Probing Higgs Boson with Vector-Boson Scattering

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AB, A. Oliveira, R. Rosenfeld, M. Thomas : JHEP 1305 (2013) 005, arXiv:1212.3860
AB, E. Boos, V. Bunichev, Y. Maravin, A. Pukov, R. Rosenfeld, M. Thomas :
arXiv:1405.1617 (Les Houches 2013: Physics at TeV Colliders. Contribution #6)
AB, M.Thomas, P.Hamers, work in progress

PARTICLE PHYSICS UNIVERSITY OF BIRMINGHAM

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OUTLINE

- Preface
  - the history and the role of vector boson scattering (VBF), V_Ls, their connection to Higgs boson physics and unitarity.
- VV→ VV process at the LHC
  - selection of the longitudinal vector bosons
  - model-independent sensitivity to HVV coupling using three main observables
- VV→ hhh at future pp colliders
  - cross section enhancement and unitarity violation
  - high sensitivity to HVV coupling
- Conclusions

Higgs Mechanism in the SM

Spontaneous breaking Yang-Mills gauge theory via fundamental scalar:

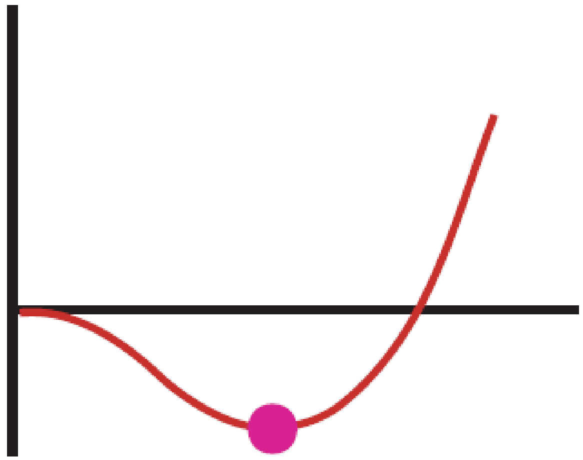
add one scalar doublet φ ***with*** $I = \frac{1}{2}, Y = +\frac{1}{2}$

$$\mathcal{L} = |D_\mu \varphi|^2 - V(|\varphi|) - \frac{1}{4}(F^a_{\mu\nu})^2 - \frac{1}{4}(G^a_{\mu\nu})^2$$

+ couplings to quarks and leptons

where $V(|\varphi|) = \mu^2 |\varphi|^2 + \lambda |\varphi^4|$ ***and*** $\mu^2 < 0$

for which $\langle \varphi \rangle \neq 0$



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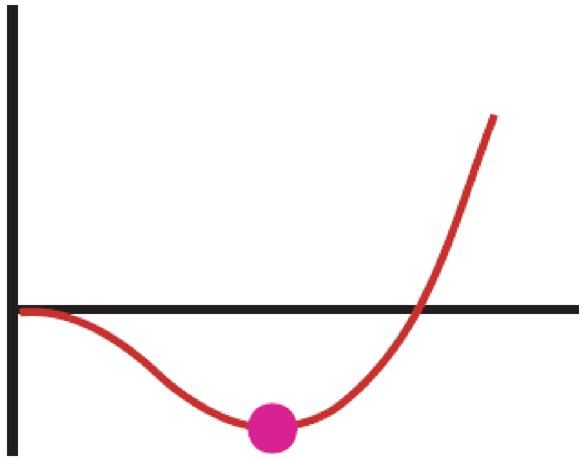

The filed φ *has the general structure*

$$\varphi(x) = \begin{pmatrix} \pi^+(x) \\ (v + h(x) + i\pi^0(x))/\sqrt{2} \end{pmatrix}$$

which be written as ("polar decomposition")

$$\varphi(x) = exp\left(i\frac{\pi^a(x)\tau^a}{v}\right)\begin{pmatrix} 0 \\ (v + h(x))/\sqrt{2} \end{pmatrix}$$

$\pi^\pm$, π^0 are Goldstone bosons
In the theory with global symmetry, they are massless.
In the theory with gauge symmetry, they are gauge degrees of freedom, and become part of W, Z

Higgs Mechanism in the SM

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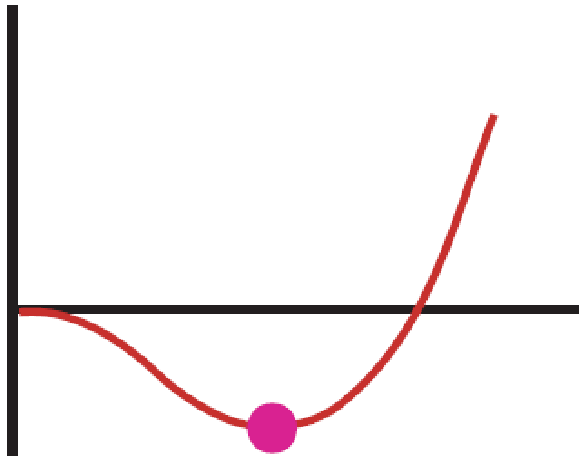

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$$\varphi(x) = \begin{pmatrix} \pi^+(x) \\ (v + h(x) + i\pi^0(x))/\sqrt{2} \end{pmatrix}$$

which be written as ("polar decomposition")

$$\varphi(x) = \Sigma(x) \begin{pmatrix} 0 \\ (v + h(x))/\sqrt{2} \end{pmatrix}$$

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Before the Higgs Boson discovery, higgsless non-linear sigma model was an option:

one can eliminate h(x) and still have EWSB via Sigma term in the Higgsless model

$$\mathcal{L}_H \to \mathcal{L}_\Sigma = \frac{v^2}{4} tr\left([\mathcal{D}^\mu \Sigma]^\dagger \mathcal{D}_\mu \Sigma \right)$$

$$\to (0 \quad v/\sqrt{2}) \left| \frac{g}{\sqrt{2}} W^+ \sigma^+ + \frac{g}{\sqrt{2}} W^- \sigma^- + \frac{g}{2} W^0 \sigma^3 + \frac{g'}{2} B \right|^2 \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

$$= \frac{v^2}{4} \left[g^2 W^+ W^- + \frac{1}{2} (-g W^0 + g' B)^2 \right]$$

- ***Goldstone bosons (pions) become the longitudinal components of vector bosons $V_L = W^\pm_L, Z_L$***

Non-linear sigma model

There are many 4D CP-conserving operators that can be written down e.g.

$$\mathcal{L}_1 = \frac{1}{2} g^2 \alpha_1 B_{\mu\nu} \mathrm{Tr}(T F^{\mu\nu})$$

$$\mathcal{L}_2 = \frac{1}{2} i g \alpha_2 B_{\mu\nu} \mathrm{Tr}(T[V^\mu, V^\nu])$$

$$\mathcal{L}_3 = i g \alpha_3 \mathrm{Tr}(F_{\mu\nu}[V^\mu, V^\nu])$$

$$\mathcal{L}_4 = \alpha_4 [\mathrm{Tr}(V_\mu V_\nu)]^2$$

$$\mathcal{L}_5 = \alpha_5 [\mathrm{Tr}(V_\mu V^\mu)]^2$$

where

$$V_\mu \equiv (D_\mu \Sigma)\, \Sigma^\dagger$$

$$T \equiv \Sigma \tau^3 \Sigma^\dagger$$

$$\Sigma(x) = \exp\left[i \frac{\varphi^a(x) \tau^a}{v} \right]$$

Appelquist, Bernard '80 ; Longitano '80

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$$\mathcal{L}_6 = \alpha_6 \mathrm{Tr}(V_\mu V_\nu) \mathrm{Tr}(T V^\mu) \mathrm{Tr}(T V^\nu)$$

$$\mathcal{L}_7 = \alpha_7 \mathrm{Tr}(V_\mu V^\mu) [\mathrm{Tr}(T V_\nu)]^2$$

$$\mathcal{L}_8 = \tfrac{1}{4} g^2 \alpha_8 [\mathrm{Tr}(T F_{\mu\nu})]^2$$

$$\mathcal{L}_9 = \tfrac{1}{2} i g \alpha_9 \mathrm{Tr}(T F_{\mu\nu}) \mathrm{Tr}(T[V^\mu, V^\nu])$$

$$\mathcal{L}_{10} = \tfrac{1}{2} \alpha_{10} [\mathrm{Tr}(T V_\mu) \mathrm{Tr}(T V_\nu)]^2$$

$$\mathcal{L}_{11} = \alpha_{11} \mathrm{Tr}[(\mathcal{D}_\mu V^\mu)^2]$$

$$\mathcal{L}_{12} = \tfrac{1}{2} \alpha_{12} \mathrm{Tr}(T \mathcal{D}_\mu \mathcal{D}_\nu V^\nu) \mathrm{Tr}(T V^\mu)$$

$$\mathcal{L}_{13} = \tfrac{1}{2} \alpha_{13} [\mathrm{Tr}(T \mathcal{D}_\mu V_\nu)]^2$$

$$\mathcal{L}_{14} = \alpha_{14} [\mathrm{Tr}(F_{\mu\nu} V^\nu) \mathrm{Tr}(T V^\mu) - \mathrm{Tr}(F_{\mu\nu} V^\mu) \mathrm{Tr}(T V^\nu)]$$

$$\mathcal{L}_{15} = 2 i \alpha_{15} \mathrm{Tr}(V_\mu \mathcal{D}_\nu V^\nu) \mathrm{Tr}(T V^\mu)$$

$$\mathcal{L}_{16} = i \alpha_{16} \mathrm{Tr}[T(\mathcal{D}_\mu V_\nu + \mathcal{D}_\nu V_\mu)] \times \mathrm{Tr}(V^\mu V^\nu)$$

$$\mathcal{L}_{17} = \tfrac{1}{2} i \alpha_{17} \mathrm{Tr}[T(\mathcal{D}_\mu V_\nu + \mathcal{D}_\nu V_\mu)] \times \mathrm{Tr}(T V^\mu) \mathrm{Tr}(T V^\nu)$$

$$\mathcal{L}_{18} = \tfrac{1}{2} i \alpha_{18} \mathrm{Tr}([V_\mu, T] \mathcal{D}^\mu \mathcal{D}^\nu V_\nu)$$

Appelquist, Bernard '80 ; Longitano '80

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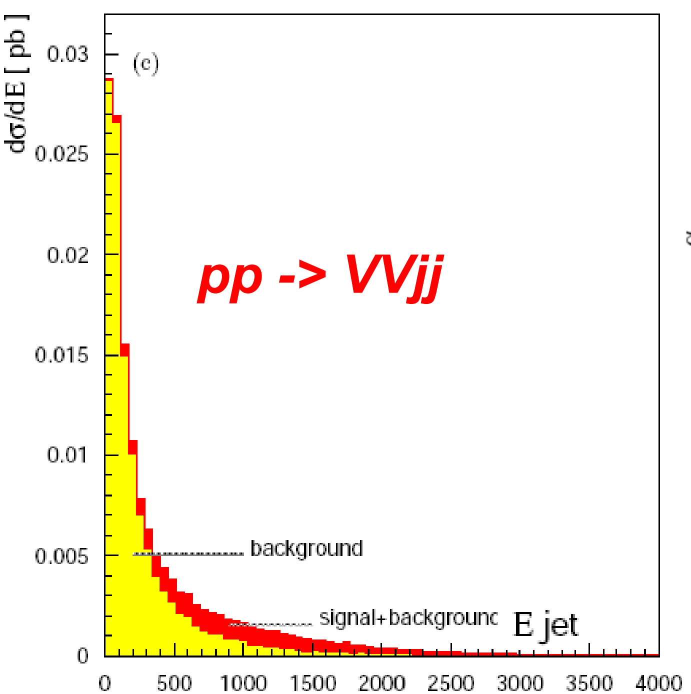
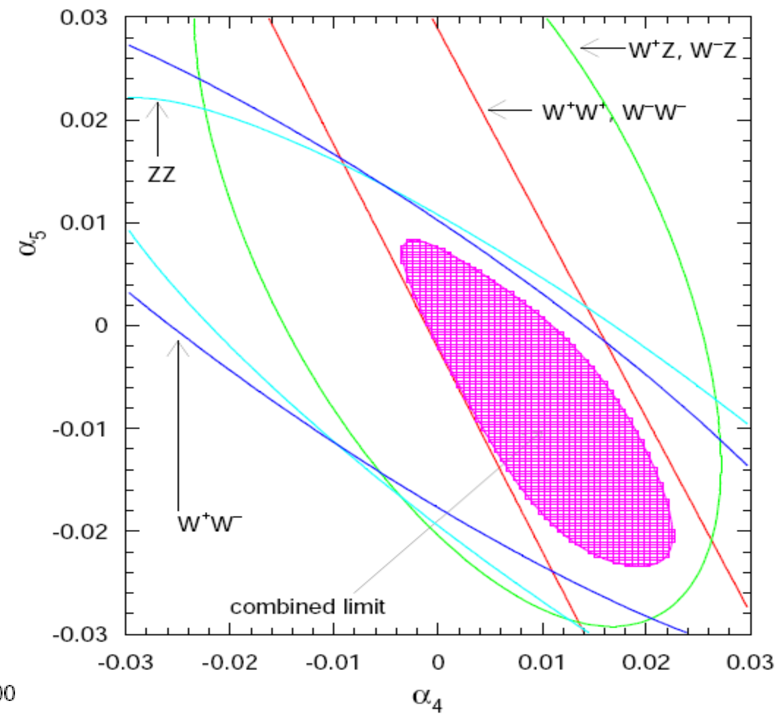
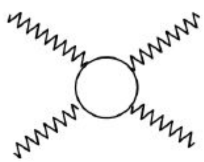
Appelquist, Bernard '80 ; Longitano '80

which can be tested at the LHC





the only quartic interactions under custodial symmetry

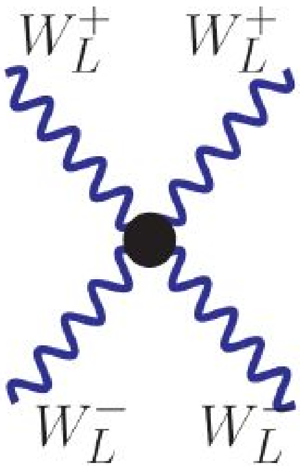


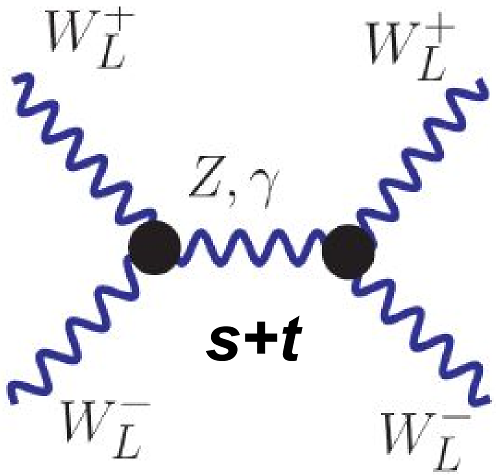
$$\mathcal{L}_4 = \alpha_4 (\mathrm{tr}\,[V_\mu V_\nu])^2$$
$$\mathcal{L}_5 = \alpha_5 (\mathrm{tr}\,[V_\mu V^\mu])^2$$

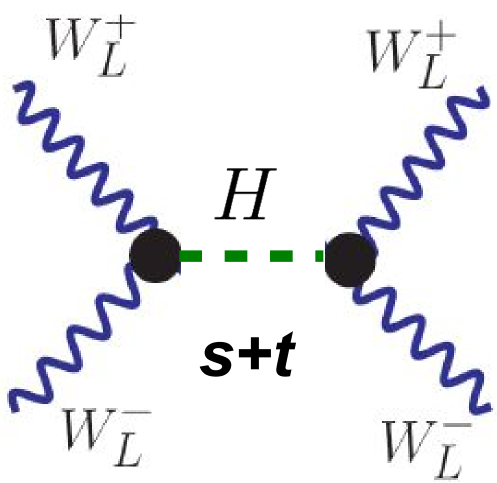
AB, Eboli, Gonzalez–Garcia, Mizukoshi, Novaes, Zacharov '98

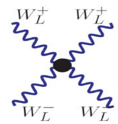
followed by
Eboli, Gonzalez-Garcia, Lietti, Novaes '00; Beyer, Kilian, Krstonosic, Monig, Reuter, Schmidt, Schroder '06; Eboli, Gonzalez–Garcia, Mizukoshi '06

On the other hand Higgs boson is one of the best candidates to unitarise VV->VV amplitude!



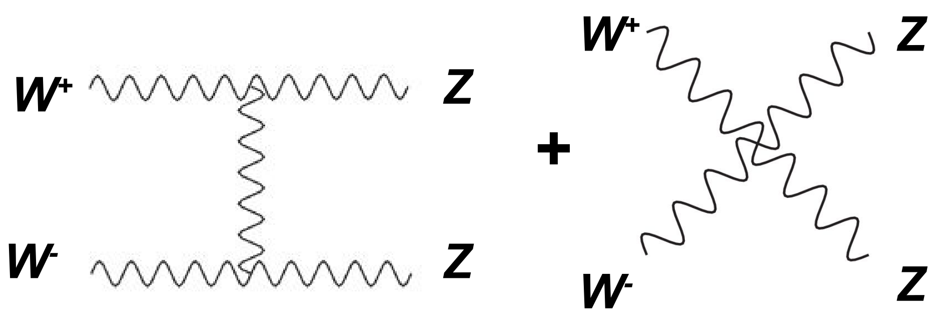


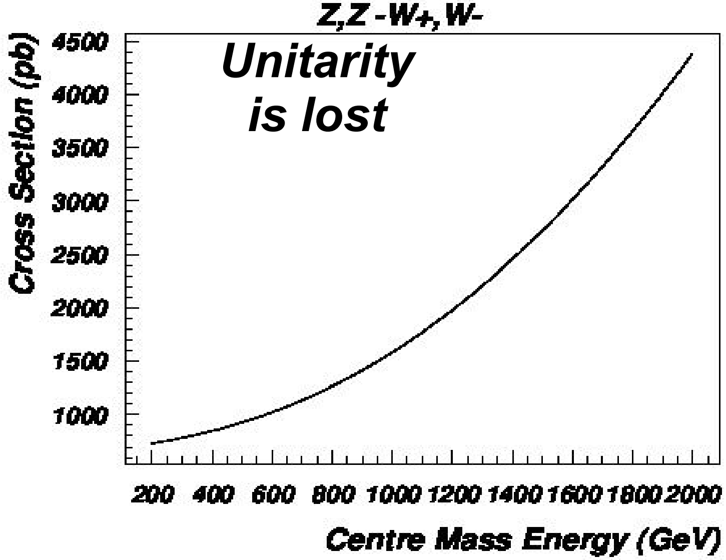


Graphs	$g^2\frac{E^4}{m_w^4}$	$g^2\frac{E^2}{m_w^2}$
	$-3+6\cos\theta+\cos^2\theta$	$+2-6\cos\theta$
s	$-4\cos\theta$	$-\cos\theta$
t	$+3-2\cos\theta-\cos^2\theta$	$-\frac{3}{2}+\frac{15}{2}\cos\theta$
Sum	0	$+\frac{1}{2}+\frac{1}{2}\cos\theta$
		$-\frac{1}{2}-\frac{1}{2}\cos\theta$
		0

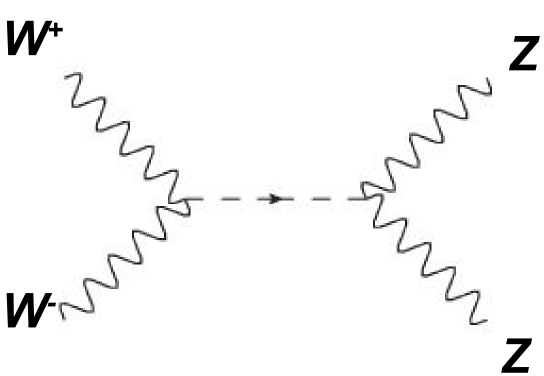
If no Higgs $\Rightarrow \mathcal{O}(E^2) \Rightarrow E < \sqrt{8\pi}v \simeq 1.2\,\mathrm{TeV}$

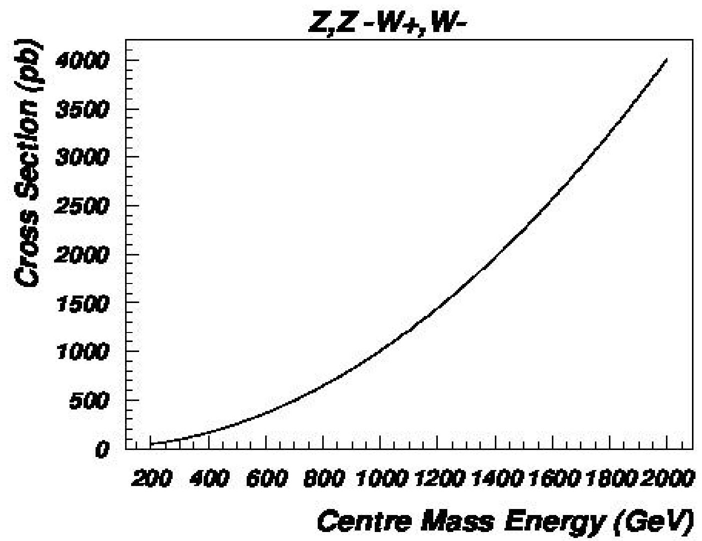
Indeed, the SM Higgs designed to do a perfect job in unitarising $V_L, V_L \to V_L, V_L$ amplitude!





$$\text{Amplitude} \propto s$$
$$\text{Cross section} \propto s^2$$





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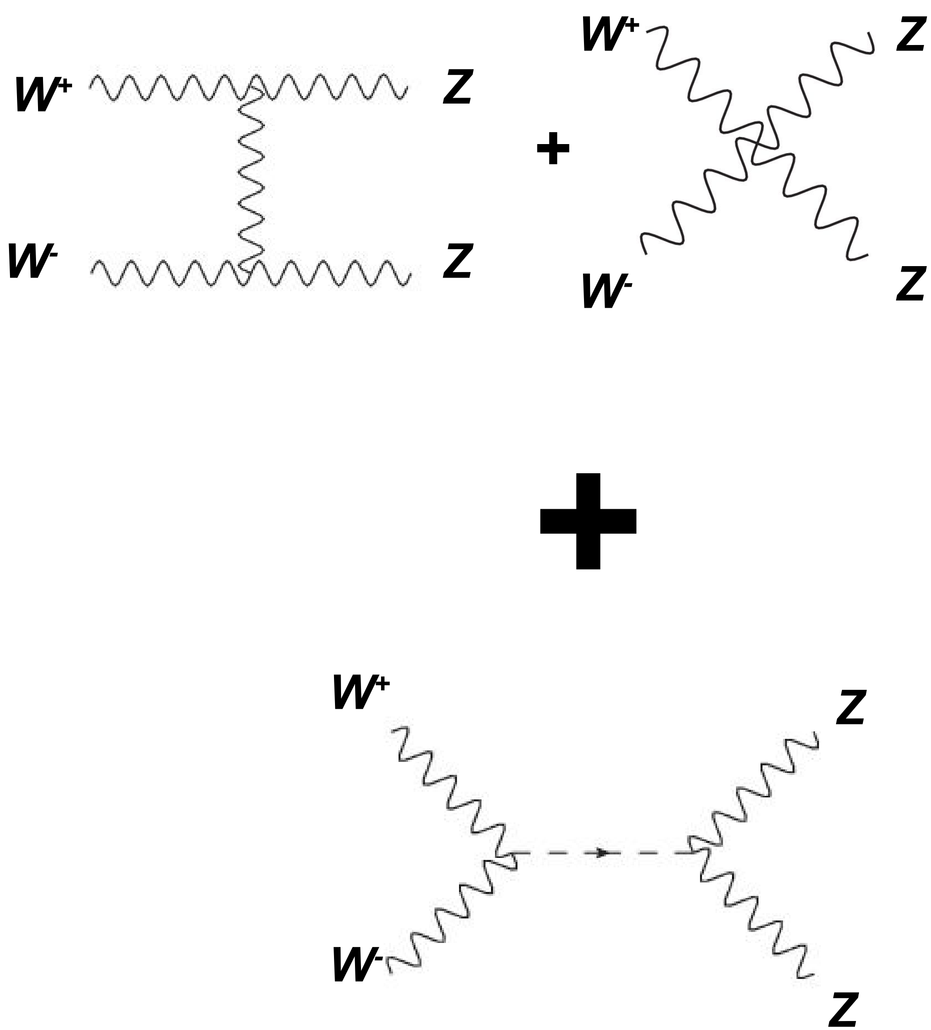

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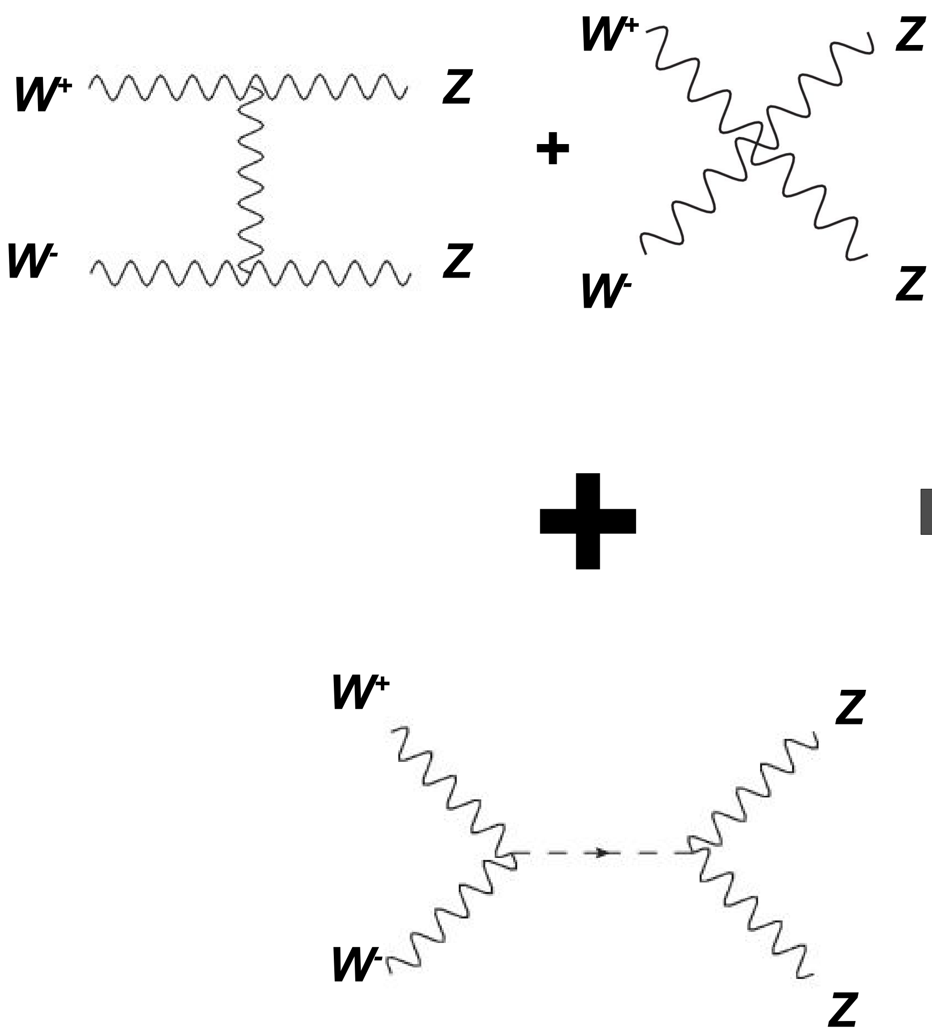
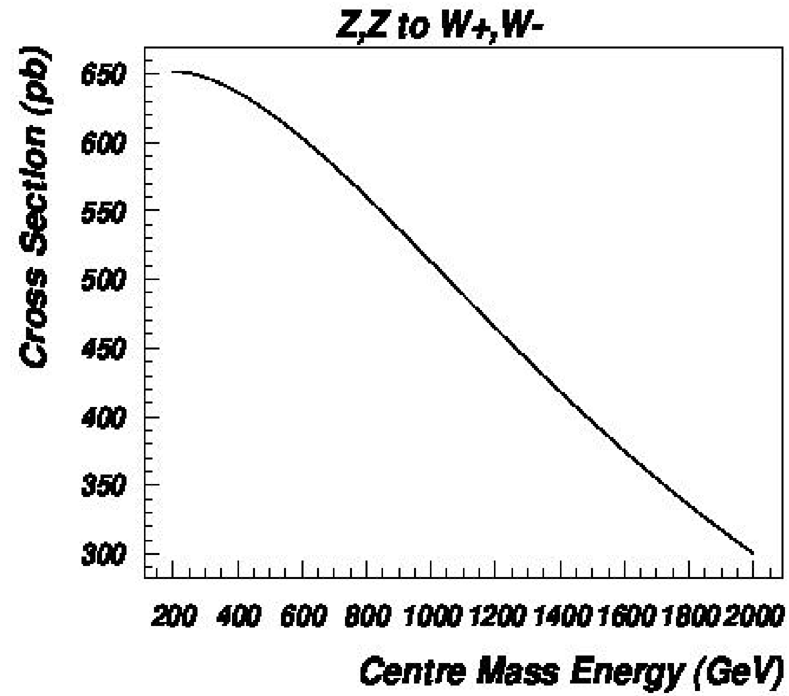




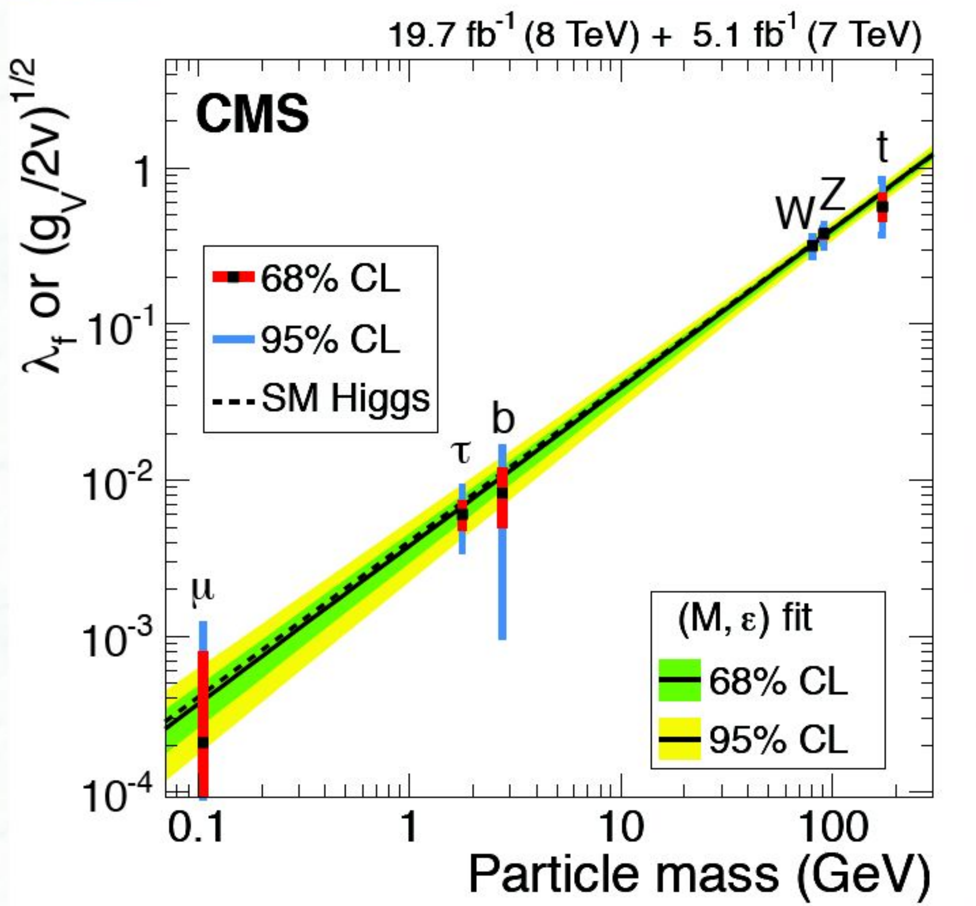
Higgs Boson Status

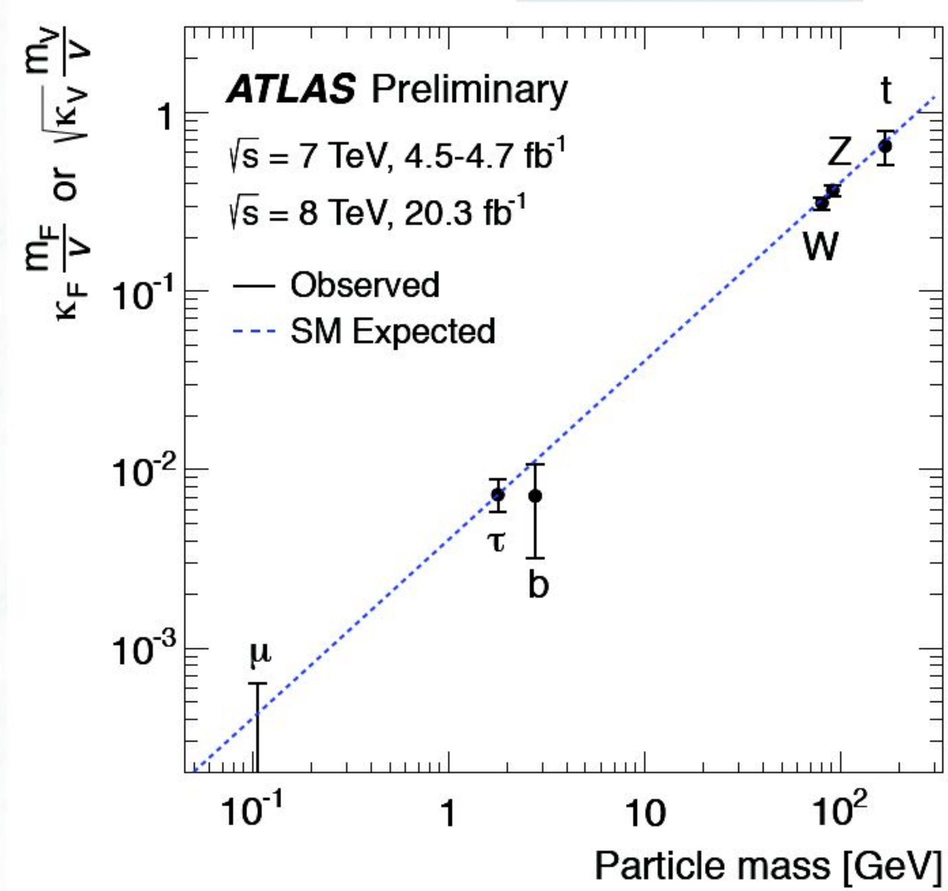
λ = Yukawa coupling for fermions
$\sqrt{g/2v}$ = couplings for W/Z bosons

EPJ C75 (2015) 5, 212

For the first time, non-universal, mass-dependent couplings observed

ATLAS-CONF-2015-007





Observation agrees with SM prediction, on one hand ...

Higgs Boson Status

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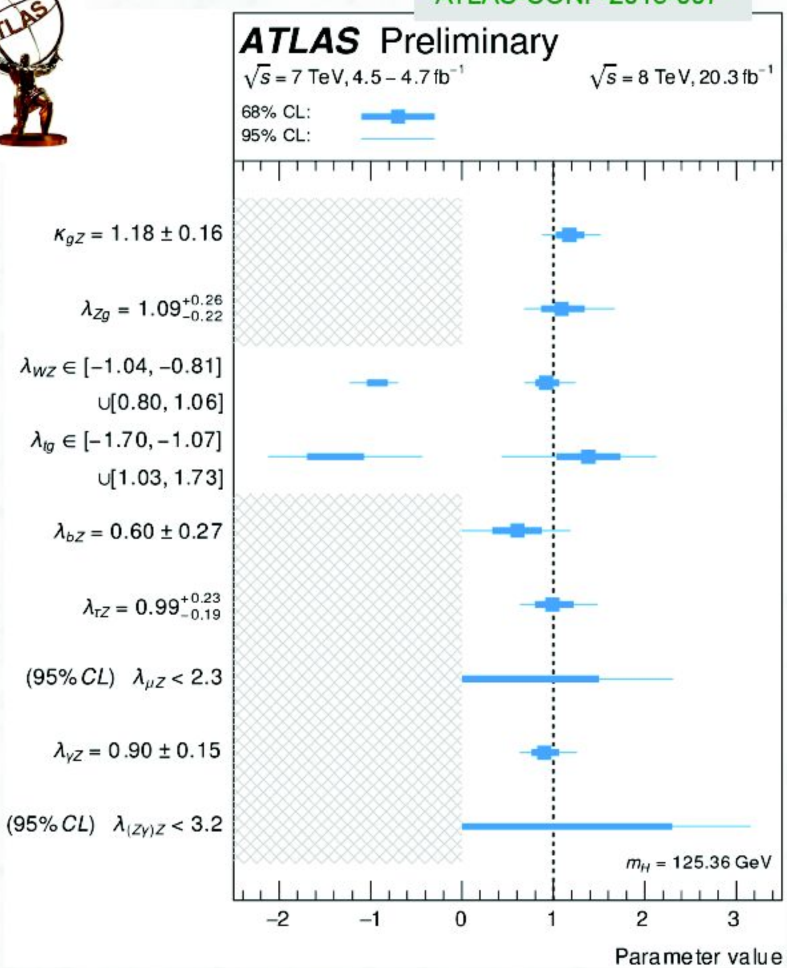
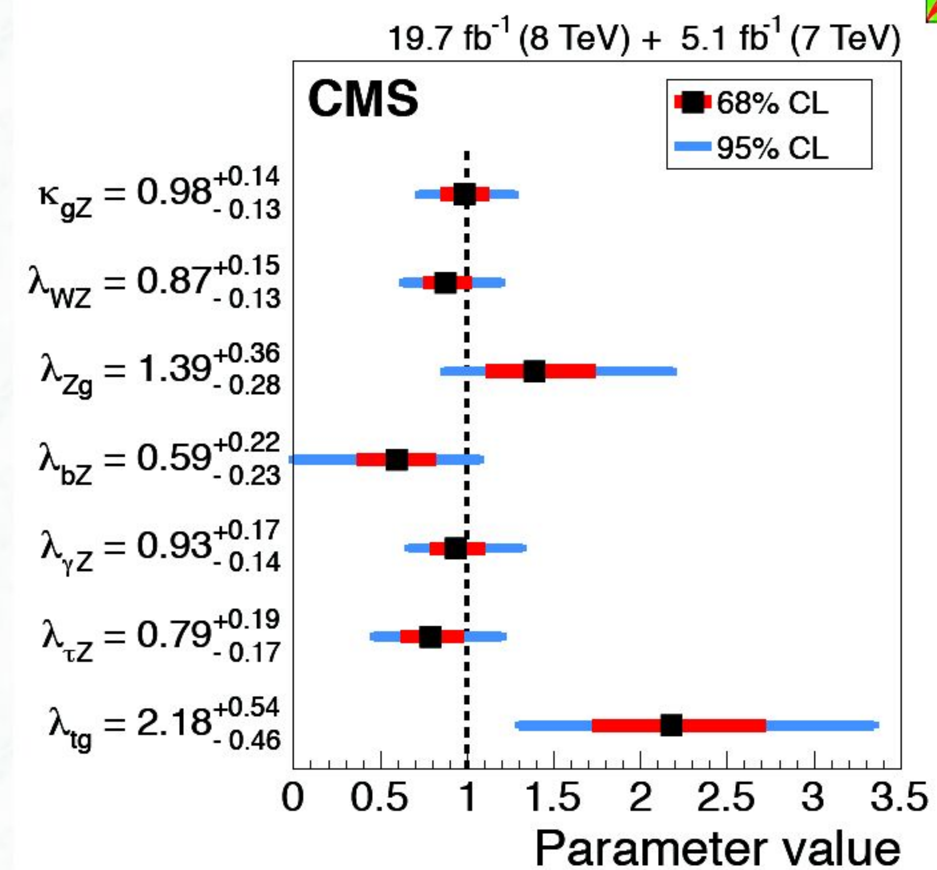


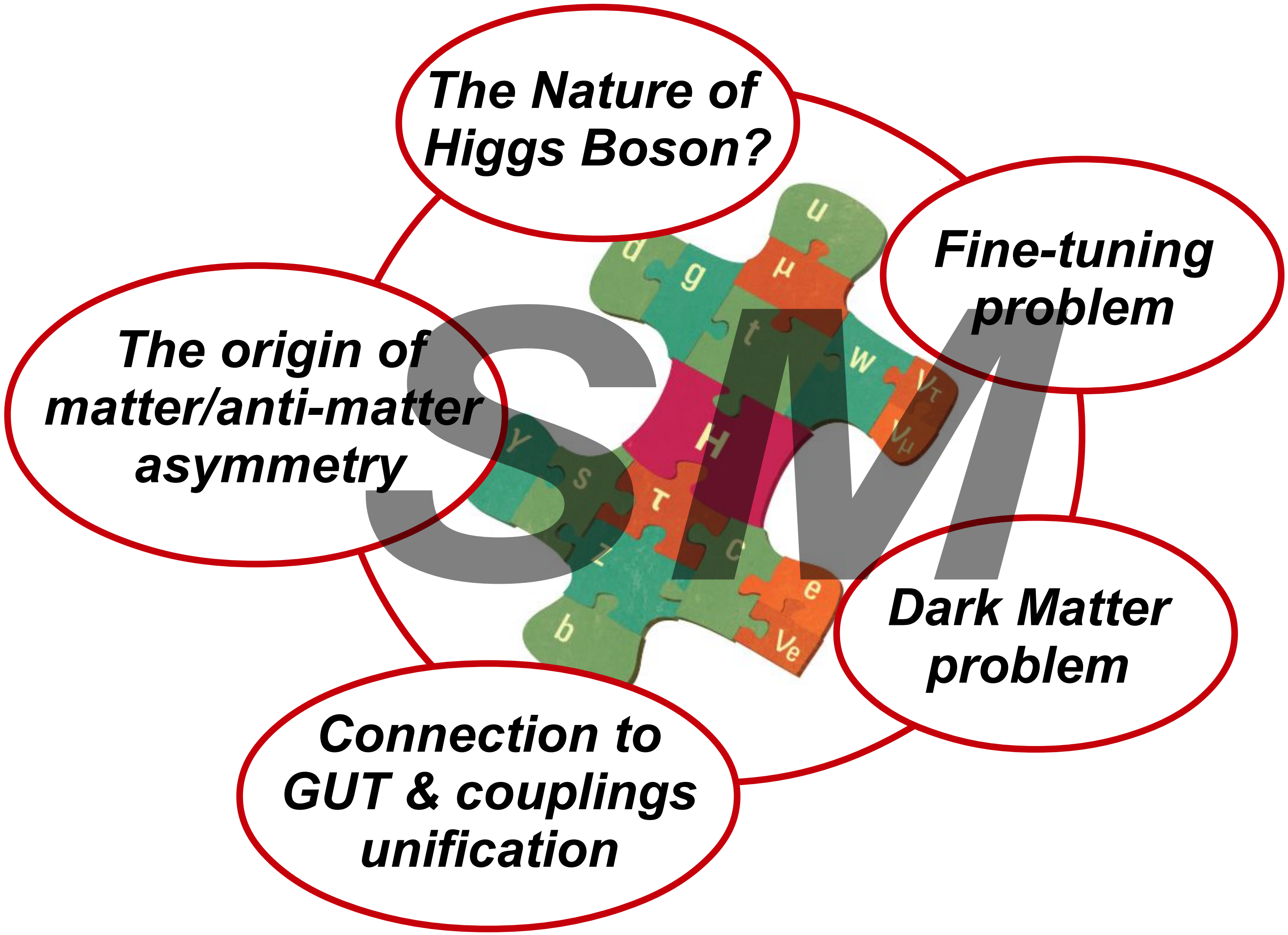
EPJ C75 (2015) 5, 212



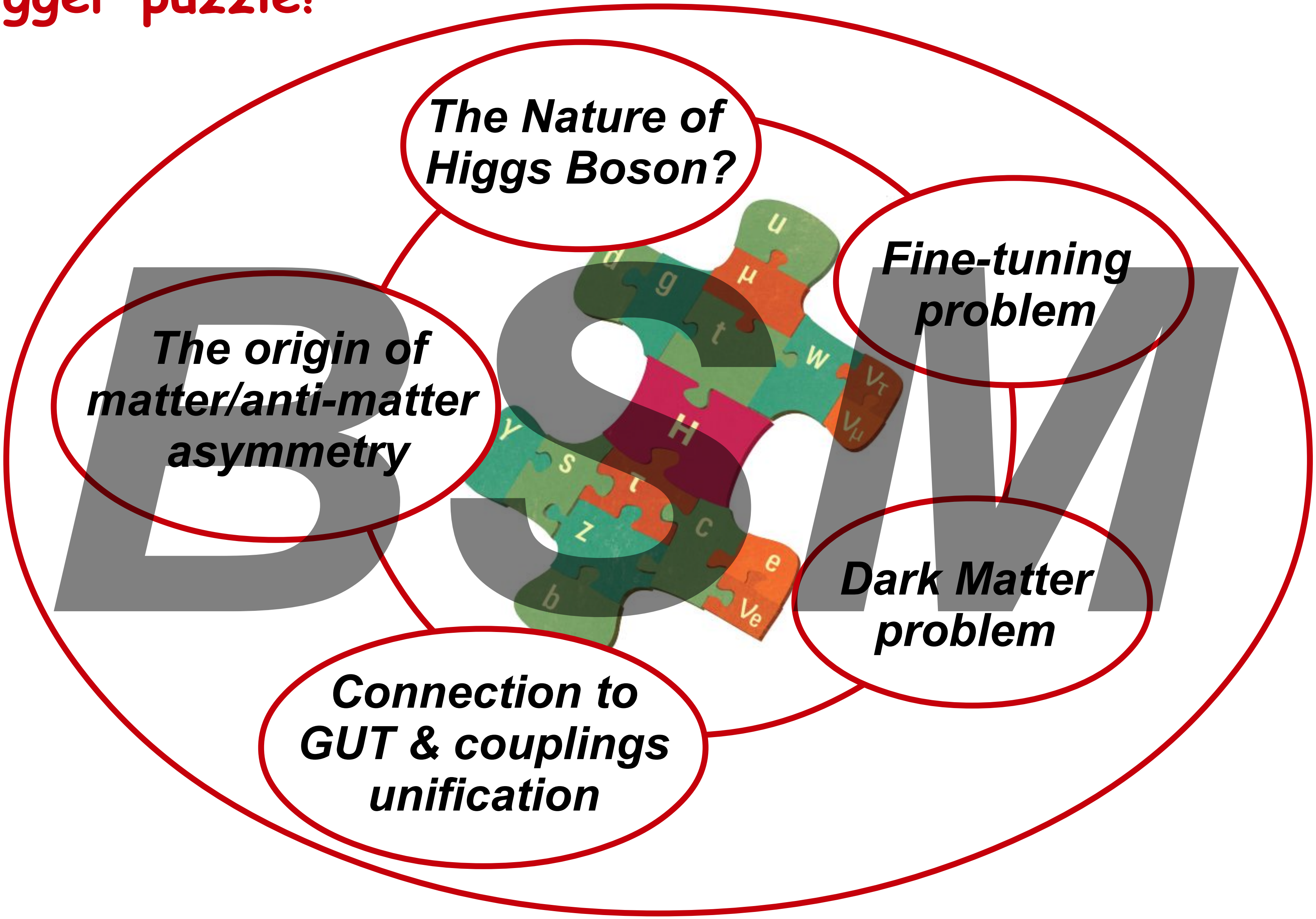
On the other hand, 10-100% window for Higgs couplings variation still open, allowing any promising BSM theory to take place

So, while Higgs Boson Discovery has completed the puzzle of the Standard model ...

But it has raised even more questions than the number of answers it has given!



Higgs boson properties are consistent with main compelling BSM theories, so the pattern we have is just a piece of a much bigger puzzle!



So, the main question is:
which
Higgs boson was discovered?!

just a few out of many recent papers on this subject ...

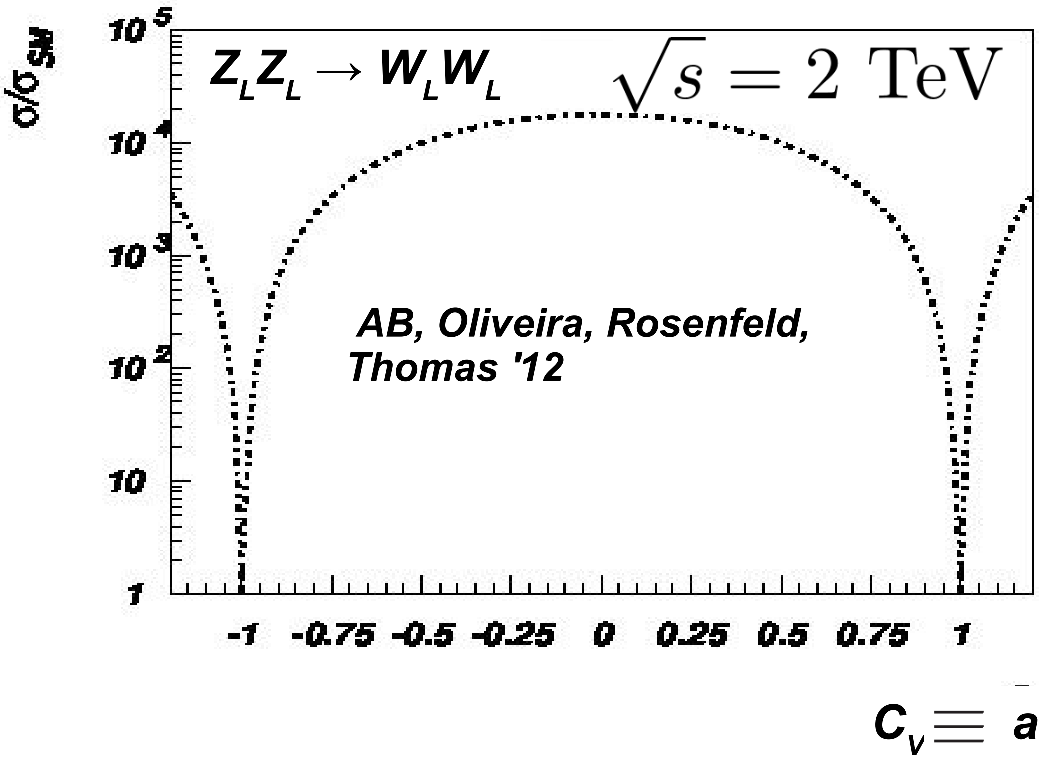
....
Bonnet,Ota,Rauch,Winter'12; Azatov,Contino,Galloway'12; Delgado,Nardini,Quiros'12; Corbett,Eboli,Gonzalez-Fraile,Gonzalez-Garcia'12; Djouadi,Moreau'13; Falkowski,Riva,Urbano'13; Baglio,Djouadi,Gröber,Mühlleitner,Quevillon,Spira'13; Dawson,Furlan,Lewis'13; Dolan,Englert,Spannowsky'13; Biswas,Gabrielli,Margaroli,Mele'13; Atwood,Sudhir,Soni'13; Belanger,Dumont,Ellwanger,Gunion,Kraml'13; Delaunay,Grojean,Perez'13; Montull,Riva,Salvioni,Torre'13;
Englert,Freitas,Muhlleitner,Plehn,Rauch,Spira,Walz'14; Ellis,Sanz,You'14;
Cacciapaglia,Deandrea,La Rochelle,Flament'14;
Kagan,Perez,Petriello,Soreq,Stoynev,Zupan'14
Brivio,Corbett,Éboli,Gavela,Gonzalez-Fraile,Gonzalez-Garcia,Merlo,Rigolin'14
Buchalla,Cata,Celis,Krause'15; Hartling,Kumar,Logan '15;
Dicus,Kao,Repko'15; Langenegger,Spira,Strebel '15;
Hernández,Dib,Zerwekh '15
....

Cancellation requires exact SM coupling!

$$\mathcal{L}_{\rm eff} = \frac{v^2}{4}\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + b_3\frac{h^3}{v^3} + \cdots\right) \mathrm{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right]$$
$$+ \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - d_3\lambda v h^3 - d_4\frac{\lambda}{4}h^4 + \cdots \qquad (U \equiv \Sigma \quad !)$$

Giudice, Grojean, Pomarol, Rattazzi '07

$$\Rightarrow \quad \mathcal{L} = C_V g_{SM} h V_L V_L + \ldots \quad \text{where } C_V = 1 \text{ in SM}$$



- ***The Large increases in $V_L V_L$ scattering, even for small deviations (~10%) from SM.***
- ***Could provide model independent way to probe Higgs boson coupling to gauge bosons (C_V).***

Case of multi-boson production

By power-counting, the scattering amplitude grows with energy as

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

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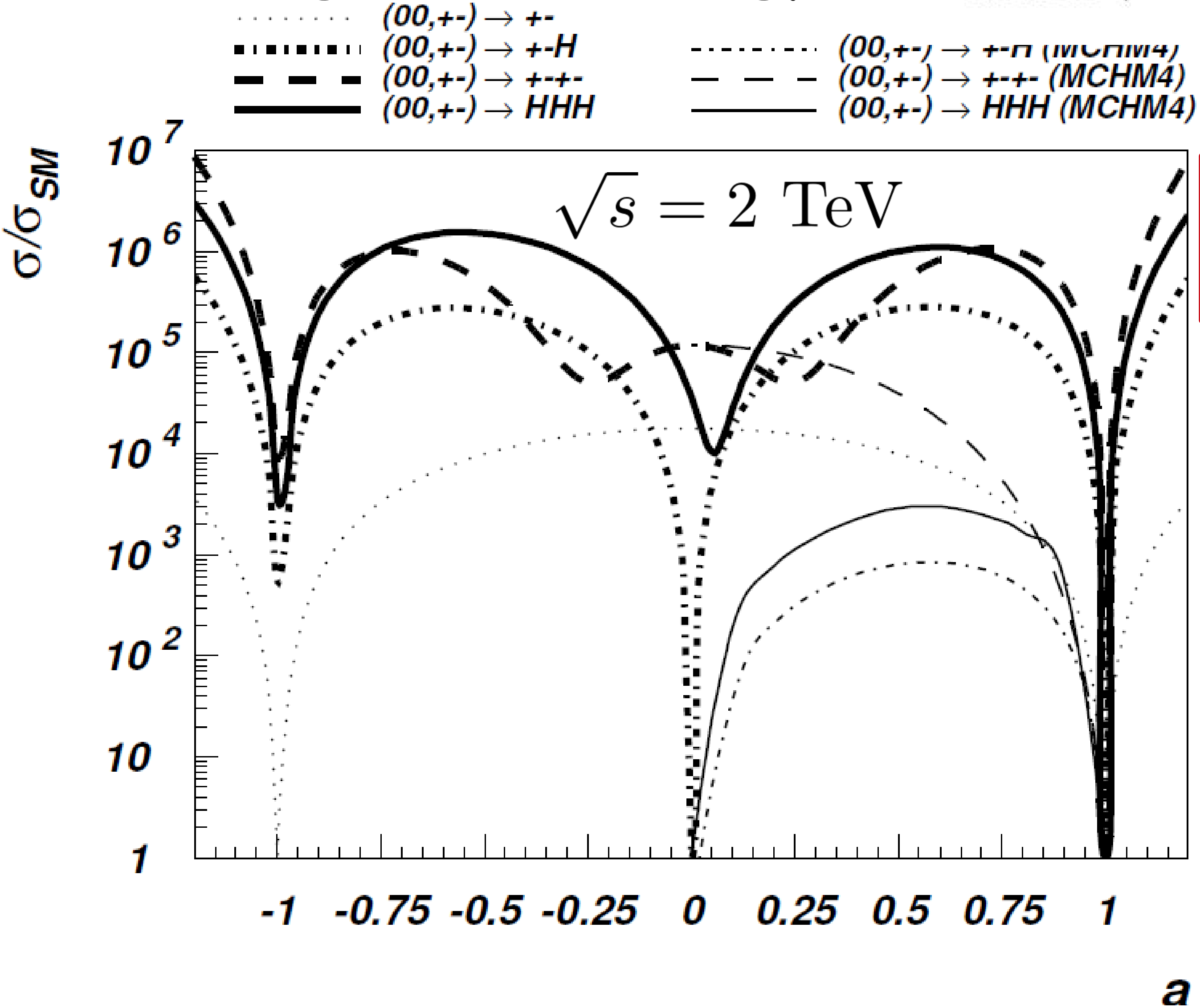
$$\sigma(2 \to n) \sim \frac{1}{s} A^2(s)\, s^{n-2}$$

So, 2→n cross section grows as s^{n-1} !

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

Case of multi-boson production

By power-counting, the scattering amplitude grows with energy as $A_{NL\sigma M}(2 \to n) \sim \frac{s}{v^n}$



and hence naively

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

Therefore, the growth of the cross section with energy is faster for larger number of particles due to the kinematical factors in the phase space!

AB, Oliveira, Rosenfeld, Thomas '12

Transverse "pollution" is one of the main problems!

- Transverse "pollution"
  - VV→ VV cross section is dominated by the transverse VV scattering – the main background!

	$\sqrt{s} = 2$ TeV	
Channel	**CX for C_V = 1 (SM) (pb)**	**CX for C_V = 0.9 (pb)**
$Z_L Z_L \rightarrow W_L W_L$	0.13	295
$ZZ \rightarrow WW$ (full)	610	655

AB, Oliveira, Rosenfeld, Thomas '12

- Despite large increases in V_L scattering, the overall effect on spin averaged cross section is moderate.
- One needs to find a way to isolate the longitudinal components of scattering, to enable us to measure C_V.

The picture at the level of pp collision is even worse ...

Process	14 TeV with (without) VBF cuts		33 TeV with (without) VBF cuts	
	a=1.0 b=1.0	a=0.9 b=1.0	a=1.0 b=1.0	a=0.9 b=1.0
$pp \to jjW^+W^-$	95.2 (1820)	99.3 (1700)	512 (5120)	540 (5790)
$pp \to jjW^+W^-h$	0.011 (0.206)	0.0088 (0.172)	0.0765 (0.914)	0.0626 (0.758)
$pp \to jjhhh$	1.16×10^{-4} (3.01×10^{-4})	0.0566 (0.0613)	0.00115 (0.00165)	1.85 (1.46)

AB, Oliveira, Rosenfeld, Thomas '12

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AB, Oliveira, Rosenfeld, Thomas '12

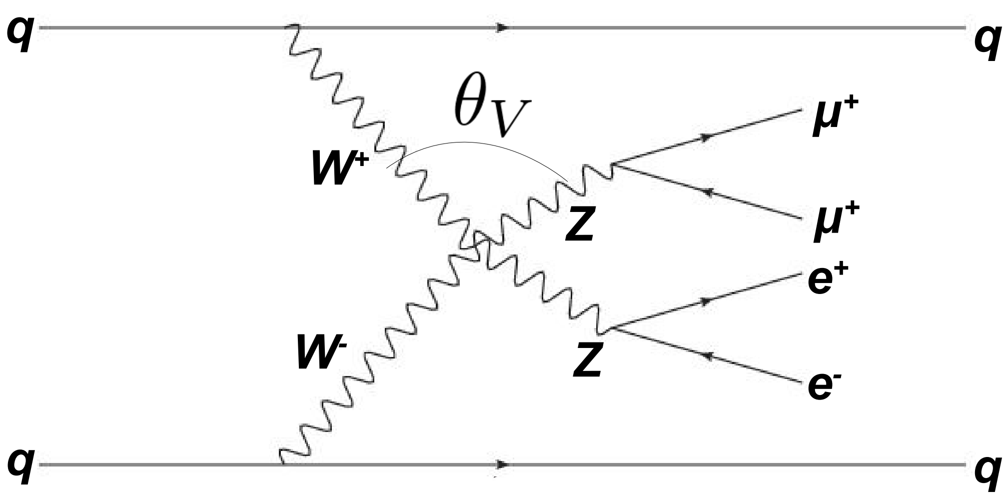
One should notice a problem here! Message: do not trust results based on the single package (Madgraph in this case) even if it quotes 1% MC error!

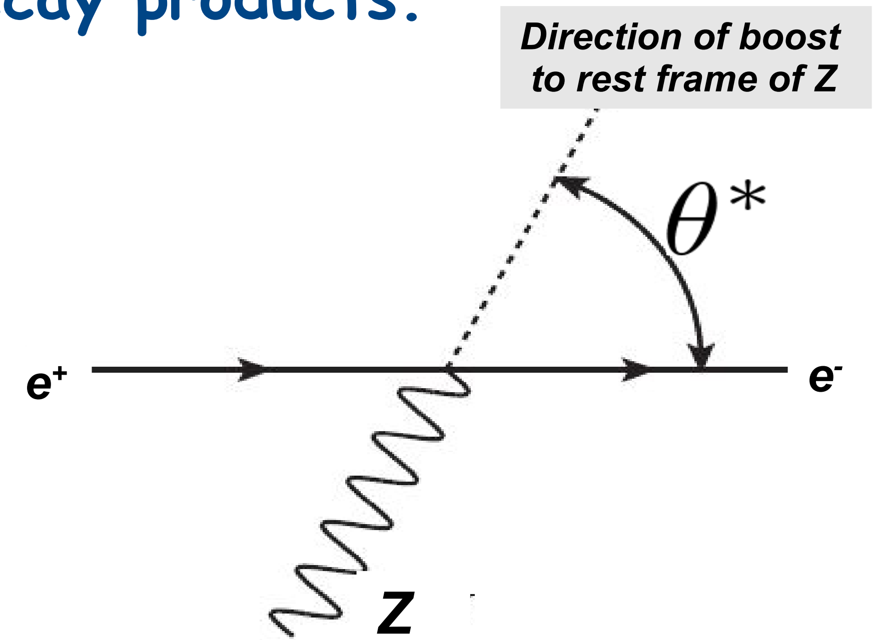
What is the next step?

- Devise optimal cuts capable of selecting the contribution from the longitudinally polarized gauge bosons.
- Hence increase sensitivity to C_V.
- 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.



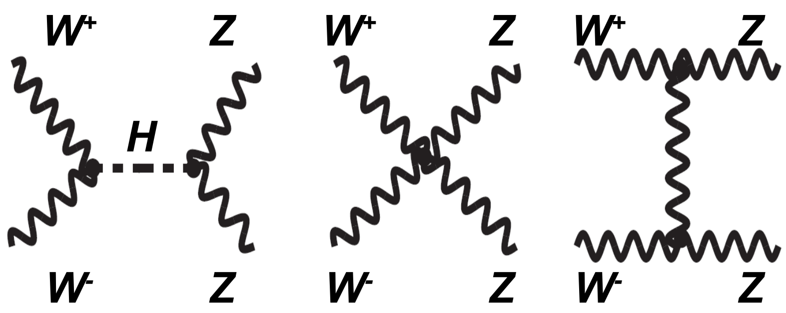


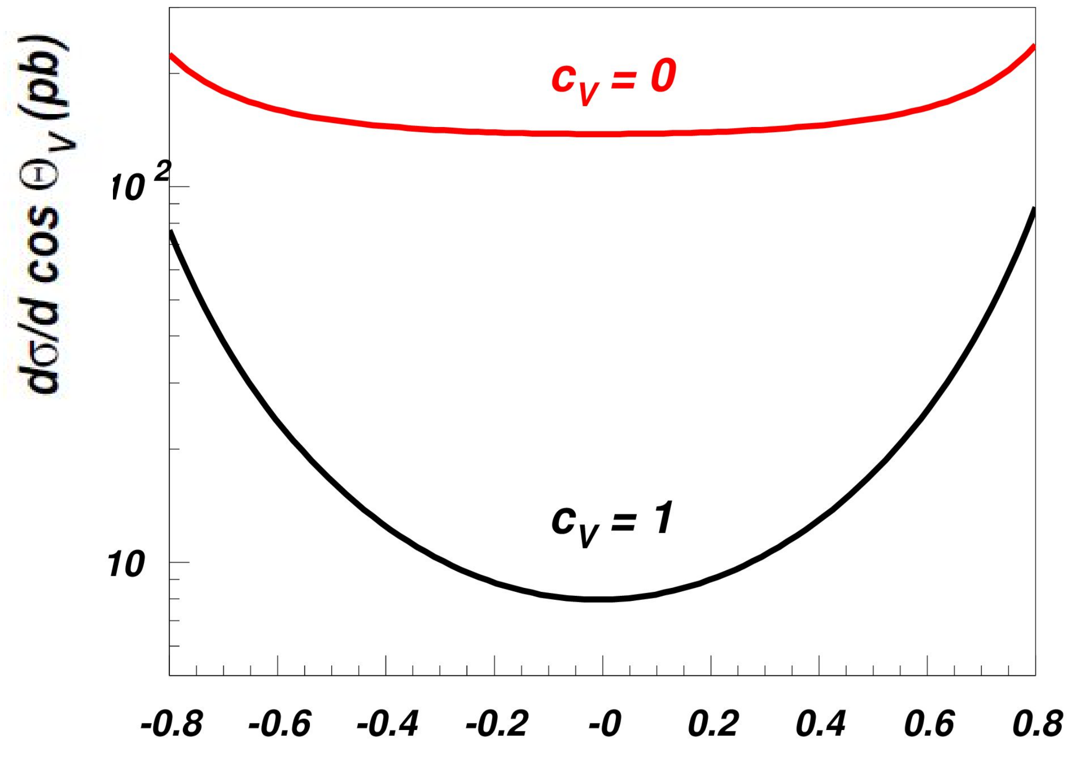
rest frame of the Z

Observable 1, θ_V

- Overall increase in cross section if C_V = 0 and much larger proportion of longitudinally polarized bosons.

$W^+W^- \to ZZ$





$\sqrt{s_{VV}} = 1\text{ TeV}$

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

Observable 1, θ_V

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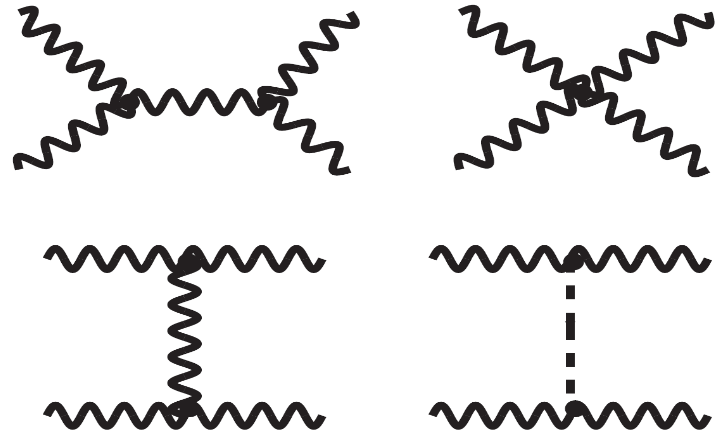

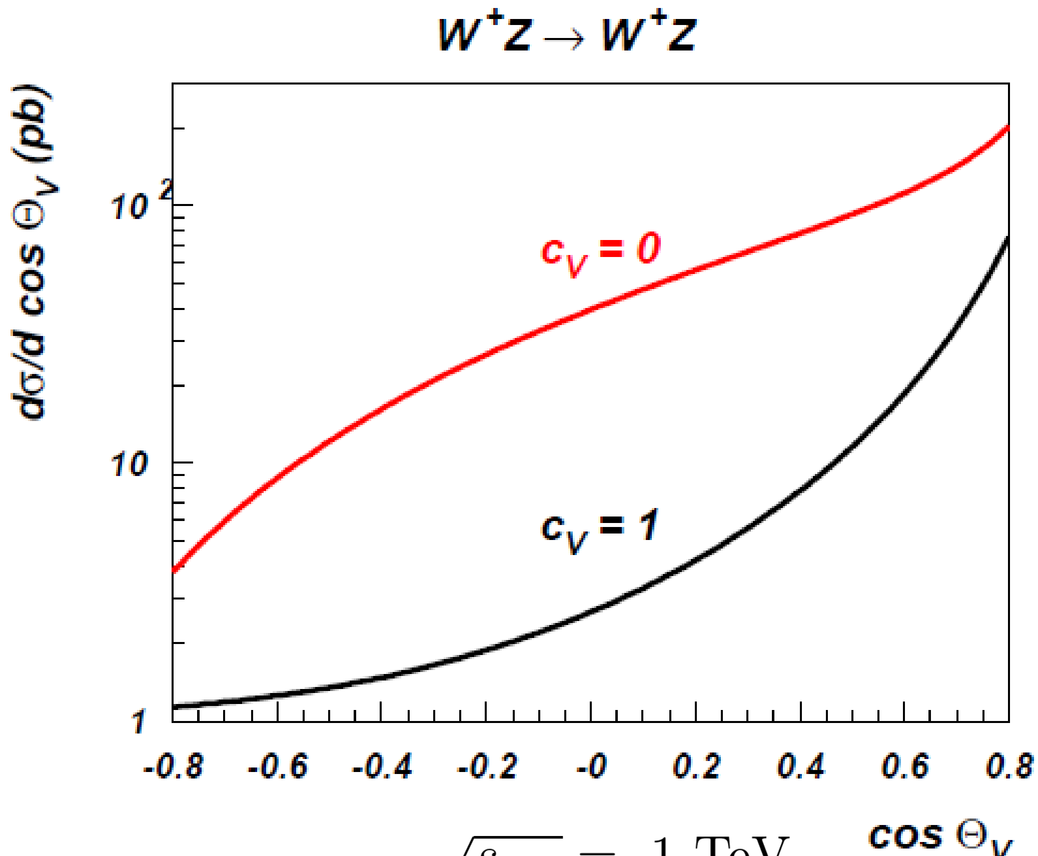

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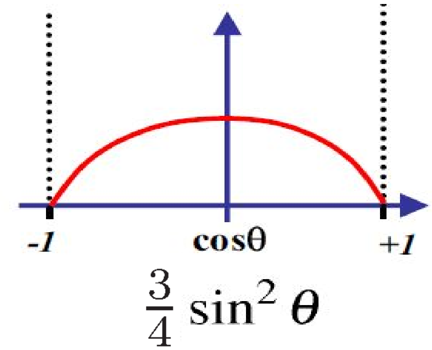
- Transversely polarised bosons have large contribution from t-channel amplitude with dominant forward-backward scattering.

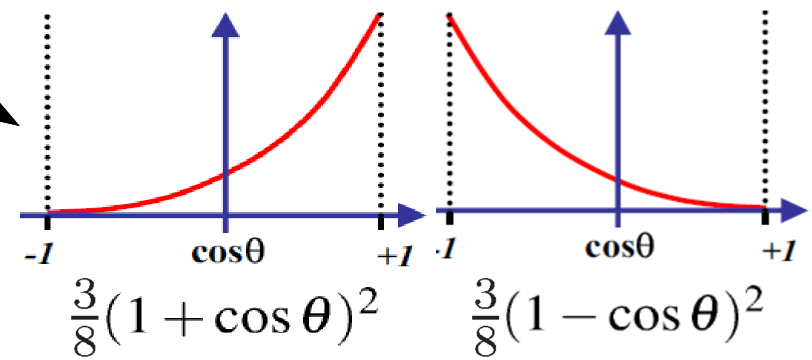
Observable 2, θ^*

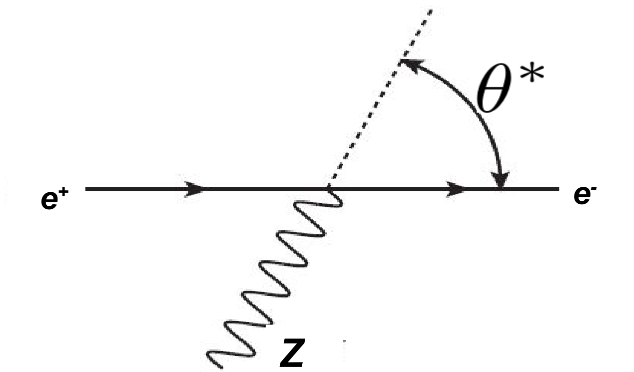
- **Distribution of decay from transverse and longitudinal polarisations.**

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

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







- **By fitting,**

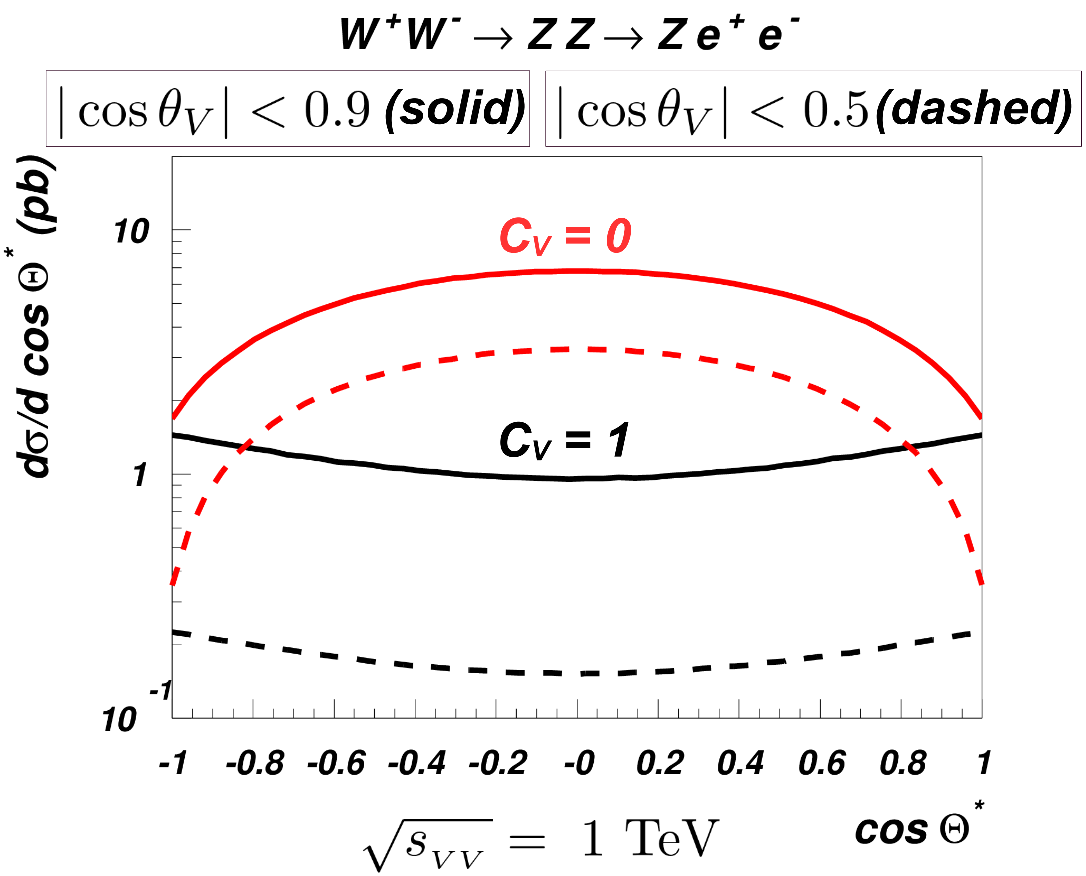
$$P(\cos\theta^*) = f_L P_L(\cos\theta^*) + f_+ P_+(\cos\theta^*) + f_- P_-(\cos\theta^*)$$

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

we can reconstruct the average polarizations of the vector bosons!

Observable 2, θ^*

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



this suggests optimal cut to increase fraction longitudinally polarised would be cut on both θ_V and θ^*.

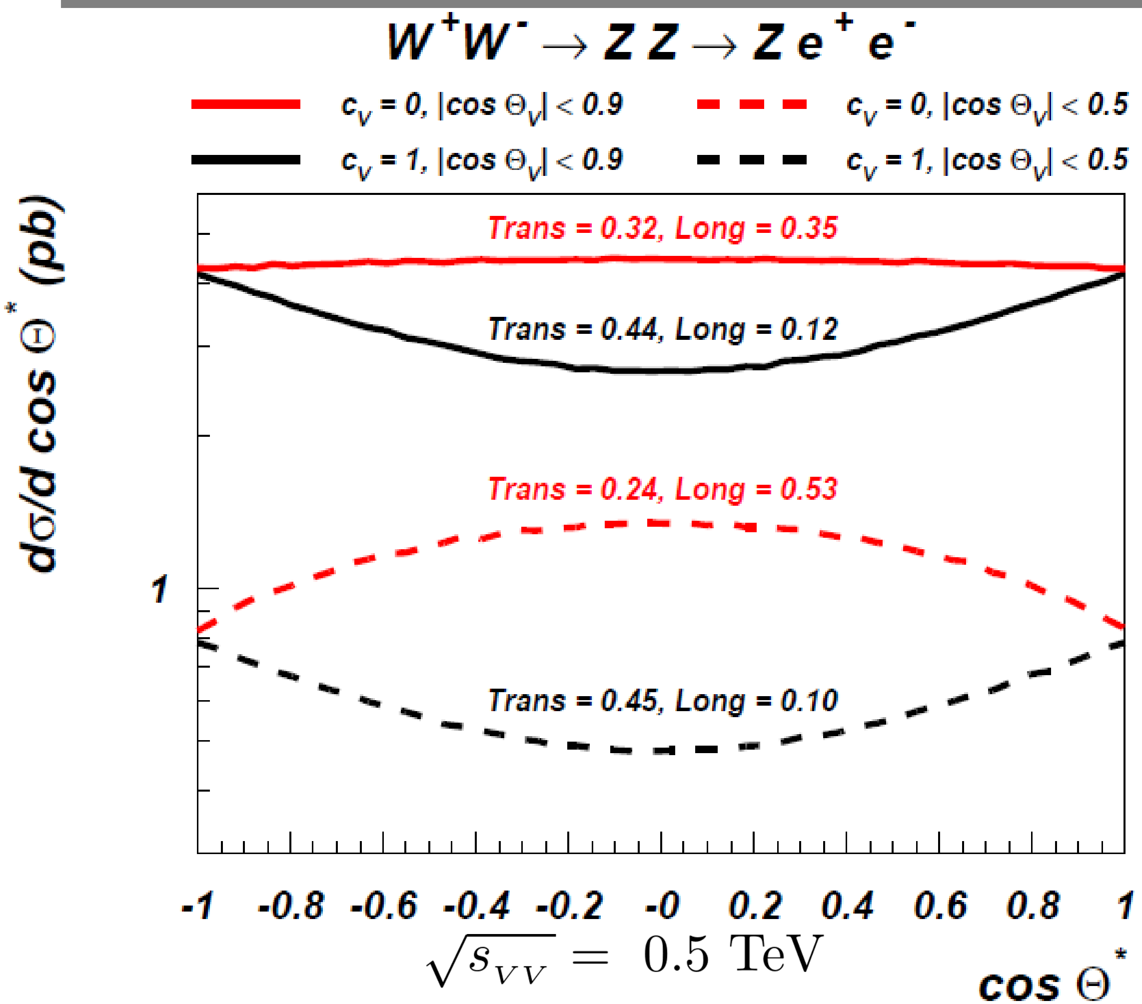
e.g. $|\cos\theta_V| < 0.5$

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

Fitting the V_L and V_T fractions

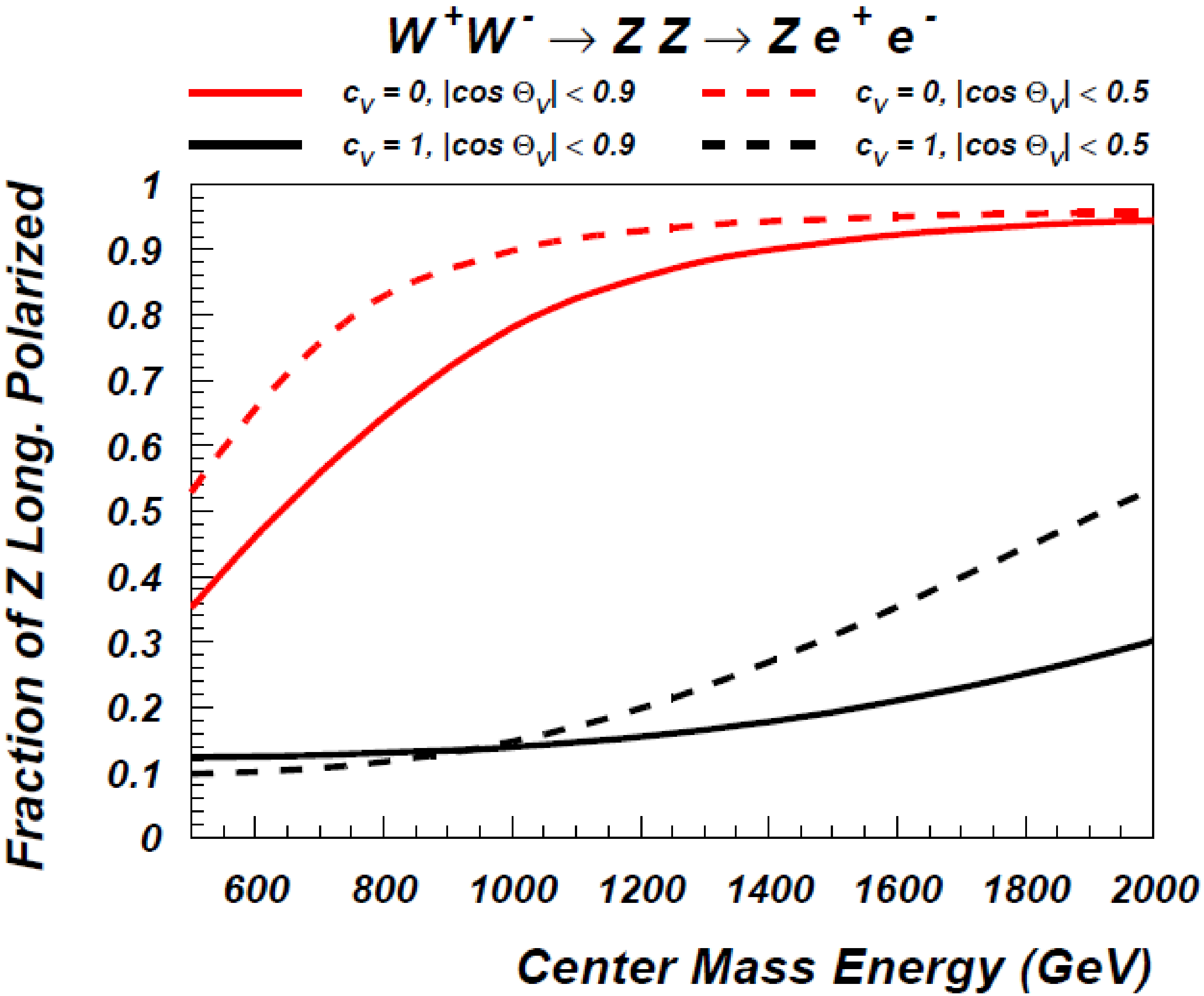
$$P(\cos\theta^*) = f_L P_L(\cos\theta^*) + f_+ P_+(\cos\theta^*) + f_- P_-(\cos\theta^*)$$

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



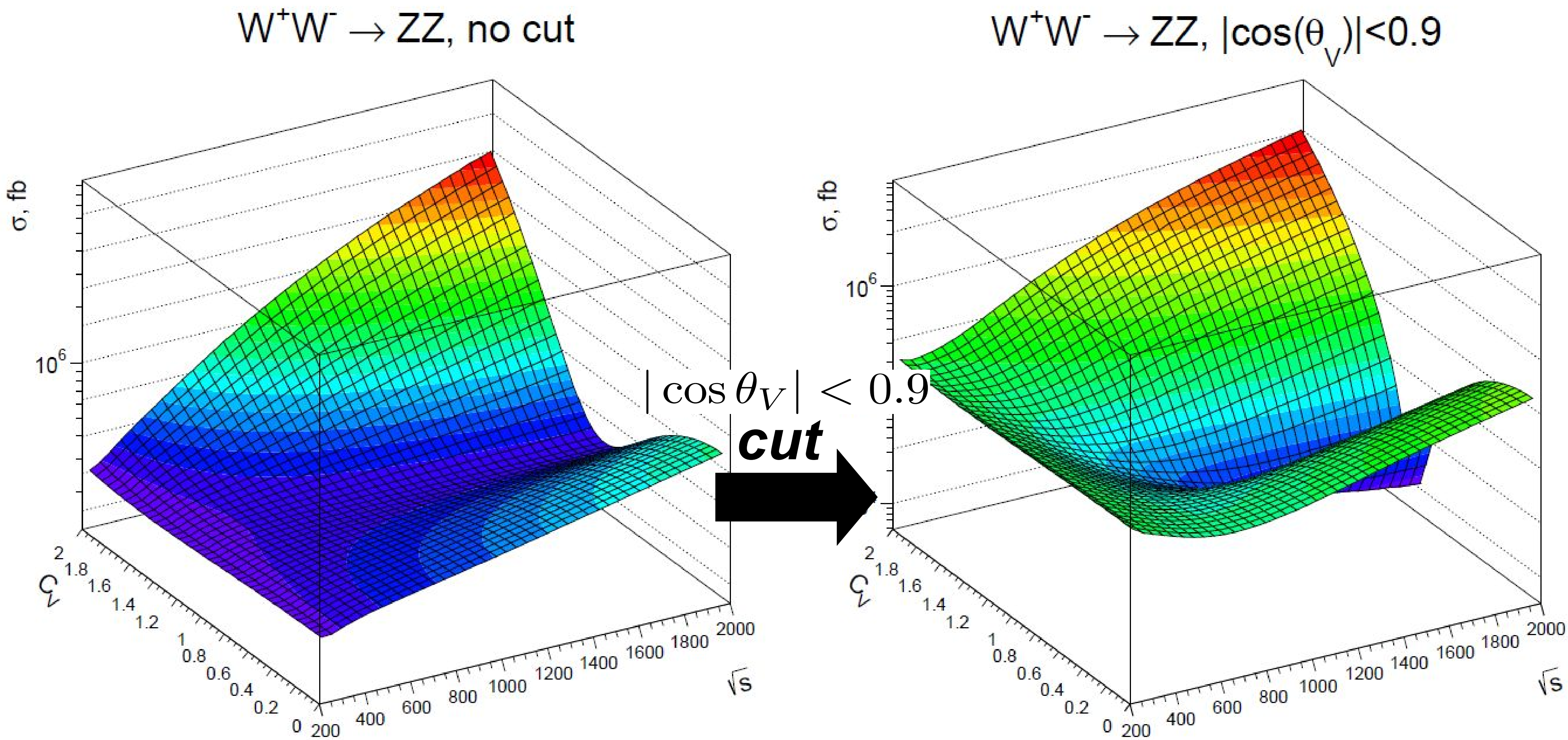
- When $C_V = 0$, the fraction of V_L is higher as expected
- $|\cos\theta_V| < 0.5$ cut increases fraction of V_Ls

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



- As $\sqrt{s_{VV}}$ increases, the V_L fraction dominates for C_V=0
- To be expected as $\sigma(V_L V_L \to V_L V_L) \propto s$
- Cut for higher $\sqrt{s_{VV}}$ respectively increases fraction of V_L s

Effect of $\cos(\theta_V)$ cut in 3D

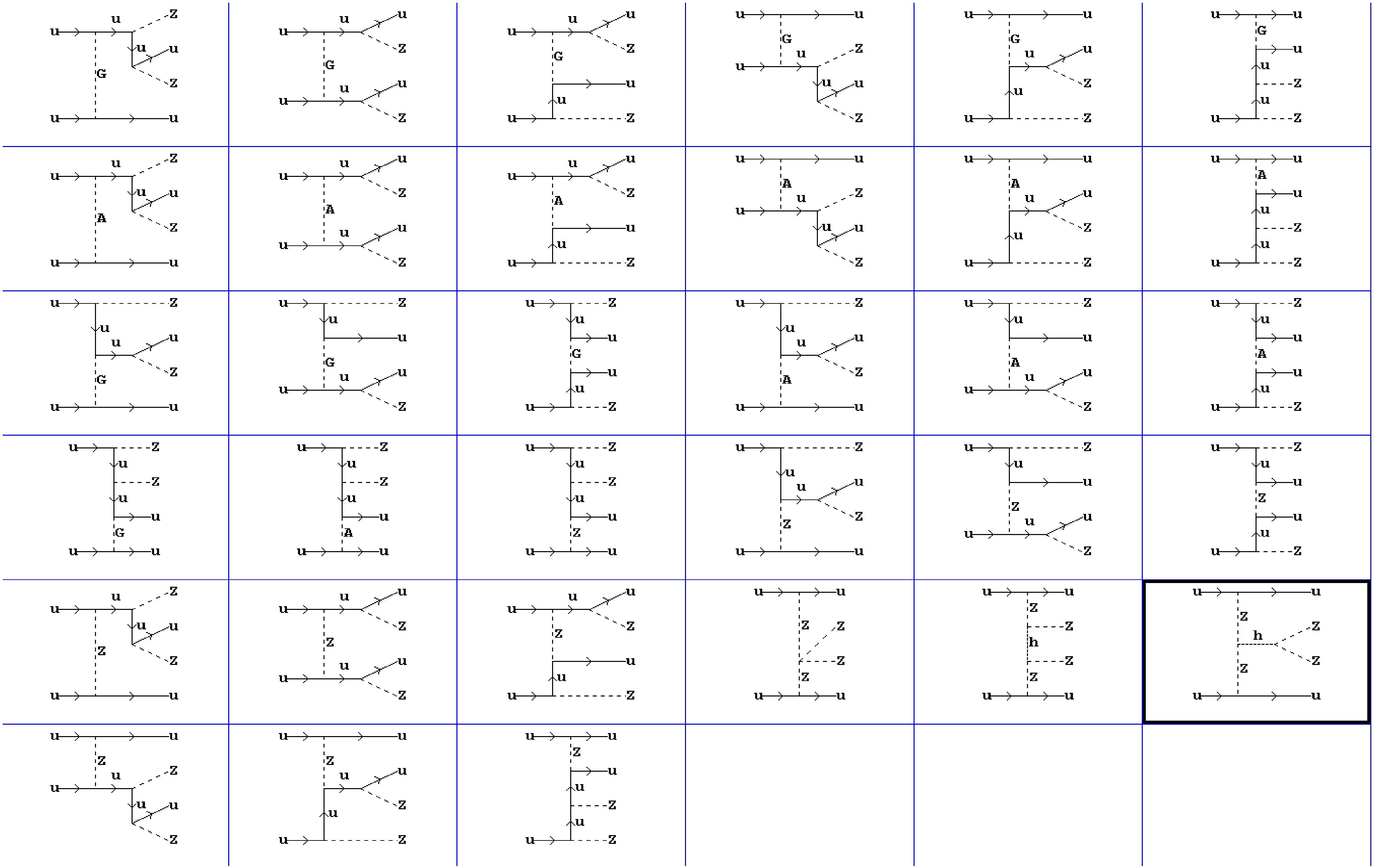


dependence on C_V becomes more pronounced after $\cos(\theta_V)$ cut which enhance relative L/T polarisation ratio of vector bosons

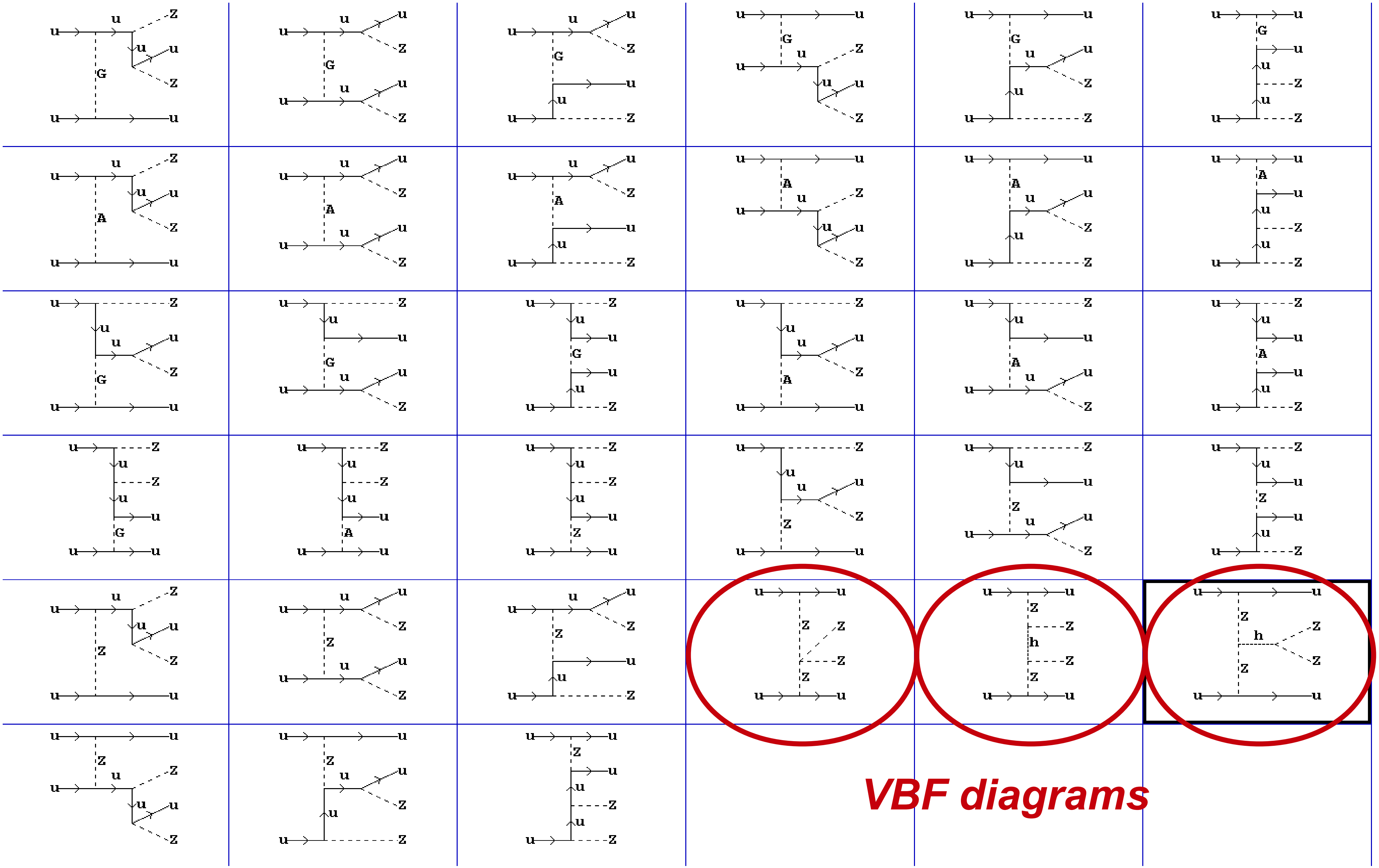
Does this work at the level of pp scattering?

- So far only discussed VV → VV at parton level.
  - The full process at LHC is much more involved – many more diagrams, large background
  - cuts may not be quite effective
- Need to study LHC sensitivity to probe fraction of longitudinal polarisation and therefore measure C_V.
- Ongoing work, so far $pp \to jjZZ \to e^+e^-\mu^+\mu^- jj$ processes has been studied
- Currently it is being extended to all relevant processes and decays

$pp \to jjZZ \to e^+e^-\mu^+\mu^-jj$ process

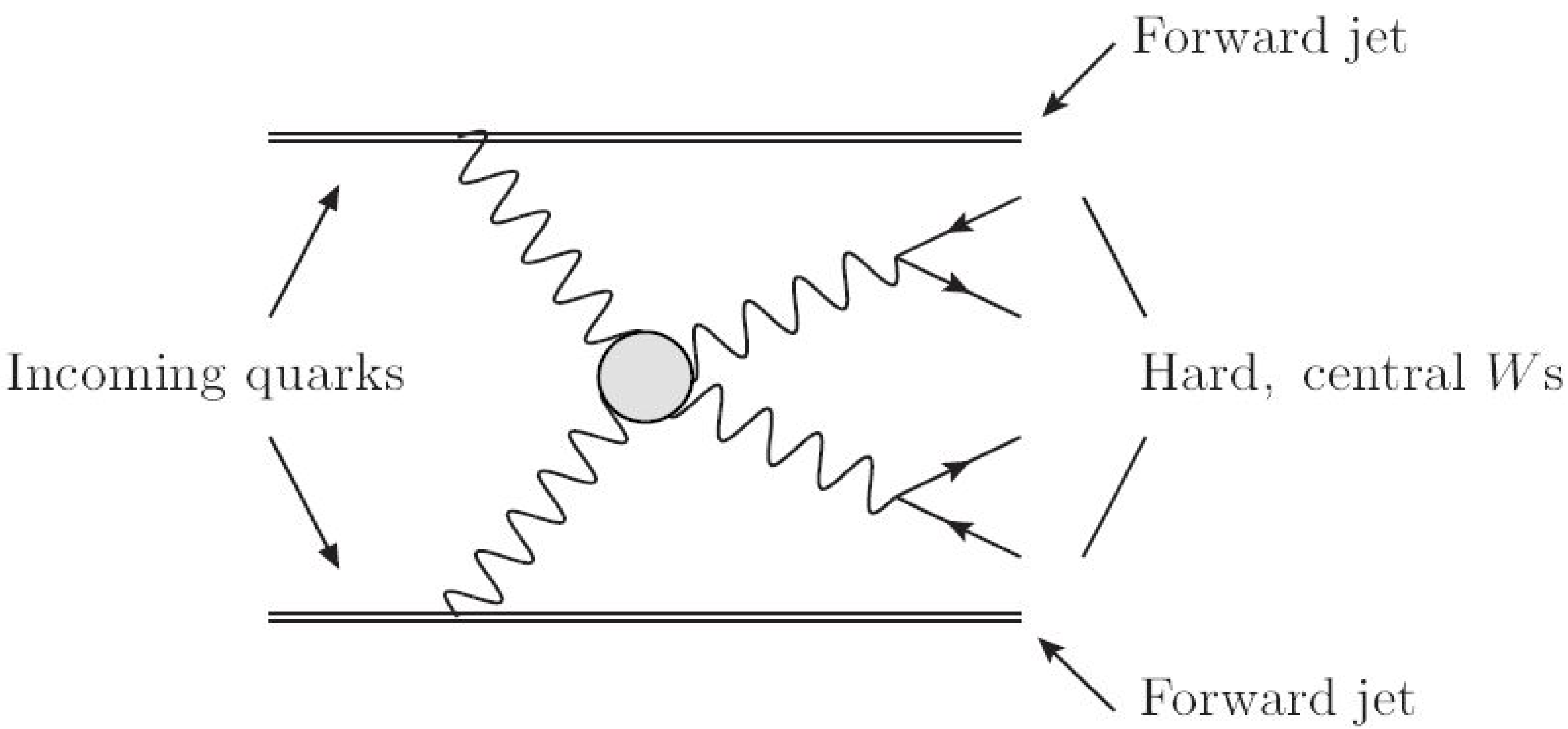


pp->jjZZ->$e^+e^-\mu^+\mu^-$jj process



$pp \to jjZZ \to e^+e^-\mu^+\mu^- jj$ process

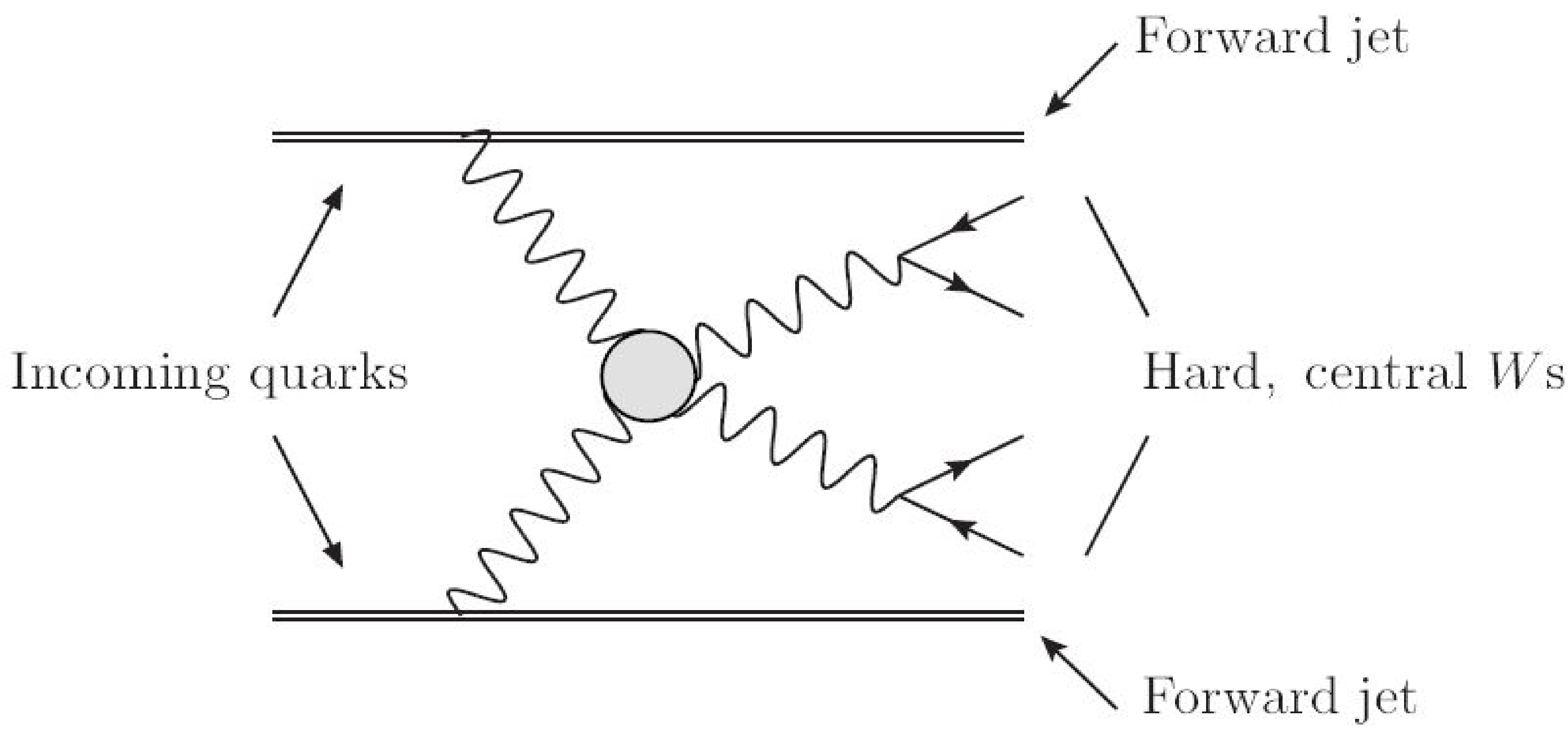
- **MADGRAPH & CalcHEP**
- **Kinematical cuts**



pp->jjZZ->$e^+e^-\mu^+\mu^-$jj process

- **MADGRAPH & CalcHEP**
- **Kinematical cuts**

Acceptance cuts:	$p_T^j > 30$ GeV, $\lvert\eta_j\rvert < 4.5$
	$p_T^e > 20$ GeV, $\lvert\eta_e\rvert < 2.5$
	$p_T^\mu > 20$ GeV, $\lvert\eta_e\rvert < 2.5$
VBF cuts:	$\Delta\eta_{jj} > 4,\ E_j > 300$ GeV
Z boson ID cuts:	$\lvert M_{ee,\mu\mu} - M_Z\rvert \leq 10$ GeV



pp->jjZZ->$e^+e^-\mu^+\mu^-$jj process

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$$\begin{aligned}
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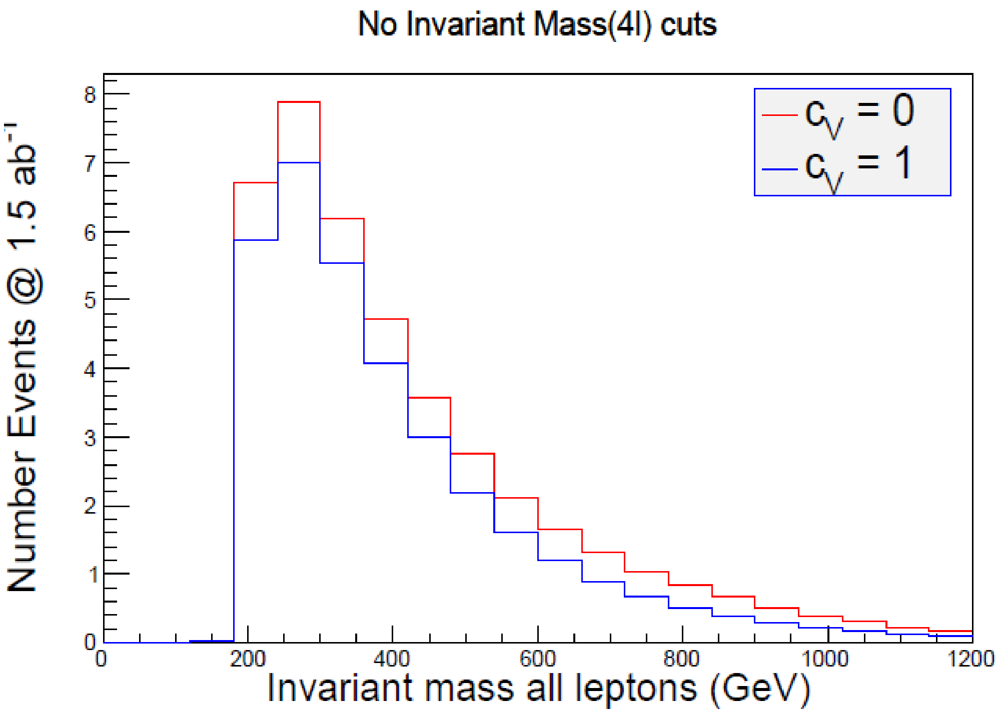
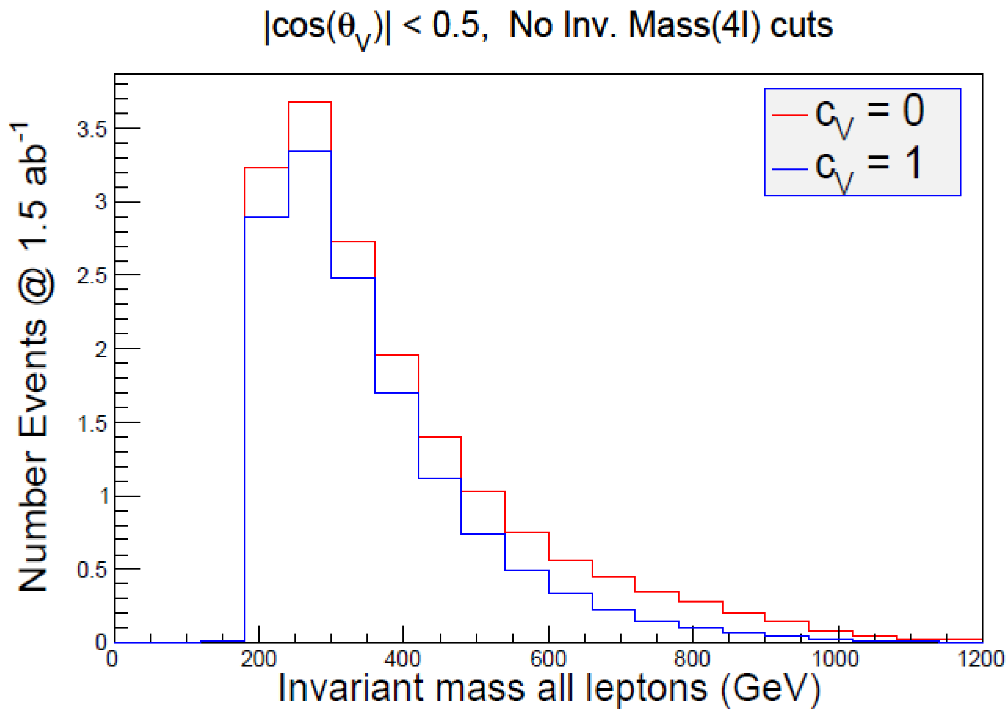
\end{aligned}$$





pp->jjZZ->$e^+e^-\mu^+\mu^-$jj process

- **Definition of θ_V from $q_1q_2 \rightarrow q_3q_4ZZ$:**

  a) find two pairs of the final and initial quarks, (q1, q3) & (q2, q4) with the minimal angle between them in cms frame

  b) find p_V^1 , p_V^2 in the initial state: p_V^1 = q3 – q1 & p_V^2 = q4 – q2

  c) find θ_V

$pp \to jjZZ \to e^+e^-\mu^+\mu^- jj$ process

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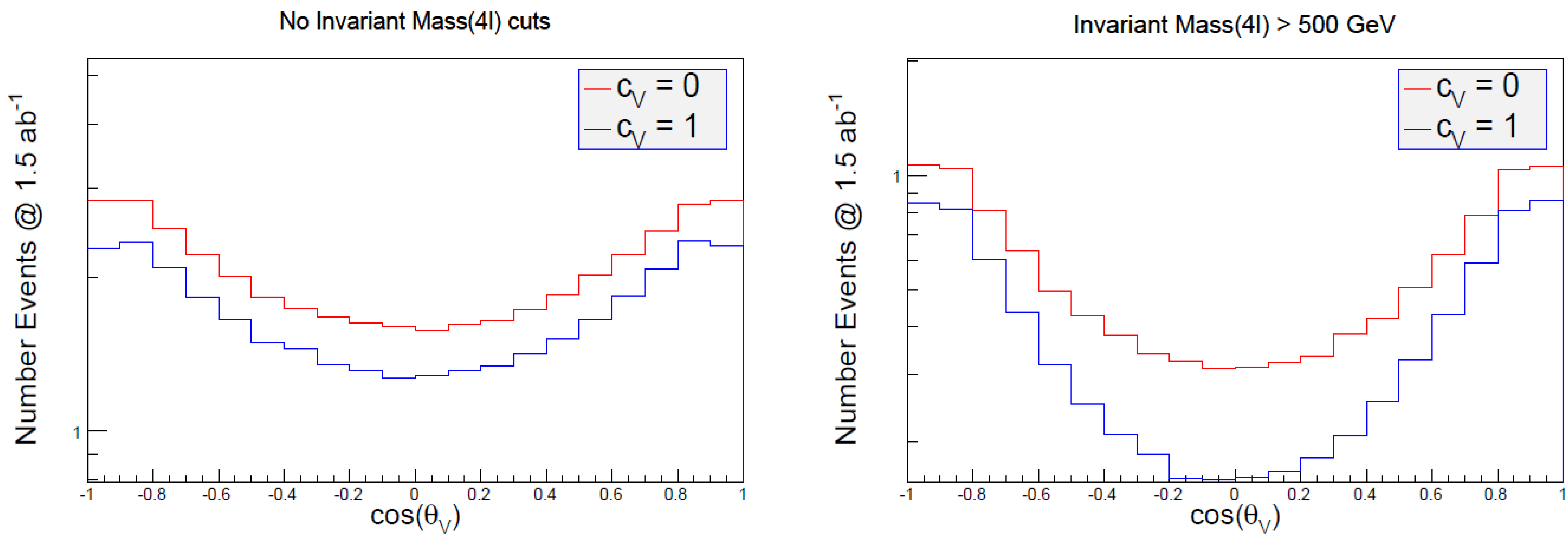
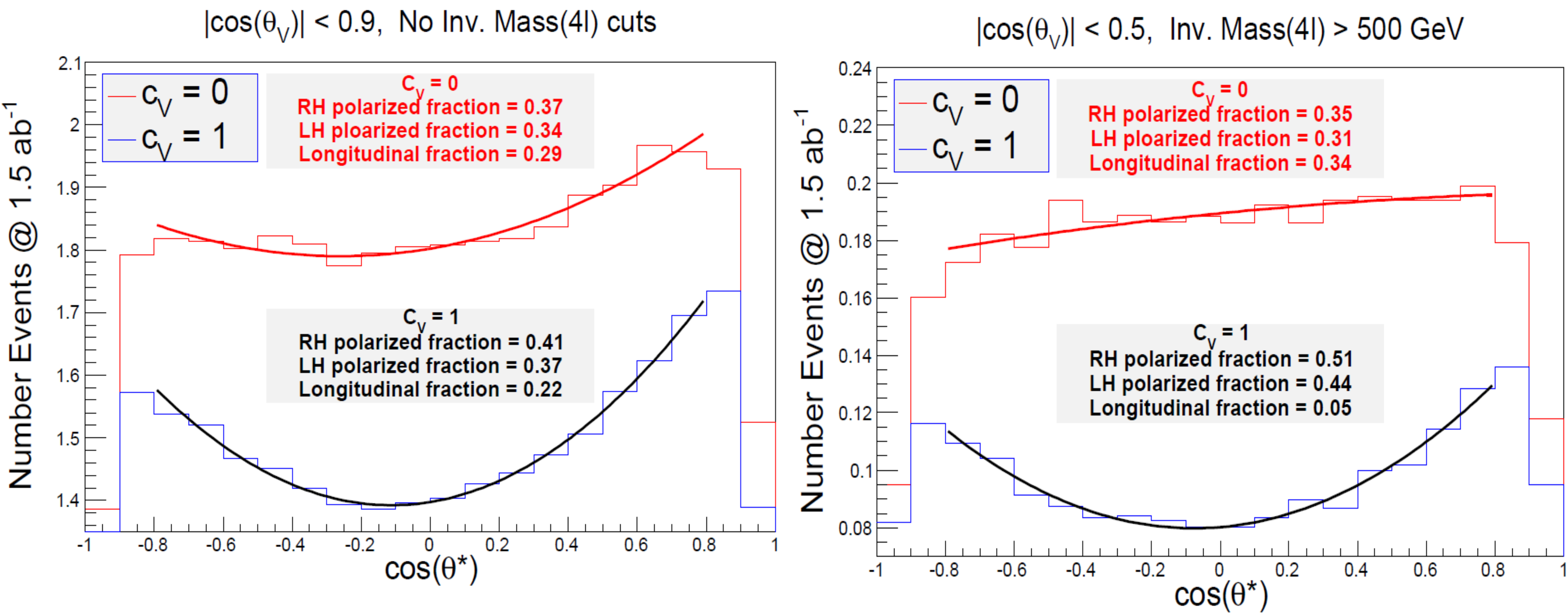


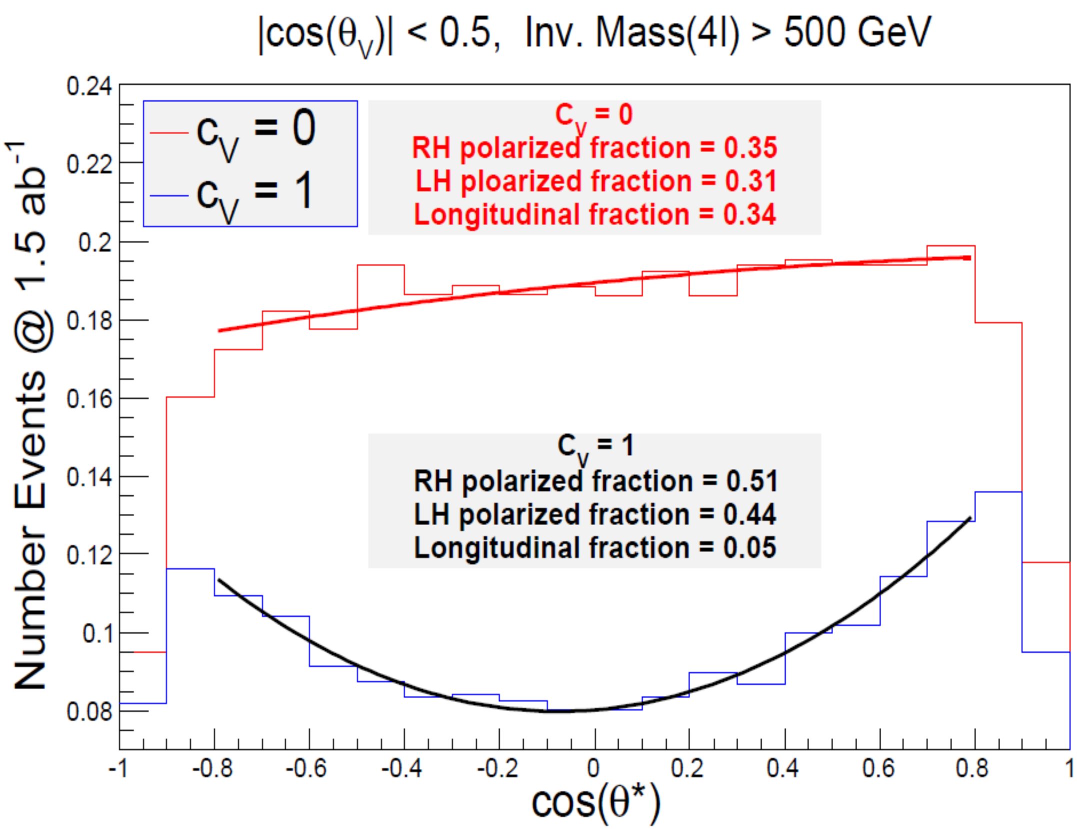
Let us find how well cuts work



$$pp \to jjZZ \to e^+e^-\mu^+\mu^-jj \qquad pp \to jjZZ \to e^+e^-\mu^+\mu^-jj$$

Let us find how well cuts work

- *Cuts used*
  - $|\cos\theta_V| < 0.5$
  - *Invariant mass (4l) > 500 GeV*
- *Large increase in longitudinal fraction from 0.05 to 0.34 for $C_V = 1$ vs $C_V = 0$.*
- *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 C_V at approx 10% with 100 fb^{-1}.*



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

Beyond the VV→VV scattering ...

Initial cuts:

$|\Delta R_{jj}| > 0.4$

$P_T^j > 50$ GeV

VBF cuts:

$|\Delta \eta_{jj}| > 5$

$E_j > 1500$ GeV

CalcHEP & Madgraph results

AB, Hamers, Thomas (work in progress)

Process	VBF cuts	13 TeV		33 TeV		100 TeV	
		$a = 1.0$	$a = 0.9$	$a = 1.0$	$a = 0.9$	$a = 1.0$	$a = 0.9$
$pp \to jjW^+W^-$	×	$9.88 \cdot 10^3$	$9.88 \cdot 10^3$	$6.06 \cdot 10^4$	$6.04 \cdot 10^4$	$3.52 \cdot 10^5$	$3.52 \cdot 10^5$
	✓	12.92	12.69	475.38	473.85	$5.49 \cdot 10^3$	$5.47 \cdot 10^3$
$pp \to jjW^+W^-h$	×	1.71	1.43	16.25	15.34	686.76	602.19
	✓	$1.26 \cdot 10^{-2}$	$8.80 \cdot 10^{-2}$	0.077	1.93	154.26	185.18
$pp \to jjhh$	×	0.51	0.36	3.49	2.93	16.97	16.97
	✓	0.02	0.01	0.77	0.77	5.56	9.20
$pp \to jjhhh$	×	$2.38 \cdot 10^{-4}$	$2.50 \cdot 10^{-2}$	$1.97 \cdot 10^{-3}$	1.37	$1.23 \cdot 10^{-2}$	46.03
	✓	$6.14 \cdot 10^{-6}$	$2.06 \cdot 10^{-3}$	$4.39 \cdot 10^{-4}$	0.75	$4.70 \cdot 10^{-3}$	41.03

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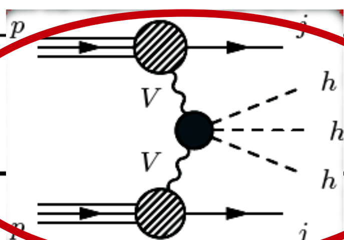
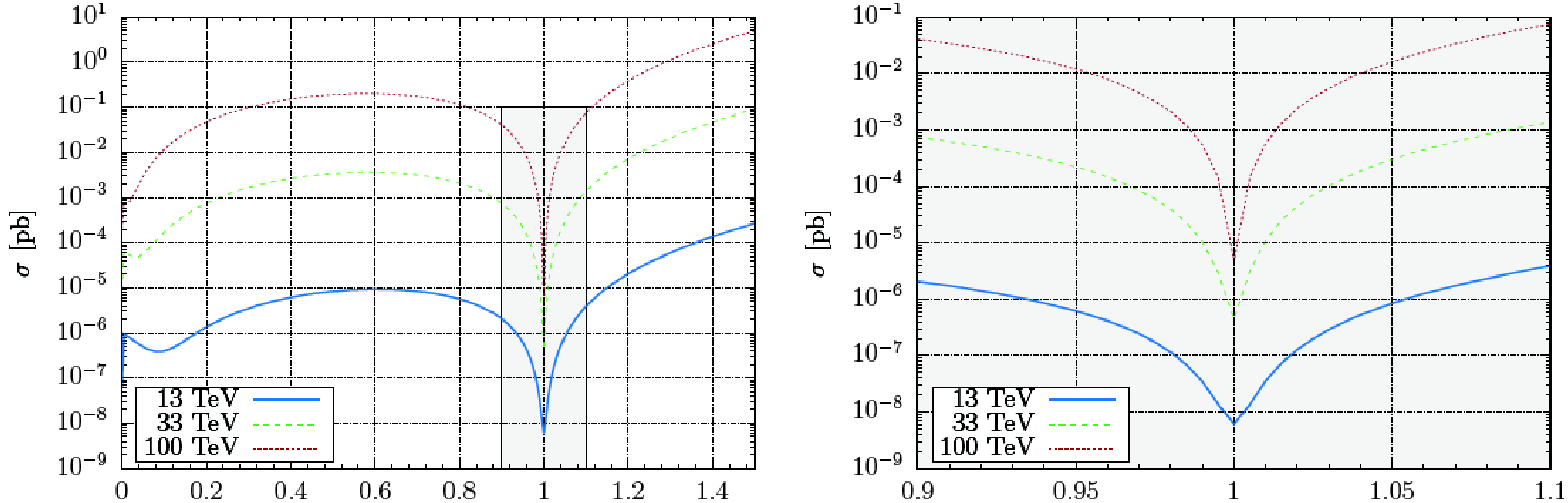
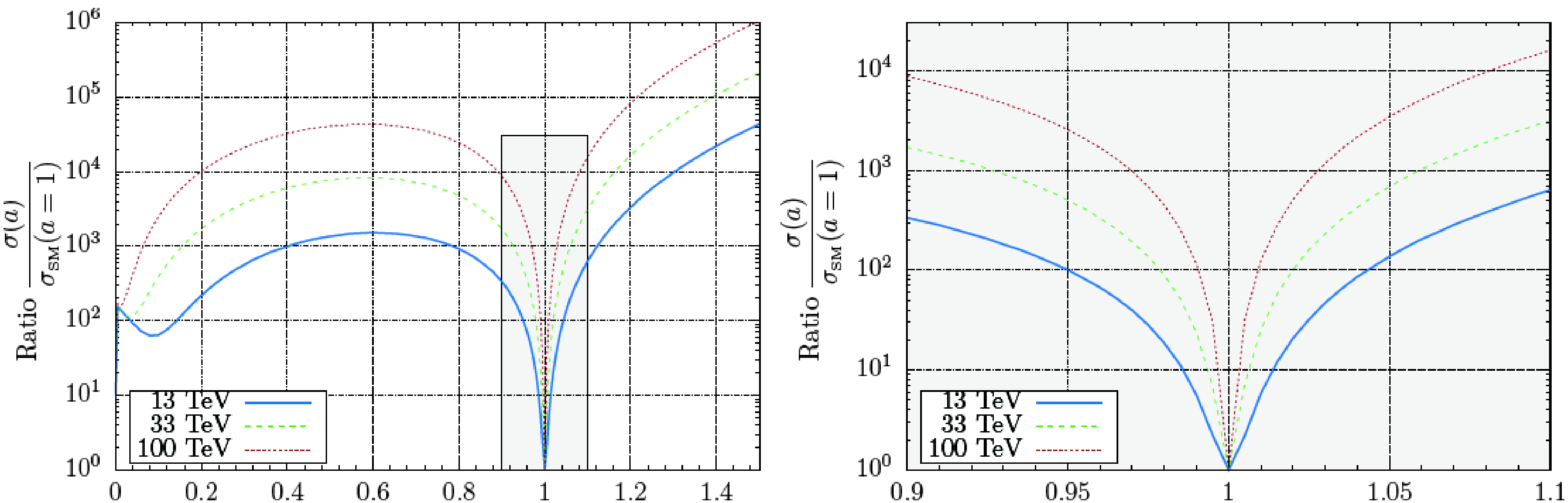


VV→ hhh can be quite promising!

pp→ jj hhh process

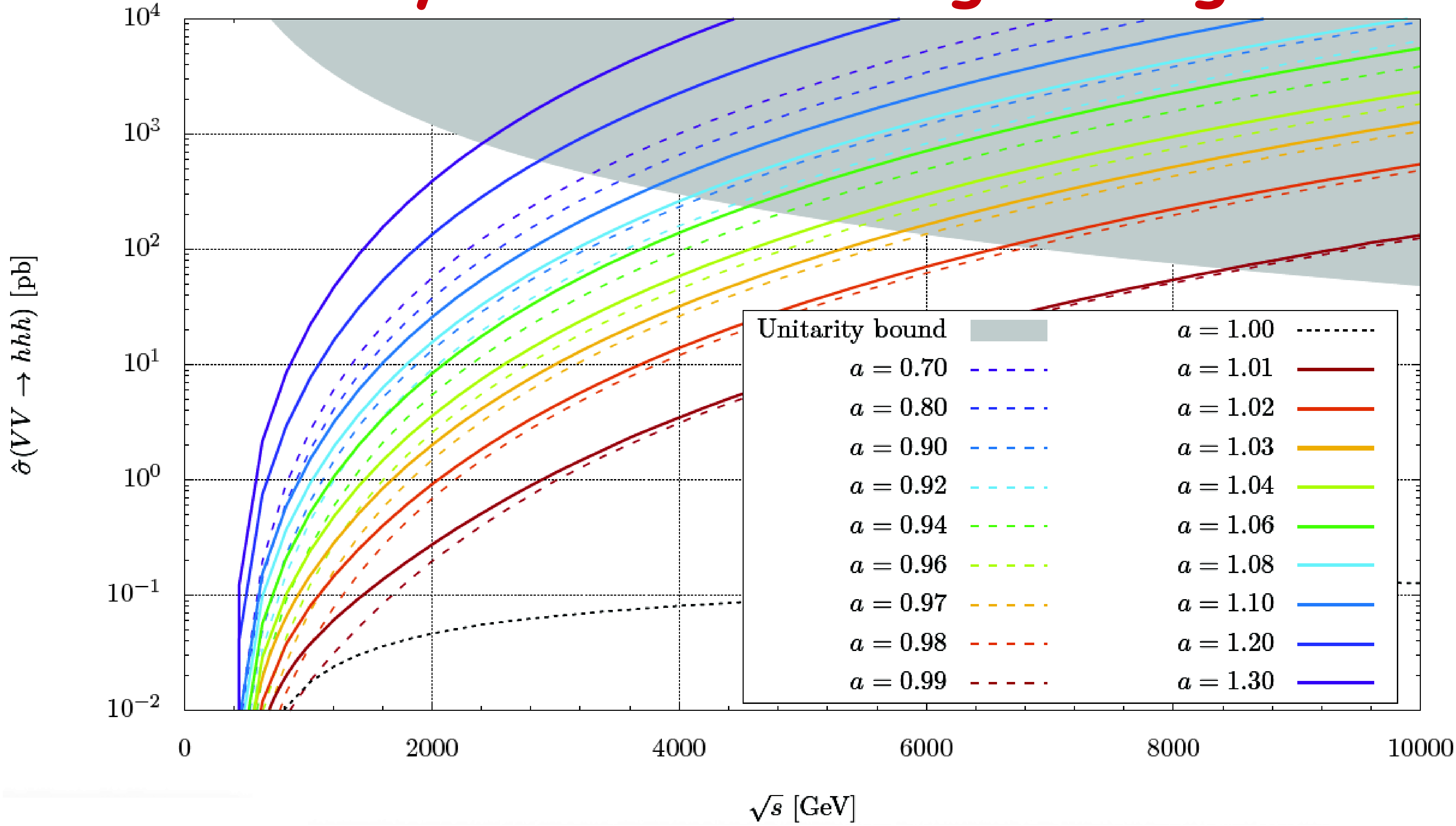


$pp \to jjhhh$ with VBF cuts

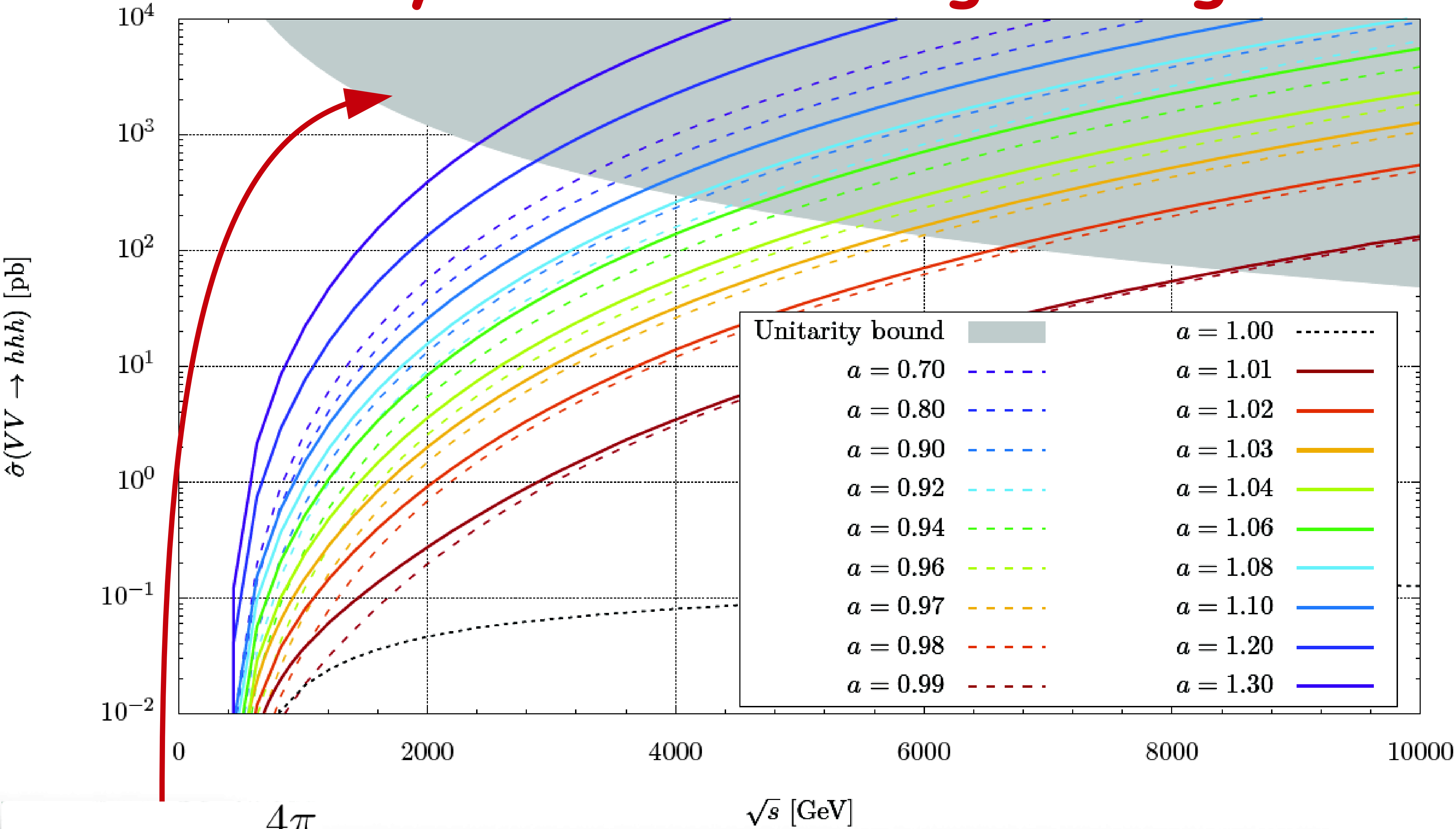


$pp \to jjhhh$ with VBF cuts

Unitarity violation at large energies

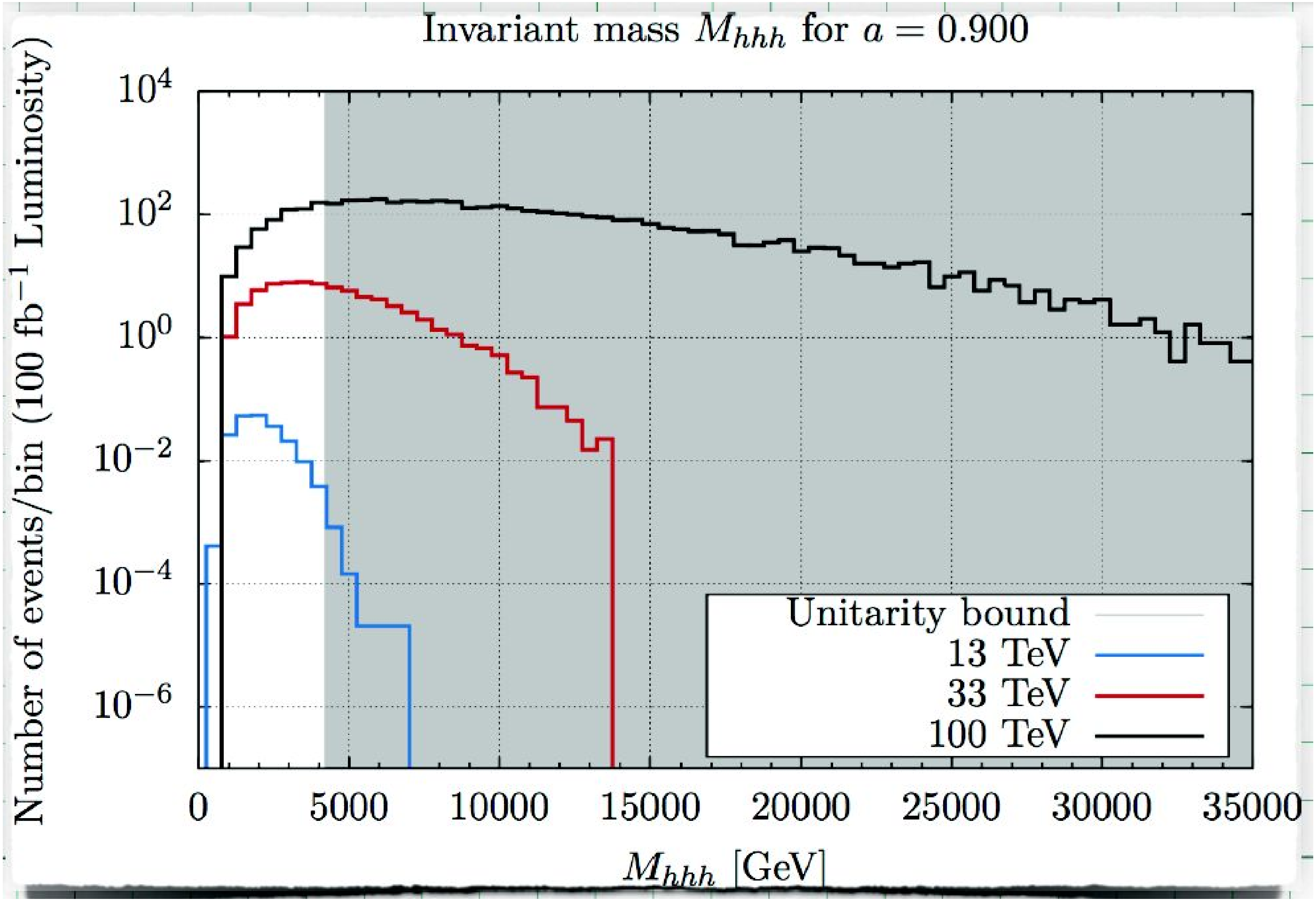


Unitarity violation at large energies



$$\sigma(2 \to n) < \frac{4\pi}{s}$$: **perturbative unitarity bound**

Unitarity violation at large energies



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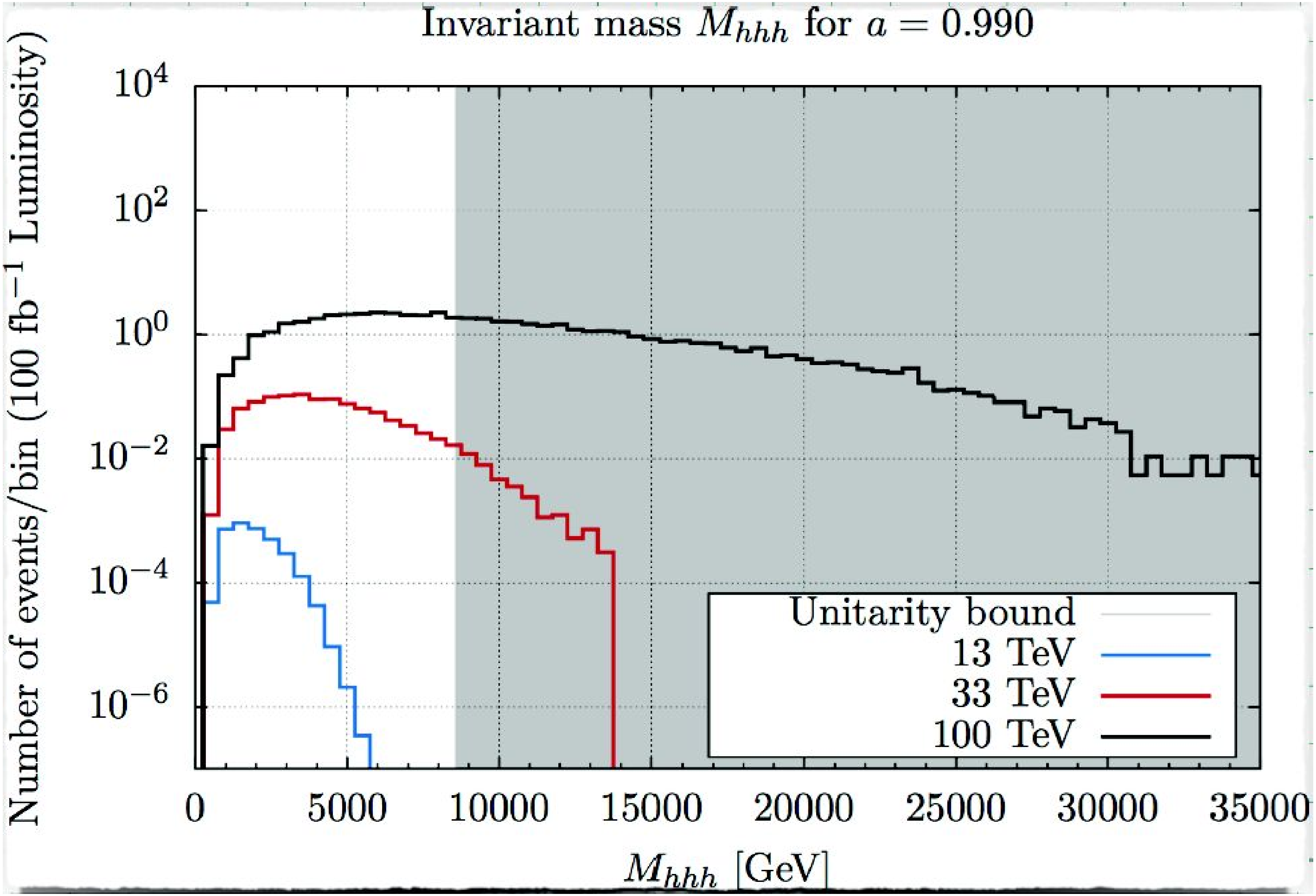

Sensitivity of the future pp colliders

Unitarity not violated

Total number of events

$\mathcal{L}_{\text{int}} = 100\,\text{fb}^{-1}$

Total number of events not violating unitarity

33 TeV: could be sensitive to signature down to 5% deviation

33 TeV				
a	$\varepsilon_{\mathcal{U}}$	σ [fb]	$\mathcal{L}_{\text{int}} \cdot \sigma$	$\mathcal{L}_{\text{int}} \cdot \sigma \cdot \varepsilon_{\mathcal{U}}$
0.70	37.14 %	3.97	397.27	147.55
0.80	44.18 %	2.61	261.24	115.41
0.90	57.79 %	0.93	93.09	53.79
0.92	61.47 %	0.64	63.76	39.19
0.94	67.48 %	0.38	38.16	25.75
0.96	77.42 %	0.18	18.12	14.03
0.97	82.31 %	0.11	10.56	8.69
0.98	88.62 %	0.05	4.86	4.30
0.99	96.61 %	0.01	1.30	1.26
1.01	96.18 %	0.01	1.41	1.35
1.02	88.41 %	0.06	5.57	4.92
1.03	79.96 %	0.13	12.76	10.21
1.04	73.08 %	0.23	23.28	17.01
1.06	62.95 %	0.55	55.42	34.89
1.08	55.69 %	1.05	104.69	58.30
1.10	50.67 %	1.72	172.06	87.18
1.20	31.25 %	9.04	904.09	282.53
1.30	22.32 %	26.16	2616.39	583.98

Sensitivity of the future pp colliders

Unitarity not violated

Total number of events

$\mathcal{L}_{\text{int}} = 100\,\text{fb}^{-1}$

Total number of events not violating unitarity

100 TeV: could be sensitive to signature down to 1% deviation

100 TeV				
a	$\varepsilon_{\mathcal{U}}$	σ [fb]	$\mathcal{L}_{\text{int}} \cdot \sigma$	$\mathcal{L}_{\text{int}} \cdot \sigma \cdot \varepsilon_{\mathcal{U}}$
0.70	7.35 %	164.05	16405.29	1205.79
0.80	7.72 %	107.51	10751.06	829.98
0.90	13.56 %	37.62	3761.54	510.06
0.92	15.96 %	26.15	2615.40	417.42
0.94	20.07 %	15.19	1519.02	304.87
0.96	22.06 %	7.44	743.67	164.05
0.97	28.31 %	4.30	429.77	121.67
0.98	35.21 %	1.98	198.20	69.78
0.99	47.24 %	0.52	51.71	24.43
1.01	47.82 %	0.55	54.68	26.15
1.02	31.00 %	2.72	226.54	70.23
1.03	25.45 %	5.18	518.47	131.95
1.04	22.35 %	9.43	947.99	211.88
1.06	16.46 %	22.50	2249.61	370.29
1.08	13.44 %	42.24	4224.29	567.74
1.10	10.11 %	69.44	6943.99	702.04
1.20	5.46 %	367.84	36684.40	2002.97
1.30	3.73 %	1054.19	105419.35	3932.14

Conclusions/Outlook

- $VV \to VV$ study
  - combination of cuts on three variables can isolate the longitudinal components of vector boson scattering
  - sensitivity is independent of that which can be deduced from direct Higgs searches
  - only HVV coupling is involved in the VBF process, so it can be measured in a much more model-independent way
  - work in progress – the complete set of ZZ, WW, WZ VBF processes should be included ; prospect to measure the HVV coupling with 10% precision at 100 fb^{-1} in a (more) model-independent way
- $VV \to$ hhh study
  - Extremely sensitive to HVV deviations from SM
  - LHC@13 TeV is not sensitive to this signature - CS is too low
  - 100 TeV pp collider could potentially probe HVV coupling at 1% level
  - work in progress – BGs are being estimated