EWK Working Group

Gauge boson pair production at LHC

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22.1.99, CERN

* **One loop corrections to the helicity amplitudes of the processes**

$q\bar{q}^{(\prime)} \to W^+W^-, Z^0Z^0, W^\pm Z^0$

$\to$ four leptons
2 leptons, 2 quarks

QCD

$q\bar{q}^{(\prime)} \to W\gamma, Z\gamma \to$ 2 leptons + γ

(L. Dixon, A. Signer, ZK)

* **NLO QCD MC programs (f90, f77) for LHC and Tevatron**

- SM calculations
- VV production with anomalous couplings

Motivations

* For hadron colliders NLO QCD prescription is a „must"

* Previous analysis are incomplete

* Most of the crucial tests of the electroweak symmetry breaking (EWSB) are related to gauge-boson pair-production

* Large QCD corrections

* NLO description with anomalous couplings

⋮

$p + \overset{(-)}{p} \to W^+W^-, W^\pm Z, ZZ$ x-sections in NLO

Spin-averaged, spin-summed cross-sections

Brown, Mikaelian, PR D19 (1979)
Brown, Mikaelian, Sahdev, PR D20 (1979)
Mikaelian, Samuel, Sahdev, PRL 43 (1979)
} LO

Ohnemus, Owens, PRD43 (1991) | ZZ
Mele, Nason, Ridolfi, NPB357 (1991) | ZZ
Ohnemus PRD 41 (1991) | WZ
Frixione, Nason, Ridolfi, NPB383 (1992) | WZ
Ohnemus PRD 44 (1991) | WW
Frixione NPB 410 (1993) | WW
} NLO

Spin correlations not averaged

J.F. Gunion, Z. Kunszt PRD 33 (1985)
helicity method
WW, WZ, ZZ, Wγ, Zγ, LEP, Tevatron, LHC
} LO

Ohnemus PRD 50 (1994)

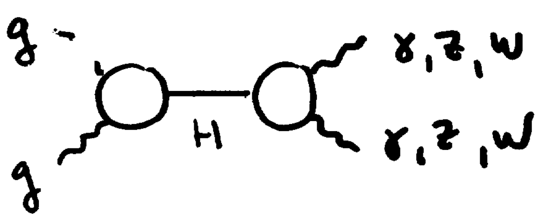
- some part of the spin correlations in NLO
- no virtual corrections

* Important signals for Higgs-production

$g + g \to H \to \gamma\gamma$

ZZ, WW } four leptons, 2 quarks 2 leptons

Signal

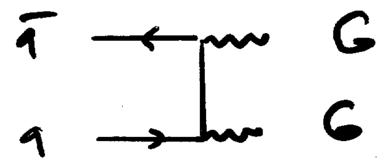


Large K-factors

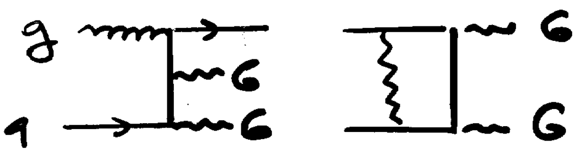
$\frac{\alpha_s}{\pi}(\pi^2 + 4)$

Backgrounds (irr.)

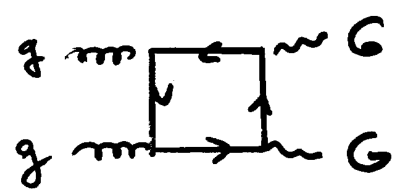
LO



NLO



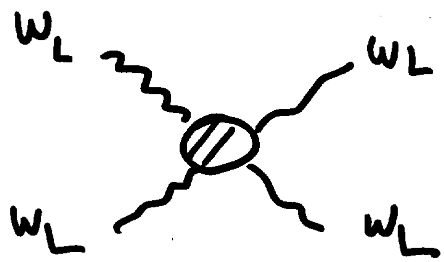
NNLO



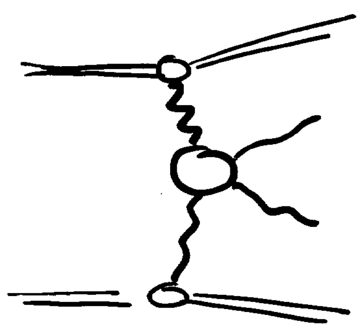
Hard work to get control with accuracy of ~ 10 %.

* EWSB without Higgs-boson ?

WW , WZ scattering



most crucial test of the EWSB



forward jet tagging

Higgs-search via $H \to W^+ W^- \to \ell^+ \ell^{-\prime} \nu_e \tilde{\nu}_{e'}$

Dreiner, Dittmar

* Two important features

① Signal: central

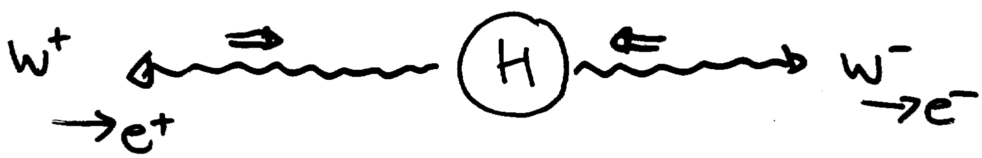
Background: forward-backward peaked

$gg \to H \to W^+ W^-$

$q\bar{q} \to W^+ W^-$

$x_1 x_2 \sim M_H^2 / s$

② Strong spin correlation



Tevatron results on gauge boson pair production

~ 20 times more events at Tevatron 2
~ 1000 — " — at LHC

* WW production — 4 lepton final states

$e\mu$, $\mu\mu$, ee + missing p_T

	DØ ($\Delta\mathcal{L} \sim 96.6\, pb^{-1}$)	CDF ($\Delta\mathcal{L} \sim 108\, pb^{-1}$)
Events	5	5
Backgrounds	3.3 ± 0.4	1.2 ± 0.3
SM	2.1 ± 0.15	3.5 ± 1.2

Backgrounds, Z, γ^*, $W\gamma$, $t\bar{t}$ production

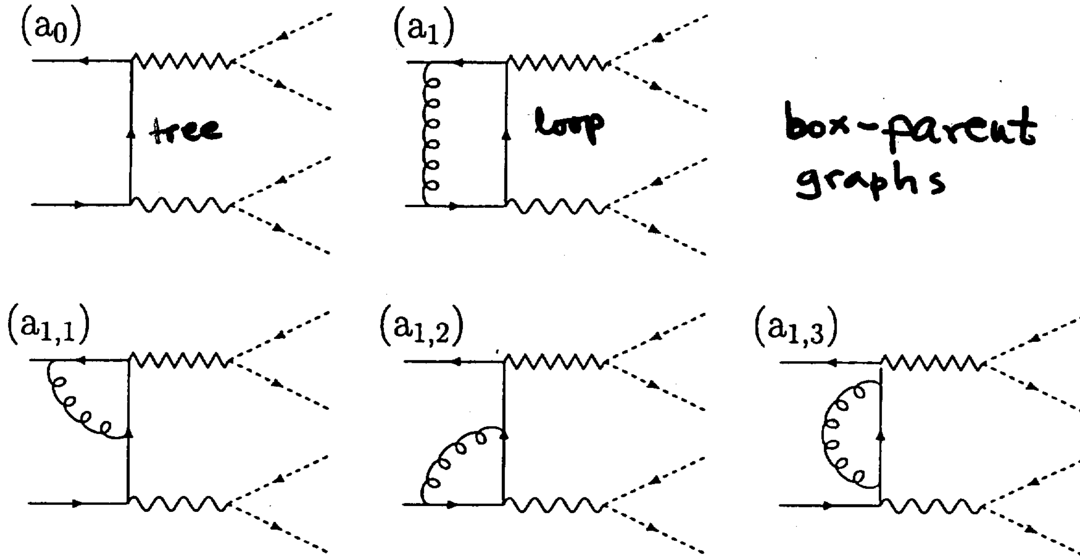
* $W\gamma$ production — $e\nu\gamma$, $\mu\nu\gamma$ final states

	DØ	CDF
Events	~ 130	~ 110
Background	~ 45	~ 26
Signal	~ 84	~ 83

* $Z\gamma$ production — 30 events with 5 background events

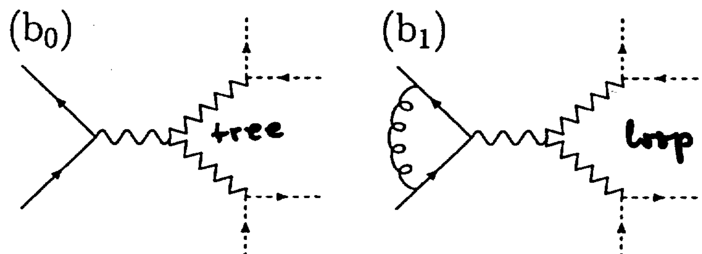
$q\bar{q} \to V_1 V_2 \to 4$ leptons

$A^{(a)}$:



box-parent graphs

$A^{(b)}$:



triangle-parent graph

- Color ordering is trivial: all diagrams have the same color factor

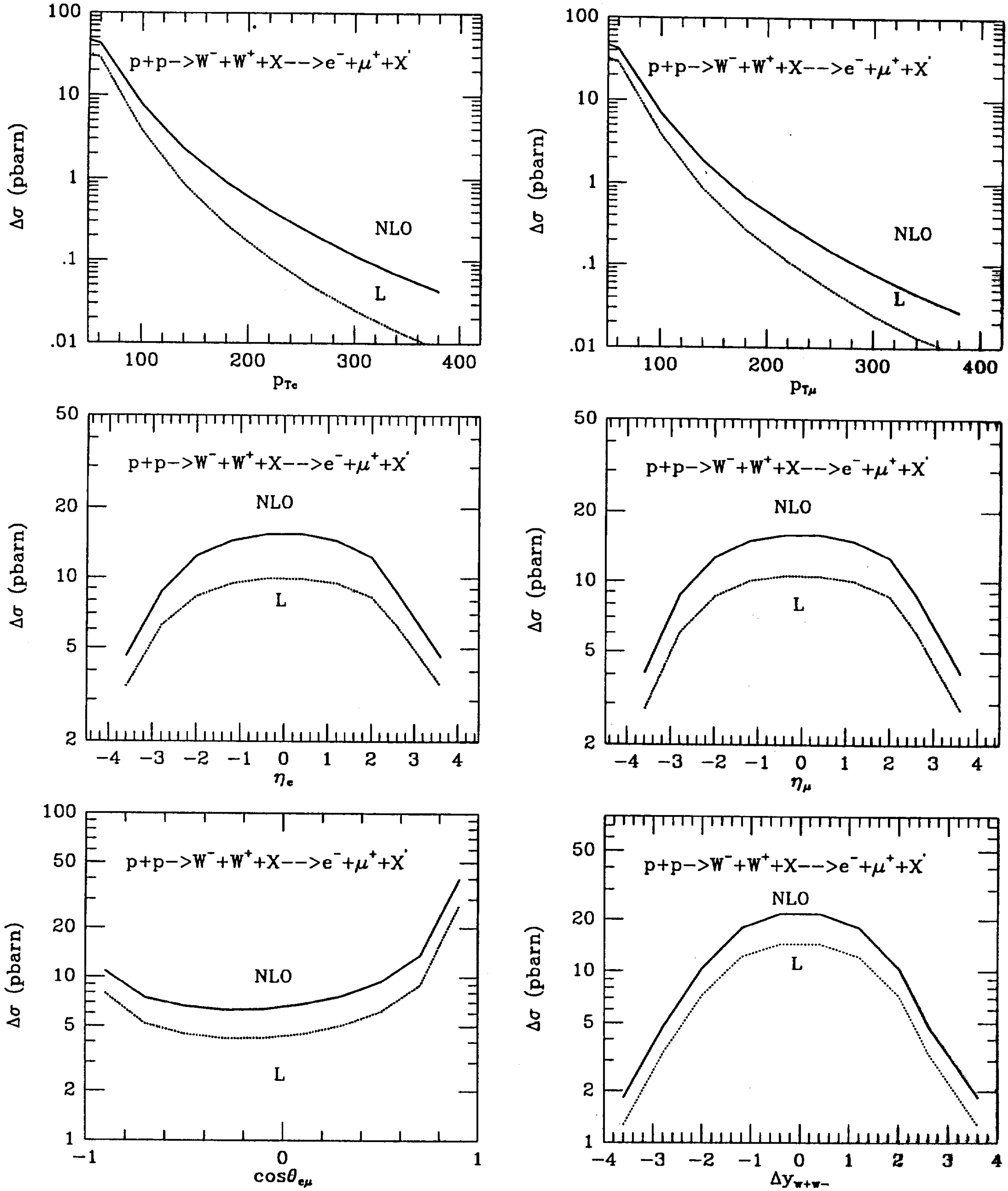
- Ordering with respect to the appearence of the electro-weak coupling

Relation to subleading-color $e^+e^- \to q\bar{q}\,Q\bar{Q}$ amplitude

Bern, Dixon, Kosower, Weinzierl

Nucl. Phys. B 489 (1997) p. 3

NLO program: leptocork
(Dixon, Sigurdsson, Kt)



Important background processes at LHC

Dressing with electroweak couplings

Example

$$\bar{q} q \to W^+ W^- \to \ell \bar{\nu}_e \bar{\ell}' \nu_{e'}$$

leptons have to be left-handed
outgoing quark is left handed

$$A^{tree}(u_1^L, u_2^R; \ell_3 \bar{\nu}_4; \bar{\ell}'_5 \nu'_6)$$

$$\propto \text{const} \cdot \left[A^{tree}(1,2,3,4,5,6) + C_{L,u} A^{tree,b}(1,2,3,4,5,6) \right]$$

$$C_{L,\{^u_d\}} = \pm 2 Q \sin^2\theta_W + \frac{s_{12}(1 \mp 2Q \sin^2\theta_W)}{s_{12} - M_Z^2}$$

As $s_{12} \to \infty$ $\quad C_L \to 1 \quad A^{tree,a} \sim - A^{tree,b}$

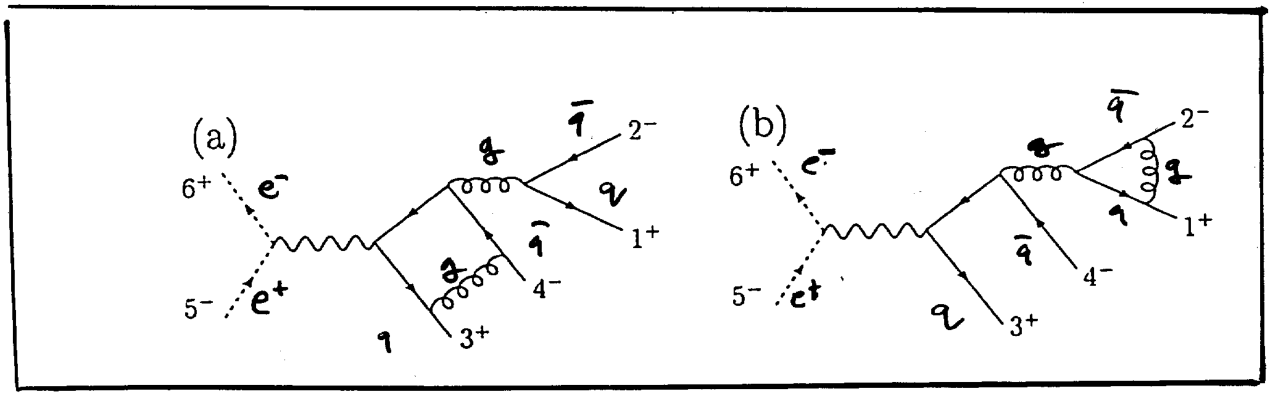
high energy cancellation

$$M^{tree}(\bar{u}u \to WW \to e\nu \ell' \nu') = \frac{1}{s_{12}} \text{const} \times$$

$$\left\{ \left| A^{tree,a}(1,2,3,4,5,6) + C_{L,u} A^{tree,b}(1,2,3,4,5,6) \right|^2 + \left| C_{R,u} A^{tree,b}(2,1,3,4,5,6) \right|^2 \right\}.$$

26

similarly for the loop contr.



Parent diagrams for $A_6^{sl}(1,2,3,4)$ i.e. the subleading-in-color part of $e^+e^- \to q\bar{q}\,Q\bar{Q}$

- (*) The quark pair $\{1,2\}$ can be replaced by a lepton pair
- (*) The virtual gluon that connects the two different quark lines can be replaced by an electroweak vector boson
- (*) The graph have to be dressed with appropriate left-handed and right-handed couplings of fermions to electroweak bosons

$O(\alpha_s)$ radiative corrections to $Wb\bar{b}$ production

$e^+e^- \to q\bar{q}Q\bar{Q}$ matrix elements again (BDKW)

- the replacement completely trivial and was already noted by BDKW
- $m_b = 0$, good approximation for most purposes

R.K. Ellis, Veseli: MC implementation

Calculation for $\sqrt{s} = 2\,TeV$

The size of the corrections is $\sim 50\%$, similar to (Z) the WW, WZ and ZZ production

Signal considered $(W^{\pm} \to e^{\pm}\nu)$

$84\,GeV < M_{bb} < 117\,GeV$

$\Delta\sigma \sim 15\,fb$ signal

$\Delta\sigma \sim 50\,fb$ background

$\varepsilon_b^2 \cdot 4 \approx O(1)$

Lance Dixon: it was easy to „undo" the „exchange" term since the symmetrized term could be traced back.

exchange $1 \leftrightarrow 6$ $2 \leftrightarrow 5$ for WW, WZ is not need

Virtual primitive amplitudes

$$A^{\alpha}(1,2,3,4,5,6) \qquad \alpha = a, b$$

$$A^{\text{tree},a} = i \frac{\langle 13\rangle [25] \langle 6|2+5|4\rangle}{s_{34}\, s_{56}\, t_{134}}$$

$$A^{\text{tree},b} = \frac{i}{s_{12}\, s_{34}\, s_{56}} \left[\langle 13\rangle [25] \langle 6|2+5|4\rangle + [24]\langle 16\rangle \langle 3|1+6|5\rangle \right]$$

$$A^{\text{loop},\alpha} = c_{\Gamma} \left[A^{\text{tree},\alpha} V + i F^{\alpha} \right]$$

$$V = -\frac{1}{\varepsilon^2}\left(\frac{\mu^2}{-s_{12}}\right)^{\varepsilon} - \frac{3}{2\varepsilon}\left(\frac{\mu^2}{-s_{12}}\right)^{\varepsilon} - 7/2$$

$$F^{b} = 0$$

Real (Bremsstrahlung) primitive amplitudes

$$A_7^{\text{tree},a} = i\frac{\langle 13\rangle}{\langle 17\rangle s_{34}s_{56}t_{134}}\left[\frac{\langle 13\rangle[34][25]\langle 6|2+5|7\rangle}{t_{256}} + \frac{\langle 6|1+3|4\rangle\langle 1|2+7|5\rangle}{\langle 72\rangle}\right]$$

$$A_7^{\text{tree},b} = i\frac{i}{\langle 17\rangle\langle 72\rangle s_{34}s_{56}t_{127}}\Big[-\langle 36\rangle[45]\langle 1|5+6](2+7)|1\rangle$$
$$+\langle 13\rangle\langle 1|2+7|4\rangle\langle 6|3+4|5\rangle - \langle 16\rangle\langle 1|2+7|5\rangle\langle 3|5+6|4\rangle\Big]$$

for positive helicity gluon ↗

for negative helicity gluon ⟶ $\underbrace{1\to 2 \quad 3\leftrightarrow 5 \quad 4\leftrightarrow 6}_{\text{flip}_1}$ $\langle ab\rangle \to [ab]$

Anomalous W^-W^+Z and $W^-W^+\gamma$ couplings

* We consider only couplings which conserves C and P

$$\mathcal{L}^V = i g_{WWV} \Big\{ g_1^V \left(W^*_{\mu\nu} W^\mu W^\nu - W_{\mu\nu} W^{*\mu} V^\nu \right) + \kappa^V W^*_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2} W^*_{\rho\mu} W^\mu{}_\nu V^{\nu\rho} \Big\}$$

Hagiwara et al.

$$g_{WW\gamma} = -e \qquad g_{WWZ} = -e \operatorname{ctg} \theta_W$$

* Five couplings $\{ g_{1Z}, \lambda^\gamma, \lambda^Z, \kappa^\gamma, \kappa^Z \}$

$$g_{1V} = 1 + \Delta g_1^V \qquad \Delta g_1^\gamma = 0$$
$$\kappa_V = 1 + \Delta \kappa^V$$

Other constraints?
$SU(2) \otimes U(1)$ invariant effective Lagrangian
$\lambda^\gamma = \lambda^Z$
less than dim 8 operators

* In momentum space

$$\Gamma^{\alpha\beta\mu}(q,\bar{q},p)/g_{WWV} = \bar{q}^\alpha g^{\beta\mu} \left(g_1^V + \kappa^V + \lambda^V \frac{q^2}{M_W^2} \right) - q^\beta g^{\alpha\mu} \left(g_1^V + \kappa^V + \lambda^V \bar{q}^2/M_W^2 \right)$$
$$+ (\bar{q}^\mu - q^\mu) \left[-g^{\alpha\beta} \left(g_1^V + \tfrac{1}{2} p^2 \frac{\lambda^V}{M_W^2} \right) + p^\alpha p^\beta \frac{\lambda^V}{M_W^2} \right]$$

This vertex will lead to violation of unitarity.

$$\mu_W = \frac{e}{2 m_W}(1 + \kappa_\gamma + \lambda_\gamma) \qquad \text{(mag. dipole)}$$

$$Q_W^e = -\frac{e}{m_W^2}(\kappa_\gamma - \lambda_\gamma) \qquad \text{(el. quadropole)}$$

$$|\Delta\kappa_V| \lesssim \left(\frac{m_W^2}{16\pi^2\Lambda^2}, \frac{m_W^2 v^2}{\Lambda^4}\right)_{max}$$

$$|\lambda_V| \lesssim \left(g^2 \frac{m_W^2}{16\pi\Lambda^2} \quad \frac{m_W^4}{\Lambda^4}\right)_{max}$$

$$\Delta g_1^V \lesssim \frac{m_W^2 v^2}{\Lambda^4}$$

dim 6 operators

$$\Delta\kappa_V,\ \Delta g_1^V \sim 0.006$$

$$\Delta\lambda_V \sim 2 \times 10^{-5}$$

Unitarization → form factors ?

$$W^+W^- \to W^+W^-$$

Standard model:

$|\Delta\kappa_\gamma| \sim 0.008$

$|\lambda_\gamma| \sim 0.002$

MSSM

$|\Delta\kappa_\gamma| \sim 0.005$

$|\lambda_\gamma| \sim 5\times10^{-5}$

LEP

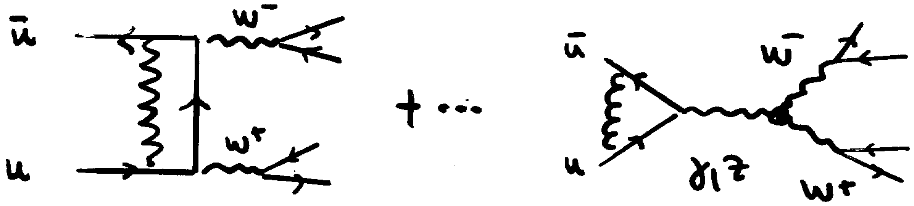
$|\Delta\kappa_\gamma| < 0.05$

$|\Delta\kappa_Z| < 0.4$

$|\lambda_\gamma|, |\lambda_Z| < 0.2$

Tree and virtual amplitudes with anom. couplings

- $W^- W^+ \to \ell(3)\,\bar\nu(4)\,\nu'(5)\,\bar\ell(6)$ production



$$A^{tree,B} = \frac{i}{2 s_{12} s_{34} s_{56}} \Big[(g_1^V + \kappa^V + \lambda^V)\big(\langle 13\rangle [24] \langle 6|1+2|5\rangle + \langle 16\rangle [25] \langle 3|5+6|4\rangle\big)$$

$$+ \langle 1|3+4|2\rangle \Big(2 g_1^V \langle 36\rangle [45] + \frac{\lambda^V}{M_W^2} \langle 3|1+2|5\rangle \langle 6|1+2|4\rangle \Big) \Big]$$

$A^{loop,A}$: same as in SM

$A^{loop,B}$: $c_\Gamma \, A^{tree,B} \, V$

$$V = -\frac{1}{\varepsilon^2}\left(\frac{\mu^2}{-s_{12}}\right)^{\varepsilon} - \frac{3}{2\varepsilon}\left(\frac{\mu^2}{-s_{12}}\right)^{\varepsilon} - \frac{7}{2}$$

Similarly simple expression for

- Bremsstrahlung primitive amplitude
- WZ, $W\gamma$ final states

Concluding Remarks

* NLO parton level MC programs are available to calculate (in two versions : f77, f90)

$$q+\bar{q} \to W^- + W^+ \to l\bar{\nu}\bar{l}'\nu$$
$$Z^0+Z^0 \to 4 \text{ lepton}$$
$$W^{\pm} Z \to l\bar{\nu}\, l\bar{l}$$

* „Bench mark cross-sections"

Physics applications → LHC workshop

σ_{LL}, σ_{LT}, σ_{TT} as function of $p_T(W)$

* Anomalous couplings can be considered in NLO QCD as well.

$\frac{d\sigma}{dE_T(l_1)\, dE_T(l_2)}$ at various values of the anomalous couplings