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Drell-Yan processes at the LHC

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

Outline

- relevance of Drell-Yan processes and motivation for precision studies

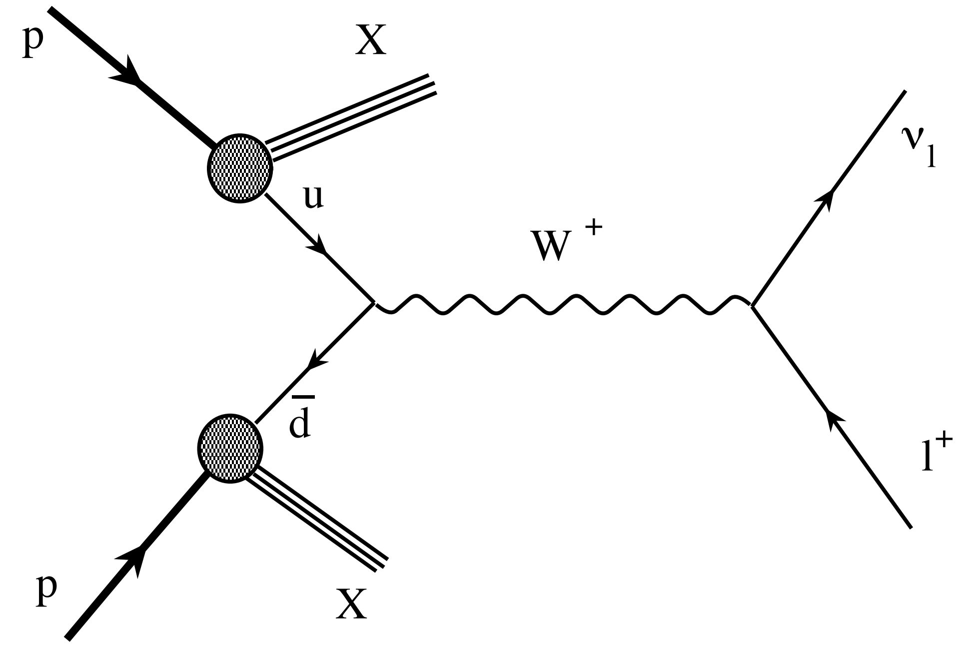
- Charged Current and Neutral Current processes
  - EW $O(\alpha)$ corrections matched with higher order QED corrections
  - photon induced processes

- impact of the EW corrections on several observables

- preliminary study to extract MW from the ratio of W and Z distributions

- combining QCD and EW radiative corrections

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

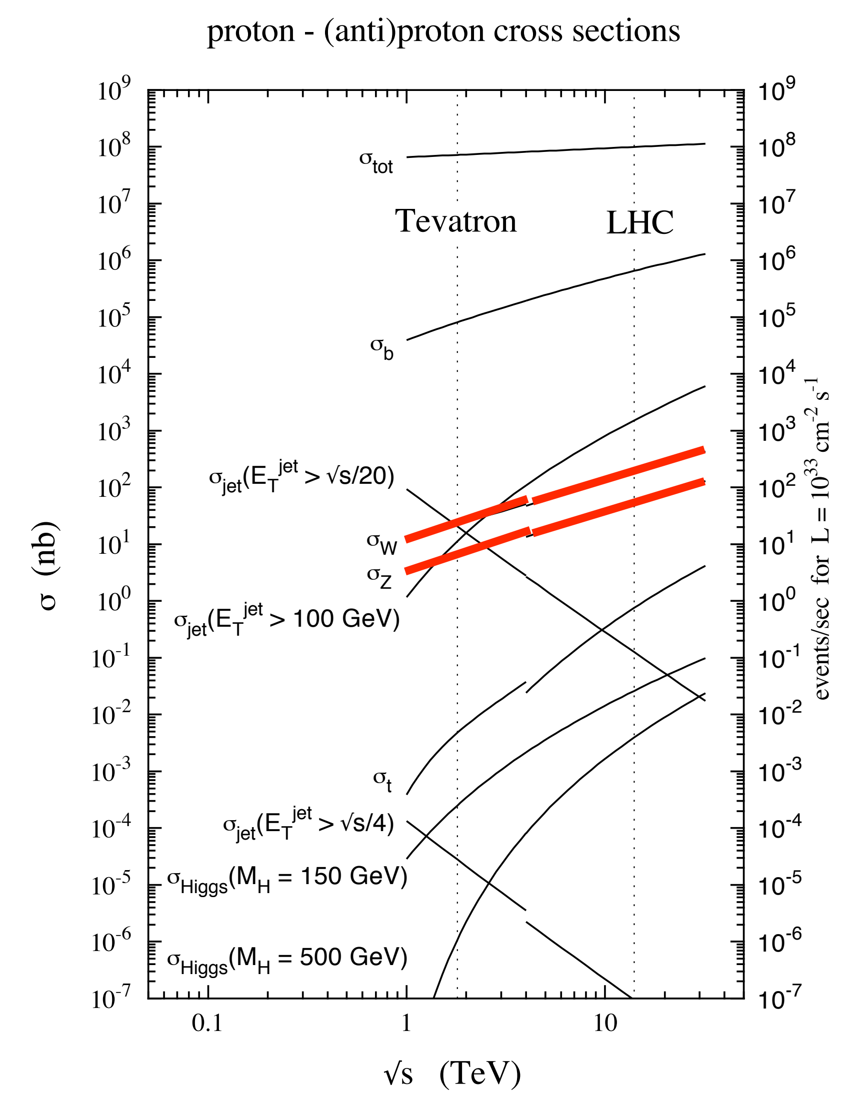
at LHC σ(W) = 30 nb i.e. 3 10^8 events with L=10 fb^-1
at LHC σ(Z) = 3.5 nb i.e. 3.5 10^7 events with L=10 fb^-1

→ 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 to SUSY particles

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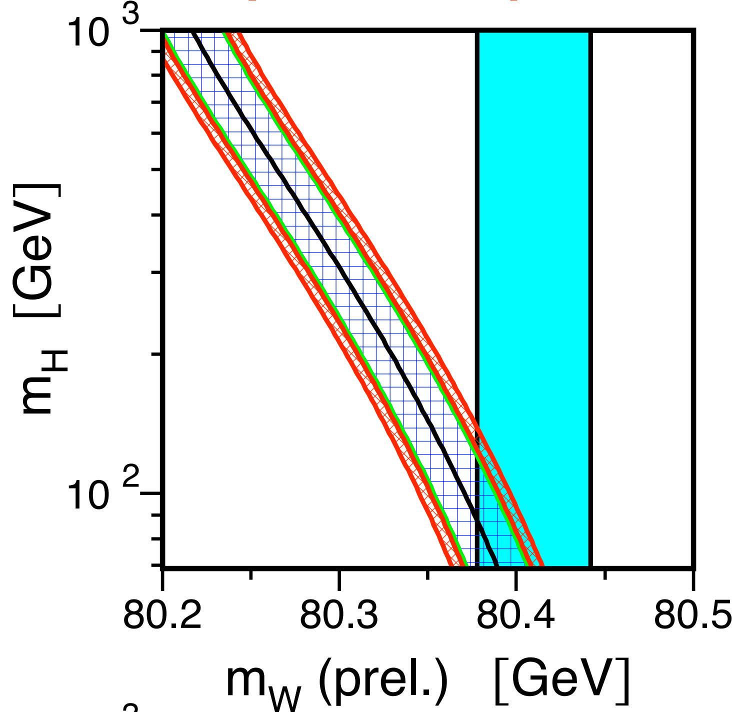
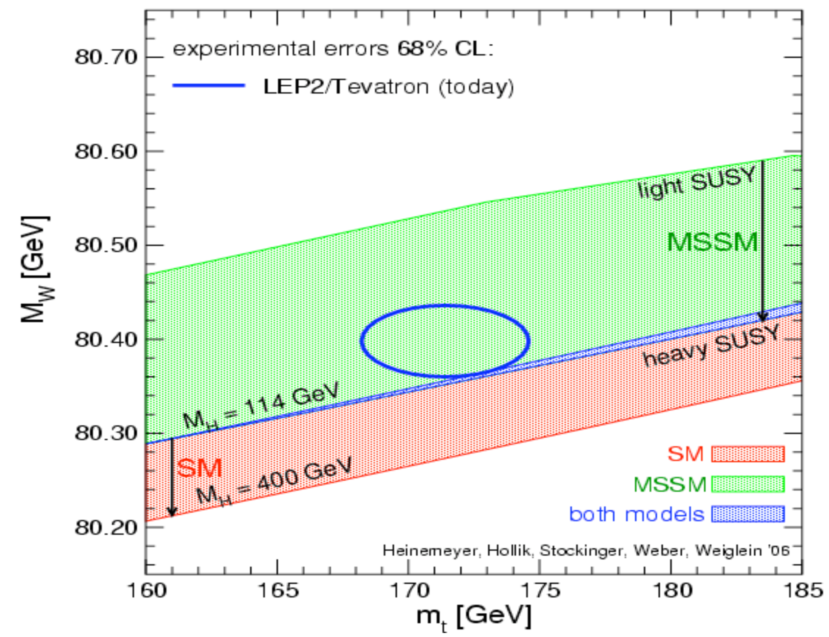
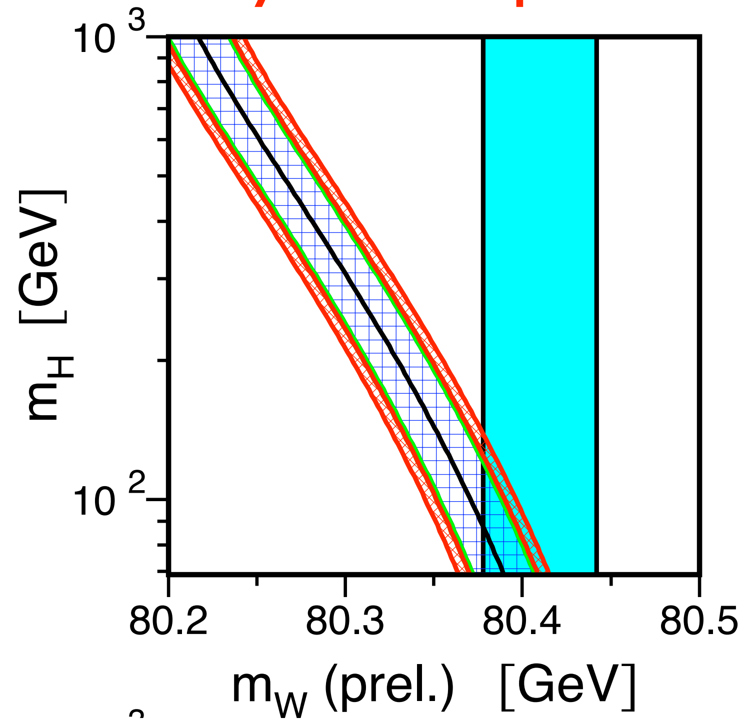


New world average:

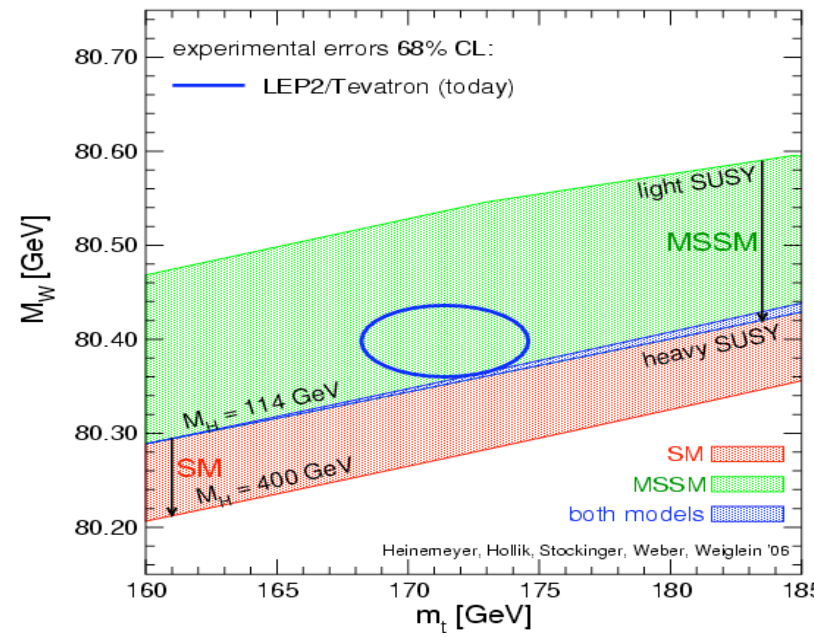


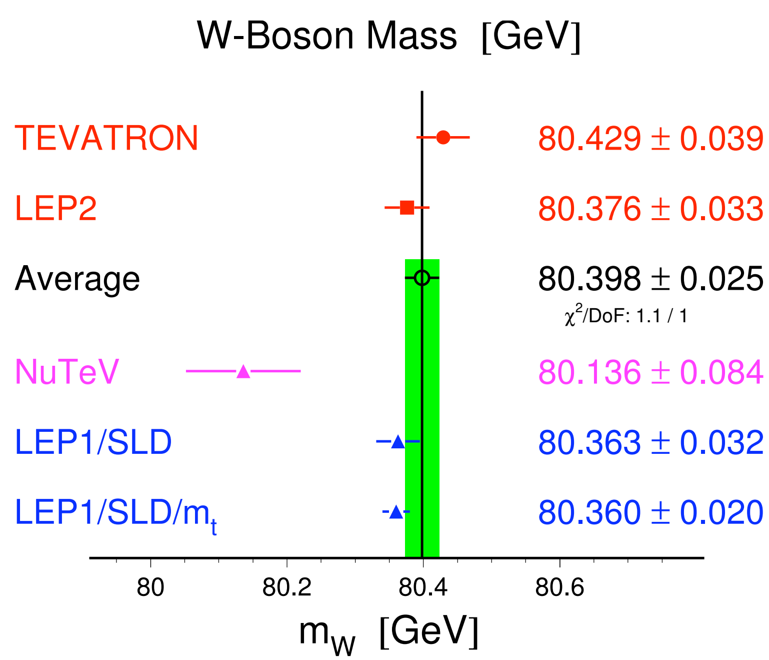
Relevance of a precise W mass measurement

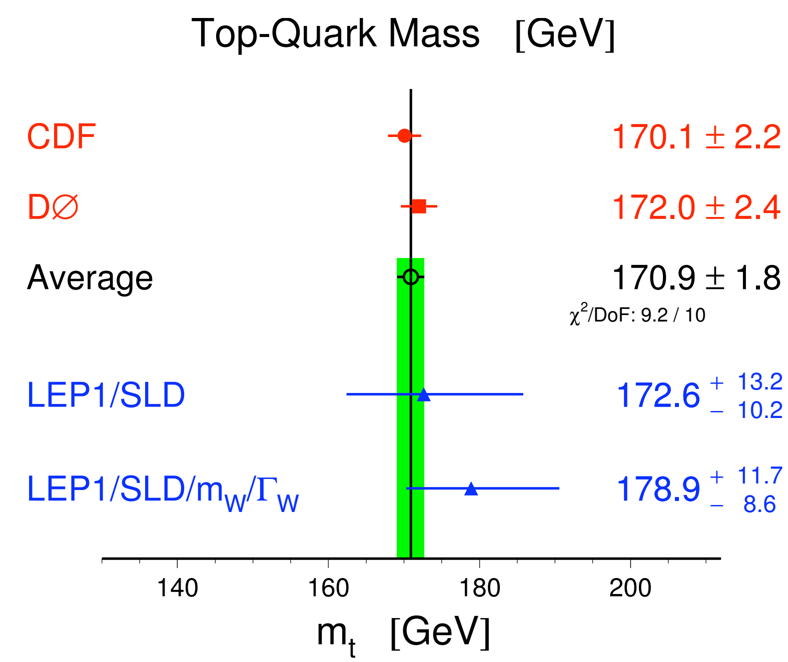
Sensitivity to the precise value of the Higgs boson mass or to SUSY particles



New world average:



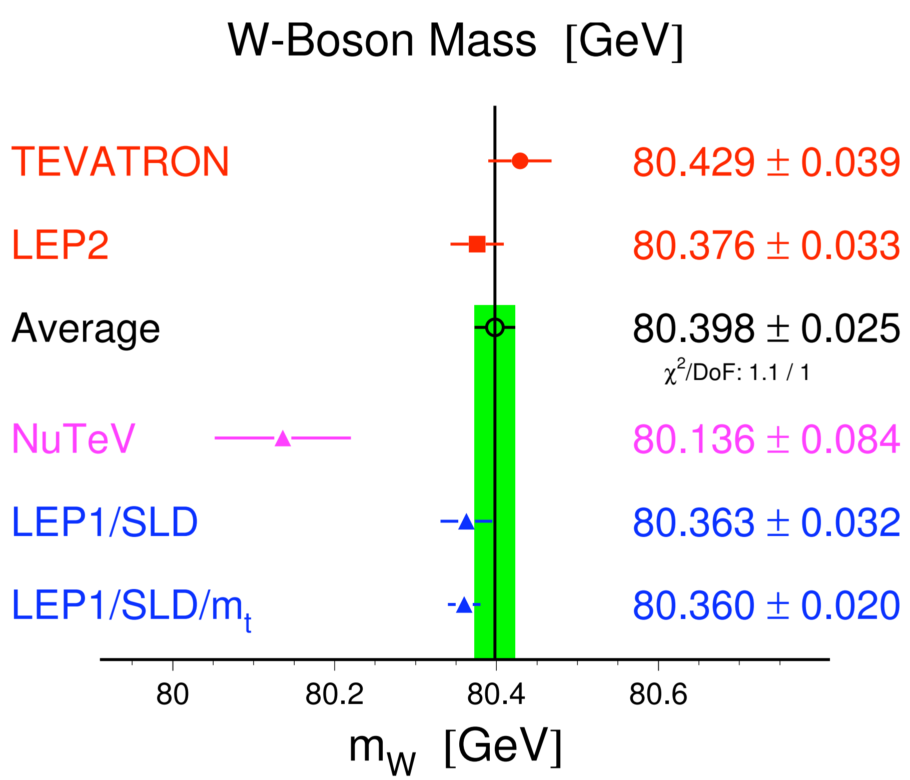


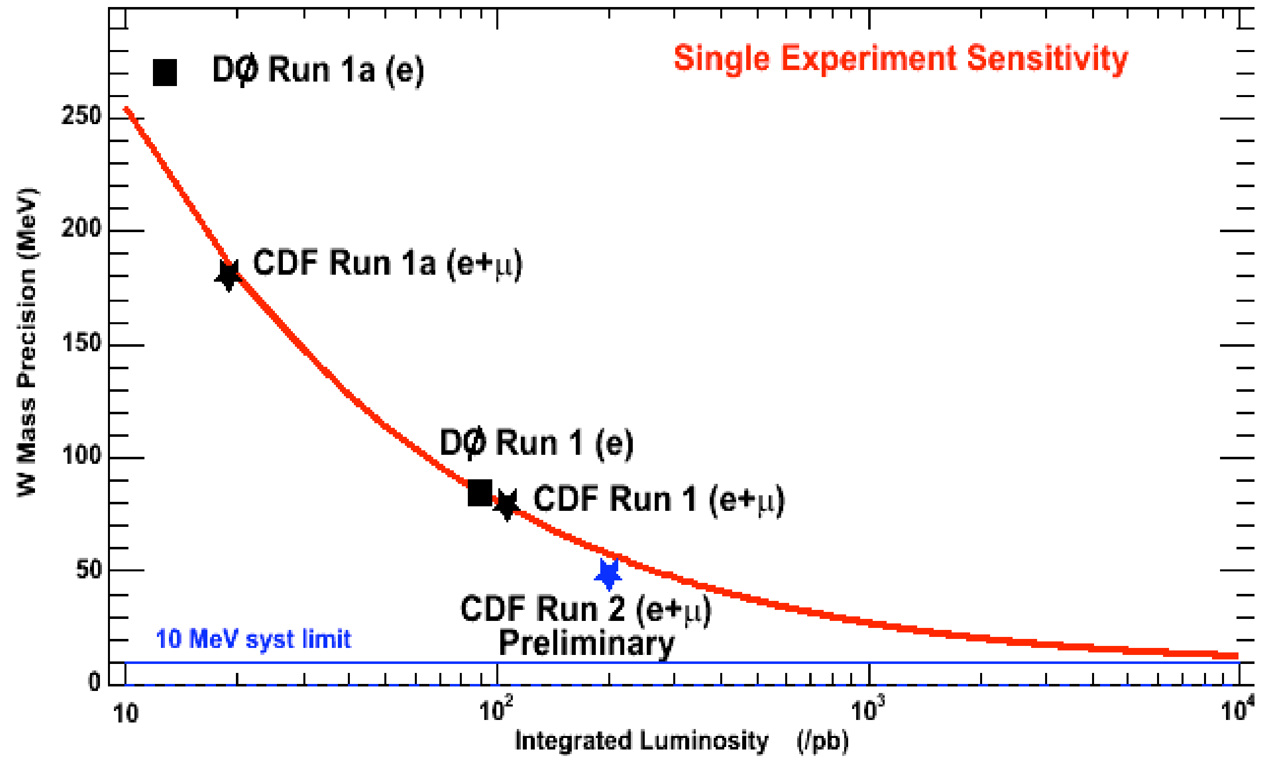


To ensure that top and W mass measurements have the same weight in the SM EW fit, the experimental errors should be related as:

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

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

- M_W measurement

error target at the LHC 15 MeV

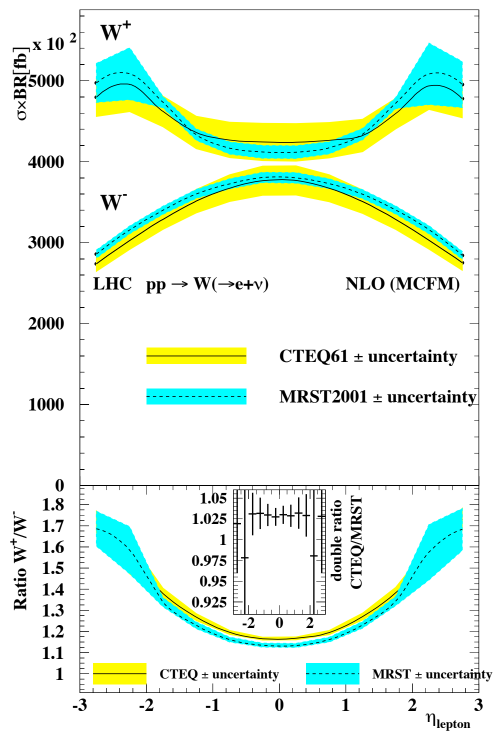
- Γ_W measurement

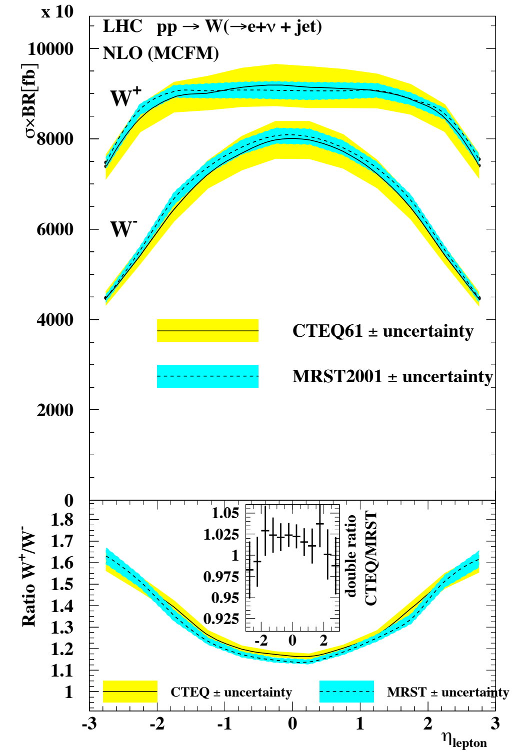
error at Tevatron: 87 MeV error target at the LHC: 30 MeV

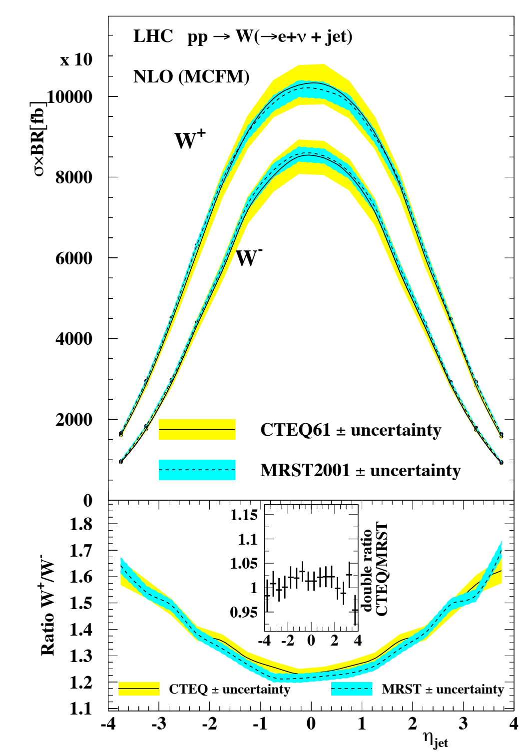
- $\sin^2\theta_{eff}^{lep}$ measurement

world average: 0.23122±0.00015 error target at the LHC: 0.00014

Constraining the *pdfs*





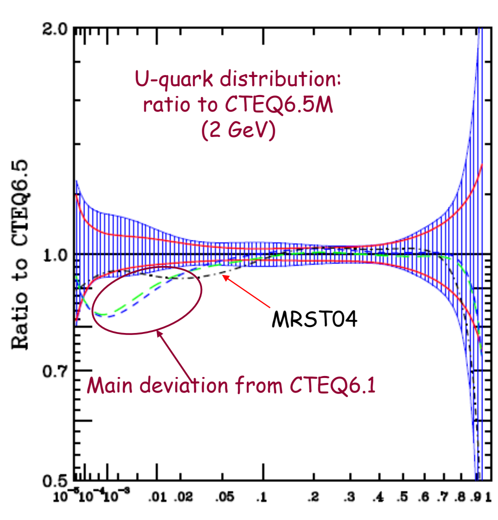


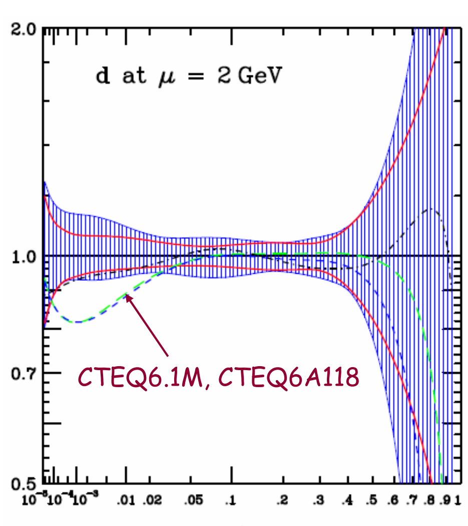
Luminosity monitoring (?)

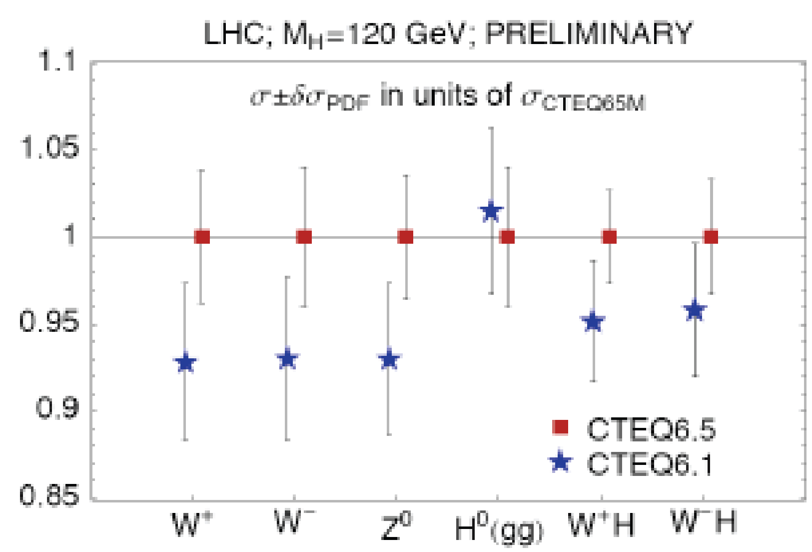
$$\int \mathcal{L}dt = \frac{1}{BR(W\to l\nu)}\,\frac{1}{\sigma^{th}(W)}\,\frac{N^{obs}}{A_W}$$

$$A_W(\eta_l^{max}) = \frac{1}{\sigma(tot)}\int_{-\eta_l^{max}}^{\eta_l^{max}} d\eta_l\,\frac{d\sigma}{d\eta_l}(cuts)$$

the recent set CTEQ6.5 throws some shadows on this approach because of the large (8%) induced theoretical uncertainties







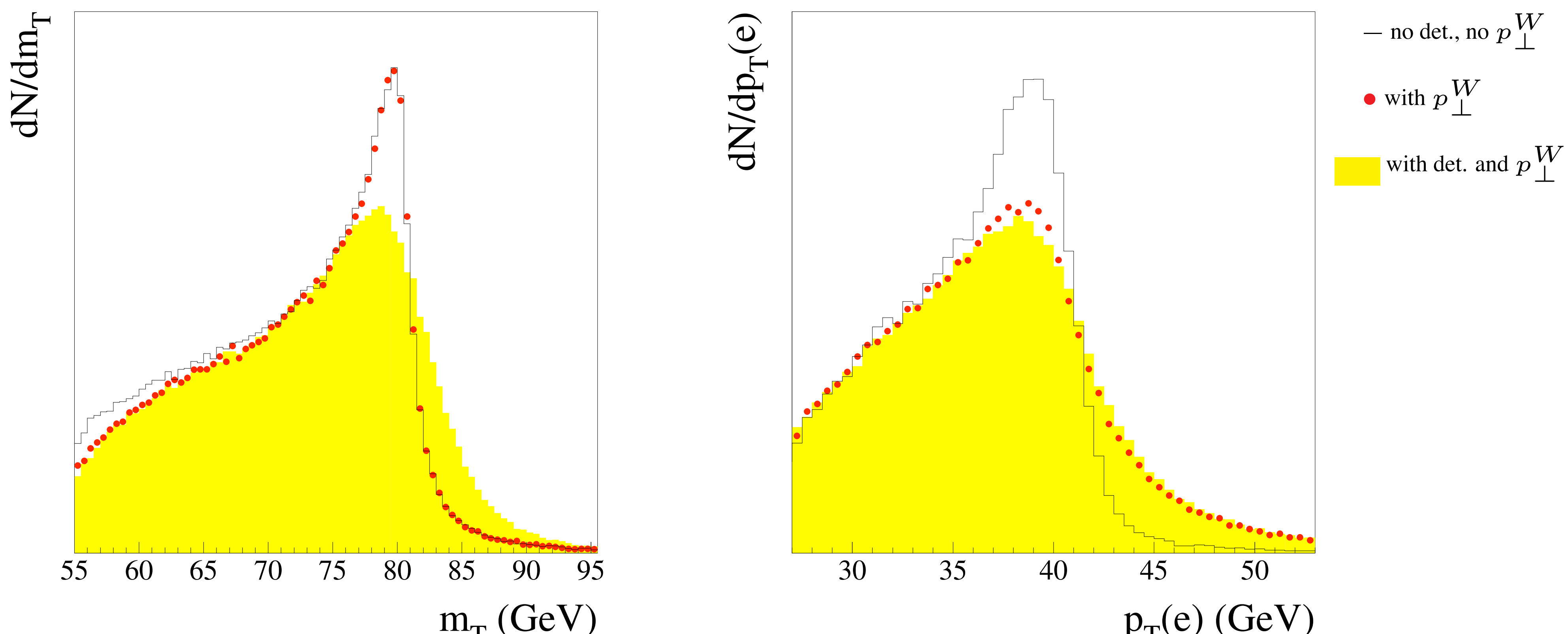
A. Cooper-Sarkar - DIS2007

very promising in the long term (it requires a careful *pdfs* validation)

The quest for precision (I)   i.e. “how do we measure MW”?

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. ptw modeling)



- Detector response effects strongly affect the distributions
- QED Final state radiation distorts the lepton $p_\perp$ 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)

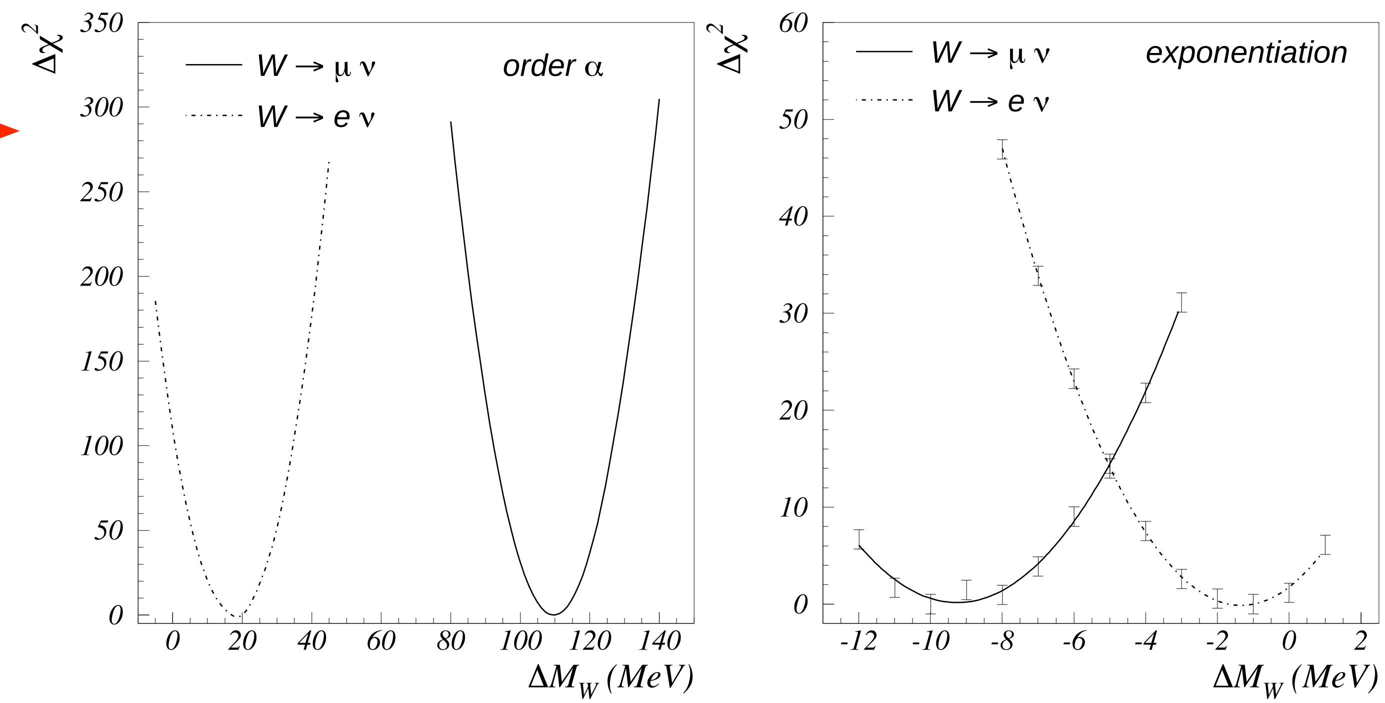
C.M. Carloni Calame et al., Phys. Rev. **D69** (2004) 037301

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)

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

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



M_W systematics

In agreement with CDF estimates
S. Malik@DIS2007

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
$u_{\|\|}$ 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

QCD approximations and tools

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

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

$\mathcal{O}(\alpha_S^2) \approx \mathcal{O}(\alpha_{\mathrm{em}}) \longrightarrow$ 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

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., *to appear*	HORACE
Multiple-photon radiation	C.M.Carloni Calame et al., JHEP 0505:019 (2005)	HORACE

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

- 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

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

- LO calculation + QED LL corrections to all orders via Parton-Shower
- exact O(alpha) 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, (α, m_W, m_Z)
  ➔ gauge boson masses as input parameters which can be fitted from the data
- numerical evalution in the G_μ scheme (CC) or ($G_\mu + \alpha(q^2)$) scheme (NC)

Partonic processes at $\mathcal{O}(\alpha)$

$u\bar{d} \to l^+\nu_l(1\gamma)$

- 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: $\log(s - m_W^2)$ ➜ $\log(s - m_W^2 + i\Gamma_W\, m_W)$
  - on-shell renormalization scheme
  - large negative EW Sudakov logs
- real bremsstrahlung corrections
  checks:
  - independence of total cross section of soft/hard separator
  - e.m. gauge invariance
  - initial state collinear logs regulated by quark masses
  - large ISR corrections: radiative return to the W resonance
- photon-induced process: additional IS collinear divergences to be subtracted

$q\bar{q} \to l^+l^-(1\gamma)$

- similar computational path as in the CC case
- delicate treatment of the Z decay width in the virtual corrections
- photon-induced process: further additional IS collinear divergences to be subtracted

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

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

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

$$\Pi_S(Q^2) \equiv \exp\left(-\frac{\alpha}{2\pi} \log\left(\frac{Q^2}{m^2}\right) \int_0^{1-\varepsilon} dx\, P(x)\right)$$ 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 $\mathcal{O}(\alpha)$

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

$$q_a(x) \to q_a(x, M^2) - \Delta q_a(x, M^2)$$

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

☺ 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

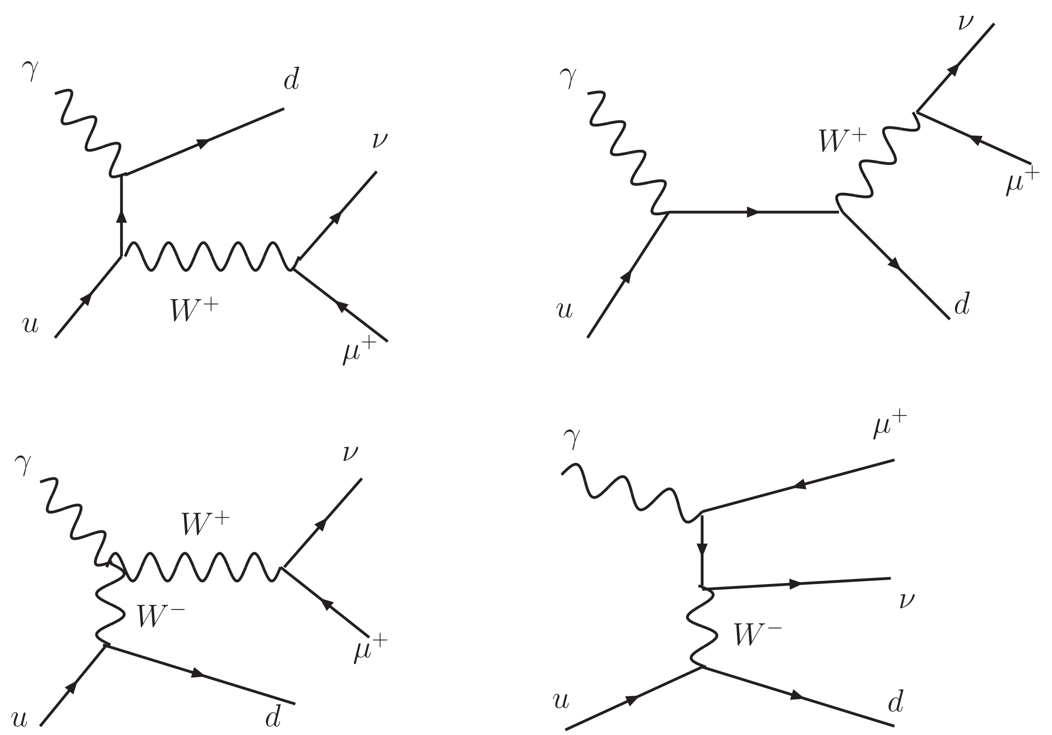
M_up	2053.07±0.22 (pb)
M_up / 50	2053.09±0.23 (pb)
M_up / 100	2052.98±0.24 (pb)

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)

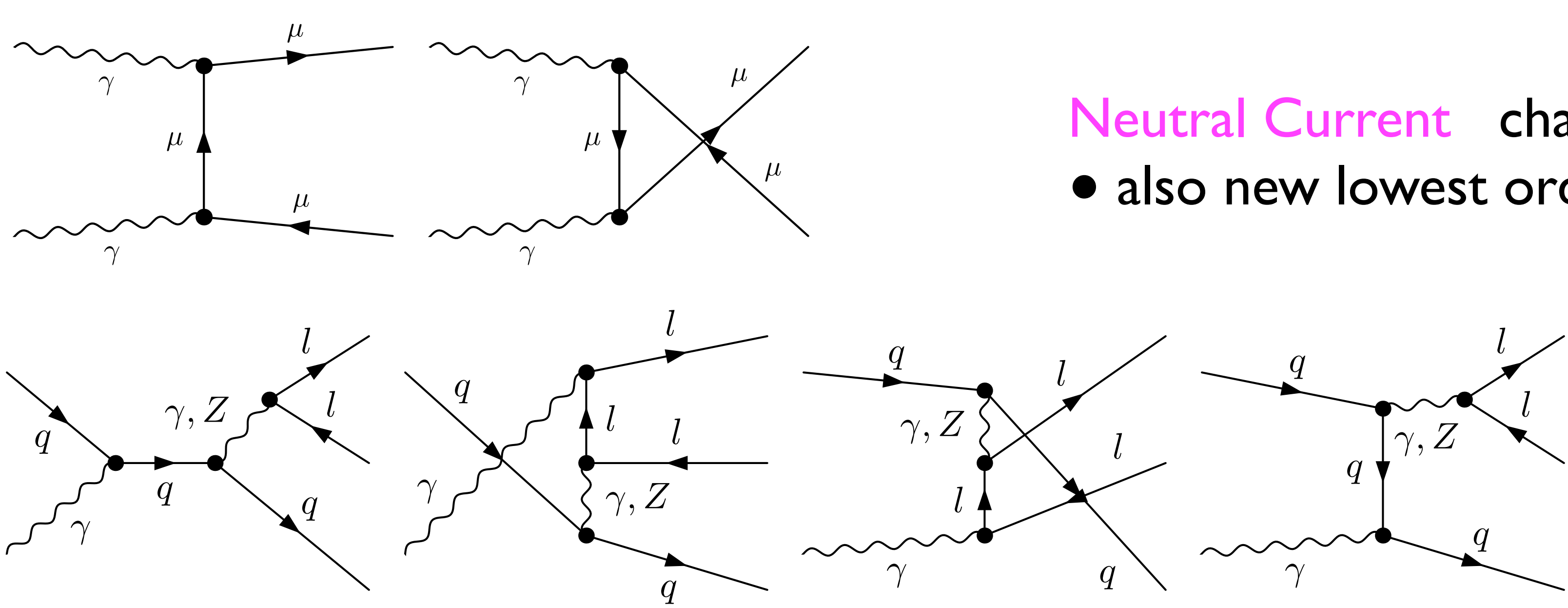
MRST 2004 QED and photon induced processes

- 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



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

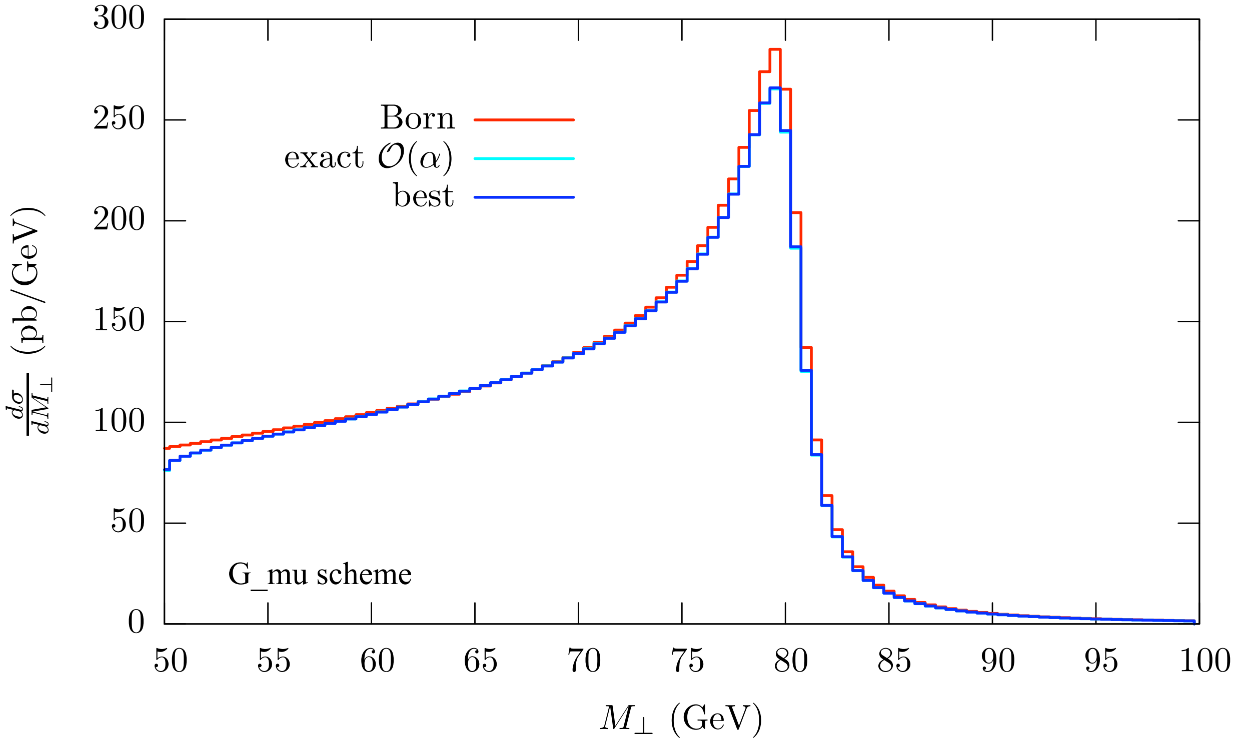
Neutral Current channel

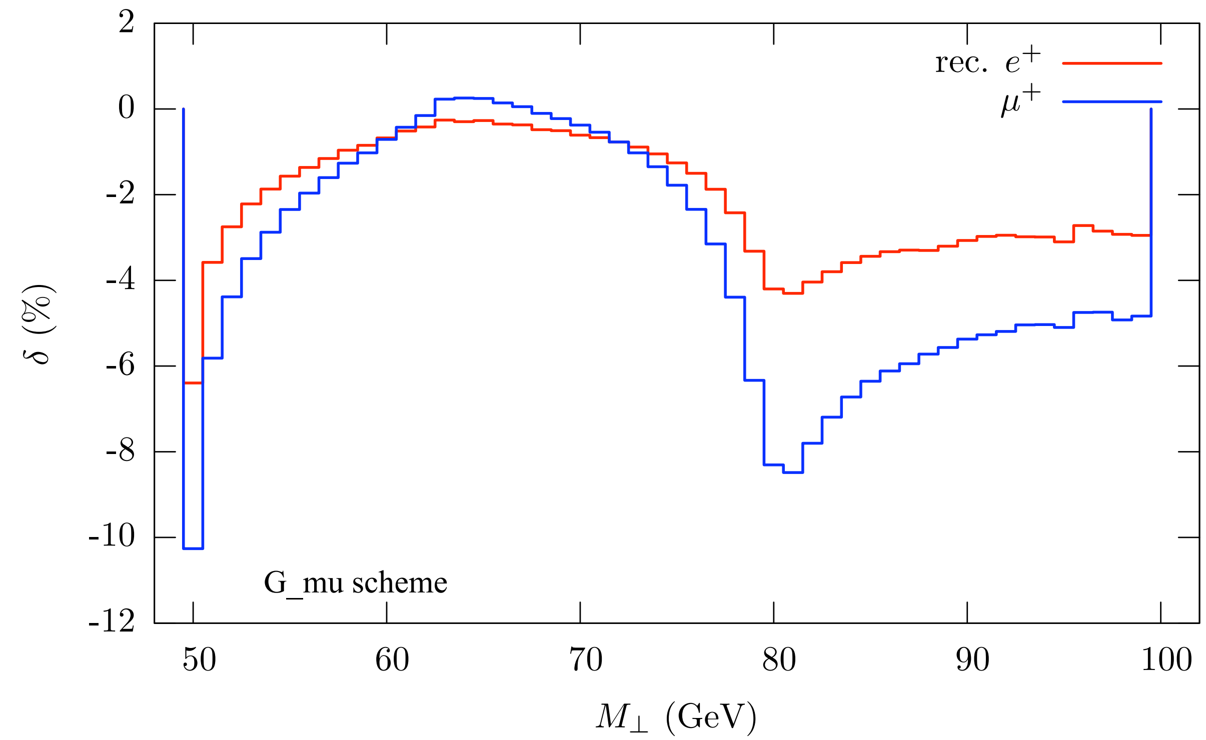
- also new lowest order partonic subprocess

W transverse mass distribution (peak region)

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

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

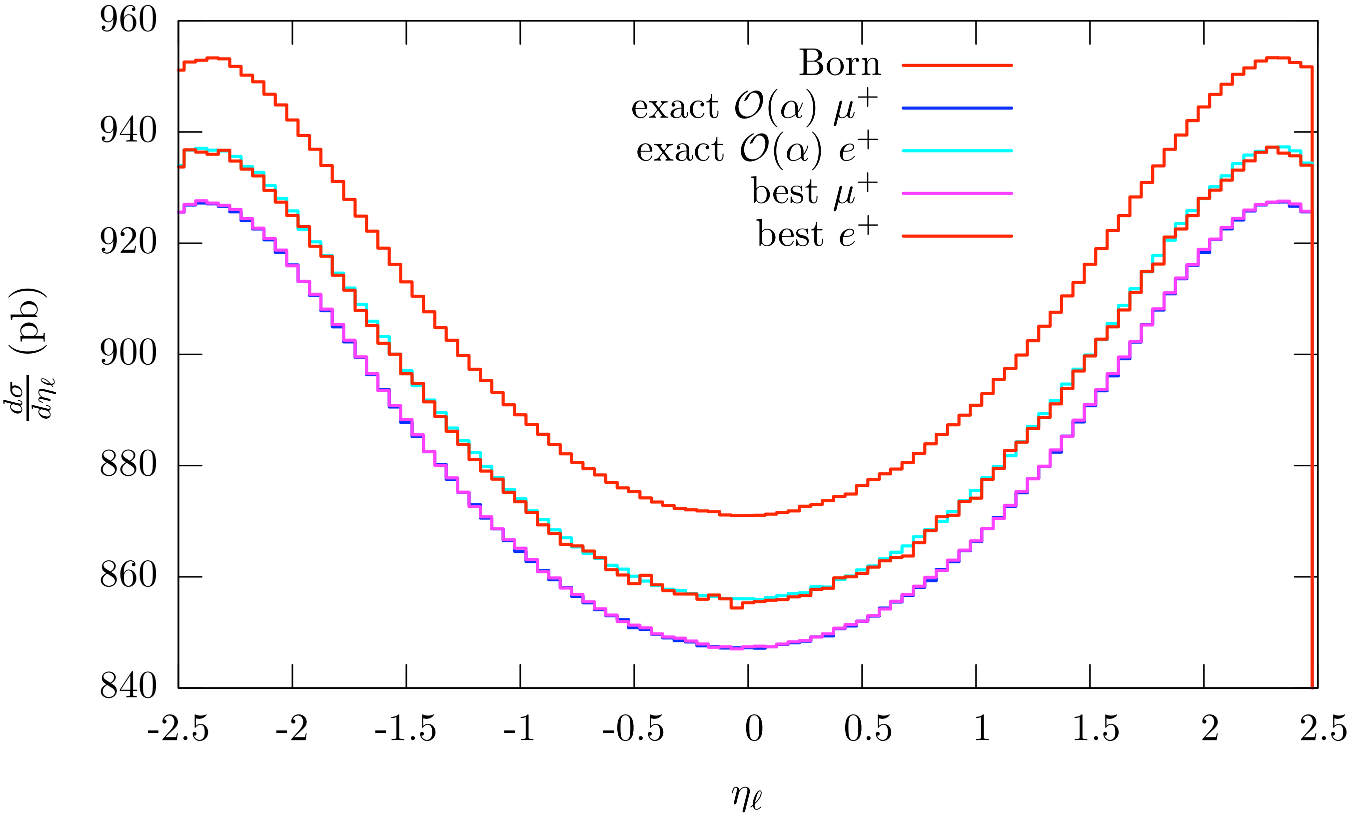


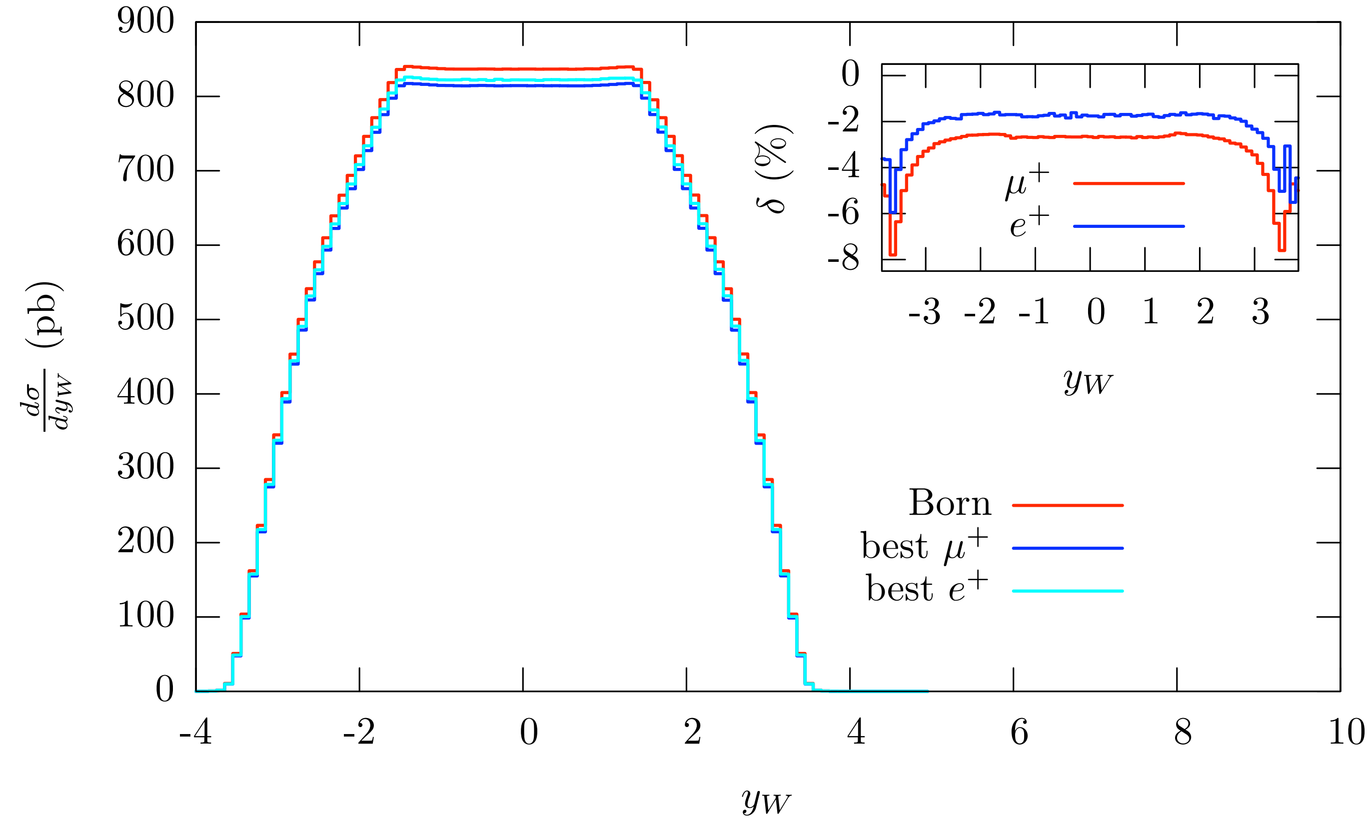


- recombined electrons show partial KLN cancelation
- bare (i.e. perfectly isolated) muons receive large final state corrections
- insensitive to photon induced processes

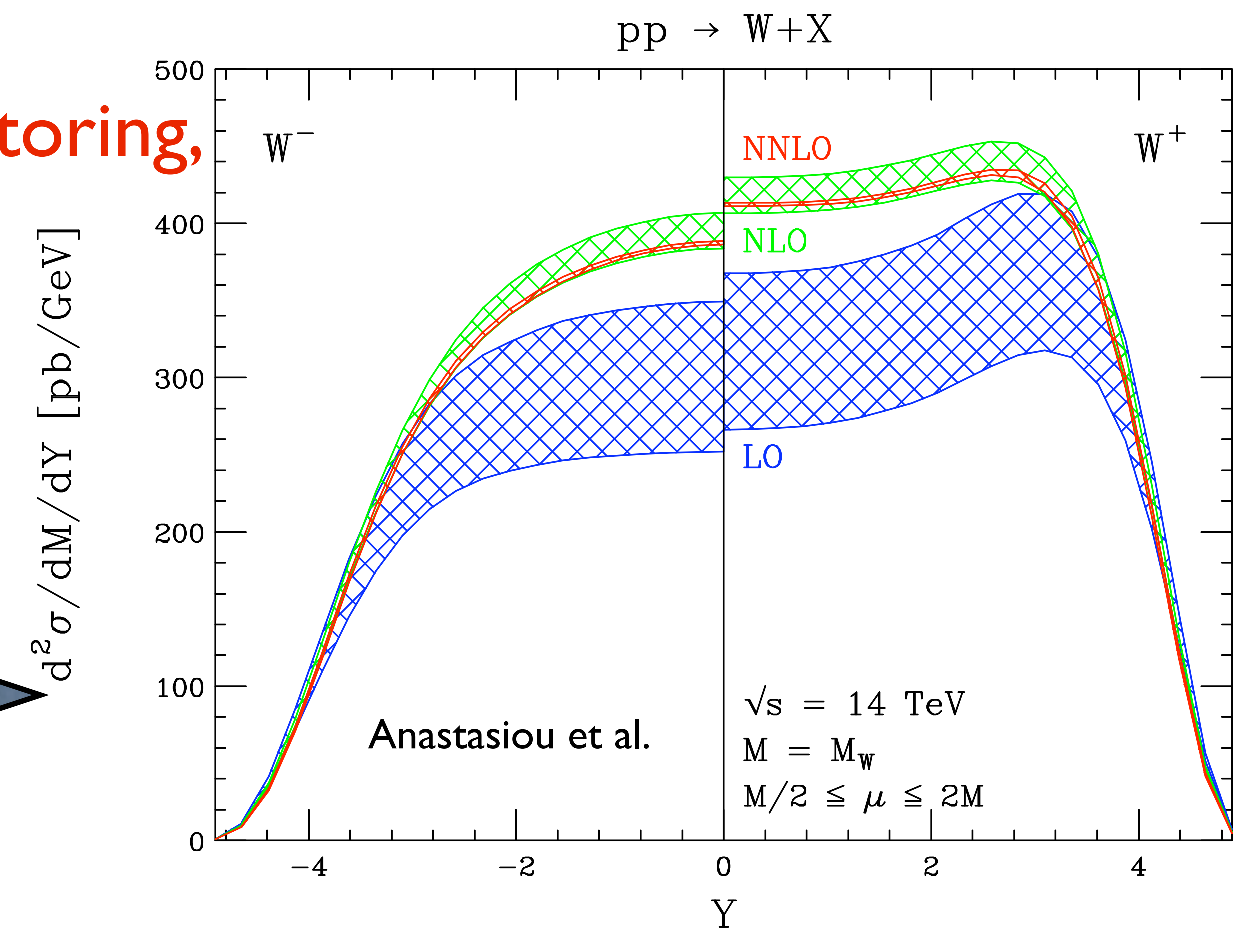
relevant for the extraction of MW

W-rapidity and lepton pseudo-rapidity distributions

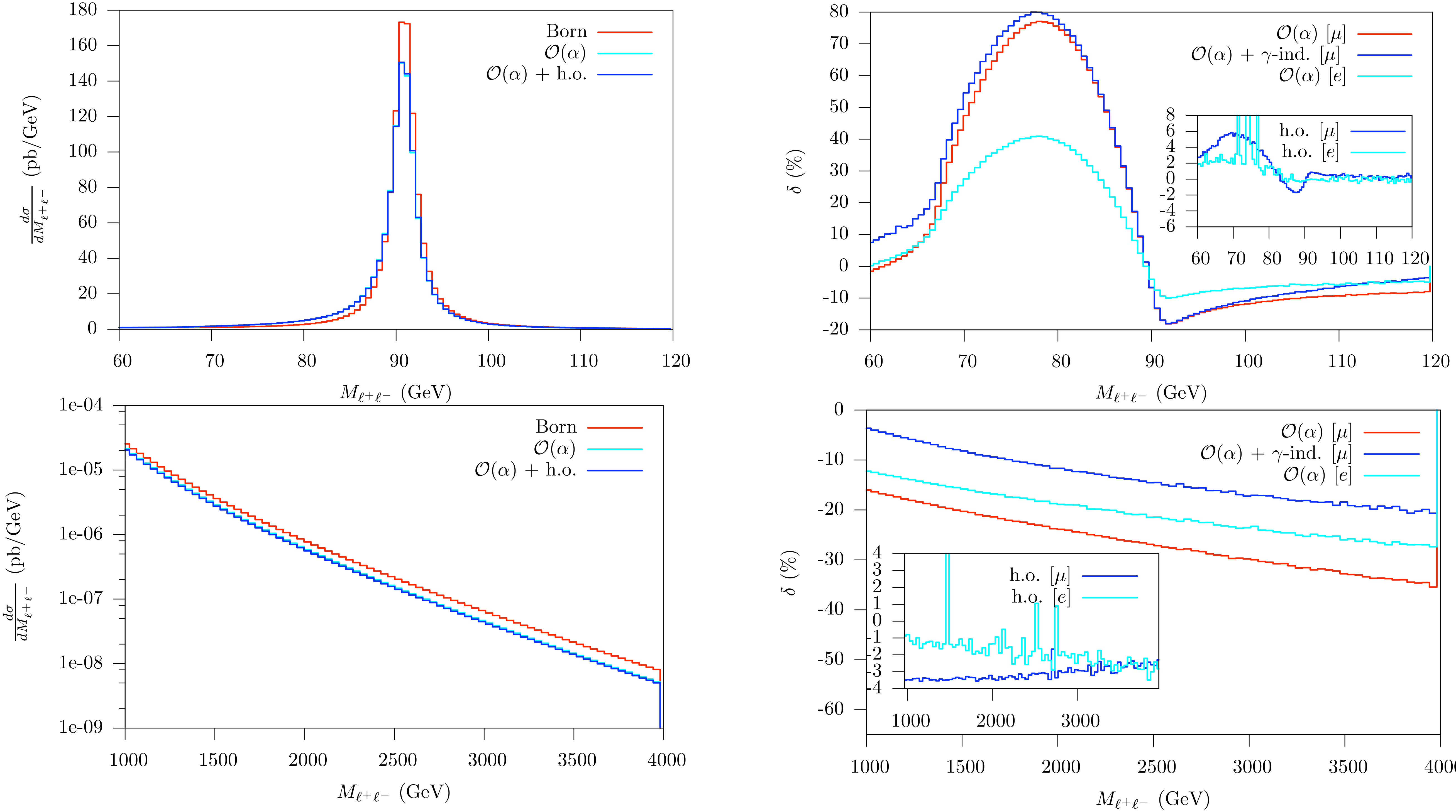




- relevant for acceptances, luminosity monitoring, *pdfs* constraining
- (flat) correction factor ranges from -2% (W) to -4% (lepton)
- of the same order of present NNLO-QCD uncertainty

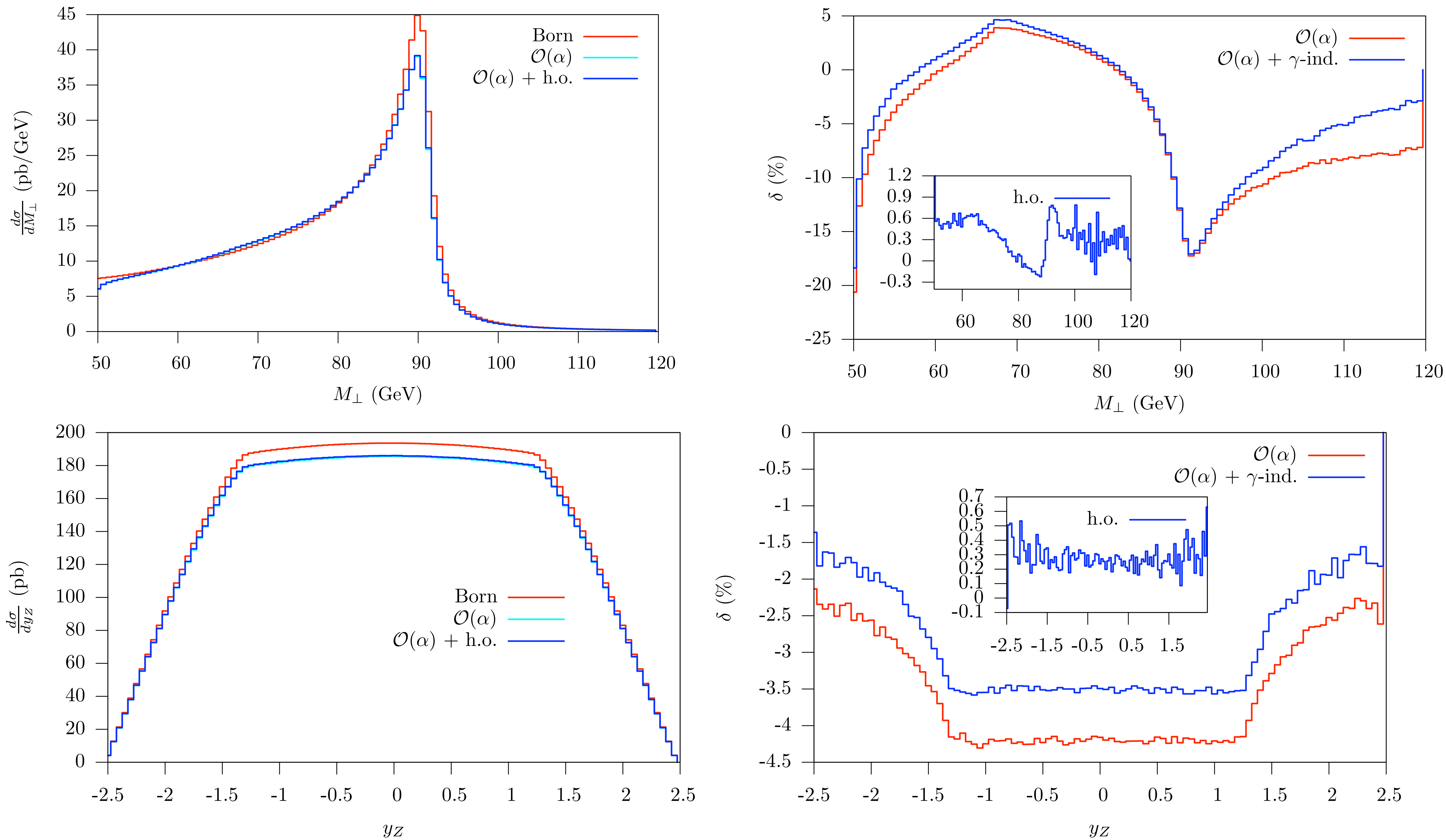


Z observables: invariant mass distribution



- 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

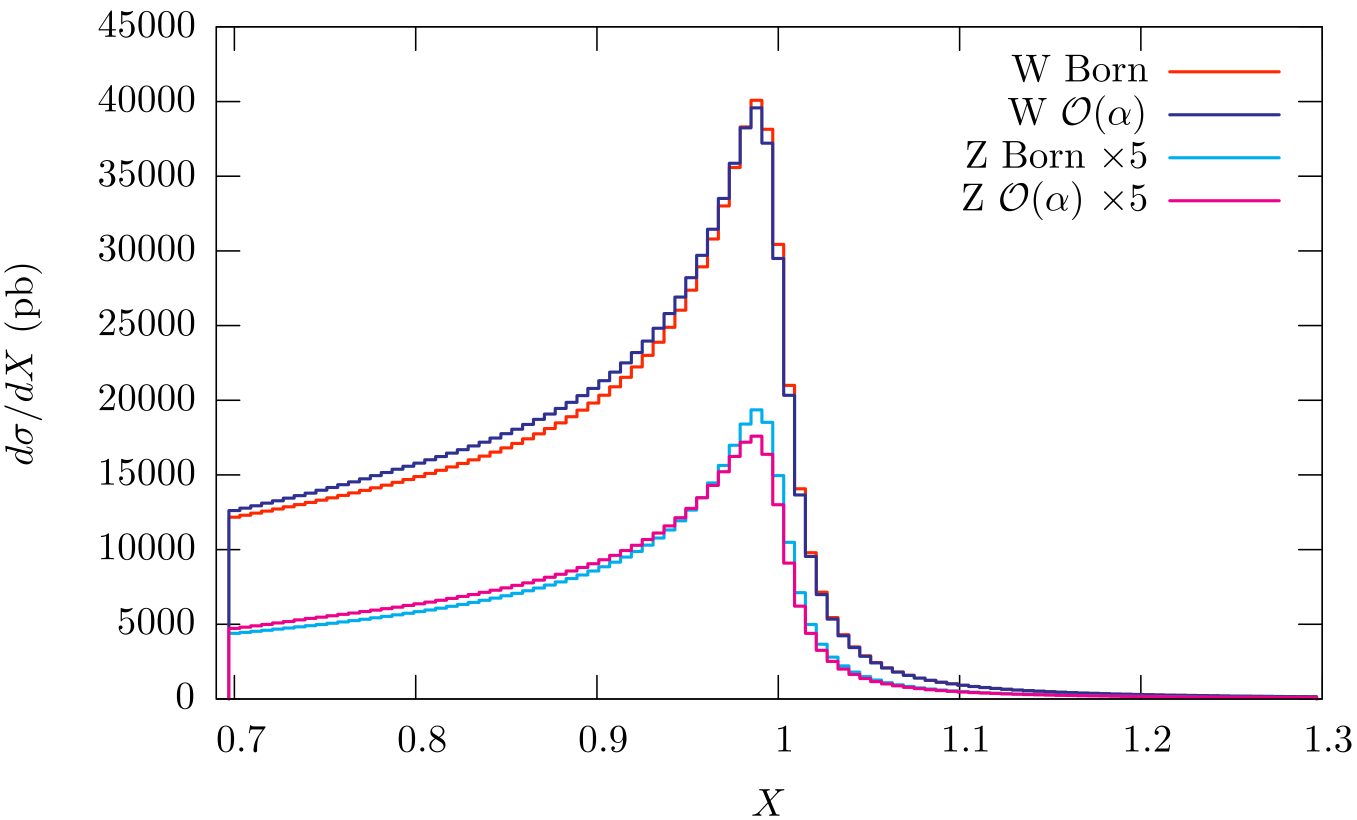
Z observables: transverse mass and Z rapidity distributions

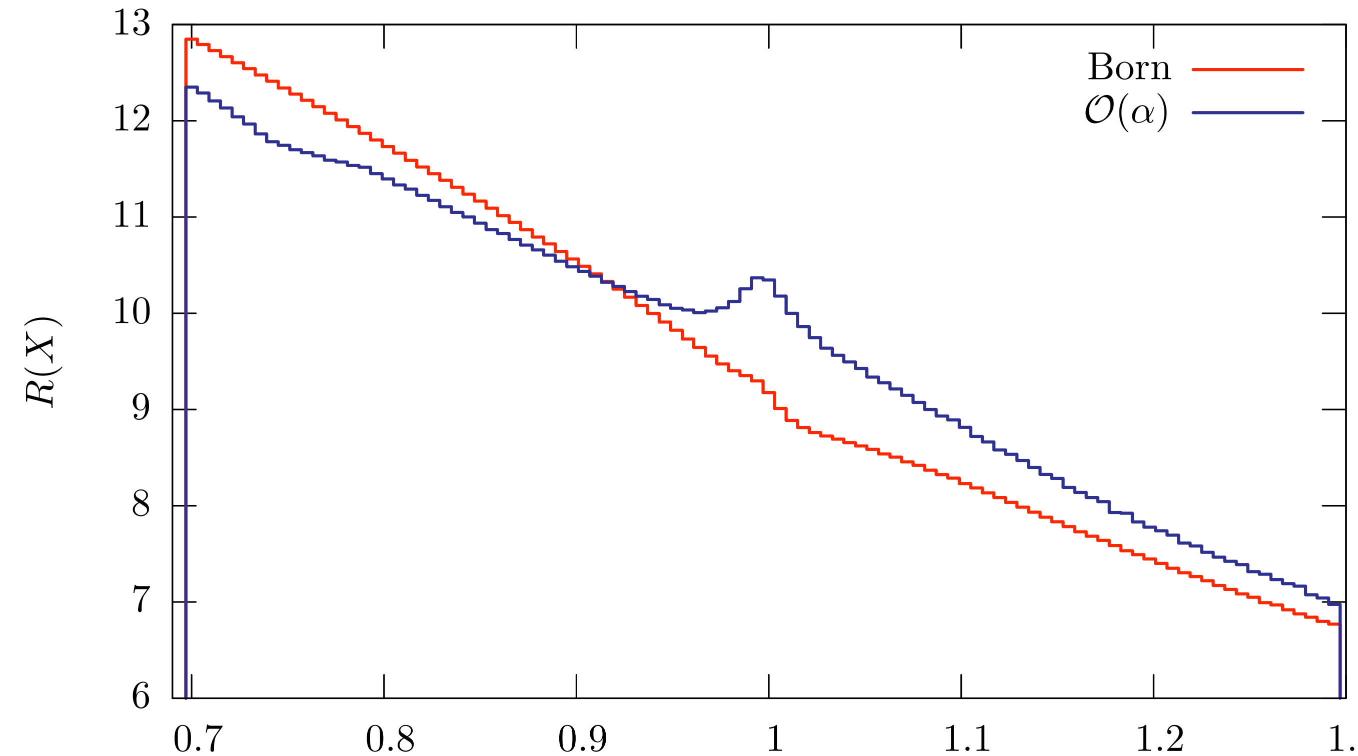


- above the Z peak, not negligible effect of the photon-induced processes

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

W/Z transverse mass ratio (preliminary)





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

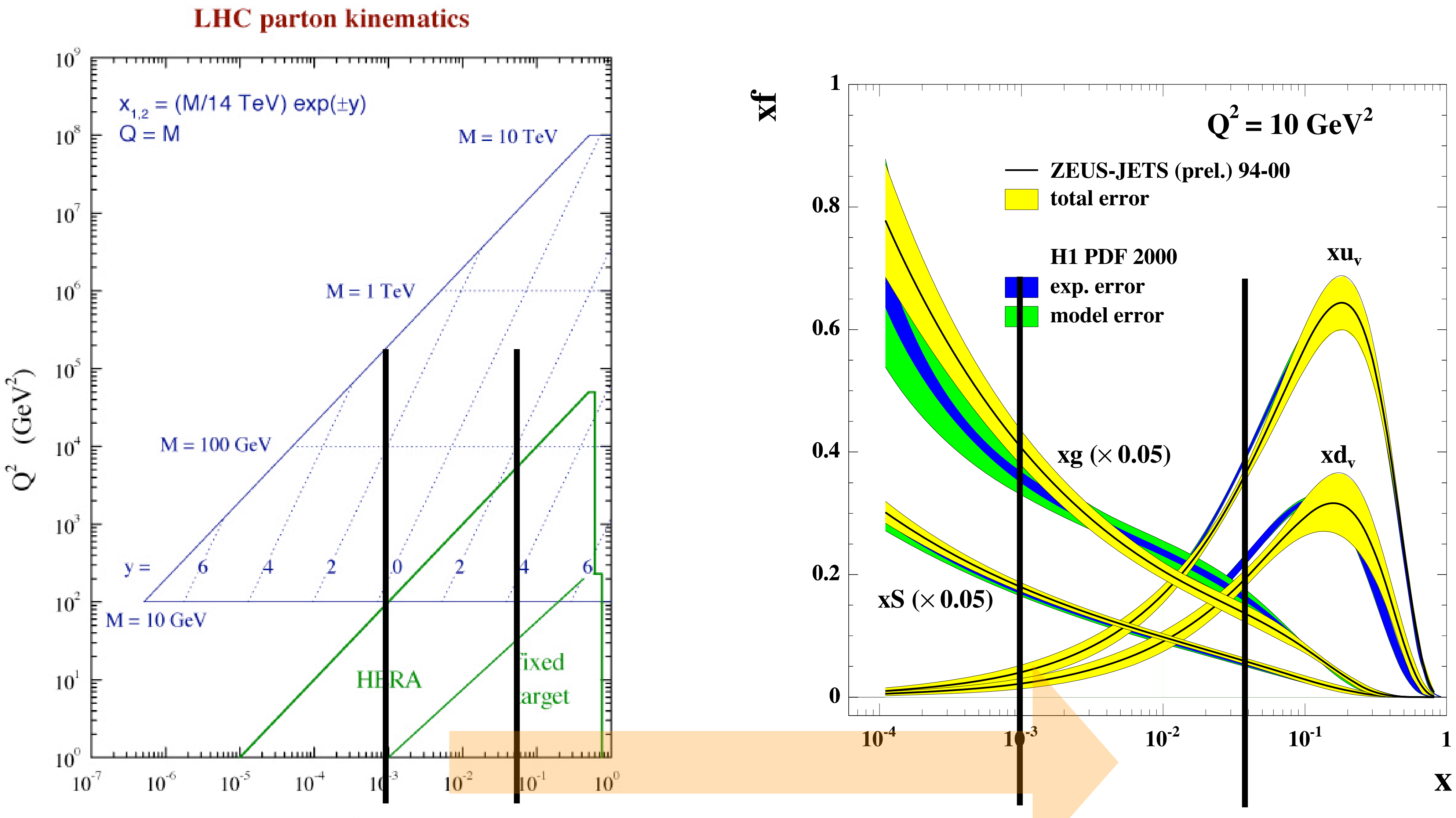
- the pQCD radiative corrections partially cancel in the ratio
  (Giele, Keller, Phys.Rev.D57:4433 (1998))
- the systematics due to the *pdf*s partially cancel in the ratio
- delicate discussion about the systematics on the acceptances
- the EW radiative corrections do not cancel in the ratio
- the ratio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

- 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

- Additive combination of QCD and EW corrections:

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

- 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

- Beyond the additive approximation, 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
$\sigma_{\rm LO}$ (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
$\sigma_{\rm LO}$ (pb)	8310(2)	8304(2)	8307.9(2)

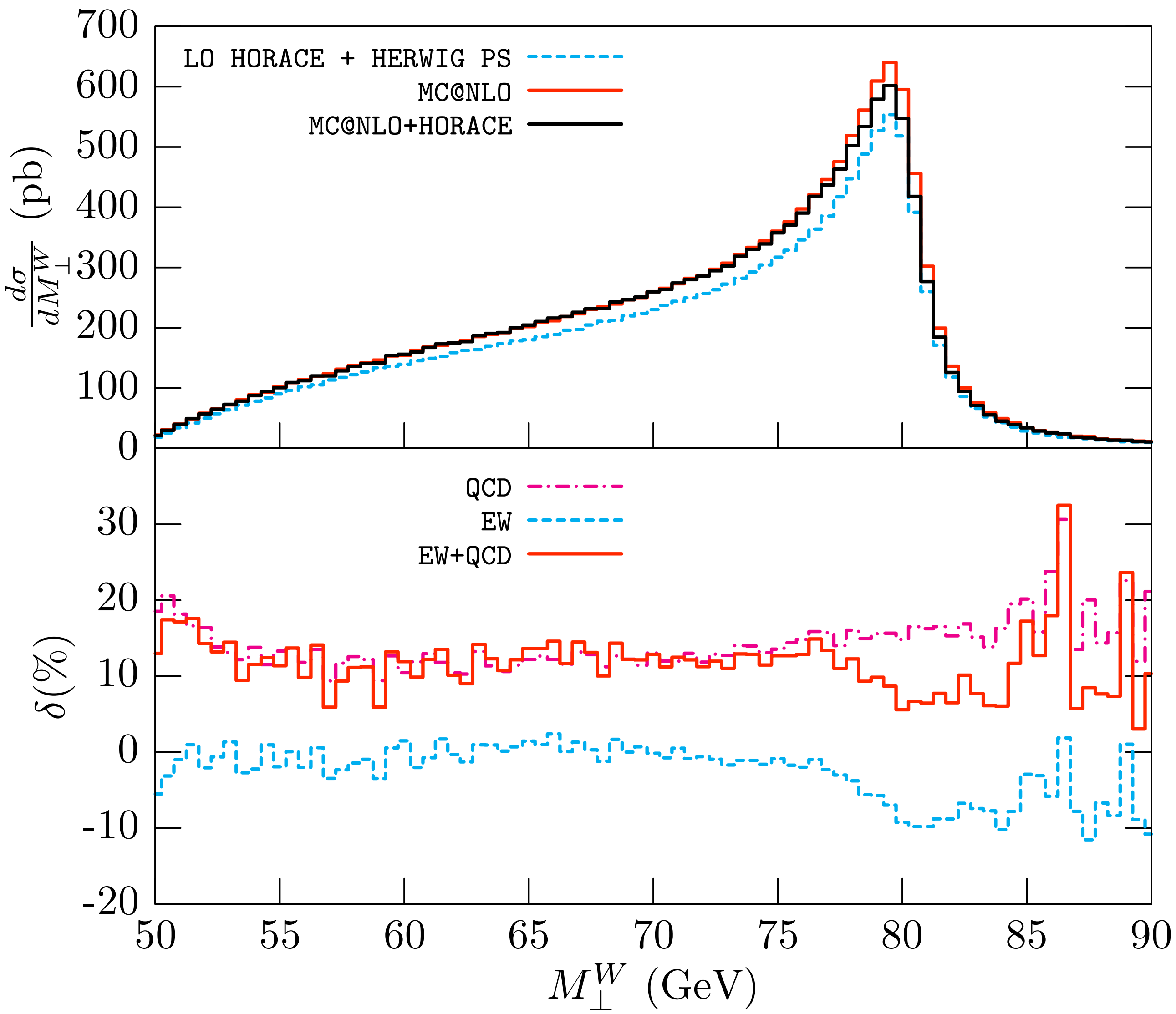
Table: MC tuning at the LHC for the LO cross section of the process $pp \to W^\pm \to \mu^\pm \nu_\mu$, using MRST2004QED with $\mu_R = \mu_F = \sqrt{p^2_{\perp,W} + M^2_W}$

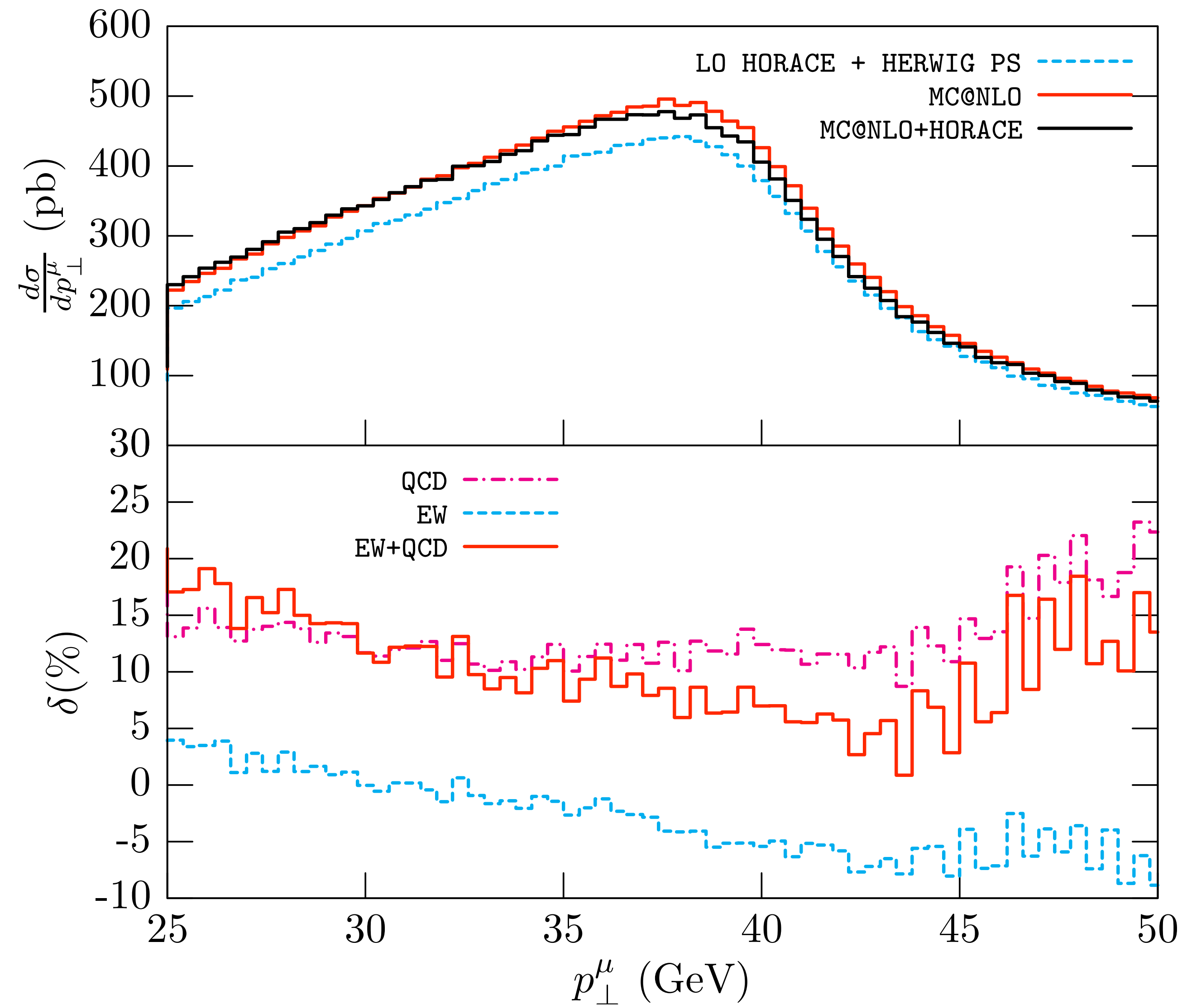
Monte Carlo	$\sigma^{\rm Tevatron}_{\rm NLO}$(pb)	$\sigma^{\rm LHC}_{\rm NLO}$(pb)
MC@NLO	2638.8(4)	20939(19)
FEWZ	2643.0(8)	21001(14)

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

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



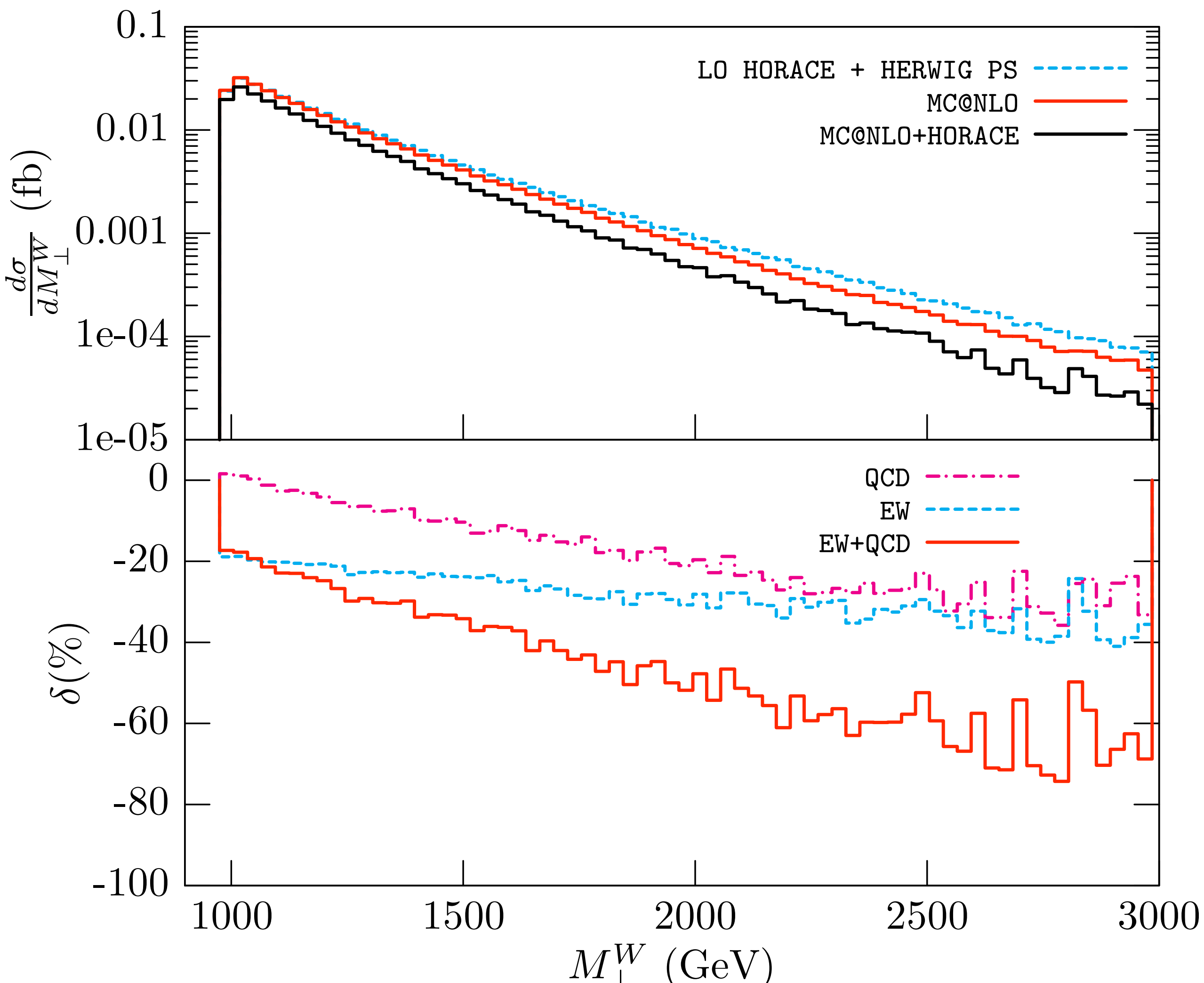


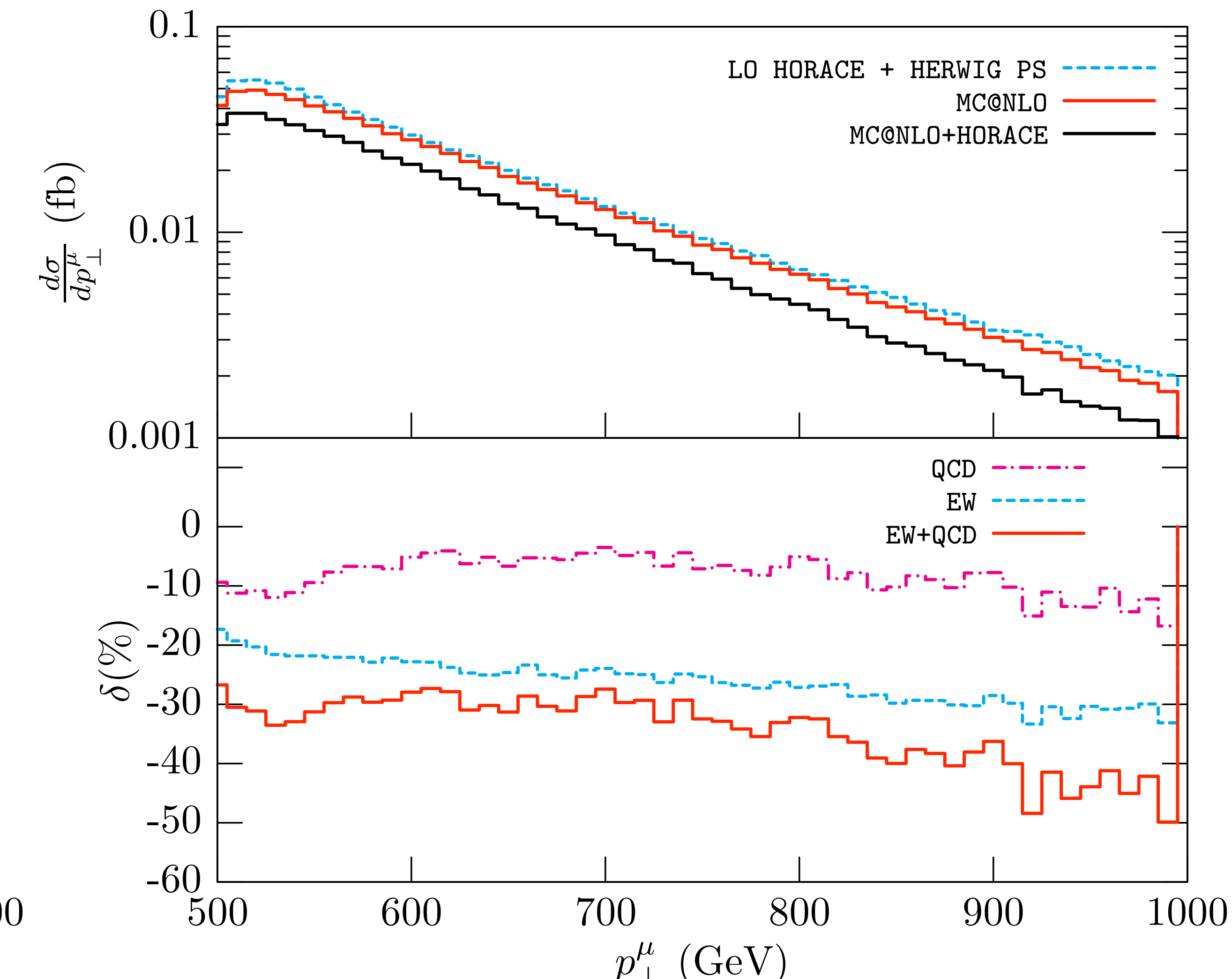
- the relative effect expressed in units Born+PS
- positive QCD corrections compensate negative EW corrections
- around the jacobian peak EW corrections mandatory to extract M_W
  only QCD-Parton Shower is not sufficient
- the convolution with QCD Parton Shower modifies
  the relative effect and shape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

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

$M_\perp^W > 1$ TeV, $\quad p_\perp^\mu > 500$ GeV

- which relation between large negative EW Sudakov logs and QCD corrections?





- the relative effect expressed in units Born+PS
- negative QCD corrections sum up with negative EW corrections
- the sum $\sim -40(-70)\%$ for $M_\perp^W \simeq 1.5(3)$ TeV and $\sim -30(-50)\%$ for $p_\perp^\mu \simeq 0.5(1)$ TeV

Conclusions

- the event generator HORACE contains almost the state of the art of 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

- the ratio of W/Z M_T distributions to extract the W mass is under study

- in the long term: unify ALPGEN and HORACE in a single generator

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

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