Multi-boson production and VBF with Higgs anomalous couplings

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JHEP 1305 (2013) 005 [arXiv:1212.3860]
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Les Houches 2013: New Physics Working Group Report [arXiv:1405.1617]
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Plan

- **Background**
  - Higgs anomalous couplings, HVV
  - Longitudinal vector bosons
  - Unitarization of vector boson scattering
  - Effective Lagrangian for anomalous couplings
- **Multi-boson production**
  - Large increases in cross section for non-SM VVH coupling
- **Measuring the anomalous VVH couplings via VBF**
  - More model independent than production gluon fusion
- **Conclusion**

Anomalous coupling

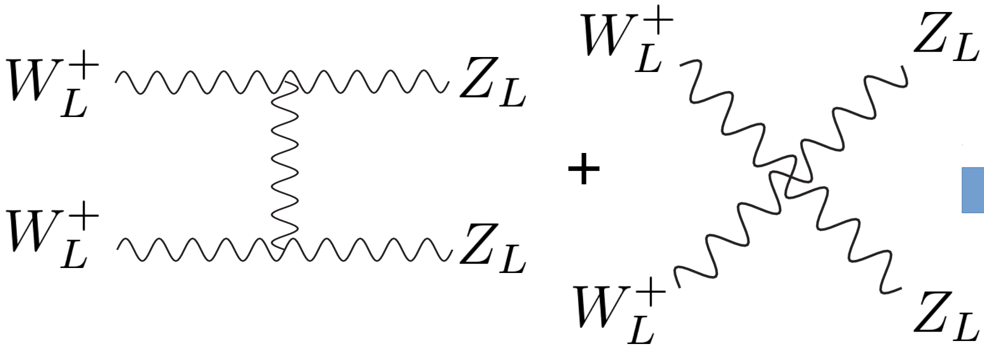
- **Anomalous couplings**
  - Non-SM Higgs-Vector boson couplings predicted by many models
  - e.g. MSSM, NMSSM, pseudo-GB Composite Higgs

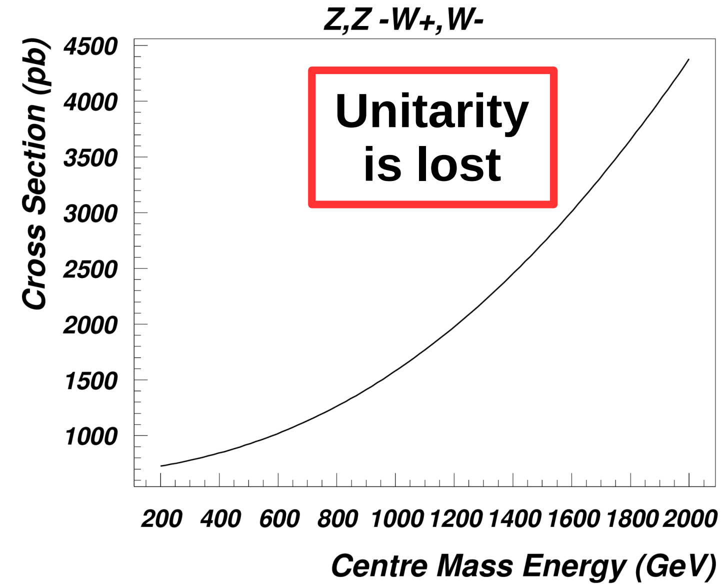
- **Longitudinal Vector Bosons, V_L**
  - Originate from EWSB Goldstones

$$\Phi = \begin{pmatrix} i\pi^+ \\ \frac{1}{\sqrt{2}}\left((h+v)+i\pi^0\right) \end{pmatrix}$$

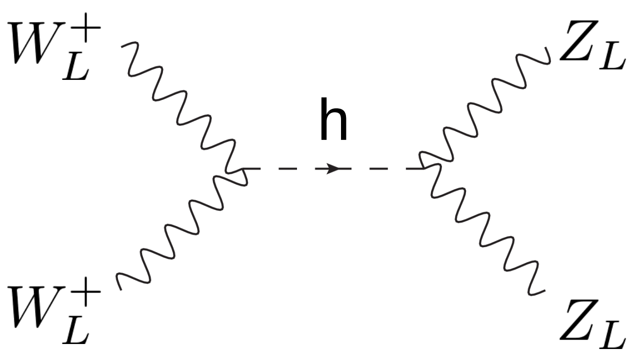
  - $V_L = W^{\pm}_L, Z_L$

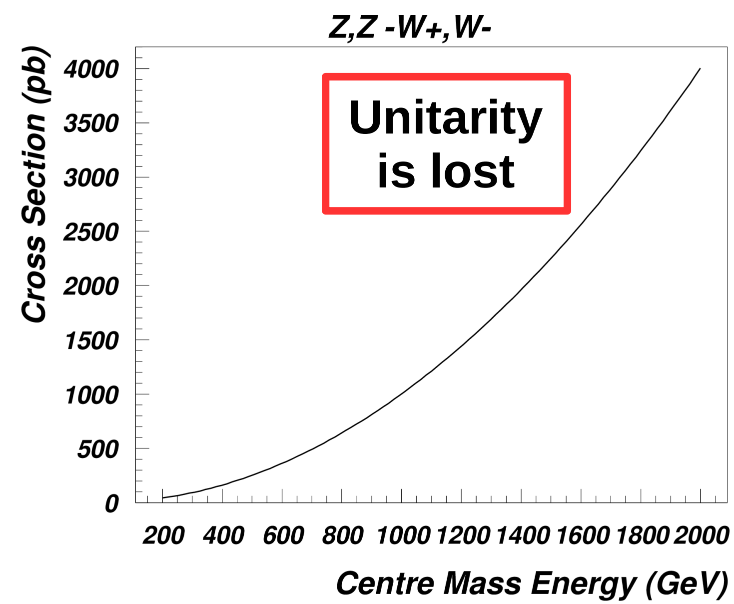
Higgs unitarizes the $V_L, V_L \rightarrow V_L, V_L$ scattering



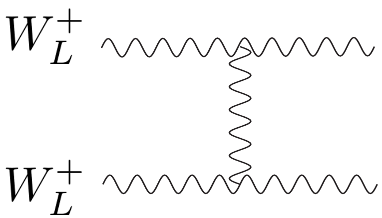


$$\text{Amplitude} \propto s$$





Higgs unitarizes the $V_L,V_L \rightarrow V_L, V_L$ scattering



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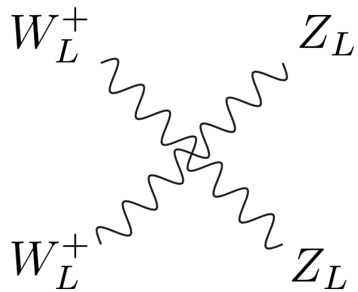

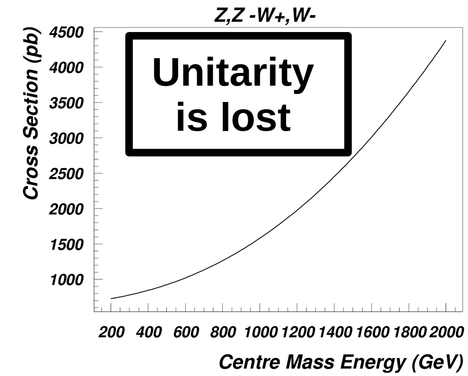

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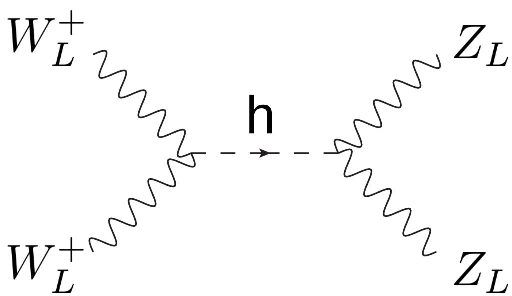

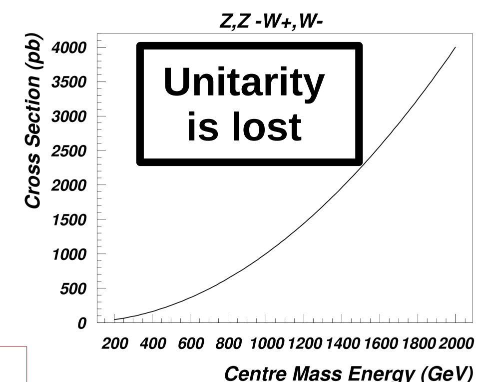

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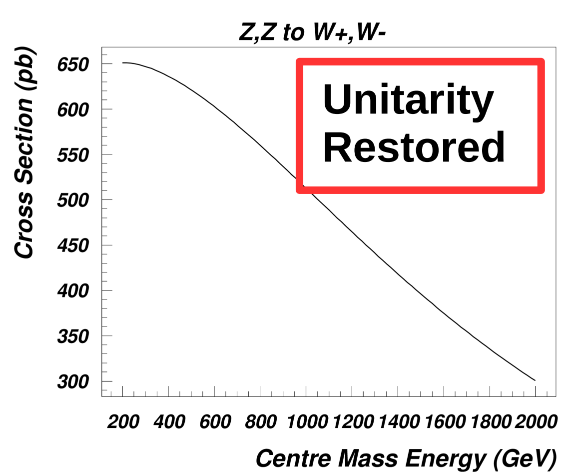


- **Cancellation** of terms linear in s from amplitudes of both diagrams.
- **Restores** unitarity.

Effective Lagrangian
Anomalous Couplings

- Enforce custodial symmetry
  - Goldstone Bosons, π_i fit into → $\Sigma = e^{\frac{i\vec{\sigma}\cdot\vec{\pi}}{v}}$
- Truncate at 2 derivative level

$$\begin{aligned} \mathcal{L}_{\rm eff} &= \frac{v^2}{4}\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + b_3\frac{h^3}{v^3} + \cdots\right) \mathrm{Tr}\left[D_\mu \Sigma D^\mu \Sigma^\dagger\right] \\ &+ \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - d_3 \lambda v h^3 - d_4 \frac{\lambda}{4} h^4 + \cdots \end{aligned}$$

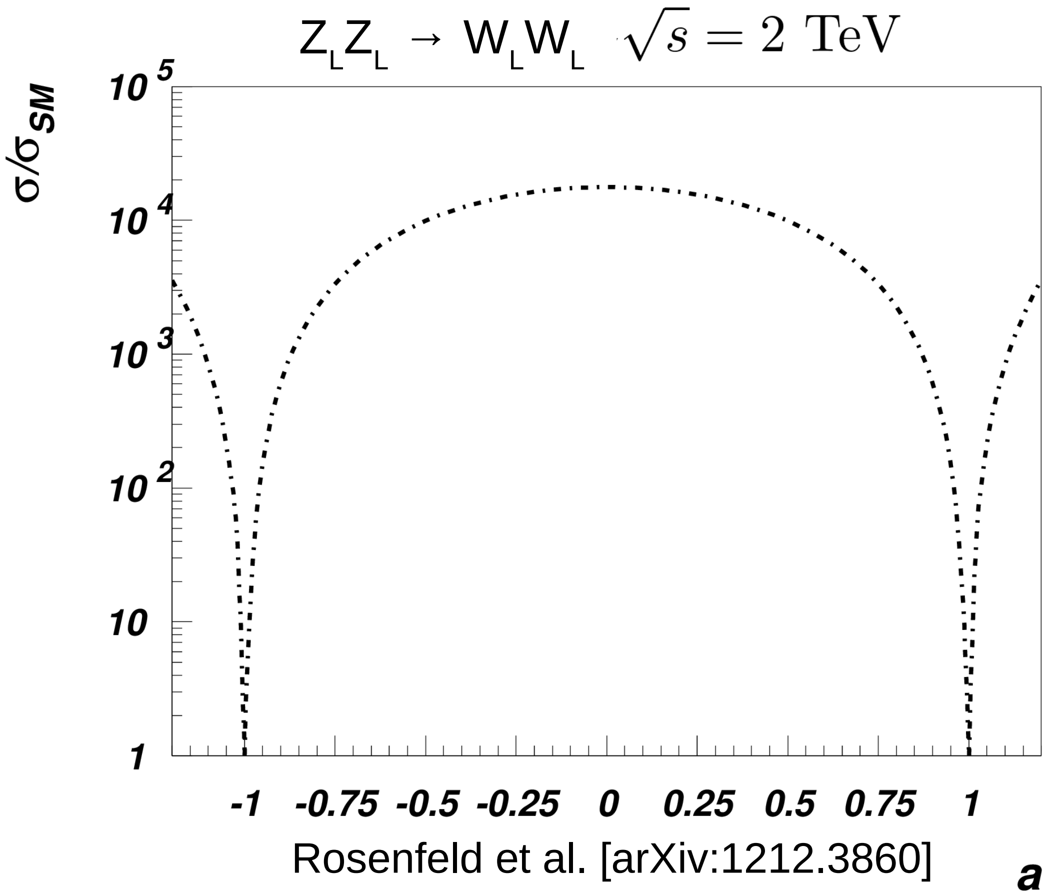
JHEP 1005 (2010) 089 [*arXiv:1002.1011*].

- SM reproduced via field redefinition if,

$$a = b = d_3 = d_4 = 1\ ,\ \ b_3 = 0$$

Cancellation requires **exact** SM coupling

$$\mathcal{L}_{\text{eff}} = \frac{v^2}{4}\left(1 + 2a\frac{h}{v} + \cdots\right)\text{Tr}\left[\partial_\mu \Sigma \partial^\mu \Sigma^\dagger\right] + \ldots$$



Rosenfeld et al. [arXiv:1212.3860]

- **Large increases** $\mathcal{O}(10^2 = 10^3)$ in $V_L V_L$ scattering, even for **small deviations** (<10%) from SM.

Amplitudes using this effective Lagrangian

$$\mathcal{A}_{Z_L,Z_L\to W_L^+,W_L^-} = \frac{s\left[(1-a^2)s - m_h^2\right]}{v^2(s-m_h^2)} \xrightarrow[s\gg m_h^2]{} (1-a^2)\frac{s}{v^2}$$

- Non-SM Higgs couplings means **cancellation is incomplete.**
- Amplitude still diverges for high energy if coupling is not standard model value.
- Scattering is **partially unitarized.**
  - $\text{Unitarity violated at } \sim 1\text{ TeV} \to 2.5\text{ TeV}$

Multi-particle production

$$\mathcal{A}_{Z_L,Z_L\to h,h,h} \propto \frac{1}{4v^3}\left[s\left(-4a^3+4ab-3b_3\right)\right.$$
$$-m_h^2\left(-8a^3+8ab+3b_3\right)$$
$$\left.+\frac{4m_h^4}{s}\left(a^3+ab-6b_3-3a^2d_3\right)+\cdots\right]$$

SM when $a=b=d_3=d_4=1$ and $b_3=0$

- Cancellation for SM values only.
- Again $\mathcal{A} \propto s$
- In general, naïve power counting gives,

$$A_{NL\sigma M}(2\to n) \sim \frac{s}{v^n}$$

Multi-particle scattering

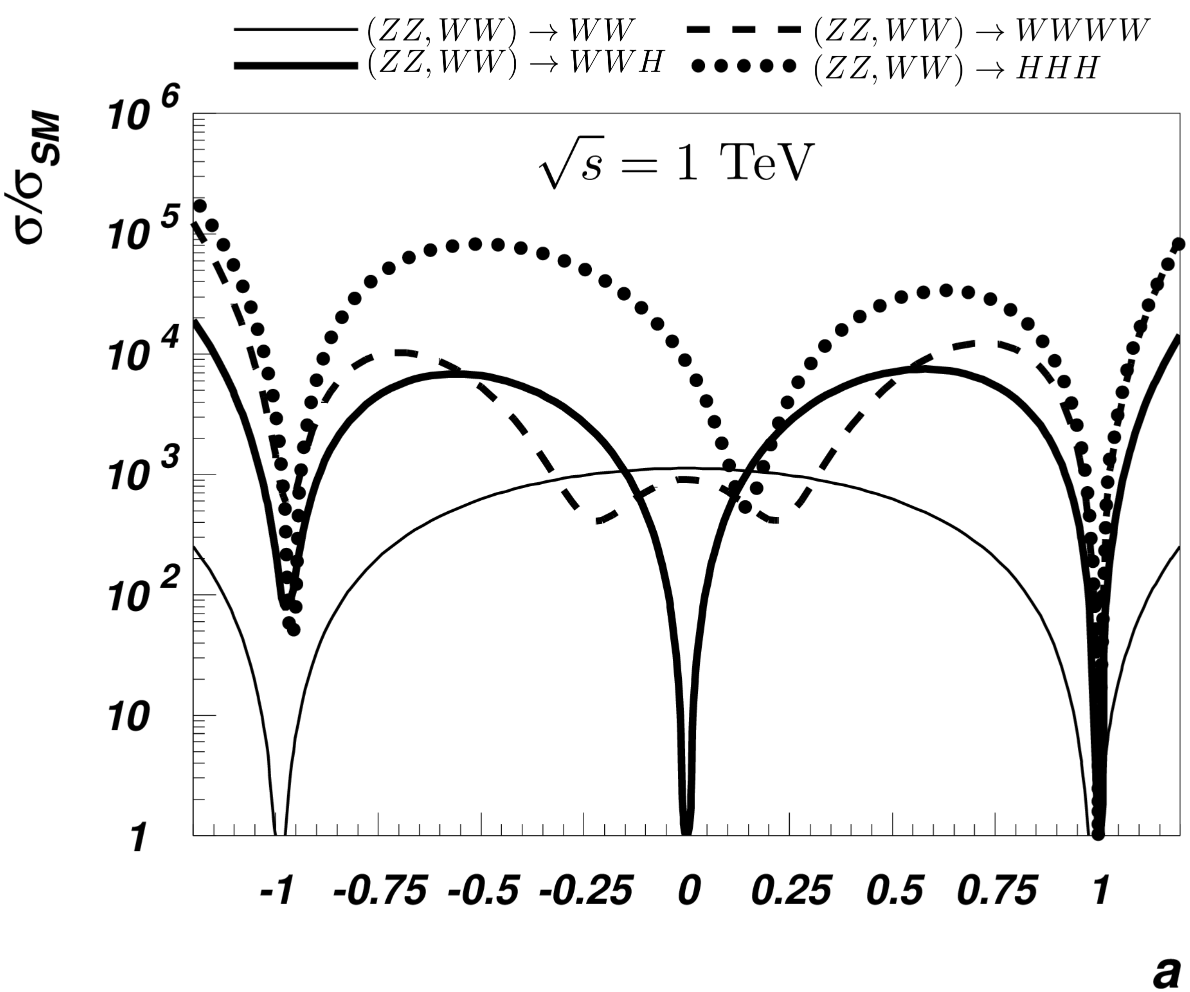
- Since the relativistic n-body phase space $\propto s^{n-2}$ for this model we expect,

$$A_{NL\sigma M}(2 \to n) \sim \frac{s}{v^n}$$

$$\sigma(2 \to n) \sim \frac{1}{s}\left(\frac{s}{v^n}\right)^2 s^{n-2} = \frac{s^{n-1}}{v^n}$$

- Therefore, we generally expect **larger increases** in cross section **for larger numbers** of final state particles.

Results – Longitudinal Polarisation Only



- In this case all other couplings kept at SM value.
- Large enhancements of order $10^3 - 10^4$ even for small (< 10%) deviations from SM.

Including Transverse Polarisation

$$\sqrt{s} = 2\ \mathrm{TeV}$$

Channel	a = 1 (SM) (pb)	a = 0.9 (pb)
$Z_L Z_L \to W^+_L W^-_L$	0.13	295
$Z Z \to W^+ W^-$	610	655
$Z_L Z_L \to W^+_L W^-_L h$	0.002	350
$Z Z \to W^+ W^- h$	10.9	46.2
$Z_L Z_L \to h h h$	0.00049	112
$Z Z \to h h h$	0.047	13.6

- Z, W means full boson (including transverse polarisation)
- Transverse polarisation masks increase in cross section of longitudinal component.
- Enhancement order 10^{2-3} still obtained where contributions from transverse bosons not large.

Proton-Proton Collisions

- Proton scattering simulated at parton level.
- VBF cuts applied to select relevant processes..

Process (14 TeV)	SM (a = 1)	a = 0.9
$pp \to jjW^+W^-$	95.2 fb	99.3 fb
$pp \to jjW^+W^-h$	0.011 fb	0.0088 fb
$pp \to jjhhh$	1.16×10^{-4} fb	0.0566 fb

- Some processes, the cross section actually decreases for non-SM couplings.
  - For $a < a_{SM}$ the decrease in contribution from transversely polarised bosons is larger than increase in V_L contribution.

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- Some processes, the cross section actually decreases for non-SM couplings.
  - For $a < a_{SM}$ the decrease in contribution from transversely polarised bosons is larger than increase in V_L contribution.
- For scattering to jjhhh, large increases still observed
  - However cross section still very small at LHC energies
  - Very challenging to detect at LHC at current energies

100 TeV Collider?

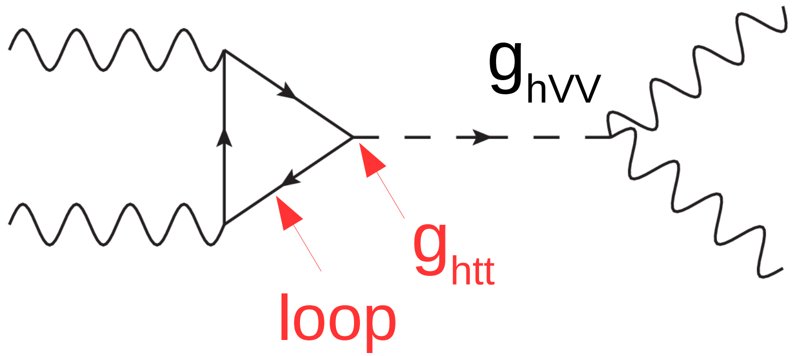
$$pp \to jjhhh$$

Coupling	Cross Section	Unitarity Violated (% of events)
a = 0.9	37.6 fb	86.4%
a = 0.99	0.52 fb	52.8%

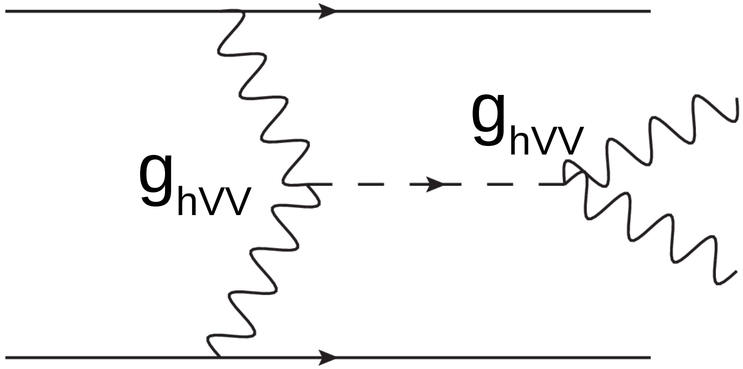
- Number of events – large with small background
- However unitarity violated in > 50% for even 1% deviation. **Model no longer valid!**
- Need to consider more UV complete theory with effects of new resonances.

Measuring Couplings

- Usual method is model dependent.



- Using VBF only depends on g_{hVV}



- More model independent.

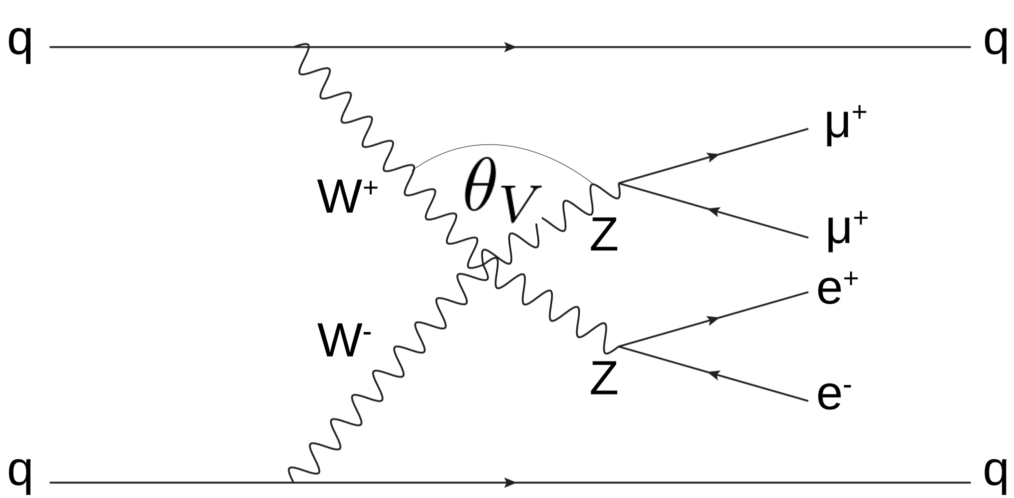
Measuring Couplings

- Longitudinal component increases more than transverse for non-SM hVV coupling, a**.**
- Therefore, ***measure longitudinal fraction*** could translate to ***measurement of coupling***.
- We show that this is possible using a combination of three main observables.
  - **Observable 1**, θ_V
  - **Observable 2,** θ^*
  - **Observable 3,** $\sqrt{s_{VV}}$ of vector boson scattering

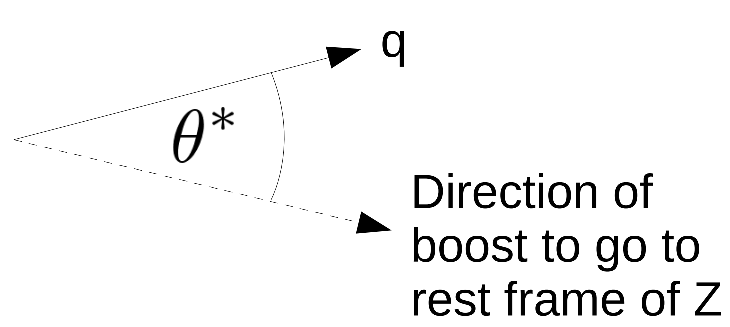
Observables $\theta_V, \theta^*, \sqrt{s_{VV}}$

- θ_V, angle **in rest frame** of vector boson scattering between incoming and outgoing vector.
- θ^*, angle in ***rest frame of decaying boson***, between fermion in the decay products and direction of boost to get to the rest frame.
- $\sqrt{s_{VV}}$ = invariant mass of all decay products.

Full Process

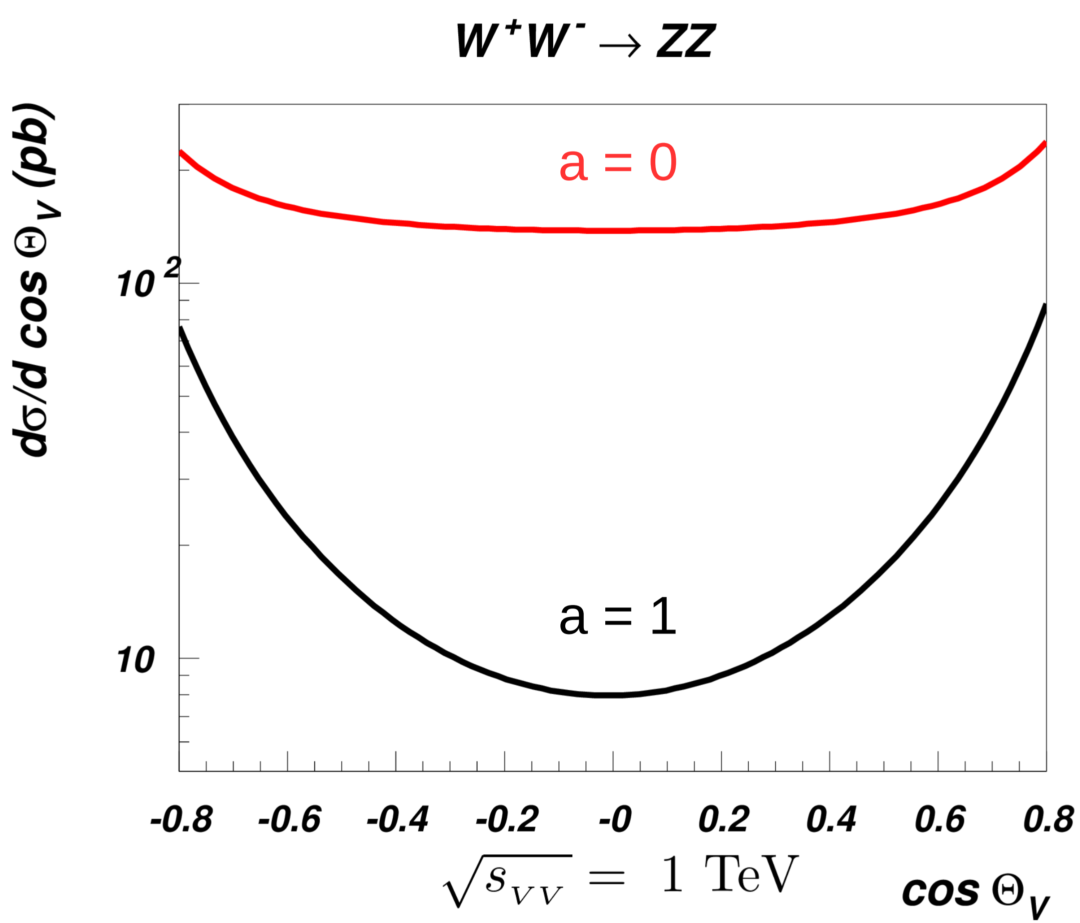


In rest frame of the Z



Observable 1, θ_V

- Overall **increase in cross section** if **a = 0**.
- The **a = 0** case has a much larger proportion of ***longitudinally polarized*** bosons.

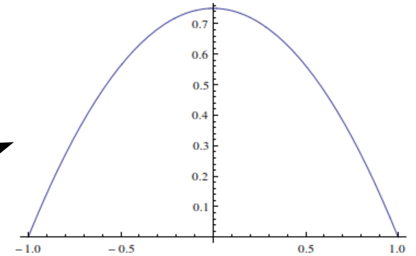


- Therefore cuts which reduce **a = 1** more than **a = 0** should increase the proportion of longitudinally polarized bosons.
- e.g. $|\cos\theta_V| < 0.5$
- Transversely polarised bosons have large t-channel amplitude with much larger forward-backward scattering.

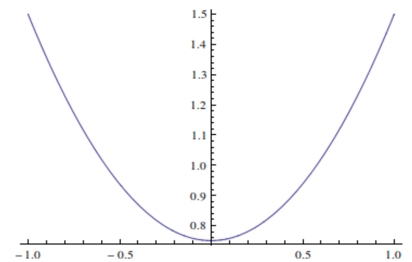
Observable 2, θ^*

- Distribution of decay from transverse and longitudinal polarisations.

$$P_L(\cos\theta^*) = \frac{3}{4}(1-\cos^2\theta^*)$$ **Longitudinal**



$$P_\pm(\cos\theta^*) = \frac{3}{8}(1\pm\cos\theta^*)^2$$ **Transverse**



- By fitting,

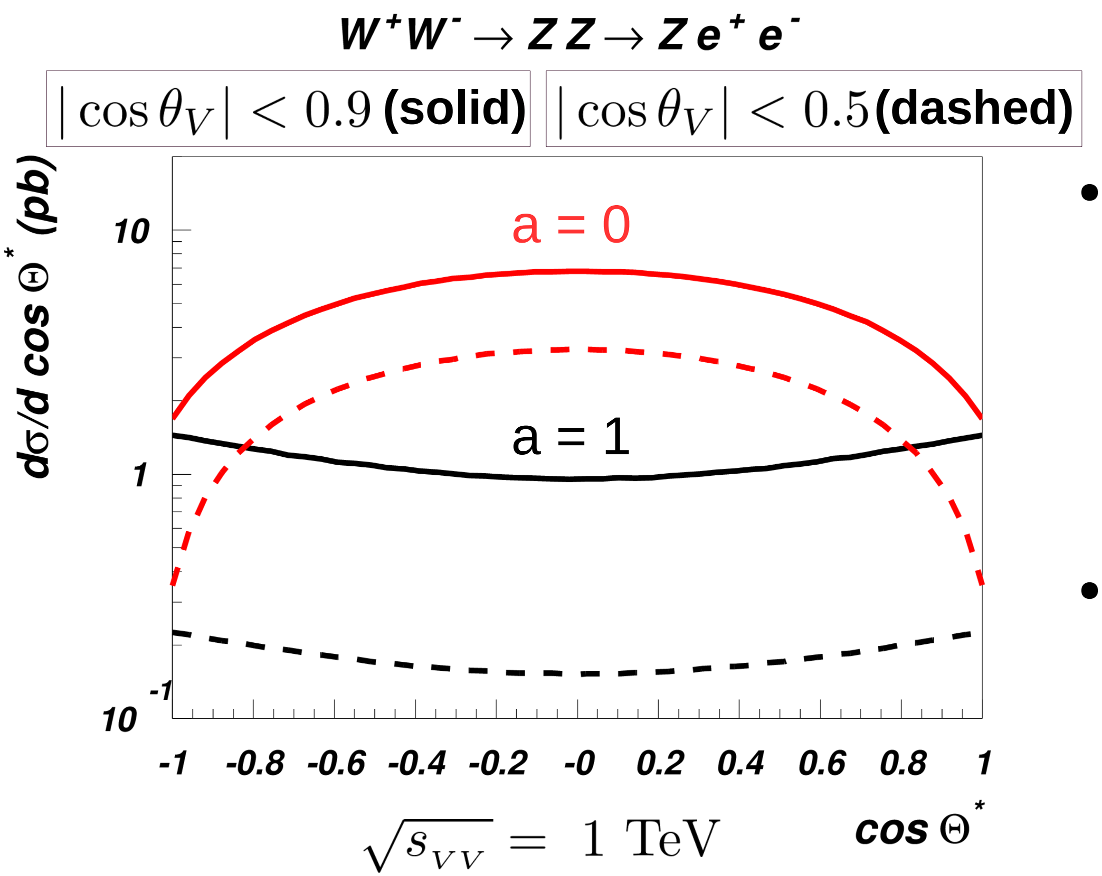
$$P(\cos\theta^*) = f_L P_L(\cos\theta^*) + f_+ P_+(\cos\theta^*) + f_- P_-(\cos\theta^*)$$

with, $f_L + f_+ + f_- = 1$

- We can **reconstruct the average polarizations** of the vector bosons.

Observable 2, θ^*

- **a = 0** has a much larger cross section for small $\cos\theta^*$ than the **a = 1** case.
- The cut $|\cos\theta_V| < 0.5$ increases this difference.



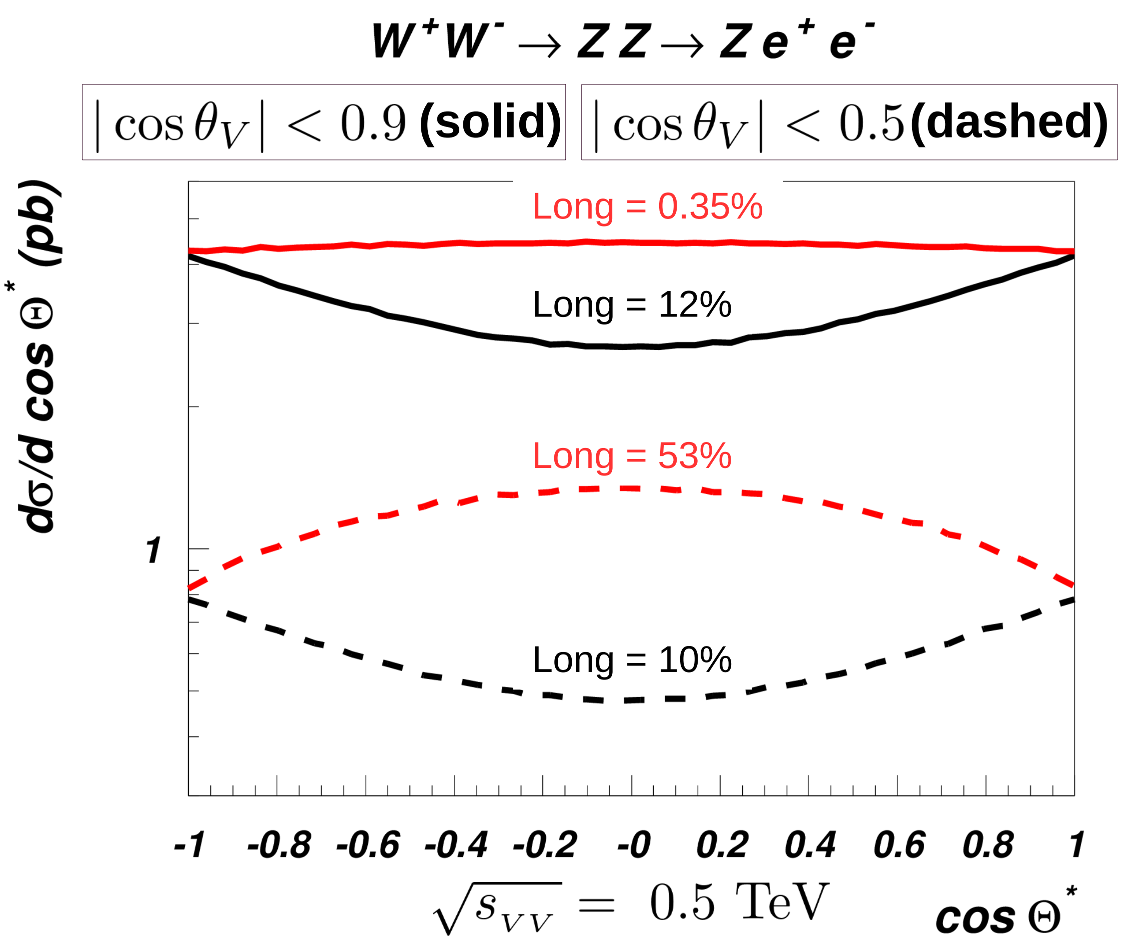
- Suggests optimal cut to increase fraction longitudinally polarised would be cut on both θ_V and θ^*.
- e.g. $|\cos\theta_V| < 0.5$

  and $|\cos\theta^*| < 0.5$

Fitting to find V_L component

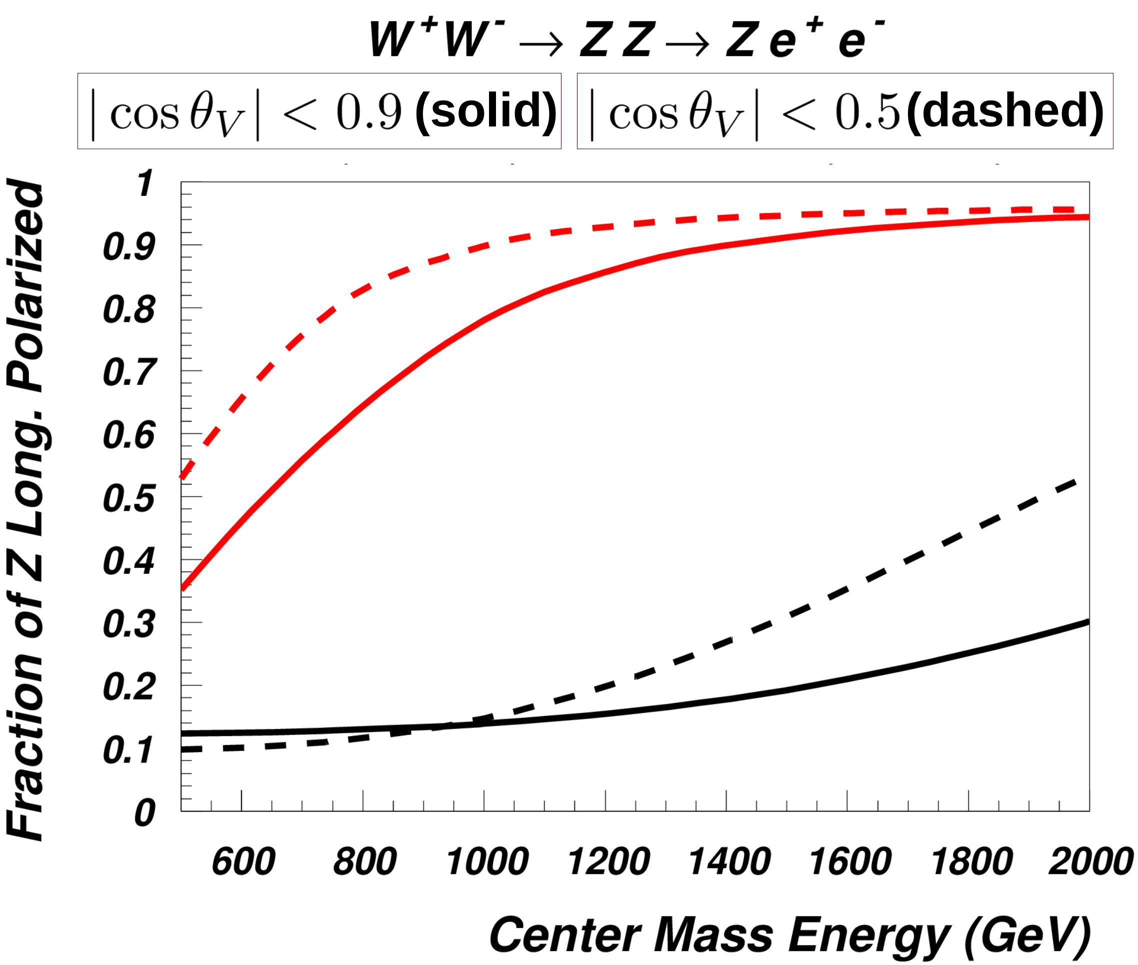
$$P(\cos\theta^*) = f_L P_L(\cos\theta^*) + f_+ P_+(\cos\theta^*) + f_- P_-(\cos\theta^*)$$

$$P_L(\cos\theta^*) = \frac{3}{4}(1 - \cos^2\theta^*) \qquad P_\pm(\cos\theta^*) = \frac{3}{8}(1 \pm \cos\theta^*)^2$$



- When a = 0, the proportion of longitudinally polarised boson is higher as expected.
- $|\cos\theta_V| < 0.5$ cut increases proportion of longitudinal bosons.

Observable 3, $\sqrt{s_{VV}}$

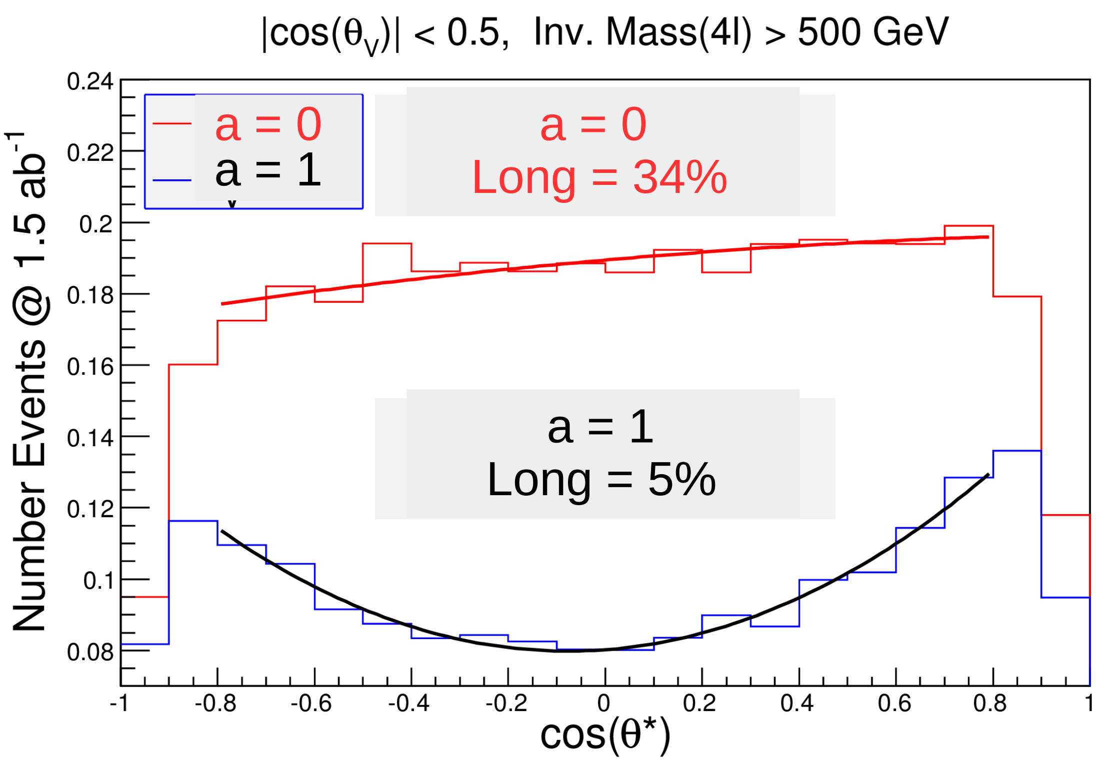


- Fitting function used to plot fraction of Z longitudinally polarized vs $\sqrt{s_{VV}}$
- As $\sqrt{s_{VV}}$ increases, longitudinal polarisation dominates.
- To be expected as $\sigma(V_L V_L \rightarrow V_L V_L) \propto s$
- **Cut for higher** $\sqrt{s_{VV}}$ will also increase fraction longitudinally polarised.

Will this work at the LHC?

- So far only discussed VV → VV at parton level.
  - Full process at LHC much messier.
  - Cuts may not work as well.
- Need to study **LHC sensitivity** to probe fraction of longitudinal polarisation and therefore measure a.
- Ongoing work. So far studied,
  - $pp \to jjZZ \to e^+e^-\mu^+\mu^-jj$
- Plan to extend to all relevant processes and decays.

Fit again to find how well cuts work in fuller process?



$$pp \rightarrow jjZZ \rightarrow e^+e^-\mu^+\mu^-jj$$

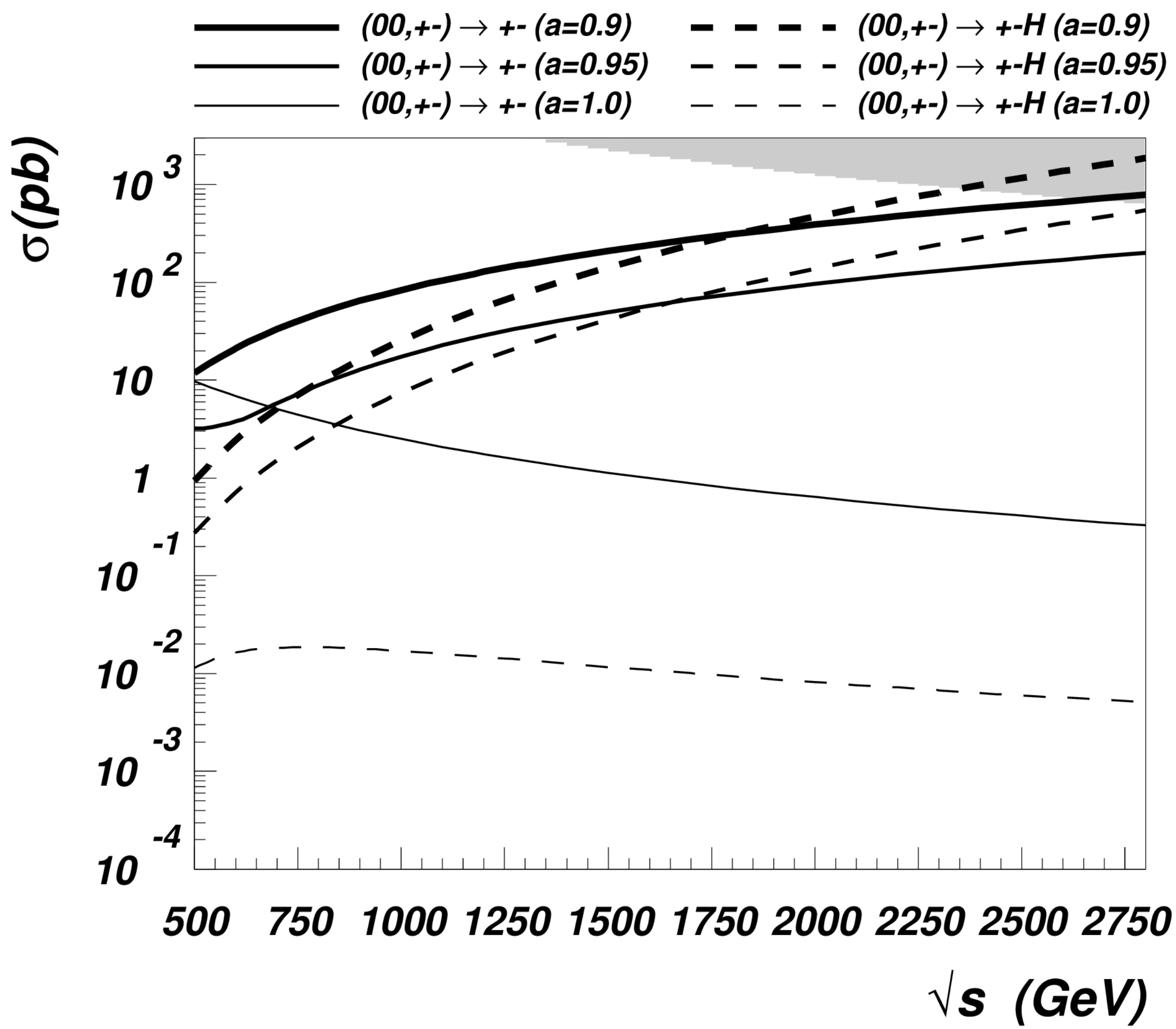
- Cuts used
  - $|\cos\theta_V| < 0.5$
  - Invariant mass (4l) > 500 GeV.
- **Large increase in longitudinal fraction** from 0.05 to 0.34, for a = 1 vs a = 0.
- Very small cross section for studied process, but should be ~ x 250 if semi-leptonic decays and complete set of processes (ZZ, WW, WZ) included.
- Expect sensitivity to a at approx 20% with 100 fb^{-1}.

Conclusions

- Very large increase in cross section for multi-boson production.
  - Total cross section will be difficult at LHC energies.
  - Cuts to reduce transversely polarised background may make this viable at the LHC.
- Measurment of HVV coupling, a.
  - Shown that a combination of cuts on 3 variables can isolate the longitudinal components of vector boson scattering.
  - Should give alternative, model independent way of measuring an anomalous HVV coupling.

END

Results



Notation

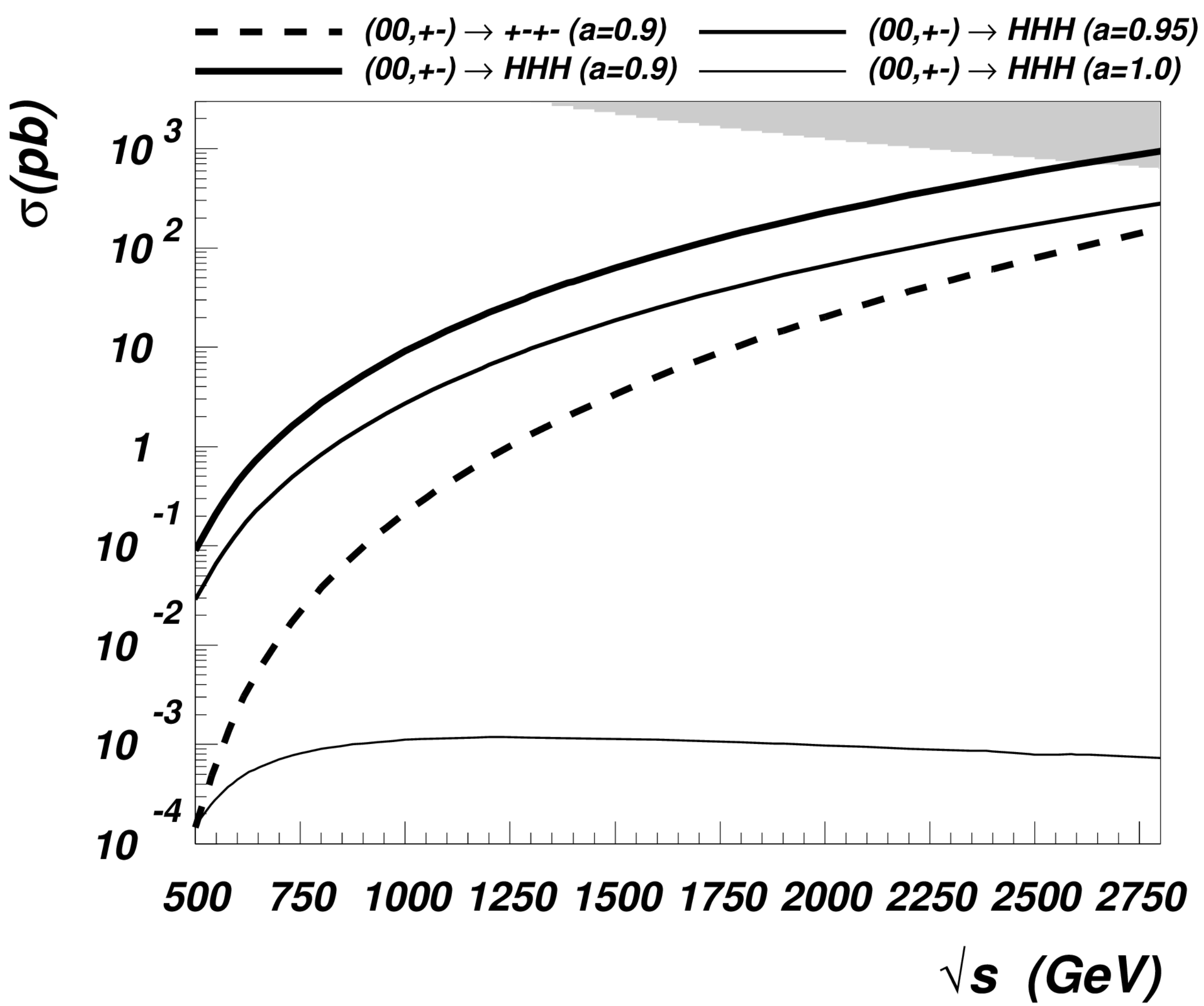
0 = Z_L

+ = W_L^+

- = W_L^-

- Grey area is unitarity bound, other couplings are SM values
- 0 = Z_L, + = W_L^+, - = W_L^-
- Cross sections increase with energy for non-SM couplings

Results



Notation

0 = Z_L

\+ = W_L^+

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- Cross section quickly stabilises for SM value only

Including Transverse Polarisation

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$Z Z \to W^+ W^- h$	10.9	46.2
$Z_L Z_L \to h h$	0.18	158
$Z Z \to h h$	7.61	15.7
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- Z, W means full boson (including transverse polarisation)