Combining electroweak and QCD corrections to Drell-Yan processes

Carlo M. Carloni Calame

INFN & University of Southampton

Workshop sul Monte Carlo, la Fisica e le Simulazioni a LHC
Frascati, 18-20 February, 2008

Outline

- Relevance of DY processes in precision studies at hadron colliders
- QCD corrections
- Electro-weak radiative corrections (as implemented in **HORACE**)
  - charged-current DY process: single $W^{\pm}$ production
  - neutral-current DY process: single γ/Z production
- Combination EW$\oplus$QCD
- Conclusions

Drell-Yan processes at hadron colliders

- easy detection: high $p_\perp$ leptons pair or lepton+missing $p_\perp$ (tipically look for $p_\perp > 25$ GeV in the central detector region)
- large cross sections. At LHC:
  - $\sigma(W) = 30\ nb$, i.e. 3×10^8 events with $\mathcal{L} = 10\ fb^{-1}$
  - $\sigma(Z) = 3.5\ nb$, i.e. 3.5×10^7 events with $\mathcal{L} = 10\ fb^{-1}$
  - no statistics limitations for precision physics
- main physics motivations (DY processes are considered "standard candles")
  - ⋆ detectors calibration
  - ⋆ PDF validation and constraint
  - ⋆ W mass and Γ measurement
  - ⋆ collider luminosity monitoring (as done at LEP with Bhabha)
  - ⋆ background to New Physics searches
- Precise theoretical prediction are strongly required

Linking theory and experiment

$$\sigma^{\text{exp}} \equiv \frac{1}{\int \mathcal{L} dt} \frac{N^{obs} - N^{bkg}}{A\ \epsilon} =$$

$$\sigma^{\text{theory}} \equiv \sum_{a,b} \int_0^1 dx_1 dx_2 f_{a,H_1}(x_1, \mu_F^2, \mu_R^2) f_{b,H_2}(x_2, \mu_F^2, \mu_R^2) \times$$
$$\times \int_\Phi d\sigma^h_{a,b}(x_1, x_2, Q^2/\mu_F^2, Q^2/\mu_R^2)$$

With DY processes, we can

- ⋆ monitor the collider luminosity, the parton luminosities, measure the PDFs
  - relevant observables: total cross section, W and Z rapidity distribution, lepton(s) rapidity distribution
  - an accuracy of $\mathcal{O}(1\%)$ is required/achievable

Frixione & Mangano '04 and refs. therein

- ⋆ measure the W mass and width from M_T^W distribution
- ⋆ discover deviations from SM physics in the distribution tails

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 exclusive NLO corrections to W/Z production (**MCFM**)

J. M. Campbell and R.K. Ellis, Phys. Rev. **D65** 113007

- fully exclusive 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

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

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

- NLO merged with **HERWIG** Parton Shower [PS] (**MC@NLO**)

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

- NLO merged with any PS (**POWHEG**)

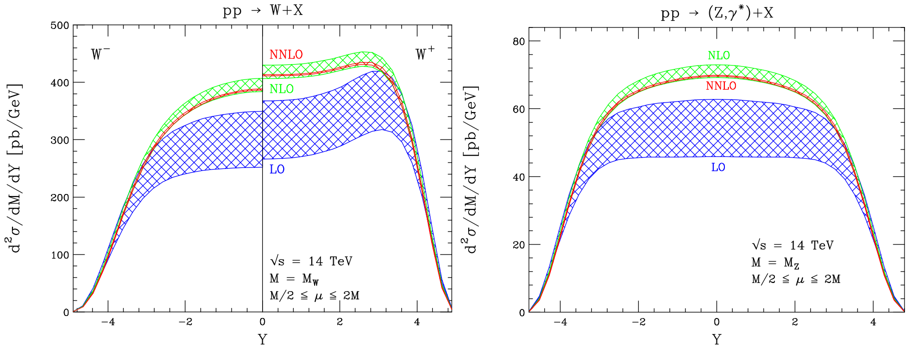
Frixione Nason Ridolfi Oleari

- Matrix elements MC (**ALPGEN**, **SHERPA**,...) matched with PS

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

High-precision QCD: W/Z rapidity @ NNLO

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



- First calculation of a differential distribution at NNLO in α_s. NNLO corrections at $\sim 2\%$ at the LHC and residual scale dependence below 1%.
- $\mathcal{O}(\alpha_S^2) \approx \mathcal{O}(\alpha_{\rm em}) \rightarrow$ need to worry about electroweak corrections!

EW calculations for W & tools

- $\mathcal{O}(\alpha)$ 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.C.C. et al., JHEP 0612:016 (2006) **HORACE**
- Multi-photon radiation
  - → C.M.C.C. et al., PRD **69**, 037301 (2004); JHEP 0612:016 (2006) **HORACE**
  - → S. Jadach, W. Płaczek, EPJC **29** 325 (2003) **WINHAC**

EW calculations for Z

- $\mathcal{O}(\alpha)$ electroweak corrections to Z production
  - ⋆ QED corrections
    - → U. Baur, *et al.*, Phys. Rev. **D57** (1998) 199 (**ZGRAD**)
  - ⋆ Complete $\mathcal{O}(\alpha)$ corrections
    - → U. Baur, *et al.*, Phys. Rev. **D65** (2002) 033007 (**ZGRAD2**)
    - → C.M.C.C. et al, JHEP 0710:109 (2007) (**HORACE**)
    - → Bardin et al., **arXiv:0711.0625 [hep-ph]** (**SANC**)
- Multi-photon radiation
  - → C.M.C.C. et al., JHEP 0505:019 (2005) + JHEP 0710:109 (2007) (**HORACE**)
  - → W. Płaczek et al., in preparation (**ZINHAC**)

NLO EW calculation (in HORACE)

As usual, the (partonic) NLO EW calculation is split into two parts (e.g. W production)

- $u\bar{d} \to \ell^+ \nu_\ell$

$$\mathcal{M}_{2\to 2} = \mathcal{M}_0 + \mathcal{M}_\alpha^{virt}(\lambda)$$

- $u\bar{d} \to \ell^+ \nu_\ell \gamma$

$$\mathcal{M}_{2\to 3} = \mathcal{M}_\alpha^{soft}(\lambda, \Delta E) + \mathcal{M}_\alpha^{hard}(\Delta E)$$

$$|\mathcal{M}_\alpha^{soft}(\lambda, \Delta E)|^2 = \delta^{soft}(\lambda, \Delta E)|\mathcal{M}_0|^2$$

⋆ $2 \to 2$ cross section

$$d\sigma_{2\to 2} = d\sigma_{SV} \propto |\mathcal{M}_0|^2 + 2\Re[\mathcal{M}_0^* \mathcal{M}_\alpha^{virt}(\lambda)] + \delta^{soft}(\lambda, \Delta E)|\mathcal{M}_0|^2$$

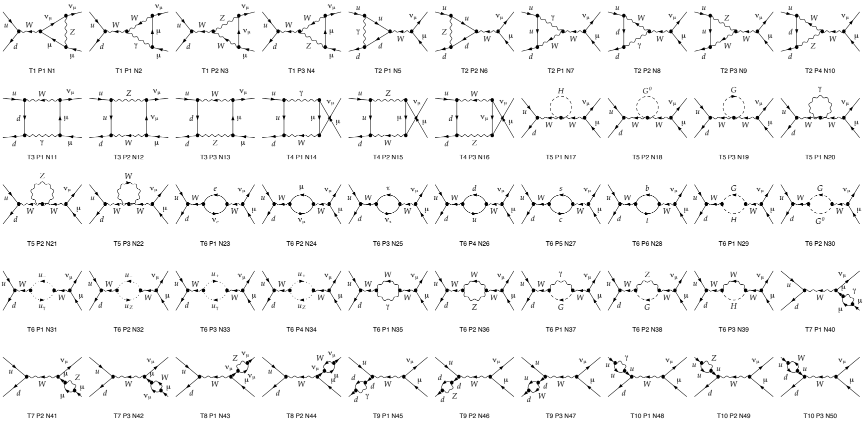
⋆ $2 \to 3$ cross section

$$d\sigma_{2\to 3} = d\sigma_H \propto |\mathcal{M}_\alpha^{hard}(\Delta E)|^2$$

- the phase space integration is performed with MC techniques
- infrared singularities are regularized with a small photon mass λ; collinear ones with a finite (unphysical) quark mass

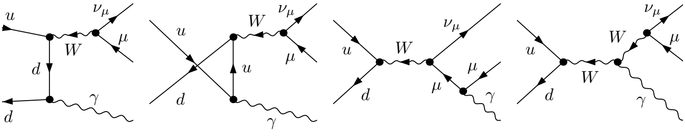
Virtual corrections

- some virtual-correction diagrams, for W production

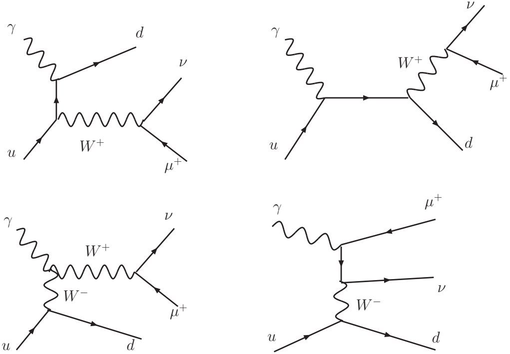


Real corrections

- + real radiation and *photon-induced* (with **MRST2004QED** PDFs) processes diagrams for W...



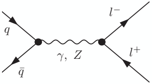
(a)



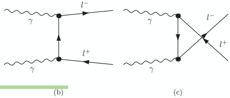
Z NLO diagrams

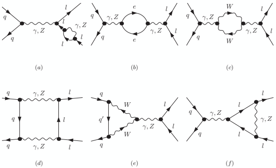
stolen to A. Vicini, seminar at “La Sapienza”, Rome, 8/11/2007

The partonic process $q\bar{q} \to l^+ l^- (1\gamma)$ at $\mathcal{O}(\alpha)$

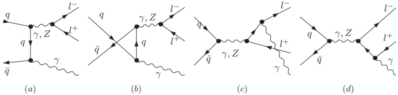


Born

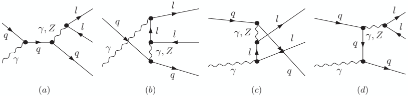




O(alpha) virtual



O(alpha) real bremsstrahlung



O(alpha) photon induced

HORACE: first version

- The Monte Carlo event generator **HORACE** was originally developed to simulate QED multi-photon radiation in DY (W & Z) processes in Leading-Log accuracy, by means of a QED PS. Only final state radiation was accounted for
- as in QCD, the QED PS solves the QED DGLAP equation, allowing for
  - ⋆ inclusion of QED LL corrections up to all orders (resummation)
  - ⋆ fully exclusive event generation (up to ∞ photons)

⋆ the QED PS is very similar to the package **PHOTOS**

→ e.g., by comparing the resummed PS and its $\mathcal{O}(\alpha)$ truncation, the effects purely due to QED higher-orders in the extraction of M_W from $M_\perp^W$ can be disentangled

Matching $\mathcal{O}(\alpha)$ RC with multi-photon radiation

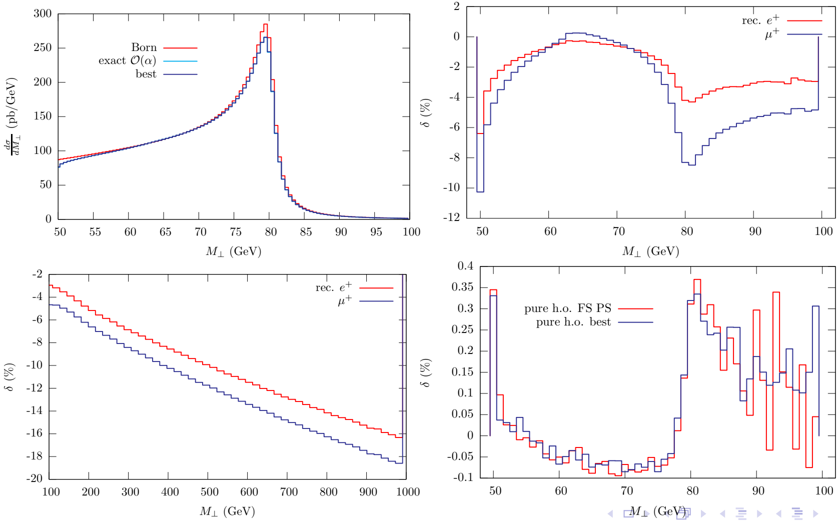
- in the new version of the generator, a matching of the LL QED PS with the exact EW $\mathcal{O}(\alpha)$ calculation is implemented, in order to
  - ⋆ preserve PS advantages (multi-photon effects, exclusive event generation)
  - ⋆ go beyond its approximation (LL accuracy, missing contributions already at $\mathcal{O}(\alpha)$)
- the matching avoids the double counting of $\mathcal{O}(\alpha)$ LL, already accounted for by the PS, and "produces" a formula well suited for Monte Carlo generation

⋆ **http://www.pv.infn.it/hepcomplex/horace.html**

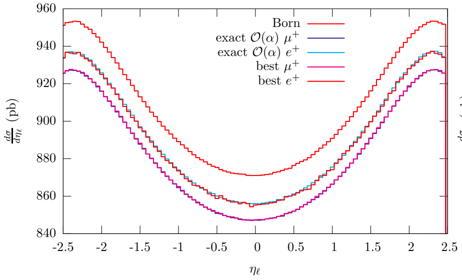
- version 3.1

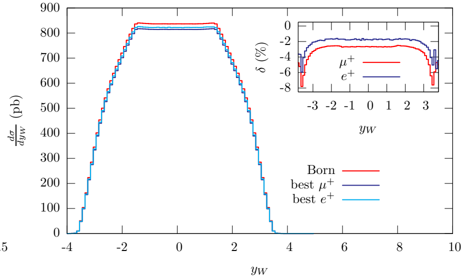
HORACE results for W

- M_T^W distribution, $\mathcal{O}(\alpha)$ effect at peak and in the tail, h.o. QED effects at peak



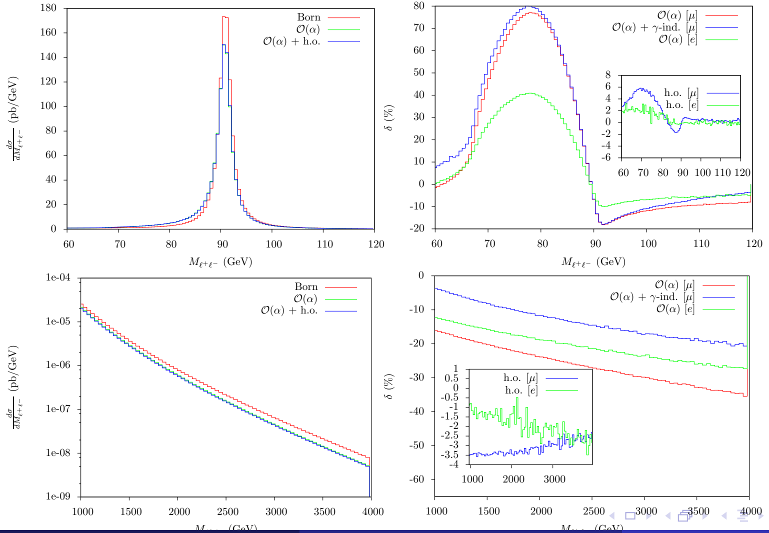
- lepton and W rapidity





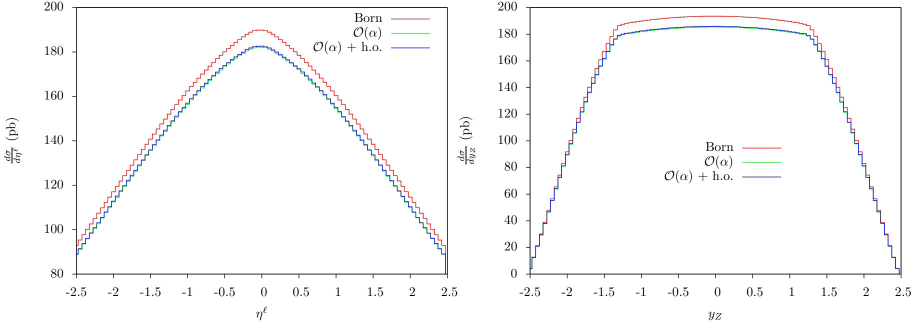
HORACE results for Z

- $M_{\ell^+\ell^-}$ distribution, $\mathcal{O}(\alpha)$ effect at peak and in the tail, h.o. QED effects at peak



HORACE results for Z

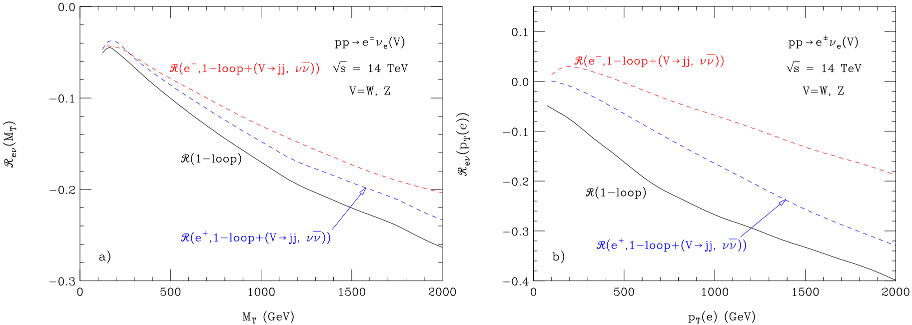
- lepton and Z rapidity



Emission of real weak bosons

U. Baur, Phys. Rev. **D** 75:013005, 2007

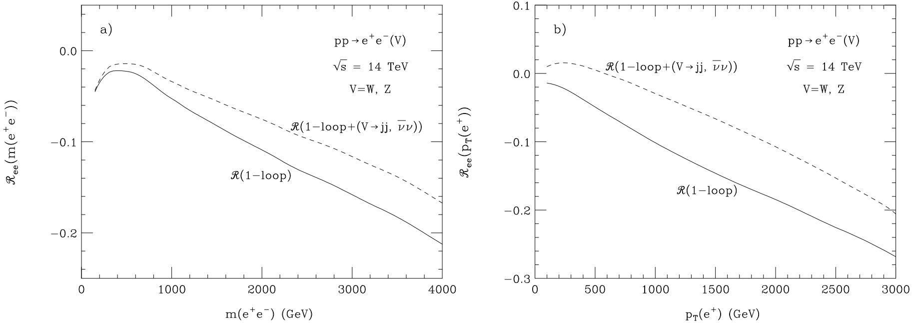
- ⋆ virtual weak corrections induce large negative effects due to Sudakov (logs)^2 in the high Q^2 region
- real radiation of (undetected) real vector bosons (partially) cancels the Sudakov effect
- e.g., $pp \to e^+\nu_e V + X \quad V \equiv W, Z \quad V \to jj, \nu\bar{\nu}, \ldots$



Emission of real weak bosons

U. Baur, Phys. Rev. **D** 75:013005, 2007

- e.g., $pp \to e^+e^-V + X \quad V \equiv W, Z \quad V \to jj, \nu\bar{\nu}, \ldots$



- partial cancellation of Sudakov (logs)^2 by real vector boson radiation

Combining EW and QCD corrections

work in progress: Balossini, CMCC, Montagna, M. Moretti, Nicrosini, Piccinini, Treccani, Vicini

- our exercise (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 ⇒ **MC@NLO**, **ALPGEN** (with PS matching according to MLM prescription, `0+1 jet`, `0+1+2 jets`)
- EW part (**HORACE**) is interfaced to **HERWIG** PS (EW ⊕ QCD LL)
  - ⋆ NLO EW is convoluted with QCD LL parton shower ⇒ $\mathcal{O}(\alpha\alpha_s)$ corrections not reliable where hard non log QCD corrections are important (e.g. high $p_\perp$ lepton distribution without cut on the W transverse 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…

⋆ we consider the charged Drell-Yan process

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

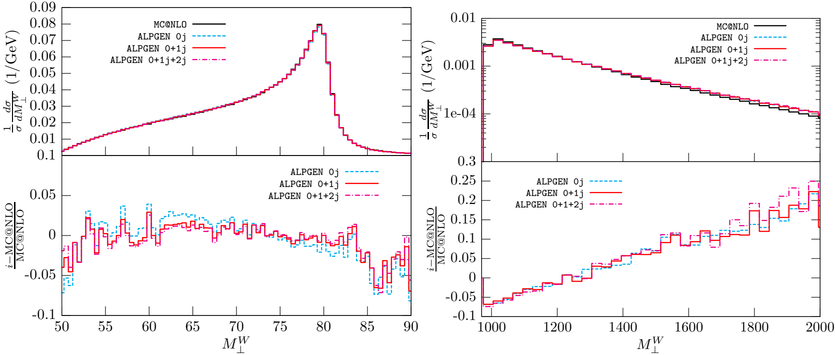
Monte Carlo	ALPGEN	FEWZ	HORACE
$\sigma_{\rm LO}$ (pb)	8310(2)	8304(2)	8307.9(2)

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

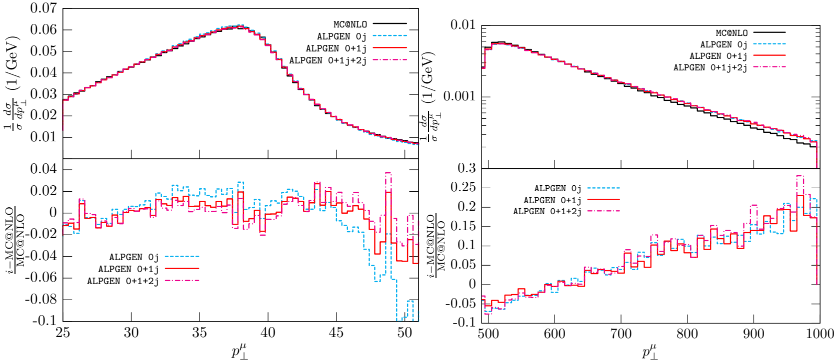
Table: MC tuning for MC@NLO and FEWZ NLO inclusive cross sections of the process $p\overset{(-)}{p} \to W^{\pm} \to \mu^{\pm}\nu_{\mu}$, with CTEQ6M (Tevatron) and MRST2004QED (LHC)

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



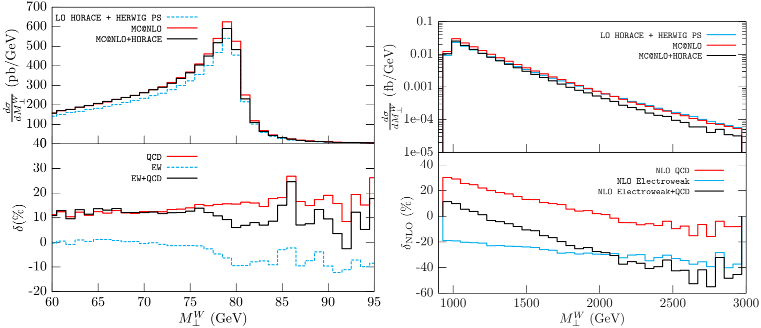
- each distribution normalized to its cross section (shape differences)

QCD @ LHC: $p_\perp^\mu$



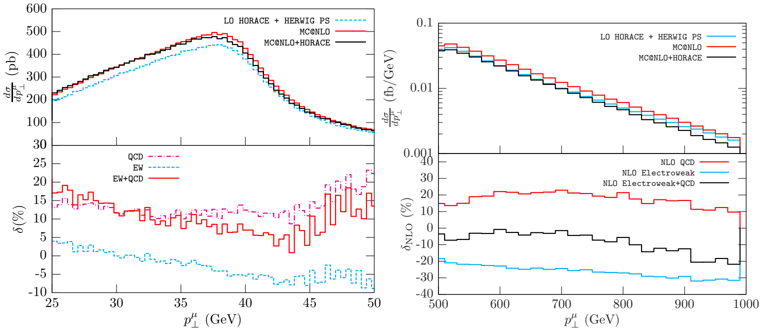
- each distribution normalized to its cross section

⋆ $p_\perp$ distribution obtained requiring $M_T^W > 1$ TeV



- absolute distributions

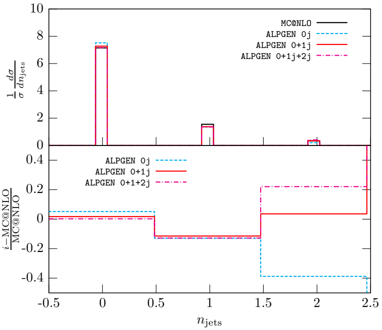
QCD $\oplus$ EW @ LHC: $p_\perp^\mu$

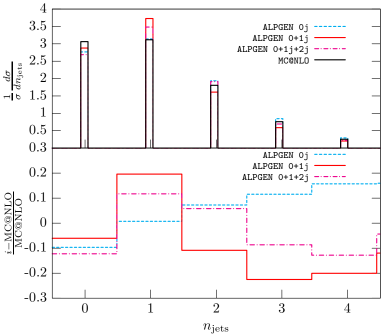


- absolute distributions

⋆ $p_\perp$ distribution obtained requiring $M_T^W > 1$ TeV

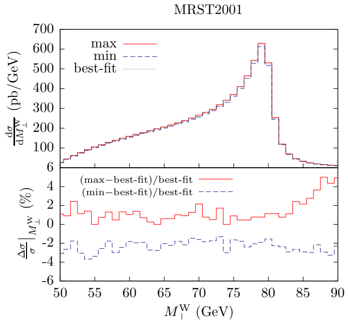
QCD @ LHC: number of jets

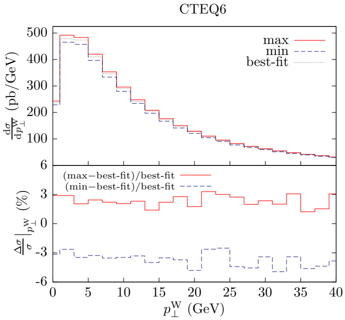




- around the peak
- in the tail

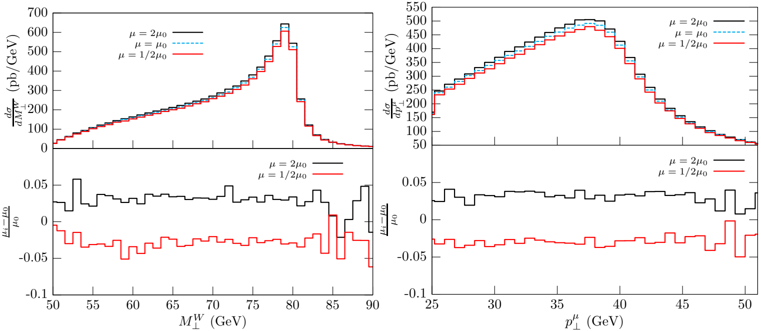
- We are studying PDF's uncertaities using the CTEQ and MRST sets (reflecting only the errors of exp. origin in the PDF parameters)





- 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)

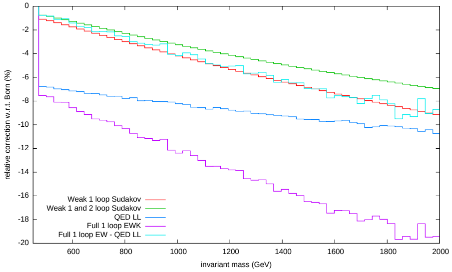
Uncertainties from scale variations

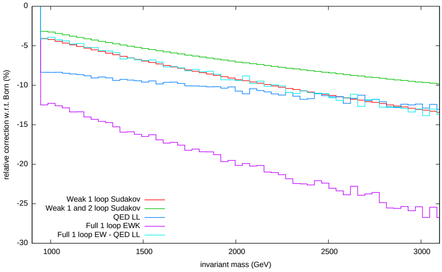


- using MC@NLO

- a similar study on EW⊕QCD is going on also for Z production in the invariant mass tail, in the context of Les Houches 2007
- here we are considering also 2-loop weak Sudakov effects

B. Jantzen, S. Pozzorini





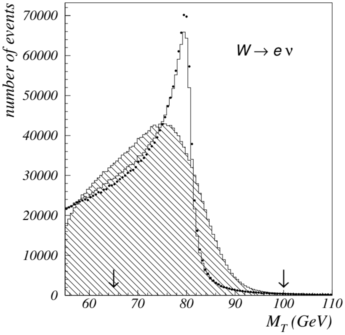
Conclusions

- Drell-Yan processes will be “standard candles” processes at LHC startup
- they’ll help to understand machine & detectors
- and will be used as calibration tools (in particular Z)
- important precision physics can be carried out
  - ⋆ very precise M_W direct measurement
  - ⋆ constraints on PDFs
  - ⋆ precise evaluation of collider luminosity
- they play a key role in the direct and indirect search for BSM physics
- theoretical predictions need to match the required accuracy. All the relevant SM effects and RC have to be well under control
  - ⋆ QCD corrections
  - ⋆ Electro-Weak corrections

BACKUP SLIDES

M_W at Hadron Colliders

- M_W is extracted from the $p_\perp^\ell$ distribution, showing a (Jacobian) peak at $M_W/2$
- more reliable is $M_T^W = \sqrt{2 p_\perp^\ell p_\perp^\nu (1 - \cos\phi_{\ell\nu})}$
  - ⋆ less sensitive to QCD corrections (e.g. $p_\perp^W$)



Future goals for ΔM_W

- ⋆ Tevatron Run II ⇒ 27 MeV
- ⋆ LHC ⇒ 15 MeV

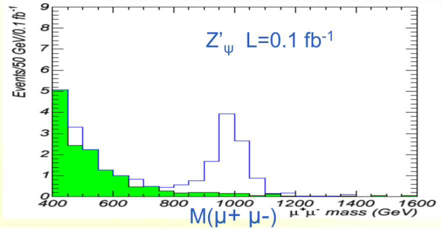
- A small ΔM_W (and Δm_{top}) will constraint the indirect limit on M_H

  $\Delta M_W = 27\ [15]$ MeV and $\Delta m_{top} = 2.7\ [1]$ GeV $\to \Delta M_H / M_H \simeq 35\ [18]\%$

Background to New Physics

DY as background to the searches of new heavy gauge bosons

from Menici's talk at IFAE 2006



- new heavy gauge bosons decay into lepton pairs
- if existing → clear signal even at low luminosity
- if not detected, SM-DY represents the main background whose precise estimate allows to put the correct lower bounds
  → need to control the background at per cent level

Is the SM prediction at large invariant masses under control ?

PS and exact $\mathcal{O}(\alpha)$ matrix elements (at parton level)

Consider the LL [$LL \equiv PS$] resummed, LL $\mathcal{O}(\alpha)$ and exact $\mathcal{O}(\alpha)$ cross sections

- $d\sigma^{\infty}_{LL} = \Pi(Q^2,\varepsilon)\ \sum_{n=0}^{\infty} \frac{1}{n!}\ |\mathcal{M}_{n,LL}|^2\ d\Phi_n$
- $d\sigma^{\alpha}_{LL} = [1 + C_{\alpha,LL}]\,|\mathcal{M}_0|^2 d\Phi_0 + |\mathcal{M}_{1,LL}|^2 d\Phi_1 \equiv d\sigma_{SV}(\varepsilon) + d\sigma_H(\varepsilon)$
- $d\sigma^{\alpha}_{exact} = [1 + C_{\alpha}]\,|\mathcal{M}_0|^2 d\Phi_0 + |\mathcal{M}_1|^2 d\Phi_1$
- $F_{SV} = 1 + (C_\alpha - C_{\alpha,LL}) \qquad F_H = 1 + \frac{|\mathcal{M}_1|^2 - |\mathcal{M}_{1,LL}|^2}{|\mathcal{M}_{1,LL}|^2}$
- $d\sigma^{\alpha}_{exact} \overset{\text{at } \mathcal{O}(\alpha)}{=} F_{SV}(1 + C_{\alpha,LL})|\mathcal{M}_0|^2 d\Phi_0 + F_H|\mathcal{M}_{1,LL}|^2 d\Phi_1$

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

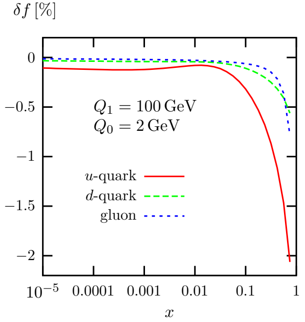
Content of the *matched* formula

- F_{SV} and $F_{H,i}$ are infrared safe and account for missing EW $\mathcal{O}(\alpha)$, avoiding double counting of QED LL
- $\left[\sigma^{\infty}_{matched}\right]_{\mathcal{O}(\alpha)} = \sigma^{\alpha}_{exact}$
- $\sigma^{\infty}_{matched}$ is “made of” exact $\mathcal{O}(\alpha)$ one-loop building blocks
- resummation of higher-order LL contributions preserved
- the cross section is still fully differential in the momenta of the final state particles (including the photons)
- the subtraction of IS mass singularities has to be generalized up to all orders in QED

⋆ successfully applied to W and Z Drell-Yan processes

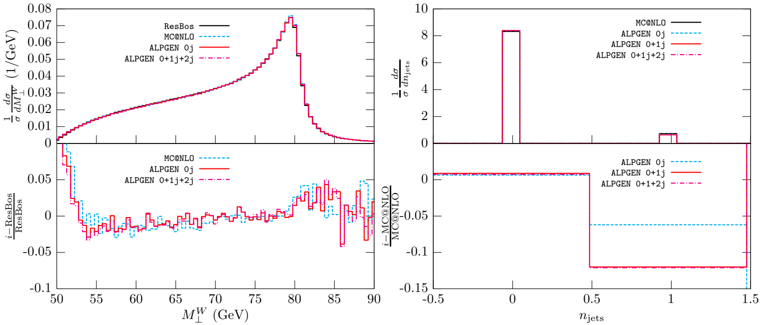
Subtraction of initial state collinear singularities

- 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) includes the QED evolution



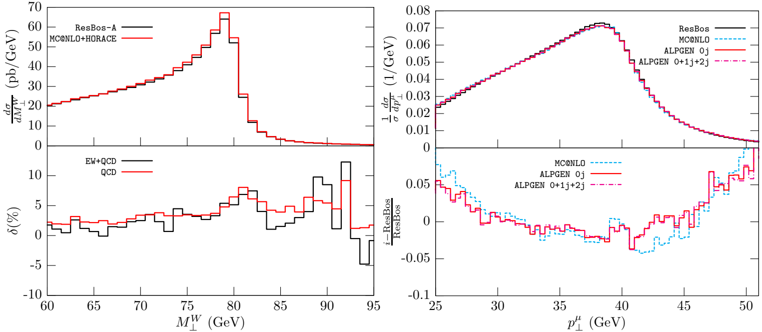
e.g. M. Roth, S. Weinzierl, PLB 590 190 (2004)

- ⋆ QED evolution modifies PDFs at 0.1% level for $x < 0.1$
- ⋆ dynamic generation of photon distr. function. Need to include photon induced processes in DY



ResBos
MC@NLO
ALPGEN 0j
ALPGEN 0+1j+2j
MC@NLO
ALPGEN 0j
ALPGEN 0+1j+2j
$\frac{1}{\sigma}\frac{d\sigma}{dM_\perp^W}$ (1/GeV)
$\frac{i-\text{ResBos}}{\text{ResBos}}$
$M_\perp^W$ (GeV)
MC@NLO
ALPGEN 0j
ALPGEN 0+1j
ALPGEN 0+1j+2j
ALPGEN 0j
ALPGEN 0+1j
ALPGEN 0+1+2j
$\frac{1}{\sigma}\frac{d\sigma}{dn_{\text{jets}}}$
$\frac{i-\text{MC@NLO}}{\text{MC@NLO}}$
n_{jets}

QCD ⊕ EW @Tevatron



PDF's uncertainties @ LHC