Combining electroweak and QCD corrections to Drell-Yan processes at hadron colliders

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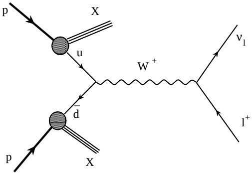
in collaboration with G. Balossini, C.M. Carloni Calame, G. Montagna, M. Moretti, F. Piccinini, M. Treccani, A. Vicini

At Fermilab and CERN

Single W/Z boson production, with $W \to \ell \nu_\ell, Z \to \ell^+ \ell^-$ decays $\Longrightarrow$ clean processes with a large cross section. They are useful



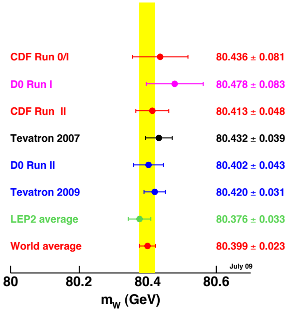
- to derive precise measurements of the electroweak parameters $M_W, \Gamma_W, \sin^2 \theta^\ell_{\rm eff}$. Relevant observables: leptons' transverse momentum $p^\ell_\perp$, W transverse mass $M^W_\perp$, ratio of W/Z distributions, forward-backward asymmetry A^Z_{FB}...
- to monitor the collider luminosity and constrain the parton distribution functions (PDFs). Relevant observables: total cross section, W rapidity y_W and charge asymmetry $A(y_\ell)$, lepton pseudorapidity η_ℓ...
- to search for new physics. Relevant observables: Z invariant mass distribution $M^Z_{\ell\ell}$ and W transverse mass $M^W_\perp$ in the high tail...

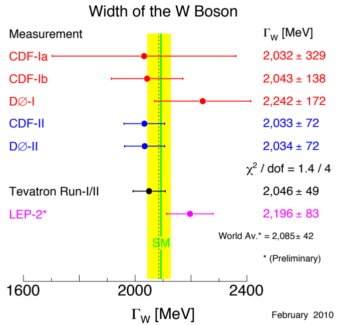
The quest for precision: W mass and width

The Tevatron Electroweak Working Group for the CDF and D0 Collaborations

arXiv:1003.2826 [hep-ex], arXiv:0908.1374 [hep-ex]

- Present experimental status:



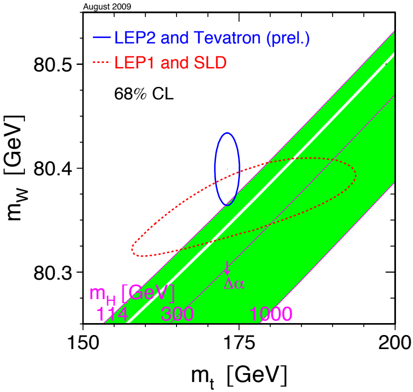


- Target ΔM_W precision $\rightarrow$ Tevatron RunII: $\sim$ 20 MeV LHC: 10-20 MeV
- Target $\Delta \Gamma_W$ precision $\rightarrow$ Tevatron RunII: $\sim$ 30 MeV LHC: $\leq$ 30 MeV

★ At the Tevatron, NLO QED corrections shift M_W by $\sim 100/200$ MeV ★

W-boson, top-quark and Higgs boson mass interconnection

The LEP EW WG, http://lepewwg.web.cern.ch/LEPEWWG/plots/summer2009/



- Compatibility test of the Standard Model and indirect bound on the Higgs-boson mass

Higher-order QCD & QCD generators

- NLO/NNLO corrections to W/Z total production rate

  G. Altarelli, R.K. Ellis and G. Martinelli, Nucl. Phys. **B157** (1979) 461

  R. Hamberg, W.L. van Neerven, T. Matsuura, Nucl. Phys. **B359** (1991) 343

- NLO calculations for $W, Z + 1, 2$ jets (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

- NLO merged with Parton Showers (MC@NLO, POWHEG)

  S. Frixione and B.R. Webber, JHEP **0206** (2002) 029, P. Nason, JHEP 0411 (2004) 040

- Multi-parton matrix elements Monte Carlos (ALPGEN, HELAC, MADEVENT, SHERPA...) matched with vetoed Parton Showers

  M.L. Mangano *et al.* , JHEP **0307** (2003) 001; A. Kanaki and C.G. Papadopoulos, Comput. Phys. Commun. **132** (2000) 306; F. Maltoni and T. Stelzer, JHEP **02** (2003) 027; F. Krauss *et al.*, JHEP **0507** (2005) 018

- fully differential NNLO corrections to W/Z production (FEWZ)

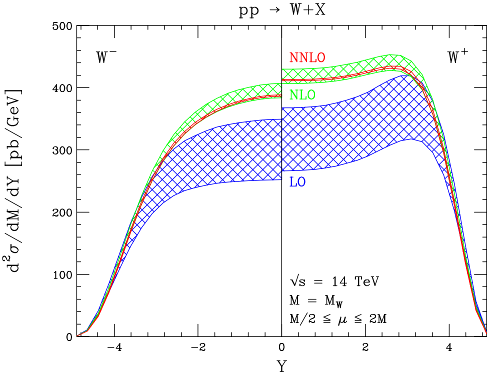
  C. Anastasiou *et al.* , Phys. Rev. **D69** (2004) 094008

  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

High-precision QCD: W/Z observables @ NNLO

C. Anastasiou *et al.*, Phys. Rev. Lett. **91** (2003) 182002
C. Anastasiou *et al.*, Phys. Rev. **D69** (2004) 094008
S. Catani, L. Cieri, G. Ferrera, D. de Florian, M. Grazzini, Phys. Rev. Lett. **103** (2009) 082001



- NNLO QCD corrections to W/Z observables at few per cent in the regions of interest (but could be much more important in general, e.g. $M_{\perp}^{W}$ below the kinematical boundary!)

$\star$ $\mathcal{O}(\alpha_S^2) \approx \mathcal{O}(\alpha_{\rm em}) \longrightarrow$ need to worry about electroweak corrections!

NLO electroweak calculations & tools (I)

- $\mathcal{O}(\alpha)$ QED corrections to W/Z lepton decays

  F.A. Berends *et al.* Z. Physik **C27** (1985) 155,365

- Electroweak corrections to W production

  ⋆ Pole approximation ($\sqrt{\hat{s}} = M_W$)

  D. Wackeroth and W. Hollik, Phys. Rev. **D55** (1997) 6788

  U. Baur, S. Keller, D. Wackeroth, Phys. Rev. **D59** (1999) 013002 WGRAD

  ⋆ Complete $\mathcal{O}(\alpha)$ corrections

  V.A. Zykunov, Eur. P. J. **C3** (2001) 9, Phys. Atom. Nucl. **69** (2006) 1522

  S. Dittmaier and M. Krämer, Phys. Rev. **D65** (2002) 073007 DK

  U. Baur and D. 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

  S. Brensing, S. Dittmaier, M. Krämer and A. Muck, Phys. Rev. **D77**:073006, 2008

- Electroweak corrections to Z production
  - ⋆ $\mathcal{O}(\alpha)$ photonic corrections

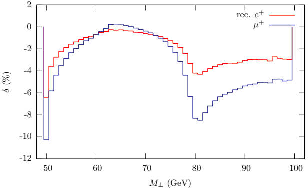
    U. Baur, S. Keller, W.K. Sakumoto, Phys. Rev. **D57** (1998) 199 ZGRAD
  - ⋆ Complete $\mathcal{O}(\alpha)$ corrections

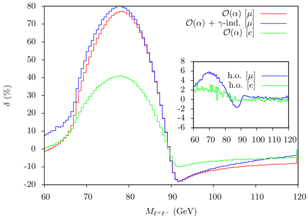
    U. Baur *et al.*, Phys. Rev. **D65** (2002) 033007 ZGRAD2

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

    V.A. Zykunov, Phys. Rev. **D75** (2007) 073019

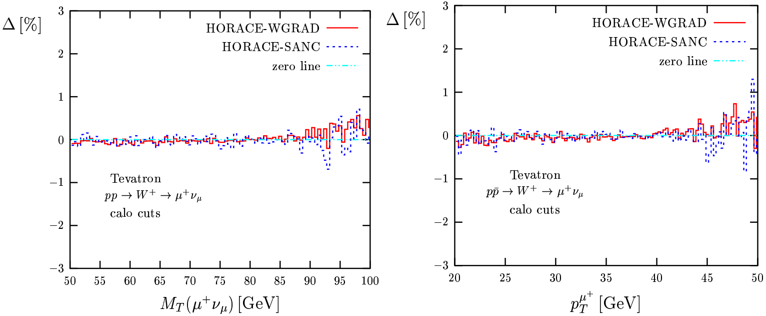
    A. Arbuzov *et al.*, Eur. Phys. J **C54**:451-460, 2008 SANC





Process and scheme – Detector modeling and lepton identification

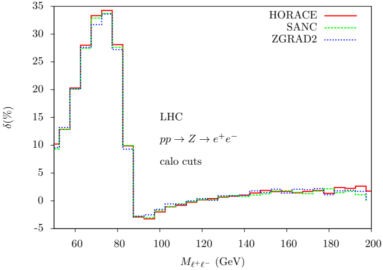
1. $p\bar{p}(pp) \to W^+ \to \ell^+ \nu_\ell (+\gamma)$ – $\alpha(0),\, G_\mu,\, M_Z \to M_W$ at two – loops
2. $\sqrt{s} = 1.96$ TeV, 14 TeV $\quad p_\perp^\ell > 20$ GeV $\quad \not{p}_\perp > 20$ GeV $\quad |\eta_\ell| < 2.5$
3. Bare (w/o recombination and smearing) and Calo (with recombination and smearing) event selection $\quad \Delta R(e,\gamma) = \sqrt{(\Delta\eta(e,\gamma))^2 + (\Delta\phi(e,\gamma))^2} < 0.1$

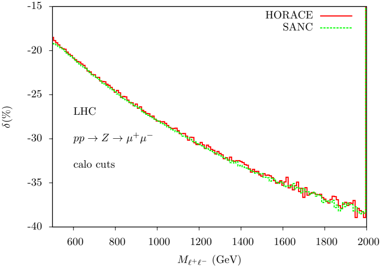


- Electroweak generators agree within their statistical precision $\longrightarrow$ NLO electroweak corrections to W production well under control!

Process and scheme – Detector modeling and lepton identification

1. $pp \to Z \to \ell^+\ell^-(+\gamma)$ – $\alpha(0),\, G_\mu,\, M_Z \;\to M_W$ at two – loops
2. $\sqrt{s} = 14$ TeV $\quad p_\perp^\ell > 20$ GeV $\quad M_{ll} > 50$ GeV $\quad |\eta_\ell| < 2.5$
3. Bare (w/o recombination and smearing) and Calo (with recombination and smearing) event selection $\quad \Delta R(e,\gamma) = \sqrt{(\Delta\eta(e,\gamma))^2 + (\Delta\phi(e,\gamma))^2} < 0.1$





- Electroweak generators agree within their statistical precision $\longrightarrow$ NLO electroweak corrections to Z production well under control!

Multiple photon corrections & tools

- Higher-order (real+virtual) QED corrections to W/Z production
  - $\to$ HORACE (Pavia): QED Parton Shower + NLO electroweak corrections to W/Z 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
  - $\to$ WINHAC (Cracow): YFS exponentiation + electroweak corrections to W decay

    S. Jadach and W. Płaczek, Eur. Phys. J. **C29** (2003) 325
- Perfect agreement between HORACE and WINHAC on multiphoton corrections to all W observables

  C.M. Carloni Calame, S. Jadach, G. Montagna, O.N. and W. Placzek, Acta Phys. Pol. **B35** (2004) 1643
- Recent effort to improve the 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

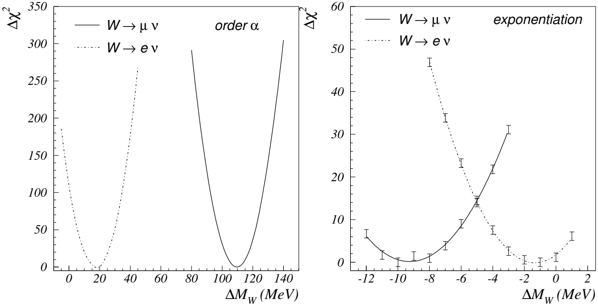
$\star$ W-mass shift due to multiphoton radiation is about 10% of that caused by one photon emission $\longrightarrow$ non-negligible for precision W mass measurements! $\star$

C.M. Carloni Calame *et al.*, Phys. Rev. **D69** (2004) 037301

Why higher-order QED is important: W mass

C.M. Carloni Calame *et al.*, Phys. Rev. **D69** (2004) 037301

Including "recombination and smearing"



$$\Delta M_W^{\alpha,e} \sim 20 \text{ MeV}$$
$$\Delta M_W^{\alpha,\mu} \sim 110 \text{ MeV}$$

$$\Delta M_W^{\infty,e} \sim 2 \text{ MeV}$$
$$\Delta M_W^{\infty,\mu} \sim 10 \text{ MeV}$$

- W-mass shift due to multiphoton radiation is about 10% of that caused by one photon emission $\longrightarrow$ non-negligible for W mass!
- strong dependence of the absolute value of the correction on the details of the detector

Combining electroweak and QCD corrections (I)

- First attempt: combination of soft-gluon resummation with NLO final-state QED corrections (plus leading EW contributions)
  Q.-H. Cao and C.-P. Yuan, Phys. Rev. Lett. **93** (2004) 042001 - ResBos−A
- QCD and electroweak corrections can be combined according to the following recipes (additive/factorized form):

Balossini, Carloni Calame, Montagna, M. Moretti, O.N., Piccinini, Treccani, Vicini, JHEP 1001:013, 2010

⊕ **Additive prescription:**

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

⊗ **Factorized prescription:**

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

Combining electroweak and QCD corrections (II)

- QCD ⇒ ResBos, MCFM, MC@NLO, ALPGEN, ...
- 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
  - ⋆ Beyond this approximation, a full two-loop $\mathcal{O}(\alpha\alpha_s)$ calculation is needed (unavailable yet)

    J.H. Kühn *et al.*, Phys.Lett. **B651** 160-165, 2007
    $\mathrm{NLO/NNLO_{EW}}$ to $pp \to Wj$
- NLO PDF used; NNLO PDF available, with corresponding error estimate; see for instance A.D. Martin *et al.*, Phys. Lett. **B652** (2007) 292, arXiv:0901.0002 [hep-ph]; A. Cafarella, C. Corianò, M. Guzzi, Comput. Phys. Commun. **179**, 665-684, 2008
- the comparison between the factorized (NLO) prescription and RESBOS-A where possible (at the Tevatron) is at the per cent level;
- 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.

Monte Carlo tuning: Tevatron and LHC

Monte Carlo	ALPGEN	FEWZ	HORACE	MCFM	ResBos-A
$\sigma_{\rm LO}$ (pb)	906.3(3)	905.4(2)	905.6(1)	905.1(1)	905.3(2)

Table: MC tuning at the Tevatron for the LO cross section with cuts of the process $p\bar{p} \to W^{\pm} \to \mu^{\pm}\nu_{\mu}$, using CTEQ6M with $\mu_R = \mu_F = \sqrt{x_1 x_2 s}$

Monte Carlo	ALPGEN	FEWZ	HORACE	MCFM
$\sigma_{\rm LO}$ (pb)	8310(2)	8306(1)	8308(1)	8305(1)

Table: MC tuning at the LHC for the LO cross section with cuts of the process $pp \to W^{\pm} \to \mu^{\pm}\nu_{\mu}$, using MRST2004QED with $\mu_R = \mu_F = \sqrt{p^2_{\perp,W} + M^2_W}$

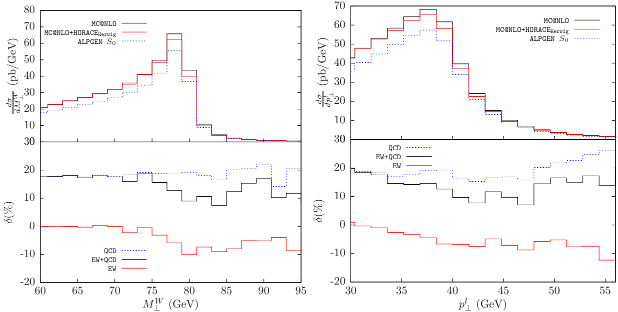
Monte Carlo	$\sigma_{\rm NLO}^{\rm Tevatron}$(pb)	$\sigma_{\rm NLO}^{\rm LHC}$(pb)
FEWZ	2635.5(4)	21058(3)
MC@NLO	2639.1(5)	21031(3)
MCFM	2640(1)	21008(2)

Table: MC tuning for FEWZ, MC@NLO and MCFM NLO inclusive cross sections of the process $\overset{(-)}{p}p \to W^{\pm} \to \mu^{\pm}\nu_{\mu}$, with CTEQ6M (Tevatron) and MRST2004QED (LHC)

- ⋆ After appropriate "tuning", and with same input parameters, cuts and PDFs, Monte Carlos agree at $\sim 0.1\%$ level (or better) ⋆

Process and scheme – Detector modeling and lepton identification

1. $p\bar{p} \to W^\pm \to \mu^\pm \nu_\mu$ $\sqrt{s} = 1.96$ TeV – G_μ scheme + $\alpha(0)$ for real γ emission
2. $p_\perp^\mu > 25$ GeV $\not{p}_\perp > 25$ GeV $|\eta_\mu| < 1.2$ $p_\perp^W \leq 50$ GeV $M_{\mu\nu} \in [50 - 200]$ GeV
3. PDF set: NLO CTEQ6M with $\mu_R = \mu_F = \sqrt{x_1 x_2 s}$

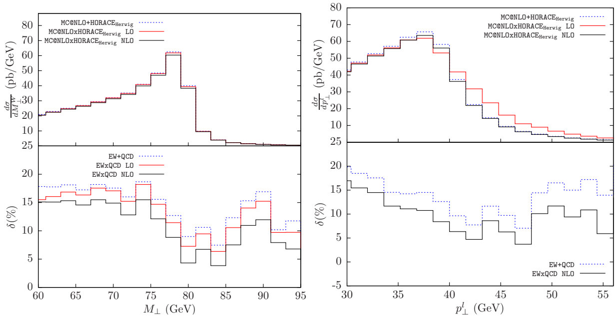


- Partial cancellation between (positive) QCD corrections and (negative) EW ones; the resulting overall corrections are between 10 and 20%
- "smearing" of the EW corrections due to convolution with QCD PS

Electroweak $\otimes$ QCD @ the Tevatron

Process and scheme – Detector modeling and lepton identification

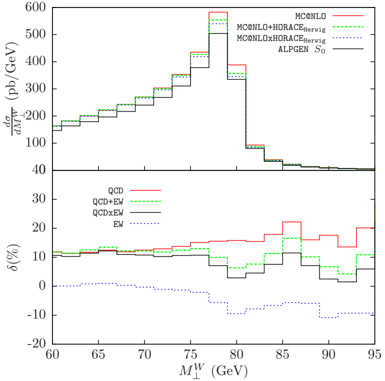
1. $p\bar{p} \to W^{\pm} \to \mu^{\pm}\nu_{\mu}$ $\sqrt{s} = 1.96$ TeV – G_{μ} scheme + $\alpha(0)$ for real γ emission
2. $p_{\perp}^{\mu} > 25$ GeV $\not{p}_{\perp} > 25$ GeV $|\eta_{\mu}| < 1.2$ $p_{\perp}^{W} \leq 50$ GeV $M_{\mu\nu} \in [50 - 200]$ GeV
3. PDF set: NLO CTEQ6M with $\mu_R = \mu_F = \sqrt{x_1 x_2 s}$

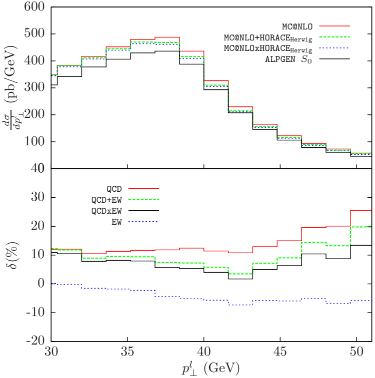


- The relative differences between the various prescriptions (additive vs factorized) are at the level of a few per cent
- the factorized prescription(s) seem to capture the bulk of QCD NNLO corrections

Process and scheme – Detector modeling and lepton identification

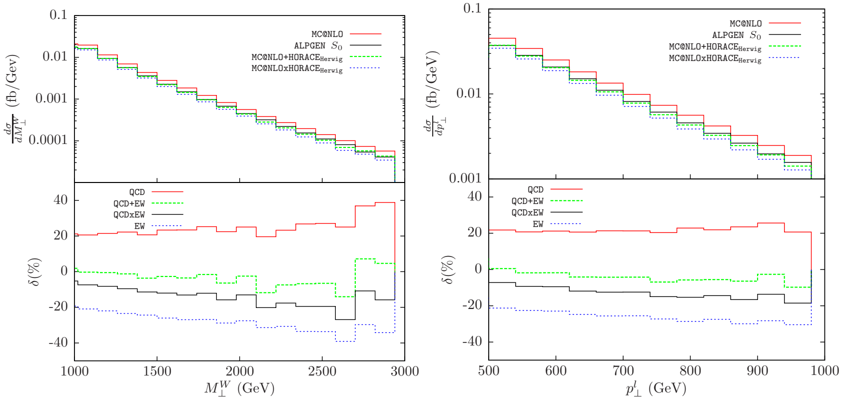
1. $pp \to W^\pm \to \mu^\pm \nu_\mu$ $\sqrt{s} = 14$ TeV – G_μ scheme + $\alpha(0)$ for real γ emission
2. $p_\perp^\mu > 25$ GeV $\not{p}_\perp > 25$ GeV $|\eta_\mu| < 2.5$ $\oplus$ (in case) $M_\perp^W > 1$ TeV
3. PDF set: NLO MRST2004QED with $\mu_R = \mu_F = \sqrt{p_{\perp,W}^2 + M_W^2}$





Electroweak $\oplus/\otimes$ QCD @ the LHC ($M_\perp^W > 1$ TeV)

★ To what extent large electroweak Sudakov logs compare with QCD corrections in the region relevant for the search of new physics at the LHC? ★



- The relative difference between additive and factorized prescription is dominated by $O(\alpha\alpha_s)$ corrections; a per cent accuracy can be attained by a complete two-loop mixed calculation
- Region interesting for W'/Z' searches, see for instance

C. Corianò, A.E. Faraggi, M. Guzzi, Phys.Rev. **D78** 015012, 2008

- Accuracy estimated by comparison between the main sources of error (PDF excluded):

Collider	$\frac{\delta\sigma}{\sigma}$ (scale var.)	$\frac{\delta\sigma}{\sigma}$ $(\oplus - \otimes)$	$\frac{\delta\sigma}{\sigma}$
Tevatron	~ 1	~ 2	2
LHC (a)	~ 2.5	~ 2	2.5
LHC (b)	~ 1.5	~ 5	5

- A more aggressive estimate of the error could be given by taking as error estimate the relative difference between the factorized prescriptions; preliminarily, a detailed comparison between factorized prescriptions and truly NNLO QCD calculations should be performed.

Conclusions

- Recent big theoretical effort towards high-precision predictions for Drell-Yan-like processes, including higher-order QCD and electroweak corrections, to keep under control theoretical systematics
- All these calculations are essential ingredients for precision studies at the Tevatron RunII and LHC
- The combination of QCD and EW corrections is mandatory for Drell-Yan physics
- Our work in progress to combine HORACE with a precise QCD program into a single EW $\otimes$ QCD generator