Vector Boson Scattering at e^+e^- machines & News from `WHIZARD`

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HELMHOLTZ GEMEINSCHAFT

DESY

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Alboteanu/Kilian/JRR, **JHEP 0811** (2008) 010;
Beyer/Kilian/Krstonošić/Mönig/JRR/Schmitt/Schröder, **EPJC 48** (2006), 353;
JRR/Kilian/Sekulla, 1307.8170; Kilian/JRR/Ohl/Sekulla, 1408.6207 + in prep.
Kilian/Ohl/JRR, EPJ **C71** (2011) 1742

CLIC 2015 Workshop, CERN, Jan. 29th, 2015

Motivation

- After discovery of light Higgs boson: what is left to do?
- Mechanism behind generating Higgs vev missing ($\Rightarrow$ Higgs physics)
- Dynamics of EW interactions: $\Longrightarrow$ Multiboson Interactions (MBI)
- Anomalous Triple Gauge Couplings: dibosons
- Anomalous Quartic Gauge Couplings: tribosons, VV scattering
- Existing studies assume: $\mathcal{P}(e^-) = 80 - 90\%$, $\mathcal{P}(e^+) = 30 - 60\%$
  - Longitudinal polarization of beams: $(V - A)$ couplings of W/Z
  - e_L and e_R different multiplets $\Rightarrow$ access completely different couplings

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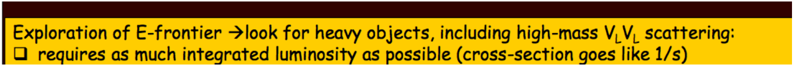
- F. Gianotti, CLIC-Workshop 2014, CERN



Exploration of E-frontier → look for heavy objects, including high-mass $V_L V_L$ scattering:

☐ requires as much integrated luminosity as possible (cross-section goes like 1/s)

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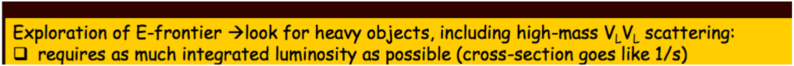


Exploration of E-frontier → look for heavy objects, including high-mass V_LV_L scattering:

☐ requires as much integrated luminosity as possible (cross-section goes like 1/s)

- Not really new: Elementary Particle Physics And Future Facilities. Proceedings, 1982 DPF Summer Study, Snowmass, USA, June 28 - July 16, 1982

Extensions of the SM

- Lagrangian of the EW SM (no fermions/QCD here):

$$\mathcal{L}_{EW} = -\frac{1}{2}\mathrm{tr}\left[W_{\mu\nu}W^{\mu\nu}\right] - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) + \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

with building blocks:

$$\begin{aligned} D_\mu &= \partial_\mu + \frac{i}{2}g\tau^I W^I_\mu + \frac{i}{2}g' B_\mu \\ W_{\mu\nu} &= \frac{i}{2}g\tau^I(\partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g\epsilon_{IJK}W^J_\mu W^K_\nu) \\ B_{\mu\nu} &= \frac{i}{2}g'(\partial_\mu B_\nu - \partial_\nu B_\mu) \end{aligned}$$

- Any EFT has higher-dimensional operators: Weinberg, 1979

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \left[\frac{a_i}{\Lambda}\mathcal{O}_i^{(5)} + \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \frac{e_i}{\Lambda^4}\mathcal{O}_i^{(8)} \cdots\right]$$

- without more fundamental theory ⇒ no clue on the scale (neither on the coefficients)

Classification of Operators (I): Dim 6

(always v^2 subtracted)

- Dimension-6 operators (CP-conserving)

$$\begin{aligned} \mathcal{O}_{WWW} &= \text{Tr}[W_{\mu\nu}W^{\nu\rho}W_\rho^{\ \mu}] \\ \mathcal{O}_{W} &= (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) \\ \mathcal{O}_{B} &= (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) \end{aligned}$$

$$\begin{aligned} \mathcal{O}_{\partial\Phi} &= \partial_\mu\left(\Phi^\dagger\Phi\right)\partial^\mu\left(\Phi^\dagger\Phi\right) \\ \mathcal{O}_{\Phi W} &= \left(\Phi^\dagger\Phi\right)\text{Tr}[W^{\mu\nu}W_{\mu\nu}] \\ \mathcal{O}_{\Phi B} &= \left(\Phi^\dagger\Phi\right)B^{\mu\nu}B_{\mu\nu} \end{aligned}$$

- Dimension-6 operators (CP-violating)

$$\begin{aligned} \mathcal{O}_{\widetilde{W}W} &= \Phi^\dagger\widetilde{W}_{\mu\nu}W^{\mu\nu}\Phi \\ \mathcal{O}_{\widetilde{B}B} &= \Phi^\dagger\widetilde{B}_{\mu\nu}B^{\mu\nu}\Phi \end{aligned}$$

$$\begin{aligned} \mathcal{O}_{\widetilde{W}WW} &= \text{Tr}[\widetilde{W}_{\mu\nu}W^{\nu\rho}W_\rho^{\ \mu}] \\ \mathcal{O}_{\widetilde{W}} &= (D_\mu\Phi)^\dagger\widetilde{W}^{\mu\nu}(D_\nu\Phi) \end{aligned}$$

	ZWW	AWW	HWW	HZZ	HZA	HAA	WWWW	ZZWW	ZAWW	AAWW
$\mathcal{O}_{WWW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{W}$	✓	✓	✓	✓	✓		✓	✓	✓	
$\mathcal{O}_{B}$	✓	✓		✓	✓					
$\mathcal{O}_{\Phi d}$			✓	✓						
$\mathcal{O}_{\Phi W}$			✓	✓	✓	✓				
$\mathcal{O}_{\Phi B}$				✓	✓	✓				
$\mathcal{O}_{\tilde{W}WW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{\tilde{W}}$	✓	✓	✓	✓	✓					
$\mathcal{O}_{\tilde{W}W}$			✓	✓	✓	✓				
$\mathcal{O}_{\tilde{B}B}$				✓	✓	✓				

Classification of Operators (II): Dim 8 (always v^2 subtracted)

- Dimension-8 operators (only $D_\mu\Phi$)

$$\begin{aligned}
\mathcal{O}_{S,0} &= \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right] \; , \\
\mathcal{O}_{S,1} &= \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right] \; ,
\end{aligned}$$

- Dimension-8 operators (only field strength/mixed)

$$\begin{aligned}
\mathcal{O}_{T,0} &= \text{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot \text{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right] \; , \\
\mathcal{O}_{T,1} &= \text{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \cdot \text{Tr}\left[W_{\mu\beta}W^{\alpha\nu}\right] \; , \\
\mathcal{O}_{T,2} &= \text{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \cdot \text{Tr}\left[W_{\beta\nu}W^{\nu\alpha}\right] \; , \\
\mathcal{O}_{T,5} &= \text{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot B_{\alpha\beta}B^{\alpha\beta} \; , \\
\mathcal{O}_{T,6} &= \text{Tr}\left[W_{\alpha\nu}W^{\mu\beta}\right] \cdot B_{\mu\beta}B^{\alpha\nu} \; , \\
\mathcal{O}_{T,7} &= \text{Tr}\left[W_{\alpha\mu}W^{\mu\beta}\right] \cdot B_{\beta\nu}B^{\nu\alpha} \; , \\
\mathcal{O}_{T,8} &= B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta} \\
\mathcal{O}_{T,9} &= B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha} \; .
\end{aligned}$$

$$\begin{aligned}
\mathcal{O}_{M,0} &= \text{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \\
\mathcal{O}_{M,1} &= \text{Tr}\left[W_{\mu\nu}W^{\nu\beta}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \\
\mathcal{O}_{M,2} &= \left[B_{\mu\nu}B^{\mu\nu}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right] \; , \\
\mathcal{O}_{M,3} &= \left[B_{\mu\nu}B^{\nu\beta}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right] \; , \\
\mathcal{O}_{M,4} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\mu\Phi\right] \cdot B^{\beta\nu} \; , \\
\mathcal{O}_{M,5} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\nu\Phi\right] \cdot B^{\beta\mu} \; , \\
\mathcal{O}_{M,6} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\nu}D^\mu\Phi\right] \; , \\
\mathcal{O}_{M,7} &= \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right] \; ,
\end{aligned}$$

Classification of Operators (III)

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0/1}$	✓	✓	✓						
$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2/3/4/5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0/1/2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

- Dim. 8 operators generate aQGCs, but not aTGCs
- generate neutral quartics
- Redundancy of the operators:
  - Equations of motion: $D_\mu W^{\mu\nu} = \Phi^\dagger (D^\nu \Phi) - (D^\nu \Phi)^\dagger \Phi + \ldots$
  - Gauge symmetry structure: $[D_\mu, D_\nu]\, \Phi \propto W_{\mu\nu} \Phi$
  - Integration by parts (up to total derivatives)
  - Leads to relations like:

$$\begin{aligned} \mathcal{O}_B &= \mathcal{O}_{\tilde{W}} + \frac{1}{2}\mathcal{O}_{WW} - \frac{1}{2}\mathcal{O}_{BB} \\ \mathcal{O}_{BW} &= -2\,\mathcal{O}_W - \mathcal{O}_{WW} \\ \mathcal{O}_{\partial W} &= -4\,\mathcal{O}_{WWW} + \text{gauge-fermion operators} \end{aligned}$$

EFT coefficients *vs.* anomalous couplings

- Switch operator bases (vertex-dep.): Snowmass EW White Paper, 1310.6708

WWWW-Vertex:

$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{8}$$

$$\alpha_4 + 2\cdot\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{8}$$

WWZZ-Vertex:

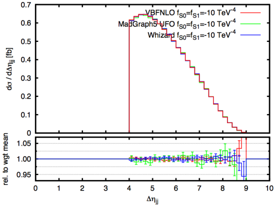
$$\alpha_4 = \frac{f_{S,0}}{\Lambda^4}\frac{v^4}{16}$$

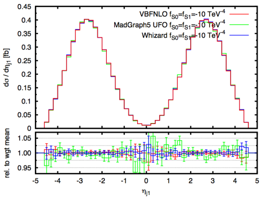
$$\alpha_5 = \frac{f_{S,1}}{\Lambda^4}\frac{v^4}{16}$$

ZZZZ-Vertex:

$$\alpha_4 + \alpha_5 = \left(\frac{f_{S,0}}{\Lambda^4} + \frac{f_{S,1}}{\Lambda^4}\right)\frac{v^4}{16}$$

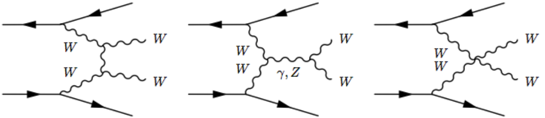
- Full agreement among generators: VBF@NLO, WHIZARD, Madgraph



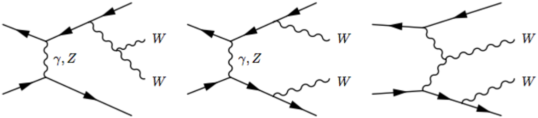


Vector Boson Scattering at e^+e^- machines

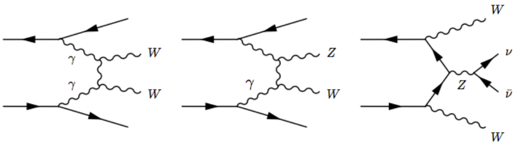
Signal



Irreducible bkgd.



(Partially) reducible bkgd.



Vector Boson Scattering

Beyer et al.,hep-ph/0604048

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

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

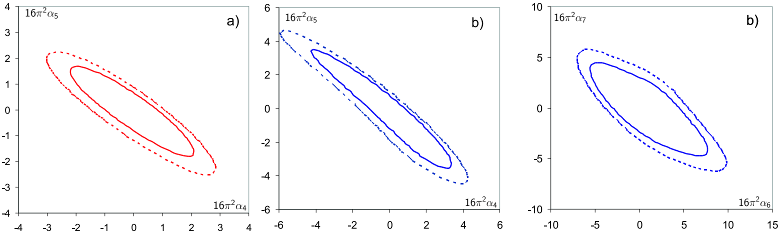
Process	Subprocess	σ [fb]
$e^+e^- \to \nu_e\bar\nu_e q\bar q q\bar q$	$WW \to WW$	23.19
$e^+e^- \to \nu_e\bar\nu_e q\bar q q\bar q$	$WW \to ZZ$	7.624
$e^+e^- \to \nu\bar\nu q\bar q q\bar q$	$V \to VVV$	9.344
$e^+e^- \to \nu e q\bar q q\bar q$	$WZ \to WZ$	132.3
$e^+e^- \to e^+e^- q\bar q q\bar q$	$ZZ \to ZZ$	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

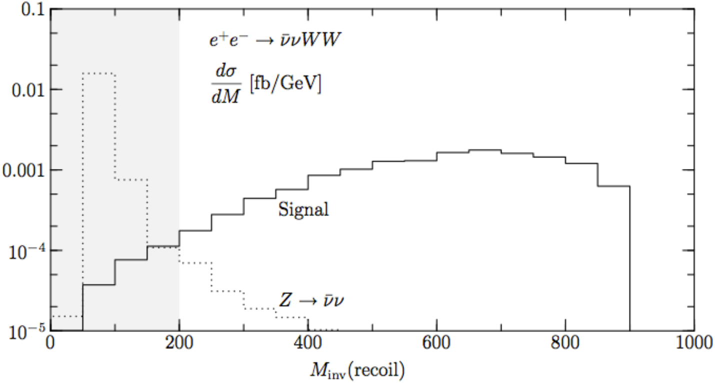
coupling	$\sigma-$	$\sigma+$
$16\pi^2\alpha_4$	-2.72	2.37
$16\pi^2\alpha_5$	-2.46	2.35
$16\pi^2\alpha_6$	-3.93	5.53
$16\pi^2\alpha_7$	-3.22	3.31
$16\pi^2\alpha_{10}$	-5.55	4.55



Vector Boson Scattering: Observables

Study of WW scattering @ 1.6 TeV

Boos/Kilian/He/Mühlleitner/Pukhov/Zerwas, hep-ph/9708310



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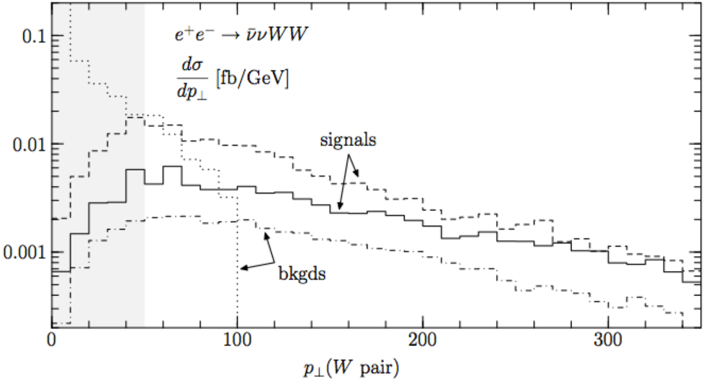

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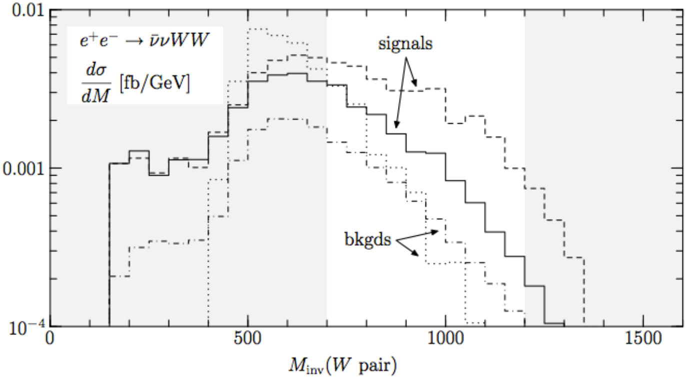


Simplified Models for VBS (and VVV): Resonances

- Resonances in all accessible spin/isospin channels
- Couplings to the Higgs and gauge sectors are unrelated and arbitrary
- Still include anomalous couplings
- Unitarization (later)

New physics in electroweak sector:

- Narrow resonances ⇒ particles (weakly interacting model)
- Wide resonances ⇒ continuum (strongly interacting model)

$SU(2)_c$ 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 ?)	—	$t^{\pm\pm}, t^\pm, t^0$

- $I = 0$: resonant in W^+W^- and ZZ scattering
- $I = 1$: resonant in W^+Z and W^-Z scattering
- $I = 2$: resonant in W^+W^+ and W^-W^- scattering

Example: a Scalar Resonance [Not counting ϕ with $M = 126$ GeV.]

- Mass M_σ.
- Coupling to the Higgs sector (Higgs and longitudinal W/Z):

$$g_L^\sigma (D_\mu \Phi)^\dagger (D^\mu \Phi)\,\sigma$$

- Coupling to the gauge sector (transversal W/Z):

$$g_T^\sigma \mathrm{tr}\left[\mathbf{W}^{\mu\nu}\mathbf{W}_{\mu\nu}\right]\,\sigma$$

Possible Origin: 2HDM isosinglet (renormalizable)

$$g_L^\sigma = O\left(\frac{1}{M_\sigma}\right) \quad \text{[tree]}, \qquad g_T^\sigma = O\left(\frac{1}{4\pi M_\sigma}\right) \quad \text{[loop]}$$

Possible Origin: new strong interactions

$$g_L^\sigma = O\left(\frac{1}{M_\sigma}\right) \quad \text{[tree]}, \qquad g_T^\sigma = O\left(\frac{1}{M_\sigma}\right) \quad \text{[tree]}$$

Interpretation as limits on resonances

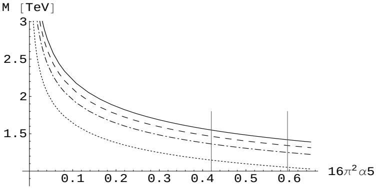
Beyer et al.,hep-ph/0604048

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

1 TeV e^+e^-

$SU(2)$ conserving scalar singlet

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

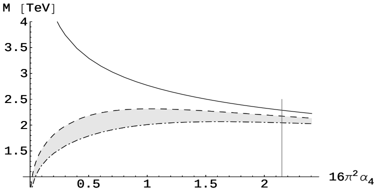


$f = 1.0$ (full), 0.8 (dash), 0.6 (dot-dash), 0.3 (dot)

$SU(2)$ broken vector triplet

needs input from TGC covariance matrix

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



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

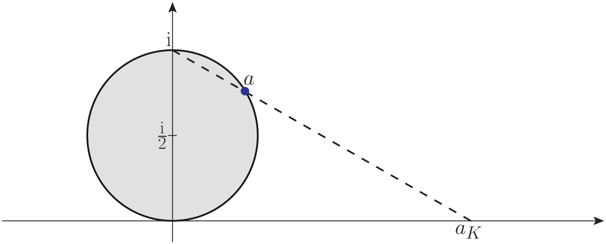
Final result:

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

Unitarizing S matrices

- Cayley transform of S matrix: $S = \frac{\mathbf{1}+\mathrm{i}K/2}{\mathbf{1}-\mathrm{i}K/2}$ Heitler, 1941; Schwinger, 1948
- "K" matrix: translates to transition operator: $T = \frac{K}{\mathbf{1}-\mathrm{i}K/2}$
- Works beyond perturbation theory, but allows perturbative expansion
- Diagonalize S matrix (partial waves):
  $\mathcal{M}(s,t,u) = 32\pi \sum_\ell (2\ell+1)\mathcal{A}_\ell(s) P_\ell(\cos\theta)$ ("Power spectrum")
- Complex eigenvalues: $t = 2a$ $k = 2a_K \Rightarrow a_K = \frac{a}{1+ia}$
- Corresponds to stereographic projection:



- Coulomb singularities Bloch/Nordsieck, 1937; Yennie/Frautschi/Suura, 1961

Unitarization Primer

Kilian/JRR/Ohl/Sekulla, 1408.6207

- Unitarization prescription not unique
- Padé (reordering pert. series) introduces artificial poles
- Form factors parameterize close-by new physics (additional parameters)

$$\frac{1}{\left(1 + \frac{s}{\Lambda_{FF}^2}\right)^n}$$

unphysical form factor scale Λ_{FF} and multipole order n

- minimal version (K or T matrix) $\Rightarrow$ just saturation no new parameters, does not rely on pert. expansion, stable against small perturbations
- Additional known features (resonances) should be implemented before unitarization

Unitarity Bound for α_4 AQGC

Bounds for α_4

$$\ell = 0 : \sqrt{s} \leq \left(\frac{6\pi}{\alpha_4}\right)^{\frac{1}{4}} v \approx \frac{0.5 \text{ TeV}}{\sqrt[4]{\alpha_4}}$$

$$\ell = 2 : \sqrt{s} \leq \left(\frac{60\pi}{\alpha_4}\right)^{\frac{1}{4}} v \approx \frac{0.9 \text{ TeV}}{\sqrt[4]{\alpha_4}}$$

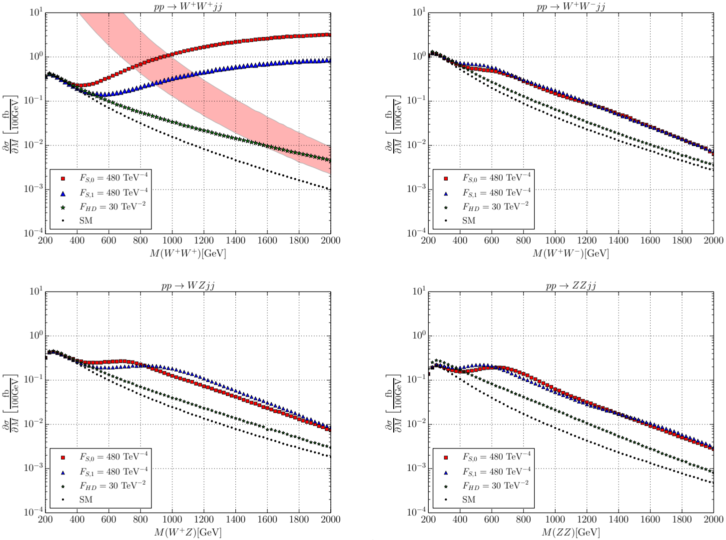
α_4 AQGC contribution to $WW \to ZZ$

$$\mathcal{A}(s,t,u) = 4\alpha_4 \frac{t^2 + u^2}{v^4}$$

- Bound depends on coupling α_4

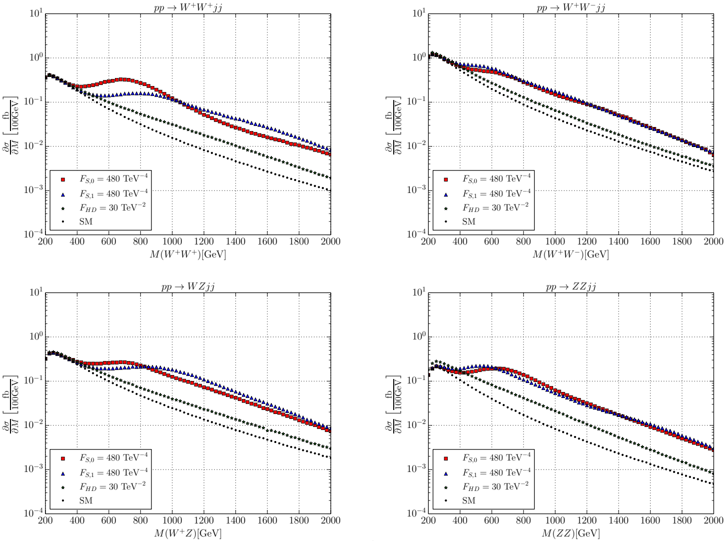
- Use strongest bound

Diboson invariant masses



General cuts: $M_{jj} > 500$ GeV; $\Delta\eta_{jj} > 2.4$; $p_T^j > 20$ GeV; $|\eta_j| < 4.5$

Diboson invariant masses



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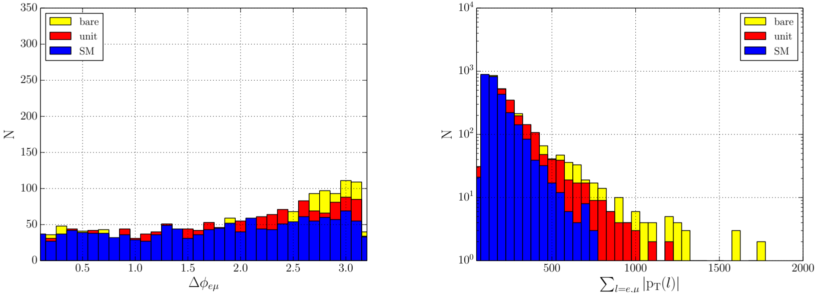
p_T and angular distributions

$pp \to e^+\mu^+\nu_e\nu_\mu jj$, $\sqrt{s} = 14$ TeV, $\mathcal{L} = 1000\,\text{fb}^{-1}$

Simulations with `WHIZARD` →

Not possible to use automated tool due to s-channel prescription

$F_{HD} = 30\,\text{TeV}^{-2}$



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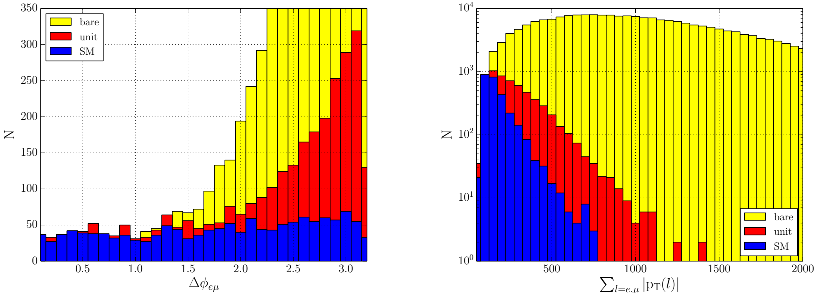
$F_{S,0} = 480\,\text{TeV}^{-4}$



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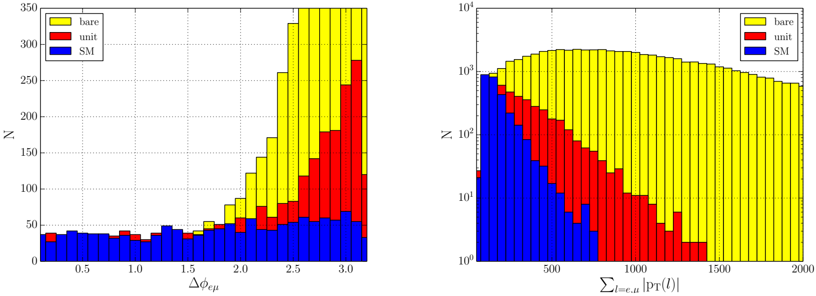

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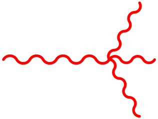
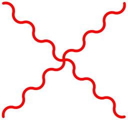
And Triple Vector Boson Production?

relate



to



??

Yes, the same Feynman graphs (in the SM), but. . . Tribosons:

- one external $W/Z/\gamma$ is always far off-shell
- Unitarization formalism not available
- different (anom.) couplings contribute (particularly for resonances)

$$\sigma(e^+e^- \to VVV) \underset{\sim}{\propto} \frac{1}{s}$$

Limits usefulness to subprocess energies in the lower range where cross section of fusion process still small

$$\sigma_{\text{VBS}}(e^+e^- \to \nu\bar{\nu}W^+W^-) \underset{\sim}{\propto} \log(s)$$

$$e^+e^- \to ZZZ$$

$$\to WWZ$$

$$ZH \quad \hookrightarrow WW \quad \hookrightarrow ZZ$$

Present in spectrum

$\to WW\gamma$ Complementary (and present at lower energies)

⇒ Important physics independent w.r.t. VBS. Don't just combine results!

Summary/Conclusions: e^+e^- VBS

- Access to (deviations from) EW sector via:
  - via diboson/triboson production and vector boson scattering
- Task: Unify LHC and LEP/ILC/CLIC descriptions (model-independent limit setting $(\alpha_4, \frac{f_{S,0}}{\Lambda_{NP}^4})$
- Simplified Models: minimally unitarized operators
- Unitarization scheme: no additional structure to the theory (model dependence minimized)
- Sensitivity rises with number of new intermediate states:
  - LHC14 sensitivity limited in pure EW sector: $\sim 1 - X$ TeV (???)
  - ILC1000 : $1.5 - 6$ TeV
  - (Tensor) Resonances very interesting Kilian/JRR/Sekulla, in preparation
- All simulations need to be updated (include light Higgs)
- Multi-TeV e^+e^- [+ pol. ?] probably best machine for VBS
- Crucial experimental tasks: hadronic W/Z separation at high energies, separation of longitudinal/transversal final W/Z

Advertisement: MBI 2015 @ DESY

2.-4. Sept. 2015, DESY, Hamburg

Switching gears: WHIZARD

WHIZARD in a Nutshell

WHIZARD universal event generator for processes at colliders: e^+e^-, pp, $p\bar{p}$, $\gamma\gamma$, ep etc.

1. O'Mega: Optimized automatic matrix elements for arbitrary elementary processes, supports SM and many BSM extensions
2. Phase-space parameterization module (very efficient PS)
3. VAMP: Generic adaptive Monte Carlo integration and (unweighted) event generation
4. CIRCE1/2: Lepton/[photon] collider beam spectra
5. Intrinsic support or external interfaces for: Feynman rules, beams cascade decays, shower, hadronization, analysis, event file formats, etc.
6. Free-format steering language SINDARIN

WHIZARD 2.2.3

release: Nov. 30, 2014

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WHIZARD 2.2.4 release: Febr. 06, 2015

The WHIZARD team: F. Bach, B. Chokoufé, W. Kilian, T. Ohl, JRR, M. Sekulla, F. Staub, C. Weiss, DESY summer students

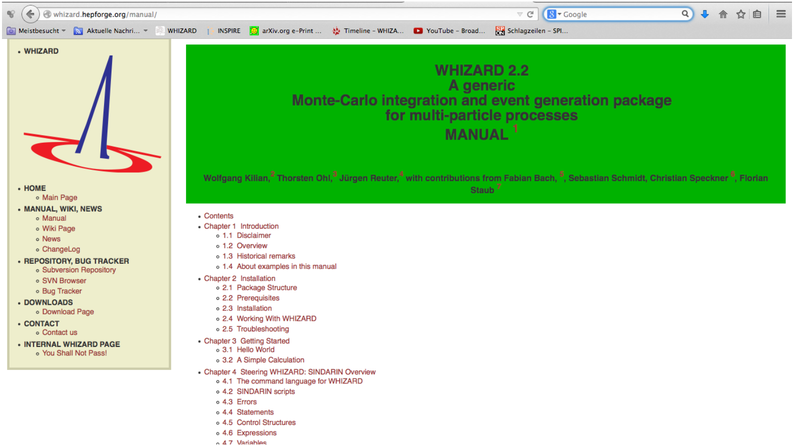
Web address: `http://projects.hepforge.org/whizard`
Standard Reference: Kilian/Ohl/JRR, EPJ **C71** (2011) 1742, arXiv:0708.4233

WHIZARD 2: Status 2010-15 – Technical Features

- `Fortran2003/2008 (gfortran 4.7.4 or newer) and OCaml (for MEs)`
- WHIZARD core: separate interface from implementation Complete object orientation
  - Replaceable modules with well-defined interface: matrix-elements, beam structure, phase space, integration, decays, shower, . . .
  - Much easier to outsource small(er) projects
  - Much better self checks, regression testing and maintainability
- OpenMP parallelization
- Operation modes: dynamic linking, static linking, library mode, shell mode
- Standard conformance: uses `autotools: automake/autoconf/libtool`
  `Installation: ./configure, make, make check, make install`
- Large self test suite: unit tests, feature tests, run tests
- Version control (`svn) at HepForge`: use of ticket system and bug tracker
- Continuous integration system (`jenkins)` linked with svn repository

WHIZARD Manual

with distribution and online: `http://whizard.hepforge.org/manual`



- **WHIZARD**
- **HOME**
  - Main Page
- **MANUAL, WIKI, NEWS**
  - Manual
  - Wiki Page
  - News
  - ChangeLog
- **REPOSITORY, BUG TRACKER**
  - Subversion Repository
  - SVN Browser
  - Bug Tracker
- **DOWNLOADS**
  - Download Page
- **CONTACT**
  - Contact us
- **INTERNAL WHIZARD PAGE**
  - You Shall Not Pass!

WHIZARD 2.2
A generic
Monte-Carlo integration and event generation package
for multi-particle processes
MANUAL [1]

Wolfgang Kilian,[2] Thorsten Ohl,[3] Jürgen Reuter,[4] with contributions from Fabian Bach, [5], Sebastian Schmidt, Christian Speckner [6], Florian Staub [7]

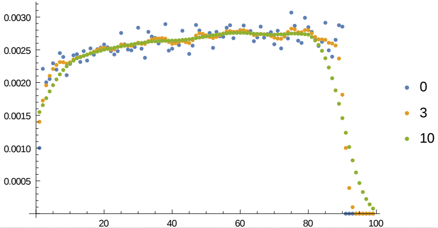
- Contents
- Chapter 1 Introduction
  - 1.1 Disclaimer
  - 1.2 Overview
  - 1.3 Historical remarks
  - 1.4 About examples in this manual
- Chapter 2 Installation
  - 2.1 Package Structure
  - 2.2 Prerequisites
  - 2.3 Installation
  - 2.4 Working With WHIZARD
  - 2.5 Troubleshooting
- Chapter 3 Getting Started
  - 3.1 Hello World
  - 3.2 A Simple Calculation
- Chapter 4 Steering WHIZARD: SINDARIN Overview
  - 4.1 The command language for WHIZARD
  - 4.2 SINDARIN scripts
  - 4.3 Errors
  - 4.4 Statements
  - 4.5 Control Structures
  - 4.6 Expressions
  - 4.7 Variables

Correlated lepton beam spectra with `Circe2`

- `Guinea-Pig++` event files too short for high lumi simulations
- Fixed width histogramming struggles with steep distributions
- `Circe1` too restrictive, assumes
  - *factorized* beam spectra: $D_{p_1 p_2}(x_1, x_2) = D_{p_1}(x_1) D_{p_2}(x_2)$
  - power laws in continuum: $D(x) = d \cdot \delta(1 - x) + c \cdot x^{\alpha}(1 - x)^{\beta}$
- `Circe2` algorithm:
  - Adapt 2D factorized variable width histogram (à la `VEGAS`) to steep part of distribution
  - smooth the correlated fluctuations with a moderate gaussian filter to suppress artifacts from limited `Guinea-Pig++` statistics
  - smooth separately continuum/boundary bins (avoid artificial beam energy spread)

Smoothing $x_{e^+} = 1$ boundary bin with Gaussian filters of width 3 and 10 bins, resp. 5 bins reasonable compromise for histograms with 100 bins.

[bins are *not equidistant*, shrink with power law towards the $x_{e^-} = 1$ boundary on RHS!]



Workflow Guinea-Pig++/Circe2/WHIZARD

1. Run `Guinea-Pig++` with

```
do_lumi=7;num_lumi=100000000;num_lumi_eg=100000000;num_lumi_gg=100000000;
```

to produce `lumi.[eg][eg].out` with (E_1, E_2) pairs.

[Large event numbers, as `Guinea-Pig++` will produce only a small fraction!]

2. Run `circe2_tool.opt` with steering file

```
{ file="ilc500/beams.circe"                       # to be loaded by WHIZARD
  { design="ILC" roots=500 bins=100 scale=250 # E in [0,1]
    { pid/1=electron pid/2=positron pol=0      # unpolarized e-/e+
      events="ilc500/lumi.ee.out" columns=2    # <= Guinea-Pig
      lumi = 1564.763360                       # <= Guinea-Pig
      iterations = 10                          # adapting bins
      smooth = 5 [0,1) [0,1)                   # Gaussian filter 5 bins
      smooth = 5 [1] [0,1) smooth = 5 [0,1) [1] } } }
```

to produce correlated beam description

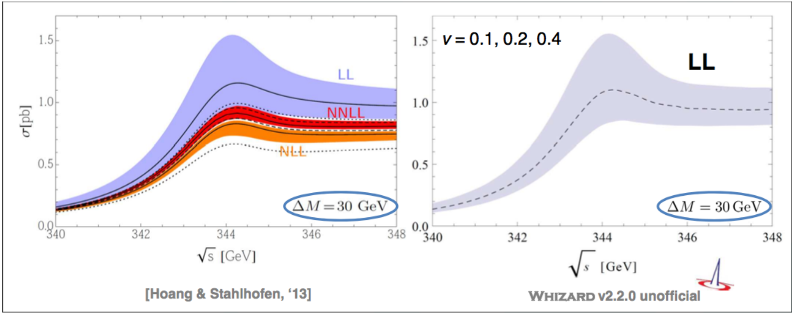
3. Run `WHIZARD` with `SINDARIN` input:

```
beams = e1, E1 => circe2
$circe2_file = "ilc500.circe"
$circe2_design = "ILC"
?circe_polarized = false
```

- Soon also files for polarized beams within distribution

Top quark threshold in e^+e^-

- e^+e^- top threshold scan offers best option for m_t
- now: analytic LL ttV form factor implemented Bach/JRR/Stahlhofen
- default parameters: $M^{1S} = 172$ GeV, $\Gamma_t = 1.5$ GeV, $\alpha_s(M^{1S}) = 0.1077$
- analytic LL unstable far off-shell: top mass cut $\Delta M_t \leq 30$ GeV



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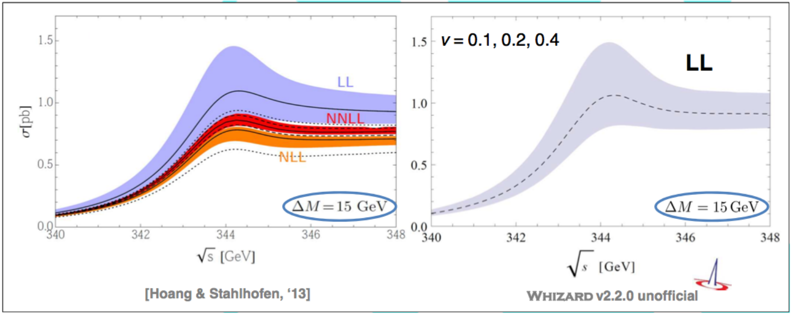


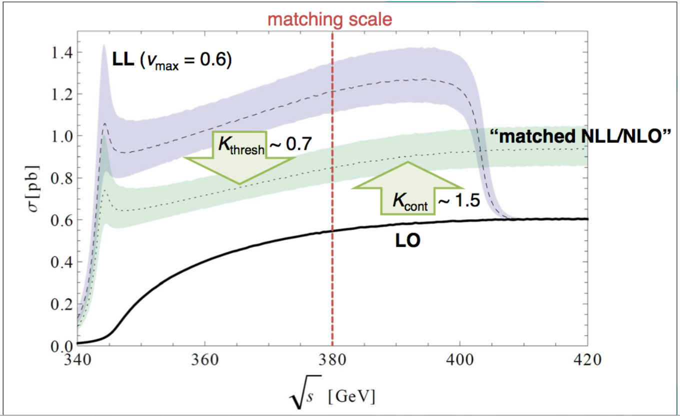
[Hoang & Stahlhofen, '13]

WHIZARD v2.2.0 unofficial

Top quark threshold in e^+e^-

- Proper NLO/NLL matched implementation — Bach/Hoang/JRR/Stahlhofen/Teubner
- `TOPPIK` code ships with `WHIZARD` — courtesy to T. Teubner

- Own model: `SM_tt_threshold`
- Parameters: `wtop`, `m1S`, `vsoft`, `match`



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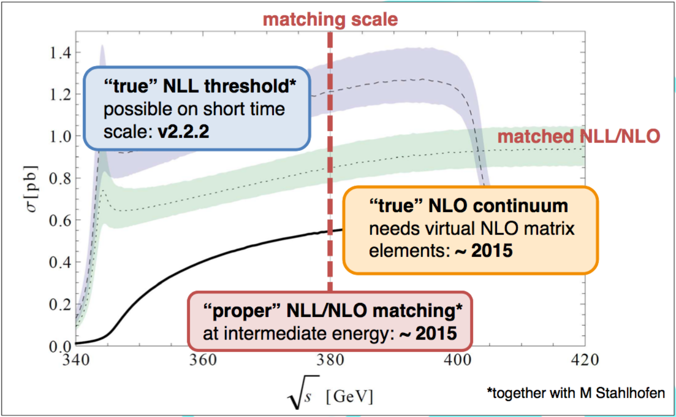

“true” NLL threshold* possible on short time scale: **v2.2.2**

“true” NLO continuum needs virtual NLO matrix elements: **~ 2015**

“proper” NLL/NLO matching* at intermediate energy: **~ 2015**

*together with M Stahlhofen

Status of NLO automation in WHIZARD

- BLHA(2) interface MC / OLP programs Speckner/JRR/Weiss, 2014 ✓
- First implementation: `GoSAM` (also `FeynArts/FormCalc`,`OpenLoops`)
- **Work flow / Plans**
  - Automatic generation of subtraction terms Speckner, 2012; Kilian/JRR/Weiss, 2014
  - proof-of-concept code in WHIZARD 2.2

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  - Special (first) focus on e^+e^- physics: top, Higgs, EW processes, BSM
  - First examples: $e^+e^- \to q\bar{q}$ and $e^+e^- \to \ell^-\ell^+q\bar{q}, \ell\nu q\bar{q}$, $e^+e^- \to t\bar{t}$

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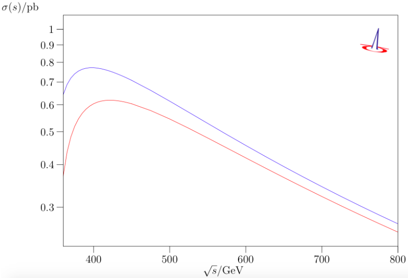
  - Plan: PowHeg box formalism for NLO processes (w/ Matching)
  - Release: `WHIZARD 3.0`



WHIZARD Outlook: upcoming releases 2.3 – 2.4 – 3.0

New features in production version 2.2

- LHAPDF 6 support, FastJet interface ✓
- ILC TDR beam spectra, CLIC (correlated) spectra (`CIRCE1/2`) ✓
- Direct Guinea-Pig interface ✓
- LCIO support test phase (✓)
- Complete Reweighting of Event Samples (incl. LHEF 2013) ✓
- Process containers: inclusive production samples (e.g. SUSY) ✓
- Automatic generation of decays, depending on the model ✓
- Simplified models for electroweak vector bosons (w/ light Higgs) ✓
- O’Mega Virtual Machine: faster + (much) smaller code Chokoufé/Ohl/JRR ✓

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Features in preparation: 2.3 – 2.4 – 3.0

- BSM: general Lorentz structures in matrix-element generator (O'Mega)
- Performance: parallelization, flavor sums, MC over helicities/colors, PS, etc.
- (N)LL/(N)LO matched e^+e^- top threshold Bach/Hoang/JRR/Stahlhofen/Teubner
- New syntax/features decays and chains (steering unstable particles):

```
process higgsstr = e1, E1 => (Z => e2, E2), (H => b, bbar)
```

- Improved matching/merging for jets/photons Chokoufé/JRR/Kilian/Weiss, ca. 2015
- Specification of QCD and electroweak order
- Automatic QCD NLO corrections (test phase)
- Matched $e^+e^- \to X$ at LO/NLO, POWHEG box Chokoufé/JRR/Weiss, 2015

2nd International WHIZARD Forum 16.-18.3.2015

- SM and BSM physics
- LHC, ILC, CLIC, FCC collider physics
- Matrix elements, models and effective theories
- QED/QCD/Weak Radiation and Merging
- Higher Orders: Automation and Interfacing
- User interfaces, computing and performace & Event formats

2nd International WHIZARD Forum

16 - 18 March 2015
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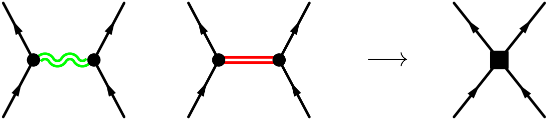
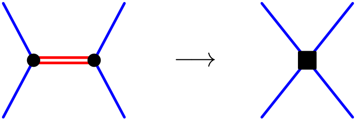
BACKUP SLIDES:

Effective EW Dim. 6 Operators

Hagiwara/Hikasa/Peccei/Zeppenfeld, 1987; Hagiwara/Ishihara/Szalapski/Zeppenfeld, 1993

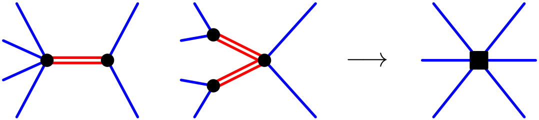


$$\mathcal{O}_{JJ}^{(I)} = \frac{1}{\Lambda^2}\mathrm{tr}\left[J^{(I)}\cdot J^{(I)}\right]$$

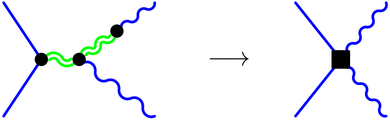


$$\mathcal{O}'_{h,1} = \frac{1}{\Lambda^2}\left((D\Phi)^\dagger\Phi\right)\cdot\left(h^\dagger(D^\Phi)\right) - \frac{v^2}{2}|D\Phi|^2$$

$$\mathcal{O}'_{hh} = \frac{1}{\Lambda^2}(\Phi^\dagger\Phi - v^2/2)\,(D\Phi)^\dagger\cdot(D\Phi)$$



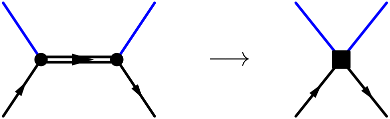
$$\mathcal{O}'_{h,3} = \frac{1}{\Lambda^2}\frac{1}{3}(\Phi^\dagger\Phi - v^2/2)^3$$



$$\mathcal{O}_{\Phi W} = -\frac{1}{\Lambda^2}\frac{1}{2}(\Phi^\dagger\Phi - v^2/2)\,\mathrm{tr}\left[W_{\mu\nu}W^{\mu\nu}\right]$$

$$\mathcal{O}_{B} = \frac{1}{\Lambda^2}\frac{i}{2}(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{\Phi B} = -\frac{1}{\Lambda^2}\frac{1}{4}(\Phi^\dagger\Phi - v^2/2)B_{\mu\nu}B^{\mu\nu}$$



$$\mathcal{O}_{Vq} = \frac{1}{\Lambda^2}\overline{q}h(\not{D}h)q$$

Integrating out resonances

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

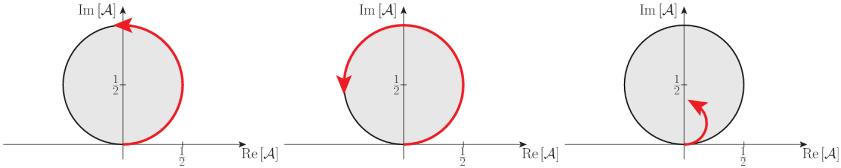
- leads to anomalous quartic couplings (aQGCs)

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

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

Unitary Description of EW interactions

- Five possible cases:
  - Amplitude perturbative, close to zero, small imag. part (SM)
  - Amplitude rises, gets imag. part, strongly interacting regime (presence of at least one dim. 8 operator)
  - Amplitude approaches maximum absolute value asymptotically
  - Turn over: new resonance
  - New inelastic channels open: eff. form factor, extra channels observable in multi-vector boson processes



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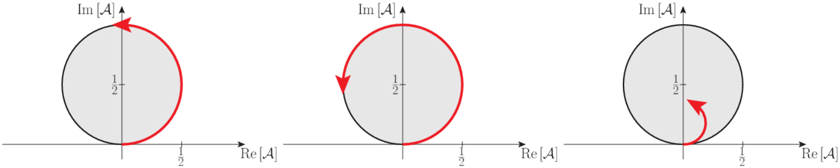
  - New inelastic channels open: eff. form factor, extra channels observable in multi-vector boson processes



- Interpretation of EFT operator coefficients changes: formally still low-energy coefficients of Taylor expansion ⇒ threshold parameters
- Complete description necessary (only) beyond threshold

Unitarity of Amplitudes

UV-incomplete theories could violate unitarity

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

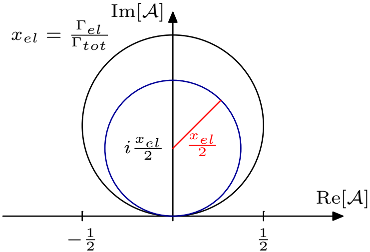
Optical Theorem (Unitarity of the S(cattering) Matrix):

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

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:

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



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

Unitarization Prescriptions

- **K-matrix unitarization prescription** Gupta, 1950; Berger/Chanowitz, 1991
  - Hermitian K-matrix interpreted as incompletely calculated approximation to true amplitude
  - $\Rightarrow$ Unitary S, T as a non-perturbativ completion of this approximation
  - Insert pert. expansion into expansion:

$$a = \frac{a_K}{1 - \mathrm{i} a_K} \Rightarrow a^{(n)} = \frac{a_0^{(1)} + \mathrm{Re}\, a_0^{(2)} + \ldots}{1 - \mathrm{i}(a_0^{(1)} + \mathrm{Re}\, a_0^{(2)} + \ldots)}$$

  - Prescription does a partial resummation of perturbative series
  - Example Dyson resummation: $a_K^{(0)}(s) = \frac{\lambda}{s - m^2} \longrightarrow a^{(0)}(s) = \frac{\lambda}{s - m^2 - \mathrm{i}\lambda}$

- **Drawbacks of (original) K-matrix:**
  - Needs to construct self-adjoint K-matrix as intermediate step
  - Problem if S-matrix is not diagonal, or ...

    there are non-perturbative contributions

- **T-matrix unitarization**
  - a_0 complex approximation to eigenvalue of true T matrix
  - use again pseudo-stereographic projection (intersection of Argand circle with line $\overline{a_0\ i}$)
  - Results in: $a = \frac{\mathrm{Re}\, a_0}{1 - \mathrm{i} a_0^*} \quad \Rightarrow a^{(n)} = \frac{a_0^{(1)} + \mathrm{Re}\, a_0^{(2)} + \ldots}{1 - \mathrm{i}(a_0^{(1)} + \mathrm{Re}\, a_0^{(2)} - \mathrm{i}\,\mathrm{Im}\, a_0^{(2)} + \ldots)}$

Form Factor

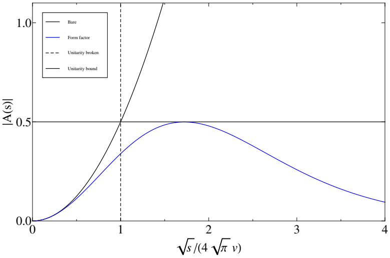
Form Factor

$$\frac{1}{\left(1+\frac{s}{\Lambda_{FF}^2}\right)^n}$$

- Use Form Factor to suppress breaking of unitarity
- Can be generally used for arbitrary anomalous operator
- Need "Fine Tuning"

Parameters

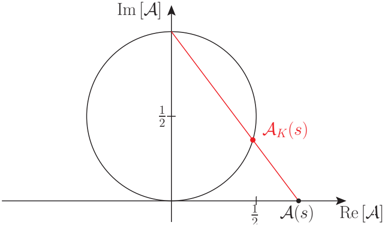
n	Chosen to prevent breaking of Unitarity
Λ_{FF}	Calculate highest possible value that satisfy real Unitarity bound ($0th$ partial wave)



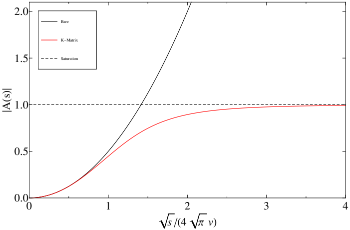
K-Matrix

K-Matrix Unitarisation

$$\mathcal{A}_K(s) = \frac{1}{\mathrm{Re}\left(\frac{1}{\mathcal{A}(s)}\right) - \mathrm{i}} = \frac{\mathcal{A}(s)}{1 - \mathrm{i}\mathcal{A}(s)} \quad \text{if } \mathcal{A}(s) \in \mathbb{R}$$



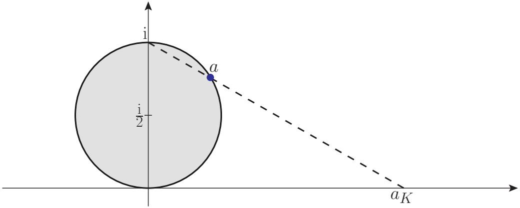
- Projection of elastic amplitudes onto Argand-Circle
- At high energies the amplitude saturises
- Is usable for complex amplitudes
- Not dependent on additional parameters



Alternative Unitarization Prescriptions

- **Comparison of T-matrix and (original) K-matrix:**
  - T-matrix does not rely on perturbation theory
  - Special treatment for non-normal T matrices (eigenvalues having imaginary parts larger than i; Riesz-Dunford operator calculus)

  1. T matrix description leads to point on the Argand circle
  2. For real a $\Rightarrow$ (original) K-matrix case
  3. a_0 on Argand circle $\Rightarrow$ left invariant
- **Thales circle construction:**



  - Defined via $\left|a - \frac{a_K}{2}\right| = \frac{a_K}{2} \;\Rightarrow\; a = \frac{1}{\mathrm{Re}\left(\frac{1}{a_0}\right) - \mathrm{i}}$
  - avoids non-normal matrices, but not single-valued around $a = 0$

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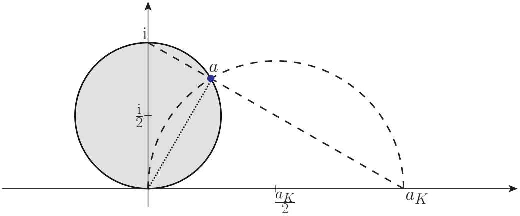

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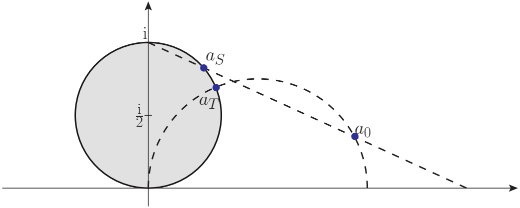

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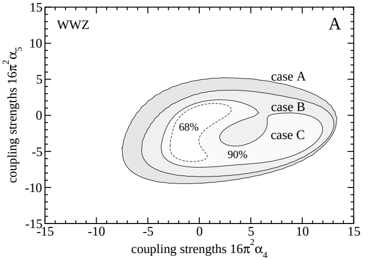
ILC Results: Triboson production

Beyer et al.,hep-ph/0604048

$e^+e^- \to WWZ/ZZZ$, 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/JRR

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

	WWZ			ZZZ	best
$16\pi^2\times$	no pol.	e^- pol.	both pol.	no pol.	
$\Delta\alpha_4^+$	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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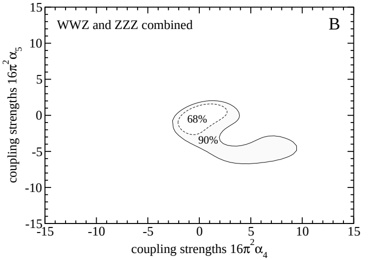

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The WHIZARD Event Generator – Release 2.2

1.0 Project started around 1999: Studies for electroweak multi-particle processes at TESLA (W, Higgs, Z)

1.5 Event samples for LC studies at SLAC

1.9 Full SM w/ QCD, beam properties, SUSY/BSM, event formats

2.1 QCD shower+matching, FeynRules support, internal density-matrix formalism (cascade decays), SINDARIN as user interface, OpenMP, . . .

2.2 Major refactoring, event reweighting, inclusive processes and selective decay chains (**production version**)

Plan Improve e^+e^- support; NLO + matching; improve user interface ⇒ adapt to specific needs of user groups

Beams and hard matrix elements

- **Hadron Colliders structured beams**
  - LHAPDF interface, most prominent PDFs directly included
  - QCD ISR and FSR (2 diff. own implementations, interface to PYTHIA)
  - Matching/merging matrix elements/showers
  - Underlying event/multiple interactions (proof of principle)
- **Hadronic events/hadronic decays + hadronic (QED) FSR** (ext.)
- **Lepton Colliders structured beams**
  - Beam structure (CIRCE1/2 module) **more later**
  - arbitrarily polarized beams (density matrices)
  - QED ISR (Skrzypek/Jadach, Kuraev/Fadin , incl. p_T distributions [caveat!])
  - [Photon collider spectra (CIRCE2 module)]
- **Hard matrix elements:**
  - Particle spins: $0, \frac{1}{2}, 1, \frac{3}{2}, 2$
  - Lorentz structures: hugh set of hard-coded structures
  - Fully general Lorentz structures foreseen for 2.3.0
  - Color structures: $\mathbf{3}, \overline{\mathbf{3}}, \mathbf{8}, [\mathbf{6}]$
  - Color flow formalism Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 2011
  - General color structures $\mathbf{6}, \mathbf{10}, \epsilon_{ijk}\phi^i\phi^j\phi^k$

WHIZARD – Overview over Physics Models

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 gauge coupl.	`SM_ac_CKM`	`SM_ac`
SM with anomalous top coupl.	`SMtop_CKM`	`SMtop`
SM for e^+e^- top threshold	—	`SM_tt_threshold`
SM with anom. Higgs coupl.	—	`SM_rx / NoH`
SM ext. for VV scattering	—	`SSC / AltH`
SM with Z'	—	`Zprime`
2HDM	`2HDM_CKM`	`2HDM`
MSSM	`MSSM_CKM`	`MSSM`
MSSM with gravitinos	—	`MSSM_Grav`
NMSSM	`NMSSM_CKM`	`NMSSM`
extended SUSY models	—	`PS/E/SSM`
Littlest Higgs	—	`Littlest`
Littlest Higgs with ungauged $U(1)$	—	`Littlest_Eta`
Littlest Higgs with T parity	—	`Littlest_Tpar`
Simplest Little Higgs (anomaly-free/univ.)	—	`Simplest[_univ]`
3-site model	—	`Threeshl`
UED	—	`UED`
SM with gravitino and photino	—	`GravTest`
Augmentable SM template	—	`Template`

new models easily: FeynRules interface Christensen/Duhr/Fuks/JRR/Speckner, 1010.3251

Interface to SARAH in the SUSY Toolbox Staub, 0909.2863; Ohl/Porod/Speckner/Staub, 1109.5147

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JRR et al. 1408.6207
Talk LCWS14 EW session 7.10.

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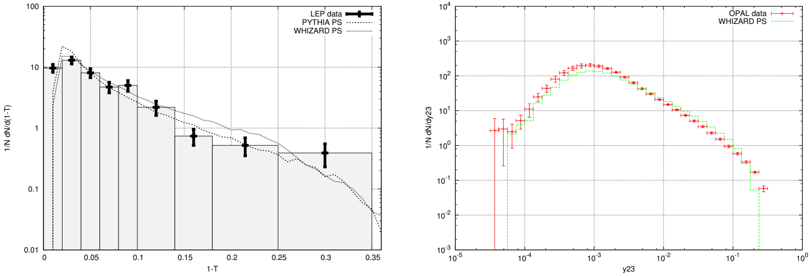
Analytic Parton Shower

Kilian/JRR/Schmidt/Wiesler, JHEP **1204** 013 (2012)

- Analytic Parton Shower:
  - no shower veto: shower history is exactly known
  - allows reweighting and maybe more reliable error estimate

- new algorithm for initial state QCD radiation



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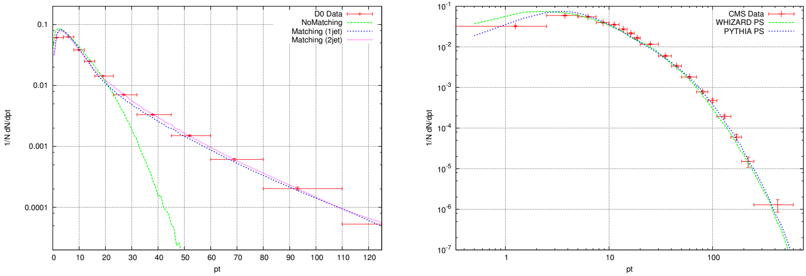

- matching with hard matrix elements, no "power-shower"
- Improvement/Tuning/Merging with higher-order matrix elements

Chokoufé/JRR