Università degli Studi di Milano

INFN Istituto Nazionale di Fisica Nucleare

Drell-Yan processes at hadron colliders

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Fermilab joint experimental-theoretical seminar
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with: C. M. Carloni Calame, G. Montagna, O. Nicrosini,
G. Balossini, F. Piccinini, M. Moretti, M. Treccani

papers: CMCC, GM, ON, AV: JHEP 0612:016 (2006), JHEP 0710:109 (2007)

workshop proceedings: hep-ph/0604120 Les Houches, Physics at TeV colliders 2005
arXiv:0705.3251 TeV4LHC: top and EW working group
arXiv:0803.0678 Les Houches, Physics at TeV colliders 2007

Outline

- relevance of Drell-Yan processes and motivation for precision studies
  - precision EW physics
  - pdf constraining
  - background to new physics searches

- Charged Current and Neutral Current processes
  - EW $O(\alpha)$ corrections matched with higher order QED corrections
  - photon induced processes

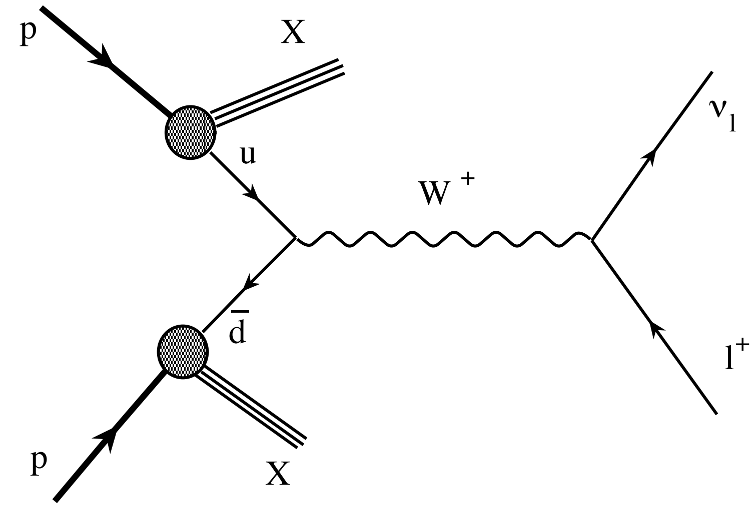
- impact of the EW corrections on several observables

- combining QCD and EW radiative corrections

- uncertainties due to the *pdf*s

controlling the predictions at the few per cent level is not a trivial task

The Drell-Yan processes



- easy detection

  high pt lepton pair or high pt lepton + missing pt

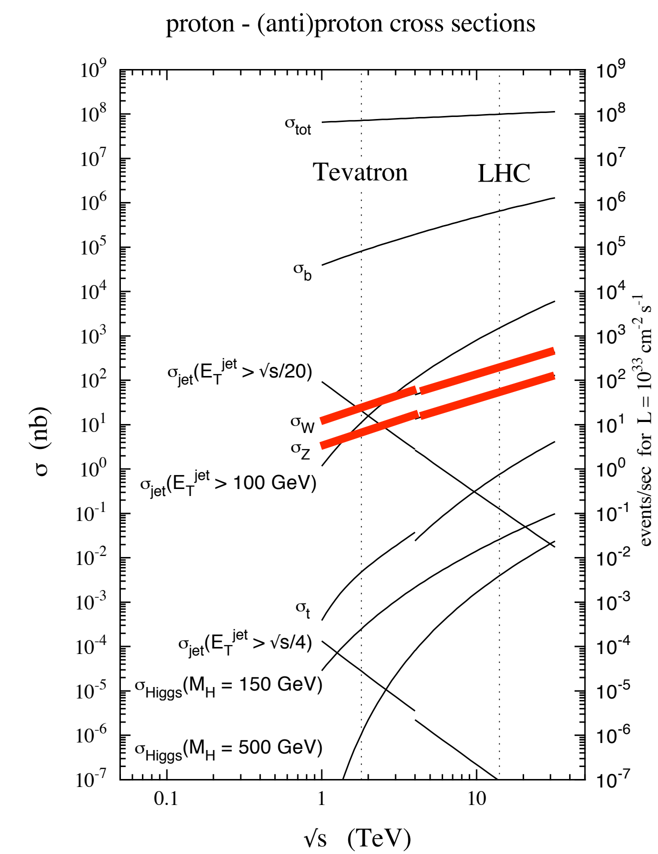
  typical cuts at the LHC (central detector region)

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

- 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 limitation to perform high precision EW measurements



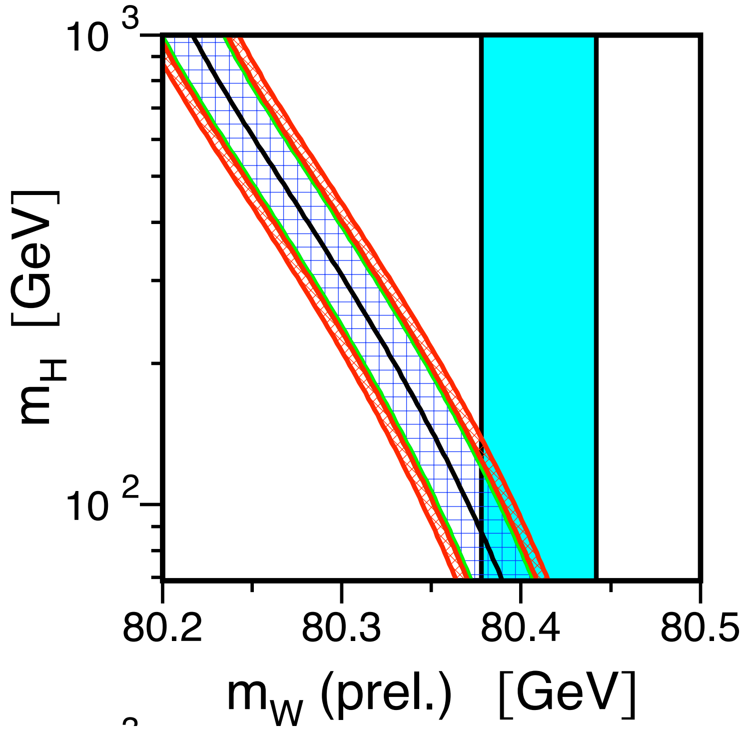
- W mass and width ➡ lepton distributions, W transverse mass, ratios W/Z distributions

- *pdf* validation, collider luminosity ➡ total cross section, W, Z rapidity, lepton pseudo-rapidity acceptances

- detector calibration ➡ W, Z mass distributions

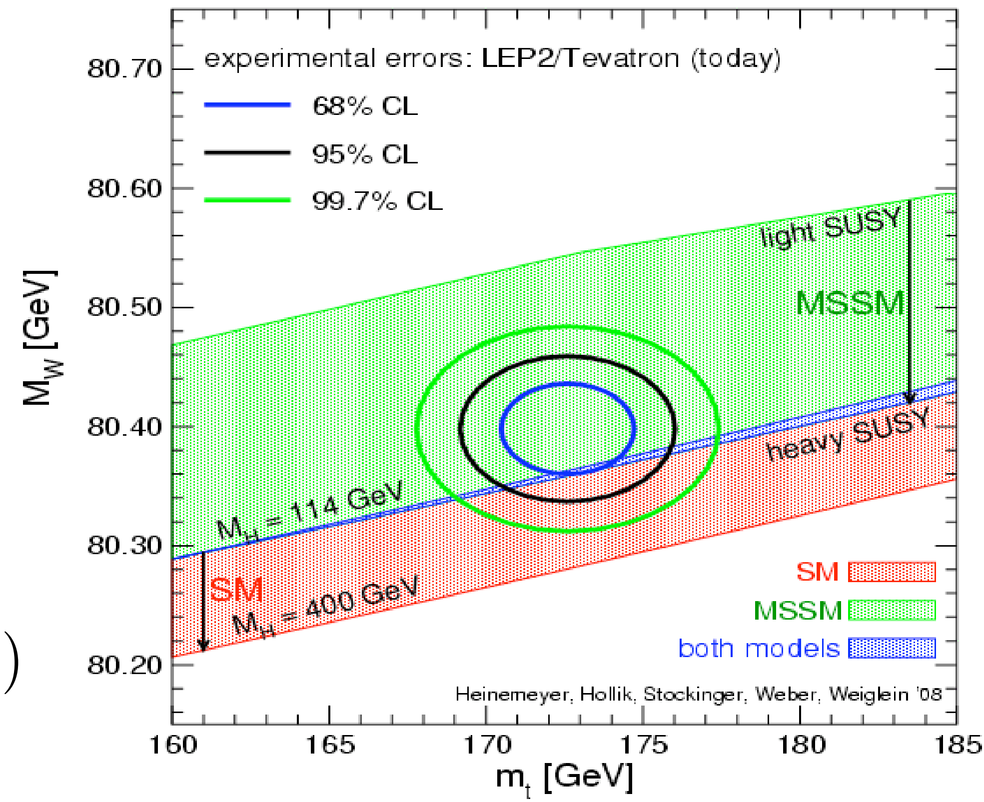
Relevance of a precise W mass measurement

Sensitivity to the precise value of the Higgs boson mass or e.g. to SUSY particles



Awramik, Czakon, Freitas, Weiglein   Degrassi, Gambino, Passera, Sirlin

$$M_W = M_W^0 - 0.0581\ \ln\left(\frac{M_H}{100\ \mathrm{GeV}}\right) - 0.0078\ln^2\left(\frac{M_H}{100\ \mathrm{GeV}}\right) - 0.085\ \left(\frac{\alpha_s}{0.118} - 1\right)$$
$$- 0.518\ \left(\frac{\Delta\alpha^{(5)}_{had}(M_Z^2)}{0.028} - 1\right) + 0.537\ \left(\left(\frac{m_t}{175\ \mathrm{GeV}}\right)^2 - 1\right)$$



$$m_W = m_W\left(\Delta r^{SM,MSSM}\right)$$

$$\Delta r^{SM,MSSM} = \Delta r^{SM,MSSM}\left(m_t, m_H, m^{SUSY}, ...\right)$$

Relevance of a precise W mass measurement

To ensure that top and W mass measurements have the same weight in the SM EW fit, the experimental errors should be related as (cfr. CERN-2000-04) :

$$\Delta m_W \sim 0.7 \times 10^{-2} \Delta m_t$$

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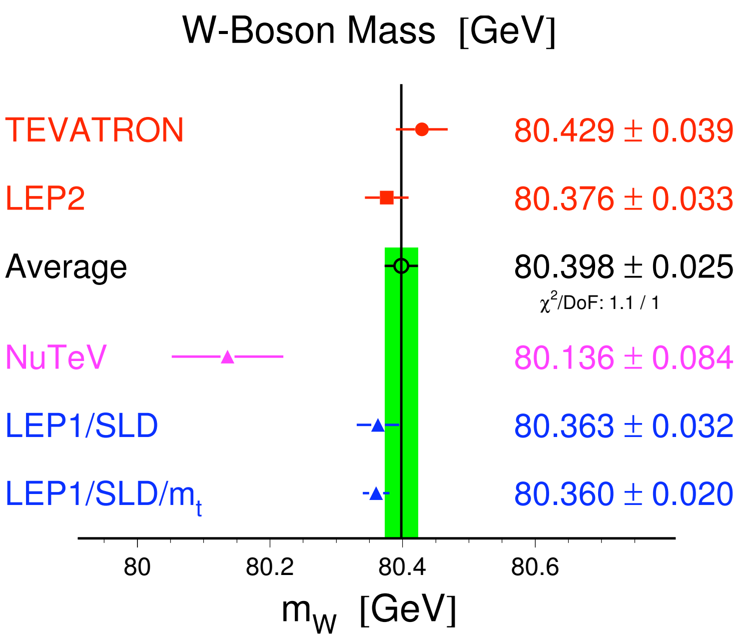
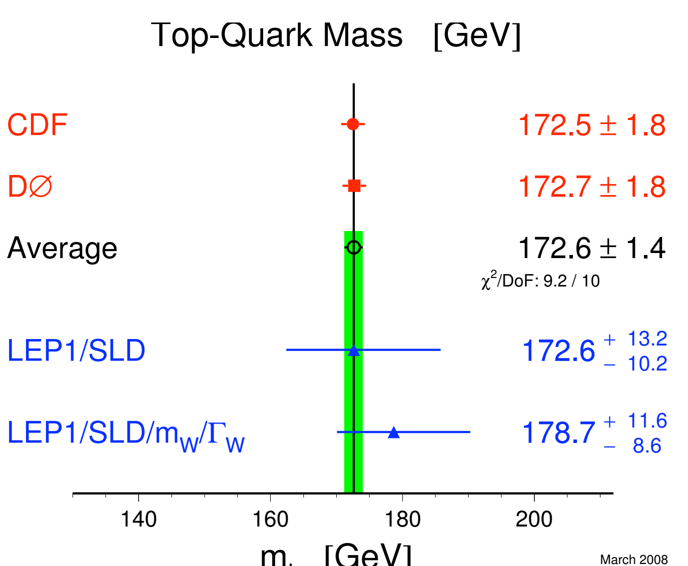
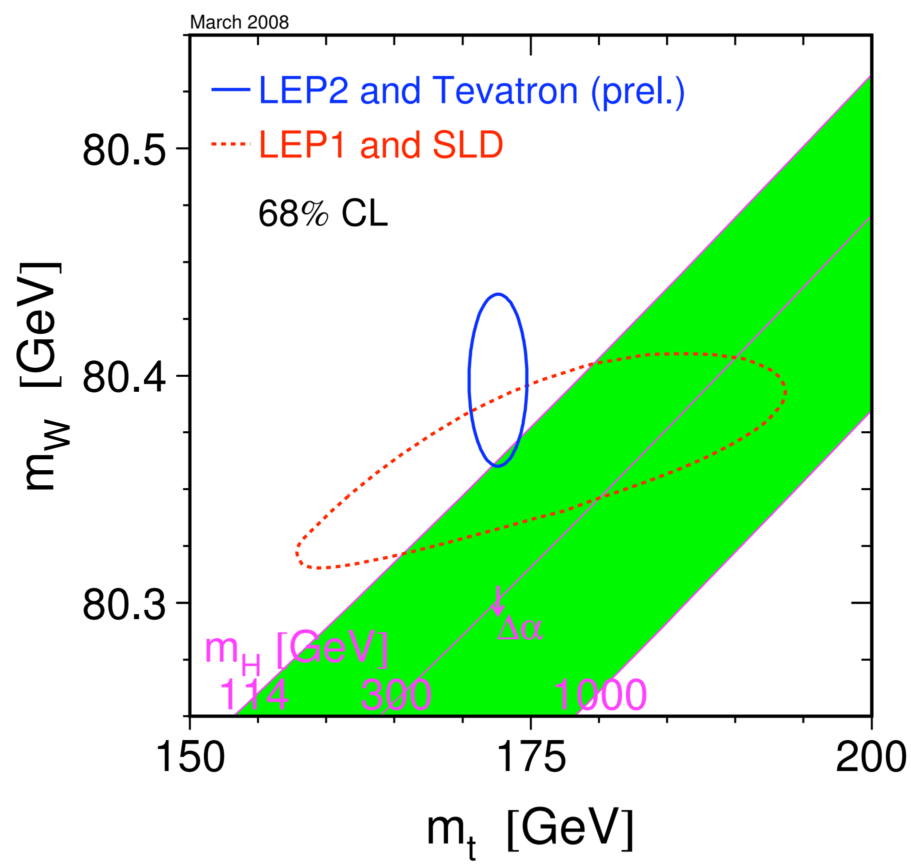
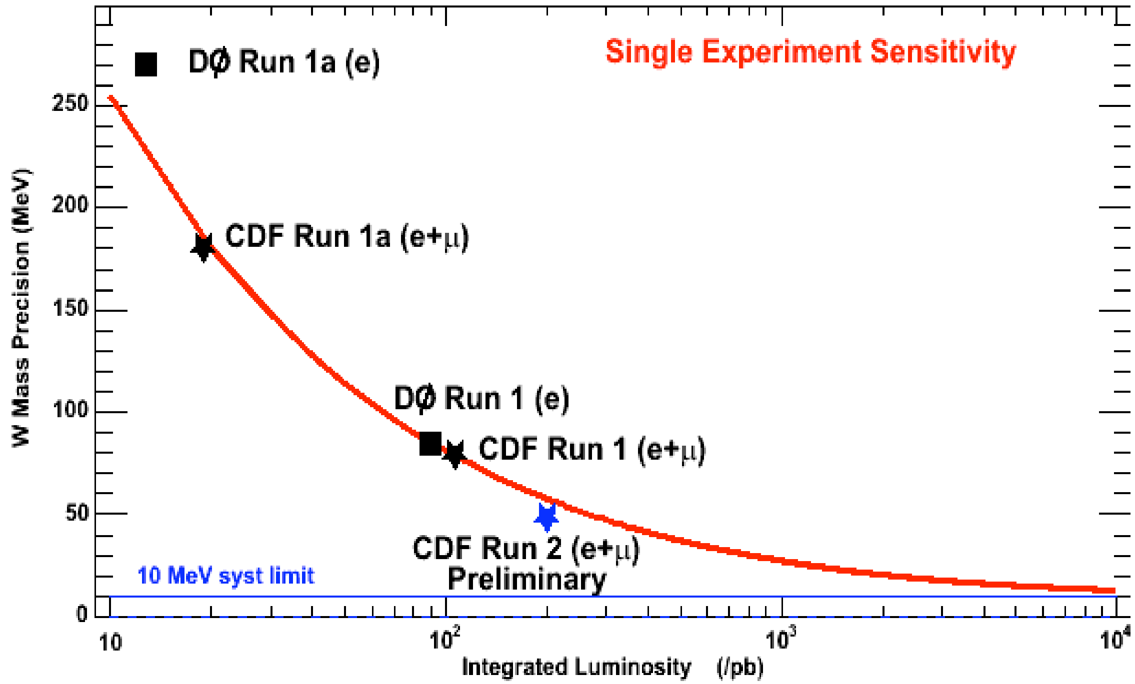






Precision measurement of EW observables



New projection with 1.5 fb^{-1} of data:

$\delta m_W < 25$ MeV with CDF

C. Hays, University of Oxford

target at LHC :

$$\Delta m_W = 15 \text{ MeV}$$

- Γ_W measurement   error at Tevatron: 58 MeV   target of Run-II: 30 MeV

- $\sin^2\theta_{eff}^{lep}$ measurement
  world average: 0.23122±0.00015   error target at the LHC: 0.00014 with 100 fb^(-1)

Constraining the *pdfs*

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The gauge bosons rapidity distributions are sensitive to the partonic content of the proton

In a simplified picture, with only up and down quarks, we consider the W charge asymmetry

$$A_W(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy} \approx \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)}$$

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In the experiment we observe leptons, whose distributions are less directly related to the *pdfs*

$$A(y_l) = \frac{\sigma(l^+) - \sigma(l^-)}{\sigma(l^+) + \sigma(l^-)}$$

$$\cos^2\theta^* = 1 - 4E_T^2/M_W^2$$

$$\sigma(l^+) - \sigma(l^-) \propto u(x_1)d(x_2)(1-\cos\theta^*)^2 + \bar{d}(x_1)\bar{u}(x_2)(1+\cos\theta^*)^2 - u(x_2)d(x_1)(1+\cos\theta^*)^2$$

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Large contribution also from charm and strange in the initial state
e.g. in inclusive CC-DY
5% at Tevatron → 25% at LHC

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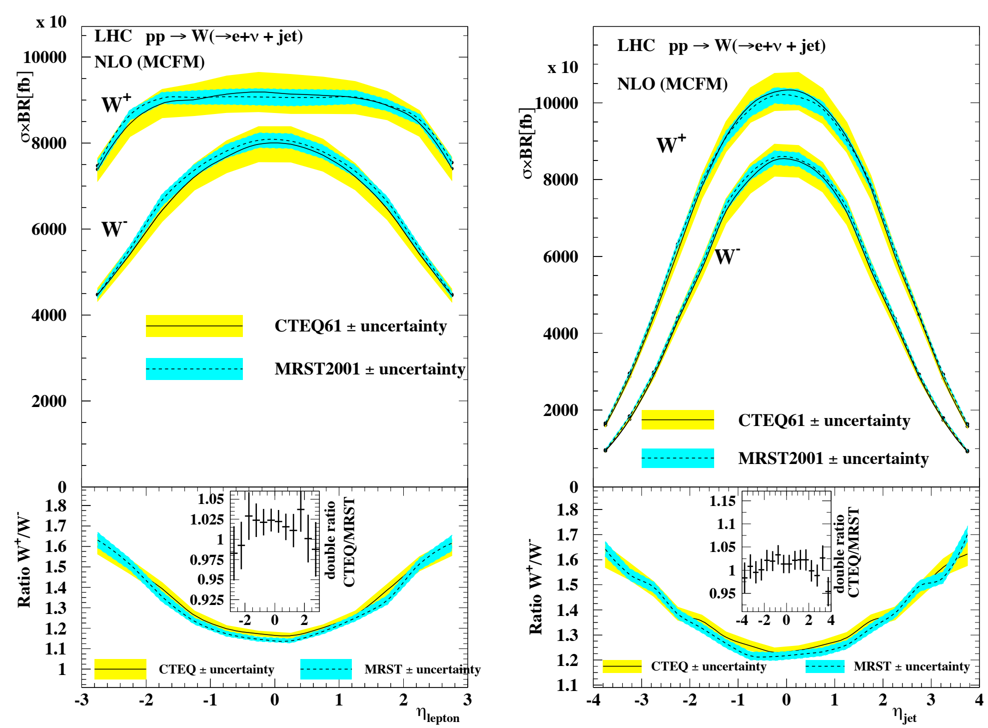
Still, the lepton pseudorapidity distribution
in inclusive DY,
or the jet pseudorapidity distribution
in the W+jet final state,
are important in constraining the *pdfs*
in the global fit of the data



H.Stenzel - HERA-LHC workshop

Luminosity monitoring (?)

DY as reference process to monitor the luminosity (like Bhabha at LEP)

$$\int \mathcal{L} dt = \frac{1}{\sigma_{th}^{tot}(pp \to l\nu)} \frac{N^{obs}}{A_W}$$

$$A_W(\eta_l^{max}) = \frac{1}{\sigma_{th}^{tot}(pp \to l\nu)} \int_{-\eta_l^{max}}^{\eta_l^{max}} d\eta_l \, \frac{d\sigma}{d\eta_l}(cuts)$$

need to precisely evaluate the detector acceptance

This approach is promising, only if we have a good control on the *pdf* uncertainties

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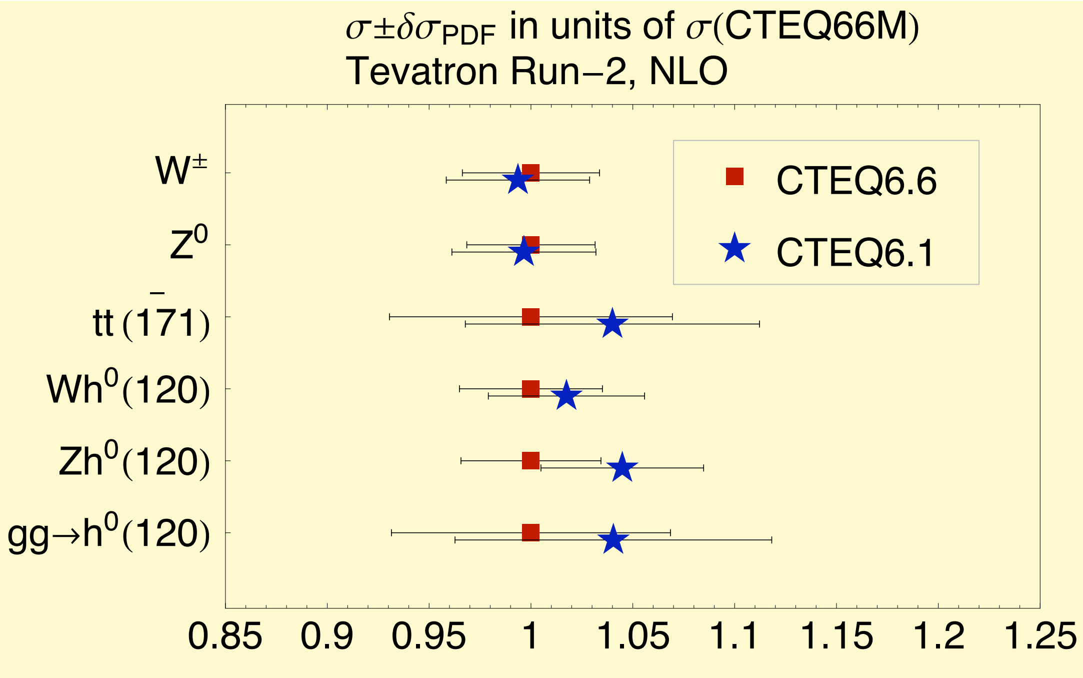
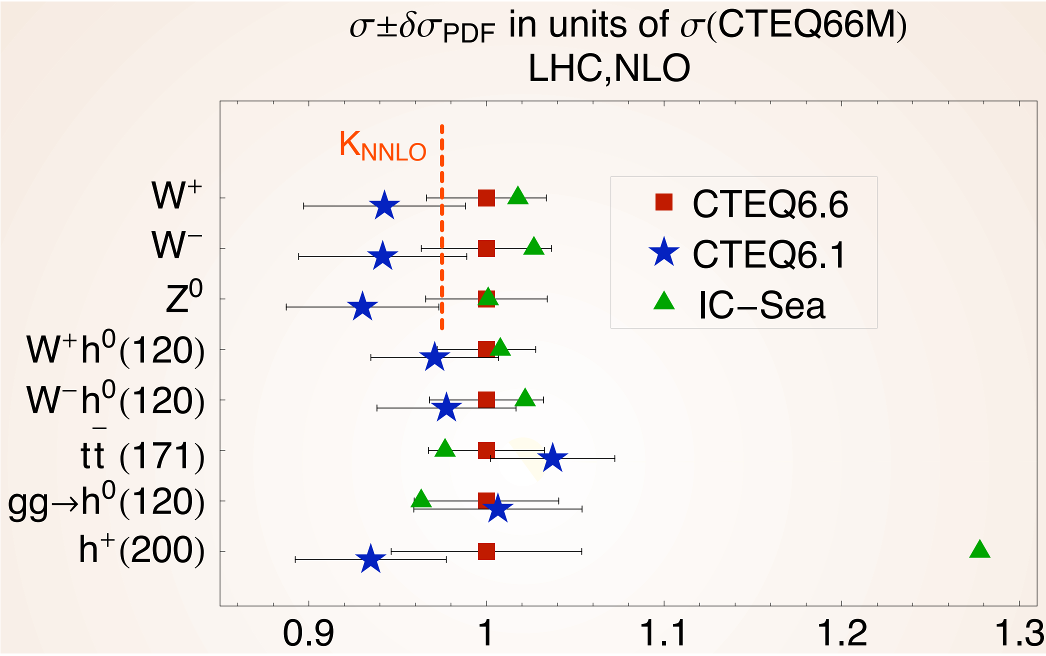
This approach is promising, only if we have a good control on the *pdf* uncertainties

all the present *pdf* sets describe well the Drell-Yan data at the Tevatron

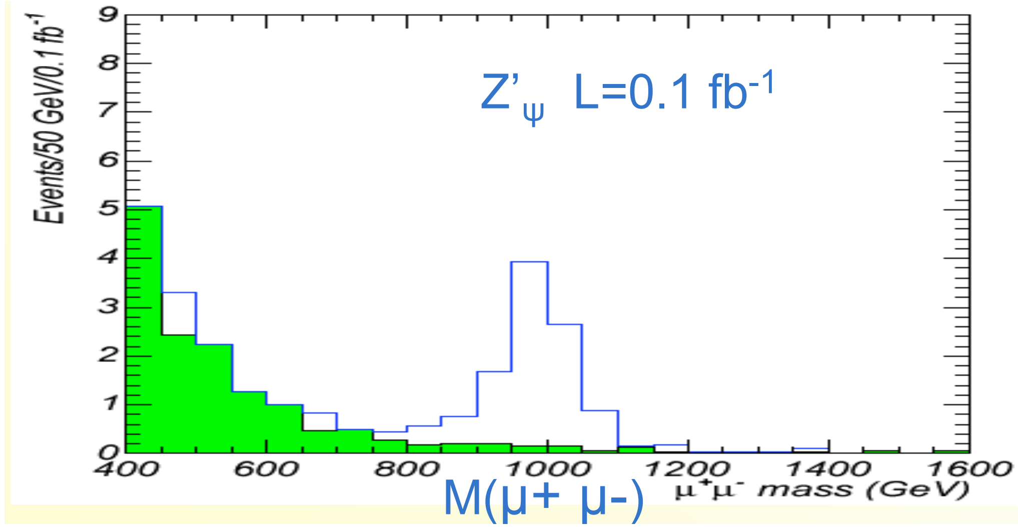
the extrapolation at the LHC is more delicate (new ranges in *x* and Q^2)





DY as background to the searches of new physics signals

from Menici's talk at IFAE 2006



- new heavy gauge bosons decay into lepton pairs
- if existing → clear signal even at low luminosity
- if not detected, SM-DY represents the main background whose precise estimate allows to put the correct lower bounds → need to control the background at per cent level
- Is the SM prediction at large invariant masses under control ?

- lepton pair as a signature in the decay of SUSY particles

NC DY as calibration tool at the Z resonance

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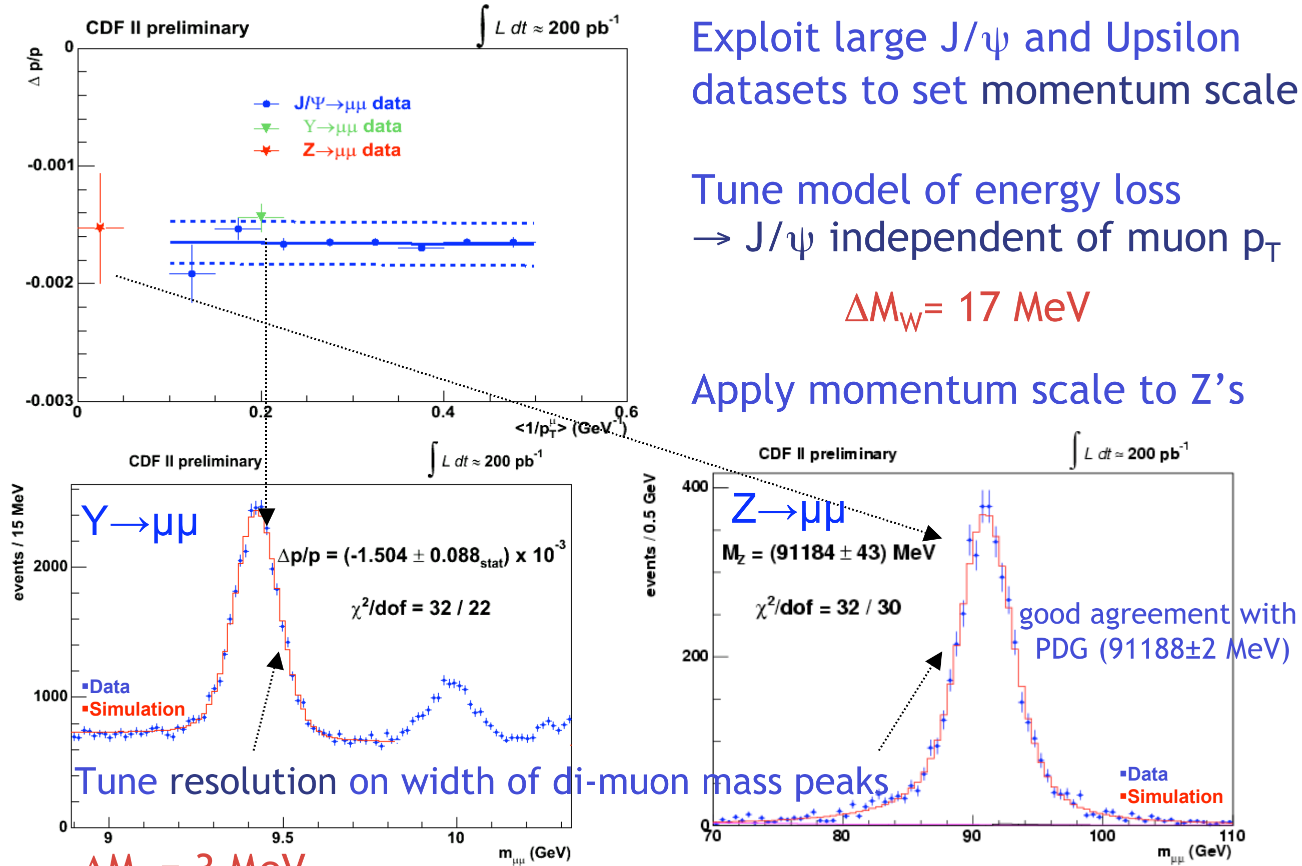


Exploit large J/ψ and Upsilon datasets to set momentum scale

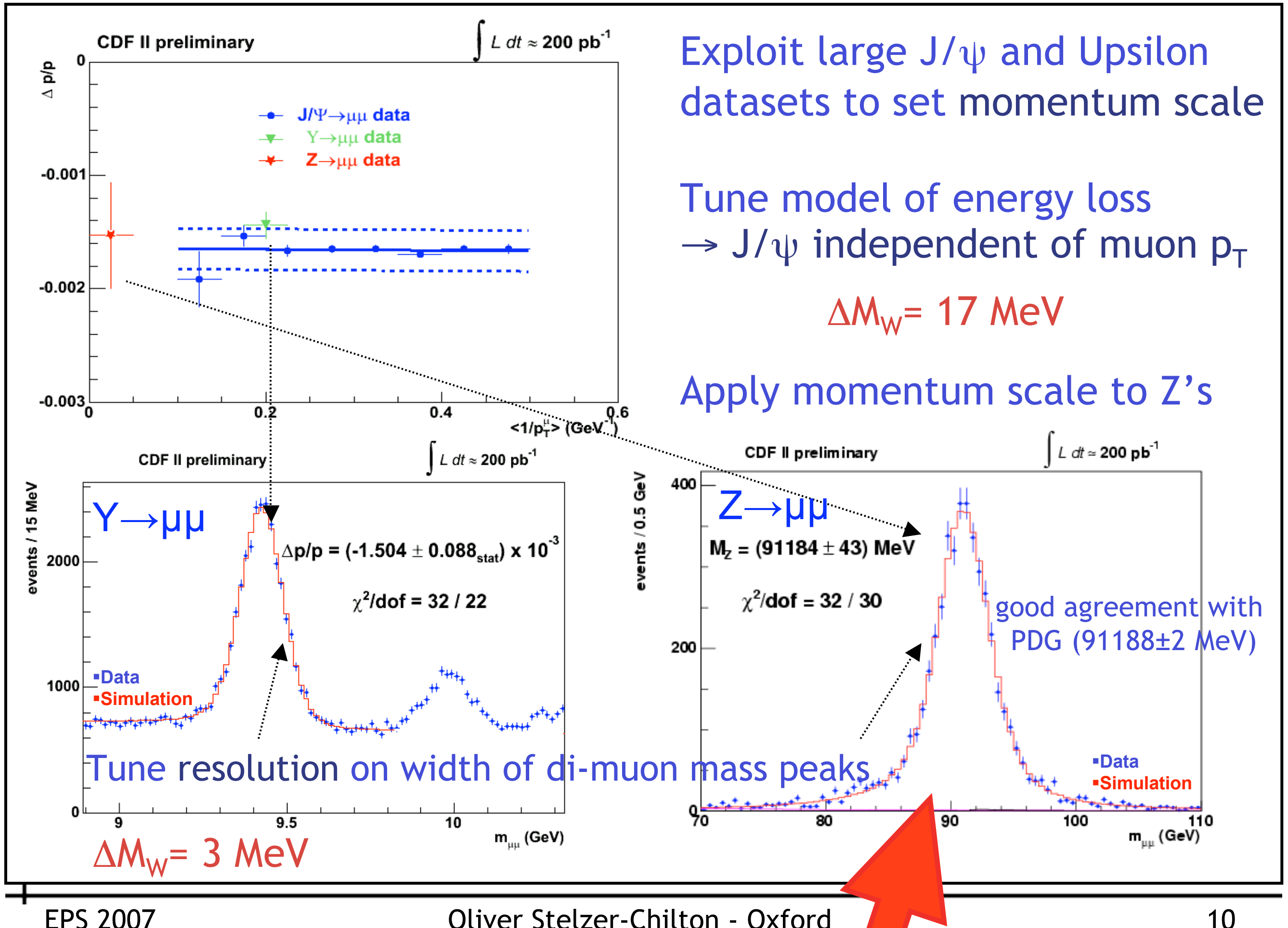
Tune model of energy loss
$\rightarrow J/\psi$ independent of muon p_T

$\Delta M_W = 17$ MeV

Apply momentum scale to Z's

$\Delta M_W = 3$ MeV

NC DY as calibration tool at the Z resonance



Relevance of QED final state radiation
to extract correctly the Z mass value from the resonance

$$\Delta M_Z^{\mathcal{O}(\alpha)} \sim 400\text{MeV} \qquad \Delta M_Z^{h.o.} \sim 40\text{MeV}$$

The error in the calibration is a systematics in the W mass measurement

QCD approximations and tools

- NLO/NNLO corrections to W/Z total production rate

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
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

- Fully differential NLO corrections to $l\bar{l}'$ (MCFM)

J. M. Campbell and R.K. Ellis, Phys.Rev.**D65**:113007

- Fully differential NNLO corrections to $l\bar{l}'$ (FEWZ)

C. Anastasiou et al., Phys.Rev. **D69** (2004) 094008
K. Melnikov and F. Petriello, hep-ph/0603182

- resummation of LL/NLL $p_\perp^W/M_W$ logs (RESBOS)

C.Balazs and C.P. Yuan, Phys.Rev. **D56** (1997) 5558

- NLO ME merged with HERWIG PS (MC@NLO)

S. Frixione and B.R.Webber., JHEP **0206**, 029 (2002)

- LO Matrix Elements Monte Carlos (ALPGEN, SHERPA,...) matched with PS

M.L.Mangano et al., JHEP **0307**, 001 (2003)
F. Krauss et al., JHEP **0507**, 018 (2005)

EW results and tools

$\mathcal{O}(\alpha_S^2) \approx \mathcal{O}(\alpha_{\rm em})$ ➡ Need to worry about EW corrections

W production

Pole approximation	D.Wackeroth and W. Hollik, PRD 55 (1997) 6788	
	U.Baur et al., PRD 59 (1999) 013002	
Exact O(alpha)	V.A. Zykunov et al., EPJC 3 (2001) 9	
	S. Dittmaier and M. Krämer, PRD 65 (2002) 073007	DK
	U. Baur and D. Wackeroth, PRD 70 (2004) 073015	WGRAD2
	A. Arbuzov et al., EPJC 46 (2006) 407	SANC
	C.M.Carloni Calame et al., JHEP 0612:016 (2006)	HORACE
Photon-induced processes	S. Dittmaier and M. Krämer, Physics at TeV colliders 2005	
	A. B.Arbuzov and R.R.Sadykov, arXiv:0707.0423	
Multiple-photon radiation	C.M.Carloni Calame et al.,PRD 69 (2004) 037301, JHEP 0612:016 (2006)	HORACE
	S.Jadach and W.Placzek, EPJC 29 (2003) 325	WINHAC
	S.Brensing, S.Dittmaier, M. Krämer and M.M.Weber, arXiv:0708.4123	DK

Z production

only QED	U.Baur et al., PRD 57 (1998) 199	
Exact O(alpha)	U.Baur et al., PRD 65 (2002) 033007	ZGRAD2
	V.A. Zykunov et al., PRD75 (2007) 073019	
	C.M.Carloni Calame et al., JHEP 0710:109 (2007)	HORACE
Multiple-photon radiation	C.M.Carloni Calame et al., JHEP 0505:019 (2005)	HORACE
	JHEP 0710:109 (2007)	

The HORACE event generator

- http://www.pv.infn.it/hepcomplex/horace.html

- developed by: C.M.Carloni Calame, G.Montagna, O.Nicrosini, A.Vicini

- exact $O(\alpha)$ radiative corrections matched with
  multiple photon radiation via QED Parton Shower
  photon induced processes

- true, fully exclusive event generator
  events saved in a Les Houches compliant form
  interfaced to LHAPDF package
  easy to interface to QCD showering programs like HERWIG or PYTHIA

- extensively checked in several rounds of tuned comparisons

Tuned comparisons of O(alpha) calculations

Les Houches workshop “Physics at TeV colliders” (May 2005)

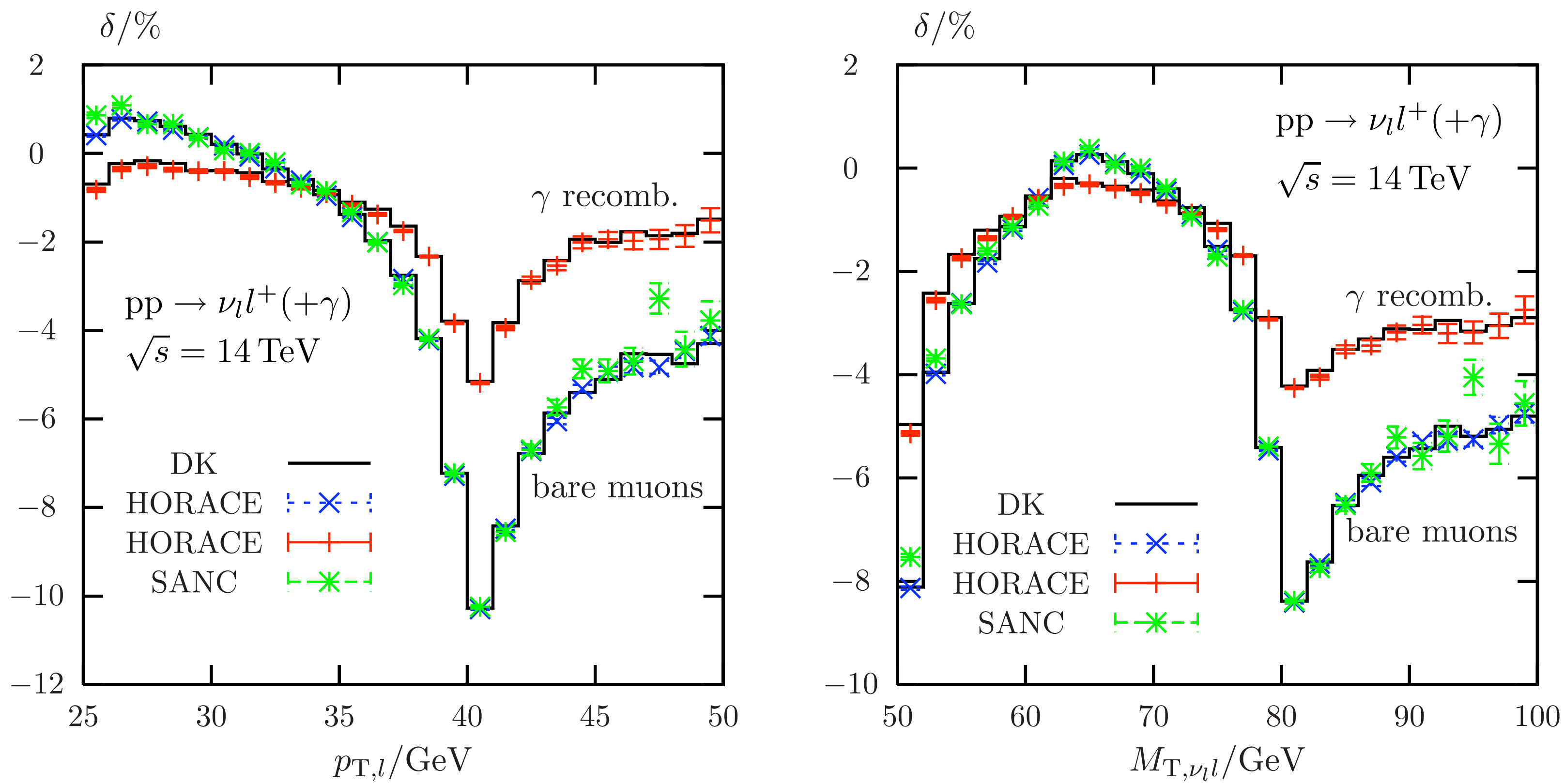


Fig. 1: Relative corrections δ as a function of the transverse-momentum $p_{\mathrm{T},l}$ and the transverse mass $M_{\mathrm{T},\nu_l l}$, as obtained from the DK, HORACE and SANC calculations. The contributions from the photon-induced processes have not been included in this comparison.

- Technical comparison: same setup (input parameters, *pdfs*, cuts, perturbative order) ⇒one expects to find the same results
- Similar comparisons during the TeV4LHC workshop

Basics of the HORACE code (both CC and NC channels)

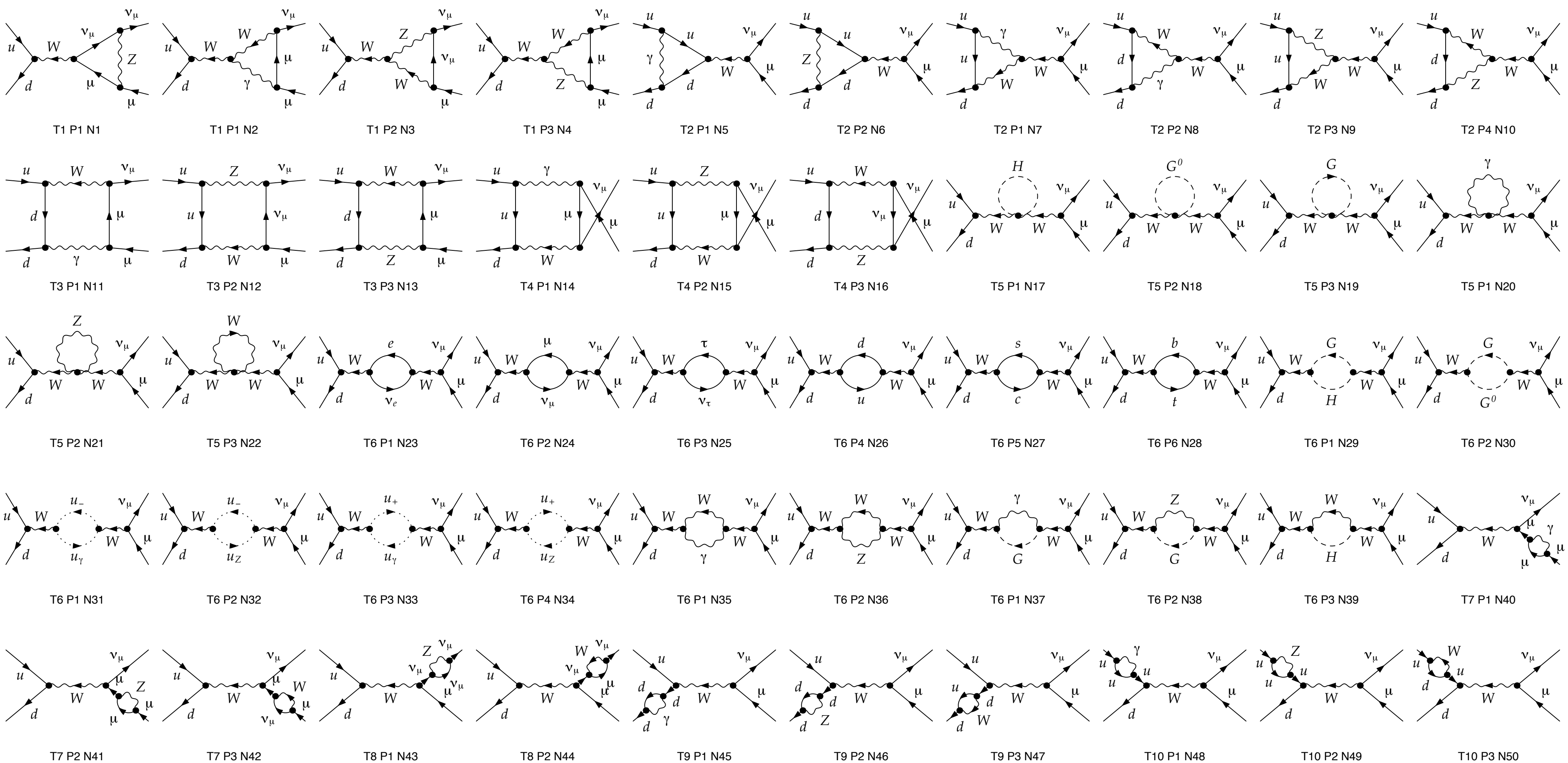
- LO calculation + QED LL corrections to all orders via Parton-Shower
- exact O(α) EW radiative corrections

➡ matching of Parton-Shower and exact results (no double countings)

- use MRST2004QED: consistent description of initial state QED radiation
  photon density in the proton ➜ photon induced processes
- subtraction procedure of IS collinear divergences to all orders
- The input parameters scheme, i.e. renormalization, $(\alpha,\, m_W,\, m_Z)$
  ➜ gauge boson masses as input parameters which can be fitted from the data
- numerical evaluation in the G_μ scheme (CC) or ($G_\mu + \alpha(q^2)$) scheme (NC)

The partonic process $u\bar{d} \to l^+ \nu_l (1\gamma)$ at $\mathcal{O}(\alpha)$

- virtual corrections


T1 P1 N1
T1 P1 N2
T1 P2 N3
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T2 P4 N10
T3 P1 N11
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T6 P2 N30
T6 P1 N31
T6 P2 N32
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T6 P4 N34
T6 P1 N35
T6 P2 N36
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T6 P2 N38
T6 P3 N39
T7 P1 N40
T7 P2 N41
T7 P3 N42
T8 P1 N43
T8 P2 N44
T9 P1 N45
T9 P2 N46
T9 P3 N47
T10 P1 N48
T10 P2 N49
T10 P3 N50

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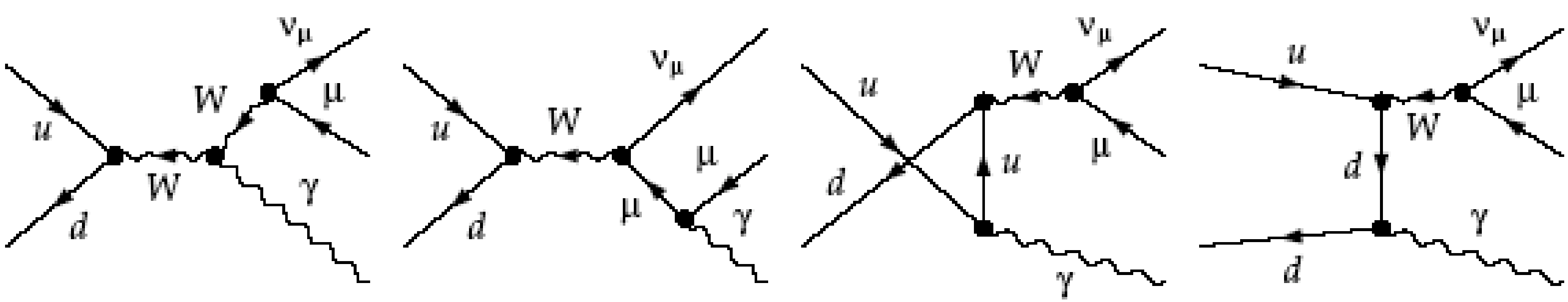
- virtual corrections

  checks:
  - UV finiteness
  - IR finiteness (when combined with soft photon emission)
  - use of two different gauges (Feynman and background)

  - fixed W decay width necessary to describe the resonance region included in all tree-level propagators and at 1-loop in all the resonant logs: $\log(s - m_W^2) \to \log(s - m_W^2 + i\Gamma_W m_W)$
  - on-shell renormalization scheme
  - large negative EW Sudakov logs

- real bremsstrahlung corrections



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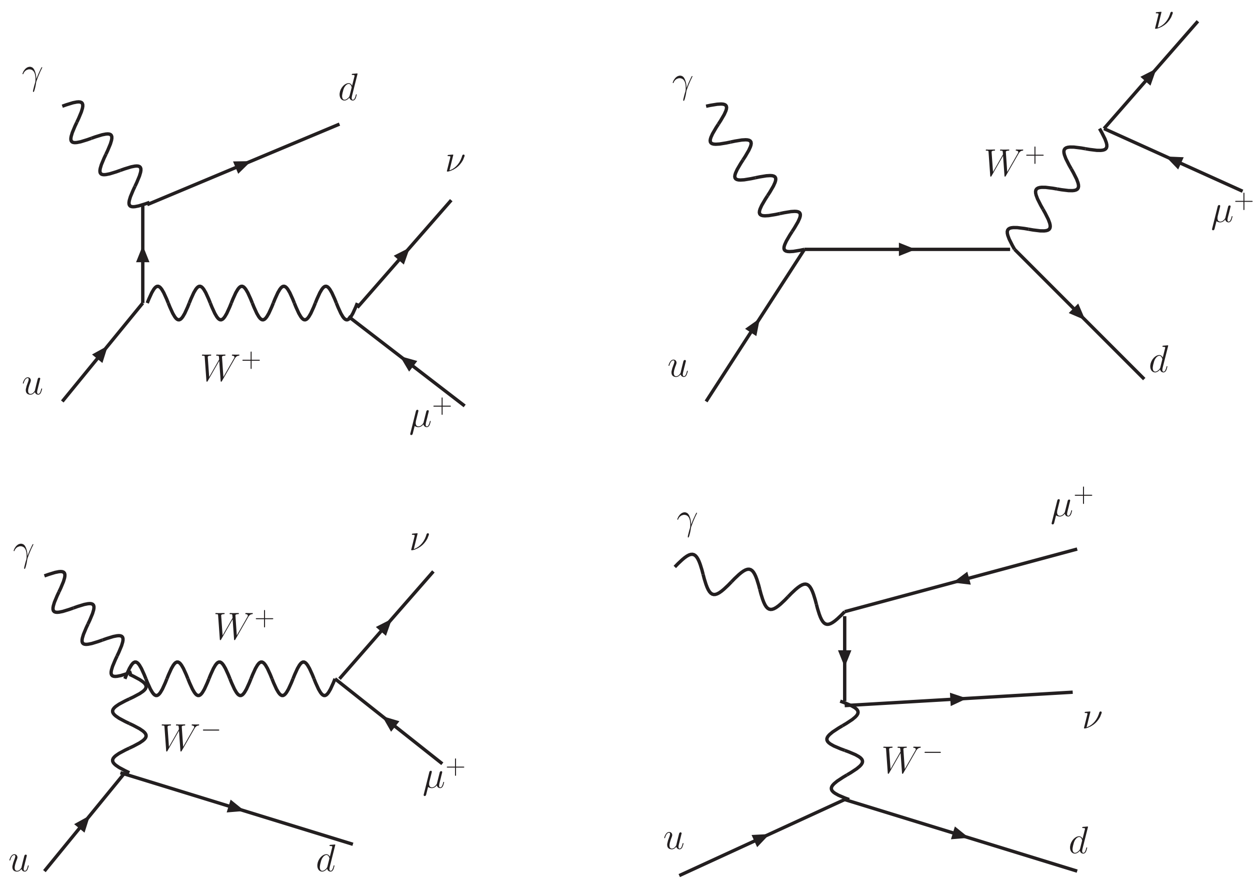
  checks:
  - independence of total cross section of soft/hard separator
  - e.m. gauge invariance (U.Baur and D.Zeppenfeld Phys.Rev.Lett.75:1002-1005,1995.)

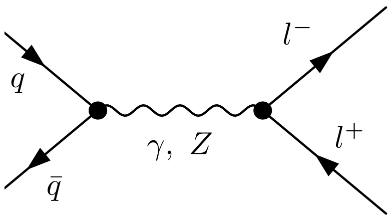
  - initial state collinear logs regulated by quark masses
  - large ISR corrections: radiative return to the W resonance

- photon induced processes

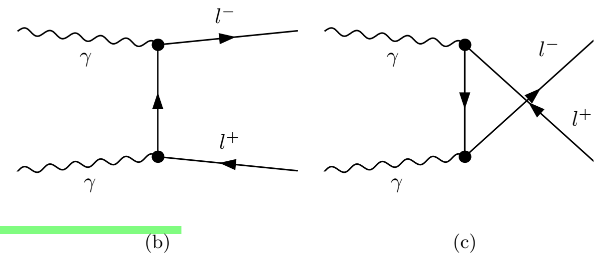
- $\gamma u \to d \mu^+ \nu_\mu$

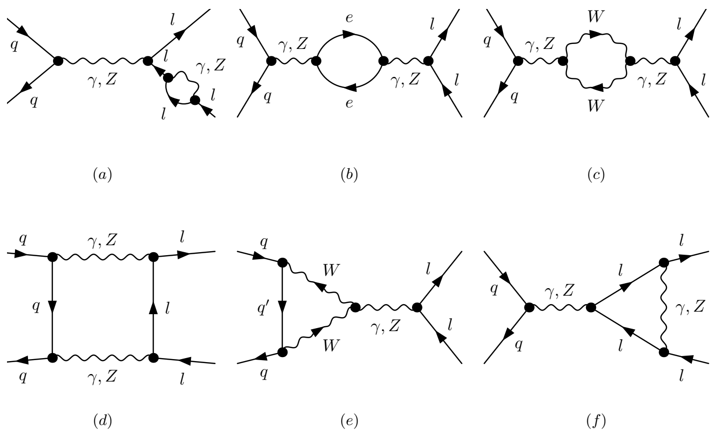


The partonic process $q\bar{q} \rightarrow l^+l^-(1\gamma)$ at $\mathcal{O}(\alpha)$

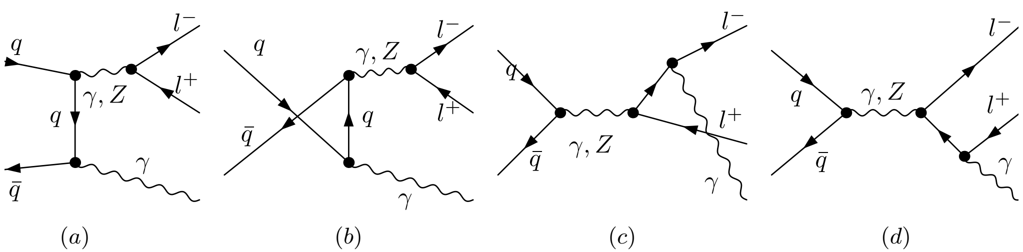


Born

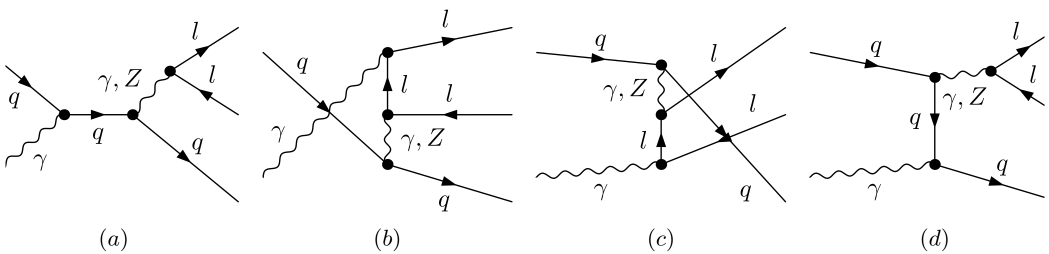




O(α) virtual



O(α) real bremsstrahlung



O(α) photon induced

Matching exact $\mathcal{O}(\alpha)$ and parton-shower results

- exact $\mathcal{O}(\alpha)$ partonic cross-section

$$d\sigma^{\alpha,ex} \equiv d\sigma^{\alpha,ex}_{SV} + d\sigma^{\alpha,ex}_{H}$$

- QED parton-shower (PS) $\mathcal{O}(\alpha)$

$$d\sigma^{\alpha,PS} = \left[\Pi_S(Q^2)\right]_{\mathcal{O}(\alpha)} d\sigma_0 + \frac{\alpha}{2\pi} P(x) I(x) dx \; dc \; d\sigma_0 \equiv d\sigma^{\alpha,PS}_{SV} + d\sigma^{\alpha,PS}_{H}$$

- resummed PS

$$d\sigma^{\infty}_{PS} =$$

$$\Pi_S(Q^2) \sum_{n=0}^{\infty} d\hat{\sigma}_0 \frac{1}{n!} \prod_{i=0}^{n} \left(\frac{\alpha}{2\pi} P(x_i) \; I(k_i) \; dx_i \; d\cos\theta_i \right)$$

$$\Pi_S(Q^2) \equiv \exp\left(-\frac{\alpha}{2\pi} \log\left(\frac{Q^2}{m^2}\right) \int_0^{1-\varepsilon} dx \; P(x)\right)$$ Sudakov form factor

$$I(k_i) = (k_i^0)^2 \sum_{j,l=1}^{N} \eta_j \eta_l \frac{p_j p_l}{(p_j k_i)(p_l k_i)}$$ photon angular spectrum

Matching exact $\mathcal{O}(\alpha)$ and parton-shower results

- exact $\mathcal{O}(\alpha)$ partonic cross-section

$$d\sigma^{\alpha,ex} \equiv d\sigma^{\alpha,ex}_{SV} + d\sigma^{\alpha,ex}_{H}$$

- parton-shower (PS) $\mathcal{O}(\alpha)$

$$d\sigma^{\alpha,PS} = \left[\Pi_S(Q^2)\right]_{\mathcal{O}(\alpha)} d\sigma_0 + \frac{\alpha}{2\pi} P(x) I(x) dx\ dc\ d\sigma_0 \equiv d\sigma^{\alpha,PS}_{SV} + d\sigma^{\alpha,PS}_{H}$$

- resummed PS + exact $\mathcal{O}(\alpha)$

$$d\sigma^{\infty}_{matched} = \Pi_S(Q^2) F_{SV} \sum_{n=0}^{\infty} d\hat{\sigma}_0 \frac{1}{n!} \prod_{i=0}^{n} \left(\frac{\alpha}{2\pi} P(x_i)\ I(k_i)\ dx_i\ d\cos\theta_i\ F_{H,i} \right)$$

$$F_{SV} = 1 + \frac{d\sigma^{\alpha,ex}_{SV} - d\sigma^{\alpha,PS}_{SV}}{d\sigma_0} \qquad F_{H,i} = 1 + \frac{d\sigma^{\alpha,ex}_{H,i} - d\sigma^{\alpha,PS}_{H,i}}{d\sigma^{\alpha,PS}_{H,i}}$$

- at $\mathcal{O}(\alpha)$ it coincides with the exact calculation

- QED higher orders coincide with pure PS

The hadronic process $pp(p\bar{p}) \to l\bar{l}X$ at $\mathcal{O}(\alpha)$

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$$\sigma(pp \to l\bar{l}X) = \sum_{a,b} \int_0^1 dx_1 dx_2 \, q_a(x_1) q_b(x_2) \, \hat{\sigma}\left(ab \to l\bar{l}(1\gamma)\right)$$

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$$\begin{aligned}
\Delta q_i(x, M^2) = & \int_x^1 dz \; q_i\left(\frac{x}{z}, M^2\right) \frac{\alpha}{2\pi} Q_i^2 \left[P_{q\to q\gamma}(z) \left(\log\left(\frac{M^2}{m_i^2}\right) - 2\log(1-z) - 1 \right) \right]_+ + f_q(z) \\
& + \; q_\gamma\left(\frac{x}{z}, M^2\right) \frac{\alpha}{2\pi} Q_i^2 \left[P_{\gamma\to q\bar{q}}(z) \left(\log\left(\frac{M^2}{m_q^2}\right) \right) \right] \; + f_\gamma(z) \qquad (3.3) \\
\Delta q_\gamma(x, M^2) = & \sum_{i=q,\bar{q}} \int_x^1 dz \; q_i\left(\frac{x}{z}, M^2\right) \frac{\alpha}{2\pi} Q_i^2 \left[P_{q\to\gamma q}(z) \left(\log\left(\frac{M^2}{m_i^2}\right) - 2\log(1-z) - 1 \right) \right]_+ + \bar{f}(z)
\end{aligned}$$

The hadronic process $pp(p\bar{p}) \to l\bar{l}X$ at $\mathcal{O}(\alpha)$

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☺ generalization to the multiple emission case: in each emission the leading singularity is removed
the integrated cross-section is independent of the initial state quark masses

Check: Total cross-section for different values of the initial state quark masses (CC channel)

Including exact $\mathcal{O}(\alpha)$ corrections

M_up	2053.07±0.22 (pb)
M_up / 50	2053.09±0.23 (pb)
M_up / 100	2052.98±0.24 (pb)

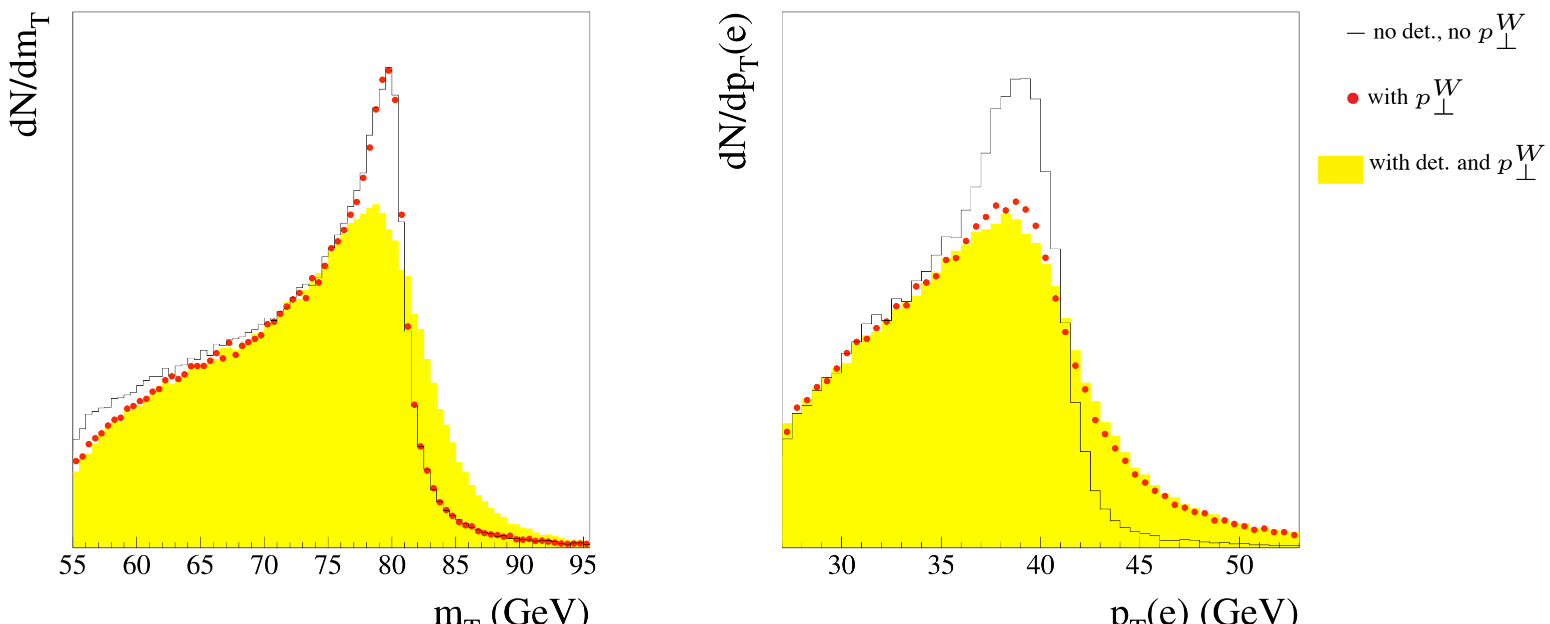
Best we can: $\mathcal{O}(\alpha)$ matched with parton-shower

M_up	2053.48±0.28 (pb)
M_up / 50	2053.73±0.32 (pb)
M_up / 100	2053.38±0.35 (pb)

The quest for precision (I) i.e. "how do we measure M_W"?

transverse mass $$M_\perp^W = \sqrt{2 p_\perp^l p_\perp^\nu \, (1 - \cos\phi_{l\nu})}$$

- reconstructed in the transverse plane
- jacobian peak at the W mass
- rather insensitive to QCD initial state radiation (e.g. $p_\perp^W$ modeling)



- Detector response effects strongly affect the distributions
- QED Final state radiation distorts the lepton $p_\perp^l$ and transverse mass distributions

→ affects the determination of M_W

→ $\mathcal{O}(\alpha)$corrections:

muons	$\Delta M_W = 168 \pm 20$ MeV
electrons	$\Delta M_W = 65 \pm 20$ MeV

The quest for precision (II)

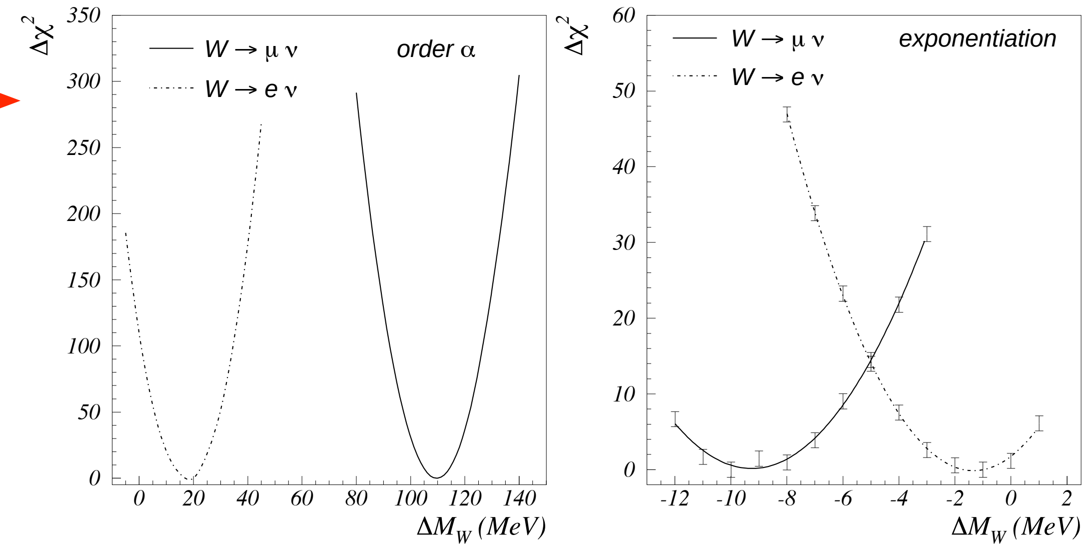
C.M. Carloni Calame et al., Phys. Rev. **D69** (2004) 037301

What is the effect of QED higher orders on the MW extraction?

Shift induced in the extraction of MW from higher order QED effects (very simplified detector for muons and electrons)

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

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



In agreement with CDF estimates
S. Malik@DIS2007

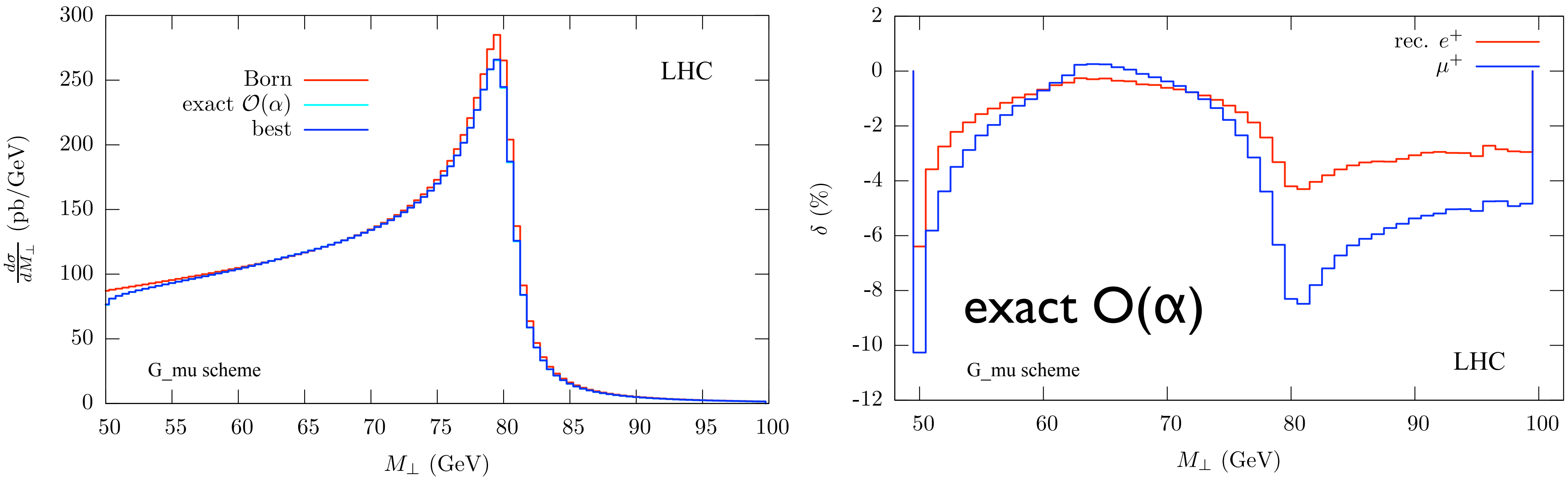
M_W systematics

CDF II preliminary L = 200

m_T Uncertainty [MeV]	Electrons	Muons	Comm
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\parallel}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

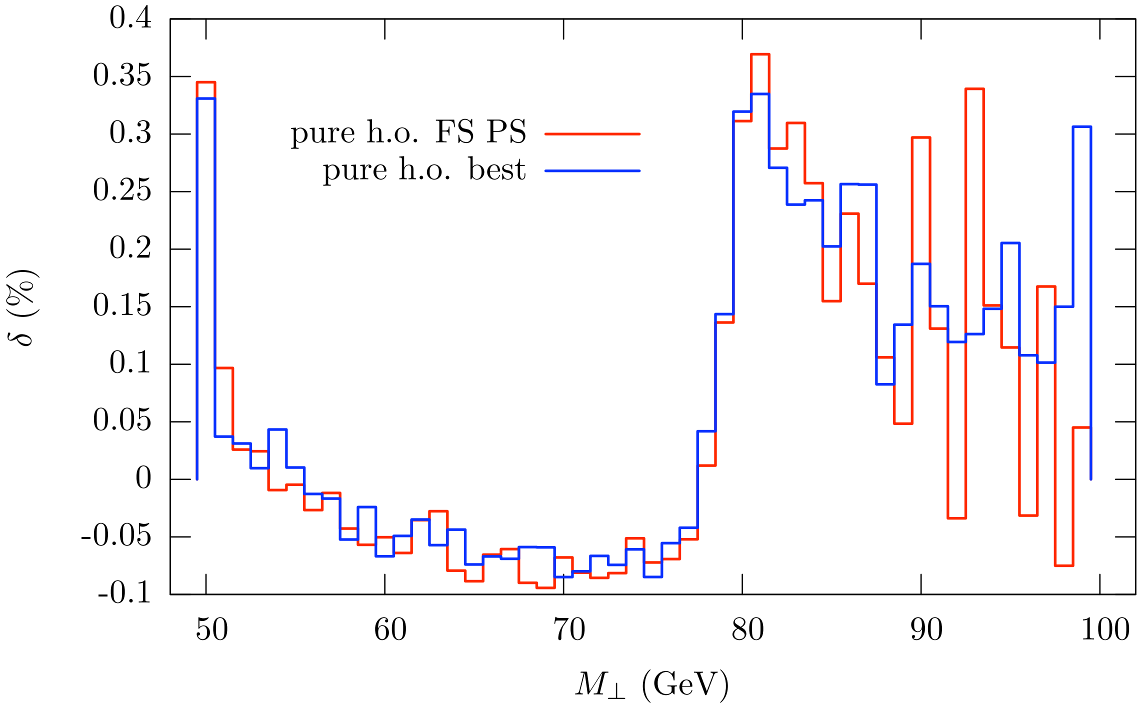
W transverse mass distribution

$$M_T^W = \sqrt{2\ p_\perp^l\ p_\perp^\nu\ (1 - \cos\phi_{l\nu})}$$

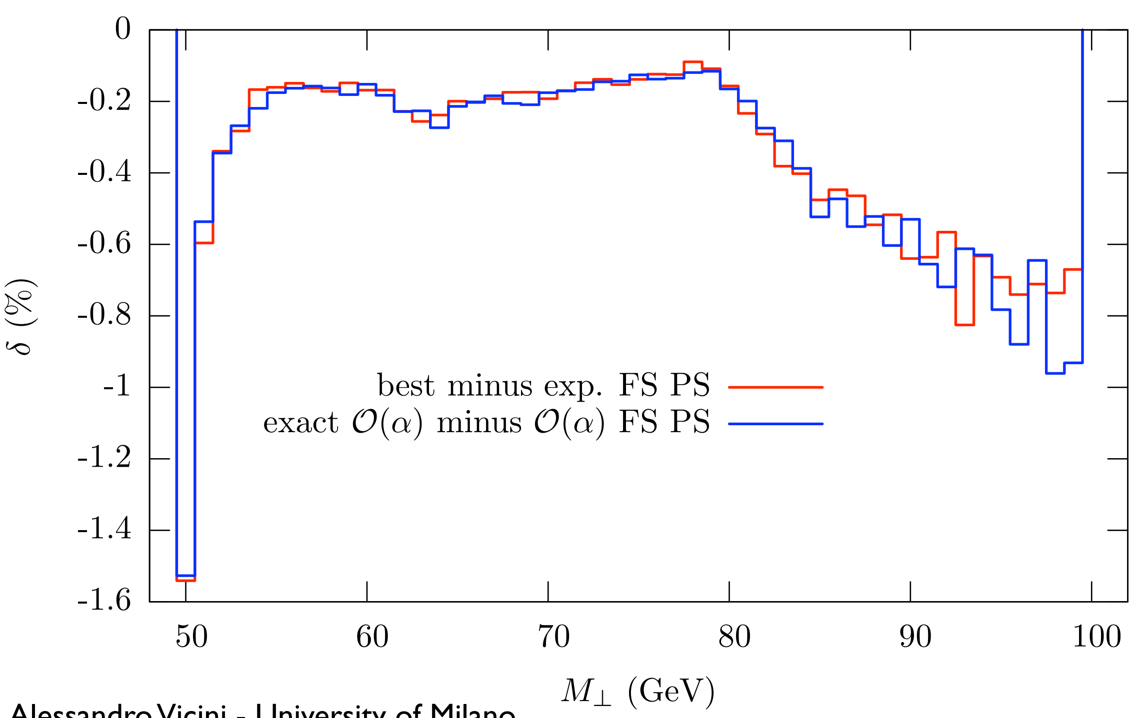


- recombined electrons show partial KLN cancelation
- bare (i.e. perfectly isolated) muons receive large final state corrections
- insensitive to photon induced processes

W transverse mass distribution: higher orders



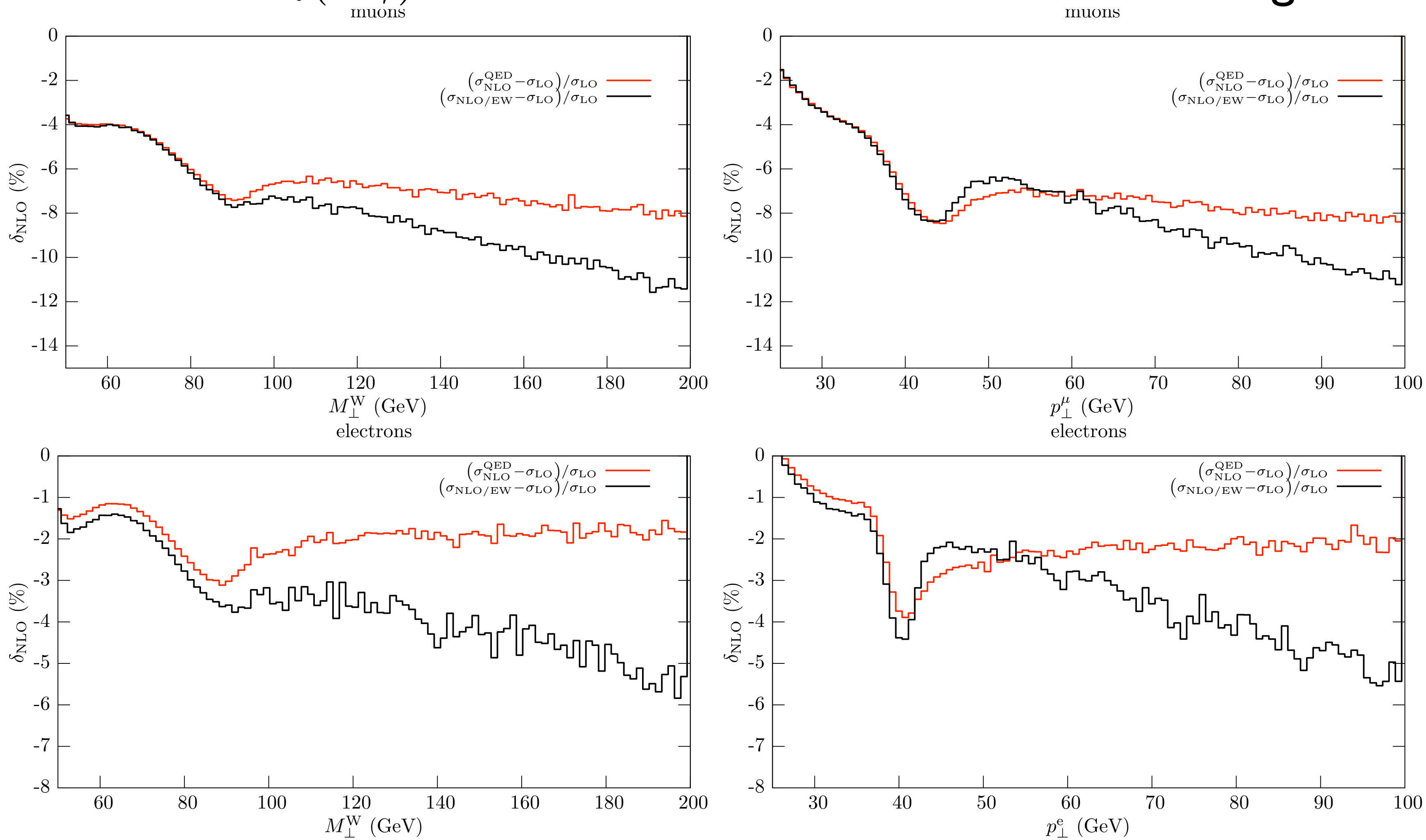
effect of multiple photon radiation



pure Parton Shower compared with the full calculation

W-width measurement and EW corrections

$p\bar{p} \to W^{\pm} \to l^{\pm}\nu_l(+\gamma)$ at Tevatron with HORACE including detector effects



Above the resonance important effect of the EW Sudakov logs

In the hard tails of the $M_{\perp}^{W}$ and $p_{\perp}^{l}$ distributions

final state QED only and full NLO-EW calculations differ at some % level

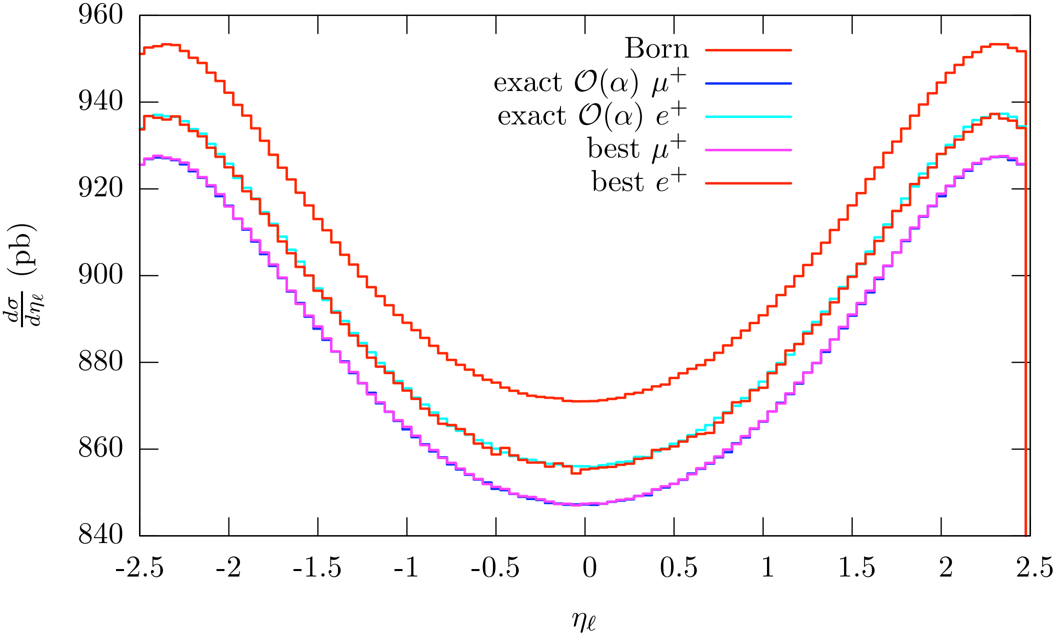
important for the precision W width measurement?

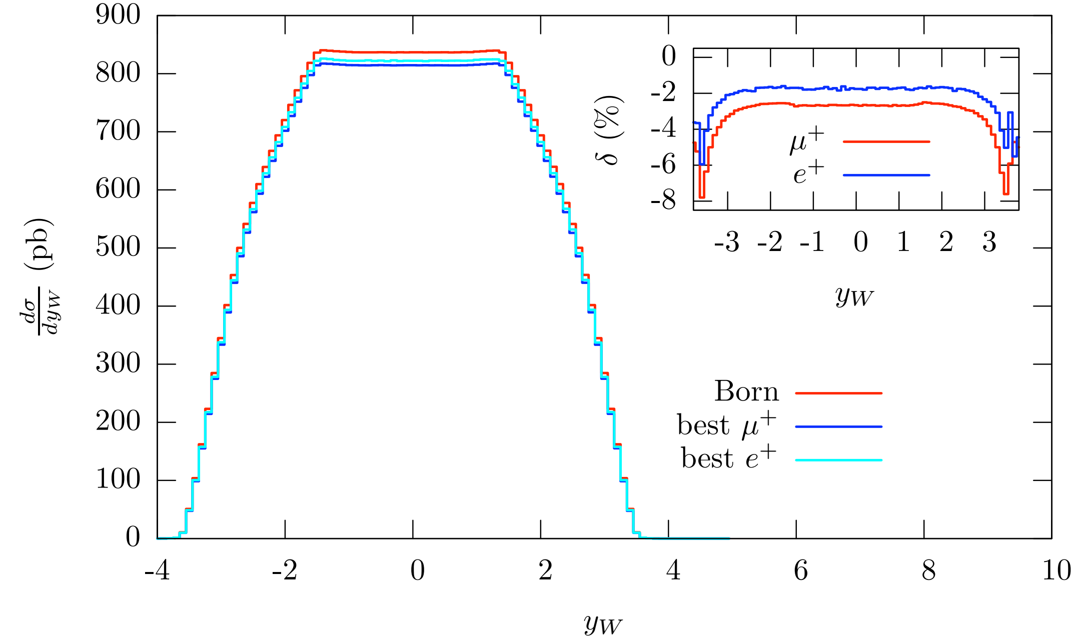
Estimates of the impact of EW corrections

D. Wackeroth in "TEV4LHC Top and Electroweak report" arXiv:0705.3251

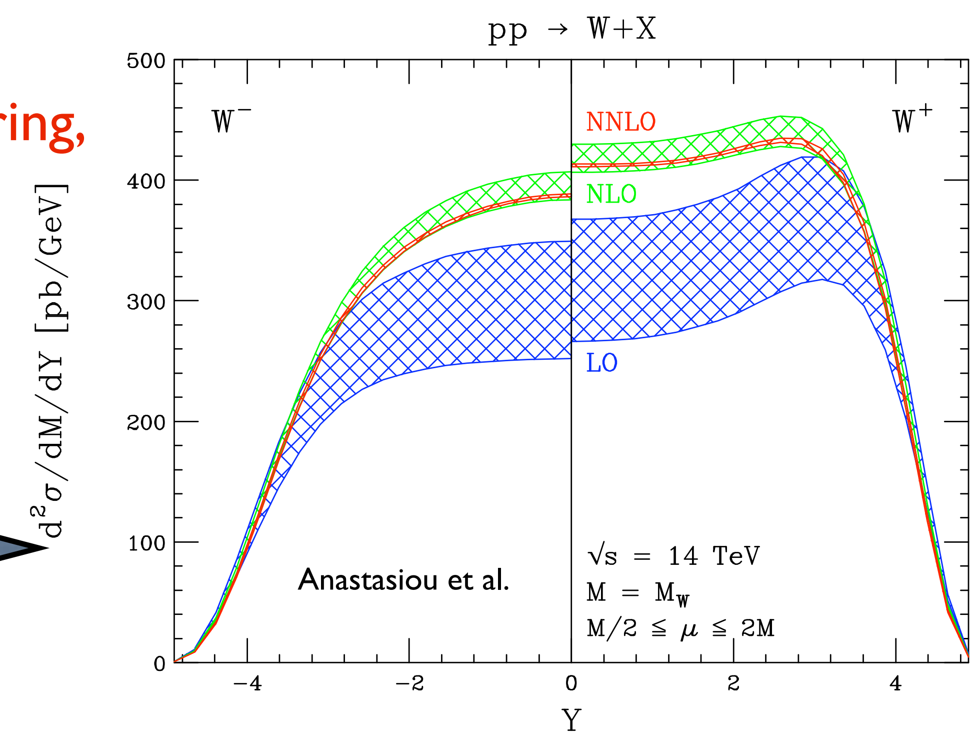
Theory includes:	Effects on observable:	Experimental precision:
final-state QED (approximation) [191]	shift in M_W: -65± 20 MeV for $W \to e\nu$ -168± 20 MeV for $W \to \mu\nu$	Tevatron RUN I: $\delta M_W^{exp.} = 59$ MeV $\delta\Gamma_W^{exp.} = 87$ MeV
full EW $\mathcal{O}(\alpha)$ corrections to resonant W production (pole approximation) [192, 193]	shift in M_W: $\approx$ 10 MeV	Tevatron RUN II: $\delta M_W^{exp.} = 27$ MeV
full EW $\mathcal{O}(\alpha)$ corrections	affects distributions at high Q^2 and direct Γ_W measurement shift in Γ_W: $\approx$ 7 MeV [189]	Tevatron RUN II: $\delta\Gamma_W^{exp.} = 25 - 30$ MeV
multiple final-state photon radiation	shift in M_W: 2(10) MeV in the $e(\mu)$ case [194]	LHC: $\delta M_W^{exp.}$=15 MeV

W-rapidity and lepton pseudo-rapidity distributions (LHC)

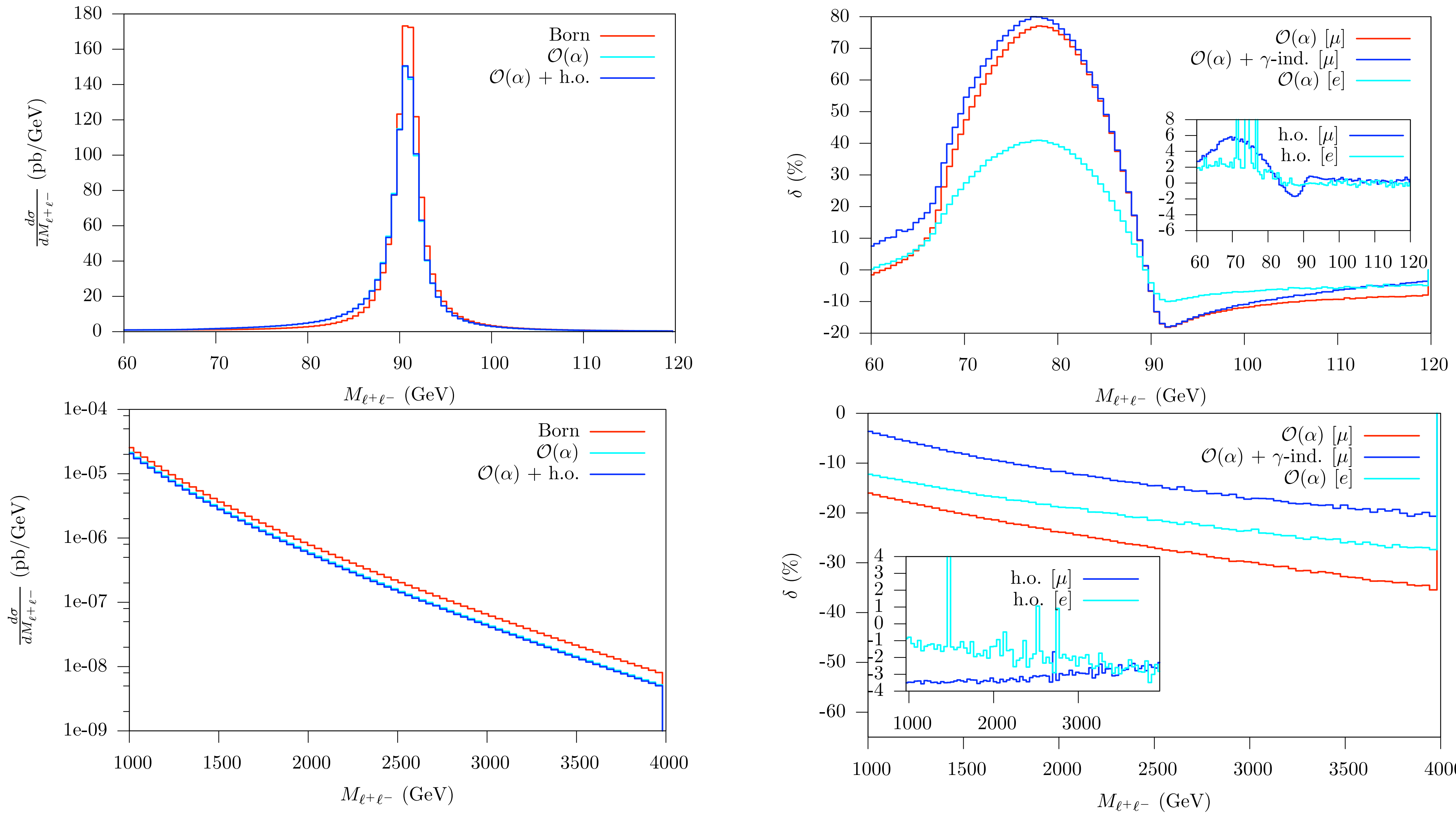




- relevant for acceptances, luminosity monitoring, *pdfs* constraining
- (flat) correction factor ranges from -2% (W) to -4% (lepton)
- of the same order of present NNLO-QCD uncertainty



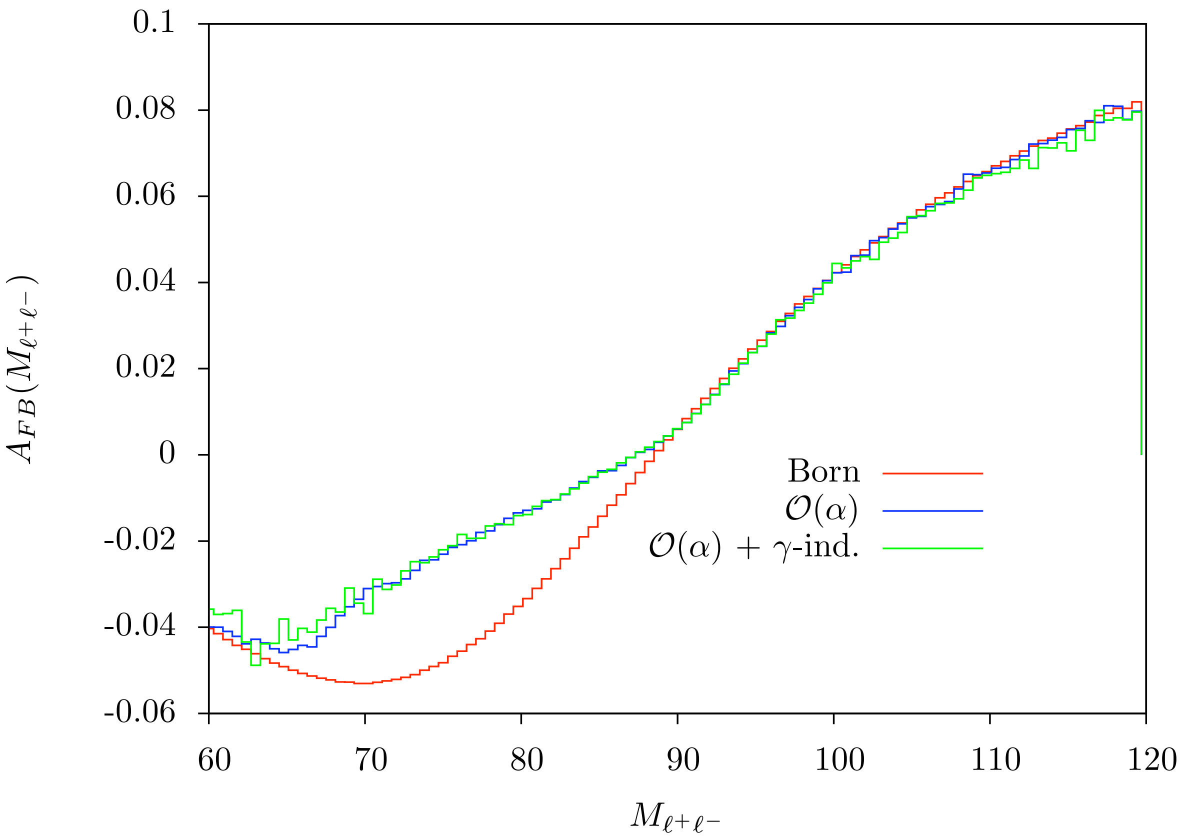
Z observables: invariant mass distribution (LHC)



- huge radiative corrections below the Z peak (final state radiation)
- in the large mass tail, large negative corrections (EW Sudakov logs)
  not negligible effect of (tree-level) photon-induced subprocess

Z observables: forward-backward asymmetry and $\sin^2\theta^{lep}_{eff}$

$$A_{FB}(M_{l^+l^-}) = \frac{F(M_{l^+l^-}) - B(M_{l^+l^-})}{F(M_{l^+l^-}) + B(M_{l^+l^-})} \qquad F(M_{l^+l^-}) = \int_0^1 d\cos\theta^* \, \frac{d\sigma}{d\cos\theta^*}, \quad B(M_{l^+l^-}) = \int_{-1}^0 d\cos\theta^* \, \frac{d\sigma}{d\cos\theta^*}$$



$$A_{FB} = b(a - \sin^2\theta^{lep}_{eff})$$

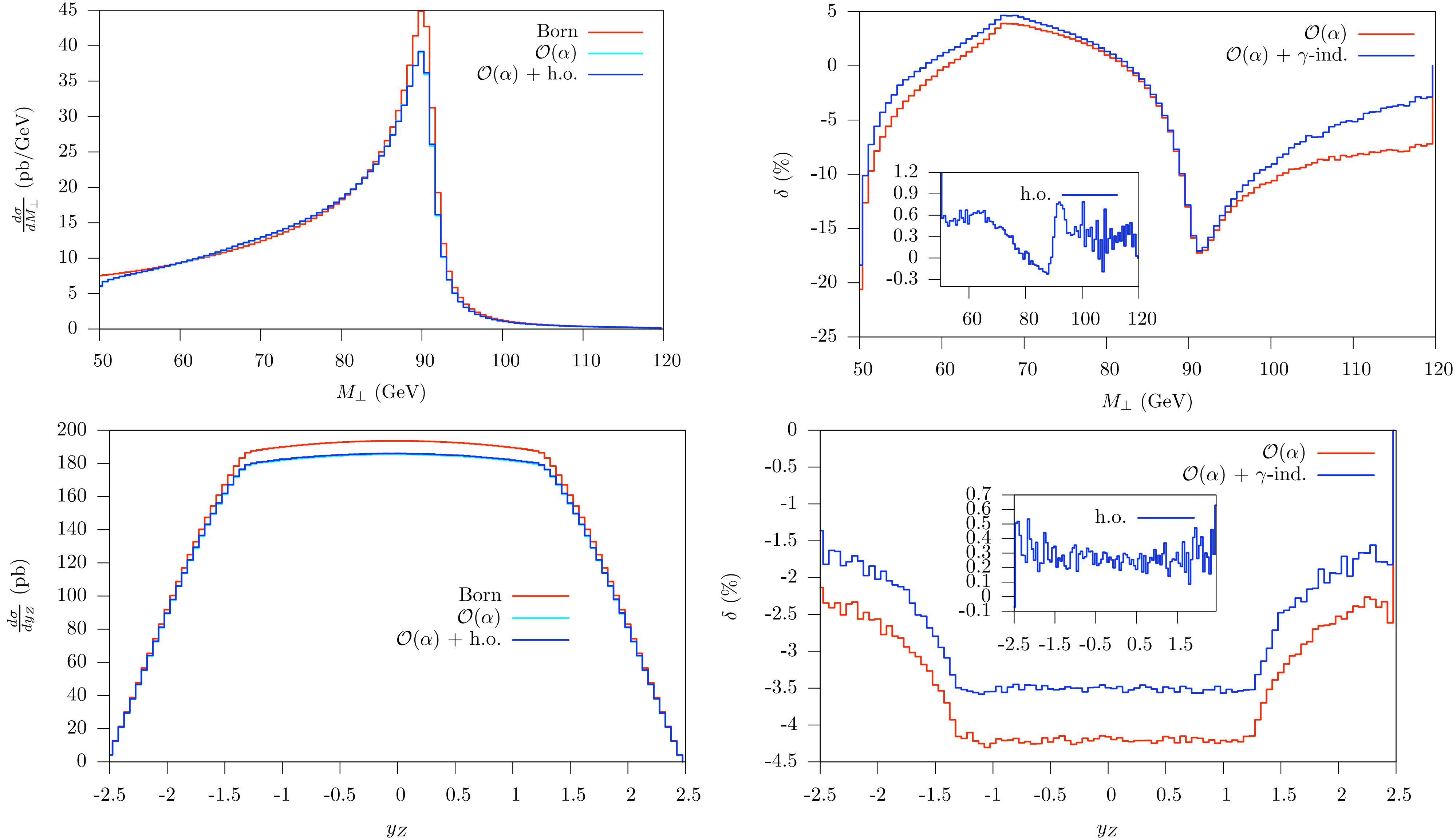
$$\Delta\sin^2\theta^{lep}_{eff} \sim 0.00014$$

(with 100 fb^{-1})

- detailed study of O(alpha) EW corrections and of the backgrounds in Baur et al., Phys.Rev.D57 (1998)199

- multiple-photon effects and photon-induced processes do not contribute significantly to this observable

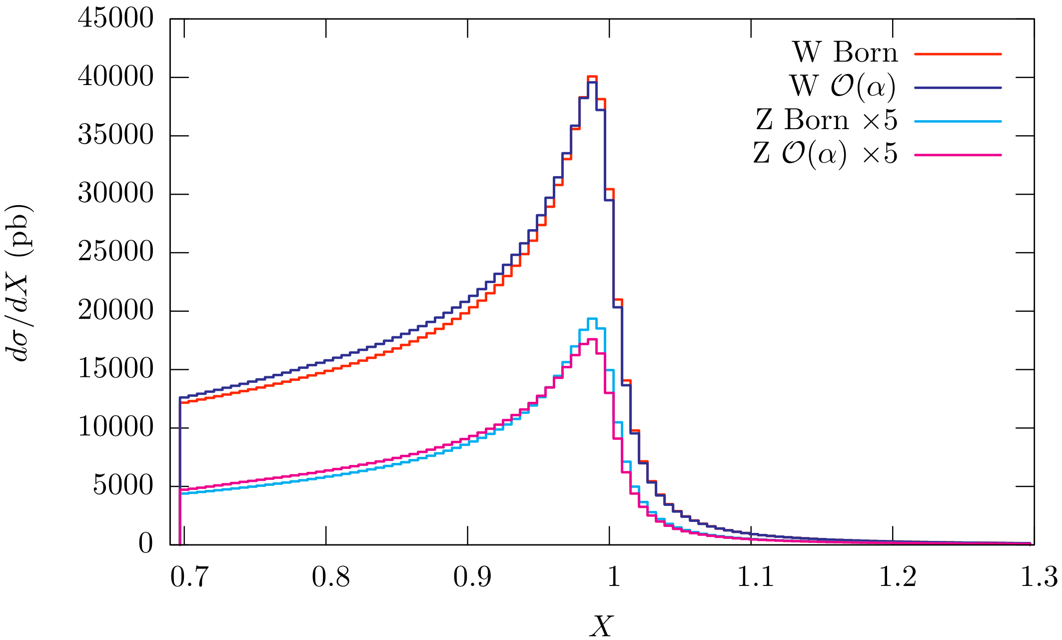
Z observables: transverse mass and Z rapidity distributions

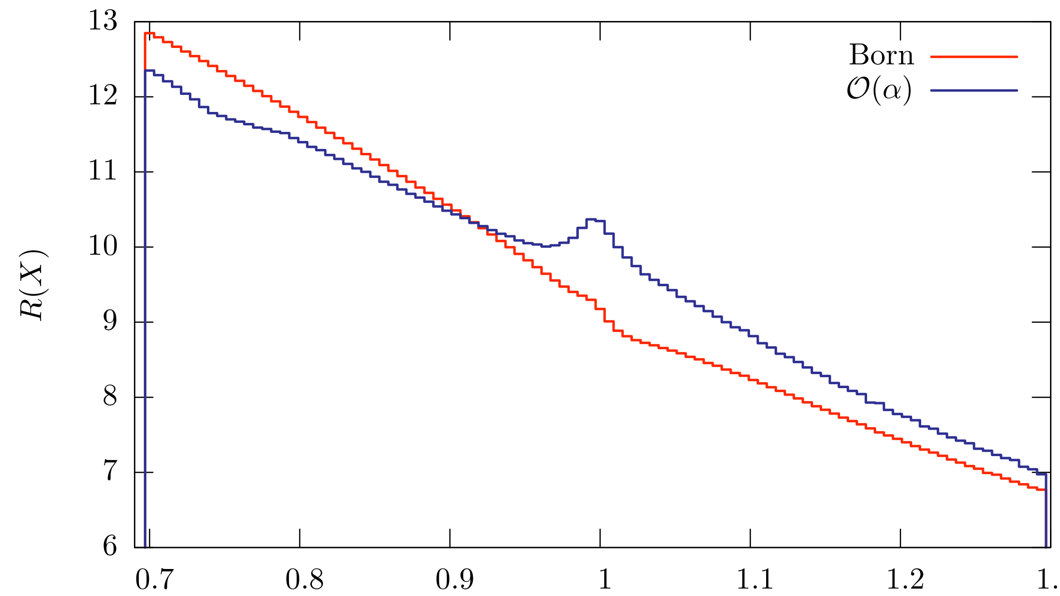


- above the Z peak, not negligible effect of the photon-induced processes

- Z rapidity: QED h.o. and photon-induced contribute at the several per mille level

W/Z transverse mass ratio (preliminary)





$$R = \left(\frac{d\sigma}{dX_W}\right) / \left(\frac{d\sigma}{dX_Z}\right), \qquad X_V = M_V^{\perp}/M_V$$

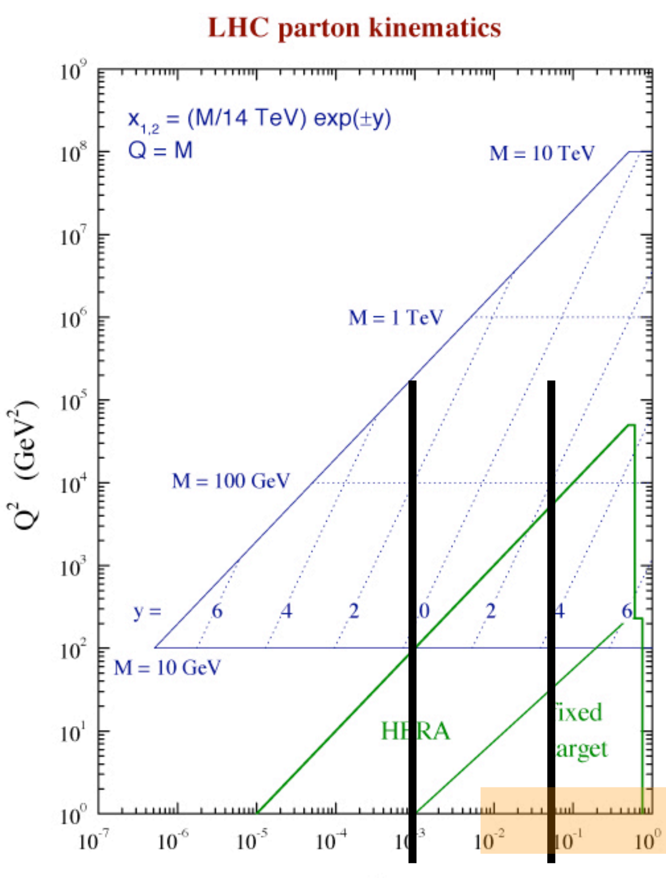
- the pQCD radiative corrections partially cancel in the ratio (Giele, Keller, Phys.Rev.D57:4433 (1998))
- the systematics due to the *pdf*s partially cancel in the ratio
- delicate discussion about the systematics on the acceptances
- the EW radiative corrections do not cancel in the ratio
- the ratio is sensitive to the precise value of M_W

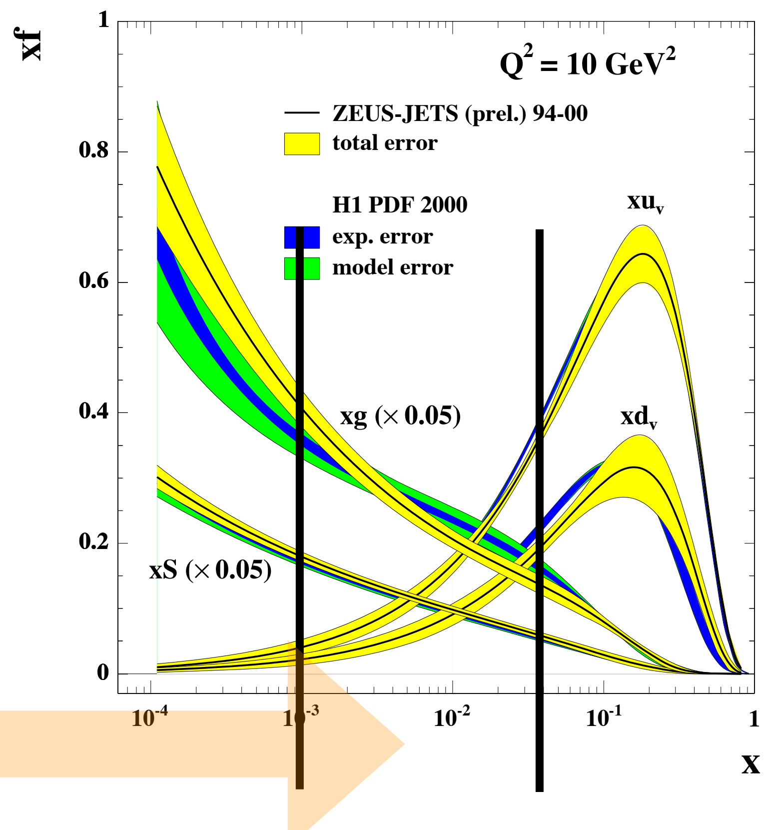
The Drell-Yan processes and QCD dynamics

- at the LHC the lepton pair is (very often) accompanied by additional jets

	N=0	N=1	N=2	N=3
Tevatron, no cuts	92.1 %	7.6 %	0.3 %	
LHC, no cuts	79 %	15 %	5 %	0.1 %
LHC, MT>1 TeV	30 %	38 %	21 %	8 %

- at LHC the cross section with N=1 enhanced by the subprocess with a gluon in the initial state (gluon density larger than at the Tevatron)
- the large MT cut forces the showering process (→enhances N=1,2,3)





Combining QCD and EW corrections

in collaboration with C. M. Carloni Calame, G. Balossini, G. Montagna, O. Nicrosini, F. Piccinini, M. Moretti, M. Treccani

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- First attempt: combination of soft-gluon resummation with final state QED corrections   Q.-H. Cao and C.-P. Yuan, Phys. Rev. Lett. **93** (2004) 042001   ResBos-A

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- Additive combination of QCD and EW corrections:

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

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- QCD = ALPGEN (with CKKM-MLM Parton Shower matching), ResBos-CSS, MC@NLO, FEWZ, MCFM

- EW = HORACE interfaced with HERWIG QCD Parton Shower

NLO-EW corrections convoluted with QCD PS ⇒ inclusion of $\mathcal{O}(\alpha\alpha_s)$ terms

not reliable when hard non collinear radiation is important

➜ a full 2-loop $\mathcal{O}(\alpha\alpha_s)$ calculation is needed

see: J.H. Kühn, A.Kulesza, S.Pozzorini, M.Schulze, hep-ph/0703283
W. Hollik, T.Kasprzik, B.A. Kniehl, arXiv:0707.2553

Monte Carlo tuning: Tevatron and LHC

Monte Carlo	ALPGEN	FEWZ	HORACE	ResBos-A
σ_{LO} (pb)	906.3(3)	906.20(16)	905.64(4)	905.26(24)

Table: MC tuning at the Tevatron for the LO cross section of the process $p\bar{p} \to W^{\pm} \to \mu^{\pm}\nu_{\mu}$, using CTEQ6M with $\mu_R = \mu_F = \sqrt{x_1 x_2 s}$

Monte Carlo	ALPGEN	FEWZ	HORACE
σ_{LO} (pb)	8310(2)	8304(2)	8307.9(2)

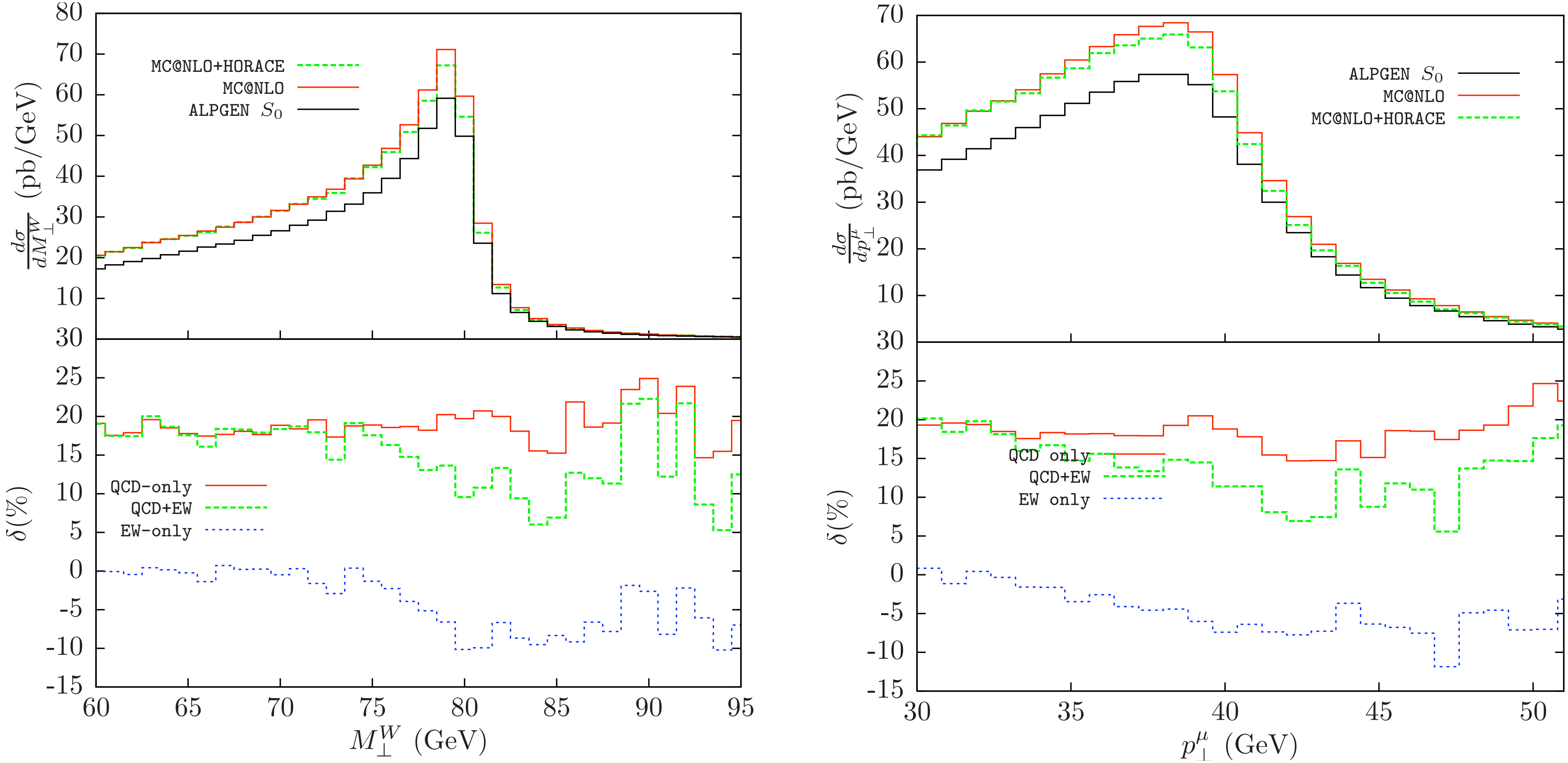
Table: MC tuning at the LHC for the LO cross section of the process $pp \to W^{\pm} \to \mu^{\pm}\nu_{\mu}$, using MRST2004QED with $\mu_R = \mu_F = \sqrt{p_{\perp,W}^2 + M_W^2}$

Monte Carlo	$\sigma_{\mathrm{NLO}}^{\mathrm{Tevatron}}(\mathrm{pb})$	$\sigma_{\mathrm{NLO}}^{\mathrm{LHC}}(\mathrm{pb})$
MC@NLO	2638.8(4)	20939(19)
FEWZ	2643.0(8)	21001(14)

Table: MC tuning for MC@NLO and FEWZ NLO inclusive cross sections of the process $\overset{(-)}{pp} \to W^{\pm} \to \mu^{\pm}\nu_{\mu}$, with CTEQ6M (Tevatron) and MRST2004QED (LHC)

- ⋆ After appropriate “tuning”, and with same input parameters and cuts, Monte Carlos agree at $\sim 0.1\%$ level (or better)

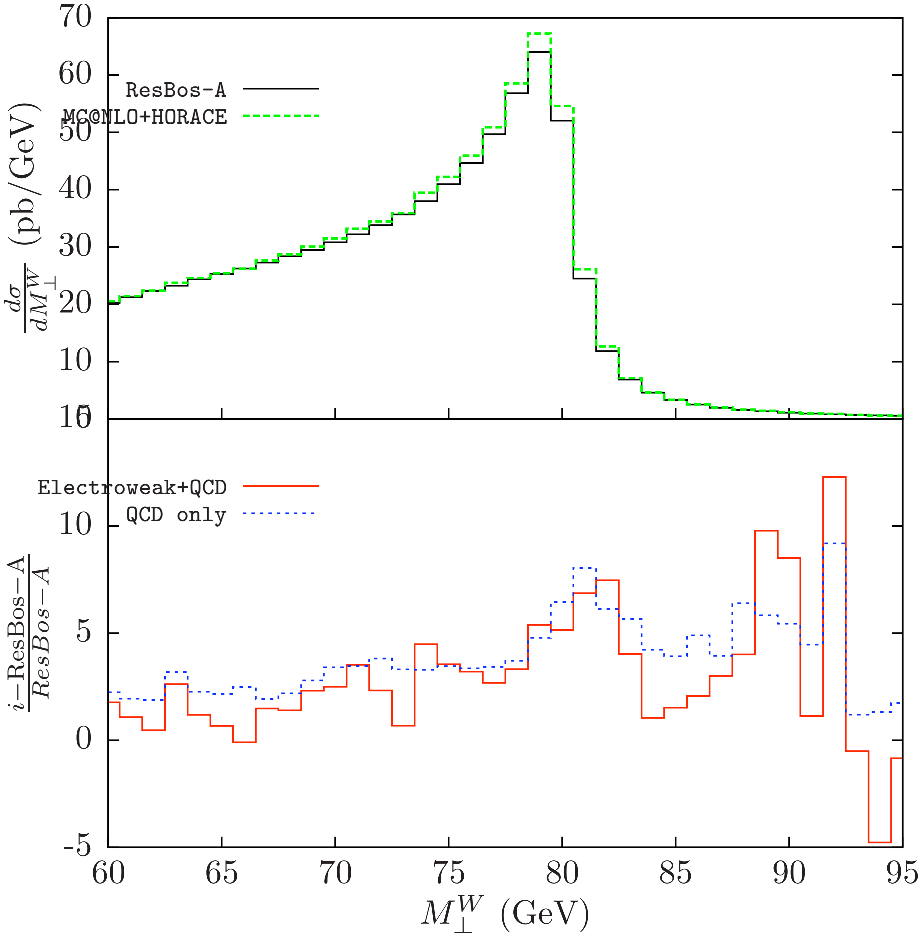
precision physics: EW + QCD @ the Tevatron

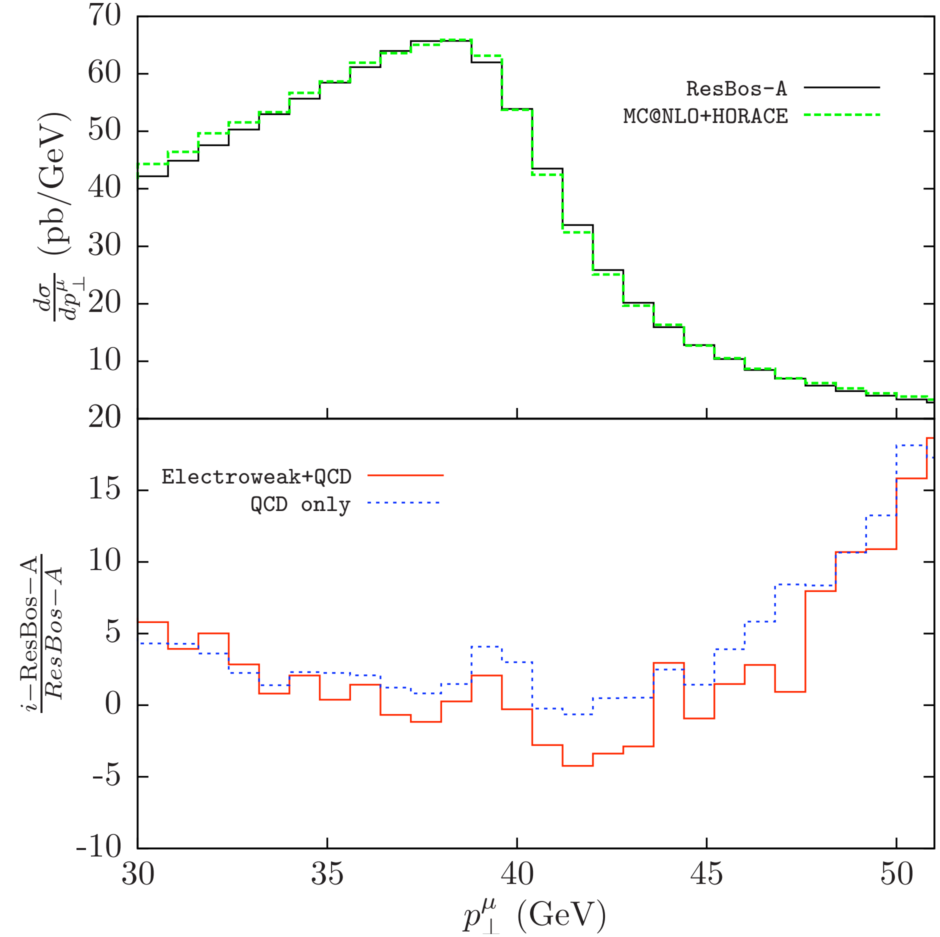


- the relative effect expressed in units Born+PS
- positive QCD corrections compensate negative EW corrections
- the convolution with QCD Parton Shower modifies the relative effect and shape of the EW corrections

precision physics: EW + QCD @ the Tevatron

Absolute comparison: ResBos(CSS)-A vs MC@NLO + HORACE





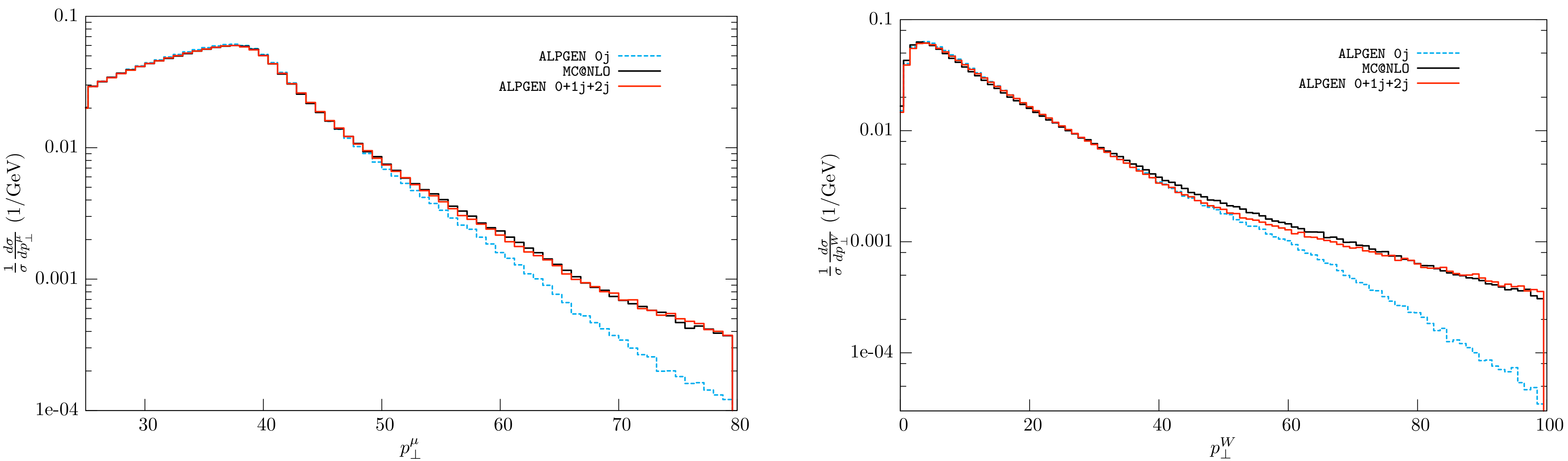
- Different normalization of the distributions
- Around the jacobian peak, agreement at a few % level
- in the soft $M_\perp^W$ tail and in the hard $p_\perp^\mu$ tail, differences can reach the 15 % level
- Around the jacobian peak, bulk of the EW effects by QED final state radiation

precision physics: QCD @ the LHC : $p_\perp^\mu$ and $p_\perp^W$ distributions

$p\bar{p} \to \mu^\pm \nu_\mu \quad \sqrt{S} = 14\text{TeV} \quad (G_\mu, M_W, M_Z) + \alpha(0)$ for real photons

$p_{\perp,l}$ and $p_{\perp,\nu} > 25\text{GeV}, \ |\eta_l| < 2.5 \ \oplus \ (possibly) \ M_\perp^W > 1$ TeV

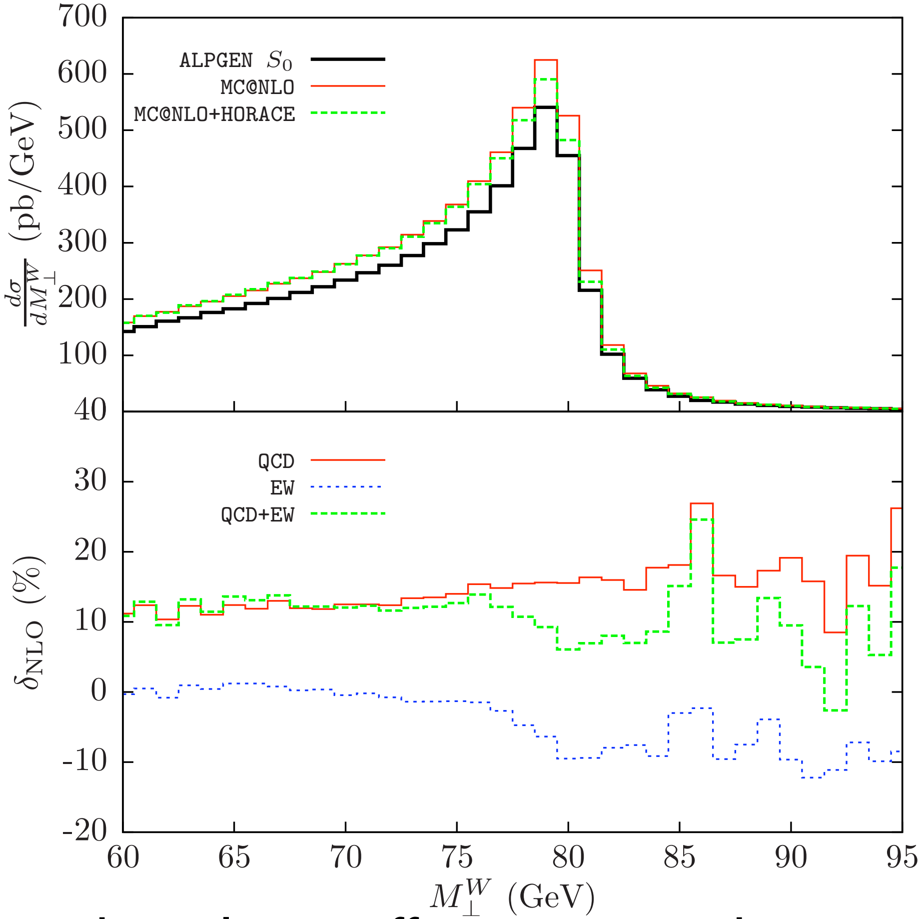
NLO MRST2004QED with $\mu_R = \mu_F = \sqrt{p_{\perp,W}^2 + M_W^2}$

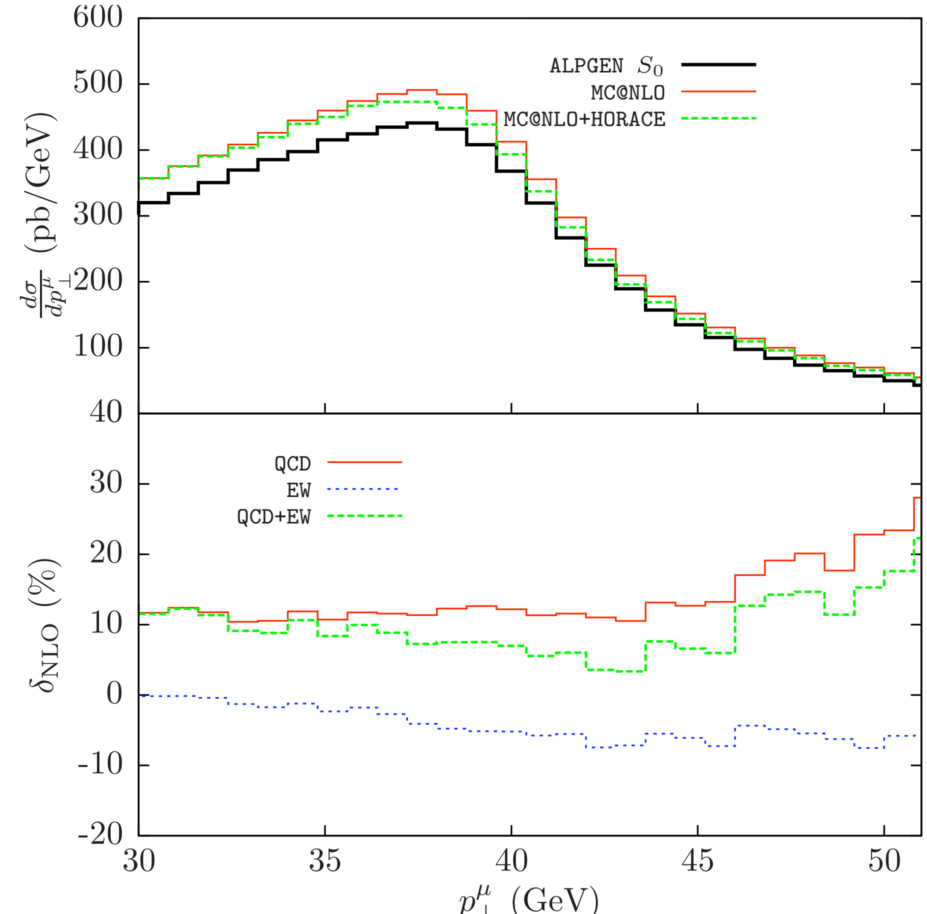


- generators normalized to their cross section ⇒ shape differences

- exact NLO with Parton Shower important in the high tails of $p_\perp^l$ and $p_\perp^W$
- agreement in the shapes predicted by MC@NLO and ALPGEN 0+1j+2j

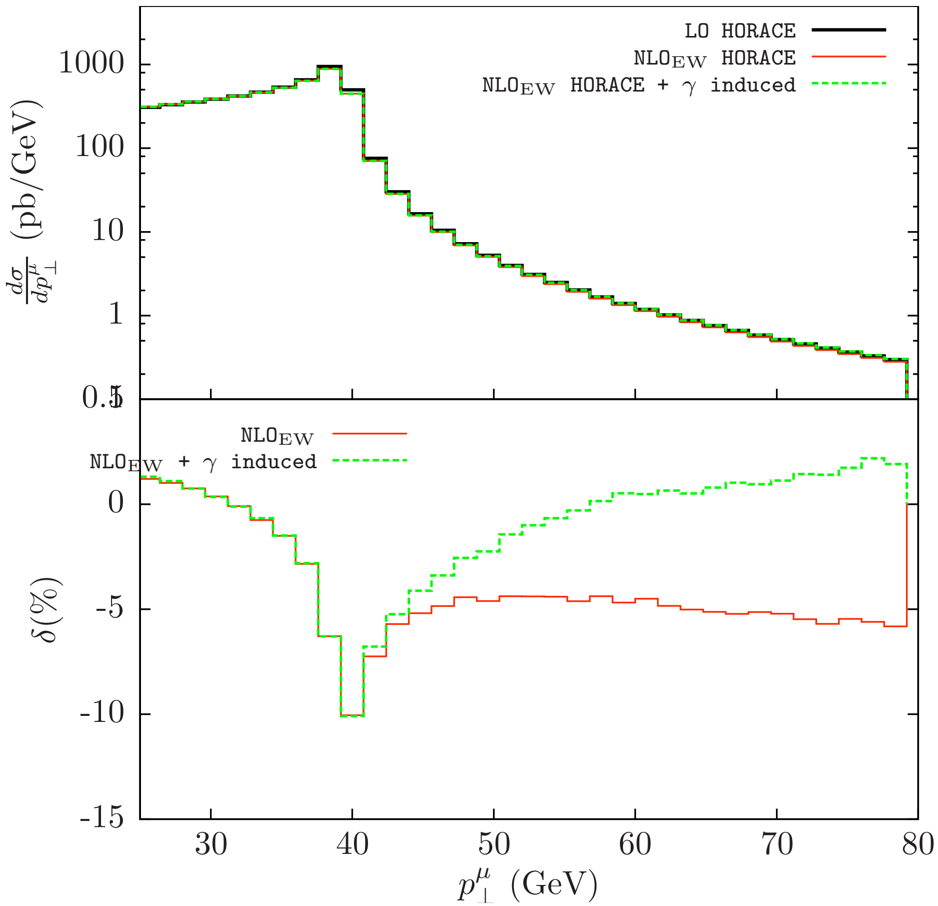
precision physics: QCD+EW @ the LHC: $M_\perp^W$ and $p_\perp^\mu$ distributions

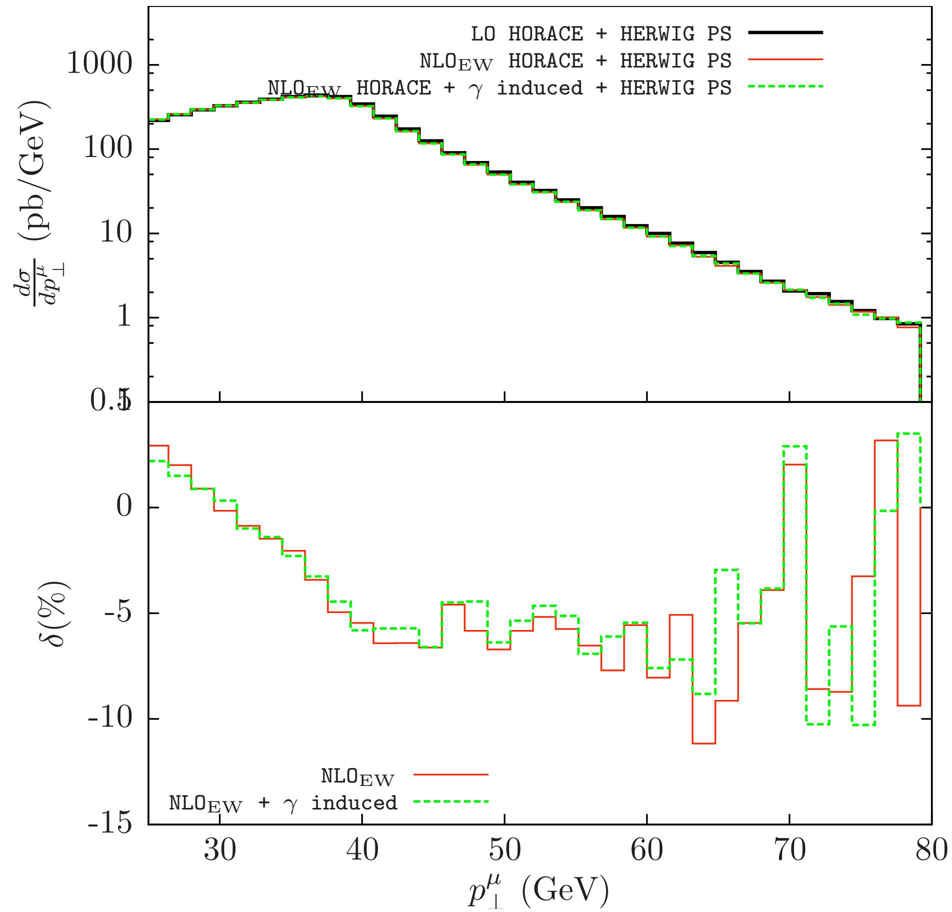




- the relative effect expressed in units Born+PS
- positive QCD corrections compensate negative EW corrections
- around the jacobian peak EW corrections mandatory to extract M_W
  only QCD-Parton Shower or only MC@NLO is not sufficient
- the convolution with QCD Parton Shower modifies
  the relative effect and shape of the EW corrections

precision physics: QCD+EW, parton shower effects

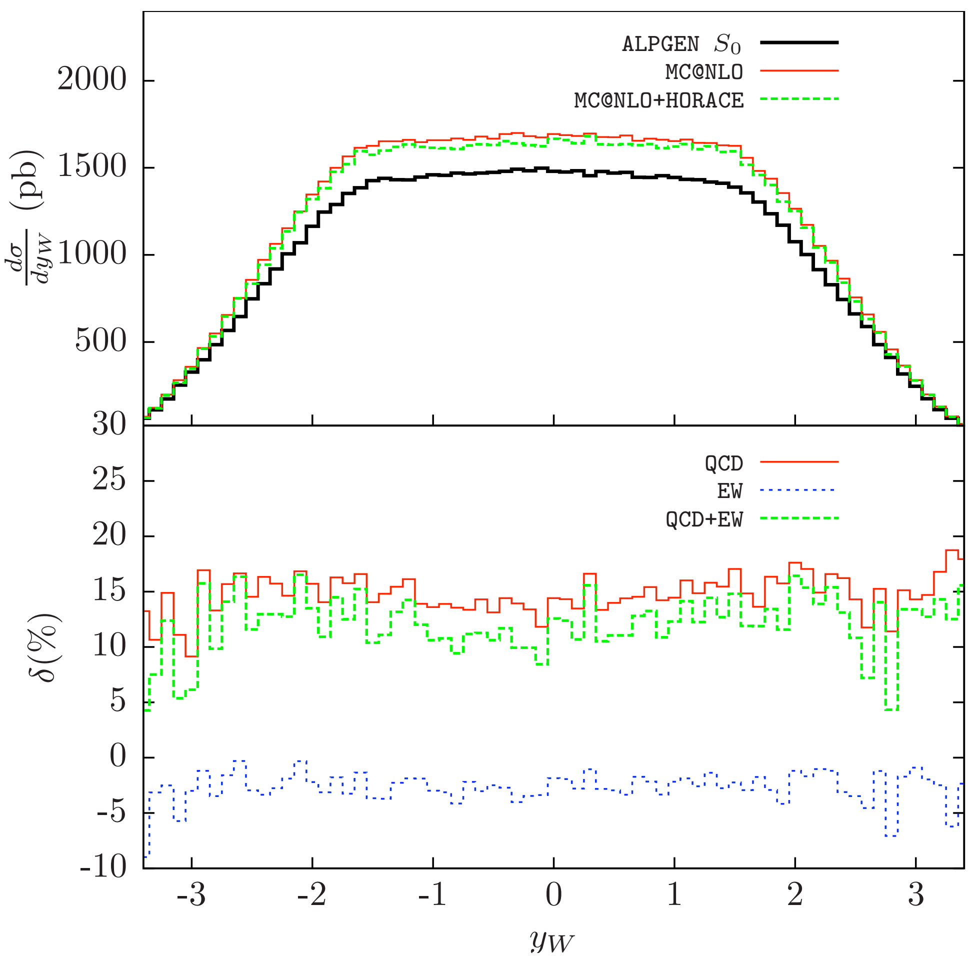


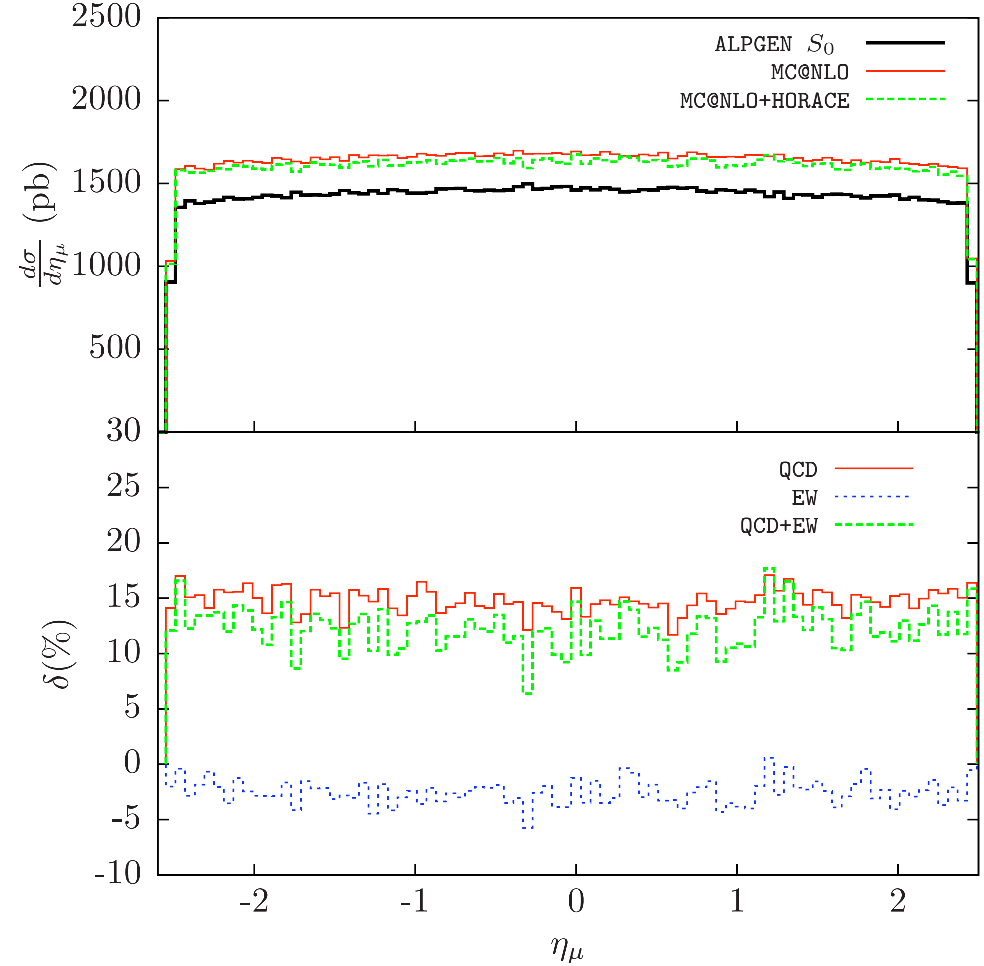


- the convolution with QCD Parton Shower modifies the relative effect and shape of the EW corrections

- the effect of the photon induced process disappear after the convolution with the Parton Shower

pdf constraining: W rapidity and lepton pseudo-rapidity distribution



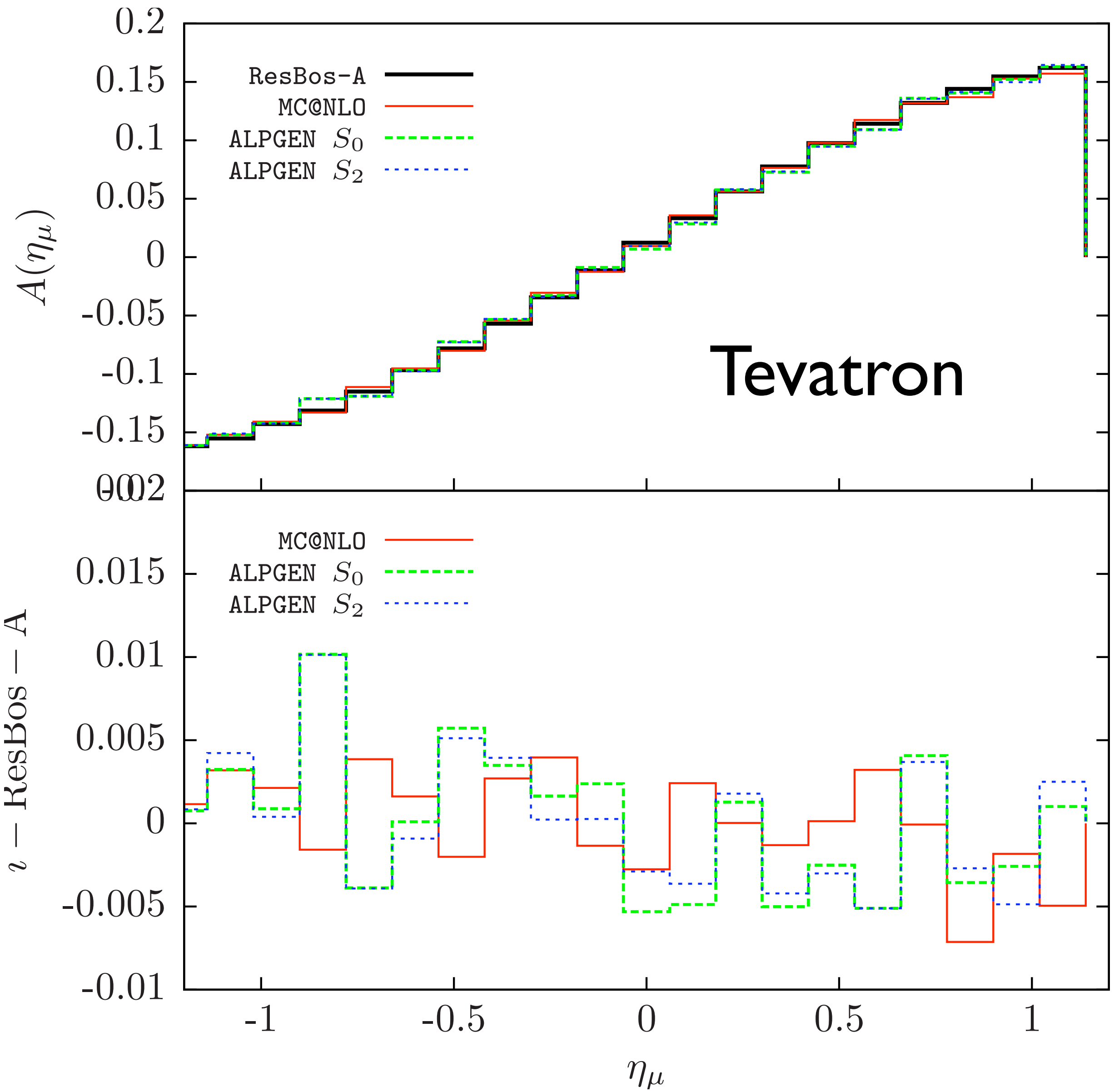


Both QCD and EW corrections are quite flat
partial cancellation +15 -3 %

The deltas are defined in unit (Born+PS)

pdf constraining: Charge asymmetry

$$A(\eta_\mu) = \frac{d\sigma^+/d\eta_\mu - d\sigma^-/d\eta_\mu}{d\sigma^+/d\eta_\mu + d\sigma^-/d\eta_\mu}$$

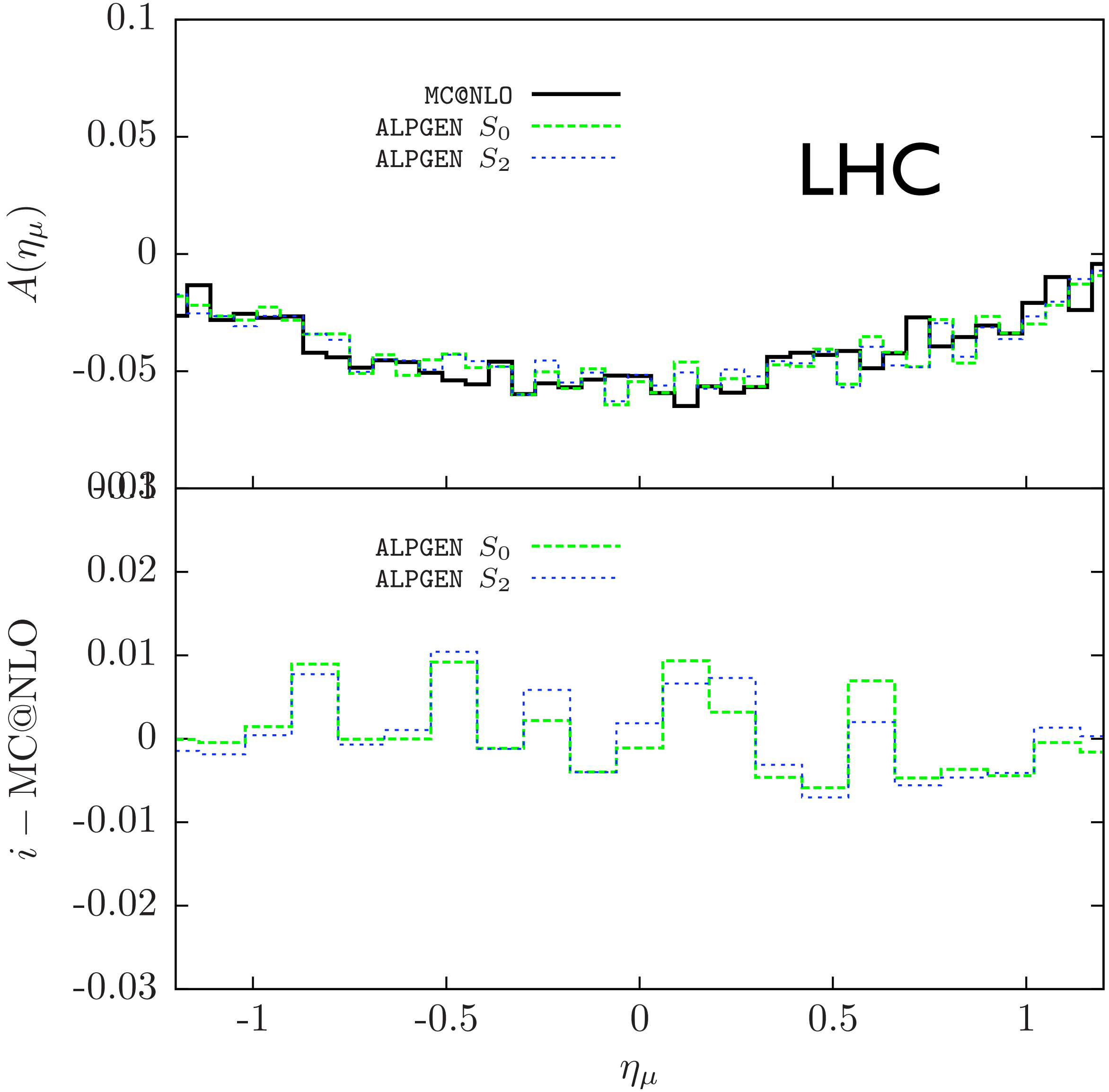


Stability of the prediction w.r.t. different generators

The asymmetry is large and changes sign

pdf constraining: Charge asymmetry

$$A(\eta_\mu) = \frac{d\sigma^+/d\eta_\mu - d\sigma^-/d\eta_\mu}{d\sigma^+/d\eta_\mu + d\sigma^-/d\eta_\mu}$$

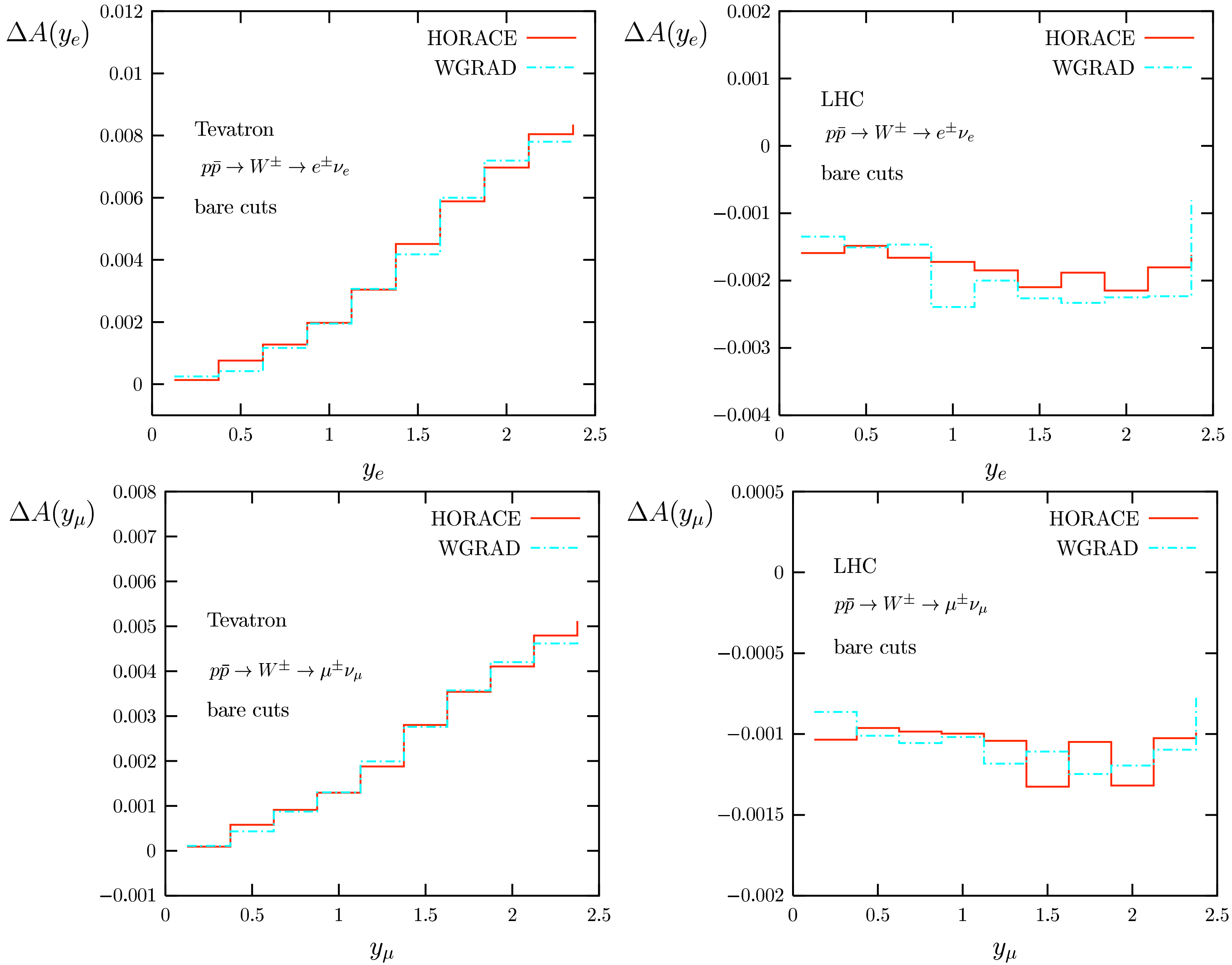


good agreement of MC@NLO and ALPGEN

The asymmetry is smaller than at the Tevatron and always negative

pdf constraining: Charge asymmetry

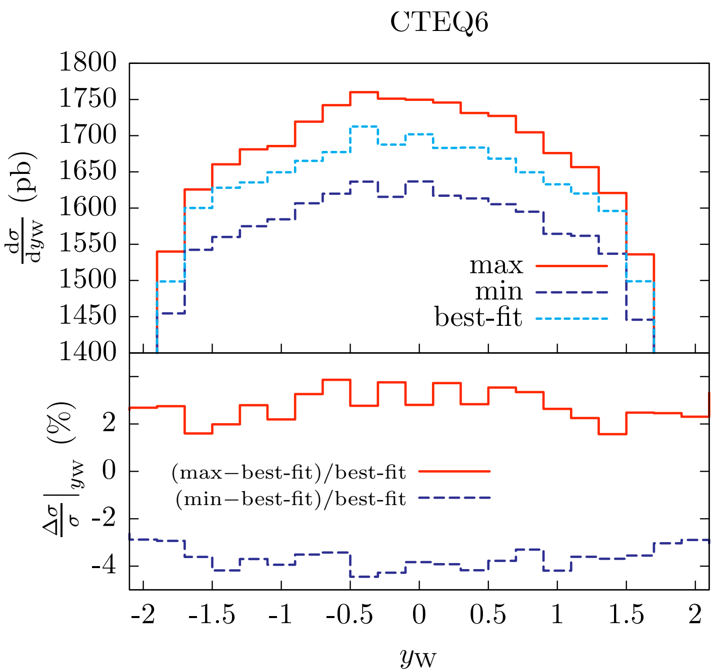
(TEV4LHC workshop)

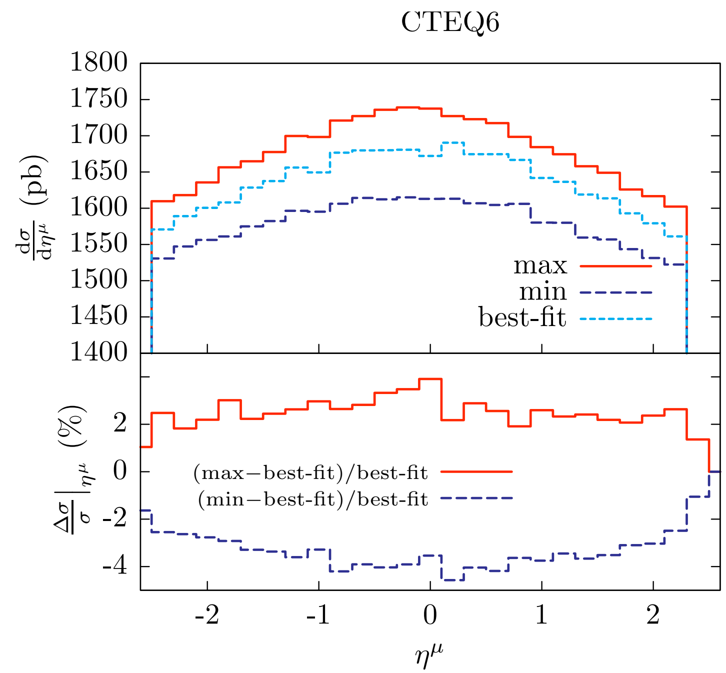


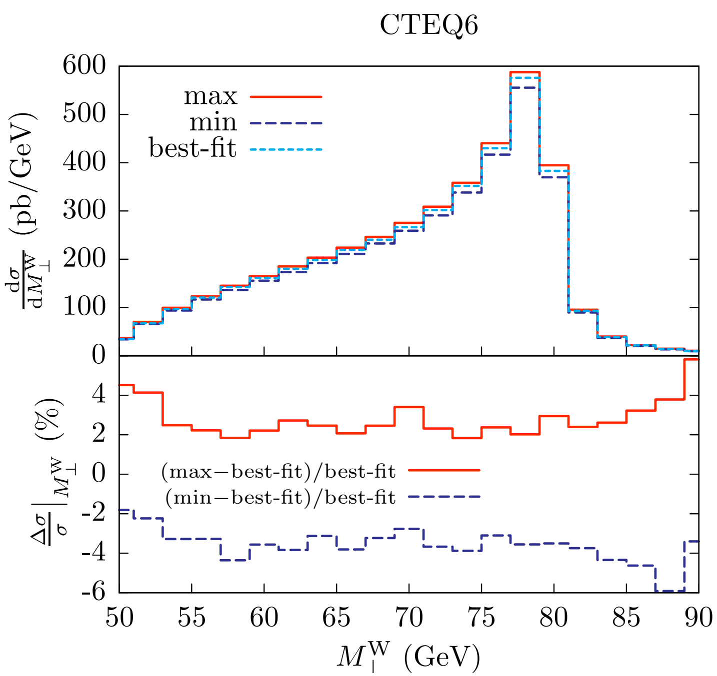
O(α) EW effects are moderate in size and well under control.

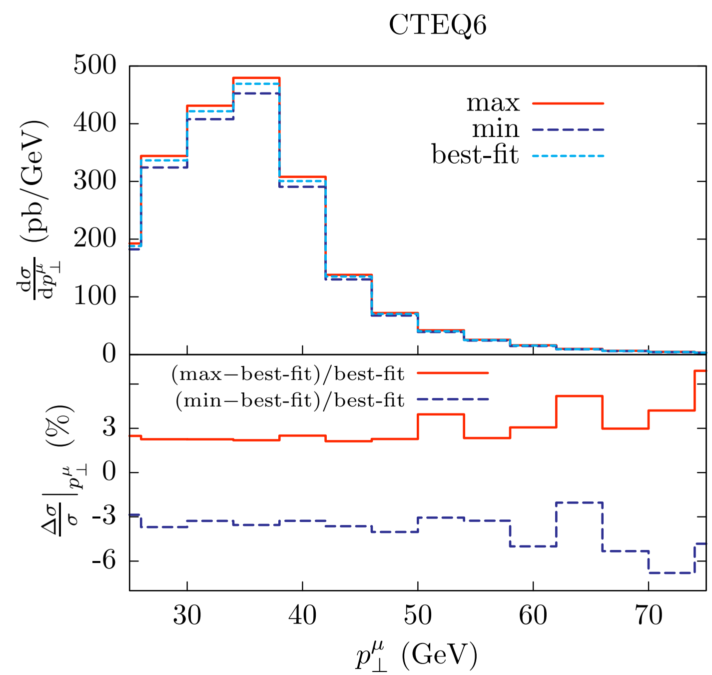
Multiple photon emission is negligible

W: uncertainties due to the *pdfs* LHC, CTEQ6.1



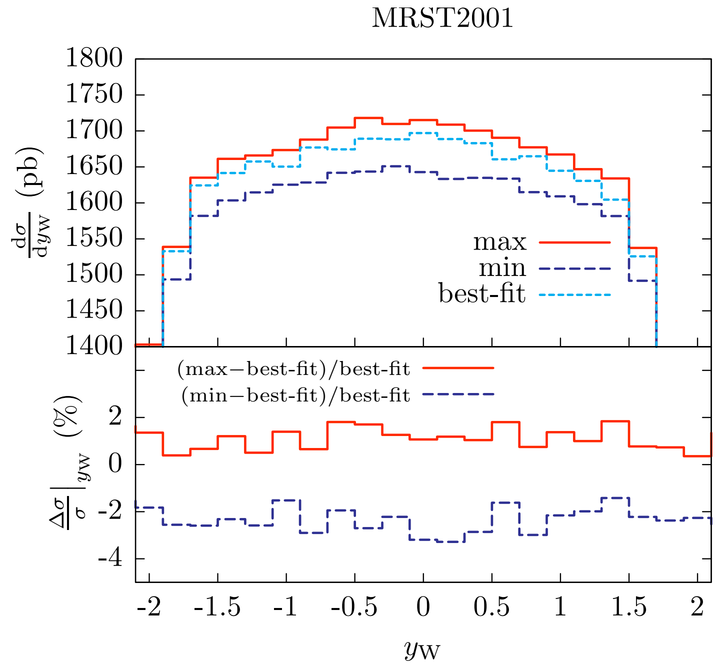


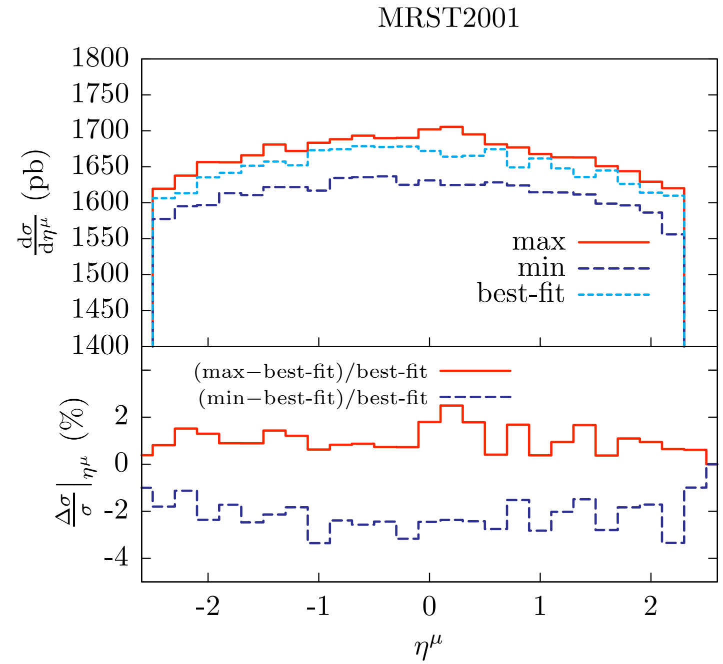


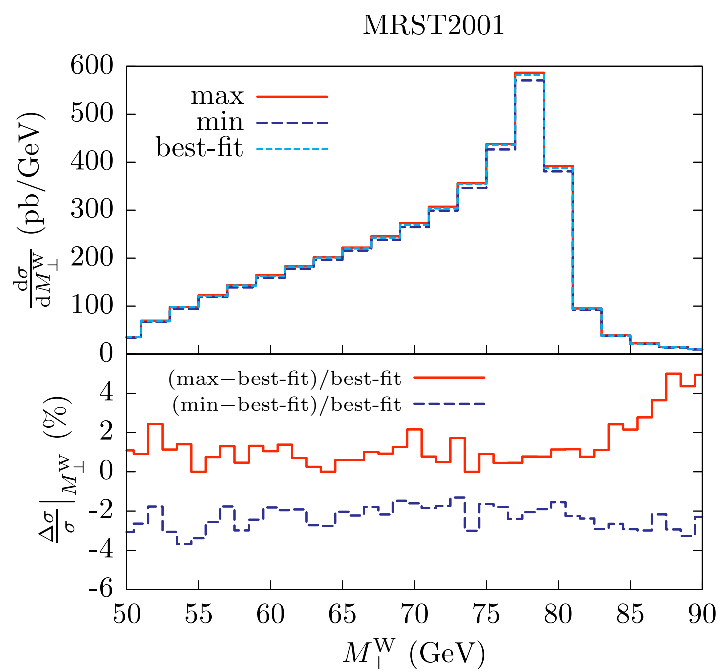


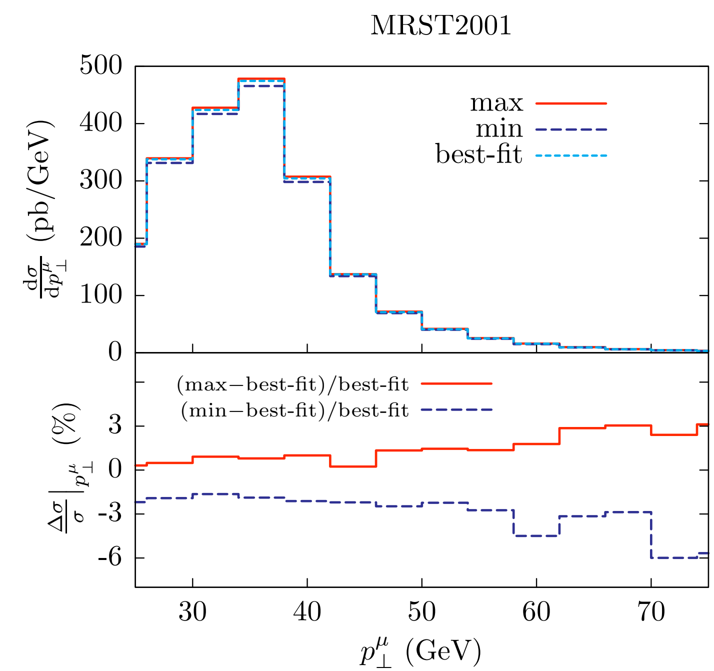
W: uncertainties due to the *pdfs* LHC, MRST2001E

The spread is about 2 times smaller w.r.t. CTEQ because of the different values of the tolerance parameter

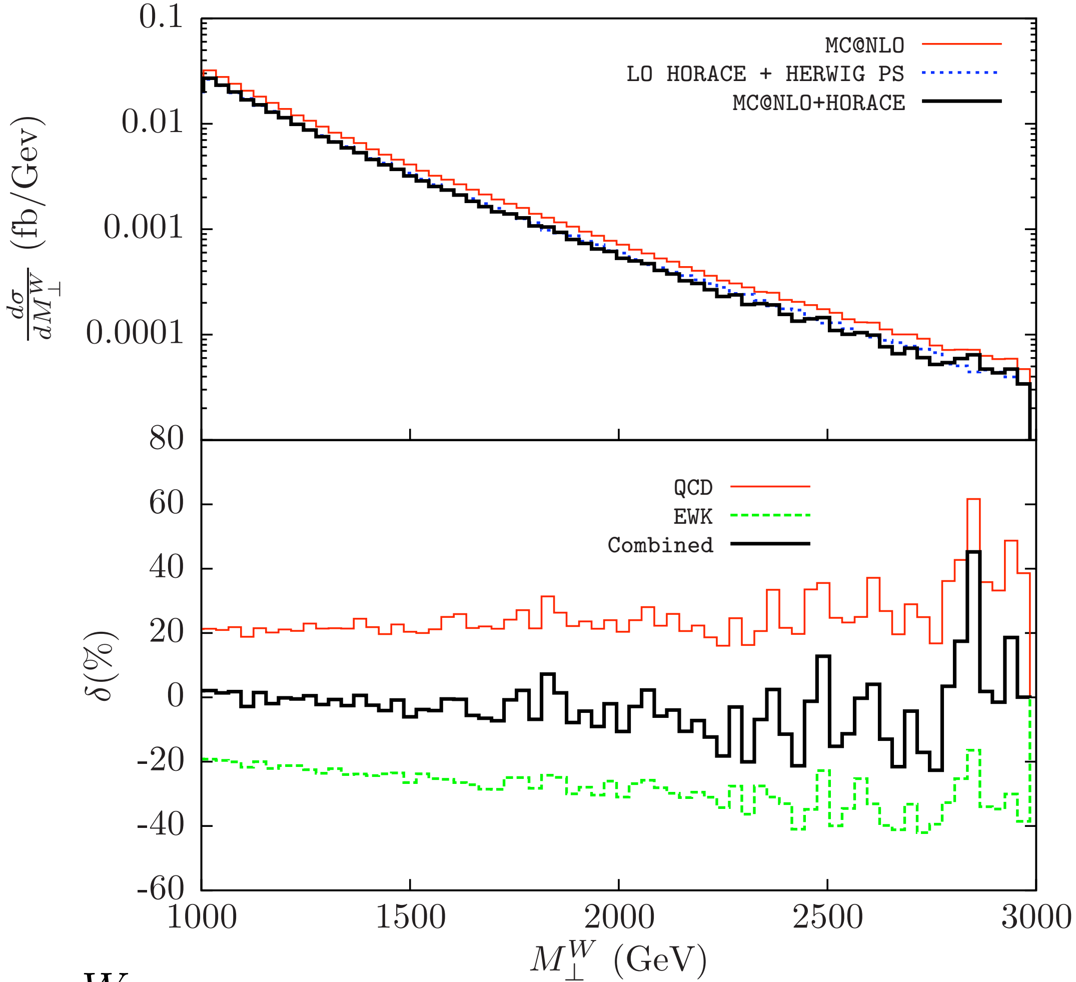


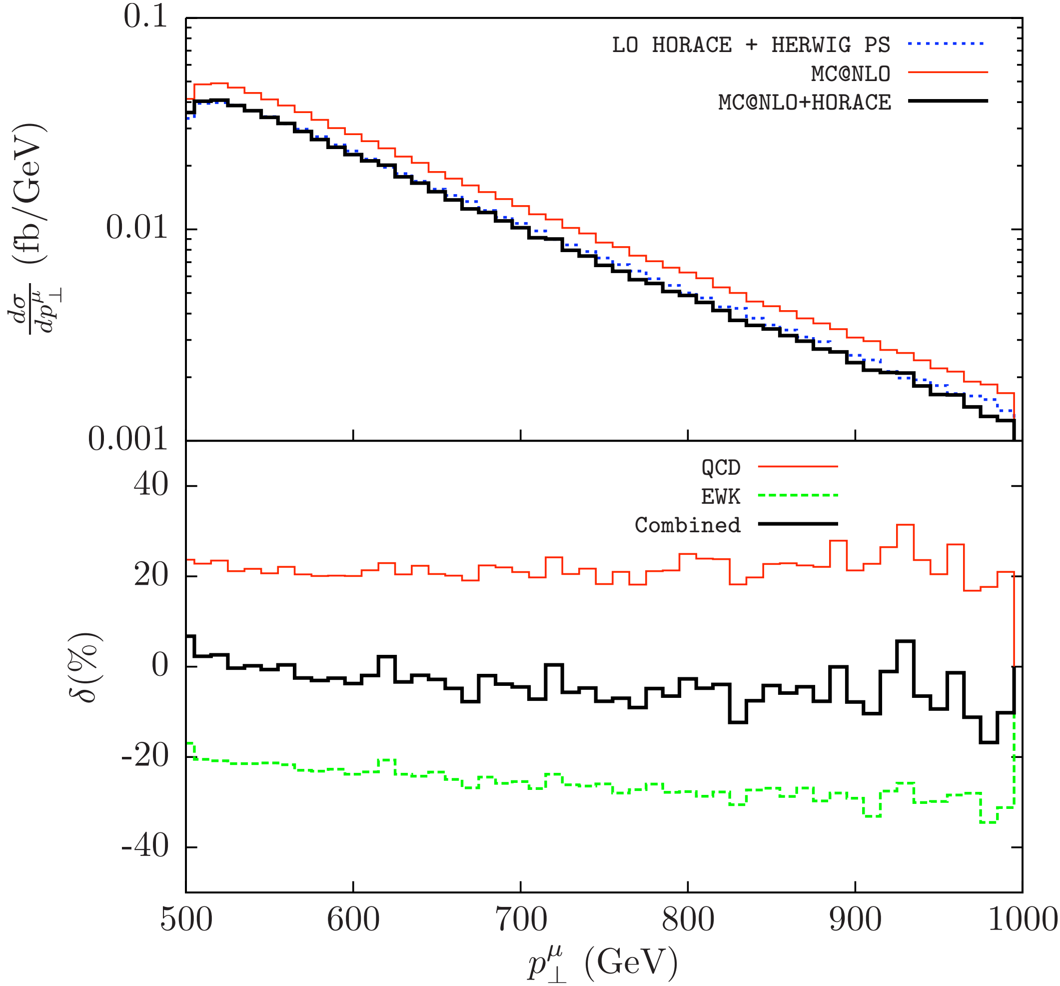






QCD+EW @ the LHC: $M_\perp^W$ and $p_\perp^\mu$ distributions





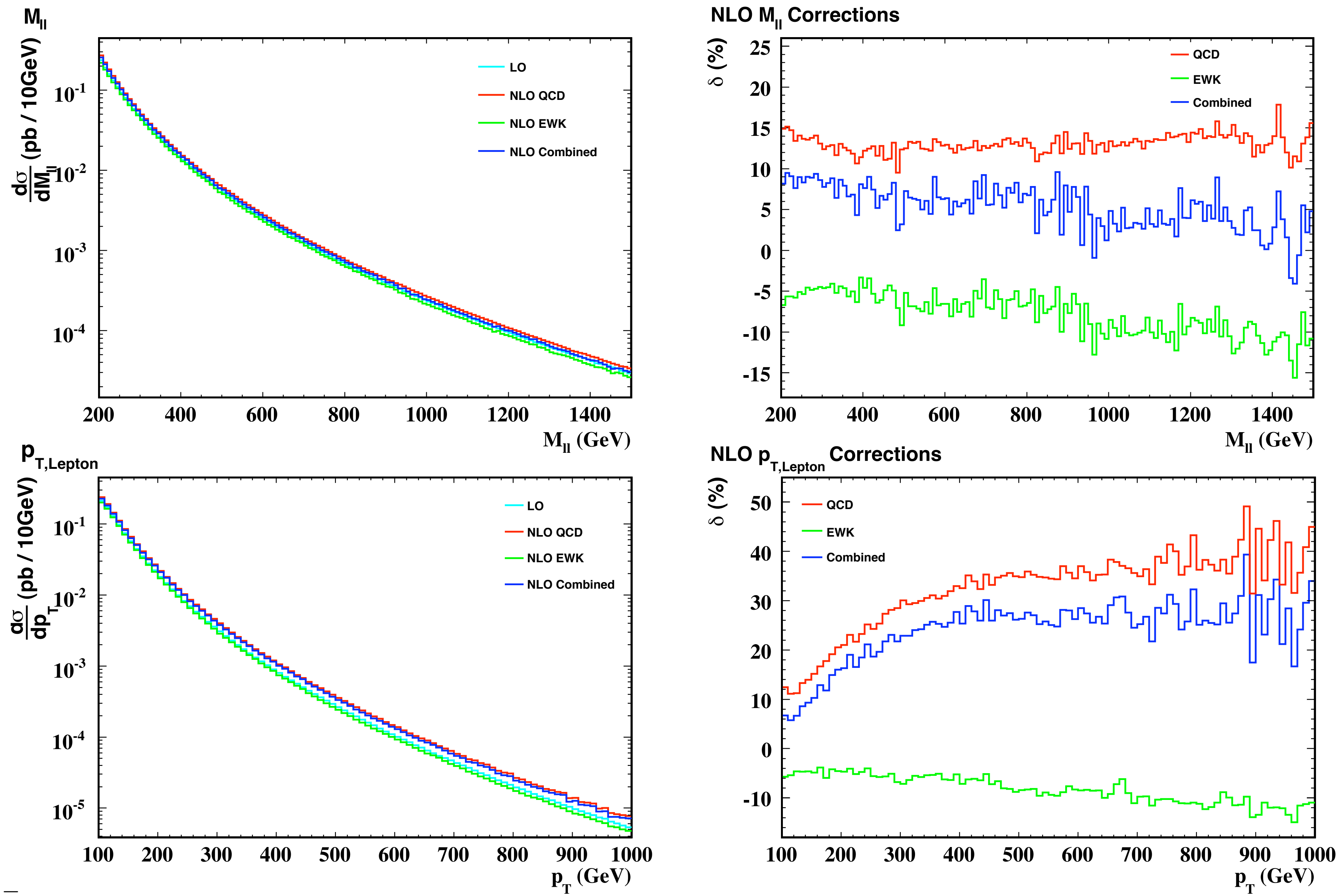
$M_\perp^W > 1\mathrm{TeV}$

Large cancellation of positive QCD and negative EW corrections

Important dependence on the choice of the *pdf* scale $\mu_F = \sqrt{M_W^2 + (p_\perp^W)^2}$

Relevant to set correct limits on the searches for heavy gauge bosons

QCD+EW @ the LHC: $M_{inv}^{e^+e^-}$ and $p_\perp^e$ distributions Les Houches 2007



$M_{inv}^{l^+l^-} > 200\text{GeV}$

The negative effect of virtual EW Sudakov logs is partially cancelled by the inclusion of undetected real Z boson emission (U. Baur, Phys.Rev.D75 (2007) 013005)

Relevant to set correct limits on the searches for heavy gauge bosons

Conclusions

- the event generator HORACE provides a detailed description of the EW corrections to CC and NC Drell-Yan processes

- a detailed phenomenological analysis demonstrates the impact of the EW corrections on several distributions and, in turn, on the measurement of several observables
  - acceptances : pdfs, luminosity
  - transverse mass : measurement of M_W (limits on Higgs, MSSM)

- a realistic description of the Drell-Yan processes requires the combination of QCD and EW corrections (possibly in a unified generator)
  - the interplay of the two sets of corrections is not trivial
  - the QCD-Parton Shower provides the correct lowest order approximation of the kinematics of these processes and modifies the impact of the EW corrections

- several sources of effects at the few percent level

- a joint experimental-theoretical effort will be important to exploit the potential of the Drell-Yan as a precision process

Back-up slides

Electroweak results with HORACE

LHC energy: √S=14 TeV *pdf*: MRST2004QED

process: $pp \to \mu^{\pm}\nu \ + X$

input scheme: $\alpha(0), \ M_W, \ M_z$

selection cuts: $p_{\perp,l}$ and $p_{\perp,\nu} > 25\mathrm{GeV}, \ |\eta_l| < 2.5$

extra cuts in photon-induced processes: $p_{\perp,jet} < 30\mathrm{GeV}, \ |\eta_{jet}| > 2.5$

QCD+EW combination: setup

Tevatron

Process and scheme – Detector modeling and lepton identification

1. $p\bar{p} \to W^{\pm} \to \mu^{\pm}\nu_{\mu}$ $\sqrt{s} = 1.96$ TeV – G_{μ} scheme + $\alpha(0)$ for real γ emission
2. $p_{\perp}^{\mu} > 25$ GeV $\not{p}_{\perp} > 25$ GeV $|\eta_{\mu}| < 1.2$ $p_{\perp}^{W} \leq 50$ GeV $M_{\mu\nu} \in [50 - 200]$ GeV
3. PDF set: NLO CTEQ6M with $\mu_R = \mu_F = \sqrt{x_1 x_2 s}$

LHC

Process and scheme – Detector modeling and lepton identification

1. $pp \to W^{\pm} \to \mu^{\pm}\nu_{\mu}$ $\sqrt{s} = 14$ TeV – G_{μ} scheme + $\alpha(0)$ for real γ emission
2. $p_{\perp}^{\mu} > 25$ GeV $\not{p}_{\perp} > 25$ GeV $|\eta_{\mu}| < 2.5$ $\oplus$ (in case) $M_{\perp}^{W} > 1$ TeV
3. PDF set: NLO MRST2004QED with $\mu_R = \mu_F = \sqrt{p_{\perp,W}^2 + M_W^2}$

$$\cos\theta^* = f \; \frac{2}{M(l^+l^-)\sqrt{M^2(l^+l^-) + p_\perp^2(l^+l^-)}} \; \left[p^+(l^-)p^-(l^+) - p^+(l^+)p^-(l^-)\right]$$

$$p^\pm = \frac{1}{\sqrt{2}}(E \pm p_z), \qquad f = 1 \text{ (Tevatron)}, \qquad f = \frac{|p_z(l^+l^-)|}{p_z(l^+l^-)} \text{ (LHC)}$$

Combining QCD and EW corrections

in collaboration with C. M. Carloni Calame, G. Balossini, G. Montagna, O. Nicrosini, F. Piccinini, M. Moretti, M. Treccani

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- The combination of QCD and EW corrections can (always) be expressed in a factorized form as

$$d\sigma = F_{SV}\ \Pi(Q^2,\varepsilon)\ \sum_{n=0}^{\infty}\prod_{i=0}^{n} F_{H,i}|\mathcal{M}_n^{LL}|^2 d\Phi_{n+2}$$

Non-factorizable terms can (always) be cast in appropriate correcting factors *F*, preserving the factorized (e.g.parton-shower) structure and
the validity of the fixed order calculation, when expanding up to that order

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At the level of distribution it is possible for instance the following rearrangement

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

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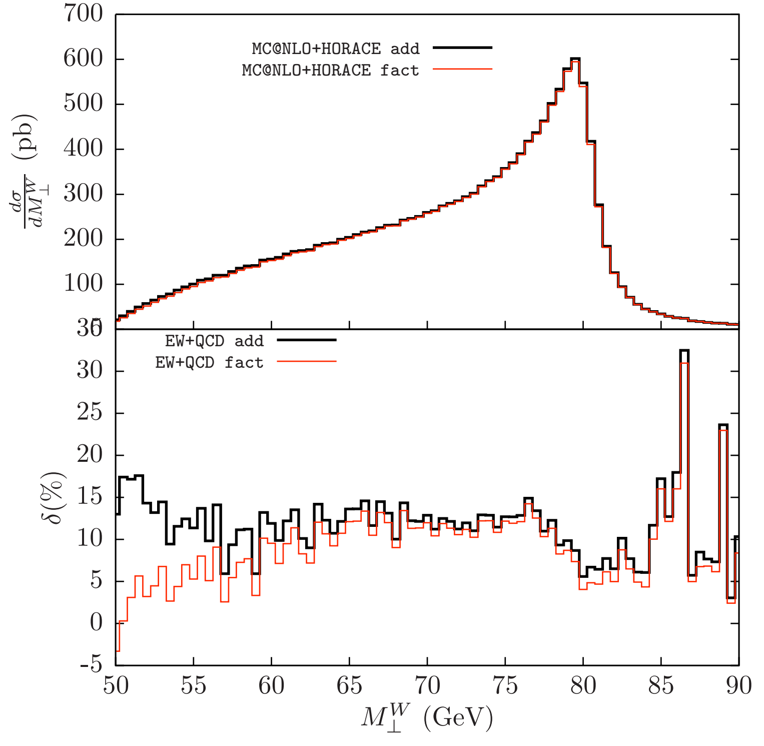
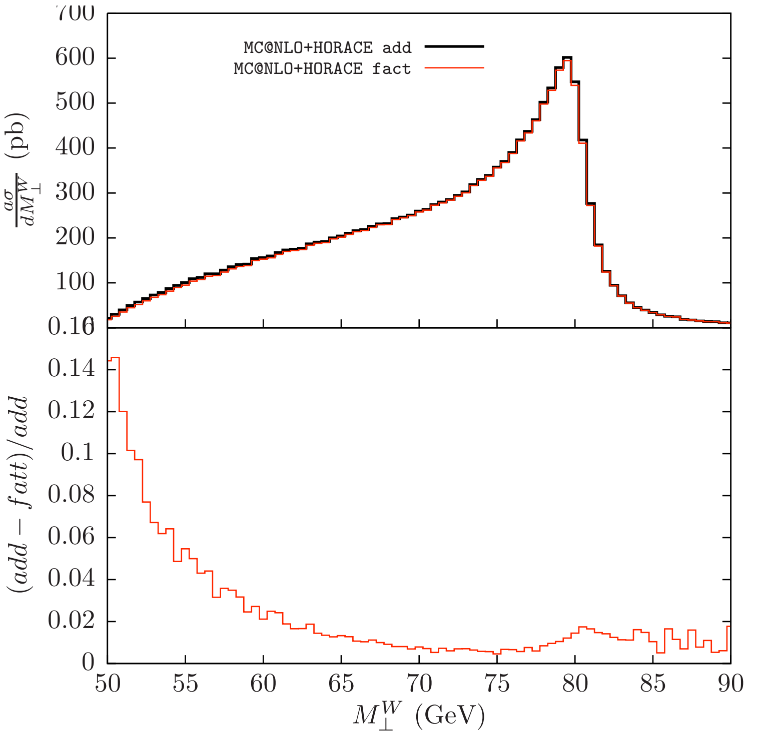
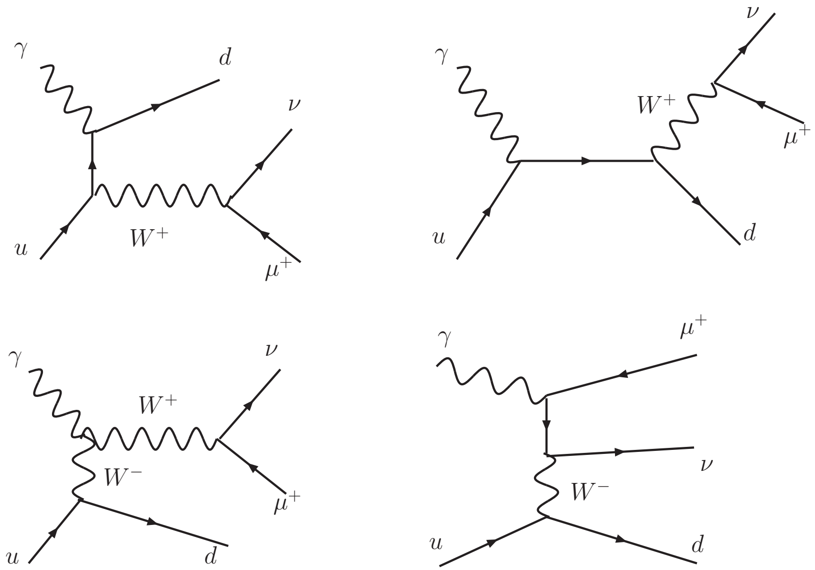
Factorized vs. additive combination of QCD and EW corrections





MRST 2004 QED and photon induced processes

- QED evolution ⇒ photon density in the proton ⇒ photon induced processes
- $\gamma u \to d \mu^+ \nu_\mu$

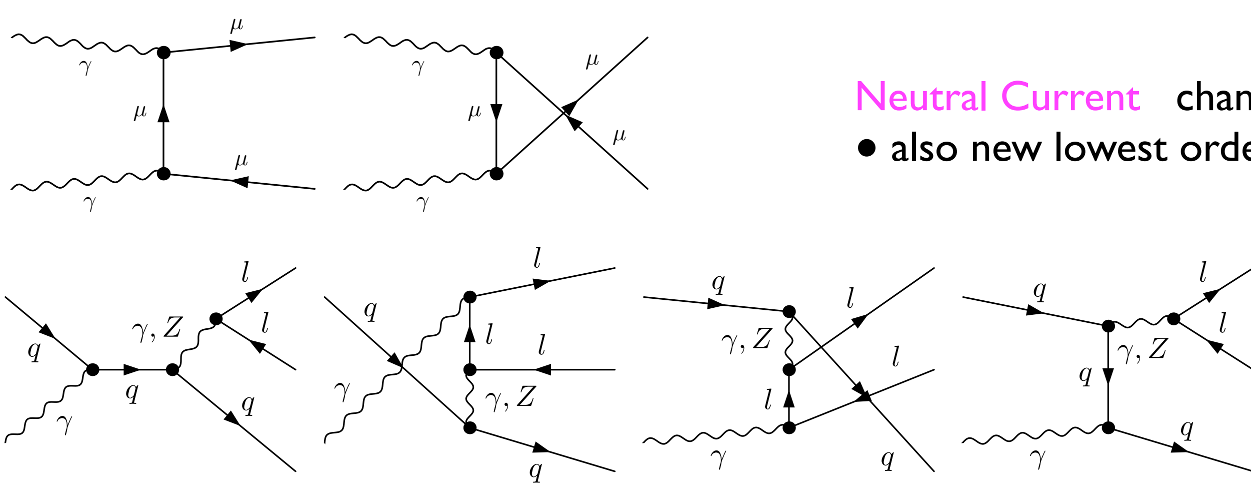


Charged Current channel

- same perturbative order as the O(α) corrections
- they contribute to the inclusive DY cross section
- depending on the cut on the final state jet, important effect on the lepton transverse momentum distribution

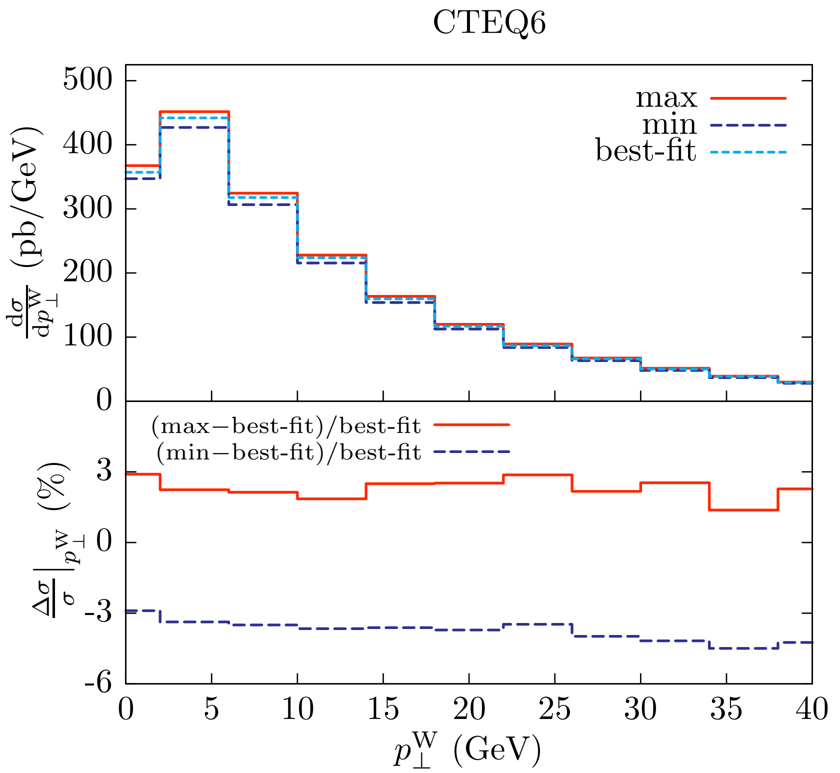
Neutral Current channel

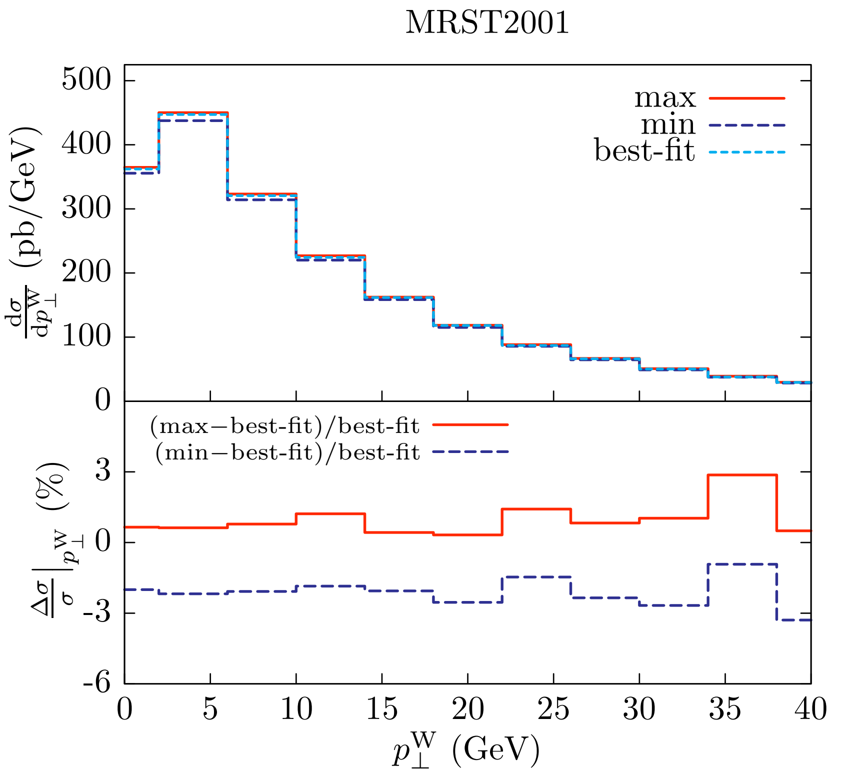
- also new lowest order partonic subprocess



(a) (b) (c) (d)

W: uncertainties due to the *pdfs* LHC





W: uncertainties due to the *pdfs* LHC

Large tail of the transverse mass distribution

Sensitive to the large-*x* part of the *pdf*