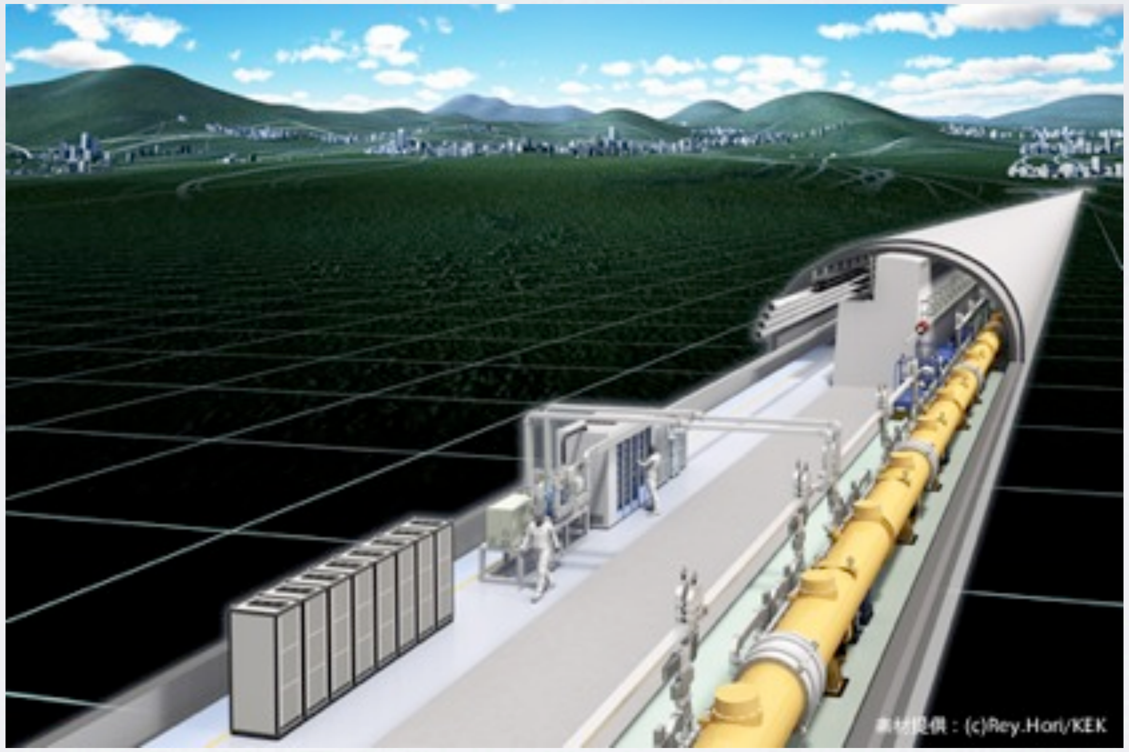
Vector Boson Scattering at the ILC (and beyond)



Jürgen R. Reuter, DESY

High-Energy Electroweak Sector

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- After discovery of light Higgs boson: what is left to do?
- Mechanism behind generating Higgs vev missing ($\Longrightarrow$ Higgs physics, trilinear Higgs etc.)
- Dynamics of electroweak interactions: $\Longrightarrow$ Multiboson Interactions (MBI)
- Processes: Dibosons, Tribosons, Vector Boson Fusion, Vector Boson Scattering
- By vector bosons EW bosons are meant, not the photon (though generally higher rate)
- 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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Not really new! Importance of longitudinal vector boson scattering

Elementary Particle Physics And Future Facilities. Proceedings, 1982 DPF Summer Study, Snowmass, USA, June 28 - July 16, 1982

Theoretical Background

- Vector Boson Scattering serves as a probe to understand core of EW dynamics
- EW dynamics can still be non-perturbative at the (multi-) TeV scale
- First evidence for like-sign *WW* scattering from both ATLAS and CMS 2014
- *VV* scattering telescope for new states in the EW sector:

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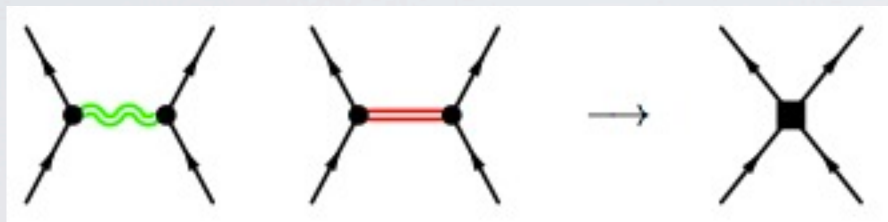
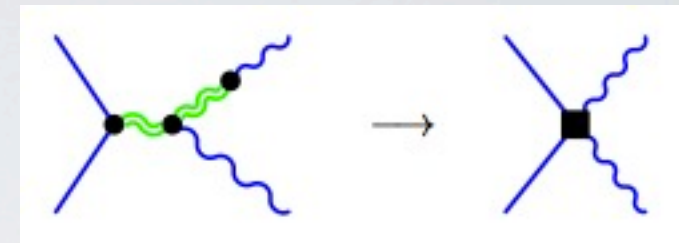
$$\mathcal{O}^{(I)}_{JJ} = \frac{1}{\Lambda^2}\mathrm{tr}\left[J^{(I)}\cdot J^{(I)}\right]$$





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

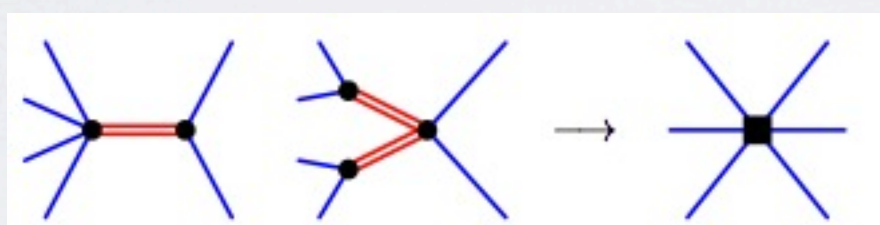
$$\mathcal{O}'_{\Phi\Phi} = \frac{1}{\Lambda^2}(\Phi^\dagger\Phi - v^2/2)\,(D\Phi)^\dagger\cdot(D\Phi)$$

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

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

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

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



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

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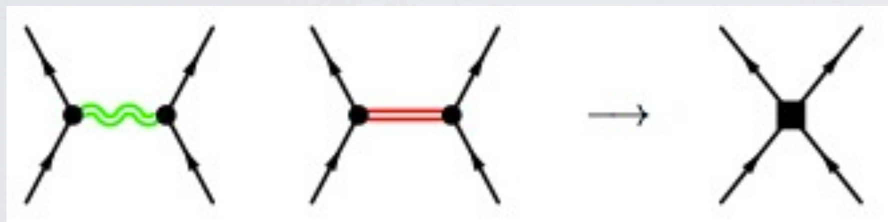

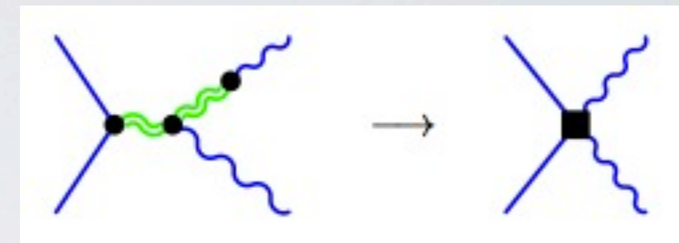

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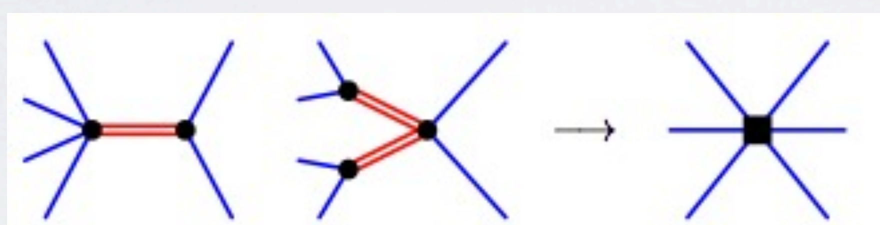

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Couplings of new states to the longitudinal / transversal diboson

	$J=0$	$J=1$	$J=2$
$I=0$	σ^0 (Higgs singlet?)	ω^0 (γ'/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 ?)	—	$t^{\pm\pm}, t^\pm, t^0$

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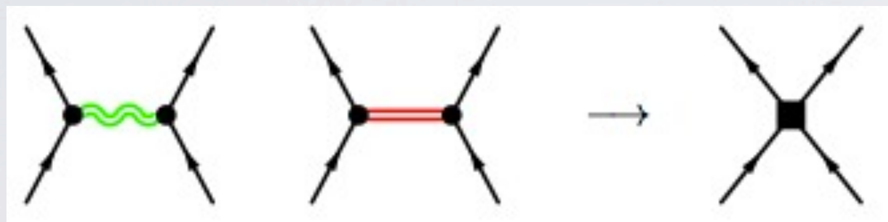

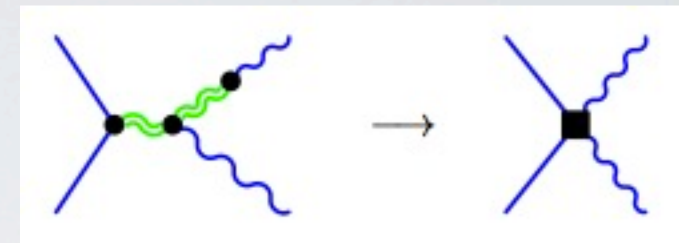

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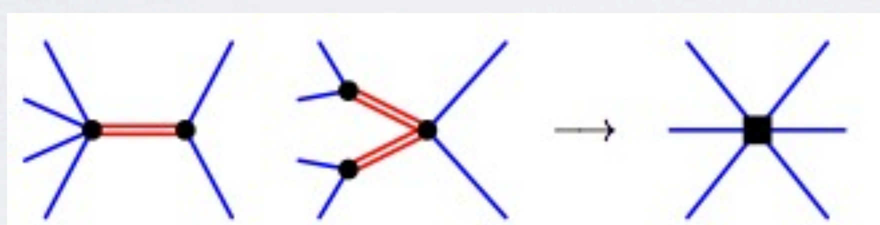

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Different power counting for weakly and strongly interacting theories

$$\frac{c_i}{\Lambda} \sim \frac{g}{4\pi\Lambda} \quad \text{vs.} \quad \frac{c_i}{\Lambda} \sim \frac{g}{\Lambda}$$

Operators and Multi(EW)-boson Physics (I)

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Dimension-6 operators for Multiboson physics (CP-conserving)

$$\mathcal{O}_{WWW} = \mathrm{Tr}[W_{\mu\nu} W^{\nu\rho} W^{\mu}_{\rho}]$$

$$\mathcal{O}_{W} = (D_\mu \Phi)^\dagger W^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_{B} = (D_\mu \Phi)^\dagger B^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_{\partial\Phi} = \partial_\mu \left(\Phi^\dagger \Phi\right) \partial^\mu \left(\Phi^\dagger \Phi\right)$$

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Dimension-6 operators for Multiboson physics (CP-violating)

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

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\end{aligned}$$

Affect the following electroweak couplings:

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

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$$\mathcal{O}_{\widetilde{W}W} = \Phi^\dagger\widetilde{W}_{\mu\nu}W^{\mu\nu}\Phi$$
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$\mathcal{O}_{\Phi d}$			✓	✓						
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$\mathcal{O}_{\Phi B}$				✓	✓	✓				
$\mathcal{O}_{\tilde{W}WW}$	✓	✓					✓	✓	✓	✓
$\mathcal{O}_{\tilde{W}}$	✓	✓	✓	✓	✓					
$\mathcal{O}_{\tilde{W}W}$			✓	✓	✓	✓				
$\mathcal{O}_{\tilde{B}B}$				✓	✓	✓				

connected to Higgs physics

Operators and Multi(EW)-boson Physics (II)

Dimension-8 operators for Multiboson physics

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

$$\mathcal{O}_{T,0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \cdot \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$
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\end{aligned}$$

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

Operators and Multi(EW)-boson Physics (II)

Dimension-8 operators for Multiboson physics

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

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

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$$\mathcal{O}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{O}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \cdot \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{O}_{M,4} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\mu\Phi\right] \cdot B^{\beta\nu}$$
$$\mathcal{O}_{M,5} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}D^\nu\Phi\right] \cdot B^{\beta\mu}$$
$$\mathcal{O}_{M,6} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\nu}D^\mu\Phi\right]$$
$$\mathcal{O}_{M,7} = \left[(D_\mu\Phi)^\dagger W_{\beta\nu}W^{\beta\mu}D^\nu\Phi\right]$$

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

- generate neutral quartic couplings

Problems in comparing to the LHC

- Project onto spin-isospin eigenamplitudes: Lee/Quigg/Thacker, 1973

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

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

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

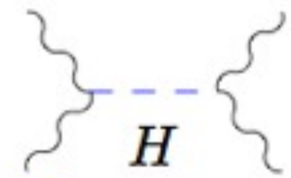
exceeds unitarity bound $|\mathcal{A}_{IJ}| \lesssim \frac{1}{2}$ at:

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

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

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

Higgs exchange:



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

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

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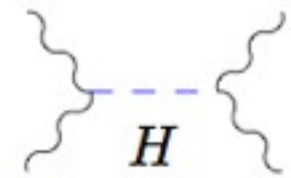

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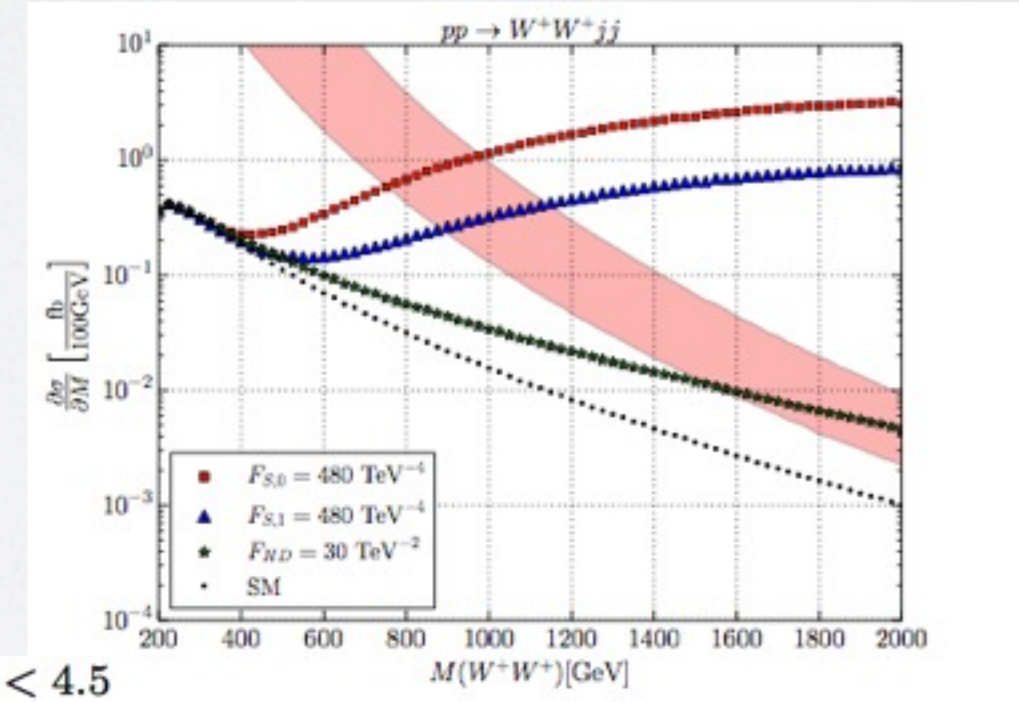
Unitarity: $M_H \lesssim \sqrt{8\pi}v \sim 1.2\,\text{TeV}$

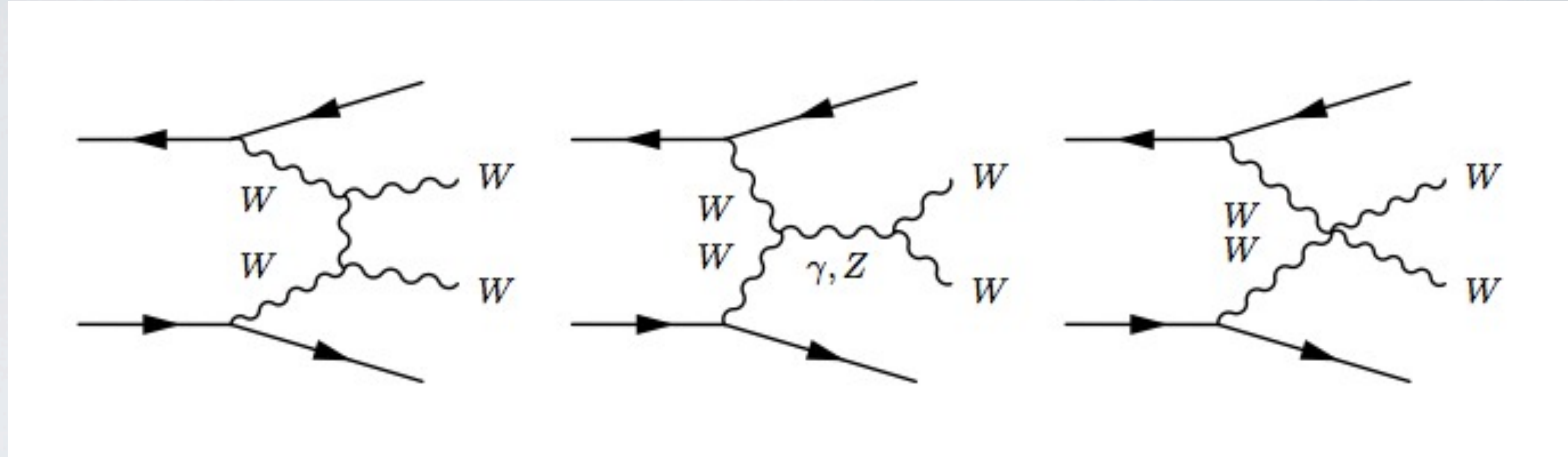
- Delicate cancellation makes VBS probe for non-standard Higgs (sector)
- Higher-dimensional operators rise with *s* (dim-6) or even s_2
- *Perturbative expansion of UV-incomplete theories may violate unitarity*



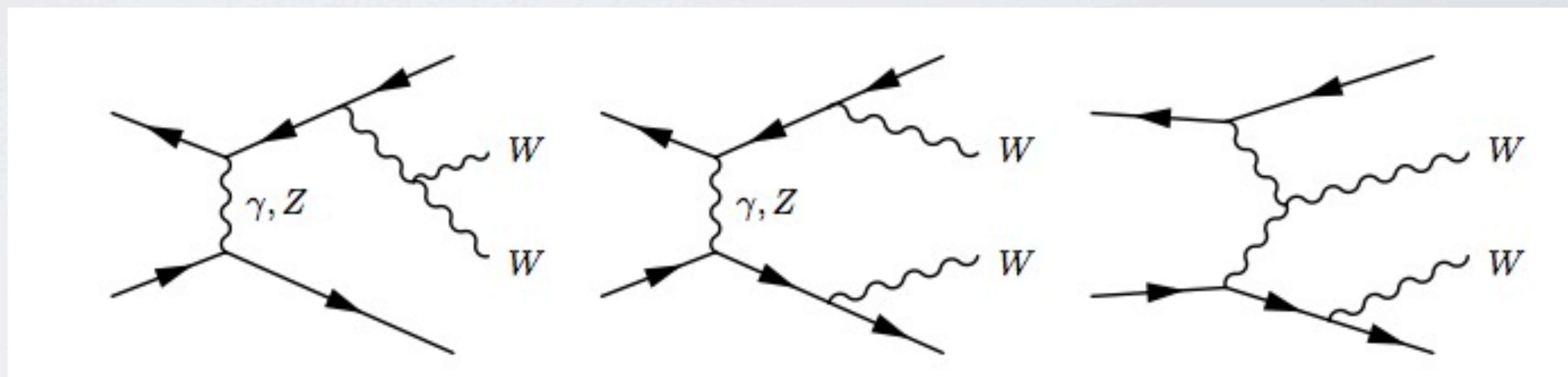
General cuts: $M_{jj} > 500$ GeV; $\Delta\eta_{jj} > 2.4$; $p_T^j > 20$ GeV; $|\eta_j| < 4.5$

Signals and Backgrounds

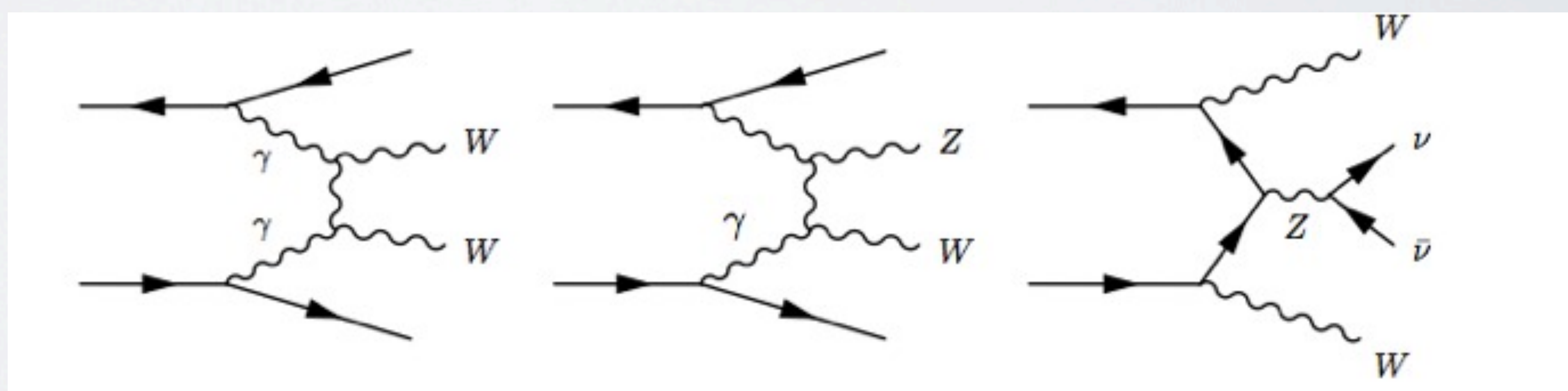
Signal:



Irreducible background:



(Partially) reducible background:



High-Energy Electroweak Sector

- Vector Boson Scattering: access to New Physics in W, Z selfcoupl. Beyer/JRR/Mönig ...., arXiv:hep-ph/0604048
- 1 TeV, 1/ ab , full 6-fermion states, P(80% e-, 60% e+), binned likelihood
- Contributing channels: WW→WW, WW→ZZ, WZ→WZ, ZZ→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

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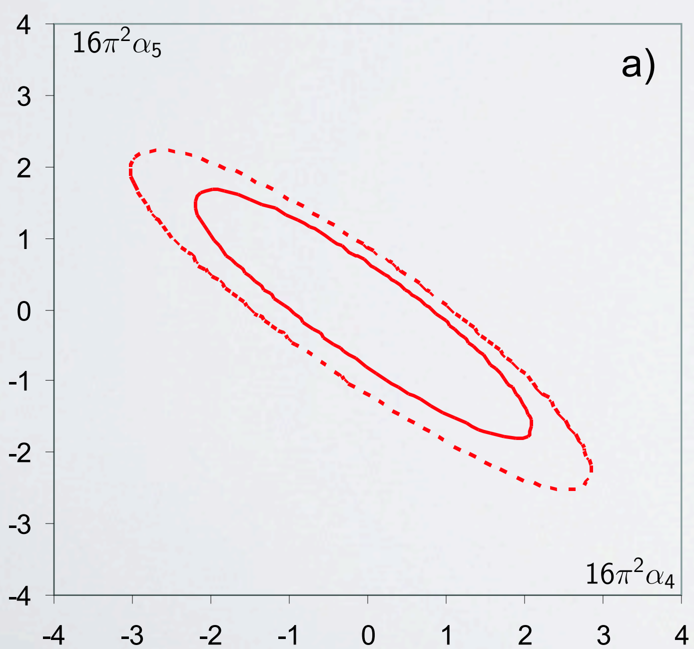

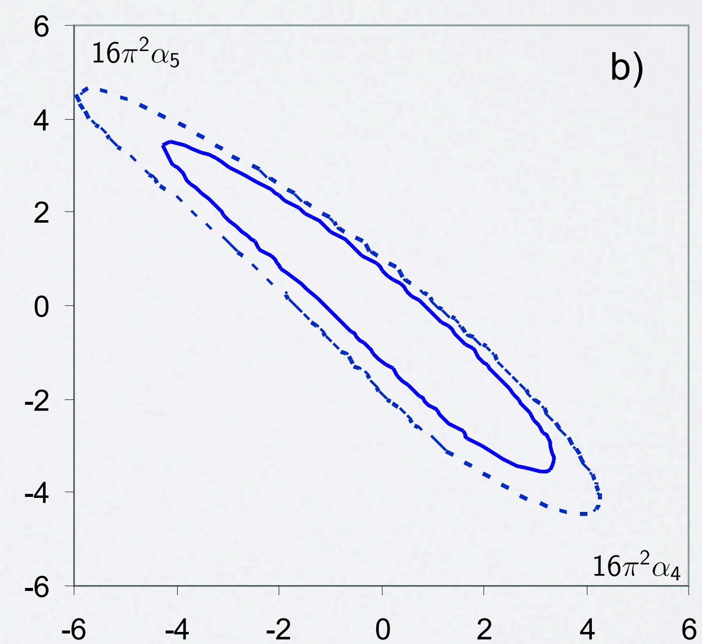

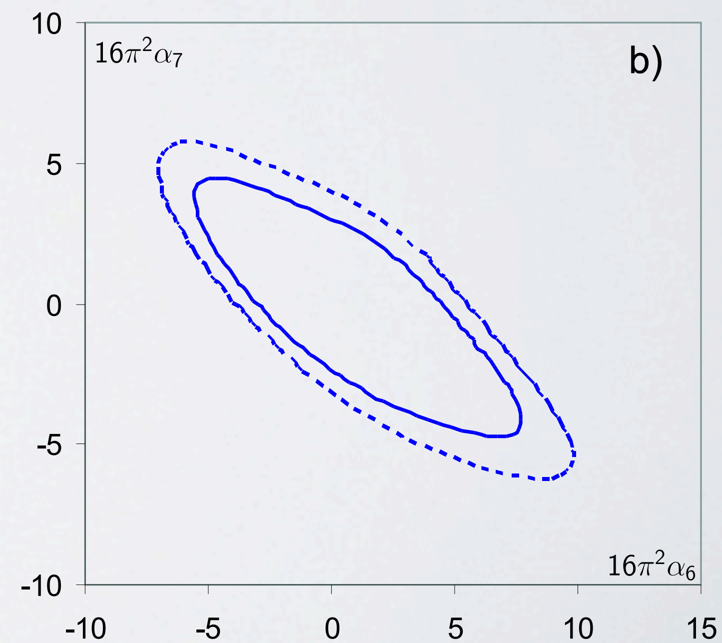

Interpretation as Limits on EW Resonances

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

Beyer/Kilian/Křstonošic/Mönig/JRR,

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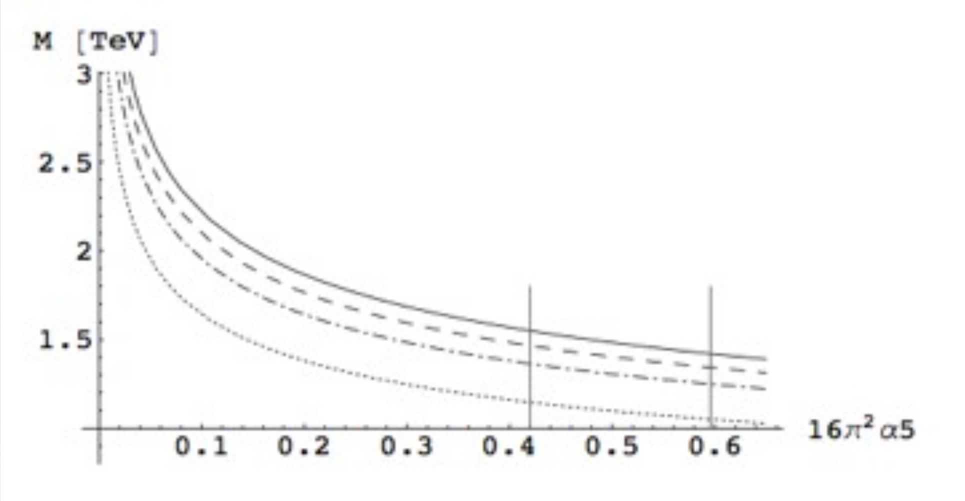
$SU(2)$ conserving scalar singlet

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

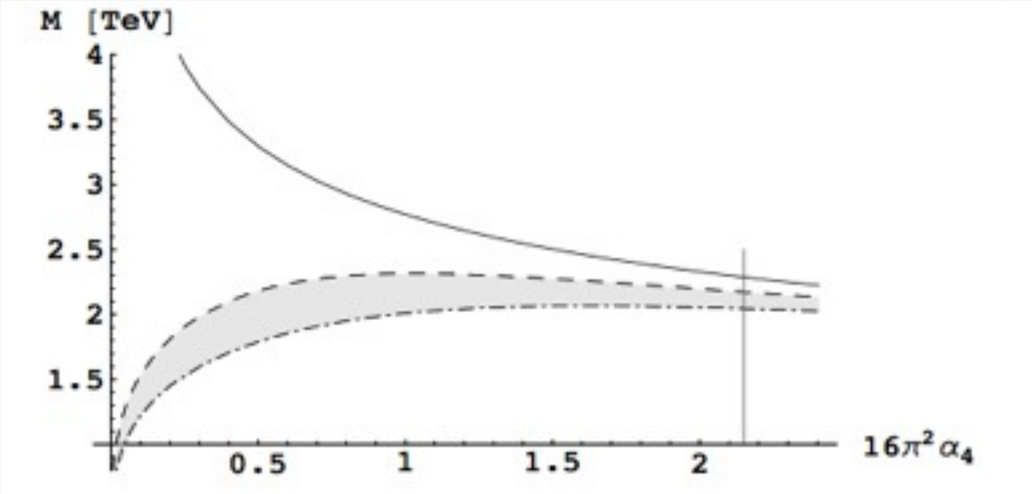
$f = 1.0$ (full), 0.8 (dash), 0.6 (dot-dash), 0.3 (dot)



$SU(2)$ broken vector triplet
needs input from TGC covariance matrix

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

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



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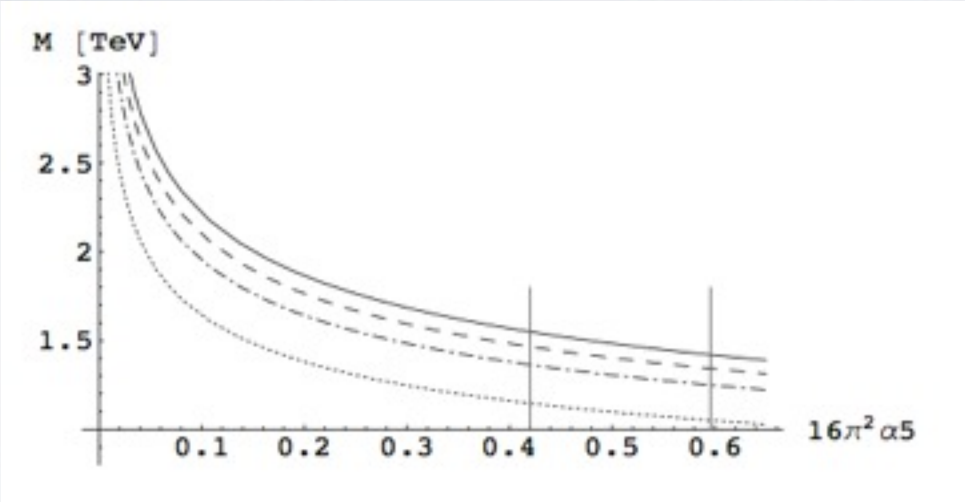

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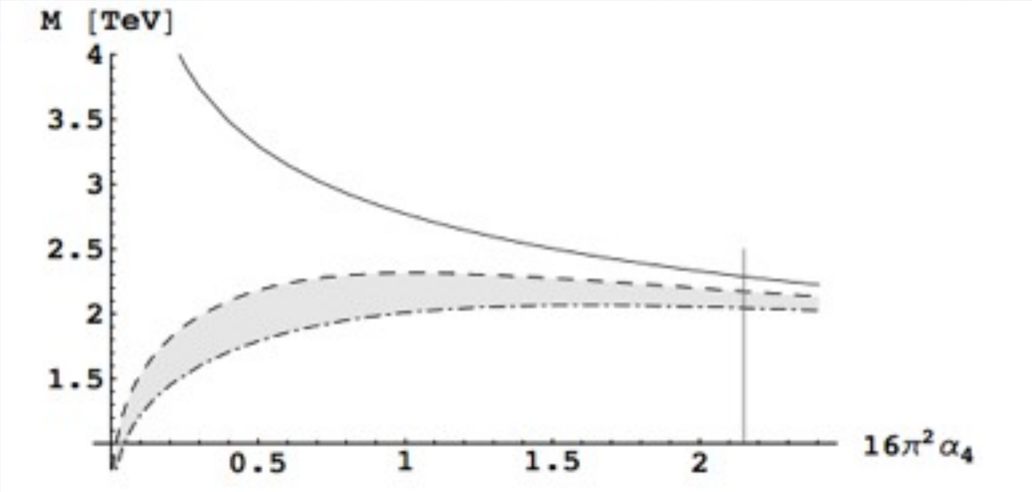

Final result:

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

High-Energy Electroweak Sector

- Access also via Triboson Production: $e^+e^- \to WWZ/ZZZ$
- Polarization populates longitudinal modes, suppresses background

A) unpolarized B) P(80% e-, 0% e+) C) P(80% e-, 60% e+)

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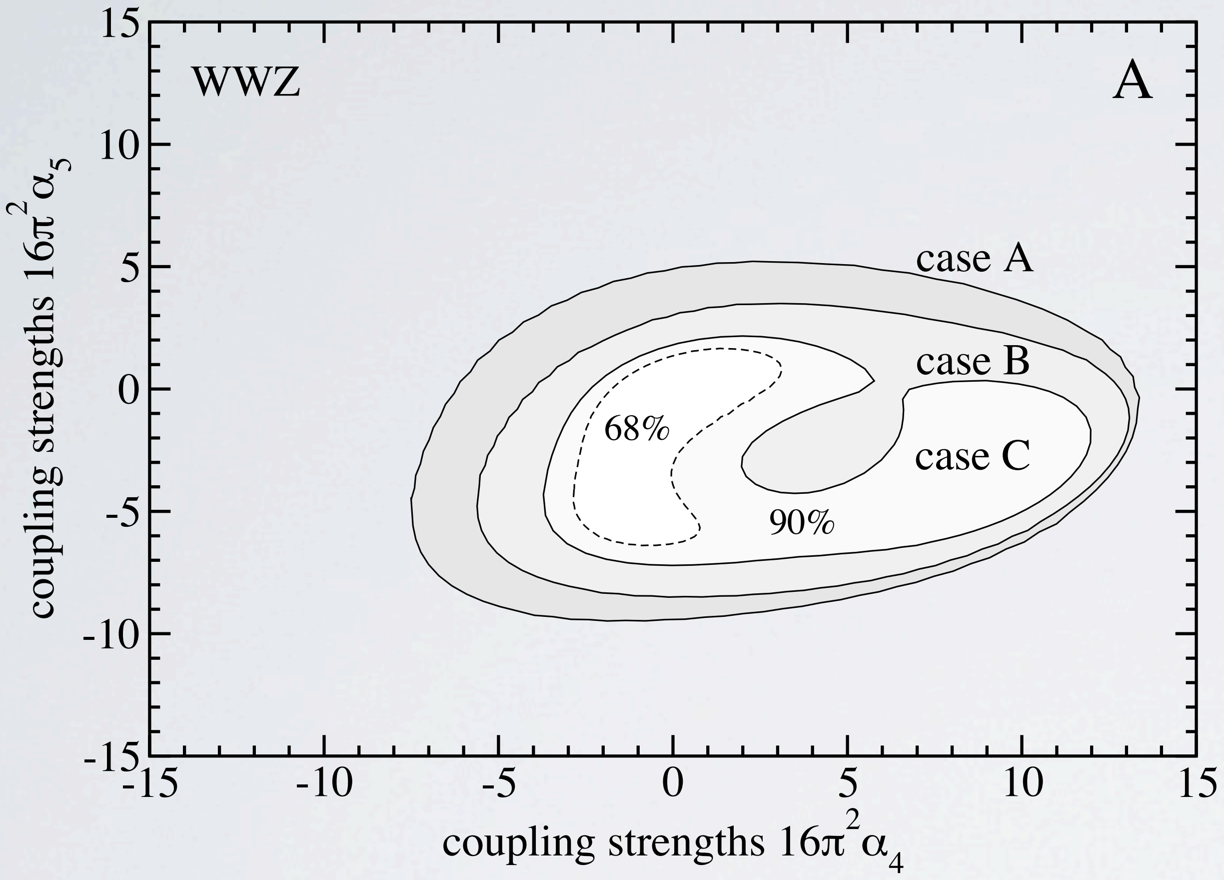

- Simulation with WHIZARD
- Fast detector simulation
- 1 TeV, 1 / ab , full 6-fermion final states
- Use of 32% full-hadronic decays
- Durham jet algorithm
- Main background: *tt* → 6 jets
- Veto against $E^2_{\text{mis}} + p^2_{\perp,\text{mis}}$
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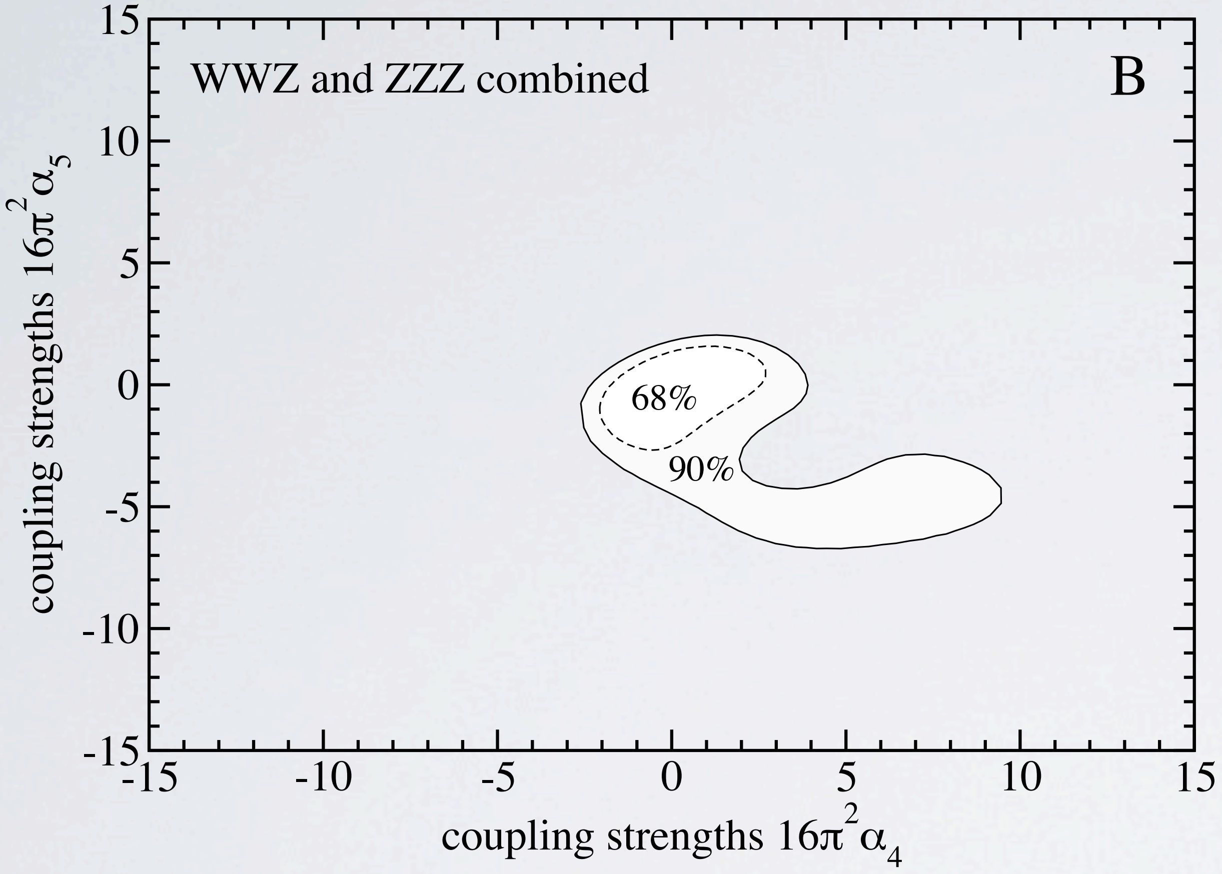

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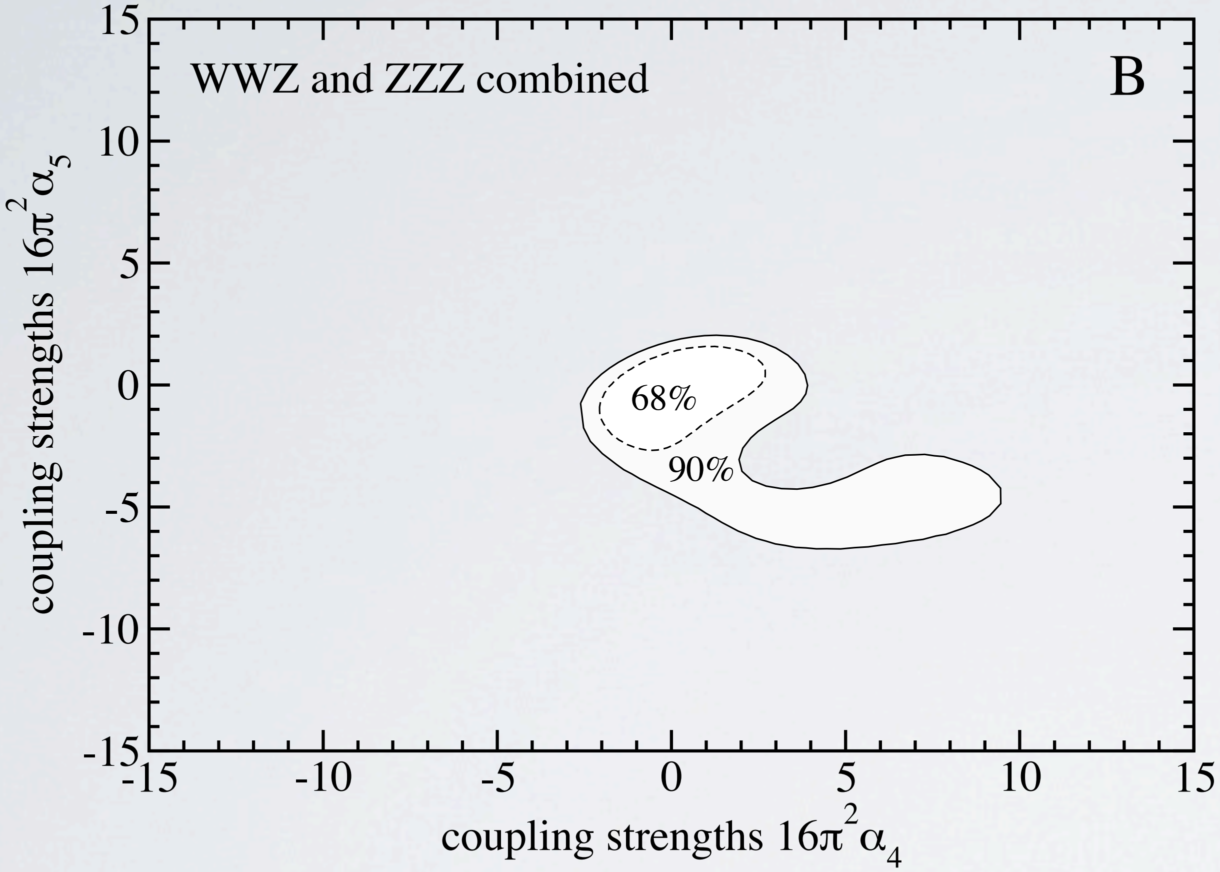

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0	1.39	1.55	1.95
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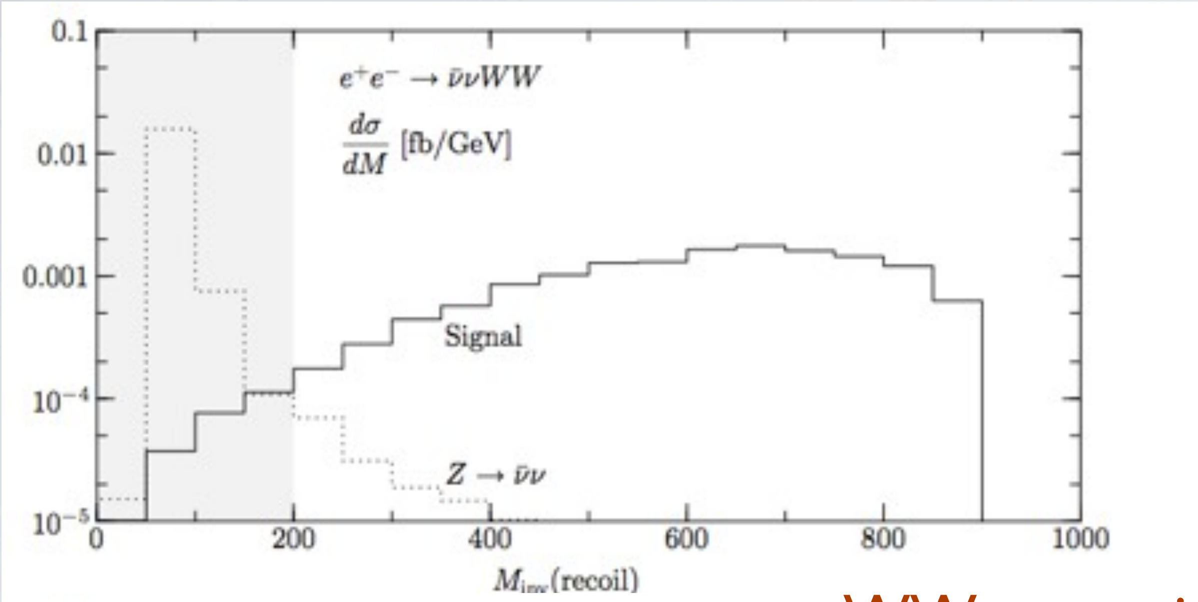
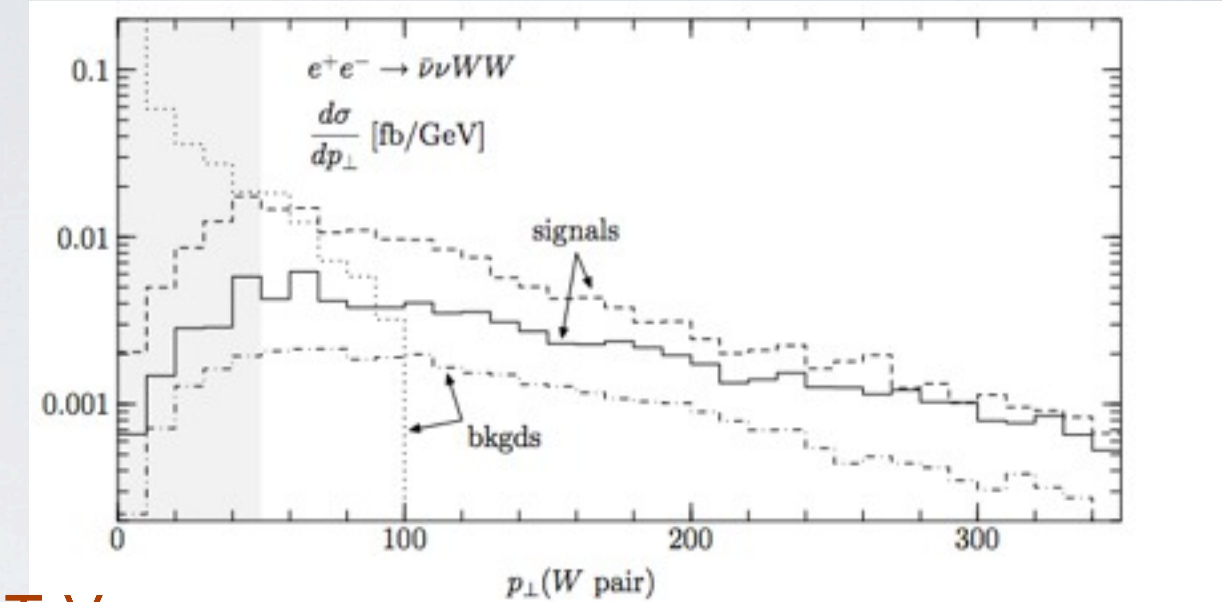
2	3.00	3.01	5.84

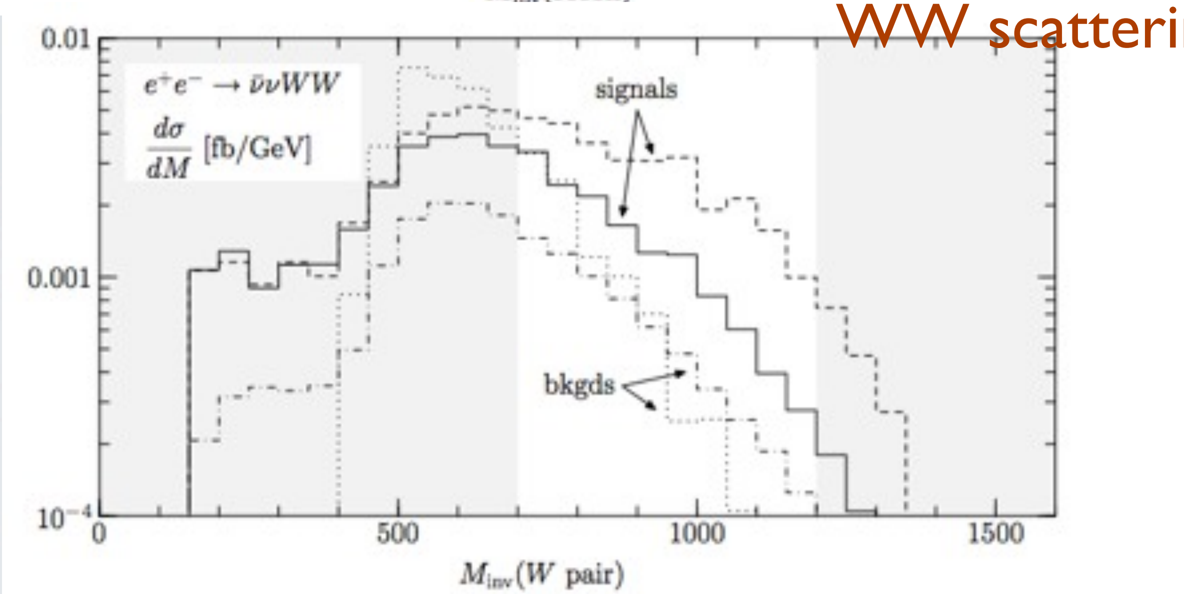
- Results for 1 TeV, but very good discovery potential already at 500 GeV
- No final conclusion on LHC reach yet: Alboteanu/Kilian/JRR, 0806.4145; Kilian/Ohl/JRR/Sekulla, 1408.6207

Observables



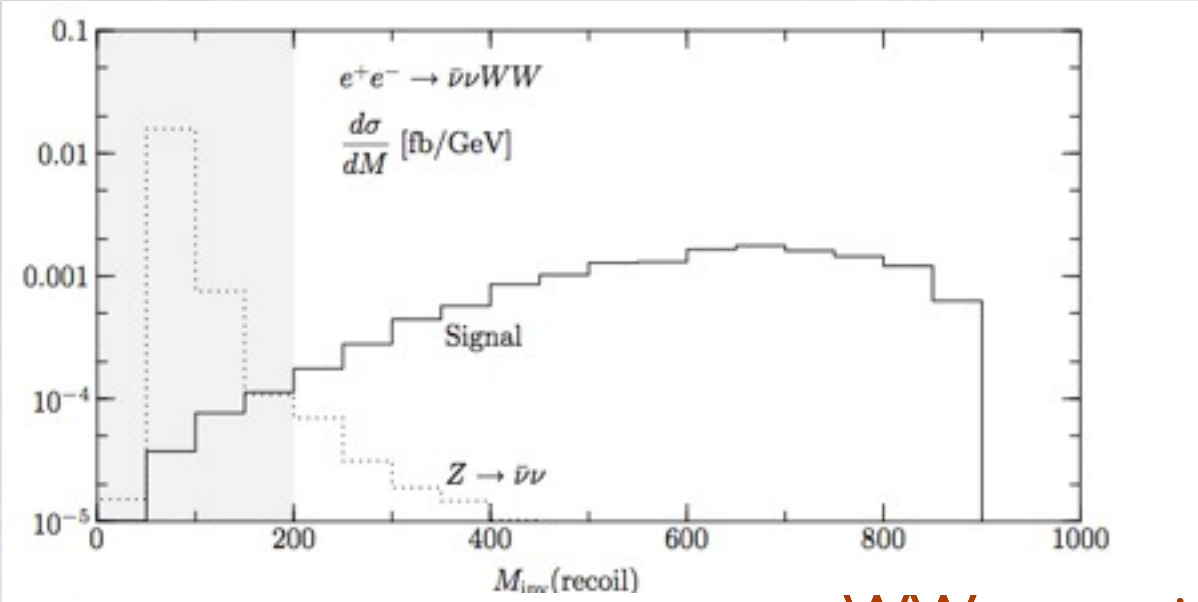


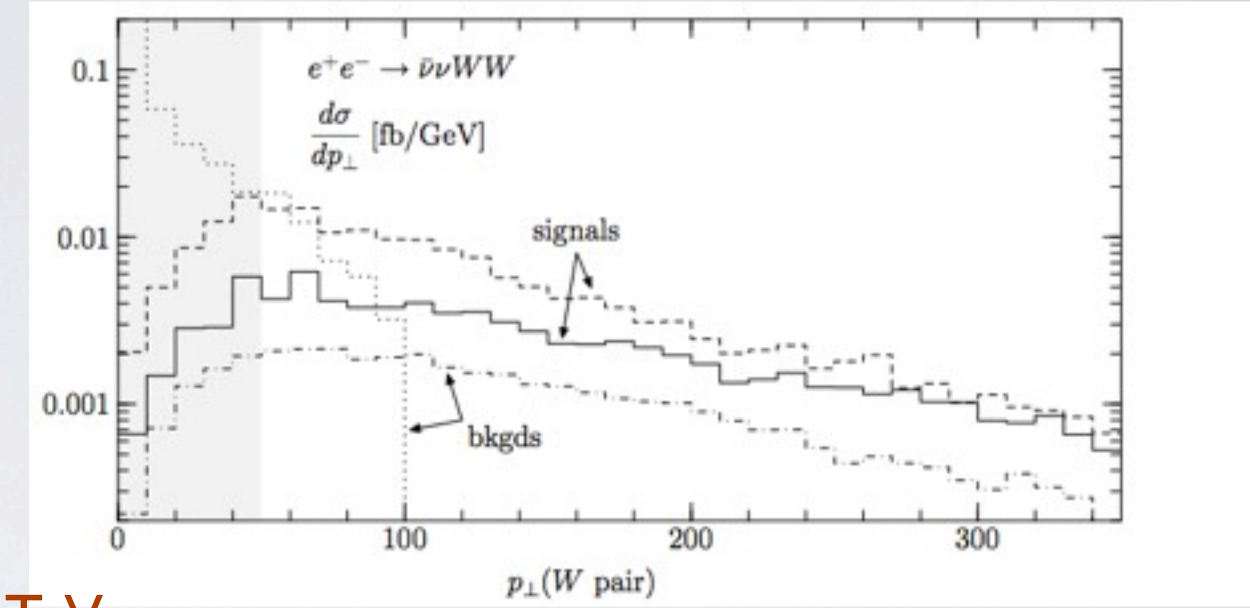
WW scattering, 1.6 TeV



Boos/Kilian/He/Mühlleitner/Pukhov/Zerwas, 1998

Observables





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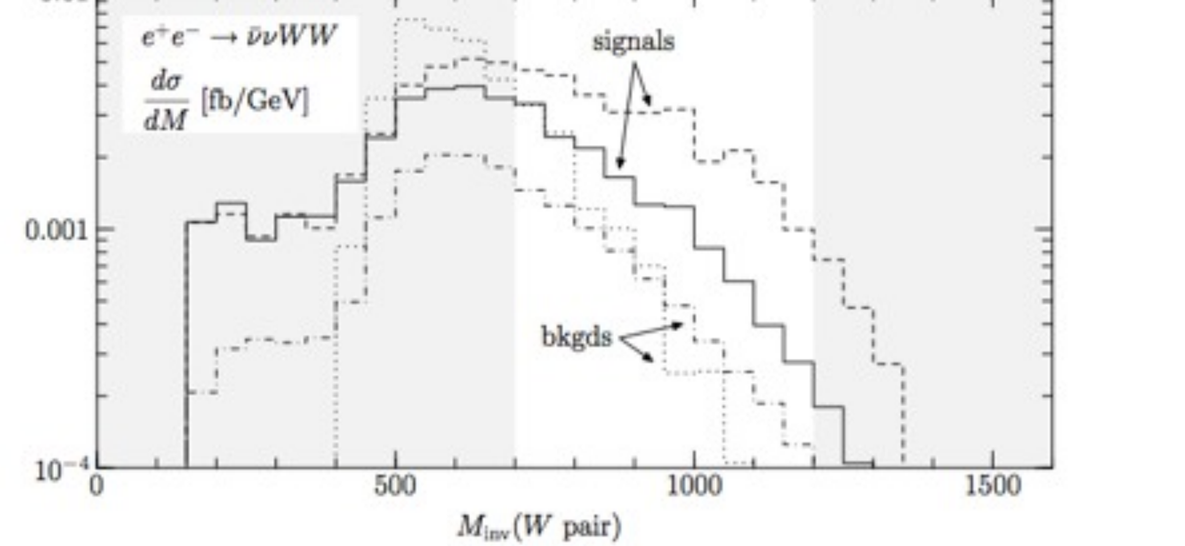

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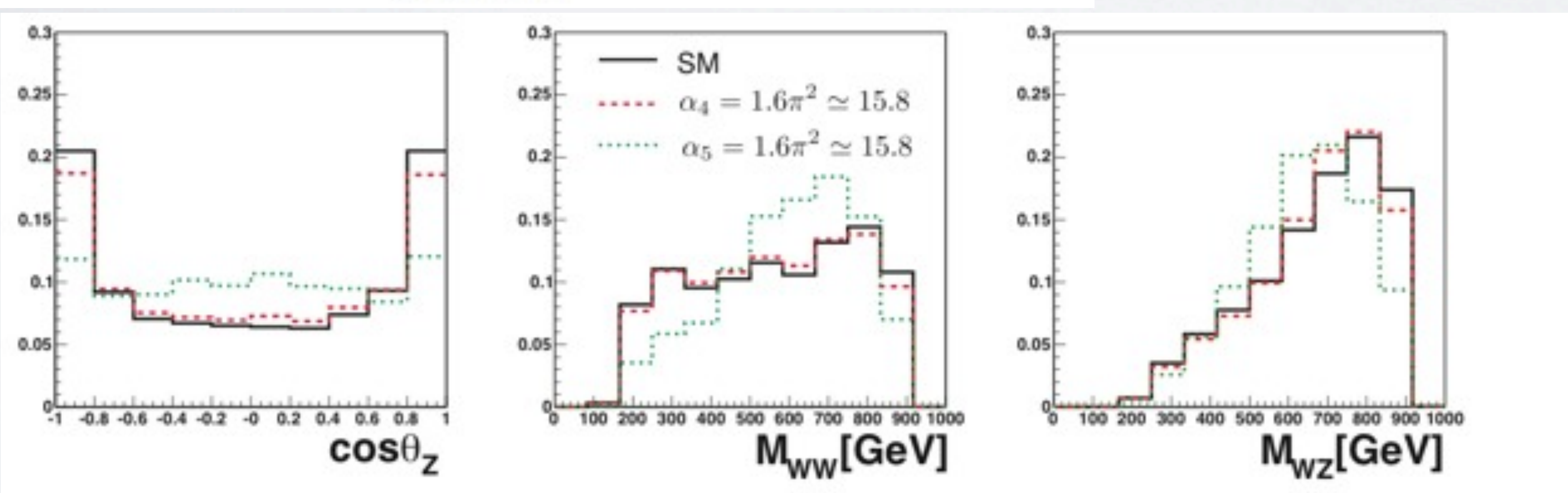

WWZ/ZZZ , 1.0 TeV

Beyer et al. , 2006

Wrap-Up and Caveats

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

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

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

$$\left.\begin{array}{l} e^+e^- \to ZZZ \\ \\ \to WWZ \end{array}\right] \begin{array}{l} ZH \\ \;\hookrightarrow WW \\ \;\hookrightarrow ZZ \end{array}$$

Present in spectrum

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

Wrap-Up and Caveats

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$$\left.\begin{array}{l} e^+e^- \to ZZZ \\ \to WWZ \end{array}\right] \begin{array}{l} ZH \\ \quad \hookrightarrow WW \\ \quad \hookrightarrow ZZ \end{array}$$

Present in spectrum

$$\to WW\gamma$$

Complementary (and present at lower energies)

- LHC immediately in unitarity endangered seas
- EFT descriptions useless unless unitarized Alboteanu/Kilian/JRR, 2008; Kilian/Ohl/JRR/Sekulla, 2014
- "Event clipping": removes dangerous (high-energy) events $\Longrightarrow$ LHC intensity-frontier
- Alternative: unitarized limits (e.g. ATLAS)
- ILC estimates need to be adapted to compare to LHC
- ILC estimates preliminary: for 800/1000/1600 GeV c.m. energy, only theory or fastsim

Wrap-Up and Caveats

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

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LHC probably better for direct resonance search, ILC for deviation search (wow, that’s new)

Conclusions and Outlook

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- Pro: ILC allows for model-independent electroweak measurements
- Con: Pays the energy tolls: severely energy limits (discussion: 500 vs. 550 vs. 600 GeV irrelevant?)
- Pro: Clean "quantum" measurement [disentangle gauge-fermion operators]
  compared to incoherent measurement at LHC
- Pro: Discriminating between longitudinal and transversal modes [Needs (pos.) polarization]
- Pro: Cleaner environment might surpass energy reach of *pp* colliders (?)
- A lot more studies needed (Theory investigations, FullSim!!!)
- Crucial ingredient: *W/Z* discrimination in fully hadronic
  environment at high energies
- Multi-TeV ee probably best-possible machine for
  these processes
- Might fly with the "LHC effect"
  (a.k.a. as experimental ingenuity)

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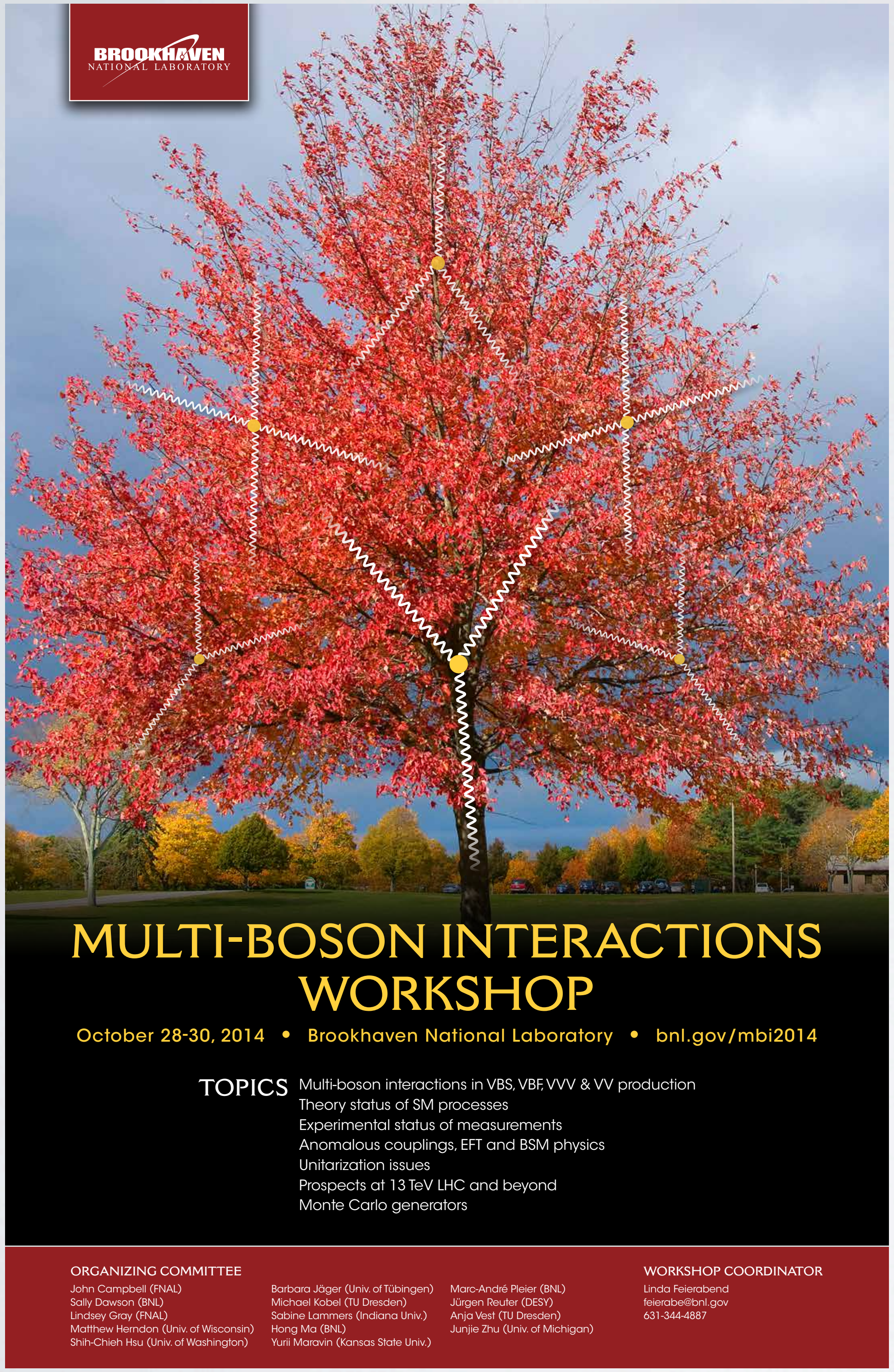
Multi-(EW)-boson Interactions at the Heart of EW Physics:



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