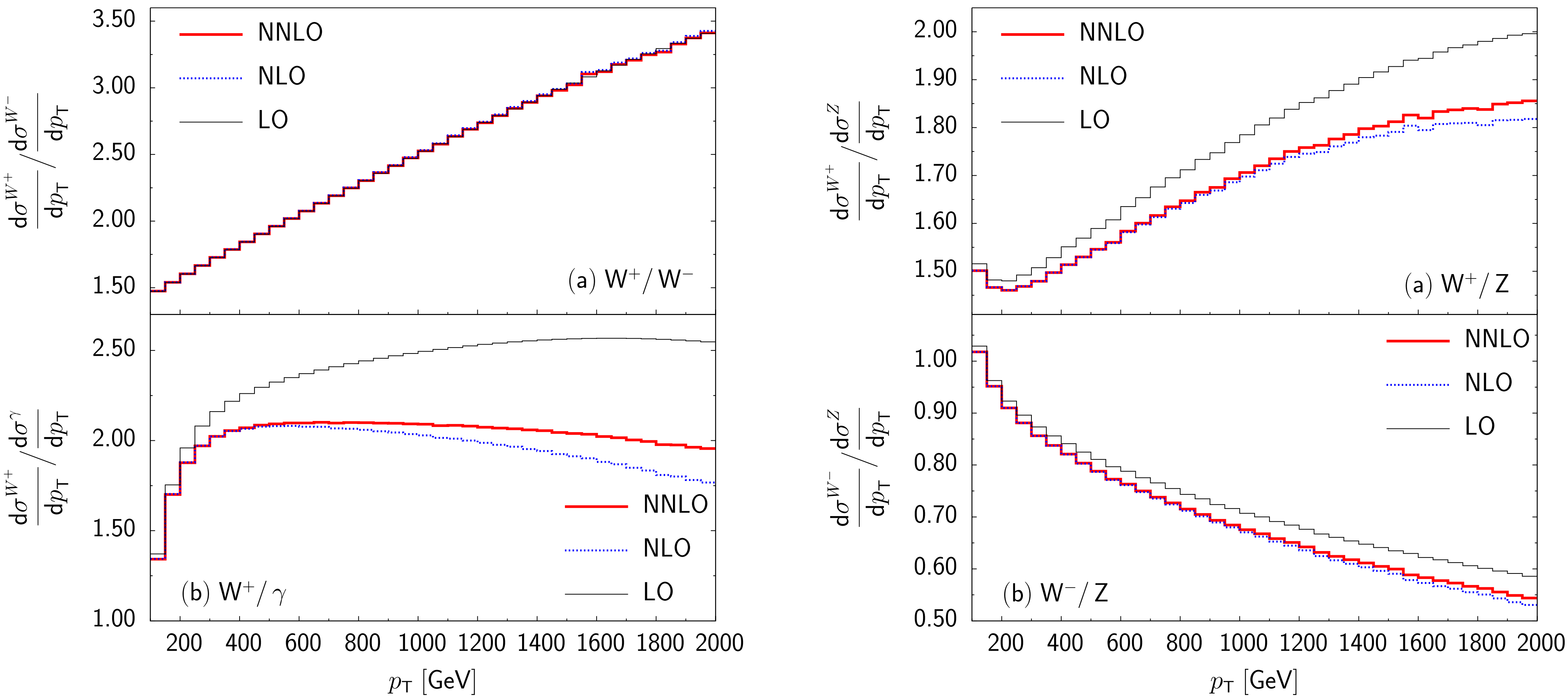
W production

additional complications:

- photon radiation as necessary part of virtual corrections (gauge invariance)
- IR singularities must be compensated by real radiation
- $p_\mathsf{T}(W) = p_\mathsf{T}(\text{jet}) + p_\mathsf{T}(\gamma)$



(related results: Dittmaier, Kasprzik, ...)



ratios are less sensitive to QCD corrections

III. W-Pair Production at the LHC

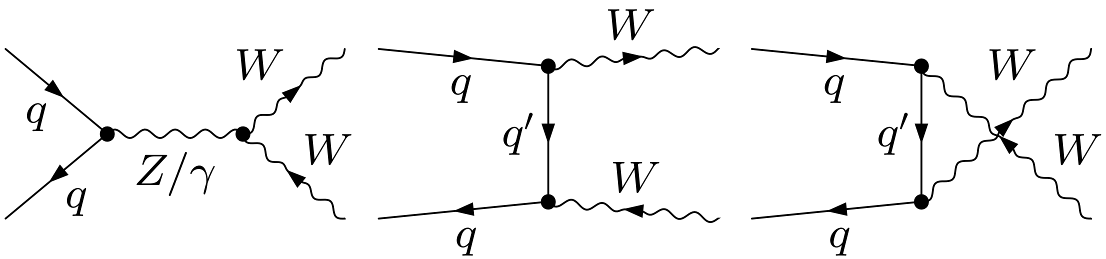
Bierweiler, Kasprzik, J.H.K., Uccirati

Two Approaches:

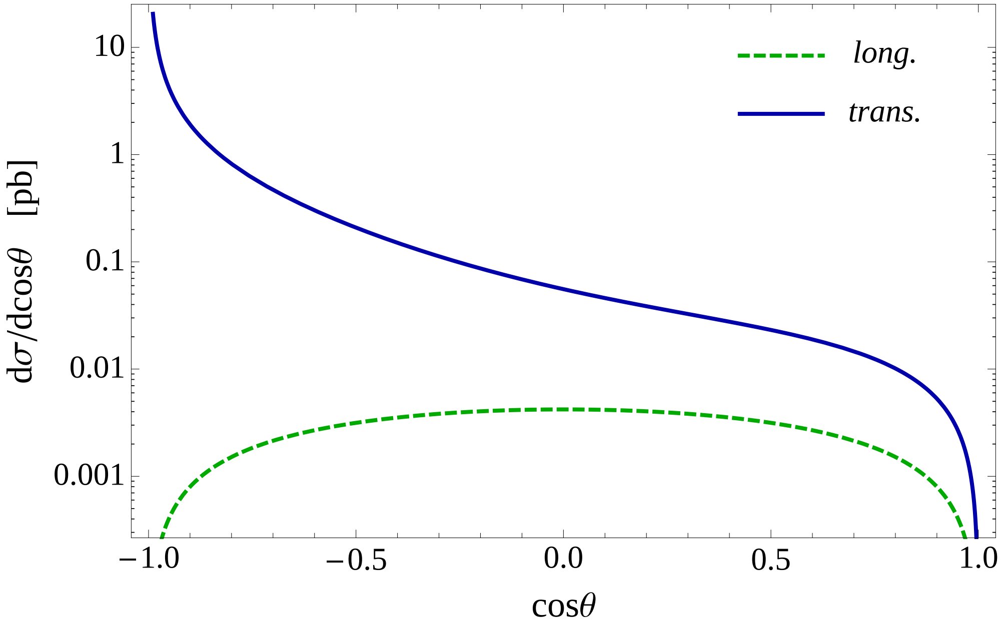
- dominant, logarithmically enhanced terms via evolution equation & separation of QED
  $\Rightarrow$ one- and two-loop terms in NNLL
  J.H.K., Metzler, Penin, Uccirati: JHEP 1106 (2011) 143
  related work based on SCET: Manohar,...

- one-loop calculation, including $M_W^2/\hat{s}$ terms and real radiation: full NLO
  Bierweiler, Kasprzik, J.H.K., Uccirati
  related work: logarithmically enhanced terms only, including W decays
  Accomando, Denner, Kaiser

Leading Order

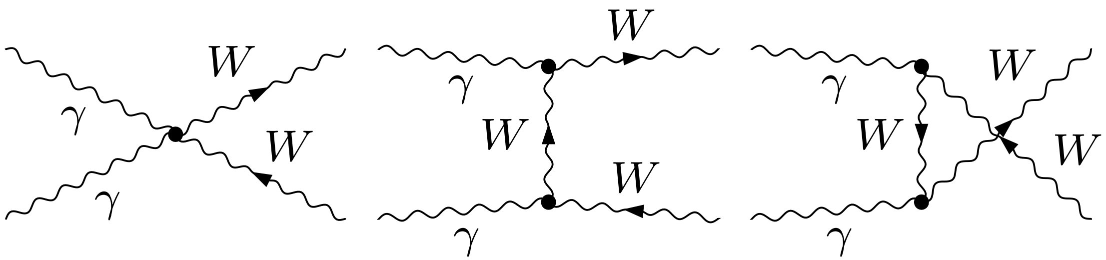


$u\bar{u} \rightarrow W^+W^-$, $\sqrt{s} = 1$ TeV

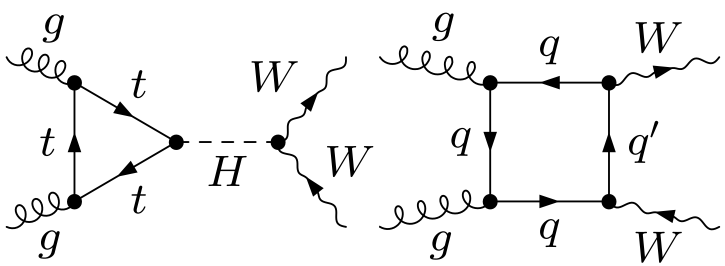


- Strong enhancement for $\Theta \rightarrow 180°$
- dominance of transverse W

Also included: $\gamma\gamma \to WW$



also included: $gg \to WW$



NLO Electroweak Corrections

- On-shell scheme (G_μ, M_W, M_Z)

- Virtual corrections IR divergent
  (regularized by m_γ, m_q), compensated by

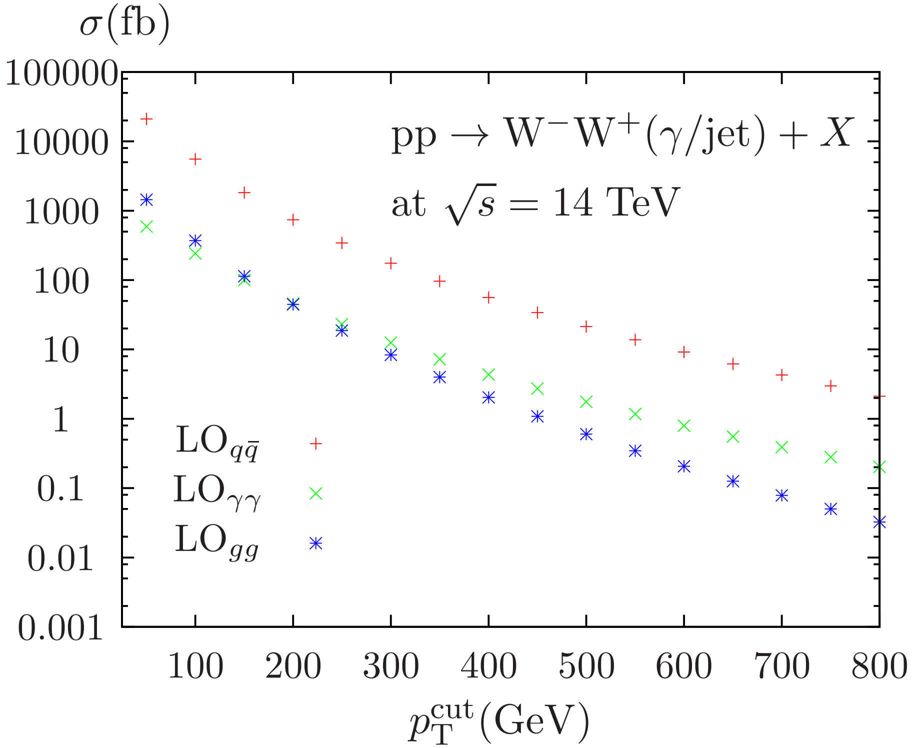
- real radiation
  remaining collinear singularities to be absorbed in PDFs

- practical implementation: use MSTW2008LO PDFs
  (impact of QED small)

- for comparison also NLO QCD corrections:
  eliminate hard jets
  (Discard jets with $p_{\mathrm{T}}^{\mathrm{jet}} > \mathrm{max}(p_{\mathrm{T}}^{W^+}/2, p_{\mathrm{T}}^{W^-}/2)$ if $p_{\mathrm{T}}^{\mathrm{jet}} > 15$ GeV, $|y^{\mathrm{jet}}| < 2.5$)

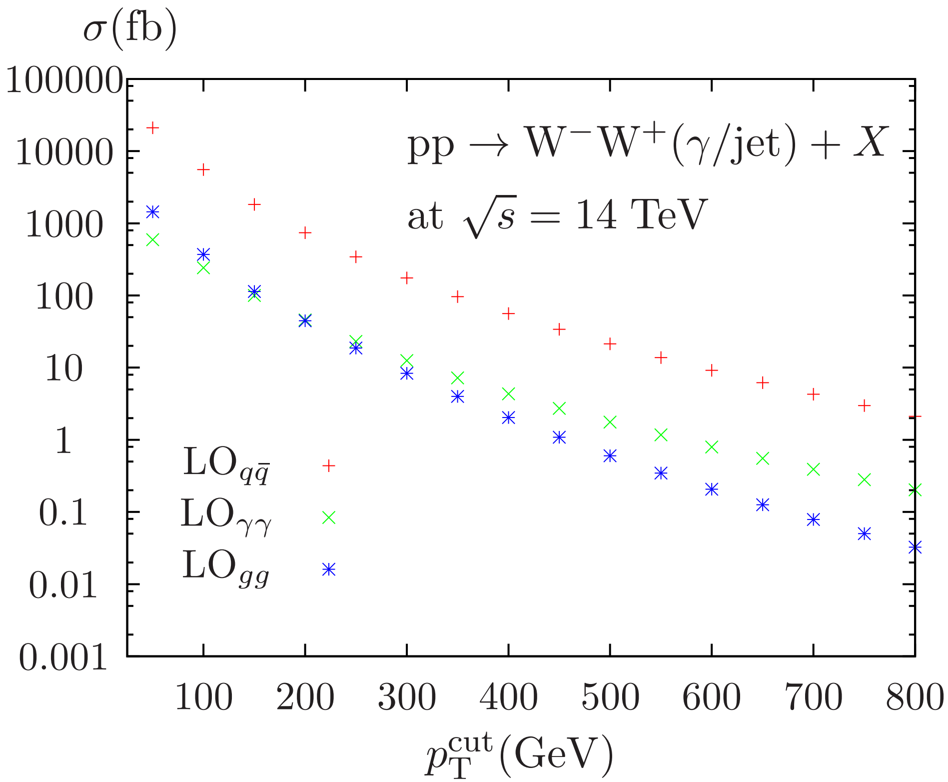
Preliminary Results

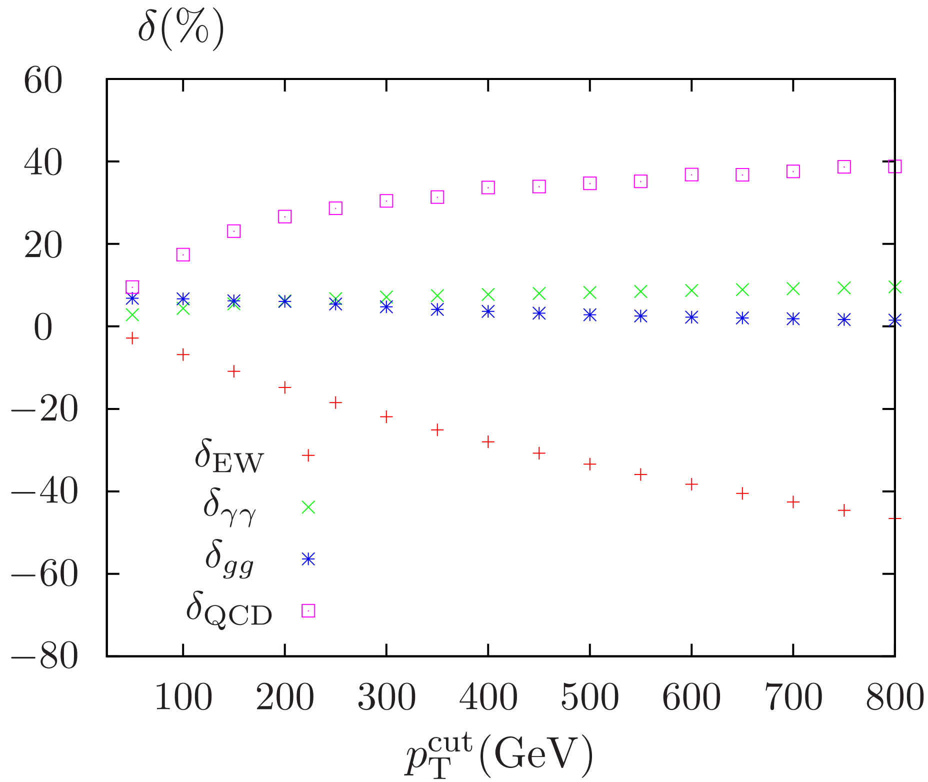
$\sigma(p_T > p_T^{\rm cut})$ at the LHC14 (preliminary)



- assume $\int \mathcal{L} = 200~\text{fb}^{-1}$
  $\Rightarrow$ 1000 WW events with $p_T >$ 1 TeV
- decreasing admixture of gg, increasing admixture of $\gamma\gamma$

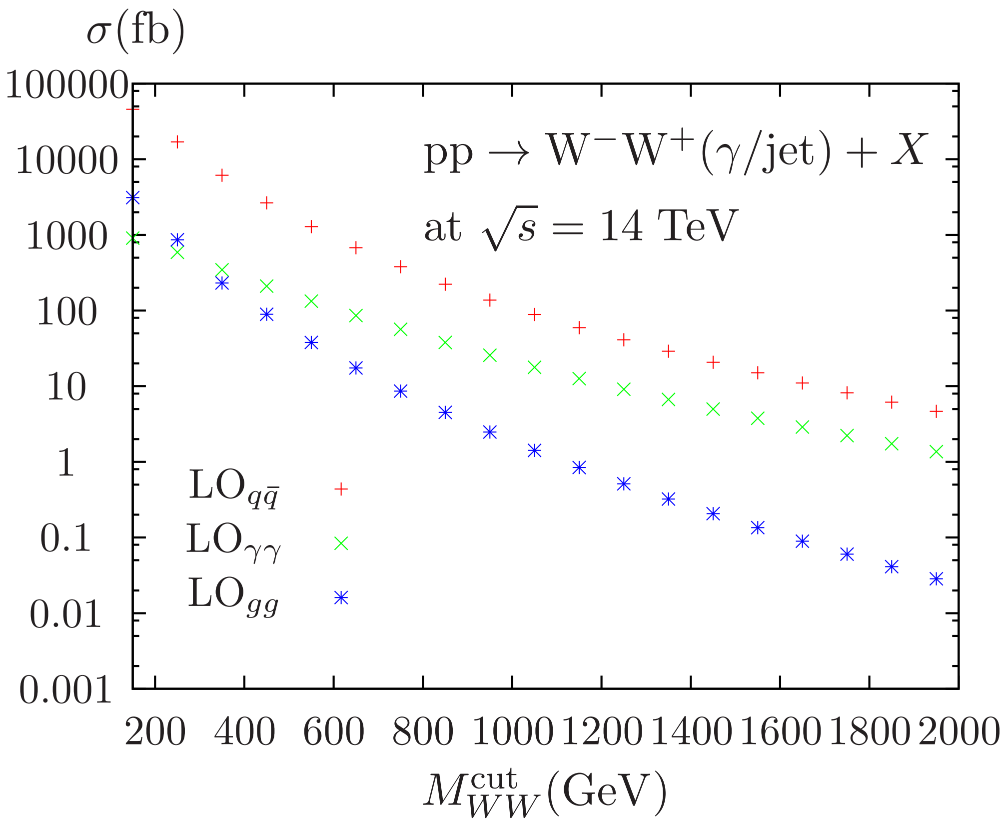
$\sigma(p_T > p_T^{\rm cut})$ at the LHC14 (preliminary)





- assume $\int \mathcal{L} = 200\ \text{fb}^{-1}$ $\Rightarrow$ 1000 WW events with $p_T >$ 1 TeV
- decreasing admixture of gg, increasing admixture of $\gamma\gamma$
- large admixture of $\gamma\gamma$ (10%!)
- large (up to 45%) negative EW corrections, comparable to QCD corrections

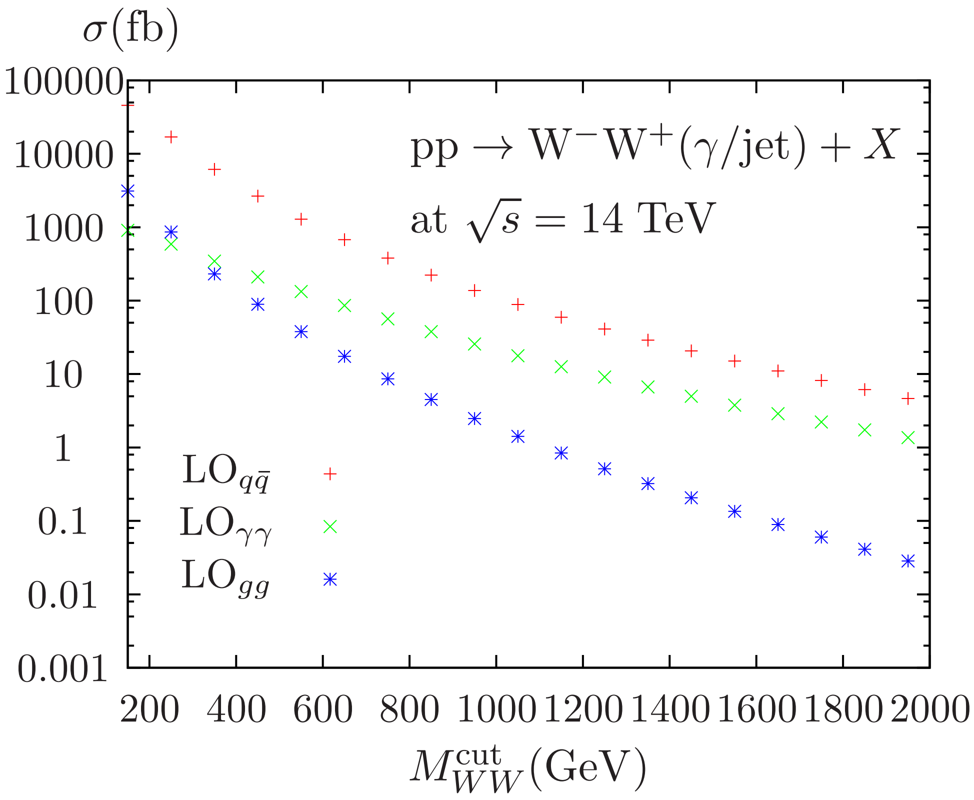
$\sigma(M_{WW} > M_{WW}^{\text{cut}})$ at the LHC14 (preliminary)

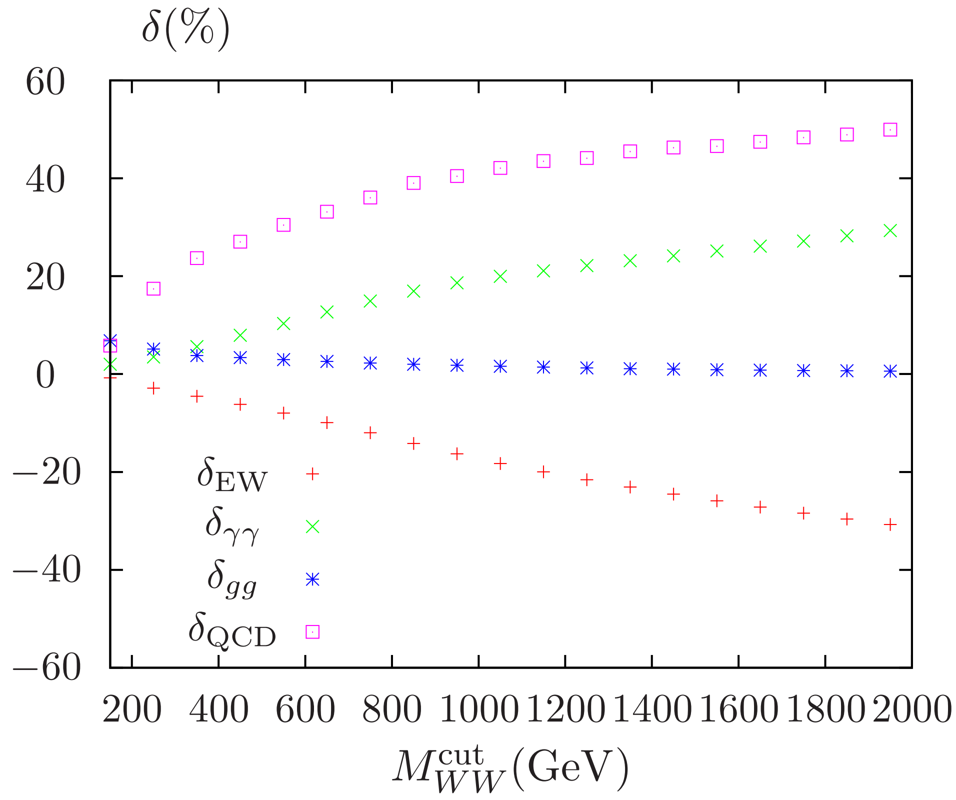


⇒ 1000 WW events with $M_{WW} > 2$ TeV

- rapidly increasing admixture of $\gamma\gamma \to WW$

$\boldsymbol{\sigma(M_{WW} > M_{WW}^{\text{cut}})}$ at the LHC14 (preliminary)





⇒ 1000 WW events with $M_{WW} > 2$ TeV

- rapidly increasing admixture of $\gamma\gamma \to WW$

- large admixture of $\gamma\gamma$ (up to 30%!)
- sizable (up to 30%) negative EW corrections, comparable to QCD corrections

No compensation between $\gamma\gamma \to WW$ and weak corrections!
Different angular distributions!

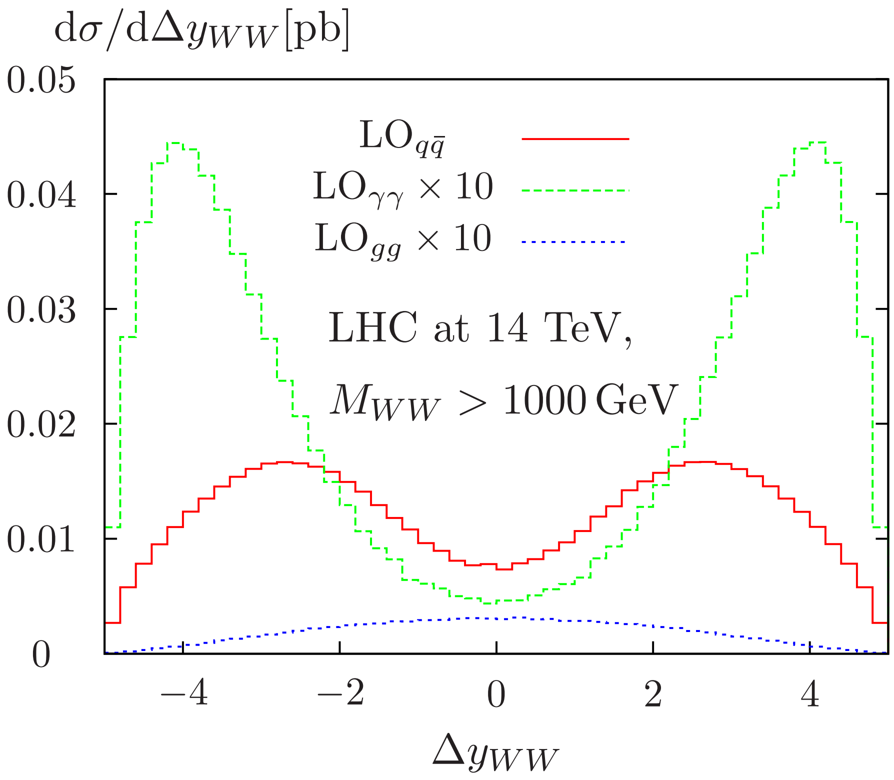
- $\sigma(\gamma\gamma \to WW) \to \frac{8\pi\alpha^2}{M_W^2}$
  $\Rightarrow$ strong enhancement in forward & backward directions

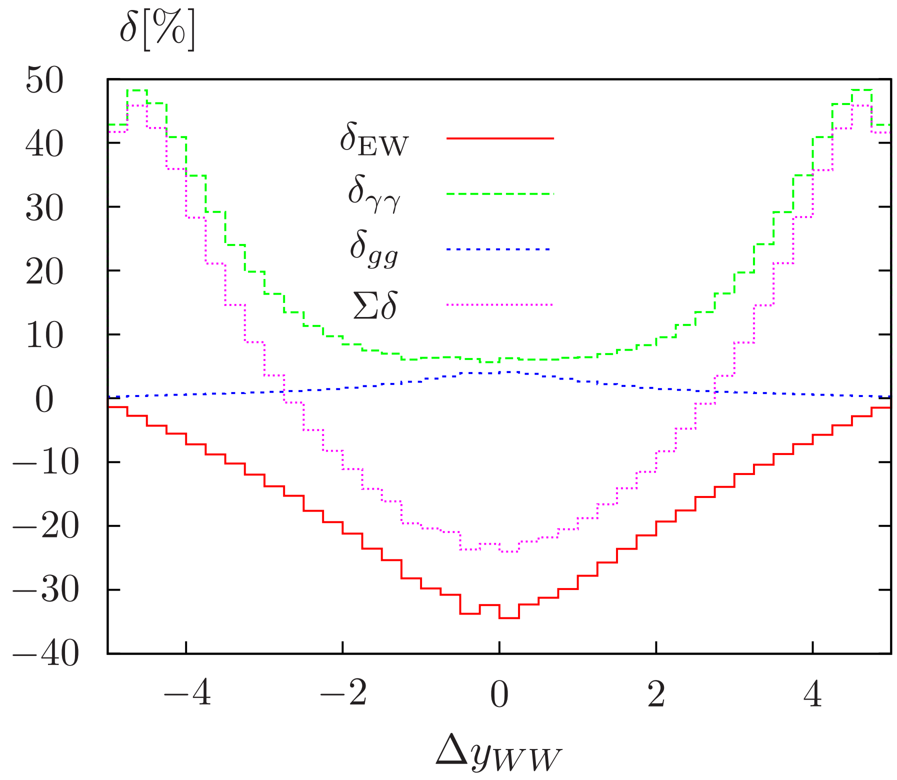
- weak corrections:
  negative Sudakov logs for large $\hat{s}$ and $\hat{t}$
  $\Rightarrow$ negative corrections for large scattering angles

- gg small, isotropic

- implications for $d\sigma/d\Delta y_{WW}$ with $\Delta y_{WW} = y_{W^+} - y_{W^-}$
  (for fixed M_{WW} this corresponds to the angular distribution!)

$d\sigma/d\Delta y_{WW}$ (preliminary)





- drastic forward-backward peaking of $\gamma\gamma \to WW$

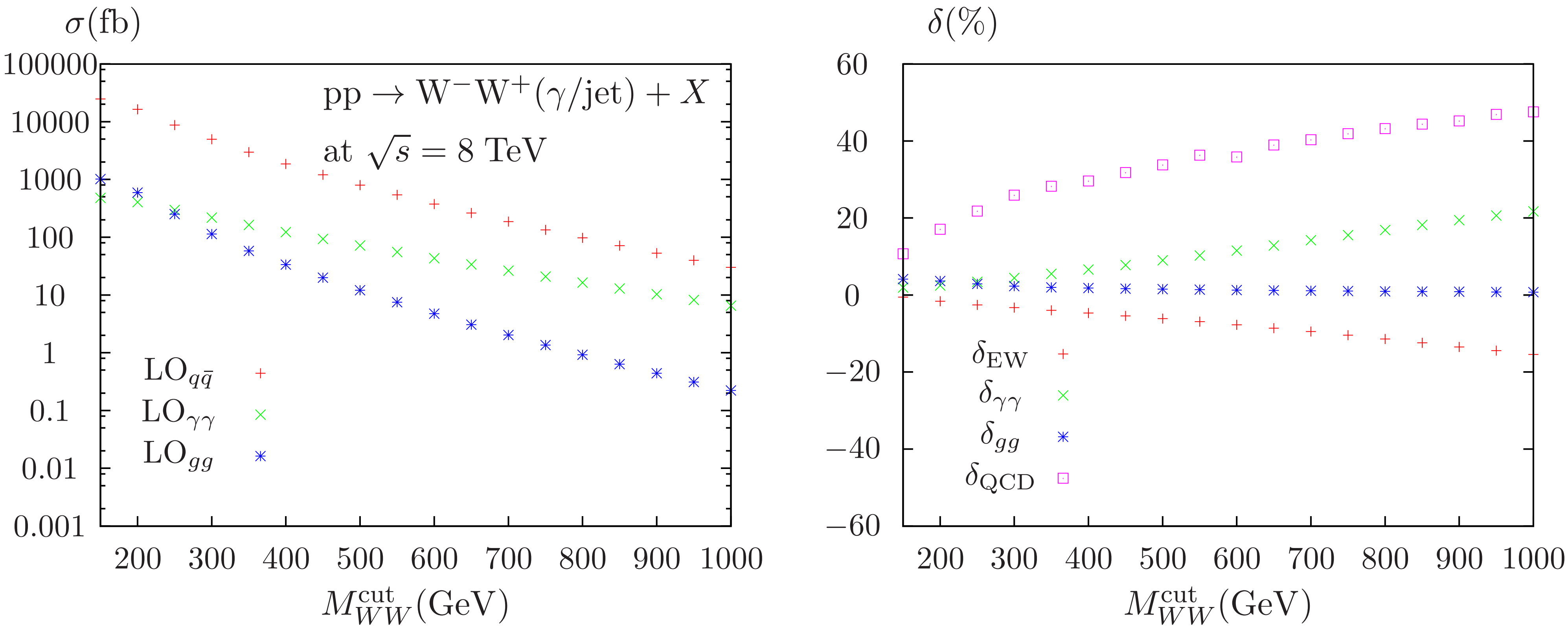
- drastic distortion of angular distribution
- $\Sigma\delta$ varies between -20% and $+45\%$ for $M_{WW} > 1$ TeV

IV. Conclusions

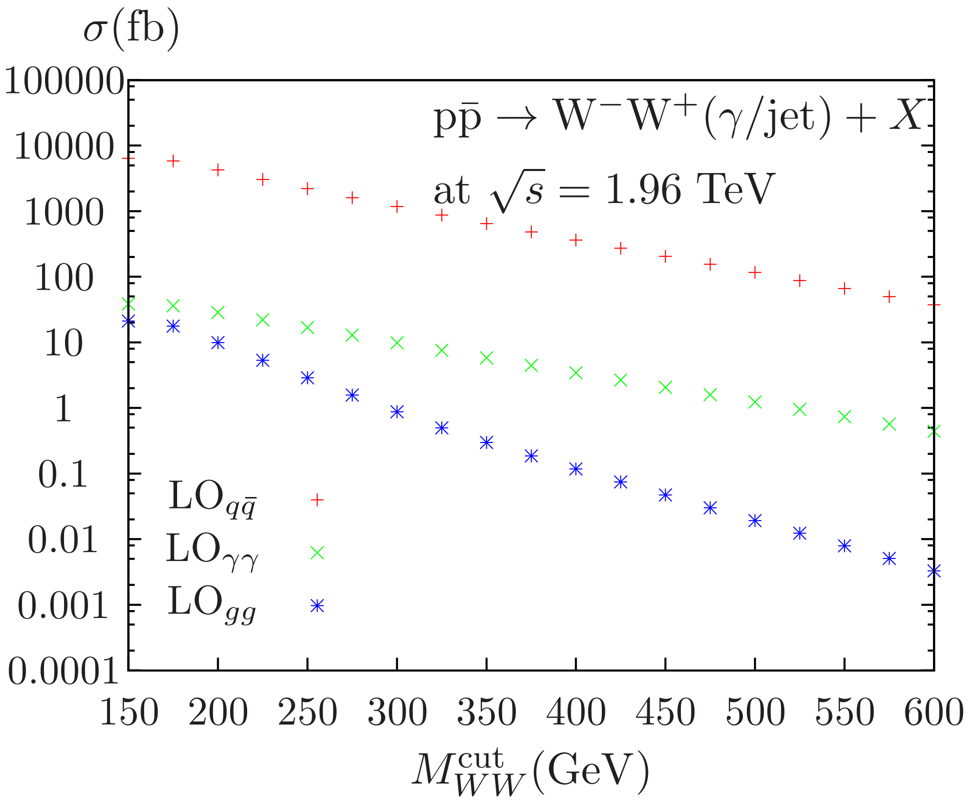
- LHC will explore the TeV-region: $\hat{s}\big/M_W^2 \gg 1$
- electroweak corrections amount to $\mathcal{O}(10\% - 30\%)$ in the interesting kinematic region
  - p_T-distributions of Z, W, γ and their ratios will be strongly affected
  - two-loop terms might become relevant
- large effects for W-pair production:
  - sizable contributions to rate and angular distributions from $\gamma\gamma \to W^+W^-$
  - $20\% - 30\%$ reduction at large $\hat{s}$ and $\hat{t}$
  - sizable modification of angular distributions, affecting $d\sigma/d\Delta y_{WW}$
- impact of "real radiation"? three-boson final states

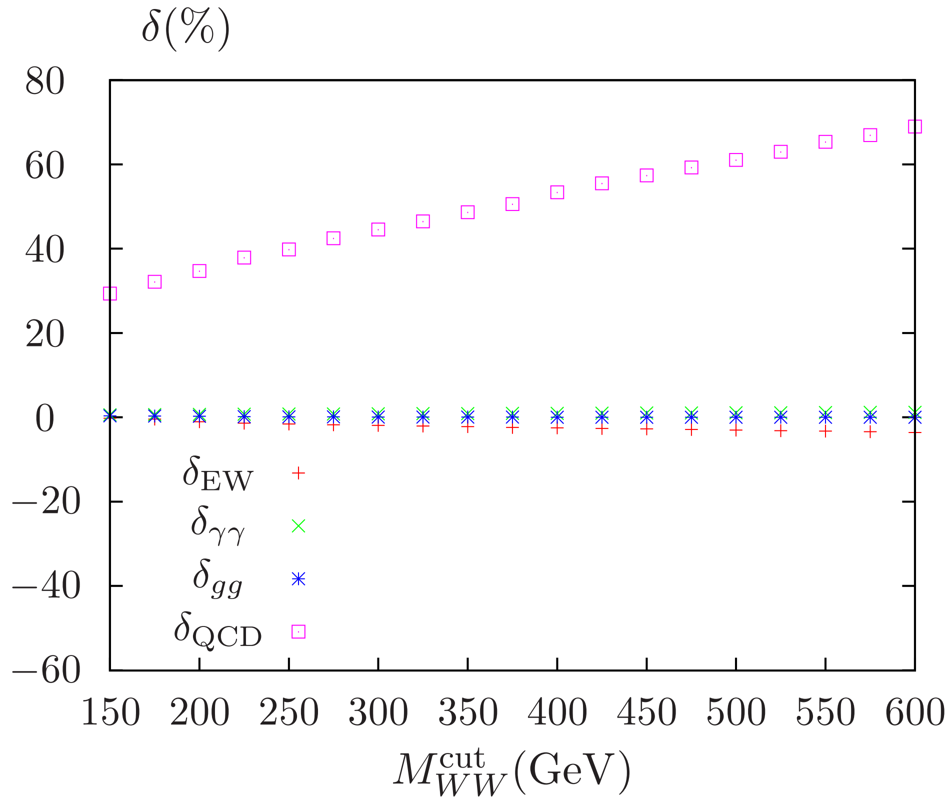
Backup

$\sigma(M_{WW} > M_{WW}^{\text{cut}})$ at the LHC8 (preliminary)

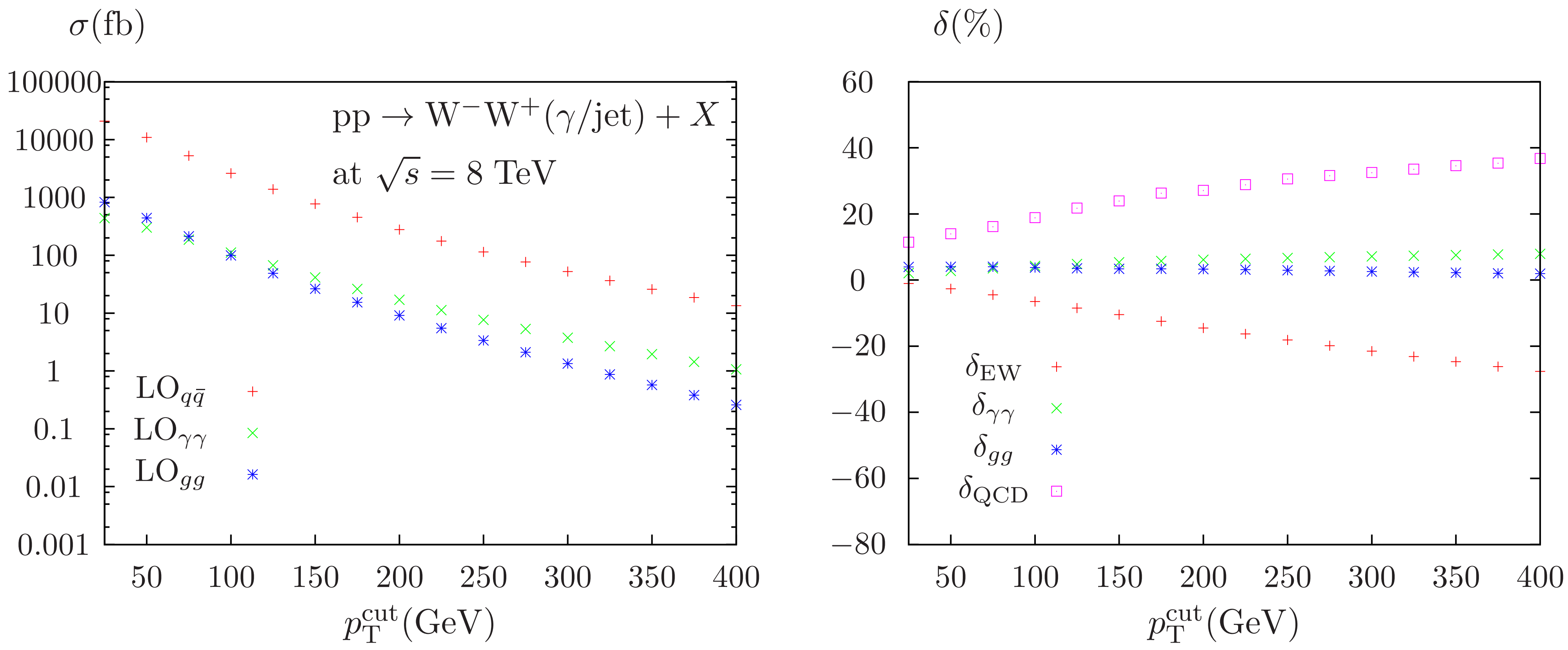


$\sigma(M_{WW} > M_{WW}^{\text{cut}})$ at the Tevatron (preliminary)





$\sigma(p_T > p_T^{\rm cut})$ at the LHC8 (preliminary)



$\sigma(p_T > p_T^{\text{cut}})$ at the Tevatron (preliminary)