Electroweak Studies with WHIZARD

Jürgen Reuter

DESY Hamburg

Snowmass Energy Frontier Meeting

Alboteanu/Kilian/JR, arXiv:0806.4145 (**JHEP**); M. Mertens, 2005; Kilian/JR/Sekulla work in progress; Beyer/Kilian/Krstonošić/Mönig/JR/Schmitt/Schröder, **EPJC 48** (2006), 353 [ILC version]

Snowmass Meeting, BNL, N.Y., Apr. 4th, 2013

WHIZARD

Kilian/Ohl/JRR: DESY/Freiburg/Siegen/Würzburg, hep-ph/0102195, EPJC 71 (2011) 1742

- Multi-Purpose event generator for collider and astroparticle physics
- Acronym: **W**, **HI**ggs, **Z**, **A**nd **R**espective **D**ecays (deprecated)
  - Fast adaptive multi-channel Monte-Carlo integration
  - Very efficient phase space and event generation
  - Optimized/-al matrix elements
    uses the color flow formalism Kilian/Ohl/JRR/Speckner, JHEP 1210 (2012) 022
  - Recent version: 2.1.1 (18.09.2012) [2.2.0 will come Apr 2013]
    `http://projects.hepforge.org/whizard`
  - Parton shower ($k^\perp$-ordered and analytic) Kilian/JRR/Schmidt/Wiesler, JHEP 1204 (2012) 013
  - Underlying Event: preliminary version
  - 2.0 Features: ME/PS matching, cascades, shared library
  - Working on: NLO automation, general Lorentz structures etc.
- Interface to `FeynRules` Christensen/Duhr/Fuks/JRR/Speckner, EPJC 72 (2012) 1990
- Versatile input language: SINDARIN

WHIZARD

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- Multi-Purpose event generator for collider and astroparticle physics
- Focus: LHC, ILC, CLIC, SM, QCD, BSM

MODEL TYPE	with CKM matrix	trivial CKM
QED with e, μ, τ, γ	–	`QED`
QCD with d, u, s, c, b, t, g	–	`QCD`
Standard model	`SM_CKM`	`SM`
SM with anomalous couplings	`SM_ac_CKM`	`SM_ac`
SM with anomalous top couplings	—	`SM_top`
SM with K matrix	—	`SM_KM`
MSSM	`MSSM_CKM`	`MSSM`
MSSM with Gravitinos	—	`MSSM_Grav`
NMSSM	`NMSSM_CKM`	`NMSSM`
extended SUSY models	—	`PSSSM`
Littlest Higgs	—	`Littlest`
Littlest Higgs with ungauged $U(1)$	—	`Littlest_Eta`
Littlest Higgs with T parity	—	`Littlest_Tpar`
Simplest Little Higgs (anomaly free)	—	`Simplest`
Simplest Little Higgs (universal)	—	`Simplest_univ`
UED	—	`UED`
3-Site Higgsless Model	—	`Threeshl`
Noncommutative SM (inoff.)	—	`NCSM`
SM with Z'	—	`Zprime`
SM with Gravitino and Photino	—	`GravTest`
Augmentable SM template	—	`Template`

easy to
implement new models

- Interface to `FeynRules`

Christensen/Duhr/Fuks/JRR/Speckner, EPJC 72 (2012) 1990

- Versatile input language: SINDARIN

Electroweak Chiral Lagrangian

Complete Lagrangian contains infinitely many parameters

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{min}} - \sum_\psi \overline{\psi}_L \Sigma M \psi_R + \beta_1 \mathcal{L}_0' + \sum_i \alpha_i \mathcal{L}_i + \frac{1}{v} \sum_i \alpha_i^{(5)} \mathcal{L}^{(5)} + \frac{1}{v^2} \sum_i \alpha_i^{(6)} \mathcal{L}^{(6)} + \ldots$$

$$\mathcal{L}_0' = \frac{v^2}{4} \operatorname{tr}[\mathbf{T}\mathbf{V}_\mu] \operatorname{tr}[\mathbf{T}\mathbf{V}^\mu]$$

$$\begin{aligned}
\mathcal{L}_1 &= \operatorname{tr}[\mathbf{B}_{\mu\nu}\mathbf{W}^{\mu\nu}] & \mathcal{L}_6 &= \operatorname{tr}[\mathbf{V}_\mu\mathbf{V}_\nu] \operatorname{tr}[\mathbf{T}\mathbf{V}^\mu] \operatorname{tr}[\mathbf{T}\mathbf{V}^\nu] \\
\mathcal{L}_2 &= i\operatorname{tr}[\mathbf{B}_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]] & \mathcal{L}_7 &= \operatorname{tr}[\mathbf{V}_\mu\mathbf{V}^\mu] \operatorname{tr}[\mathbf{T}\mathbf{V}_\nu] \operatorname{tr}[\mathbf{T}\mathbf{V}^\nu] \\
\mathcal{L}_3 &= i\operatorname{tr}[\mathbf{W}_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu]] & \mathcal{L}_8 &= \tfrac{1}{4}\operatorname{tr}[\mathbf{T}\mathbf{W}_{\mu\nu}] \operatorname{tr}[\mathbf{T}\mathbf{W}^{\mu\nu}] \\
\mathcal{L}_4 &= \operatorname{tr}[\mathbf{V}_\mu\mathbf{V}_\nu] \operatorname{tr}[\mathbf{V}^\mu\mathbf{V}^\nu] & \mathcal{L}_9 &= \tfrac{i}{2}\operatorname{tr}[\mathbf{T}\mathbf{W}_{\mu\nu}] \operatorname{tr}[\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]] \\
\mathcal{L}_5 &= \operatorname{tr}[\mathbf{V}_\mu\mathbf{V}^\mu] \operatorname{tr}[\mathbf{V}_\nu\mathbf{V}^\nu] & \mathcal{L}_{10} &= \tfrac{1}{2}\left(\operatorname{tr}[\mathbf{T}\mathbf{V}_\mu] \operatorname{tr}[\mathbf{T}\mathbf{V}^\mu]\right)^2
\end{aligned}$$

Indirect info on new physics in $\beta_1, \alpha_i, \ldots$ (Flavor physics only in M)

Electroweak precision observables (LEP I/II, SLC):

$$\begin{aligned}
\Delta S &= -16\pi\alpha_1 & \alpha_1 &= 0.0026 \pm 0.0020 \\
\Delta T &= 2\beta_1/\alpha_{\text{QED}} & \beta_1 &= -0.00062 \pm 0.00043 \\
\Delta U &= -16\pi\alpha_8 & \alpha_8 &= -0.0044 \pm 0.0026
\end{aligned}$$

Anomalous triple and quartic gauge couplings

$$\mathcal{L}_{TGC} = \mathrm{ie}\left[g_1^\gamma A_\mu \left(W_\nu^- W^{+\mu\nu} - W_\nu^+ W^{-\mu\nu} \right) + \kappa^\gamma W_\mu^- W_\nu^+ A^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2} W_\mu^{-\ \nu} W_{\nu\rho}^+ A^{\rho\mu} \right]$$
$$+ \mathrm{ie}\frac{c_\mathrm{w}}{s_\mathrm{w}} \left[g_1^Z Z_\mu \left(W_\nu^- W^{+\mu\nu} - W_\nu^+ W^{-\mu\nu} \right) + \kappa^Z W_\mu^- W_\nu^+ Z^{\mu\nu} + \frac{\lambda^Z}{M_W^2} W_\mu^{-\ \nu} W_{\nu\rho}^+ Z^{\rho\mu} \right]$$

SM values: $g_1^{\gamma,Z} = \kappa^{\gamma,Z} = 1$, $\lambda^{\gamma,Z} = 0$ and $\delta_Z = \frac{\beta_1 + g'^2 \alpha_1}{c_\mathrm{w}^2 - s_\mathrm{w}^2}$ $\quad g_{1/2}^{VV'} = 1$, $h^{ZZ} = 0$

$$\Delta g_1^\gamma = 0 \qquad \Delta\kappa^\gamma = g^2(\alpha_2 - \alpha_1) + g^2\alpha_3 + g^2(\alpha_9 - \alpha_8)$$
$$\Delta g_1^Z = \delta_Z + \frac{g^2}{c_\mathrm{w}^2}\alpha_3 \qquad \Delta\kappa^Z = \delta_Z - g'^2(\alpha_2 - \alpha_1) + g^2\alpha_3 + g^2(\alpha_9 - \alpha_8)$$

$$\Delta g_1^{\gamma\gamma} = \Delta g_2^{\gamma\gamma} = 0 \qquad \Delta g_2^{ZZ} = 2\Delta g_1^{\gamma Z} - \frac{g^2}{c_\mathrm{w}^4}(\alpha_5 + \alpha_7)$$
$$\Delta g_1^{\gamma Z} = \Delta g_2^{\gamma Z} = \delta_Z + \frac{g^2}{c_\mathrm{w}^2}\alpha_3 \qquad \Delta g_1^{WW} = 2c_\mathrm{w}^2 \Delta g_1^{\gamma Z} + 2g^2(\alpha_9 - \alpha_8) + g^2\alpha_4$$
$$\Delta g_1^{ZZ} = 2\Delta g_1^{\gamma Z} + \frac{g^2}{c_\mathrm{w}^4}(\alpha_4 + \alpha_6) \qquad \Delta g_2^{WW} = 2c_\mathrm{w}^2 \Delta g_1^{\gamma Z} + 2g^2(\alpha_9 - \alpha_8) - g^2(\alpha_4 + 2\alpha_5)$$
$$h^{ZZ} = g^2\left[\alpha_4 + \alpha_5 + 2(\alpha_6 + \alpha_7 + \alpha_{10})\right]$$

Anomalous triple and quartic gauge couplings

$$
\begin{aligned}
\mathcal{L}_{QGC} = {} & e^2 \left[g_1^{\gamma\gamma} A^\mu A^\nu W_\mu^- W_\nu^+ - g_2^{\gamma\gamma} A^\mu A_\mu W^{-\nu} W_\nu^+ \right] \\
& + e^2 \frac{c_\mathrm{w}}{s_\mathrm{w}} \left[g_1^{\gamma Z} A^\mu Z^\nu \left(W_\mu^- W_\nu^+ + W_\mu^+ W_\nu^- \right) - 2 g_2^{\gamma Z} A^\mu Z_\mu W^{-\nu} W_\nu^+ \right] \\
& + e^2 \frac{c_\mathrm{w}^2}{s_\mathrm{w}^2} \left[g_1^{ZZ} Z^\mu Z^\nu W_\mu^- W_\nu^+ - g_2^{ZZ} Z^\mu Z_\mu W^{-\nu} W_\nu^+ \right] \\
& + \frac{e^2}{2 s_\mathrm{w}^2} \left[g_1^{WW} W^{-\mu} W^{+\nu} W_\mu^- W_\nu^+ - g_2^{WW} \left(W^{-\mu} W_\mu^+ \right)^2 \right] + \frac{e^2}{4 s_\mathrm{w}^2 c_\mathrm{w}^4} h^{ZZ} (Z^\mu Z_\mu)^2
\end{aligned}
$$

SM values: $g_1^{\gamma,Z} = \kappa^{\gamma,Z} = 1$, $\lambda^{\gamma,Z} = 0$ and $\delta_Z = \frac{\beta_1 + g'^2 \alpha_1}{c_\mathrm{w}^2 - s_\mathrm{w}^2}$ $\quad g_{1/2}^{VV'} = 1$, $h^{ZZ} = 0$

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$$\Delta g_1^{\gamma Z} = \Delta g_2^{\gamma Z} = \delta_Z + \frac{g^2}{c_\mathrm{w}^2}\alpha_3 \qquad \Delta g_1^{WW} = 2 c_\mathrm{w}^2 \Delta g_1^{\gamma Z} + 2 g^2 (\alpha_9 - \alpha_8) + g^2 \alpha_4$$

$$\Delta g_1^{ZZ} = 2\Delta g_1^{\gamma Z} + \frac{g^2}{c_\mathrm{w}^4}(\alpha_4 + \alpha_6) \qquad \Delta g_2^{WW} = 2 c_\mathrm{w}^2 \Delta g_1^{\gamma Z} + 2 g^2 (\alpha_9 - \alpha_8) - g^2 (\alpha_4 + 2\alpha_5)$$

$$h^{ZZ} = g^2 \left[\alpha_4 + \alpha_5 + 2(\alpha_6 + \alpha_7 + \alpha_{10}) \right]$$

Parameters and Scales, Resonances

α_i measurable at ILC and LHC

- $\alpha_i \ll 1$ (LEP)
- $\alpha_i \gtrsim 1/16\pi^2 \approx 0.006$ (renormalize divergencies, $16\pi^2\alpha_i \gtrsim 1$)

Translation of parameters into new physics scale Λ: $\alpha_i = v^2/\Lambda^2$

- Operator normalization is arbitrary
- Power counting can be intricate

To be specific: consider resonances that couple to EWSB sector
Resonance mass gives detectable shift in the α_i

- Narrow resonances $\Rightarrow$ particles
- Wide resonances $\Rightarrow$ continuum

$\beta_1 \ll 1 \;\Rightarrow SU(2)_c$ custodial symmetry (weak isospin, broken by hypercharge $g' \neq 0$ and fermion masses)

	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs ?)	ω^0 $(\gamma'/Z'\ ?)$	f^0 (Graviton ?)
$I=1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ $(W'/Z'\ ?)$	$a^\pm, a^0$
$I=2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$t^{\pm\pm}, t^\pm, t^0$

accounts for weakly and strongly interacting models

Integrating out resonances

Consider leading order effects of resonances on EW sector:

$$\mathcal{L}_\Phi = z\left[\Phi\left(M_\Phi^2 + DD\right)\Phi + 2\Phi J\right] \qquad \Rightarrow \qquad \mathcal{L}_\Phi^{\text{eff}} = -\frac{z}{M^2}JJ + \frac{z}{M^4}J(DD)J + \mathcal{O}(M^{-6})$$

- Simplest example: scalar singlet σ:

$$\mathcal{L}_\sigma = -\frac{1}{2}\left[\sigma(M_\sigma^2 + \partial^2)\sigma - g_\sigma v \sigma \mathrm{tr}\left[\mathbf{V}_\mu \mathbf{V}^\mu\right] - h_\sigma \mathrm{tr}\left[\mathbf{T}\mathbf{V}_\mu\right]\mathrm{tr}\left[\mathbf{T}\mathbf{V}^\mu\right]\right]$$

- Effective Lagrangian

$$\mathcal{L}_\sigma^{\text{eff}} = \frac{v^2}{8M_\sigma^2}\left[g_\sigma \mathrm{tr}\left[\mathbf{V}_\mu \mathbf{V}^\mu\right] + h_\sigma \mathrm{tr}\left[\mathbf{T}\mathbf{V}_\mu\right]\mathrm{tr}\left[\mathbf{T}\mathbf{V}^\mu\right]\right]^2$$

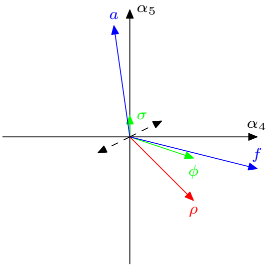
- leads to anomalous quartic couplings

$$\alpha_5 = g_\sigma^2\left(\frac{v^2}{8M_\sigma^2}\right) \qquad \alpha_7 = 2g_\sigma h_\sigma\left(\frac{v^2}{8M_\sigma^2}\right) \qquad \alpha_{10} = 2h_\sigma^2\left(\frac{v^2}{8M_\sigma^2}\right)$$

- Special case: SM Higgs with $g_\sigma = 1$ and $h_\sigma = 0$

Taxonomy of resonances/Loops

Resonance	σ	ϕ	ρ	f	a
$\Gamma[g^2M^2/(64\pi v^2)]$	6	1	$\frac{4}{3}\left(\frac{v^2}{M^2}\right)$	$\frac{1}{5}$	$\frac{1}{30}$
$\Delta\alpha_4[(16\pi\Gamma/M)(v^4/M^4)]$	0	$\frac{1}{4}$	$\frac{3}{4}$	$\frac{5}{2}$	$-\frac{5}{8}$
$\Delta\alpha_5[(16\pi\Gamma/M)(v^4/M^4)]$	$\frac{1}{12}$	$-\frac{1}{12}$	$-\frac{3}{4}$	$-\frac{5}{8}$	$\frac{35}{8}$



- Loop corrections to LET can be switched on/off:

  (μ renormalization scale)

$$A_C^{\text{1-loop}}(s,t,u) = \frac{1}{16\pi^2}\left[\left(\frac{1}{2}\ln\frac{\mu^2}{|s|} + 8C_5\right)\frac{s^2}{v^4} + \left(\frac{t(s+2t)}{6v^4}\ln\frac{\mu^2}{|t|} + 4C_4\frac{t^2}{v^4}\right) + (t \leftrightarrow u)\right],$$

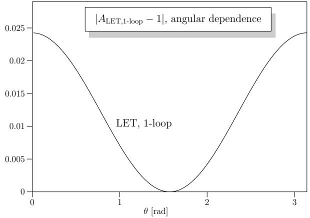
- Finite scheme-dep. matching coefficients/NLO counterterms

  (e.g. heavy Higgs regulator $\mu = M_H$ Dawson/Willenbrock, 1989)

$$C_4 = -\frac{1}{18} \approx -0.056, \qquad C_5 = \frac{9\pi}{16\sqrt{3}} - \frac{37}{36} \approx -0.0075.$$

$$\alpha_4^{(1)} = \frac{1}{16\pi^2}\left(C_4 - \frac{1}{12}\ln\frac{\mu^2}{\mu_0^2}\right)$$

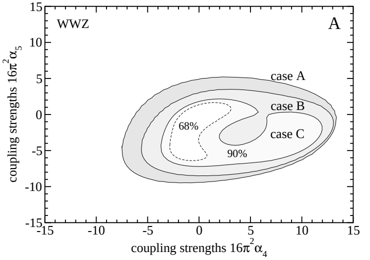
$$\alpha_5^{(1)} = \frac{1}{16\pi^2}\left(C_5 - \frac{1}{24}\ln\frac{\mu^2}{\mu_0^2}\right)$$



ILC Results: Triboson production

$e^+e^- \to WWZ/ZZZ$, dep. on $(\alpha_4+\alpha_6)$, $(\alpha_5+\alpha_7)$, $\alpha_4+\alpha_5+2(\alpha_6+\alpha_7+\alpha_{10})$

Polarization populates longitudinal modes, suppresses SM bkgd.



Simulation with WHIZARD Kilian/Ohl/JR

1 TeV, $1\,\mathrm{ab}^{-1}$, full 6-fermion final states, SIMDET fast simulation

Observables: M^2_{WW}, M^2_{WZ}, $\sphericalangle(e^-, Z)$

A) unpol., B) 80% e^-_R, C) 80% e^-_R, 60% e^+_L

$16\pi^2\times$	WWZ no pol.	WWZ e^- pol.	WWZ both pol.	ZZZ no pol.	best
$\Delta\alpha_4^+$	9.79	4.21	1.90	3.94	1.78
$\Delta\alpha_4^-$	-4.40	-3.34	-1.71	-3.53	-1.48
$\Delta\alpha_5^+$	3.05	2.69	1.17	3.94	1.14
$\Delta\alpha_5^-$	-7.10	-6.40	-2.19	-3.53	-1.64

32 % hadronic decays

Durham jet algorithm

Bkgd. $t\bar{t} \to 6$ jets

Veto against $E^2_{\mathrm{mis}} + p^2_{\perp,\mathrm{mis}}$

No angular correlations yet

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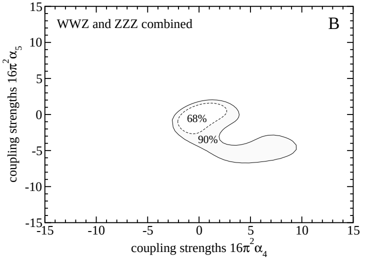

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Vector Boson Scattering

1 TeV, $1\ \mathrm{ab}^{-1}$, full $6f$ final states, 80 % e_R^-, 60 % e_L^+ polarization, binned likelihood

Contributing channels: $WW \to WW, WW \to ZZ, WZ \to WZ, ZZ \to ZZ$

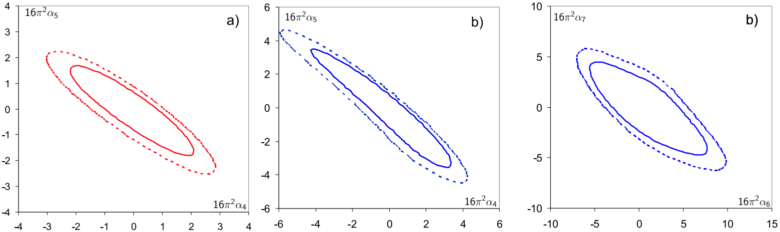
Process	Subprocess	σ [fb]
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$WW \to WW$	23.19
$e^+e^- \to \nu_e\bar{\nu}_e q\bar{q}q\bar{q}$	$WW \to ZZ$	7.624
$e^+e^- \to \nu\bar{\nu}q\bar{q}q\bar{q}$	$V \to VVV$	9.344
$e^+e^- \to \nu e q\bar{q}q\bar{q}$	$WZ \to WZ$	132.3
$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to ZZ$	2.09
$e^+e^- \to e^+e^- q\bar{q}q\bar{q}$	$ZZ \to W^+W^-$	414.
$e^+e^- \to b\bar{b}X$	$e^+e^- \to t\bar{t}$	331.768
$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to W^+W^-$	3560.108
$e^+e^- \to q\bar{q}q\bar{q}$	$e^+e^- \to ZZ$	173.221
$e^+e^- \to e\nu q\bar{q}$	$e^+e^- \to e\nu W$	279.588
$e^+e^- \to e^+e^- q\bar{q}$	$e^+e^- \to e^+e^- Z$	134.935
$e^+e^- \to X$	$e^+e^- \to q\bar{q}$	1637.405

$SU(2)_c$ conserved case, all channels

coupling	$\sigma-$	$\sigma+$
$16\pi^2\alpha_4$	-1.41	1.38
$16\pi^2\alpha_5$	-1.16	1.09

$SU(2)_c$ broken case, all channels

coupling	$\sigma-$	$\sigma+$
$16\pi^2\alpha_4$	-2.72	2.37
$16\pi^2\alpha_5$	-2.46	2.35
$16\pi^2\alpha_6$	-3.93	5.53
$16\pi^2\alpha_7$	-3.22	3.31
$16\pi^2\alpha_{10}$	-5.55	4.55

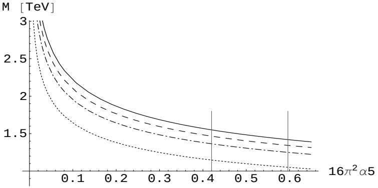


Interpretation as limits on resonances

Consider the width to mass ratio, $f_\sigma = \Gamma_\sigma / M_\sigma$

$SU(2)$ conserving scalar singlet

$$M_\sigma = v \left(\frac{4\pi f_\sigma}{3\alpha_5} \right)^{\frac{1}{4}}$$

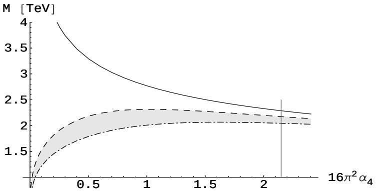


$f = 1.0$ (full), 0.8 (dash), 0.6 (dot-dash), 0.3 (dot)

$SU(2)$ broken vector triplet

needs input from TGC covariance matrix

$$M_{\rho^\pm} = v \left(\frac{12\pi\alpha_4 f_{\rho^\pm}}{\alpha_4^2 + 2(\alpha_2^\lambda)^2 + s_w^2(\alpha_4^\lambda)^2/(2c_w^2)} \right)^{\frac{1}{4}}$$



upper/lower limit from λ_Z, grey area: magnetic moments

Final result:

Spin	$I = 0$	$I = 1$	$I = 2$
0	1.55	–	1.95
1	–	2.49	–
2	3.29	–	4.30

Spin	$I = 0$	$I = 1$	$I = 2$
0	1.39	1.55	1.95
1	1.74	2.67	–
2	3.00	3.01	5.84

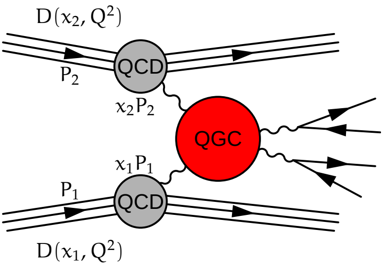
Anomalous Gauge Couplings at LHC

ILC: Beyer/Kilian/Krstonošić/Mönig/JR/Schröder/Schmidt, 2006
LHC: Mertens, 2006; Kilian/Kobel/Mader/JR/Schumacher

Anomalous quartic gauge couplings, by chiral EW Lagrangian:

$$\mathcal{L}_4 = \alpha_4 \frac{g^2}{2} \left\{ \left[(W^+W^+)(W^-W^-) + (W^+W^-)^2 \right] + \frac{2}{c_W^2}(W^+Z)(W^-Z) + \frac{1}{2c_W^4}(ZZ)^2 \right\}$$
$$\mathcal{L}_5 = \alpha_5 \frac{g^2}{2} \left\{ (W^+W^-)^2 + \frac{2}{c_W^2}(W^+W^-)(ZZ) + \frac{1}{2c_W^4}(ZZ)^2 \right\}$$

(all leptons, incl. τ):



$$pp \to jj(ZZ/WW) \to jj\ell^-\ell^+\nu_\ell\bar{\nu}_\ell$$

$$\sigma \approx 40\,\text{fb}$$

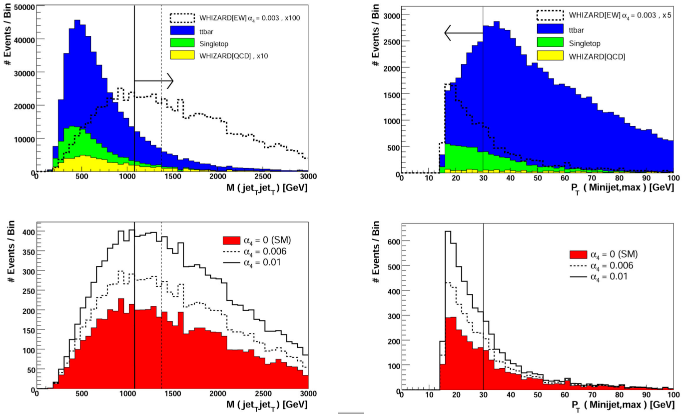
Background:

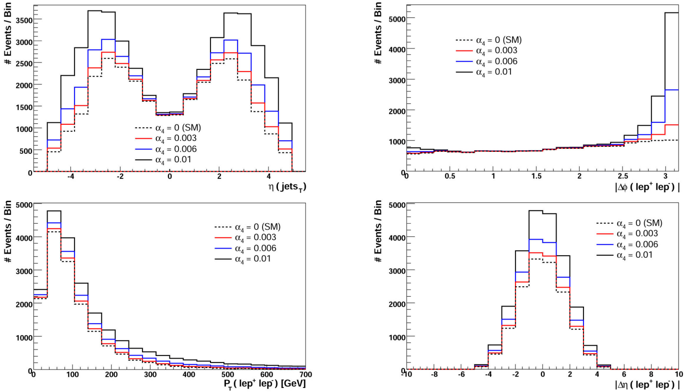
- $t\bar{t} \to WbWb$, $\sigma \approx 52$ pb
- Single t, misrec. jet: $\sigma \approx 4.8$ pb
- QCD: $\sigma \approx 0.21$ pb

Tagging and Cuts:

- $\ell\ell jj$-Tag, $\eta_{tag}^{min} < \eta_\ell < \eta_{tag}^{max}$, b-Veto
- $|\Delta\eta_{jj}| > 4.4$, $M_{jj} > 1080$ GeV
- Minijet-Veto: $p_{T,j} < 30$ GeV
- $E_j > 600, 400$ GeV, $p_{T,j}^1 > 60, 24$ GeV

Improves $S/\sqrt{B}$ from 3.3 to 29.7



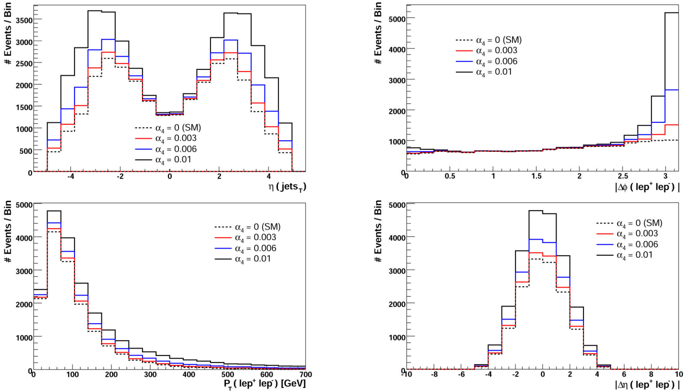


Results: (1σ Sensitivity to αs)

Coupl.	ILC ($1\,\mathrm{ab}^{-1}$)	LHC ($100\,\mathrm{fb}^{-1}$)
α_4	0.0088	0.00160
α_5	0.0071	0.00098

Limits for Λ [TeV]:

Spin	$I=0$	$I=1$	$I=2$
0	1.39	1.55	1.95
1	1.74	2.67	–
2	3.00	3.01	5.84



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Unitarity of Amplitudes

UV-incomplete theories could violate unitarity

Cross section: $\sigma = \int d\Omega \frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} |\mathcal{M}|^2$

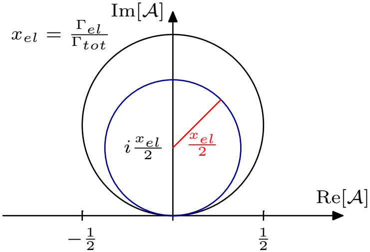
Optical Theorem (Unitarity of the S(cattering) Matrix):

$$\sigma_{\text{tot}} = \text{Im}\left[\mathcal{M}_{ii}(t=0)\right]/s \qquad t = -s(1-\cos\theta)/2$$

Partial wave amplitudes: $\mathcal{M}(s,t,u) = 32\pi \sum_\ell (2\ell+1) \mathcal{A}_\ell(s) P_\ell(\cos\theta)$

Assuming only elastic scattering:

$$\sigma_{\text{tot}} = \sum_\ell \frac{32\pi(2\ell+1)}{s} |\mathcal{A}_\ell|^2 \stackrel{!}{=} \sum_\ell \frac{32\pi(2\ell+1)}{s} \text{Im}\left[\mathcal{A}_\ell\right] \quad \Rightarrow \quad \boxed{|\mathcal{A}_\ell|^2 = \text{Im}\left[\mathcal{A}_\ell\right]}$$



Argand circle $\boxed{\left|\mathcal{A}(s) - \frac{i}{2}\right| = \frac{1}{2}}$

Resonance: $\mathcal{A}(s) = \frac{-M\Gamma_{\text{el}}}{s - M^2 + iM\Gamma_{\text{tot}}}$

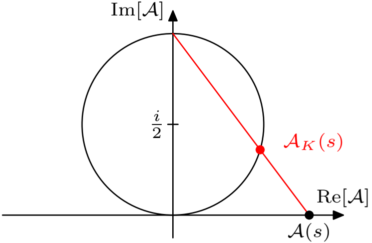
Counterclockwise circle, radius $\frac{x_{el}}{2}$

Pole at $s = M^2 - iM\Gamma_{\text{tot}}$

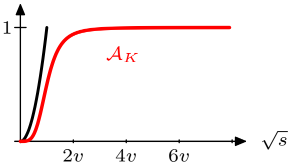
K-Matrix Unitarization and friends

K-Matrix unitarization

$$\mathcal{A}_K(s) = \frac{\mathcal{A}(s)}{1 - i\mathcal{A}(s)} = \mathcal{A}(s)\frac{1 + i\mathcal{A}(s)}{1 + \mathcal{A}(s)^2}$$



Unitarization by infinitely heavy and wide resonance



- Low-energy theorem (LET): $\frac{s}{v^2}$
- K-Matrix amplitude: $|\mathcal{A}(s)|^2 = \frac{s^2}{s^2+v^4} \overset{s\to\infty}{\longrightarrow} 1$
- Poles $\pm iv$: M_0, Γ large

Padé unitarization

separates higher chiral orders

$$\mathcal{A}_P(s) = \frac{\mathcal{A}^{(0)}(s)^2}{\mathcal{A}^{(0)}(s) - \mathcal{A}^{(1)}(s) - i\mathcal{A}^{(0)}(s)^2}$$

each partial wave dominated by single resonance

"Naive" Unitarization

Extreme case:

$$\mathcal{A}_N(s) = e^{i\mathcal{A}(s)} \sin\mathcal{A}(s)$$

Infinitely many resonances becoming denser for $s \to \infty$

BSM Unitarized Resonances: e.g. Scalar Singlet

Assumptions:

- LHC is able to detect a resonance in the EW sector
- Further resonances might exist, but out of reach or not detectable
- Describe 1st resonance by correct amplitude
- Use K-matrix unitarization to define a consistent model

Example: Scalar Singlet

- $\mathcal{L}_\sigma = -\frac{1}{2}\sigma\left(M_\sigma^2 + \partial^2\right)\sigma + \frac{g_\sigma v}{2}\sigma \mathrm{tr}\left[\mathbf{V}_\mu \mathbf{V}^\mu\right]$
- Feynman rules: $\sigma w^+ w^- : \; -\frac{2ig_\sigma}{v}(k_+ \cdot k_-) \qquad \sigma zz : \; -\frac{2ig_\sigma}{v}(k_1 \cdot k_2)$
- Amplitude (s-channel exchange): $\boxed{\mathcal{A}^\sigma(s,t,u) = \frac{g_\sigma^2}{v^2}\frac{s^2}{s-M^2}}$
- Isospin eigenamplitudes:

$$
\begin{aligned}
\mathcal{A}_0^\sigma(s,t,u) &= \frac{g_\sigma^2}{v^2}\left(3\frac{s^2}{s-M^2} + \frac{t^2}{t-M^2} + \frac{u^2}{u-M^2}\right) \\
\mathcal{A}_1^\sigma(s,t,u) &= \frac{g_\sigma^2}{v^2}\left(\frac{t^2}{t-M^2} - \frac{u^2}{u-M^2}\right) \\
\mathcal{A}_2^\sigma(s,t,u) &= \frac{g_\sigma^2}{v^2}\left(\frac{t^2}{t-M^2} + \frac{u^2}{u-M^2}\right)
\end{aligned}
$$

Unitarizing the scalar singlet

Alboteanu/Kilian/JR, 2008

$$\mathcal{A}_{00}^{\sigma}(s) = 3\frac{g_\sigma^2}{v^2}\frac{s^2}{s-M^2} + 2\frac{g_\sigma^2}{v^2}\mathcal{S}_0(s) \qquad \mathcal{A}_{02}^{\sigma}(s) = 2\frac{g_\sigma^2}{v^2}\mathcal{S}_2(s) = \mathcal{A}_{22}^{\sigma}(s)$$

$$\mathcal{A}_{11}^{\sigma}(s) = 2\frac{g_\sigma^2}{v^2}\mathcal{S}_1(s) \qquad \mathcal{A}_{13}^{\sigma}(s) = 2\frac{g_\sigma^2}{v^2}\mathcal{S}_3(s)$$

$$\mathcal{A}_{20}^{\sigma}(s) = 2\frac{g_\sigma^2}{v^2}\mathcal{S}_0(s)$$

- S-wave coefficients no longer polynomial, e.g.:

$$\mathcal{S}_0(s) = M^2 - \frac{s}{2} + \frac{M^4}{s}\log\frac{s}{s+M^2}$$

- s-channel pole must be explicitly subtracted:

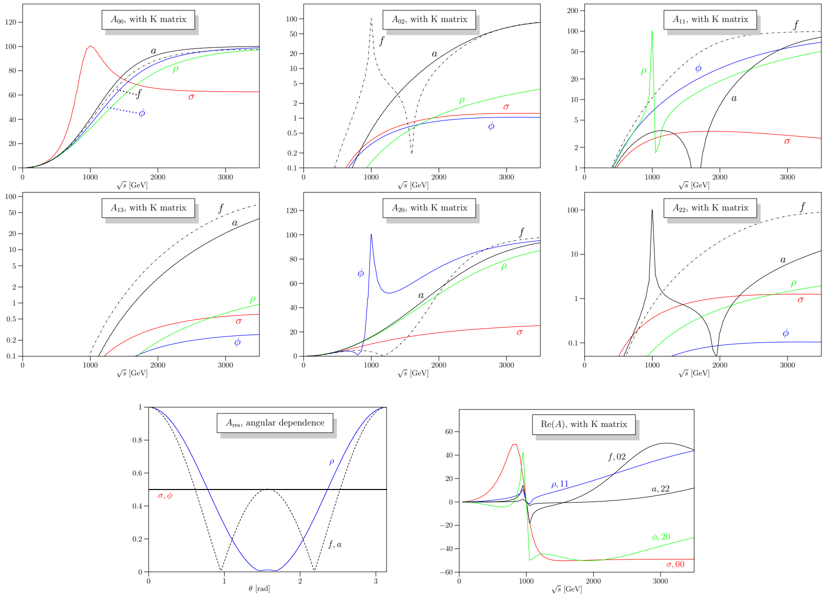
$$A_{IJ}(s) = A_{IJ}^{(0)}(s) + F_{IJ}(s) + \frac{G_{IJ}(s)}{s-M^2},$$

  - $F_{IJ}(s)$ is finite
  - $G_{IJ}(s) \propto s$ (vector), $\propto s^2$ (scalar, tensor)

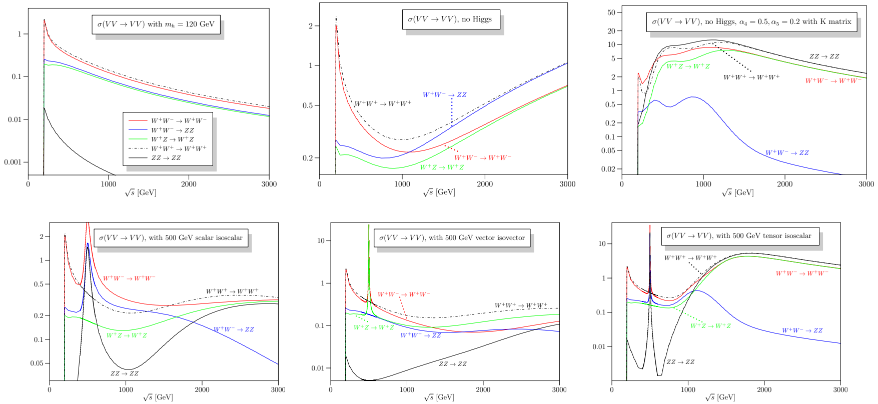
$$\hat{A}_{IJ}(s) = \frac{A_{IJ}(s)}{1-\frac{i}{32\pi}A_{IJ}(s)} = A_{IJ}^{(0)}(s) + 32\pi i \Delta A_{IJ}(s),$$

$$\boxed{\Delta A_{IJ}(s) = 32\pi i\left(1+\frac{i}{32\pi}A_{IJ}^{(0)}(s)+\frac{s-M^2}{\frac{i}{32\pi}G_{IJ}(s)-(s-M^2)\left[1-\frac{i}{32\pi}\left(A_{IJ}^{(0)}(s)+F_{IJ}(s)\right)\right]}\right)}$$

Eigenamplitudes



“Partonic” cross sections

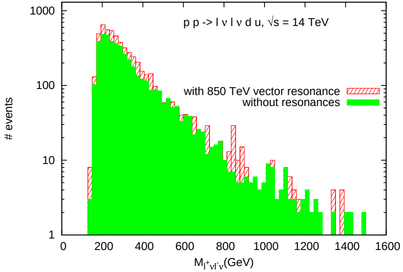


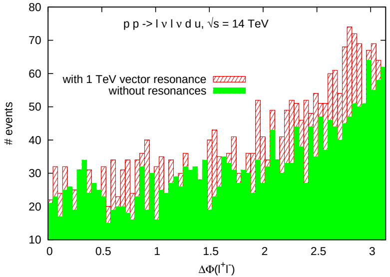
- $\sigma(\mathcal{VV} \to \mathcal{VV})$ in nb $\qquad M_R = 500$ GeV
- all amplitudes K-matrix unitarized
- Cut of 15° around the beam axis

LHC Example: Vector Isovector

Alboteanu/Kilian/JR, 2008

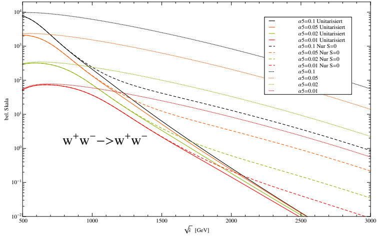
- Example: 850 GeV vector resonance, coupling $g_\rho = 1$
- (Theory) Cuts:
  - $p_\perp(\ell\nu) > 30$ GeV
  - $|\delta R(\ell\nu)| < 1.5$
  - $\theta(u/d) > 0.5°$
- Integrated luminosity: 225 fb^{-1}
- Discriminator: angular correlations $\Delta\phi(\ell\ell)$
- Ongoing ATLAS study
  - More kinematic observables
  - Comparison and validation phase
  - first reproduce SM
  - then anom. couplings/BSM resonances

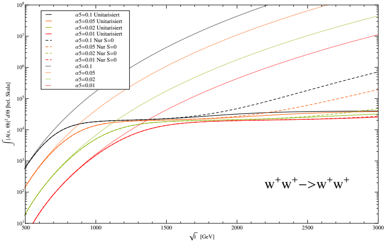




Including Higgs Operators

- Higgs has been discovered (sic!)
- Include more operators, e.g. $(D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)$, $(\partial(\Phi^\dagger\phi))^2$: usually called $\mathcal{O}_B$, $\mathcal{O}_W$, $\mathcal{O}_{WW}$, $\mathcal{O}_{WWW}$ etc.
- both anom. V^3 + V^4 and HVV etc. couplings !
- Implemented for an ATLAS study in WHIZARD





- Ongoing theoretical study

Kilian/JRR/Sekulla, 2013

- Very preliminary results

Summary/Conclusions

- New Physics in EW effective Lagrangian (SM + higher-dim. op.)
- Triple/Quartic gauge couplings measured either
  - via diboson production
  - via triple boson production
  - via vector boson scattering
- Unified description for ILC vs. LHC/CLIC difficult
- EFT approach for low-energy regime, unitarized by form factors in resonance scheme at high energies
- interpreted as resonances coupled to EW bosons
- “Correct” description for first resonance (also [very] broad)
- Beyond that: assure unitarity (K matrix)
- Sensitivity rises with number of intermediate states:
  - LHC sensitivity limited in pure EW sector: $0.6 - 2$ TeV
  - ILC : $1.5 - 6$ TeV
- All effective ops. in WHIZARD: simulations for LHC, ILC, CLIC, μ coll.
- More and intensive studies needed (FOR ALL COLLIDERS!)

Unitarity in the EW sector: SM

- Project out isospin eigenamplitudes

Lee,Quigg,Thacker, 1973

$$\mathcal{A}_\ell(s) = \frac{1}{32\pi}\int_{-s}^{0}\frac{dt}{s}\mathcal{A}(s,t,u)P_\ell(1+2t/s) \qquad \cos\theta = 1+2t/s$$

Remember Legendre polynomials: $P_0(s) = 1$ $\quad P_1(s) = \cos\theta$ $\quad P_2(s) = (3\cos^2\theta - 1)/2$

- SM longitudinal isospin eigenamplitudes ($\mathcal{A}_{I,\text{spin}=J}$):

$$\mathcal{A}_{I=0} = 2\frac{s}{v^2}P_0(s) \qquad \mathcal{A}_{I=1} = \frac{t-u}{v^2} = \frac{s}{v^2}P_1(s) \qquad \mathcal{A}_{I=2} = -\frac{s}{v^2}P_0(s)$$

$$\boxed{\mathcal{A}_{0,0} = \frac{s}{16\pi v^2}} \qquad \boxed{\mathcal{A}_{1,1} = \frac{s}{96\pi v^2}} \qquad \boxed{\mathcal{A}_{2,0} = -\frac{s}{32\pi v^2}}$$

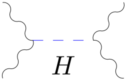
exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

$$I = 0: \qquad E \sim \sqrt{8\pi}v = 1.2\,\text{TeV}$$

$$I = 1: \qquad E \sim \sqrt{48\pi}v = 3.5\,\text{TeV}$$

$$I = 2: \qquad E \sim \sqrt{16\pi}v = 1.7\,\text{TeV}$$

Higgs exchange:



$$\mathcal{A}(s,t,u) = -\frac{M_H^2}{v^2}\frac{s}{s-M_H^2}$$

Unitarity: $M_H \lesssim \sqrt{8\pi}v \sim 1.2\,\text{TeV}$

Isospin decomposition

- Lowest order chiral Lagrangian (incl. anomalous couplings)

$$\mathcal{L} = -\frac{v^2}{4}\mathrm{tr}\left[\mathbf{V}_\mu \mathbf{V}^\mu\right] + \alpha_4 \mathrm{tr}\left[\mathbf{V}_\mu \mathbf{V}_\nu\right] \mathrm{tr}\left[\mathbf{V}^\mu \mathbf{V}^\nu\right] + \alpha_5 \left(\mathrm{tr}\left[\mathbf{V}_\mu \mathbf{V}^\mu\right]\right)^2$$

- Leads to the following amplitudes: $s = (p_1 + p2)^2 \quad t = (p1 - p3)^2 \quad u = (p1 - p4)^2$

$$\boxed{\mathcal{A}(s,t,u) =:} \qquad \begin{aligned} \mathcal{A}(w^+w^- \to zz) &= \frac{s}{v^2} + 8\alpha_5 \frac{s^2}{v^4} + 4\alpha_4 \frac{t^2+u^2}{v^4} \\ \mathcal{A}(w^+z \to w^+z) &= \frac{t}{v^2} + 8\alpha_5 \frac{t^2}{v^4} + 4\alpha_4 \frac{s^2+u^2}{v^4} \\ \mathcal{A}(w^+w^- \to w^+w^-) &= -\frac{u}{v^2} + (4\alpha_4 + 2\alpha_5)\frac{s^2+t^2}{v^4} + 8\alpha_4 \frac{u^2}{v^4} \\ \mathcal{A}(w^+w^+ \to w^+w^+) &= -\frac{s}{v^2} + 8\alpha_4 \frac{s^2}{v^4} + 4(\alpha_4 + 2\alpha_5)\frac{t^2+u^2}{v^4} \\ \mathcal{A}(zz \to zz) &= 8(\alpha_4+\alpha_5)\frac{s^2+t^2+u^2}{v^4} \end{aligned}$$

- (Clebsch-Gordan) Decomposition into isospin eigenamplitudes

$$\begin{aligned} \mathcal{A}(I=0) &= 3\mathcal{A}(s,t,u) + \mathcal{A}(t,s,u) + \mathcal{A}(u,s,t) \\ \mathcal{A}(I=1) &= \mathcal{A}(t,s,u) - \mathcal{A}(u,s,t) \\ \mathcal{A}(I=2) &= \mathcal{A}(t,s,u) + \mathcal{A}(u,s,t) \end{aligned}$$

The Effective W approximation

- $M_{\mathcal{V}}$, $\hat{t}_i$ small corrections, $\mathcal{V}$ nearly onshell:

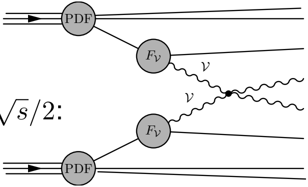
$$\boxed{\sigma(q_1 q_2 \to q_1' q_2' \mathcal{V}_1' \mathcal{V}_2') \approx \sum_{\lambda_1,\lambda_2} \int dx_1\, dx_2\, F^{\lambda_1}_{q_1 \to q_1' \mathcal{V}_1}(x_1)\, F^{\lambda_2}_{q_2 \to q_2' \mathcal{V}_2}(x_2)\, \sigma^{\lambda_1 \lambda_2}_{\mathcal{V}_1 \mathcal{V}_2 \to \mathcal{V}_1' \mathcal{V}_2'}(x_1 x_2 s)}$$

- In addition to Weizsäcker-Williams: longitudinal polarisation

$$F^{+}_{q \to q' \mathcal{V}}(x) = \frac{(V-A)^2 + (V+A)^2 (1-x)^2}{16\pi^2 \quad x} \left[\ln \left(\frac{p^2_{\perp,\mathrm{max}} + (1-x) m^2_{\mathcal{V}}}{(1-x) m^2_{\mathcal{V}}} \right) - \frac{p^2_{\perp,\mathrm{max}}}{p^2_{\perp,\mathrm{max}} + (1-x) m^2_{\mathcal{V}}} \right]$$

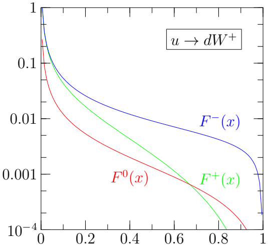
$$F^{-}_{q \to q' \mathcal{V}}(x) = \frac{(V+A)^2 + (V-A)^2 (1-x)^2}{16\pi^2 \quad x} \left[\ln \left(\frac{p^2_{\perp,\mathrm{max}} + (1-x) m^2_{\mathcal{V}}}{(1-x) m^2_{\mathcal{V}}} \right) - \frac{p^2_{\perp,\mathrm{max}}}{p^2_{\perp,\mathrm{max}} + (1-x) m^2_{\mathcal{V}}} \right]$$

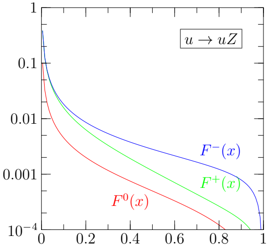
$$F^{0}_{q \to q' \mathcal{V}}(x) = \frac{V^2 + A^2}{8\pi^2} \, \frac{2(1-x)}{x} \, \frac{p^2_{\perp,\mathrm{max}}}{p^2_{\perp,\mathrm{max}} + (1-x) m^2_{\mathcal{V}}}$$



- Dominant contribution from small $\mathcal{V}$ virtualities
- Transverse momentum cutoff $p_{\perp,\mathrm{max}} \leq (1-x)\sqrt{s}/2$:
  - longitudinal pol.: finite for $p_{\perp,\mathrm{max}} \to \infty$
  - Transversal pol.: logarithmic singularity

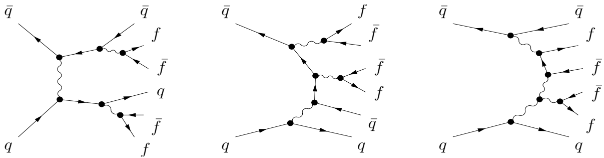
- EWA structure functions: W (left) and Z (right)





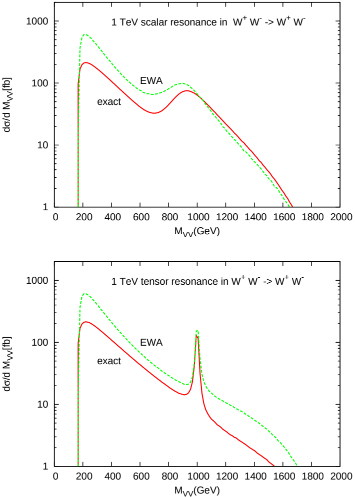
  - Emission from u, $\sqrt{s} = 2$ TeV
  - preferred at high energy: transversal emission

- Problem: Irreducible background to weak-boson scattering



  - Double ISR/FSR
  - t-channel like diagrams

- Coulomb-singularity (peak): cut on $p_{T,V} \gtrsim 30$ GeV



- Effective W approx. vs. WHIZARD full matrix elements
- Shapes/normalization of distributions heavily affected
- **EWA: Sideband subtraction completely screwed up!**