

Combining NLO QCD and Electroweak Radiative Corrections to W boson Production at Hadron Colliders in the POWHEG Framework

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Working Group on Electroweak Precision Measurements at the LHC

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Present QED uncertainty in M_W measurement

- CDF, arXiv:1203.0275: $\delta M_W(\text{QED})=4 \text{ MeV}$
ResBos¹+PHOTOS², HORACE³ used to assess impact of full EW $\mathcal{O}(\alpha)$ corrections
- D0, arXiv:1203.0293: $\delta M_W(\text{QED})=7 \text{ MeV}$
ResBos+PHOTOS, WGRAD⁴ used to assess impact of full EW $\mathcal{O}(\alpha)$ corrections

¹C.Balazs and C.-P. Yuan, Phys. Rev. **D56**, 5558 (1997)

²P.Golonka and Z.Was, EPJC 45 (2006)

³ C.M. Carloni Calame, G. Montagna, O. Nicrosini and A. Vicini, JHEP 0612 (2006) 016

⁴U.Baur,S.Keller and D.W., Phys. Rev. **D59**, 013002 (1999)

Previous Studies of Combined QCD and EW Effects

There have been previous studies of the interplay of QCD and EW corrections to charged current Drell Yan (CCDY)

- Q.-H. Cao, C.-P. Yuan, PRL 93 (2004)

$$\Rightarrow \underbrace{\text{RESBOS}}_{\substack{\text{NLO QCD+resummed IS soft gluon radiation}}} + \underbrace{\text{NLO FS QED radiation}}_{\substack{\text{dominant EW effect}}}$$

\Rightarrow shapes of $m_T^{\nu_e}$ and $p_{T e^+}$ distributions imply EW, QCD interference effects
see also: N.Adam et al. (MC@NLO+PHOTOS), JHEP 0809

- G. Balossini et.al., JHEP 1001:013 (2010)

$$\Rightarrow \underbrace{\text{MC@NLO}}_{\substack{\text{NLO QCD matched to HERWIG}}} + \text{HORACE} \otimes \text{HERWIG}$$

\Rightarrow also a factorized combination of EW and QCD
 \Rightarrow shapes of $m_T(W)$ and $p_T(\mu)$ distributions imply EW, QCD interference effects

our implementation:

$$\text{POWHEG_ew-BW} = (\underbrace{\text{NLO EW}}_{\text{WGRAD2}} + \underbrace{\text{NLO QCD}}_{\text{POWHEG_W}}) \otimes (\text{PYTHIA or HERWIG})$$

WGRAD2

WGRAD2^{1,2} is a MC code for charged-current (CC) Drell-Yan with full NLO EW corrections

$$d\sigma = \sum_{\text{flavors}} dx_1 dx_2 f_1(x_1) f_2(x_2) \left[d\hat{\sigma}_B + \underbrace{d\hat{\sigma}_{v+s}}_{\sim \delta_s} + \int_{1,2} \frac{dz}{z} \underbrace{d\hat{\sigma}_{HC}(z)}_{\sim \delta_c} + \int_{\delta_s, \delta_c} d\Phi_{rad} d\hat{\sigma}_{H\bar{C}} \right]$$

- soft, collinear divergences treated with 2-cutoff phase space slicing technique
⇒ dependence on δ_s and δ_c must cancel in physical result
- **options/switches:** gauge invariant FS, IS, interference subsets of photon radiation for separate study

¹U.Baur and D.Wackerlo, Phys. Rev. **D70**, 073015 (2004), hep-ph/0405191

²U.Baur,S.Keller and D.Wackerlo, Phys. Rev. **D59**, 013002 (1999), hep-ph/9807417

POWHEG-BOX

POsitive Weight Hardest Event Generator^{4,5,6}

- contains NLO QCD corrections matched to Parton Shower (PYTHIA and HERWIG) for several processes (POWHEG-BOX)
- POWHEG method:
 1. generate events with the hardest radiation at NLO
 2. feed events into PYTHIA/HERWIG, all showering is softer than the first, hardest event
- POWHEG master formula:

$$d\sigma = \sum_{\text{flavors}} \bar{B}(\Phi_n) d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\min}) + \sum_{\alpha_r} \frac{\left[d\Phi_{\text{rad}} \Delta(\Phi_n, k_T > p_T^{\min}) R(\Phi_{n+1}) \right]}{B(\Phi_n)} \right\}$$

- $\bar{B} \Rightarrow$ exact NLO differential cross-section \Rightarrow FKS subtraction
- $\Delta(\Phi_n, k_T) \Rightarrow$ Sudakov form-factor \Rightarrow ensures hardest event

⁴P.Nason,*JHEP* **0411** (2004) 040, hep-ph/0409146

⁵S.Frixione,P.Nason and C. Oleari,*JHEP* **0711** (2007) 070, arXiv:0709.2092

⁶S.Alioli,P.Nason,C. Oleari and E.Re,*JHEP* **1006** (2010) 043, arXiv:1002.2581

⁷S.Alioli,P.Nason,C. Oleari and E.Re,*JHEP* **0807** (2008) 060, arXiv:0805.4802

WGRAD2+POWHEG-W

We incorporate the EW corrections into \bar{B} :

see C. Bernaciak, D.W., arXiv:1201.4804, for details

$$\begin{aligned}\bar{B}(\Phi_2) = & B(\Phi_2) + V_{\text{QCD}}(\Phi_2) + \textcolor{blue}{V_{\text{EW}}}(\Phi_2) + \int_{\oplus} \frac{dz}{z} [G_{\oplus, \text{QCD}}(\Phi_{2,\oplus}) + \textcolor{blue}{G_{\oplus, \text{EW}}}(\Phi_{2,\oplus})] \\ & + \int_{\ominus} \frac{dz}{z} [G_{\ominus, \text{QCD}}(\Phi_{2,\ominus}) + \textcolor{blue}{G_{\ominus, \text{EW}}}(\Phi_{2,\ominus})] + \sum_{\alpha_r \in \text{IS}} \int d\Phi_{\text{rad}, IS} [\hat{R}(\Phi_3) + \textcolor{blue}{R_{\text{EW}}}(\Phi_3)]\end{aligned}$$

- ⇒ $V_{\text{EW}}(\Phi_2)$ virtual + soft finite EW corrections
 - ⇒ switch for resonant/non-resonant (box diagrams) effects
- ⇒ $G_{\text{EW}}(\Phi_2, z)$ IS and FS collinear EW pieces
- ⇒ $R_{\text{EW}}(\Phi_3)$ finite real piece - IS and FS together
 - ⇒ switch for IS, FS, interference QED radiation
- ⇒ finite charged lepton mass effects included

Resulting public code available within POWHEG-BOX as subprocess W_ew-BW

Crosschecks and Validation

WGRAD2 results are reproduced from POWHEG-W_BW by turning off NLO QCD:

	Tevatron, W^+	LHC, W^+	LHC, W^-
WGRAD2	362.55(2) pb	1059.6(1) pb	759.26(3) pb
POWHEG-W_BW	362.4(2) pb	1059.0(5) pb	758.7(8) pb

Check of independence on PSS parameters, δ_s and δ_c :

(δ_s, δ_c)	Tevatron, W^+	LHC, W^+	LHC, W^-
0.01, 0.005	362.4(2) pb	1059.0(5) pb	758.7(8) pb
0.01, 0.001	362.4(2) pb	1059.1(7) pb	759.2(5) pb
0.001, 0.0005	362.3(2) pb	1059.4(9) pb	759.4(5) pb
0.001, 0.0001	362.3(2) pb	1059.2(8) pb	759.3(5) pb

Process: $W^\pm \rightarrow \mu^\pm \nu_\mu$ **Bare Cuts:** $p_T(\mu^\pm), p_T(\nu_\mu) > 25\text{GeV}$, $|\eta_\mu| < 1$

EW+POWHEG-W+QED PS

Implementation of EW corrections in POWHEG by L. Barze et al.,
arXiv:1202.0465:

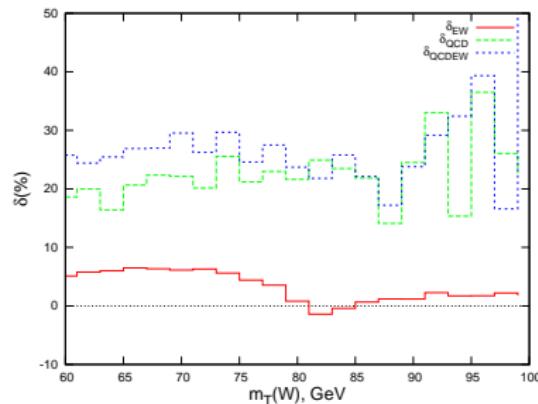
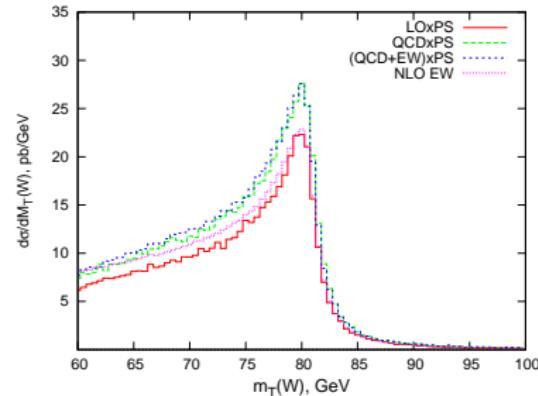
- Virtual $\mathcal{O}(\alpha)$ corrections from S.Dittmaier and M.Krämer, PRD 65 (2002), and checked against HORACE
- soft and collinear photon radiation is treated in the same way as light partons
- NLO EW and QCD are both interfaced to QCD and QED shower MCs
- Multiple photon radiation included (PHOTOS)

Resulting public code available within POWHEG-BOX as subprocess
W_ew-BMNNP

$M_T(W)$ Distributions - Tevatron, bare cuts

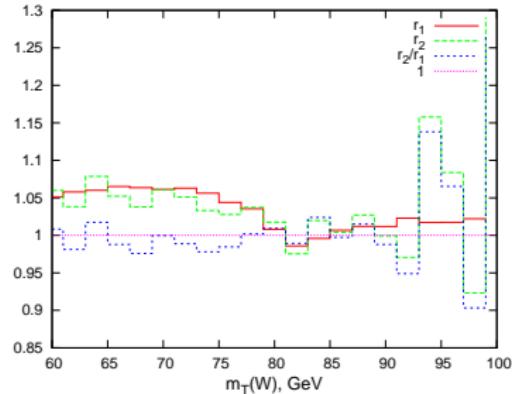
$p\bar{p} \rightarrow W^+ \rightarrow \mu^+\nu_\mu$, $\sqrt{S} = 1.96$ TeV, Pythia showering from C.Bernaciak, D.W., arXiv:1201.4804

$$M_T(W) = \sqrt{2p_T(\ell)p_T(\nu)(1-\cos(\Delta(\phi_{\ell\nu})))}$$



- fits of $d\sigma/dM_T(W)$ used to measure M_W
 ⇒ lineshape sensitive to FS QED effects
 around Jacobian peak due to collinear
 logs $\sim \alpha \log(m_l^2/\hat{s})$
- $\delta_a = \left[\left(\frac{d\sigma_a}{d\mathcal{O}} - \frac{d\sigma_{LO}}{d\mathcal{O}} \right) / \frac{d\sigma_{LO}}{d\mathcal{O}} \right] \times 100$

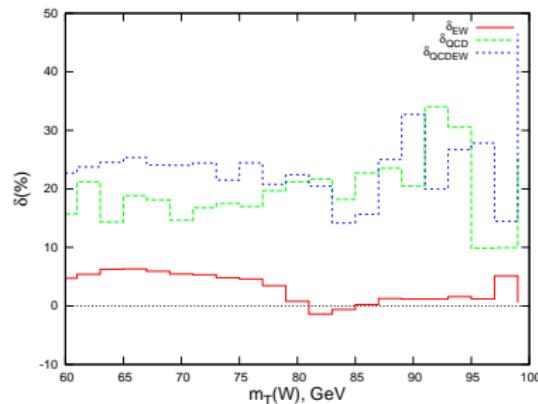
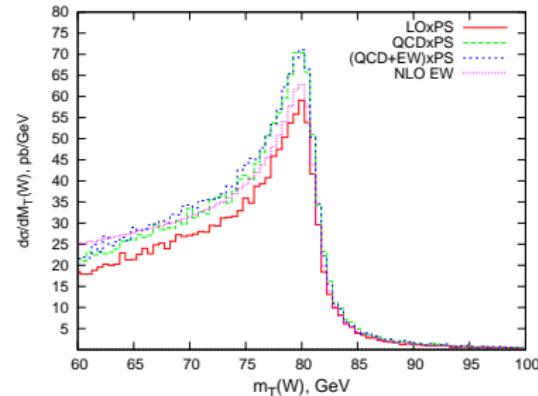
$$\bullet \quad r_1 = \frac{d\sigma_{EW}}{d\mathcal{O}} / \frac{d\sigma_{LO}}{d\mathcal{O}}, \quad r_2 = \frac{d\sigma_{(QCD+EW)xPS}}{d\mathcal{O}} / \frac{d\sigma_{QCDxPS}}{d\mathcal{O}}$$



$M_T(W)$ Distributions - LHC, bare cuts

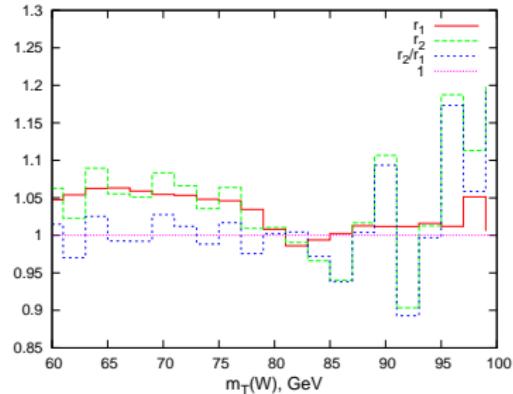
$pp \rightarrow W^+ \rightarrow \mu^+ \nu_\mu$, $\sqrt{S} = 7$ TeV, Pythia showering from C.Bernaciak, D.W., arXiv:1201.4804

$$M_T(W) = \sqrt{2p_T(\ell)p_T(\nu)(1-\cos(\Delta(\phi_{\ell\nu})))}$$

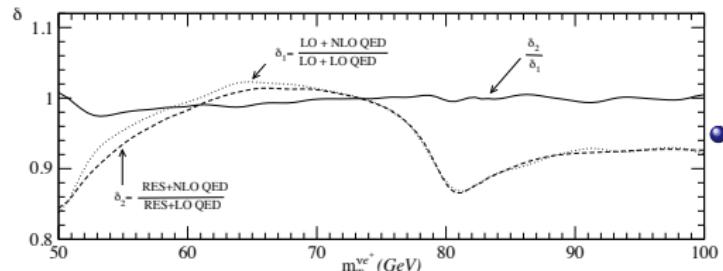


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 $\log s \sim \alpha \log(m_I^2/\hat{s})$
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$$\bullet r_1 = \frac{d\sigma_{EW}}{d\mathcal{O}} / \frac{d\sigma_{LO}}{d\mathcal{O}}, \quad r_2 = \frac{d\sigma_{(QCD+EW)xPS}}{d\mathcal{O}} / \frac{d\sigma_{QCDxPS}}{d\mathcal{O}}$$

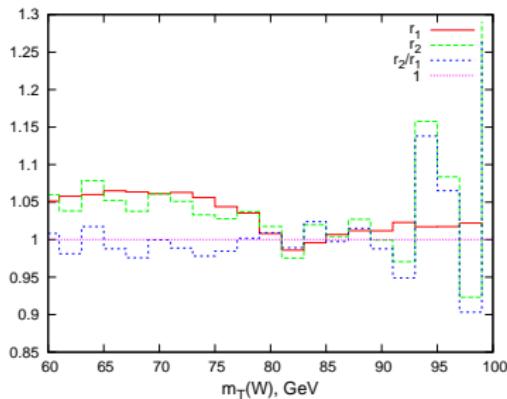


Resbos+FS QED



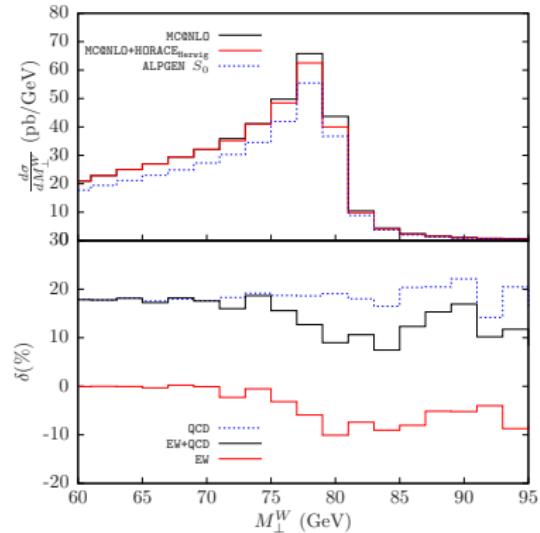
• $\frac{\delta_2}{\delta_1}, \frac{r_2}{r_1} \sim 1$, $M_T(W)$ distribution exhibits no visible $\alpha\alpha_s$ interference effects.

- from Q.-H. Cao, C.-P. Yuan, PRL 93 (2004)
- Tevatron, $\sqrt{S} = 1.96$ TeV
- LO+LO QED \rightarrow LO only
- LO+NLO QED \rightarrow FS NLO only
- RES+LO QED \rightarrow NLO QCD+IS gluon resummation only
- RES+NLO QED \rightarrow NLO QCD+IS gluon resummation and FS NLO QED



from C.Bernaciak, D.W., arXiv:1201.4804

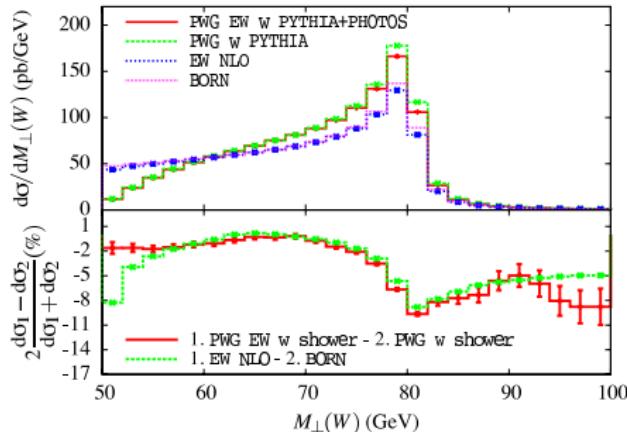
HORACE+MC@NLO



- similar behavior EW in presence of QCD retains its shape

- from G. Balossini et.al., JHEP 1001:013, arXiv:0907.0276
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EW+POWHEG+QED PS

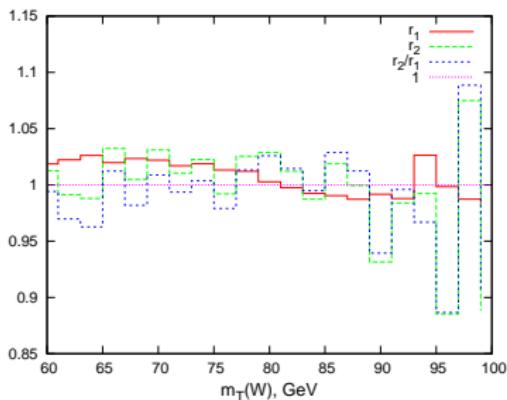
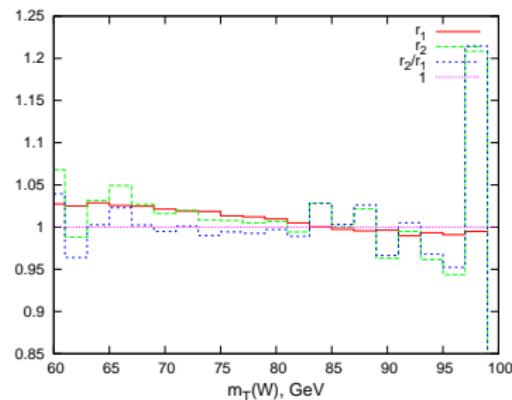
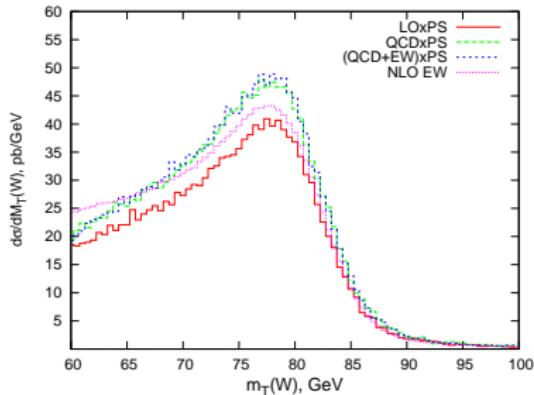
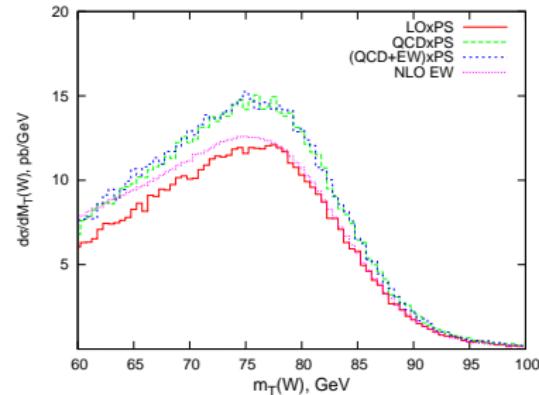


- similar behavior *EW in presence of QCD retains its shape*

- from L. Barze et al.,
arXiv:1202:0465
- $pp \rightarrow W^+ \rightarrow \mu^+ \nu_\mu$, LHC,
 $\sqrt{S} = 7$ TeV
- G_μ input scheme

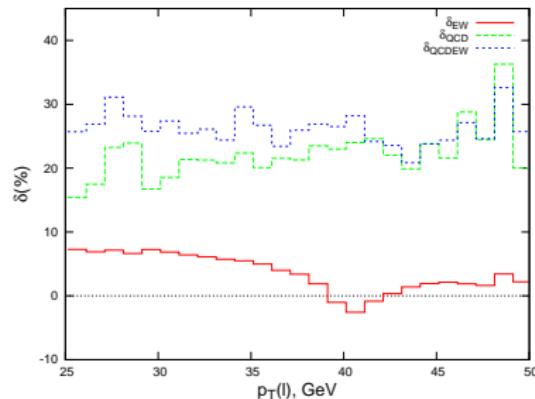
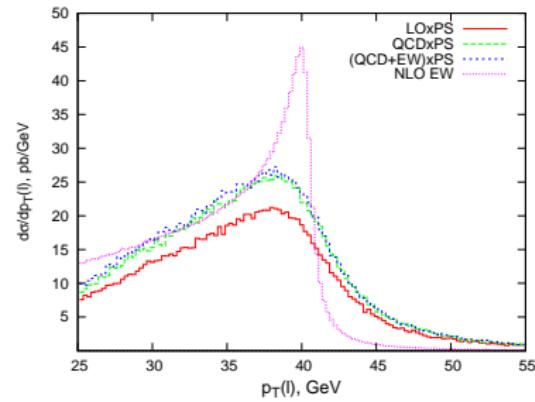
$M_T(W)$ Distributions - Tevatron and LHC, calometric cuts

subtle interference effects are washed out by smearing from C.Bernaciak, D.W., arXiv:1201.4804



$p_T(\mu)$ Distributions - Tevatron

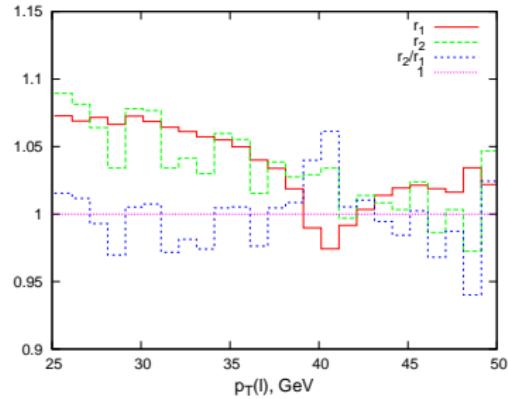
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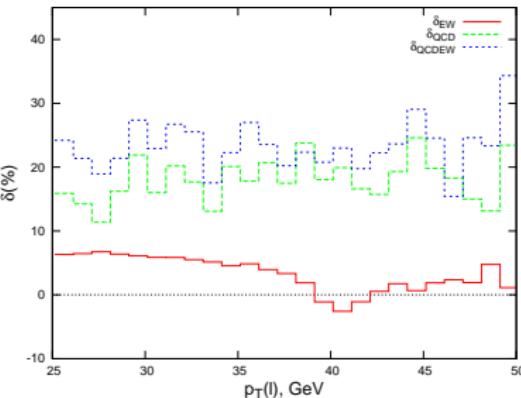
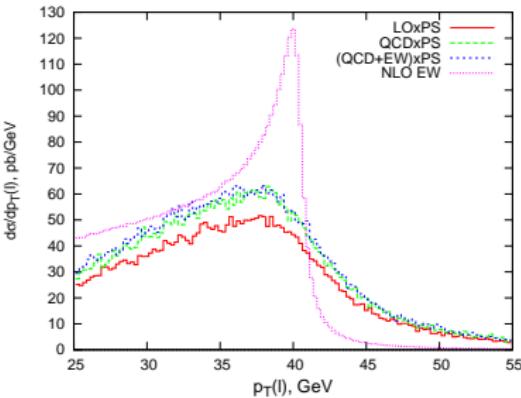
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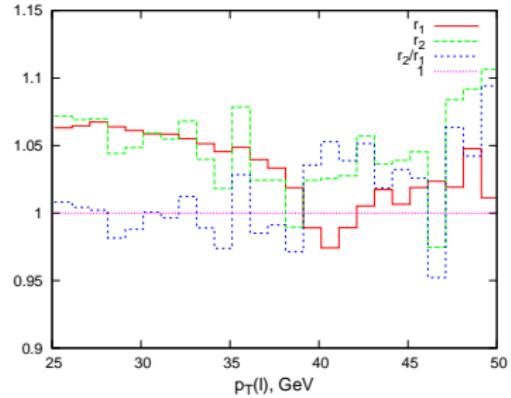
$p_T(\mu)$ Distributions - LHC

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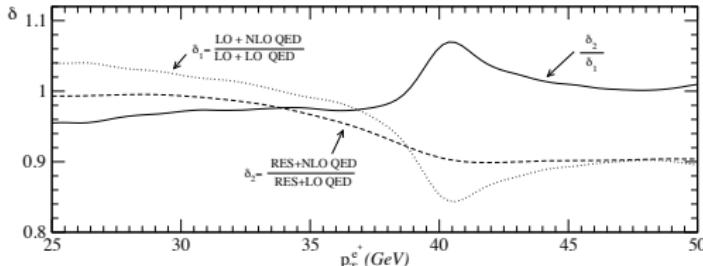


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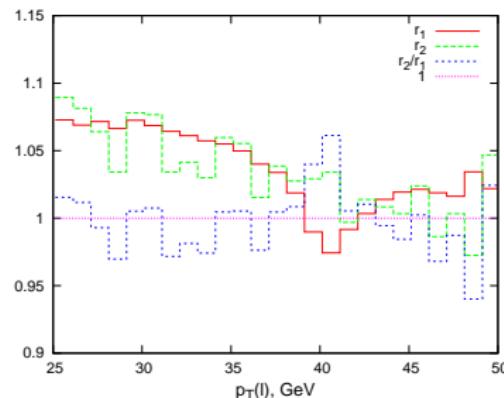


ResBos+FS QED



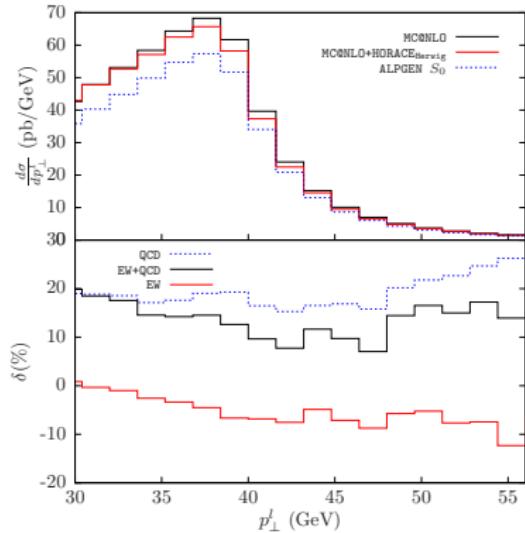
$\frac{\delta_2}{\delta_1}, \frac{r_2}{r_1}$ show deviation from unity
 \rightarrow indicator of $\alpha\alpha_s$ interference.

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from C.Bernaciak, D.W., arXiv:1201.4804

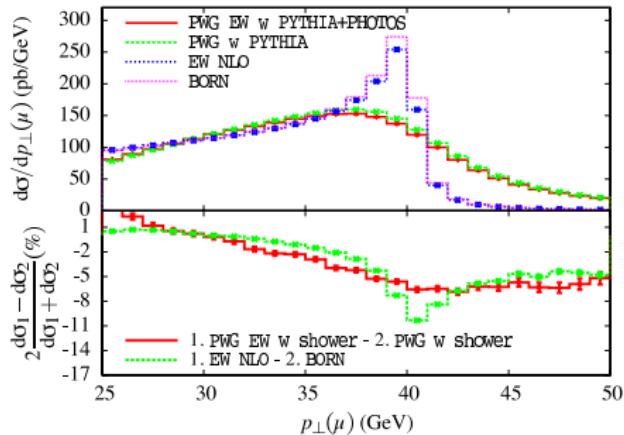
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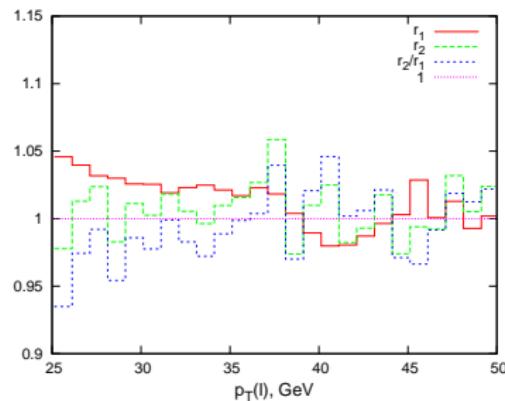
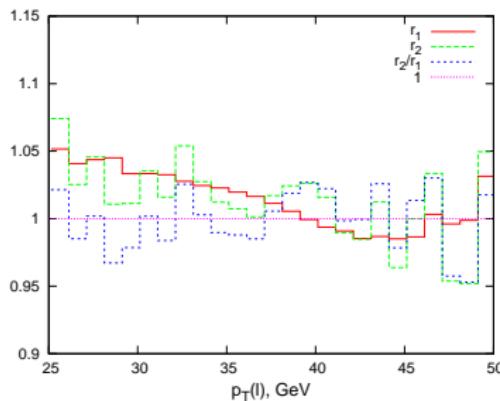
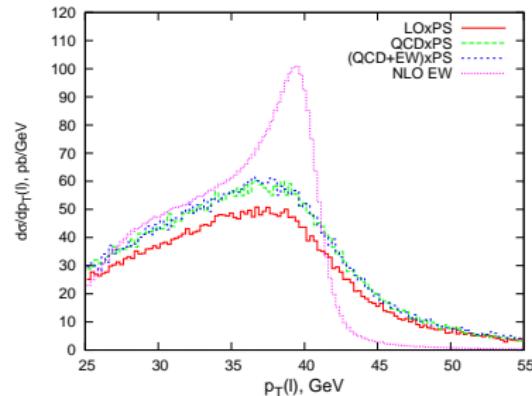
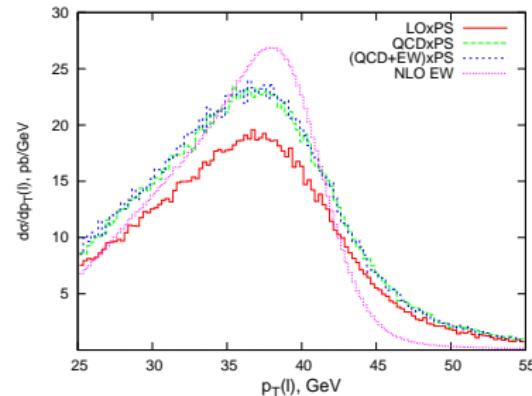
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$p_T(\mu)$ Distributions - Tevatron and LHC, calometric cuts

subtle interference effects are washed out by smearing

from C.Bernaciak, D.W., arXiv:1201.4804



Summary: QCD + EW Effects on Distributions

What can we conclude about effects of *combined* EW and QCD corrections on $\frac{d\sigma}{dM_T(W)}$ and $\frac{d\sigma}{dp_T(l)}$?

$$r_2 = \underbrace{\frac{d\sigma_{(QCD+EW) \times PS}}{d\mathcal{O}} / \frac{d\sigma_{QCD \times PS}}{d\mathcal{O}}}_{\text{effect of EW corrections on } \frac{d\sigma}{dp_T(\mu)} \text{ in presence of QCD}}$$

$$\text{not the same as } r_1 = \underbrace{\frac{d\sigma_{EW}}{d\mathcal{O}} / \frac{d\sigma_{LO}}{d\mathcal{O}}}_{\text{effect of EW corrections only}}$$

if it was, $\frac{r_2}{r_1} \simeq 1$

- $\mathcal{R} = \frac{r_2}{r_1}$ deviation from unity implies non-additive (interference) EW, QCD effects $\Rightarrow p_T(l)$
- however, realistic detector simulations dampen these interference effects!
- but still, understanding of interplay of QCD and EW corrections to Drell-Yan important to pin down QED uncertainty in M_W measurement.

Work in progress

- Tuned comparison of the two implementations of EW corrections in POWHEG
- Detailed study of QCD+EW effects with realistic lepton identification requirements
- ZGRAD2+POWHEG-Z and inclusion of h.o. EW Sudakov effects

Note:

Not included in both POWHEG implementations are photon-induced processes, which require QED PDFs.

See also P.Richardson et al., arXiv:1011.5444: EW $\mathcal{O}(\alpha)$ corrections with SANC+HERWIG or PYTHIA8.