Combining electroweak and QCD corrections to weak boson production at hadron colliders

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LoopFest VI
Fermilab, April 16 –18, 2007

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

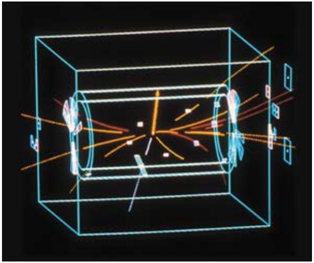
and also based on work and collaboration with
A. Arbuzov, D. Bardin, U. Baur, M. Bellomo, S. Dittmaier, S. Jadach,
M. Krämer, G. Polesello, W. Płaczek, V. Vercesi, D. Wackeroth...

At CERN, about 20 years ago...

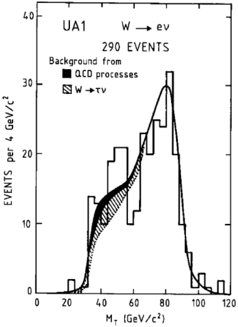
The Nobel Prize in Physics 1984
to C. Rubbia and S. van der Meer

“for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

One of the first W particles

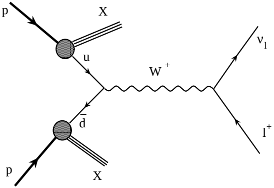


D. Denegri
The discovery of the W and Z
Physics Report **403** (2004) 107



...at Fermilab today and at CERN, in the near future

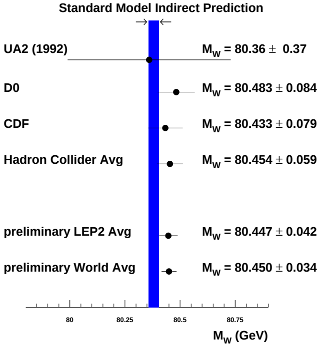
Single W/Z boson production: clean process with a large cross section ($\sim 300(35) \times 10^6$ events/year for $\mathcal{L}_{\mathrm{LHC}} = 10\ fb^{-1}$). It is useful



- to derive precise measurements of the electroweak parameters $M_W, \Gamma_W, \sin^2\theta^{\ell}_{\mathrm{eff}}$. 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 $\delta M_W/M_W \sim 7 \to 2 \times 10^{-4}$

- Present (official) experimental status TeVEWWG, Phys. Rev. **D70** (2004) 092008



Future goals:

Target ΔM_W precision:

- ⋆ Tevatron RunII: $\sim$ 25 MeV
- ⋆ LHC: 15-20 MeV

Target $\Delta \Gamma_W$ precision:

- ⋆ Tevatron RunII: 30 MeV
- ⋆ LHC: $\leq$ 30 MeV

⋆ At the Tevatron, NLO QED corrections shift M_W by ~ 100 MeV ⋆

electron channel: -65 ± 20 MeV
muon channel: -168 ± 20 MeV

Higher-order QCD & QCD generators

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

G. Altarelli, R.K. Ellis, M. Greco and G. Martinelli, Nucl. Phys. **B246** (1984) 12

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

- resummation of leading/next-to-leading $p_\perp^W/M_W$ 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`, `SHERPA`...) matched with vetoed Parton Showers

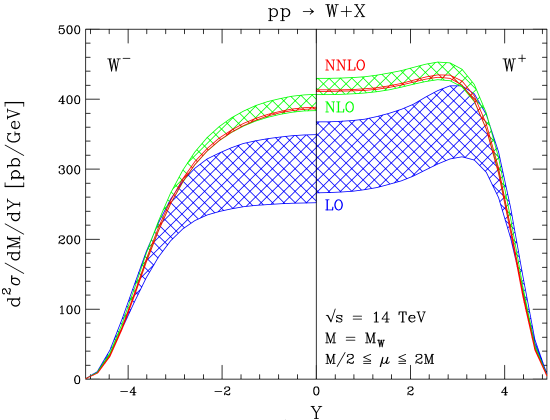
M.L. Mangano *et al.* , JHEP **0307** (2003) 001
F. Krauss *et al.*, JHEP **0507** (2005) 018

- 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



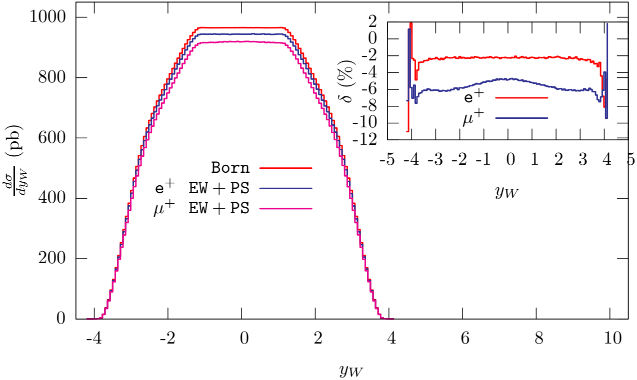
- NNLO QCD corrections to W/Z rapidity at $\sim 2\%$ at the LHC and residual scale dependence below 1%
- $\mathcal{O}(\alpha_S^2) \approx \mathcal{O}(\alpha_{\rm em}) \longrightarrow$ need to worry about electroweak corrections!

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



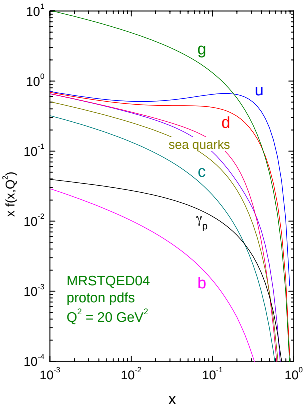
- NLO electroweak corrections to W rapidity are of the same order of NNLO QCD and PDFs uncertainty $\longrightarrow$ relevant for precision luminosity and PDFs constraints!

NLO electroweak calculations & tools

- $\mathcal{O}(\alpha)$ 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`
- 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`

QED initial-state singularities & QED-improved PDFs

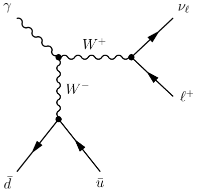
MRST2004QED

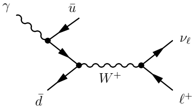


- QED initial-state collinear singularities are universal $\longrightarrow$ can be absorbed into PDFs
- effect of QED evolution on PDFs through DGLAP equation is small ($\sim$ 0.1% for $x < 1$)

H. Spiesberger, Phys. Rev. **D52** (1995) 4936
M. Roth and S. Weinzierl, Phys. Lett. **B590** (2004) 190
A.D. Martin *et al.*, Eur. Phys. J. **C39** (2005) 155

- dynamic generation of photon parton distribution $\longrightarrow$ photon induced processes enter the game

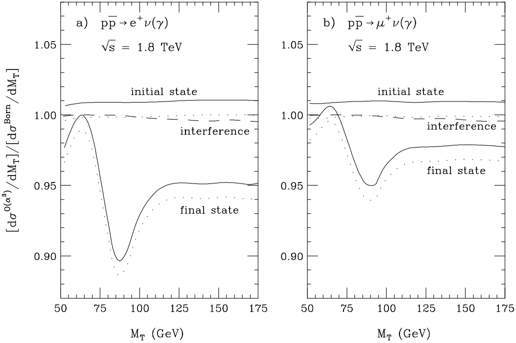




Electroweak vs final-state photon corrections

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

Pole approximation

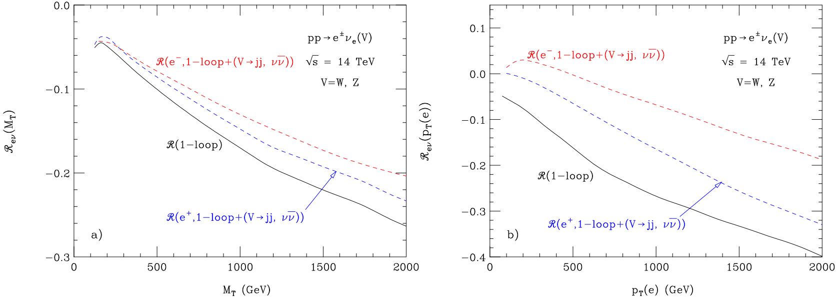


- Around the W peak, electroweak corrections amount to several per cents and are dominated by final-state photon radiation
- final-state photon radiation (FSR) modifies the shape of the distributions and is important because it contains mass logarithms of the form $\log(\hat{s}/m_\ell^2)$ $\longrightarrow$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

Electroweak Sudakov logs

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 NLO$_{\mathrm{EW}}$ calculations



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

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

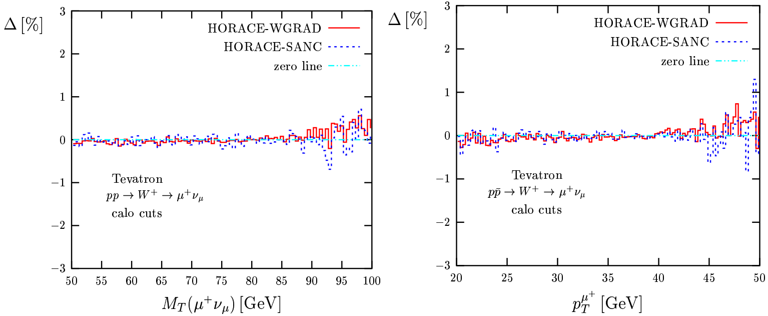
TeV4LHC tuned comparisons

C. E. Gerber *et al.*, `FERMILAB-CONF-07-052`

Courtesy of D. Wackeroth

Process and scheme – Detector modeling and lepton identification

1. $p\bar{p}(pp) \to W^+ \to \ell^+\nu_\ell(+\gamma)$ – $\alpha(0),\, G_\mu,\, M_Z \to M_W$ at two – loops
2. $\sqrt{s} = 1.96$ TeV, 14 TeV $\quad p_{\perp,l} > 20$ GeV $\quad \not{p}_\perp > 20$ GeV $\quad |\eta_l| < 2.5$
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 ⟶ 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
  - → `HORACE` (Pavia): QED Parton Shower + NLO electroweak corrections to W/Z production (Z production available soon)

    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
  - → `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 *et al.*, 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)

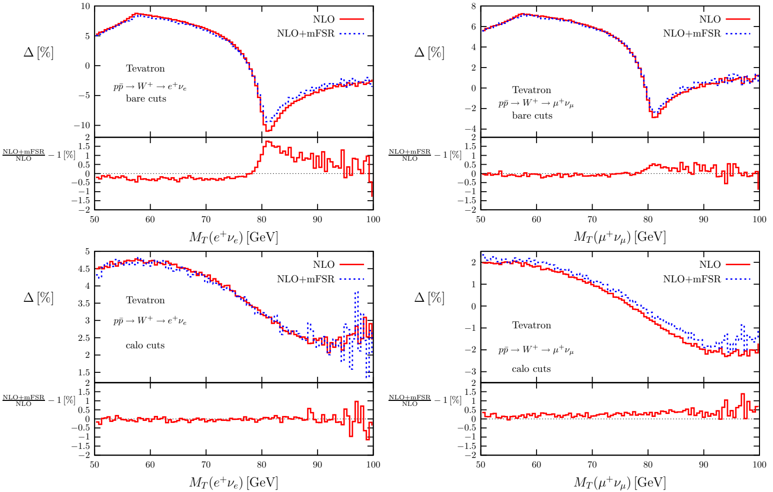
  K. Hamilton and P. Richardson, JHEP **0607** (2006) 010
  P. Golonka and Z. Was, Eur. Phys. J. **C45** (2006) 97

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

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

Multiple photon corrections by HORACE

C. E. Gerber *et al.*, `FERMILAB-CONF-07-052`
Courtesy of D. Wackeroth



- For bare $e - \mu$ multiple photon corrections enhance the NLO electroweak corrections by $\sim 1.5\% - 0.5\%$. For calo $e - \mu$ they survive for μ only.

Combining electroweak and QCD corrections

- 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`

- Electroweak and QCD 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 ⇒ `ResBos`, `MC@NLO`, `ALPGEN` (with CKKW-MLM Parton Shower matching and standard matching parameters), `FEWZ`, ...
- 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 not reliable when hard non-collinear QCD radiation is important
  - ⋆ 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`
$\text{NLO/NNLO}_{\text{EW}}$ to $pp \to Wj$

Monte Carlo “tuning”: Tevatron and LHC

Monte Carlo	`ALPGEN`	`FEWZ`	`HORACE`	`ResBos-A`
$\sigma_{\rm LO}$ (pb)	906.3(3)	906.20(16)	905.64(4)	905.26(24)

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`
$\sigma_{\rm LO}$ (pb)	8310(2)	8304(2)	8307.9(2)

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	$\sigma^{\rm Tevatron}_{\rm NLO}(\rm pb)$	$\sigma^{\rm LHC}_{\rm NLO}(\rm pb)$
`MC@NLO`	2638.8(4)	20939(19)
`FEWZ`	2643.0(8)	21001(14)

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

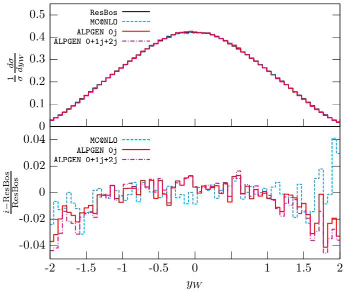
★ After appropriate “tuning”, and with same input parameters, cuts and PDFs, Monte Carlos agree at $\sim 0.1\%$ level (or better) ★

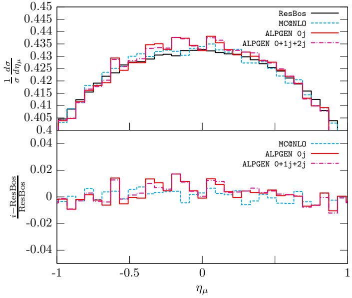
QCD @ the Tevatron (I)

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 $|\eta_\mu| < 1.2$ $p_\perp^W \le 50$ GeV $M_{\mu\nu} \in [50 - 200]$ GeV
3. NLO CTEQ6M with $\mu_R = \mu_F = \sqrt{x_1 x_2 s}$

★ QCD generators are normalized to the corresponding integrated cross section, to point out the shape differences. Relative deviations w.r.t. `ResBos` ★

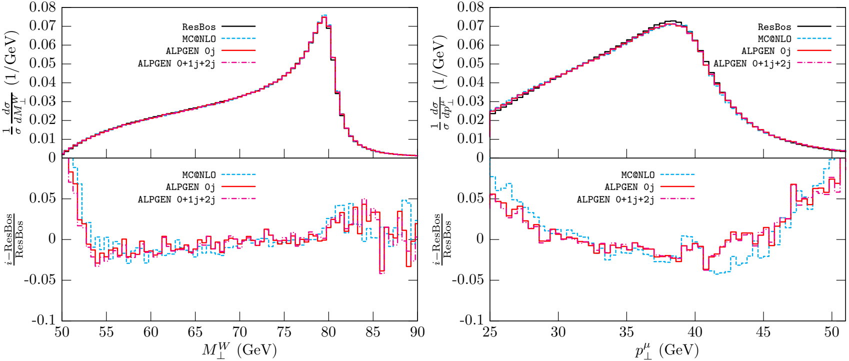




- For W rapidity and lepton pseudorapidity QCD generators agree at the ~ 1 % level

QCD @ the Tevatron (II)

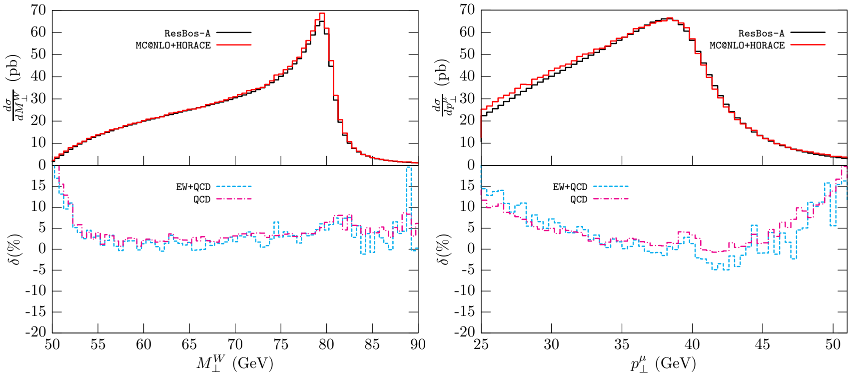
★ QCD generators are normalized to the corresponding integrated cross section, to point out the shape differences. Relative deviations w.r.t. `ResBos` ★



- For $M_\perp^W$ and $p_\perp^\ell$ QCD generators agree at a few % level around the jacobian peak
- In the soft $M_\perp^W$ tail and in the $p_\perp^\ell$ tails the QCD differences can reach the $5 \div 10$ % level

Electroweak $\otimes$ QCD @ the Tevatron

★ Absolute comparison: `ResBos-A` vs `MC@NLO` + `HORACE` $_{\texttt{HERWIG PS}}$



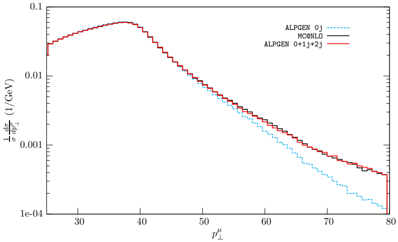
- For $M_\perp^W$ and $p_\perp^\ell$ the relative differences (including normalization) are at a few % level around the jacobian peak and can reach the $\sim 10 \div 15$ % level in the tails
- These deviations are dominated by QCD effects

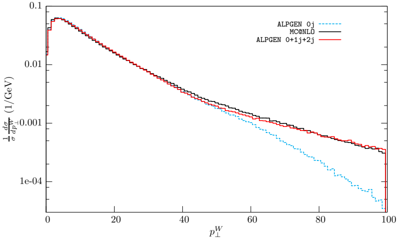
QCD @ the LHC

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 $|\eta_{\mu}| < 2.5$ $\oplus$ (eventually) $M_{\perp}^{W} > 1$ TeV
3. NLO MRST2004QED with $\mu_R = \mu_F = \sqrt{p_{\perp,W}^2 + M_W^2}$

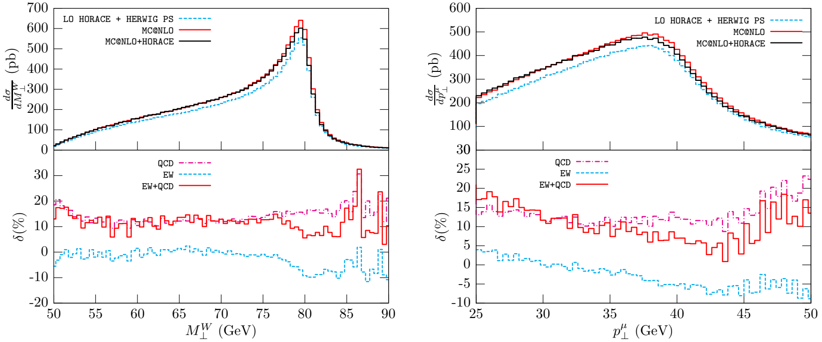
★ QCD generators are normalized to the corresponding integrated cross section, to point out the shape differences. ★





- NLO/Matched matrix elements corrections w.r.t. QCD Parton Shower are important in the high tails of $p_{\perp}^{l}$ and $p_{\perp}^{W}$
- There is a substantial agreement in the shapes predicted by `MC@NLO` and `ALPGEN`

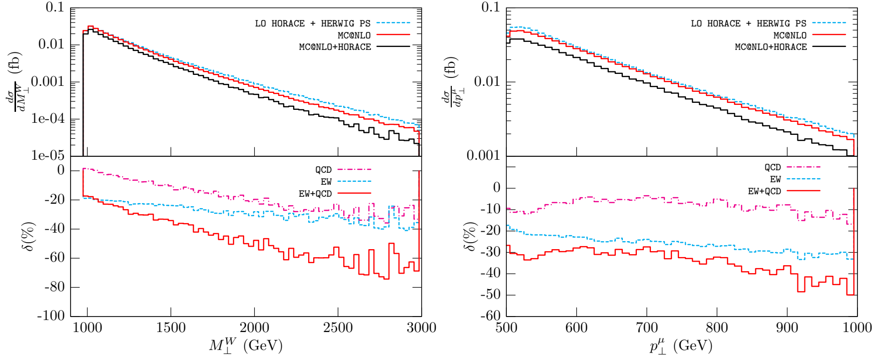
Electroweak $\otimes$ QCD @ the LHC



- Convolution with QCD Parton Shower modifies the relative size and shape of electroweak corrections
- For both $M_\perp^W$ and $p_\perp^l$ (NLO) QCD corrections are positive and tend to compensate electroweak contributions
- Around the jacobian peak their interplay is crucial for a precise M_W extraction and can't be accounted for by a QCD Parton Shower approach

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? ★



- For both $M_\perp^W$ and $p_\perp^l$ (NLO) QCD corrections are negative and sum up to negative electroweak Sudakov logs
- Their sum is $\sim -40(-70)\%$ for $M_\perp^W \simeq 1.5(3)$ TeV and $\sim -30(-50)\%$ for $p_\perp^l \simeq 0.5(1)$ TeV $\longrightarrow$ need to include two-loop electroweak Sudakov logs
- ...But in this region there is a handful of events

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
- It would be advisable to combine the state-of-the-art of electroweak and QCD corrections into a single, unified generator
- Precision measurements with per cent accuracy at hadron colliders are very challenging!
- Work in progress to
  - ⋆ complete the study of combining electroweak and QCD contributions to $p\overset{(-)}{p} \to \mathrm{lepton} + X$ (including $\mathtt{FEWZ}/\mathtt{MCFM}$ and study of PDFs uncertainties)
  - ⋆ make $\mathtt{HORACE}$ available for electroweak corrections to Z production and compare with independent calculations
  - ⋆ scrutinize the electroweak and QCD systematics to the so-called "scaled observables method"

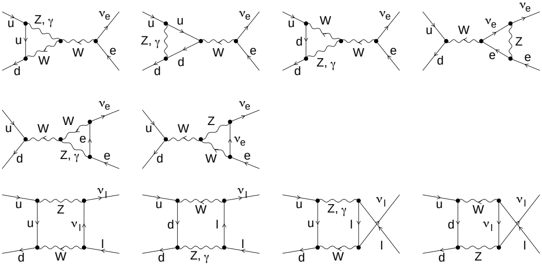
    W. Giele and S. Keller, Phys. Rev. **D57** (1998) 4433
  - ⋆ Long term: combine $\mathtt{HORACE}$ with $\mathtt{ALPGEN}$ into a single EW $\otimes$ QCD generator

Backup slides

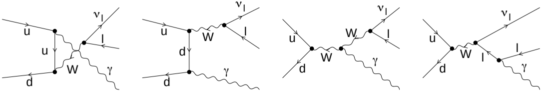
Backup slides

Electroweak Feynman diagrams

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



- bremsstrahlung corrections (→ collinear singularities)



Matching NLO electroweak with QED Parton Shower

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

- NLO ($\mathcal{O}(\alpha)$) electroweak cross section

$$d\sigma^{\alpha}_{\rm ew} \equiv d\sigma^{\alpha,ex} \equiv d\sigma^{\alpha,ex}_{SV} + d\sigma^{\alpha,ex}_{H}$$

- $\mathcal{O}(\alpha)$ Parton Shower (PS) cross section

$$d\sigma^{\alpha,PS} = [\Pi_S(Q^2)]_{\mathcal{O}(\alpha)} d\sigma_0 + \frac{\alpha}{2\pi} P_{ff}(x) I(k) dx\, dc\, d\hat{\sigma}_0 = \\ \equiv d\sigma^{\alpha,PS}_{SV} + d\sigma^{\alpha,PS}_{H}$$

- Resummed PS

$$d\sigma^{\infty}_{PS} = \Pi_S(Q^2)\; F_{sv}\; \sum_{n=0}^{\infty} d\hat{\sigma}_0 \frac{1}{n!} \prod_{i=0}^{n} \left[\frac{\alpha}{2\pi} P_{ff}(x_i) I(k_i) dx_i dc_i \; F_{H,i} \right]$$

where $F_{SV} = 1 + \frac{d\sigma^{\alpha,ex}_{SV} - d\sigma^{\alpha,PS}_{SV}}{d\sigma_0}$ and $F_{H,i} = 1 + \frac{d\sigma^{\alpha,ex}_{H,i} - d\sigma^{\alpha,PS}_{H,i}}{d\sigma^{\alpha,PS}_{H,i}}$

- $\left[\sigma^{\infty}_{\rm matched}\right]_{\mathcal{O}(\alpha)}$ = $\sigma^{\alpha}_{\rm exact}$, avoiding NLO double counting and preserving quark mass independence and exponentiation of QED leading logs

W^+ cross section (pb) at LHC	$\mathcal{O}(\alpha)$	matched
m_q	4410.98 ± 0.20	4412.14 ± 0.26
$m_q/10$	4410.92 ± 0.26	4411.89 ± 0.33
$m_q/100$	4410.99 ± 0.29	4411.92 ± 0.50

Matching NLO electroweak with QED Parton Shower

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

- NLO ($\mathcal{O}(\alpha)$) electroweak cross section

$$d\sigma^{\alpha}_{\rm ew} \equiv d\sigma^{\alpha,ex} \equiv d\sigma^{\alpha,ex}_{SV} + d\sigma^{\alpha,ex}_{H}$$

- $\mathcal{O}(\alpha)$ Parton Shower (PS) cross section

$$d\sigma^{\alpha,PS} = [\Pi_S(Q^2)]_{\mathcal{O}(\alpha)} d\sigma_0 + \frac{\alpha}{2\pi} P_{ff}(x) I(k) dx\, dc\, d\hat{\sigma}_0 = \\ \equiv d\sigma^{\alpha,PS}_{SV} + d\sigma^{\alpha,PS}_{H}$$

- Resummed PS + NLO electroweak

$$d\sigma^{\infty}_{\rm matched} = \Pi_S(Q^2)\, F_{sv} \sum_{n=0}^{\infty} d\hat{\sigma}_0 \frac{1}{n!} \prod_{i=0}^{n} \left[\frac{\alpha}{2\pi} P_{ff}(x_i) I(k_i) dx_i dc_i\, F_{H,i} \right]$$

where $F_{SV} = 1 + \frac{d\sigma^{\alpha,ex}_{SV} - d\sigma^{\alpha,PS}_{SV}}{d\sigma_0}$ and $F_{H,i} = 1 + \frac{d\sigma^{\alpha,ex}_{H,i} - d\sigma^{\alpha,PS}_{H,i}}{d\sigma^{\alpha,PS}_{H,i}}$

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$m_q/100$	4410.99 ± 0.29	4411.92 ± 0.50

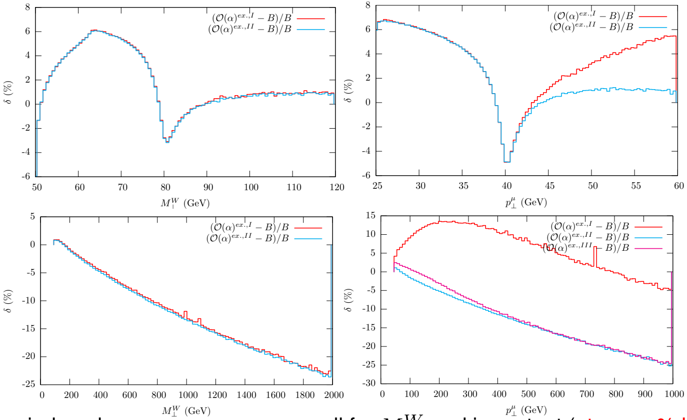
γ-induced processes vs NLO electroweak (LHC)

★ Legenda $pp \to W^{\pm} \to \mu^{\pm}\nu(+\gamma)$ with MRTS2004QED – $\alpha(0), M_W, M_Z$ scheme

I. with γ induced processes, without jet cut

II. without γ induced processes (pure NLO electroweak)

III. with γ induced processes, with jet cut ($p_\perp^{\text{jet}} < 30$ GeV and $|\eta^{\text{jet}}| > 2.5$)



- γ induced processes are very small for $M_\perp^W$ and important (at some % level) for $p_\perp^\ell$ at the LHC (everywhere negligible at the Tevatron)
- γ induced processes are strongly suppressed by jet cuts and overwhelmed by QCD effects at high $p_\perp^\ell$

NLO electroweak corrections to Z observables (LHC)

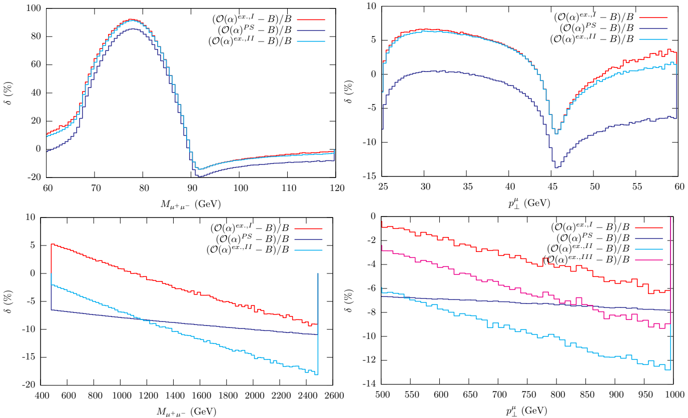
★ Legenda $pp \to \gamma/Z \to \mu^+\mu^- (+\gamma)$ with MRTS2004QED – $\alpha(0), M_W, M_Z$ scheme

I. with γ induced processes, without jet cut

II. without γ induced processes (pure NLO electroweak)

III. with γ induced processes, with jet cut ($p_\perp^{\rm jet} < 30$ GeV and $|\eta^{\rm jet}| > 2.5$)

IV. QED Parton Shower approximation



- non-negligible γ induced effects both for $M_{l^+l^-}$ and $p_\perp^\ell$ in the hard tails
- large corrections due to Sudakov logs not accounted for by QED PS

W/Z transverse mass ratio: scaled observables method

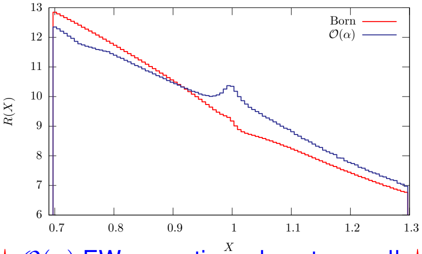
- the ratio $\frac{d\sigma}{dM_\perp^W} / \frac{d\sigma}{dM_\perp^Z}$ can be used to measure M_W, being slightly sensitive to pQCD corrections

W. Giele and S. Keller, Phys. Rev. **D57** (1998) 4433

- defining $X_V \equiv \frac{M_\perp^V}{M_V}$:

$$\left.\frac{d\sigma}{dM_\perp^W}\right|_{\text{predicted}} = \frac{M_Z}{M_W} \times R \times \left.\frac{d\sigma}{dM_\perp^Z}\right|_{\text{measured}}$$

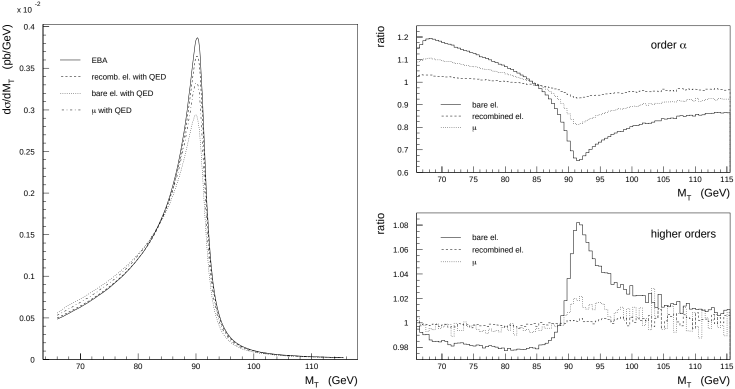
where $R \equiv \frac{d\sigma}{dX_W} / \frac{d\sigma}{dX_Z}$, the predicted $M_\perp^W$ distribution can be used to extract M_W ...



★ $\mathcal{O}(\alpha)$ EW corrections do not cancel! ★

Higher-order QED corrections to Z production: M_T^Z

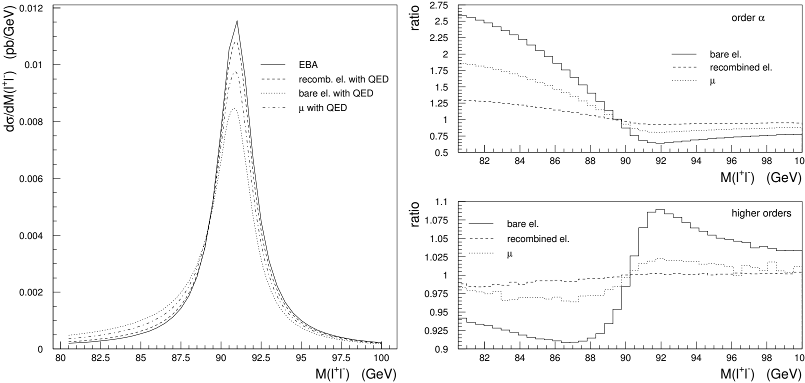
C.M. Carloni Calame *et al.* JHEP **05** (2005) 019



- Multiple photon corrections to Z transverse mass are $\sim 2\%$ for bare muons and a few per mille level for calorimetric electrons.

Higher-order QED corrections to Z production: $M_{\ell\ell}$

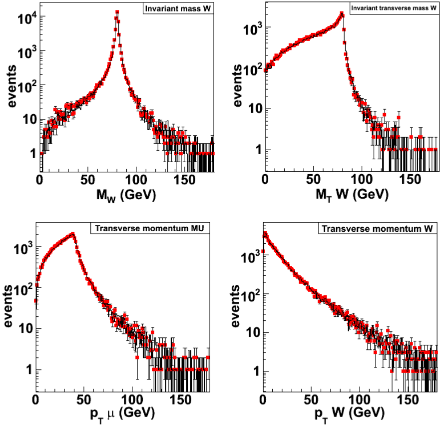
C.M. Carloni Calame *et al.* JHEP **05** (2005) 019



- Multiple photon corrections to Z production are also needed, because important W systematics are strongly related to Z parameters extraction and statistics

HORACE & QCD showering MCs

- HORACE is “Les Houches Accord” compliant. Its events can be passed through QCD Parton Shower & hadronization MCs
- e.g. HORACE (with QED PS) +PYTHIA vs. PYTHIA+PHOTOS



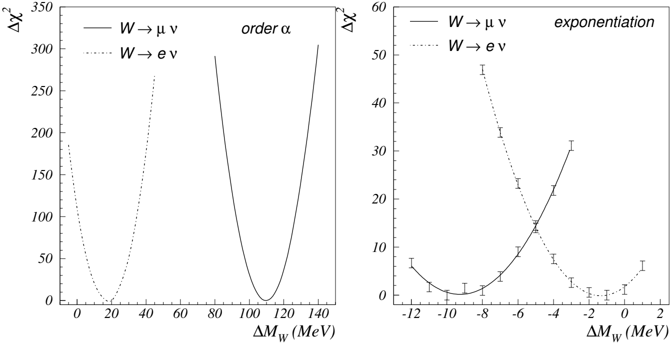
courtesy of M. Bellomo and G. Polesello (ATLAS)

- ● HORACE+PYTHIA
- — PYTHIA+PHOTOS

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!

TeV4LHC tuned comparisons

C. E. Gerber *et al.*, `FERMILAB-CONF-07-052`

Tevatron, $p\bar{p} \to W^+ \to e^+\nu_e$ Courtesy of D. Wackeroth						
	bare cuts			calo cuts		
	LO [pb]	NLO [pb]	Δ [%]	LO [pb]	NLO [pb]	Δ [%]
HORACE	773.509(5)	791.14(2)	2.279(3)	733.012(5)	762.21(3)	3.983(4)
SANC	773.510(2)	791.04(8)	2.27(1)	733.024(2)	762.03(9)	3.96(1)
WGRAD2	773.516(5)	791.01(5)	2.268(7)	733.004(6)	762.00(5)	3.956(6)
Tevatron, $p\bar{p} \to W^+ \to \mu^+\nu_\mu$						
	bare cuts			calo cuts		
	LO [pb]	NLO [pb]	Δ [%]	LO [pb]	NLO [pb]	Δ [%]
HORACE	773.509(5)	804.18(2)	3.965(3)	732.913(6)	738.16(3)	0.716(4)
SANC	773.510(2)	804.07(6)	3.951(7)	732.908(2)	738.01(5)	0.696(7)
WGRAD2	773.516(5)	804.11(1)	3.955(2)	732.917(6)	738.00(1)	0.693(2)
LHC, $pp \to W^+ \to e^+\nu_e$						
	bare cuts			calo cuts		
	LO [pb]	NLO [pb]	Δ [%]	LO [pb]	NLO [pb]	Δ [%]
HORACE	5039.11(4)	5140.6(1)	2.014(2)	4924.17(4)	5115.5(2)	3.886(4)
SANC	5039.21(1)	5139.5(5)	1.99(1)	4925.31(1)	5113.5(4)	3.821(9)
WGRAD2	5039.16(7)	5139.6(6)	1.99(1)	4924.15(5)	5114.1(6)	3.86(1)
LHC, $pp \to W^+ \to \mu^+\nu_\mu$						
	bare cuts			calo cuts		
	LO [pb]	NLO [pb]	Δ [%]	LO [pb]	NLO [pb]	Δ [%]
HORACE	5039.11(4)	5230.5(2)	3.798(4)	4925.16(5)	4944.5(2)	0.393(4)
SANC	5039.21(1)	5229.4(3)	3.775(7)	4925.31(1)	4942.5(5)	0.349(9)
WGRAD2	5039.16(7)	5229.9(1)	3.786(3)	4925.30(7)	4943.0(1)	0.360(3)

TeV4LHC: lepton identification criteria

C. E. Gerber *et al.*, `FERMILAB-CONF-07-052`

Courtesy of D. Wackeroth

Tevatron and LHC	
electrons	muons
combine e and γ momentum four vectors, if $\Delta R(e,\gamma) < 0.1$	reject events with $E_\gamma > 2$ GeV for $\Delta R(\mu,\gamma) < 0.1$
reject events with $E_\gamma > 0.1\ E_e$ for $0.1 < \Delta R(e,\gamma) < 0.4$	reject events with $E_\gamma > 0.1\ E_\mu$ for $0.1 < \Delta R(\mu,\gamma) < 0.4$

Table: Summary of lepton identification requirements.

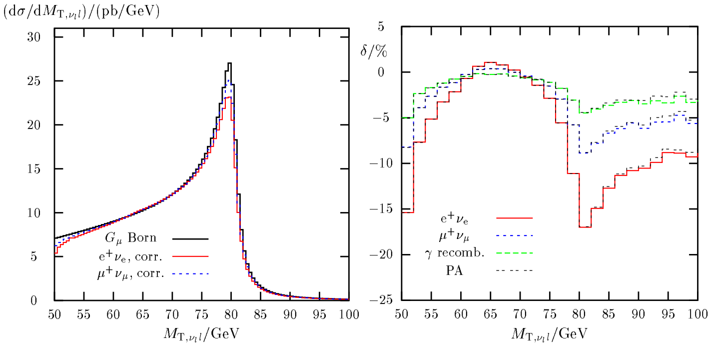
where

$$\Delta R(e,\gamma) = \sqrt{(\Delta\eta(e,\gamma))^2 + (\Delta\phi(e,\gamma))^2},$$

- ⋆ Uncertainties in the energy measurements of the charged leptons in the detector are simulated by Gaussian smearing of the particle four-momentum vector with standard deviation σ based on the DØ(upgrade) and ATLAS specifications.

Photon radiation and lepton identification

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



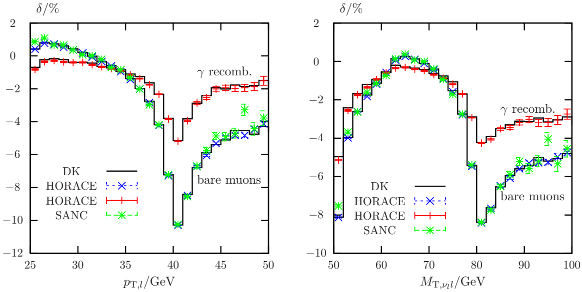
- Lepton identification requirements (and detector effects) strongly affect final-state photon radiation (“the KLN theorem at work”)
- Pole approximation agrees with the full calculation within a few 0.1% around the W resonance

Les Houches tuned comparisons

C. Buttar *et al.*, `hep-ph/0604120`

Process and scheme – Detector modeling and lepton identification

1. $pp \to W^+ \to \ell^+\nu_\ell(+\gamma)$ – G_μ scheme + $\alpha(0)$ for real γ emission
2. $\sqrt{s} = 14\ \mathrm{TeV} \quad p_{\mathrm{T},\ell} > 25\ \mathrm{GeV} \quad \not{p}_{\mathrm{T}} > 25\ \mathrm{GeV} \quad |\eta_\ell| < 1.2$
3. $R_{l\gamma} = \sqrt{(\eta_l - \eta_\gamma)^2 + \phi_{l\gamma}^2} \leq 0.1 \Rightarrow$ electron/photon recombination



- Perfect agreement between independent calculations!

Les Houches tuned comparisons

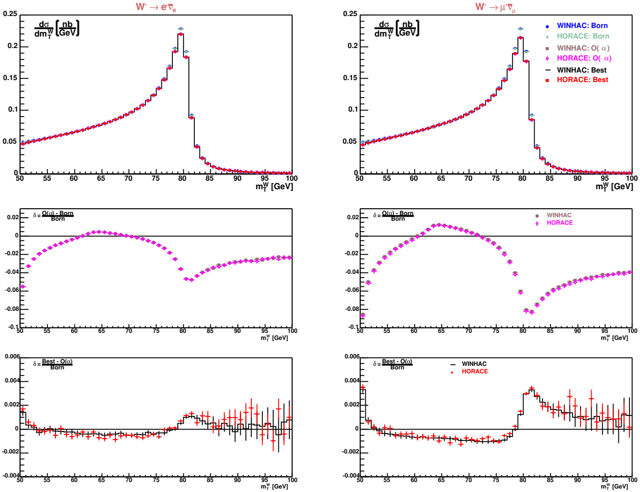
C. Buttar *et al.*, `hep-ph/0604120`

$pp \rightarrow \nu_l l^+ (+\gamma)$ @ $\sqrt{s} = 14$ TeV (with MRSTQED04)

$p_{T,l}/\text{GeV}$	25–∞	50–∞	100–∞	200–∞	500–∞	1000–∞
σ_0/pb						
DK	2112.2(1)	13.152(2)	0.9452(1)	0.11511(2)	0.0054816(3)	0.00026212(1)
HORACE	2112.21(4)	13.151(6)	0.9451(1)	0.11511(1)	0.0054812(4)	0.00026211(2)
SANC	2112.22(2)	13.1507(2)	0.94506(1)	0.115106(1)	0.00548132(6)	0.000262108(3)
WGRAD	2112.3(1)	13.149(1)	0.94510(5)	0.115097(5)	0.0054818(2)	0.00026209(2)
$\delta_{e+\nu_e}/\%$						
DK	−5.19(1)	−8.92(3)	−11.47(2)	−16.01(2)	−26.35(1)	−37.92(1)
HORACE	−5.23(1)	−8.98(1)	−11.49(1)	−16.03(1)	−26.36(1)	−37.92(2)
WGRAD	−5.10(1)	−8.55(5)	−11.32(1)	−15.91(2)	−26.1(1)	−38.2(2)
$\delta_{\mu+\nu_\mu}/\%$						
DK	−2.75(1)	−4.78(3)	−8.19(2)	−12.71(2)	−22.64(1)	−33.54(2)
HORACE	−2.79(1)	−4.84(1)	−8.21(1)	−12.73(1)	−22.65(1)	−33.57(1)
SANC	−2.80(1)	−4.82(2)	−8.17(2)	−12.67(2)	−22.63(2)	−33.50(2)
WGRAD	−2.69(1)	−4.53(1)	−8.12(1)	−12.68(1)	−22.62(2)	−33.6(2)
$\delta_{\text{recomb}}/\%$						
DK	−1.73(1)	−2.45(3)	−5.91(2)	−9.99(2)	−18.95(1)	−28.60(1)
HORACE	−1.77(1)	−2.51(1)	−5.94(1)	−10.02(1)	−18.96(1)	−28.65(1)
SANC	−1.89(1)	−2.56(1)	−5.97(1)	−10.02(1)	−18.96(1)	−28.61(1)
WGRAD	−1.71(1)	−2.32(1)	−5.94(1)	−10.11(2)	−19.08(3)	−28.73(6)
$\delta_{\gamma q}/\%$						
DK	+0.071(1)	+5.24(1)	+13.10(1)	+16.44(2)	+14.30(1)	+11.89(1)

HORACE **vs** WINHAC: $M_{\perp}^{W}$

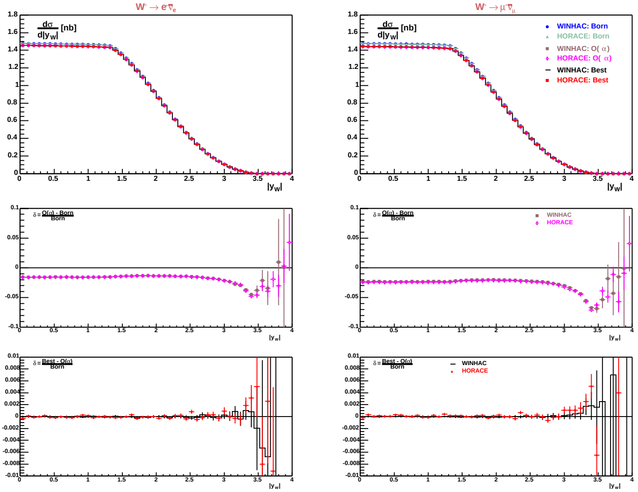
C.M. Carloni Calame *et al.*, Acta Phys. Pol. **B35** (2004) 1643



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

HORACE vs WINHAC: W rapidity

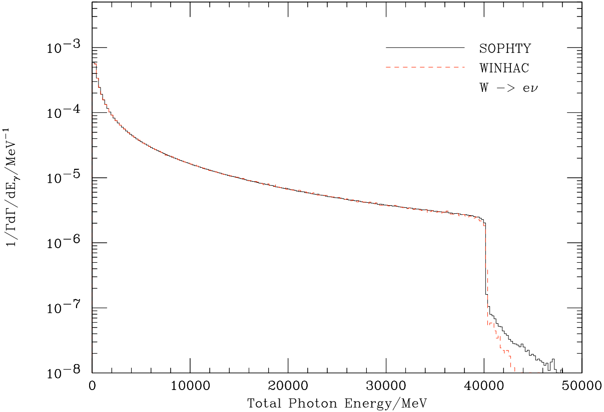
C.M. Carloni Calame *et al.*, Acta Phys. Pol. **B35** (2004) 1643



- $\mathcal{O}(\alpha)$ corrections at 2/5% level for recombined e/bare μ

HERWIG+SOPHTY vs WINHAC

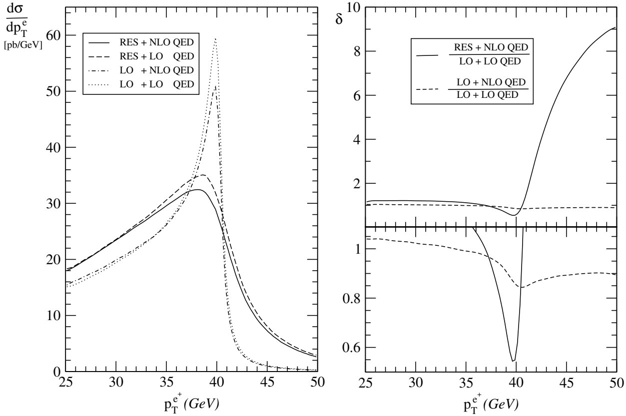
K. Hamilton and P. Richardson, JHEP **0607** (2006) 010



Matching soft-gluon resummation with NLO QED

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

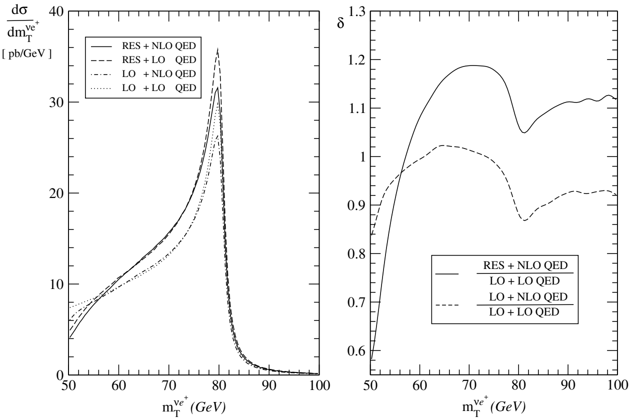
`ResBos-A`



- QCD resummation and NLO QED differently modify the shape of p_T^ℓ and reach $\sim -45\%$ → need to merge QCD and EW generators!

Matching soft-gluon resummation with NLO QED: M_T^W

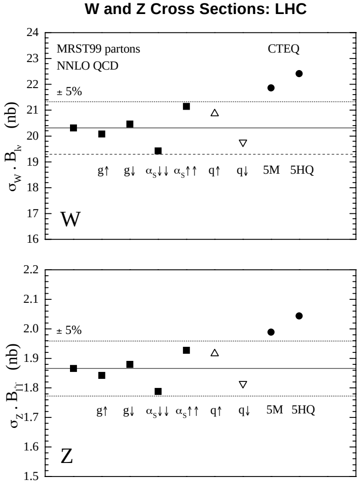
Q.-H. Cao and C.-P. Yuan, Phys. Rev. Lett. **93** (2004) 042001

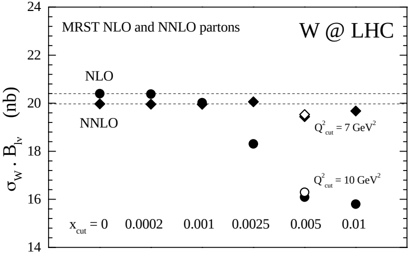


- QCD resummation ($\sim +6\%$ at the peak) is compensated by NLO QED ($\sim -12\%$) → need to merge QCD and EW generators!!

PDFs and total rates

A.D. Martin *et al.*, Eur. Phys. J. **C35** (2004) 325
A.D. Martin *et al.*, Eur. Phys. J. **C14** (2000) 133

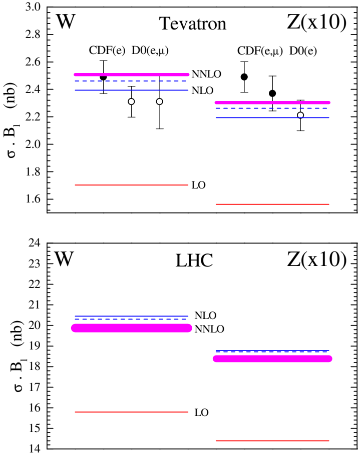

W and Z Cross Sections: LHC



- Present PDFs uncertainty $\sim 3\% - 5\%$ at the LHC

QCD predictions for W/Z total rates

R. Hamberg, W.L. van Neerven, T. Matsuura, Nucl. Phys. **B359** (1991) 343
A.D. Martin *et al.*, Eur. Phys. J. **C19** (2001) 313

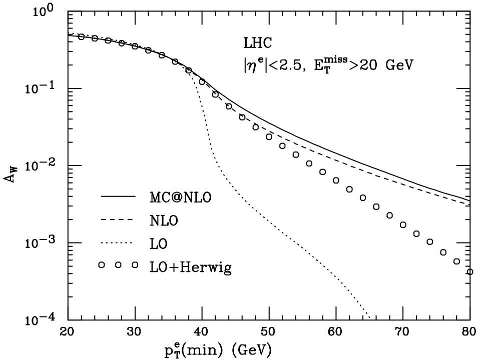


- Good convergence of α_s expansion. NLO-NNLO difference $\sim$ 2% at the LHC

MC@NLO corrections to acceptances

S. Frixione and M.L. Mangano, JHEP **0405** (2004) 056

$$\sigma^{\rm exp}(W) = \frac{1}{{\rm BR}(W \to l\nu)} \frac{1}{\int \mathcal{L} dt} \frac{N^{\rm obs}}{A_W}$$

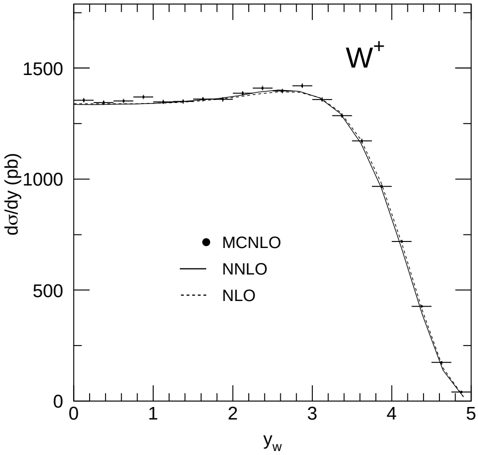


- Overall QCD uncertainty (NLO + Parton Shower corrections, spin correlations, PDFs and scale uncertainties) at $\sim 2\%$ level

NNLO QCD vs MC@NLO

Courtesy of G. Polesello

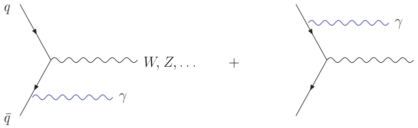
See also K. Melnikov and F. Petriello, `hep-ph/0603182`



- For an inclusive sample NNLO and MC@NLO agree well!

QED initial-state collinear singularities

- QED initial-state collinear singularities are universal → can be absorbed into PDFs, as in QCD



$$
\begin{aligned}
f(x) \quad \rightarrow \quad & f(x,\mu_F^2) - \int_x^1 \frac{dz}{z}\, f\left(\frac{x}{z},\mu_F^2\right) \frac{\alpha}{2\pi} Q_q^2 \\
& \times \left\{ \ln\left(\frac{\mu_F^2}{m_q^2}\right) [P_{ff}(z)]_+ - [P_{ff}(z)\,(2\ln(1-z)+1)]_+ + C(z) \right\}
\end{aligned}
$$

$$
C(z) = \left\{ \begin{array}{cc} 0 & \overline{\text{MS}} \\ \left[P_{ff}(z)\left(\ln\left(\frac{1-z}{z}\right)-\frac{3}{4}\right)+\frac{9+5z}{4}\right]_+ & \text{DIS} \end{array} \right.
$$

The Parton Shower algorithm

- the PS is a MC solution of the QED DGLAP equation

$$Q^2\frac{\partial}{\partial Q^2}D(x,Q^2) = \frac{\alpha}{2\pi}\int_x^1 \frac{dt}{t}P_+(t)D(\tfrac{x}{t},Q^2)$$

- the solution can be cast in the form

$$D(x,Q^2) \;=\; \Pi_S(Q^2)\sum_{n=0}^{\infty}\int\frac{\delta(x-x_1\cdots x_n)}{n!}\prod_{i=0}^{n}\left[\frac{\alpha}{2\pi}P(x_i)\,L\,dx_i\right]$$

  - ⋆ $\Pi_S(Q^2) \equiv e^{-\frac{\alpha}{2\pi}LI_+}$ is the Sudakov form factor, $I_+ \equiv \int_0^{1-\epsilon}P(x)dx$, $L \equiv \log\frac{Q^2}{m^2}$ and ϵ soft/hard separator
- the PS MC algorithm reproduces this solution
- at NLO, the resulting cross section has a leading log accuracy

Fitting the W mass

χ^2 fits to Monte Carlo pseudo-data for the M_T^W spectrum with

- $\sqrt{s} = 2$ TeV $\quad p_T(\ell) > 25$ GeV $\quad |\eta(\ell)| < 1.2 \quad \not{p}_T > 25$ GeV
- lepton identification requirements based on Tevatron analyses (e.g., if $\Delta R_{e\gamma} = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.2$, e and γ momenta are recombined)
- particles' momenta are smeared according to RunII DØ detector specifications

$$\chi^2(M_W) = \sum_{i=bins} (\sigma_{i,exp} - \sigma_{i,\alpha})^2 / (\Delta\sigma^2_{i,exp} + \Delta\sigma^2_{i,\alpha})$$

histogram: no lepton identification criteria, no detector effects
markers: with lepton identification criteria
shaded: with lepton identification criteria and detector effects
arrows: fitting region, 65 GeV $< M_T < 100$ GeV