Higgs characterisation

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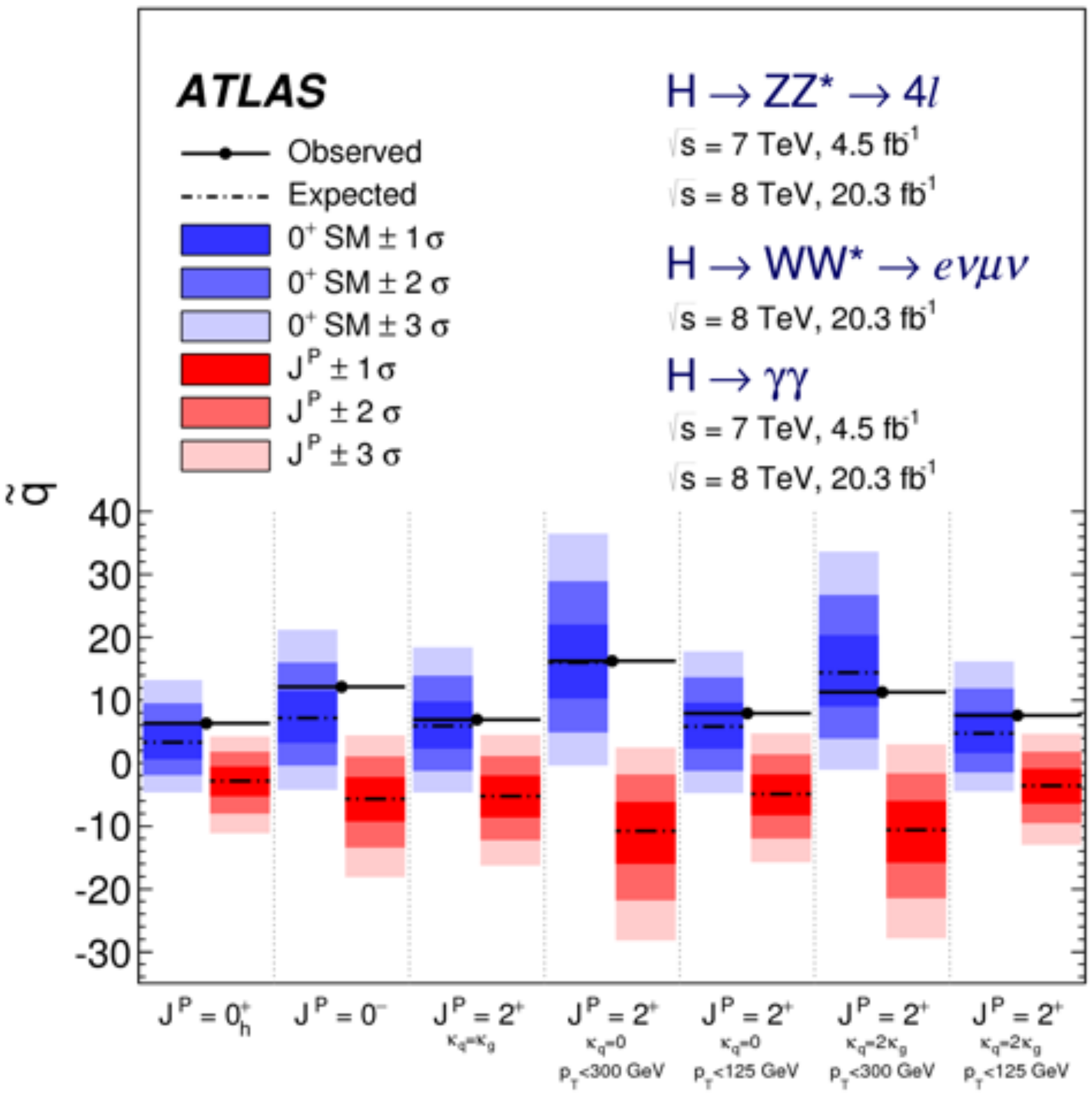
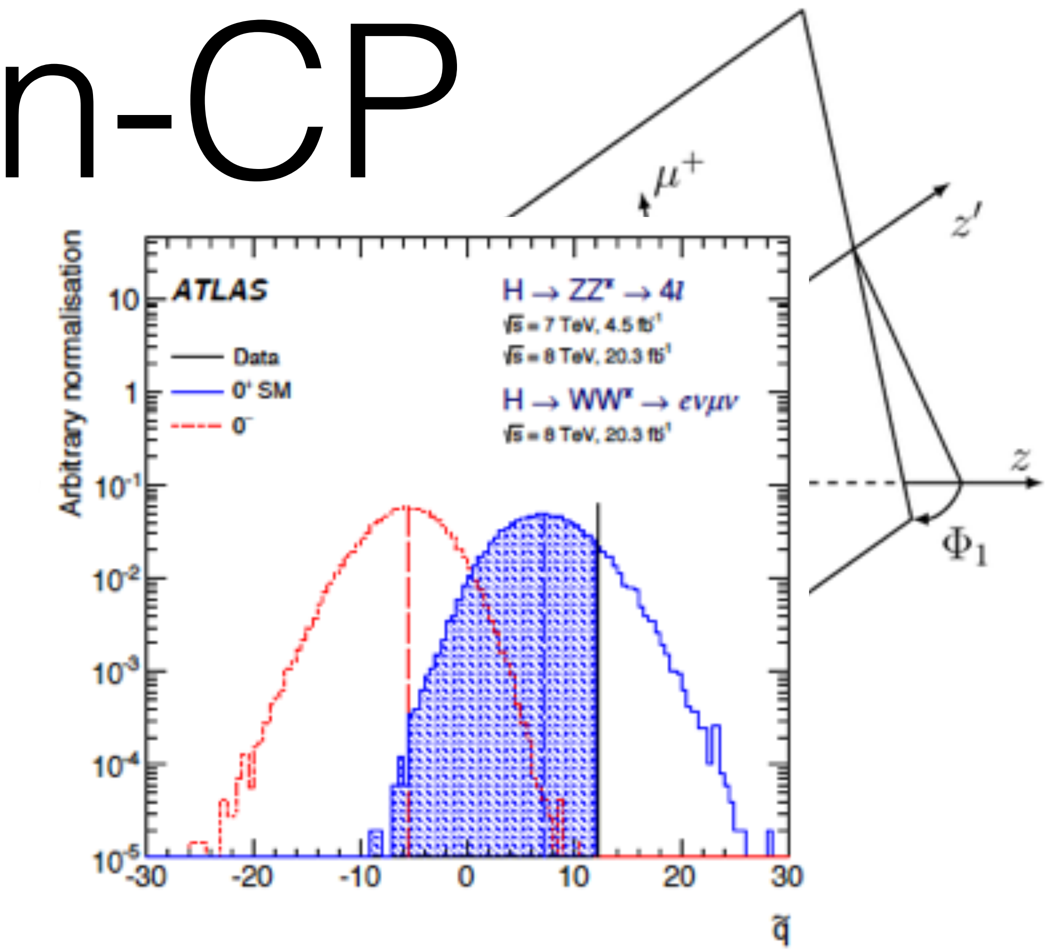
We would like to thank the organisers:
Sabine, Hans Peter, Tilman, and Veronica!

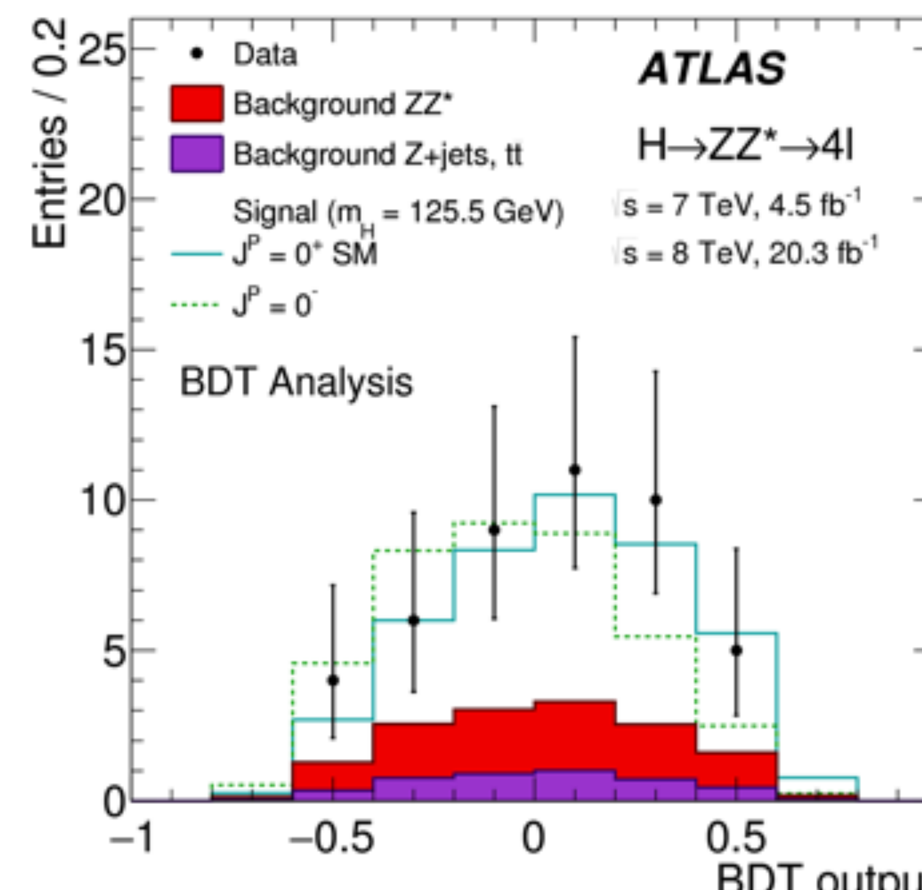
by Will Davey

h(125) spin-CP

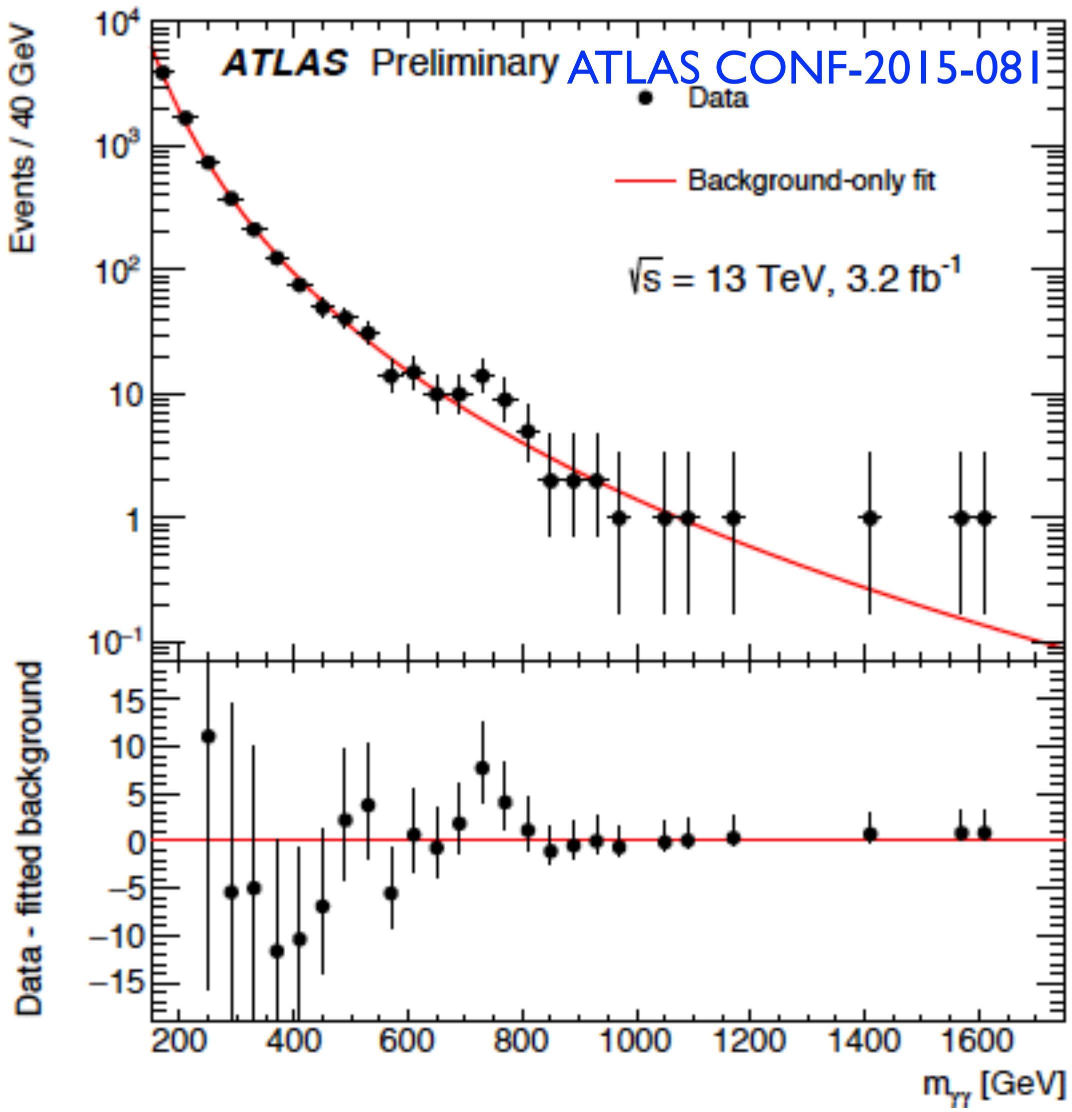
$J^P = 0^+$ strongly favoured

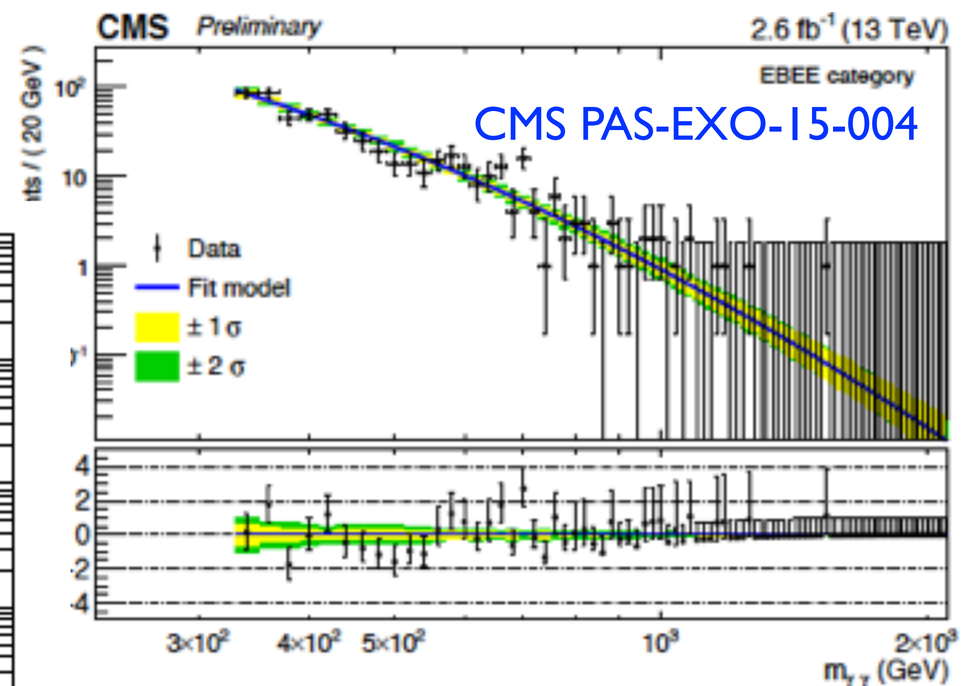


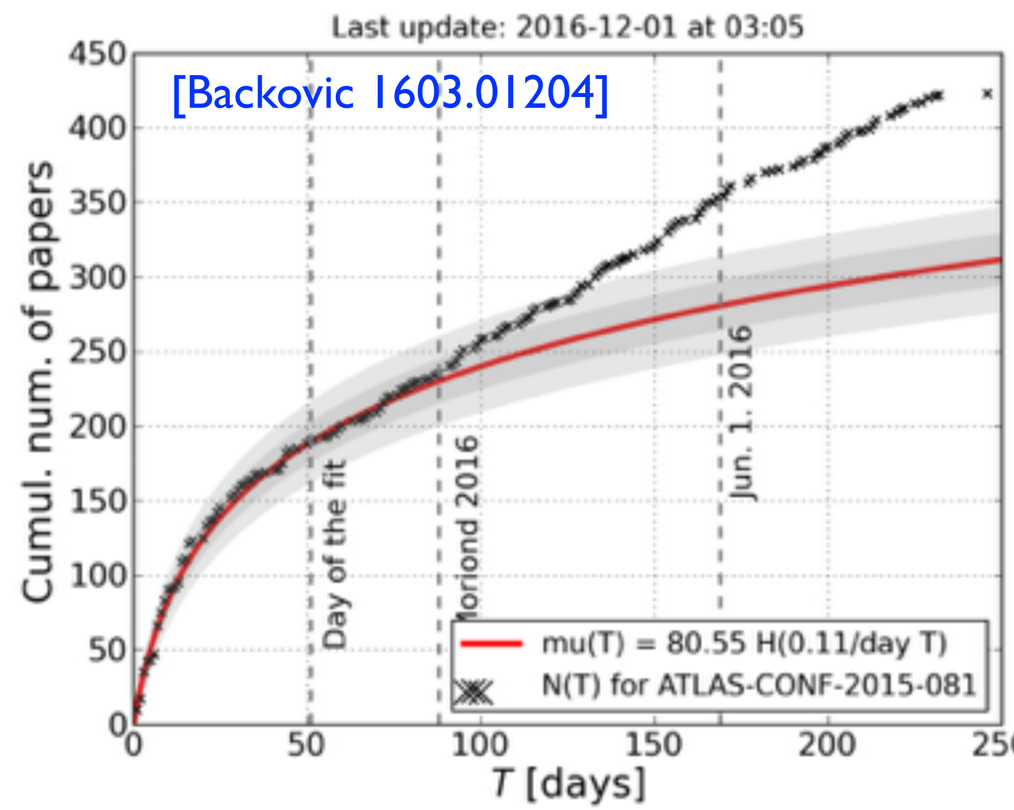




A year ago…


ATLAS Preliminary
ATLAS CONF-2015-081
Data
Background-only fit
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
Events / 40 GeV
Data - fitted background
$m_{\gamma\gamma}$ [GeV]

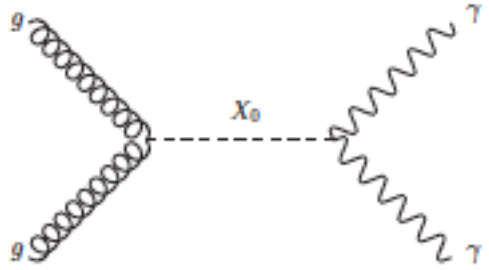

CMS Preliminary
2.6 fb^{-1} (13 TeV)
EBEE category
CMS PAS-EXO-15-004
Data
Fit model
± 1 σ
± 2 σ
$m_{\gamma\gamma}$ (GeV)


Last update: 2016-12-01 at 03:05
[Backovic 1603.01204]
Cumul. num. of papers
T [days]
Day of the fit
Moriond 2016
Jun. 1. 2016
mu(T) = 80.55 H(0.11/day T)
N(T) for ATLAS-CONF-2015-081

BSM resonance characterisation

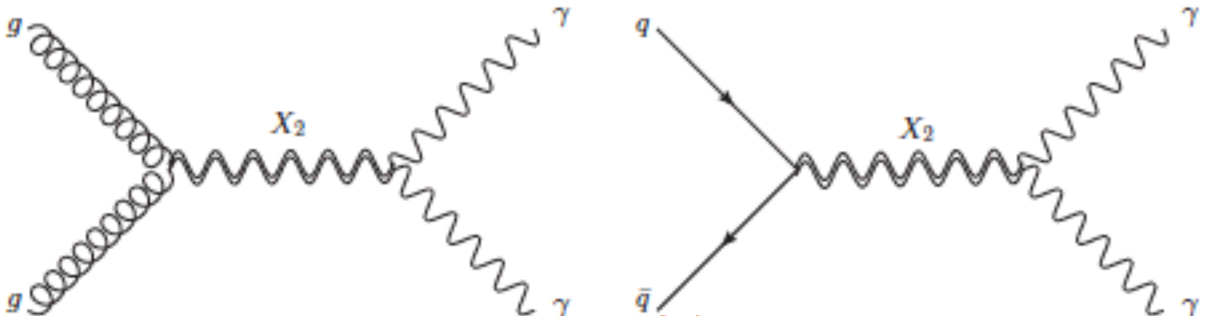
Martini, KM, Sengupta [1601.05729, PRD]
Bernon, Goudelis, Kraml, KM, Sengupta [1603.03421, JHEP]

$$\mathcal{L}_0^g = \frac{1}{4\Lambda}\left[\overset{(\sim)}{\kappa}_g\, G^a_{\mu\nu}\overset{(\sim)}{G}{}^{a,\mu\nu} + \overset{(\sim)}{\kappa}_\gamma\, A_{\mu\nu}\overset{(\sim)}{A}{}^{\mu\nu}\right] X_0\,,$$

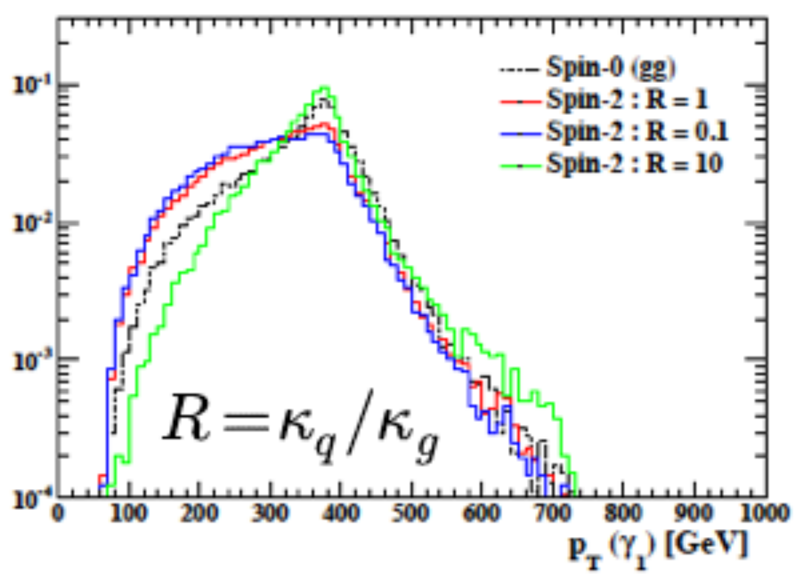


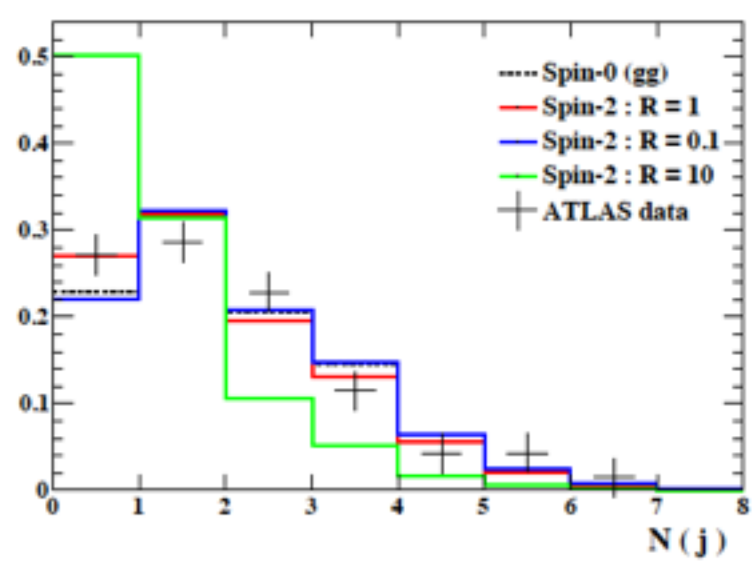
spin-0?

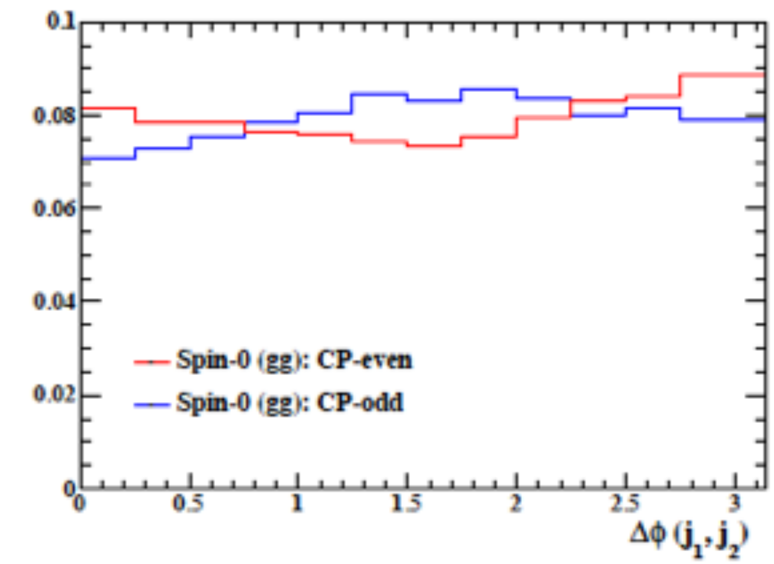
$$\mathcal{L}_2 = -\frac{1}{\Lambda}\left[\kappa_g\, T^g_{\mu\nu} + \kappa_q\, T^q_{\mu\nu} + \kappa_\gamma\, T^\gamma_{\mu\nu}\right] X_2^{\mu\nu}\,,$$



spin-2?







BSM workflow at the LHC

- take a BSM model (symmetry, particle contents,…), i.e. Lagrangian
  - derive the Feynman rules — FeynRules
    - draw Feynman diagrams for our interesting any processes
      - compute the amplitude (squared)
        - generate events

      Grace, MadGraph, Whizard, CompHEP, CalcHEP, FDC, Gosam
          - parton-shower/hadronisation — Herwig, Pythia, Sherpa
            - detector simulation — Fastjet, Delphes
              - analysis — GAMBIT, Checkmate, FastLim, MadAnalysis

micrOMEGAs
MadDM

H-boson observation, evidence, precision, ...

- 2012 July
  - Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC
  - Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC
- 2013 July
  - Evidence for the spin-0 nature of the Higgs boson
- 2013 October
  - Physics Nobel Prize [F. Englert (Brussels) and P. Higgs (Edinburgh)]
- 2015 Spring
  - LHC Run-II

looking for deviations from the SM ⇔ Higgs precision

Higgs quantum numbers in weak boson fusion

Christoph Englert,[a] **Dorival Gonçalves-Netto,**[b] **Kentarou Mawatari**[c] **and Tilman Plehn**[b]

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[b] *Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, 69120 Heidelberg, Germany*

[c] *Theoretische Natuurkunde and IIHE/ELEM, Vrije Universiteit Brussel, and International Solvay Institutes, Pleinlaan 2, B-1050 Brussels, Belgium*

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Abstract: Recently, the ATLAS and CMS experiments have reported the discovery of a Higgs like resonance at the LHC. The next analysis step will include the determination of its spin and CP quantum numbers or the form of its interaction Lagrangian channel-by-channel. We show how weak-boson-fusion Higgs production and associated ZH production can be used to separate different spin and CP states.

JHEP01(2013)148

Higgs Characterisation (HC)

via the FeynRules and MadGraph5_aMC@NLO frameworks

- HC provides an automated NLO(QCD)+PS accurate tool and predictions to accomplish the most general and accurate characterisation of Higgs interactions in the main production and decay modes at the LHC.
- The code is publicly available at the FeynRules repository: https://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation

- HC1: "A framework for Higgs characterisation" JHEP11(2013)043 [1306.6464]
  Artoisenet, de Aquino, Demartin, Frederix, Frixione, Maltoni, Mandal, Mathews, Mawatari, Ravindran, Seth, Torrielli, Zaro
  ➡ HC framework based on the effective filed theory (EFT) approach
- HC2: "Higgs characterisation via VBF/VH: NLO and parton-shower effects" EPJC74(2014)2710 [1311.1829]
  Maltoni, Mawatari, Zaro
  ➡ VBF and VH @ automated NLO+PS
- HC3: "Higgs characterisation at NLO in QCD: CP properties of the top Yukawa" EPJC74(2014)3065 [1407.5089]
  Demartin, Maltoni, Mawatari, Page, Zaro
  ➡ GF (H+jets) and ttH @ automated NLO+PS
- HC4: "Higgs production in association with a single top quark at the LHC" EPJC75(2015)267 [1504.00611]
  Demartin, Maltoni, Mawatari, Zaro
  ➡ tH @ automated NLO+PS
- HC5: "tWH associated production at the LHC" EPJCxx(2016)xxx [1607.05862]
  Demartin, Maier, Maltoni, Mawatari, Zaro
  ➡ tWH @ automated NLO+PS

Tools for Higgs Physics

Cross Section

ggF
HIGLU (NNLO QCD+NLO EW)
iHixs (NNLO QCD+NLO EW)
FeHiPro (NNLO QCD+NLO EW)
HNNLO, HRes (NNLO+NNLL QCD)
SusHi (NNLO QCD)
RGHiggs (NNLO+NNNLL QCD)
ggHiggs (approx. NNNLO QCD)

VBF
VV2H (NLO QCD)
VBFNLO (NLO QCD)
HAWK (NLO QCD+EW)
VBF@NNLO (NNLO QCD)

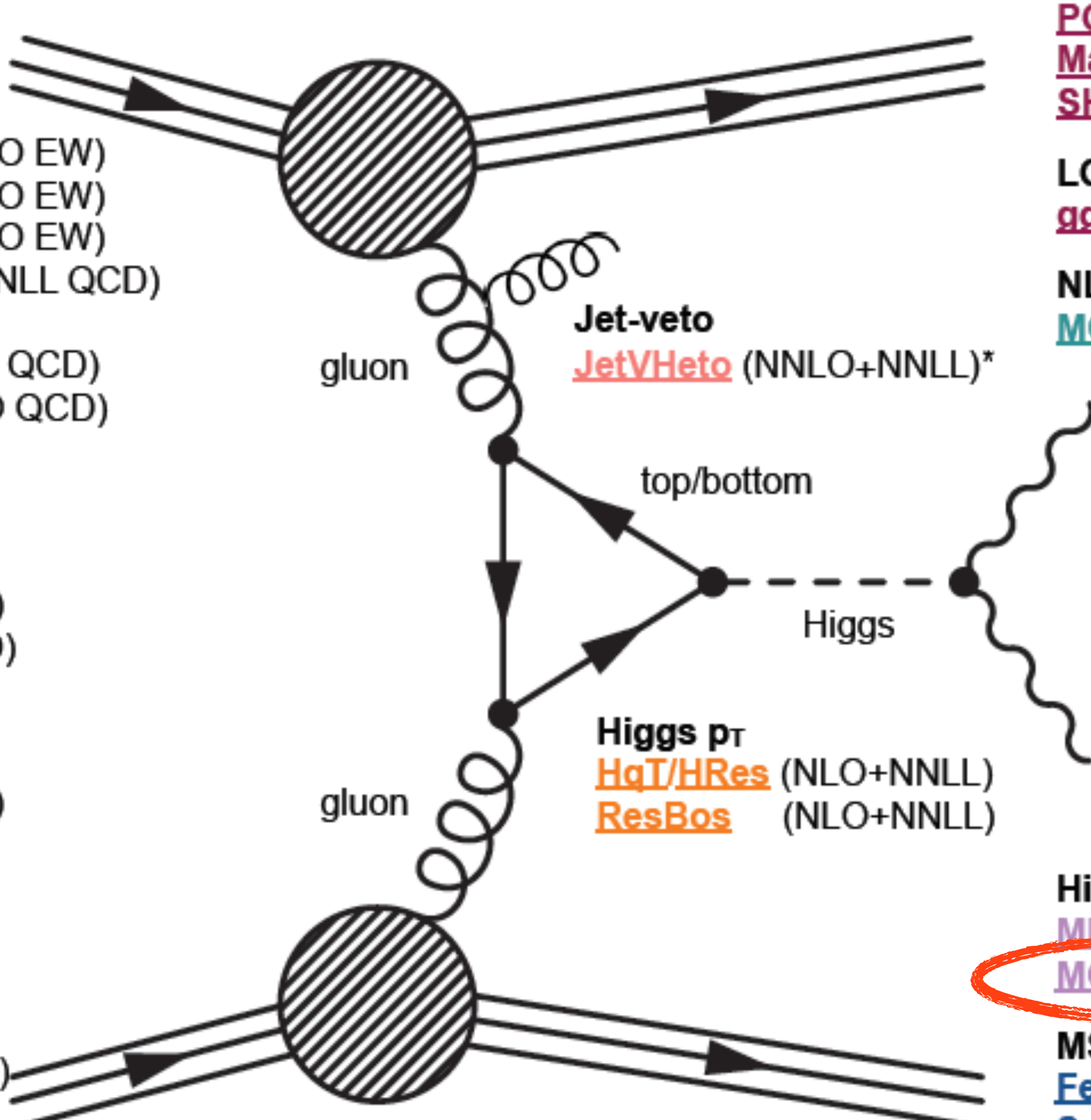
WH/ZH
V2HV (NLO QCD)
HAWK (NLO QCD+EW)
VH@NNLO (NNLO)

ttH
HQQ (LO QCD)

bbH
bbh@NNLO (NNLO QCD)

HH
HPAIR (NLO QCD)

+ private codes.



Jet-veto
JetVHeto (NNLO+NNLL)*

Higgs p_T
HqT/HRes (NLO+NNLL)
ResBos (NLO+NNLL)

PDF: MSTW, CTEQ, NNPDF, etc.
LHAPDF, HOPPET, APFEL

NLO MC
POWHEG MiNLO
MadGrapn5_aMC@NLO
SHERPA MEPS@NLO

LO MC
gg2VV

NLO ME
MCFM, MG5_aMC@NLO

Higgs Decay
HDECAY (NLO++)
Prophecy4f (NLO)

Higgs Properties
MELA/JHU, MEKD
MG5_aMC@NLO (HC)

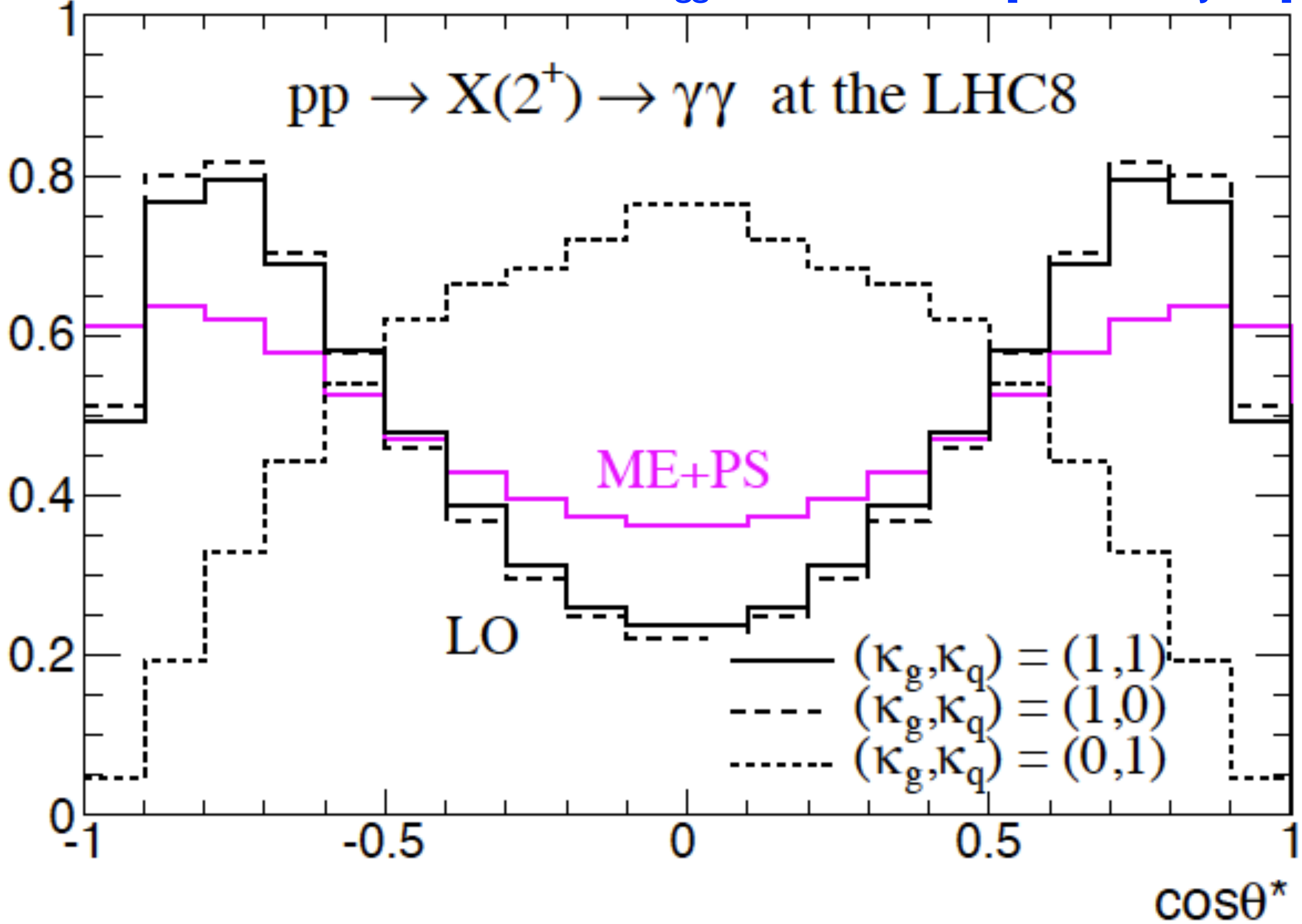
MSSM/2HDM
FeynHiggs, CPSuperH
SusHi+2HDMC
HIGLU+HDECAY

* NLO+NNLL in differential

Compiled by R. Tanaka, Jan. 2014

pp>X>γγ

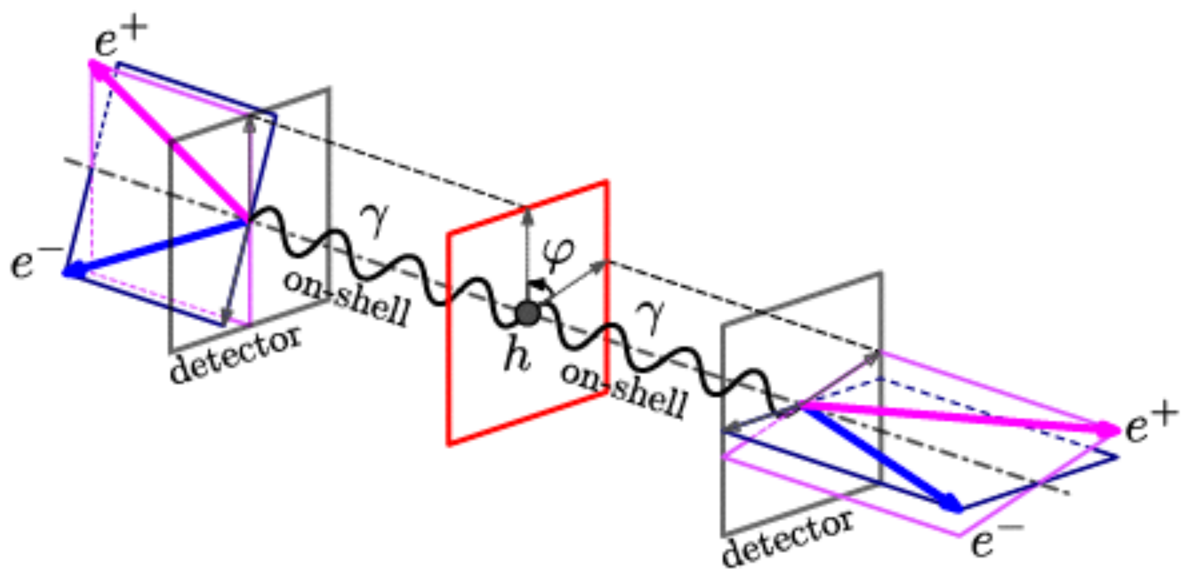
Higgs characterisation [1306.6464, JHEP]



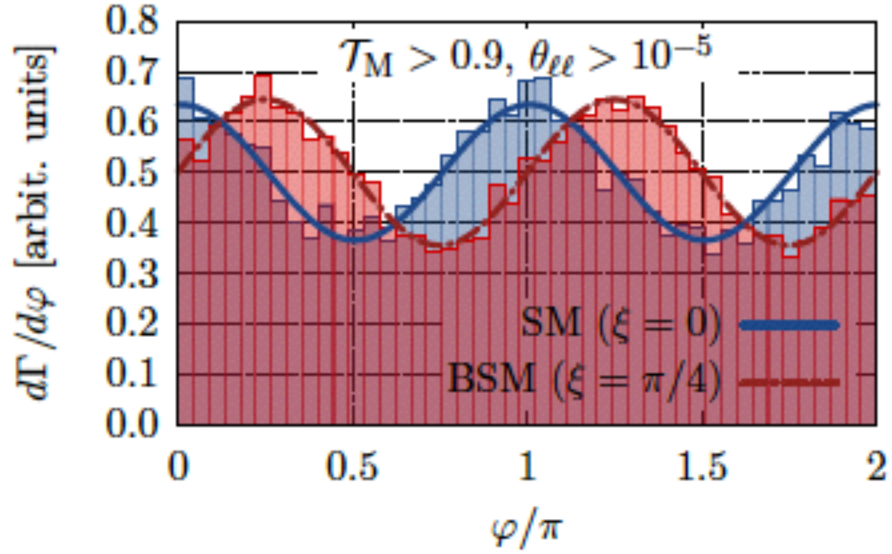
$$\frac{d\sigma(gg)}{d\cos\theta^*} \propto |d^2_{22}(\theta^*)|^2 + |d^2_{2-2}(\theta^*)|^2 = \frac{1}{8}(1 + 6\cos^2\theta^* + \cos^4\theta^*)\,,$$

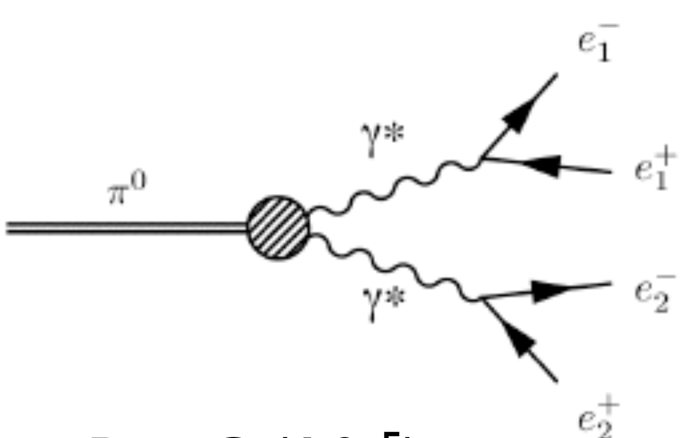
$$\frac{d\sigma(q\bar{q})}{d\cos\theta^*} \propto |d^2_{12}(\theta^*)|^2 + |d^2_{1-2}(\theta^*)|^2 = \frac{1}{2}(1 - \cos^4\theta^*)\,.$$

pp>X>γγ>4e



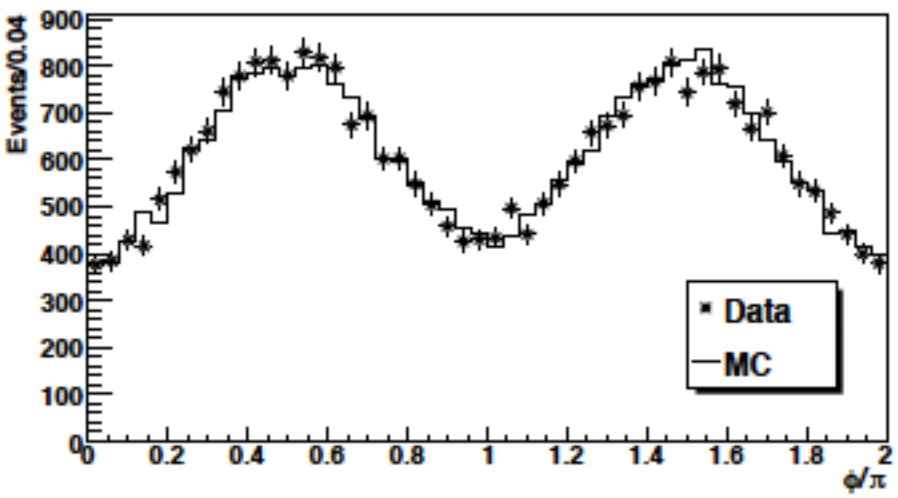
Bishara et al. [1312.2955, JHEP]





B∼O(10^{-5})

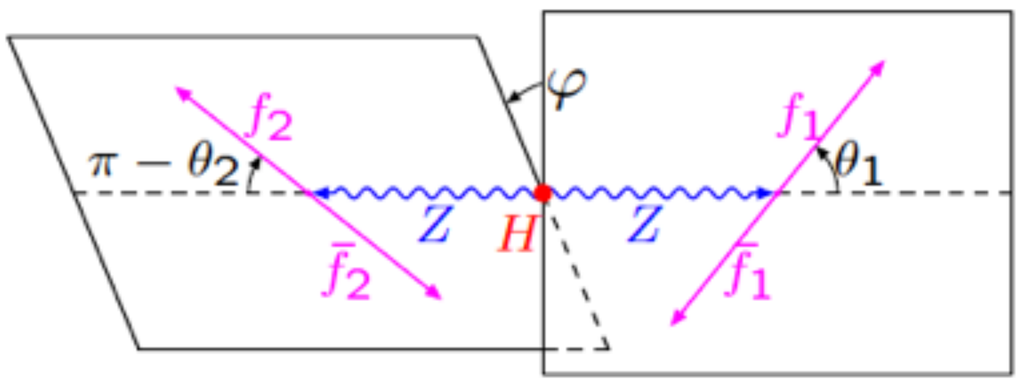
KTeV collaboration [0802.2064, PRL]

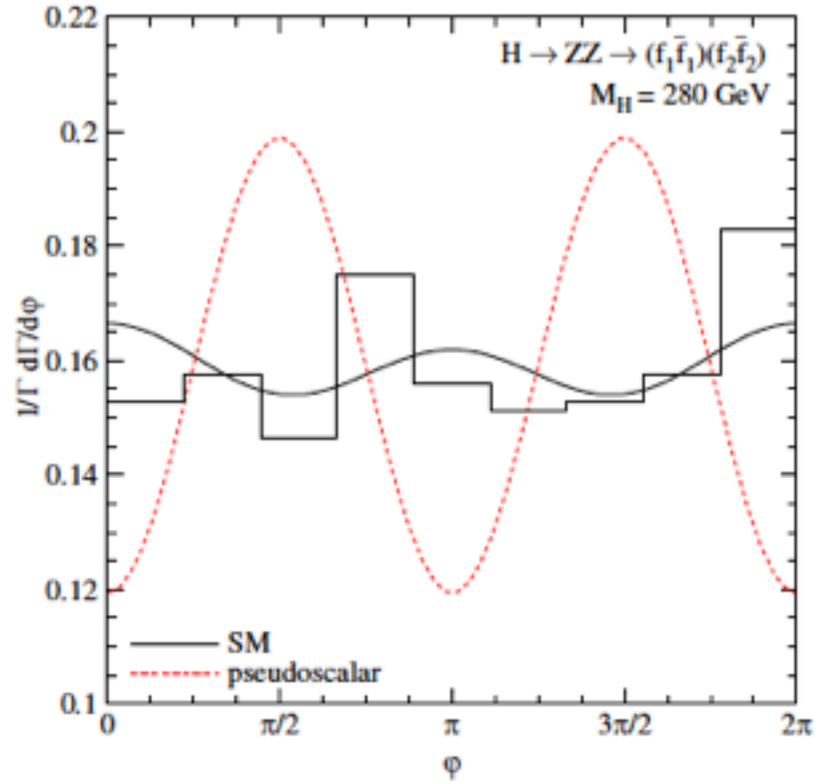


$$d\sigma/d\Delta\phi \sim 1 \pm A\cos 2\Delta\phi$$

X>ZZ>4leptons

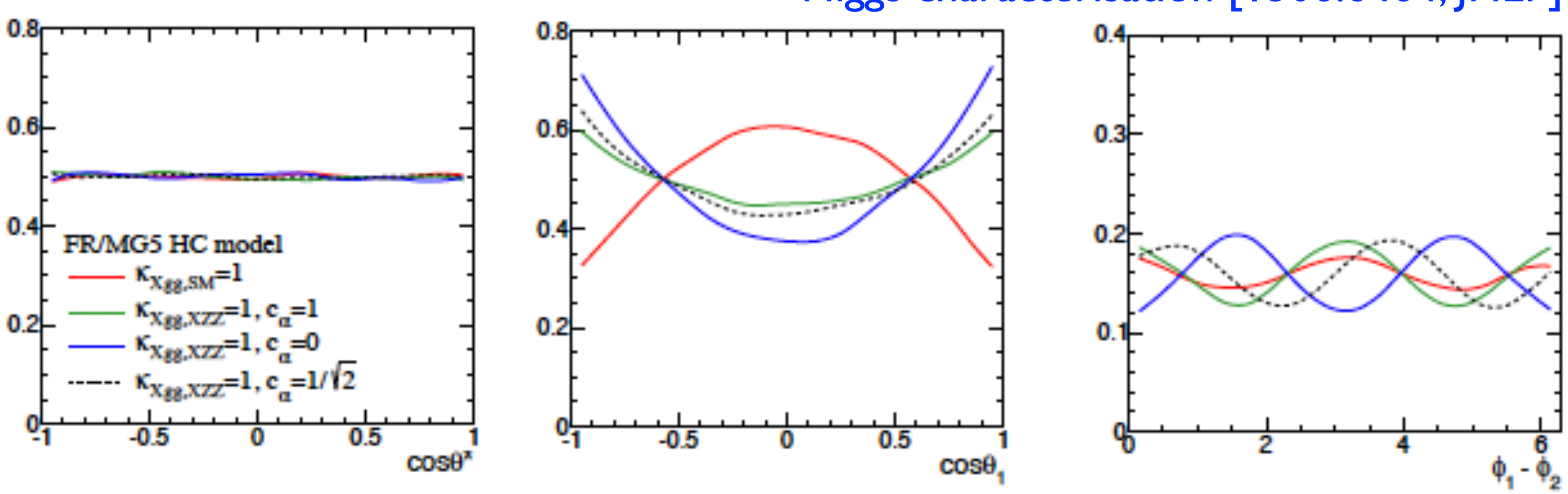
Choi, Miller, Muhlleitner, Zerwas [hep-ph/0210077, PLB]





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

Higgs characterisation [1306.6464, JHEP]

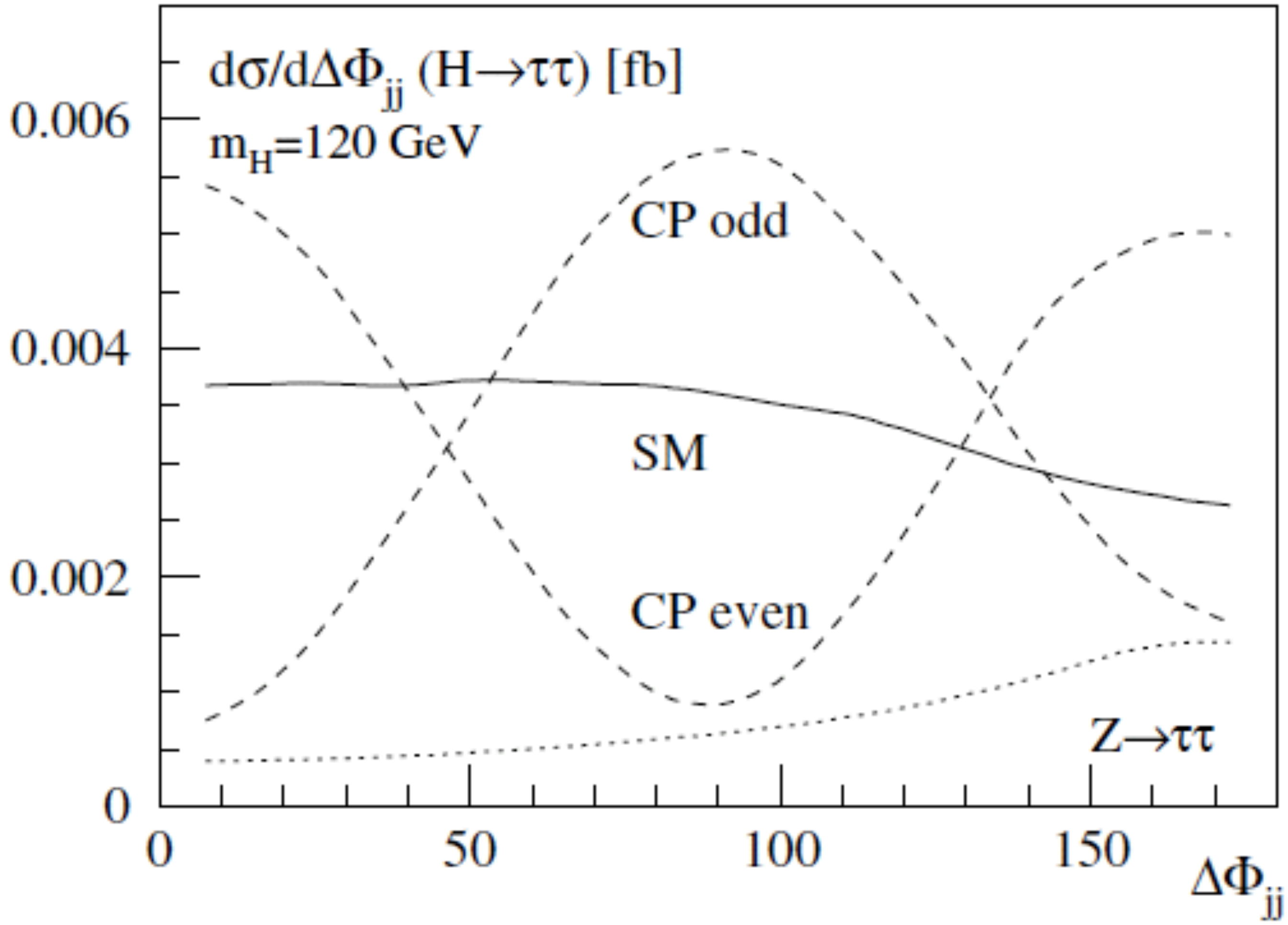


$d\sigma/d\Delta\phi \sim$ const. for $0^+_{\rm SM}$

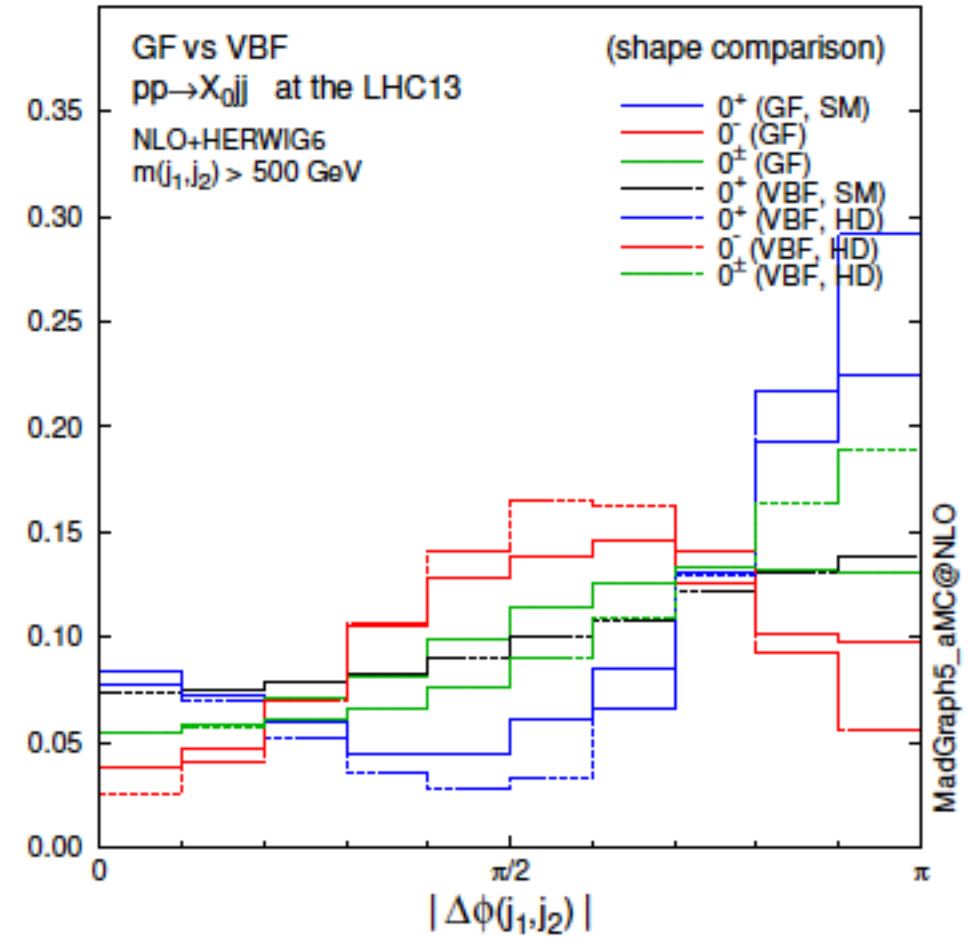
$d\sigma/d\Delta\phi \sim 1 \pm A\cos 2\Delta\phi$ for $0^\pm_{\rm D5}$

pp>Xjj (VBF: vector boson fusion)

Plehn, Rainwater, Zeppenfeld [hep-ph/0105325, PRL]



Demartin, Maltoni, KM, Page, Zaro [1407.5089, EPJC]



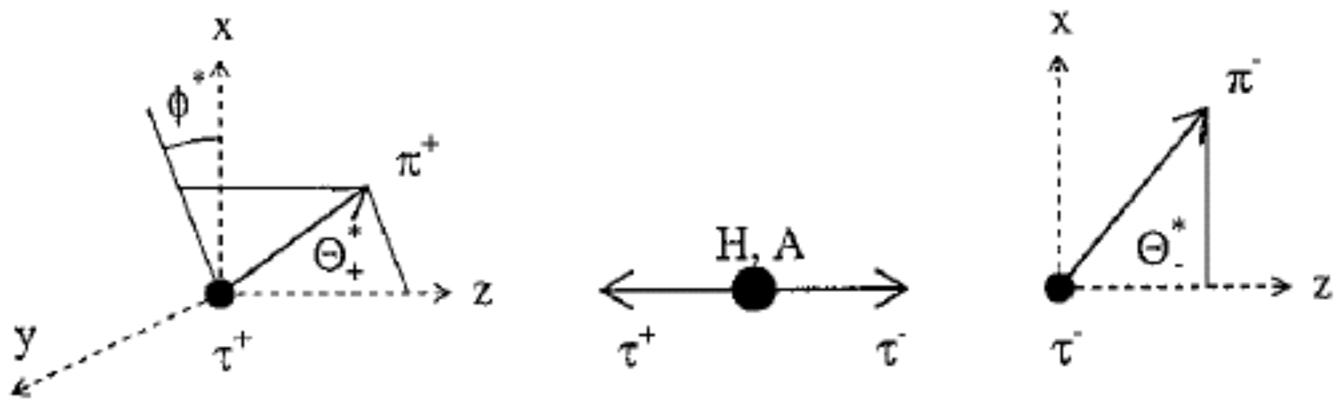
$$\mathcal{L}_{0^+_{\rm SM}} = g_{0^+_{\rm SM}} V_\mu V^\mu X_0$$
$$\mathcal{L}_{0^+_{\rm D5}} = g_{0^+_{\rm D5}} V_{\mu\nu} V^{\mu\nu} X_0$$
$$\mathcal{L}_{0^-_{\rm D5}} = g_{0^-_{\rm D5}} V_{\mu\nu} \widetilde{V}^{\mu\nu} X_0$$

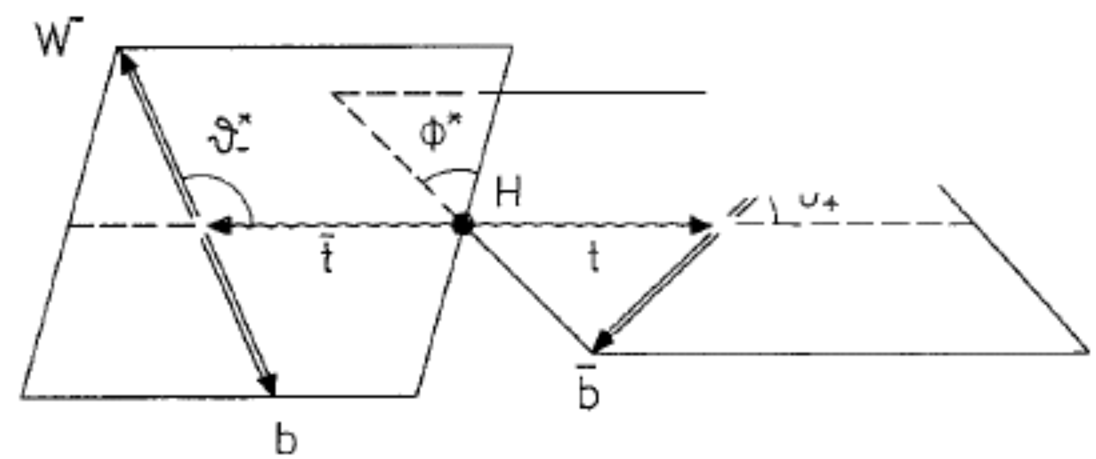
$d\sigma/d\Delta\phi \sim$ const. for $0^+_{\rm SM}$

$d\sigma/d\Delta\phi \sim 1 \pm A\cos 2\Delta\phi$ for $0^\pm_{\rm D5}$

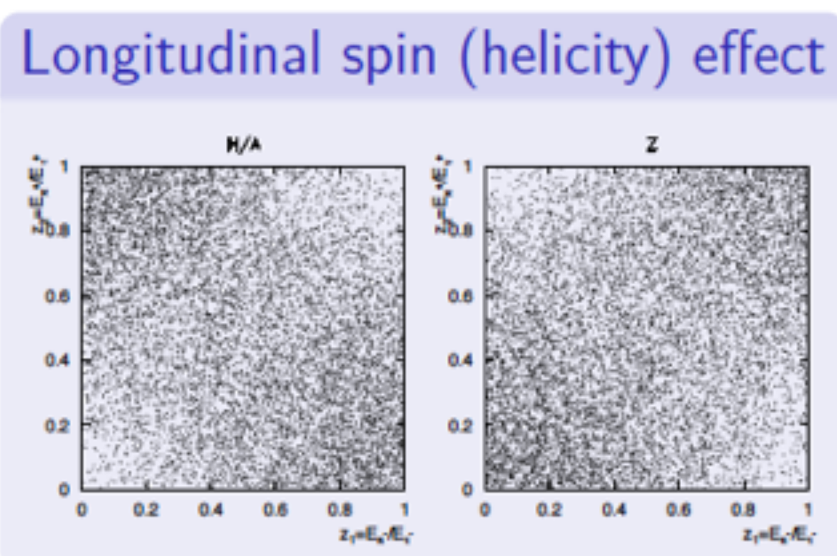
X>ττ

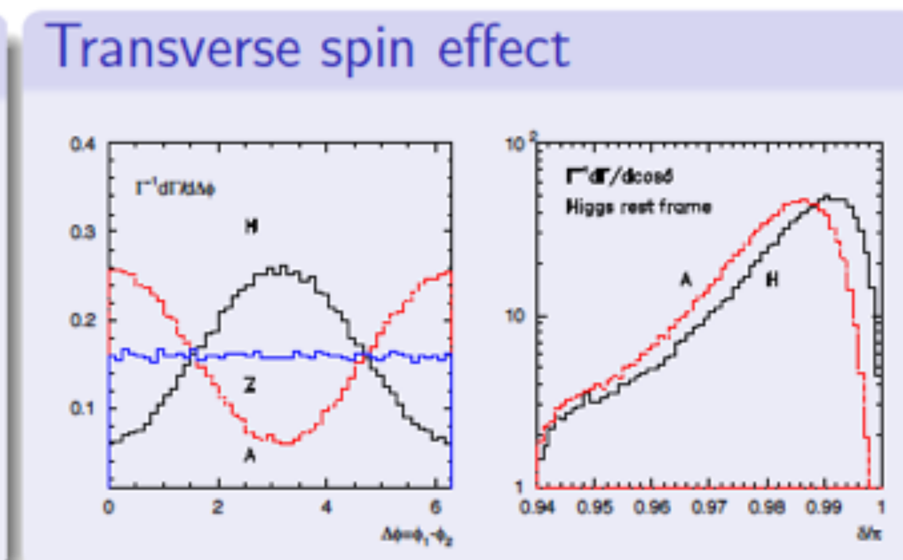
Kramer, Kuhn, Stong, Zerwas [hep-ph/9404280, ZPC]



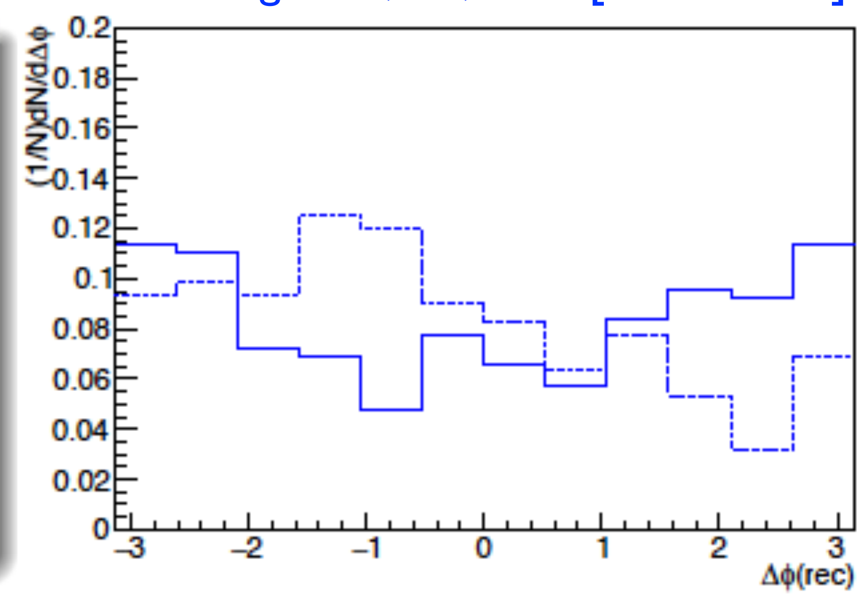


Hagiwara, Li, KM, Nakamura [1212.6247, EPJC]





Hagiwara, Ma, Mori [1609.00943]

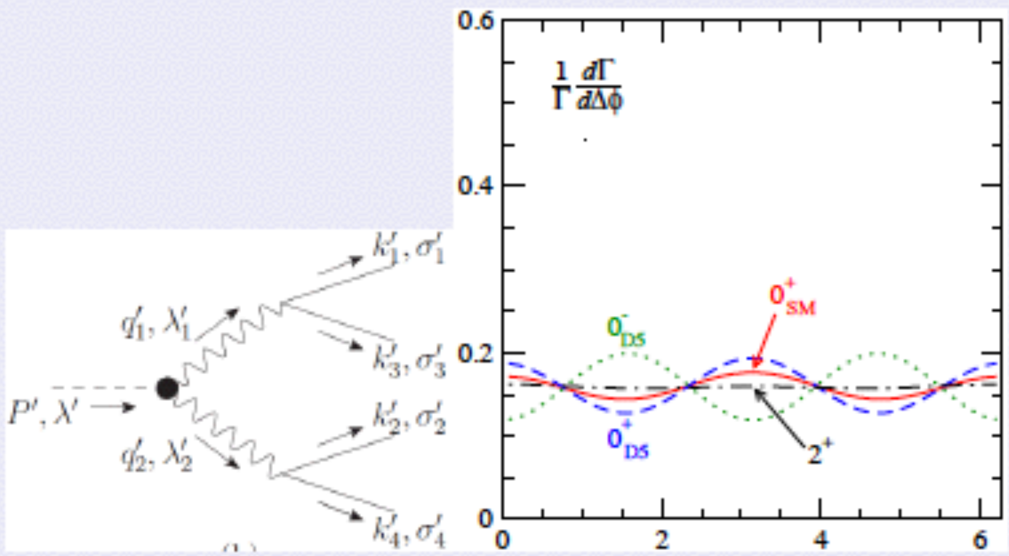


$d^2\Gamma/dz_1 dz_2 \sim 1 \mp z_1 z_2$ for spin-0/1, $d\Gamma/d\Delta\phi \sim 1 \mp A\cos\Delta\phi$ for $0^\pm$

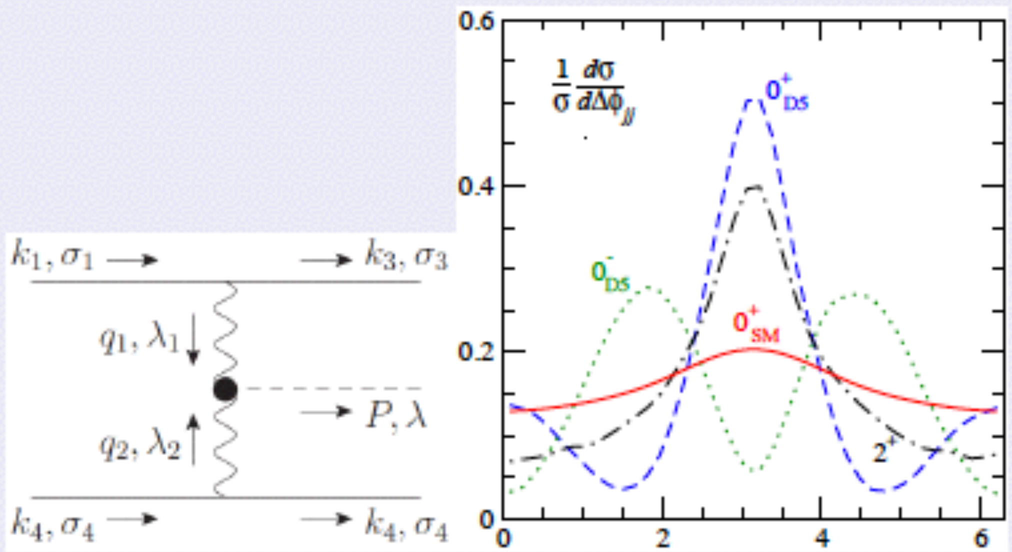
Spin/parity determination with gauge bosons

Hagiwara, Li, KM [0905.4314, JHEP]
Englert, Goncalves-Netto, KM, Plehn [1212.0843, JHEP]

$X \to ZZ^* \to 4\ell$



Vector boson fusion (VBF)

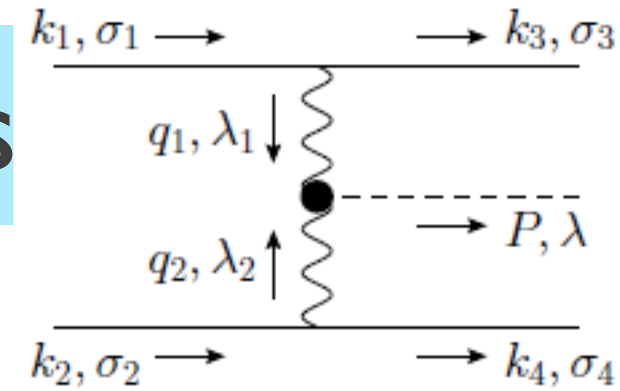


$d\sigma/d\Delta\phi \sim \text{const. for } 0^+_{\rm SM}, \quad d\sigma/d\Delta\phi \sim 1 \pm A\cos 2\Delta\phi \text{ for } 0^\pm_{\rm D5}.$

Nontrivial azimuthal angle correlations of the decay planes ($X \to ZZ$) and the jets (VBF) can be explained as the quantum interference among different helicity states of the intermediate vector-bosons.

Contents

The VBF helicity amplitudes



The helicity amplitudes for VBF processes

$$\mathcal{M}^{\lambda}_{\sigma_1\sigma_3,\sigma_2\sigma_4} = J^{\mu'_1}(k_1,k_3;\sigma_1,\sigma_3)\frac{-g_{\mu'_1\mu_1}+\frac{q_{1\mu'_1}q_{1\mu_1}}{m_V^2}}{q_1^2-m_V^2}J^{\mu'_2}(k_2,k_4;\sigma_2,\sigma_4)\frac{-g_{\mu'_2\mu_2}+\frac{q_{2\mu'_2}q_{2\mu_2}}{m_V^2}}{q_2^2-m_V^2}\Gamma^{\mu_1\mu_2}_{XVV}(q_1,q_2;\lambda)^*$$

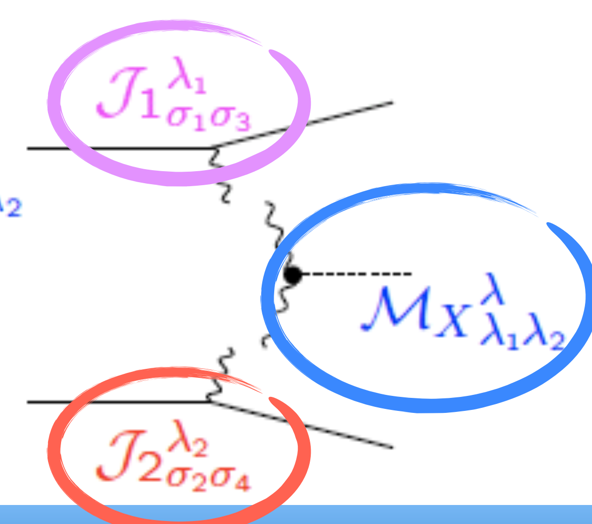
can be expressed by using

completeness relation $\quad -g_{\mu'\mu}+\frac{q_{i\mu'}q_{i\mu}}{q_i^2} = \sum_{\lambda_i=\pm,0}(-1)^{\lambda_i+1}\epsilon_{\mu'}(q_i,\lambda_i)^*\epsilon_{\mu}(q_i,\lambda_i)$

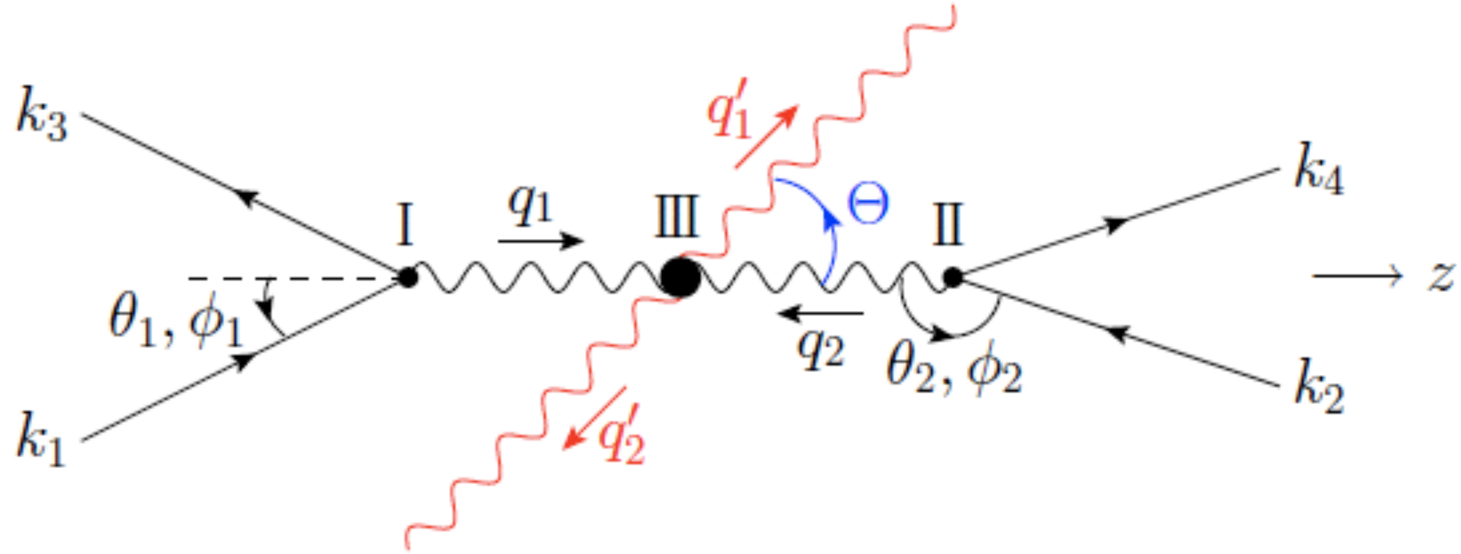
current conservation $\quad q_{i\mu}J^{\mu}(k_i,k_{i+2};\sigma_i,\sigma_{i+2})=0$

as the product of the three helicity amplitudes summed over the polarization of the intermediate vector-bosons:

$$\begin{aligned}\mathcal{M}^{\lambda}_{\sigma_1\sigma_3,\sigma_2\sigma_4} = &\frac{1}{q_1^2-m_V^2}J^{\mu'_1}(k_1,k_3;\sigma_1,\sigma_3)\sum_{\lambda_1=\pm,0}(-1)^{\lambda_1+1}\epsilon_{\mu'_1}(q_1,\lambda_1)^*\epsilon_{\mu_1}(q_1,\lambda_1)\\ &\times\frac{1}{q_2^2-m_V^2}J^{\mu'_2}(k_2,k_4;\sigma_2,\sigma_4)\sum_{\lambda_2=\pm,0}(-1)^{\lambda_2+1}\epsilon_{\mu'_2}(q_2,\lambda_2)^*\epsilon_{\mu_2}(q_2,\lambda_2)\\ &\times\Gamma^{\mu_1\mu_2}_{XVV}(q_1,q_2;\lambda)^*\\ = &\frac{1}{(q_1^2-m_V^2)(q_2^2-m_V^2)}\sum_{\lambda_1=\pm,0}\sum_{\lambda_2=\pm,0}\mathcal{J}1^{\lambda_1}_{\sigma_1\sigma_3}\,\mathcal{J}2^{\lambda_2}_{\sigma_2\sigma_4}\,\mathcal{M}X^{\lambda}_{\lambda_1\lambda_2}\end{aligned}$$



Kinematics



I) q_1 Breit frame ($Q_1 = \sqrt{-q_1^2}$, $0 < \theta_1 < \pi/2$):

$$q_1^\mu = k_1^\mu - k_3^\mu = (0, 0, 0, Q_1)$$
$$k_1^\mu = \frac{Q_1}{2\cos\theta_1}(1, \sin\theta_1\cos\phi_1, \sin\theta_1\sin\phi_1, \cos\theta_1)$$
$$k_3^\mu = \frac{Q_1}{2\cos\theta_1}(1, \sin\theta_1\cos\phi_1, \sin\theta_1\sin\phi_1, -\cos\theta_1)$$

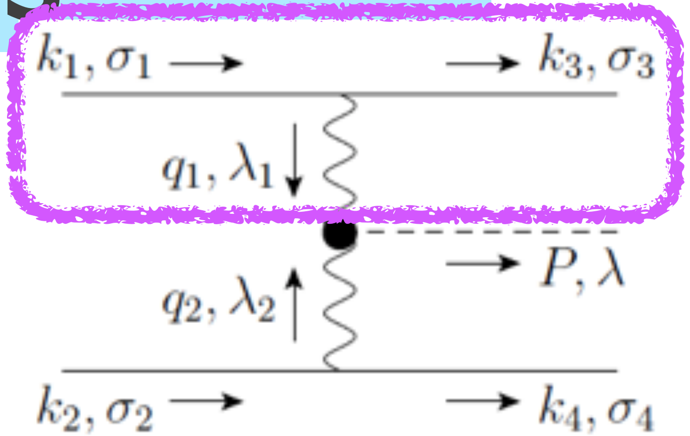
II) q_2 Breit frame ($Q_2 = \sqrt{-q_2^2}$, $\pi/2 < \theta_2 < \pi$):

$$q_2^\mu = k_2^\mu - k_4^\mu = (0, 0, 0, -Q_2)$$
$$k_2^\mu = -\frac{Q_2}{2\cos\theta_2}(1, \sin\theta_2\cos\phi_2, \sin\theta_2\sin\phi_2, \cos\theta_2)$$
$$k_4^\mu = -\frac{Q_2}{2\cos\theta_2}(1, \sin\theta_2\cos\phi_2, \sin\theta_2\sin\phi_2, -\cos\theta_2)$$

III) VBF frame (X rest frame):

$$q_1^\mu + q_2^\mu = P^\mu = {q'_1}^\mu + {q'_2}^\mu = (M, 0, 0, 0)$$
$$q_1^\mu = \frac{M}{2}\left(1 - \frac{Q_1^2 - Q_2^2}{M^2}, 0, 0, \beta\right); \qquad {q'_1}^\mu = \frac{M}{2}\left(1 + \frac{{Q'_1}^2 - {Q'_2}^2}{M^2}, \beta'\sin\Theta, 0, \beta'\cos\Theta\right)$$
$$q_2^\mu = \frac{M}{2}\left(1 - \frac{Q_2^2 - Q_1^2}{M^2}, 0, 0, -\beta\right); \qquad {q'_2}^\mu = \frac{M}{2}\left(1 + \frac{{Q'_2}^2 - {Q'_1}^2}{M^2}, -\beta'\sin\Theta, 0, -\beta'\cos\Theta\right)$$

Current amplitudes



$$\mathcal{J}^{\lambda_i}_{i\sigma_i\sigma_{i+2}} = (-1)^{\lambda_i+1} J^\mu(k_i, k_{i+2}; \sigma_i, \sigma_{i+2})\, \epsilon_\mu(q_i, \lambda_i)^*$$

- Quark current vectors

$$J^\mu_{Vff'}(k_i, k_{i+2}; \sigma_i, \sigma_{i+2}) = g^{Vff'}_{\sigma_i}\, \bar{u}_{f'}(k_{i+2}, \sigma_{i+2})\, \gamma^\mu\, u_f(k_i, \sigma_i)$$

- Wavefunctions for the quarks

$$u(k_1,+) = \sqrt{2E_1}\begin{pmatrix} 0 \\ 0 \\ \cos(\theta_1/2) \\ \sin(\theta_1/2)\, e^{i\phi_1} \end{pmatrix}; \quad u(k_1,-) = \sqrt{2E_1}\begin{pmatrix} -\sin(\theta_1/2)\, e^{-i\phi_1} \\ \cos(\theta_1/2) \\ 0 \\ 0 \end{pmatrix}$$

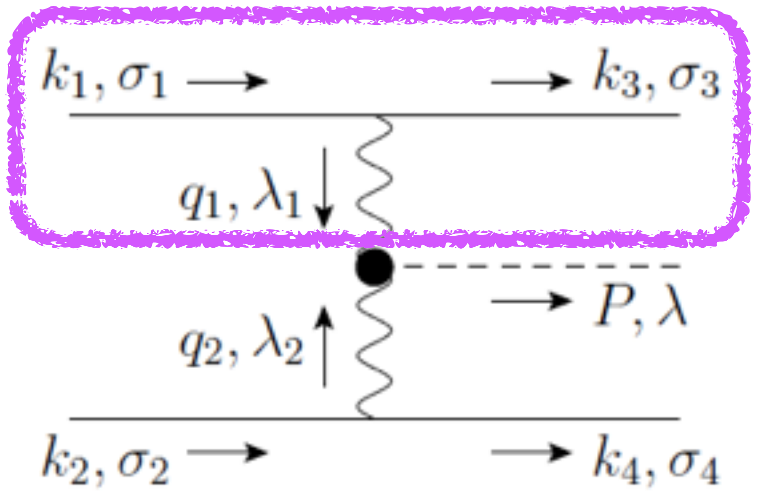
$$u(k_3,+) = \sqrt{2E_1}\begin{pmatrix} 0 \\ 0 \\ \sin(\theta_1/2) \\ \cos(\theta_1/2)\, e^{i\phi_1} \end{pmatrix}; \quad u(k_3,-) = \sqrt{2E_1}\begin{pmatrix} -\cos(\theta_1/2)\, e^{-i\phi_1} \\ \sin(\theta_1/2) \\ 0 \\ 0 \end{pmatrix}$$

- Wavefunctions for the t-channel vector-bosons

$$\epsilon^\mu(q_1, \pm) = \frac{1}{\sqrt{2}}(0, \mp 1, -i, 0)$$

$$\epsilon^\mu(q_1, 0) = (1, 0, 0, 0)$$

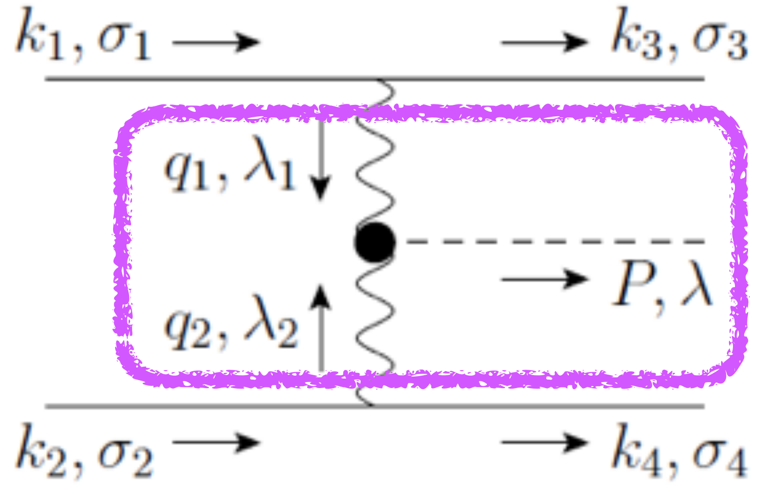
Current helicity amplitudes



$\mathcal{J}_{1\,\sigma_1\sigma_3}^{\ \lambda_1}$ (quark)	
$\mathcal{J}_{1\,++}^{\ +} = -\left(\mathcal{J}_{1\,--}^{\ -}\right)^*$	$\frac{1}{2\cos\theta_1}(1+\cos\theta_1)\, e^{-i\phi_1}$
$\mathcal{J}_{1\,++}^{\ 0} = \mathcal{J}_{1\,--}^{\ 0}$	$-\frac{1}{\sqrt{2}\cos\theta_1}\sin\theta_1$
$\mathcal{J}_{1\,++}^{\ -} = -\left(\mathcal{J}_{1\,--}^{\ +}\right)^*$	$-\frac{1}{2\cos\theta_1}(1-\cos\theta_1)\, e^{i\phi_1}$
$\mathcal{J}_{1\,+-}^{\ \lambda_1} = \mathcal{J}_{1\,-+}^{\ \lambda_1}$	0

- The amplitudes with a transversely (longitudinally) polarized VB do (not) have a phase.
- The phases are opposite between those with transverse polarization.

XVV vertex



- $VV \rightarrow X$ fusion amplitudes:

$$\mathcal{M}_{X^{\lambda}_{\lambda_1\lambda_2}} = \epsilon_\mu(q_1,\lambda_1)\,\epsilon_\nu(q_2,\lambda_2)\,\Gamma^{\mu\nu}_{XVV}(q_1,q_2;\lambda)^*$$

- Effective Lagrangian:

$$\mathcal{L}_{H,A} = -\frac{1}{4} g_{Hgg} H F^a_{\mu\nu} F^{a,\mu\nu} - \frac{1}{4} g_{Agg} A F^a_{\mu\nu} \tilde{F}^{a,\mu\nu}$$

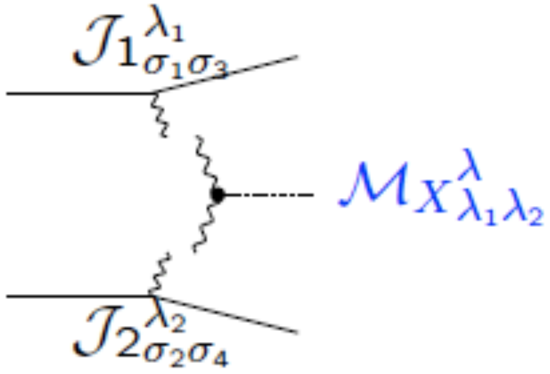
$$\mathcal{L}_G = -\frac{1}{\Lambda} T^{\mu\nu} G_{\mu\nu}$$

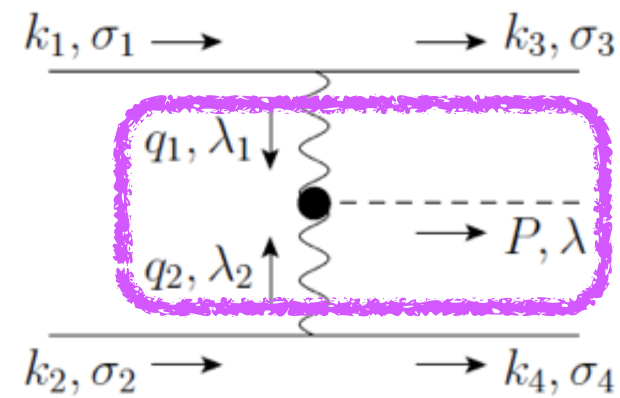
- XVV vertex:

X	(λ)	V	$\Gamma^{\mu\nu}_{XVV}/g_{XVV}$
H	(0)	W, Z	$g^{\mu\nu}$
H	(0)	$\gamma, Z/\gamma, g$	$q_1 \cdot q_2\, g^{\mu\nu} - q_2^\mu q_1^\nu$
A	(0)	$\gamma, Z/\gamma, g$	$\epsilon^{\mu\nu\alpha\beta} q_{1\alpha} q_{2\beta}$
G	$(\pm 2, \pm 1, 0)$	W, Z, γ, g	$\epsilon_{\alpha\beta}\,\hat{\Gamma}^{\alpha\beta\mu\nu}_{GVV}$

* $\epsilon^{\alpha\beta}(P,\lambda)$: *the polarization tensor;* $\hat{\Gamma}^{\alpha\beta\mu\nu}_{GVV}(q_1,q_2)$: *the GVV vertex*

$VV \to H/A$ amplitudes





		CP-even		CP-odd
λ	$(\lambda_1\lambda_2)$	H(WBF)	H(loop-induced)	A
0	$(\pm\pm)$	-1	$-\frac{1}{2}(M^2+Q_1^2+Q_2^2)$	$\mp\frac{i}{2}\sqrt{(M^2+Q_1^2+Q_2^2)^2-4Q_1^2Q_2^2}$
0	(00)	$\frac{M^2+Q_1^2+Q_2^2}{2Q_1Q_2}$	Q_1Q_2	0

The helicity amplitudes for the CP-even/odd Higgs boson productions via off-shell vector-bosons, $\hat{\mathcal{M}}_X{}^{\lambda}_{\lambda_1\lambda_2}$, in the VBF frame. M is the Higgs boson mass, and Q_1 and Q_2 are magnitudes of the four-momentum squared of the vector bosons.

For $Q_1, Q_2 \ll M$, where the VBF contributions dominant,

- WBF H: produced by the longitudinally polarized vector-bosons.
- GF H/A: produced by the transversely polarized vector-bosons.

$VV \to G$ amplitudes

λ	$(\lambda_1\lambda_2)$	G
± 2	$(\pm\mp)$	$-(M^2+Q_1^2+Q_2^2)$
± 1	(± 0)	$\frac{1}{\sqrt{2}M}Q_2(M^2-Q_1^2+Q_2^2)$
± 1	$(0\mp)$	$\frac{1}{\sqrt{2}M}Q_1(M^2+Q_1^2-Q_2^2)$
0	$(\pm\pm)$	$\frac{1}{\sqrt{6}M^2}\left[(Q_1^2-Q_2^2)^2+M^2(Q_1^2+Q_2^2)\right]$
0	(00)	$-\frac{4}{\sqrt{6}}Q_1Q_2$

For $Q_1, Q_2 \ll M$, the $\lambda = \pm 2$ states are dominantly produced through the collisions of the vector-bosons which have the opposite-sign transverse polarization.

Azimuthal correlations for Higgs bosons

The $J = 0$ VBF amplitudes are the sum of the three amplitudes:

$$\mathcal{M}^{\lambda=0}_{\sigma_1\sigma_3,\sigma_2\sigma_4} = \frac{1}{(Q_1^2+m_V^2)(Q_2^2+m_V^2)} \sum_{\lambda_1=\pm,0} \sum_{\lambda_2=\pm,0} \mathcal{J}1^{\lambda_1}_{\sigma_1\sigma_3} \mathcal{J}2^{\lambda_2}_{\sigma_2\sigma_4} \mathcal{M}_X{}^{\lambda=0}_{\lambda_1\lambda_2}$$

$$\sim \mathcal{J}1^{+}_{\sigma_1\sigma_3} \mathcal{J}2^{+}_{\sigma_2\sigma_4} \mathcal{M}_X{}^{0}_{++} e^{-i(\phi_1-\phi_2)} + \mathcal{J}1^{0}_{\sigma_1\sigma_3} \mathcal{J}2^{0}_{\sigma_2\sigma_4} \mathcal{M}_X{}^{0}_{00} + \mathcal{J}1^{-}_{\sigma_1\sigma_3} \mathcal{J}2^{-}_{\sigma_2\sigma_4} \mathcal{M}_X{}^{0}_{--} e^{i(\phi_1-\phi_2)}$$

The squared amplitudes are

$$\sum_{\sigma_{1,\cdots,4}} \left|\mathcal{M}^{\lambda=0}_{\sigma_1\sigma_3,\sigma_2\sigma_4}\right|^2 = \Sigma_0 + \Sigma_1 \cos\Delta\phi + \Sigma_2 \cos 2\Delta\phi \quad (\Delta\phi \equiv \phi_1 - \phi_2)$$

The azimuthal correlation is manifestly expressed by the interference among different helicity states of the intermediate vector-bosons.

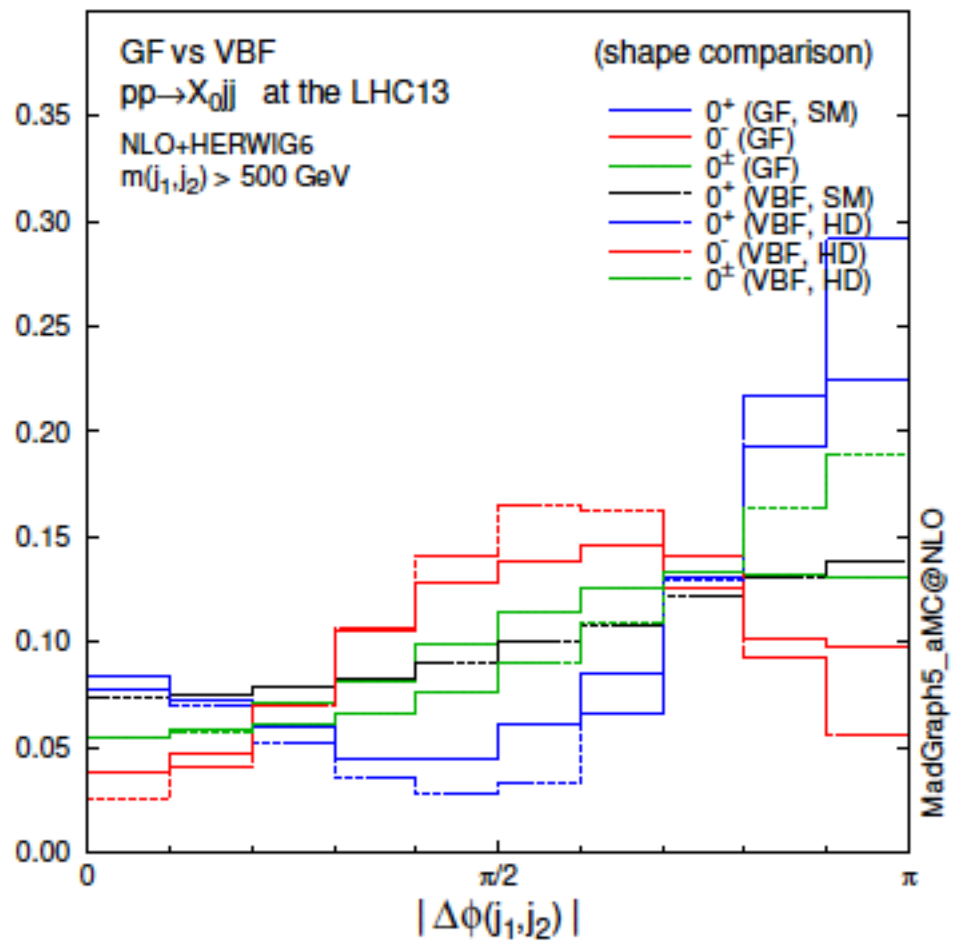
The different tensor structures of the XVV couplings give rise to the different azimuthal angle dependences:

H(WBF) : $\mathcal{M}_{00} \gg \mathcal{M}_{++} = \mathcal{M}_{--} \Rightarrow d\hat{\sigma}/d\Delta\phi \sim$ constant

H(GF) : $\mathcal{M}_{00} \ll \mathcal{M}_{++} = \mathcal{M}_{--} \Rightarrow d\hat{\sigma}/d\Delta\phi \sim \Sigma_0 + |\Sigma_2| \cos 2\Delta\phi$

A : $\mathcal{M}_{00} = 0,\ \mathcal{M}_{++} = -\mathcal{M}_{--} \Rightarrow d\hat{\sigma}/d\Delta\phi \sim \Sigma_0 - |\Sigma_2| \cos 2\Delta\phi$

ΔΦ distributions for Higgs bosons

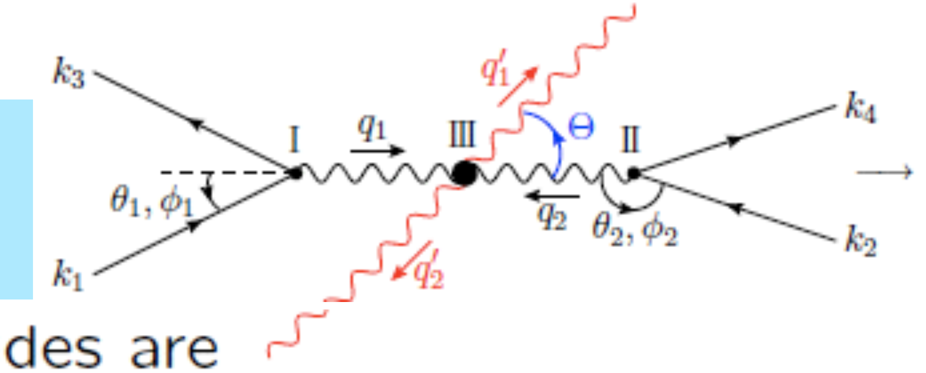


$$H(\text{WBF}) \Rightarrow d\sigma/d\Delta\phi \sim \text{constant}$$

$$H(\text{GF}) \Rightarrow d\sigma/d\Delta\phi \sim \Sigma_0 + |\Sigma_2| \cos 2\Delta\phi$$

$$A \Rightarrow d\sigma/d\Delta\phi \sim \Sigma_0 - |\Sigma_2| \cos 2\Delta\phi$$

Azimuthal correlations for gravitons



The VBF G production plus its 2-body decay amplitudes are

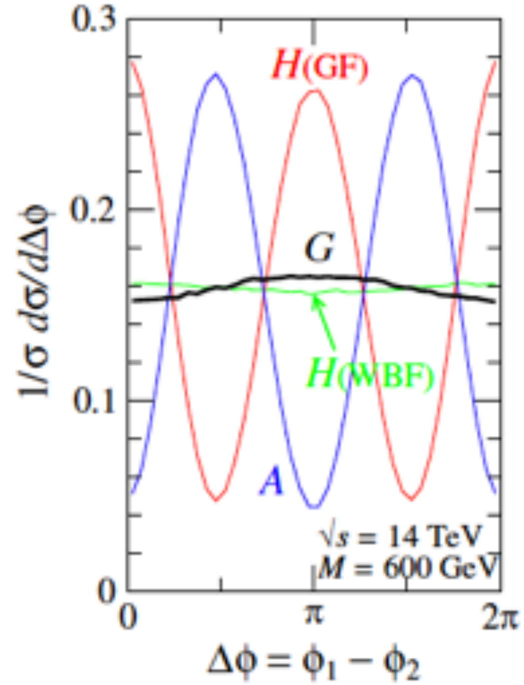
$$\mathcal{M}_{\sigma_{1,\cdots,4};\sigma_{5,6}} = \frac{1}{Q_1^2 Q_2^2} \sum_{\lambda_1} \sum_{\lambda_2} \mathcal{J}1^{\lambda_1}_{\sigma_1\sigma_3} \mathcal{J}2^{\lambda_2}_{\sigma_2\sigma_4} \mathcal{M}G^{\lambda=\lambda_1-\lambda_2}_{\lambda_1\lambda_2} \frac{d^2_{\lambda,\lambda'}(\Theta)}{P^2 - M^2 + iM\Gamma} \mathcal{M}'^{\lambda'=\sigma_5-\sigma_6}_{G\sigma_5\sigma_6}$$

$$\sim \quad \mathcal{J}1^{+}_{\sigma_1\sigma_3} \mathcal{J}2^{-}_{\sigma_2\sigma_4} \mathcal{M}G^{+2}_{+-} e^{-i(\phi_1+\phi_2)} d^2_{+2,\lambda'}(\Theta)$$

$$+ \mathcal{J}1^{-}_{\sigma_1\sigma_3} \mathcal{J}2^{+}_{\sigma_2\sigma_4} \mathcal{M}G^{-2}_{-+} e^{i(\phi_1+\phi_2)} d^2_{-2,\lambda'}(\Theta)$$

The squared amplitudes are

$$\sum_{\sigma_{1,\cdots,4}} \left| \mathcal{M}_{\sigma_{1,\cdots,4};\sigma_{5,6}} \right|^2 = \Sigma_0 + \Sigma_1 \cos 2\Phi \qquad (\Phi \equiv \phi_1 + \phi_2)$$



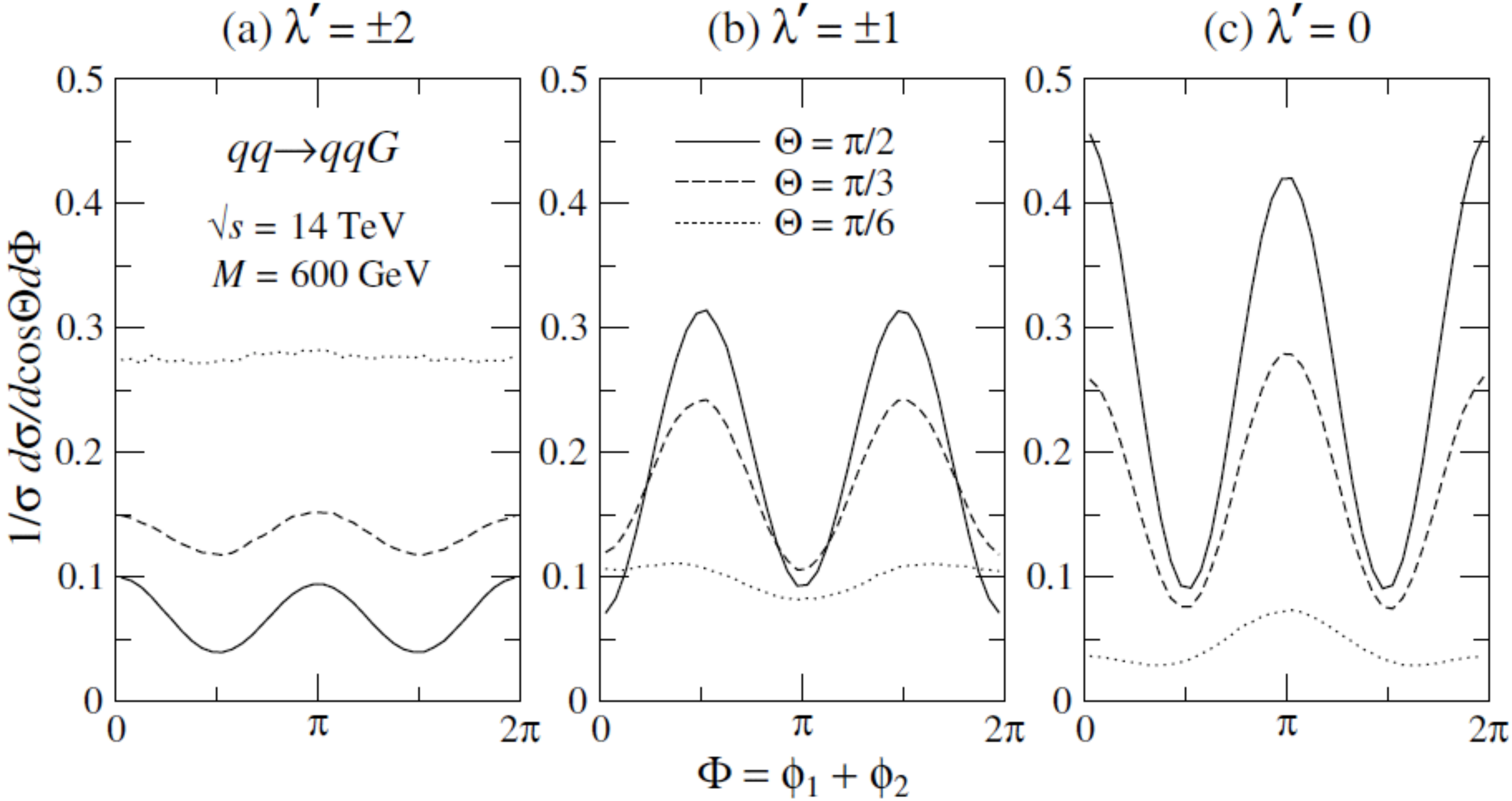
where

$$\Sigma_0 \propto \left(d^2_{+2,\lambda'}(\Theta)\right)^2 + \left(d^2_{-2,\lambda'}(\Theta)\right)^2 = \begin{cases} \frac{1}{8}(1 + 6\cos^2\Theta + \cos^4\Theta) & \text{for } \lambda' = \pm 2 \\ \frac{1}{2}(1 - \cos^4\Theta) & \text{for } \lambda' = \pm 1 \\ \frac{3}{4}\sin^4\Theta & \text{for } \lambda' = 0 \end{cases}$$

$$\Sigma_1 \propto 2\, d^2_{+2,\lambda'}(\Theta)\, d^2_{-2,\lambda'}(\Theta) = \begin{cases} +\frac{1}{8}\sin^4\Theta & \text{for } \lambda' = \pm 2 \\ -\frac{1}{2}\sin^4\Theta & \text{for } \lambda' = \pm 1 \\ +\frac{3}{4}\sin^4\Theta & \text{for } \lambda' = 0 \end{cases}$$

$\Longrightarrow$ The azimuthal Φ correlations depend on Θ and λ'.

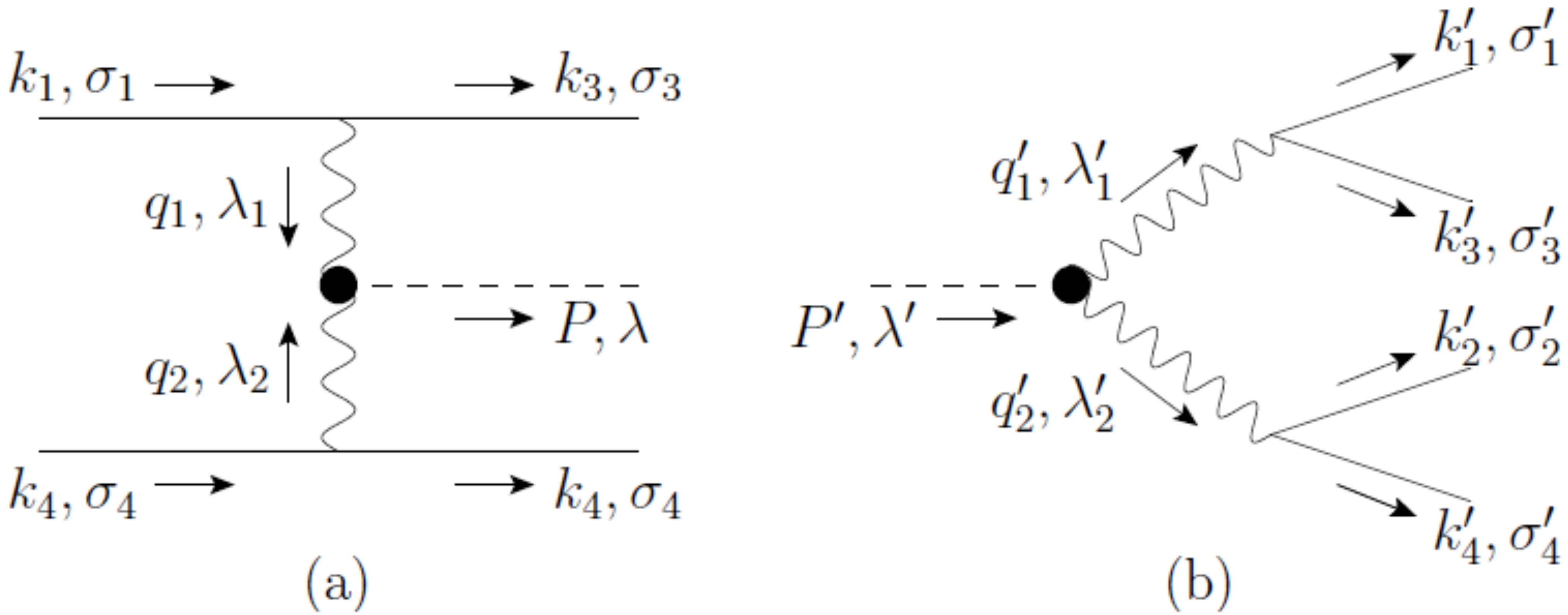
Φ distributions for gravitons



$$d\sigma/d\cos\Theta d\Phi \sim \Sigma_0 + \Sigma_1 \cos 2\Phi; \quad \Sigma_1 \propto \begin{cases} +\frac{1}{8}\sin^4\Theta & \text{for } \lambda' = \pm 2 \\ -\frac{1}{2}\sin^4\Theta & \text{for } \lambda' = \pm 1 \\ +\frac{3}{4}\sin^4\Theta & \text{for } \lambda' = 0 \end{cases}$$

The Θ and λ' dependent azimuthal Φ correlations !

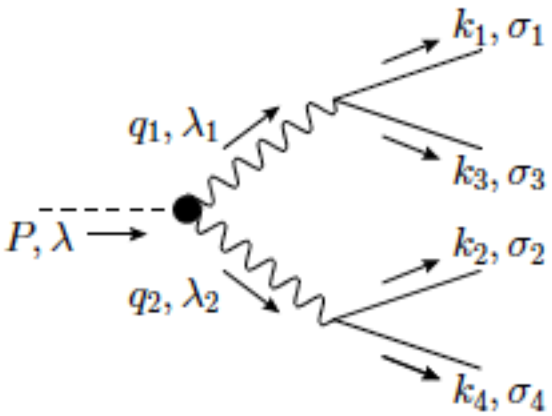
X decay to a vector-boson pair



Angular correlations in heavy-particle decays are also promising tools to determine their properties.

The process of X decays into 4 jets/leptons via a vector-boson pair is related by crossing symmetry to the VBF process.

The helicity amplitude formalism



The helicity amplitudes for $X \to VV \to 4f$

$$\mathcal{M}^{\lambda}_{\sigma_1\sigma_3,\sigma_2\sigma_4} = \Gamma^{\mu_1\mu_2}_{XVV}(q_1,q_2;\lambda)\,\frac{-g_{\mu_1'\mu_1}+\frac{q_{1\mu_1'}q_{1\mu_1}}{m_V^2}}{q_1^2-m_V^2}\,J^{\mu_1'}(k_1,k_3;\sigma_1,\sigma_3)\frac{-g_{\mu_2'\mu_2}+\frac{q_{2\mu_2'}q_{2\mu_2}}{m_V^2}}{q_2^2-m_V^2}J^{\mu_2'}(k_2,k_4;\sigma_2,\sigma_4)$$

can be expressed by using

completeness relation $\quad -g_{\mu'\mu}+\frac{q_{i\mu'}q_{i\mu}}{q_i^2} = \sum_{\lambda_i=\pm,0} \epsilon_{\mu'}(q_i,\lambda_i)^*\,\epsilon_\mu(q_i,\lambda_i)$

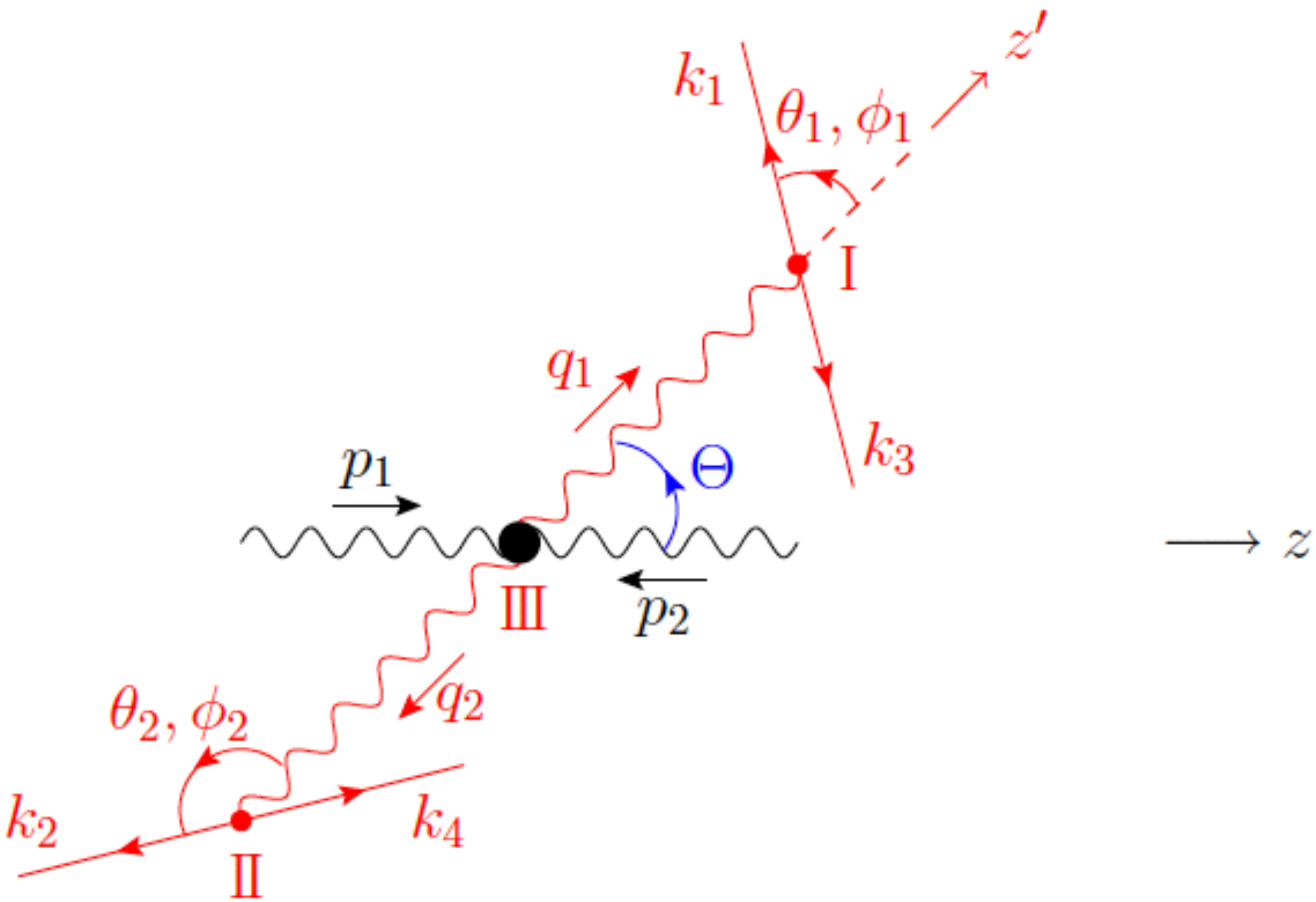
current conservation $\quad q_{i\mu}J^\mu(k_i,k_{i+2};\sigma_i,\sigma_{i+2}) = 0$

as the product of the three helicity amplitudes summed over the polarization of the intermediate vector-bosons:

$$\begin{aligned}\mathcal{M}^{\lambda}_{\sigma_1\sigma_3,\sigma_2\sigma_4} &= \Gamma^{\mu_1\mu_2}_{XVV}(q_1,q_2;\lambda)\\ &\quad\times\frac{1}{q_1^2-m_V^2}J^{\mu_1'}(k_1,k_3;\sigma_1,\sigma_3)\sum_{\lambda_1=\pm,0}\epsilon_{\mu_1'}(q_1,\lambda_1)\,\epsilon_{\mu_1}(q_1,\lambda_1)^*\\ &\quad\times\frac{1}{q_2^2-m_V^2}J^{\mu_2'}(k_2,k_4;\sigma_2,\sigma_4)\sum_{\lambda_2=\pm,0}\epsilon_{\mu_2'}(q_2,\lambda_2)\,\epsilon_{\mu_2}(q_2,\lambda_2)^*\\ &= \frac{1}{(q_1^2-m_V^2)(q_2^2-m_V^2)}\sum_{\lambda_1=\pm,0}\sum_{\lambda_2=\pm,0}\mathcal{M}_X{}^{\lambda}_{\lambda_1\lambda_2}\,\mathcal{J}_1{}^{\lambda_1}_{\sigma_1\sigma_3}\,\mathcal{J}_2{}^{\lambda_2}_{\sigma_2\sigma_4}\end{aligned}$$

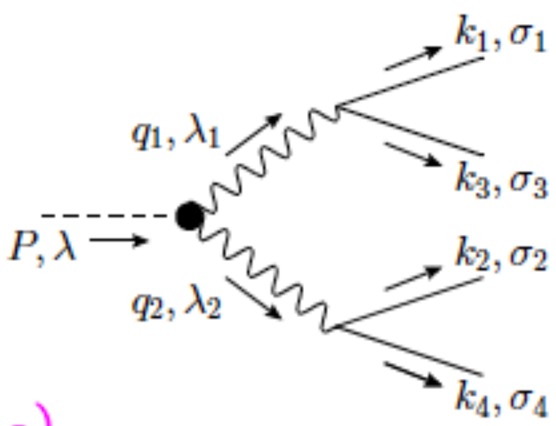
Note: The total amplitudes are generally the coherent sum of the 9 amplitudes which have the different helicity combinations of the decaying vector-bosons.

Kinematics for $gg/q\bar{q} \to X \to VV \to (f\bar{f})(f\bar{f})$



Note: The azimuthal angles (ϕ_1 and ϕ_2) are measured individually from the X production-decay ($gg/q\bar{q} \to X \to VV$) plane.

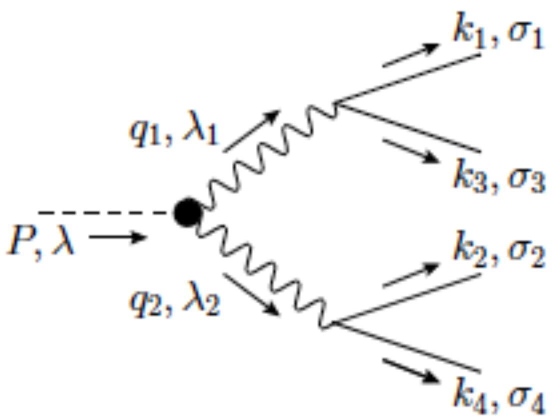
Current amplitudes



$$\mathcal{J}_{i\,\sigma_i\sigma_{i+2}}^{\lambda_i} = \epsilon_\mu(q_i,\lambda_i)\, J^\mu_{Vff'}(k_i,k_{i+2};\sigma_i,\sigma_{i+2})$$
$$= \epsilon_\mu(q_i,\lambda_i)\, g^{Vff'}_{\sigma_i}\, \bar{u}_{f'}(k_{i+2},\sigma_{i+2})\,\gamma^\mu\, u_f(k_i,\sigma_i)$$

	$\mathcal{J}_{1\,\sigma_1\sigma_3}^{\lambda_1}$	
•	$\mathcal{J}_{1\,+-}^{\,+} = -(\mathcal{J}_{1\,-+}^{\,-})^*$	$\frac{1}{2}(1+\cos\theta_1)\,e^{i\phi_1}$
•	$\mathcal{J}_{1\,+-}^{\,0} = \mathcal{J}_{1\,-+}^{\,0}$	$\frac{1}{\sqrt{2}}\sin\theta_1$
•	$\mathcal{J}_{1\,+-}^{\,-} = -(\mathcal{J}_{1\,-+}^{\,+})^*$	$\frac{1}{2}(1-\cos\theta_1)\,e^{-i\phi_1}$
	$\mathcal{J}_{1\,++}^{\lambda_1} = \mathcal{J}_{1\,--}^{\lambda_1}$	0

Note: The amplitudes for transversely polarized vector-bosons have a phase, $e^{+i\phi_1}$ or $e^{-i\phi_1}$, while those for londitudinal ones do not.



$X \to VV$ decay amplitudes

in the $q_{1,2}^2 \to m_V^2$ limit ($\beta = \sqrt{1 - 4m_V^2/M^2}$)

λ	$(\lambda_1\lambda_2)$	H	A	G
± 2	$(\pm\mp)$	$\cdot$	$\cdot$	$-M^2$
± 1	$(\pm 0), (0\mp)$	$\cdot$	$\cdot$	$\sqrt{\frac{1}{2}(1-\beta^2)}M^2$
0	$(\pm\pm)$	-1	$\mp\frac{i}{2}\beta M^2$	$-\frac{1}{\sqrt{6}}(1-\beta^2)M^2$
0	(00)	$(1+\beta^2)/(1-\beta^2)$	0	$-\frac{1}{\sqrt{6}}(2-\beta^2)M^2$

- light H ($\beta \to 0; M \sim 2m_V$): decay into both longitudinally- and transversely-polarized VBs.
- heavy H ($\beta \to 1; M \gg m_V$): decay into the longitudinally-polarized VBs.
- A: decay only into transversely-polarized VBs.
- G ($\beta \to 1$): decay into both longitudinally- and $(\lambda_1\lambda_2) = (\pm\mp)$ transversely-polarized VBs.

Azimuthal correlations for Higgs bosons

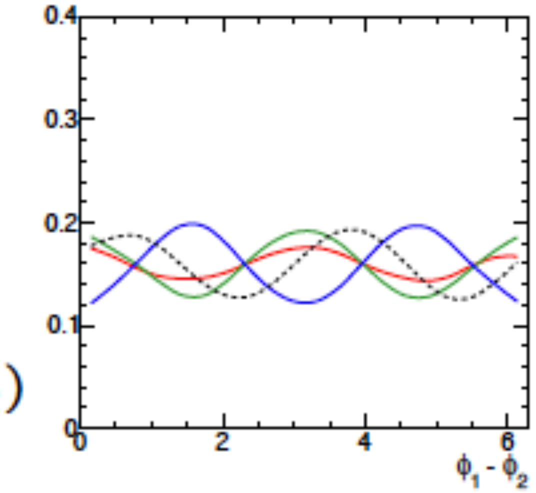
The $J = 0$ total amplitudes are the sum of the three amplitudes:

$$\mathcal{M}^{\lambda=0}_{\sigma_1\sigma_3,\sigma_2\sigma_4} = \frac{1}{(q_1^2 - m_V^2)(q_2^2 - m_V^2)} \sum_{\lambda_1=\pm,0} \sum_{\lambda_2=\pm,0} \mathcal{M}X^{\lambda=0}_{\lambda_1\lambda_2} \mathcal{J}1^{\lambda_1}_{\sigma_1\sigma_3} \mathcal{J}2^{\lambda_2}_{\sigma_2\sigma_4}$$

$$\sim \mathcal{M}X^0_{++} \mathcal{J}1^+_{\sigma_1\sigma_3} \mathcal{J}2^+_{\sigma_2\sigma_4} e^{-i(\phi_1-\phi_2)} + \mathcal{M}X^0_{00} \mathcal{J}1^0_{\sigma_1\sigma_3} \mathcal{J}2^0_{\sigma_2\sigma_4} + \mathcal{M}X^0_{--} \mathcal{J}1^-_{\sigma_1\sigma_3} \mathcal{J}2^-_{\sigma_2\sigma_4} e^{i(\phi_1-\phi_2)}$$

Therefore, the squared amplitudes are generally given by

$$\sum_{\sigma_{1,\cdots,4}} \left|\mathcal{M}^{\lambda=0}_{\sigma_1\sigma_3,\sigma_2\sigma_4}\right|^2 = \Sigma_0 + \Sigma_1 \cos\Delta\phi + \Sigma_2 \cos 2\Delta\phi \quad (\Delta\phi \equiv \phi_1 - \phi_2)$$



The azimuthal correlation is manifestly expressed by the interference among different helicity states of the intermediate vector-bosons.

The different tensor structures of the H/A coupling to a Z-pair give rise to the different azimuthal angle dependences:

$H_{\text{(heavy)}}$: $\mathcal{M}_{00} \gg \mathcal{M}_{++} = \mathcal{M}_{--}$ $\Rightarrow d\Gamma/d\Delta\phi \sim$ constant

$H_{\text{(light)}}$: $\mathcal{M}_{00} \sim \mathcal{M}_{++} = \mathcal{M}_{--}$ $(\Sigma_1 \ll 1)$ $\Rightarrow d\Gamma/d\Delta\phi \sim \Sigma_0 + |\Sigma_2| \cos 2\Delta\phi$

A : $\mathcal{M}_{00} = 0,\ \mathcal{M}_{++} = -\mathcal{M}_{--}$ $\Rightarrow d\Gamma/d\Delta\phi \sim \Sigma_0 - |\Sigma_2| \cos 2\Delta\phi$

Higgs CP in ttH/tH

Demartin, Maltoni, KM, Page, Zaro [1407.5089, EPJC]

```
./bin/mg5_aMC
>import model HC_NLO_X0
>generate p p > x0 t t~ [QCD]
>output
>launch
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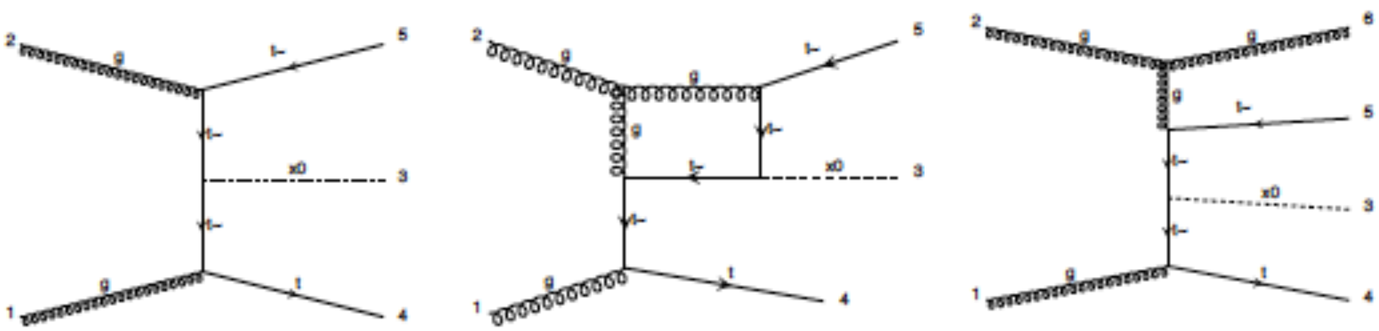

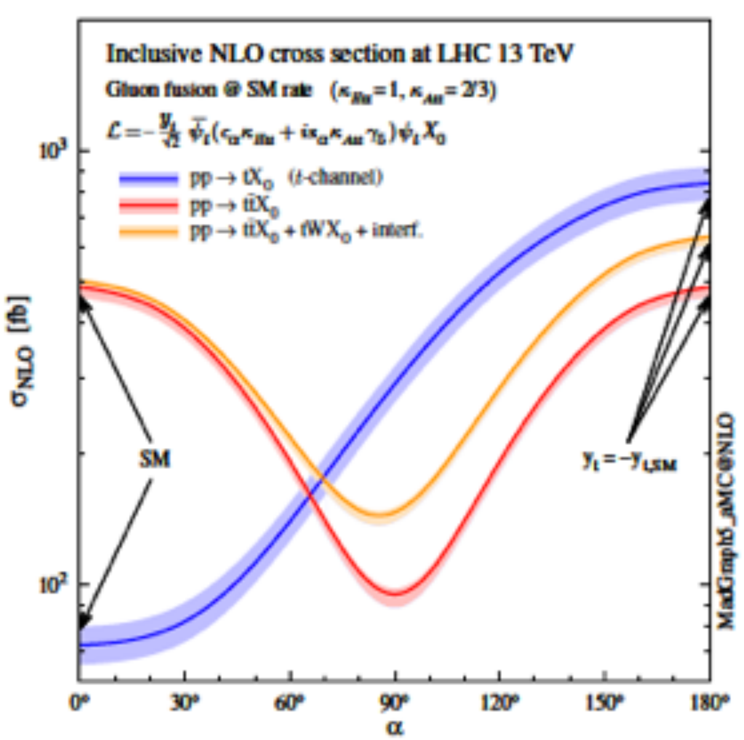

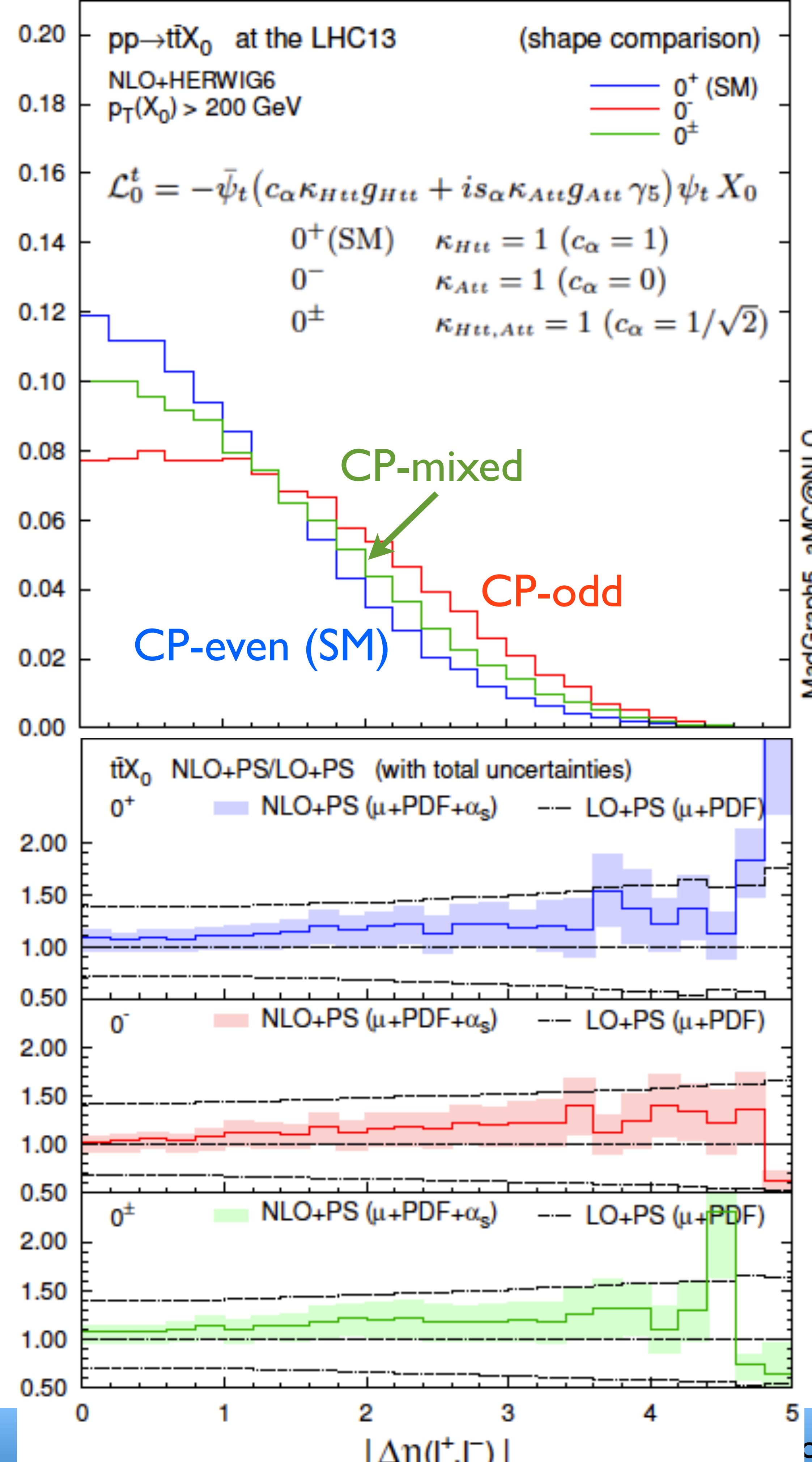

Summary

- I discussed
  - how we can determine the Higgs spin/parity at the LHC.
  - azimuthal correlations in the various processes are sensitive to the Higgs CP property.
  - the correlations can be explained as the quantum interference among different helicity states of the intermediate particles.