# Combining QCD and electroweak corrections to Drell-Yan at the LHC

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# Outline

- Relevance of $W/Z$ physics at the LHC
  - ⋆ precise measurement of $M_W$
  - ⋆ luminosity monitor
  - ⋆ PDFs constraint
- Ingredients for precision calculations:
- QCD corrections
- PDFs and the effects of their uncertainties on observables
- Combining QCD & EW corrections: first “experiments” on charged DY with available generators for LHC
- Summary

# Relevance of $W/Z$ physics at LHC/Tevatron

- DY processes easy to be detected (lepton plus missing energy or leptonic pair)
- large cross sections ($\sim 30$ nb for $W$ production at LHC)
- standard candles for detector calibrations
- at high luminosity
  - ⋆ precise measurement of $M_W \Rightarrow$ constraint on consistency of electroweak data; $\delta M_W \simeq 15$ MeV, together with $\delta m_t \simeq 2$ GeV $\Rightarrow$ $\delta m_H \simeq$ 35%
  - ⋆ and also $\Gamma_W$, $\sin^2 \vartheta_{eff}$
  - ⋆ hadron/parton luminosity monitors
  - ⋆ new physics searches in the high mass tail of the leptonic pair
- $W/Z$ in association with jets as backgrounds to other processes, *e.g.*
  - ⋆ $W/Zb\bar{b}$ and $W/Zjj$ irreducible background to associated Higgs production with vector bosons
  - ⋆ $Wb\bar{b}jj$ and $W+4j$ main background to $t\bar{t}$ production
  - ⋆ $W/Z+2$ fwd jets backgrounds to Higgs production through WBF

# Status of QCD calculations (& tools)

- 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

  W.L. van Neerven and E.B. Zijlstra, Nucl. Phys. **B382** (1992) 11

- Fully differential NNLO corrections to $l\bar{l}'$ (FEWZ)

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

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

- resummation of LL/NLL $p_T^W/M_W$ logs (RESBOS)

  C. Balazs and C.P. Yuan, Phys. Rev. **D56** (1997) 5558

- NLO ME merged with HERWIG PS (MC@NLO)

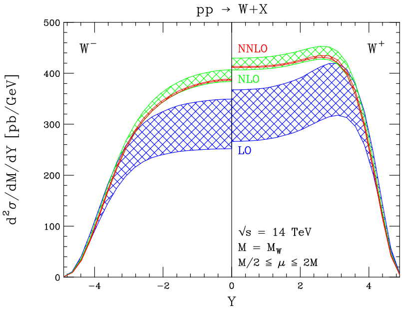
  S. Frixione and B.R. Webber, JHEP **0206** (2002) 029

- Matrix elements Monte Carlos (ALPGEN, SHERPA,...) matched with PS

  M.L. Mangano et al., JHEP **0307**, 001 (2003)

  F. Krauss et al., JHEP **0507**, 018 (2005)

# NNLO effects




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

| $Np_{\perp}^{e,\min}$ (GeV) | NLO | NNLO |
|---|---|---|
| 20 | 0.487, 0.488, 0.489 | 0.497, 0.492, 0.491 |
| 30 | 0.379, 0.378, 0.378 | 0.379, 0.376, 0.377 |
| 40 | 0.127, 0.125, 0.122 | 0.161, 0.155, 0.152 |
| 50 | 0.0312, 0.0295, 0.0277 | 0.0427, 0.0397, 0.0387 |

acceptances ($\sigma_{\rm cuts}/\sigma_{\rm inclusive}$) at NLO and NNLO for various choices of $p_{\perp}^{e,\min}$ and $\mu = M_W/2,\ M_W$ and $2M_W$

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

# EW calculations & tools

- $\mathcal{O}(\alpha_S^2) \approx \mathcal{O}(\alpha_{\rm em}) \rightarrow$ need to worry about electroweak corrections!
- Electroweak corrections to $W$ production
  - ⋆ Pole approximation ($\sqrt{\hat{s}} = M_W$)
    - → D. Wackeroth and W. Hollik, PRD **55** (1997) 6788
    - → U. Baur et al., PRD **59** (1999) 013002
  - ⋆ Complete $\mathcal{O}(\alpha)$ corrections
    - → V.A. Zykunov et al., EPJC **3** 9 (2001)
    - → S. Dittmaier and M. Krämer, PRD **65** (2002) 073007 — DK
    - → U. Baur and D. Wackeroth, PRD **70** (2004) 073015 — WGRAD2
    - → A. Arbuzov, et al., EPJC **46**,407 (2006) — SANC
    - → C.M. Carloni Calame. et al., JHEP12 016 (2006) — HORACE
- Multi-photon radiation
  - → C.M. Carloni Calame et al., PRD **69**, 037301 (2004), JHEP 0505:019 (2005), JHEP12 016 (2006) — HORACE
  - → S. Jadach, W. Płaczek, EPJC **29** 325 (2003) — WINHAC

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# Main effects of electroweak radiative corrections

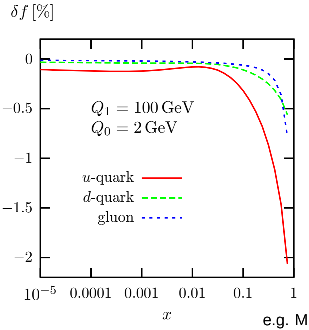
- final state (FS) QED radiation distorts the $M_T$ spectrum, higher orders QED radiation can affect the measurement of $M_W$ at the level of the aimed experimental accuracy
- $[\Delta M_W]_\alpha \sim$ 100 MeV
- $[\Delta M_W]_\infty \sim$ 10 MeV
- at high $W$ transverse/invariant mass large Sudakov logs appear $\sim \log^2 Q^2/M_W^2$
- The HORACE event generator includes both the exact $\mathcal{O}(\alpha)$ ew calculation consistently matched with the resummed Leading Logarithmic corrections in the QED parton shower approach

Carloni Calame, Montagna, Nicrosini, Vicini, JHEP12 016 (2006)

- A new version (still to be released) includes also ew corrections (matched to QEDPS) to the neutral Drell-Yan process

# Subtraction of initial state collinear singularities

- IS quark masses regularize the collinear QED divergencies
- the QED IS singularities have to be subtracted from the hard cross section [in analogy with NLO QCD], since they are already accounted in the (QED) evolution of PDFs
- the set MRSTQED (2004) (the only one!) includes the QED evolution




e.g. M. Roth, S. Weinzierl, PLB 590 190 (2004)

⋆ QED evolution modifies PDFs at 0.1% level for $x < 0.1$

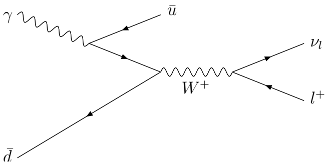
# Subtraction of IS singularities

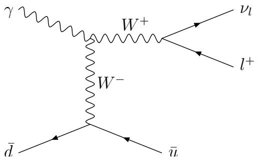
- at $\mathcal{O}(\alpha)$ the subtraction is performed by modifying PDFs ($DIS$ or $\overline{MS}$ scheme)
  - $q_i(x,\mu^2) \to q_i(x,\mu^2) - \int_x^1 \frac{dz}{z} q_i\left(\frac{x}{z},\mu^2\right) \frac{Q_q^2\alpha}{2\pi}\left(\log\frac{\mu^2}{m_q^2} - 1\right) P_+(z)$
  - the leading singularities $\propto \log s/m_q^2$ are removed in the integrated cross section
- it has been generalized to the QED resummed & matched cross section (see JHEP 12 016 (2006))
  e.g., $W^+$ cross section (nb) at LHC within some cuts

| | $\mathcal{O}(\alpha)$ | matched |
|---|---|---|
| $m_q$ | $4410.98 \pm 0.20$ | $4412.14 \pm 0.26$ |
| $m_q/10$ | $4410.92 \pm 0.26$ | $4411.89 \pm 0.33$ |
| $m_q/100$ | $4410.99 \pm 0.29$ | $4411.92 \pm 0.50$ |

# Also $\gamma$ among the partons in the proton

- dynamic generation of photon distr. function
- At $\mathcal{O}(\alpha)$ also photon induced processes contribute



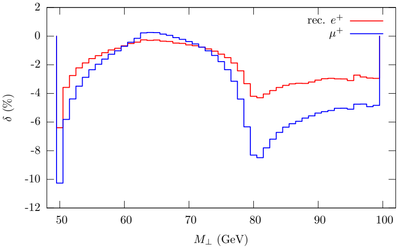



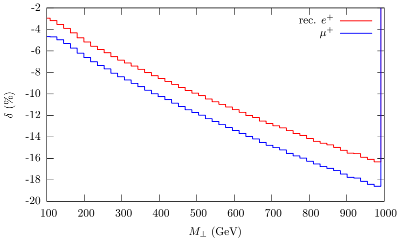

- They give a non trivial contribution to the $p_\perp^W$ and $p_\perp^l$ distribution

# $\mathcal{O}(\alpha)$ EW results

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

- LHC, $pp \to W^+ \to \ell^+ \nu_\ell$, $p_{\perp,\ell}$ and $p_{\perp,\nu} > 25$ GeV, $|\eta_\ell| < 2.5$
- $\mathcal{O}(\alpha)$ EW corrections to the $M_T$ distribution

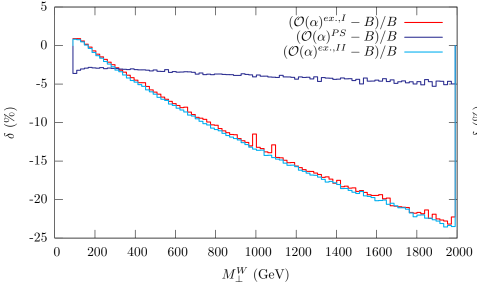


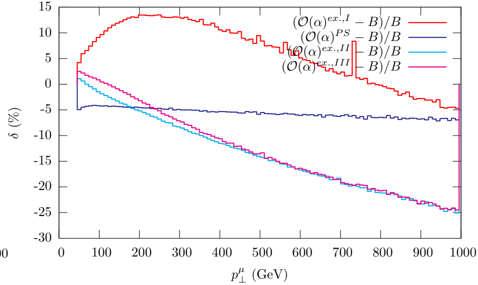




- $\mathcal{O}(\alpha)$ corrections at $5\%$ - $10\%$ level around the peak
- increasingly large in the $M_T$ tail due to the presence of the EW Sudakov (logs)$^2$, $\alpha_W \log^2 \frac{s}{M_Z^2}$
- Negative effects of Sudakov logs partially compensated by real emission of undetected vector bosons (e.g. $pp \to e\nu V + X$, $V \to \nu\bar{\nu}$ or $V \to jj$)

U. Baur, Phys. Rev. D75, 013005, 2007

# Effects of $\gamma$ induced processes



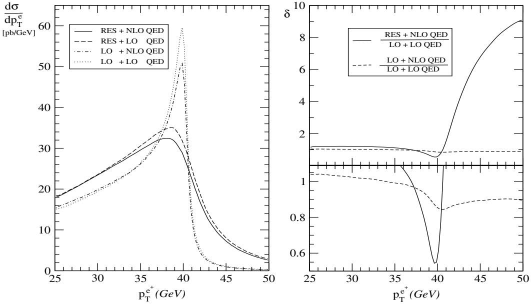




- The effect is in general not negligible at the LHC
- They produce an additional jet in the final state $\Rightarrow$ their effect can be reduced by imposing a central jet veto strategy

# Combining EW and QCD corrections

- it would be useful to combine EW and QCD corrections, for a better theoretical prediction of DY observables
- first study by Cao & Yuan, combining RESBOS with FS $\mathcal{O}(\alpha)$ corrections $\Rightarrow$ RESBOSA

Cao and Yuan PRL 93 042001 (2004) and hep-ph/0401171




- While the two corrections factorize for $M_T^{l\nu}$, their relation is more involved for the lepton $p_\perp$ distribution

# Combining EW and QCD corrections

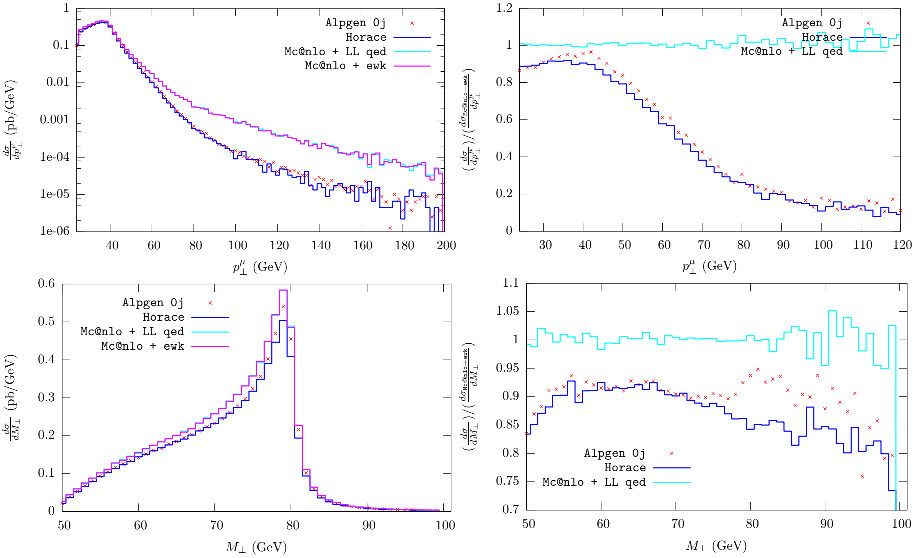
- our attempt (preliminary results) is based on the following formula

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

- best QCD $\Rightarrow$ `MC@NLO`, `ALPGEN` (with CKKW PS matching according to MLM prescription, `0+1 jet`, `0+1+2 jets`)
- EW part (`HORACE`) is interfaced to `HERWIG` PS (EW $\otimes$ QCD LL)
  - ⋆ NLO EW is convoluted with QCD LL parton shower $\Rightarrow \mathcal{O}(\alpha\alpha_s)$ corrections not reliable where hard non log QCD corrections are important (e.g. high $p_\perp$ lepton distribution without cut on the $W$ invariant mass). In this case a two-loop calculation needed for a sound estimate of $\mathcal{O}(\alpha\alpha_s)$ effects

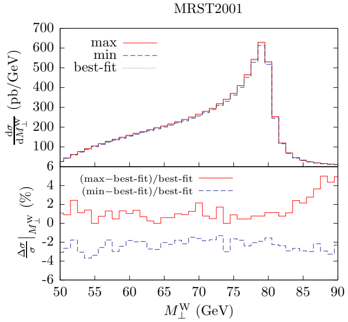
⋆ not suited for true event generation…

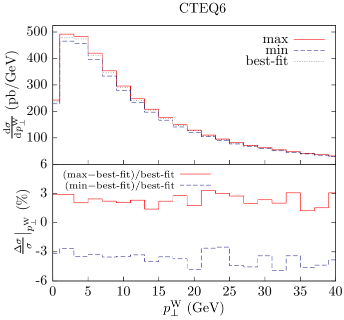
# QCD $\oplus$ EW: Lepton $p_\perp$ and $M_\perp$



# PDF's uncertainties

- For precision predictions for D-Y, PDF's uncertainties need to be estimated
- We are studying them within the context of LHAPDF with error estimates (reflecting only the errors of exp. origin in the PDF parameters)



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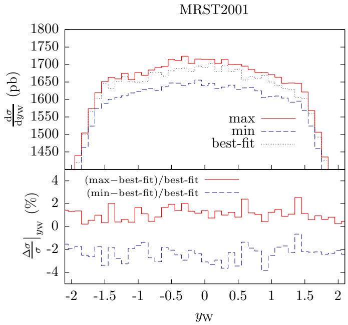


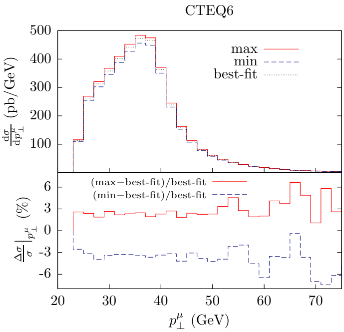


- the error estimate given by CTEQ is sistematically larger than the one with MRST: this can be ascribed to the different value for the parameter $T$ (tolerance) used in the fits ($\sqrt{50}$ for MRST and $10$ for CTEQ)

# Summary

- D-Y physics at hadron colliders is very important for several reasons
  - detector calibration
  - hadron/parton luminosity
  - PDF constraints
  - precision electroweak measurement
  - new physics searches
- We have already sophisticated tools including NLO corrections (QCD and EW) matched to parton shower event generators
- At the LHC $\gamma-$induced processes have to be considered (in the theoretical predictions or in the data analysis)
- PDFs give an additional source of uncertainty, very important with the aim of a $\mathcal{O}(1\%)$ total accuracy
- Under study the combined effects of QCD & EW corrections
- in the future a unified generator for QCD & EW corrections would be desirable ...

$\rightarrow$ see next talk by B. Ward