Electroweak corrections to gauge-boson pair production processes at the LHC including leptonic W/Z decays

Stefan Dittmaier

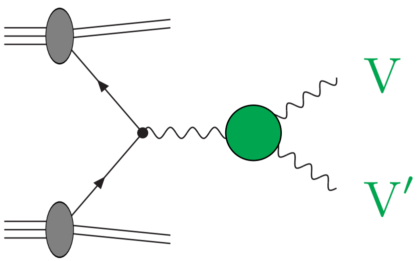
Albert-Ludwigs-Universität Freiburg

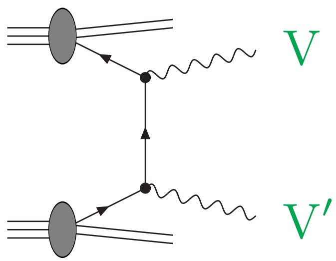
(based on collaboration with B.Biedermann, M.Billoni, A.Denner, L.Hofer, B.Jäger, L.Salfelder;
results partially published in arXiv:1601.07787 (to appear in PRL); see also JHEP 1312 (2013) 043)

Contents

Introduction

Electroweak di-boson production at the LHC





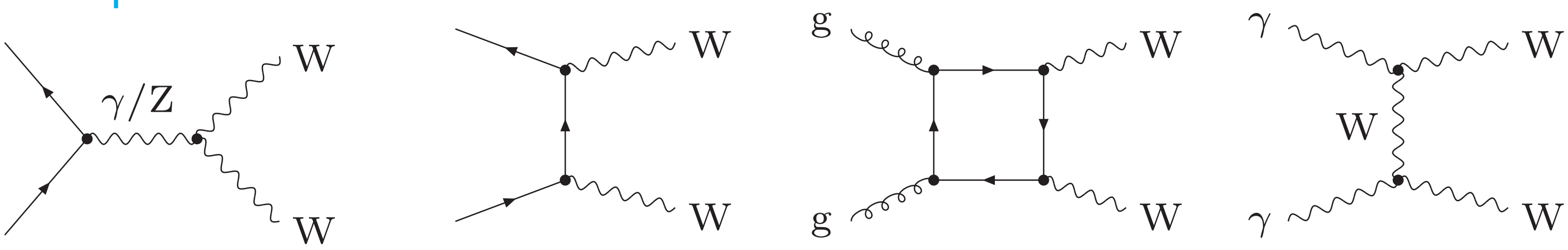
$\mathrm{V, V' = \gamma, Z, W^{\pm}}$

Physics issues:

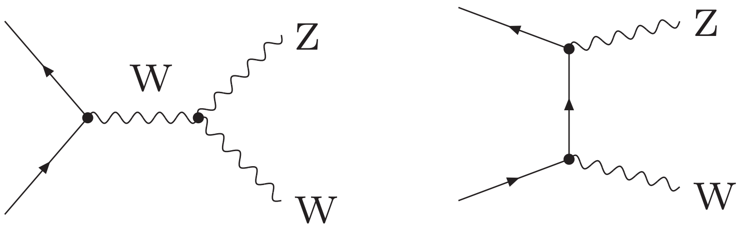
- triple-gauge-boson couplings, especially at high momentum transfer
  - ◇ EW corrections significant
  - ◇ anomalous TGC: "formfactor approach" to switch off unitarity violation
    $\hookrightarrow$ element of arbitrariness, avoid when possible
- important background processes
  - ◇ to Higgs production, $\mathrm{H \to WW^*/ZZ^* \to 4}f$
    $\hookrightarrow$ invariant masses below VV thresholds,
    proper description of off-shell $V^*V^* \to 4f$ production required !
  - ◇ to searches at high invariant masses
    $\hookrightarrow$ EW corrections

Complementarity in WW / WZ / ZZ production

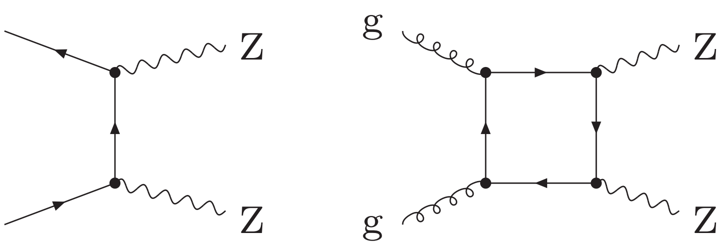
WW production:



WZ production:

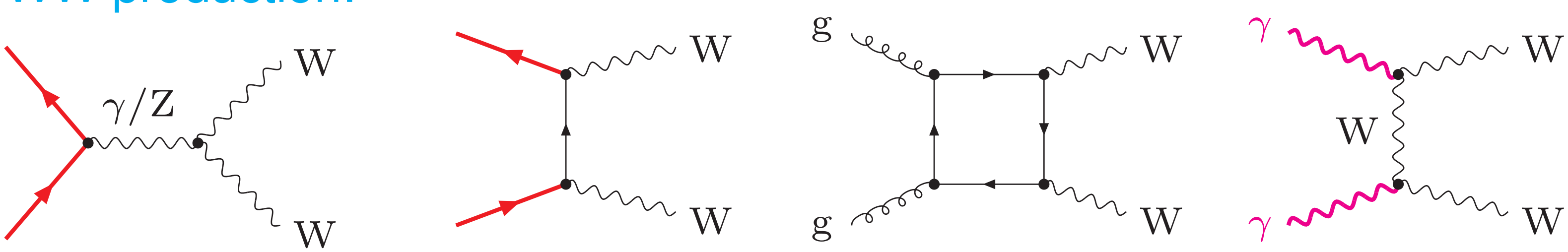


ZZ production:

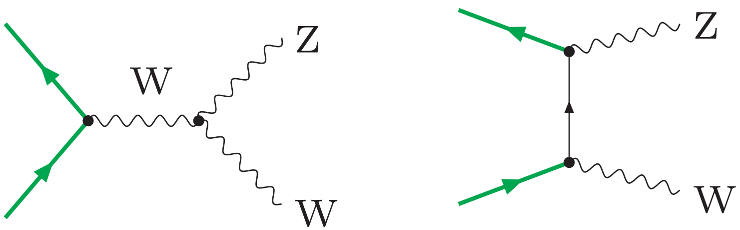


Complementarity in WW / WZ / ZZ production

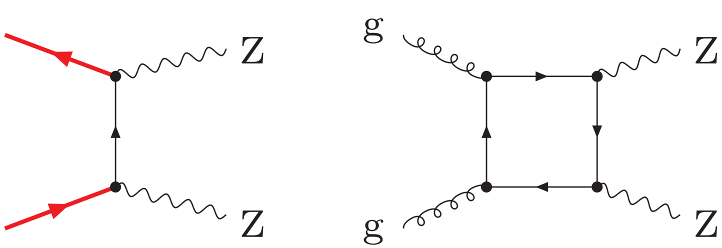
WW production:



WZ production:



ZZ production:

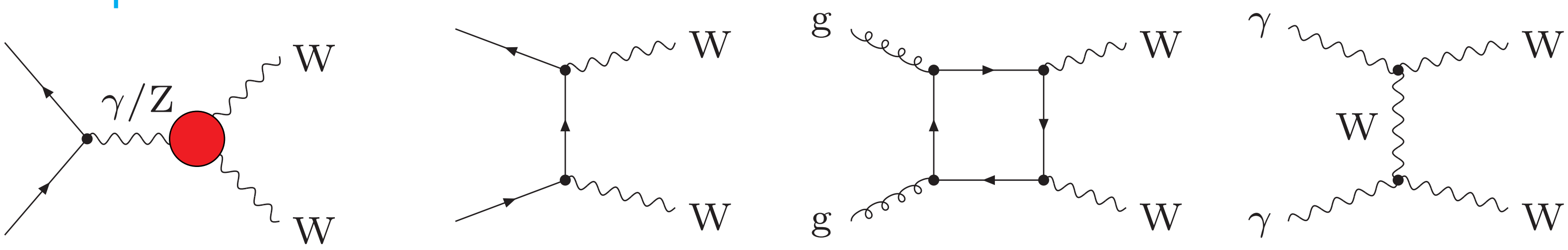


Sensitivity to different PDF combinations:

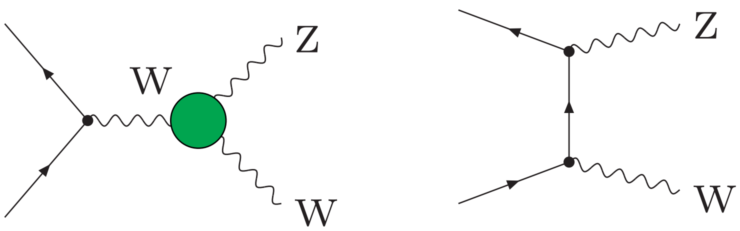
- $q\bar{q}$ in $\mathrm{WW/ZZ}$
- $u\bar{d}/d\bar{u}$ in $\mathrm{W^+Z/W^-Z}$
- $\gamma\gamma$ in WW

Complementarity in WW / WZ / ZZ production

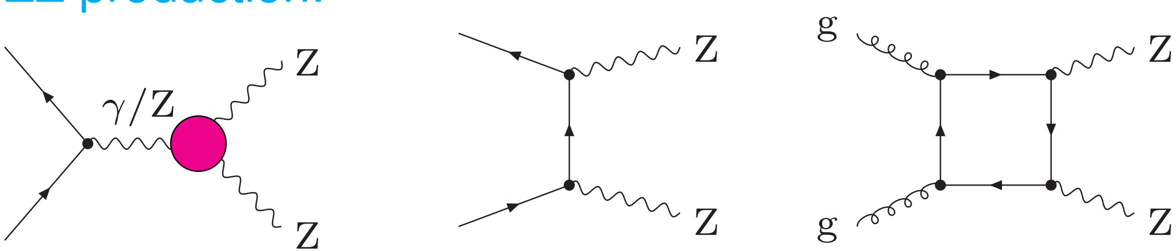
WW production:



WZ production:



ZZ production:

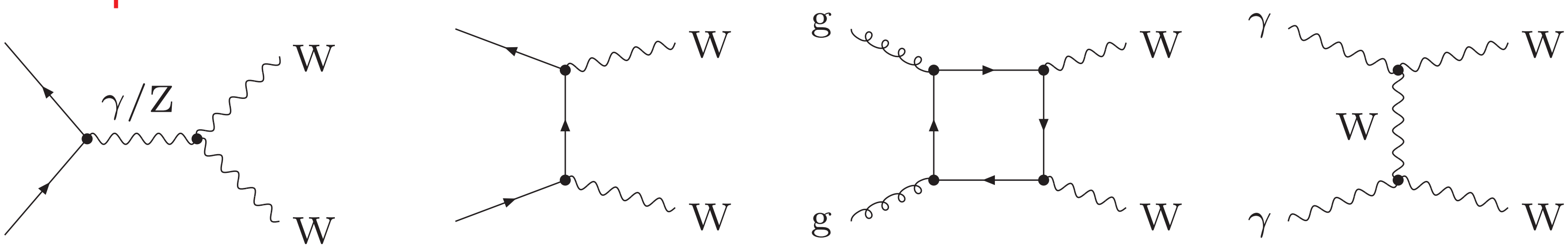


Sensitivity to different anomalous TGCs:

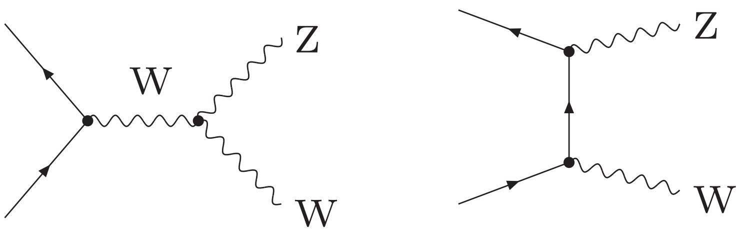
- overlay of $\gamma\mathrm{WW}/\mathrm{ZWW}$ in WW
- only ZWW in WZ
- $\gamma\mathrm{ZZ}/\mathrm{ZZZ}$ in ZZ

Complementarity in WW / WZ / ZZ production

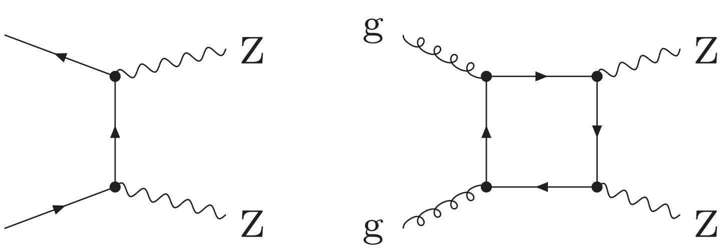
WW production:



WZ production:

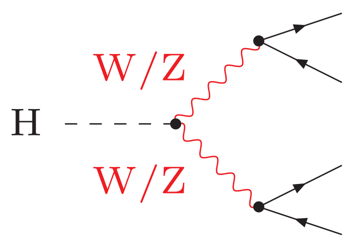


ZZ production:



Background to Higgs production
in channel $\mathrm{H} \to \mathrm{WW}^*/\mathrm{ZZ}^* \to 4f$

$\hookrightarrow$ off-shell calculation
particularly important for WW/ZZ !



State-of-the-art predictions

$W\gamma/Z\gamma$ (with leptonic decays)

- NNLO QCD Grazzini, Kallweit, Rathlev '14,'15
- NLO EW Denner, S.D., Hecht, Pasold '14,'15

WW, WZ, ZZ

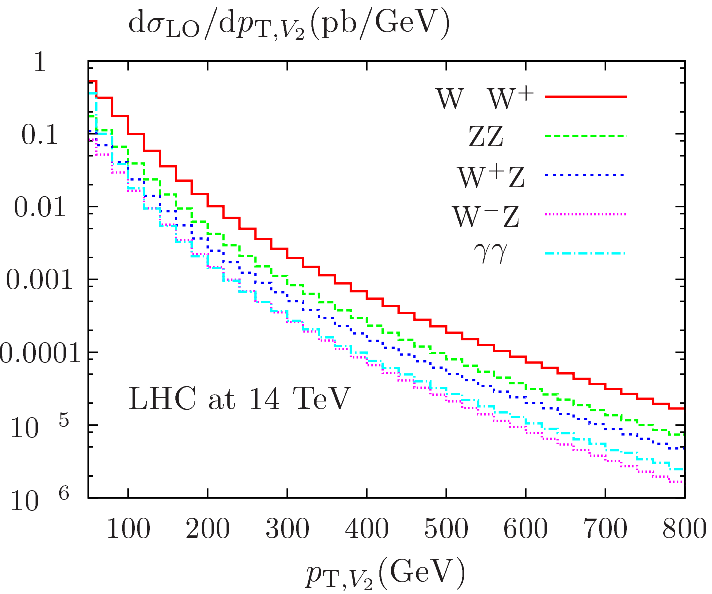
- NNLO QCD
  - ◇ ZZ (on-shell and off-shell) Cascioli et al. '14; Grazzini, Kallweit, Rathlev '15
  - ◇ WW (on-shell) Gehrmann et al. '14
  - ◇ $gg \to VV \to 4$ leptons Binoth et al. '05,'06

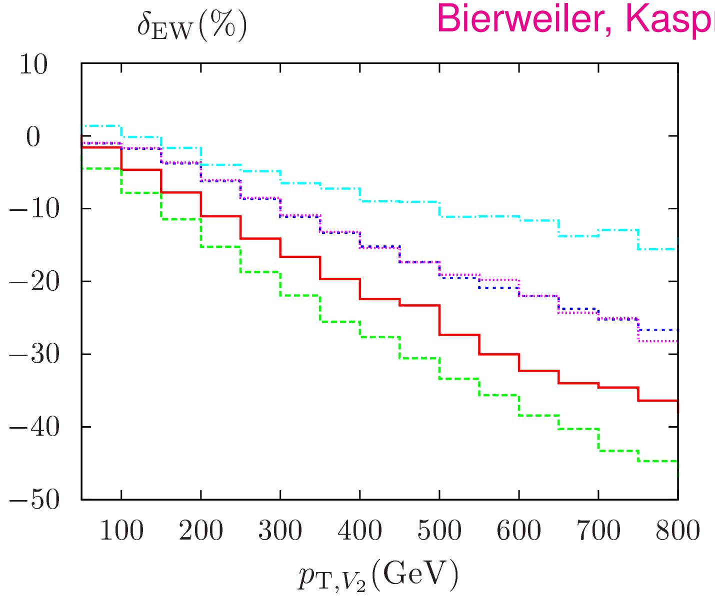
    + NLO corrections for on-shell V's Caola et al. '15
- NLO EW
  - ◇ stable W/Z bosons Bierweiler, Kasprzik, Kühn '12/'13; Baglio, Le, Weber '13
  - ◇ $pp \to WW \to 4$ leptons in DPA Billoni, S.D., Jäger, Speckner '13
  - ◇ approximative inclusion in HERWIG++ Gieseke, Kasprzik, Kühn '14
  - ◇ full off-shell calculations in progress ($pp \to \mu^+\mu^-e^+e^-$ completed)

    Biedermann et al. '16

EW corrections to massive di-boson production (stable/on-shell W/Z bosons)

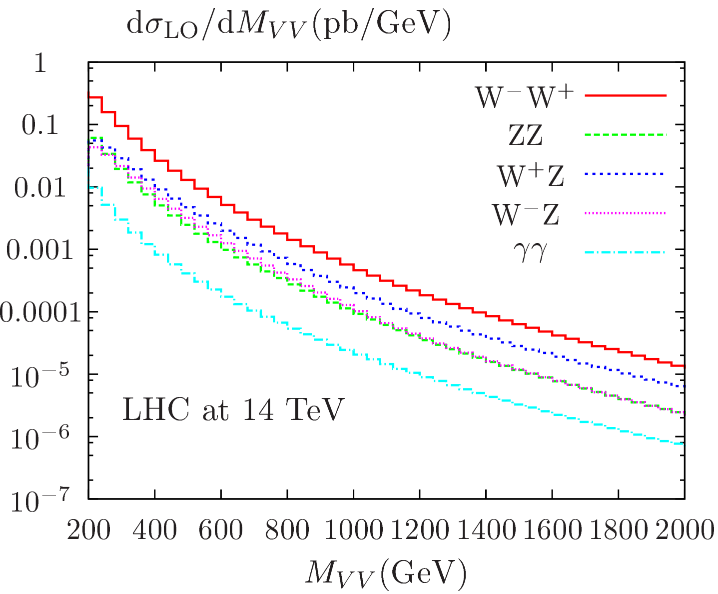
Bierweiler, Kasprzik, Kühn '13

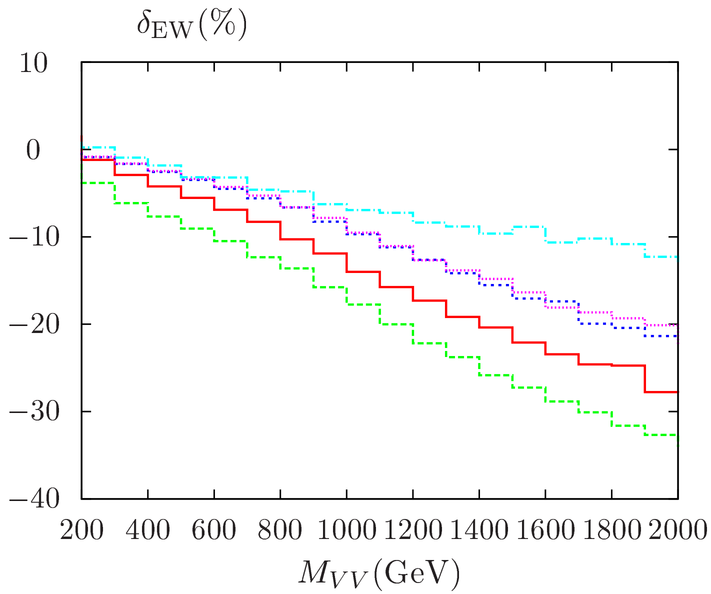




EW corrections

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



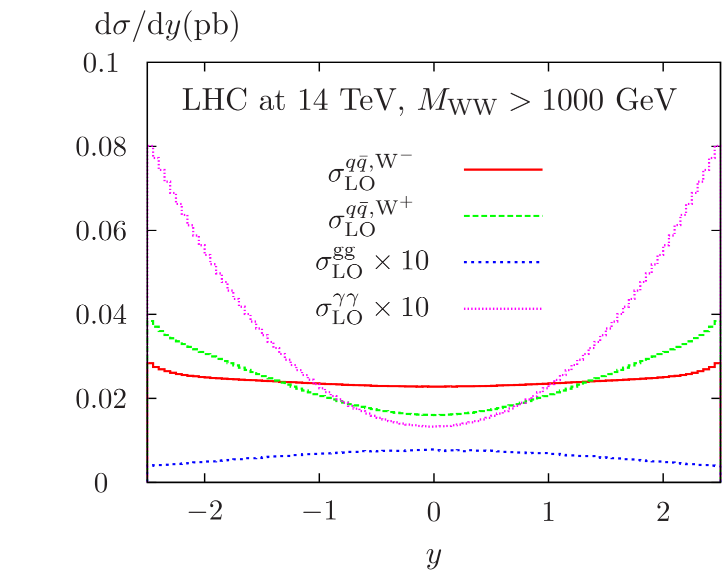


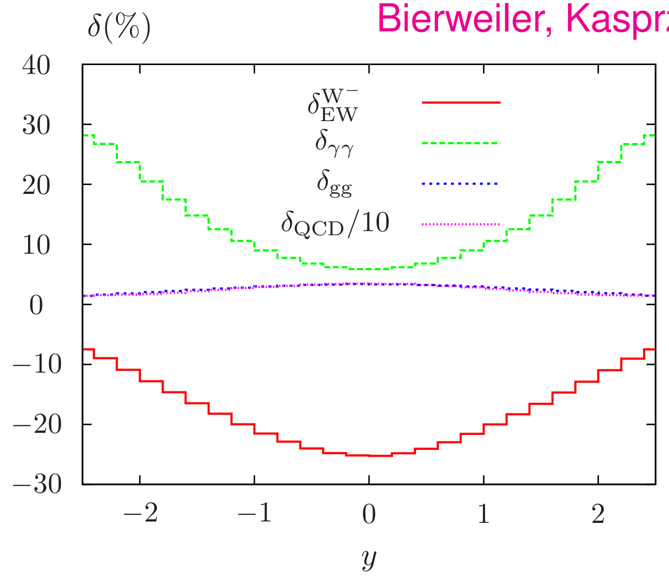
Note:

- M_{VV} not accessible for W final states
- on-shell approximation not applicable for $M_{VV} < M_{V_1} + M_{V_2}$

EW corrections to WW production (stable/on-shell W bosons)

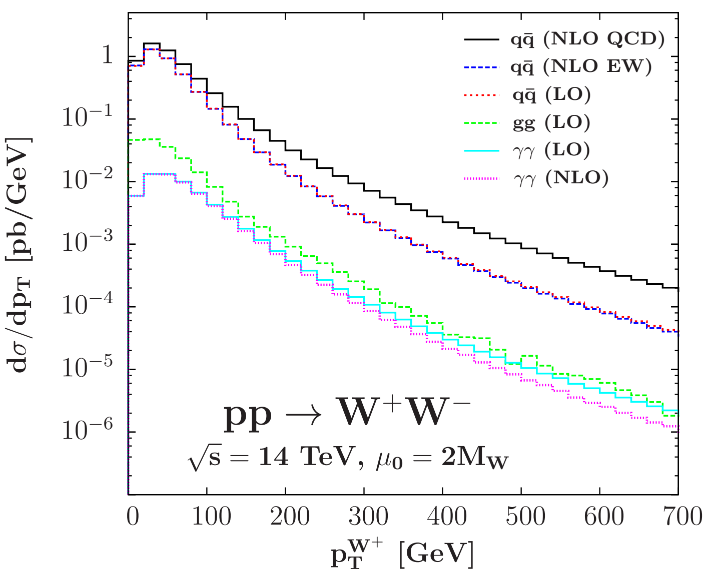
Bierweiler, Kasprzik, Kühn '12

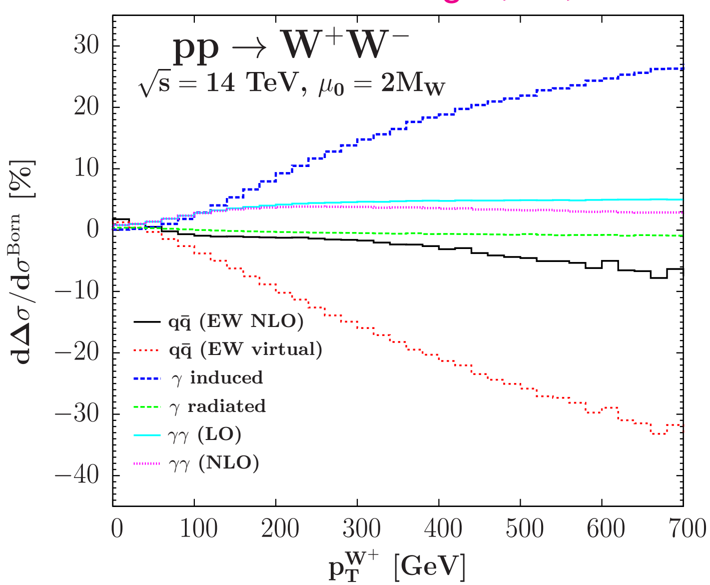




Note:
large contribution by $\gamma\gamma$ channel for high invariant WW masses !

Baglio, Le, Weber '13



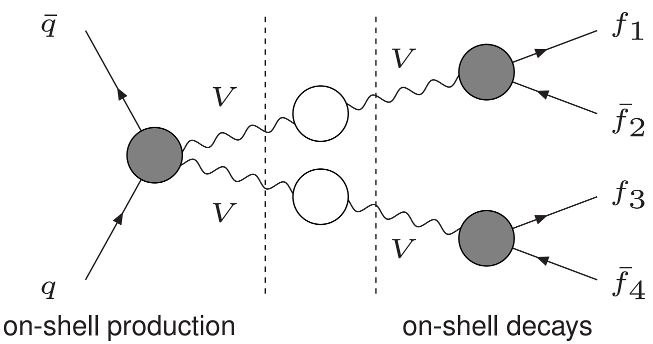


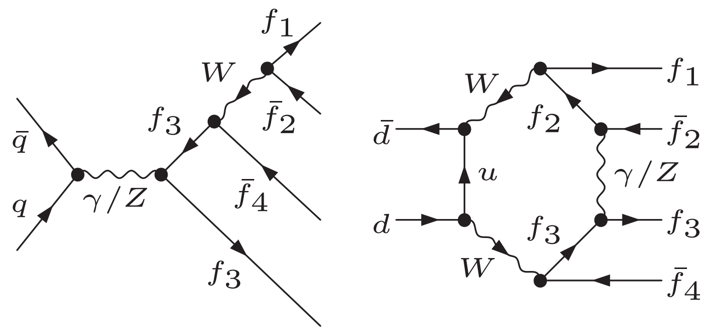
Note:
large impact of $q\gamma$ collisions killed by jet veto

Details of the calculation

EW corrections with leptonic W/Z decays

Double-pole approximation (DPA) vs. Full off-shell $q\bar{q} \to 4f$ calculation





DPA:

- expansion about resonance poles
  $\hookrightarrow$ factorizable & non-factorizable corrs.
- not many diagrams ($2\to2$ production)

\+ numerically fast

– validity only for $\sqrt{\hat{s}} > 2M_V + \mathcal{O}(\Gamma_V)$

- error estimate for $\sqrt{\hat{s}} \lesssim 0.5{-}1\,\mathrm{TeV}$:
  $\Delta \sim \frac{\alpha}{\pi}\frac{\Gamma_V}{M_V}\log(\ldots) \sim 0.5{-}2\%$

Full off-shell:

- off-shell calculation with complex-mass scheme
- many off-shell diagrams ($\sim 10^3$/channel)

– CPU intensive

\+ NLO accuracy everywhere

- global error estimate:
  $\Delta \sim \delta_{\mathrm{NNLO\,EW}} \sim \delta^2_{\mathrm{NLO\,EW}}$

Approaches compared for $\mathrm{e}^+\mathrm{e}^- \to \mathrm{WW} \to 4f$ Denner, S.D., Roth, Wieders '05

New: $\mathrm{pp} \to \mathrm{WW} \to 4f$ Biedermann et al. (in preparation)

Details of the full $4f$ NLO calculation

Virtual corrections

- one version diagrammatically as for $e^+e^- \to WW \to 4f$ Denner et al. '05
- another version based on recursive method with RECOLA Actis et al. '13
- some checks done with FEYNARTS/FORMCALC in the framework of POLE Accomando et al. '05
- W/Z resonances treated in the *complex-mass scheme*
- loop integrals evaluated with COLLIER

Real corrections and Monte Carlo integration

- IR singularities treated with dipole subtraction Catani, Seymour '96; S.D. '99; S.D. et al. '08
- collinear-unsafe ("bare") and "dressed" leptons supported
- multi-channel Monte Carlo integration

γ-induced contributions

- $\gamma\gamma$ collisions included in LO (small contributions)
- $q\gamma$ contributions taken into account

Two independent calculations of all ingredients

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'05

'13

POLE

et al. '05

'99; S.D. et al. '08

Collier – Hepforge http://collier.hepforge.org/private/index.html

Collier is hosted by Hepforge, IPPP Durham

COLLIER

A Complex One-Loop LIbrary with Extended Regularizations

Released on April 25!

Authors

Ansgar Denner	*Universität Würzburg, Germany*
Stefan Dittmaier	*Universität Freiburg, Germany*
Lars Hofer	*Universitat de Barcelona, Spain*

Features of the library

COLLIER is a fortran library for the numerical evaluation of one-loop scalar and tensor integrals appearing in perturbative relativistic quantum field theory with the following features:

- scalar and tensor integrals for high particle multiplicities
- dimensional regularization for ultraviolet divergences
- dimensional regularization for soft infrared divergences (mass regularization for abelian soft divergences is supported as well)
- dimensional regularization or mass regularization for collinear mass singularities
- complex internal masses (for unstable particles) fully supported (external momenta and virtualities are expected to be real)
- numerically dangerous regions (small Gram or other kinematical determinants) cured by dedicated expansions
- two independent implementations of all basic building blocks allow for internal cross-checks
- cache system to speed up calculations

If you use Collier for a publication, please cite all the references listed here!

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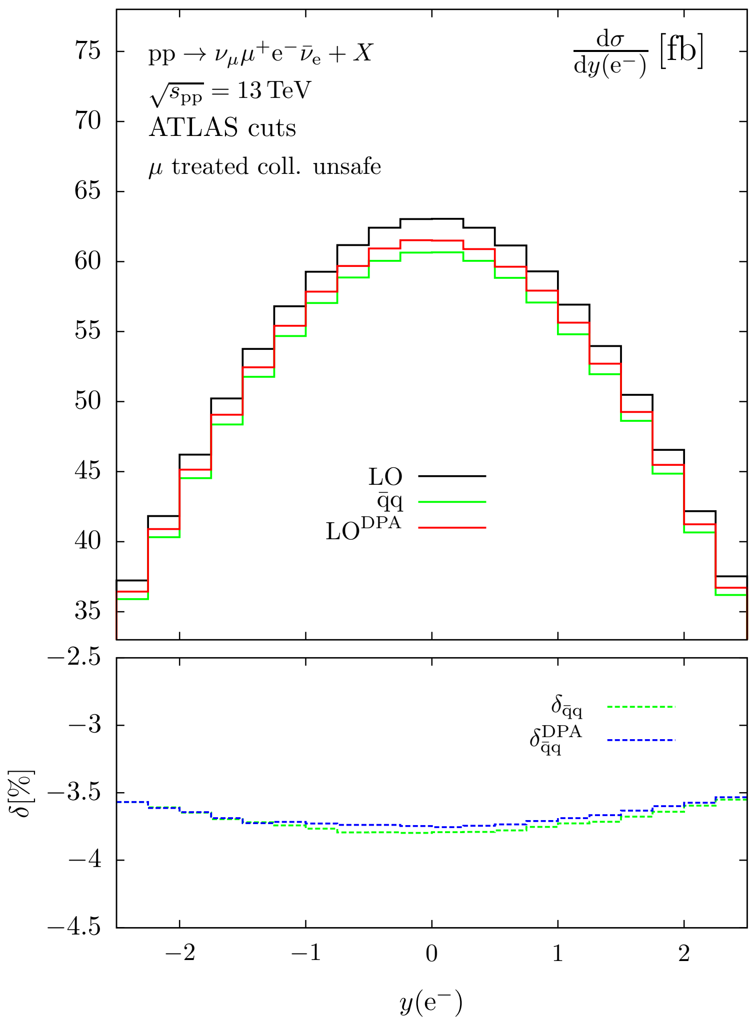
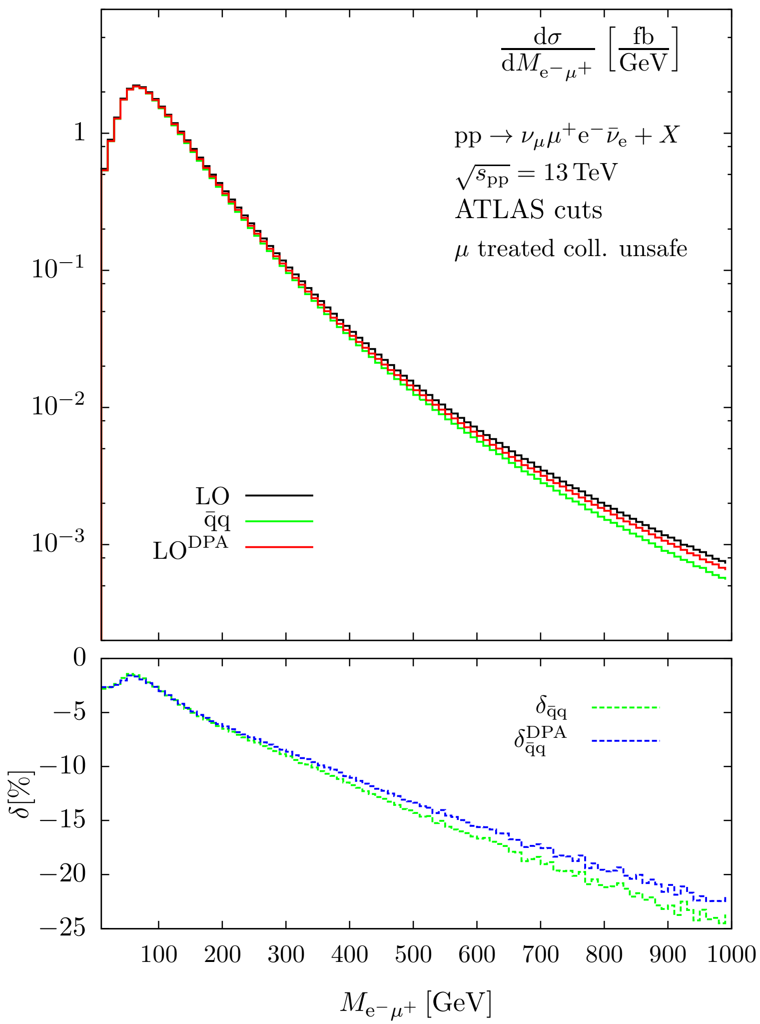
Two independent calculations of all ingredients

Results for $\mathrm{pp} \to \nu_\mu \mu^+ \mathrm{e}^- \bar{\nu}_\mathrm{e} + X$

DPA versus full off-shell EW correction in $\mathrm{pp} \to \nu_\mu \mu^+ \mathrm{e}^- \bar{\nu}_\mathrm{e} + X$ Biedermann et al. '16

Rapidity and invariant-mass distributions **Preliminary!**

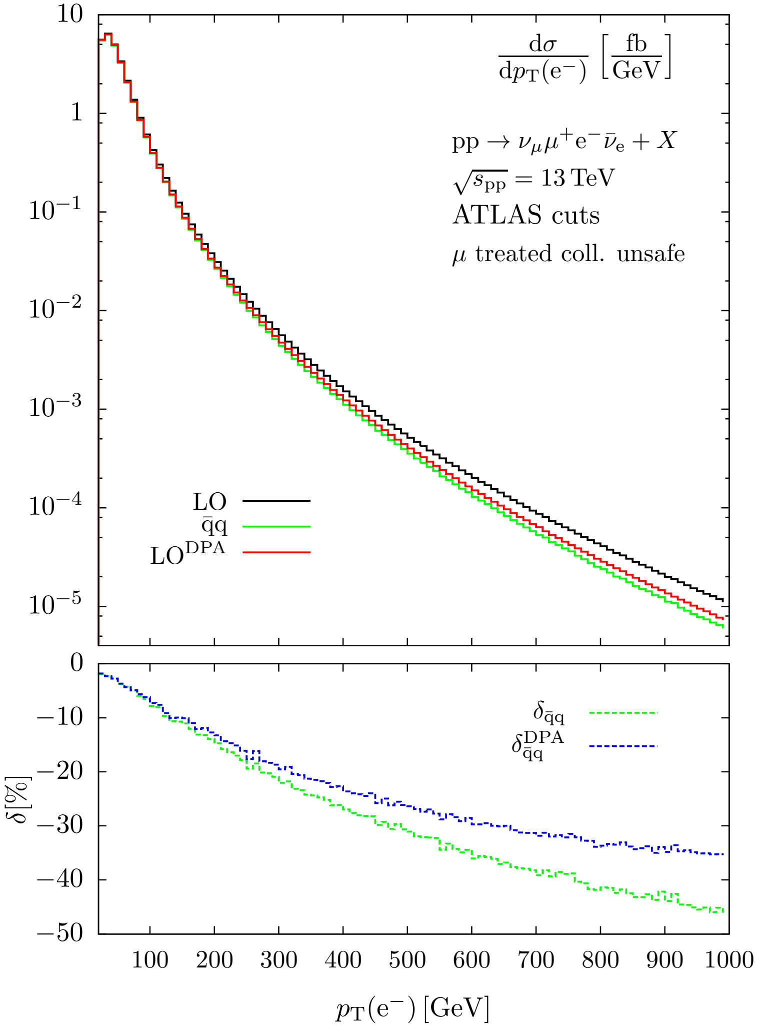


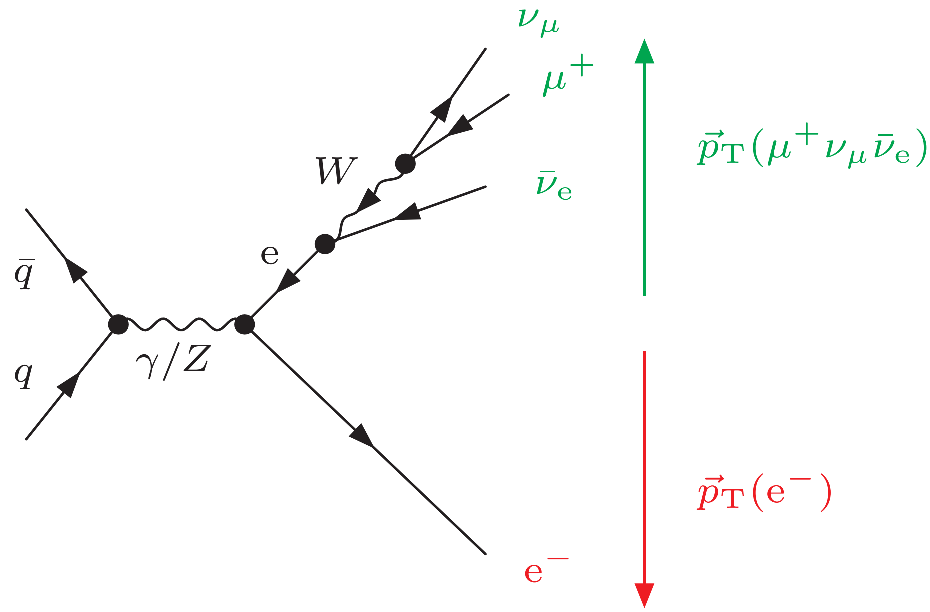


Level of agreement as expected (dominance of doubly-resonant diagrams)

DPA versus full off-shell EW correction in $\mathrm{pp} \to \nu_\mu \mu^+ \mathrm{e}^- \bar{\nu}_\mathrm{e} + X$ Biedermann et al. '16

Transverse-momentum distribution of a single lepton **Preliminary!**



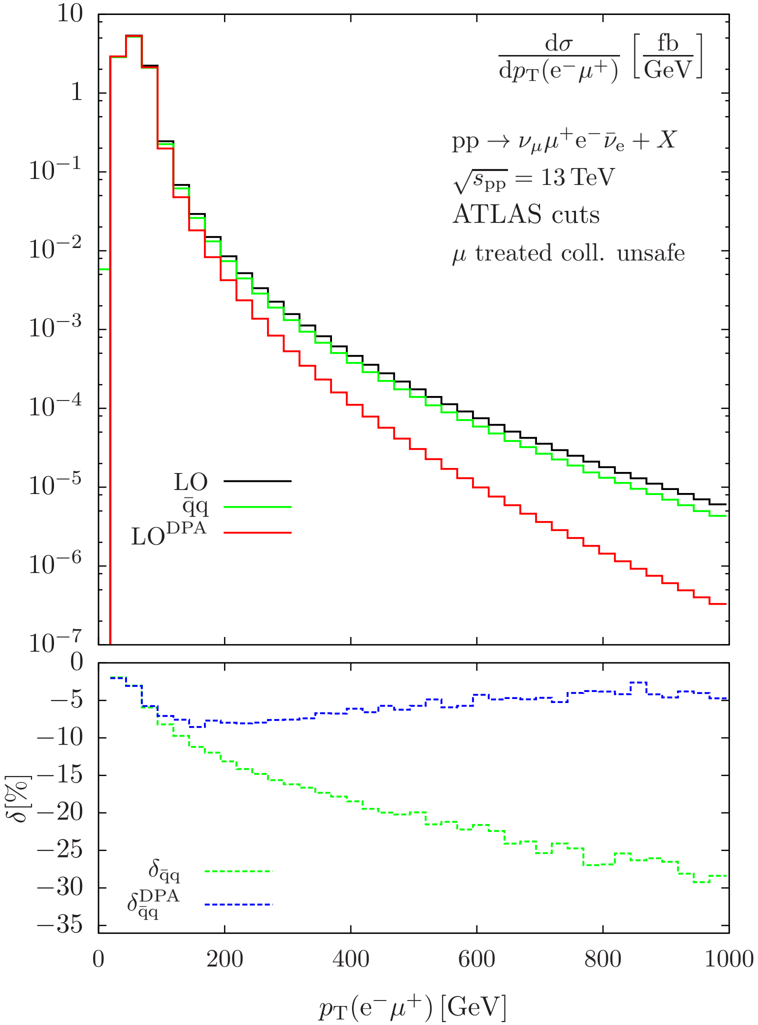


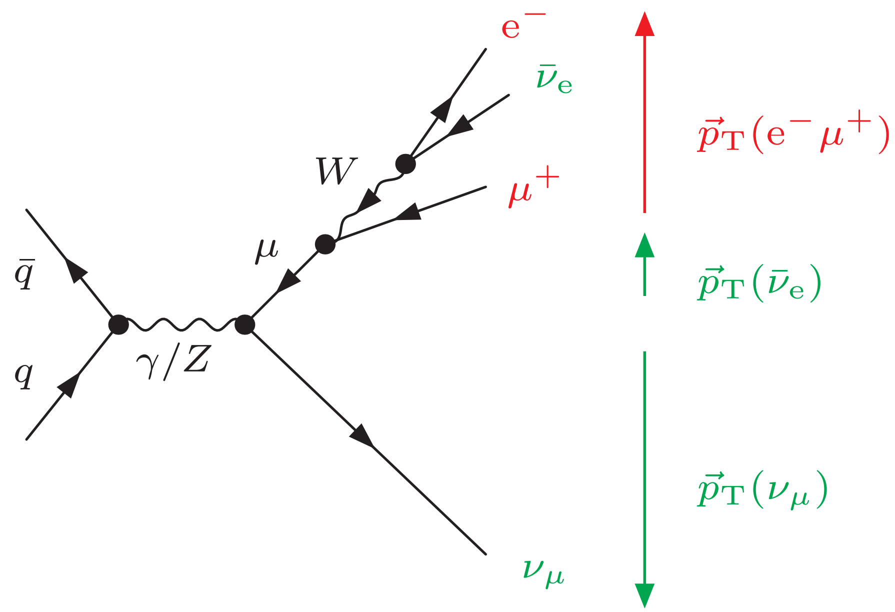
Impact of singly-resonant diagrams where e^- takes recoil from $(\mu^+\nu_\mu\bar{\nu}_\mathrm{e})$

Agreement degrades for $p_\mathrm{T} \gtrsim 300\,\mathrm{GeV}$, since off-shell diagrams get enhanced

DPA versus full off-shell EW correction in $\mathrm{pp} \to \nu_\mu \mu^+ \mathrm{e}^- \bar{\nu}_\mathrm{e} + X$ Biedermann et al. '16

Transverse-momentum distribution of the charged lepton pair **Preliminary!**





- Double resonance extremely suppressed !
- Dominance of singly-resonant diagrams where $(\mathrm{e}^-\mu^+)$ recoil against $(\nu_\mu\bar{\nu}_\mathrm{e})$

DPA fails for $p_\mathrm{T} \gtrsim 200\,\mathrm{GeV}$, since off-shell production dominates!

Results for $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + X$

A Higgs background study for $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + X$ Biedermann et al. '16

Setup (inspired by ATLAS)

$$p_\mathrm{T}(\ell_i) > 6\,\mathrm{GeV}, \quad |y(\ell_i)| < 2.5, \quad \Delta R(\ell_i, \ell_j) = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2} > 0.2$$

$$40\,\mathrm{GeV} < M_{\ell_1^+\ell_1^-} < 120\,\mathrm{GeV}, \qquad 12\,\mathrm{GeV} < M_{\ell_2^+\ell_2^-} < 120\,\mathrm{GeV}$$

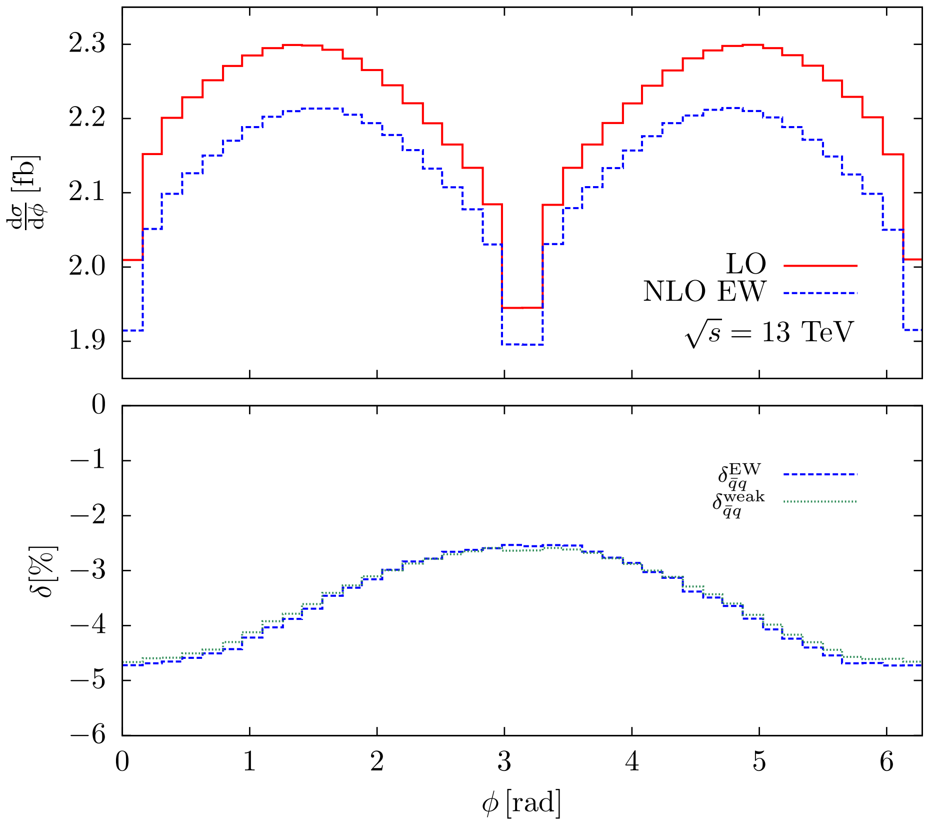
Integrated cross section

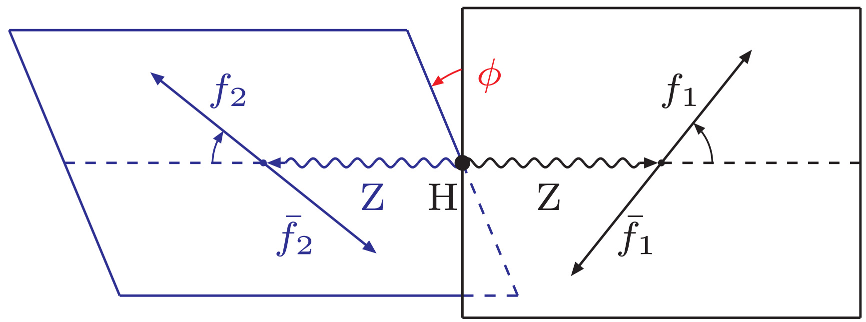
$\sqrt{s}$ [TeV]	$\sigma^{\mathrm{LO}}_{\bar{q}q}$ [fb]	$\delta^{\mathrm{EW}}_{\bar{q}q}$ [%]	$\delta^{\mathrm{weak}}_{\bar{q}q}$ [%]
7	7.3293(4)	−3.4	−3.3
8	8.4704(2)	−3.5	−3.4
13	13.8598(3)	−3.6	−3.6
14	14.8943(8)	−3.6	−3.6

- weak corrections moderate
- photonic corrections negligible
  (due to inclusiveness of the event selection)
- deviation of δ from on-shell ZZ calculation $\sim$ 1%

A Higgs background study for $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + X$ Biedermann et al. '16

Distribution in the angle between decay planes

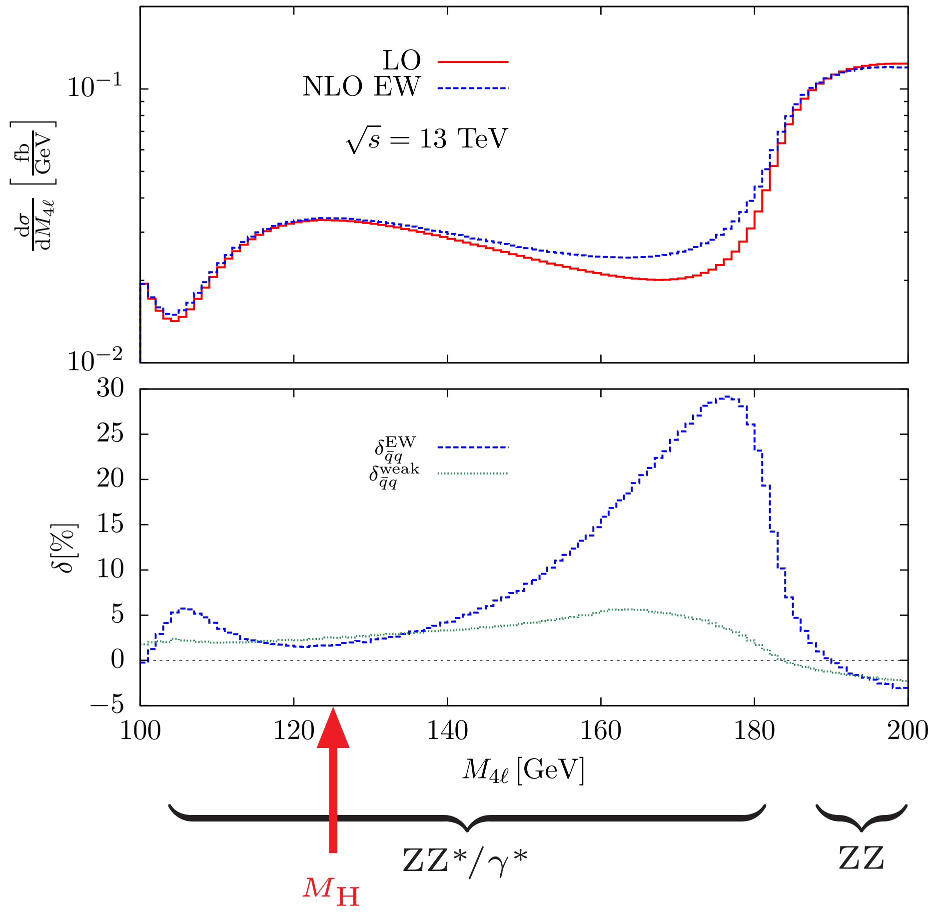




- observable dominated by resonant ZZ production
- corrections mostly resemble corrections to the integrated cross section
- photonic corrections extremely suppressed
  (insensitivity of ϕ to collinear photon emission off leptons)

A Higgs background study for $\mathrm{pp} \to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^- + X$ Biedermann et al. '16

Distribution in the 4-lepton invariant mass



- large radiative tails in photonic corrections below thresholds (known effect ...)
- weak corrections $\sim \mathcal{O}(5\%)$
  with sign change in transition from on-shell ZZ to off-shell ZZ^*/γ^* region

Conclusions

Di-boson production at the LHC

- sensitive to non-Abelian gauge-boson self-interactions
- important background
  - to new-physics searches and
  - to precision Higgs analyses in $\mathrm{pp} \to \mathrm{H} \to \mathrm{WW/ZZ} \to 4f$

$\Rightarrow$ Precise predictions with QCD and EW corrections required

Recent progress at the precision frontier

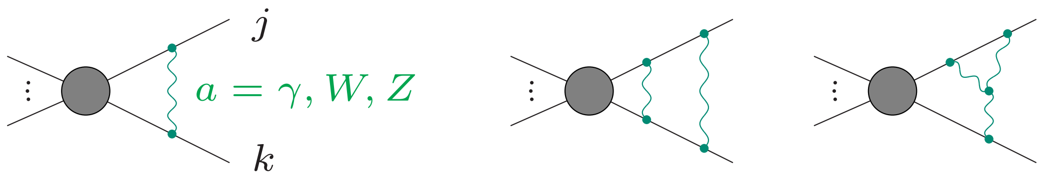
- QCD corrections:
  - NNLO to direct VV' production (Vs partially off-shell)
  - NLO to loop-induced channels $\mathrm{gg} \to VV$ (on-shell)
  - resummations, parton-shower matching
- This talk: NLO EW corrections to $\mathrm{pp} \to \mathrm{WW/ZZ} \to 4$ leptons fully including off-shell effects
  - limitations of double-pole approximation at large p_T revealed
  - interesting behaviour below ZZ threshold

$\Rightarrow$ SM predictions in good shape!

Backup slides

Electroweak 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

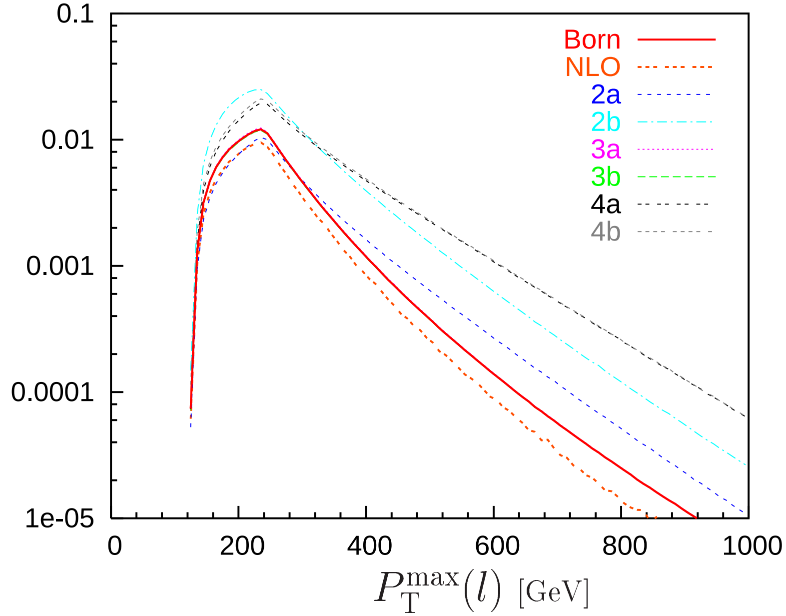
Extensive theoretical studies at fixed perturbative (1-/2-loop) order and suggested resummations via evolution equations

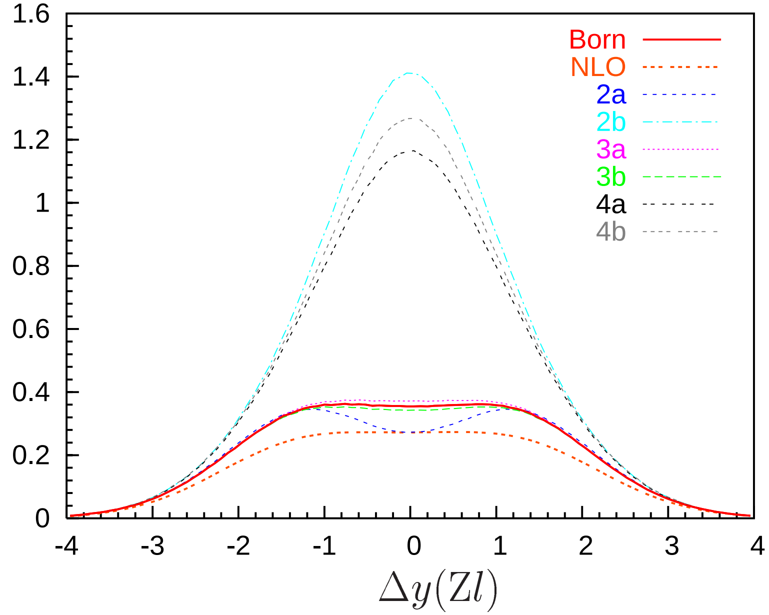
Beccaria et al.; Beenakker, Werthenbach; Ciafaloni, Comelli; Denner, Pozzorini; Fadin et al.; Hori et al.; Melles; Kühn et al., Denner et al., Manohar et al. '00–

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

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

Accomando, Kaiser '05





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

$$\lambda_Z = \lambda_\gamma, \quad \Delta\kappa_Z = \Delta g_1^Z - \tan^2\theta_W \Delta\kappa_\gamma$$

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

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

Note:

- EW corrections and anomalous couplings distort distributions
- neglect of EW corrections can mimick anomalous couplings

Width schemes for LO calculations and gauge invariance

Naive propagator substitutions in full tree-level amplitudes:

$$\frac{1}{k^2-m^2} \to \frac{1}{k^2-m^2+\mathrm{i}m\Gamma(k^2)} \qquad \text{in all propagators}$$

- constant width $\Gamma(k^2) = \text{const.}$ $\to$ U(1) respected, SU(2) “mildly” violated
- running width $\Gamma(k^2) \neq \text{const.}$ $\to$ U(1) and SU(2) violated

  $\hookrightarrow$ results can be totally wrong !

Fudge factor approaches:

Multiply full amplitudes without widths with

factors $\frac{p^2-m^2}{p^2-m^2+\mathrm{i}m\Gamma}$ for each potentially resonant propagator

$\hookrightarrow$ gauge invariant, but spurious factors of $\mathcal{O}(\Gamma/m)$

Complex-mass scheme: (see lecture 1)

Consistent use of complex masses everywhere (including couplings)

For W/Z bosons: $M_V^2 \to \mu_V^2 = M_V^2 - \mathrm{i}M_V\Gamma_V, \quad V = \mathrm{W}, \mathrm{Z}$

complex weak mixing angle: $c_\mathrm{W}^2 = 1 - s_\mathrm{W}^2 = \frac{\mu_\mathrm{W}^2}{\mu_\mathrm{Z}^2}$

$\hookrightarrow$ gauge invariance fully respected

Gauge-invariant width schemes @ NLO

Problem much more complicated than at LO !   (would fill own lectures)

Complex-Mass Scheme (CMS)   Denner, S.D., Roth, Wieders ’05

- complex, but straightforward renormalization
- NLO everywhere in phase space
- loop integrals with complex masses

Pole Approximation (PA)   (= leading term of pole expansion)

- corrections decomposed into two types
  - ◇ factorizable: corrections to on-shell production / decay
  - ◇ non-factorizable: soft photon/gluon exchange between production / decays
- NLO in neighbourhood of resonances
- PA involves less diagrams than CMS $\rightarrow$ higher multiplicities possible

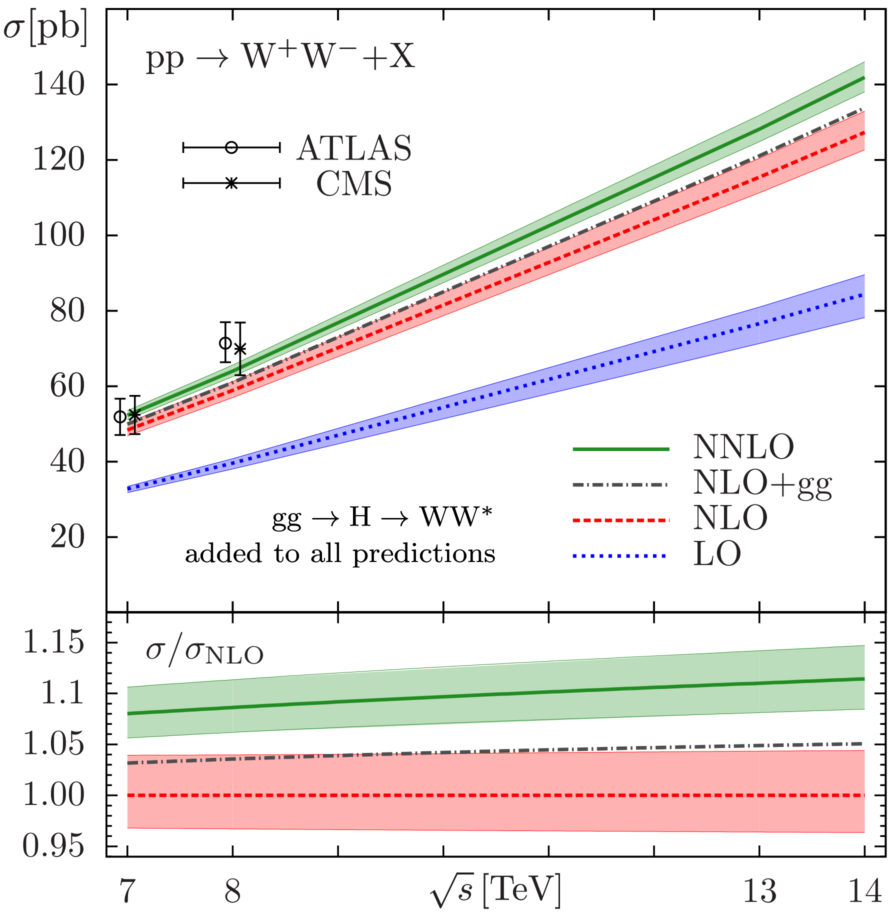
Effective Field Theories   Beneke et al. ’03,’04; Hoang,Reisser ’04

- involves pole expansions $\rightarrow$ NLO in neighbourhood of resonances
- formal elegance $\rightarrow$ e.g. combination with resummations

$\hookrightarrow$ **For details & examples see literature ...**

WW production – NNLO QCD theory versus experiment

Gehrmann et al. '14



Subtlety:

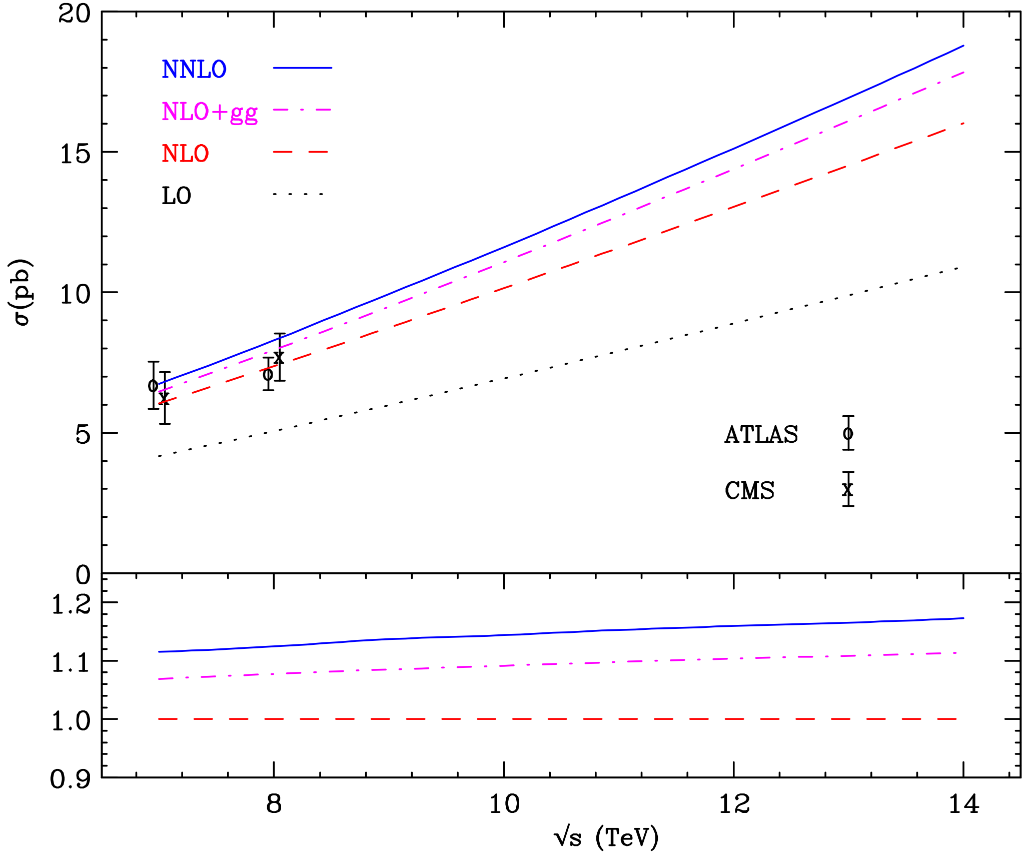
Separation of single-t and $t\bar{t}$ contributions @ NNLO QCD

$\hookrightarrow$ b-jet veto, etc.

- good agreement of experimental results with NNLO QCD
- NNLO QCD correction $\sim 7(12)\%$ @ $8(13)\,\mathrm{TeV}$, scale uncertainty $\lesssim 3\%$
- gg contribution $\sim 7(8)\%$ @ $8(13)\,\mathrm{TeV}$
- LHC run 2: higher energy & higher statistics $\rightarrow$ EW corrections important

ZZ production – NNLO QCD theory versus experiment

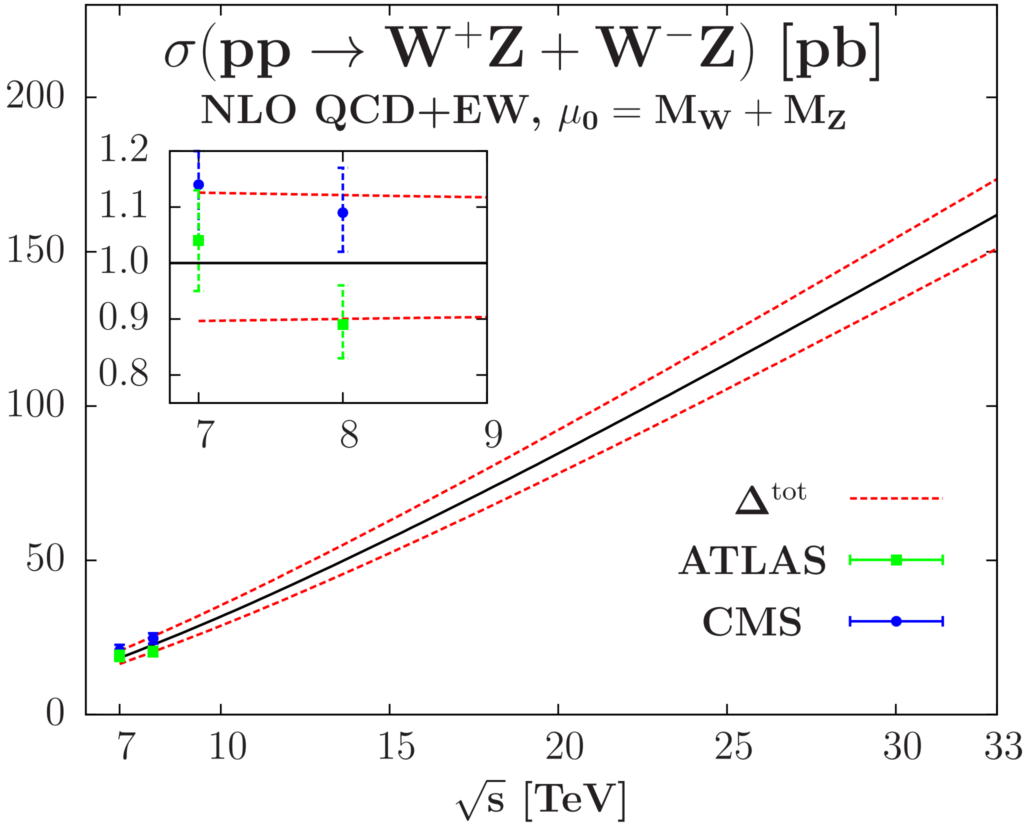
Cascioli et al. '14



- good agreement of experimental results with NNLO QCD
- NNLO QCD correction $\sim 12(17)\%$ @ $8(13)\,\mathrm{TeV}$, scale uncertainty $\lesssim 3\%$
- gg contribution $\sim 7(10)\%$ @ $8(13)\,\mathrm{TeV}$
- LHC run 2: higher energy & higher statistics $\rightarrow$ EW corrections important

WZ production – NLO QCD theory versus experiment

Baglio, Le, Weber et al. '13



- good agreement of experimental results with NLO QCD
- NLO QCD scale uncertainty $\sim 3\%$, $\quad \Delta_{\mathrm{PDF}+\alpha_s} \sim 4\%$
- LHC run 2: higher energy & higher statistics
  $\hookrightarrow$ NNLO QCD and NLO EW corrections important