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Precision calculations
for electroweak measurements

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Zürich, August 22nd 2016

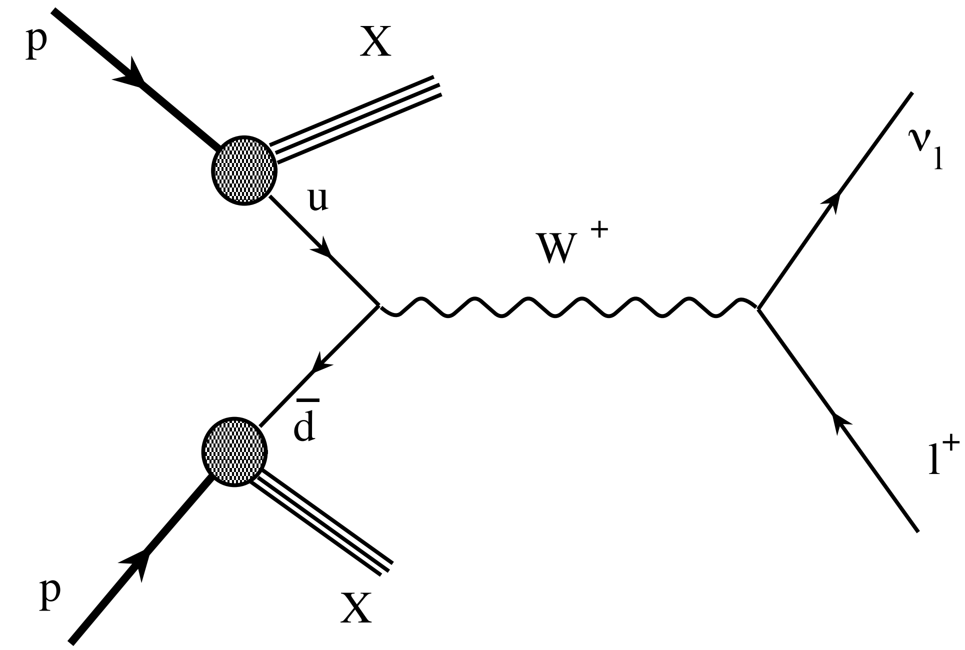
DY report arXiv:1606.02330
and work in collaboration with Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini

Plan of the talk

- The Drell-Yan process and its complexity in view of high-precision measurements
- Recent developments in the evaluation of higher-order radiative corrections
- Recent developments in the implementation of simulation codes
- Estimate of uncertainties affecting the EW measurements

A comparison of codes for the simulation of the Drell-Yan process can be found in arXiv:1606.02330

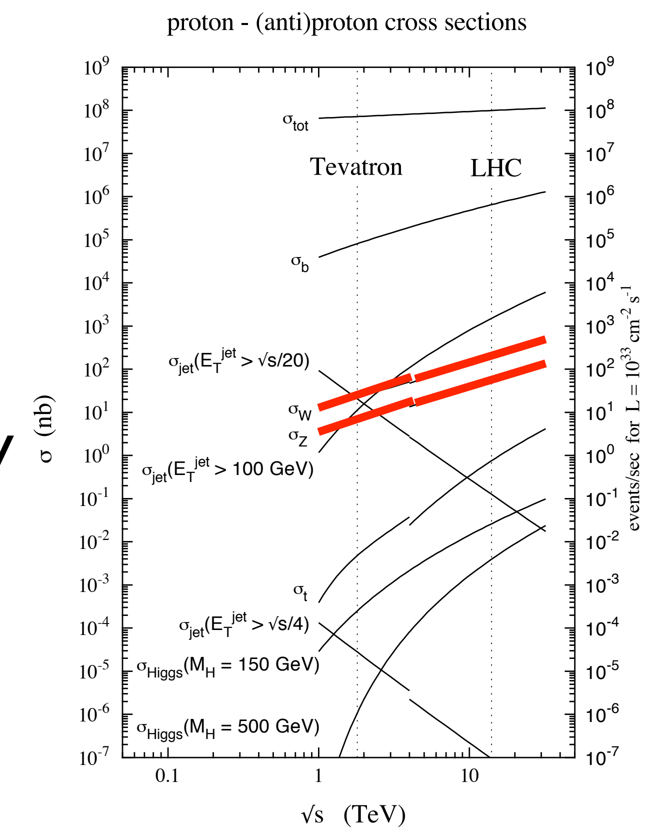
The Drell-Yan process



- easy detection
  high pt lepton pair or high pt lepton + missing pt

  typical cuts at the LHC (central detector region)

$$p_{\perp,l} \text{ and } p_{\perp,\nu} > 25\text{GeV}, \ \ |\eta_l| < 2.5$$



- large cross section
  at LHC σ(W) = 30 nb i.e. 3 10^8 events with L=10 fb^-1
  at LHC σ(Z) = 3.5 nb i.e. 3.5 10^7 events with L=10 fb^-1

→ no statistical limitations to perform high-precision measurements
  the LHC experiments already reached the Tevatron statistical sensitivity
  the discussion is all about experimental and theoretical systematics

- physical relevance the DY processes (CC and NC) are crucial
  - to measure the gauge boson masses and widths
  - to constrain the proton PDFs and to monitor the collider luminosity
  - as a background to several new physics searches

- the neutrino in the charged-current process
  it is not possible to measure the longitudinal component
  of the neutrino momentum
  → in turn it is not possible to measure the lepton-pair invariant mass or rapidity

The Drell-Yan process

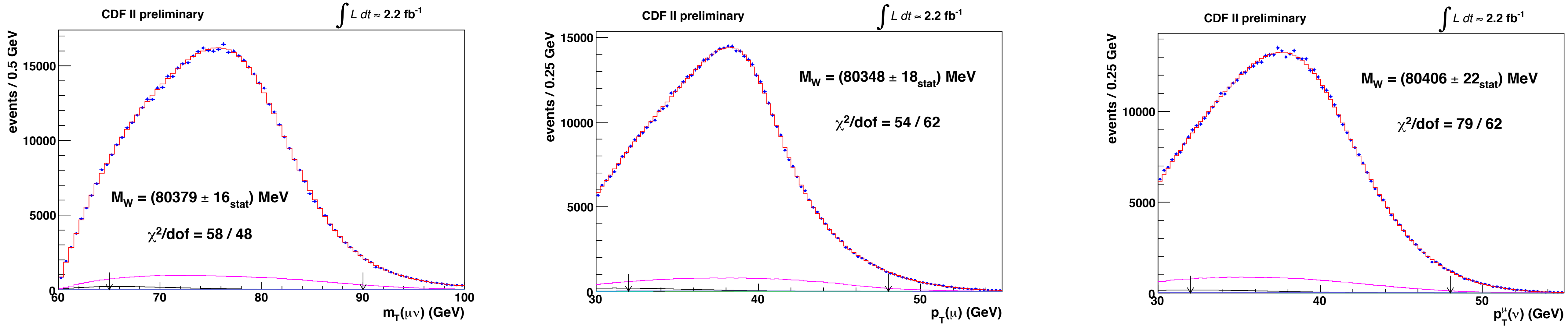
Observables quantities accessible via counting experiments
cross sections and asymmetries

Pseudo-Observables quantities that are functions of the cross section and symmetries
require a model to be properly defined
- the Z boson mass at LEP as the pole of the Breit-Wigner resonance factor
- the W mass at hadron collider as the fitting parameter of a template fit procedure
  the templates are computed in a model (typically the SM)

Template fit
- several histograms describing a differential distribution are computed with the highest available theoretical accuracy and degree of realism in the detector simulation letting the fit parameter (e.g. MW) vary in a range
- the histogram that best describes the data selects the preferred, i.e. measured, MW value

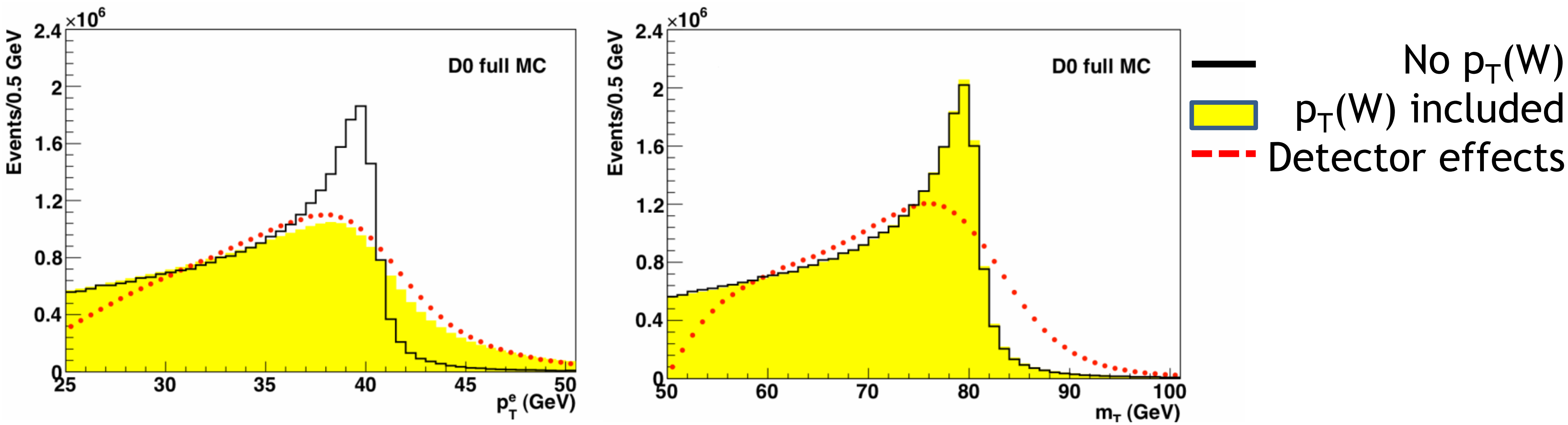
- the result of the fit depends on the hypotheses used to compute the templates
  these hypotheses should be treated as theoretical systematic errors
- more accurate calculations, properly implemented in Monte Carlo event generators are needed to reduce this systematic error

MW determination at hadron colliders: observables and techniques



- MW extracted from the study of the lepton-pair transverse mass, lepton transverse momentum, missing transverse momentum distributions thanks to the jacobian peak that enhances the sensitivity to MW

- Transverse mass: important detector smearing effects, moderate impact from the ptW modelling
  Lepton pt: moderate detector effects, extremely sensitive to the ptW modelling



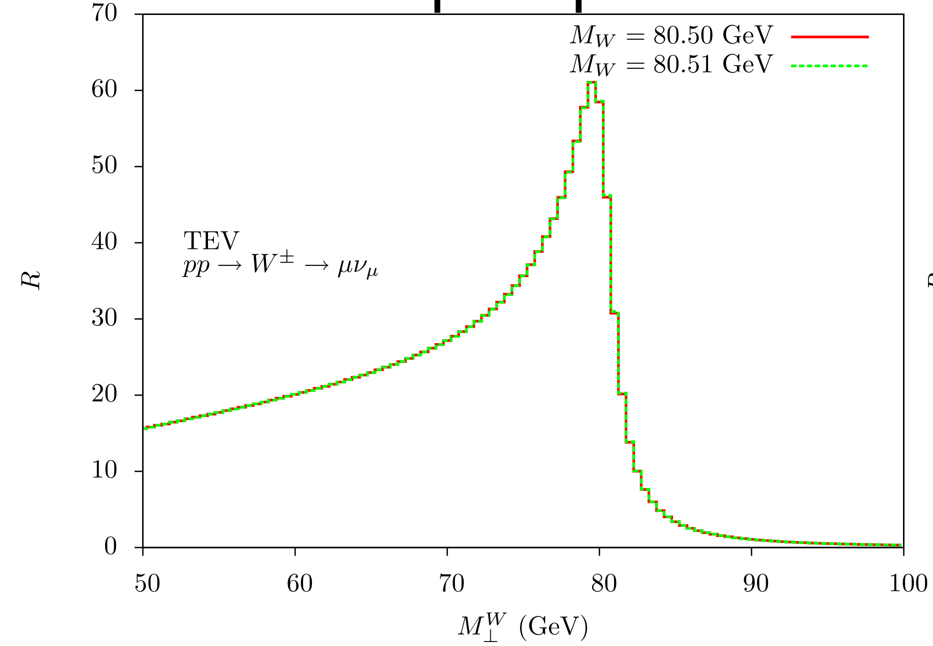
the ptW modelling strongly depends on the all-order treatment of the QCD corrections

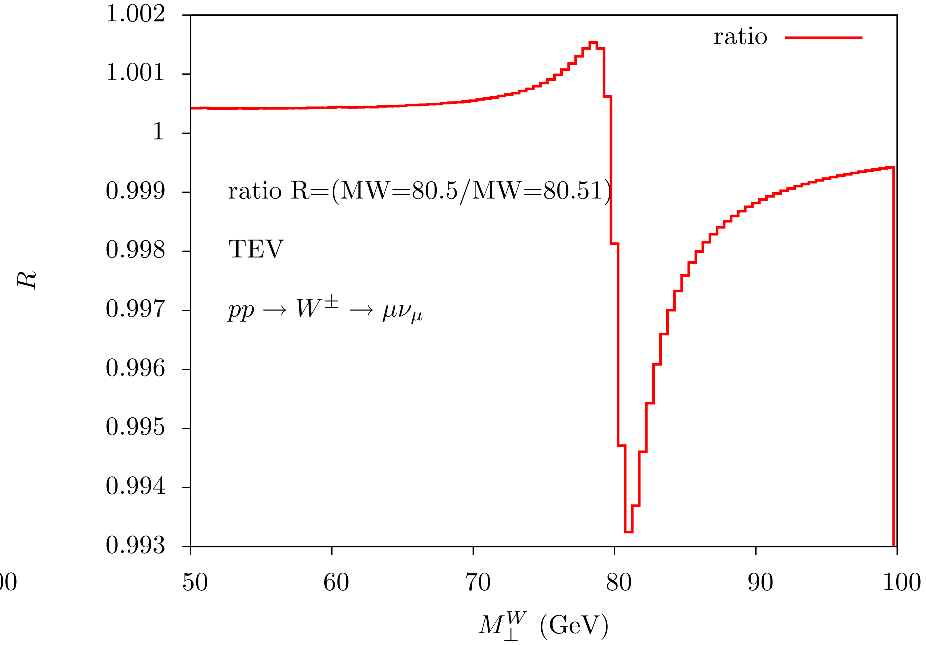
- MW is extracted from the study of the shape of the distributions

MW determination at hadron colliders: observables and techniques

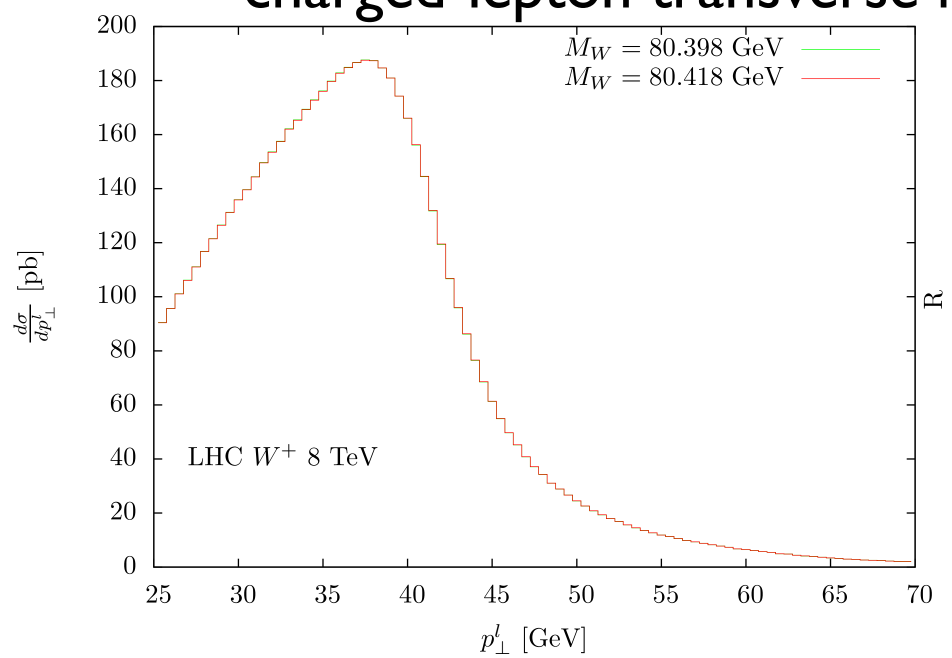
- Challenging shape measurement:
  a distortion at the few per mil level of the distributions yields a shift of O(10 MeV) of the MW value

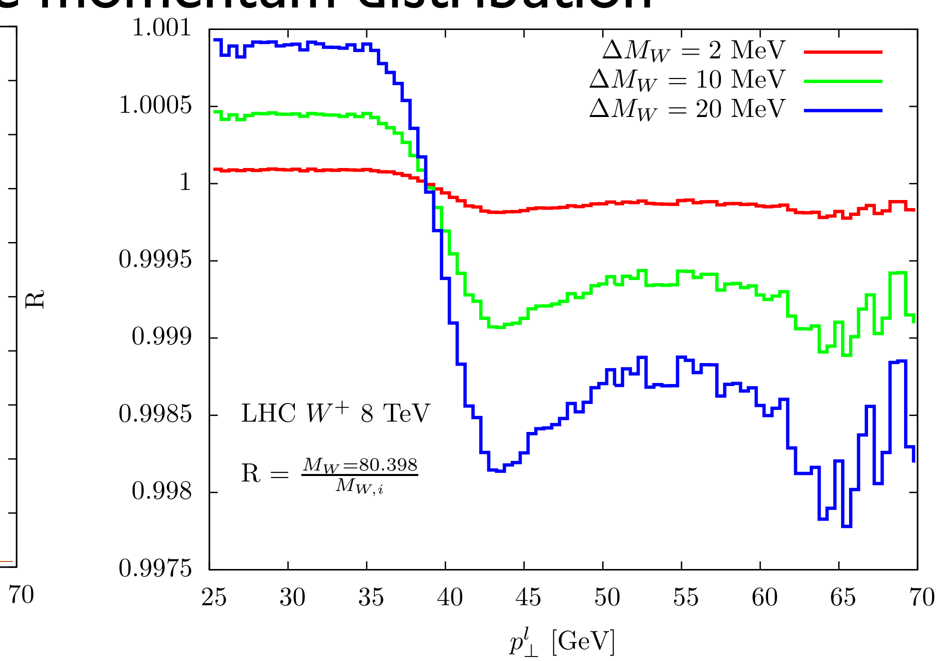
lepton-pair transverse mass distribution





charged-lepton transverse momentum distribution





- Which corrections shall we need to keep under control?

Breakdown of uncertainties on MW estimated by CFD and D0

CDF, arXiv:1311.0894

m_T fit uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	0	0	0
Lepton tower removal	2	3	2
Recoil scale	5	5	5
Recoil resolution	7	7	7
Backgrounds	3	4	0
PDFs	10	10	10
W boson p_T	3	3	3
Photon radiation	4	4	4
Statistical	16	19	0
Total	23	26	15

p_T^ℓ fit uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	1	2	0
Lepton tower removal	0	0	0
Recoil scale	6	6	6
Recoil resolution	5	5	5
Backgrounds	5	3	0
PDFs	9	9	9
W boson p_T	9	9	9
Photon radiation	4	4	4
Statistical	18	21	0
Total	25	28	16

D0, arXiv:1310.8628

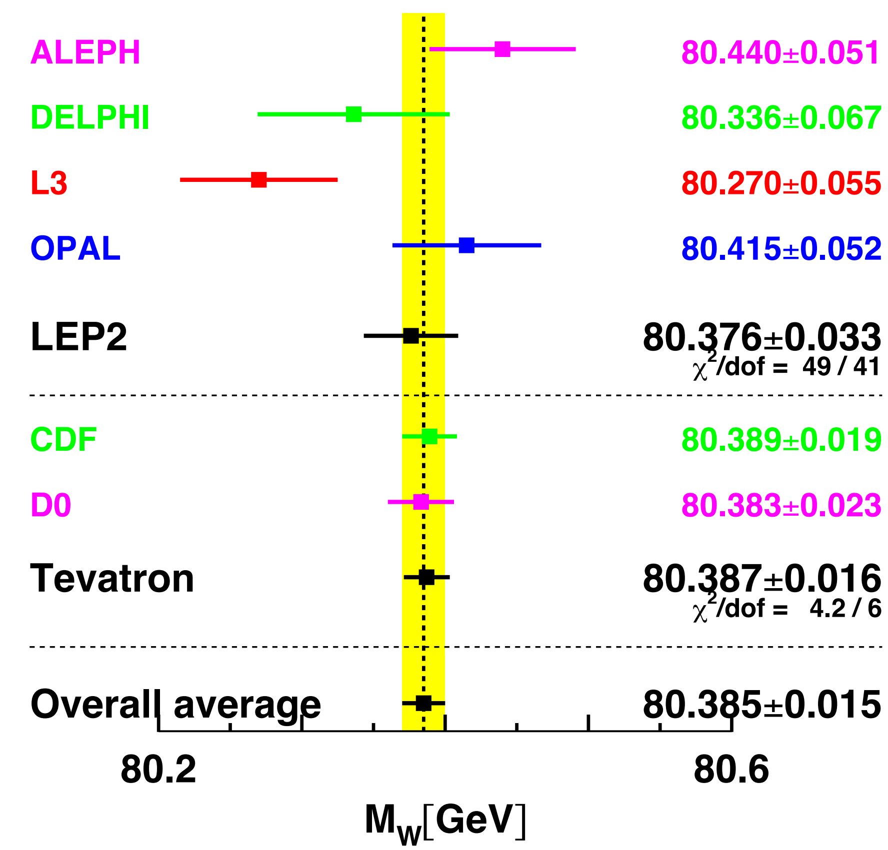
Source	Section	m_T	p_T^e	$\not{E}_T$
Experimental				
Electron Energy Scale	VII C 4	16	17	16
Electron Energy Resolution	VII C 5	2	2	3
Electron Shower Model	V C	4	6	7
Electron Energy Loss	V D	4	4	4
Recoil Model	VII D 3	5	6	14
Electron Efficiencies	VII B 10	1	3	5
Backgrounds	VIII	2	2	2
$\sum$(Experimental)		18	20	24
W Production and Decay Model				
PDF	VI C	11	11	14
QED	VI B	7	7	9
Boson p_T	VI A	2	5	2
$\sum$(Model)		13	14	17
Systematic Uncertainty (Experimental and Model)		22	24	29
W Boson Statistics	IX	13	14	15
Total Uncertainty		26	28	33

3 items of theoretical systematic uncertainty
are framed in red in the CDF and D0 tables

are weak effects relevant? do we need only QED?

perturbative QCD uncertainties are not quoted

what is the correct procedure to evaluate
perturbative and non-perturbative QCD uncertainties?



Perturbative expansion of the Drell-Yan cross section

$$\sigma_{tot} = \sigma_0 + \alpha_s \sigma_{\alpha_s} + \alpha_s^2 \sigma_{\alpha_s^2} + \ldots$$
$$+ \alpha \sigma_{\alpha} + \alpha^2 \sigma_{\alpha^2} + \ldots$$
$$+ \alpha\alpha_s \, \sigma_{\alpha\alpha_s} + \alpha\alpha_s^2 \, \sigma_{\alpha\alpha_s^2} + \ldots$$

QCD
EW
mixed QCDxEW

QCD

G. Altarelli, R.K.Ellis, G. Martinelli, Nucl.Phys.. **B157** (1979) 461 G. Altarelli, R.K.Ellis, M. Greco, G. Martinelli, Nucl.Phys.. **B246** (1984) 12	NLO-QCD
R. Hamberg, W. L. van Neerven, T. Matsuura, Nucl.Phys. **B359** (1991) 343 W. L. van Neerven and E.B. Zijstra, Nucl.Phys. **B382** (1992) 11	total NNLO-QCD
S. Catani, L. Cieri, D. de Florian, G. Ferrera, M. Grazzini, Nucl. Phys. B888 (2014) 75 T. Ahmed, M. Mahakhud, N. Rana, V. Ravindran Phys.Rev.Lett.113 (2014) 112002	total N3LO -QCD soft
C. Anastasiou et al., Phys.Rev. **D69** (2004) 094008 K. Melnikov and F. Petriello, hep-ph/0603182	fully differential NNLO-QCD

EW

S. Dittmaier and M. Krämer, PRD 65 (2002) 073007 U. Baur and D. Wackeroth, PRD 70 (2004) 073015	W NLO-EW fully differential
U.Baur et al., PRD 65 (2002) 033007	Z NLO-EW fully differential

The MW determination is a shape measurement:
- the O(α) QED-FSR corrections shift MW by O(100 MeV)
- the large O(α_s) QCD K-factor is less relevant for MW than an accurate description of multiple gluon emissions

Only-QCD and only-EW results, separately available, have to be combined to obtain a realistic description of the data

Perturbative expansion of the Drell-Yan cross section

$$\sigma_{tot} = \sigma_0 + \alpha_s \sigma_{\alpha_s} + \alpha_s^2 \sigma_{\alpha_s^2} + \ldots$$
$$+ \alpha \sigma_{\alpha} + \alpha^2 \sigma_{\alpha^2} + \ldots$$
$$+ \alpha \alpha_s \, \sigma_{\alpha\alpha_s} + \alpha \alpha_s^2 \, \sigma_{\alpha\alpha_s^2} + \ldots$$

QCD

EW

mixed QCDxEW

mixed QCDxEW

Exact O($\alpha\alpha_s$) results for DY processes are not available

A. Czarnecki, J.H. Kühn, Phys. Rev. Lett. 77 (1996) 3955
A. Kotikov, J.H. Kühn, O. Veretin, Nucl. Phys. B 788 (2008) 47
D. Kara, Nucl. Phys. B 877 (2013) 683

W and Z boson decay at O(ααs)

W.B. Kilgore, C. Sturm, Phys.Rev.D85 (2012) 033005

mixed QCDxQED virtual corrections to DY processes

S. Dittmaier, A. Huss, C. Schwinn, Null.Phys.B885 (2014) 318
S. Dittmaier, A. Huss, C. Schwinn, Null.Phys.B904 (2016) 216

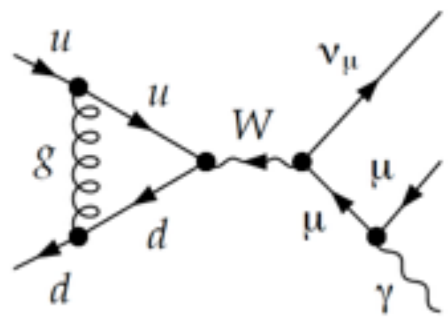
O(ααs) corrections to DY processes in pole approximation

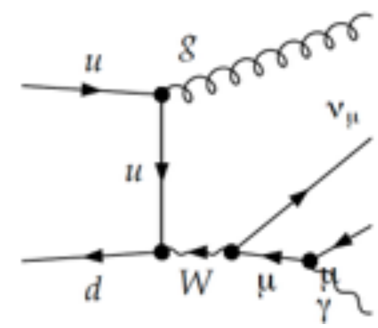
R. Bonciani, S. Di Vita, P. Mastrolia, U. Schubert, arXiv:1604.08581

full set of Master Integrals for the evaluation of virtual O(ααs) corrections to DY processes (MW=MZ)

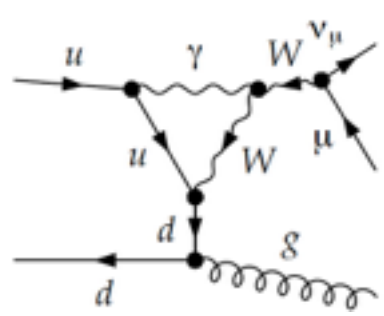
Classification of mixed $O(\alpha\alpha_s)$ QCDxEW corrections

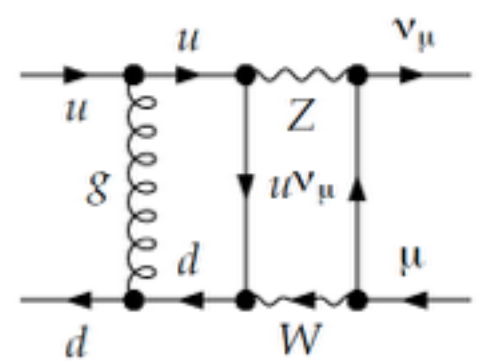
- The bulk of the $O(\alpha\alpha_s)$ corrections relevant for the MW determination, i.e. at the W(Z) resonance, can be obtained with a combination of QCD-ISR and QED-FSR corrections, providing:
  - the QCD K-factor and of gauge boson kinematical distributions
  - the leading QED effects on the distributions of the final state leptons
  - the bulk of these effects is already available in several Monte Carlo event generators





- The full set of $O(\alpha\alpha_s)$ corrections (challenging 2-loop calculation) is not yet available

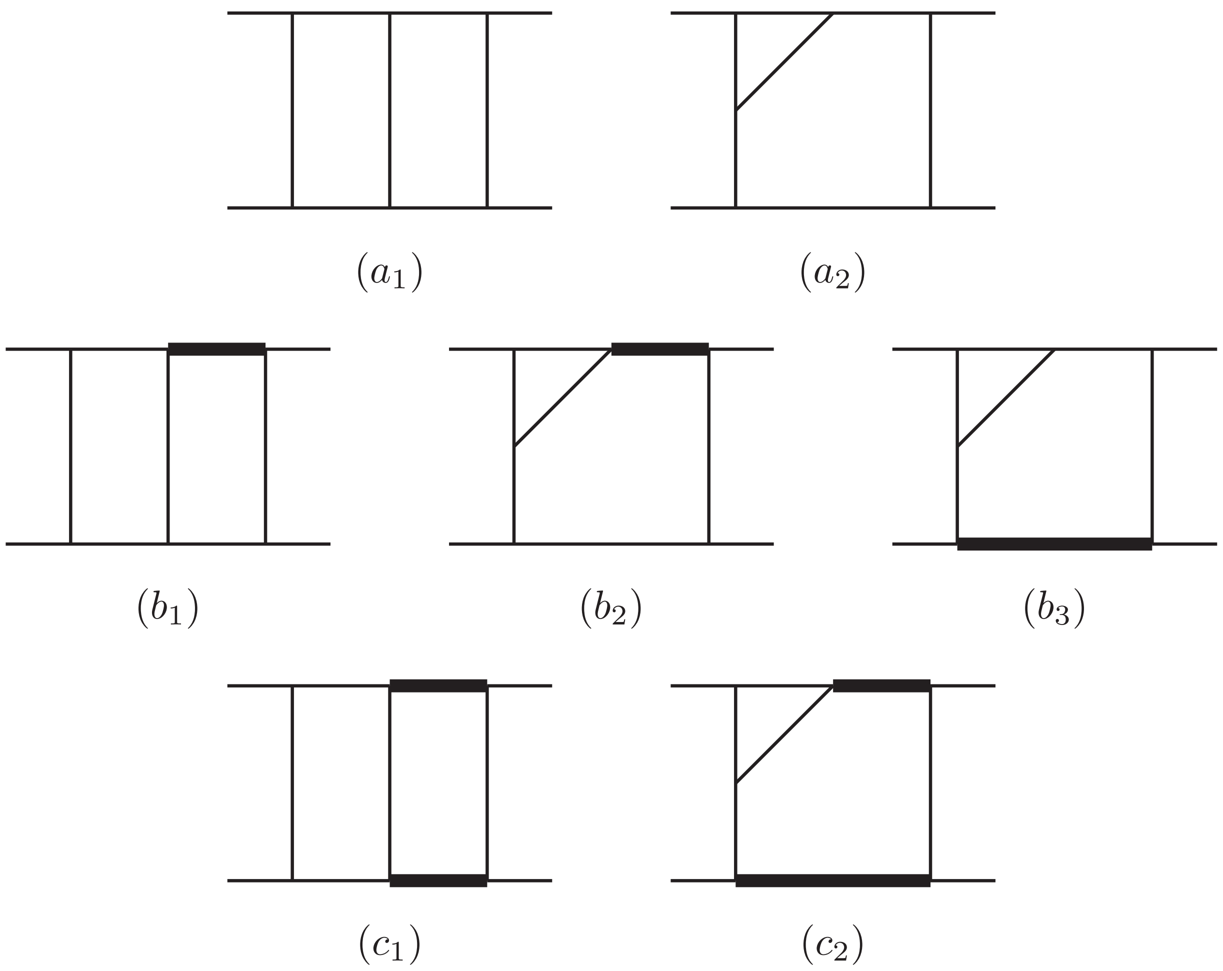




- A very important step forward is given by the evaluation in arXiv:1604.08581 of all the relevant Master Integrals

Master Integrals for the evaluation of DY processes at $O(\alpha\alpha_s)$

R. Bonciani, S. Di Vita, P. Mastrolia, U. Schubert, arXiv:1604.08581



thin lines massless
thick lines massive
topologies **b** and **c** were not known

2 masses topologies evaluated with the same mass

SM results, where both W and Z appear,
can be evaluated with an expansion in ΔM=MZ-MW

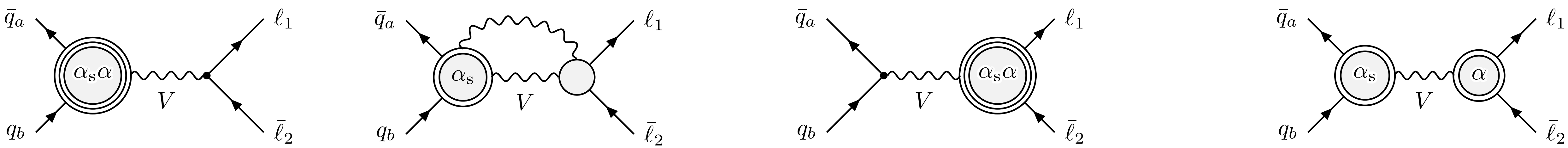
49 MI identified (8 massless, 24 1-mass, 17 2-masses)
solution of differential equations expressed in terms of
iterated integrals (mixed Chen-Goncharov representation)

O(αα$_s$) corrections in pole approximation

S. Dittmaier, A. Huss, C. Schwinn, Nucl.Phys.B885 (2014) 318, Nucl.Phys.B904 (2016) 216

- The pole approximation provides a good description of the W (Z) region, as it has already been checked for the pure NLO-EW corrections

- At O(αα$_s$) there are 4 groups of contributions



- The last group yields the dominant correction to the process, due to factorizable corrections QCD-initial x QED-final

$$\sigma_{\mathrm{NNLO}_{s\otimes ew}} = \sigma_{\mathrm{NLO}_s} + \alpha\,\sigma_\alpha + \alpha\alpha_s\,\sigma^{\mathrm{prod}\times\mathrm{dec}}_{\alpha\alpha_s} \qquad \delta^{\mathrm{prod}\times\mathrm{dec}}_{\alpha\alpha_s} = \frac{\alpha\alpha_s\,\sigma^{\mathrm{prod}\times\mathrm{dec}}_{\alpha\alpha_s}}{\sigma_{\mathrm{LO}}}$$

full result
pole approximation

$$\sigma^{\mathrm{naive\,fact}}_{\mathrm{NNLO}_{s\otimes ew}} = \sigma_{\mathrm{NLO}_s}(1+\delta_\alpha)$$

naive factorization

$$\frac{\sigma_{\mathrm{NNLO}_{s\otimes ew}} - \sigma^{\mathrm{naive\,fact}}_{\mathrm{NNLO}_{s\otimes ew}}}{\sigma_{\mathrm{LO}}} = \delta^{\mathrm{prod}\times\mathrm{dec}}_{\alpha\alpha_s} - \delta_\alpha\delta'_{\alpha_s}$$

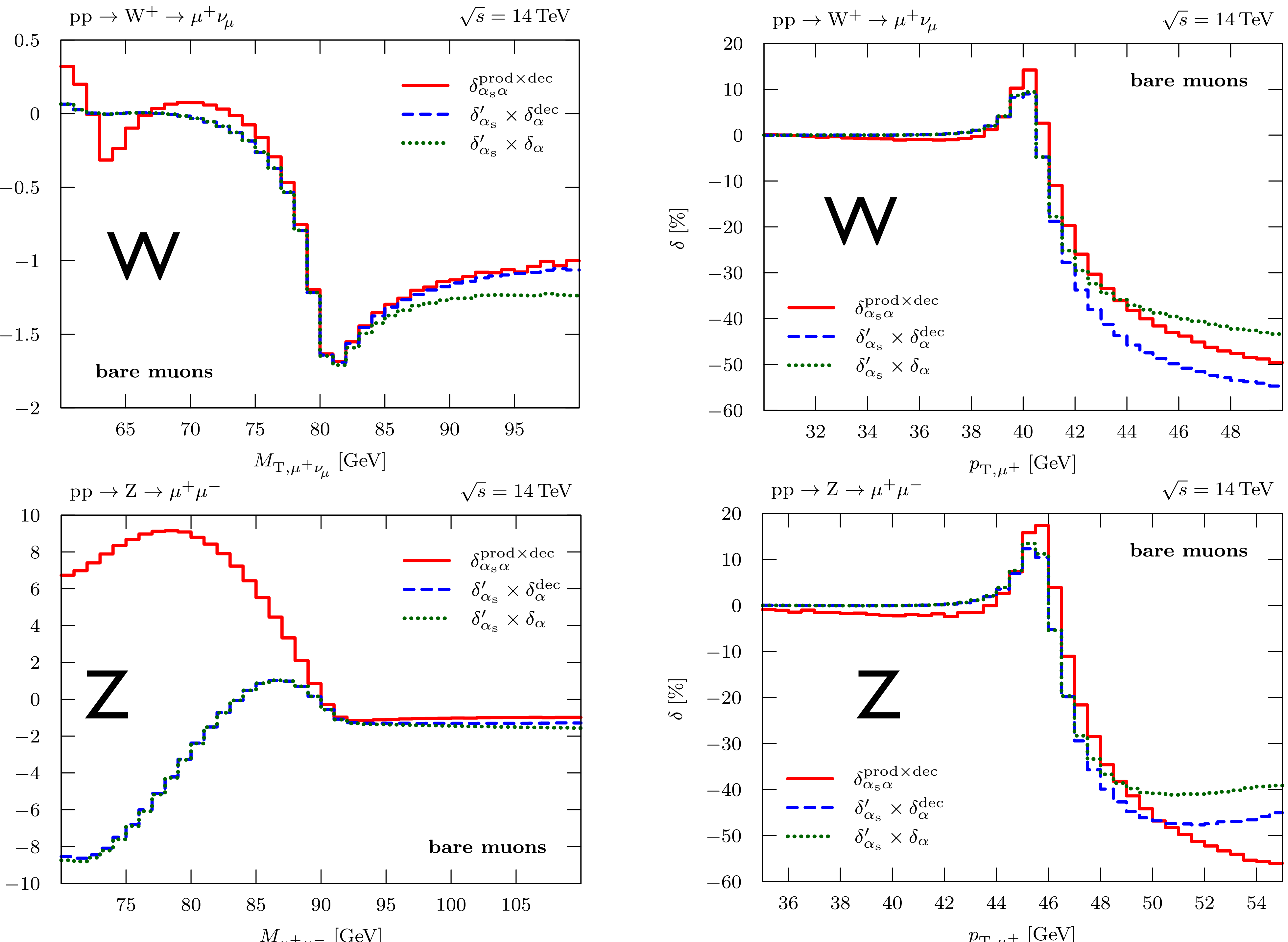
test of the validity of the naive factorization

the δ are the inclusive correction factor

- We need to compare these results with the O(αα$_s$) terms available in Monte Carlo (POWHEG)

O(αα$_s$) corrections in pole approximation

S. Dittmaier, A. Huss, C. Schwinn, Nucl.Phys.B885 (2014) 318, Nucl.Phys.B904 (2016) 216



full result
pole approximation

QED-FSR

NLO-EW

the difference between red and the others tests the naive factorization

the difference between green and blue tests the impact of weak corr. and the pole approximation

the naive factorization works nicely for the W transverse mass, at the resonance

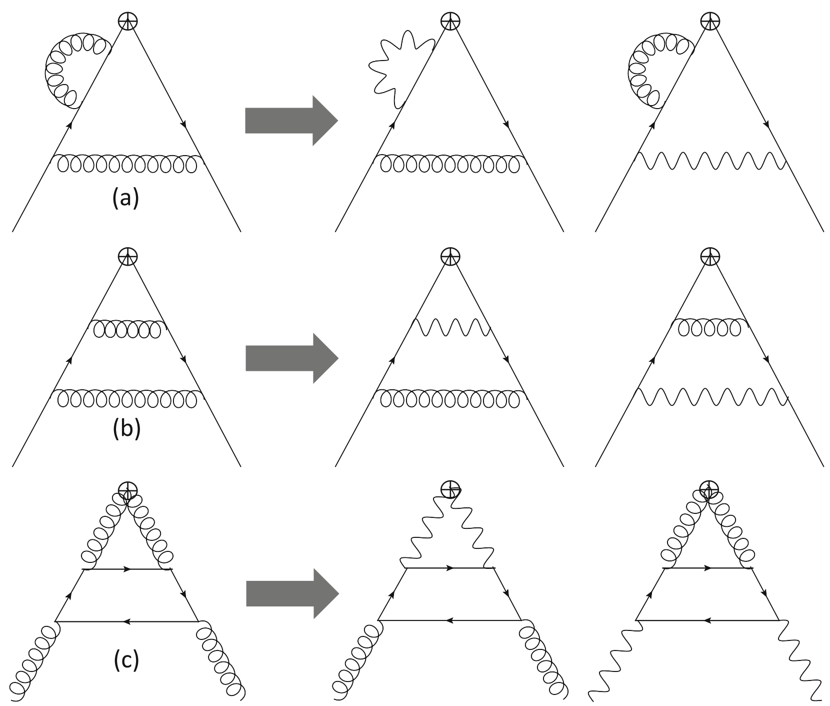
fails in the lepton pt case, where the kinematical interplay of photons and gluons is crucial

fails in the Z invariant mass, where the large FSR correction is modulated by ISR QCD radiation and requires exact kinematics

Splitting functions at O(αα$_s$)

D. de Florian, G.F.R. Sborlini, G. Rodrigo, Eur.Phys.J. C76 (2016) no.5, 282 , arXiv:1606.02887

starting from the expressions by Curci-Furmanski-Petronzio



needed for a complete subtraction in partonic calculations of initial state collinear singularities at O(αα$_s$)

not sufficient for a consistent PDF evolution at the same order

$$
\begin{aligned}
P_{q\gamma}^{(1,1)} = \frac{C_F\, C_A\, e_q^2}{2} \Big\{ & 4 - 9x - (1-4x)\ln(x) - (1-2x) \\
& \times \ln^2(x) + 4\ln(1-x) + p_{qg}(x)\Big[2\ln^2\Big(\frac{1-x}{x}\Big) \\
& - 4\ln\Big(\frac{1-x}{x}\Big) - \frac{2\pi^2}{3} + 10\Big]\Big\}, \qquad (26)
\end{aligned}
$$

$$
\begin{aligned}
P_{g\gamma}^{(1,1)} = C_F\, C_A \Big(\sum_{j=1}^{n_F} e_{q_j}^2\Big) \Big\{ & -16 + 8x + \frac{20}{3}x^2 + \frac{4}{3x} \\
& - (6+10x)\ln(x) - 2(1+x)\ln^2(x)\Big\}, \qquad (27)
\end{aligned}
$$

$$
P_{\gamma\gamma}^{(1,1)} = -C_F\, C_A \Big(\sum_{j=1}^{n_F} e_{q_j}^2\Big)\,\delta(1-x), \qquad (28)
$$

$$
\begin{aligned}
P_{qg}^{(1,1)} = \frac{T_R\, e_q^2}{2} \Big\{ & 4 - 9x - (1-4x)\ln(x) - (1-2x) \\
& \times \ln^2(x) + 4\ln(1-x) + p_{qg}(x)\Big[2\ln^2\Big(\frac{1-x}{x}\Big) \\
& - 4\ln\Big(\frac{1-x}{x}\Big) - \frac{2\pi^2}{3} + 10\Big]\Big\},
\end{aligned}
$$

$$
\begin{aligned}
P_{\gamma g}^{(1,1)} = T_R \Big(\sum_{j=1}^{n_F} e_{q_j}^2\Big) \Big\{ & -16 + 8x + \frac{20}{3}x^2 + \frac{4}{3x} \\
& - (6+10x)\ln(x) - 2(1+x)\ln^2(x)\Big\},
\end{aligned}
$$

$$
P_{gg}^{(1,1)} = -T_R \Big(\sum_{j=1}^{n_F} e_{q_j}^2\Big)\,\delta(1-x),
$$

$$
\begin{aligned}
P_{qq}^{S(1,1)} &= P_{q\bar{q}}^{S(1,1)} = 0, && (32) \\
P_{qq}^{V(1,1)} &= -2\, C_F\, e_q^2 \Big[\Big(2\ln(1-x) + \frac{3}{2}\Big)\ln(x)\, p_{qq}(x) \\
&\quad + \frac{3+7x}{2}\ln(x) + \frac{1+x}{2}\ln^2(x) + 5(1-x) \\
&\quad + \Big(\frac{\pi^2}{2} - \frac{3}{8} - 6\zeta_3\Big)\delta(1-x)\Big], && (33) \\
P_{q\bar{q}}^{V(1,1)} &= 2\, C_F\, e_q^2\, [4(1-x) + 2(1+x)\ln(x) \\
&\quad + 2 p_{qq}(-x) S_2(x)], && (34) \\
P_{gq}^{(1,1)} &= C_F\, e_q^2 \Big[-(3\ln(1-x) + \ln^2(1-x))\, p_{gq}(x) \\
&\quad + \Big(2 + \frac{7}{2}x\Big)\ln(x) - \Big(1 - \frac{x}{2}\Big)\ln^2(x) \\
&\quad - 2x\ln(1-x) - \frac{7}{2}x - \frac{5}{2}\Big], && (35) \\
P_{\gamma q}^{(1,1)} &= P_{gq}^{(1,1)}, && (36)
\end{aligned}
$$

Available simulation tools

- analytic resummation of log(ptV/MV) with NNLL accuracy: ResBos arXiv:hep-ph/9704258
  with NNLO-QCD + NNLL accuracy DYRes arXiv:1507.06937

- QED FSR multiple photon description:
  Photos Comput.Phys.Commun. 79 (1994) 291-308
  HORACE 1.0 hep-ph/0303102, hep-ph/0502218
  PYTHIA QED arXiv:0710.3820

- NLO-EW corrections :
  WZGRAD hep-ph/9807417, hep-ph/0108274
  RADY hep-ph/0109062, arXiv:0911.2322
  SANC arXiv:hep-ph/0506110 , arXiv:0711.0625

- event generator with NLO-EW + QED-PS: HORACE 3.1 hep-ph/0609170, arXiv:0710.1722

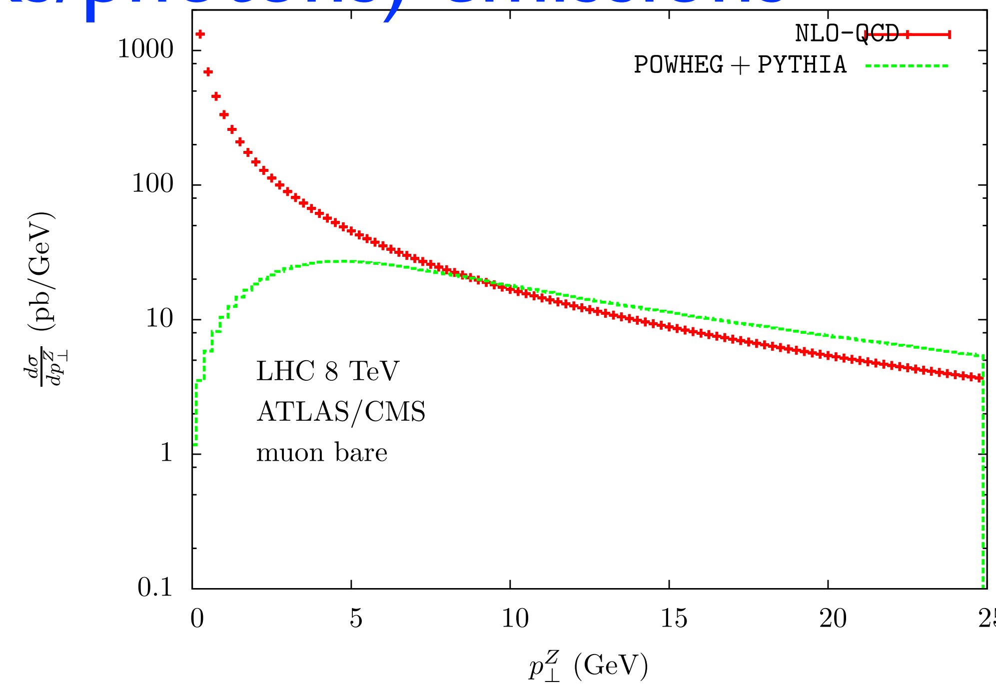
- event generator with NLO-QCD + QCD-PS:
  POWHEG arXiv:0805.4802
  MC@NLO arXiv:hep-ph/0204244

- event generator with NLO-(QCD+EW) + (QCD+QED)-PS: POWHEG arXiv:1201.4804, arXiv:1202.0465, arXiv:1302.4606

- event generator with NNLO-QCD + QCD-PS accuracy:
  DYNNLOPS arXiv:1407.2940
  SHERPA@NNLO with UN^{2}LOPS arXiv:1405.3607

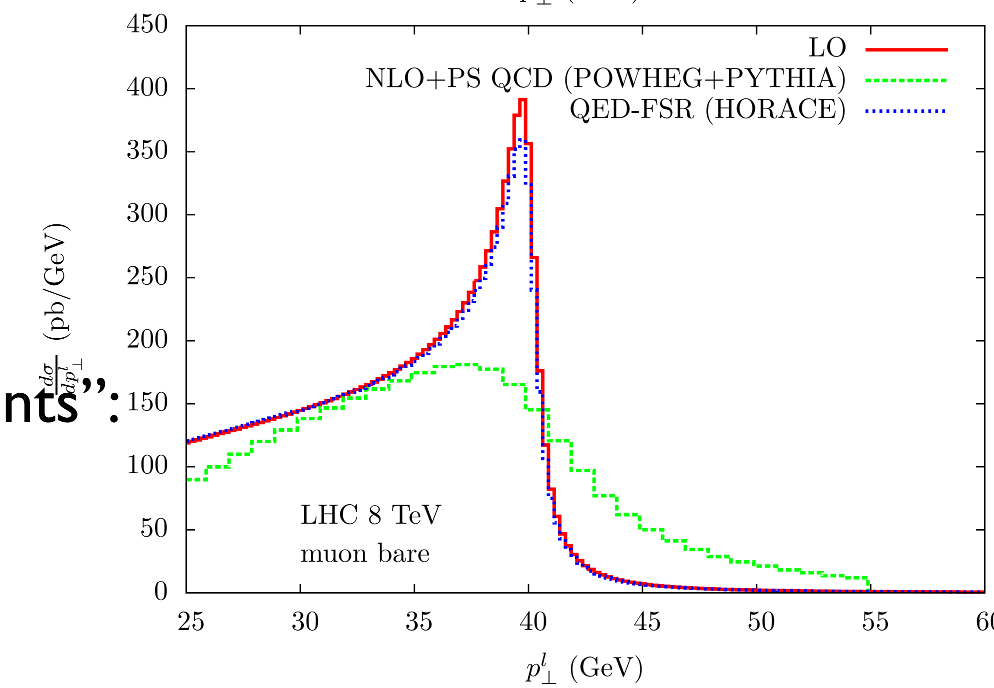
Relevance of multiple parton (gluons/quarks/photons) emissions

Initial State QCD radiation yields collinear divergences
→ divergence of the gauge boson PT distr
in fixed order calculations
after resummation,
Sudakov suppression and regular behavior for PT →0



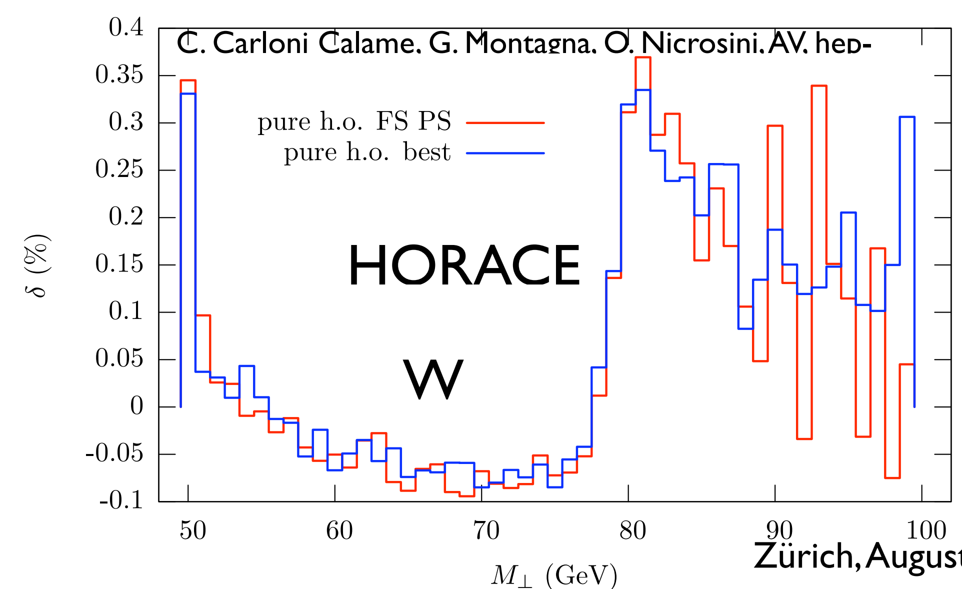
Multiple initial State QCD radiation completely reshuffles
the lepton momenta
yielding the first realistic description of the
lepton transverse momentum distribution

The lepton transverse momentum has two main "components":
the decay of the gauge boson at rest
the recoil of the gauge boson against QCD radiation



Final State QED radiation from leptons
(logarithmic enhancement ~ log(ŝ/m²))
strongly distorts the lepton distributions

if one final state photon shifts the fitted value of MW
by more than 100 MeV,
the effect of additional radiation is of (-10%)
of the first contribution, still very large



Report on precision calculations for DY   Alioli et al, arXiv:1606.02330

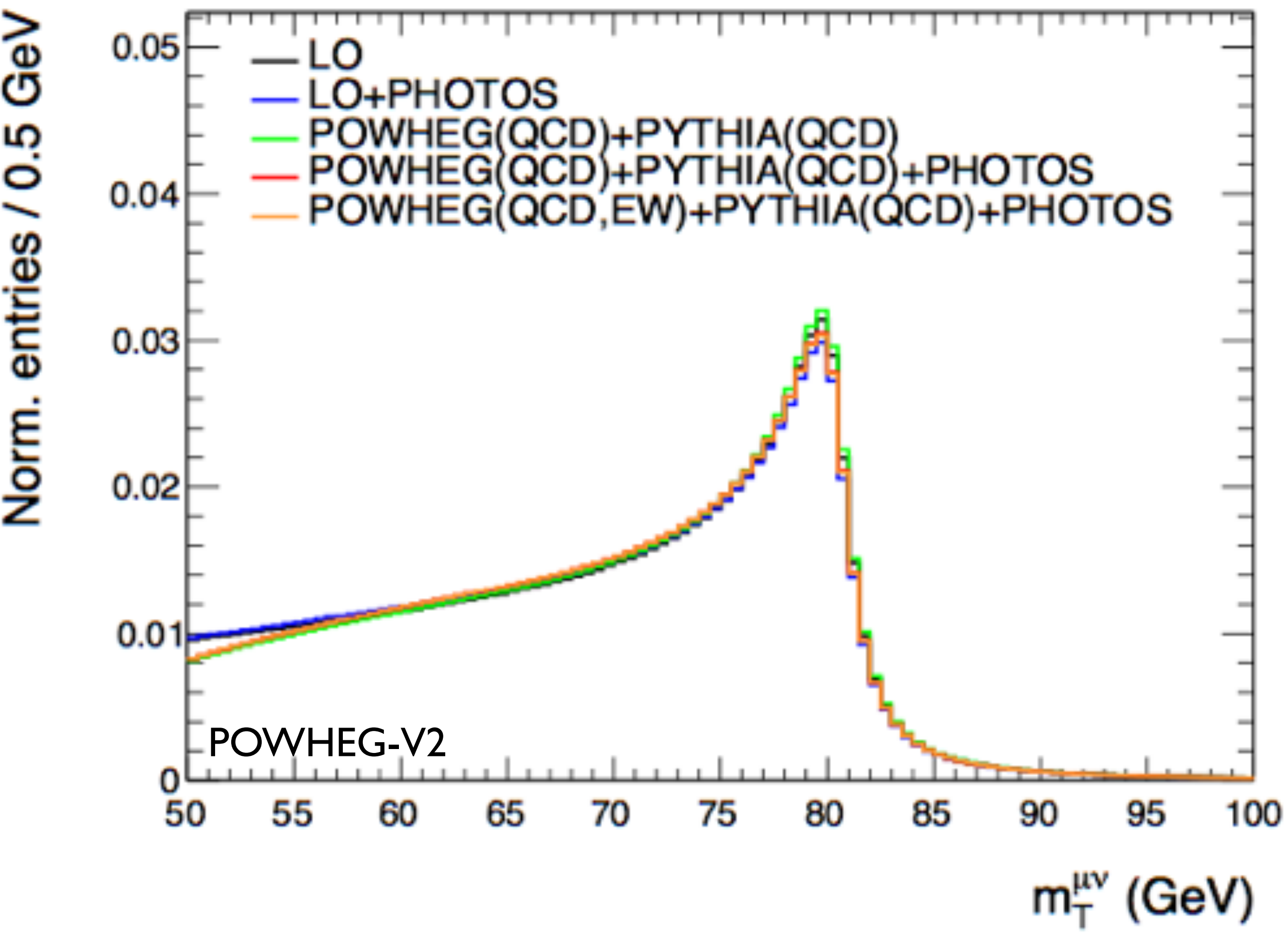
- modern MC event generators are complex tools,
  their results out-of-the-box should be checked before starting any analysis
  → first goal of the report: provide a set of benchmark results computed by the authors of the codes

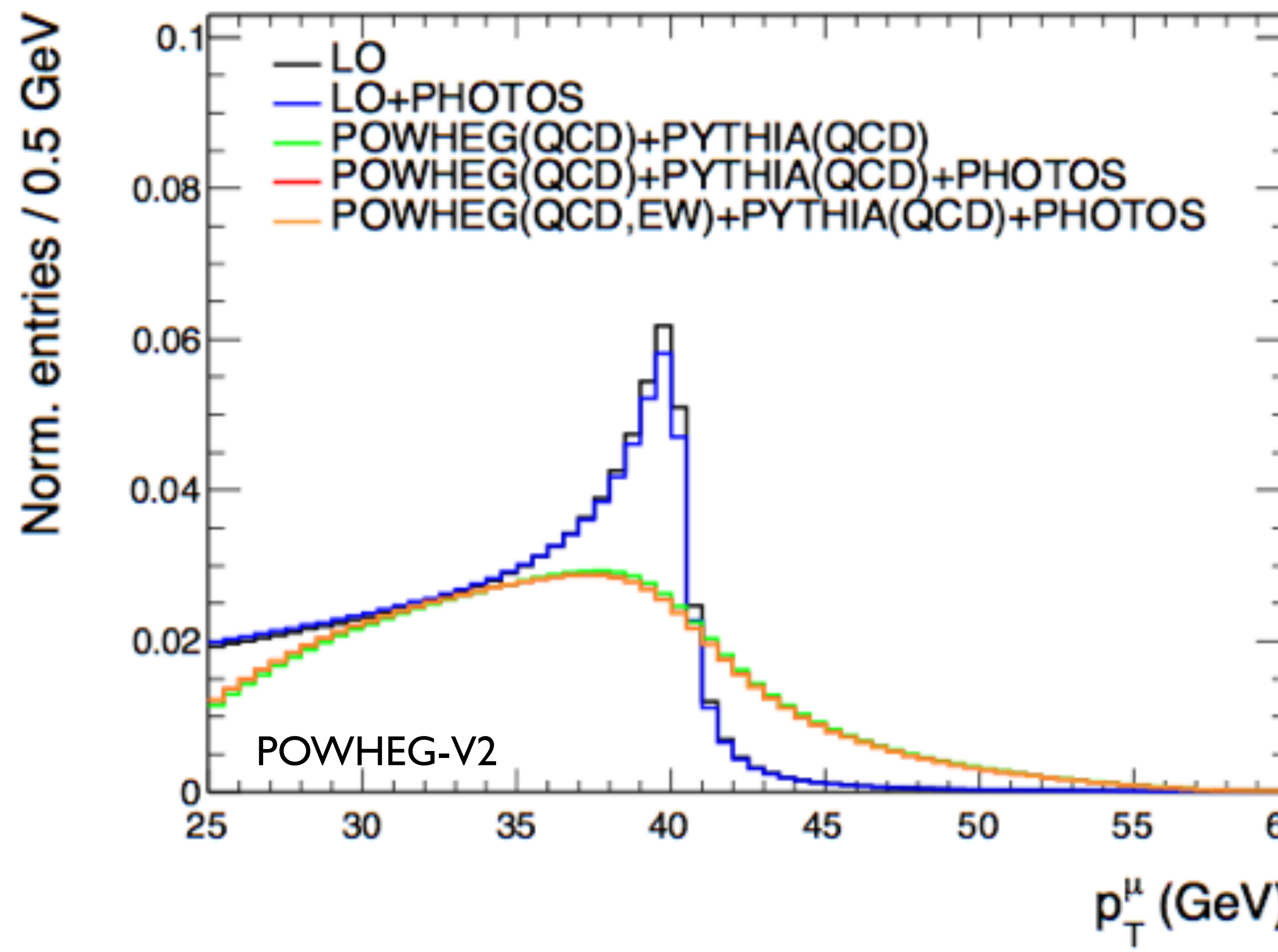
- the relevance of different available higher-order corrections can be appreciated only in a systematic classification framework, with a common unit that allows a sensible comparison
  → second goal of the report: higher-order corrections expressed as percentage corrections using (N)NLO results as unit

- combination of (fixed- and all-orders) QCD and EW corrections
  → third goal of the report: discussion of some available analytical and MC results

- the residual theoretical uncertainty is a complex topic, observable dependent;
  the report does not make an assessment of the uncertainty
  but provides some examples useful to spot the dominant sources of ambiguity

Combination of QCD and EW corrections: POWHEG results





- LO vs LO+PHOTOS shows the bulk of FSR-QED effect, the LO shape is preserved

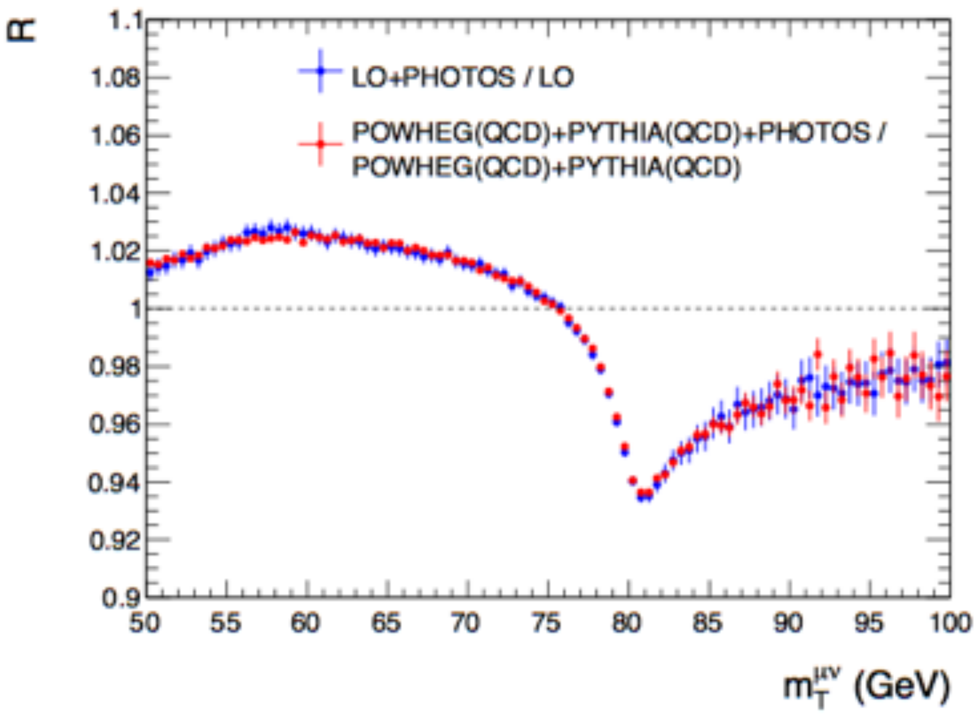
- POWHEG(QCD)+PYTHIA(QCD) shows the huge impact of QCD corrections on the lepton pt
  mild W MT

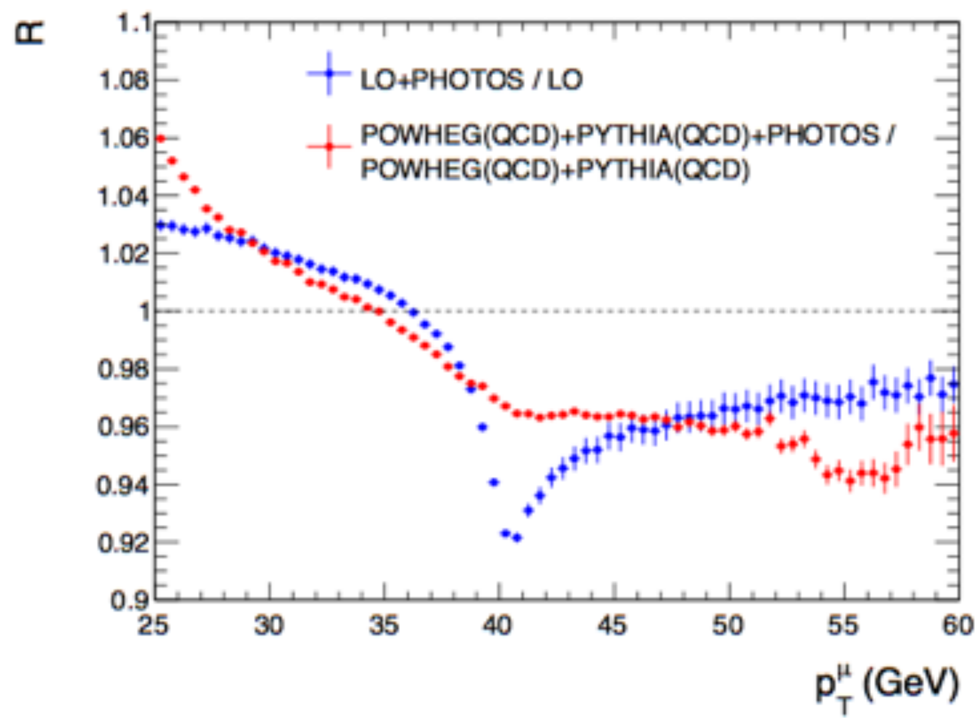
- POWHEG(QCD)+PYTHIA(QCD)+PHOTOS shows the impact of i) QED-FSR
  ii) mixed QCDxQED terms
  on top of the pure QCD description

- POWHEG(QCD,EW)+PYTHIA(QCD)+PHOTOS adds subdominant QED/EW terms
  absent in PHOTOS

Combination of QCD and EW corrections: POWHEG results

Do QCD corrections preserve the QED effects ?





the difference between red and blue is due to mixed QCDxQED terms

(these effects are already taken into account in the Tevatron and LHC analyses)

What is the impact of the full set of NLO-EW corrections?

POWHEG(QCD,EW) +PYTHIA(QCD) + PHOTOS

vs

POWHEG(QCD) + PYTHIA(QCD) + PHOTOS

Crucial role played by the algorithm that matches fixed-order results and Parton Shower in presence of two competing interactions

→ see talk by Homero Martinez on Thursday (MC session)

One remark on POWHEG

- POWHEG NLO-(QCD+EW)
  - it has NLO-(QCD+EW) accuracy on the total cross section
  - it describes with exact matrix elements the hardest parton (gluon, quark, photon) emission
  - it includes to all orders QCD and QED effects via Parton Shower

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

the virtual QCD and EW corrections

are included in the Bbar function, factored in front of the curly bracket

contribute to the correct normalisation of the distributions independent of the number of additional partons

have a minor role when we consider the shape of the distributions

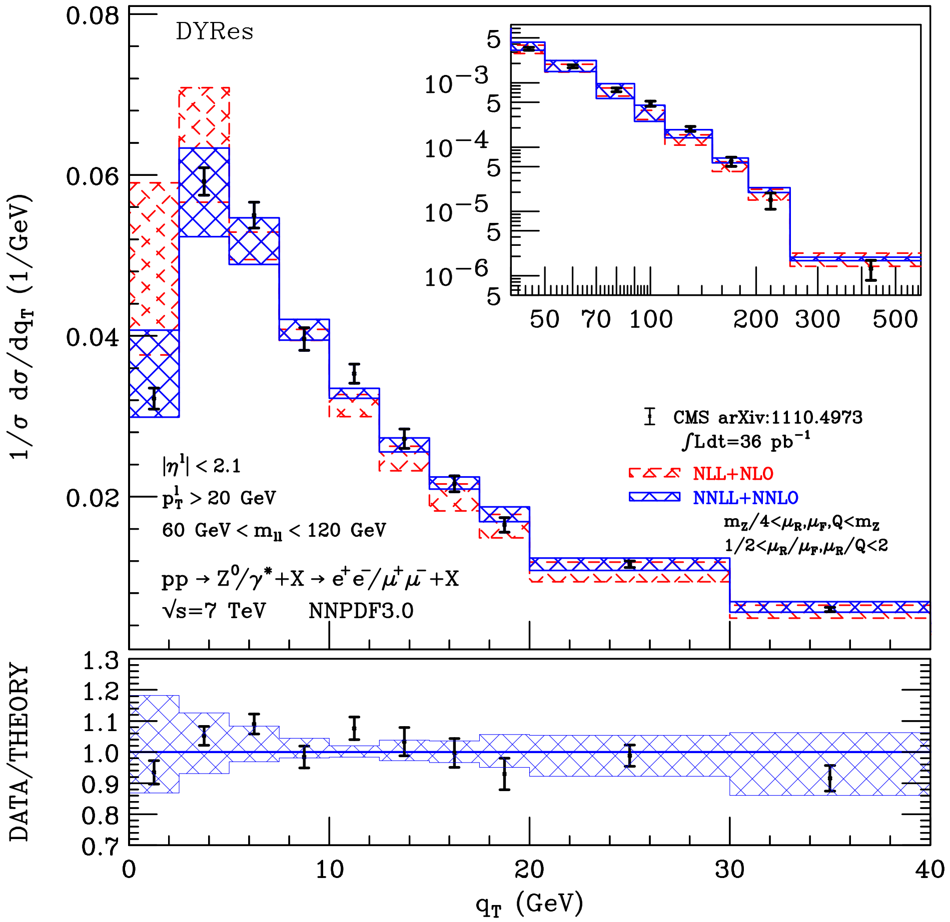
this structure differs with respect to fixed-order calculations

where virtual corrections modify the contribution only of the lowest multiplicity cross section (no additional partons)

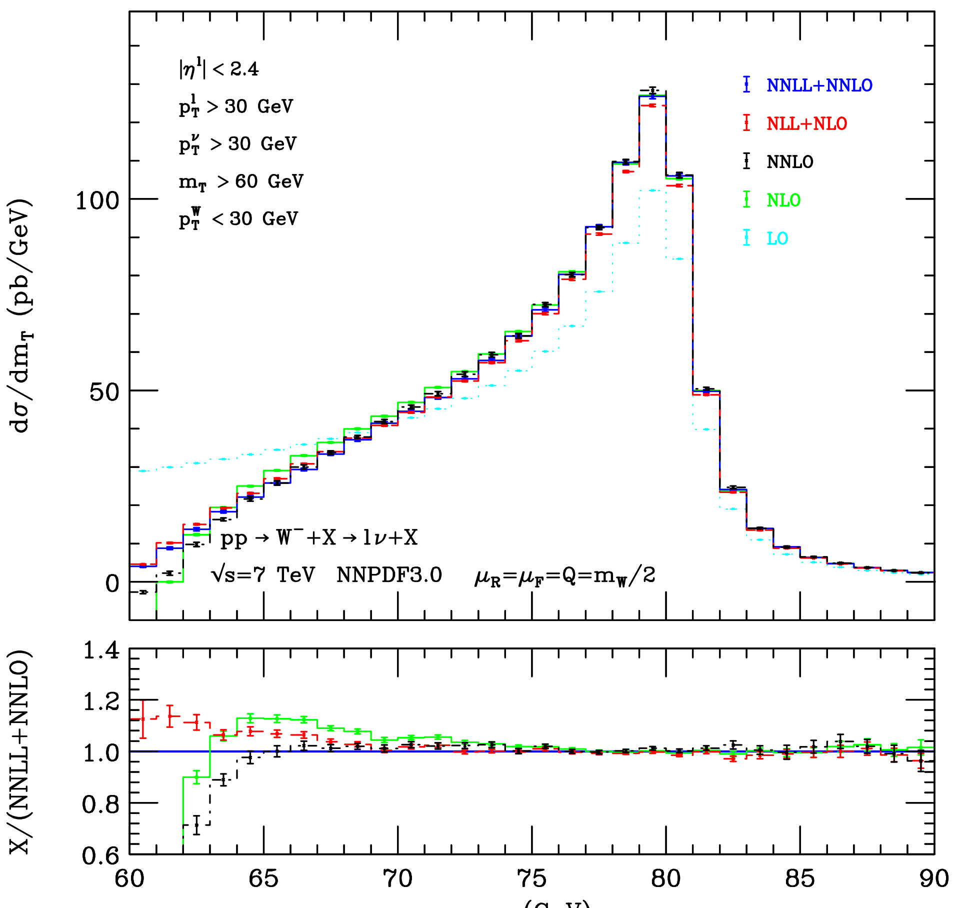
and in turn the shape of the distributions

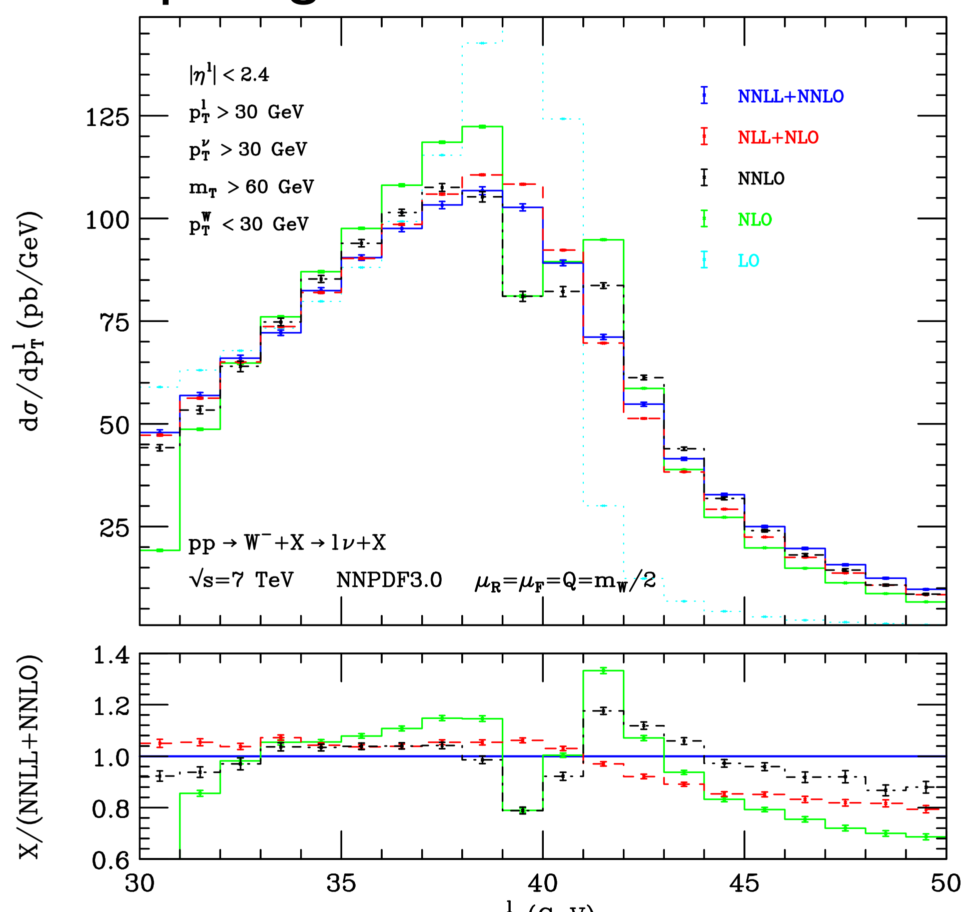
DYRes (NNLO-QCD + NNLL) with leptonic decays

S. Catani, D. de Florian, G. Ferrera, M. Grazzini, arXiv:1507.06937



- NNLO accuracy on the total xsec matched with NNLL accuracy in the description of the low ptZ region
- good description of ptZ data in pure pQCD within the theory uncertainty bands no urgent need of a non-perturbative component
- remarkable stability of the MT distribution at the jacob. peak when including higher order corrections
- the lepton pt distribution is distorted at few % level when comparing NLL+NLO w.r.t. NNLL+NNLO



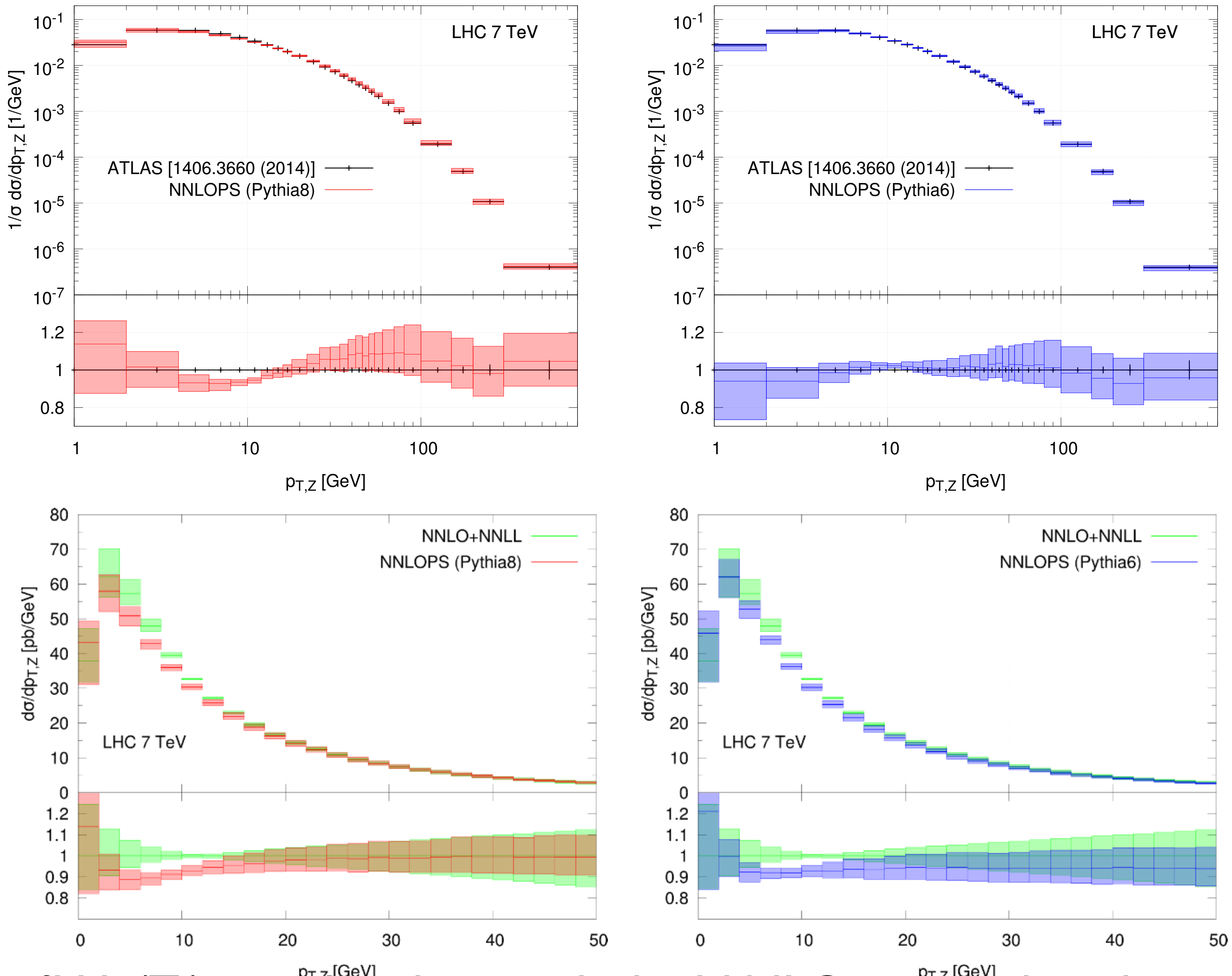


DYNNLOPS

- Matching of NNLO-QCD matrix elements with QCD-PS

  DYNNLOPS — A.Karlberg, E.Re, G.Zanderighi, arXiv:1407.2940

  UN²LOPS+NNLO — S.Hoeche, Y.Li, S.Prestel, arXiv:1405.3607



- Improvement of Wj (Zj) samples, done with the MiNLO approach and a modified Sudakov form factor
- The distribution has NLO accuracy through the whole ptV range
- The NNLO accuracy on the inclusive observables is based on the rescaling with DYNNLO results
- The uncertainty bands have been obtained varying with a combination of ren./fact. scale variations of the Wj/Zj MiNLO generator and of the DYNNLO simulation

UN²LOPS + NNLO

- Matching of NNLO-QCD matrix elements with QCD-PS

  DYNNLOPS — A.Karlberg, E.Re, G.Zanderighi, arXiv:1407.2940

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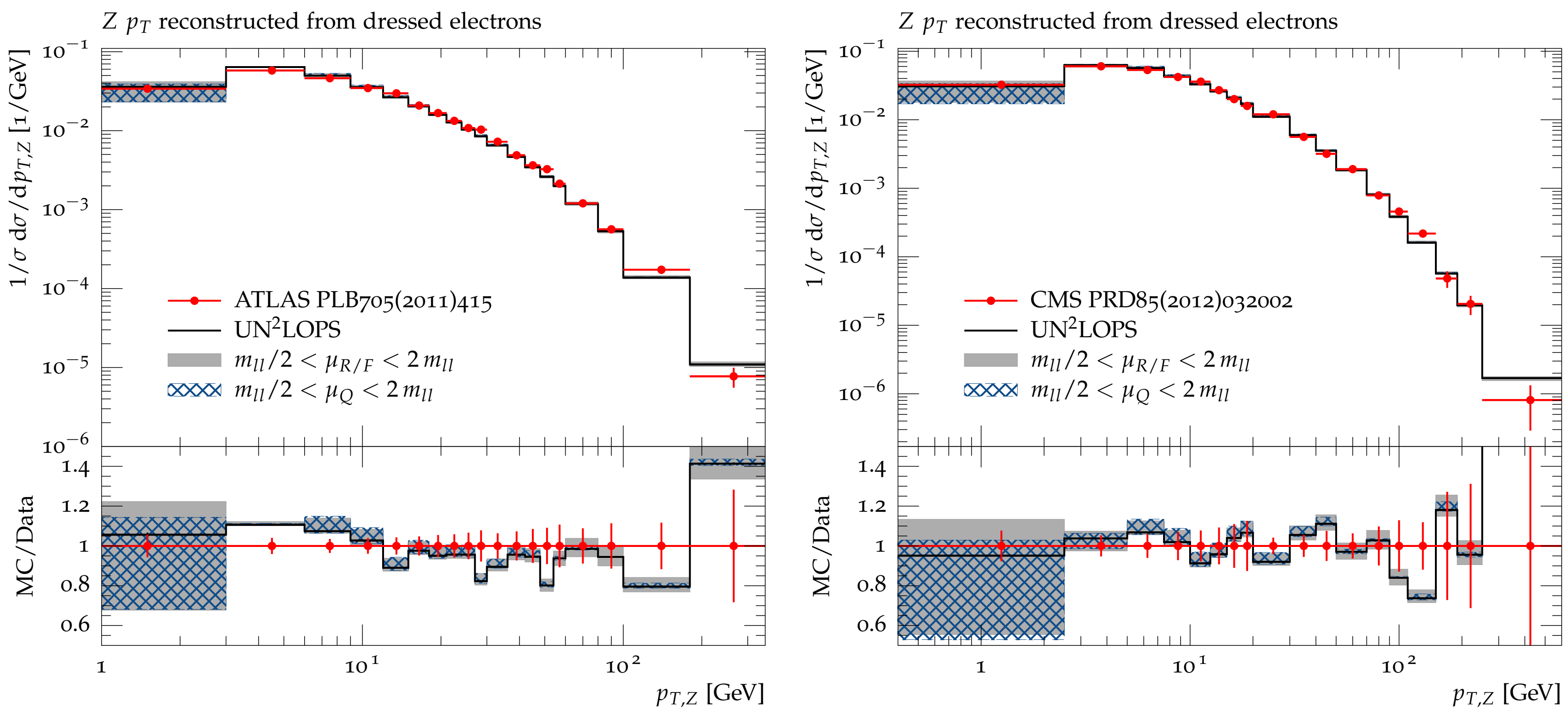
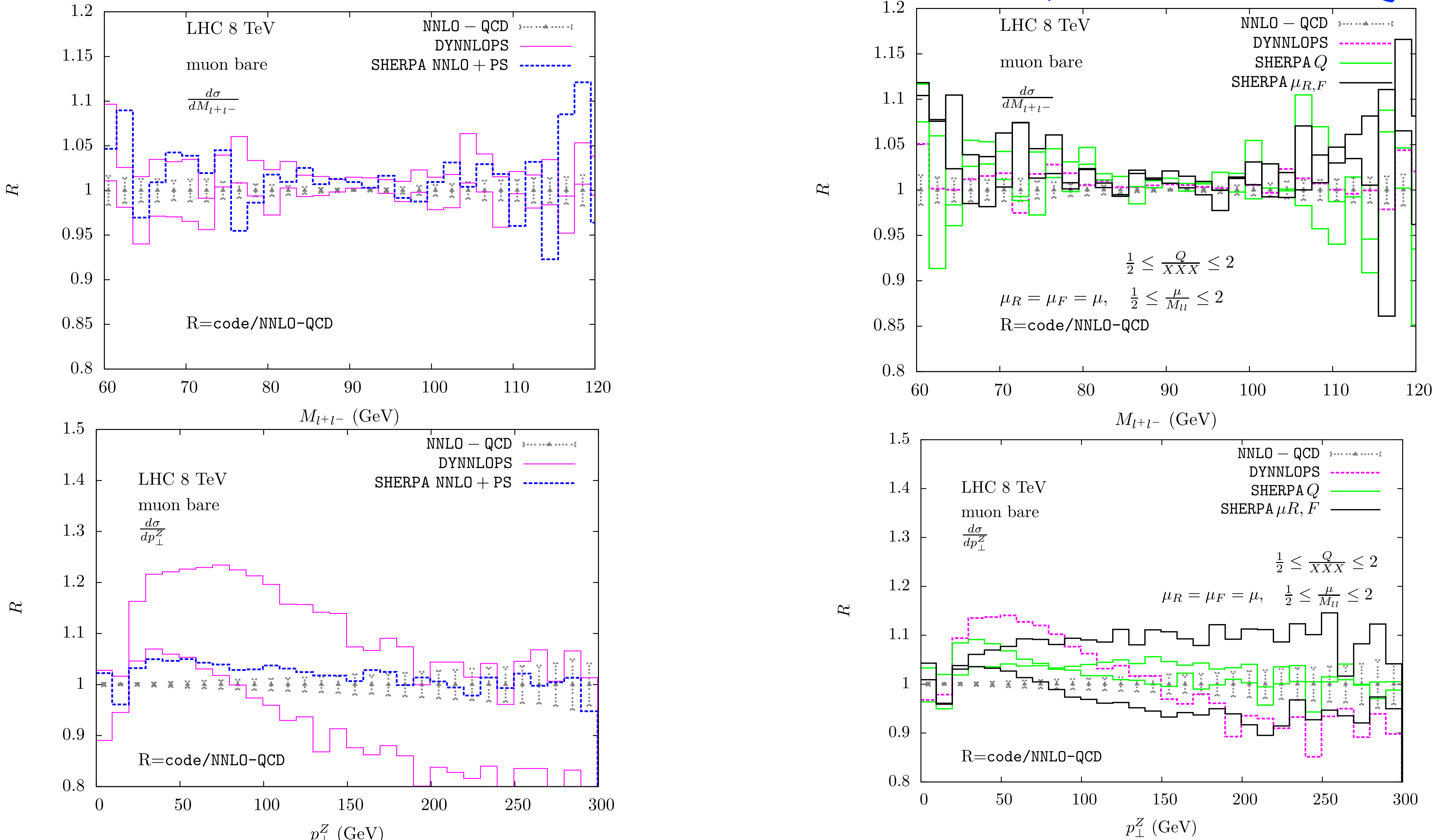


- The UNLOPS scheme merges 0-jet and 1-jet samples (it requires a merging scale), it preserves the accuracy on the total xsec with the definition of a 0-jet bin which is not showered
- The UN²LOPS scheme extends the approach at O(alphas²)

- Important differences in the definition of the uncertainty bands between DYNNLOPS and UN²LOPS

Benchmark results: differential distributions, NNLO+PS QCD



Comparison of two different NNLO+PS matching schemes (DYNNLOPS and SHERPA UN²LOPS)

The impact of higher-order corrections is expressed in units NNLO-QCD.

Different definitions of the uncertainty bands (DYNNLOPS uses 21 scale combinations, SHERPA separate muR, muF and Q variations)

The two matchings differ only by several percent (improvement w.r.t. NLO+PS) for ptV, but the uncertainty bands are not yet negligible.

We need a systematic study of the matching uncertainties on ptZ, analogous to the one for the Higgs ptH of Bagnaschi, Harlander, Mantler, AV, Wiesemann, arXiv:1510.08850

Impact of EW corrections on the MW determination

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, in preparation

	Templates accuracy: LO	M_W shifts (MeV)			
		$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$	
	Pseudodata accuracy	M_T	p_T^ℓ	M_T	p_T^ℓ
1	HORACE only FSR-LL at $\mathcal{O}(\alpha)$	-94±1	-104±1	-204±1	-230±2
2	HORACE FSR-LL	-89±1	-97±1	-179±1	-195±1
3	HORACE NLO-EW with QED shower	-90±1	-94±1	-177±1	-190±2
4	HORACE FSR-LL + Pairs	-94±1	-102±1	-182±2	-199±1
5	PHOTOS FSR-LL	-92±1	-100±2	-182±1	-199±2

estimate of shifts based on a template fit approach (see H. Martinez talk for details)

- the first final state photon dominates the correction on MW
- multiple photon radiation has still a sizeable O(-10%) effect
- subleading QED and weak effects are negligible, O(1-2 MeV)
- additional pair production is not negligible, with a shift ranging from 3 to 5 MeV
- the agreement between PHOTOS and HORACE QED-PS is acceptable, given the subleading differences of the two implementations

Is the impact of EW corrections preserved in a QCD environment ?

	Templates accuracy: LO Pseudodata accuracy	M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	p_T^ℓ	$W^+ \to e^+\nu$ M_T	p_T^ℓ
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5	PHOTOS FSR-LL	-92±1	-100±2	-182±1	-199±2

	Templates: NLO-QCD+QCD_{PS} Pseudodata accuracy	QED FSR	M_W shifts (MeV) $W^+ \to \mu^+\nu$ M_T	p_T^ℓ	$W^+ \to e^+\nu$(dres) M_T	p_T^ℓ
1	NLO-QCD+$(QCD+QED)_{PS}$	PYTHIA	-95.2 ± 0.6	-400 ± 3	-38.0 ± 0.6	-149 ± 2
2	NLO-QCD+$(QCD+QED)_{PS}$	PHOTOS	-88.0 ± 0.6	-368 ± 2	-38.4 ± 0.6	-150 ± 3
3	NLO-(QCD+EW)+$(QCD+QED)_{PS}$	PYTHIA	-101.8 ± 0.4	-423 ± 2	-45.0 ± 0.6	-179 ± 2
4	NLO-(QCD+EW)+$(QCD+QED)_{PS}$	PHOTOS	-94.2 ± 0.6	-392 ± 2	-45.2 ± 0.6	-181 ± 2
5	NLO-(QCD+EW)+$(QCD+QED)_{PS}$(two-rad)	PYTHIA	-89.0 ± 0.6	-371 ± 3	-38.8 ± 0.6	-157 ± 3
6	NLO-(QCD+EW)+$(QCD+QED)_{PS}$(two-rad)	PHOTOS	-88.6 ± 0.6	-370 ± 3	-39.2 ± 0.6	-159 ± 2

Lepton-pair transverse mass: yes!

Lepton transverse momentum: no, the shift are sizeably amplified

(these effects are already taken into account in the Tevatron and LHC analyses)

Effect of the NLO-EW matching on subleading QED contributions

PHOTOS and PYTHIA-QED Parton Showers share Leading-Logarithmic accuracy
differ at subleading level in the collinear region

The matching with the exact O(α) matrix elements shifts the differences one order higher

	Templates: NLO-QCD+QCD_{PS}		M_W shifts (MeV)			
			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
	Pseudodata accuracy	QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
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Estimate of EW uncertainties via input scheme variation

- a full NNLO-EW calculation is not available (only leading QED $O(\alpha^2)$ contributions available)

	Templates accuracy: LO		M_W shifts (MeV) $W^+ \to \mu^+\nu$	
	Pseudodata accuracy	Input scheme	M_T	p_T^ℓ
1	HORACE NLO-EW	α_0	-101±1	-117±2
2		$G_\mu - I$	-112±1	-130±1
3		$G_\mu - II$	-101±1	-117±1
4	HORACE NLO-EW+QED-PS	α_0	-70±1	-81±1
5		$G_\mu - I$	-72±2	-83±1
6		$G_\mu - II$	-72±1	-82±2

- different input schemes introduce different subsets of higher order corrections, beyond the formal accuracy of the calculation
  → the comparison probes the size of NNLO-EW corrections related to the LO couplings

- at fixed order NLO-EW α_0 and G_μ schemes differ by O(10 MeV):
  the virtual corrections affect only the 0-photons contribution to the distributions
  change of shape

- in the matched HORACE formulation the difference is reduced at the O(1 MeV) level (negligible)
  because the virtual corrections act in a prefactor common to all the events
  (with different photon multiplicities) and do not affect the shape of the distributions

- how do these uncertainties behave when convoluted with QCD radiation?

Comments on the assessment of the theoretical uncertainty

- several higher-order effects which are available (i.e. implemented in at least one code) have been classified in arXiv:1606.02330
  they are not an uncertainty,
  they should be either added in the simulations or quoted in the theoretical systematic error
  e.g. at $O(\alpha^2)$ additional lepton-pair production

- all the missing higher orders which are not available can only be guessed
  the estimate is observable dependent
  - for observables stable under the inclusion of radiative effects (rapidity, invariant/transverse mass)
    the QCD uncertainty can be studied e.g. with canonical scale variations
    the propagation to mixed QCDxEW corrections should be safely stable

  - for observables sensitive to radiative effects it is necessary to use matched calculations
    → the QCD uncertainty should account also for the matching uncertainty
    → careful extrapolation from purely EW estimates to QCDxEW estimates
    e.g lepton-pair production effect on the lepton ptl distribution in presence of QCD

Comments on the QCD uncertainties

- The MW determination requires not only the fit of CC-DY observables
  but also, for calibration purposes, several ancillary measurements of NC-DY quantities like e.g.
  · lepton-pair invariant mass ($M_{\ell\ell}$)
  · transverse momentum (ptZ)

  These additional observables form a more constrained system,
  with more information and possibly with reduced uncertainties

- A QCD uncertainty on MW is present
  because our templates are computed at finite order in perturbation theory.

  It has to be estimated including all the CC and NC observables involved in the fit

- The QCD scales (renormalisation, factorisation, resummation) have no physical meaning
  (the exact result is independent of them) and can not be measured.

  A convenient choice of the QCD scales may optimise the χ^2 of the global fit
  can not remove the QCD uncertainty

Comments on the QCD uncertainties

- The QCD uncertainty is due to a list of partially entangled factors:
  - pQCD scales (renormalization, factorisation, resummation)
  - matching uncertainty (POWHEG vs MC@NLO vs SHERPA; DYNNLOPS vs UN2LOPS)
  - size of non-perturbative transverse momentum contributions, Parton Shower tune
  - collinear PDF uncertainty (entering also in the Parton Shower tune)
  - initial state heavy quarks treatment

- A variation of each of these parameters in the CC-DY observables alone may lead to an overestimate of the uncertainty on MW

→ the inclusion of the NC DY "ancillary" calibration observables is needed to perform a consistent estimate of the uncertainty

we are fitting all these observables in the same model:
some choices have to be consistent
(e.g. if we used a given PDF replica in NC-DY, we should use the same in CC-DY simulation)
other choices are less constrained (e.g. pQCD scales in CC-DY and NC-DY)

the correlation (if any) of the observables reduces the uncertainty on the MW determination
(ratios W/Z are one possible example of combination, not the most general one)

→ the inclusion of more DY observables (CC and NC) may help to further constrain the system:
e.g. the role of a MW measurement from ptl at LHCb to reduce the PDF uncertainty

Impact of a LHCb MW measurement in the combination with ATLAS/CMS results

G.Bozzi, L.Citelli, M.Vesterinen, AV, arXiv:1508.06954

- using the standard acceptance cuts
  for ATLAS/CMS (called **G**) and for LHCb (called **L**) and both W charges
  we study the MW determination from the lepton pt distribution
  assuming that a LHCb measurement becomes available

  - PDF uncertainty on MW according to PDF4LHC (NNPDF3.0, MMHT2014)

$$\delta_{\text{PDF}} = \begin{pmatrix} \mathbf{G}^+ & 24.8 \\ \mathbf{G}^- & 13.2 \\ \mathbf{L}^+ & 27.0 \\ \mathbf{L}^- & 49.3 \end{pmatrix}$$

  - correlation matrix ρ w.r.t. PDF variation of the replicas of the NNPDF3.0 set
    → non negligible anticorrelation
    consequence of the sum rules satisfied by the PDFs
    it appears because we probe different rapidity regions

$$\rho = \begin{pmatrix} & \mathbf{G}^+ & \mathbf{G}^- & \mathbf{L}^+ & \mathbf{L}^- \\ \mathbf{G}^+ & 1 & & & \\ \mathbf{G}^- & -0.22 & 1 & & \\ \mathbf{L}^+ & -0.63 & 0.11 & 1 & \\ \mathbf{L}^- & -0.02 & -0.30 & 0.21 & 1 \end{pmatrix}.$$

  - the linear combination that minimizes the final uncertainty on MW
    is given by the coefficients α

$$m_W = \sum_{i=1}^{4} \alpha_i m_{W\ i} \qquad \alpha = \begin{pmatrix} \mathbf{G}+ & 0.30 \\ \mathbf{G}- & 0.45 \\ \mathbf{L}+ & 0.21 \\ \mathbf{L}- & 0.04 \end{pmatrix}$$

- the exercise is robust under conservative assumptions for the LHCb main systematic uncertainties
  and guarantees a reduction by 30% of the PDF uncertainty estimated for ATLAS/CMS alone

- potential serious bottleneck for a measurement based on ptl: ptW modeling in the LHCb acceptance

Conclusions

- Continuous progress in DY studies: new analytical calculations ($O(\alpha\alpha_s)$ corrections)
  implementation of new codes (QCD, QCDxEW)

- The completion of the systematic comparison of DY simulation codes in arXiv:1606.02330

  - allows us to discuss the size of purely QCD and purely EW higher-order corrections

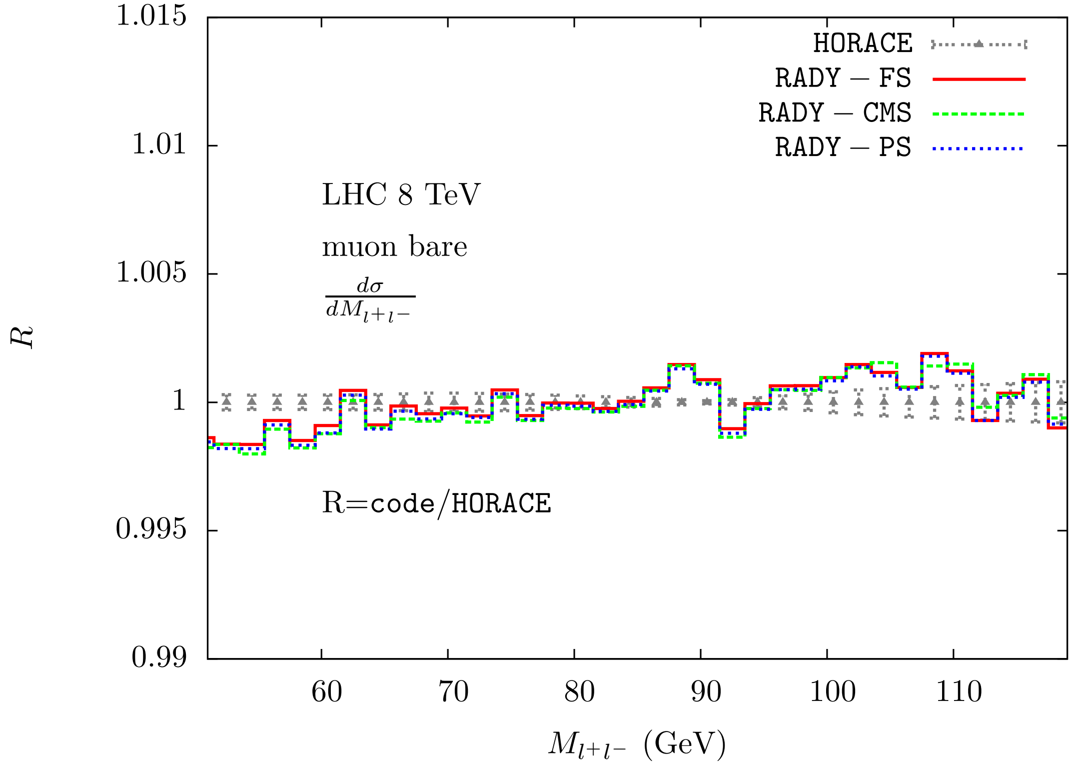
  - allows us to discuss on a solid ground the combination of QCD and EW corrections once the individual QCD and EW components are under control (cfr. the POWHEG example)
  - the precise size of the mixed QCDxEW corrections depends on the formulation of the code, which can be understood also thanks to recent analytical progresses

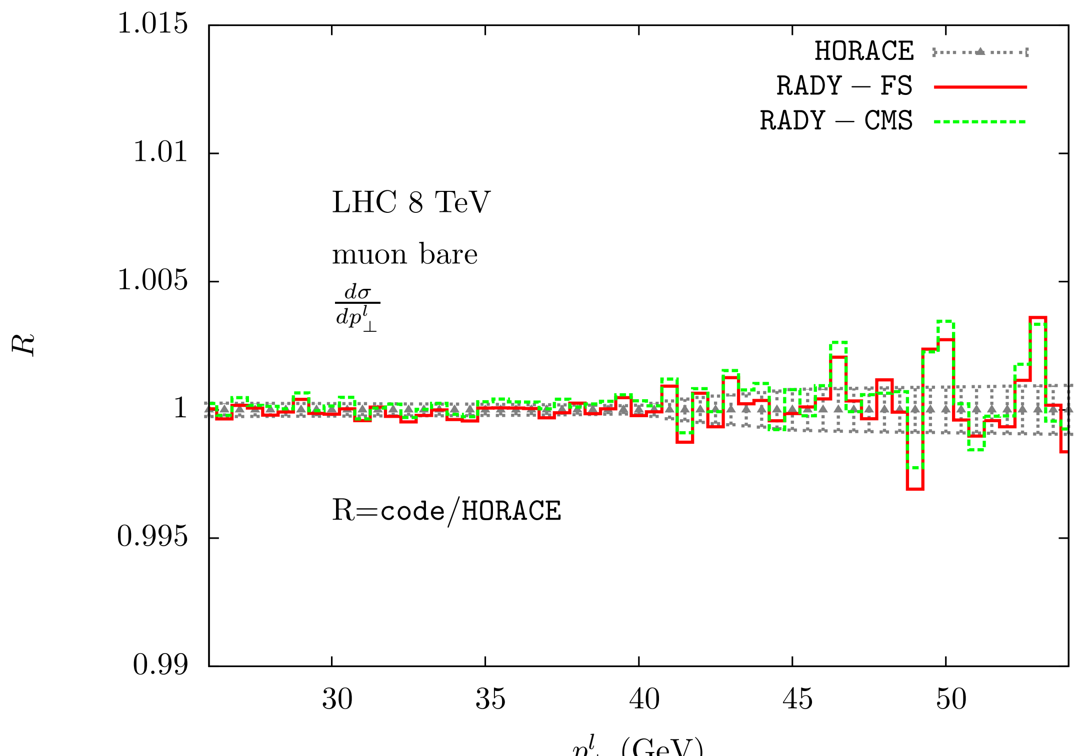
- The estimate of the theoretical uncertainties on MW, due to yet unknown corrections, is underway
  - it requires a clear definition of the set of observables that are simultaneously studied to perform a consistent QCD analysis
  - purely EW uncertainties on MW are small (beware of additional soft lepton pairs)
  - progress in the estimate of subleading $O(\alpha\alpha_s)$ (corrections and uncertainties)

Back-up slides

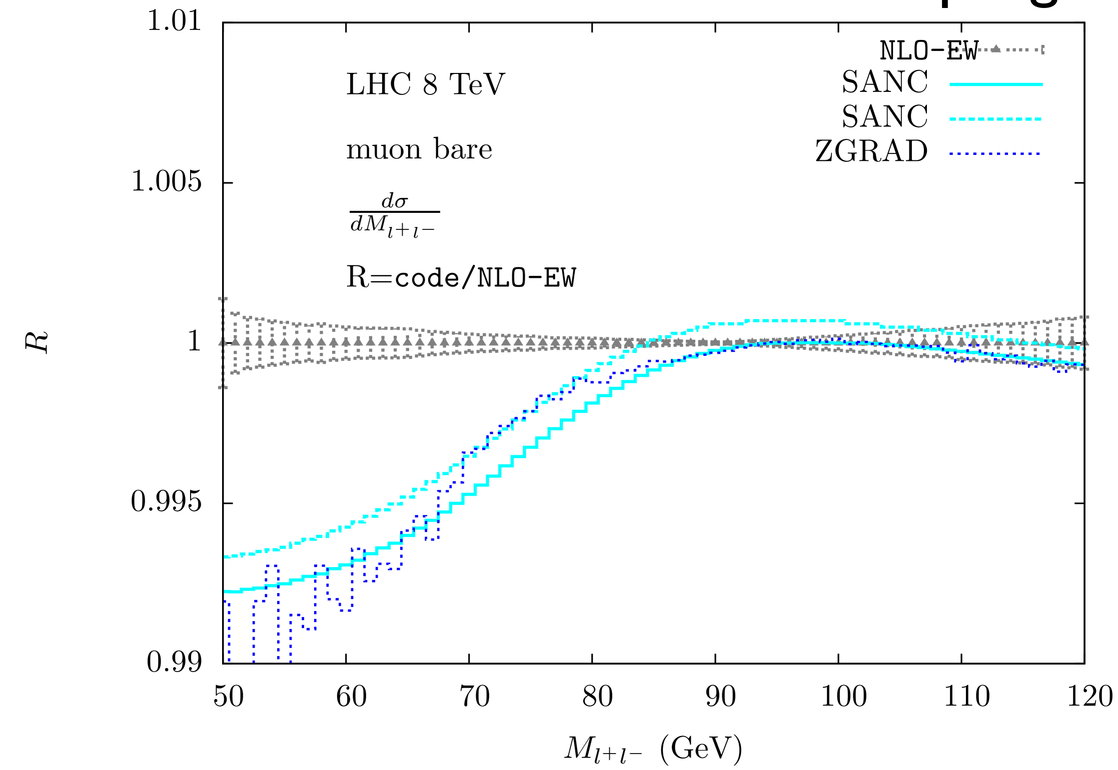
Benchmark results: differential distributions, EW inputs

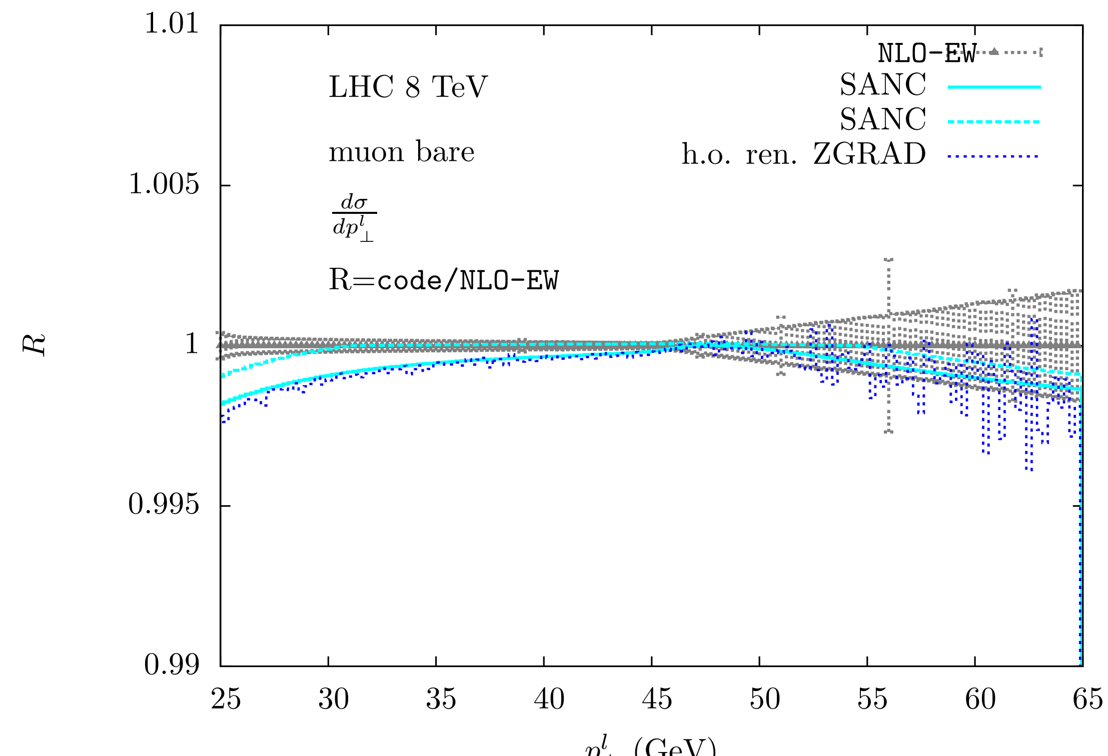
different definitions of the renormalized Z mass





inclusion of universal higher orders via redefinition of the LO couplings

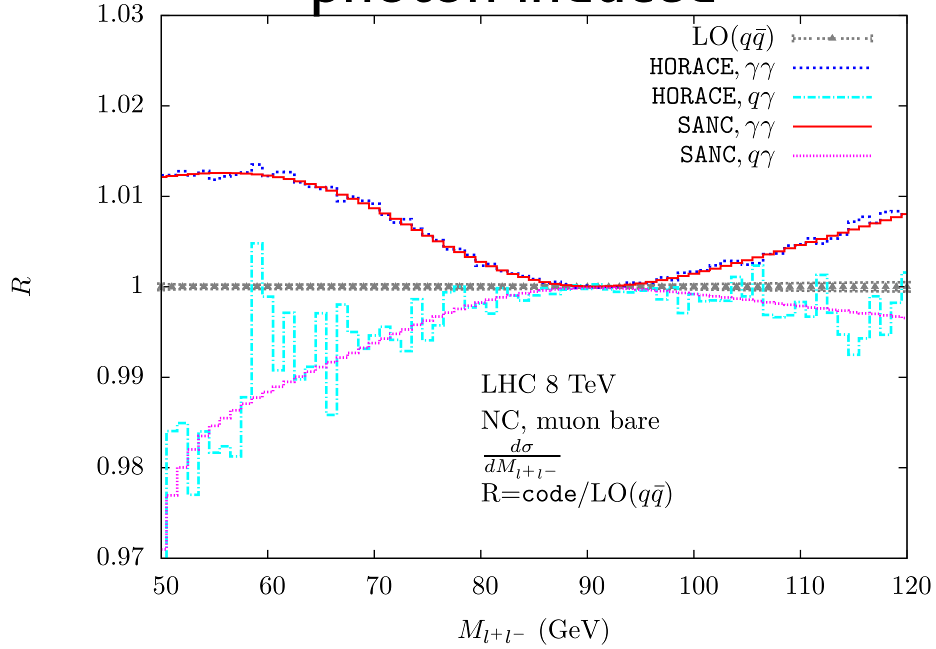




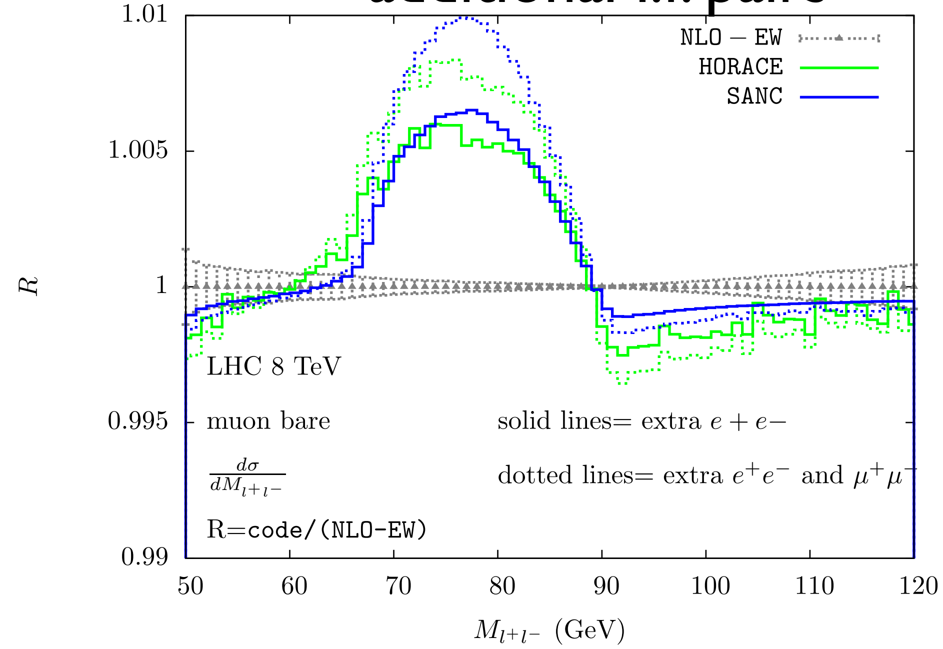
The impact of the O(α²) and higher corrections is expressed in units NLO-EW.

Benchmark results: lepton-pair invariant mass, EW higher orders

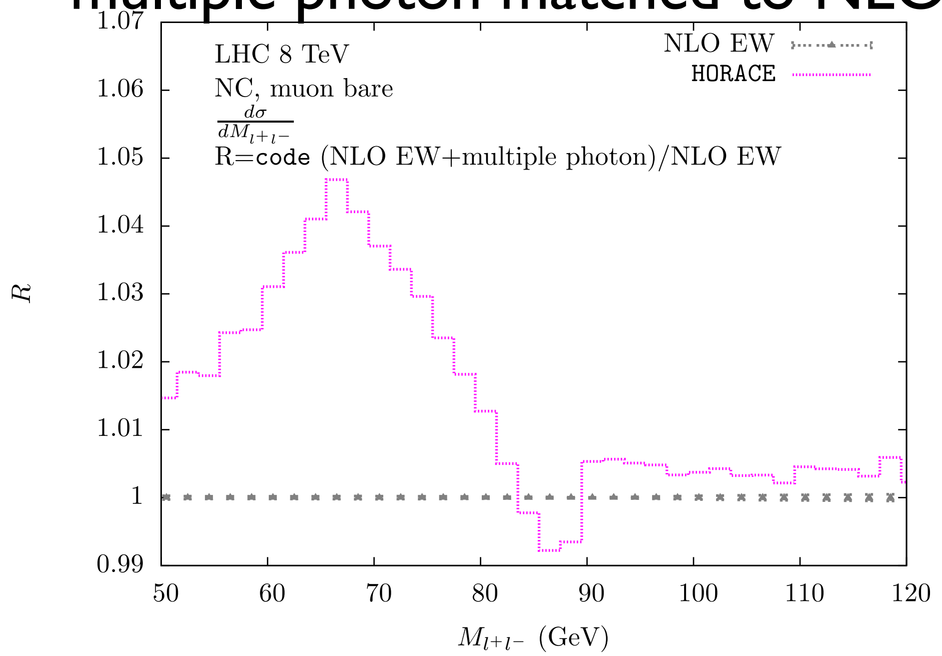
photon induced



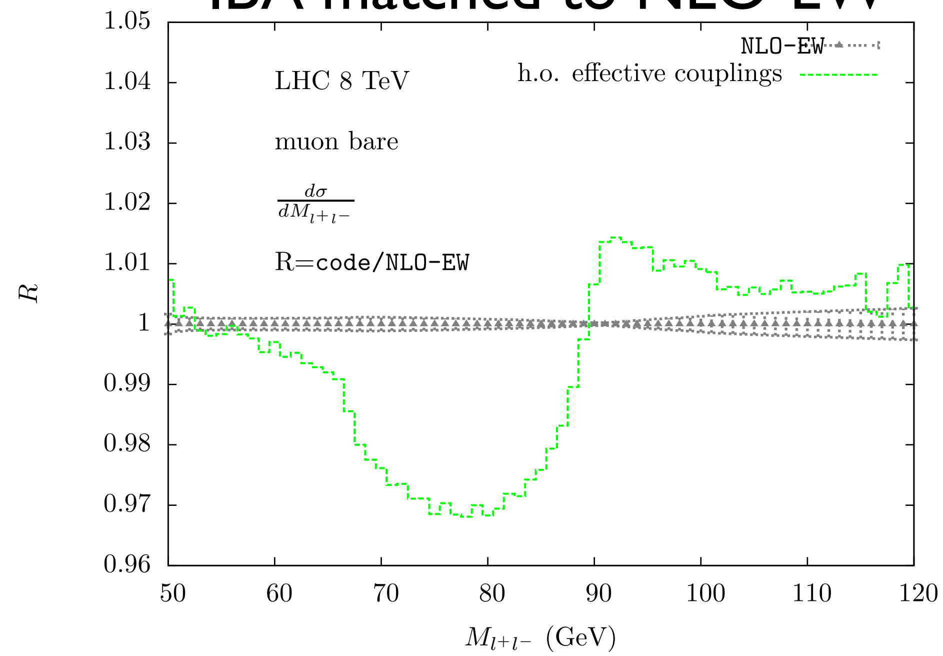
additional l.f. pairs



multiple photon matched to NLO-EW



IBA matched to NLO-EW

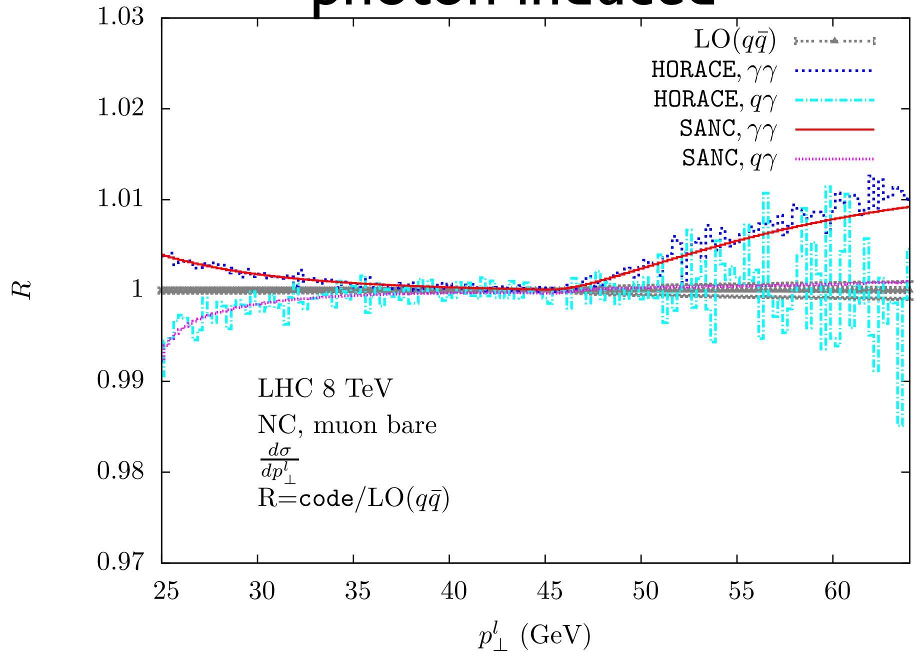


The impact of the O(α²) and higher corrections is expressed in units NLO-EW.

The effects are of O(1%), with the exception of the left tail of the Z resonance where the large (+85%) FSR corrections enhances in turn all the O(α²) terms

Benchmark results: lepton pt, EW higher orders

photon induced



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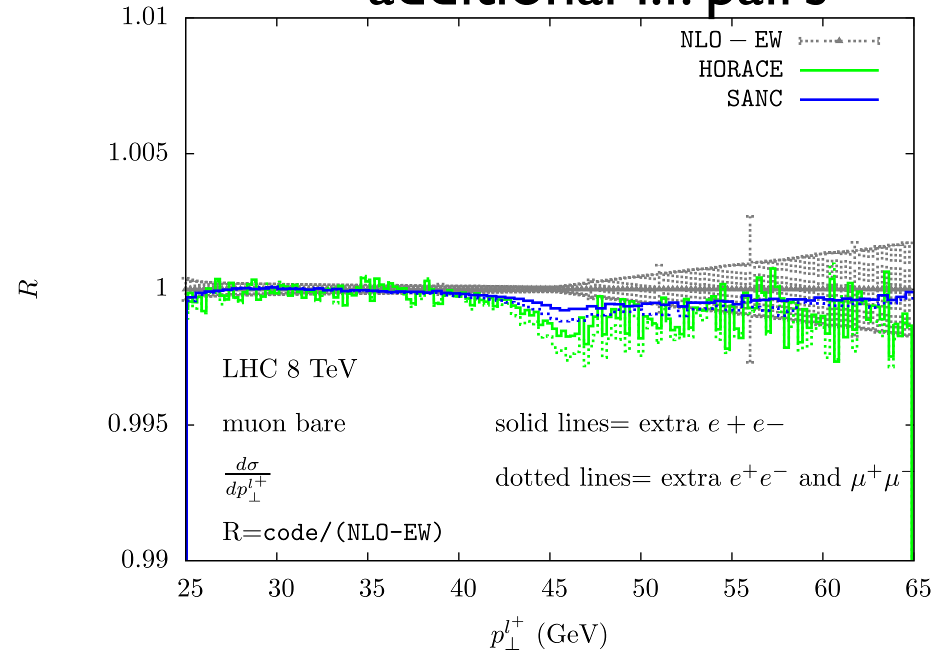
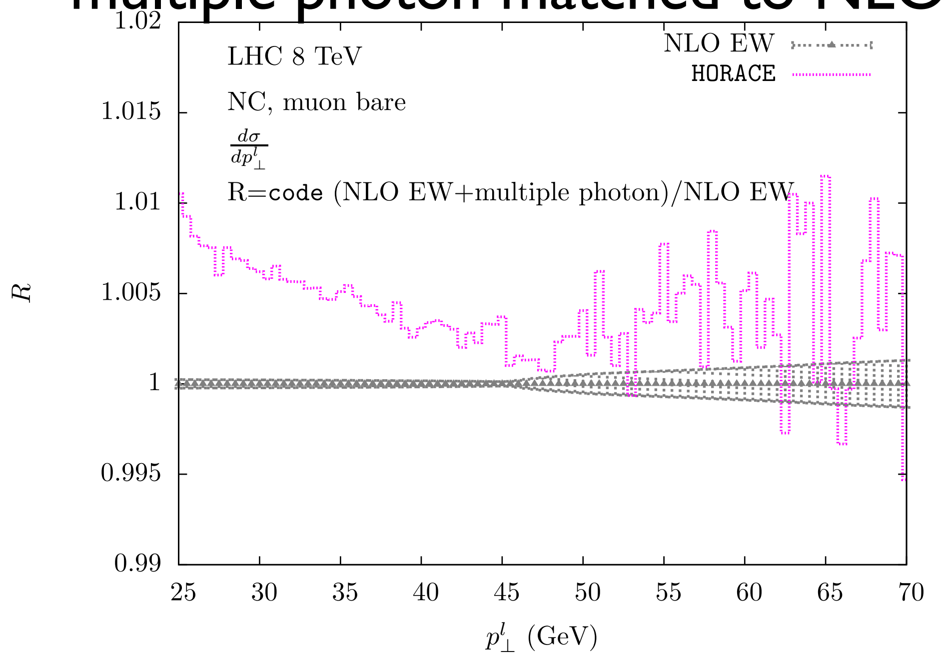
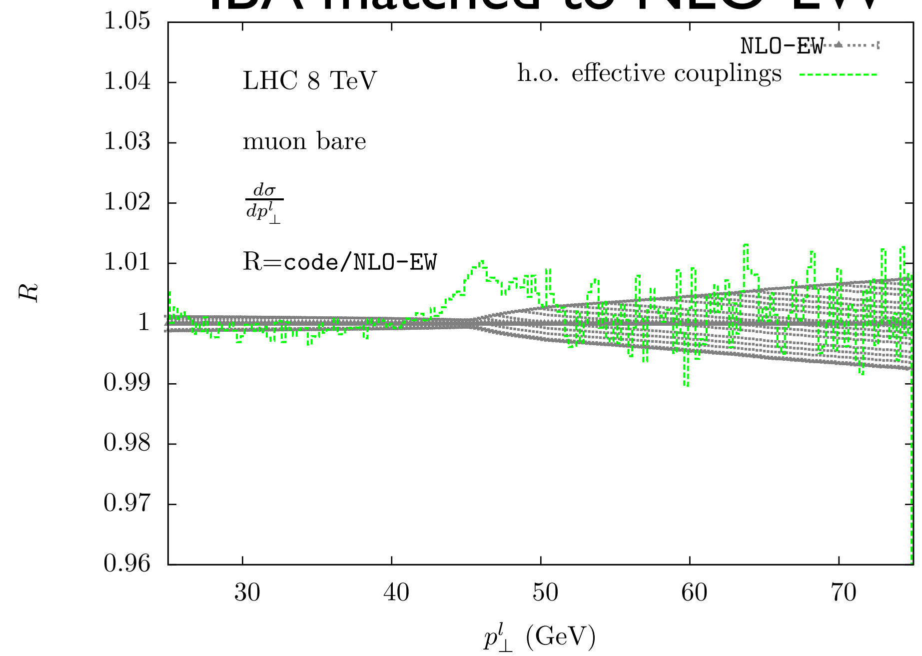


multiple photon matched to NLO-EW



IBA matched to NLO-EW



The impact of the O(α^2) and higher corrections is expressed in units NLO-EW.

The effects are at the subpercent level