Status of (Higgs and) EW cross-sections for the LHC

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Outline

- Introduction
- Drell-Yan
  - Higher order QCD corrections
  - Higher order electroweak corrections
  - Recipes for inclusion of NLO QCD matched with PS $\oplus/\otimes$ NLO EWK matched with QED PS
- Higgs (no time to cover it in this talk)
  - Higher order corrections to production processes
  - Higher order corrections to branching ratios

see also talks by F. Petriello and R. Boughezal

Introduction

Two items where precise calculations will be soon relevant at LHC:

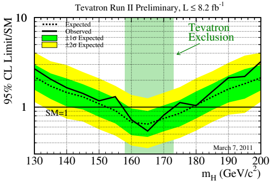
- CC and NC Drell-Yan
- Higgs

with $\mathcal{L} = 2.9$ pb^{-1} at LHC systematics of

- 1.1% related to PDF's
- 1.4% due to theoretical uncertainties

on a total 3.1% for $\sigma(W \to \mu\nu_\mu)$

CMS arXiv:1012.2466



Tevatron Higgs exclusion limits sensitive to theoretical uncertainties

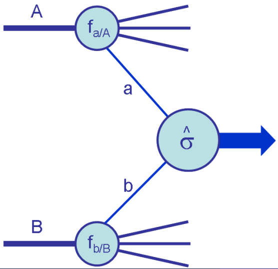
J. Baglio et al., Phys. Lett. B699 (2011) 368

Introduction

Factorization theorem

$$\sigma_{AB} = \sum_{ab} \int dx_a \quad dx_b \quad f_{a/A}(x_a, \mu_F^2)\, f_{b/B}(x_b, \mu_F^2)$$
$$\times \quad [\hat{\sigma}_{ab}(\mu_F^2, \mu_R^2, x_a p_a, x_b p_b)$$
$$+ \quad \mathcal{O}\left(\frac{\Lambda^n_{QCD}}{Q^n}\right)$$

see talk by S. Forte for state of the art of PDF's



- Higgs: Γ_H small ($m_H < 200$ GeV) $\Rightarrow$ production cross section in NWA $\times$ decay
- NWA approximation not enough for DY

Higher-order QCD & generators

- Multi-parton matrix elements Monte Carlos (ALPGEN, HELAC, MADEVENT, SHERPA...) matched with vetoed Parton Showers
- NLO calculations for $W, Z \to l\bar{l}'$ (DYRAD, MCFM)

  W.T. Giele, E.W.N. Glover and D.A. Kosower, Nucl. Phys. **B403** (1993) 633

  J.M. Campbell and R.K. Ellis, Phys. Rev. **D65** (2002) 113007
- soft-gluon resummation of leading/next-to-leading logs (ResBos)

  C. Balazs and C.P. Yuan, Phys. Rev. **D56** (1997) 5558
- fully differential NNLO corrections to W/Z production (FEWZ, DYNNLO)

  K. Melnikov and F. Petriello, Phys. Rev. Lett. **96** (2006) 231803, Phys. Rev. **D74** (2006) 114017

  S. Catani, L. Cieri, G. Ferrera, D. de Florian, M. Grazzini, Phys. Rev. Lett. **103** (2009) 082001

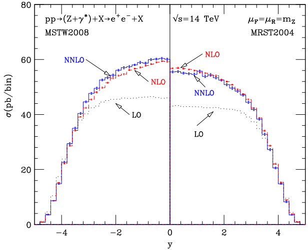
  S. Catani, G. Ferrera, M. Grazzini, JHEP **1005** (2010) 006
- NNLL resummation of W/Z transverse momentum

  G. Bozzi, S. Catani, G. Ferrera, D. de Florian, M. Grazzini, Phys. Lett. **B696** (2011) 207
- NLO merged with Parton Showers (MC@NLO, POWHEG)

  S. Frixione and B.R. Webber, JHEP **0206** (2002) 029

  P. Nason, JHEP 0411 (2004) 040; S. Alioli et al., JHEP 0807 (2008) 060, JHEP 1006 (2010) 043

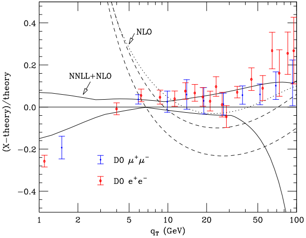
NC DY @14 TeV



S. Catani, L. Cieri, G. Ferrera, D. de Florian, M. Grazzini,

Phys. Rev. Lett. **103** (2009) 082001

q_T^Z @Tevatron



G. Bozzi, S. Catani, G. Ferrera, D. de Florian, M. Grazzini,

Phys. Lett. **B696** (2011) 207

- deviations of $\mathcal{O}(\%)$ between NLO and NNLO
- larger deviations due to PDF's

EWRC for DY processes & generators

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

- ⋆ **Pole approximation**
  Wackeroth, Hollik, Phys. Rev. D55 (1997) 6788;
  Baur, Keller, Wackeroth, PRD59 (1999) 013002;
  WGRAD

- ⋆ **Complete $\mathcal{O}(\alpha)$ corrections**
  V.A. Zykunov, Eur. P. J. **C3** (2001) 9,
  Phys. Atom. Nucl. 69 (2006) 1522;
  Dittmaier, Krämer, Phys. Rev. D65 (2002) 073007;
  Baur, Wackeroth, Phys. Rev. D70 (2004) 073015;
  WGRAD2

  A. Arbuzov *et al.*, Eur. Phys. J. C46 (2006) 407;
  SANC

  C.M. Carloni Calame *et al.*, JHEP 12 (2006) 016;
  HORACE

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

- ⋆ **$\mathcal{O}(\alpha)$ photonic corrections**
  Baur, Keller, Sakumoto, PRD57 (1998) 199;
  ZGRAD

- ⋆ **Complete $\mathcal{O}(\alpha)$ corrections**
  U. Baur *et al.*, Phys. Rev. **D65** (2002) 033007;
  ZGRAD2

  C.M. Carloni Calame *et al.*, JHEP **10** (2007) 190;
  HORACE

  V.A. Zykunov, Phys. Rev. **D75** (2007) 073019;
  A. Arbuzov *et al.*, Eur. Phys. J **C54**:451-460, 2008;
  SANC

  S. Dittmaier and M. Huber, JHEP 01 (2010) 060.

Higher order electroweak corrections

- Multi-photon radiation
  - Higher-order (real+virtual) QED corrections to $W/Z/\gamma^*$ production
    - $\rightarrow$ HORACE: QED PS + NLO EWRC to $W/Z/\gamma^*$ production

      C.M. Carloni Calame *et al.*, Phys. Rev. **D69** (2004) 037301;
      C.M. Carloni Calame *et al.*, JHEP **05** (2005) 019; JHEP **12** (2006) 016; JHEP **10** (2007) 190;
    - $\rightarrow$ WINHAC: YFS exponentiation + $\mathcal{O}(\alpha)$ EWRC to W decay

      S. Jadach and W. Płaczek, Eur. Phys. J. **C29** (2003) 325
    - $\rightarrow$ WINHAC⊕SANC: YFS exponentiation + $\mathcal{O}(\alpha)$ EWRC to W

      Bardin, Bondarenko, Jadach, Kalinowskaya, Placzek, Acta Phys. Pol. B40 (2009) 75
  - Improved treatment of multiphoton radiation in HERWIG(++) (with SOPHTY via YFS) and PHOTOS (via QED Parton Shower)

    K. Hamilton and P. Richardson, JHEP **0607** (2006) 010
    P. Golonka and Z. Was, Eur. Phys. J. **C45** (2006) 97
  - Higher order QED FSR with collinear structure funcions

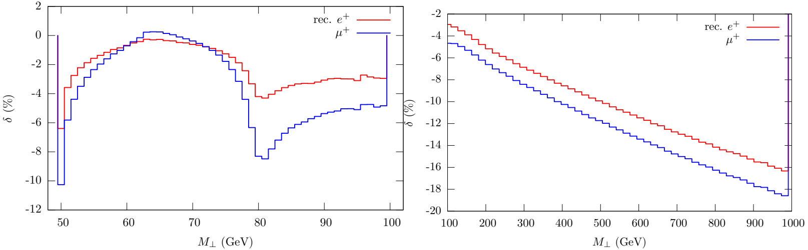
    S. Dittmaier and M. Huber, JHEP 01 (2010) 060
- Higher order effects from couplings ($\Delta\alpha(M_Z)^n$, $\Delta\rho^2$, $\Delta\alpha(M_Z)\Delta\rho$)
- Higher orders from two-loop leading Sudakov logs $(\alpha_W \log^2 \frac{s}{M_W^2})$

A. Denner, B. Jantzen and S. Pozzorini, Nucl. Phys. **D761** (2007) 1
B. Jantzen *et al.*, Nucl. Phys. **D731** (2005) 188

Typical EW effects for W production

Carloni Calame, Montagna, Nicrosini, Vicini, JHEP 12 016 (2006)

- final state (FS) QED radiation distorts the M_T spectrum
- higher orders QED radiation affect the measurement of M_W at the level of $[\Delta M_W]_\alpha \sim$ 100 MeV $\qquad [\Delta M_W]_\infty \sim$ 10% of $[\Delta M_W]_\alpha$



- $\mathcal{O}(\alpha)$ corrections at 5% - 10% level around the peak and increasingly large in the M_T tail due to the presence of the EW Sudakov logs[2]

QCD - EWK corrections interference

- Perturbatively the QCD - EW interference is a two-loop effect

$$d\sigma = d\sigma_0 + d\sigma_{\alpha_s} + d\sigma_{\alpha} + d\sigma_{\alpha_s^2} + d\sigma_{\alpha\alpha_s} + d\sigma_{\alpha^2} + \ldots$$

- A two loop $\mathcal{O}(\alpha\alpha_s)$ calculation would involve
  - virtual corrections at $\mathcal{O}(\alpha\alpha_s)$
  - EWK corrections to $l\bar{l}^{(\prime)}+$ jet
  - QCD corrections to $l\bar{l}^{(\prime)} + \gamma$
  - PDF's with NNLO accuracy at $\mathcal{O}(\alpha\alpha_s)$
- However the bulk of the effects are in the soft/collinear regions where factorization holds
  - in the factorized limit, $\mathcal{O}(\alpha\alpha_s)$ terms given by $\mathcal{O}(\alpha) \otimes \mathcal{O}(\alpha_s)$
  - moreover for the specific case of DY at the $V(= W, Z)$ peak the largest part of EW corrections comes from photon emission from external lepton leg(s)

What is available in simulation tools

- the LL factorized approach (with higher order resummation) is available for instance in PS event generators (e.g.)
  - HERWIG +PHOTOS
  - HERWIG++, SHERPA, PYTHIA and PYTHIA8 have their own QED shower
  - HERWIG++ and SHERPA use YFS formalism for QED radiation from W and Z decays
- Resbos family includes QED final state corrections + pure weak corrections in the form of I(mproved)B(orn)A(pproximation) taking into account leading corrections (running couplings)
- the level of precision of this kind of approach at the W/Z peak (at LHC energies, 7-10-14 TeV) has been preliminarily tested in

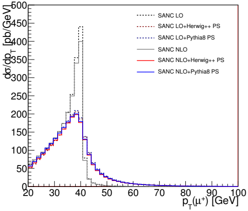
  N. Adam, V. Halyo and S.A. Yost, JHEP bf 11 (2010) 074; JHEP bf 05 (2008) 062; JHEP bf 09 (2008) 133

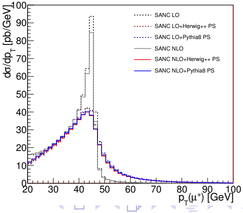
  by comparing HERWIG + PHOTOS with HERWIG +HORACE which includes QED PS matched to the exact NLO EWK calculation
  $\Rightarrow$ differences at the level of 1-2% on cross sections

SANC interfaced to HERWIG++ and PYTHIA8

P. Richardson, R.R. Sadykov and A.A. Sapronov, M.H. Seymour, P.Z. Skands, arXiv:1011.5444[hep-ph]

- The EW NLO calculation of SANC has been implemented in the LO PS HERWIG++ and PYTHIA8
- The shower algorithms have been modified to handle photon-induced hard processes
- PS multiphoton emission switched off to avoid double counting with NLO EWK calculation
- main differences due to shower model expected to become smaller once matrix element corrections are switched on





- using different generators, a recipe to combine QCD and electroweak corrections has been proposed according to the following recipes (additive/factorized form):

G. Balossini *et al.*, JHEP 1001:013, 2010

⊕ **Additive prescription:**

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

⊗ **Factorized prescription:**

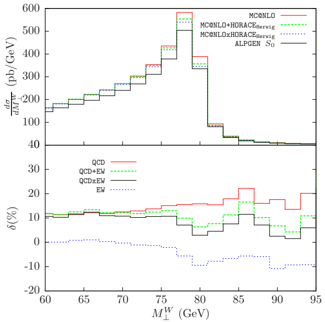
$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}}\right]_{\text{QCD}\otimes\text{EW}} = \left(1 + \frac{\left[\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}}\right]_{\text{QCD}} - \left[\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}}\right]_{\texttt{HERWIG}\ \text{PS}}}{\left[\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}}\right]_{\text{(N)LO}}}\right) \times \left\{\left[\frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}}\right]_{\text{EW}}\right\}_{\texttt{HERWIG}\ \text{PS}}$$

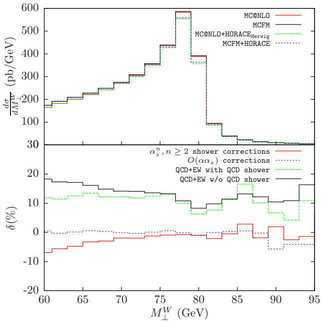
Combining EWK and QCD corrections

- QCD ⇒ ResBos, MCFM, MC@NLO, POWHEG, ...
- EW ⇒ Electroweak + multiphoton corrections from HORACE convoluted with HERWIG QCD Parton Shower
  - ⋆ NLO electroweak corrections are interfaced to QCD Parton Shower evolution ⇒ $\mathcal{O}(\alpha\alpha_s)$ corrections reliable only at LL level
  - not reliable when hard non collinear QCD radiation is important (e.g. p_T^W and p_T^l for nearly on shell W)
- Additive and factorized prescription have Same $O(\alpha)$, $O(\alpha_s)$ and leading $O(\alpha_s^2)$ content
- Differences at $O(\alpha\alpha_s)$ and $O(\alpha_s^2)$ non-leading-log
- (N)LO normalization of factorized prescription is an issue for observables starting from $\mathcal{O}(\alpha_s)$ (e.g. p_T^W)
- difference between additive and factorized prescription gives an estimate of the impact of $\mathcal{O}(\alpha\alpha_s)$ contributions

$M_\perp^W$ @ LHC

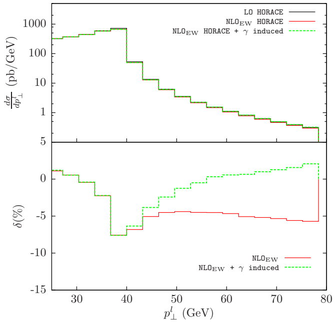
G. Balossini *et al.*, JHEP 1001:013, 2010

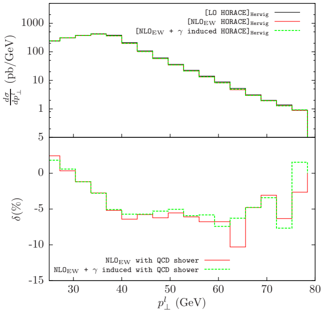




- QCD shower evolution very important below peak
- $\mathcal{O}(\alpha\alpha_s)$ corrections play a role above peak

G. Balossini *et al.*, JHEP 1001:013, 2010





- Large difference on $p_\perp^l$ before and after parton-showering of γ-induced processes

Some summary numbers

G. Balossini *et al.*, JHEP 1001:013, 2010

LHC a): LHC@ 14 TeV; LHC b): LHC @ 14 TeV with $M_T > 1$ TeV

$\delta(\%)$	NLO QCD	NLL QCD	NLO EW	Shower QCD	$O(\alpha\alpha_s)$
Tevatron	8	16.8	-2.6	-1.3	~ 0.5
LHC a	-2	12.4	-2.6	1.4	~ 0.5
LHC b	21.8	20.9	-21.9	-0.6	~ 5

Table: Relative effect of the main sources of QCD, EW and mixed radiative corrections to the integrated cross sections for the Tevatron, LHC a) and LHC b).

$\delta(\%)$	$\delta\sigma/\sigma$ (scale)	$\delta\sigma/\sigma$ (FA)	$\delta\sigma/\sigma$
Tevatron	~ 1	~ 2	2
LHC a	~ 2.5	~ 2	2.5
LHC b	~ 1.5	~ 5	5

Table: Estimate of the present theoretical accuracy for the calculation of the integrated cross section at the Tevatron, LHC a and LHC b.

Summary and Outlook

- QCD corrections
  - knowledge of QCD corrections at NNLO implemented in two parton level MC programs
  - resummation of W/Z transverse momentum at NNLL accuracy
- Electroweak corrections
  - complete $\mathcal{O}(\alpha)$ available in different dedicated generators
  - LL resummation of QED corrections consistently matched with NLO EWK corrections
- recent activity to combine QCD and NLO EWK corrections
- current work in progress on matching QCD and EWK higher order effects in a single generator
  - interface of HORACE with POWHEG — L. Barzè, F.P., HORACE and POWHEG teams
  - interface of W/ZGRAD with POWHEG — C. Bernaciak, D. Wackeroth
  - development of HERWIRI — S. Joseph, S. Majhi, B.F.L. Ward, S.A. Yost, PRD81 (2010) 076008
- time is over, for the state of the art of theoretical predictions for Higgs cross sections see arXiv:1101.0593[hep-ph] (and talks by R. Boughezal and F. Petriello)