Overview of electroweak corrections for LHC processes

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thanks to G. Montagna, M. Moretti and O. Nicrosini for collaboration and discussions

Outline

- Introduction
- General features of EW loop calculations
- Processes relevant for the low luminosity run @7 TeV
  - Drell-Yan
  - $W/Z+$ jet production
  - $t\bar{t}$ production
- Processes relevant for high luminosity/energy
  - γ production at large transverse momenta
  - Vector boson pair production
  - (SM) Higgs physics
    - Two-loop corrections to $gg \to H$
    - Two-loop corrections to $H \to \gamma\gamma$
    - Associate WH and ZH production
    - VBF Higgs production
  - single top

Introduction: why EWRC at LHC?

- EWRC are expected to be usually small, $\mathcal{O}(\alpha_{\rm em})$, possibly enhanced by logs of Sudakov or electromagnetic origin

see previous talk by J.H. Kühn

- EWRC can be expected to be relevant for processes mediated at tree-level by EW interactions (e.g. DY, VBF Higgs production)
- provided the level of theoretical precision induced by QCD corrections is very good, e.g.
  - DY processes are known at QCD NNLO level ($\alpha_s^2 \simeq \alpha_{\rm em}$)
  - QCD corrections to VBF Higgs production are usually $\mathcal{O}$(few %)
- EWRC to processes mediated at tree-level by QCD and EW bosons are expected to be less relevant. A generic diagram of EWRC to QCD tree-level production can be seen also as a QCD RC diagram to EW tree-level

General features of EWRC calculations

- EWRC involve the evaluation of virtual diagrams with both massive unstable particles (W, Z and H) and massless photons,
- $m_\gamma = 0 \Rightarrow$ IR and collinear divergences
- real photon radiation has to be included (as in NLO QCD)
- QED corrections depend strongly on experimental event selection
- virtual corrections with unstable particles can break gauge inv.
- the Complex Mass Scheme has been fully developed for one-loop calculations, which allows to preserve gauge invariance. It amounts to use the complex pole ($M^2 - i\Gamma M$) everywhere, also in loop diagrams and in couplings ($\sin^2\vartheta = 1 - M_W^2/M_Z^2$). Unitarity violations are shifted to higher orders.

A. Denner, S. Dittmaier, M. Roth, D. Wackeroth, Nucl. Phys. B560 (1999) 33
A. Denner, S. Dittmaier, Nucl. Phys. B160 (Proc. Suppl.) (2006) 22
A. Denner, S. Dittmaier, M. Roth, L.H. Wieders, Nucl. Phys. B724 (2005) 247

- recent extension of the Complex Mass Scheme to two-loop level

S. Actis and G. Passarino, Nucl. Phys. B777 (2007) 100
G. Passarino, C. Sturm and S. Uccirati, Phys. Lett. B655 (2007) 298

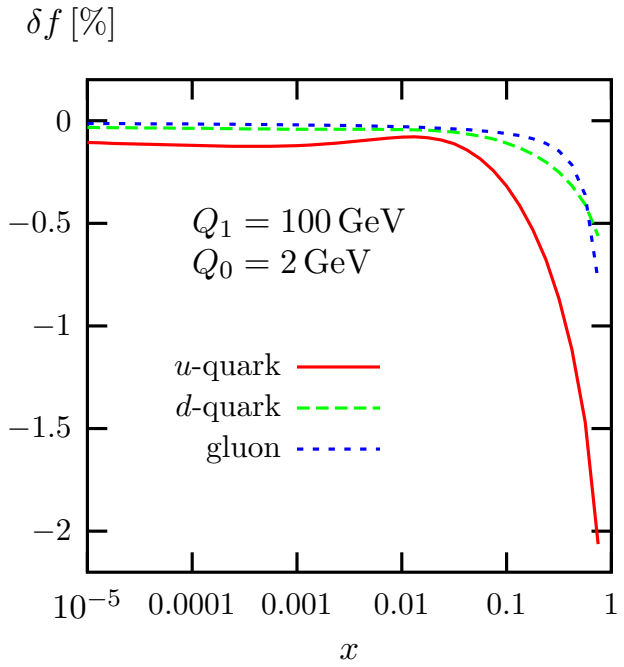
Input parameter scheme

In the gauge sector in principle we can adopt different sets of input parameters, e.g.:

- $\alpha(0)$, M_Z, M_W
  This scheme enhances artificially the radiative corrections because they contain the running of α from the scale $Q^2 = 0$ to a high energy scale induced by light fermions ($\Delta\alpha(Q^2)$)
- $\alpha(M_Z)$, M_Z, M_W
  Writing the tree-level in term of $\alpha(M_Z)$ absorbs the running of α from $Q^2 = 0$ to $Q = M_Z^2$, ($\Delta\alpha(M_Z) \sim 6\%$), minimizing the radiative corrections
- G_μ, M_Z, M_W
  In this case the effective coupling appearing in the tree-level is Δr, which contains the radiative corrections to μ decay. Δr contains explicitely $\Delta\alpha$ and also $\Delta\rho \sim 1\%$, which is a universal correction $\sim G_\mu m_t^2$

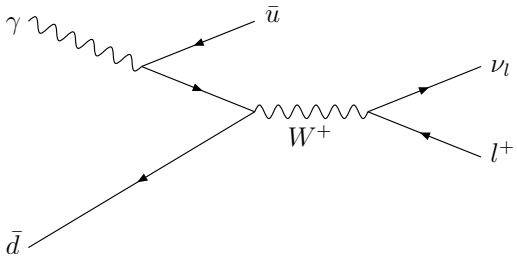
EWRC: initial state singularities

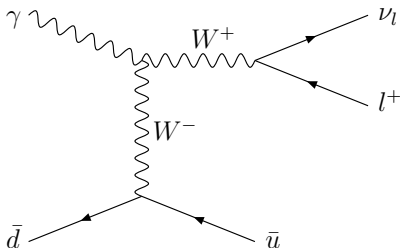
- QED IS collinear singularities have to be subtracted from the hard cross section [in analogy with NLO QCD], since they are already accounted in the (QED) evolution of PDFs
- the set MRSTQED (2004) (the only one up to now) includes the QED evolution (and QCD at NLO)



e.g. M. Roth, S. Weinzierl, PLB 590 190 (2004)

- ⋆ QED evolution modifies PDFs at 0.1% level for $x < 0.1$
- ⋆ dynamic generation of photon distr. function. Need to include photon induced processes. E.g.: DY





- usually they give a small effect

EWRC for DY processes

$W^{\pm} \to l\nu$

- ⋆ Pole approximation
  Wackeroth, Hollik, Phys. Rev. D55 (1997) 6788;
  Baur, Keller, Wackeroth, PRD59 (1999) 013002;

  WGRAD

- ⋆ Complete $\mathcal{O}(\alpha)$ corrections

  V.A. Zykunov, Eur. P. J. **C3** (2001) 9,
  Phys. Atom. Nucl. 69 (2006) 1522;
  Dittmaier, Krämer, Phys. Rev. D65 (2002) 073007;
  Baur, Wackeroth, Phys. Rev. D70 (2004) 073015;

  WGRAD2

  A. Arbuzov *et al.*, Eur. Phys. J. C46 (2006) 407;

  SANC

  C.M. Carloni Calame *et al.*, JHEP 12 (2006) 016;

  HORACE

  Brensing, Dittmaier, Krämer, Mück Phys. Rev. D77 073006, 2008;

$Z \to l^+l^-$

- ⋆ $\mathcal{O}(\alpha)$ photonic corrections
  Baur, Keller, Sakumoto, PRD57 (1998) 199;

  ZGRAD

- ⋆ Complete $\mathcal{O}(\alpha)$ corrections
  U. Baur *et al.*, Phys. Rev. **D65** (2002) 033007;

  ZGRAD2

  C.M. Carloni Calame *et al.*, JHEP **10** (2007) 190;

  HORACE

  V.A. Zykunov, Phys. Rev. **D75** (2007) 073019;
  A. Arbuzov *et al.*, Eur. Phys. J **C54**:451-460, 2008;

  SANC

  S. Dittmaier and M. Huber, JHEP 01 (2010) 060.

Higher order corrections

- Higher-order (real+virtual) QED corrections to $W/Z/\gamma^*$ production
  - $\rightarrow$ HORACE: QED PS + NLO EWRC to $W/Z/\gamma^*$ production

    C.M. Carloni Calame *et al.*, Phys. Rev. **D69** (2004) 037301;
    C.M. Carloni Calame *et al.*, JHEP **05** (2005) 019; JHEP **12** (2006) 016; JHEP **10** (2007) 190;
  - $\rightarrow$ WINHAC: YFS exponentiation + $\mathcal{O}(\alpha)$ EWRC to W decay

    S. Jadach and W. Płaczek, Eur. Phys. J. **C29** (2003) 325
  - $\rightarrow$ WINHAC$\oplus$SANC: YFS exponentiation + $\mathcal{O}(\alpha)$ EWRC to W

    Bardin, Bondarenko, Jadach, Kalinowskaya, Placzek, Acta Phys. Pol. B40 (2009) 75
- Improved treatment of multiphoton radiation in HERWIG(++) (with SOPHTY via YFS) and PHOTOS (via QED Parton Shower)

  K. Hamilton and P. Richardson, JHEP **0607** (2006) 010
  P. Golonka and Z. Was, Eur. Phys. J. **C45** (2006) 97
- Higher order QED FSR with collinear structure funcions

  S. Dittmaier and M. Huber, JHEP 01 (2010) 060
  Brensing, Dittmaier, Krämer, Mück, PRD77 (2008) 073006
- Higher order effects from couplings ($\Delta\alpha(M_Z)^n$, $\Delta\rho^2$, $\Delta\alpha(M_Z)\Delta\rho$)
- Higher orders from two-loop leading Sudakov logs

  A. Denner, B. Jantzen and S. Pozzorini, Nucl. Phys. **D761** (2007) 1
  B. Jantzen *et al.*, Nucl. Phys. **D731** (2005) 188

Tuned comparisons

- TeV4LHC Workshop

C. E. Gerber *et al.*, FERMILAB-CONF-07-052
arXiv.0705.3251 [hep-ph]

- Les Houches 2007 Workshop

C. Buttar *et al.*, arXiv:0803.0678 [hep-ph]

- HORACE and WINHAC comparisons on multiphoton corrections to all W observables

C.M. Carloni Calame, S. Jadach, G. Montagna, O.N. and W. Placzek, Acta Phys. Pol. **B35** (2004) 1643

Electroweak generators agree within their statistical precision

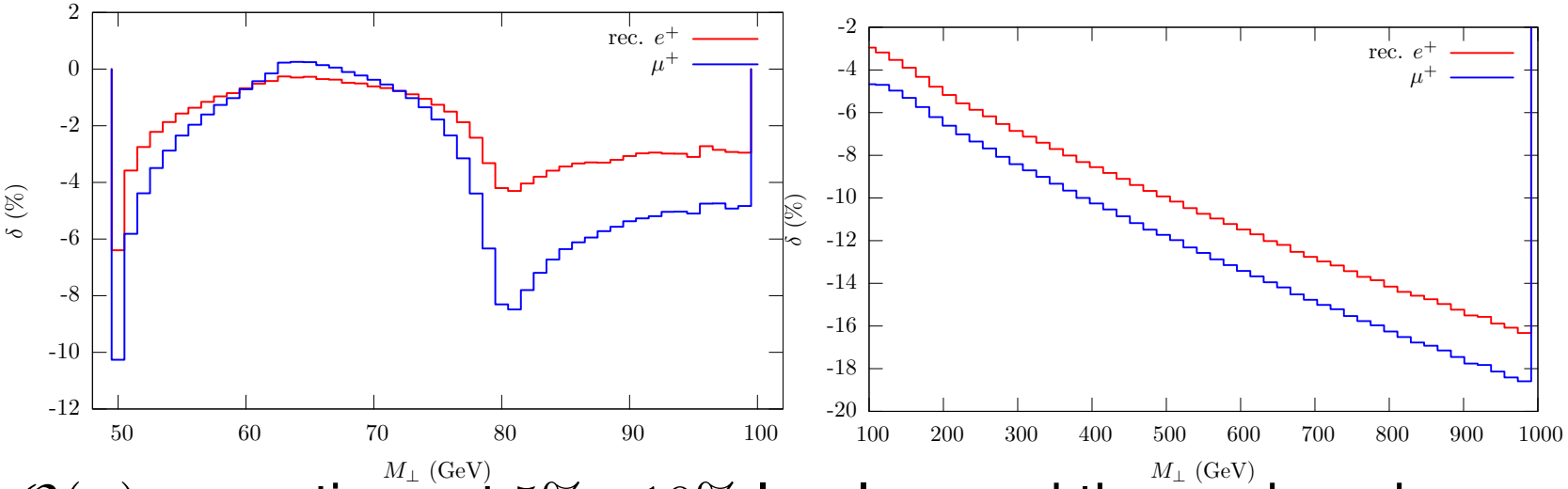
$\longrightarrow$ NLO EWRC to W/Z production well under control

$\mathcal{O}(\alpha)$ EW results for W production

Carloni Calame, Montagna, Nicrosini, Vicini, JHEP 12 016 (2006)

- final state (FS) QED radiation distorts the M_T spectrum, higher orders QED radiation can affect the measurement of M_W at the level of the aimed experimental accuracy
- $[\Delta M_W]_\alpha \sim$ 100 MeV $\qquad [\Delta M_W]_\infty \sim$ 10% of $[\Delta M_W]_\alpha$

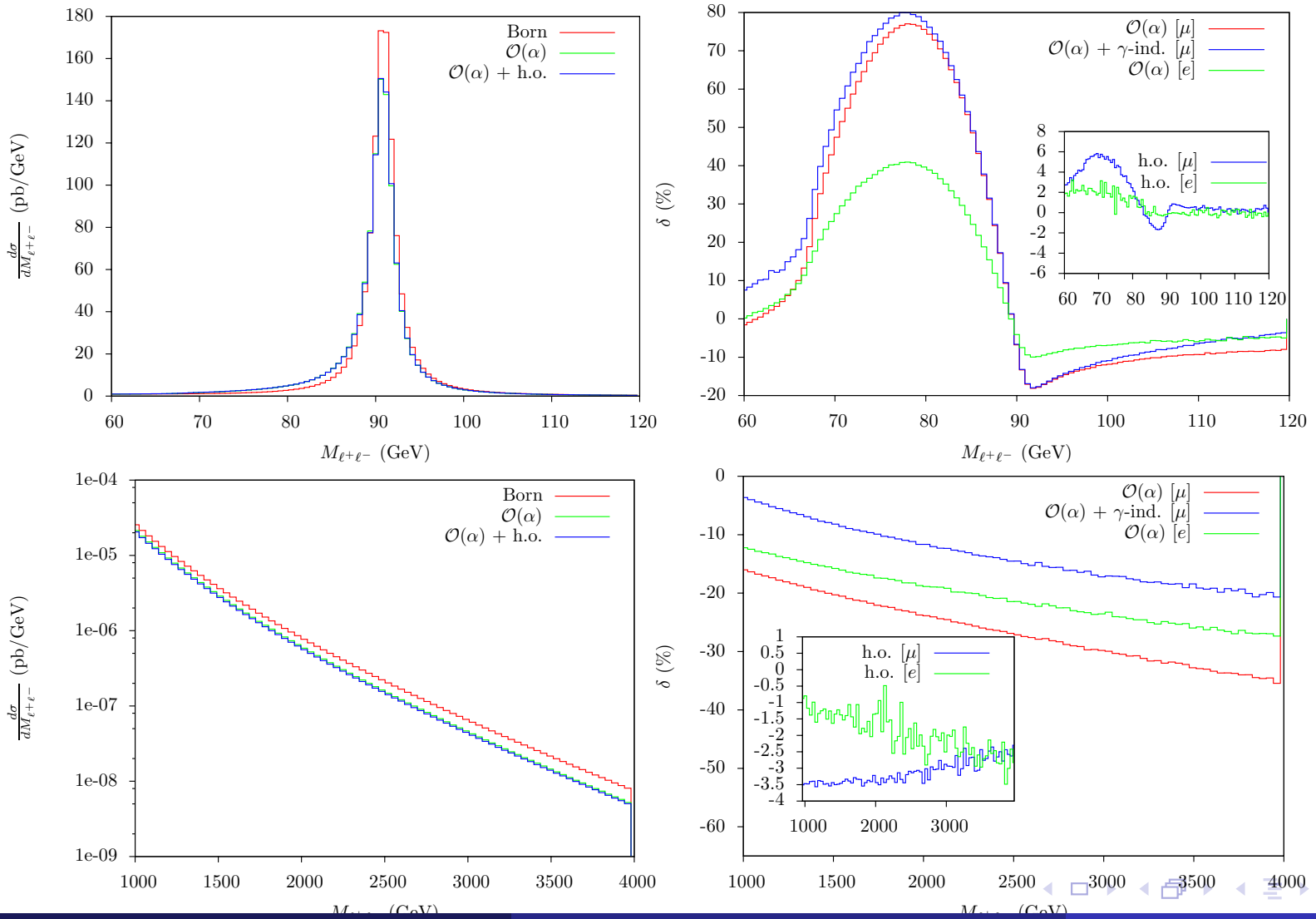
see the talk by A. Vicini



- $\mathcal{O}(\alpha)$ corrections at 5% - 10% level around the peak and increasingly large in the M_T tail due to the presence of the EW Sudakov (logs)^2, $\alpha_W \log^2 \frac{s}{M_W^2}$

EW effects for Z

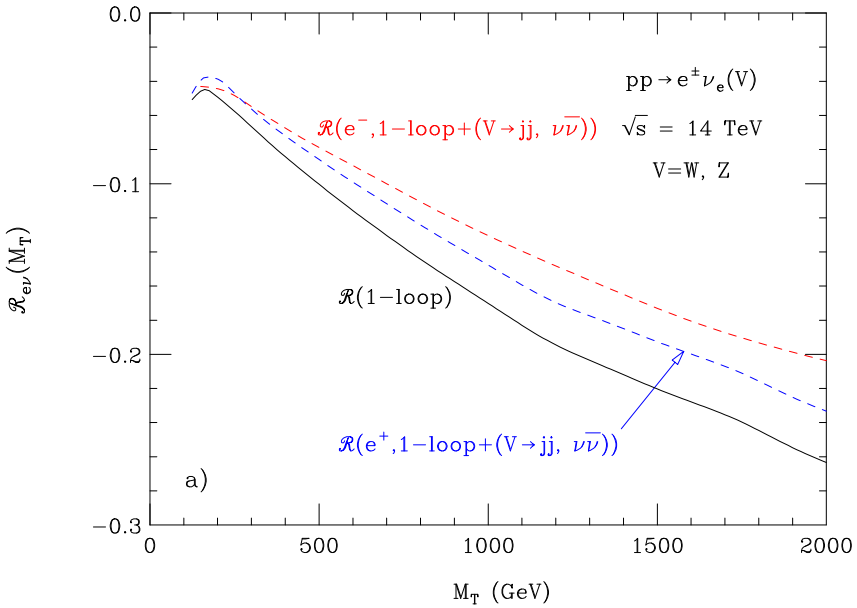
- $M_{\ell^+\ell^-}$ distribution, $\mathcal{O}(\alpha)$ effect at peak and in the tail, h.o. QED effects at peak

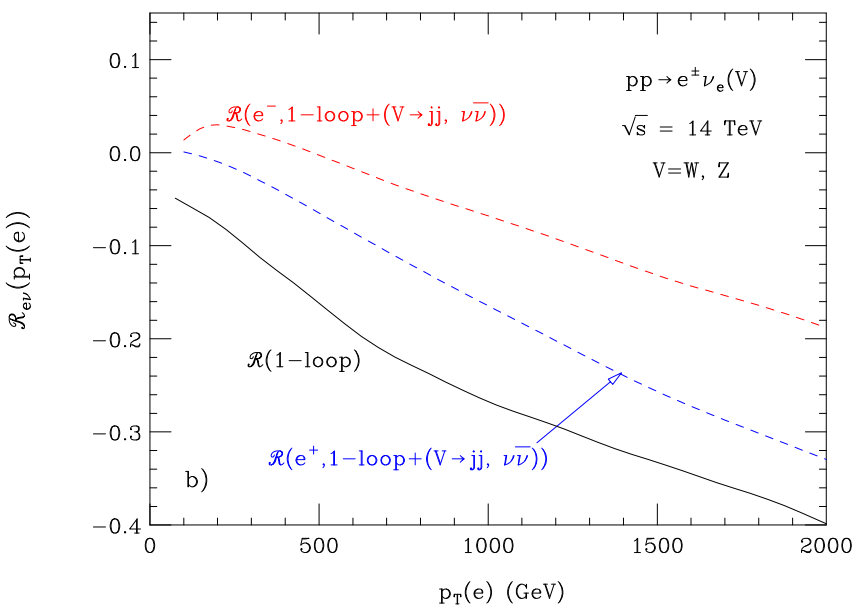


Emission of real weak bosons

U. Baur, Phys. Rev. **D** 75:013005, 2007

- ⋆ virtual weak corrections induce large negative effects due to Sudakov (logs)^2 in the high Q^2 region
- real radiation of (undetected) real vector bosons (partially) cancels the Sudakov effect
- e.g., $pp \to e^+ \nu_e V + X \quad V \equiv W, Z \quad V \to jj, \nu\bar{\nu}, \ldots$





Combining electroweak and QCD corrections (I)

- First attempt: combination of soft-gluon resummation with NLO final-state QED corrections (plus leading EW contributions)

  Q.-H. Cao and C.-P. Yuan, Phys. Rev. Lett. **93** (2004) 042001 - `ResBos-A`

- QCD and electroweak corrections can be combined according to the following recipes (additive/factorized form):

G. Balossini *et al.*, JHEP 1001:013, 2010

$\oplus$ **Additive prescription:**

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}\oplus\text{EW}} = \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{EW}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{LO}}\right\}_{\texttt{HERWIG}\ \text{PS}}$$

$\otimes$ **Factorized prescription:**

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}\otimes\text{EW}} = \left(1 + \frac{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\texttt{HERWIG}\ \text{PS}}}{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{(N)LO}}}\right) \times \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{EW}}\right\}_{\texttt{HERWIG}\ \text{PS}}$$

Combining electroweak and QCD corrections (II)

- QCD $\Rightarrow$ ResBos, MCFM, MC@NLO, POWHEG, ...
- EW $\Rightarrow$ Electroweak + multiphoton corrections from HORACE convoluted with HERWIG QCD Parton Shower
  - ⋆ NLO electroweak corrections are interfaced to QCD Parton Shower evolution $\Rightarrow \mathcal{O}(\alpha\alpha_s)$ corrections reliable only at LL level
  - ⋆ Beyond this approximation, a full two-loop $\mathcal{O}(\alpha\alpha_s)$ calculation is needed (unavailable yet)

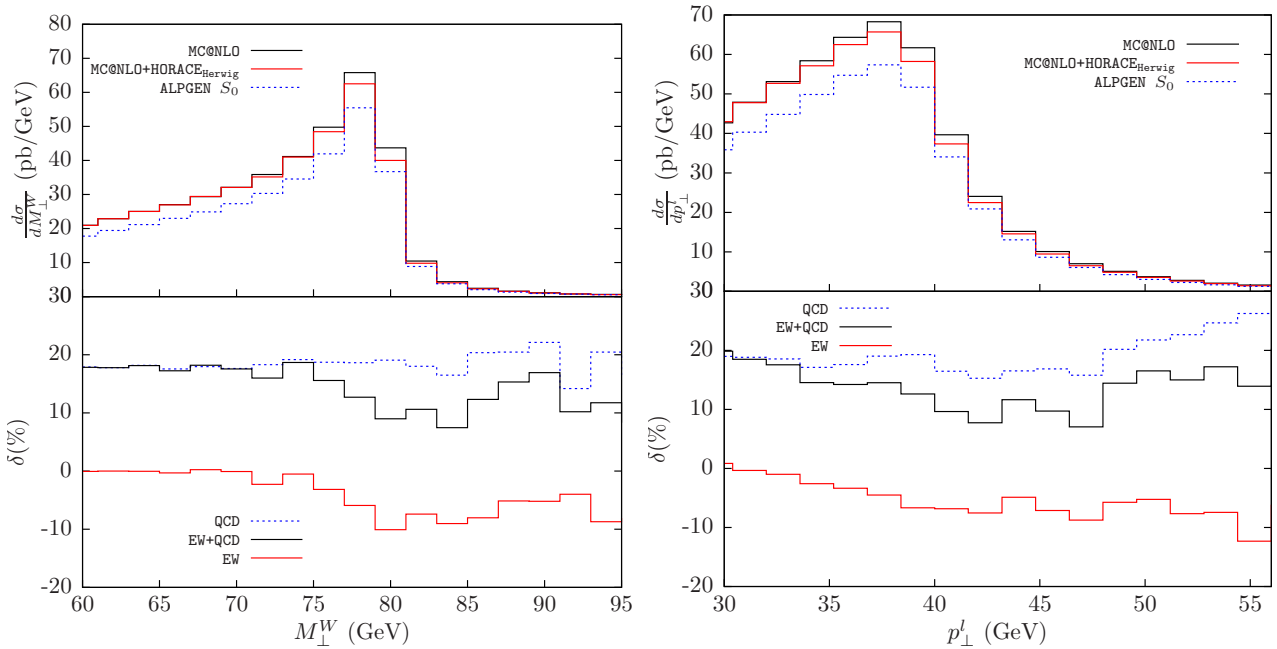
J.H. Kühn *et al.*, Phys.Lett. **B651** 160-165, 2007
$\mathrm{NLO/NNLO_{EW}}$ to $pp \to Wj$

- the comparison between the factorized (NLO) prescription and RESBOS-A where possible (at the Tevatron) is at the per cent level;
- Same $O(\alpha)$, $O(\alpha_s)$ and leading $O(\alpha_s^2)$ content.; Differences at $O(\alpha\alpha_s)$ and $O(\alpha_s^2)$ non-leading-log.

Electroweak $\oplus$ QCD @ the Tevatron

Process and scheme – Detector modeling and lepton identification

1. $p\bar{p} \to W^{\pm} \to \mu^{\pm}\nu_{\mu}$ $\sqrt{s} = 1.96$ TeV – G_{μ} scheme + $\alpha(0)$ for real γ emission
2. $p_{\perp}^{\mu} > 25$ GeV $\not{p}_{\perp} > 25$ GeV $|\eta_{\mu}| < 1.2$ $p_{\perp}^{W} \leq 50$ GeV $M_{\mu\nu} \in [50 - 200]$ GeV
3. PDF set: NLO CTEQ6M with $\mu_R = \mu_F = \sqrt{x_1 x_2 s}$



- Partial cancellation between (positive) QCD corrections and (negative) EW ones; the resulting overall corrections are between 10 and 20%
- "smearing" of the EW corrections due to convolution with QCD PS

Electroweak $\otimes$ QCD @ the Tevatron

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1. $p\bar{p} \to W^{\pm} \to \mu^{\pm}\nu_{\mu}$ $\sqrt{s} = 1.96$ TeV – G_{μ} scheme + $\alpha(0)$ for real γ emission
2. $p_{\perp}^{\mu} > 25$ GeV $\not{p}_{\perp} > 25$ GeV $|\eta_{\mu}| < 1.2$ $p_{\perp}^{W} \leq 50$ GeV $M_{\mu\nu} \in [50 - 200]$ GeV
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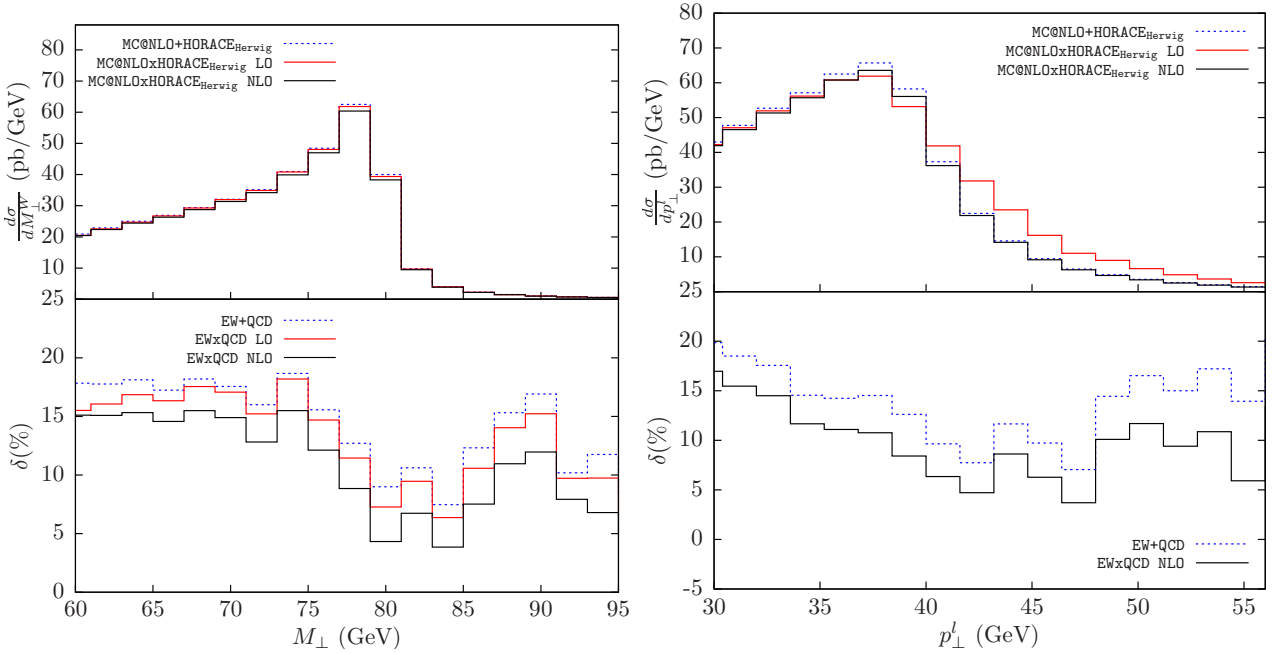
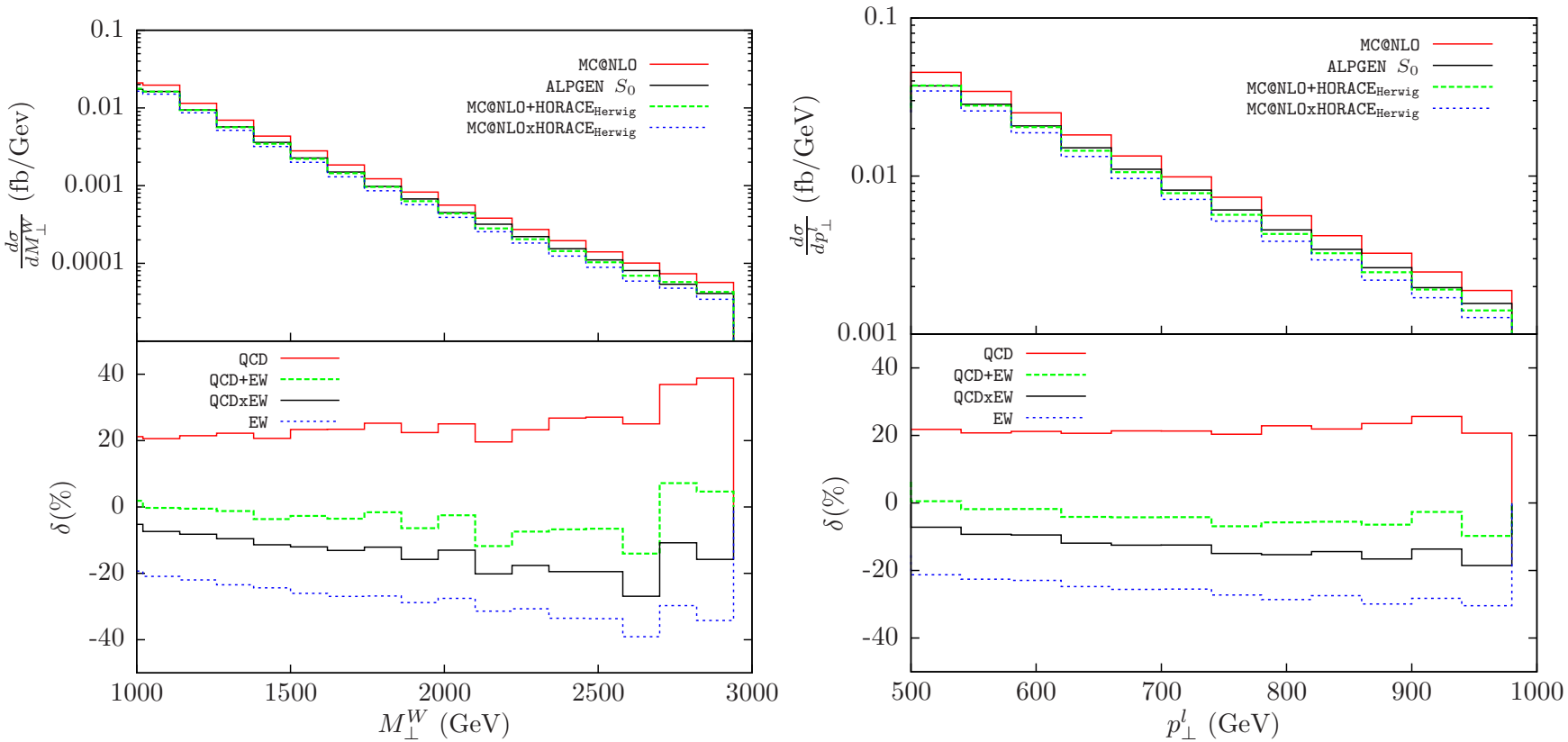


- The relative differences between the various prescriptions (additive vs factorized) are at the level of a few per cent
- the factorized prescription(s) seem to capture the bulk of QCD NNLO corrections

Electroweak $\oplus/\otimes$ QCD @ the LHC: W ($M_\perp^W > 1$ TeV)

★ To what extent large electroweak Sudakov logs compare with QCD corrections in the region relevant for the search of new physics at the LHC? ★



- The relative difference between additive and factorized prescription is dominated by $O(\alpha\alpha_s)$ corrections; a per cent accuracy can be attained by a complete two-loop mixed calculation.

$W/Z + 1$ jet

see the talk by J.H. Kühn

- W/Z production with large transverse momentum is an important ingredient for precise knowledge of DY (it is a building block of two-loop $\mathcal{O}(\alpha\alpha_s)$)
- EWRC to $W+$ jet signature have been studied in the on-shell approximation, deriving also asymptotic expressions for the in the high energy limit

J.H. Kühn, A. Kulesza, S. Pozzorini, M. Schulze, PLB651 (2007) 160;
W. Hollik, T. Kasprzik, B.A. Kniehl, NPB790 (2008) 138

- Analogously for the $Z+$ jet signature

J.H. Kühn, A. Kulesza, S. Pozzorini, M. Schulze, NPB727 (2005) 368; PLB609 (2005) 277;
E. Maina, S. Moretti, D.A. Ross, PLB593 (2004) 143; Erratum ibid. B614 (2005) 216

- Complete EWRC to $W(\to l\nu_l)+$ jet, including finite W width effects through Complex Mass Scheme and photon induced processes

Denner, Dittmaier, Kasprzik, Mück, JHEP 08 (2009) 075

$t\bar{t}$ production

- Complete $\mathcal{O}(\alpha)$ pure weak corrections have been calculated for both $q\bar{q}$ and gg channels

  J.H. Kühn, A. Scharf, P. Uwer, Eur. Phys. J. C51 (2007) 37; C45 (2006) 139
  W. Bernreuther, M. Fücker, Z.-G. Si, PRD78 (2008) 017503; PRD74 (2006) 113005, PLB633 (2006) 54

  Effects numerically small. They reach the level of 10-20% for the tail of the p_t or m_{tt} distributions

- Recent analysis of the remaining QED corrections, including also photon induced process of the form $g\gamma \to t\bar{t}$

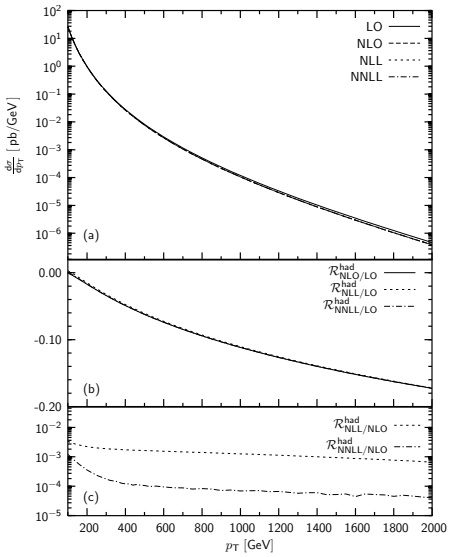
  W. Hollik, M. Kollar, Phys. Rev. D77 (2008) 014008

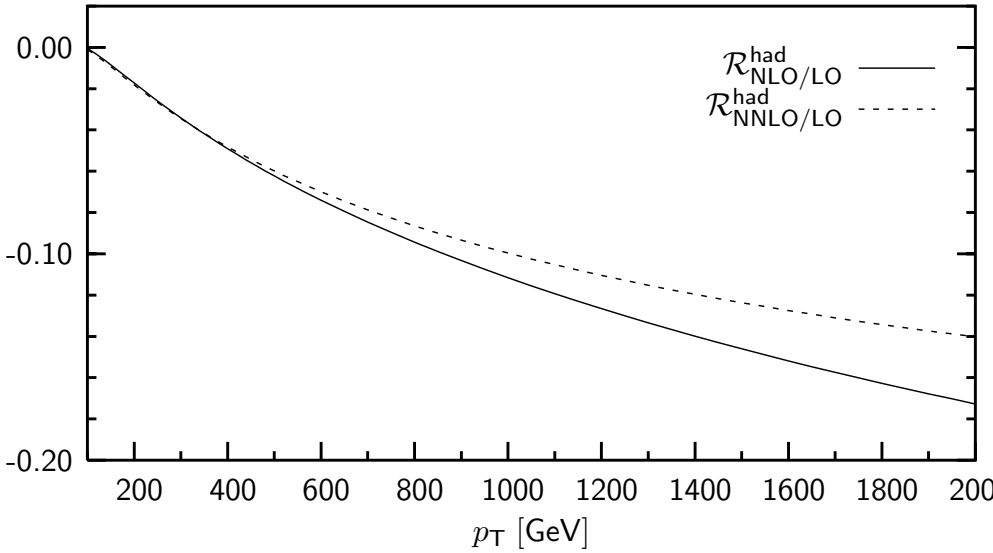
  Also in this case small effects, at the level of few %

$\gamma + 1$ jet

- Exact one-loop weak corrections plus leading logarithmic two-loop corrections to
  - $q\bar{q} \to \gamma g$
  - $gq \to \gamma q$
  - $g\bar{q} \to \gamma \bar{q}$

Kühn, Kulesza, Pozzorini, Schulze, JHEP 03 (2006) 059





- The logarithmic approximation works very well

vector boson pair production

- $W\gamma$ and $Z\gamma$

Accomando, Denner, Meier, Eur. Phys. J. C47 (2006) 125

  - $\mathcal{O}(\alpha)$ EWRC
    - $pp \to \nu_l \bar{l} \gamma$
    - $pp \to \nu_l \bar{\nu}_l \gamma$
    - $pp \to l^+ l^- \gamma$
  - virtual corrections in leading pole approximation
  - real corrections taken into account exactly
  - reduction of the cross section of about 5% induced by EWRC

- WZ, ZZ and WW

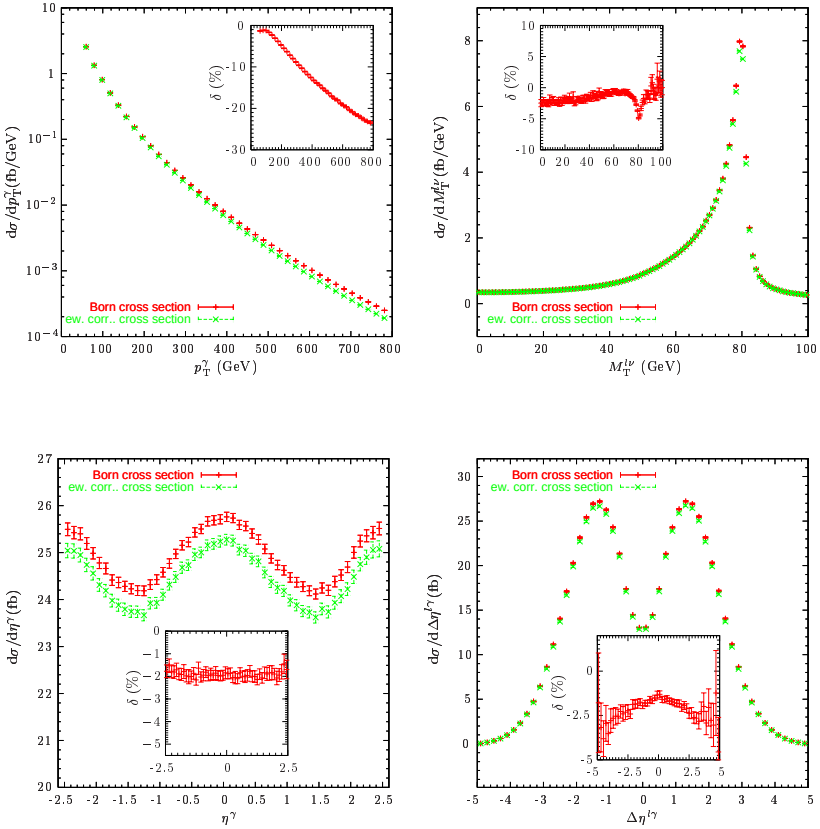
Accomando, Denner, Kaiser, Nucl. Phys. B706 (2005) 325

  - Logarithmic $\mathcal{O}(\alpha)$ EWRC for $pp \to 4f$
  - Only leptonic final states are considered
  - virtual corrections in double pole approximation
  - real corrections taken into account exactly
  - reduction of the cross section of about 5% – 30% induced by EWRC

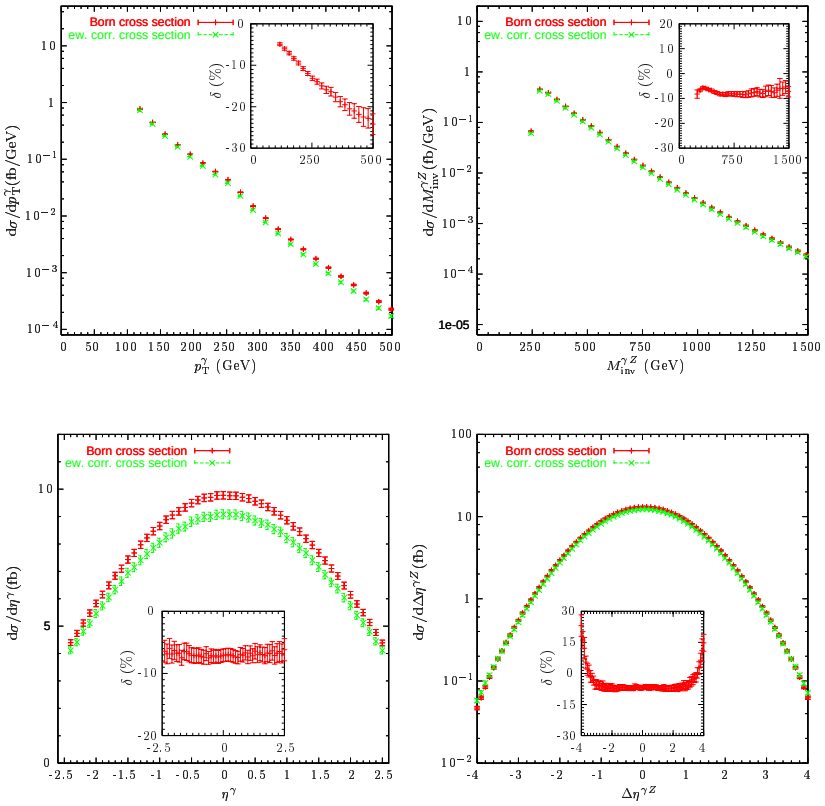
example of distributions for $W\gamma$ and $Z\gamma$

Accomando, Denner, Meier, Eur. Phys. J. C47 (2006) 125

$pp \to \nu_l \bar{l} \gamma$



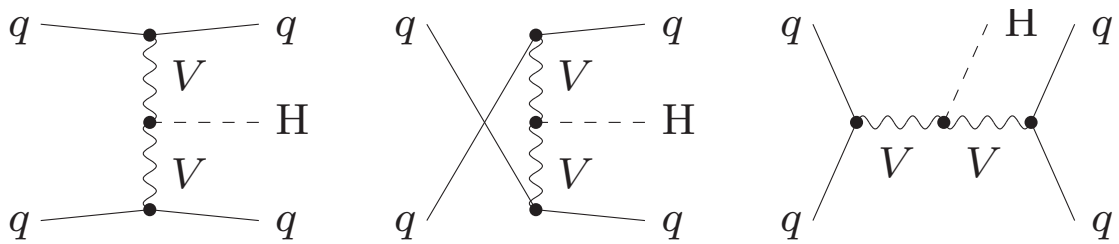
$pp \to l^+ l^- \gamma$

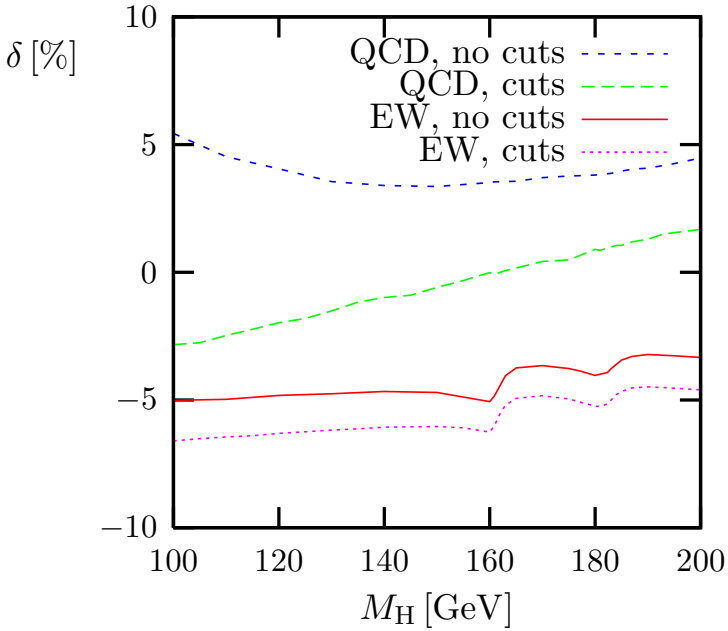


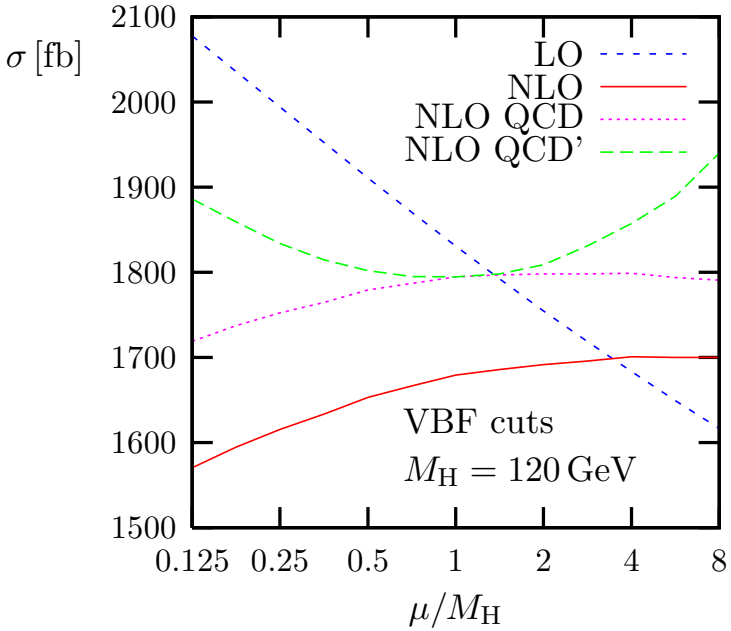
Higgs production in VBF

- Complete NLO EW $\otimes$ QCD corrections

M. Ciccolini, A. Denner, S. Dittmaier, Phys. Rev. Lett. 99 (2007) 161803





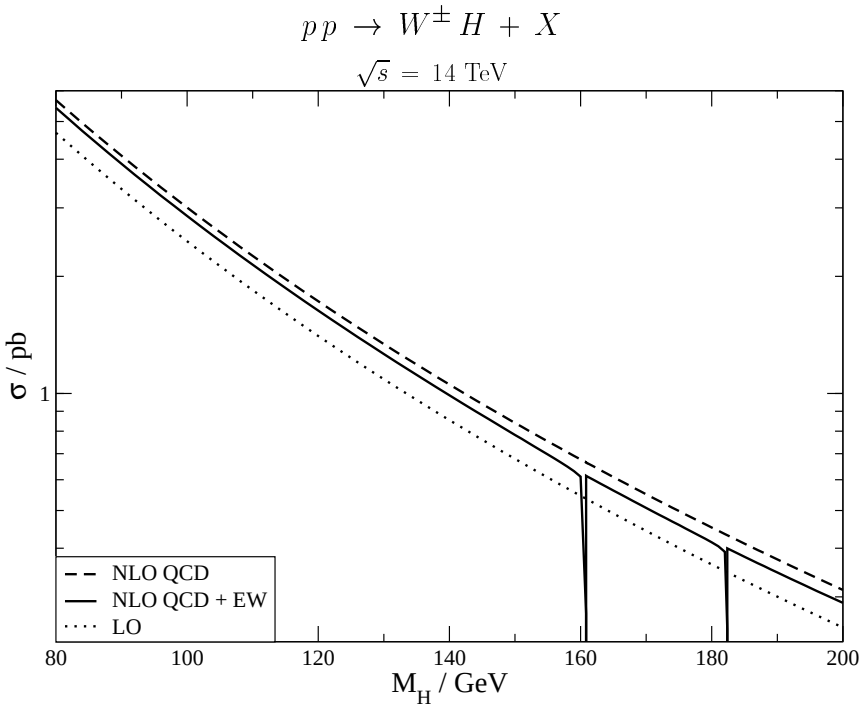


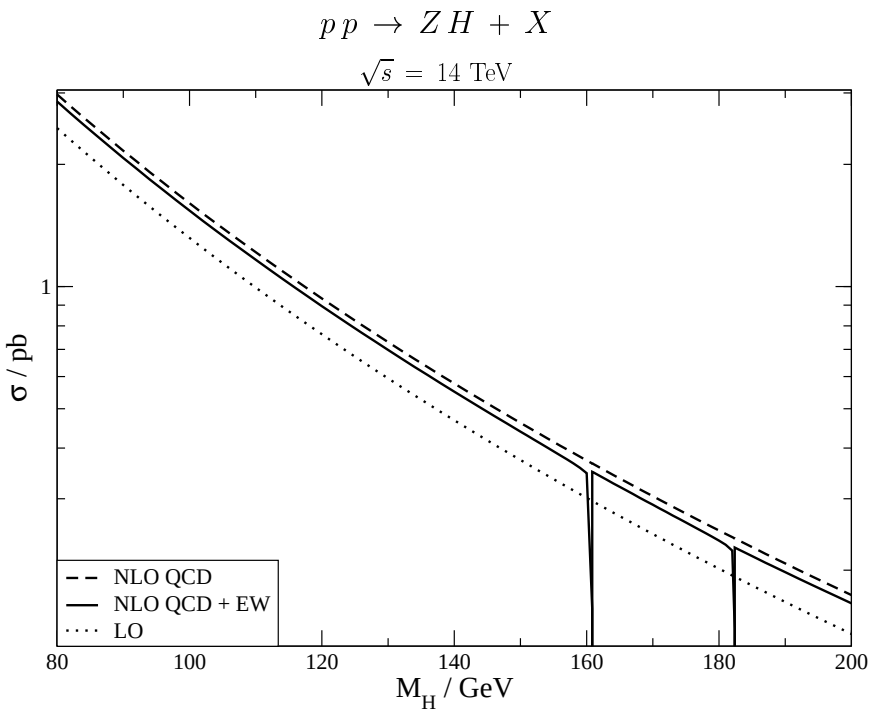
- EWRC of the same size (and opposite sign) of the QCD RC

Associate HW and HZ production

- Exact $\mathcal{O}(\alpha)$ radiative corrections, including QED

M.L. Ciccolini, S. Dittmaier and M. Krämer, Phys. Rev. D68 (2003) 073003

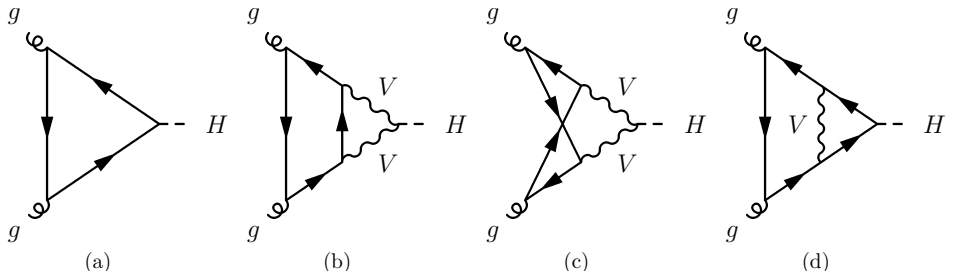




- EWRC at the level of 5-10% (negative). The peaks are due to the lack of complex masses

Higgs production through gluon fusion

The NLO EWRC to $gg \to$ Higgs are now completed



- light fermion contributions

  Aglietti, Bonciani, Degrassi, Vicini, PLB595 (2004) 432; PLB600 (2004) 57

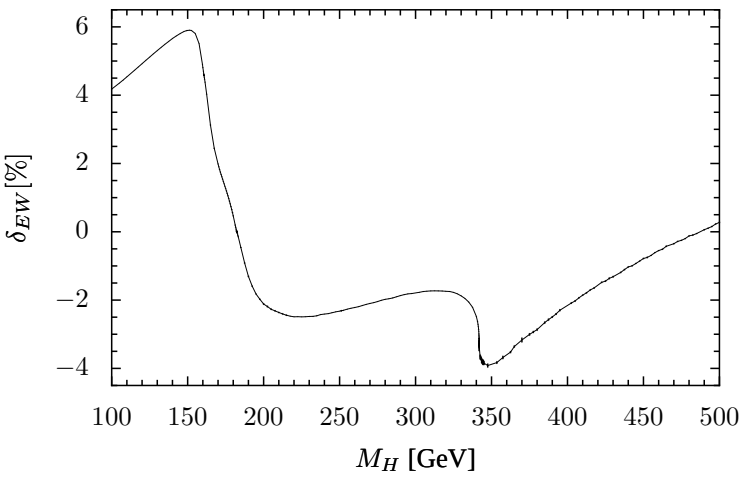
- terms involving the top quark using an expansion in m_H/m_W

  Degrassi, Maltoni, PLB600 (2004) 255

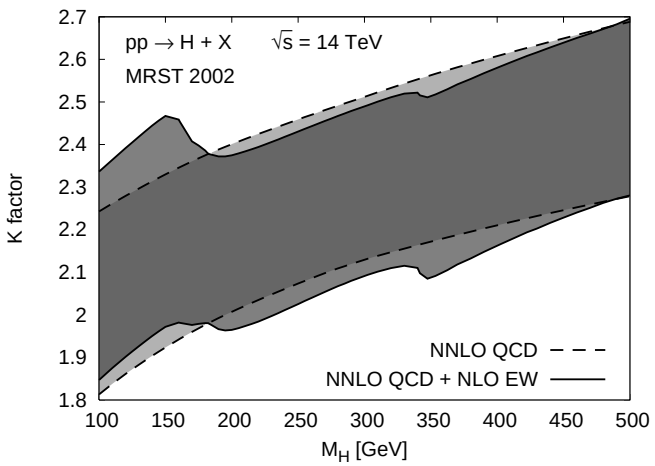
- Complete analysis with the Complex Mass Scheme, with no limitations on m_H

  Actis, Passarino, Sturm, Uccirati, PLB670 (2008) 12

Higgs production through gluon fusion



Relative EW contribution to partonic cross section $\sigma(gg \to H)$



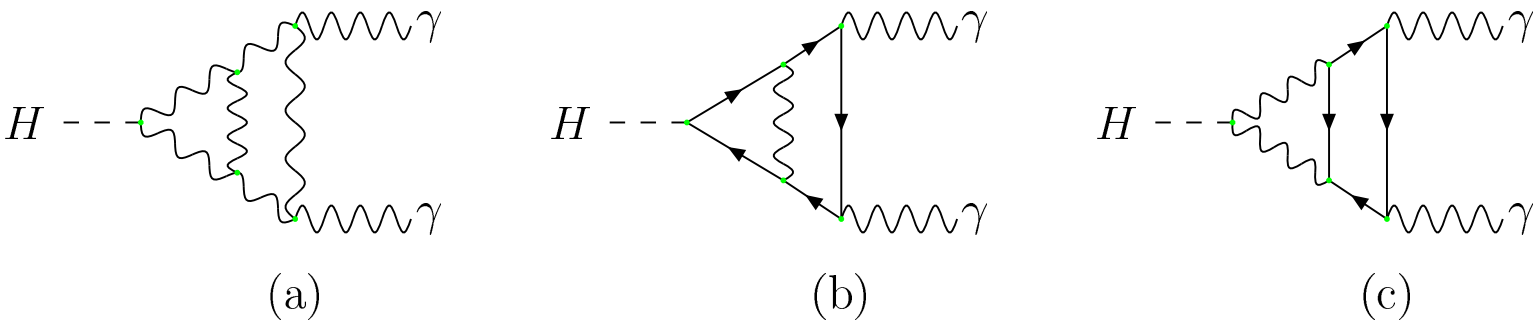
Uncertainty band modified by EWRC

Actis, Passarino, Sturm, Uccirati, PLB670 (2008) 12

$H \to \gamma\gamma$

- Complete EW NLO two-loop calculation available as an expansion in $m_H/2m_W$

G. Degrassi, F. Maltoni, Nucl. Phys. B724 (2005) 183



- Total EWRC: $-4\% \lesssim \delta_{EW} \lesssim 0\%$ for 100 GeV $\lesssim 150$ GeV
- Compensation between EW and QCD RC at the 1% level
- Complete two-loop calculation with Complex Mass Scheme

G. Passarino, C. Sturm, S. Uccirati, PLB 655 (2007) 298

$H \to 4$ fermions decay

- Exact $\mathcal{O}(\alpha)$ QED matched to QED Parton Shower radiative corrections to $H \to 4$ leptons H24F

C.M. Carloni Calame et al., NPB (Proc. Suppl.) 157 (2006) 73; PoS HEP2005 (2006) 307

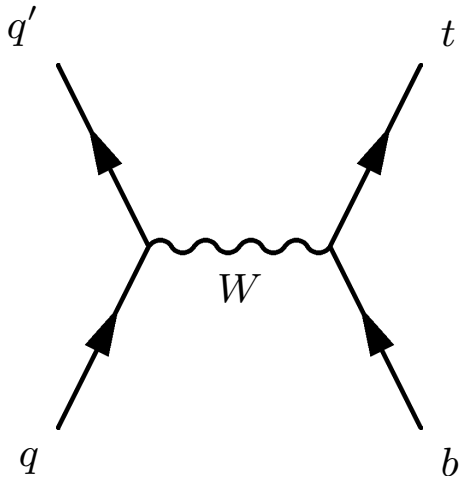
- Impact on m_H determination interfacing H24F to ALPGEN

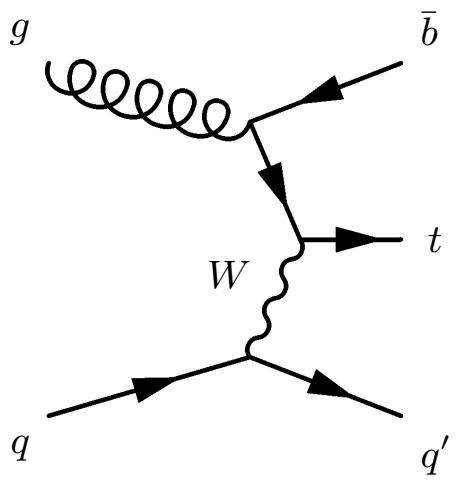
Process	$\lvert\Delta\rvert(QED)^{(\alpha)}$	$\lvert\Delta(QED)^{(\mathrm{exp})} - \Delta(QED)^{(\alpha)}\rvert$
$e^+e^-e^+e^-$	160 MeV	$\leq$ 20 MeV
$e^+e^-\mu^+\mu^-$	340 MeV	$\lesssim$ 50 MeV
$\mu^+\mu^-\mu^+\mu^-$	600 MeV	$\sim$ 100 MeV

- Exact EW+QCD $\mathcal{O}(\alpha)$ RC to $H \to 4$ fermions Prophecy4f including one- and two-loop corrections $\sim G_\mu M_H^2$ and $G_\mu^2 M_H^4$, QED higher order FSR with structure function formalism

Bredenstein, Denner, Dittmaier, Weber, PRD74 (2006) 013004; JHEP 0702 (2007) 080

single top production





$\sigma(\text{Tevatron}) \simeq 1\,\text{pb}$

$\sigma(\text{LHC@7TeV}) \simeq 5\,\text{pb}$

$\sigma(\text{LHC@14TeV}) \simeq 10\,\text{pb}$

$\sigma(\text{Tevatron}) \simeq 2\,\text{pb}$

$\sigma(\text{LHC@7TeV}) \simeq 60\,\text{pb}$

$\sigma(\text{LHC@14TeV}) \simeq 150\,\text{pb}$

- Amplitudes proportional to Wtb coupling
- $\Rightarrow$ direct measurement of $|V_{tb}|$

single top

- NLO + higher order QCD corrections known (contained in size)

Stelzer, Sullivan, Willenbrock; Cao, Schwienhorst, Yuan

Frixione, Laenen, Motylinski; Kidonakis

Campbell, Frederix, Maltoni, Tramontano

- EW + SUSY corrections (some benchmark points) at few % level

Beccaria et al., PRD 77 (2008) 113018

- present PDF induced uncertainty at few % level

$\Rightarrow$ single top allows a "model independent" determination of $|V_{tb}|$

- also for the more difficult channel $pp \to tW$, the complete EWRC are available

M. Beccaria et al., Eur. Phys. J. C53 (2008) 257

Summary

- EW radiative corrections will become relevant also at an hadronic collider like LHC, because of its high energy (giving access to the Sudakov dominance) and because of its project luminosity, which allows precision measurements
- at present for a large number of processes the EWRC have already been studied
- For some of them, in particular DY, it is mandatory a thorough investigation of the interplay between QCD and EW corrections, in order to pin down the theoretical uncertainty