EW NLO Calculations

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Contents

Intention of the talk

$\hookrightarrow$ discussion of the relevance and structure of EW corrections for LHC physics and highlight some recent progress

(i.e. recent progress in $\mathrm{e^+e^-}$ physics not covered, such as $\mathrm{e^+e^-} \to \mathrm{3jets}, 4f$, etc.)

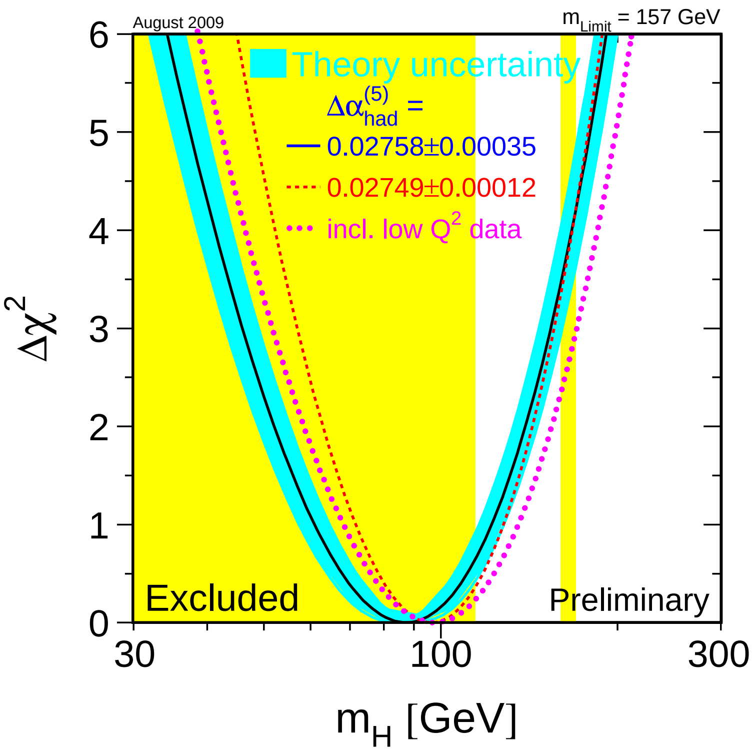
Introduction

Experiments at LEP/SLC/Tevatron

- confirmation of Standard Model as quantum field theory
  (quantum corrections significant)
- top mass m_t indirectly constrained by quantum corrections
  $\leftrightarrow$ in agreement with m_t measurement of Tevatron
- Higgs mass M_H indirectly constrained by quantum corrections
  $\hookrightarrow$ impact on Higgs searches

Great success of precision physics

- $M_\mathrm{H} > 114.4\,\mathrm{GeV}$ (LEPHIGGS '02)
  $\mathrm{e^+e^-} \not\to \mathrm{ZH}$ at LEP2
- $M_\mathrm{H} < 160\,\mathrm{GeV}$ and $M_\mathrm{H} > 170\,\mathrm{GeV}$
  $\mathrm{p\bar{p}} \not\to \mathrm{H} \to \mathrm{WW}$ at Tevatron (CDF/D0 '09)
- $M_\mathrm{H} < 157\,\mathrm{GeV}$ (LEPEWWG '09)
  fit to precision data
  i.e. via **EW radiative corrections**



Electroweak corrections

... structure and tricky issues

Features of and issues in EW precision calculations

Relevance and size of EW corrections

generic size $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$ suggests NLO EW $\sim$ NNLO QCD
but systematic enhancements possible, e.g.

- by photon emission
  $\hookrightarrow$ kinematical effects, mass-singular log's $\propto \alpha \ln(m_\mu/Q)$ for bare muons, etc.
- at high energies
  $\hookrightarrow$ EW Sudakov log's $\propto (\alpha/s_W^2) \ln^2(M_W/Q)$ and subleading log's

Instability of W and Z bosons

- realistic observables have to be defined via decay products (leptons, γ's, jets)
- off-shell effects $\sim \mathcal{O}(\Gamma/M) \sim \mathcal{O}(\alpha)$ are as important as NLO EW corrections

Instability of Higgs boson(s)

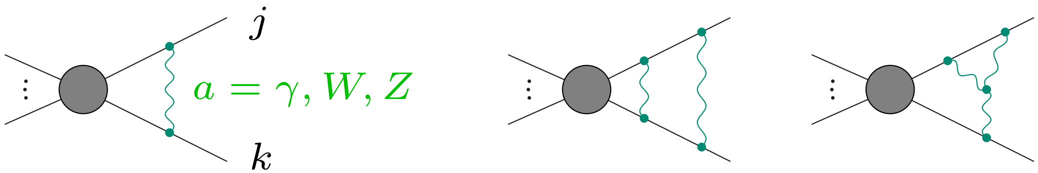
- easy to handle for small Higgs masses where $\Gamma_H \ll M_H$
- leads to complicated resonance processes if Γ_H/M_H not small

EW corrections to PDFs at hadron colliders

induced by factorization of collinear initial-state singularities

Electroweak radiative corrections at high energies

Sudakov logarithms induced by soft gauge-boson exchange



etc.

+ sub-leading logarithms from collinear singularities

Typical impact on $2 \to 2$ reactions at $\sqrt{s} \sim 1\,\mathrm{TeV}$:

$$\delta_{\mathrm{LL}}^{1-\mathrm{loop}} \sim -\frac{\alpha}{\pi s_{\mathrm{W}}^2} \ln^2\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq -26\%, \qquad \delta_{\mathrm{NLL}}^{1-\mathrm{loop}} \sim +\frac{3\alpha}{\pi s_{\mathrm{W}}^2} \ln\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq 16\%$$

$$\delta_{\mathrm{LL}}^{2-\mathrm{loop}} \sim +\frac{\alpha^2}{2\pi^2 s_{\mathrm{W}}^4} \ln^4\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq 3.5\%, \qquad \delta_{\mathrm{NLL}}^{2-\mathrm{loop}} \sim -\frac{3\alpha^2}{\pi^2 s_{\mathrm{W}}^4} \ln^3\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq -4.2\%$$

$\Rightarrow$ Corrections still relevant at 2-loop level

Note: differences to QED / QCD where Sudakov log's cancel

- massive gauge bosons W, Z can be reconstructed
  $\hookrightarrow$ no need to add "real W, Z radiation"
- non-Abelian charges of W, Z are "open" $\to$ Bloch–Nordsieck theorem not applicable

Extensive theoretical studies at fixed perturbative (1-/2-loop) order and suggested resummations via evolution equations

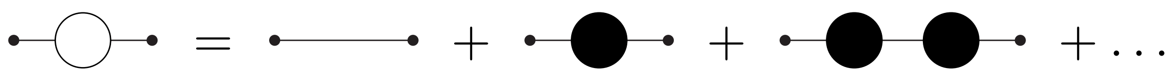
Beccaria et al.; Beenakker, Werthenbach; Ciafaloni, Comelli; Denner, Pozzorini; Fadin et al.; Hori et al.; Melles; Kühn et al., Denner et al. '00–'0

Problem of unstable particles:

description of resonances requires resummation of propagator corrections

$\hookrightarrow$ mixing of perturbative orders potentially violates gauge invariance

Dyson series and propagator poles (scalar example)



$$G^{\phi\phi}(p) = \frac{\mathrm{i}}{p^2 - m^2} + \frac{\mathrm{i}}{p^2 - m^2}\,\mathrm{i}\Sigma(p^2)\,\frac{\mathrm{i}}{p^2 - m^2} + \ldots = \frac{\mathrm{i}}{p^2 - m^2 + \Sigma(p^2)}$$

$\Sigma(p^2) =$ renormalized self-energy, $m =$ ren. mass

stable particle: $\mathrm{Im}\{\Sigma(p^2)\} = 0$ at $p^2 \sim m^2$

$\hookrightarrow$ propagator pole for real value of p^2,
renormalization condition for physical mass m: $\Sigma(m^2) = 0$

unstable particle: $\mathrm{Im}\{\Sigma(p^2)\} \neq 0$ at $p^2 \sim m^2$

$\hookrightarrow$ location μ^2 of propagator pole is complex,
possible definition of mass M and width Γ: $\mu^2 = M^2 - \mathrm{i}M\Gamma$

Proposed solutions at NLO:

- naive fixed-width schemes:

$$\frac{1}{p^2 - M^2} \to \frac{1}{p^2 - M^2 + \mathrm{i}M\Gamma}$$ in all or at least in resonant propagators

$\hookrightarrow$ breaks gauge invariance only mildly (?),
but partial inclusion of widths in loops screws up singularity structure

- pole expansions Stuart '91; Aeppli et al. '93, '94; etc.

$\hookrightarrow$ consistent, gauge invariant,
but not reliable at threshold or in off-shell tails of resonances

- effective field theory approach Beneke et al. '04,'07; Hoang, Reisser '04

$\hookrightarrow$ gauge invariant, involves pole expansions,
can be combined with threshold expansions,
offers framework for resummations (e.g. Coulomb Singularity at thresholds)

- complex-mass scheme Denner, S.D., Roth, Wieders '05

$\hookrightarrow$ gauge invariant, valid everywhere in phase space

The complex-mass scheme at NLO

Basic idea: mass^2 = location of propagator pole in complex p^2 plane

$\hookrightarrow$ consistent use of complex masses everywhere !

Application to gauge-boson resonances:

- replace $M_\mathrm{W}^2 \;\to\; \mu_\mathrm{W}^2 = M_\mathrm{W}^2 - \mathrm{i}M_\mathrm{W}\Gamma_\mathrm{W}, \qquad M_\mathrm{Z}^2 \;\to\; \mu_\mathrm{Z}^2 = M_\mathrm{Z}^2 - \mathrm{i}M_\mathrm{Z}\Gamma_\mathrm{Z}$

  and define (complex) weak mixing angle via $c_\mathrm{W}^2 \;=\; 1 - s_\mathrm{W}^2 \;=\; \frac{\mu_\mathrm{W}^2}{\mu_\mathrm{Z}^2}$

- virtues:
  - ◇ gauge-invariant result (Slavnov–Taylor identities, gauge-parameter independence)
    $\hookrightarrow$ unitarity cancellations respected !
  - ◇ perturbative calculations as usual (loops and counterterms)
  - ◇ no double counting of contributions (bare Lagrangian unchanged !)

- drawbacks:
  - ◇ unitarity-violating spurious terms of $\mathcal{O}(\alpha^2)$ $\to$ but beyond NLO accuracy !
    (from t-channel/off-shell propagators and complex mixing angle)
  - ◇ complex gauge-boson masses also in loop integrals

Electroweak effects in PDFs

Analogy to QCD-improved parton model:

Collinear splittings $q \to q\gamma$, $\gamma \to q\bar{q}$ lead to quark mass singularities

$\hookrightarrow$ absorb $\alpha \ln m_q$ singularities via factorization into redefined PDFs

Before 2004: no $\mathcal{O}(\alpha)$-corrected PDFs available

$\hookrightarrow$ factorization of collinear singularities in $\mathcal{O}(\alpha)$ in $\overline{\mathrm{MS}}$ scheme

but: neglect $\mathcal{O}(\alpha)$ effects in PDFs

Estimate of neglected $\mathcal{O}(\alpha)$ effects in PDFs: Spiesberger '95, '99; Roth, Weinzierl '04

$$\Delta(\mathrm{PDF}) \lesssim 0.3\% \; (1\%) \quad \text{for} \quad x < 0.1 \; (0.4), \quad \mu_{\mathrm{fact}} \sim M_{\mathrm{W}}$$

Since 2004: MRST2004QED set of $\mathcal{O}(\alpha)$-corrected PDFs

Martin, Roberts, Stirling, Thorne '0

$\hookrightarrow$ new PDFs should be used if EW $\mathcal{O}(\alpha)$ corrections are included

- use appropriate factorization scheme for $\mathcal{O}(\alpha)$ corrections (= DIS like)
- additional real corrections from photons in initial state
- find processes to measure $\mathcal{O}(\alpha)$ induced photon distribution

  MRST2004QED: start PDF from model assumption

Electroweak corrections

... EW gauge-boson production

EW precision observables

Most important precision observables:

- M_W (direct measurement vs. muon decay)
  - ◇ mixed QCD/EW 2-loop corrections known — Djouadi, Verzegnassi '87; Djouadi '88; Kniehl, Kühn, Stuart '88; Kniehl, Sirlin '93 Djouadi, Gambino '94
  - ◇ complete EW 2-loop corrections known — Freitas, Hollik, Walter, Weiglein '00 Awramik, Czakon '02 Onishchenko, Veretin '02
  - ◇ improvements by 3-/4-loop $\Delta\rho$ — Avdeev et al. '94; Chetyrkin, Kühn, Steinhauser '95 v.d.Bij et al. '00; Faisst et al. '03; Boughezal, Tausk, v.d.Bij '05 Schröder, Steinhauser '05; Chetyrkin et al. '06 Czakon, Boughezal '06

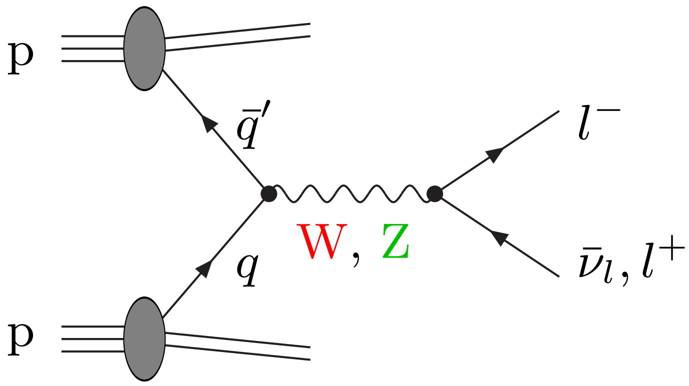
  $\hookrightarrow$ theoretical uncertainty $\Delta M_\mathrm{W} \sim 4\,\mathrm{MeV}$

- $\sin^2\theta_\mathrm{eff}^\mathrm{lept}$ (from various asymmetries)
  - ◇ mixed QCD/EW 2-loop and 3-loop $\Delta\rho$ corrections as for M_W
  - ◇ complete EW 2-loop corrections known — Awramik, Czakon, Freitas, Weiglein '04 Hollik, Meier, Uccirati '05,'06 Awramik, Czakon, Freitas '06

  $\hookrightarrow$ theoretical uncertainty $\Delta\sin^2\theta_\mathrm{eff}^\mathrm{lept} \sim 5\times10^{-5}$

$\hookrightarrow$ Theoretical predictions in good shape for LHC

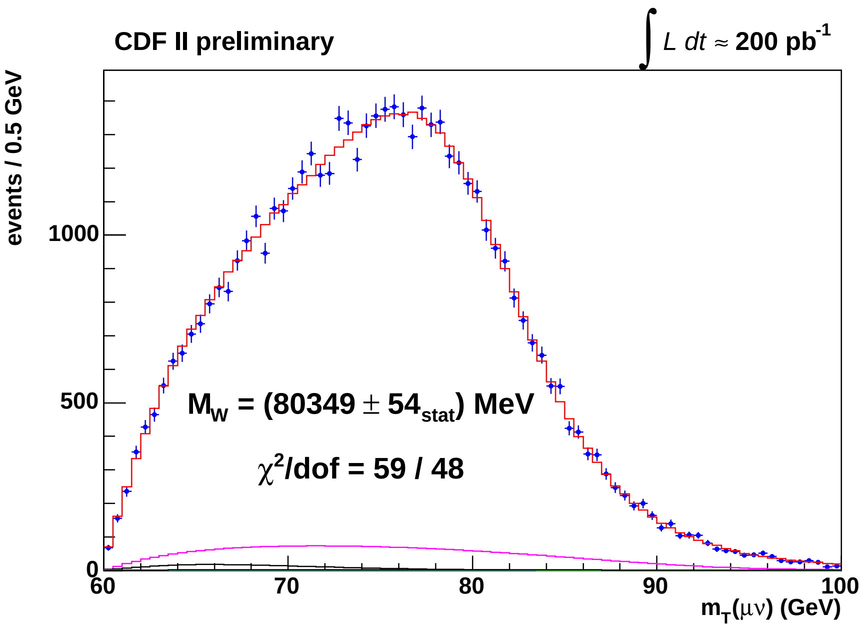
W- and Z-boson production at hadron colliders

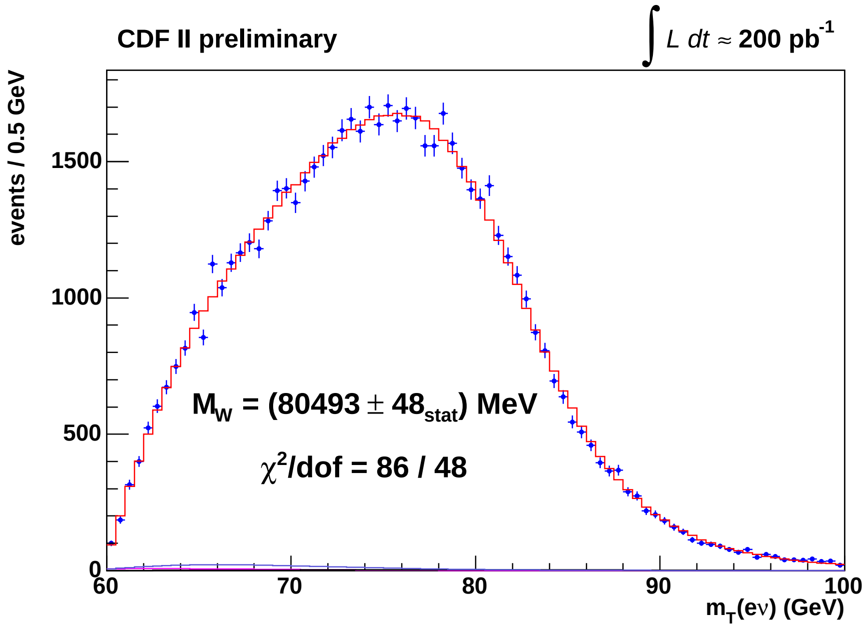


Physics goals:

- M_Z $\rightarrow$ detector calibration by comparing with LEP1 result
- $\sin^2\theta_{\text{eff}}^{\text{lept}}$ $\rightarrow$ comparison with results of LEP1 and SLC
- M_W $\rightarrow$ improvement to $\Delta M_W \sim 15\,\text{MeV}$, strengthen EW precision tests (W/Z shape comparisons even sensitive to $\Delta M_W \sim 7\,\text{MeV}$ at LHC)
  Besson et al. '08
- decay widths Γ_Z and Γ_W from M_{ll} or $M_{T,l\nu_l}$ tails
- search for Z' and W' at high M_{ll} or $M_{T,l\nu_l}$
- information on PDFs or parton–parton luminosities

Fits of M_{W} to W transverse mass at the Tevatron





Theory prediction based on QCD resummations (improved by some EW corrections)

Result from CDF Run II: $M_{\mathrm{W}} = 80.413 \pm 0.048\,\mathrm{GeV}$

Result from D0 Run II: $M_{\mathrm{W}} = 80.402 \pm 0.043\,\mathrm{GeV}$

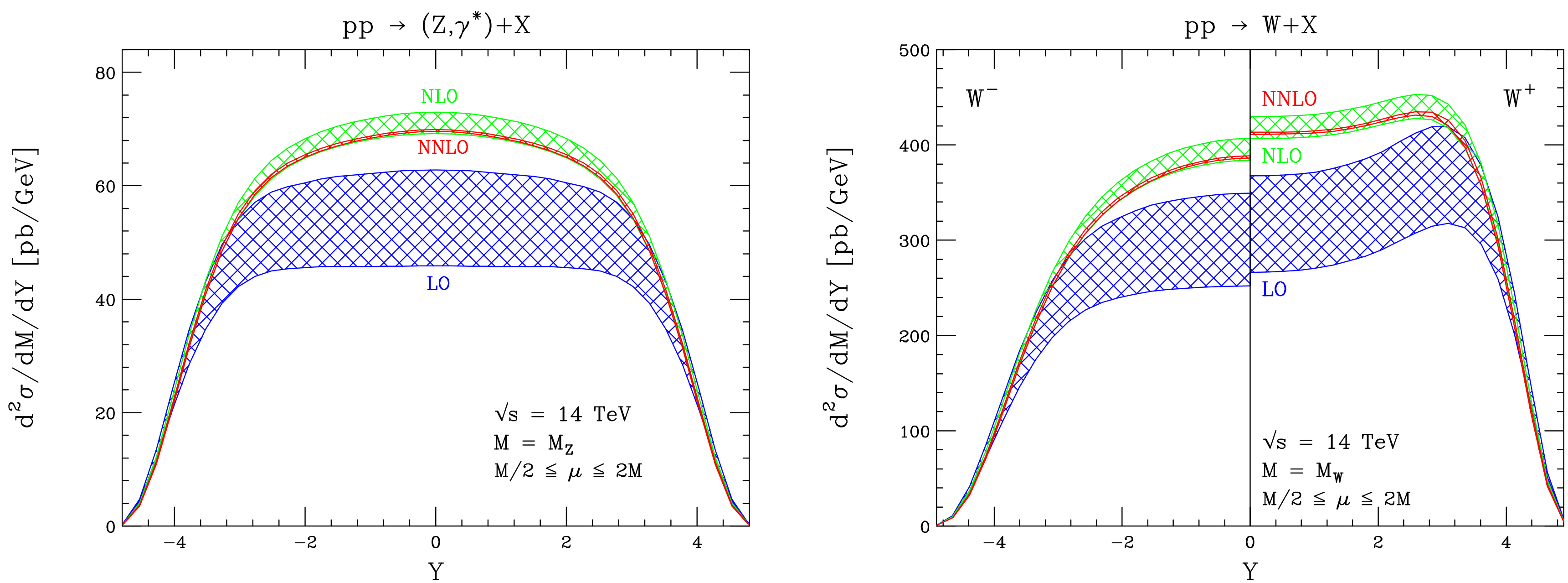
CDF/D0 combination 2009: $M_{\mathrm{W}} = 80.420 \pm 0.031\,\mathrm{GeV}$ (from Fermilab homepage)

Result from LEP: $M_{\mathrm{W}} = 80.376 \pm 0.033\,\mathrm{GeV}$

World average 2009: $M_{\mathrm{W}} = 80.399 \pm 0.023\,\mathrm{GeV}$

NNLO QCD corrections for single W/Z production

- total cross section — Hamberg, v.Neerven, Matsuura ’91; v.Neerven, Zijlstra ’92; Harlander, Kilgore ’02
- $\mathrm{W/Z}$ rapidity distribution — Anastasiou et al. ’03



- fully differential cross section $\mathrm{pp}(\to \mathrm{W}) \to l\nu_l + X$ — Melnikov, Petriello ’06; Catani et al. ’09

Further improvements:

- Soft-gluon resummation (partially combined with γ emission) — Balazs, Yuan ’97; Landry et al. ’02; Cao, Yuan ’04
- NLO EW corrections

Combination of QCD $\oplus$ EW corrections still in progress

NLO EW corrections to W/Z production:

- NLO EW correction to W production — Baur, Keller, Wackeroth '98; S.D., Krämer '02; Baur, Wackeroth '04; Arbuzov et al. '05; Carloni Calame et al. '06
- NLO EW correction to Z production — Baur, Keller, Sakumoto '97; Baur, Wackeroth '99; Brein, Hollik, Schappacher '99; Arbuzov et al. '06
- multi-photon radiation via leading logs — Baur, Stelzer '99; Carloni Calame et al. '03; Placzek, Jadach '04; Brensing et al. '07
- NLO SUSY corrections in the MSSM — Brensing et al. '07

Comparison of NLO EW corrections to W production:

$\mathrm{pp} \to \nu_l l^+(+\gamma)$ at $\sqrt{s} = 14\,\mathrm{TeV}$ — Les Houches SMH proceedings '06

$M_{\mathrm{T},\nu_l l}/\mathrm{GeV}$	$50-\infty$	$100-\infty$	$200-\infty$	$500-\infty$	$1000-\infty$	$2000-\infty$
σ_0/pb						
DK	$2112.2(1)$	$13.152(2)$	$0.9452(1)$	$0.057730(5)$	$0.0054816(3)$	$0.00026212(1)$
$\delta_{\mu^+\nu_\mu}/\%$						
DK	$-2.75(1)$	$-5.03(2)$	$-7.98(1)$	$-14.43(1)$	$-21.99(1)$	$-32.15(1)$
HORACE	$-2.77(1)$	$-5.08(1)$	$-8.01(1)$	$-14.44(1)$	$-21.99(1)$	$-32.16(1)$
SANC	$-2.76(2)$	$-5.06(2)$	$-7.96(2)$	$-14.41(2)$	$-21.94(2)$	$-32.12(2)$
WGRAD	$-2.69(1)$	$-4.84(1)$	$-7.96(1)$	$-14.48(1)$	$-22.03(1)$	$-32.3(1)$

Large corrections at high transverse W mass $M_{\mathrm{T},\nu_l l}$ (and high invariant Z mass)

Combination of NLO QCD and EW corrections in progress

Issue unambiguously fixed only by calculating the 2-loop $\mathcal{O}(\alpha\alpha_s)$ corrections, until then rely on approximations and to estimate the uncertainties:

- Comparison of two extreme alternatives:

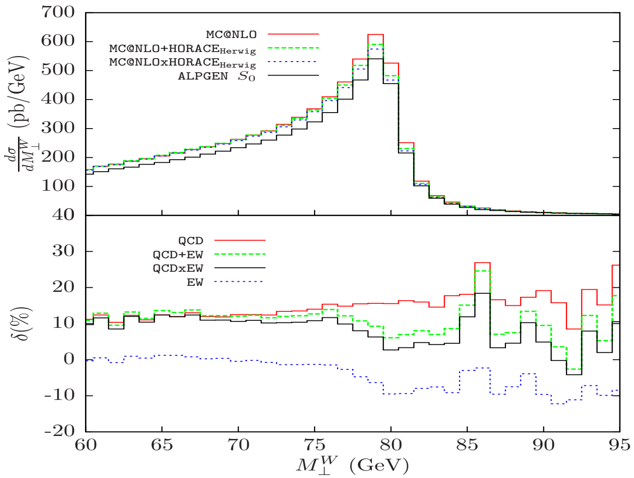
  $$(1 + \delta_{\rm QCD}^{\rm NLO} + \delta_{\rm EW}^{\rm NLO})$$

  versus

  $$(1 + \delta_{\rm QCD}^{\rm NLO}) \times (1 + \delta_{\rm EW}^{\rm NLO})$$

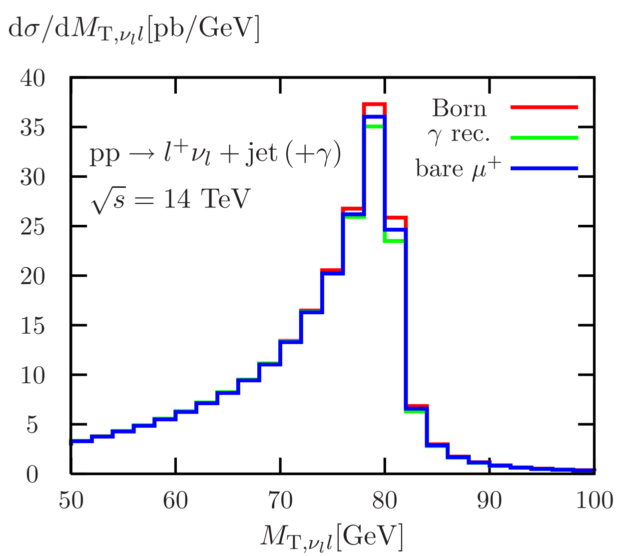
  $\hookrightarrow$ underlines significance of $\mathcal{O}(\alpha\alpha_s)$ effects

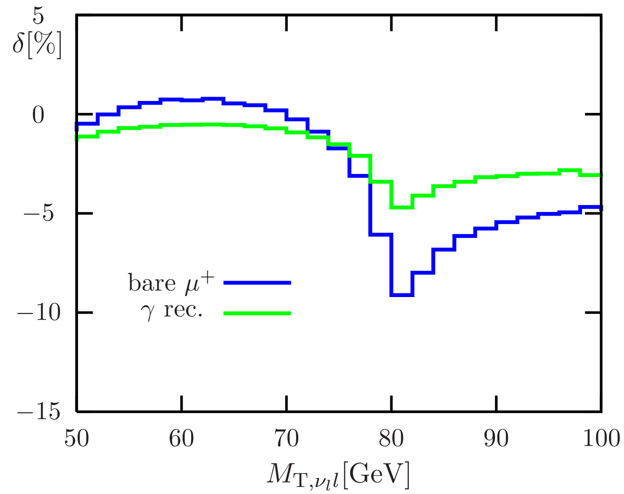
Balossini et al. '09



- Compare EW corrections for $\rm V$ and $\rm V + jet$ production

Denner, S.D., Kasprzik, Mück '09





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$$\left(1+\delta_{\rm QCD}^{\rm NLO}+\delta_{\rm EW}^{\rm NLO}\right)$$

versus

$$\left(1+\delta_{\rm QCD}^{\rm NLO}\right)\times\left(1+\delta_{\rm EW}^{\rm NLO}\right)$$

$\hookrightarrow$ underlines significance of $\mathcal{O}(\alpha\alpha_s)$ effects

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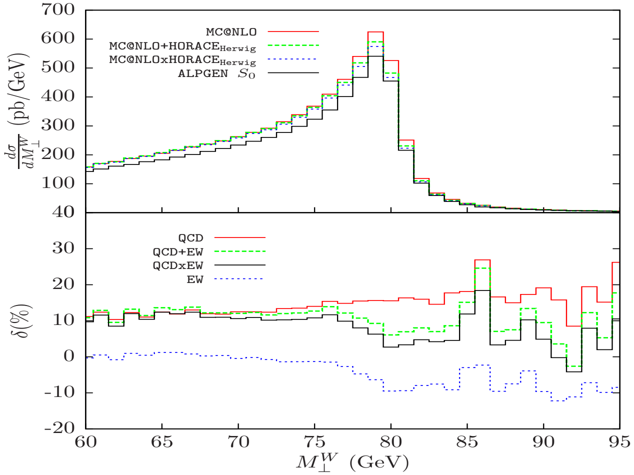

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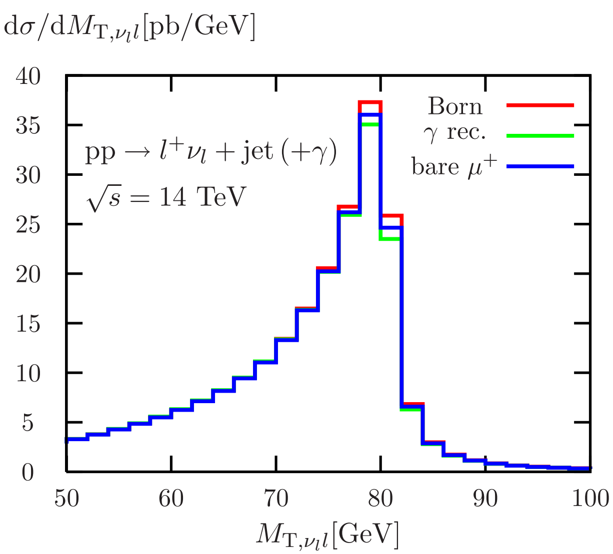
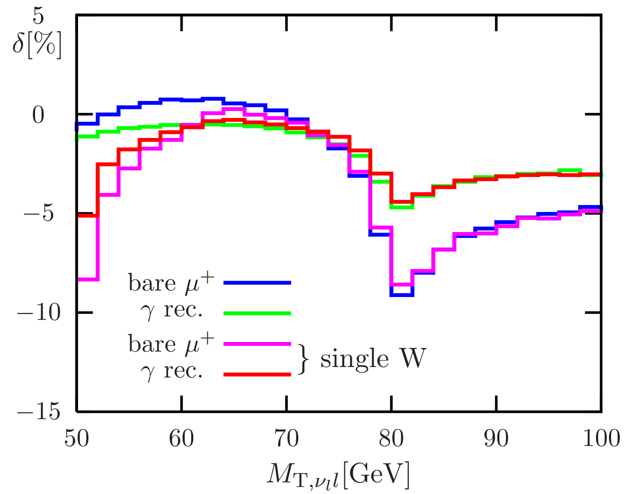




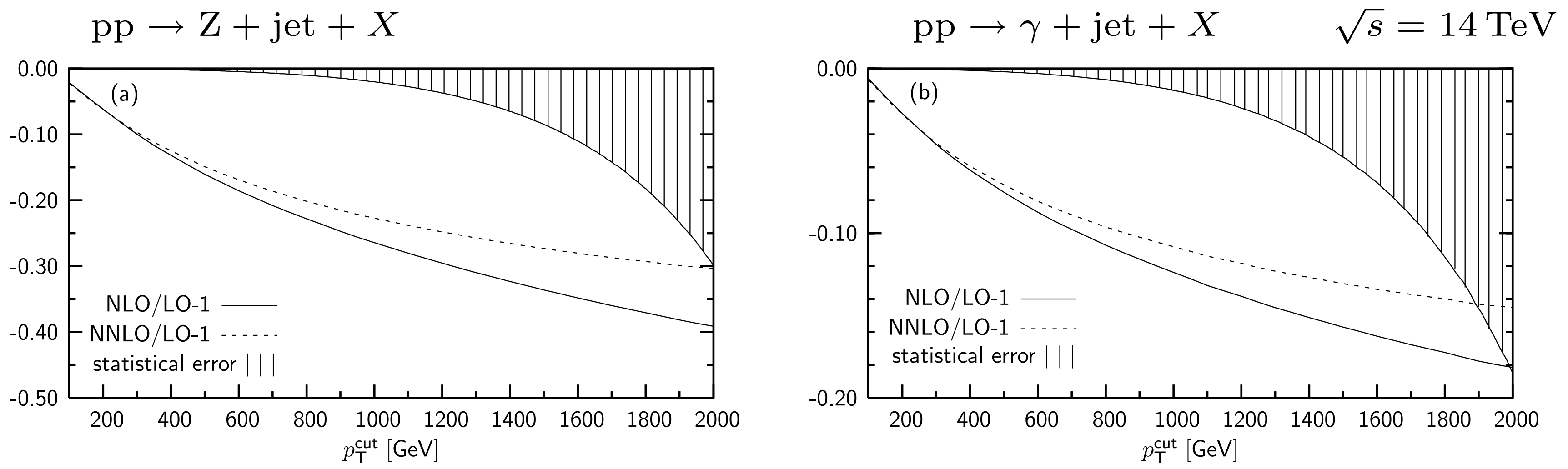
relative EW corrections practically identical near Jacobian peak

$\hookrightarrow$ supports factorization approach

Gauge-boson + jet production

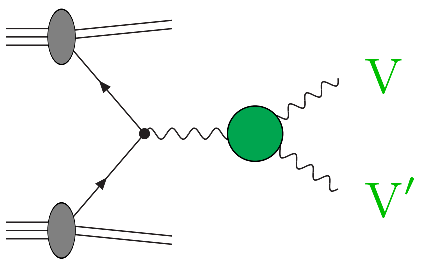
EW corrections

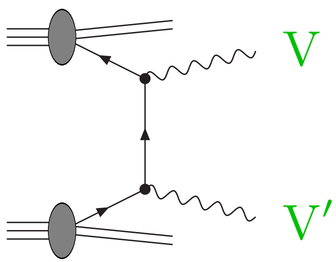
- $\mathrm{pp} \to \mathrm{V} + \mathrm{jet} + X \quad (\mathrm{V} = \gamma, \mathrm{Z})$
  - ◇ weak $\mathcal{O}(\alpha)$ correction $\sim -(5{-}15)\%$ for $p_\mathrm{T} \lesssim 500\,\mathrm{GeV}$ Maina, Moretti, Ross '04
  - ◇ (NLO + NNLL) EW corrections Kühn, Kulesza, Pozzorini, Schulze '04,'05



- $\mathrm{pp} \to \mathrm{W} + \mathrm{jet} + X$
  - ◇ NLO EW corrections for on-shell W bosons Kühn, Kulesza, Pozzorini, Schulze '07; Hollik, Kasprzik, Kniehl '07
  - ◇ NLO QCD $\oplus$ EW corrections for leptonically decaying W bosons Denner, S.D., Kasprzik, Mück '09

Di-boson production





$\mathrm{V}, \mathrm{V}' = \gamma, \mathrm{Z}, \mathrm{W}^{\pm}$

Physics issues:

- triple-gauge-boson couplings at high momentum transfer
- dynamics of longitudinal massive gauge bosons at high energies
  $\mathrm{W_L}, \mathrm{Z_L} \sim$ Goldstone bosons $\quad \rightarrow$ scalar sector

  strongly interacting longitudinal W/Z bosons if no Higgs exists
  $\hookrightarrow$ unitarity requires resonances
- important class of background processes to many searches (e.g. $\mathrm{H} \to \mathrm{VV} \to 4f$)

Requirements on adequate predictions:

- full LO matrix elements for $q\bar{q} \to 4f$ (spin correlations, off-shell effects)
  $\hookrightarrow$ respect gauge invariance
- NLO QCD and EW corrections

EW corrections to gauge-boson pair production

- $\mathrm{pp}(\to \mathrm{W}\gamma) \to l\bar{\nu}\gamma + X$ Accomando, Denner, Pozzorini '01; Accomando, Denner, Meier '05

  $\mathcal{O}(\alpha)$ correction in pole approximation

  $\hookrightarrow \ \delta \sim -5\% \, (-24\%)$ for $p_{\mathrm{T},\gamma} \gtrsim 350\,\mathrm{GeV}\,(700\,\mathrm{GeV})$

- $\mathrm{pp} \to \mathrm{Z}\gamma + X$ Hollik, Meier '04 and $\mathrm{pp}(\to \mathrm{Z}\gamma) \to ll\gamma + X$ Accomando, Denner, Meier '05

  complete $\mathcal{O}(\alpha)$ correction for on-shell Z bosons / in pole approximation

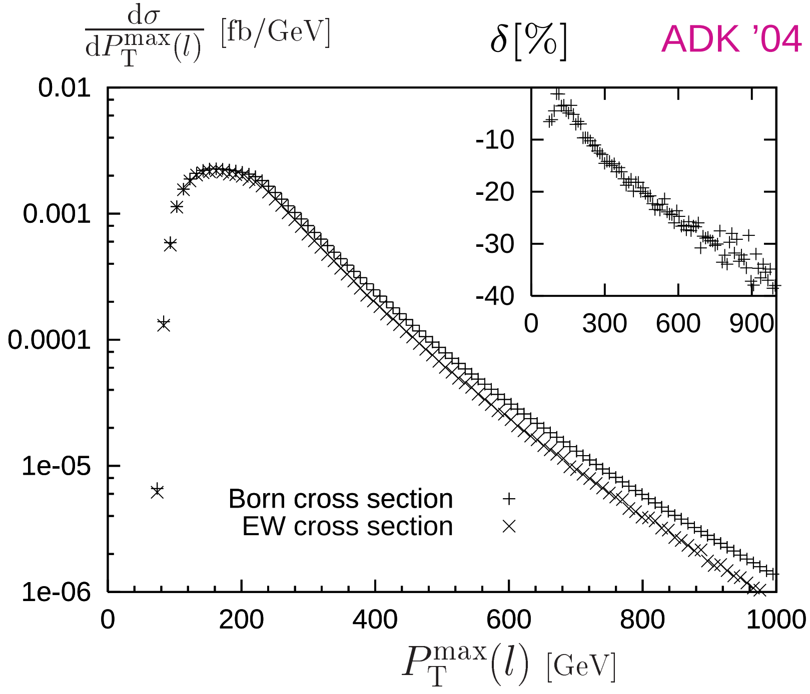
  $\hookrightarrow \ \delta \sim -20\%$ for $M_{\gamma\mathrm{Z}} \lesssim 2\,\mathrm{TeV}$

- $\mathrm{pp}(\to \mathrm{WW}, \mathrm{WZ}, \mathrm{ZZ}) \to 4\,\mathrm{leptons} + X$

  Accomando, Denner, Pozzorini '01
  Accomando, Denner, Kaiser '04

  $\mathcal{O}(\alpha)$ correction in high-energy and pole approximations

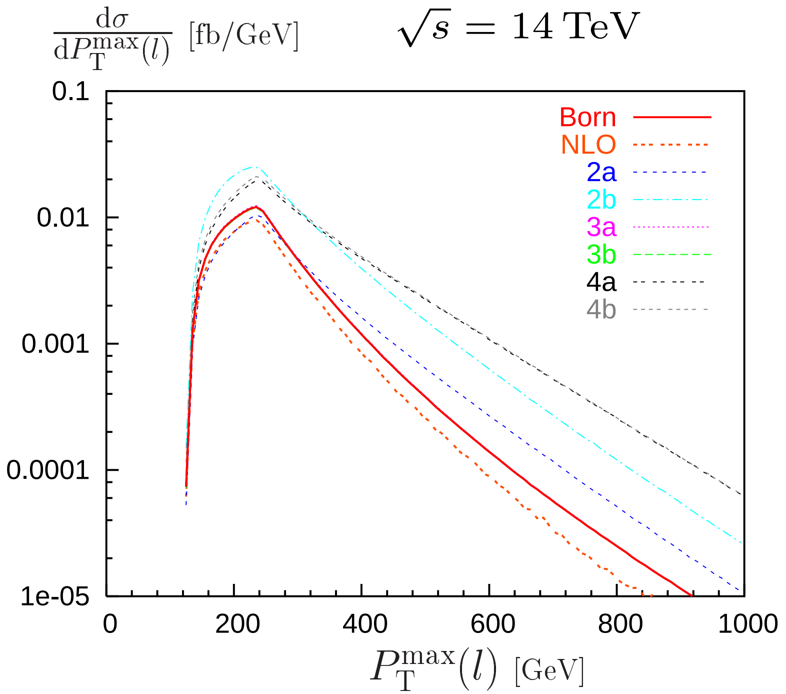
$\mathrm{pp} \to \mathrm{WZ} \to \mathrm{e}\nu_{\mathrm{e}}\mu^+\mu^-$ at $\sqrt{s} = 14\,\mathrm{TeV}$

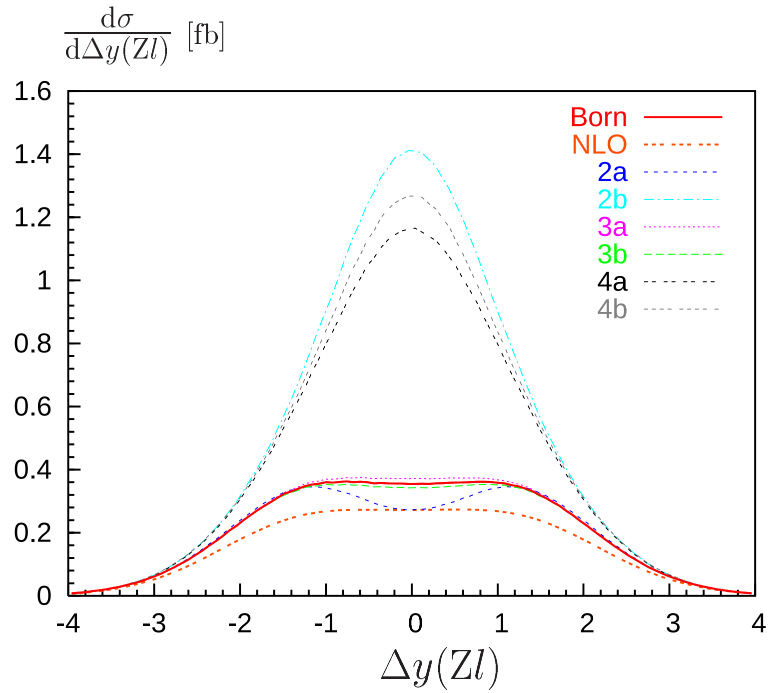


EW corrections vs. anomalous TGCs in gauge-boson pair production

Study for $\mathrm{pp}(\to \mathrm{WW}, \mathrm{WZ}) \to 4\,\mathrm{leptons} + X$ Accomando, Kaiser ’05

$\mathrm{pp} \to \mathrm{WZ} \to \mathrm{e}\nu_\mathrm{e}\mu^+\mu^-$
$\sqrt{s} = 14\,\mathrm{TeV}$





Scenario	Δg_1^Z	$\Delta\kappa_\gamma$	λ_γ
Born	0	0	0
2a/2b	± 0.02	0	0
3a/3b	0	± 0.04	0
4a/4b	0	0	± 0.02

$$\lambda_\mathrm{Z} = \lambda_\gamma, \quad \Delta\kappa_\mathrm{Z} = \Delta g_1^\mathrm{Z} - \tan^2\theta_\mathrm{W}\Delta\kappa_\gamma$$

formfactor rescaling ($\Lambda = 1\,\mathrm{TeV}$):

$$\Delta Y \to \frac{\Delta Y}{(1+\hat{s}/\Lambda^2)^2}, \quad \Delta Y = \Delta g_1^\mathrm{Z}, \Delta\kappa_\gamma, \lambda_\gamma$$

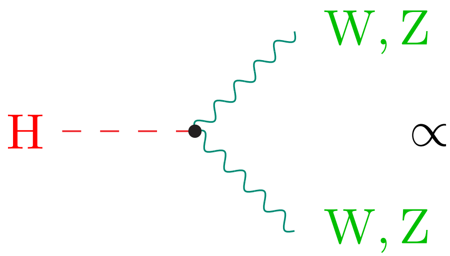
Note: in general both corrections and anomalous couplings distort distributions

Electroweak corrections

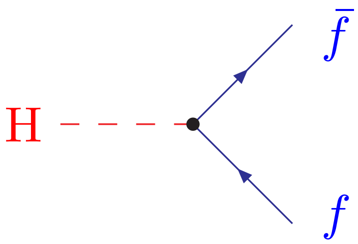
... Higgs-boson production

Higgs search at present and future colliders

Higgs bosons couple proportional to particle masses:



$\propto M_{\mathrm{W}}$

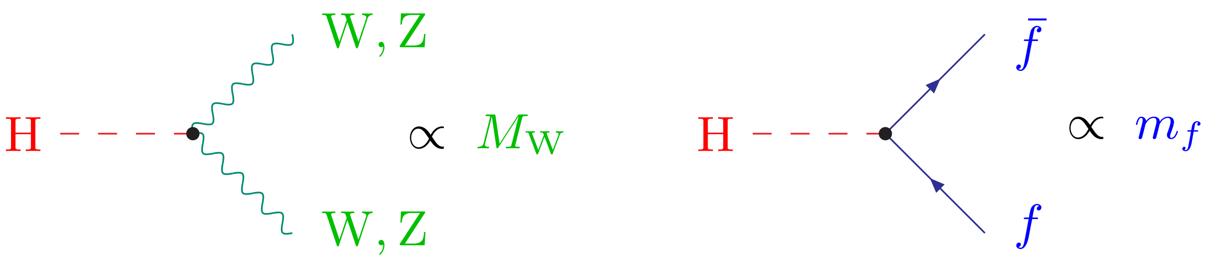


$\propto m_f$

$\Rightarrow$ Higgs production mainly via coupling to W/Z bosons or top quarks

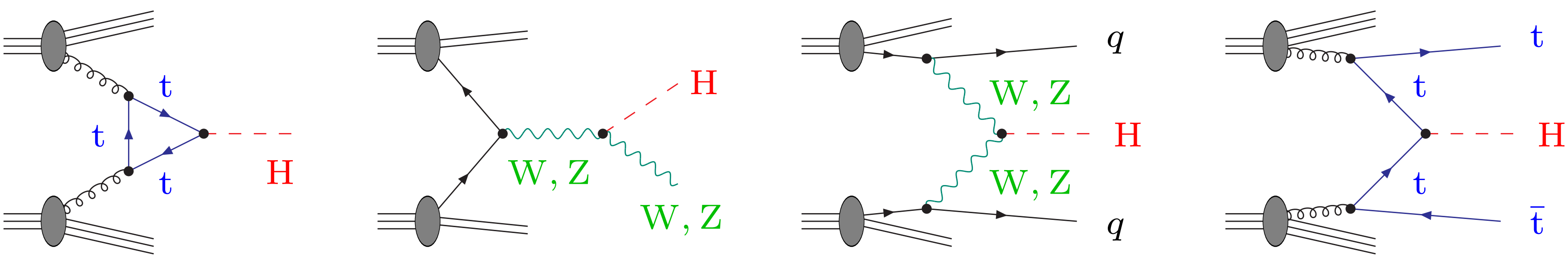
Higgs search at present and future colliders

Higgs bosons couple proportional to particle masses:



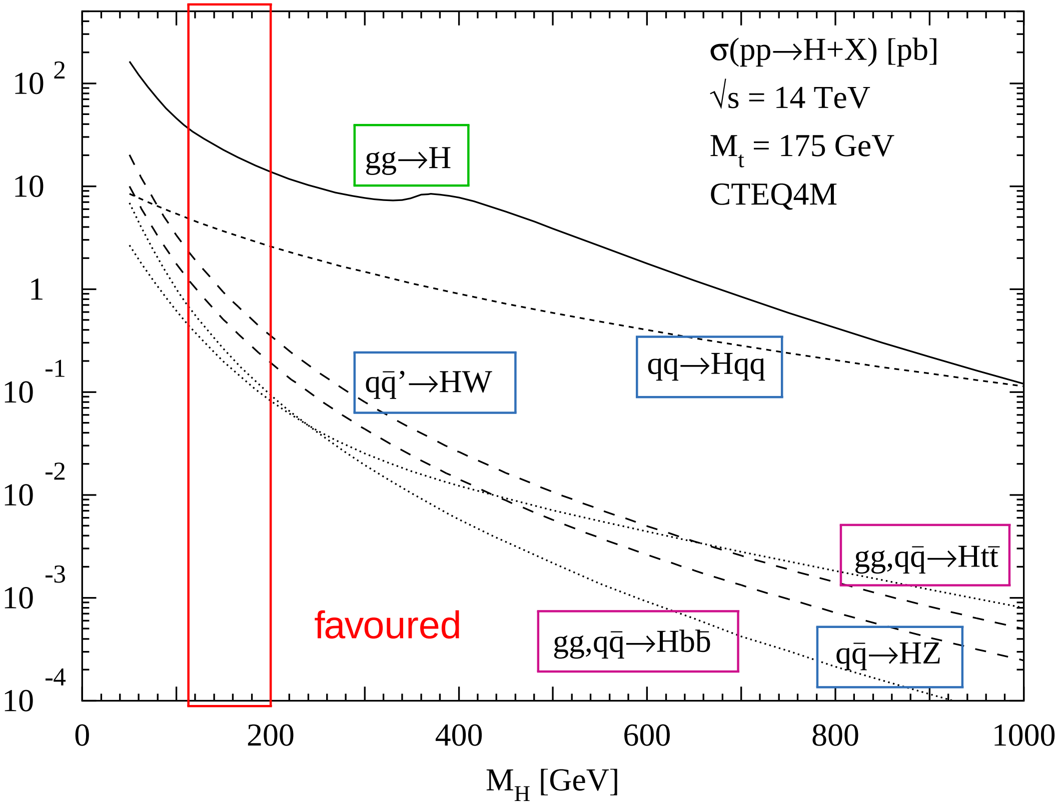
⇒ Higgs production mainly via coupling to W/Z bosons or top quarks

Processes at hadron colliders ($p\bar{p}/pp$):

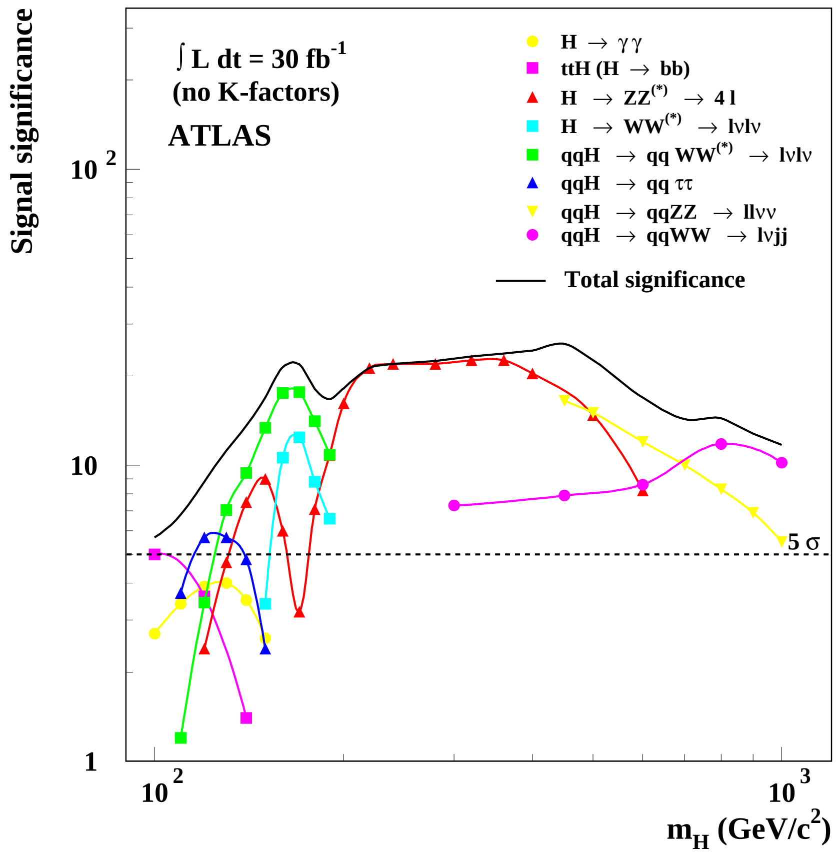


Cross sections and significance of the Higgs signal at the LHC

Spira et al. '98



ATLAS '04



Typical size perturbative corrections at next-to-leading order (NLO):

QCD: $\mathcal{O}(\alpha_s) \sim 10{-}100\%$ Electroweak: $\mathcal{O}(\alpha) \sim 10\%$

$\hookrightarrow$ calculate / control higher orders to reduce theoretical uncertainty down to the level of PDF ($q\bar{q} \sim 5\%$, $gg \sim 10\%$) and experimental uncertainties

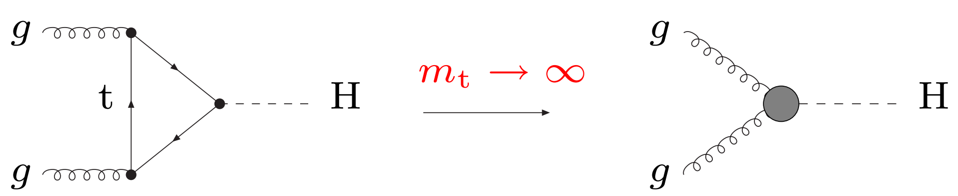
Complication: task requires "multi-loop" or "multi-leg" computations

A multi-loop example: Higgs production via gluon fusion at the LHC

- QCD corrections:
  - ◇ complete NLO correction known — Graudenz, Spira, Zerwas '93; Djouadi, Graudenz, Spira, Zerwas '95
  - ◇ NNLO correction known in limit $m_\mathrm{t} \to \infty$ — Harlander, Kilgore '01,'02; Catani, de Florian, Grazzini '01; Anastasiou, Melnikov '02; Ravindran, Smith, v.Neerven '03,'04; Anastasiou, Melnikov, Petriello '04

$$K = \frac{\sigma_\mathrm{NNLO}}{\sigma_\mathrm{LO}} \sim 2.0$$

  - ◇ resummations / virtual / soft terms to NNNLO in limit $m_\mathrm{t} \to \infty$ — Catani et al. '03; Moch, Vogt '05; Laenen, Magnea '05; Idilbi, Ji, Ma, Yuan '05; Ravindran '05,'06; Ravindran, Smith, v.Neerven '06; Ahrens, Becher, Neubert, Yang '08; Pak, Rogal, Steinhauser '09

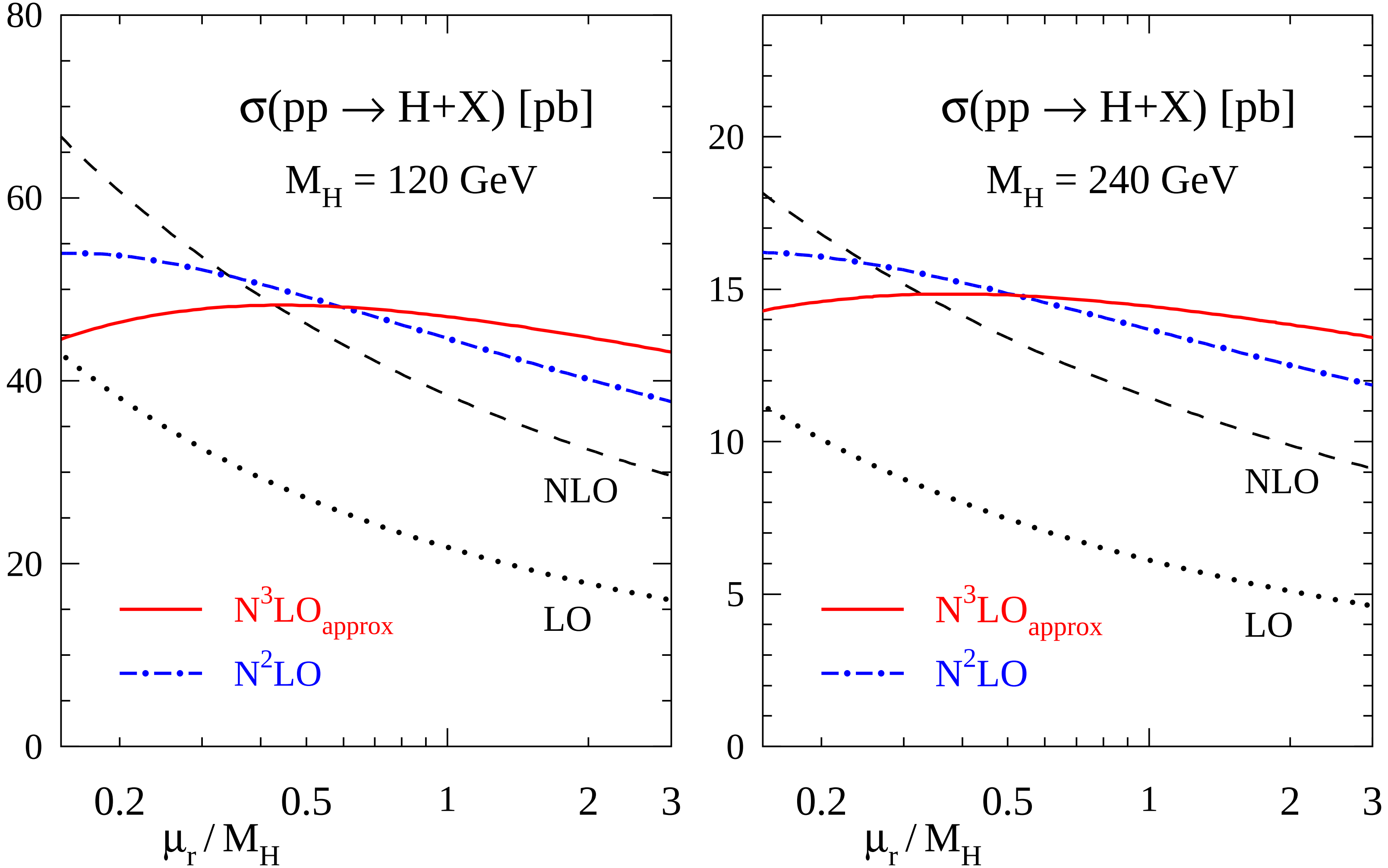


- EW corrections
  - ◇ complete NLO correction known $\sim \mathcal{O}(5\%)$ — Aglietti, Bonciani, Degrassi, Vicini '04,'06; Degrassi, Maltoni '04; Actis, Passarino, Sturm, Uccirati '08
  - ◇ mixed $\mathcal{O}(\alpha\alpha_\mathrm{s})$ corrections for small M_H — Anastasiou, Boughezal, Petriello '08

- Combination of production in NNLO QCD with Higgs decays
  - ◇ $\mathrm{H} \to \gamma\gamma$ — Anastasiou, Melnikov, Petriello '05; Catani, Grazzini '07
  - ◇ $\mathrm{H} \to \mathrm{WW} \to l\nu l\nu$ — Anastasiou, Dissertori, Stöckli '07; Grazzini '08; Anastasiou, Dissertori, Stöckli, Webber '08
  - ◇ $\mathrm{H} \to \mathrm{ZZ} \to 4l$ — Grazzini '08

QCD scale dependence of predictions for inclusive $gg \to H$

Moch, Vogt '05



Reduction of renormalization-scale dependence with increasing orders !

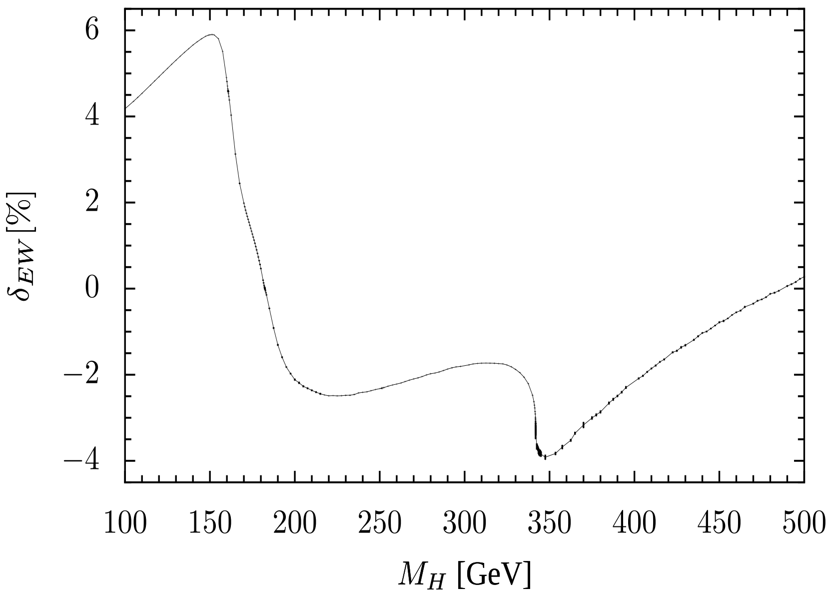
$\hookrightarrow$ residual scale uncertainty $\lesssim 5\text{–}10\%$

Recent error estimate with MSTW2008 NNLO: $\delta_{\mathrm{PDF}} \lesssim 3\%$ de Florian, Grazzini '09

NLO EW corrections

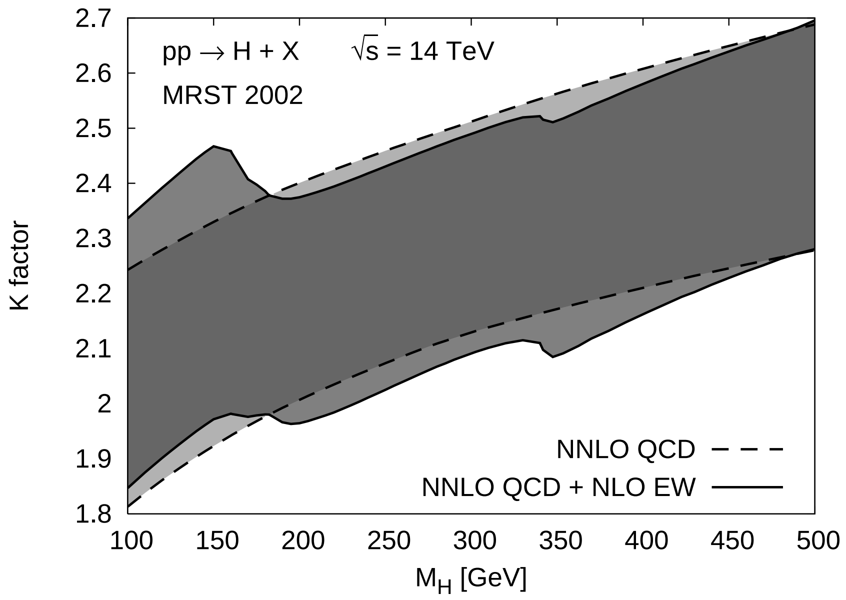
Actis, Passarino, Sturm, Uccirati '08

Correction to partonic cross section:



K factors for pp cross section:

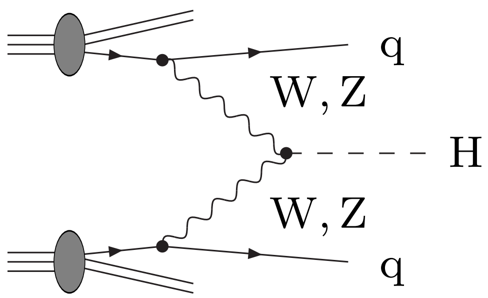
(band width: $M_\mathrm{H}/2<\mu_\mathrm{R/F}<2M_\mathrm{H}, \quad \mu_\mathrm{R}/2<\mu_\mathrm{F}<2\mu_\mathrm{R}$)



EW corrections ...

- matter at the 5% accuracy level
- show non-trivial structures near WW, ZZ, $\mathrm{t\bar{t}}$ thresholds
  $\hookrightarrow$ properly described via complex-mass scheme (real masses lead to unphysical peaks)
- mixed $\mathcal{O}(\alpha\alpha_\mathrm{s})$ corrections for small M_H Anastasiou, Boughezal, Petriello '08
  suggest factorization of QCD and EW corrections within good accuracy

A multi-leg example: Higgs production via weak vector-boson fusion (VBF)



colour exchange between quark lines suppressed

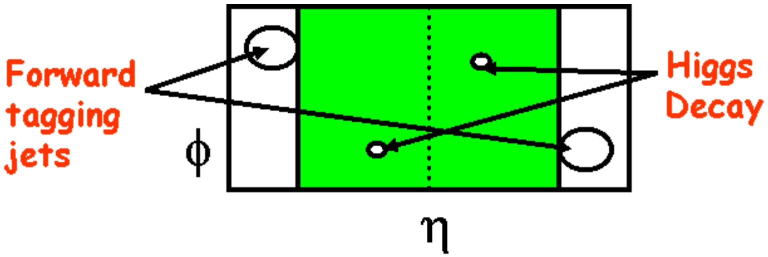
$\Rightarrow$ small QCD corrections

Han, Valencia, Willenbrock '92; Spira '98;
Djouadi, Spira '00; Figy, Oleari, Zeppenfeld '03

$\hookrightarrow$ t-channel approximation (vertex corrections)

VBF cuts and background suppression:

signature $=$ Higgs + 2jets



- 2 hard "tagging" jets demanded:

  $p_{\mathrm{Tj}} > 20\,\mathrm{GeV}, \quad |y_{\mathrm{j}}| < 4.5$

- tagging jets forward–backward directed:

  $\Delta y_{\mathrm{jj}} > 4, \quad y_{\mathrm{j1}} \cdot y_{\mathrm{j2}} < 0.$

$\hookrightarrow$ Suppression of background

- from other (non-Higgs) processes,
  such as $\mathrm{t\bar{t}}$ or WW production Zeppenfeld et al. '94-'99

- induced by Higgs production via gluon fusion,
  such as $gg \to gg\mathrm{H}$ Del Duca et al. '06; Campbell et al. '06

Work on radiative corrections to the production of Higgs+2jets

- NLO QCD corrections to VBF in "t-channel approximation" (vertex corrections)
  - ◇ total cross section Han, Valencia, Willenbrock '92; Spira '98; Djouadi, Spira '00
  - ◇ distributions Figy, Oleari, Zeppenfeld '03; Berger, Campbell '04

  $\hookrightarrow$ impact $\sim\ 5\text{–}10\%$

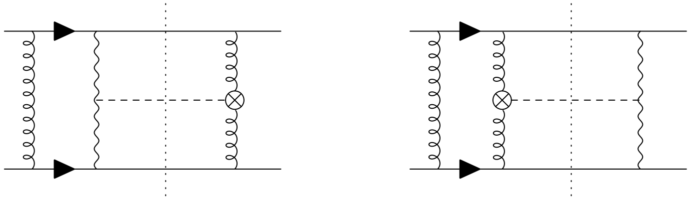
- NLO QCD corrections to gluon-initiated channels Campbell, R.K.Ellis, Zanderighi '06 (effective $\mathrm{H}gg$ coupling)

  $\hookrightarrow$ contribution to VBF $\sim\ 5\%$ Nikitenko, Vazquez '07 (NLO scale uncertainty $\sim 35\%$)

- (full) NLO QCD+EW corrections to VBF Ciccolini, Denner, S.D. '07

  $\hookrightarrow$ NLO QCD $\sim$ NLO EW $\sim\ 5\text{–}10\%$

- QCD loop-induced interferences between VBF and gluon-initiated channels



Andersen, Binoth, Heinrich, Smillie '07
Bredenstein, Hagiwara, Jäger '08

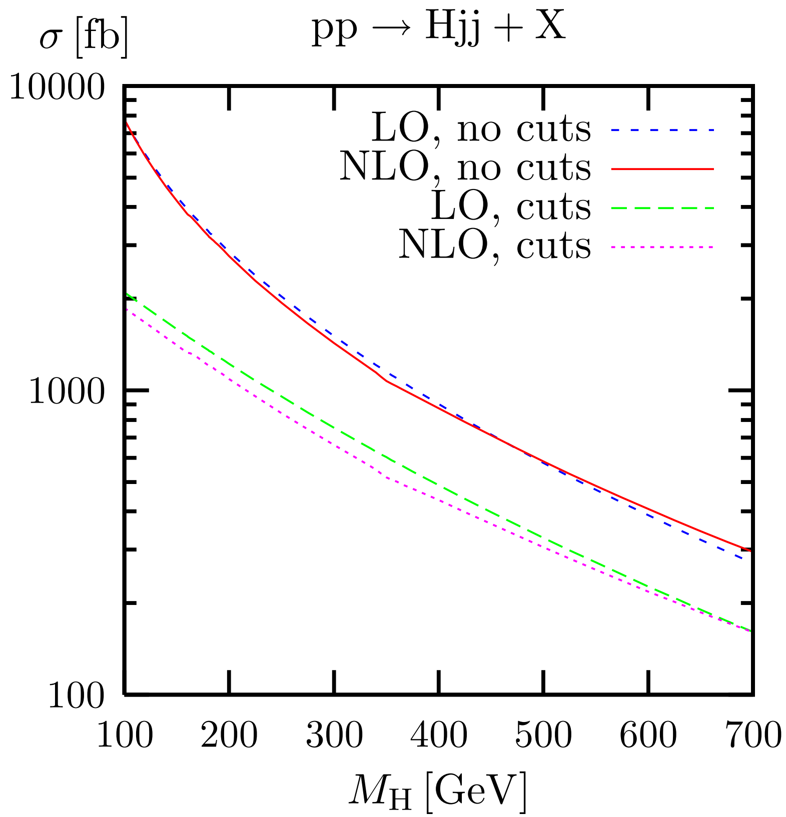
$\rightarrow$ impact $\lesssim\ 10^{-3}\,\%$ (negligible!)

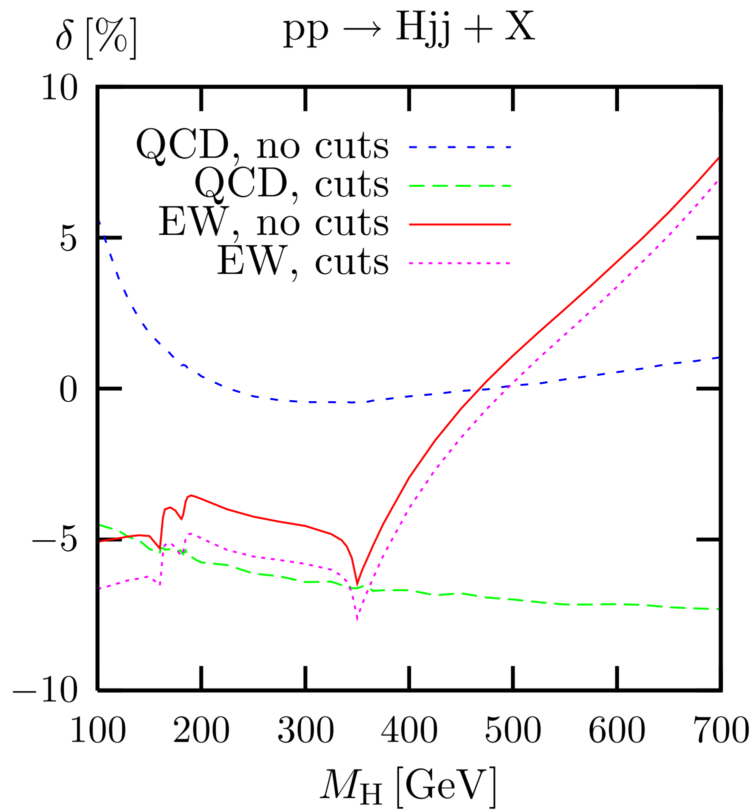
- SUSY QCD+EW corrections Hollik, Plehn, Rauch, Rzehak '08

  $\hookrightarrow$ $|\mathrm{MSSM}-\mathrm{SM}|\ \lesssim\ 1\%$ for SPS points ($2\text{–}4\%$ for low SUSY scales)

Integrated VBF cross section at NLO QCD $\oplus$ EW

Ciccolini, Denner, S.D. '07



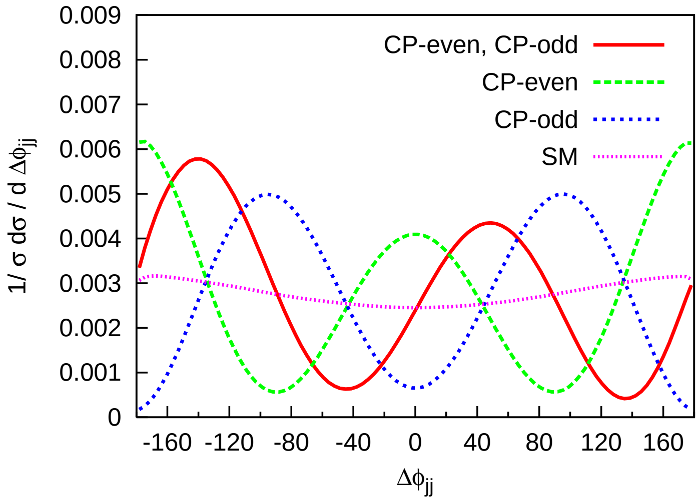


- QCD and EW corrections are of same generic size
- $\mathrm{W/Z}$ resonances in s-channels described via complex-mass scheme
- sensitivity to cuts: large for QCD, small for EW corrections
- heavy-Higgs corrections at $M_\mathrm{H} \sim 700\,\mathrm{GeV}$: $\underbrace{G_\mu M_\mathrm{H}^2}_{\text{1-loop}} \sim \underbrace{(G_\mu M_\mathrm{H}^2)^2}_{\text{2-loop}} \sim 4\%$
  $\hookrightarrow$ breakdown of perturbation theory

Distribution in the azimuthal angle difference $\Delta\phi_{\rm jj}$ of the tagging jets

Sensitivity to non-standard effects:

Hankele, Klämke, Zeppenfeld, Figy '06



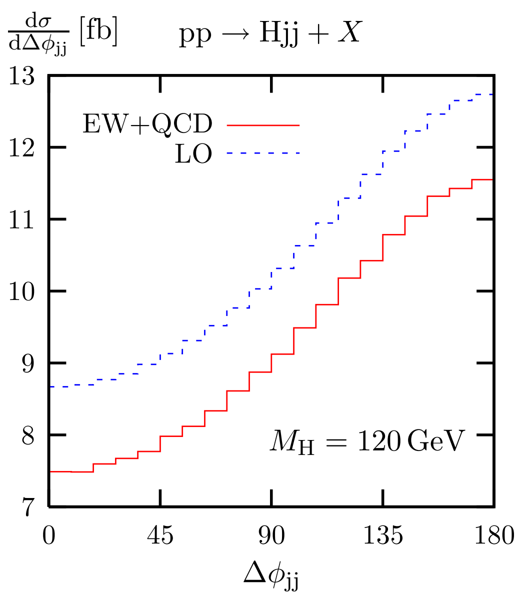
(Individual contributions
without SM)

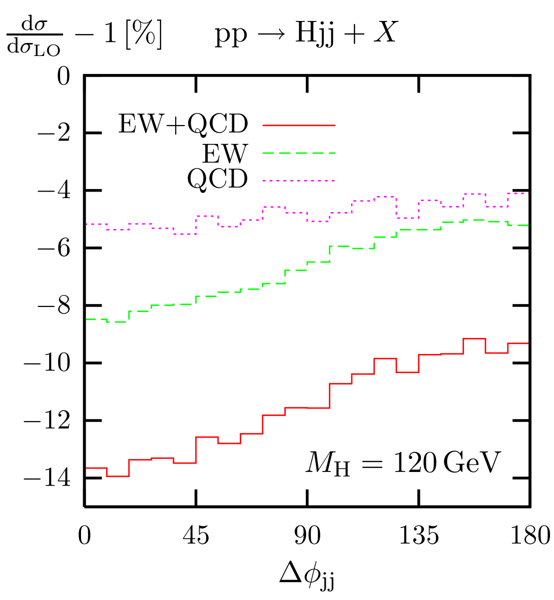
CP-even: $\mathcal{L} \propto H W^{+}_{\mu\nu} W^{-,\mu\nu}$

CP-odd: $\mathcal{L} \propto H \tilde{W}^{+}_{\mu\nu} W^{-,\mu\nu}$

Corrections to the $\Delta\phi_{\rm jj}$ distribution:

Ciccolini, Denner, S.D. '07



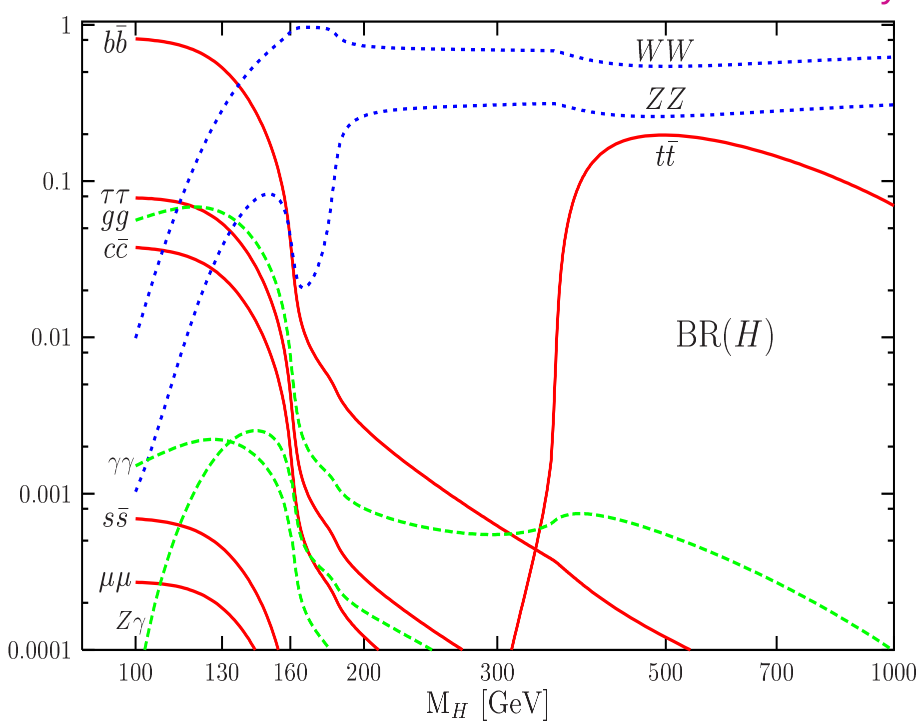


Neglected corrections
could be misinterpreted
as non-standard couplings

Electroweak corrections

... Higgs-boson decay

NLO EW corrections to Higgs-boson decays



- $\mathrm{H} \to f\bar{f}$
  Bardin, Vilenskii, Khristova '91
  Dabelstein, Hollik '92; Kniehl '92

- $\mathrm{H} \to \gamma\gamma$
  full 2-loop result known
  (Actis,) Passarino, Sturm, Uccirati '07,'08

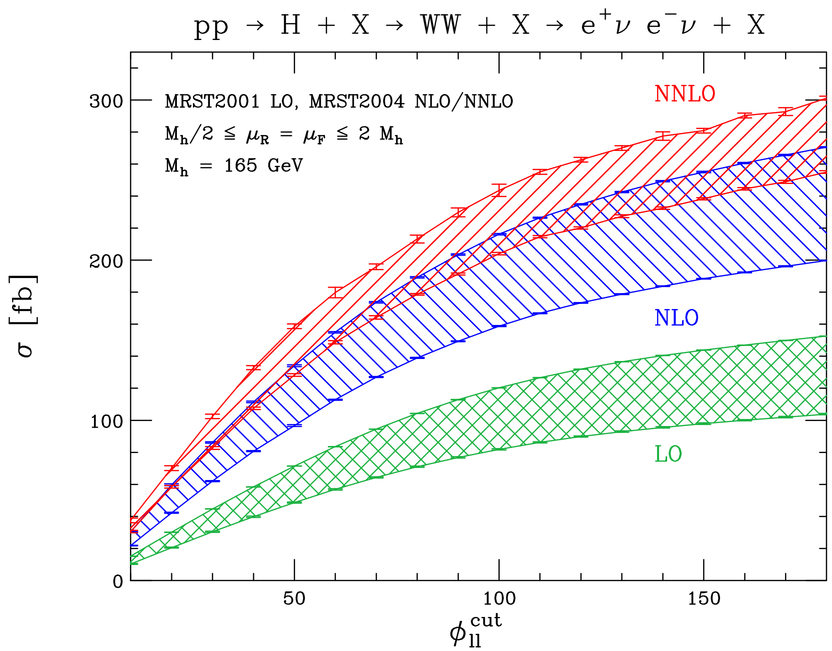
- $\mathrm{H} \to \mathrm{gg}$
  full 2-loop result known
  (same calculation as for $\mathrm{gg} \to \mathrm{H}$)
  Actis, Passarino, Sturm, Uccirati '08

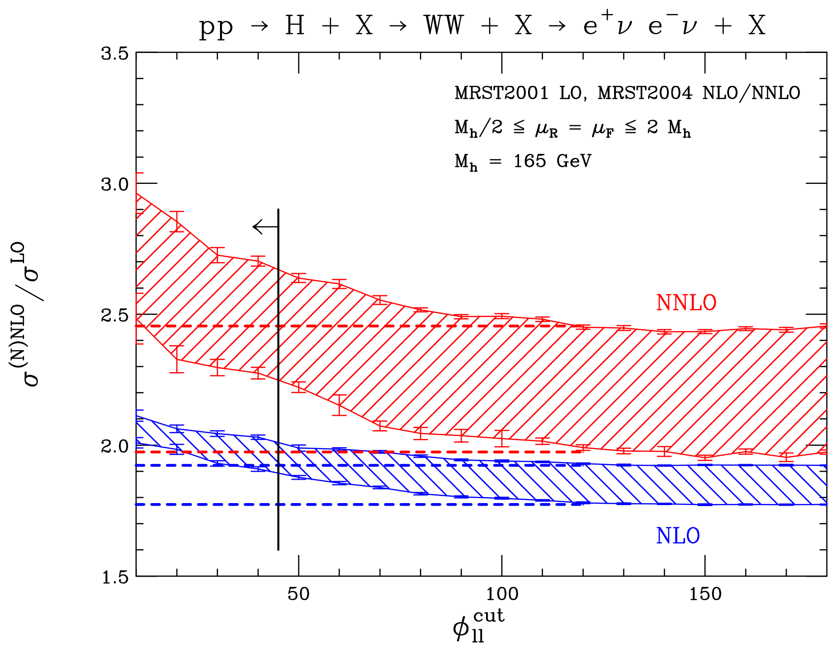
- $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$
  - for stable W/Z bosons Fleischer, Jegerlehner '81; Kniehl '91; Bardin, Vilenskii, Khristova '91
  - for off-shell/decaying W/Z bosons $\to$ *Prophecy4f* MC generator Bredenstein, Denner, S.D., Weber '06

$\hookrightarrow$ NLO EW corrections known for most important SM Higgs decays

Combination of Higgs production and decay $\mathrm{H} \to \mathrm{WW} \to ll\nu\nu$

Anastasiou, Dissertori, Stöckli '07





$\phi_{ll} =$ angle between charged decay leptons in the transverse plane

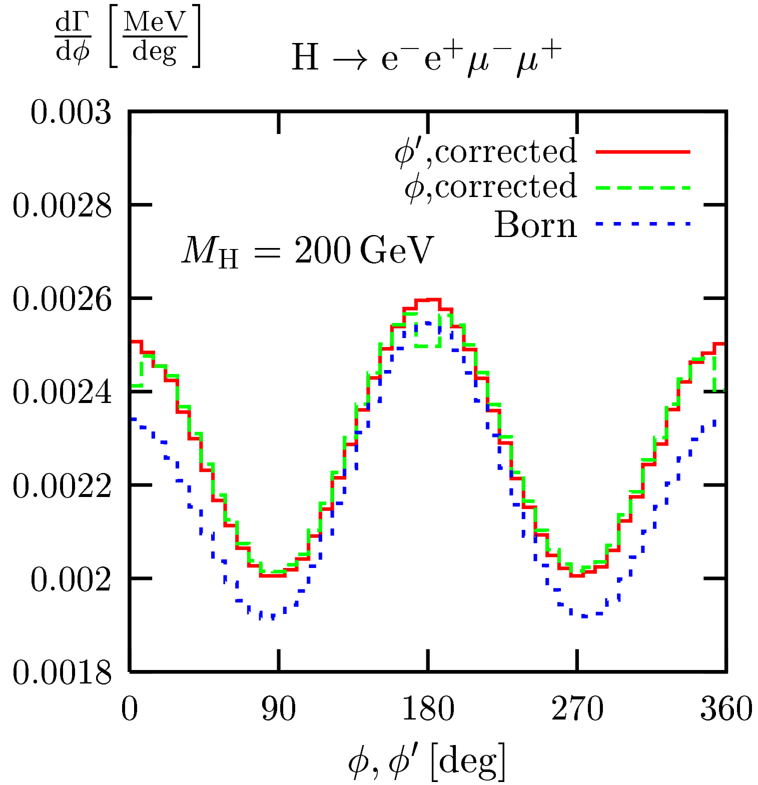
K factors in general depend on decay phase space.

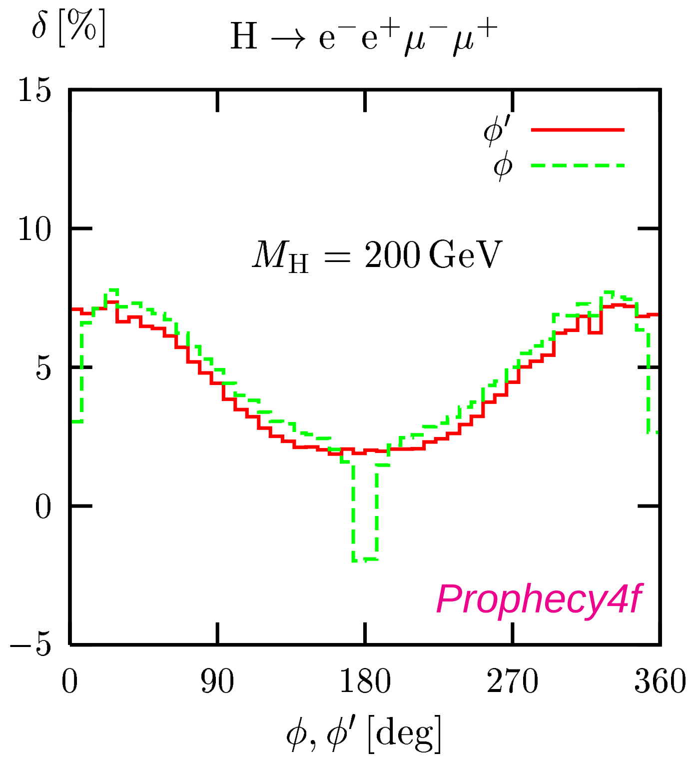
Comment on EW corrections to $\mathrm{H} \to \mathrm{WW/ZZ} \to 4l$ decays

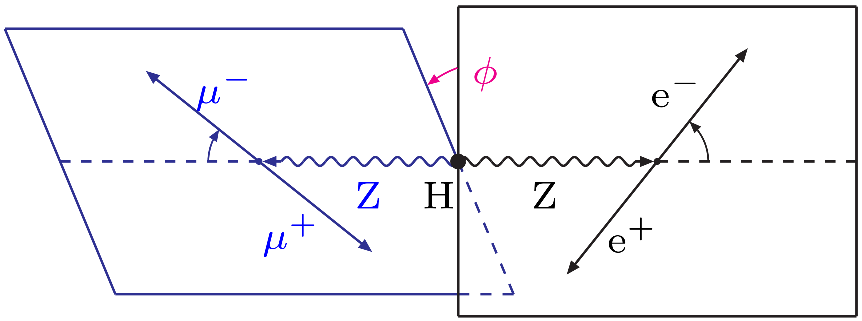
Bredenstein, Denner, S.D., Weber ’06

$\hookrightarrow$ $5{-}10\%$ effects that in general distort shapes of distributions

An example:







$$\cos\phi = \frac{\left(\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mathrm{e}^-}\right)\left(-\mathbf{p}_{\mu^-\mu^+} \times \mathbf{p}_{\mu^-}\right)}{\left|\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mathrm{e}^-}\right|\left|-\mathbf{p}_{\mu^-\mu^+} \times \mathbf{p}_{\mu^-}\right|}$$

$$\cos\phi' = \frac{\left(\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mathrm{e}^-}\right)\left(\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mu^-}\right)}{\left|\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mathrm{e}^-}\right|\left|\mathbf{p}_{\mathrm{e}^-\mathrm{e}^+} \times \mathbf{p}_{\mu^-}\right|}$$

Conclusions

EW corrections — where we are:

- NLO EW corrections for multi-leg processes

  $\hookrightarrow$ diagrammatic approach successfully applied up to $2 \to 4$ ($\mathrm{ee} \to 4f$, $\mathrm{ee} \to \nu\nu\mathrm{HH}$)

- 2-loop calculations
  - ◇ EW corrections to decays or vertex corrections (M_W, $\sin^2\theta_\mathrm{eff}^\mathrm{lept}$, $gg \to \mathrm{H}$)
  - ◇ 2-loop amplitudes for massless $2 \to 2$ and $1 \to 3$ with one off-shell leg known
  - ◇ subtraction techniques yield first results (e.g. $2 \to 1$ processes, $\mathrm{ee} \to 3\mathrm{j}$ in NNLO QCD)

- Corrections to resonance processes

  $\hookrightarrow$ pole expansions, effective field theories, complex-mass scheme

- Structure of EW corrections at high energies

  $\hookrightarrow$ 1-loop structure completely, 2-loop structure partially known; resummation suggested

... and what we still need:

- proper combination of QCD and EW corrections
- matching of matrix element calculations and parton showers at NLO QCD $\oplus$ EW
- update of NLO EW corrected PDFs
- consistent inclusion of particle decays including the relevant corrections
- recursive or unitarity-based loop techniques for EW corrections
- but: *“Poor is that man who has got no patience.”* William Shakespeare