Electroweak Precision Physics at the LHC

Alexander Mück
RWTH Aachen University

Standard Model @ LHC

IPPP Durham, April 12, 2011

Outline

- EW precision physics

  Where is EW precision achievable at the LHC?

  Where are EW corrections particularly important?

- specific EW issues

  How to treat resonances?

  How to treat photons?

- Calculations + tools for EW precision

  Which calculations are available?

  Which tools are available?

- Summary and questions

Prerequisites

LHC is a discovery machine!

Prerequisites

LHC as a tool for precision physics

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN

Prerequisites

LHC as a tool for precision physics

requirements:

- high experimental accuracy
- precise theoretical prediction

Prerequisites

LHC as a tool for precision physics

requirements:

- high experimental accuracy
- precise theoretical prediction

problems (to solve):

- hadron collider environment
- understand QCD (in signal and background)
    - Leading order (LO) up to 100% uncertainty
    - Next-to-leading order (NLO) needed everywhere
    - NNLO needed for high precision (some exceptions)

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN
RWTH

Prerequisites

LHC as a tool for precision physics

requirements:

- high experimental accuracy
- precise theoretical prediction

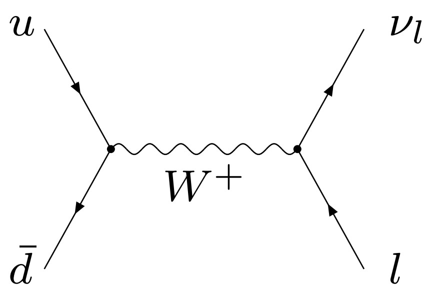
problems (to solve):

- hadron collider environment
- understand QCD (in signal and background)
  - Leading order (LO) up to 100% uncertainty
  - Next-to-leading order (NLO) needed everywhere
  - NNLO needed for high precision (some exceptions)

$\longrightarrow$ most of the talks at this workshop

Precision Channels

Charged-current Drell-Yan:



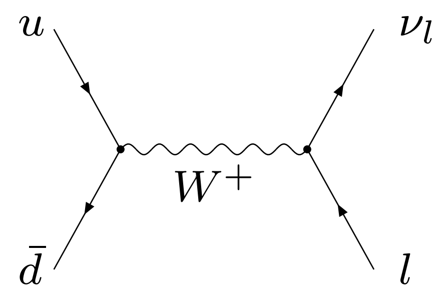
$$pp \to W^\pm \to l^\pm \nu_l$$

- clean signal: lepton + missing p_{T}
- huge cross section: $\sigma_{W^+ \to \mu^+ \nu_\mu} = 3$ nb (Atlas cuts at 7 TeV)

Precision Channels

Charged-current Drell-Yan:

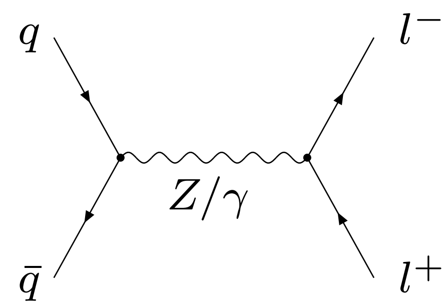
$$pp \to W^{\pm} \to l^{\pm}\nu_l$$



- clean signal: lepton + missing p_{T}
- huge cross section: $\sigma_{W^+ \to \mu^+ \nu_\mu} = 3$ nb (Atlas cuts at 7 TeV)

Neutral-current Drell-Yan:

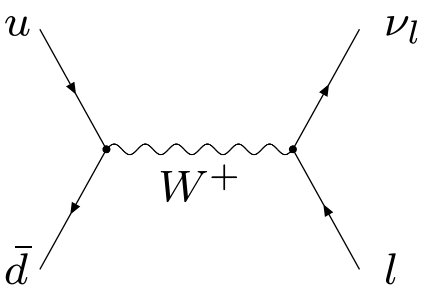
$$pp \to Z/\gamma \to l^+ l^-$$



- clean signal: charged lepton pair
- huge cross section: $\sigma_{Z \to \mu^+ \mu^-} = 0.5$ nb (Atlas cuts at 7 TeV)

Precision Channels

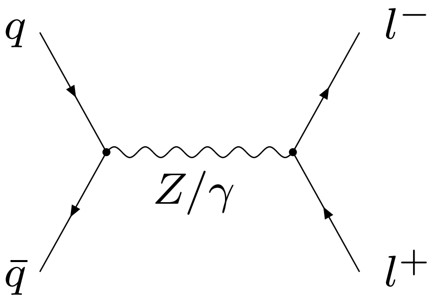
Charged-current Drell-Yan:



$$pp \to W^\pm \to l^\pm \nu_l$$

- clean signal: lepton + missing p_T
- huge cross section: $\sigma_{W^+\to\mu^+\nu_\mu} = 3$ nb (Atlas cuts at 7 TeV)

Neutral-current Drell-Yan:



$$pp \to Z/\gamma \to l^+ l^-$$

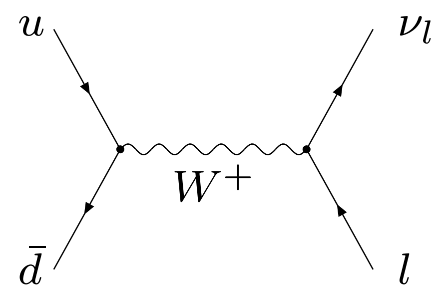
- clean signal: charged lepton pair
- huge cross section: $\sigma_{Z\to\mu^+\mu^-} = 0.5$ nb (Atlas cuts at 7 TeV)

Useful tool: calibration, luminosity, PDFs, QCD understanding

Precision Channels

Charged-current Drell-Yan:

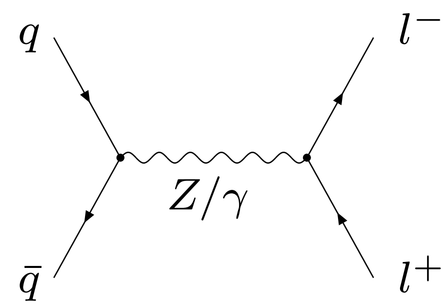
$$pp \to W^{\pm} \to l^{\pm}\nu_l$$



- clean signal: lepton + missing p_{T}
- huge cross section: $\sigma_{W^+\to\mu^+\nu_\mu} = 3$ nb (Atlas cuts at 7 TeV)

Neutral-current Drell-Yan:

$$pp \to Z/\gamma \to l^+l^-$$



- clean signal: charged lepton pair
- huge cross section: $\sigma_{Z\to\mu^+\mu^-} = 0.5$ nb (Atlas cuts at 7 TeV)

Useful tool: calibration, luminosity, PDFs, QCD understanding

Precision measurements: M_W, Γ_W, $\sin\theta_{\mathrm{eff}}^{\mathrm{lept}}$ (↔ LEP)

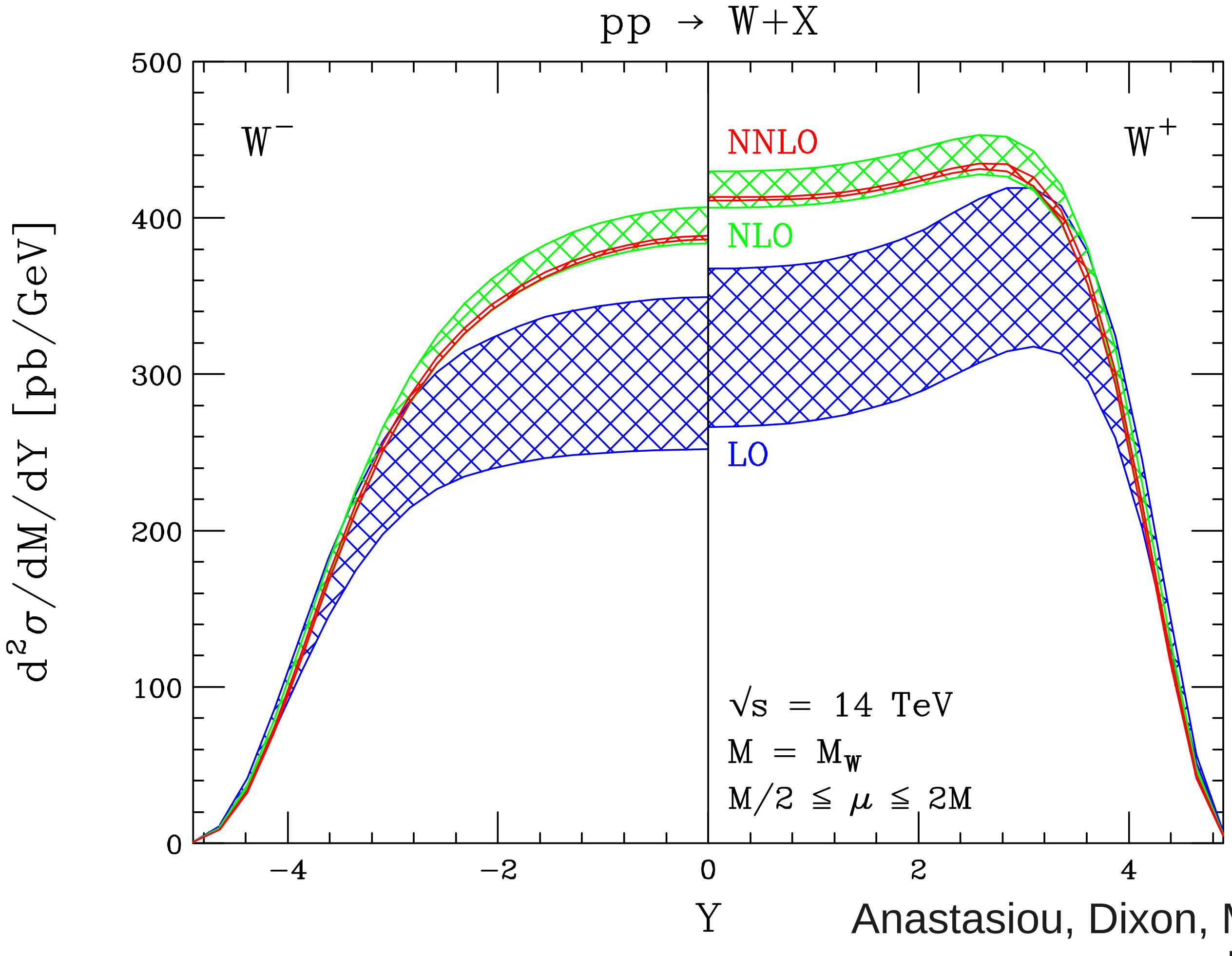
QCD Predictions for DY

NNLO QCD:

- total cross section — v.Neerven, Zijlstra [NPB **382** (1992) 11]; Harlander, Kilgore [hep-ph/0201206]
- rapidity distributions — Anastasiou et al. [hep-ph/0312266]
- fully differential cross sections — Melnikov, Petriello [hep-ph/0609070]; Catani et al. [arXiv:0903.2120]

QCD Predictions for DY

Rapidity distribution: 1% uncertainty at NNLO



Anastasiou, Dixon, Melnikov, Petriello
[hep-ph/0312266]

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN
RWTH

QCD Predictions for DY

NNLO QCD:

- total cross section — v.Neerven, Zijlstra [NPB **382** (1992) 11]
  Harlander, Kilgore [hep-ph/0201206]
- rapidity distributions — Anastasiou et al. [hep-ph/0312266]
- fully differential cross sections — Melnikov, Petriello [hep-ph/0609070]
  Catani et al. [arXiv:0903.2120]

further QCD improvements:

- NNNLO in soft + virtual approximation — Moch, Vogt [hep-ph/0508265]
- soft gluon resummation for $p_{\mathrm{T},W}$ distribution (Resbos)
  Balasz, Yuan [hep-ph/9704258]
  Ellis, Veseli [hep-ph/9706526]
  Cao,Yuan [hep-ph/0401026]
- NLO plus parton shower (MC@NLO, Powheg)
  Frixione, Nason, Webber [hep-ph/0305252]
  Alioli, Nason, Oleari, Re [arXiv:0805.4802]

EW corrections

generic size:

- expect percent level corrections
- naive comparison with QCD: $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$

  $\Rightarrow$ needed for high precision observables (like Drell-Yan)
- choose α appropriately (G_μ scheme for Drell-Yan)

EW corrections

generic size:

- expect percent level corrections
- naive comparison with QCD: $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$

  $\Rightarrow$ needed for high precision observables (like Drell-Yan)
- choose α appropriately (G_μ scheme for Drell-Yan)

(logarithmically) enhanced EW corrections:

- at high energies: Sudakov logs $\propto \alpha \to \alpha \log^2(Q/M_W)$)
- in peaked distribution from photon radiation

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN
RWTH

EW corrections

generic size:

- expect percent level corrections
- naive comparison with QCD: $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2)$

  $\Rightarrow$ needed for high precision observables (like Drell-Yan)
- choose α appropriately (G_μ scheme for Drell-Yan)

(logarithmically) enhanced EW corrections:

- at high energies: Sudakov logs $\propto \alpha \to \alpha \log^2(Q/M_W)$)
- in peaked distribution from photon radiation

enhanced EW corrections in BSM models:

- e.g. in $b\bar{b} \to H$

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN

Sudakov logs

interesting observables at $\sqrt{s} \gg M_{\mathrm{W,Z}}$ at the LHC

- Z'/W' searches in invariant mass tails
- Z/W at high p_{T} in Z/W + jet

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN

Sudakov logs

interesting observables at $\sqrt{s} \gg M_{\mathrm{W,Z}}$ at the LHC

- new physical scale: expect log enhanced corr.

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN

Sudakov logs

interesting observables at $\sqrt{s} \gg M_{\mathrm{W,Z}}$ at the LHC

- new physical scale: expect log enhanced corr.
- soft exchange of virtual massive vector bosons

$\Rightarrow$ 1-loop corrections: $\alpha \log^2(s/M_W^2)$ (Sudakov logs)

(also subleading and angular dependent logs)

Sudakov logs

interesting observables at $\sqrt{s} \gg M_{\mathrm{W,Z}}$ at the LHC

- new physical scale: expect log enhanced corr.
- soft exchange of virtual massive vector bosons

  $\Rightarrow$ 1-loop corrections: $\alpha \log^2(s/M_W^2)$ (Sudakov logs)

  (also subleading and angular dependent logs)
- expect tens of percent corrections at highest LHC energies

Sudakov logs

interesting observables at $\sqrt{s} \gg M_{\mathrm{W,Z}}$ at the LHC

- new physical scale: expect log enhanced corr.
- soft exchange of virtual massive vector bosons

  $\Rightarrow$ 1-loop corrections: $\alpha \log^2(s/M_W^2)$ (Sudakov logs)

  (also subleading and angular dependent logs)
- expect tens of percent corrections at highest LHC energies
- leading two-loop corrections important Fadin et al. [hep-ph/9910338]

  Ciafaloni, Cornelli [hep-ph/0001142]

  Hori et al. [hep-ph/0007329]

  Melles [hep-ph/0108221]

  Beenakker, Werthenbach [hep-ph/0112030]

  Denner, Melles, Pozzorini [hep-ph/0301241]

  Jantzen, Kühn, Penin, Smirnov [hep-ph/0504111]

  [hep-ph/0509157]

  Denner, Jantzen, Pozzorini [hep-ph/0608326]

Sudakov logs

interesting observables at $\sqrt{s} \gg M_{\mathrm{W,Z}}$ at the LHC

- new physical scale: expect log enhanced corr.
- soft exchange of virtual massive vector bosons

  $\Rightarrow$ 1-loop corrections: $\alpha \log^2(s/M_W^2)$ (Sudakov logs)

  (also subleading and angular dependent logs)
- expect tens of percent corrections at highest LHC energies
- leading two-loop corrections important
- partial compensation from real W and Z emission

Ciafaloni, Cornelli [hep-ph/0604070]

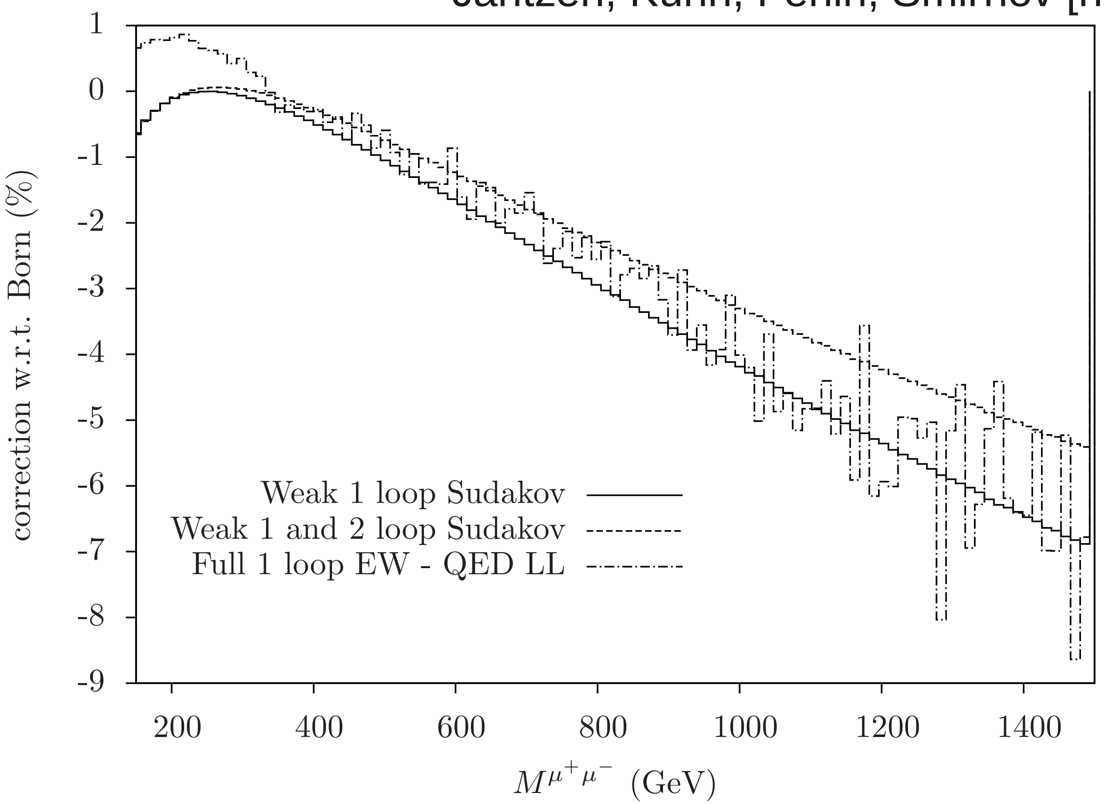
Baur [hep-ph/0611241]

Sudakov logs

example 1: dimuon invariant mass tail

- full one-loop EW corrections from HORACE
- Sudakov logs in analytic form

Jantzen, Kühn, Penin, Smirnov [hep-ph/0504111]



Les Houches 2007 [arXiv:0803.0678]

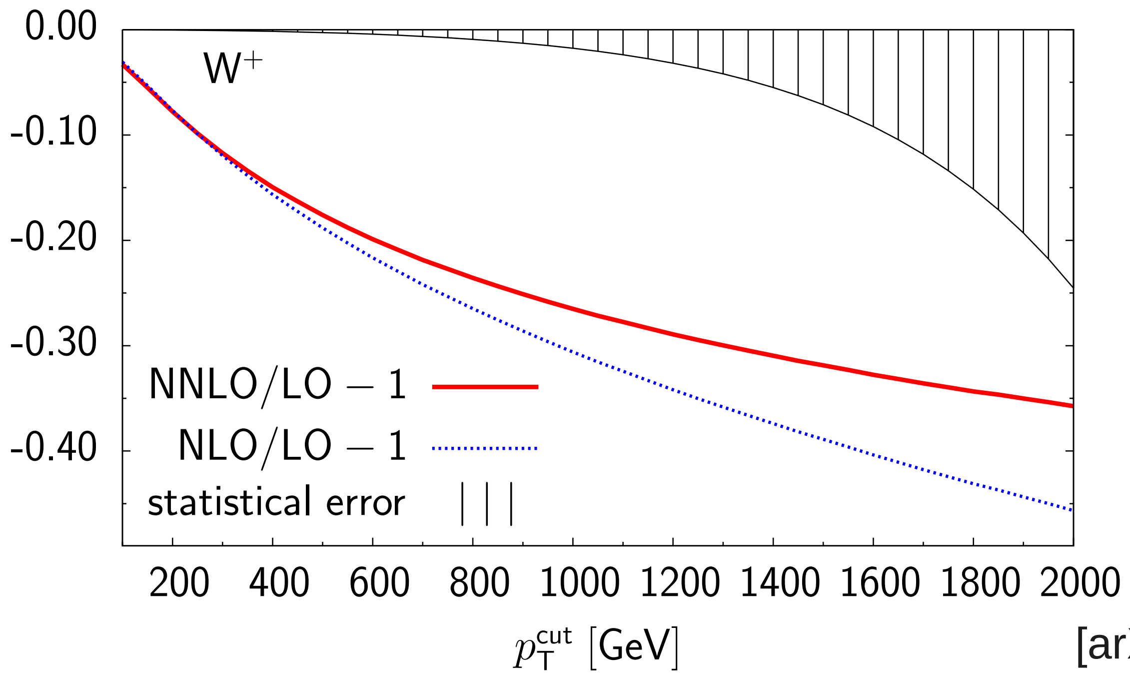
Sudakov logs

example 2: W bosons at high p_{T}

- full NLO EW and NLL 2-loop result

  Kühn, Kulesza, Pozzorini, Schulze [arXiv:0708.0476]

- compared to statistical LHC error (300 fb^{-1},$\sqrt{s} = 14$ TeV)

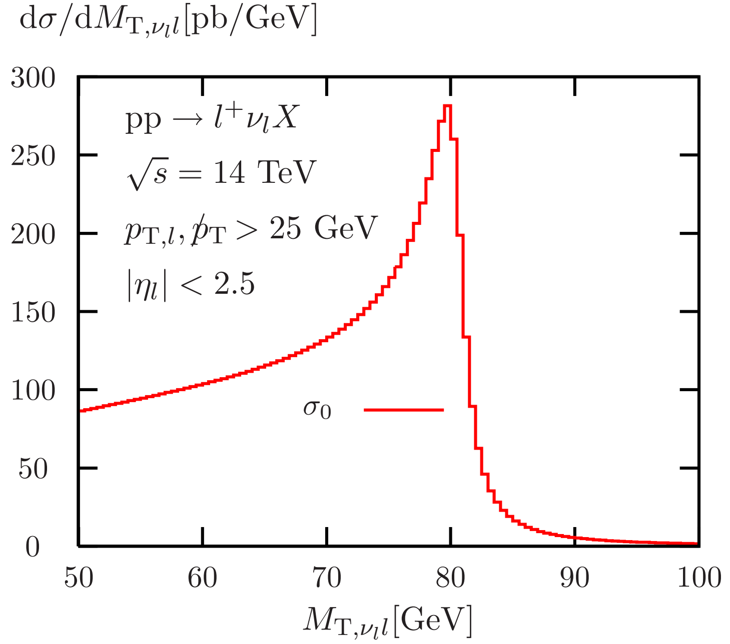


[arXiv:0708.0476]

Precision measurement M_W

W mass M_W from fit to distributions

- transverse mass: $M_{\mathrm{T}} = \sqrt{2\, p_{\mathrm{T},l}\, p_{\mathrm{T}}^{\mathrm{miss}}\, (1 - \cos\phi_{\nu_l l})}$
- transverse momentum: $p_{\mathrm{T},l}$



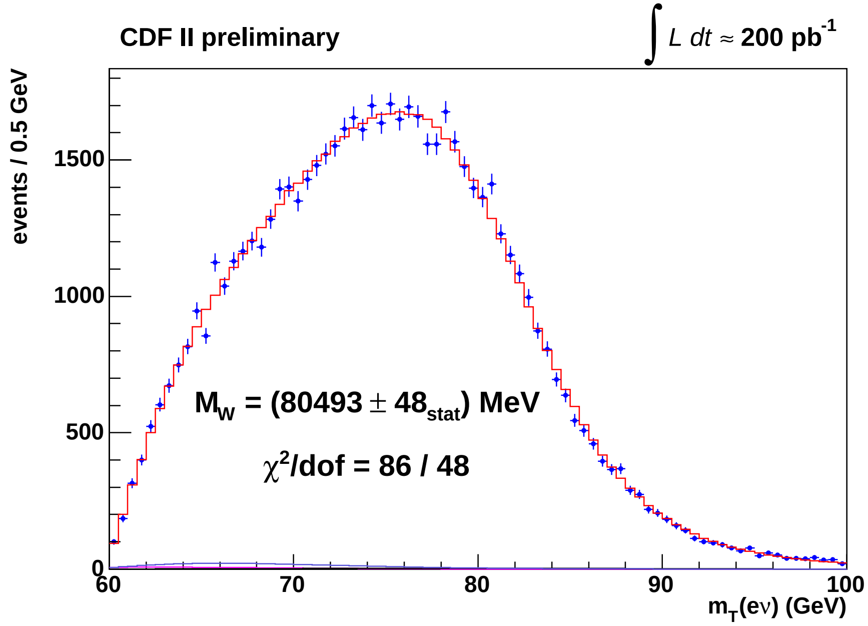
Jacobian peak at $M_{\mathrm{T}} = M_{\mathrm{W}}$

$\mathrm{d}\sigma/\mathrm{d}M_{\mathrm{T}}$ and $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T},l}$ equivalent at tree-level

Precision measurement M_W

W mass M_W from fit to distributions

- transverse mass: $M_\mathrm{T} = \sqrt{2\, p_{\mathrm{T},l}\, p_\mathrm{T}^\mathrm{miss}\, (1 - \cos\phi_{\nu_l l})}$
- transverse momentum: $p_{\mathrm{T},l}$



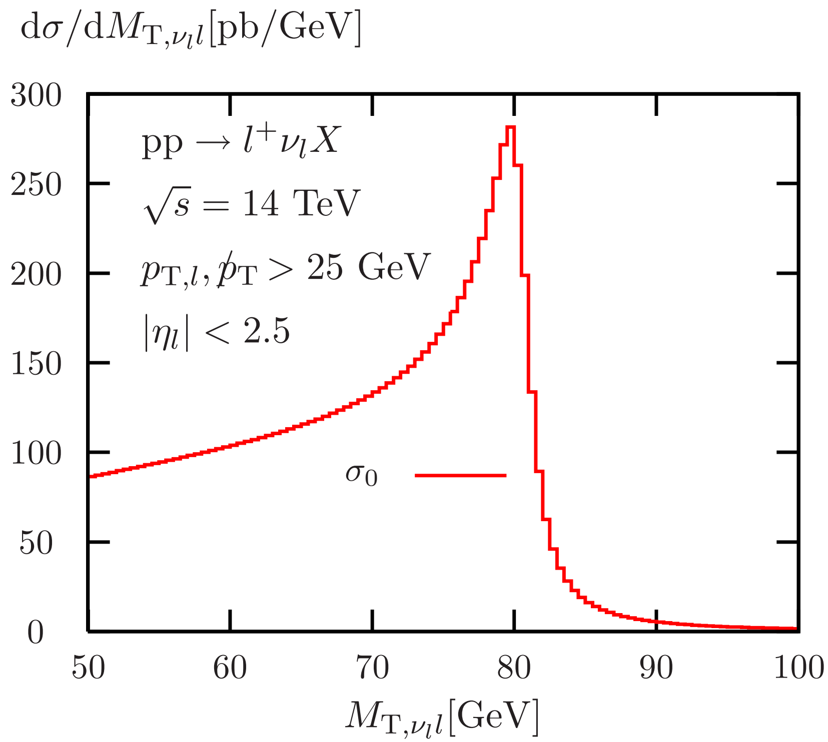
- combined Tevatron:

  $M_W = 80.420 \pm 0.031$ GeV
  (already beats LEP)

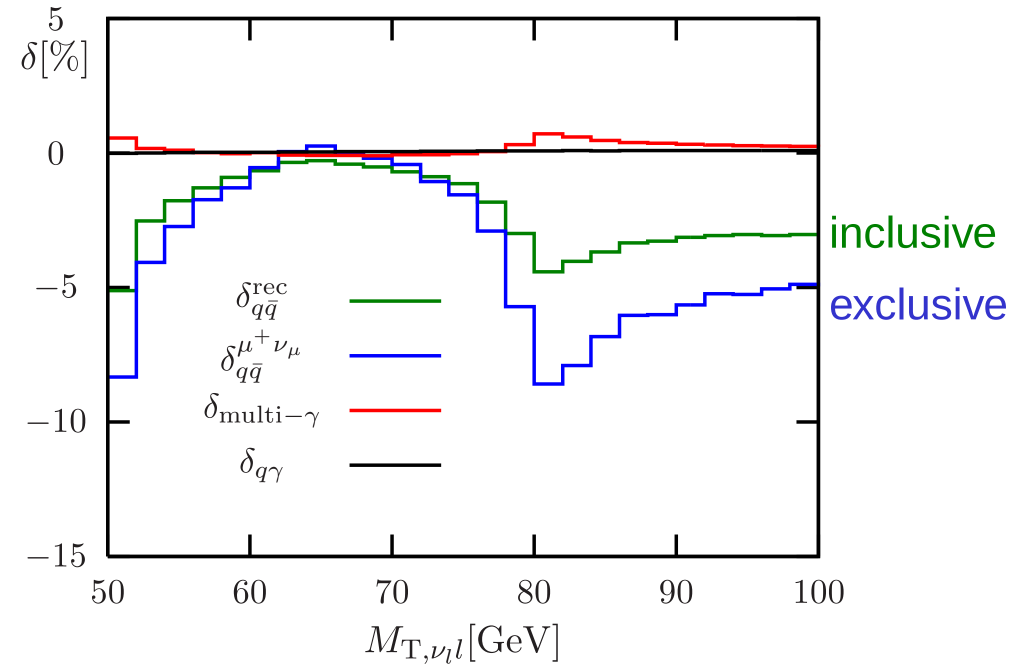
- Ultimate LHC goal: 10 MeV error
  (use data from $pp \to Z \to l^+ l^-$)

EW corrections: distributions

The transverse-mass distribution:



Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]

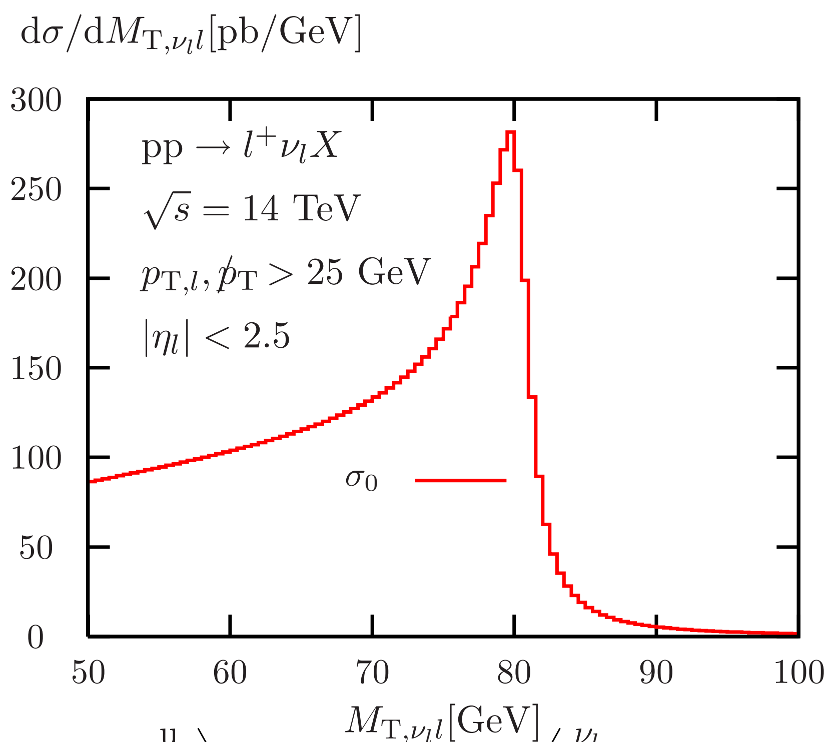


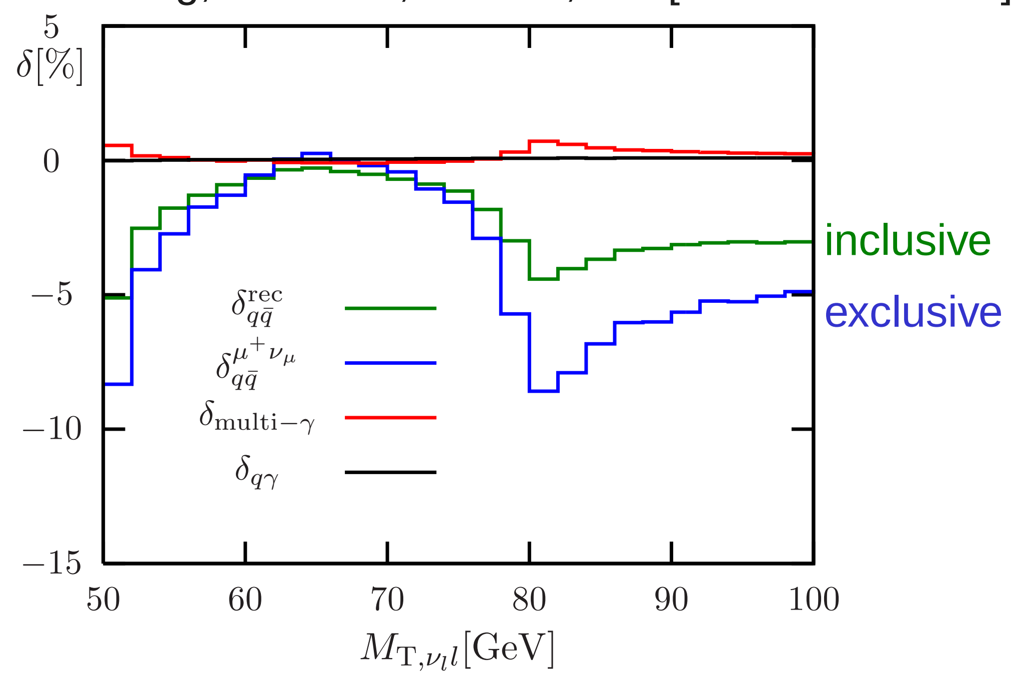
How to treat final state photons?

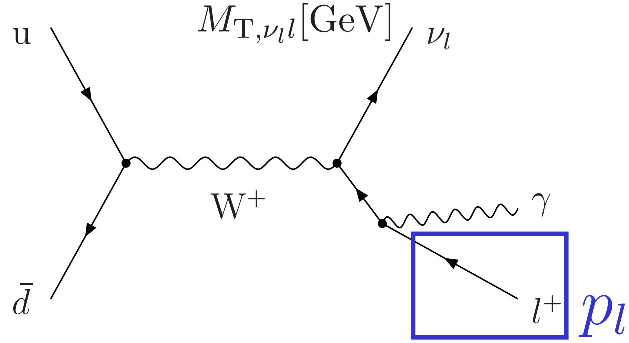
EW corrections: distributions

The transverse-mass distribution:

Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]





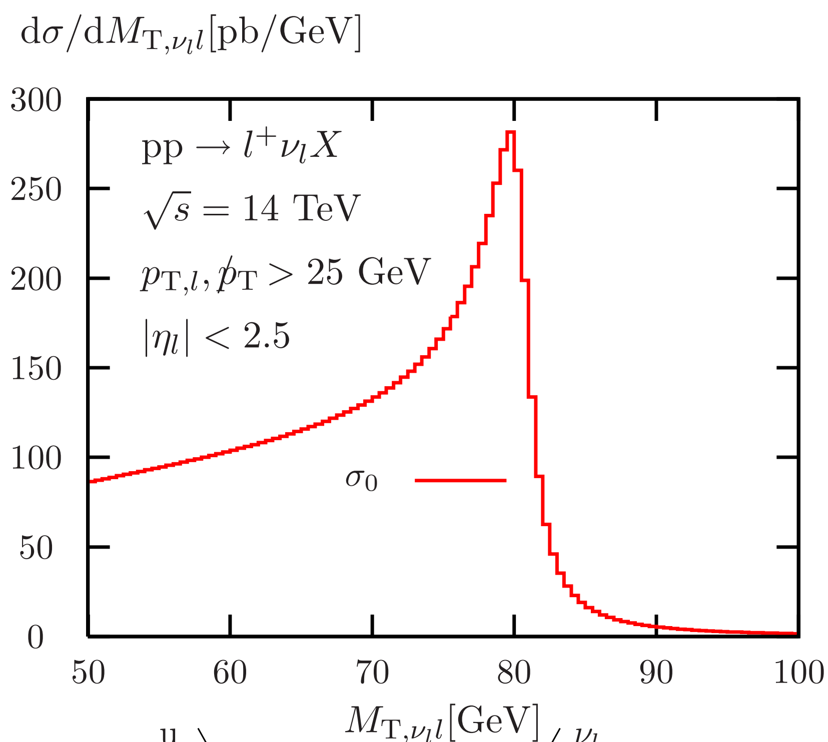


exclusive (bare) leptons (muons)

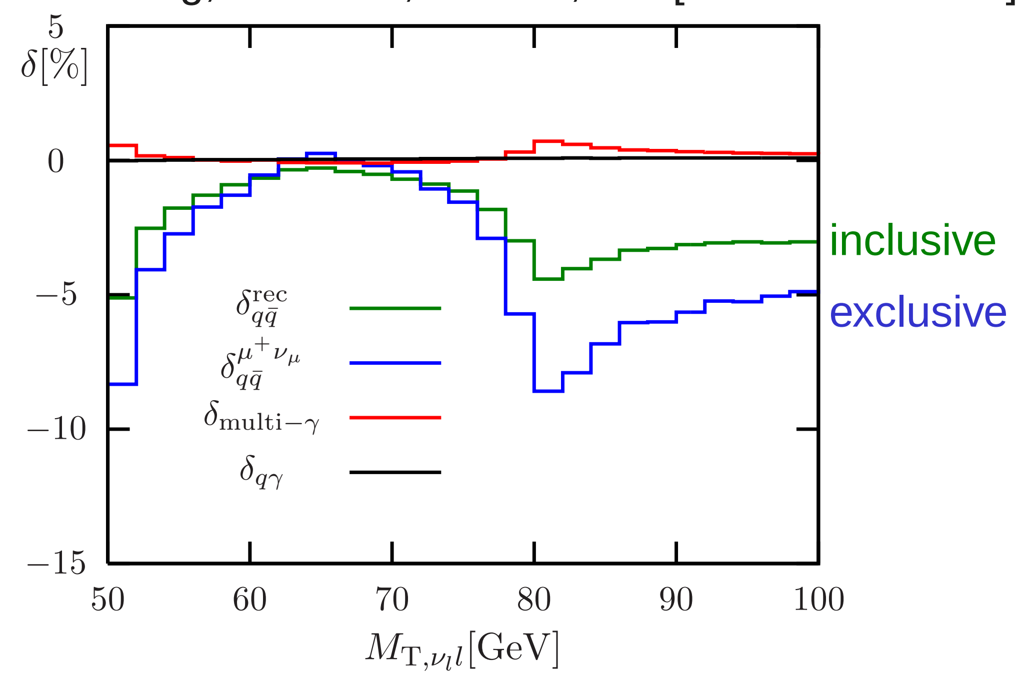
$\Rightarrow \alpha \log(M_W^2/M_l^2)$ corrections

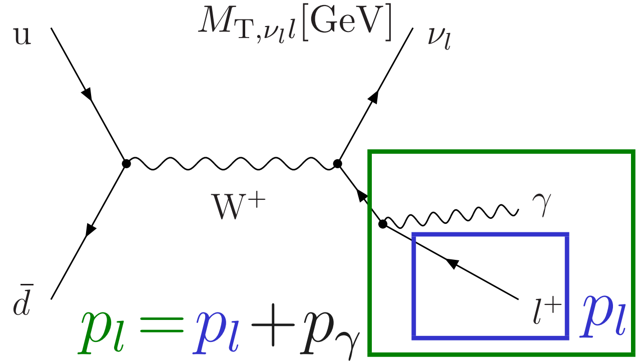
EW corrections: distributions

The transverse-mass distribution:



Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]





$p_l = p_l + p_\gamma$
(for collinear photons)

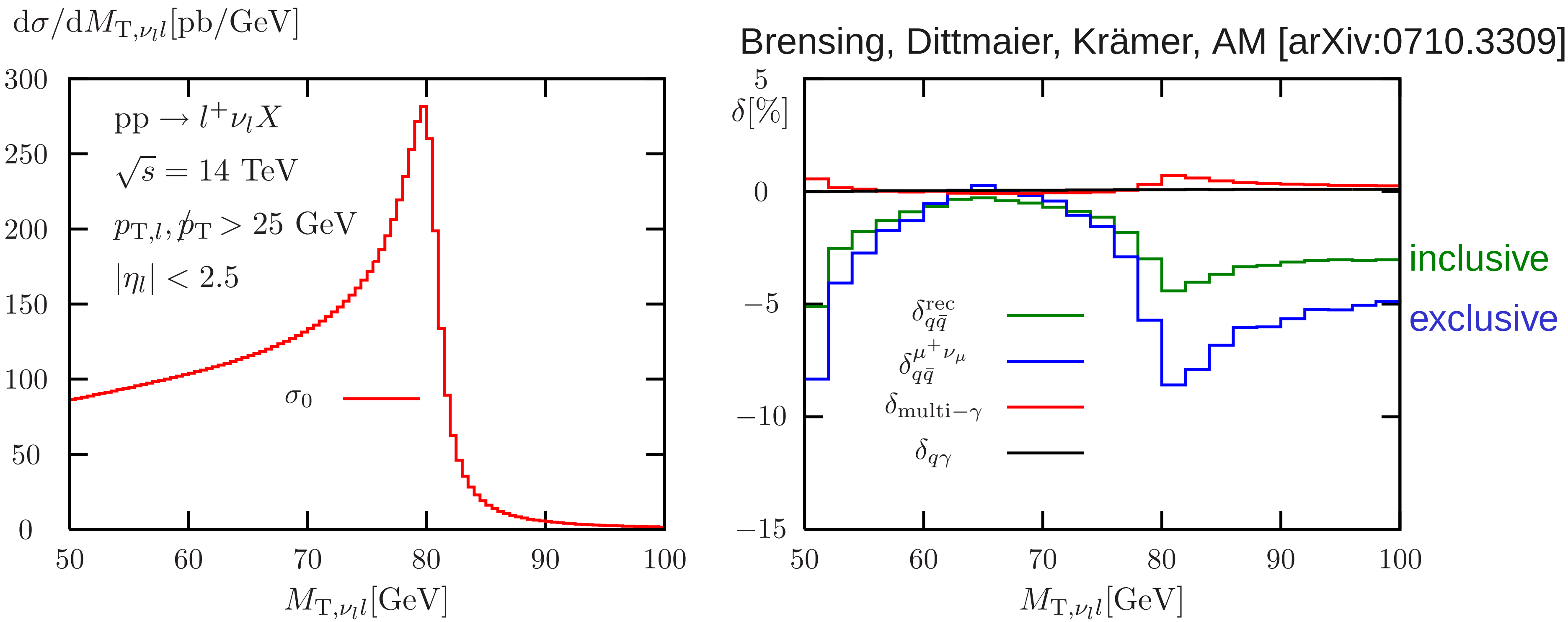
exclusive (bare) leptons (muons)
$\Rightarrow \alpha \log(M_W^2/M_l^2)$ corrections

inclusive leptons (electrons)
$\Rightarrow$ no mass logs (KLN theorem)

EW corrections: distributions

The transverse-mass distribution:

Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]



$\Rightarrow \sim$ 170 (65) MeV shift for M_W for $\mu^\pm$ ($e^\pm$) channel
CDF [hep-ex/0007044]

$\Rightarrow \sim$ 10 MeV shift for M_W from multi-γ final state radiation

Tools for Drell-Yan

Full NLO EW corrections available

Charged-Current DY:

Zykunov [hep-ph/0107059]
Dittmaier, Krämer [hep-ph/0109062]
Baur, Wackeroth [hep-ph/0405191]
Arbuzov et al. [hep-ph/0506110]
Carloni Calame et al. [hep-ph/0609170]

Neutral-Current DY:

Baur et al. [hep-ph/0108274]
Zykunov [hep-ph/0509315]
Carloni Calame, Montagna, Nicrosini, Vicini [arXiv:0710.1722]
Arbuzov et al. [arXiv:0711.0625]

Tools for Drell-Yan

Public codes for NLO EW corrections:

- HORACE

  Carloni Calame, Montagna, Nicrosini, Vicini [arXiv:0710.1722]

- WGRAD/ZGRAD2

  Baur, Wackeroth [hep-ph/0405191]
  Baur, Brein, Hollik, Schappacher, Wackeroth [hep-ph/0108274]

- SANC

  Arbuzov, et al. [arXiv:0711.0625]
  Arbuzov, et al. [hep-ph/05061101]
  Richardson, Sadykov, Sapronov, Seymour, Skands [arXiv:1011.5444]
  $\rightarrow$ interface with Herwig++ and Pythia8

Tools for Drell-Yan

Public codes for NLO EW corrections:

- HORACE
- WGRAD/ZGRAD2
- SANC

Multi-photon emission:

- HORACE — NLO EW matched with QED parton shower
  Carloni Calame, Montagna, Nicrosini,Treccani [hep-ph/0303102]
- WINHAC — YFS exp., NLO EW from SANC for CC-DY
  Placzek, Jadach [hep-ph/0302065]
  Bardin, Bondarenko, Jadach, Kalinovskaya, Placzek [arXiv:0806.3822]
- W/ZGRAD — Structure function approach+NLO EW
  see also: Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]
  Dittmaier, Huber [arXiv:0911.2329]

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN RWTH

Tools for Drell-Yan

Public codes for NLO EW corrections:

- HORACE
- WGRAD/ZGRAD2
- SANC

Multi-photon emission:

- HORACE — NLO EW matched with QED parton shower
- WINHAC — YFS exp., NLO EW from SANC for CC-DY
- W/ZGRAD — Structure function approach+NLO EW

Multi-purpose tools with/for FSR:

- PHOTOS — Golonka, Was [hep-ph/0506026]
- Herwig++, Pythia8
- ResBos — Cao,Yuan [hep-ph/0401026]

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN
RWTH

Tools for Drell-Yan

Public codes for NLO EW corrections:

- HORACE
- WGRAD/ZGRAD2
- SANC

Multi-photon emission:

- HORACE — NLO EW matched with QED parton shower
- WINHAC — YFS exp., NLO EW from SANC for CC-DY
- W/ZGRAD — Structure function approach+NLO EW

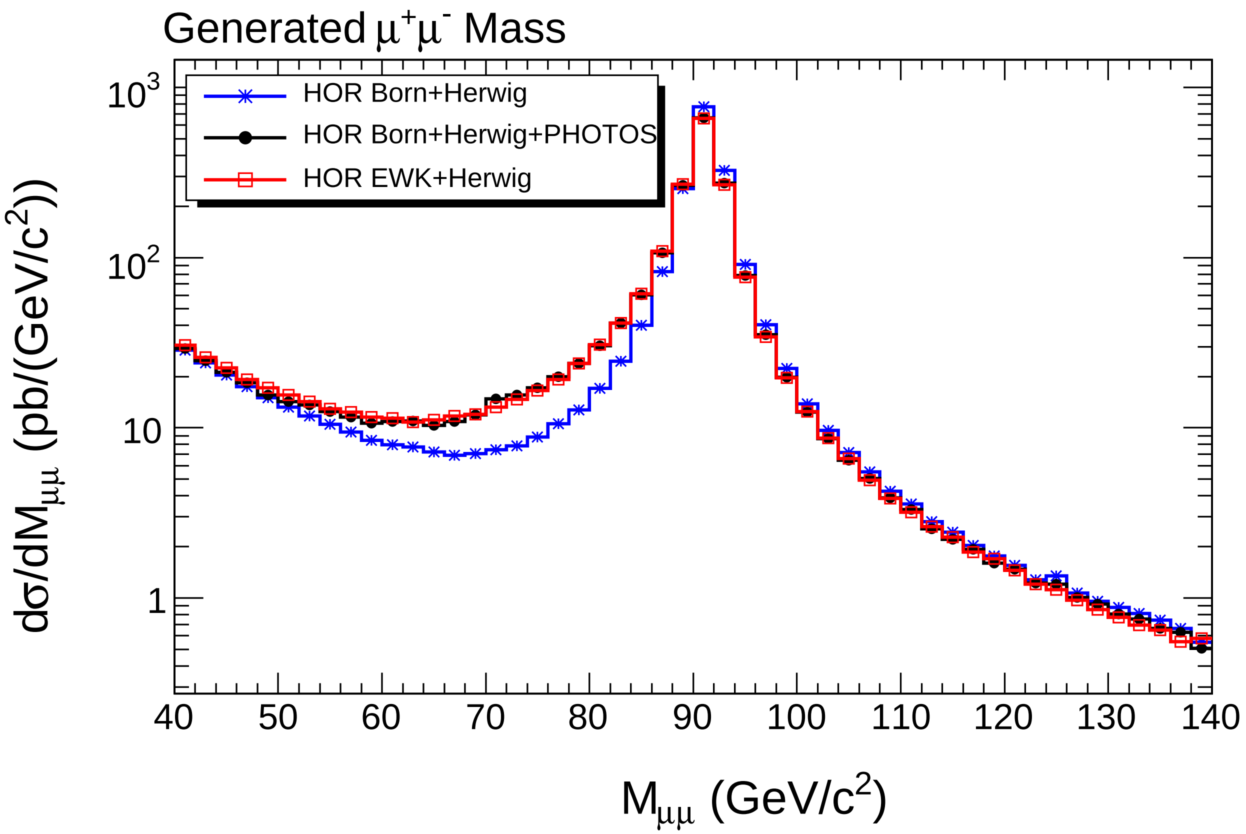
Multi-purpose tools with/for FSR:

- PHOTOS — Golonka, Was [hep-ph/0506026]
- Herwig++, Pythia8
- ResBos — Cao,Yuan [hep-ph/0401026]

easy to use $\leftrightarrow$ precision

Z-boson lineshape

- Z lineshape for calibration (LEP as reference)

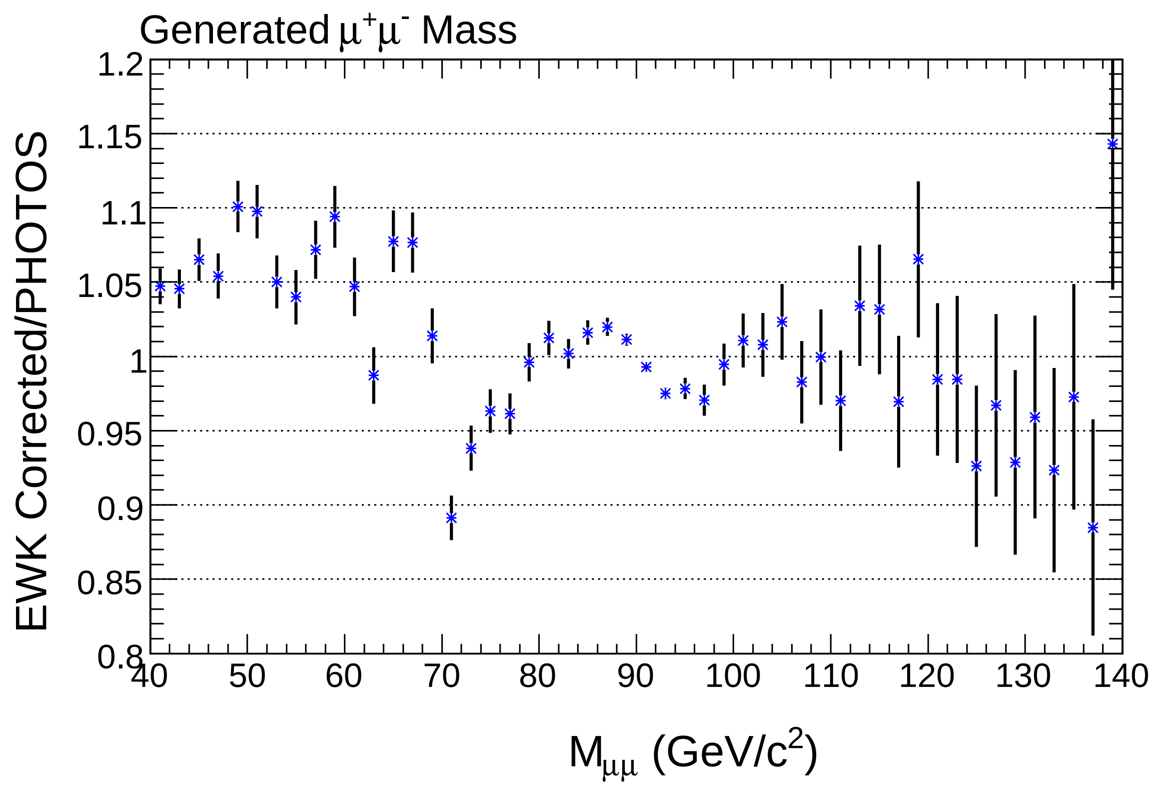


Les Houches 2007 [arXiv:0803.0678]

Z-boson lineshape

- Z lineshape for calibration (LEP as reference)
- How precise does the prediction have to be?

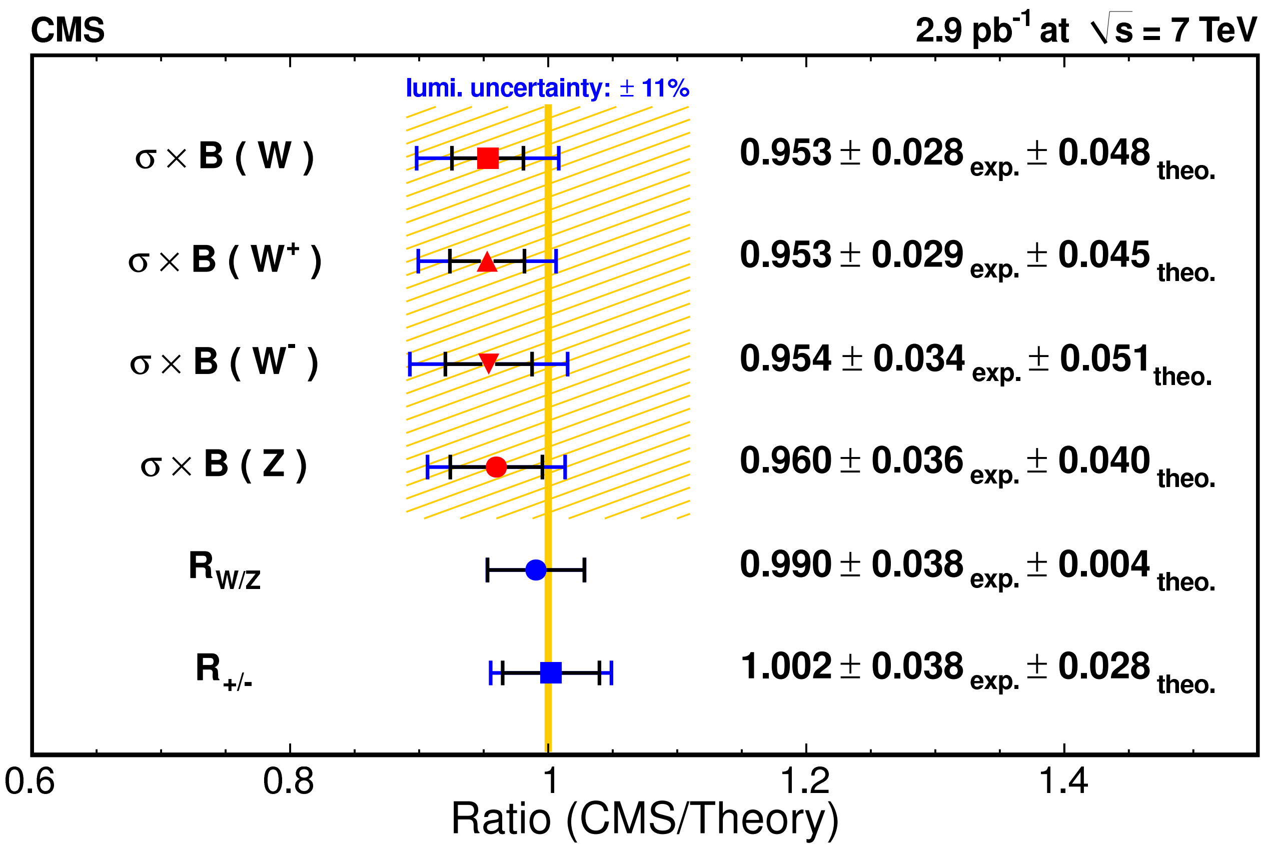
PHOTOS $\leftrightarrow$ HORACE (NLO EW matched to parton shower)



Les Houches 2007 [arXiv:0803.0678]

More precision observables

Cross section ratios



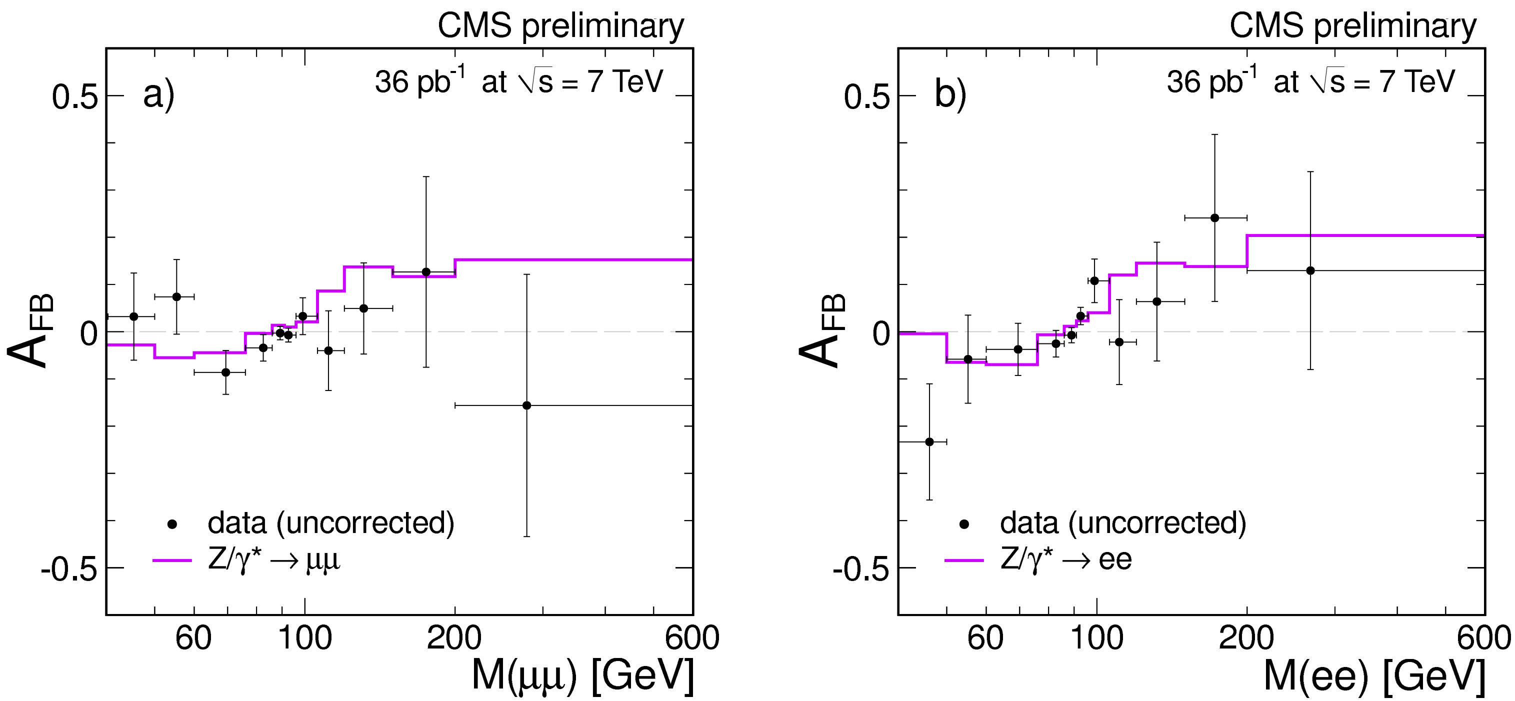
← Theory error from NNLO QCD

CMS [arXiv:1012.2466]

More precision observables

A_{FB} and $\sin^2\theta_{\mathrm{eff}}$

CMS [CMS PAS EWK-10-011]



$$\Rightarrow \sin^2\theta_{\mathrm{eff}} = 0.2287 \pm 0.0077(\mathrm{stat.}) \pm 0.0036(\mathrm{syst.})$$

$\hookrightarrow$ 0.0018 from FSR

$\Rightarrow$ room for improvement

(goal: $\delta\sin^2\theta_{\mathrm{eff}} = 0.0002$, LEP: $\sin^2\theta_{\mathrm{eff}} = 0.23153 \pm 0.00016$)

QCD $\otimes$ EW corrections

Theory status:

- QCD: NNLO, resummation, parton shower matching
- EW: NLO, leading higher order contributions

QCD $\otimes$ EW corrections

Theory status:

- QCD: NNLO, resummation, parton shower matching
- EW: NLO, leading higher order contributions
- combined EW and QCD corrections?

QCD $\otimes$ EW corrections

Theory status:

- QCD: NNLO, resummation, parton shower matching
- EW: NLO, leading higher order contributions
- combined EW and QCD corrections?

full (2-loop) $\mathcal{O}(\alpha\alpha_s)$ corrections not known

$\rightarrow$ different possible choices for the combination:

Balossini et al. [arXiv:0907.0276]

additive:

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\mathrm{QCD+EW}} = \left\{\frac{d\sigma}{d\mathcal{O}}\right\}_{\mathrm{QCD}} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\mathrm{EW}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\mathrm{LO}}\right\}_{\mathrm{HERWIG\ PS}}$$

factorized:

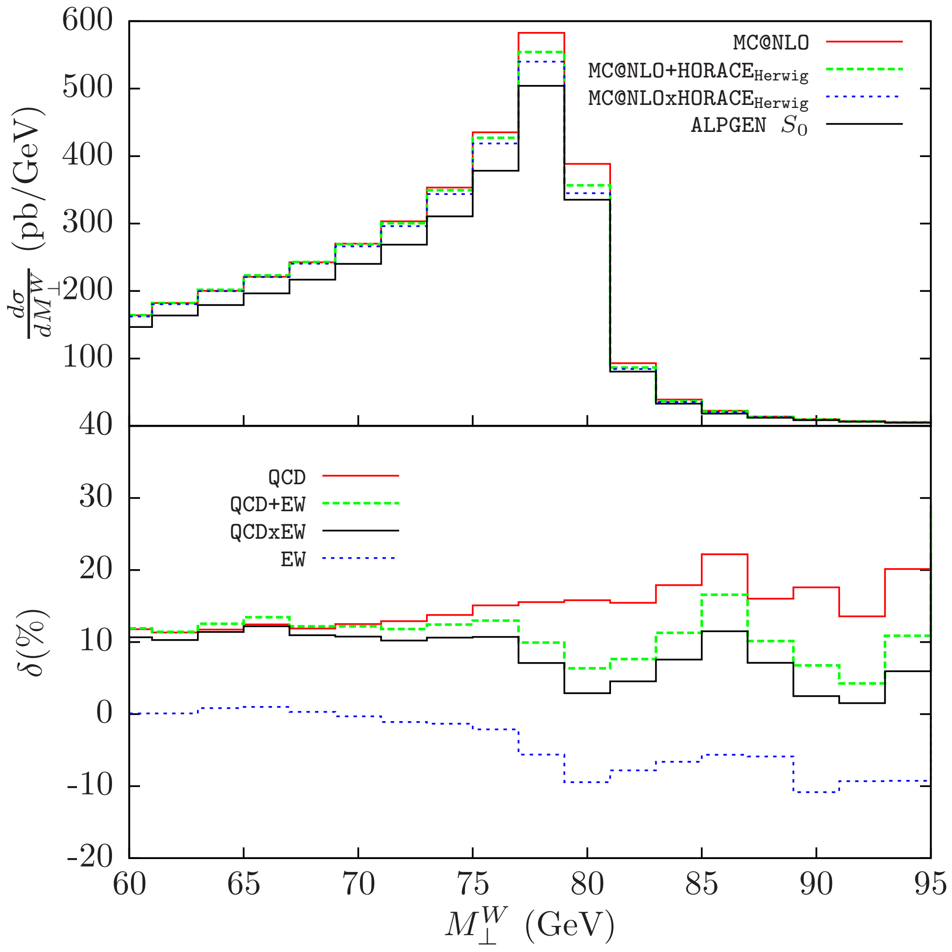
$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\mathrm{QCDxEW}} = \left(1 + \frac{[d\sigma/d\mathcal{O}]_{\mathrm{MC@NLO}} - [d\sigma/d\mathcal{O}]_{\mathrm{HERWIG\ PS}}}{[d\sigma/d\mathcal{O}]_{\mathrm{LO/NLO}}}\right) \times \left\{\frac{d\sigma}{d\mathcal{O}_{\mathrm{EW}}}\right\}_{\mathrm{HERWIG\ PS}}$$

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

RWTH

QCD $\otimes$ EW corrections

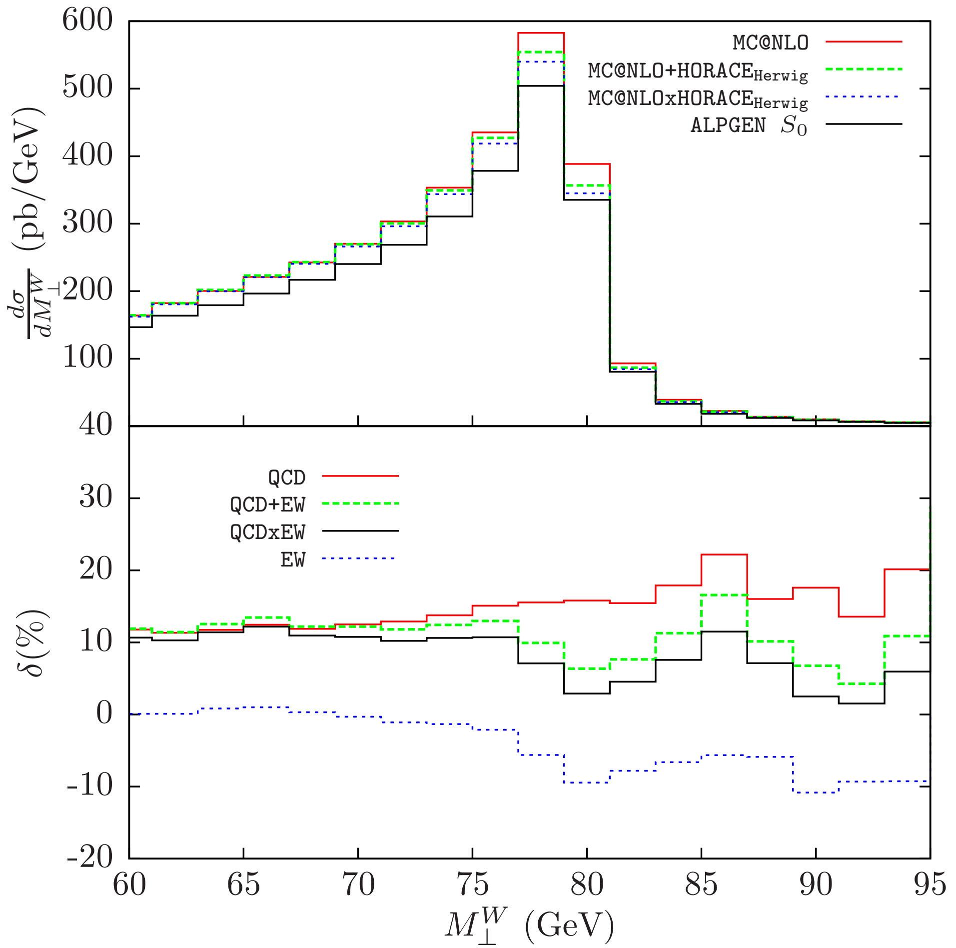
Example: W production at the LHC:



RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN
RWTH

QCD $\otimes$ EW corrections

Example: W production at the LHC:



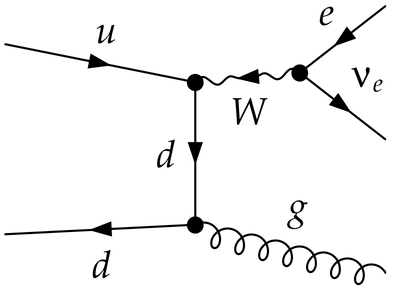
remaining ambiguity?

full $\mathcal{O}(\alpha\alpha_s)$:
$\rightarrow$ work in progress

hard QCD radiation + EW corrections:
$\rightarrow$ W/Z+jet production

W/Z+jet production

$$pp \to \mathrm{W} + \mathrm{jet} \to l\nu_l + \mathrm{jet}$$
$$pp \to \mathrm{W} + \mathrm{jet} \to ll + \mathrm{jet}$$



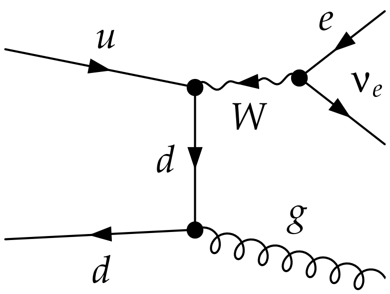
- simple processes . . .

  . . . but leptons, $p_{\mathrm{T,\,miss}}$, jet(s)

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN

W/Z+jet production

$$pp \to \mathrm{W} + \mathrm{jet} \to l\nu_l + \mathrm{jet}$$
$$pp \to \mathrm{W} + \mathrm{jet} \to ll + \mathrm{jet}$$



- simple processes . . .

. . . but leptons, $p_{\mathrm{T,\,miss}}$, jet(s)

Theoretical status:

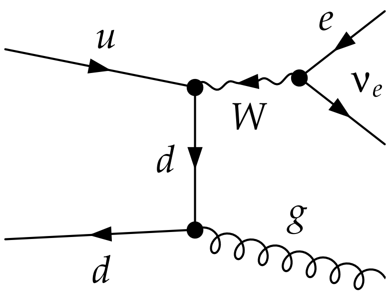
- NLO QCD corrections known and available

DYRAD: Giele et al. [hep-ph/9302225]
MCFM: Campbell, Ellis [hep-ph/0202176]
and as part of NNLO single W: Melnikov, Petriello [hep-ph/0609070]
Catani et al. [arXiv:0903.2120]

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN

W/Z+jet production

$$pp \to \mathrm{W} + \mathrm{jet} \to l\nu_l + \mathrm{jet}$$
$$pp \to \mathrm{W} + \mathrm{jet} \to ll + \mathrm{jet}$$



- simple processes . . .

  . . . but leptons, $p_{\mathrm{T,\,miss}}$, jet(s)

Theoretical status:

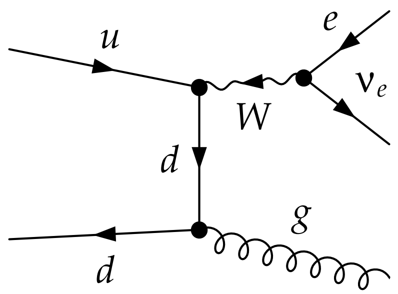
- NLO QCD corrections known and available
- EW corrections for stable (on-shell) W bosons

Kühn, Kulesza, Pozzorini, Schulze [hep-ph/0703283], [arXiv:0708.0476]

Hollik, Kasprzik, Kniehl [arXiv:0707.2553]

W/Z+jet production

$$pp \to \mathrm{W} + \mathrm{jet} \to l\nu_l + \mathrm{jet}$$
$$pp \to \mathrm{W} + \mathrm{jet} \to ll + \mathrm{jet}$$



- simple processes ...

  ... but leptons, $p_{\mathrm{T,\,miss}}$, jet(s)

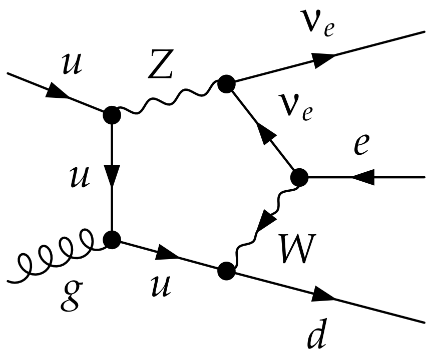
Theoretical status:

- NLO QCD corrections known and available
- EW corrections for stable (on-shell) W bosons
- Complete EW corrections available

W+jet: Denner, Dittmaier, Kasprzik, AM [arXiv:0906.1656]
Z+jet: Denner, Dittmaier, Kasprzik, AM [arXiv:1103.0914]

EW corrections

Complete EW corrections:

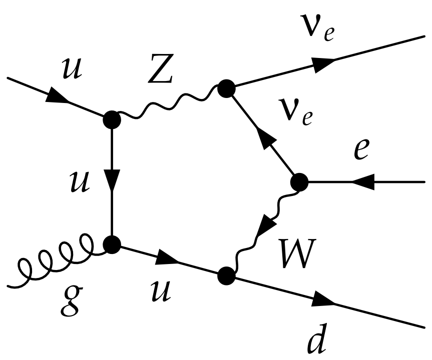


+
$\mathcal{O}$(100) diagrams for W,
$\mathcal{O}$(200) diagrams for Z
per partonic channel

- physical final state
- all off-shell effects included
- part of the $\mathcal{O}(\alpha\alpha_s)$ corrections for incl. W production

EW corrections

Complete EW corrections:



+
$\mathcal{O}$(100) diagrams for W,
$\mathcal{O}$(200) diagrams for Z
per partonic channel

- physical final state
- all off-shell effects included
- part of the $\mathcal{O}(\alpha\alpha_s)$ corrections for incl. W production

Common issues for EW calculations:

- How to treat resonances?
- How to treat final-state photons?
- What about initial-state photons?

Resonances

- naive fixed-width scheme
  - $\frac{1}{p^2 - M^2} \rightarrow \frac{1}{p^2 - M^2 + iM\Gamma}$
  - breaks gauge invariance (mildly?)
  - singularity structure at NLO screwed up

Resonances

- naive fixed-width scheme
- pole expansions

Stuart ['91], Aeppli et al. ['93,'94], etc.

  - gauge invariant
  - not reliable at threshold or in off-shell tails

Resonances

- naive fixed-width scheme
- pole expansions
- effective field theory approach

Beneke, Chapovsky, Signer,Zanderighi [hep-ph/0312331,hep-ph/0401002]
Fleming, Hoang, Mantry, Stewart [hep-ph/0703207]

  - gauge invariant
  - valid at threshold
  - framework for resummations

  - for specific observables only (e.g. total cross section)

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN RWTH

Resonances

- naive fixed-width scheme
- pole expansions
- effective field theory approach
- complex mass scheme

Denner, Dittmaier, Roth, Wieders [hep-ph/0505042]

  - use complex W and Z masses everywhere by means of complex renormalization:

$$M_{\mathrm{V},0}^2 = \mu_{\mathrm{V}}^2 + \delta\mu_V^2$$

with: $M_{\mathrm{V},0}^2$ = bare mass $(\mathrm{V} = \mathrm{W}, \mathrm{Z})$
μ_{V}^2 = ren. complex mass
$\delta\mu_V^2$ = complex counterterm

  - $\Rightarrow$ complex $s_{\mathrm{W}}^2 = 1 - \mu_{\mathrm{W}}^2/\mu_{\mathrm{Z}}^2$
  - loop-integrals for complex masses needed
  - unitarity-violating beyond NLO accuracy
  - gauge invariant
  - valid everywhere in phase space

Photons

How to deal with photon radiation from bare leptons?

- keep physical lepton mass in the amplitudes

  $\Rightarrow$ numerical integration of large logarithms necessary

- subtraction formalism also for non-collinear safe observables

  $\Rightarrow$ muon-mass logarithms extracted analytically

  Dittmaier, Kabelschacht, Kasprzik [arXiv:0802.1405]

Photons

How to deal with photon radiation from bare leptons?

- keep physical lepton mass in the amplitudes

  $\Rightarrow$ numerical integration of large logarithms necessary
- subtraction formalism also for non-collinear safe observables

  $\Rightarrow$ muon-mass logarithms extracted analytically

What about photons in the proton?

- initial state photon emission $\Rightarrow$ collinear singularity
- absorb singularity into PDF $\leftrightarrow$ include QED effects in PDF fit

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN
RWTH

Photons

How to deal with photon radiation from bare leptons?

- keep physical lepton mass in the amplitudes
  $\Rightarrow$ numerical integration of large logarithms necessary
- subtraction formalism also for non-collinear safe observables
  $\Rightarrow$ muon-mass logarithms extracted analytically

What about photons in the proton?

- initial state photon emission $\Rightarrow$ collinear singularity
- absorb singularity into PDF $\leftrightarrow$ include QED effects in PDF fit
- include QED in DGLAP evolution
  $\Rightarrow$ photon density inside the proton: MRSTQED2004 PDF
  Martin, Roberts, Stirling, Thorne [hep-ph/0411040]
- other PDF sets are in principle inconsistent at NLO EW
  $\Rightarrow$ but numerical effect expected to be small

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

Photons

How to deal with photon radiation from bare leptons?

- keep physical lepton mass in the amplitudes
  $\Rightarrow$ numerical integration of large logarithms necessary
- subtraction formalism also for non-collinear safe observables
  $\Rightarrow$ muon-mass logarithms extracted analytically

What about photons in the proton?

- initial state photon emission $\Rightarrow$ collinear singularity
- absorb singularity into PDF $\leftrightarrow$ include QED effects in PDF fit
- include QED in DGLAP evolution
  $\Rightarrow$ photon density inside the proton: MRSTQED2004 PDF
  Martin, Roberts, Stirling, Thorne [hep-ph/0411040]
- other PDF sets are in principle inconsistent at NLO EW
  $\Rightarrow$ but numerical effect expected to be small
- additional $\mathcal{O}(\alpha)$ correction: photon-induced processes

Photons II

Treat final-state photons like another parton?

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN

Photons II

Treat final-state photons like another parton?

- Yes: Photon–jet recombination mandatory for infrared safe observables (poles in q $\rightarrow$ qγ splitting)

Photons II

Treat final-state photons like another parton?

- Yes: Photon–jet recombination mandatory for infrared safe observables (poles in $q \to q\gamma$ splitting)
- No: a gluon in a gluon-photon jet can become soft (in accidentally collinear configurations) $\Rightarrow$ IR singularity

Photons II

Treat final-state photons like another parton?

- Yes: Photon–jet recombination mandatory for infrared safe observables (poles in $q \to q\gamma$ splitting)
- No: a gluon in a gluon-photon jet can become soft (in accidentally collinear configurations) $\Rightarrow$ IR singularity
- soft gluon pole cancelled by virt. QCD corr. to V+photon

Photons II

Treat final-state photons like another parton?

- Yes: Photon–jet recombination mandatory for infrared safe observables (poles in q $\rightarrow$ qγ splitting)
- No: a gluon in a gluon-photon jet can become soft (in accidentally collinear configurations) $\Rightarrow$ IR singularity
- soft gluon pole cancelled by virt. QCD corr. to V+photon

The problem: V+jet $\Leftrightarrow$ V+photon

- do not distinguish (also calculate V+γ and its NLO QCD corr.)
- or use a sophisticated isolation — Frixione [hep-ph/9801442]
- or cut on photon energy fraction z_γ inside a jet

Photons II

Treat final-state photons like another parton?

- Yes: Photon–jet recombination mandatory for infrared safe observables (poles in q $\to$ qγ splitting)
- No: a gluon in a gluon-photon jet can become soft (in accidentally collinear configurations) $\Rightarrow$ IR singularity
- soft gluon pole cancelled by virt. QCD corr. to V+photon

The problem: V+jet $\Leftrightarrow$ V+photon

- do not distinguish (also calculate V+γ and its NLO QCD corr.)
- or use a sophisticated isolation Frixione [hep-ph/9801442]
- or cut on photon energy fraction z_γ inside a jet

$\Rightarrow$ this is what we want; But: not infrared safe

Photons II

Treat final-state photons like another parton?

- Yes: Photon–jet recombination mandatory for infrared safe observables (poles in q $\to$ qγ splitting)
- No: a gluon in a gluon-photon jet can become soft (in accidentally collinear configurations) $\Rightarrow$ IR singularity
- soft gluon pole cancelled by virt. QCD corr. to V+photon

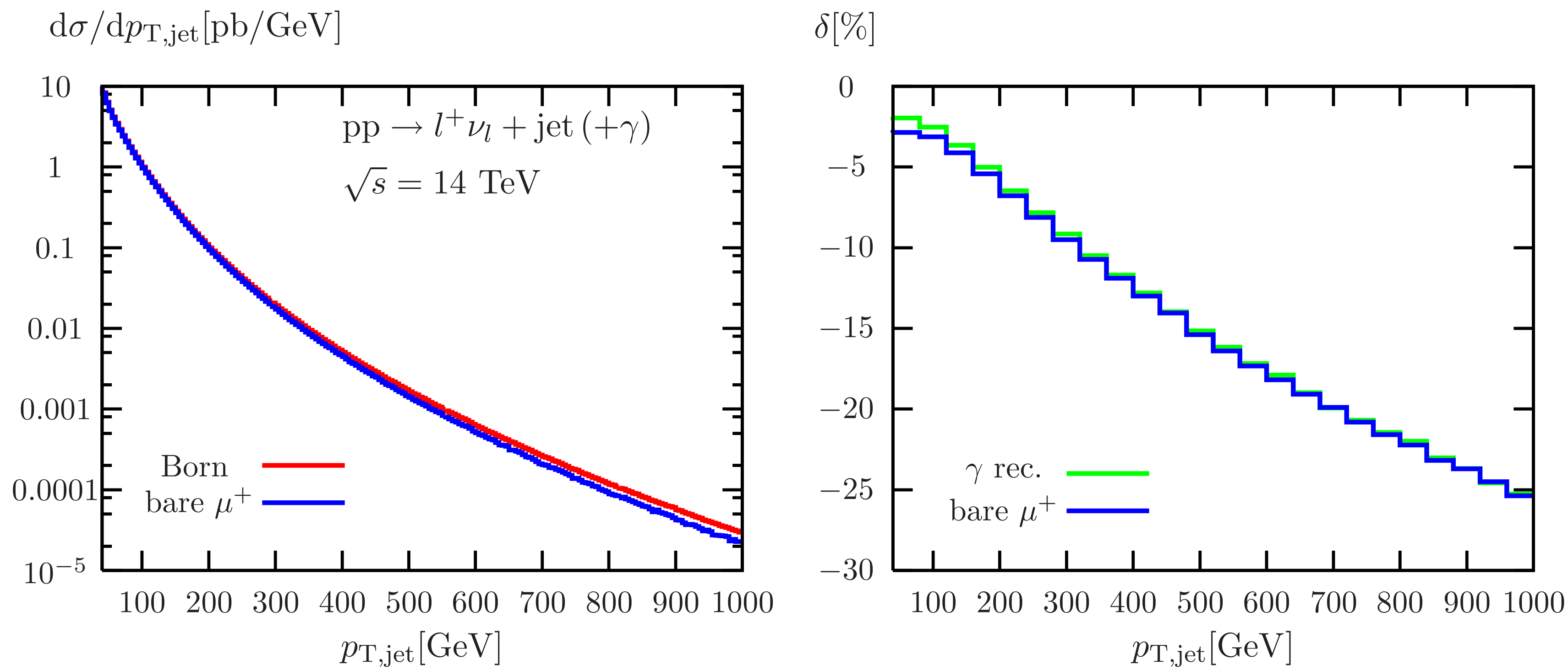
The problem: V+jet $\Leftrightarrow$ V+photon

- do not distinguish (also calculate V+γ and its NLO QCD corr.)
- or use a sophisticated isolation Frixione [hep-ph/9801442]
- or cut on photon energy fraction z_γ inside a jet
  $\Rightarrow$ isolate singularity analytically ($\to$ subtraction formalism)
  $\Rightarrow$ absorb singularity into measured quark-to-photon fragmentation function

selected W/Z+jet results

$p_{\mathrm{T,jet}}$ distribution for W+jet at the LHC:

Denner, Dittmaier, Kasprzik, AM [arXiv:0906.1656]

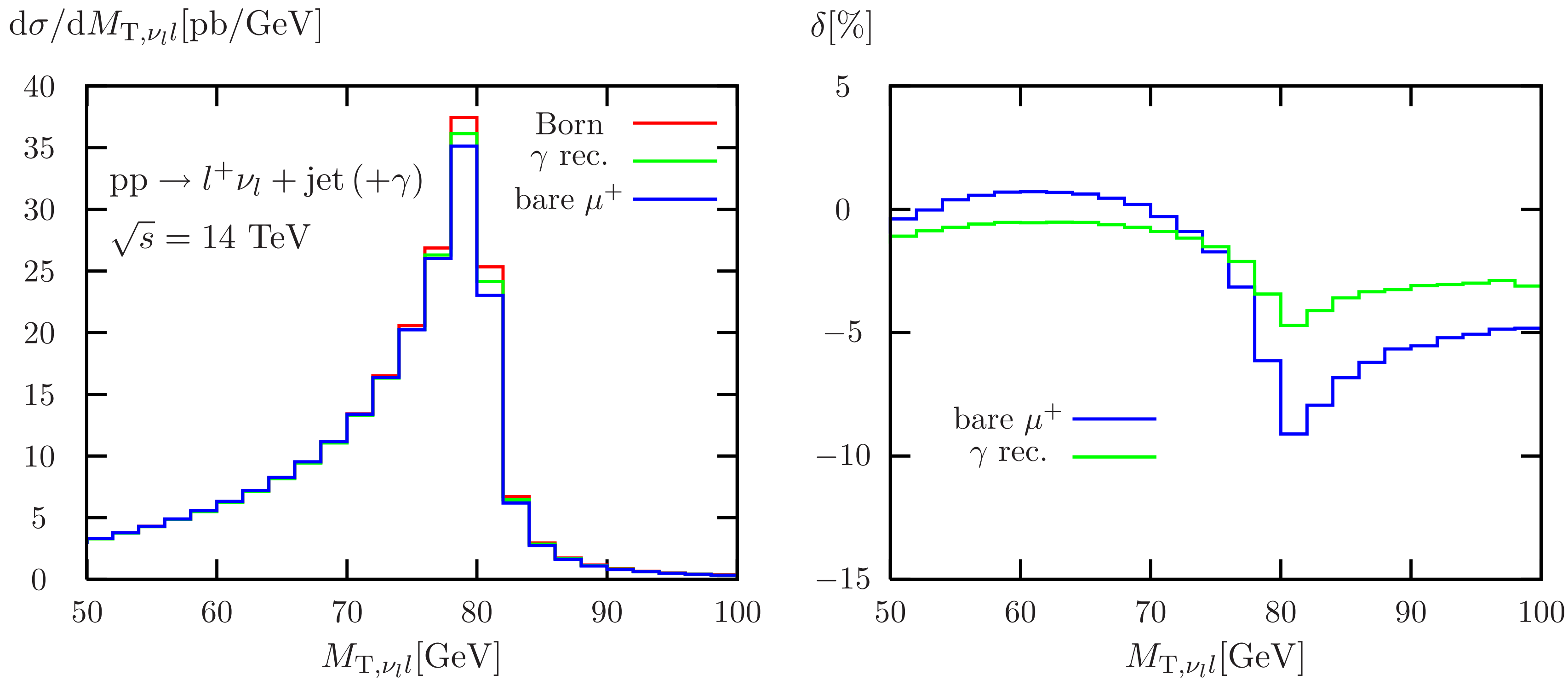


large corrections at large energies (Sudakov logs)
(on-shell W good approximation)

selected W/Z+jet results

M_T distribution for the LHC: $M_{\mathrm{T},l\nu_l} = \sqrt{2\,p_{\mathrm{T},l}\,p_\mathrm{T}^\mathrm{miss}\,(1-\cos\phi_{\nu_l l})}$

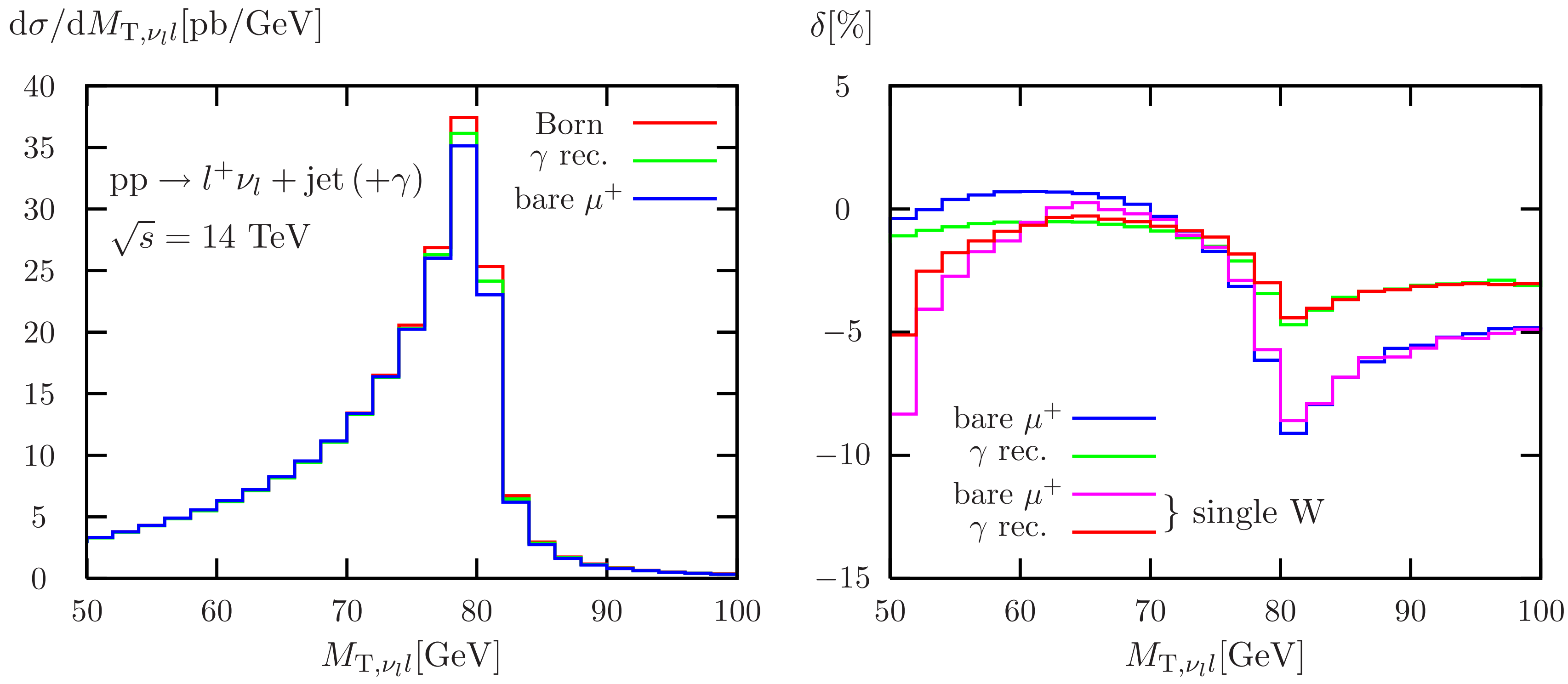
Denner, Dittmaier, Kasprzik, AM [arXiv:0906.1656]



selected W/Z+jet results

M_T distribution for the LHC: $$M_{\mathrm{T},l\nu_l} = \sqrt{2\,p_{\mathrm{T},l}\,p_\mathrm{T}^\mathrm{miss}\,(1-\cos\phi_{\nu_l l})}$$

Denner, Dittmaier, Kasprzik, AM [arXiv:0906.1656]



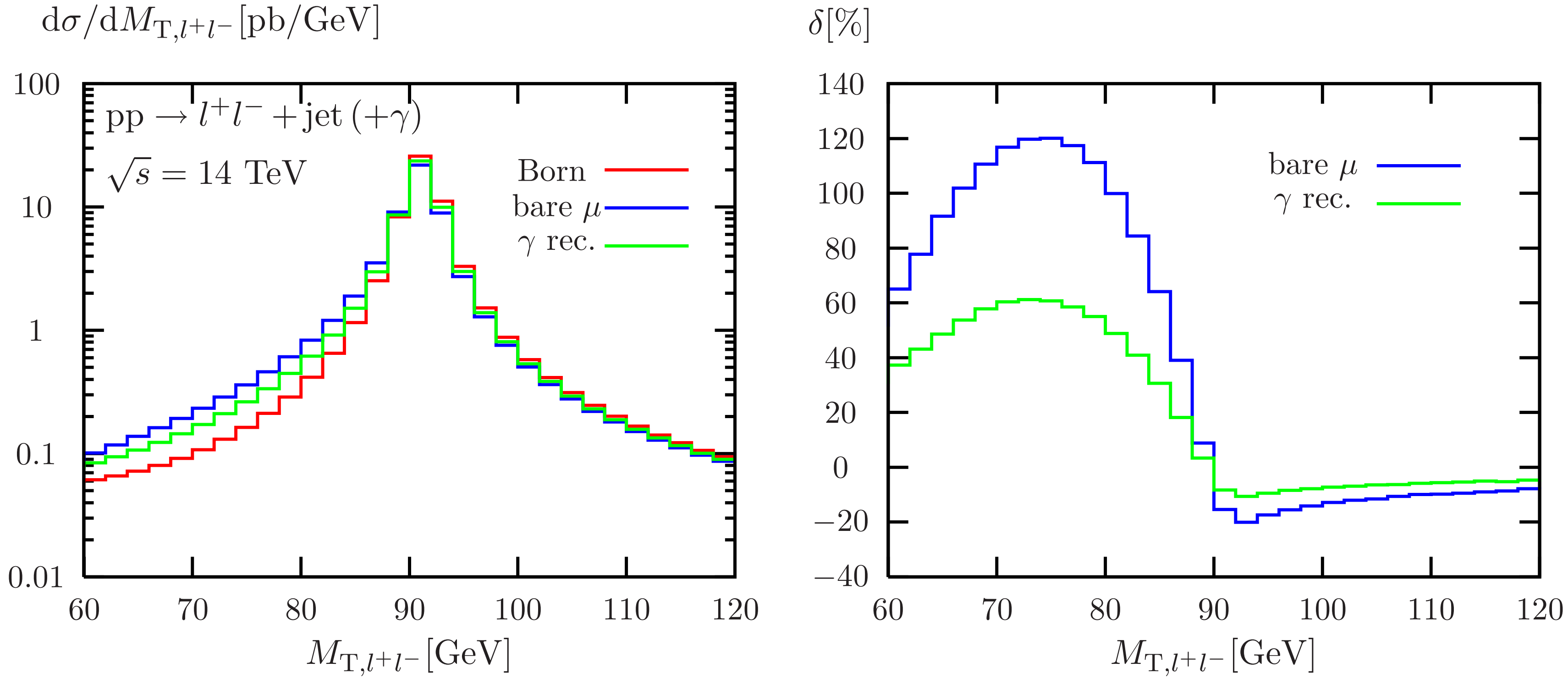
corrections very similar to single W production

$\Rightarrow$ supports factorization for QCD$\otimes$QED corrections

selected W/Z+jet results

Z lineshape in Z+jet events at the LHC:

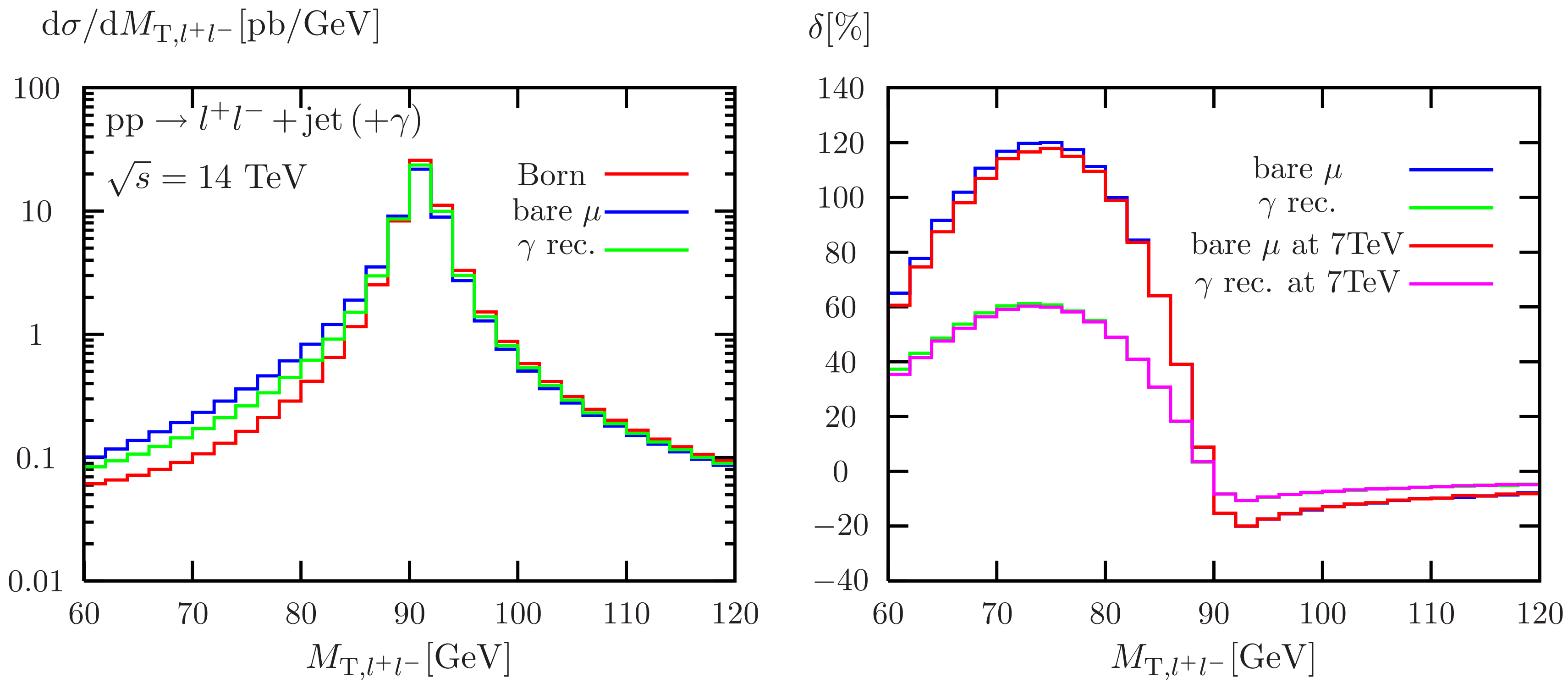
Denner, Dittmaier, Kasprzik, AM [arXiv:1103.0914]



selected W/Z+jet results

Z lineshape in Z+jet events at the LHC:

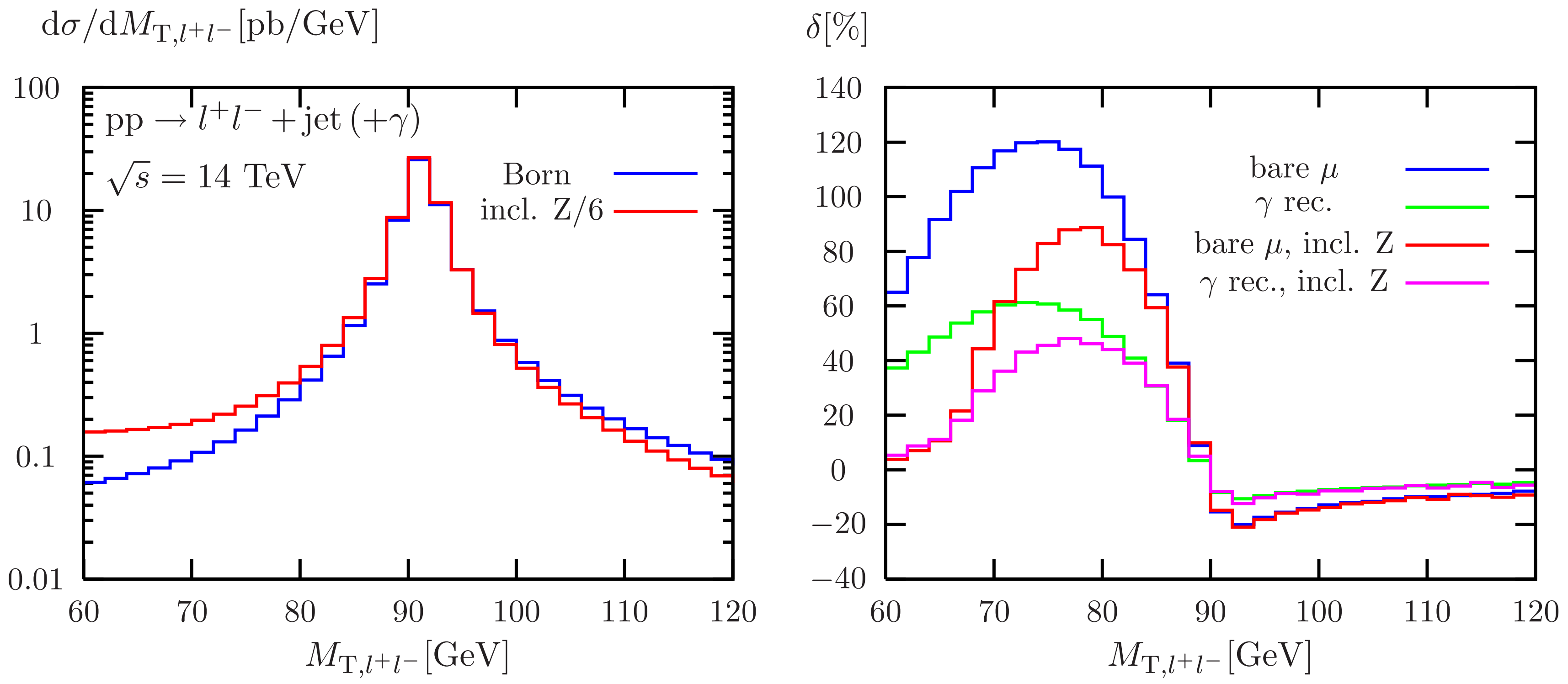
Denner, Dittmaier, Kasprzik, AM [arXiv:1103.0914]



corrections hardly differ at 7 TeV

selected W/Z+jet results

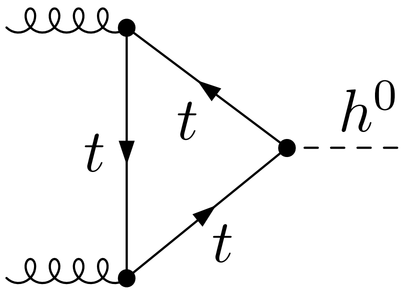
comparison with inclusive Z production:



lineshape (and corrections) depends on $p_{T,Z}$ in the tail

Higgs in Gluon-Fusion

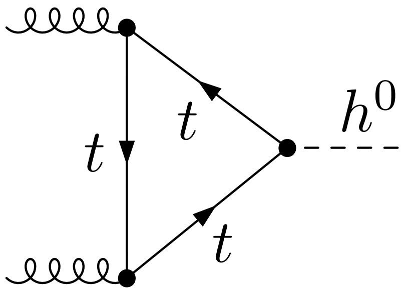
- dominant production process at LHC
- enormous efforts for the QCD prediction

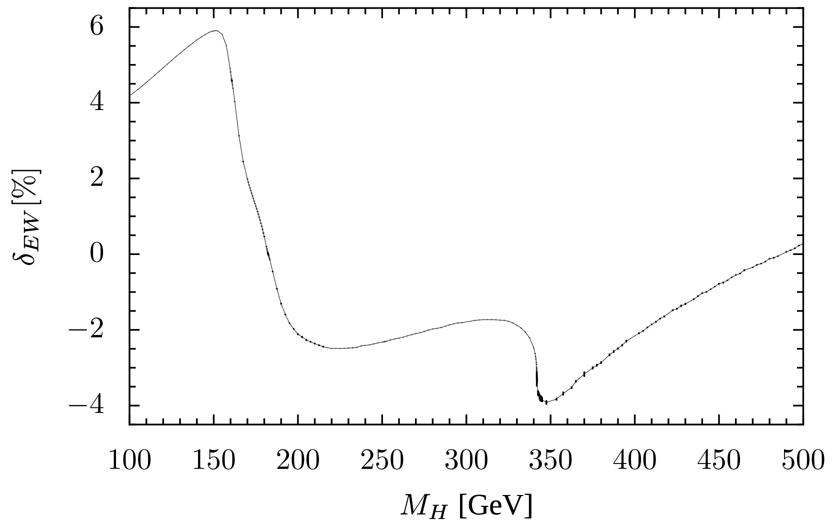


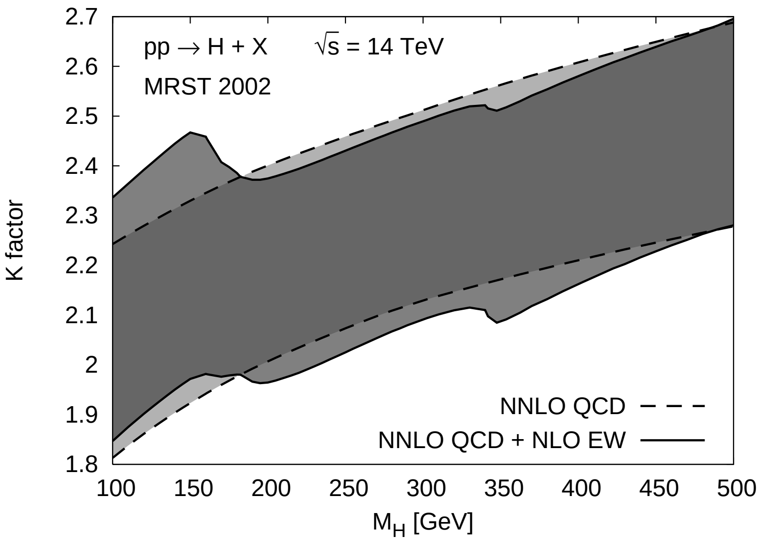
RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

Higgs in Gluon-Fusion

- dominant production process at LHC
- enormous efforts for the QCD prediction
- full NLO (2-loop) EW corrections







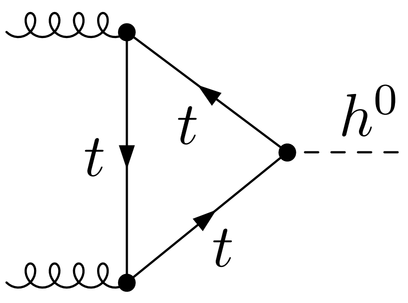
Actis, Passarino, Sturm, Uccirati [arXiv:0809.1301]

- non-trivial threshold behaviour inside loops (WW,ZZ,$t\bar{t}$)

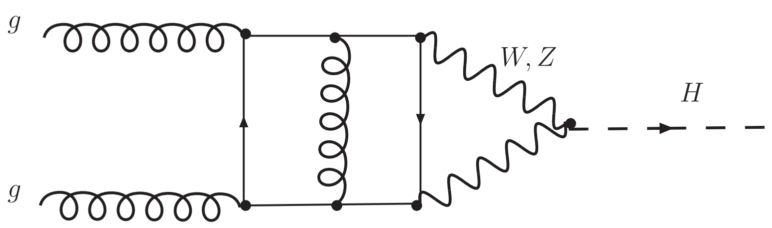
  $\Rightarrow$ complex-mass scheme at two loops

Higgs in Gluon-Fusion

- dominant production process at LHC
- enormous efforts for the QCD prediction
- full NLO (2-loop) EW corrections
- mixed $\mathcal{O}(\alpha\alpha_s)$ corrections (light fermion loops)



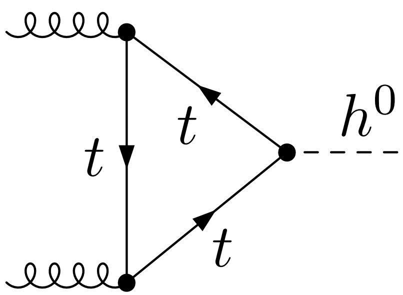
Anastasiou, Boughezal, Petriello [arXiv:0811.3458]



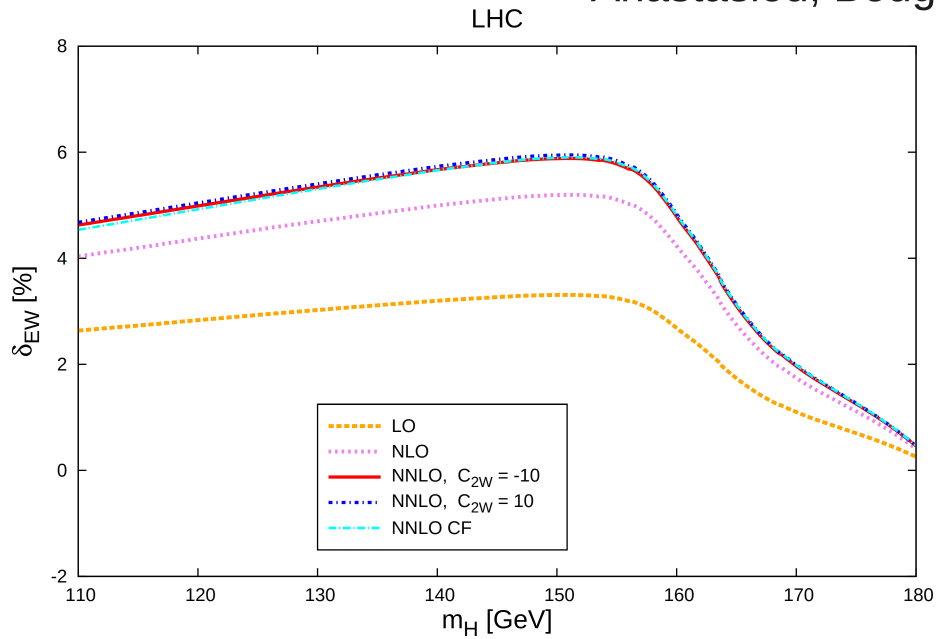
$\Rightarrow$ effective theory approach

Higgs in Gluon-Fusion

- dominant production process at LHC
- enormous efforts for the QCD prediction
- full NLO (2-loop) EW corrections
- mixed $\mathcal{O}(\alpha\alpha_s)$ corrections (light fermion loops)

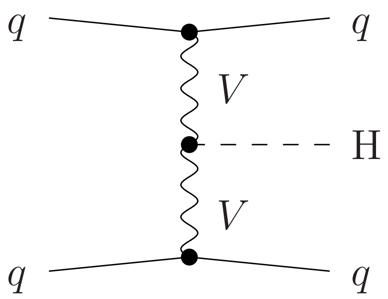


Anastasiou, Boughezal, Petriello [arXiv:0811.3458]



supports factorization of EW and QCD corrections

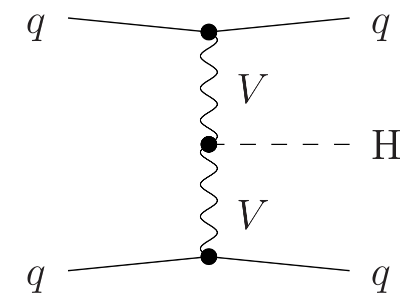
Higgs in VBF



- important Higgs discovery channel
- measurement of HVV couplings
- powerful cuts for background suppression
- small QCD uncertainty: $\pm 4\%$ (DIS like process) $\rightarrow$ VBFNLO

Figi, Oleari, Zeppenfeld [hep-ph/0306109]

Higgs in VBF

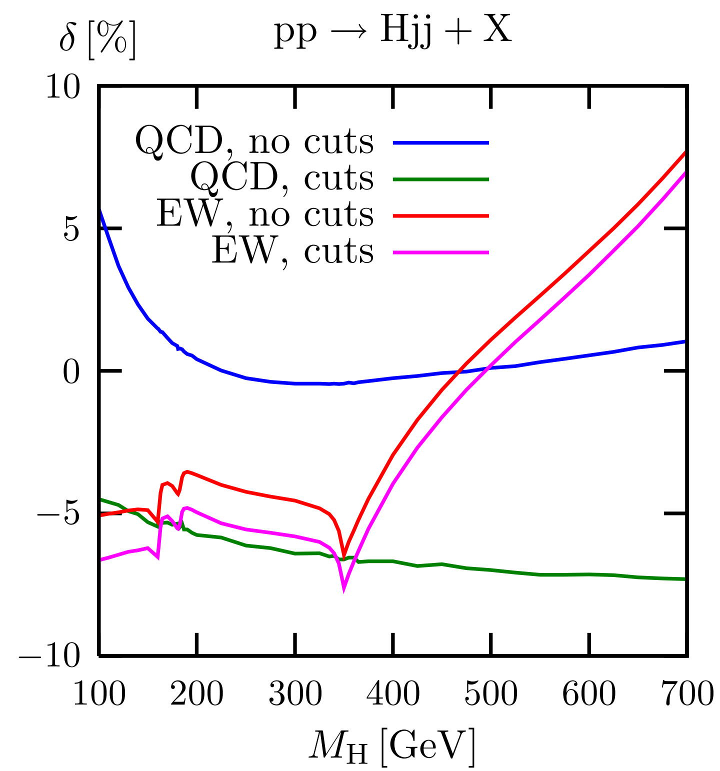


- important Higgs discovery channel
- measurement of HVV couplings
- powerful cuts for background suppression
- small QCD uncertainty: $\pm 4\%$ (DIS like process) $\rightarrow$ VBFNLO
- EW corrections
  Ciccolini, Denner, Dittmaier [arXiv:0710.4749]

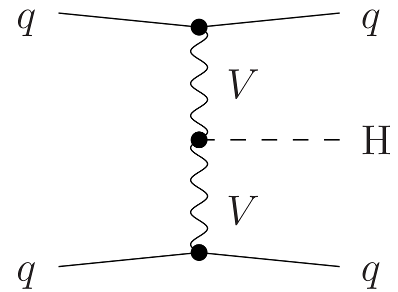
  no VBF approximations

  flexible tool: HAWK

  Denner, Dittmaier, AM [http://omnibus.uni-freiburg.de/∼sd565/programs/hawk/hawk.html]



Higgs in VBF

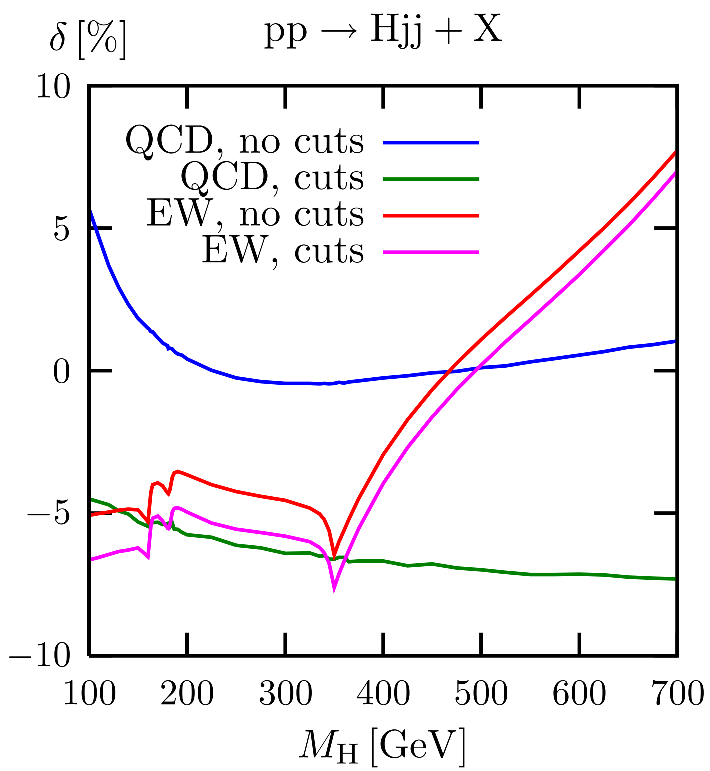


- important Higgs discovery channel
- measurement of HVV couplings
- powerful cuts for background suppression
- small QCD uncertainty: $\pm 4\%$ (DIS like process) $\rightarrow$ VBFNLO
- EW corrections
  Ciccolini, Denner, Dittmaier [arXiv:0710.4749]

  no VBF approximations

  flexible tool: HAWK
  Denner, Dittmaier, AM [http://omnibus.uni-freiburg.de/∼sd565/programs/hawk/hawk.html]

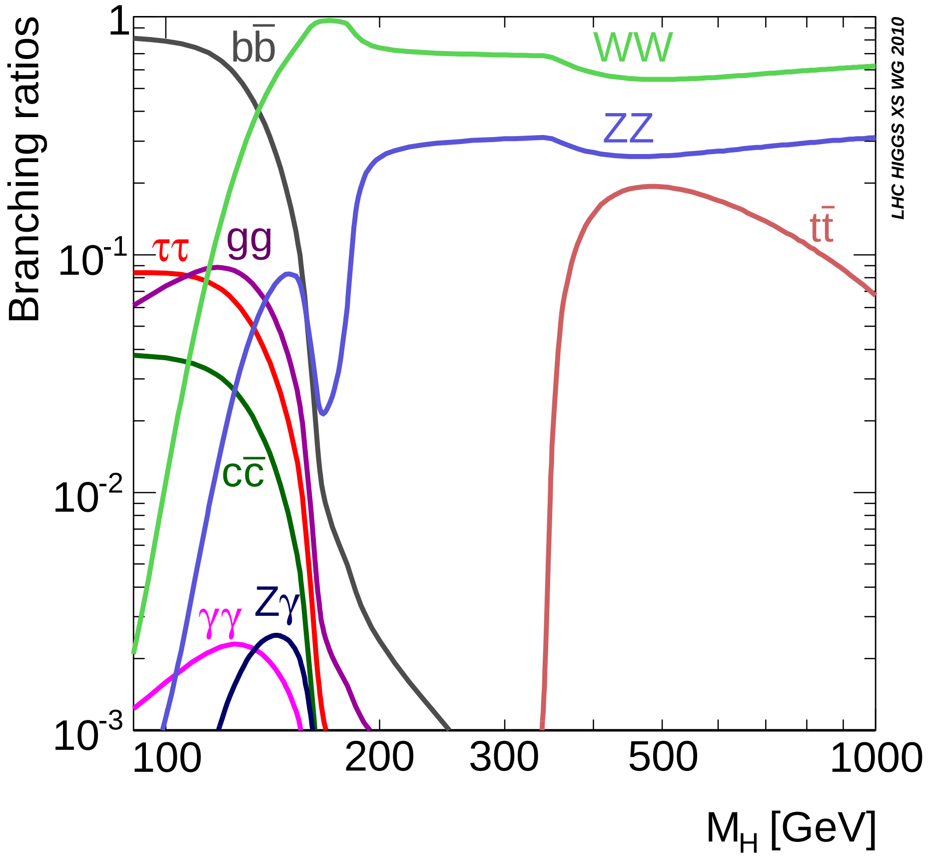
  $\Rightarrow$ Higgsstrahlung included
  (leptonic V decays: available soon)



Higgs Decays

NLO EW corrections to Higgs boson decays:

- $\mathrm{H} \to f\bar{f}$
  Bardin, Vilensky, Khristova
  [Sov.J.Nucl.Phys. 53 (1991) 152]
  Dabelstein, Hollik
  [Z.Phys. C53 (1992) 507]
  Kniehl
  [Nucl.Phys. B376 (1992) 3]
- $\mathrm{H} \to \gamma\gamma$
  Passarino, Sturm, Uccirati
  [arXiv:0707.1401]
- $\mathrm{H} \to gg$
  Actis, Passarino, Sturm, Uccirati
  [arXiv:0809.1301]



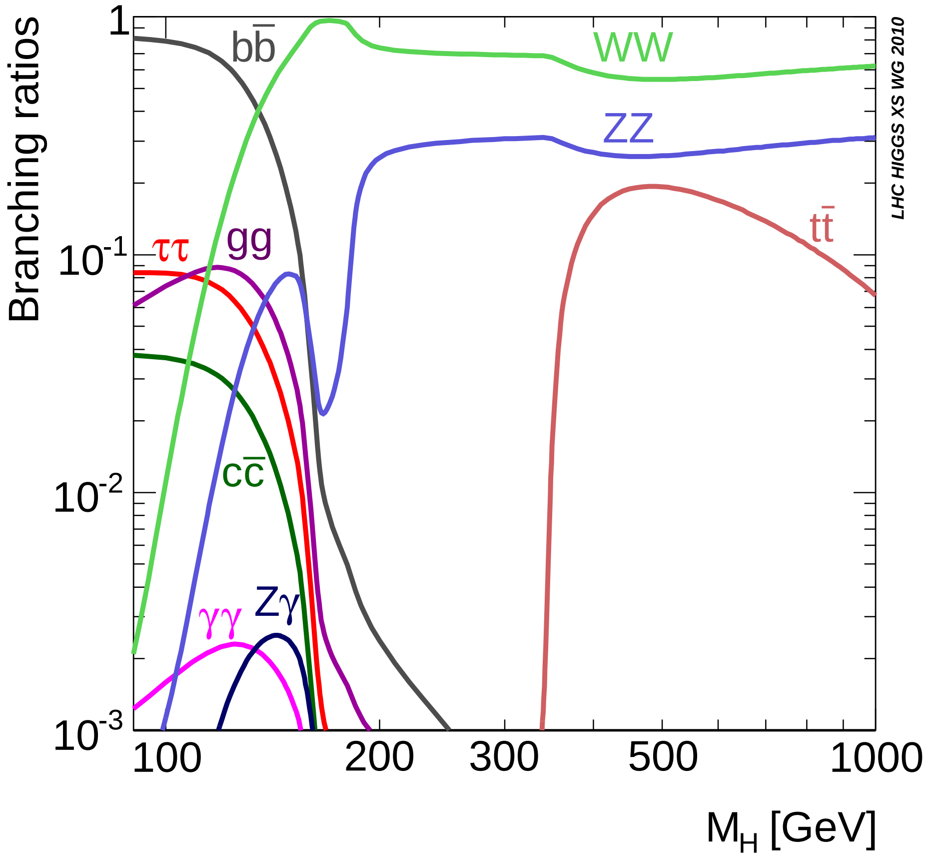
LHC Higgs Cross Section Working Group [arXiv:1101.0593]

all included in HDECAY
(together with QCD corrections)
Djouadi, Kalinowski, Spira [hep-ph/9704448]

Higgs Decays

NLO EW corrections to Higgs boson decays:

- $\mathrm{H} \to f\bar{f}$
  Bardin, Vilensky, Khristova
  [Sov.J.Nucl.Phys. 53 (1991) 152]
  Dabelstein, Hollik
  [Z.Phys. C53 (1992) 507]
  Kniehl
  [Nucl.Phys. B376 (1992) 3]
- $\mathrm{H} \to \gamma\gamma$
  Passarino, Sturm, Uccirati
  [arXiv:0707.1401]
- $\mathrm{H} \to gg$
  Actis, Passarino, Sturm, Uccirati
  [arXiv:0809.1301]



- $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$

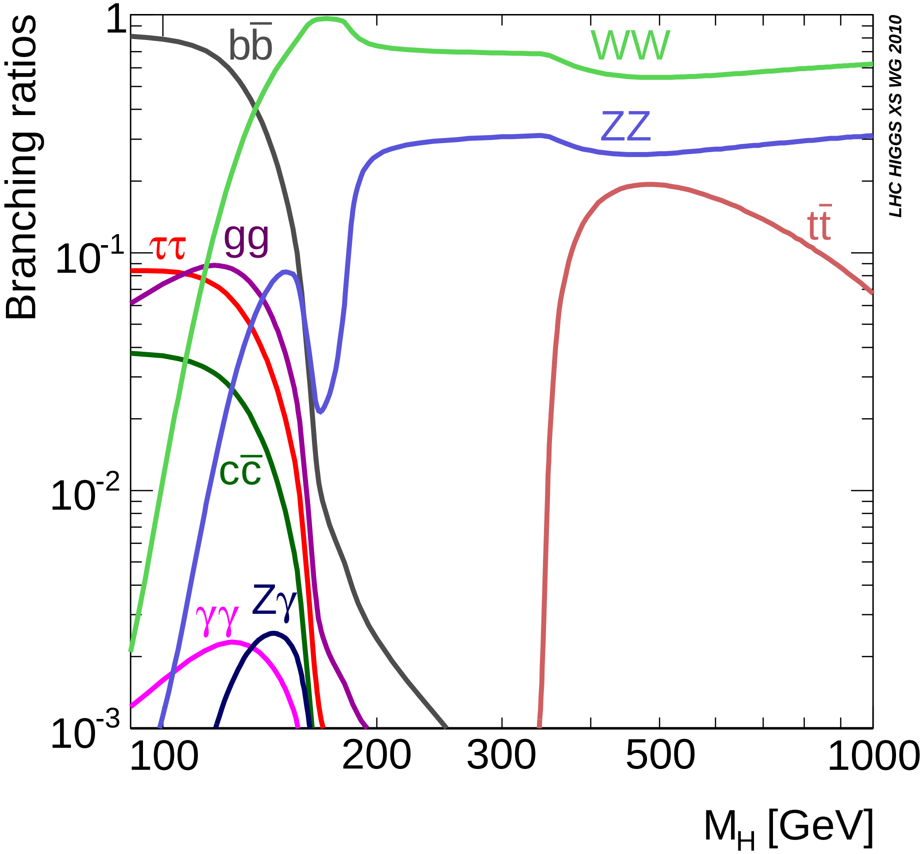
  for off-shell/decaying W/Z bosons

Bredenstein, Denner, Dittmaier, Weber [hep-ph/0611234]

Higgs Decays

NLO EW corrections to Higgs boson decays:

- $\mathrm{H} \to f\bar{f}$
  Bardin, Vilensky, Khristova
  [Sov.J.Nucl.Phys. 53 (1991) 152]
  Dabelstein, Hollik
  [Z.Phys. C53 (1992) 507]
  Kniehl
  [Nucl.Phys. B376 (1992) 3]
- $\mathrm{H} \to \gamma\gamma$
  Passarino, Sturm, Uccirati
  [arXiv:0707.1401]
- $\mathrm{H} \to gg$
  Actis, Passarino, Sturm, Uccirati
  [arXiv:0809.1301]



- $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$
  $\Rightarrow$ Prophecy4f MC generator

Bredenstein, Denner, Dittmaier, AM, Weber
[http://omnibus.uni-freiburg.de/∼sd565/programs/prophecy4f/prophecy4f.html]

Summary

LHC is a tool for precision physics (e.g. $M_{\mathrm{W}}, \Gamma_{\mathrm{W}}, \sin\theta_{\mathrm{eff}}^{\mathrm{lept}}, \ldots$)

Electroweak corrections at the LHC:

- important for any precision measurement (percent level)
- enhancements in specific cases
  - collinear photon radiation
  - Sudakov Logs at high energies
- many calculations are available
- Tools are available (in particular for Drell-Yan)

Outlook/Questions:

- Theory: more on $\mathcal{O}(\alpha\alpha_s)$?
  missing calculations? missing observables?
- Analysis: efficiency $\leftrightarrow$ accuracy? missing observables?

Back-up slides

non collinear-safe subtract.

- usual subtraction procedure:

$$\int \mathrm{d}\Phi_{n+1}\,|\mathcal{M}|^2 = \int \mathrm{d}\Phi_{n+1}\left(|\mathcal{M}|^2 - |\mathcal{M}_{\mathrm{Sub}}|^2\right) + \int \mathrm{d}\Phi_n \int \mathrm{d}k_\gamma\,|\mathcal{M}_{\mathrm{Sub}}|^2$$

- clever choice of $|\mathcal{M}_{\mathrm{Sub}}|^2$

  $\Rightarrow \left(|\mathcal{M}|^2 - |\mathcal{M}_{\mathrm{Sub}}|^2\right)$ is integrable

  $\Rightarrow \int \mathrm{d}k_\gamma\,|\mathcal{M}_{\mathrm{Sub}}|^2$ can be done analytically

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

RWTH

non collinear-safe subtract.

- usual subtraction procedure:

$$\int \mathrm{d}\Phi_{n+1}\, |\mathcal{M}|^2 = \int \mathrm{d}\Phi_{n+1} \left(|\mathcal{M}|^2 - |\mathcal{M}_{\mathrm{Sub}}|^2 \right) + \int \mathrm{d}\Phi_n \int \mathrm{d}k_\gamma\, |\mathcal{M}_{\mathrm{Sub}}|^2$$

  - $\mathcal{M}_{\mathrm{Sub}} = \sum_f \mathcal{M}_{\mathrm{Sub}}(p_{\mathrm{jet}}, z_f)$ where $z_f \to p_f^0/(p_f^0 + p_\gamma^0),\, p_{\mathrm{jet}} \to p_f^0 + p_\gamma^0$ for collinear events
  - only cuts on p_{jet}, no cuts on p_f $\Rightarrow$ cuts independent of z_f

    $\Rightarrow z_f$ integration can be done analytically

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN RWTH

non collinear-safe subtract.

- usual subtraction procedure:

$$\int \mathrm{d}\Phi_{n+1}\,|\mathcal{M}|^2 = \int \mathrm{d}\Phi_{n+1}\left(|\mathcal{M}|^2 - |\mathcal{M}_{\mathrm{Sub}}|^2\right) + \int \mathrm{d}\Phi_n \int \mathrm{d}k_\gamma\,|\mathcal{M}_{\mathrm{Sub}}|^2$$

  - $\mathcal{M}_{\mathrm{Sub}} = \sum_f \mathcal{M}_{\mathrm{Sub}}(p_{\mathrm{jet}}, z_f)$ where $z_f \to p_f^0/(p_f^0 + p_\gamma^0)$, $p_{\mathrm{jet}} \to p_f^0 + p_\gamma^0$ for collinear events
  - only cuts on p_{jet}, no cuts on p_f $\Rightarrow$ cuts independent of z_f

    $\Rightarrow$ z_f integration can be done analytically

- non-collinear safe implementation:
  - no recombination: cuts on p_f allowed
  - cut on z_f in $\mathcal{M}_{\mathrm{Sub}}$ to ensure cancellation of singularities
  - integrate over z_f in $\mathrm{d}k_\gamma$ numerically

    (soft divergence treated via Plus-distribution in analogy to treatment of initial-state emitters/spectators)

photon–jet recombination

What does z_γ cut imply?

- sensitivity to $q \rightarrow q\gamma$ splitting
- non-perturbative corrections to be included

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN
RWTH

photon–jet recombination

What does z_γ cut imply?

- sensitivity to $\mathrm{q} \to \mathrm{q}\gamma$ splitting
- non-perturbative corrections to be included
- introduce quark-to-photon fragmentation function $D_{q\to\gamma}(z_\gamma, \mu_F)$
  - measured in hadronic Z decays at LEP ($\mathrm{Z} \to \mathrm{q\bar{q}} \to \mathrm{q\bar{q}}\gamma$)
  - using ALEPH fit:

$$D_{q\to\gamma}(z_\gamma, \mu_F) = \frac{\alpha Q_q^2}{2\pi} P_{q\to\gamma}(z_\gamma) \left(\ln \frac{m_q^2}{\mu_F^2} + 2 \ln z_\gamma + 1 \right) + D_{q\to\gamma}^{\mathrm{ALEPH}}(z_\gamma, \mu_F),$$

where

$$D_{q\to\gamma}^{\mathrm{ALEPH}}(z_\gamma, \mu_F) = \frac{\alpha Q_q^2}{2\pi} \left(P_{q\to\gamma}(z_\gamma) \ln \frac{\mu_F^2}{(1-z_\gamma)^2 \mu_0^2} + C \right)$$

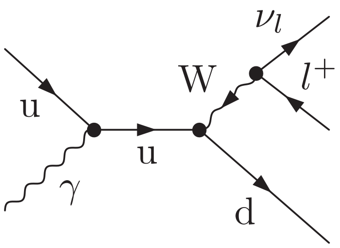
$$P_{q\to\gamma}(z_\gamma) = \frac{1 + (1-z_\gamma)^2}{z_\gamma}$$

up to $\mathcal{O}(\alpha^3\alpha_s)$ in W/Z+jet

- also full NLO QCD corrections
  - variable (phase-space dependent) scale supported

up to $\mathcal{O}(\alpha^3\alpha_s)$ in W/Z+jet

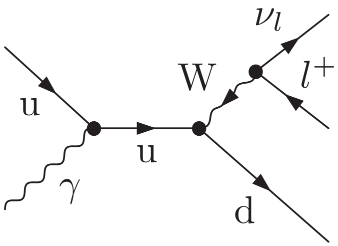
- also full NLO QCD corrections
  - variable (phase-space dependent) scale supported
- photon-induced processes



at NLO QCD
(phenomenologically irrelevant)

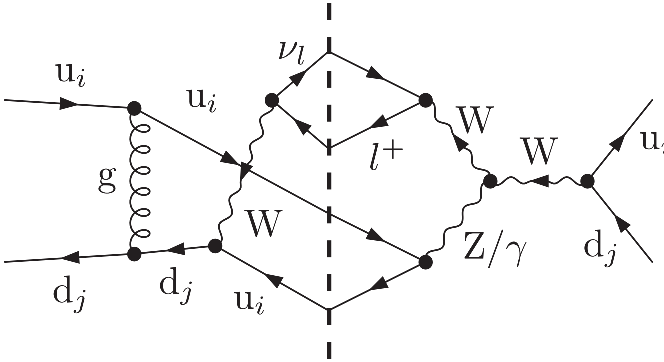
up to $\mathcal{O}(\alpha^3\alpha_s)$ in W/Z+jet

- also full NLO QCD corrections
  - variable (phase-space dependent) scale supported
- photon-induced processes



at NLO QCD
(phenomenologically irrelevant)

- QCD-EW interference terms in 4-quark processes



(phenomenologically irrelevant,
dropped for Z+jet)

RHEINISCH-
WESTFÄLISCHE
TECHNISCHE
HOCHSCHULE
AACHEN
RWTH

MC programs for W/Z+jet

two completely independent calculations

- in mutual agreement

- FeynArts 1.0 [Böhm, Denner, Küblbeck]
  in-house Mathematica Routines
  loop integral library: DD [Dittmaier]
  Vegas integration

- FeynArts 3.2,FormCalc 3.1 [Hahn]
  loop integral library: Coli [Denner]
  Pole [Meier, AM]
  - using Weyl-van der Waerden formalism
    Dittmaier [hep-ph/9805445]
  - automatic generation of subtraction/slicing terms
  - automatic multi-channeling using Lusifer
    Dittmaier, Roth [hep-ph/0206070]

Setup for W/Z+jet

basic cuts

- $p_{\mathrm{T},l/\mathrm{miss}/\mathrm{jet}} >$ 25 GeV
- $|y_{l/\mathrm{jet}}| <$ 2.5
- lepton isolation: $R_{l,\mathrm{jet}} > 0.5$
- photon-energy fraction inside jets: $z_\gamma < 0.7$

recombination

- do not recombine photons and muons (bare μ^+)
- photons and electrons: $R_{\gamma,l} < 0.1$ (γ rec.)
- photons and partons: $R_{\gamma,\mathrm{jet}} < 0.5$

renormalization and factorization scale

- fixed scale ($\mu = M_{\mathrm{W/Z}}$)
- variable scale: $\mu = \sqrt{M^2_{\mathrm{W/Z}} + p_{\mathrm{T}}^{\mathrm{had}}}$ (our default choice)

QCD corrections

$p_{T,jet}$ distribution for the LHC:

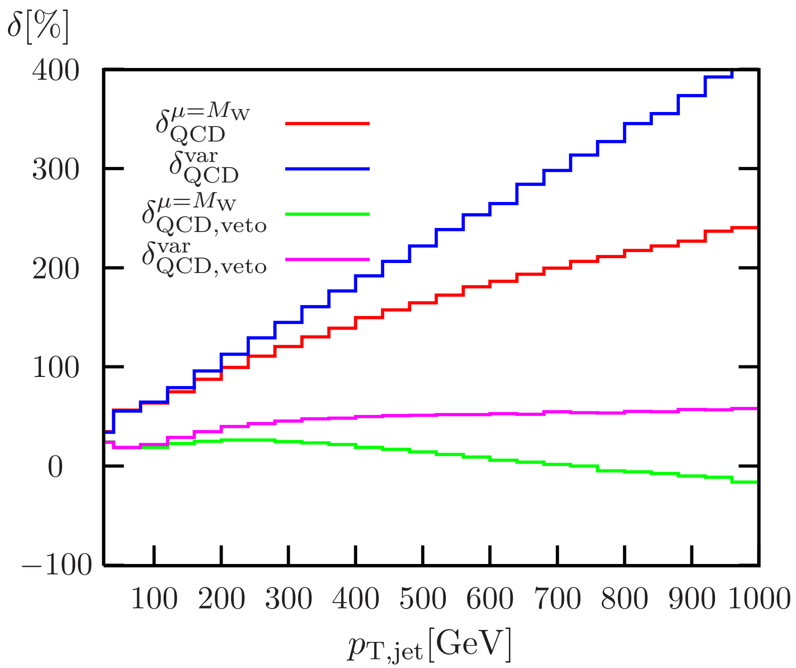
huge NLO QCD corrections:

new kinematical configuration:

back-to-back jets balance p_T

⇒ 2 jet events with W emission

⇒ no genuine QCD correction for W+jet

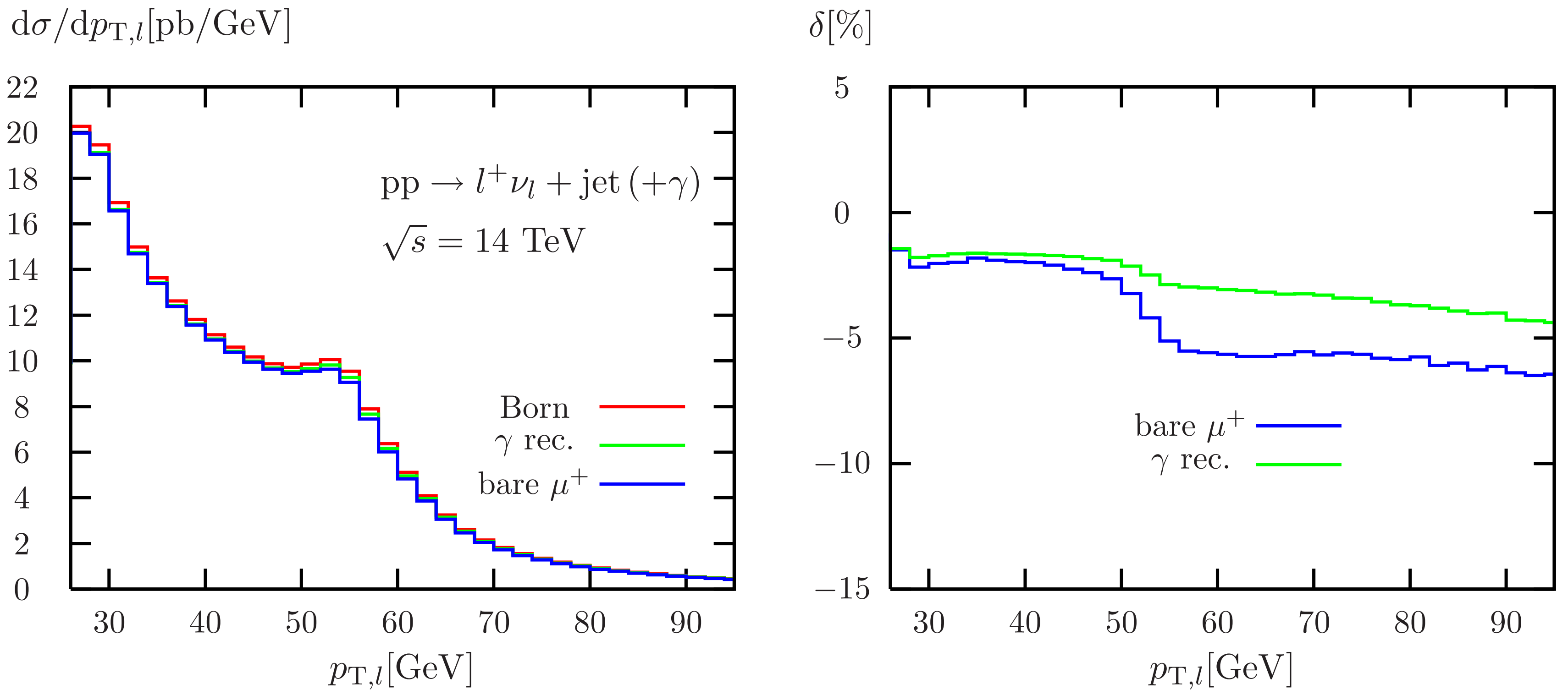


use simple jet veto:

veto second jet with $p_T > \frac{1}{2}\, p_T^{lead.}$

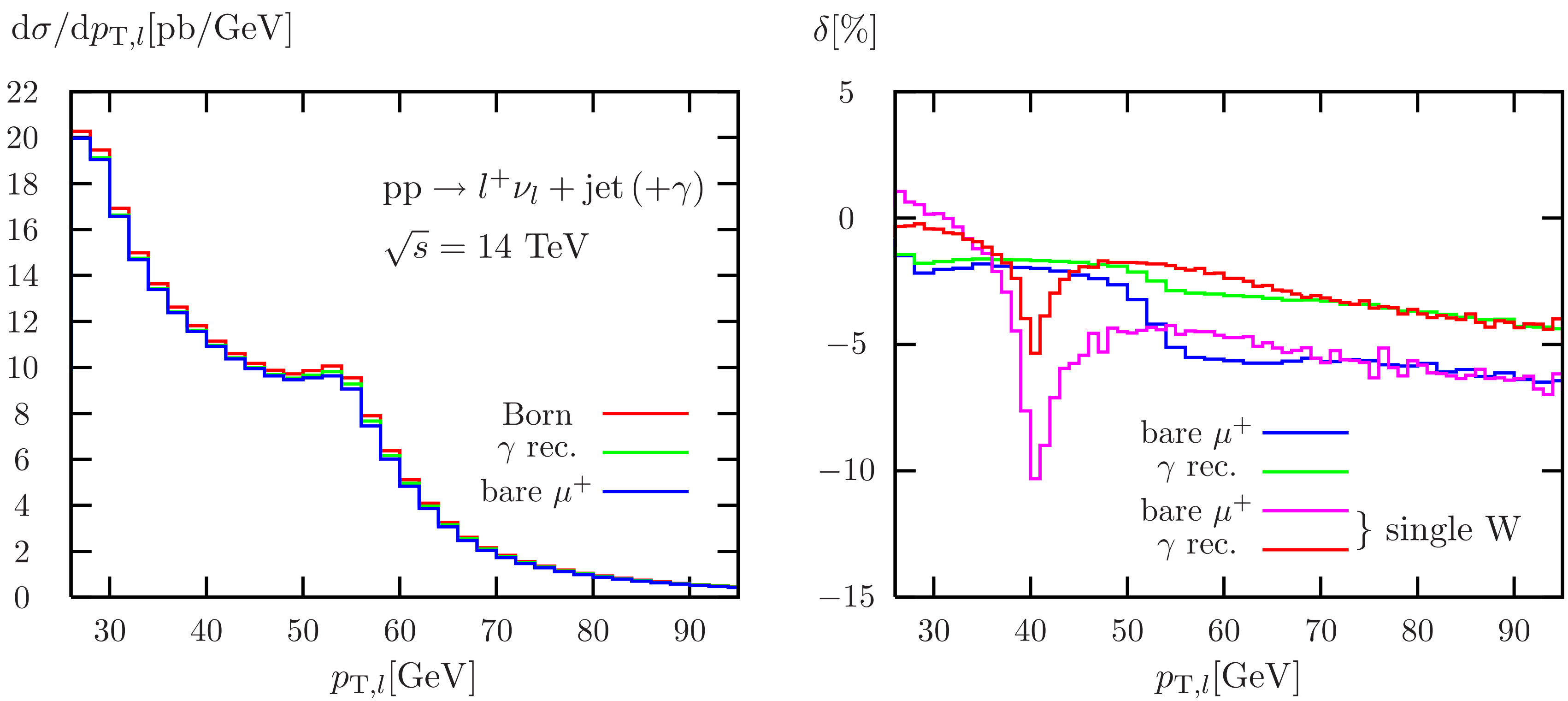
EW corrections

p_T distribution for the LHC:
(similar results for the Tevatron)



EW corrections

p_{T} distribution for the LHC:
(similar results for the Tevatron)



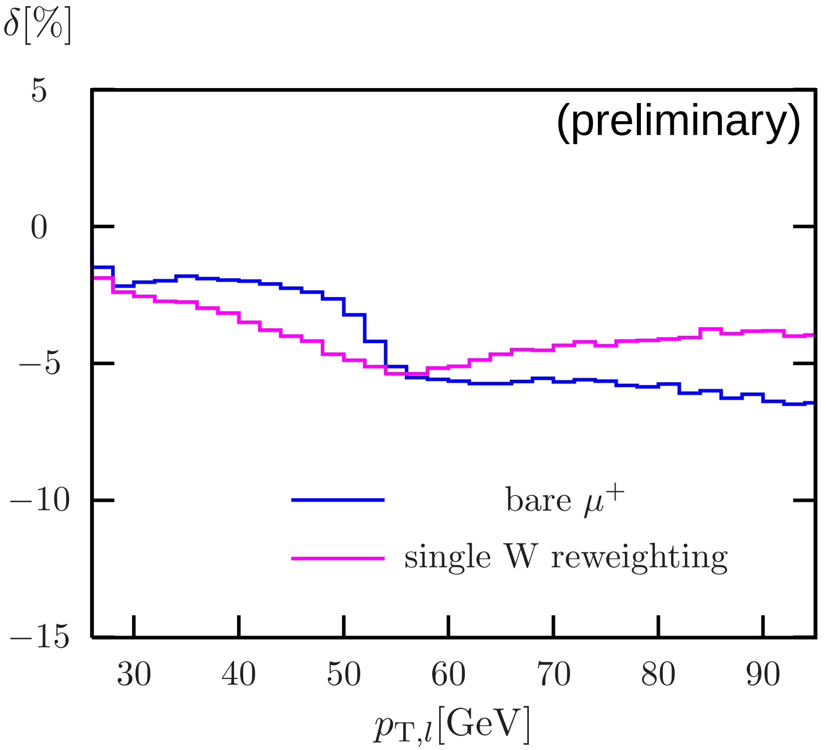
no similarity to single W production

single W vs. W+jet

p_{T} distribution for the LHC:

single W reweighting:

- boost W+jet event to W-boson rest frame
- reweight event with EW correction for single W in rest-frame $p_{T,l}$ bin

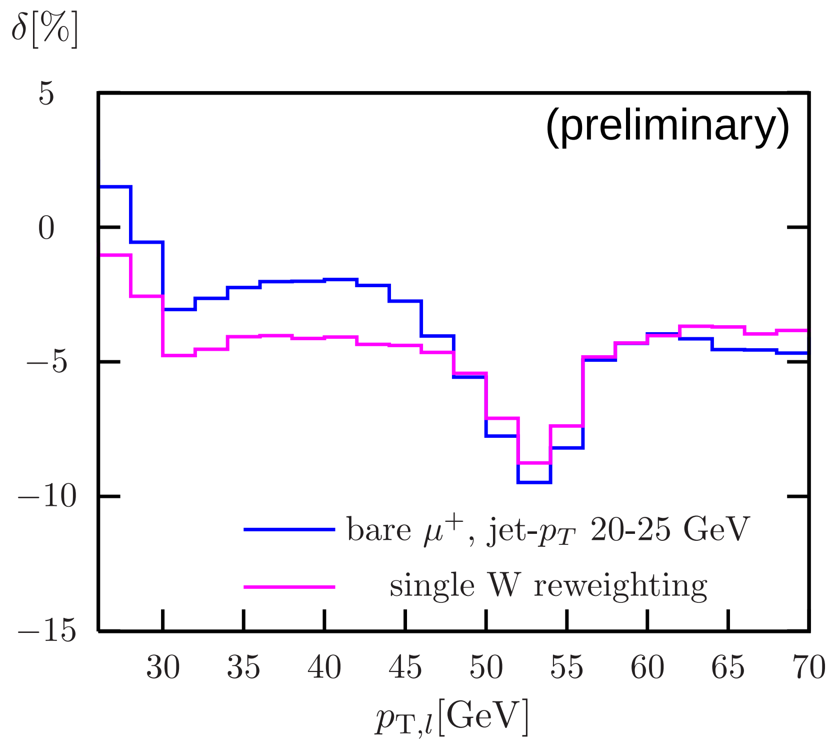


still big differences due to high-p_T jets

single W vs. W+jet

p_{T} distribution for the LHC:

- only look at jets with $p_{T,\mathrm{jet}} = 20 - 25$ GeV

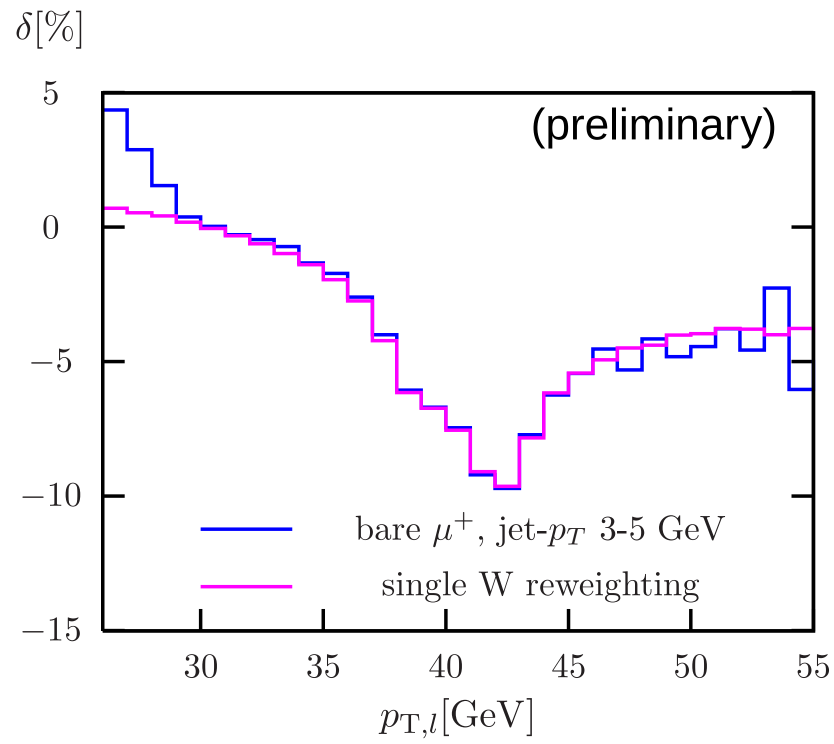


good but not perfect agreement

single W vs. W+jet

p_{T} distribution for the LHC:

- only look at jets with $p_{T,\mathrm{jet}} = 3 - 5$ GeV
- cross-section not reliably predicted in this region
- one can still estimate the EW corrections for the limited kinematical region



very good agreement