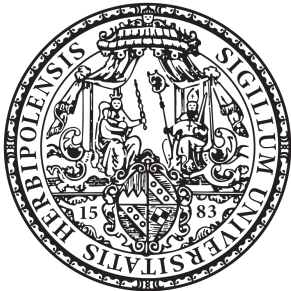


# Electroweak and QCD corrections to $W + \text{Photon}$ production



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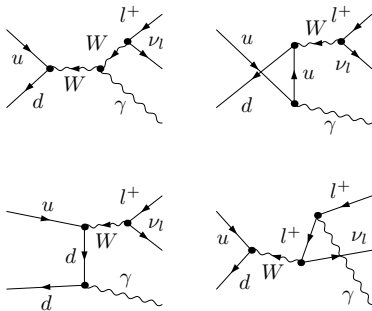
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# Motivation



- Testing the Standard Model
- Anomalous triple gauge coupling  $WW\gamma \rightarrow$  deviation from SM  
 $\rightarrow$  new interactions
- Search of new particles that decay to  $W\gamma$   
 $\rightarrow$  background for new physics

## Overview

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### Leading-order cross section

- for on-shell (stable)  $W$  bosons [Brown,Sahdev,Mikaelian '79]

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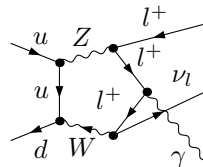
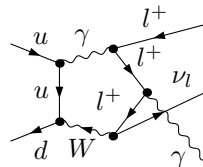
### QCD corrections

- on-shell  $W$  bosons [Smith,Thomas, van Neerven '89; Ohnemus '93]
- including leptonic decays in narrow-width approximation and anomalous couplings [Baur,Han,Ohnemus '93]
- full NLO QCD amplitudes including leptonic decays [Dixon,Kunszt,Signer '98]
  - Monte Carlo Program with leptonic decays in NWA [Florian,Signer '00]
  - also available in MCFM [Campbell,Ellis,Williams '11]
- first results of complete NNLO calculation [Grazzini '14]

# Overview

## EW corrections

- $q\bar{q}$ -channel in Leading-Pole Approximation, Pentagons in Extended Soft Photon Approximation  $\rightarrow$  POLE [Accomando,Denner,Meier '05]
- Several open tasks:
  - inclusion of all off-shell effects
  - photon-induced contributions
  - non-collinear-safe observables



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## Technical overview

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### virtual EW corrections

- 280 one-loop diagrams up to pentagons (50 boxes, 16 pentagons)
- resonant  $W$ -boson propagators  $\rightarrow$  complex-mass scheme

[Denner,Dittmaier '06]

## Technical overview

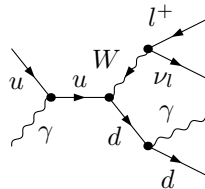
### virtual EW corrections

- 280 one-loop diagrams up to pentagons (50 boxes, 16 pentagons)
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[Denner,Dittmaier '06]

### photon-induced contributions

- photon-PDFs necessary  
 $\rightarrow \mathcal{O}(\alpha)$ -corrected NNPDF2.3QED
- well defined separation between  $W + \gamma$   
and  $W + \text{jet}$  needed



## Technical background

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### Details of calculations:

- Matrix element generation based on Feynman diagrams
- Code based on the program **Pole** [Accomando,Denner,Meier '05]  
→ based on **FormCalc** and **Feynarts** [Hahn,Perez-Victoria '99],[Hahn '01]
- Integration: Monte-Carlo-Generator **LUSIFER** [Dittmaier,Roth '02]
- Scalar integrals: **COLLIER** [Denner,Dittmaier,Hofer '14]
- Second independent calculation → Freiburg group

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### Soft and collinear singularities:

- IR singularities → Dipole subtraction formalism  
(collinear-safe and non-collinear-safe observables)
- Collinear photon–jet configurations → Quark-to-photon fragmentation function
- Initial-state singularities factorized into renormalized PDFs

## Collinear-safe vs. non-collinear-safe observables

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**collinear-safe:** (final-state electrons)

- collinear fermion-photon system is treated as one particle
- sum of fermion and photon momentum enter phase-space cuts and is used for histogram binning  
⇒ recombination
- full integration over energy fraction of the photon in the fermion-photon system

## Collinear-safe vs. non-collinear-safe observables

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- sum of fermion and photon momentum enter phase-space cuts and is used for histogram binning  
⇒ recombination
- full integration over energy fraction of the photon in the fermion-photon system

### **non-collinear-safe:** (final-state muons) [Dittmaier, Kabelschacht, Kasprzik '08]

- not all photons around a charged particle are treated inclusively
- phase-space cut on energy fraction of the photon for a fixed cone around the fermion  
⇒  $\alpha \ln m_f$  contributions remain in the integral

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## General setup

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### NLO-QCD-corrected cross section:

$$\sigma^{\text{NLO QCD}} = \sigma^0 + \Delta\sigma^{\text{NLO QCD}},$$

$$\Delta\sigma^{\text{NLO QCD}} = \sigma_{\text{real}}^{\alpha_s} + \sigma_{\text{virt}}^{\alpha_s} + \sigma_{\text{col}}^{\alpha_s} + \sigma_{\text{frag}}^{\alpha_s}.$$



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### EW corrections:

$$\begin{aligned}\Delta\sigma_{q\bar{q}}^{\alpha} &= \sigma_{q\bar{q},\text{real}}^{\alpha} + \sigma_{q\bar{q},\text{virt}}^{\alpha} + \sigma_{q\bar{q},\text{col}}^{\alpha}, \\ \Delta\sigma_{q\gamma}^{\alpha} &= \sigma_{q\gamma,\text{real}}^{\alpha} + \sigma_{q\gamma,\text{col}}^{\alpha} + \sigma_{q\gamma,\text{frag}}^{\alpha}.\end{aligned}$$

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### EW corrections:

$$\Delta\sigma_{q\bar{q}}^{\alpha} = \sigma_{q\bar{q},\text{real}}^{\alpha} + \sigma_{q\bar{q},\text{virt}}^{\alpha} + \sigma_{q\bar{q},\text{col}}^{\alpha},$$

$$\Delta\sigma_{q\gamma}^{\alpha} = \sigma_{q\gamma,\text{real}}^{\alpha} + \sigma_{q\gamma,\text{col}}^{\alpha} + \sigma_{q\gamma,\text{frag}}^{\alpha}.$$

### Combination of QCD and EW corrections:

$$\sigma^{\text{NLO}} = \sigma^{\text{LO}} (1 + \delta_{\text{QCD}}) (1 + \delta_{\text{EW},q\bar{q}} + \delta_{\text{EW},q\gamma}),$$

$$\delta_{\text{QCD}} = \frac{\sigma^{\text{NLO QCD}} - \sigma^{\text{LO}}}{\sigma^{\text{LO}}}, \quad \delta_{\text{EW},q\bar{q}} = \frac{\Delta\sigma_{q\bar{q}}^{\alpha}}{\sigma^0}, \quad \delta_{\text{EW},q\gamma} = \frac{\Delta\sigma_{q\gamma}^{\alpha}}{\sigma^0}.$$

## Results for total cross section

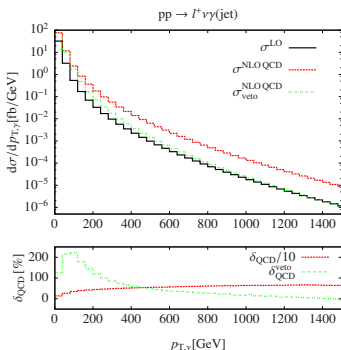
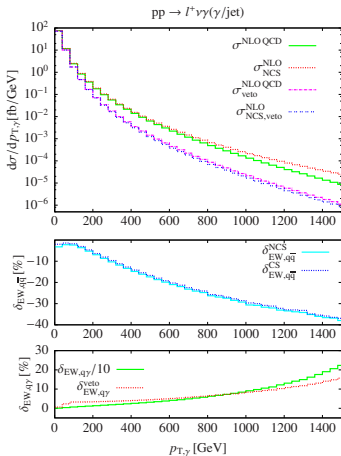
$pp \rightarrow l^+ \nu_l \gamma + X$			
$\sqrt{s}/\text{TeV}$	7	8	14
$\sigma^{\text{LO}}/\text{fb}$	1037.28(5)	1157.10(5)	1447.99(4)
$\delta_{\text{EW},q\bar{q}}^{\text{NCS}}/\%$	-3.15	-3.14	-3.15
$\delta_{\text{EW},q\bar{q}}^{\text{CS}}/\%$	-1.95	-1.94	-1.95
$\delta_{\text{EW},q\gamma}/\%$	1.04	1.10	1.30
$\delta_{\text{EW},q\gamma}^{\text{veto}}/\%$	0.74	0.76	0.84
$\delta_{\text{QCD}}/\%$	122.33(4)	128.30(5)	153.61(3)
$\delta_{\text{QCD}}^{\text{veto}}/\%$	112.47(4)	117.15(5)	135.97(9)

[Denner,Dittmaier,Hecht,Pasold in prep.]

PDFs with photonic contributions: NNPDF2.3QED NLO [arxiv:1308.0598]

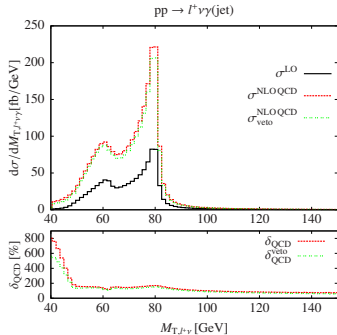
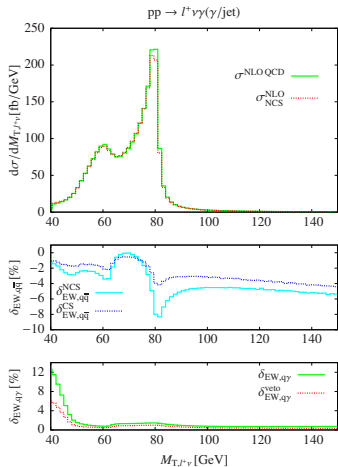
Standard cuts motivated by ATLAS [arXiv:1407.8150] and CMS [arXiv:1308.6832]

# Transverse momentum distribution for photon



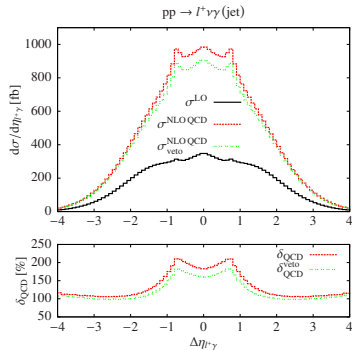
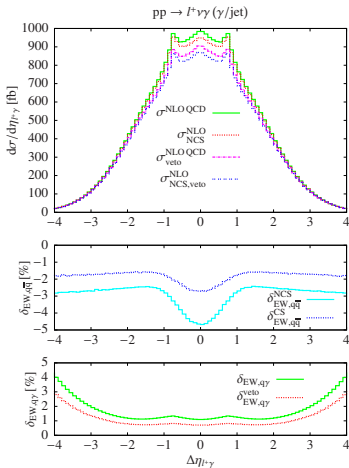
- Large QCD corrections
- Large corrections from  $q\gamma$   
→ reducible by jet veto
- Jet veto:  $q\bar{q}$ -induced EW corrections are dominating

# Transverse mass distribution lepton–neutrino pair



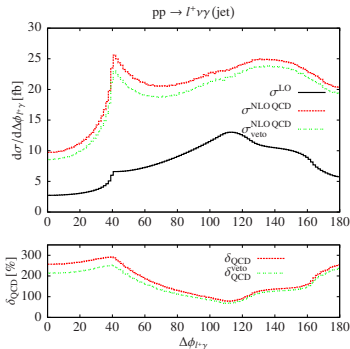
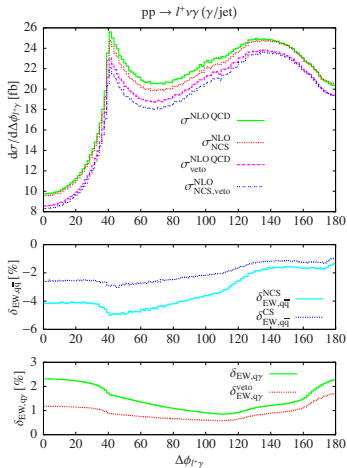
- Peak around 60 GeV
- QCD corrections  $\mathcal{O}(150\%)$
- EW corrections up to  $-8\%$

# Rapidity difference for charged lepton and photon



- QCD corrections up to 200%  
→ large shape distortions
- EW corrections up to 5%  
→ large shape distortions

# Azimuthal angle difference for lepton and photon



- QCD corrections up to 300%  
→ large shape distortions
- EW corrections up to 5%

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## Conclusion

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- full calculation of NLO corrections to  $W + \gamma$  production
  - all off-shell effects are included
  - including photon-induced contributions
  - Dipole subtraction for collinear-safe and non-collinear-safe observables
  - Quark-to-photon fragmentation function
    - well defined separation between  $W + \gamma$  and  $W + \text{jet}$
- huge QCD corrections → NNLO corrections necessary
- sizeable EW corrections ( $p_T$  distributions) with / without jet veto

**Impacts of aTGC's ⇒ talk by Markus Hecht**