QED/EW/QCD corrections for Drell-Yan processes

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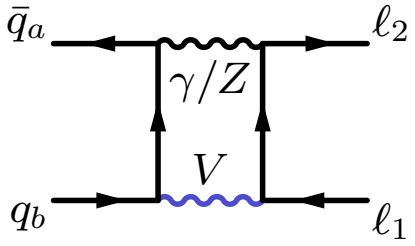
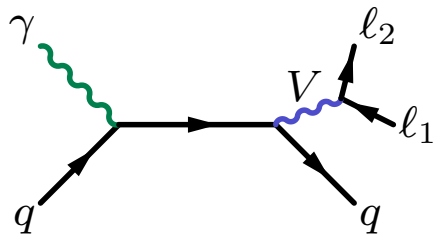
EW-corrections

Features of EW corrections



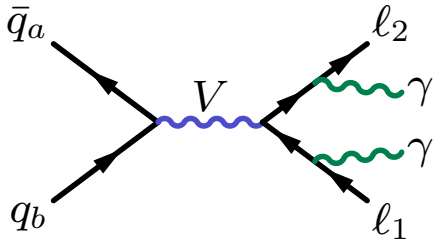
- connecting initial and final state
- consistent treatment of decay widths necessary (e.g. complex mass scheme)
- reconstruction of "bare" muons
  $\Rightarrow$ logarithmic dependence $\sim \alpha \log\left(m_\mu^2/\hat{s}\right)$



- Photon-induced processes ($\Rightarrow$ LUXQED PDF (Manohar et al. 16))

Dominant effects beyond NLO

- multi-photon radiation (Baur/Stelzer 99; Carloni Calame et al. 03, `Photos`: Golonka/Was 06)
- NNLO Sudakov logarithms $\alpha^2 \log^{4,3}(\hat{s}/M_W^2)$ (e.g. Kühn et al. 04/07; Becher/Garcia i Tormo 13)
- Universal weak corrections ($\Delta\rho^{(2)}$: Consoli/Hollik/Jegerlehner 89)



NLO automation enters similar state as for QCD

public release in current/next versions of one-loop frameworks

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$	σ^{LO} [fb]	σ^{NLO}_{EW} [fb]	$\Delta\sigma^{LO}$ [σ]	[‰]	$\Delta\sigma^{NLO}_{EW}$ [σ]	[‰]
average	448.5414[31]	438.1902[56]				
MUNICH+OPENLOOPS	448.5468[45]	438.1920[75]	+1.6	+0.01	+0.4	+0.00
MOCANLO+RECOLA	448.538[10]	438.193[13]	−0.4	−0.01	+0.2	+0.01
SHERPA+GOSAM/OPENLOOPS/RECOLA	448.5364[46]	438.186[11]	−1.4	−0.01	−0.4	−0.01
MADGRAPH5_AMC@NLO	448.541[40]	438.113[70]	−0.0	−0.00	−1.1	−0.18

(LesHouches 2017)

Implementations in multi-purpose MCs

not (yet) optimized for DY precision physics

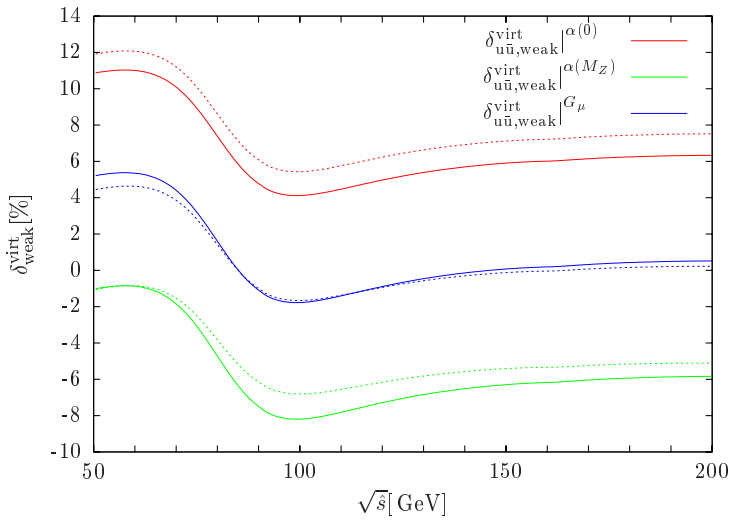
- strict fixed-order NLO EW in complex mass scheme, fixed Breit-Wigner propagators $1/(p^2 - M_V^2 + \mathrm{i}M_V\Gamma_V)$
- Treatment of IR singularities with techniques used in QCD
  - assumes massless leptons, recombination with photon radiation
  - dedicated treatment of muon mass effects so far only in parton-level programs

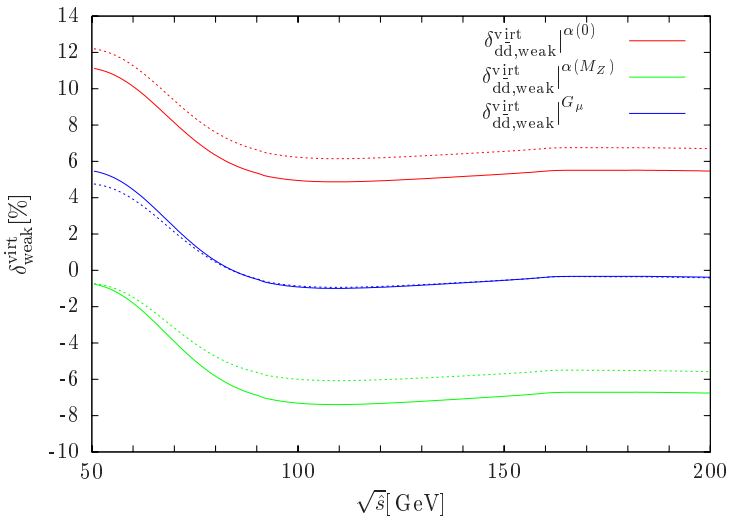
EW-corrections

Useful EW input parameter set: $\alpha,\ M_z,\ M_W,\ M_H,\ m_f,\ V_{\mathrm{CKM}}$
with on-shell definition $c_w = \frac{M_W}{M_Z}$

- Possible definitions for α:
  - $\alpha(0)$ appropriate for real-photon emission
  - $\alpha(M_Z) = \alpha(0)/(1 - \Delta\alpha(M_Z))$ avoids sensitivity to m_q
  - $\alpha_{G_\mu} = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 s_w^2 = \alpha(0)(1 + \Delta r)$ absorbes universal weak corrections to charged current

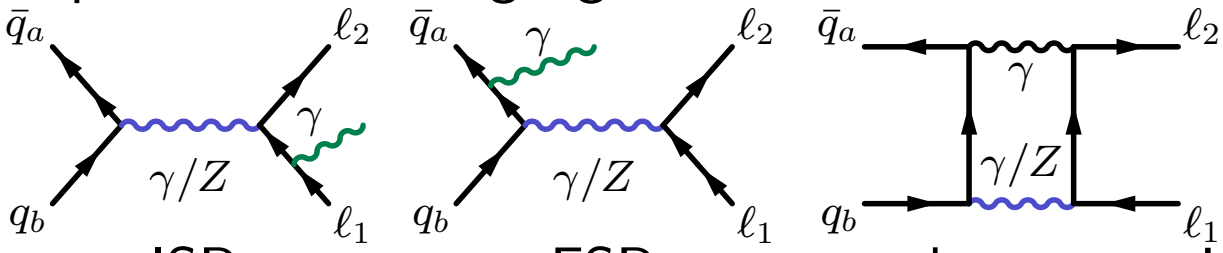
Weak corr. to NC-DY with (dashed)/without leading two-loop terms: (Dittmaier/Huber 09)





Neutral-current DY: consistent subclasses of corrections

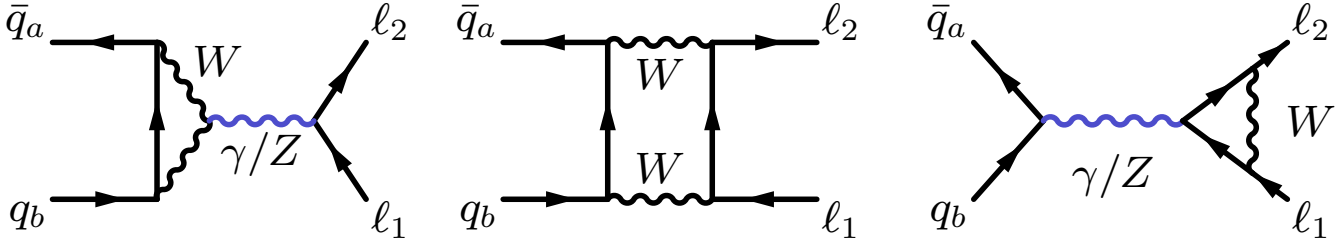
QED: separate classes of gauge invariant corrections



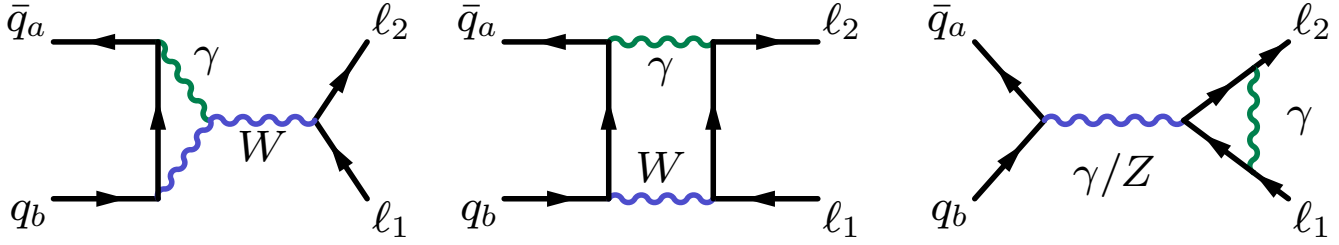
ISR FSR box corrections

simplifies combination of QED corrections and higher-order weak corrections, e.g. resummed propagators

"genuine" weak corrections related by gauge invariance



Charged-current DY: no QED/weak separation due to γ-W vertex

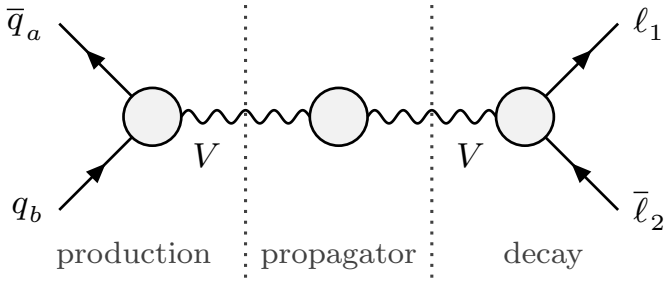


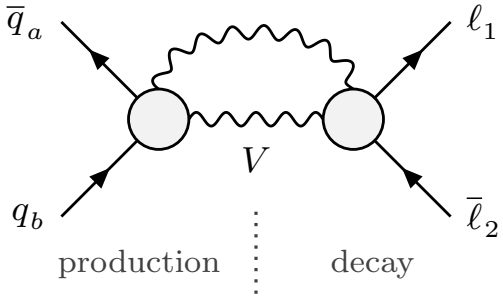
Pole scheme: (Stuart 91; Aeppli/v.Oldenbourgh/Wyler 93)

Expand for $p_V^2 \sim \mu_V^2$ with complex pole $\mu_V^2 = M_V^2 - \mathrm{i} M_V \Gamma_V$

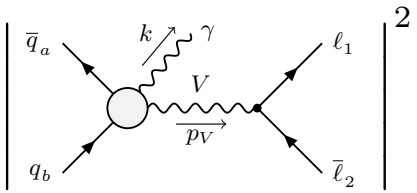
- Factorizable corrections to on-shell prod. and decay
- Non-fact. soft-photon corrections

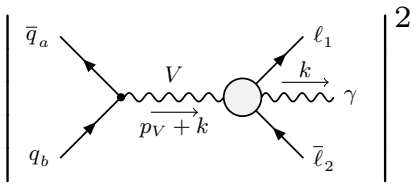
Virtual corrections

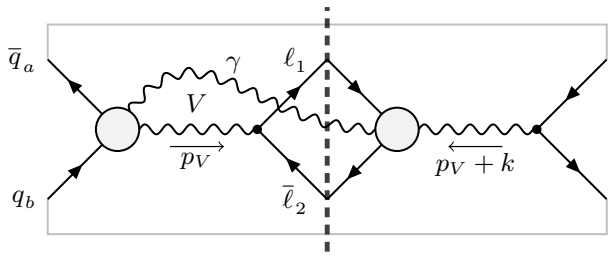




Real corrections



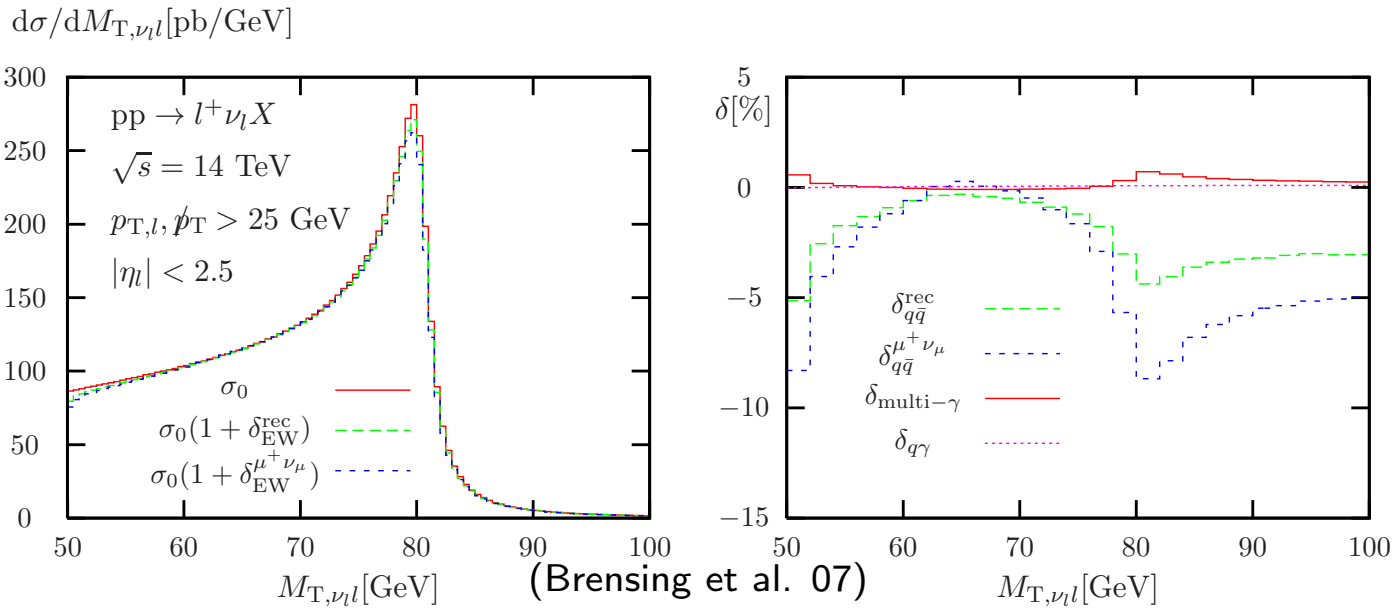




fact.-initial fact.-final non-factorizable

Numerical results of EW corrections for charged-current DY

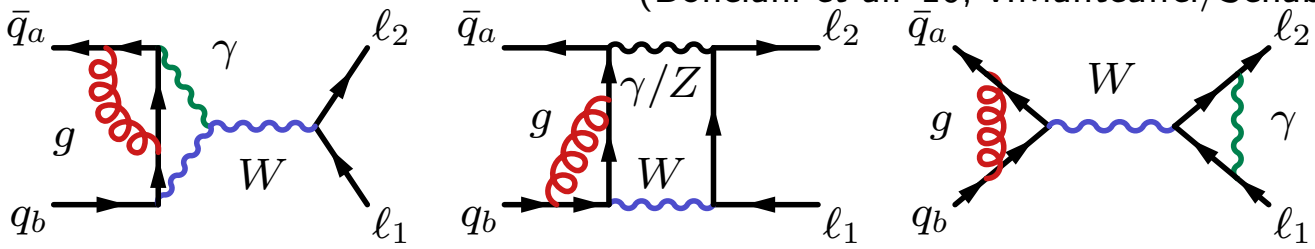
- $\sim 10\%$ corrections; distort shape of resonance
- multi$-\gamma$ radiation 1%-effect.
- Effect on M_W measurement:
  - NLO: $\Delta M_W \approx 100$ MeV,
  - multi-γ: $\Delta M_W \approx 10$ MeV



(Brensing et al. 07)

NNLO QCD⊗EW corrections for DY:

Full two-loop calculation in progress (Bonciani et al. 16; v.Manteuffel/Schabinger 17)



Approximations to full QCD⊗EW effects:

- Additive/multiplicative combinations; simulation of FSR

  (Cao et al. 04; Balossini et al. 09; Richardson et al. 10; Li/Petriello 12; Jadach et al. 16)

- EW corrections in NLO-matched QCD parton showers

  (Bernaciak/Wackeroth 12; Barzè et al. 12/13; Carloni Calame et al.; Mück/Oymanns 16)

- Application of pole expansion (Dittmaier/Huss/CS 14/15)

Impact on M_W-measurement: (Dittmaier/Huss/CS 15; Carloni Calame et al. 16)

$$|\Delta M_W^{\mathrm{NNLO}}| \approx 15 \text{ MeV}$$

(approximately included in current analysis through NLO-QCD+Photos)

Mixed QCD-EW corrections

Parton-level combinations:

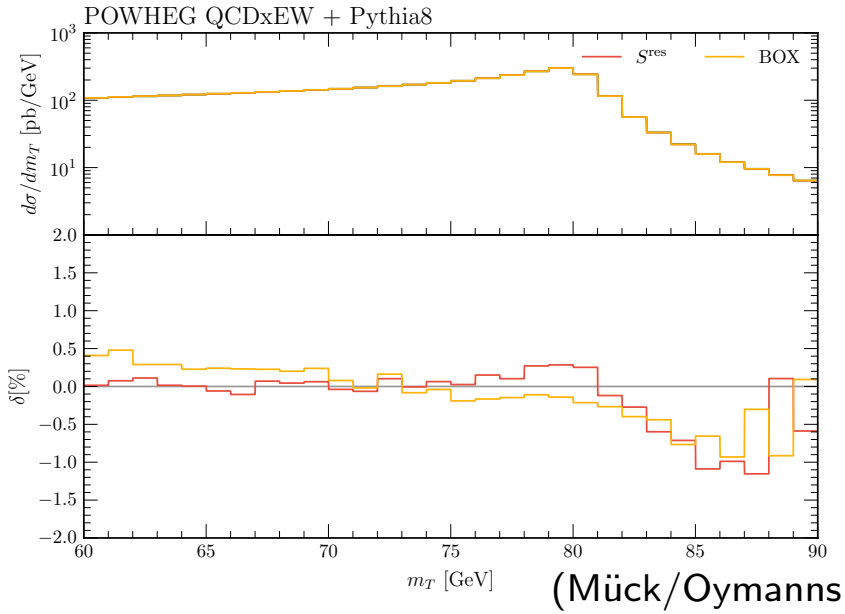
- Additive: $\sigma^{\text{NLO}}_{\text{QCD+EW}} = \sigma_{\text{LO}} + \Delta\sigma^{\text{NLO}}_{\text{QCD}} + \Delta\sigma^{\text{NLO}}_{\text{EW}} = \sigma_{\text{LO}} K^{\text{NLO}}_{\text{QCD}} + \Delta\sigma^{\text{NLO}}_{\text{EW}}$
- Multiplicative: $\sigma^{\text{NLO}}_{\text{QCD}\times\text{EW}} = \sigma^{\text{NLO}}_{\text{QCD+EW}} + \frac{\Delta\sigma^{\text{NLO}}_{\text{QCD}}\Delta\sigma^{\text{NLO}}_{\text{EW}}}{\sigma_{\text{LO}}} = \sigma^{\text{NLO}}_{\text{EW}} K^{\text{NLO}}_{\text{QCD}}$

  (schematic, ignores e.g. use of PDFs at different order)
  - expected to capture factorizing soft-QCD/Sudakov-EW effects leading to large corrections
  - misses simultaneous hard photon and gluon emission, non-factorizing virtual effects
  - scale appropriate for $K^{\text{NLO}}_{\text{QCD}}$ might be changed by γ-FSR
- Use $\sigma^{\text{NLO}}_{\text{QCD}\times\text{EW}} - \sigma^{\text{NLO}}_{\text{QCD+EW}}$ as error estimate?
  - likely overestimates error in regions dominated by soft-QCD/Sudakov-EW (where corrections are large)
  - appropriate elsewhere (where corrections are small)

Matching of NLO-EW corrections to QCD shower

(Bernaciak/Wackeroth 12; Barzè et al. 12/13; Carloni Calame et al.; Mück/Oymanns 16)

- Modelling of $\mathcal{O}(\alpha_s\alpha)$ effects from collinear gluon emission
- Needs resonance aware matching ($\mathcal{O}(\%)$ effects)



(Mück/Oymanns 16)

Merging of $V + 1, 2$ jets with NLO EW in `OpenLoops+Sherpa`: (Kallweit et al. 15)

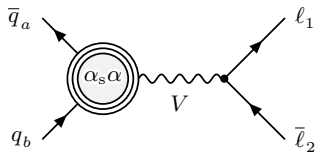
- includes real-gluon emission of NNLO $\mathcal{O}(\alpha_s\alpha)$ corrections
- so far only in EW_{virt} approximation

  (appropriate for Sudakov effects, full NLO-EW needed for precision near resonances)

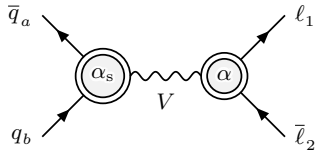
EW/QCD corrections in pole approximation (Dittmaier/Huss/CS 14/15)

(+ corresponding real-virtual and double real)

- Factorizable initial (partial results: Kotikov/Kühn/Veretin 07; Bonciani 11)

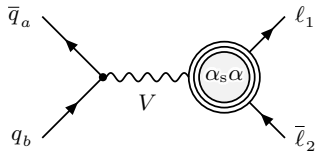


- Factorizable initial×final (expected to be dominant)

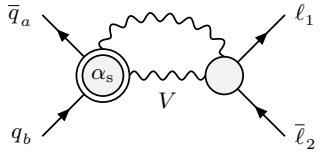


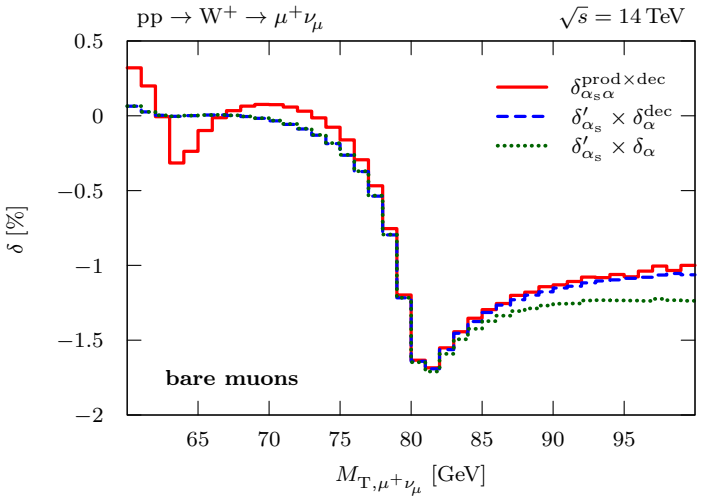
- Factorizable final×final

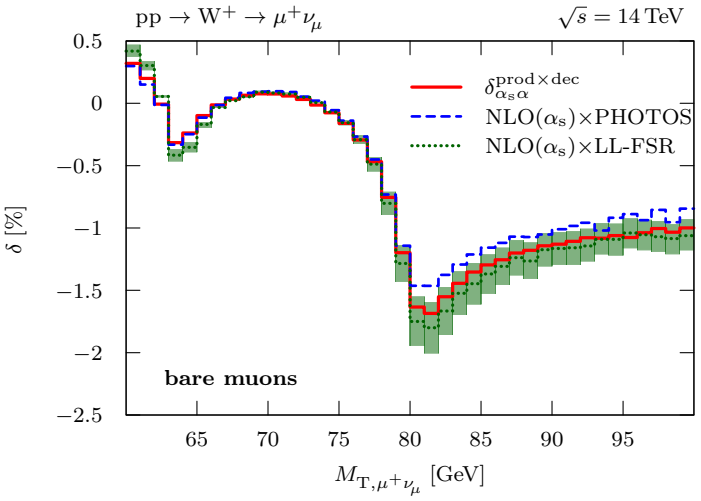
(finite counterterm from Djouadi/Gambino 93; negligible effect)



- Non-factorizable corrections (numerically negligible)







Comparison of different approximations:

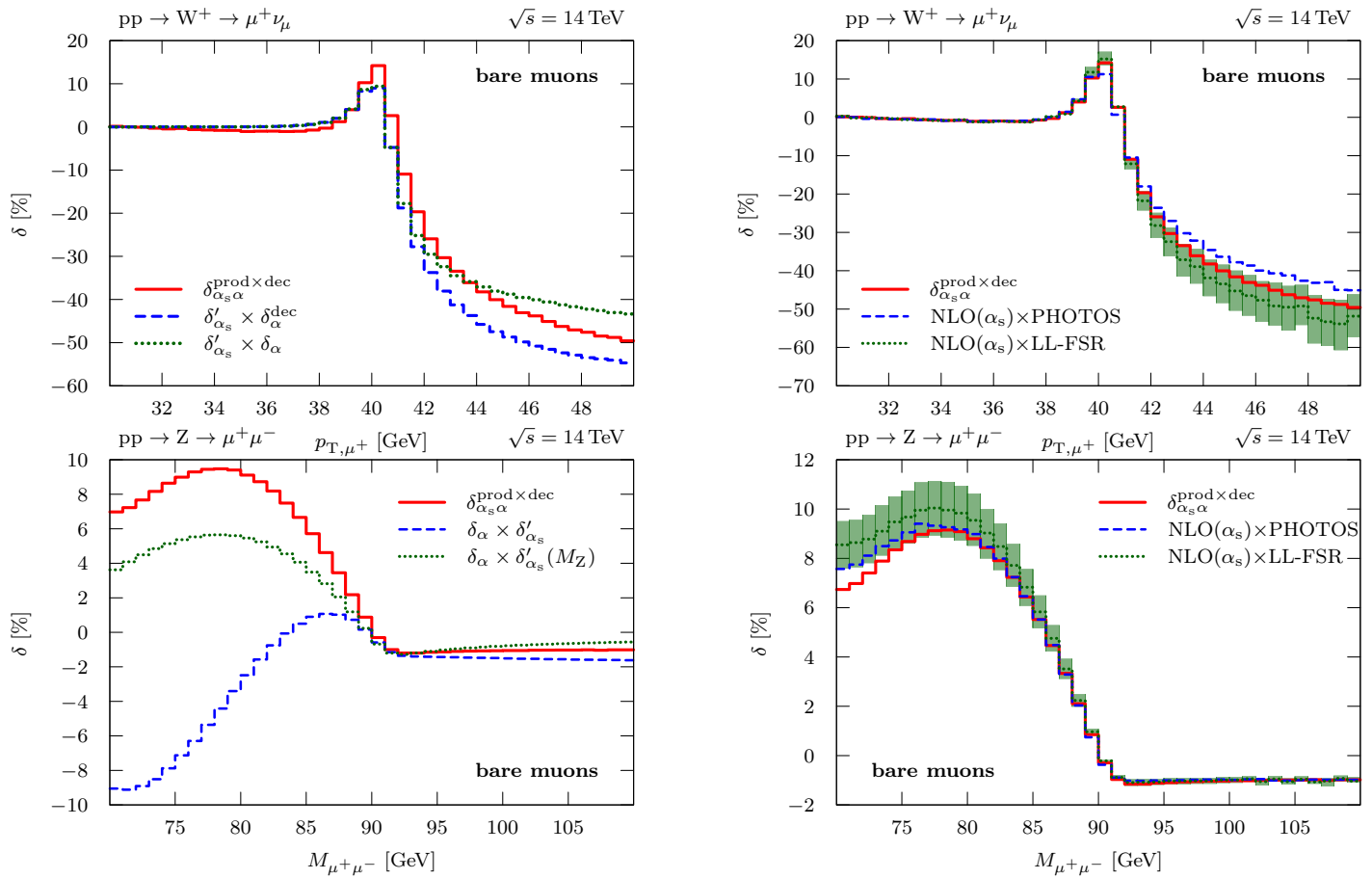
- $\delta^{\text{prod}\times\text{dec}}_{\alpha_s\alpha}$: factorizable initial-final $\mathcal{O}(\alpha_s\alpha)$ corrections
- Naive product of NLO corrections

$$\delta'_{\alpha_s}\delta_\alpha = \left(\frac{\sigma^{\text{NLO}_s}-\sigma^0}{\sigma^{\text{LO}}}\right) \times \frac{\Delta\sigma^{\text{NLO}_{\text{ew}}}}{\sigma^0}$$

where $\sigma^{\text{LO}}/\sigma^0$: LO/NLO PDFs

- $\text{NLO}(\alpha_s)\otimes$ LL^{1}FSR: NLO QCD cross section convoluted with LL-FSR structure function
- $\text{NLO}(\alpha_s)\otimes$ PHOTOS: NLO QCD cross section with single photon emission generated with γ-shower (Golonka/Was 06)

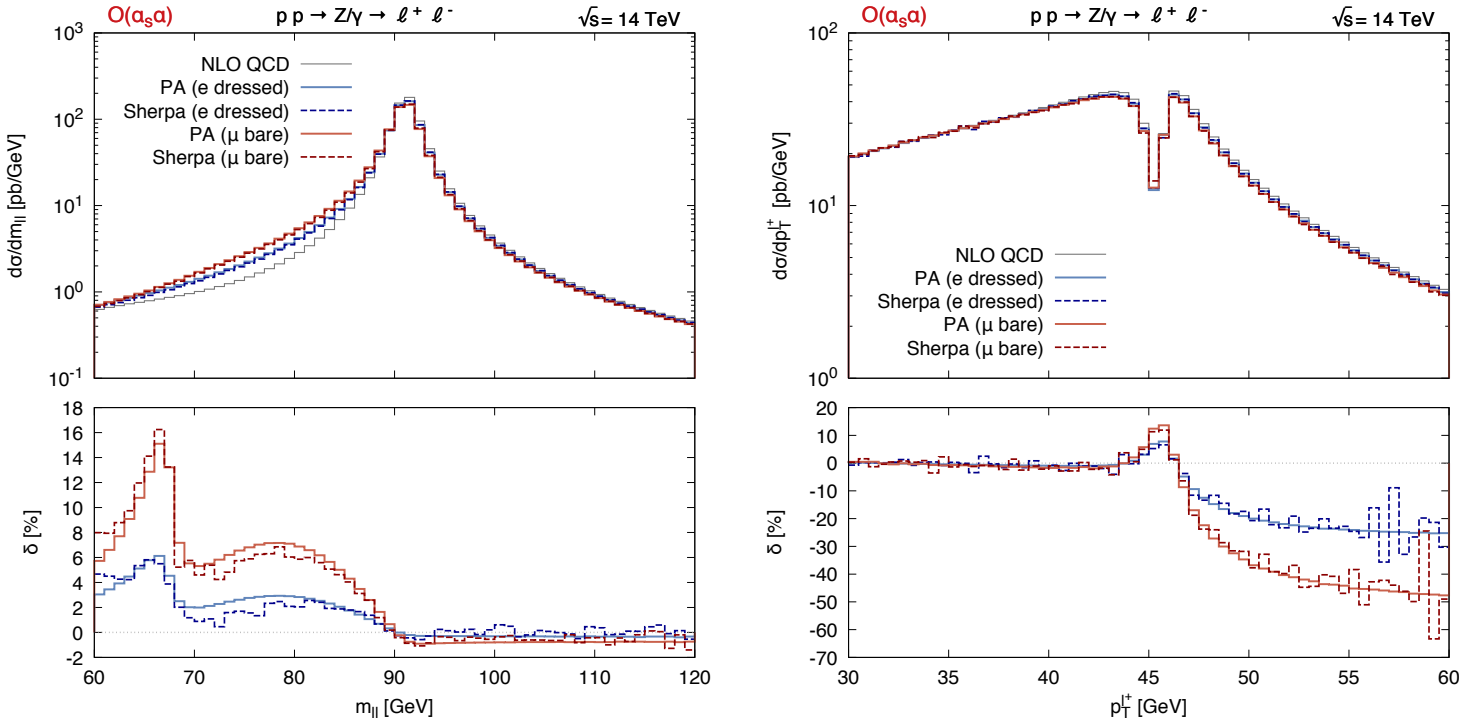
Mixed QCD-EW corrections



- naive product of K-factors only appropriate for observables dominated by resonance and insensitive to ISR
- reasonable agreement of LL-FSR with full result.

  (comparison to YFS photon resummation in Sherpa: Huss/Schönherr in Les Houches 15)

Comparison of factorizable initial-final $\mathcal{O}(\alpha_s\alpha)$ corrections to YFS photon resummation in Sherpa: (Huss/Schönherr in Les Houches 15)



good agreement, although some different effects included:

- YFS-Sherpa includes multi-photon emission
- Pole approx. includes finite weak NLO corrections

Summary

NLO-EW

- new features compared to QCD

  (lepton mass-effects, input parameter schemes, EW gauge invariance, finite widths)
- automated NLO-EW in multi-purpose MCs not yet tailored to DY-precision physics (treatment of lepton masses, IBA,...)
- First examples of Matching/Multi-jet merging of EW corrections (resonance-aware matching; so far merging in $\mathrm{EW}_{\mathrm{virt}}$ approx.)

Mixed EW/QCD corrections

- no full calculations available yet
- Approaches for EW precision physics near W/Z resonances:
  - pole approximation: initial-final corrections known.
  - POWHEG matching of NLO EW and QCD shower
- dominant effects captured by matching NLO QCD+EW to multi-photon radiation in collinear limit.
- To do: tuned comparison of PA to $\mathcal{O}(\alpha_s\alpha)$-contrib. of PS

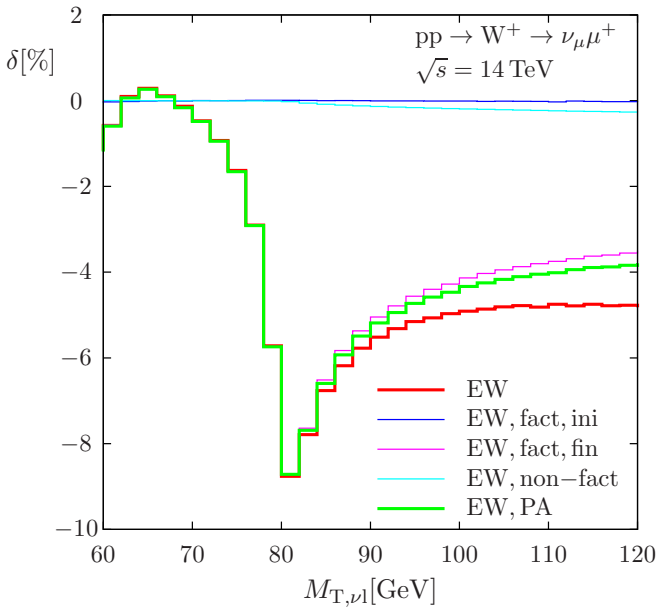
Backup slides

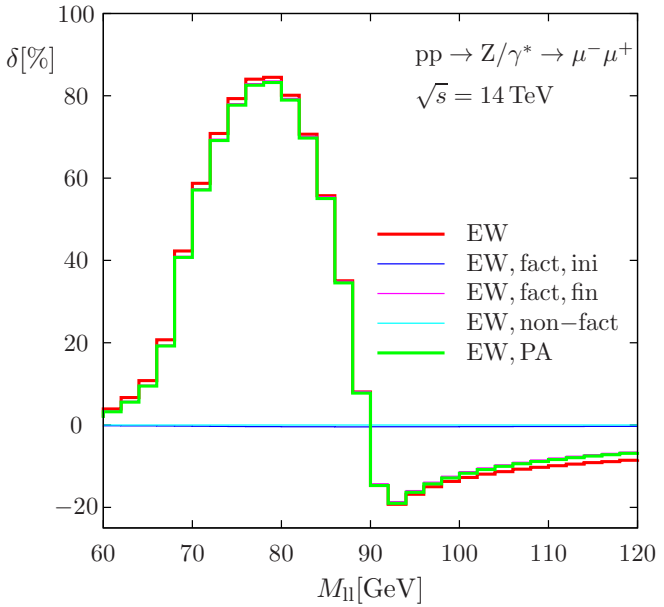
Application of pole approximation to EW corrections at NLO

(Wackeroth/Hollik 96; Baur et al. 98;

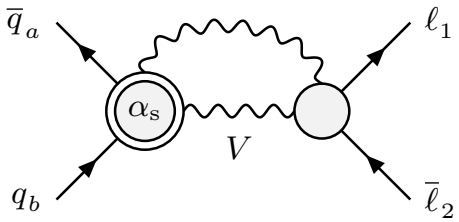
Dittmaier/Krämer 01; Dittmaier/Huss/CS 14)

- 0.1% accuracy near peak
- final-state factorizable corrections dominant
- initial-state factorizable and soft non-factorizable corrections suppressed





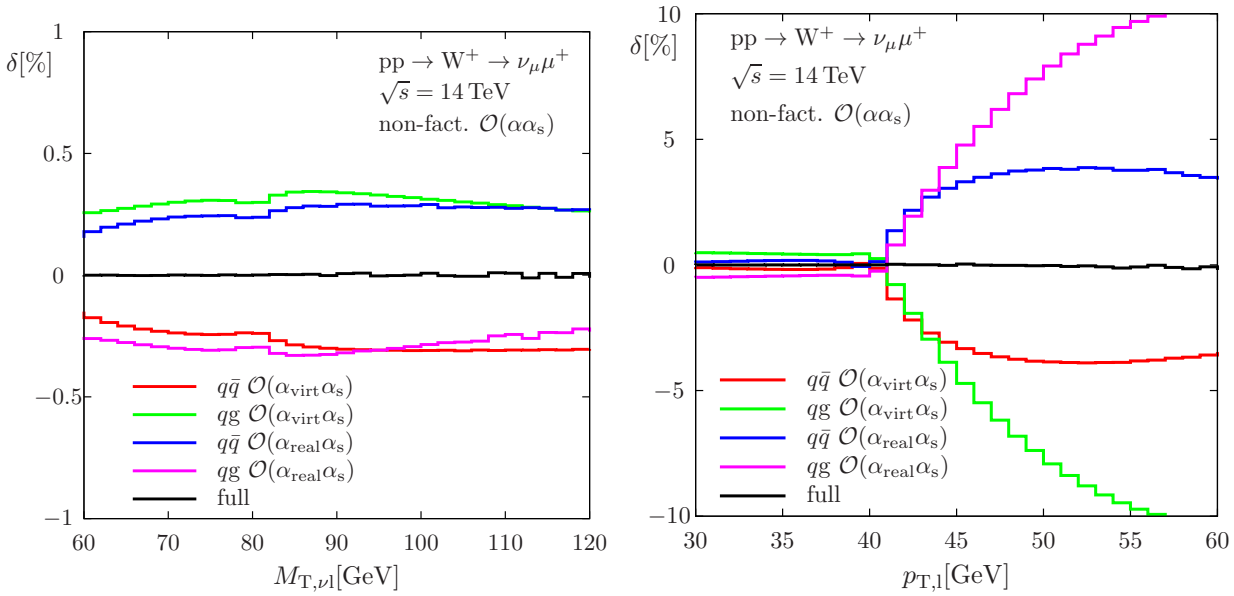
Non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections



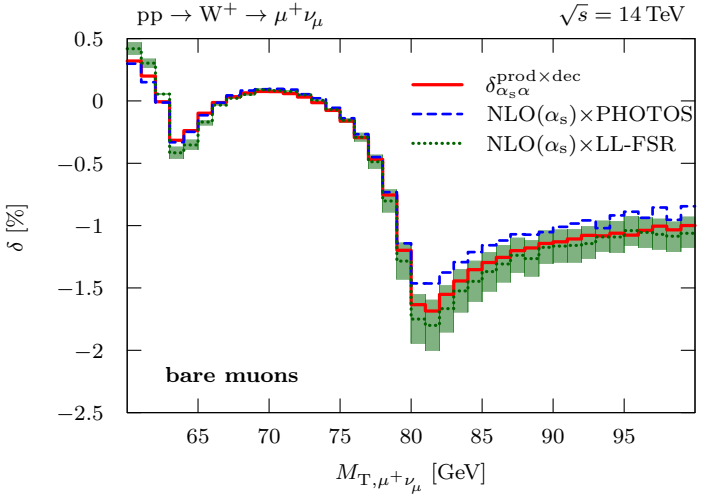
Numerical results:

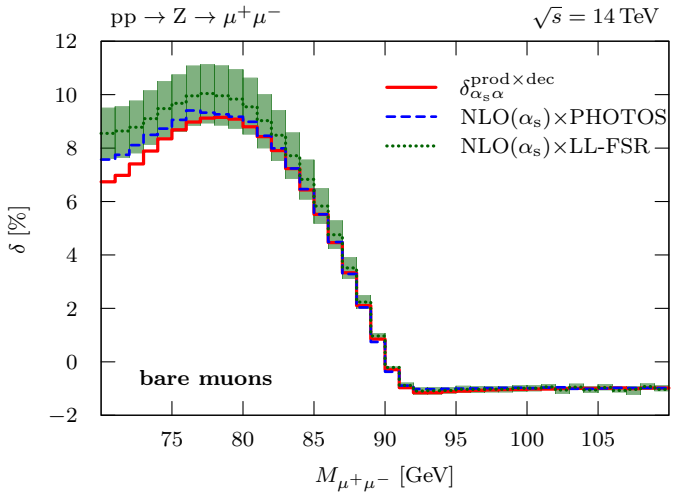
practically complete cancellation of real and virtual corrections

(defined separately through soft slicing with $\Delta E_\gamma \ll \Gamma_V$ in real corrections)



Comparison of $\mathcal{O}(\alpha_s\alpha)$ corrections in pole-approximation to leading-logarithmic approximation to FSR





- LL1FSR: Convolution of NLO QCD cross section with one-loop structure function

$$\Gamma_{\ell\ell}^{\mathrm{LL},1}(z,Q^2) = \frac{\beta_\ell}{4}\left(\frac{1+z^2}{1-z}\right)_+ \,,\; \beta_\ell = \frac{2\alpha(0)}{\pi}\left[\ln\left(\frac{Q^2}{m_\ell^2}\right)-1\right]$$

- Photos: NLO QCD with γ-shower restricted to single emission

(Golonka/Was 06)

$\Rightarrow$ reasonable agreement of LL approximation with full result.

Estimate effect of higher-order corrections on M_W measurement:

- χ^2 fit of $M_{T,\nu\ell}$ distribution in interval

  $$M_{T,\nu\ell} = 64.4 - 90.5\,\text{GeV}$$

  with $\Delta M_{T,\nu\ell} = 1\text{GeV}$ bins

- "Templates": LO prediction for

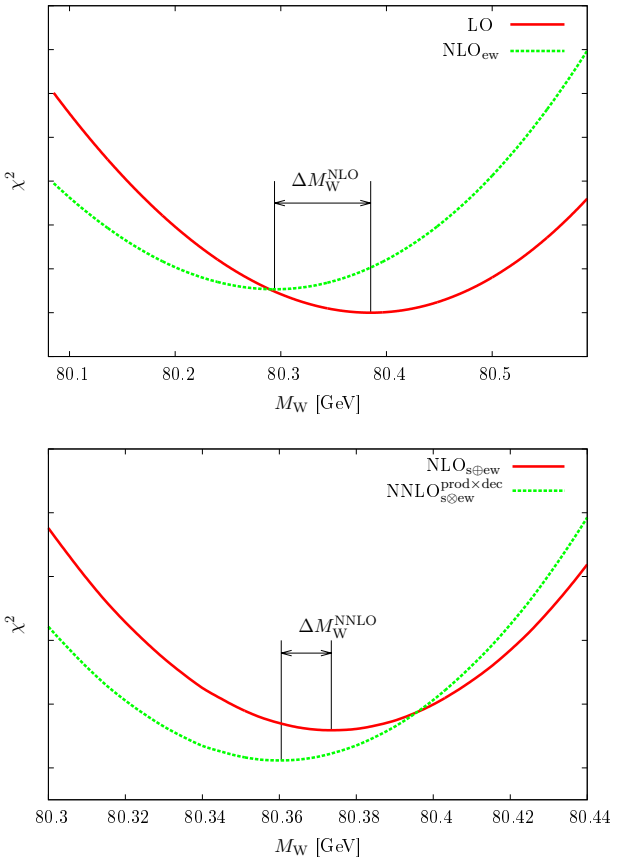
  $$M_W = \begin{cases} 80.085 \ldots 80.785\,\text{GeV}, & (\Delta M_W = 10\,\text{MeV}) \\ 80.285 \ldots 80.485\,\text{GeV}, & (\Delta M_W = 5\,\text{MeV}) \end{cases}$$

- "Data": different theory predictions

  (normalized to same σ in $M_{T,\nu\ell}$ interval)

- Shift from LO $\to$ NLO$_{\text{EW}}$:

  $$|\Delta M_W^{\text{NLO}}| \approx 90\text{MeV}$$



- Shift from NLO$_{\text{EW+QCD}}$ $\to$ NNLO$^{\text{prod-dec}}$

  $$|\Delta M_W^{\text{NNLO}}| \approx 14\ \text{MeV}$$

  (partially included in current analysis through NLO-QCD+Photos)

PS matching for DY

Implementation in POWHEG BOX (Carloni Calame et al. 16)

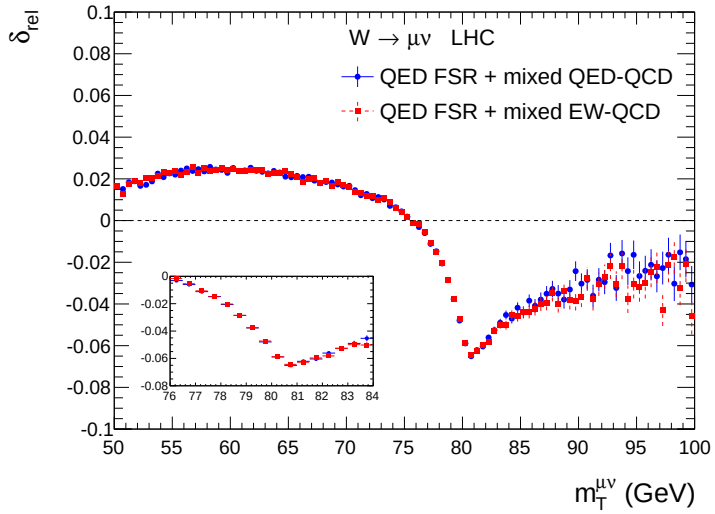
- Full NLO EW and QCD corrections matched to QCD and photon showers (Pythia/Photos)
- $\texttt{POWHEG}_{\texttt{two-rad}}$: generate first photon and gluon emissions with POWHEG (removes spurious $\mathcal{O}(\alpha_s\alpha)$ effect in Barzè et al. 12/13)

  (independent implementation using resonance-improved POWHEG: Mück/Oymanns 16)

$\Rightarrow$ includes approximation to initial-final QCD$\otimes$ EW corrections + additional multi-gluon/photon emission

- $\mathcal{O}(\alpha_s)\otimes$Photos in good agreement with matched NLO-EW
- discrepancies to Pythia photon shower reduced by matching

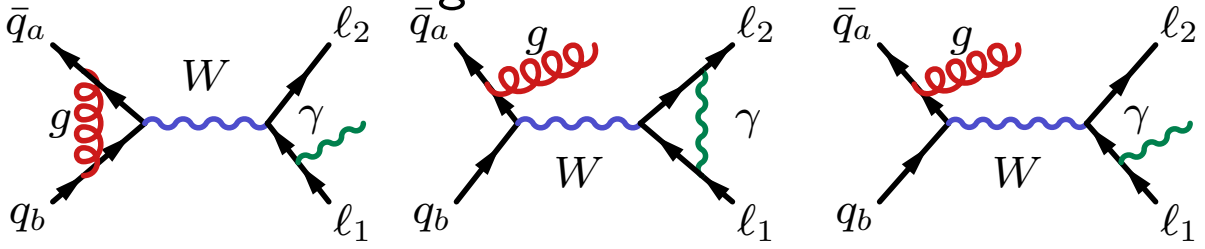
$\Rightarrow$ matching to NLO-EW for reliable prediction



PS matching for DY

Common to calculations with PS and in pole approximation:

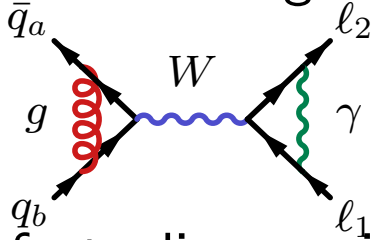
- Initial $\times$ final fact. diagrams included in POWHEG BOX:



Differences to pole approximation

- Only first emission in double-real correction
  treated exactly in POWHEG
- POWHEG includes multiple gluon/photon radiation;
  partial initial-initial corrections

Double-virtual initial $\times$ final fact. diagram not included in POWHEG



Double-real initial $\times$ final fact. diagram included in POWHEG