State-of-the-art of theory predictions for Drell-Yan processes

Christian Schwinn

— Univ. Freiburg —

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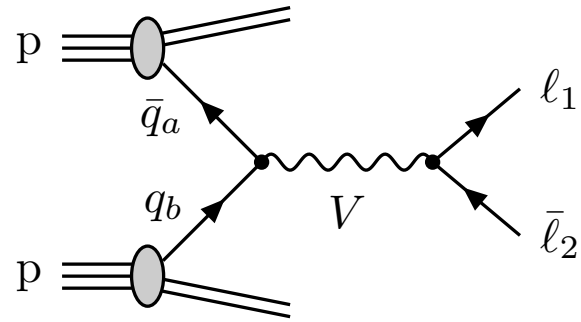
Drell-Yan processes:

- "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

Drell-Yan processes:

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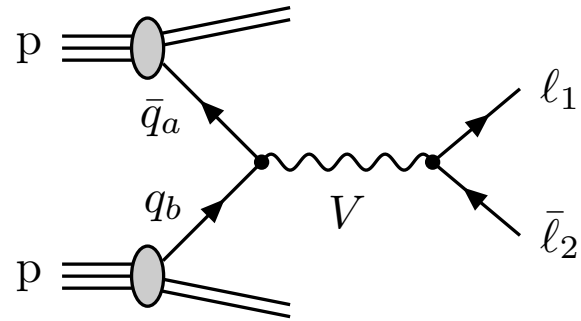
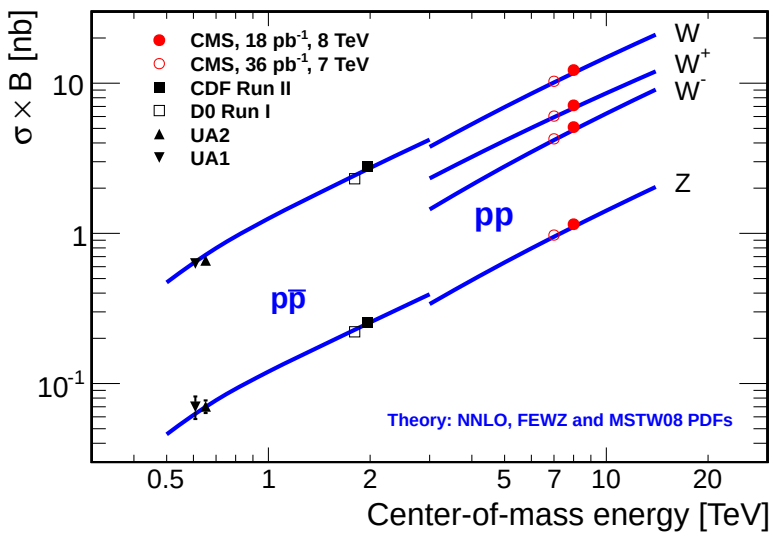
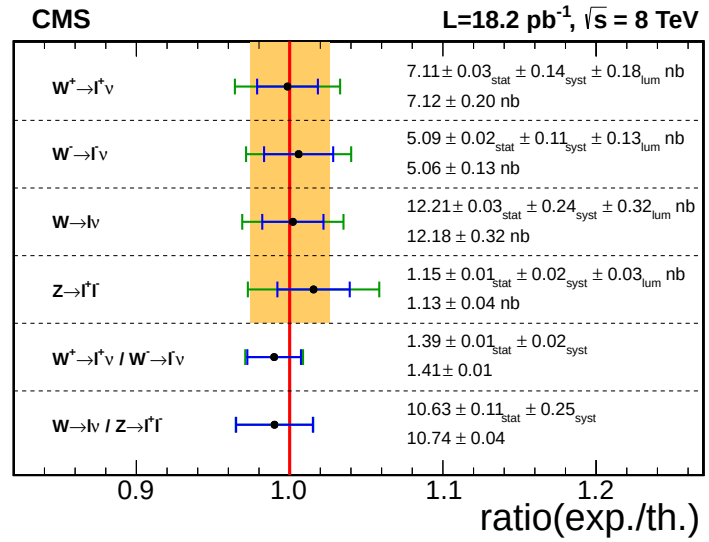


Total cross sections: consistent with NNLO QCD





Introduction

Les Houches 2013: Physics at TeV Colliders
Standard Model Working Group Report

Conveners

Higgs physics: SM issues
D. De Florian (Theory), M. Kado (ATLAS), A. Korytov (CMS),
S. Dittmaier (Electroweak Contact)

SM: Loops and Multilegs
N. Glover (Theory), J. Huston (ATLAS), G. Dissertori (CMS),
S. Dittmaier (Electroweak Contact)

Tools and Monte Carlos
F. Krauss (Theory), J. Butterworth (ATLAS), K. Hamilton (MC-NLO Contact),
G. Soyez (Jets Contact)

Process	State of the Art	Desired
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD and @ NNLO QCD+EW NNLO+PS

1.1.3 Final states involving EW Gauge Bosons

V: Vector-boson production is one of the key benchmark processes at hadron colliders. Experimentally, the cross sections can be measured with great precision (on the order of 1–2%, excluding luminosity uncertainties [94,95]), while the current best theoretical calculations at NNLO QCD and NLO EW have small uncertainties (see, e.g., Ref. [96] and references therein). The resulting comparisons of data to theory thus serve both as precision tests of QCD and sensitive probes of PDFs. For example, measurements of W and Z boson rapidity distributions have indicated that the strange quark distribution may be larger than presented in current PDFs [97]. To take full advantage of the experimental precision, it is necessary to know the cross section to NNNLO QCD and NNLO QCD+EW, and to implement such a cross section in a NNLO+PS format.

Progress towards wishlist

Process	State of the Art	Desired
V	$d\sigma$(lept. V decay) @ NNLO QCD $d\sigma$(lept. V decay) @ NLO EW	$d\sigma$(lept. V decay) @ NNNLO QCD and @ NNLO QCD+EW NNLO+PS

N^{3}LO QCD Very recent result: (Anastasiou et al. 15)

total cross section for $gg \to H$ at N^{3}LO in expansion around threshold $\Rightarrow$ appears feasible for DY

NNLO+PS First steps:

- Combinations of NNLO V and NLO $V + j$ in parton shower (UN^{2}LOPS, Höche/Li/Prestel 14; NNLOPS, Karlberg/Re/Zanderighi 14)
- General framework proposed (Alioli et al. 13)

NNLO QCD+EW approx. schemes for dominant corrections

- Implementation of NLO EW in QCD parton showers (Bernaciak/Wackeroth 12, Barzé et al. 12/13)
- Pole approximation in resonance region (Dittmaier/Huss/CS 14)

QCD status

NNLO calculations:

- Inclusive cross section (Hamberg et al. 91; Harlander/Kilgore 02)
- differential distributions (Anastasiou et al. 06)

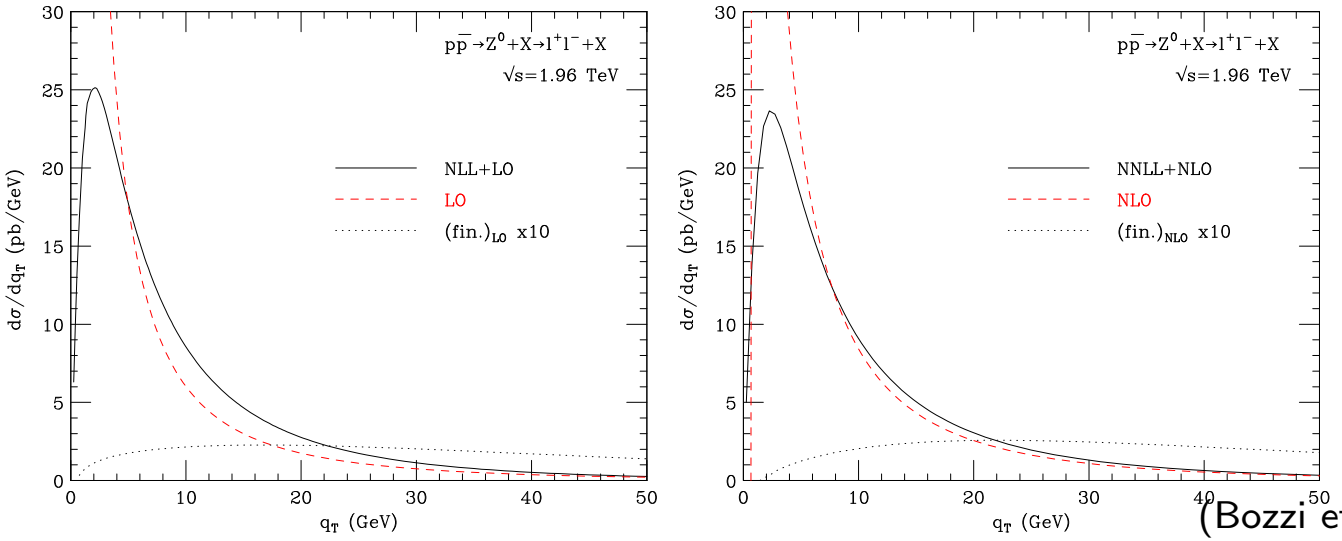
State-of-the art tools:

- 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
  available in public programs:
  FEWZ (Melnikov/Petriello 06; Gavin et al. 10/12), DYNNLO (Catani et al. 09)
- NNLL analytic resummation at small p_T
  RESBOS (Balazs/Yuan 97; Guzzi et al. 13), DYqT(Bozzi et al. 10),

p_T distributions

- Vector-boson p_T first generated in $q\bar{q} \to Vg$, $qg \to Vq$
  $\Rightarrow$ inclusive DY at NLO $\Leftrightarrow$ p_T-spectrum at LO
- resummation of large logs $\alpha_s \log^2(p_T/M_V)$ at small p_T needed
  - parton shower: LL+partial NLL resummation
  - analytic resummation (Collins/Soper/Sterman 85, SCET formulations)
  - implementations at NNLL (RESBOS: Balazs/Yuan 97; Guzzi et al. 13, DYqT: Bozzi et al. 10, Becher et al. 11, Banfi et al. 12)

    differences in matching to fixed order, scale choices, non-perturbative effects



(Bozzi et al. 10)

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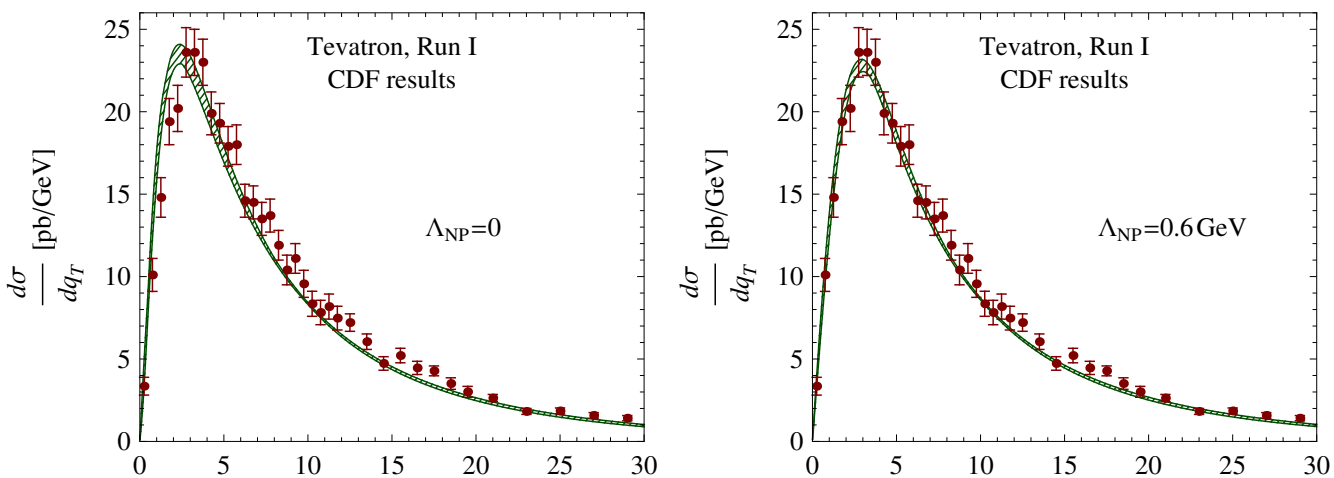


(Becher et al. 11)

Incorporating NNLO effects in parton showers

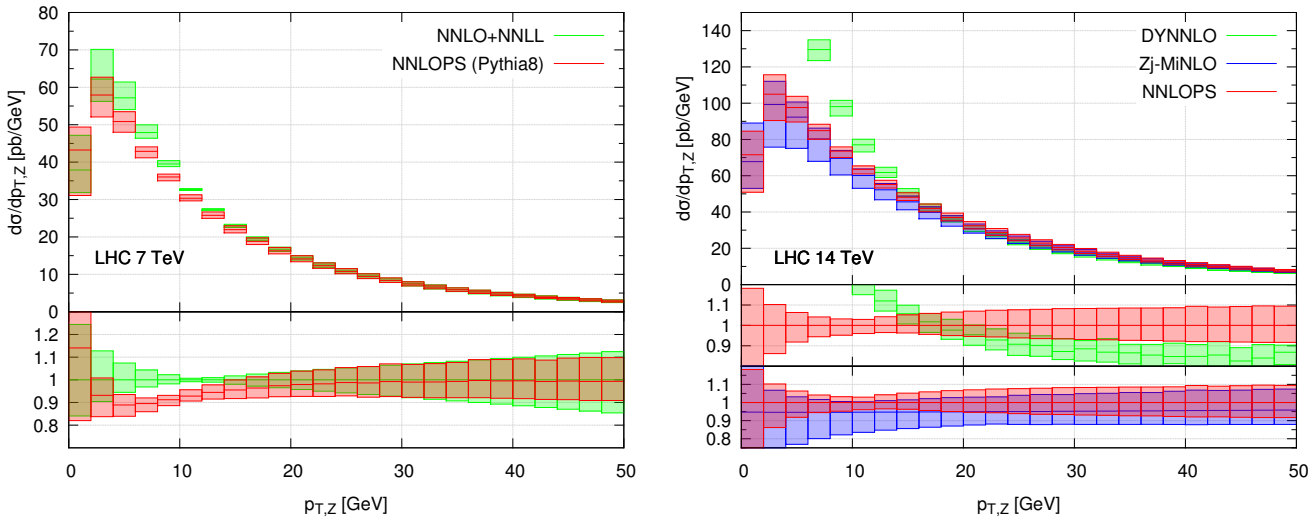
- Starting point: NLO $V + j$ matched to parton shower
- Two implementations:

UN^{2}LOPS (Höche/Li/Prestel 14)

Include 2-loop virtual corrections with jet veto

NNLOPS (Karlberg/Re/Zanderighi 14)

Reweigh NLO $V + j$ distributions from `POWHEG/MINLO` (Hamilton et al. 12) with `DYNNLO` (Catani et al. 09)

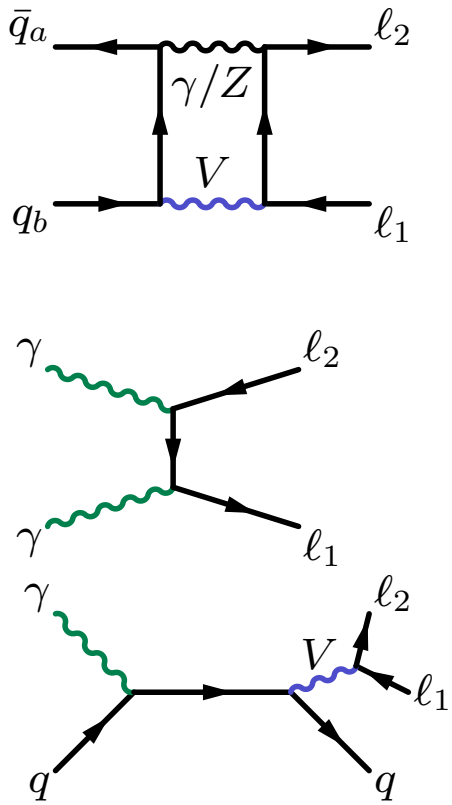


Features of EW corrections

- 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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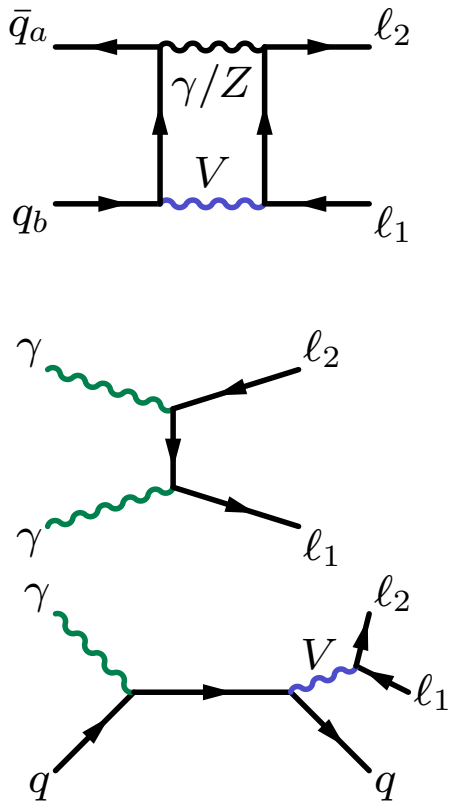
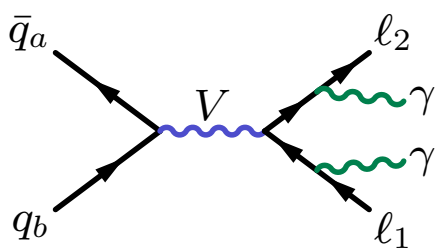


Dominant effects beyond NLO

- 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)



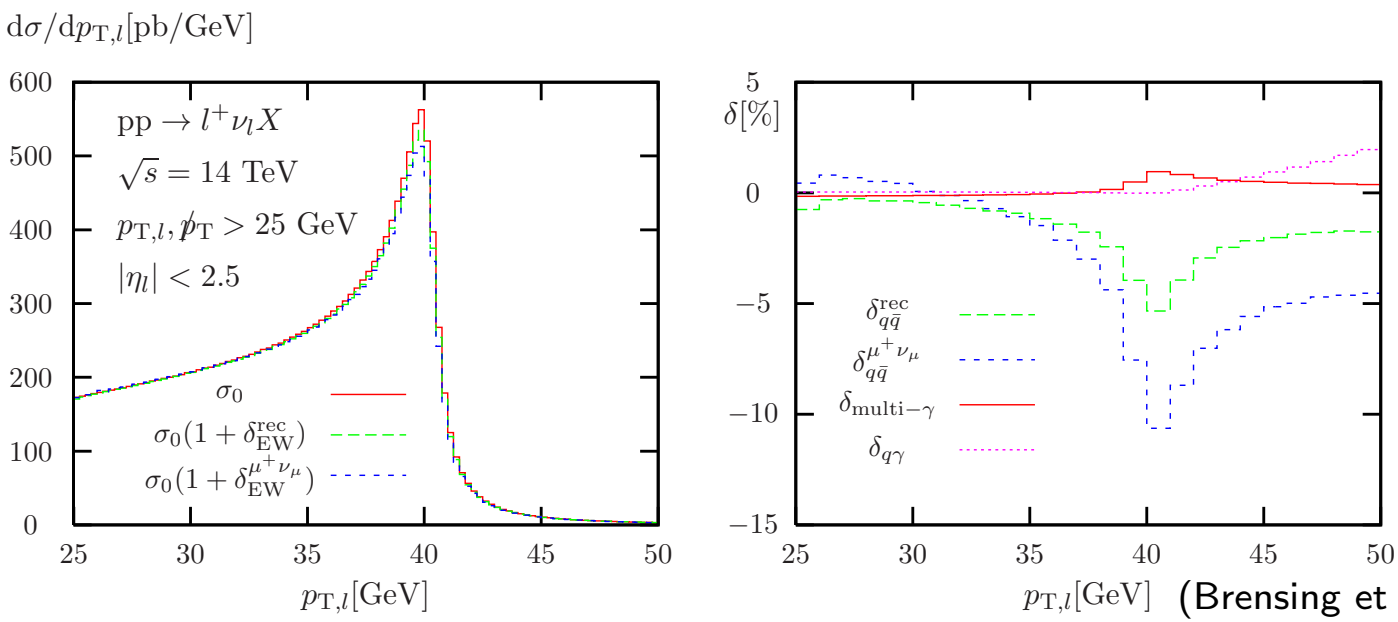
Full NLO-EW (Dittmaier/Krämer 01; Baur et al. 01;...)

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)

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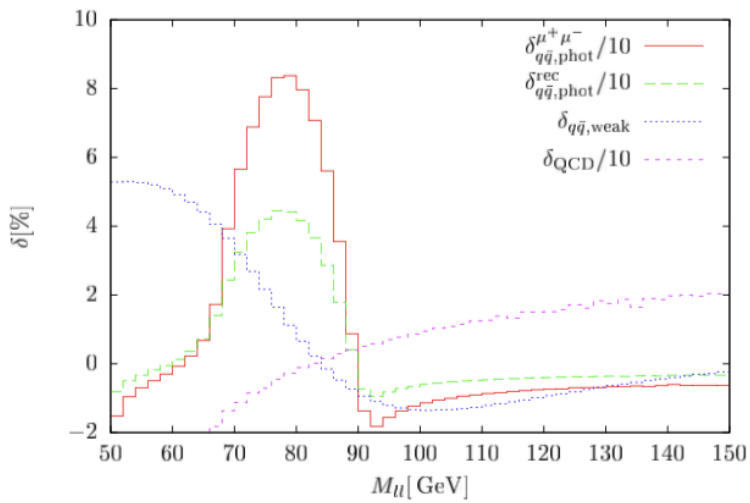
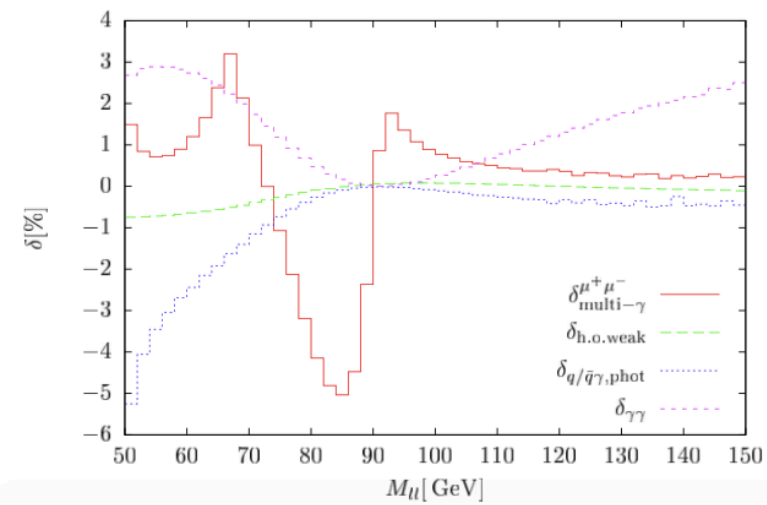




(Huber/Dittmaier 09)

EW corrections

Sudakov logarithms $\sim \alpha \log(\hat{s}/M_V^2)$
become more important at LHC13/14! (Snowmass study 1308.1430)

Numerical impact of Sudakov logarithms (from S. Dittmaier)

Neutral current: $pp \to \ell^+\ell^-$ at $\sqrt{s} = 14\,\text{TeV}$ (based on S.D./Huber arXiv:0911.2329)

$M_{\ell\ell}/\text{GeV}$	50−∞	100−∞	200−∞	500−∞	1000−∞	2000−∞
σ_0/pb	738.733(6)	32.7236(3)	1.48479(1)	0.0809420(6)	0.00679953(3)	0.000303744(1)
$\delta^{\text{rec}}_{\text{q}\bar{\text{q}},\text{phot}}/\%$	−1.81	−4.71	−2.92	−3.36	−4.24	−5.66
$\delta_{\text{q}\bar{\text{q}},\text{weak}}/\%$	−0.71	−1.02	−0.14	−2.38	−5.87	−11.12
$\delta^{(1)}_{\text{Sudakov}}/\%$	0.27	0.54	−1.43	−7.93	−15.52	−25.50
$\delta^{(2)}_{\text{Sudakov}}/\%$	−0.00046	−0.0067	−0.035	0.23	1.14	3.38

no Sudakov domination!

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

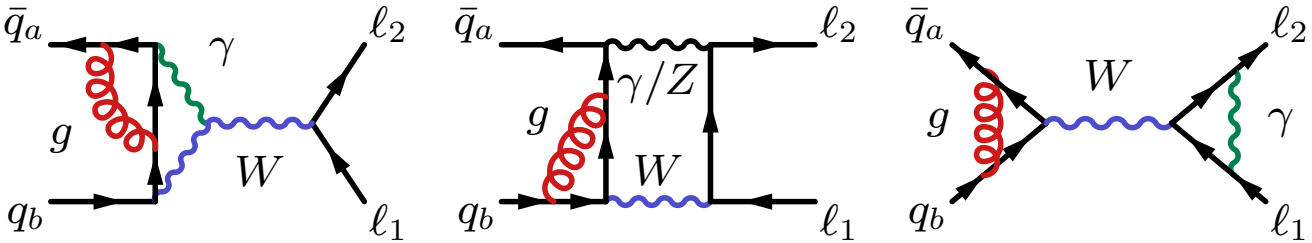
$M_{\text{T},\nu_\ell\ell}/\text{GeV}$	50−∞	100−∞	200−∞	500−∞	1000−∞	2000−∞
σ_0/pb	4495.7(2)	27.589(2)	1.7906(1)	0.084697(4)	0.0065222(4)	0.00027322(1)
$\delta^{\mu^+\nu_\mu}_{\text{q}\bar{\text{q}}}/\%$	−2.9(1)	−5.2(1)	−8.1(1)	−14.8(1)	−22.6(1)	−33.2(1)
$\delta^{\text{rec}}_{\text{q}\bar{\text{q}}}/\%$	−1.8(1)	−3.5(1)	−6.5(1)	−12.7(1)	−20.0(1)	−29.6(1)
$\delta^{(1)}_{\text{Sudakov}}/\%$	0.0005	0.5	−1.9	−9.5	−18.5	−29.7
$\delta^{(2)}_{\text{Sudakov}}/\%$	−0.0002	−0.023	−0.082	0.21	1.3	3.8

Sudakov domination!

Sudakov dominance requires both $\hat{s} \gg M_V^2$ and $|\hat{t}| \gg M_V^2$.

Mixed QCD ⊗ EW corrections not calculated yet:

NNLO calculation with different mass scales, finite widths:



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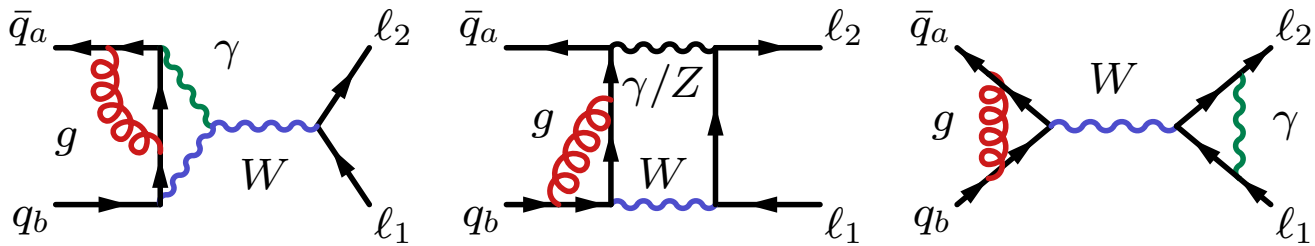


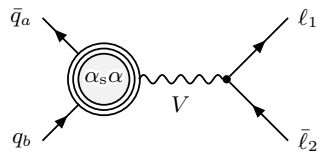
Several ingredients or approximations known:

- 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; Bonciani 11, Kilgore/Sturm 12)
- Implementation of EW corrections in NLO-matched QCD parton showers (Bernaciak/Wackeroth 12; Barzè et al. 12)
- Application of pole scheme near resonance (Dittmaier/Huss/CS 14 and in progress)

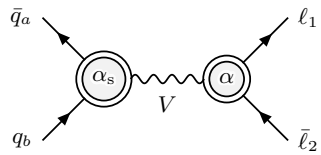
EW/QCD corrections in pole approximation (Dittmaier/Huss/CS)

(+ corresponding real-virtual and double real)

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

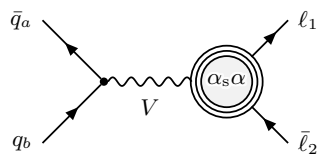


- Factorizable initial×final (expected to be dominant, preliminary results)

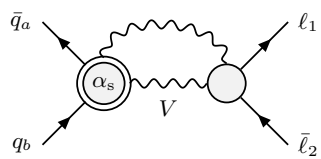


- Factorizable final×final

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



- Non-factorizable corrections (completed, numerically negligible)

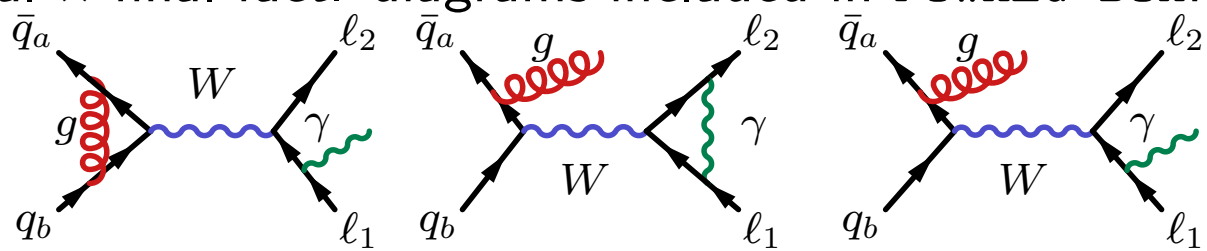


Implementation in `POWHEG BOX` (Barzè et al. 12/13)

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

Common to calculation in pole approximation:

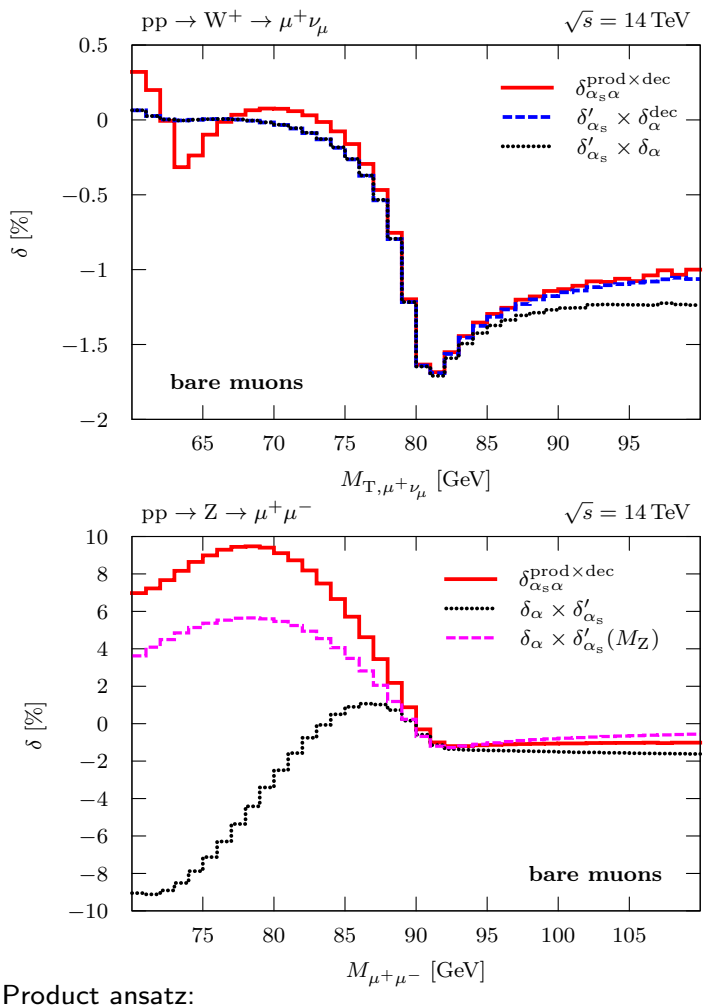
- Initial $\times$ final fact. diagrams included in `POWHEG BOX`:

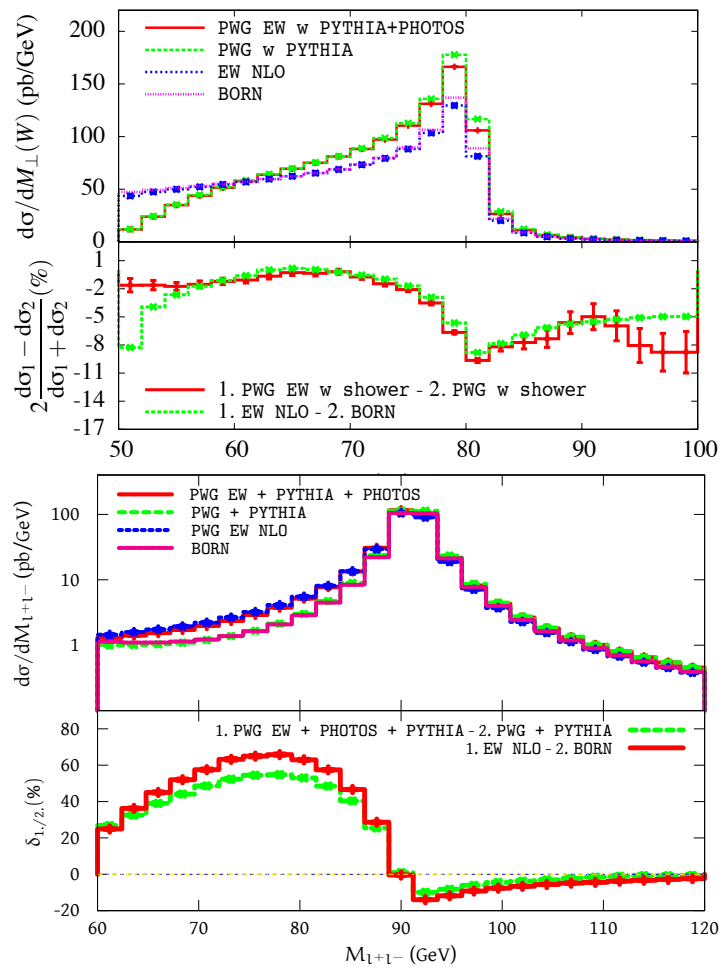


Differences to pole approximation

- 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:

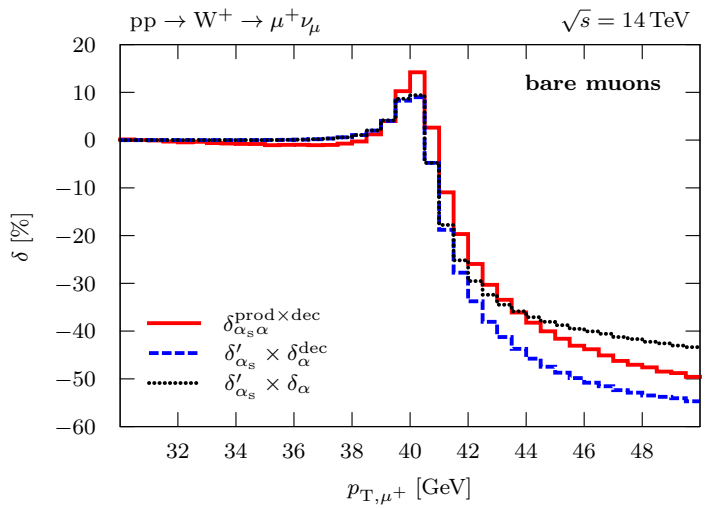
$$\delta_\alpha \delta'_{\alpha_s} = \left(\frac{\sigma^{\mathrm{NLO}_s} - \sigma^0}{\sigma^{\mathrm{LO}}} \right) \times \frac{\Delta\sigma^{\mathrm{NLO}_{ew}}}{\sigma^0}$$

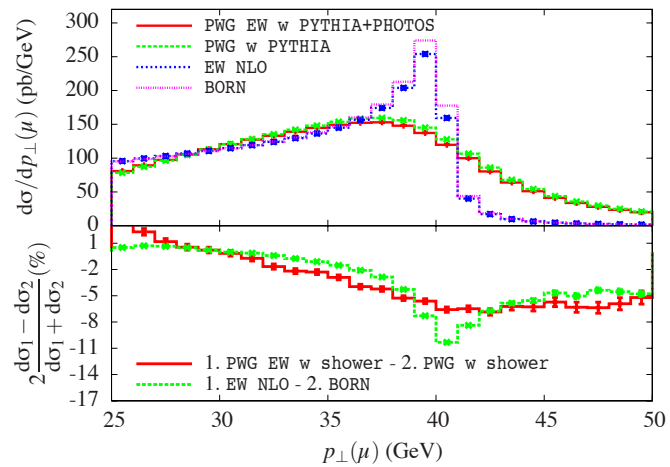
with $\sigma^{\mathrm{LO}}/\sigma^0$: LO/NLO PDFs)

(Barzé et al. 11)

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

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)

Summary

Drell-Yan processes at LHC

important for EW precision physics (M_W, $\sin\theta_w$)

Established tools for NNLO QCD, NNLL resummation, NLO EW

Progress on NNLO+PS matching

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

two approaches: pole expansion; EW corrections in `POWHEG`

- In general no naive factorization of K-factors
- estimated impact of $\sim 9\,\mathrm{MeV}$ on M_W measurement
- outlook: comparison of the two approaches

Not discussed: PDF issues:

- PDF uncertainties on M_W measurement

  (e.g./ Rojo/Vicini 13, Quackenbusch/Sullivan 15)

- potential to constrain photon PDF in DY

  (Dittmaier/Huber 09; Boughezal et al. 13)

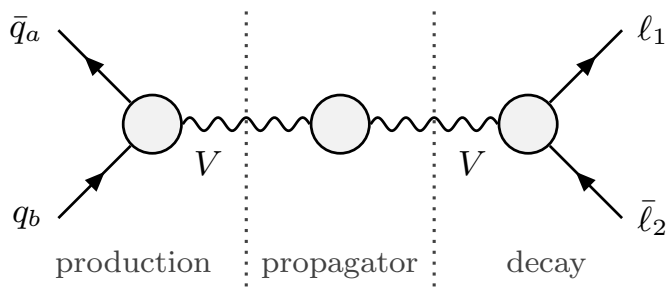
Backup slides

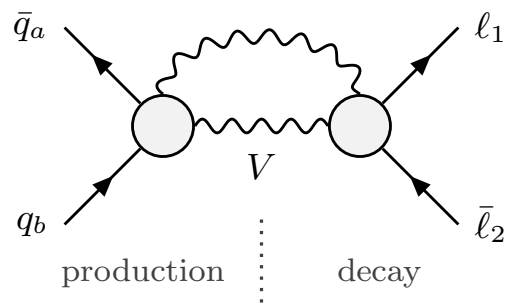
Pole scheme: (Stuart 91; Aeppli/v.Oldenbourgh/Wyler 93)

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

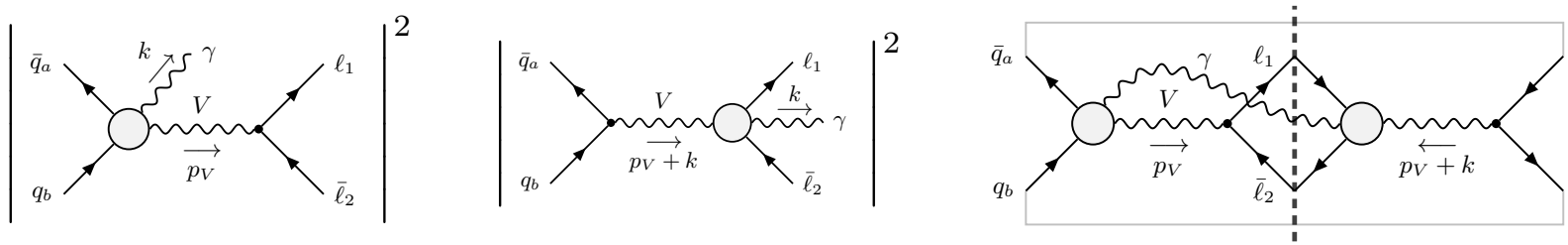
- Factorizable corrections to on-shell prod. and decay
- Non-fact. soft-photon corrections

Virtual corrections





Real corrections



Pole approximation

Numerical results

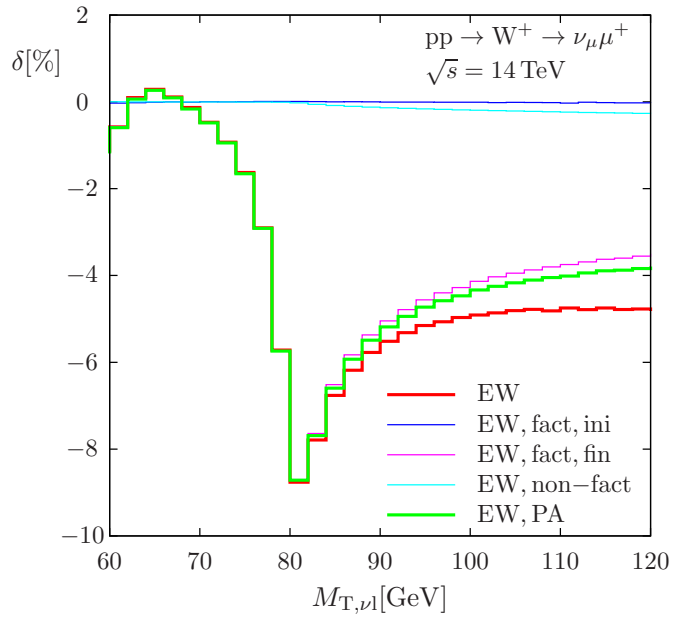
of NLO EW corrections

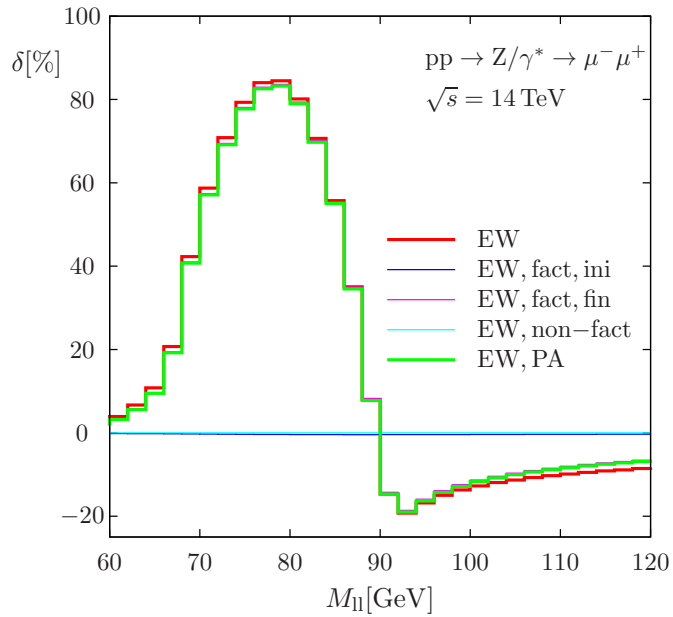
- corrections up to -20%; distort shape of resonance
- comparison of pole approx. to full EW NLO corrections: (Dittmaier/Krämer; Baur et al. 01) 0.1% accuracy near peak
- final-state factorizable corrections dominant
- soft non-factorizable corrections suppressed

(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 , $|\eta_l| < 2.5$, $E_T^{\rm miss} > 25$ GeV)

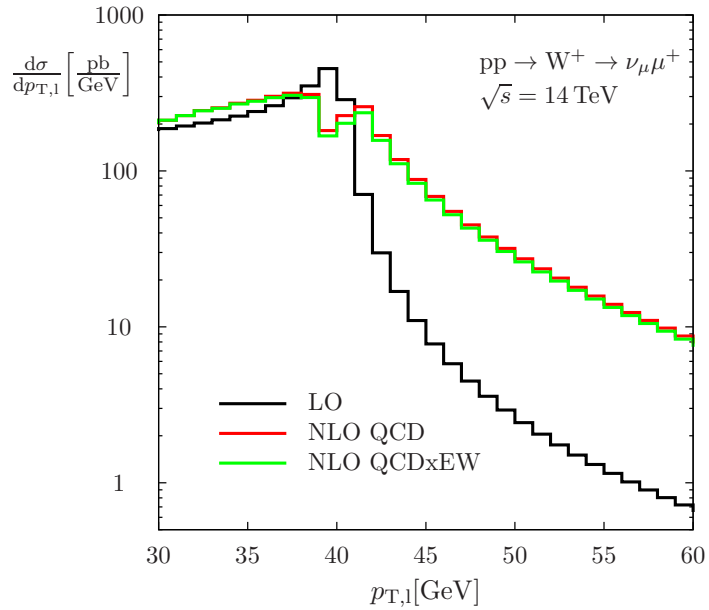


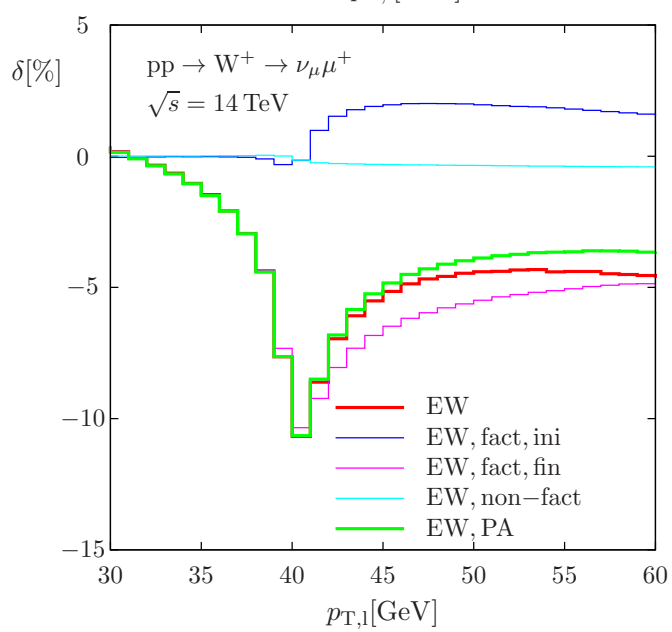


Numerical results
of NLO EW corrections

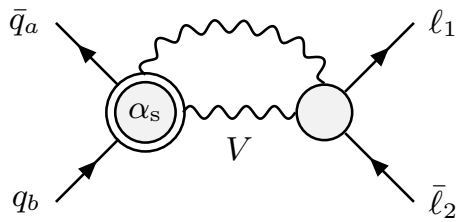
- corrections up to -20%; distort shape of resonance
- comparison of pole approx. to full EW NLO corrections: (Dittmaier/Krämer; Baur et al. 01) 0.1% accuracy near peak
- final-state factorizable corrections dominant
- soft non-factorizable corrections suppressed

(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 , $|\eta_l| < 2.5$, $E_T^{\rm miss} > 25$ GeV)





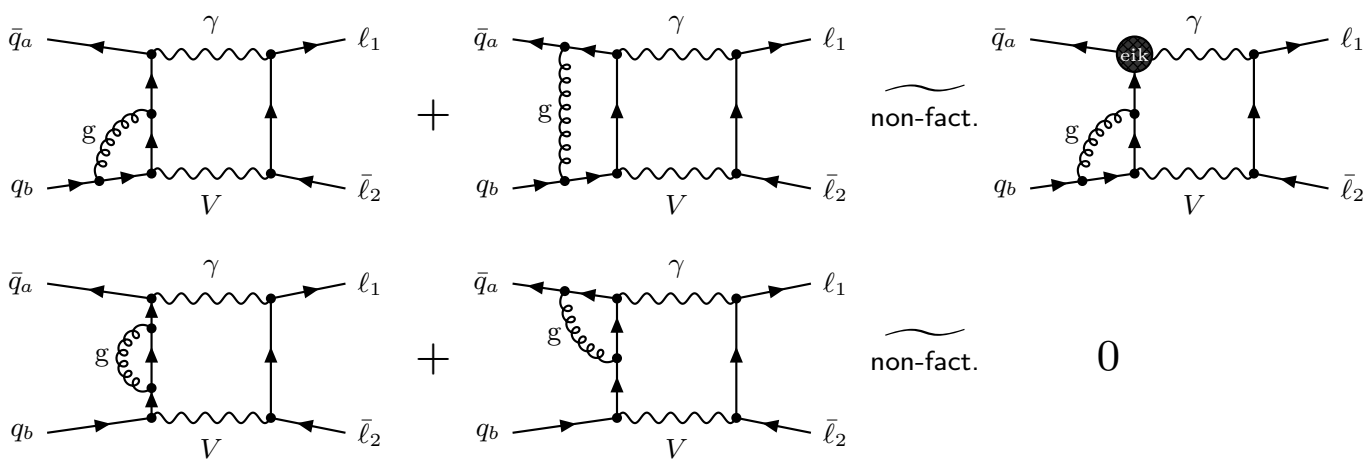
Non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections



Analytical cancellations:

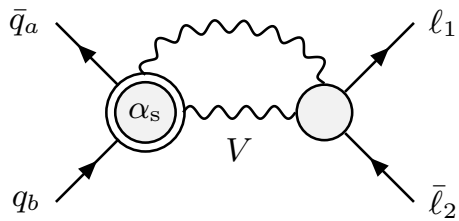
general diagrammatic argument (based on Yennie/Frautschi/Suura 61)

verified by explicit calculation using Mellin-Barnes/EFT methods



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

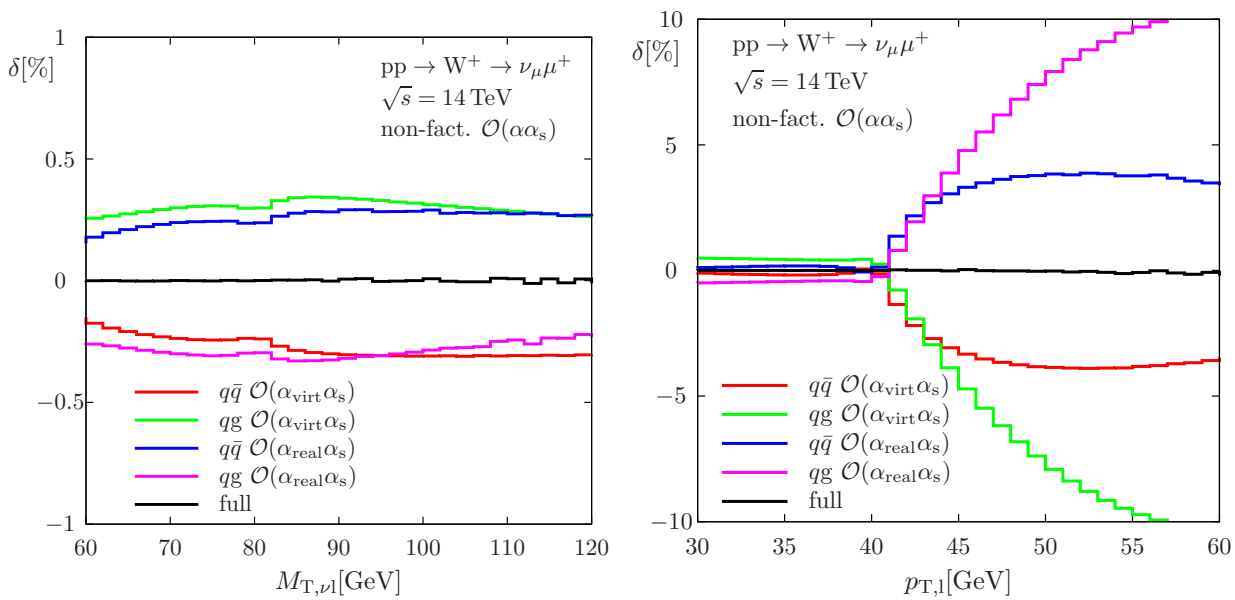
Non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections



Numerical results:

practically complete cancellation of real and virtual corrections

(defined separately through unphysical cut $\Delta E_\gamma \ll \Gamma_V$ in real corrections)



Effect on M_W measurement

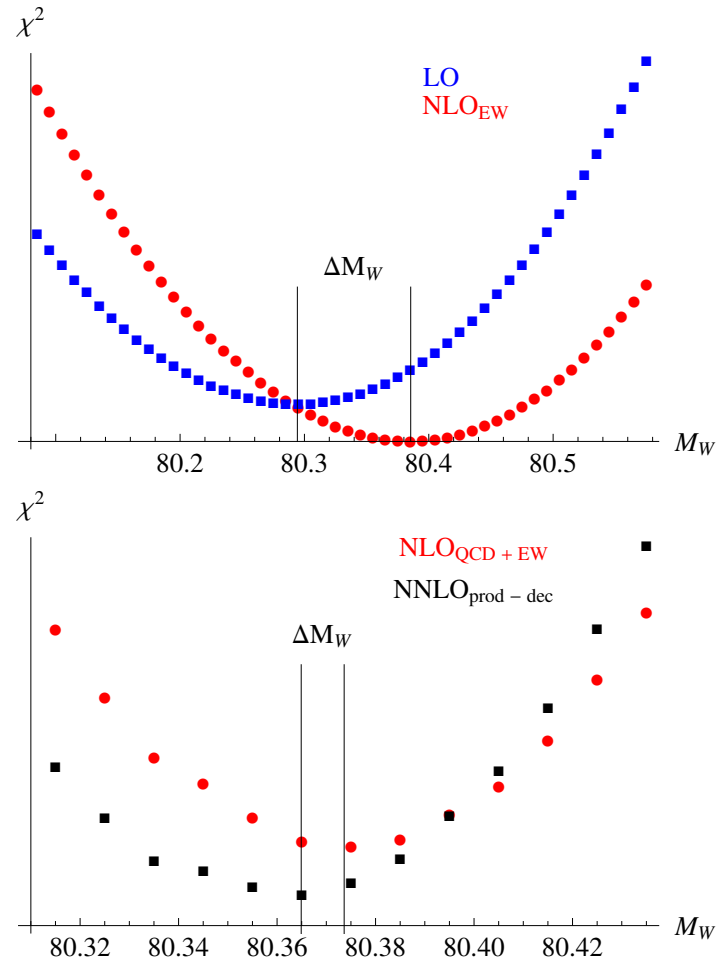
Estimate effect of higher-order corrections on M_W measurement:

- Bin-by bin χ^2 fit in $M_{T,\nu\ell}$
- "Templates": LO prediction for $M_W = 80.085 \ldots 80.785\,\mathrm{GeV}$ with $\Delta M_W = 0.01\,\mathrm{GeV}$.
- "Data": different theory predictions
- Normalize to same σ in $M_{T,\nu\ell}$ interval
- Shift from LO $\to$ NLO$_{\mathrm{EW}}$:

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

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

$$\Delta M_W^{\mathrm{NNLO}} \approx 9 \text{ MeV}$$



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

Pole scheme

Pole decomposition: expand around complex pole of propagator

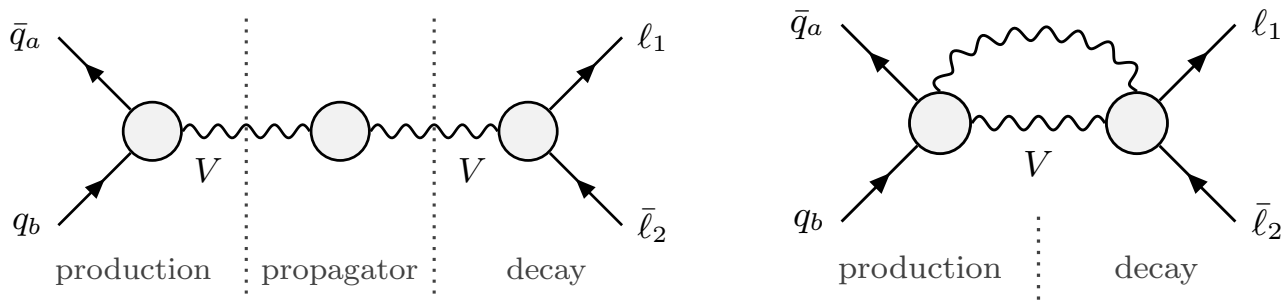
$\mu^2 = M^2 - \mathrm{i}M\Gamma$

$$\mathcal{A}(s) = \frac{R(s)}{s - M^2 + \Sigma(s)} + N(s)$$

$$= \frac{R(\mu^2)}{s-\mu^2}\,\frac{1}{1+\Sigma'(\mu^2)} + \left[\frac{R(s)}{s - M^2 + \Sigma(s)} - \frac{R(\mu^2)}{s-\mu^2}\,\frac{1}{1+\Sigma'(\mu^2)}\right] + N(s)$$

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

Virtual corrections



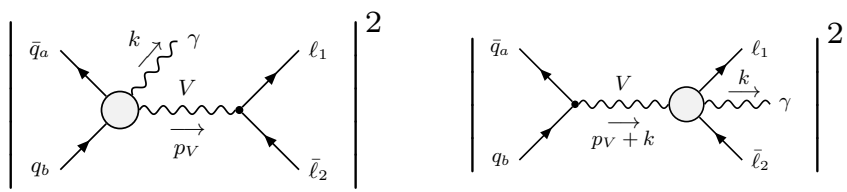
Real corrections

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