Report on the comparison of codes for the simulation of Drell-Yan processes

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participants:
S.Alioli, A.B.Arbuzov, D.Yu.Bardin, L.Barze, C.Bernaciak, S.G.Bondarenko, J.Campbell, S.Dittmaier, G.Ferrera, D.de Florian, M.Grazzini, L.V.Kalinovskaya, M.Kraemer, P.Lenzi, Y.Li, G.Montagna, A.Mueck, P.Nason, O.Nicrosini, F.Petriello, F.Piccinini, W.Plazczek, E.Re, A.A.Sapronov, A.Vicini, D.Wackeroth, Z.Was,...

Motivations

- The measurement of EW parameters is precision physics
  which requires the understanding, both theoretical and experimental, of the observables
  at the per mille level
- The perfect tool that includes all the available informations in a unique framework does not exist
- The detailed comparison of the different available simulation codes
  can help to merge coherently their content

- Two codes that have the same perturbative approximation,
  the same input parameters (couplings, masses, PDFs),
  the same setup (choice of scales, acceptance cuts),
  should yield exactly the same results, within the accuracy of the numerical integration.

- The results of different codes can be meaningfully combined
  only if they satisfy the previous point (in their common part).

Goals

- to verify at any time that a given code works properly according to what its authors have foreseen, producing public benchmarks

- to demonstrate explicitly the level of agreement of different codes that include identical subsets of radiative corrections

- to expose the impact of different subsets of higher-order corrections and of differences in their implementations

- to discuss the impact of some recipes used to combine different sets of radiative corrections

Strategy

1) tuned comparison of the codes
= technical check that they agree,
when they use the same setup and with the same perturbative approximation

2) definition of a suitable input scheme
that minimizes the size of higher-order corrections and
still allows for the comparison of QCD and EW predictions
in this scheme, fixed-order benchmark results with (N)NLO accuracy

3) quantitative evaluation of the size of higher-order corrections, beyond NLO results
sensible comparison of the impact of different h.o. QCD and EW subsets
expressed as percentage variations with respect to the benchmarks

4) comparison of different recipes of combination of h.o. corrections, e.g. QCD and EW

Participants

- NNLO QCD: DYNNLO, FEWZ, SHERPA M.Grazzini, D.de Florian, G.Ferrera; F.Petriello, Y.Li; S.Hoeche, Y.Li, S.Prestel
- NLO QCD⊗Parton Shower: POWHEG, SHERPA S.Alioli, P.Nason, E.Re; S.Hoeche, Y.Li, S.Prestel
- NNLO QCD⊗Parton Shower: SHERPA S.Hoeche, Y.Li, S.Prestel
- QED PS/SF: HORACE, PHOTOS, RADY G.Montagna, O.Nicrosini, A.Vicini; Z.Was; S.Dittmaier, M.Krämer, A.Mück
- NLO EW: HORACE, RADY, SANC, WINHAC, WZGRAD G.Montagna, O.Nicrosini, A.Vicini; A.Arbuzov, D.Bardin, S.Bondarenko, L.Kalinowskaya; W.Plazek; S.Dittmaier, M.Krämer, A.Mück; D.Wackeroth
- NLO EW⊗QED PS/YFS/SF: HORACE, RADY, WINHAC G.Montagna, O.Nicrosini, A.Vicini; W.Plazek; S.Dittmaier, M.Krämer, A.Mück
- NLO QCD+NLO EW: RADY, SANC, POWHEG_BMNNP, POWHEG_BW S.Dittmaier, M.Krämer, A.Mück; A.Arbuzov, D.Bardin, S.Bondarenko, L.Kalinowskaya; L.Barze, G.Montagna, P.Nason, O.Nicrosini, F.Piccinini; C.Bernaciak, D.Wackeroth
- NNLO QCD+NLO EW: FEWZ F.Petriello, Y.Li
- (NLO QCD+NLO EW)⊗Pythia: POWHEG_BMNNP, POWHEG_BW L.Barze, G.Montagna, P.Nason, O.Nicrosini, F.Piccinini; C.Bernaciak, D.Wackeroth
- (NLO QCD+NLO EW)⊗Pythia⊗PHOTOS: POWHEG_BMNNP L.Barze, G.Montagna, P.Nason, O.Nicrosini, F.Piccinini

Tuned comparisons: the setup

- numerical values of all the input parameters

$$
\begin{aligned}
G_\mu = 1.1663787\times 10^{-5}\ \mathrm{GeV}^{-2}, &\quad \alpha = 1/137.035999074, \quad \alpha_s \equiv \alpha_s(M_Z^2) = 0.12018\\
M_Z = 91.1876\ \mathrm{GeV}, &\quad \Gamma_Z = 2.4952\ \mathrm{GeV}\\
M_W = 80.385\ \mathrm{GeV}, &\quad \Gamma_W = 2.085\ \mathrm{GeV}\\
M_H = 125\ \mathrm{GeV}, &\\
m_e = 0.510998928\ \mathrm{MeV}, &\quad m_\mu = 0.1056583715\ \mathrm{GeV}, \quad m_\tau = 1.77682\ \mathrm{GeV}\\
m_u = 0.06983\ \mathrm{GeV}, &\quad m_c = 1.2\ \mathrm{GeV}, \quad m_t = 173.5\ \mathrm{GeV}\\
m_d = 0.06984\ \mathrm{GeV}, &\quad m_s = 0.15\ \mathrm{GeV}, \quad m_b = 4.6\ \mathrm{GeV}\\
|V_{ud}| = 0.975, &\quad |V_{us}| = 0.222\\
|V_{cd}| = 0.222, &\quad |V_{cs}| = 0.975\\
|V_{cb}| = |V_{ts}| = |V_{ub}| &= |V_{td}| = |V_{tb}| = 0 \qquad (2)
\end{aligned}
$$

- input scheme (α_0, MW, MZ)

  (choice motivated by the existence of earlier detailed comparisons)

- PDF set MSTW2008nlo (MSTW2008nnlo for NNLO-QCD results), MSbar factorization

- scales: μ_r=μf=M(l nu) in DY-CC, μ_r=μf=M(l+l-) in DY-NC

- acceptance cuts

$$
\begin{aligned}
\text{Tevatron}: &\quad p_T(\ell) > 25\ \mathrm{GeV}, \quad |\eta(\ell)| < 1, \quad \not{p}_T > 25\ \mathrm{GeV}, \quad \ell = e,\ \mu,\\
\text{LHC}: &\quad p_T(\ell) > 25\ \mathrm{GeV}, \quad |\eta(\ell)| < 2.5, \quad \not{p}_T > 25\ \mathrm{GeV}, \quad \ell = e,\ \mu,\\
\text{LHCb}: &\quad p_T(\ell) > 20\ \mathrm{GeV},\ 2 < \eta(\ell) < 4.5, \quad \not{p}_T > 20\ \mathrm{GeV}, \quad \ell = e,\ \mu(
\end{aligned}
$$

- distinction between electrons and muons in final state

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

Tuned comparison: total cross sections

code	LO	NLO QCD	NLO EW μ	NLO EW e	NNLO QCD
HORACE	2897.38(8)	×	2988.2(1)	2915.3(1)	×
WZGRAD	2897.33(2)	×	2987.94(5)	2915.39(6)	×
RADY	2897.35(2)	2899.2(4)	2988.01(4)	2915.38(3)	×
SANC	2897.30(2)	2899.7(6)	2987.77(3)	2915.00(3)	×
DYNNLO	2897.32(5)	2899(1)	×	×	
FEWZ	2897.2(1)	2899.4(3)	×	×	3012(2)
POWHEG-w	2897.34(4)	2899.41(9)	×	×	×
POWHEG_BW	2897.4(1)	2899.2(3)	2987.5(6)		×
POWHEG_BMNNP	2897.36(5)		2988.49(7)		×

Table 3: Tuned comparison of total cross sections (in pb) for $pp \to W^+ \to l^+\nu_l + X$ at the 8 TeV LHC, with ATLAS/CMS cuts and *bare* leptons.

code	LO	NLO-EW μ calo	NLO EW e calo
HORACE	2897.38(8)	2899.0(1)	3003.5(1)
WZGRAD	2897.33(2)	2898.33(5)	3003.33(6)
RADY	2897.35(2)	2898.37(4)	3003.36(4)
SANC	2897.30(2)	2898.18(3)	3003.00(4)

Table 4: Tuned comparison of total cross sections (in pb) $pp \to W^+ \to l^+\nu_l + X$ at the 8 TeV LHC, with ATLAS/CMS cuts and *calorimetric* leptons.

code	LO	NLO QCD	NLO EW μ	NLO EW e	NNLO QCD
HORACE	2008.84(5)	×	2076.48(9)	2029.15(8)	×
WZGRAD	2008.95(1)	×	2076.51(3)	2029.26(3)	×
RADY	2008.93(1)	2050.5(2)	2076.62(2)	2029.29(2)	×
SANC	2008.926(8)	2050.5(4)	2076.56(2)	2029.19(3)	×
DYNNLO	2008.89(3)	2050.2(9)	×	×	
FEWZ	2008.9	2049.9(2)	×	×	2104(1)
POWHEG-w	2008.93(3)	2050.14(5)	×	×	×
POWHEG_BW					×
POWHEG_BMNNP	2008.94(3)		2078.03(2)		×

Table 5: Tuned comparison of total cross sections (in pb) for $pp \to W^- \to l^-\bar{\nu}_l + X$ at the 8 TeV LHC, with ATLAS/CMS cuts and *bare* leptons.

code	LO	NLO-EW μ calo	NLO EW e calo
HORACE	2008.84(5)	2013.67(7)	2085.42(8)
WZGRAD	2008.95(1)	2013.42(3)	2085.26(3)
RADY	2008.93(1)	2013.49(2)	2085.37(2)
SANC	2008.926(8)	2013.48(2)	2085.24(4)

Table 6: Tuned comparison of total cross sections (in pb) for $pp \to W^- \to l^-\bar{\nu}_l + X$ at the 8 TeV LHC, with ATLAS/CMS cuts and *calorimetric* leptons.

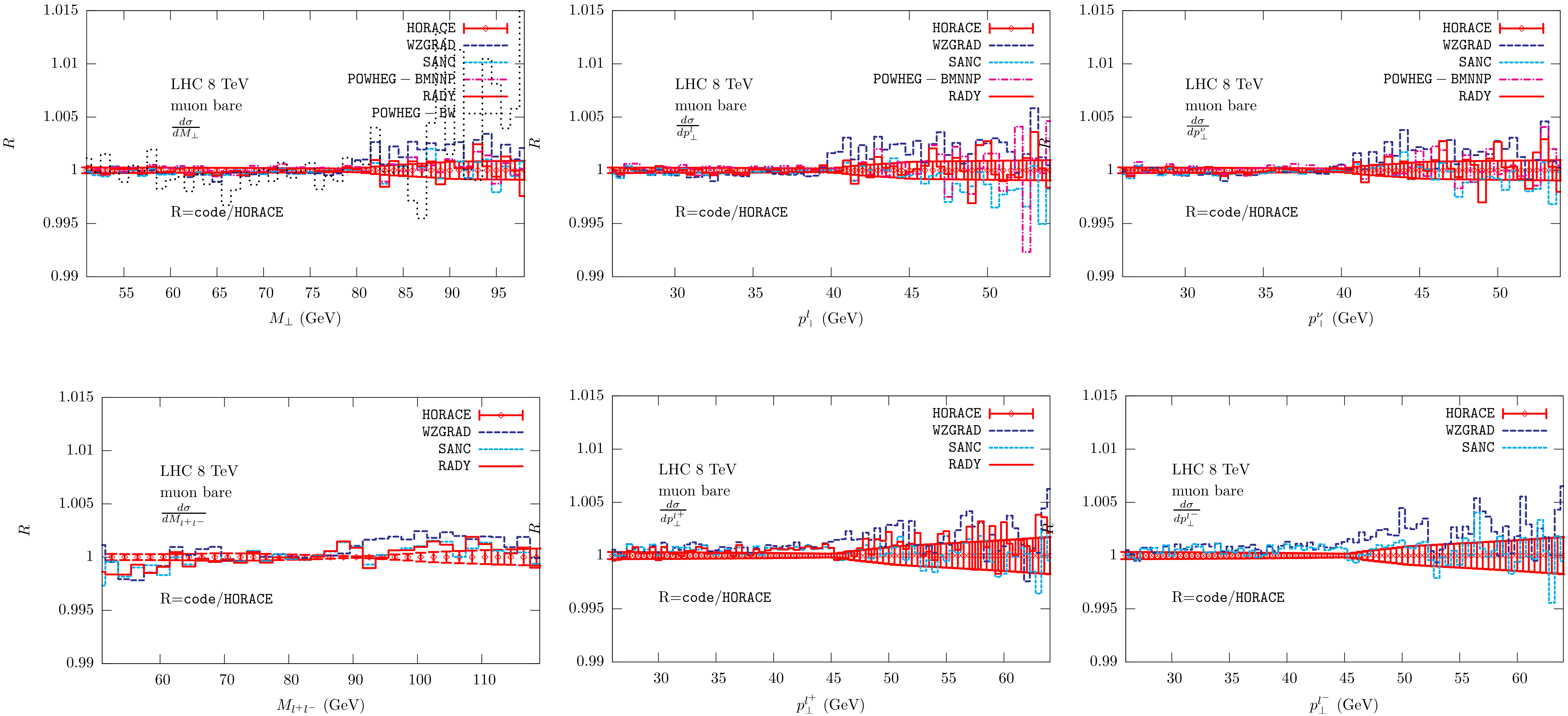
code	LO	NLO QCD	NLO EW μ	NLO EW e	NNLO QCD
HORACE	431.033(9)	×	438.74(2)	422.08(2)	×
WZGRAD	431.048(7)	×	439.166(6)	422.78(1)	×
RADY	431.047(4)	458.16(3)	438.963(4)	422.536(5)	×
SANC	431.050(2)	458.20(5)	439.004(5)	422.56(1)	×
DYNNLO	431.043(8)	458.2(2)	×	×	
FEWZ	431.00(1)	458.1			469.5(3)
POWHEG-z	431.08(4)	458.19(8)	×	×	×
POWHEG_BMNNP	431.046(9)				×

Table 7: Tuned comparison of total cross sections (in pb) for $pp \to \gamma, Z \to l^-l^+ + X$ at the 8 TeV LHC, with ATLAS/CMS cuts and *bare* leptons.

code	LO	NLO-EW μ calo	NLO EW e calo
HORACE	431.033(9)	407.67(1)	439.68(2)
WZGRAD	431.048(7)	407.852(7)	440.29(1)
RADY	431.047(4)		440.064(5)
SANC	431.050(2)	407.687(5)	440.09(1)

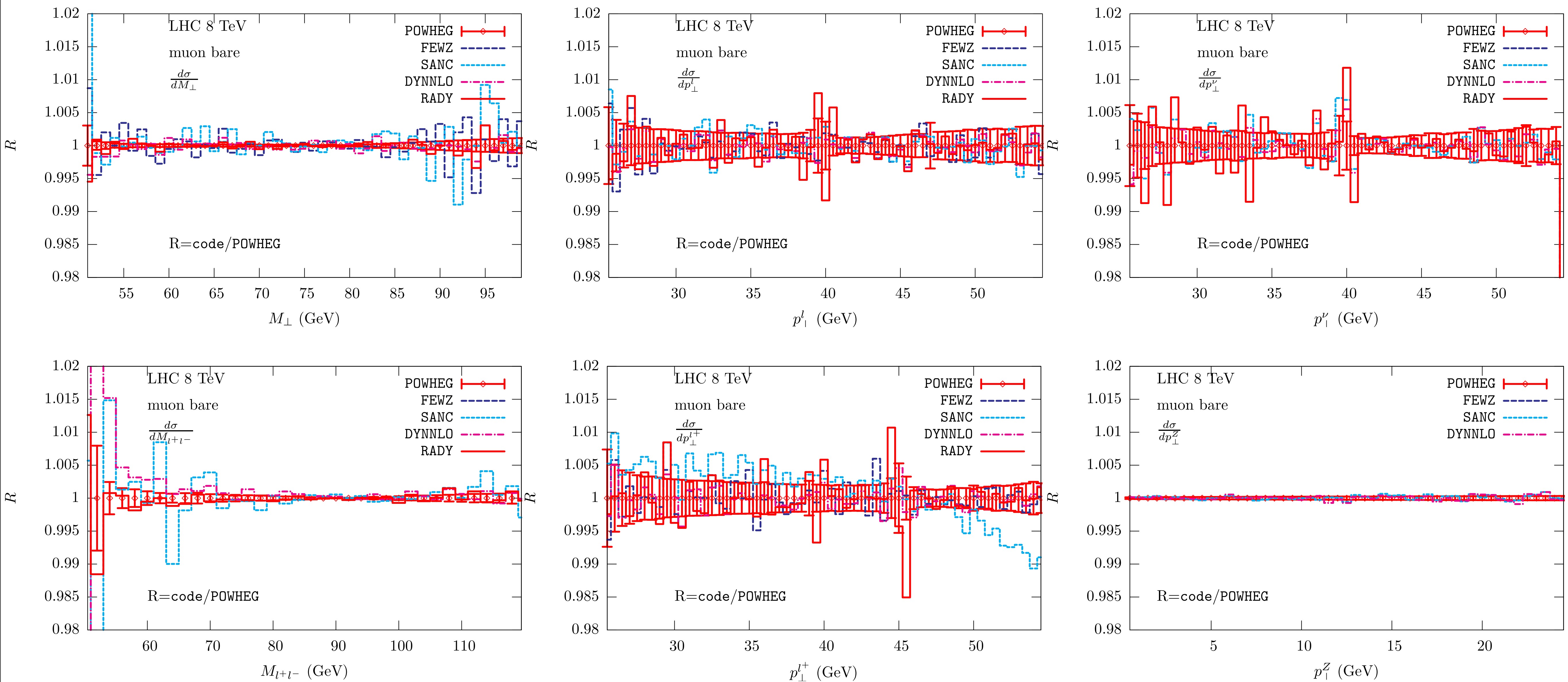
Table 8: Tuned comparison of total cross sections (in pb) for $pp \to \gamma, Z \to l^+l^- + X$ at the 8 TeV LHC, with ATLAS/CMS cuts and *calorimetric* leptons.

Tuned comparison: differential distributions EW



- agreement at the per mil level at the jacobian peak, deviations are smaller than 5 per mil in the tails

Tuned comparison: differential distributions QCD



- agreement at the per mil level at the jacobian peak,

  statistical fluctuations in any case smaller than 5 per mil

Input schemes and recommended, *benchmark*, choice

(g, g', v) must be expressed in terms of physical observables

Gmu scheme: (G_μ, m_W, m_Z)

most natural choice to parametrize EW processes

Gmu expresses the strength of the CC interaction
and reabsorbs in its definition large rad.corr.

drawback: the coupling of the photon α_μ~ 1/132
is larger than α(0)~1/137 "natural" value
for an on-shell photon

α(0) scheme: $(\alpha(0), m_W, m_Z)$

it solves the problem of the photon coupling
but
-it introduces a dependence on the light-quark masses
-it leaves large logarithmic rad.corr. in higher orders
→not recommended

modified Gmu scheme: recommended solution

the LO couplings are evaluated with Gmu
the NLO-EW corrections are evaluated with α(0)
in the NLO-EW calculations, the O(α) relation $G_\mu/\sqrt{2} = g^2/(8\, m_W^2)\,(1+\Delta r)$ must be used
to avoid double counting with the diagrammatic contribution

this choice simultaneously assigns to the real-photon coupling its "natural" value and
reabsorbs large rad.corr. in the Gmu definition
does not depend on the light-quark mass values

Benchmark numbers: the setup

same inputs and setup as in the tuned comparison, with few exceptions:

constant width approach for *W* and *Z*

$$M_Z = 91.1535 \text{ GeV}, \qquad \Gamma_Z = 2.4943 \text{ GeV}$$
$$M_W = 80.358 \text{ GeV}, \qquad \Gamma_W = 2.084 \text{ GeV}$$

additional cut on the lepton-pair transverse mass, in the CC processes $M_\perp(l\nu) > 40\,\text{GeV}$

input scheme: modified Gmu scheme

Benchmark numbers: NLO total cross sections

code	LO	NLO QCD	NLO EW μ	NLO EW e calo	NNLO QCD
HORACE	3109.65(8)	×	3022.8(1)		×
WZGRAD	3109.66(3)	×	3022.68(4)		×
RADY					×
SANC	3109.66(2)		3022.53(4)	3038.91(5)	×
DYNNLO		3092.3(9)	×	×	3210(15)
FEWZ		3089.1(3)	×	×	3206(2)
POWHEG-w		3090.4(2)	×	×	×
POWHEG_BW					×
POWHEG_BMNNP					×

Table 9: $pp \to W^+ \to l^+\nu_l$ cross sections (in pb) at the 8 TeV LHC, with ATLAS/CMS cuts and bare leptons.

code	LO	NLO QCD	NLO EW μ	NLO EW e calo	NNLO QCD
HORACE	2156.36(6)	×	2101.17(8)		×
WZGRAD	2156.48(1)	×	2101.23(2)		×
RADY					×
SANC	2156.46(2)		2101.31(4)	2110.69(4)	×
DYNNLO		2189.3(7)	×	×	2233(8)
FEWZ		2187.1(1)	×	×	2238(1)
POWHEG-w		2187.72(6)	×	×	×
POWHEG_BW					×
POWHEG_BMNNP					×

Table 10: $pp \to W^- \to l^-\bar{\nu}_l$ cross sections (in pb) at the 8 TeV LHC, with ATLAS/CMS cuts and bare leptons.

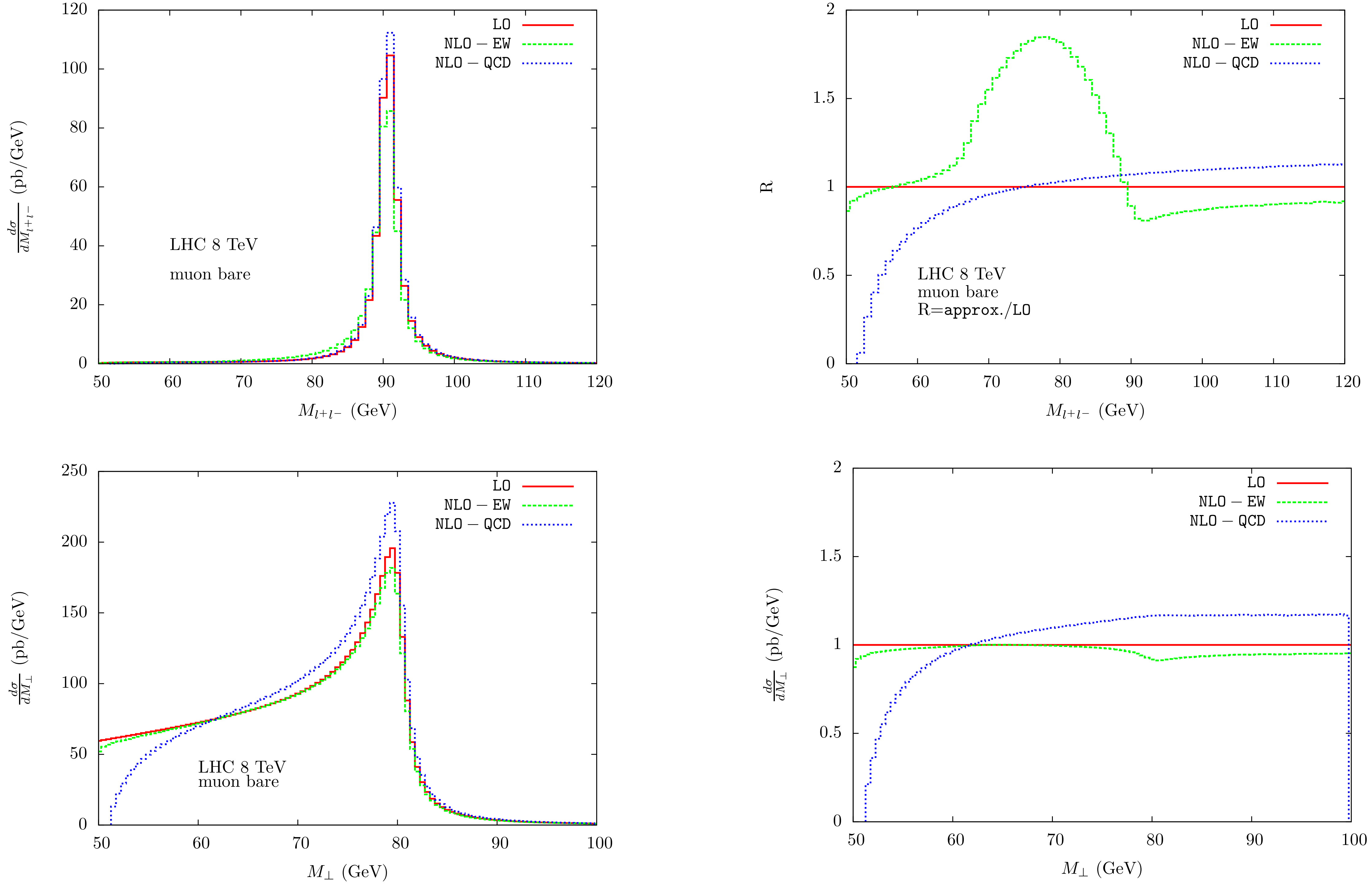
code	LO	NLO QCD	NLO EW μ	NLO EW e calo	NNLO QCD
HORACE	462.663	×	443.638		×
WZGRAD	462.681(3)	×	443.726(5)		×
RADY					×
SANC	462.675(2)		443.794(4)		×
DYNNLO		491.94(5)	×	×	501.6(4)
FEWZ		491.62(4)			504.6(3)
POWHEG-z		491.744(4)	×	×	×
POWHEG_BMNNPV					×

Table 11: $pp \to \gamma, Z \to l^-l^+$ cross sections (in pb) at the 8 TeV LHC, with ATLAS/CMS cuts and bare leptons.

input scheme: modified Gmu scheme

in (quick) progress:
collection of all the numbers to fill these tables

Benchmark numbers: NLO differential distributions



the different codes agree in the prediction of the NLO-QCD and NLO-EW corrections in the modified Gmu input scheme

benchmark tables for the main observables can serve as a test of the use of the codes

from this solid starting point it is possible to quantify the impact of h.o. rad.corr.

Radiative corrections: higher order QCD effects

the QCD expansion can be organized with respect to $L_V \equiv \log\left(\frac{p_\perp^V}{M_V}\right)$

$$
\begin{aligned}
\sigma \;=\; & \sigma_0 \;+ \\
& A_1\,\alpha_s L_V + B_1\,\alpha_s \;+ && \longleftarrow \text{NLO-QCD} \\
& A_2\,\alpha_s^2 L_V^2 + B_2\,\alpha_s^2 L_V + C_2\,\alpha_s^2 \;+ && \longleftarrow \text{NNLO-QCD} \\
& A_3\,\alpha_s^3 L_V^3 + B_3\,\alpha_s^3 L_V^2 + C_3\,\alpha_s^3 L_V + D_3\,\alpha_s^3 \;+ \ldots && \longleftarrow \text{NNNLO-QCD}
\end{aligned}
$$

↑ LL-QCD ↑ NLL-QCD ↑ NNLL-QCD ....

the first row NLO-QCD is common and tested at high precision for all the QCD codes

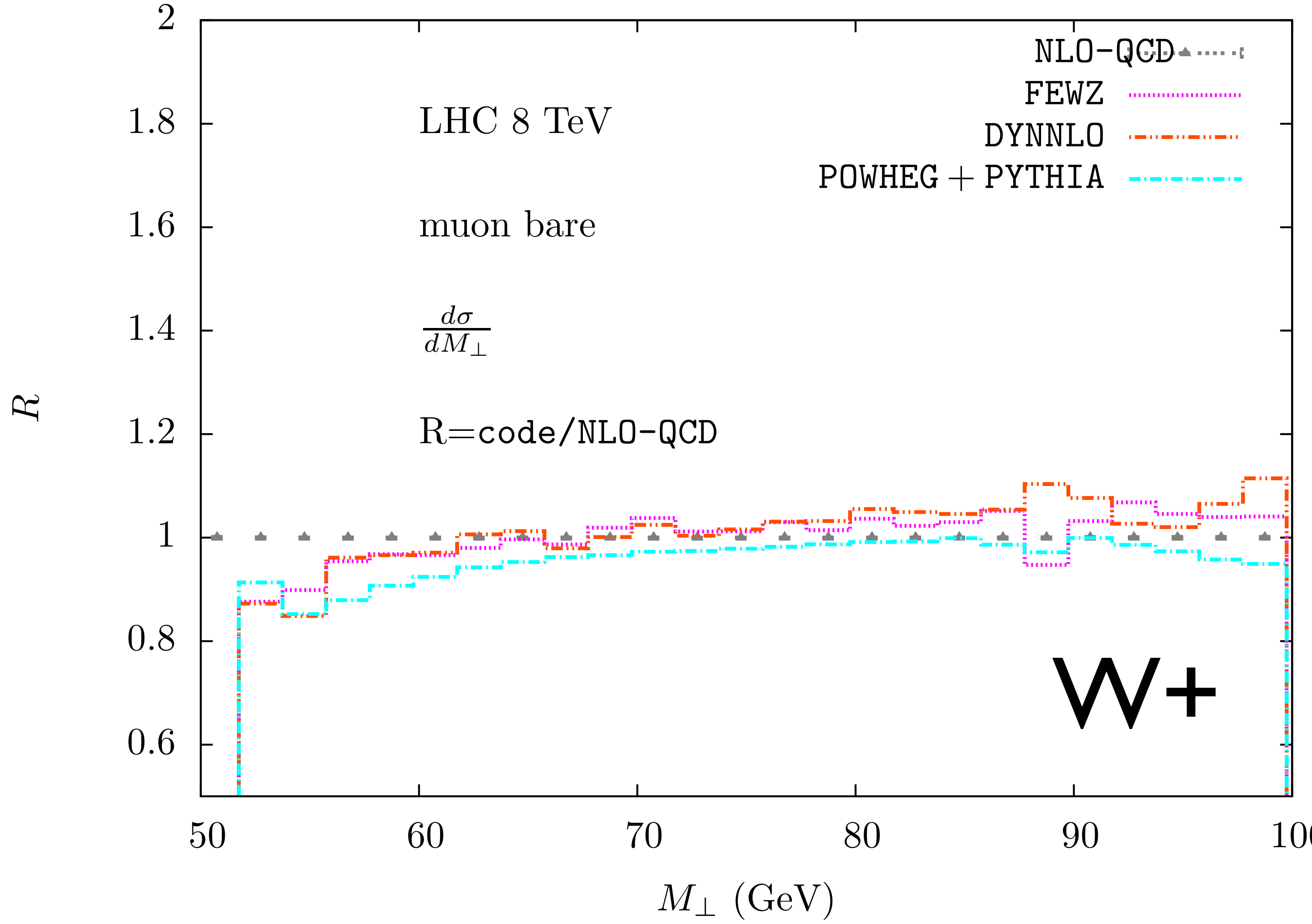
we can evaluate the size of some subsets of h.o. corrections, like e.g.:
- NNLO-QCD
- (N)LL-QCD resummed via Parton Shower

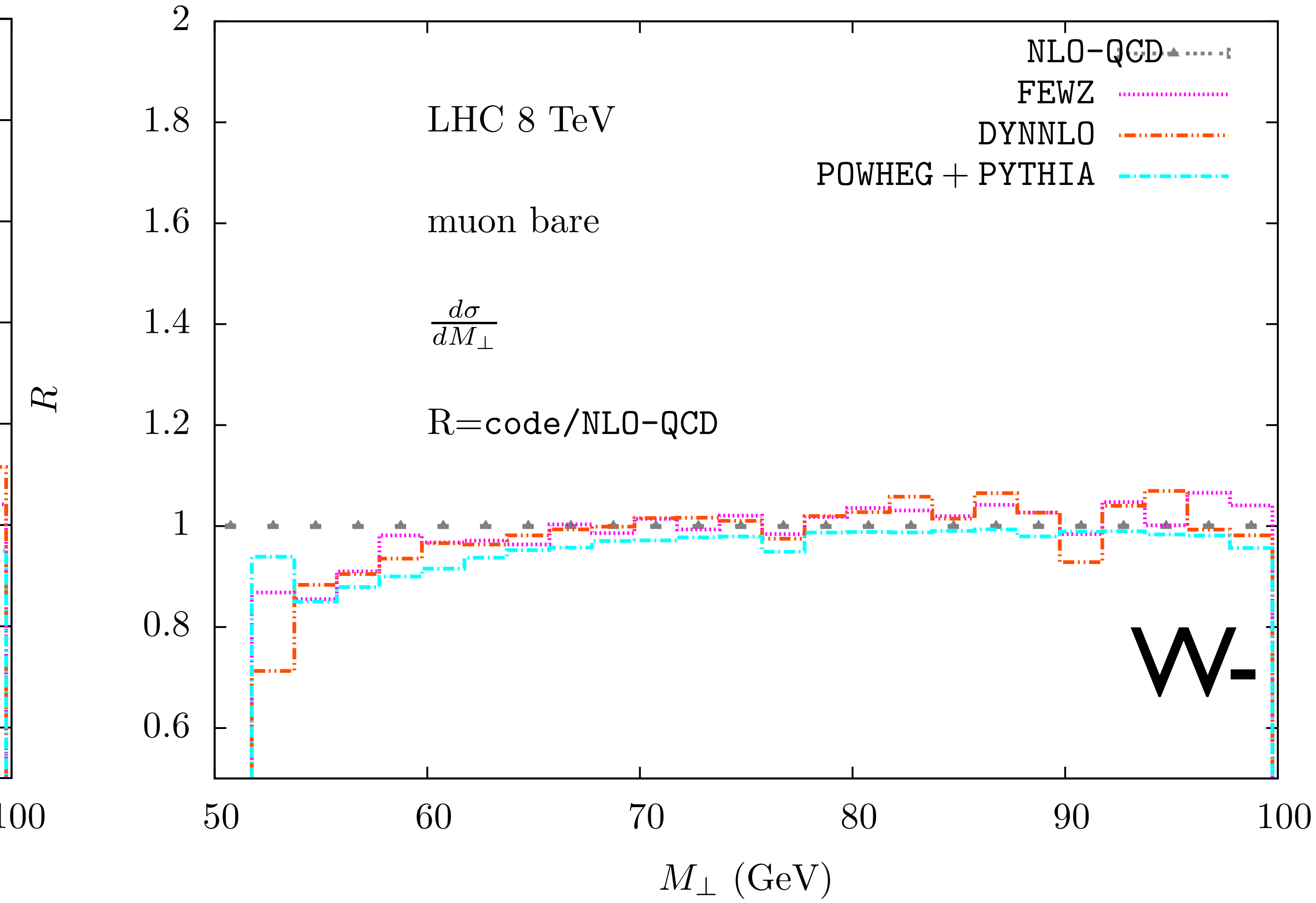
all the effects shown in the next slides are of $O(\alpha_s^2)$ and higher

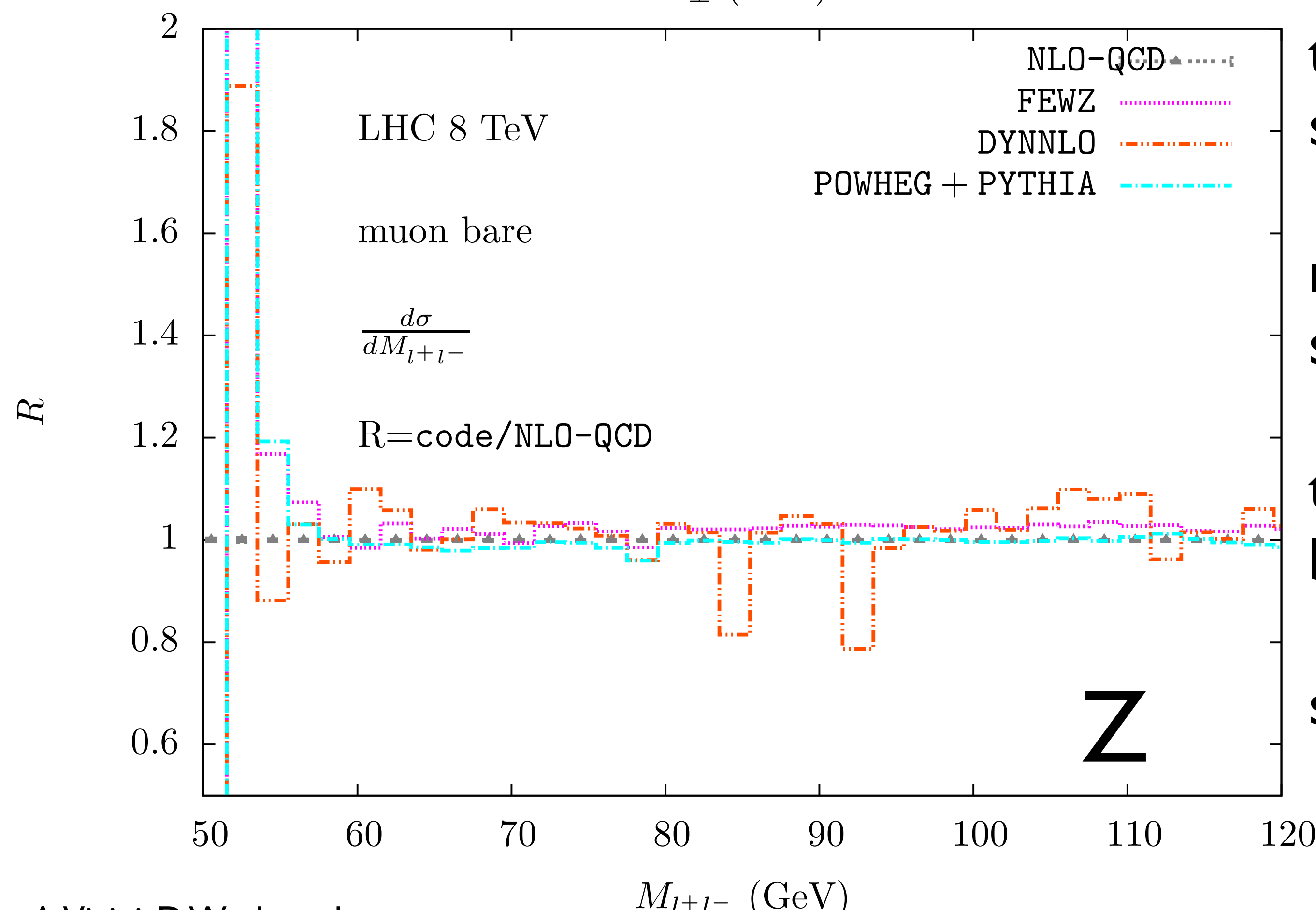
caveat

the representation of the higher-order effects is a delicate issue, that depends on the observable
when the resummation is needed, fixed-order corrections are meaningless

Radiative corrections: higher order QCD effects, transv./inv. mass







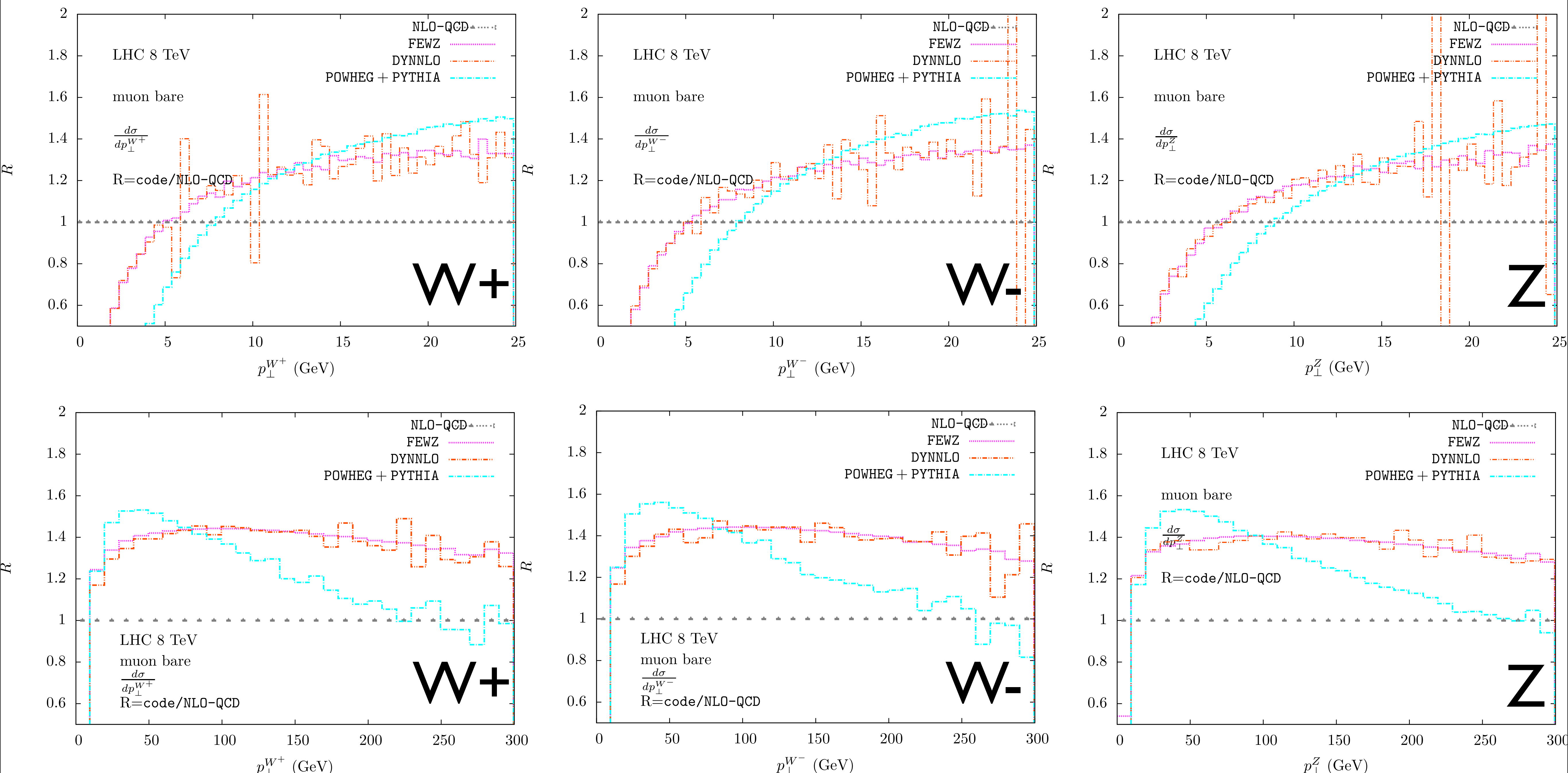
the two available NNLO-QCD codes agree within statistical uncertainties

no log enhancement → the QCD corrections are slowly varying in the whole mass region

the QCD-PS on top of NLO has an effect only because of the acceptance cuts

small, quite flat, NNLO-QCD K-factor

Radiative corrections: higher order QCD effects, lepton-pair pt

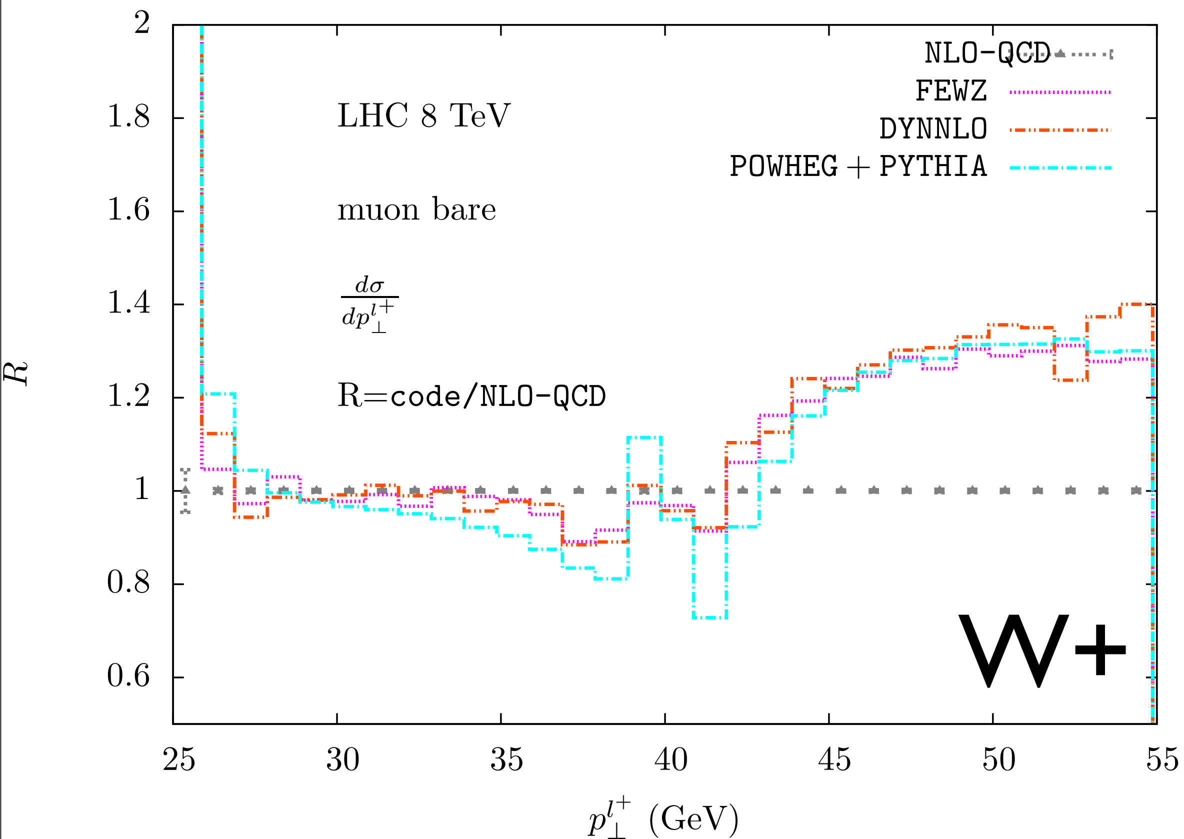


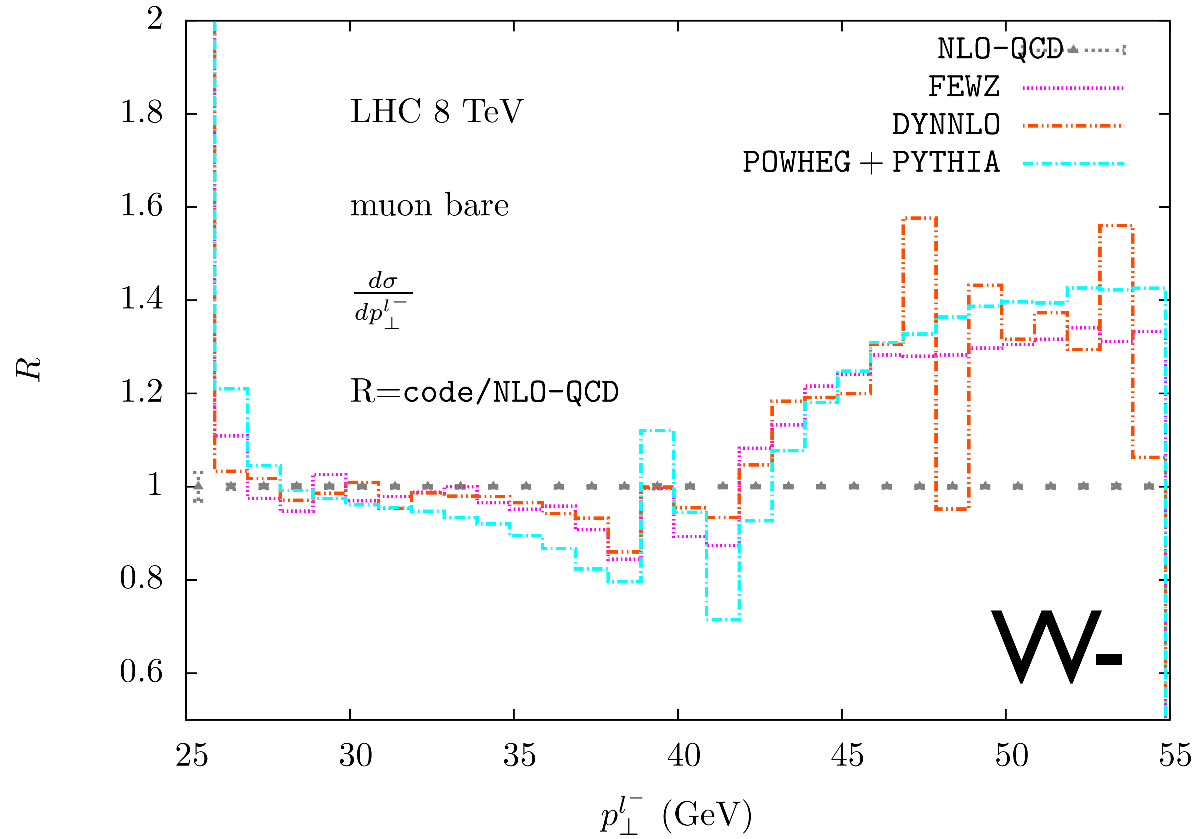
the two available NNLO-QCD codes agree within statistical uncertainties

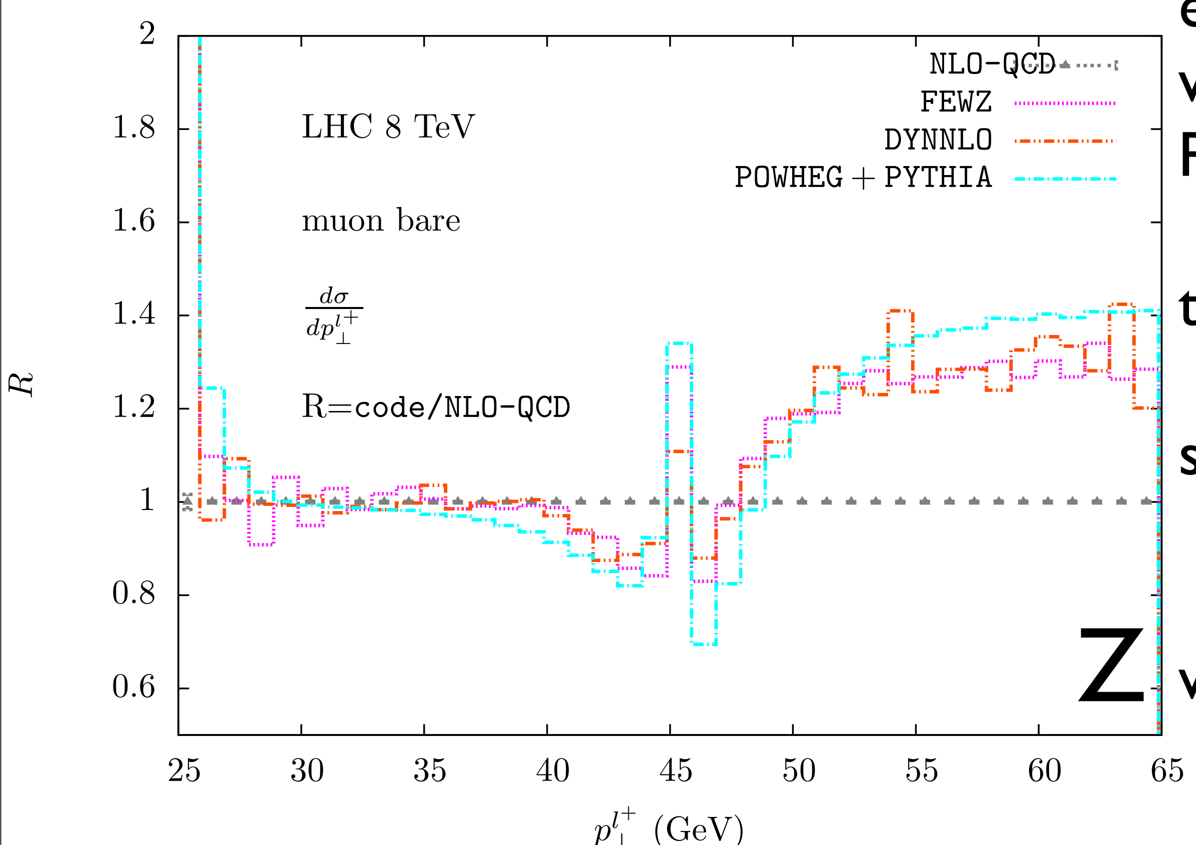
the fixed-order distributions are divergent for vanishing lepton-pair transverse momentum
→ the comparison NNLO/NLO is not sensible

at large transverse momentum, POWHEG tends to the fixed order distribution
the NNLO extra subprocesses are sizeable

Radiative corrections: higher order QCD effects, lepton pt







excluding the jacobian peak region,
where only a resummed expression makes sense,
POWHEG+PYTHIA follows the NNLO curve

the h.o. effects are sizeable O(30%) above the jacobian peak

several % of the difference
between POWHEG+PYTHIA and NNLO

we need NNLO predictions matched with
resummation/QCD-PS

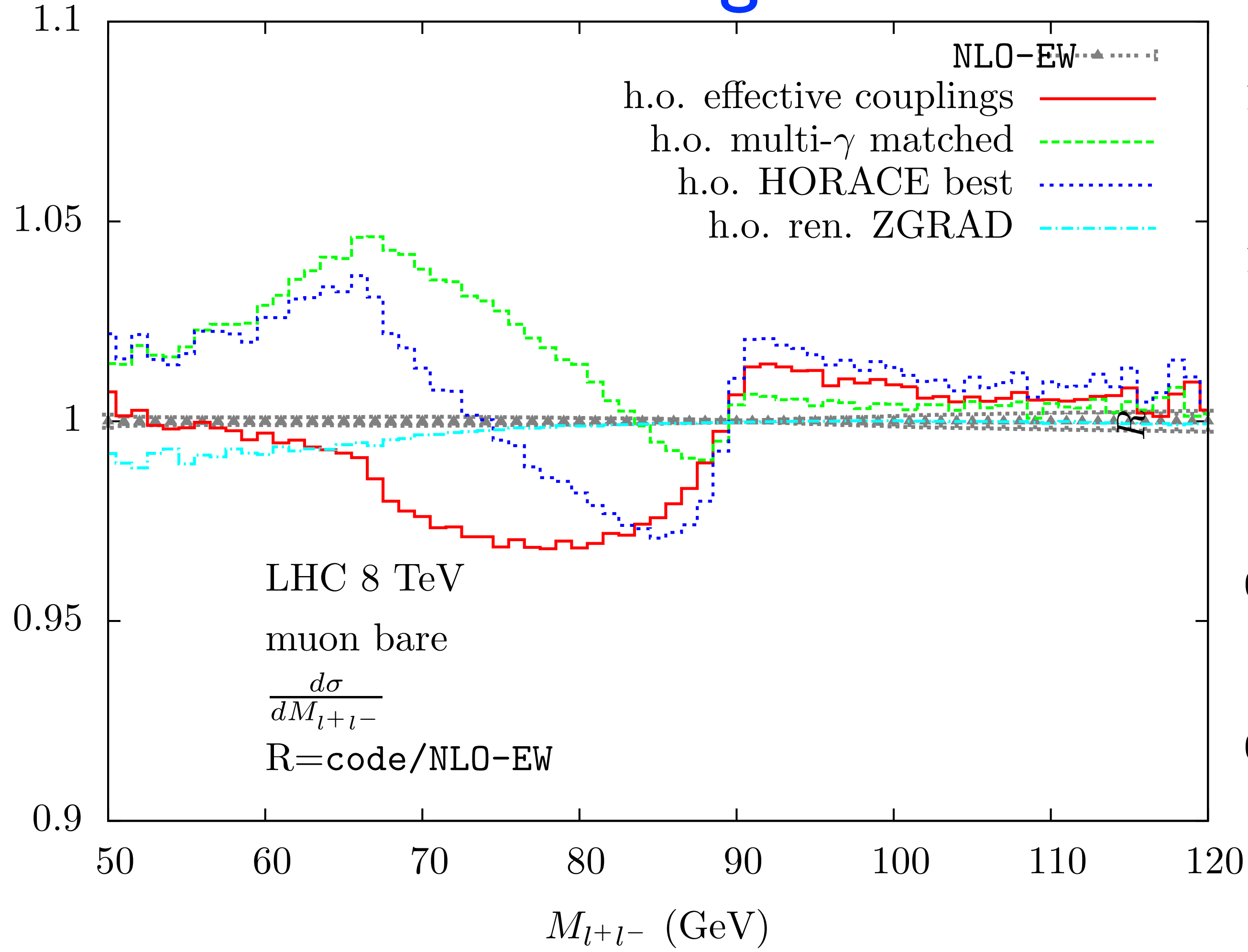
Radiative corrections: higher order EW effects

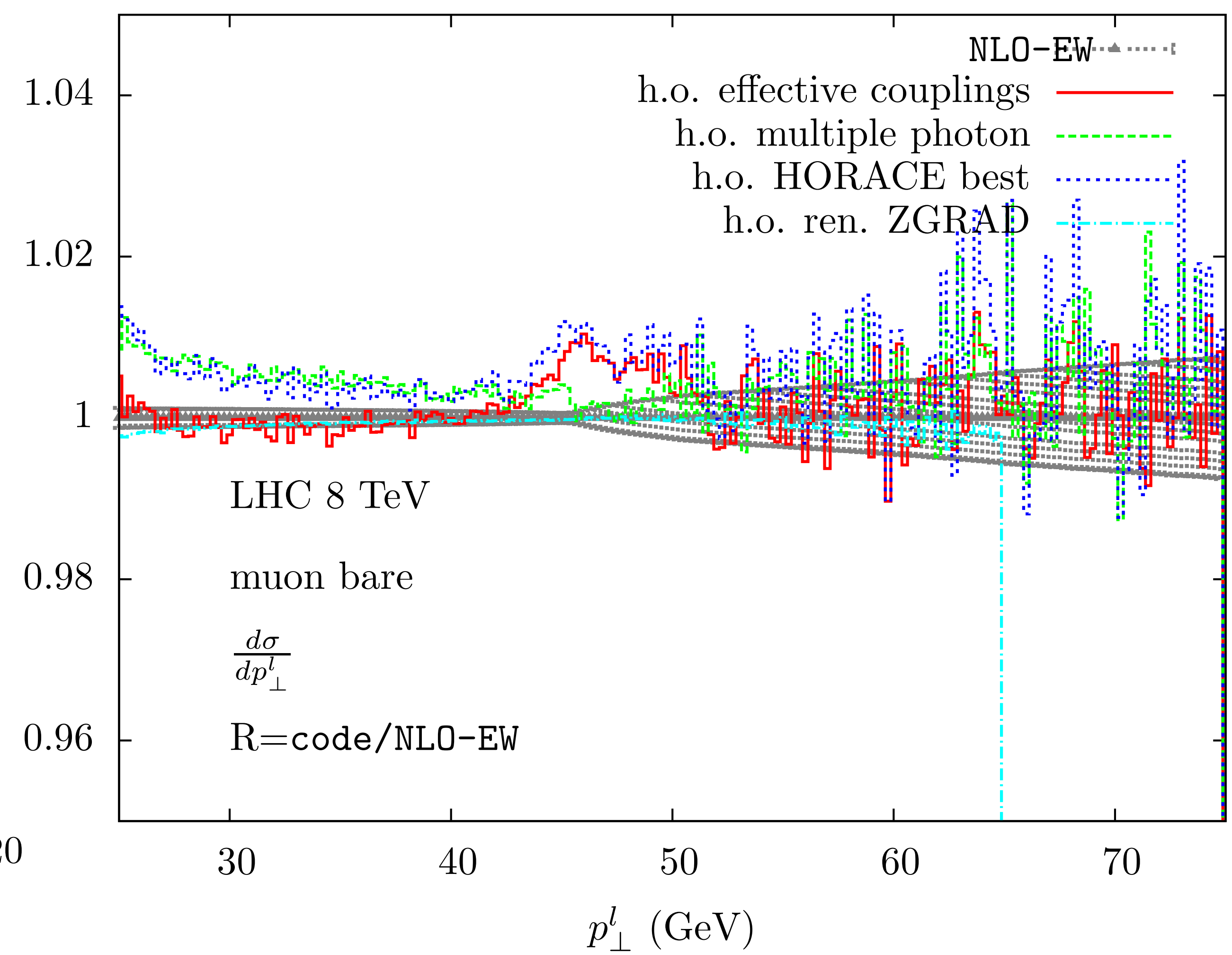
the NLO-EW is common and tested at high precision for all the EW codes

we can evaluate the size of some subsets of h.o. corrections, like e.g.:
- h.o. via renormalization
- h.o. via running effective couplings
- effects of multiple photon radiation matched with NLO-EW
- ...

all the effects shown in the next slides are of $O(\alpha^2)$ and higher

Radiative corrections: higher order EW effects





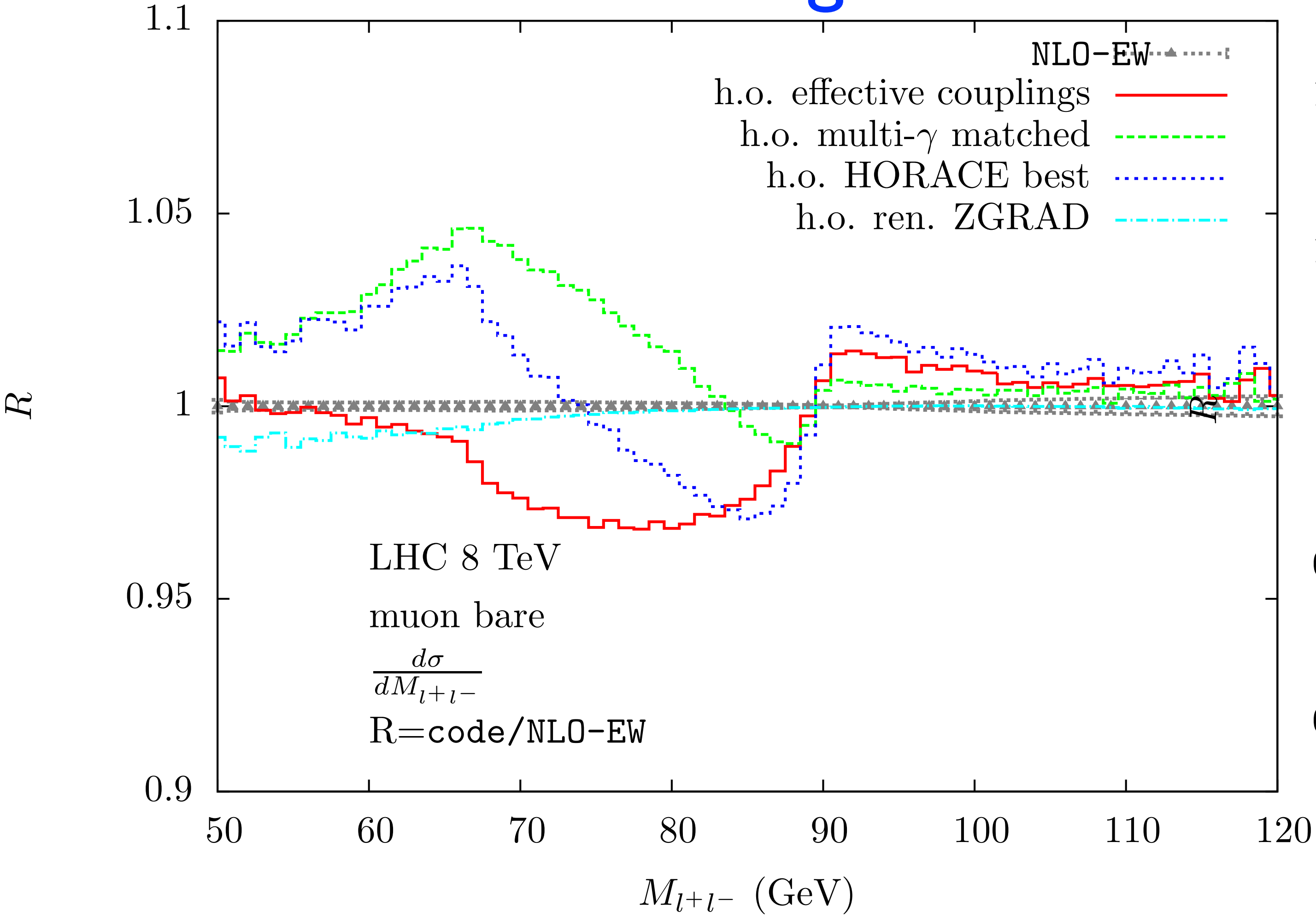
all the effects shown are of O(α²) and higher; preliminary first examples

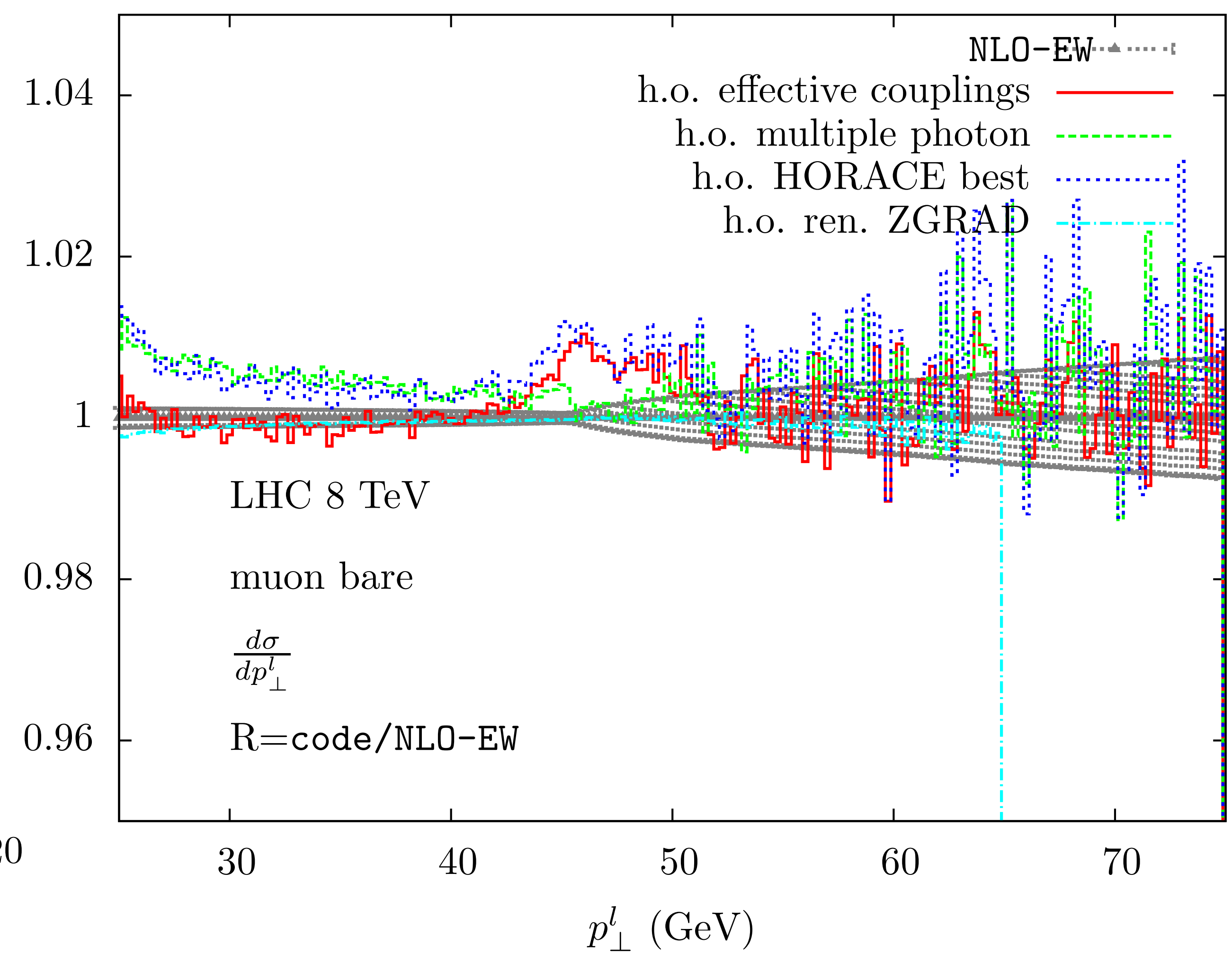
universal higher order corrections in the definition of the counterterms (light blue)

$$\delta m_Z^2 = \mathcal{R}e\left(\Sigma^Z(m_Z^2)\right) \rightarrow \delta m_Z^2 = \mathcal{R}e\left(\Sigma^Z(m_Z^2) - \frac{(\hat{\Sigma}^{\gamma Z}(m_Z^2))^2}{m_Z^2 + \hat{\Sigma}^{\gamma}(m_Z^2)}\right)$$

$$\frac{\delta m_Z^2}{m_Z^2} - \frac{\delta m_W^2}{m_W^2} \rightarrow \frac{\delta m_Z^2}{m_Z^2} - \frac{\delta m_W^2}{m_W^2} - \Delta\rho^{h.o.}$$

Radiative corrections: higher order EW effects





all the effects shown are of $O(\alpha^2)$ and higher

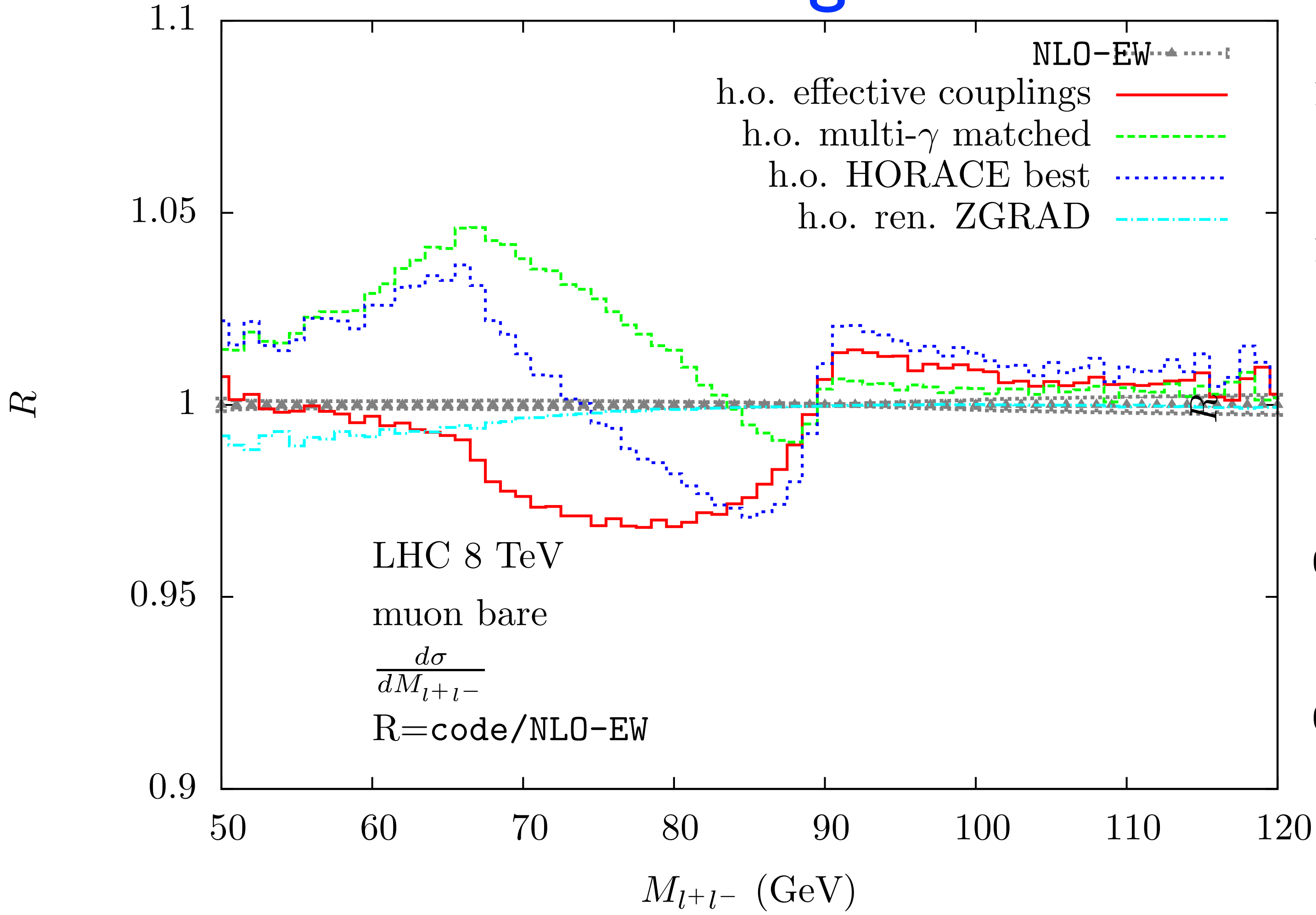
h.o. via running effective couplings (red line)
the LO couplings are dressed, avoiding double counting with the NLO-EW results

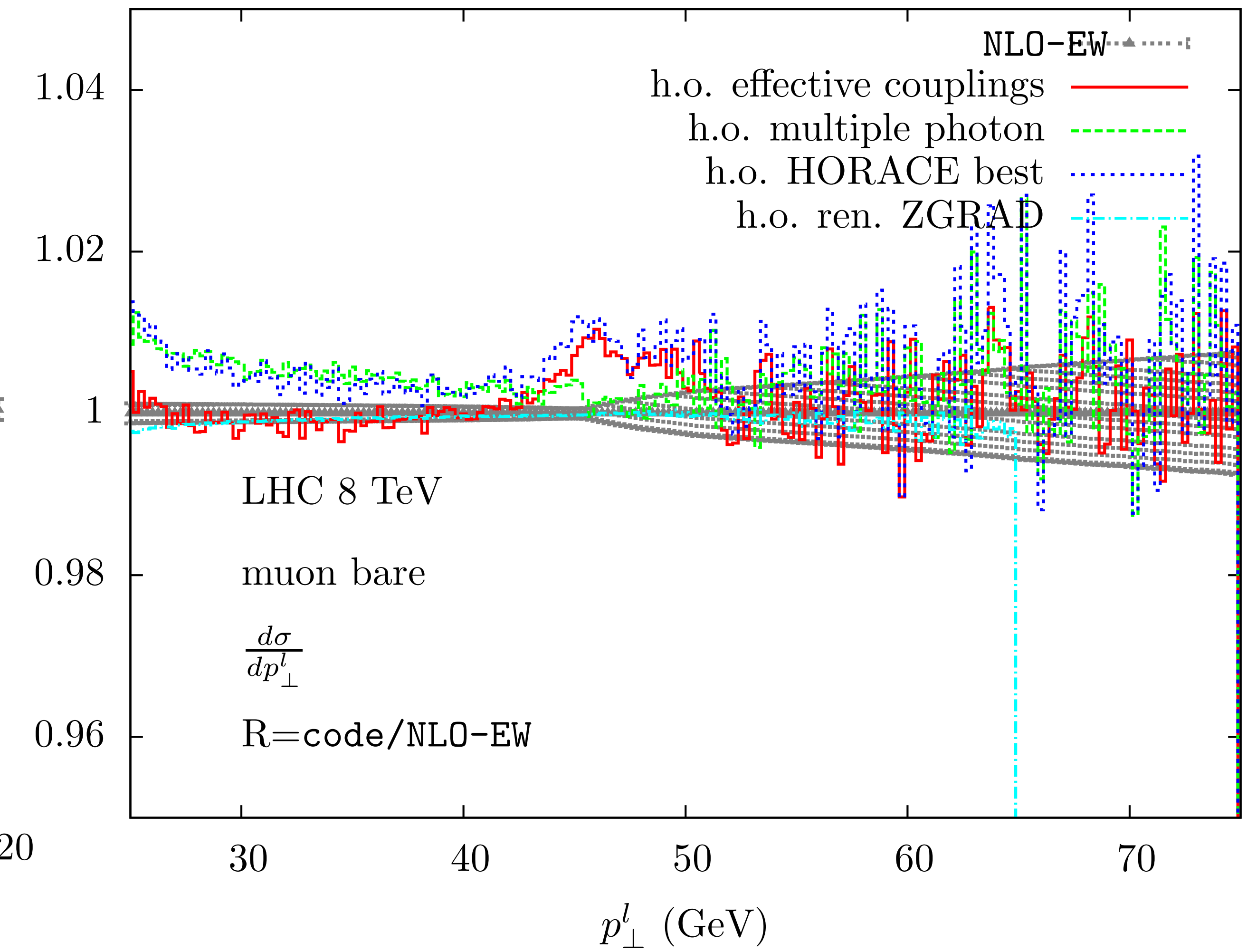
$$e^2 \to e^2(q^2) = e^2 / \left(1 - \Delta\alpha(q^2)\right) \qquad G_\mu \to G_\mu \frac{\rho_{fi}(q^2)}{(1 - \delta\rho_{irr})}$$

$$\frac{i\,g}{c_\theta}\gamma^\mu(\tilde{v}_f - a_f\gamma_5) \qquad \tilde{v}_f = T_f - 2Q_f\kappa_f(q^2)s_\theta^2$$

the huge radiative correction below the Z resonance amplifies
the $O(\alpha^2)$ effects due to the running of the photon coupling and to the modified Z couplings

Radiative corrections: higher order EW effects





all the effects shown are of $O(\alpha^2)$ and higher

multiple photon radiation consistently matched with the exact NLO-EW calculation (green line)

matching of QED Parton Shower with exact NLO-EW calculation discussed in HORACE, POWHEG
the complete result, physically well defined, can be consistently compared to the NLO-EW results

below the Z resonance the $O(\alpha^2)$ effects of this class are at the few per cent level

Combination of QCD and EW effects

$$\sigma_{tot} = \sigma_{LO} + \alpha\sigma_{\alpha} + \alpha^2\sigma_{\alpha^2} + \ldots + \alpha_s\sigma_{\alpha_s} + \alpha_s^2\sigma_{\alpha_s^2} + \ldots + \alpha\alpha_s\sigma_{\alpha\alpha_s} + \alpha\alpha_s^2\sigma_{\alpha\alpha_s^2} + \ldots$$

only NLO-EW, NLO-QCD and NNLO-QCD exactly known

how well can we approximate the O(αα_s) corrections,
given the available QCD and EW codes?
(see talk by A.Huss on O(αα_s) in the pole approximation)

how can we include resummation effects?

$$\mathcal{O} = \mathcal{O}_{LO}\left(1 + \delta_{QCD}^{NLO+NNLO} + \delta_{EW}^{NLO}\right)$$

1) purely additive prescription (at NNLO-QCD FEWZ,
at NLO-QCD SANC, RADY)

$$\mathcal{O} = \mathcal{O}_{LO}\left(1 + \delta_{QCD}^{NLO+NNLO}\right)\left(1 + \delta_{EW}^{NLO}\right)$$

2) factorized use of (differential) K-factors

Combination of QCD and EW effects

$$\sigma_{tot} = \sigma_{LO} + \alpha\sigma_\alpha + \alpha^2\sigma_{\alpha^2} + \dots \quad \alpha_s\sigma_{\alpha_s} + \alpha_s^2\sigma_{\alpha_s^2} + \dots \quad \alpha\alpha_s\sigma_{\alpha\alpha_s} + \alpha\alpha_s^2\sigma_{\alpha\alpha_s^2} + \dots$$

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2) factorized use of (differential) K-factors

- difference with respect to

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\Phi_n) d\Phi_n \left\{ \Delta^{f_b}\left(\Phi_n, p_T^{min}\right) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\, \theta(k_T - p_T^{min})\, \Delta^{f_b}(\Phi_n, k_T)\, R(\Phi_{n+1})\right]_{\alpha_r}^{\bar{\Phi}_n^{\alpha_r} = \Phi_n}}{B^{f_b}(\Phi_n)} \right\}$$

· POWHEG accounts for multiple emission effects
· the kinematics of multiple emissions is exact (fully differential)

- the POWHEG basic formula · is additive in the overall normalization,
  · it describes exactly one parton emission (photon/gluon/quark) (but NOT two partons)
  · includes in a factorized form mixed and higher order corrections via (QCD+QED)-PS
  in particular the bulk of the O(αα_s) corrections
  (but it has NOT O(αα_s) accuracy)

- in observables like the lepton pt distribution, strongly sensitive to QCD showering,
  terms of O(αα_s^p) completely modify the shape of the pure O(α) EW result

What's next

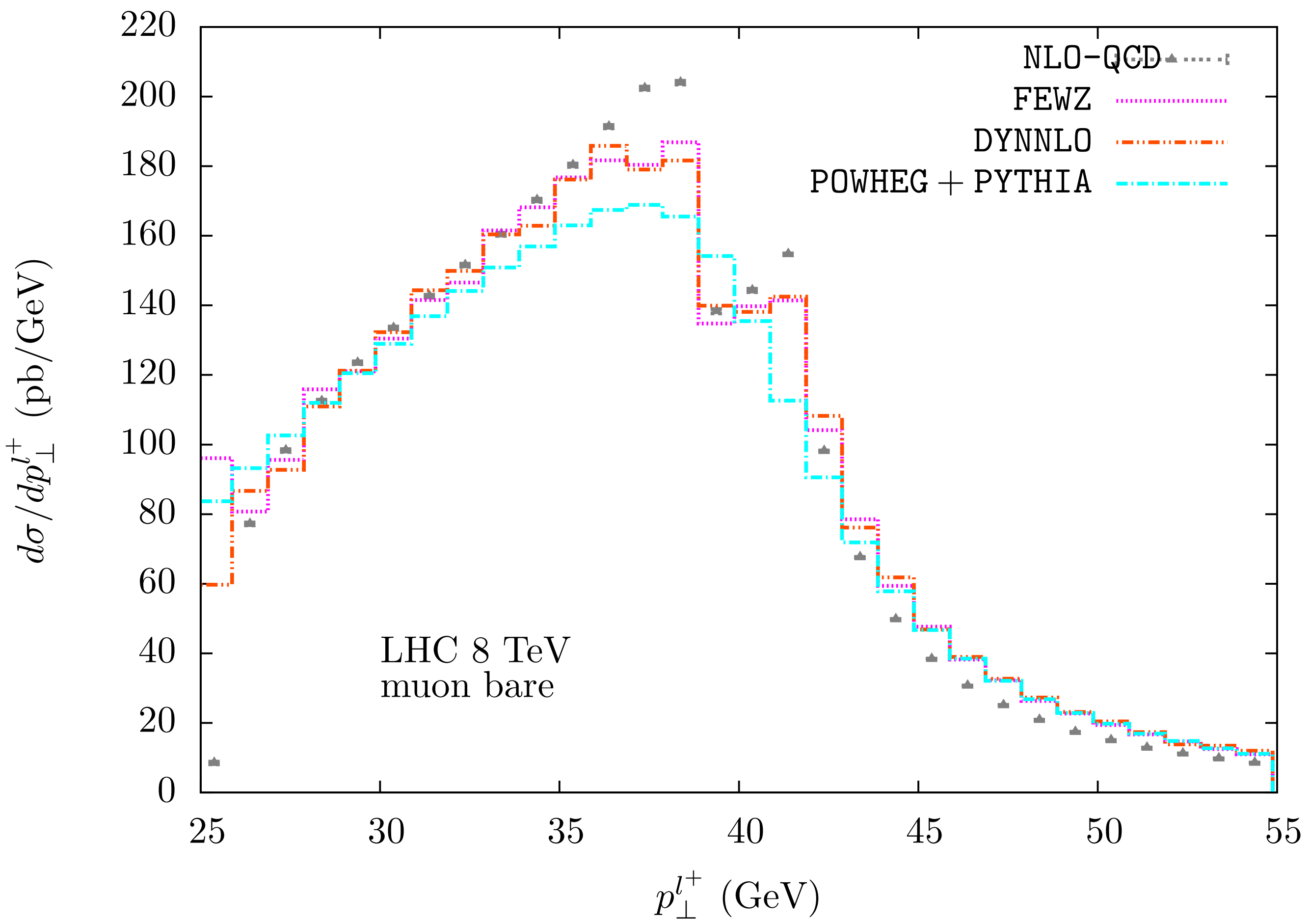
- collect all the remaining results for the benchmark setup
- finalize the discussion on the QCDxEW interplay and on the EW higher-order effects
- benchmarking of the effects of photon-induced processes

- the quantitative assessment of many available higher order corrections
  is the starting point to initiate a discussion about the "best prediction" of DY observables
  and their uncertainty

typical open question:
with the best available event generators,
what is the precision that we can reach and where do we have to improve?
(e.g. the development of NNLO+PS approaches improves the QCD predictions,
how should we merge this results with the best EW results?)

Back-up slides

Radiative corrections: higher order QCD effects, lepton pt



the lepton transverse momentum distribution, in fixed order, shows a double peak due to the divergent contributions at vanishing gauge boson momentum

only the inclusion of multiple parton emissions, e.g. via QCD-PS, makes the shape smooth, with one peak