Electroweak corrections

Stefan Dittmaier

Albert-Ludwigs-Universität Freiburg

Relevance of EW corrections @ LHC

- 2015: LHC run 2 @ $13{-}14\,\mathrm{TeV}$ starting
  $\hookrightarrow$ energy reach extends deeper into TeV range
  $\hookrightarrow$ $\delta_{\mathrm{EW}} \sim$ some 10%
- integrated LHC luminosity will reach some $100\,\mathrm{fb}^{-1}$
  $\hookrightarrow$ many measurements at several-% level
  $\hookrightarrow$ typical size of δ_{EW}
- planned high-precision measurements: XS ratios, M_{W}, $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$
  $\hookrightarrow$ δ_{EW} is crucial ingredient

Spirit of this talk

- describe salient features of EW corrections, in particular enhancement effects
- give brief survey of results for Higgs physics at the LHC, in particular emphasizing recent developments

Contents

Electroweak corrections

... general features

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

EW corrections to PDFs at hadron colliders

induced by factorization of collinear initial-state singularities, new: photon PDF

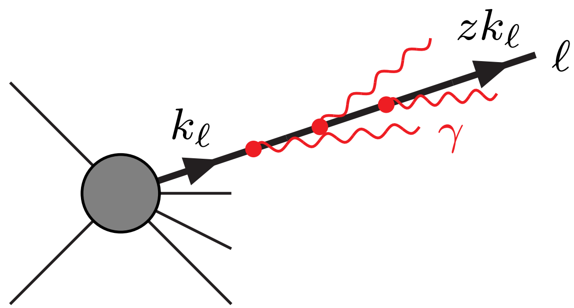
Instability of W and Z bosons

- 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 part of the NLO EW corrections

Combining QCD and EW corrections in predictions

- how to merge results from different calculations
- reweighting procedures in MC's

Collinear final-state radiation (FSR) off leptons



Leading logarithmic effect is universal:

$$\sigma_{\mathrm{LL,FSR}} = \underbrace{\int \mathrm{d}\sigma^{\mathrm{LO}}(k_l)}_{\text{hard scattering}} \int_0^1 \mathrm{d}z \; \underbrace{\Gamma_{\ell\ell}^{\mathrm{LL}}(z, Q^2)}_{\text{leading-log structure function, } Q \text{ = typ. scale}} \; \Theta_{\mathrm{cut}}(zk_l)$$

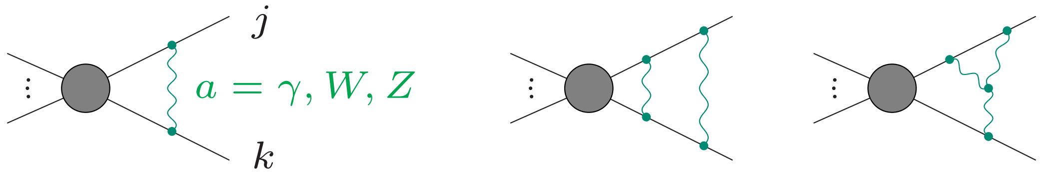
- $\Gamma_{\ell\ell}^{\mathrm{LL}}(z,Q^2)$ known to $\mathcal{O}(\alpha^5)$ + soft exponentiation, equivalent description by QED parton showers
- $\mathcal{O}(\alpha)$ approximation: $\Gamma_{\ell\ell}^{\mathrm{LL},1}(z,Q^2) = \frac{\alpha(0)}{2\pi}\left[\ln\left(\frac{Q^2}{m_\ell^2}\right) - 1\right]\left(\frac{1+z^2}{1-z}\right)_+$
- log-enhanced corrections for "bare" leptons (muons) $\quad\rightarrow\quad$ large radiative tails
- KLN theorem: mass-singular FSR effects cancel if $(\ell\gamma)$ system is inclusive (full integration over z)
- full FSR not universal, in general not even separable from other EW corrections

Recommendations for experimentalists:

- no unfolding or subtraction of FSR effects !
  $\hookrightarrow$ would introduce untransparent conventions for non-universal EW corrections
- use concept of "dressed leptons" if reduction of large FSR effects is desirable
  (recombination of collinear $\ell\gamma$ configurations, analogous to QCD jet algorithms)

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–'08

Electroweak radiative corrections at high energies (continued)

- NLO EW high-energy logs – an approximation for full NLO EW ?
  - – miss finite contributions of $\mathcal{O}(\alpha)$ and photonic radiation effects
  - + simple approximation in Sudakov regime:

    s and $|t|$ large for $2 \to 2$ $\Rightarrow$ large p_T or M_T !
  - – fail in non-Sudakov regime:

    e.g. s large, but $|t|$ NOT large for $2 \to 2$ $\Rightarrow$ e.g. large M_{ll} in Drell–Yan !
  - + generically included in ALPGEN Chiesa, Montagna, Piccinini et al. '13
- Real W and Z emission processes
  - ◇ not fully separable from underlying process

    (e.g. hadronically decaying W/Z's in jet environment)
  - ◇ partially compensate negative virtual EW corrections

    $\hookrightarrow$ strongly dependent on W/Z reconstruction / separation

Recommendations:

- full NLO EW corrections whenever possible
- careful validations of logarithmic approximations against full results
- real W/Z emission: full ME calculations via multipurpose LO MC's

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

- absorption of $\alpha \ln m_q$ singularities via factorization into redefined PDFs
- $\mathcal{O}(\alpha)$ corrections to all PDFs
  $\hookrightarrow$ typical impact: $\Delta(\mathrm{PDF}) \lesssim 0.3\%\ (1\%)$ for $x \lesssim 0.1\ (0.4)$, $\mu_{\mathrm{fact}} \sim M_{\mathrm{W}}$
- photon PDF
  $\hookrightarrow$ typically add $\mathcal{O}(1\%)$ to cross sections, but with large uncertainties

NNPDF2.3QED = NNPDF set with $\mathcal{O}(\alpha)$ corrections

Ball et al. [NNPDF collaboration] '13

- currently best PDF prediction at (N)NLO QCD + NLO EW
- PDF samples for error estimate provided
- photon PDF fitted to DIS and Drell–Yan data $(10^{-5} \lesssim x \lesssim 10^{-1})$
  $\hookrightarrow$ better future constraints via $\gamma\gamma \to \mu^+\mu^-, \mathrm{W}^+\mathrm{W}^-$ for larger x ?
- but: (small) scheme ambiguity remains in $\mathcal{O}(\alpha)$

Electroweak corrections

... to Higgs-boson decays

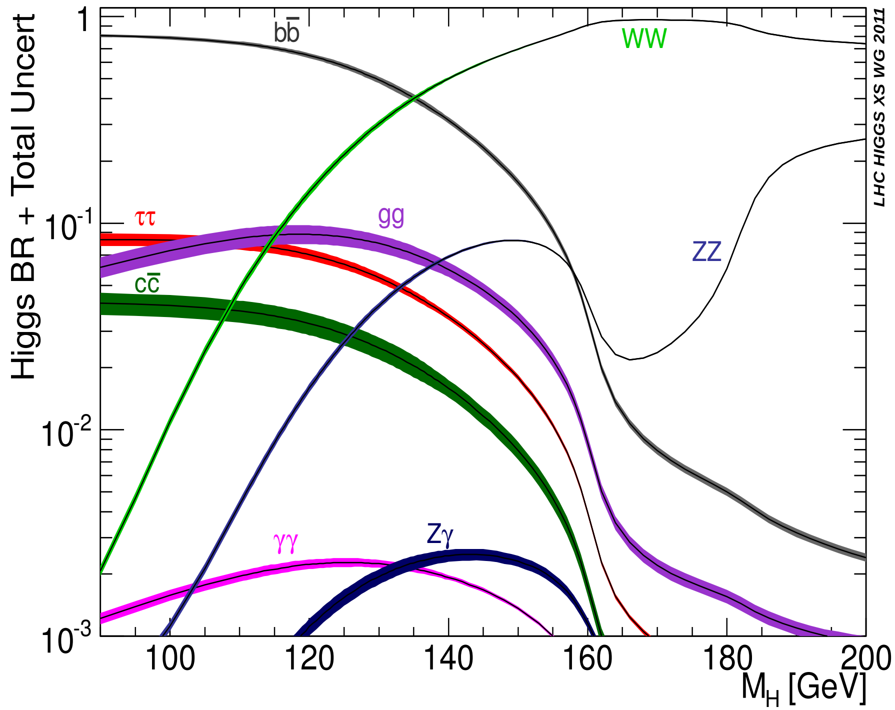
NLO EW corrections to Higgs-boson decays

- $\mathrm{H} \to f\bar{f}$
  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

Hdecay + Prophecy4f

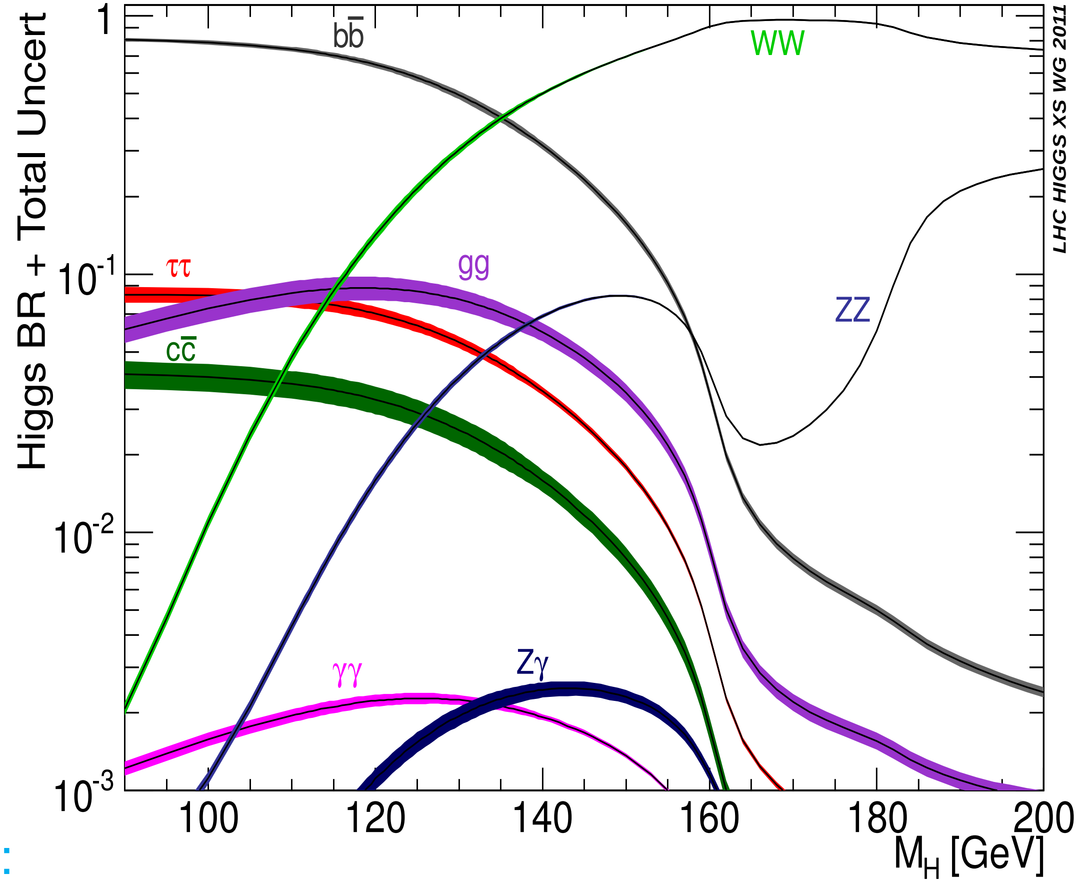


- $\mathrm{H} \to \mathrm{WW/ZZ}$
  - stable $\mathrm{W/Z}$ bosons — Fleischer, Jegerlehner '81; Kniehl '91; Bardin, Vilenskii, Khristova '91
  - $\mathrm{H} \to \mathrm{W}^{(*)}\mathrm{W}^{(*)}/\mathrm{Z}^{(*)}\mathrm{Z}^{(*)} \to 4f$: *Prophecy4f* — Bredenstein et al. '06
  - $\mathrm{H} \to \mathrm{Z}^{(*)}\mathrm{Z}^{(*)} \to 4\ell$: *Hto4l* (NLO + elmg. PS) — Boselli et al. '15

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

BRs of the SM Higgs boson

LHC Higgs XS WG 2011



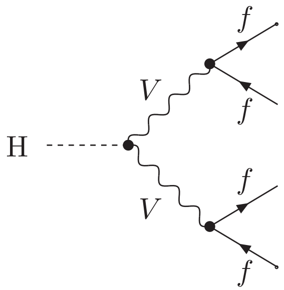
Parametric + theoretical uncertainty:

M_{H} [GeV] $\mathrm{H} \to$	$\mathrm{b\bar{b}}$	$\tau^+\tau^-$	$\mathrm{c\bar{c}}$	gg	$\gamma\gamma$	WW	ZZ	
120	3%	6%	12%	10%	5%	5%	5%	$\leftarrow$ driven by $\Gamma_{\mathrm{H}\to\mathrm{b\bar{b}}}$
150	4%	3%	10%	8%	2%	1%	1%	
200	5%	3%	10%	8%	2%	$< 0.1\%$	$< 0.1\%$	

EW corrections significant in predictions for $\Gamma_{\mathrm{H}\to X}$ and $\mathrm{BR}_{\mathrm{H}\to X}$

Survey of Feynman diagrams for NLO corrections to $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$

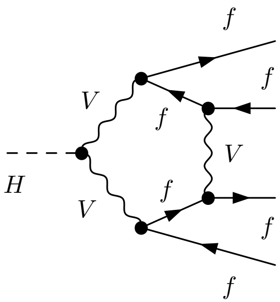
Lowest order:



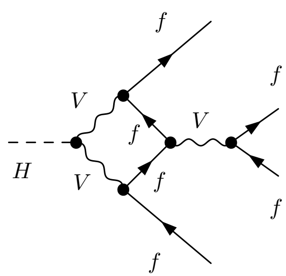
Typical one-loop diagrams:

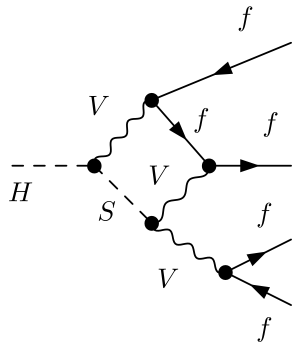
diagrams = $\mathcal{O}(200-400)$

pentagons

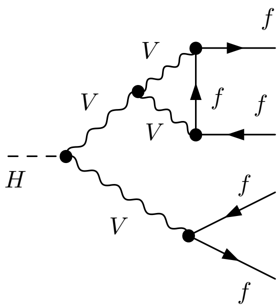


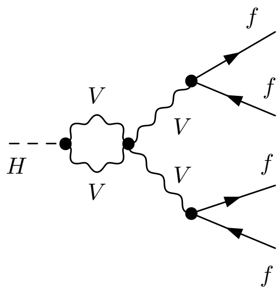
boxes



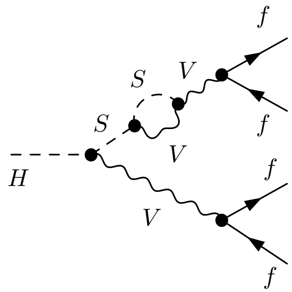


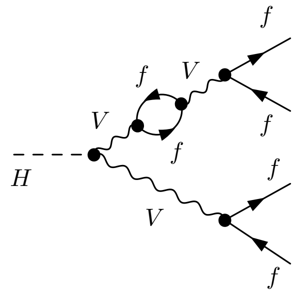
vertices





self-energies

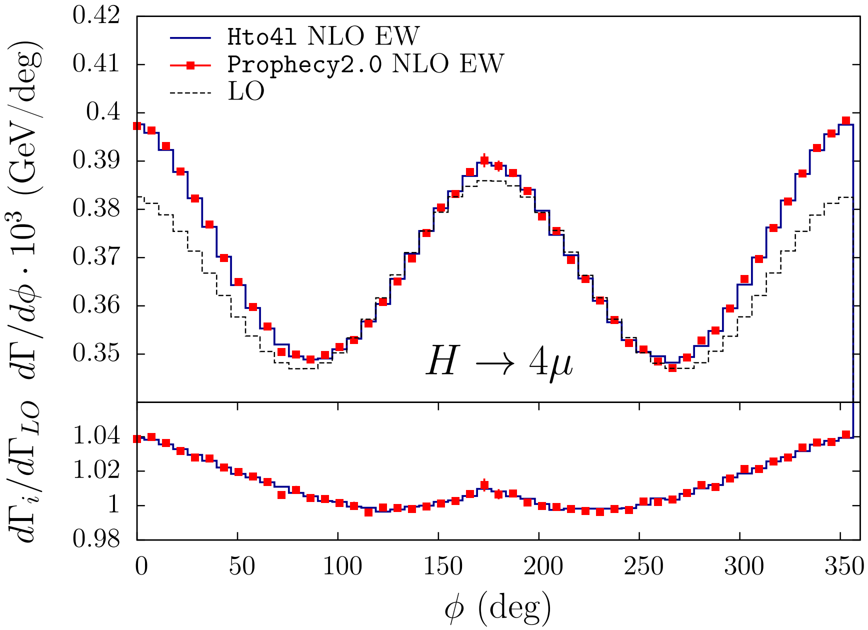


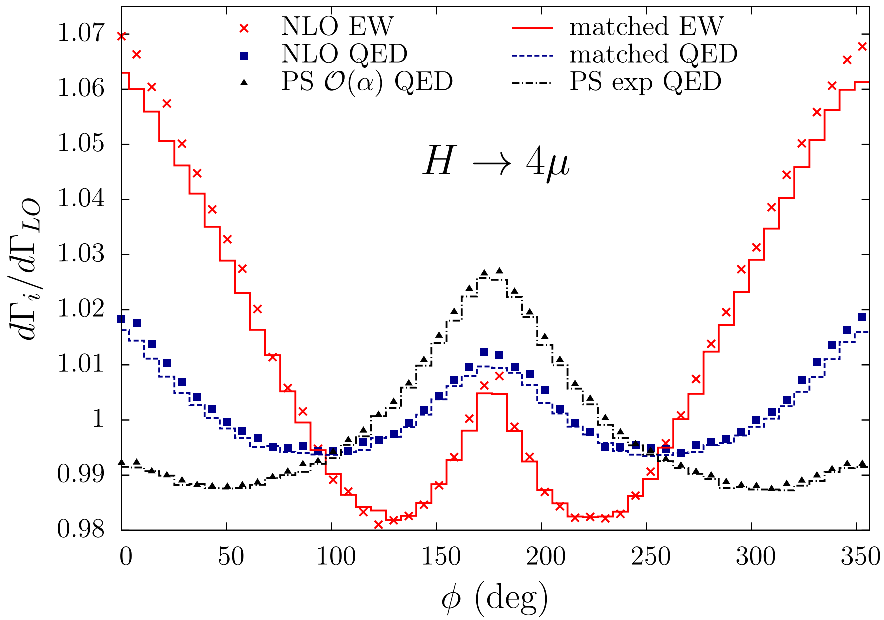


$+$ tree graphs with real gluon or photons

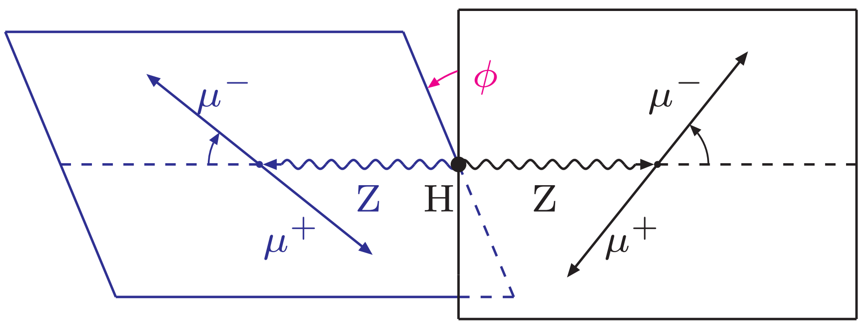
Example: corrections to distribution in angle between Z decay planes

Boselli et al. '15





- $5-10\%$ NLO effects distorting shapes
- genuine weak corrections $\sim 2-5\%$
- good agreement between *Prophecy4f* and *Hto4l* at NLO
- elmg. shower effects $\sim 0.5-1\%$
- PS approximation totally off

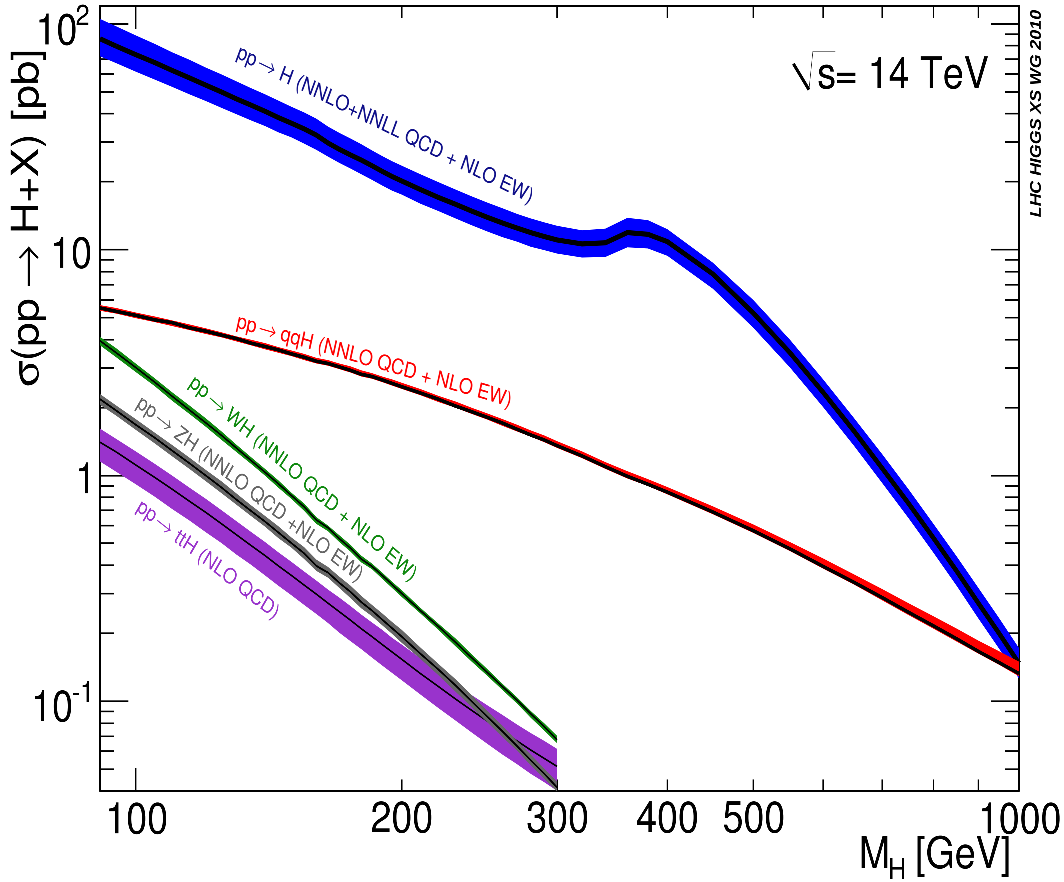


Electroweak corrections

... to Higgs-boson production

SM Higgs XS predictions for the LHC at $\sqrt{s} = 14\,\mathrm{TeV}$

LHC Higgs XS WG 2010–



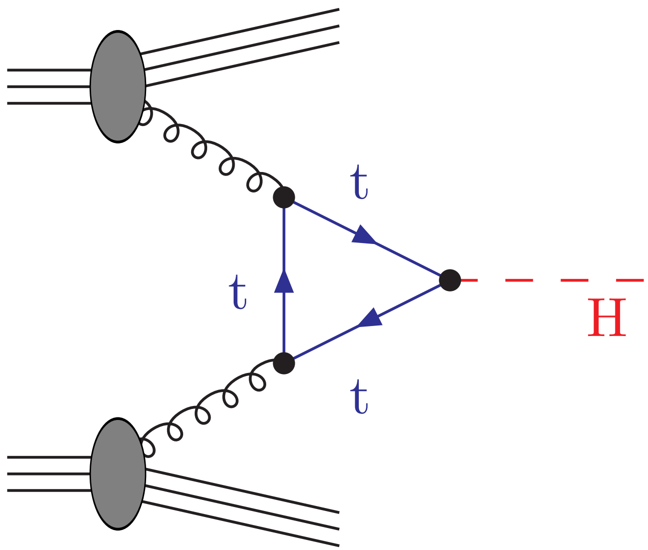
Rough numbers:

$M_{\mathrm{H}} = 125\,\mathrm{GeV}$	Uncertainties		NLO/NNLO/NNLO+	
	scale	PDF4LHC	QCD	EW
ggF	11%	7%	$>100\%$	5%
VBF	1%	3%	5%	5%
WH	1%	4%	20%	7%
ZH	4%	4%	35%	5%
ttH	9%	9%	20%	$1\text{–}2\%$

EW corrections

$\sim\ \mathcal{O}(\text{uncertainties})$

Higgs production via gluon fusion



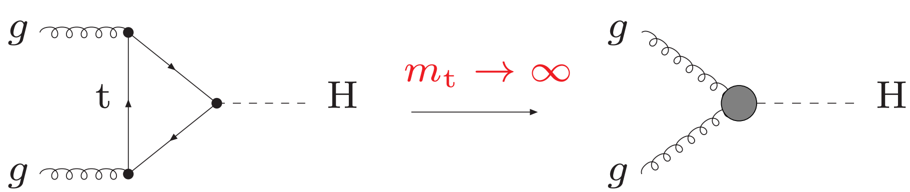
Corrections to Higgs-boson production via gluon fusion

- QCD corrections:
  - full NLO, NNLO via expansions

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

Graudenz, Spira, Zerwas ’93
Djouadi, Graudenz, Spira, Zerwas ’95
...
Marzani et al. ’08
Pak, Rogal, Steinhauser ’09
Harlander, Ozeren ’09

  - NNNLO in limit $m_{\mathrm{t}} \to \infty$



Chetyrkin et al. ’98,’06; Moch/Vogt ’05;
Schröder/Steinhauser ’06; Baikov et al. ’09;
Gehrmann et al. ’10,’12; Duhr/Gehrmann ’13;
Li/Zhu ’13; Kilgore ’13; Hoeschele et al.’13;
Buehler/Lazopoulos ’13;
Anastasiou et al. ’13–’15

  - resummations

Catani et al. ’03; Moch, Vogt ’05
Laenen, Magnea ’05; Idilbi, Ji, Ma, Yuan ’05
Ravindran ’05,’06; Ravindran, Smith, v.Neerven ’0
Ahrens, Becher, Neubert, Yang ’08,’11
Berger et al. ’10; Stewart, Tackmann ’11
Banfi, (Monni,) Salam, Zanderighi ’12
Becher, Neubert ’12

- EW corrections
  - complete NLO correction known $\sim \mathcal{O}(5\%)$

Aglietti, Bonciani, Degrassi, Vicini ’04,’06
Degrassi, Maltoni ’04
Actis, Passarino, Sturm, Uccirati ’08

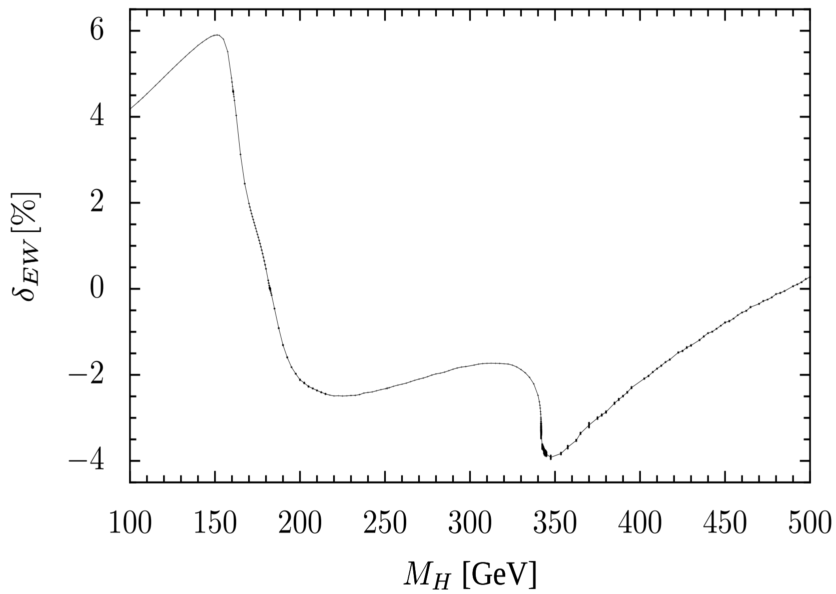
  - mixed $\mathcal{O}(\alpha\alpha_{\mathrm{s}})$ corrections for small M_{H}

Anastasiou, Boughezal, Petriello ’08

NLO EW corrections

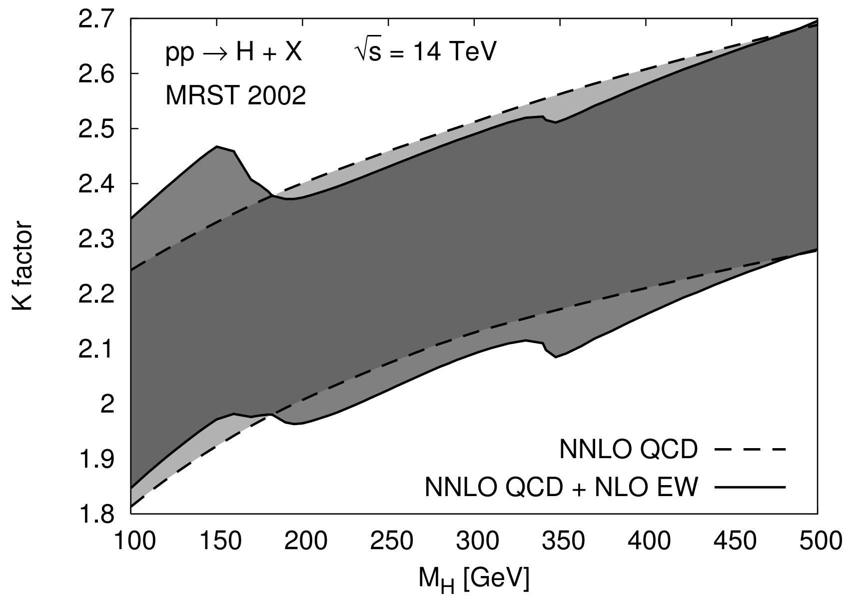
Actis, Passarino, Sturm, Uccirati '08

Correction to partonic cross section:

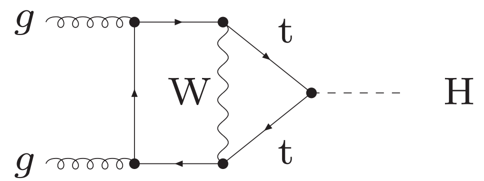


K factors for pp cross section:

(band width: $M_H/2 < \mu_{R/F} < 2M_H$, $\mu_R/2 < \mu_F < 2\mu_R$)



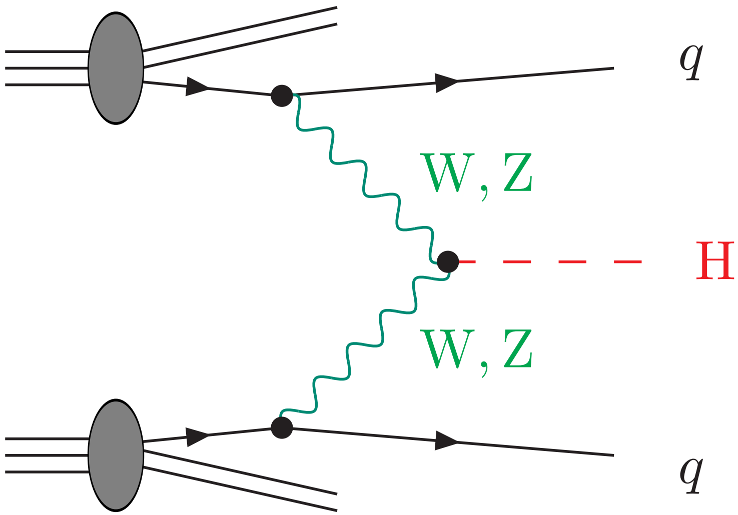
EW corrections ...



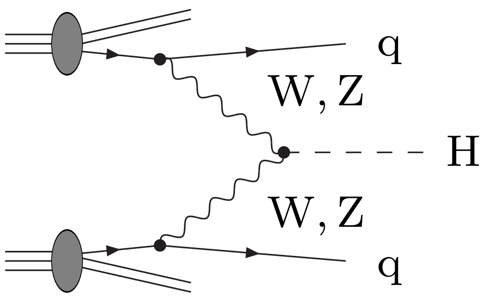
etc.

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

Higgs production via vector-boson fusion



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



colour exchange between quark lines suppressed

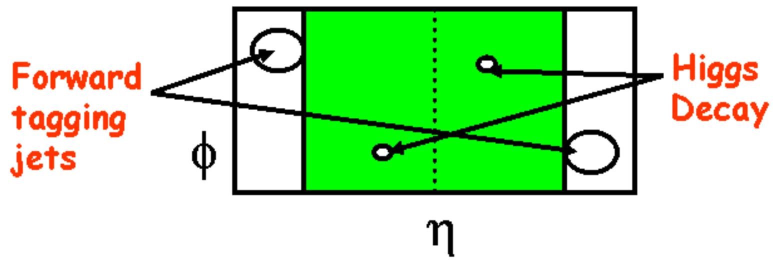
$\Rightarrow$ small QCD corrections

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 DIS-like approximation
  - ◇ total cross section — Han, Valencia, Willenbrock '92; Spira '98; Djouadi, Spira '00
  - ◇ distributions — Figy, Oleari, Zeppenfeld '03; Berger, Campbell '04
  - ◇ matching with parton shower (POWHEG) — Nason, Oleari '09

- (full) NLO QCD+EW corrections to VBF — Ciccolini, Denner, Dittmaier '07; Figy, Palmer, Weiglein '10 (DIS-like EW)

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

- NNLO QCD corrections to VBF in DIS-like approximation — Bolzoni, Maltoni, Moch, Zaro '10

  $\hookrightarrow$ NNLO QCD $\sim 1{-}2\%$

- NLO QCD corrections to $\mathrm{gg} \to \mathrm{Hgg}$, etc. — Campbell, R.K.Ellis, Zanderighi '06

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

- QCD loop-induced interferences between VBF and Hgg-initiated channels — Andersen, Binoth, Heinrich, Smillie '07; Bredenstein, Hagiwara, Jäger '08

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

- loop-induced VBF in gg scattering — Harlander, Vollinga, Weber '08

  $\hookrightarrow$ impact $\sim 0.1\%$

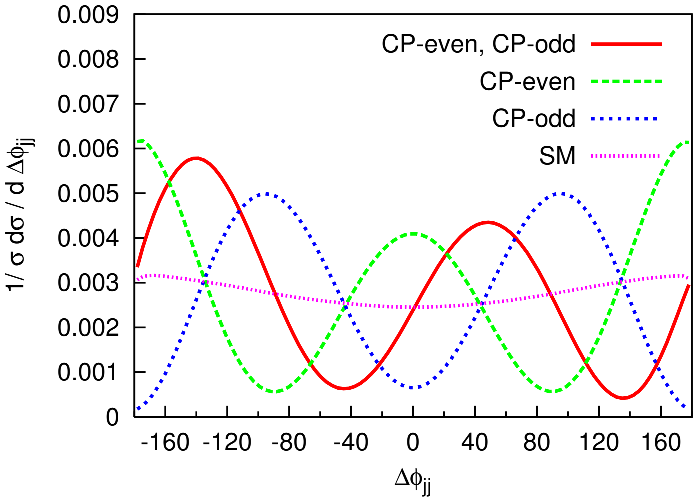
- SUSY QCD+EW corrections — Hollik, Plehn, Rauch, Rzehak '08

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

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

Sensitivity to non-standard effects:

Hankele, Klämke, Zeppenfeld, Figy ’06



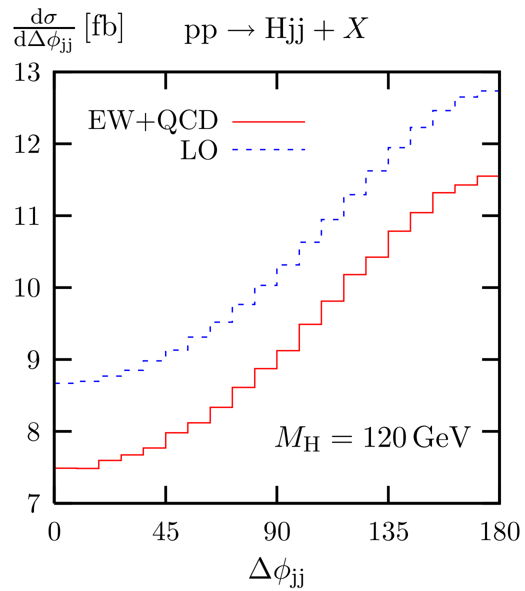
(Individual contributions without SM)

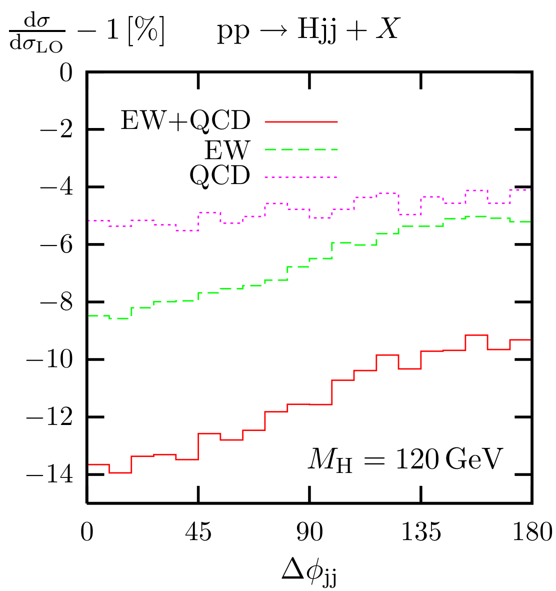
CP-even: $\mathcal{L} \propto HW^{+}_{\mu\nu}W^{-,\mu\nu}$

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

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

Ciccolini, Denner, Dittmaier ’07

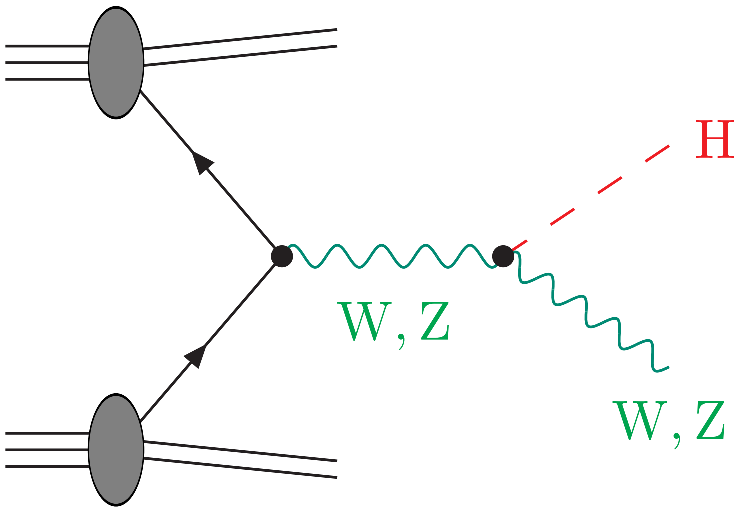




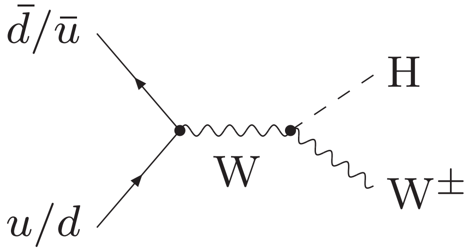
HAWK

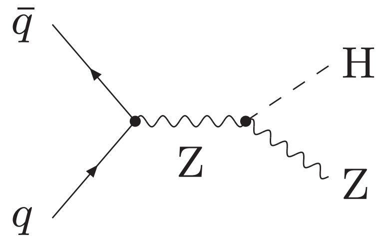
Neglected corrections could be misinterpreted as non-standard couplings

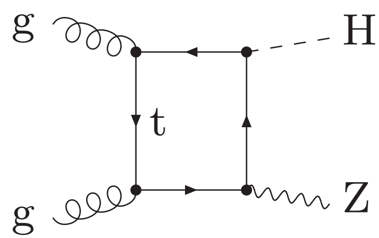
Production via Higgs-strahlung



Current status of theoretical predictions







- NLO QCD: corrections entirely Drell–Yan like
  Han, Willenbrock '91; Ohnemus, Stirling '93; Baer, Bailey, Owens '93
  VV2H (Spira); MCFM (Campbell, R.K.Ellis)
- NLO EW: stable W/Z bosons, total XS
  Ciccolini, Dittmaier, Krämer '03

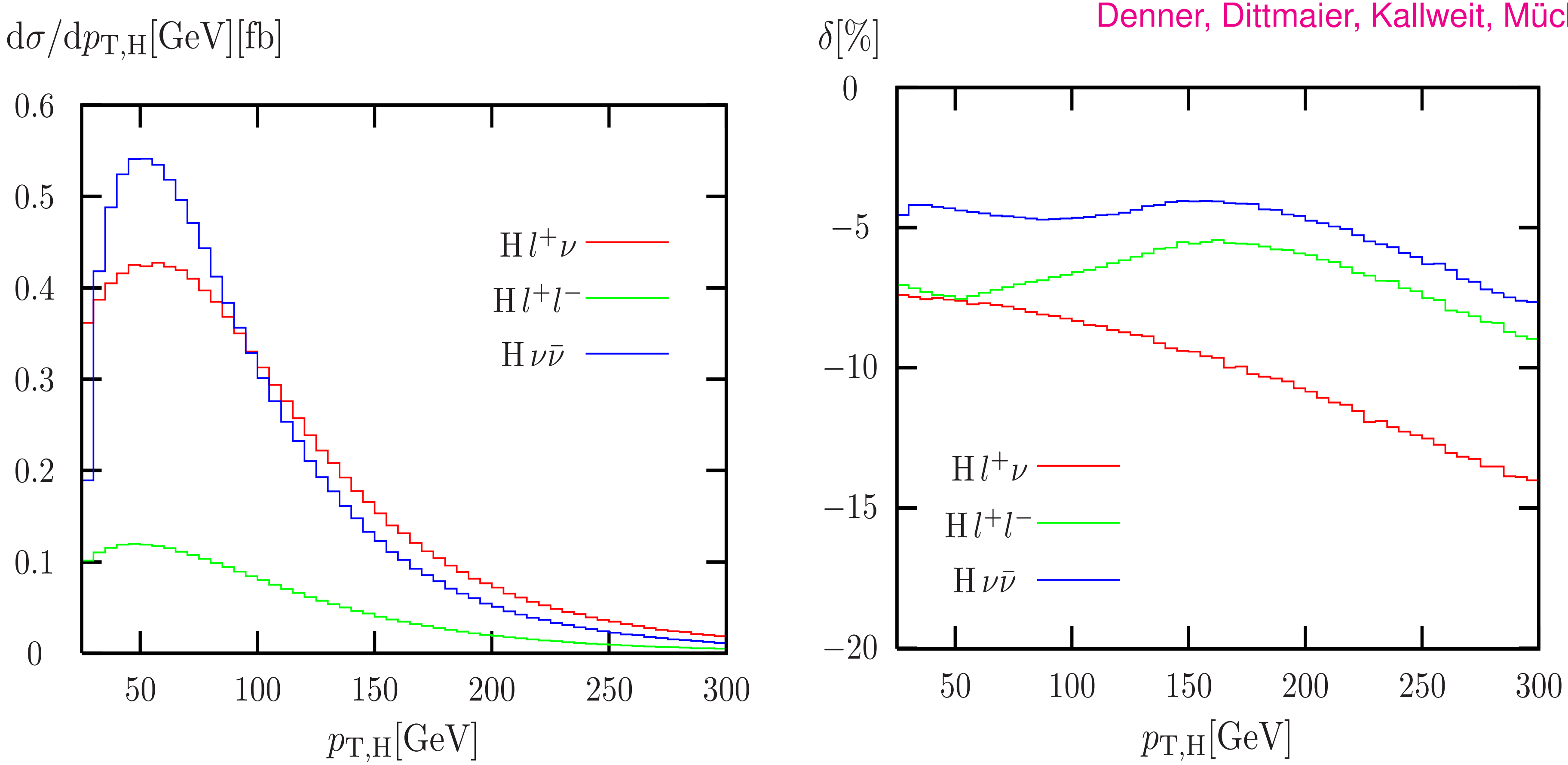
  W/Z decays, differential XS via HAWK
  Denner, Dittmaier, Kallweit, Mück '11
- NNLO QCD: stable W/Z bosons, DY part for total XS, $\mathrm{gg} \to \mathrm{ZH}$
  Brein, Djouadi, Harlander '03 (VH@NNLO)

  WH/ZH with W/Z decay, DY part for differential XS
  Ferrera, Grazzini, Tramontano '11,'14

  non-DY parts, total XS
  Brein, Harlander, Wiesemann, Zirke '11
- NNNLO QCD: $\mathrm{gg} \to \mathrm{ZH}$ @ NLO QCD, stable Z boson, total XS
  Altenkamp, Dittmaier, Harlander, Rzehak, Zirke '12

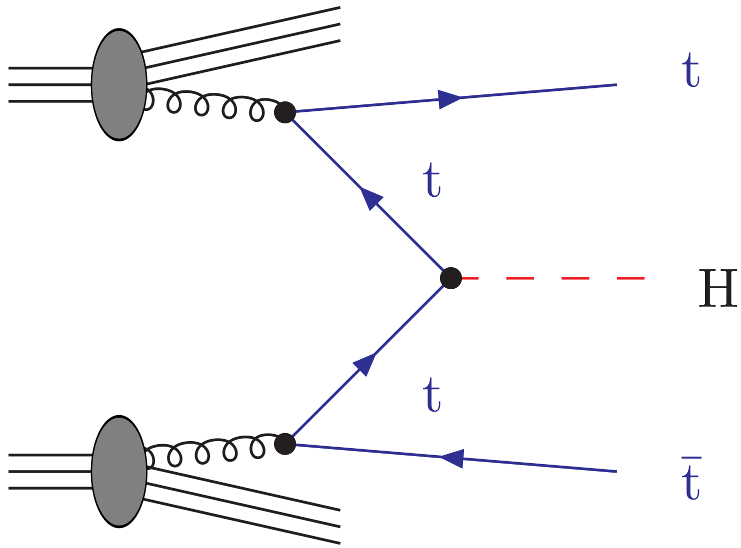
NLO EW corrections to the $p_{\mathrm{T,H}}$ distributions

Denner, Dittmaier, Kallweit, Mück ’11



- δ_{EW} for $p_{\mathrm{T,H}} \lesssim 100\,\mathrm{GeV}$ roughly reflects corrections to total cross sections
- size of corrections increases with increasing $p_{\mathrm{T,H}}$,
  e.g. $\mathrm{H}\ell^+\nu$: $\quad \delta_{\mathrm{EW}} < -11\% \quad$ for $\quad p_{\mathrm{T,H}} > 200\,\mathrm{GeV}$

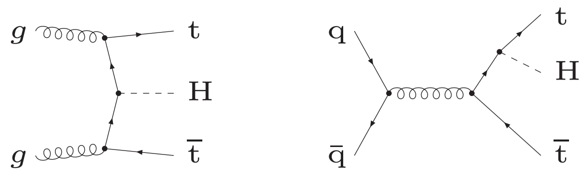
Production of $\mathrm{t\bar{t}H}$ final states



Survey of LO/NLO contributions to $t\bar{t}H$ production

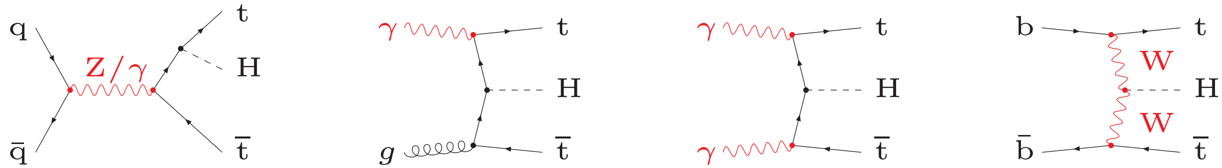
- QCD tree:

  $\mathcal{M}_{\mathrm{QCD},0}$



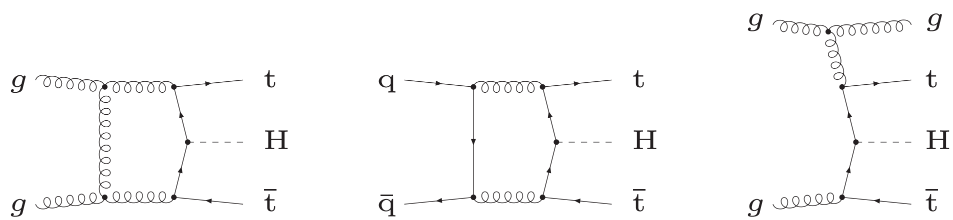
- EW tree:

  $\mathcal{M}_{\mathrm{EW},0}$



- QCD NLO:

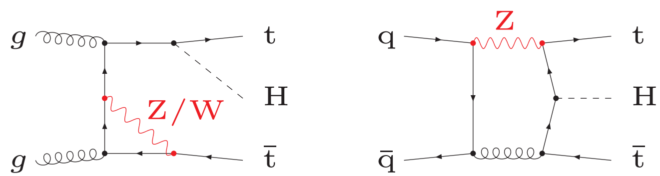
  $\mathcal{M}_{\mathrm{QCD},1}$



etc.

- Weak NLO:

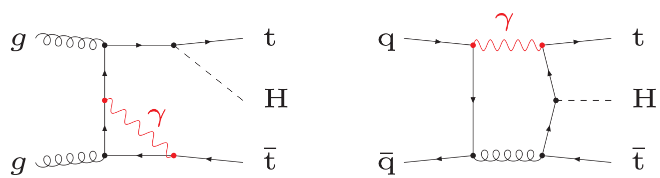
  $\mathcal{M}_{\mathrm{weak},1}$



$$\& \quad \mathcal{M}^{q\bar{q}}_{\mathrm{QCD},1} \times \left(\mathcal{M}^{q\bar{q}}_{\mathrm{weak},0}\right)^* + \ \dots$$

- Photonic NLO:

  $\mathcal{M}_{\mathrm{phot},1}$



$$\& \quad \mathcal{M}^{q\bar{q}}_{\mathrm{QCD},1} \times \left(\mathcal{M}^{q\bar{q}}_{\mathrm{phot},0}\right)^* + \ \dots$$

Known corrections to $\mathrm{t\bar{t}H}$ production

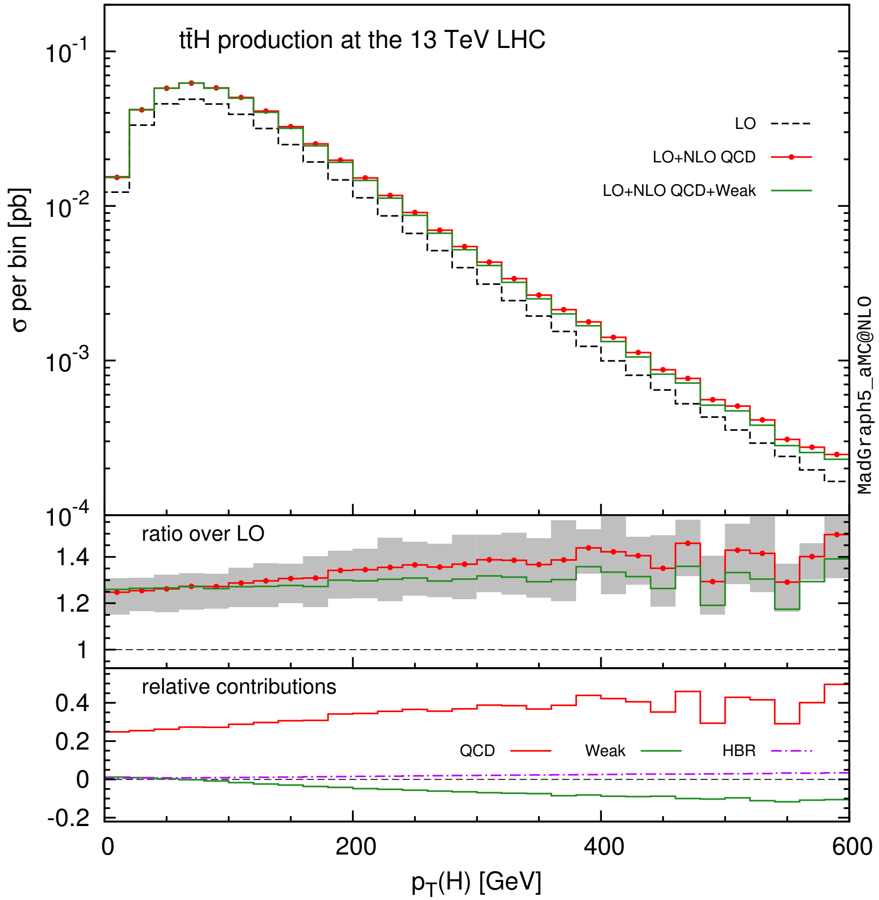
- NLO QCD corrections
  Beenakker et al. '01,'02; Dawson et al. '01,'02

- QCD parton-shower matching via *aMC@NLO, PowHel, MadSpin, Sherpa*
  Frederix et al. '11; Garzelli et al. '11; Artoisenet et al. '12; LHC HXS WG '13

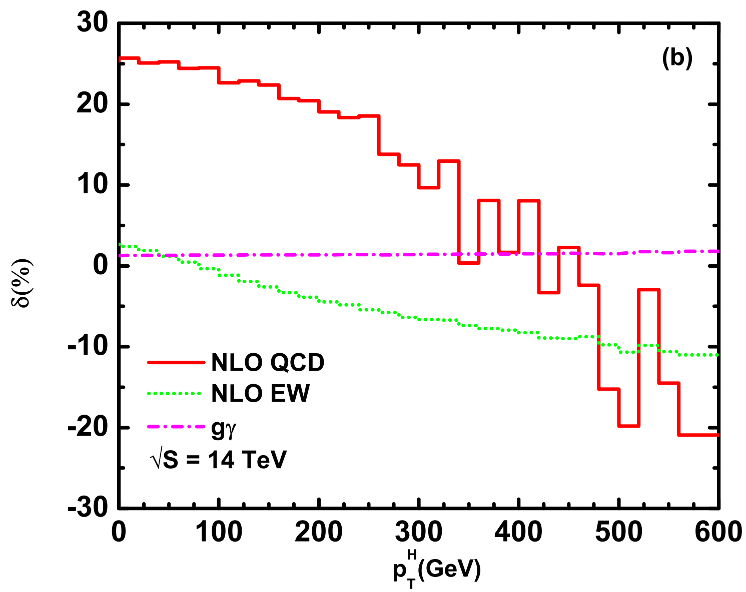
- EW corrections
  - ◇ EW tree + EW NLO + real $\mathrm{W/Z/H}$ emission (HBR) in *MadGraph5 aMC@NLO*
    Frixione et al. '14,'15
  - ◇ EW tree + EW NLO with *FeynArts/FormCalc/LoopTools*
    Zhang et al. '14

NLO EW corrections to the $p_{\mathrm{T,H}}$ distribution in $\mathrm{t\bar{t}H}$ production

Frixione et al. '14



Zhang et al. '14



- EW corrections $\sim 1{-}2\%$ for σ_{tot}
- weak corrections grow to $\sim -10\%$ for $p_{\mathrm{T,H}} \gtrsim 400{-}500\,\mathrm{GeV}$
- EW corrections mostly swamped by QCD uncertainties

Summary & outlook

EW corrections to Higgs production and decay

- known at NLO for all relevant SM Higgs processes
- generic size in inclusive quantities $\delta\sigma_{\mathrm{EW}} \sim 5{-}10\%$
  $\hookrightarrow$ non-negligible at aimed level of precision
- larger corrections in differential cross sections
  $\hookrightarrow$ enhancements at high scales (e.g. in $p_{\mathrm{T,H}}$),
  distortion of distributions (angular, invariant mass, etc.)
- EW corrections in BSM Higgs physics widely unknown (MSSM is exception)

Lessons for Higgs couplings analyses

- preliminary recipe: rescaling of $\sigma_{\mathrm{pp}\to\mathrm{H}\dots}$ and BR$(\mathrm{H} \to X)$
  $\hookrightarrow$ screws up SM (inconsistent model)
  $\hookrightarrow$ EW corrections ill-defined $\quad \to$ their size goes to theoretical uncertaintites
- a consistent approach at the EW higher-order levels requires
  - ◇ consistent quantum-field-theoretical models, such as SM or specific BSM models
  - ◇ model-independent analyses properly based on effective field theories
    $\hookrightarrow$ non-standard operators and their renormalization

... more homework for HiggsTools theorists !

Backup slides

Input parameter schemes

SM input parameters: (natural choice)

α_s, α, M_W, M_Z, M_H, m_f, V_{CKM}

Issues:

- Setting of α: process-specific choice to
  - ◇ avoid sensitivity to non-preturbative light-quark masses
  - ◇ minimize universal EW corrections

  Schemes: fix M_W, M_Z and α
  - ◇ $\alpha(0)$-scheme: relevant for external photon
  - ◇ $\alpha(M_Z)$-scheme: relevant for internal photons at high energies (γ^*)
  - ◇ G_μ-scheme: $\alpha_{G_\mu} = \sqrt{2} G_\mu M_W^2 (1 - M_W^2/M_Z^2)/\pi$, relevant for W, Z
- Warnings / pitfalls:
  - ◇ α must not be set diagram by diagram, but global factors like $\alpha(0)^m \alpha_{G_\mu}^n$ in gauge-invariant contributions mandatory !
  - ◇ weak mixing angle: $s_W \neq$ free parameter if M_W and M_Z are fixed !
  - ◇ Yukawa couplings are uniquely fixed by fermion masses !

Electroweak radiative corrections at high energies (continued)

Example: Drell–Yan production

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

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

no Sudakov domination!

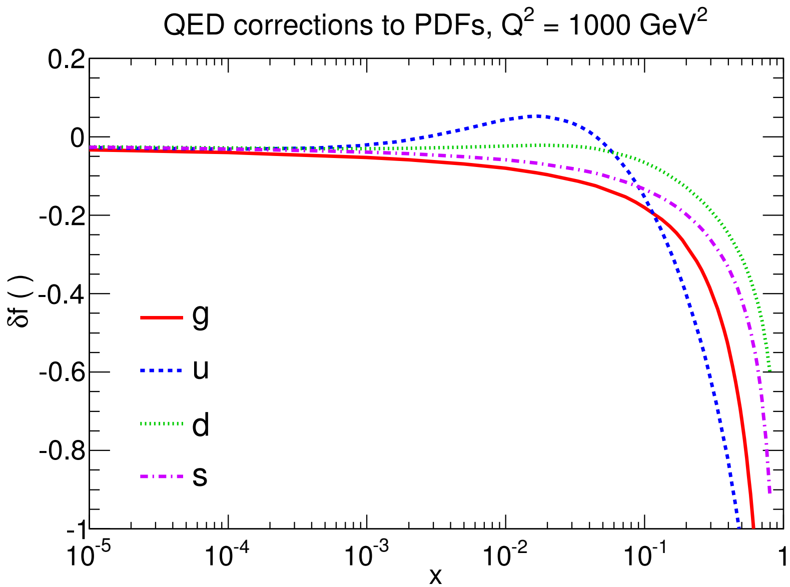
Charged current: $\mathrm{pp} \to \ell^+\nu_\ell$ at $\sqrt{s} = 14\,\mathrm{TeV}$ (based on Brensing et al. arXiv:0710.3309)

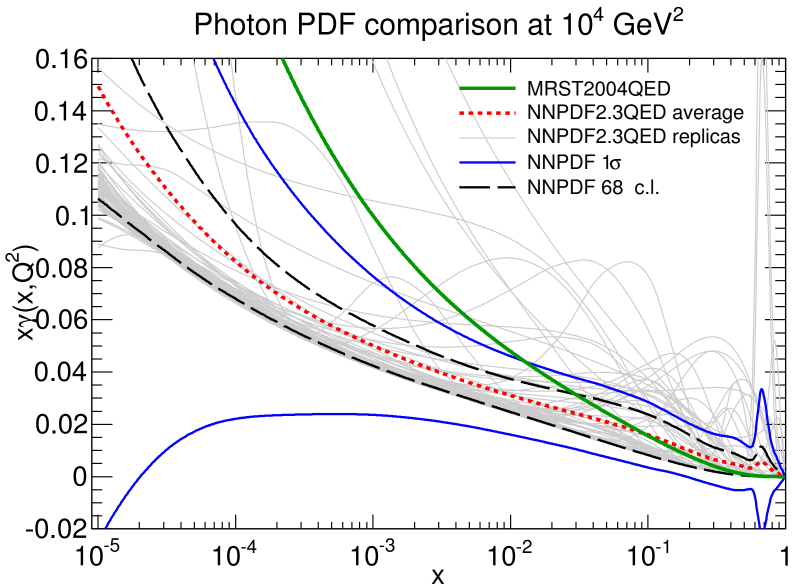
$M_{\mathrm{T},\nu_\ell\ell}/\mathrm{GeV}$	$50-\infty$	$100-\infty$	$200-\infty$	$500-\infty$	$1000-\infty$	$2000-\infty$
σ_0/pb	$4495.7(2)$	$27.589(2)$	$1.7906(1)$	$0.084697(4)$	$0.0065222(4)$	$0.00027322(1)$
$\delta^{\mu^+\nu_\mu}_{\mathrm{q\bar{q}}}/\%$	$-2.9(1)$	$-5.2(1)$	$-8.1(1)$	$-14.8(1)$	$-22.6(1)$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

Sudakov domination!

Electroweak effects in PDFs (continued)

NNPDF2.3QED PDF set



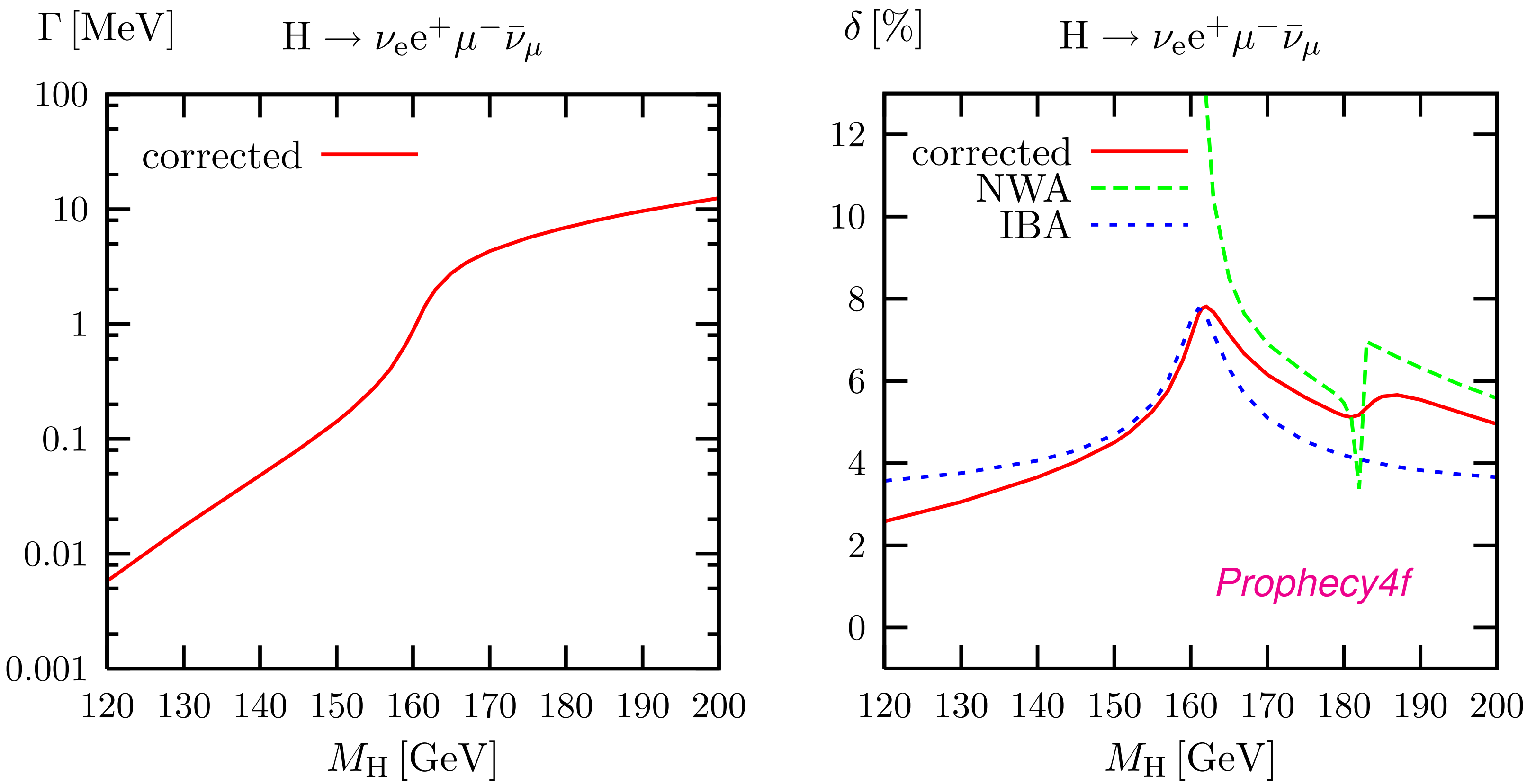


Photon PDF:

- agreement with old $\gamma_{\mathrm{MRST}}(x)$ for $x \gtrsim 0.03$, but $\gamma_{\mathrm{NNPDF}}(x) < \gamma_{\mathrm{MRST}}(x)$ for smaller x
- lack of experimental information for $x \gtrsim 0.1$
  $\hookrightarrow$ constrained via $\gamma\gamma \to \mu^+\mu^-, \mathrm{W^+W^-}$ for larger x in the future ?

Partial H width for $\mathrm{H} \to \mathrm{WW} \to \nu_e e^+ \mu^- \bar{\nu}_\mu$

Bredenstein, Denner, Dittmaier, Weber '06



$$\delta = \frac{\Gamma}{\Gamma_{\mathrm{Born}}} - 1$$

↑ Coulomb singularity at $M_\mathrm{H} \sim 2M_\mathrm{W}$

↑ threshold effect in loops at $M_\mathrm{H} \sim 2M_\mathrm{Z}$

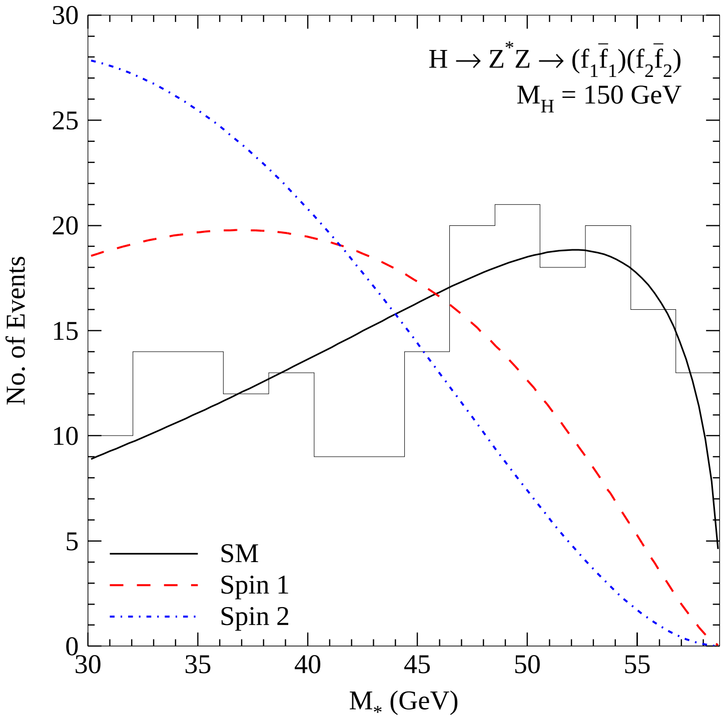
NWA = "narrow-width approximation" (on-shell W bosons)

IBA = "improved Born approximation" (universal corrections)

Corrections $\sim$ 4–8%, NWA not useful for $M_\mathrm{H} \lesssim 165\,\mathrm{GeV}$

Important distributions in $\mathrm{H} \to \mathrm{ZZ} \to f_1 \bar{f}_1 f_2 \bar{f}_2$

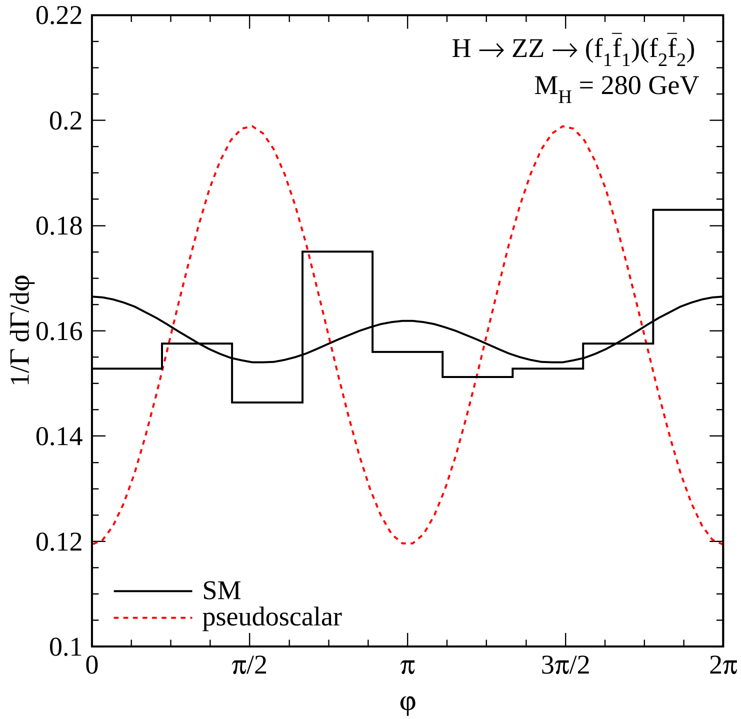
Invariant Z mass:

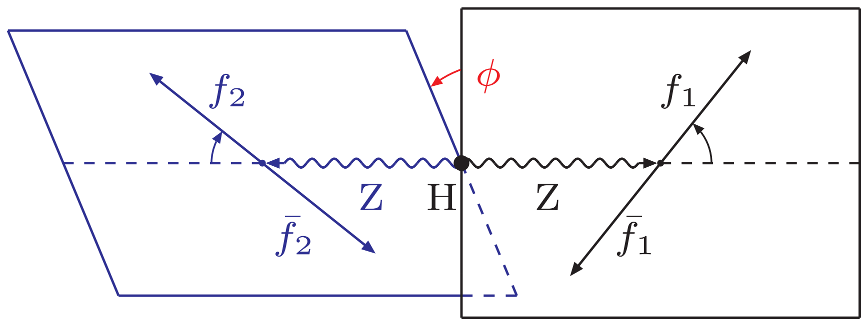


$$M_* = M_{f_1 \bar{f}_1}$$

Angle between Z decay planes:

Choi, Miller, Mühlleitner, Zerwas ’02



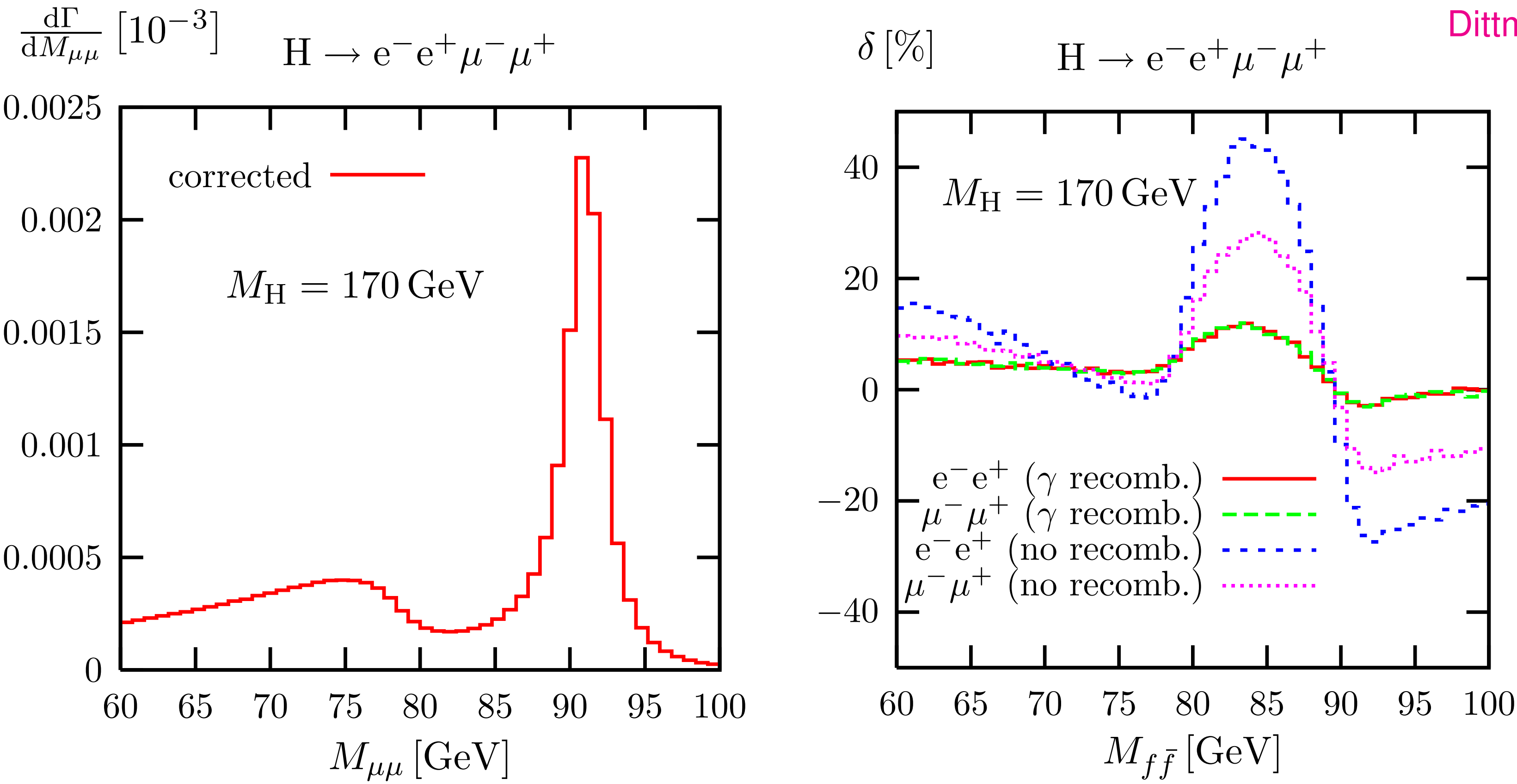


Histograms = SM simulation for $L = 300\,\mathrm{fb}^{-1}$

$\hookrightarrow$ distributions sensitive to spin and parity

Distribution of invariant Z mass in $\mathrm{H} \to \mathrm{ZZ} \to \mathrm{e^-e^+}\mu^-\mu^+$

Bredenstein, Denner, Dittmaier, Weber '06



Prophecy4f

γ recombination if $M_{\mathrm{e}\gamma/\mu\gamma} < 5\,\mathrm{GeV}$

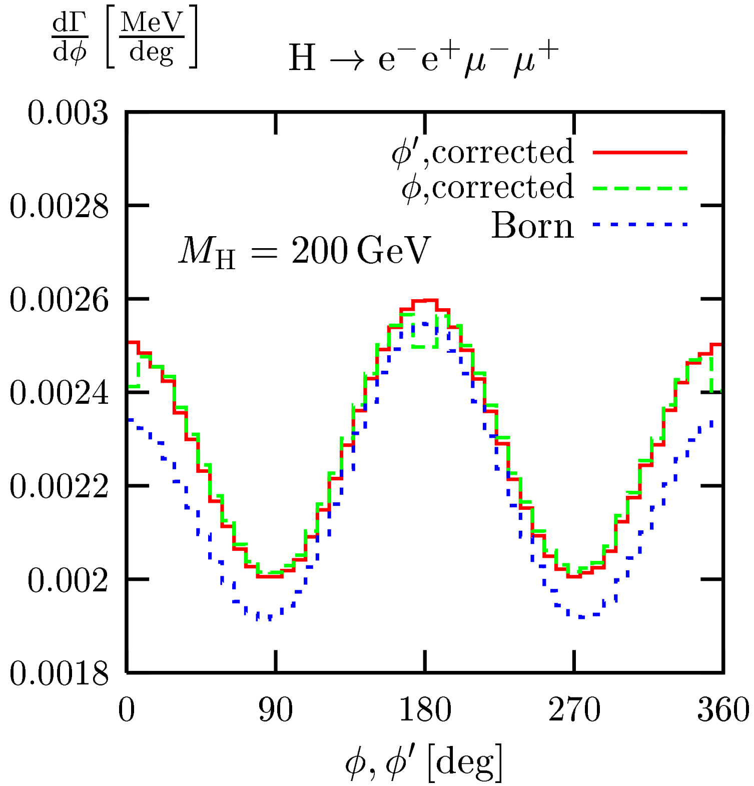
Large corrections due to photon emission in Z reconstruction

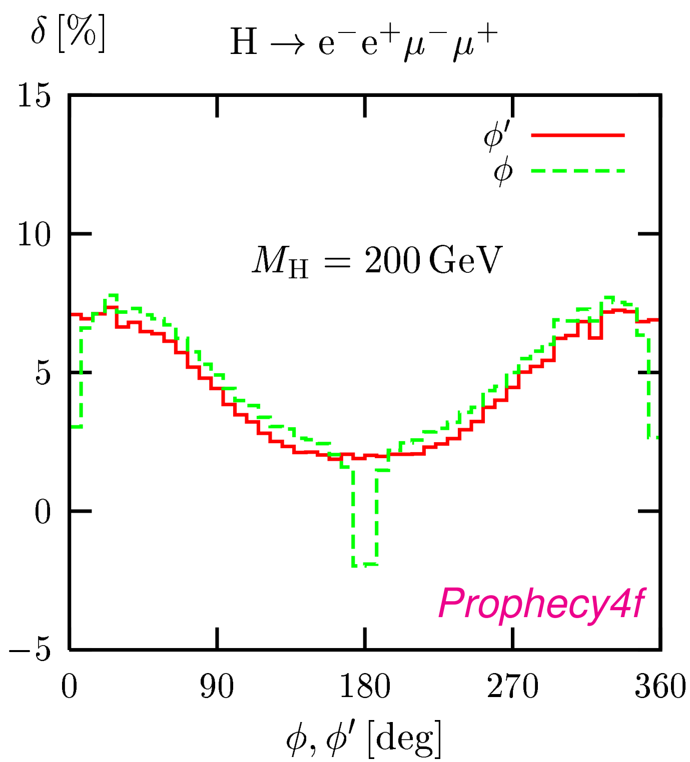
Corrections to distribution in angle between Z decay planes

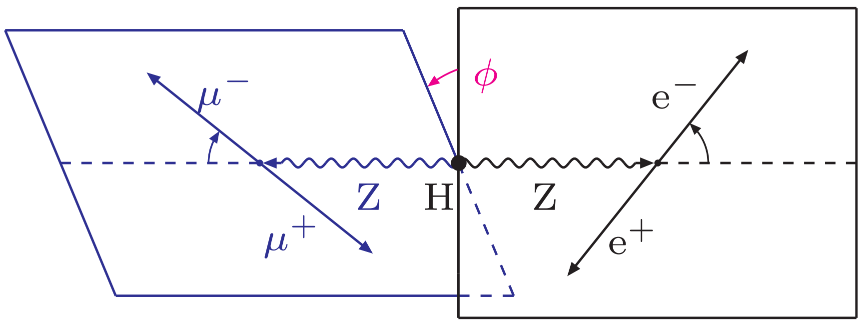
Bredenstein, Denner, Dittmaier, Weber '06

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

An example:







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

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

Total cross section: NNLO QCD and NLO EW corrections

LHC Higgs XS report
CERN-2011-002, arXiv:1101.0593 [hep-ph]

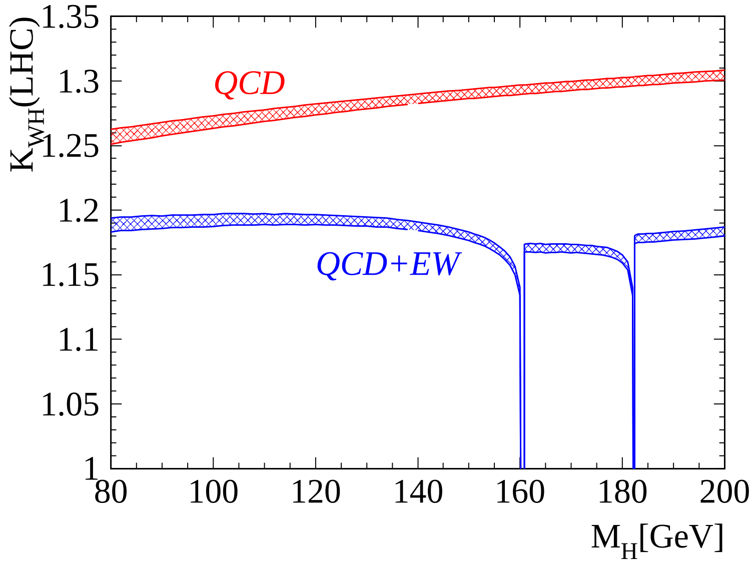
$$\sigma_{\mathrm{WH}} = \sigma_{\mathrm{WH}}^{\mathrm{VH@NNLO}} \times (1+\delta_{\mathrm{WH,EW}})$$

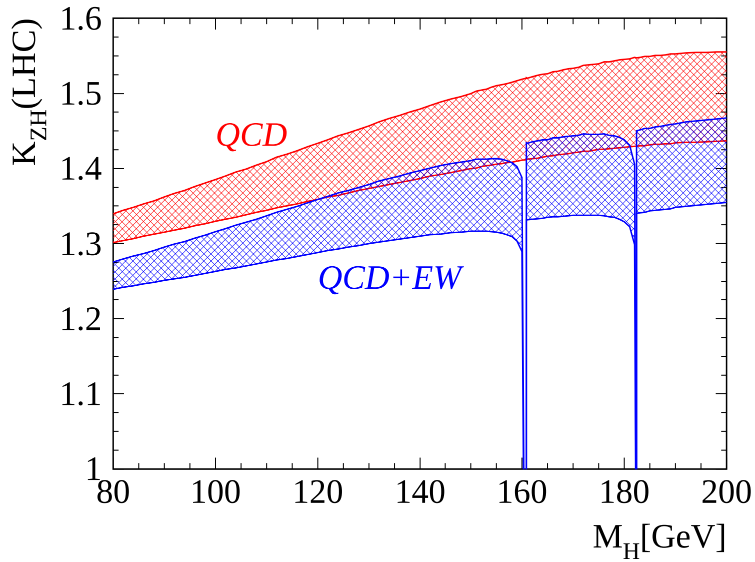
$$\sigma_{\mathrm{ZH}} = \sigma_{\mathrm{ZH}}^{\mathrm{VH@NNLO}} \times (1+\delta_{\mathrm{ZH,EW}}) + \sigma_{\mathrm{gg}\to\mathrm{ZH}}$$

Note:
$\delta_{\mathrm{VH,EW}}$ insensitive to PDFs !

K factors for $\mathrm{pp} \to \mathrm{VH} + X$ @ $\sqrt{s} = 14\,\mathrm{TeV}$:

Brein et al. & Ciccolini et al. ’04





- typical size of corrections: $\mathcal{O}(\alpha_s^2) \sim \mathcal{O}(\alpha) \sim 5\text{--}10\%$
- spikes at $M_\mathrm{H} = 2M_\mathrm{W}$ and $M_\mathrm{H} = 2M_\mathrm{Z}$
  = perturbative artifacts from WW/ZZ threshold
  $\hookrightarrow$ require inclusion of W/Z decays (see below)

Differential cross section: (N)NLO QCD and NLO EW corrections

LHC Higgs XS report
CERN-2012-002, arXiv:1201.3084 [hep-ph]

$$\mathrm{d}\sigma_{\mathrm{WH}} = \mathrm{d}\sigma_{\mathrm{WH}}^{\mathrm{VH@NNLO(DY)}} \times (1 + \delta_{\mathrm{WH,EW}})$$

$$\mathrm{d}\sigma_{\mathrm{ZH}} = \mathrm{d}\sigma_{\mathrm{ZH}}^{\mathrm{VH@NLO}} \times (1 + \delta_{\mathrm{ZH,EW}})$$

Again:
$\delta_{\mathrm{VH,EW}}$ insensitive to PDFs !

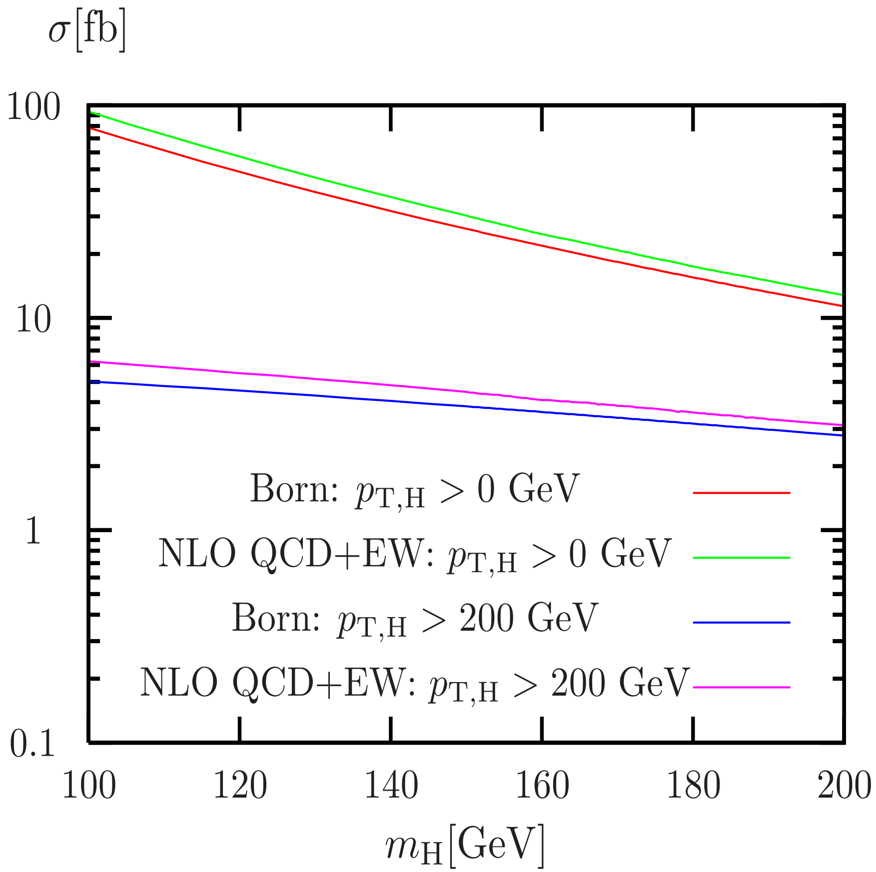
Features:

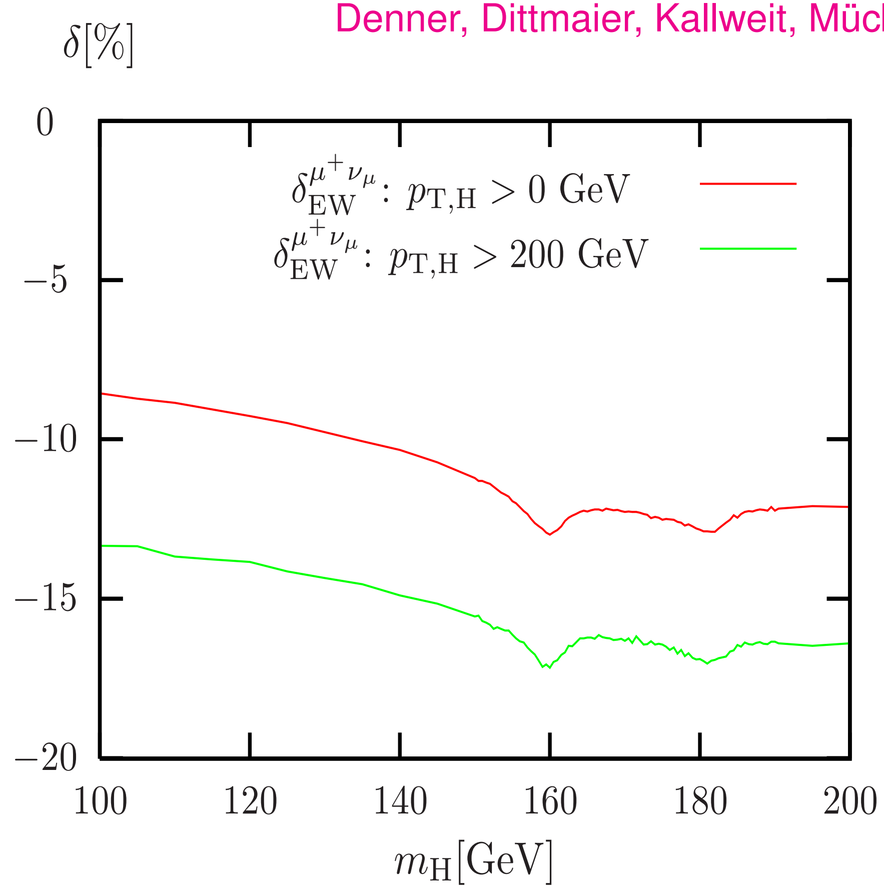
- NNLO QCD for WH/ZH in Drell–Yan-like approximation
  Ferrera, Grazzini, Tramontano '11,'14
- NLO EW (+QCD) calculated with HAWK
  Denner, Dittmaier, Kallweit, Mück '11
- size of corrections and TH uncertainties larger than for σ_{tot}

channel	$\mathrm{H}\ell^+\nu_\ell$	$\mathrm{H}\ell^-\bar{\nu}_\ell$	$\mathrm{H}\ell^+\ell^-$	$\mathrm{H}\nu_\ell\bar{\nu}_\ell$
$\delta_{\mathrm{EW}}^{\mathrm{bare}}/\%$	-14	-14	-11	-7
$\Delta_{\mathrm{PDF}}/\%$	±5	±5	±5	±5
$\Delta_{\mathrm{scale}}/\%$	±2	±2	±2	±2
$\Delta_{\mathrm{HO}}/\%$	±1	±1	±7	±7

NLO EW corrections to the integrated cross section of $\mathrm{pp} \to \mathrm{H}\ell^+\nu_\ell + X$

Denner, Dittmaier, Kallweit, Mück '11

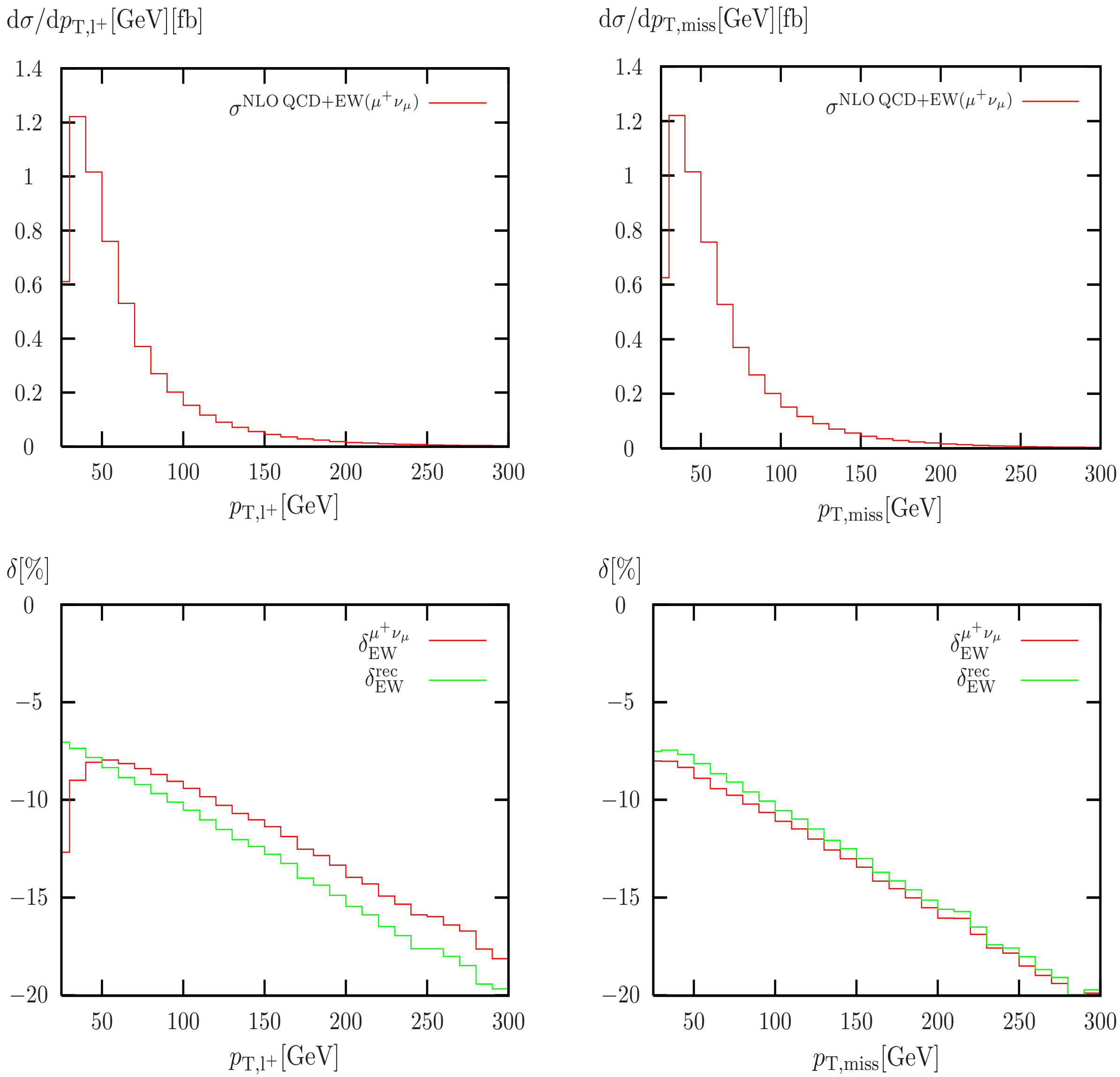




- sound behaviour of δ_{EW} near WW/ZZ thresholds
- size of EW corrections increases for boosted-Higgs scenario wrt σ_{tot} !

NLO EW corrections to $p_{\mathrm{T},\ell}$ and $p_{\mathrm{T,miss}}$ distributions for $\mathrm{pp} \to \mathrm{H}\ell^{+}\nu_{\ell} + X$

Denner, Dittmaier, Kallweit, Mück ’11



“bare muons”: no γ recombination

$\hookrightarrow$ collinear μ and γ assumed separable

$\hookrightarrow$ mass-singular corrections $\propto \alpha \ln m_{\mu}$

“rec”: recombination of collinear γ

$\hookrightarrow$ collinear $\mu\gamma \;=\; \widetilde{\mu\gamma}$ quasiparticle

$\hookrightarrow$ no mass-singular corrections

$\hookrightarrow$ EW corrections mostly of non-universal origin (not simply FSR!)