Probing Higgs Boson with VBS

Alexander Belyaev

Southampton U & RAL

AB, O. Eboli, C. Gonzalez-Garcia, K.Mizukoshi, S.Novaes, I. Zacharov, hep-ph/9805229
AB, A. Oliveira, R. Rosenfeld, M. Thomas, 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.Schaefers, arXiv:1801.10157

OUTLINE

- Preface
  - the Higgs and vector boson scattering
- $VV \to VV$ process at the LHC
  - selection of the longitudinal vector bosons
  - model-independent sensitivity to HVV coupling using three main observables
- $VV \to hhh$ at future pp colliders
  - cross section enhancement, high sensitivity to HVV coupling
- Conclusions

Before Higgs discovery: non-linear Σ-model

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

e.g.

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

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

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

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

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

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

Before Higgs discovery: non-linear Σ-model

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Appelquist, Bernard '80 ; Longitano '80

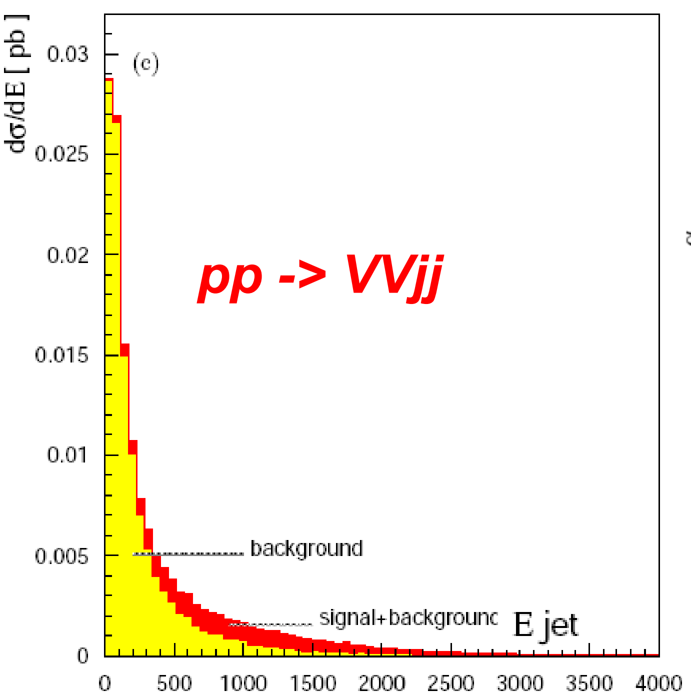
Before Higgs discovery: non-linear Σ-model

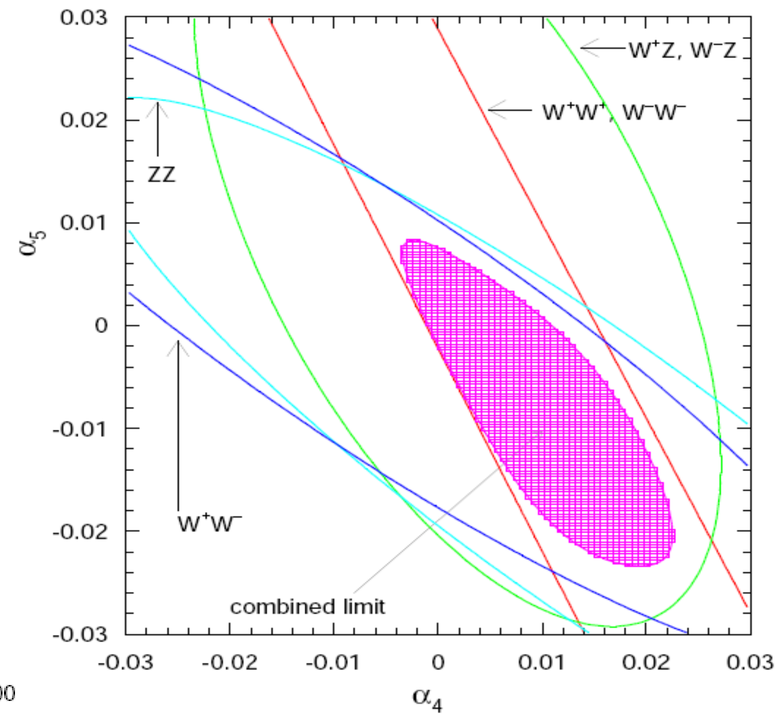
There are many 4D CP-conserving operators that can be written down

$$\mathfrak{L}_1 = \tfrac{1}{2} g^2 \alpha_1 B_{\mu\nu} \mathrm{Tr}(TF^{\mu\nu})$$
$$\mathfrak{L}_2 = \tfrac{1}{2} i g \alpha_2 B_{\mu\nu} \mathrm{Tr}(T[V^\mu, V^\nu])$$
$$\mathfrak{L}_3 = i g \alpha_3 \mathrm{Tr}(F_{\mu\nu}[V^\mu, V^\nu])$$
$$\mathfrak{L}_4 = \alpha_4 [\mathrm{Tr}(V_\mu V_\nu)]^2$$
$$\mathfrak{L}_5 = \alpha_5 [\mathrm{Tr}(V_\mu V^\mu)]^2$$
$$\mathfrak{L}_6 = \alpha_6 \mathrm{Tr}(V_\mu V_\nu)\mathrm{Tr}(TV^\mu)\mathrm{Tr}(TV^\nu)$$
$$\mathfrak{L}_7 = \alpha_7 \mathrm{Tr}(V_\mu V^\mu)[\mathrm{Tr}(TV_\nu)]^2$$
$$\mathfrak{L}_8 = \tfrac{1}{4} g^2 \alpha_8 [\mathrm{Tr}(TF_{\mu\nu})]^2$$
$$\mathfrak{L}_9 = \tfrac{1}{2} i g \alpha_9 \mathrm{Tr}(TF_{\mu\nu})\mathrm{Tr}(T[V^\mu, V^\nu])$$
$$\mathfrak{L}_{10} = \tfrac{1}{2} \alpha_{10} [\mathrm{Tr}(TV_\mu)\mathrm{Tr}(TV_\nu)]^2$$
$$\mathfrak{L}_{11} = \alpha_{11} \mathrm{Tr}[(\mathfrak{D}_\mu V^\mu)^2]$$
$$\mathfrak{L}_{12} = \tfrac{1}{2} \alpha_{12} \mathrm{Tr}(T\mathfrak{D}_\mu \mathfrak{D}_\nu V^\nu)\mathrm{Tr}(TV^\mu)$$
$$\mathfrak{L}_{13} = \tfrac{1}{2} \alpha_{13} [\mathrm{Tr}(T\mathfrak{D}_\mu V_\nu)]^2$$
$$\mathfrak{L}_{14} = \alpha_{14} [\mathrm{Tr}(F_{\mu\nu} V^\nu)\mathrm{Tr}(TV^\mu) - \mathrm{Tr}(F_{\mu\nu} V^\mu)\mathrm{Tr}(TV^\nu)]$$
$$\mathfrak{L}_{15} = 2 i \alpha_{15} \mathrm{Tr}(V_\mu \mathfrak{D}_\nu V^\nu)\mathrm{Tr}(TV^\mu)$$
$$\mathfrak{L}_{16} = i \alpha_{16} \mathrm{Tr}[T(\mathfrak{D}_\mu V_\nu + \mathfrak{D}_\nu V_\mu)] \times \mathrm{Tr}(V^\mu V^\nu)$$
$$\mathfrak{L}_{17} = \tfrac{1}{2} i \alpha_{17} \mathrm{Tr}[T(\mathfrak{D}_\mu V_\nu + \mathfrak{D}_\nu V_\mu)] \times \mathrm{Tr}(TV^\mu)\mathrm{Tr}(TV^\nu)$$
$$\mathfrak{L}_{18} = \tfrac{1}{2} i \alpha_{18} \mathrm{Tr}([V_\mu, T]\mathfrak{D}^\mu \mathfrak{D}^\nu V_\nu)$$

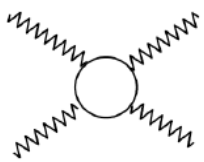
Appelquist, Bernard '80 ; Longitano '80

which can be tested at the LHC





the only quartic interactions under custodial symmetry



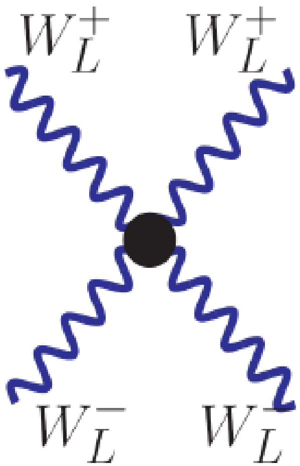
$$\mathcal{L}_4 = \alpha_4 (\mathrm{tr}\,[V_\mu V_\nu])^2$$
$$\mathcal{L}_5 = \alpha_5 (\mathrm{tr}\,[V_\mu V^\mu])^2$$

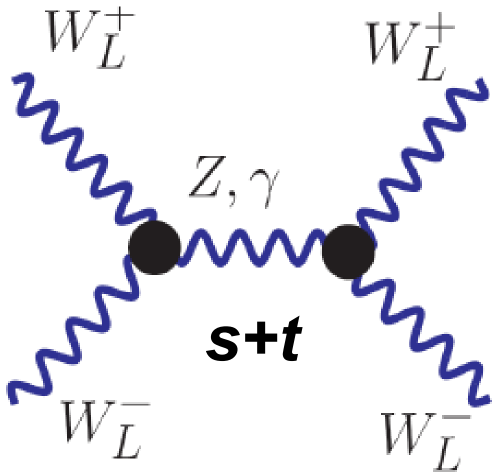
AB, Eboli, Gonzalez–Garcia, Mizukoshi, Novaes, Zacharov '98

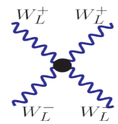
followed by

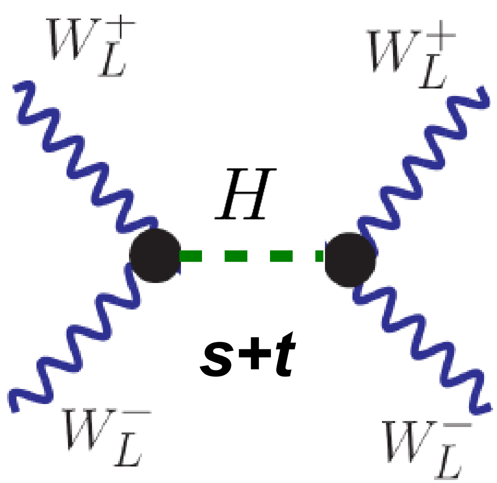
Eboli, Gonzalez-Garcia, Lietti, Novaes '00; Beyer, Kilian, Krstonosic, Monig, Reuter, Schmidt, Schroder '06; Eboli, Gonzalez–Garcia, Mizukoshi '06

But we have been expecting Higgs boson as it nicely unitarises 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 $\Rightarrow \mathcal{O}(E^2) \Rightarrow E < \sqrt{8\pi} v \simeq 1.2\,\mathrm{TeV}$

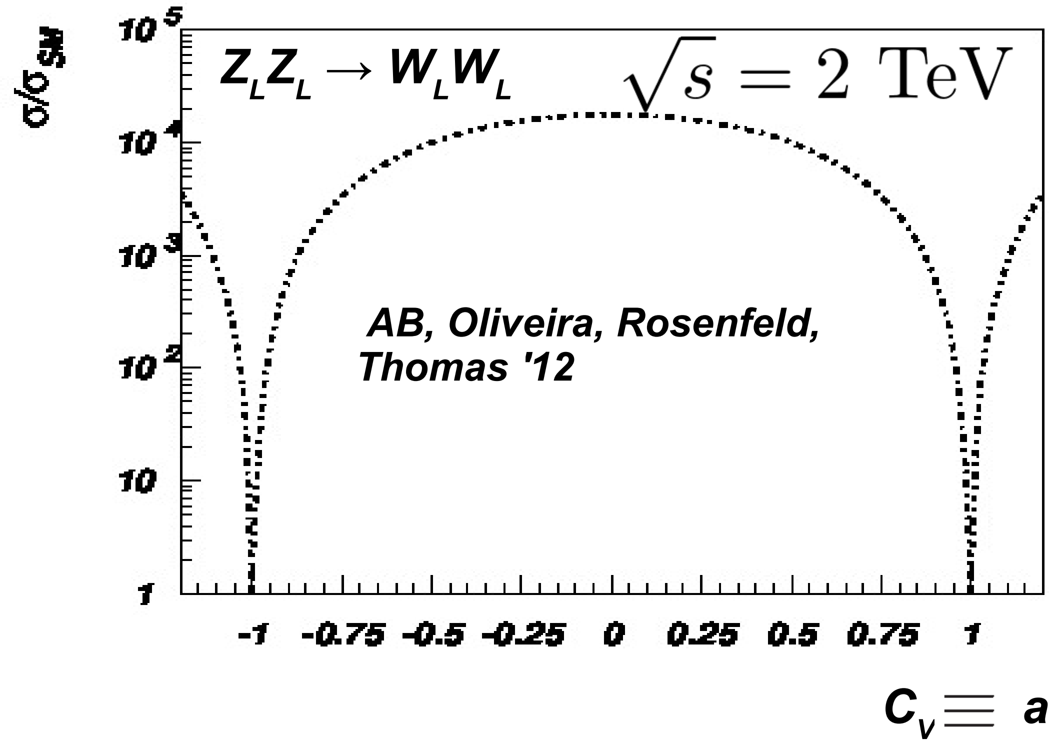
Cancellation requires exact SM coupling!

$$\mathcal{L}_{\text{eff}} = \frac{v^2}{4}\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + b_3\frac{h^3}{v^3} + \cdots\right)\text{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right]$$

Giudice, Grojean, Pomarol, Rattazzi '07

$$+ \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - d_3 \lambda v h^3 - d_4 \frac{\lambda}{4} h^4 + \cdots \qquad (U \equiv \Sigma \quad !)$$

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



- ***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

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

Case of multi-boson production

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

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

The cross section is expressed via Amplitude and the phase space as

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

Case of multi-boson production

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

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

The cross section is expressed via Amplitude and the phase space as

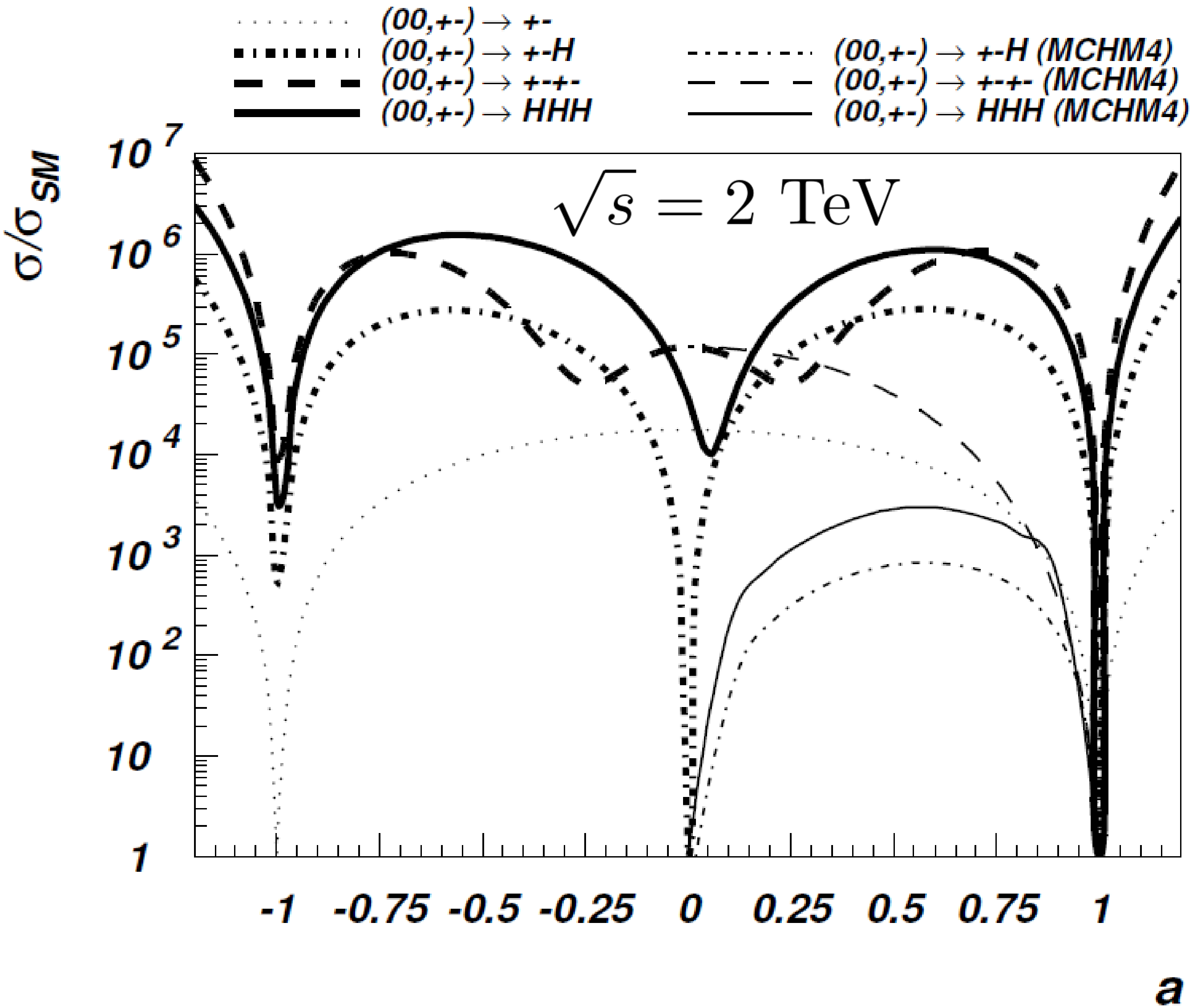
$$\sigma(2 \to n) \sim \frac{1}{s} \mathcal{A}^2(s)\, s^{n-2}$$

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"**
  - **$VV \to VV$ cross section is dominated by the transverse VV scattering – the main background!**

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

Transverse "pollution"at the level of pp collisions: similar problem

Process	14 TeV		33 TeV	
	with (without) VBF cuts		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

Transverse "pollution"at the level of pp collisions: similar problem

Process	14 TeV		33 TeV	
	with (without) VBF cuts		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

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

The ideas and results of our Les Houches 2013 team

(AB, E. Boos, V. Bunichev, Y. Maravin, A. Pukov, R. Rosenfeld, M. Thomas)

- Devise optimal cuts capable of selecting the contribution from the V_Ls
- Hence increase and optimise sensitivity to C_V

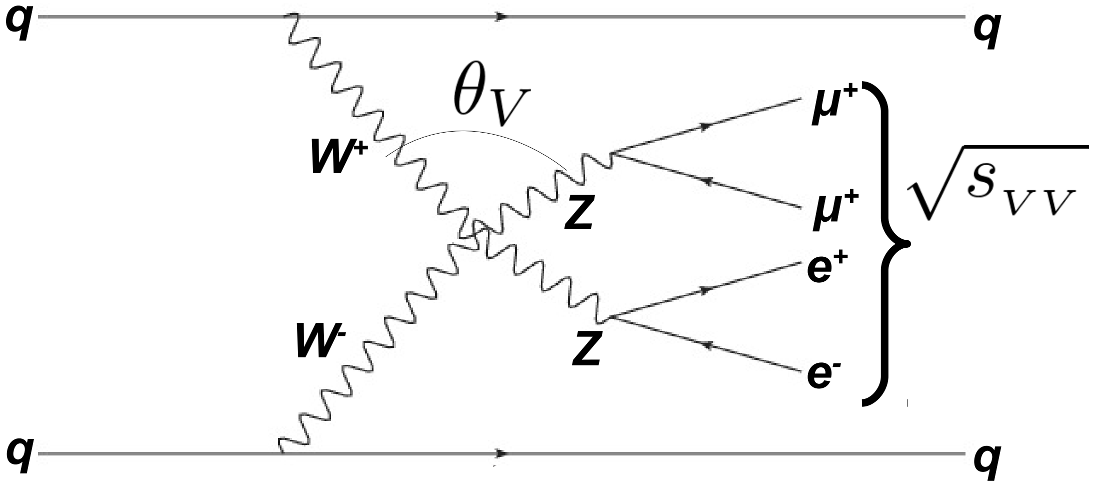
The ideas and results of our Les Houches 2013 team

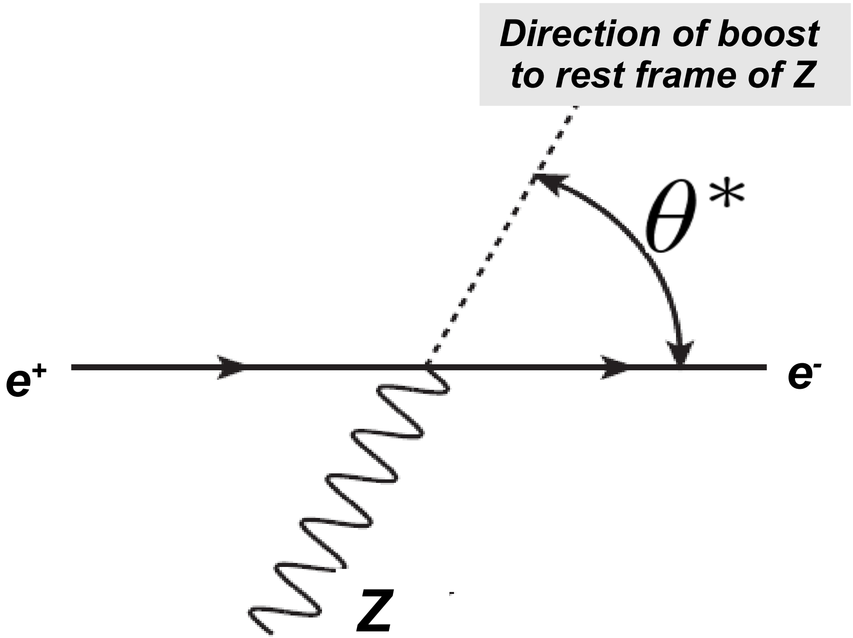
(AB, E. Boos, V. Bunichev, Y. Maravin, A. Pukov, R. Rosenfeld, M. Thomas)

- Devise optimal cuts capable of selecting the contribution from the V_Ls
- Hence increase and optimise sensitivity to C_V
- We have found that this can be done using a combination of three main observables:
  - Observable 1, θ_V
  - Observable 2, θ^*
  - Observable 3, $\sqrt{s_{VV}}$

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

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

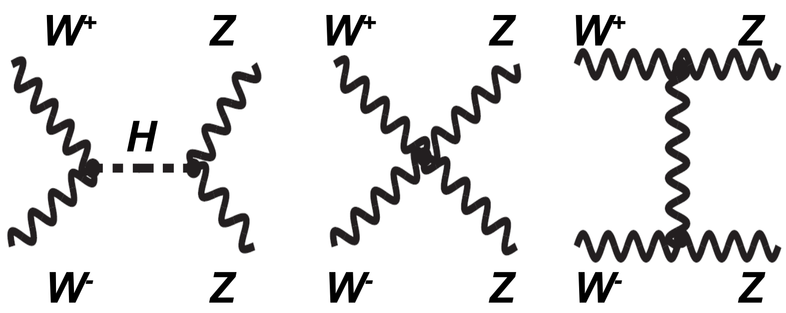




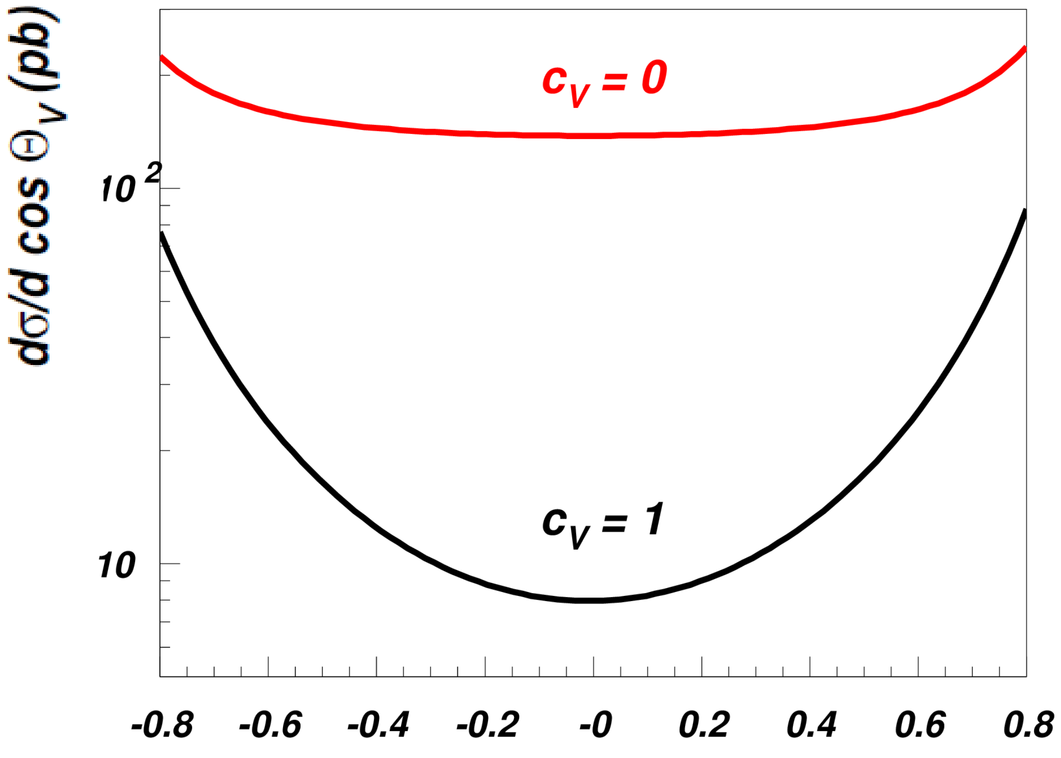
rest frame of the Z

Observable 1, θ_V

- Overall increase in cross section if $C_V \neq 1$ and much larger fraction of longitudinally polarized bosons in the central region



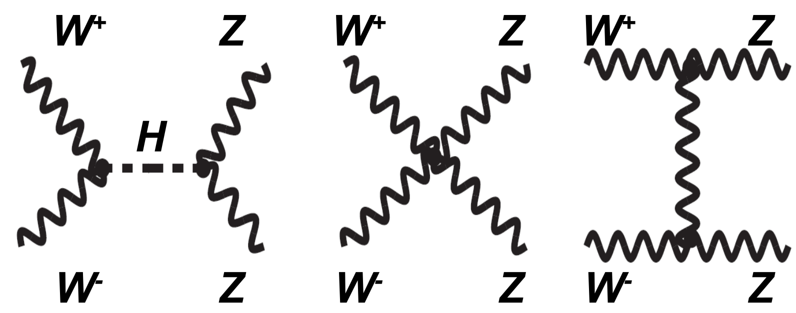
$W^+W^- \to ZZ$

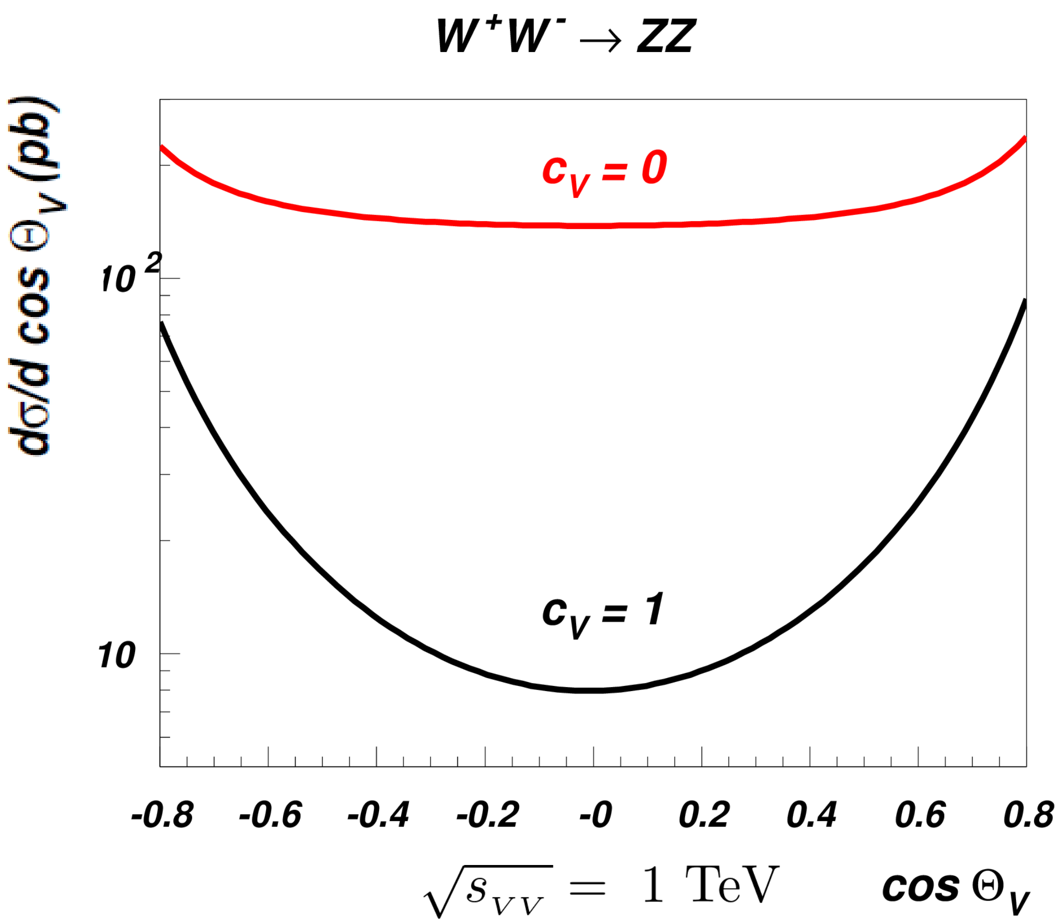


$\sqrt{s_{VV}} = 1$ TeV

Observable 1, θ_V

- Overall increase in cross section if $C_V \neq 1$ and much larger fraction of longitudinally polarized bosons in the central region

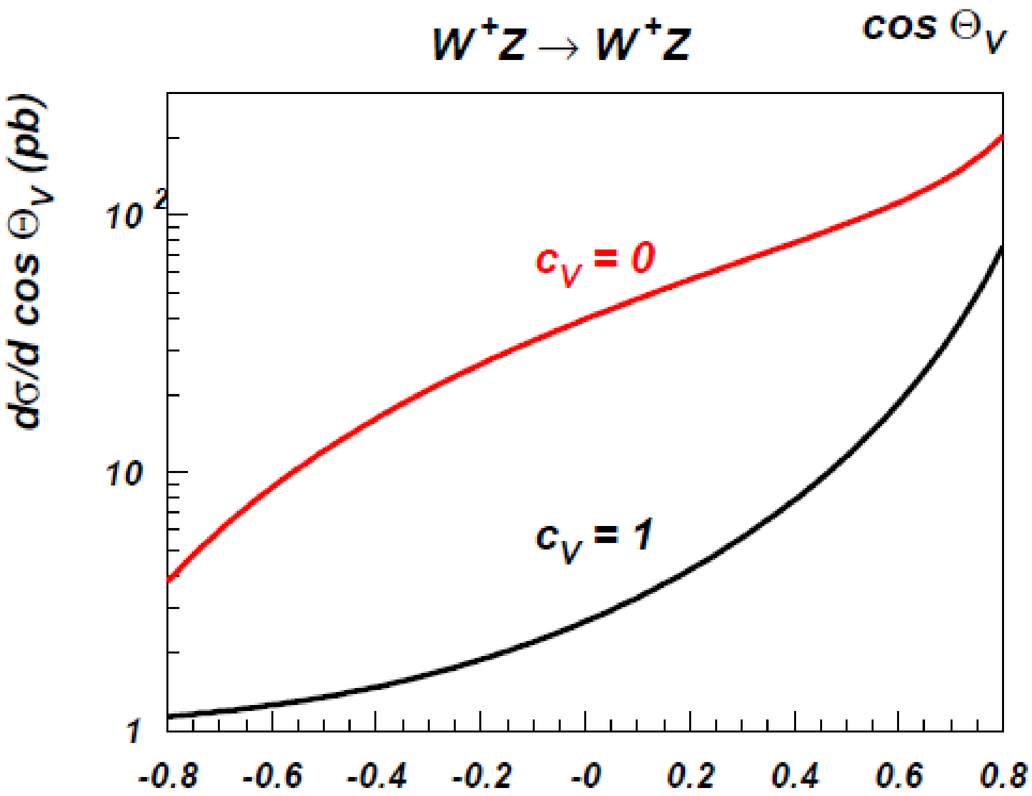




- Transversely polarised bosons have large contribution from t-channel amplitude with dominant forward-backward scattering
- Therefore cuts which reduce $C_V = 1$ more than $C_V \neq 1$ should increase the fraction of longitudinally polarized bosons. e.g. $|\cos\theta_V| < 0.5$

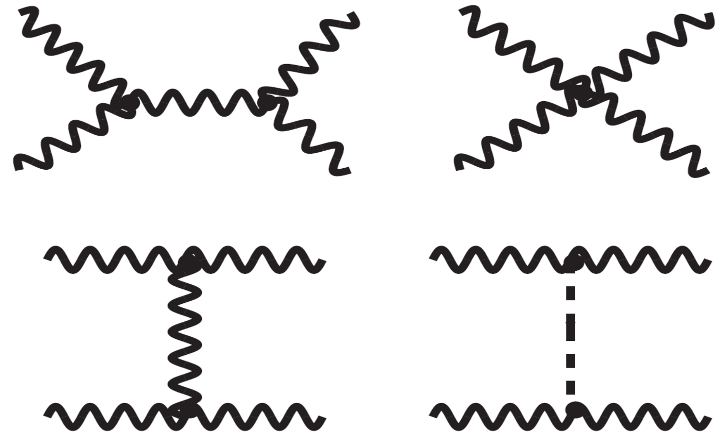
Observable 1, θ_V

- **Overall increase in cross section if $C_V \neq 1$ and much larger fraction of longitudinally polarized bosons in the central region**



cos Θ_V

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

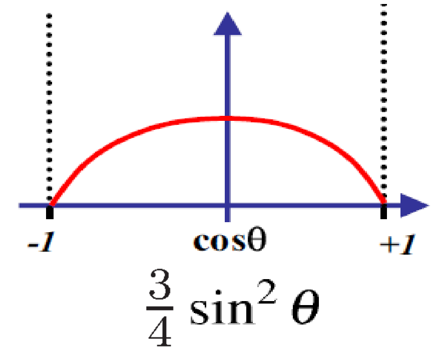


- **Transversely polarised bosons have large contribution from t-channel amplitude with dominant forward-backward scattering**
- **Therefore cuts which reduce $C_V = 1$ more than $C_V \neq 1$ should increase the fraction of longitudinally polarized bosons.**
  e.g. $|\cos\theta_V| < 0.5$

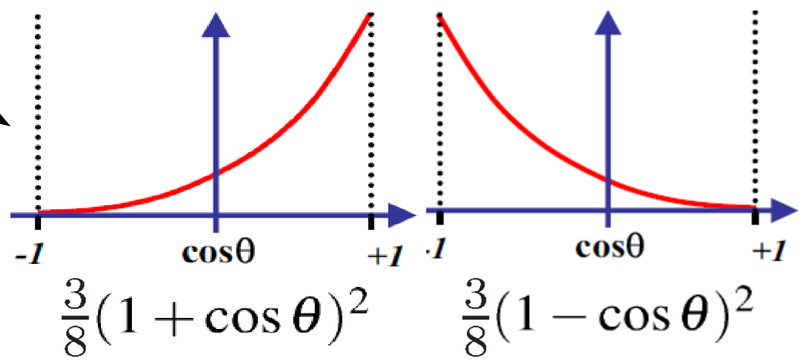
Observable 2, θ^*

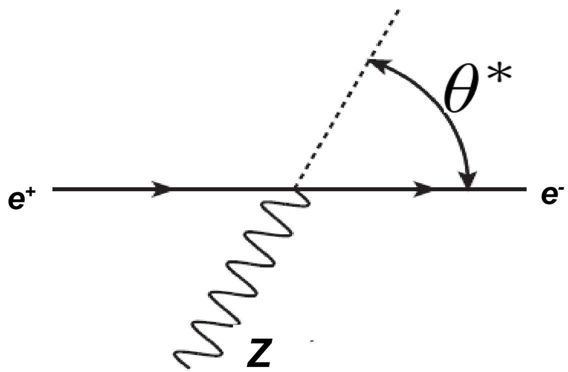
- **Distribution of decay from transverse and longitudinal polarisations.**

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



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





- **By fitting,**

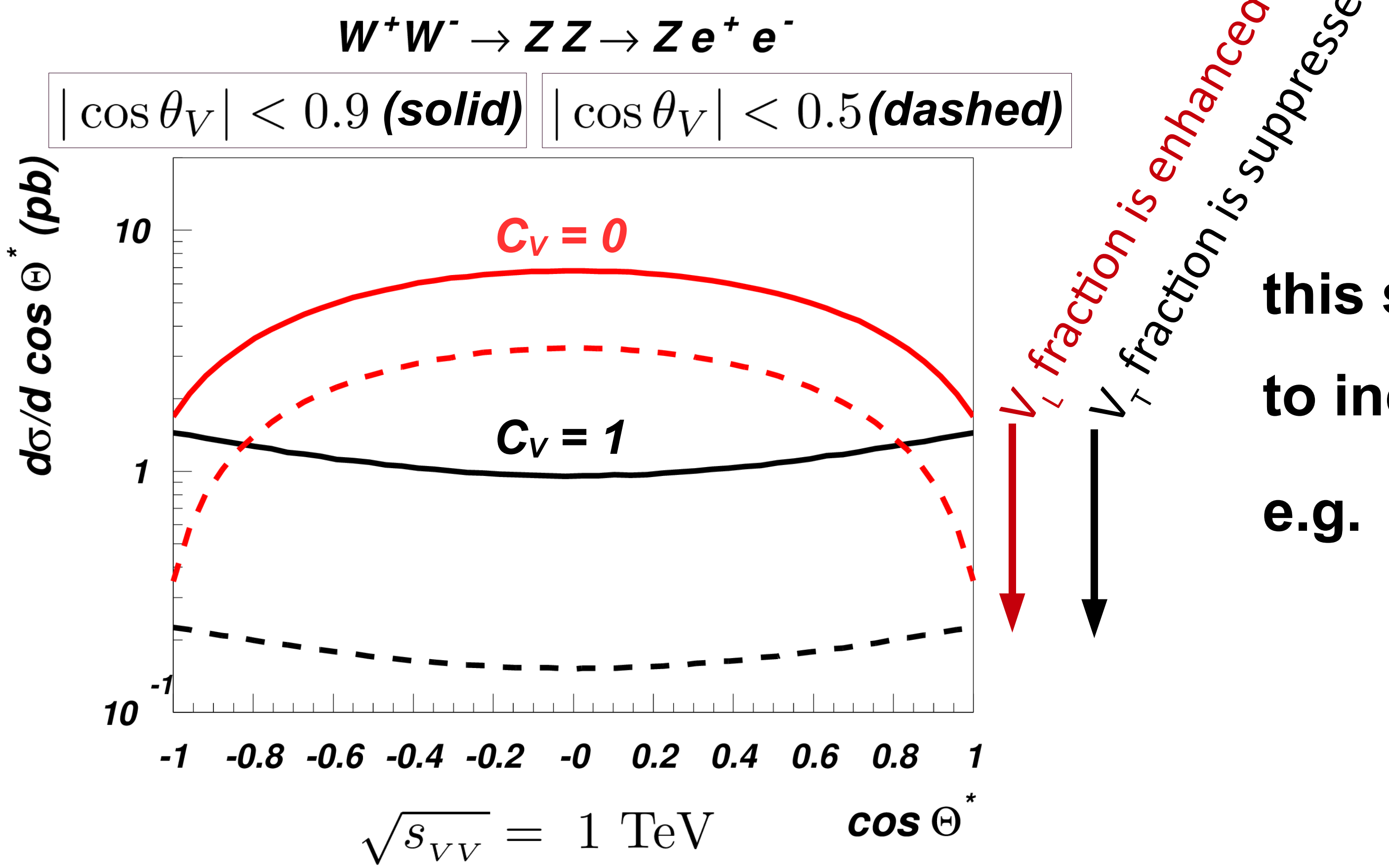
$$P(\cos\theta^*) = f_L P_L(\cos\theta^*) + f_+ P_+(\cos\theta^*) + f_- P_-(\cos\theta^*)$$

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 $\cos\theta^*$ (V_L fraction is enhanced) than the $C_V = 1$ case
- The cut $|\cos\theta_V| < 0.5$ increases this difference



this suggests θ_V, θ^* cuts to increase fraction of V_L

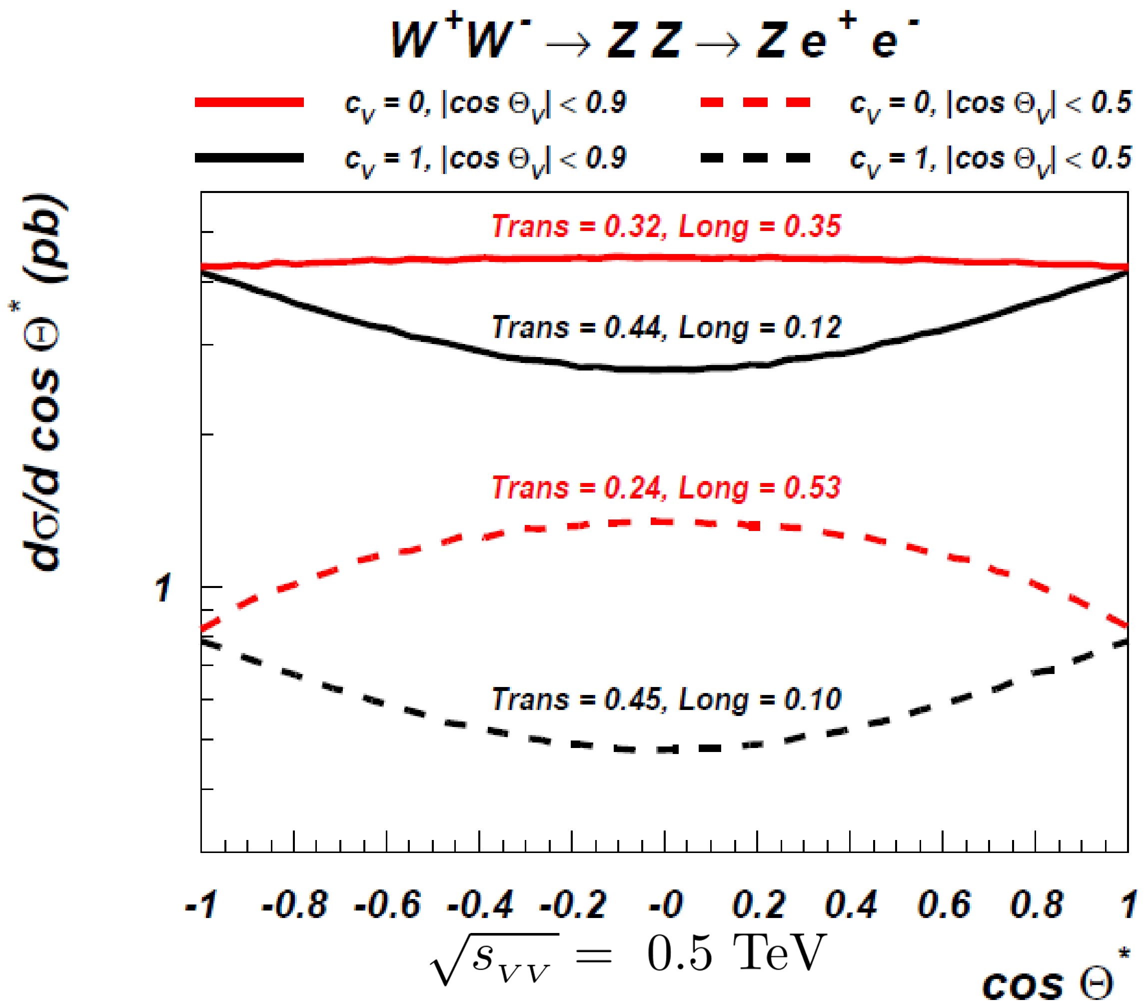
e.g. $|\cos\theta_V| < 0.5$

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

Fitting the V_L and V_T fractions

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

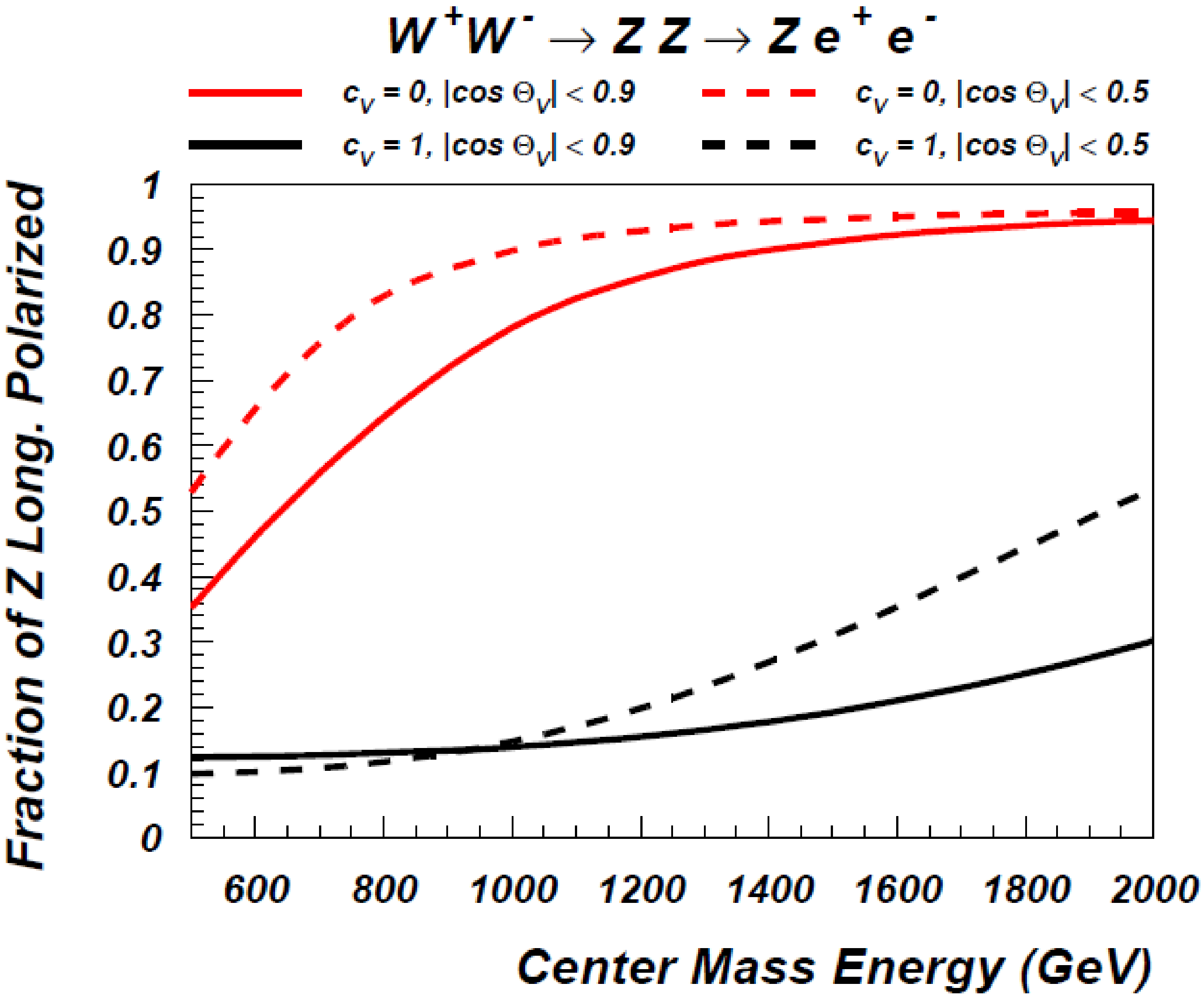
$$P_L(\cos\theta^*) = \frac{3}{4}(1-\cos^2\theta^*) \qquad P_\pm(\cos\theta^*) = \frac{3}{8}(1\pm\cos\theta^*)^2$$



$\sqrt{s_{VV}} = 0.5$ TeV

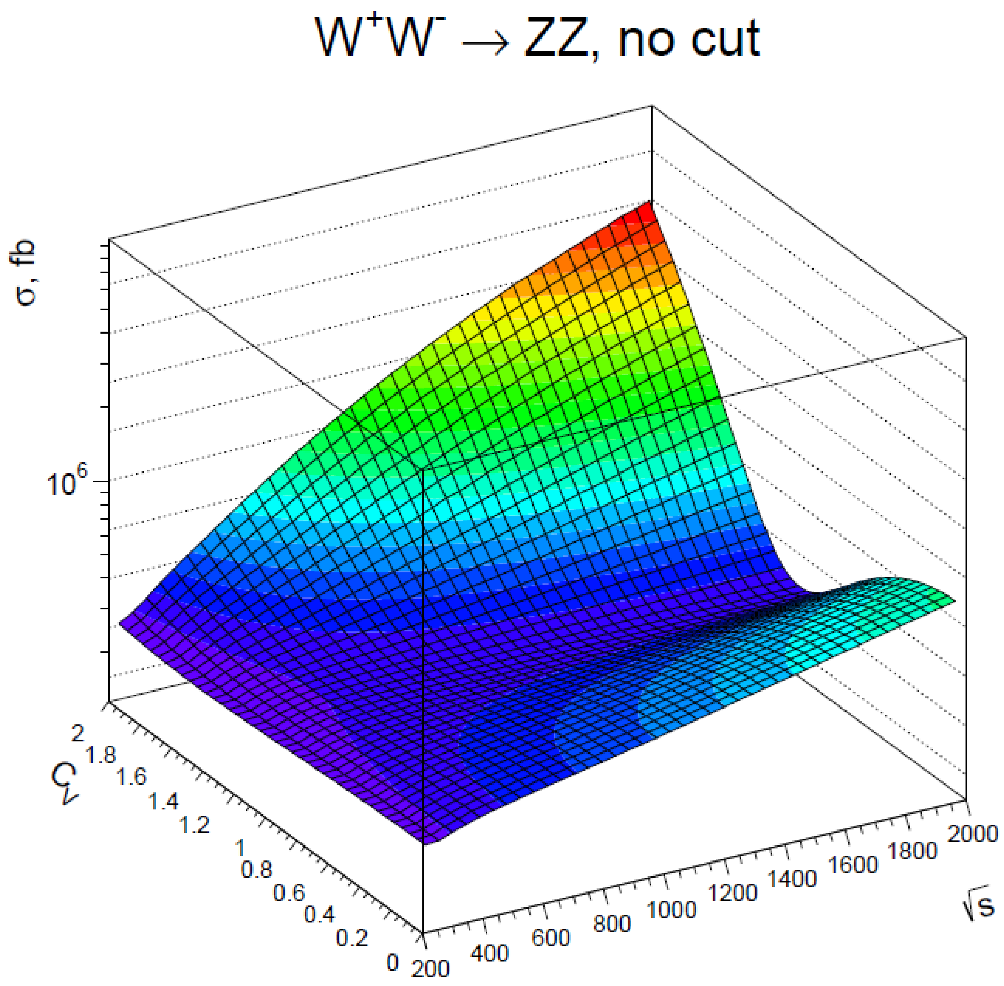
- **When $C_V = 0$, the fraction of V_L is higher, as expected**
- $|\cos\theta_V| < 0.5$ **cut increases fraction of V_Ls**

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

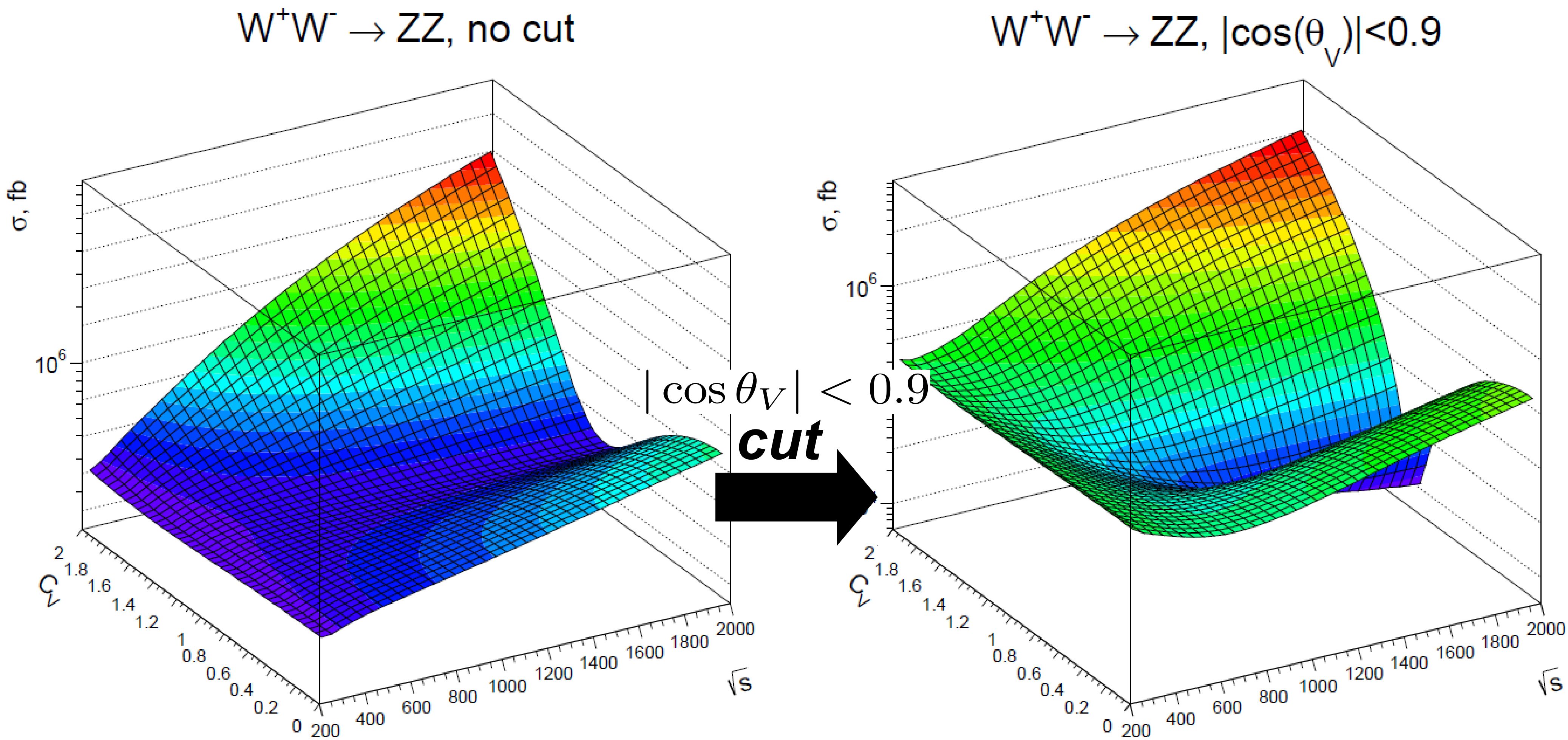


- As $\sqrt{s_{VV}}$ increases, the V_L fraction dominates for C_V=0
- To be expected as $\sigma(V_L V_L \to V_L V_L) \propto s$
- Cut for higher $\sqrt{s_{VV}}$ respectively increases fraction of V_L s

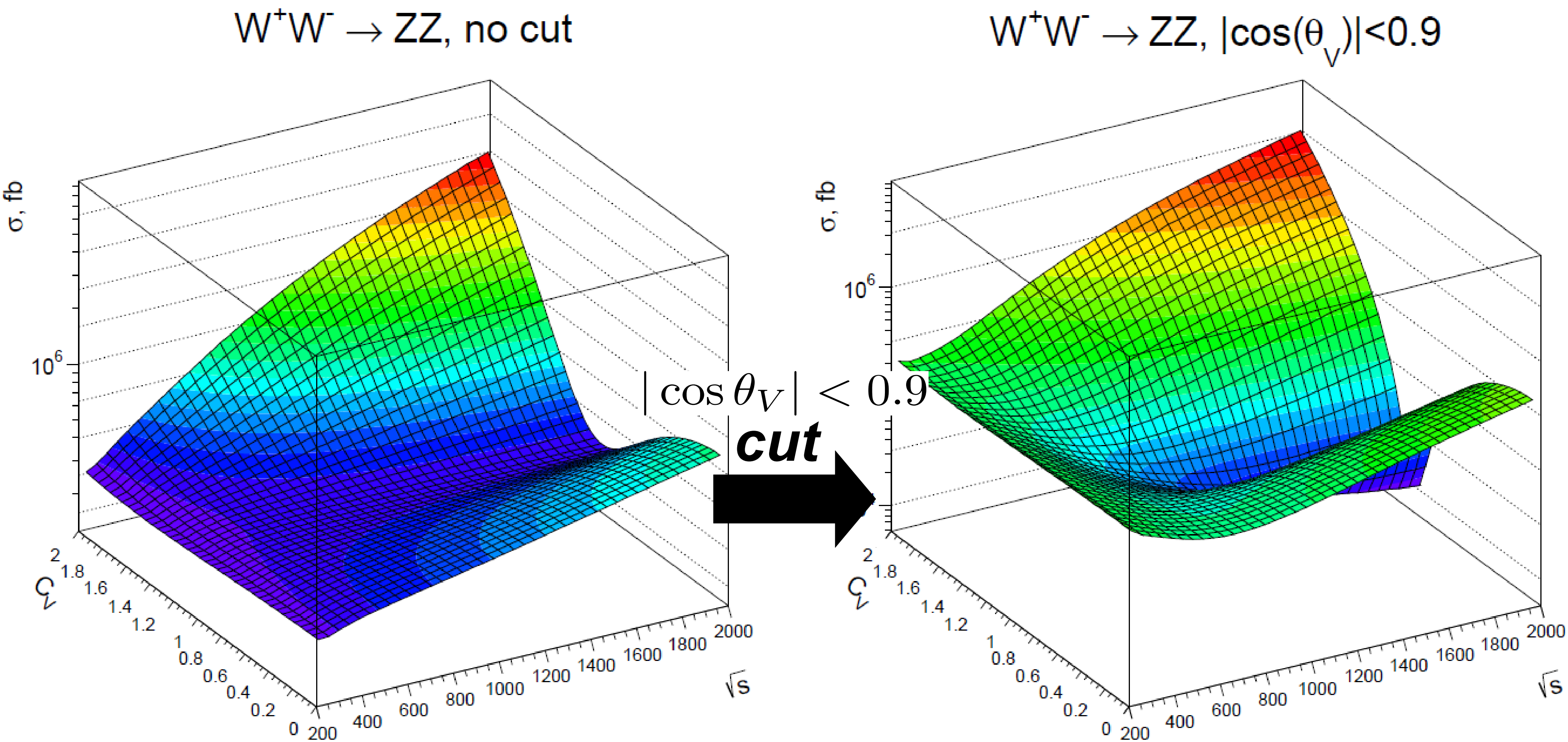
Effect of $\cos(\theta_V)$ cut in 3D



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



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

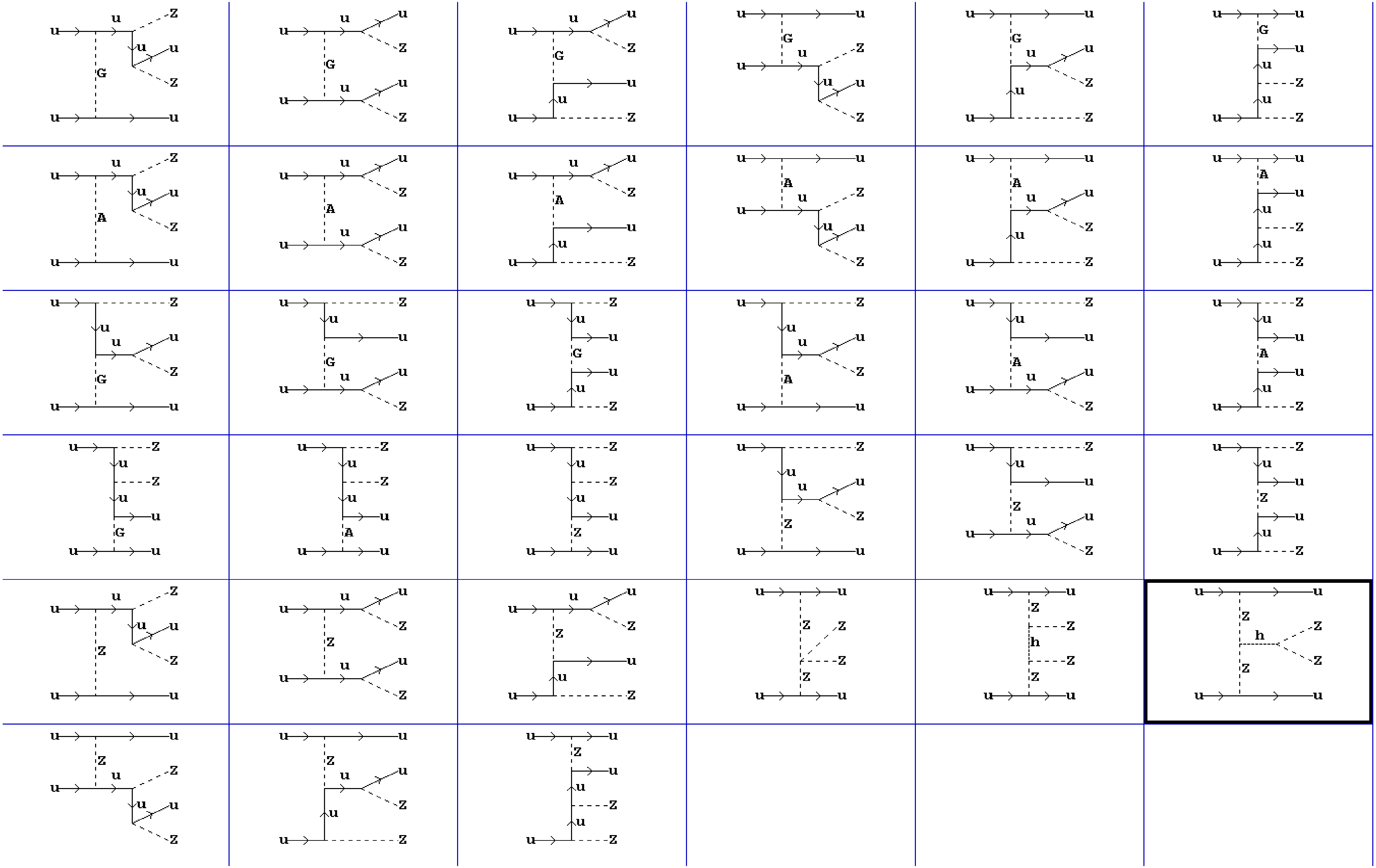


dependence on C_V becomes more pronounced after $\cos(\theta_V)$ cut which enhance relative L/T polarisation ratio of vector bosons

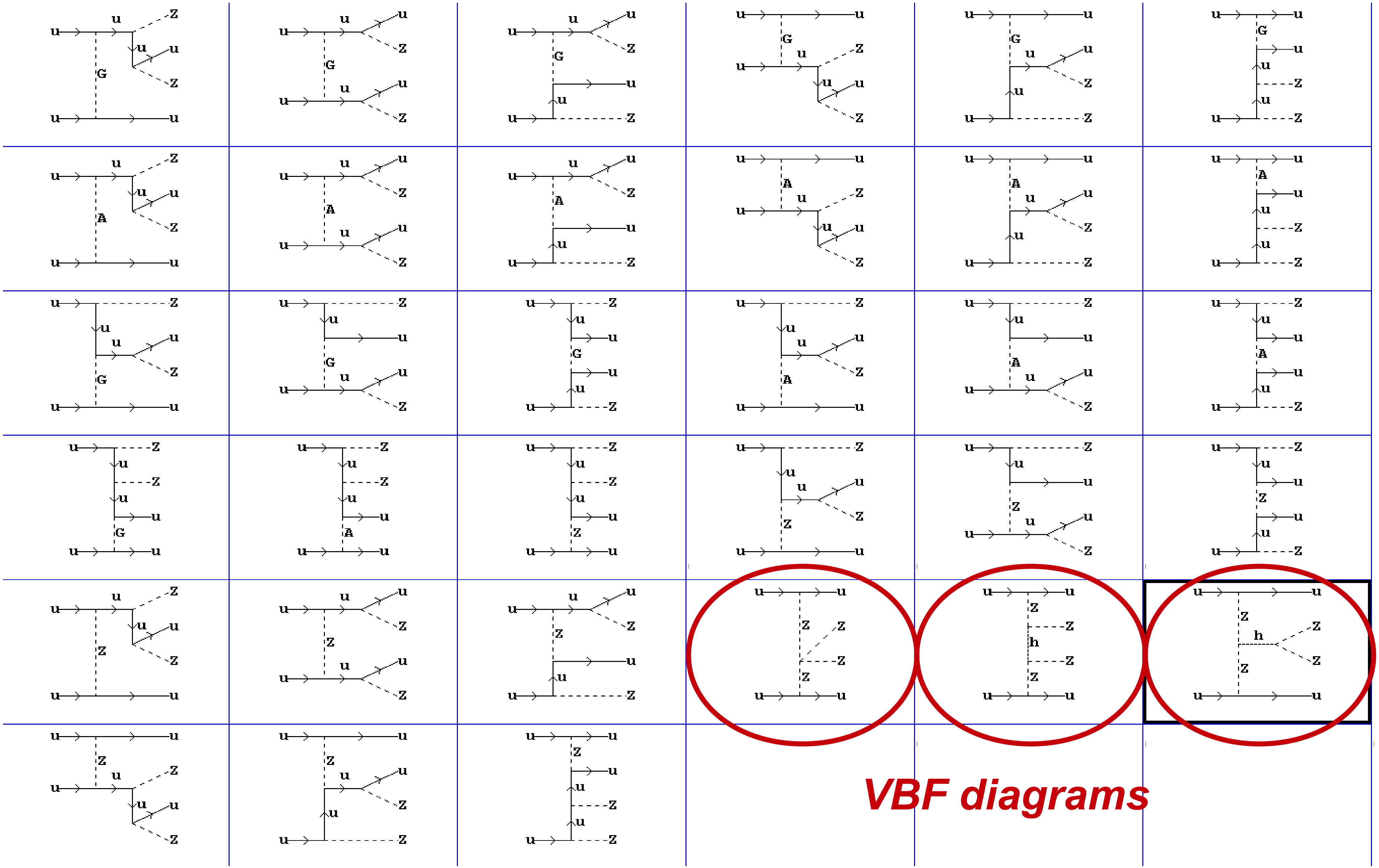
The level of pp scattering

- So far only discussed VV $\rightarrow$ 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
- So far $pp \to jjZZ \to e^+e^-\mu^+\mu^-jj$ processes has been studied
- The plan is to extend it to all relevant processes and decays

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

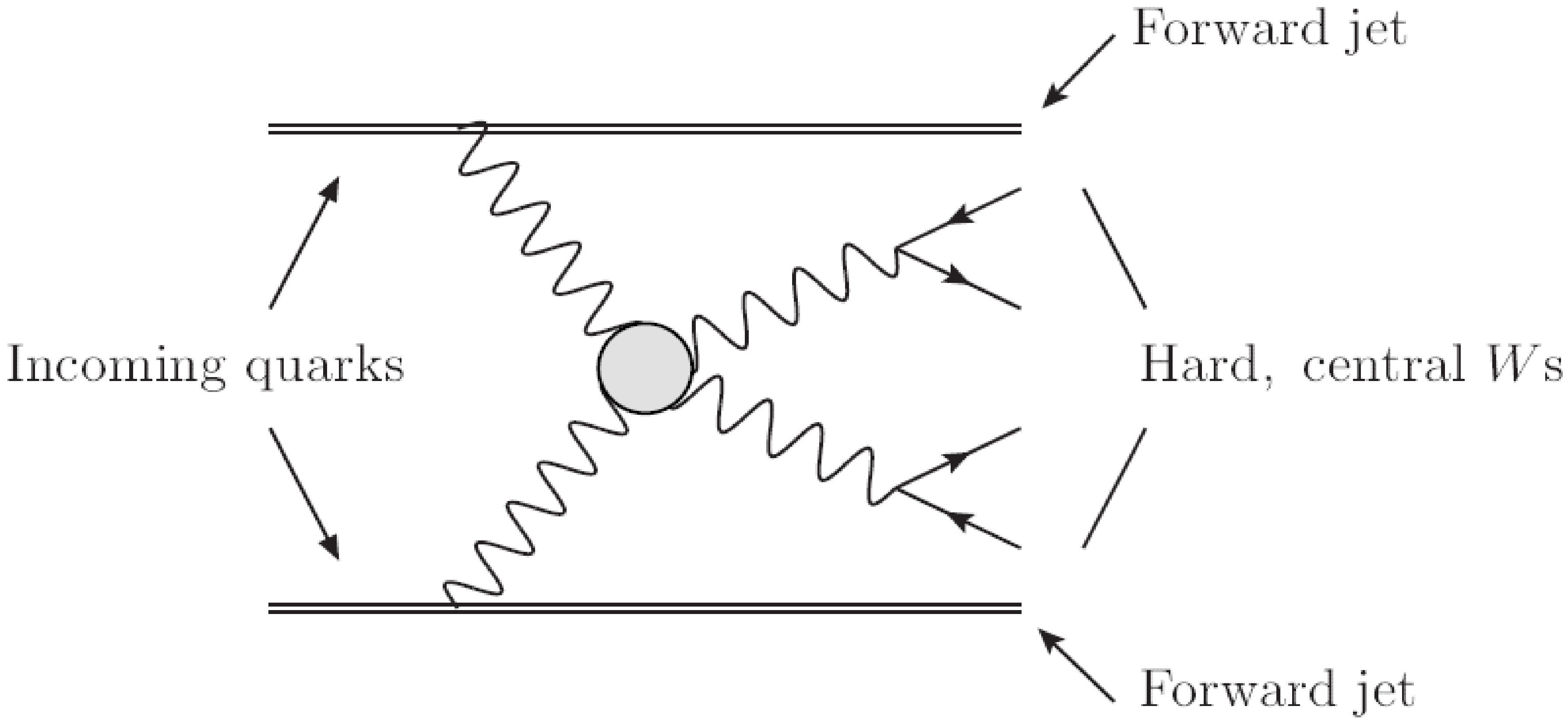


pp→ jjZZ→ $e^+e^-\mu^+\mu^-$jj process



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

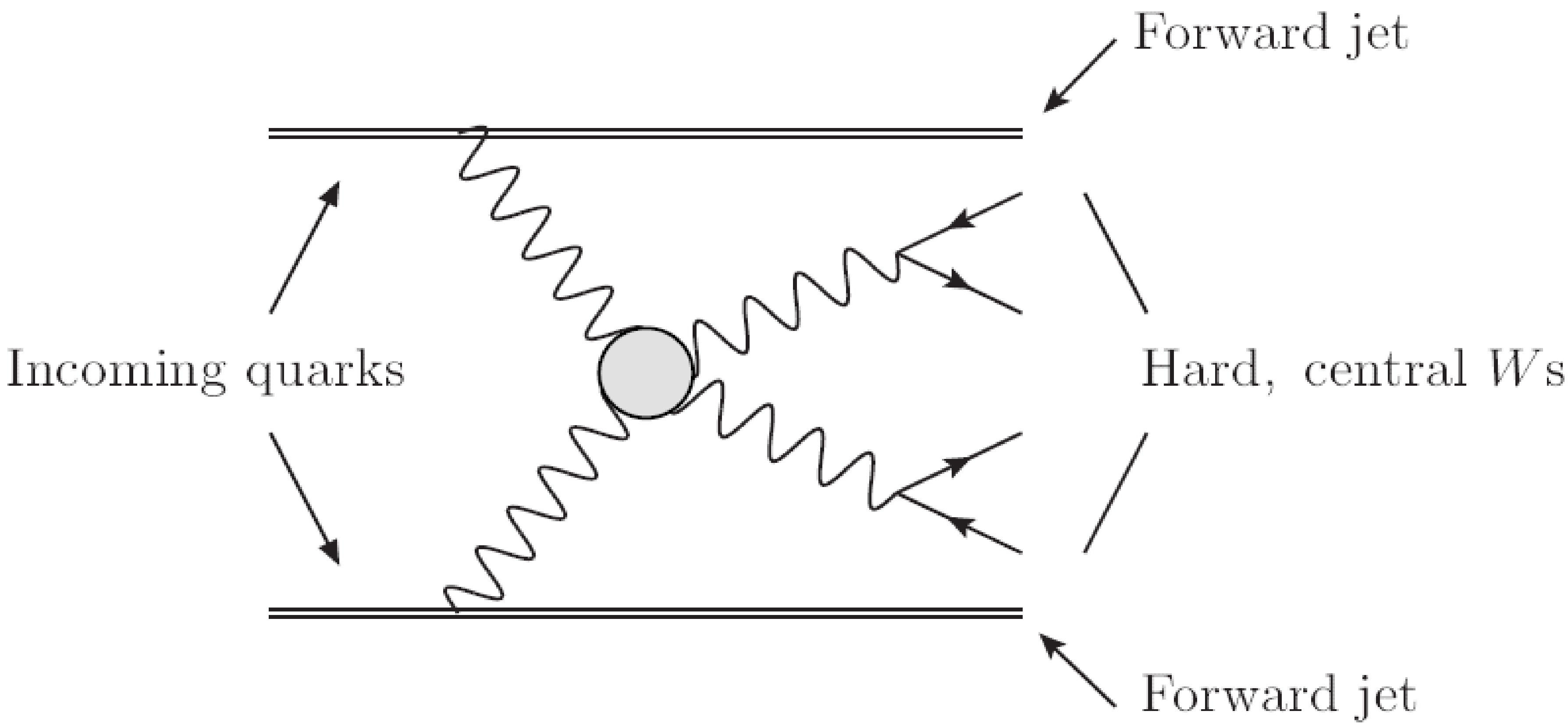
- **MADGRAPH & CalcHEP**
- **Kinematical cuts**



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

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

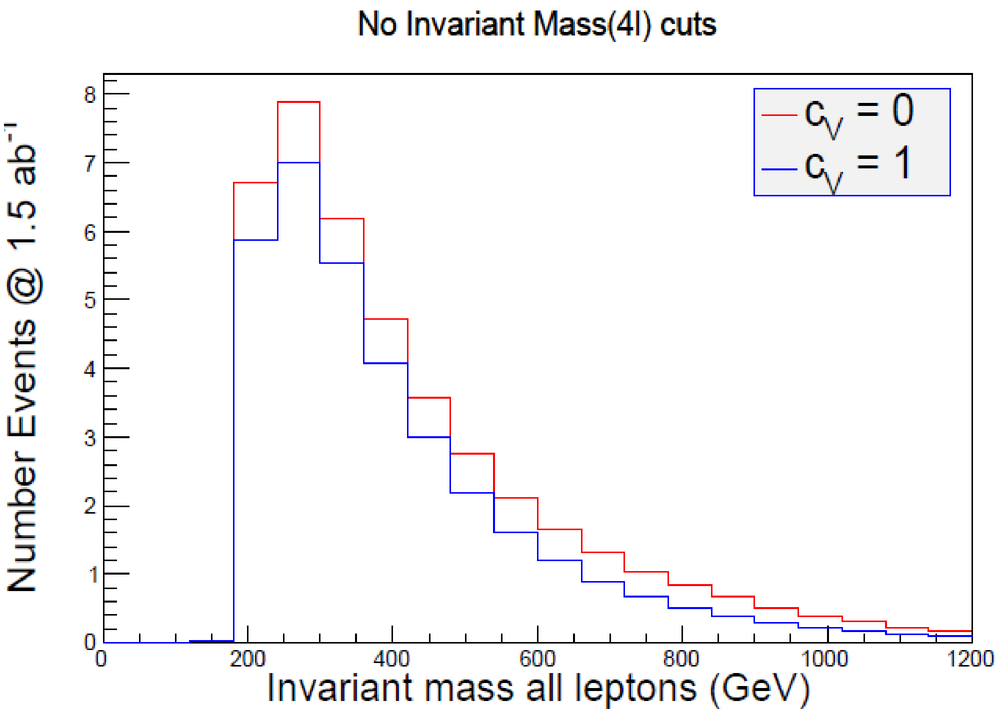
Acceptance cuts:	$p_T^j > 30$ GeV, $\lvert\eta_j\rvert < 4.5$
	$p_T^e > 20$ GeV, $\lvert\eta_e\rvert < 2.5$
	$p_T^\mu > 20$ GeV, $\lvert\eta_e\rvert < 2.5$
VBF cuts:	$\Delta\eta_{jj} > 4,\ E_j > 300$ GeV
Z boson ID cuts:	$\lvert M_{ee,\mu\mu} - M_Z\rvert \le 10$ GeV

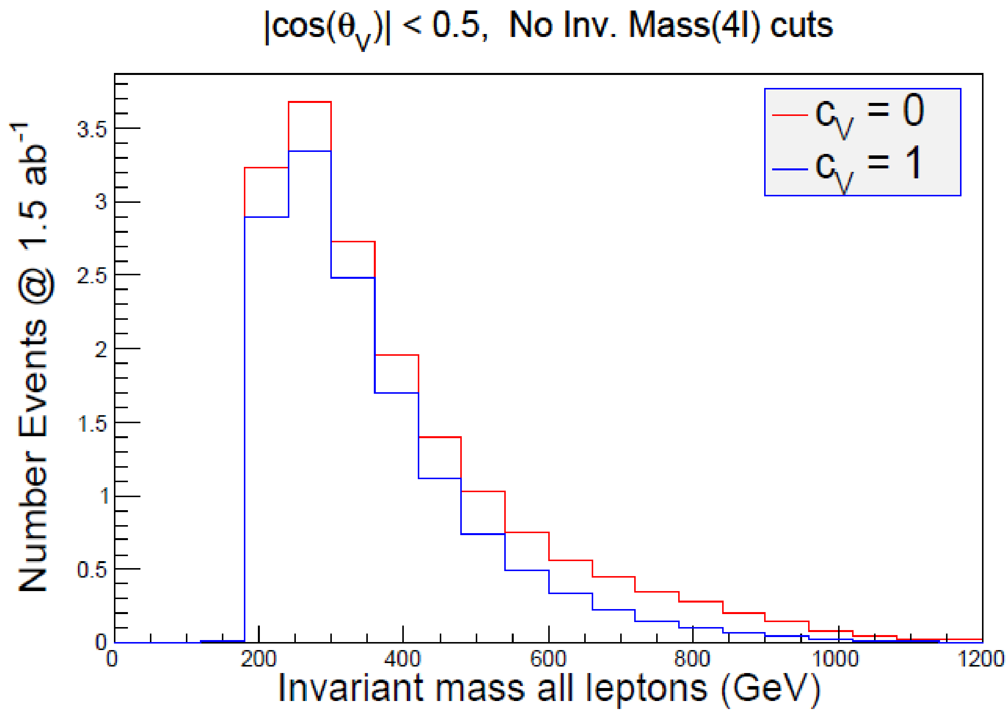


$pp \to jjZZ \to e^+e^-\mu^+\mu^- jj$ process

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

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





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

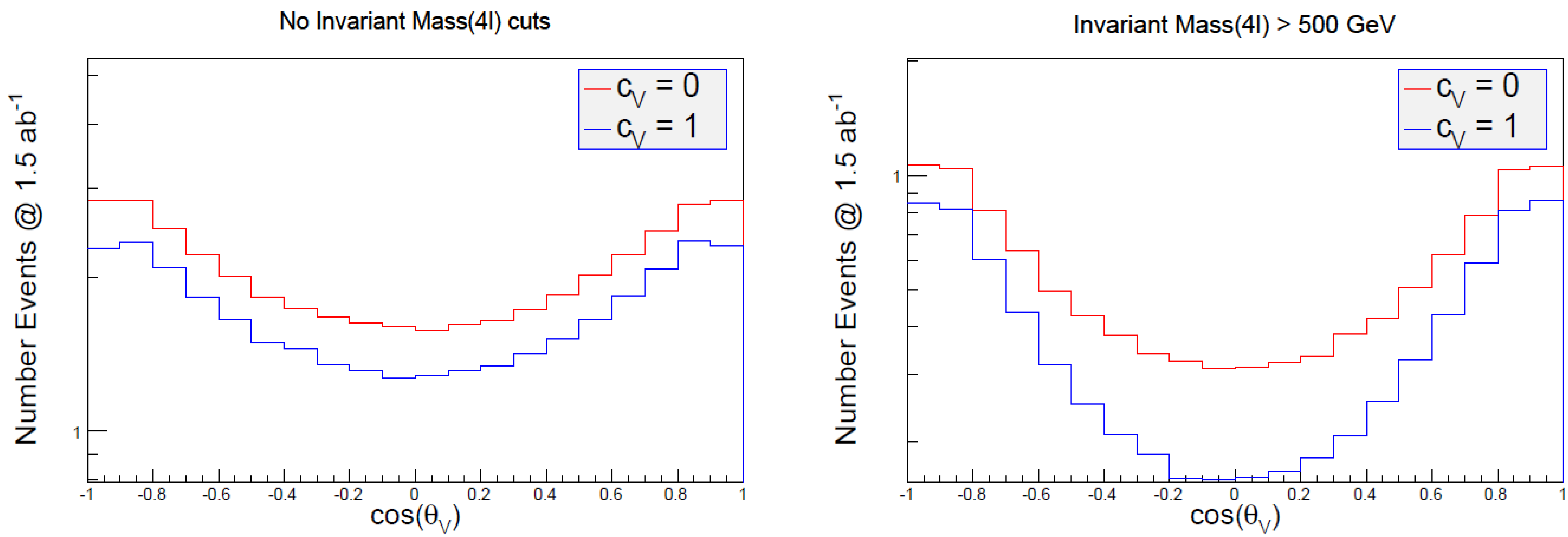
$pp \to jjZZ \to e^+e^-\mu^+\mu^- jj$ process

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

  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: $p_V^1 = q3 - q1$ & $p_V^2 = q4 - q2$

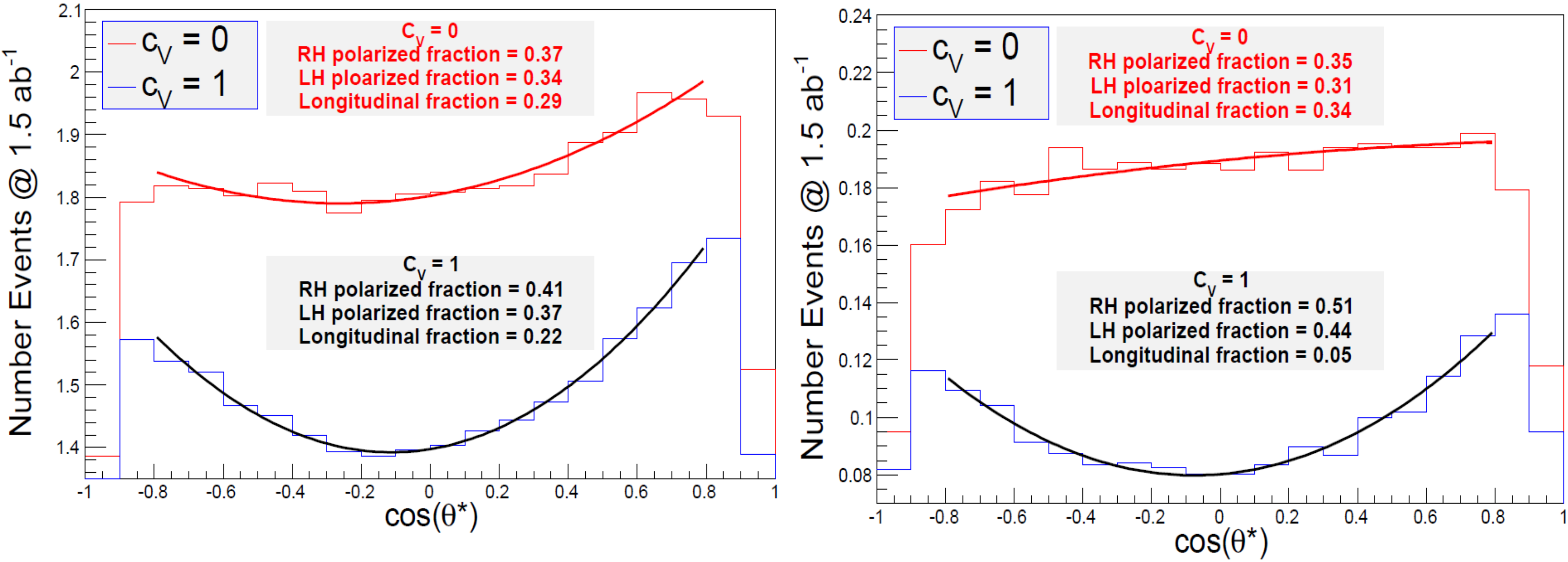
  c) find θ_V



Effect of the cuts

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

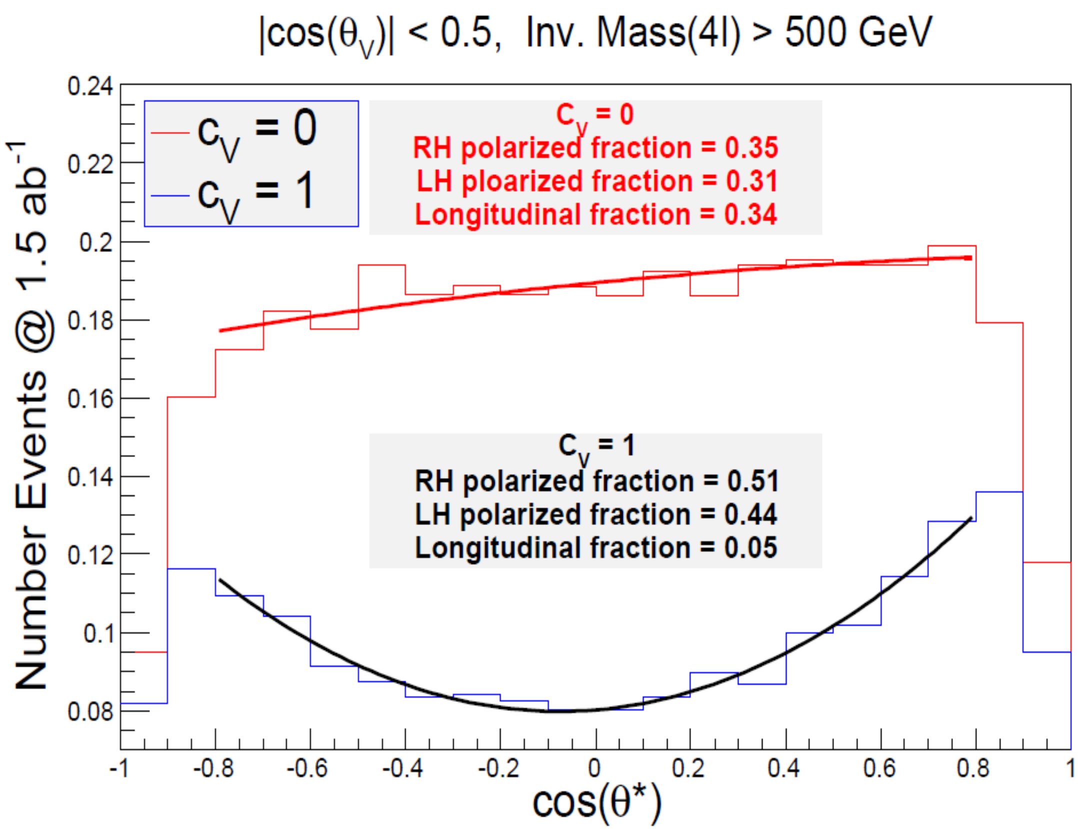
$|\cos(\theta_V)| < 0.9$, No Inv. Mass(4l) cuts $\quad$ $|\cos(\theta_V)| < 0.5$, Inv. Mass(4l) > 500 GeV



Effect of the cuts

- ***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}***

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



- **This was our estimation in 2014, now we need to explore details**
  - **check how the shape of θ^* distributions for V_L, V_R changes with the cuts and use the proper fitting to find the respective fractions**
  - **use PHASE, 6 final state fermions Accomando, Ballestero, Maina**

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

Beyond the VV→VV scattering ...

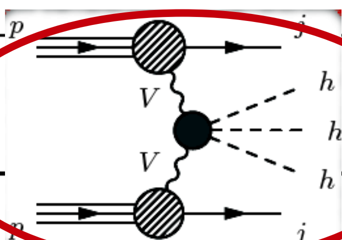
Initial cuts:
$|\Delta R_{jj}| > 0.4$
$P_T^j > 50$ GeV

VBF cuts:
$|\Delta\eta_{jj}| > 5$
$E_j > 1500$ GeV

CalcHEP & Madgraph results

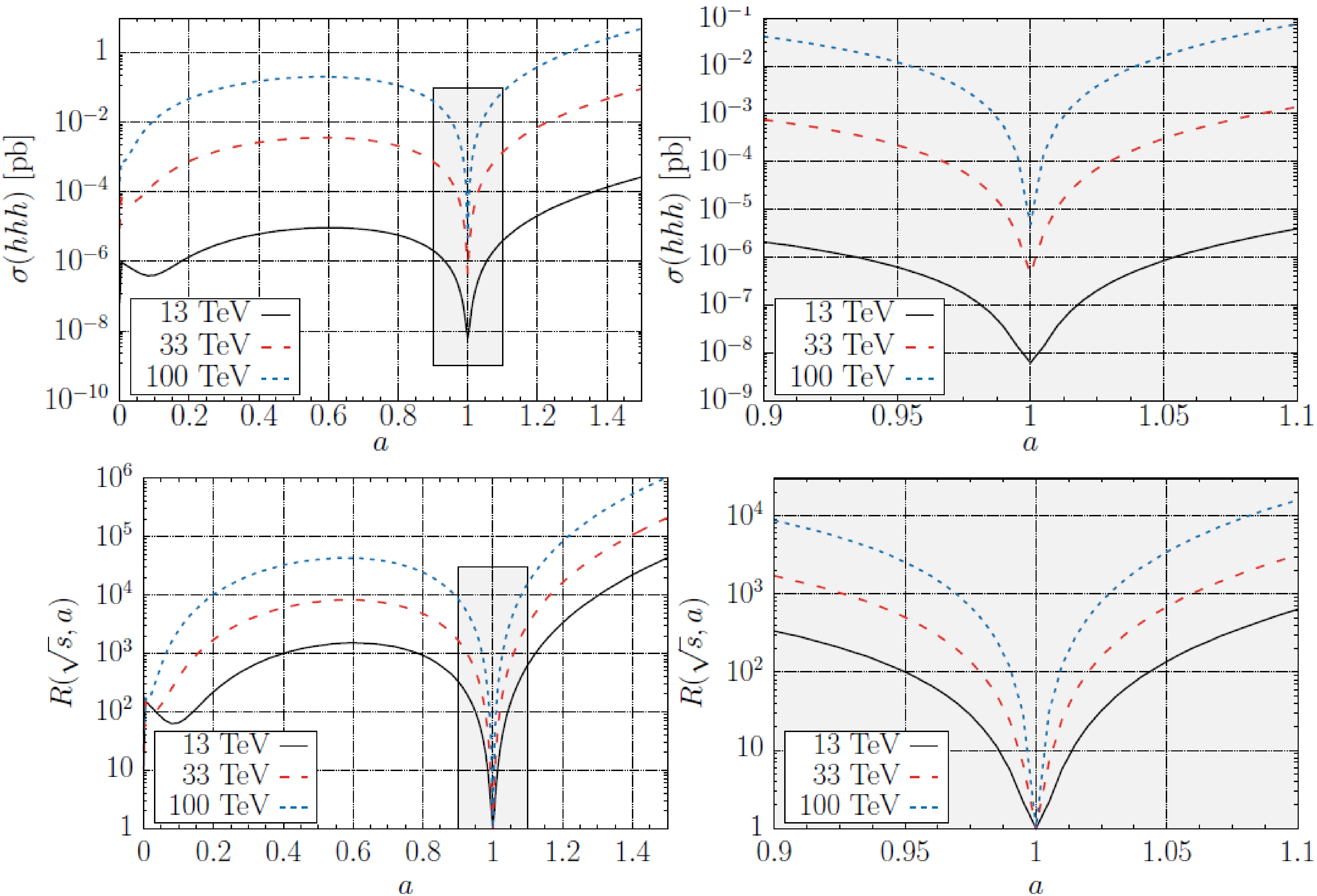
AB, Hamers, Thomas
arXiv:1801.10157

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
	×	$2.38 \cdot 10^{-4}$	$2.50 \cdot 10^{-2}$	$1.97 \cdot 10^{-3}$	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

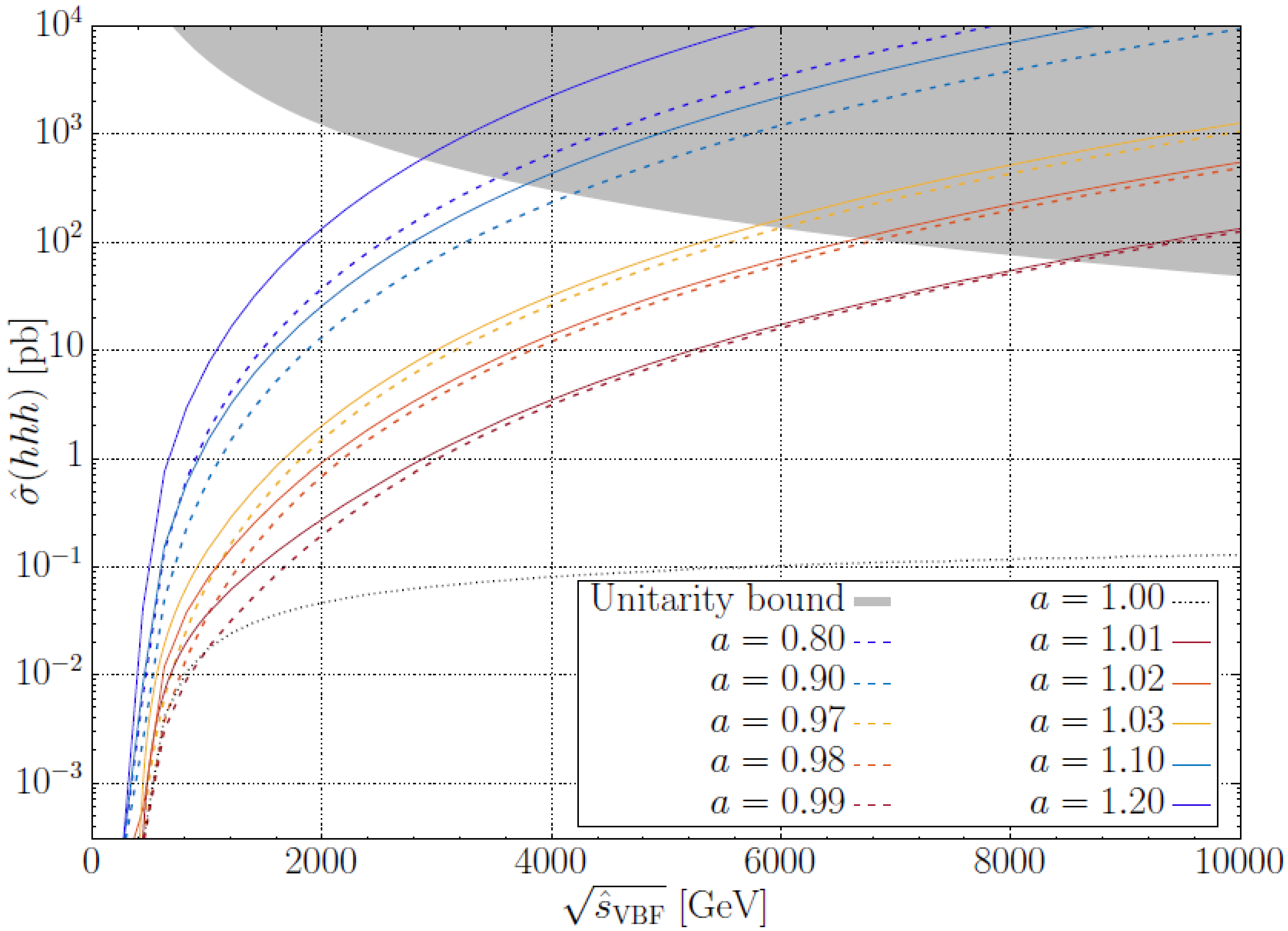


VV→ hhh can be quite promising!

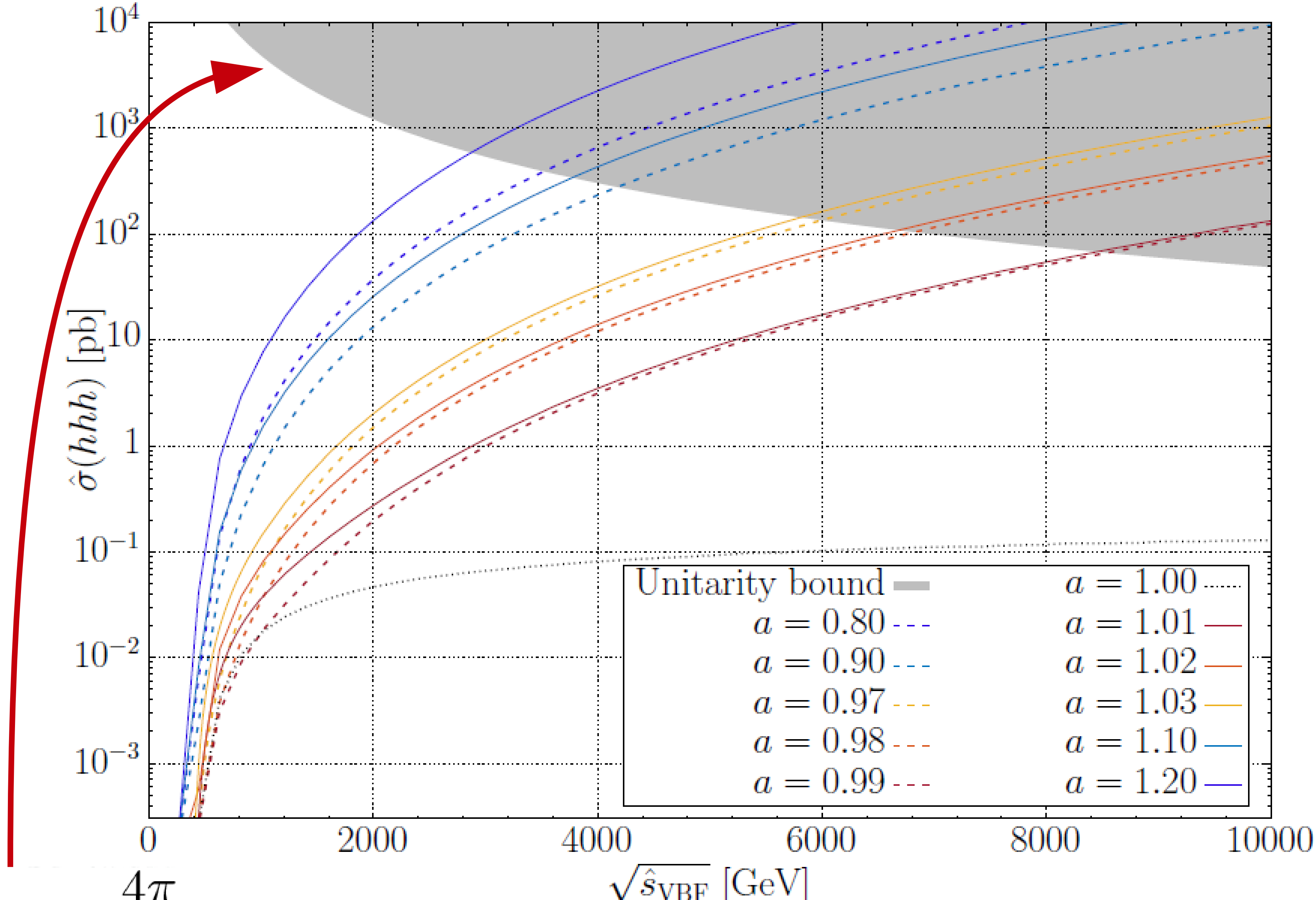
pp→ jj hhh process: $R_{\sqrt{s}}(a) = \frac{\sigma^{pp\to jjhhh}(a)}{\sigma^{pp\to jjhhh}(a{=}1)}$



Unitarity violation at large energies

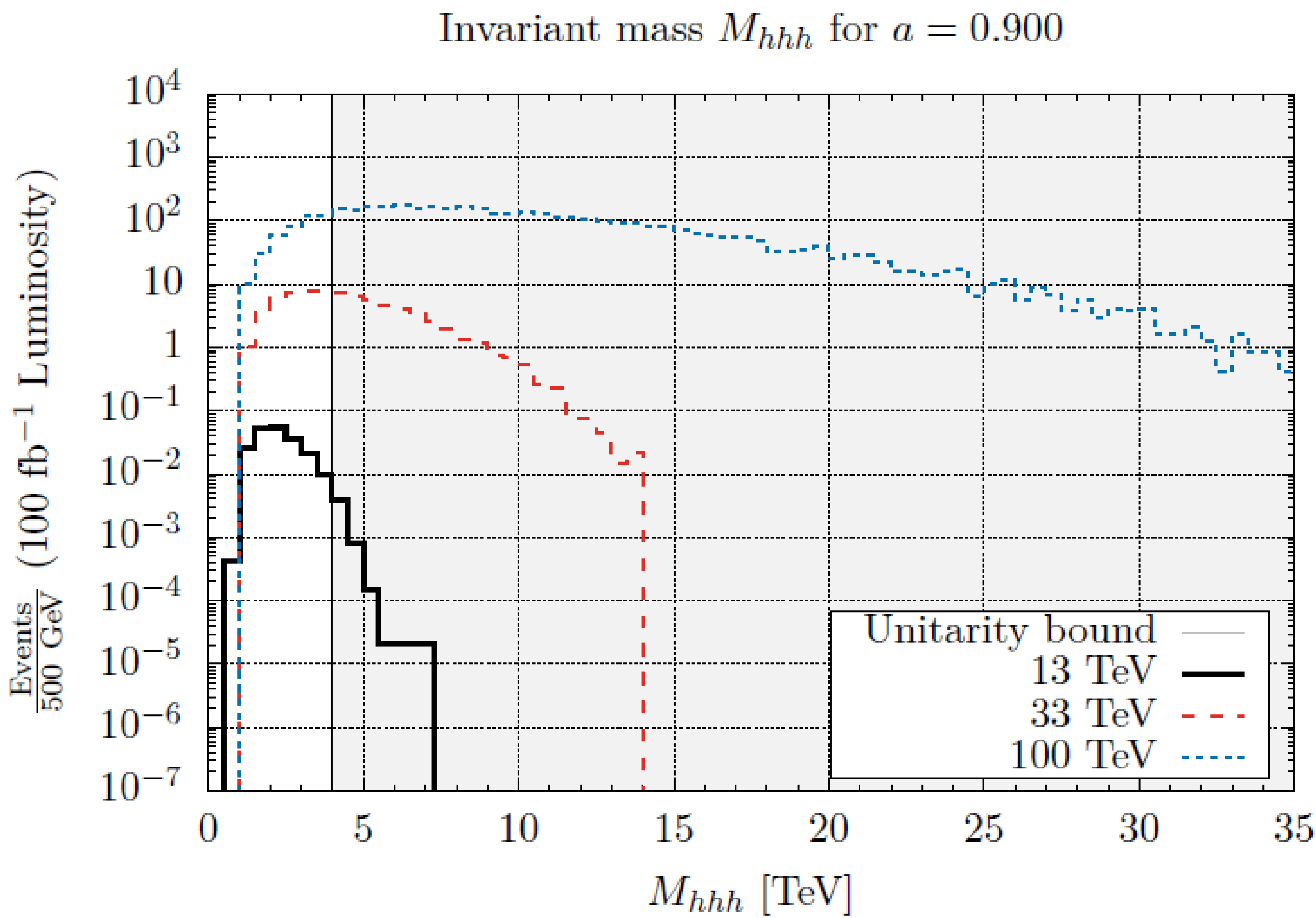


Unitarity violation at large energies

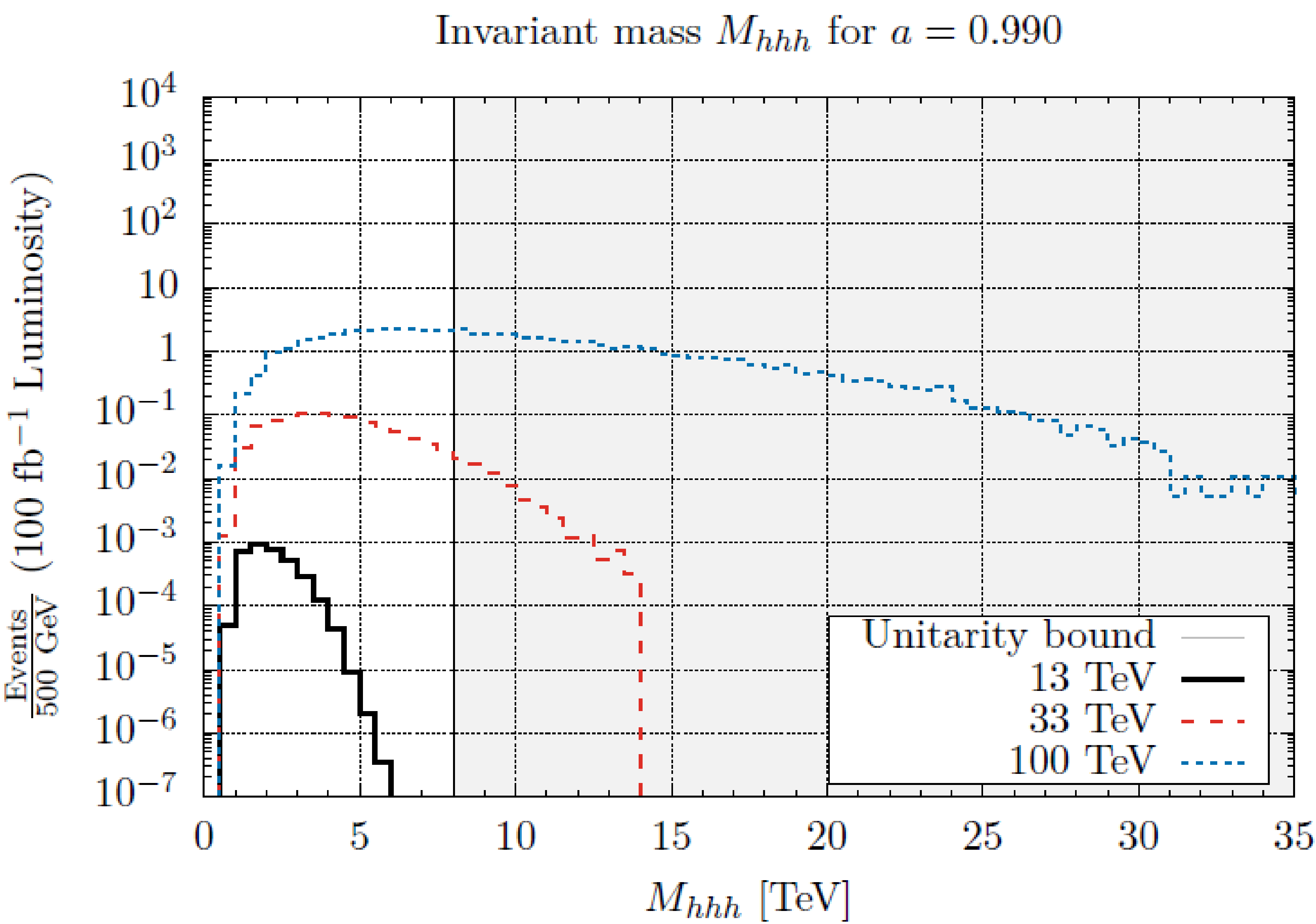


$$\sigma(2 \to n) < \frac{4\pi}{s}$$ **: perturbative unitarity bound**

Unitarity violation at large energies



Unitarity violation at large energies



Sensitivity of the 33 TeV pp collider

Unitarity not violated

Total number of events

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

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]	$\mathcal{L}_{\mathrm{int}} \cdot \sigma$	$\mathcal{L}_{\mathrm{int}} \cdot \sigma \cdot \varepsilon_{\mathcal{U}}$
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 100 TeV pp collider

Unitarity not violated

Total number of events

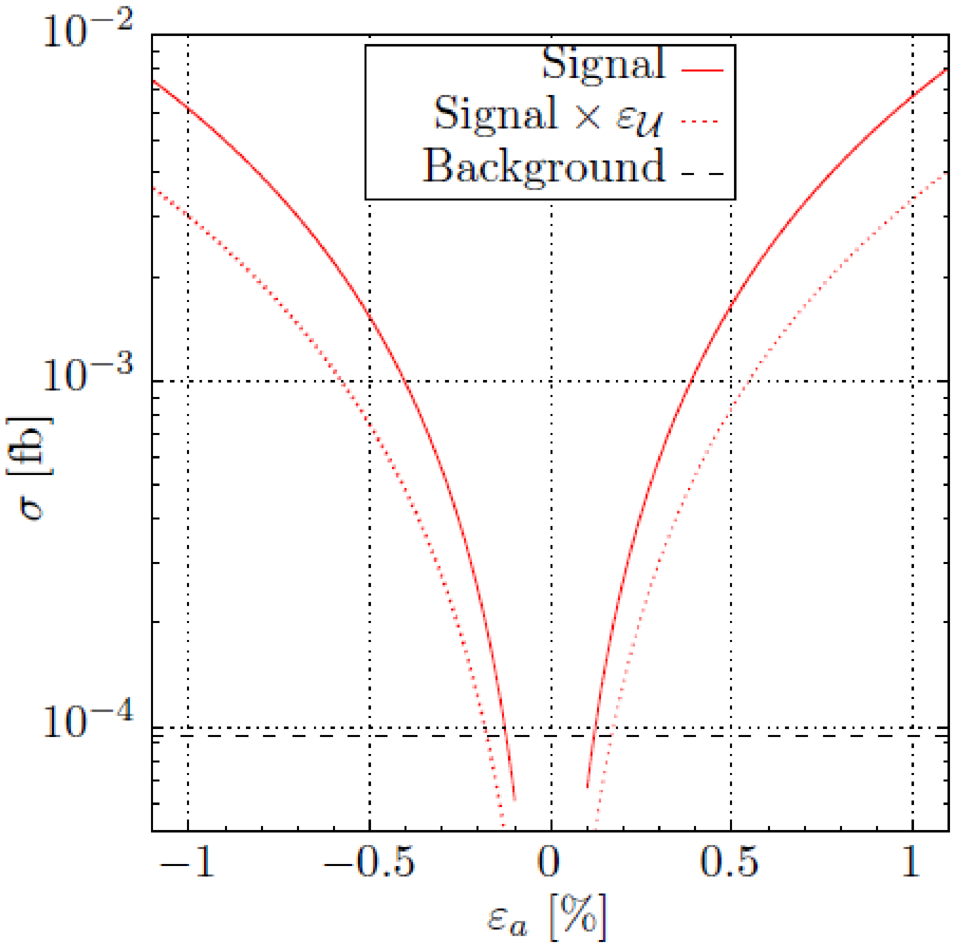
$\mathcal{L}_{\text{int}} = 100\,\text{fb}^{-1}$

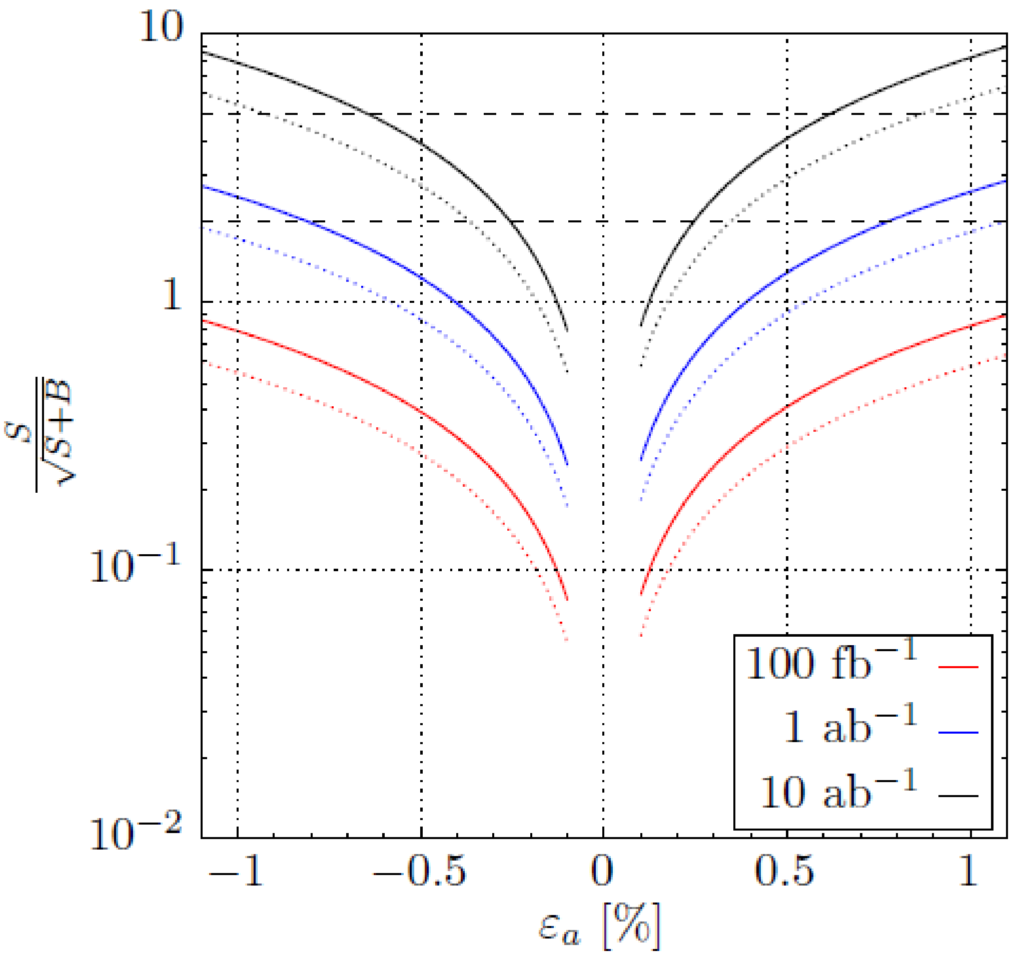
Total number of events not violating unitarity

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

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

Potential of 100 TeV pp collider to probe HVV coupling





HVV coupling can be potentially probed with the permille accuracy, close look at the unitarisation should be taken

Conclusions/Outlook

- VV→VV study
  - extremely important process for model-independent exploration of Higgs properties
  - combination of cuts on three variables can potentially isolate the longitudinal components of vector boson scattering
  - sensitivity is independent of that which can be deduced from direct Higgs searches
  - HVV coupling i 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→ hhh study
  - very 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 permille level