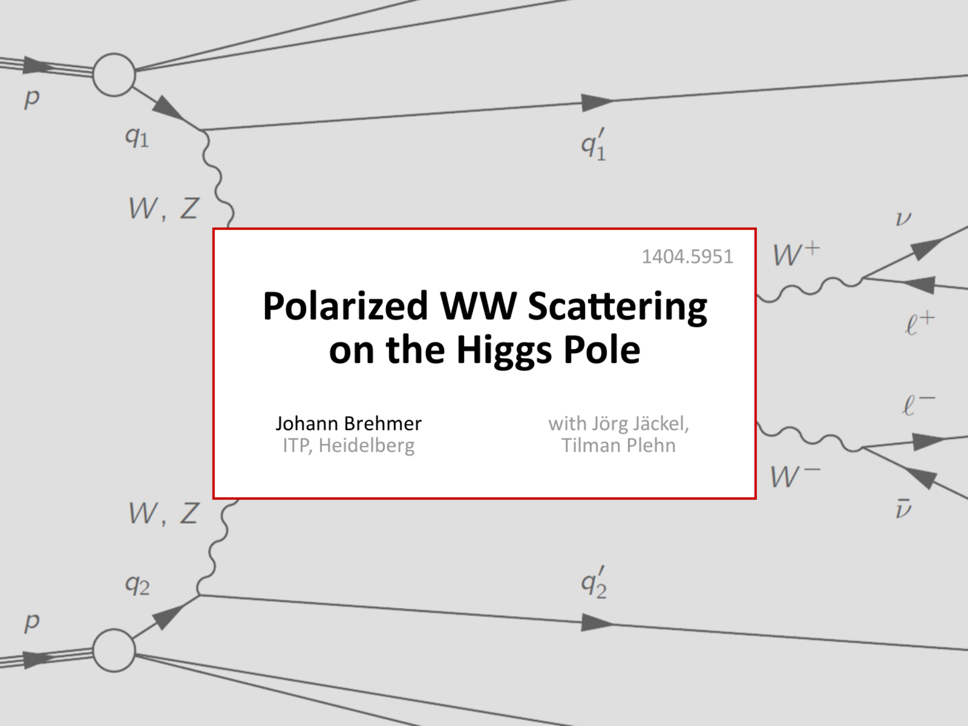

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Polarized WW Scattering on the Higgs Pole

Johann Brehmer
ITP, Heidelberg

with Jörg Jäckel,
Tilman Plehn

Electroweak symmetry breaking (EWSB)

- EWSB reconciles the $W^\pm$, Z masses with gauge invariance
- General description:

$$\left.\begin{array}{l} SU(2)_L \times U(1)_Y \text{ gauge symmetry} \\ \text{Gauge bosons } W^i_\mu, B_\mu \\ \text{Some object } \Sigma \end{array}\right\} \xRightarrow{\Sigma \text{ acquires } vev} \left\{\begin{array}{l} U(1)_Q \\ \text{Massive } W^\pm_\mu, Z_\mu \\ \end{array}\right.$$

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$V(\phi)$: 

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$U(1)_Q$
Massive $W^{\pm}_\mu$, Z_μ
Scalar H

- Alternatives to a fundamental Higgs:
  - No Higgs (Technicolor, . . .)
  - Composite Higgs (Little Higgs, Holographic Higgs, . . .)

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- Alternatives after the Higgs discovery:
  - ~~No Higgs (Technicolor, ...)~~
  - Composite Higgs (Little Higgs, Holographic Higgs, ...)

Contents

Gauge boson polarisations

- Counting degrees of freedom:

$$\overbrace{\underbrace{2}_{\text{transverse}} + \underbrace{1}_{\text{longitudinal}}}^{\text{Massive } W^{\pm}} \stackrel{?!}{=} \overbrace{\underbrace{2}_{\text{transverse}}}^{\text{Gauge boson}}$$

Gauge boson polarisations

- Counting degrees of freedom:

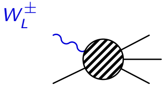
$$\overbrace{\underset{\text{transverse}}{2} + \underset{\text{longitudinal}}{1}}^{\text{Massive } W^{\pm}} = \overbrace{\underset{\text{transverse}}{2}}^{\text{Gauge boson}} + \overbrace{\underset{\text{scalar}}{1}}^{\text{Goldstone } w_{\pm}}$$

Gauge boson polarisations

- Counting degrees of freedom:

Massive $W^{\pm}$				Gauge boson		Goldstone $w_{\pm}$
2	$+$	1	$=$	2	$+$	1
transverse		longitudinal		transverse		scalar

- Equivalence theorem:



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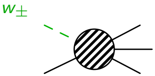

$+\,\mathcal{O}\left(\frac{m_W}{E}\right)$

[Cornwall et al., 1974; Lee at al., 1977]

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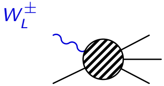

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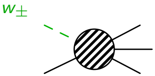

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[Cornwall et al., 1974; Lee at al., 1977]

- Longitudinal modes dominate for high energies:

$$p^\mu = (E,0,0,p_3)^\mu \qquad \varepsilon_T^\mu = \frac{1}{\sqrt{2}}(0,1,\pm i,0)^\mu \qquad \varepsilon_L^\mu = \frac{1}{m_W}(p_3,0,0,E)^\mu$$

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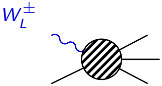

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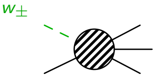

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- New Physics can affect W_L, W_T differently

A simple model

- Idea: measure coupling of H to longitudinal and transverse W separately
- SM:

$$\mathcal{L}_{\mathsf{SM}} \supset \quad g_{\mathsf{SM}}\, H W^+_{L\,\mu} W_L^{-\,\mu} + \quad g_{\mathsf{SM}}\, H W^+_{T\,\mu} W_T^{-\,\mu}$$

- Our model:

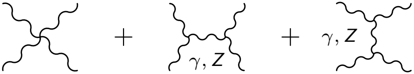
$$\mathcal{L}_{\mathsf{pol}} \supset a_L\, g_{\mathsf{SM}}\, H W^+_{L\,\mu} W_L^{-\,\mu} + a_T\, g_{\mathsf{SM}}\, H W^+_{T\,\mu} W_T^{-\,\mu}$$

with parameters $a_L, a_T \in \mathbb{R}$

Contents

WW scattering and unitarity

- $W_L^+ W_L^- \to W_L^+ W_L^-$ scattering in the SM in the limit $s \gg m_H^2$:



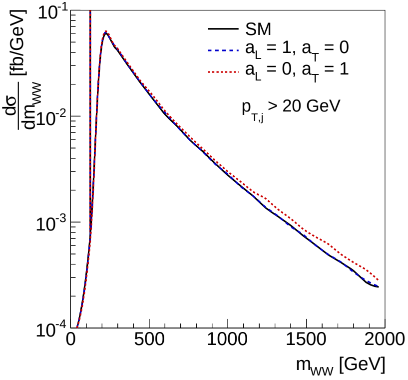
$$= \quad i\frac{s+t}{v^2} + \dots$$

$$= \quad -i\frac{s+t}{v^2} + \dots$$

- Models with HW_LW_L coupling different from the SM: unitarity violation at $\sqrt{s} \gtrsim 1$ TeV

Classical approach: *WW* scattering at large energies

[Bagger et al., 94 – 95; Butterworth et al., 02; Ballestrero et al., 09 – 12; . . .]



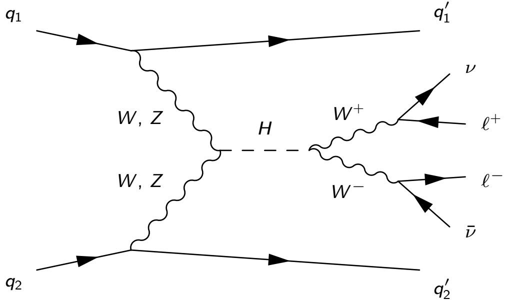
- Theoretically well motivated
  - W_L equivalent to Goldstones
- Measurement prospects dim
  - Low rates
  - Large scale uncertainties

[Han et al., 09]

Contents

Our approach: *WW* scattering on the Higgs pole

- Higgs production in weak boson fusion, $H \to W^+W^- \to \ell^+\nu\ \ell^-\bar{\nu}$



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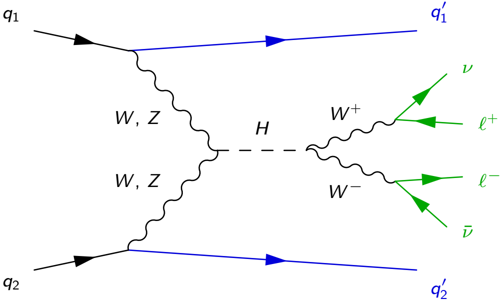
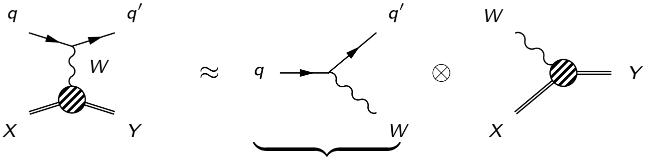


- Choice of observables:
  - Leptons, E_T^{miss} sensitive to final polarisations... works and has been done

    [Han et al., 09]
  - Tagging jets sensitive to initial polarisations (our focus)

Motivation: the effective W approximation (EWA)



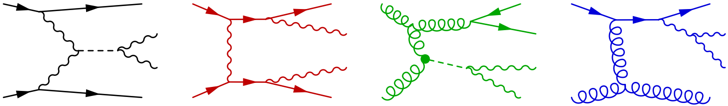
$$\sim \frac{p_T^3}{(m_W^2+p_T^2)^2} \text{ for transverse } W,$$
$$\sim \frac{p_T\, m_W^2}{(m_W^2+p_T^2)^2} \text{ for longitudinal } W$$

[Kane et al., 84; Dawson, 85]

- Implication for WBF:
  - Hard tagging jets $\leftrightarrow$ transverse initial W
  - Soft tagging jets $\leftrightarrow$ longitudinal initial W

Simulation details

- LHC at $\sqrt{s} = 13$ TeV
- Processes (parton level):
  - WBF $H \to W^+W^- + 2$ jets at $\mathcal{O}(\alpha^4)$
  - Continuum $W^+W^- + 2$ jets at $\mathcal{O}(\alpha^4)$
  - GF $H \to W^+W^- + 2$ jets at $\mathcal{O}(\alpha_{ggH}\alpha_s^2\alpha)$
  - Continuum $W^+W^- + 2$ jets at $\mathcal{O}(\alpha_S^2\alpha^2)$



- Acceptance cuts:

Leptons	Tagging jets
$\lvert\eta(\ell)\rvert < 2.5$	$\lvert\eta(j)\rvert < 5.0$
$p_T(\ell) > 10$ GeV	$p_T(j) > 25$ GeV
$p_T(\ell_1) > 20$ GeV	$m_{jj} > 500$ GeV
	$\eta(j_1) \cdot \eta(j_2) < 0$
$p_T^{\text{miss}} > 20$ GeV	$\Delta\eta_{jj} > 4.2$

Contents

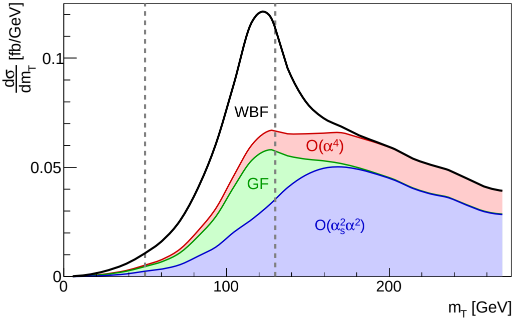
Higgs-resonance selection

- Transverse mass m_T:

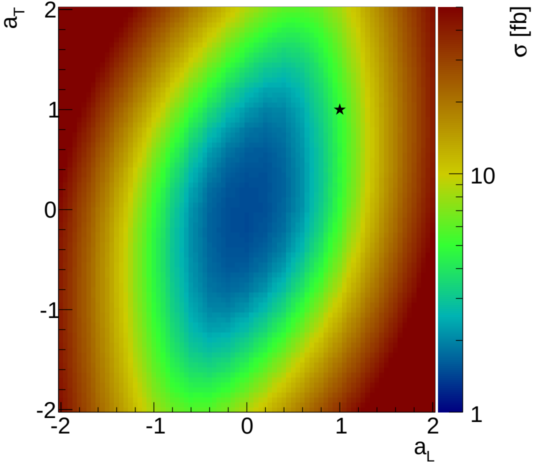
$$m_T^2 = \left(E_{T,\ell\ell} + E_{T,\nu\nu}\right)^2 - \left(\mathbf{p}_{T,\ell\ell} + \mathbf{p}_T^{\text{miss}}\right)^2$$

$$E_{T,\ell\ell} = \sqrt{\mathbf{p}_{T,\ell\ell}^2 + m_{\ell\ell}^2} \qquad E_{T,\nu\nu} = \sqrt{\mathbf{p}_T^{\text{miss}\,2} + m_{\ell\ell}^2}$$

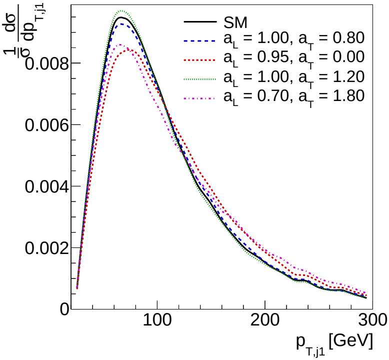
- Higgs-resonance cut: $50\ \text{GeV} < m_T < 130\ \text{GeV}$



Resonance rate



Leading jet p_T



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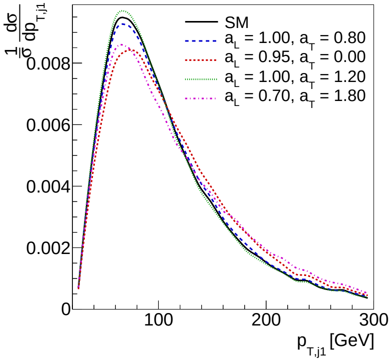
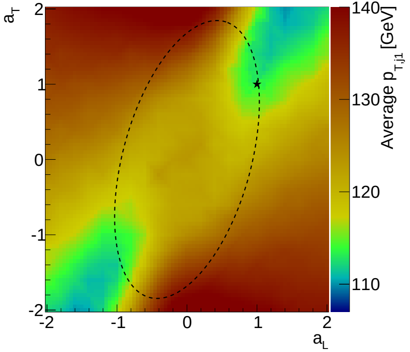
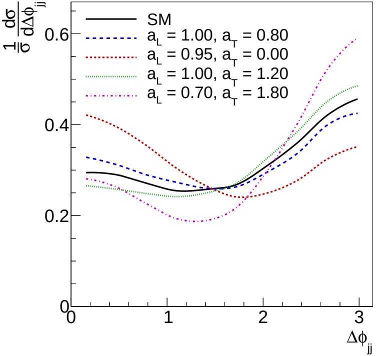




Angular correlation between jets



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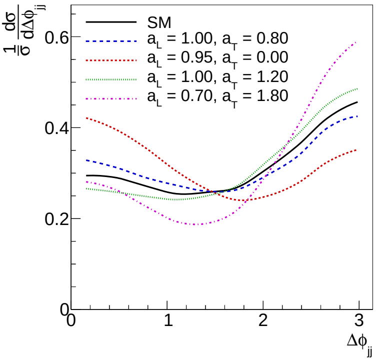
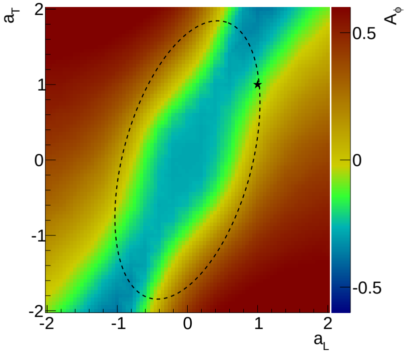


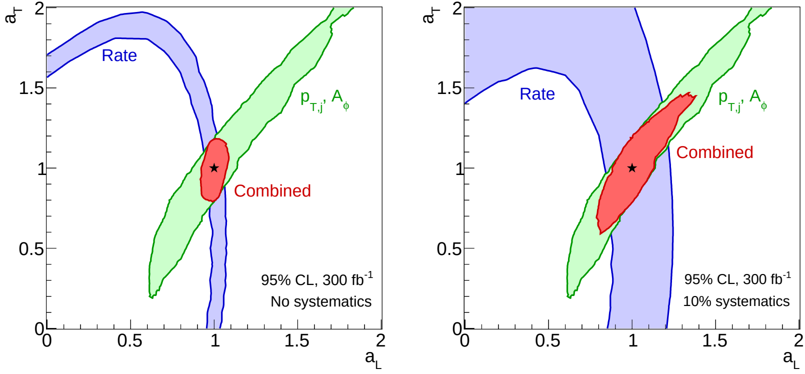


$$A_\phi = \frac{\sigma(\Delta\phi_{jj} < \frac{\pi}{2}) - \sigma(\Delta\phi_{jj} > \frac{\pi}{2})}{\sigma(\Delta\phi_{jj} < \frac{\pi}{2}) + \sigma(\Delta\phi_{jj} > \frac{\pi}{2})}$$

[Eboli et al., 00; Plehn et al., 02, . . .]

Significance at LHC Run II

Expected exclusion regions after 300 fb^{-1}, assuming no signal:

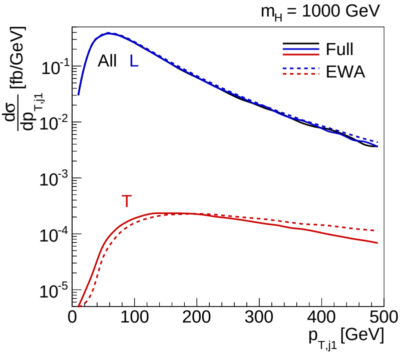


Conclusions

- W polarisations linked to structure of symmetry breaking
- WW scattering at Higgs resonance:
  tagging jets probe polarisations of initial WW pair
  - Jet p_T
  - $\Delta\phi$ between jets
- Longitudinal and transverse Higgs–gauge couplings can be probed at $\mathcal{O}(20\%)$ after 300 fb^{-1} of data at 13 TeV

Contents

Validity of the EWA



- $m_H < 2m_W$: on-shell assumption not valid anymore
  $\Rightarrow$ cannot use EWA at Higgs resonance

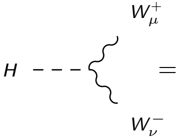
Effective field theory

- New physics at large energies → effective operators at low energies
- Models with composite Higgs can e. g. generate

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_W}{\Lambda^2} \left(D_\mu \phi\right)^\dagger \hat{W}^{\mu\nu} \left(D_\nu \phi\right)$$

[Giudice et al., 07]

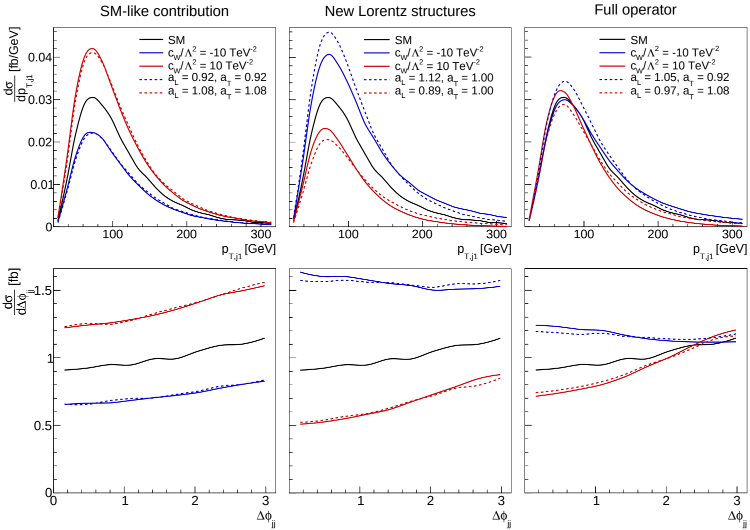
- Modification of HWW vertex:



$$= igm_W \left[\left(1 + \frac{c_W}{2\Lambda^2} m_H^2\right) \eta_{\mu\nu} + \frac{c_W}{2\Lambda^2} \left(p_\mu^H p_\nu^+ + p_\mu^- p_\nu^H\right) \right]$$

  - First term scales SM vertex $\quad \longleftrightarrow \quad a_L = a_T = 1 + \frac{c_W}{2\Lambda^2} m_H^2$
  - Second term only affects longitudinal W $\quad \longleftrightarrow \quad a_L$ is momentum-dependent, $a_T = 0$

Dimension-6 operator vs simple model



Polarisations and reference frames