Probing the Higgs and Beyond via the HVV vertex at the LHC.

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Plan:

◇ Introduction.

◇ Issues:

– How do we establish the tensor structure of HVV i.e. HZZ and HWW vertex separately using the **VBF process and VH** production? A small digression on $H \to Z^*Z$.

– How do we look for contributions from higher dimensional operators and distinguish it from the SM vertex? **Identify new observables here**.

– Effect of the BSM vertex on the kinematic distributions and hence on search strategies for non-SM bosons?**Do we throw the baby with bathwater?**

Plots are from:

1)RG, D.J. Miller, M. Muhlleitner : JHEP 0712 (2007) 31

2)A. Djouadi, R.G., B. Mellado and K. Mohan, Phys.Lett. B723 (2013) 307-313 (1301.4965).

3)S. Biswal, R.G., B. Mellado, S. Raychaudhuri Phys.Rev.Lett. 109 (2012) 261801

4)R.G., K. Mohan, D. Miller and C. White: arXiv:1306.2573

5)A. Djouadi, R.G. et al, PRL 100, 051801 (2008), R. G., C. Hangst, M. Muhlleitner, S. D. Rindani and P. Sharma, EPJC **71**, 1681 (2011), [arXiv:1103.5404 [hep-ph]].

- Just the discovery of the Higgs boson is not sufficient to validate the minimal SM.

- We need to establish the strength and the tensor structure of the Higgs couplings to all the matter and gauge particles.

Observation in the WW channel crucially uses the spin 0 nature of the higgs to reduce the background!

Observed agreement between the WW and the ZZ channel **therefore** is a strong indication against spin 2.

Experimental analyses show more and more consistency of the observed state with $J^{CP} = 0^{++}$

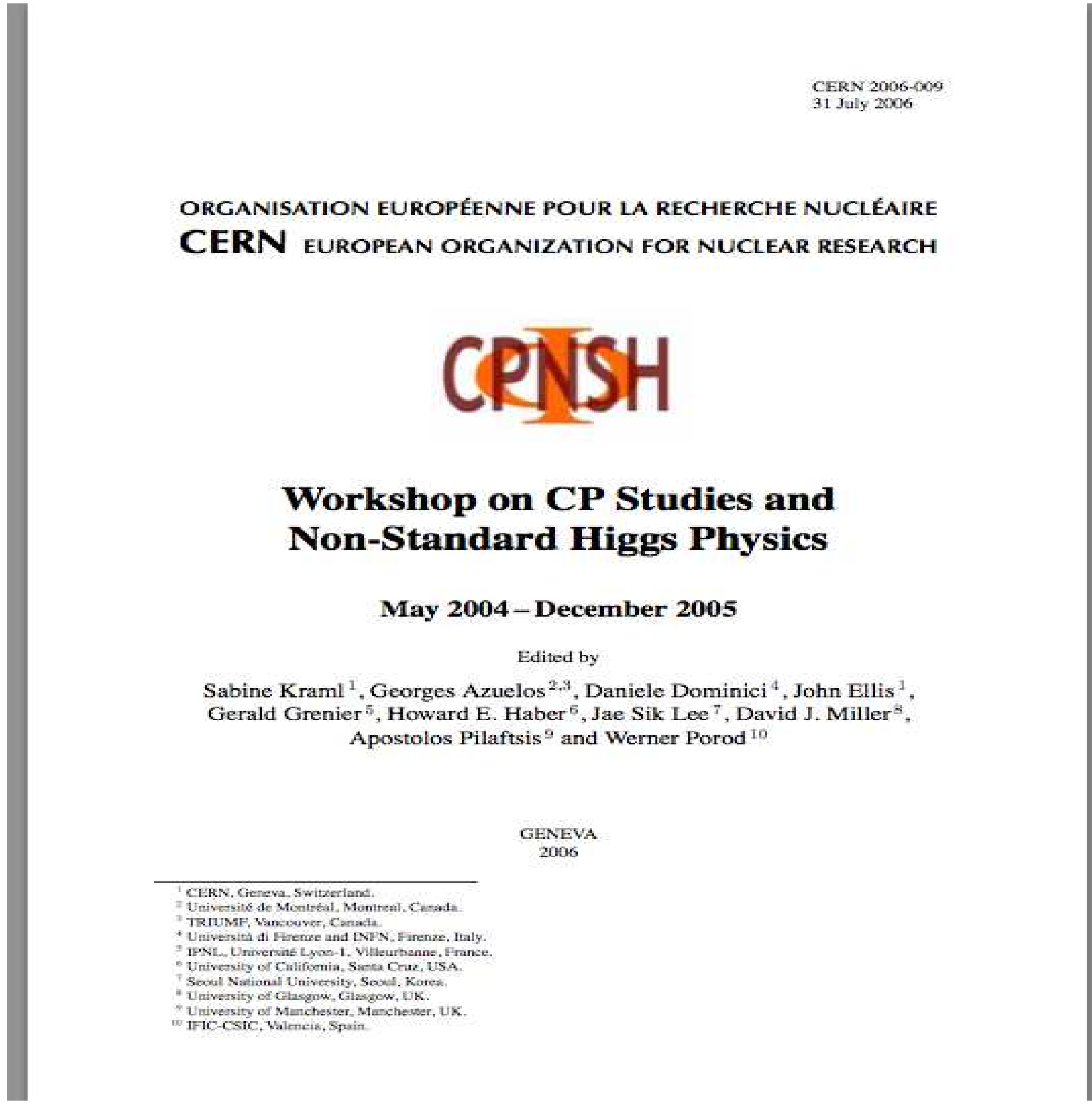
1. Can we change this 'consistency' statements into 'determination'?

2. Probe for BSM: eg. CP-mixing or spin 2.

Methods for extracting information on spin and parity of the Higgs. Very rich subject.

A partial summary of the studies can be found:

Phys. Rept. 426 (2006) 47 , hep-ph/0404024: R.G. Maria Krawczyk.., CPNSH report hep-ph/0608079


CERN 2006-009
31 July 2006

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CPNSH

Workshop on CP Studies and Non-Standard Higgs Physics

May 2004 – December 2005

Edited by

Sabine Kraml [1], Georges Azuelos [2,3], Daniele Dominici [4], John Ellis [1], Gerald Grenier [5], Howard E. Haber [6], Jae Sik Lee [7], David J. Miller [8], Apostolos Pilaftsis [9] and Werner Porod [10]

GENEVA
2006

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Higgs Couplings with pair of gauge bosons (ZZ/WW) and the pair of heavy fermions (t/τ) are largest.

Study these in a model independent way

$$\phi_i f\bar{f} \;:\; -\bar{f}(a_f + i b_f \gamma_5) f \frac{g m_f}{2 m_W}, \textbf{(mixedCP)}$$

$$VV\phi_i \;:\; c_V \frac{g m_V^2}{m_W} g_{\mu\nu} \quad \textbf{(CPeven)}, \quad (\mathrm{V = W/Z \quad tree})$$

$$: \; p_\mu q_\nu / m_V^2 \quad \textbf{(CPeven)}; \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma / m_Z^2 \quad \textbf{(CPodd)}, (\mathrm{loop\ level})$$

In more detail:

$$V_{HVV}^{\mu\nu} = \frac{i g m_Z}{\cos\theta_W}\left[a_V\, g_{\mu\nu} + b_V \frac{(p\cdot q g_{\mu\nu} - p_\mu q_\nu)}{m_V^2} + c_V\, \epsilon_{\mu\nu\alpha\beta} \frac{p^\alpha q^\beta}{m_V^2}\right],$$

Warning: through the talk small modifications in the notation for the anomalous vertex.

SM limit: $a_f, a_V = 1$ and $b_V, c_V = 0$

What can give rise to a_f, b_f and a_V, b_V different from those expected in the SM?

1)A CP odd scalar.

2)CP violation in the Higgs sector.

Example: MSSM, Multihiggs doublet models

3)Higher dimensional operators induced by loops and/or in composite Higgs models.

4) Spin of the resonance different from 0

Composite Higgs Models:

For example:

1) Roberto Contino, C. Grojean and collaborators: 1204.4817, 1303.3876 and references therein.

2)E. Masso and V. Sanz, Phys. Rev.D **87**, 033001 (2013) [arXiv:1211.1320 [hep-ph]] Constraints from LHC and LEP.

3) S. Willenbrock et al: 1304.1789, 1306.3380

a_V usually less than 1 (I.Low etal, JHEP04 (2010) 126), but can be greater than 1. In multihiggs models a_v HAS to be less than 1!

No guideline to what could be the strength of the CP violating vertex if it should exist, apart from the obvious Λ suppression.

What do we know for sure about the new state?

It has integral spin.

It can not be spin 1 : Yang's Theorem.

Observed numbers of $\gamma\gamma$ and ZZ events consistent with loop induced coupling to $\gamma\gamma$ and tree level to ZZ. $\Rightarrow$ has to be dominantly CP even.

In fact from rates alone the CP odd component has been constrained: Djouadi and Moreau (1303.6591), K. Cheung, J.S. Lee (1302.3794), Talk here

The analysis of angular distributions of the decay leptons in $ZZ \to 4\ell$ and $\gamma\gamma$ channel supports the spin 0 interpretation/ discriminates against spin 2.

Decay through ZZ to 4 lepton pairs.

Decay to $\gamma\gamma$ pair.

Production in WW/ZZ fusion

Production of Higgs in association with a vector boson.

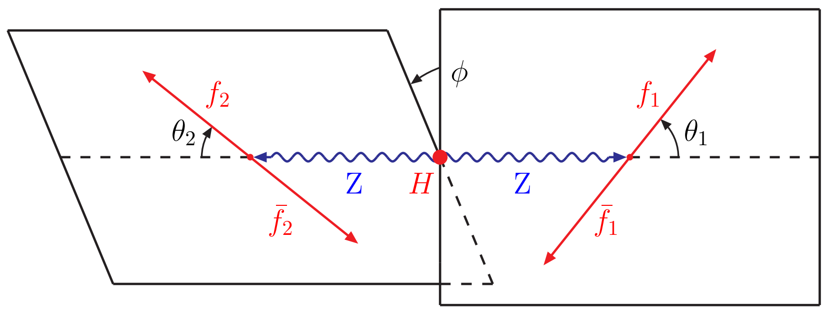
[1]

Use of $\phi \to ZZ^{(*)} \to 4l$ Choi, D. Miller, Mühlleitner & Zerwas Below $\phi \to ZZ$ threshold, one Z is virtual $\to$ can examine threshold behaviour Choi et al, PLB 553 (2003) 61 to determine the spin, Barger et al, PRD 49 (1994)79 to determine the CP. *The distribution is sensitive to both the spin and parity of the resonance and CP mixing*

Establishing spin and parity of Higgs was expected to be futuristic. But Multivariate Techniques made it study of today! A. De Rujula, J. Lykken, M. Pierini, C. Rogan and M. Spiropulu, PRD 82, 013003 (2010) [arXiv:1001.5300 [hep-ph]], S. Bolognesi, Y. Gao, A. V. Gritsan, K. Melnikov, M. Schulze, N. V. Tran and A. Whitbeck, PR D **86**, 095031 (2012)[arXiv:1208.4018 [hep-ph]].

2]

The definition of the polar angles θ_i $(i = 1, 2)$ and the azimuthal angle ϕ. In the rest frame of H.



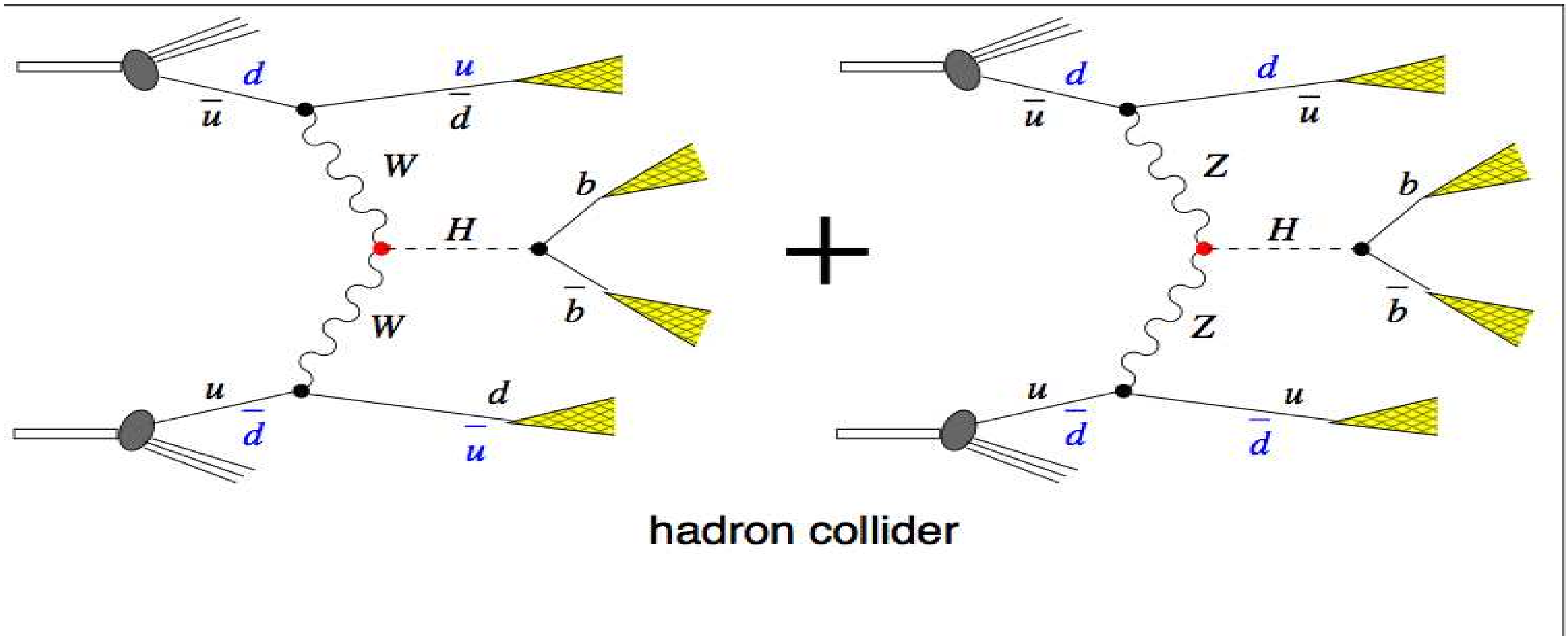
Available complete analytic expression for the triple diff. crosssection. (for example: RG, Miller and Muhlleitner : JHEP 0712 (2007) 31)

Gao et al, A De Rujula et al: for all spin/parity cases.

MELA: basically these and a bit more.

VBF: Zeppenfeld, Plehn, Rainwater: Look at distribution between the azimuthal angle between the two tagging *forward* jets.

Higgs + 2 jet production: VBF



Note: HZZ and HWW both contribute and can not be separated.

One can use VBF to study CP properties for spin 0.

Issues: subject of a lot of careful studies.

Extension of this study for spin2 : Zeppenfeld, Frank and Rauch: 1211.3658

Few observations:

No need of detailed kinematical reconstruction of the decay products of the Higgs. That is good.

But

1] If all the three terms are present in comparable strength then they can conspire to produce a ϕ distribution which is SM like!

2] Separate study of HWW and HZZ coupling is not possible.

In fact this separation not possible at e^+e^- colliders either. R.G., Biswal et al: Phys.Rev. D79 (2009) 035012,Phys.Rev. D73 (2006) 035001

Only possible at LHeC: RG, Biswal et al: Phys.Rev.Lett. 109 (2012) 261801

Study of VH can change the situation!

I will show you results from our new VBF study where we

1)Identify additional observables which can be complementary to ϕ.

2)Show how those observables also probe spin 2.

3)These new observables show that the acceptances of the BSM contribution and SM contribution to the standard SM inspired cuts for VBF are very different and hence identify new topologies where BSM (spin 2 or higher dimensional operators) can be probed.

Study using VH:

Show how using VH one can in fact probe the structure for HWW and HZZ vertex separately, *at the LHC.*

Overlap of ideas with three other papers:

1) C. Englert, D. Goncalves-Netto, K. Mawatari and T. Plehn, [arXiv:1212
[hep-ph]].

2) J. Frank, M. Rauch and D. Zeppenfeld, [arXiv:1211.3658 [hep-ph]].

3) J. Ellis, V. Sanz and T. You, [arXiv:1303.0208 [hep-ph]].

We use an effective vertex of the form given earlier. In slightly different notation:

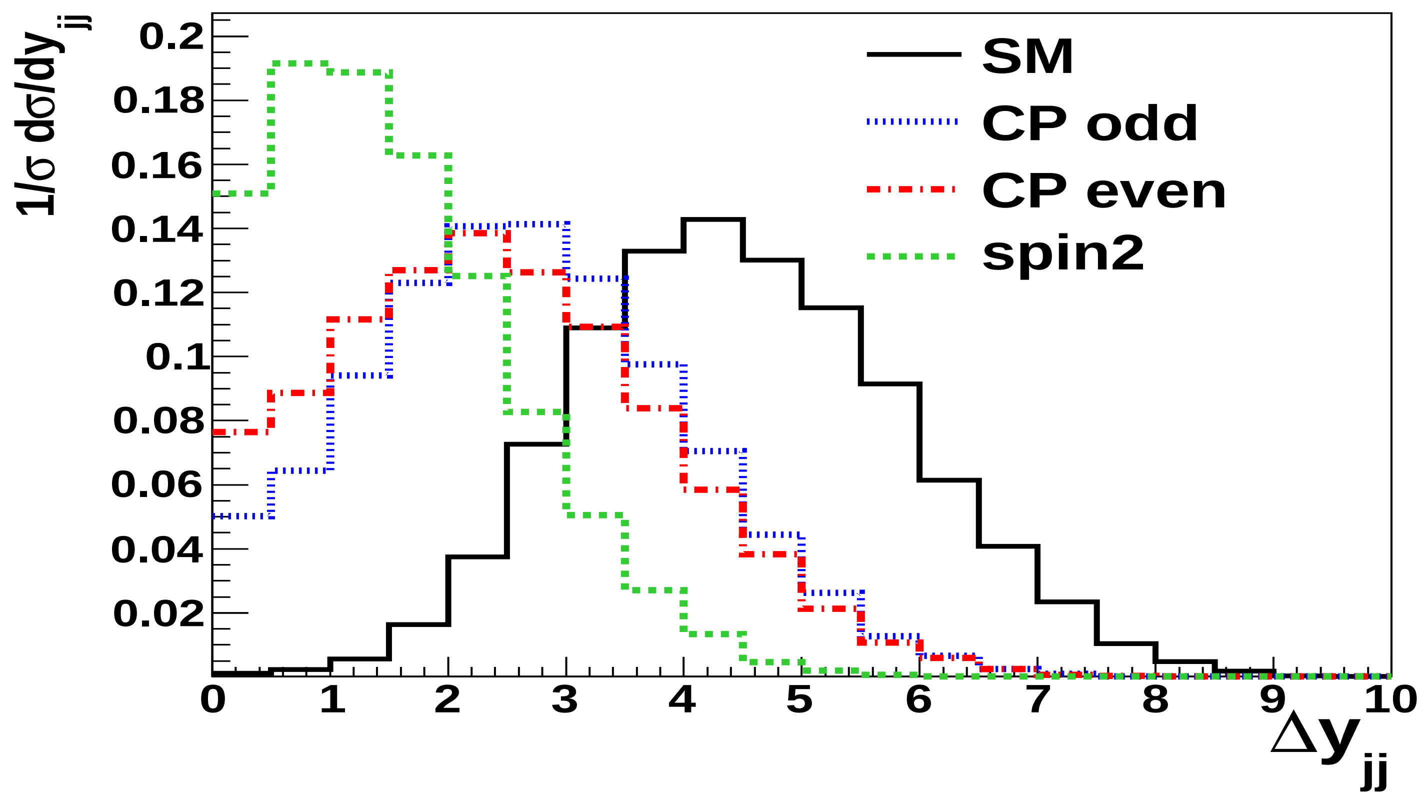
$$\Gamma^{\text{SM}}_{\mu\nu} = -gM_V\, g_{\mu\nu}$$
$$\Gamma^{\text{BSM}}_{\mu\nu}(p,q) = \frac{g}{M_V}\left[\lambda\,(p\cdot q\, g_{\mu\nu} - p_\nu q_\mu) + \lambda'\ \epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

For Spin 2:

$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda}T_{\alpha\beta}\,(f_1 g_{\mu\nu}B^{\mu\alpha}B^{\nu\beta} + f_2 g_{\mu\nu}W^{\mu\alpha}W^{\nu\beta})$$

This is the same as used by Frank, Zeppenfeld and Rauch.

The BSM vertices have factors involving four momenta. This affects not just the $\Delta\phi_{jj}$ distributions but also the distributions in Δy_{jj} and p_T of the jets. m_{jj} distributions remain the same.



Δy_{jj} distributions more QCD like shifted to lower values for ALL the BSM operators: $0^+, 0^-$ and 2.

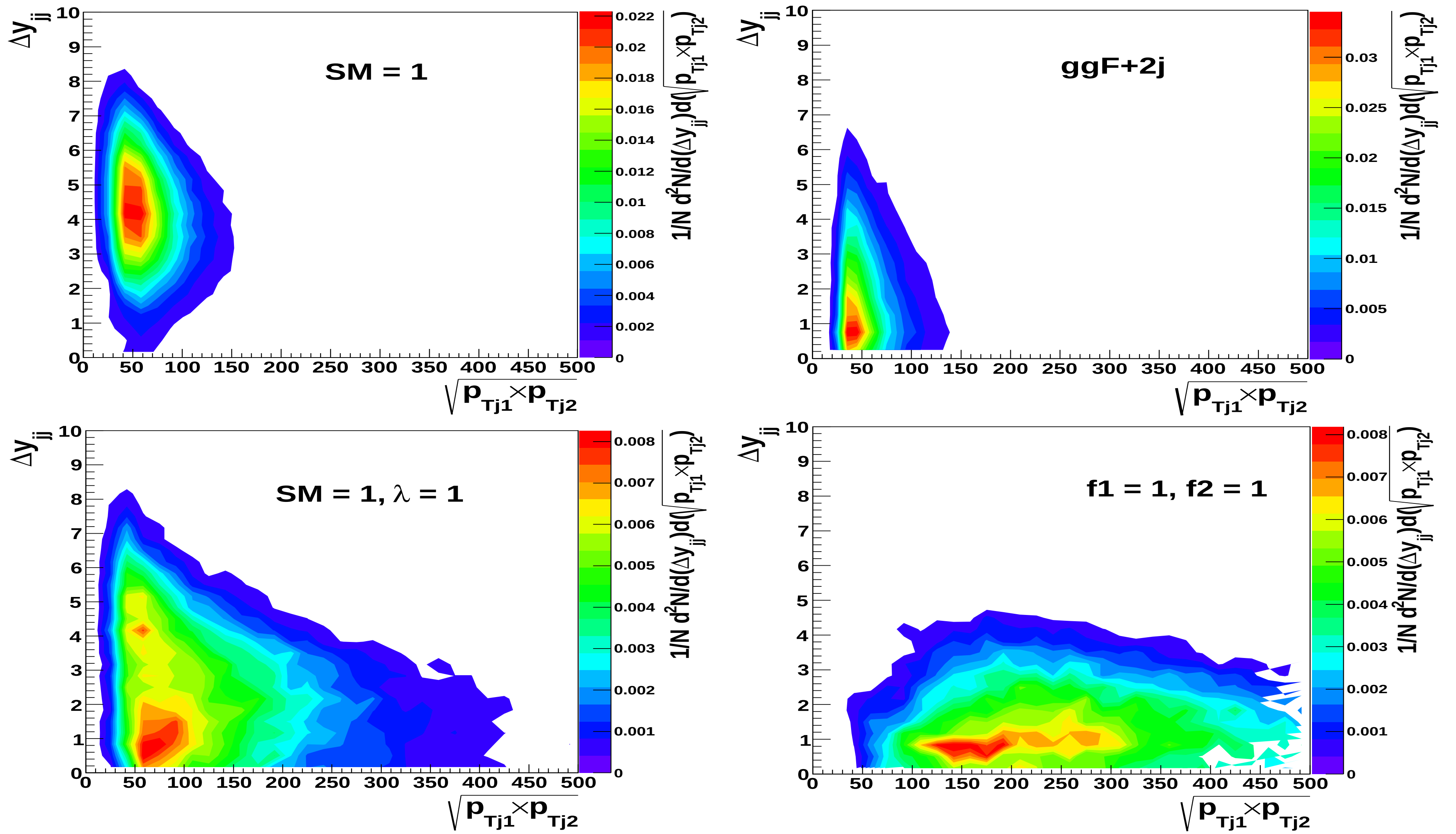
The distribution distinguishes SM from BSM.

Not capable of distinguishing between 0^+ and 0^- BSM operators.

Can be understood in terms of analytical form of the matrix element.

Distinguishes between spin 2 and spin 0 : (SM, BSM: 0^+ or 0^-) in any case.

Acceptance to VBF cuts will be difft. for difft. operators!


SM = 1
ggF+2j
SM = 1, λ = 1
f1 = 1, f2 = 1
Δy_{jj}
$\sqrt{p_{Tj1} \times p_{Tj2}}$
$1/N\ d^2N/d(\Delta y_{jj})d(\sqrt{p_{Tj1} \times p_{Tj2}})$

VH with $V \to jj$ also contributes subdominantly to H + 2jets topology.

	SM EW Hjj		BSM 0^+		0^-		2^+		SM ggF+2j
Process	VBF	VH	VBF	VH	VBF	VH	VBF	VH	
Acceptance	0.06	0.04	0.59	0.12	0.55	0.18	0.93	0.75	0.10
σ (fb)	0.14	0.04	1.43	0.29	1.35	0.43	2.25	0.86	0.27
$\sigma^{EW}_{BSM}/\sigma^{EW}_{SM}$	-	-	8.8		8.7		17.4		-

Acceptance of BSM contribution to the usual VBF cuts is very different from the SM case.

BSM vertices tend to populate a region of the phase-space where the production of the SM Higgs boson is significantly depleted.

New region at large $\sqrt{P_{Tj1}P_{Tj2}}$ and low Δy_{jj}.

At 8 TeV with $25 fb^{-1}$ one has sensitivity to for pure BSM scalar of 1.4σ and for spin 2 5σ, using these new EW kinematic region.

When λ, λ' are small (0.1) then Δy_{jj} distributions more SM like.

If values of **both** λ or λ' are large, the Δy_{jj} distribution will be BSM like.

For SM $+\lambda = \lambda' = 1$ the ϕ_{jj} distribution looks like the SM ! If values of **both** λ or λ' are large, the Δy_{jj} distribution will be BSM like. So ϕ_{jj} does not work but Δy_{jj} works !

For small λ, λ' Δy_{jj} does not work, but then ϕ_{jj} works.

The study points out kinematical distributions in addition to $\Delta\phi_{jj}$ which distinguishes the SM from the BSM operators.

New phase space region for probing the BSM operators in EW Higgs $+ jj$ production.

But no capability of separating WWH from ZZH

Also apart from ϕ_{jj} no capability of separation between 0^+ and 0^- operators.

Momentum dependence of the anomalous vertex makes the p_T distributions and ΔY_{HV} harder.

This is in addition to the change in HV invariant mass distribution (suggested by Ellis, Veronica Sanz and You)

We study next the VH production, with $H \to b\bar{b}$ and $V \to leptons$ with boosted H.

But at present only for spin 0.

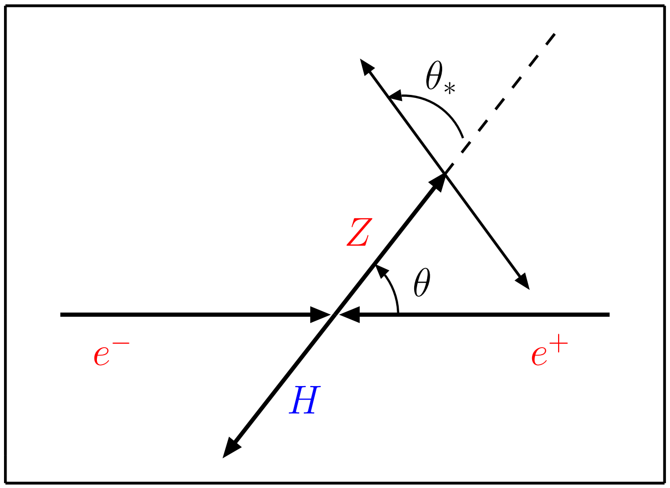
The idea is the following: Use boosted Higgs, do jet substructure analysis and use the jet direction as the the direction of the Higgs.

Using the information on the V and H momentum one can reconstruct the hard scattering rest frame and construct different angles, just like in e^+e^- case.

The beauty:

These angles can distinguish SM operators from BSM operators and also the two BSM operators **from each other.**

The momentum dependence of the BSM vertex, makes the use of boosted kinematics especially useful to probe the BSM contribution.



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta\, d\cos\theta_*} = \frac{9M_Z^2\gamma^2/4s}{\beta^2+12M_Z^2/s}\left\{\sin^2\theta\sin^2\theta_* + \frac{1}{2\gamma^2}[1+\cos^2\theta][1+\cos^2\theta_*] + \frac{1}{2\gamma^2}\frac{2\,v_e a_e}{(v_e^2+a_e^2)}\frac{2\,v_f a_f}{(v_f^2+a_f^2)}4\cos\theta\cos\theta_*\right\},$$

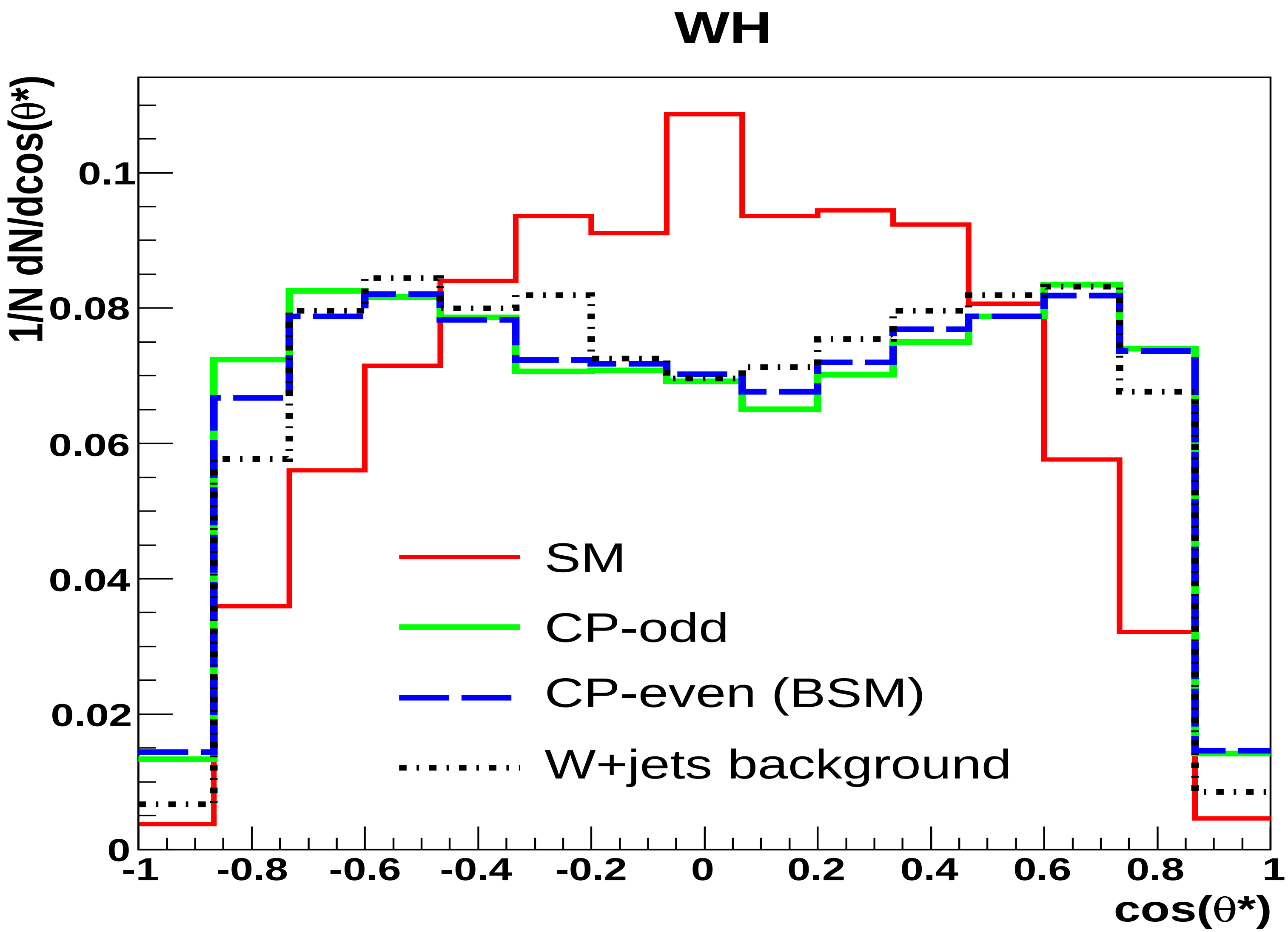
$\theta_* =$ Angle made by the momentum vector of the lepton in the rest frame of the V with the direction of the V in laboratory.

$$\cos\theta^* = \frac{\vec{p}_{l_1}^{\,(V)} \cdot \vec{p}_V}{|\vec{p}_{l_1}^{\,(V)}|\,|\vec{p}_V|} \quad , \qquad \cos\delta^+ = \frac{\vec{p}_{l_1}^{\,(V)} \cdot (\vec{p}_V \times \vec{p}_H)}{|\vec{p}_{l_1}^{\,(V)}|\,|\vec{p}_V \times \vec{p}_H|}$$

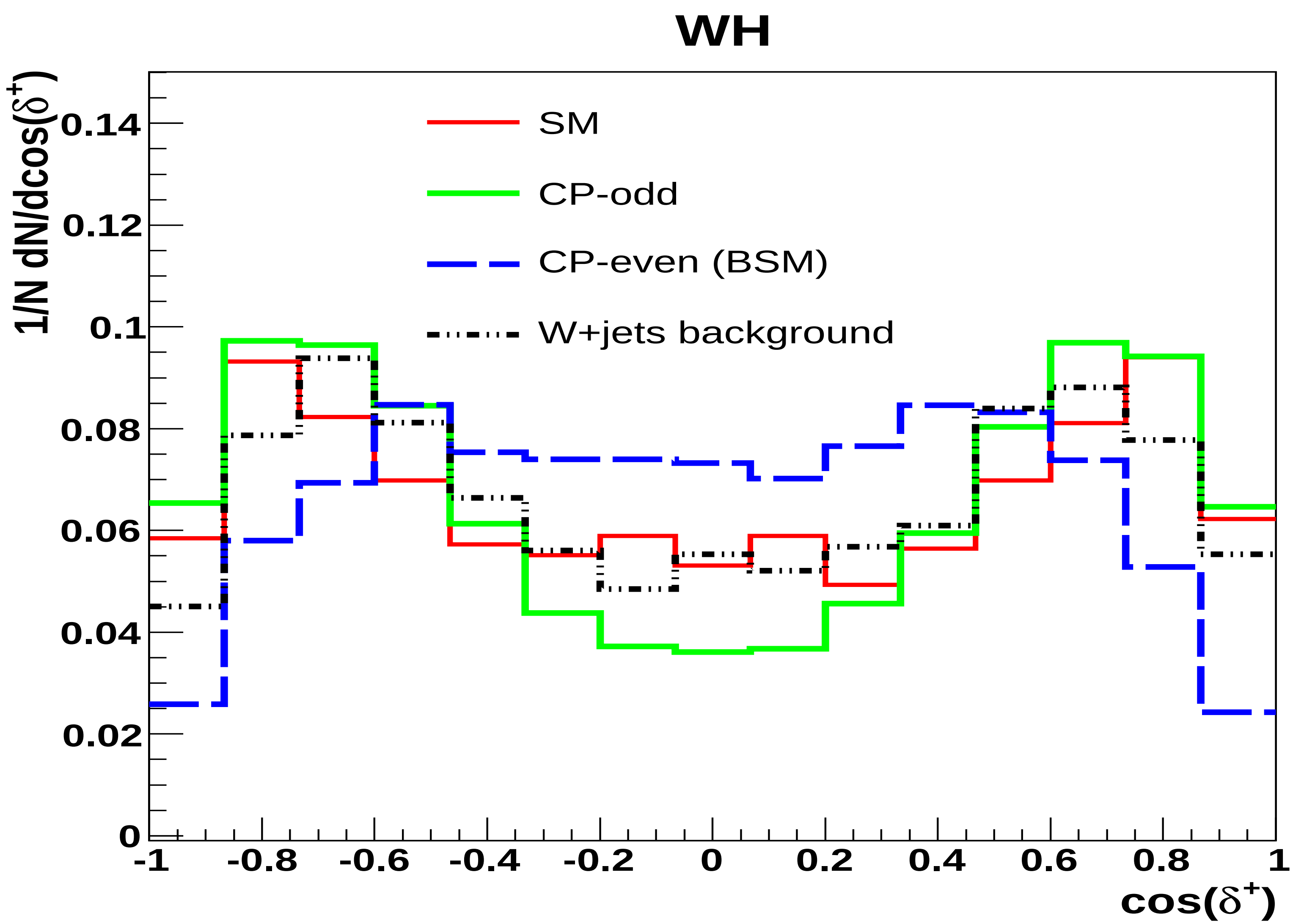
$$\cos\delta^- = \frac{(\vec{p}_{l_1}^{\,(H-)} \times \vec{p}_{l_2}^{\,(H-)}) \cdot \vec{p}_V}{|(\vec{p}_{l_1}^{\,(H-)} \times \vec{p}_{l_2}^{\,(H-)})||\vec{p}_V|}$$

$\vec{p}_X^{\,(Y)}$ means momentum of X in rest frame of Y.

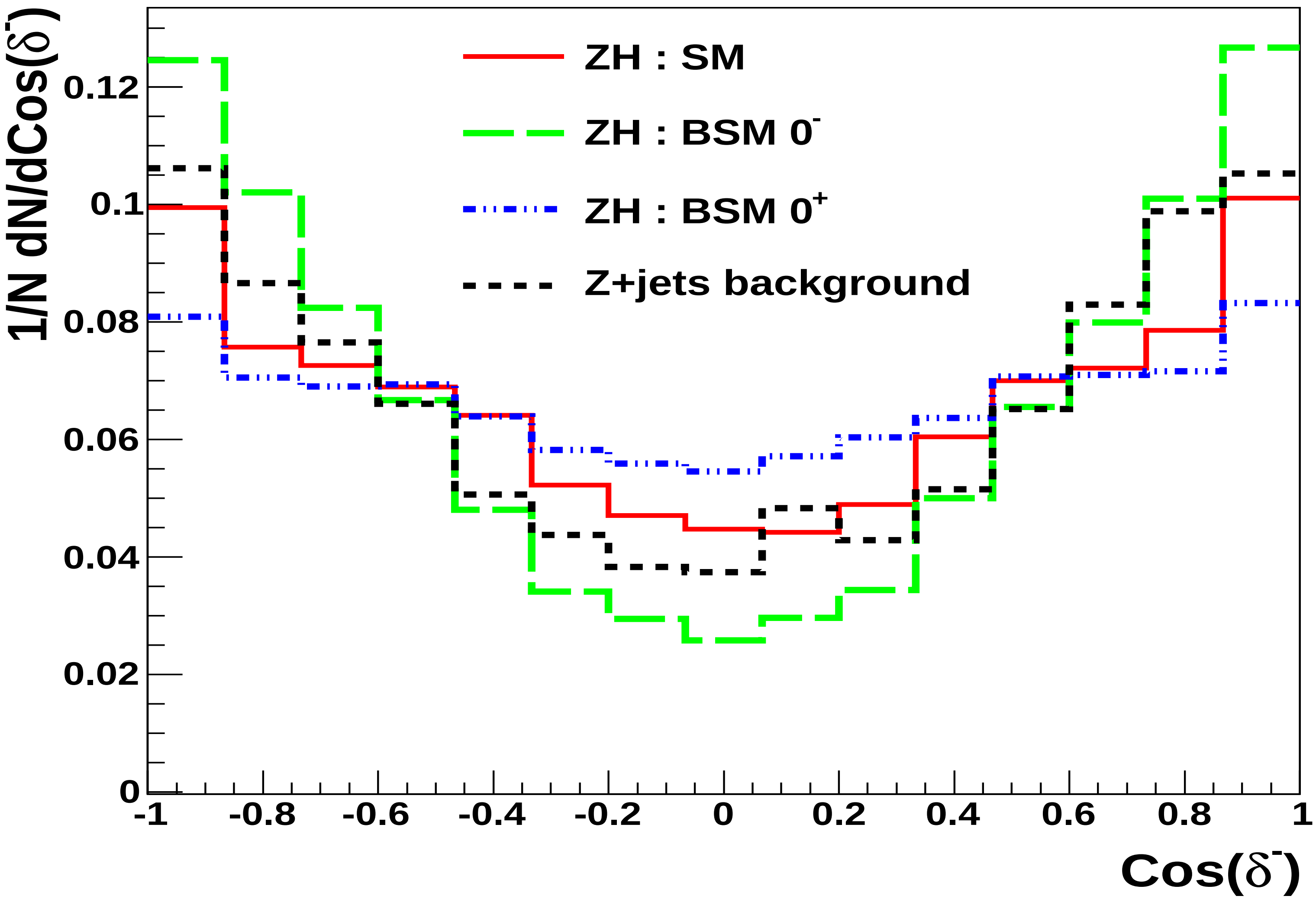
Use Fastjet package for Higgs reconstruction as a fat jet.


WH
1/N dN/dcos(θ*)
0.1
0.08
0.06
0.04
0.02
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cos(θ*)
SM
CP-odd
CP-even (BSM)
W+jets background

WH


WH
SM
CP-odd
CP-even (BSM)
W+jets background
1/N dN/dcos(δ+)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cos(δ+)

WH


1/N dN/dCos(δ⁻)
0.12
0.1
0.08
0.06
0.04
0.02
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Cos(δ⁻)
ZH : SM
ZH : BSM 0⁻
ZH : BSM 0⁺
Z+jets background

ZH

θ^* distribution discriminates between the SM on one hand and BSM on the other!

But background and BSM operators similar.

For other distributions the separation between SM and BSM as well as background clear.

For ZH dominant background Z + jets whereas for WH it is W + jets and $t\bar{t}$.

Two interesting results.

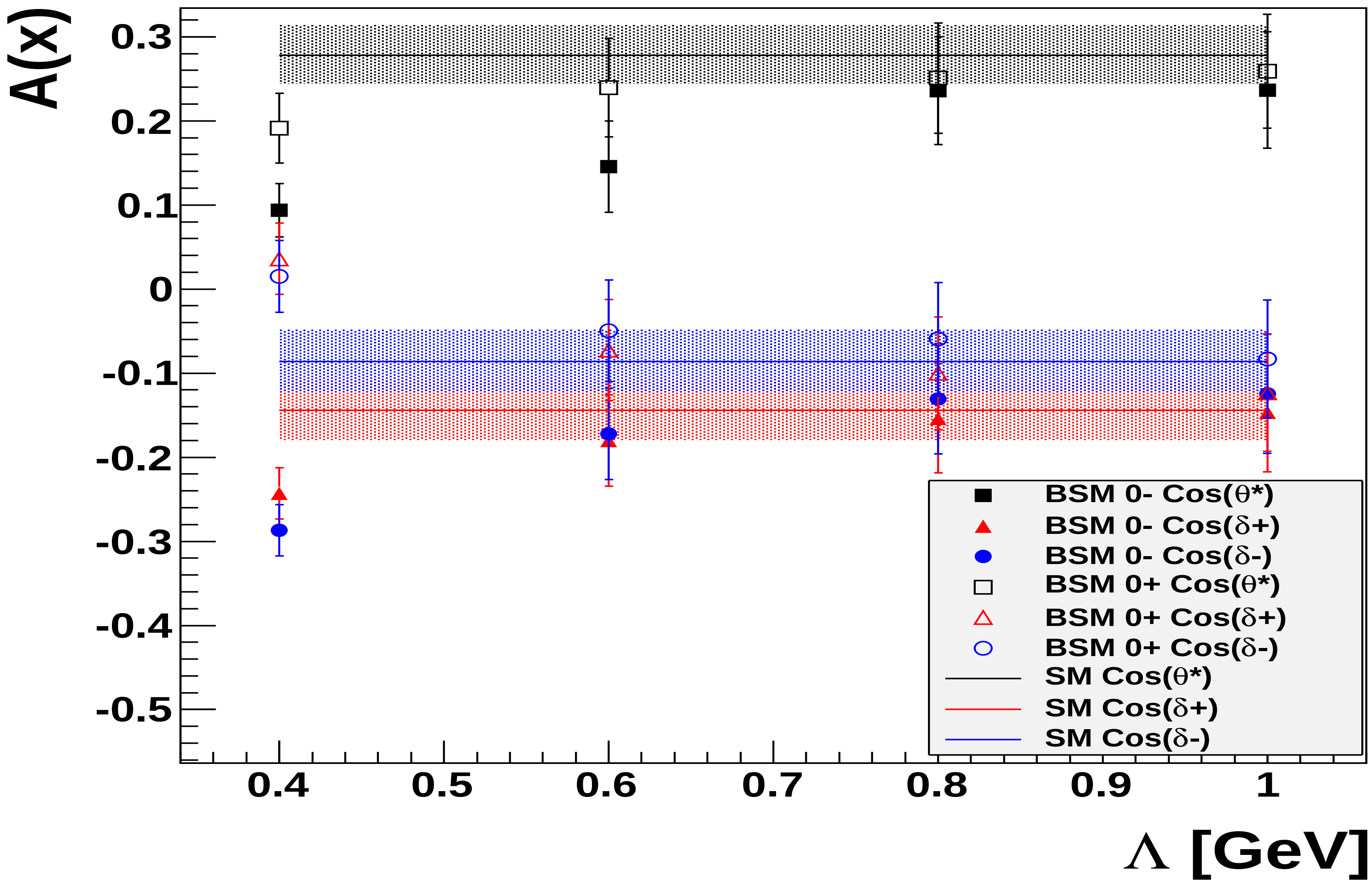
Again the acceptance of the cuts for boosted Higgs higher for BSM contribution. Hence the analysis increases sensitivity to BSM operators.

One can construct asymmetries out of these distributions which are different for different operators for δ^{+}, δ^{-} which are caused by interference effects.

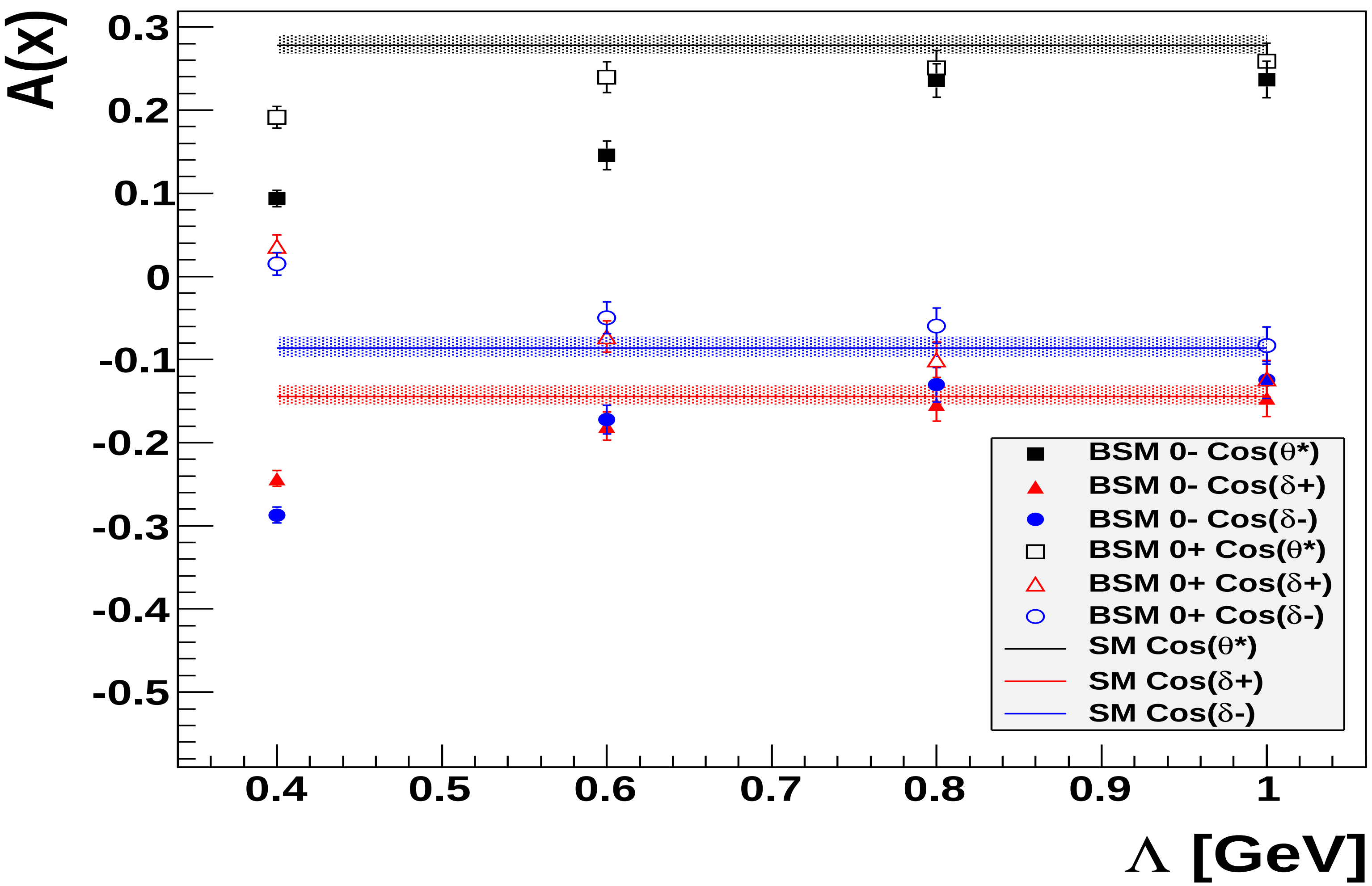
Channel	VH_{SM}	V+jets	$t\bar{t}$	Single top	$VH^{0^+}_{BSM}$	$VH^{0^-}_{BSM}$
ZH	0.12	0.23	0	0	0.48	0.73
WH	0.36	0.28	0.13	0.06	1.45	2.14

The coefficients λ and λ' so adjusted that the BSM cross-section is the same as the SM *before* cuts. Cross-section in femtobarn after the cuts.

Asymmetries	ZH_{SM}	ZH^{0-}_{BSM}	ZH^{0+}_{BSM}	Z+jets
$A(\cos\theta^*)$	0.35	-0.05	-0.02	0.07
$A(\cos\delta^+)$	-0.207	-0.262	0.088	-0.188
$A(\cos\delta^-)$	-0.209	-0.435	-0.103	-0.321



WH Asymmetry, errors and possibilities of measurement.



WH Asymmetry, errors for 3000 fb^{-1}.

- Rates themselves can be used to prove consistency with 0^+ hypothesis and constrains the 0^- component to about 0.68. But unambiguous information can only come from angular distributes and $t\bar{t}H$.

- $H \to Z^*Z, \gamma\gamma$ do provide information on HZZ vertex and hence for spin and CP. Should be able to even probe CP violation with high luminosity.

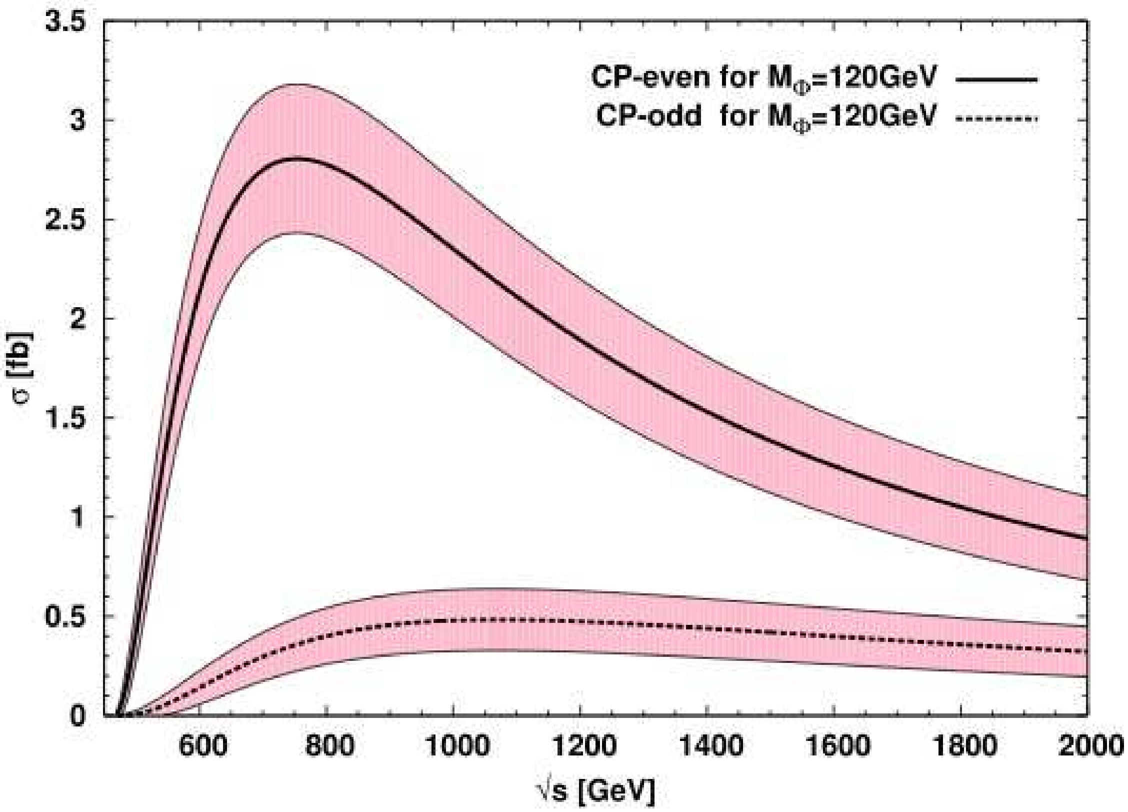
- VBF and VH kinematics changed due to BSM vertices. $\Delta y_{jj}, P_{Tj}$ along with the ϕ_{jj} can provide discrimination between SM and BSM. But separation between HZZ and HWW not possible.

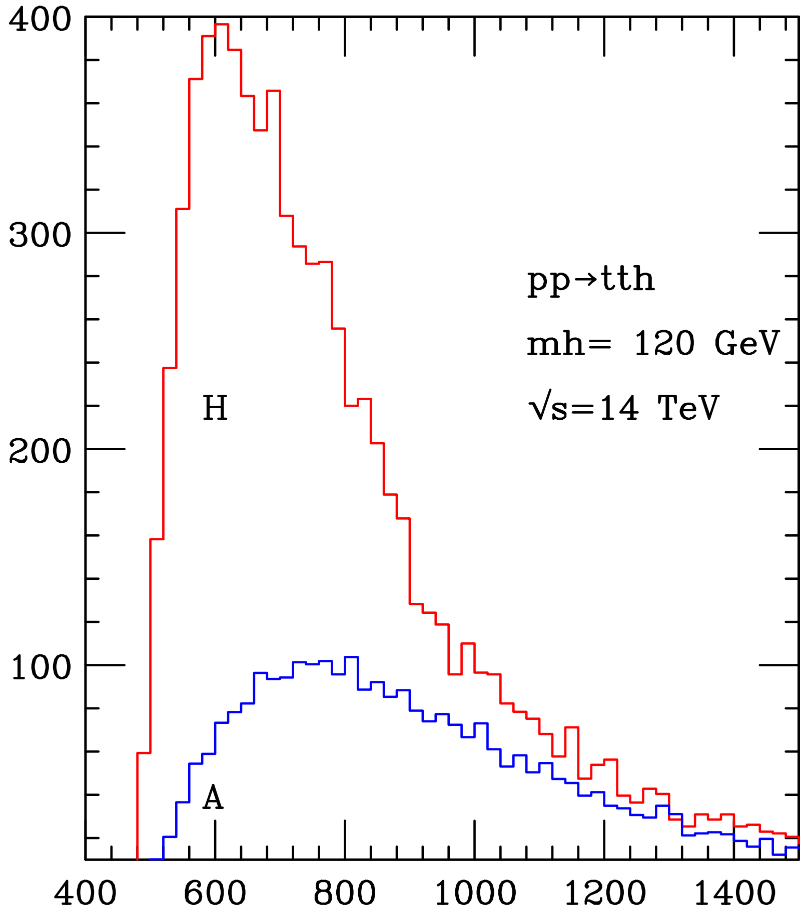
- New phase space region which will have higher sensitivity to BSM vertex identified. Even with 25 fb^{-1} at 8 TeV for Graviton 5σ is possible.

- Using VH and $H \to b\bar{b}$ we have identified new angular distributions which have enhanced sensitivity to BSM CP violating operator. Further, boosted VH analysis increases sensitivity to higher dimensional operators.

$e^+e^- \to t\bar{t}H$ has a different threshold rise for scalar and pseudoscalar:

ZPC 71, 1681

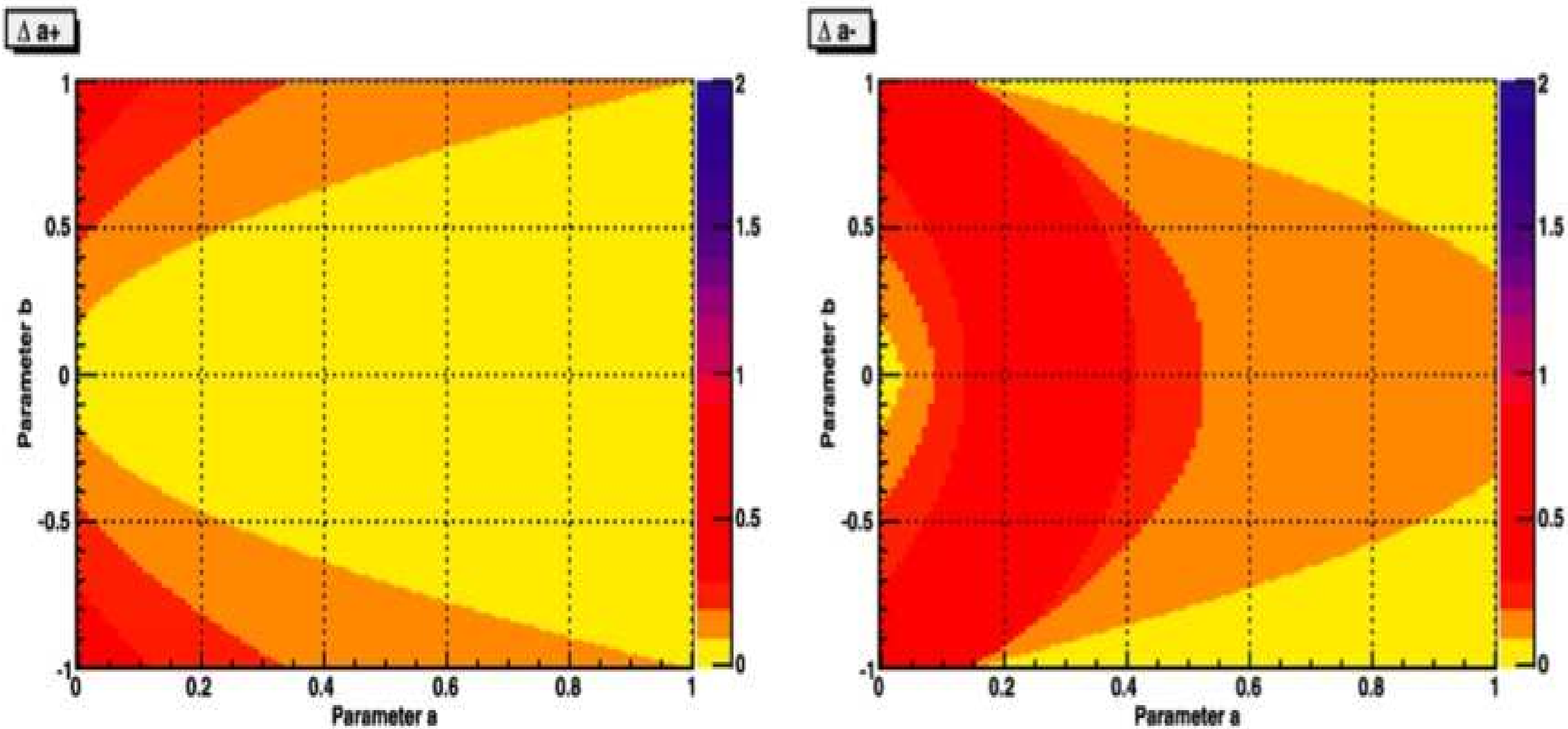




So this can be used at high luminosity to determine the CP and also to clean up the background

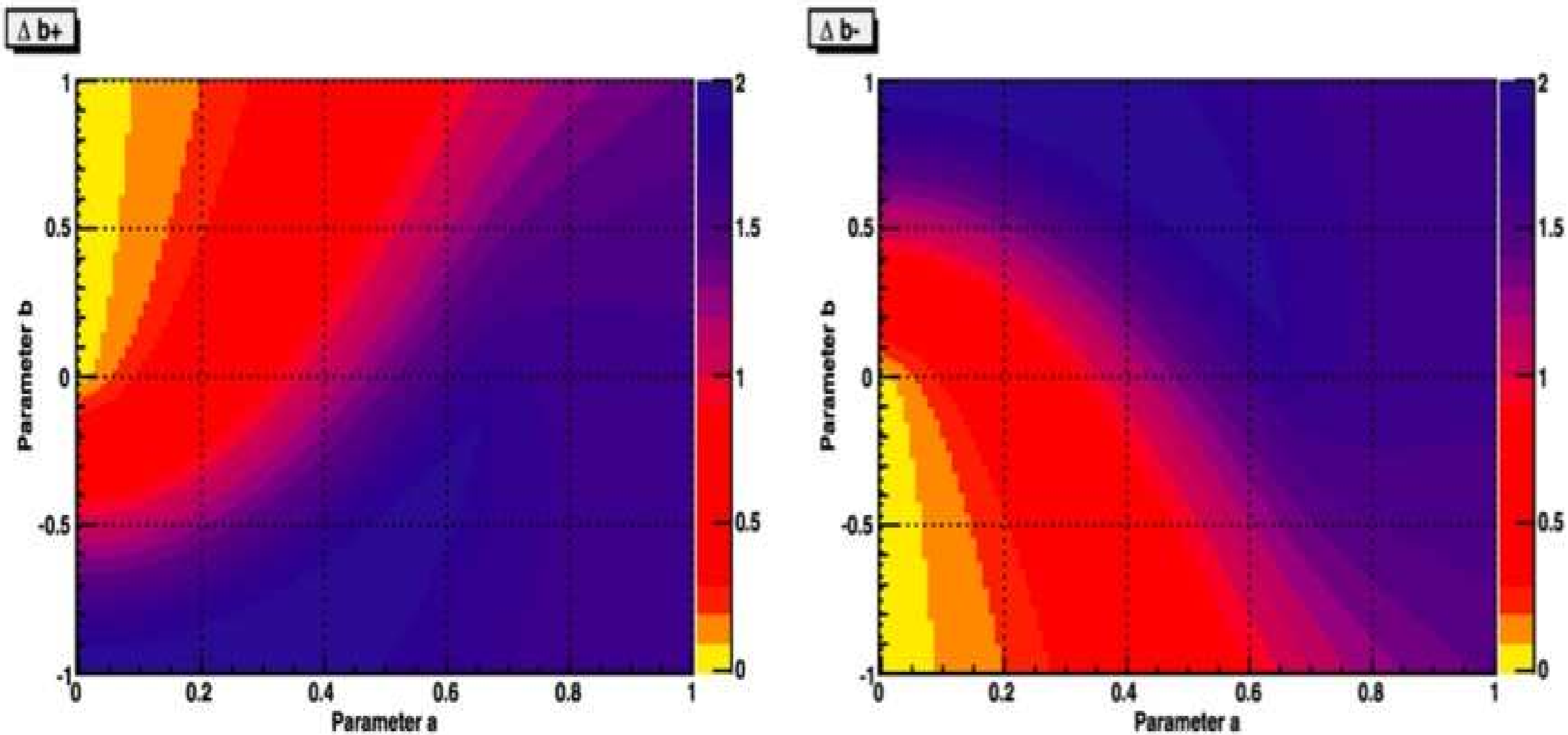
BACKUP SLIDES

Using σ, top polarisation R.G. et al, PRL **100**, 051801 (2008) and CP violating asymmetry R.G. et al, PRL..., D. Atwood, S. Bar-Shalom, G. Eilam, A. Soni, Phys. Rep. 347, 1 (2001) at the ILC:

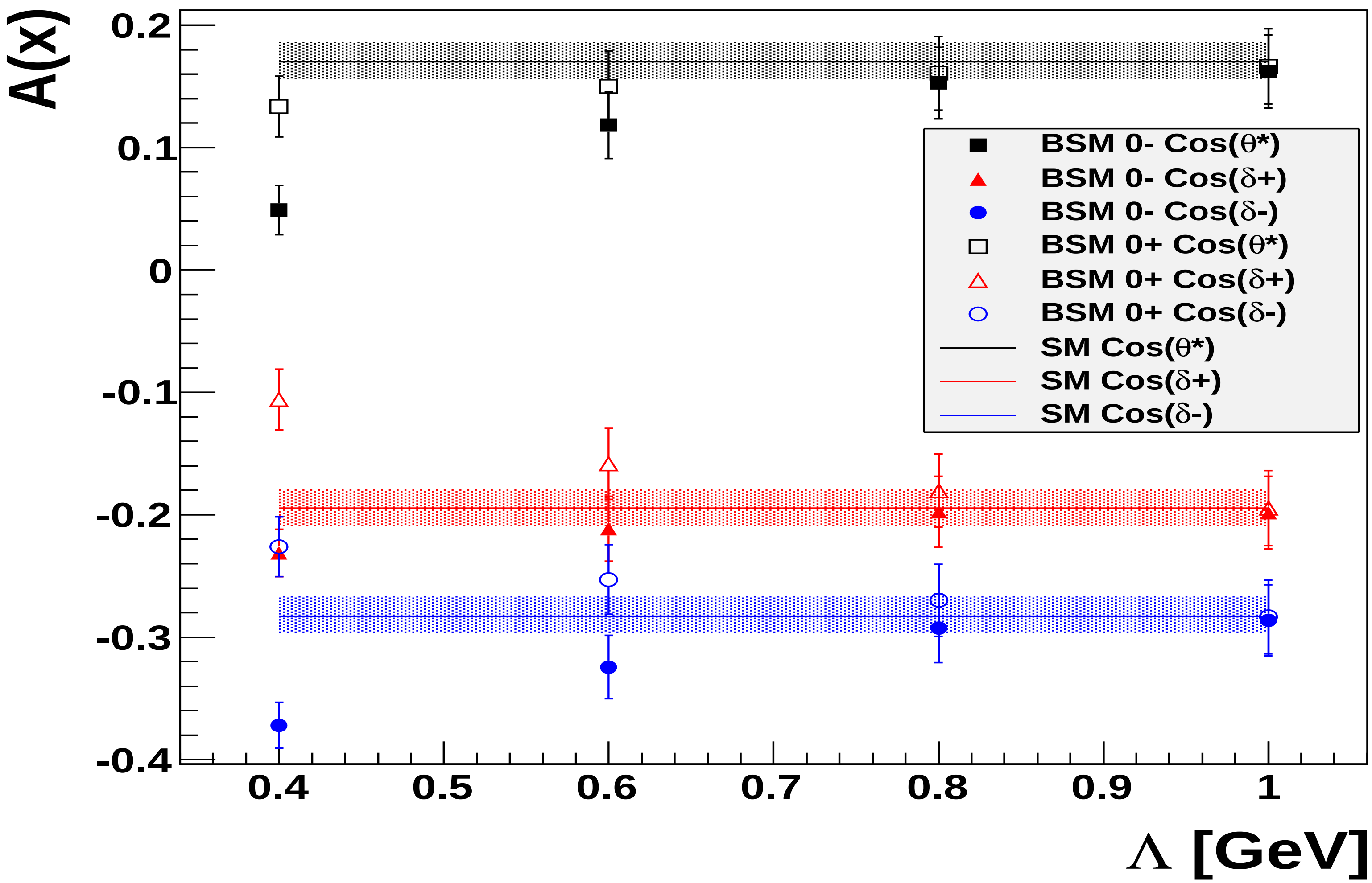


R.G. et al, EPJC 71, 1681 (2011)

Using σ, top polarisation R.G. et al, PRL **100**, 051801 (2008) and CP violating asymmetry R.G. et al, PRL..., D. Atwood, S. Bar-Shalom, G. Eilam, A. Soni, Phys. Rep. 347, 1 (2001) at the ILC:



R.G. et al, EPJC 71, 1681 (2011)



ZH Asymmetry, errors and possibilities of measurement.

Effective Lagrangians:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \equiv \mathcal{L}_{SM} + \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{F_1} + \Delta\mathcal{L}_{F_2}$$

dimension-6 operators
(only those relevant for Higgs physics)

⋮

The list of dim=6 operators of the effective Lagrangian has been known in the literature since long time

Buchmuller and Wyler
NPB 268 (1986) 621

Minimal and complete list first appeared in:

Grzadkowski et al.
JHEP 1010 (2010) 085

Effective Lagrangians:

$$
\begin{aligned}
\Delta\mathcal{L}_{SILH} = & \frac{\bar{c}_H}{2v^2}\,\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\,\lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c.\right) \\
& + \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\,{g'}^2}{m_W^2}\,H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}\,,
\end{aligned}
$$

- Various extensions of the SM can have several Higgs bosons with different CP properties : e.g. MSSM has two CP-even and one CP-odd states.

- To study the effects beyond SM, we need to establish the CP eigenvalues for the Higgs states if CP is conserved, and measure the mixing between CP-even and CP-odd states if it is not.

- One possible explanation of Baryon Asymmetry can be found in terms of CP violation in Higgs sector.

For Spin 0:

$$\mathcal{L}_{VVH} = \mathcal{L}_{SM} + \frac{g_W^2}{2\Lambda_1^2}\Phi^\dagger\,\Phi\,W_{\mu\nu}\,W^{\mu\nu} + \frac{g_W^2}{2\Lambda_2^2}\Phi^\dagger\,\Phi\,\tilde{W}_{\mu\nu}\,W^{\mu\nu},$$

This corresponds to an effective vertex of the form given earlier. In slightly different notation:

$$\Gamma^{\mathrm{SM}}_{\mu\nu} = -gM_V\,g_{\mu\nu}$$

$$\Gamma^{\mathrm{BSM}}_{\mu\nu}(p,q) = \frac{g}{M_V}\left[\lambda\,(p\cdot q\,g_{\mu\nu} - p_\nu q_\mu) + \lambda'\;\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

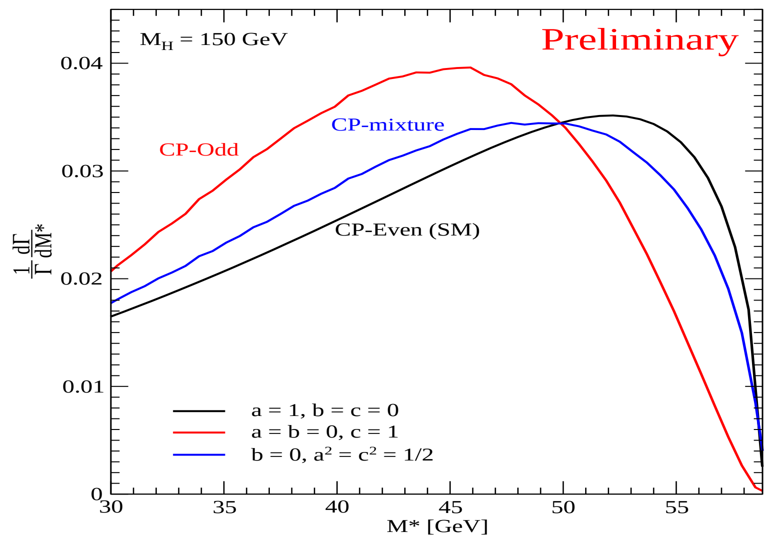
$c_V = \lambda' = 1$ means $\Lambda_2 = 2\sqrt{2}M_W$.

For Spin 2:

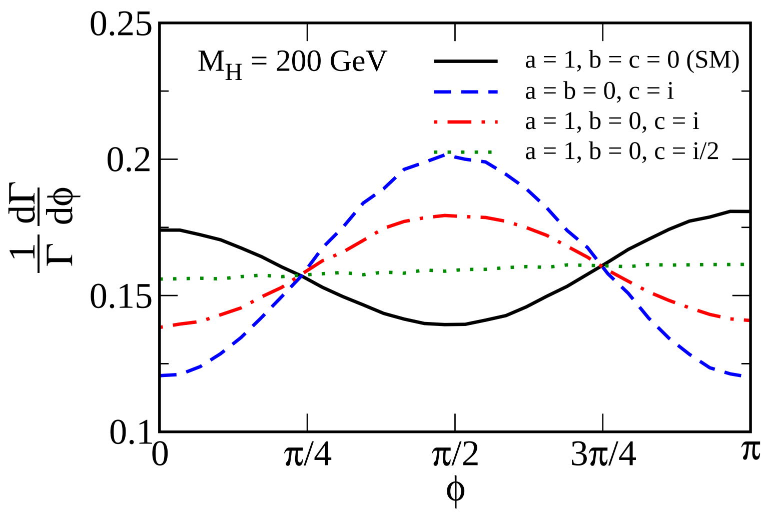
$$\mathcal{L}_{\text{eff}} = \frac{1}{\Lambda} T_{\alpha\beta} \left(f_1 g_{\mu\nu} B^{\mu\alpha} B^{\nu\beta} + f_2 g_{\mu\nu} W^{\mu\alpha} W^{\nu\beta} \right)$$

Λ is the high scale and f_1, f_2 are the form factors.

Mixed CP: R.G., Muhelleitner, Miller JHEP 0712 (2007) 31



Distribution in ϕ ; the angle between the planes of the fermion pairs coming from the Z boson decays.



MELA: analysis uses this and more.

We have implemented the effective Lagrangian with higher dimensional operators:

1)CP even/CP odd operators for spin 0 (i.e $0^+, 0^-$)

2)spin 2 graviton couplings

Has been implemented in Feynrules and generated matrix elements using MADGRAPH.

So in principle this can be made available to experimentalists and we should be able to do so if people are interested.

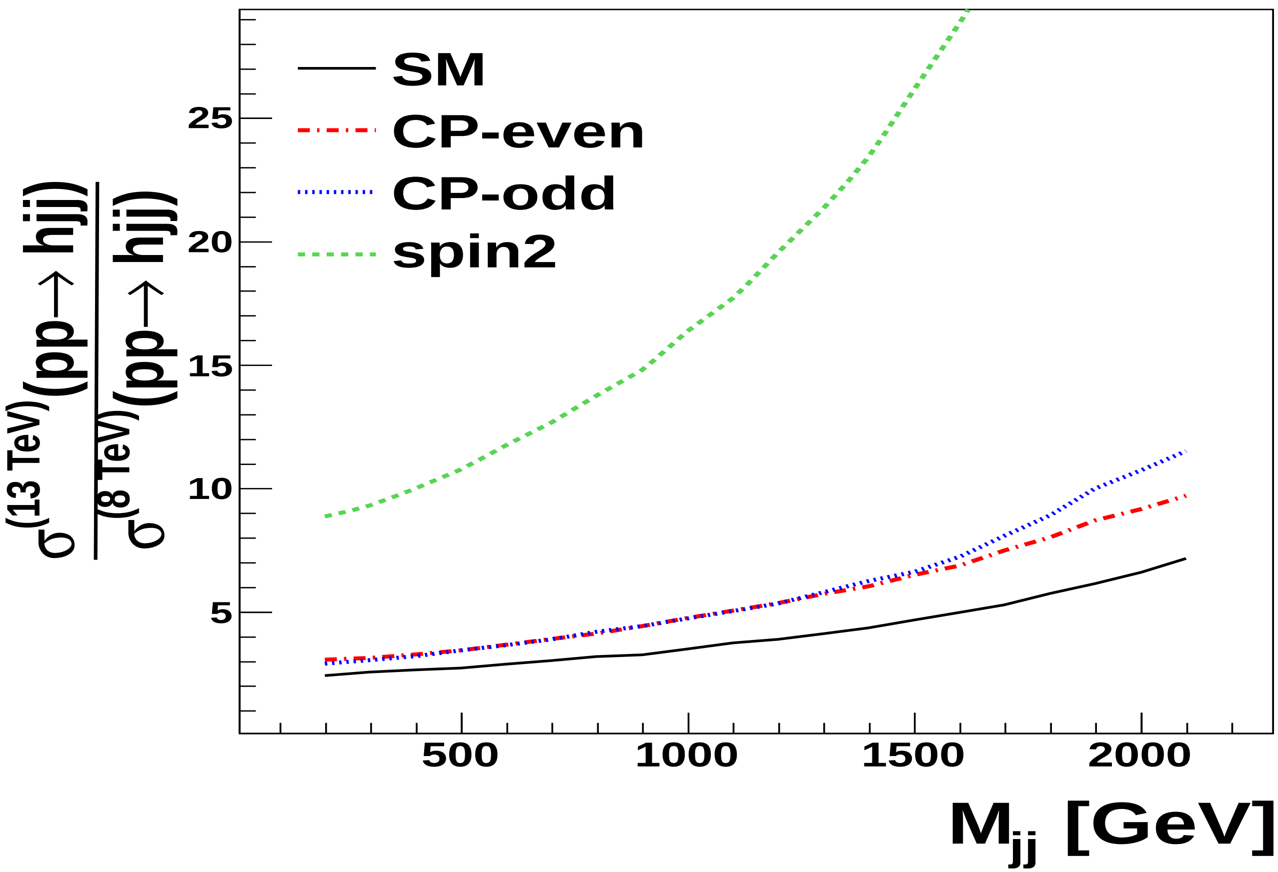
The Lagrangian we have implemented for Spin 0:

$$\mathcal{L}_{VVH} = \mathcal{L}_{SM} + \frac{g_W^2}{2\Lambda_1^2}\Phi^\dagger\,\Phi\,W_{\mu\nu}\,W^{\mu\nu} + \frac{g_W^2}{2\Lambda_2^2}\Phi^\dagger\,\Phi\,\tilde{W}_{\mu\nu}\,W^{\mu\nu},$$

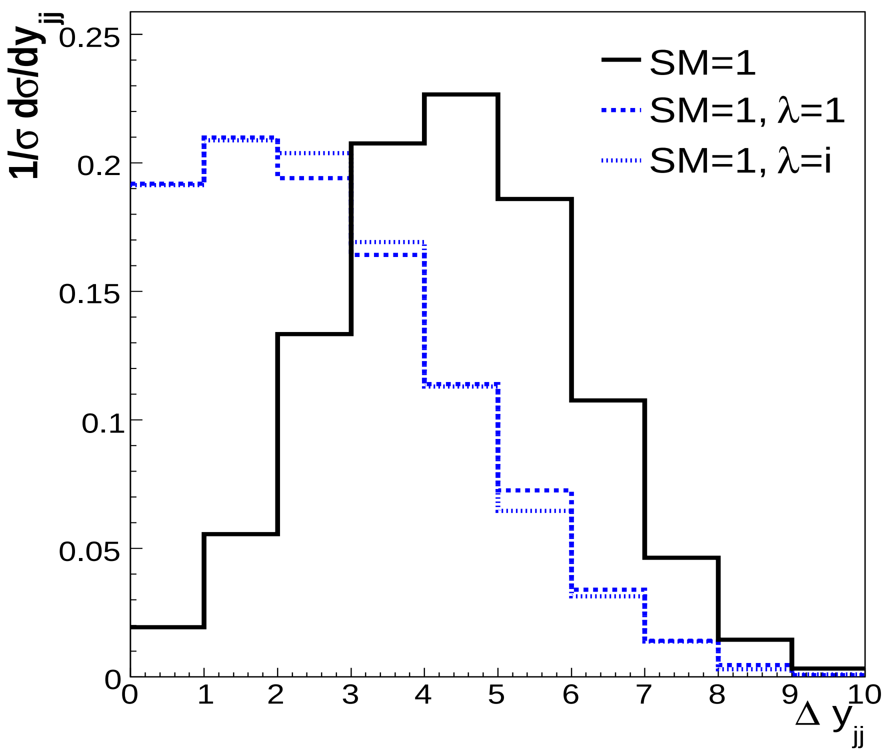
This corresponds to an effective vertex of the form given earlier. In slightly different notation:

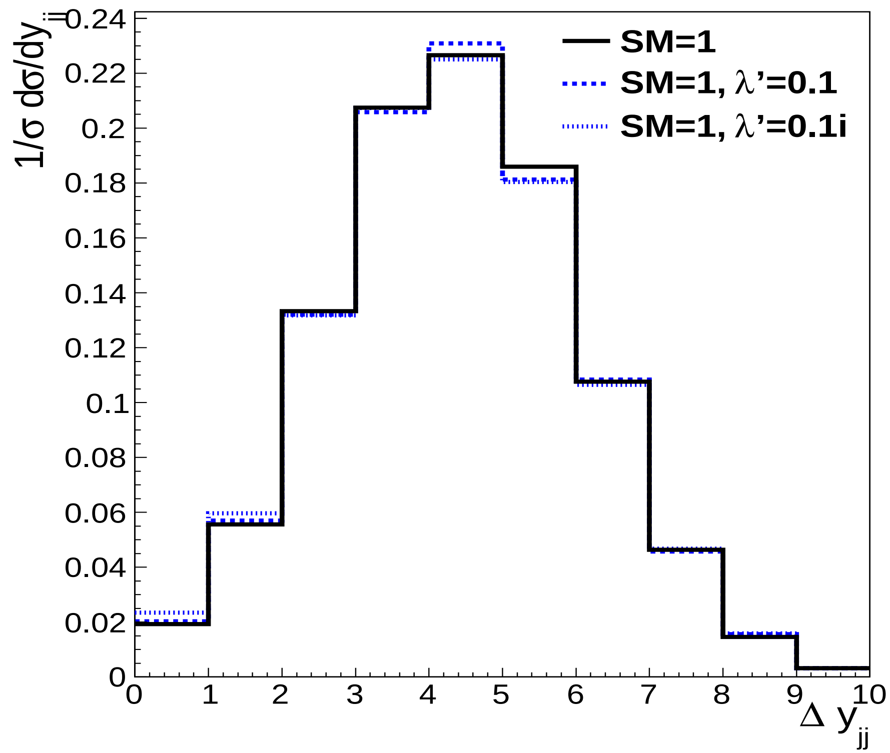
$$\begin{aligned}\Gamma^{\mathrm{SM}}_{\mu\nu} &= -gM_V\,g_{\mu\nu}\\ \Gamma^{\mathrm{BSM}}_{\mu\nu}(p,q) &= \frac{g}{M_V}\left[\lambda\,(p\cdot q\,g_{\mu\nu} - p_\nu q_\mu) + \lambda'\;\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]\end{aligned}$$

The increase in rates for SM and BSM as we go from 8 to 13 TeV will be different. So just the ratios of cross-section at two energies can distinguish between the SM operator and BSM operators.



The normalized distributions did not involve λ, λ' or f_1, f_2.





Look at mixture : SM full strength + CP odd as a fn of scale Λ. Earlier $\lambda' = 1$ corresponds to $\Lambda = 2\sqrt{2}M_W$.