UNIVERSITÀ DEGLI STUDI DI MILANO

Comparison of QED-FSR tools
Horace, Photos, Pythia-QED

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Few comparisons of QED-FSR tools available in the literature

- HORACE-old vs WINHAC hep-ph/0402235
- PHOTOS vs HORACE-old arXiv:1510.02458
- PYTHIA-QED vs PHOTOS (vs HORACE-old) arXiv:1612.02841

Disclaimer: I refer to the papers for the details about the individual plots

codes evolved from 2004 to 2016 → non-uniform comparison

Comparison of tools simulating QED-FSR to all orders: generalities

All QED tool describing FSR to all orders share some general features.

- The inclusion to all orders of radiation in the soft limit allows to recover the "classical" limit, i.e. the vanishing probability of observing a bare, naked, charged particle.
  This behaviour is due to the exponential suppression of the Sudakov form factor.

- The Kinoshita-Lee-Nauenberg theorem states the cancellation of mass (collinear) singularities for observables inclusive over radiation.
  The sensitivity to these large logarithms remains for exclusive observables (e.g. bare leptons)

- Comparison of tools according to their:
  → fixed-order accuracy
  → logarithmic accuracy

- Differences arise in higher-orders because of:
  → different resummation formalism → different inclusion of subleading terms
  → algorithmic implementations

- Matching fixed NLO-EW and all-orders QED-PS results pushes the differences to NNLO-EW reducing some discrepancies present before matching

The comparison of tools provides hints about the size of higher-order terms → of missing h.o.

Classification of EW radiative corrections

Fermion masses regulate collinear emission → mass logarithm $L \equiv \log\left(\frac{s}{m_l^2}\right)$
Final state lepton masses are physical parameters

Perturbative expansion in α
at each order, classification w.r.t. powers of L

$$
\begin{aligned}
\sigma \;=\; & a_0 \;+ \\
& a_1\,\alpha L + b_1\,\alpha \;+ \\
& a_2\,\alpha^2 L^2 + b_2\,\alpha^2 L + c_2\,\alpha^2 \;+ \\
& a_3\,\alpha^3 L^3 + b_3\,\alpha^3 L^2 + c_3\,\alpha^3 L + d_3\,\alpha^3 \;+ \ldots
\end{aligned}
$$

WGRAD
DK
HORACE-matched
SANC

Photos
HORACE-matched
DKM
Winhac

various codes include different subsets

numerical simulation of final state QED multiple photon emission via Parton Shower (Photos, HORACE)
matching of NLO-EW results with complete QED Parton Shower (HORACE)

different FSR models handle in a different way the columns of this expansion

HORACE vs WINHAC comparison: hep-ph/0402235

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

- HORACE and WINHAC are two Monte Carlo event generators

- HORACE is run in its "old" mode, i.e. including only QED-FSR via Parton Shower

LL accuracy,
energy extracted according to $P_{q\gamma}(z)$,
angles extracted according to $1/(1-\beta\cos\theta)$
in 2004 muon mass neglected, electron mass kept

effects studied at · $O(\alpha)$ (truncated PS)
· to all orders (best)

- WINHAC includes FSR via $O(\alpha)$ YFS exponentiation

exact to all orders in the IR limit
up to $O(\alpha)$ for the non IR contributions
non-IR photonic terms beyond $O(\alpha)$ are approximated
subleading logarithmic terms included in the YFS scheme

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

HORACE vs WINHAC comparison: hep-ph/0402235

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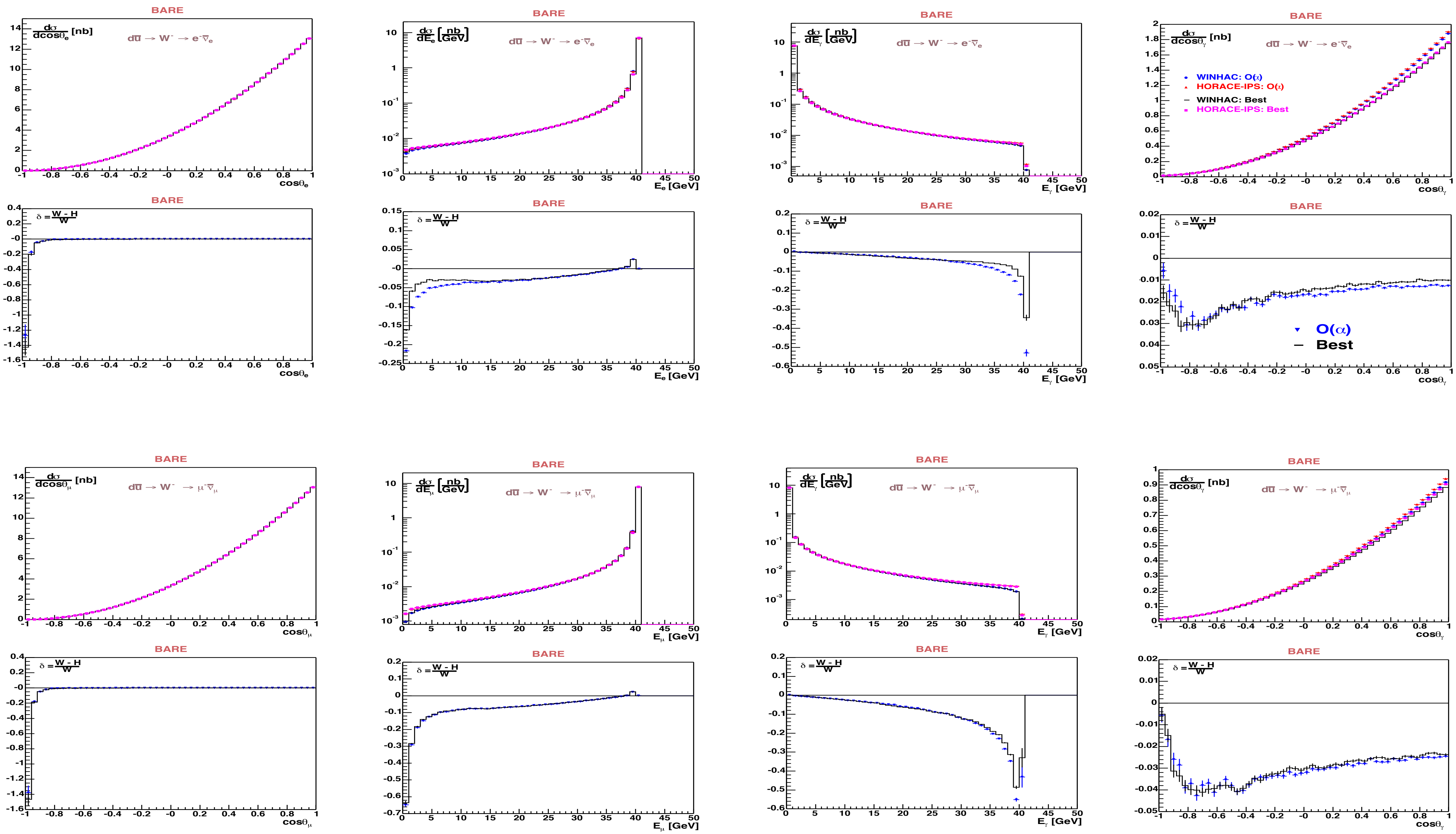
parton-level comparison



electron

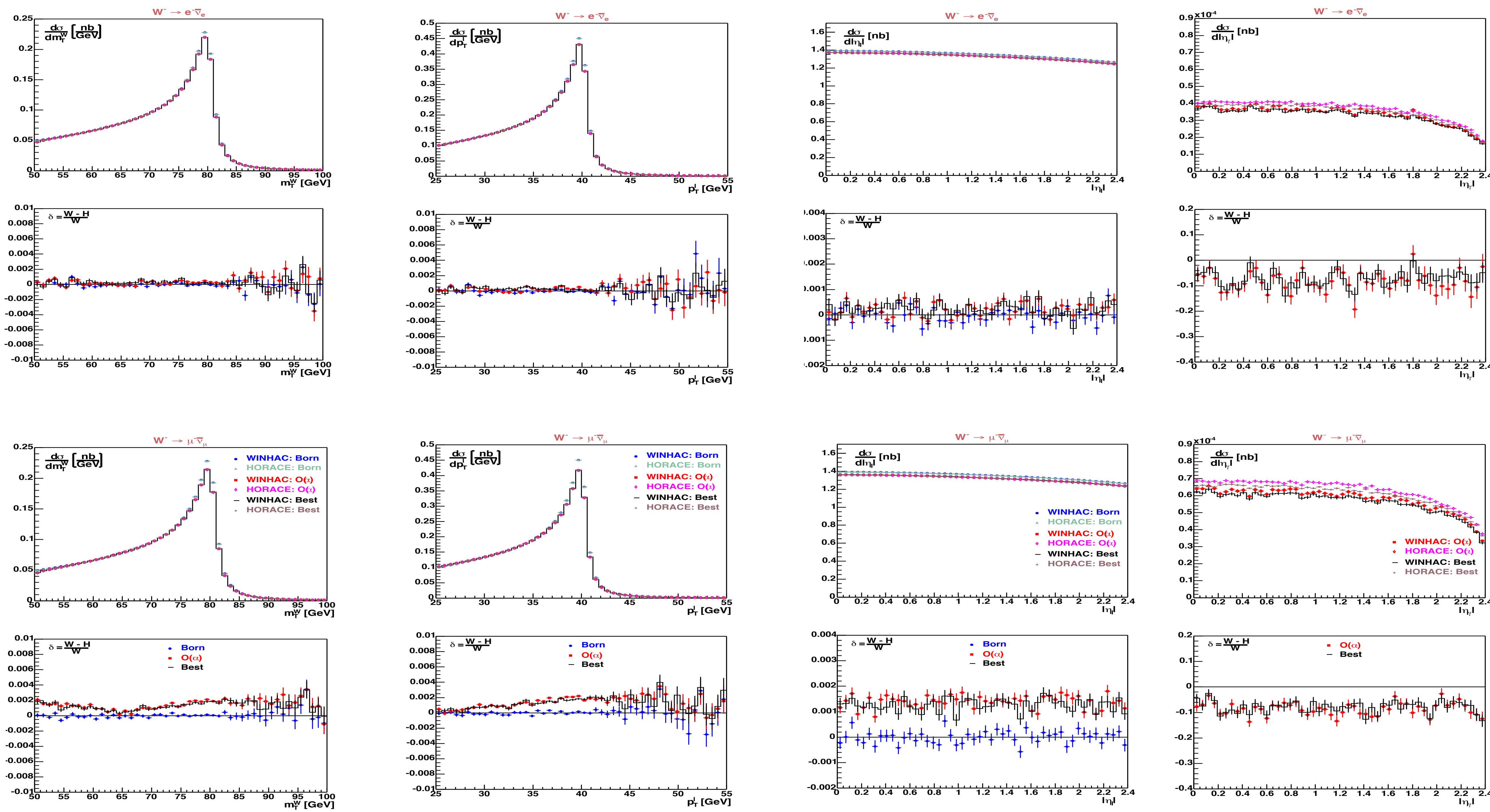
muon

lepton polar angle | lepton energy | hardest γ energy | hardest γ polar angle

HORACE vs WINHAC comparison: hep-ph/0402235

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

hadron-level comparison



electron

muon

lepton-pair transverse mass

charged lepton transverse momentum

charged lepton pseudorapidity

hardest γ pseudorapidity

HORACE vs WINHAC comparison: hep-ph/0402235

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

- Very good agreement for the fiducial xsecs

- Differential distributions agree in general at the 0.1% level
  exceptions (discrepancies up to 10%) occur in very suppressed phase-space corners
  in the parton level comparison

- when a O(0.2%) systematic difference is observed at hadron level,
  it is due to the different treatment of subleading O(α) terms
  while higher-order corrections are in very good agreement

- neglecting the muon mass, in the 2004 version of HORACE,
  was the main cause of the O(0.2%) systematic difference for leptonic observables

- photonic observables could differ at the O(%) level,
  again because of different treatment of subleading O(α) terms

HORACE vs PHOTOS comparison: arXiv:1510.02458

A.V. Kotwal, B. Jayatilaka

- HORACE is run in its “old” mode, i.e. including only QED-FSR via Parton Shower
  LL accuracy,
  energy extracted according to $P_{q\gamma}(z)$,
  angles extracted according to $1/(1-\beta\cos\theta)$
  lepton masses (both muon and electron) are kept (at variance with hep-ph/0402235)
  effects studied to all orders (best)

- PHOTOS uses the exact first-order matrix element of W and Z boson decay
  for the photon emission kernel.

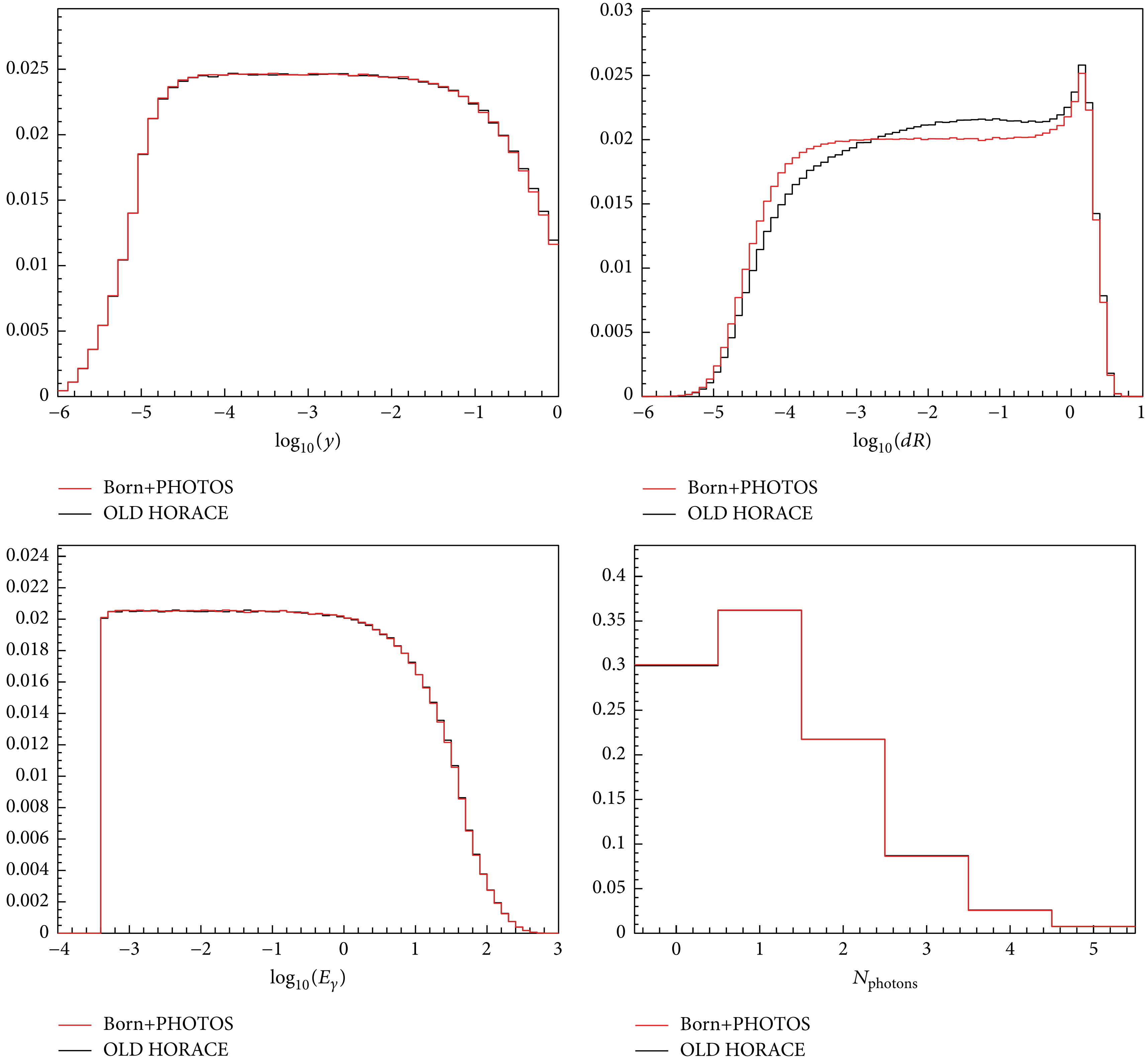
For multiphoton radiation, PHOTOS uses an iterative solution for this kernel, developed on the basis of an exact and complete phase-space parametrization.

This ensures not only resummation of leading-logarithm contributions of higher orders, but also the infrared region of the phase space being accurately simulated.

HORACE vs PHOTOS comparison: arXiv:1510.02458

A.V. Kotwal, B. Jayatilaka

pp→e+e- + nγ



$$y_\gamma = \frac{E_\gamma}{E_\gamma + E_l}$$

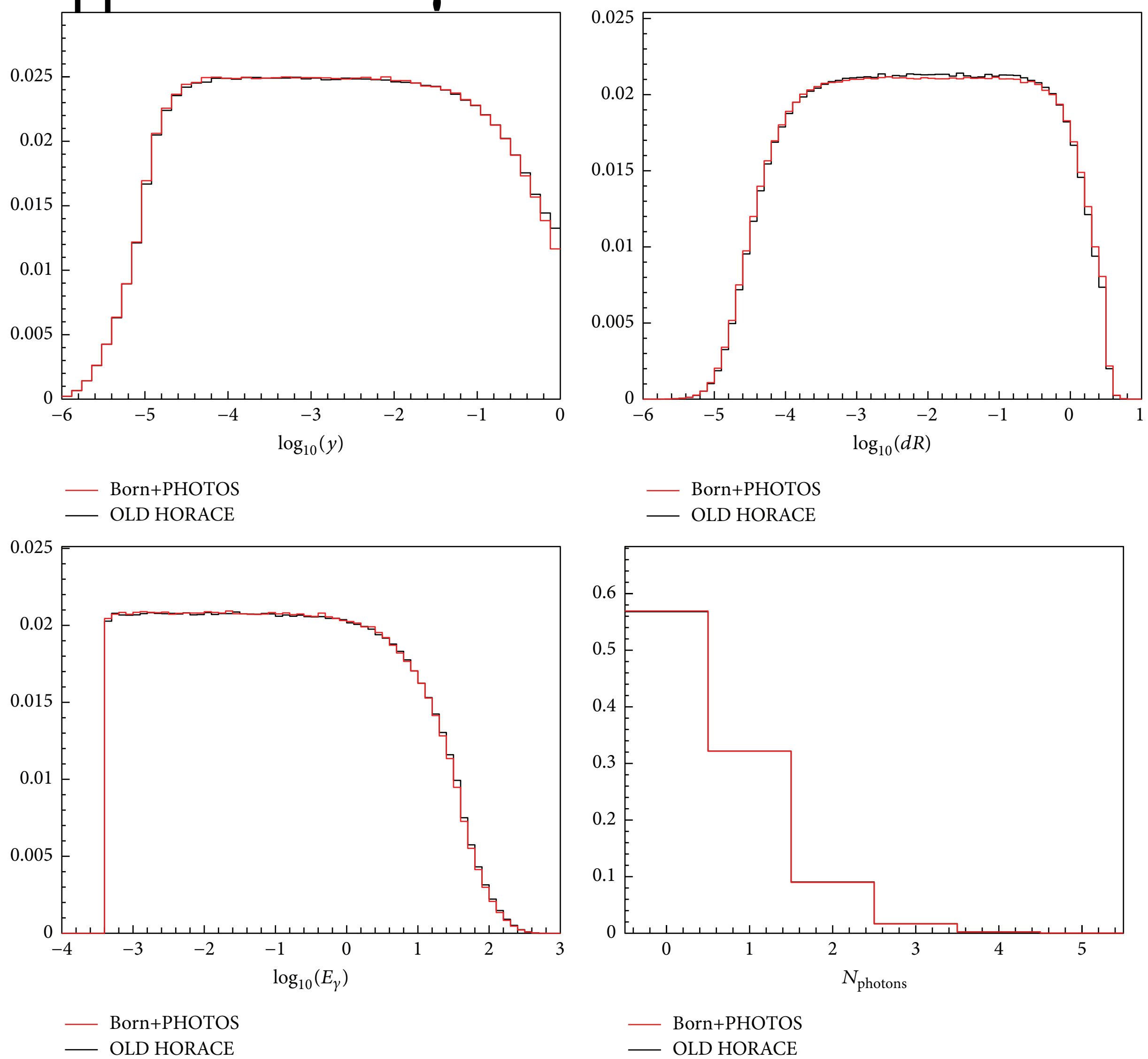
$$dR = \sqrt{(\Delta\eta_{l\gamma})^2 + (\Delta\phi_{l\gamma})^2}$$

the discrepancy for log(dR) disappears in the muon case

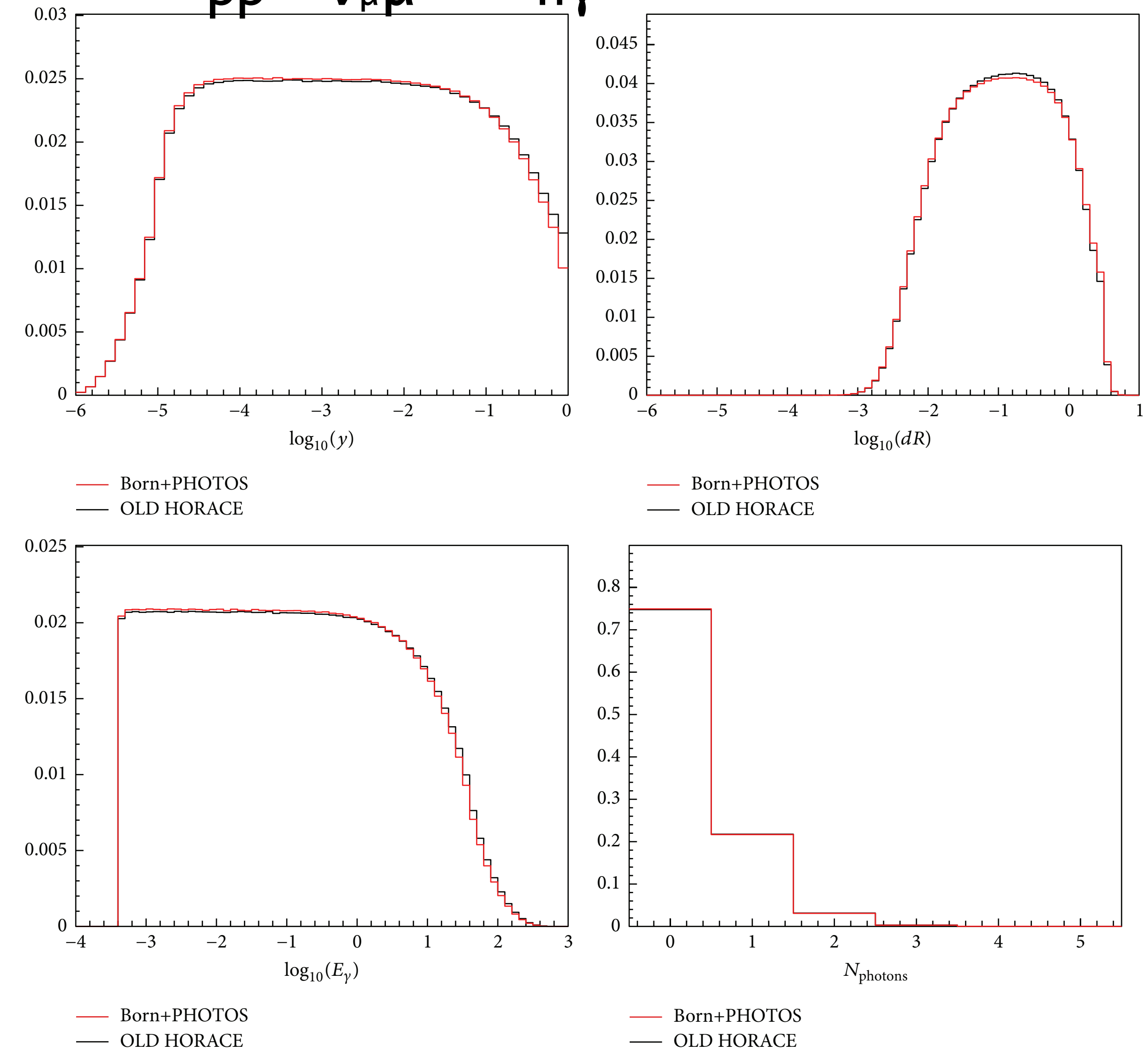
HORACE vs PHOTOS comparison: arXiv:1510.02458

A.V. Kotwal, B. Jayatilaka

pp→$\nu_e e^+$ + nγ



pp→$\nu_\mu \mu^+$ + nγ



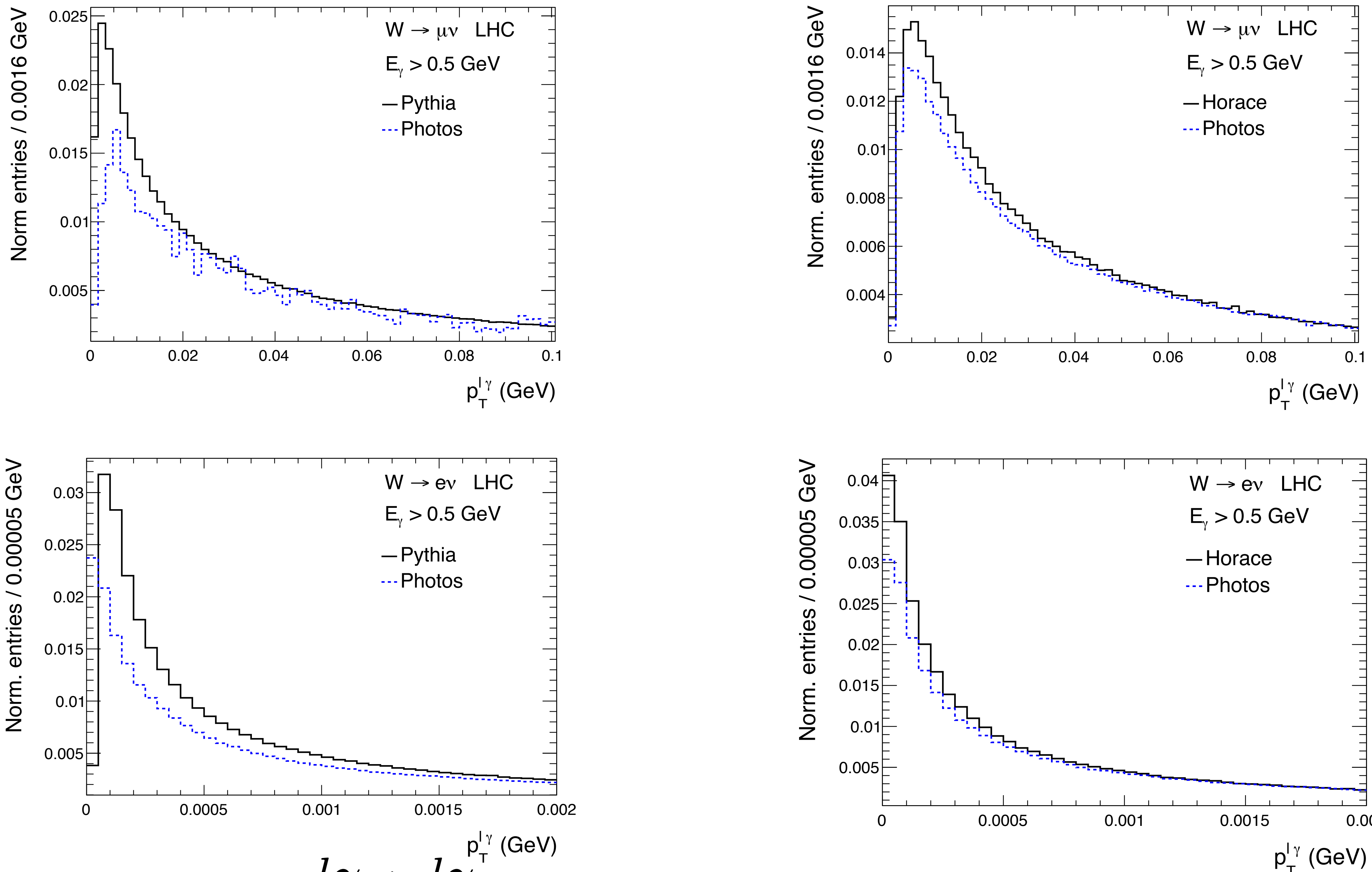
the agreement in the W case, for both electron and muon channels, is remarkable

the Z → l+l- nγ has a stronger (w.r.t. W) radiation pattern, that enhances possible differences
visible in the muon case, almost negligible in the electron case

PHOTOS vs PYTHIA-QED vs HORACE comparison: arXiv:1612.02841

C.M. Carloni Calame, M. Chiesa, H. Martinez, G. Montagna, O. Nicrosini, F. Piccinini, A. Vicini

relative lepton-photon pT, in presence of a cut $E_\gamma > 0.5$ GeV



muon

electron

PYTHIA-QED $dp_T^{l\gamma}/p_T^{l\gamma}$

HORACE
PHOTOS $d\sigma/d\cos\theta_{l\gamma} \propto 1/(1-\beta\cos\theta_{l\gamma})$

PHOTOS vs PYTHIA-QED comparison: arXiv:1612.02841

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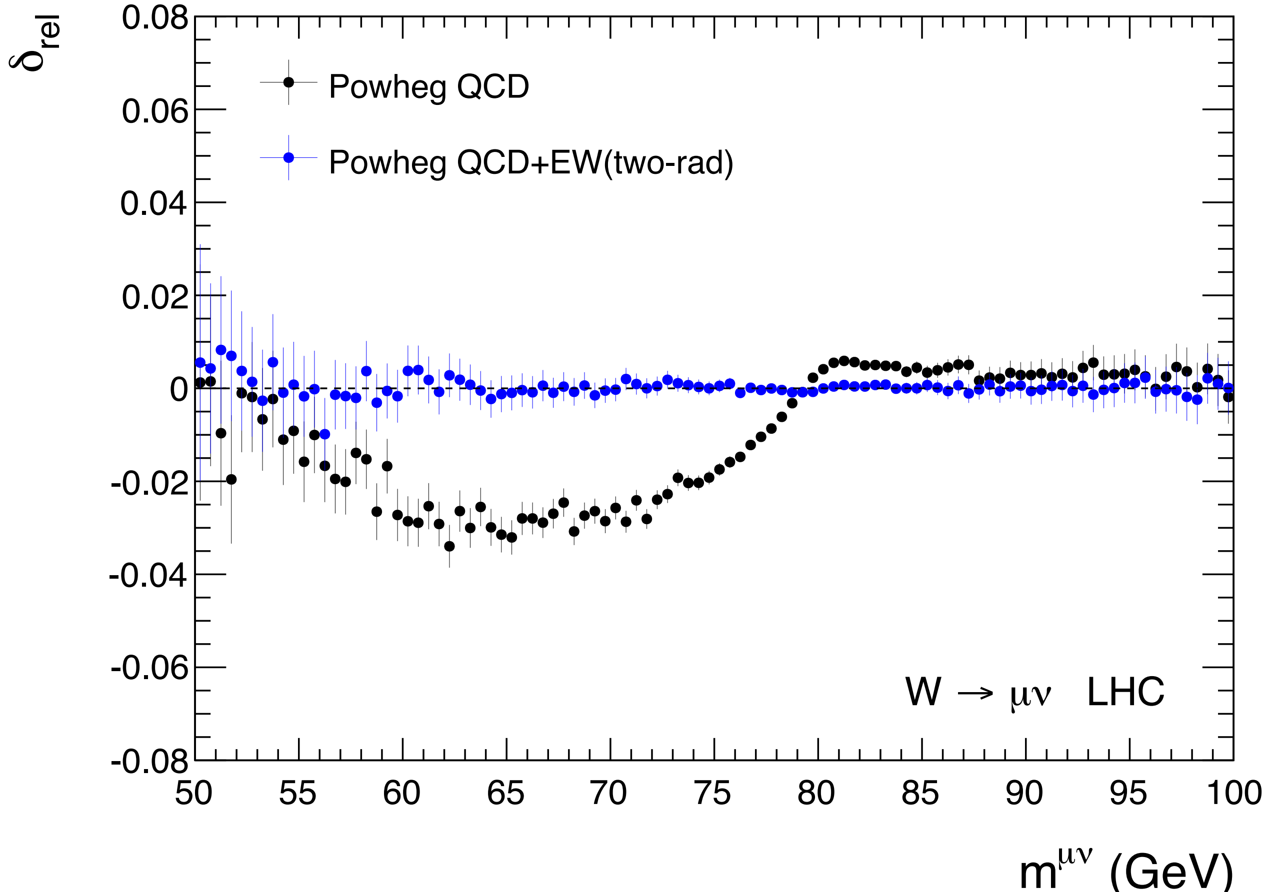
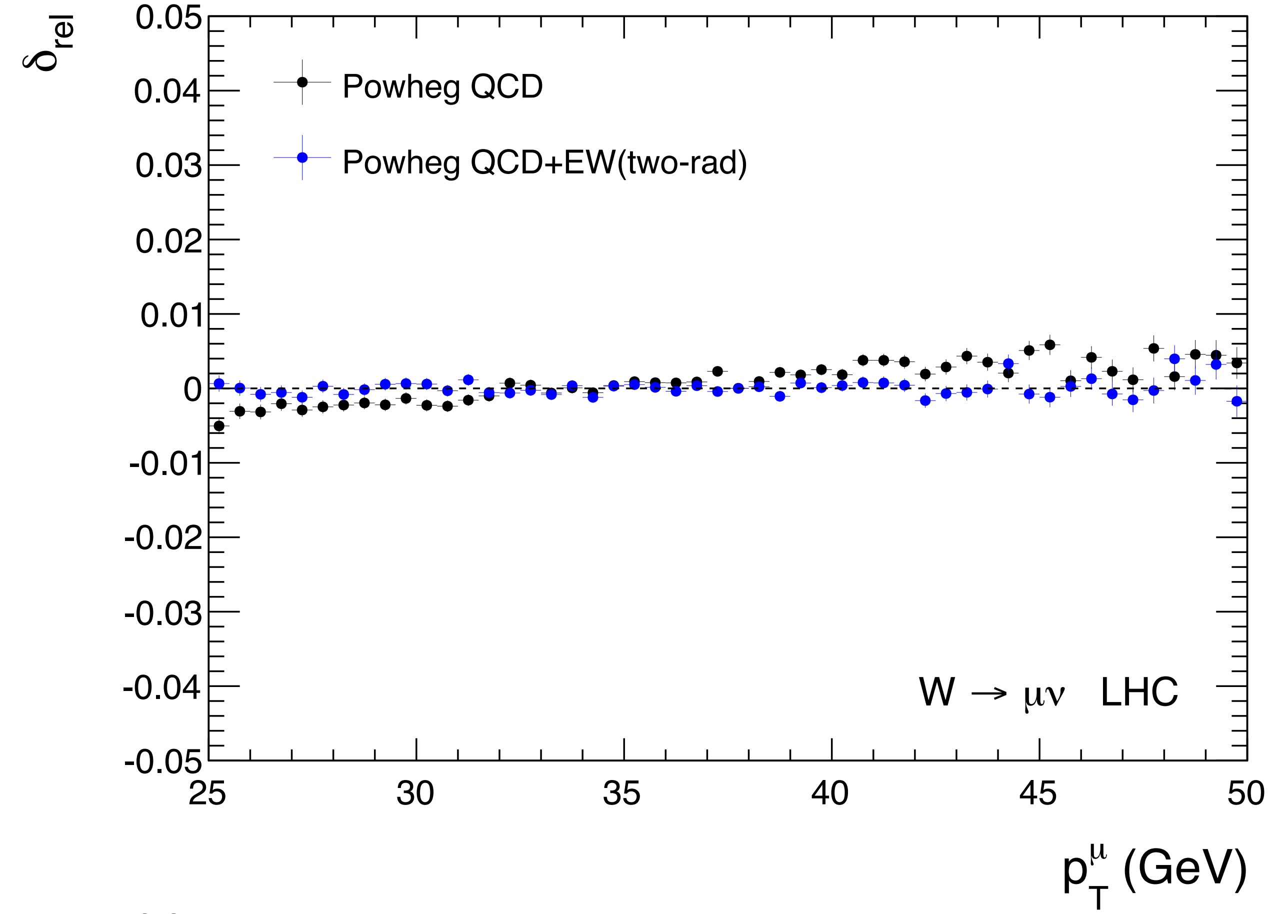




Ratio:

(POWHEG⊗ PYTHIA-QED) / (POWHEG⊗ PHOTOS)

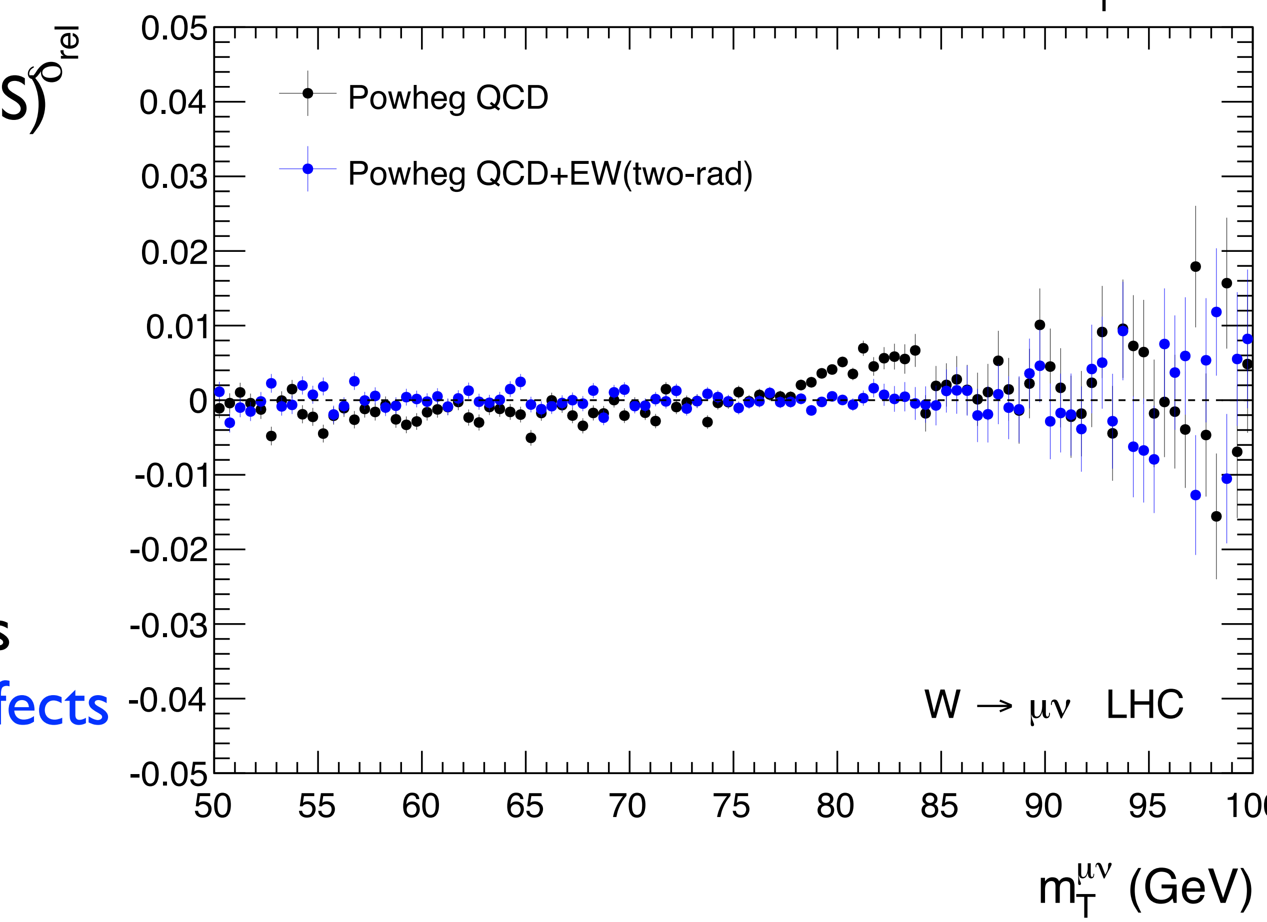
POWHEG versions (identical QCD shower):

black: POWHEG-QCD

blue: POWHEG-(QCD+EW)

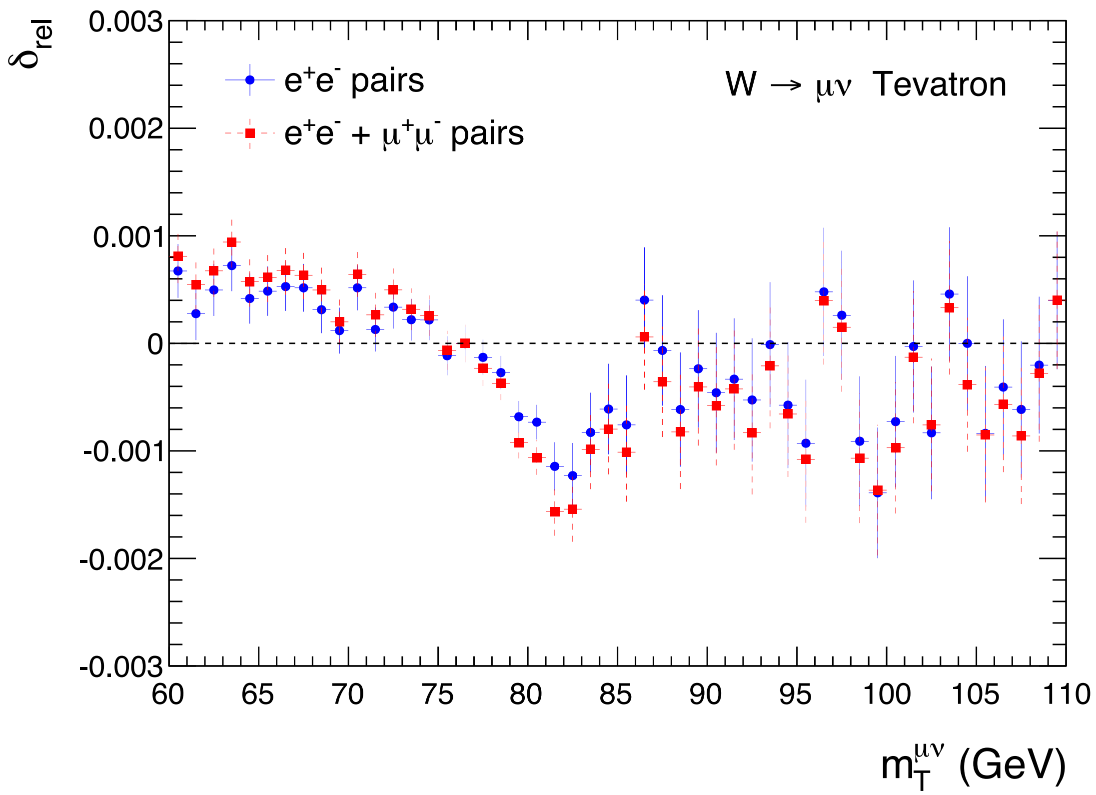
black dots show the impact of O(α) subleading terms

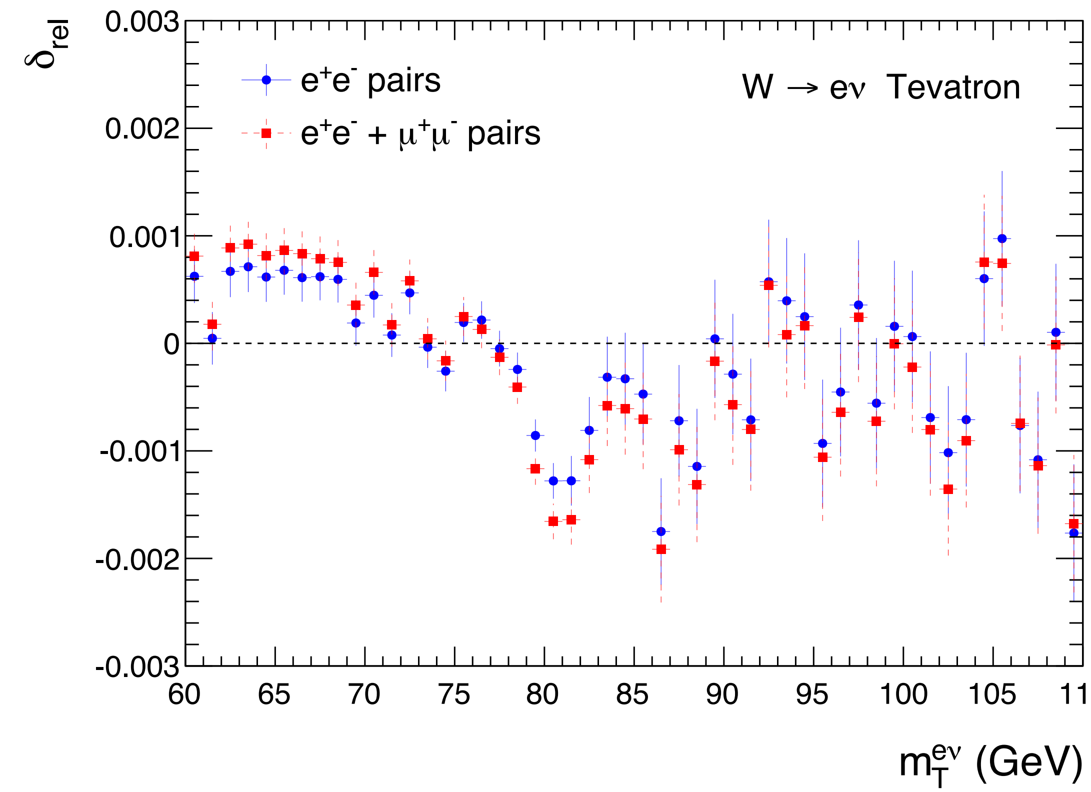
blue dots (after matching) show O(α²) subheading effects



Leading O(α^2) term: light-pair production in the HORACE shower

C.M. Carloni Calame, M. Chiesa, H. Martinez, G. Montagna, O. Nicrosini, F. Piccinini, A. Vicini





δ = [(QED-FSR with additional pairs) / (QED-FSR without additional pairs) -1]

additional class of higher-order terms of O($\alpha^2 L^2$) not due to the treatment of photon kinematics

Conclusions

Higher-order corrections available in various codes should all be included in a "best ideal" tool

The spread of different predictions provides hints about the size of the uncertainty
Uncertainty defined as "size of missing higher orders" can only be guessed

QED-FSR models differ by the inclusion of subleading terms

Matching with a given fixed-order matrix element (LO-EW vs NLO-EW)
sets the overall scale of ambiguities:
→ at LO ambiguities appear at $O(\alpha)$ and are relevant in view of precision measurements
→ after matching with NLO-EW ambiguities of $O(\alpha^2)$ appear to be phenomenologically small

Future comparisons

different implementations of
matching of full NLO-EW matrix elements with QED-PS from all external charged legs
differ
not only because of the QED-PS model
but also because of the matching recipe (e.g. HORACE vs POWHEG)