Impact of QED/EW corrections on mW measurement: WINHAC

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Outline

1. WINHAC version 1.37
   - Basics
   - QED effects
   - EW corrections
   - QCD effects
2. Cross-checks
   - QED FSR
   - Electroweak (EW) corrections
3. EW corrections and QCD parton shower
   - Total EW and “weak” corrections + QCD PS
   - Higher-order (beyond NLO) QED corrections
   - Treatment of QED ISR
   - Beyond QED FSR
4. Outlook
   - Matching with NLO QCD
   - WINHAC++/ZINHAC

▷ WP and S. Jadach, EPJ **C39** (2003) 325; WP, PoS **EPS-HEP2009** (2009) 340; WP, S. Jadach, M.W. Krasny, Acta Phys. Pol. **B44** (2013) 2171.
→ 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.

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

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

  $\rightarrow$ Multiphoton radiation.
  $\rightarrow$ Precise description of one hard and arbitrary many soft photons.
  $\rightarrow$ Two and more hard photons described less precisely, but generated.
  $\triangleright$ **ISR** (initial-state radiation) subtructed in a gauge-invariant way – to be generated by parton-shower MC (PYTHIA, HERWIG, ...) together with QCD effects.
- In **neutral-current DY processes** (with $Z + \gamma$) multiphoton **FSR** generated by **PHOTOS**; as option also for charged-current DY processes (for tests).

  $\rightarrow$ Resummation of LL effects improved with ME corrections.

- $\mathcal{O}(\alpha)$ electroweak (EW) corrections from SANC group (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.

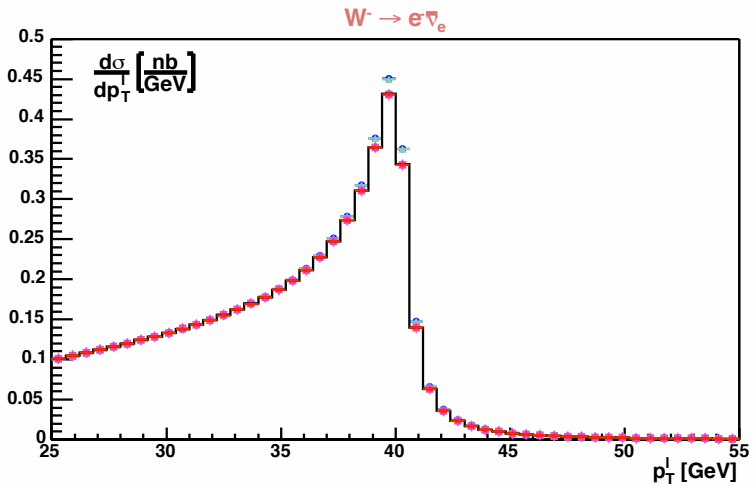
  in a gauge-invariant way.

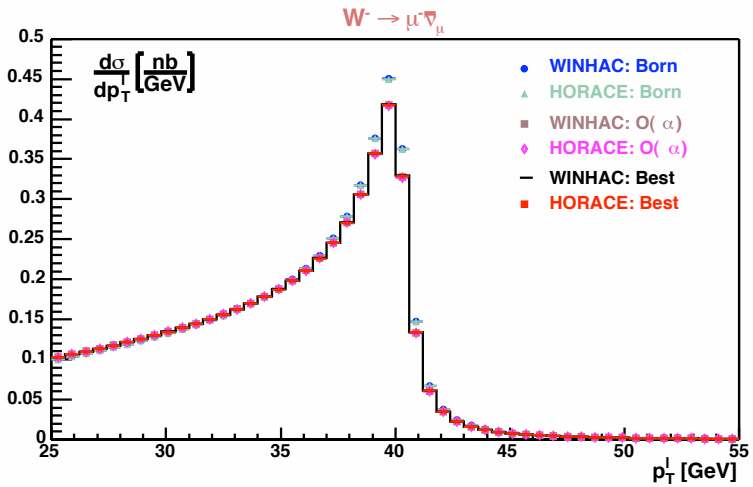
$\rightarrow$ D. Bardin, S. Bondarenko, S. Jadach, L. Kalinovskaya, WP, Acta Phys. Pol. **B40** (2009) 75.

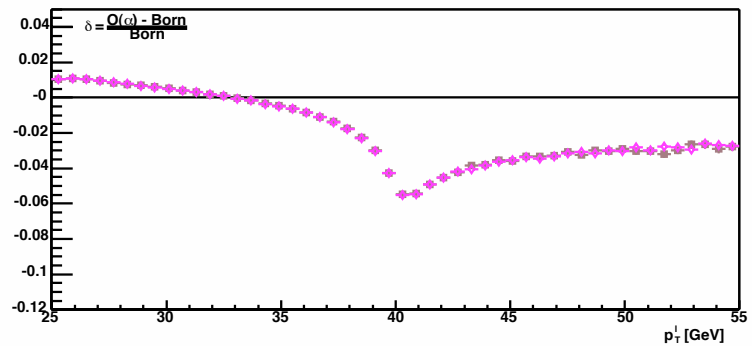
- Interface through **Les Houches Accord** (LHA) file format to QCD/QED parton shower (PS) generator PYTHIA 6.4 (or any other PS generator using this format).
  a) ordinary disk files can be used,
  b) UNIX named (FIFO) pipes instead of files can be used: faster (communication through RAM), simpler (generation 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):
  * less universal (for some limited PYTHIA set-up),
  – useful for some dedicated studies, eg. **M_W measurement**
    ▷ see: M.W. Krasny et al., EPJ **C69** (2010) 379 and refs. therin,
  – includes correction for PYTHIA6 transverse lepton momenta distributions $\rightarrow$ good agreement with MC@NLO,
    ▷ see: M.W. Krasny and WP, Acta Phys. Pol. **B43** (2012) 1981.

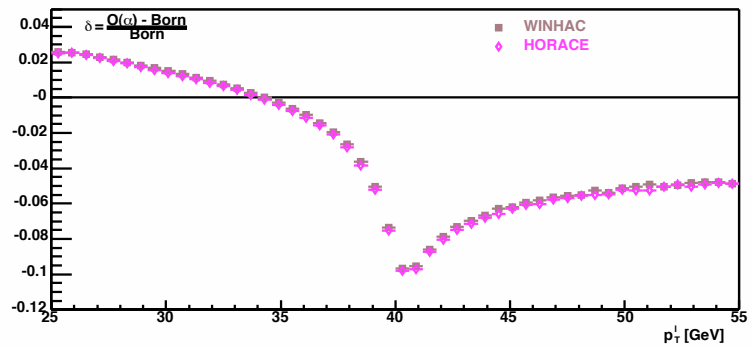
- Comparisons with MC event generator **HORACE** at $\mathcal{O}(\alpha)$ and with higher-order corrections (exponentiation, LL-resummation – PS-type algorithm)
  - $\rightarrow$ agreement at the level 0.1% or better for total cross sections as well as main distributions.
  - $\triangleright$ C.M. Carloni Calame, S. Jadach, G. Montagna, O. Nicrosini and WP, Acta Phys. Pol. **B35** (2004) 1643.

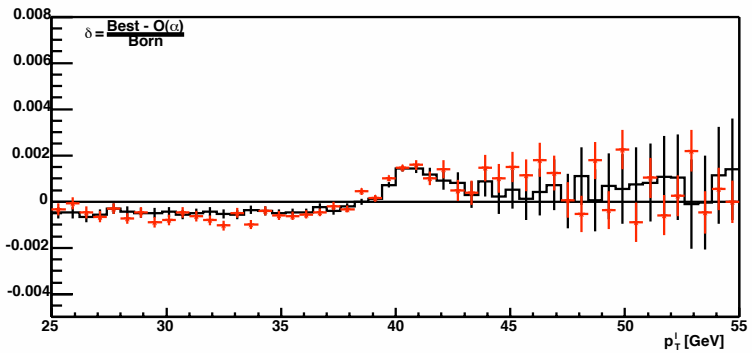
QED FSR

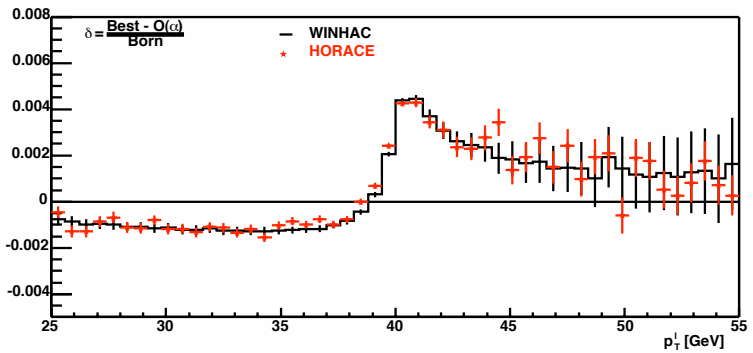

W⁻ → e⁻ν̄e
dσ/dp_T^l [nb/GeV]
p_T^l [GeV]


W⁻ → μ⁻ν̄μ
dσ/dp_T^l [nb/GeV]
WINHAC: Born
HORACE: Born
WINHAC: O(α)
HORACE: O(α)
WINHAC: Best
HORACE: Best
p_T^l [GeV]


δ = O(α) - Born / Born
p_T^l [GeV]


δ = O(α) - Born / Born
WINHAC
HORACE
p_T^l [GeV]


δ = Best - O(α) / Born
p_T^l [GeV]


δ = Best - O(α) / Born
WINHAC
HORACE
p_T^l [GeV]

- Comparisons with **SANC** MC integrator (based on VEGAS) at $\mathcal{O}(\alpha)$

  $\rightarrow$ agreement below 0.1% for total cross sections as well as main distributions for "YFS-like" ISR-subtraction scheme.

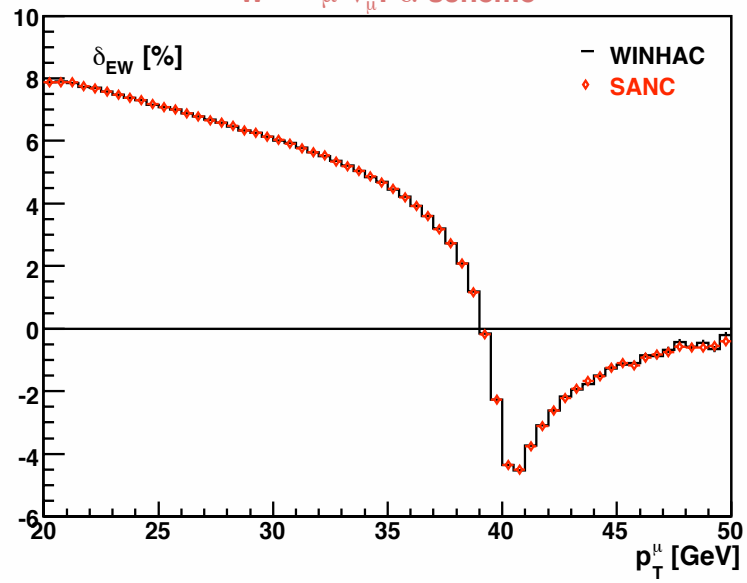
  $\triangleright$ D. Bardin, S. Bondarenko, S. Jadach, L. Kalinovskaya, WP, Acta Phys. Pol. **B40** (2009) 75.

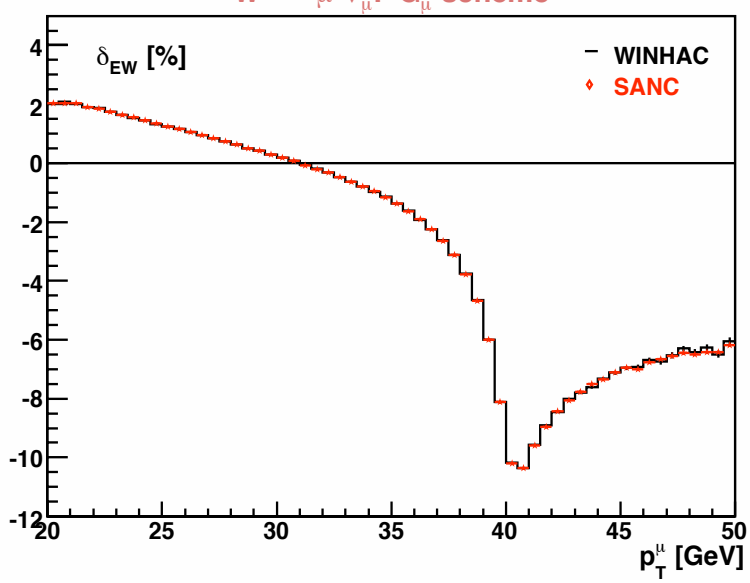
Total cross sections:

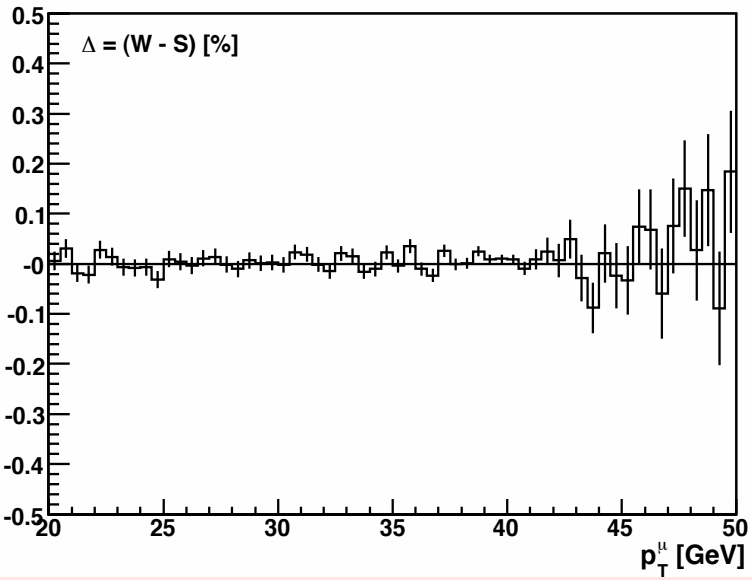
LHC, $pp \to W^+ + X \to e^+\nu_e + X$						
	α-scheme			G_μ-scheme		
	LO [pb]	NLO [pb]	$\delta_{\rm EW}$ [%]	LO [pb]	NLO [pb]	$\delta_{\rm EW}$ [%]
SANC-$\overline{\rm MS}$	5039.19(2)	5139.33(5)	1.987(1)	—	—	—
SANC-YFS	5039.19(2)	5137.53(3)	1.952(1)	5419.18(2)	5208.48(3)	−3.888(1)
WINHAC	5039.06(11)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

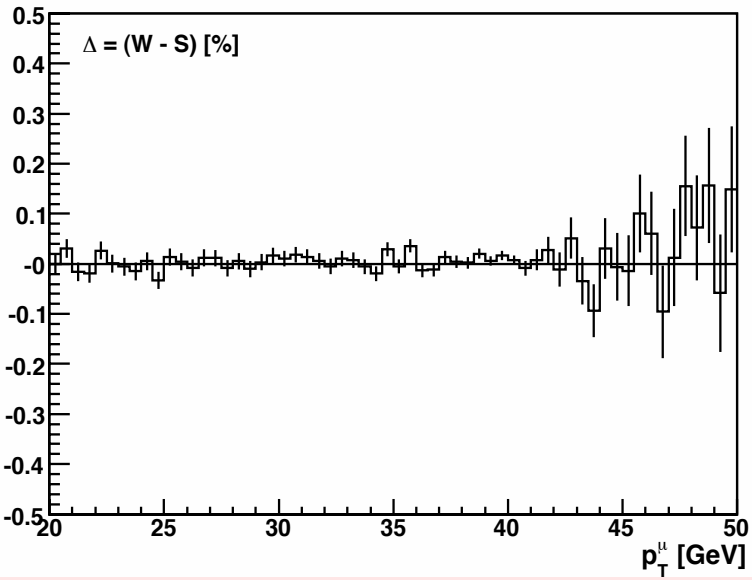
LHC, $pp \to W^+ + X \to \mu^+\nu_\mu + X$						
	α-scheme			G_μ-scheme		
	LO [pb]	NLO [pb]	$\delta_{\rm EW}$ [%]	LO [pb]	NLO [pb]	$\delta_{\rm EW}$ [%]
SANC-$\overline{\rm MS}$	5039.20(2)	5229.58(6)	3.778(1)	—	—	—
SANC-YFS	5039.20(2)	5227.73(2)	3.741(1)	5419.19(2)	5305.47(3)	−2.098(1)
WINHAC	5039.03(11)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

Electroweak (EW) corrections









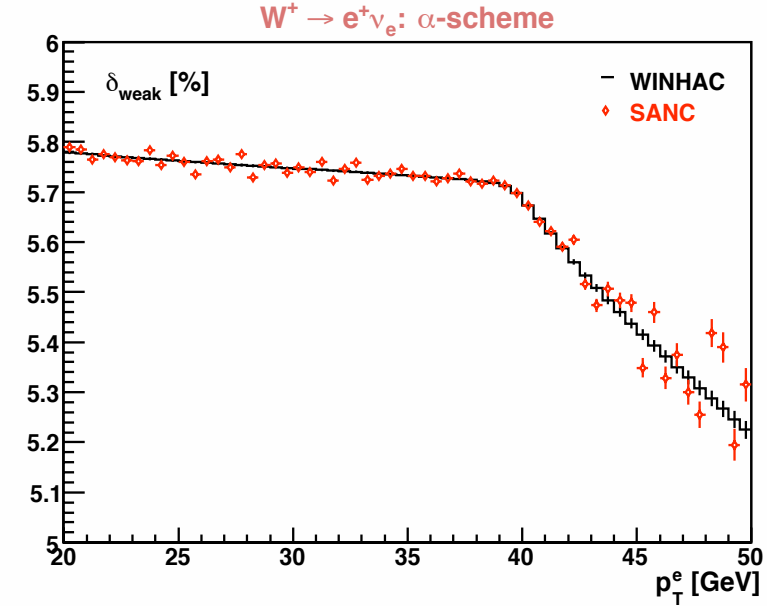
- $\mathcal{O}(\alpha)$ **"weak"** (virtual) corrections
  $\rightarrow$ agreement at the level 0.01% or better!

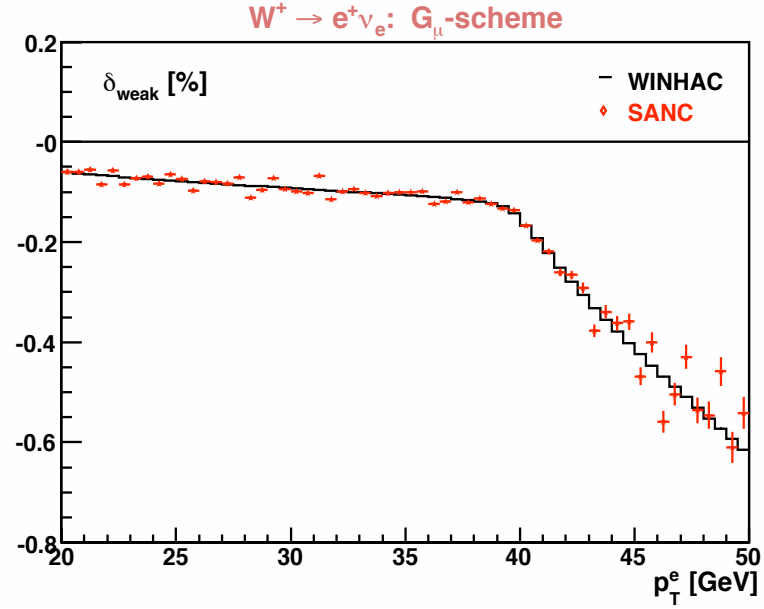
$$\delta_{\text{weak}} = \delta^{\text{EW}}_{\text{soft-virt}} - \delta^{\text{YFS}}_{\text{soft-virt}}\,, \qquad \delta^{\text{YFS}}_{\text{soft-virt}} = \delta^{\text{YFS}}_{\text{ISR}} + \delta^{\text{YFS}}_{\text{Int}} + \delta^{\text{YFS}}_{\text{FSR}}\,,$$

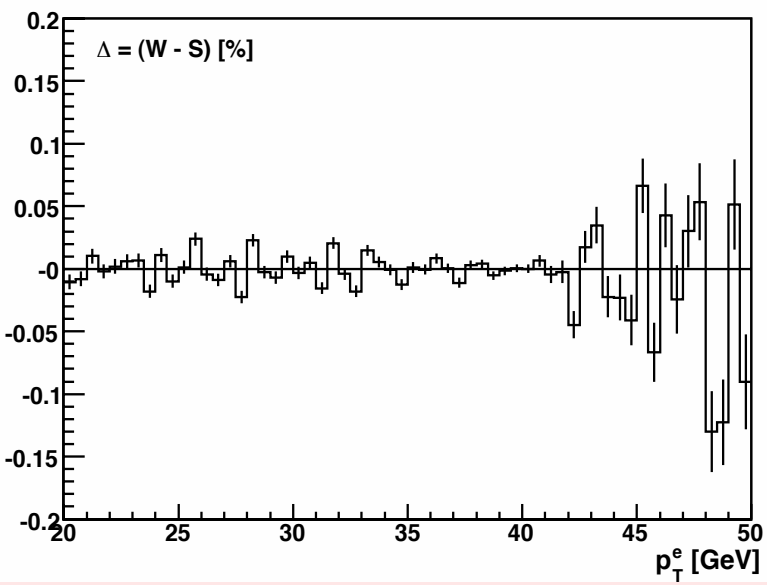
where $\delta^{\text{YFS}}_{\text{soft-virt}}$ – gauge-invariant dominant QED corrections
(YFS IR factor + remaining QED corr. $\sim \frac{\alpha}{2\pi} Q_f [\ln(s/m_f^2) - 1]$)

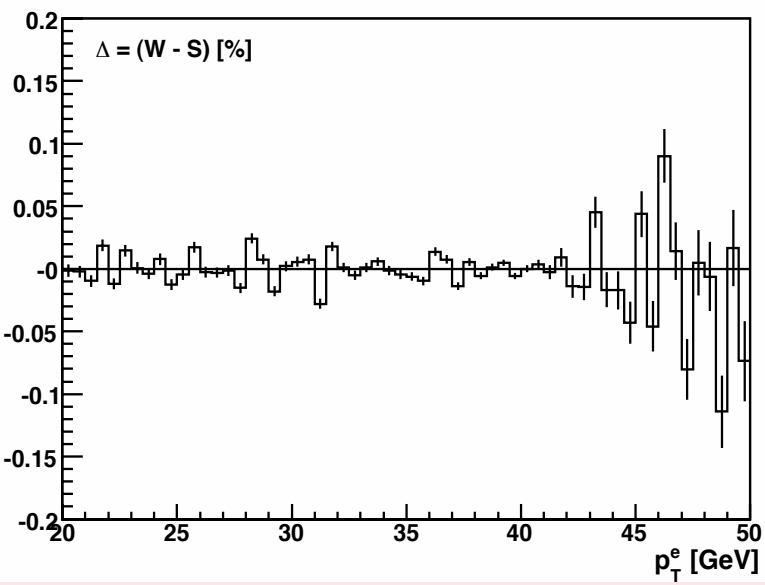
δ_{weak} [%]		
LHC, $pp \to W^+ + X \to e^+\nu_e + X$		
	α-scheme	G_μ-scheme
SANC	5.7223(2)	−0.1175(2)
WINHAC	5.7220(3)	−0.1177(0)
LHC, $pp \to W^+ + X \to \mu^+\nu_\mu + X$		
	α-scheme	G_μ-scheme
SANC	5.7286(2)	−0.1109(2)
WINHAC	5.7220(2)	−0.1177(0)

Electroweak (EW) corrections









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

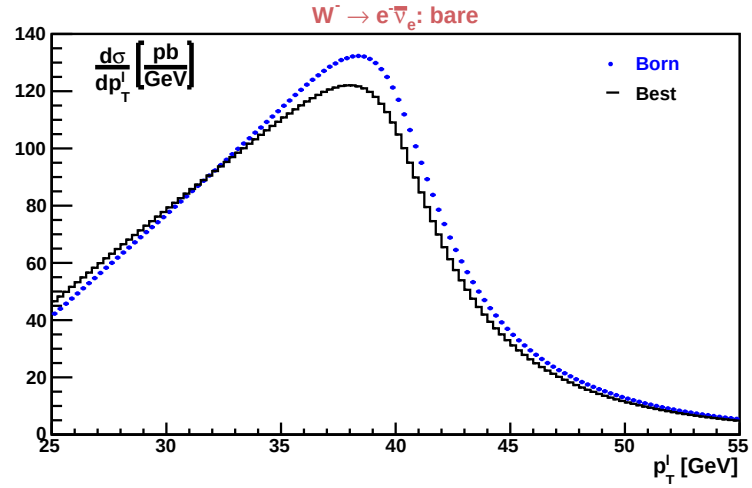
- $\sqrt{s} = 8\,\text{TeV}$,
- $p_T^l > 25\,\text{GeV}, \quad |\eta_l| < 2.5, \quad E_T^{\text{mis}} > 25\,\text{GeV}, \quad l = e, \mu$,
- **"calo"** selection criteria:

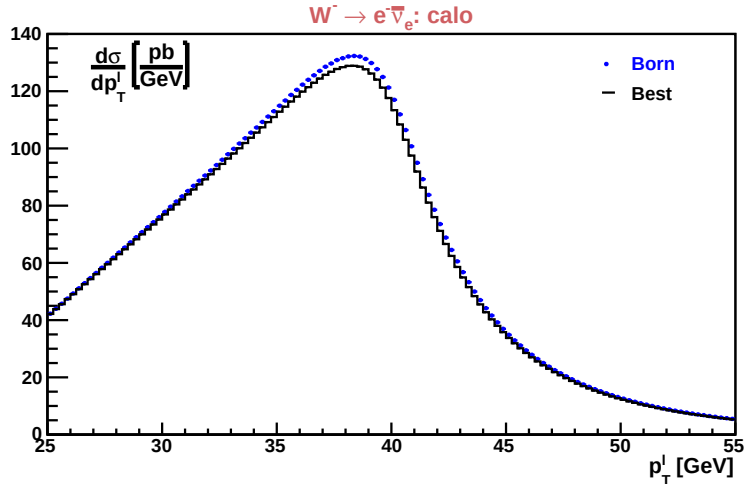
electrons	muons
combine e and γ four vectors, if $\Delta R(e,\gamma) < 0.1$	reject events with $E_\gamma > 2\,\text{GeV}$ for $\Delta R(\mu,\gamma) < 0.1$
reject events with $E_\gamma > 0.1\,E_e$ for $\Delta R(e,\gamma) < 0.4$	reject events with $E_\gamma > 0.1\,E_\mu$ for $\Delta R(\mu,\gamma) < 0.4$

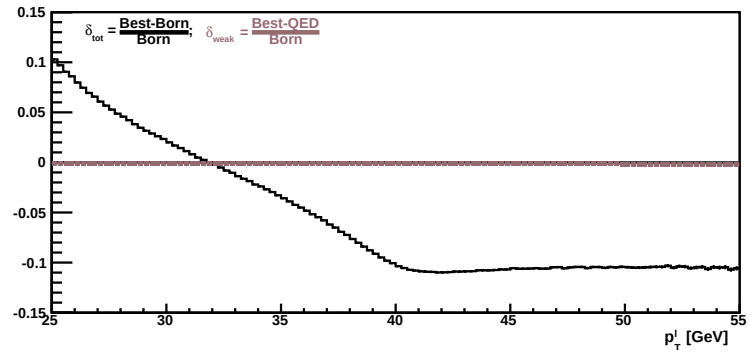
$$\Delta R(l,\gamma) = \sqrt{(\phi_l - \phi_\gamma)^2 + (\eta_l - \eta_\gamma)^2}.$$

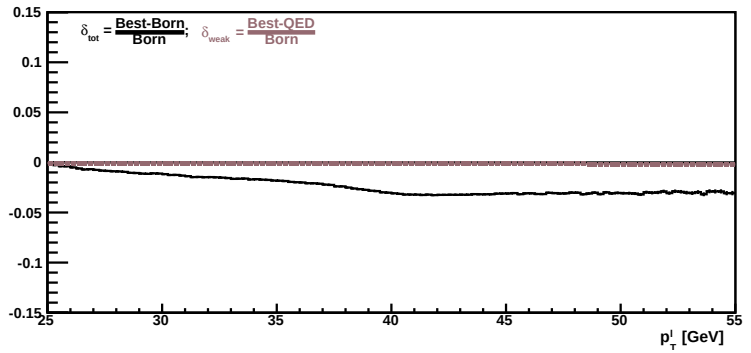
- No detector smearing.
- E_T^{mis} and M_T^W constructed using neutrino four momenta.
- G_μ**-scheme.**
- **MSTW2008NLO** parametrisation for PDFs.
- **Perugia 2011** tune (ITUNE = 350) used in PYTHIA 6.4.26.

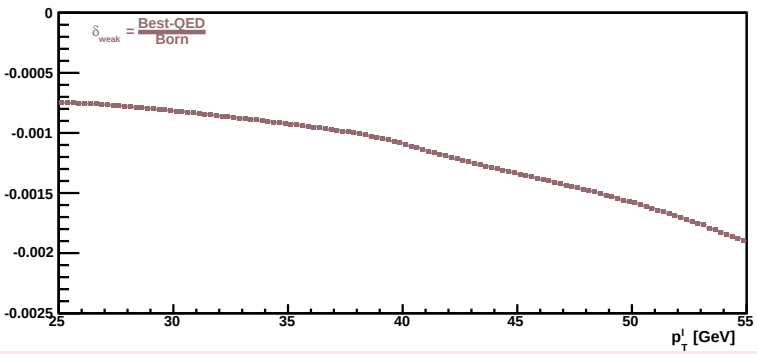
Total EW and "weak" corrections + QCD PS

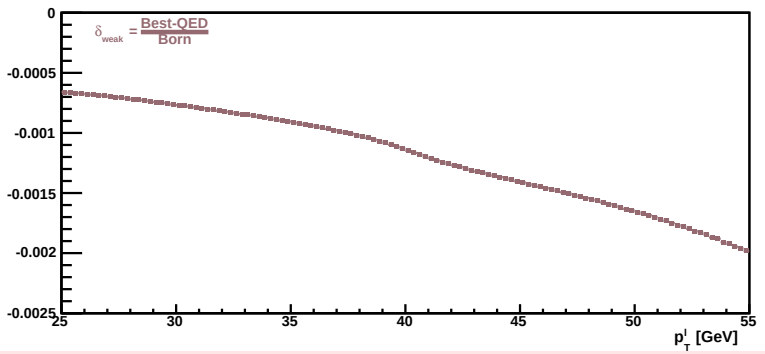




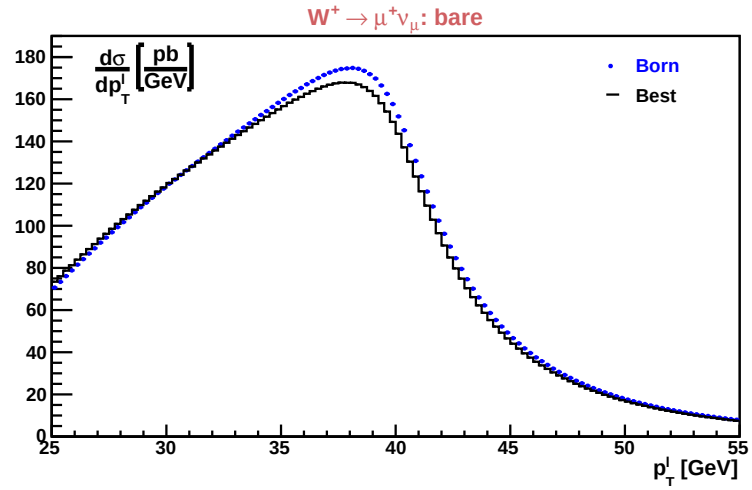


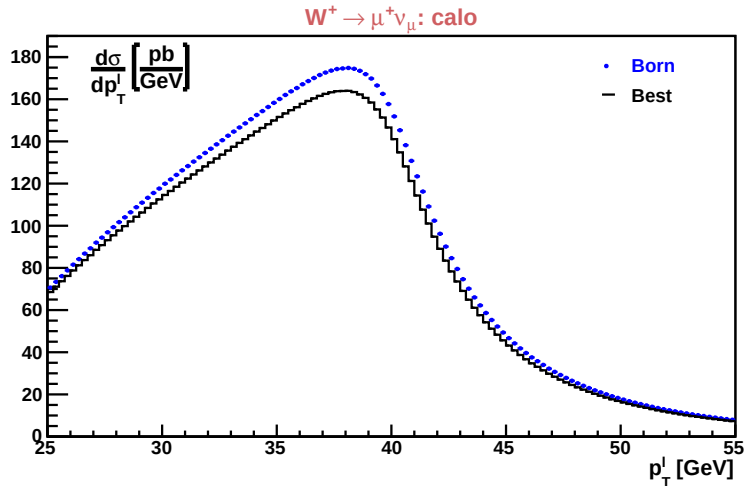


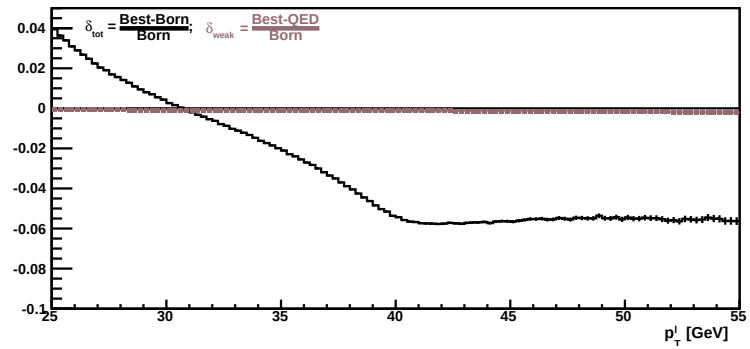


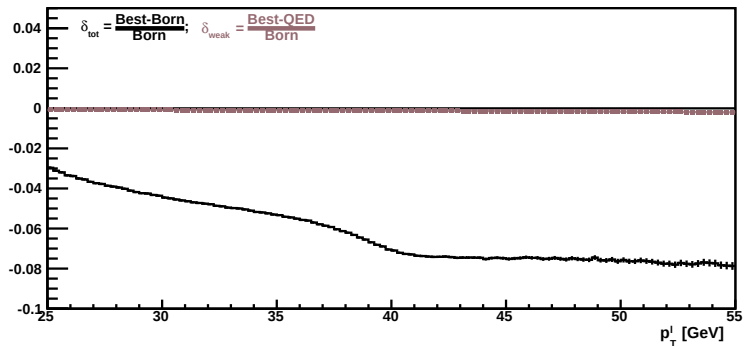


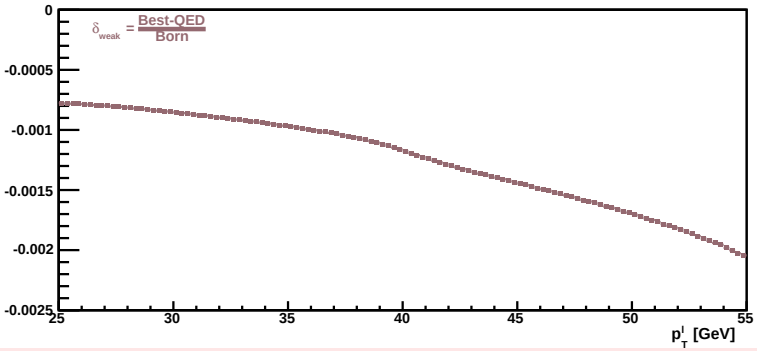
Total EW and "weak" corrections + QCD PS

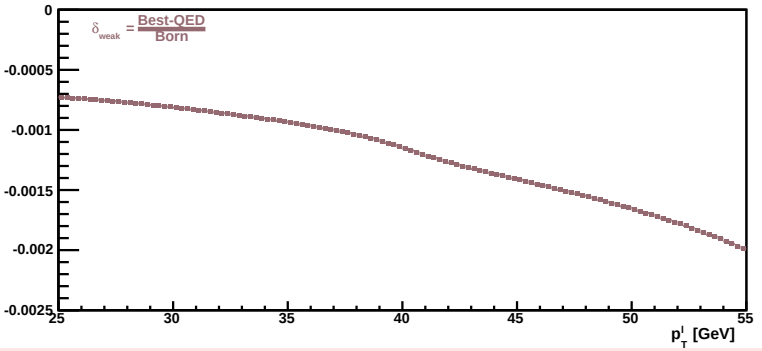






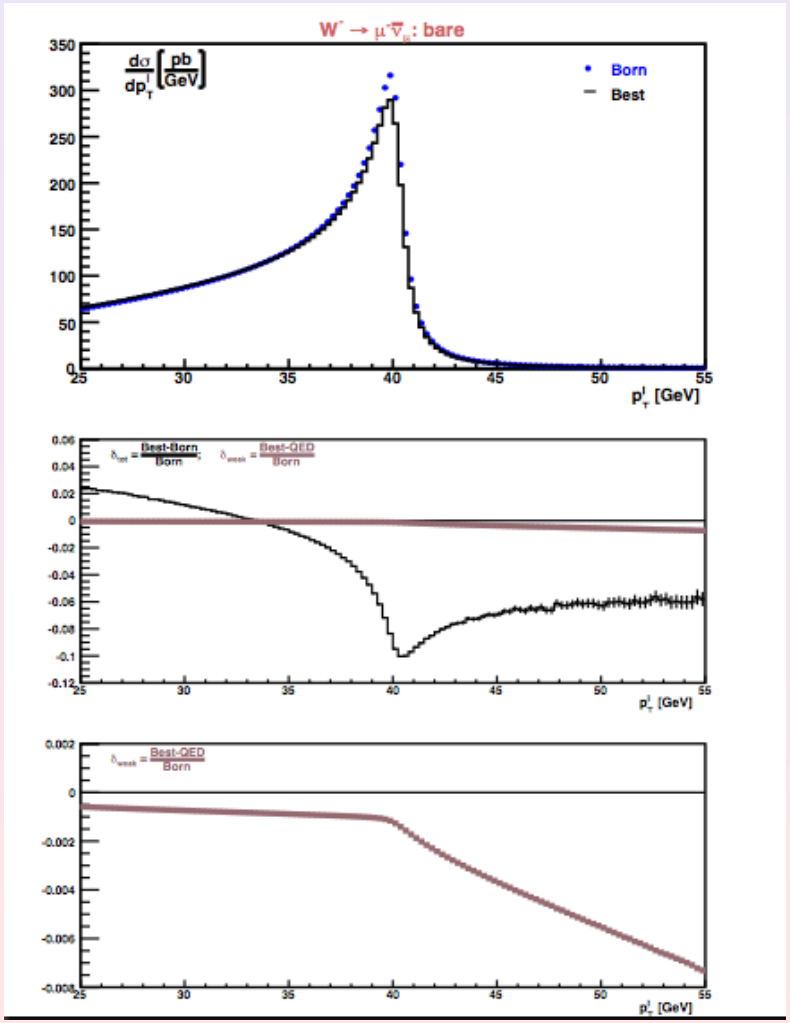


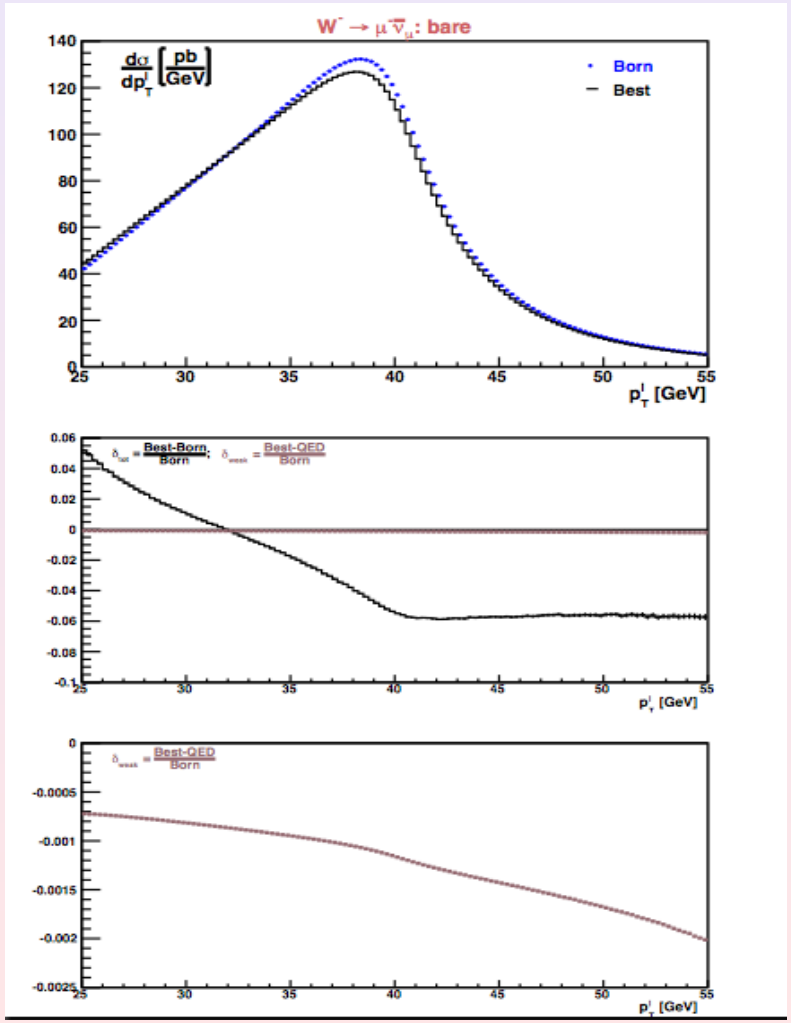




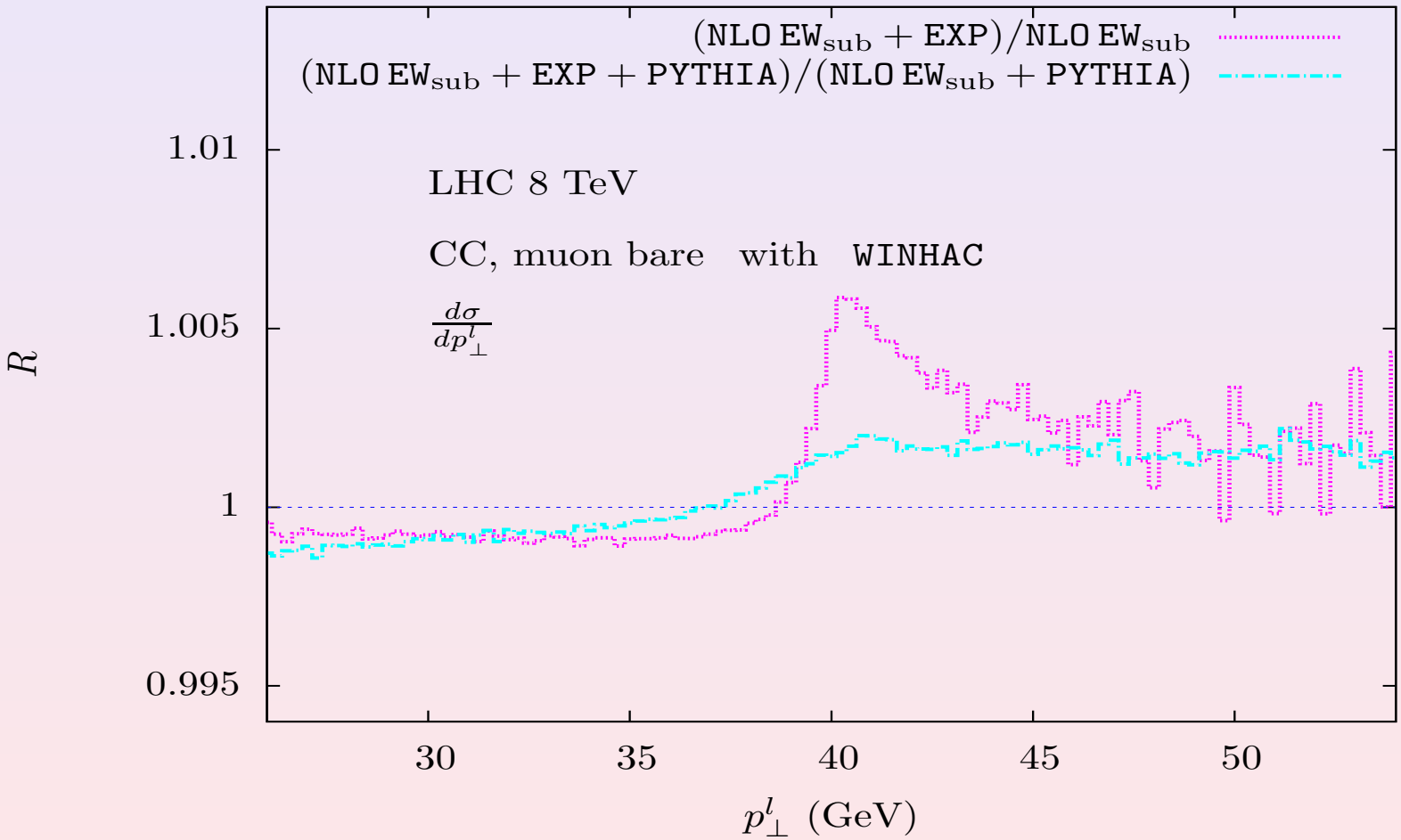
Total EW and "weak" corrections + QCD PS

No QCD PS ⟷ With QCD PS





No QCD PS $\longleftrightarrow$ With QCD PS



$\rightarrow$ LHC EWWG: A. Alioli *et al.*, EPJ **C77** (2017) 280.

- **QED radiation** from **quarks** is by factor $\sim$ **100 weaker** than **QCD radiation**!
  $\rightarrow$ e.g. T. Sjöstrand, Yellow Report CERN 92-04 (1992) 89
- **QED ISR** in DY processes **should not** be generated from **'bare'** quarks **without including QCD** effects!
- The best way is to generate **QED ISR intertwined with QCD ISR** in **Parton Shower Monte Carlo (PSMC)**, eg. HERWIG, PYTHIA, SHERPA.
- **EW MC generator** should provide **QED-ISR-subtracted EW corrections** to DY processes.
- $\overline{\text{MS}}$**/DIS subtraction** scheme is **not** suited for **MC event generator** – not fully exclusive, partly integrated!

▷ **QED ISR subtraction** in WINHAC – two options:

1. **YFS-like** method:
   - Real-hard radiation part
     → all ISR ME subtracted in gauge-invariant way.
   - Virtual + real-soft radiation part
     → subtracted YFS IR factor + terms $\sim \frac{\alpha}{2\pi} Q_q^2 [\ln(s/m_q^2) - 1]$.

   ⇒ PSMC does not exactly match these subtractions → some sub-leading QED ISR terms missing (numerically small!).

2. **Dipole-subtraction** method (DSM):
   → Subtracts *radiation dipoles* used in PSMC for QED ISR:

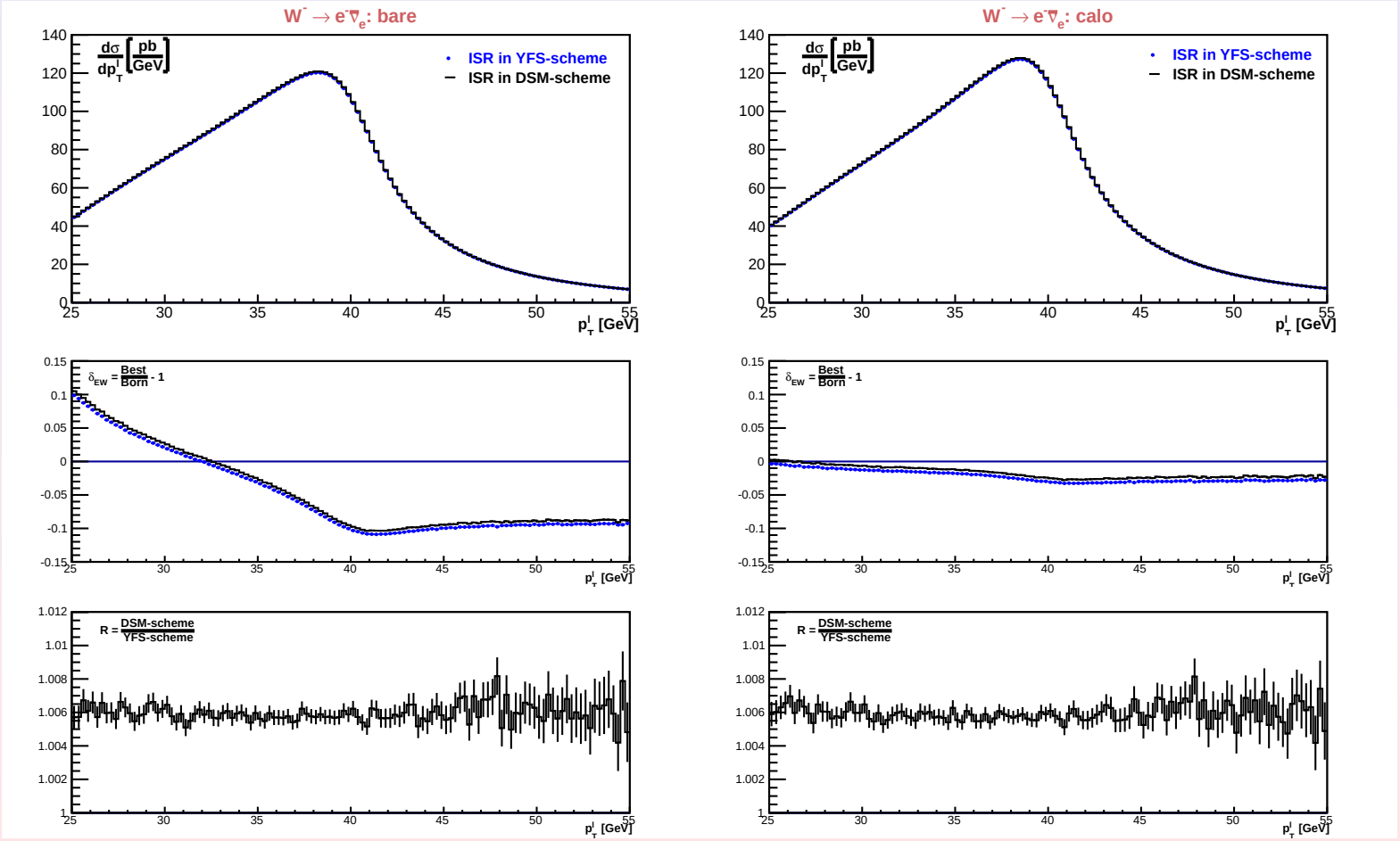
$$\mathcal{D}_q(z) = \left(\frac{\alpha}{\pi}\right) Q_q^2 \left\{ \delta(1-z) \left[\left(\ln \frac{s}{m_q^2} - 1 \right) \ln \varepsilon + \frac{3}{4} \ln \frac{s}{m_q^2} - 1 \right] + \theta(1-z-\varepsilon) \left[\frac{1+z^2}{2(1-z)} \ln \frac{s}{m_q^2} - \frac{z}{1-z} \right] \right\}$$

(where ε – soft-photon cut-off).

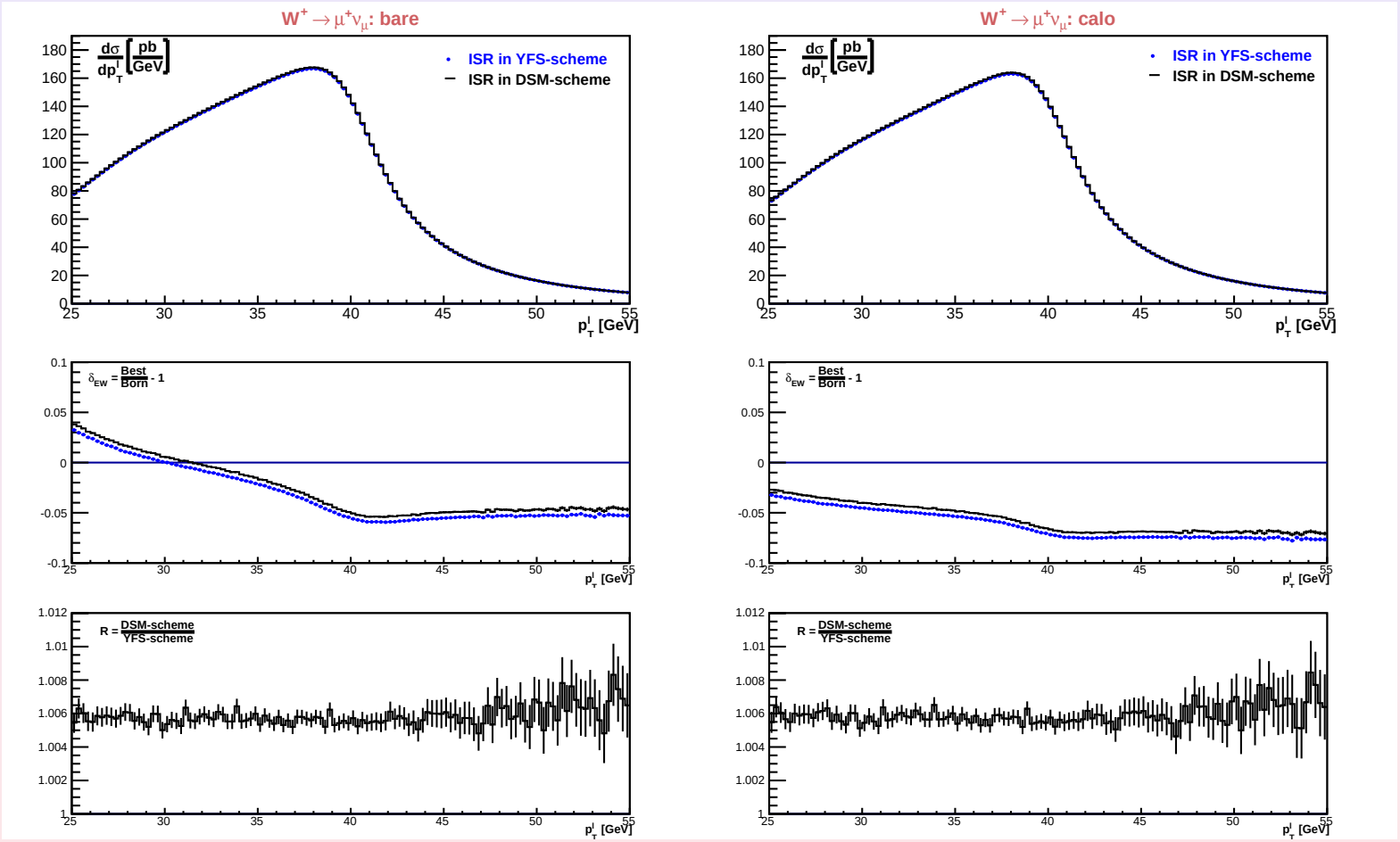
– matched with YFS exponentiation.

Treatment of QED ISR

YFS-like subtraction $\longleftrightarrow$ DSM subtraction



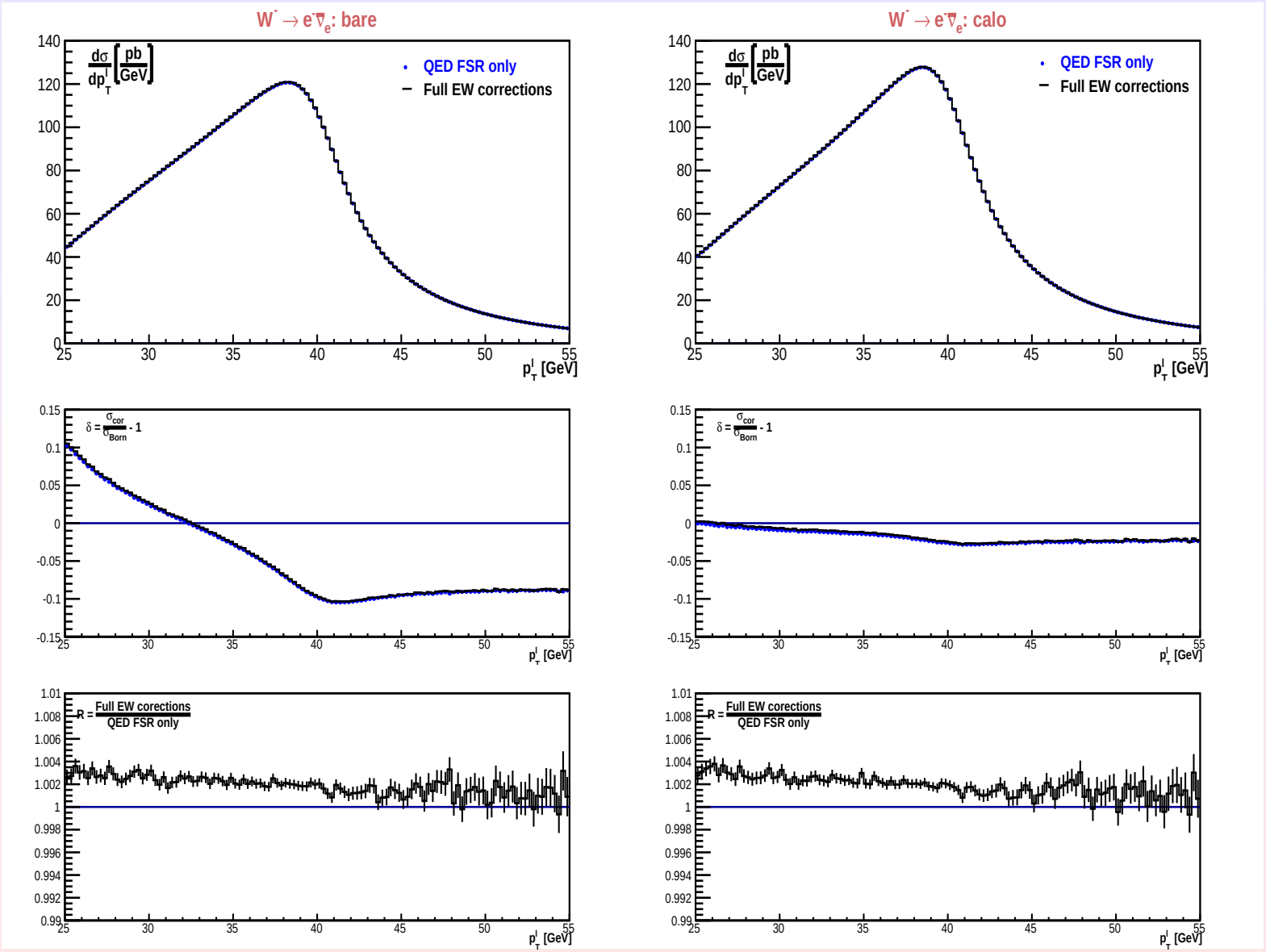
YFS-like subtraction $\longleftrightarrow$ DSM subtraction



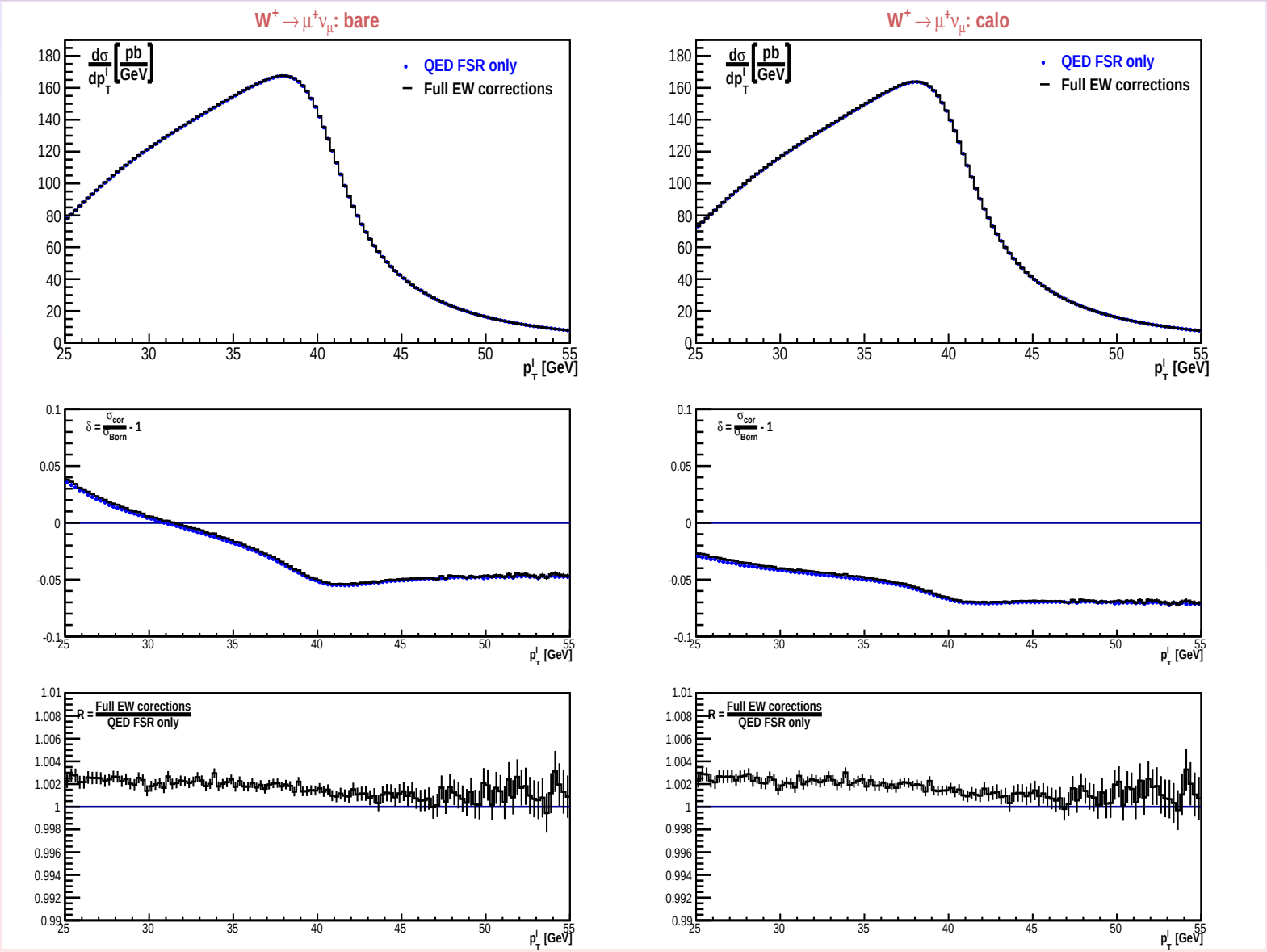
▷ Difference flat for most observables – at the level of 0.5%

→ Smaller than PDFs/luminosity errors

Beyond QED FSR



Beyond QED FSR



▷ EW corrections beyond QED FSR up to 0.4%, with slight slope

- **KrkNLO** method for applying **fixed-order QCD NLO** corrections to **LO PSMC**:
  S. Jadach, WP, S. Sapeta, A. Siódmok, M. Skrzypek, JHEP **1510** (2015) 052; EPJ **C76** (2016) 649;
  S. Jadach *et al.*, EPJ **C77** (2017) 164.
  - QCD **NLO** corrections applied to **PSMC** based on Catani–Seymour dipoles (HERWIG, SHERPA) by simple MC **re-weighting of PS events**.
  - PDFs in so-called **MC factorisation** scheme needed – method for obtaining them from $\overline{MS}$ PDFs provided.

→ Combining **WINHAC** with **KrkNLO** (event-by-event):

1. **EW events** generated by **WINHAC** and **written** in required format (LHA, etc.) to **FIFO pipe** (or file).
2. WINHAC events **read** from **FIFO pipe** (or file) by HERWIG to generate **QCD/QED PS** and apply **KrkNLO** corrections.

WINHAC++: C++ version of WINHAC in progress ...

- Designed as object-oriented MC event generator with the use of modern software engineering methods and tools.
- Most of code rewritten in C++.
- Building/linking/installing process managed with `cmake`.
- Input in `XML`.
- Interfaces to **HepMC** and **LHA** event records.
- Interface to **Pythia8** through LHA format (FIFO pipes can be used).

▷ Started by K. Sobol, Acta Phys. Pol. **B42** (2011) 1605.

▷ ... and continued by Ł. Gaża.

ZINHAC: similar generator for $(Z+\gamma)$ in C++ in progress ...

→ Implemented QED FSR corrections at $\mathcal{O}(\alpha)$ YFS exp.

▷ A. Siódmok, PhD thesis, 2010.