UNIVERSITÀ DEGLI STUDI DI MILANO

Istituto Nazionale di Fisica Nucleare

Recent theoretical developments in W/Z production

Alessandro Vicini

University of Milano, INFN Milano

Copenhagen, April 12th 2012

Plan of the talk

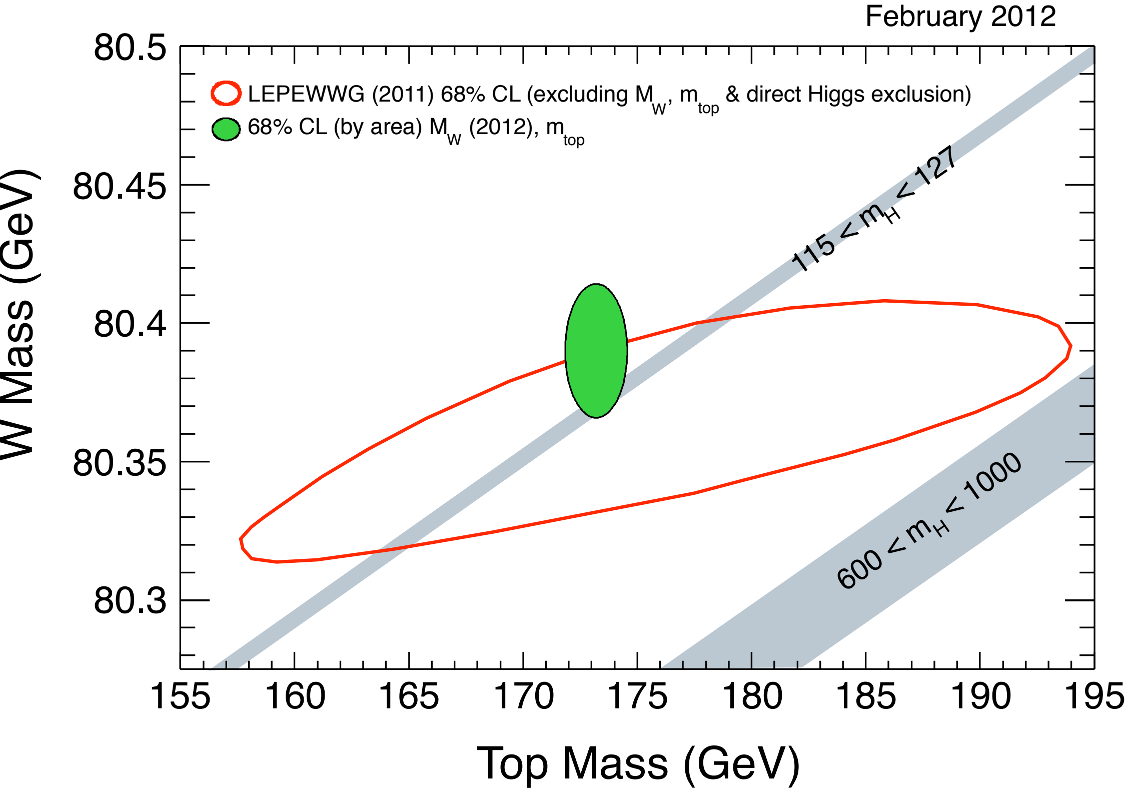
- combined QCD+EW corrections to CC Drell-Yan in POWHEG

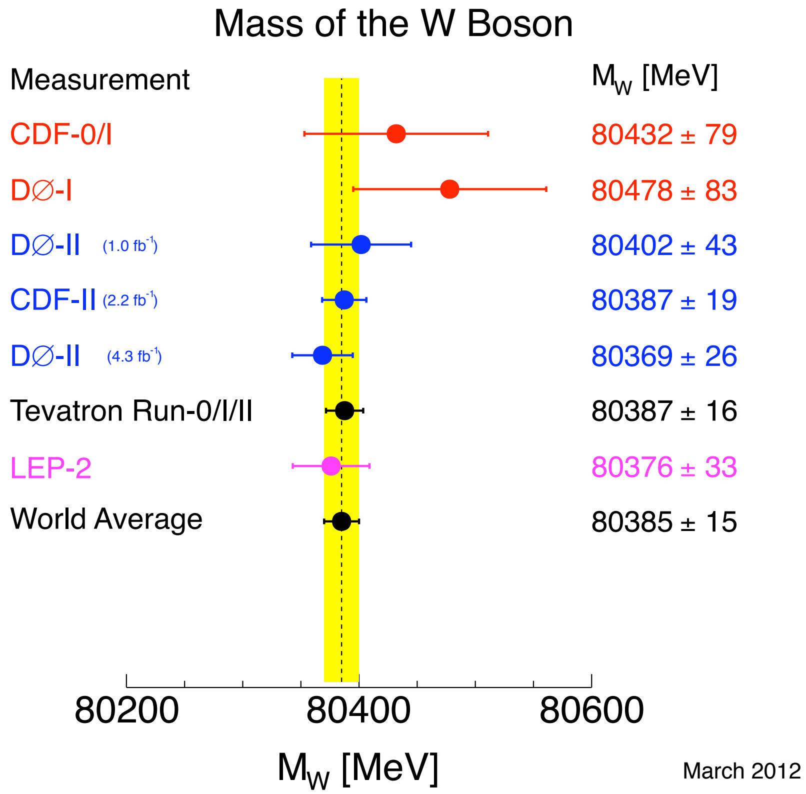
  Bernaciak, Wackeroth, arXiv:1201.4804
  Barzè, Montagna, Nason, Nicrosini, Piccinini, arXiv:1202.0465

- PDF issues in precision measurements

Motivations

A precise measurement of MW provides a crucial test of the SM





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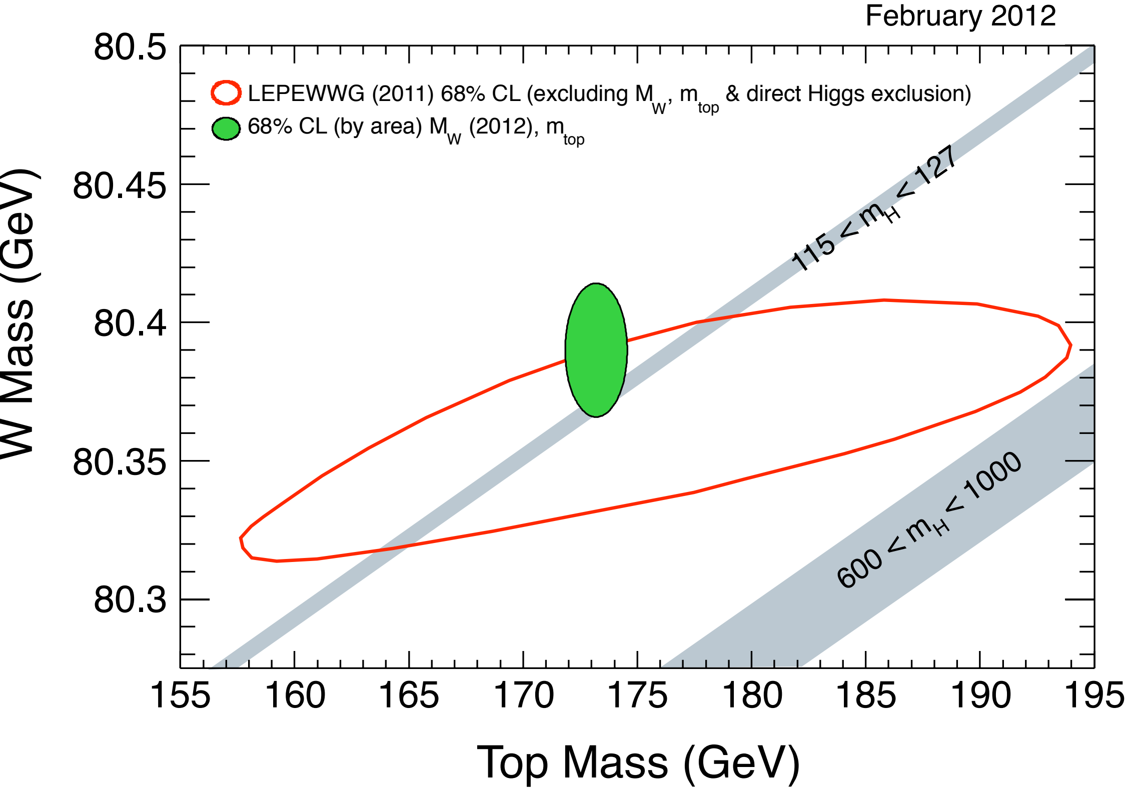
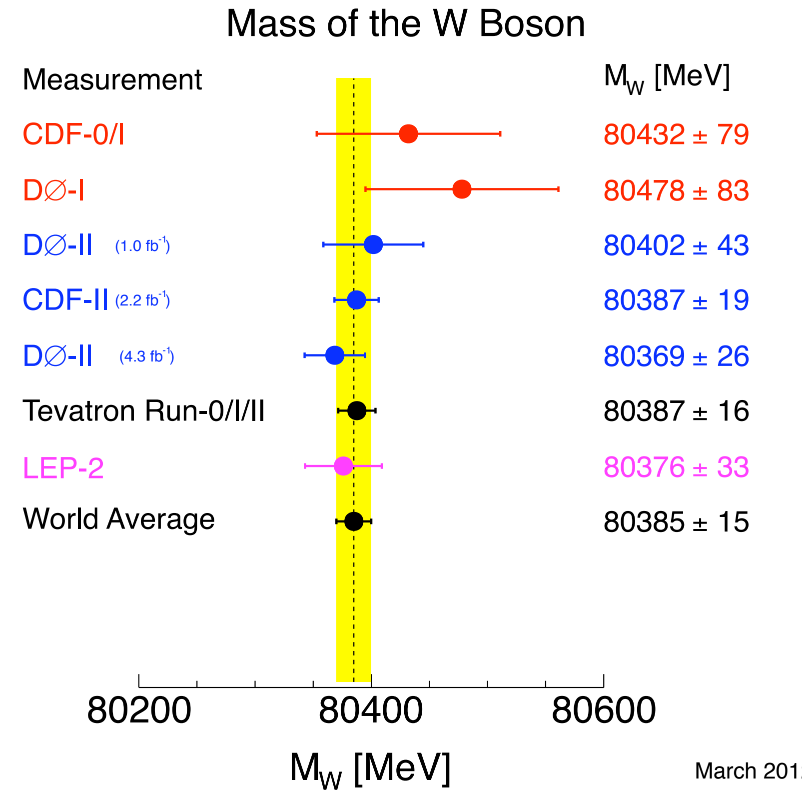
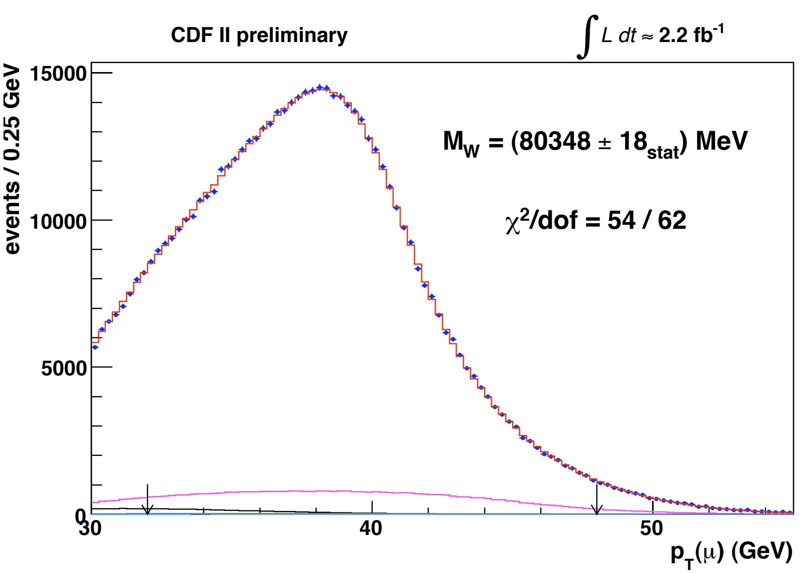
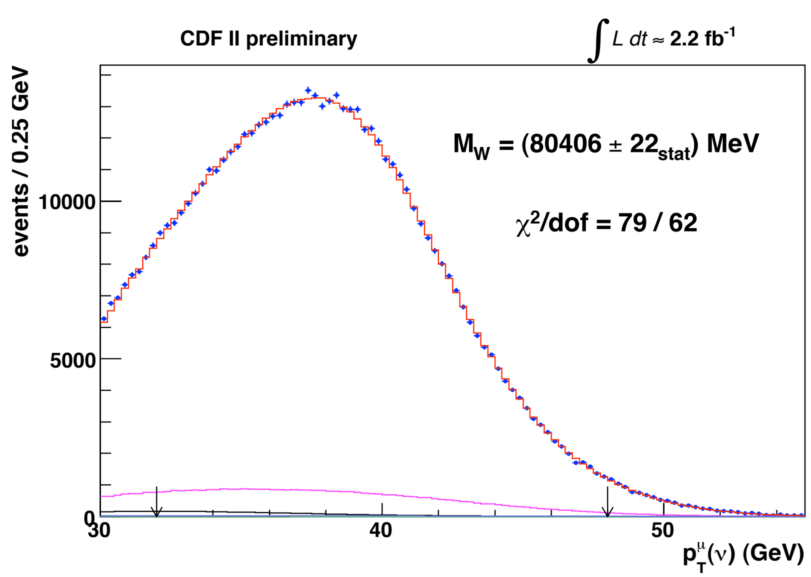
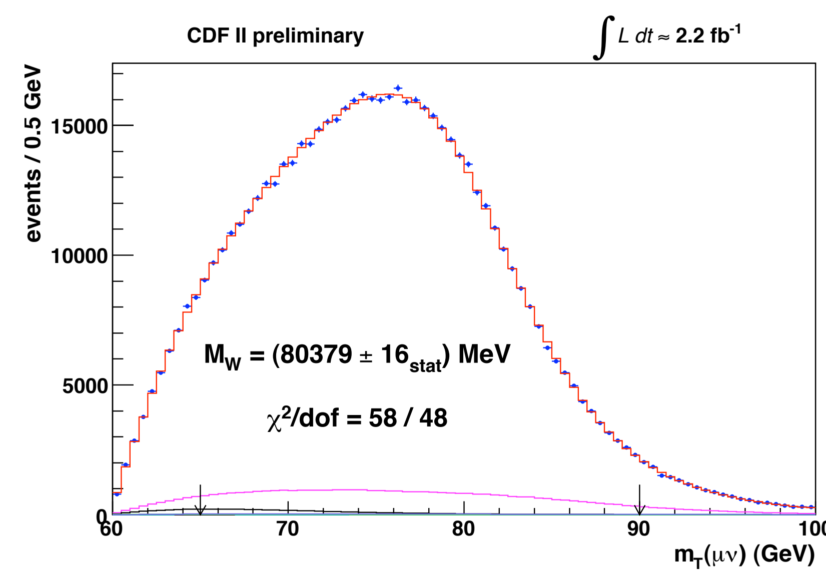




MW is extracted with a template fit technique of various distributions of CC-DY
An event generator that includes the best available results in terms of radiative corrections is necessary to minimize the theoretical systematic error in the fit







Perturbative expansion of the Drell-Yan cross section

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

QCD

$$+ \boxed{\alpha\sigma_\alpha + \alpha^2\sigma_{\alpha^2} + \ldots}$$

EW

$$+ \boxed{\alpha\alpha_s\ \sigma_{\alpha\alpha_s} + \alpha\alpha_s^2\ \sigma_{\alpha\alpha_s^2} + \ldots}$$

mixed QCDxEW

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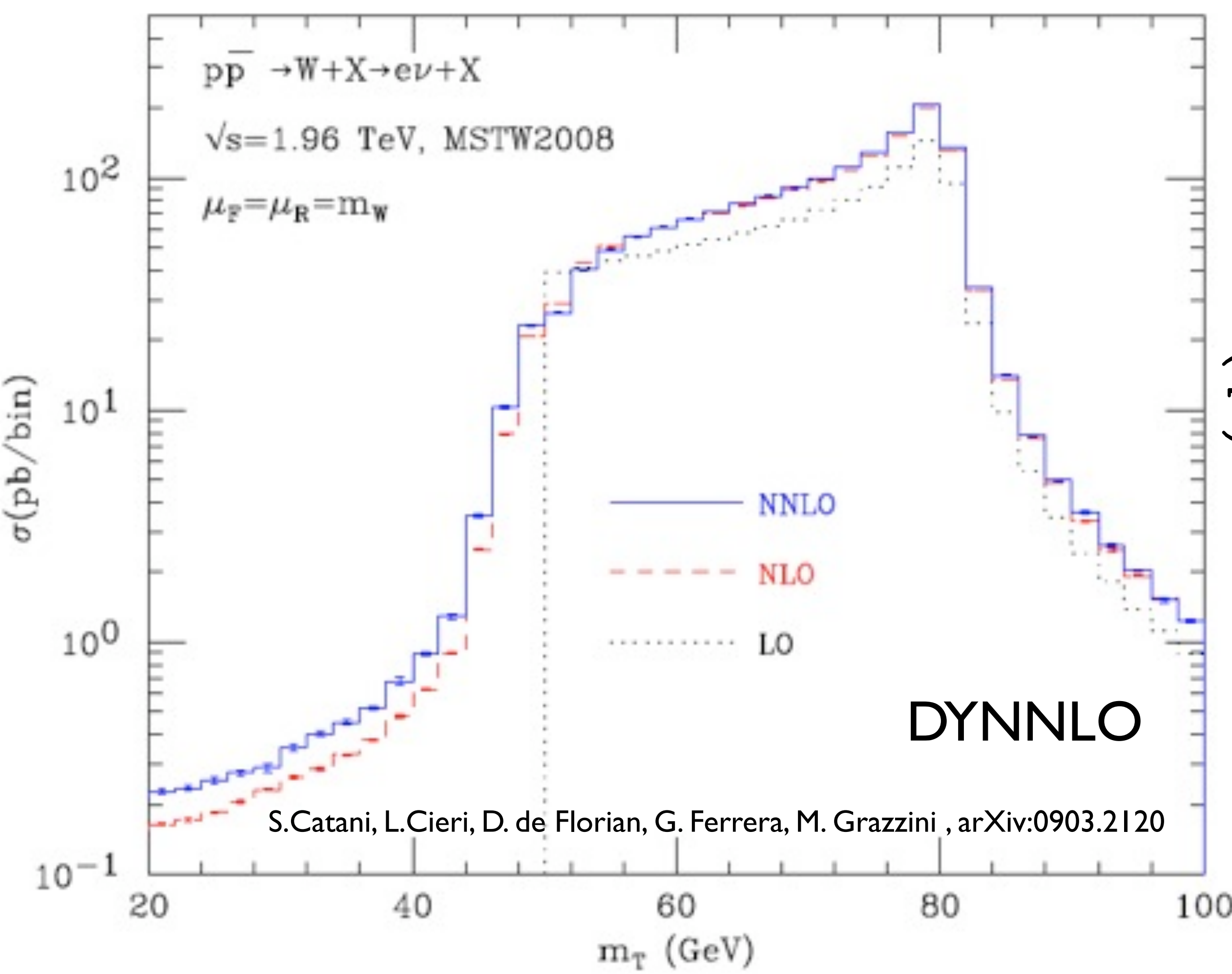
MCFM,FEWZ,DYNNLO

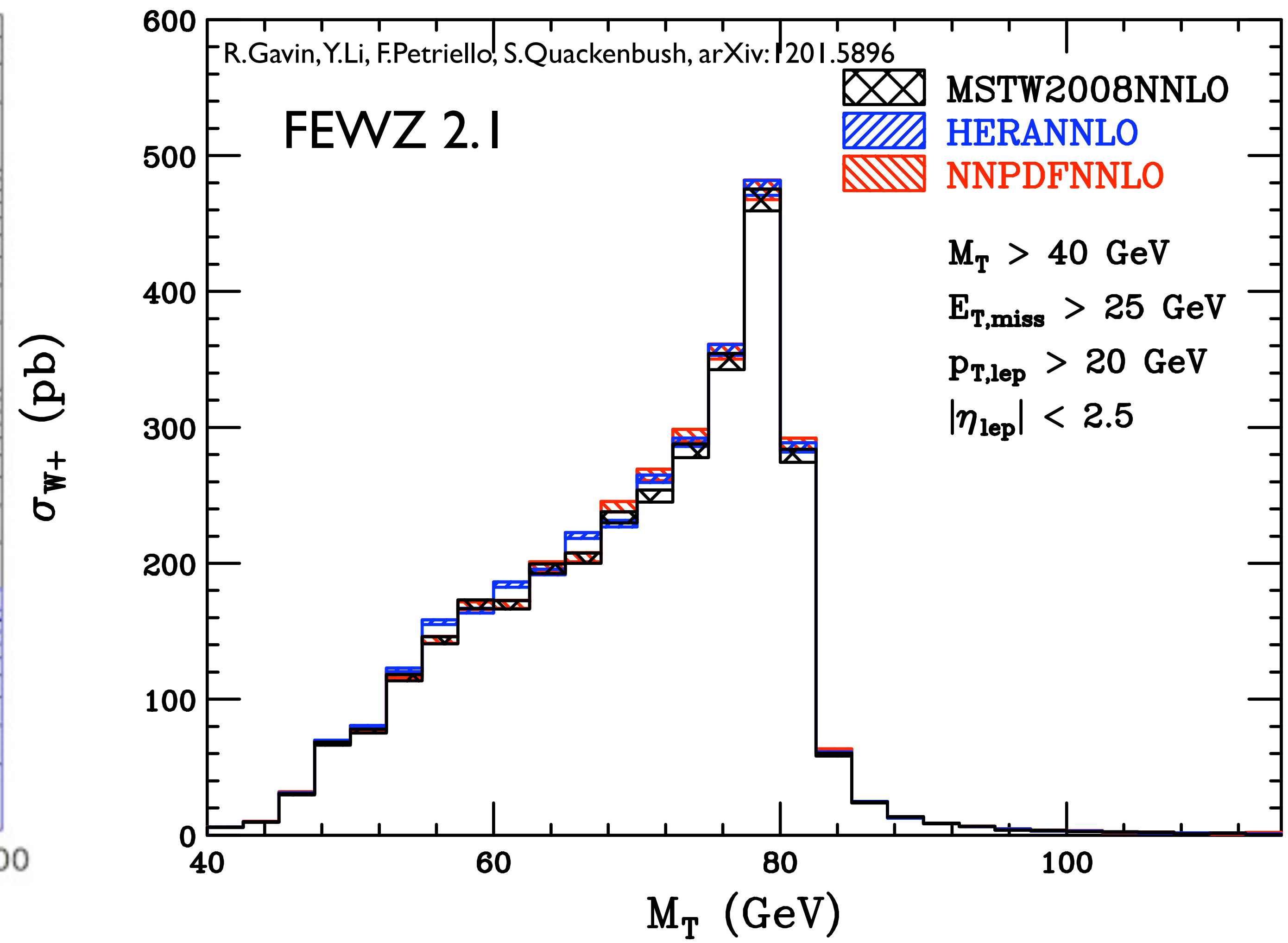
$$+ \boxed{\alpha \sigma_\alpha} + \alpha^2 \sigma_{\alpha^2} + \dots$$

WGRAD, DK, HORACE, SANC

$$+ \alpha\alpha_s\, \sigma_{\alpha\alpha_s} + \alpha\alpha_s^2\, \sigma_{\alpha\alpha_s^2} + \dots$$

Fixed order corrections exactly evaluated and available in simulation codes





Perturbative expansion of the Drell-Yan cross section

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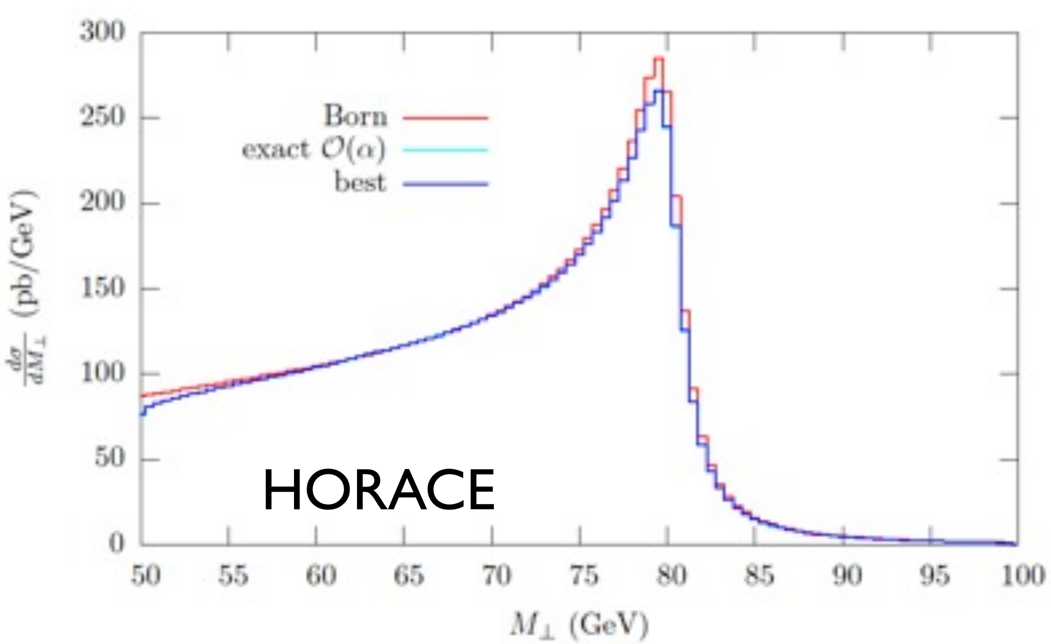
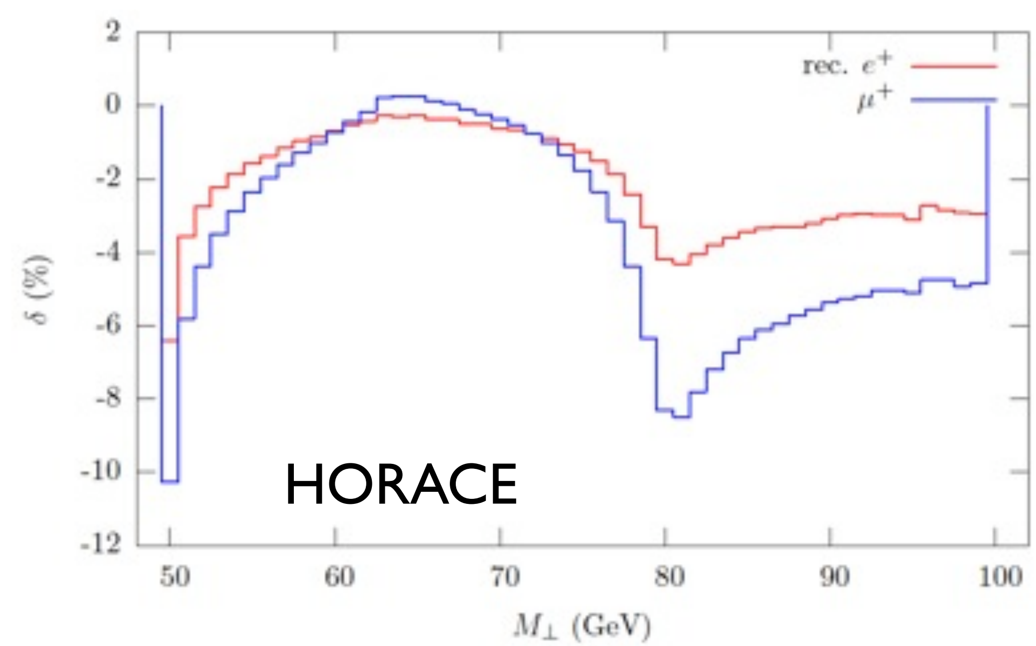




The change of the final state lepton distribution yields a huge shift in the extracted MW value

$$\Delta M_W^\alpha = 110 \text{ MeV}$$

Perturbative expansion of the Drell-Yan cross section

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

Fixed order corrections exactly evaluated and available in simulation codes

Subsets of corrections partially evaluated or approximated

$O(\alpha^2)$

- EW Sudakov logs J.Kühn, A.Kulesza, S.Pozzorini, M.Schulze, Nucl.Phys.B797:27-77,2008, Phys.Lett.B651:160-165,2007, Nucl.Phys.B727:368-394,2005.
- QED LL
- QED NLL (approximated)
- additional light pairs (approximated)

O(αα_s)

- EW corrections to ffbar+jet production
- QCD corrections to ffbar+gamma production

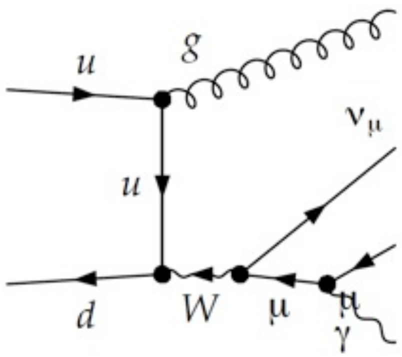
A.Denner, S.Dittmaier, T.Kasprzik, A.Mueck, arXiv:0909.3943, arXiv:1103.0914

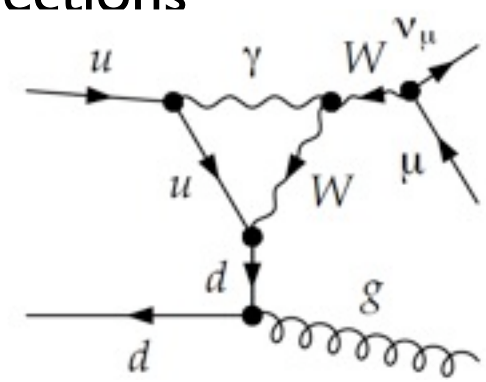
Mixed QCDxEW corrections the Drell-Yan cross section

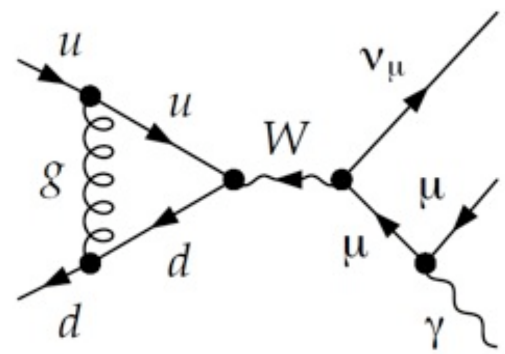
$$\begin{aligned}\sigma_{tot} &= \sigma_0 + \alpha_s\sigma_{\alpha_s} + \alpha_s^2\sigma_{\alpha_s^2} + \dots\\ &+ \alpha\sigma_\alpha + \alpha^2\sigma_{\alpha^2} + \dots\\ &+ \boxed{\alpha\alpha_s\,\sigma_{\alpha\alpha_s}} + \alpha\alpha_s^2\,\sigma_{\alpha\alpha_s^2} + \dots\end{aligned}$$

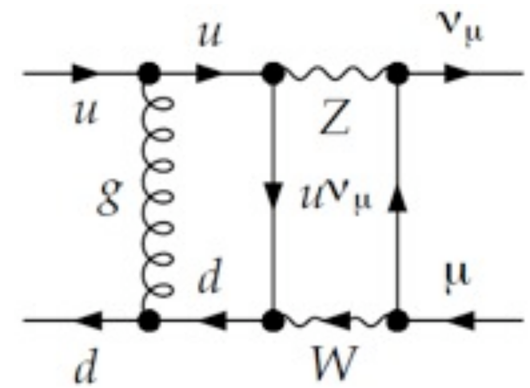
The first mixed QCDxEW corrections include different contributions:

- emission of two real additional partons (one photon + one gluon/quark)
- emission of one real additional parton (one photon with QCD virtual corrections, one gluon/quark with EW virtual corrections)
- two-loop virtual corrections







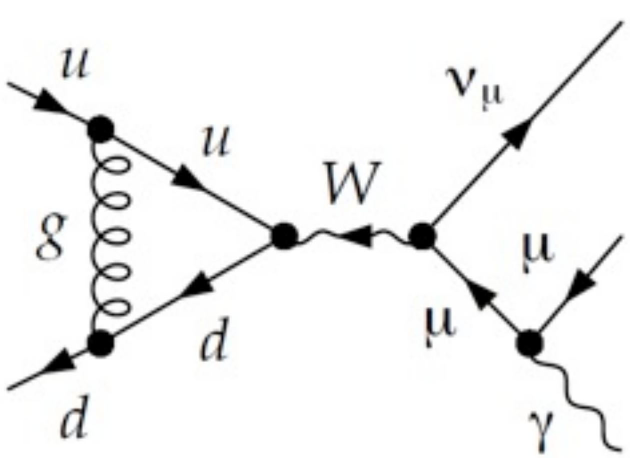


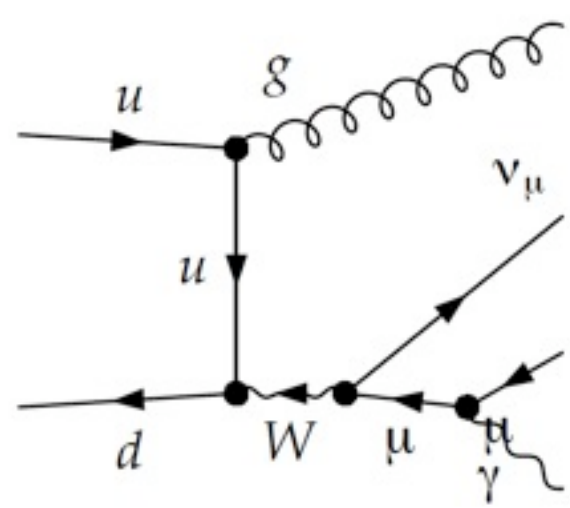
- an exact complete calculation is not yet available, neither for DY nor for single gauge boson production

W.B. Kilgore, C. Sturm, arXiv:1107.4798

The bulk of the mixed QCDxEW corrections, relevant for a precision MW measurement, is factorized in QCD and EW contributions:

(leading-log part of final state QED radiation) X (leading-log part of initial state QCD radiation || NLO-QCD contribution to the K-factor)





In any case, a fixed order description of the process is not sufficient...

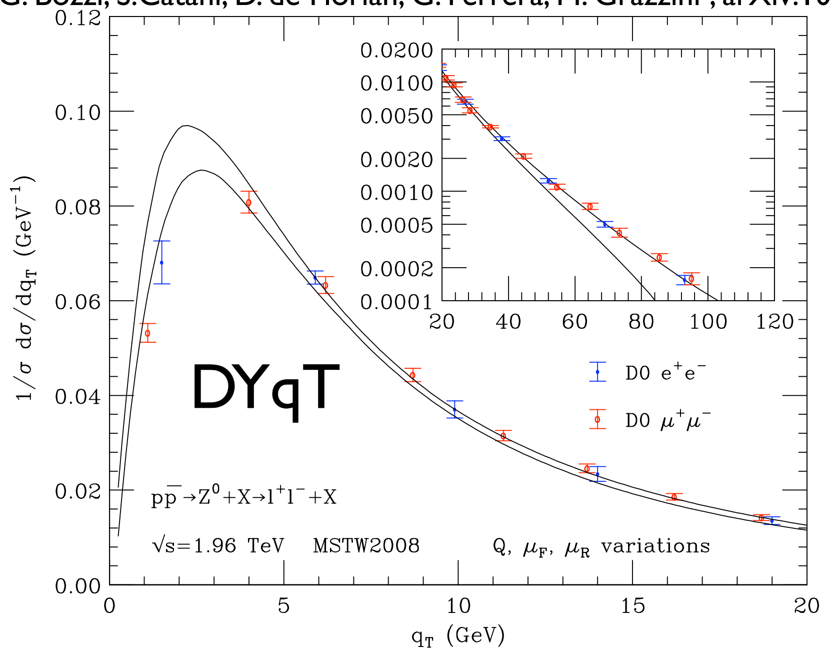
The relevance of multiple gluon/photon emission

numerical simulation of IS QCD multiple gluon emission via Parton Shower (Herwig, Pythia, Sherpa)

matching of NLO-QCD results with QCD Parton Shower (MC@NLO, POWHEG)

analytical resummation of initial state QCD multiple gluon emission (Resbos, DYqT)

G. Bozzi, S.Catani, D. de Florian, G. Ferrera, M. Grazzini , arXiv:1007.2351



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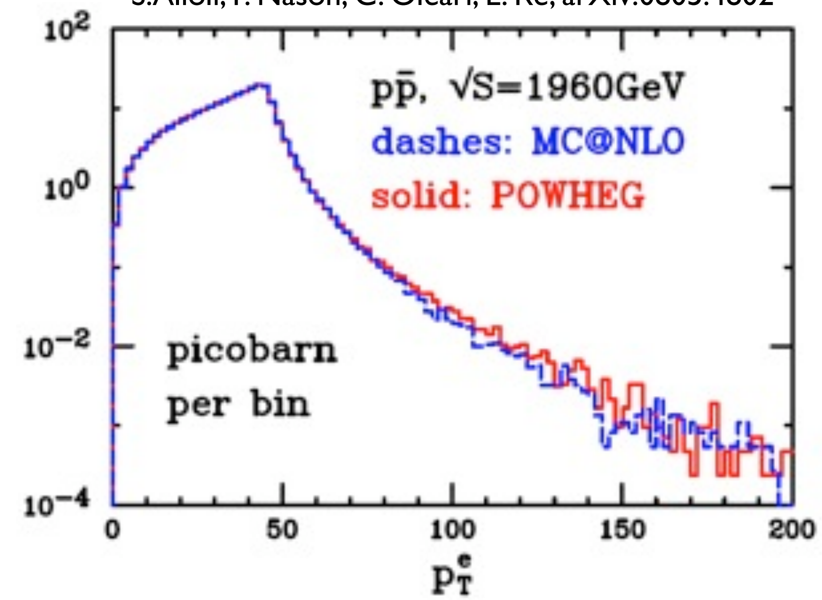

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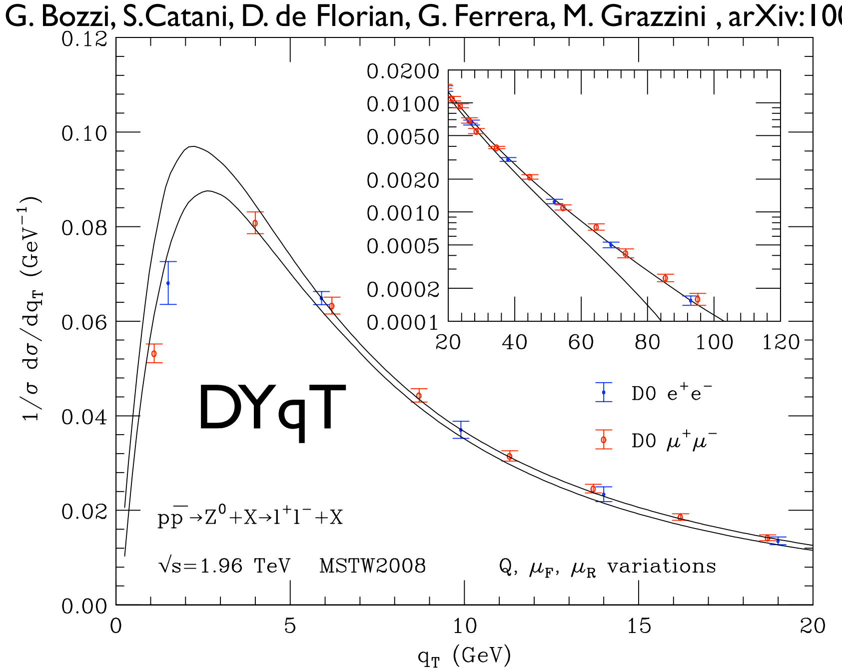

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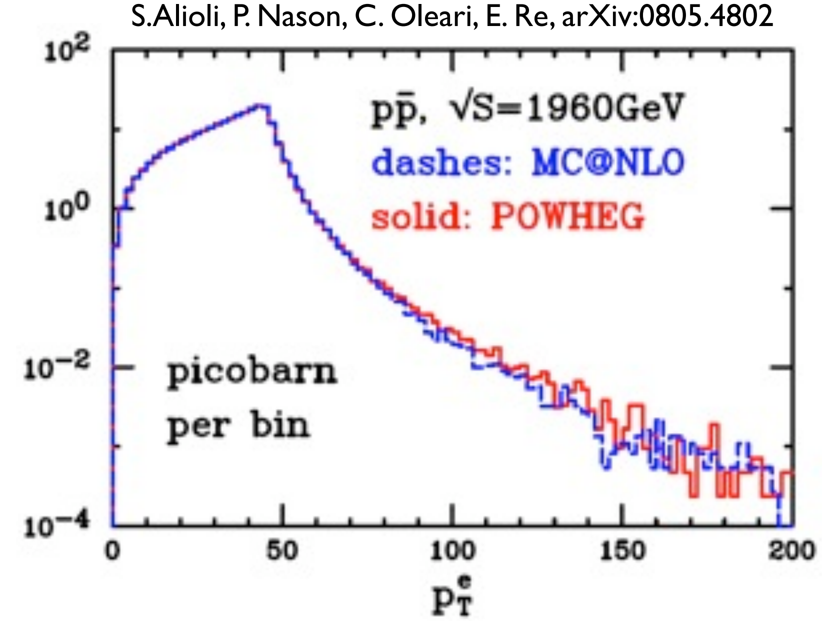
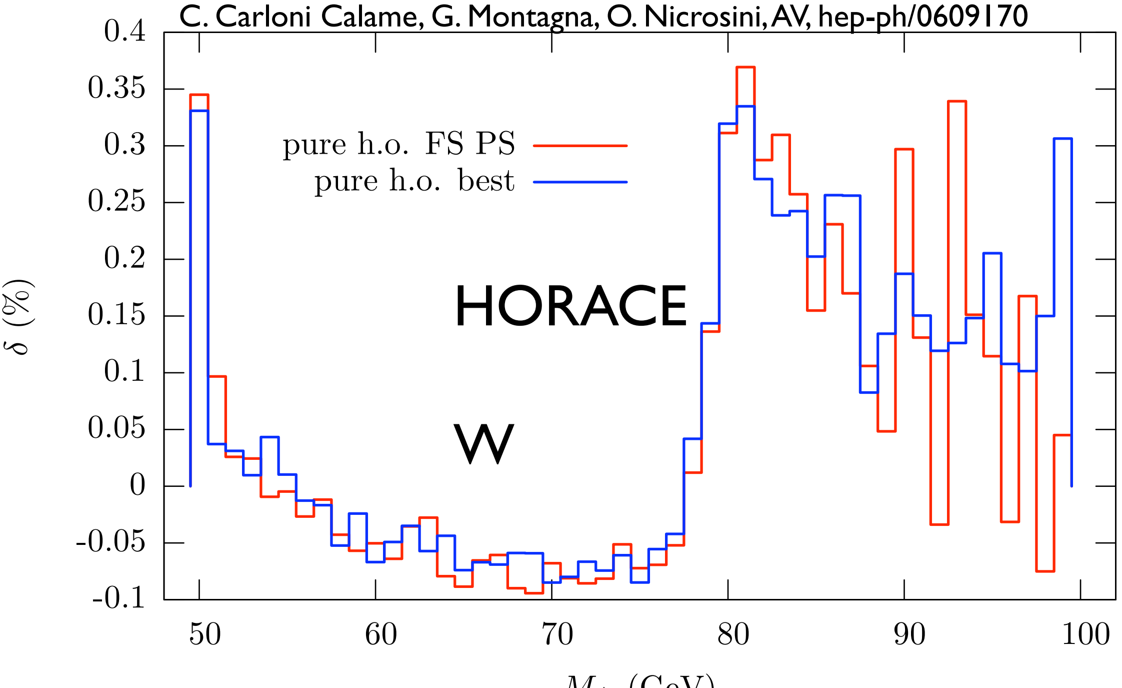


numerical simulation of final state QED multiple photon emission via Parton Shower (Photos, HORACE)

matching of NLO-EW results with complete QED Parton Shower (HORACE)

C. Carloni Calame, G. Montagna, O. Nicrosini, AV, hep-ph/0609170



Shift induced in the extraction of MW from higher order QED effects

$$\Delta M_W^{\alpha} = 110 \text{ MeV}$$

$$\Delta M_W^{exp} = -10 \text{ MeV}$$

Previous combinations of QCD and EW corrections to Drell-Yan

LL approximation in Shower MC

no tuned comparisons on these tools

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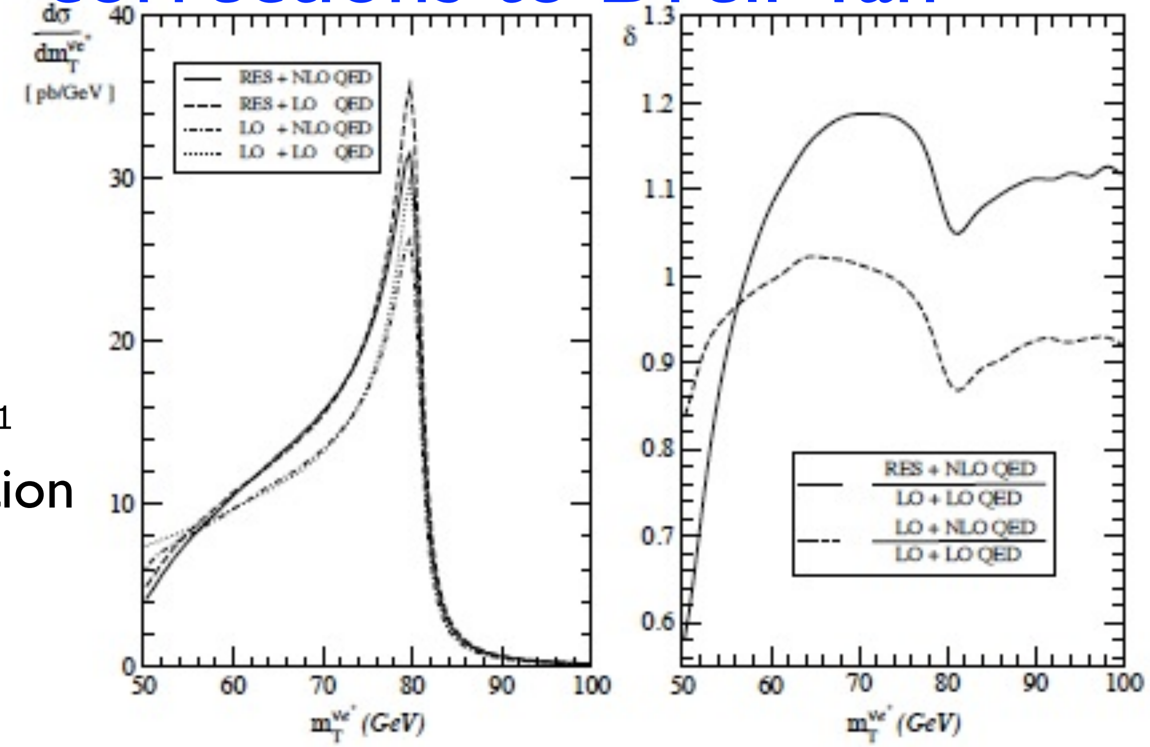
Resbos-A

Q.-H. Cao and C.-P. Yuan, Phys. Rev. Lett. **93** (2004) 042001

soft gluon resummation + NLO final state QED radiation



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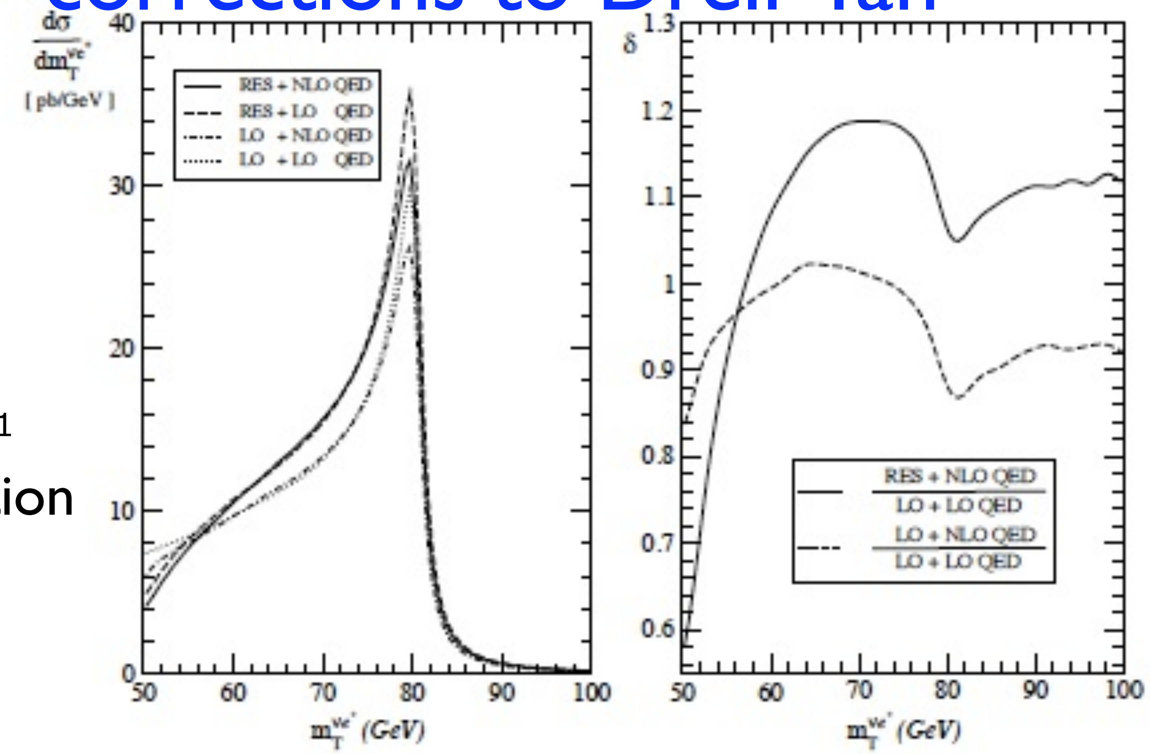

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factorized prescription

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{QCD\otimes EW} = \left(1+\frac{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{MC@NLO}-\left[\frac{d\sigma}{d\mathcal{O}}\right]_{HERWIG\ PS}}{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{LO/NLO}}\right)\times\left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{EW}\right\}_{HERWIG\ PS}$$

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$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{QCD\oplus EW} = \left\{\frac{d\sigma}{d\mathcal{O}}\right\}_{QCD} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{EW} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{Born}\right\}_{HERWIG\ PS}$$

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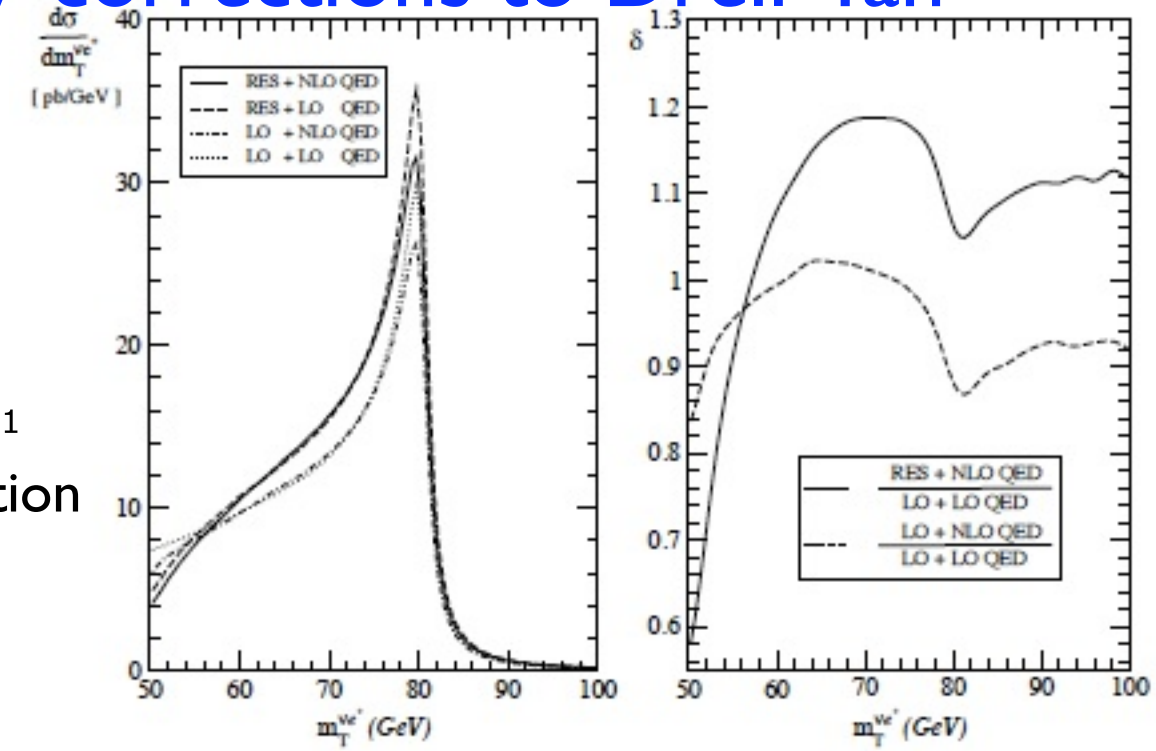

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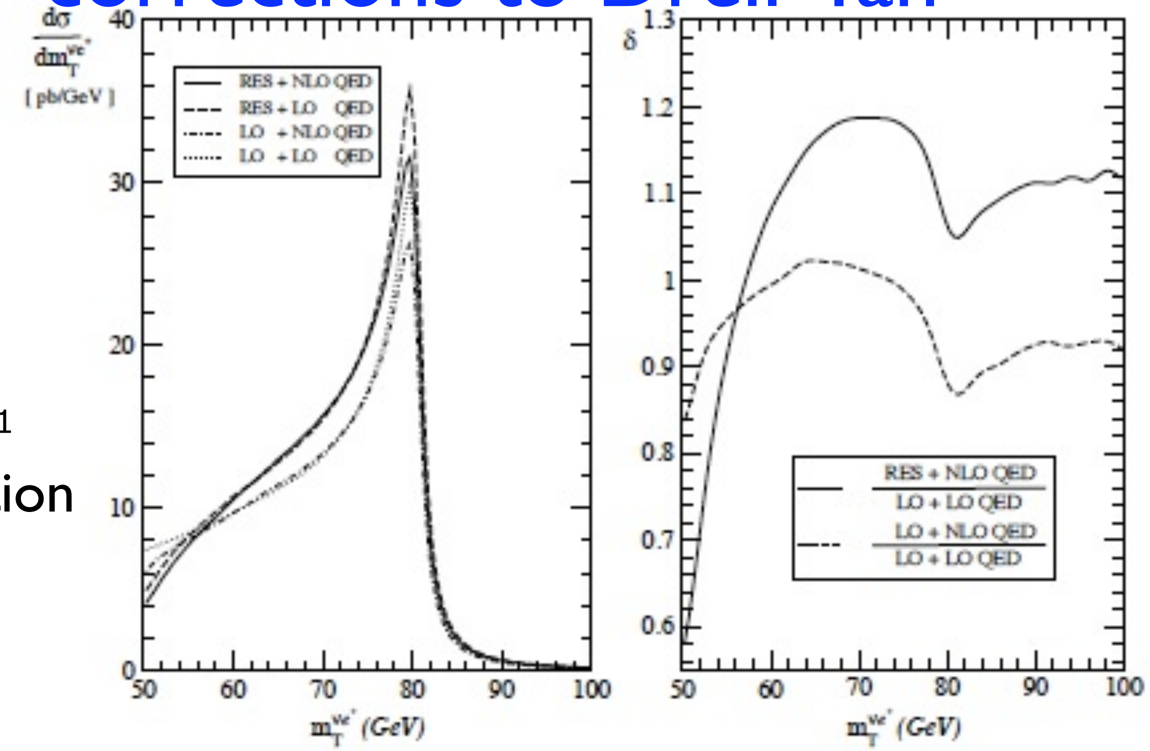

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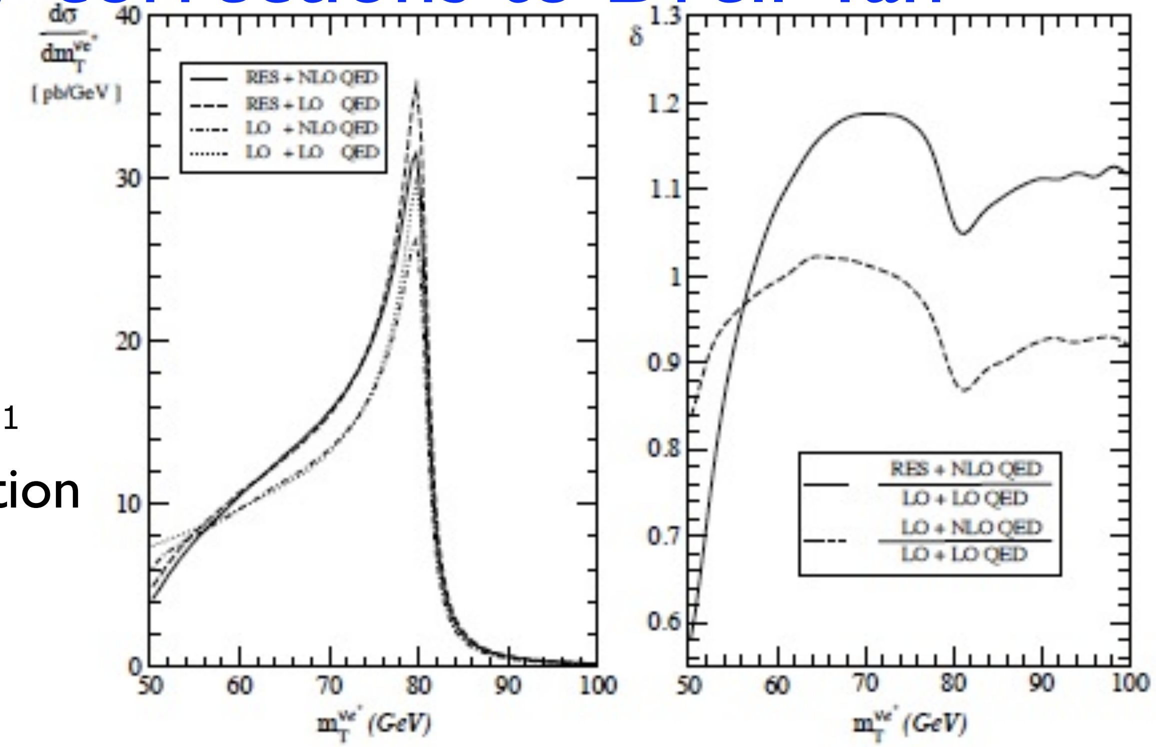

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The POWHEG method (Nason 2004, Frixione Nason Oleari 2007, Alioli Nason Oleari Re 2009)

matching NLO-QCD matrix elements with QCD Parton Shower

- avoiding double counting between the first emission (hard matrix element) and the PS radiation
- generating positive weight events
- independent of the details of the (vetoed) shower adopted

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

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- NLO-(QCD+EW) accuracy of the total cross section: inclusion of virtual corrections,
  integral over the whole phase space of (subtracted) real matrix element

$$\bar{B}^{f_b}(\Phi_n) = \left[B(\Phi_n) + V(\Phi_n) \right]_{f_b} + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \int \left[\theta\left(k_T(\Phi_{n+1}) - p_T\right)\, R(\Phi_{n+1}) \right]_{\alpha_r}^{\bar{\Phi}_n^{\alpha_r} = \Phi_n} d\Phi_{rad}$$
$$+ \sum_{\alpha_\oplus \in \{\alpha_\oplus | f_b\}} \int \frac{dz}{z}\, G_\oplus^{\alpha_\oplus}(\Phi_{n,\oplus}) + \sum_{\alpha_\ominus \in \{\alpha_\ominus | f_b\}} \int \frac{dz}{z}\, G_\ominus^{\alpha_\ominus}(\Phi_{n,\ominus})$$

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- (N)LO-(QCD+QED) accuracy of the real emission probability: exact real matrix elements,

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

- NLO-(QCD+EW) accuracy of the total cross section: inclusion of virtual corrections,
integral over the whole phase space of (subtracted) real matrix element

$$\bar{B}^{f_b}(\Phi_n) = \left[B(\Phi_n) + V(\Phi_n) \right]_{f_b} + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \int \left[\theta\left(k_T(\Phi_{n+1}) - p_T\right)\ R(\Phi_{n+1}) \right]_{\alpha_r}^{\bar{\Phi}_n^{\alpha_r} = \Phi_n} d\Phi_{rad}$$
$$+ \sum_{\alpha_\oplus \in \{\alpha_\oplus | f_b\}} \int \frac{dz}{z}\ G_\oplus^{\alpha_\oplus}(\Phi_{n,\oplus}) + \sum_{\alpha_\ominus \in \{\alpha_\ominus | f_b\}} \int \frac{dz}{z}\ G_\ominus^{\alpha_\ominus}(\Phi_{n,\ominus})$$

- (N)LO-(QCD+QED) accuracy of the real emission probability: exact real matrix elements,
are used also in the Sudakov form factor (instead of the collinear splitting function)

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

The POWHEG method (Nason 2004, Frixione Nason Oleari 2007, Alioli Nason Oleari Re 2009)

matching NLO-QCD matrix elements with QCD Parton Shower

- avoiding double counting between the first emission (hard matrix element) and the PS radiation
- generating positive weight events
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- The curly bracket, integrated over the whole phase space, is equal to 1 :
  the NLO accuracy of the total cross section is preserved

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- The curly bracket, integrated over the whole phase space, is equal to 1 :
  the NLO accuracy of the total cross section is preserved

- The POWHEG (first) emission is by construction the hardest:
  HERWIG/PYTHIA are bound to radiate partons with lower virtuality (transverse momentum)

Inclusion in POWHEG of the exact O(α) corrections (NLO-EW)

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

- the final state may contain 0 or 1 additional partons
  the parton can be 1 gluon or 1 photon (qqbar subprocess) or 1 quark (qg subprocess)

- the virtuality (transverse momentum) of the emitted parton sets the largest virtuality that the Parton Shower can reach

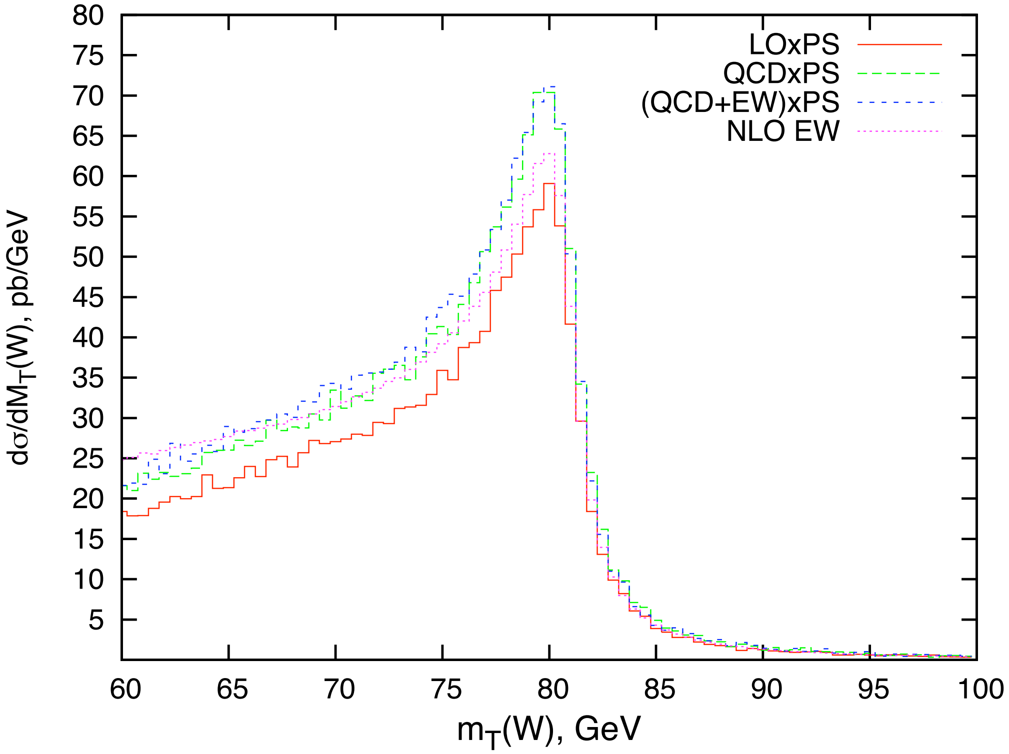
- the Parton Shower can be a pure QCD shower (BW) or a mixed QCD/QED shower (BMNNP)

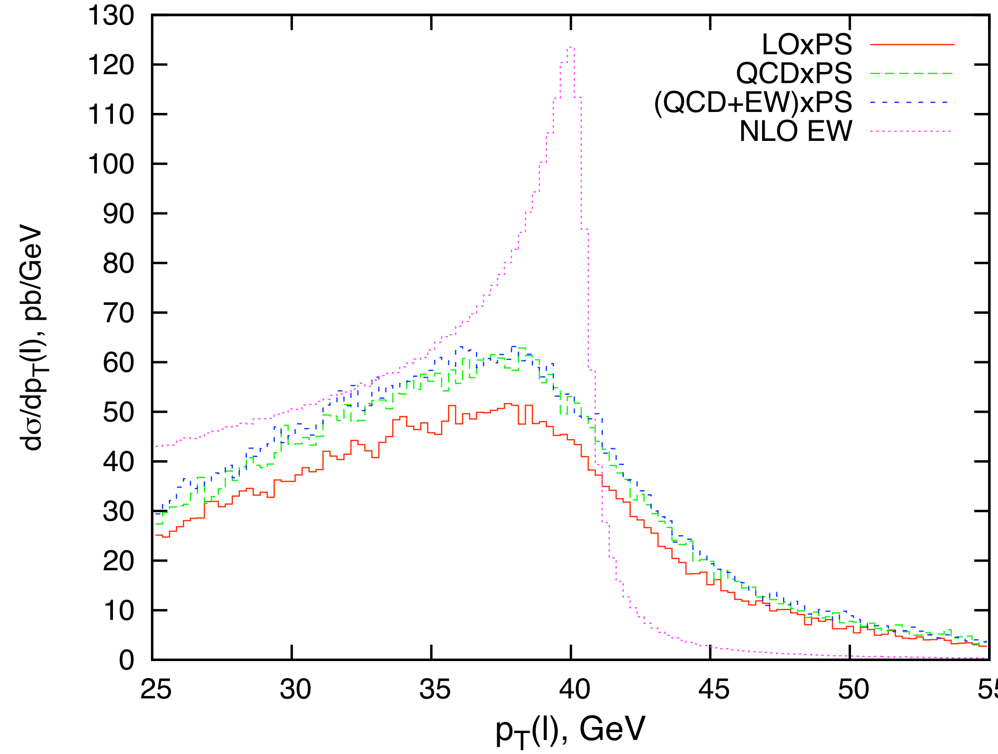
- the process has three regions of collinear singularity, associated to the emission of
  one final state photon, one initial state photon, one initial state gluon/quark
  the Sudakov form factor is given by the product of the three individual form factors, for the three regions of collinearity

- the soft/collinear divergences have been regularized
  by phase-space slicing and final state lepton masses (BW) or
  in a mixed scheme using dimensional regularization to treat the quark and photon singularities
  and the lepton mass as natural cut-off of the final state mass singularities (BMNNP)

- the virtual corrections have been implemented according to the WGRAD results (BW)
  or reproducing independently the HORACE results (BMNNP) with the option of working in the complex mass scheme

BW results Bernaciak, Wackeroth, arXiv:1201.4804 LHC muon bare





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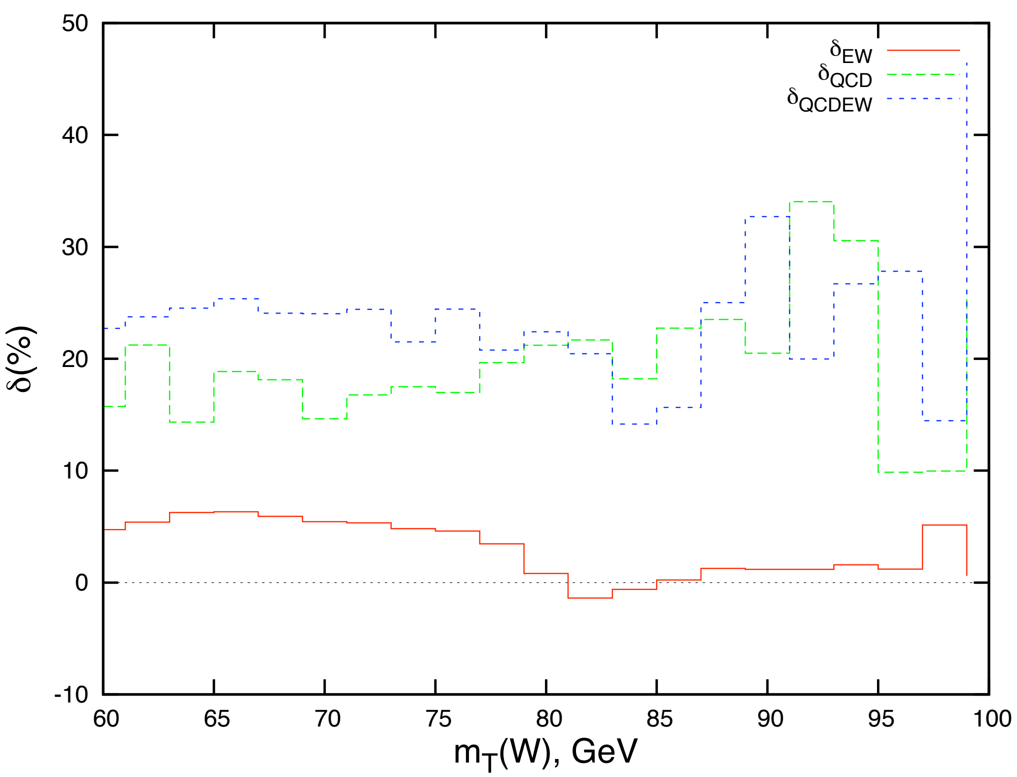

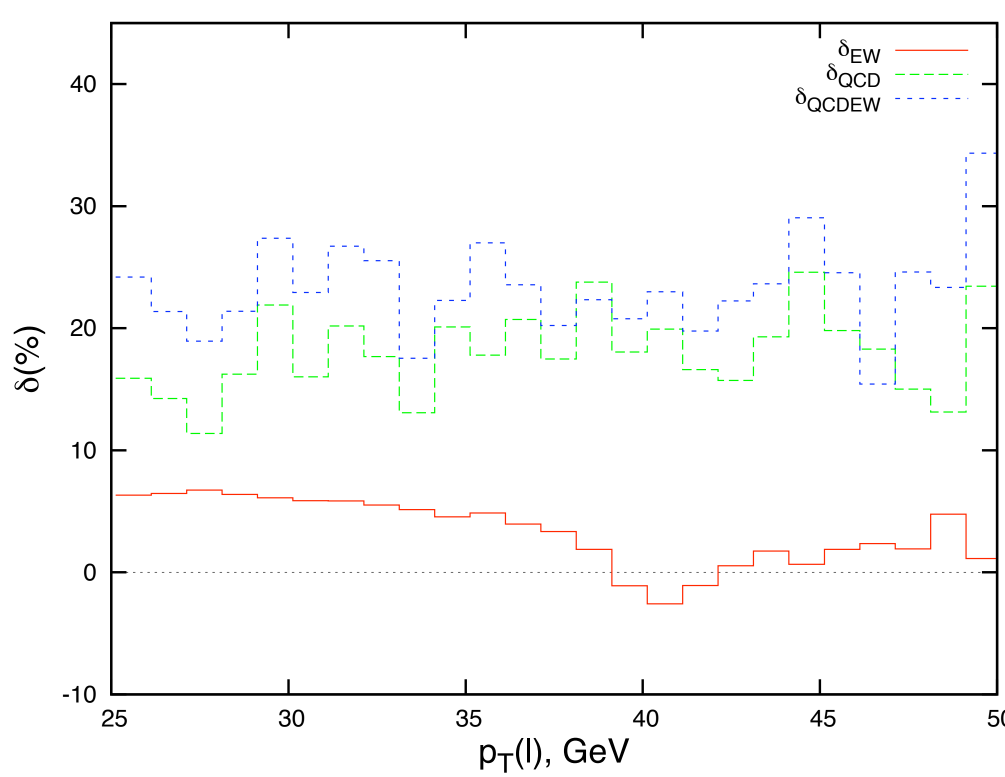

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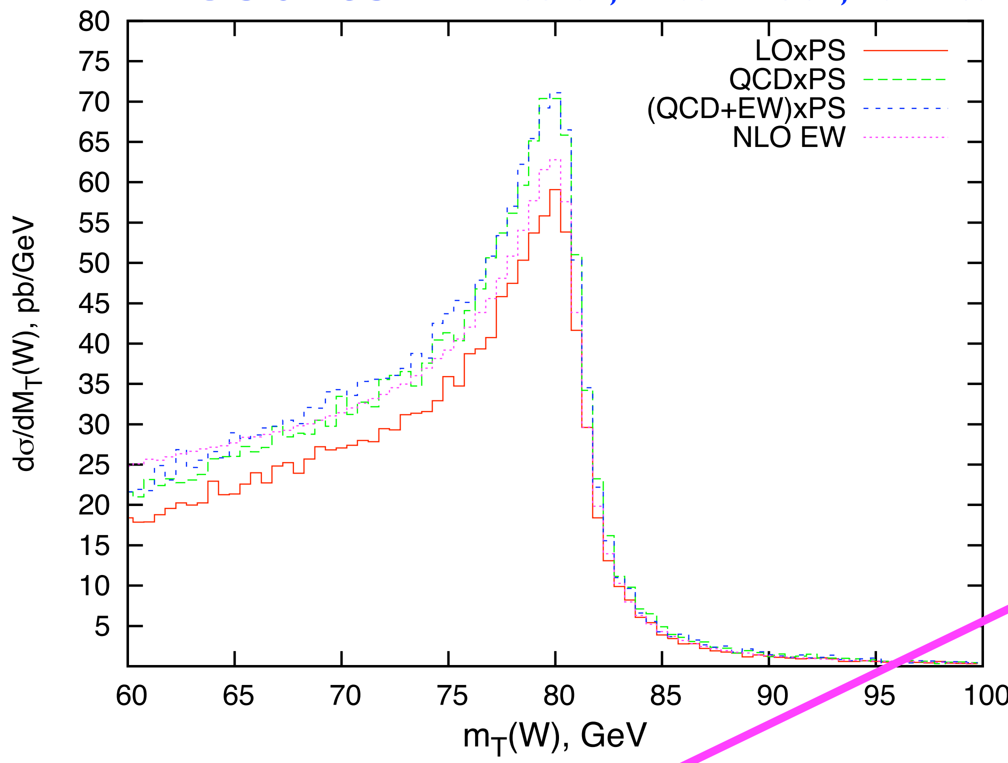

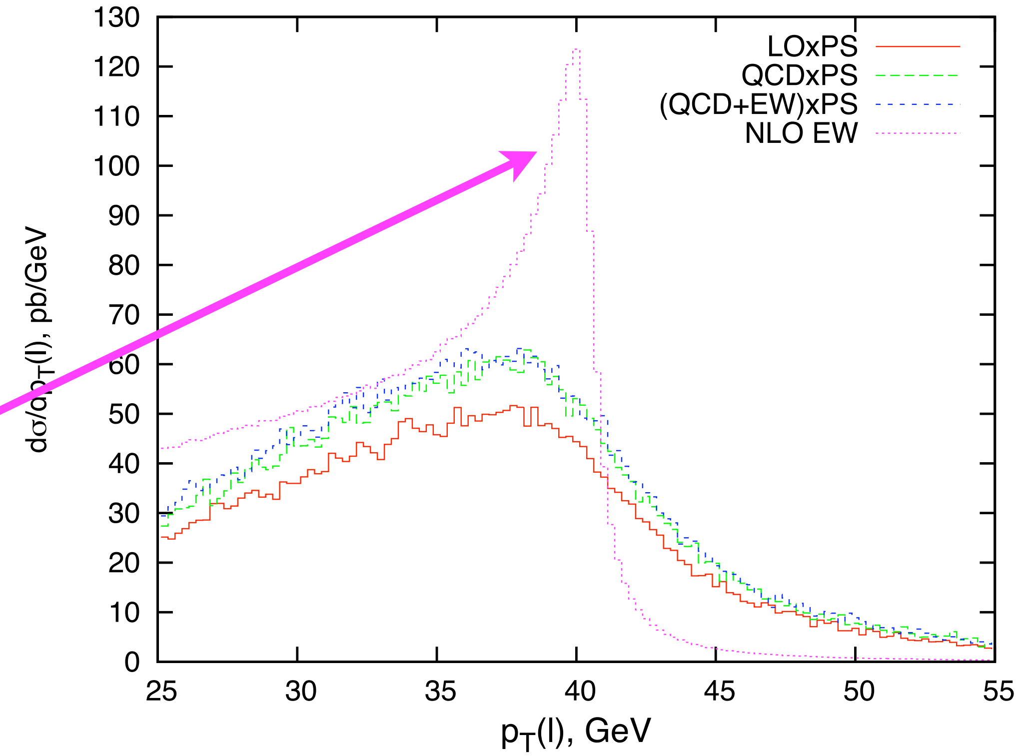

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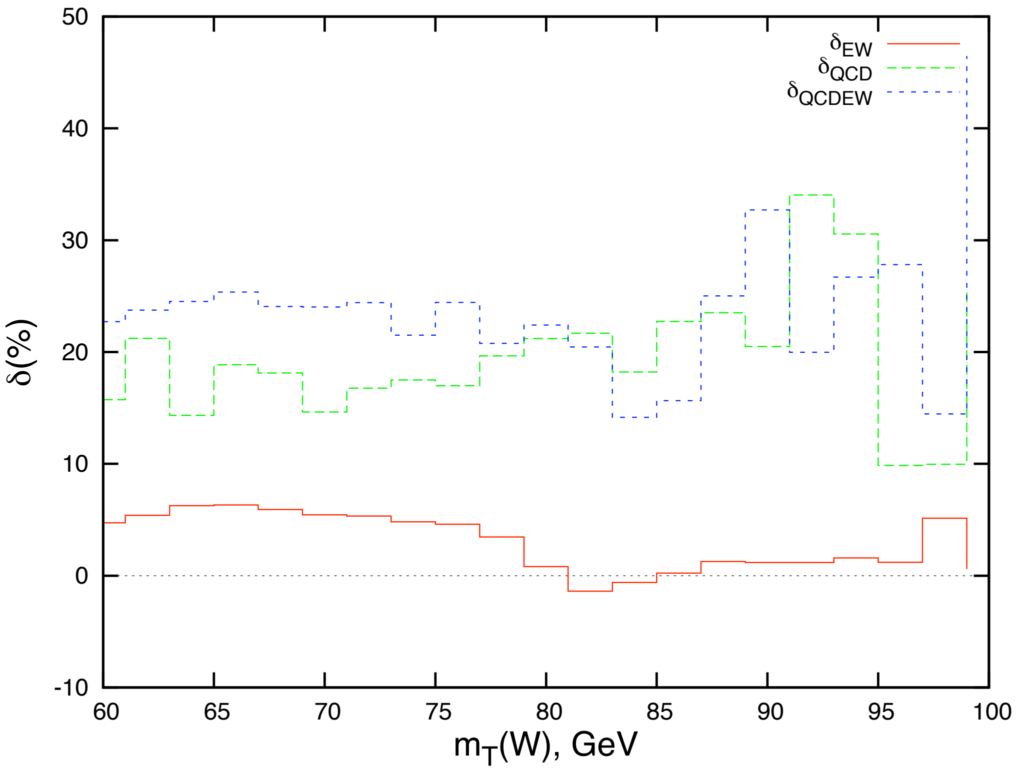

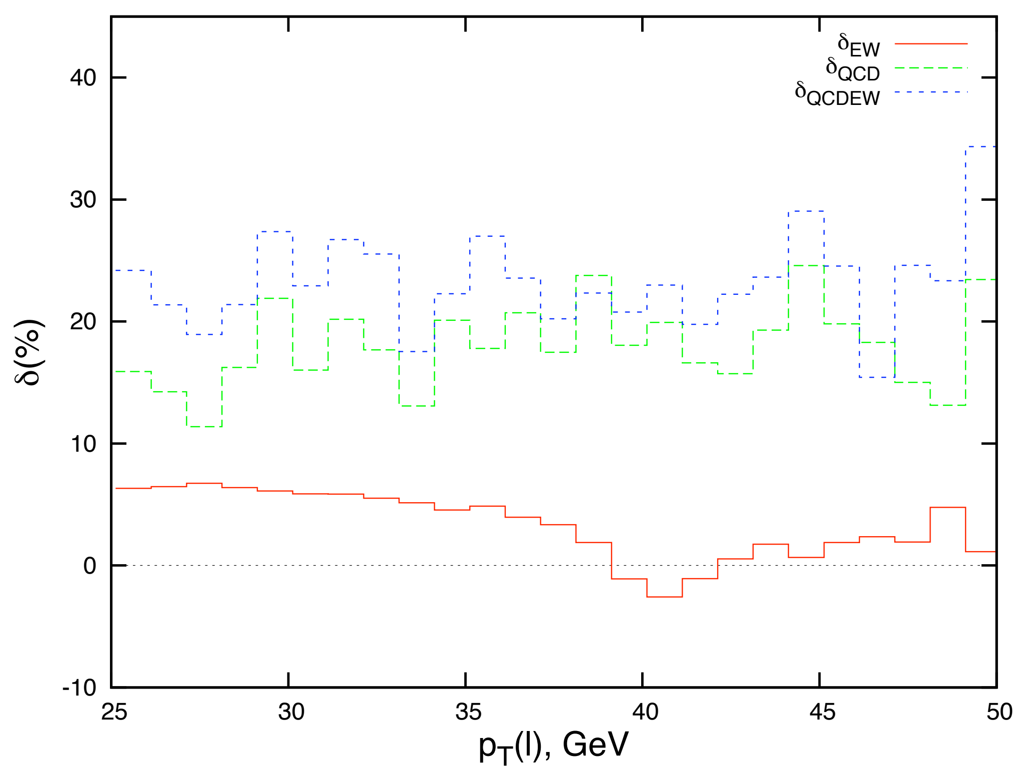

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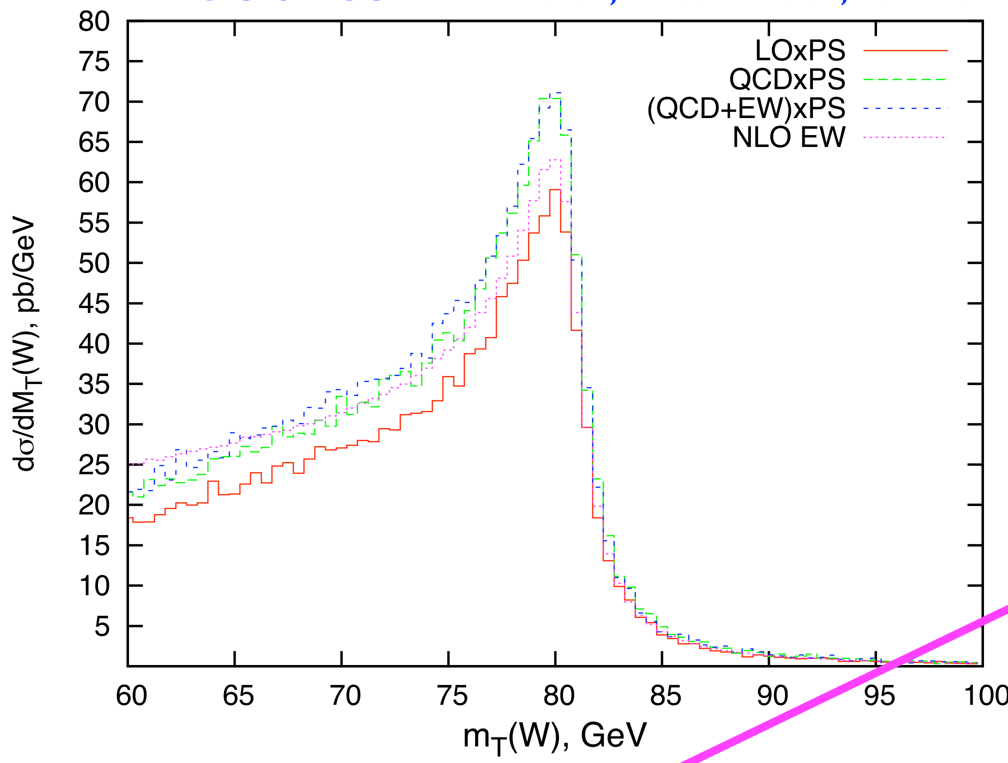

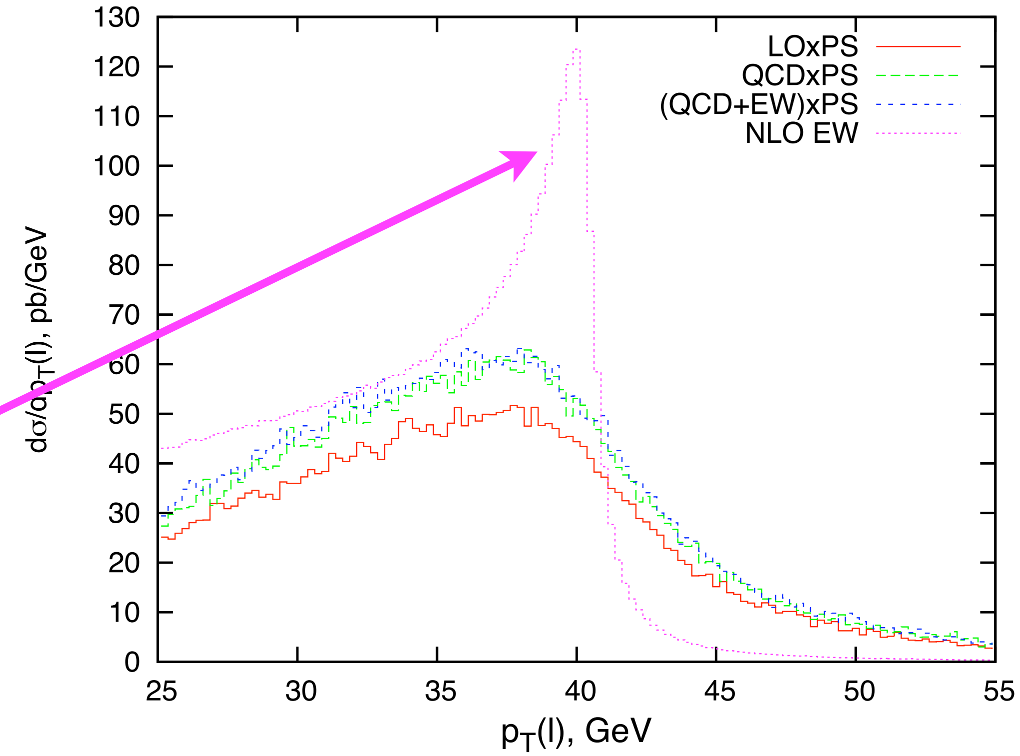

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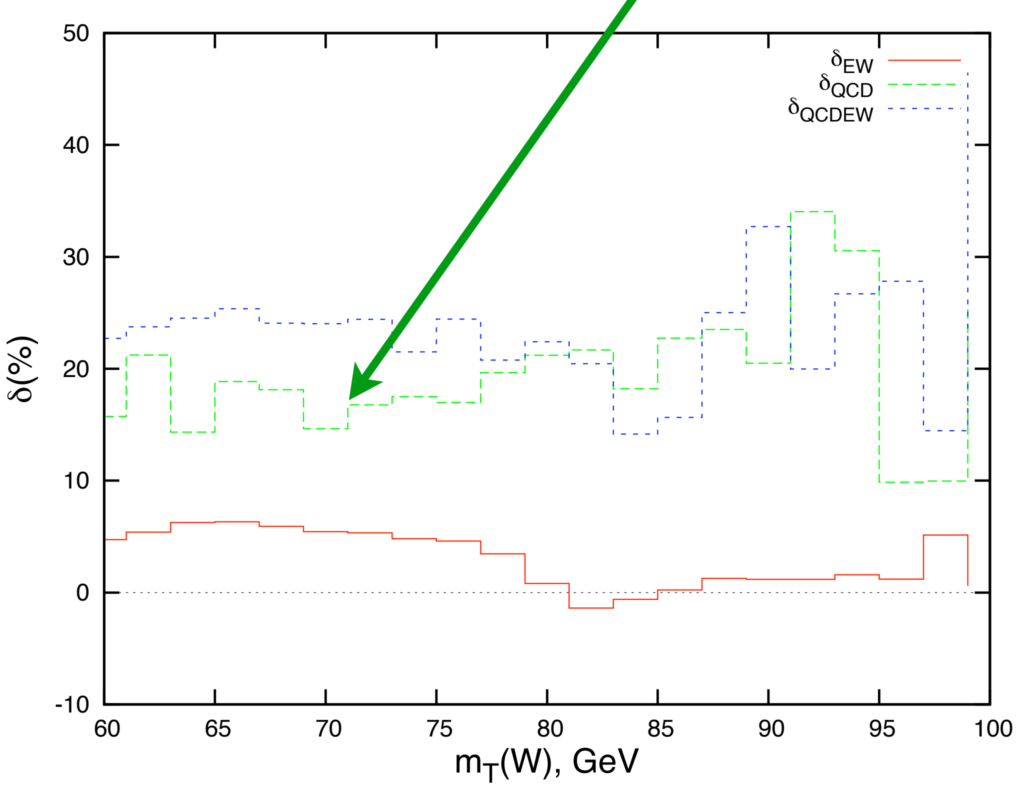

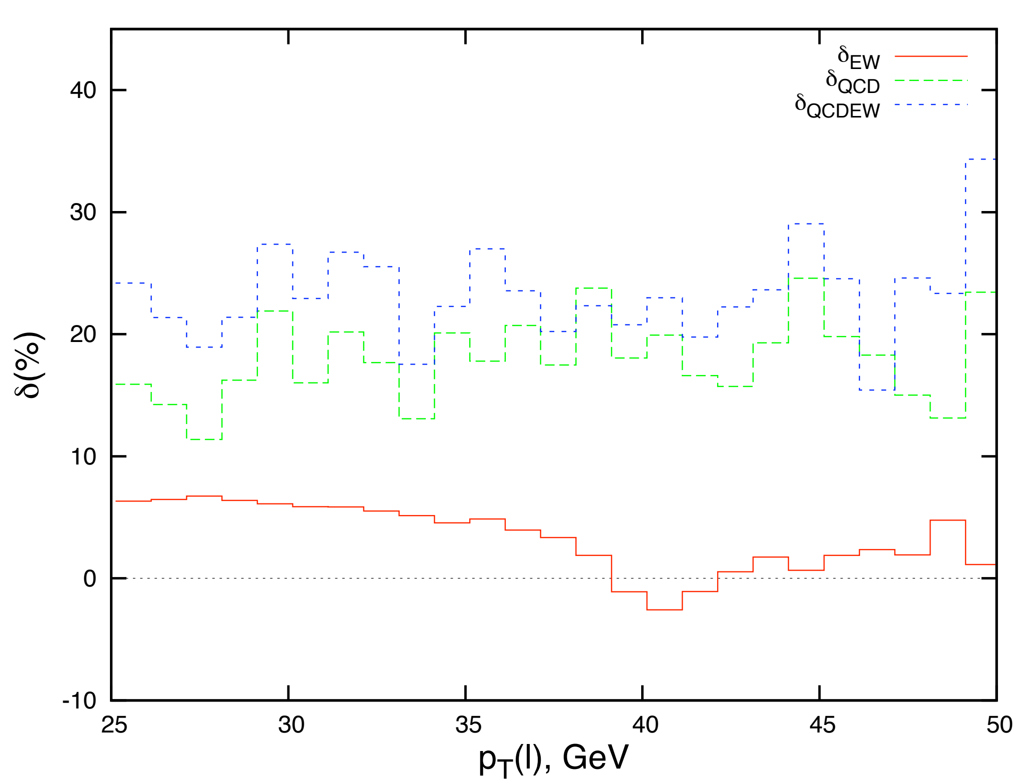

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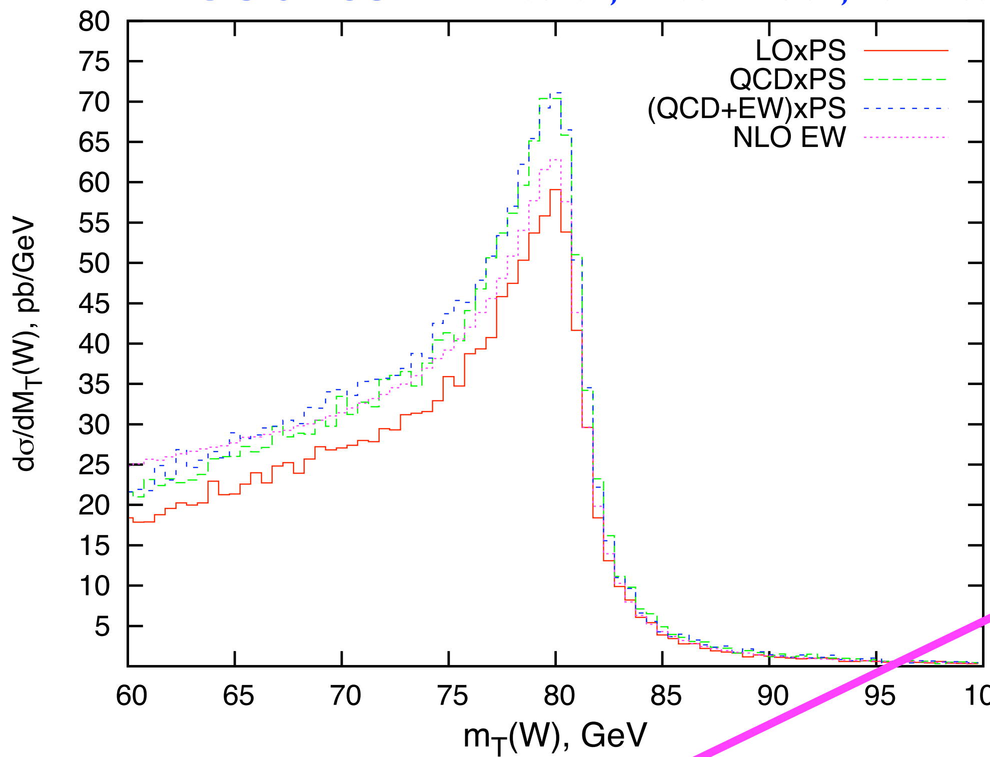

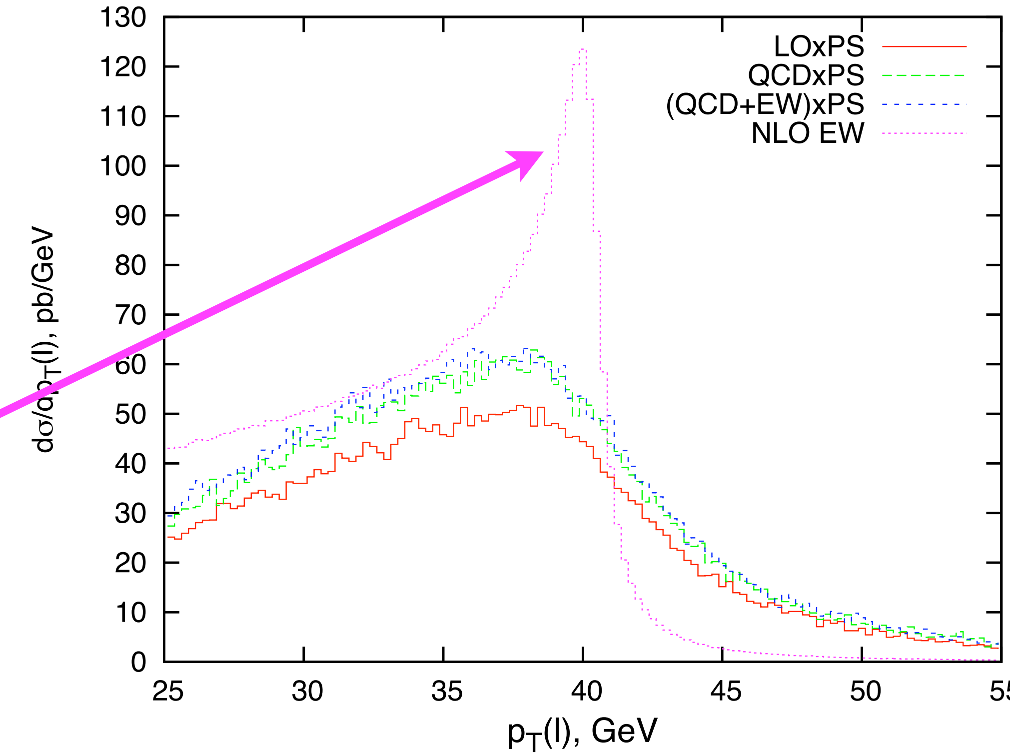

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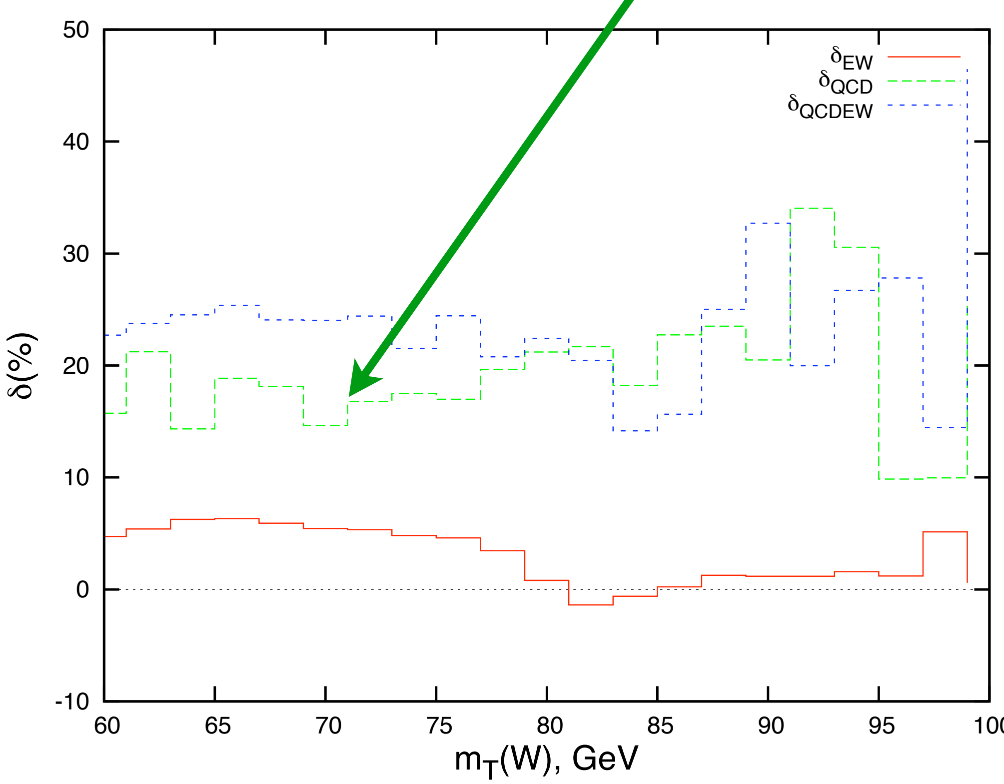
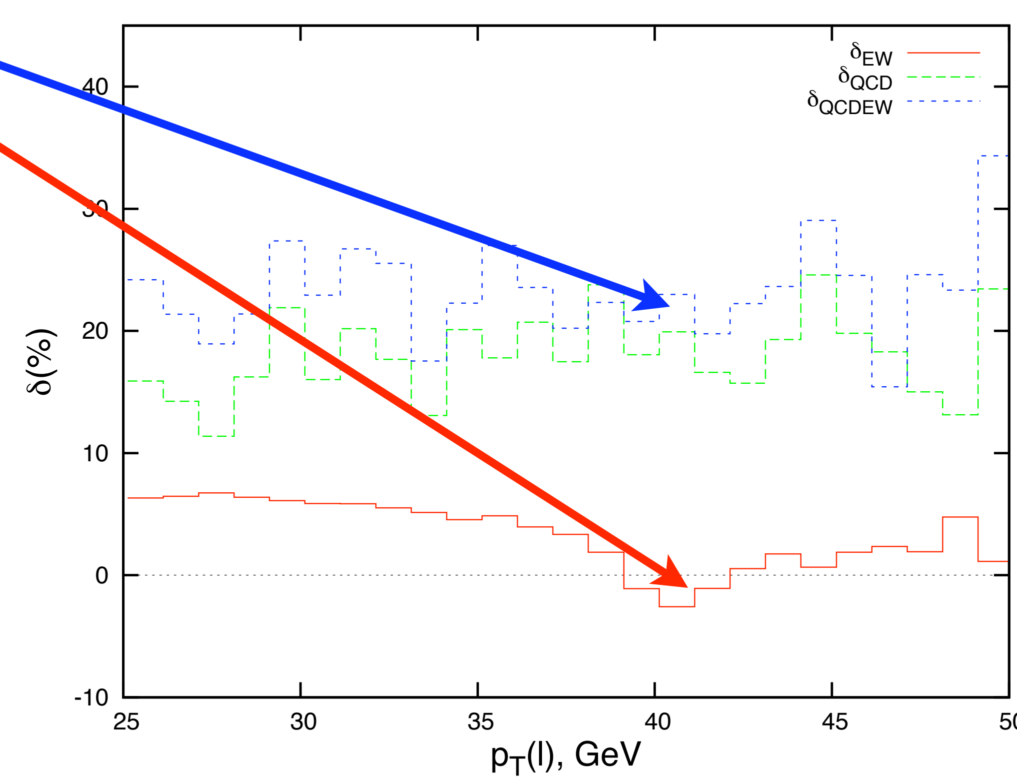
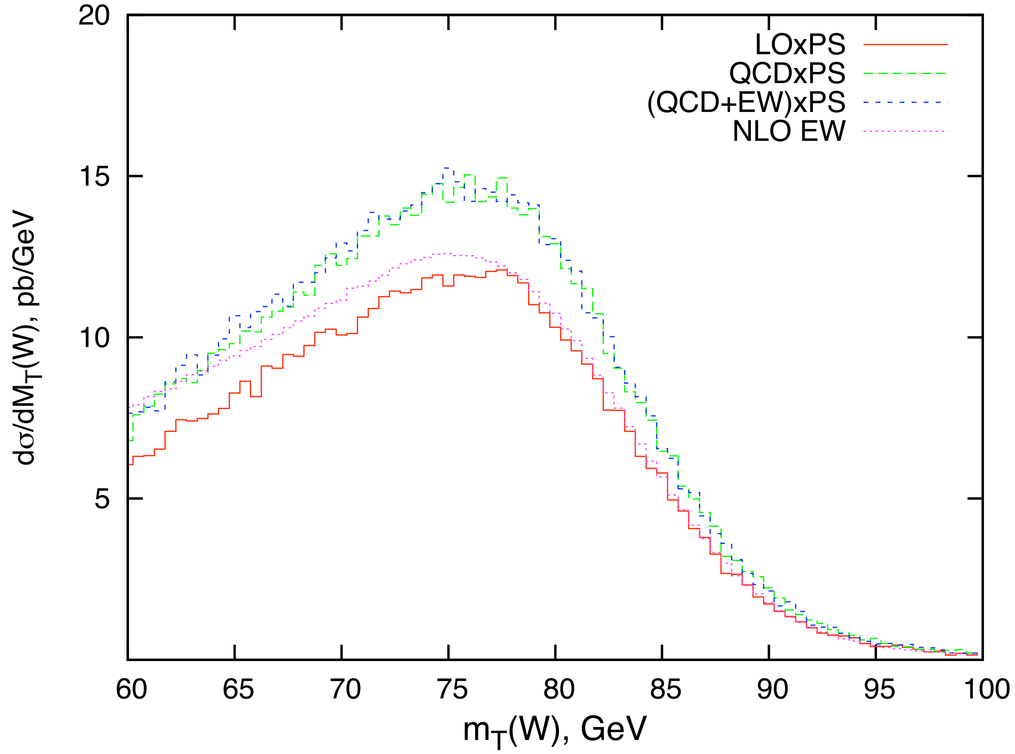
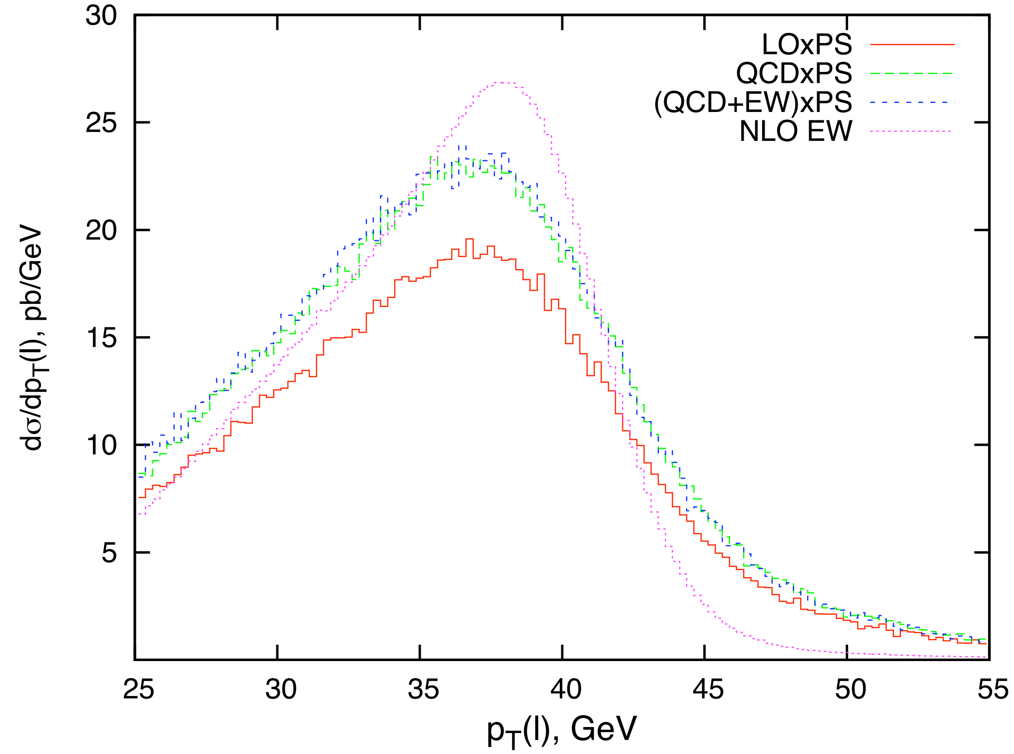




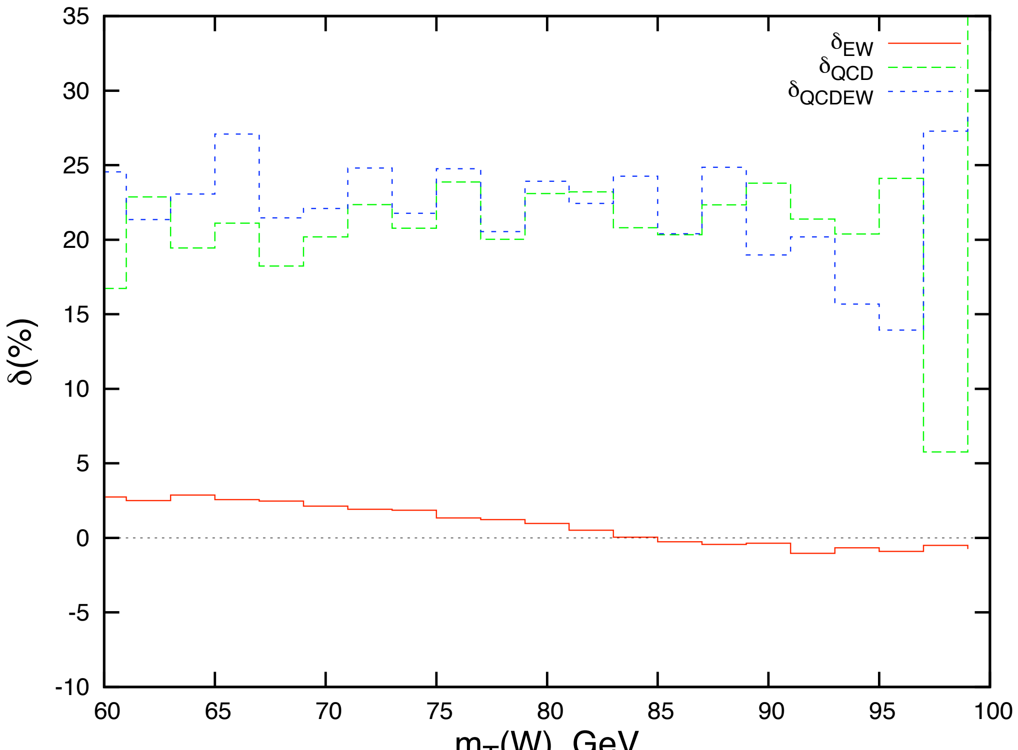
BW results Bernaciak, Wackeroth, arXiv:1201.4804

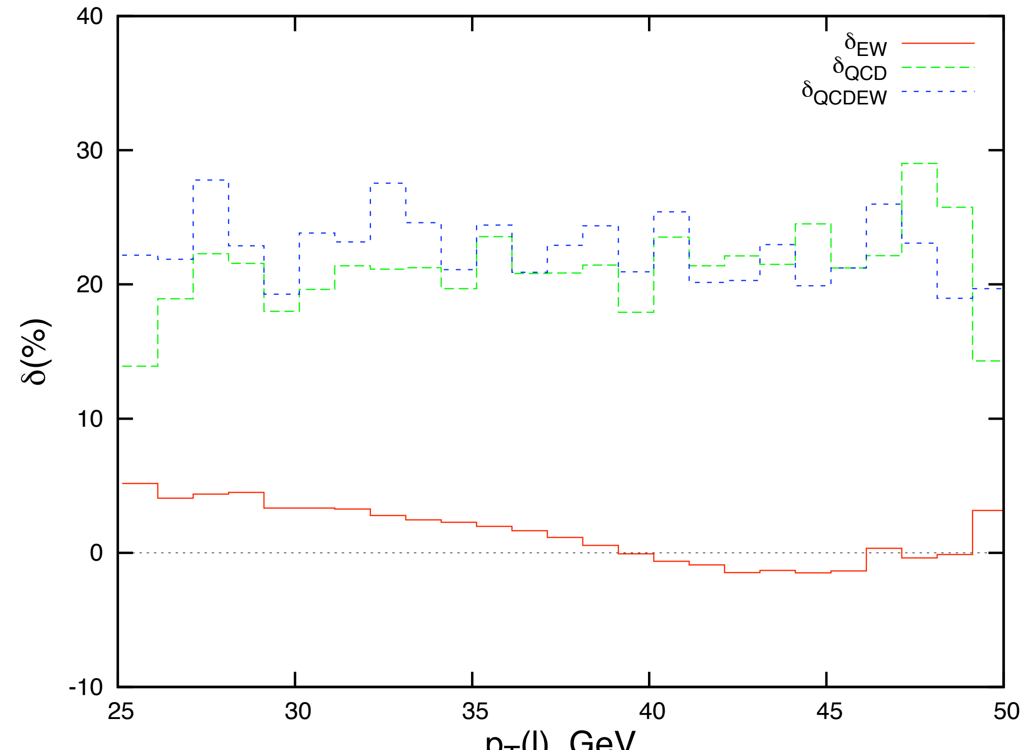
Tevatron muon calo





- the NLO-EW curves do NOT include the QCD Parton Shower (δ is relative to pure LO)
- the calorimetric effects smear the peaked shape of the lepton transverse momentum (BEFORE QCD showering)
- despite the statistical fluctuations, it is possible to recognize that EW effects are preserved also after showering





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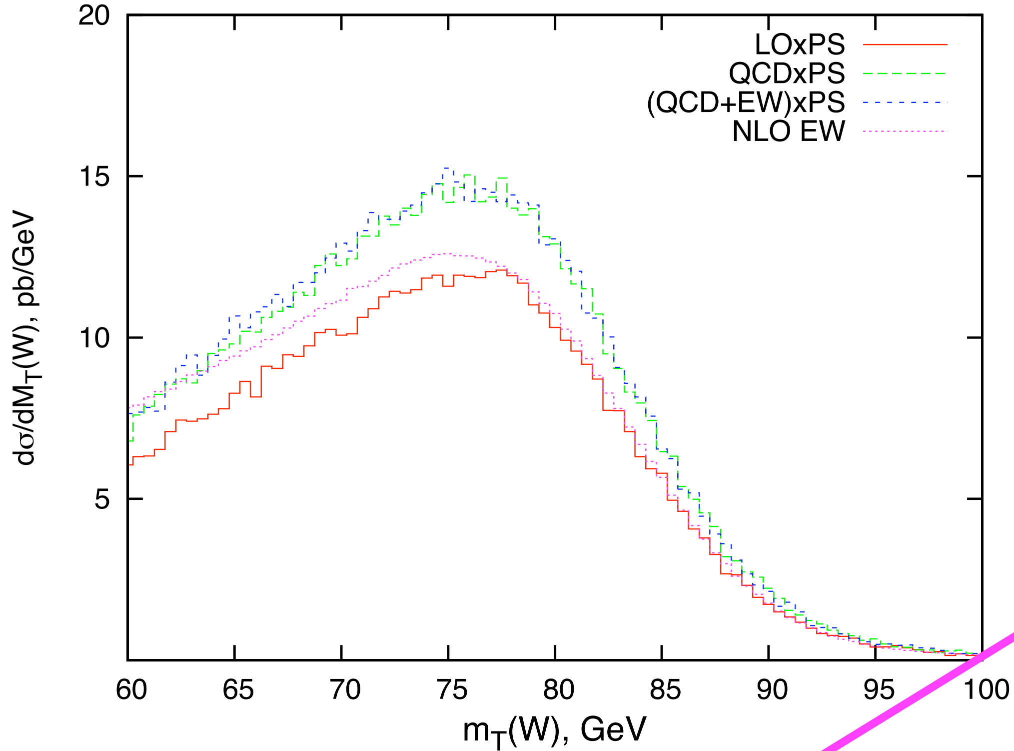

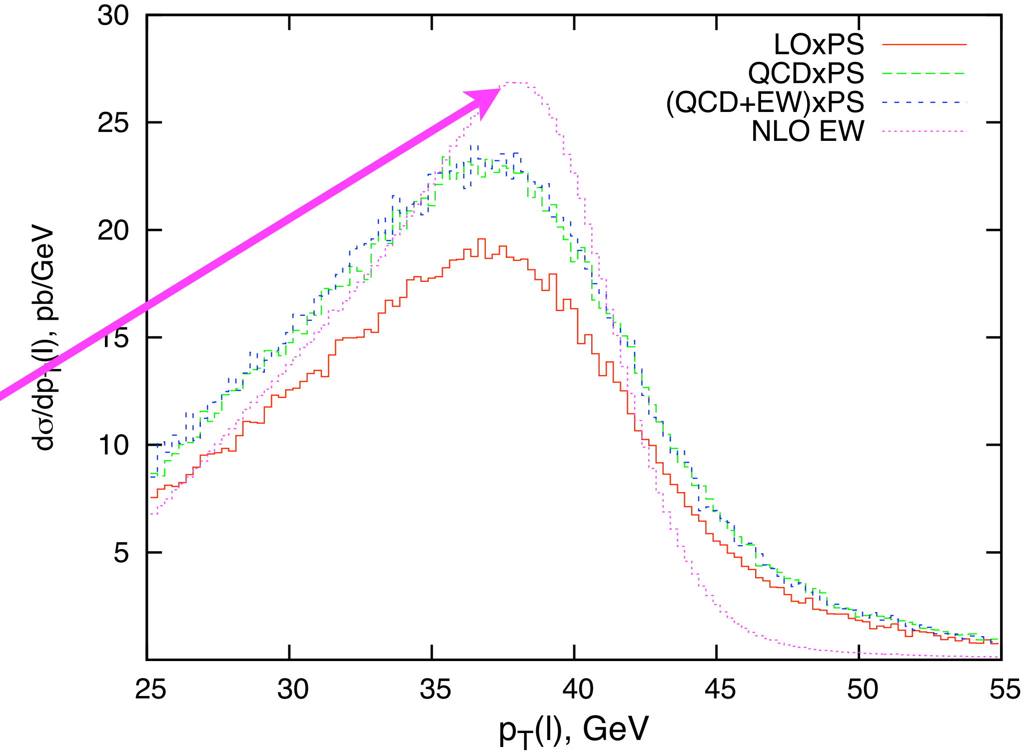

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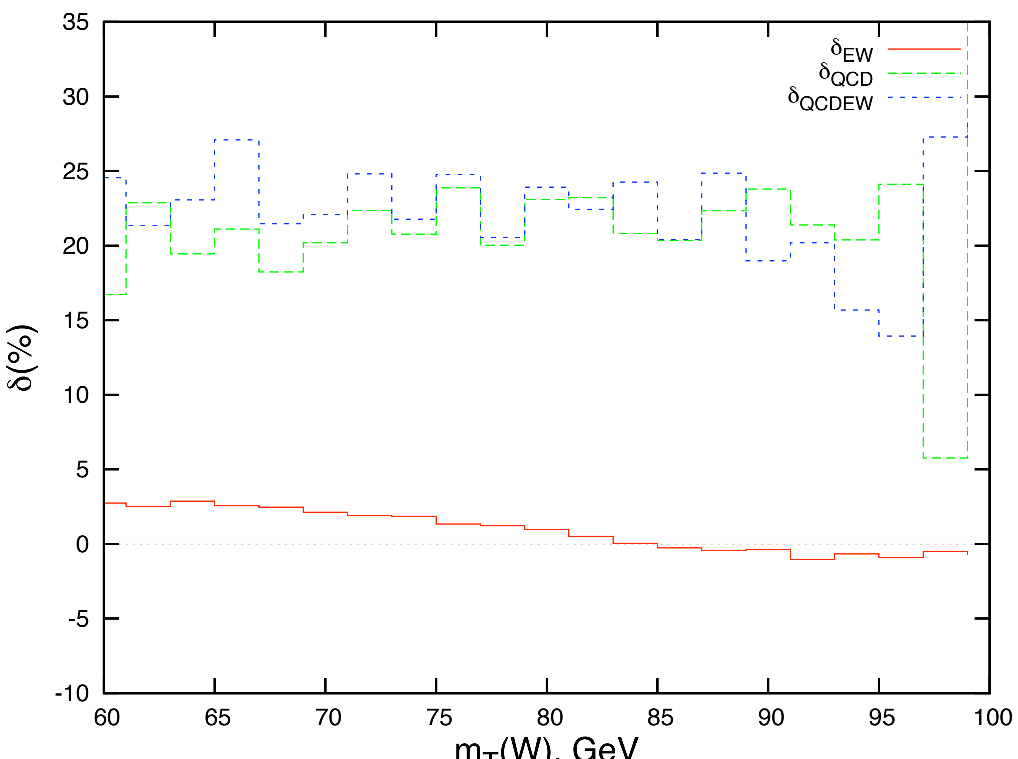
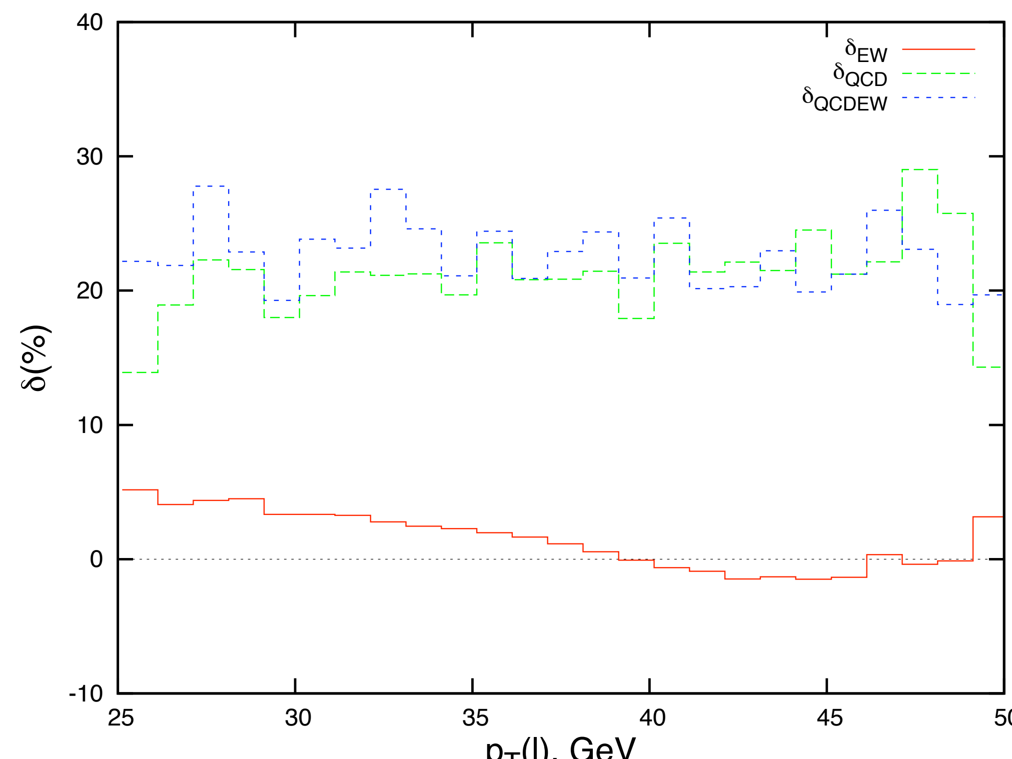
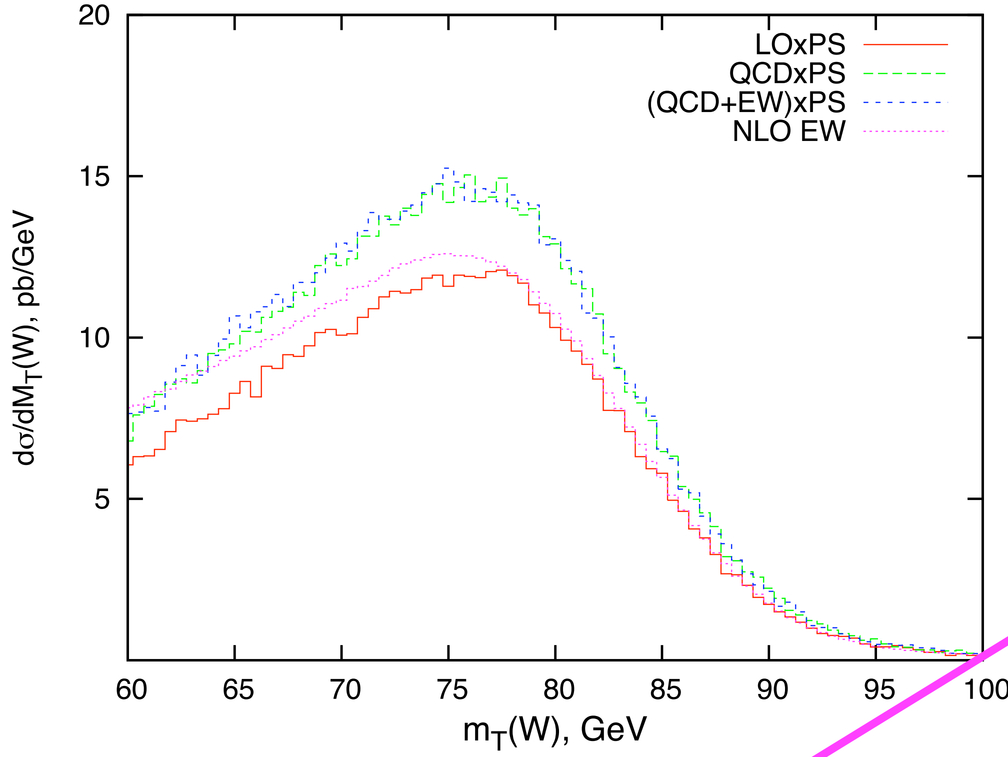
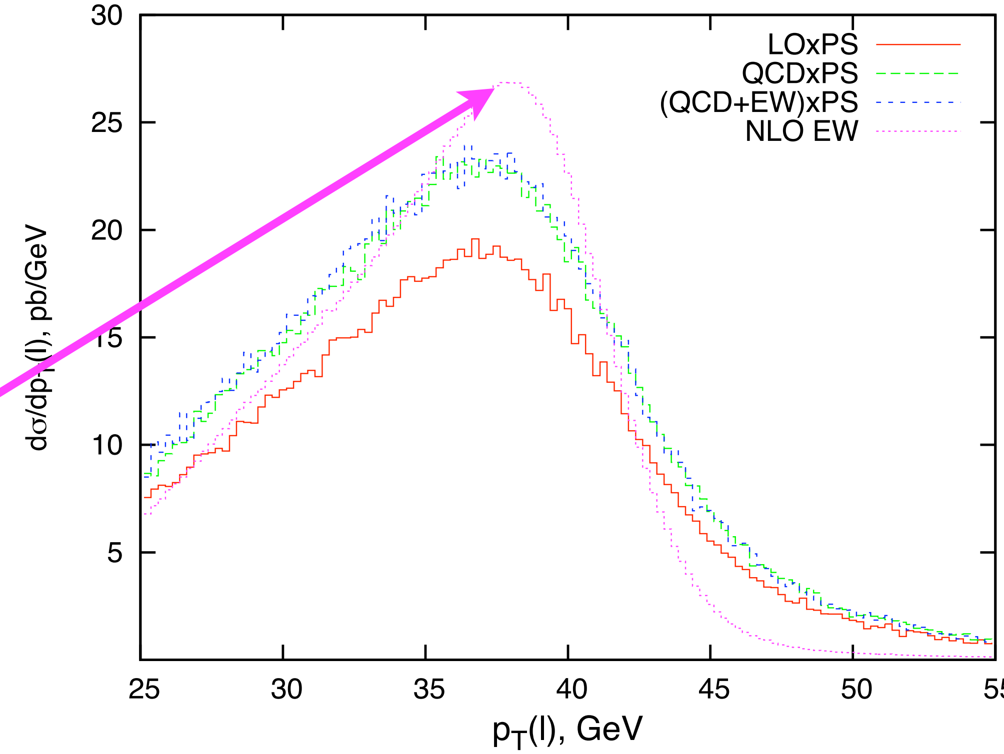




BW results Bernaciak, Wackeroth, arXiv:1201.4804 — Tevatron muon calo





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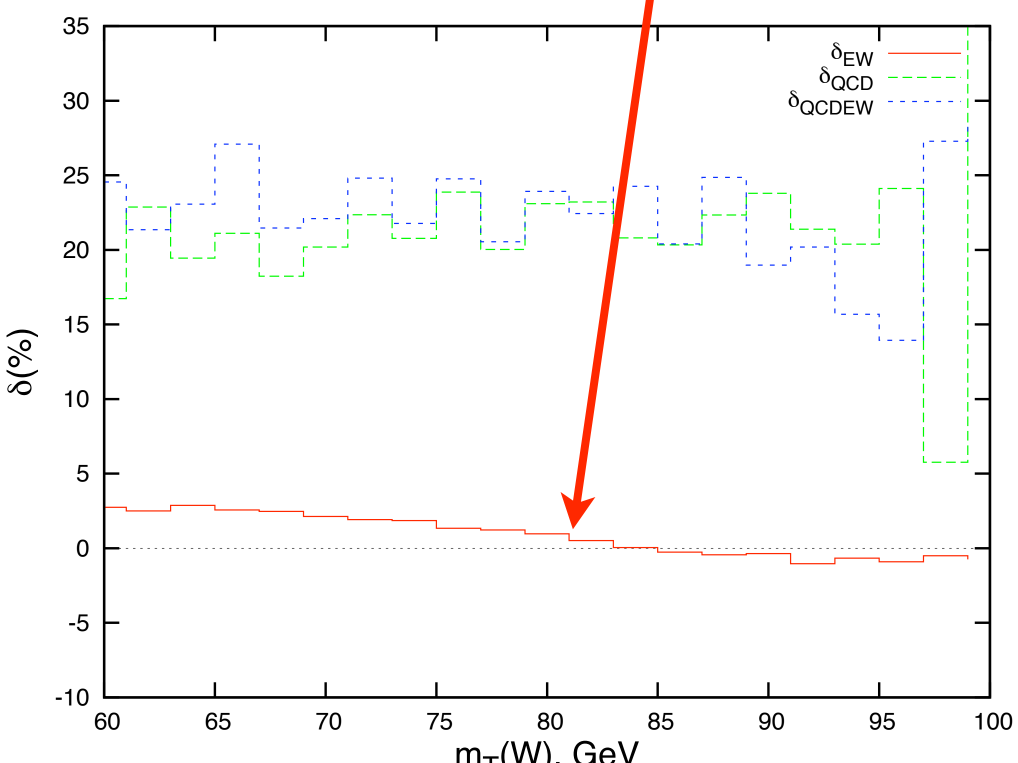

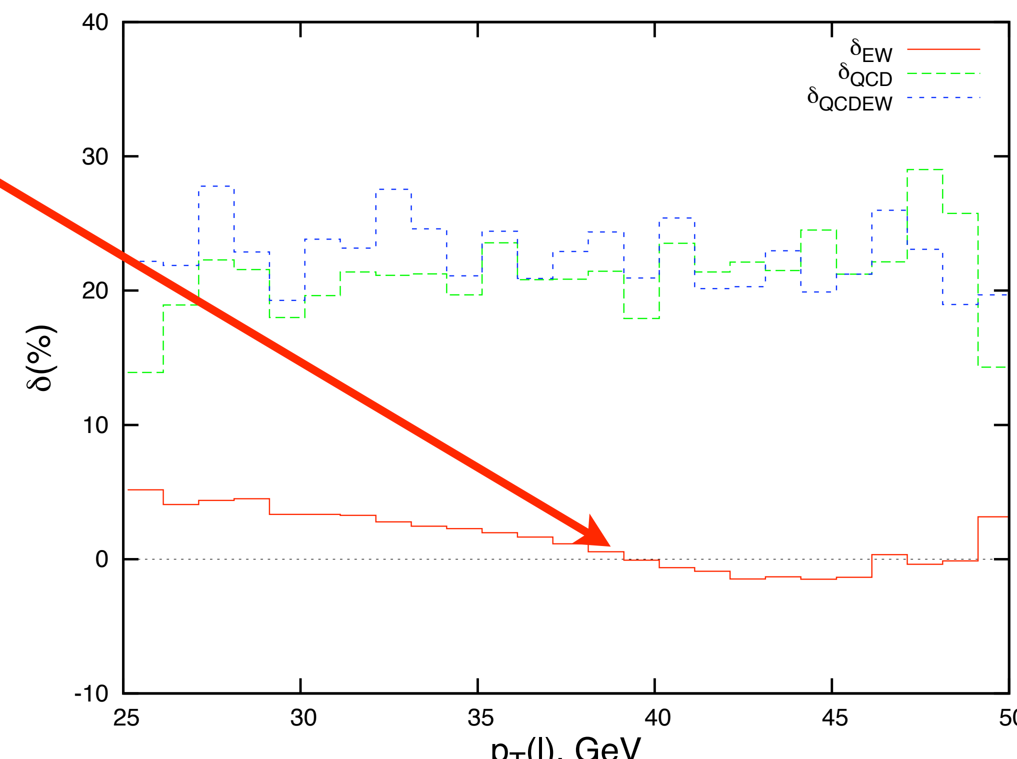

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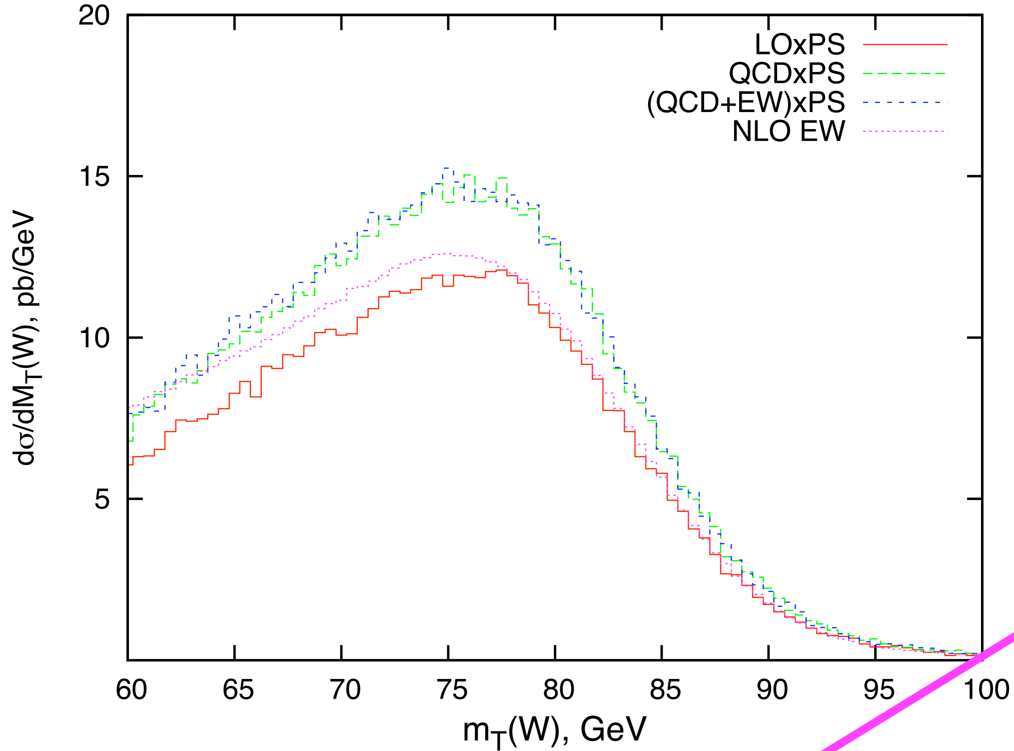
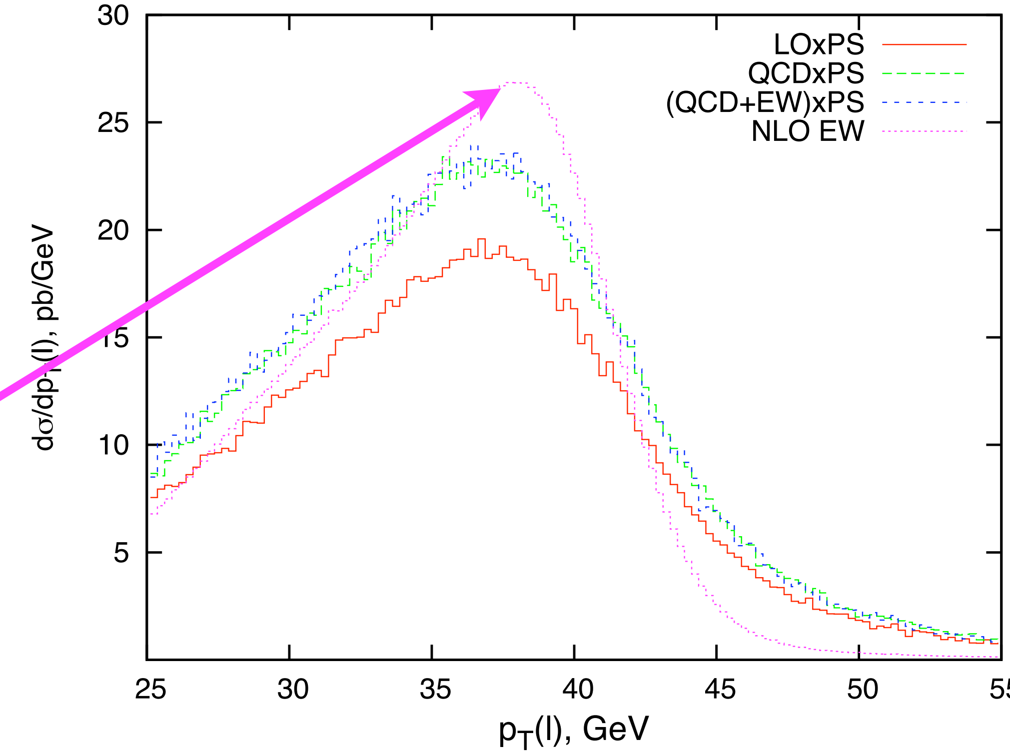
Tevatron muon calo





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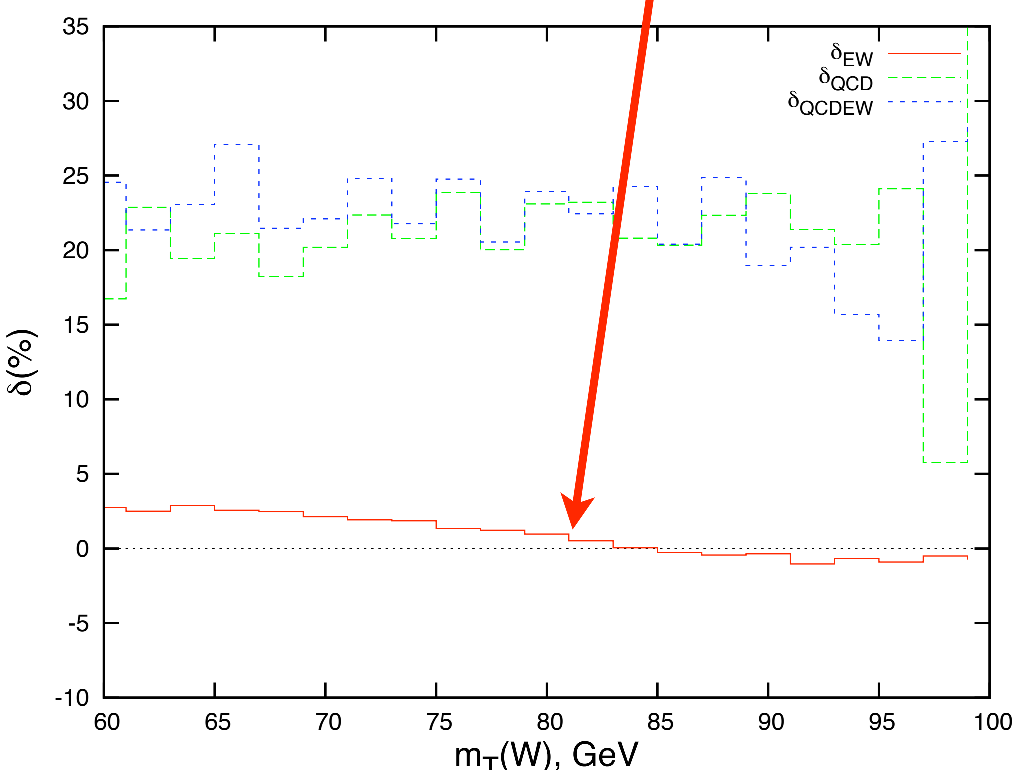
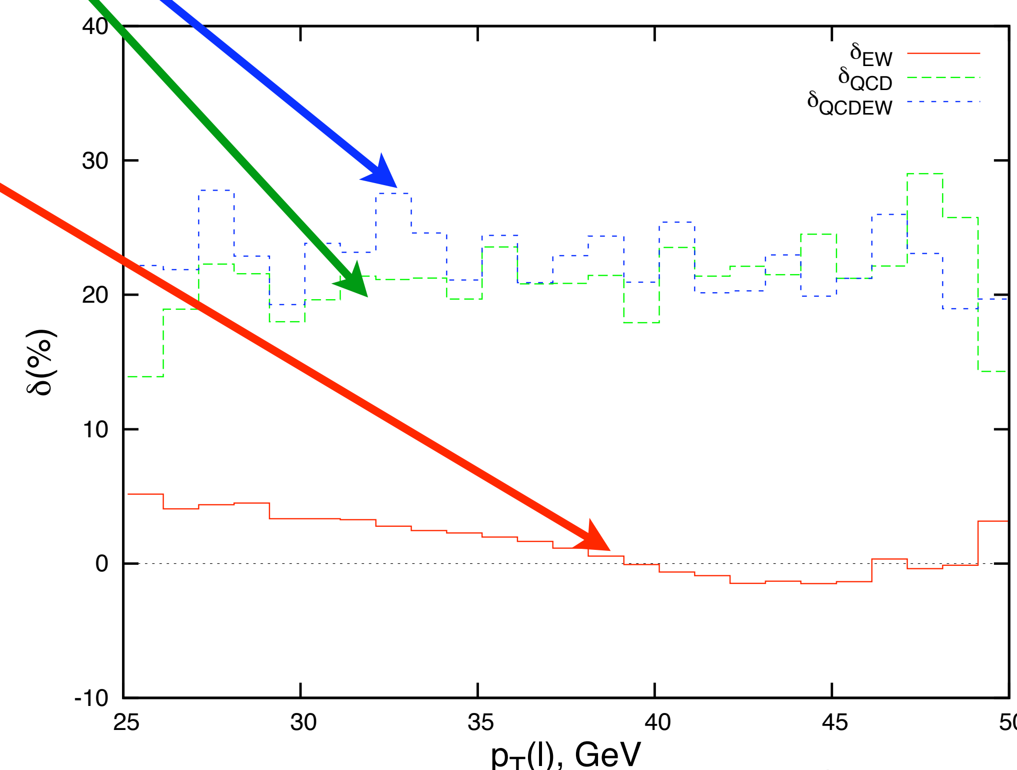
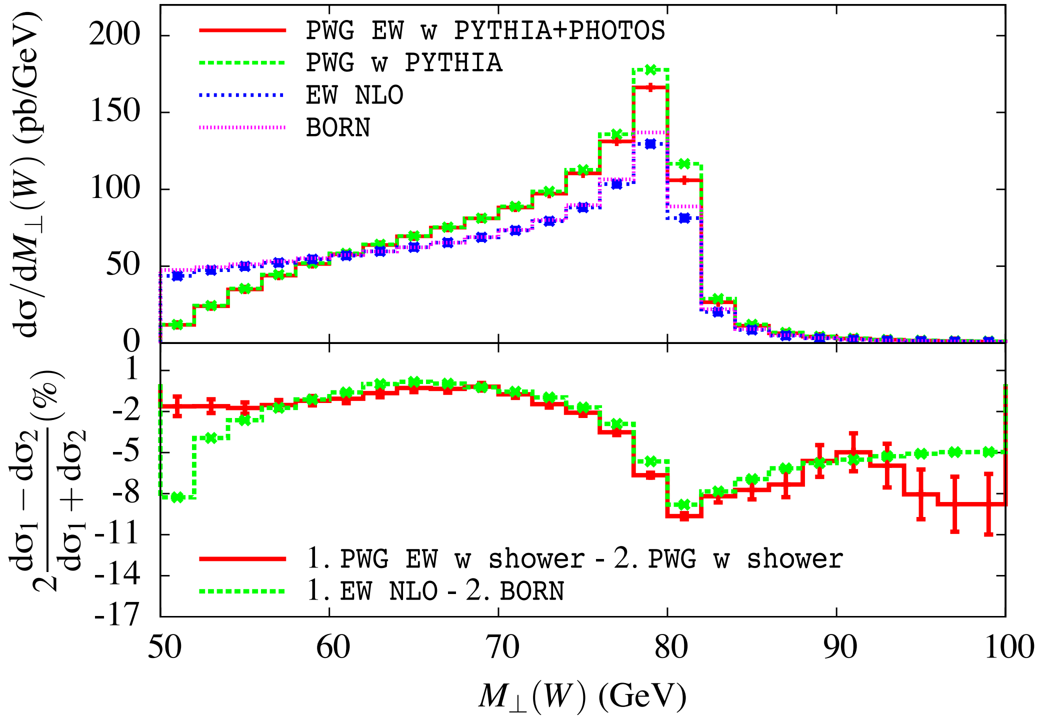
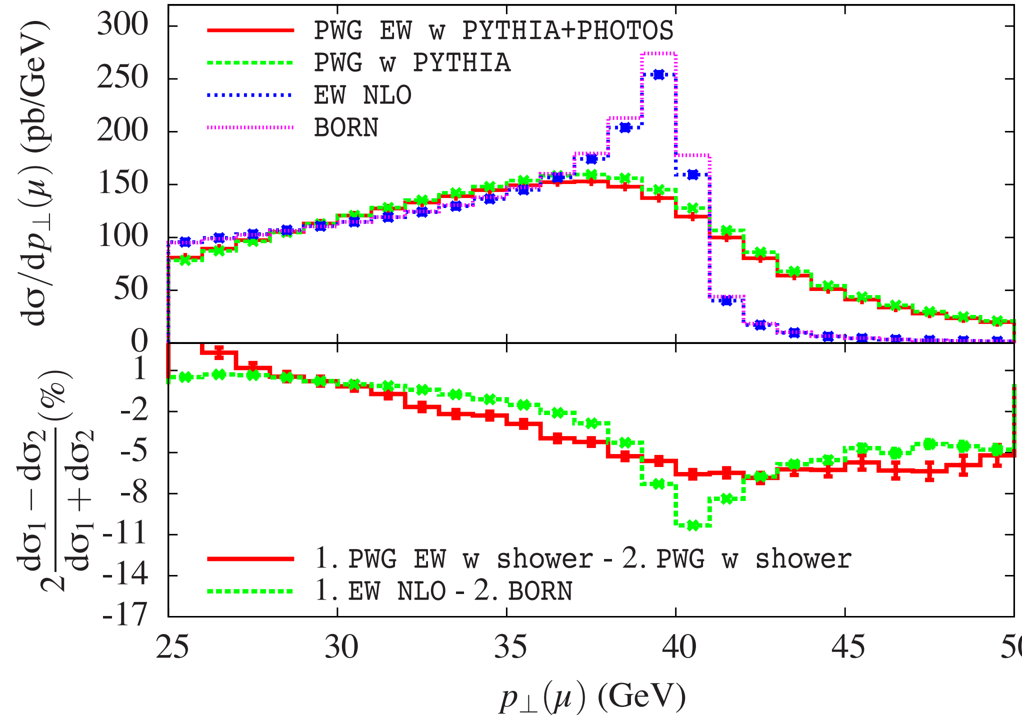




BMNNP results

Barzè, Montagna, Nason, Nicrosini, Piccinini, arXiv:1202.0465





- all the results in the Gμ input scheme; multiple photon radiation included with PHOTOS
- the transverse mass is stable against QCD corrections → also the NLO-EW effects are preserved after showering
- the lepton transverse momentum is more sensitive to multiple gluon radiation
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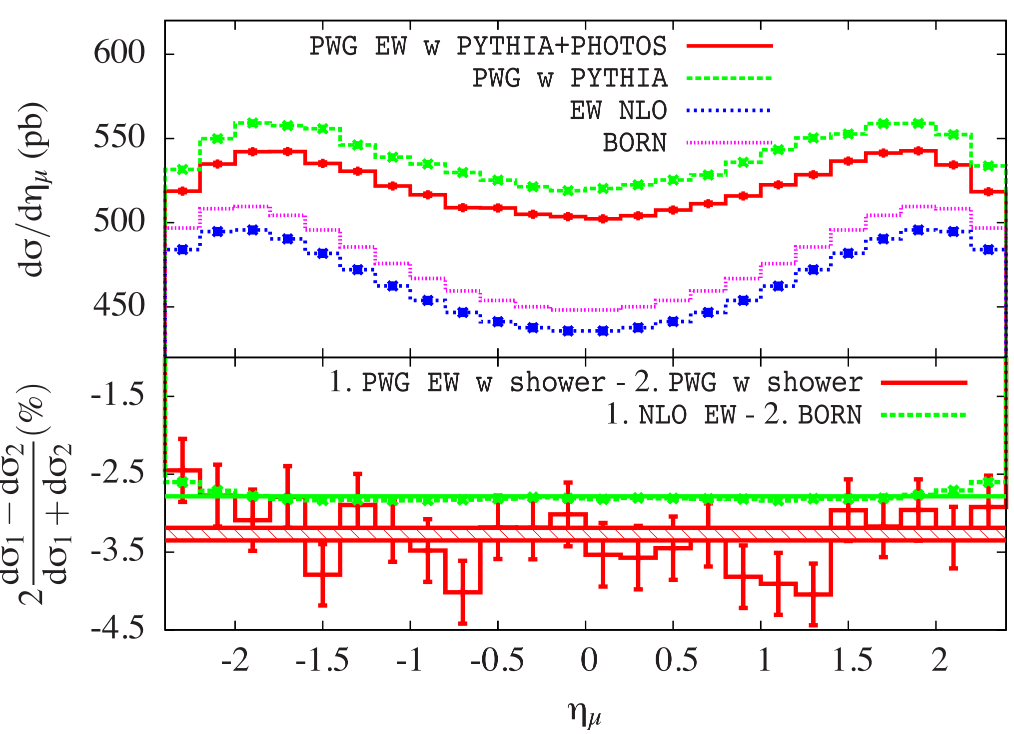
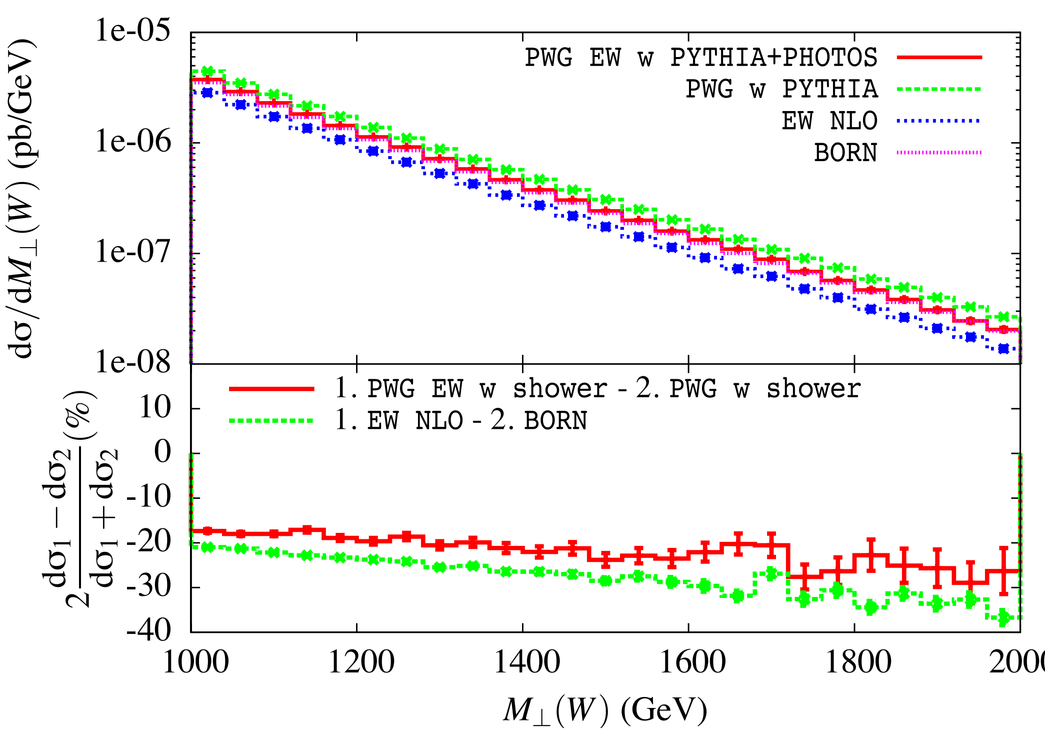
- the interplay between QCD and EW corrections yields effects at the per cent level





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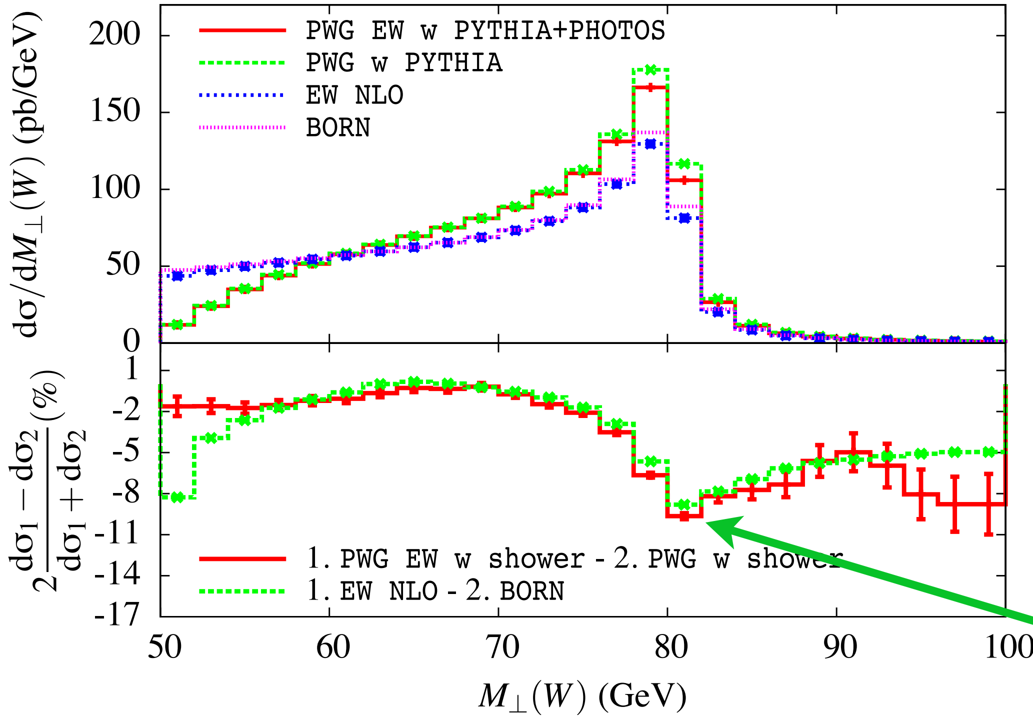

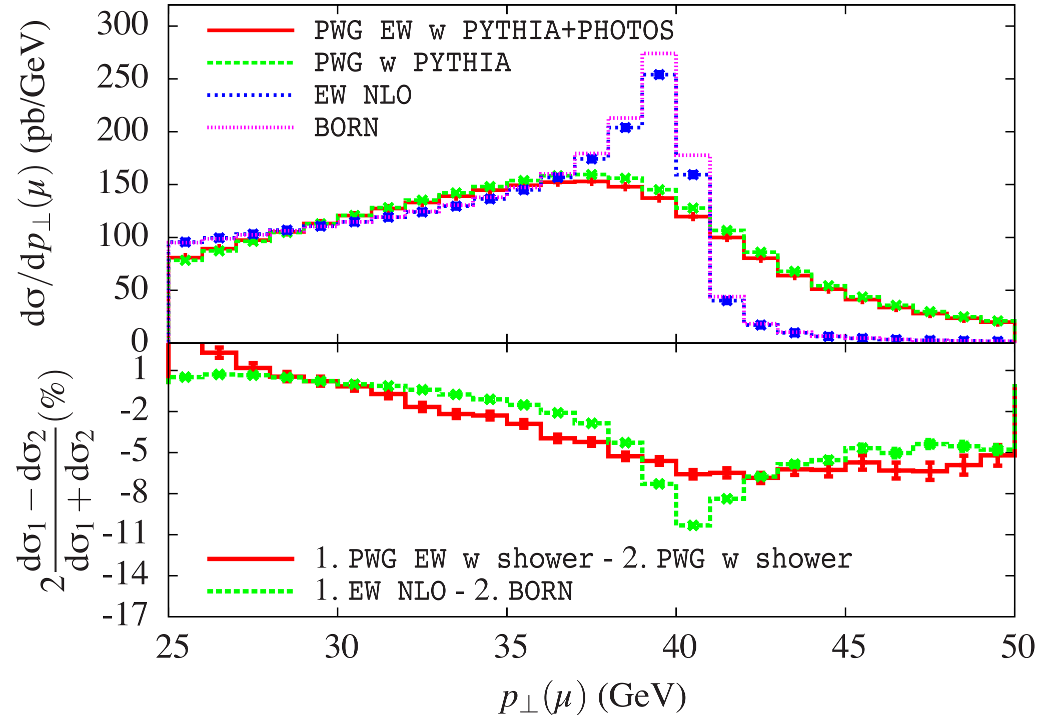

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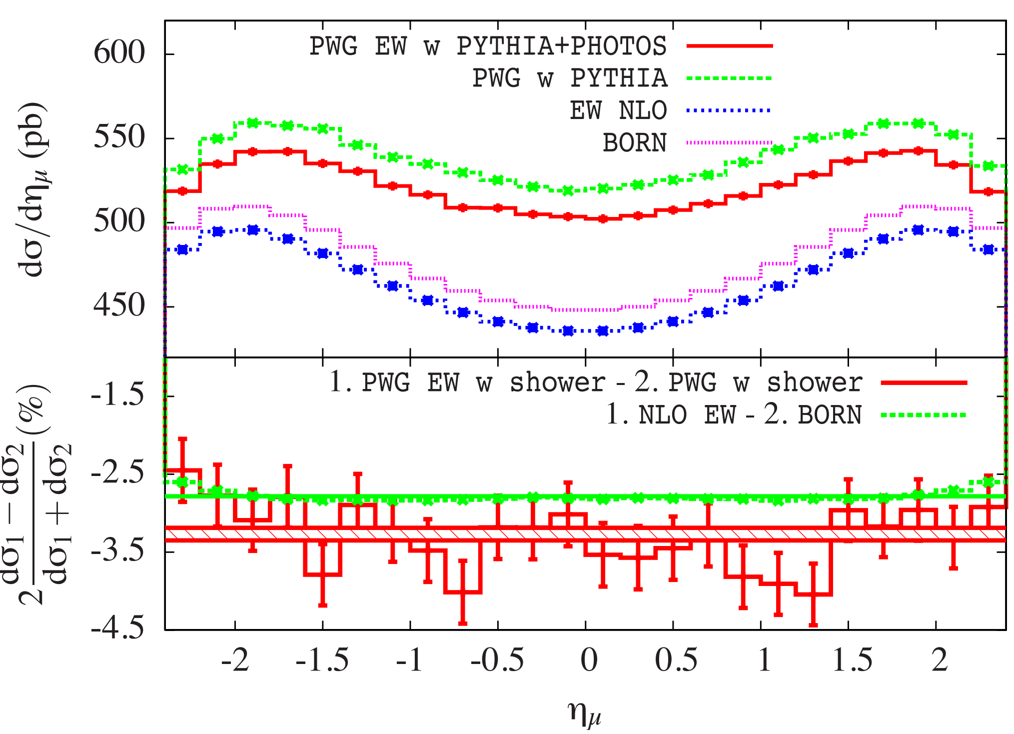

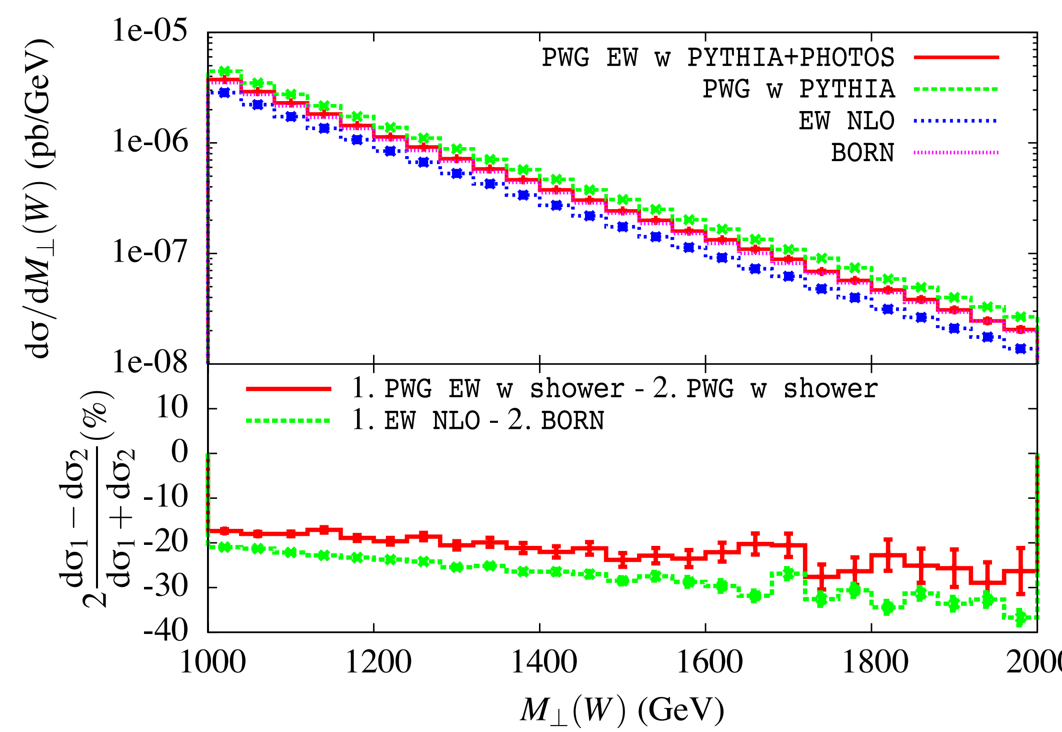

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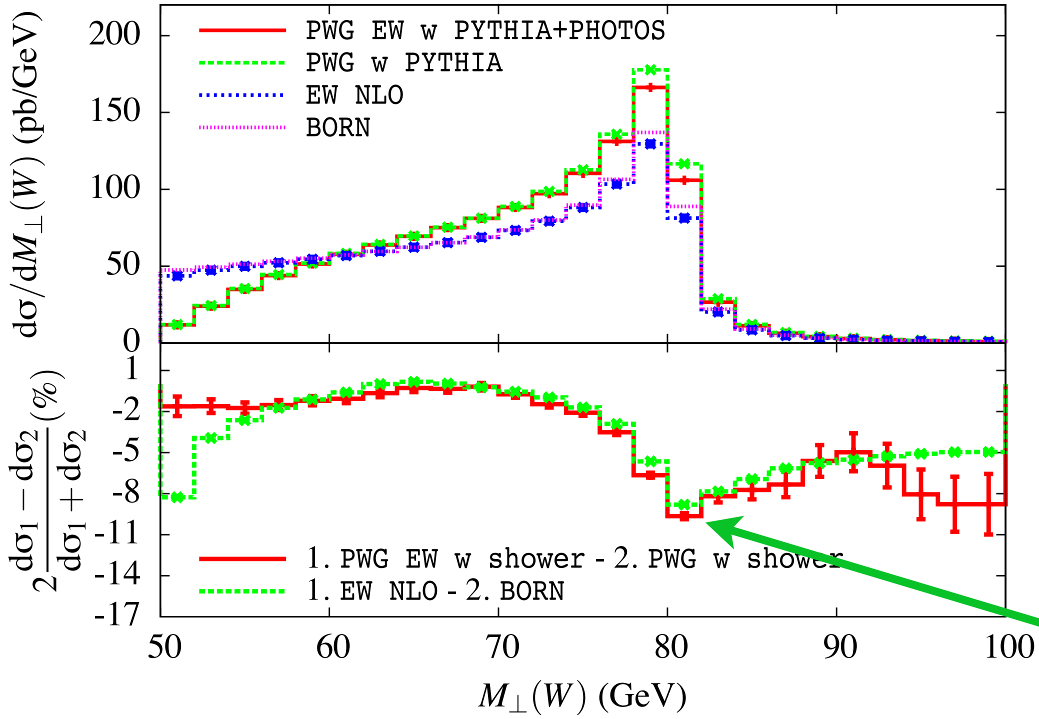

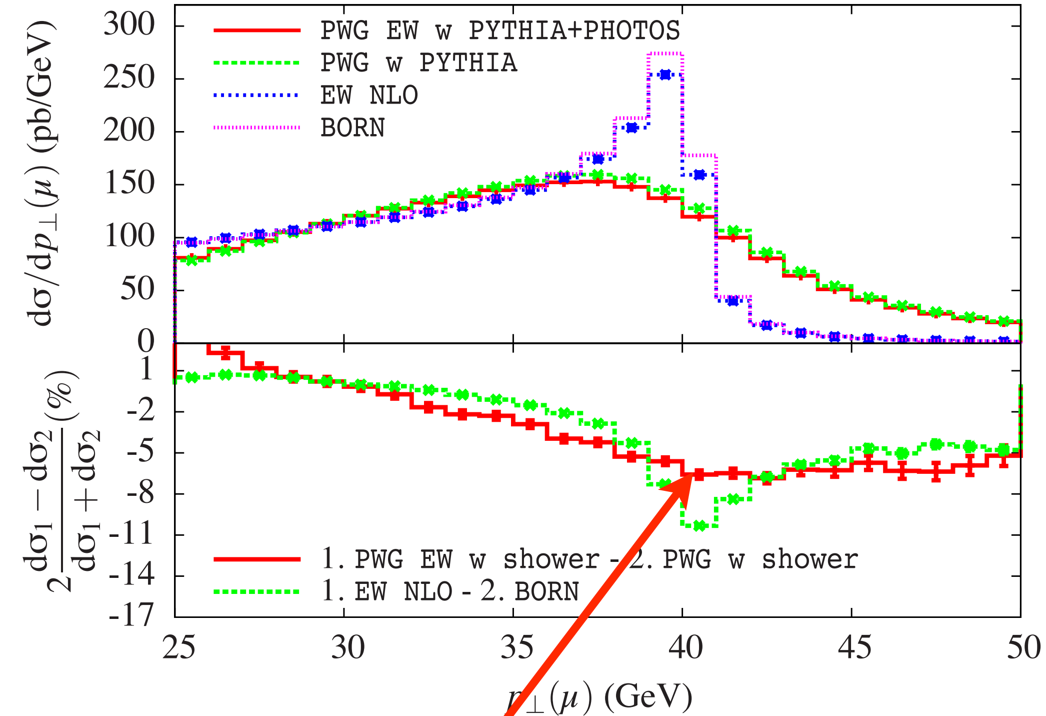

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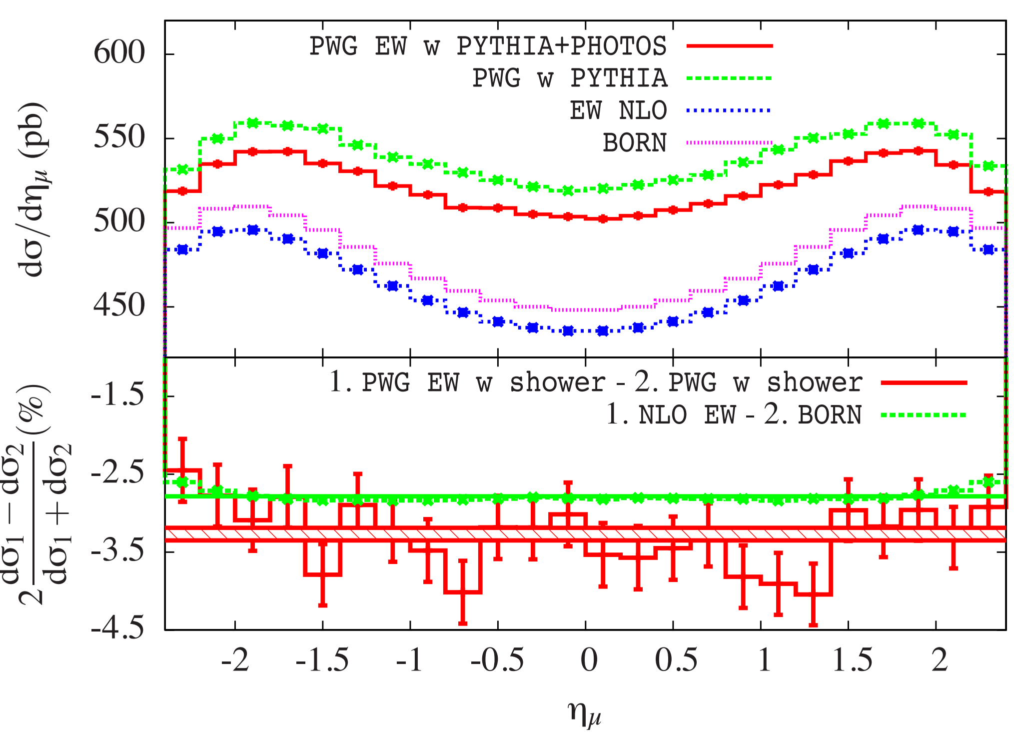
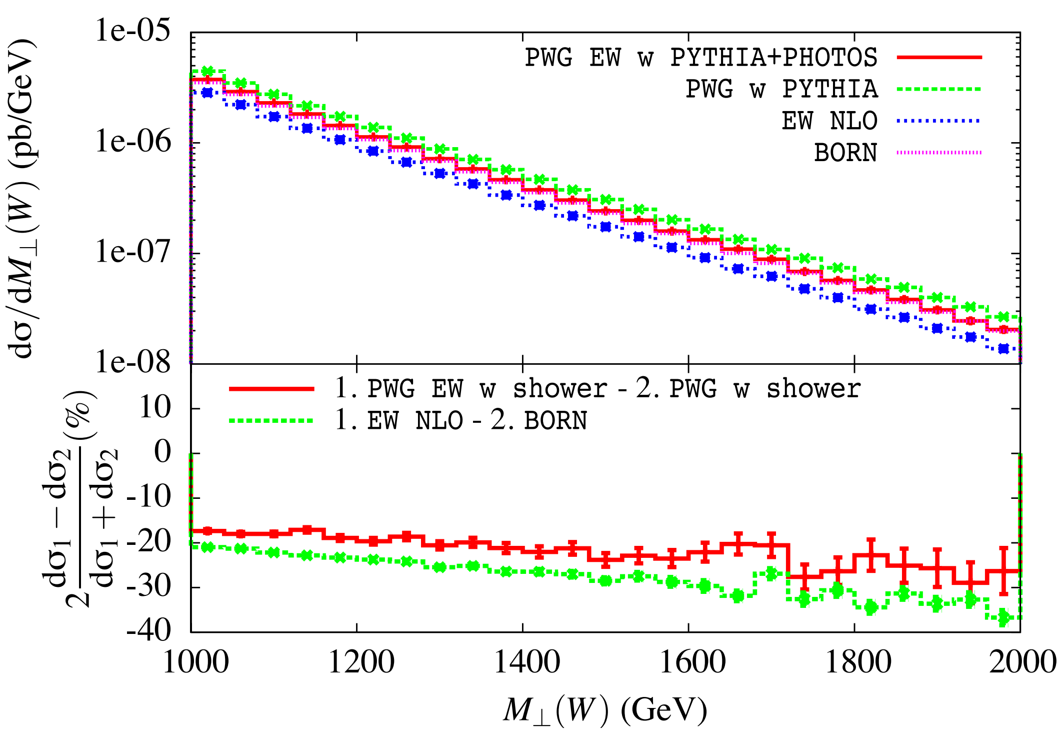
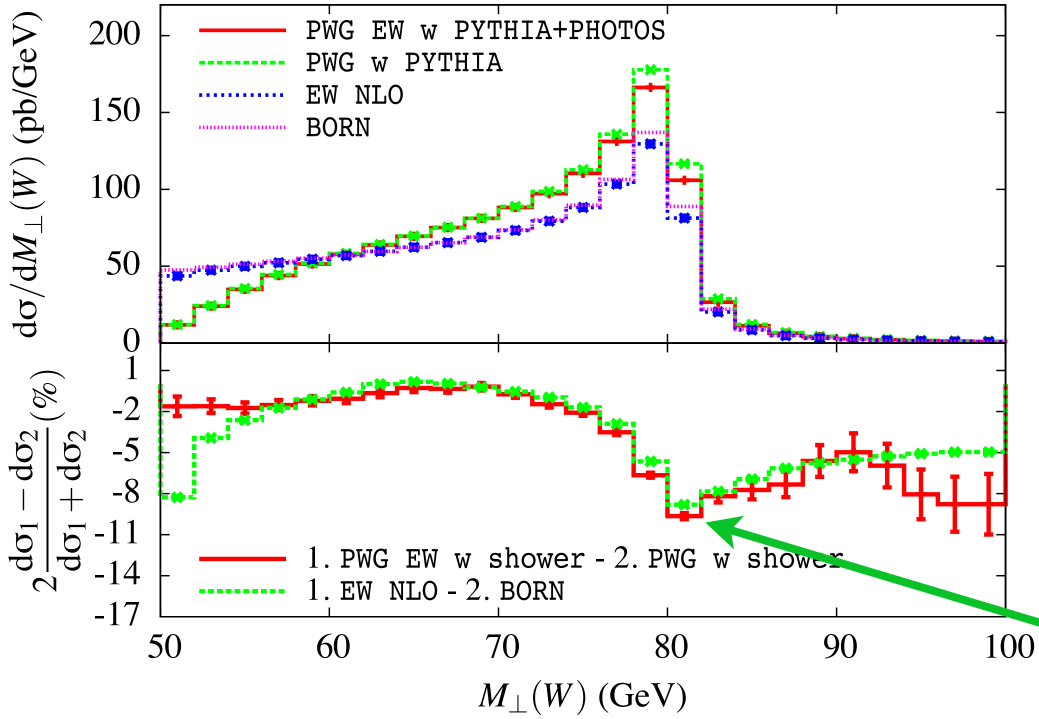
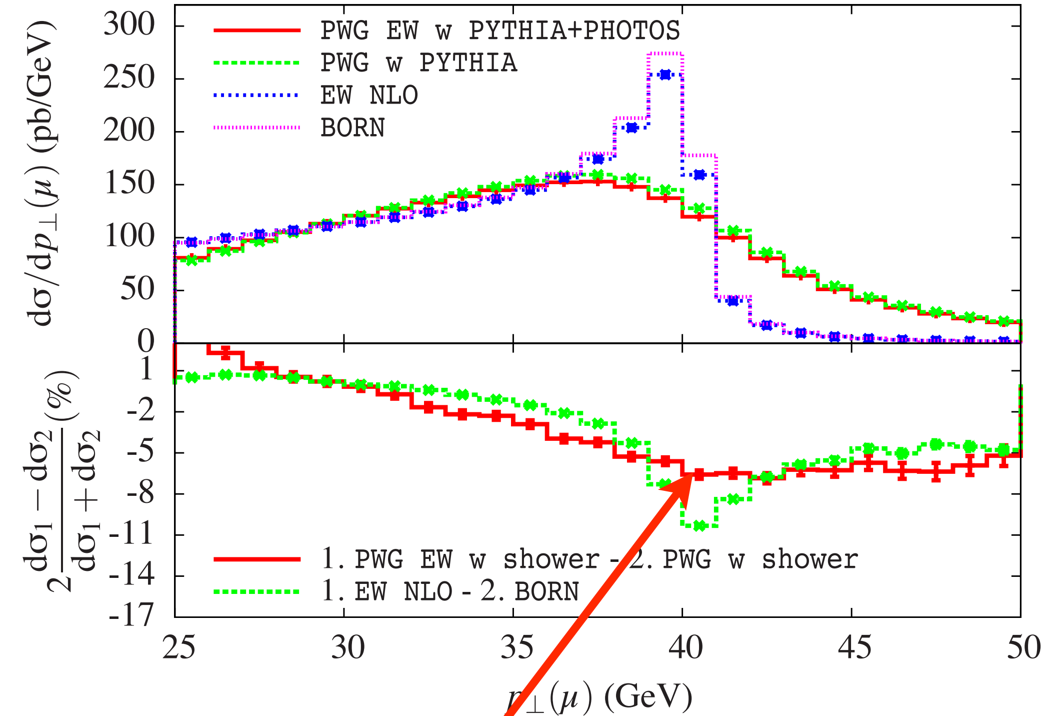




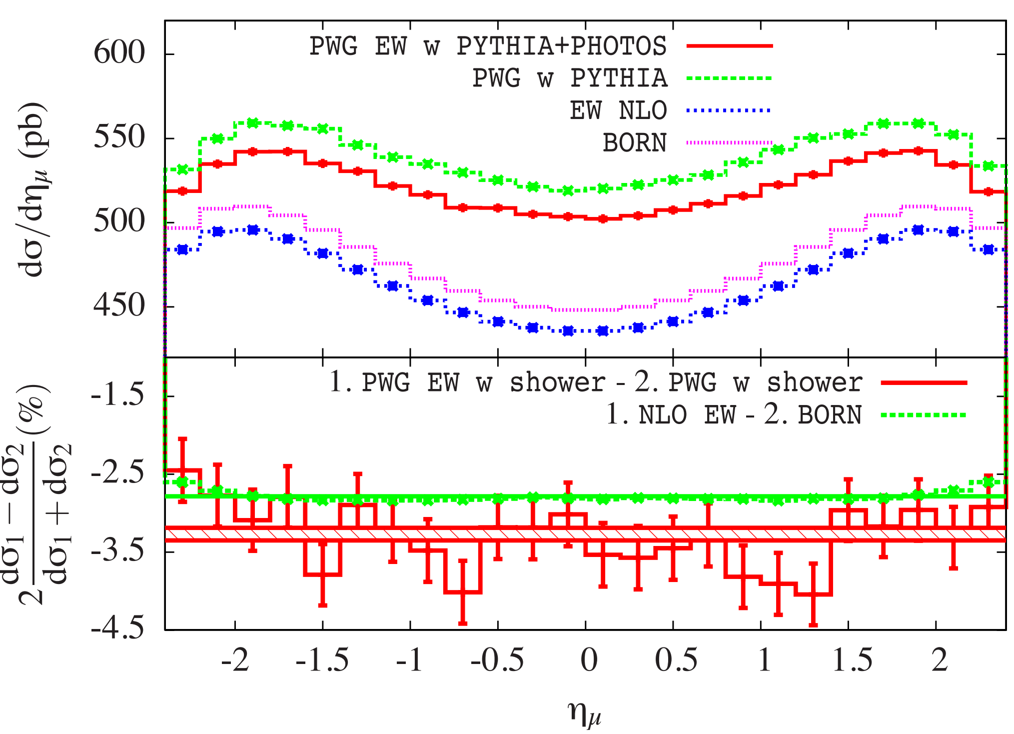
BMNNP results

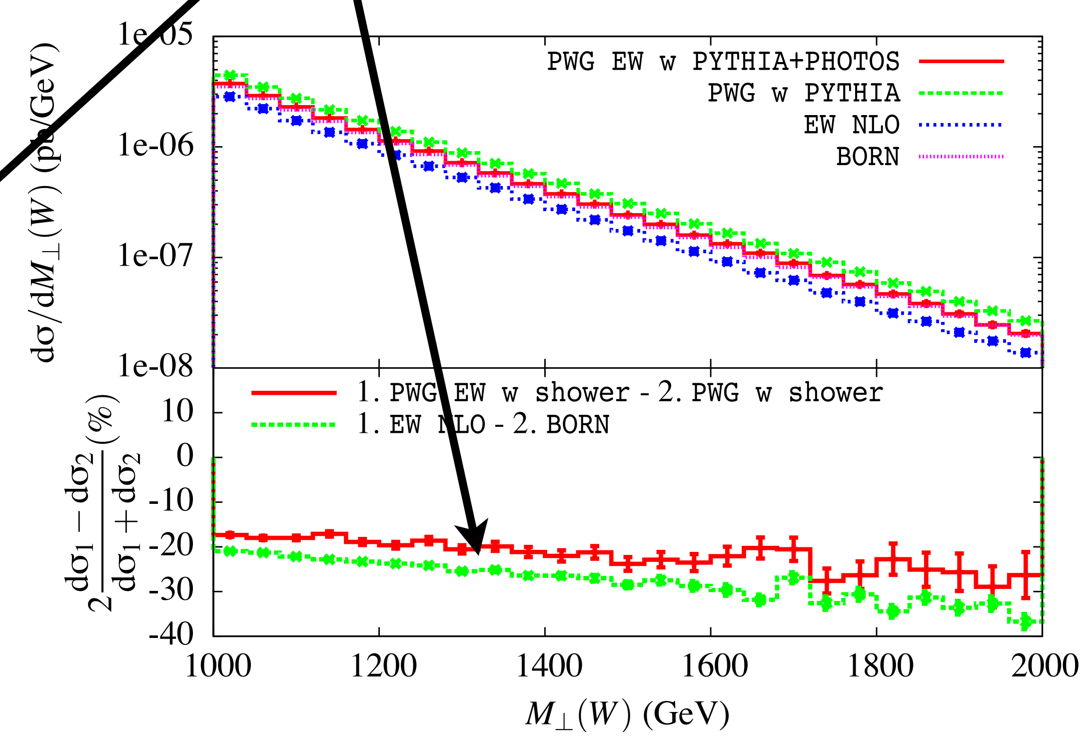
Barzè, Montagna, Nason, Nicrosini, Piccinini, arXiv:1202.0465





- all the results in the Gμ input scheme; multiple photon radiation included with PHOTOS
- the transverse mass is stable against QCD corrections → also the NLO-EW effects are preserved after showering
- the lepton transverse momentum is more sensitive to multiple gluon radiation
  the sharp peak due to EW corrections is reduced by the QCD-Parton Shower
- the interplay between QCD and EW corrections yields effects at the per cent level





Summary on POWHEG (QCD+EW) for CC Drell-Yan

- two independent implementation of the CC DY are available in the POWHEG-BOX
  http://powhegbox.mib.infn.it/

- the inclusion of the exact NLO-(QCD+EW) corrections matched with
  QCD or QCD/QED Parton Shower guarantees, in one single tool:
  - the correct NLO normalization of the total cross section
  - the exact description of the first real emission of one parton (gluon/quark/photon)
  - the correct matching with multiple gluon/photon emission
  - the inclusion of the leading factorizable $O(\alpha\alpha_s)$ corrections

- the effects of QCD showering on top of the NLO-EW effects tends
  1) to reduce the most pronounced effects at the jacobian peak
  2) to yield additional corrections at the % level

- the factorized Ansatz implicit in the basic POWHEG formula respects the classical limit of vanishing cross section in the case of complete absence of radiation

- the subtraction of IS QED collinear singularities is consistent only with MRST2004QED,
  where the evolution kernel of the parton densities includes also a QED term;
  updated PDF set including QED effects would be welcome!

Uncertainties on MW from Tevatron measurement. arXiv:1204.0042

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Hadronic recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
Experimental subtotal	10
Parton distributions	10
QED radiation	4
$p_T(W)$ model	5
Production subtotal	12
Total systematic uncertainty	15
W-boson statistics	12
Total uncertainty	19

Table 1: Uncertainties for the combined result on M_W from CDF [?].

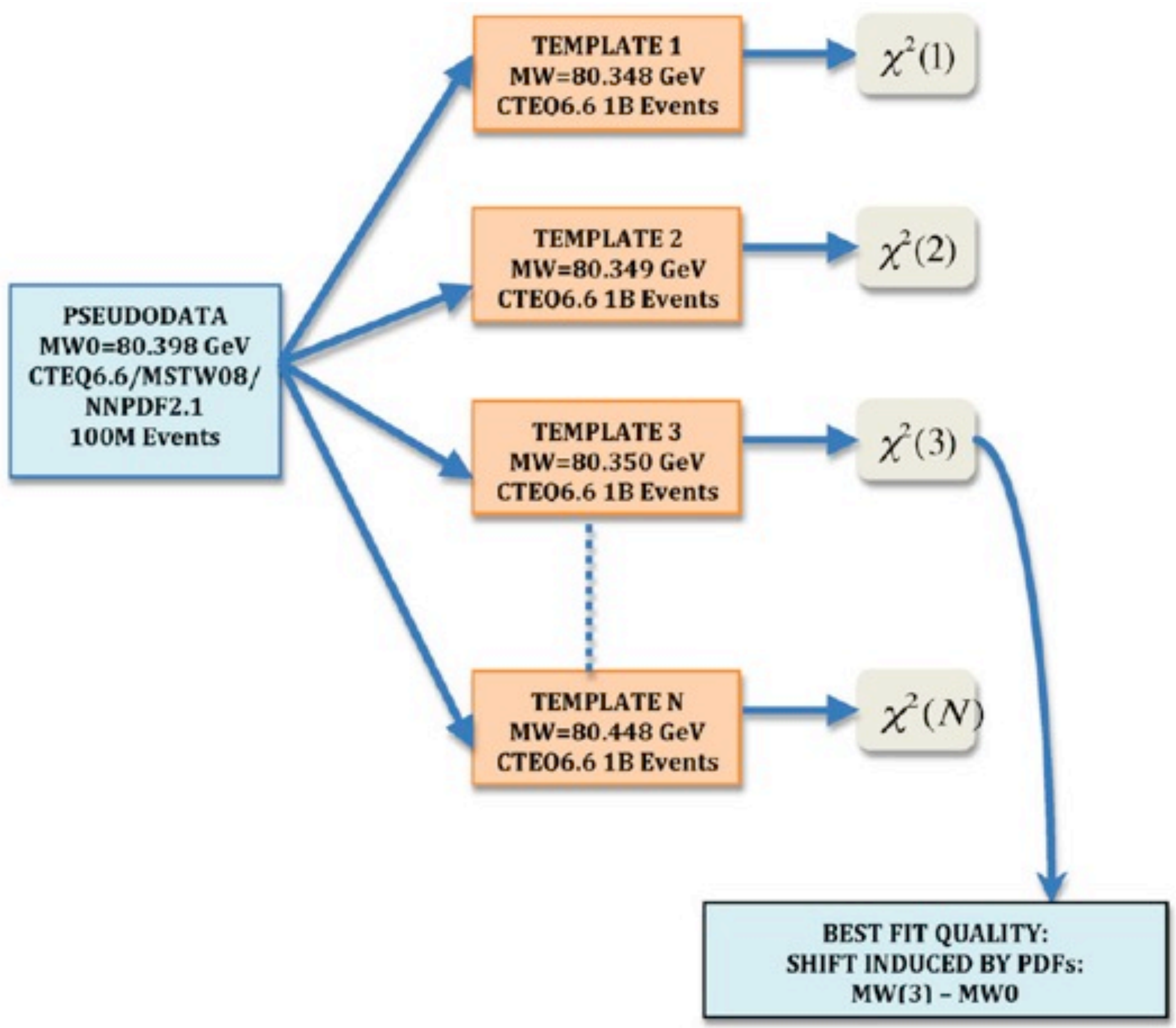
- the estimate of the QED error is based on a comparison between PHOTOS, W/ZGRAD2 and HORACE;
  at this level of accuracy a full EW study is necessary
  the new POWHEG QCD+EW offers the possibility to perform a consistent, exact at NLO, combined analysis

- the pQCD uncertainty is absent and is traded for the uncertainty on P_T(W)
  analytical tools like DYqT can help to quantify the QCD uncertainty, by appropriate choice and variation of renormalization, factorization and resummation scales
  how good is the description of the data in pure pQCD?

- The estimate of the uncertainty induced by the PDFs has been studied in detail in G. Bozzi et al, , arXiv:1104.2056 and found to be of O(5 MeV); what is the origin of the discrepancy?
  If 10 MeV is confirmed, the PDF error would start to be a limiting factor

Estimate of the error on MW induced by the PDFs (G. Bozzi et al, arXiv:1104.2056)

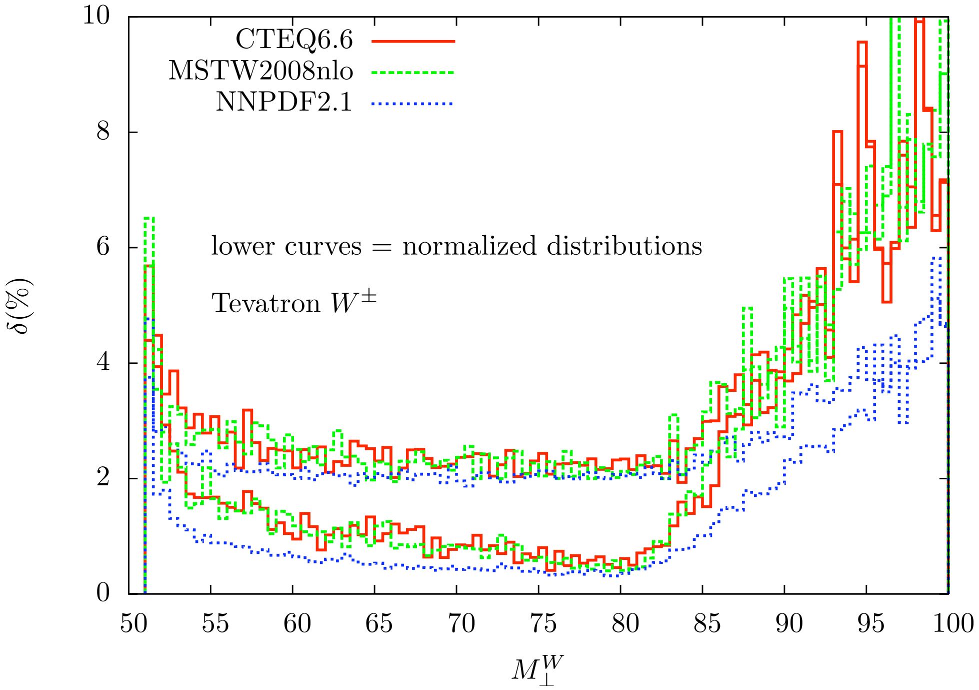
- each PDF replica is used to generate a set of pseudodata, with a fixed value MW_0
- a very accurate set of template distributions has been prepared, varying only MW, with a reference(CTEQ6.6) PDF replica
- the same code, DYNNLO, has been used to generate both, pseudodata and templates → only effect probed is the PDF one



- the MW shift expresses the distance between the PDF replica under study and the reference replica

- the PDF error is obtained combining the different MW results from each replica, according to the formulae recommended by the PDF collaborations

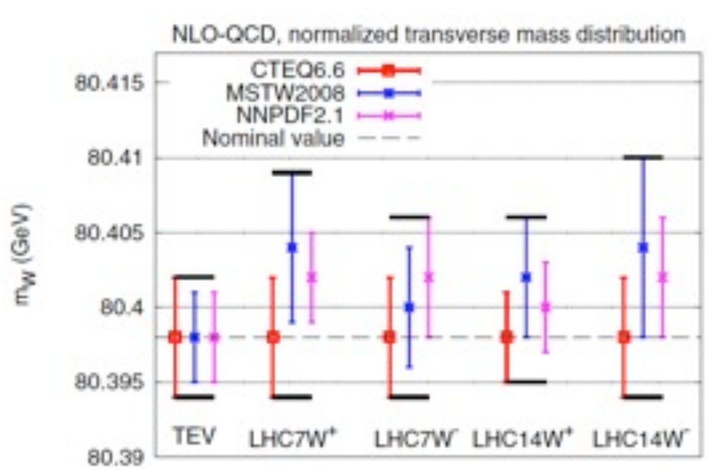
Estimate of the error on MW induced by the PDFs



- the PDF effect on MW is obtained by studying the transverse mass normalized distributions: different PDF normalization should not be accounted for by a MW shift

- the templates and the pseudodata are computed with the same generator in the same experimental setup: in first approximation the PDF effects factorize w.r.t. all the other theoretical and experimental factors

	CTEQ6.6		MSTW2008		NNPDF2.1		
	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$m_W \pm \delta_{\rm pdf}$	$\langle\chi^2\rangle$	$\delta_{\rm pdf}^{\rm tot}$
Tevatron, $W^{\pm}$	80.398 ± 0.004	1.42	80.398 ± 0.003	1.42	80.398 ± 0.003	1.30	4
LHC 7 TeV W^+	80.398 ± 0.004	1.22	80.404 ± 0.005	1.55	80.402 ± 0.003	1.35	8
LHC 7 TeV W^-	80.398 ± 0.004	1.22	80.400 ± 0.004	1.19	80.402 ± 0.004	1.78	6
LHC 14 TeV W^+	80.398 ± 0.003	1.34	80.402 ± 0.004	1.48	80.400 ± 0.003	1.41	6
LHC 14 TeV W^-	80.398 ± 0.004	1.44	80.404 ± 0.006	1.38	80.402 ± 0.004	1.57	8



- the accuracy of the templates, to avoid spurious fluctuations, is very important because many effects are of O(5 MeV): it is a highly demanding task from the computational point of view, already at NLO-QCD

- if confirmed, the PDF error is moderate at the Tevatron, but also at the LHC, even before the use of the LHC data

- an analogous study for the lepton transverse momentum distribution is ongoing (need for a resummed QCD calculation)

Conclusions

- two independent implementations of QCD+EW corrections to CC DY in POWHEG
  allow a new series of high precision studies,
  needed for high precision measurements of EW parameters like MW

- in many cases these high precision studies are highly demanding from the computational point of view
  great care must be adopted to understand the statistical uncertainties of the fitting tools