# Report of the working group on cross sections for single boson production

Alessandro Vicini
University of Milano, INFN Milano

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in collaboration with Doreen Wackeroth

# Plan of the talk

- Introduction
- tuned comparisons: discussion of the results
- computation of “best” results and their interpretation

# Working group on the comparison of codes for Drell-Yan like final states

- participants
  HORACE, RADY, SANC, WZGRAD
  WINHAC, PHOTOS
  DYNNLO, FEWZ
  POWHEG (pure QCD and QCD+EW)

- main goals of the WG
  - check/demonstrate the level of agreement of different codes in a given setup and with a common fixed perturbative approximation (technical level)
  - assess the impact of higher-order perturbative corrections, which are not available in all the codes
  - from the spread of all the available "best" results of each code, estimate the size of missing higher-order corrections and of remaining uncertainties

- there is not a single code able to provide the best description for all the observables
  → a dedicated discussion for every single observable is necessary

# Setup for the tuning of the codes and choice of observables

- numerical values of all the input parameters

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

- input scheme ($\alpha_0$, MW, MZ)

in the calculation of best results we adopted
a value for MW, MZ, GammaW, GammaZ
in fixed-width scheme, compatible with the PDG value

- PDF set MSTW2008nlo

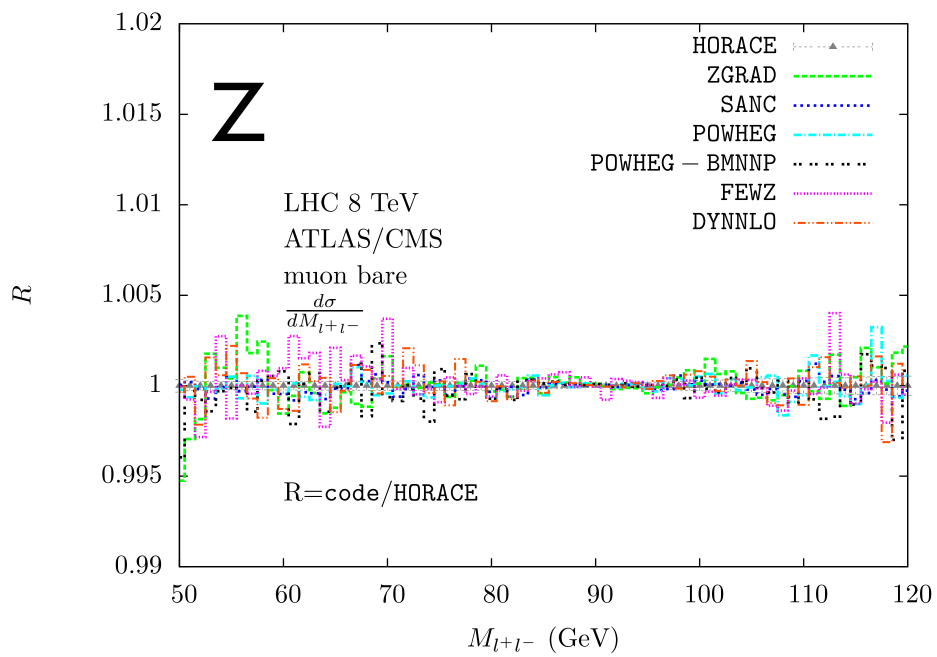
- acceptance cuts

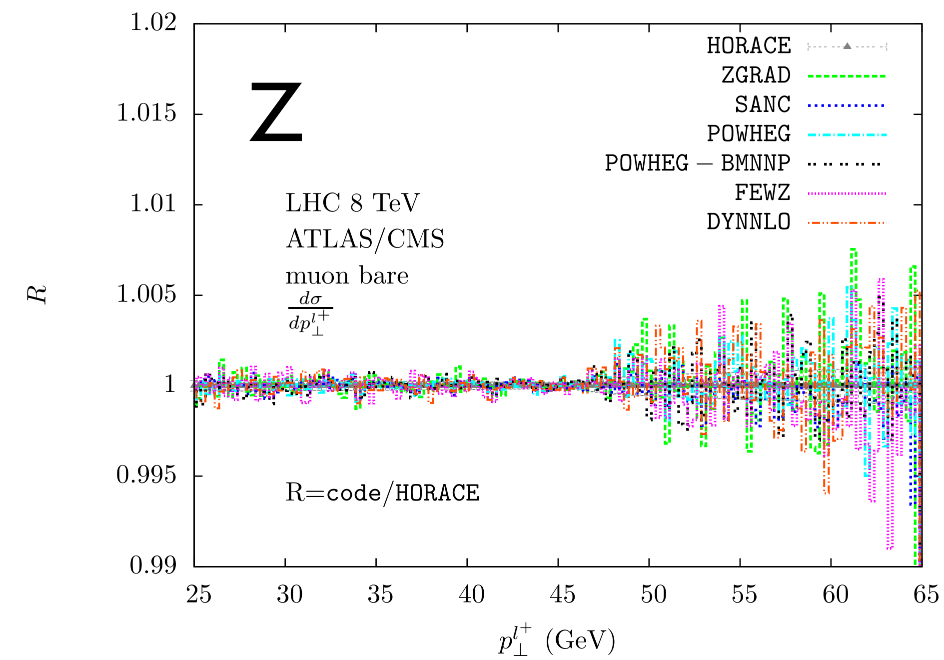
$$
\begin{aligned}
\text{Tevatron}: &\quad p_T(\ell) > 25\ \text{GeV}, \quad |\eta(\ell)| < 1, \quad \not{p}_T > 25\ \text{GeV}, \quad \ell = e,\, \mu, \\
\text{LHC}: &\quad p_T(\ell) > 25\ \text{GeV}, \quad |\eta(\ell)| < 2.5, \quad \not{p}_T > 25\ \text{GeV}, \quad \ell = e,\, \mu, \\
\text{LHCb}: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

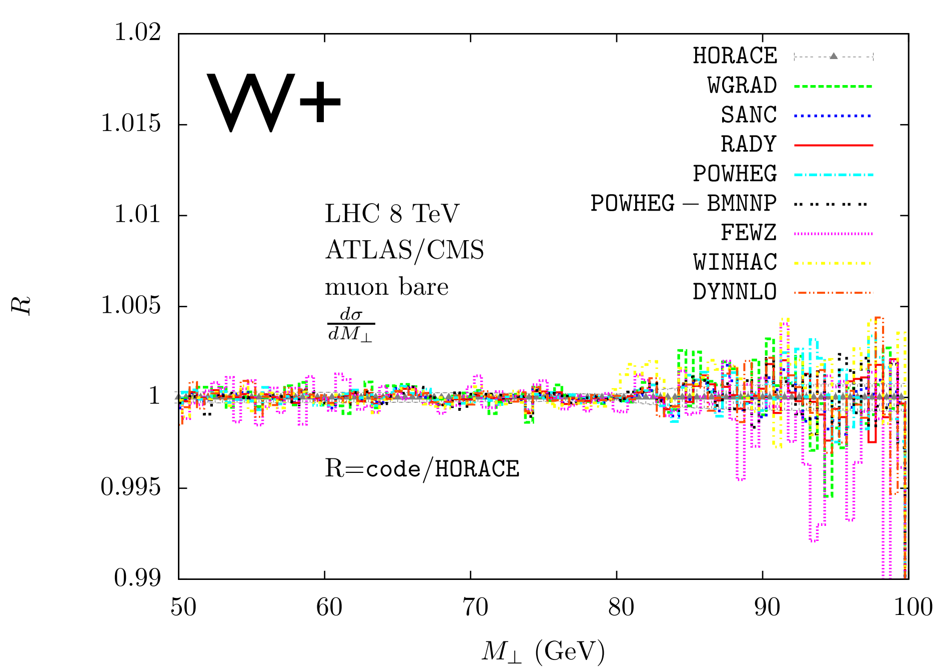
- distinction between electrons and muons in final state

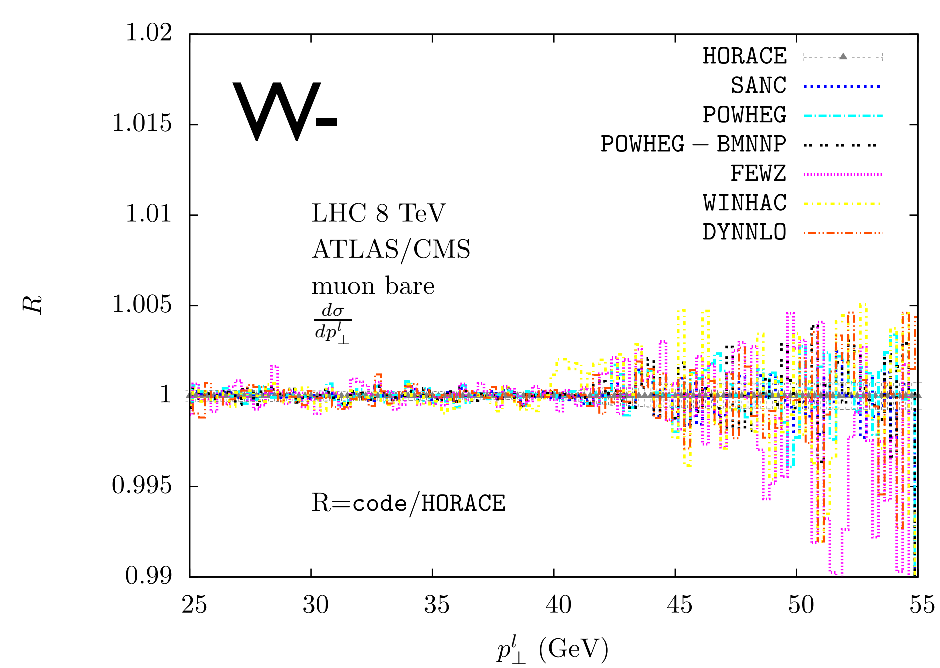
# Tuned comparison at LO

- ratio of the predictions of different codes, divided by one reference result



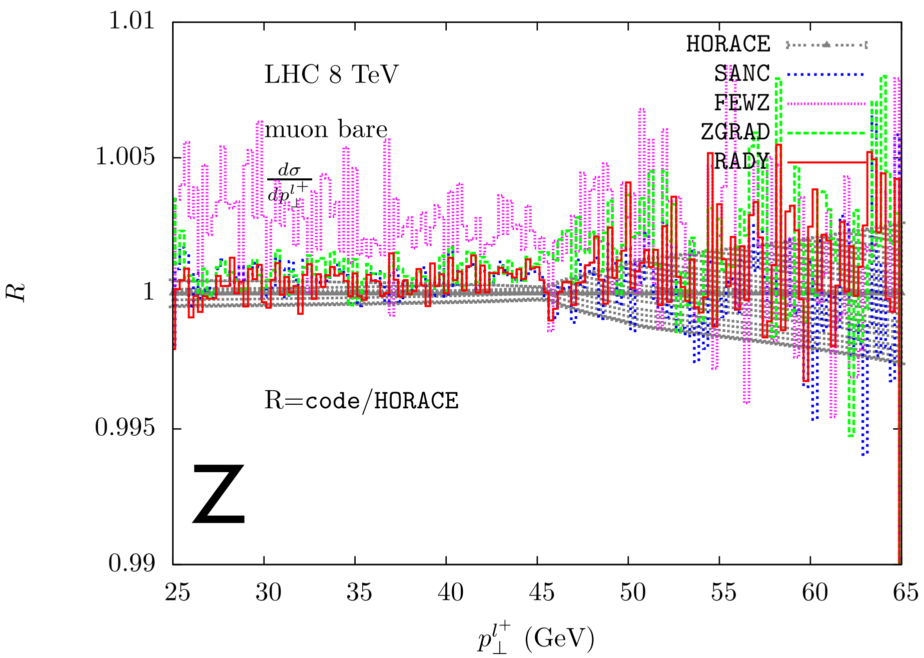



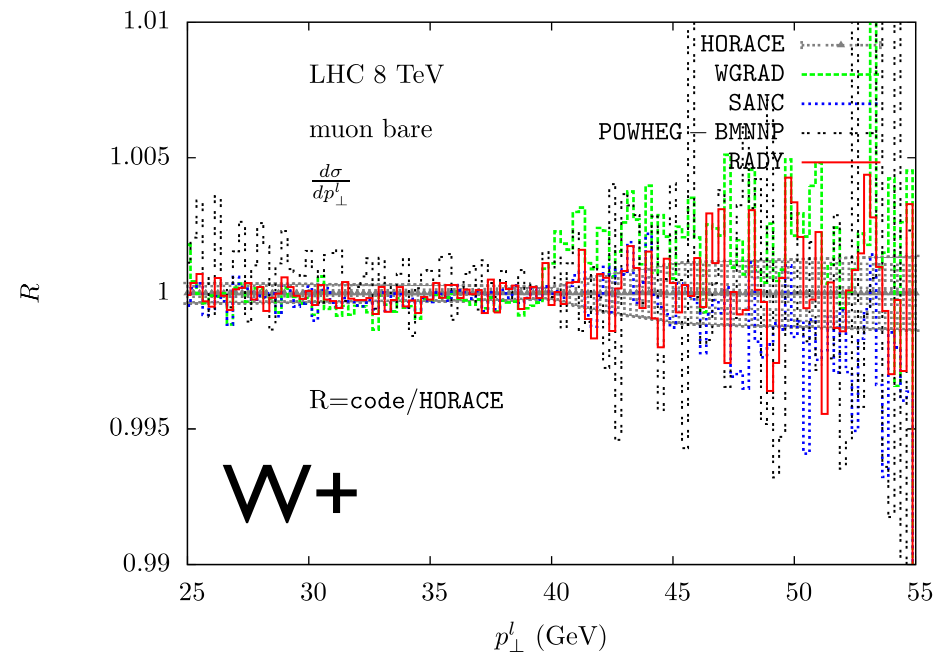



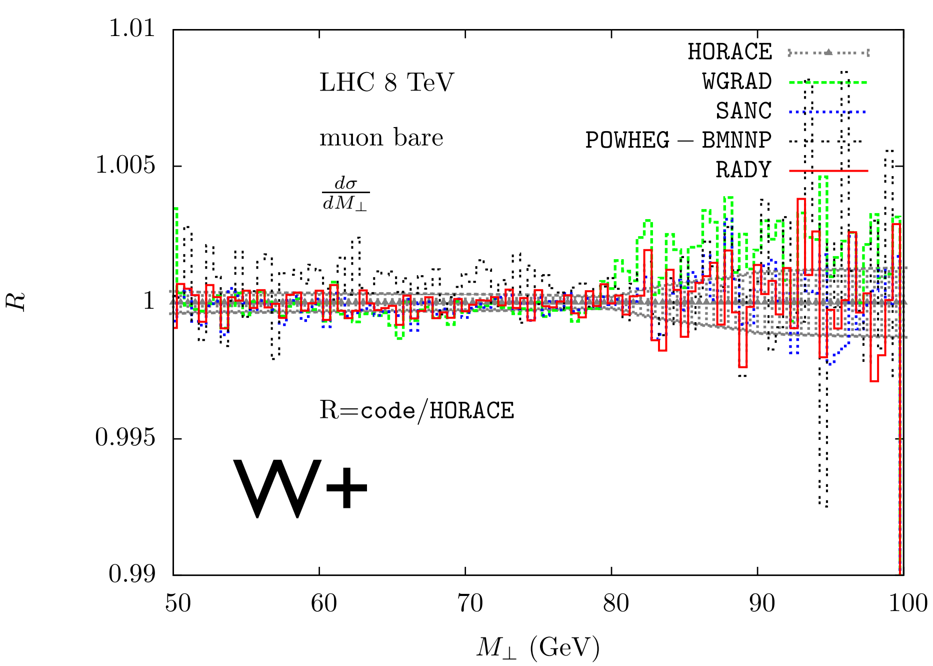



# Tuned comparison at NLO-EW

- ratio of the predictions of different codes, divided by one reference result



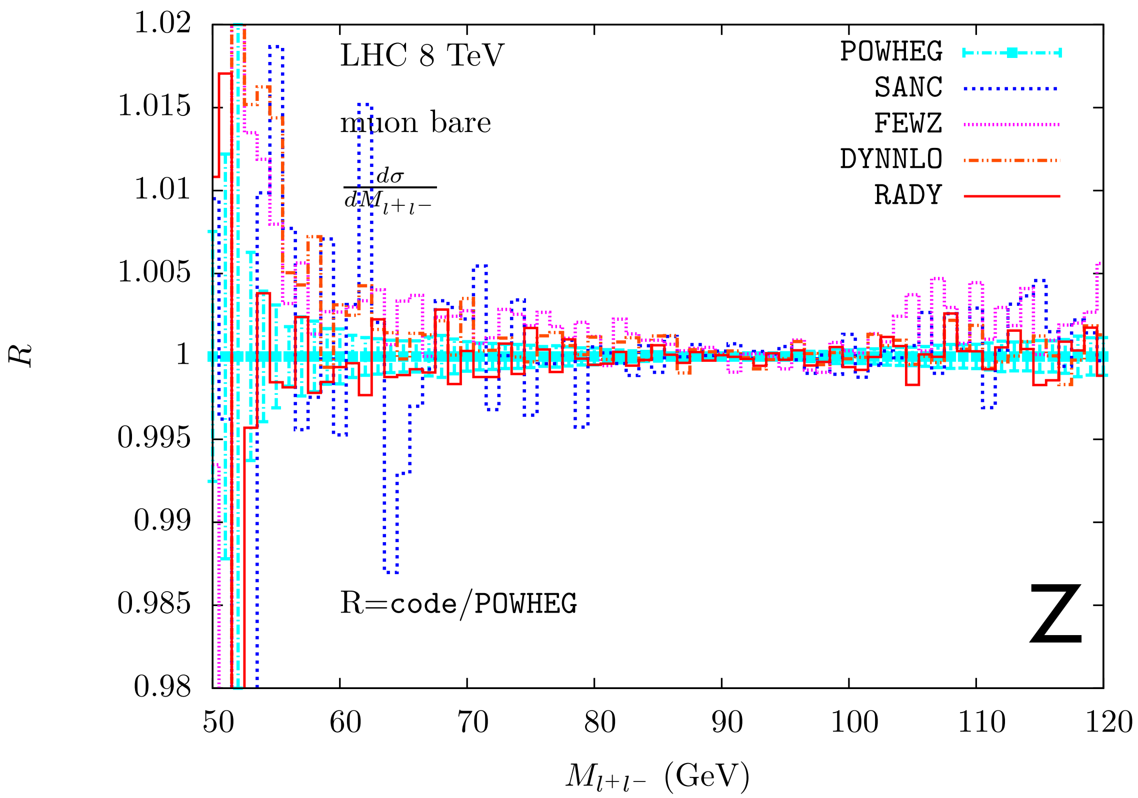



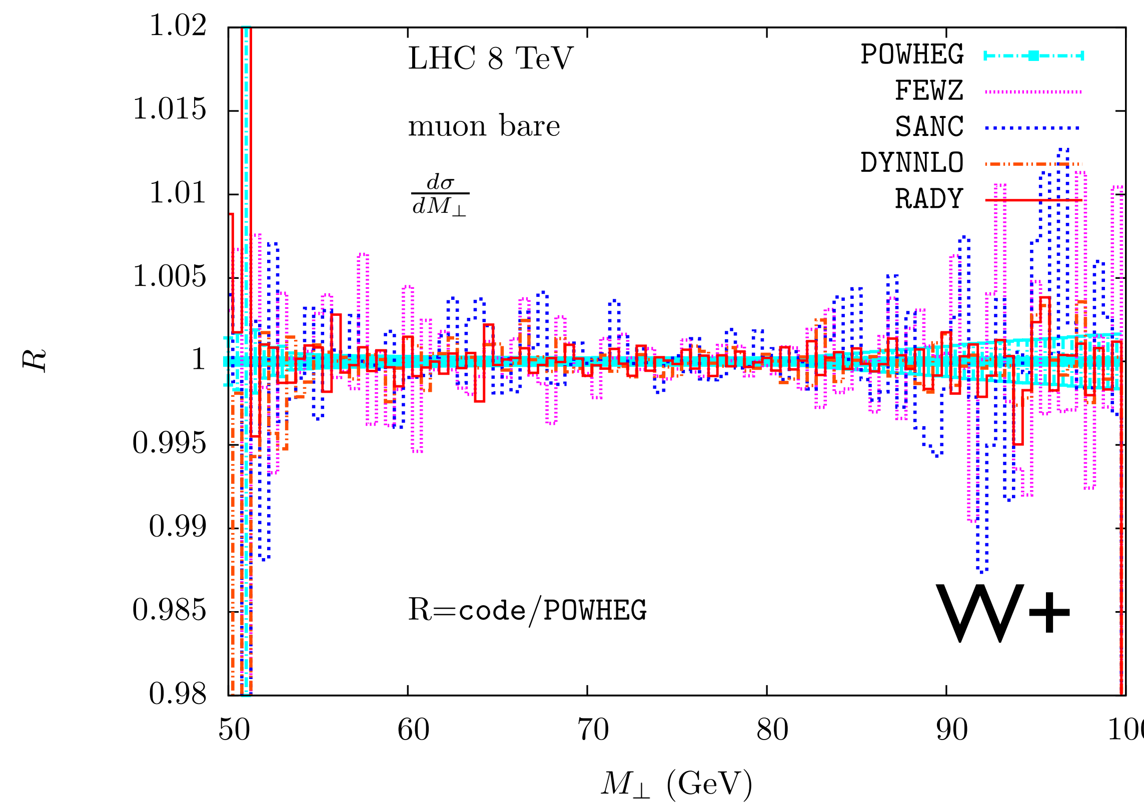

the level of agreement is at the 1-2 per mille level at the jacobian peak and within 0.5% elsewhere

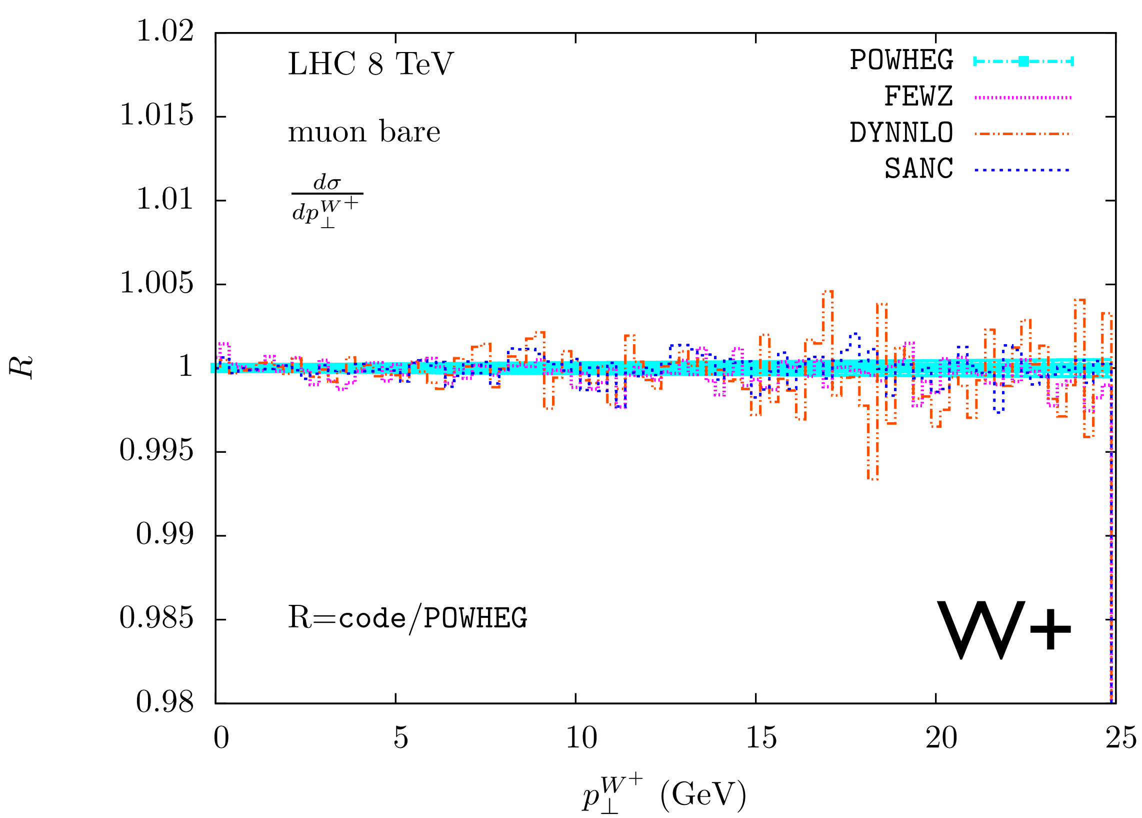
the very fine binning enhances the residual fluctuations

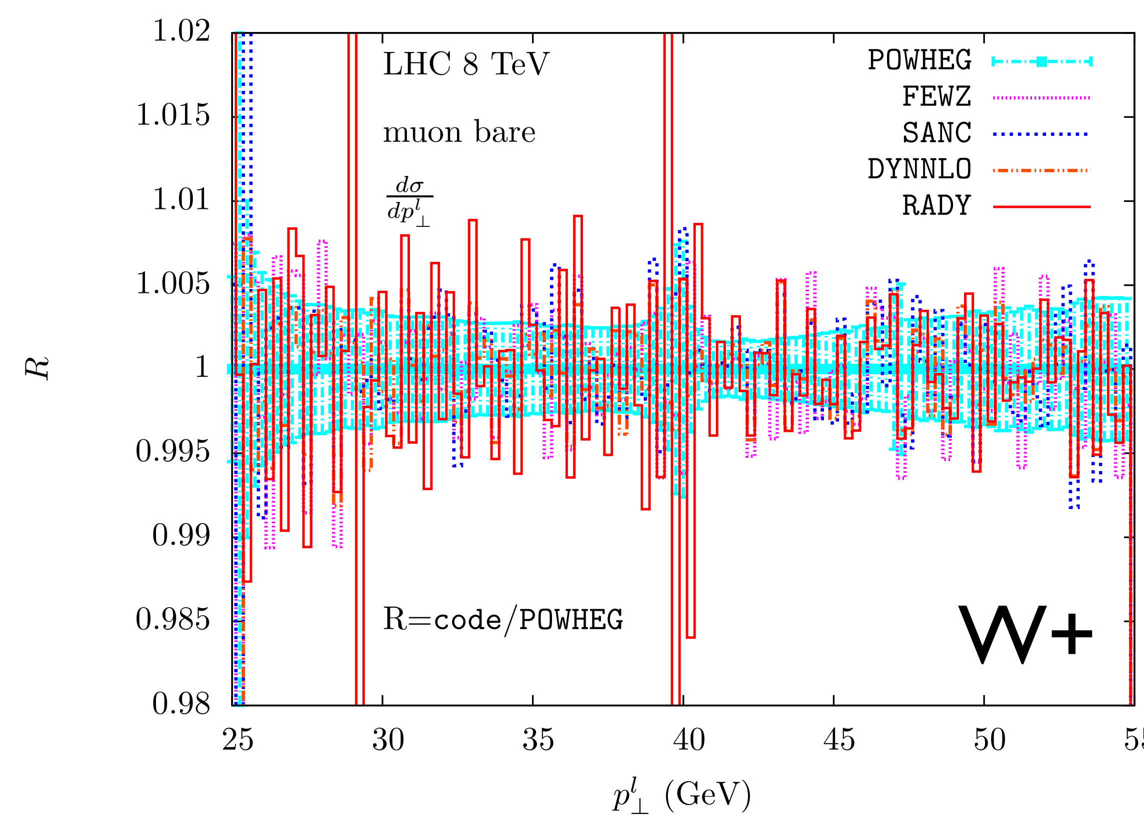
# Tuned comparison at NLO-QCD

- ratio of the predictions of different codes, divided by one reference result



# Example of cross sections comparison

| code | LO | NLO QCD | NLO EW $\mu$ | NLO EW $e$ | NNLO QCD | NLO QCD+EW |
|---|---|---|---|---|---|---|
| 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) | 2988.02(4) | | | |
| 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 | | | | | | |
| POWHEG_BMNNP | 2897.36(5) | | 2989.85(4) | | | |

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

# Discussion on the outcome of the tuned comparison

- we checked the level of agreement of different codes
  in a given setup (input parameters, acceptance cuts, PDFs)
  and with a common fixed perturbative approximation (LO, NLO-QCD, NLO-EW)
  (77 pages illustrating all the observables)

- the level of agreement on the differential distributions is at the level of ~0.1%
  at the jacobian peak at NLO-EW and at NLO-QCD

- it ranges from 1to 5 per mille level above the resonances
  where the MC statistics starts to be a technical problem

- the decay-width prescription is strongly connected to the implementation of NLO-EW
  corrections and induces $O(\alpha^2)$ effects at the 1 per mille level

# Best predictions, higher-order corrections and theoretical uncertainties

0) After the tuning, the codes yield the "same results" with NLO-QCD (or NLO-EW) accuracy

1) We choose an input scheme (improved Gmu scheme)
that provides a simple and accurate description of the Z resonance
Also in this scheme the tuning is fulfilled, at NLO (in progress a systematic check).

2) We allow to switch on: input scheme improvements, higher-order corrections
→ the predictions are now different, the spread is due to terms beyond NLO

We assess the impact of available (at least in one code) higher-order perturbative corrections, by expressing their percentual impact w.r.t. NLO results (which are common to all the codes)

We estimate the size of missing higher orders or uncertainties by measuring the spread of the predictions of different codes, formally equivalent

# Input scheme for the calculation of "best" predictions

- improved Gmu scheme as reference choice for the coupling constants

  1) everywhere the amplitude is expressed in terms of $(\alpha_0, MW, MZ)$

  2) the whole result is rescaled by $\left(\frac{\alpha_{G_\mu}}{\alpha_0}\right)^2$, i.e. the LO couplings are expressed with Gmu

  3) in NLO-EW calculations, subtract $2\,\Delta r\,\sigma_{LO}$ to avoid double countings

- advantages:
  a) the LO couplings reabsorb the bulk of the corrections due to $\Delta r$
  b) the scheme can be easily applied to both EW and QCD calculations
  c) real photon radiation is described with its appropriate coupling

- further improvements of the couplings are possible,
  but are left to the discussion of higher order corrections

- this scheme represents a convenient choice to describe physics at the MW, MZ scale

# Higher-order corrections available and remaining theoretical uncertainties

- QCD

  available
  - NNLO-QCD fixed order corrections
  - multiple QCD radiation via Parton Shower matched with NLO-QCD results
  - analytic resummation of the lepton-pair transverse momentum distribution

  uncertainties
  - determination of the Parton-Shower non-perturbative parameters
  - ambiguities in the matching of NLO results with Parton Shower
  - scale uncertainties

- EW

  available
  - multiple-photon radiation via QED Parton Shower matched with NLO-EW results
  - leading 2-loop EW Sudakov logs
  - resummation of photon vacuum polarization effects
  - inclusion of universal renormalization corrections in the LO couplings
  - radiation of additional light-fermion pairs (leading terms)
  - photon-induced processes

  uncertainties
  - input-scheme choice
  - prescription for the decay-width treatment
  - NLL-QED terms not covered by QED Parton Shower
  - subleading 2-loop EW Sudakov logs

# Higher-order corrections available and remaining theoretical uncertainties

- QCDxEW

  available

  · (QCD)xPHOTOS

  · (N)NLO-QCD + NLO-EW additive prescription

  · POWHEG NLO-(QCD+EW) x (QCD+QED)-Parton Shower

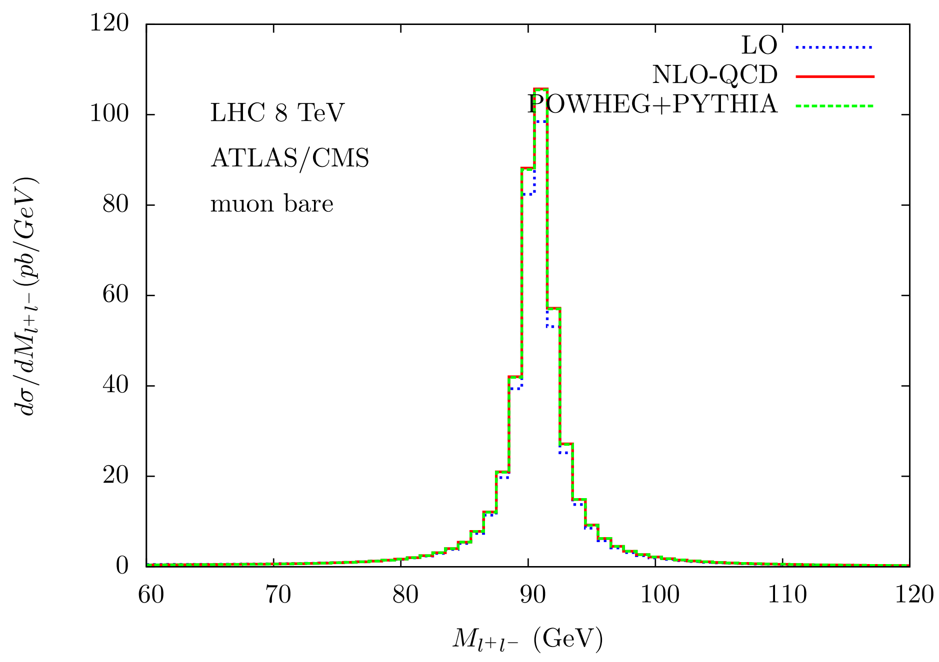
  uncertainties

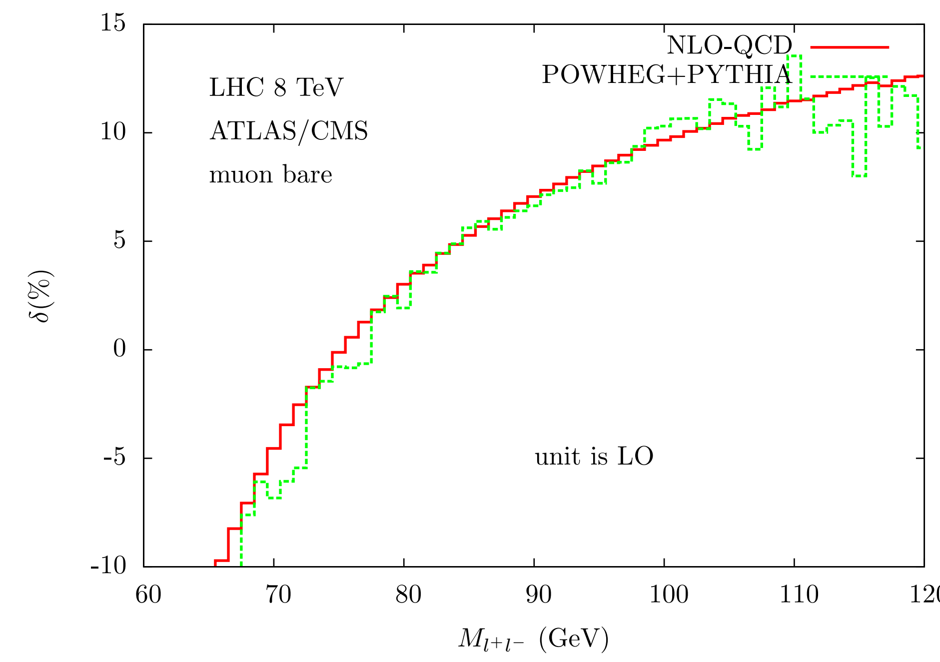
  · missing $O(\alpha\alpha_s)$ corrections that could improve/fix the matching prescription

  · missing modern (QCD+QED) proton PDFs

# Lepton-pair invariant mass distribution in QCD

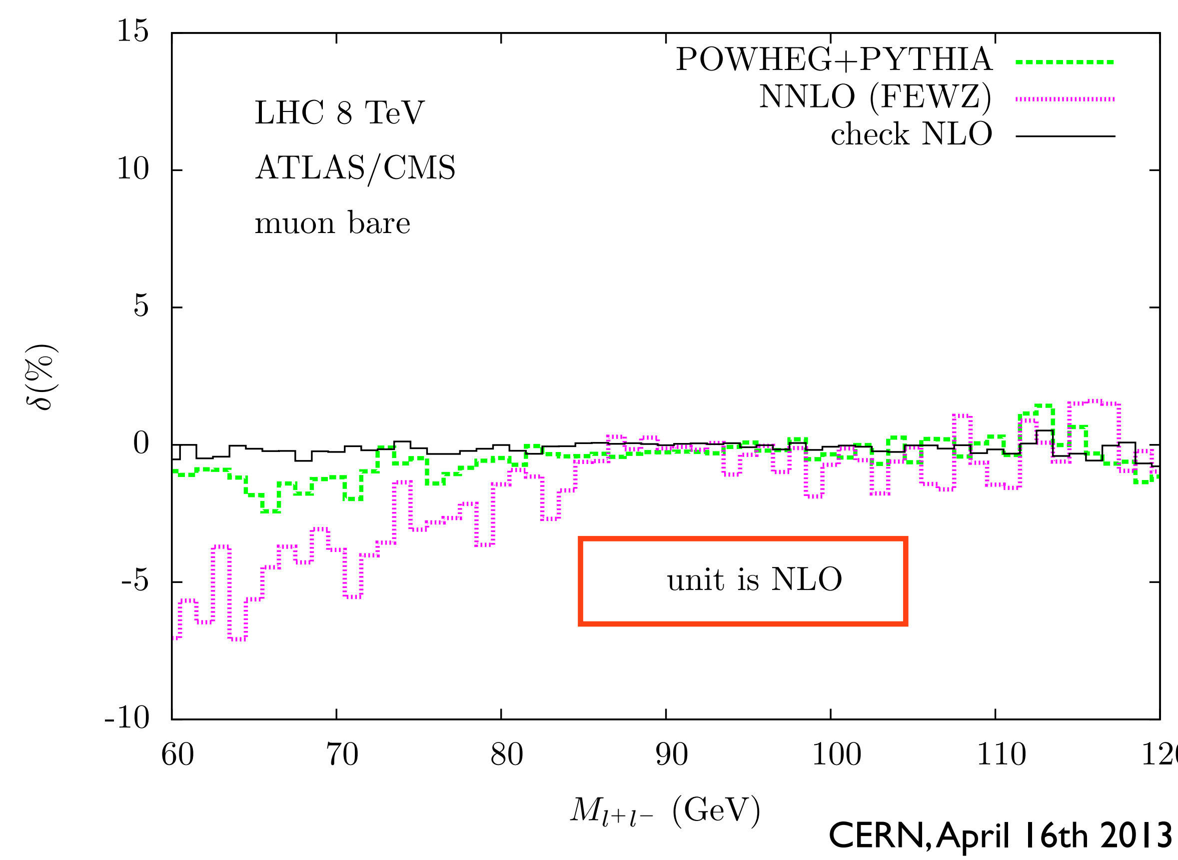
(numerical results from the tuned comparison setup, analogous numbers in the best setup are in progress)




- NLO-QCD corrections over LO predictions are monotonic
- resummation of multiple-gluon emissions has tiny impact

- NNLO-QCD corrections show up in the low tail



# Lepton-pair transverse mass distribution in QCD

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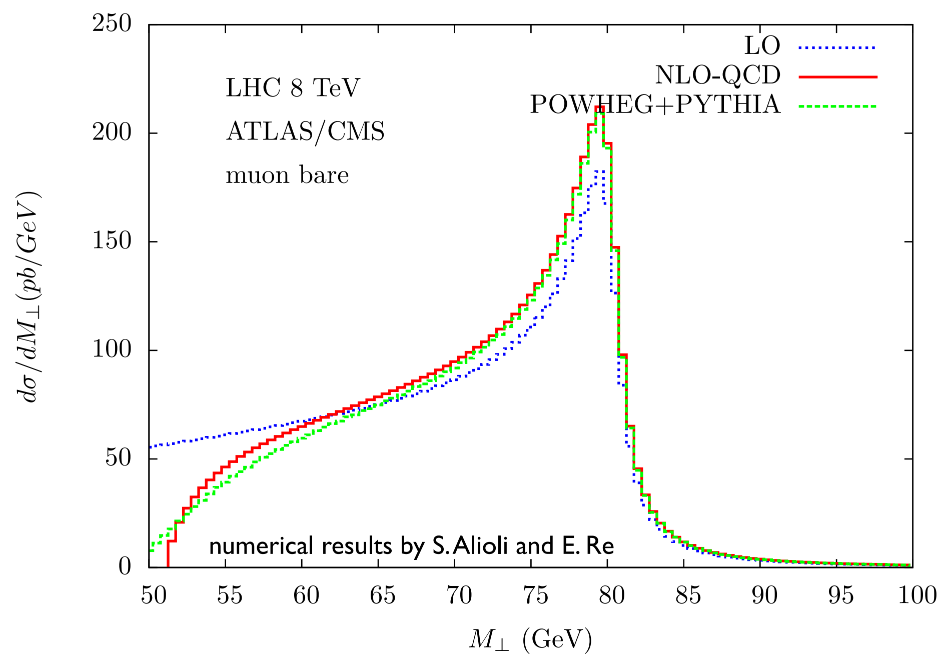
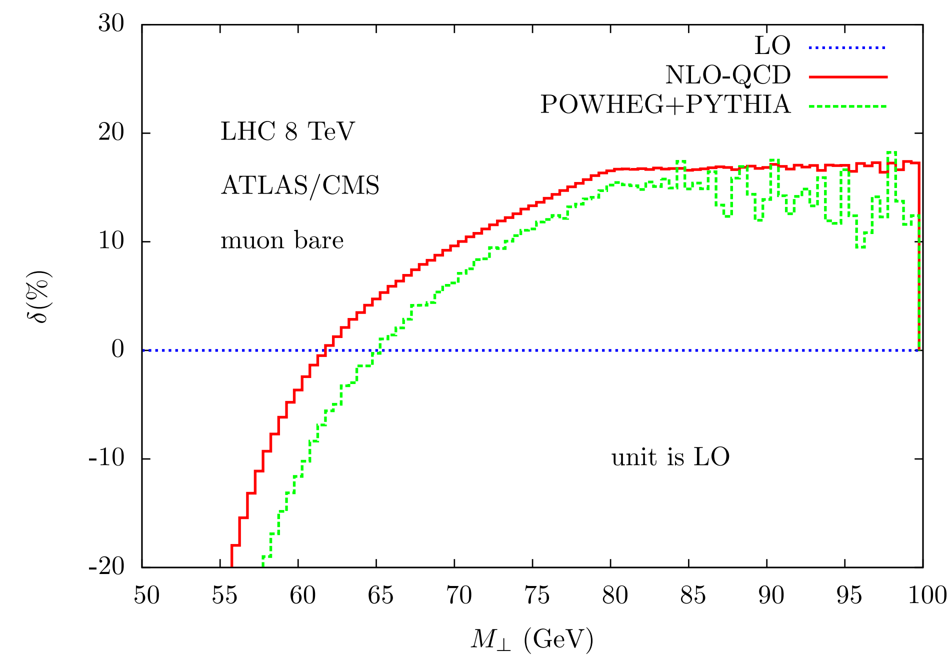


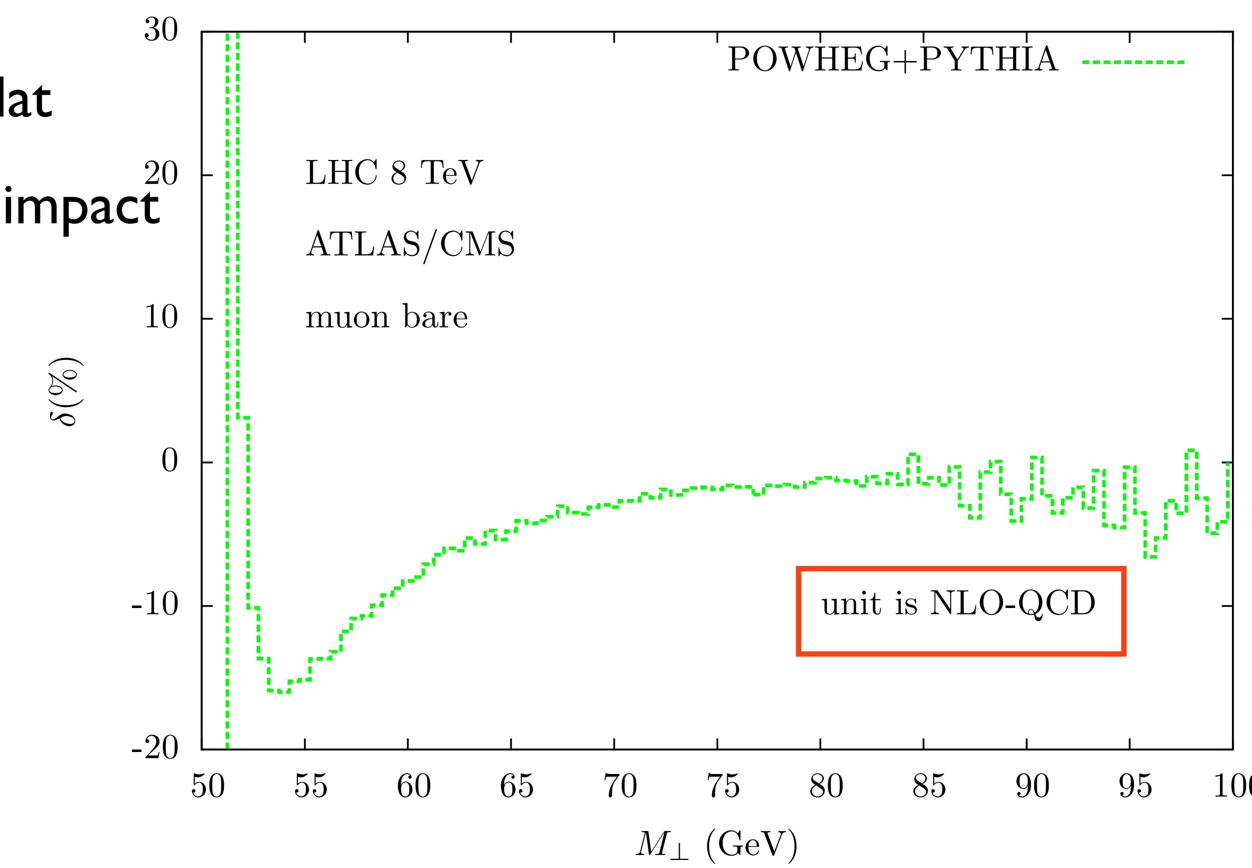




- NLO-QCD corrections over LO predictions are quite flat
- resummation of multiple-gluon emissions has moderate impact
- in units NLO-QCD, the impact of the Parton Shower

  is almost flat and ranges between -5% and 0

- similar comparison between

  NNLO-QCD and NLO-QCD (in progress)



# Observables starting in higher orders

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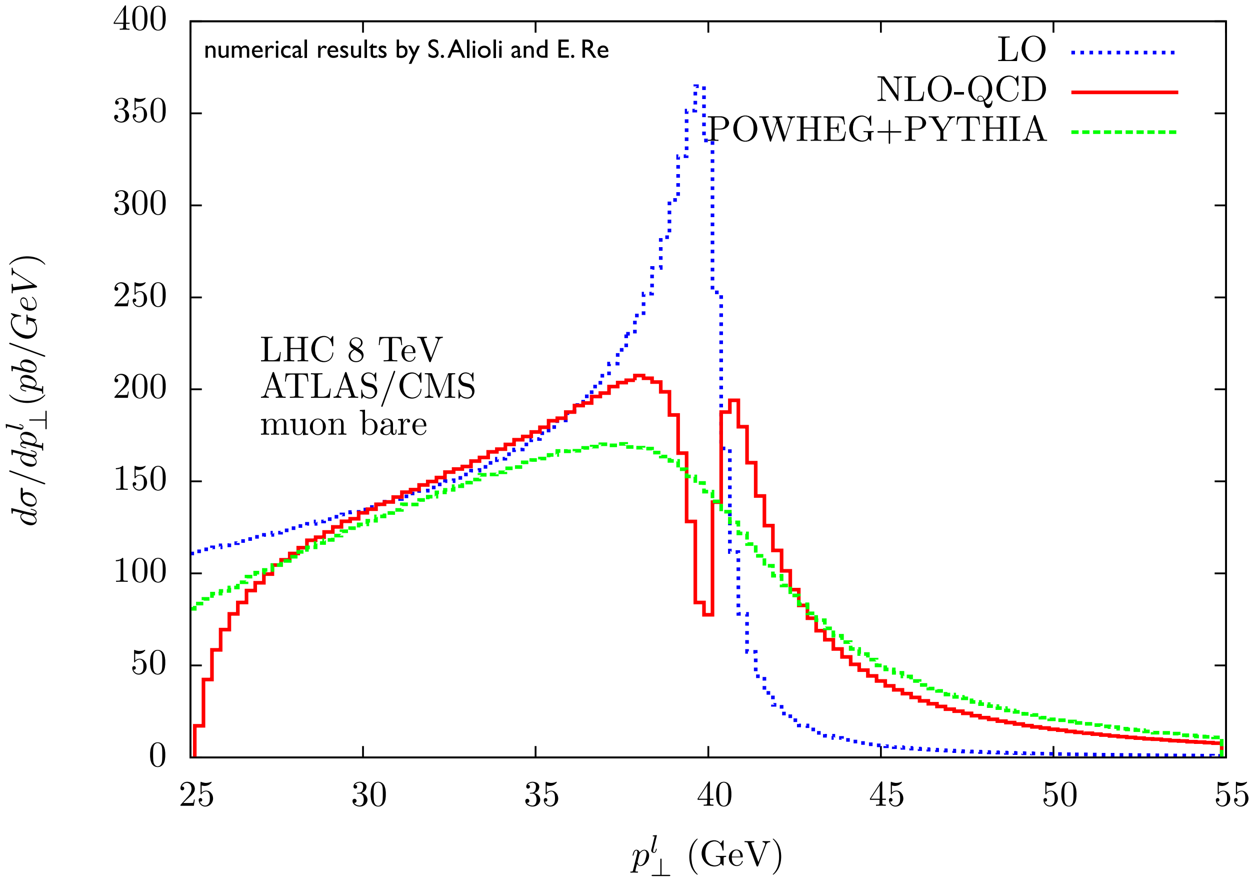


- at LO only the W decay generates the lepton pt with Gamma_W smearing effect in the right tail
- at NLO-QCD the lepton pt receives contributions from
  - · the W recoil against QCD radiation (singular at ptW→0)
    → need to resum multiple-gluon emissions
  - · the subprocess qg→qlν
- matching NLO-QCD with Parton Shower smears the distribution
  → sensitivity to the resummation details

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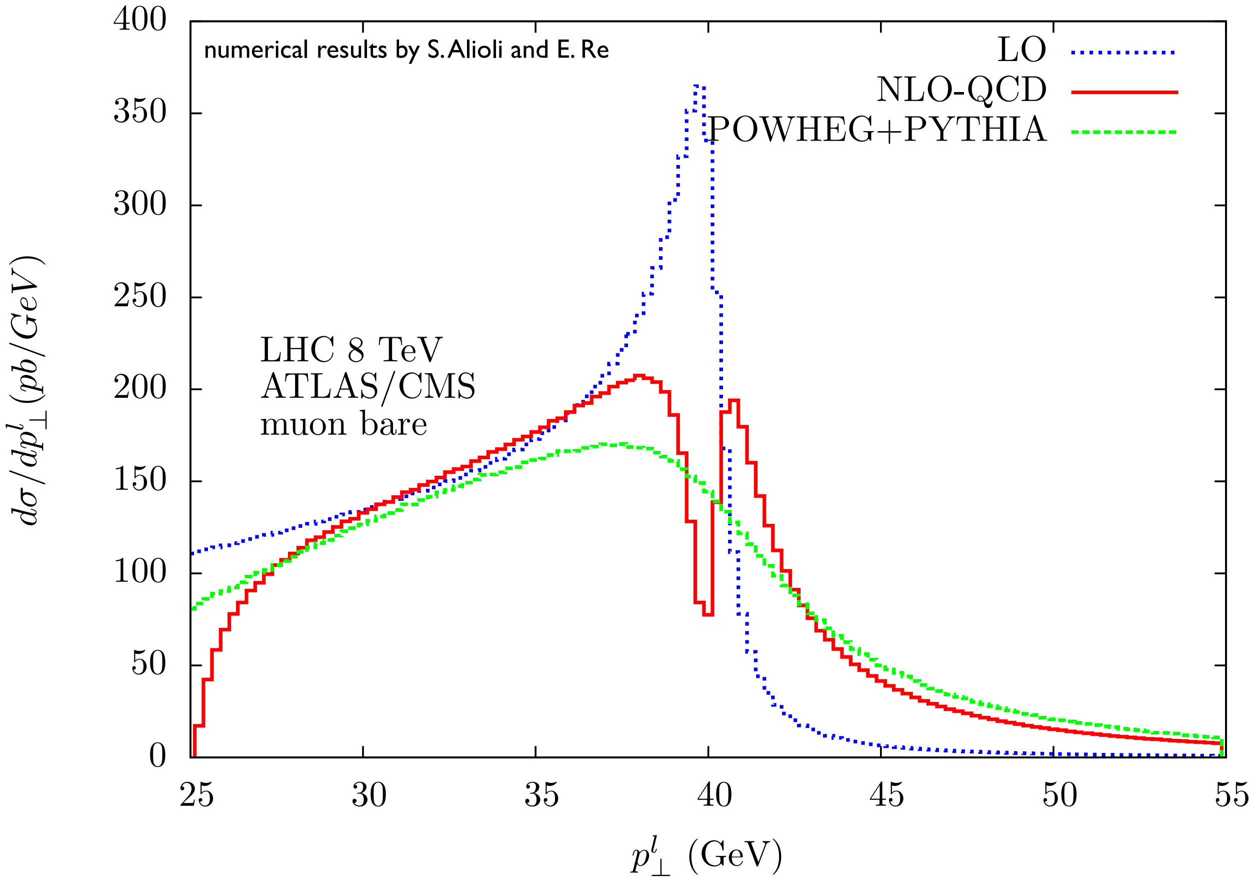


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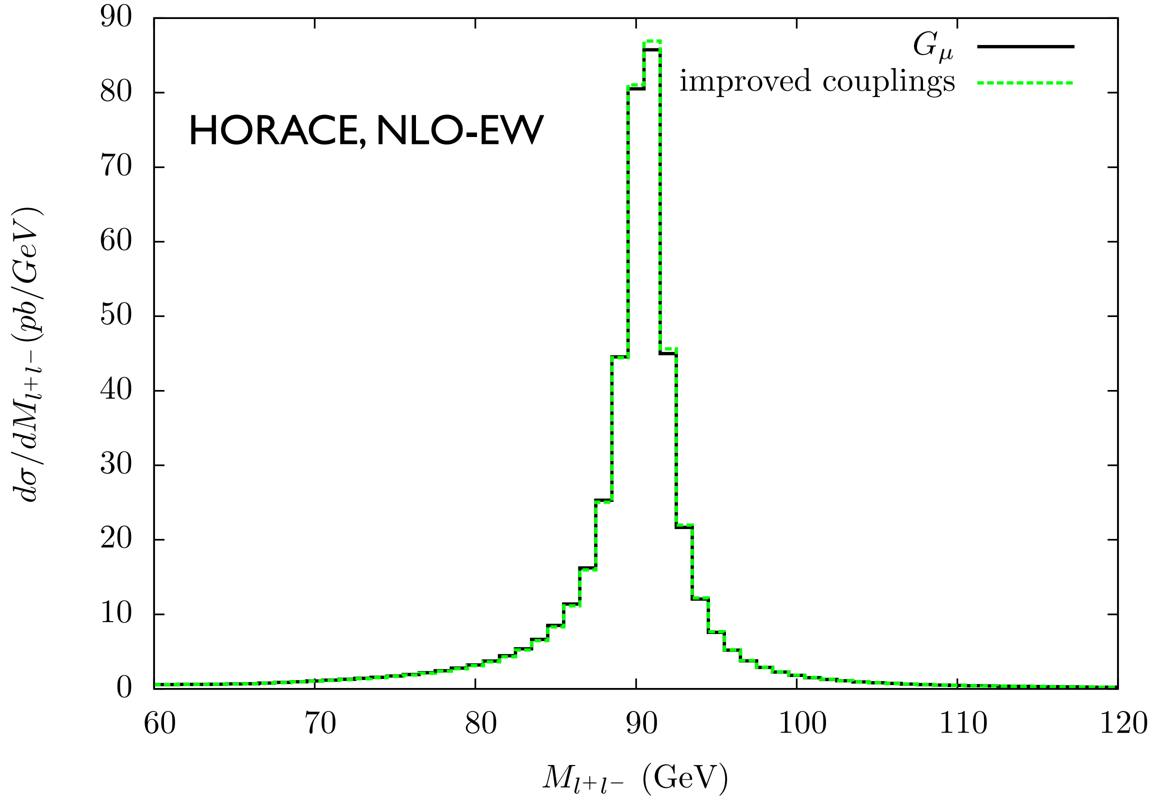
  → sensitivity to the resummation details

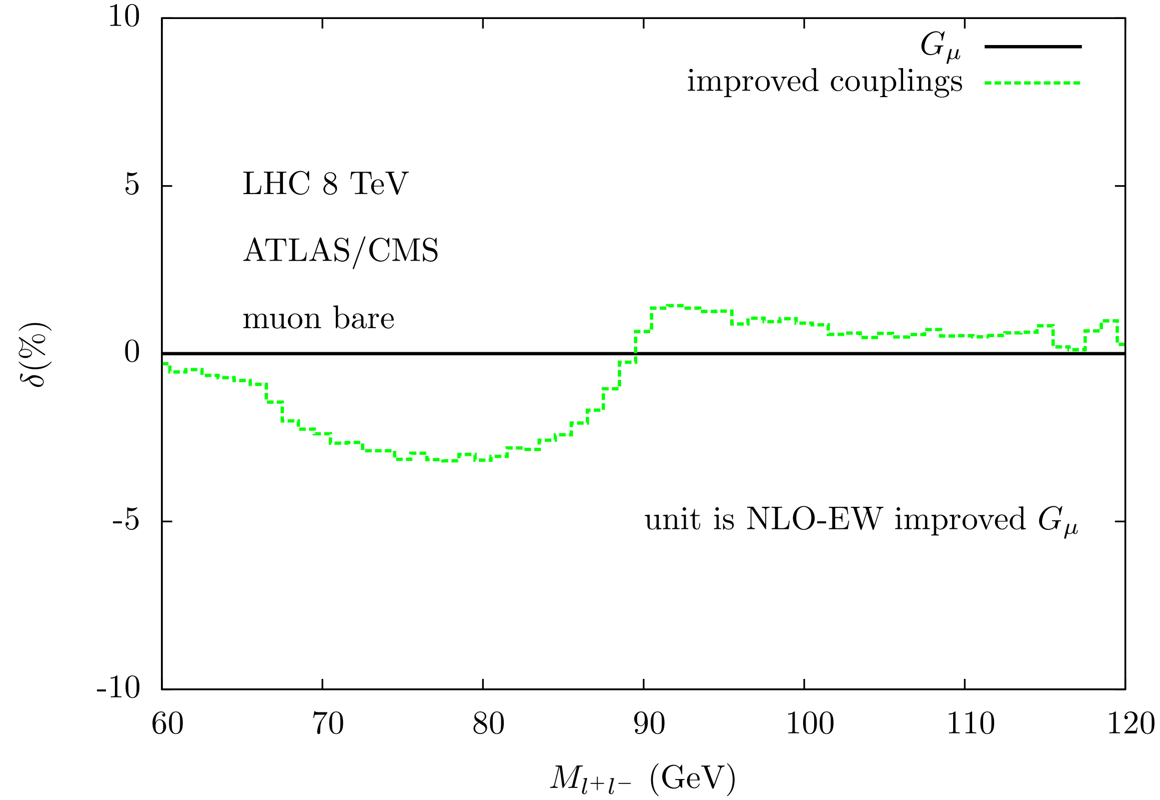
In this case there are not NLO benchmark results, useful to express higher order effects.
The tuning procedure has a purely technical meaning,
necessary in view of the inclusion of resummation effects.

Both analytical resummation techniques (e.g. DYqT) and the matching of NLO-QCD with PS impose a unitarity constraint,
i.e. the total cross section, in absence of cuts, reproduces the fixed order result,
→once the tuning is satisfied it is possible to compare the distributions

in the EW case, the impact of higher order corrections can be expressed in terms of NLO-EW

# Two examples of subsets of EW corrections



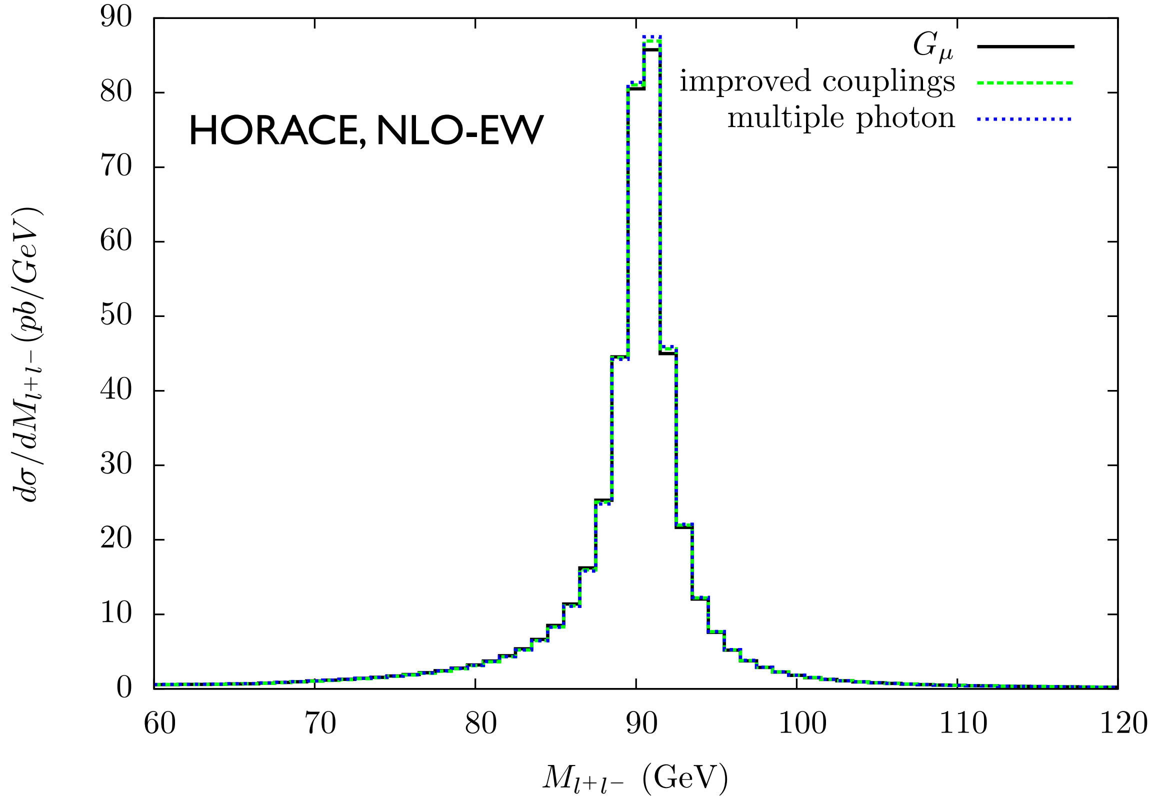



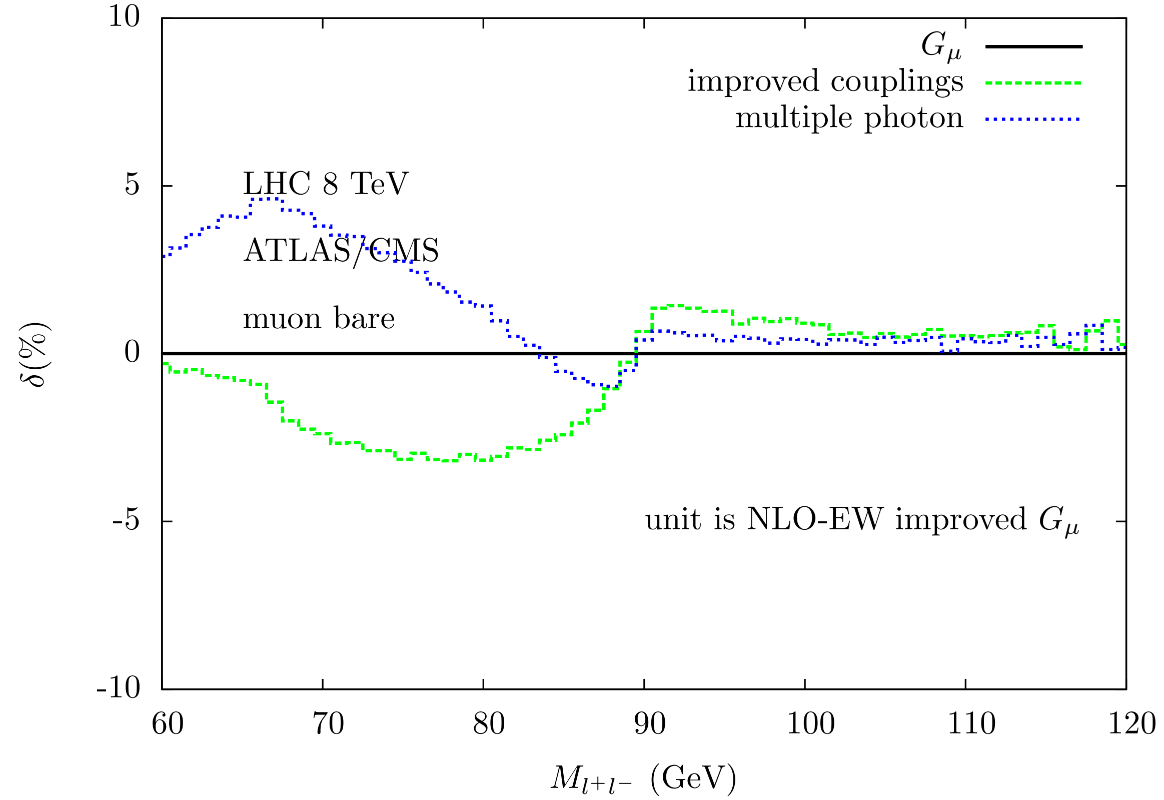

- reference results computed at NLO-EW in the improved-Gmu scheme
- best results computed with a modification of LO couplings

  resummation of photon vacuum polarization contribution in the photon exchange diagram ($\alpha \rightarrow \alpha(Q^2)$ )

  insertion of universal higher order corrections in the Z couplings ($\rho$ factor, $\Delta\kappa$ factor)
- the green line shows the effect of $O(\alpha^2)$ corrections
- the present work concerns the classification of the impact of these higher order effects

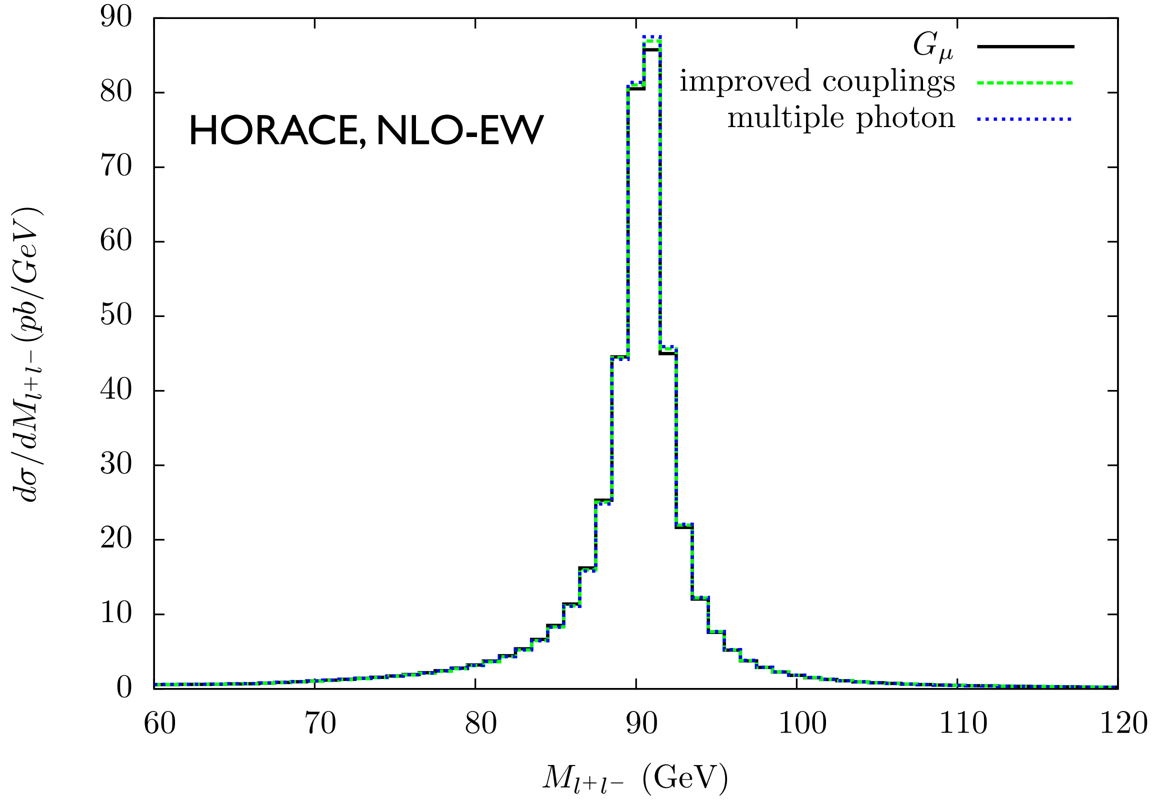
# Two examples of subsets of EW corrections

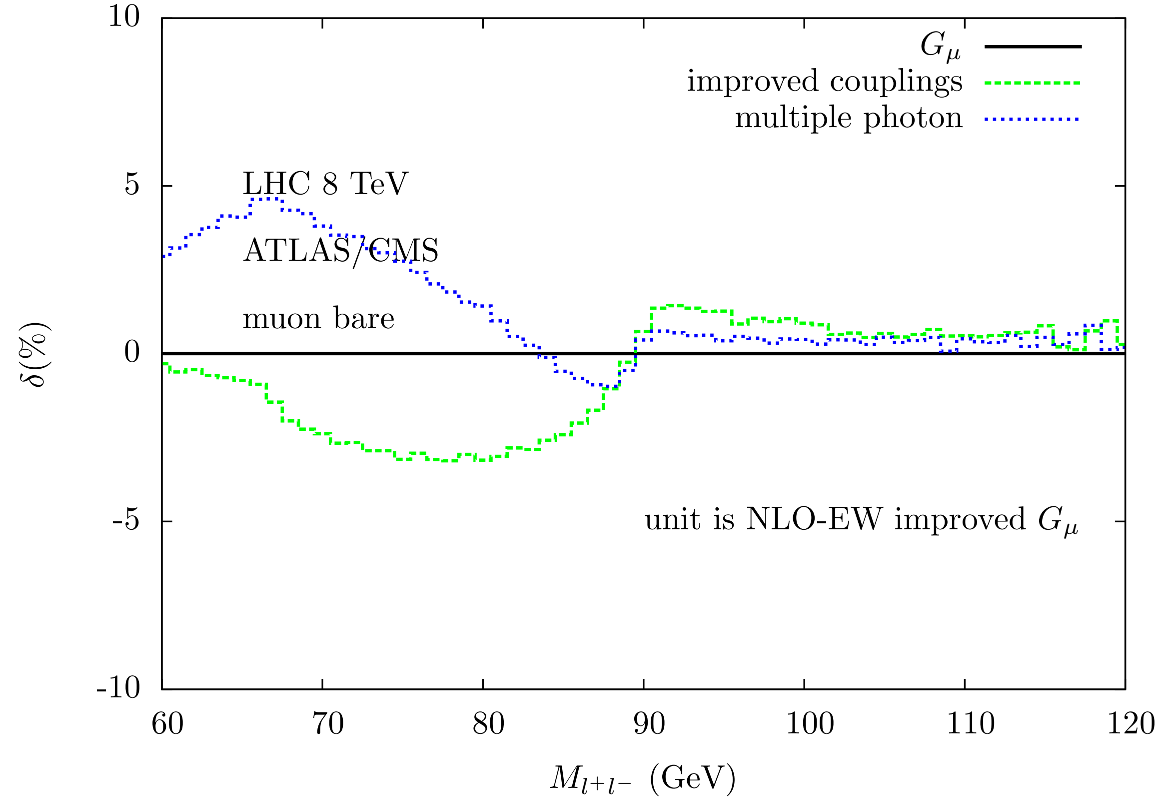



- effect of multiple photon radiation from all the charged legs, matched with NLO-EW results, beyond the first emission ( $O(\alpha^2)$ and higher )

# Two examples of subsets of EW corrections




- for each curve, we are comparing, when available, the results of different codes/approaches (e.g. for multiple photon radiation we have, in different approaches and approximations HORACE, PHOTOS, PYTHIA, RADY, WINHAC)

  the difference can be interpreted, in some cases, as due to specific subsets of radiative corrections

  in other cases as an intrinsic uncertainty, which can be fixed only by NNLO-EW calculation

# Status of the comparison

- all the codes have very good agreement at LO
- approximately 2/3 of the groups have computed NLO benchmark predictions in the Gmu-improved scheme
- we have a few examples of "best" predictions, with all the higher-order subsets switched on
- given the smaller size of the effects, MC statistics is becoming an issue

- ongoing: classification of all the explicitly known higher order (beyond NLO) effects
  in terms of our benchmark NLO results
- next steps: discussion about residual uncertainties and about combination of effects (e.g. QCDxEW)

# Comparison of diboson cross sections and distributions

- last December first call for a similar study applied to diboson production cross sections
- codes that have expressed interest in the comparison are:

  aMC@NLO, GoSam, MCFM, Open Loops, POWHEG, SHERPA, VBFNLO
- a setup has been prepared to fix the details (input parameters, acceptance cuts)

  for the calculation of the simplest final states (starting e.g. from $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu$ )
- a preliminary list of observables has been prepared

☹ a few points of the setup still have to be discussed, to find an agreement between the groups

- first trial runs by VBF@NLO and Gosam in the last two weeks