Uli Baur and precision physics with W and Z bosons

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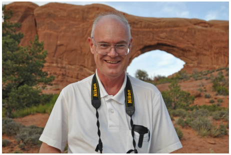


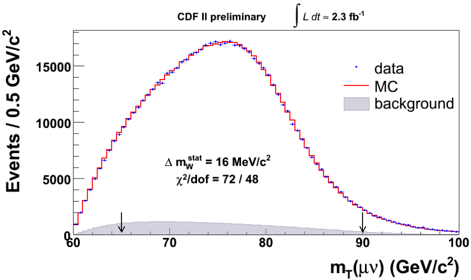
Precision physics with W and Z bosons

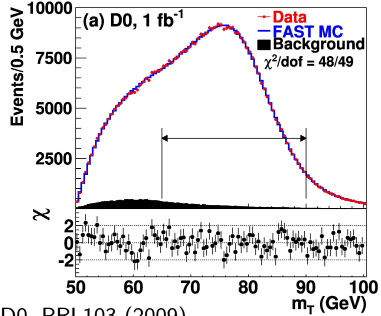
W and Z production processes are one of the theoretically best understood, most precise probes of the SM.

- Test of the SM as a fully-fledged Quantum Field Theory: sensitivity to multi-loop and non-universal radiative corrections.
- Check of the consistency of the SM by comparing direct with indirect measurements of model parameters, e.g., $m_{top}, M_W, \sin^2\theta_{eff}$.
- Constraint on the SM Higgs boson mass.
- Search for indirect signals of Beyond-the-SM (BSM) physics in form of small deviations from SM predictions.
- Exclusion of or constraints on BSM physics.

Tevatron precision rivals LEP/SLC precision

$$M_T(l\nu_l) = \sqrt{p_T^l p_T^\nu (1 - \cos(\Phi_l - \Phi_\nu))}$$





CDF, www-cdf.fnal.gov

D0, PRL103 (2009)

CDF: $\delta M_W = 48$ MeV (200 pb^{-1}) PRL99 (2007), PRD77 (2008)

D0: $\delta M_W = 43$ MeV (1 fb^{-1}) PRL103 (2009)

Tevatron combined: TEVEWWG, arXiv:0908.1374[hep-ex], 1003:2826

$M_W = 80.420 \pm 0.031$ GeV and $\Gamma_W = 2.046 \pm 0.049$ GeV

see Ashutosh Kotwal's talk

EW precision physics at hadron colliders

EW precision physics at the Tevatron and the LHC has many facets:

- Precision measurements of the W mass, W width and $\sin^2\theta_{eff}$:
  $d\sigma/dM_T, d\sigma/dp_T(l)$ and ratio of σ_Z and σ_W, and A_{FB}
- Detector calibration and luminosity monitoring:
  M_Z, Γ_Z from $d\sigma/dM(ll)$ at the Z peak and $\sigma_{W,Z}$
- Constraints on quark PDFs:
  W charge asymmetry and Z rapidity distributions
- Search for BSM physics, e.g., heavy new gauge bosons (Z'):
  A_{FB} and $d\sigma/dM(ll)$ at high $M(ll)$
- Search for anomalous triple and quartic EW gauge boson self couplings in VV and VVV production:
  $\sigma_{VV,VVV}$, p_T distributions, radiation zeros

Status of predictions for W/Z observables

QCD corrections:

- NLO and NNLO QCD (up to $\mathcal{O}(\alpha_s^2)$): total cross sections ($\sigma_{W,Z}$) and fully differential distributions
  R.Hamberg *et al.*, NPB359 (1991); W.L.van Neerven *et al*, NBP382 (1992); W.T.Giele *et al*, NPB403 (1993)
  L.Dixon *et al.*, hep-ph/031226; K.Melnikov, F.Petriello, hep-ph/0603182; S.Catani *et al.*, PRL103 (2009), JHEP1005 (2010); R.Gavin *et al*, 1011.3540[hep-ph]
- NLO QCD corrections matched to an all-order resummation of large logarithms $\ln^n(q_T/Q)$ (at NLL and NNLL accuracy) (Q: W/Z virtuality, q_T: W/Z transverse momentum).
  C.Balazs, C.-P.Yuan, PRD56 (1997) (ResBos); G.Bozzi *et al*, NPB815 (2009), 1007.2351 [hep-ph]
- NLO QCD corrections matched to a parton shower such as HERWIG (MC@NLO) or POWEG.
  S.Frixione, B.R.Webber, hep-ph/0612272; S.Alioli *et al*, JHEP0807 (2008)
- $W + n$-jets ($n \leq 4$) and $Z + n$-jets ($n \leq 3$) at NLO QCD.
  C.F.Berger *et al.* (2010,2009); K.Ellis *et al* (2009); J.Campbell *et al* (2002); and references therein

Status of predictions for W/Z observables

Electroweak corrections:

- EW $\mathcal{O}(\alpha)$ corrections
  U.Baur *et al*, PRD59 (1999), U.Baur *et al*, PRD65 (2002); C.M.Carloni Calame *et al*, JHEP05 (2005)
  U.Baur, D.W., PRD70 (2004);S.Dittmaier, M.Krämer, PRD65 (2002); A.Andonov *et al*, EPJC46 (2006); Arbuzov *et al*, EPJC54 (2008); S.Dittmaier, M.Huber, JHEP60 (2010).
- Multiple final-state photon radiation
  W.Placzek *et al*, EPJC29 (2003); C.M.Carloni Calame *et al*, PRD69 (2004); S.Brensing *et al*, PRD77 (2008)
- Logarithmic enhanced EW corrections at high energies (EW-like Sudakov logarithms)
  J.H.Kühn, Acta Phys.Polon.B39 (2008) (brief review); S.Brensing *et al*, PRD77 (2008).
- EW corrections to $W + 1$-jet and $Z + 1$-jet production
  W.Hollik *et al* (2008); S.Dittmaier *et al*, JHEP0908 (2009); J.H.Kühn, *et al*, NPB797 (2008); A.Denner *et al.*, 1011.6674[hep-ph].

Public MC programs for W/Z precision physics

HORACE: Electroweak $\mathcal{O}(\alpha)$ corrections and multiple photon radiation from initial and final-state leptons as solution of QED DGLAP evolution for lepton SF. EW-like Sudakov logarithms. Interface to MC@NLO.
C.M.Carloni Calame *et al*, PRD69 (2004); JHEP0612 (2006)

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

RESBOS: NLO QCD corrections and all-order soft-gluon resummation. Final-state QED $\mathcal{O}(\alpha)$ corrections. C.Balazs, C.P.Yuan, PRD56 (1997)

`http://www.pa.msu.edu/ balazs/ResBos/`

WGRAD2/ZGRAD2: Electroweak $\mathcal{O}(\alpha)$ corrections.

U.Baur *et al* PRD65 (2002), U.Baur, D.W., PRD70 (2004)

`http://ubhex.physics.buffalo.edu/∼baur/zgrad2.tar.gz`

`http://ubpheno.physics.buffalo.edu/∼dow/wgrad.tar.gz`

SANC: Electroweak $\mathcal{O}(\alpha)$ and NLO QCD corrections.
A. Arbuzov *et al*, EPJ.C54 (2008); EPJ.C46 (2006); arXiv:0901.2785 `http://sanc.jinr.ru`

FEWZ: NNLO QCD corrections (fully exclusive).
K.Melnikov, F.Petriello, hep-ph/0603182; L.Dixon *et al.*, hep-ph/031226

`http://www.phys.hawaii.edu/ kirill/FEHiP.htm`

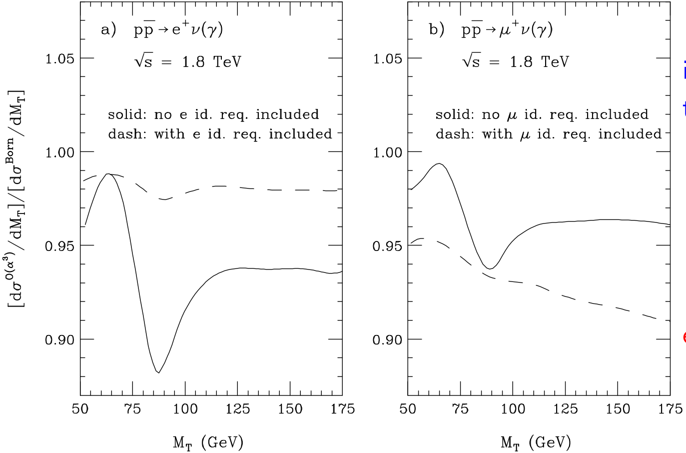
and also DYRAD, MCFM, MC@NLO, Powheg, WINHAC, PHOTOS

Characteristics of EW corrections to W/Z production

- Final-state photon radiation (FSR):
  in sufficiently inclusive observables the mass singularities completely cancel (KLN theorem). But, depending on the experimental set up, large contributions of the form $\alpha \log(s/m_l^2)$ can survive.
- Initial-state photon radiation (ISR):
  mass singularities always survive but are absorbed by universal collinear counterterms to the parton distribution functions (mass factorization done in complete analogy to QCD):
  - introduces dependence on QED factorization scheme (in analogy to QCD, a *DIS* and $\overline{MS}$ scheme has been introduced)
  - PDFs including QED corrections have been made available by the MRST collaboration A.D.Roberts *et al.*, EPJC39 (2005).
- Electroweak corrections at large energies, $s \gg M_{W,Z}^2$:
  Sudakov-like contributions of the form $\alpha \log^2(s/M_{Z,W}^2)$ can significantly enhance one-loop corrections.

Impact of EW corrections on $M_T(l\nu)$ at the Tevatron

$$M_T = \sqrt{2p_T(l)p_T(\nu)(1-\cos\Phi^{l\nu})}$$

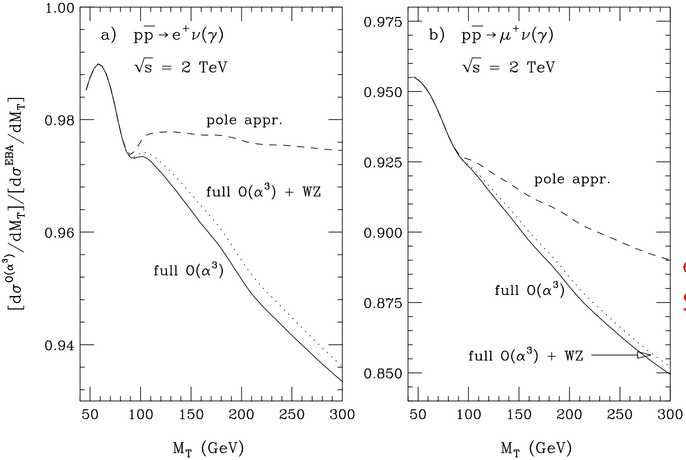


inclusive vs.exclusive treatment of photon

effect of $\log(s/m_\mu^2)$

from U.Baur *et al*, PRD59 (1999)

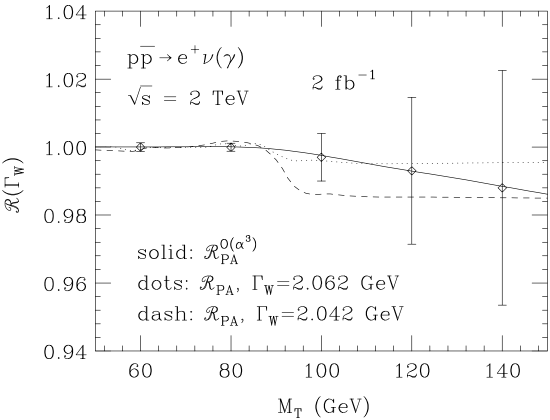
Pole approximation vs. full $\mathcal{O}(\alpha)$ calculation of $p\bar{p} \to W^+ \to l^+\nu$ at the Tevatron



effect of EW Sudakov-like logs

from U.Baur, D.W., PRD70 (2004)

Impact of non-resonant EW corrections on Γ_W at the Tevatron



$$\frac{\{[d\sigma/dM_T]/\sigma_W\}_{\Gamma_W^{SM}}}{\{[d\sigma/dM_T]/\sigma_W\}_{\Gamma_W}} \propto \frac{\Gamma_W}{\Gamma_W^{SM}}$$

input: $\Gamma_W^{SM} = 2.072$ GeV

size of non-res. corr. is of same order as effects due to non-SM values of Γ_W

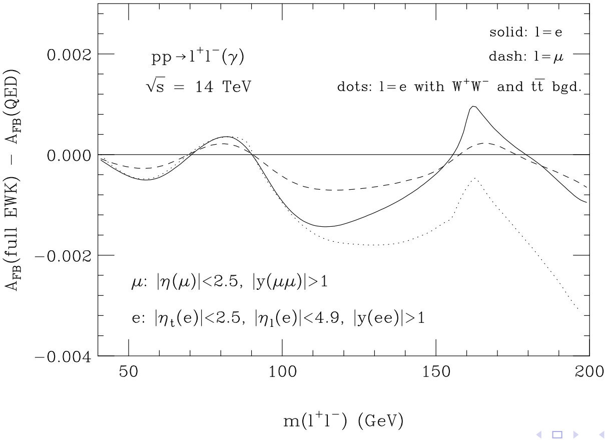
χ^2 fit: ignoring these corrections shifts Γ_W by -7.2 MeV ($\delta\Gamma_W^{exp} = 49$ MeV)

from U.Baur, D.W., PRD70 (2004)

Distinct signature of weak corrections in Z production

The impact of genuine weak $\mathcal{O}(\alpha)$ corrections on A_{FB} at the LHC

from U.Baur, W.Hollik, C.Schappacher, D.W., PRD65 (2002)



observable ?

Enhanced EW corrections at high energies

- At energies $\sqrt{s} \gg M_{W,Z}$ EW corrections are enhanced by

$$\alpha^L \log^N(\frac{s}{M_V^2}) \;\; ; \;\; 1 \leq N \leq 2L \; (L = 1(1 - loop), \ldots)$$

  Origin: Remnants of UV singularities after renormalization + soft/collinear ISR and FSR emission of virtual and real W/Z bosons.

  In contrast to QED and QCD, also in inclusive observables these corrections do not completely cancel.

  W/Z mass is physical cut-off: real W/Z radiation is usually not included, since it leads to a different initial/final state.

- EW logarithmic corrections to 4-fermion processes are known up to 2-loop N^3LL order and are available in form of compact analytical formula.

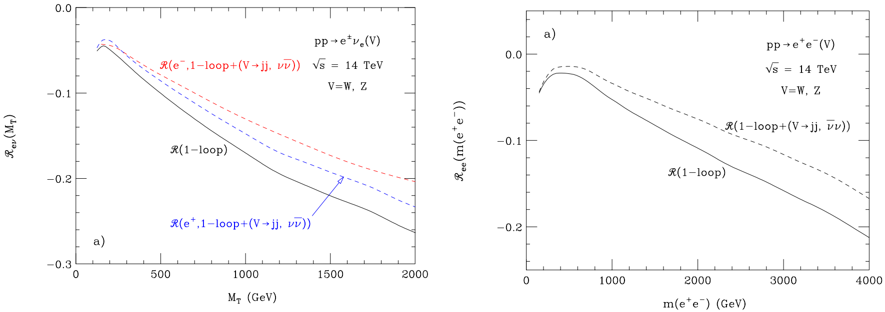
  for a brief review, see, e.g., J.H. Kühn, Acta Phys.Polon.B39 (2008); G.Bell *et al*, 1004.4117 [hep-ph]; Jui-yu Chiu *et al*, PRD77 (2008) (SCET)

Enhanced EW corrections at high energies

Are they really that large ?

Large virtual corrections may be partially canceled by real W/Z radiation, which strongly depends on the experimental setup. see, e.g., G.Bell *et al.*, 1004.4117[hep-ph]

An example: Impact of real weak gauge boson radiation on $M_T(l\nu)$ and M_{ee} distributions at the LHC



from U.Baur, PRD75 (2007)

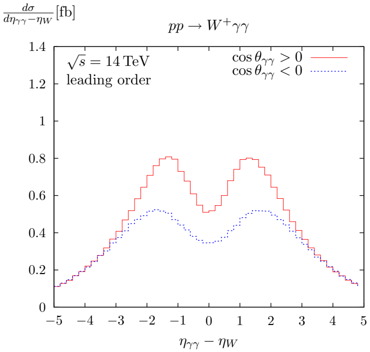
Precision Physics with VV, VVV observables

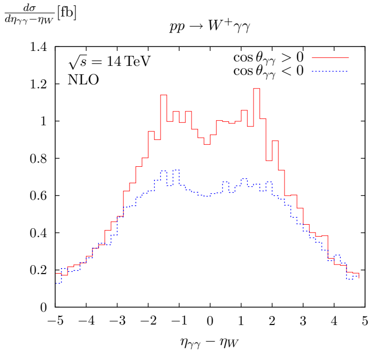
- EW gauge boson pair and triple production directly probes the non-abelian gauge structure of the SM.
- Search for non-standard gauge boson self couplings allowed by Lorentz invariance and gauge invariance provide a unique indirect way to look for signals of new physics in a model-independent way.
- Improved constraints on anomalous triple-gauge boson couplings (TGCs) and quartic couplings (QGCs) will probe scales of new physics in the multi-TeV range.

see Tao Han's talk

Prelim. results for $W\gamma\gamma$ production at NLO QCD

Separation of W and $\gamma\gamma$ pair in η at LO and NLO QCD at the LHC:
Radiation zero fills up





from M.Weber, U.Baur, D.W., 1001.2688[hep-ph]

Final thoughts

- Electroweak physics at hadron colliders offers plentiful and unique opportunities to test the SM and search for signals of physics beyond the SM.
- Uli's work greatly contributed to realizing these opportunities at the Tevatron by making sure that theoretical predictions are under control, by making them accessible to experimentalists, and by searching for ever new ways to explore intriguing QFT features of the SM.
- Uli's dedication to bridging the gap between theory and experiment is exactly the kind of collaboration between theorists and experimentalists that is needed for the interpretation of LHC data. His example and reserach work will continue to have an impact also in the LHC era.