UNIVERSITÀ DEGLI STUDI
DI MILANO

INFN
Istituto Nazionale
di Fisica Nucleare

Combining QCD and EW corrections to the charged current Drell-Yan process

Alessandro Vicini

University of Milano, INFN Milano

DIS2007, Munich, April 17th 2007

with: C. M. Carloni Calame, G. Balossini, G. Montagna, O. Nicrosini, F. Piccinini, M. Moretti, M. Treccani

Outline

- Relevance of Drell-Yan processes and motivation for precision studies

- Ingredients of precision calculations:

  QCD, EW corrections
  photon induced processes
  combining QCD and EW corrections

- Phenomenological results

Goals

- Why do we need both QCD and EW corrections?
- Study QCD-EW interplay on different observables: $M_\perp^W$, $p_\perp^\mu$
- Test the feasibility of measurements at the 5% (1%?) level

Relevance of DY and motivations for precision studies

- easy detection: high pt lepton-pair
  (at LHC in association with large jet multiplicities)
- large cross section
  at LHC σ(W) = 30 nb i.e. 3 10^8 events with L=10 fb^-1
- (with jets) background to important signals (t tbar, Higgs production)

- precision measurement of EW observables
  at LHC error on MW ~15MeV; NLO-QED induce $\Delta M_W \sim -100$ MeV
- *pdf*'s validation
  at LHC new range of values in *x* and Q^2
- luminosity monitoring
  error on pdf's and acceptances → error on the proton-proton luminosity

- background to the search for new heavy gauge bosons
  large radiative corrections in the large mass tails

QCD results and 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)

EW results and 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

The HORACE event generator

- http://www.pv.infn.it/hepcomplex/horace.html

- developed by: C.M.Carloni Calame, G.Montagna, O.Nicrosini, A.Vicini

- state of the art of EW radiative corrections to DY processes
  exact O(α) radiative corrections matched with
  multiple photon radiation via QED Parton Shower

- true, fully exclusive event generator
  events saved in a Les Houches compliant form
  interfaced to LHAPDF package
  easy to interface to QCD showering programs like HERWIG or PYTHIA

- MRST2004QED, QED evolution ⇒ photon density in the proton

  ⇒ photon induced processes

Combining QCD and EW corrections

- First attempt: combination of soft-gluon resummation with final state QED corrections Q.-H. Cao and C.-P. Yuan, Phys. Rev. Lett. **93** (2004) 042001 ResBos-A

- Additive combination of QCD and EW corrections:

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

- QCD = ALPGEN (with CKKM-MLM Parton Shower matching), ResBos-CSS, MC@NLO, FEWZ, MCFM
- EW = HORACE interfaced with HERWIG QCD Parton Shower

  NLO-EW corrections convoluted with QCD PS ⇒ inclusion of $\mathcal{O}(\alpha\alpha_s)$ terms

  not reliable when hard non collinear radiation is important

- Beyond the additive approximation, a full 2-loop $\mathcal{O}(\alpha\alpha_s)$ calculation is needed

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 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 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	$\sigma^{\rm Tevatron}_{\rm NLO}$(pb)	$\sigma^{\rm LHC}_{\rm NLO}$(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)

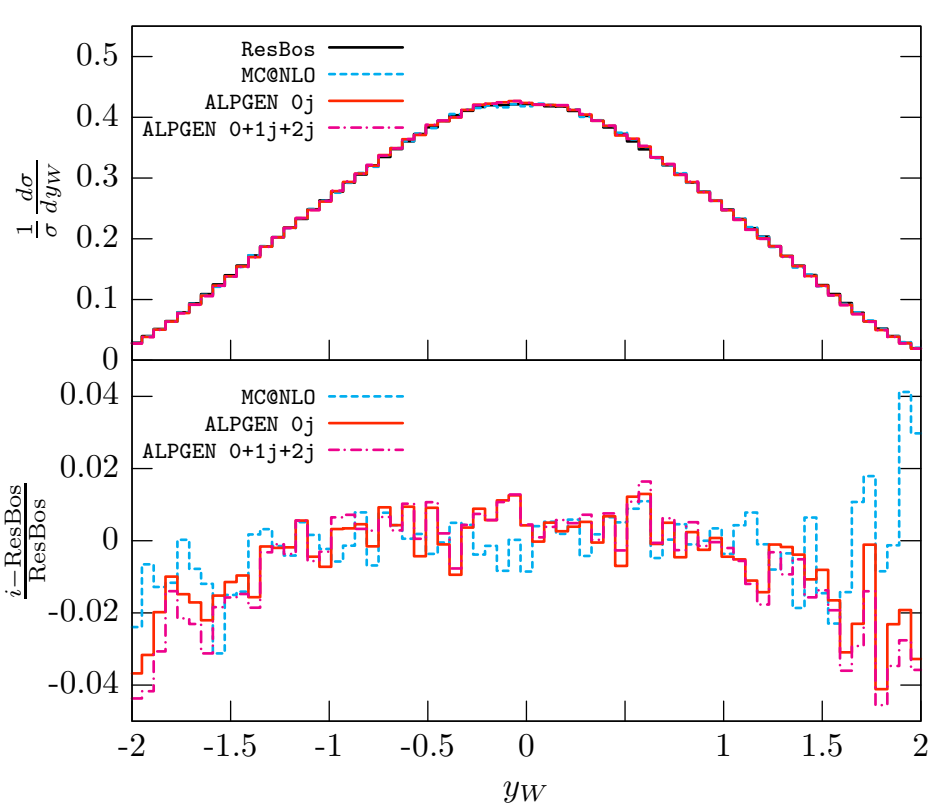
- ⋆ After appropriate "tuning", and with same input parameters and cuts, Monte Carlos agree at $\sim 0.1\%$ level (or better)

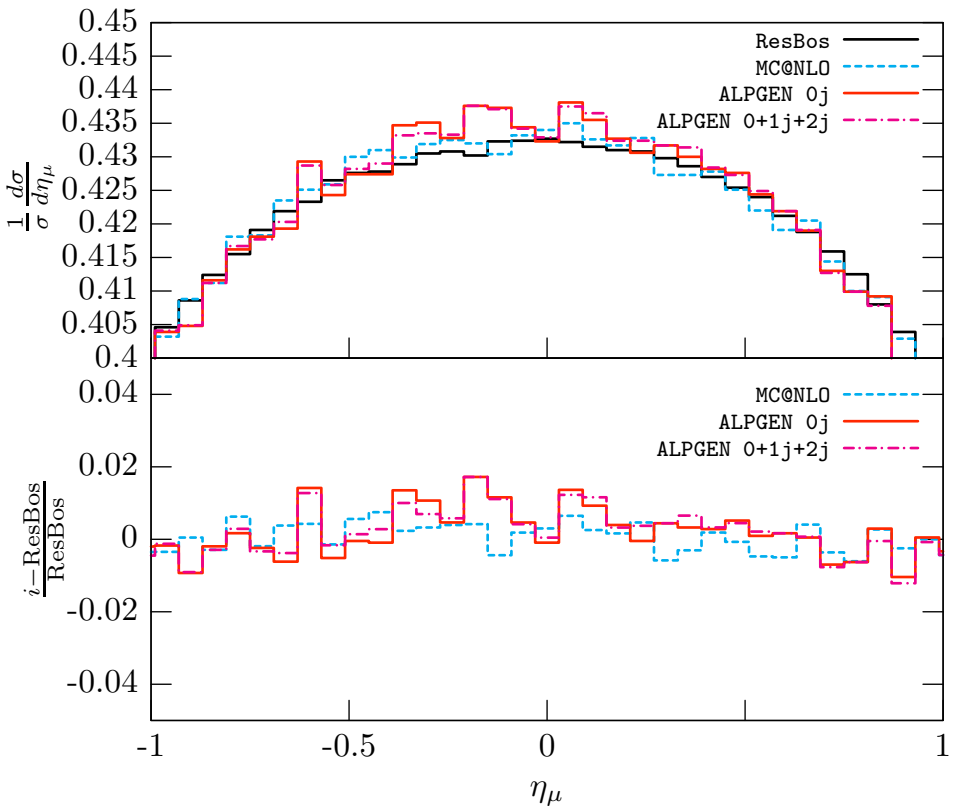
QCD @ Tevatron: W rapidity and lepton pseudo-rapidity

$$p\bar{p} \to \mu^{\pm}\nu \quad \sqrt{S} = 1.96\text{TeV} \quad (G_\mu, M_W, M_Z) + \alpha(0) \text{ for real photons}$$

$$p_{\perp,l} \text{ and } p_{\perp,\nu} > 25\text{GeV}, \ |\eta_l| < 1.2, \ \ p_\perp^W \leq 50\text{GeV}, \ \ 50 \leq M_{\mu\nu}^{inv} \leq 200\text{GeV}$$

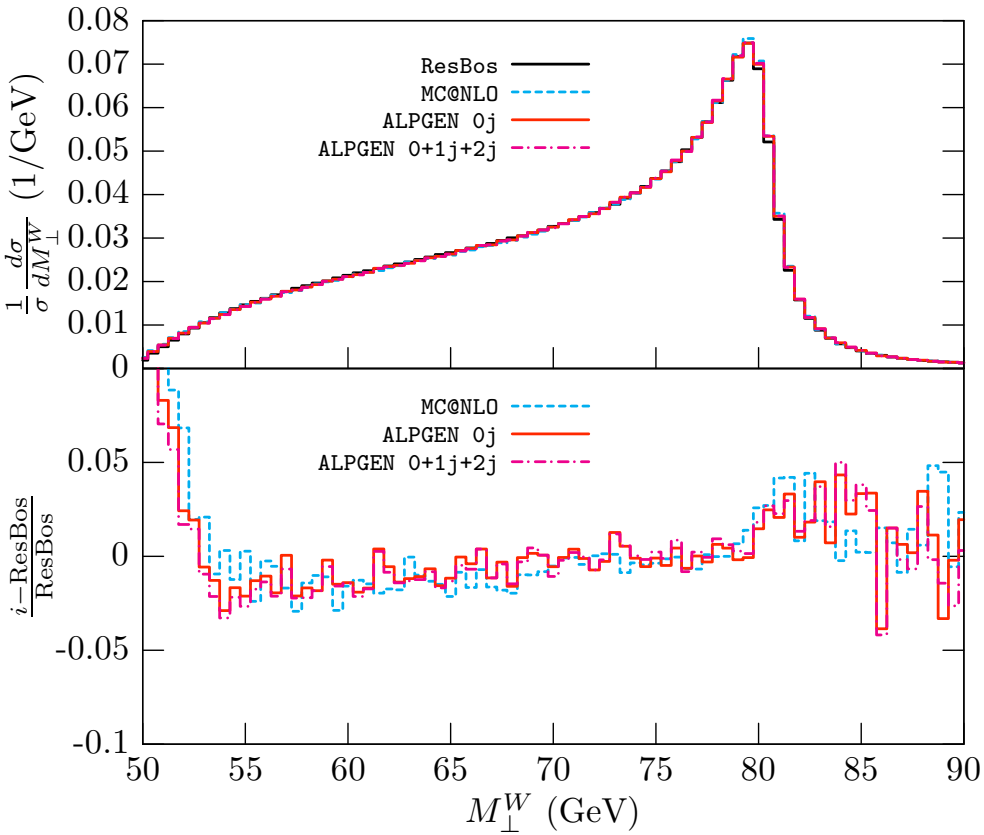
$$NLO\ CTEQ6m \text{ with } \mu_R = \mu_F = \sqrt{x_1 x_2 S}$$

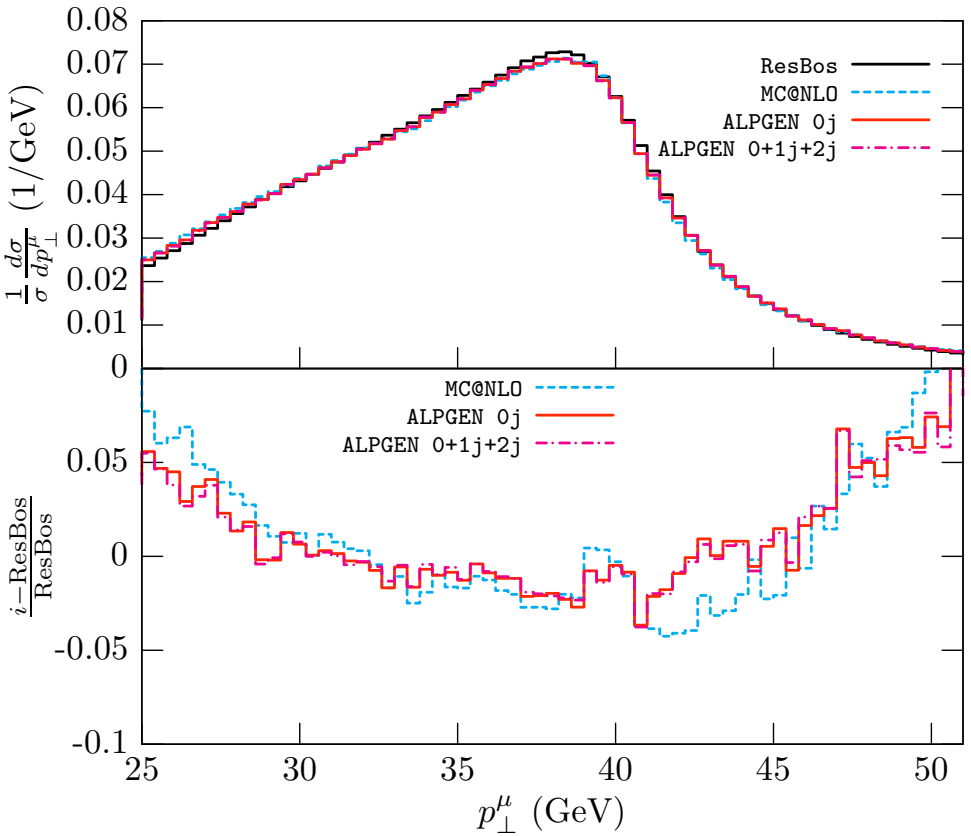




- generators normalized to their cross section ⇒ shape differences
- for W rapidity and lepton pseudo-rapidity, generator agreement at 1 % level

QCD @ the Tevatron: $M_\perp^W$ and $p_\perp^\mu$ distributions



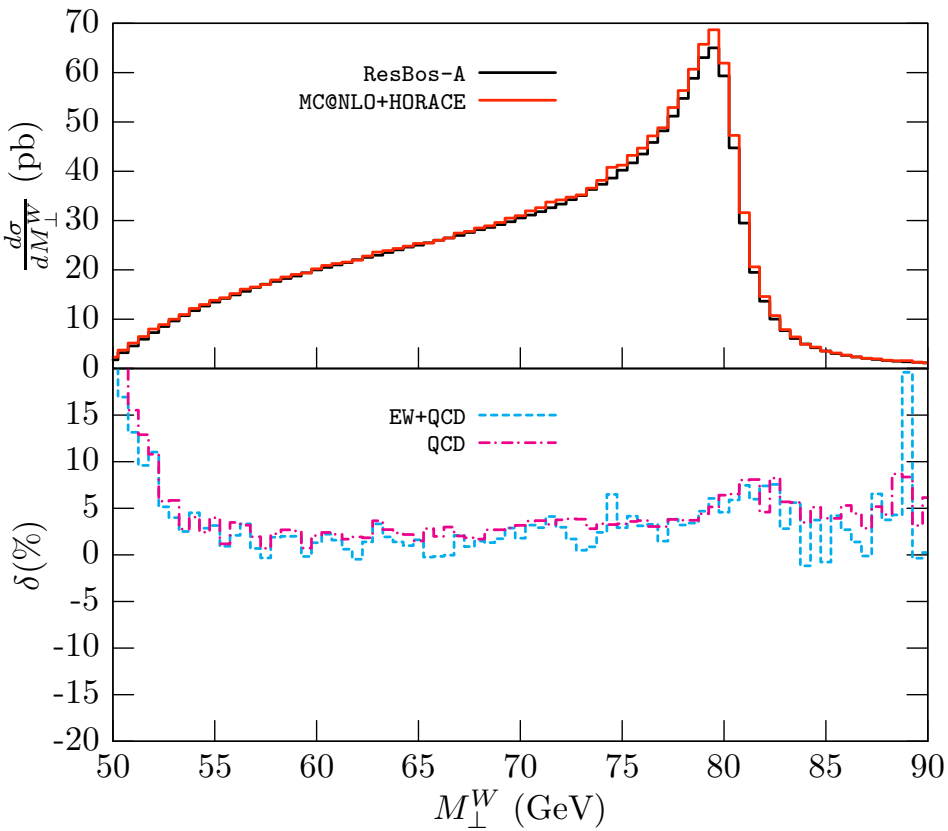


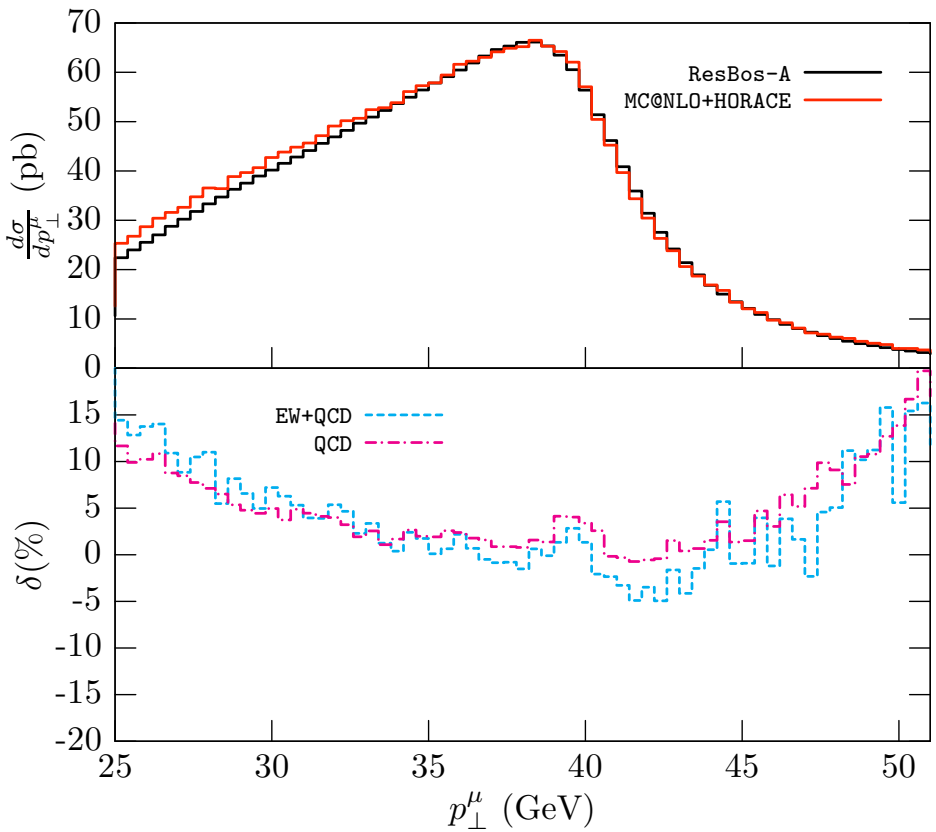
- generators normalized to their cross section ⇒ shape differences

- Around the jacobian peak, agreement at the few % level
- in the soft $M_\perp^W$ tail and in the hard $p_\perp^\mu$ tail, differences can reach the 10 % level

EW + QCD @ the Tevatron

Absolute comparison: ResBos(CSS)-A vs MC@NLO + HORACE





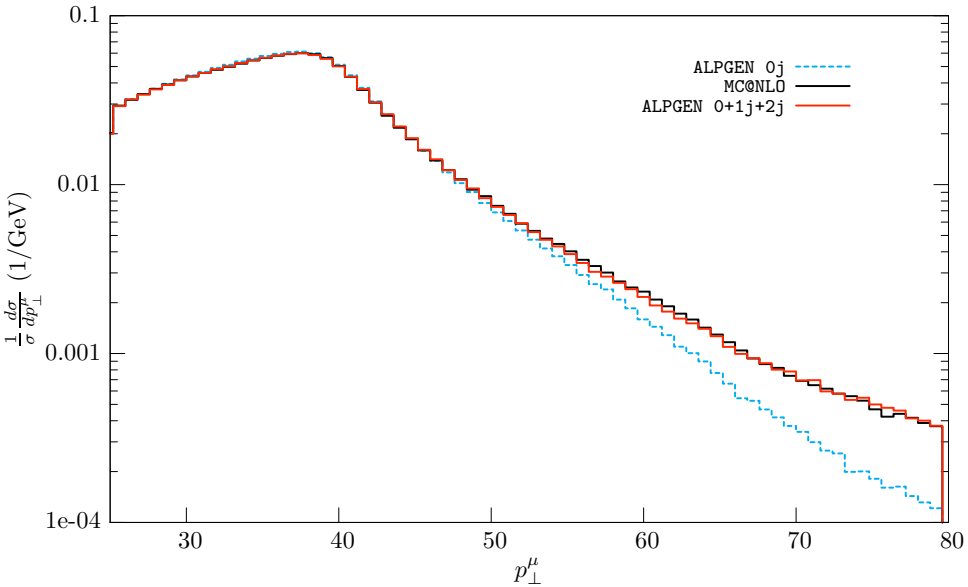
- Different normalization of the distributions
- Around the jacobian peak, agreement at a few % level
- in the soft $M_\perp^W$ tail and in the hard $p_\perp^\mu$ tail, differences can reach the 15 % level
- Around the jacobian peak, bulk of the EW effects by QED final state radiation

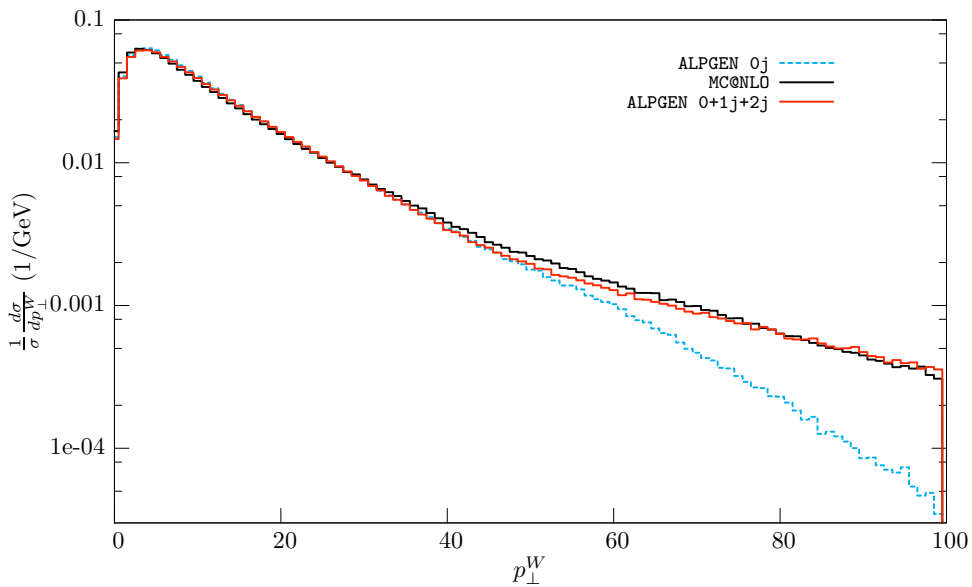
QCD @ the LHC : $p_\perp^\mu$ and $p_\perp^W$ distributions

$p\bar{p} \to \mu^\pm \nu_\mu \quad \sqrt{S} = 14\text{TeV} \quad (G_\mu, M_W, M_Z) + \alpha(0)$ for real photons

$p_{\perp,l}$ and $p_{\perp,\nu} > 25\text{GeV}$, $|\eta_l| < 2.5 \oplus (possibly)\ M_\perp^W > 1$ TeV

NLO MRST2004QED with $\mu_R = \mu_F = \sqrt{p_{\perp,W}^2 + M_W^2}$

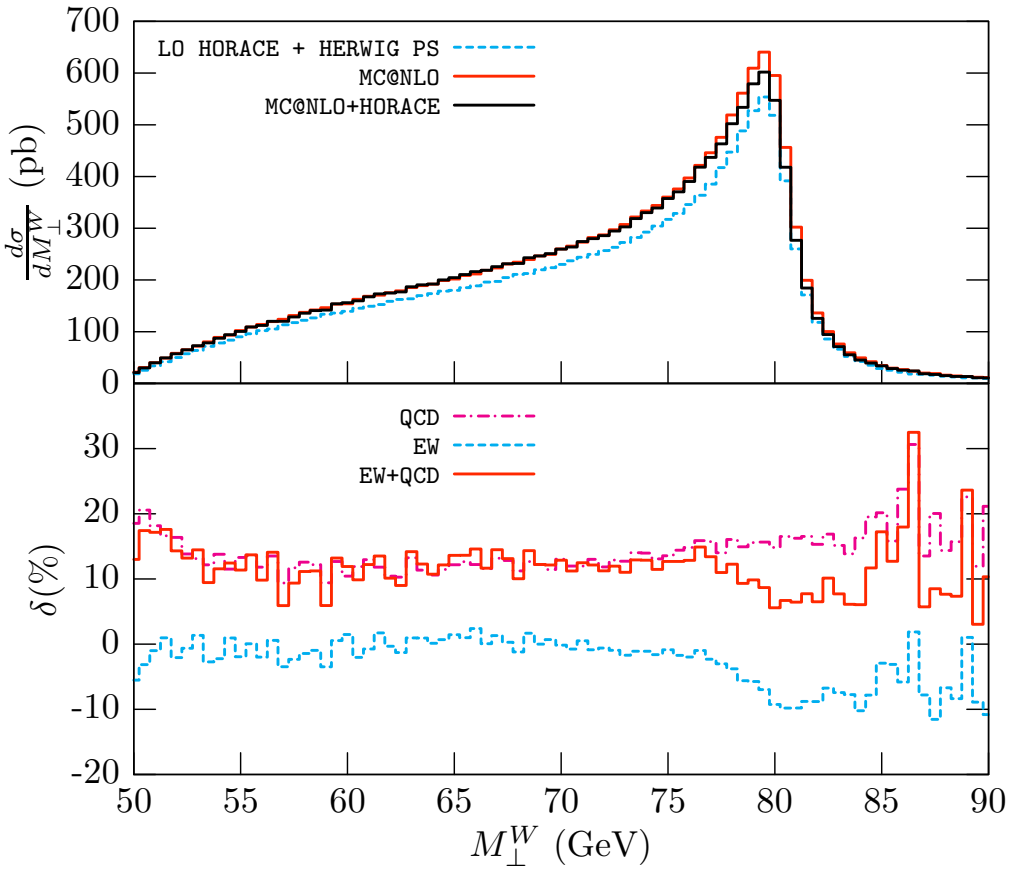


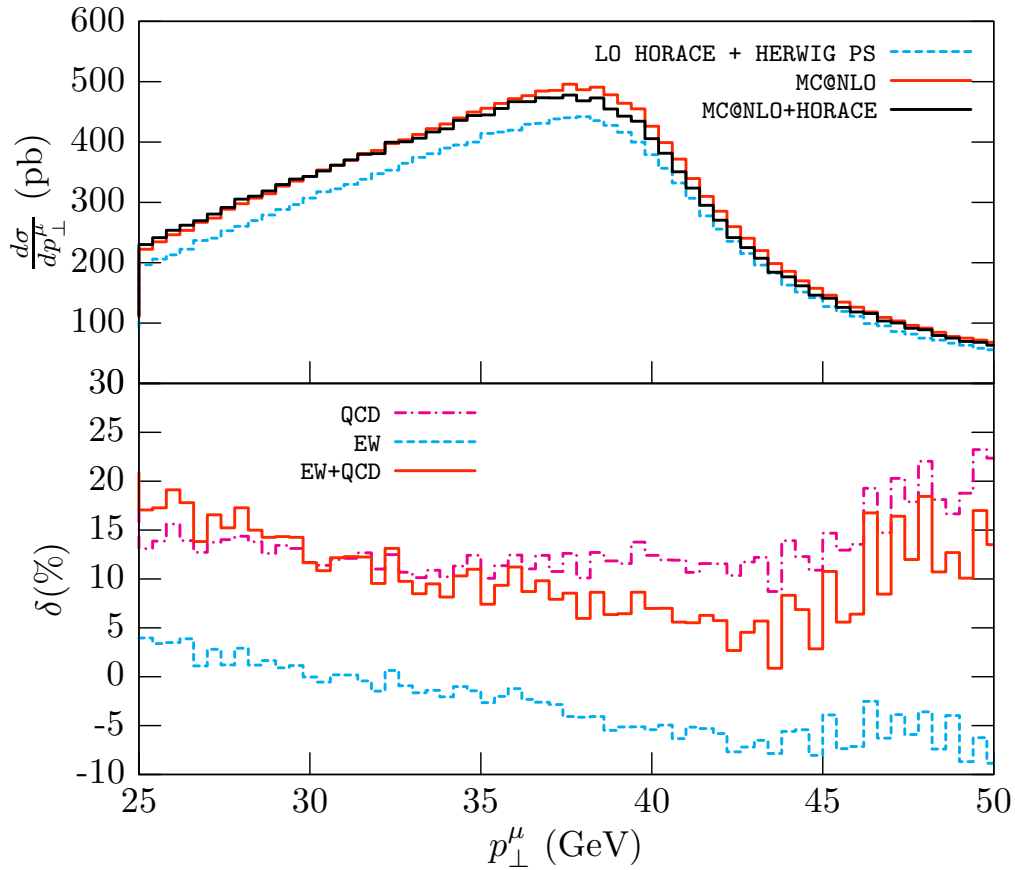


- generators normalized to their cross section ⇒ shape differences

- exact NLO with Parton Shower important in the high tails of $p_\perp^l$ and $p_\perp^W$
- agreement in the shapes predicted by MC@NLO and ALPGEN

QCD+EW @ the LHC: $M_\perp^W$ and $p_\perp^\mu$ distributions



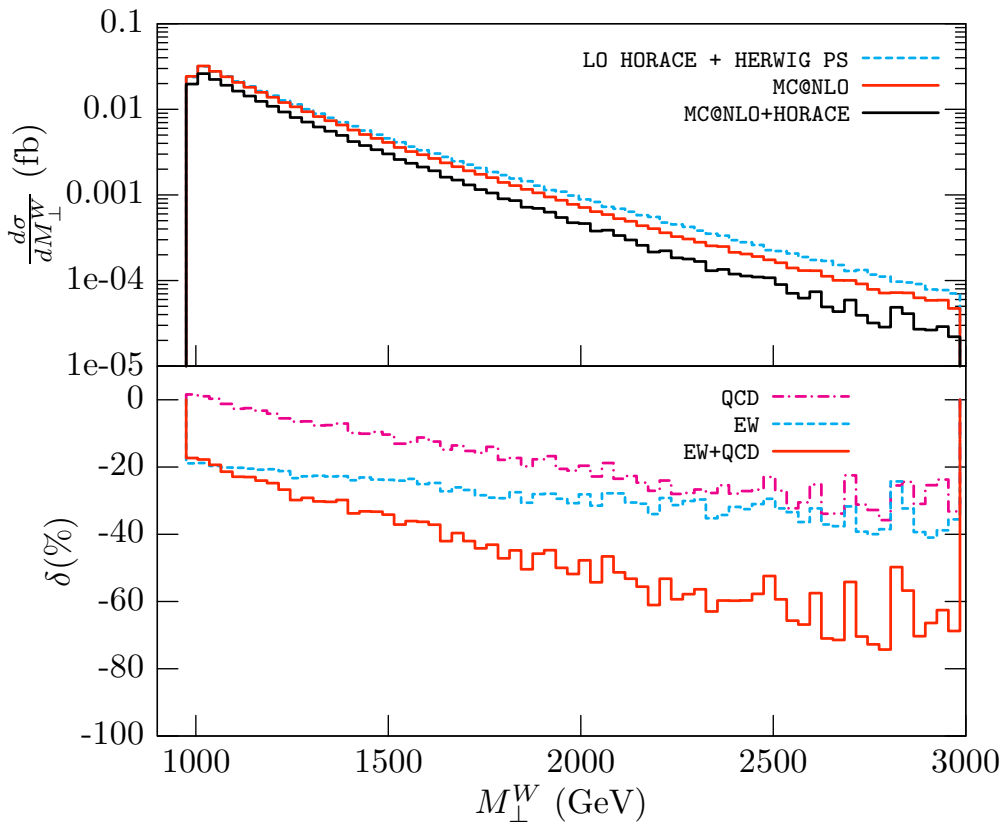


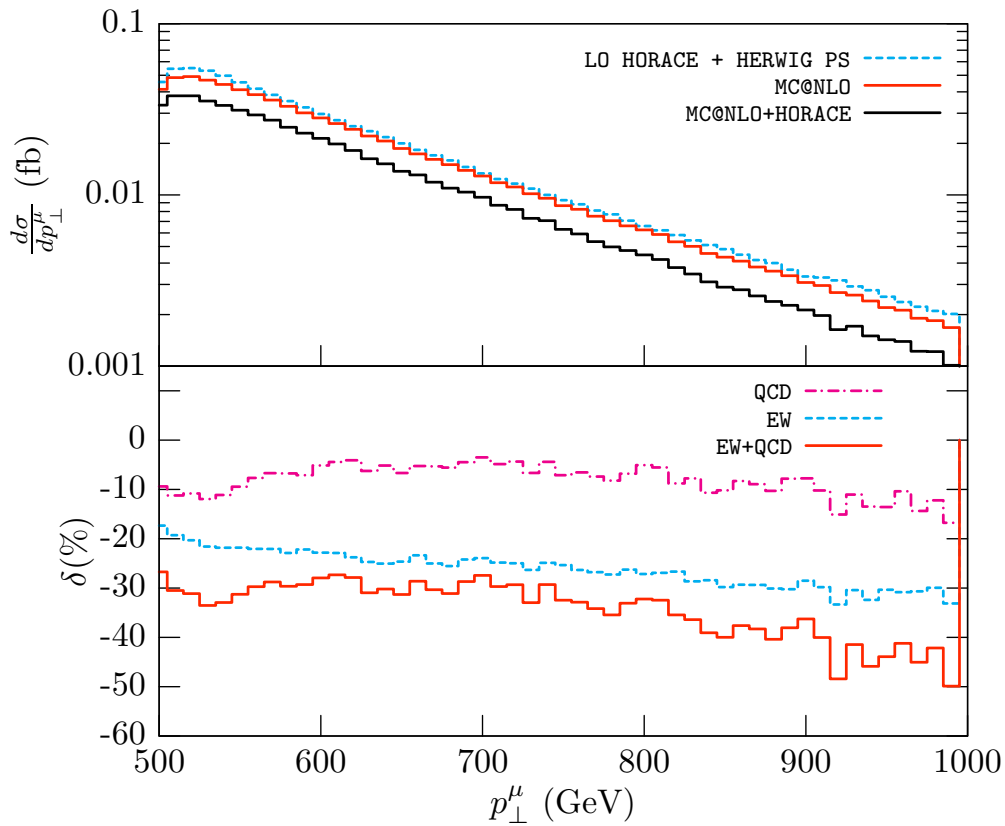
- positive QCD corrections compensate negative EW corrections
- around the jacobian peak EW corrections mandatory to extract M_W only QCD-Parton Shower is not sufficient
- the convolution with QCD Parton Shower modifies the relative effect and shape of the EW corrections

QCD+EW @ the LHC: $M_\perp^W$ and $p_\perp^\mu$ distributions

$M_\perp^W > 1$ TeV, $\quad p_\perp^\mu > 500$ GeV

- which relation between large negative EW Sudakov logs and QCD corrections?

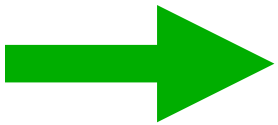




- negative QCD corrections sum up with negative EW corrections
- the sum $\sim -40(-70)\%$ for $M_\perp^W \simeq 1.5(3)$ TeV and $\sim -30(-50)\%$ for $p_\perp^\mu \simeq 0.5(1)$ TeV
- ...but in this region there is a very tiny cross section

Conclusions

- Drell-Yan processes: very high precision measurements (with % accuracy) at the Tevatron and the LHC



need both QCD and EW corrections
possibly unified in a single event generator (not yet available)

- HORACE: state of the art of the EW radiative corrections to DY processes: charged current (and now also neutral current) channel

- QCD+EW: additive combination of $\mathcal{O}(\alpha_s) + \mathrm{QCD\ PS}$ and of $\mathcal{O}(\alpha) + \mathrm{QCD\ PS}$
  EW corrections are necessary to:
  - describe the jacobian peak ($\Rightarrow M_W$ measurement)
  - describe the large mass/momentum tails ($\Rightarrow$ new boson searches)

- in progress:
  - complete the QCD comparison (including FEWZ and MCFM)
  - study the EW effects on the W mass measurement with the scaled observables method
  - long term: combine HORACE+ALPGEN into a single generator

Back-up slides

Electroweak results with HORACE

LHC energy: $\sqrt{S}$=14 TeV *pdf*: MRST2004QED

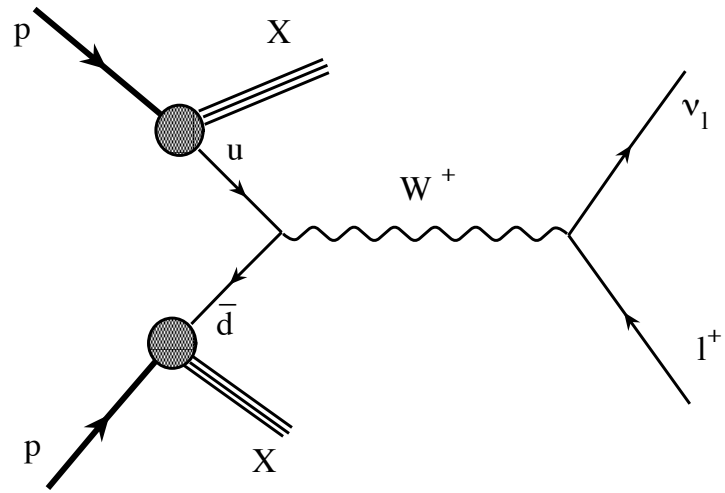
process: $pp \to \mu^{\pm}\nu \ + X$

input scheme: $\alpha(0),\ M_W,\ M_Z$

selection cuts: $p_{\perp,l}$ and $p_{\perp,\nu} > 25\mathrm{GeV},\ |\eta_l| < 2.5$

extra cuts in photon-induced processes: $p_{\perp,jet} < 30\mathrm{GeV},\ |\eta_{jet}| > 2.5$

Relevance of Drell-Yan processes

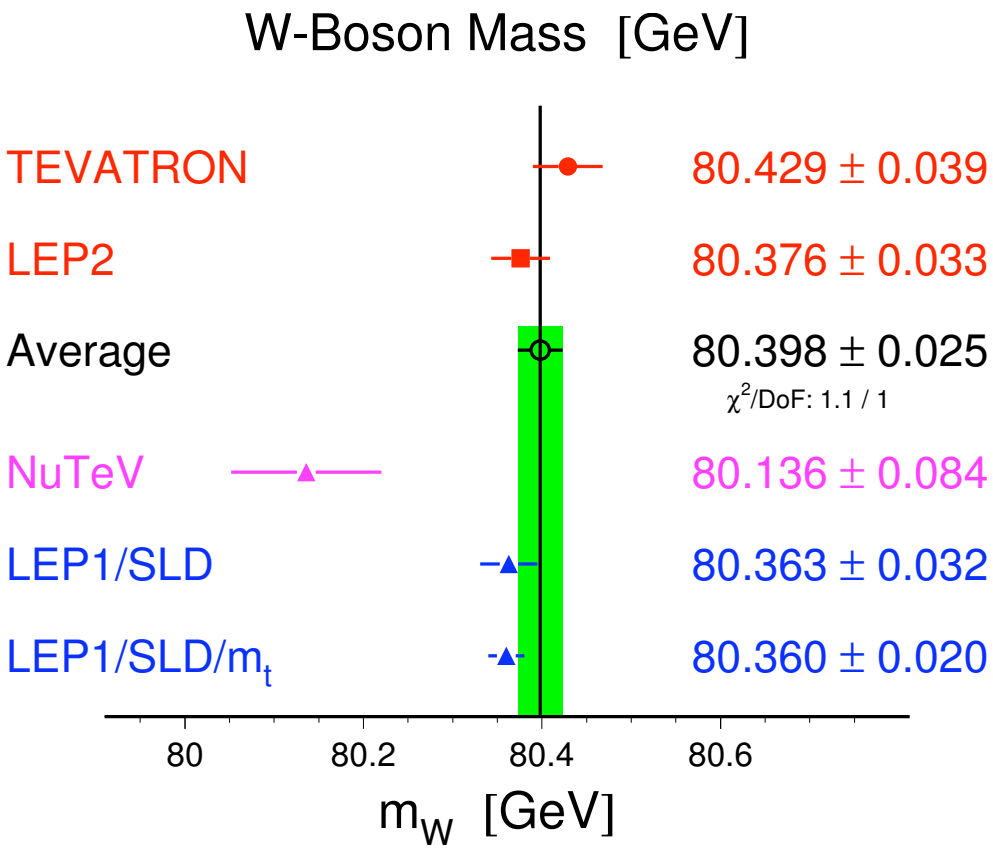


- easy detection: lepton+missing energy
  or lepton pair
- large cross section (at LHC σ(W) = 30 nb,
  3 10^8 events with L=10 fb^-1)

  ⇒ standard candle for detector calibration
- W/Z + jets: background to other processes

  e.g.
  - $W/Z b\bar{b}$ and $W/Z jj$ irreducible background to associated Higgs production with vector bosons
  - $W b\bar{b} jj$ and $W + 4j$ main background to $t\bar{t}$ production
  - $W/Z + 2$ fwd jets backgrounds to Higgs production through WBF

The quest for precision



Target precision

Tevatron Run-II: $20 - 30$ MeV

LHC: 15 MeV

NLO-QED corrections at Tevatron → $\Delta M_W \sim -100$ MeV

electron channel: $\Delta M_W = -65 \pm 20$ MeV

muon channel: $\Delta M_W = -168 \pm 20$ MeV

Motivations for precise predictions (at % level or better)

- precision measurement of $M_W,\ \Gamma_W,\ \sin^2\theta^{lep}_{eff}$
  at high luminosity at the LHC

$$\delta M_W = 15\mathrm{MeV} \ + \ \delta m_t = 2\mathrm{GeV} \implies \delta m_H = 35\%$$
$$\delta \Gamma_W = 30\mathrm{MeV} \qquad \delta \sin^2\theta^{lep}_{eff} = 1.4 \cdot 10^{-4}$$

- *parton density functions* validation
  LHC will explore a new range of values of *x* and Q^2
  DY processes will allow to test/validate/constrain the present sets of *pdf*'s and their pQCD evolution (e.g. can we neglect small-*x* effects?)

- luminosity monitoring:
  assuming a very precise knowledge of the DY process it is possible to use it to measure the proton-proton luminosity

$$\sigma^{\mathrm{exp}} \equiv \frac{1}{\mathrm{BR}(W \to \ell\nu)} \frac{1}{\int \mathcal{L} dt} \frac{N^{obs}}{A} = \sigma^{\mathrm{theory}} \equiv \sum_{ab} \mathcal{P}_{ab} \otimes \hat{\sigma}_{ab}$$

- background to new heavy gauge boson searches:
  the DY processes represent one of the main backgrounds to the search of new heavy gauge bosons; the radiative corrections play an important role (both EW and QCD)

The HORACE event generator II

matching formula

$$d\sigma_{\infty}^{matched} = \Pi_S(Q^2,\varepsilon) F_{SV} \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=0}^{n} F_{H,i} \; |\mathcal{M}_{n,LL}|^2 d\Phi_n$$

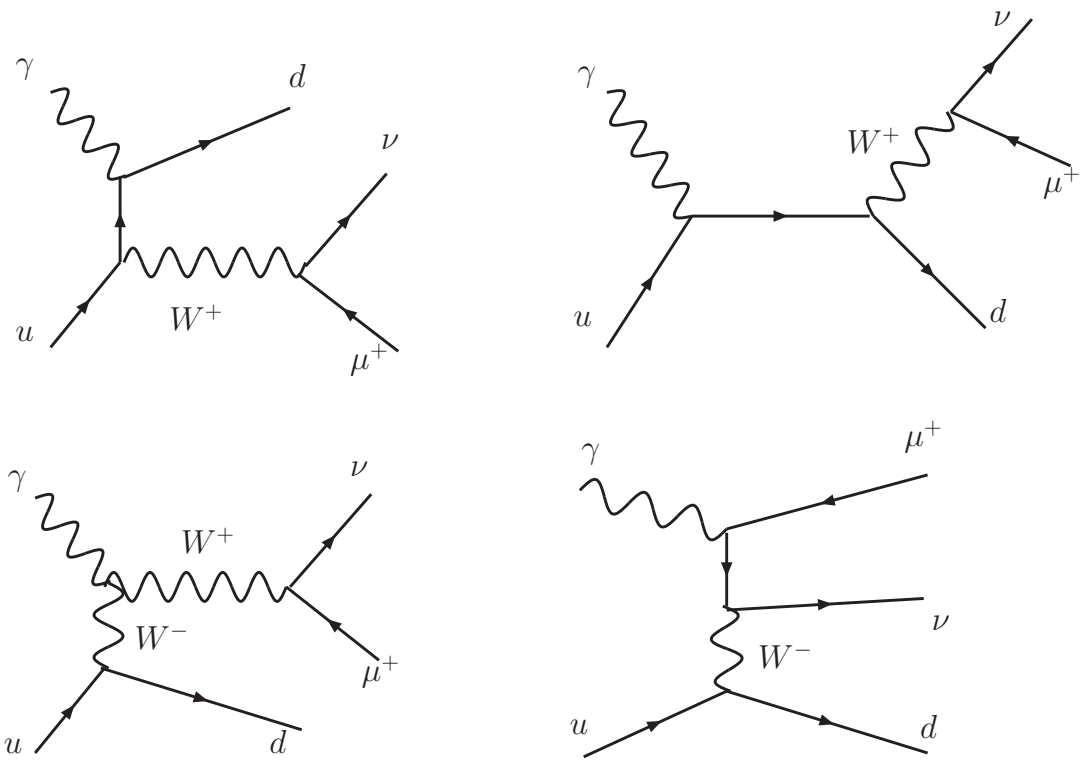
- expanded at O(α), it coincides with the exact NLO result
- the factors F_SV and F_H,i add the corrections missing in the PS approximation

subtraction of IS collinear divergences

- quark masses regularize the IS collinear divergences
- the IS collinear divergences have to be subtracted (in analogy to NLO-QCD), because they are already accounted for in the *pdf* evolution and to cancel the dependence from the unphysical quark masses
- the set MRST 2004 QED includes the QED evolution
- the QED evolution modifies the *pdf*'s by 0.1% for x<0.1
- QED evolution ⇒ photon density in the proton ⇒ photon induced processes

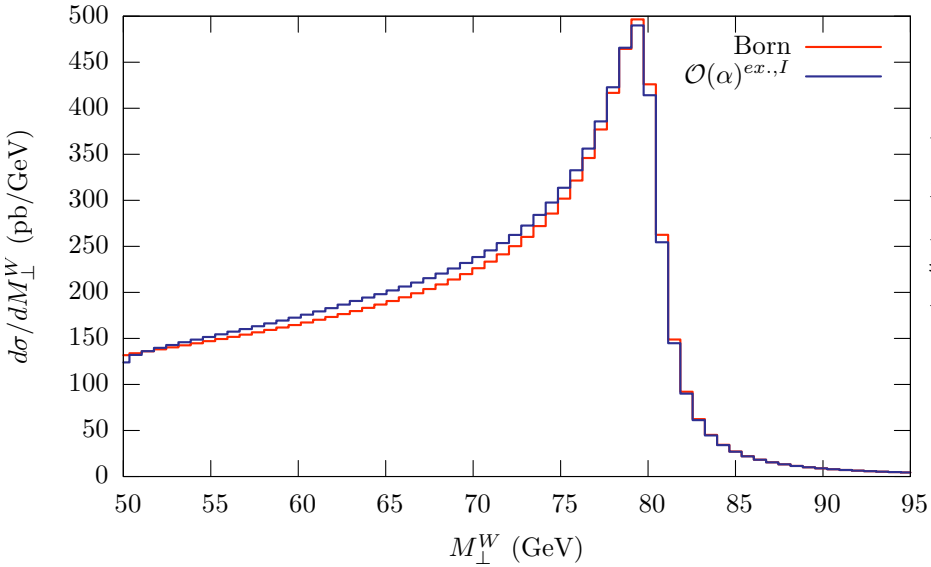
MRST 2004 QED and photon induced processes

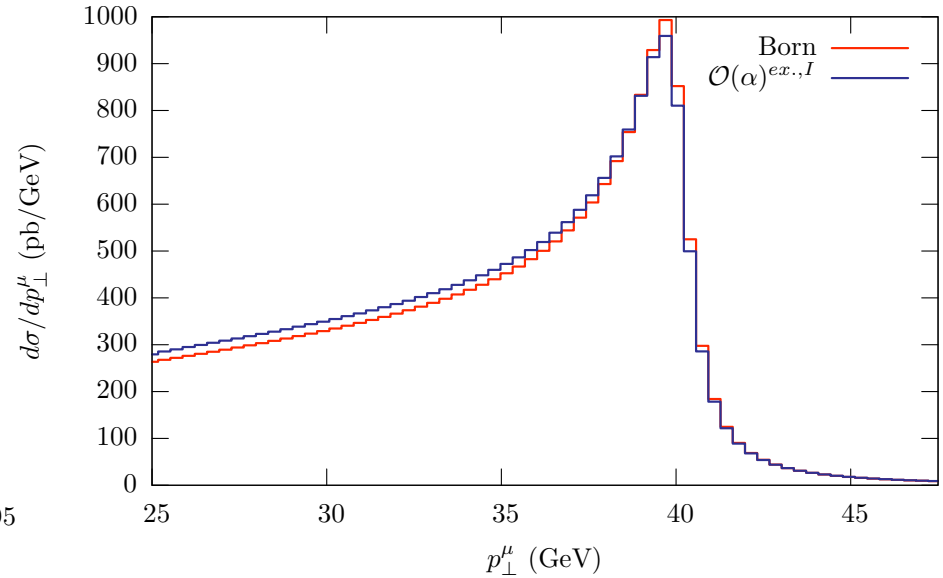
- QED evolution ⇒ photon density in the proton ⇒ photon induced processes
  - $\gamma u \to d\mu^+\nu_\mu$

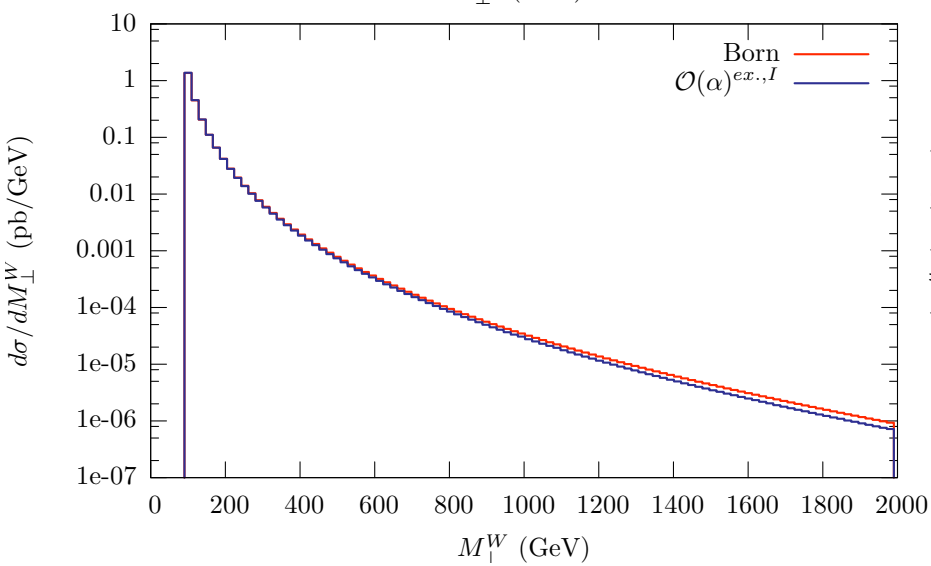


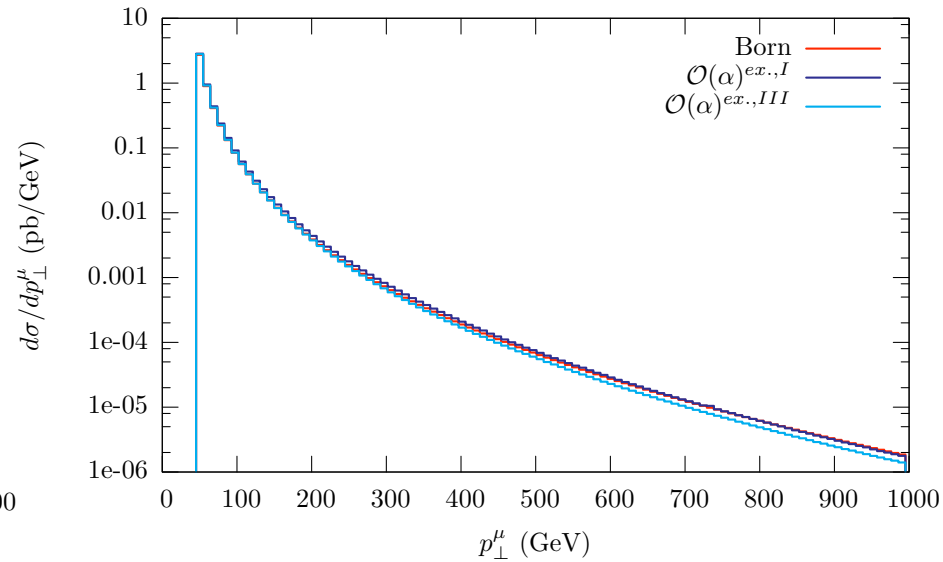
- same perturbative order as the O(α) corrections
- they contribute to the inclusive DY cross section (1 extra jet in the final state)
- depending on the cut on the final state jet, important effect on the lepton transverse momentum distribution

EW results with HORACE:



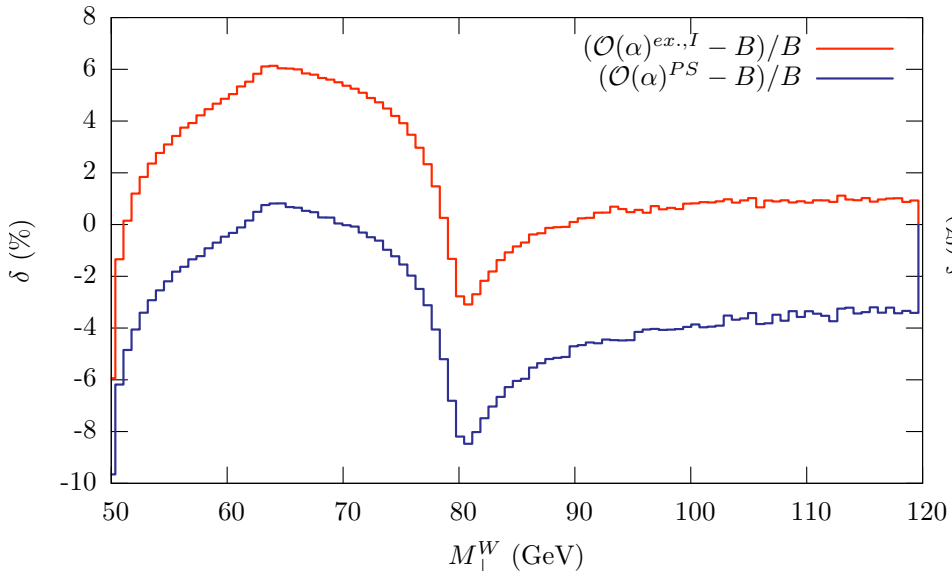


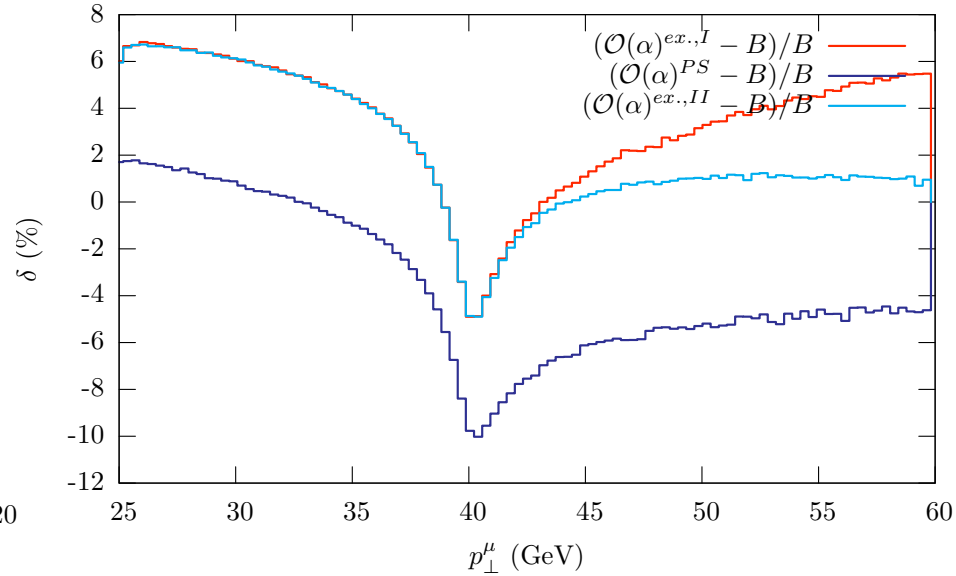


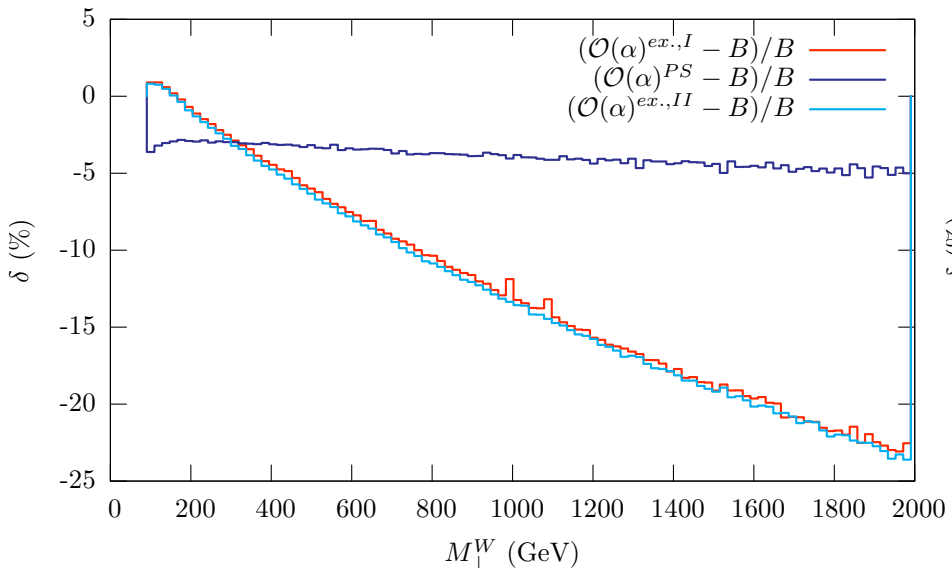


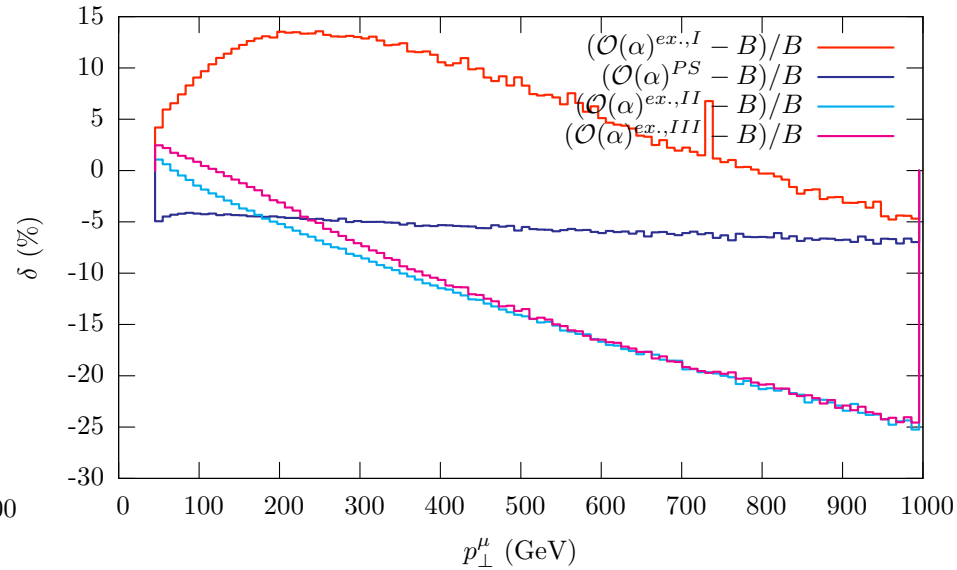
- the transverse mass $M_T^W = \sqrt{2\ p_\perp^l\ p_\perp^\nu\ (1-\cos\phi_{l\nu})}$ has a jacobian peak at MW

EW results with HORACE: relative corrections









- α(0) scheme ⇒ from PS to exact O(α) large effect due to self-energies
- the photon induced processes do not affect the transverse mass distribution (red vs. light blue)
  they change significantly the lepton pt distribution
  they can be suppressed with an appropriate cut on the extra jet (pink vs light blue)