WINHAC – the Monte Carlo event generator for single W-boson production IN HAdronic Collisions

WIESŁAW PŁACZEK

Marian Smoluchowski Institute of Physics
Jagiellonian University
ul. Reymonta 4, 30-059 Kraków, Poland.

e-mail: Wieslaw.Placzek@uj.edu.pl

in collaboration with: S. Jadach, IFJ PAN, Kraków.

⇒ http://cern.ch/placzek/winhac/

Outline

- Introduction.
- The Yennie–Frautschi–Suura exponentiation in leptonic W decays.
- The Monte Carlo event generator WINHAC and its numerical tests
- Electroweak corrections beyond pole appoximation.
- Other important features of WINHAC 1.30.
- Summary.
- Outlook.

Drell–Yan processes

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

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

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

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

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

▶ **Cross section – factorization formula:**

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

where $a, b \in \{g, d, \bar{d}, u, \bar{u}, s, \bar{s}, c, \bar{c}, b, \bar{b}\}$ – parton flavours;

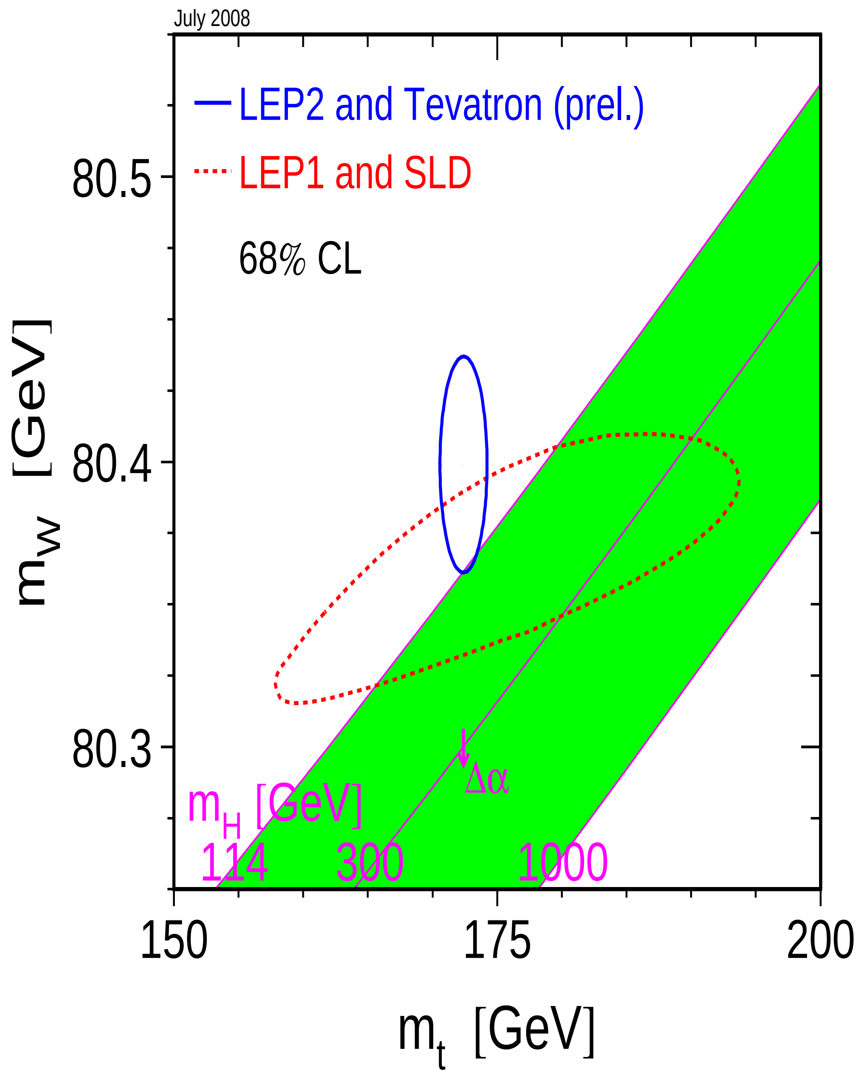
$f_{a/h}(x, Q^2)$ – the parton distribution function (PDF) of a parton a in a hadron h for the Bjorken variable x and hard-process scale Q^2;

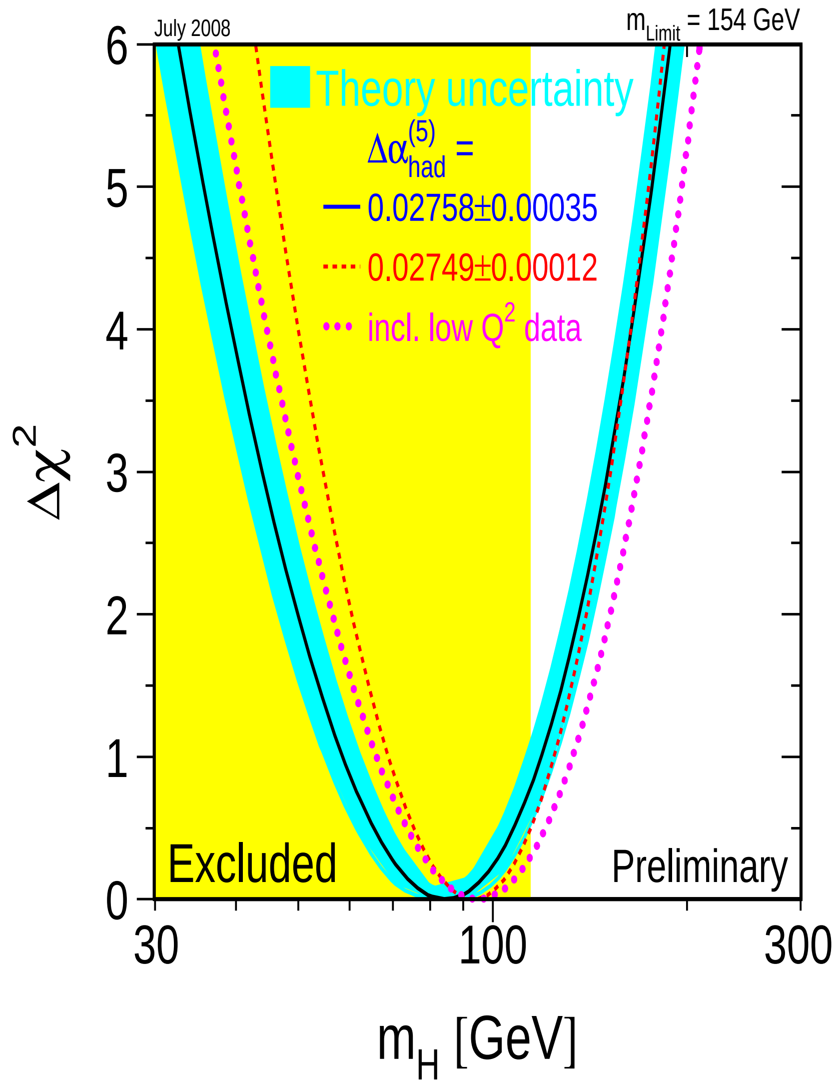
$\sigma_{ab}(Q^2)$ – the parton-level cross section for the hard process.

Why to investigate W/Z-boson production processes?

- To improve precision of some SM parameters values, e.g. $M_W,\ \Gamma_W,\ \sin^2\theta_W,\ \alpha_s$
  - ▷ PDG 2008: $\delta M_W = 25$ MeV, $\delta\Gamma_W = 41$ MeV, $\delta(M_{W^+} - M_{W^-}) = 600$ MeV,
    while: $\delta M_Z = 2.1$ MeV, $\delta\Gamma_Z = 2.3$ MeV.
- To get better constraints on the **Higgs boson mass**
  - ▷ Indirectly from SM fits
  - $\longrightarrow$ Requirements: $\delta M_W \approx 0.7\times 10^{-2}\delta m_t$ (for equal weights in χ^2 tests)
    $\Rightarrow$ LHC: $\delta M_W < 10$ MeV ($\delta M_W/M_W < 0.02\%$)
- To test the SM to a higher precision level.
- To search for **"new physics"**, e.g. through longitudinally polarized W-boson interactions (if there is no Higgs boson?!), etc.
- Background for other processes, e.g. **Higgs boson** production, "new physics" particles (e.g. Kaluza–Klein towers in extra-dimensions scenarios).
- Z production is the important **"standard candle"** process (normalisation, callibration, etc.).

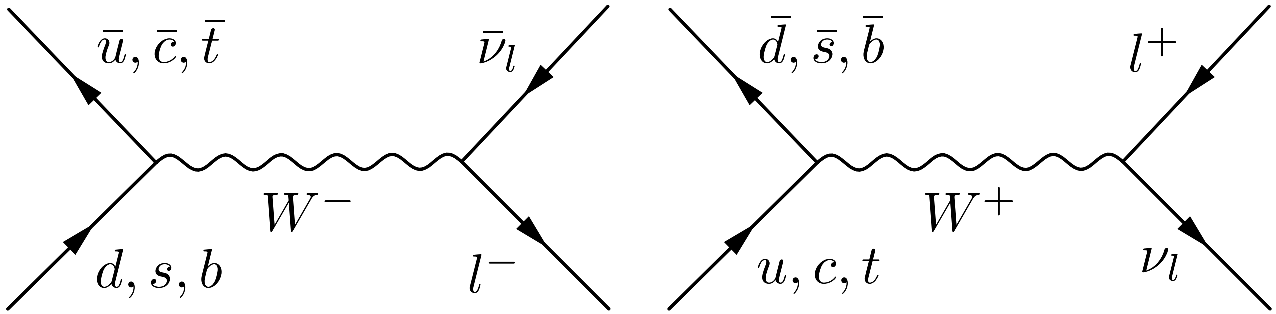
LEP EWWG 2008



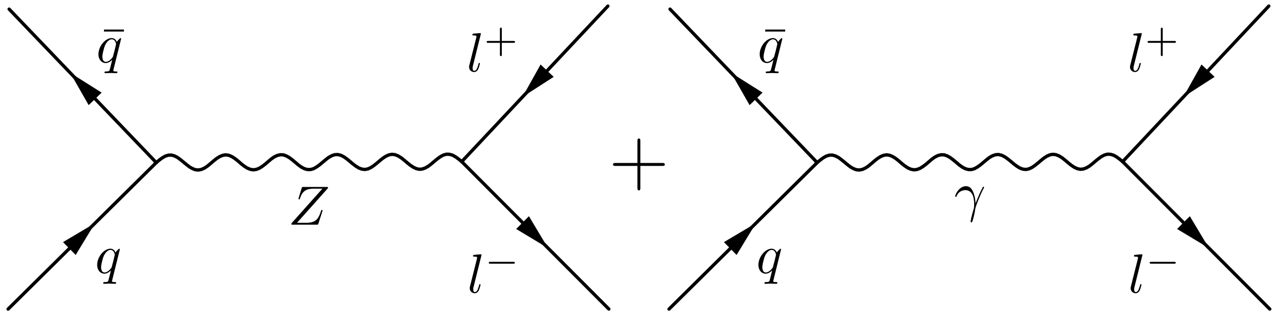


Basic processes at the parton level

- **Charged currents:** $W^{\pm}$

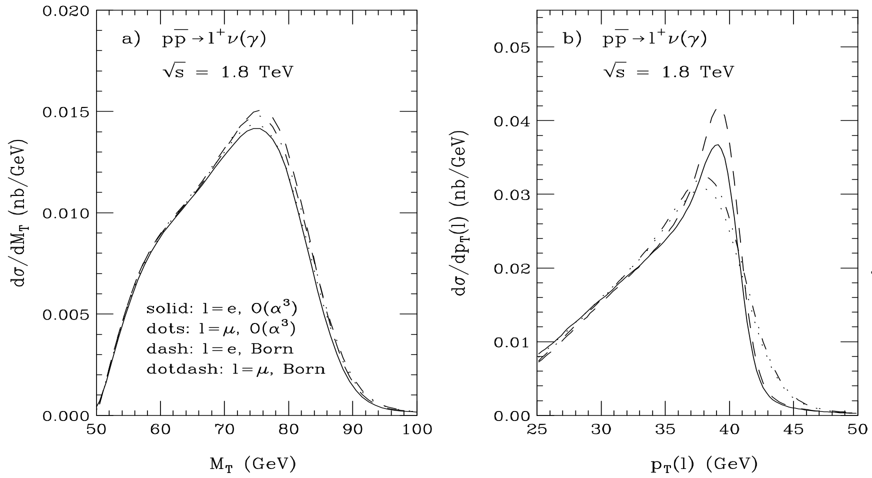


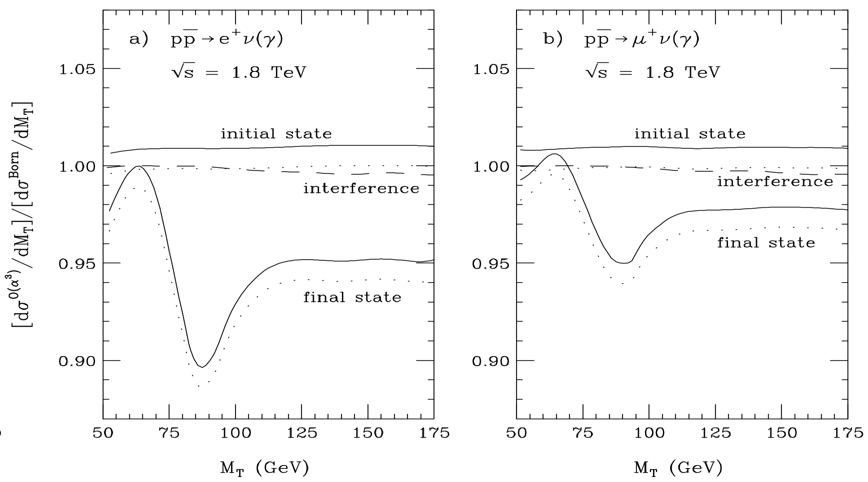
- **Neutral currents:** $Z + \gamma$



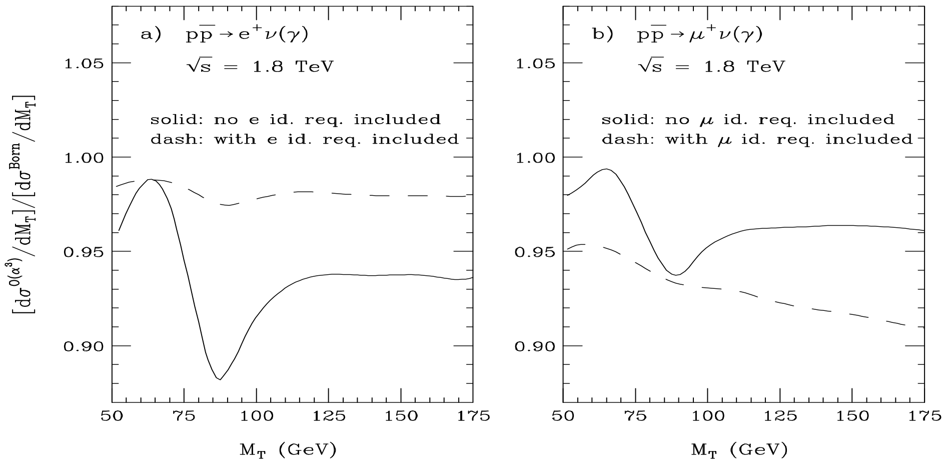
▷ **Hadron colliders:** M_W **from** W **transverse mass** M_T **or charged lepton** p_T

$\longrightarrow$ Tevatron: $\mathcal{O}(\alpha)$ radiative corrections [Baur, Keller & Wackeroth, Phys. Rev. **D59** (1998) 013002]





BARE vs. CALO acceptances

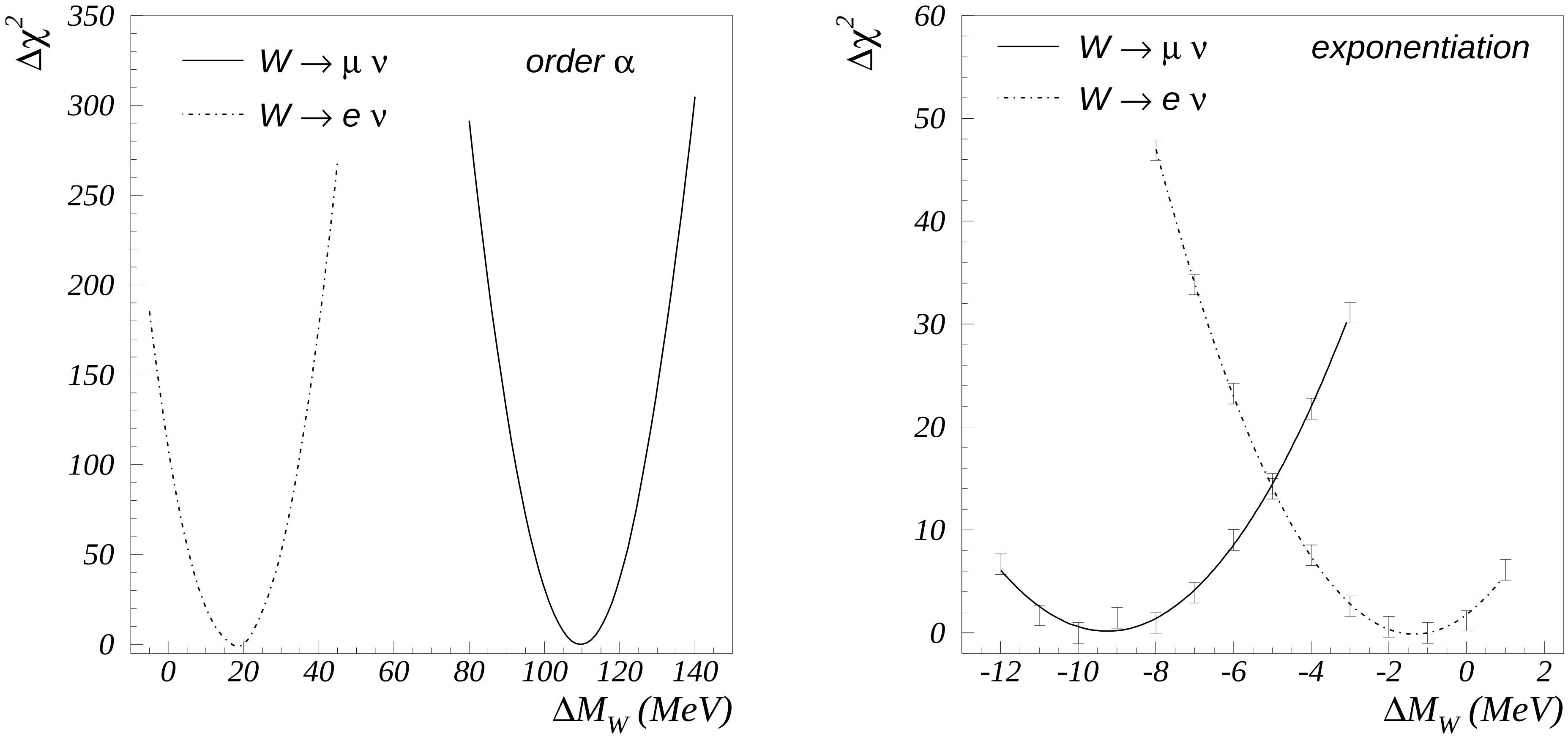


▷ FSR effects are large and acceptance dependent: ΔM_W can be $> 100\,\mathrm{MeV}$!

▷ **Hadron colliders:** **FSR effects on M_W fits to transverse W mass distributions**

C.M. Carloni Calame, G. Montagna, O. Nicrosini and M. Treccani,

Phys. Rev. **D69** (2004) 037301; hep-ph/0303102.

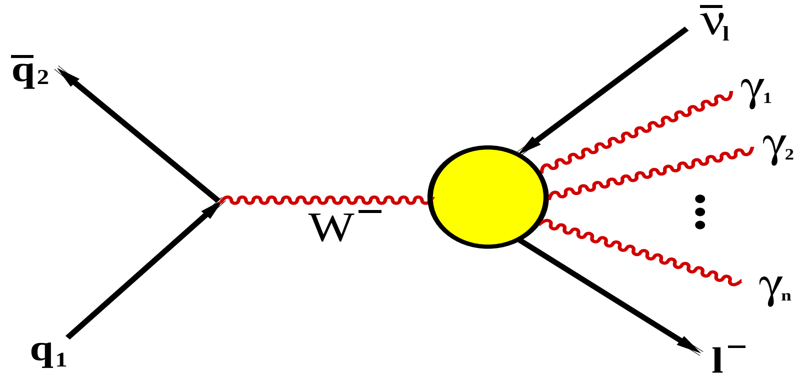


- ΔM_W can be $> 100\,\mathrm{MeV}$ from the $\mathcal{O}(\alpha)$ FSR corrections!
- $\Delta M_W \sim 10\,\mathrm{MeV}$ from higher-order FSR corrections!

▷ Single W-boson production in hadron collisions

- We consider the process:

$$q_1(p_1) + \bar{q}_2(p_2) \longrightarrow W^{\pm}(Q) \longrightarrow l(q_l) + \nu(q_\nu) + \gamma(k_1) + \ldots + \gamma(k_n), \quad (n = 0, 1, \ldots)$$



► $\mathcal{O}(\alpha)$ Yennie–Frautschi–Suura (YFS) exponentiated cross section:

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

where

$$\rho_n^{(1)} = e^{Y(Q,q_l;k_s)} \frac{1}{n!} \prod_{i=1}^{n} \frac{d^3 k_i}{k_i^0} \tilde{S}(Q, q_l, k_i) \theta(k_i^0 - k_s)\, \delta^{(4)} \left(p_1 + p_2 - q_l - q_\nu - \sum_{i=1}^{n} k_i \right)$$
$$\times \left[\bar{\beta}_0^{(1)}(p_1, p_2, q_l, q_\nu) + \sum_{i=1}^{n} \frac{\bar{\beta}_1^{(1)}(p_1, p_2, q_l, q_\nu, k_i)}{\tilde{S}(Q, q_l, k_i)} \right].$$

▷ More details:

- **YFS Form Factor** – gauge-invariant resummation of IR contributions:

$$Y(Q,q_l;k_s) = \underbrace{2\alpha \Re B(Q,q_l;m_\gamma)}_{virtual\ photons} + \underbrace{2\alpha \tilde{B}(Q,q_l;m_\gamma,k_s)}_{real\ photons};$$

where

$$B(Q,q;m_\gamma) = \frac{i}{8\pi^3}\int \frac{d^4k}{k^2-m_\gamma^2+i\varepsilon}\left(\frac{2q-k}{k^2-2kq+i\varepsilon} - \frac{2Q-k}{k^2-2kQ+i\varepsilon}\right)^2,$$

$$\tilde{B}(Q,q;m_\gamma,k_s) = -\frac{1}{8\pi^2}\int_{k^0<k_s}\frac{d^3k}{k^0}\left(\frac{q}{kq} - \frac{Q}{kQ}\right)^2,$$

▷ Four-momentum transfer between charged particles:

$$t = (Q-q_l)^2 = \left(q_\nu + \sum_i k_i\right)^2 \geq 0$$

⟶ Different t domain than in production or scattering processes!

▷ We calculated this YFS formfactor in any Lorentz frame and for arbitrary particle masses ⟶ numerically stable representations!

! Special care had to be taken for the cases of $t=0$ and W-rest frame (to avoid numerical instabilities).

- **The non-IR YFS functions:**

a) **Zero** real hard photons:

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

where: $\bar{\beta}_0^{(0)} = \dfrac{1}{8s\,(2\pi)^2}\,\dfrac{1}{12}\sum\left|\mathcal{M}^{(0)}\right|^2$ $\longleftarrow$ Born-like contribution

▶ $\mathcal{O}(\alpha)$ electroweak virtual corrections:

$$\delta^{(1)}(Q,q_l,q_\nu) = \delta^{(1)}_{\rm EW}(Q,q_l,q_\nu;m_\gamma) - 2\alpha\Re B(Q,q_l;m_\gamma)$$

$\longrightarrow$ $\mathcal{O}(\alpha)$ EW correction library from SANC, D. Bardin et al..

▶ QED-like corrections only: [based on: Marciano & Sirlin, Phys. Rev. **D8** (1973) 3612]

$$\delta^{(1)}_{\rm QED}(Q,q_l) = \frac{\alpha}{\pi}\left(\ln\frac{M}{m_l}+\frac{1}{2}\right)$$

b) **One** real hard photon:

$$\bar{\beta}_1^{(1)}(p_1,p_2,q_l,q_\nu,k) = \frac{1}{16s\,(2\pi)^5}\,\frac{1}{12}\sum\left|\mathcal{M}^{(1)}\right|^2 - \tilde{S}(Q,q_l,k)\bar{\beta}_0^{(0)}(p_1,p_2,q_l,q_\nu),$$

where: $\tilde{S}(Q,q_l,k) = -\dfrac{\alpha}{4\pi^2}\left(\dfrac{Q}{kQ}-\dfrac{q_l}{kq_l}\right)^2$ $\longleftarrow$ soft-photon factor

▷ Matrix elements:

$$\mathcal{M}^{(0)}(\sigma_1,\sigma_2;\tau_1,\tau_2) = \frac{1}{Q^2 - M_W^2 + iM_W\Gamma_W} \sum_{\lambda=1,2,3} \mathcal{M}_P^{(0)}(\sigma_1,\sigma_2;\lambda)\, \mathcal{M}_D^{(0)}(\lambda;\tau_1,\tau_2)$$

$$\mathcal{M}^{(1)}(\sigma_1,\sigma_2;\tau_1,\tau_2,\kappa) = \frac{1}{Q^2 - M_W^2 + iM_W\Gamma_W} \sum_{\lambda=1,2,3} \mathcal{M}_P^{(0)}(\sigma_1,\sigma_2;\lambda)\, \mathcal{M}_D^{(1)}(\lambda;\tau_1,\tau_2,\kappa)$$

► Spin amplitudes in Weyl-spinor representation [cf. Hagiwara & Zeppenfeld, NP **B274** (1986) 1]:

a) Born-level W production:

$$\mathcal{M}_P^{(0)}(\sigma_1,\sigma_2;\lambda) = -\frac{ieV_{f_1 f_2}}{\sqrt{2}s_W}\, \omega_{-\sigma_1}(p_1)\, \omega_{\sigma_2}(p_2)\, \sigma_2\, S\left(p_2, \epsilon_W^*(Q,\lambda), p_1\right)^-_{-\sigma_2,\sigma_1}$$

b) Born-level W decay:

$$\mathcal{M}_D^{(0)}(\lambda;\tau_1,\tau_2) = -\frac{ieCV_{f_1 f_2}}{\sqrt{2}s_W}\, \omega_{-\tau_1}(q_1)\, \omega_{\tau_2}(q_2)\, \tau_2\, S\left(q_1, \epsilon_W(Q,\lambda), q_2\right)^-_{\tau_1,-\tau_2}$$

c) W decay with single real-photon radiation:

$$\mathcal{M}_D^{(1)}(\lambda;\tau_1,\tau_2,\kappa) = -\frac{ie^2CV_{f_1 f_2}}{\sqrt{2}s_W}\, \omega_{-\tau_1}(q_1)\, \omega_{\tau_2}(q_2)\, \tau_2$$

$$\times \left\{ \left(\frac{Q_{f_1}\, q_1\cdot\epsilon_\gamma^*}{k\cdot q_1} - \frac{Q_{f_2}\, q_2\cdot\epsilon_\gamma^*}{k\cdot q_2} - \frac{Q_W\, Q\cdot\epsilon_\gamma^*}{k\cdot Q} \right) S\left(q_1, \epsilon_W(Q,\lambda), q_2\right)^-_{\tau_1,-\tau_2} \right.$$

$$+ \frac{Q_{f_1}}{2\,k\cdot q_1} S\left(q_1, \epsilon_\gamma^*(k,\kappa), k, \epsilon_W(Q,\lambda), q_2\right)^-_{\tau_1,-\tau_2} - \frac{Q_{f_2}}{2\,k\cdot q_2} S\left(q_1, \epsilon_W(Q,\lambda), k, \epsilon_\gamma^*(k,\kappa), q_2\right)^-_{\tau_1,-\tau_2}$$

$$\left. - \frac{Q_W\, k\cdot\epsilon_W}{k\cdot Q} S\left(q_1, \epsilon_\gamma^*(k,\kappa), q_2\right)^-_{\tau_1,-\tau_2} + \frac{Q_W\, \epsilon_W\cdot\epsilon_\gamma^*}{k\cdot Q} S\left(q_1, k, q_2\right)^-_{\tau_1,-\tau_2} \right\}$$

→ **Spin amplitudes can be evaluated in any frame and for $m_f \neq 0$!**

Monte Carlo algorithm for multiphoton radiation

▷ Lorentz frame choice for low-level MC generation of multiphoton radiation

▶ W-boson decay $\longrightarrow$ W-rest frame (seems most natural)

▷ Construction of MC algorithm:

$\longrightarrow$ Step-by-step simplification of the YFS formula for the cross section, compensated with appropriate MC weights – until Poissonian distribution is obtained.

$\longrightarrow$ Generation of random variables and evaluation of compensating weights – in the opposite way to the above simplification process.

$\longrightarrow$ Construction of a MC event in terms of particle flavours and 4-momenta.

▷ MC event generator **WINHAC** $\longrightarrow$ current released version: **1.30**

W. Płaczek and S. Jadach, Eur. Phys. J. **C29** (2003) 325.

$\longrightarrow$ Full-hadron level (Tevatron, LHC): quark x and Q^2 generated with the help of the adaptive cellular MC sampler **FOAM** of S. Jadach, according to parton distribution functions (PDFs) – provided by some external library (currently `PDFLIB` or `LHAPDF`).

$\longrightarrow$ http://cern.ch/placzek/winhac/

Comparisons of two independent MC programs

- **HORACE:** C.M. Carloni Calame, G. Montagna, O. Nicrosini and M. Treccani,

  ▷ Phys. Rev. **D69** (2004) 037301; hep-ph/0303102.

  The MC program for Drell–Yan processes (both W and Z) with higher-order QED corrections included by means of a parton-shower algorithm: numerical solution of the QED DGLAP evolution equation in the non-singlet channel, with non-zero lepton and photon p_T generated at each branching.

- **WINHAC:** W. Płaczek and S. Jadach, Eur. Phys. J. **C29** (2003) 325; hep-ph/0302065.

  Single-W production at hadron colliders with the $\mathcal{O}(\alpha)$ YFS exclusive exponentiation.

▷ **Observables:** → Measurement

1. W-boson transverse mass: $m_T^W = \sqrt{2p_T^l\, p_T^\nu\, (1 - \cos\Delta\phi_{l\nu})}$, → W mass
2. W-boson rapidity: $y_W = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$, → parton luminosities
3. charged lepton transverse momentum: $p_T^l = \sqrt{p_x^2 + p_y^2}$, → W mass
4. charged lepton pseudorapidity: $\eta_l = -\ln\tan\frac{\theta}{2}$, → parton luminosities
5. hardest photon transverse momentum and pseudorapidity: $p_T^\gamma,\ \eta_\gamma$.

LHC: proton–proton collisions at $E_{\rm CMS} = 14$ TeV.

Selection criteria from the ATLAS and CMS collaborations:

- charged lepton transverse momentum: $p_T^l > 25\,{\rm GeV}$,
- charged lepton pseudorapidity: $|\eta_l| < 2.4$,
- missing transverse energy: $E_T^{\rm miss} > 25\,{\rm GeV}$,
- no jet in the event with: $p_T^j > 30\,{\rm GeV}$,
- the recoil system (against the W) transverse momentum: $p_T^{\rm recoil} < 20\,{\rm GeV}$,
- the size of an electron cluster (criteria for recombination of photons with electrons): $d\eta_e \times d\phi_e = 0.075 \times 0.175$,
- no photon recombination with muons.

▷ PDF parametrization used in tests: MRS (G)

▶ **Results published in:**

C.M. Carloni Calame, S. Jadach, G. Montagna, O. Nicrosini and W. Płaczek,

Acta Physica Polonica **B35** (2004) 1643; hep-ph/0402235.

Parton-level total cross section at $E_{\mathrm{CMS}}^{q\bar{q}'} = M_W$

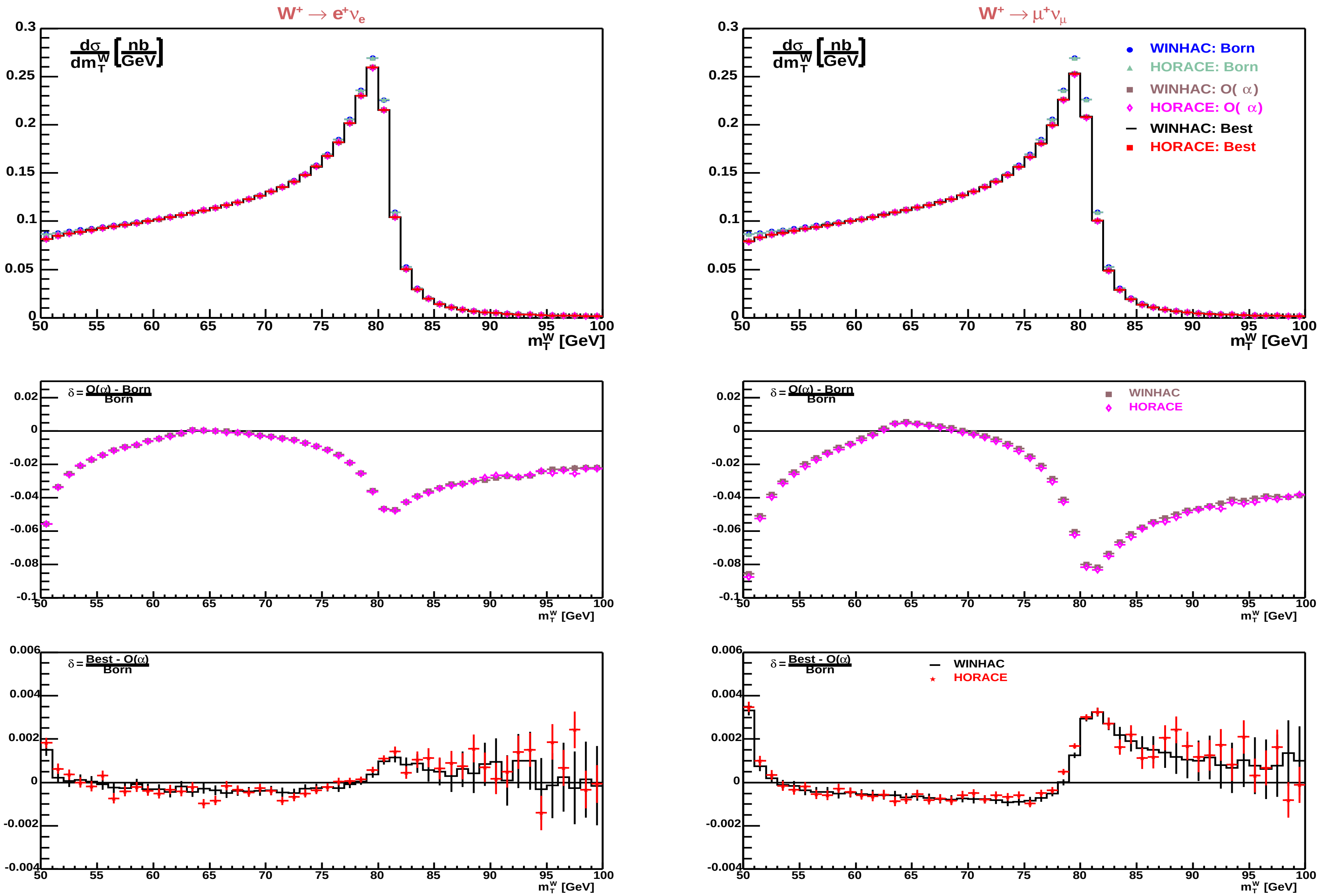
Program	σ^{tot} [nb]: NO CUTS		
	Born	$\mathcal{O}(\alpha)$	Best
Electrons			
HORACE	$8.88722\,(00)$	$8.88721\,(00)$	$8.88721\,(0)$
WINHAC	$8.88715\,(20)$	$8.88552\,(12)$	$8.88401\,(5)$
$\delta =$ (W − H)/W	$-0.8\,(2.3) \times 10^{-5}$	$-1.9\,(0.1) \times 10^{-4}$	$-3.60\,(0.06) \times 10^{-4}$
Muons			
HORACE	$8.88722\,(00)$	$8.88632\,(1)$	$8.88632\,(1)$
WINHAC	$8.88720\,(13)$	$8.88533\,(6)$	$8.88440\,(5)$
$\delta =$ (W − H)/W	$-0.2\,(1.4) \times 10^{-5}$	$-1.11\,(0.07) \times 10^{-4}$	$-2.16\,(0.06) \times 10^{-4}$

Hadron-level total cross section at the LHC

Program	$\sigma^{\rm tot}$ [nb]: WITH CUTS		
	Born	$\mathcal{O}(\alpha)$	Best
$W^- \longrightarrow e^-\bar{\nu}_e$			
HORACE	3.23633 (12)	3.18707 (13)	3.18696 (13)
WINHAC	3.23629 (09)	3.18779 (07)	3.18765 (06)
$\delta =$ (W − H)/W	$-1.2\,(4.6) \times 10^{-5}$	$2.3\,(0.5) \times 10^{-4}$	$2.2\,(0.5) \times 10^{-4}$
$W^- \longrightarrow \mu^-\bar{\nu}_\mu$			
HORACE	3.23632 (12)	3.15990 (12)	3.16013 (13)
WINHAC	3.23630 (07)	3.16418 (06)	3.16409 (05)
$\delta =$ (W − H)/W	$-0.6\,(4.3) \times 10^{-5}$	$1.35\,(0.05) \times 10^{-3}$	$1.25\,(0.05) \times 10^{-3}$
$W^+ \longrightarrow e^+\nu_e$			
HORACE	4.39341 (16)	4.32186 (17)	4.32187 (18)
WINHAC	4.39328 (13)	4.32286 (10)	4.32273 (08)
$\delta =$ (W − H)/W	$-3.0\,(4.7) \times 10^{-5}$	$2.3\,(0.5) \times 10^{-4}$	$2.0\,(0.5) \times 10^{-4}$
$W^+ \longrightarrow \mu^+\nu_\mu$			
HORACE	4.39340 (16)	4.28255 (16)	4.28326 (16)
WINHAC	4.39336 (10)	4.28837 (08)	4.28848 (08)
$\delta =$ (W − H)/W	$-0.9\,(4.3) \times 10^{-5}$	$1.36\,(0.05) \times 10^{-3}$	$1.22\,(0.05) \times 10^{-3}$

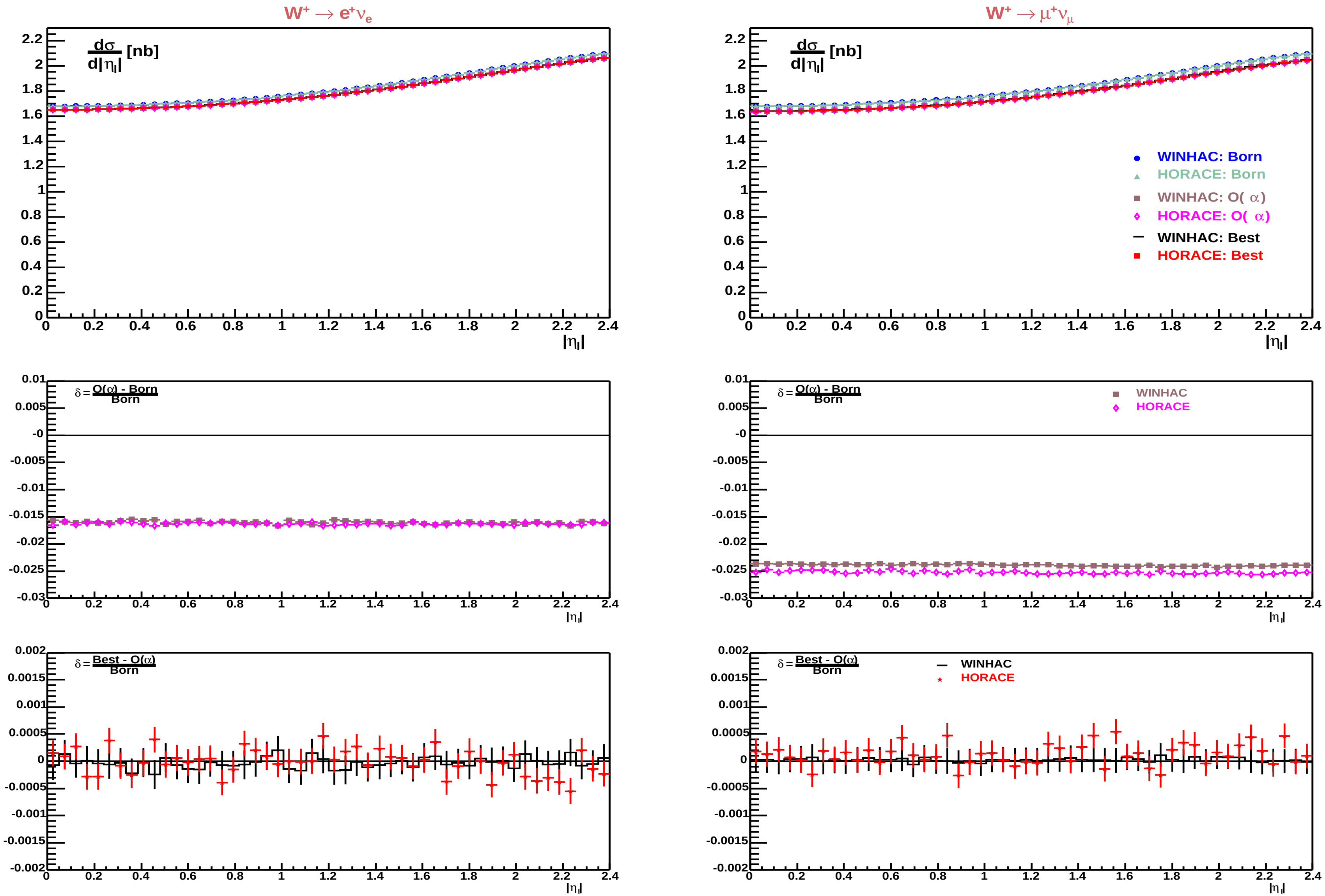
QED corrections @ LHC

W-boson transverse mass M_T for: $W^+ \to l^+ \nu_l$

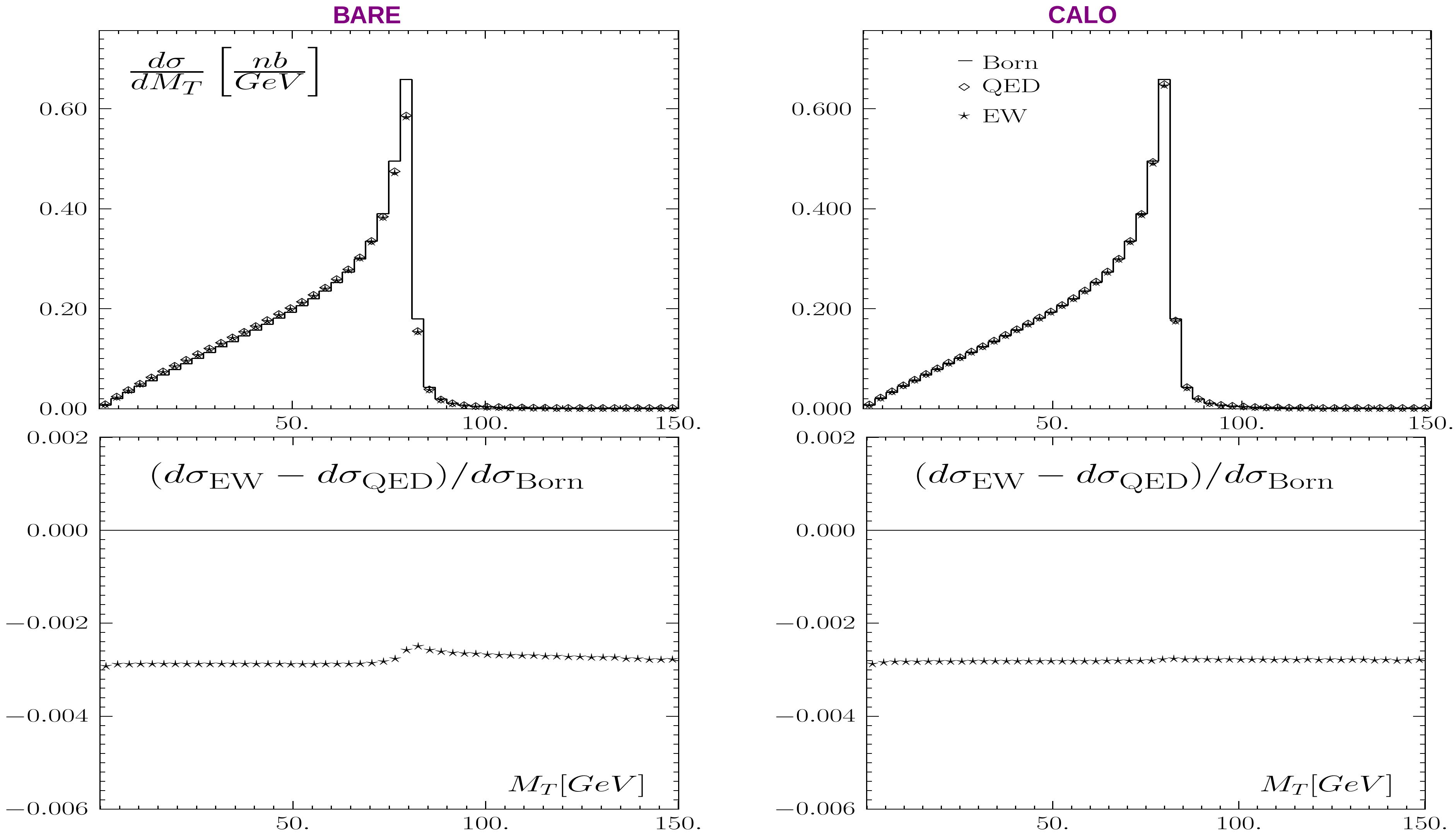


QED corrections @ LHC

Charged lepton pseudorapidity η_l for: $W^+ \to l^+\nu_l$

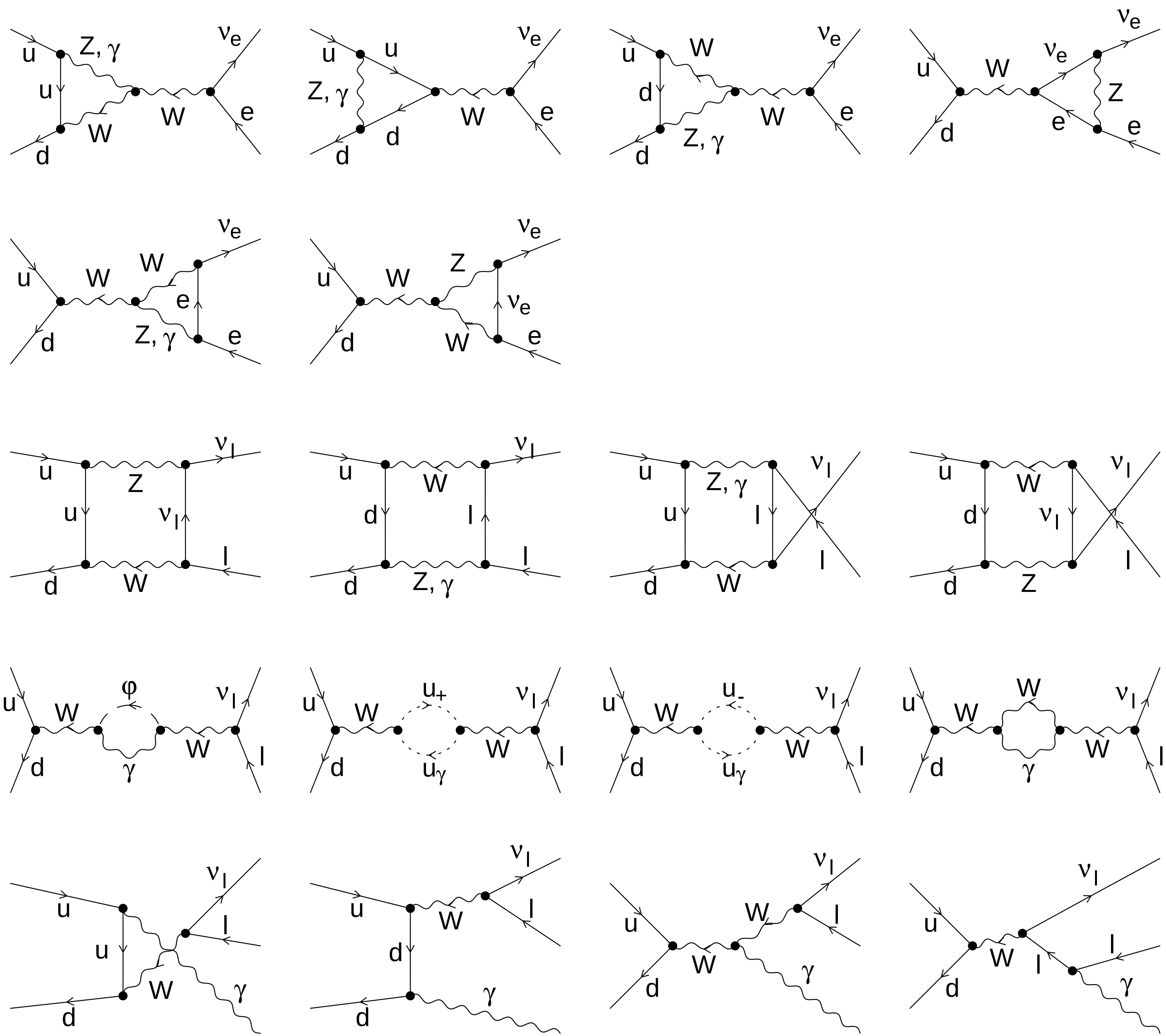


WINHAC: W-boson transverse mass M_T for $W^+ \to e^+\nu_e$



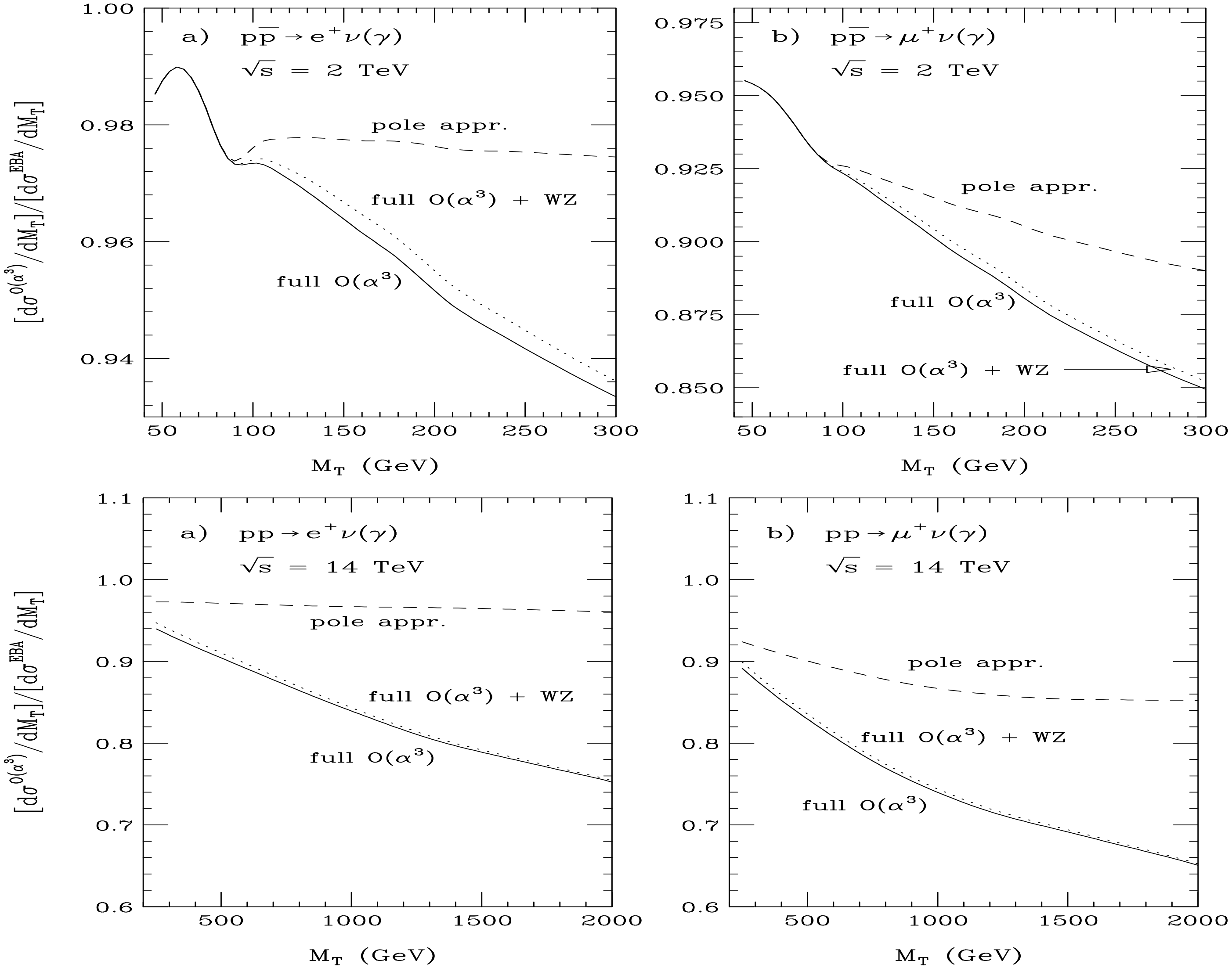
$\mathcal{O}(\alpha)$ **EW corrections in pole approximation (PA)** – from SANC (D.Yu. Bardin et al.)

EW corrections beyond pole appoximation



EW corrections beyond pole appoximation

Full $\mathcal{O}(\alpha)$ EW radiative corrections at **LHC:** U. Baur and D. Wackeroth, hep-ph/0405191.



▷ Full EW correction are important for large W invariant masses (new physics searches).

Main problem: QED ISR!

- Standard theoretical calculation $\longrightarrow$ results depend on quark masses $\sim \ln(Q^2/m_q^2)$.
  ▷ What to put for m_q?

- Possible solution:
  ▶ **Absorb QED ISR into PDFs in the same way as QCD ISR.**
  ▷ Match $\mathcal{O}(\alpha)$ EW matrix element with such PDFs using some factorization scheme, (usually $\overline{\rm MS}$ or DIS) at some factorization scale (usually the hard process scale).

- Fitting of PDF parametrizations should be done with evolution equations (usually DGLAP) including QED terms, e.g. MRST2004QED.
  ▶ QED effects for PDFs at LHC are at the per-mille level!

- QED radiation is usually generated by parton-shower MCs together with QCD radiation, e.g. **PYTHIA**, **HERWIG**.
  ▷ However, this is done neither in $\overline{\rm MS}$ nor in DIS scheme!

▶ **How to match $\mathcal{O}(\alpha)$ EW radiative corrections with parton-shower MCs?**

New in version 1.30

- After decomposition of W-boson propagator QED corrections can be divided into three classes: **ISR**, **FSR** and **I-F interferences**.
  - ▷ Problem: For charged EW currents virtual corrections cannot be split in a gauge-ivariant way into pure QED and pure weak ones.
  - ▶ Possible solution: One can identify gauge-invariant subsets of virtual corrections that are of QED origin.
- **ISR** can be left for **parton-shower Monte Carlo**, while **FSR** and **I-F interferences** can be dealt with **EW Monte Carlo**.
- In **WINHAC** **interferences** need to be added in: YFS form factor, IR $\tilde{S}$-factor and non-IR $\bar{\beta}$-functions.
  - ▷ Additional weights:

$$w_Y = e^{Y_{\rm Int+FSR} - Y_{\rm FSR}}, \qquad w_{\tilde{S}} = \prod_{i=1}^{n} \frac{\tilde{S}_{\rm Int+FSR}(k_i)}{\tilde{S}_{\rm FSR}(k_i)}$$

  - ▷ $\bar{\beta}_0^{(1)}$-function: virtual correction $\delta_{\rm Int}^{virt}$ is needed.
  - ▷ $\bar{\beta}_1^{(1)}$-function: interference matrix element for real-photon radiation is needed.

- IR $\tilde{S}$-factor:

$$\tilde{S}_{\rm Int+FSR} = \tilde{S}_{\rm tot} - \tilde{S}_{\rm ISR} = (\tilde{S}_{ul} - \tilde{S}_{uW}) + (\tilde{S}_{dl} - \tilde{S}_{dW}),$$

where

$$\tilde{S}_{ij} \equiv \tilde{S}(p_i, p_j, k) = -\frac{\alpha}{4\pi^2} |Q_i Q_j| \left(\frac{p_i}{kp_i} - \frac{p_j}{kp_j} \right)^2 .$$

- YFS form factor – similarly:

$$Y_{\rm Int+FSR} = Y_{\rm tot} - Y_{\rm ISR} = (Y_{ul} - Y_{uW}) + (Y_{dl} - Y_{dW}),$$

- $\mathcal{O}(\alpha)$ virtual EW corrections to $\bar{\beta}_0^{(1)}$-function:

$$\delta^{virt}_{\rm Int+FSR} = \underbrace{\delta^{v+s}_{\rm tot}(\{m_q\}, \epsilon)}_{\textbf{from SANC (D. Bardin et al.)}} - \delta^{v+s}_{\rm ISR}(\{m_q\}, \epsilon) - Y_{\rm Int+FSR}(\epsilon)$$

  ▶ Independence of quark masses m_q and soft-photon cut-off ϵ checked numerically!

- $\mathcal{O}(\alpha)$ real-photon corrections to $\bar{\beta}_1^{(1)}$-function:

  ▶ We add interference matrix element for single-photon radiation

$$|\mathcal{M}_{\rm Int}|^2 = 2{\rm Re}\left(\mathcal{M}_{\rm ISR}\mathcal{M}^*_{\rm FSR}\right)$$

  within the spin-amplitude formalism as for FSR.

Three schemes for QED-like Virtual $+$ Soft-Real $\mathcal{O}(\alpha)$ Radiative Corrections

- MS-scheme – motivated by Marciano–Sirlin prescription for FSR, i.e. only log-terms retained in virtual QED corrections:

$$\delta_{\rm ISR}^{\rm MS}(s,m_d,m_u;\epsilon) = \frac{\alpha}{\pi}\Bigg\{ \left[Q_d^2\left(\ln\frac{s}{m_d^2}-1\right)+Q_u^2\left(\ln\frac{s}{m_u^2}-1\right)-1\right]\ln\epsilon + Q_d^2\left(\frac{3}{4}\ln\frac{s}{m_d^2}-\frac{\pi^2}{6}\right)+Q_u^2\left(\frac{3}{4}\ln\frac{s}{m_u^2}-\frac{\pi^2}{6}\right)+1\Bigg\}$$

where $\epsilon = 2k_s/\sqrt{s}$ – dimenionless soft-photon cut-off.

- YFS-scheme – YFS form factor $+$ term $\sim \frac{1}{2}Q_i^2[\ln(s/m_i^2)-1]$:

$$\delta_{\rm ISR}^{\rm YFS} = \delta_{\rm ISR}^{\rm MS} + \frac{\alpha}{\pi}\left\{(Q_d^2+Q_u^2)\left(\frac{\pi^2}{3}-1\right)-\frac{\pi^2}{3}\right\}$$

- HW-scheme – based on: W. Hollik and D. Wackeroth, Phys. Rev. **D55** (1997) 6788:

$$\delta_{\rm ISR}^{\rm HW} = \delta_{\rm ISR}^{\rm YFS} + \frac{\alpha}{\pi}\left\{\frac{3\pi^2}{8}+\frac{1}{2}\right\}$$

▶ **In a similar way we obtained QED-like virtual $+$ soft-real corrections for FSR and I-F interferences.**

- D. Bardin, S. Bondarenko, S. Jadach, L. Kalinovskaya, W. Płaczek,
  "Implementation of SANC EW corrections in WINHAC Monte Carlo generator",
  Acta Phys. Polon. **B40** (2009) 75; arXiv:0806.3822 [hep-ph]
- **Process:** $$pp \to W^+ \to \ell^+ \nu_\ell \,.$$
- **Parameters:**

$$
\begin{aligned}
G_\mu &= 1.16637 \times 10^{-5}\ \mathrm{GeV}^{-2}, & \alpha &= 1/137.03599911, \quad \alpha_s(M_Z^2) = 0.1176, \\
M_Z &= 91.1876\ \mathrm{GeV}, & \Gamma_Z &= 2.4924\ \mathrm{GeV}, \\
M_W &= 80.37399\ \mathrm{GeV}, & \Gamma_W &= 2.0836\ \mathrm{GeV}, \\
M_H &= 115\ \mathrm{GeV}, & & \\
m_e &= 0.51099892\ \mathrm{MeV}, & m_\mu &= 0.105658369\ \mathrm{GeV}, \quad m_\tau = 1.77699\ \mathrm{GeV}, \\
m_u &= 0.06983\ \mathrm{GeV}, & m_c &= 1.2\ \mathrm{GeV}, \quad m_t = 174\ \mathrm{GeV} \\
m_d &= 0.06984\ \mathrm{GeV}, & m_s &= 0.15\ \mathrm{GeV}, \quad m_b = 4.6\ \mathrm{GeV} \\
|V_{ud}| = 0.975, \quad |V_{us}| &= 0.222, & |V_{cd}| &= 0.222, \quad |V_{cs}| = 0.975, \\
|V_{cb}| = |V_{ts}| = |V_{ub}| &= |V_{td}| = |V_{tb}| = 0.
\end{aligned}
$$

- **"Bare" cuts:** $p_T(\ell) > 20\ \mathrm{GeV}, \quad |\eta(\ell)| < 2.5, \quad p\!\!\!/_T > 20\ \mathrm{GeV}, \quad \ell = e,\, \mu\,,$

▶ **SANC** – MC integrator (based on VEGAS) was used in our comparisons.

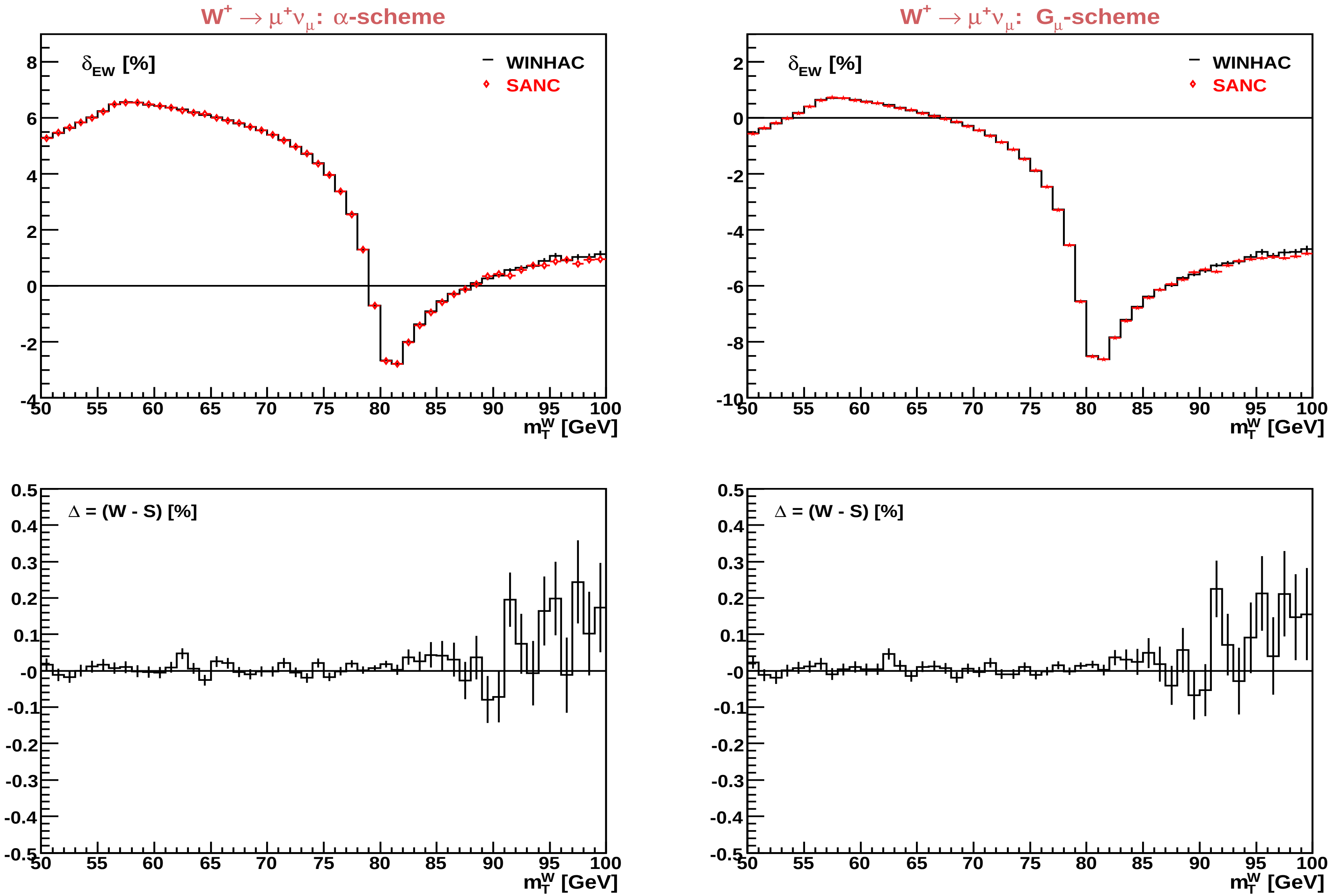
Total cross sections:

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	$5039.03(11)$	$5227.87(14)$	$3.745(2)$	$5419.01(12)$	$5305.59(14)$	$-2.094(2)$

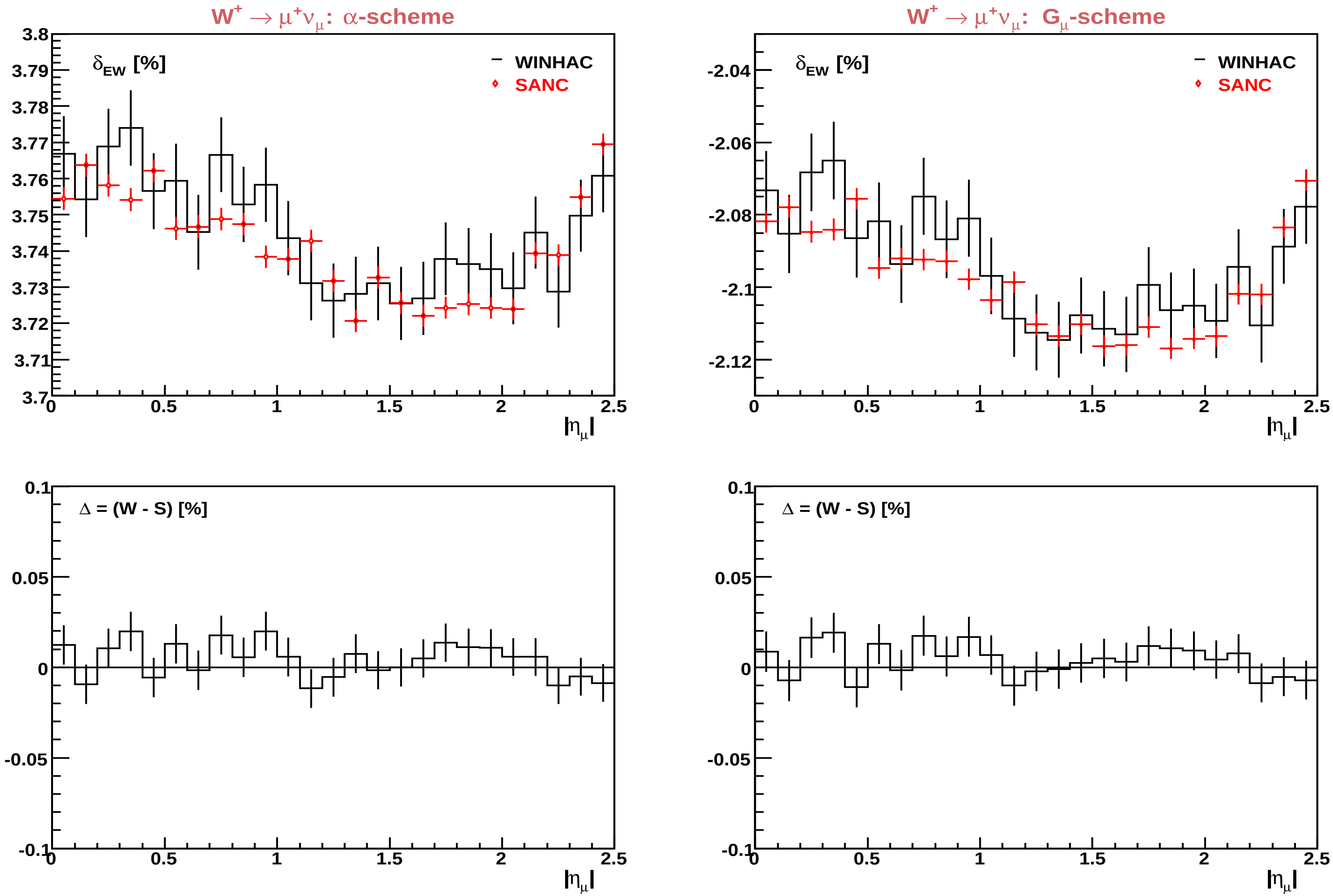
Tuned WINHAC ↔ SANC comparisons at $\mathcal{O}(\alpha)$

$\mathcal{O}(\alpha)$ EW: $M_T(l\nu)$ for the muon channel



Tuned WINHAC $\leftrightarrow$ SANC comparisons at $\mathcal{O}(\alpha)$

$\mathcal{O}(\alpha)$ EW: $|\eta_l|$ for the muon channel



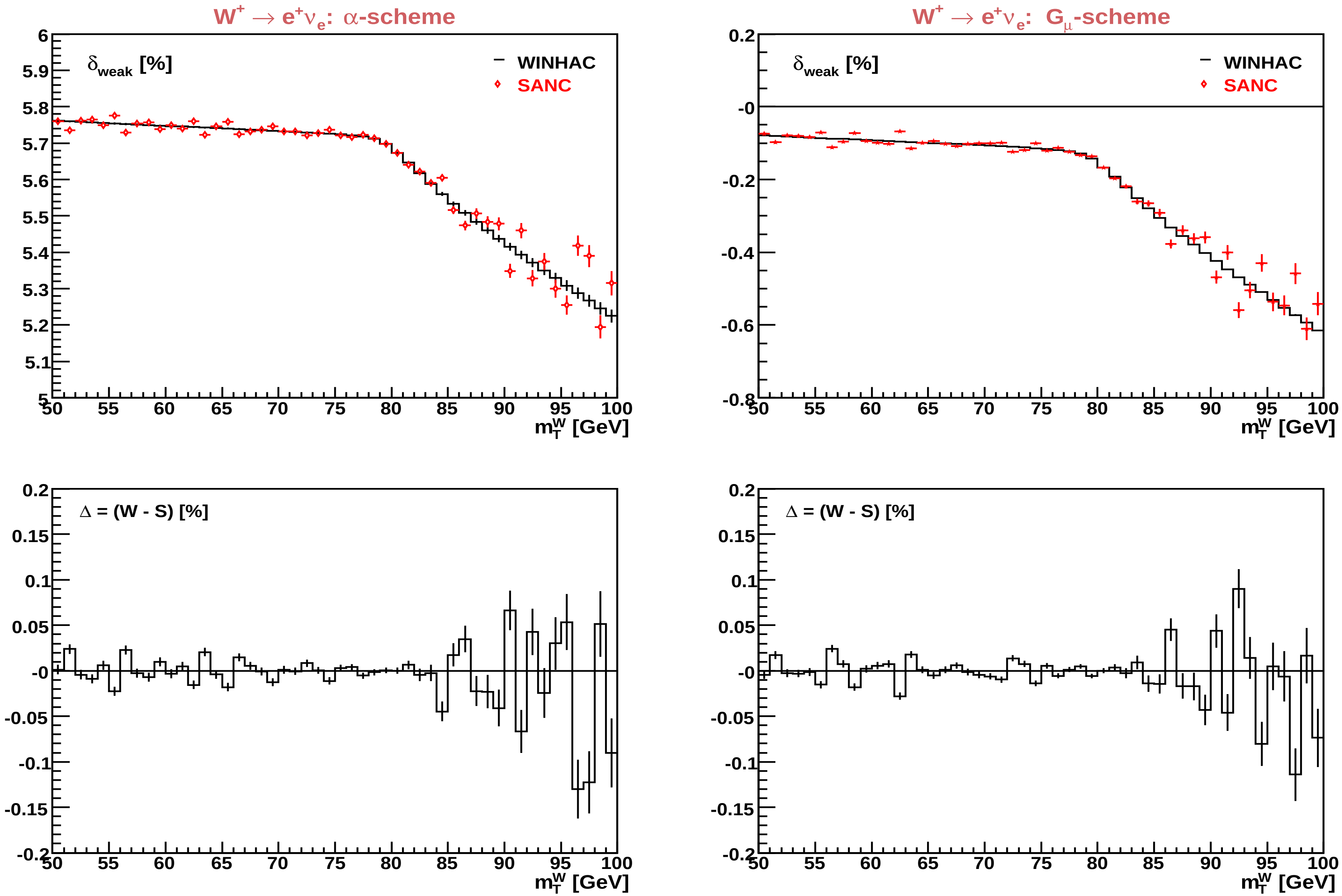
$\mathcal{O}(\alpha)$ "pure weak" corrections

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

$\delta_{\rm weak}$ [%]		
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	$5.7220(2)$	$-0.1177(0)$

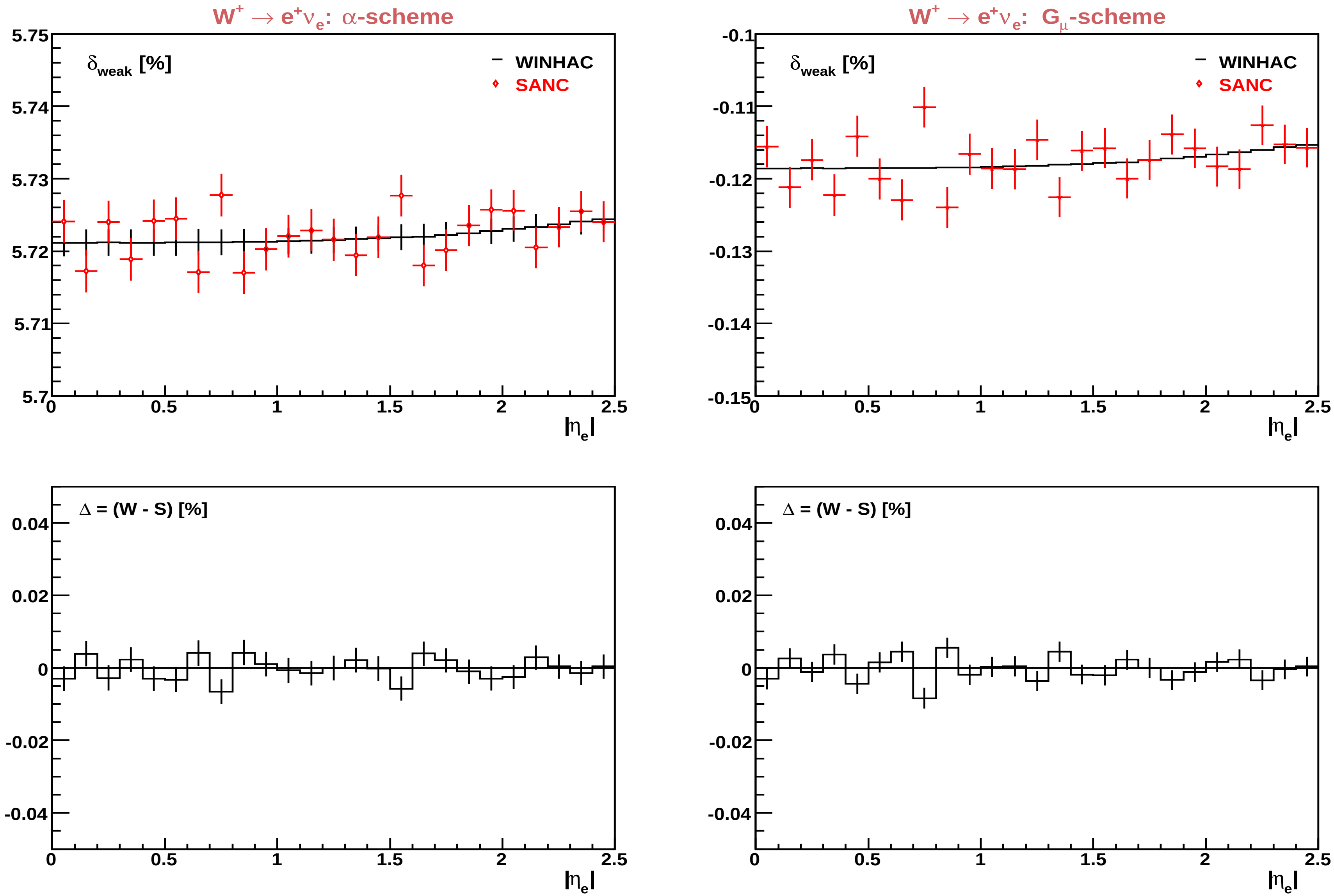
Tuned WINHAC ↔ SANC comparisons at $\mathcal{O}(\alpha)$

$\mathcal{O}(\alpha)$ weak: $M_T(l\nu)$ for the electron channel



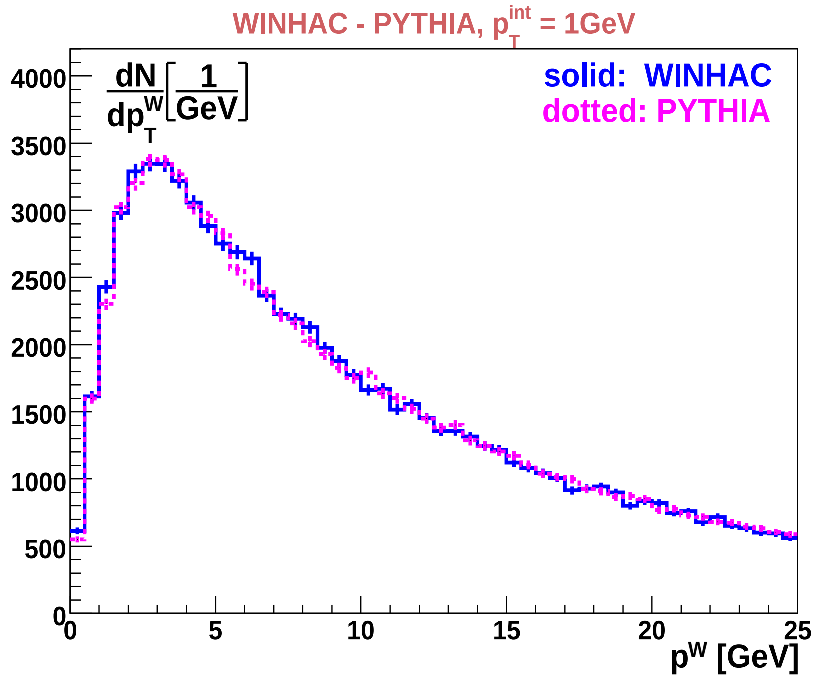
Tuned WINHAC ↔ SANC comparisons at $\mathcal{O}(\alpha)$

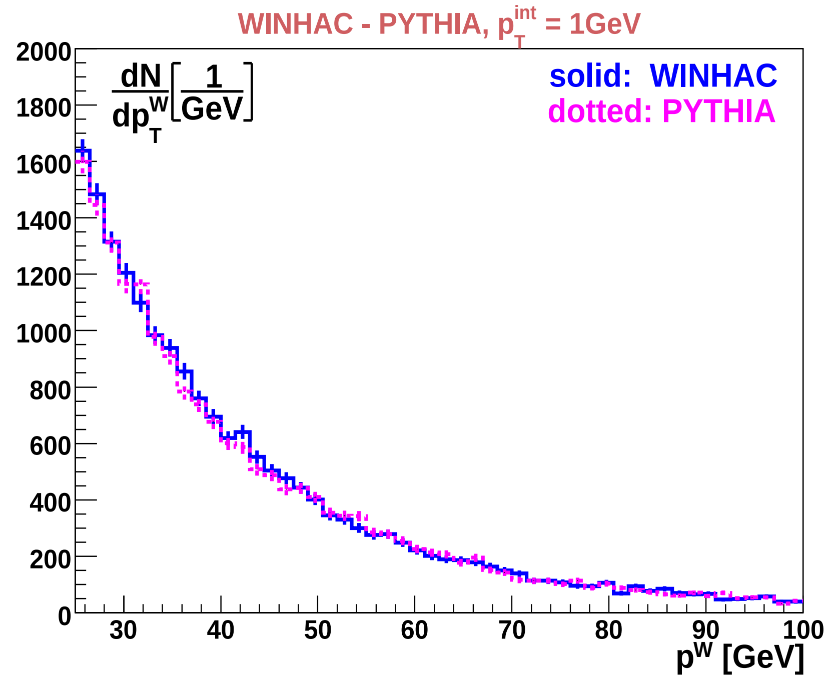
$\mathcal{O}(\alpha)$ weak: $|\eta_l|$ for the electron channel



Other important features of WINHAC 1.30

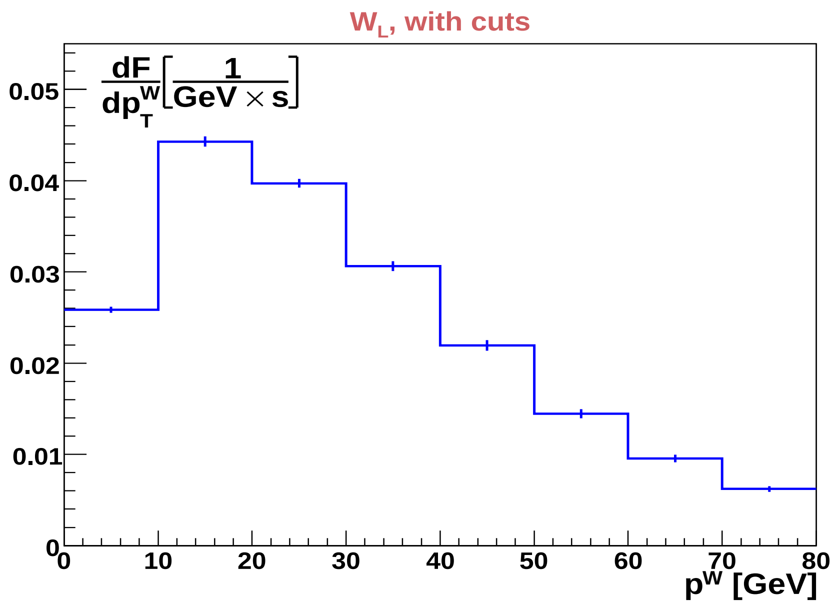
- Interface to **PYTHIA** for ISR parton shower (QCD + QED), beam-remnants treatment and hadronization $\Rightarrow W$ **bosons have non-zero** p_T**!**

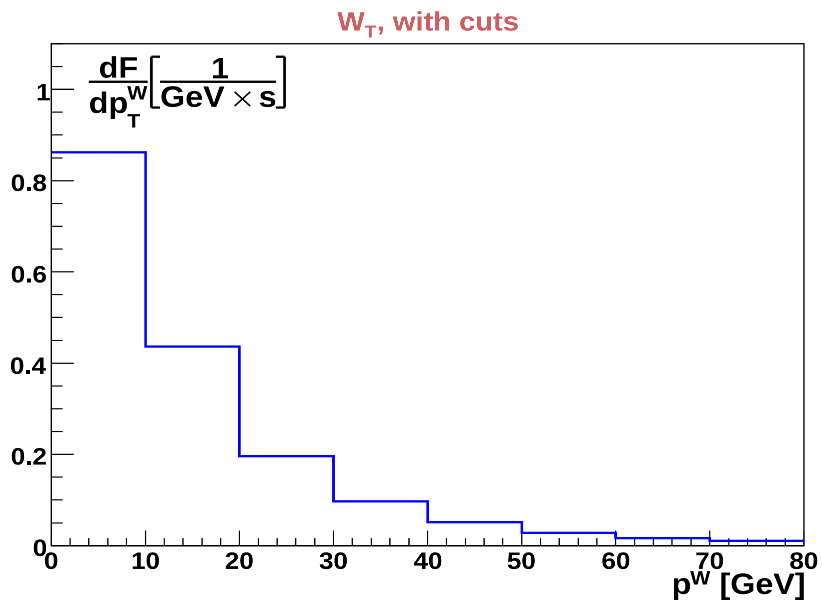


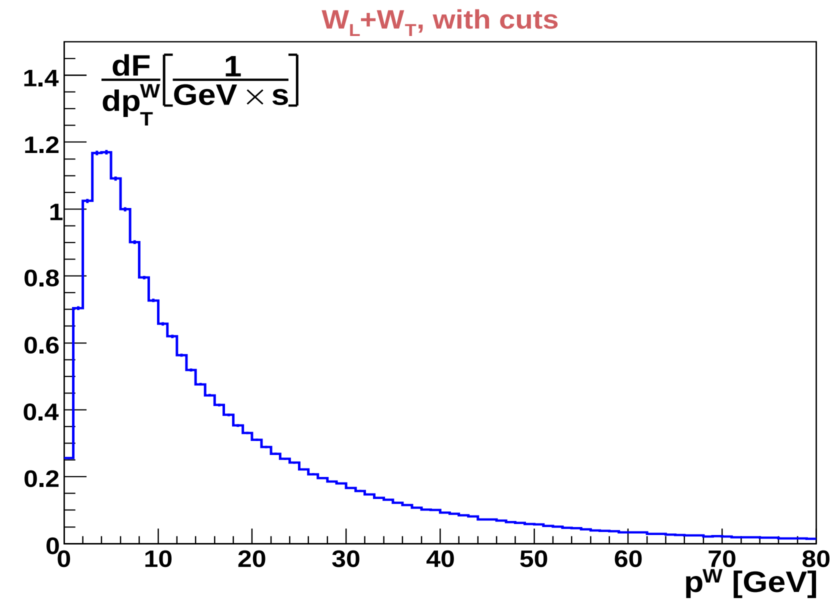


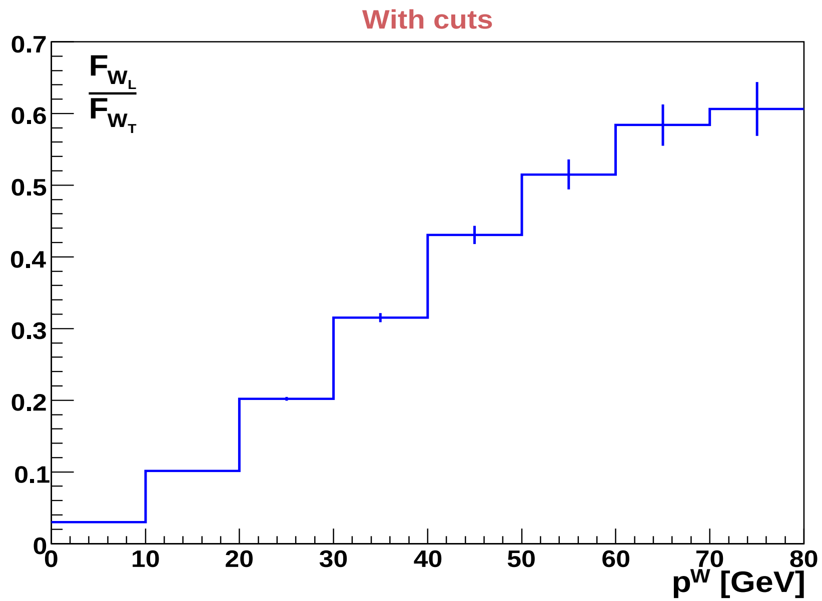
- Single-W production in **any nucleus–nucleus collisions**.
- Neutral current Drell–Yan process ($Z + \gamma$) at the Born level has been added and interfaced with **PYTHIA**.
- Possibility of generating both weighted and unweighted ($w = 1$) events for polarized Ws (i.e. longitudinal W_L and transverse W_T).

Polarized-W distributions









Numerical results for LHC – using SANC EWC modules for CC DY v. 1.03

$$p + p \longrightarrow W^+ + X \longrightarrow \nu_\mu + l^+ + X, \qquad |\eta_\mu| < 1.2; \qquad \int dt\mathcal{L} \approx 10\, fb^{-1}$$

p_T^μ [GeV]	> 25	> 50	> 100	> 200	> 500	> 1000
No QCD						
σ_0 [pb]	2150.1 (5)	14.09 (4)	1.007 (8)	0.109 (2)	0.0041 (2)	0.00018 (3)
$\delta_1^{\rm EW}$ [%]	−2.700 (17)	−6.27 (19)	−9.86 (65)	−13 (2)	−26 (6)	−38 (17)
$\delta_{\rm exp}^{\rm EW}$ [%]	−2.691 (14)	−6.09 (15)	−9.02 (48)	−13 (1)	−23 (4)	−34 (11)
$\delta_1^{\rm weak}$ [%]	−0.070 (0)	−1.31 (1)	−4.26 (5)	−8.0 (2)	−16 (1)	−23 (5)
$\delta_{\rm exp}^{\rm weak}$ [%]	−0.066 (0)	−1.24 (0)	−3.99 (4)	−7.4 (2)	−14 (1)	−20 (4)
With QCD (PYTHIA)						
σ_0 [pb]	2278.0 (5)	222.2 (2)	15.49 (5)	1.16 (1)	0.028 (2)	0.0009 (3)
$\delta^{\rm QCD}$ [%]	+6	+1477	+1438	+964	+583	+400
$\delta_1^{\rm EW}$ [%]	−2.547 (16)	−4.31 (5)	−4.44 (20)	−6.38 (70)	−17 (4)	−43 (21)
$\delta_{\rm exp}^{\rm EW}$ [%]	−2.524 (13)	−4.19 (4)	−4.25 (16)	−5.99 (56)	−13 (3)	−23 (17)
$\delta_1^{\rm weak}$ [%]	−0.064 (0)	−0.15 (0)	−0.38 (0)	−0.97 (2)	−2.8 (2)	−5 (2)
$\delta_{\rm exp}^{\rm weak}$ [%]	−0.061 (0)	−0.14 (0)	−0.35 (0)	−0.91 (2)	−2.6 (2)	−4 (2)

Summary

- **WINHAC** is a Monte Carlo event generator for the charged current Drell–Yan process (single-W production with leptonic decays) in proton–proton, proton–antiproton, proton–nucleus and nucleus–nucleus collisions.
- It features multiphoton effects within the Yennie–Frautchi–Suura exclusive exponentiation scheme with $\mathcal{O}(\alpha)$ electroweak corrections.
- It allows for polarized W-boson production.
- It is interfaced with **PYTHIA 6.4** for the QCD parton shower and hadronization.
- It has been cross-checked numerically to high precision with independent programs: **HORACE** and **SANC**.

Outlook

- Interfacing with other QCD MCs, e.g. **HERWIG**, etc.
- Inclusion of CMC-type ISR parton-shower generator $\longrightarrow$ work in progress (S. Jadach et al.).
- Including NLO QCD corrections and matching them with parton shower.
- A similar MC program for single-Z production (i.e. neutral current Drell–Yan process): **ZINHAC** $\longrightarrow$ work in progress (with A. Siódmok).
- Using **WINHAC/ZINHAC** for testing various methods of precision measurements of SM parameters at LHC, e.g. M_W, Γ_W, $\sin^2\theta_W$, α_s $\longrightarrow$ work in progress, cf. hep-ph/0702251, 0812.2571 [hep-ph] (with M.W. Krasny, F. Fayette, A. Siódmok, K. Rejzner).
- Using polarized W/Z options in **WINHAC/ZINHAC** to develop methods for testing electroweak-symmetry breaking at LHC $\longrightarrow$ work in progress, cf. hep-ph/0503215 (with M.W. Krasny, S. Jadach).
- Implementing beyond Standard Model (BSM) physics in **WINHAC/ZINHAC**, e.g. anomalous couplings, extra bosons, etc.
- Rewriting **WINHAC** in C++ $\longrightarrow$ work in progress (with K. Sobol, P. Stecko).