Theoretical Monte Carlo tools for describing W and Z boson production at Large Hadron Collider

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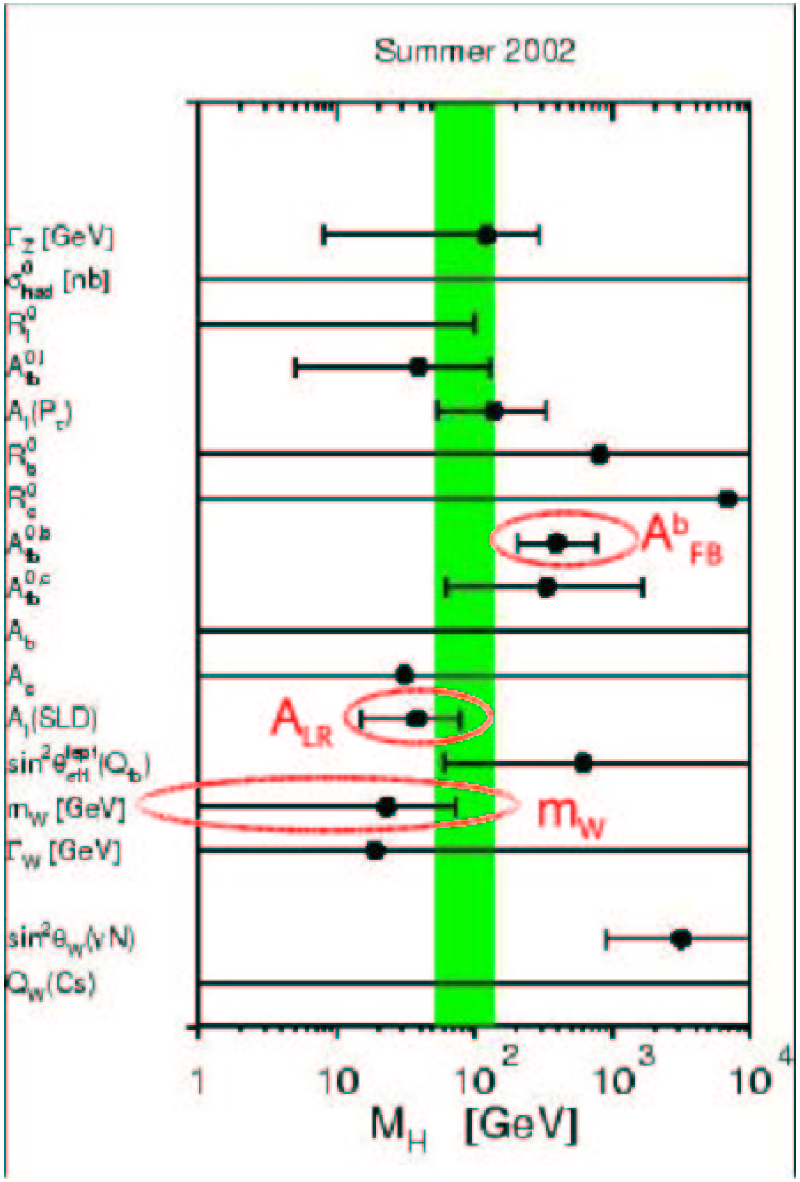
Introduction

- Experiments at Large Hadron Collider will offer good quality very high statistics data (millions of events) on the production of the W and Z bosons.
- It will be highly nontrivial task to exploit them fully in order to measure very precisely mass of W, anomalous couplings, find signals of the presence of new physics at multi-TeV scales, measure precisely parton luminosities etc.
- For this purpose one needs a new class of the Monte Carlo tools which incorporate high quality, beyond-the-leading-order QCD, QED and Electroweak calculations, which do not exists yet.
- In this talk I shall define more precisely what is needed and where are we presently on the development path of these tools.

EW precision SM tests: Where are we now?

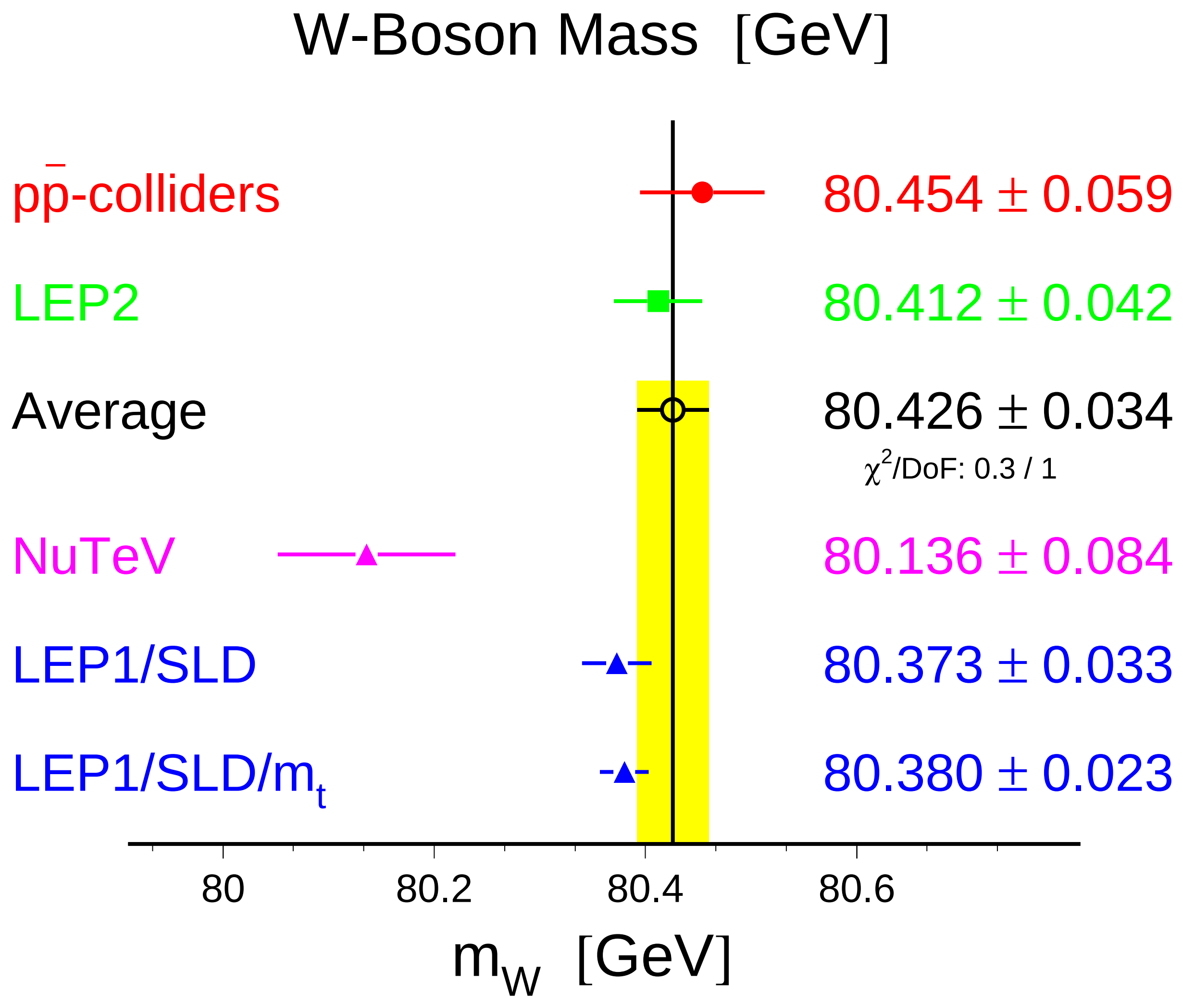


Higgs mass prediction is used here as a “meter” measuring the “predictivity power” of a given experimental data input, in the precision SM tests (and beyond?):

- Large difference between $\sin^2_{eff}$ from A_{LR} and A^b_{FB}
- M_W mass (measure directly) is not yet “competitive” at all!

(source: talk of G. Altarelli)

W mass measurement, direct and indirect, winter 2003



Expectations for EW observables at LHC

NOW $\longrightarrow$ LHC:

δM_W:	34MeV $\rightarrow$ 15MeV	($d\sigma/dM_T^l$)
$\delta \sin^2_{\rm eff}$:	$17 \cdot 10^{-5} \rightarrow 15 \cdot 10^{-5}$	($pp \rightarrow Z$)
$\Delta\kappa_\gamma, \Delta\lambda_\gamma$:	$1 \cdot 10^{-2} \rightarrow 3 \cdot 10^{-3}$	($pp \rightarrow VV$)
δM_t:	5GeV $\rightarrow$ 1GeV	($ljjb$)

- M_W increasingly important player in the SM precision tests
- EW mixing angle measured as precisely as in LEP (?)
- Anomalous vector boson couplings constrained factor 10 better
- Parton luminosities to be measured with 1% precision

EW precision SM tests: **Where do we go?**

Errors of the experimental data, present and anticipated:

	now	Tev. Run IIA	Run IIB	Run IIB*	LHC
$\delta \sin^2\theta_{\rm eff}(\times 10^5)$	17	78	29	20	14–20
δM_W [MeV]	33	27	16	12	15
δm_t [GeV]	5.1	2.7	1.4	1.3	1.0

Again indirect prediction of the Higgs mass used as a “meter”:

$\delta M_H/M_H$ *from:*	M_W	$\sin^2\theta_{\rm eff}$	all
now	106 %	60 %	58 %
Tevatron Run IIA	72 %	39 %	35 %
Tevatron Run IIB	37 %	33 %	25 %
Tevatron Run IIB*	30 %	29 %	23 %
LHC	22 %	25 %	18 %

From hep-ph/0202001, Snowmass 2001, P1WG1 group report.

Why emphasis on TOOLS?

- Main problem 10 years ago:

  Wish-list of ANY physics observables $\longrightarrow$ **Specs of LHC and its detectors?**

- Main question NOW:

  For observables accessible at LHC $\longrightarrow$ **How to measure them efficiently?**

Desired specs of TOOLS for EW observables at LHC

Observable∈process	EW	QED	QCD	MC type
$M_W \in$ W,Z	Impr. Born	$\mathcal{O}(\alpha)_{\rm exp}$ FSR!	pdf(x,pT), NLO?	events!
$\sin^2\theta_{EW} \in$ Z	$\mathcal{O}(\alpha, \alpha^2_{Sud.})$	$\mathcal{O}(\alpha)_{\rm exp}$ FSR!	NLO	events!
Anom. coupl.∈ VV	$\mathcal{O}(\alpha)$	$\mathcal{O}(\alpha)$	NLO! NNLO?	events!
Parton $\mathcal{L} \in$ W,Z	$\mathcal{O}(\alpha)$	$\mathcal{O}(\alpha)_{\rm exp}$ FSR?	NLO! NNLO?	events?

! $\equiv$ mandatory,

? $\equiv$ to be checked...

None of the existing TOOLS fulfill the above specifications

Process-wise

- **Single W and $Z+\gamma$ production (1V, Drell-Yan-likes)**

  Main objectives at LHC for 1V measurements:

  - Measurement of M_W from both (W and Z!) processes
  - Looking for deviations from the SM at high masses 200GeV-2TeV
  - Determining "parton luminosities" with $\sim 1\%$ precision

- **The double vector boson WW, WZ production processes:**

  - will be great source of information on the gauge boson anomalous couplings at TeV scale
  - and may possibly give hints on the nature of the non-abelian symmetry breaking,
  - have to be implemented in a good quality MCs, also because they are background to many other important processes.

Existing EW+QCD tools for $pp \rightarrow$V and $pp \rightarrow$VV, where V=W,Z

Required at least $\mathcal{O}(\alpha)$ electroweak or NLO QCD, none has both!

Tool	Process	EW	QCD	MC type
WGRAD	W	$\mathcal{O}(\alpha)$	pdf(x),LO	histogrs.
ZGRAD2	Z	$\mathcal{O}(\alpha)$	pdf(x),LO	histogrs.
WINHAC	W	QED FSR $\mathcal{O}(\alpha)_{\rm EEX}$	pdf(x),LO	events
HORACE	W,Z	QED FSR part.sh.	pdf(x),LO	events
SANC	W,Z	$\mathcal{O}(\alpha)$	???	events?
RESBOS	W, Z	LO	pdf(x,pT),NLO	histogrs.
DYRAD	V+(0j-1j)	LO	pdf(x),NLO	histogrs.
MCFM	V,VV	LO	pdf(x),NLO	histogrs.
DKS	WW, WZ, ZZ	LO, Anom.Coup.	pdf(x),NLO	histogrs.
dFS	Wγ, Zγ	LO, Anom.Coup.	pdf(x),NLO	histogrs.
MC@NLO	WW	LO	part.sh. NLO	events
MC@NLO	W or Z	LO	part.sh. NLO	events

Existing EW tools for $pp \to$V, $pp \to$VV (2003)

- **WGRAD** Baur, Keller and Wackeroth, Phys.Rev.D59:013002,1999 [hep-ph/9807417], W
  http://ubpheno.physics.buffalo.edu/∼dow/wgrad.html
- **ZGRAD2** Baur, Brein, Hollik, Schappacher and Wackeroth, Phys.Rev.D65:033007,2002 [hep-ph/0108274], Z
  http://ubpheno.physics.buffalo.edu/∼dow/
- **RESBOS** Balazs and Yuan, Phys.Rev.D56 (1997) 5558, [hep-ph/9704258], W,Z **http://www.pa.msu.edu/ balazs/ResBos/**
- **DYRAD** W.T. Giele, E.W.N. Glover, D.A. Kosower, Nucl.Phys.B403:633-670,1993 [hep-ph 9302225], V+j
  Inclusive 0-jet and 1-jet production in association with a vector boson
  http://theory.fnal.gov/people/giele/dyrad.html
- **WINHAC** W. Placzek, S. Jadach, hep-ph/0302065
  http://placzek.home.cern.ch/placzek/winhac/
- **HORACE** C.M.Carloni Calame, G.Montagna, O.Nicrosini, M.Treccani, hep-ph/0303102

Existing EW tools for $pp \to$V, $pp \to$VV (2003)

- **MC@NLO** S. Frixione, B.R. Webber, JHEP 0206:029,2002, [hep-ph/0204244], VV
  http://www.hep.phy.cam.ac.uk/theory/webber/MCatNLO/
- **DKS** L. Dixon, Z. Kunszt, A. Signer , Phys. Rev. D60 (1999) 114037 [hep-ph/9907305], VV
  http://www.itp.phys.ethz.ch/staff/dflorian/codes.html
- **dFS (invented name)** D. de Florian, A. Signer [hep-ph/0002138], Wγ, Zγ
  http://www.itp.phys.ethz.ch/staff/dflorian/codes.html
- **MCFM** J.M.Campbell, R.K.Ellis, Phys. Rev. D60:113006 (1999), [hep-ph/9905386], WW, WZ, ZZ, ...
  http://mcfm.fnal.gov/
- **SORRY FOR OMISSIONS!!!**

Conclusions of the EW group MC4LHC workshop, August 2003

- In spite of the rich legacy of “Tevatron codes”, it is fair to say that there is no single (MC) TOOL fully adequate for any EW observable nor parton luminosity measurement at LHC.
- New MCs combining first order EW and QCD seem to appear on the horizon.
- Plans for systematic test of tools for EW@LHC should materialize.

Newcoming EW TOOLS (2003/4)

- **WINHAC + SANC**

  $pp \to W, Z$, EW $\mathcal{O}(\alpha)$, QED FSR $\mathcal{O}(\alpha)_{\rm exp}$, pdf(x,pT?) NLO?

  Cracow and Dubna, in progress

- **HORACE**

  of Pavia group

- **RESBOS**

  QCD-NLO and QED-FSR pure $\mathcal{O}(\alpha^1)$ (no expon.)

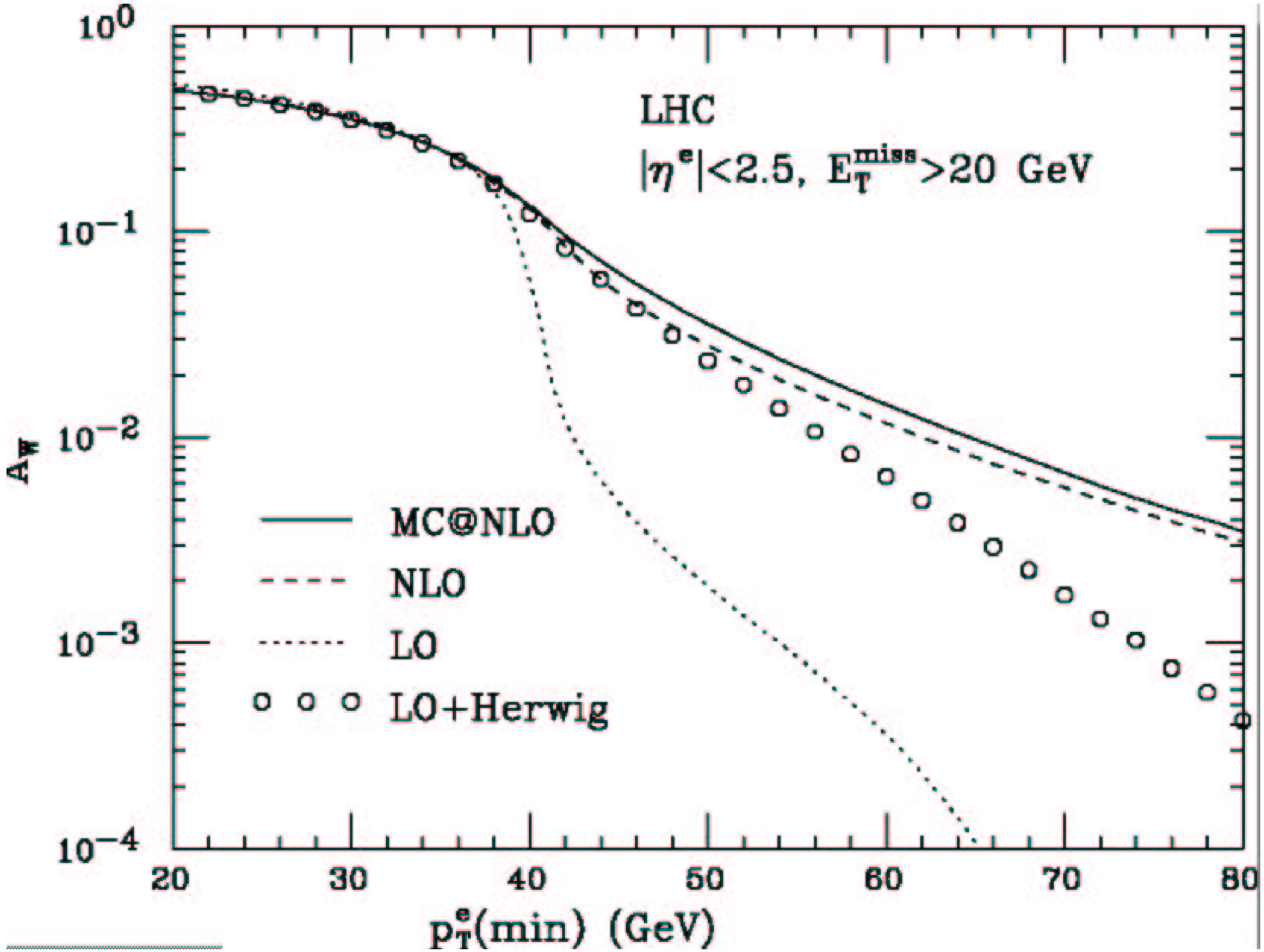
  Q.-H. Cao and C.-P. Yuan, hep-ph/0401026.

- **RESBOS + (Z)WGRAD + WINDEC**

  $pp \to W, Z$, EW $\mathcal{O}(\alpha)$, QED FSR $\mathcal{O}(\alpha)_{\rm exp}$, QCD pdf(x,pT), NLO

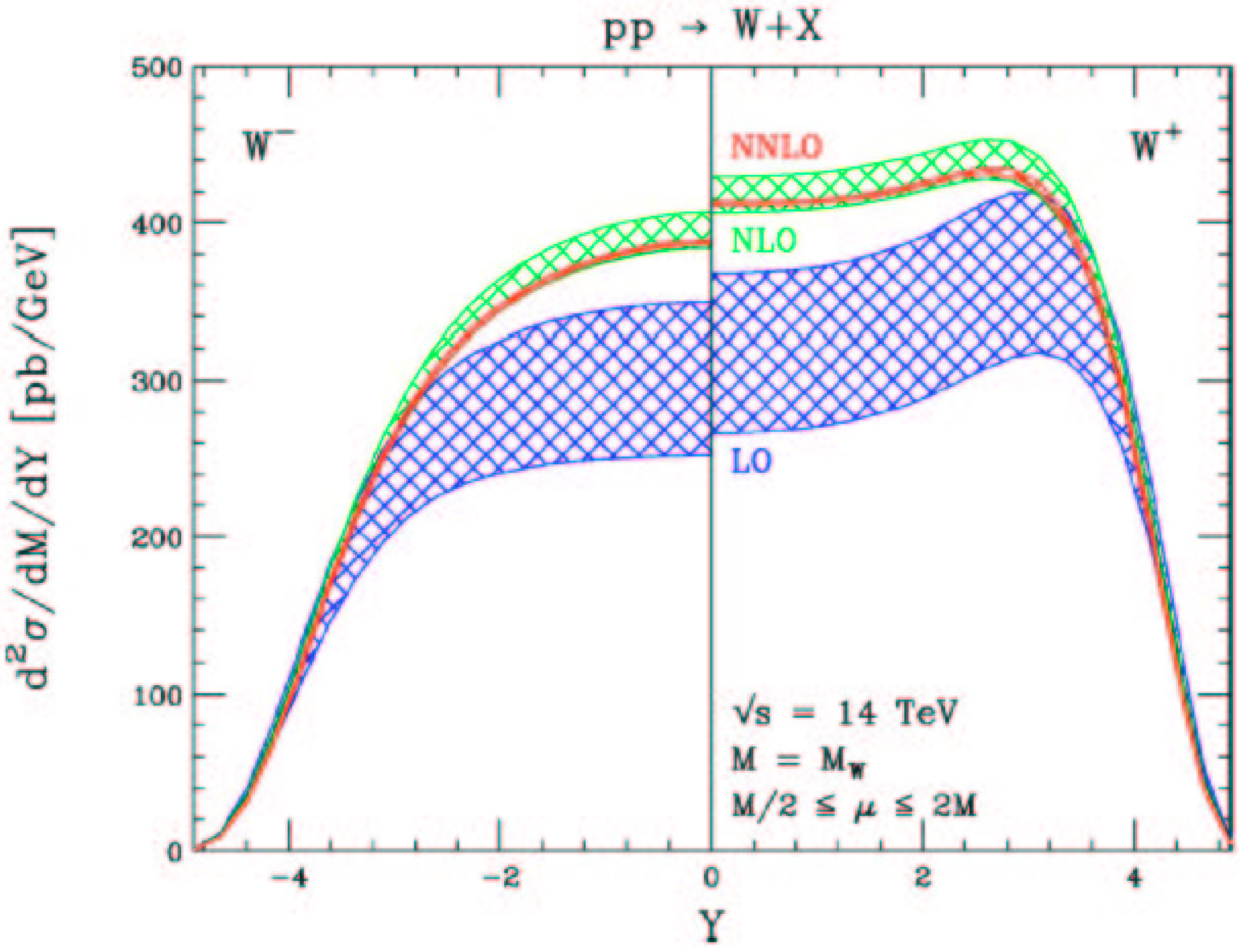
  U. Baur and D. Wackeroth, still to materialize...

Recent QCD NLO calculations (2003/4)



- Parton shower NLO: Frixione and Mangano using MC@NLO (JHEP05, 2004, 056)
  - For $p_e^T > 20$GeV and $|\eta_e| < 2.5$ QCD theory error $\delta\sigma/\sigma \geq$2%.
  - Parton shower $\sim 1\%$, NNLO $\sim 1\%$, PDF ~ 1% (determination of lumi!)
  - Spin effects crucial, QED FSR to be added.
  - What about δM_W?

Recent QCD NLO calculations (2003/4)



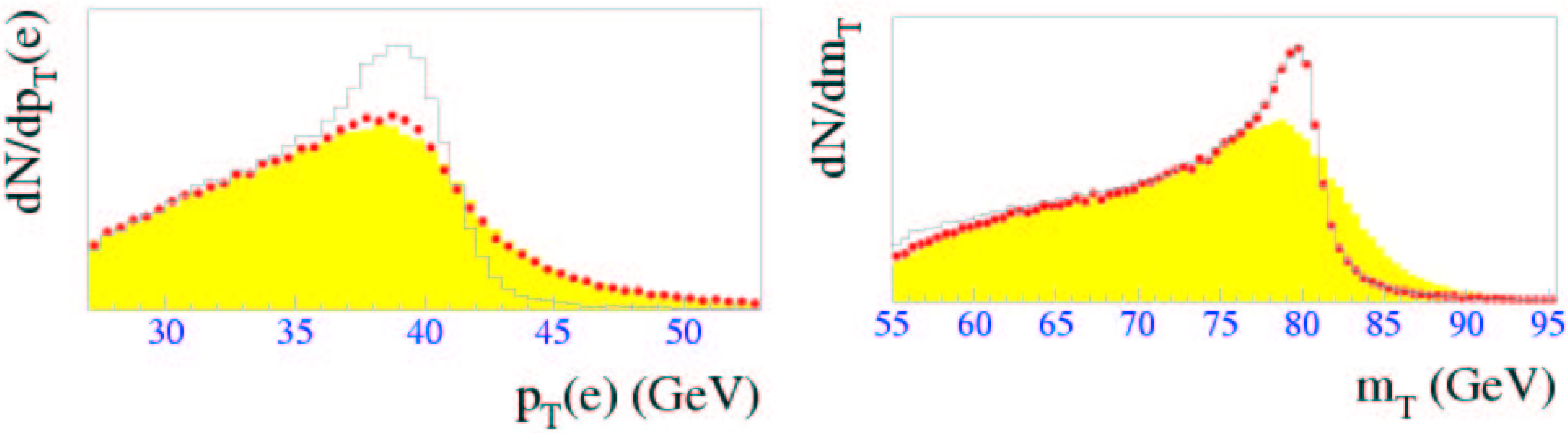
- C. Anastasiou et.al. Phys.Rev.D69:094008,2004, W rapidity distr. at NNLO
- Estimated QCD theretical errors $\leq 1\%$, fantastic!!!
  - Calculation too inclusive for the practical applications.
  - No QED ISR, even LL.

Importance of QED FSR in M_W measurements

Expected error budget of the W-mass measurement at LHC

Source	CDF Run Ib	ATLAS or CMS	$W \to l\nu$, one lepton species
	30K evts, 84 pb^{-1}	60M evts, 10fb^{-1}	
Statistics	65 MeV	< 2 MeV	
Lepton scale	75 MeV	15 MeV	most serious challenge
Energy resolution	25 MeV	5 MeV	known to 1.5% from Z peak
Recoil model	33 MeV	5 MeV	scales with Z statistics
W width	10 MeV	7 MeV	$\Delta\Gamma_W \approx 30$ MeV (Run II)
PDF	15 MeV	10 MeV	
Radiative decays	20 MeV	<10 MeV	(improved Theory calc)
$P_T(W)$	45 MeV	5 MeV	$P_T(Z)$ from data, $P_T(W)/P_T(Z)$ from theory
Background	5 MeV	5 MeV	
TOTAL	113 MeV	$\leq$ 25MeV	Per expt, per lepton species

How is M_W measured at Tevatron?



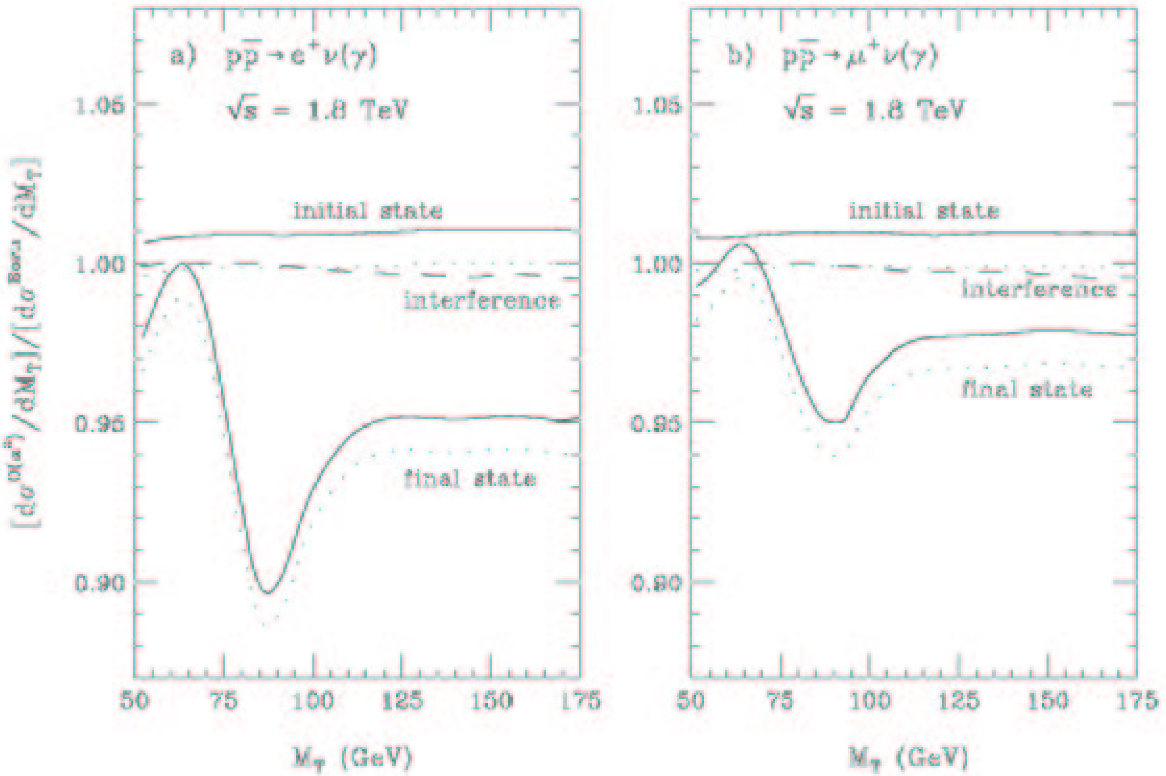
- Transv. mass $M_T = (2p_T^l p_T^\nu(1 - cos\phi_{l\nu}))^{1/2}$ unaffected by smearing due to p_T^W. (Plot is from hep-ph/0108272, Red dots: added p_T^W, Yellow: added detector eff.)
- Mass of W is fitted in Tevatron from the M_T distribution.
- Uncertainty due to p_T^W enters back through experim. cuts, hence the net gain is in fact small. Use of p_T^l is reconsidered.
- Distribution of p_T^W is modeled using leptonic decays of Z. LHC will profit here from Z statistics much larger than in Tevatron.
- New method: scaling M_T distribution from Z decay.
- The biggest EW/QED effect is form QED FSR, see next slide.

M_W measurement, QED effects in Tevatron measurements

Source of uncertainty	$W \to e\nu$	$W \to \mu\nu$	common
Lepton scale	75	85	
Lepton resolution	25	20	
PDFs	15	15	15
p_T^W	15	20	3
Recoil	37	35	
Higher order QED	20	10	5
Trigger & Lepton ID bias	–	$15 \oplus 10$	
Backgrounds	5	25	
Total	92	103	16

- Error budget in CDF measurement of M_W, Phys.Rev. D64 (2001)
- The shift of M_W was estimated:
  - 60 ± 20MeV in $W \to e\nu$ channel,
  - 168 ± 10MeV in $W \to \mu\nu$ channel.

W mass measurement, QED effects



- Plotted are $\mathcal{O}(\alpha)$ results from hep-ph/0108272 (Baur, Keller and Wackeroth).
- ISR and ISR$\otimes$FSR interference are negligible
- Influence of FSR in W decay is very large, $\delta M_W = 70 - 170$MeV. $\mathcal{O}(\alpha)$ is not enough to control it! Multiphoton FSR absolutely necessary!
- **Two multiphoton MCs recently available: WINHAC (Krakow) and HORACE (Pavia).**

More on QED ISR

QED ISR is absorbed in PDFs

- Spiesberger, Phys. Rev. D52 (1995) 4936
- Roth and Weinzierl, Phys. Lett B590 (2004) 190
- MRST done but publication still "in preparation",
  (see http://agenda.cern.ch/fullAgenda.php?ida=a044163)
- Generally QED ISR correction to PDF is $\sim 0.2\%$, except $x > 0.1$

$\mathcal{O}(\alpha)$ EW corrections to W production

- Corrections to M_T^W close to M_W are sufficient in the “pole approximation” PA,
  Ditmaier and Kramer, Phys. Rev. D65 (2002)
- At large M_T PA is not good enough and for M_T $\sim$1TeV even EW Sudakov logs has to be resumed! But only $\sim 10^2$ events.
  See Baur and Wackeroth, hep-ph/0405191.

QED FSR in M_W measurement; beyond $\mathcal{O}(\alpha^1)$

Comparisons of two indepenedent MC programs

- **HORACE:** C.M. Carloni Calame, G. Montagna, O. Nicrosini and M. Treccani,
  ▷ Phys. Rev. **D69** (2004) 037301; hep-ph/0303102.
  The MC program for Drell–Yan processes (both W and Z) with higher-order QED corrections included by means of a parton-shower algorithm: numerical solution of the QED DGLAP evolution equation in the non-singlet channel, with non-zero lepton and photon p_T generated at each branching.
- **WINHAC:** W. Płaczek and S. Jadach, Eur. Phys. J. **C29** (2003) 325; hep-ph/0302065.
  Single-W production at hadron colliders with the $\mathcal{O}(\alpha)$ YFS exclusive exponentiation. (Exact infrared limit. part of higher-order non-IR corrections included) $\mathcal{O}(\alpha)$ EW corrections for W decay.
- **Dont forget PHOTOS!**

▷ **Observables:** → Measurement

1. W-boson transverse mass: $m_T^W = \sqrt{2p_T^l\, p_T^\nu\, (1-\cos\Delta\phi_{l\nu})}$, → W mass
2. W-boson rapidity: $y_W = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$, → parton luminosities
3. charged lepton transverse momentum: $p_T^l = \sqrt{p_x^2+p_y^2}$, → W mass
4. charged lepton pseudorapidity: $\eta_l = -\ln\tan\frac{\theta}{2}$, → parton luminosities
5. hardest photon transverse momentum and pseudorapidity: p_T^γ, η_γ.

Generic LHC detector selection criteria

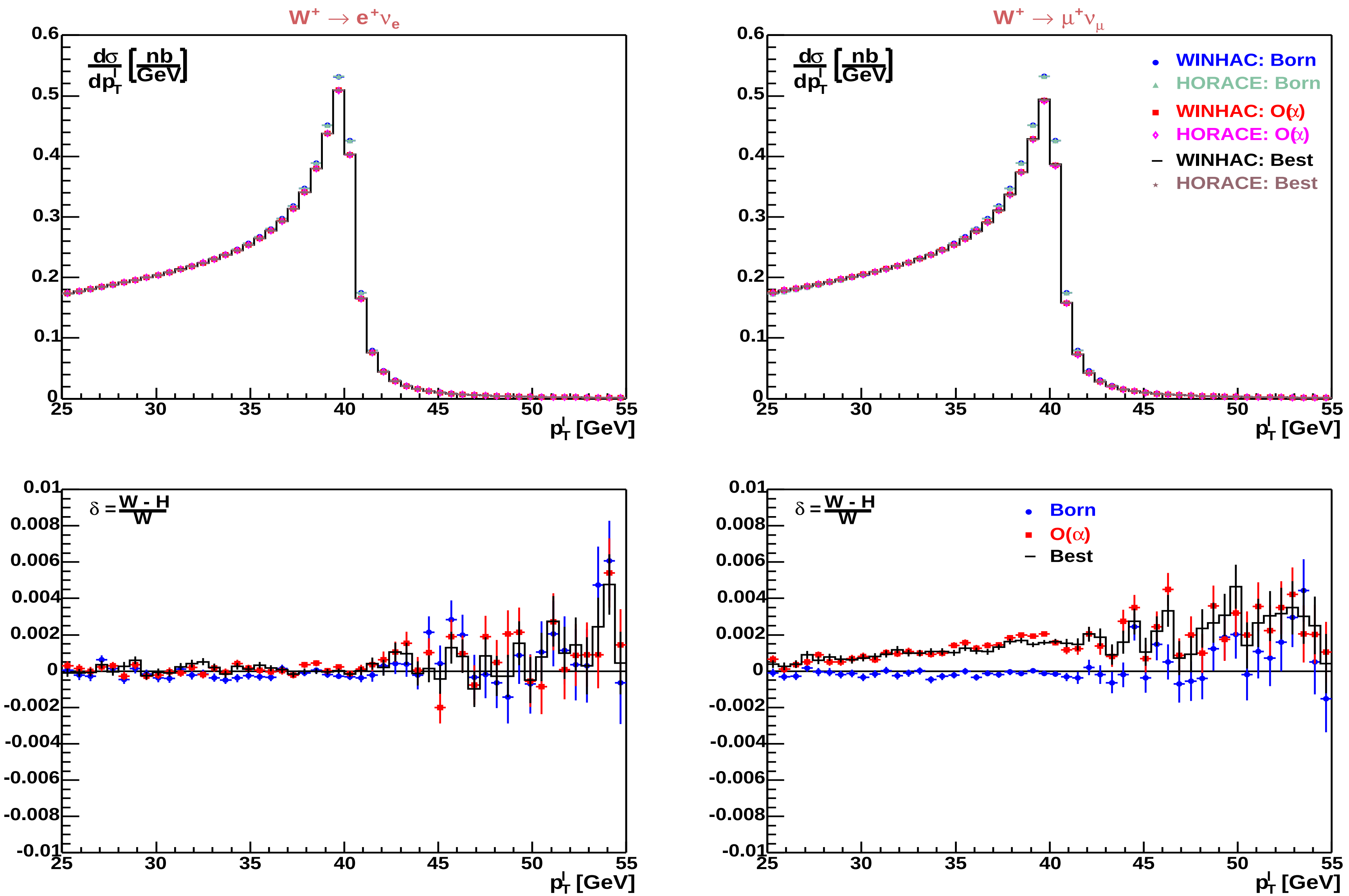
- Charged lepton transverse momentum: $p_T^l > 25\,\mathrm{GeV}$,
- Charged lepton pseudorapidity: $|\eta_l| < 2.4$,
- Missing transverse energy: $E_T^{\mathrm{miss}} > 25\,\mathrm{GeV}$,
- No jest in the event with: $p_T^j > 30\,\mathrm{GeV}$,
- The recoil system (against the W) transverse momentum: $p_T^{\mathrm{recoil}} < 20\,\mathrm{GeV}$,
- The size of an electron cluster (criteria for recombination of photons with electrons): $d\eta_e \times d\phi_e = 0.075 \times 0.175$,
- No photon recombination with muons.

▷ PDF parametrization used in tests: MRS (G)

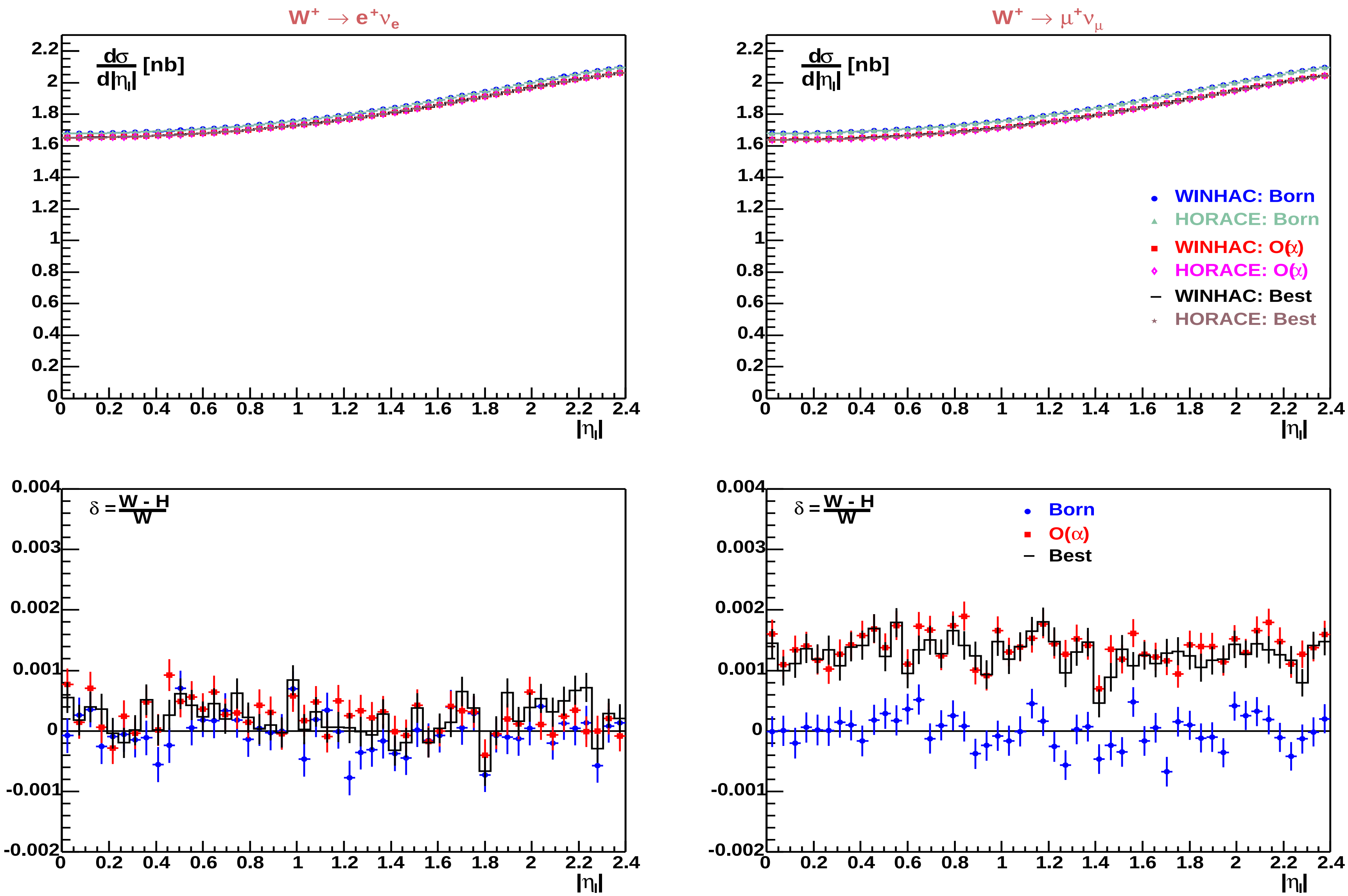
▷ Results published in:

C.M. Carloni Calame, S. Jadach, G. Montagna, O. Nicrosini and W. Płaczek, Acta Physica Polonica **B35** (2004) 1643; hep-ph/0402235.

Charged lepton transverse momentum p_T^l for: $W^+ \to l^+ \nu_l$



Charged lepton pseudorapidity η_l for: $W^+ \to l^+ \nu_l$



W mass shifts due to QED FSR beyond $\mathcal{O}(\alpha)$

- Authors of the HORACE have translated beyond $\mathcal{O}(\alpha)$ QED FSR corrections to M_T into shifts of M_W.
- Their results, Carloni Calame et.al. PRD69 (2004), for Tevatron energy and selection criteria are the following:
  - $W \to e\nu$ $\Delta M_W = 2$MeV, ($\mathcal{O}(\alpha)$: 20MeV)
  - $W \to \mu\nu$ $\Delta M_W = 10$MeV ($\mathcal{O}(\alpha)$: 120MeV)
- Conclusions:QED FSR can be controlled at the $\delta M_W \sim 2$MeV level for arbitrary realistic selections (cuts) at Tevatron/LHC experiments.

Conclusions

- Complete MC tools for EW+QCD precision ($\sim 1\%$) predictions for LHC still not available.
  Partial incomplete solutions come close to specs.
- Progress done in a recent couple of years, for "semi-inclusive" QCD observables, NLLO PDFs, NLLO distributions, matching NLO with parton shower, etc.
- More effort needed to implement QCD+QED predictions in form of the high quality exclusive MC tools (MC simulators providing events)
- More effort to create "numerical benchmarks", elaborate more detailed evaluation/estimation of theoretical errors, etc.