ElectroWeak & QCD corrections to Drell-Yan Processes

Oreste Nicrosini

Istituto Nazionale Fisica Nucleare, Sezione di Pavia
Oreste.Nicrosini@pv.infn.it

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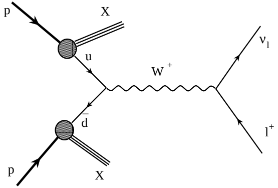
with G. Balossini, C.M. Carloni Calame, G. Montagna, M. Moretti, F. Piccinini, M. Treccani, A. Vicini

and also based on work and collaboration with
A. Arbuzov, D. Bardin, U. Baur, M. Bellomo, S. Dittmaier, S. Jadach, M. Krämer, G. Polesello, W. Płaczek, V. Vercesi, D. Wackeroth...

At Fermilab today and at CERN, in the near future

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

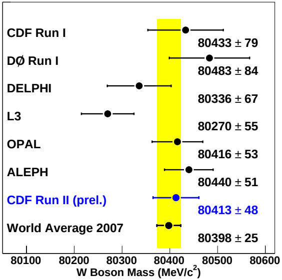


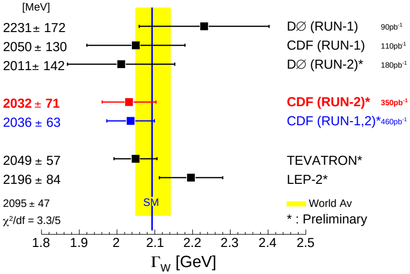
- to derive precise measurements of the electroweak parameters M_W, Γ_W, $\sin^2\theta^\ell_{\rm eff}$. Relevant observables: leptons' transverse momentum $p^\ell_\perp$, W transverse mass $M^W_\perp$, ratio of W/Z distributions, forward-backward asymmetry A^Z_{FB}...
- to monitor the collider luminosity 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

T. Aaltonen *et al.*, CDF Coll., Phys.Rev.Lett. **99** (2007) 151801
T. Aaltonen *et al.*, CDF Coll., `arXiv:0708.3642 [hep-ex]`

- Present experimental status: at CDF RunII the world's single most precise measurements of M_W and Γ_W





- Target ΔM_W precision $\rightarrow$ Tevatron RunII: $\sim$ 20 MeV LHC: 15-20 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 ★

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 corrections merged with HERWIG Parton Shower (MC@NLO)

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

- 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

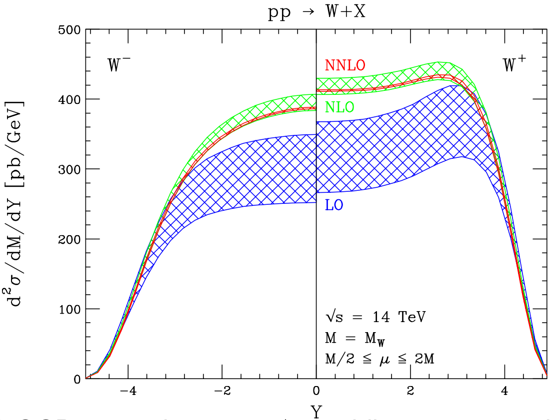
- fully differential NNLO corrections to W/Z production (FEWZ)

  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

High-precision QCD: W/Z rapidity @ NNLO

C. Anastasiou *et al.*, Phys. Rev. Lett. **91** (2003) 182002
C. Anastasiou *et al.*, Phys. Rev. **D69** (2004) 094008



- NNLO QCD corrections to W/Z rapidity at $\sim$ 2% at the LHC and residual scale dependence below 1%

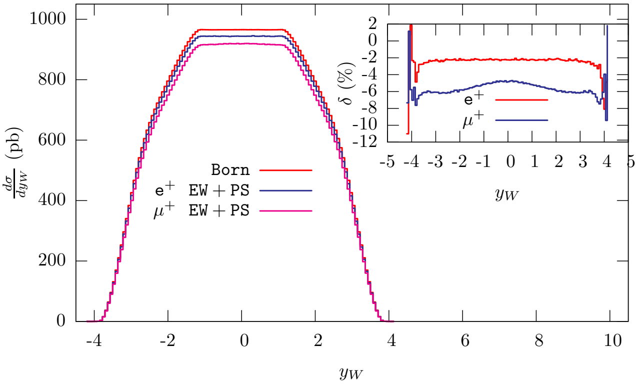
$\star$ $\mathcal{O}(\alpha_S^2) \approx \mathcal{O}(\alpha_{\rm em}) \longrightarrow$ need to worry about electroweak corrections!

Electroweak corrections to W rapidity

C.M. Carloni Calame *et al.*, JHEP **0612** (2006) 016

$pp \to W^+ \to \ell^+ \nu_\ell (+\gamma)$ at LHC

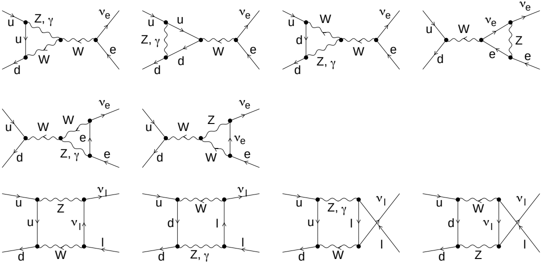
G_μ scheme and including detector effects



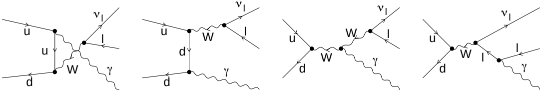
- NLO electroweak corrections to W rapidity are of the same order of NNLO QCD and PDFs uncertainty $\longrightarrow$ relevant for precision luminosity and PDFs constraints!

Electroweak Feynman diagrams

⋆ virtual one-loop corrections (→ electroweak Sudakov logs)



⋆ bremsstrahlung corrections (→ collinear singularities: universal initial-state singularities reabsorbed into PDFs, as in NLO QCD calculations)



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, `arXiv:0710.3309 [hep-ph]`

NLO electroweak calculations & tools (II)

- 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

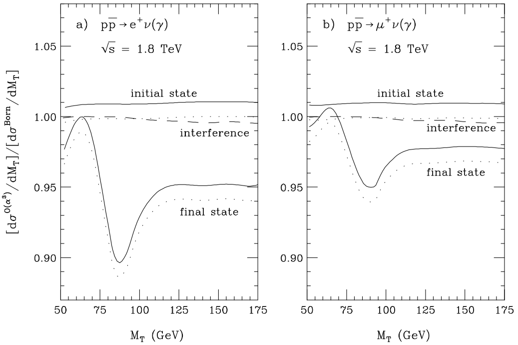
    V.A. Zykunov, Phys. Rev. **D75** (2007) 073019

    A. Arbuzov *et al.*, `arXiv:0711.0625 [hep-ph]` SANC

Electroweak corrections & W mass

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

Pole approximation

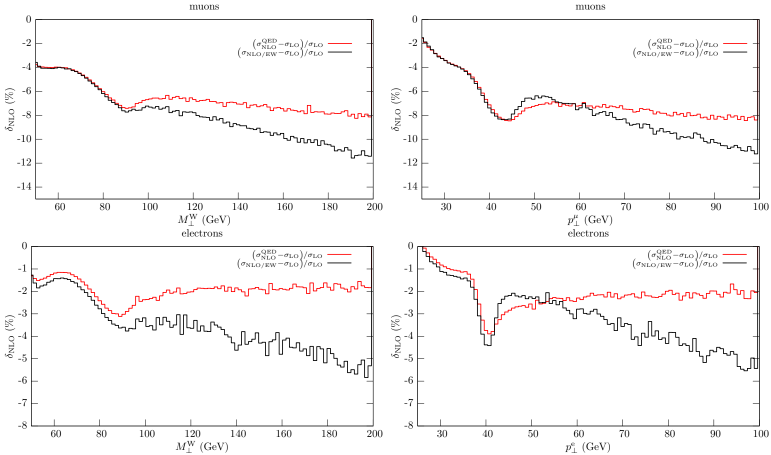


- Around the W peak, electroweak corrections amount to several per cents and are dominated by final-state photon radiation (FSR) $\longrightarrow$ $\Delta M_W^{\rm FSR} \sim$ 100 MeV at the Tevatron
- FSR modifies the shape of the distributions and is sizeable because it contains mass logarithms of the form $\log(\hat{s}/m_\ell^2)$ $\longrightarrow$ need to exponentiate FSR!

Electroweak corrections & W width

$p\bar{p} \to W^{\pm} \to \ell^{\pm}\nu_\ell(+\gamma)$ at the Tevatron, by HORACE

G_μ scheme and including detector effects

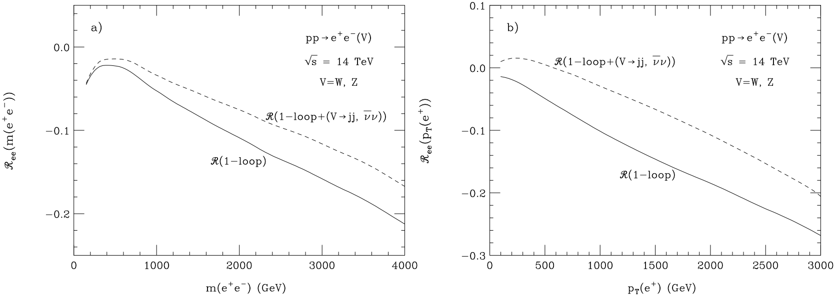


- In the hard tails of $M_\perp^W$ and $p_\perp^\ell$ predictions including QED FSR only differ at some % level from the complete NLO electroweak calculation $\longrightarrow$ important for precision W width measurement?

Electroweak Sudakov logs & new physics

S. Dittmaier and M. Krämer, Phys. Rev. **D65** (2002) 073007
U. Baur *et al.*, Phys. Rev. **D65** (2002) 033007
U. Baur and D. Wackeroth, Phys. Rev. **D70** (2004) 073015

Complete $\mathrm{NLO_{EW}}$ calculations



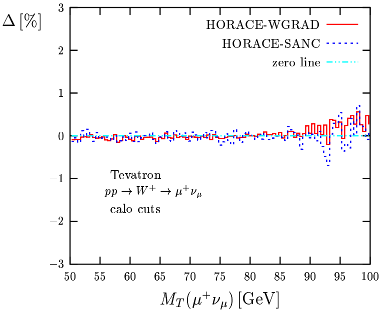
- Pole approximation fails for $M_\perp^W$ or $M_{\ell^+\ell^-} \gg M_V \quad V = W, Z$, due to large Sudakov ew logs $-(\alpha/\pi)\log^2(\hat{s}/M_V^2) \longrightarrow$ important for new physics searches!
- radiation of (undetected) real vector bosons partially cancels the Sudakov logs, e.g. $pp \to e^+e^-V + X \quad V = W, Z \quad V \to jj, \nu\bar{\nu}, \ldots$

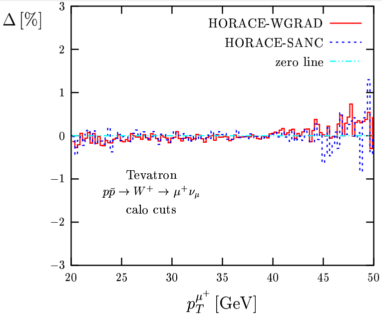
U. Baur, Phys. Rev. **D75** (2007) 013005

Courtesy of D. Wackeroth

Process and scheme – Detector modeling and lepton identification

1. $p\bar{p}(pp) \to W^+ \to \ell^+\nu_\ell(+\gamma)$ – $\alpha(0)$, G_μ, $M_Z \to M_W$ 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!
- Comparisons on electroweak corrections to Z production in progress

Multiple photon corrections & tools

- Higher-order (real+virtual) QED corrections to W/Z production
  - $\rightarrow$ 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
  - $\rightarrow$ 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

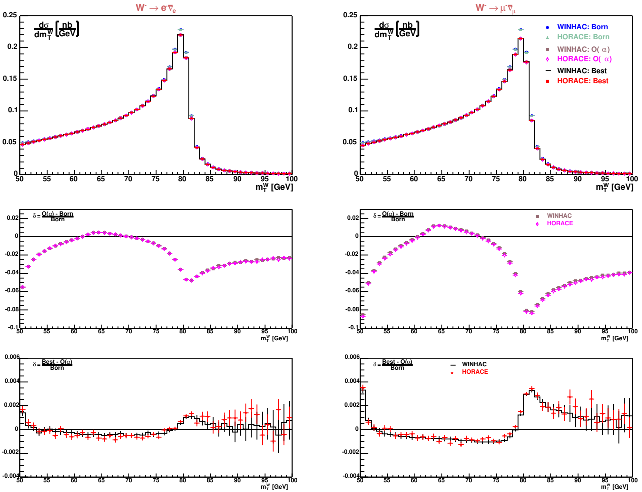
  P. Golonka and Z. Was, Eur. Phys. J. **C45** (2006) 97

★ 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! ★

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

HORACE vs WINHAC: $M_\perp^W$

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

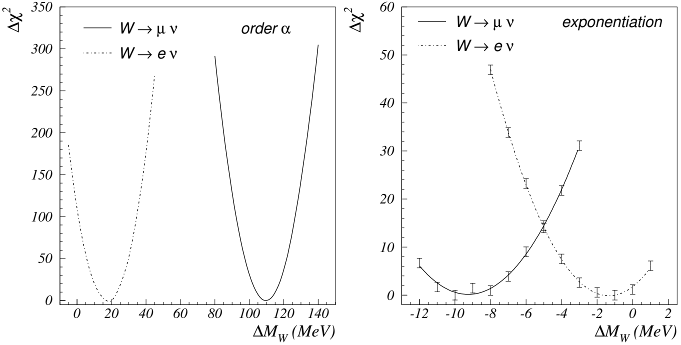


- Same effect of multiple photon radiation $\sim 0.2 - 0.5\%$ around W peak

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

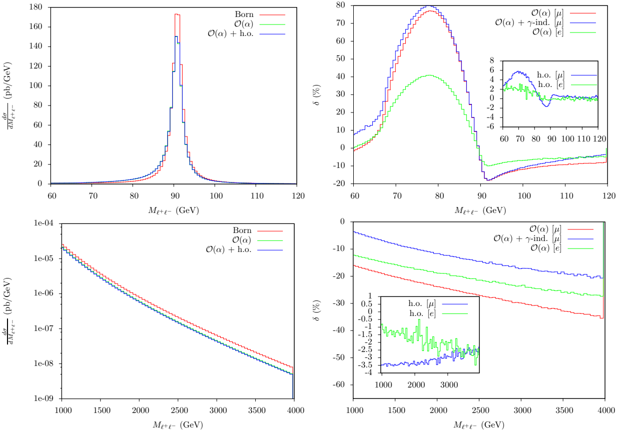
$\Delta M_W^{\infty,e} \sim$ 2 MeV
$\Delta M_W^{\infty,\mu} \sim$ 10 MeV

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

Electroweak corrections & Z parameters

$pp \to Z \to \ell^+\ell^-(+\gamma)$ at the LHC, by HORACE

C.M. Carloni Calame *et al.*, JHEP **10** (2007) 109



- Huge corrections around the Z peak, dominated by f.s.r.; important corrections in the hard i.m. tail, due to combined photonic and Sudakov corrections; exponentiation of photonic corrections at some % level

Combining electroweak and QCD corrections (I)

- First attempt: combination of soft-gluon resummation with NLO final-state QED corrections

  Q.-H. Cao and C.-P. Yuan, Phys. Rev. Lett. **93** (2004) 042001
  `ResBos-A`

- QCD and QED corrections can be combined in a YFS resummation context, taking into account shower/matrix element matching

  B.F.L. Ward and S.A. Yost, Acta Phys. Polon. **B38** (2007) 2395-2403, and refs. therein

- New parton shower MC for W/Z production at the LHC, combining Constrained MC's for the evolution of single hadron beam into a single MC for IS QCD radiation under development (QCD@NLO, EW and FSR ME, ...)

  S. Jadach, W. Placzek, M. Skrzypek, P. Stephens and Z. Was, Acta Phys. Polon. **B38** (2007) 2305-2318,

  and refs. therein

Combining electroweak and QCD corrections (II)

- QCD and electroweak corrections can be combined in factorized form to arrive at

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

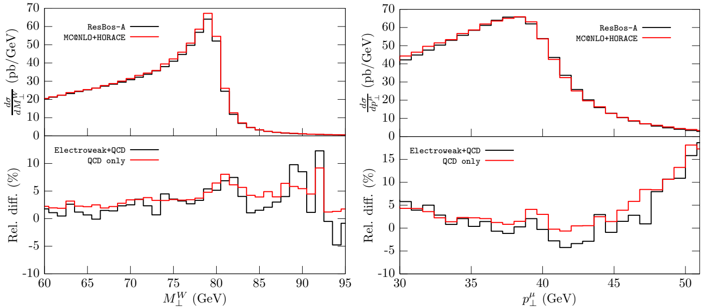
- QCD $\Rightarrow$ `ResBos`, `MCFM`, `MC@NLO`, `ALPGEN` (with MLM Parton Shower matching and standard matching parameters), ...
- EW $\Rightarrow$ Electroweak + multiphoton corrections from `HORACE` convoluted with `HERWIG` QCD Parton Shower
  - ⋆ NLO electroweak corrections are interfaced to QCD Parton Shower evolution $\Rightarrow$ $\mathcal{O}(\alpha\alpha_s)$ 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.*, `hep-ph/0703283`
NLO/NNLO$_{\text{EW}}$ to $pp \to Wj$

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 $\mu_R = \mu_F = \sqrt{x_1 x_2 s}$

★ **Absolute comparison:** ResBos−A vs MC@NLO + HORACE $_{\text{HERWIG PS}}$ (using the ResBos−A grids publicly available on the web)

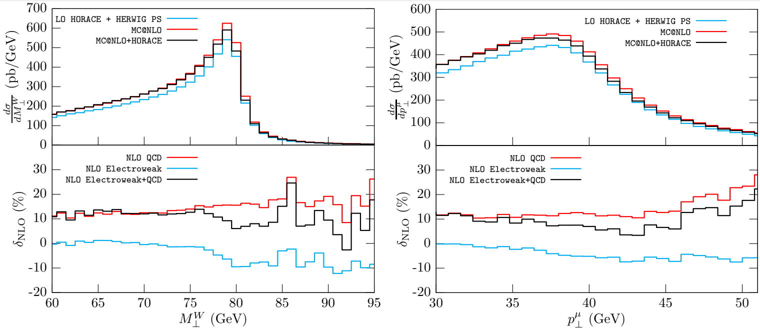


- The relative differences between the two tools are at $\sim$ 5 % level around the jacobian peak and can reach the $\sim 10 \div 15$ % level in the hard tails. It would be interesting to compare with ResBos−A including the Y perturbative term.

Electroweak $\otimes$ QCD @ the LHC

Process and scheme – Detector modeling and lepton identification

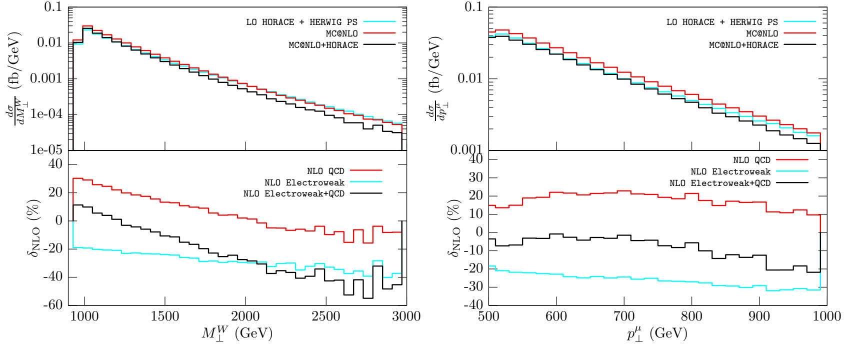
1. $pp \to W^{\pm} \to \mu^{\pm}\nu_{\mu}$ $\sqrt{s} = 14$ TeV – G_{μ} scheme + $\alpha(0)$ for real γ emission
2. $p_{\perp}^{\mu} > 25$ GeV $\not{p}_{\perp} > 25$ GeV $|\eta_{\mu}| < 2.5$ $\oplus$ (in case) $M_{\perp}^{W} > 1$ TeV
3. PDF set: NLO MRST2004QED with $\mu_R = \mu_F = \sqrt{p^2_{\perp,W}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



- Around the W peak, for both $M_{\perp}^{W}$ and $p_{\perp}^{\ell}$ NLO QCD corrections are positive and tend to compensate negative electroweak contributions
- Convolution with QCD Parton Shower modifies the relative size and broadens the shape of electroweak corrections

Electroweak ⊗ 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? ★



- In the high $M_\perp^W$ and $p_\perp^\ell$ tails, NLO QCD corrections can become negative and partially compensate the large negative electroweak Sudakov logs
- Their sum is $\sim -10(-40)\%$ for $M_\perp^W \simeq 1.5(3)$ TeV and $\sim 0(-20)\%$ for $p_\perp^\ell \simeq 0.5(1)$ TeV $\longrightarrow$ need to include two-loop electroweak Sudakov logs.

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

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
- Multiple photon corrections are a computable source of systematic uncertainty in W parameters measurement and should be included in the experimental analysis
- It would be advisable to use the state-of-the-art of electroweak and QCD calculations
- Our work in progress to
  - ★ compare HORACE predictions for Z production observables with independent calculations (SANC, ZGRAD)
  - ★ scrutinize the electroweak and QCD systematics to the so-called "scaled observables method"
  - ★ Long term: combine HORACE with a precise QCD program into a single EW $\otimes$ QCD generator