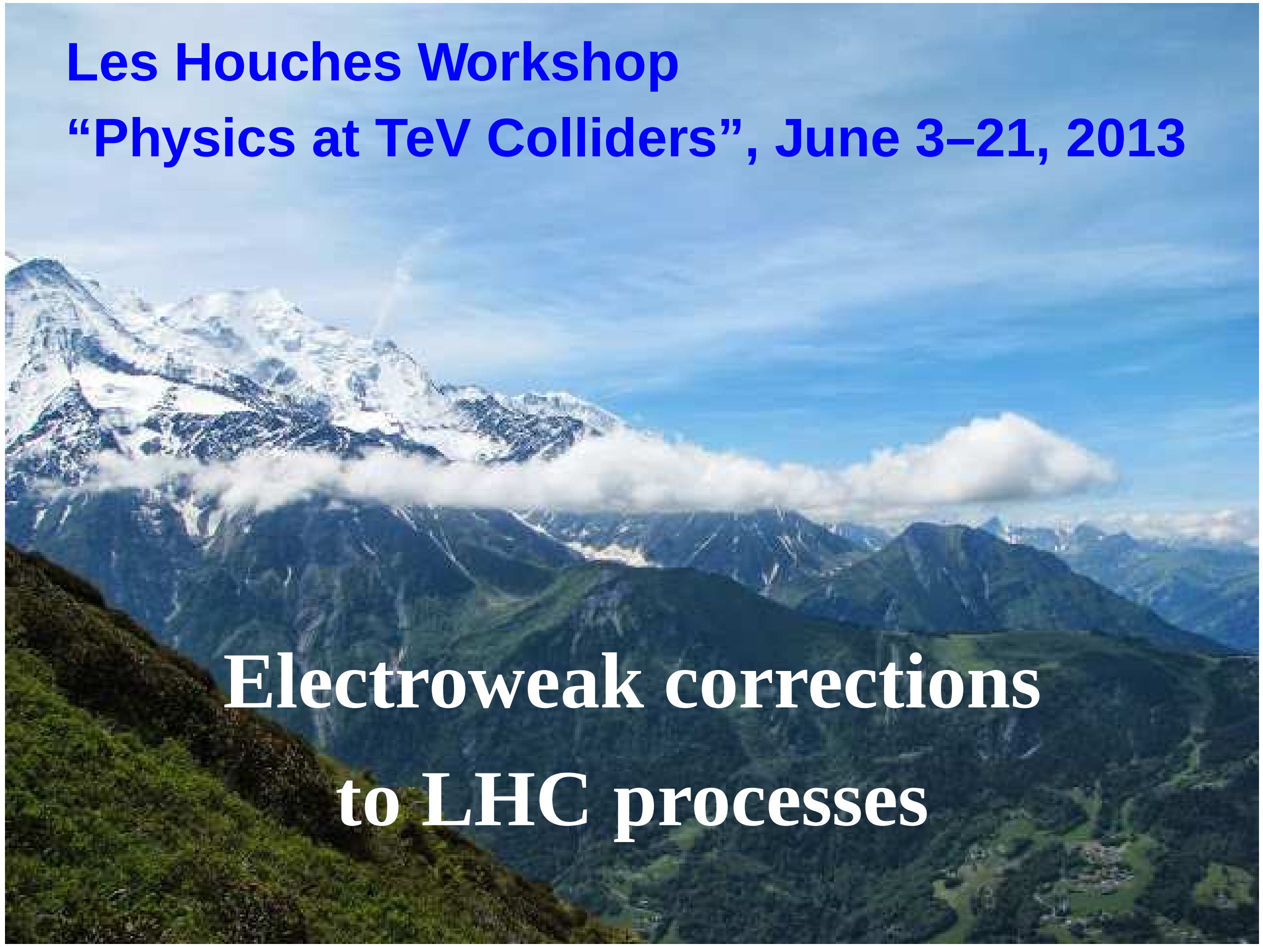


Les Houches Workshop
“Physics at TeV Colliders”, June 3–21, 2013

Electroweak corrections to LHC processes

Stefan Dittmaier
Albert-Ludwigs-Universität Freiburg

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

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

Instability of Higgs boson(s)

- small off-shell effects 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 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

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

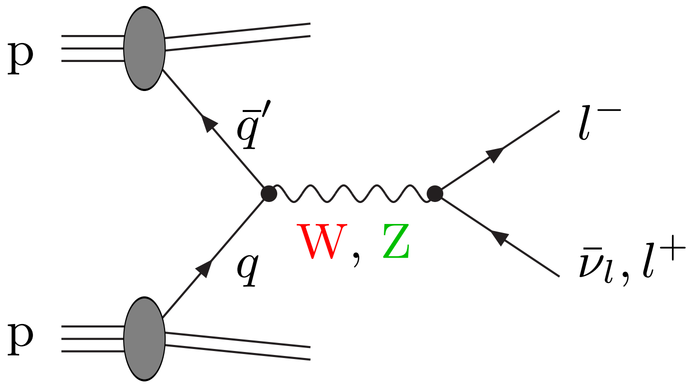
Since 2004: MRST2004QED set of $\mathcal{O}(\alpha)$-corrected PDFs Martin, Roberts, Stirling, Thorne '04

- additional real corrections from photons in initial state
  $\hookrightarrow$ typically $\mathcal{O}(1\%)$, but with large uncertainties
- uncertainty of γ PDF $\sim$ $\mathcal{O}(20\%)$ or more
- But: MRST2004QED outdated
  $\hookrightarrow$ recipe: use only γ PDF from MRST2004QED, but other PDFs from state-of-the-art PDFs

Electroweak corrections

... Drell–Yan-like W/Z production

W- and Z-boson production at hadron colliders



Physics goals:

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

NLO EW corrections to W/Z production:

- NLO EW correction to W production — S.D., Krämer '01; Zykunov '01; Baur, Wackeroth '04; Arbuzov et al. '05 Carloni Calame et al. '06; S.D./Huber '09
- NLO EW correction to Z production — Baur, Keller, Sakumoto '97; Baur, Wackeroth '99 Brein, Hollik, Schappacher '99; Zykunov '05; Arbuzov et al. '06; Carloni Calame et al. '07; S.D., Huber '09
- multi-photon radiation via leading logs — Baur, Stelzer '99; Carloni Calame et al. '03 Placzek, Jadach '04; Brensing et al. '07; S.D., Huber '09
- photon-induced processes — Arbuzov, Sadykov '07; Brensing et al. '07; Carloni Calame et al. '07; S.D., Huber '09
- POWHEG matching of QCD/EW corrections — Bernaciak, Wackeroth '12; Barze et al. '13
- NLO SUSY corrections in the MSSM — Brensing et al. '07; S.D., Huber '09
- steps towards $\mathcal{O}(\alpha\alpha_{\mathrm{s}})$ corrections (virtual corrections) — Bonciani '11

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

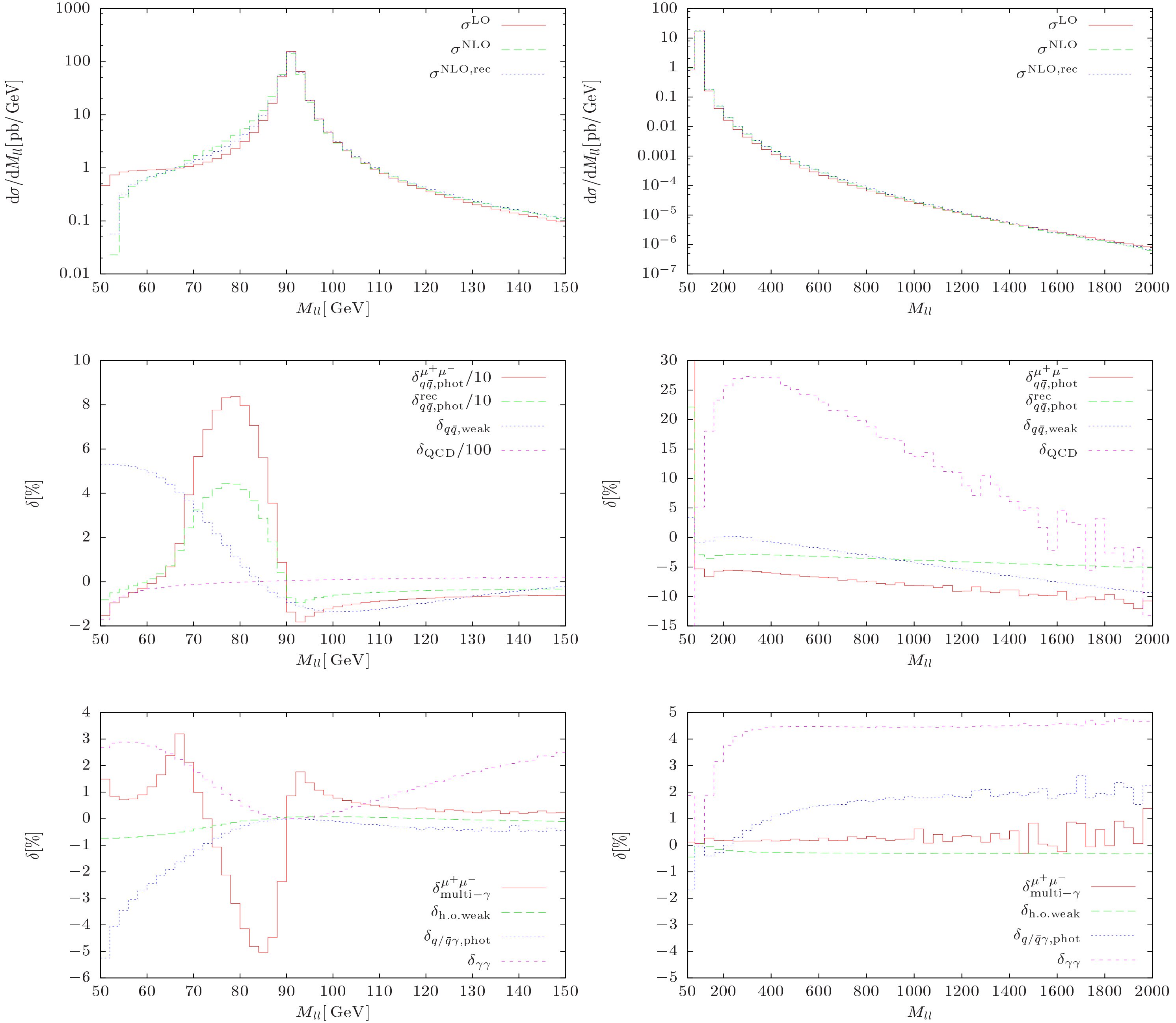
$M_{\mathrm{T},\nu_l l}/\mathrm{GeV}$	$50-\infty$	$100-\infty$	$200-\infty$	$500-\infty$	$1000-\infty$	$2000-\infty$
σ_0/pb						
DK	$2112.2(1)$	$13.152(2)$	$0.9452(1)$	$0.057730(5)$	$0.0054816(3)$	$0.00026212(1)$
$\delta_{\mu^+\nu_\mu}/\%$						
DK	$-2.75(1)$	$-5.03(2)$	$-7.98(1)$	$-14.43(1)$	$-21.99(1)$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

Comments:

- Large corrections at transverse / invariant W/Z masses (EW Sudakov logs, etc.)
- technical agreement between NLO EW results of different groups good ($\sim 0.1\%$)
  $\hookrightarrow$ ongoing tuned comparison within LPCC "LHC EW Working Group"
- relevance of photon-induced processes for photon PDF ?!
- relevance of $\mathcal{O}(\alpha\alpha_\mathrm{s})$ corrections for M_W determination ?!

Corrections to Z production – overview

S.D., Huber ’09



$\gamma\gamma \to l^+l^-$ – a handle on the photon PDF ?

Impact of $\gamma\gamma$ and $q\gamma$ channels enhanced above Z pole !

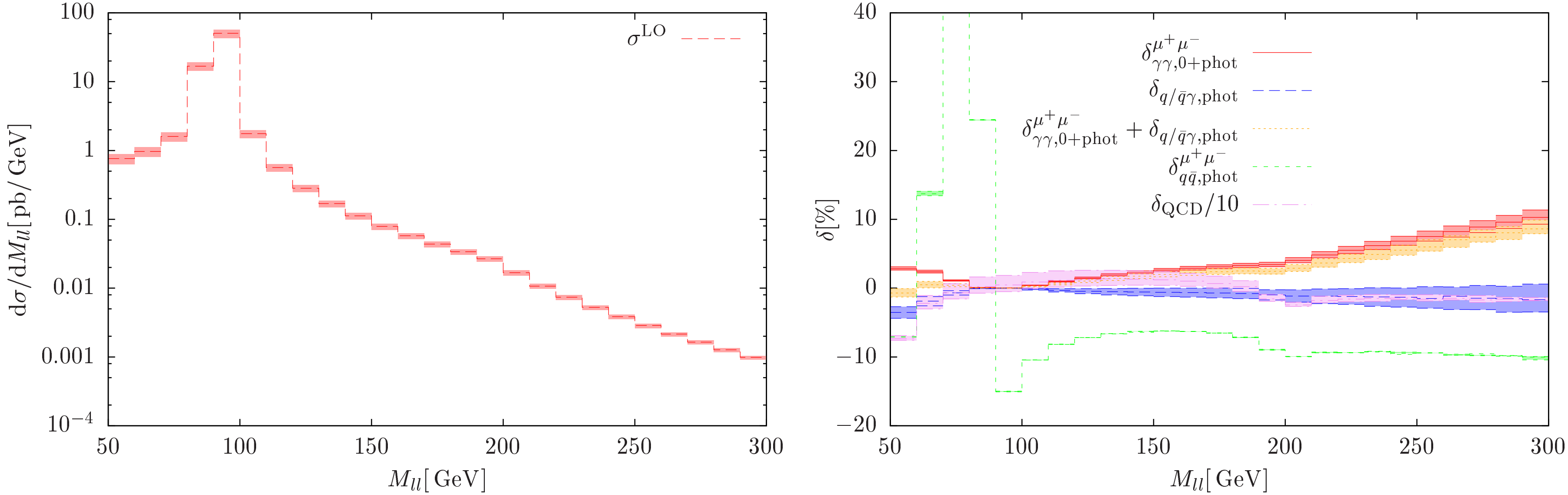
Note: $\gamma\gamma$ channel prefers scattering angles $\theta^* \to 0, \pi$!

LO kinematics: $M_{ll} = \sqrt{\hat{s}}, \quad p_{\mathrm{T},l} = \frac{1}{2}\sqrt{\hat{s}}\sin\theta^* = \frac{1}{2}M_{ll}\sin\theta^*$

$\hookrightarrow$ Enhance $\gamma\gamma$ channel by cuts on $p_{\mathrm{T},l}$?!

Scenario (c): $p_{\mathrm{T},l^\pm} < 100\,\mathrm{GeV}$

S.D., Huber '09



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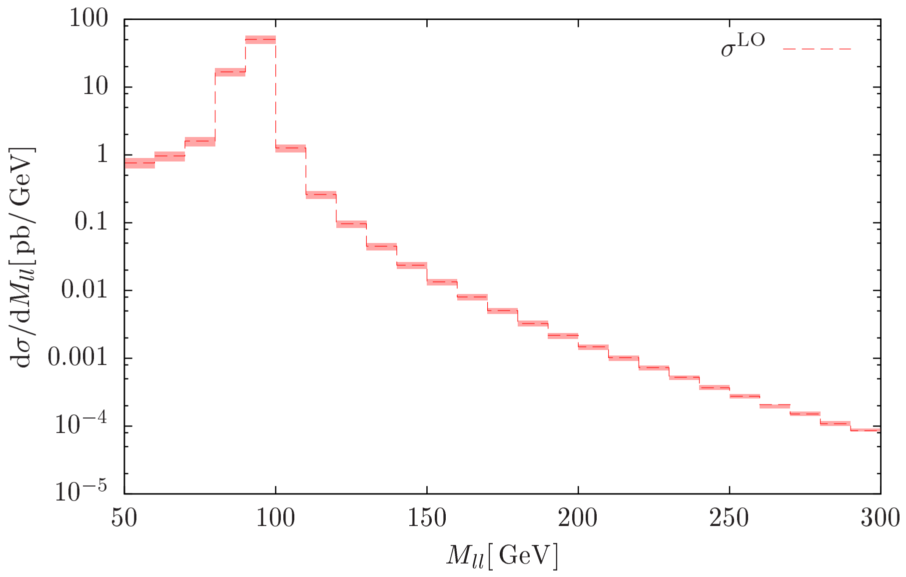
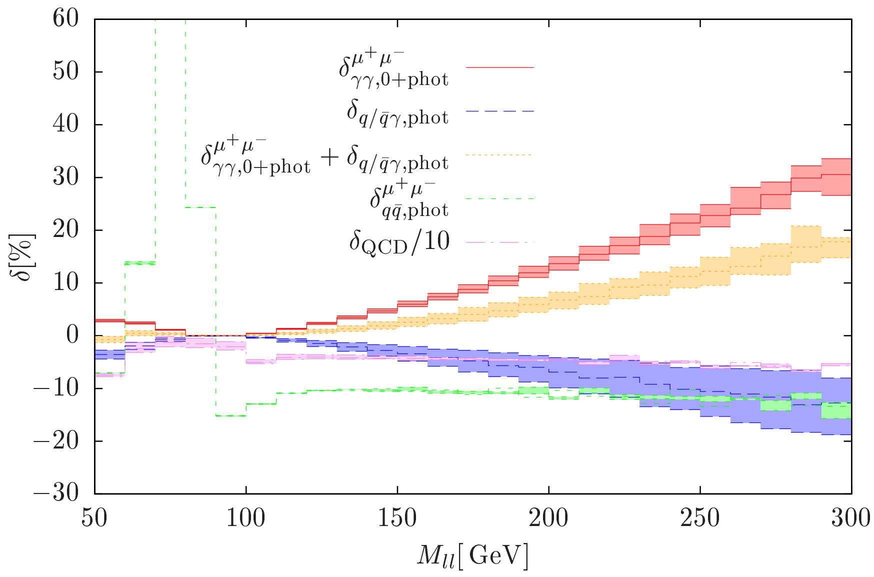
$\hookrightarrow$ Enhance $\gamma\gamma$ channel by cuts on $p_{\mathrm{T},l}$?!

Scenario (b): $p_{\mathrm{T},l^\pm} < 50\,\mathrm{GeV}$

S.D., Huber '09





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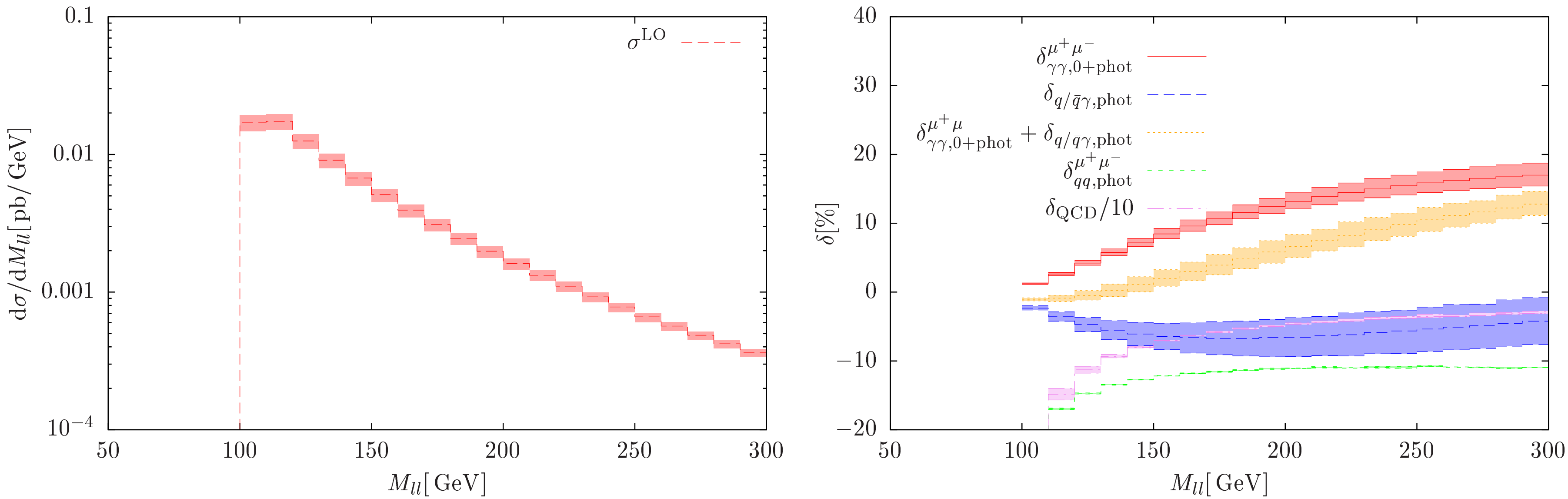
$\hookrightarrow$ Enhance $\gamma\gamma$ channel by cuts on $p_{\mathrm{T},l}$?!

Scenario (a): $p_{\mathrm{T},l^\pm} < M_{ll}/4 \quad (\sin\theta^* < \frac{1}{2}$ in LO) S.D., Huber '09



Combination of NLO QCD and EW corrections

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

Comparison of two extreme alternatives:

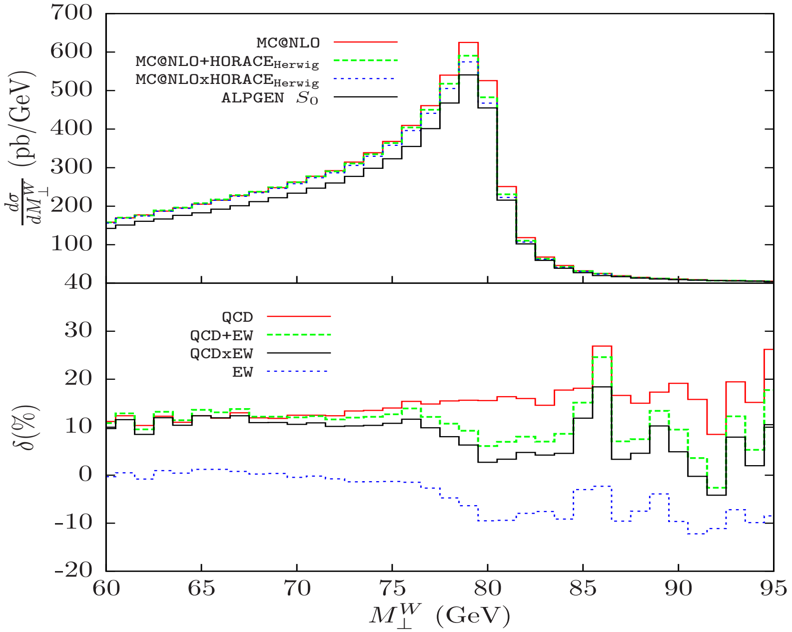
$$(1 + \delta_{\rm QCD}^{\rm NLO} + \delta_{\rm EW}^{\rm NLO})$$

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



NLO EW corrections to W/Z production with additional hard jets

NLO QCD + EW completely known

- for off-shell W/Z bosons including decays
- with photon-induced processes
- with proper γ/jet separation (photon fragmentation function)

In detail:

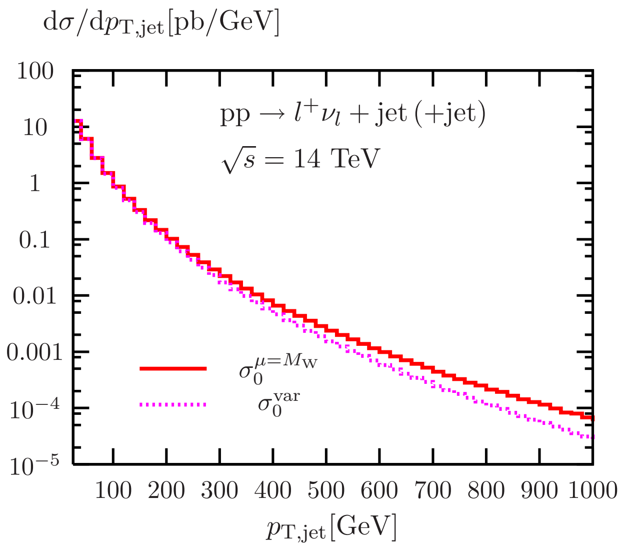
- W bosons:
  - $\mathrm{W}+1\,\mathrm{jet}$, stable W boson — Kühn, Kulesza, Pozzorini, Schulze ’07; Hollik, Kasprzik, Kniehl ’07
  - $\mathrm{W}+1\,\mathrm{jet} \to l\nu_l + 1\,\mathrm{jet}$ — Denner, S.D., Kasprzik, Mück ’09
  - no results yet on $\mathrm{W}+\geq 2\,\mathrm{jets}$

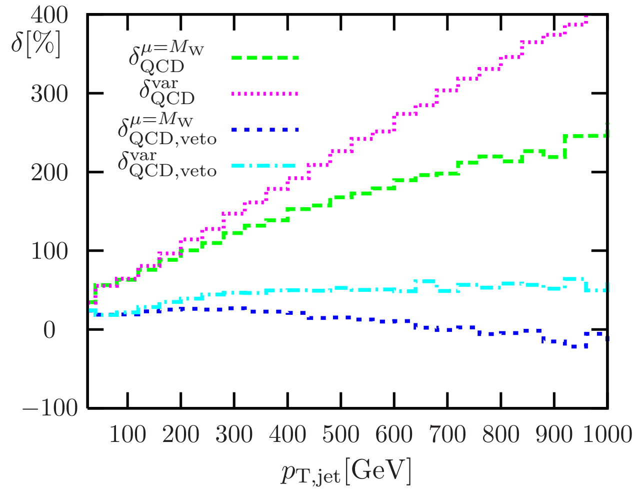
- Z bosons:
  - $\mathrm{Z}+1\,\mathrm{jet}$, stable Z boson — Maina, Moretti, Ross ’04; Kühn, Kulesza, Pozzorini, Schulze ’04
  - $\gamma + 1\,\mathrm{jet}$ — Maina, Moretti, Ross ’04; Kühn, Kulesza, Pozzorini, Schulze ’05
  - $\mathrm{Z}/\gamma^* + 1\,\mathrm{jet} \to l^+l^- + 1\,\mathrm{jet}$ — Denner, S.D., Kasprzik, Mück ’11
  - $\mathrm{Z}+1\,\mathrm{jet} \to \bar{\nu}_l\nu_l + 1\,\mathrm{jet}$ — Denner, S.D., Kasprzik, Mück ’12
  - $\mathrm{Z}+2\,\mathrm{jets}$, stable Z boson — Actis et al. ’12
  - no results yet on $\mathrm{Z}+\geq 3\,\mathrm{jets}$

Transverse-momentum distribution of the hardest jet

QCD corrections:

Denner et al. '09



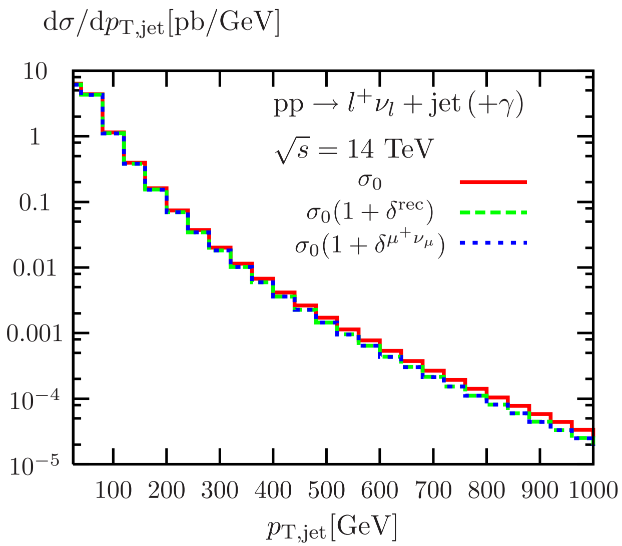


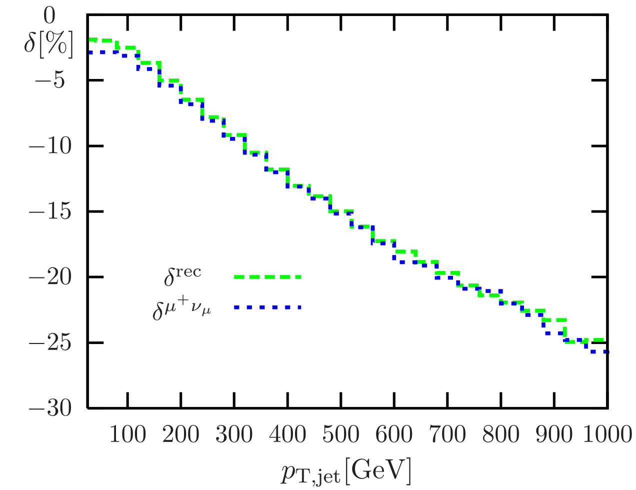
Large positive corrections from W+2jets (mainly back-to-back jets)

↪ significant reduction of corrections via jet veto

EW corrections:

Denner et al. '09



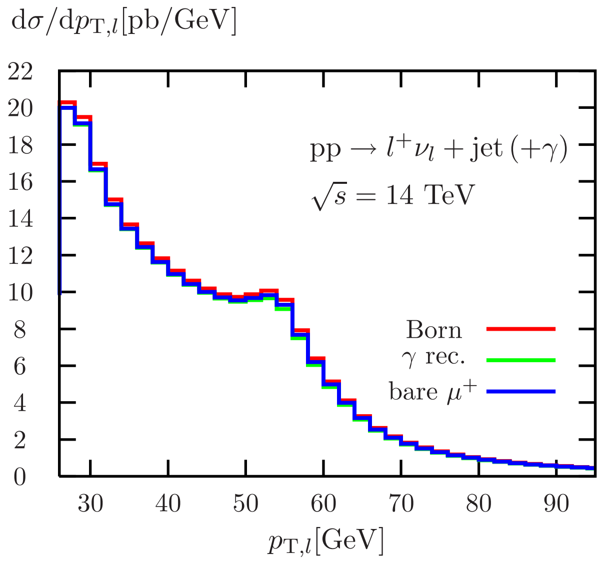


Large neg. corrections due to EW Sudakov logs

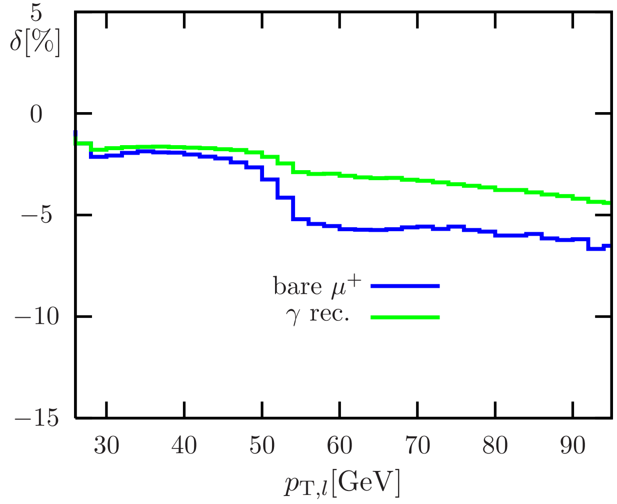
↪ qualitative agreement with previous results for on-shell Ws Kühn et al. '07 Hollik et al. '07

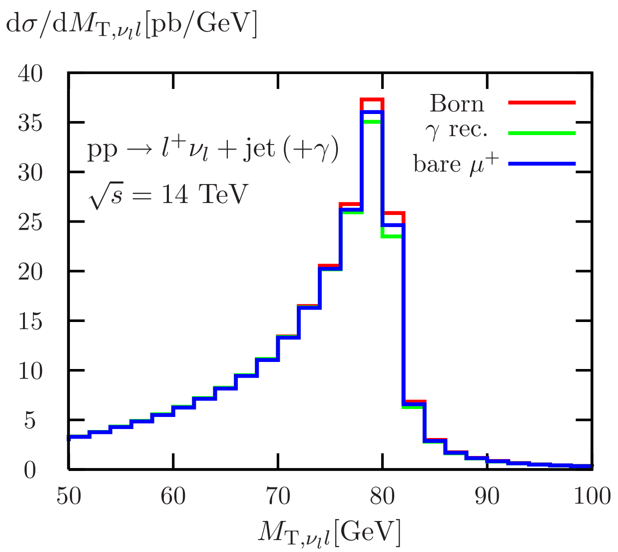
Comparison of EW corrections to W+jet and single (jet-inclusive) W production

$\hookrightarrow$ interesting for W-mass determination via single-W production

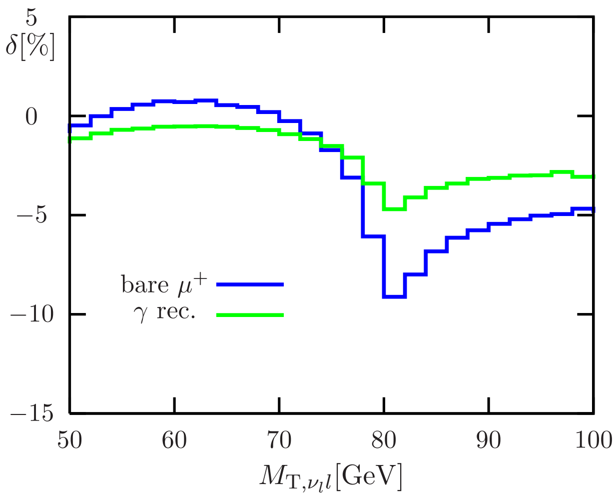


Denner et al. '09





Denner et al. '09



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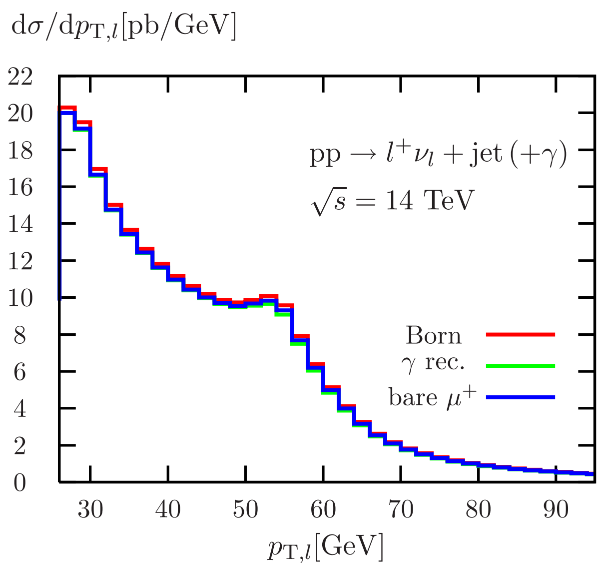
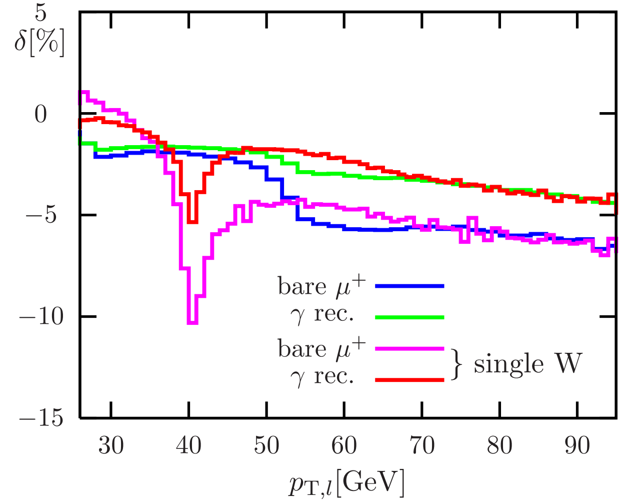


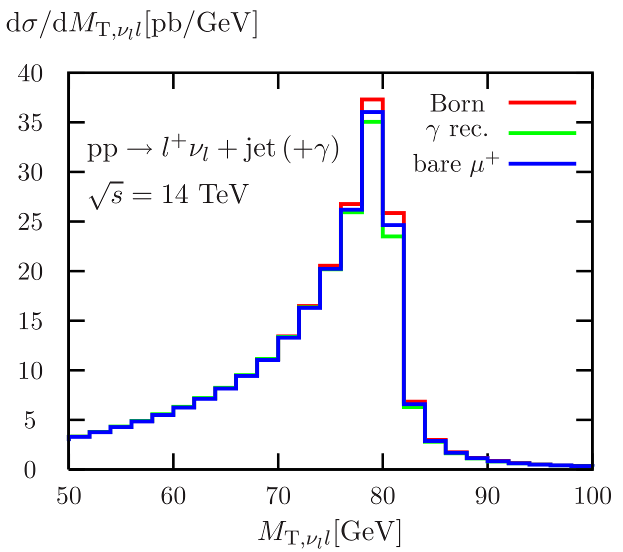
Denner et al. ’09



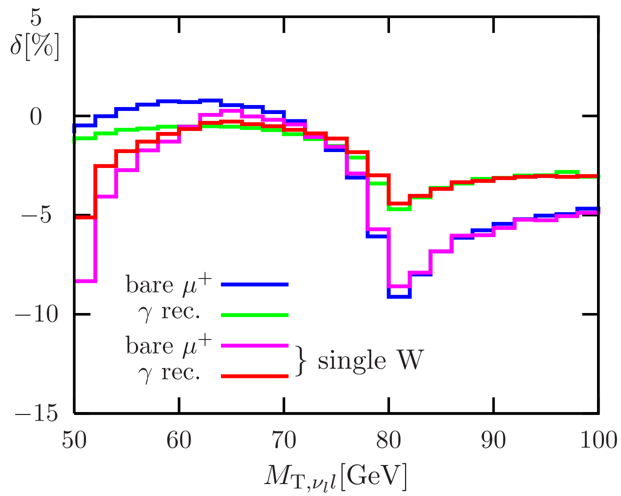
relative EW corrections
completely different

For single-W in NLO EW, see

Baur et al. ’98/’04
S.D./Krämer ’01
Arbuzov et al. ’06
Carloni Calame et al. ’06



Denner et al. ’09



relative EW corrections
practically identical
near Jacobian peak

Electroweak corrections

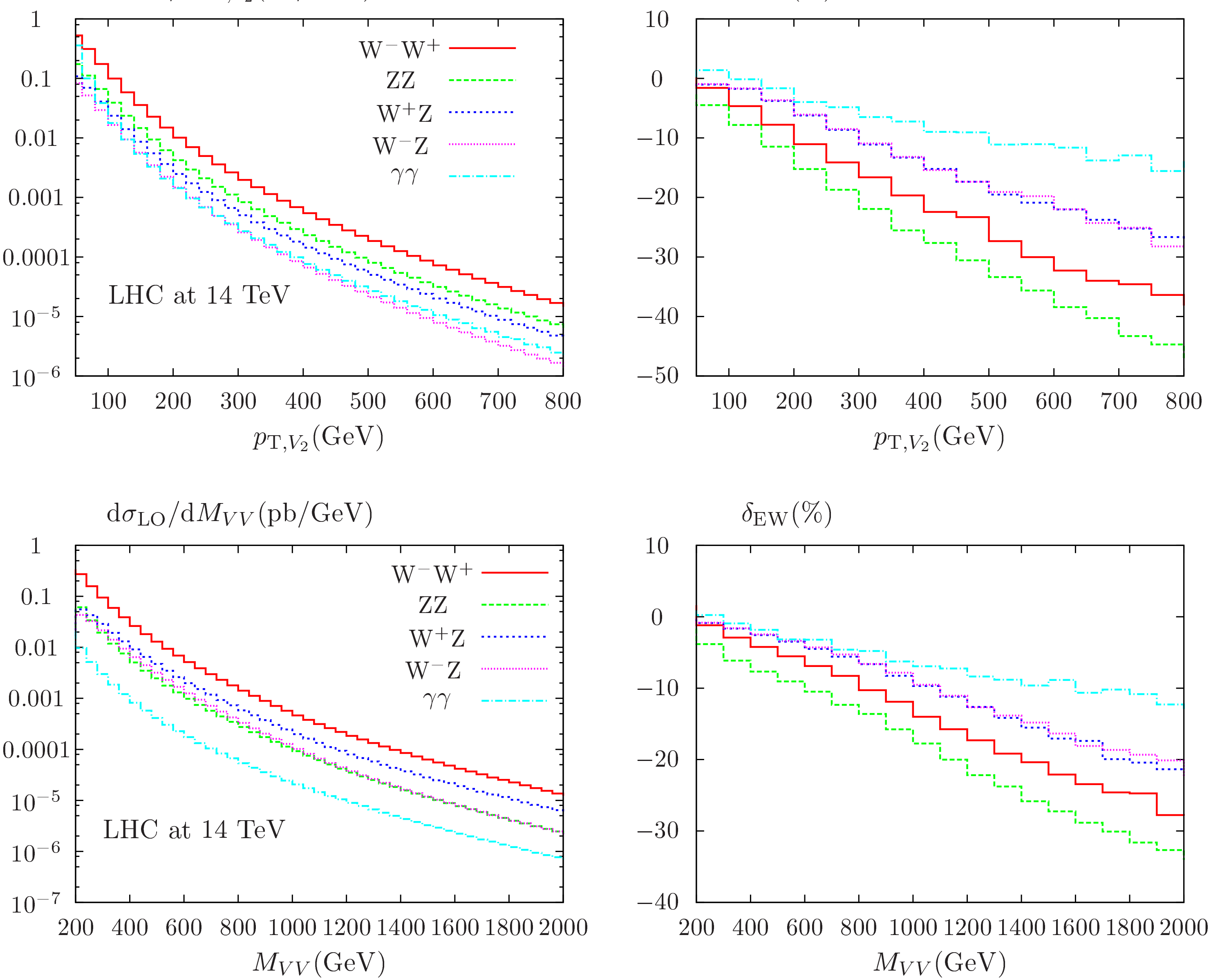
... to di-boson production

NLO EW corrections to EW di-boson production

- $\mathrm{W}\gamma \to l\nu_l + \gamma$
  - ◇ high-energy approximation Accomando, Denner, Pozzorini '01
  - ◇ W decay in leading pole approximation Accomando, Denner, Meier '05
- $\mathrm{Z}\gamma$
  - ◇ stable Z boson Hollik, Meier '04
  - ◇ $\mathrm{Z}\gamma \to l^+l^-/\nu_l\bar{\nu}_l + \gamma$, Z decay in leading pole approximation
    Accomando, Denner, Meier '05
- $\mathrm{WW}, \mathrm{WZ}, \mathrm{ZZ}$
  - ◇ high-energy approximation, stable W/Z bosons Accomando, Denner, Pozzorini '01; Accomando, Denner, Kaiser '04
  - ◇ full NLO (with LO $\gamma\gamma \to \mathrm{WW}$), stable W/Z bosons Bierweiler, Kasprzik, Kühn '12/'13
  - ◇ no EW corrections with W/Z decays yet

EW corrections to massive di-boson production

Bierweiler, Kasprzik, Kühn ’13



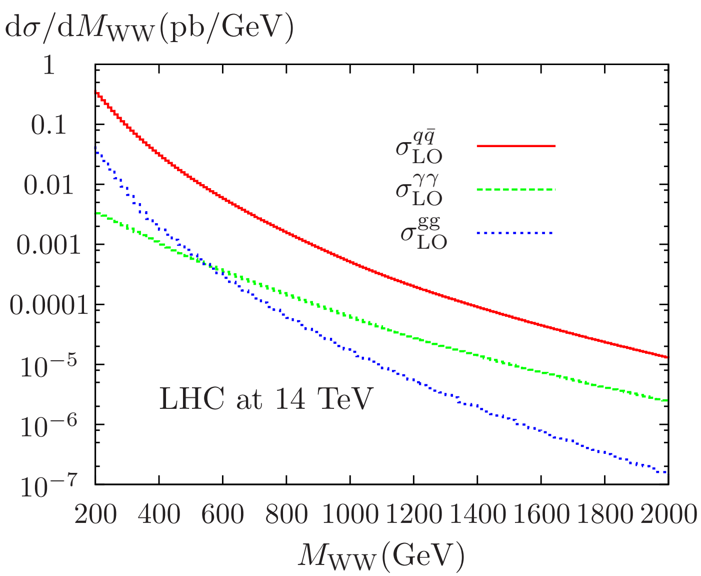
EW corrections

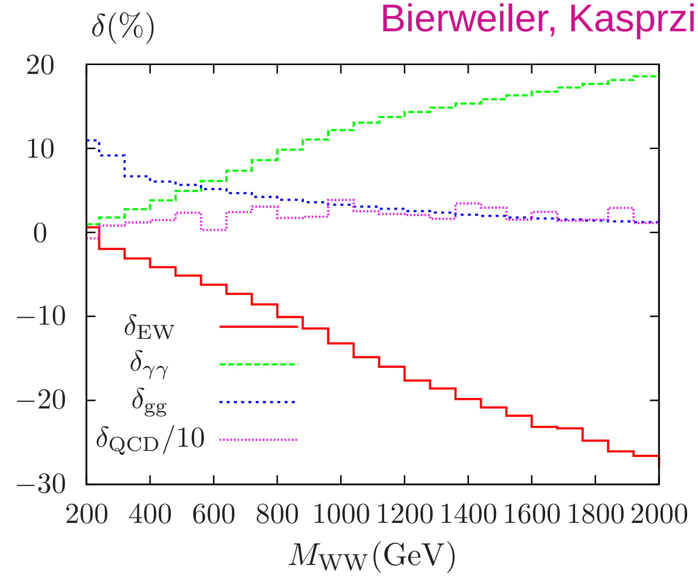
- small for integrated XS
- growing in distributions for larger scales

Distortion of distributions can mimick anomalous couplings !

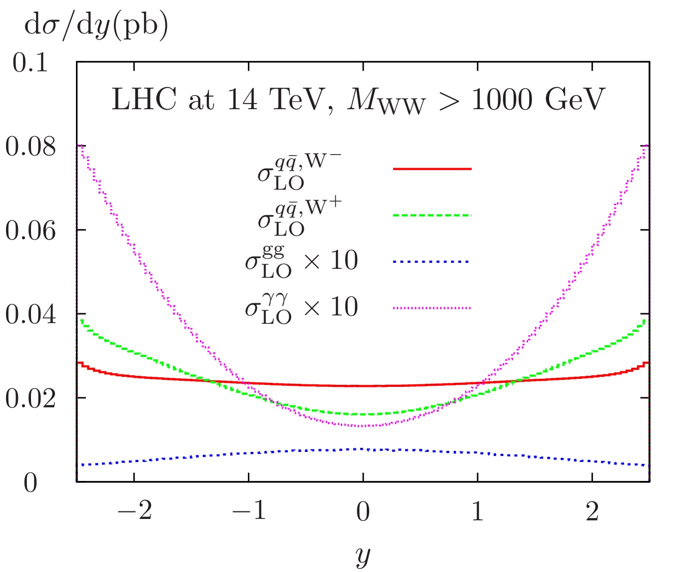
Survey of corrections to WW production

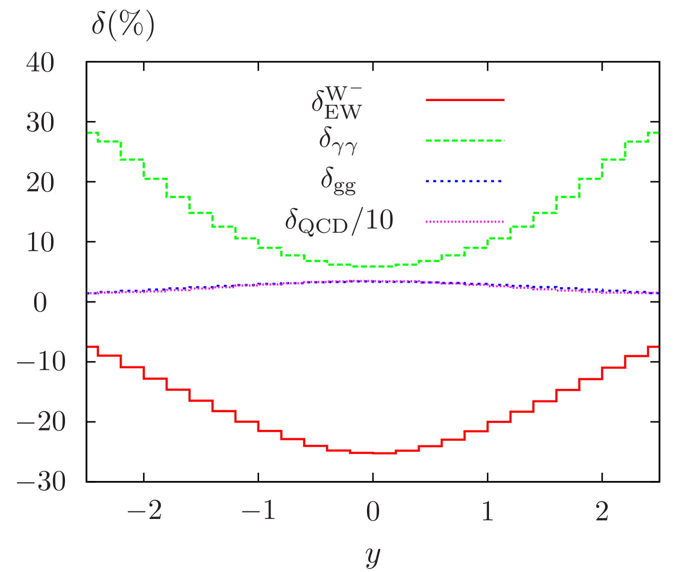
Bierweiler, Kasprzik, Kühn ’12





Note:
large contribution by
$\gamma\gamma$ channel for high
invariant WW masses !





Electroweak corrections

... to jet and heavy-quark production

NLO EW corrections to jet and heavy-quark production

- $\mathrm{pp} \to 2\,\mathrm{jets}$ Moretti, Nolten, Ross '05,'06; Scharf (prelim.) '09; S.D., Huss, Speckner '12

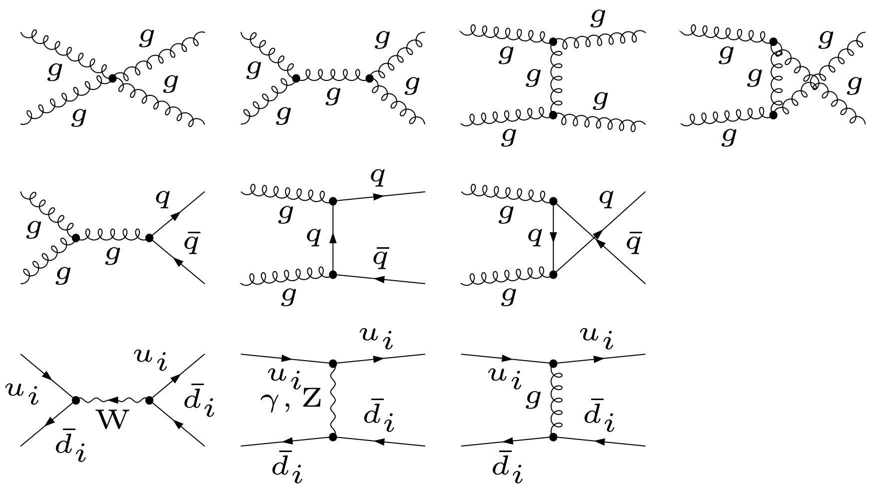
  no EW corrections available for $\mathrm{pp} \to \geq 3\,\mathrm{jets}$

- $\mathrm{pp} \to \mathrm{t\bar{t}}$
  - ◇ SM correction — Beenakker et al. '94; Moretti, Nolten, Ross '06; Kühn, Scharf, Uwer '06,'13; Bernreuther, Fücker, Si '08; Hollik, Kollar '08
  - ◇ THDM and MSSM — Hollik, Mösle, Wackeroth '97
  - ◇ no EW corrections with top-quark decays yet

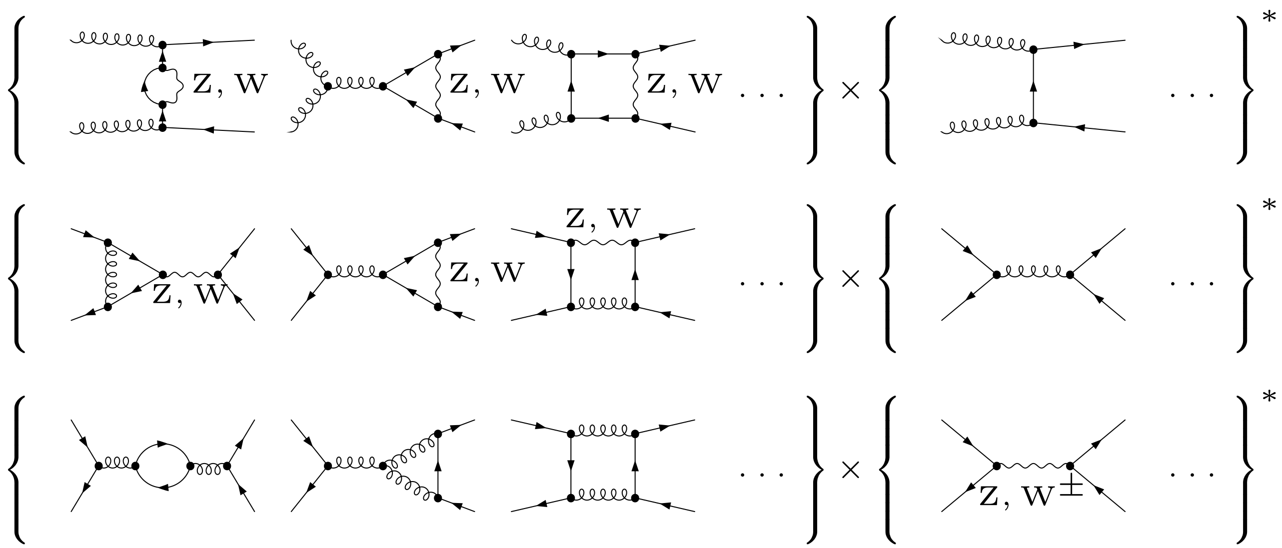
- $\mathrm{pp} \to \mathrm{b\bar{b}}$ Maina, Moretti, Nolten, Ross '03; Kühn, Scharf, Uwer '09

EW corrections to dijet production – typical contributions

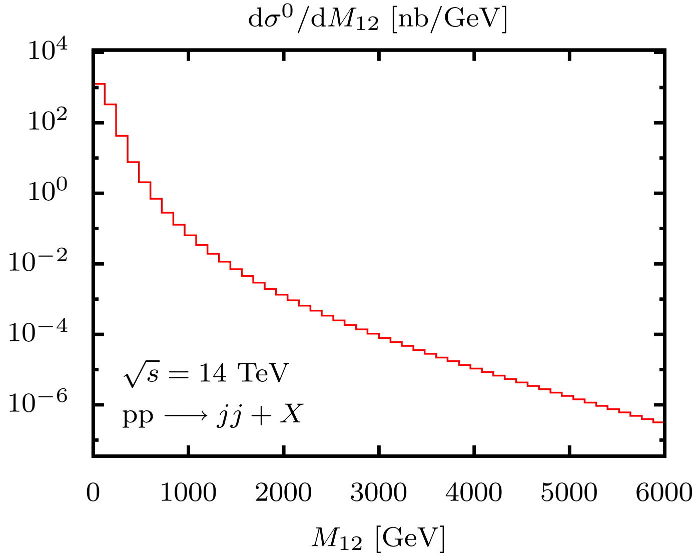
Tree contributions: $\mathcal{O}(\alpha_s^2)$, $\mathcal{O}(\alpha_s\alpha)$, $\mathcal{O}(\alpha^2)$

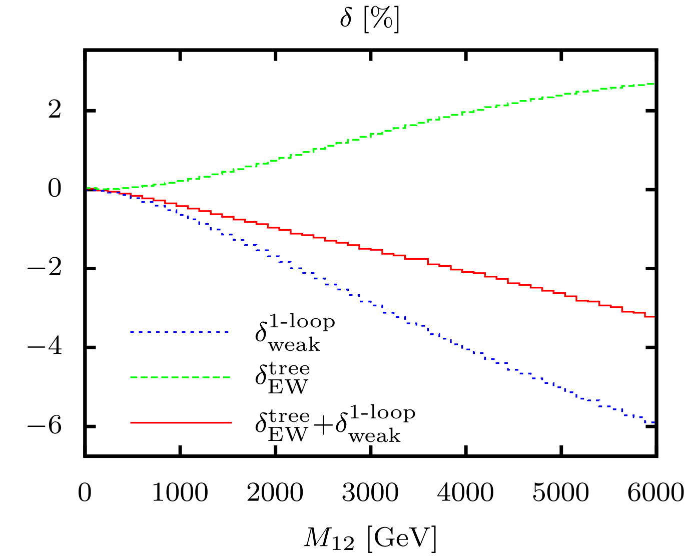


Loop contributions: $\mathcal{O}(\alpha_s^2\alpha)$



Weak corrections to dijet production – numerical results

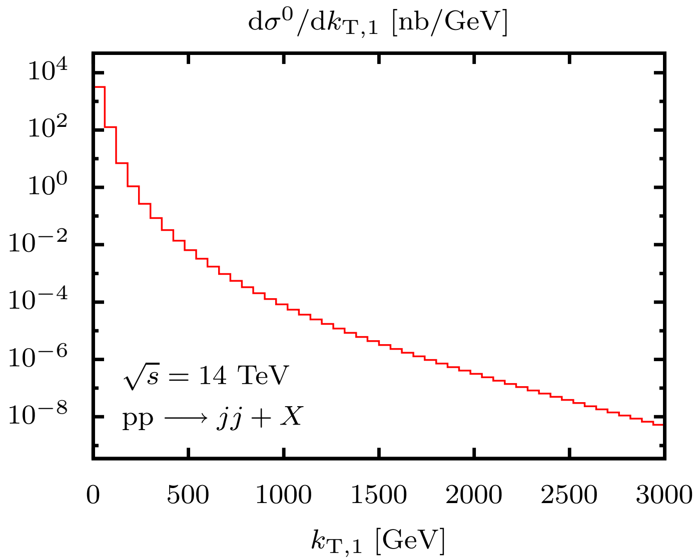


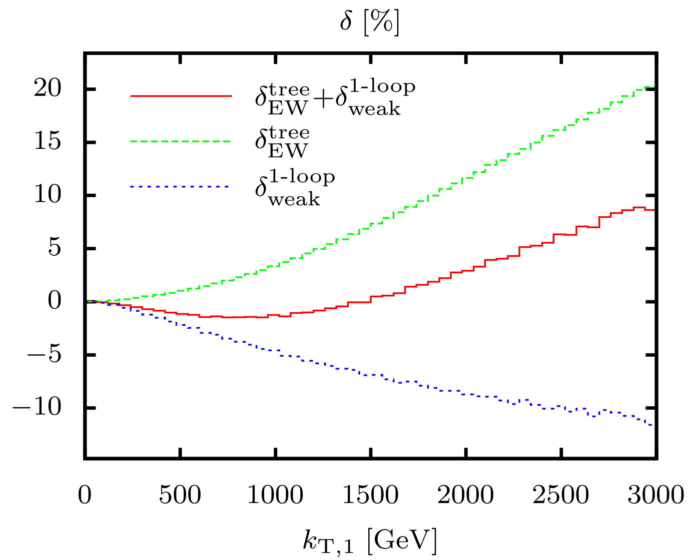


S.D., Huss, Speckner '12

Weak corrections

- small for integrated XS
- growing in distributions for larger scales

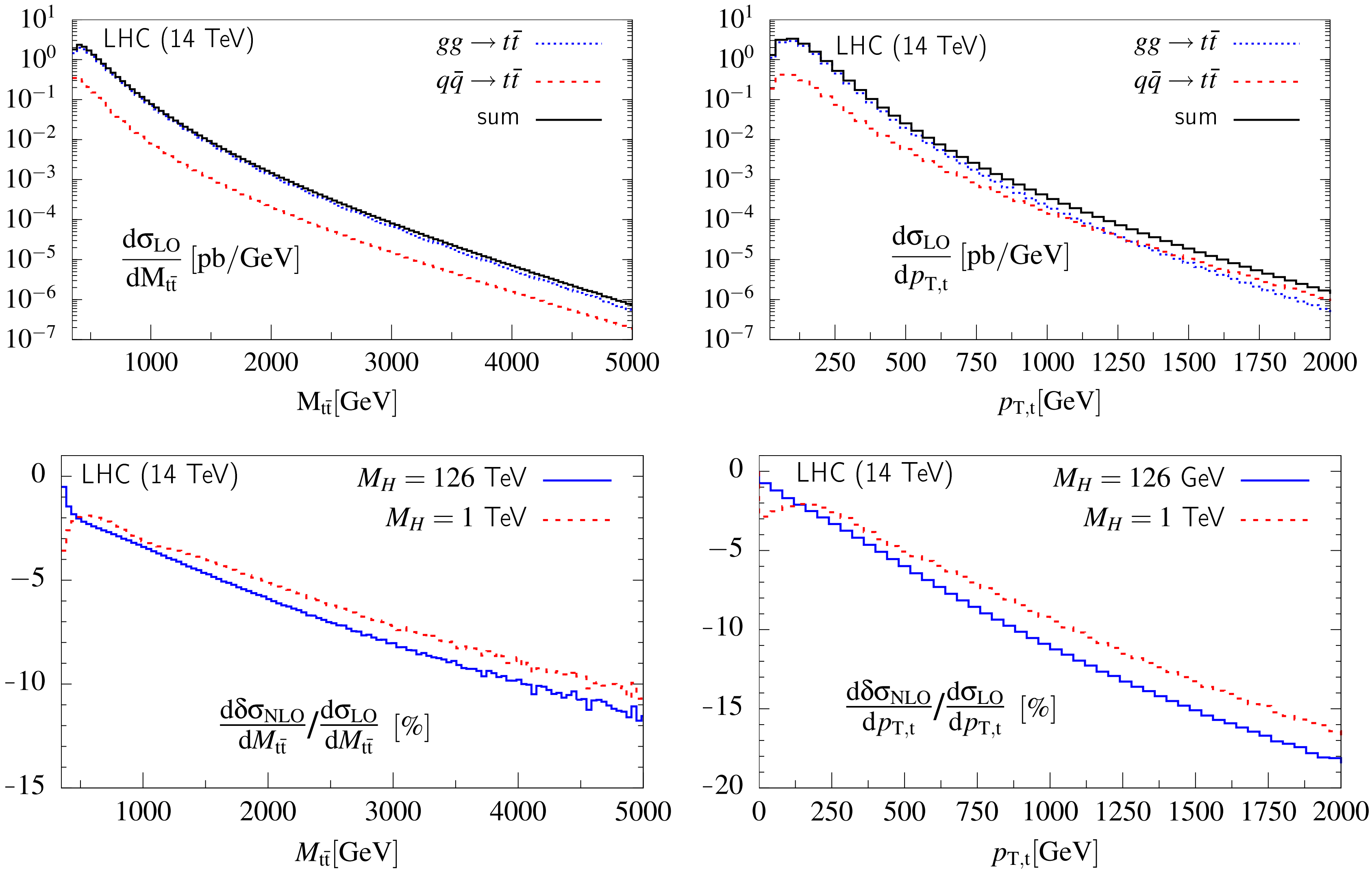




Cancellations between tree and loop corrections (cut-sensitive!)

Weak corrections to $t\bar{t}$ production

Kühn, Scharf, Uwer '13



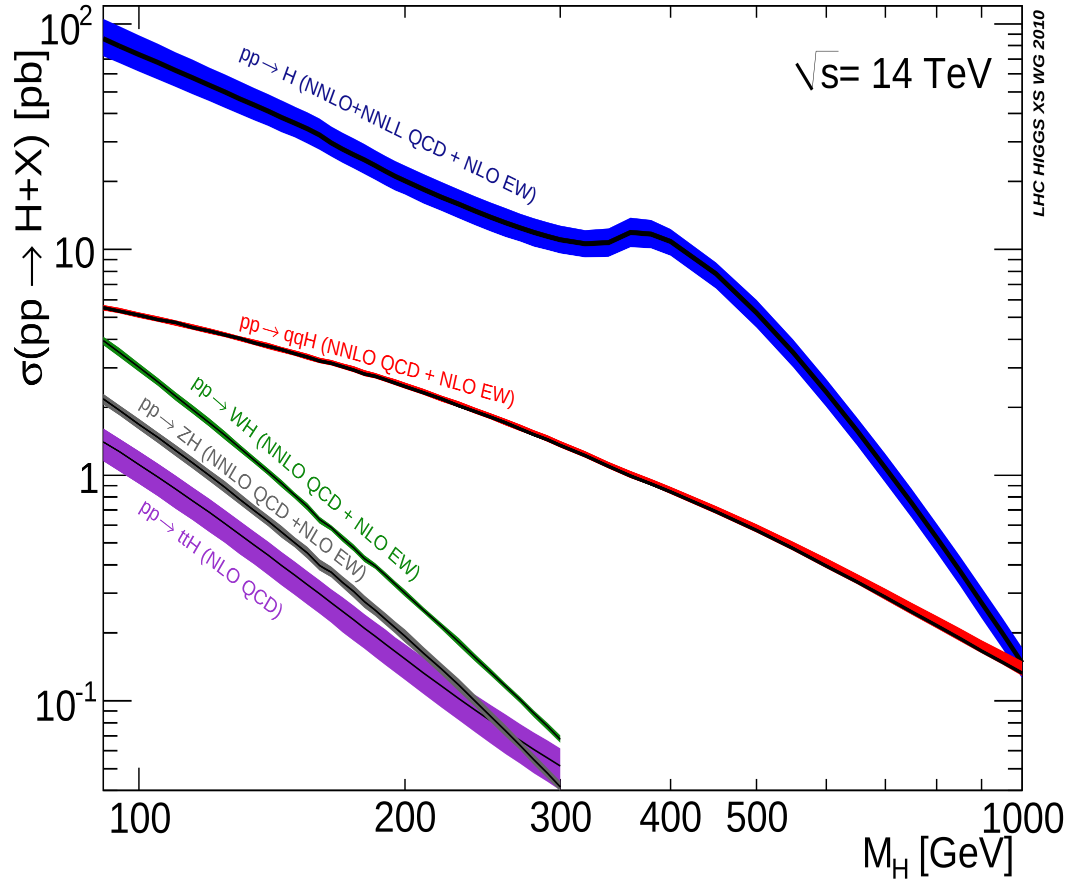
Weak corrs:
- weak corrections small for integrated XS
- growing in distributions for larger scales
- interesting M_{H} dependence at threshold ("Yukawa singularity")

Electroweak corrections

... Higgs-boson production

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

LHC Higgs XS WG 2010

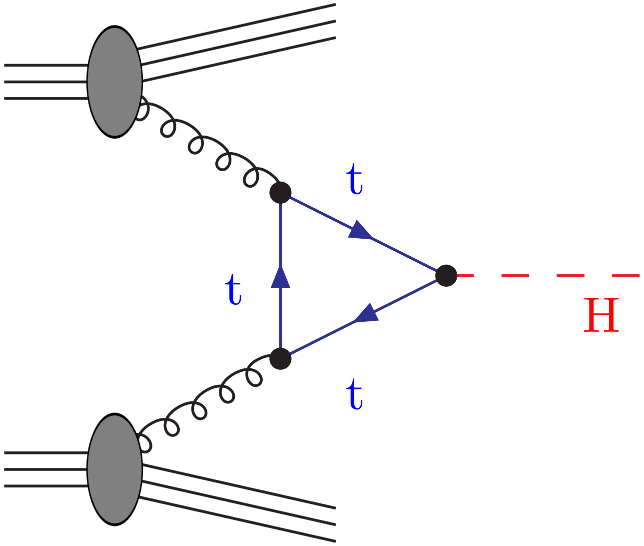


Rough numbers:

	M_H	Uncertainties scale	Uncertainties PDF4LHC	NLO/NNLO/NNLO+ QCD	NLO/NNLO/NNLO+ EW
ggF	$< 500\,\mathrm{GeV}$	$6-14\%$	7%	$>100\%$	5%
VBF	$< 500\,\mathrm{GeV}$	1%	$3-4\%$	5%	5%
WH	$< 200\,\mathrm{GeV}$	1%	$3-4\%$	30%	$5-10\%$
ZH	$< 200\,\mathrm{GeV}$	$2-4\%$	$3-4\%$	45%	5%
ttH	$< 200\,\mathrm{GeV}$	10%	9%	$15-20\%$	?

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

Higgs production via gluon fusion



Corrections to Higgs-boson production via gluon fusion

- QCD corrections:
  - ◇ complete NLO correction known

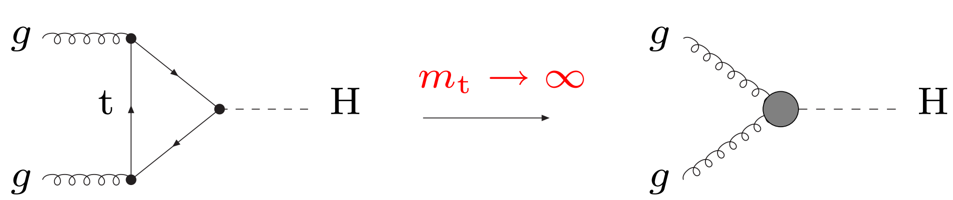
    Graudenz, Spira, Zerwas ’93
    Djouadi, Graudenz, Spira, Zerwas ’95

  - ◇ NNLO correction known as expansion for $m_t \to \infty$ matched with $\hat{s} \to \infty$

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

    Harlander, Kilgore ’01,’02
    Catani, de Florian, Grazzini ’01
    Anastasiou, Melnikov ’02
    Ravindran, Smith, v.Neerven ’03,’04
    Anastasiou, Melnikov, Petriello ’04
    Marzani et al. ’08
    Pak, Rogal, Steinhauser ’09
    Harlander, Ozeren ’09

  - ◇ resummations / virtual / soft terms to NNLO in limit $m_t \to \infty$



    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,’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

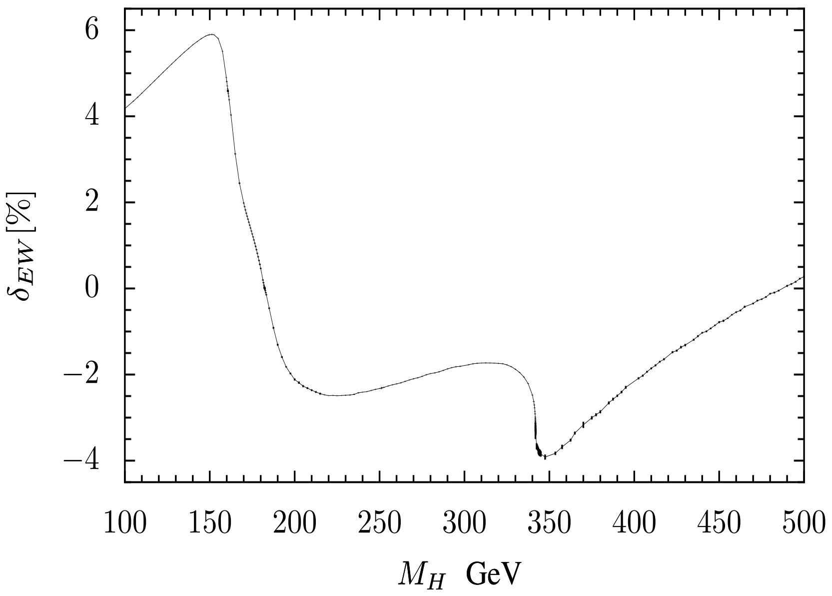
  - ◇ mixed $\mathcal{O}(\alpha\alpha_s)$ corrections for small M_H

    Anastasiou, Boughezal, Petriello ’08

NLO EW corrections

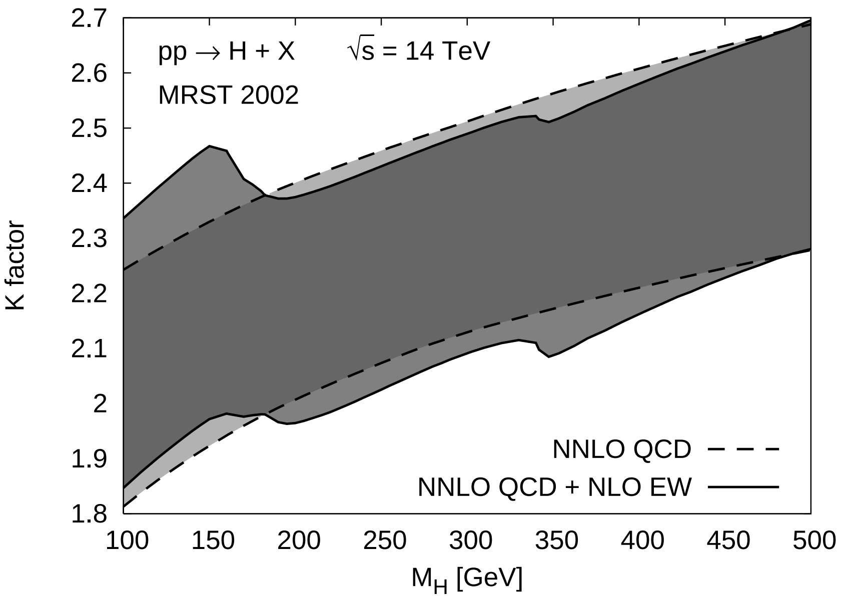
Actis, Passarino, Sturm, Uccirati '08

Correction to partonic cross section:



K factors for pp cross section:

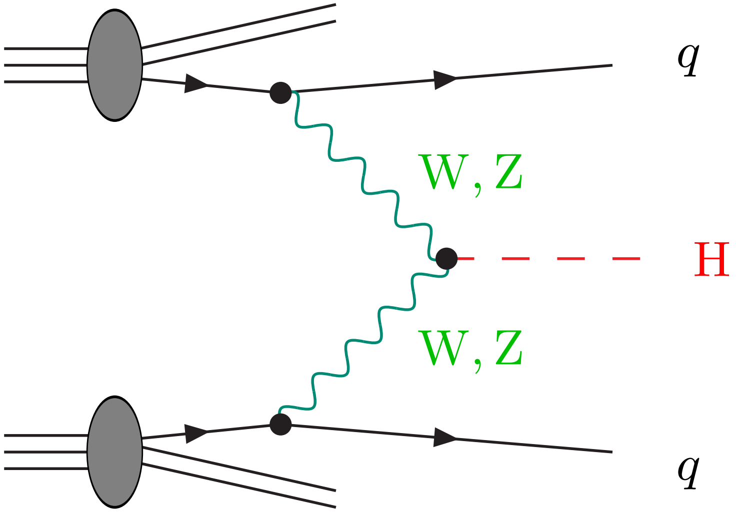
(band width: $M_\mathrm{H}/2 < \mu_\mathrm{R/F} < 2M_\mathrm{H}$, $\mu_\mathrm{R}/2 < \mu_\mathrm{F} < 2\mu_\mathrm{R}$)



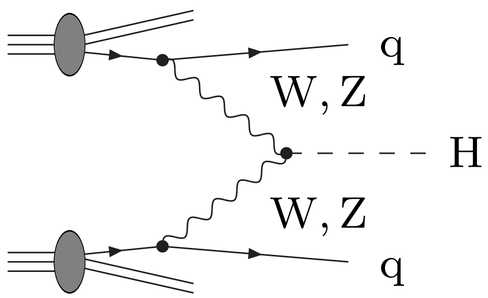
EW corrections ...

- 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

Higgs production via vector-boson fusion



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



colour exchange between quark lines suppressed

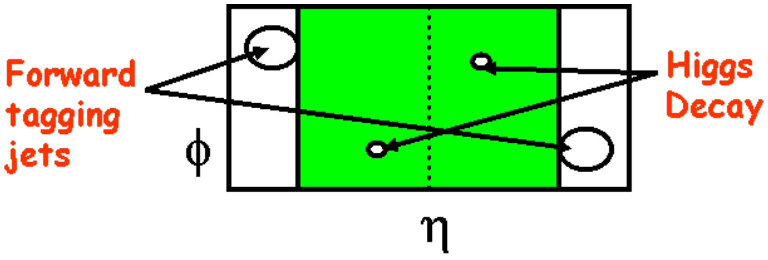
$\Rightarrow$ small QCD corrections

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, S.D. '07; Figy, Palmer, Weiglein '10 (DIS-like EW)

  $\hookrightarrow$ NLO QCD $\sim$ NLO EW $\sim$ $5\text{–}10\%$
- NNLO QCD corrections to VBF in DIS-like approximation — Bolzoni, Maltoni, Moch, Zaro '10

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

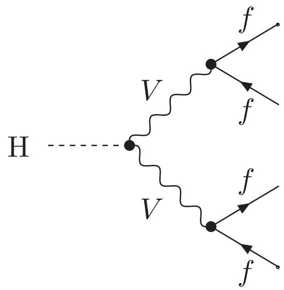
  $\hookrightarrow$ impact $\lesssim 10^{-3}\,\%$ (negligible!) — Andersen, Binoth, Heinrich, Smillie '07; Bredenstein, Hagiwara, Jäger '08
- loop-induced VBF in gg scattering — Harlander, Vollinga, Weber '08

  $\hookrightarrow$ impact $\sim$ 0.1%
- SUSY QCD+EW corrections — Hollik, Plehn, Rauch, Rzehak '08

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

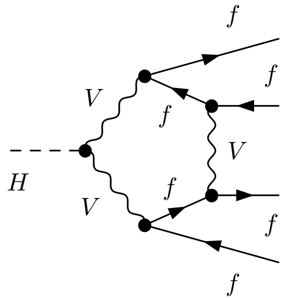
Survey of Feynman diagrams for NLO corrections

Lowest order:

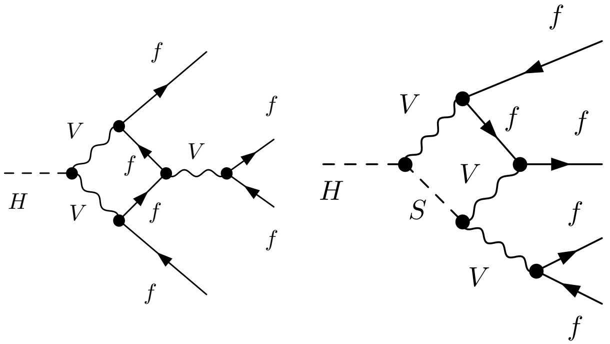


Typical one-loop diagrams: # diagrams = $\mathcal{O}(200{-}400)$

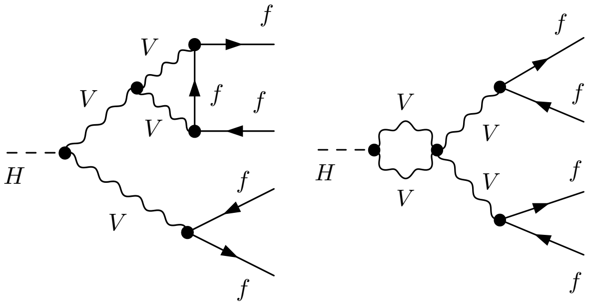
pentagons



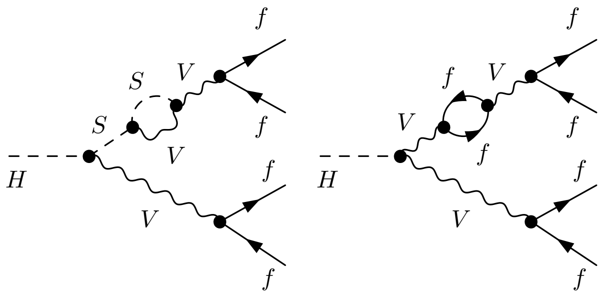
boxes



vertices



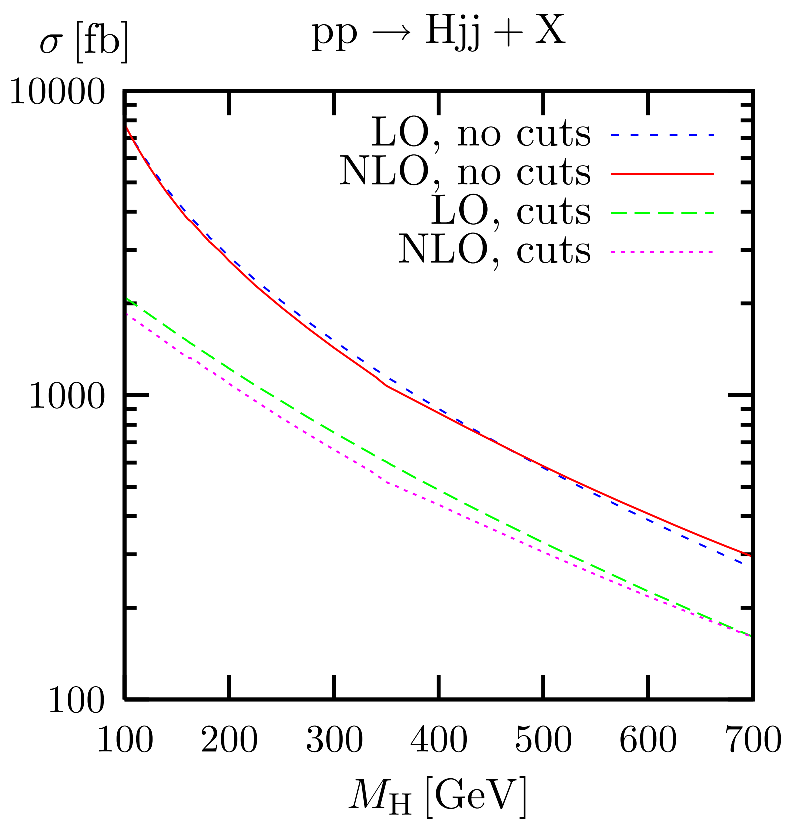
self-energies

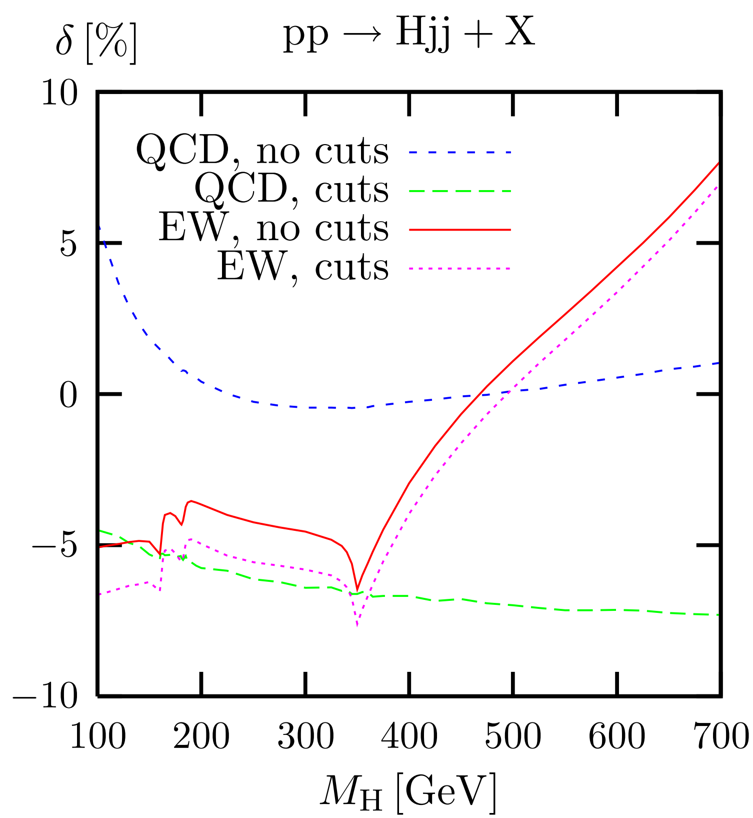


$+$ tree graphs with real gluon or photons

Note: amplitudes recycled from NLO corrections to $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$ Bredenstein, Denner, S.D., Weber '06

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





Ciccolini, Denner, S.D. '07

HAWK

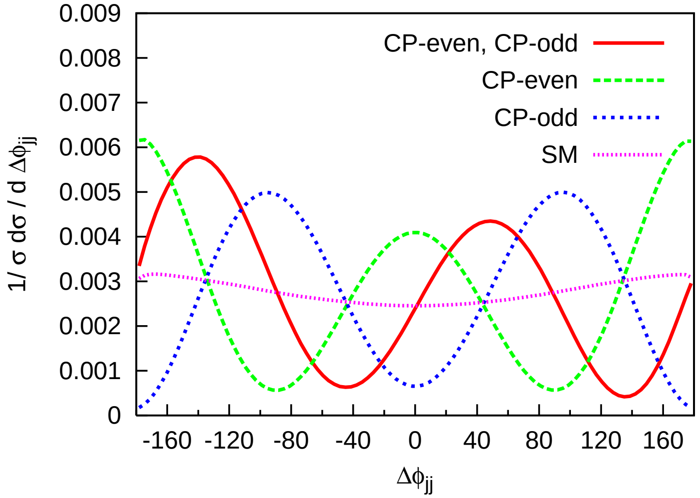
- QCD and EW corrections are of same generic size
- $\mathrm{W/Z}$ resonances in s-channels described via complex-mass scheme
- sensitivity to cuts: large for QCD, small for EW corrections
- heavy-Higgs corrections at $M_\mathrm{H} \sim 700\,\mathrm{GeV}$: $\underbrace{G_\mu M_\mathrm{H}^2}_{\text{1-loop}}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

  $\hookrightarrow$ breakdown of perturbation theory

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

Sensitivity to non-standard effects:

Hankele, Klämke, Zeppenfeld, Figy '06



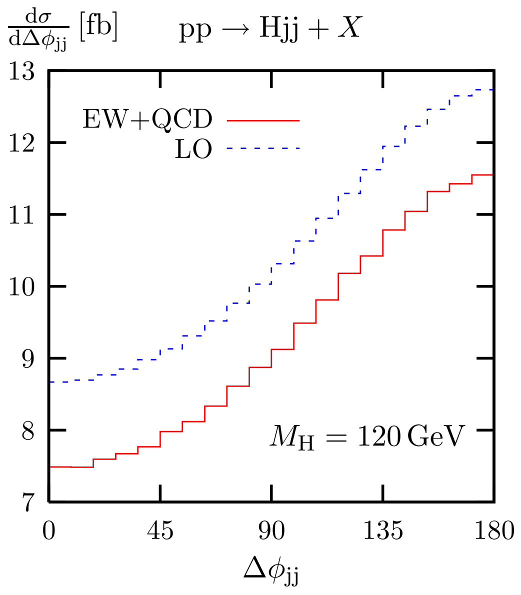
(Individual contributions without SM)

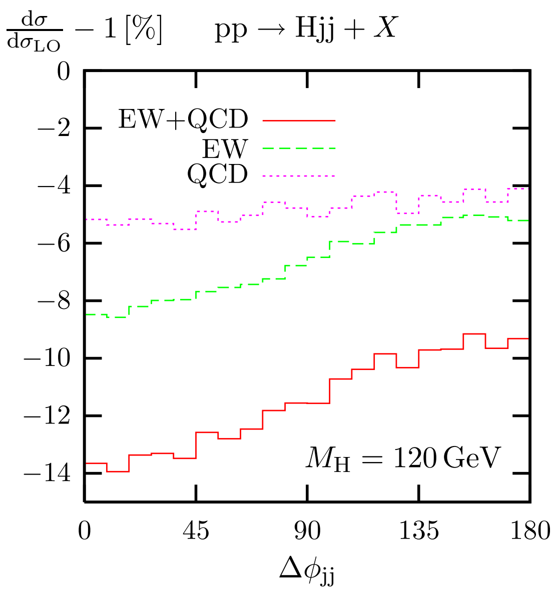
CP-even: $\mathcal{L} \propto H W^{+}_{\mu\nu} W^{-,\mu\nu}$

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

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

Ciccolini, Denner, S.D. '07

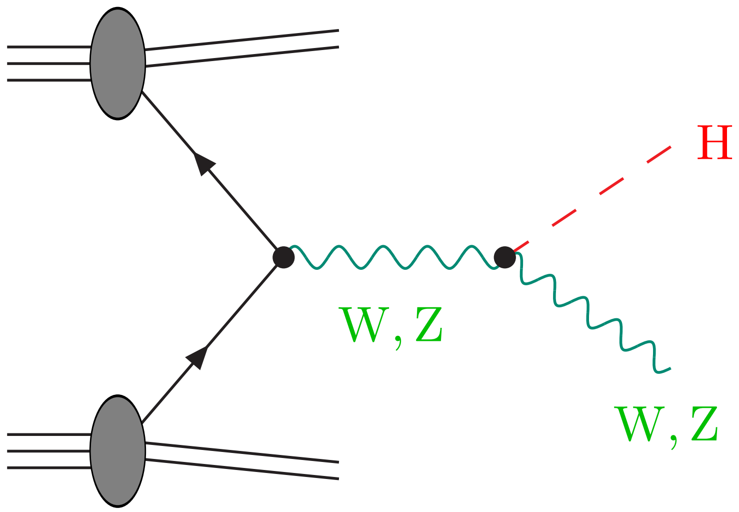




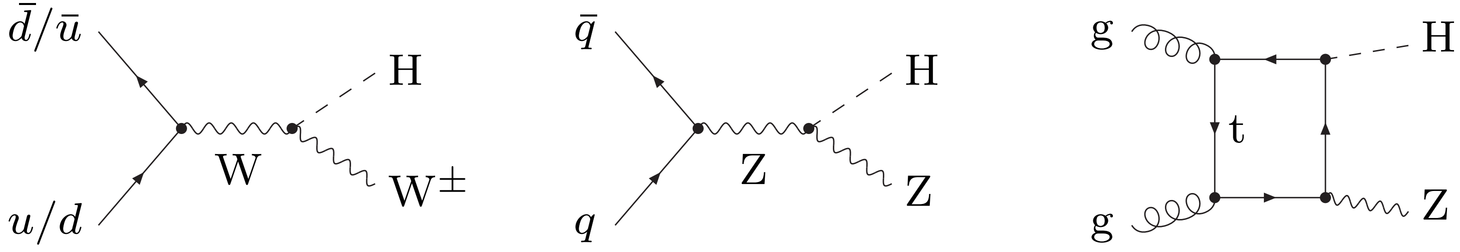
HAWK

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, S.D., Krämer '03
  W/Z decays, differential XS via HAWK
  Denner, S.D., 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 with W decay, DY part for differential XS
  Ferrera, Grazzini, Tramontano '11
  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, SD, Harlander, Rzehak, Zirke '12

Total cross section: NNLO QCD and NLO EW corrections

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

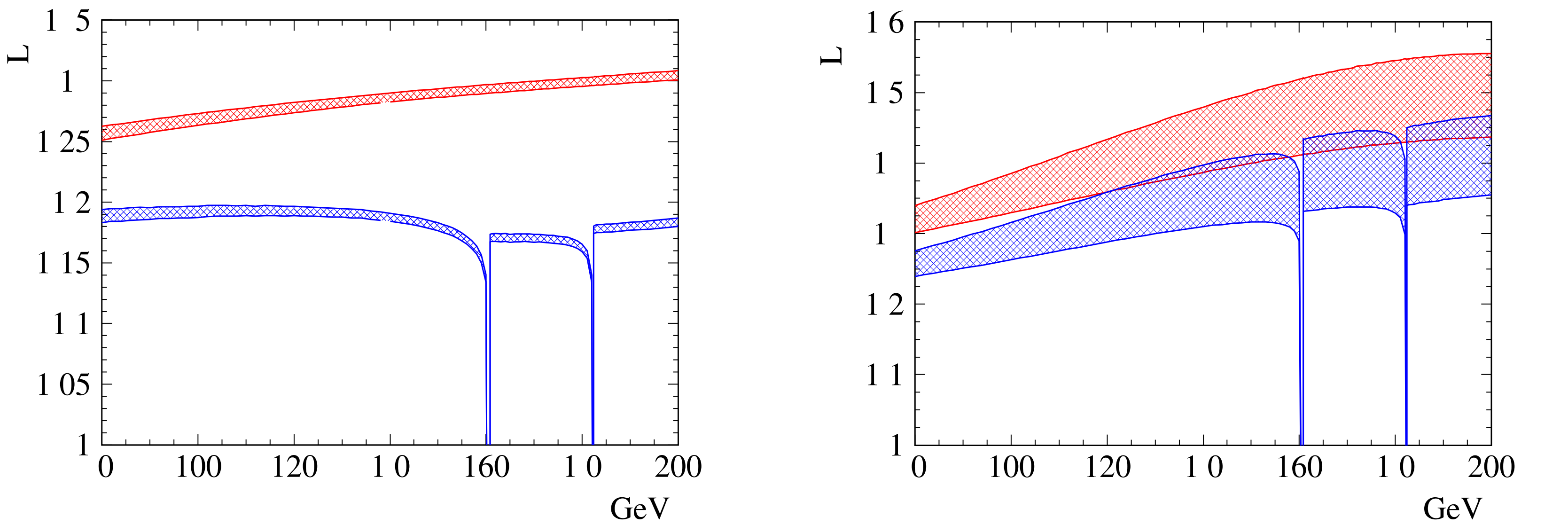
$$\sigma_{\mathrm{WH}} = \sigma_{\mathrm{WH}}^{\mathrm{VH@NNLO}} \times (1 + \delta_{\mathrm{WH,EW}})$$

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

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: $\mathcal{O}(\alpha_s^2) \sim \mathcal{O}(\alpha) \sim 5{-}10\%$
- 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]

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

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

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

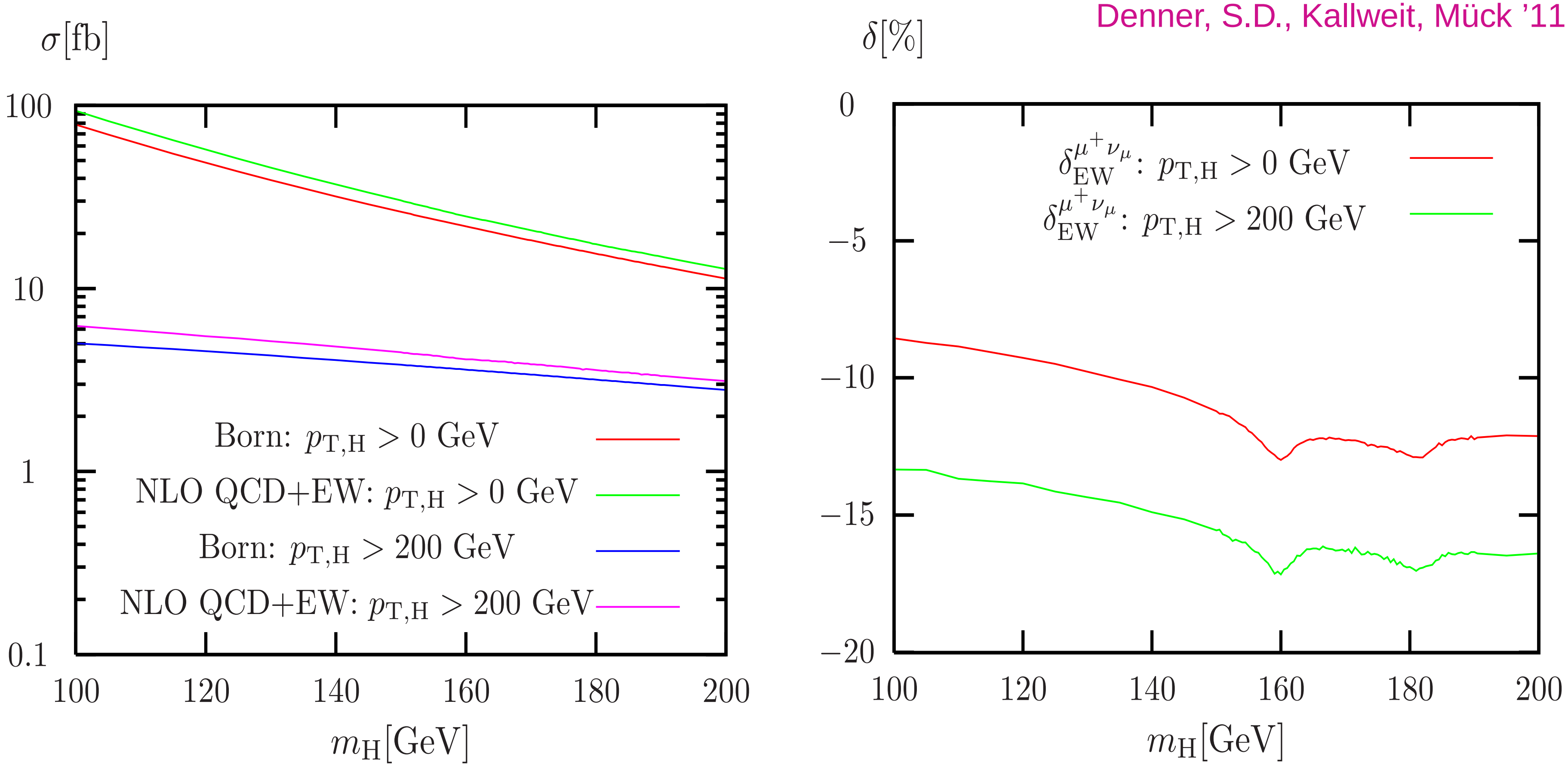
Features:

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

channel	$\mathrm{Hl}^+\nu_\mathrm{l}$	$\mathrm{Hl}^-\bar{\nu}_\mathrm{l}$	$\mathrm{Hl}^+\mathrm{l}^-$	$\mathrm{H}\nu_\mathrm{l}\bar{\nu}_\mathrm{l}$
$\delta_{\mathrm{EW}}^{\mathrm{bare}}/\%$	-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 $\mathrm{pp} \to \mathrm{H}\ell^+\nu_\ell + X$

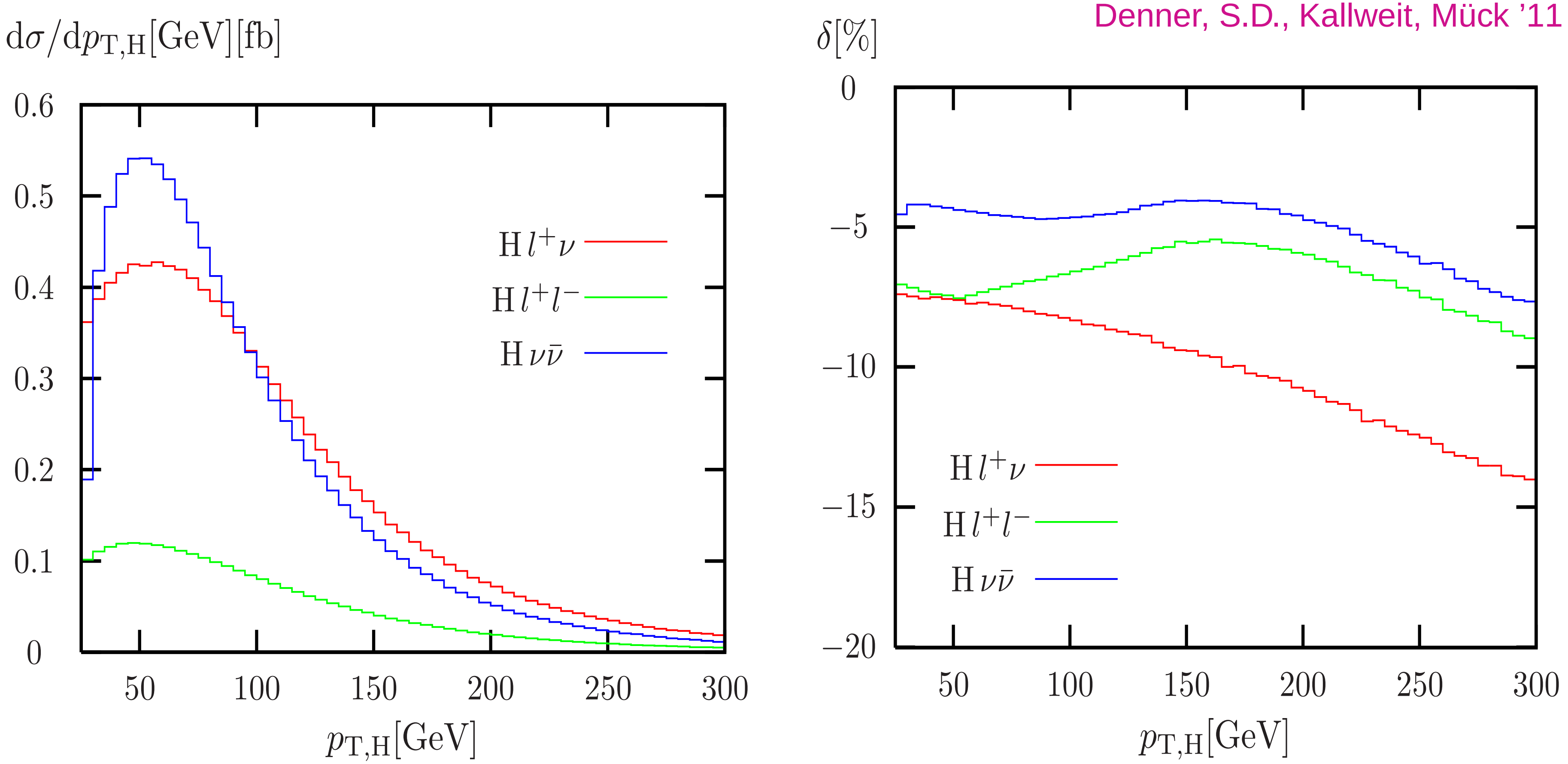
Denner, S.D., Kallweit, Mück '11



- 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 the $p_{\mathrm{T,H}}$ distributions

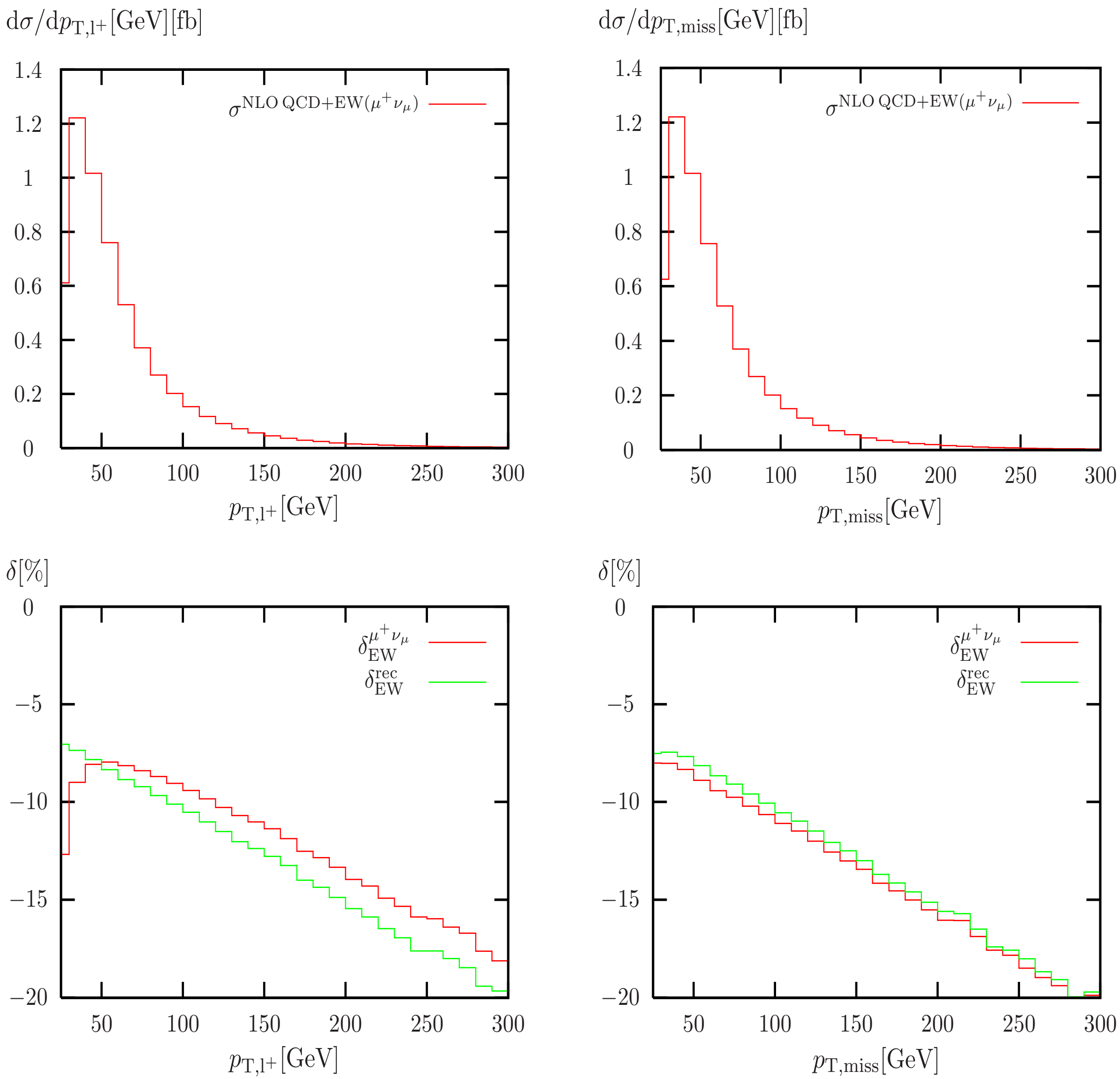
Denner, S.D., Kallweit, Mück ’11



- 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. $\mathrm{H}\ell^+\nu$: $\delta_{\mathrm{EW}} < -11\%$ for $p_{\mathrm{T,H}} > 200\,\mathrm{GeV}$

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, S.D., 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

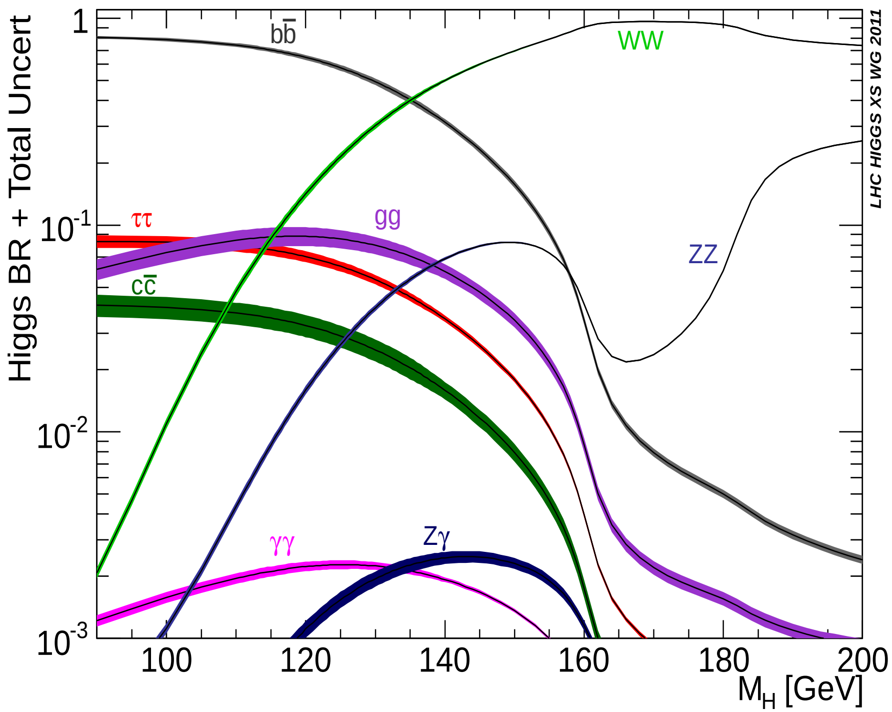
$\hookrightarrow$ EW corrections mostly of non-universal origin (not simply FSR!)

... 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 Bredenstein, Denner, S.D., Weber '06

Hdecay + Prophecy4f



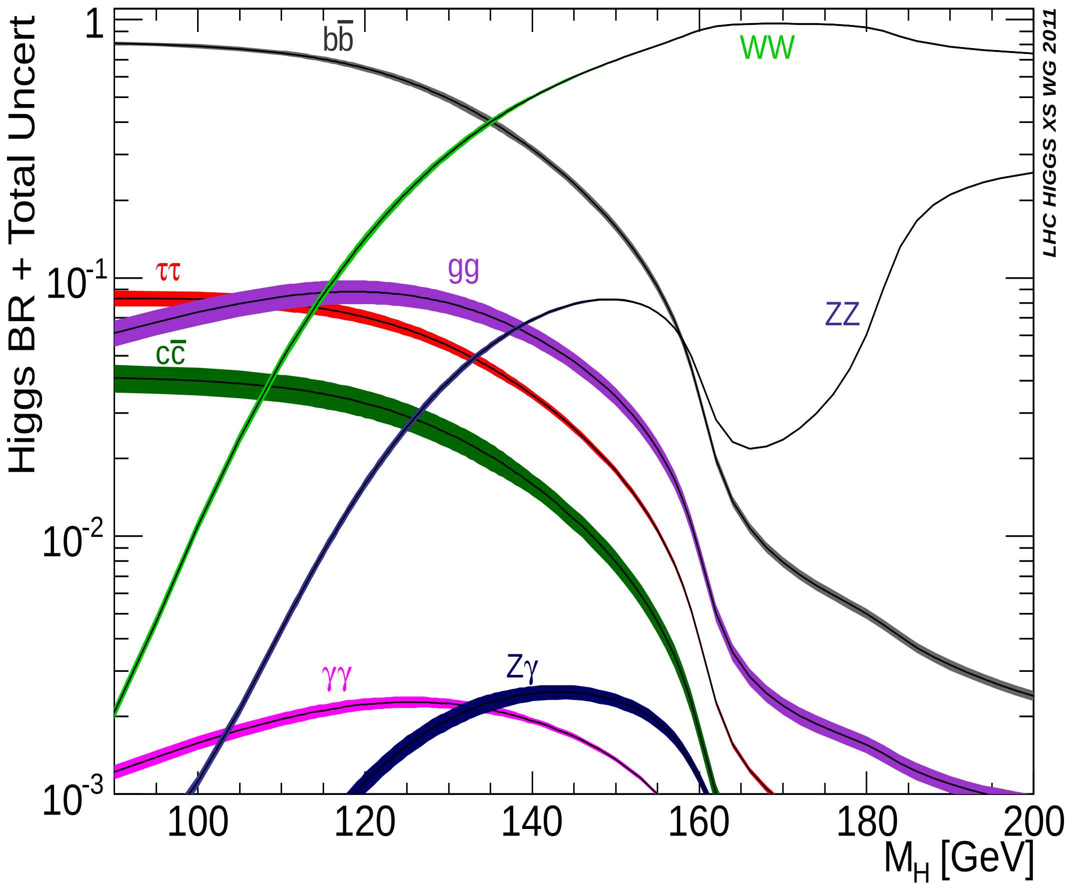
↪ NLO EW corrections known for most important SM Higgs decays

Tools

- HDECAY: all $1 \to 2$ decays (integrated) Djouadi, Kalinowski, Mühlleitner, Spira
- PROPHECY4F: $\mathrm{H} \to 4f$ decays (integrated & differential) Bredenstein, Denner, S.D., Mück, Weber

BRs of the SM Higgs boson

LHC Higgs XS WG 2011



Parametric + theoretical uncertainty:

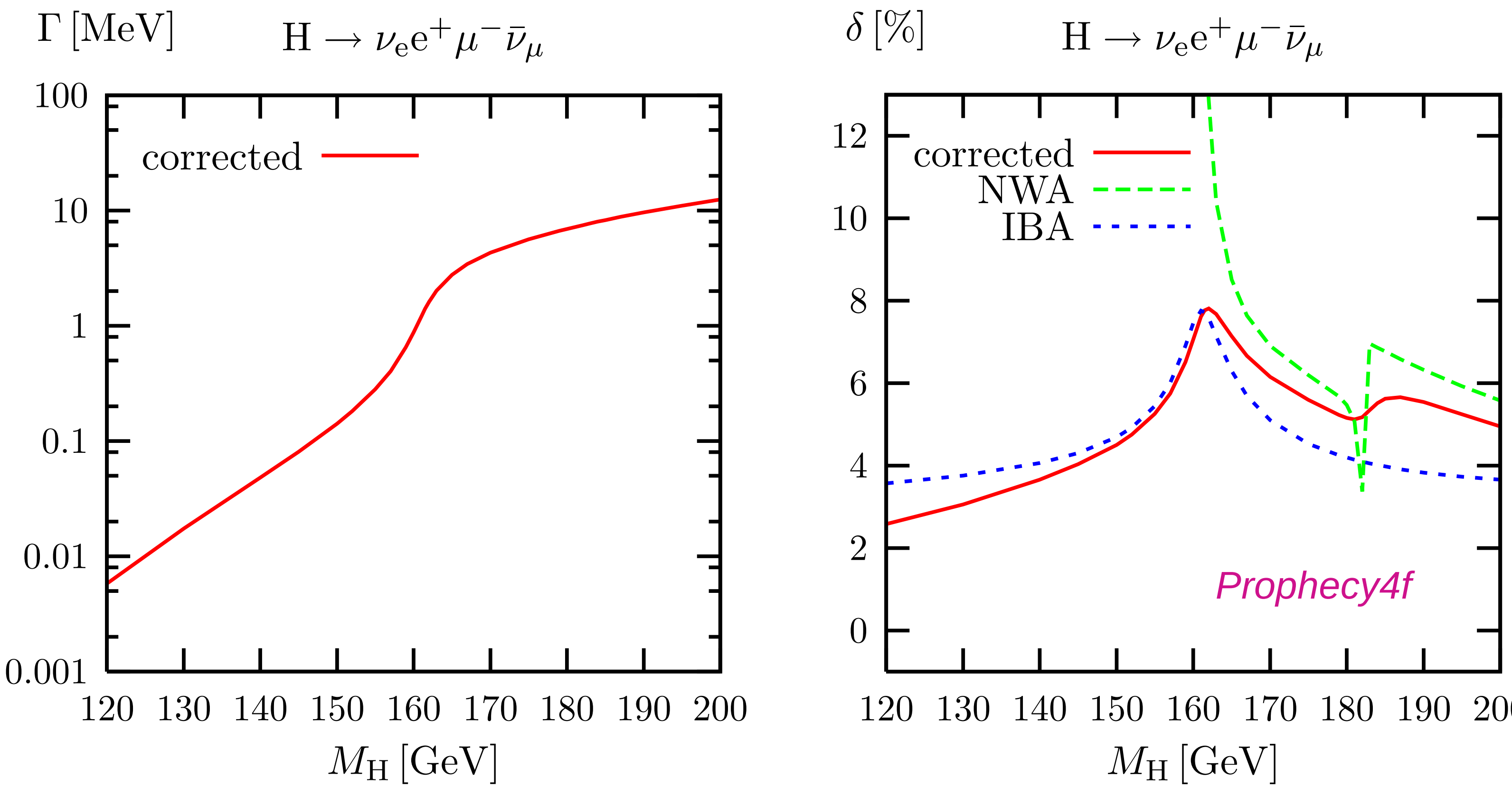
$M_{\rm H}$[GeV]	H $\to$ $b\bar{b}$	$\tau^+\tau^-$	$c\bar{c}$	gg	$\gamma\gamma$	WW	ZZ
120	3%	6%	12%	10%	5%	5%	5%
150	4%	3%	10%	8%	2%	1%	1%
200	5%	3%	10%	8%	2%	$<0.1\%$	$<0.1\%$

$\leftarrow$ driven by $\Gamma_{\rm H\to b\bar{b}}$

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

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

Bredenstein, Denner,
S.D., Weber ’06



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

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

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

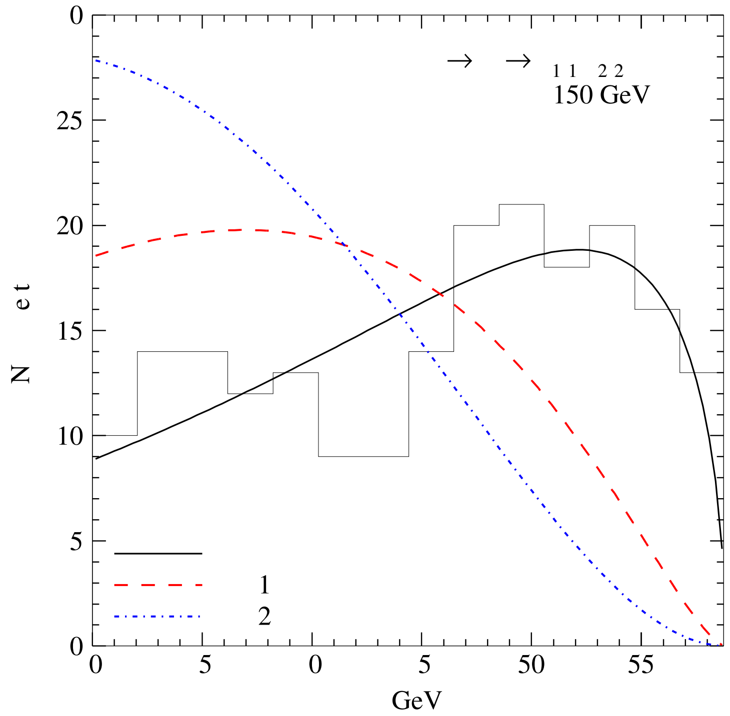
NWA = “narrow-width approximation” (on-shell W bosons)

IBA = “improved Born approximation” (universal corrections)

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

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

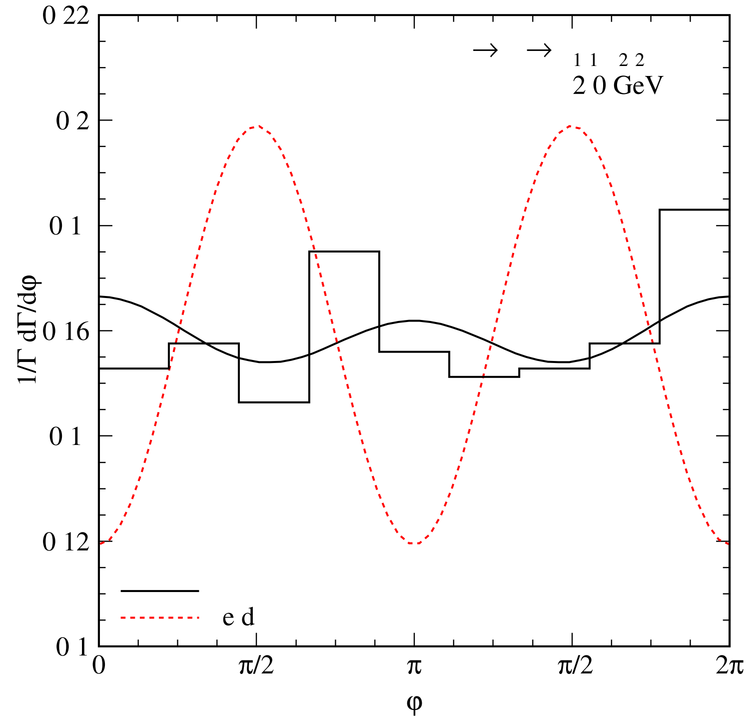
Invariant Z mass:

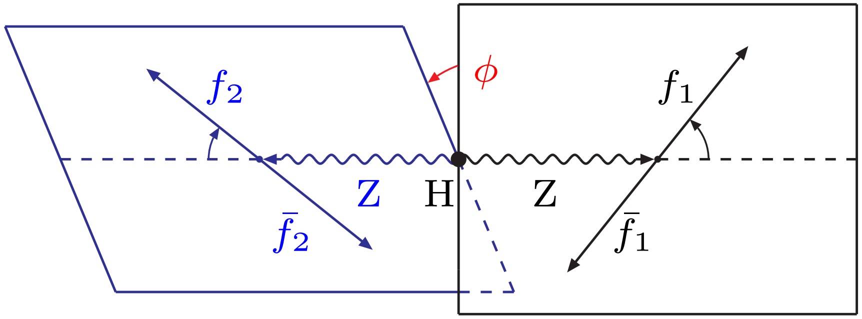


$$M_* = M_{f_1 \bar{f}_1}$$

Angle between Z decay planes:

Choi, Miller, Mühlleitner, Zerwas ’02



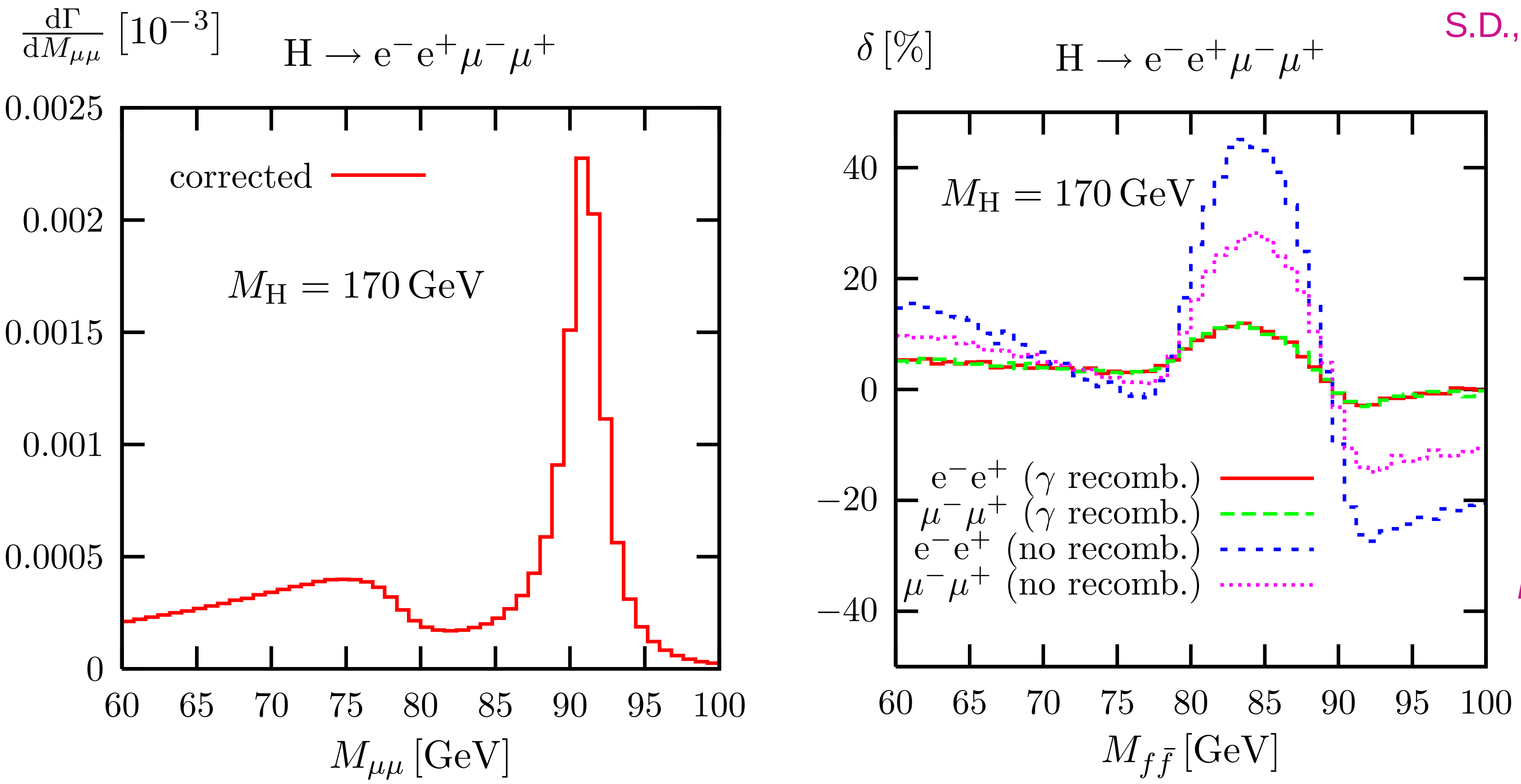


Histograms = SM simulation for $L = 300\,\mathrm{fb}^{-1}$

$\hookrightarrow$ distributions sensitive to spin and parity

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

Bredenstein, Denner, S.D., Weber '06



Prophecy4f

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

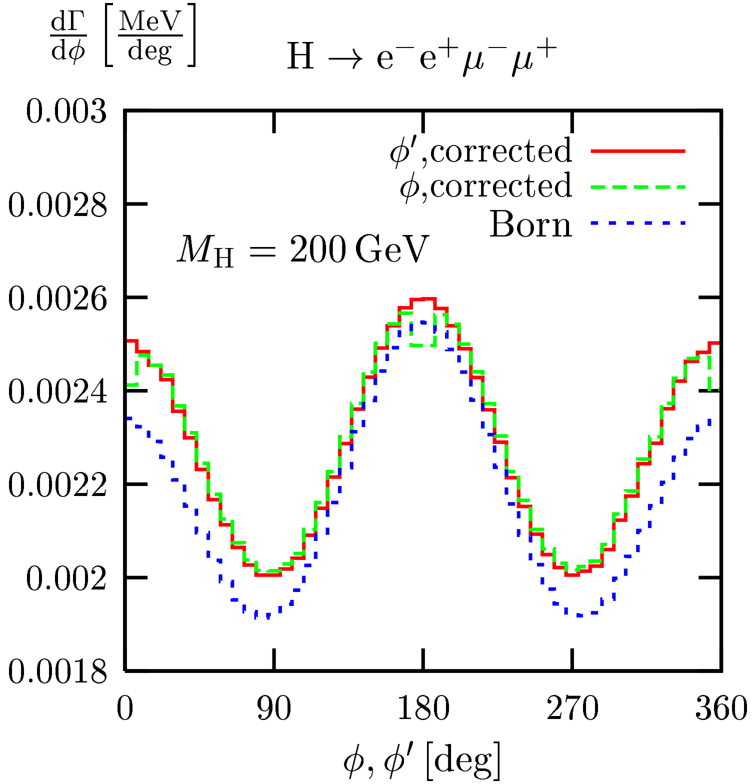
Large corrections due to photon emission in Z reconstruction

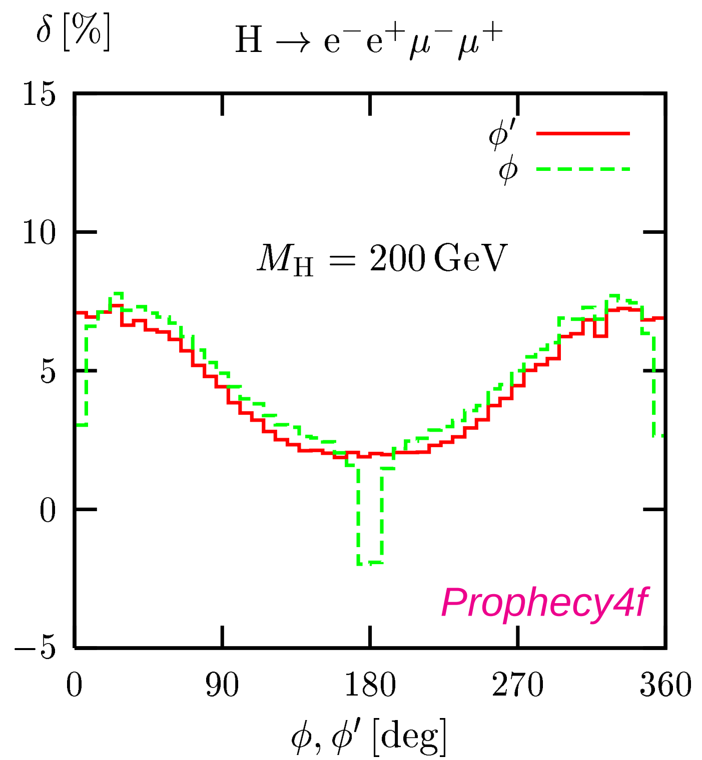
Corrections to distribution in angle between Z decay planes

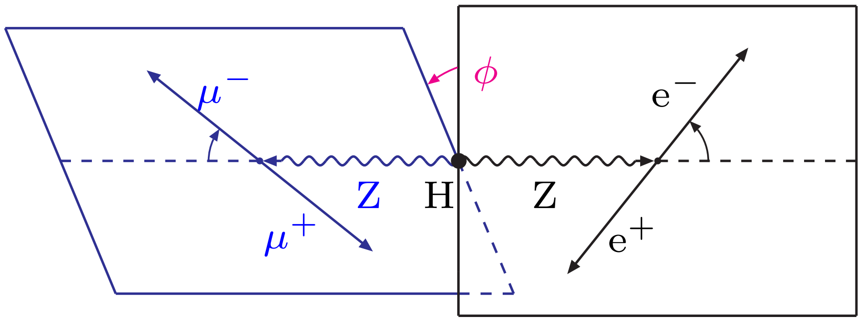
Bredenstein, Denner, S.D., Weber '06

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

An example:







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

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

Summary & outlook

EW corrections ...

- ... are of generic size $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$,
  but show systematic enhancements
  - at high energies by Sudakov logs ($\sim 10{-}50\%$ in TeV range)
  - by photon emission, in particular off muons
    (kinematic distortions, $\alpha \ln(m_\mu/Q)$ enhancement)
- ... involve complications due to
  - off-shell effects of W/Z bosons
    $\hookrightarrow$ gauge-invariant treatment of off-shell effects and decays !
  - photon-induced channels
- ... require some extra ingredients such as
  - photon–jet separation for signatures with hard jets
    (quark–photon fragmentation function or isolation à la Frixione)
  - $\mathcal{O}(\alpha)$-corrected PDFs

“Missing” NLO EW calculations

- $\mathcal{O}(\alpha\alpha_s)$ corrections to Drell–Yan processes
- $\mathrm{W} + \geq 2\,\mathrm{jets}$, $\mathrm{Z} + \geq 3\,\mathrm{jets}$
- di-boson production with full off-shell effects / decays
- triple gauge-boson production: $\mathrm{pp} \to \mathrm{WWW}$
- vector-boson scattering: $\mathrm{pp(WW \to WW) \to WW} + 2\,\mathrm{jets}$, etc.
- $\geq 3\,\mathrm{jet}$ production
- off-shell $\mathrm{t\bar{t}}$ production with top-quark decays
- $\mathrm{t\bar{t}H}$ production
- more ?!

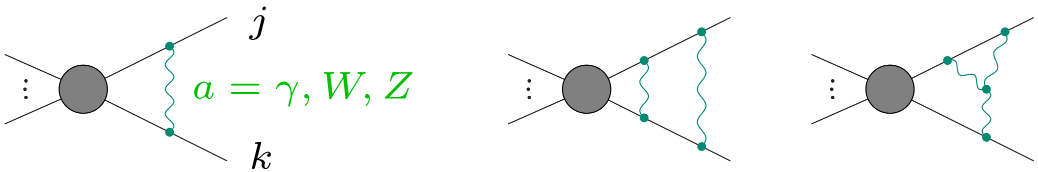
Possible EW projects at Les Houches

- press ahead with the tuned comparison of precision calculations for Drell-Yan processes carried out in the framework of the LPCC EW Group
- compare prescriptions for combining QCD and EW corrections
- implementation of corrections (in particular EW) in Monte Carlo programs via BLHA (e.g. in SHERPA)
- more ?!

Backup slides

Electroweak radiative corrections at high energies

Sudakov logarithms induced by soft gauge-boson exchange



etc.

+ sub-leading logarithms from collinear singularities

Typical impact on $2 \rightarrow 2$ 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" $\rightarrow$ 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

Photon–jet separation via photon fragmentation function $D_{q\to\gamma}$

Why?

- collinear quarks and photons have to be recombined $\to$ quasiparticle
  otherwise corrections $\propto \ln(m_q^2/Q^2)$ $\to$ perturbative "IR instability"
- quark and gluon jets cannot be distinguished event by event
  $\hookrightarrow$ common recombination required for quarks/gluons with photons

  $\Rightarrow$ $\underbrace{(g_{\mathrm{hard}} + \gamma_{\mathrm{soft}})}_{\text{EW corr. to X+jet}}$ and $\underbrace{(g_{\mathrm{soft}} + \gamma_{\mathrm{hard}})}_{\text{QCD corr. to X+}\gamma}$ both appear as 1 jet

Solution:

- exclude events with photon energy fraction $z_\gamma = \dfrac{E_\gamma}{E_{\mathrm{jet}} + E_\gamma} > z_0$
  for $(\mathrm{jet} + \gamma)$ quasiparticles (chosen value $z_0 = 0.7$)
- subtract convolution of LO cross section with

$$D_{q\to\gamma}^{\overline{\mathrm{MS}}}(z_\gamma, \mu_{\mathrm{fact}})\Big|_{\mathrm{mass.reg.}} = \frac{\alpha Q_q^2}{2\pi} P_{q\to\gamma}(z_\gamma)\left[\ln\frac{m_q^2}{\mu_{\mathrm{fact}}^2} + 2\ln z_\gamma + 1\right] \quad \longleftarrow \text{cancels coll. singularities}$$

$$+ \; D_{q\to\gamma}^{\mathrm{ALEPH}}(z_\gamma, \mu_{\mathrm{fact}}) \quad \longleftarrow \text{non-perturbative part fitted to ALEPH data}$$

where $P_{q\to\gamma}(z_\gamma) = \frac{1+(1-z_\gamma)^2}{z_\gamma}$ = quark-to-photon splitting function

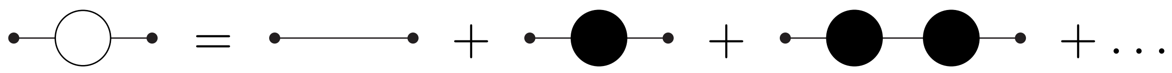
The complex-mass scheme for unstable particles

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

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

Comparison to other proposals:

- naive fixed-width schemes:

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

$\hookrightarrow$ 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; Hoang, Reisser '04

$\hookrightarrow$ gauge invariant, involves pole expansions,
but can be combined with threshold expansions

- complex-mass scheme Denner, S.D., Roth, Wackeroth '99; Denner, S.D., Roth, Wieders '05

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