# Electroweak Corrections at High Energy

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- General features of electroweak corrections
- Automation of electroweak NLO corrections
- Electroweak corrections for specific processes at LHC

# Relevance of electroweak corrections @ LHC

- LHC runs @ $13\,\mathrm{TeV}$
  $\hookrightarrow$ energy reach extends deeper into TeV range
  $\hookrightarrow$ electroweak corrections (EWC) $\sim$ some $10\%$

- integrated LHC luminosity will reach some $100\,\mathrm{fb}^{-1}$
  $\hookrightarrow$ many measurements at several-per-cent level
  $\hookrightarrow$ typical size of EWC

- planned high-precision measurements: cross-section ratios, $M_\mathrm{W}$, $\sin^2\theta^\mathrm{lept}_\mathrm{eff}$
  $\hookrightarrow$ EWC are crucial

- Les Houches wishlist 2013 and update 2015:
  list of LHC processes where NLO EWC (and NNLO QCD) are needed

## Intent of this talk

- describe salient features of EWC
  in particular sources of large effects

- give brief survey of results for specific process classes
  emphasizing recent developments

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# Features of electroweak corrections

# Expected size of electroweak corrections

| coupling | | typical correction |
|---|---|---|
| electromagnetic coupling | $\alpha(0) \sim \frac{1}{137}$ | $\frac{\alpha(0)}{2\pi} \sim 0.11\%$ |
| charged weak coupling | $\frac{\alpha}{2s_\mathrm{w}^2} \sim 2.2\alpha$ | $\frac{\alpha}{4\pi s_\mathrm{w}^2} \sim 0.25\%$ |
| enhanced top coupling | $\frac{\alpha}{2s_\mathrm{w}^2}\frac{m_\mathrm{t}^2}{M_\mathrm{W}^2} \sim 10\alpha$ | $\frac{\alpha}{4\pi s_\mathrm{w}^2}\frac{m_\mathrm{t}^2}{M_\mathrm{W}^2} \sim 1.3\%$ |

$s_\mathrm{w}^2 = 1 - \frac{M_\mathrm{W}^2}{M_\mathrm{Z}^2}$

multiplied by $\mathcal{O}(1)$ factors

example: $\mathrm{pp} \to \mathrm{Hjj}$: EWC $\sim 4 \times \frac{\alpha}{4\pi s_\mathrm{w}^2}\frac{m_\mathrm{t}^2}{M_\mathrm{W}^2} \sim 5\%$

further enhancements by large logarithms:

- electromagnetic logarithms:
  - initial-state radiation at LEP: $\alpha \ln \frac{M_\mathrm{Z}^2}{m_\mathrm{e}^2} \sim 24\alpha \Rightarrow 3.0\%$
  - final-state QED corrections at LHC for exclusive muons
    $$\alpha \ln \frac{M_\mathrm{Z}^2}{m_\mu^2} \sim 13\alpha \Rightarrow 1.7\%$$
- electroweak Sudakov corrections at $\sqrt{s} = 1\,\mathrm{TeV}$:
  $$\frac{\alpha}{2s_\mathrm{w}^2} \ln^2 \frac{s}{M_\mathrm{W}^2} \sim 57\alpha \Rightarrow 6.6\%$$

$\Rightarrow$ expect EWC up to several $10\%$ at LHC

# Input-parameter schemes

SM input parameters: $\alpha_s$, $\alpha$, $M_W$, $M_Z$, $M_H$, $m_f$, $V_{CKM}$ (natural set)

Setting of $\alpha$: process-specific choice to

- minimise universal EW corrections
- avoid sensitivity to non-perturbative light-quark masses

popular schemes: fix $M_W$, $M_Z$ and $\alpha$

- $\alpha(0)$ scheme: appropriate for external photon
- $\alpha(M_Z)$ scheme: appropriate for internal photons ($\gamma^*$) at high energies
  $\alpha(M_Z)/\alpha(0) \approx 1.06$
- $G_\mu$ scheme: $\alpha_{G_\mu} = \sqrt{2} G_\mu M_W^2 (1 - M_W^2/M_Z^2)/\pi$,
  appropriate for W bosons (Z bosons) $\alpha_{G_\mu}/\alpha(0) \approx 1.03$
  $G_\mu$ precisely measured in $\mu$ decay

differences can amount to $10\%$ and more for high powers of $\alpha$

- $\mathrm{pp} \to \mathrm{WW}$: $\sigma \propto \alpha^2$, $[\alpha_{G_\mu}/\alpha(0)]^2 - 1 \approx 6\%$ $[\alpha(M_Z)/\alpha(0)]^2 - 1 \approx 12\%$
- $\mathrm{pp} \to \mathrm{WWZ}$: $\sigma \propto \alpha^3$, $[\alpha_{G_\mu}/\alpha(0)]^3 - 1 \approx 10\%$

suitable choice of $\alpha$ crucial $\Rightarrow$ reduces missing higher-order corrections

# Input-parameter schemes

Warning: EW gauge invariance must be respected!

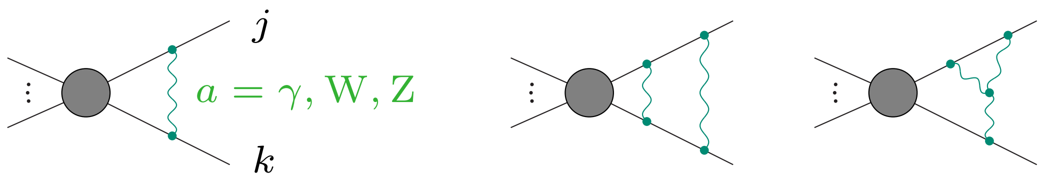
$\Rightarrow$ parameter relations must be maintained

- $\alpha$ must not be set diagram by diagram
  - different values of $\alpha$ in gauge-invariant contributions possible
  - global factors like $\alpha(0)^m \alpha_{G_\mu}^n$ possible
- weak mixing angle: $\sin\theta_{\mathrm{w}} = s_{\mathrm{w}} = \sqrt{1 - M_{\mathrm{W}}^2/M_{\mathrm{Z}}^2}$

  fixed once $M_{\mathrm{W}}$ and $M_{\mathrm{Z}}$ are fixed !
- Yukawa couplings are uniquely fixed by fermion masses !

# Electroweak Sudakov logarithms

Sudakov logarithms induced by soft gauge-boson exchange




etc.

+ sub-leading logarithms from collinear singularities

typical impact on $2 \to 2$ reactions at $\sqrt{s} \sim 1\,\mathrm{TeV}$:

$$\delta^{1-\text{loop}}_{\text{LL}} \sim -\frac{\alpha}{\pi s_{\mathrm{w}}^2} \ln^2 \frac{s}{M_{\mathrm{W}}^2} \simeq -26\%, \qquad \delta^{1-\text{loop}}_{\text{NLL}} \sim +\frac{3\alpha}{\pi s_{\mathrm{w}}^2} \ln \frac{s}{M_{\mathrm{W}}^2} \simeq 16\%$$

$$\delta^{2-\text{loop}}_{\text{LL}} \sim +\frac{\alpha^2}{2\pi^2 s_{\mathrm{w}}^4} \ln^4 \frac{s}{M_{\mathrm{W}}^2} \simeq 3.5\%, \qquad \delta^{2-\text{loop}}_{\text{NLL}} \sim -\frac{3\alpha^2}{\pi^2 s_{\mathrm{w}}^4} \ln^3 \frac{s}{M_{\mathrm{W}}^2} \simeq -4.2\%$$

$\Rightarrow$ corrections still relevant at 2-loop level

Note: differences to QED / QCD where Sudakov logarithms cancel

- non-Abelian charges of inc. particles “open” $\to$ Bloch–Nordsieck theorem not applicable
- massive gauge bosons $\mathrm{W}$, $\mathrm{Z}$ can be reconstructed
  $\hookrightarrow$ no need to add real $\mathrm{W}$, $\mathrm{Z}$ radiation

extensive theoretical studies at fixed perturbative (1-/2-loop) order and suggested resummations via evolution equations Beccaria et al.; Beenakker, Werthenbach; Ciafaloni, Comelli; Denner, Pozzorini; Fadin et al.; Hori et al.; Melles; Kühn et al., Denner et al. ’00–’08

# Electroweak corrections in Sudakov approximation

- Sudakov logarithms have simple universal origin (IR and UV regime)
  $\Rightarrow$ known for arbitrary processes at NLO (not mass suppressed at LO)

  Denner, Pozzorini '01

- provide simple estimate for one-loop corrections at level of $\sim 5\%$
  rules of thumb:
  contribution of double logarithms per external line: $\delta_i = -C_i \frac{\alpha}{4\pi} \ln^2 \frac{s}{M_W^2}$

| particle | $C_i$ | $\delta_i(1\,\mathrm{TeV})$ | particle | $C_i$ | $\delta_i(1\,\mathrm{TeV})$ |
|---|---|---|---|---|---|
| W boson | $\frac{2}{s_w^2}$ | $14\%$ | left-handed lepton | $\frac{s_w^2+3c_w^2}{4s_w^2 c_w^2}$ | $5.7\%$ |
| Z boson | $\frac{2c_w^2}{s_w^2}$ | $11\%$ | right-handed lepton | $\frac{1}{c_w^2}$ | $2\%$ |
| photon | $2$ | $3\%$ | left-handed quark | $\frac{s_w^2+27c_w^2}{36s_w^2 c_w^2}$ | $5.2\%$ |
| H boson | $\frac{s_w^2+3c_w^2}{4s_w^2 c_w^2}$ | $5.7\%$ | right-handed quark | $\frac{4}{9c_w^2}$ | $0.9\%$ |

  additional mixing contributions for $\gamma$ and $\mathrm{Z}$ mixing

- implementation of weak corrections in Sudakov approximation
  - $\mathrm{pp} \to \mathrm{Z}(\to \nu\bar{\nu}) + \{1,2,3\}$ jets — Chiesa et al. '13 (Alpgen)
  - $\mathrm{pp} \to \mathrm{Z} \to l^+l^-$, $\mathrm{pp} \to \mathrm{t\bar{t}}$, $\mathrm{pp} \to 2$ jets — Campbell, Wackeroth, Zhou '15 (MCFM)

# Electroweak corrections at high energies: example

## Example: Drell–Yan production

(courtesy of S. Dittmaier)

**Charged current:** $\mathrm{pp} \to l^+\nu_l$ at $\sqrt{s} = 14\,\mathrm{TeV}$ (based on Brensing et al. arXiv:0710.3309)

| $M_{\mathrm{T},\nu_l l}/\mathrm{GeV}$ | $50-\infty$ | $100-\infty$ | $200-\infty$ | $500-\infty$ | $1000-\infty$ | $2000-\infty$ |
|---|---|---|---|---|---|---|
| $\sigma_0/\mathrm{pb}$ | 4495.7(2) | 27.589(2) | 1.7906(1) | 0.084697(4) | 0.0065222(4) | 0.00027322(1) |
| $\delta_{q\bar{q}}^{\mu^+\nu_\mu}/\%$ | −2.9(1) | −5.2(1) | −8.1(1) | −14.8(1) | −22.6(1) | −33.2(1) |
| $\delta_{q\bar{q}}^{\mathrm{rec}}/\%$ | −1.8(1) | −3.5(1) | −6.5(1) | −12.7(1) | −20.0(1) | −29.6(1) |
| $\delta_{\mathrm{Sudakov}}^{(1)}/\%$ | 0.0005 | 0.5 | −1.9 | −9.5 | −18.5 | −29.7 |
| $\delta_{\mathrm{Sudakov}}^{(2)}/\%$ | −0.0002 | −0.023 | −0.082 | 0.21 | 1.3 | 3.8 |

$M_{\mathrm{T},\nu_l l}$ large $\Rightarrow s, t$ large

Sudakov domination!

**Neutral current:** $\mathrm{pp} \to l^+l^-$ at $\sqrt{s} = 14\,\mathrm{TeV}$ (based on Dittmaier/Huber arXiv:0911.2329)

| $M_{ll}/\mathrm{GeV}$ | $50-\infty$ | $100-\infty$ | $200-\infty$ | $500-\infty$ | $1000-\infty$ | $2000-\infty$ |
|---|---|---|---|---|---|---|
| $\sigma_0/\mathrm{pb}$ | 738.733(6) | 32.7236(3) | 1.48479(1) | 0.0809420(6) | 0.00679953(3) | 0.000303744(1) |
| $\delta_{q\bar{q},\mathrm{phot}}^{\mathrm{rec}}/\%$ | −1.81 | −4.71 | −2.92 | −3.36 | −4.24 | −5.66 |
| $\delta_{q\bar{q},\mathrm{weak}}/\%$ | −0.71 | −1.02 | −0.14 | −2.38 | −5.87 | −11.12 |
| $\delta_{\mathrm{Sudakov}}^{(1)}/\%$ | 0.27 | 0.54 | −1.43 | −7.93 | −15.52 | −25.50 |
| $\delta_{\mathrm{Sudakov}}^{(2)}/\%$ | −0.00046 | −0.0067 | −0.035 | 0.23 | 1.14 | 3.38 |

sizeable contribution from small $t$ region

no Sudakov domination!

# EW corrections beyond Sudakov logarithms

- Sudakov regime not always relevant ($s_{ij} = 2k_i k_j \gg M_\mathrm{W}^2$ *for all momenta* $k_i \neq k_j$)
  - Sudakov appr. not applicable to processes with resonances ($s_\mathrm{res} \not\gg M_\mathrm{W}^2$)
  - Sudakov approximation not applicable to processes/observables dominated by $t$-channel diagrams ($t \not\gg M_\mathrm{W}^2$)
    $\Rightarrow$ additional potentially large logarithms of the form $\log(t/s) \sim 2\log\theta$
  - relevance depends on observable
    e.g. Drell-Yan at LHC: large $p_{\mathrm{T},l}$ probes Sudakov regime
    large $M_{ll}$ receives sizeable contributions from small $t$ Dittmaier et al. '10
- real corrections should be included
  - real photon radiation $\Rightarrow$ large effects
  - real massive vector-boson radiation Baur '06, Bell et al. '10

  $\Rightarrow$ partial cancellation of enhanced logarithmic corrections
  strongly dependent on W/Z reconstruction and separation
- at LHC often sizeable contributions from energies below $1\,\mathrm{TeV}$

$\Rightarrow$ exact calculations of NLO EW corrections preferable if possible

# QED-corrected parton distributions

Consistent treatment of EWC $\Rightarrow$ QED-corrected parton distributions
analogous to QCD-improved parton model

collinear photon emission from initial-state quarks $q \to q\gamma$
and collinear photon splitting $\gamma \to q\bar{q}$
$\Rightarrow$ mass singularities in EWC
$\Rightarrow$ absorb singularities into quark and photon distribution functions

- EWC depend on factorization scale $\mu_{\text{fact,QED}}$
- $\mathcal{O}(\alpha)$ corrections to all PDFs
- photon as parton in hadrons $\Rightarrow$ new photon PDF

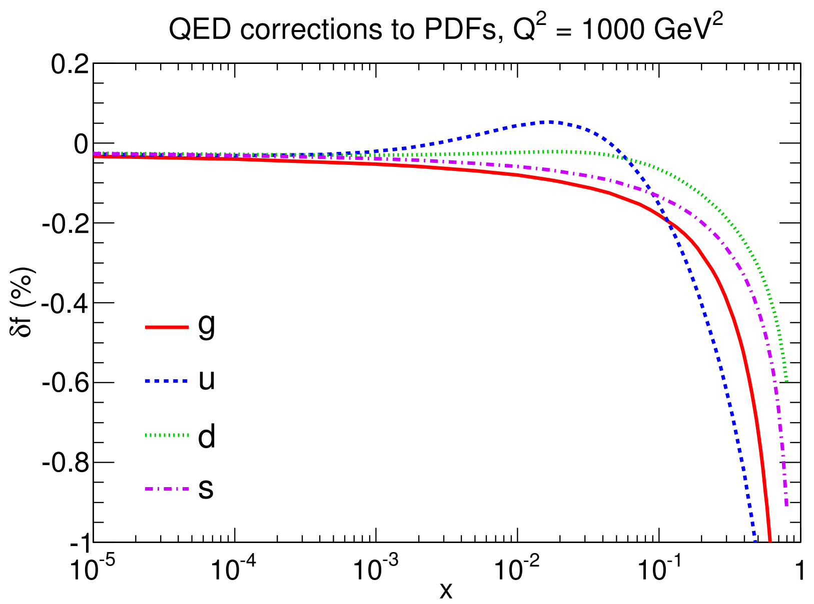
PDFs including QED corrections:

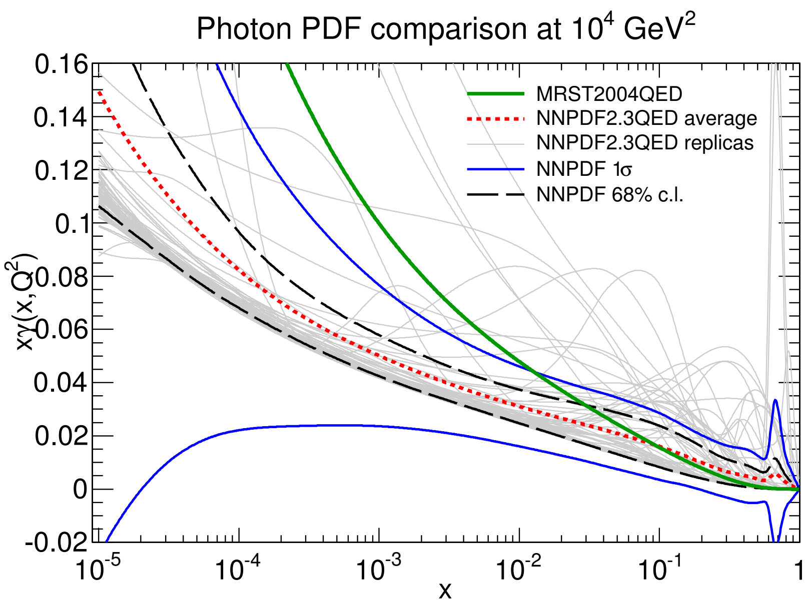
- MRST2004QED Martin et al. '04, only set including $\mathcal{O}(\alpha)$ until 2013, outdated
- NNPDF2.3QED Ball et al. '13 [NNPDF collaboration]
  $\Rightarrow$ currently best PDF set (N)NLO QCD + NLO EW
  photon PDF fitted to DIS and Drell–Yan data ($10^{-5} \lesssim x \lesssim 10^{-1}$)

# QED effects in PDFs

## NNPDF2.3QED PDF set

Ball et al. ’13 [NNPDF collaboration]




QED corrections to PDFs

- $\lesssim 0.1\%$ for $x < 0.1$,
  per-cent effects for $x > 0.1$

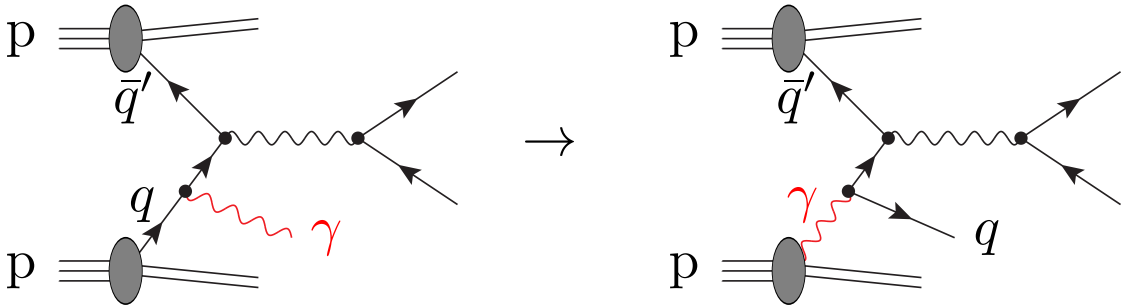
Photon PDF:

- agreement with old $\gamma_{\mathrm{MRST}}(x)$ for $x \gtrsim 0.03$,
  but $\gamma_{\mathrm{NNPDF}}(x) < \gamma_{\mathrm{MRST}}(x)$ for smaller $x$
- lack of experimental information for $x \gtrsim 0.1$
  $\hookrightarrow$ constrained via $\gamma\gamma \to \mu^+\mu^-, \mathrm{W}^+\mathrm{W}^-$
  for larger $x$ in the future ?

# Photon-induced processes

Photons as partons $\Rightarrow$ photon-induced processes

- result from crossing of photonic bremsstrahlung corrections
(in all $qq$, $q\bar{q}$, $\bar{q}\bar{q}$ initiated processes)

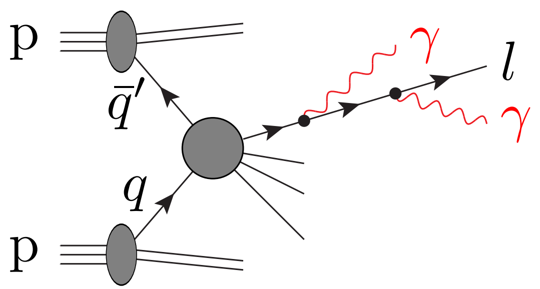



- LO contribution from $\gamma\gamma$ for production of charged particles in $\mathrm{gg}$, $q\bar{q}$ channels (e.g. in $\mu^+\mu^-$, $\mathrm{W^+W^-}$ production)

relevance

- $q\gamma$ contributes at per-cent level if $q\mathrm{g}$ channels exist
(gluon PDFs are larger than photon PDFs for typical LHC processes)
- more significant contributions if no QCD counterparts exist
e.g. $\gamma\gamma$ contributions up to 10% in certain regions of phase space for
$\gamma\gamma \to l^+l^-$ Dittmaier, Huber '10; Carloni Calame et al. '07, Boughezal, Li, Petriello '13
$\gamma\gamma \to \mathrm{W^+W^-}$ Bierweiler et al. '12; Baglio, Ninh, Weber '13; Billoni et al. '13

# Collinear final-state radiation off leptons




Universal logarithmically enhanced corrections

$$\propto \alpha^n \ln^n(m_l^2/Q^2)$$

from final-state radiation

possible treatments:

- “bare leptons” (typical for muons, non-collinear-safe (NCS) case)
  photons are experimentally separated from leptons
  collinear singularities regularised by lepton mass
  $\Rightarrow$ logarithmically enhanced corrections $\Rightarrow$ large radiative tails
- “calorimetric/dressed leptons” (typical for electrons, collinear safe (CS))
  recombination of leptons with (collinear) photons (inclusive treatment)
  $\Rightarrow$ mass-singular logarithms cancel, collinear-safe observables,
  predictions depend on photon-recombination scheme
- dedicated photonic parton showers, e.g. PHOTOS
  Placzek, Jadach ’03; Carloni Calame et al. ’04; Golonka, Was ’07

full FSR not universal, in general not separable from other EW corrections
combination of PHOTOS with full EW corrections difficult in practice

# Combination of EW corrections with QCD and MC

Combination of NLO QCD and EW corrections:

- additive: $1+\delta^{\rm NLO} = 1+\delta^{\rm NLO}_{\rm QCD}+\delta^{\rm NLO}_{\rm EW}$
- multiplicative: $1+\delta^{\rm NLO} = (1+\delta^{\rm NLO}_{\rm QCD})(1+\delta^{\rm NLO}_{\rm EW})$

} variants differ at $\mathcal{O}(\alpha\alpha_{\rm s})$

soft and collinear corrections factorise $\Rightarrow$ multiplicative combination preferable

$$\frac{{\rm d}\sigma}{{\rm d}x} = \frac{{\rm d}\sigma_{\rm QCD}}{{\rm d}x}\Big(1+\delta^{\rm NLO}_{\rm EW}(x)\Big) + \frac{{\rm d}\sigma_{\gamma}}{{\rm d}x} + \ldots$$

- used for Higgs production in VBF and WH/ZH to combine NLO EW and NNLO QCD calculations   Higgs cross-section working group '13
- useful for including EW corrections in event generators via reweighting
  Anderson et al '10; Gieseke, Kasprzik, Kühn '14
- correction factor should capture dominant phase-space dependence
  treats photon radiation inclusively
  $\Rightarrow$ kinematic effects of hard emission neglected
- reweighting in generators should be checked against fully differential results

# Automation of electroweak corrections

# Automation of QCD NLO corrections

NLO QCD automation established: several (public) tools exist

| tool | method | collaboration |
|---|---|---|
| ROCKET | generalized unitarity | Ellis et al. |
| BLACKHAT | generalized unitarity | Berger et al. |
| NJET | generalized unitarity | Badger et al. |
| HELAC-NLO | 4-dimensional (OPP) integrand reduction | Bevilacqua et al. |
| MADLOOP | 4-dimensional (OPP) integrand reduction | Hirschi et al. |
| GOSAM | $d$-dimensional integrand reduction | Cullen et al. |
| FORMCALC | $d$-dimensional integrand reduction | Hahn et al. |
| OPENLOOPS | recursion relations for “open loops” | Cascioli et al. |
| RECOLA | recursion relations for “open loops” | Actis et al. |

crucial ingredients

- recursive calculation of amplitudes
- generalized unitaritiy
- reduction at integrand level
- improved reduction methods for tensor integrals

# Automation of EW NLO corrections

Methods can be transferred to full SM!

Complications mainly in calculation of loops:

- more contributions (diagrams, off-shell currents)
- more and very different mass scales
  $\hookrightarrow$ numerical stability more problematic
- more complicated renormalization (more parameters)
- mixing of QCD and EW contributions (expansion in two couplings)
- chiral structure of weak interactions (treatment of $\gamma_5$)
- more complicated treatment of unstable particles
  (decay width = EW one-loop effect $\Rightarrow$ gauge invariance non trivial)

solutions exist!

# Automation of EW NLO corrections

Automation of EW NLO is just happening!

tools in preparation:

| tool | collaboration | published applications |
|---|---|---|
| GOSAM | Chiesa et al. | $\mathrm{pp} \to \mathrm{W} + 2\ \mathrm{jets}$ |
| MADGRAPH5_AMC@NLO | Frixione et al. | $\mathrm{pp} \to \mathrm{t\bar{t}} + \{\mathrm{H}, \mathrm{Z}, \mathrm{W}\}$ |
| OPENLOOPS | Pozzorini et al. | $\mathrm{pp} \to \mathrm{W} + \{2\ \mathrm{jets}, 3\ \mathrm{jets}\}$ |
| RECOLA | Actis et al. | $\mathrm{pp} \to \mathrm{jj}l^+l^-$ |

some results presented in the following

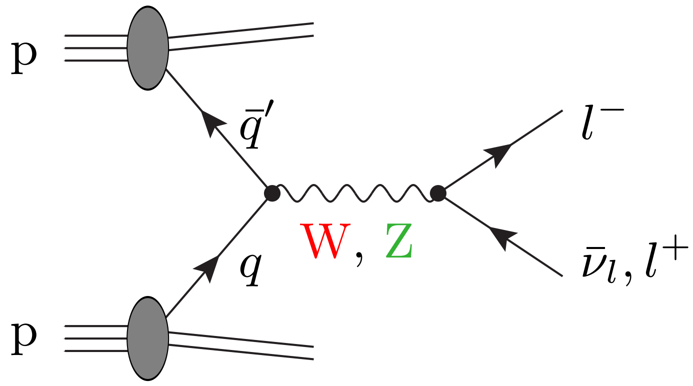
see also talks at Radcor-Loopfest 2015 conference:
https://hepconf.physics.ucla.edu/radcor-loopfest/

Comparison of tools started within Les Houches 2015 workshop.

# Electroweak corrections for specific processes at LHC

# Electroweak corrections to single vector-boson production

# Drell–Yan-like W and Z-boson production




large cross sections: $\sigma(W) = 20\,\mathrm{nb}$
$\sigma(Z) = 1.9\,\mathrm{nb}$

Physics goals:

- $\sigma$, $\mathrm{d}\sigma$ $\rightarrow$ precision SM studies
- $M_\mathrm{Z}$ $\rightarrow$ detector calibration by comparing with LEP1 result
- $\sin^2\theta_\mathrm{eff}^\mathrm{lept}$ with $\delta\sin^2\theta_\mathrm{eff}^\mathrm{lept} \sim 0.00014$ $\rightarrow$ comparison with results of LEP1 and SLC
- $M_\mathrm{W}$ $\rightarrow$ improvement over $\Delta M_\mathrm{W} \sim 15\,\mathrm{MeV}$, strengthen EW precision tests (W/Z shape comparisons sensitive to $\Delta M_\mathrm{W} \sim 7\,\mathrm{MeV}$ Besson et al. '08, Baak et al. '13)
- decay widths $\Gamma_\mathrm{Z}$ and $\Gamma_\mathrm{W}$ from $M_{ll}$ or $M_{\mathrm{T},l\nu_l}$ tails
- search for $\mathrm{Z}'$ and $\mathrm{W}'$ at high $M_{ll}$ or $M_{\mathrm{T},l\nu_l}$
- information on PDFs, determination of collider luminosity

# Known corrections to W/Z production

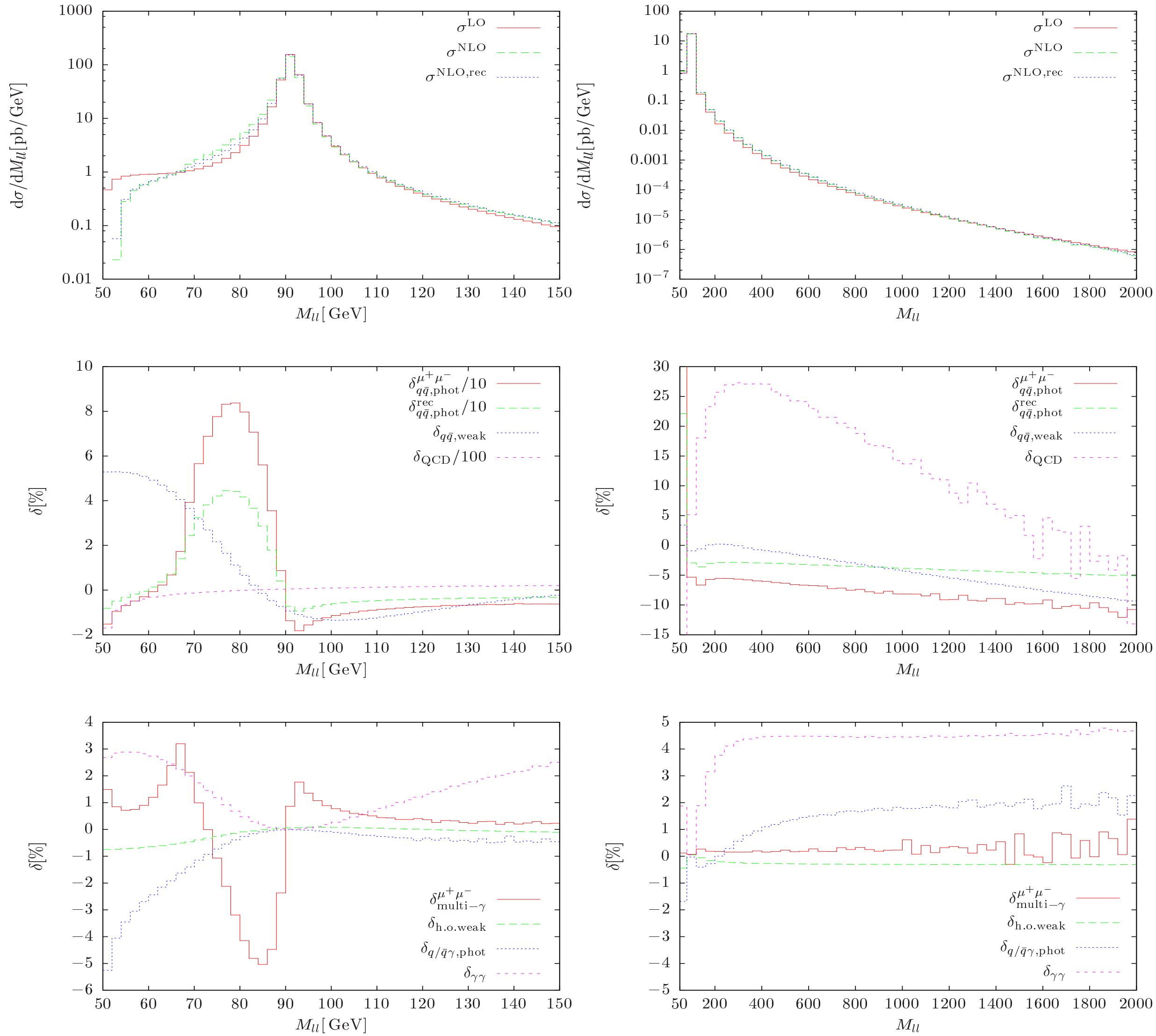
NNLO QCD and NLO EW corrections to W/Z production

- NNLO QCD correction — Hamberg et al. ’91; Harlander, Kilgore ’02; Anastasiou et al. ’03; Melnikov, Petriello ’06; Catani et al. ’09; Gavin et al. ’10,’12
- QCD resummations / parton showers — Arnold, Kauffman ’91; Balazs et al. ’95; ... many contributions
- NLO EW corrections to $\mathrm{W}$ production — Baur, Keller, Wackeroth ’98; Zykunov ’01; Dittmaier, Krämer ’01; Baur, Wackeroth ’04; Arbuzov et al. ’05; Carloni Calame et al. ’06; Brensing et al. ’07
- NLO EW corrections to $\mathrm{Z}$ production — Baur, Keller, Sakumoto ’97; Baur, Wackeroth ’99; Brein, Hollik, Schappacher ’99; Baur et al. ’02; Zykunov ’05; Arbuzov et al. ’06; Carloni Calame et al. ’07; Dittmaier, Huber ’09
- multi-photon radiation via leading logs — Baur, Stelzer ’99; Carloni Calame et al. ’03, ’05; Placzek, Jadach ’03; Brensing et al. ’07; Dittmaier, Huber ’09
- photon-induced processes — Dittmaier, Krämer ’06; Arbusov, Sadykov ’07; Brensing et al. ’07; Carloni Calame et al. ’07; Dittmaier, Huber ’09
- POWHEG matching of QCD/EW corrections — Bernaciak, Wackeroth ’12; Barze et al. ’13
- $\mathcal{O}(\alpha\alpha_{\mathrm{s}})$ corrections — Kotikov et al. ’07; Bonciani ’11; Kilgore, Sturm ’11; Dittmaier, Huss, Schwinn ’14

# Corrections to dilepton mass in Z production

$\mathrm{pp} \to \mathrm{Z} \to l^+l^-$ (14 TeV LHC)

Dittmaier, Huber '09

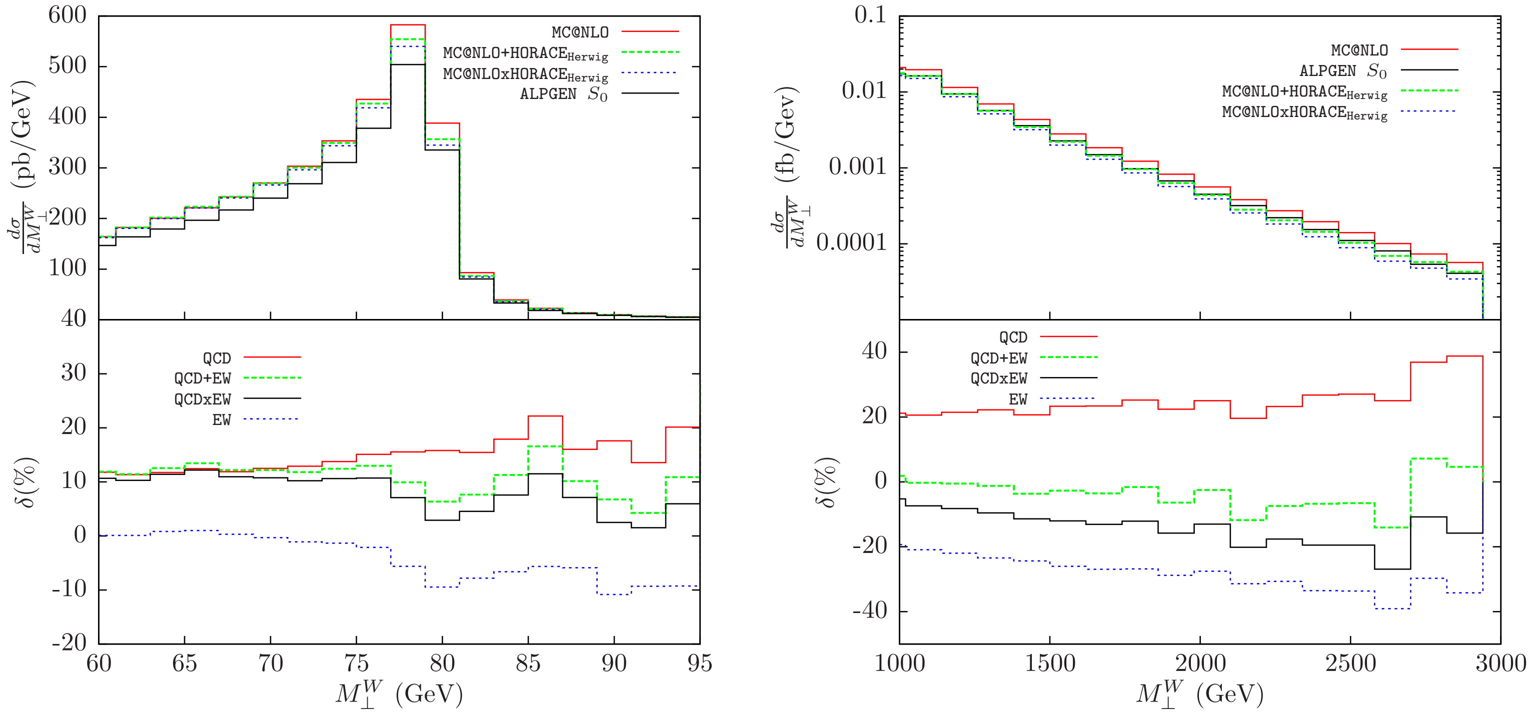



- photonic corrections
  - large radiative tail for $M_{ll} < M_{\mathrm{Z}}$
  - multi-photon radiation significant
  - recombination reduces corrections
- weak corrections significant for $M_{ll} \gg M_{\mathrm{Z}}$
- $\gamma\gamma$ channel significant off resonance

# Combination of NLO QCD and EW corrections

$\mathrm{pp} \to \mathrm{W} \to \mu\nu$ (14 TeV LHC)

Balossini et al. '09




- $M_{\mathrm{W,T}} \sim M_{\mathrm{W}}$: negative EW corrections compensate positive QCD corrections
  EW corrections mandatory around Jacobian peak $(-10\%)$
- $M_{\mathrm{W,T}} \gg M_{\mathrm{W}}$: large negative EW corrections (Sudakov logarithms)
  cancel positive QCD corrections
- different ways of combining QCD and EW corrections
  extreme alternatives: $(1+\delta_{\mathrm{QCD}}^{\mathrm{NLO}}+\delta_{\mathrm{EW}}^{\mathrm{NLO}})$ versus $(1+\delta_{\mathrm{QCD}}^{\mathrm{NLO}})\times(1+\delta_{\mathrm{EW}}^{\mathrm{NLO}})$
  difference at per-cent level with shape distortion $\Rightarrow$ $\mathcal{O}(\alpha\alpha_{\mathrm{s}})$ calculation needed

# $\mathcal{O}(\alpha_s\alpha)$ corrections in pole approximation

pole approximation: leading term in expansion about resonance pole

Stuart '91; Aeppli et al. '93, '94; ...

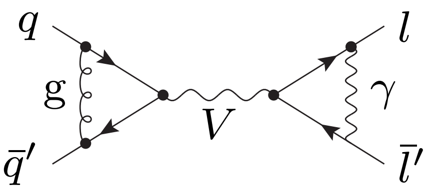
$$\mathcal{M} = \frac{R(p^2)}{p^2 - m^2} + N(p^2) \to \underbrace{\frac{R(m^2)}{p^2 - m^2 + \mathrm{i}m\Gamma}}_{\text{pole approximation}} + \underbrace{\frac{R(p^2) - R(m^2)}{p^2 - m^2} + N(p^2)}_{\text{suppressed by } \Gamma/m}$$

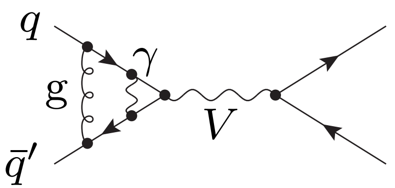
$\Rightarrow$ gauge-invariant definition of resonant contributions

two types of corrections in pole approximation:

- factorisable corrections
  (production and decay factorise)
  dominant contribution from
  $[\mathcal{O}(\alpha_s)$ to $q\bar{q}' \to V] \otimes$
  $[\mathcal{O}(\alpha)$ to $V \to l\bar{l}']$

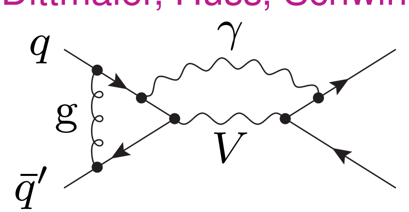
Dittmaier, Huss, Schwinn '15




- non-factorisable corrections
  (connect production and decay)
  virtual and real corrections cancel $\Rightarrow$
  non-factorisable $\mathcal{O}(\alpha_s\alpha)$ corrections $< 0.1\%$

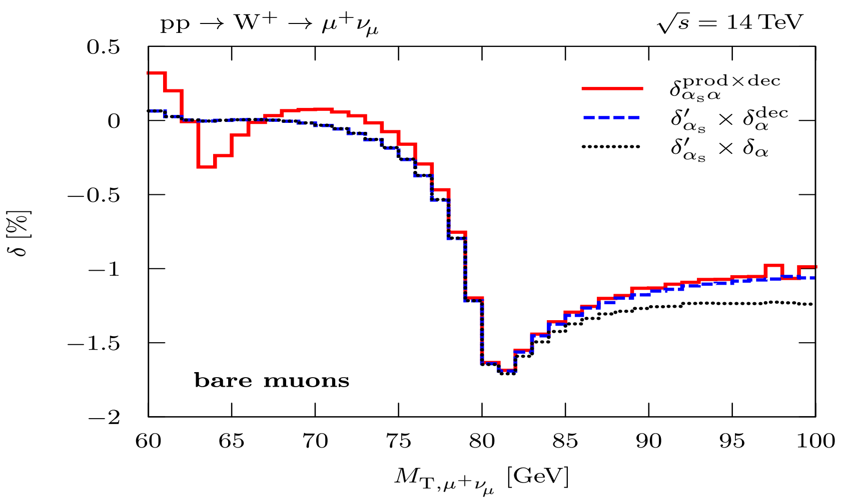
Dittmaier, Huss, Schwinn '14

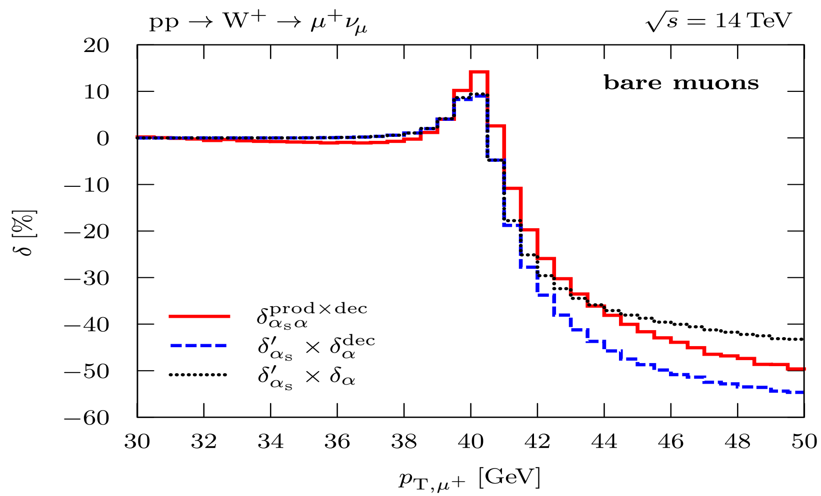


# $\mathcal{O}(\alpha_s\alpha)$ corrections in pole approximation

factorizable initial-final corrections to $\mathrm{W}^+$ production — Dittmaier, Huss, Schwinn: Radcor '15

- (solid red line) best prediction $\delta_{\alpha_s\alpha}^{\mathrm{prod}\times\mathrm{dec}}$
- (dashed blue line) naive product (NLO QCD) $\times$ (NLO EW)$_{\mathrm{dec}}$
- (dotted black line) naive product (NLO QCD) $\times$ (NLO EW)




- $\delta_{\alpha_s\alpha}^{\mathrm{prod}\times\mathrm{dec}}$ well approximated by naive product $\delta'_{\alpha_s} \times \delta_{\alpha}^{\mathrm{dec}}$
- naive factorization deteriorates for $p_{\mathrm{T},\mu} > M_{\mathrm{W}}/2$ (enhancement from large QCD corrections)

$\Rightarrow$ quality of naive product depends on observable and implementation
(further studies in progress)

# Electroweak corrections to vector-boson production with additional hard jets

# Known corrections to W/Z + jet production

## EW corrections for on-shell vector bosons

- weak $\mathcal{O}(\alpha)$ correction to $\mathrm{Z}+1\,\mathrm{jet}$ — Maina, Moretti, Ross ’04
- NLO EW to $\mathrm{W/Z}+1\,\mathrm{jet}$ — Kühn et al. ’04–’07, Hollik et al. ’07, ’15
- NLO EW to $\mathrm{W}+2\,\mathrm{jets}$ — Chiesa, Greiner, Tramontano ’15 — GOSAM
- NLO EW to $\mathrm{W}_{\mathrm{(stable)}}+\leq 3\,\mathrm{jets}$ — Kallweit et al. ’14 — OpenLoops

## NLO QCD corrections for off-shell vector bosons decaying into leptons

- NLO QCD to $\mathrm{W/Z}+\leq 5\,\mathrm{jets}$ — ... Berger et al. ’09,’10; Ellis et al. ’09; Bern et al. ’11–’13; Goetz et al. ’14 — Blackhat

## EW corrections for off-shell vector bosons decaying into leptons

- NLO EW to $\mathrm{W/Z}+1\,\mathrm{jet}$ — Denner et al. ’09–’12
- NLO EW to $\mathrm{Z}+2\,\mathrm{jets}$ — Denner et al. ’14 — Recola

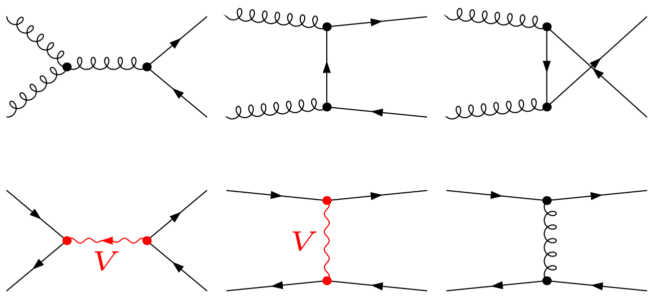
## NNLO QCD corrections for off-shell vector bosons decaying into leptons

- NNLO QCD to $\mathrm{W}+1\,\mathrm{jet}$ — Boughezal et al. ’15

# W/Z + higher jet multiplicities @ NLO QCD+EW

Note: QCD and EW orders mix for $\mathrm{W/Z} + \geq 2\,\mathrm{jets}$

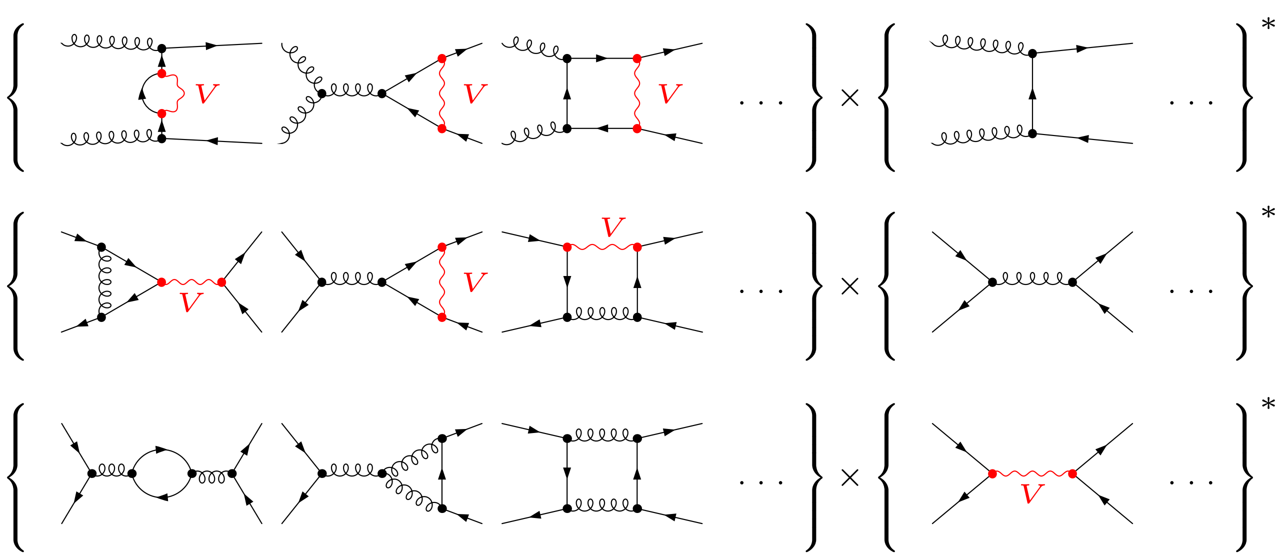
Tree contributions: $\mathcal{O}(\alpha_\mathrm{s}^2)$, $\mathcal{O}(\alpha_\mathrm{s}\alpha)$, $\mathcal{O}(\alpha^2)$ (for cross section)




(W/Z emission suppressed in graphs)

$V = \gamma, \mathrm{Z}, \mathrm{W}$

Loop contributions: $\mathcal{O}(\alpha_\mathrm{s}^2\alpha)$ = "NLO EW"

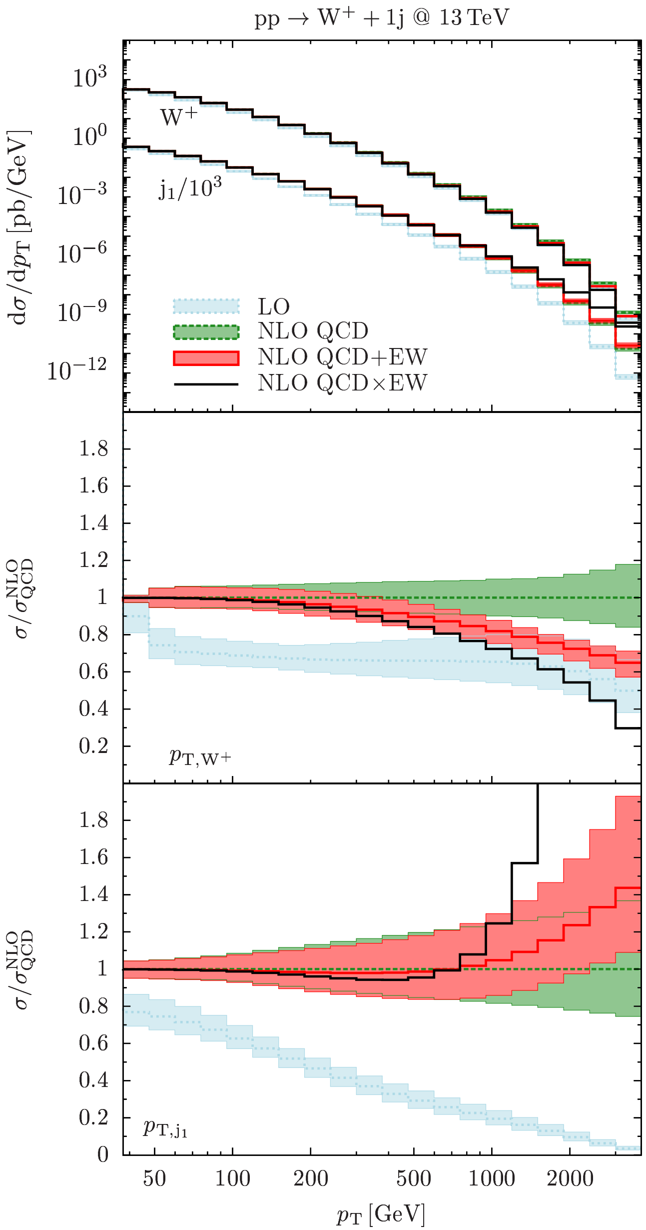



EWC to LO QCD matrix elements

EWC to LO QCD matrix elements

QCD corr. to LO QCD-EW interference

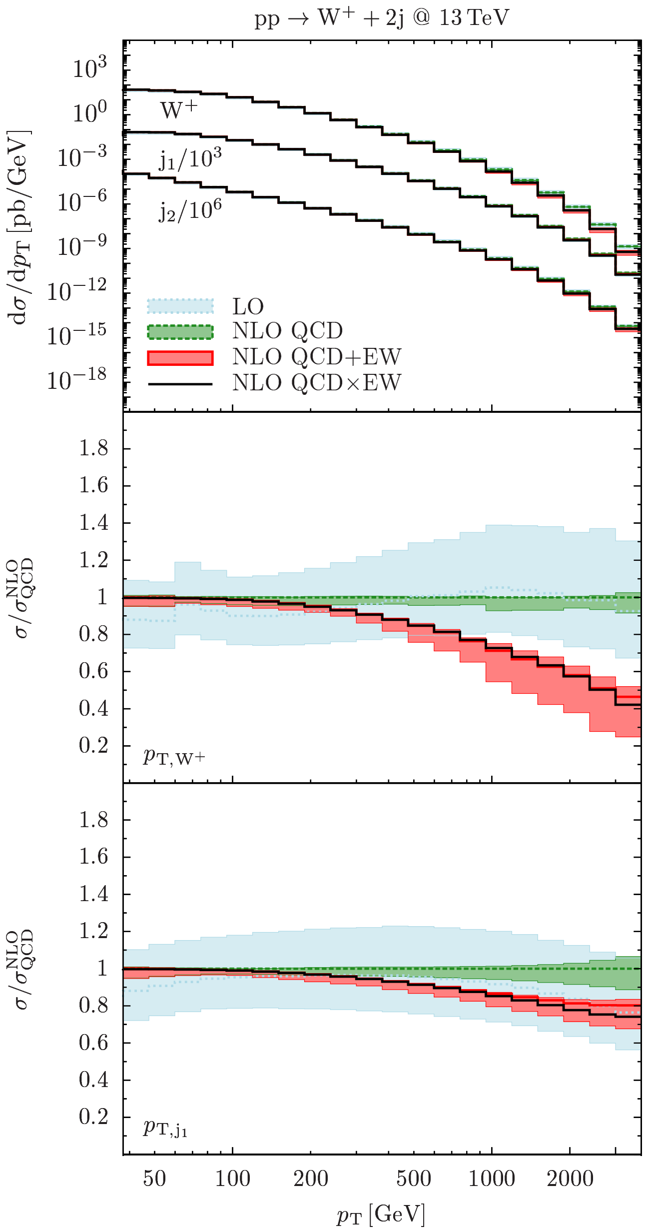
# NLO results for W + jets production




$W + 1j$ Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '14 OpenLoops

- normalisation to $\sigma^{NLO}_{QCD}$
- $\mu_{ren/fact} = \hat{H}_T/2 = \sum_{partons} E_T/2$
- QCD corrections: Rubin, Salam, Sapeta '10
  "giant $K$ factors" in $W + 1j$ due to real emission
  (soft W's, hard jets recoiling against each other)
  $\hookrightarrow$ multi-jet merging important (or apply jet veto)
- EW corrections: effects at high scales
  - negative EW Sudakov corrections larger than QCD unc. for $p_{T,W} > 300\,\text{GeV}$
  - large positive tree-like contribution for large $p_{T,j}$ (from $qq \to qqW$ QCD-EW interference)
- combination of QCD and EW corrections:
  - QCD × EW versus QCD + EW:
    large difference since QCD and EW sizeable !

# NLO results for W + jets production

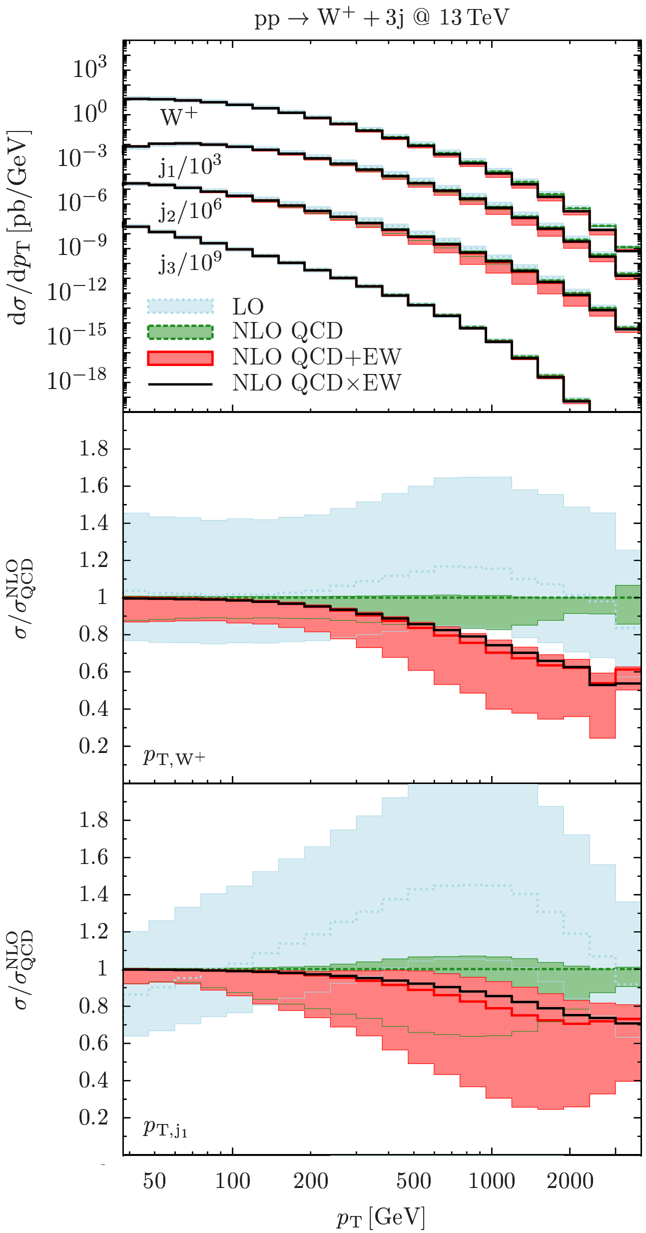



$\mathrm{W}+2\,\mathrm{j}$ Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr '14

OpenLoops

- normalisation to $\sigma^{\mathrm{NLO}}_{\mathrm{QCD}}$
- $\mu_{\mathrm{ren/fact}} = \hat{H}_{\mathrm{T}}/2 = \sum_{\mathrm{partons}} E_{\mathrm{T}}/2$
- QCD corrections:
  small and stable
  (configurations with soft $\mathrm{W}$'s already at leading order)
- EW corrections: effects at high scales
  - negative EW Sudakov corrections
  - positive tree-like contribution visible for large $p_{\mathrm{T,j}}$ (from $qq \to qq\mathrm{Wg}$ QCD-EW interference)
- combination of QCD and EW corrections:
  - QCD × EW versus QCD + EW:
    good agreement

# NLO results for W + jets production

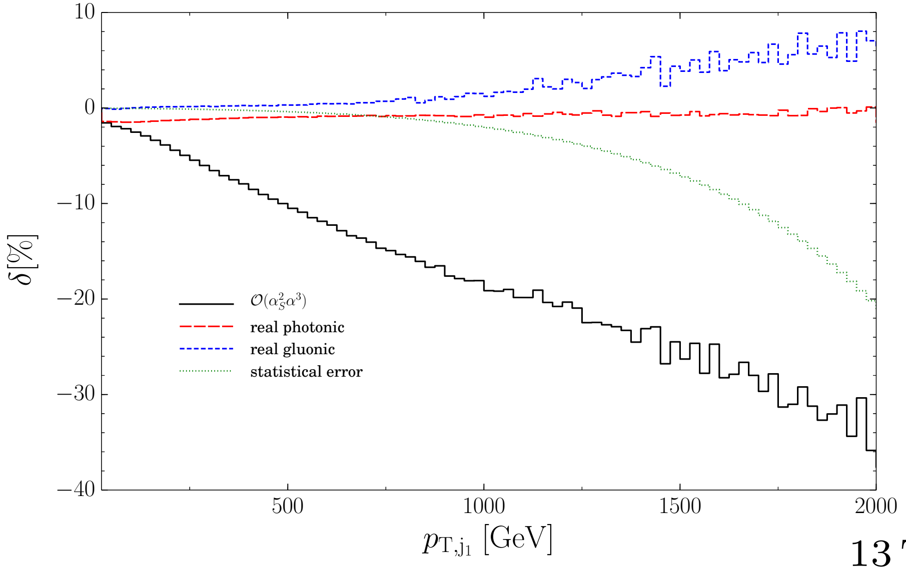



$\mathrm{W}+3\,\mathrm{j}$ Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr ’14
OpenLoops

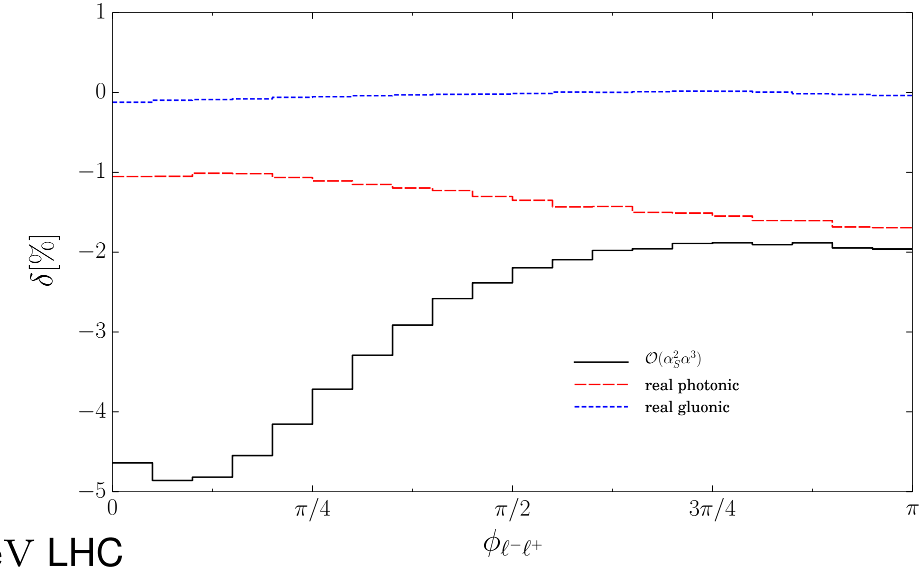
- normalisation to $\sigma^{\mathrm{NLO}}_{\mathrm{QCD}}$
- $\mu_{\mathrm{ren/fact}} = \hat{H}_{\mathrm{T}}/2 = \sum_{\mathrm{partons}} E_{\mathrm{T}}/2$
- QCD corrections:
  sizeable negative correction for $p_{\mathrm{T,j}}$ distribution around $1\,\mathrm{TeV}$ for standard scale
- EW corrections: effects at high scales
  - negative EW Sudakov corrections
  - Sudakov suppression in tails of all $p_{\mathrm{T}}$ distributions
- combination of QCD and EW corrections:
  - QCD × EW versus QCD + EW:
    QCD + EW might overestimate EWC because of negative QCD corrections

# NLO results for $l^+l^- + 2j$ production

## Transverse momentum of leading jet




## azimuthal angle between leptons




13 TeV LHC

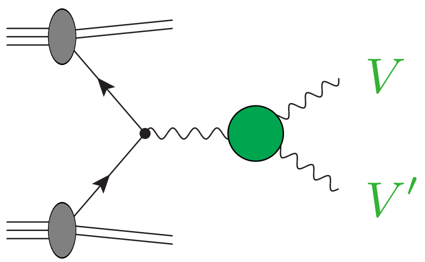
- EWC sizeable for large $p_T$
  dominated by virtual corrections
  (Sudakov logarithms)
  exceed $300\,\mathrm{fb}^{-1}$ statistical error
- real photonic corrections small
- real gluonic corrections reach several per cent for large $p_T$

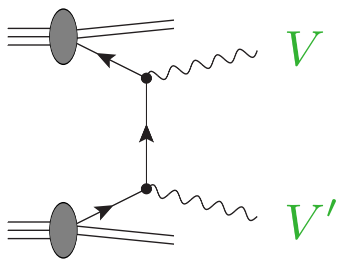
- virtual EW corrections distort distribution by $3\%$
- real photonic corrections small
- real gluonic corrections small
  (QCD corrections to QCD-EW interference $qq \to qql^+l^-\mathrm{g}$)

Denner, Hofer, Scharf, Uccirati '14 Recola

# Electroweak corrections to vector-boson pair production

# Vector-boson pair production




$V, V' = \gamma, \mathrm{Z}, \mathrm{W}^{\pm}$

$$\sigma(\mathrm{WW}) \sim 100\,\mathrm{pb}$$
$$\sigma(\mathrm{W}^{\pm}\mathrm{Z}) \sim 30/20\,\mathrm{pb}$$
$$\sigma(\mathrm{ZZ}) \sim 15\,\mathrm{pb}$$

Physics issues:

- triple-gauge-boson couplings, in particular at high momentum transfer
  $\Rightarrow$ EW corrections significant
- important class of background processes
  - to searches at high invariant masses (e.g. supersymmetry)
    $\Rightarrow$ EW corrections
  - to Higgs production, $\mathrm{H} \to VV \to 4f$
    $\hookrightarrow$ invariant masses below VV thresholds
    proper description of off-shell VV production required

# Known corrections to $VV$ production

NLO EW and NNLO QCD corrections:

$\mathrm{W}\gamma/\mathrm{Z}\gamma$ (with leptonic decays)

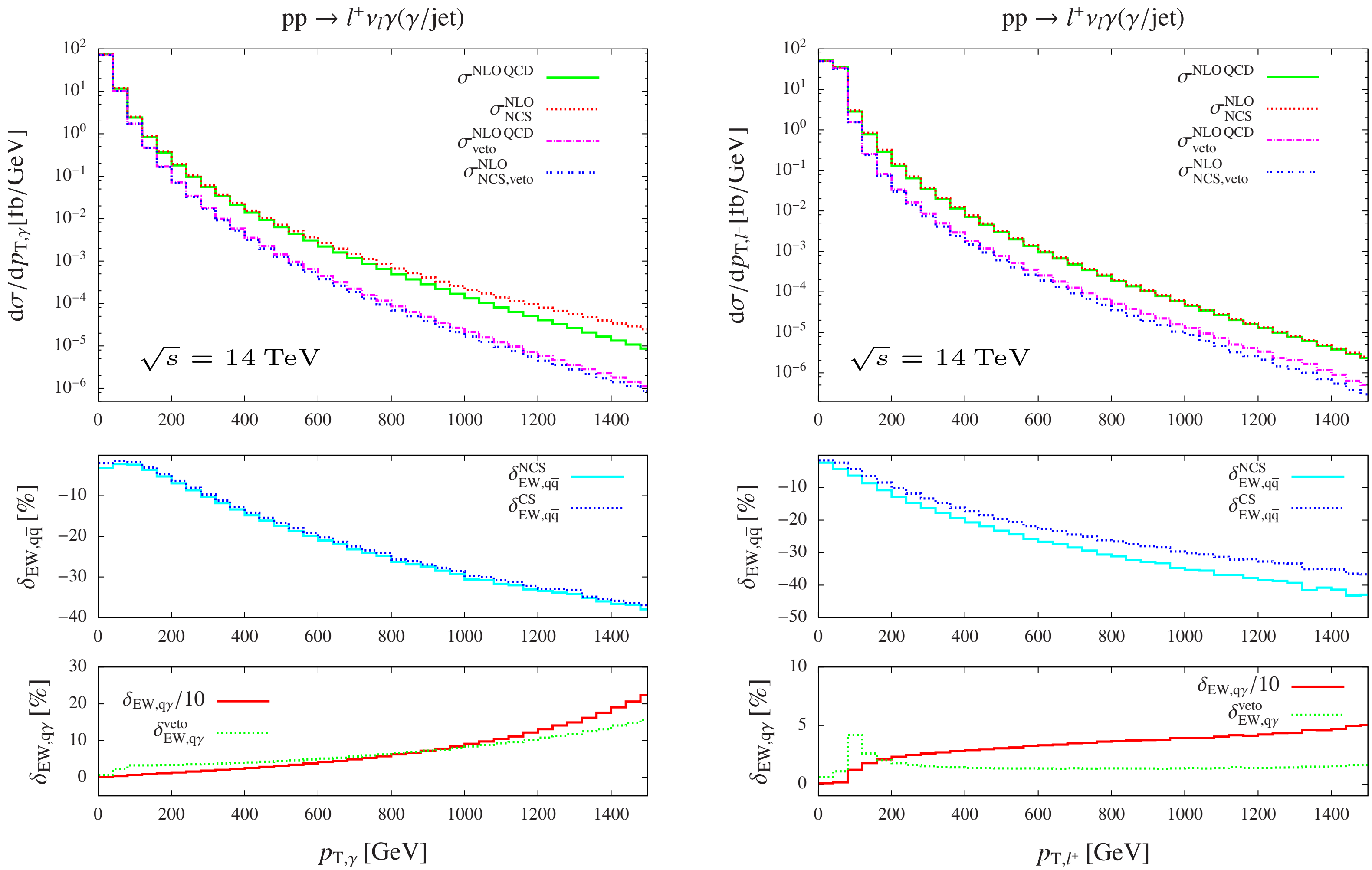
- NNLO QCD Grazzini, Kallweit, Rathlev ’14,’15
- NLO EW Denner, Dittmaier, Hecht, Pasold ’14 ($\mathrm{Z}\gamma$ in preparation)

$\mathrm{WW}, \mathrm{WZ}, \mathrm{ZZ}$

- NNLO QCD
  - $\mathrm{ZZ}$ (on-shell, total inclusive x-section) Cascioli et al. ’14
  - $\mathrm{WW}$ (on-shell, total inclusive x-section) Gehrmann et al. ’14
  - $\mathrm{gg} \to VV \to 4$ leptons Binoth et al. ’05,’06
- NLO EW
  - stable W/Z bosons Bierweiler, Kasprzik, Kühn, Uccirati ’12/’13; Baglio, Le, Weber ’13
  - approximative inclusion in HERWIG++ (via correction factor) Gieseke, Kasprzik, Kühn ’14
  - $\mathrm{pp} \to \mathrm{WW} \to 4$ leptons in DPA Billoni, Dittmaier, Jäger, Speckner ’13
  - full off-shell calculation in progress Denner et al.

# EW corrections for $p_T$ distr. in W$\gamma$ production

Denner, Dittmaier, Hecht, Pasold ’14

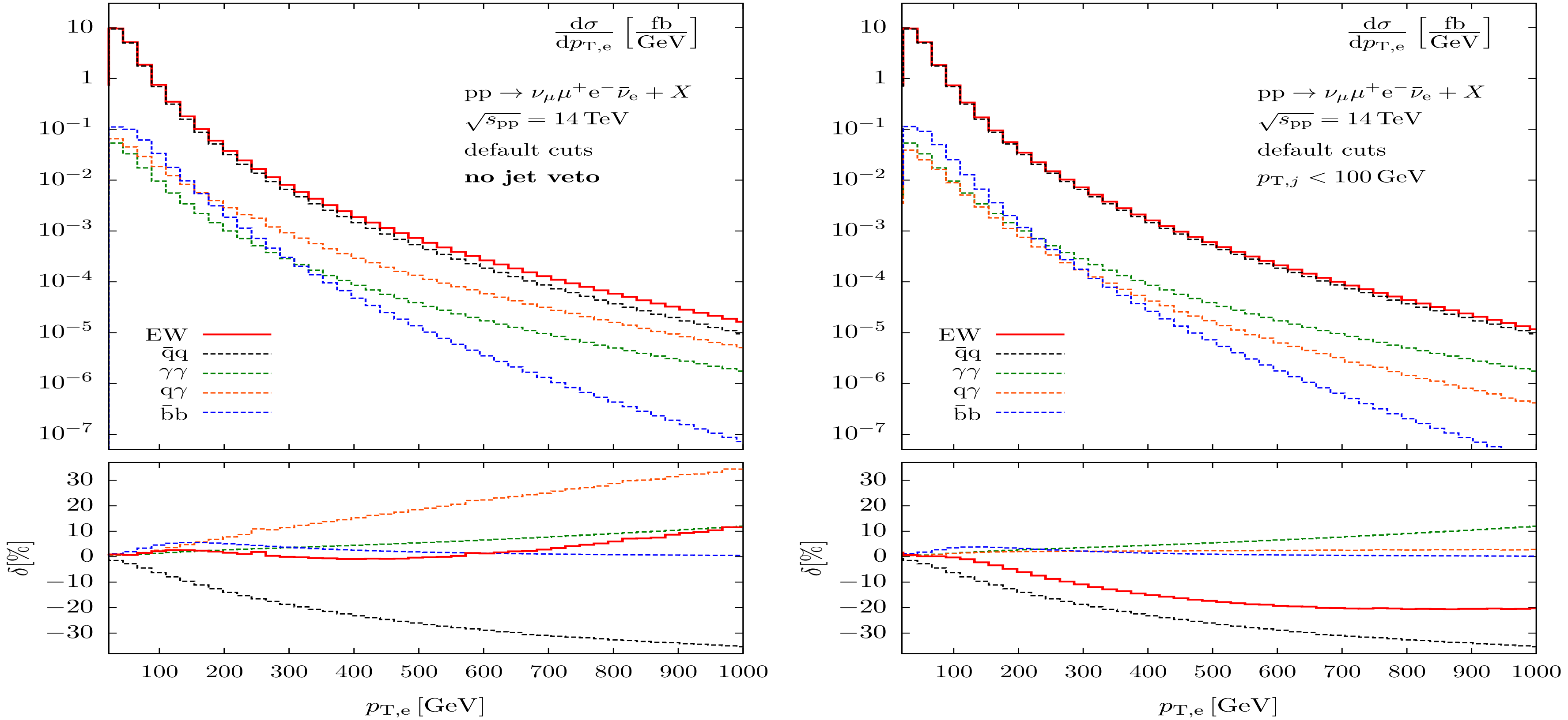



- EW corrections $\sim -30\%$ in TeV range (CS=collinear-safe, NCS=non-collinear-safe)
- $\gamma$-induced corrections non-negligible in TeV range (even with jet veto: $p_{\text{T,j}} > 100\,\text{GeV}$)
  $\hookrightarrow$ reduction of $\gamma$ PDF uncertainties mandatory !

# EWC to WW production with W leptonic decays

EWC in double-pole approximation

Billoni, Dittmaier, Jäger, Speckner ’13




- Sudakov corrections to $qq$ channel reach $-30\%$
- $\gamma\gamma$ contribution significant for large energies
- $q\gamma$ contribution suppressed by jet veto (otherwise overwhelmed by QCD corrections)
- realistic cuts on W decays can modify EW corrections at level of some per cent

# Electroweak corrections to top and Higgs production processes

# State of the art

Higgs-production processes (stable Higgs boson!)

- NLO EW corrections to gluon fusion, $\mathrm{gg} \to \mathrm{H}$ (2-loop!)

  Actis et al '09; (Aglietti et al '04, '06; Degrassi, Maltoni '04)

- NLO EW corrections to vector-boson fusion, $qq \to \mathrm{Hjj}$

  Ciccolini, Denner, Dittmaier '07; Figy, Palmer, Weiglein '10

- NLO EW corrections to Higgs strahlung, $qq \to \mathrm{H}l\nu$

  Denner et al. '11 [$qq \to \mathrm{H}V$ for stable $V$: Ciccolini, Dittmaier, Krämer '03 ]

- NLO EW corrections to Higgs production in association with a top pair, $qq \to \mathrm{Ht\bar{t}}$

  Frixione et al. '14, Zhang Yu et al. '14

Top-production processes (stable top quark!)

- NLO EW corrections to top-pair production $\mathrm{pp} \to \mathrm{t\bar{t}}$

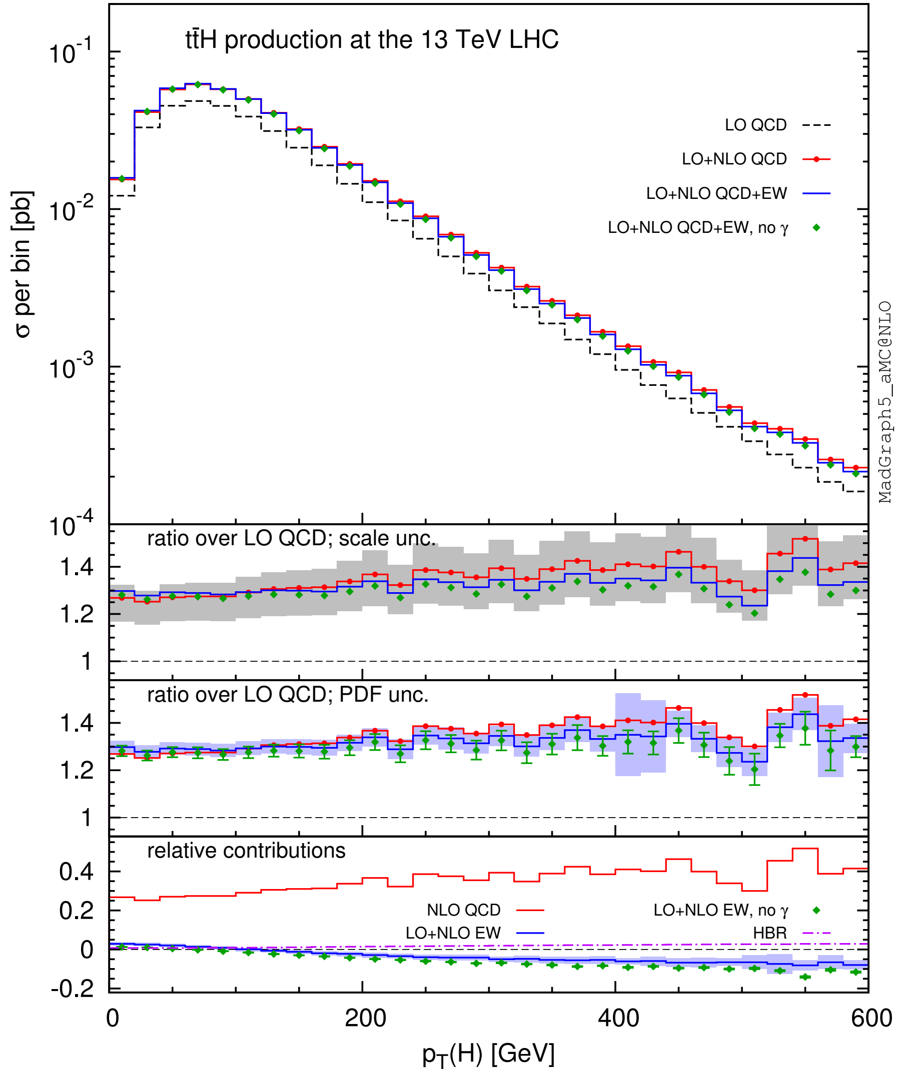
  Kühn, Scharf, Uwer '06, '07, 13'; Bernreuther, Fücker, Si '06; Moretti, Nolten, Ross '06 (Beenakker et al. '94)

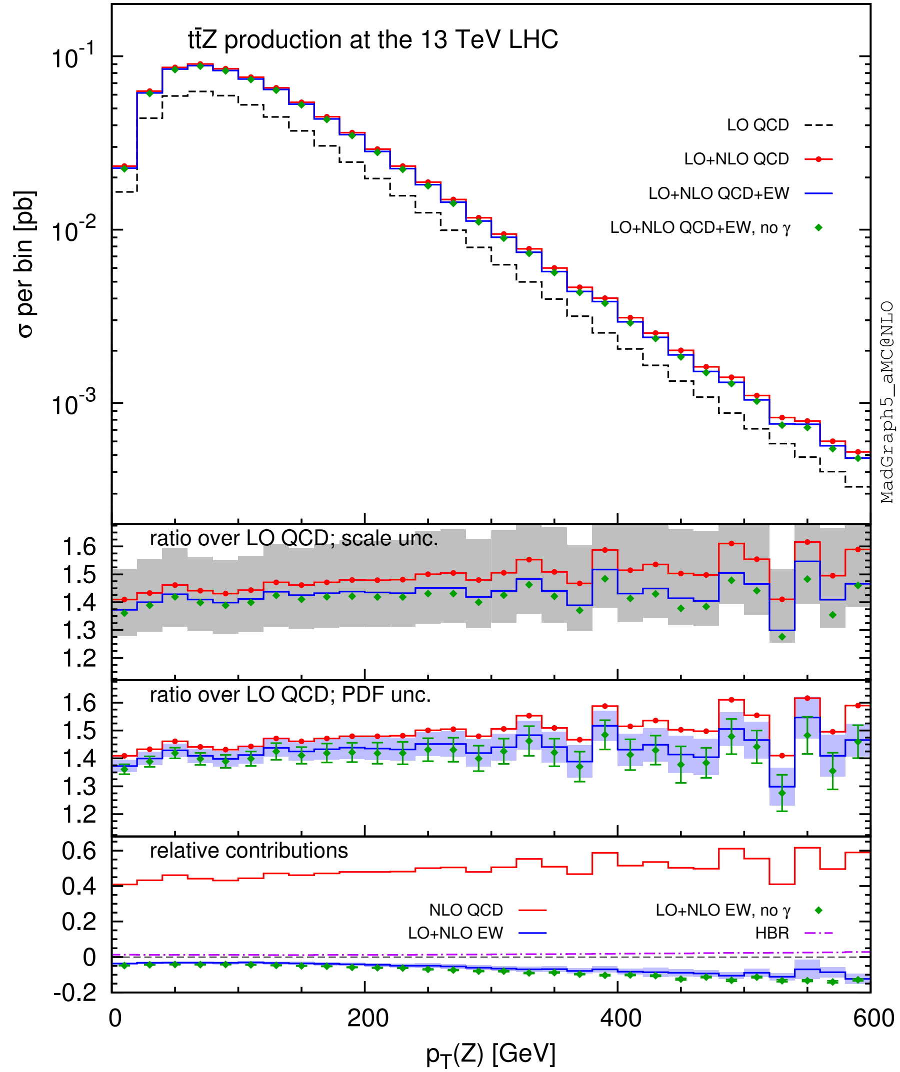
- NLO EW corrections to top-pair production in association with heavy vector bosons, $\mathrm{pp} \to \mathrm{t\bar{t}}V$ Frixione et al. '14

# EW corrections to $t\bar{t}H$ and $t\bar{t}Z$ distribution

## Transverse momentum distribution of Higgs boson/Z boson

Frixione et al. ’15



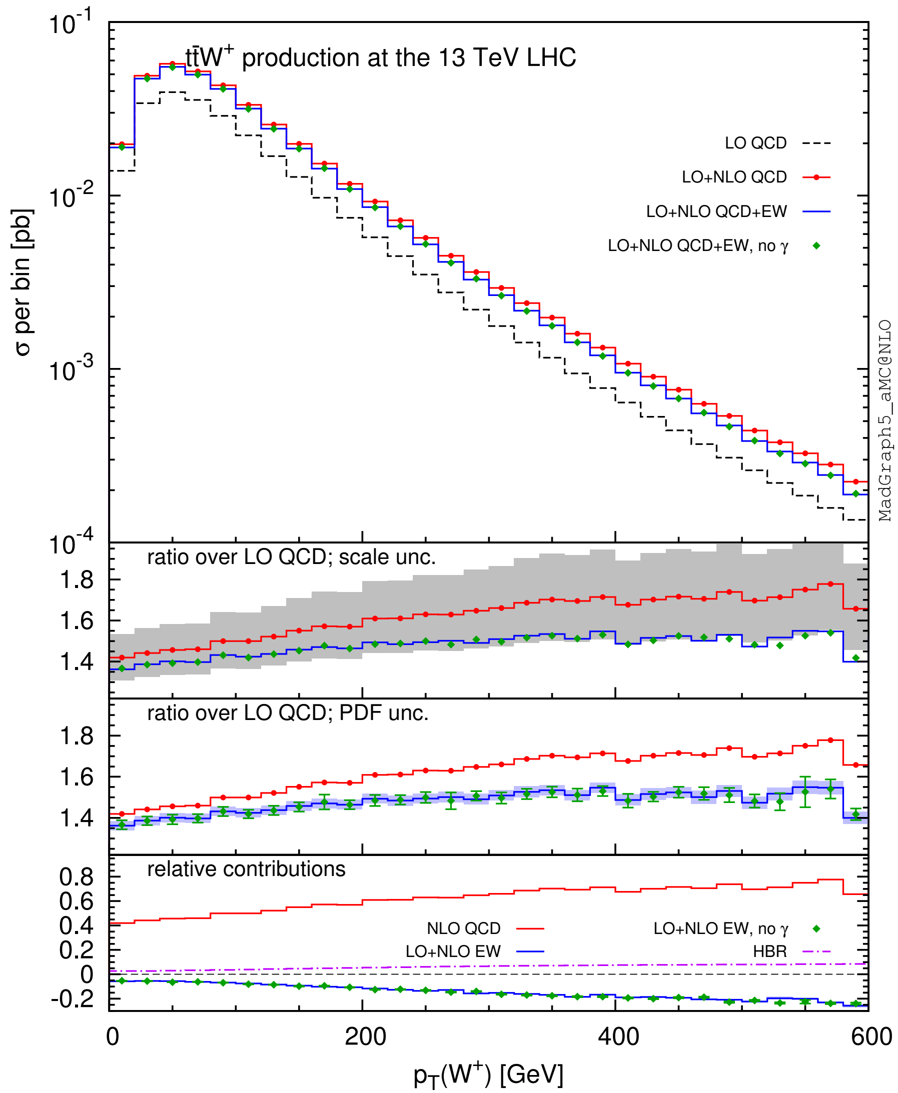



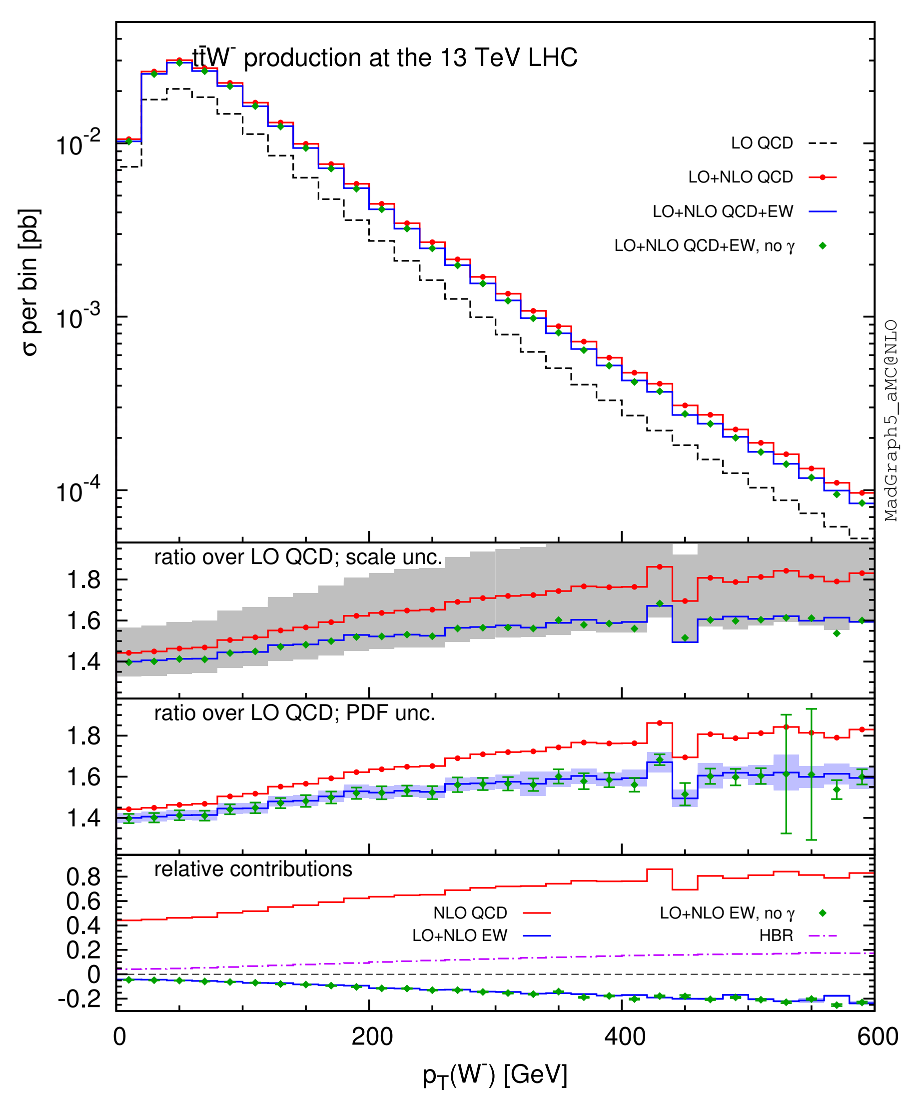

Sizeable contribution of photon-induced processes

# EW corrections to $\mathrm{t\bar{t}W^{+}}$ and $\mathrm{t\bar{t}W^{-}}$ distribution

## Transverse momentum distribution of W boson

Frixione et al. ’15




EW corrections of same size as QCD scale uncertainty

# EW corrections to $\mathrm{t\bar{t}H}/V$ production

Observations:

Frixione, Hirschi, Pagani, Shao, Zaro ’15 (MadGraph5_aMC@NLO)

- relative EW corrections @ $13\,\mathrm{TeV}$ LHC
  inclusive scenario: no cuts
  boosted scenario: $p_{\mathrm{T,t}}, p_{\mathrm{T,H}}, p_{\mathrm{T,Z}}, p_{\mathrm{T,W}} > 200\,\mathrm{GeV}$

| process | $\mathrm{t\bar{t}H}$ | $\mathrm{t\bar{t}Z}$ | $\mathrm{t\bar{t}W^+}$ | $\mathrm{t\bar{t}W^-}$ | scheme |
|---|---|---|---|---|---|
| inclusive scenario | $-1.2\%$ | $-3.8\%$ | $-7.7\%$ | $-6.7\%$ | $\alpha(M_\mathrm{Z})$ |
| inclusive scenario | $+1.8\%$ | $-0.7\%$ | $-4.5\%$ | $-3.5\%$ | $G_\mu$ |
| boosted scenario | $-8.2\%$ | $-11.1\%$ | $-19.2\%$ | $-18.3\%$ | $\alpha(M_\mathrm{Z})$ |

  modest impact for inclusive scenario, sizeable for boosted case
  $\Rightarrow$ EW corrections needed for precision study of $\mathrm{t\bar{t}}V$ production

- heavy-boson radiation ($\mathrm{t\bar{t}}VV$ final states) might be responsible for detectable effects (in particular for $\mathrm{t\bar{t}W}$: $4–15\%$)

# Electroweak corrections to other processes

# NLO EW corrections for other LHC processes

## Recent calculations:

- NLO QCD and EW corrections to $WW$+jet production with leptonic $W$-boson decays at LHC    Li Wei-Hua et al. '15
- NLO QCD + NLO EW corrections to $WZZ$ productions with leptonic decays at the LHC    Shen Yong-Bai et al. '15
- NLO corrections to $WWZ$ production at the LHC
  Dao Thi Nhung, Le Duc Ninh, Marcus M. Weber '13

## Earlier calculations:

- EW corrections to single-top production    Beccaria et al '06 '08, Bardin et al. '10
- EW corrections to di-jet production
  Moretti, Nolton, Ross '06; Dittmaier, Huss, Speckner '12

Apologies for any omissions!

# NLO EW corrections for ILC processes

## Recent calculations:

- Electroweak radiative corrections to $\mathrm{W^+W^-}\gamma$ production at the ILC
  Chong Chen et al. '14
- Full $\mathcal{O}(\alpha)$ electroweak radiative corrections to $\mathrm{t\bar{t}}\gamma$ and $\mathrm{e^+e^-}\gamma$ at the ILC with GRACE-Loop
  P.H. Khiem et al. '14
- Full one-loop electroweak corrections to $\mathrm{e^+e^-} \to \mathrm{ZH}\gamma$ at a Higgs factory
  Ning Liu et al. '14

Apologies for any omissions!

# Conclusions

# Conclusions

- Electroweak corrections (EWC) are relevant for LHC processes
- EWC particularly large in tails of distributions or near resonances
- approximate treatments of EWC
  - leading Sudakov logarithms
  - appropriate correction factors in MC generators
  - naive factorization for $\mathcal{O}(\alpha\alpha_\mathrm{s})$ corrections
- automation of NLO EWC is in progress
- full EWC involve many new features and subtleties
  - parton distributions including QED corrections
  - photon-induced processes (large uncertainty from photon PDF)
  - photon–jet separation
  - consistent treatment of resonances $(\mathrm{W}, \mathrm{Z}, \mathrm{t}, \mathrm{H}, \ldots)$
  - interplay between QCD and EW corrections
  - parton showers with EW effects

Thank you

for your attention!