Drell-Yan processes at the LHC

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Firenze, October 1st 2007

Outline

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

- Charged Current and Neutral Current processes
  - EW $O(\alpha)$ corrections matched with higher order QED corrections
  - photon induced processes

- impact of the EW corrections on several observables

- preliminary study to extract $M_W$ from the ratio of $W$ and $Z$ distributions

- combining QCD and EW radiative corrections
The Drell-Yan processes

- easy detection
  high pt lepton pair or high pt lepton + missing pt

  typical cuts at the LHC (central detector region)

  \( p_{\perp,l} \) and \( p_{\perp,\nu} > 25 \text{GeV}, \ |\eta_l| < 2.5 \)

- large cross section
  at LHC \( \sigma(W) = 30 \text{ nb} \) i.e. \( 3 \times 10^8 \) events with \( L=10 \text{ fb}^{-1} \)
  at LHC \( \sigma(Z) = 3.5 \text{ nb} \) i.e. \( 3.5 \times 10^7 \) events with \( L=10 \text{ fb}^{-1} \)

  no statistical limitation to perform high precision EW measurements

- \( W \) mass and width
  lepton distributions
  \( W \) transverse mass ratios \( W/Z \) distributions

- pdf validation
  total cross section
  \( W, Z \) rapidity
  lepton pseudo-rapidity acceptances

- detector calibration
  \( W, Z \) mass distributions

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Relevance of a precise $W$ mass measurement

Sensitivity to the precise value of the Higgs boson mass or to SUSY particles
Relevance of a precise W mass measurement

Sensitivity to the precise value of the Higgs boson mass or to SUSY particles

New world average:

- $m_W$ (prel.) [GeV]
- $m_H$ [GeV]

$W$ (prel.) [GeV]

$H$ [GeV]

$M_W$ [GeV]

$M_H$ [GeV]

$Q_W$ [GeV]

Measurement

% $\pm$ 0.02758 $\pm$ 0.00035

$/pm$ 0.118 $\pm$ 0.003

$mt$ = 172.7 $\pm$ 2.9 GeV
Relevance of a precise $W$ mass measurement

Sensitivity to the precise value of the Higgs boson mass or to SUSY particles

To ensure that top and $W$ mass measurements have the same weight in the SM EW fit, the experimental errors should be related as:

$$\Delta m_W \sim 0.7 \times 10^{-2} \Delta m_t$$
Precision measurement of EW observables

**W-Boson Mass [GeV]**

- TEVATRON: 80.429 ± 0.039
- LEP2: 80.376 ± 0.033
- Average: 80.398 ± 0.025
- NuTeV: 80.136 ± 0.084
- LEP1/SLD: 80.363 ± 0.032
- LEP1/SLD/mt: 80.360 ± 0.020

\[ \chi^2/\text{DoF}: 1.1 / 1 \]

**New projection with 1.5 fb^{-1} of data:**
\[ \delta m_W < 25 \text{ MeV} \text{ with CDF} \]

C. Hays, University of Oxford

- \( M_W \) measurement
  - Error target at the LHC: 15 MeV

- \( \Gamma_W \) measurement
  - Error at Tevatron: 87 MeV
  - Error target at the LHC: 30 MeV

- \( \sin^2 \theta_{lep}^{eff} \) measurement
  - World average: 0.23122±0.00015
  - Error target at the LHC: 0.00014
Constraining the pdfs

\[ \int \mathcal{L} dt = \frac{1}{BR(W \rightarrow l\nu)} \frac{1}{\sigma^{\text{th}}(W)} \frac{N_{\text{obs}}}{A_W} \]

the recent set CTEQ6.5 throws some shadows on this approach because of the large (8\%) induced theoretical uncertainties

very promising in the long term (it requires a careful pdfs validation)
The quest for precision (I) i.e. “how do we measure $M_W$”?

- **Detector response effects** strongly affect the distributions
- **QED Final state radiation** distorts the lepton $p_\perp$ and transverse mass distributions, affecting the determination of $M_W$

**transverse mass**

$$M_W^\perp = \sqrt{2p^l_\perp p^\nu_\perp (1 - \cos \phi_{l\nu})}$$

- reconstructed in the transverse plane
- jacobian peak at the $W$ mass
- rather insensitive to QCD initial state radiation (e.g. $p_{TW}$ modeling)

$\mathcal{O}(\alpha)$ corrections:

- *muons* $\Delta M_W = 168 \pm 20$ MeV
- *electrons* $\Delta M_W = 65 \pm 20$ MeV
What is the effect of QED higher orders on the MW extraction?

Shift induced in the extraction of MW from higher order QED effects (very simplified detector for muons and electrons)

\[ \Delta M_W^\alpha = 110 \text{ MeV} \]

\[ \Delta M_W^{exp} = -10 \text{ MeV} \]

In agreement with CDF estimates
S. Malik@DIS2007
QCD approximations and tools

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


- Fully differential NLO corrections to $l\bar{l}'$ (MCFM)


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

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

- resummation of LL/NLL $p_\perp^W/M_W$ logs (RESBOS)


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


- LO 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

\[ \mathcal{O}(\alpha_S^2) \approx \mathcal{O}(\alpha_{\text{em}}) \]

Need to worry about EW corrections

**W production**

- **Pole approximation**
  - D. Wackeroth and W. Hollik, PRD 55 (1997) 6788
  - U. Baur et al., PRD 59 (1999) 013002

- **Exact O(alpha)**
  - V. A. Zykunov et al., EPJC 3 (2001) 9
  - S. Dittmaier and M. Krämer, PRD 65 (2002) 073007
  - C. M. Carloni Calame et al., JHEP 0612:016 (2006)

- **Photon-induced processes**
  - S. Dittmaier and M. Krämer, Physics at TeV colliders 2005

- **Multiple-photon radiation**
  - S. Jadach and W. Placzek, EPJC 29 (2003) 325

**Z production**

- **only QED**
  - U. Baur et al., PRD 57 (1998) 199

- **Exact O(alpha)**
  - U. Baur et al., PRD 65 (2002) 033007
  - V. A. Zykunov et al., PRD 75 (2007) 073019
  - C. M. Carloni Calame et al., to appear

- **Multiple-photon radiation**
  - C. M. Carloni Calame et al., JHEP 0505:019 (2005)

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The HORACE event generator

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

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

- exact $O(\alpha)$ 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
Basics of the HORACE code (both CC and NC channels)

- LO calculation + QED LL corrections to all orders via Parton-Shower
- exact $O(\alpha)$ EW radiative corrections
- matching of Parton-Shower and exact results (no double countings)
- use MRST2004QED: consistent description of initial state QED radiation photon density in the proton $\rightarrow$ photon induced processes
- subtraction procedure of IS collinear divergences to all orders
- The input parameters scheme, i.e. renormalization, $(\alpha, m_W, m_Z)$ $\rightarrow$ gauge boson masses as input parameters which can be fitted from the data
- numerical evaluation in the $G_\mu$ scheme (CC) or $(G_\mu + \alpha(q^2))$ scheme (NC)
Partonic processes at $\mathcal{O}(\alpha)$

$u\bar{d} \rightarrow l^+ \nu_l (1\gamma)$

- virtual corrections
  - checks:
    - UV finiteness
    - IR finiteness (when combined with soft photon emission)
    - use of two different gauges (Feynman and background)
  - fixed W decay width necessary to describe the resonance region
    included in all tree-level propagators and at 1-loop in all the resonant logs:
    \[ \log(s - m_W^2) \rightarrow \log(s - m_W^2 + i\Gamma_W m_W) \]
  - on-shell renormalization scheme
  - large negative EW Sudakov logs

- real bremsstrahlung corrections
  - checks:
    - independence of total cross section of soft/hard separator
    - e.m. gauge invariance
    - initial state collinear logs regulated by quark masses
    - large ISR corrections: radiative return to the W resonance

- photon-induced process: additional IS collinear divergences to be subtracted

$q\bar{q} \rightarrow l^+ l^- (1\gamma)$

- similar computational path as in the CC case
- delicate treatment of the Z decay width in the virtual corrections
- photon-induced process: further additional IS collinear divergences to be subtracted
Matching exact $\mathcal{O}(\alpha)$ and parton-shower results

• **exact** $\mathcal{O}(\alpha)$ partonic cross-section
  \[ d\sigma^{\alpha,ex} \equiv d\sigma_{SV}^{\alpha,ex} + d\sigma_{H}^{\alpha,ex} \]

• **parton-shower (PS) $\mathcal{O}(\alpha)$**
  \[ d\sigma^{\alpha,PS} = \left[ \Pi_S(Q^2) \right]_{\mathcal{O}(\alpha)} d\sigma_0 + \frac{\alpha}{2\pi} P(x) I(x) dx \, dc \, d\sigma_0 \equiv d\sigma_{SV}^{\alpha,PS} + d\sigma_{H}^{\alpha,PS} \]

• **resummed PS**
  \[
  d\sigma_{PS}^\infty = \\
  \Pi_S(Q^2) \sum_{n=0}^{\infty} d\hat{\sigma}_0 \frac{1}{n!} \prod_{i=0}^{n} \left( \frac{\alpha}{2\pi} P(x_i) I(k_i) \, dx_i \, d\cos \theta_i \right)
  \]

\[
\Pi_S(Q^2) \equiv \exp \left( -\frac{\alpha}{2\pi} \log \left( \frac{Q^2}{m^2} \right) \int_0^{1-\varepsilon} dx \, P(x) \right) \quad \text{Sudakov form factor}
\]

\[
I(k_i) = (k_i^0)^2 \sum_{j,l=1}^{N} \eta_j \eta_l \frac{p_j p_l}{(p_j k_i)(p_l k_i)} \quad \text{photon angular spectrum}
\]
Matching exact $\mathcal{O}(\alpha)$ and parton-shower results

- **exact** $\mathcal{O}(\alpha)$ partonic cross-section
  
  $$d\sigma^{\alpha, \text{ex}} \equiv d\sigma^{\alpha, \text{ex}}_{SV} + d\sigma^{\alpha, \text{ex}}_H$$

- **parton-shower (PS) $\mathcal{O}(\alpha)$**
  
  $$d\sigma^{\alpha, \text{PS}} = \left[ \Pi_S(Q^2) \right]_{\mathcal{O}(\alpha)} d\sigma_0 + \frac{\alpha}{2\pi} P(x) I(x) dx \, dc \, d\sigma_0 \equiv d\sigma^{\alpha, \text{PS}}_{SV} + d\sigma^{\alpha, \text{PS}}_H$$

- **resummed PS + exact $\mathcal{O}(\alpha)$**
  
  $$d\sigma_{\text{matched}}^{\infty} =$$
  
  $$\Pi_S(Q^2) F_{SV} \sum_{n=0}^{\infty} d\hat{\sigma}_0 \frac{1}{n!} \prod_{i=0}^{n} \left( \frac{\alpha}{2\pi} P(x_i) I(k_i) \, dx_i \, d\cos \theta_i \, F_{H,i} \right)$$

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

- **at $\mathcal{O}(\alpha)$** it coincides with the exact calculation

- **QED higher orders coincide with pure PS**
The hadronic process $pp(p\bar{p}) \rightarrow \ell\bar{\ell}X$ at $O(\alpha)$

$$\sigma(pp \rightarrow \ell\bar{\ell}X) = \sum_{a, b} \int_0^1 dx_1 dx_2 q_a(x_1)q_b(x_2) \hat{\sigma}(ab \rightarrow \ell\bar{\ell}(1\gamma))$$

$q_a(x) \rightarrow q_a(x, M^2) - \Delta q_a(x, M^2)$

$$\Delta q_i(x, M^2) = \int_x^1 dz \frac{x}{z} Q_i(z) \frac{\alpha}{2\pi} \left[ P_{q\rightarrow q\gamma}(z) \left( \log \frac{M^2}{m_i^2} - 2 \log(1-z) - 1 \right) \right] + f_q(z)$$

$$+ q_{\gamma} \frac{x}{z} Q_i(z) \left[ P_{\gamma\rightarrow q\bar{q}}(z) \left( \log \frac{M^2}{m_{\gamma}^2} \right) \right] + f_{\gamma}(z)$$

$$\Delta q_{\gamma}(x, M^2) = \sum_{i=q, \bar{q}} \int_x^1 dz \frac{x}{z} Q_i(z) \frac{\alpha}{2\pi} \left[ P_{q\rightarrow q\gamma}(z) \left( \log \frac{M^2}{m_i^2} - 2 \log(1-z) - 1 \right) \right] + \bar{f}(z)$$

**Generalization to the multiple emission case:** in each emission the leading singularity is removed the integrated cross-section is independent of the initial state quark masses

Check: Total cross-section for different values of the initial state quark masses (CC channel)

<table>
<thead>
<tr>
<th>Including exact $O(\alpha)$ corrections</th>
<th>Best we can: $O(\alpha)$ matched with parton-shower</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{up}}$</td>
<td>2053.07±0.22 (pb)</td>
</tr>
<tr>
<td>$M_{\text{up}} / 50$</td>
<td>2053.09±0.23 (pb)</td>
</tr>
<tr>
<td>$M_{\text{up}} / 100$</td>
<td>2052.98±0.24 (pb)</td>
</tr>
</tbody>
</table>
MRST 2004 QED and photon induced processes

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

**Charged Current channel**
- same perturbative order as the $O(\alpha)$ corrections
- they contribute to the inclusive DY cross section
- depending on the cut on the final state jet, important effect on the lepton transverse momentum distribution

**Neutral Current channel**
- also new lowest order partonic subprocess

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\[ M_T^W = \sqrt{2 \ p_\perp \ p_\perp' \ (1 - \cos \phi_{\ell \nu})} \]

- reconstructed in the transverse plane
- jacobian peak at the $W$ mass
- rather insensitive to QCD initial state radiation (e.g. ptw modeling)

- recombined electrons show partial KLN cancelation
- bare (i.e. perfectly isolated) muons receive large final state corrections
- insensitive to photon induced processes

relevant for the extraction of MW
W-rapidity and lepton pseudo-rapidity distributions

- relevant for acceptances, luminosity monitoring, 
  *pdfs* constraining
- (flat) correction factor ranges from -2% (W) to -4% (lepton)
- of the same order of present NNLO-QCD uncertainty

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Z observables: invariant mass distribution

- huge radiative corrections below the Z peak (final state radiation)
- in the large mass tail, large negative corrections (EW Sudakov logs)
  not negligible effect of (tree-level) photon-induced subprocess
Z observables: transverse mass and Z rapidity distributions

- above the Z peak, not negligible effect of the photon-induced processes

- Z rapidity: QED h.o. and photon-induced contribute at the per mille level
W/Z transverse mass ratio (preliminary)

\[ R = \left( \frac{d\sigma}{dX_W} \right) / \left( \frac{d\sigma}{dX_Z} \right), \quad X_V = \frac{M_V^\perp}{M_V} \]

- the pQCD radiative corrections partially cancel in the ratio (Giele, Keller, Phys.Rev.D57:4433 (1998))
- the systematics due to the *pdfs* partially cancel in the ratio
- delicate discussion about the systematics on the acceptances
- the EW radiative corrections do not cancel in the ratio
- the ratio is very sensitive to the precise value of \( M_W \)
The Drell-Yan processes and QCD dynamics

- at the LHC the lepton pair is (very often) accompanied by additional jets

<table>
<thead>
<tr>
<th></th>
<th>N=0</th>
<th>N=1</th>
<th>N=2</th>
<th>N=3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron, no cuts</td>
<td>92.1 %</td>
<td>7.6 %</td>
<td>0.3 %</td>
<td></td>
</tr>
<tr>
<td>LHC, no cuts</td>
<td>79 %</td>
<td>15 %</td>
<td>5 %</td>
<td>0.1 %</td>
</tr>
<tr>
<td>LHC, MT&gt;1 TeV</td>
<td>30 %</td>
<td>38 %</td>
<td>21 %</td>
<td>8 %</td>
</tr>
</tbody>
</table>

- at LHC the cross section with N=1 enhanced by the subprocess with a gluon in the initial state (gluon density larger than at the Tevatron)
- the large MT cut forces the showering process (→ enhances N=1,2,3)

LHC parton kinematics

\[
x_{1,2} = \frac{M}{14 \text{ TeV}} \exp(y)
\]

\[
Q = M
\]

\[
x_f^2 = 10 \text{ GeV}^2
\]
Combining QCD and EW corrections

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

• Additive combination of QCD and EW corrections:

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

• $QCD = \text{ALPGEN}$ (with CKKM-MLM Parton Shower matching), ResBos-CSS, MC@NLO, FEWZ, MCFM

• $EW = \text{HORACE}$ interfaced with HERWIG QCD Parton Shower

  NLO-EW corrections convoluted with QCD PS $\Rightarrow$ 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


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Monte Carlo tuning: Tevatron and LHC

<table>
<thead>
<tr>
<th>Monte Carlo</th>
<th>ALPGEN</th>
<th>FEWZ</th>
<th>HORACE</th>
<th>ResBos-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{LO}$ (pb)</td>
<td>906.3(3)</td>
<td>906.20(16)</td>
<td>905.64(4)</td>
<td>905.26(24)</td>
</tr>
</tbody>
</table>

**Table:** MC tuning at the Tevatron for the LO cross section of the process $p\bar{p} \rightarrow W^\pm \rightarrow \mu^\pm \nu_\mu$, using CTEQ6M with $\mu_R = \mu_F = \sqrt{x_1 x_2 s}$

<table>
<thead>
<tr>
<th>Monte Carlo</th>
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<th>FEWZ</th>
<th>HORACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{LO}$ (pb)</td>
<td>8310(2)</td>
<td>8304(2)</td>
<td>8307.9(2)</td>
</tr>
</tbody>
</table>

**Table:** MC tuning at the LHC for the LO cross section of the process $pp \rightarrow W^\pm \rightarrow \mu^\pm \nu_\mu$, using MRST2004QED with $\mu_R = \mu_F = \sqrt{p_{\perp,W}^2 + M_W^2}$

<table>
<thead>
<tr>
<th>Monte Carlo</th>
<th>$\sigma_{NLO}^{Tevatron}$ (pb)</th>
<th>$\sigma_{NLO}^{LHC}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC@NLO</td>
<td>2638.8(4)</td>
<td>20939(19)</td>
</tr>
<tr>
<td>FEWZ</td>
<td>2643.0(8)</td>
<td>21001(14)</td>
</tr>
</tbody>
</table>

**Table:** MC tuning for MC@NLO and FEWZ NLO inclusive cross sections of the process $(pp) \rightarrow W^\pm \rightarrow \mu^\pm \nu_\mu$, 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+EW @ the LHC: \( M_W \) and \( p_{\mu}^{\perp} \) distributions

- the relative effect expressed in units Born+PS
- positive QCD corrections compensate negative EW corrections
- around the jacobian peak EW corrections mandatory to extract 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: $M^W_W$ and $p^\mu_\perp$ distributions

$M^W_W > 1$ TeV, $p^\mu_\perp > 500$ GeV

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

- the relative effect expressed in units Born+PS
- negative QCD corrections sum up with negative EW corrections
- the sum $\sim -40(-70)\%$ for $M^W_W \simeq 1.5(3)$ TeV and $\sim -30(-50)\%$ for $p^\mu_\perp \simeq 0.5(1)$ TeV

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Firenze, October 1st 2007
Conclusions

• the event generator **HORACE** contains almost the state of the art of EW corrections to CC and NC Drell-Yan processes

• a detailed phenomenological analysis demonstrates the **impact of the EW corrections** on several distributions and, in turn, on the measurement of several observables
  - acceptances : pdfs, luminosity
  - transverse mass : measurement of $M_W$ (limits on Higgs, MSSM)

• a realistic description of the Drell-Yan processes requires the combination of **QCD and EW** corrections (possibly in a unified generator)
  - the interplay of the two sets of corrections is not trivial
  - the QCD-Parton Shower provides the correct lowest order approximation of the kinematics of these processes and modifies the impact of the EW corrections

• the ratio of $W/Z$ $M_T$ distributions to extract the $W$ mass is under study

• in the long term: unify ALPGEN and HORACE in a single generator
Back-up slides
Electroweak results with HORACE

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

$pdf$: MRST2004QED

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

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

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

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