Studies of final-state photon radiation and mixed EW + QCD higher-order corrections in the process $p\overset{(-)}{p} \longrightarrow W^{\pm} \longrightarrow \ell^{\pm}\nu$.

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LHC Theory Initiative Fellows Meeting
Fermilab, October 29-30 2009

In collaboration with Doreen Wackeroth - SUNY University at Buffalo

Research funded by NSF LHC Theory Initiative Fellowship

Drell Yan Process - Motivation

Charged Current (CC) & Neutral Current (NC) Drell-Yan - valuable physics

- single W,Z production large σ and clear signatures $W \to \ell + \not{E}_T$ or $Z \to \ell^+\ell^-$
- collider luminosity monitoring
- detector calibration
- better measurements of parton distribution functions (PDF's)
- Precise predictions and measurements of M_W together with m_t constrain the value of M_H
- DØ+CDF average $M_W = 80.420 \pm 0.031$ GeV — Tevatron EW Working Group 2009
  $\Rightarrow$ 9.3 MeV of uncertainty from radiative corrections
- anticipated LHC measurement of ΔM_W to within 15 MeV — Haywood *et al* 2000

  $\Rightarrow$ precise theoretical handling of higher-order QCD and EW corrections

Existing Higher Order Corrections to W, Z boson production

- Complete $\mathcal{O}(\alpha)$ EW
  - **WGRAD2**: charged current DY — Baur, Wackeroth *et al* 2004
  - **SANC**: charged and neutral current DY — Arbuzov *et al* 2006
  - **ZGRAD2**: neutral current DY — Baur *et al* 2002
- Complete $\mathcal{O}(\alpha)$ EW + multiple final-state photon radiation
  - **HORACE**: QED Parton Shower Approach — Calame *et al* 2004,2005,2006
  - **WINHAC**: YFS exponentiation — Jadach, Placzek 2003

    $\Longrightarrow$implementations of mFSR within very good agreement — Calame, Jadach *et al* 2004
- NNLO QCD
  - **FEWZ** — Melnikov, Petriello 2006

    $\Longrightarrow$ NNLO QCD corrections are on the same order as NLO EW corrections
- NLO QCD or soft gluon resummation + final-state NLO QED
  - **ResBos-A**: various boson processes — Balazs, Yuan 1997; Landry *et al*1997
- soft gluon resummation + final-state NLO QED — Cao, Yuan 2004
  - full impact of mixed EW and QCD effects is unknown
- Goal is to combine WGRAD2, ZGRAD2 with mFSR and QCD higher-order effects into one Monte Carlo tool - WZGRAD

1. Multiple Final State Photon Radiation (mFSR)

Yennie-Frautschi-Suura Exponentiation — Yennie, Frautschi, Suura 1961

- WINHAC
- all order exponentiation of soft + virtual photonic corrections

QED Parton Shower — Calame *et al* 2000, 2004

- HORACE
- iterative solution to QED DGLAP evolution equation
- HORACE study shows dominance of mFSR over $\mathcal{O}(\alpha)$ EW corrections (WGRAD)

QED Structure Function — Gribov, Lipatov 1972; Cacciari *et al* 1991; Skrzypek 1992

- QED DGLAP solved with combo of Mellin Transform and iterative techniques
- each splitting contributes a term $\sim \alpha \log \frac{\hat{s}}{m_l^2}$ resumming logs to include multiple photon emission $\longrightarrow$ largest higher order effect

mFSR with QED Structure Function Approach

- **Factorized Hybrid**

Gribov, Lipatov 1972
Skrzypek, Jadach 1990
Skrzypek 1992

$$D(z,\hat{s}) = \underbrace{\frac{exp[\frac{\eta}{2}(\frac{3}{4}-\gamma_E)]}{\Gamma(1+\frac{\eta}{2})}\frac{\eta}{2}(1-z)^{\frac{\eta}{2}-1}}_{\text{exponentiation of soft photons, valid } z\sim 1} \underbrace{\left\{f_o(z)+\eta f_1(z)+\eta^2 f_2(z)\right\}}_{\text{factorized, finite order non-soft terms}}$$

- **Additive Hybrid**

$$D(z,\hat{s}) = \frac{exp[\frac{\eta}{2}(\frac{3}{4}-\gamma_E)]}{\Gamma(1+\frac{\eta}{2})}\frac{\eta}{2}(1-z)^{\frac{\eta}{2}-1} + \eta g_1(z) + \eta^2 g_2(z) + \eta^3 g_3(z)$$

Implementation of mFSR

$$\sigma_{mFSR} = \int_0^1 dz \underbrace{\int dx_1 dx_2 \sum_{x_1,x_2} F_q(x_1,Q^2)\, F_{\bar{q}}(x_2,Q^2)\, \sigma_o(x_1x_2S)}_{hadronic\ cross-section} D(z,\hat{s})\Theta(\text{cuts})$$

- at $\mathcal{O}(\alpha)$ large logs ($\eta = \alpha \log\frac{\hat{s}}{m_l^2}$) are present in WGRAD2 - must employ **matching procedure** to avoid double counting
  $\Longrightarrow$ Extract $\mathcal{O}(\alpha)$, leading-log (LL), term from $D^{NS}(z,\hat{s})$
  $\Longrightarrow$ subtract this term from the full mFSR cross-section and add the complete $\mathcal{O}(\alpha)$ EW cross-section

$$\sigma_{\text{WGRAD3}} = \sigma_{\text{WGRAD2}} + \sigma_{\text{mFSR}} - \sigma_{LL} - \sigma_o$$

Results of Tuned Comparison, WGRAD2 $\longrightarrow$ WGRAD3

- Brensing *et al* - full $\mathcal{O}(\alpha)$ EW + mFSR via QED SF approach — Brensing *et al* 2008
- cross-checked WGRAD3 mFSR implementation for pp $\rightarrow W^+ \rightarrow \mu^+\nu_\mu$
- tuned = same cuts, input parameters, **just QED - agrees within error**

$$\delta_{\mathrm{mFSR}-\gamma} = \left[\frac{\sigma_{\mathrm{mFSR}} - \sigma_{\mathrm{LL}}}{\sigma_{\mathrm{o}}}\right] - 1$$

$\sqrt{s}$ =14 TeV	$p_{T,\mu} < 25$ (GeV)		$p_{T,\mu} < 50$ (GeV)	
	WGRAD3	Brensing et.al.	WGRAD3	Brensing et.al
σ_{o} (pb)	4495.9(2)	4495.7(2)	27.590(2)	27.589(2)
$\delta_{\mathrm{mFSR}\text{-}\gamma}$ (%)	0.122(3)	$0.12^{+0.03}_{-0.02}$	0.320(3)	$0.31^{+0.08}_{-0.07}$

- **next, cross-check with HORACE**-determine ΔM_W in analogy with CDF, DØmethods
- determine ΔM_W due to mFSR from χ^2 fit to M_T distribution
  - $M_T = \sqrt{2p_T(\ell)p_T(\nu)(1-\cos(\phi^{\ell\nu}))}$
- HORACE analysis with Run II cuts predicts $\Delta M_W \sim 10$ MeV in muon channel, a few MeV in electron channel — Calame *et al* 2004

NLO QCD

- NLO QCD corrections only in initial-state, only 7 diagrams!
  $\Longrightarrow$ at this order, both $q\bar{q}$ and $q(\bar{q})g$ induced diagrams
  $\Longrightarrow$ self energies, vertex, real gluon and quark radiation

$$|M_{NLO}|^2 = |M_o|^2 + 2Re[M_o M_v^*] + |M_r|^2$$

$$\Rightarrow M_r = \frac{1}{2}\left[M_{q\bar{q},1} + M_{q\bar{q},2} + M_{qg,1} + M_{qg,2}\right]$$

- real phase space managed with **two-cutoff phase space slicing method**
  - two cutoffs (δ_s,δ_c) separate 2$\longrightarrow$3 phase space into three regions - soft, collinear, hard
  - δ_s and δ_c cancel numerically - checkpoint Harris, Owens 2002
- virtual correction is UV finite
- remaining hard, finite $2 \longrightarrow 3$ cross-section is evaluated numerically
- initial-state collinear gluon singularities factorized into PDF'S

NLO QCD + Parton Shower effects

Recipe for QCD Corrections

$$d\sigma^{\text{NLO}}_{\text{QCD}} = \int dx_1 dx_2 \sum_{x_1, x_2} \widetilde{F}_q(x_1, Q^2)\, \widetilde{F}_{\bar{q}}(x_2, Q^2)\, d\hat{\sigma}^{\text{NLO}}_{\text{QCD}}$$

$$\Rightarrow d\hat{\sigma}^{\text{NLO}}_{\text{QCD}} = d\hat{\sigma}_{\text{o+virt}} + \underbrace{d\hat{\sigma}_{soft} + d\hat{\sigma}_{collinear} + d\hat{\sigma}_{hard}}_{\text{real portion}}$$

- **this is current, preliminary status of WZGRAD**
- **include initial-state PS - beyond QCD effects O**(α_s)
- POWHEG method — Frixione, Nason, Oleari 2007
  - provides method for properly matching PS with NLO QCD
  - handles phase space with dipole subtraction methods
- SHERPA — Gleisberg *et al* 2009
  - more general purpose

Plans for Phenomenological Studies with WZGRAD

- switch between factorized, additive QED structure functions-maybe QED PS or YFS implementation?
- determine $\Delta M_{W,Z}$ due to different corrections
- Question: how to get meaningful results without calculating full $\mathcal{O}(\alpha\alpha_s)$ Balossini *et al* suggest a strategy:

Balossini *et al* 2009

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

- Hints at $\mathcal{O}(\alpha\alpha_s)$ Effects
  - combine corrections so as to capture *some* exact two loop effects?

Conclusions

- Drell Yan processes are relevant and still have much to say about the SM
- WGRAD2 and ZGRAD2 are combined along with NLO QCD and mFSR into one MC generator
- next, match QCD with parton shower - POWHEG/SHERPA?
- study impact on EW observables - p_T, M_T distributions, $\Delta M_{W,Z}$, $\Gamma_{W,Z}$, with different combinations of corrections
- WZGRAD would provide opportunity to study mixed EW and QCD effects - may hint at impact of complete $\mathcal{O}(\alpha\alpha_s)$ corrections