Electroweak corrections to DY-type processes

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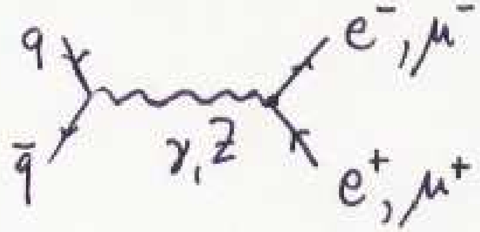
EW Tools for the LHC
CERN, 28 July 2003

- Overview
- Single Z production
- Single W production
- Higgs boson production:
  Higgs-strahlung from W and Z

Essential input from S. Dittmaier (MPI)

DY-type processes

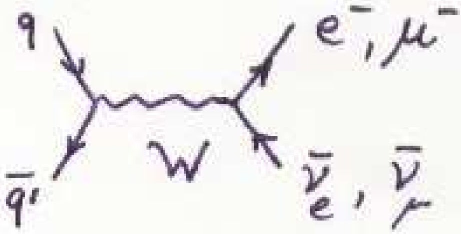
$q\bar{q} \to \gamma, Z \to \ell^+\ell^-$



$$\hat{s} = (m_{\ell^-} + m_{\ell^+})^2$$

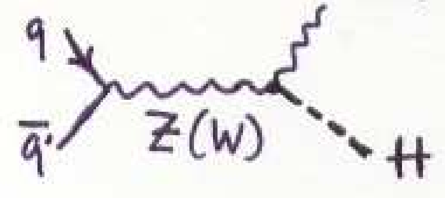
- around Z : precision measurements
  $\sin^2\Theta_{eff}(M_Z^2) \leftrightarrow$ LEP, SLC
- reference process (Standard Model) with high accuracy $\to$ parton distributions
  $\to$ new physics (Z')

$q\bar{q}' \to W^- \to \ell^- \bar{\nu}_\ell$



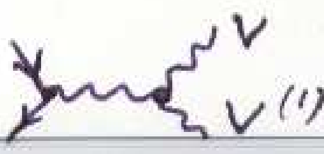
- precision measurement of M_W
- reference process (SM) with high accuracy
  $\to$ parton distributions
  $\to$ new physics (W')

$q\bar{q}' \to WH, \; q\bar{q} \to ZH$



- Higgs discovery
  M_H measurement

$q\bar{q}^{(\prime)} \to VV^{(\prime)}$ [$V = \gamma, Z, W$]



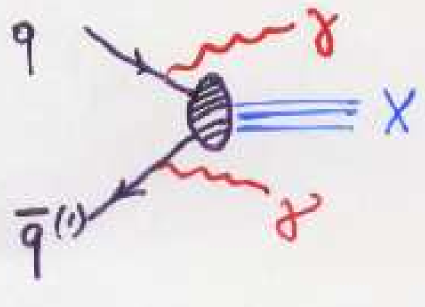
Electroweak corrections

- **QED corrections**
  - virtual photons + real photon bremsstrahlung
  - IR-divergent, mass singular
  - in general not gauge-invariant

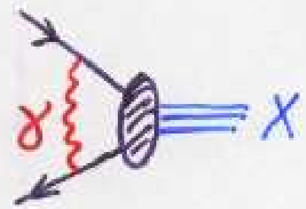
- **non-QED [purely weak] corrections**
  - IR finite, UV divergent → renormalization
  - complete quantum structure of SM
  - typical size of NNLO-QCD corrections

QED corrections ↗ non-universal ↘ universal

universal:



IR + mass-singular part of ISR radiation from quarks and ISR virtual photons



Mass singularities ...

...from the initial state: $\alpha \ln(m_{\mathrm{d,u}})$ terms.

QED $\overline{\mathrm{MS}}$ factorization
(analogously to QCD $\overline{\mathrm{MS}}$ factorization!)

de Rujula, Petronzio, Savoy-Navarro '79
Kripfganz, Perlt '88
Spiesberger '95
Baur, Keller, Wackeroth '98

$\Rightarrow$ absorption of singularities into renormalized PDFs $q(x)$:

$$q_0(x) = q(x) - \int_x^1 \frac{\mathrm{d}z}{z}\, q\left(\frac{x}{z}, M^2\right) \frac{\alpha}{2\pi} Q_q^2 \left[\frac{1+z^2}{1-z}\left\{\ln\left(\frac{M^2}{m_q^2}\right) - 2\ln(1-z) - 1\right\}\right]_+$$

Note: $\mathcal{O}(\alpha)$ correction should be included into DGLAP evolution of PDFs !

Not done yet, but approximate inclusion leads to small effects (order of other uncertainties in PDFs). Spiesberger '95

...from the final state: $\alpha \ln(m_l)$ terms.

$\Rightarrow$ large impact on $p_{\mathrm{T},l}$ and $M_{\mathrm{T},l\nu_l}$ distributions

but: singular terms cancel in $\int \mathrm{d}^3\mathbf{k}_\gamma$ around $l^\pm$ direction.

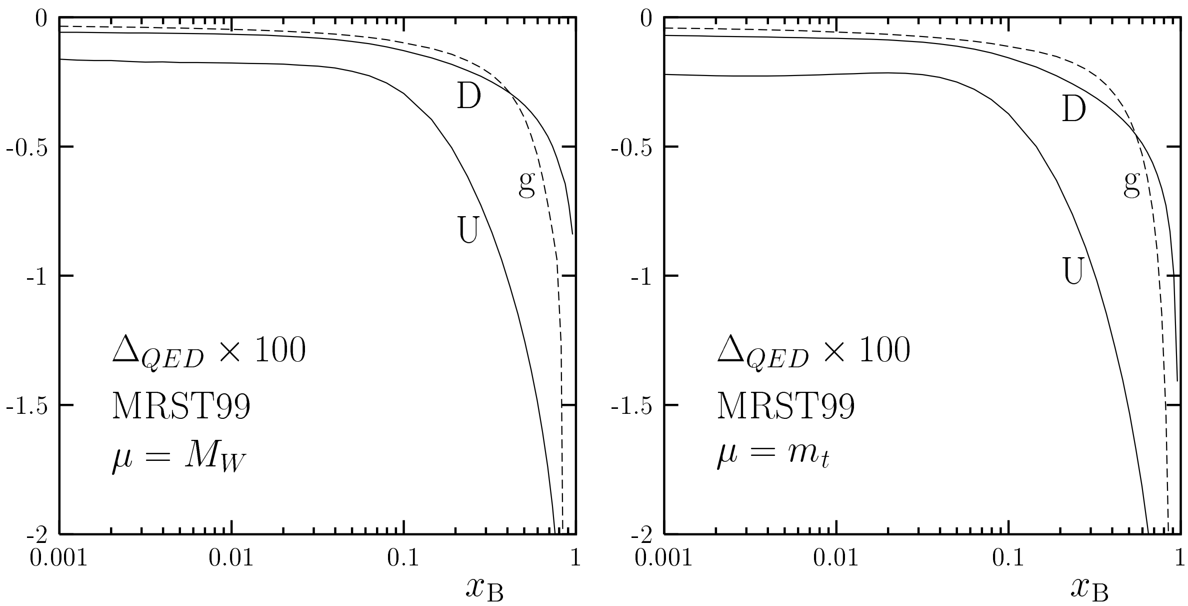
$\Rightarrow$ strong sensitivity to photon recombination

QED-modified evolution equation for quark distribution
[Spiesberger]

$$\frac{d}{dt}q_f(x,t) = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dz}{z}\left[P_{q/q}(z,t)q_f(x/z,t) + P_{q/g}(z,t)g(x/z,t)\right]$$
$$+\frac{\alpha(t)}{2\pi}\int_x^1 \frac{dz}{z}P^{\gamma}_{q/q}(z,t)q_f(x/z,t)$$

QED splitting function:

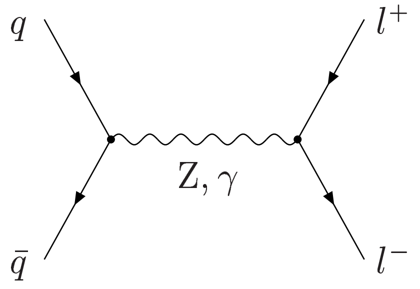
$$P^{\gamma}_{q/q}(z) = Q_f^2\left[\frac{1+z^2}{(1-z)_+} + \frac{3}{2}\delta(1-z)\right]$$



$$U = u + \bar{u}, \quad D = d + \bar{d}$$

Z-boson production: $\mathbf{pp \to Z \to \boldsymbol{l}^+\boldsymbol{l}^-}$

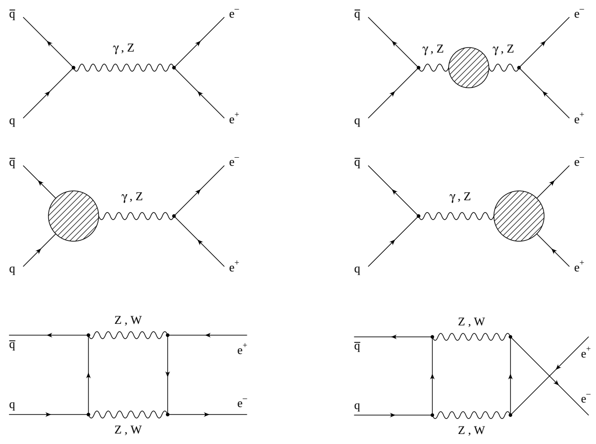
- Non-resonant background from s-channel γ exchange:



- Gauge invariant separation of photonic $\mathcal{O}(\alpha)$ corrections

  $\Rightarrow$ Splitting in QED and pure weak $\mathcal{O}(\alpha)$ corrections

- Near resonance:
  - weak corrections absorbed in effective couplings
  - box diagrams with WW, ZZ negligible



Electroweak corrections to $\mathrm{pp} \to \mathrm{Z} \to l^+l^-$

- Berends, Kleiss '85:
  FSR from decay $\mathrm{Z} \to l^+l^-(\gamma)$,
  ISR, interferences, and weak corrections neglected
- Baur, Keller, Sakumoto '97:
  $\mathcal{O}(\alpha)$ QED corrections, non-photonic (purely weak) corrections neglected
- Baur, Stelzer '99:
  Two-photon radiation $q\bar{q} \to l^+l^-\gamma\gamma$.
- Baur, Brein, Hollik, Schappacher, Wackeroth 2001
  complete $\mathcal{O}(\alpha)$ corrections
  MC Generator **ZGRAD2**

see also:

Yellow Report CERN-2000-04

parton cross section, parton CMS

- effective Born approximation (EBA)

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\Omega} \sim \mathcal{A}_0 \,(1+\cos^2\theta) \;+\; \mathcal{A}_1 \,\cos\theta$$

$$\mathcal{A}_0 = Q_q^2 Q_l^2 \, e(\hat{s})^4 \;+\; 2 v_q v_l Q_q Q_l \, e(\hat{s})^2 \, \mathrm{Re}\, \chi(\hat{s}) \;+\; (v_q^2 + a_q^2)(v_l^2 + a_l^2)\, |\chi(\hat{s})|^2$$

$$\mathcal{A}_1 = 4 Q_q Q_l a_q a_l \, e(\hat{s})^2 \, \mathrm{Re}\, \chi(\hat{s}) \;+\; 8 v_q a_q v_l a_l \, |\chi(\hat{s})|^2$$

Z couplings:

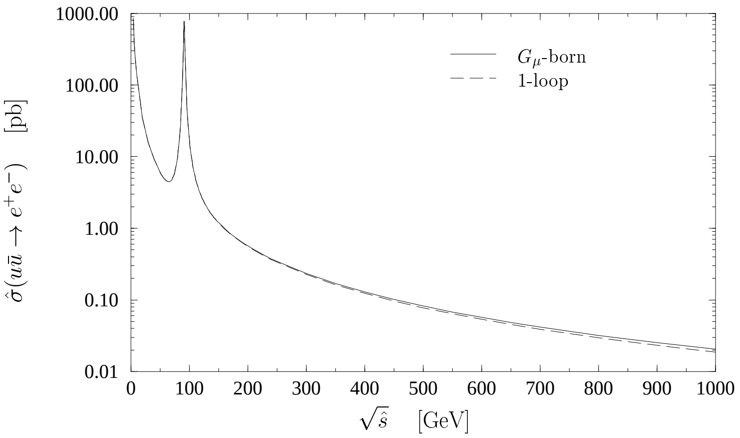
$$v_f = I_3^f - 2 Q_f \sin^2\theta_{\mathrm{eff}}, \quad a_f = I_3^f,$$

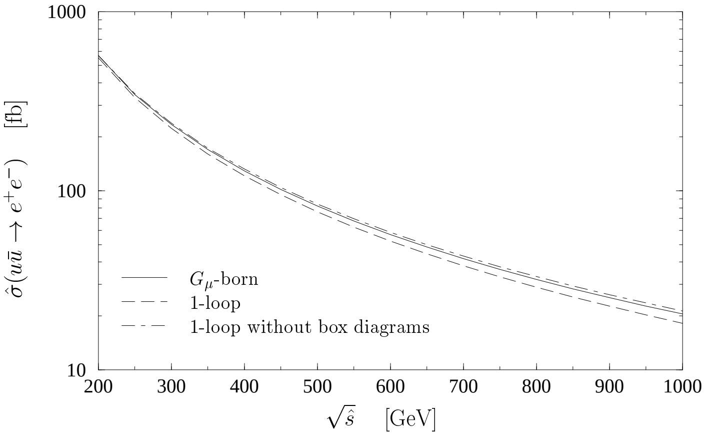
running charge:

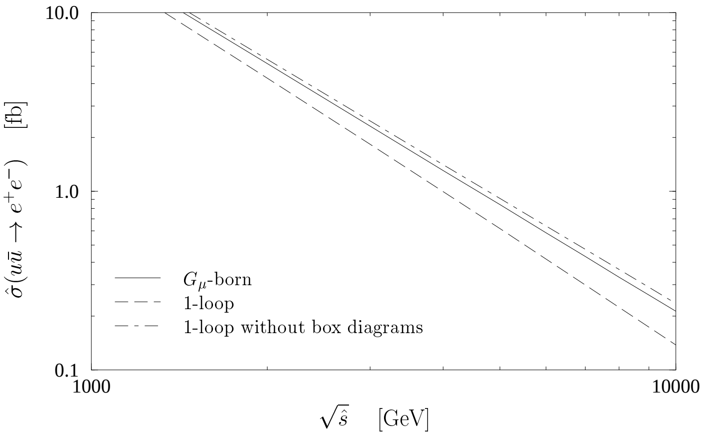
$$e(\hat{s})^2 = \frac{4\pi\alpha}{1-\Delta\alpha(\hat{s})}\,;$$

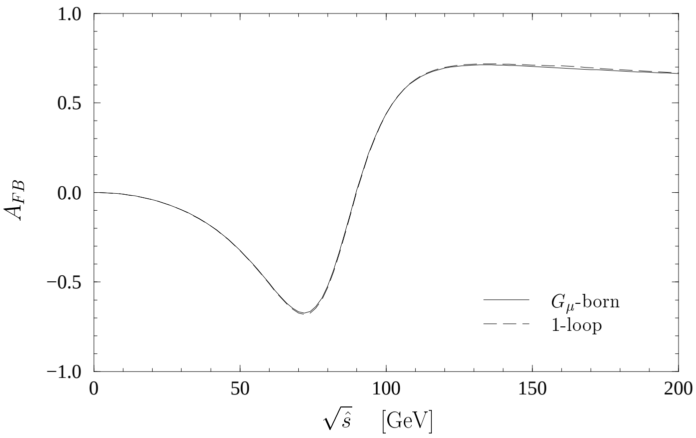
Z propagator + overall normalization:

$$\chi(\hat{s}) = (G_\mu M_Z^2 \sqrt{2})^2 \, \frac{\hat{s}}{\hat{s} - M_Z^2 + \mathrm{i}\hat{s}\Gamma_Z/M_Z}\,,$$

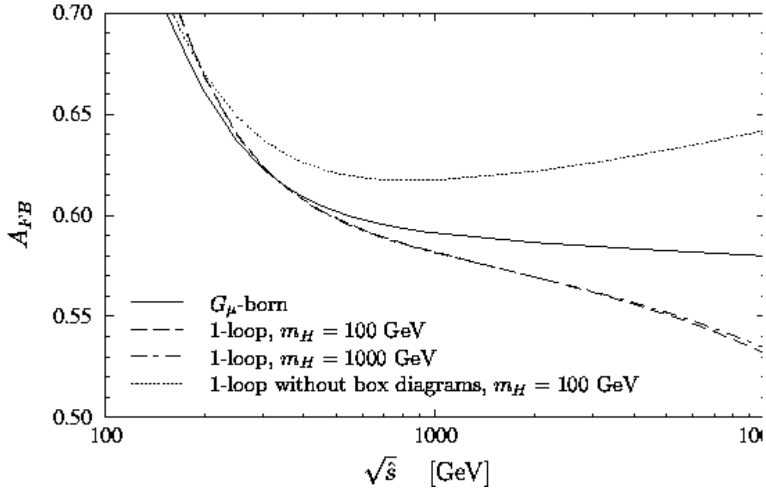

G_μ-born
1-loop
1000.00
100.00
10.00
1.00
0.10
0.01
$\hat{\sigma}(u\bar{u} \to e^+e^-)$ [pb]
0
100
200
300
400
500
600
700
800
900
1000
$\sqrt{\hat{s}}$ [GeV]


1000
100
10
$\hat{\sigma}(u\bar{u} \to e^+e^-)$ [fb]
G_μ-born
1-loop
1-loop without box diagrams
200
300
400
500
600
700
800
900
1000
$\sqrt{\hat{s}}$ [GeV]


10.0
1.0
0.1
$\hat{\sigma}(u\bar{u} \to e^+e^-)$ [fb]
G_μ-born
1-loop
1-loop without box diagrams
1000
10000
$\sqrt{\hat{s}}$ [GeV]



1.0
0.5
0.0
−0.5
−1.0
A_{FB}
0
50
100
150
200
$\sqrt{\hat{s}}$ [GeV]
G_μ-born
1-loop



0.70
0.65
0.60
0.55
0.50
A_{FB}
100
1000
$\sqrt{\hat{s}}$ [GeV]
G_μ-born
1-loop, $m_H = 100$ GeV
1-loop, $m_H = 1000$ GeV
1-loop without box diagrams, $m_H = 100$ GeV

Purely weak corrections to $\mathrm{pp} \to \mathrm{Z} \to l^+l^-$

Cross sections for high invariant masses $M_{l^+l^-}$:

δ_{weak} = purely weak correction

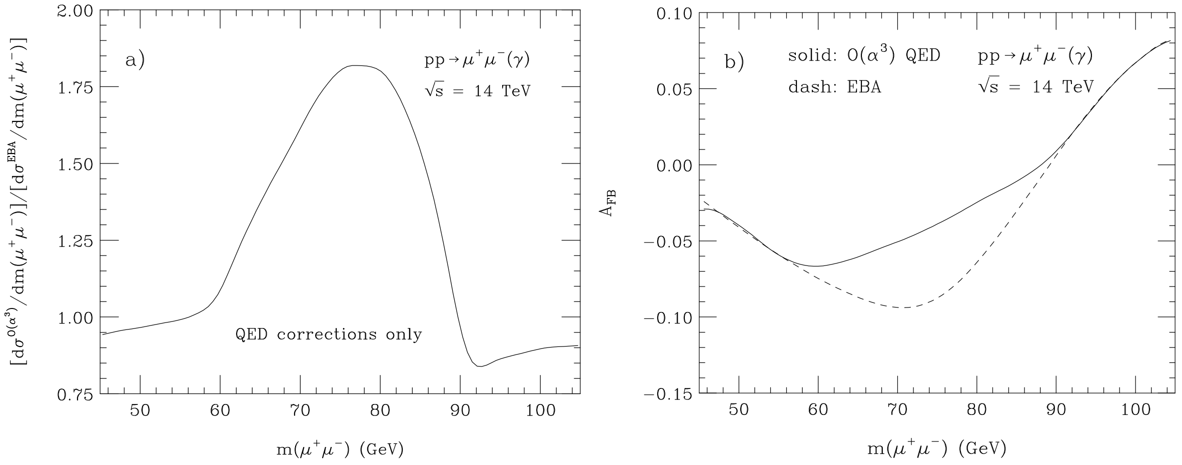
δ_{exp} = estimated exp. error at the LHC ($\mathcal{L} = 100\,\mathrm{fb}^{-1}$)

$M_{\mathrm{e^+e^-}}/\,\mathrm{TeV}$	$\sigma_{\mathrm{Born}}/\,\mathrm{fb}$	$\sigma_{\mathrm{corr}}/\,\mathrm{fb}$	$\delta_{\mathrm{weak}}/\%$	$\delta_{\mathrm{exp}}/\%$
0.9 – 1.1	6.2157	5.6253	−9.5	3
1.1 – 1.5	3.5076	3.1475	−10.3	4
1.5 – 1.75	0.6028	0.5307	−12.0	9.5
1.75 – 2.0	0.2669	0.2324	−12.9	14
2.0 – 2.5	0.1888	0.1583	−16.2	17
2.5 – 3.0	0.04906	0.04023	−18.0	30
3.0 – 4.0	0.01817	0.01462	−19.5	50

$\Rightarrow$ large and significant impact of pure weak corrections:

terms like $\alpha \ln^2(s/M_\mathrm{Z}^2)$

Effect of QED corrections [Baur et al.]



Forward-backward asymmetry:

$$A_{\mathrm{FB}} = \frac{F-B}{F+B}$$

with

$$F = \int_0^1 \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}\,\mathrm{d}\cos\theta^*, \qquad B = \int_{-1}^0 \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}\,\mathrm{d}\cos\theta^*.$$

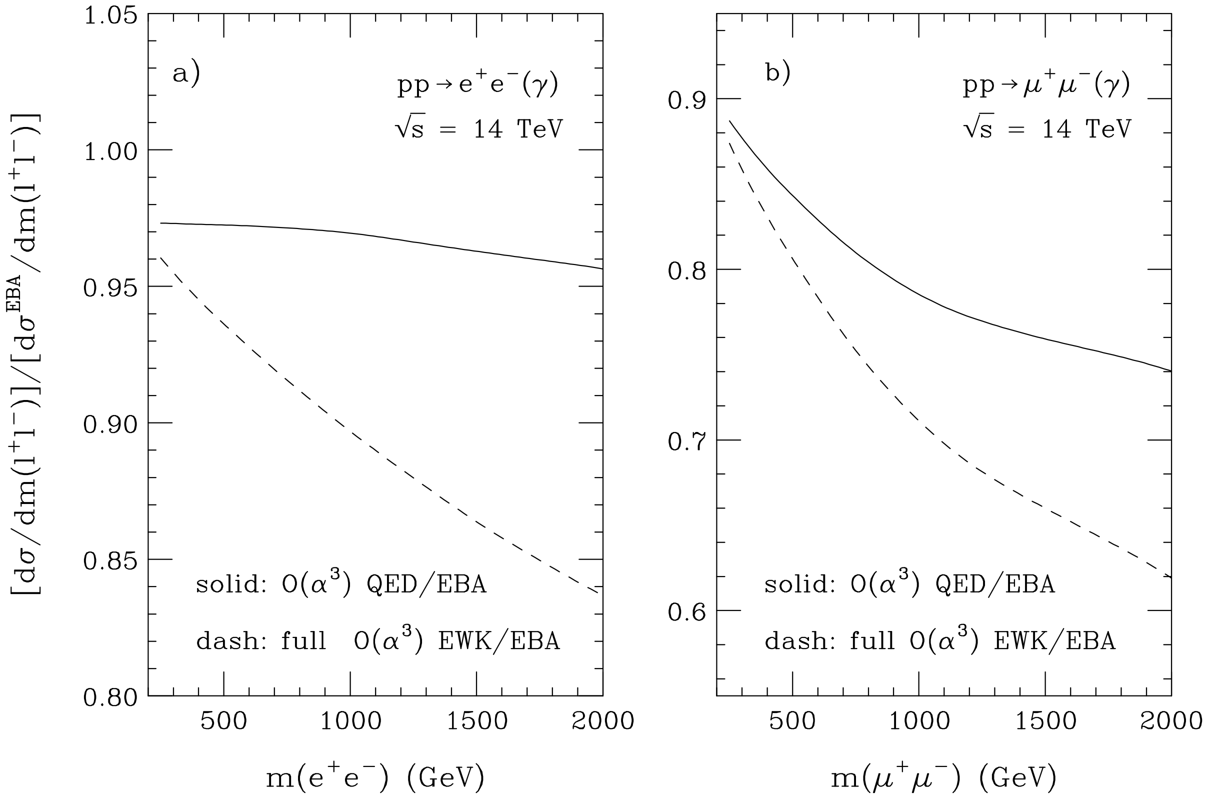
$\cos\theta^*$ in $\ell^+\ell^-$ rest frame:

$$\cos\theta^* = \frac{|p_z(\mu^+\mu^-)|}{p_z(\mu^+\mu^-)}\,\frac{2}{m(\mu^+\mu^-)\sqrt{m^2(\mu^+\mu^-)+p_T^2(\mu^+\mu^-)}}\,\cdot$$

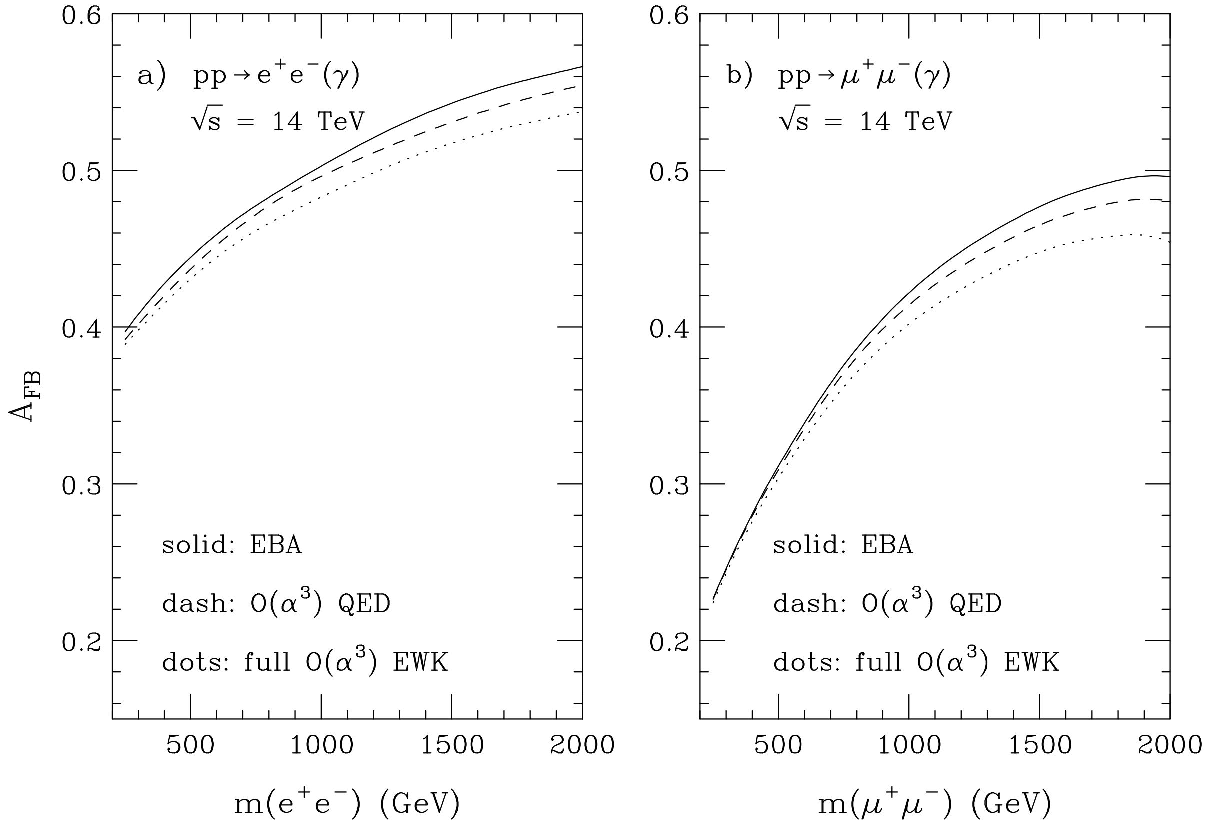
$$\cdot\,\left[p^+(\mu^-)p^-(\mu^+) - p^-(\mu^-)p^+(\mu^+)\right]$$

Notation:

$$p^\pm = \frac{1}{\sqrt{2}}\,(E \pm p_z)\,,$$



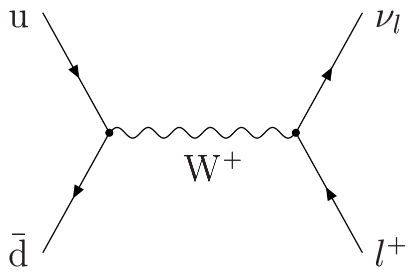
a)
$pp \to e^+e^-(\gamma)$
$\sqrt{s}$ = 14 TeV
solid: $O(\alpha^3)$ QED/EBA
dash: full $O(\alpha^3)$ EWK/EBA
$[d\sigma/dm(l^+l^-)]/[d\sigma^{EBA}/dm(l^+l^-)]$
$m(e^+e^-)$ (GeV)
b)
$pp \to \mu^+\mu^-(\gamma)$
$\sqrt{s}$ = 14 TeV
solid: $O(\alpha^3)$ QED/EBA
dash: full $O(\alpha^3)$ EWK/EBA
$m(\mu^+\mu^-)$ (GeV)



a) $pp \to e^+e^-(\gamma)$
$\sqrt{s}$ = 14 TeV
solid: EBA
dash: $O(\alpha^3)$ QED
dots: full $O(\alpha^3)$ EWK
A_{FB}
$m(e^+e^-)$ (GeV)
b) $pp \to \mu^+\mu^-(\gamma)$
$\sqrt{s}$ = 14 TeV
solid: EBA
dash: $O(\alpha^3)$ QED
dots: full $O(\alpha^3)$ EWK
$m(\mu^+\mu^-)$ (GeV)

Single W production

Lowest-order amplitude:



$$\mathcal{M}_0 \sim \frac{1}{s - M_\mathrm{W}^2 + \mathrm{i} M_\mathrm{W} \Gamma_\mathrm{W}(s)}$$

Finite-width treatments:

constant width: $\Gamma_\mathrm{W}(s) = \Gamma_\mathrm{W}$,

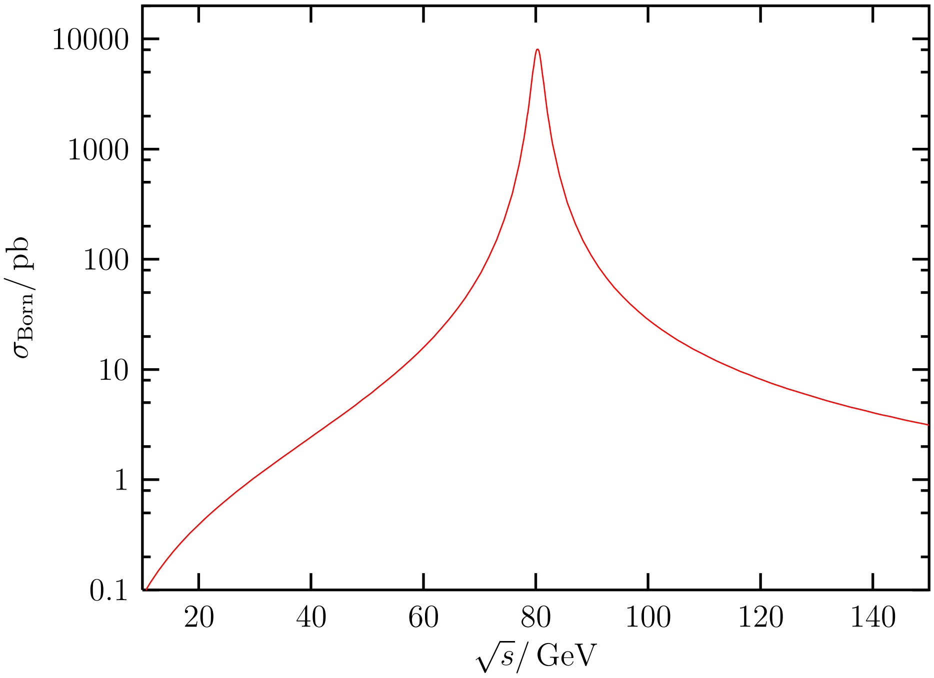
running width: $\Gamma_\mathrm{W}(s) = \Gamma_\mathrm{W} \dfrac{s}{M_\mathrm{W}^2}$.

[at tree level both treatments are equivalent]

Bardin, Leike, Riemann, Sachwitz '88
Hollik, Wackeroth '97

$$M_\mathrm{W}|_\mathrm{run} = M_\mathrm{W}/\sqrt{1 + \Gamma_\mathrm{W}^2/M_\mathrm{W}^2}|_\mathrm{const} \approx M_\mathrm{W}|_\mathrm{const} - 27\,\mathrm{MeV}.$$

Lowest-order parton cross section:



Electroweak corrections:

- Berends, Kleiss '85:
  FSR from decay W $\rightarrow l\nu_l(\gamma)$,
  ISR, interferences, and weak corrections neglected

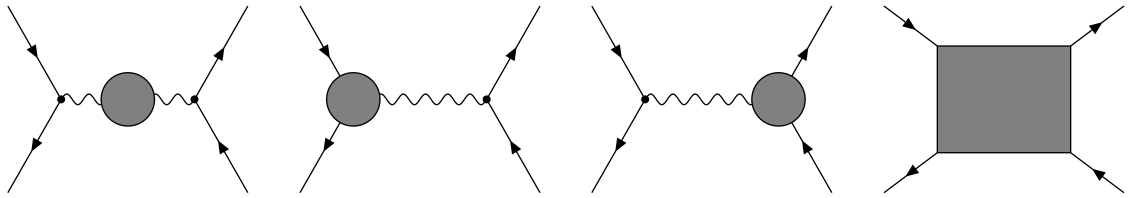
- Baur, Keller, Wackeroth '98:
  $\mathcal{O}(\alpha)$ corrections to resonant W production,
  non-resonant corrections neglected
  (based on Hollik, Wackeroth '97)
  MC Generator WGRAD

- Dittmaier, Krämer 2001:
  Full $\mathcal{O}(\alpha)$ corrections

see also:

Yellow Report CERN-2000-04

Virtual one-loop corrections



W self-energy   Wud and $Wl\nu_l$ vertex corrections   box corrections

+ wave-function renormalization for external fermions

Factorization of one-loop amplitude: $\mathcal{M}_{\text{virt}} = \delta_{\text{virt}}\,\mathcal{M}_0$

$$\Rightarrow \; |\mathcal{M}_0 + \mathcal{M}_{\text{virt}}|^2 = |\mathcal{M}_0|^2\,(1 + 2\,\mathrm{Re}\;\delta_{\text{virt}})$$

Treatment of resonating terms:

- All Breit–Wigner-type terms contained in $|\mathcal{M}_0|^2$.
- Resonant logarithms in δ_{virt} from photonic corrections:

$$\ln(s - M_{\mathrm{W}}^2) \;\rightarrow\; \ln(s - M_{\mathrm{W}}^2 + \mathrm{i}M_{\mathrm{W}}\Gamma_{\mathrm{W}}).$$

Treatment of singularities:

- UV: dimensional regularization,
- IR: infinitesimal photon mass m_γ,
- collinear: small fermion masses m_f.

Pole approximation (PA) for virtual corrections

Idea: extraction of resonating part of amplitude.

$\Rightarrow$ Consistent expansion about gauge-invariant pole in complex s-plane respects gauge invariance.

Actual procedure:

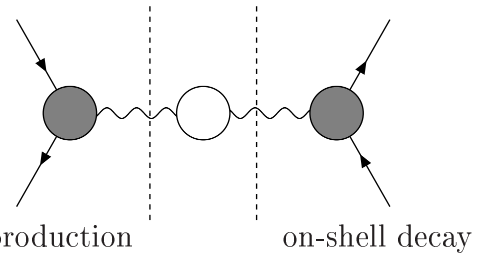
Splitting of resonating contributions into *factorizable* and *non-factorizable* corrections.

$$\delta_{\mathrm{virt,PA}} = \delta_{\mathrm{virt},fact} + \delta_{\mathrm{virt},nonfact}.$$

(analogously to treatment of $e^+e^- \to WW \to 4f$ by Denner, Dittmaier, Roth, Wackeroth '99)

Factorizable corrections:

$$\delta_{\mathrm{virt},fact} = \delta_{\mathrm{virt,u\bar{d}\to W^+}} + \delta_{\mathrm{virt,W^+}\to l^+\nu_l}$$



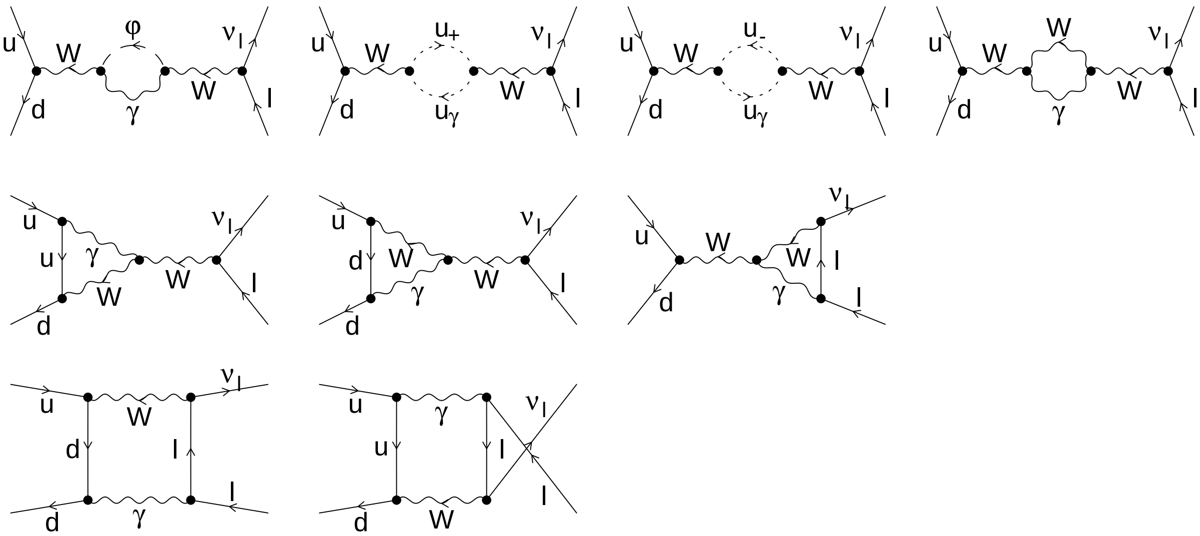
Features of $\delta_{\mathrm{virt},fact}$:

- gauge-invariant,
- respects spin correlations.

Non-factorizable corrections:

$$\delta_{\text{virt},nonfact} = \delta_{\text{virt}}\big|_{\text{resonant}} - \delta_{\text{virt},fact}.$$

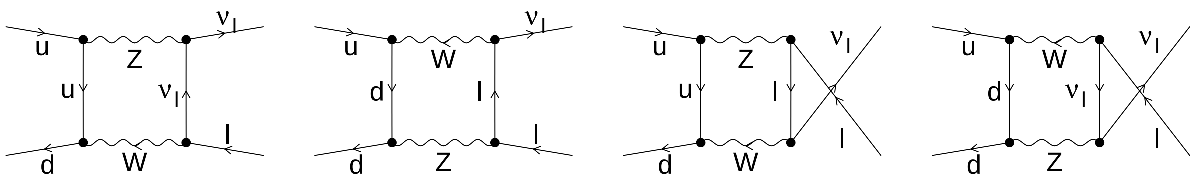
Only photonic diagrams contribute



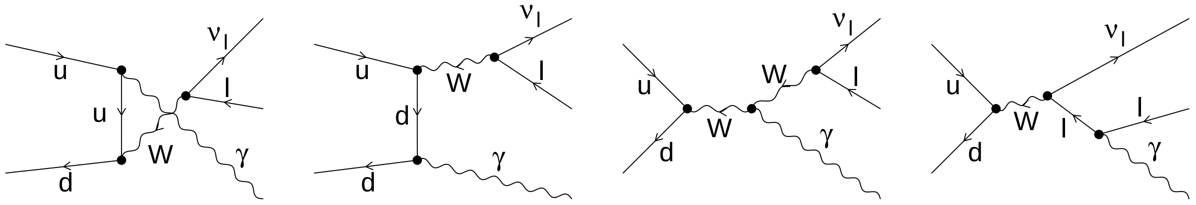
Features of $\delta_{\text{virt},nonfact}$:

- gauge-invariant,
- free of fermion-mass singularities,
- compensates IR divergences of on-shell W's in $\delta_{\text{virt},fact}$,
- contains all $\ln(s - M_{\mathrm{W}}^2 + \mathrm{i}M_{\mathrm{W}}\Gamma_{\mathrm{W}})$ terms.

Neglected non-resonant corrections in PA:



Real bremsstrahlung corrections



amplitude: $\mathcal{M}_{\text{real}} = \varepsilon^*_\mu(k)\, T^\mu.$

em. Ward identity: $k_\mu T^\mu = 0.$

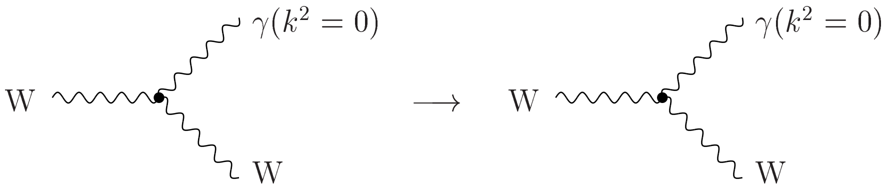
gauge-invariant introduction of Γ_{W}:

- constant width: $\Gamma_{\text{W}}(s) = \Gamma_{\text{W}}.$

  $\Rightarrow$ Ward identity respected.

- running width: $\Gamma_{\text{W}}(s) = \Gamma_{\text{W}}\,\dfrac{s}{M_{\text{W}}^2}.$

  $\Rightarrow$ Ward identity respected if γWW vertex is modified:



$\times \left(1 + \dfrac{\Gamma_{\text{W}}}{M_{\text{W}}}\right)$

Baur, Zeppenfeld '95
Argyres et al. '95

Note: modification originates from fermion-loop correction to γWW vertex.

Numerical results

Input data: M_W, M_Z, M_H, m_f, and
$(c_\mathrm{W}^2 = 1 - s_\mathrm{W}^2 = M_\mathrm{W}^2/M_\mathrm{Z}^2)$

- $\alpha(0)$: large universal corrections from

$$\begin{aligned}
\Delta\alpha(Q^2) &= \frac{\alpha}{3\pi}\sum_{f\neq\mathrm{t}} N_\mathrm{C}^f Q_f^2 \ln\left(\frac{Q^2}{m_f^2}\right) + \dots, \text{ with } Q \sim M_\mathrm{W}, \\
\Delta\rho &= \frac{3\alpha m_\mathrm{t}^2}{16\pi s_\mathrm{W}^2 M_\mathrm{W}^2}, \\
\mathrm{d}\sigma_\mathrm{corr} &= \mathrm{d}\sigma_\mathrm{Born}\left[1 + 2\Delta\alpha(Q^2) - \frac{2c_\mathrm{W}^2}{s_\mathrm{W}^2}\Delta\rho + \dots\right].
\end{aligned}$$

- $\alpha(M_\mathrm{Z}^2)$: absorption and resummation of $\Delta\alpha(Q^2)$

$$\begin{aligned}
\alpha(Q^2) &= \frac{\alpha(0)}{1 - \Delta\alpha(Q^2)}, \\
\mathrm{d}\sigma_\mathrm{corr} &= \mathrm{d}\sigma'_\mathrm{Born}\,[1 - \frac{2c_\mathrm{W}^2}{s_\mathrm{W}^2}\Delta\rho + \dots].
\end{aligned}$$

- G_μ: additional absorption of $\Delta\rho$

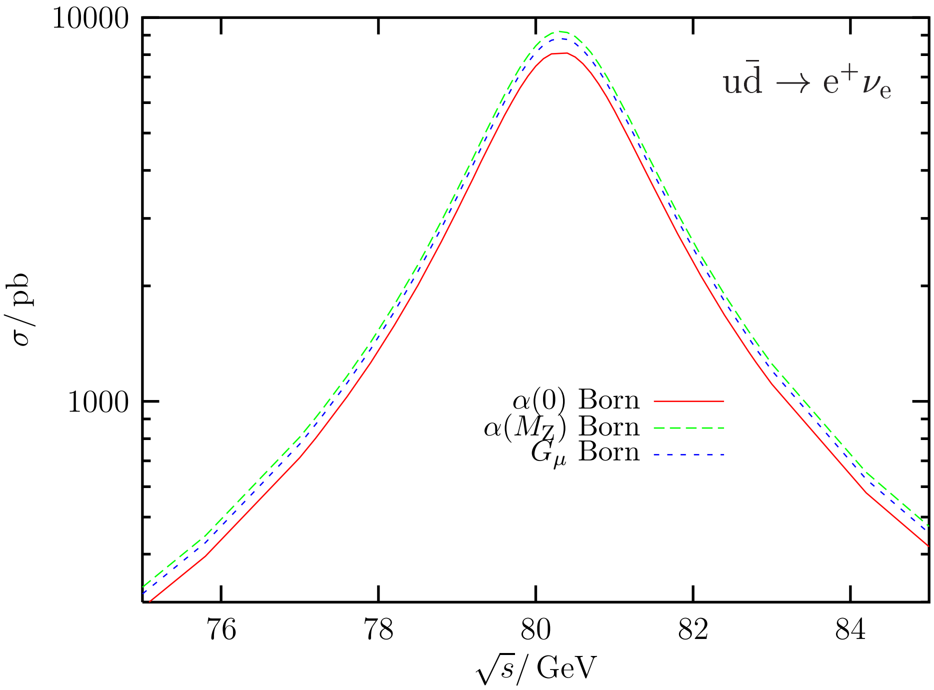
$$\begin{aligned}
G_\mu &= \frac{\pi\alpha(0)}{\sqrt{2}s_\mathrm{W}^2 M_\mathrm{W}^2(1-\Delta r)}, \\
\Delta r &= \Delta\alpha(M_\mathrm{W}^2) - \frac{c_\mathrm{W}^2}{s_\mathrm{W}^2}\Delta\rho.
\end{aligned}$$

Default setup:

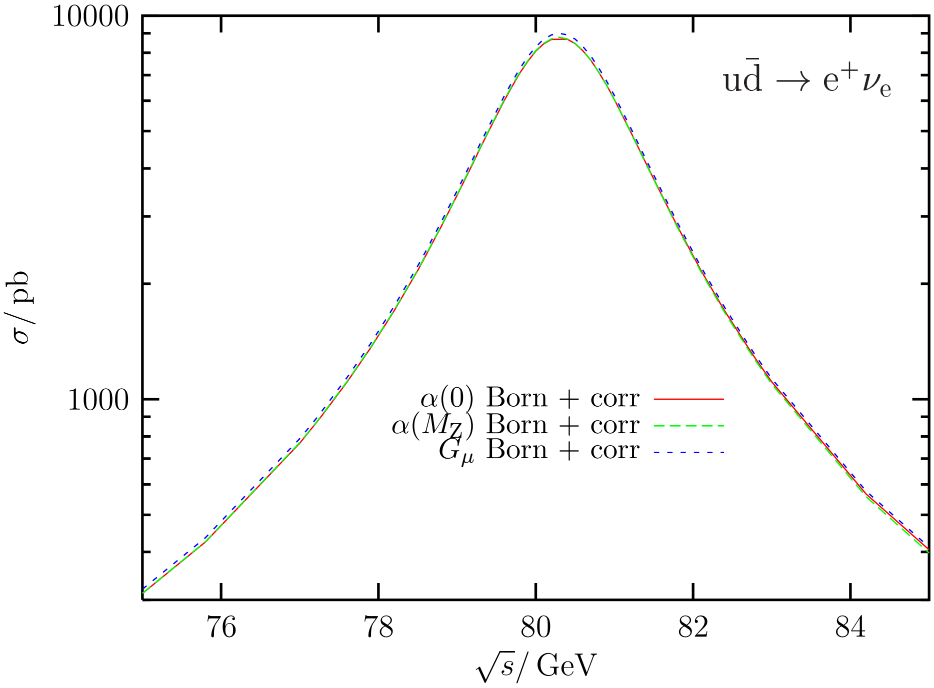
- G_μ scheme,
- constant width Γ_W,
- no QCD corrections,
- CTEQ4L parton distributions.

Reduction of input scheme dependence

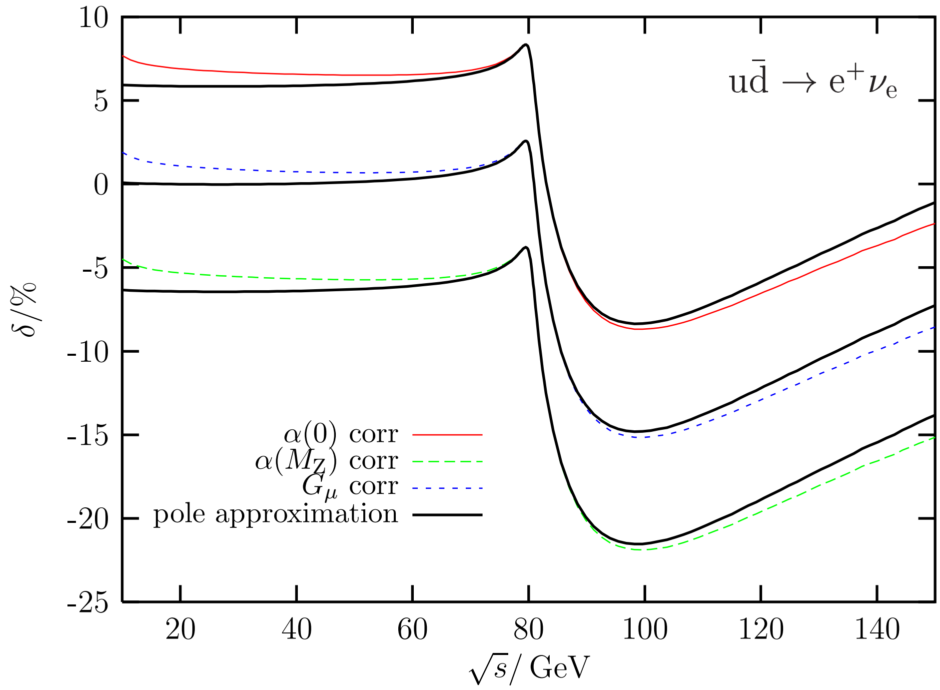
Lowest-order parton cross sections:



Inclusion of $\mathcal{O}(\alpha)$ corrections:



Full $\mathcal{O}(\alpha)$ corrections versus pole approximation



Accuracy of PA:

$$\delta - \delta_{\mathrm{PA}} \sim \frac{\alpha}{\pi} \ln\left(\frac{M_\mathrm{W}^2}{s}\right) \ln(\ldots)$$

$$|\delta - \delta_{\mathrm{PA}}| \lesssim 0.2\% \quad \text{for} \quad 70\,\mathrm{GeV} < \sqrt{s} < 90\,\mathrm{GeV}$$

$$|\delta - \delta_{\mathrm{PA}}| \lesssim 0.4\% \quad \text{for} \quad 60\,\mathrm{GeV} < \sqrt{s} < 100\,\mathrm{GeV}$$

$$|\delta - \delta_{\mathrm{PA}}| \lesssim 0.7\% \quad \text{for} \quad 40\,\mathrm{GeV} < \sqrt{s} < 120\,\mathrm{GeV}$$

$$|\delta - \delta_{\mathrm{PA}}| \lesssim 1.1\% \quad \text{for} \quad 20\,\mathrm{GeV} < \sqrt{s} < 140\,\mathrm{GeV}$$

Results for LHC cross sections [Dittmaier, Krämer]

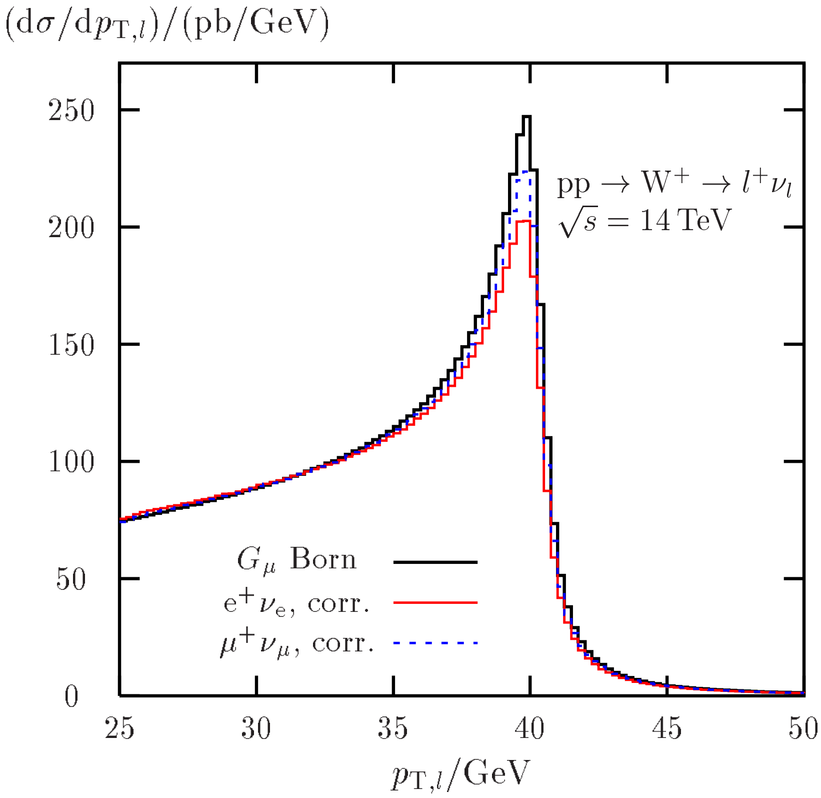
Phase-space cuts:

- $p_{\mathrm{T},l} > 25\,\mathrm{GeV}, \quad |\eta_l| < 1.2, \quad l = \mathrm{e}, \mu,$
- $\not{p}_{\mathrm{T}} > 25\,\mathrm{GeV}.$

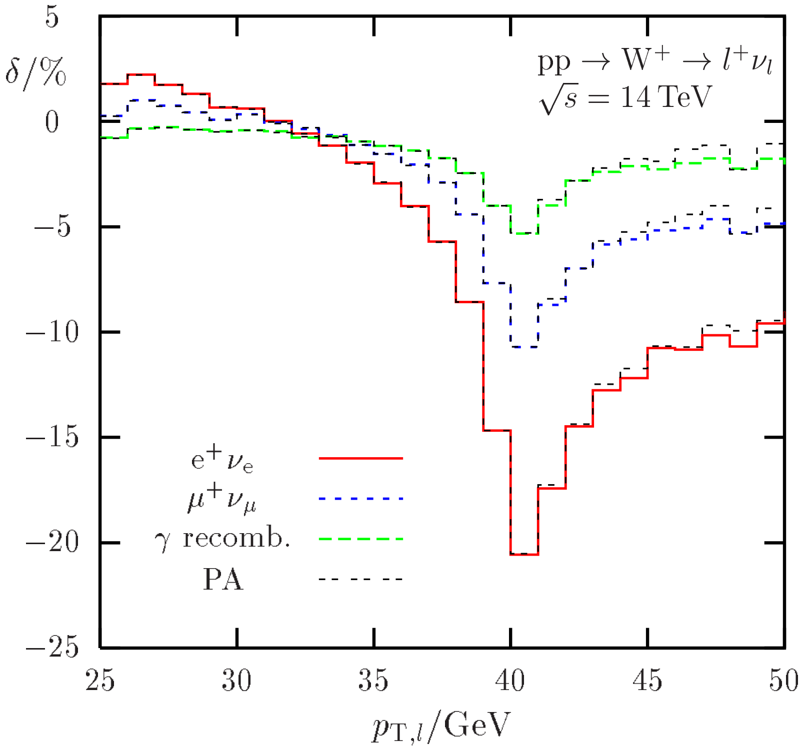
Integrated cross section:

$$
\begin{aligned}
\sigma_{\mathrm{Born}} &= 1.92\,\mathrm{nb}, \\
\sigma_{\mathrm{corr,e^+\nu_e}} &= 1.82\,\mathrm{nb} \qquad (\delta = -5.2\%), \\
\sigma_{\mathrm{corr,\mu^+\nu_\mu}} &= 1.87\,\mathrm{nb} \qquad (\delta = -2.6\%).
\end{aligned}
$$

$p_{\mathrm{T},l}$ distribution:



$\mathcal{O}(\alpha)$ corrections to the $p_{\mathrm{T},l}$ distribution:



$\Rightarrow$ No significant difference between full correction and PA (at least for not too large $p_{\mathrm{T},l}$).

Quality of pole approximation (PA):

PA fails above W resonance

$\mathrm{pp} \to \nu_l l^+(+\gamma)$ at $\sqrt{s} = 14\,\mathrm{TeV}$						
$p_{\mathrm{T},l}/\mathrm{GeV}$	25–∞	50–∞	100–∞	200–∞	500–∞	1000–∞
σ_0/pb	1933.5(3)	11.50(1)	0.8198(4)	0.1015(1)	0.005277(1)	0.0003019(1)
$\delta_{\mathrm{e}^+\nu_\mathrm{e}}/\%$	−5.5(1)	−9.2(1)	−11.8(1)	−16.5(1)	−27.5(2)	−39.1(1)
$\delta_{\mathrm{e}^+\nu_\mathrm{e},\mathrm{PA}}/\%$	−5.4(1)	−8.0(1)	−7.3(1)	−7.8(1)	−10.3(2)	−13.0(1)
$\delta_{\mu^+\nu_\mu}/\%$	−2.9(1)	−4.9(1)	−8.5(1)	−13.1(1)	−23.4(1)	−34.5(1)
$\delta_{\mu^+\nu_\mu,\mathrm{PA}}/\%$	−2.8(1)	−3.5(1)	−4.0(1)	−4.4(1)	−6.2(1)	−8.5(1)
$\delta_{\mathrm{rec}}/\%$	−1.8(1)	−2.7(1)	−6.2(1)	−10.2(1)	−19.6(1)	−29.6(1)
$\delta_{\mathrm{rec,PA}}/\%$	−1.8(1)	−1.5(1)	−1.6(1)	−1.6(1)	−2.4(1)	−3.6(1)
$\Delta(2^{\pm 1} M_\mathrm{W})/\%$	±0.1	±0.1	±0.1	±0.1	±0.1	±0.2
$\Delta(M_{\mathrm{T},\nu_l l})/\%$	−0.0	0.0	0.1	0.2	0.5	0.8

Higgs-Strahlung from W and Z

complete $O(\alpha)$ EW corrections:
Ciccolini, Dittmaier, Krämer (2003)

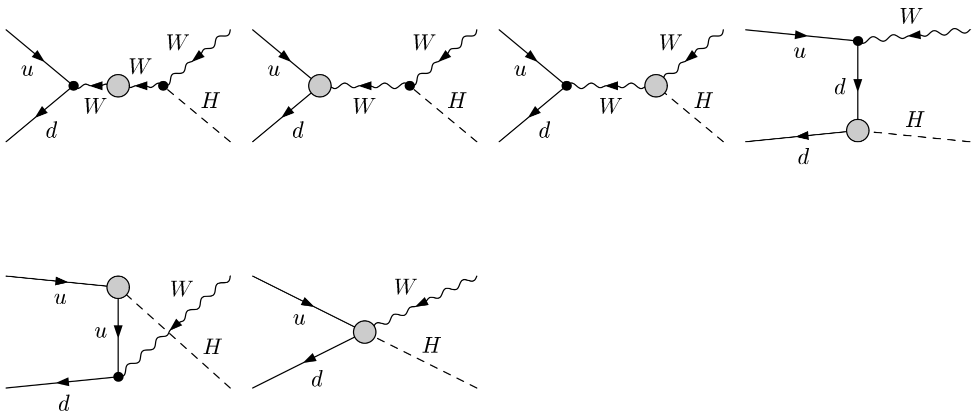


Figure 2: Contributions of different vertex functions to $u\bar{d} \to WH$.

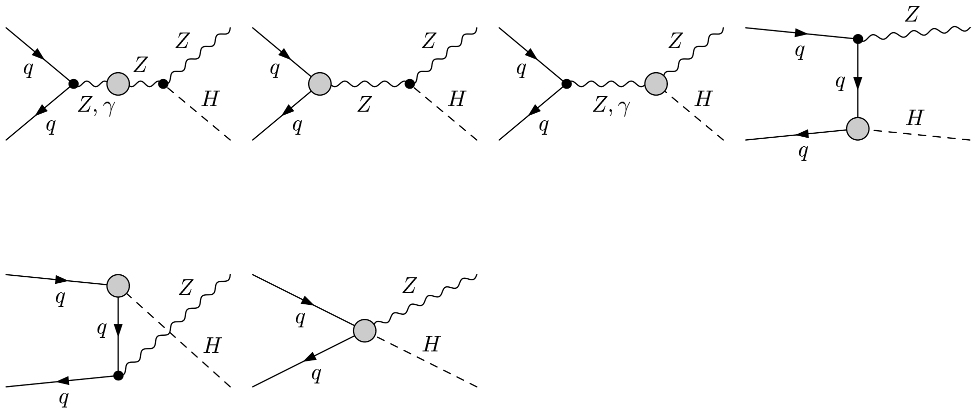


Figure 3: Contributions of different vertex functions to $q\bar{q} \to ZH$.

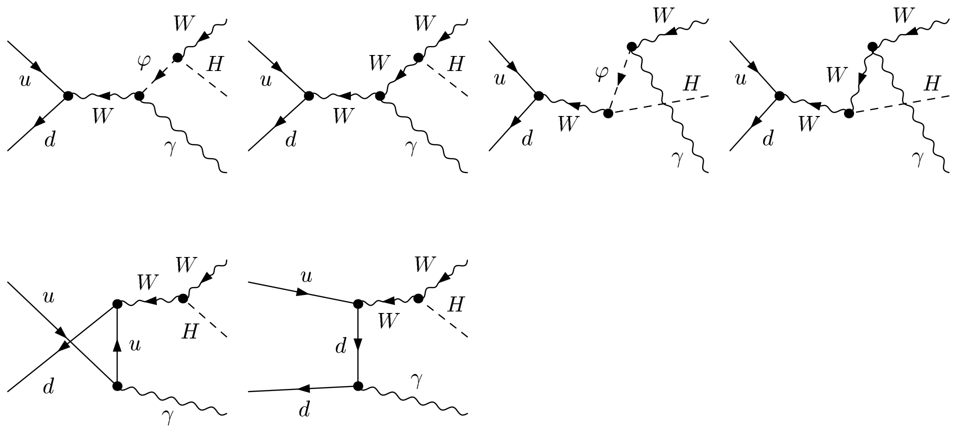


Figure 9: Bremsstrahlung diagrams for $u\bar{d} \to WH + \gamma$.

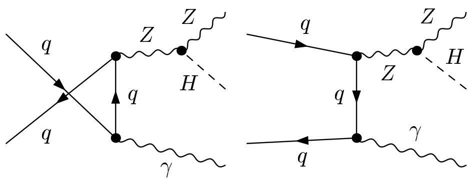
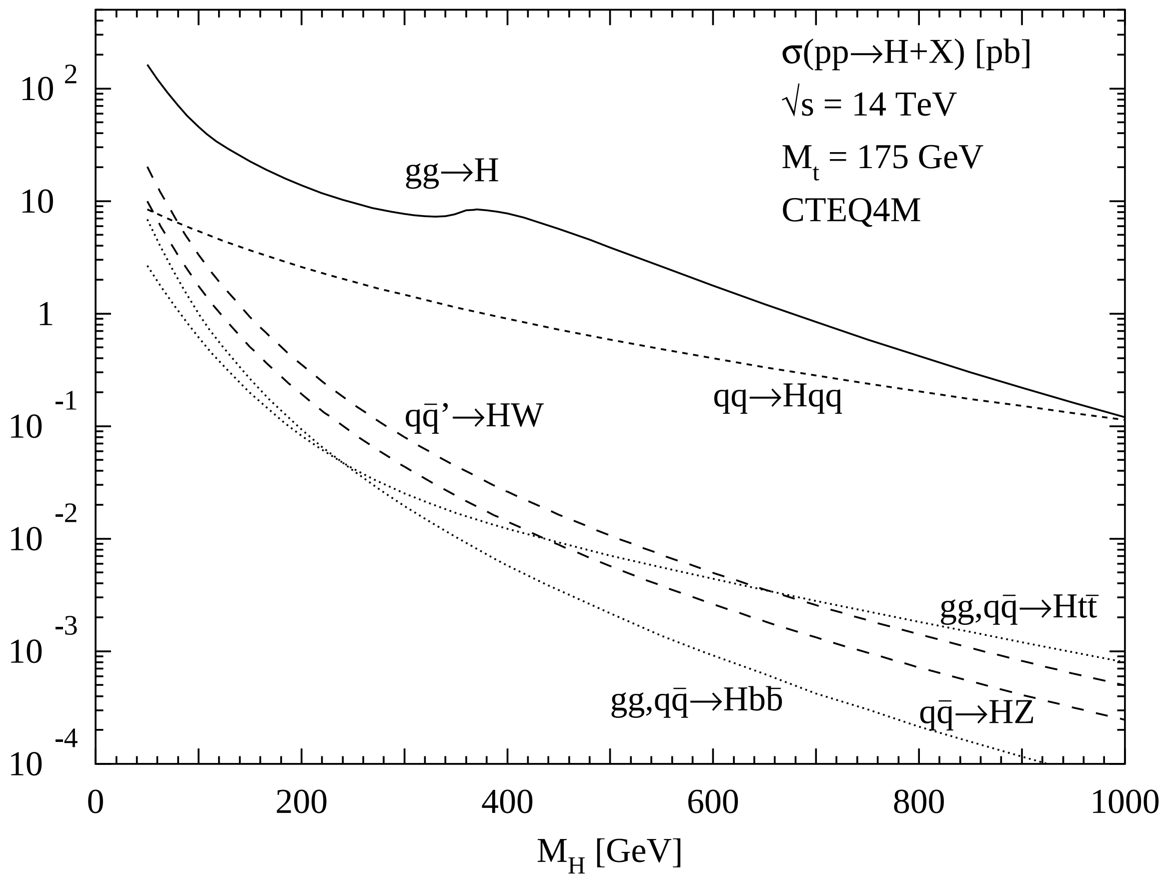


Figure 10: Bremsstrahlung diagrams for $q\bar{q} \to ZH + \gamma$.


σ(pp→H+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4M
gg→H
qq→Hqq
qq̄'→HW
gg,qq̄→Htt̄
gg,qq̄→Hbb̄
qq̄→HZ
10^2
10
1
10^-1
10^-2
10^-3
10^-4
0
200
400
600
800
1000
M_H [GeV]

[Spira]

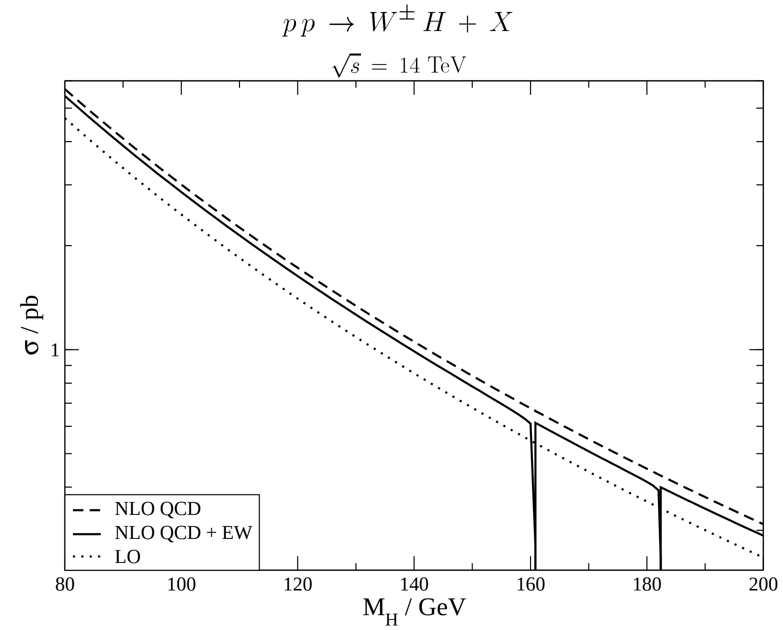


Figure 21: Total cross section for $pp \to W^{\pm}H + X$ at the LHC ($\sqrt{s} = 14$ TeV) in LO, NLO QCD, and including NLO QCD and electroweak corrections in the G_μ-scheme.

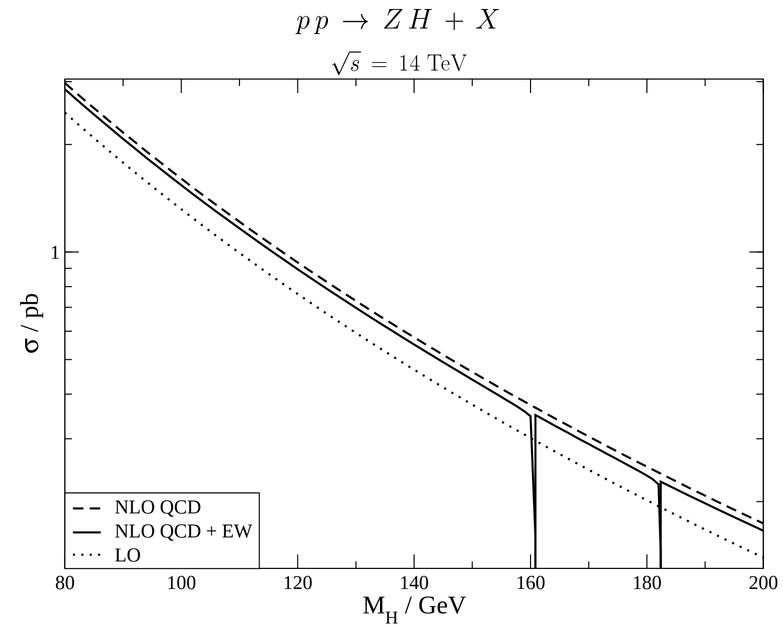


Figure 22: Total cross section for $pp \to ZH + X$ at the LHC ($\sqrt{s} = 14$ TeV) in LO, NLO QCD, and including NLO QCD and electroweak corrections in the G_μ-scheme.

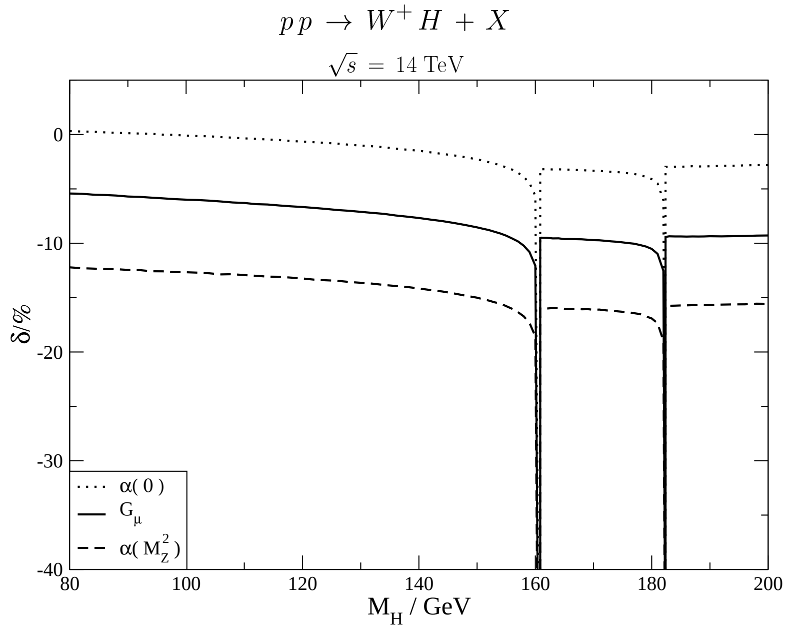


Figure 13: Relative electroweak correction δ as a function of the Higgs-boson mass for the total cross section $pp \to W^+H + X$ ($\sqrt{s} = 14$ TeV).

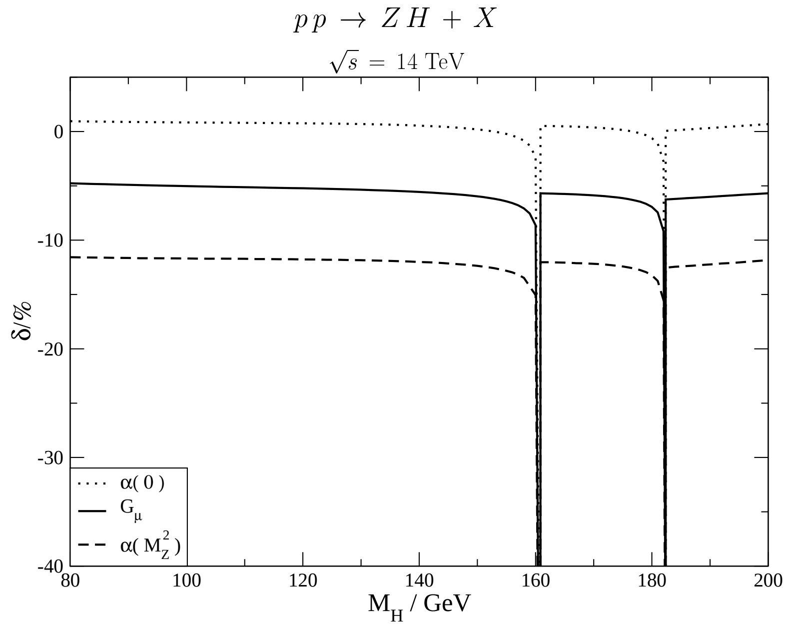


Figure 14: Relative electroweak correction δ as a function of the Higgs-boson mass for the total cross section $pp \to ZH + X$ ($\sqrt{s} = 14$ TeV).

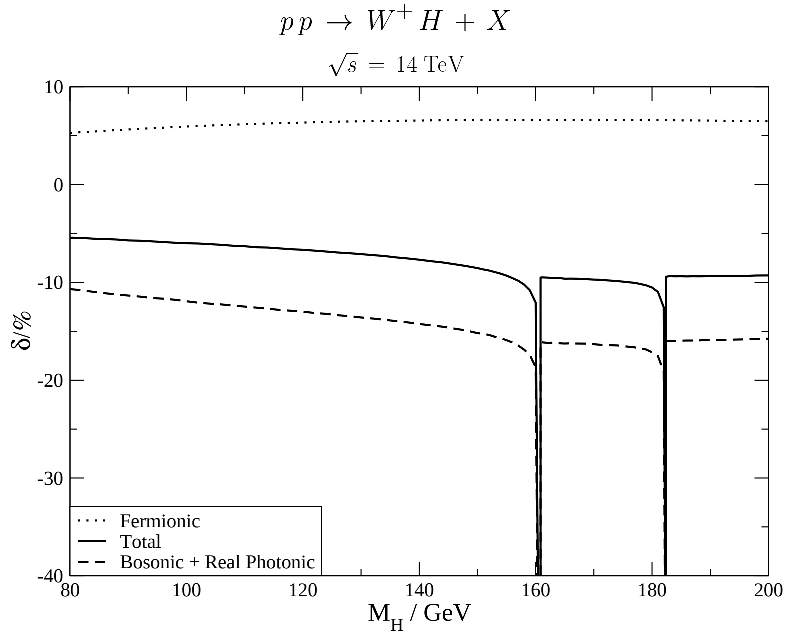


Figure 17: Different contributions to the relative electroweak correction δ in the G_μ-scheme as a function of the Higgs-boson mass for the total cross section $pp \to W^+H + X$ ($\sqrt{s} = 14$ TeV).

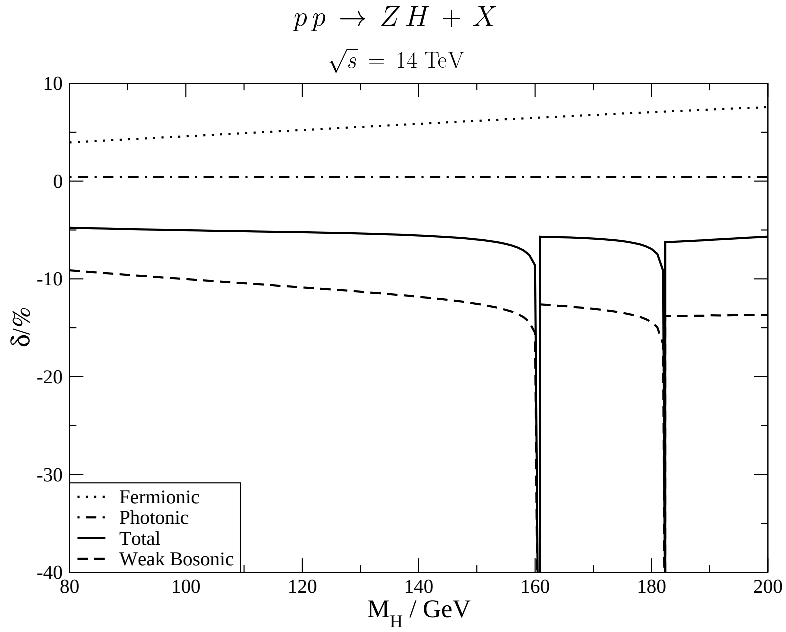


Figure 18: Different contributions to the relative electroweak correction δ in the G_μ-scheme as a function of the Higgs-boson mass for the total cross section $pp \to ZH + X$ ($\sqrt{s} = 14$ TeV).

Conclusions

Electroweak corrections to $\mathrm{pp} \to \mathrm{W/Z} \to ll'$:

- Full $\mathcal{O}(\alpha)$ corrections known (resonant and non-resonant), particularly important for
  - mass determinations,
  - cross sections at high invariant masses of ll'
- Photon radiation:
  - small effects from $\overline{\mathrm{MS}}$ renormalization of PDFs in $\mathcal{O}(\alpha)$
  - large effects, in particular from FSR
  - modification of corrections by photon recombination
  - inclusion of higher-order effects required

Electroweak corrections to $\mathrm{pp} \to HW/HZ$:

- complete $\mathcal{O}(\alpha)$ contribution known
- together with NNLO QCD, stabilize predictions considerably

Electroweak corrections to $\mathrm{pp} \to VV \quad (V = \gamma, Z, W)$:

- work in progress