Status of WINHAC Monte Carlo

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Outline:

- Introduction.
- The Yennie–Frautschi–Suura exponentiation in leptonic W decays.
- The Monte Carlo event generator WINHAC.
- Numerical results – parton level.
- Numerical results – hadron level.
- Summary and outlook.

presented by MACIEJ SKRZYPEK

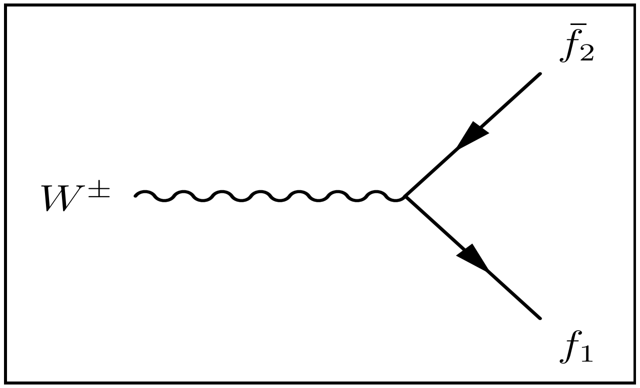
Why to investigate W-boson production processes?

- To measure the Standard Model (SM) parameters, e.g. $M_W,\ \Gamma_W$
  - ▷ PDG 2004: $\Delta M_W = 38$ MeV, $\Delta\Gamma_W = 41$ MeV,
    while: $\Delta M_Z = 2.1$ MeV, $\Delta\Gamma_Z = 2.3$ MeV.
- To test the SM, in particular its non-Abelian nature through triple and quartic gauge-boson couplings (TGC: WWV and QGC: WWV_1V_2).
- 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: $\Delta M_W \approx 15$ MeV ($\Delta M_W / M_W \approx 0.02\%$)
- To search for **“new physics”**, e.g. anomalous TGCs and QGCs, longitudinally polarized W-boson interactions (e.g. if there is no Higgs boson?!), etc.
- To measure parton distribition functions (PDF) and parton luminosities at the LHC.
- Background for other processes, e.g. **Higgs boson** production, “new physics” particles (like Kaluza-Klein towers in extra-dimensions scenarios).

W-boson decay:

▷ Born-level process: $W^{\pm} \longrightarrow f_1 + \bar{f}_2,$

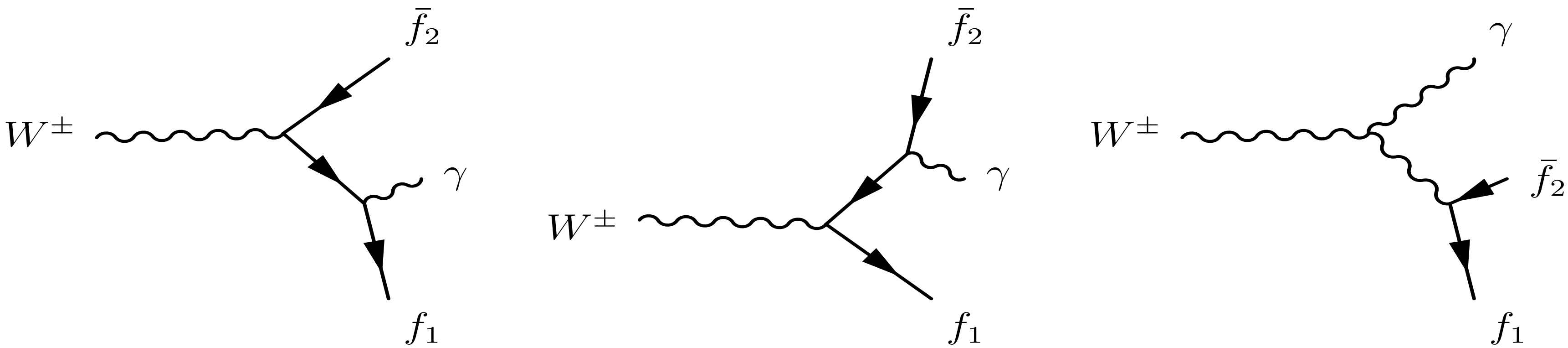
where $f_1, f_2 \in SU(2)_L$ doublets with $I_3^{f_1} = -I_3^{f_2}$.



Basic difference with Z-boson decay:

W is charged $\Rightarrow$ different electric charge flow and photon radiation from W-boson line

▷ Single photon radiation (in the unitary gauge):



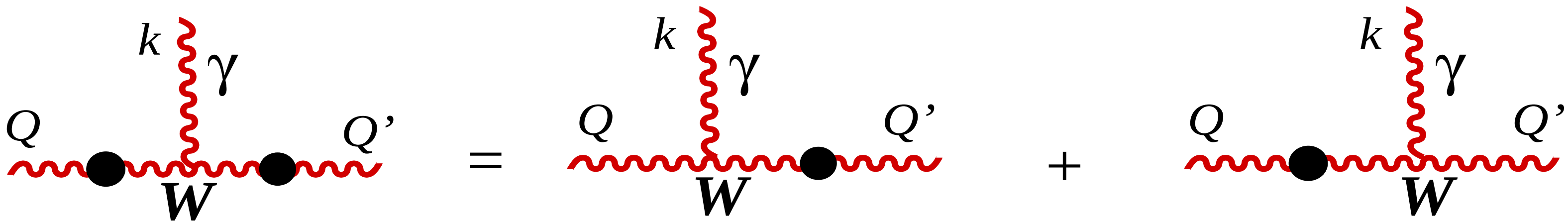
- In actual processes:

▶ W-bosons in the intermediate state $\rightarrow$ W width must be included (preferably through the complex-pole definition)

The YFS exponentiation in leptonic W decays

▷ Photon emission from intermediate W-boson line

⟶ Partial-fraction decomposition of W propagators:



$$\frac{1}{Q^2 - M_W^2 + iM_W\Gamma_W} \times \frac{1}{Q'^2 - M_W^2 + iM_W\Gamma_W} = \underbrace{\frac{1}{k^2 + 2kQ'}\,\frac{1}{Q'^2 - M_W^2 + iM_W\Gamma_W}}_{\leftarrow\ \text{radiative production}} + \underbrace{\frac{1}{Q^2 - M_W^2 + iM_W\Gamma_W}\,\frac{1}{k^2 - 2kQ}}_{\text{radiative decay}\ \rightarrow}$$

⟹ Radiative corrections can be decomposed into:

a) radiative corrections to W production,

b) radiative corrections to W decay,

c) their interferences (non-factorizable).

▷ In resonance W production the non-factorizable corrections are negligible

⟶ corrections to W-production and W-decay stages can be treated separately!

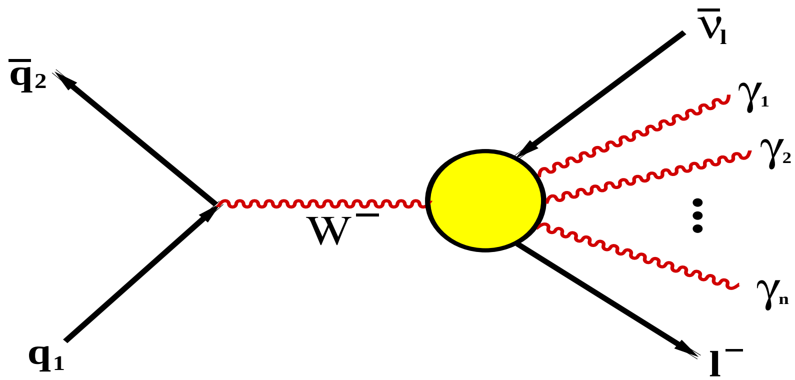
Here we investigate radiative corrections to leptonic W decays

The YFS exponentiation in leptonic W decays

▷ 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:

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

where

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

The YFS exponentiation in leptonic W decays

▷ More details:

- **YFS FormFactor** – 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:

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

$\longrightarrow$ Different t domain than in production or scattering processes!

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

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

▷ The virtual-photon IR function for $t > 0$ reads:

$$2\alpha\Re B(Q,q;m_\gamma) = \frac{\alpha}{\pi}\left\{[\,\nu A(Q,q)-1\,]\,\ln\frac{m_\gamma^2}{Mm} + \frac{1}{2}A_1(Q,q) - \nu A_3(Q,q)\right\},$$

$$A(Q,q) = \frac{1}{\lambda}\ln\frac{\lambda+\nu}{Mm},$$

$$A_1(Q,q) = \frac{M^2-m^2}{t}\ln\frac{M}{m} - \frac{2\lambda^2}{t}A(Q,q) - 2,$$

$$A_3(Q,q) = A(Q,q)\,\ln\frac{2\lambda}{Mm} + \frac{1}{\lambda}\left[\frac{1}{4}\left(\ln\frac{\lambda+\nu}{M^2} + 2\ln\frac{\lambda-\nu+M^2}{t}\right)\ln\frac{\lambda+\nu}{M^2}\right.$$
$$+\frac{1}{4}\left(\ln\frac{\lambda+\nu}{m^2} - 2\ln\frac{\lambda+\nu-m^2}{m^2}\right)\ln\frac{\lambda+\nu}{m^2}$$
$$\left.+\frac{1}{2}\ln\eta\ln(1+\eta) - \frac{1}{2}\ln\zeta\ln(1+\zeta) + \Re\mathrm{Li}_2(-\eta) - \Re\mathrm{Li}_2(-\zeta)\right],$$

$$\nu = Qq,\quad \lambda = \sqrt{(\nu-Mm)(\nu+Mm)},\quad Q^2 = M^2,\ q^2 = m^2,\ M > m\,,$$

$$t = M^2 + m^2 - 2\nu,\qquad Mm \le \nu < \frac{1}{2}\left(M^2+m^2\right),$$

$$\eta = \frac{m^2 t}{2\lambda(2\lambda+\nu-m^2)},\qquad \zeta = \frac{\lambda+\nu}{m^2}\,\eta\,.$$

▷ The real-photon IR function for $t > 0$ reads:

$$\tilde{B}(Q,q;m_\gamma,k_s) = \frac{\alpha}{\pi}\left\{[\,\nu A(Q,q)-1\,]\,\ln\frac{4k_s^2}{m_\gamma^2} - \frac{M^2}{2}A_4(Q,Q) - \frac{m^2}{2}A_4(q,q) - \nu A_4(Q,q)\right\}$$

$$A_4(p,p) = \frac{1}{p^2\beta}\ln\frac{1-\beta}{1+\beta}, \qquad \beta = \frac{|\vec{p}|}{p^0},$$

$$A_4(Q,q) = \frac{1}{\kappa}\left\{\ln\left|\frac{V^2}{t}\right|\sum_{i=0}^{1}(-1)^{n+1}\,[\,X(z_i;y_1,y_4,y_2,y_3)+R(z_i)\,]\right\},$$

$$R(z) = Y_{14}(z)+Y_{21}(z)+Y_{32}(z)-Y_{34}(z)+\frac{1}{2}X(z;y_1,y_2,y_3,y_4)X(z;y_2,y_3,y_1,y_4),$$

$$Y_{ij}(z) = 2Z_{ij}(z)+\frac{1}{2}\ln^2\left|\frac{z-y_i}{z-y_j}\right|, \qquad Z_{ij}(z) = \Re\mathrm{Li}_2\left(\frac{y_j-y_i}{z-y_i}\right),$$

$$X(z;a,b,c,d) = \ln\left|\frac{(z-a)(z-b)}{(z-c)(z-d)}\right|, \qquad z_0 = \frac{|\vec{q}|}{T}, \quad z_1 = \frac{|\vec{Q}|}{T}-1;$$

where

$$y_1 = -\frac{1}{2T}\left[T+\Omega-\frac{\omega\delta+\kappa}{t}V\right], \qquad y_2 = y_1 - \frac{\kappa V}{tT},$$

$$y_3 = -\frac{1}{2T}\left[T-\Omega+\frac{\omega\delta+\kappa}{V}\right], \qquad y_4 = y_3 + \frac{\kappa}{TV};$$

$$\kappa = \sqrt{(\omega^2-t)(\delta^2-t)}, \qquad \delta = M-m, \quad \omega = M+m,$$

$$T = \sqrt{\Delta^2-t}, \quad V = \Delta+T, \qquad \Delta = Q^0-q^0, \quad \Omega = Q^0+q^0.$$

The YFS exponentiation in leptonic W decays

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

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

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

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

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

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

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

The YFS exponentiation in leptonic W decays

▷ **Matrix elements:**

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

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

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

a) Born-level W production:

$$\mathcal{M}_P^{(0)}(\sigma_1,\sigma_2;\lambda) = -\frac{ieV_{f_1f_2}}{\sqrt{2}s_W}\,\omega_{-\sigma_1}(p_1)\,\omega_{\sigma_2}(p_2)\,\sigma_2\,S\left(p_2,\epsilon_W^*(Q,\lambda),p_1\right)^-_{-\sigma_2,\sigma_1}$$

b) Born-level W decay:

$$\mathcal{M}_D^{(0)}(\lambda;\tau_1,\tau_2) = -\frac{ieCV_{f_1f_2}}{\sqrt{2}s_W}\,\omega_{-\tau_1}(q_1)\,\omega_{\tau_2}(q_2)\,\tau_2\,S\left(q_1,\epsilon_W(Q,\lambda),q_2\right)^-_{\tau_1,-\tau_2}$$

c) W decay with single real-photon radiation:

$$\mathcal{M}_D^{(1)}(\lambda;\tau_1,\tau_2,\kappa) = -\frac{ie^2CV_{f_1f_2}}{\sqrt{2}s_W}\,\omega_{-\tau_1}(q_1)\,\omega_{\tau_2}(q_2)\,\tau_2$$

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

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

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

→ **Spin amplitudes evaluated numerically for arbitrary fermion masses!**

The Monte Carlo event generator WINHAC

- **Monte Carlo algorithm for multiphoton radiation:**

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

▶ Our previous MC generators:

a) ISR in annihilation processes ⟶ initial-beams CMS

b) FSR in neutral boson decays ⟶ final-state fermion-pair CMS

c) Bhabha scattering ⟶ electron/positron Breit frames

▶ W-boson decay ⟶ W-rest frame (seems most natural)

▷ Construction of MC algorithm:

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

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

⟶ Construction of a MC event in terms of particle flavours and 4-momenta.

▷ MC event generator **WINHAC**: W. Płaczek and S. Jadach, Eur. Phys. J. **C29** (2003) 325.

⟶ 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) from the **PDFLIB** package. ⟶ http://cern.ch/placzek

Numerical results – parton level

• Basic tests at the parton level

▷ Test of spin amplitudes and MC algorithm:

⟶ To reproduce Born-level and $\mathcal{O}(\alpha)$ results from the YFS exponentiation

a) Born cross section:

$$\sigma_0^{\rm WH} = \int \frac{d^3 q_l}{q_l^0}\frac{d^3 q_\nu}{q_\nu^0}\,\rho_0^{(0)}\,e^{-Y}$$

$$\sigma_0^{\rm An} = \frac{\alpha^2\pi|V_{ij}|^2}{36 s_W^4} \times \frac{s}{(s-M_W^2)^2+M_W^2\Gamma_W^2}$$

Calculation	σ_0^{tot} [nb]		
	e	μ	τ
Analytical (massless)	8.8872	8.8872	8.8872
WINHAC	$8.8869\,(2)$	$8.8873\,(2)$	$8.8808\,(2)$

b) $\mathcal{O}(\alpha)$ corrected cross section:

$$\sigma_1^{\rm WH} = \int \frac{d^3 q_l}{q_l^0}\frac{d^3 q_\nu}{q_\nu^0}\,\delta^{(4)}(p_1+p_2-q_l-q_\nu)\,\bar\beta_0^{(0)}\left[1+\delta_{\rm QED}^{(1)}+Y\right]$$
$$+\int \frac{d^3 q_l}{q_l^0}\frac{d^3 q_\nu}{q_\nu^0}\frac{d^3 k}{k^0}\,\delta^{(4)}(p_1+p_2-q_l-q_\nu-k)\left[\bar\beta_1^{(1)}+\tilde S\bar\beta_0^{(0)}\right]\theta(k^0-k_s)\,,$$

$$\delta_1^{\rm An} = \frac{\alpha}{\pi}\left(\frac{77}{24}-\frac{\pi^2}{3}\right) \approx -1.89\times 10^{-4} \quad \text{(massless)}$$

Calculation	$\delta_1 = \sigma_1^{tot}/\sigma_0^{tot} - 1$		
	e	μ	τ
WINHAC	$-1.5\,(3)\times 10^{-4}$	$-2.2\,(3)\times 10^{-4}$	$-0.3\,(2)\times 10^{-4}$

Numerical results – parton level

▶ Hard photon spectrum at $\mathcal{O}(\alpha)$

$$\delta_1^h(k_0) = \frac{1}{\sigma_1^{tot}} \int_{E_0} dE_\gamma \frac{d\sigma_1}{E_\gamma} \times 100\%$$

$$E_0 = k_0 \times E_{\rm CM}/2, \qquad E_{\rm CM} = 90 \text{ GeV}$$

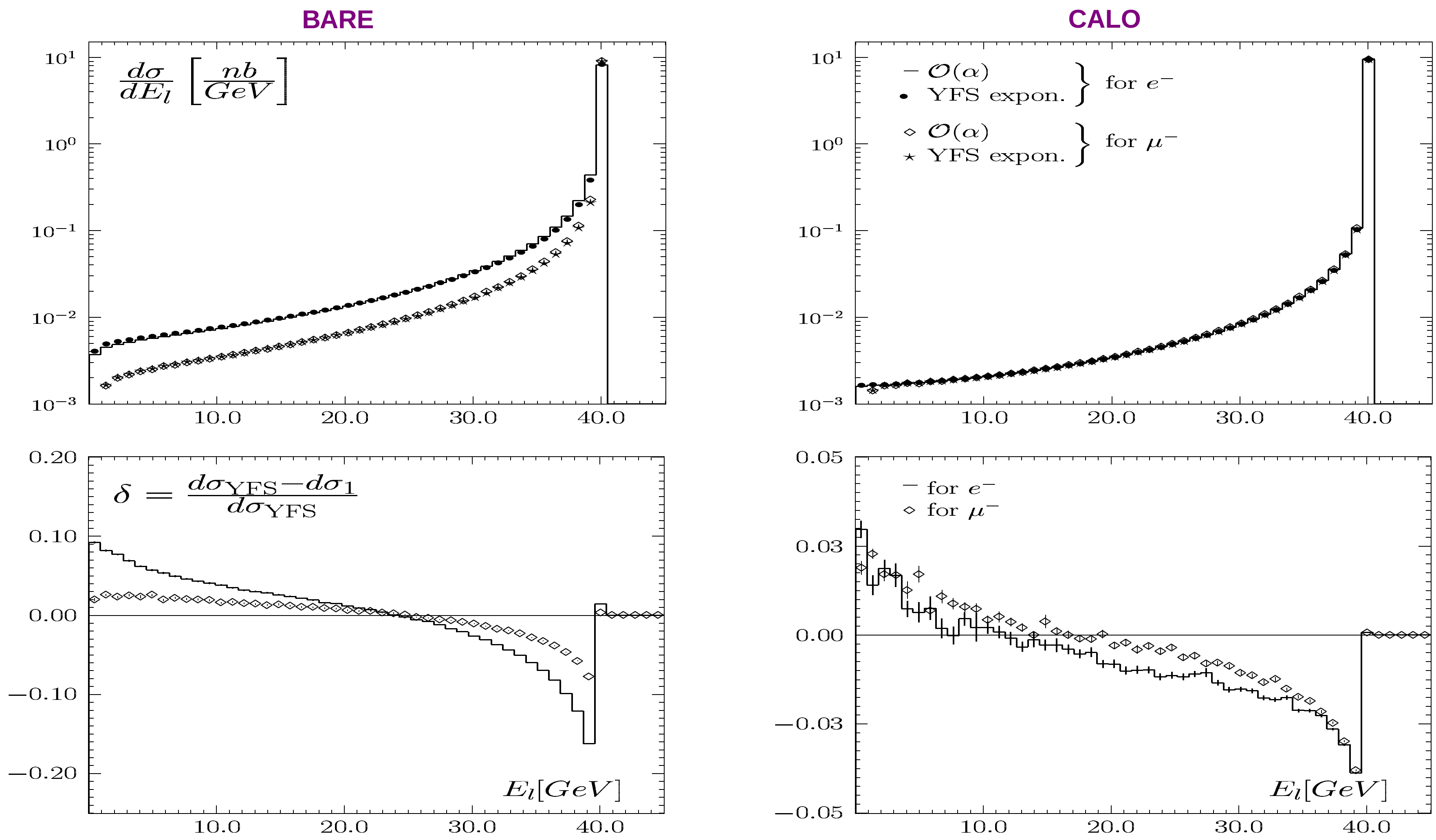
B&K: Berends & Kleiss, ZP **C27** (1985) 365

k_0	e		μ	
	WINHAC	B&K	WINHAC	B&K
0.01	19.69 (3)	19.7	10.11 (2)	10.1
0.05	11.61 (2)	11.6	5.92 (1)	5.9
0.10	8.31 (2)	8.3	4.22 (1)	4.2
0.15	6.47 (2)	6.5	3.27 (1)	3.3
0.20	5.23 (1)	5.2	2.63 (1)	2.6
0.30	3.61 (1)	3.6	1.80 (1)	1.8
0.40	2.57 (1)	2.6	1.27 (1)	1.3
0.50	1.84 (1)	1.8	0.91 (1)	0.9
0.60	1.29 (1)	1.3	0.63 (1)	0.6
0.70	0.86 (1)	0.9	0.42 (1)	0.4
0.80	0.52 (1)	0.5	0.25 (1)	0.2
0.90	0.24 (1)	0.2	0.11 (1)	0.1

WINHAC reproduces very well Born and $\mathcal{O}(\alpha)$ calculations!

Numerical results – parton level

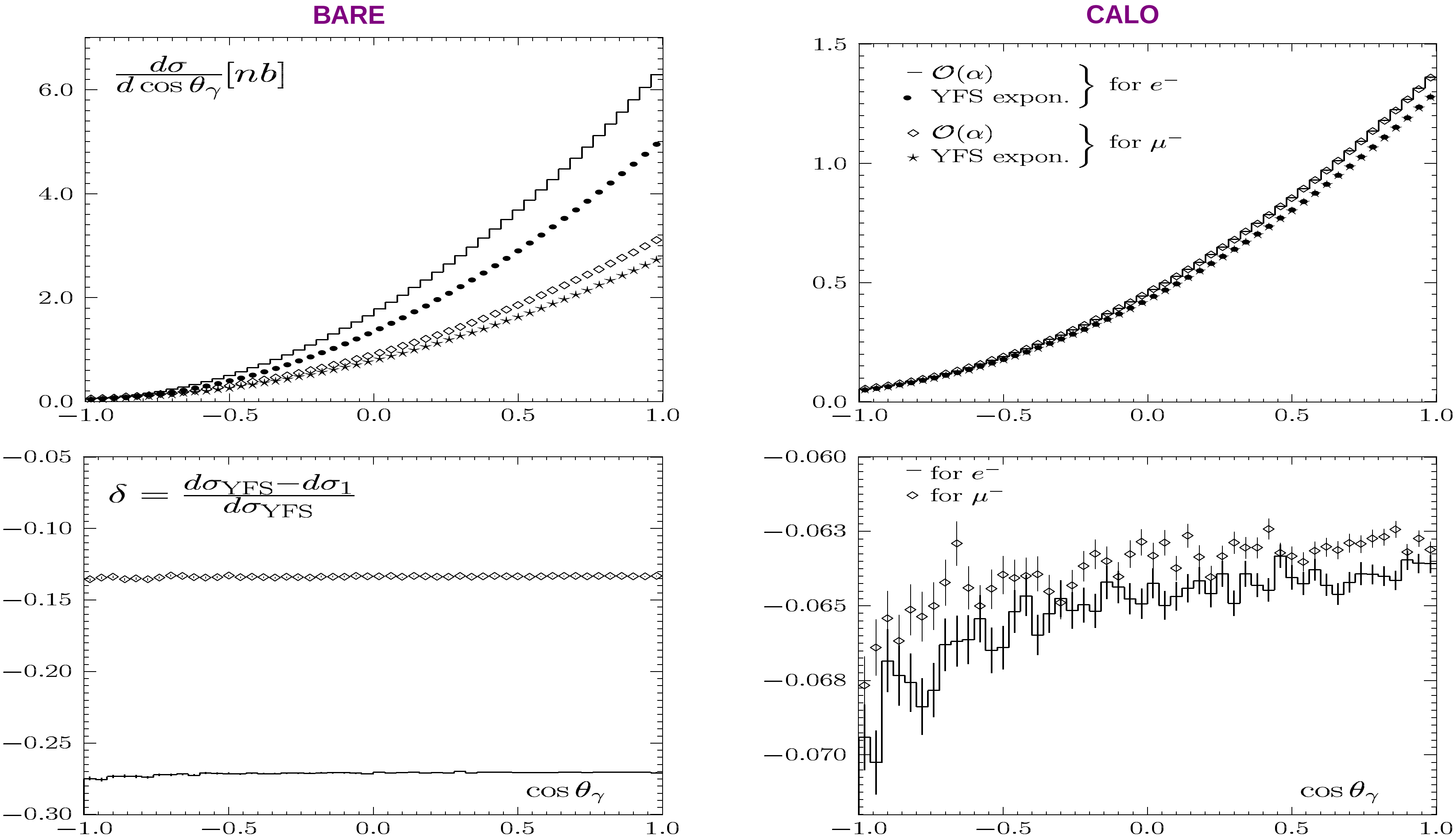
- **Parton level distributions – higher-order FSR effects:**
  - ▷ Charged-lepton energy E_l



CALO: Photons recombined with charged lepton if $\angle(l,\gamma) \leq 5^\circ$.

Numerical results – parton level

▷ *Cosine* of hardest-photon polar angle $\cos\theta_\gamma$:



CALO: Photons recombined with charged lepton if $\angle(l,\gamma) \leq 5^\circ$.

Higher-order QED FSR effects are sizeable and acceptance dependent!

Comparisons of two indepenedent 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. Pł aczek 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:** $\longrightarrow$ Measurement

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

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 jest 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 $E_{\rm CMS}^{q\bar{q}'} = M_W$

Program	$\sigma^{\rm tot}$ [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	$-0.2\,(1.4) \times 10^{-5}$	$-1.11\,(0.07) \times 10^{-4}$	$-2.16\,(0.06) \times 10^{-4}$

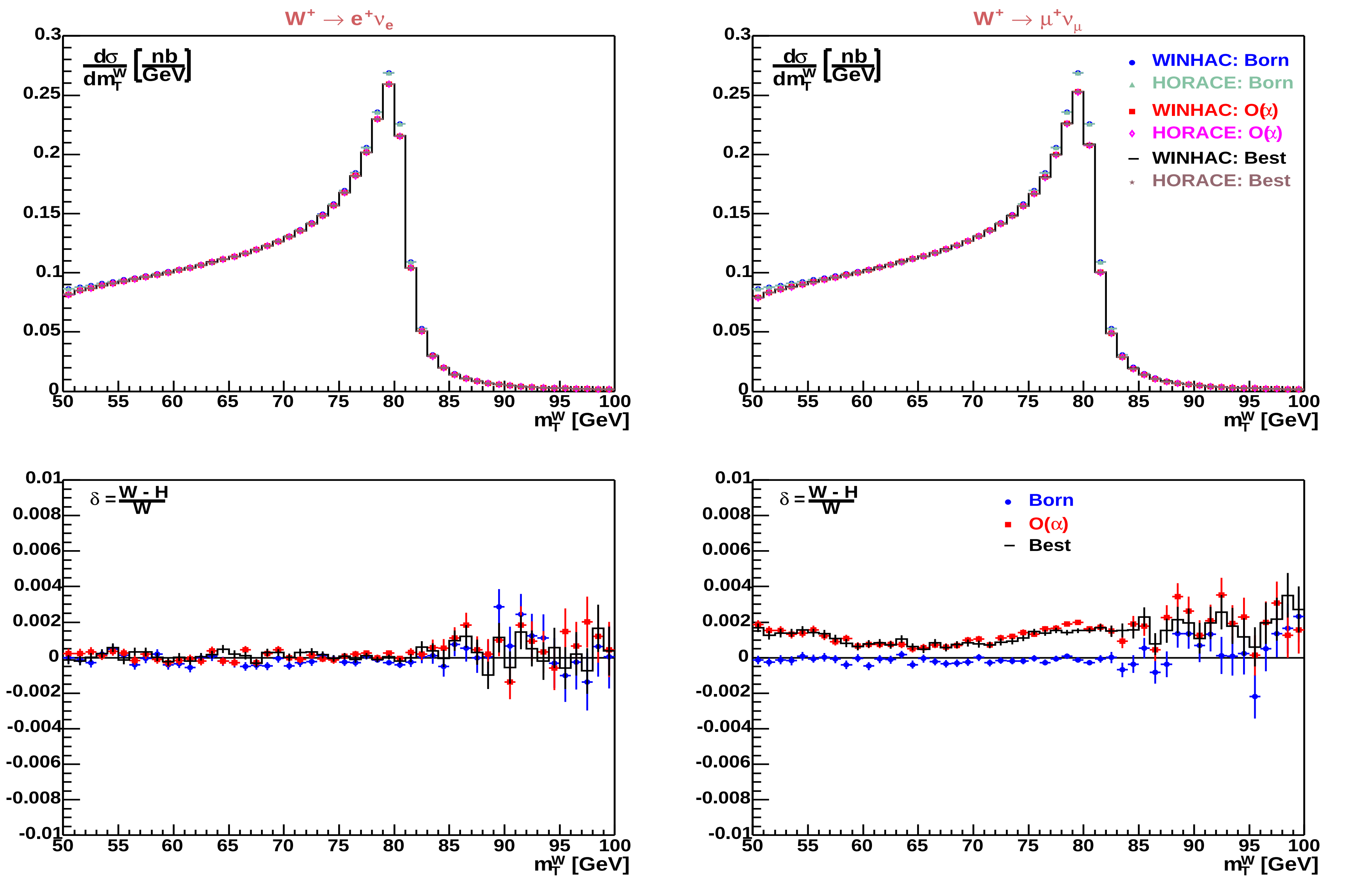
WINHAC ↔ HORACE comparisons @ LHC

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	$-0.9\,(4.3) \times 10^{-5}$	$1.36\,(0.05) \times 10^{-3}$	$1.22\,(0.05) \times 10^{-3}$

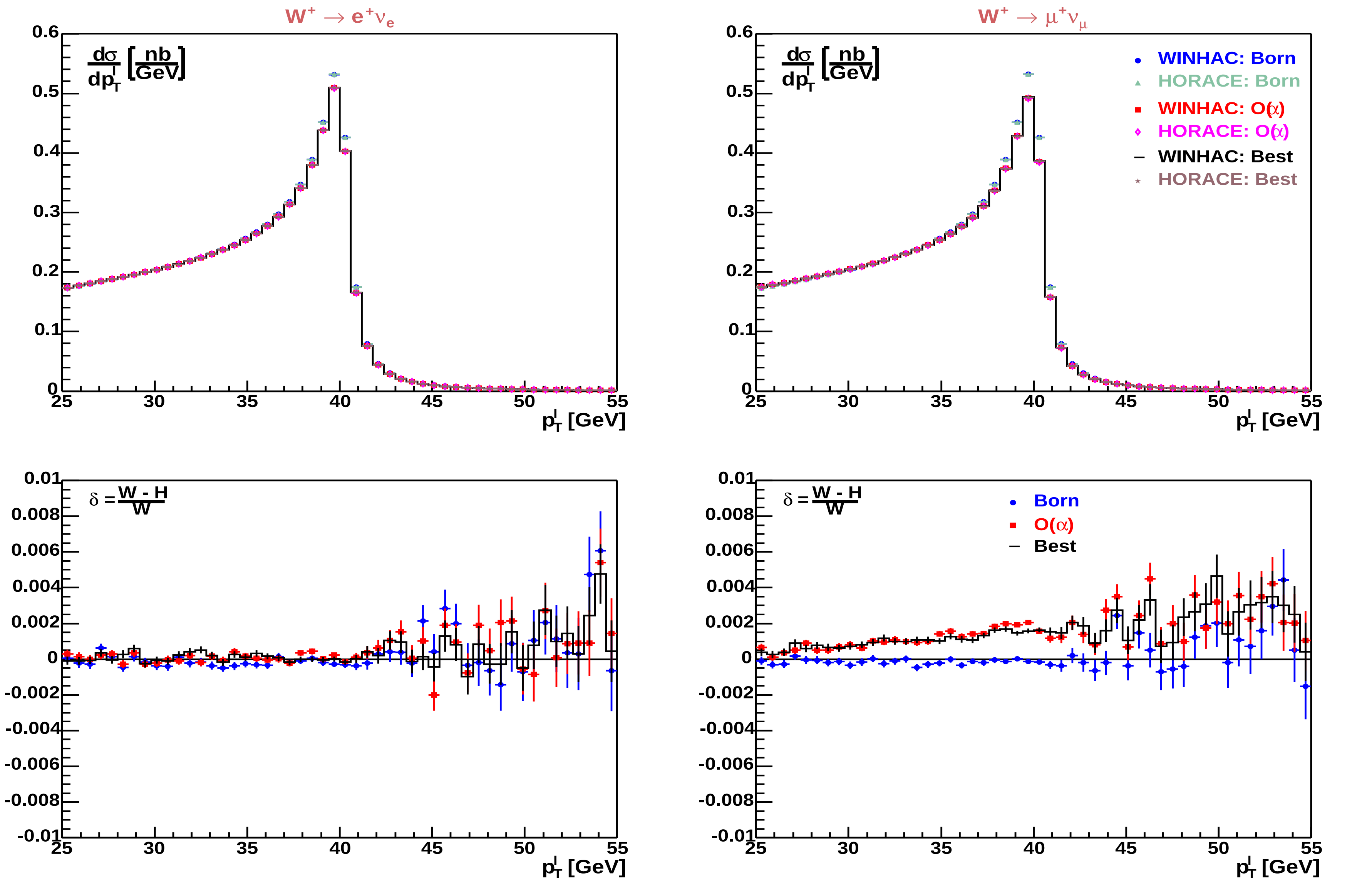
WINHAC ↔ HORACE comparisons @ LHC

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



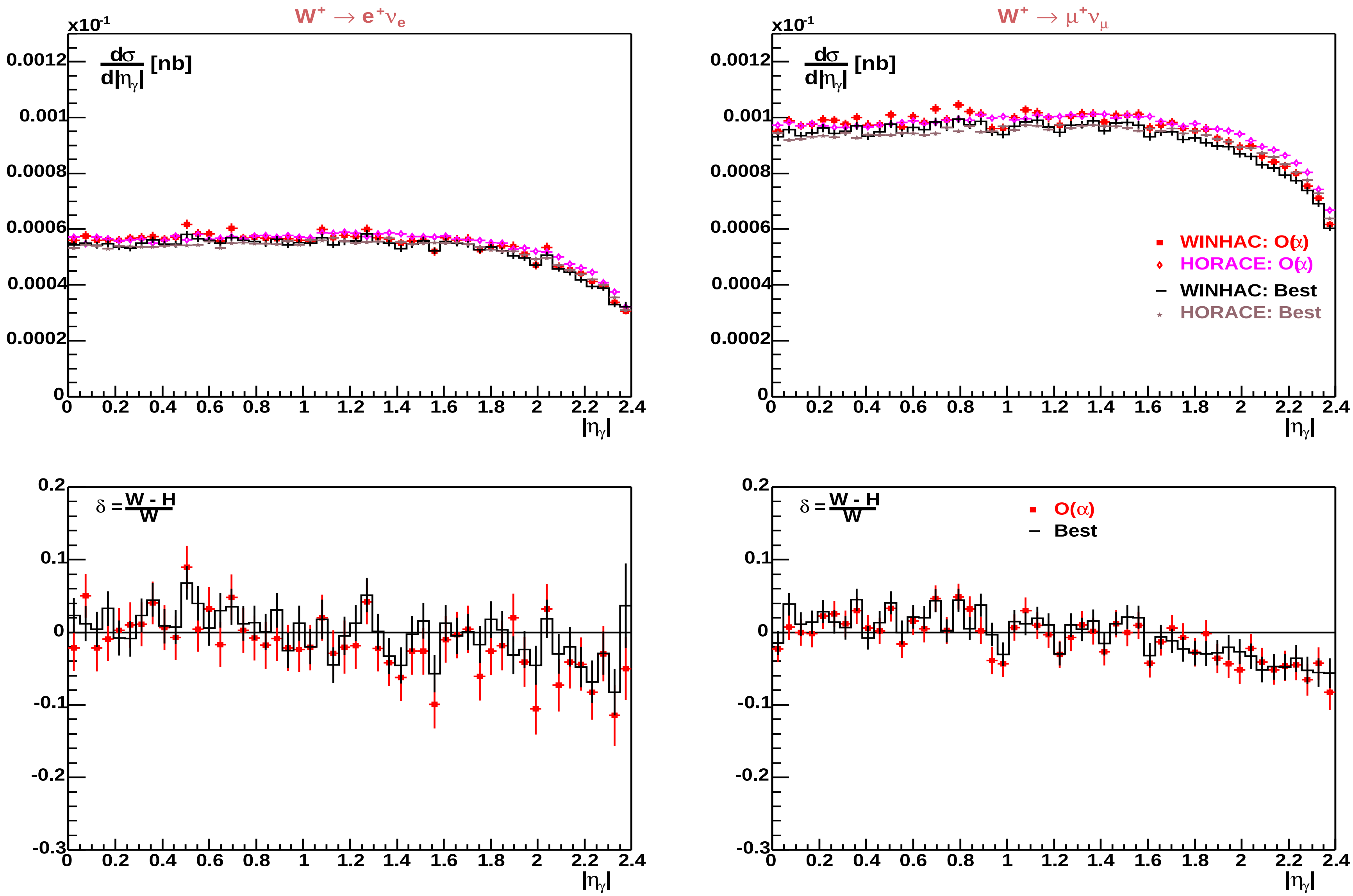
WINHAC ↔ HORACE comparisons @ LHC

Charged lepton transverse momentum p_T^l for: $W^+ \to l^+ \nu_l$



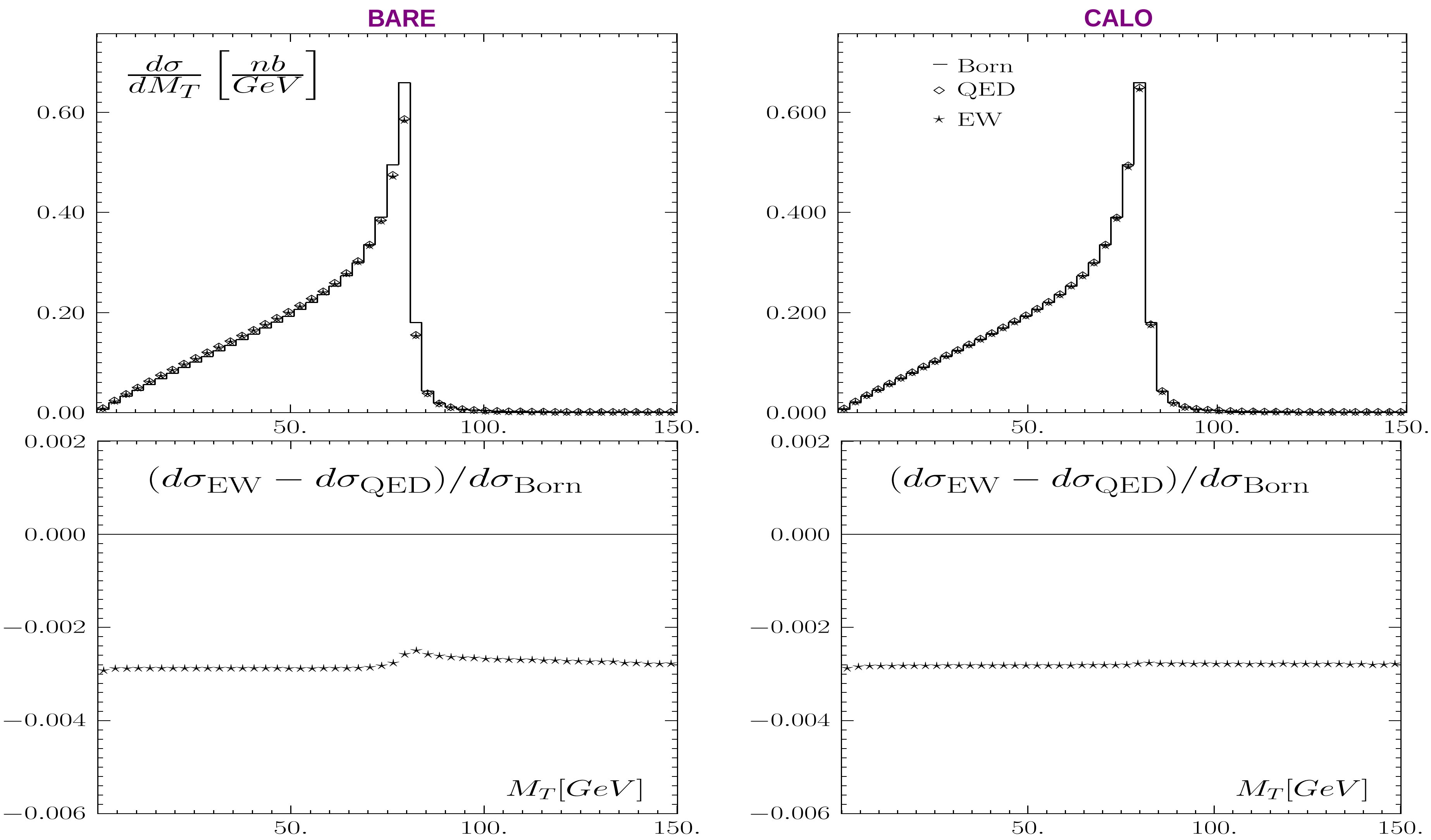
WINHAC ↔ HORACE comparisons @ LHC

Hardest photon pseudorapidity η_γ for: $W^+ \to l^+\nu_l$



▷ Cuts and acceptances like in the parton-level tests

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



Summary

- We calculated multiphoton radiation in leptonic W-boson decays in the Yennie–Frautschi–Suura exclusive exponentiation scheme.
- An appropriate Monte Carlo algorithm has been constructed.
- The above has been implemented in the MC event generator **WINHAC** for single W-boson production in hadronic collisions (Tevatron/LHC).
  - ▷ Acceptance efficiency: $\approx 50\%$
  - ▷ CPU time: $\approx 10,000$ events per second on Pentium IV, 2.4 GHz.
- Cross-checks with independent calculations at the parton level have been performed up to $\mathcal{O}(\alpha)$.
- Comparisons with the independent MC program HORACE have been performed at the parton- as well as at the hadron-level. A good agreement has been found for QED FSR effects at $\mathcal{O}(\alpha)$ and also for higher-order corrections.
  - ▷ Higher-order FSR corrections (exponentiation) can be important for precision W-boson mass measurement at LHC for BARE-like event selections.
- $\mathcal{O}(\alpha)$EW correction for leptonic W decays at the LHC are at the level of 0.3%

Outlook

- Inclusion of $\mathcal{O}(\alpha)$ corrections in the YFS scheme for the full process:

$$q\bar{q}' \to W^{\pm} \to l\nu_l$$

– currently under way (YFS exponentiation for initial-final interferences done, $\mathcal{O}(\alpha)$ corrections with $\overline{\mathrm{MS}}$-subtracted QED ISR done for the electron channel).

▷ In collaboration with the SANC team (D. Bardin et al., JINR Dubna).

- Inclusion of QCD effects in W production, e.g. p_T^W distribution is important for M_W measurement through W transverse mass!

▷ QCD ISR parton shower (according to DGLAP, CCFM, etc.) – currently our main effort (with good progress!)

▷ NLO QCD for the hard process – important for high-p_T^W regime.

- Interfacing with hadronization packages (PYTHIA, HERWIG, etc.).

- A similar MC program for single-Z production: ZINHAC (work in progress).

- MC programs for vector-boson pair production at hadron colliders – based on KoralW, YFSWW and YFSZZ for e^+e^- colliders.