BEH characterization with FeynRules and MadGraph5

Kentarou Mawatari

(Vrije Universiteit Brussel and International Solvay Institutes)

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K.Hagiwara, T.Li, KM, J.Nakamura [arXiv:1212.6247]
P. de Aquino, F.Maltoni, KM, M.Zaro et al, in progress

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Brout-Englert-Higgs

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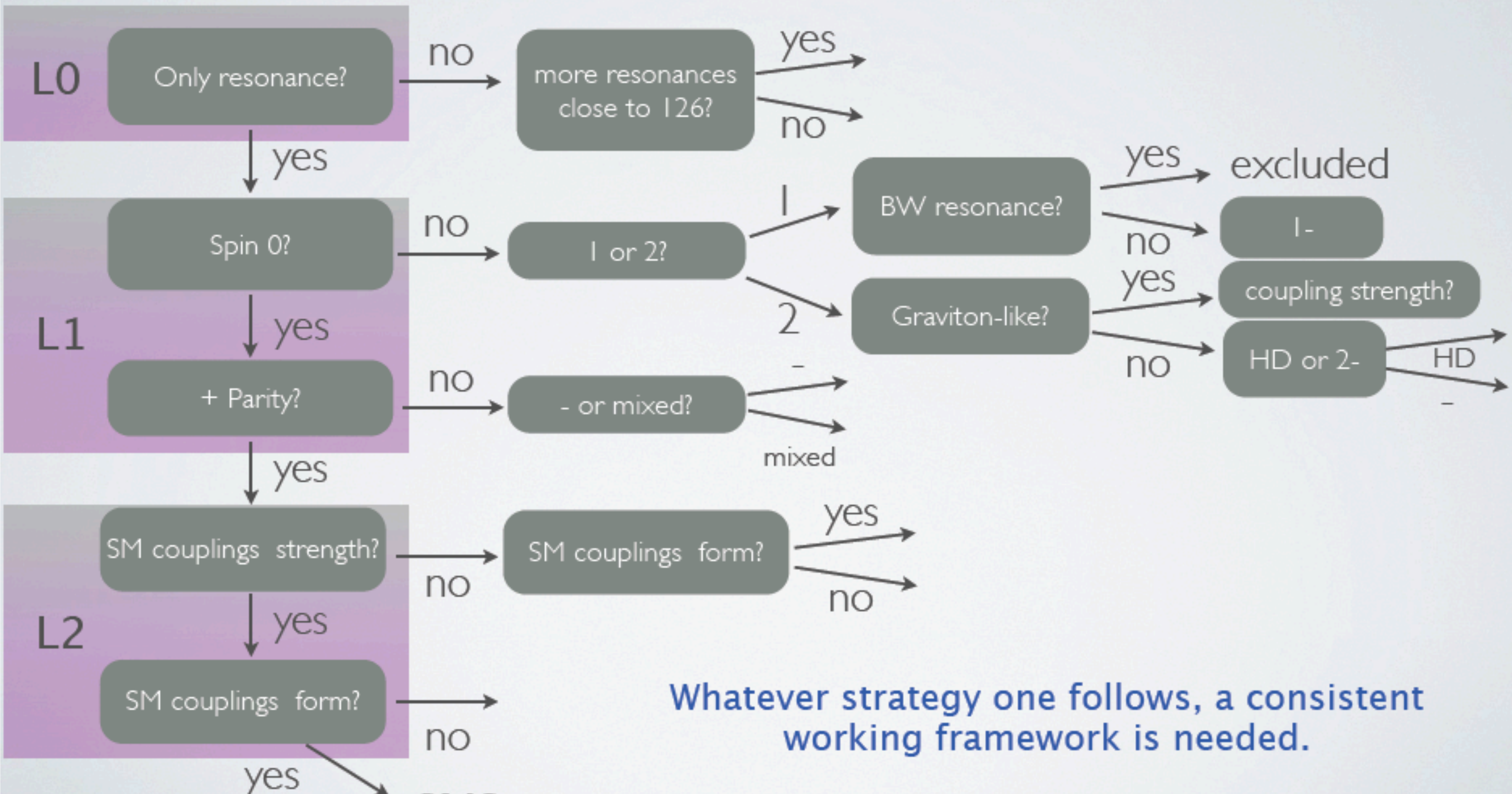
MADGRAPH 5

To test the properties of new particles, and to compare the most precise predictions existent for data and look for differences.



Whatever strategy one follows, a consistent working framework is needed.

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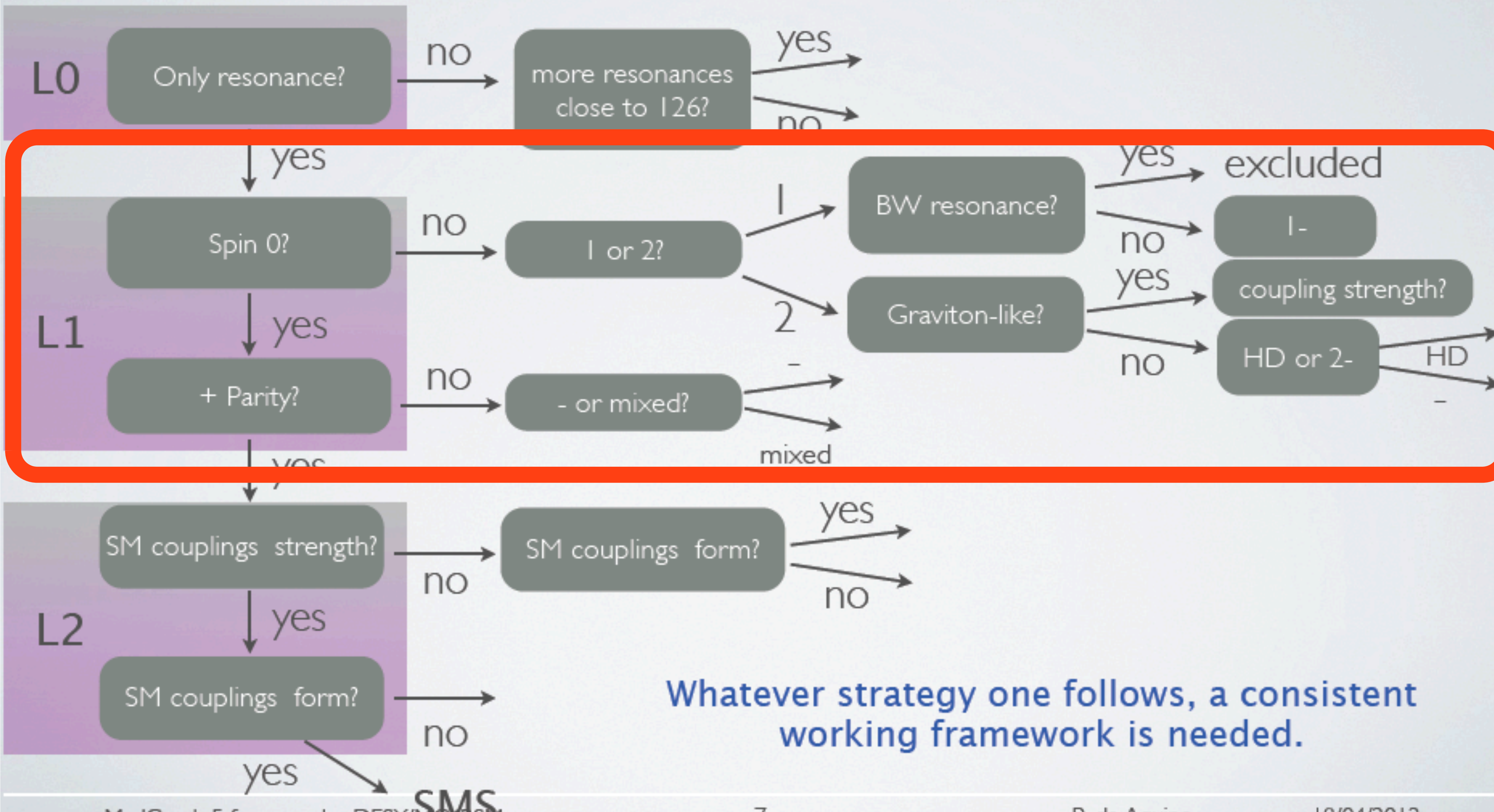

Whatever strategy one follows, a consistent working framework is needed.

Higgs Characterization with FeynRules

Artoisenet, de Aquino, Frederix, Maltoni, Mandal, Mathews, KM, Ravindran, Seth, Torrielli, Zaro (in progress)

- We implemented an effective Lagrangian featuring bosons
  $X(J^P=0^+,0^-,1^+,1^-,2^+,2^-)$
  in FeynRules (http://feynrules.irmp.ucl.ac.be).

- The new states can couple to SM particles via interactions of the minimal (and next-to-minimal) dimensions, e.g. for X-Z-Z:

$$\mathcal{L}_0 = \Big[\cos\alpha\big(\kappa_{\rm SM} g_{HZZ} Z_\mu Z^\mu - \frac{1}{4}\frac{\kappa_V}{\Lambda} Z_{\mu\nu}Z^{\mu\nu}\big) - \sin\alpha\frac{1}{4}\frac{\kappa_V}{\Lambda} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\Big] X_0$$

$$\mathcal{L}_1 = \Big[-\kappa_{V_3}(\partial^\nu Z_\mu)Z_\nu - \kappa_{V_5}\epsilon_{\mu\nu\rho\sigma}Z^\nu(\partial^\rho Z^\sigma)\Big] X_1^\mu$$

$$\mathcal{L}_2 = \Big[-\frac{\kappa_V}{\Lambda}T^Z_{\mu\nu} - \frac{\kappa_{V_1}}{\Lambda^3}(\partial_\nu(\partial_\mu\frac{1}{4}Z_{\rho\sigma}Z^{\rho\sigma})) - \frac{\kappa_{V_2}}{\Lambda^3}(\partial_\nu(\partial_\mu\frac{1}{4}Z_{\rho\sigma}\tilde{Z}^{\rho\sigma}))\Big] X_2^{\mu\nu}$$

- κ_i : dimensionless coupling parameters
- $\cos\alpha$: mixing between 0^+ and 0^- parameters
- Λ : theory cutoff scale

The parametrization is based on the recent work [Englert, Goncalves-Netto, KM, Plehn (2013)].

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Higgs Characterization model

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1. Flexibility: it is straightforward to modify the model to extend it further in case of need, by adding further interactions, for example of higher-dimensions.
2. Modularity/Automation: all relevant production and decay modes can be studied within the same model, from gluon-gluon fusion to VBF as well as VH and ttH can be considered.

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3. Accuracy: higher-order effects can be easily accounted for, by generating multi-jet merged samples or computing NLO corrections with automatic framework.

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2. Modularity/Automation

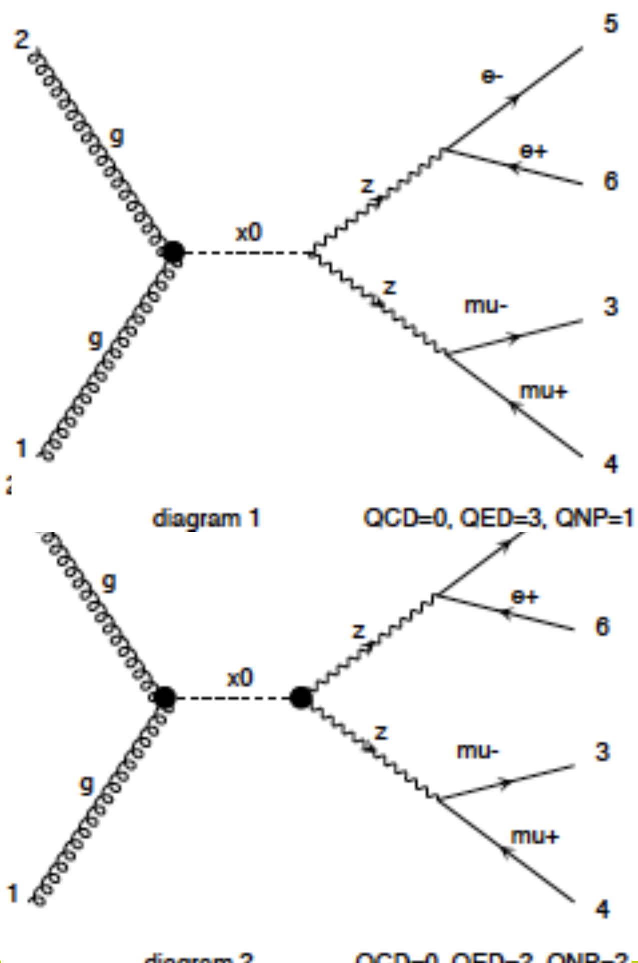
- All relevant production and decay modes can be studied within the same model:

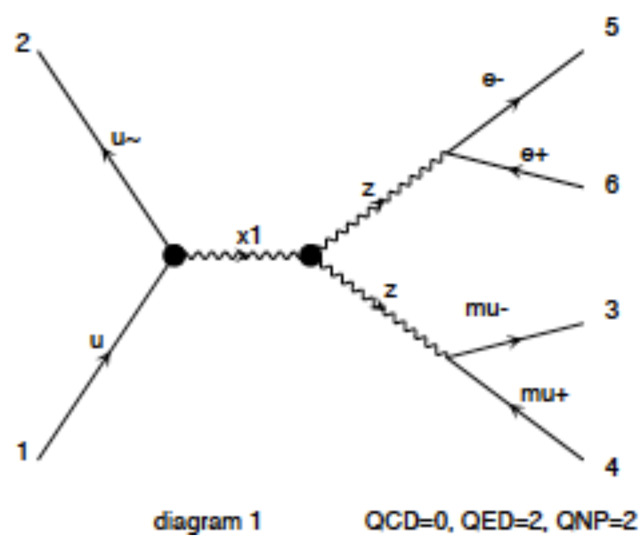
  a. $X \to VV \to 4l$
  b. $X \to \gamma\gamma$
  c. jjX (VBF)
  d. VX/ttX
  e. $X \to \tau\tau$

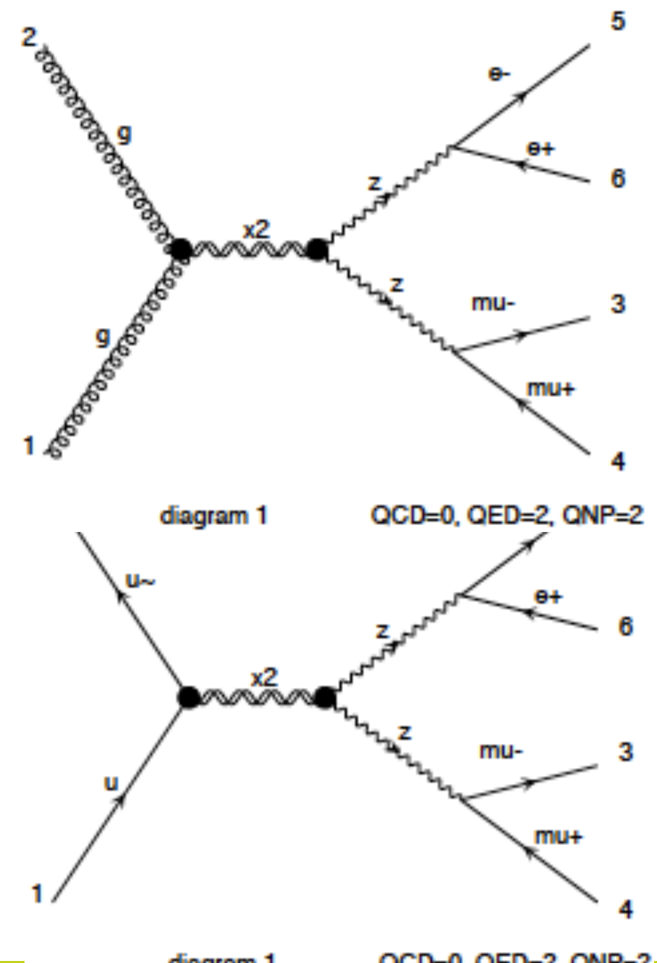
a. X→VV→4l

- Higgs Characterization with MadGraph5:

```
./bin/mg5
>import model XCharac
>generate p p > x0, x0 > mu- mu+ e- e+
>output
>launch
```







JHU comparison: X→ZZ→4l

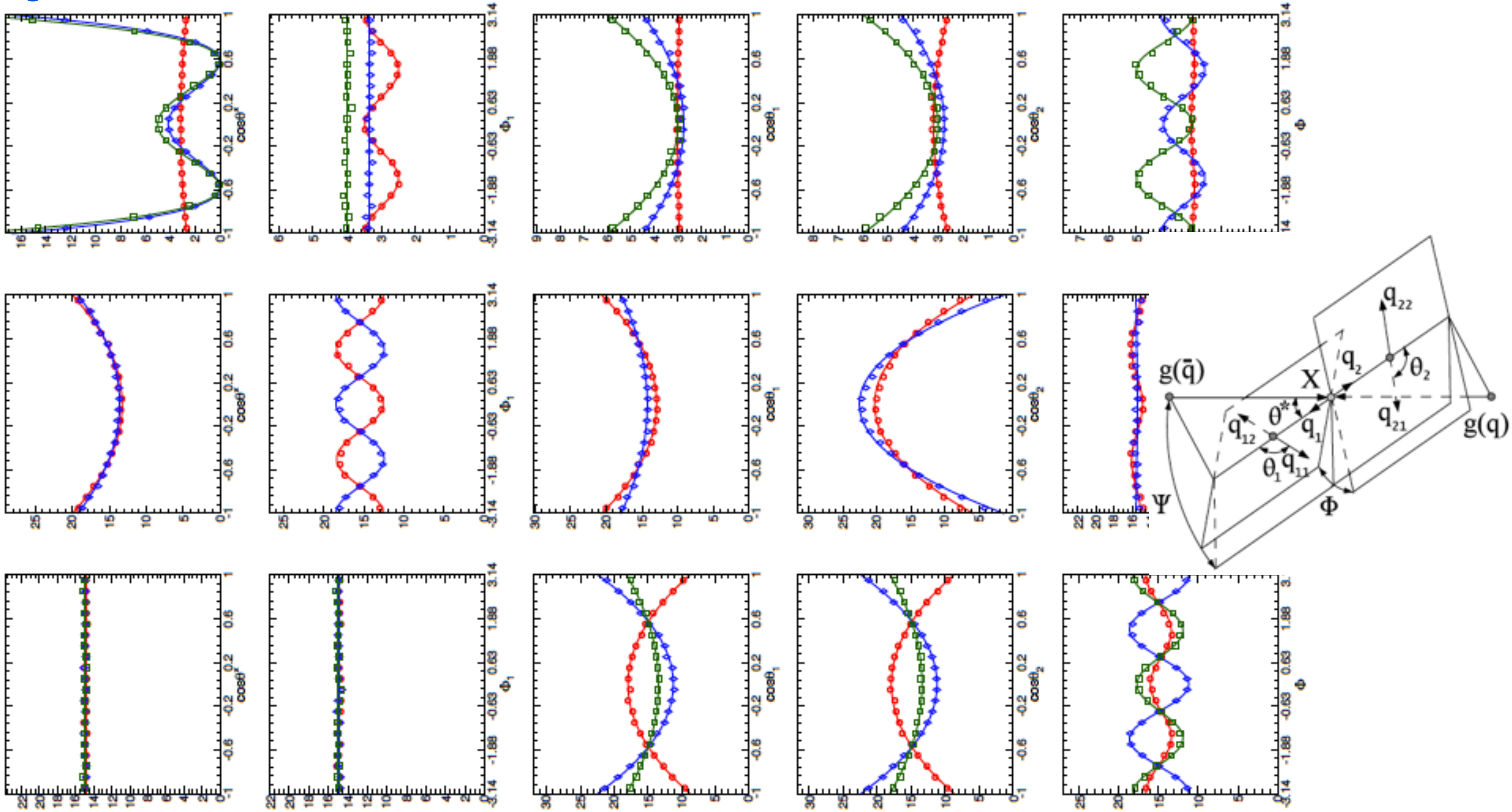
angular distributions

Bolognese et al. (2012): JHU-Generator

spin-2

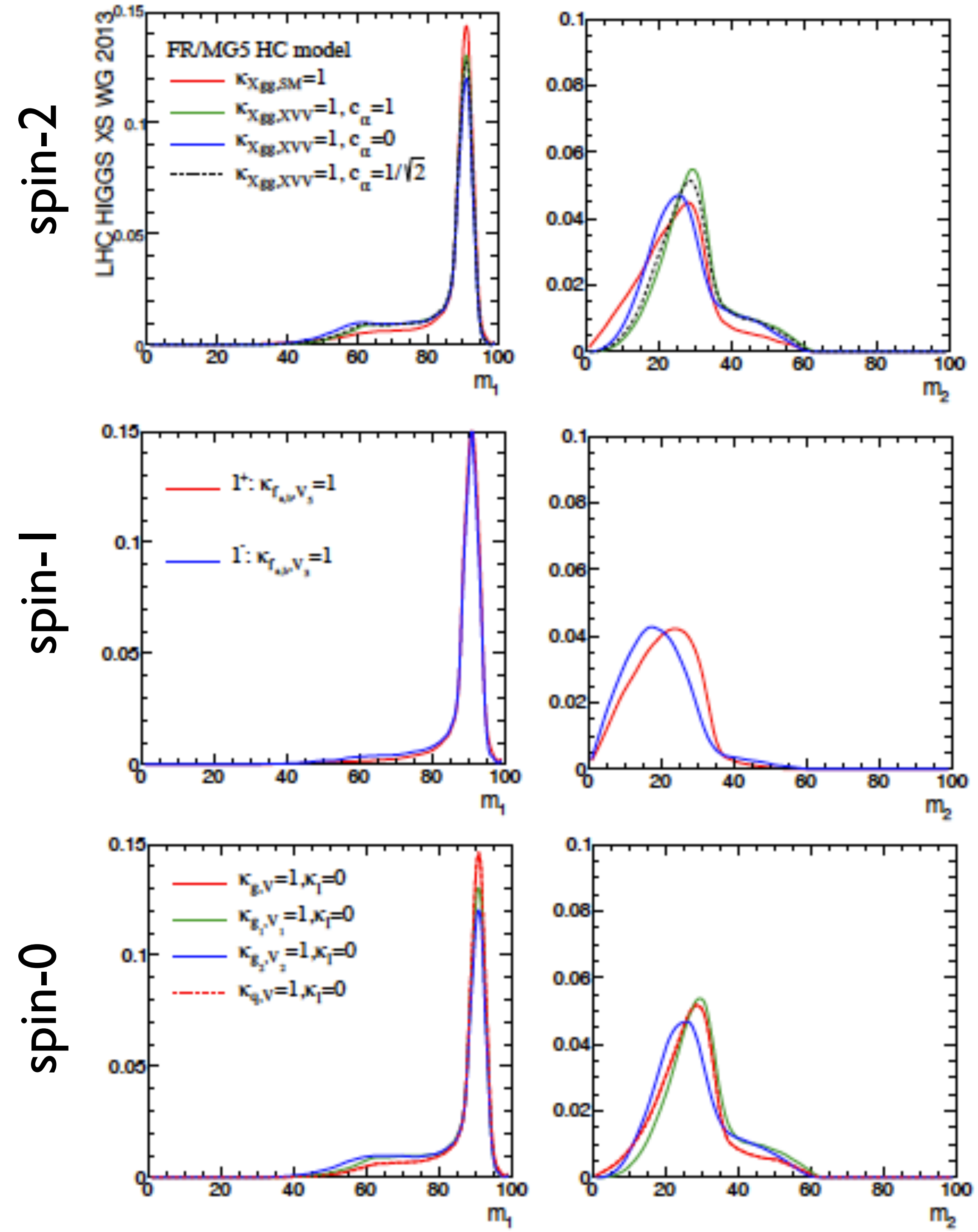
spin-1

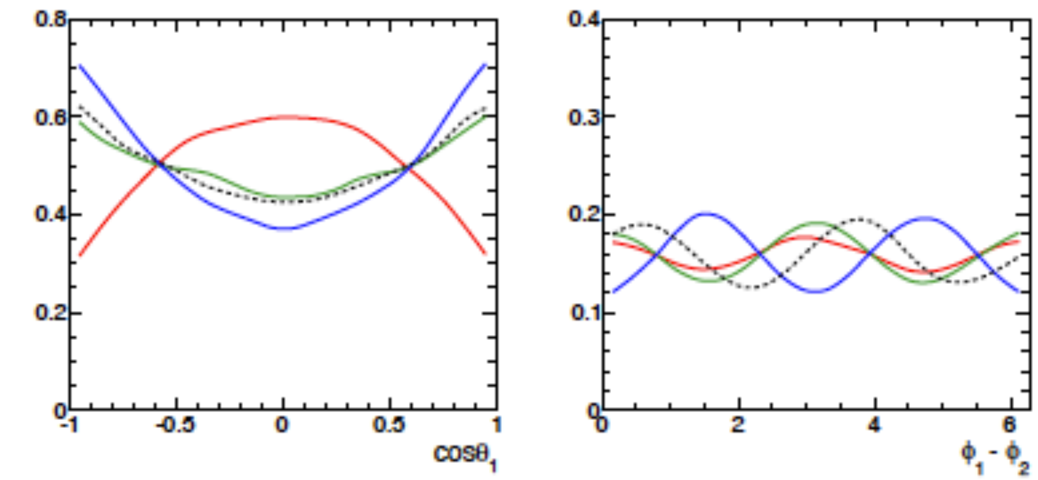
spin-0



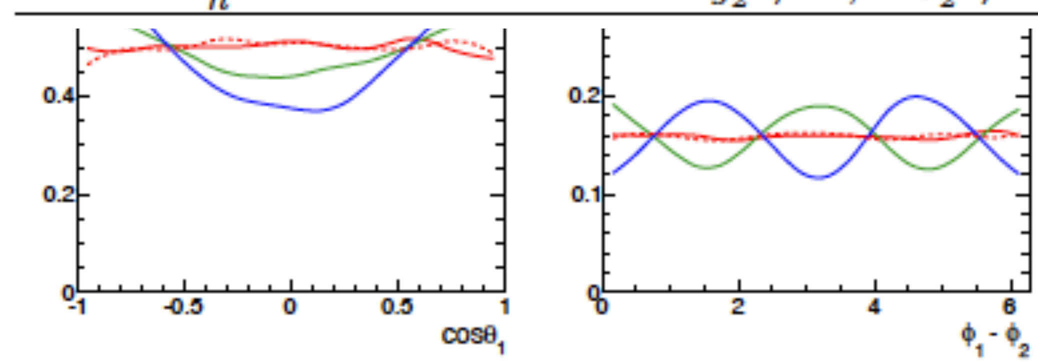
JHU comparison: X→ZZ→4l

FR/MG5 HC model





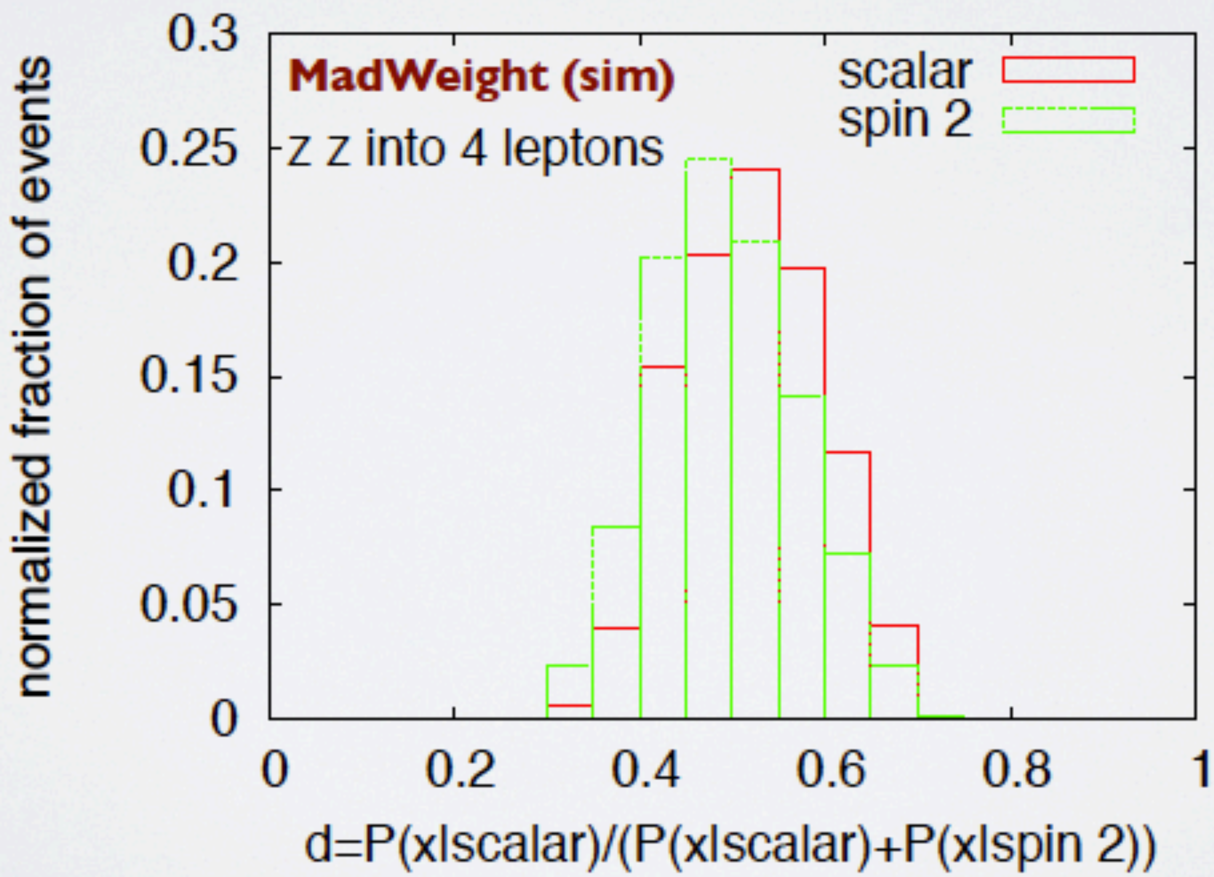
JHU scenario	HC parameter choice
0_m^+	$\kappa_{Hgg} \neq 0,\ \kappa_{SM} \neq 0,\ c_\alpha = 1$
0_h^+	$\kappa_{Hgg} \neq 0,\ \kappa_{HVV} \neq 0,\ c_\alpha = 1$
0^-	$\kappa_{Agg} \neq 0,\ \kappa_{AVV} \neq 0,\ c_\alpha = 0$
1^+	$\kappa_{fu_a} = \kappa_{fu_b} = \kappa_{fd_a} = \kappa_{fd_b} \neq 0,\ \kappa_{V_5} \neq 0$
1^-	$\kappa_{fu_a} = \kappa_{fu_b} = \kappa_{fd_a} = \kappa_{fd_b} \neq 0,\ \kappa_{V_3} \neq 0$
2_m^+	$\kappa_g \neq 0,\ \kappa_V \neq 0$
2_h^+	$\kappa_{g_1} \neq 0,\ \kappa_{V_1} \neq 0$
2_h^-	$\kappa_{g_2} \neq 0,\ \kappa_{V_2} \neq 0$



MEM METHOD

The matrix element method builds upon the information that can be gathered from the amplitude squared to define a likelihood.

$$P(\boldsymbol{x}_i, \alpha) = \frac{1}{\sigma^{obs}} \frac{1}{N} \sum_{\text{jet perm.}} \int d\phi_{\boldsymbol{y}} |M|^2(\boldsymbol{y}) W(\boldsymbol{x}_i, \boldsymbol{y}) Acc(x)$$



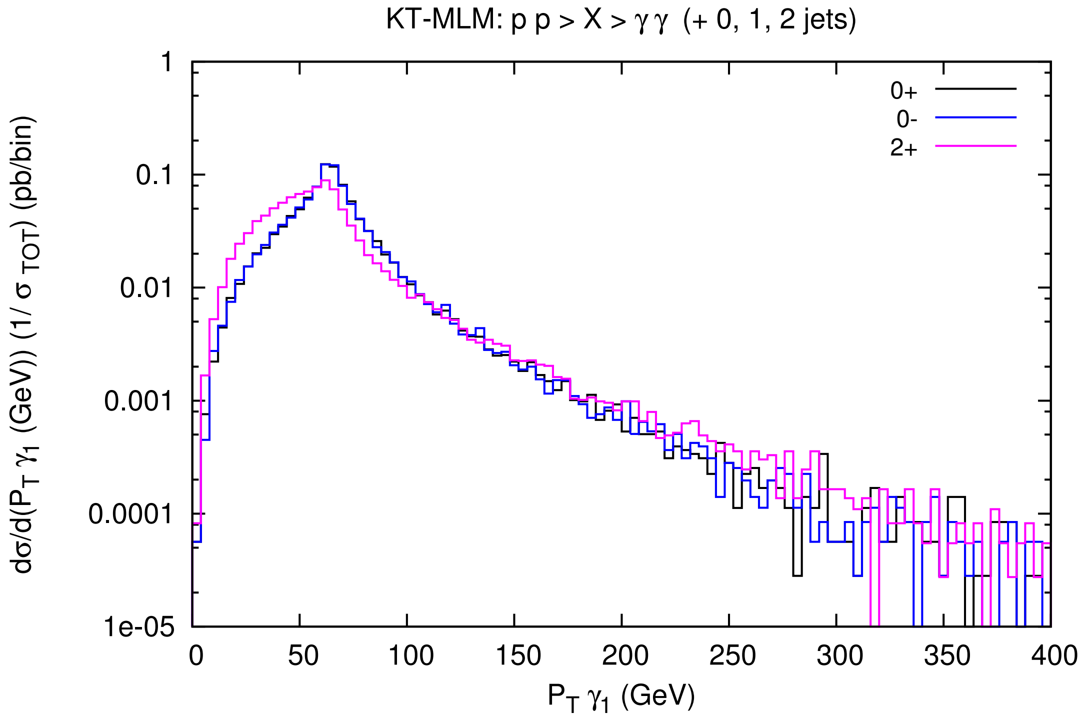
Spin-parity: results

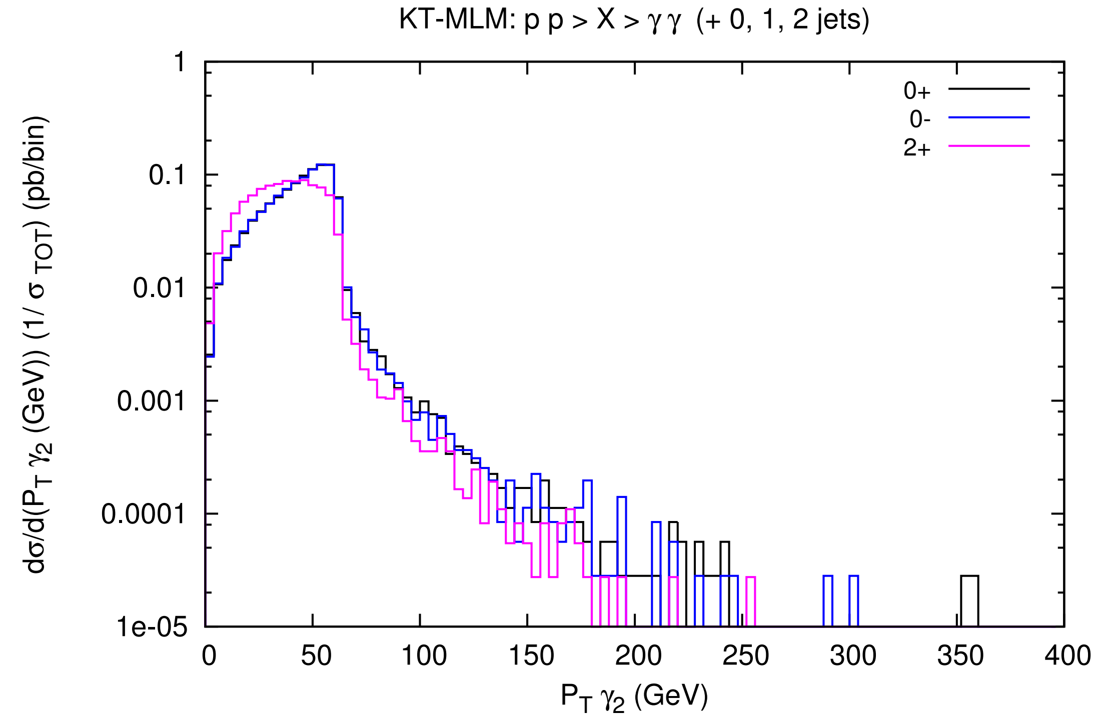
	Expected [σ]		Observed (μ from data)		
	μ=1	μ from data	P(q > Obs | alternative) [σ]	P(q > Obs | SM Higgs) [σ]	CLs [%]
$gg \to 0^-$	2.8	2.6	3.3	-0.5	0.16
$gg \to 0h^+$	1.8	1.7	1.7	+0.0	8.1
$qq \to 1^+$	2.6	2.3	> 4.0	-1.7	< 0.1
$qq \to 1^-$	3.1	2.8	> 4.0	-1.4	< 0.1
$gg \to 2m^+$	1.9	1.8	2.7	-0.8	1.5
$qq \to 2m^+$	1.9	1.7	4.0	-1.8	< 0.1

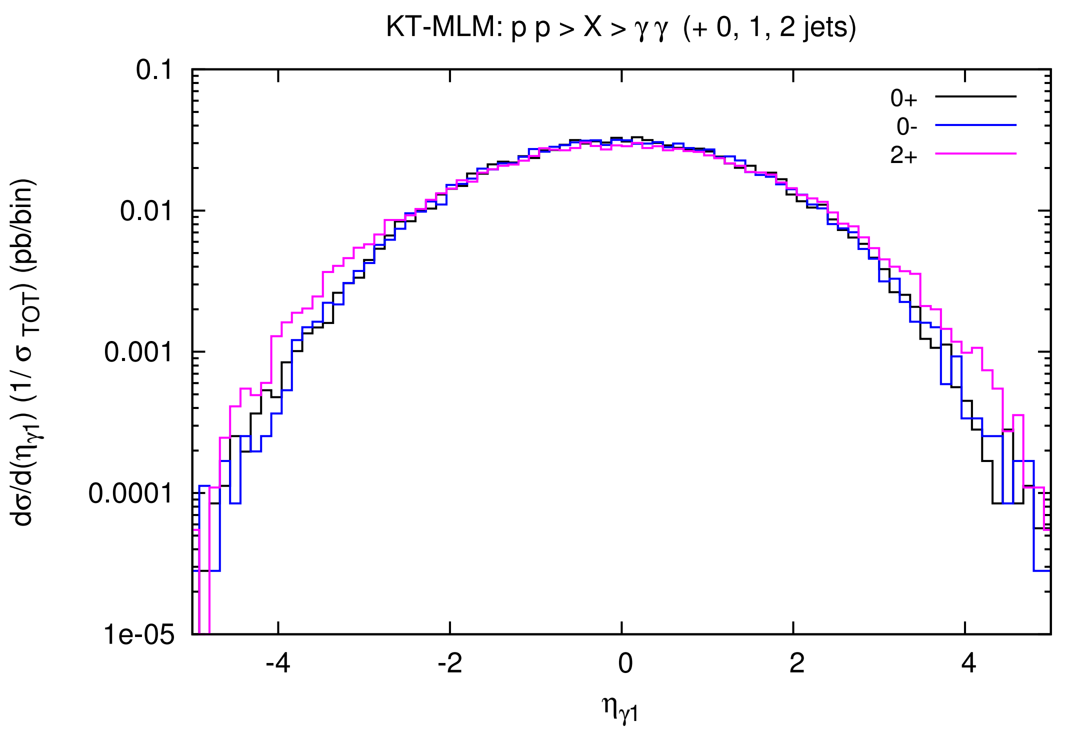
Assuming spin-0, fitting for CP-odd contribution gives
$f_{a3} = 0.00^{+0.23}_{-0.00}$ (more in backup)

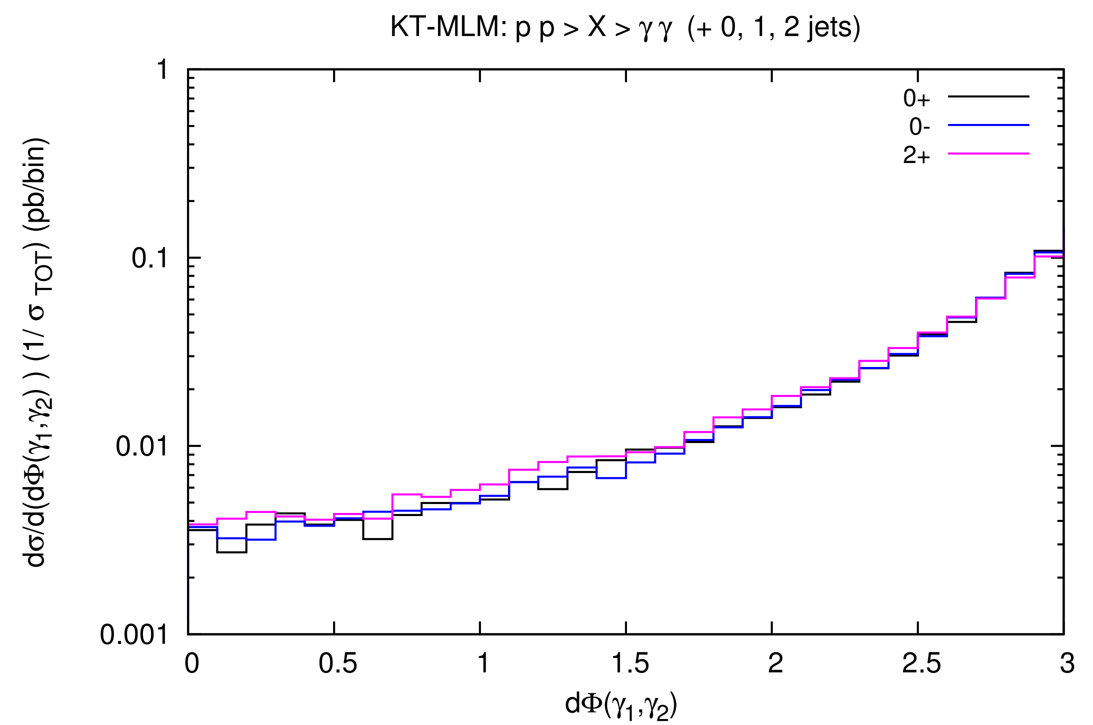
The studied pseudo-scalar, spin-1 and spin-2 models are excluded at 95% CL or higher

b. X→γγ


KT-MLM: p p > X > γ γ (+ 0, 1, 2 jets)
0+
0-
2+
dσ/d(P_T γ_1 (GeV)) (1/ σ_TOT) (pb/bin)
P_T γ_1 (GeV)


KT-MLM: p p > X > γ γ (+ 0, 1, 2 jets)
0+
0-
2+
dσ/d(P_T γ_2 (GeV)) (1/ σ_TOT) (pb/bin)
P_T γ_2 (GeV)


KT-MLM: p p > X > γ γ (+ 0, 1, 2 jets)
0+
0-
2+
dσ/d(η_γ1) (1/ σ_TOT) (pb/bin)
η_γ1

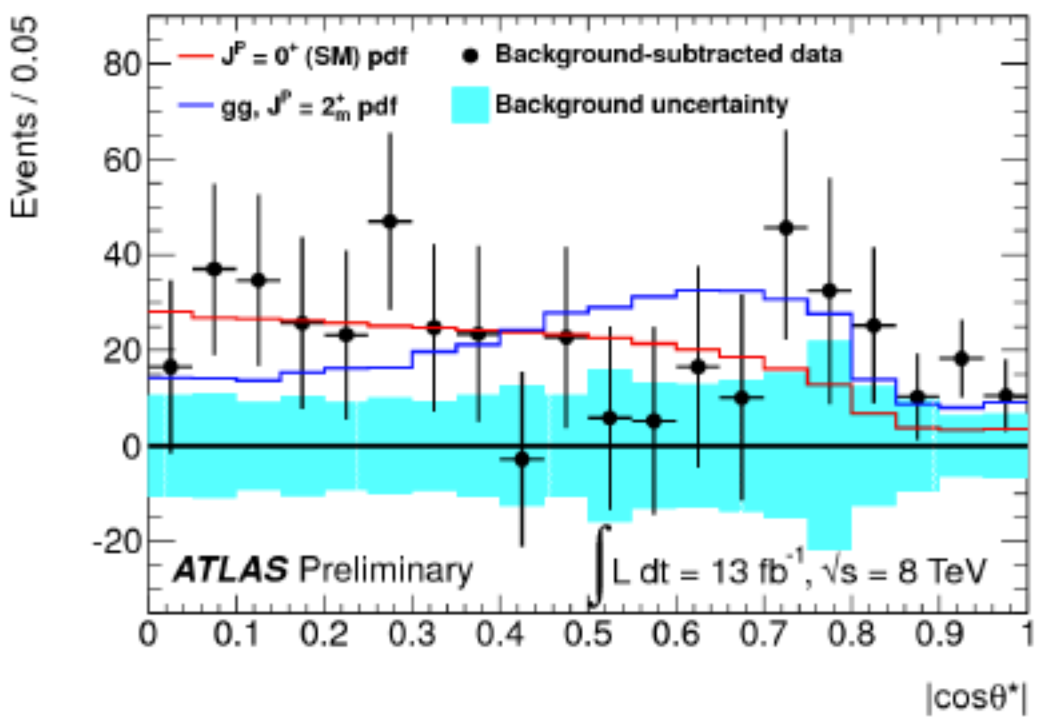

KT-MLM: p p > X > γ γ (+ 0, 1, 2 jets)
0+
0-
2+
dσ/d(dΦ(γ_1,γ_2)) (1/ σ_TOT) (pb/bin)
dΦ(γ_1,γ_2)

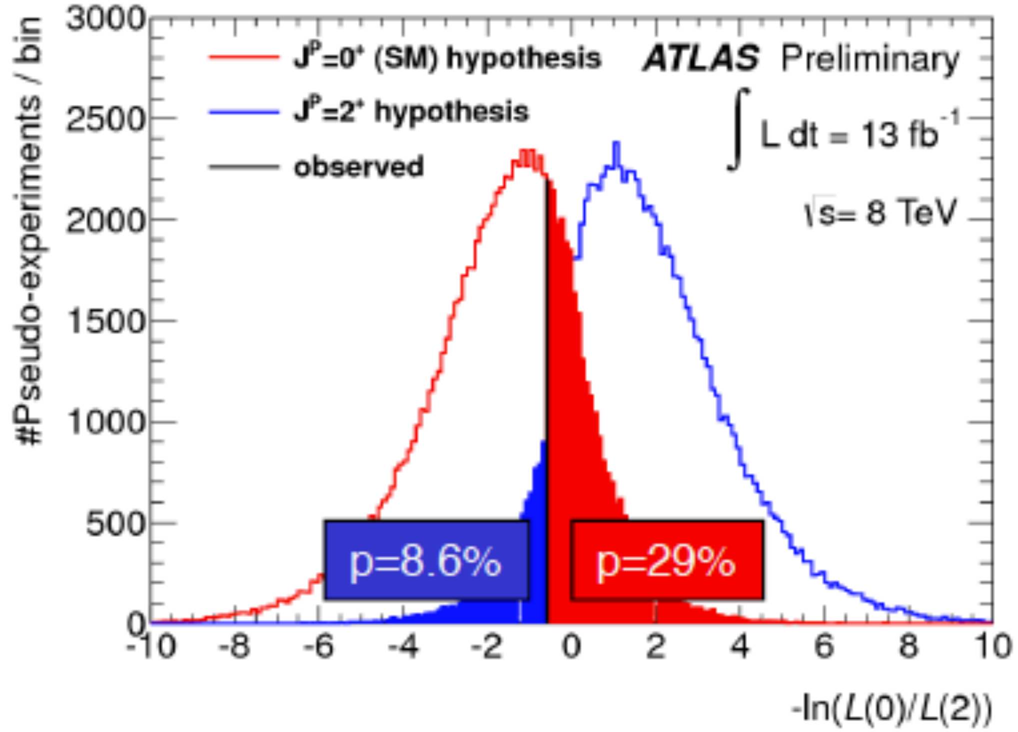
Spin studies with H→γγ

[analysis using 13 fb^{-1} of 8 TeV data]

ATLAS-CONF-2012-168

- From distribution of polar angle θ* of the photons in the resonance rest frame
  - Compare dN/d|cosθ*| for:
    - spin-0$^+$ hypothesis: flat before cuts
    - spin-2$^+$ hypothesis: ~ $1+6\cos^2\theta^* + \cos^4\theta^*$ for G-like gg production [minimal coupling model]
  - Signal region: events within ±1.5σ around the peak (m_H=126.5 GeV)
  - Normalisation and distribution of dN/d|cosθ*| for background from data (side-bands)



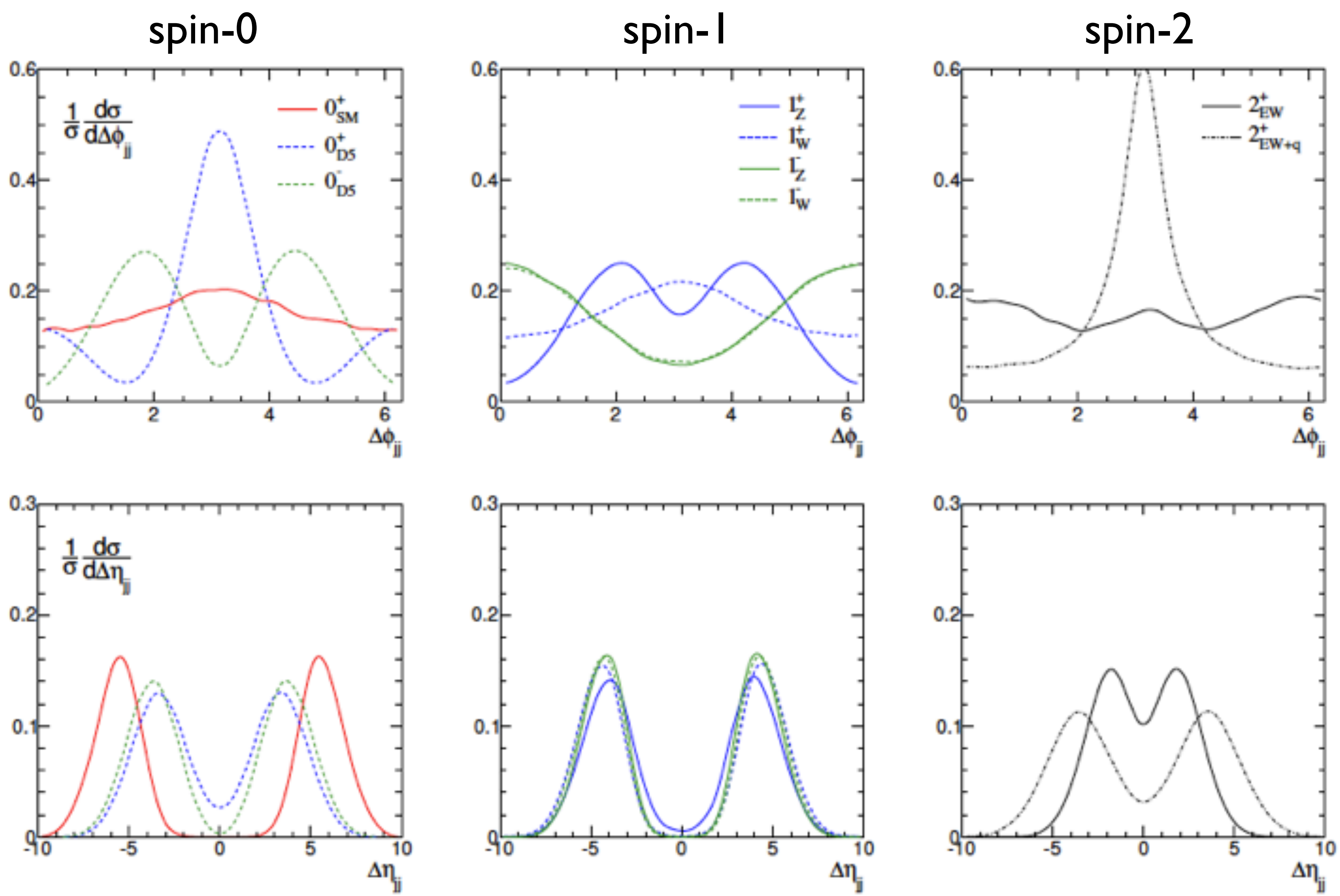


- ➢ Spin-2$^+$ hypothesis expected exclusion CL_s at 93% [for 100% gg spin-2 production]
- ➢ Observation compatible with spin-0$^+$, slightly favored over spin-2$^+$ hypothesis

c. pp→jjX (VBF)

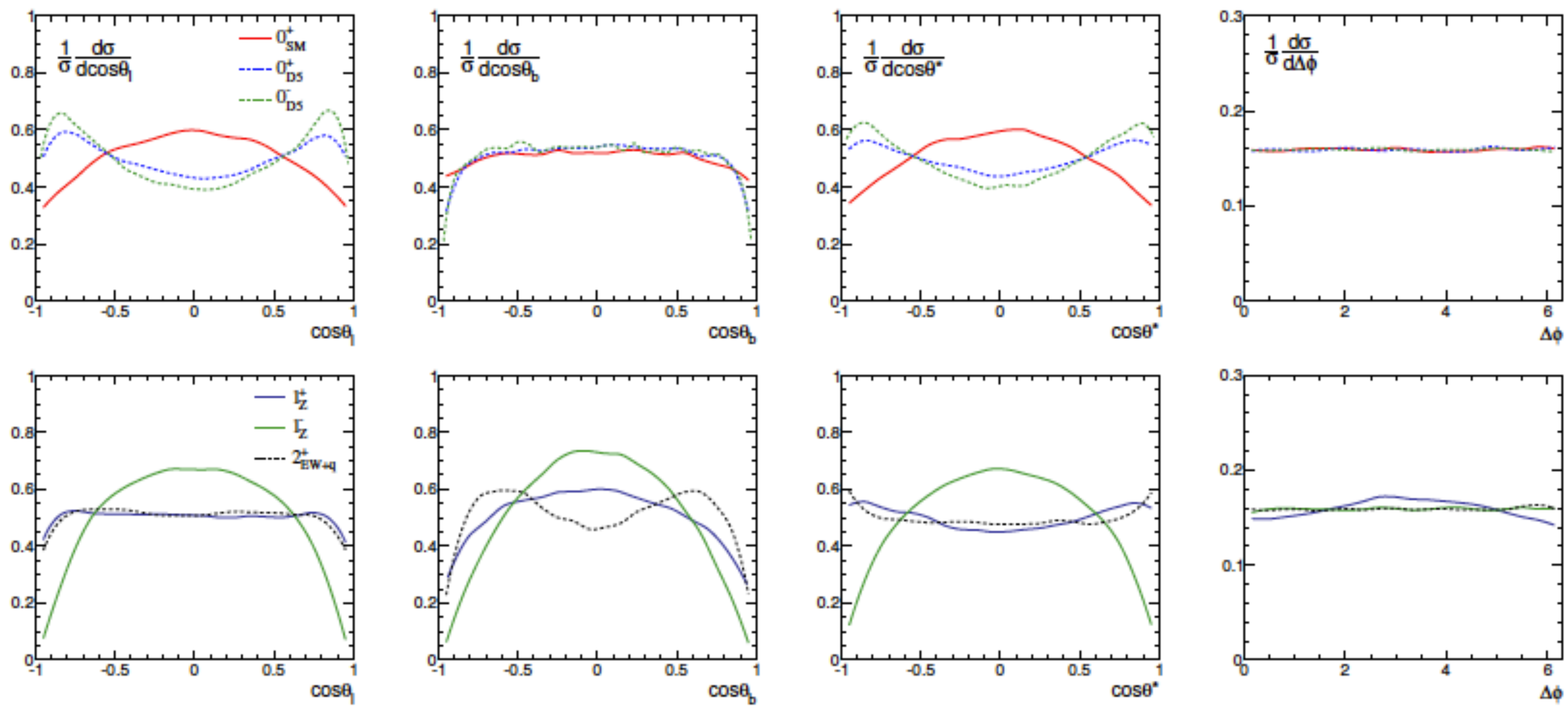
di-jet correlations

Englert, Goncalves-Netto, KM, Plehn (2013)

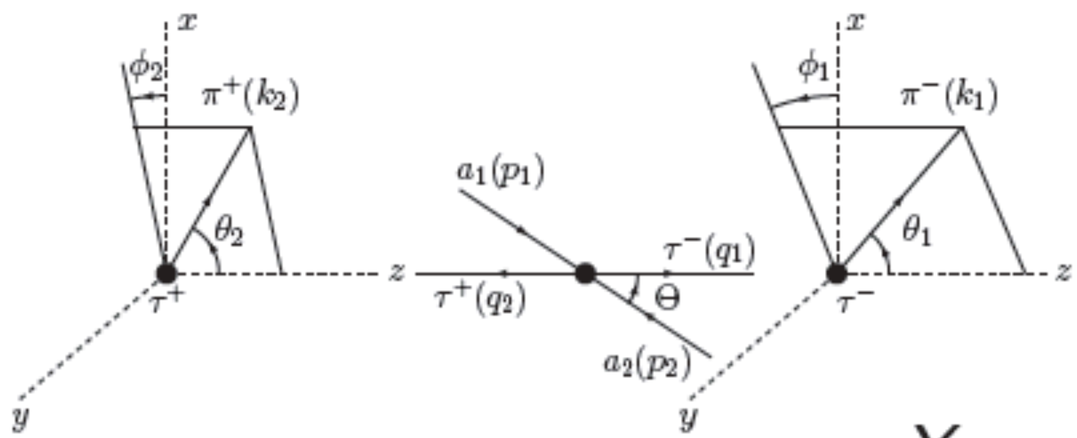


d. pp→ZX

Englert, Goncalves-Netto, KM, Plehn (2013)



e. X→ττ

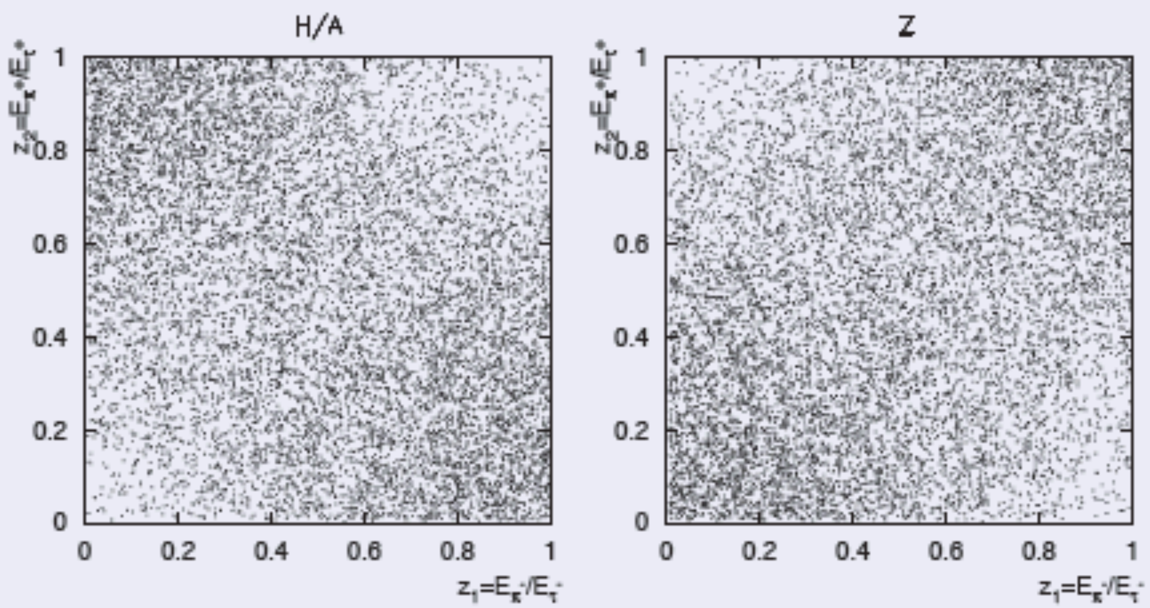


[Bullock, Hagiwara, Martin, NPB(1993)]
[Krämer, Kühn, Stong, Zerwas, ZPC(1994)]
[Pierzchala, Richter-Was, Was, Worek, APPB(2001,2002,...)]

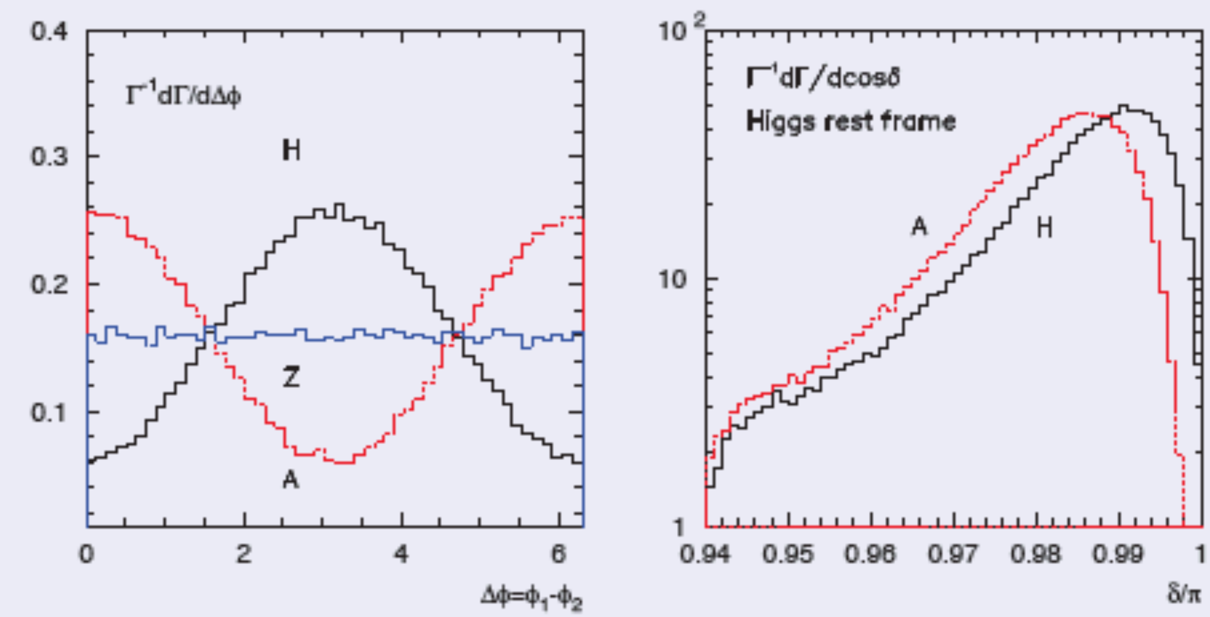
[Hagiwara, Li, KM, Nakamura, 1212.6247]

$$pp \to X \to \tau^+\tau^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$$

Longitudinal spin (helicity) effect



Transverse spin effect



$d^2\Gamma/dz_1dz_2 \sim 1 \mp z_1z_2$ for spin-0/1, $\quad d\Gamma/d\Delta\phi \sim 1 \mp A\cos\Delta\phi$ for $0^\pm$

τ could be a spin/parity analyzer!

TauDecay

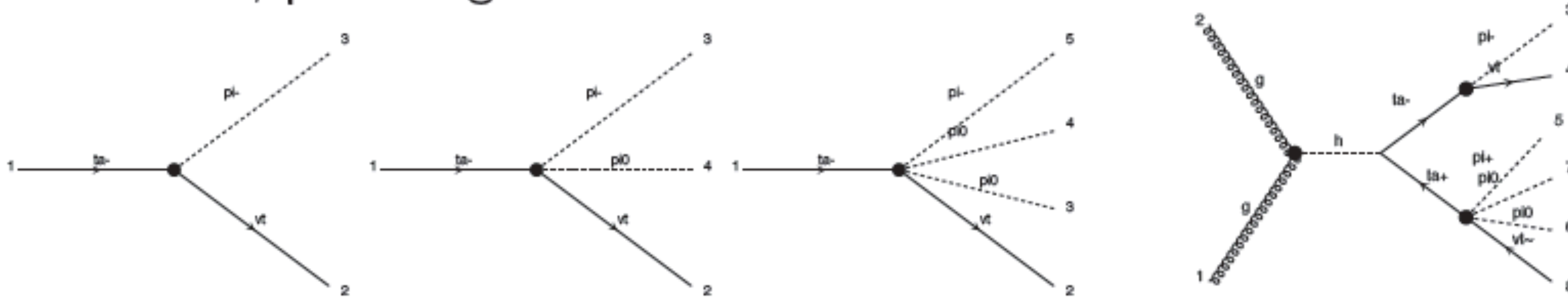
a library to simulate polarized tau decays via FeynRules/MadGraph5

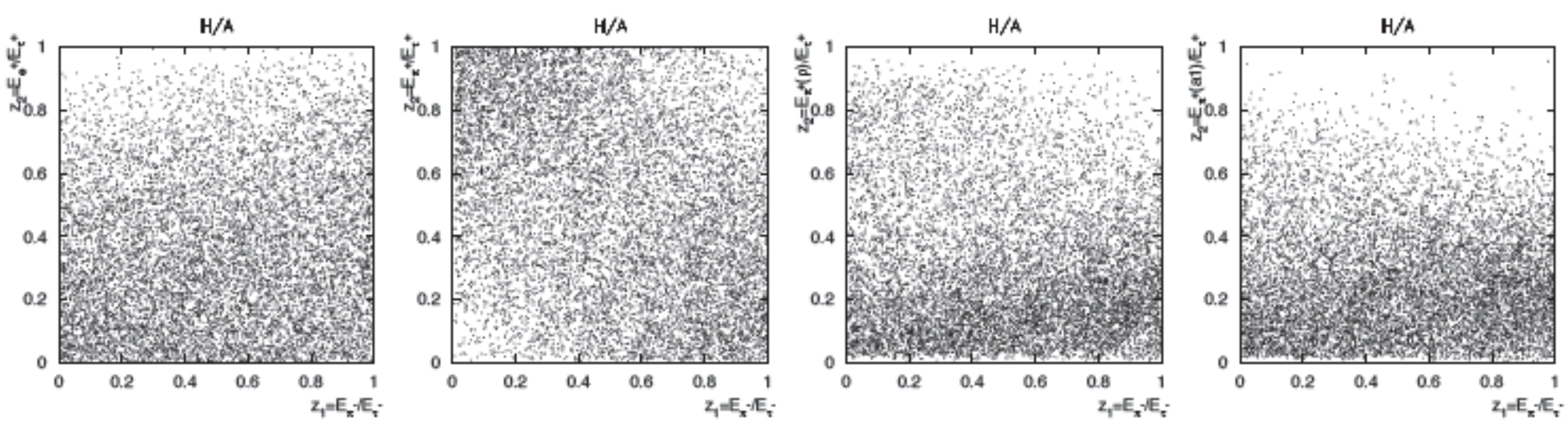
We implemented the effective Lagrangians [Hagiwara, Li, KM, Nakamura, 1212.6247]

$$\mathcal{L}_\pi = \sqrt{2} G_F f_\pi \cos\theta_C \, \bar{\tau}\gamma^\mu P_L \nu_\tau \, \partial_\mu \pi^- + h.c.$$

$$\mathcal{L}_\rho = 2 G_F \cos\theta_C F_\rho(Q^2) \, \bar{\tau}\gamma^\mu P_L \nu_\tau \, (\pi^0 \partial_\mu \pi^- - \pi^- \partial_\mu \pi^0) + h.c.$$

into FeynRules, providing the model file for MadGraph5.

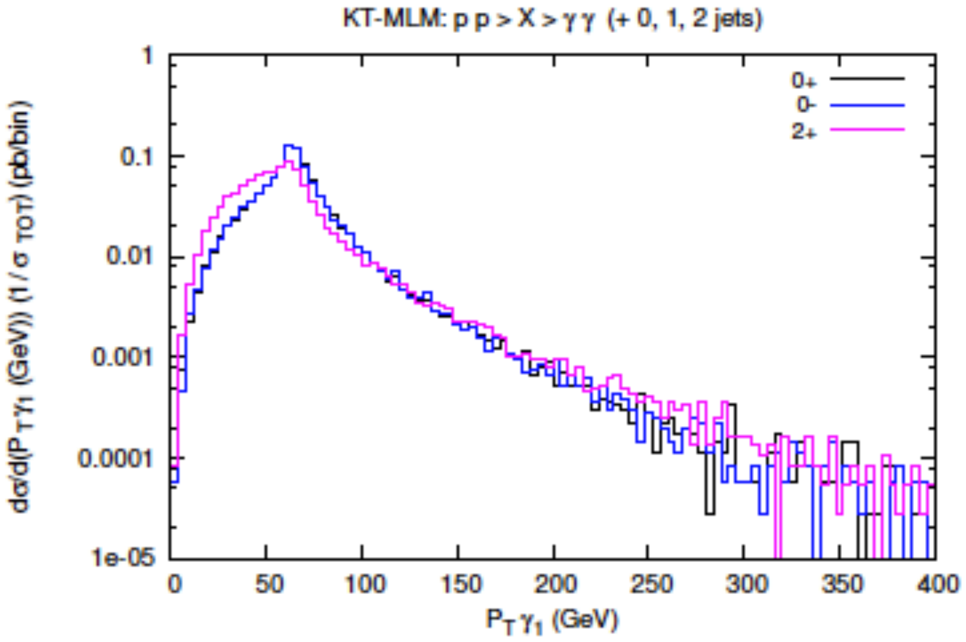


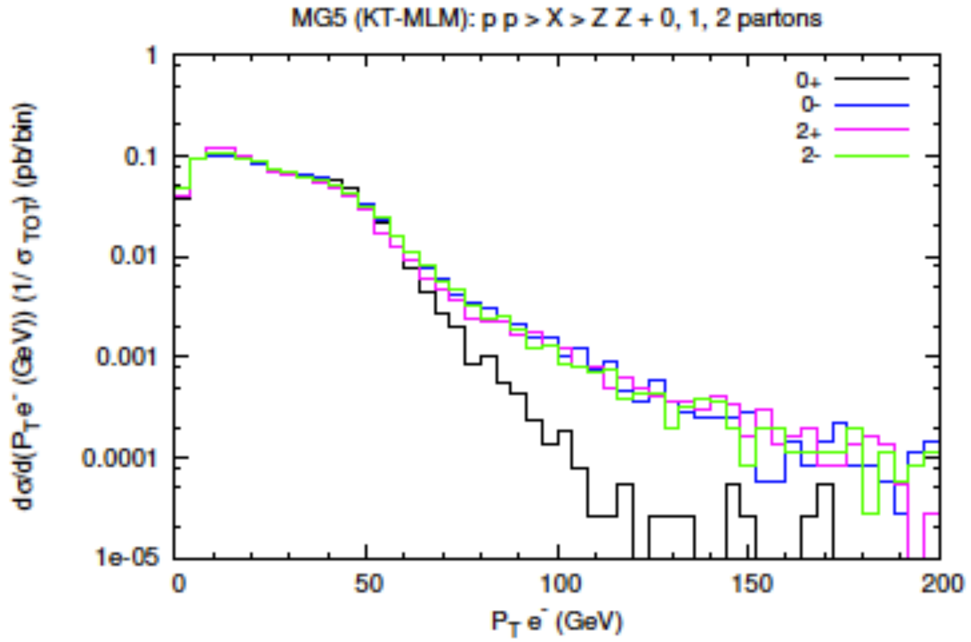


Full spin correlations for any kinds of new physics models can be generated for free.

3. Accuracy with ME-PS merging

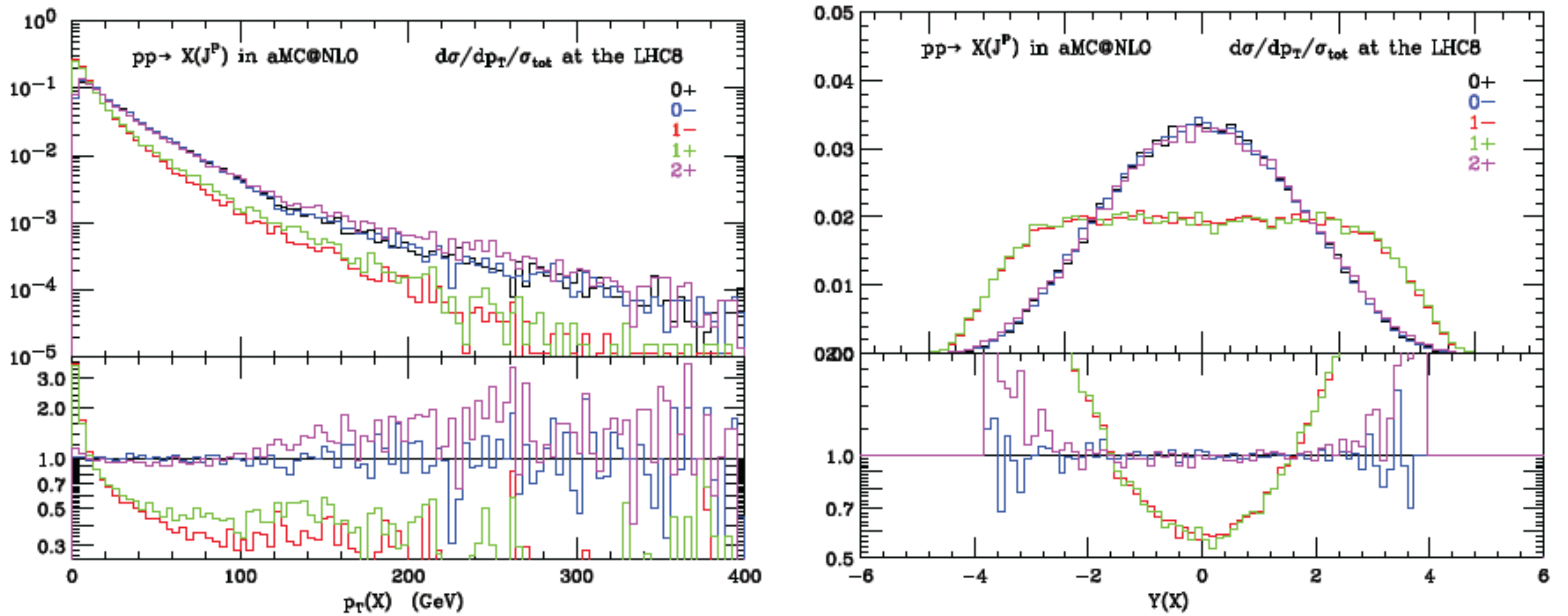
- Higher-order effects can be easily accounted for, by generating multi-jet merged samples with automatic framework.





3. Accuracy with aMC@NLO

- Higher-order effects can be easily accounted for, by computing NLO corrections with automatic framework.



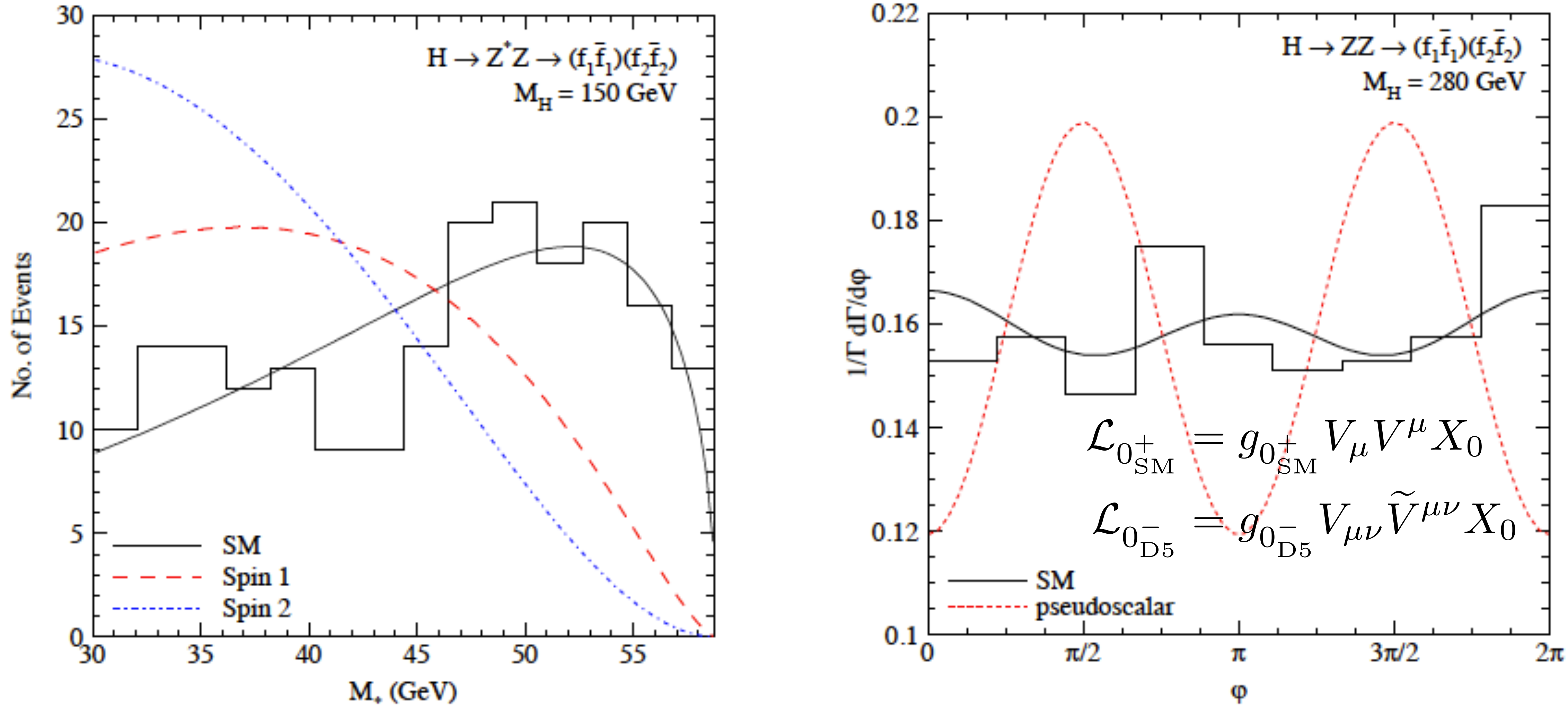
Outlook

- After the discovery of a BEH-like resonance at the LHC, the main focus of the analyses now is the determination of the Higgs Lagrangian.
- This includes
  - the structure of the operators, linked to the spin/parity of the 'Higgs' boson.
  - an independent measurement of the coupling strength.
- Our FR/MG5 Higgs Characterization model is ready for the spin/parity determination.

back-up

X→VV decay

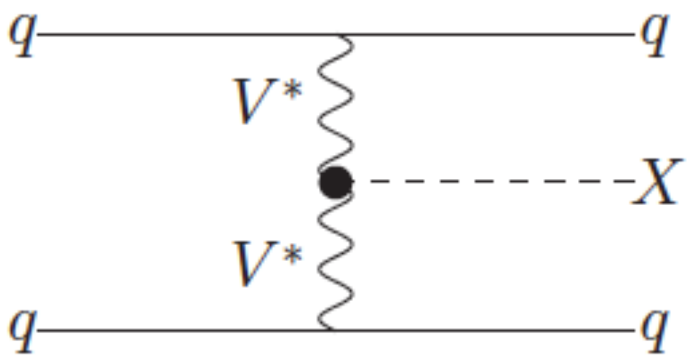
Choi, Miller, Muhlleitner, Zerwas (2003)



The off-shell Z mass and the azimuthal correlations between the Z decay planes reflect the XVV tensor structures.

Xjj production -- vector boson fusion

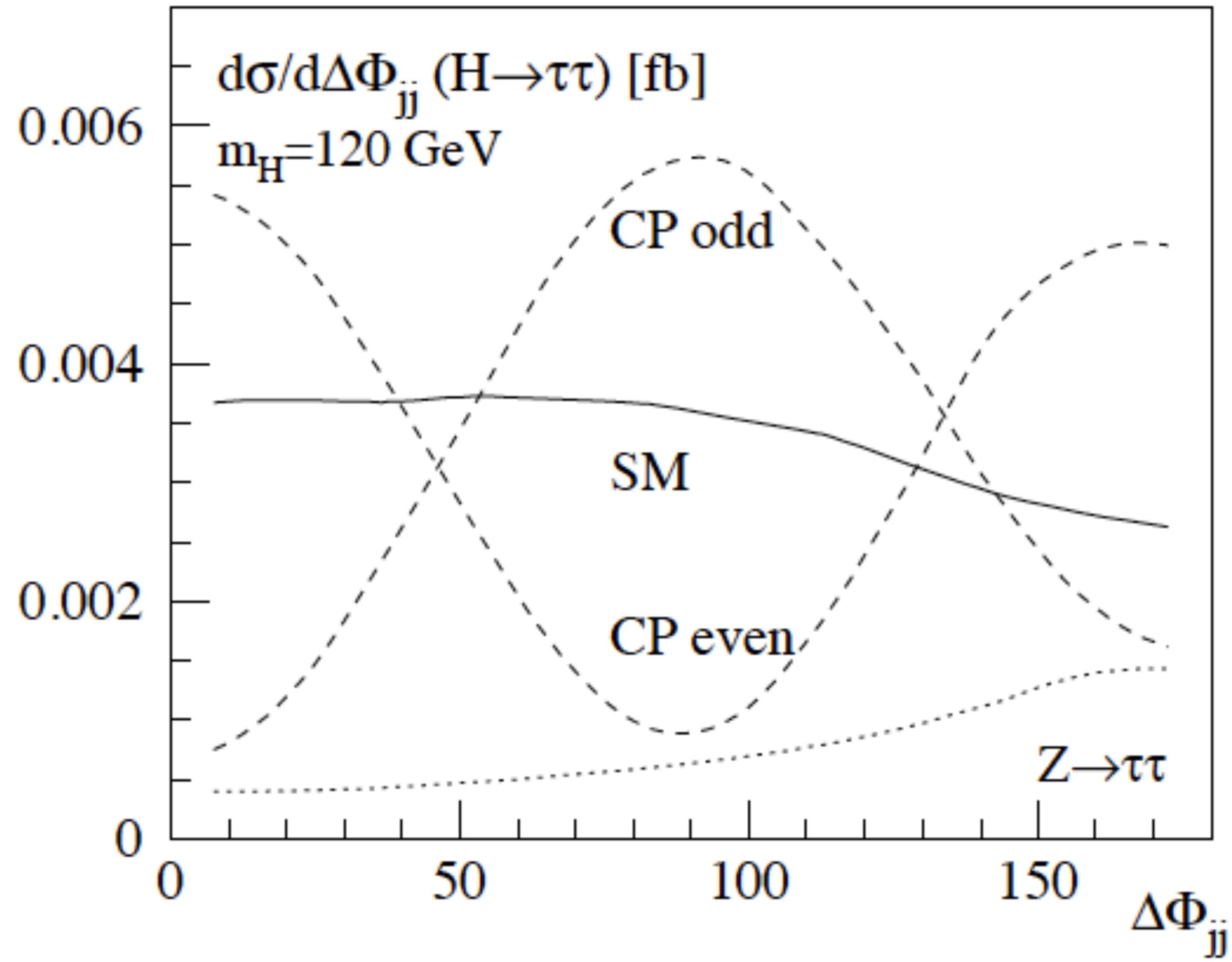
Plehn, Rainwater, Zeppenfeld (2002)



$$\mathcal{L}_{0^+_{\rm SM}} = g_{0^+_{\rm SM}} V_\mu V^\mu X_0$$

$$\mathcal{L}_{0^+_{\rm D5}} = g_{0^+_{\rm D5}} V_{\mu\nu} V^{\mu\nu} X_0$$

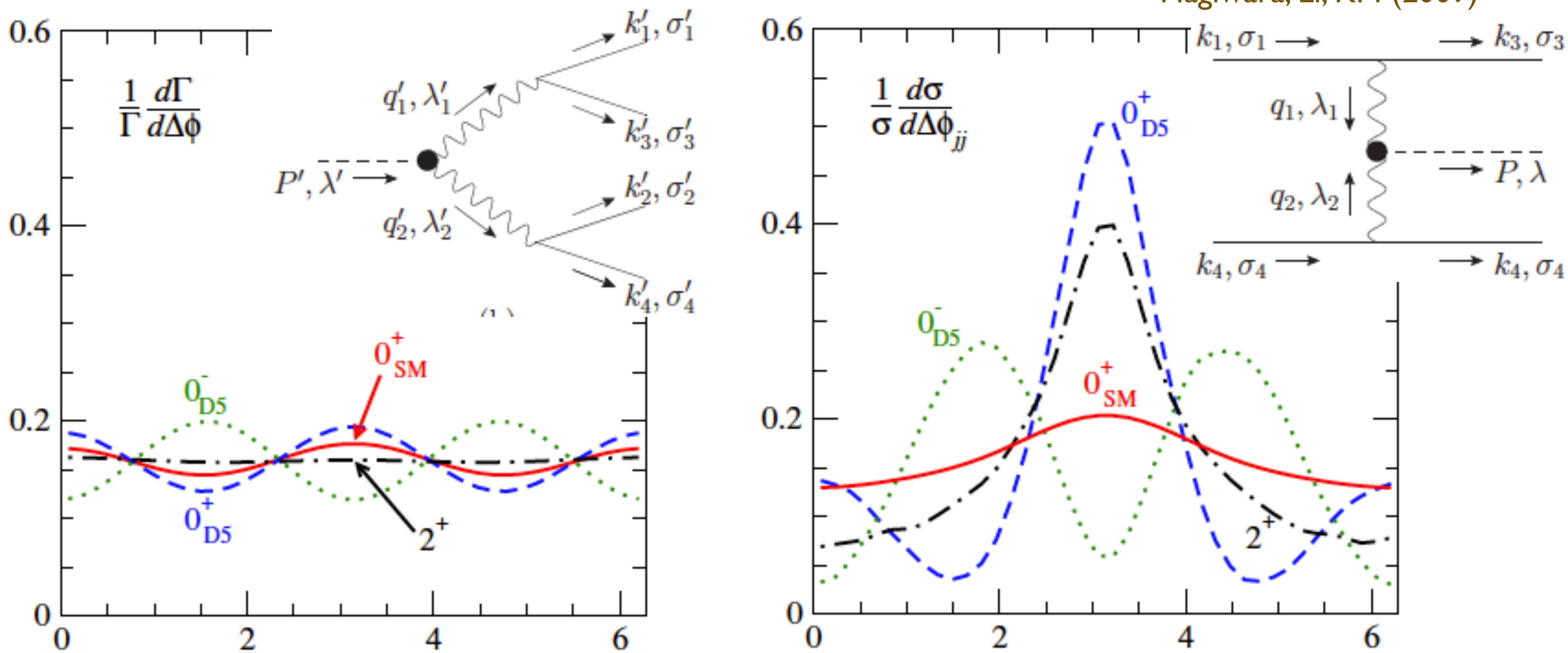
$$\mathcal{L}_{0^-_{\rm D5}} = g_{0^-_{\rm D5}} V_{\mu\nu} \widetilde{V}^{\mu\nu} X_0$$



The azimuthal correlations between the forward tagging jets reflect the XVV tensor structures.

X→VV decay vs. VBF production

Hagiwara, Li, KM (2009)



$d\sigma/d\Delta\phi \sim \text{const. for } 0^+_{\rm SM}, \quad d\sigma/d\Delta\phi \sim 1 \pm A\cos 2\Delta\phi \text{ for } 0^\pm_{\rm D5}$

Nontrivial azimuthal correlations can be explained as the quantum interference among different helicity states of the intermediate vector-bosons.