NNLO Mixed QCD-EW corrections to Drell-Yan processes in the resonance region

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based on S. Dittmaier, A. Huss, CS, Nucl.Phys. B885 (2014) 318, arXiv:1403.3216 [hep-ph]; arXiv:1405.6897 [hep-ph] and work in progress

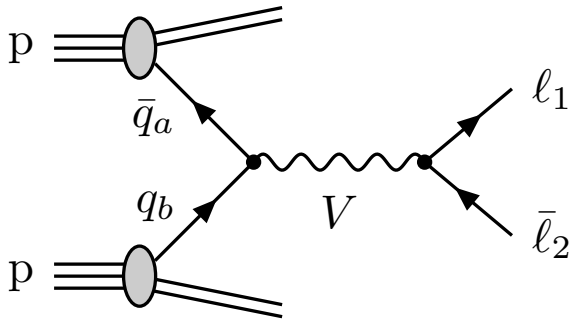
Drell-Yan processes:

- "Neutral current":

$$\bar{q}_a(p_a) + q_b(p_b) \to \ell^+(k_1) + \ell^-(k_2) + X$$

- "Charged current":

$$\bar{q}_a(p_a) + q_b(p_b) \to \ell(k_1) + \nu_\ell(k_2) + X$$



Phenomenological relevance:

- important "standard candles" (Luminosity, PDFs)
- new-physics searches at high p_T (Z')
- precision electroweak physics (M_W, $\sin\theta_W$)

Theoretical laboratory:

- QCD factorization
- early applications of NLO, NNLO
- development of resummation methods

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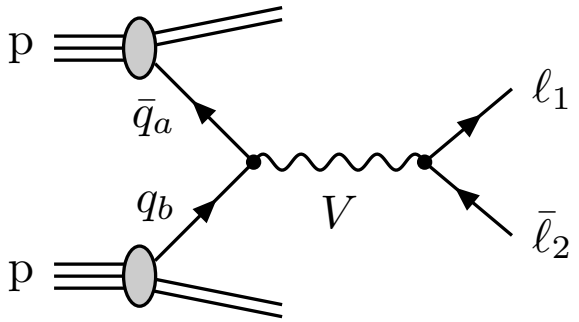
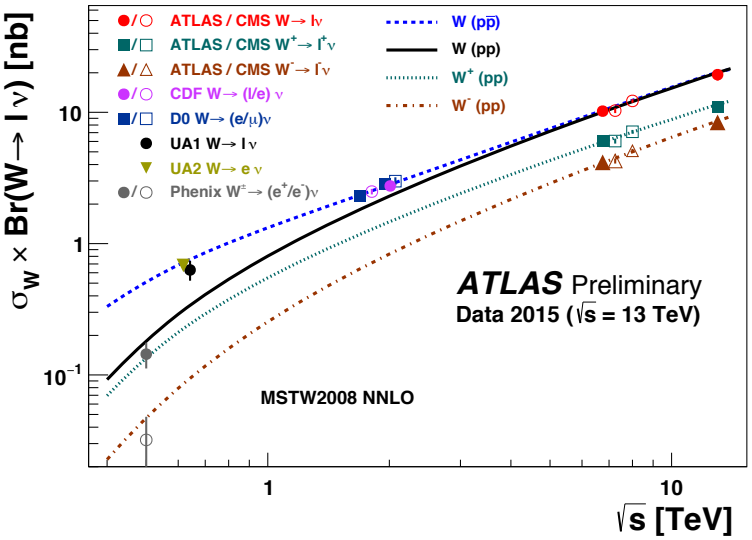
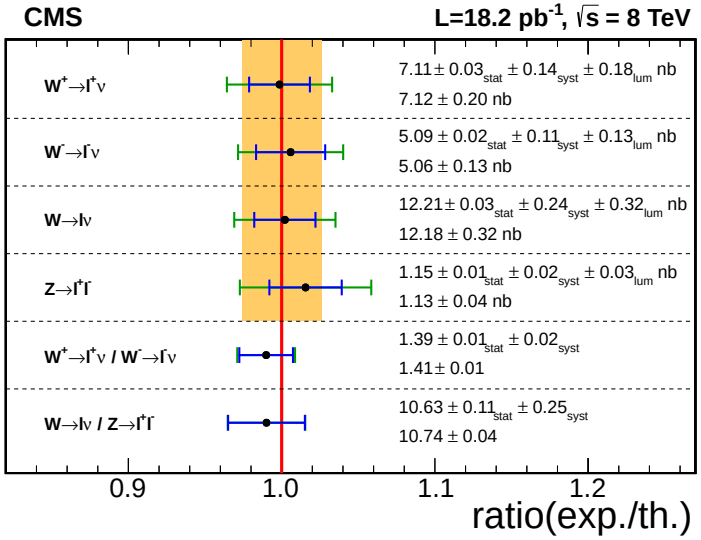


Total cross sections: consistent with NNLO QCD





Key observables

- Invariant mass M_{ll} of lepton pair for neutral current DY
- Transverse lepton momentum $p_{T,\ell}$
- Transverse mass

$$M_{T,\nu\ell} = \sqrt{2\, p_{T,\ell}\, E_T^{\text{miss}} (1 - \cos\phi_{\nu\ell})}$$

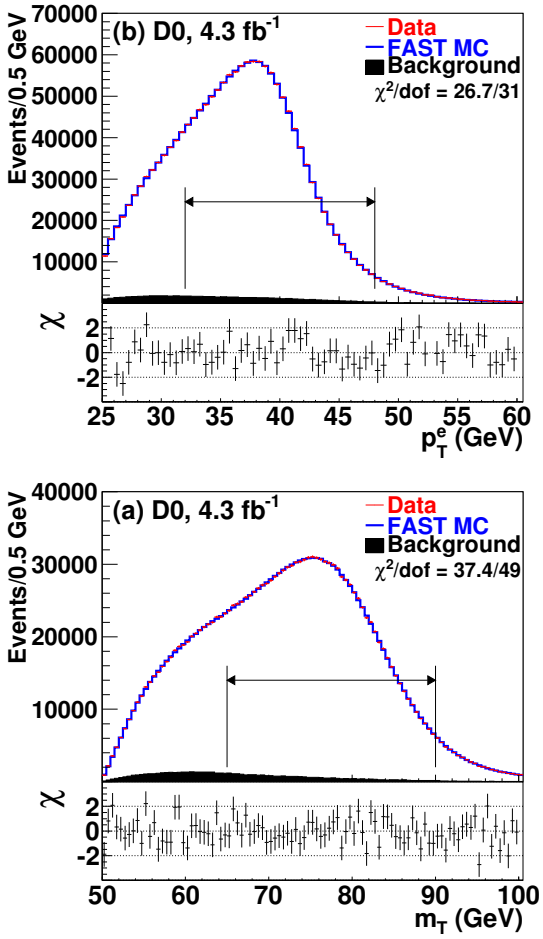
Tevatron results

- $M_W = 80.387 \pm 0.016\,\text{GeV}$
- Direct measurement of Γ_W

$$\Gamma_W = 2.046 \pm 0.049\,\text{GeV}$$

LHC prospects: $\Delta M_W \sim 5$–$8\,\text{MeV}$

(Limited by pileup and PDF uncertainties:
e.g. Rojo/Vicini 13, Quackenbusch/Sullivan 15,
Bozzi et al. 15)



(arXiv:1310.8628 [hep-ex])

Theory status

QCD:

- NLO calculations matched to parton showers

  MC@NLO (Frixione/Webber 06), POWHEG (Alioli et al. 08; Hamilton et al. 08), SHERPA (Höche et al.)

- NNLO partonic differential cross sections

  FEWZ (Melnikov/Petriello 06; Gavin et al. 10/12), DYNNLO (Catani et al. 09)

  NNLO+PS (Höche/Li/Prestel; Karlberg/Re/Zanderighi 14; Alioli et al. 15)

- NNLL analytic resummation at small p_T

  RESBOS (Balazs/Yuan 97; Guzzi et al. 13), DYqT(Bozzi et al. 10),

EW

- full NLO (Dittmaier/Krämer 01; Baur et al. 01;...)

  implemented in W/ZGRAD (Bauer et al.),

  Horace (Carloni Calame et al.), RADY (Dittmaier), FEWZ (Li/Petriello 12),

  SANC (Arbuzov et al.)

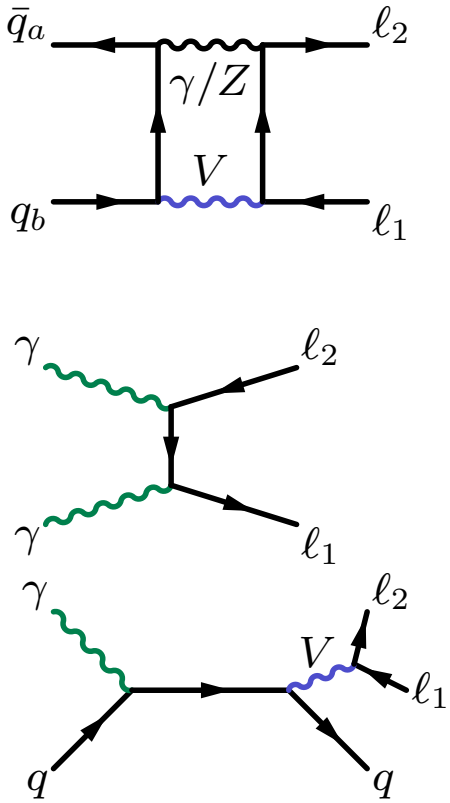
- Multi-γ radiation using Photos (Golonka/Was 06), Horace

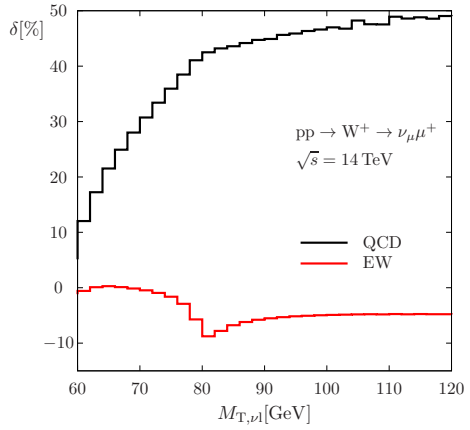
Features of EW corrections

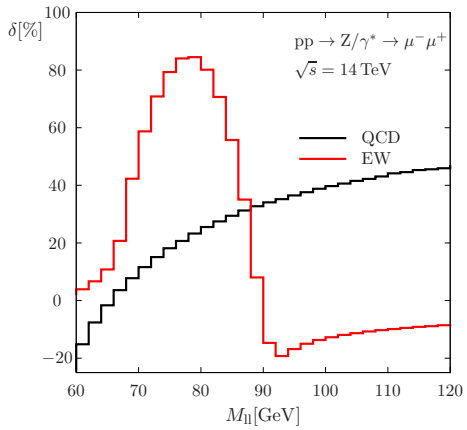
- connecting initial and final state
- consistent treatment of decay widths necessary (e.g. complex mass scheme)

$$\log\left(\hat{s} - M_V^2\right) \to \log\left(\hat{s} - M_V^2 + \mathrm{i}M_V\Gamma_V\right)$$

- reconstruction of "bare" muons
  $\Rightarrow$ logarithmic dependence $\sim \alpha \log\left(m_\mu^2/\hat{s}\right)$
- Photon-induced production processes
  (recent photon PDF: NNPDF2.3QED)







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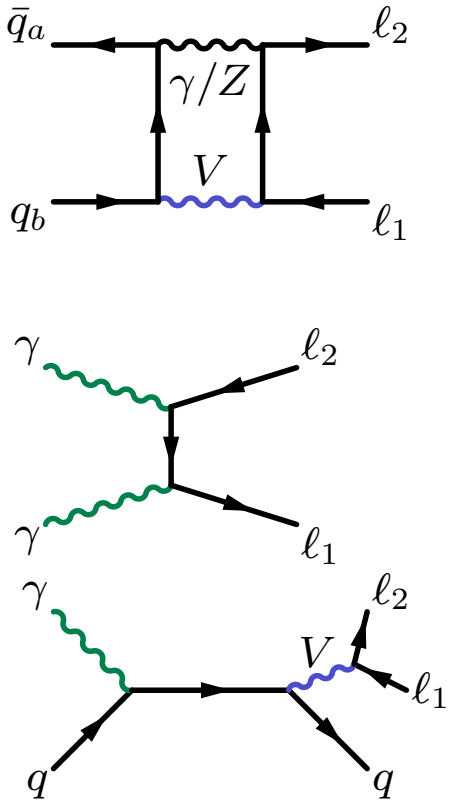
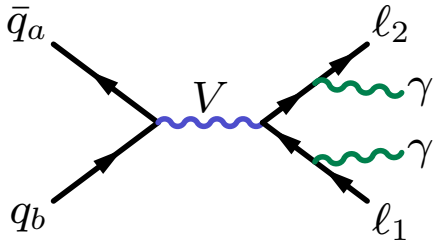


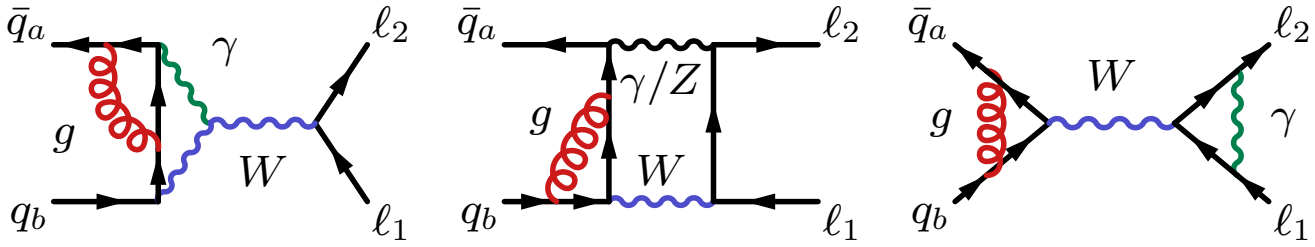
Dominant effects beyond NLO

- multi-photon radiation (Baur/Stelzer 99; Carloni Calame et al. 03, `Photos`: Golonka/Was 06)
- Sudakov logarithms $\alpha \log(\hat{s}/M_W^2)$ at large $\hat{s}$
  (e.g. Kühn et al. 07; Becher/Garcia i Tormo 13)



Mixed QCD ⊗ EW corrections not calculated yet:

NNLO calculation with different mass scales, finite widths:



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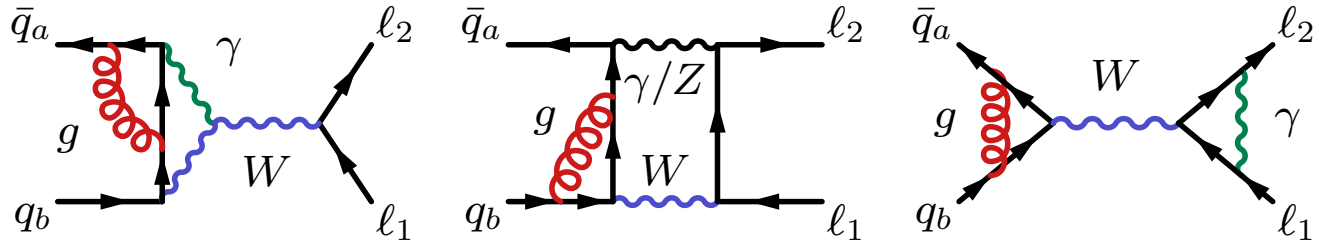


Several ingredients or approximations known:

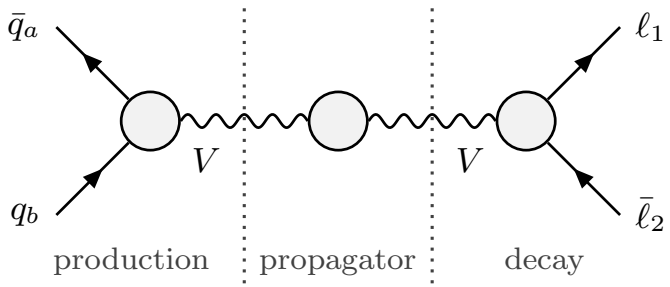
- Additive/multiplicative combinations (Cao et al. 04; Balossini et al. 09; Richardson et al. 10; Li/Petriello 12)
- Two loop results (Czarnecki/Kühn 96; Kara 13, Kotikov/Kühn/Veretin 07; Kilgore/Sturm 12; work in progress by Bonciani et al.)
- Implementation of EW corrections in NLO-matched QCD parton showers (Bernaciak/Wackeroth 12; Barzè et al. 12/13)
- Application of pole scheme near resonance (Dittmaier/Huss/CS 14 and in progress)

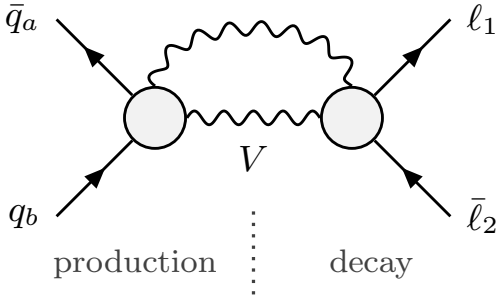
Pole scheme: (Stuart 91; Aeppli/v.Oldenbourgh/Wyler 93)

Expand around complex pole of propagator $\mu^2 = M^2 - \mathrm{i}M\Gamma$

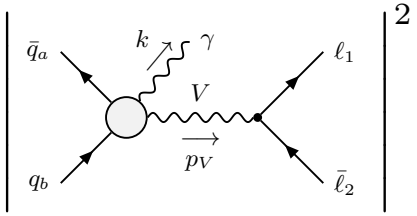
- Factorizable corrections to on-shell prod. and decay
- Non-fact. soft-photon corrections

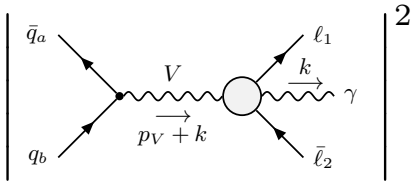
Virtual corrections

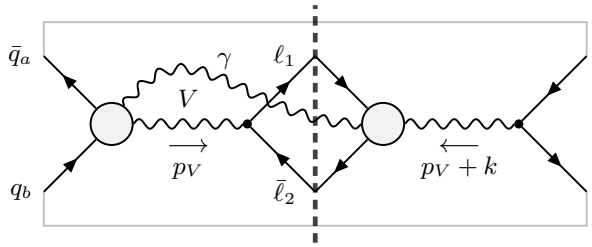




Real corrections







fact.-initial fact.-final non-factorizable

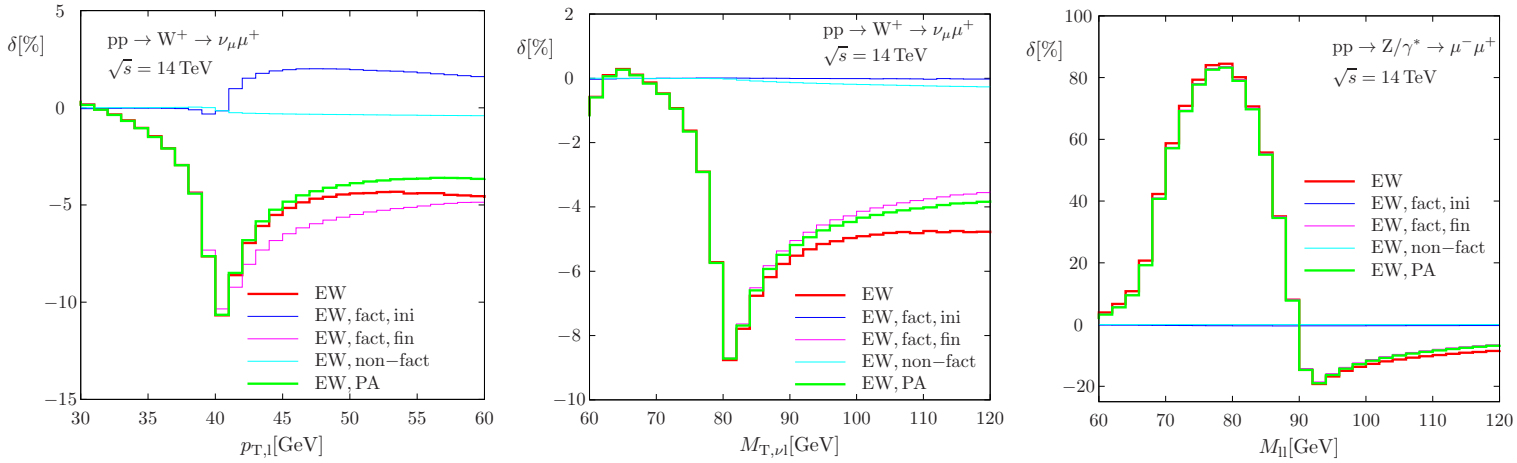
Pole scheme: (Stuart 91; Aeppli/v.Oldenbourgh/Wyler 93)

Expand around complex pole of propagator $\mu^2 = M^2 - \mathrm{i}M\Gamma$

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

Application to EW corrections at NLO

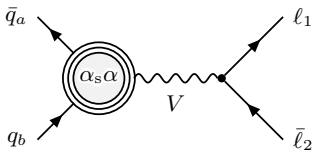
- 0.1% accuracy near peak
- final-state factorizable corrections dominant
- soft non-factorizable corrections suppressed



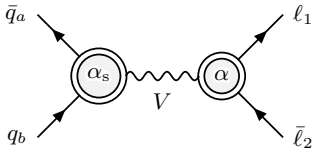
EW/QCD corrections in pole approximation (Dittmaier/Huss/CS)

(+ corresponding real-virtual and double real)

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

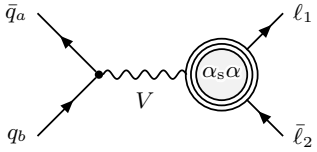


- Factorizable initial×final (expected to be dominant, to be published soon)

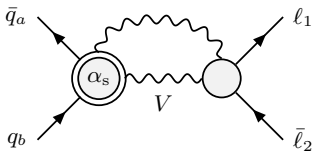


- Factorizable final×final

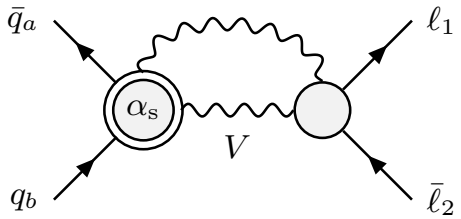
(from counterterm, can be obtained from Djouadi/Gambino 93)



- Non-factorizable corrections (completed, numerically negligible)



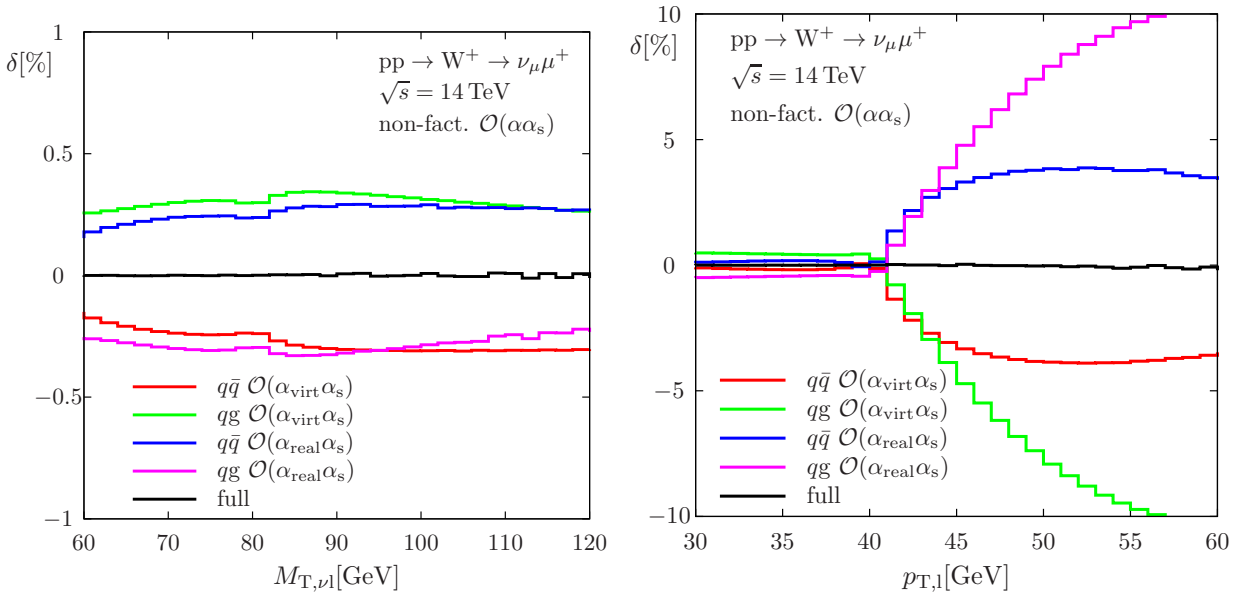
Non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections



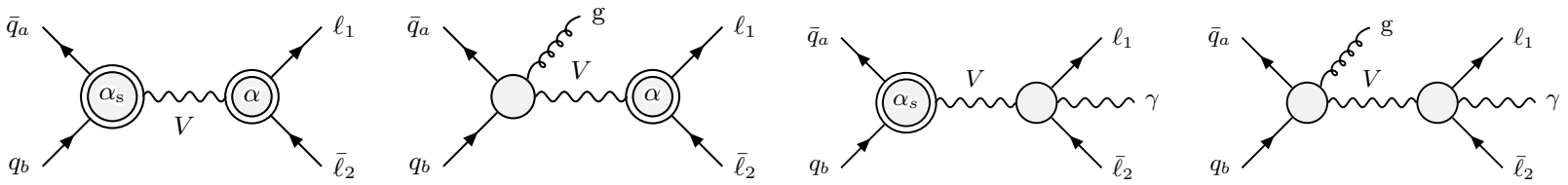
Numerical results:

practically complete cancellation of real and virtual corrections

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

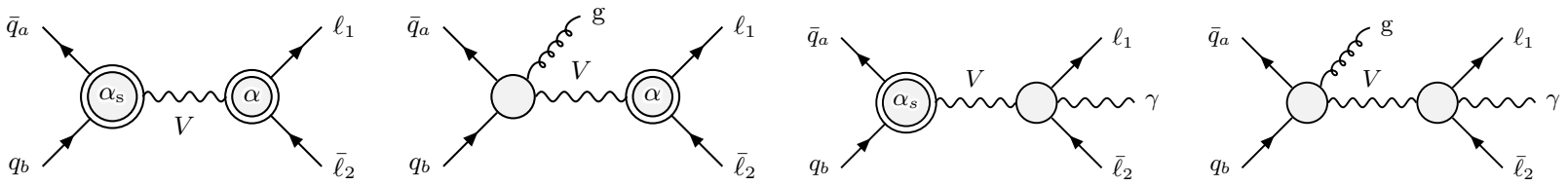


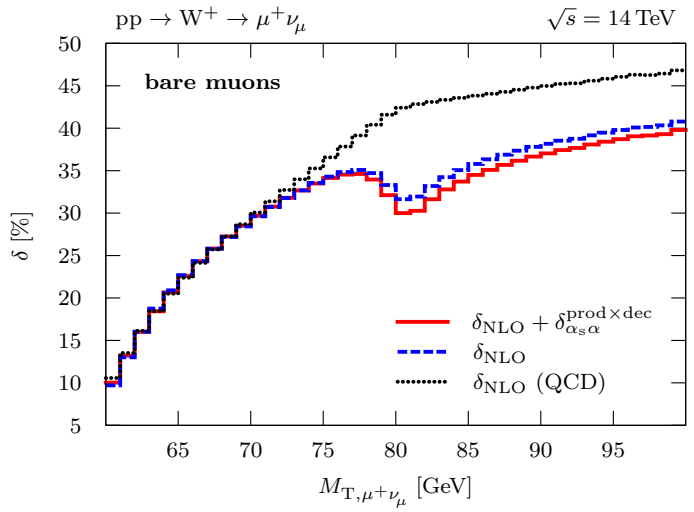
Factorizable initial$_{\mathrm{QCD}}\otimes$ final$_{\mathrm{EW}}$ corrections (Dittmaier/Huss/CS in progress)

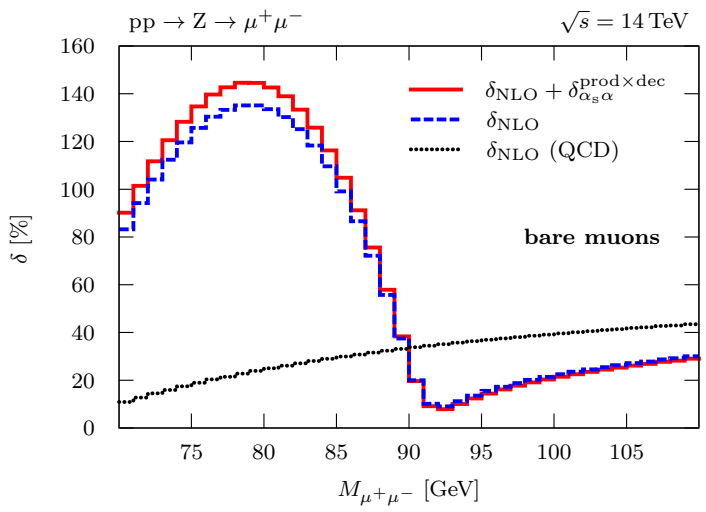


- double-virtual, real-virtual and double-real contributions
- mainly reducible to products of NLO QCD and EW corrections
- IR singularities regularized using extension of dipole-subtraction to decay processes (Basso/Ditmaier/Huss/Oggero 15)

Factorizable initial$_{\text{QCD}}\otimes$ final$_{\text{EW}}$ corrections (Dittmaier/Huss/CS in progress)

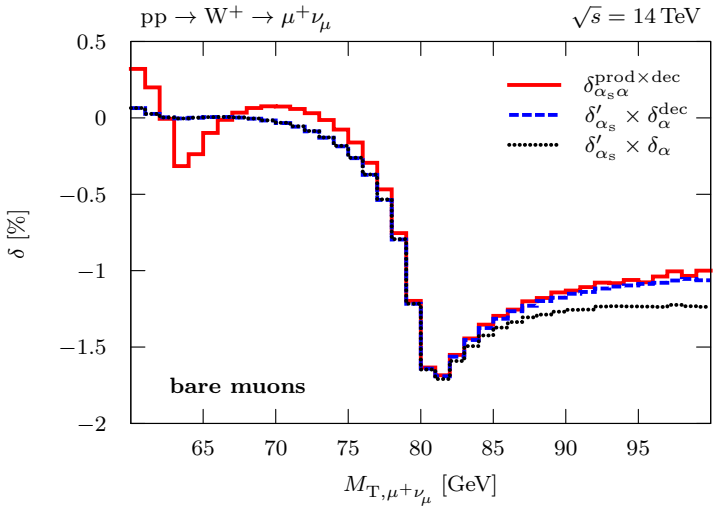


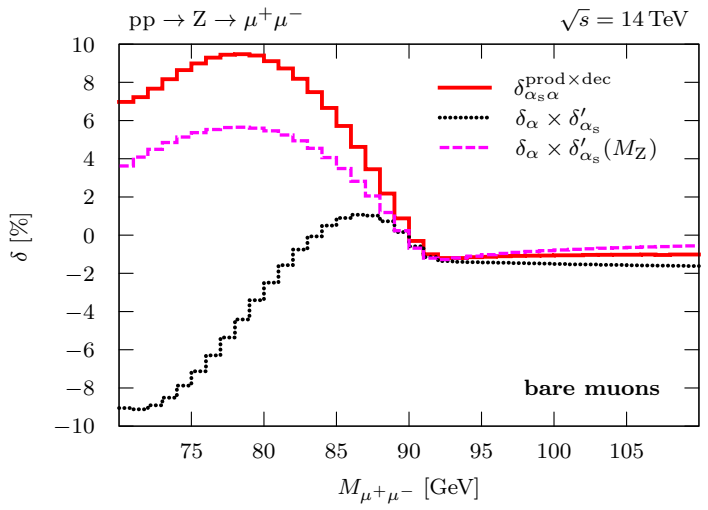




$\Rightarrow$ NNLO EW$\otimes$ QCD corrections of $1-10\%$.

Comparison of $\mathcal{O}(\alpha_s\alpha)$ corrections in pole-approximation to naive product of EW and QCD corrections

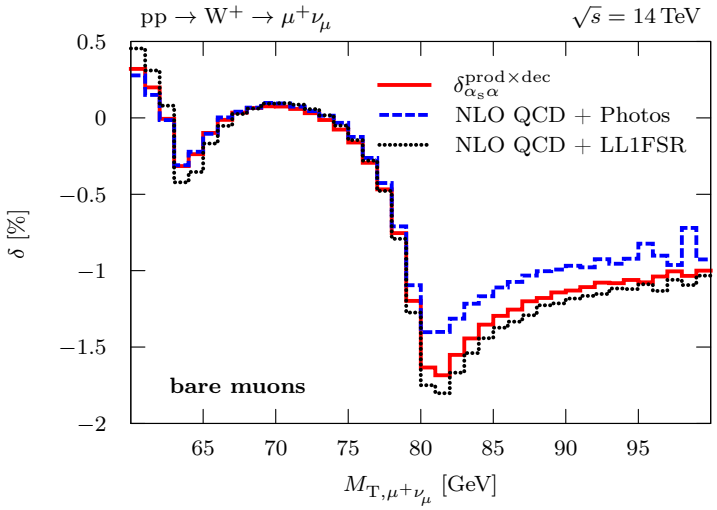


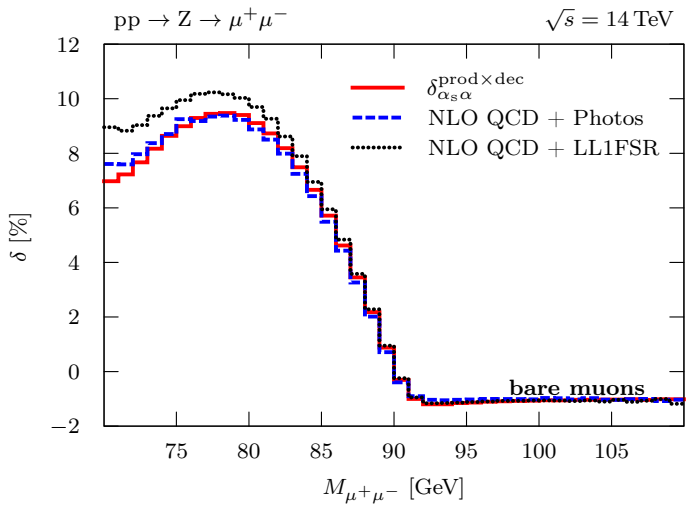


(Product ansatz: $\delta'_{\alpha_s}\,\delta_\alpha = \left(\frac{\sigma^{\mathrm{NLO}_s} - \sigma^0}{\sigma^{\mathrm{LO}}}\right) \times \frac{\Delta\sigma^{\mathrm{NLO}_{ew}}}{\sigma^0}$ with $\sigma^{\mathrm{LO}}/\sigma^0$: LO/NLO PDFs)

$\Rightarrow$ naive product only reasonable for observables dominated by resonance and insensitive to ISR

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

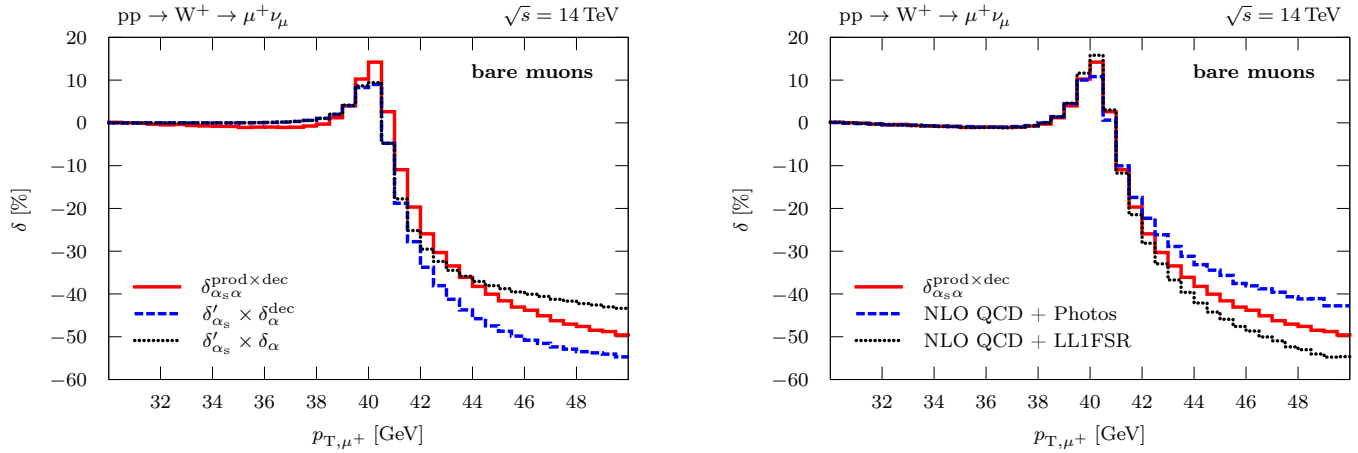
$$\Gamma^{\mathrm{LL},1}_{\ell\ell}(z,Q^2) = \frac{\beta_\ell}{4}\left(\frac{1+z^2}{1-z}\right)_+ , \quad \beta_\ell = \frac{2\alpha(0)}{\pi}\left[\ln\left(\frac{Q^2}{m_\ell^2}\right) - 1\right]$$

- Photos: NLO QCD with γ-shower restricted to single emission (Golonka/Was 06)

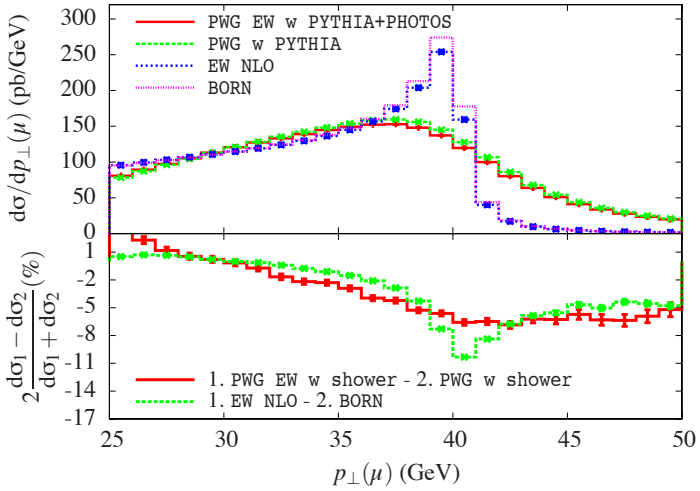
$\Rightarrow$ reasonable agreement of LL approximation with full result.

Mixed EW/QCD corrections: results

Comparison of $\mathcal{O}(\alpha_s\alpha)$ corrections for $p_{\mathrm{T},\ell}$ spectrum:
no naive factorization, better description by LL FSR



Parton shower resummation in POWHEG (Barzé et al. 12)



$\delta_{1/2}=(\sigma_1-\sigma_2)/\frac{1}{2}(\sigma_1+\sigma_2)$

Effect on M_W measurement

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

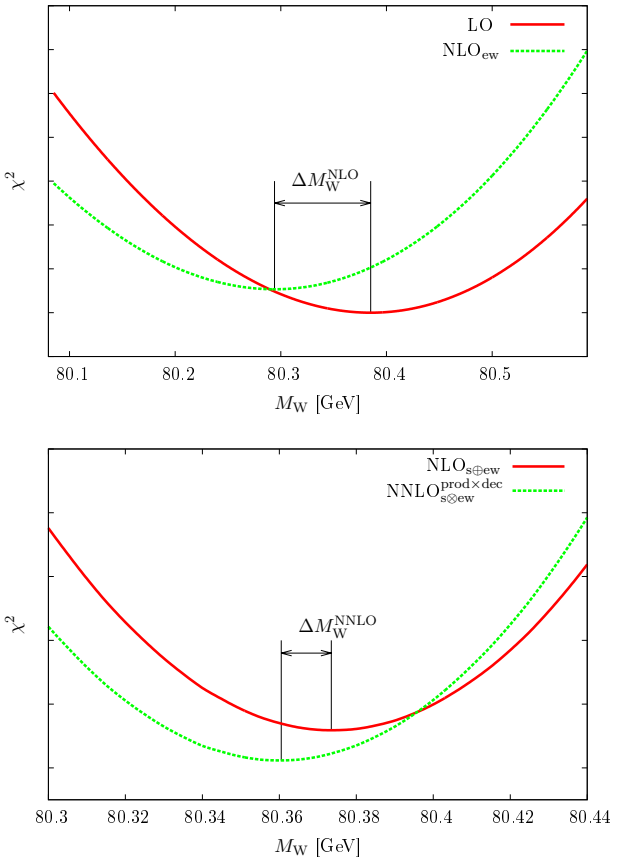
  $$M_W = \begin{cases} 80.085 \ldots 80.785\,\text{GeV}, & (\Delta M_W = 10\,\text{MeV}) \\ 80.285 \ldots 80.485\,\text{GeV}, & (\Delta M_W = 5\,\text{MeV}) \end{cases}$$

- "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$^{\text{prod}-\text{dec}}$

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

(Similar size as effect from multi-photon radiation, Carloni Calame et al. 03)

Summary

DY processes near resonance important for EW precision physics

Pole approximation near resonance

- expansion for $p_V^2 - M_V^2 \sim M_V \Gamma_V$
- factorizable corrections to on-shell production and decay, non-factorizable corrections

Mixed EW/QCD corrections at $\mathcal{O}(\alpha\alpha_s)$ in pole expansion

- negligible numerical effect of non-fact. corrections
- initial/final fact. corrections computed:
  - In general no naive factorization of K-factors
  - Estimated impact of $\sim 14\,\mathrm{MeV}$ on M_W measurement
  - reasonable agreement with LL approx. to FSR

Outlook initial-initial fact. corrections;
comparison to POWHEG implementations
matching to parton shower or analytic p_T resummation

Backup slides

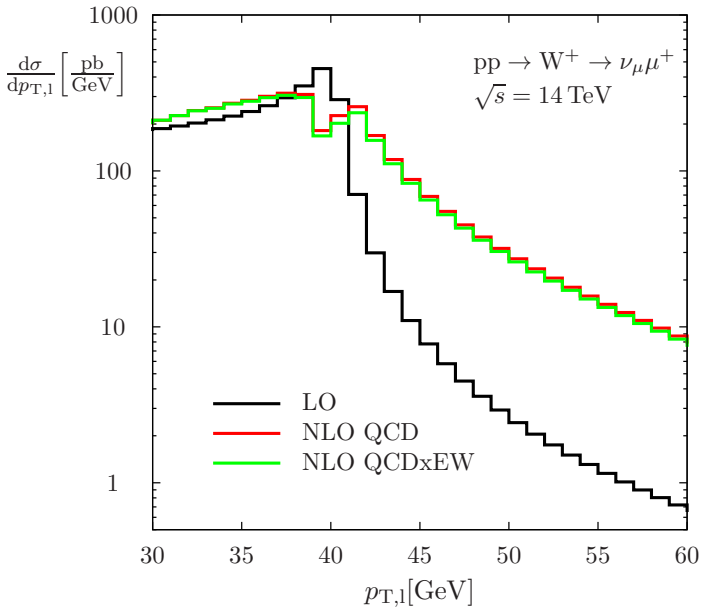
Numerical results
of NLO EW corrections

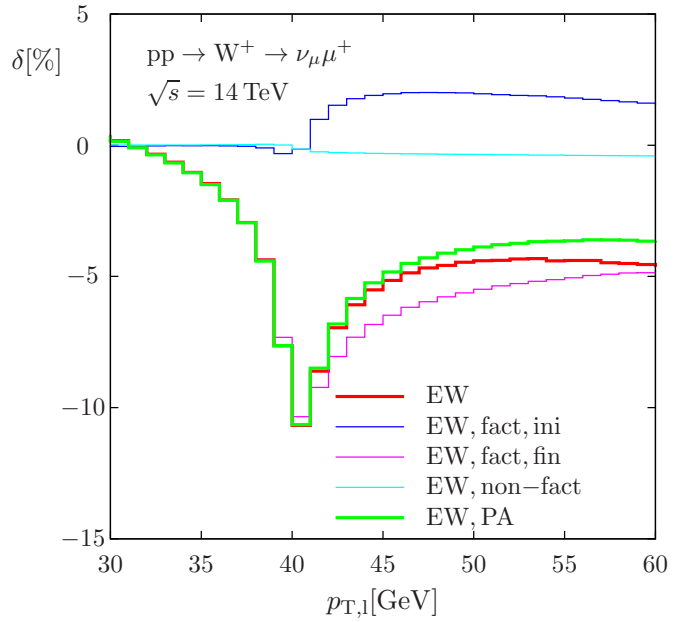
- corrections up to -20%; distort shape of resonance
- comparison of pole approx. to full EW NLO corrections: (Dittmaier/Krämer; Baur et al. 01) 0.1% accuracy near peak
- final-state factorizable corrections dominant
- soft non-factorizable corrections suppressed

(NNPDF2.3 PDFs, $\mu_r = \mu_f = M_W$

G_μ scheme, $\alpha_{G_\mu} = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right)$.

$p_{T,l} > 25$ GeV , $|\eta_l| < 2.5$, $E_T^{\text{miss}} > 25$ GeV)





Full NLO-EW

(Dittmaier/Krämer 01; Baur et al. 01;...)

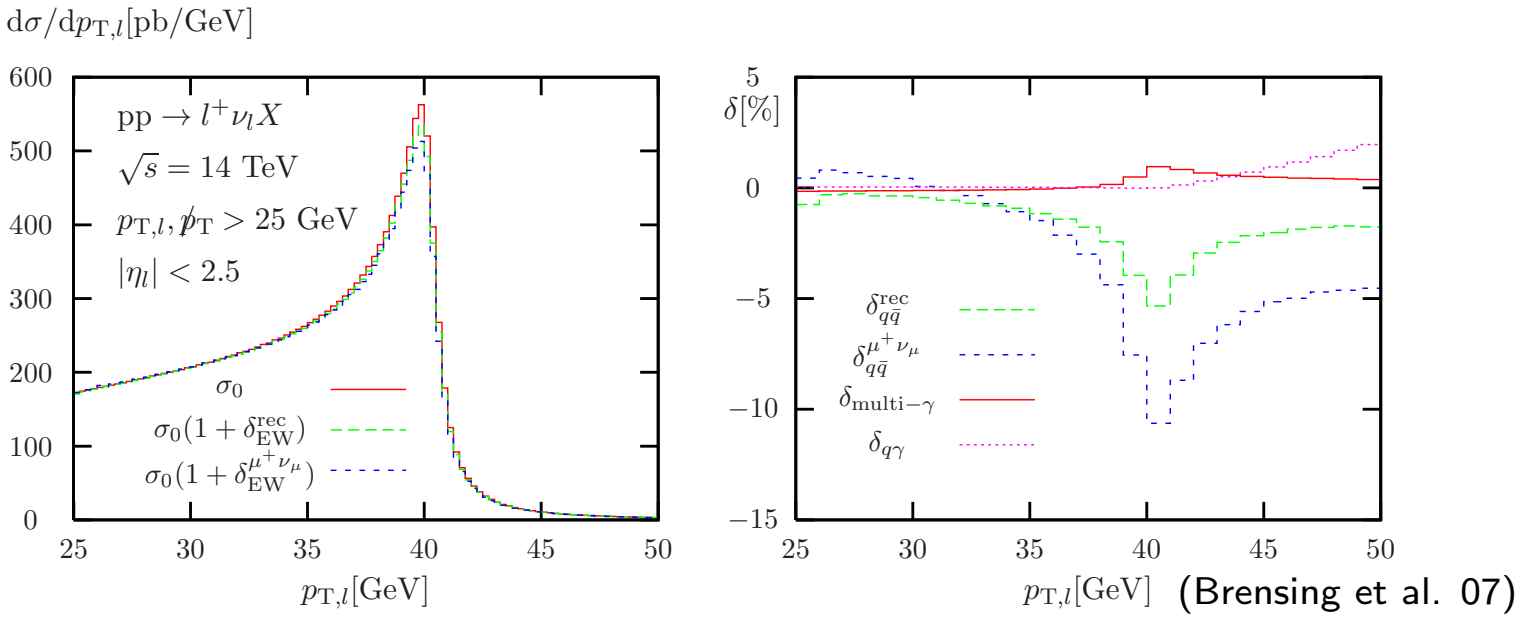
implemented in `W/ZGRAD` (Bauer et al.), `RADY`(Dittmaier),

`Horace` (Carloni Calame et al.), `FEWZ` (Li/Petriello 12), `SANC` (Arbuzov et al.)

Numerical results

- corrections distort shape of resonance; up to $+80/-20\%$.
- multi$-\gamma$ radiation $1-5\%$-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)

Full NLO-EW (Dittmaier/Krämer 01; Baur et al. 01;...)

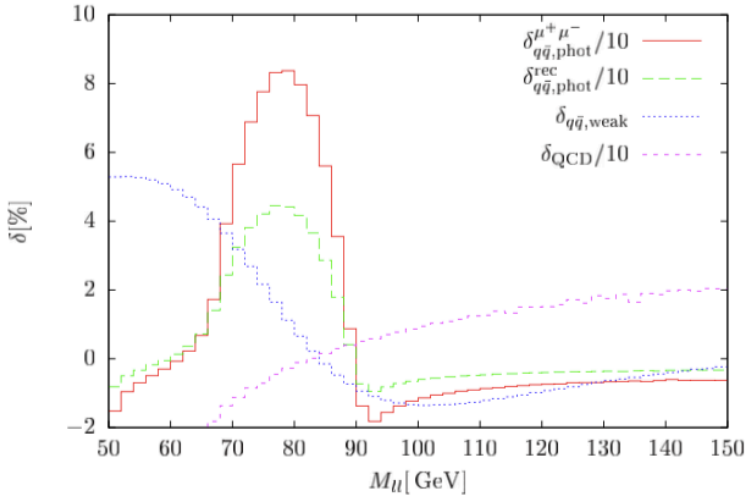
implemented in `W/ZGRAD` (Bauer et al.), `RADY`(Dittmaier),

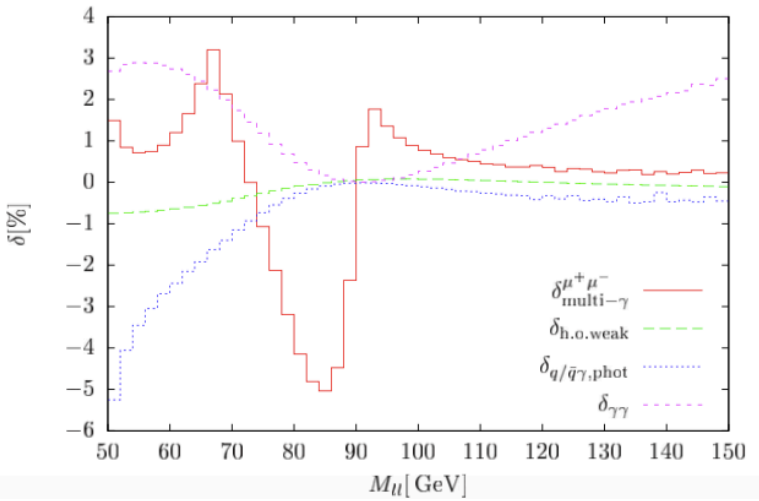
`Horace` (Carloni Calame et al.), `FEWZ` (Li/Petriello 12), `SANC` (Arbuzov et al.)

Numerical results

- corrections distort shape of resonance; up to $+80/-20\%$.
- multi$-\gamma$ radiation $1-5\%$-effect.
- Effect on M_W measurement:

  NLO: $\Delta M_W \approx 100$ MeV, multi-γ: $\Delta M_W \approx 10$ MeV





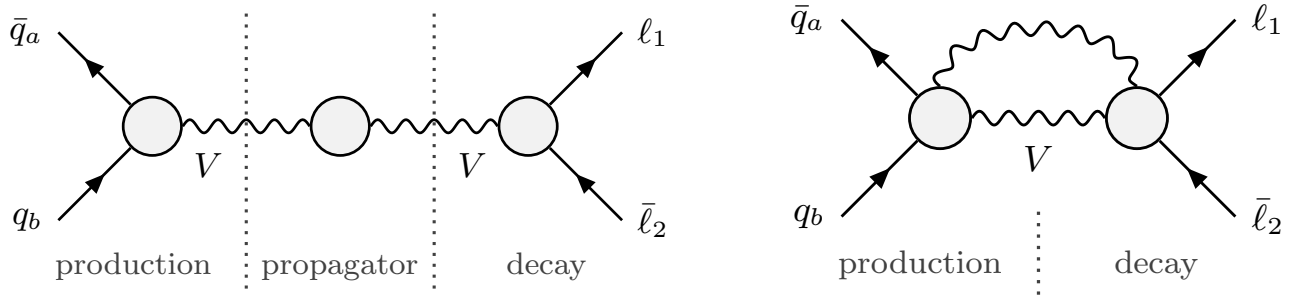
(Huber/Dittmaier 09)

Pole decomposition: expand around complex pole of propagator

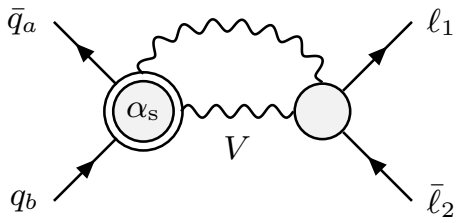
$$\mu^2 = M^2 - \mathrm{i}M\Gamma$$

$$\begin{aligned}
\mathcal{A}(s) &= \frac{R(s)}{s - M^2 + \Sigma(s)} + N(s) \\
&= \frac{R(\mu^2)}{s-\mu^2}\,\frac{1}{1+\Sigma'(\mu^2)} + \left[\frac{R(s)}{s - M^2 + \Sigma(s)} - \frac{R(\mu^2)}{s-\mu^2}\,\frac{1}{1+\Sigma'(\mu^2)}\right] + N(s) \\
&= \underbrace{\frac{R(\mu^2)}{s-\mu^2}\,\frac{1}{1+\Sigma'(\mu^2)}}_{\text{factorizable corrections}} + \underbrace{\left[\frac{R(s)}{s - M^2 + \Sigma(s)} - \frac{R(\mu^2)}{s-\mu^2}\,\frac{1}{1+\Sigma'(\mu^2)}\right]_{s\to\mu^2}}_{\text{non-factorizable corrections}} + \text{non-res.}
\end{aligned}$$

Virtual corrections



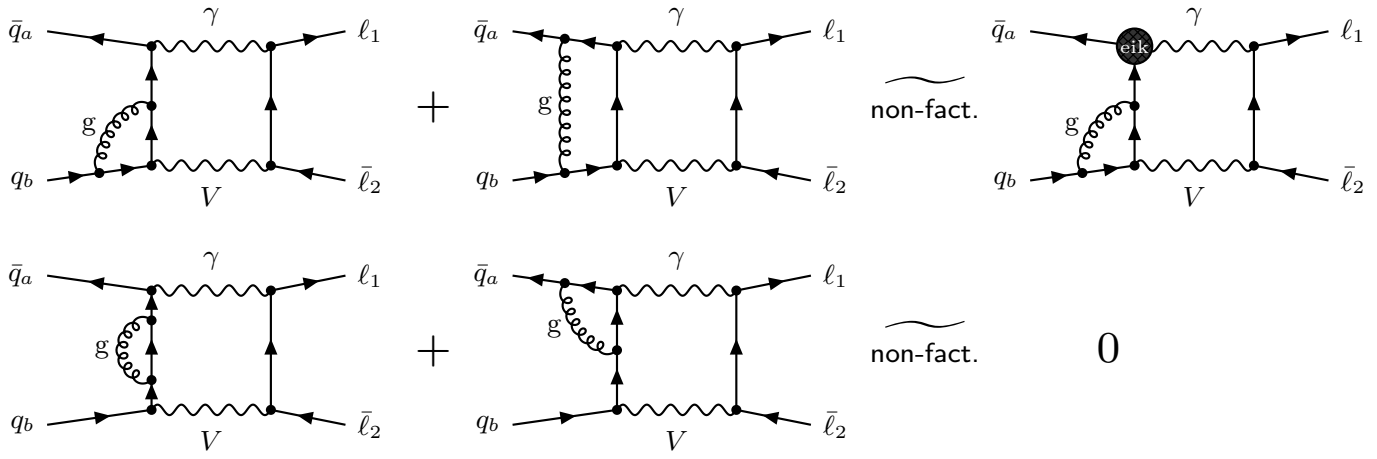
Non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections



Analytical cancellations:

general diagrammatic argument (based on Yennie/Frautschi/Suura 61)

verified by explicit calculation using Mellin-Barnes/EFT methods

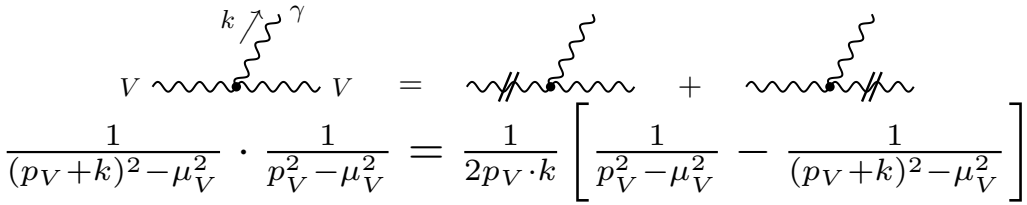


$\Rightarrow$ express NNLO corrections in terms of NLO correction factors

Real corrections

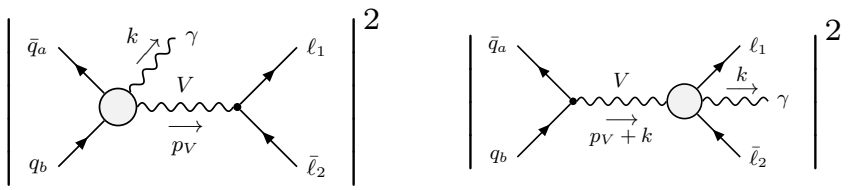
Treatment of real corrections in pole scheme (Denner et al. 97, see also Falgari et al. 13)

Split photon emission off W-line into initial and final-state parts:



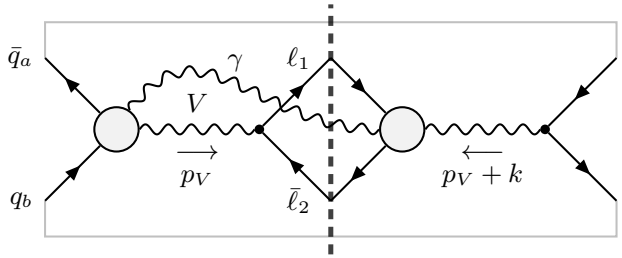
$$\frac{1}{(p_V+k)^2-\mu_V^2}\cdot\frac{1}{p_V^2-\mu_V^2}=\frac{1}{2p_V\cdot k}\left[\frac{1}{p_V^2-\mu_V^2}-\frac{1}{(p_V+k)^2-\mu_V^2}\right]$$

Factorizable corrections to on-shell production and decay:



treated without kinematic approximation

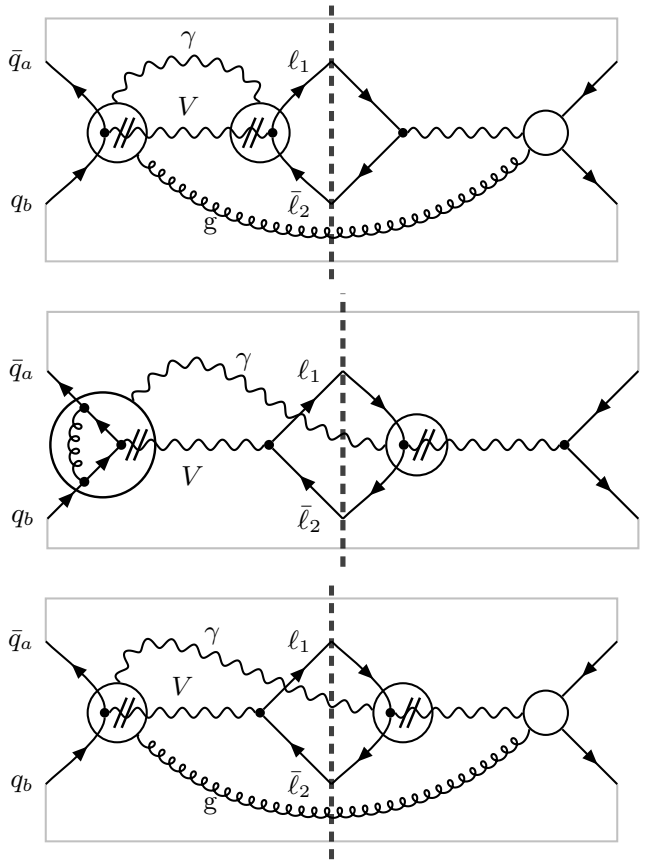
Non-fact. corrections: resonance enhancement from soft photons



Real nonfactorizable corrections:

- Three classes:
  - i) real QCD $\times$ virtual EW
  - ii) virtual QCD $\times$ real photonic
  - iii) double real
- similar simplifications as for double-virtual corrections

$\Rightarrow$ soft-photon corrections to V and $V + j$ production factorize from lower-order QCD process

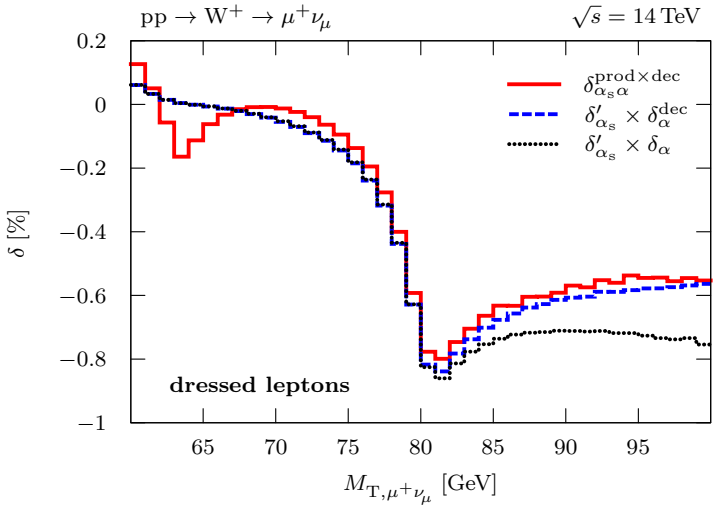


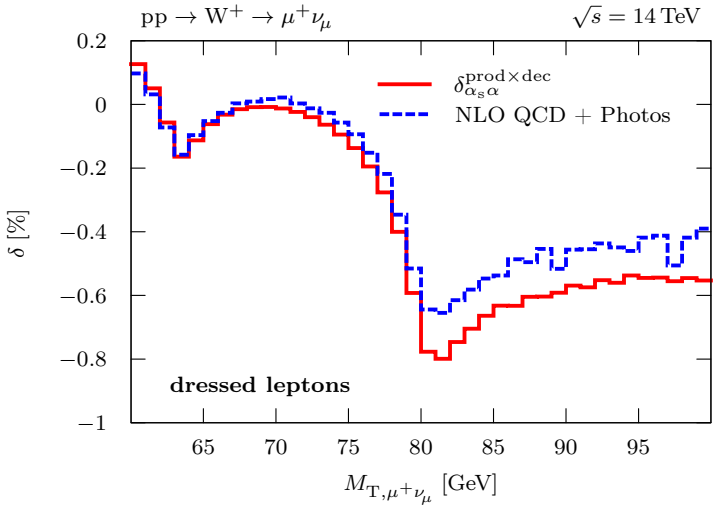
- only soft singularities in non-fact. soft-photon corrections
  $\Rightarrow$ regularize by cut $\Delta E_\gamma \ll \Gamma_V$ in real corrections, add analytically integrated contributions to virtual corrections

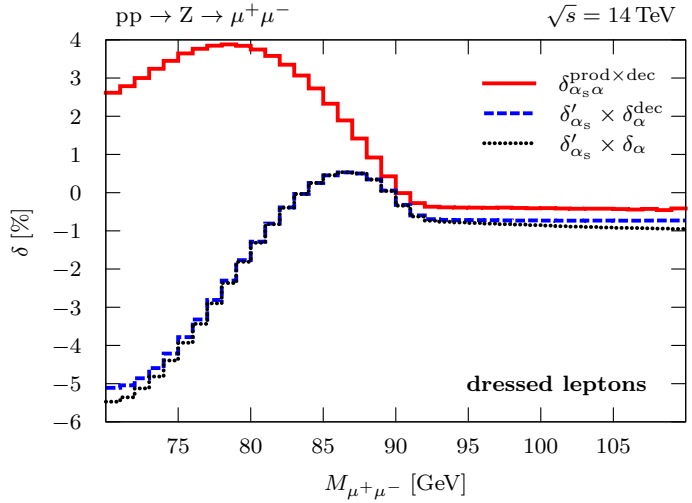
Mixed EW/QCD corrections: results

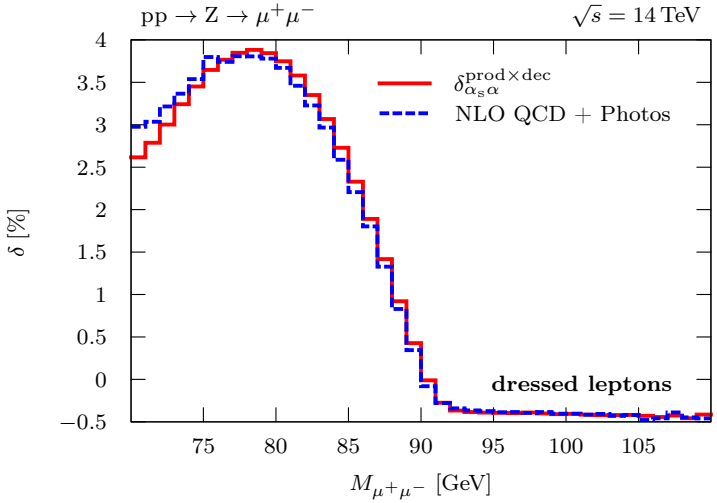
Comparison of $\mathcal{O}(\alpha_s\alpha)$ corrections in pole-approximation

for electrons with photon recombination ($R_{\ell\gamma} = \sqrt{(\eta_\ell - \eta_\gamma)^2 + (\phi_\ell - \phi_\gamma)} < 0.1$)









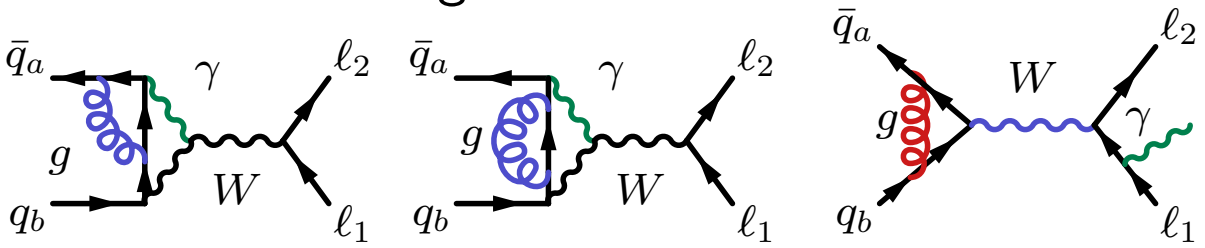
Parton shower implementation of $\mathcal{O}(\alpha_s\alpha)$ corrections

Implementation in POWHEG BOX (Barzè et al. 12/13)

- Full NLO EW and QCD corrections
- matched to Pythia parton shower
- multi-photon radiation generated with Photos

Common to calculation in pole approximation:

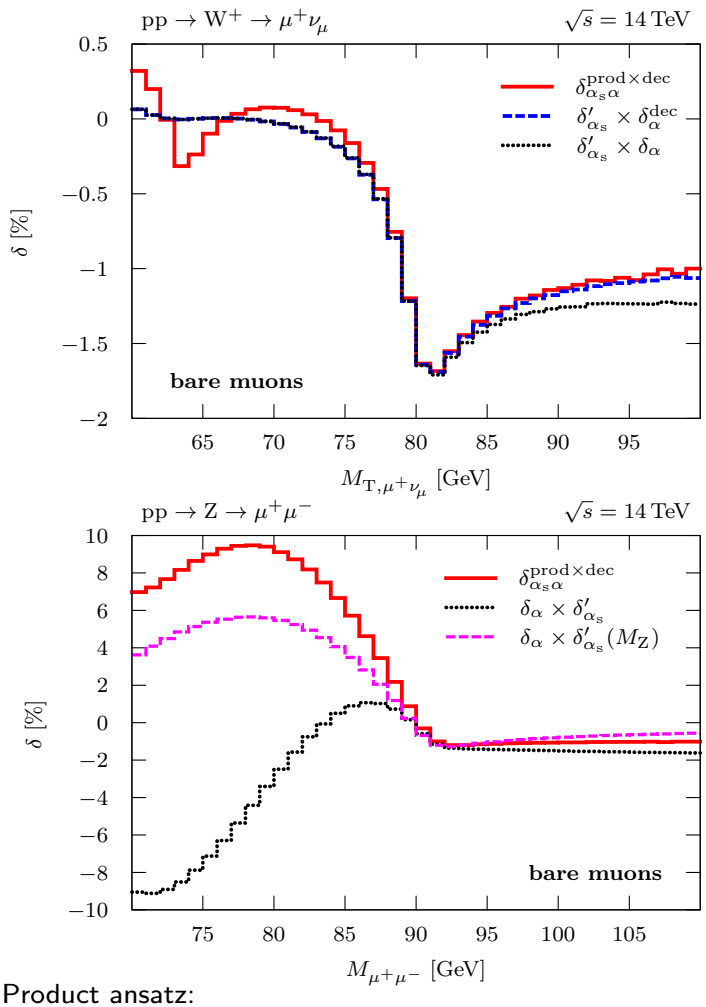
- Initial $\times$ final fact. diagrams included in POWHEG BOX:



Differences to pole approximation

- Only first emission in double-real correction treated exactly in POWEG
- POWEG includes multiple gluon/photon radiation

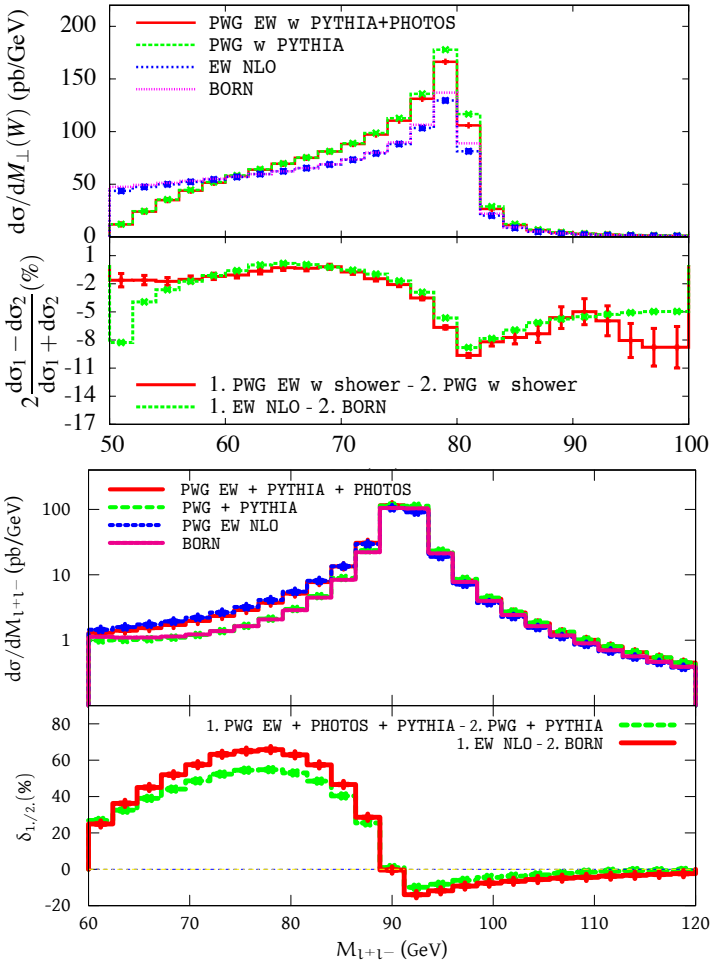
EW/QCD corrections in pole approximation vs POWHEG



(Product ansatz:

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

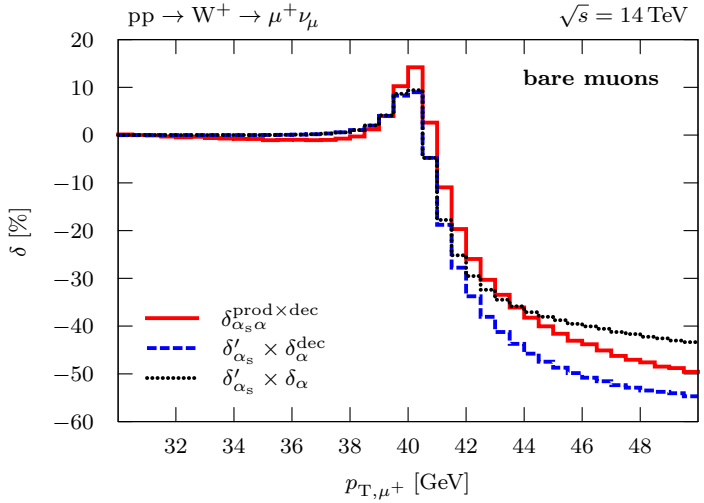
with $\sigma^{\mathrm{LO}}/\sigma^0$: LO/NLO PDFs)

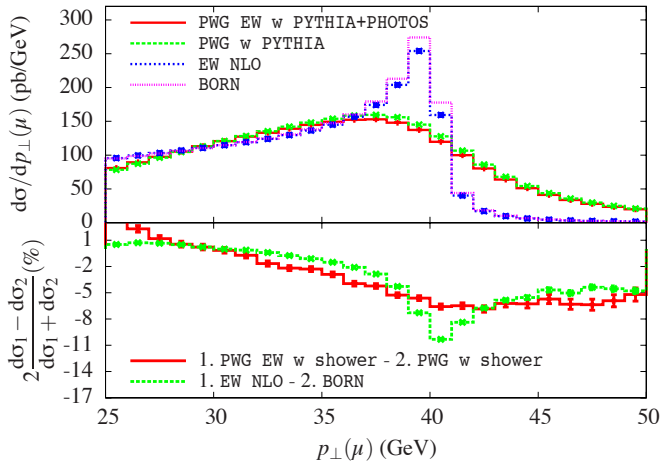


(Barzé et al. 12)

($\delta_{1/2} = (\sigma_1 - \sigma_2)/\frac{1}{2}(\sigma_1 + \sigma_2)$)

EW/QCD corrections in pole approximation vs POWHEG





⇒ naive product only appropriate for observables dominated by resonance and insensitive to recoil

- Comparison of EW/QCD pole approximation to structure function/shower approach to FSR in progress (Dittmaier/Huss/CS)