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Introduction to WGRAD/ZGRAD

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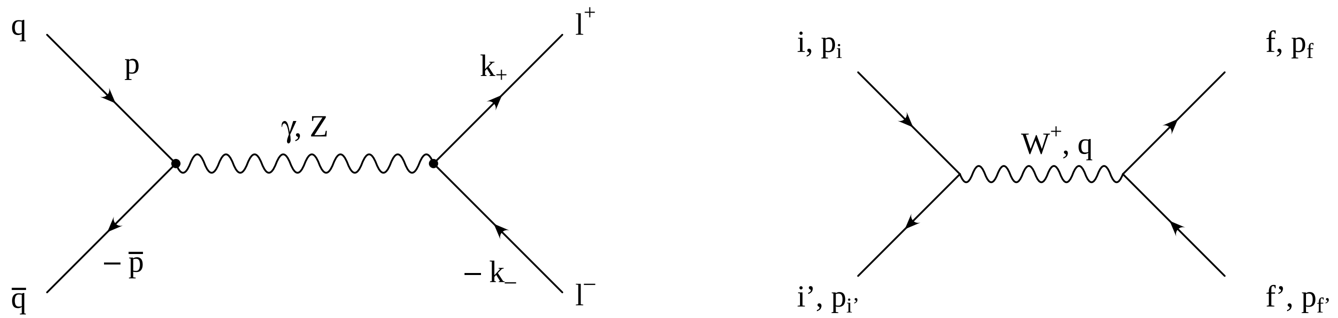
I. Overview of Theory: Precise predictions for W/Z production at hadron colliders

W/Z production



Status of higher-order calculations

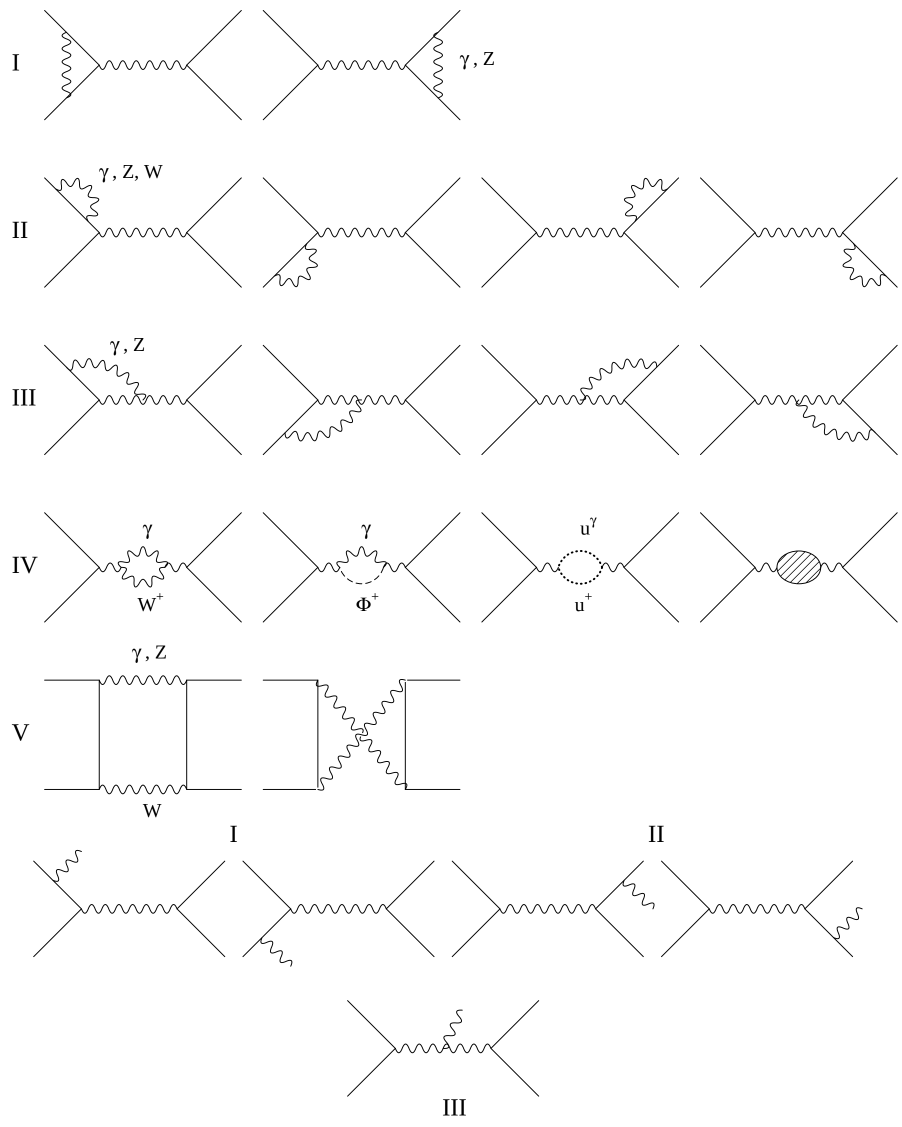
- Z boson production:
  complete QED $\mathcal{O}(\alpha)$ contribution (ZGRAD) U.Baur *et al*, PRD57 (1998)
  complete electroweak $\mathcal{O}(\alpha)$ contribution (ZGRAD2) U.Baur *et al*, PRD65 (2002).

Status of higher-order calculations: W boson production:

M_W extracted from $M_T(l\nu)$ at RUN I: $\delta M_W^{exp} = 59$ MeV	
final state QED (approximation) F.A.Berends *et al*, Z.Phys.C27 (1985)	Shift due to FSR (RUN I): -65± 20 (-168± 20) MeV in the electron (muon) case. $\delta M_W^{theory} = 10 - 20$ MeV
M_W extracted from $M_T(l\nu)$ at RUN II: $\delta M_W^{exp} = 27$ MeV	
full $\mathcal{O}(\alpha)$ contribution to resonant W production in a pole approx. W.Hollik, D.W, PRD55 (1997) U.Baur *et al*, PRD59 (1998)	shift in M_W: $\delta M_W = 10$ MeV
full $\mathcal{O}(\alpha)$ electroweak corrections S.Dittmaier,M.Krämer, PRD65 (2002) L.Akhushevich *et al*(2003); U.Baur, D.W. in prep.	high Q^2, Γ_W
real two-photon radiation in W, Z production U.Baur *et al*, PRD61 (2000)	significantly changes shape of M_T
multiple final state photon radiation W.Placzek *et al*, hep-ph/0302065 C.M.Carloni Calame *et al*, hep-ph/0303102	$\delta M_W = 2(10)$ MeV in the $e(\mu)$ case

The Feynman diagrams contributing to W production at $\mathcal{O}(\alpha^3)$:

shaded loop: non-photonic contributions (i.e. f,H,Z,W in loop)



Treatment of mass singularities (same for Z boson production)

$$d\hat{\sigma}^{(0+1)} = d\hat{\sigma}^{(0)} \left[1 + 2\mathcal{R}e(\tilde{F}^{initial}_{weak} + \tilde{F}^{final}_{weak})(M_W^2)\right]$$

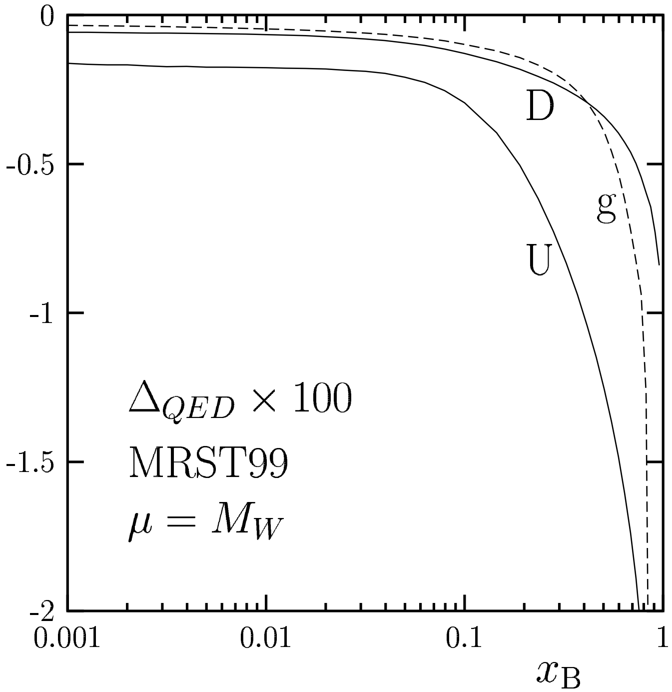
$$+ \sum_{\substack{a=initial,final,\\ interf.}} \left[d\hat{\sigma}^{(0)}\, F^a_{QED}(\hat{s},\hat{t}) + d\hat{\sigma}^a_{2\to 3}\right] + d\hat{\sigma}_{non-res.}(\hat{s},\hat{t})$$

from W.Hollik, D.W., PRD55, 6788 (1997)

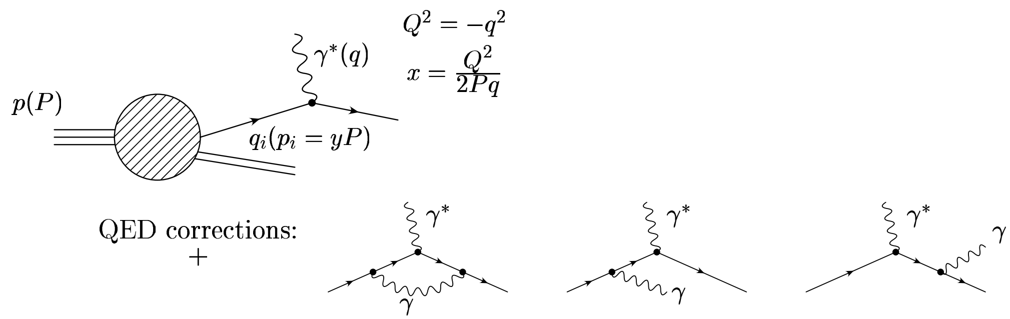
$F^{initial,final}_{QED}$ and $d\hat{\sigma}^{initial,final}_{2\to 3}$ contain large mass singular logarithms: $\alpha \ln(\hat{s}/m_f^2)$

- Final-state radiation (FSR):
  in sufficiently inclusive observables the mass singularities completely cancel (KLN theorem).
- Initial-state radiation (ISR):
  mass singularities always survive but can be absorbed by universal collinear counterterms to the parton distribution functions (in complete analogy to QCD).
  U.Baur *et al.*, PRD59 (1999)
  - introduces dependence on QED factorization scheme (in analogy to QCD, a DIS and $\overline{MS}$ scheme has been introduced)
  - currently no PDFs available which include QED corrections but the effects of QED on the PDFs are expected to be small (except at large x).

The impact of QED corrections on PDFs



from H.Spiesberger, LHC report, hep-ph/0003275 (GLAP)



$$q_i(x, Q^2) = q_i(x) \left[1 + \frac{\alpha}{\pi} Q_i^2 \left\{1 - \ln\delta_s - \ln^2\delta_s + \left(\ln\delta_s + \frac{3}{4}\right) \ln\left(\frac{Q^2}{m_i^2}\right) - \frac{1}{4}\lambda_{FC} f_{v+s}\right\}\right]$$

$$+ \int_x^{1-\delta_s} \frac{dz}{z} q_i\left(\frac{x}{z}\right) \frac{\alpha}{2\pi} Q_i^2 \left\{\frac{1+z^2}{1-z} \ln\left(\frac{Q^2}{m_i^2}\frac{1}{(1-z)^2}\right) - \frac{1+z^2}{1-z} + \lambda_{FC} f_c\right\}$$

from U.Baur *et al* PRD59 (1998)

II. Overview of Implementation in WGRAD

- WGRAD is a parton level MC programs that compute cross sections to W production via the Drell-Yan mechanism.

- The calculation is based on the full matrix elements for massless fermions, including the complete electroweak $\mathcal{O}(\alpha)$ corrections (real+virtual photons and weak 1-loop corrections).

- The matching of soft and collinear singularities beween virtual and real corrections is done using phase space slicing:

$$E_\gamma < \delta_s \sqrt{\hat{s}}/2 \quad ; \quad (1 - \cos\theta_{i\gamma}) < \delta_c$$

- WGRAD generates weighted events: one weight for events with $2 \to 2$ kinematics and one for $2 \to 3$ kinematics (hard photon).
  Both weights depend on δ_s, δ_c, but this dependence cancels in the sum.
  The corresponding momenta are stored in `ptwo(4,2),pthree(4,3)`,
  (1: electron or muon , 2: neutrino, 3: photon).

- The integration is done using RENO, a version of VEGAS.

As usual, the structure is determined by phase space generation ($d\Phi^{(n)}$) and computation of matrix elements squared ($|\mathcal{M}|^2$):

$$d\sigma = d\Phi^{(n)} dx_1 dx_2 f_i(x_1) f_j(x_2) |\mathcal{M}(b_1, b_2, p_1, ..., p_n)|^2$$

with

$$|\mathcal{M}|^2 = |\mathcal{M}^{(0)}|^2 \, [1 + 2\mathcal{R}e(\tilde{F}_{weak}^{initial} + \tilde{F}_{weak}^{final})(M_W^2)]$$
$$+ \sum_{\substack{a=initial,final,\\ interf.}} |\mathcal{M}^{(0)}|^2 \, F_{QED}^a(\hat{s}, \hat{t}, \delta_{s,c}) + |\mathcal{M}_{non-res.}|^2(\hat{s}, \hat{t}) +$$
$$+ \sum_{\substack{a=initial,final,\\ interf.}} |\mathcal{M}_{2\to 3}|_a^2(\delta_{s,c})$$

$2 \to 3$ weight in blue and $2 \to 4$ weight in red.

Negative weights, re-weighting: see discussion in proc. of *QCD and Weak Boson Physics in Run2* (hep-ex/0011009).

Initialization and Choice of Options (inputfile)

`wopt`	constant width (1) or running width (2)
	(W width is calculated, see `subroutine winput`)
`mw`	W mass $\Rightarrow M_H, M_W$ has to be in a certain range (see `subroutine winput`)
`ppswitch`	Tevatron (1) or LHC (2)
`test`(1)	W^+ (1) or W^-(2) production
`test`(2)	e (1) or μ(2) final state
`test`(3)	only inital (1) or only final (2) or only interference (3)
	or complete set of corrections (4)
`qnonr`	non-resonant not included (2) or included (1) (slow)
`test`(4)	option for final state only: full (1) or a la Berends et al (2)
`test`(10)	choice of recombination and smearing (see `cuts.f`)
`test`(9)	only LO (0) or NLO with LO subtracted (1) or NLO (2)
`test`(8)	choice of QED factorization/renormalization scale
`collcut`	choice for final state only: without (0) or with (1) collinear cut δ_c.
	If `collcut`=1, a recombination procedure has to be applied.

Initialization and Choice of Options, cont.

inputfile cont.	
choice of cuts (see `cuts.f`) and PDFs and number of events for integration with RENO	
switches in main program	
`dsdc`	switch for study of δ_s, δ_c dependence,
	`dsdc=0`: fixed choice of $\delta_{s,c}$, always $\delta_c < \delta_s$ and smaller than 0.1
`lfc`	$\overline{MS}$ (0) or DIS (1) QED factorization scheme
`rs`	center of mass energy (in GeV)
switches in subroutine `winput`	
`rep`	choice of input scheme (for both amplitude and W width)
	$\alpha(0)$ (1) or G_μ (2) scheme (see `kern.f`)
`qcd`	QCD corrections to W width can be included (`qcd`=1)