Drell–Yan processes with WINHAC

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Outline

Drell–Yan processes

- Charged-current DY process – single-$W^{\pm}$ production:

$$h_1 + h_2 \quad \longrightarrow \quad W^{\pm} + X \quad \longrightarrow \quad l^{\pm} + \overset{(-)}{\nu_l} + X\,,$$

- Neutral-current DY process – single-Z/γ production:

$$h_1 + h_2 \quad \longrightarrow \quad Z/\gamma + X \quad \longrightarrow \quad l^- + l^+ + X\,,$$

where $l = e,\, \mu$ and $h_1, h_2 \in \{p, \bar{p}, N\}$.

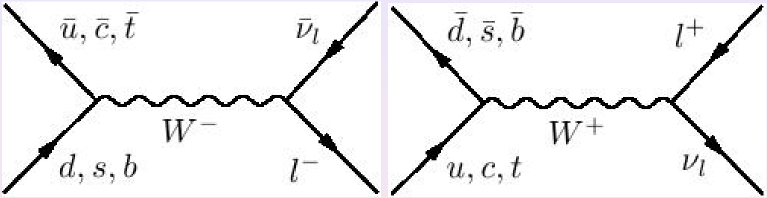
Cross section – factorization formula:

$$\sigma = \sum_{a,b} \int dx_1 dx_2\, f_{a/h_1}(x_1, Q^2)\, f_{b/h_2}(x_2, Q^2)\, \hat{\sigma}_{ab}(Q^2)\,,$$

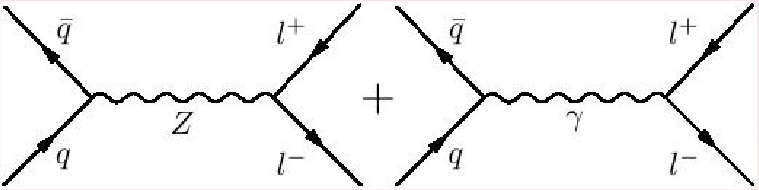
where $a, b \in \{g, d, \bar{d}, u, \bar{u}, s, \bar{s}, c, \bar{c}, b, \bar{b}\}$ – parton flavours;
$f_{a/h}(x, Q^2)$ – the parton distribution function (PDF) of a parton a in a hadron h for the Bjorken x and hard-process scale Q^2;
$\hat{\sigma}_{ab}(Q^2)$ – the parton-level cross section for the hard process.

Parton-level Feynman diagrams

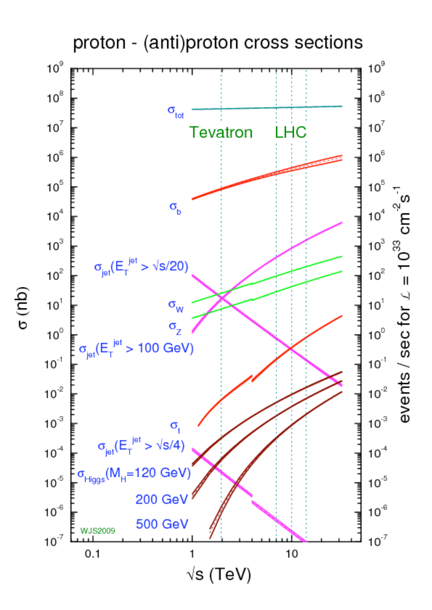
- Charged currents: W^- & W^+



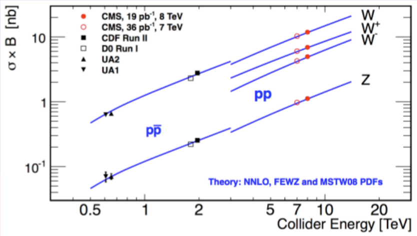
- Neutral currents: $Z + \gamma$



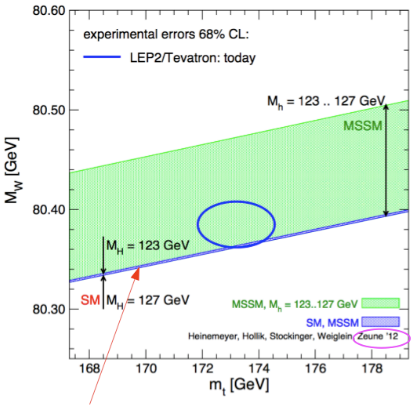
- To improve precision of some Standard Model (SM) parameters, in particular $M_W,\ \Gamma_W,\ \sin^2\theta_W$.
  ▷ PDG 2012: $\delta M_W = 15\,\mathrm{MeV}, \quad \delta\Gamma_W = 42\,\mathrm{MeV}$,
  while: $\delta M_Z = 2.1\,\mathrm{MeV}, \quad \delta\Gamma_Z = 2.3\,\mathrm{MeV}$.
  $\rightarrow\ \delta(M_{W^+} - M_{W^-}) = 600\,\mathrm{MeV}!$
- To get better **indirect** estimate of the **Higgs-boson mass**
  ▷ From SM fits
  $\rightarrow$ Requirements: $\delta M_W \approx 0.007\delta m_t$ (for equal weights in χ^2 tests)
  $\Rightarrow$ **LHC: $\delta M_W \sim 5\,\mathrm{MeV}$** $(\delta M_W/M_W < 0.01\%)$
- For **consistency tests** of SM at higher precision levels.
- To search for **new physics**, e.g. W', Z' or other extra vector bosons.
- Important **"standard candle"** processes $\rightarrow$ normalisation, calibration, PDF fits, etc.
- **Background** for other processes (both SM and BSM) – due to large cross sections.



LHC: $\sigma_{W^+} > \sigma_{W^-}$ $(f_u > f_d$ in $pp)$

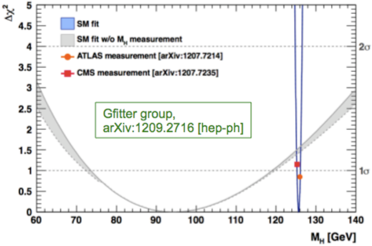


W boson mass



In the context of the standard model, the mass of the new boson discovered by ATLAS+CMS is inside this blue band.

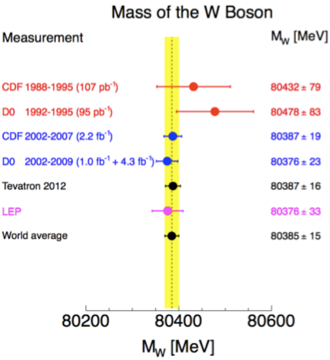
Comparison of indirect constraints on the Standard Model Higgs boson and the direct measurements of the mass of the new boson discovered by ATLAS and CMS:



Consistent at the 1.3 σ level.

W boson mass

Current state of the art:



Projections:

DØ: analyse full data set
significantly extend eta coverage
=> 15 MeV uncertainty
(not including improvements in PDFs)

CDF: analyse full dataset
=> 10 MeV uncertainty
(including improvements in PDFs;
which are expected from
measurements of W charge asymmetry)

LHC: 10 MeV to 5 MeV, ultimately

Current measurements of boson p_T, rapidity spectra
W charge asymmetry,
W+c jet (c.f. QCD plenary on Wednesday), ...
are critical steps toward this goal.

The next "quantum leap" in precision could come from a machine like e.g. TLEP (0.5 MeV uncertainty).

Observables, methods and cuts

- **One of the *W* decay products is neutrino which escapes detection!**
  $\Rightarrow$ One has to rely on observables in the transverse plane w.r.t. beam directions.
- Observables most sensitive to M_W:
  1. Transverse momentum of *W*-decay charged lepton:

$$p_T^l = \sqrt{(p_x^l)^2 + (p_y^l)^2}$$

  2. *W*-boson transverse mass:

$$m_T^W = \sqrt{2 p_T^l \, p_T^\nu \, (1 - \cos \Delta\phi_{l\nu})},$$

where $\vec{p}_T^{\,\nu}$ is reconstructed using '**hadronic recoil**' against *W* in the transverse plane **– difficult at LHC!?**.

- p_T^l distribution for on-shell W production (i.e. $\Gamma_W = 0$):

$$\frac{d\sigma}{\sigma\, dp_T^l} = \frac{6p_T^l}{M_W^2}\left[1 - \left(\frac{\sqrt{2}p_T^l}{M_W}\right)^2\right]\left[1 - \left(\frac{2p_T^l}{M_W}\right)^2\right]^{-\frac{1}{2}},$$

$\Rightarrow$ Jacobian peak at: $\boxed{p_T^l = \frac{1}{2}M_W}$ (smeared a bit by $\Gamma_W > 0$)

- Similar peak in W transverse mass distribution for:

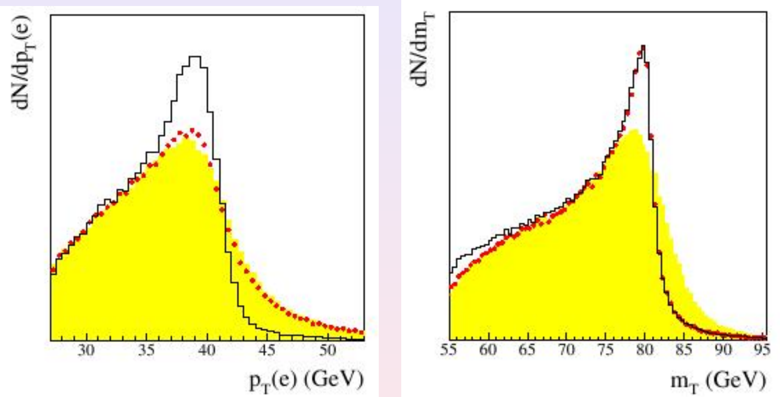
$$m_T^W = M_W.$$

- Typical detection/selection cuts for ATLAS and CMS:

$$p_T^l > 20\,\mathrm{GeV}, \quad |\eta_l| < 2.5, \quad E_T^{\mathrm{miss}} > 25\,\mathrm{GeV}.$$

Observables, methods and cuts

- $p_T^W > 0$ and detectors resolution effects on p_T^l and m_T^W:



solid line: $p_T^W = 0$,

red dots: $p_T^W > 0$ **(mainly QCD ISR effects)**,

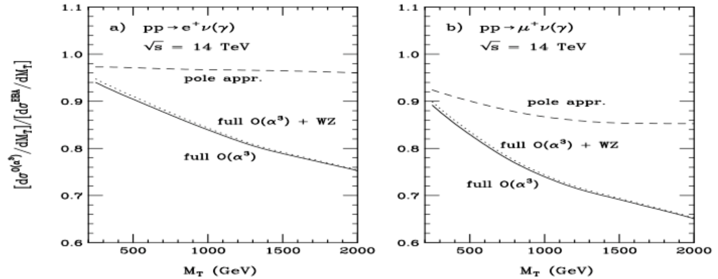
yellow area: $p_T^W > 0$ + **detector resolution effects**.

EW effects

- Dominant effects due to QED final-state radiation (FSR):
  - FSR $\mathcal{O}(\alpha)$ corrections $\Rightarrow$ $\Delta M_W > 100\,\text{MeV}$,
  - FSR exponentiation beyond $\mathcal{O}(\alpha)$ $\Rightarrow$ $\Delta M_W \sim 10\,\text{MeV}$.

  $\rightarrow$ see e.g. C.M. Carloni Calame et al., hep-ph/0303102.
- Are other EW corrections important for $\delta M_W \simeq 5\,\text{MeV}$ precision? $\rightarrow$ to be assessed for concrete experimental measurement methods!

▷ EW corrections beyond QED FSR are sizeable for high p_T^l and high m_T^W values $\rightarrow$ BSM searches!



(U. Baur & D. Wackeroth, hep-ph/0405191)

▷ WP and S. Jadach, EPJ **C39** (2003) 325; WP, PoS **EPS-HEP2009** (2009) 340.
→ http://cern.ch/placzek/winhac

Monte Carlo event generator for **Drell–Yan processes** in **proton–proton**, **proton–antiproton**, **proton–nucleus** and **nucleus–nucleus** collisions:

- mainly for **charged-current processes** (with $W^{\pm}$),
- includes also **neutral-current processes** (with $Z+\gamma$).

→ **Main options:**

- **weighted** or **unweighted** (weight=1) events possible;
- for weighted events **parallel weights** can be computed – corresponding to various contributions/effects/corrections, PDF errors – in a single run;
- **polarised** W-bosons (L, T, left, right) in various frames;
- various EW parameter options: fixed or running W/Z-boson width, α-scheme or G_μ-scheme, etc.

QED effects

- $\mathcal{O}(\alpha)$ **Yennie–Frautshi–Suura (YFS) exclusive exponentiation** for:
  a) **FSR** (final-state radiation),
  b) **FSR** $+$ **IFI** (initial-final interferences),

  in **charged-current DY processes** (with $W^{\pm}$).

  → Multiphoton radiation.
  → Precise description of one hard and arbitrary many soft photons.
  → Two and more hard photons described less precisely, but generated.
  ▷ **ISR** (initial-state radiation) subtructed in a gauge-invariant way ('YFS scheme') – to be generated by parton-shower MC (PYTHIA, HERWIG, etc.) together with QCD effects.

- Multiphoton **FSR** generated by **PHOTOS** in **neutral-current DY processes** (with $Z + \gamma$).[1]

  → Resummation of LL effects improved with ME corrections.

[1] Also possible for charged-current DY processes.

EW corrections

- $\mathcal{O}(\alpha)$ EW corrections from **SANC** system (D. Bardin et al.) included within YFS exponentiation scheme in two versions:
  - a) for W decays only,
  - b) for full charged-current DY process.
- Possibility of splitting full EW corrections into (and computing, e.g. through parallel weights):
  - a) “QED-like” corrections,
  - b) “weak” correctios.

  in a gauge-invariant way.

$\longrightarrow$ D. Bardin, S. Bondarenko, S. Jadach, L. Kalinovskaya, WP, Acta Phys. Polon. **B40** (2009) 75.

- **Parton-level CC DY process:**

$$q_1(p_1)+\bar{q}_2(p_2) \longrightarrow W^{\pm}(Q) \longrightarrow l(q_l)+\nu(q_\nu)+\gamma(k_1)+\ldots+\gamma(k_n),\; n \geq 0.$$

- $\mathcal{O}(\alpha)$ Yennie–Frautschi–Suura (YFS) exponentiation:

$$\sigma^{\rm tot}_{\rm YFS} = \sum_{n=0}^{\infty} \int \frac{d^3 q_l}{q_l^0} \frac{d^3 q_\nu}{q_\nu^0} \rho_n^{(1)}(p_1,p_2,q_1,q_2,k_1,\ldots,k_n),$$

where

$$\rho_n^{(1)}(p_1,p_2,q_1,q_2,k_1,\ldots,k_n) = e^{Y(p_1,p_2,q_l;k_s)} \frac{1}{n!} \prod_{i=1}^{n} \frac{d^3 k_i}{k_i^0} \tilde{S}(p_1,p_2,q_l,k_i)\,\theta(k_i^0-k_s)$$

$$\delta^{(4)}\left(p_1+p_2-q_l-q_\nu-\sum_{i=1}^{n} k_i\right)\left[\bar{\beta}_0^{(1)}(p_1,p_2,q_l,q_\nu)+\sum_{i=1}^{n}\frac{\bar{\beta}_1^{(1)}(p_1,p_2,q_l,q_\nu,k_i)}{\tilde{S}(p_1,p_2,q_l,k_i)}\right]$$

- **Non-IR** YFS functions:
  1. **Virtual** EW correctios:

$$\bar{\beta}_0^{(1)}(p_1,p_2,q_l,q_\nu) = \bar{\beta}_0^{(0)}(p_1,p_2,q_l,q_\nu)\left[1+\delta^{(1)}_{\rm EW}(p_1,p_2,q_l,q_\nu)\right]$$

  2. **Real-photon** corrections: $\bar{\beta}_1^{(1)}(p_1,p_2,q_l,q_\nu,k)$

- Interface through **Les Houches Accord** (LHA) file format to QCD/QED parton shower (PS) generator PYTHIA 6.4 (or any other PS generator using this format).
  a) ordinary disk files can be used,
  b) UNIX named (FIFO) pipes instead of files can be used: faster (communication through RAM), simpler (generation in a single run), no disk-space overloading, no need to manage temporary files, high statistics easily generated.
- **Internal** inferface to PYTHIA 6.4 (PYTHIA routines called directly from WINHAC code) – faster:
  - $*$ less universal (for some limited PYTHIA set-up),
  - – but useful for some dedicated studies,
    - ▷ see: M.W. Krasny et al., EPJ **C69** (2010) 379 and refs. therein,
  - – includes correction for PYTHIA6 transverse lepton momenta distributions $\rightarrow$ good agreement with MC@NLO,
    - ▷ see: M.W. Krasny and WP, Acta Phys. Polon. **B43** (2012) 1981.

Cross-checks

- Comparisons with MC event generator **HORACE** at $\mathcal{O}(\alpha)$ and with higher-order corrections (exponentiation, LL-resummation)
  - $\longrightarrow$ agreement at the level 0.1% or better for total cross sections as well as for distributions.
  - ▷ C.M. Carloni Calame, S. Jadach, G. Montagna, O. Nicrosini and WP, Acta Phys. Polon. **B35** (2004) 1643.
- Comparisons with **SANC** MC integrator (based on VEGAS) at $\mathcal{O}(\alpha)$
  - $\longrightarrow$ agreement below 0.1% for total cross sections as well as for distributions for "YFS-like" ISR-subtraction scheme.
  - ▷ D. Bardin, S. Bondarenko, S. Jadach, L. Kalinovskaya, WP, Acta Phys. Polon. **B40** (2009) 75.

Cross-checks

Total cross sections and $\mathcal{O}(\alpha)$ EW corrections:

LHC, $pp \to W^+ + X \to e^+\nu_e + X$						
	α-scheme			G_μ-scheme		
	LO [pb]	NLO [pb]	$\delta_{\rm EW}$ [%]	LO [pb]	NLO [pb]	$\delta_{\rm EW}$ [%]
SANC-$\overline{\rm MS}$	5039.19(2)	5139.33(5)	1.987(1)	—	—	—
SANC-YFS	5039.19(2)	5137.53(3)	1.952(1)	5419.18(2)	5208.48(3)	−3.888(1)
WINHAC	5039.06(11)	5138.04(16)	1.966(3)	5419.04(12)	5209.04(12)	−3.874(3)

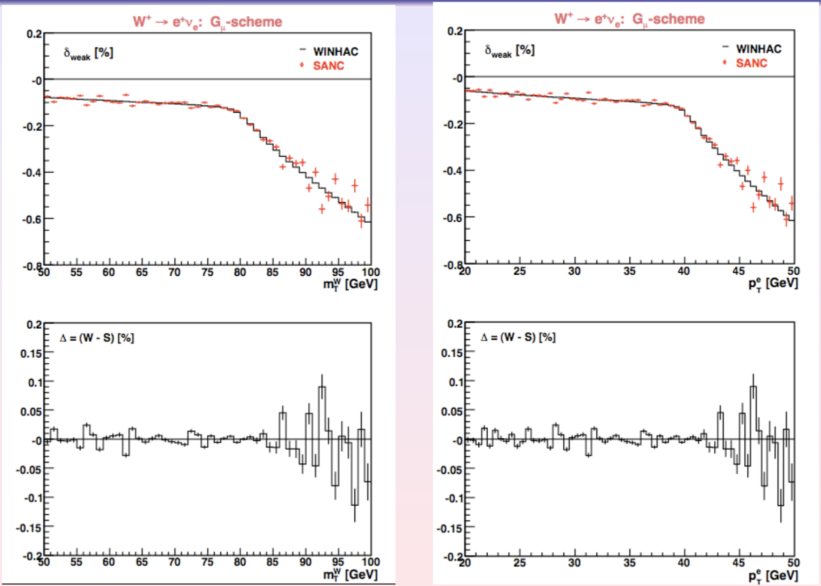
LHC, $pp \to W^+ + X \to \mu^+\nu_\mu + X$						
	α-scheme			G_μ-scheme		
	LO [pb]	NLO [pb]	$\delta_{\rm EW}$ [%]	LO [pb]	NLO [pb]	$\delta_{\rm EW}$ [%]
SANC-$\overline{\rm MS}$	5039.20(2)	5229.58(6)	3.778(1)	—	—	—
SANC-YFS	5039.20(2)	5227.73(2)	3.741(1)	5419.19(2)	5305.47(3)	−2.098(1)
WINHAC	5039.03(11)	5227.87(14)	3.745(2)	5419.01(12)	5305.59(14)	−2.094(2)

$$\delta_{\rm weak} = \delta^{\rm EW}_{\rm softvirt} - \delta^{\rm YFS}_{\rm softvirt}\,, \qquad \delta^{\rm YFS}_{\rm softvirt} = \delta^{\rm YFS}_{\rm ISR} + \delta^{\rm YFS}_{\rm Int} + \delta^{\rm YFS}_{\rm FSR}\,,$$

where $\delta^{\rm YFS}_{\rm softvirt}$ – gauge-invariant dominant QED corrections.

$\delta_{\rm weak}$ [%]		
LHC, $pp \to W^+ + X \to e^+\nu_e + X$		
	α-scheme	G_μ-scheme
SANC	5.7223(2)	−0.1175(2)
WINHAC	5.7220(3)	−0.1177(0)
LHC, $pp \to W^+ + X \to \mu^+\nu_\mu + X$		
	α-scheme	G_μ-scheme
SANC	5.7286(2)	−0.1109(2)
WINHAC	5.7220(2)	−0.1177(0)

Cross-checks



▷ Change of slopes at $m_T^W \approx 80\,\text{GeV}$ and $p_T^l \approx 40\,\text{MeV}$ $\rightarrow \Delta M_W$?

Set-up as defined by EWWG for EW precision measurements at the LHC, CERN, October 9, 2012:

(comparisons of various programs under way)

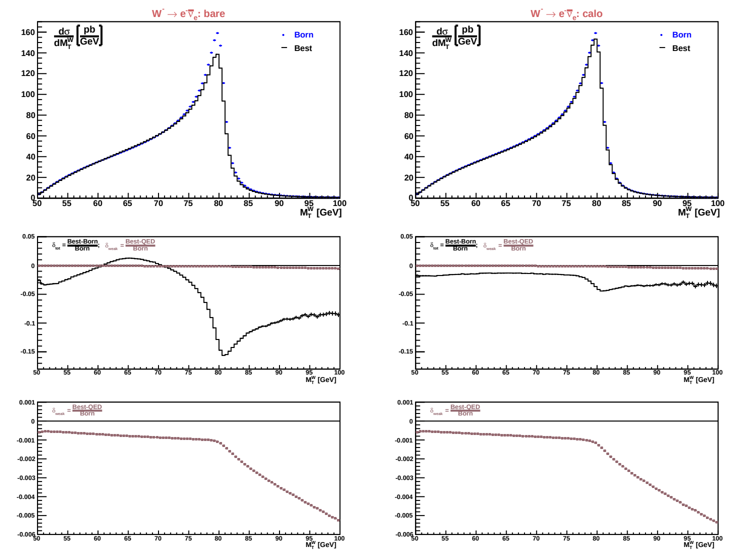
- $\sqrt{s} = 8\,\mathrm{TeV}$,
- $p_T^l > 25\,\mathrm{GeV}$, $|\eta_l| < 2.5$, $E_T^{\mathrm{mis}} > 25\,\mathrm{GeV}$, $l = e, \mu$,
- **"calo"** selection criteria:

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

$$\Delta R(l,\gamma) = \sqrt{(\phi_l - \phi_\gamma)^2 + (\eta_l - \eta_\gamma)^2}.$$

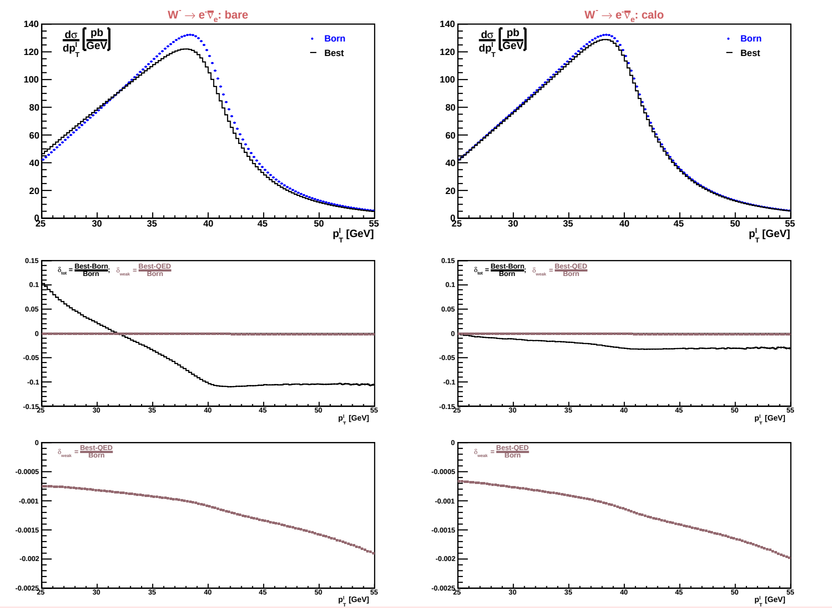
- No detector smearing.
- E_T^{mis} and M_T^W construced using neutrino four momenta.
- G_μ**-scheme.**
- **MSTW2008NLO** parametrisation for PDFs.
- **Perugia 2011** tune (ITUNE = 350) used in PYTHIA 6.4.26.

EW + QCD effects



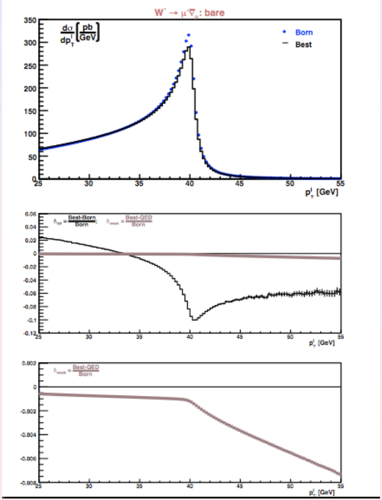
▷ Note: M_T^W reconstructed using neutrino momentum!

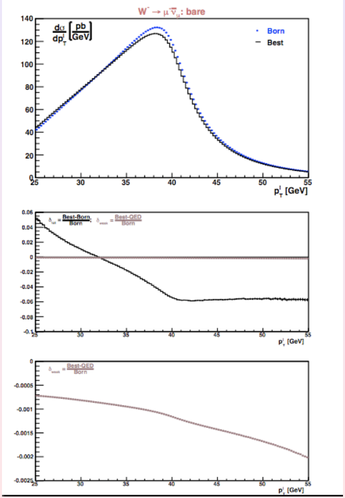
EW + QCD effects



EW + QCD effects

p_T^l: No QCD PS $\longleftrightarrow$ With QCD PS





▷ **For realistic predictions EWC must be combined with QCD PS!**

EW and QCD effects at LHC: 14 TeV

$$W^+ \longrightarrow \mu^+ + \nu_\mu$$

p_T^μ [GeV]	>25	>50	>100	>200	>500	>1000
No QCD						
σ_0 [pb]	4779.03 (16)	30.340 (14)	1.943 (3)	0.178 (1)	0.0051 (1)	0.00015 (1)
$\delta_{\rm EW}$ [%]	-2.748 (3)	-6.10 (3)	-8.7 (1)	-12.8 (4)	-21.4 (1.3)	-28 (5)
$\delta_{\rm weak}$ [%]	-0.108 (0)	-1.193 (1)	-3.88 (1)	-7.36 (4)	-15.7 (3)	-23 (2)
With QCD PS (PYTHIA 6)						
σ_0 [pb]	4096.13 (15)	254.86 (4)	10.025 (8)	0.683 (2)	0.0114 (2)	0.00024 (2)
$\delta_{\rm EW}$ [%]	-2.548 (3)	-4.99 (1)	-4.98 (6)	-7.1 (2)	-13.2 (1.8)	-20 (11)
$\delta_{\rm weak}$ [%]	-0.113 (0)	-0.250 (0)	-0.91 (0)	-2.16 (1)	-7.0 (2)	-15 (2)

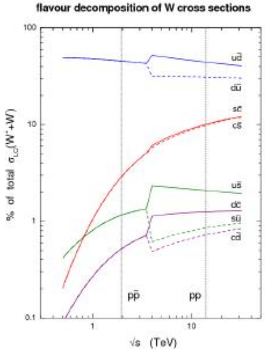
$$W^- \longrightarrow \mu^- + \bar{\nu}_\mu$$

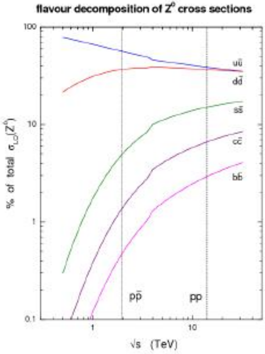
p_T^μ [GeV]	>25	>50	>100	>200	>500	>1000
No QCD						
σ_0 [pb]	3720.10 (12)	22.452 (11)	1.211 (2)	0.0.0971 (4)	0.00211 (3)	0.000052 (2)
$\delta_{\rm EW}$ [%]	-2.612 (3)	-6.16 (3)	-8.9 (1)	-12.9 (4)	-21.6 (1.5)	-32 (5)
$\delta_{\rm weak}$ [%]	-0.106 (0)	-1.094 (1)	-3.72 (1)	-7.13 (4)	-14.4 (3)	-22 (2)
With QCD PS (PYTHIA 6)						
σ_0 [pb]	3234.28 (12)	247.49 (4)	10.931 (8)	0.832 (2)	0.0133 (3)	0.00027 (4)
$\delta_{\rm EW}$ [%]	-2.406 (3)	-4.85 (1)	-4.47 (5)	-5.5 (2)	-8.7 (1.3)	-15 (8)
$\delta_{\rm weak}$ [%]	-0.110 (0)	-0.210 (0)	-0.59 (0)	-1.10 (1)	-2.8 (1)	-5 (1)

▷ **EW corrections considerably affected by QCD PS at high p_T^l!**

M_W: Tevatron ↔ LHC

Differences in quark composition of DY processes





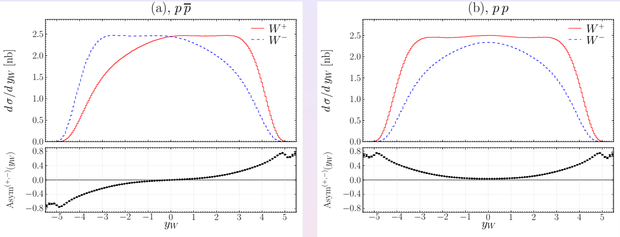
BERGE, NADOLSKY, AND OLNESS PHYSICAL REVIEW D **73**, 013002 (2006)

TABLE I. Partial contributions $\sigma_{q\bar{q}'}/\sigma_{tot}$ of quark-antiquark annihilation subprocesses to the total Born cross sections in W^+ and Z^0 boson production at the Tevatron and LHC (in percent).

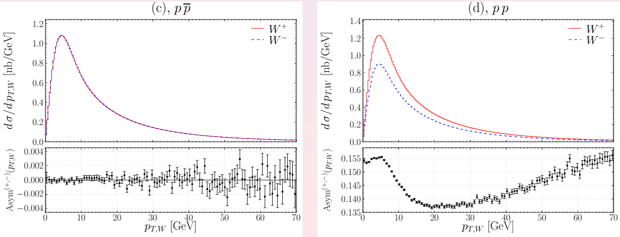
	W^+					W^-					Z^0				
Subprocesses	$u\bar{d}$	$u\bar{s}$	$c\bar{d}$	$c\bar{s}$	$c\bar{b}$	$d\bar{u}$	$s\bar{u}$	$d\bar{c}$	$s\bar{c}$	$b\bar{c}$	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	$b\bar{b}$
Tevatron Run-2	90	2	1	7	0	90	2	1	7	0	57	35	5	2	1
LHC	74	4	1	21	0	67	2	3	28	0	36	34	15	9	6

M_W: Tevatron ↔ LHC

Differences in W rapidity distributions

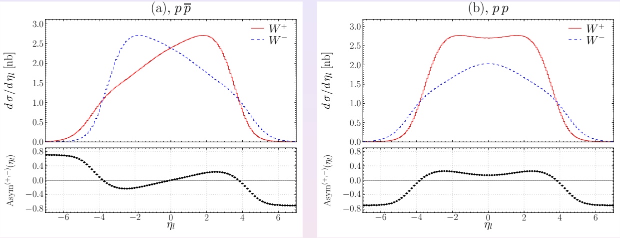


Differences in W transverse momentum distributions

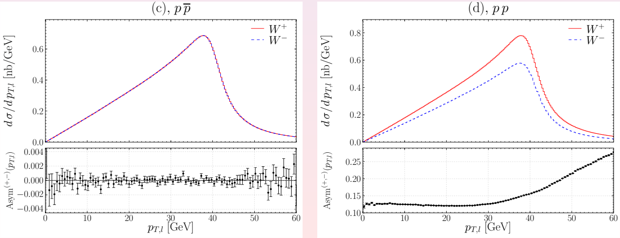


M_W: Tevatron ↔ LHC

Differences in charged-lepton pseudorapidity distributions



Differences in charged-lepton transverse momentum distributions



M_W: Tevatron ↔ LHC

- **Tevatron:**

$$W^+ \leftrightarrow W^- \ \textbf{symmetry}$$

$\Rightarrow$ charge-blind analysis possible, i.e. $W^+ + W^-$

$\rightarrow$ some experimental biases between l^+ and l^- can be cross-checked/eliminated

- **LHC:**

$$W^+ \leftrightarrow W^- \ \textbf{asymmetry}$$

$\Rightarrow$ charge-blind analysis **NOT** possible!

$\rightarrow$ We propose to measure $(M_W^+ - M_W^-)$ and $(M_W^+ + M_W^-)$ using four dedicated experimental observables.

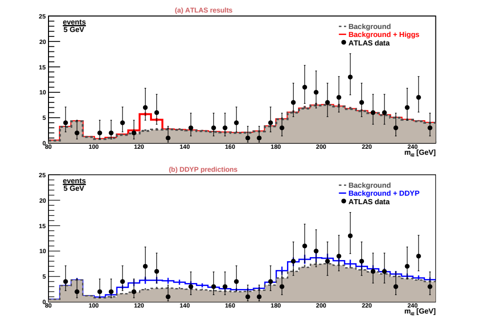
1. F. Fayette, M.W. Krasny, WP, A. Siódmok, Eur. Phys. J. **C63** (2009) 33; arXiv:0812.2571 [hep-ph].
2. M.W. Krasny, F. Dydak, F. Fayette, WP, A. Siódmok, Eur. Phys. J. **C69** (2010) 379; arXiv:1004.2597 [hep-ex].

▷ Based on detailed likelihood study using $\sim 10^{10}$ Monte Carlo events generated with **WINHAC**.

Double Drell–Yan processes

- ATLAS and CMS: $\sigma^{exp}_{WW} > \sigma^{th}_{WW}$, $\sigma^{exp}_{ZZ} > \sigma^{th}_{ZZ}$.
- Contribution of **double-parton scatterings** (DPS) producing **double Drell–Yan processes** (DDYP)?
- Could they influence/mimic Higgs-boson signal in *ZZ* and *WW* decay channels?

▷ M.W. Krasny and WP, arXiv:1305.1769 [hep-ph].



- DDYP ‘peak’ in the Higgs-signal region results from exp. cuts.
- This extreme case requires correlation of $q\bar{q}$-pairs in proton ~ 0.1 fm (not excluded by experiment and theory!)

- **WINHAC** – an efficient and flexible Monte Carlo event generator for charged and neutral-current Drell–Yan processes in pp, $p\bar{p}$ and heavy-ion collisions.
  - It includes multiphoton FSR and IF interference effects within the YFS exclusive exponetiation scheme with $\mathcal{O}(\alpha)$ EW corrections.
  - For QCD effects and hadronisation/decays it is interfaced with PYTHIA 6.4.
- C++ versions of WINHAC: **WINHAC++** for $W^{\pm}$ and **ZINHAC++** for Z/γ – quite advanced.
  - Designed as object-oriented Monte Carlo event generators with the use of modern software engineering methods and tools.
  - Building/linking/installing process managed with cmake.
  - Input in XML.
  - Interfaces to **HepMC** and **LHA** event records.
  - Interface to **Pythia8** through LHA format (with FIFO pipes).
  - In future to be interfaced with **KrkCMC** for NLO QCD PS.