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

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— RWTH Aachen —

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based on S. Dittmaier, A. Huss, CS: Nucl.Phys. B885 (2014) 318, arXiv:1403.3216 [hep-ph]
Nucl.Phys. B904 (2016) 216, arXiv:1511.08016 [hep-ph]



Introduction

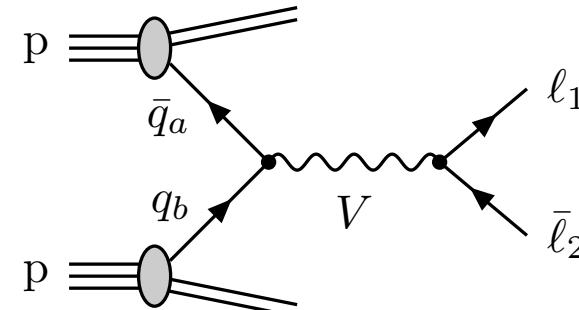
Drell-Yan processes:

- “Neutral current”:

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

- “Charged current”:

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



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

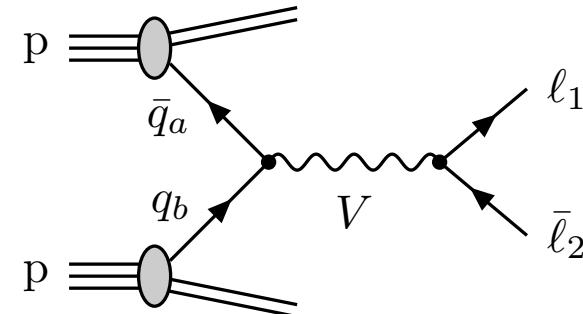
Drell-Yan processes:

- “Neutral current”:

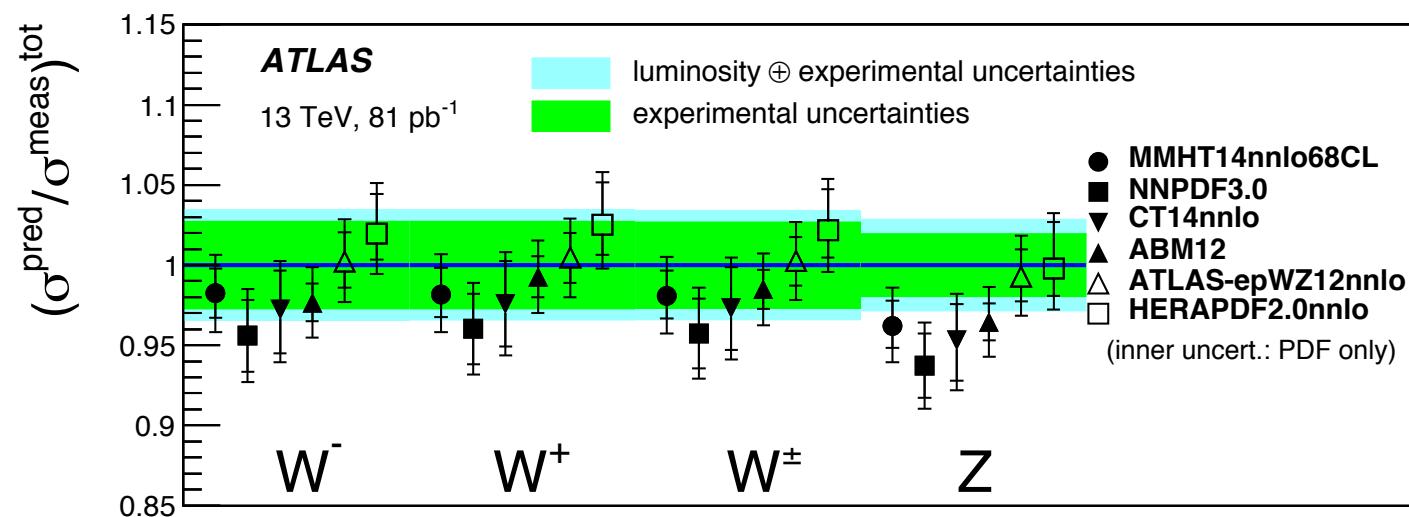
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- “Charged current”:

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



Total cross sections: consistent with NNLO QCD



Theory status

QCD:

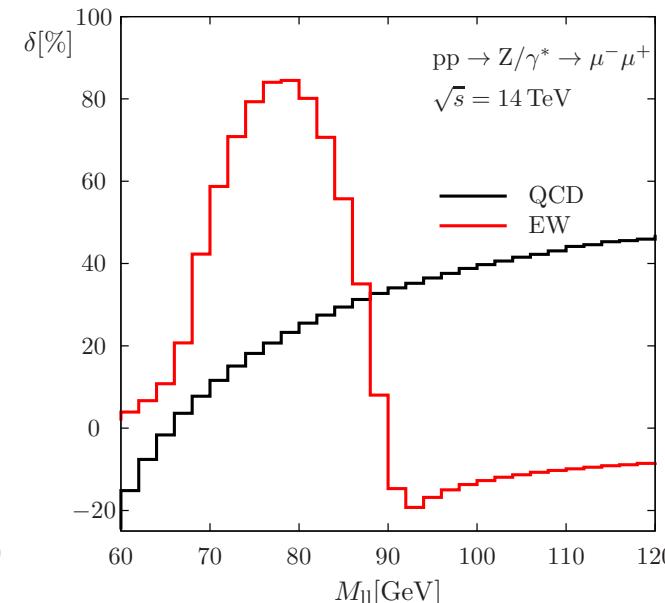
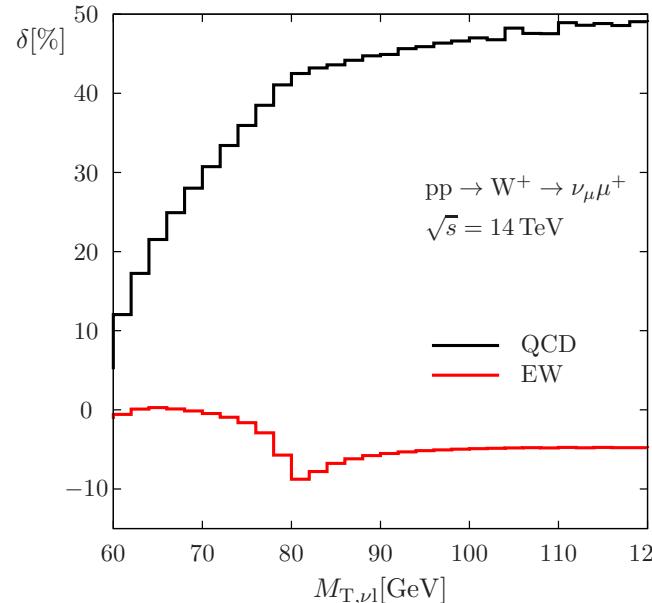
- **NLO** calculations matched to **parton showers**
MC@NLO (Frixione/Webber 06), **POWHEG** (Alioli et al. 08; Hamilton et al. 08),
SHERPA (Höche et al.)
- **NNLO** partonic differential cross sections
FEWZ (Melnikov/Petriello 06; Gavin et al. 10/12), **DYNNLO** (Catani et al. 09)
NNLO+PS (Höche/Li/Prestel; 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**

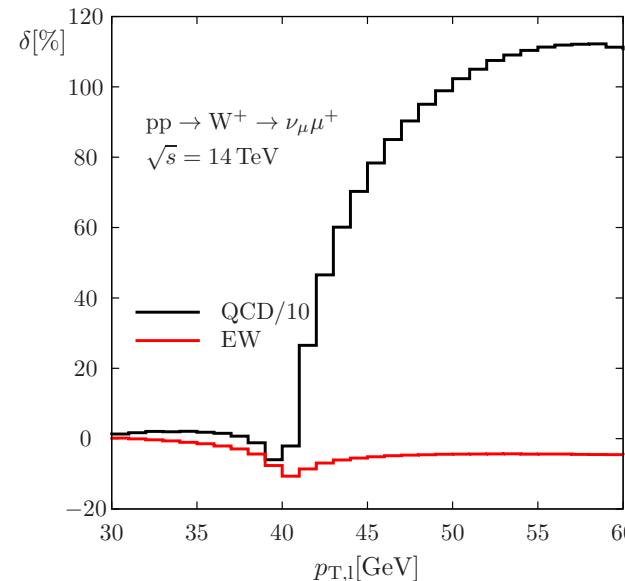
Size of corrections observable-dependent:

- Transverse mass $M_{T,\nu\ell} = \sqrt{2 p_{T,\ell} E_T^{\text{miss}} (1 - \cos \phi_{\nu\ell})}$: moderate EW corrections
- Invariant mass M_{ll} of lepton pair for neutral current DY: large corrections due to photonic FSR
- Transverse lepton momentum $p_{T,\ell}$: soft-gluon resummation required near Jacobian peak $p_{T,\ell} \sim M_W/2$



Size of corrections observable-dependent:

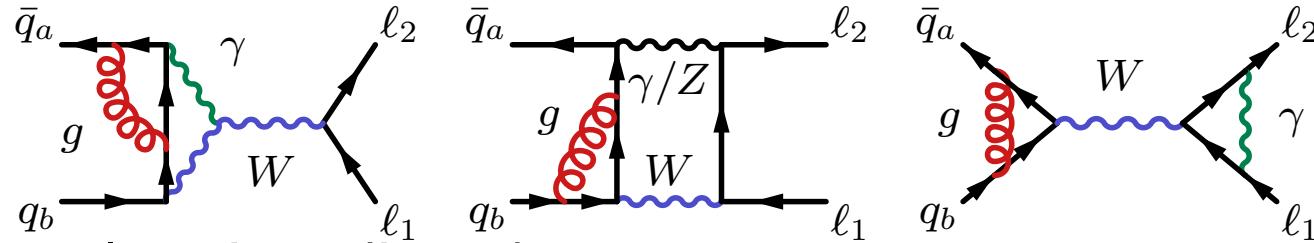
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QCD \otimes EW corrections

Mixed QCD \otimes EW corrections not calculated yet:

NNLO calculation with different mass scales, finite widths:



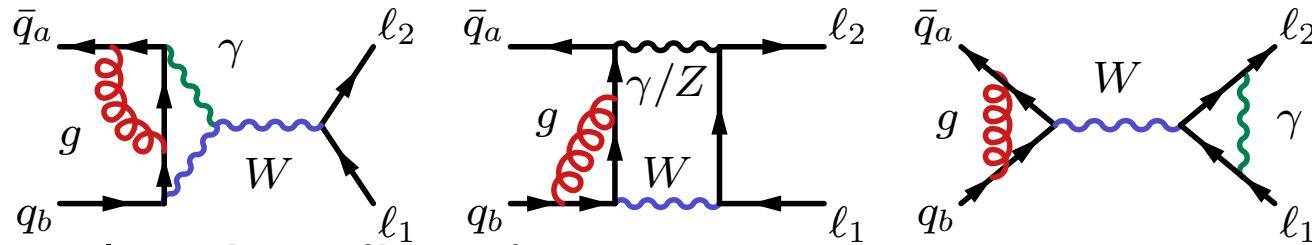
some two-loop ingredients known

$(\mathcal{O}(\alpha_s \alpha))$ corrections to Z/W decay widths: Czarnecki/Kühn 96; Kara 13,

two-loop amplitudes: Kotikov/Kühn/Veretin 07; Kilgore/Sturm 12; Bonciani et al. 16)

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Approximations to full QCD \otimes 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)
- Implementation of EW corrections in NLO-matched
QCD parton showers (Bernaciak/Wackerlo 12; Barzè et al. 12/13)
- Application of pole scheme near resonance
(Dittmaier/Huss/CS 14/15)

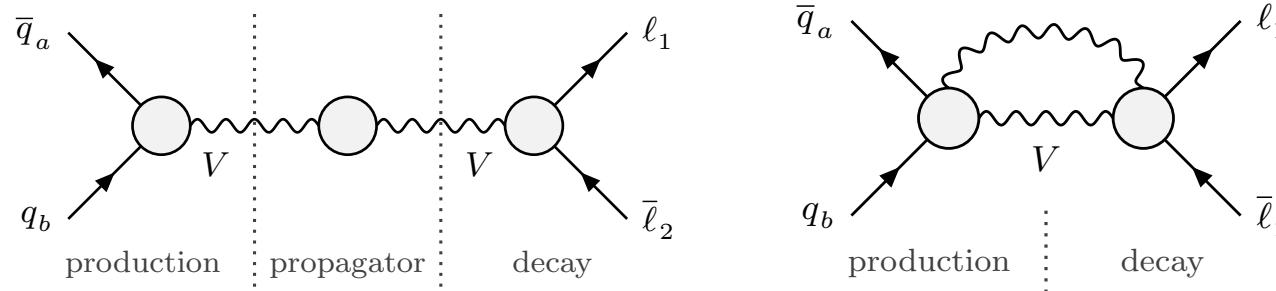
Pole scheme:

(Stuart 91; Aeppli/v.Oldenbourg/Wyler 93)

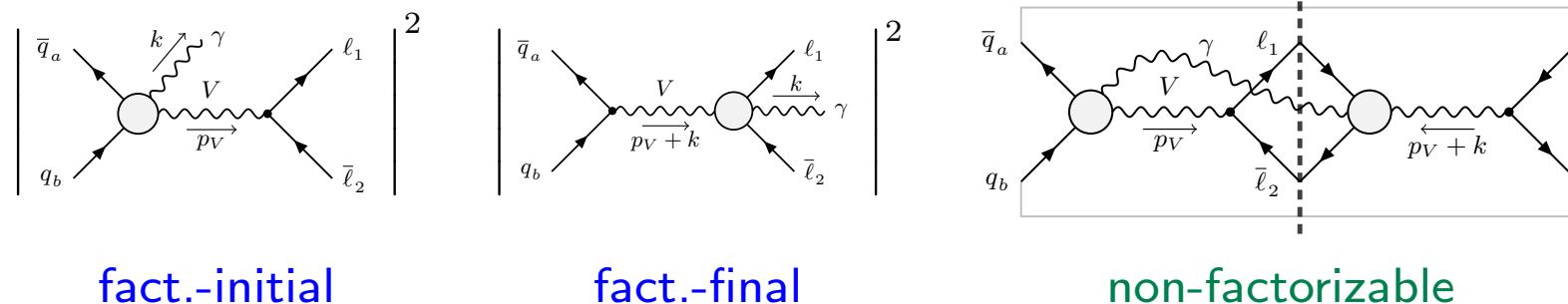
Expand for $p_V^2 \sim \mu_V^2$ with **complex pole** $\mu_V^2 = M_V^2 - iM_V\Gamma_V$

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

Virtual corrections



Real corrections

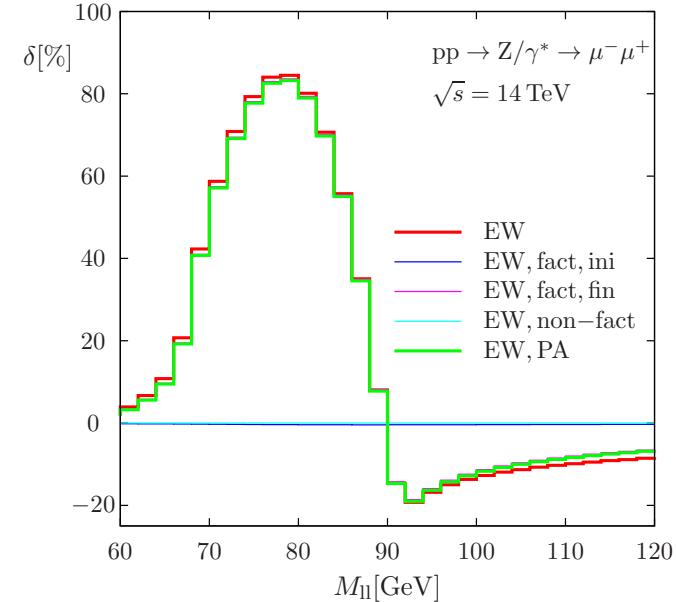
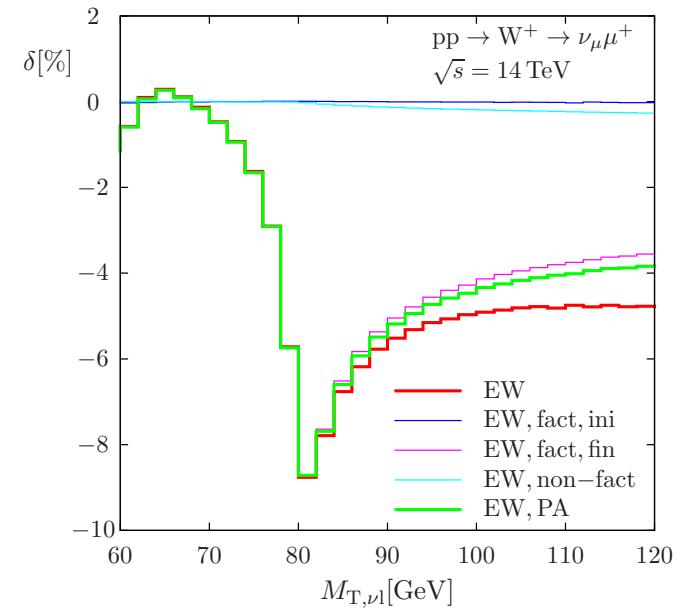


Pole approximation

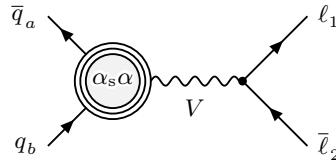
Application of pole approximation to EW corrections at NLO

(Wackerlo/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



Factorizable initial_{QCD} \times initial_{EW} corrections (not known yet)

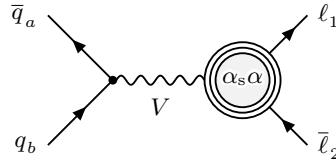


- Two-loop corrections to on-shell W/Z production

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

- must be combined with double-real/real-virtual contributions using IR subtraction/slicing scheme.
- expected to be subdominant since photonic ISR small.

Factorizable final_{QCD} \times final_{EW} corrections (Dittmaier/Huss/CS 15)

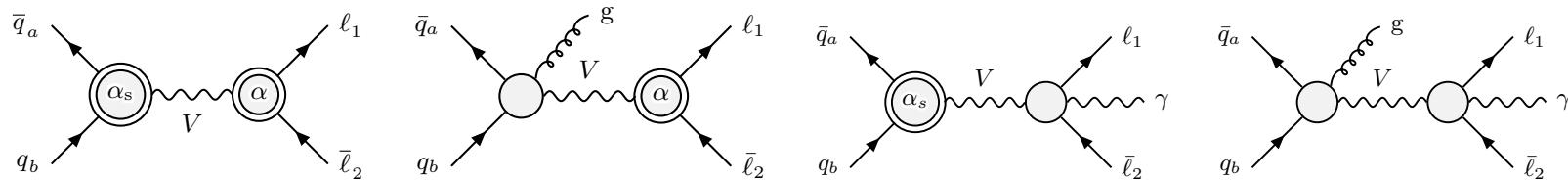


- finite counterterm contributions from $\mathcal{O}(\alpha_s \alpha)$ self energies
- numerically negligible

(Djouadi/Gambino 93)

Factorizable initial_{QCD} \otimes final_{EW} corrections

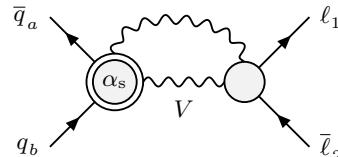
(Dittmaier/Huss/CS 15)



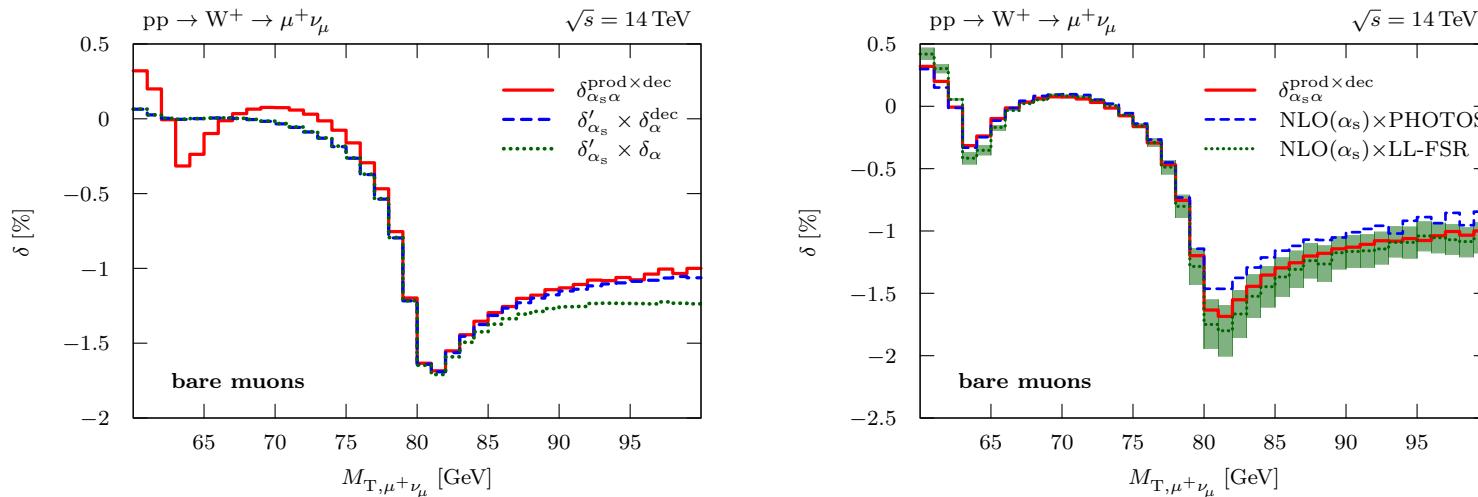
- expected to be dominant part of NNLO $\text{EW} \otimes \text{QCD}$ corrections near resonance
- double-virtual, real-virtual and double-real contributions
- IR singularities regularized using extension of **dipole-subtraction** to decay processes (Basso/Ditmaier/Huss/Oggero 15)

Non-factorizable corrections

(Dittmaier/Huss/CS 14)



- NLO QCD amplitudes dressed with soft-photon factors
- numerically negligible



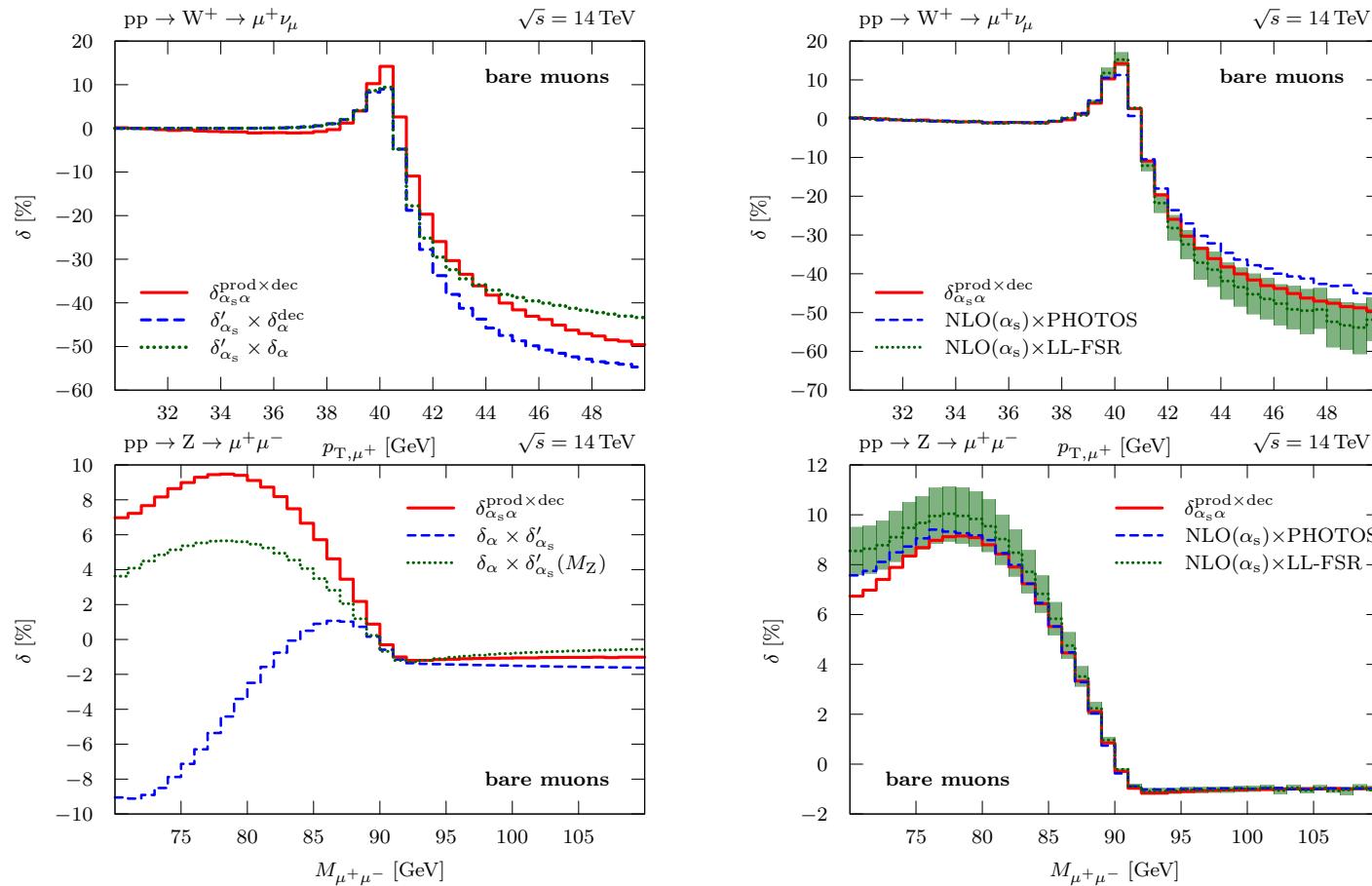
Comparison of different approximations:

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

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

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

Mixed EW/QCD corrections: results



- 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)

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

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

- “Data”: different theory predictions

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

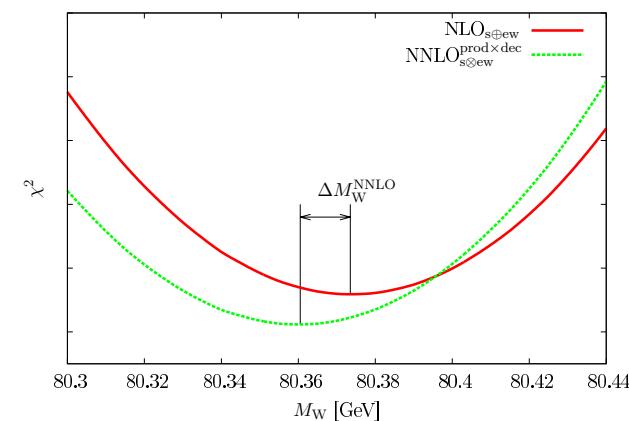
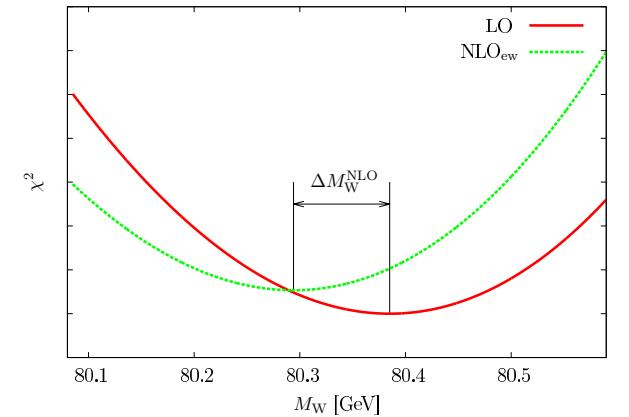
- Shift from LO \rightarrow NLO_{EW}:

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

- Shift from NLO_{EW+QCD} \rightarrow NNLO^{prod-dec}

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

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



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 ~ 14 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

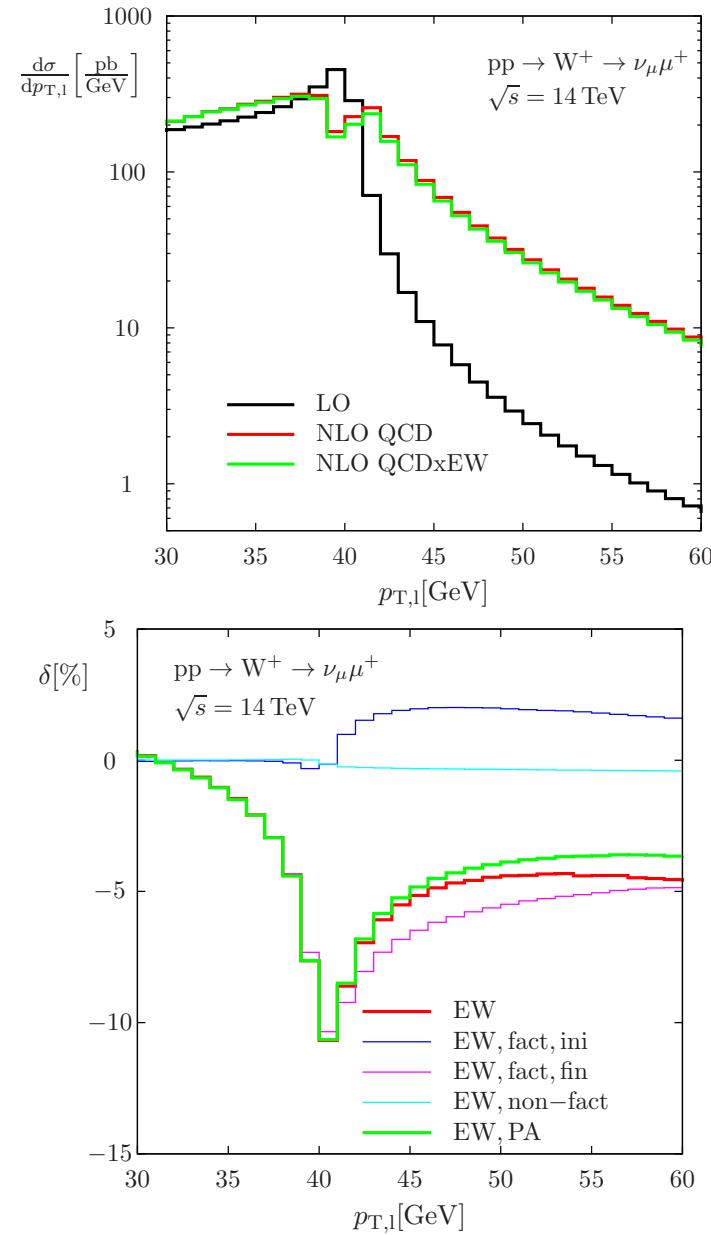
Backup slides

12

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, $\alpha_{G_\mu} = \frac{\sqrt{2}}{\pi} G_\mu M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right)$.
 $p_{T,l} > 25 \text{ GeV}$, $|\eta_l| < 2.5$, $E_T^{\text{miss}} > 25 \text{ GeV}$)



Full NLO-EW

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

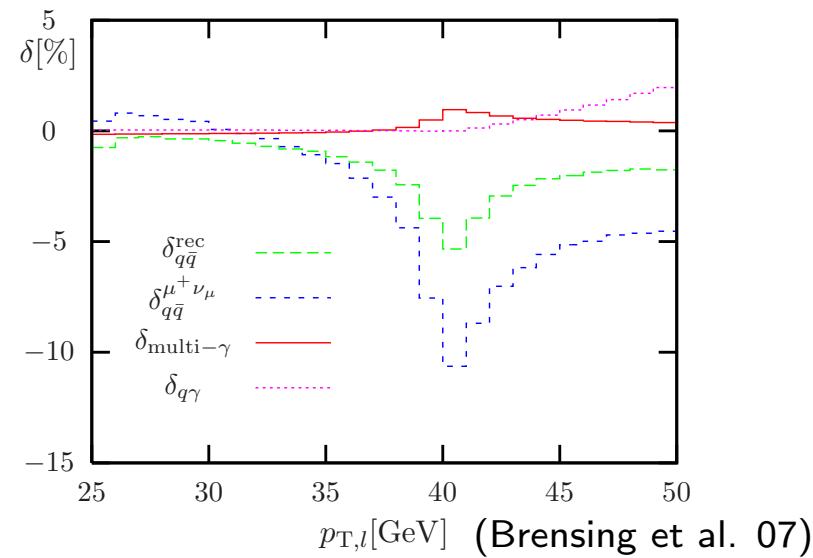
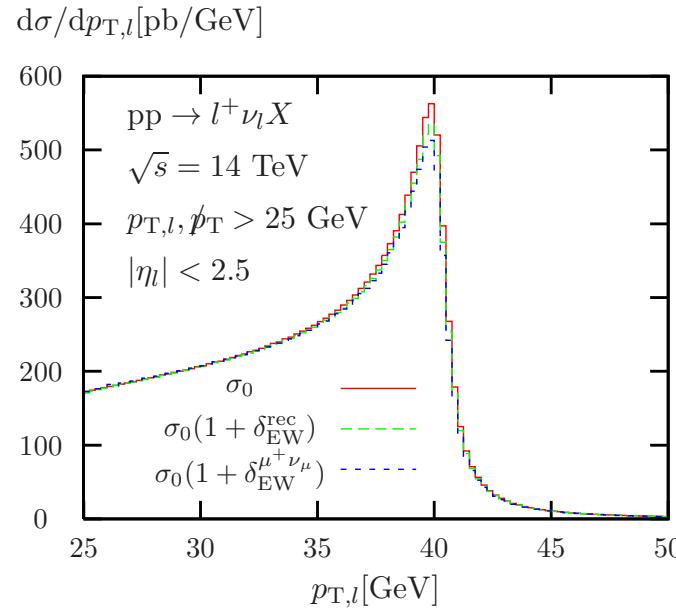
implemented in **W/ZGRAD** (Bauer et al.), **RADY**(Dittmaier),

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- γ** radiation $1-5\%$ -effect.
- Effect on M_W measurement:

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



Full NLO-EW

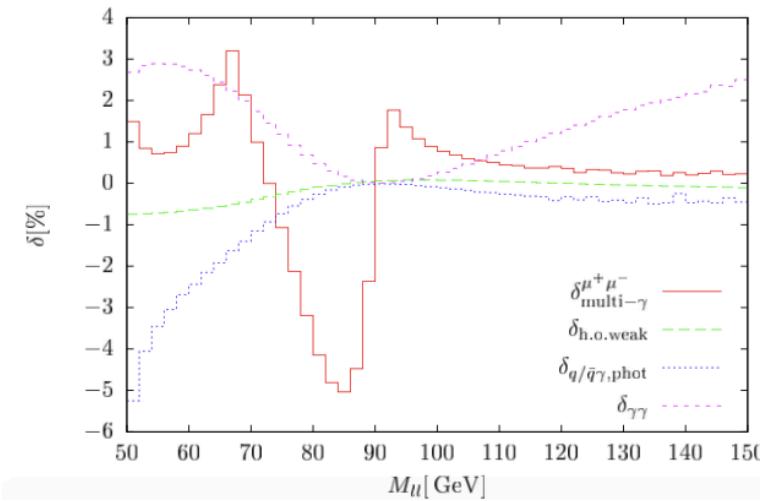
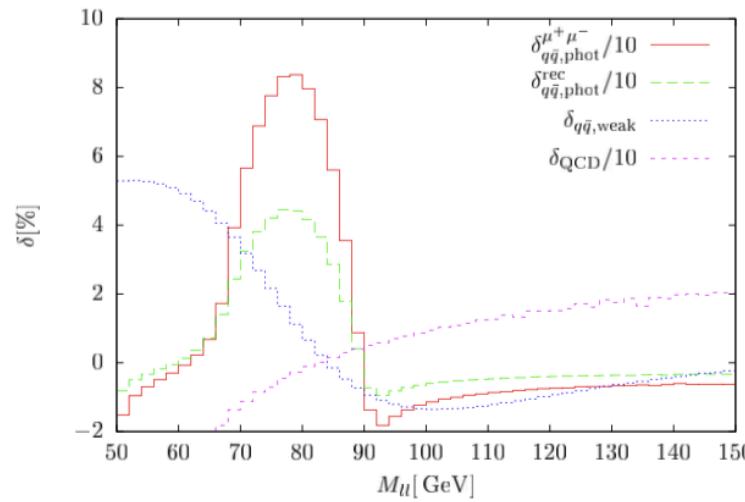
(Dittmaier/Krämer 01; Baur et al. 01;...)

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- γ** radiation 1 – 5%-effect.
- Effect on M_W measurement:
NLO: $\Delta M_W \approx 100$ MeV, **multi- γ** : $\Delta M_W \approx 10$ MeV



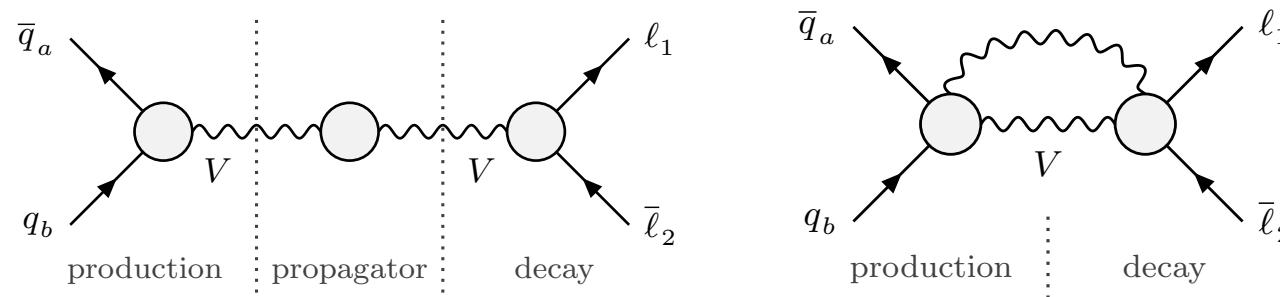
(Huber/Dittmaier 09)

Pole decomposition: expand around **complex pole** of propagator

$$\mu^2 = M^2 - iM\Gamma$$

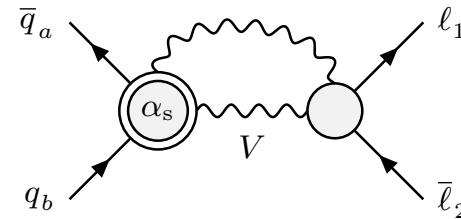
$$\begin{aligned} \mathcal{A}(s) &= \frac{R(s)}{s - M^2 + \Sigma(s)} + N(s) \\ &= \underbrace{\frac{R(\mu^2)}{s - \mu^2} \frac{1}{1 + \Sigma'(\mu^2)}}_{\text{factorizable corrections}} + \left[\frac{R(s)}{s - M^2 + \Sigma(s)} - \frac{R(\mu^2)}{s - \mu^2} \frac{1}{1 + \Sigma'(\mu^2)} \right] + N(s) \\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

Virtual corrections



Pole scheme

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

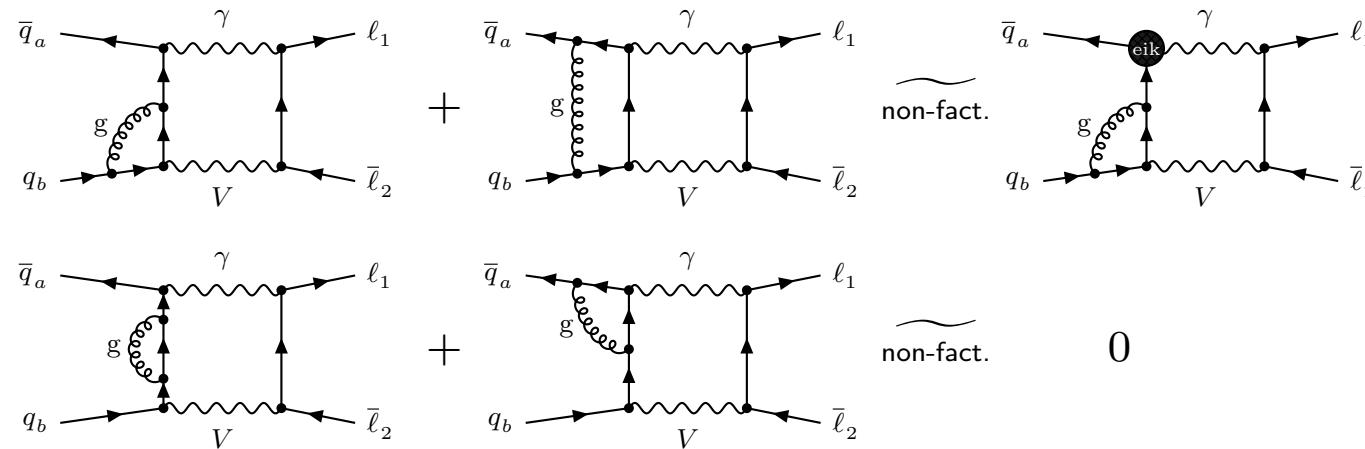


Analytical cancellations:

general diagrammatic argument

(based on Yennie/Frautschi/Suura 61)

verified by explicit calculation using Mellin-Barnes/EFT methods



⇒ express NNLO corrections in terms of NLO correction factors

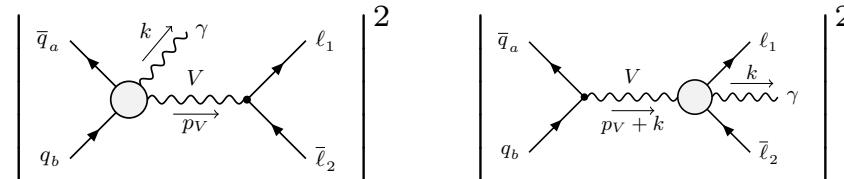
Treatment of real corrections in pole scheme (Denner et al. 97, see also Falgari et al. 13)

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

$$V \xrightarrow[p_V+k]{} \gamma \xrightarrow{k} V = \gamma \cancel{V} + \cancel{V} \gamma$$

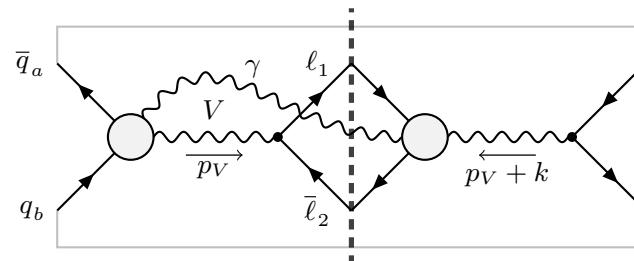
$$\frac{1}{(p_V+k)^2 - \mu_V^2} \cdot \frac{1}{p_V^2 - \mu_V^2} = \frac{1}{2p_V \cdot k} \left[\frac{1}{p_V^2 - \mu_V^2} - \frac{1}{(p_V+k)^2 - \mu_V^2} \right]$$

Factorizable corrections to on-shell production and decay:



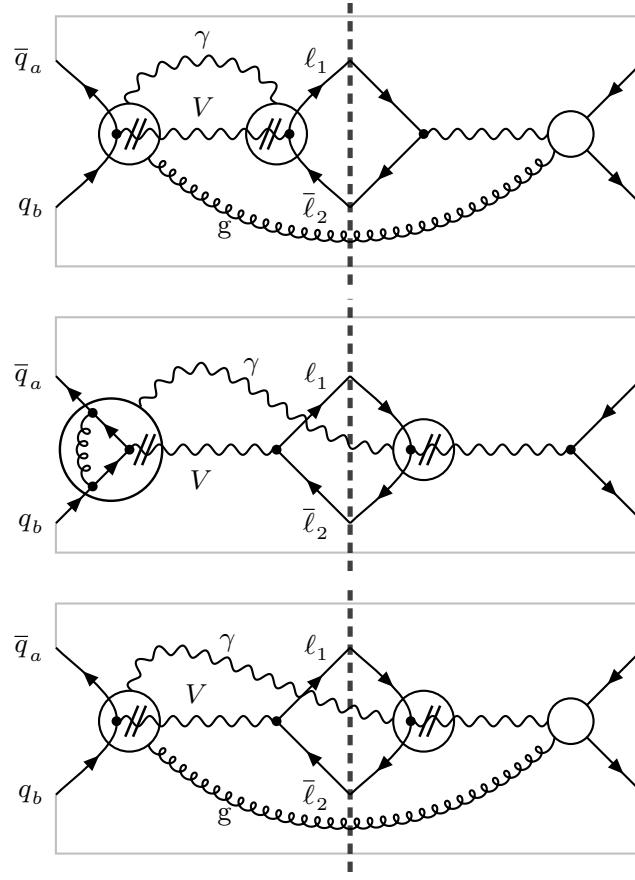
treated without kinematic approximation

Non-fact. corrections: resonance enhancement from soft photons

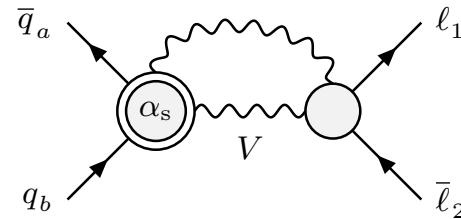


Real nonfactorizable corrections:

- 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



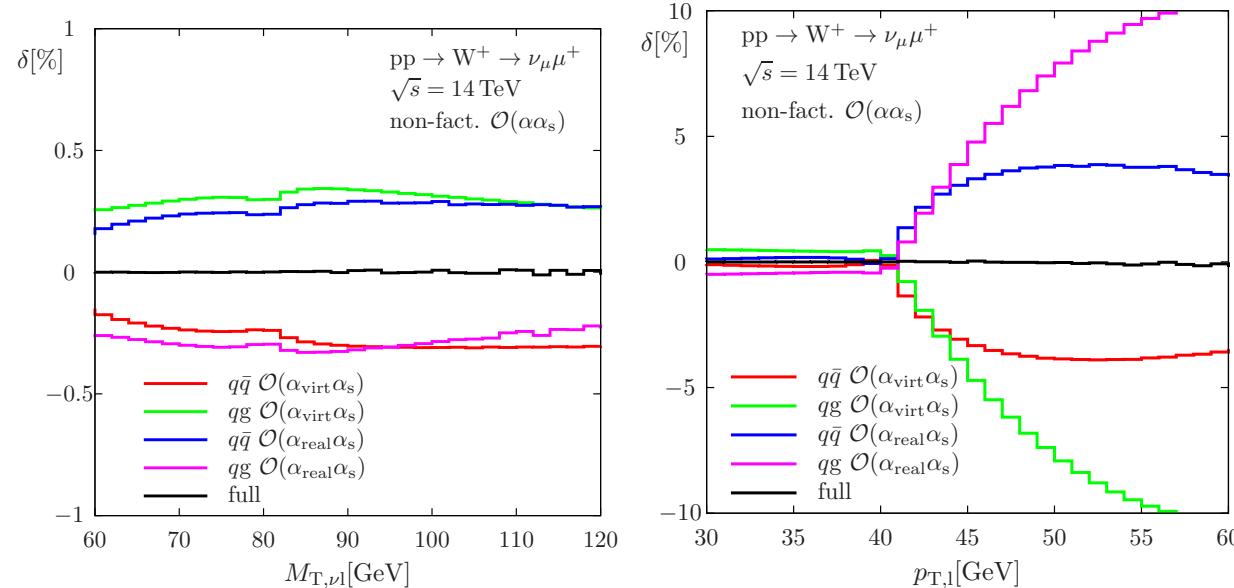
Non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections



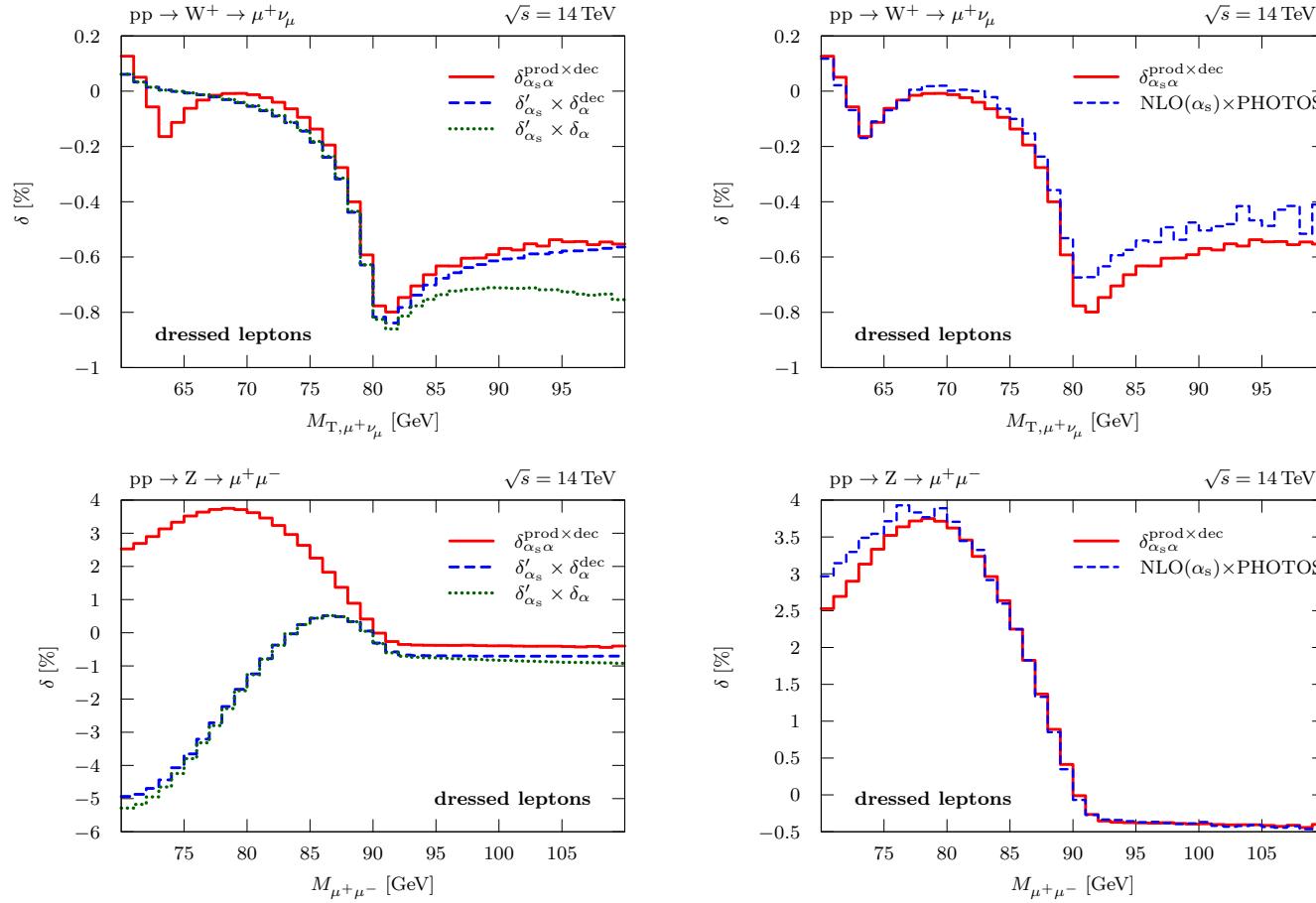
Numerical results:

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



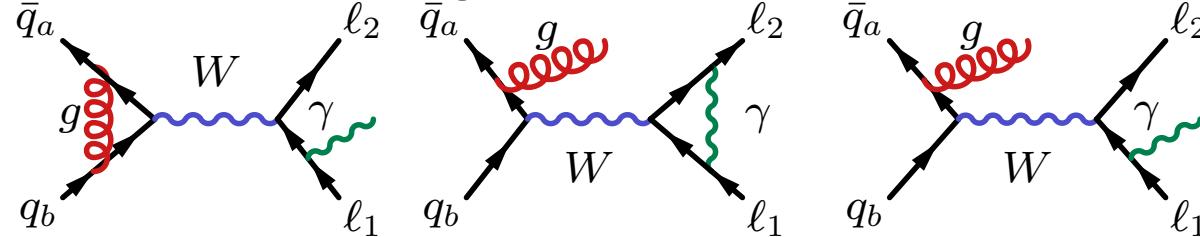
Implementation in POWHEG BOX

(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:

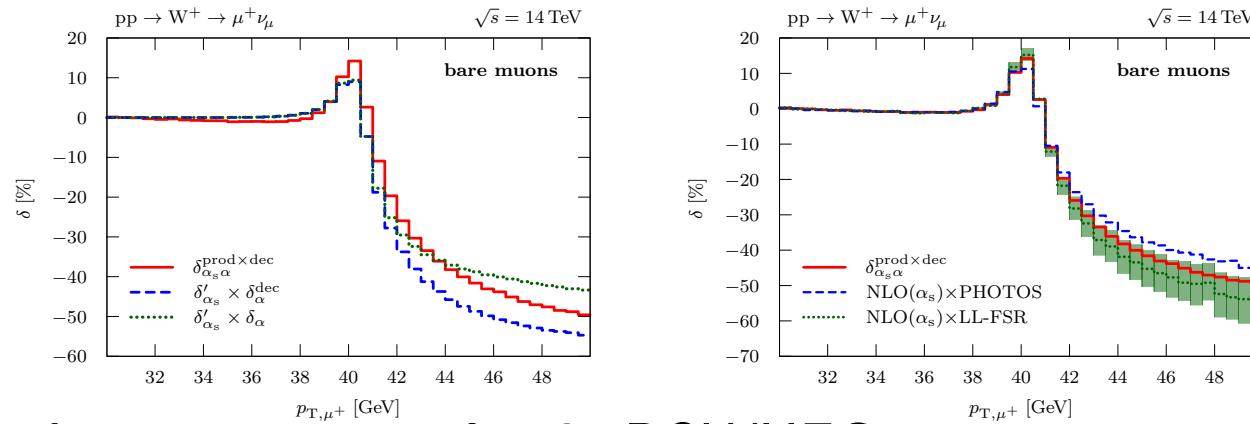
- Initial \times final fact. diagrams included in POWHEG BOX:



Differences to pole approximation

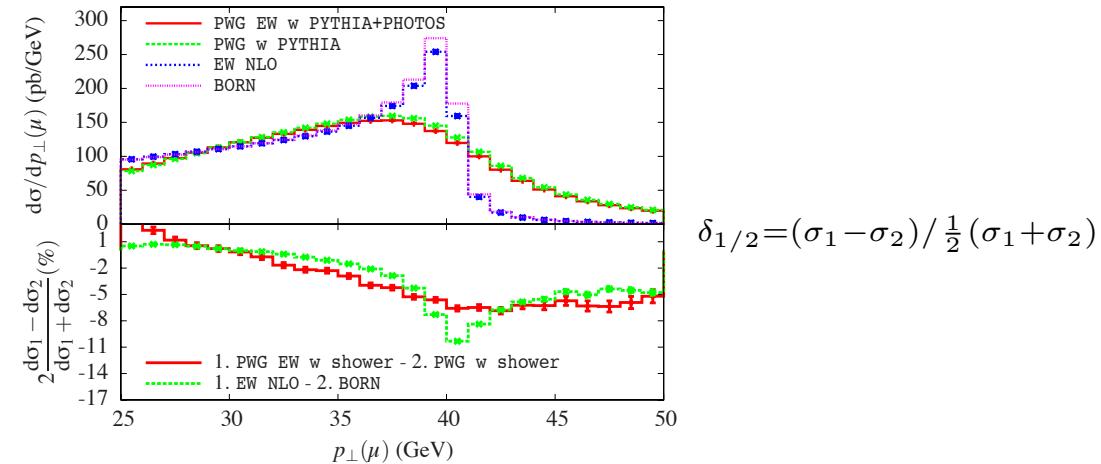
- Only first emission in double-real correction treated exactly in POWEG
- POWEG includes multiple gluon/photon radiation

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

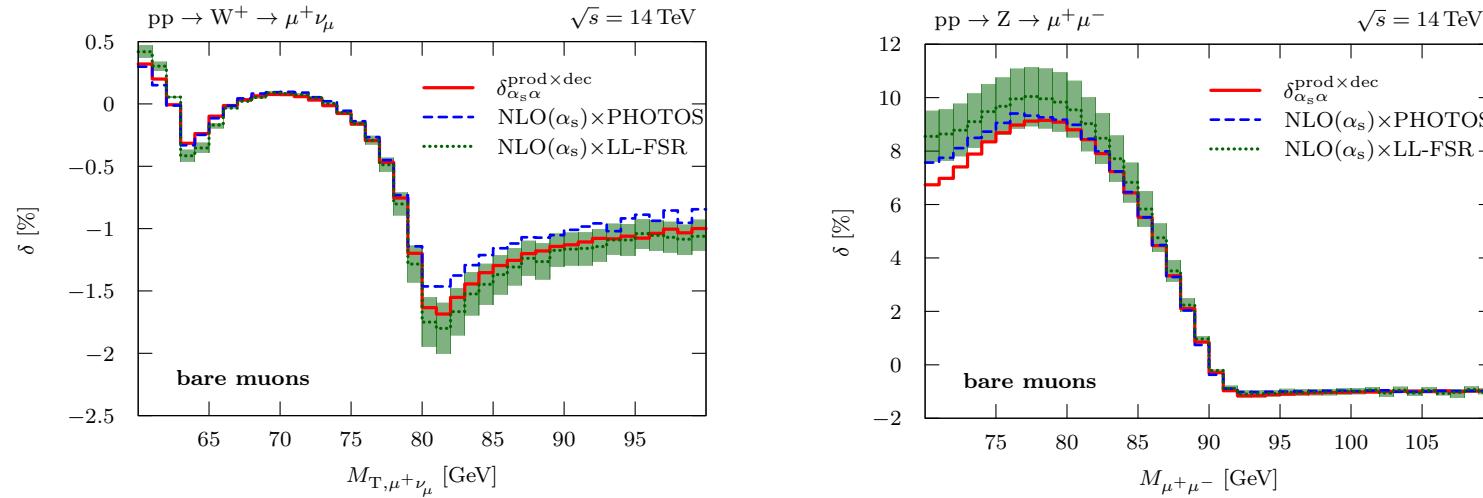


Parton shower resummation in POWHEG

(Barzé et al. 12)



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



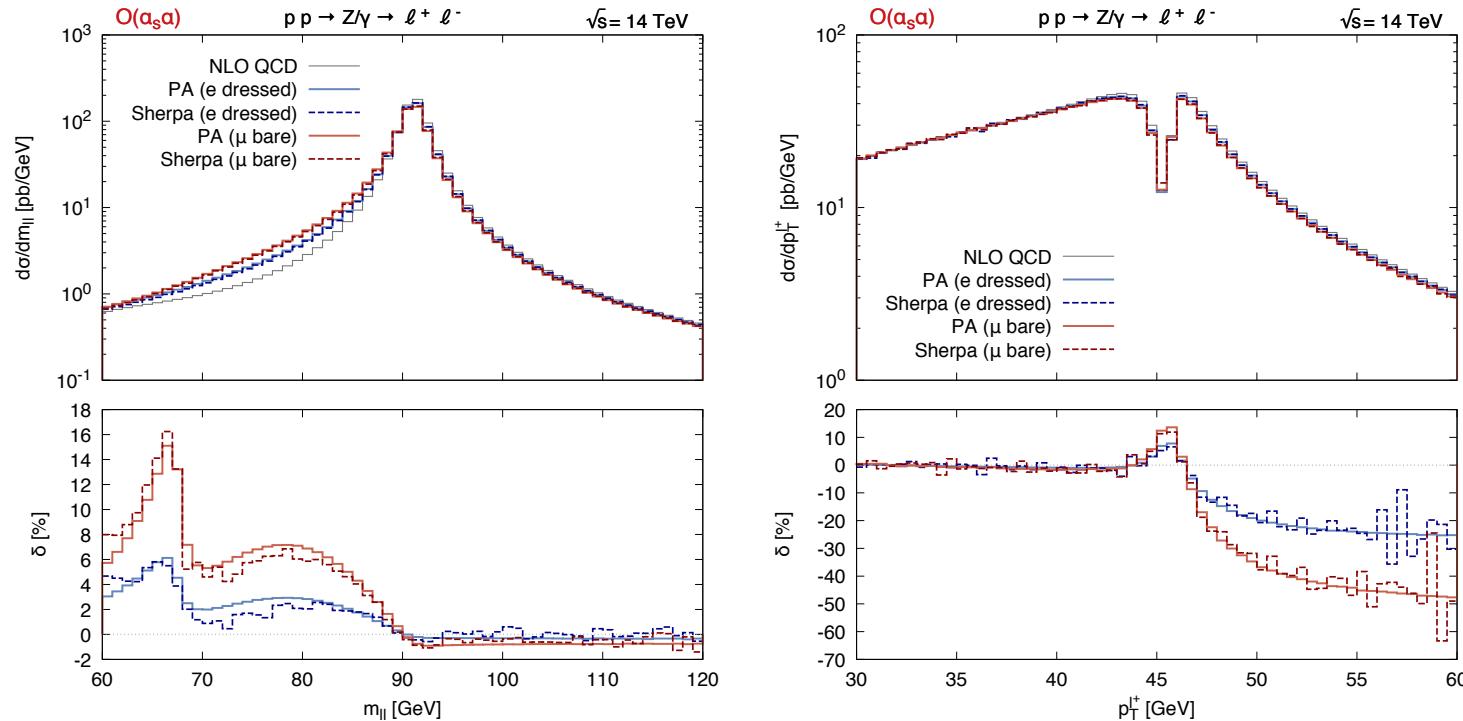
- LL1FSR: Convolution of NLO QCD cross section with one-loop structure function

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

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

⇒ reasonable agreement of LL approximation with full result.

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