Measuring the Higgs Quantum Numbers

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Dorival Gonçalves Netto
in collaboration with C. Englert (Durham U.),
K. Mawatari (Vrije U. Brussel) & T. Plehn (U. Heidelberg)

ITP - Universität Heidelberg

Institut für Theoretische Physik
Ruprecht-Karls Universität Heidelberg

Motivation

ATLAS and CMS reported discovery of a Higgs-like resonance with mass ~126 GeV

- How can we know that it is really the Higgs boson?

  We need to confirm the structure of the Higgs Lagrangian from the data.

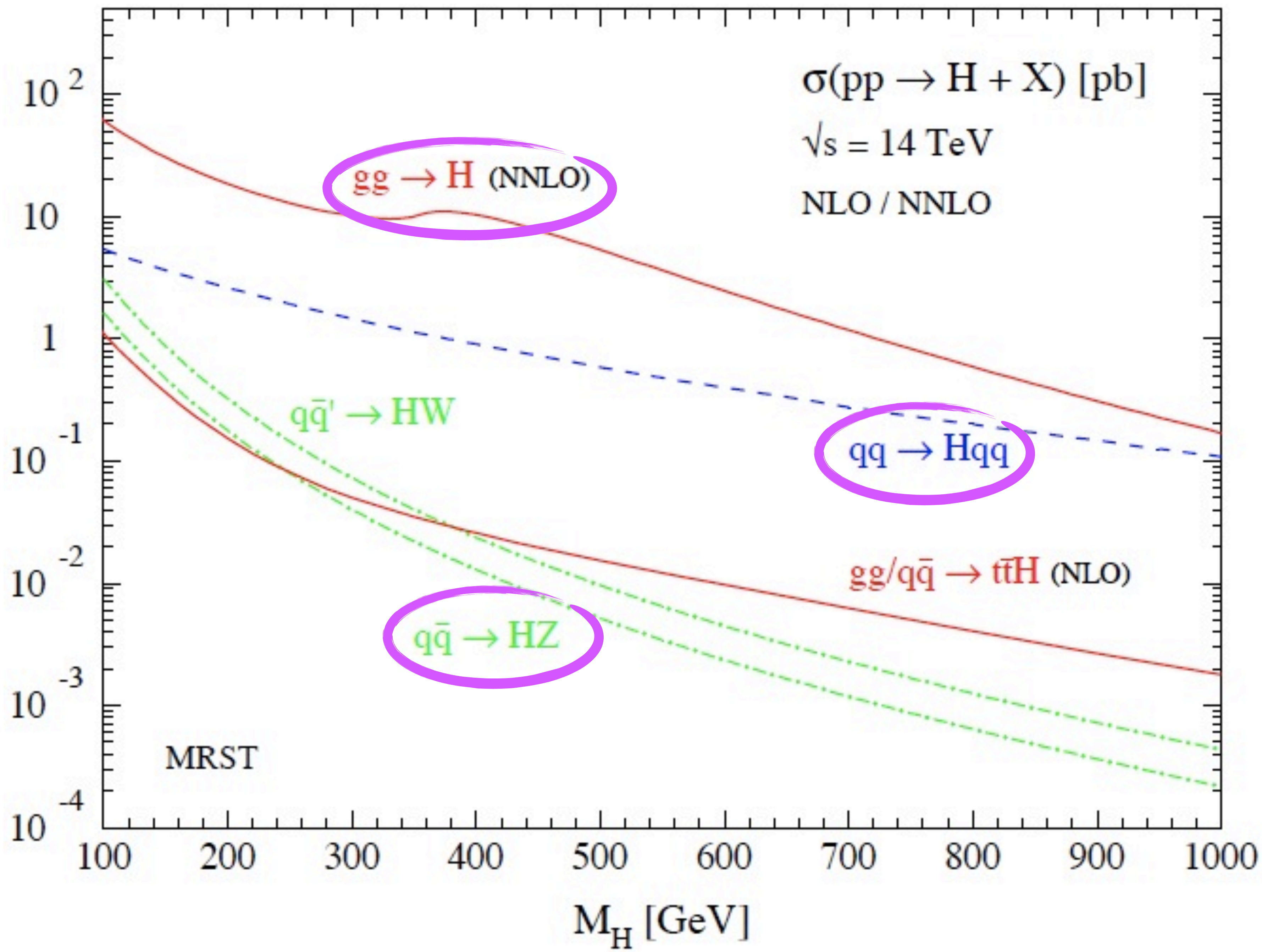
→ Check the Spin and CP nature

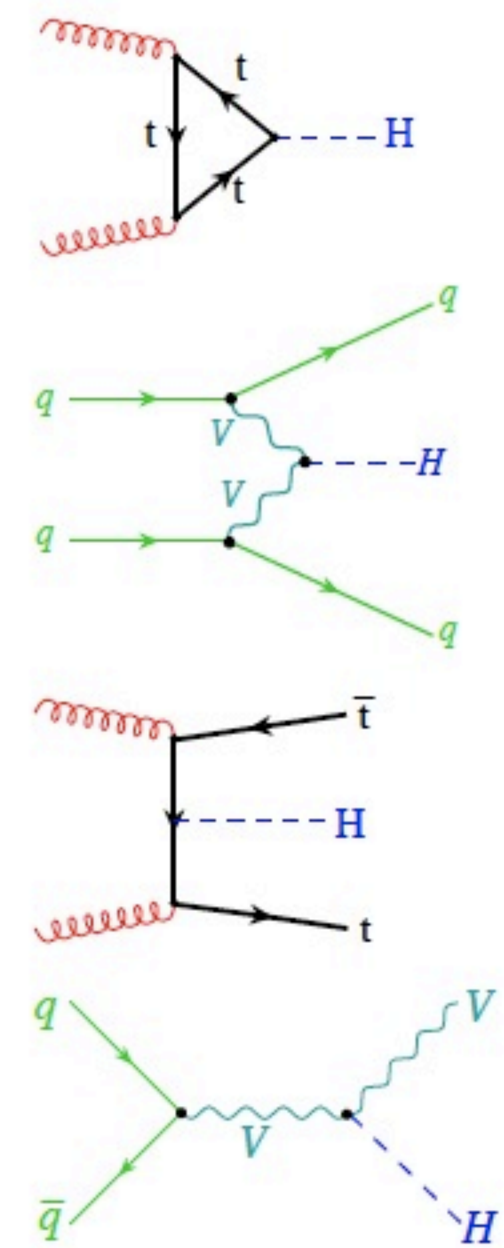
→ Check the operator basis

→ Then measure its couplings to the other particles

- We propose to determine the coupling structure, spin and CP nature using angular correlations via WBF (and associated ZH production).

Higgs Production at the LHC



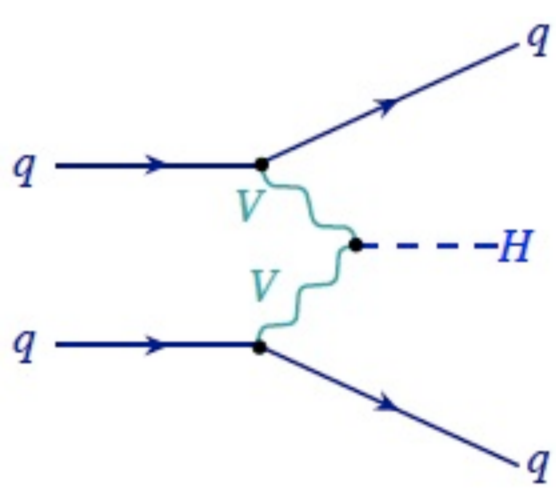


Lagrangian

- Spin zero:

$$\mathcal{L}_0 = g_1^{(0)}\, H V_\mu V^\mu - \frac{g_2^{(0)}}{4}\, H\, V_{\mu\nu} V^{\mu\nu} - \frac{g_3^{(0)}}{4}\, A\, V_{\mu\nu} \widetilde{V}^{\mu\nu} - \frac{g_4^{(0)}}{4}\, H\, G_{\mu\nu} G^{\mu\nu} - \frac{g_5^{(0)}}{4}\, A\, G_{\mu\nu} \widetilde{G}^{\mu\nu}$$

CP even and odd scalars $X = H, A$; $V = W, Z$ and $G = \text{gluon}$



Lagrangian

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CP even and odd scalars $X = H, A$; $V = W, Z$ and $G = \text{gluon}$

- Spin one:

$$\begin{aligned}\mathcal{L}_1 = & \; i g_1^{(1)} (W^+_{\mu\nu} W^{-\mu} - W^-_{\mu\nu} W^{+\mu})\, Y^{(e)\nu} + i g_2^{(1)} W^+_\mu W^-_\nu \; Y^{(e)\mu\nu} \\ & + g_3^{(1)} \epsilon^{\mu\nu\rho\sigma} (W^+_\mu \overleftrightarrow{\partial}_\rho W^-_\nu) Y^{(e)}_\sigma + i g_4^{(1)} W^+_{\sigma\mu} W^{-\mu\nu} Y^{(e)\sigma}_\nu \\ & - g_5^{(1)} W^+_\mu W^-_\nu (\partial^\mu Y^{(o)\nu} + \partial^\nu Y^{(o)\mu}) + i g_6^{(1)} W^+_\mu W^-_\nu \widetilde{Y}^{(o)\mu\nu} + i g_7^{(1)} W^+_{\sigma\mu} W^{-\mu\nu} \widetilde{Y}^{(o)\sigma}_\nu \\ & + g_8^{(1)} \epsilon^{\mu\nu\rho\sigma} Y^{(e)}_\mu Z_\nu (\partial_\rho Z_\sigma) + g_9^{(1)} Y^{(o)}_\mu (\partial_\nu Z^\mu) Z^\nu \; .\end{aligned}$$

- Spin two:

$$\mathcal{L}_2 = -g_1^{(2)}\; G_{\mu\nu} T^{\mu\nu}_V - g_2^{(2)}\; G_{\mu\nu} T^{\mu\nu}_G - g_3^{(2)}\; G_{\mu\nu} T^{\mu\nu}_f$$

Models

	initial state	couplings	
$0^+_{\rm SM}$	qq	$g_1^{(0)}$	SM Higgs scalar (D3 coupling to W, Z)
$0^+_{\rm D5}$	qq	$g_2^{(0)}$	scalar (D5 coupling to W, Z)
$0^-_{\rm D5}$	qq	$g_3^{(0)}$	pseudo-scalar (D5 coupling to W, Z)
$0^+_{\rm D5g}$	qq, qg, gg	$g_4^{(0)}$	scalar (D5 coupling to gluons)
$0^-_{\rm D5g}$	qq, qg, gg	$g_5^{(0)}$	pseudo-scalar (D5 coupling to gluons)
1^-_W	qq	$g_5^{(1)} = g_6^{(1)}$	D4 couplings to W
1^-_Z	qq	$g_9^{(1)}$	vector coupling to Z
1^+_W	qq	$g_1^{(1)} = g_2^{(1)}$	D4 couplings to W
1^+_Z	qq	$g_8^{(1)}$	axial-vector coupling to Z
$2^+_{\rm EW}$	qq	$g_1^{(2)}$	tensor coupling to W, Z
$2^+_{\rm EW+q}$	qq	$g_1^{(2)} = g_3^{(2)}$	tensor coupling to W, Z and fermions
$2^+_{\rm QCD}$	qq, qg, gg	$g_2^{(2)}$	tensor coupling to gluons
2^+	qq, qg, gg	$g_1^{(2)} = g_2^{(2)} = g_3^{(2)}$	graviton-like tensor

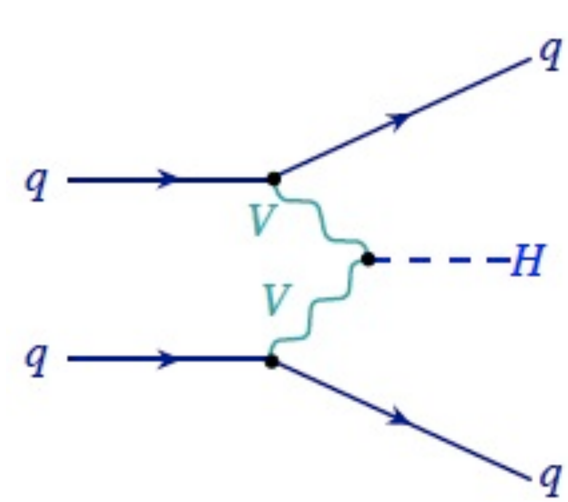
Hadron collider observables

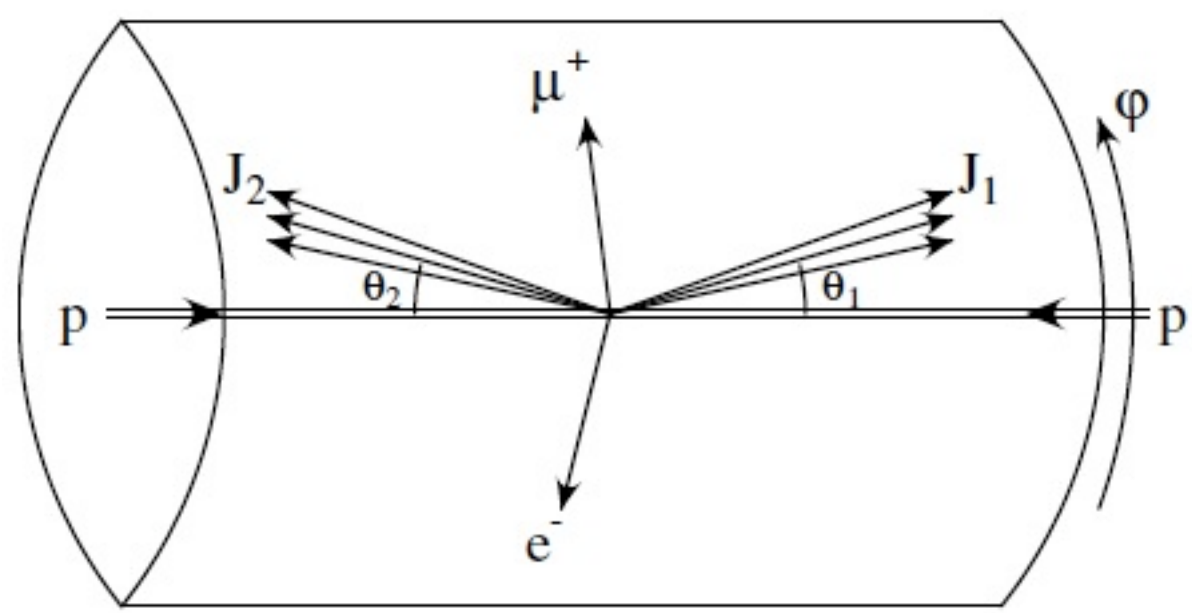
- The momentum of a produced particle is expressed by the polar angle θ and the azimuthal angle Φ from the collision point, where the z-axis is taken along the beam axis.

- Rapidity η is often used instead of θ: $\eta = -1/2 \ln \tan(\theta/2)$

  $\eta \sim 0 \Leftrightarrow \theta \sim 90°$ (central region)

  $\eta \sim 2.5 \Leftrightarrow \theta \sim 10°$ (forward region)





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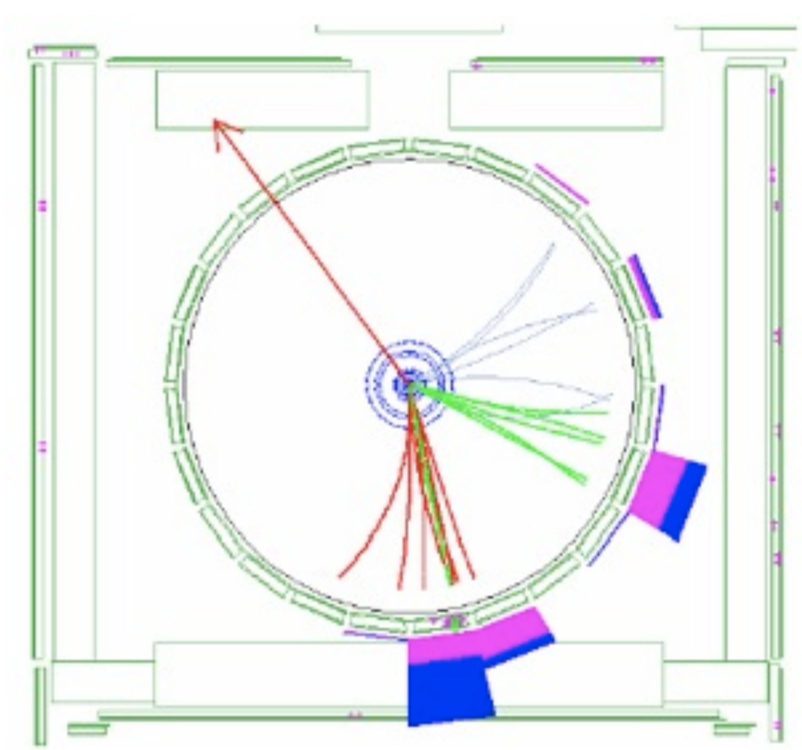
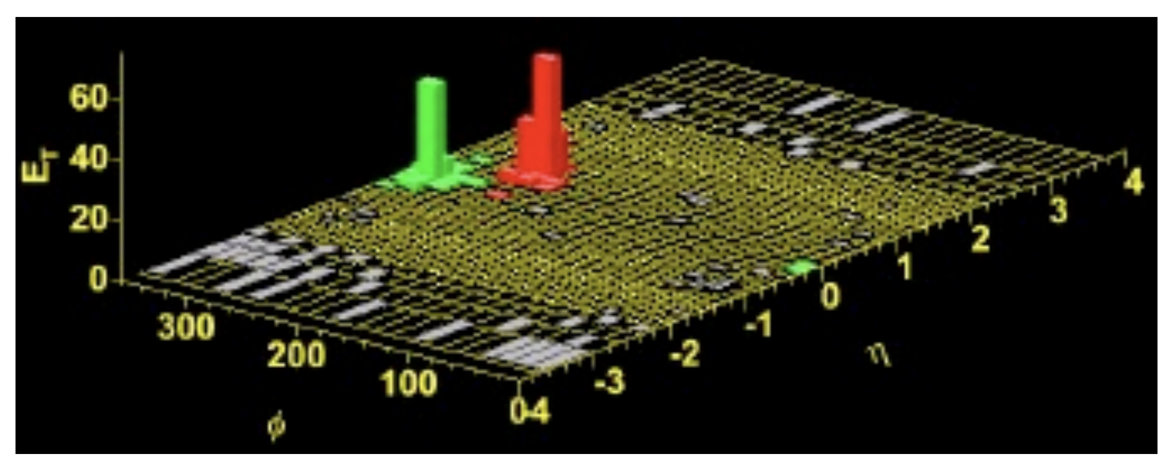
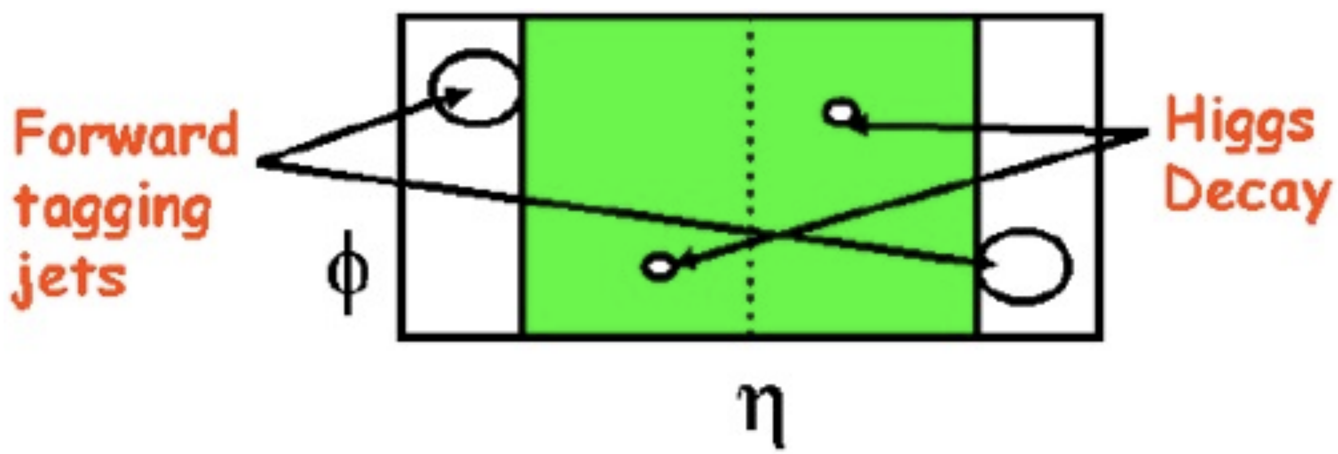


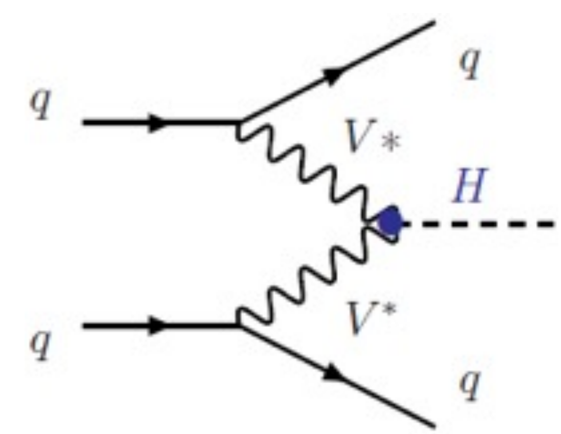


Hadron collider observables

- VBF distinctive jet Kinematics:

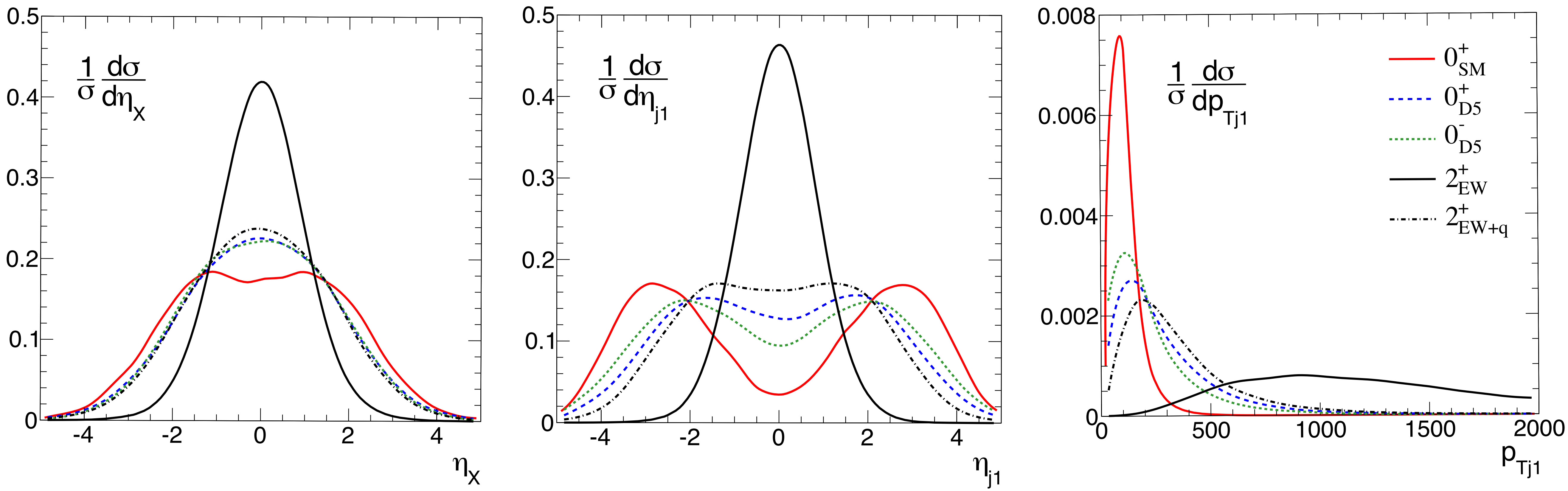


- $VBF : q_1 q_2 \to j_1 j_2 \, (X \to d\bar{d})$



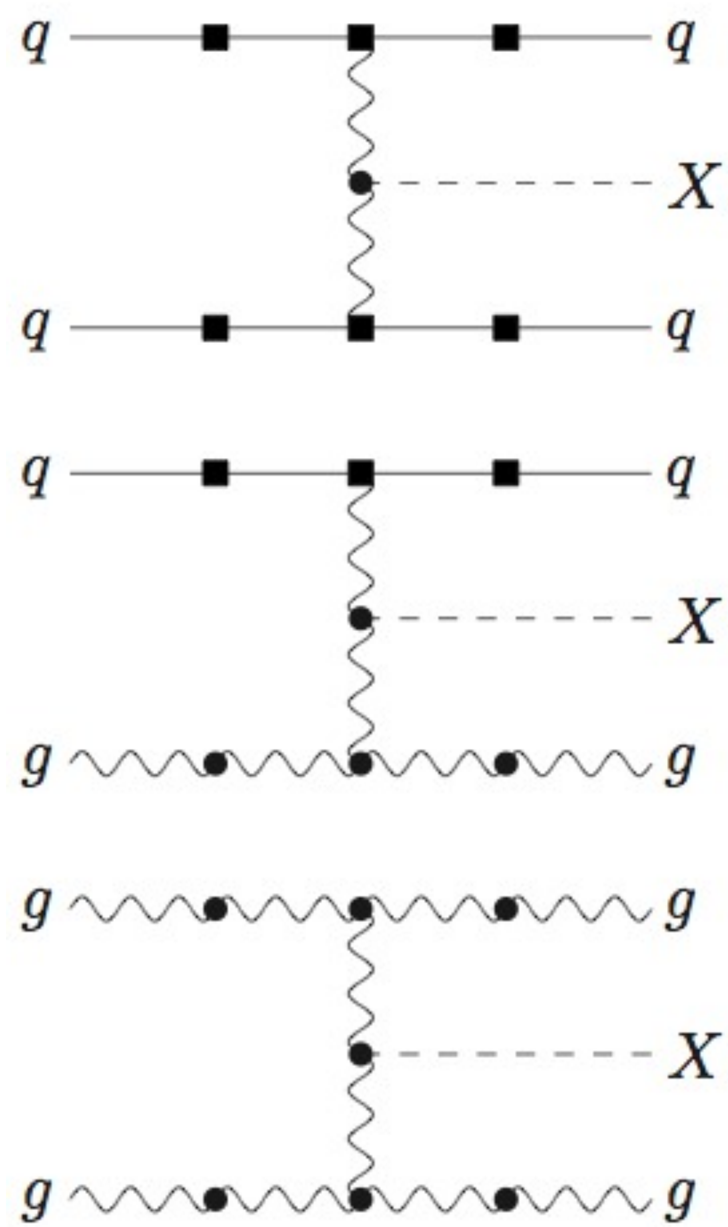
➡ $\{\Delta\eta_{mn}, \Delta\phi_{mn}\} \quad \text{for} \quad m, n = j_{1,2}, X, d, \bar{d}$

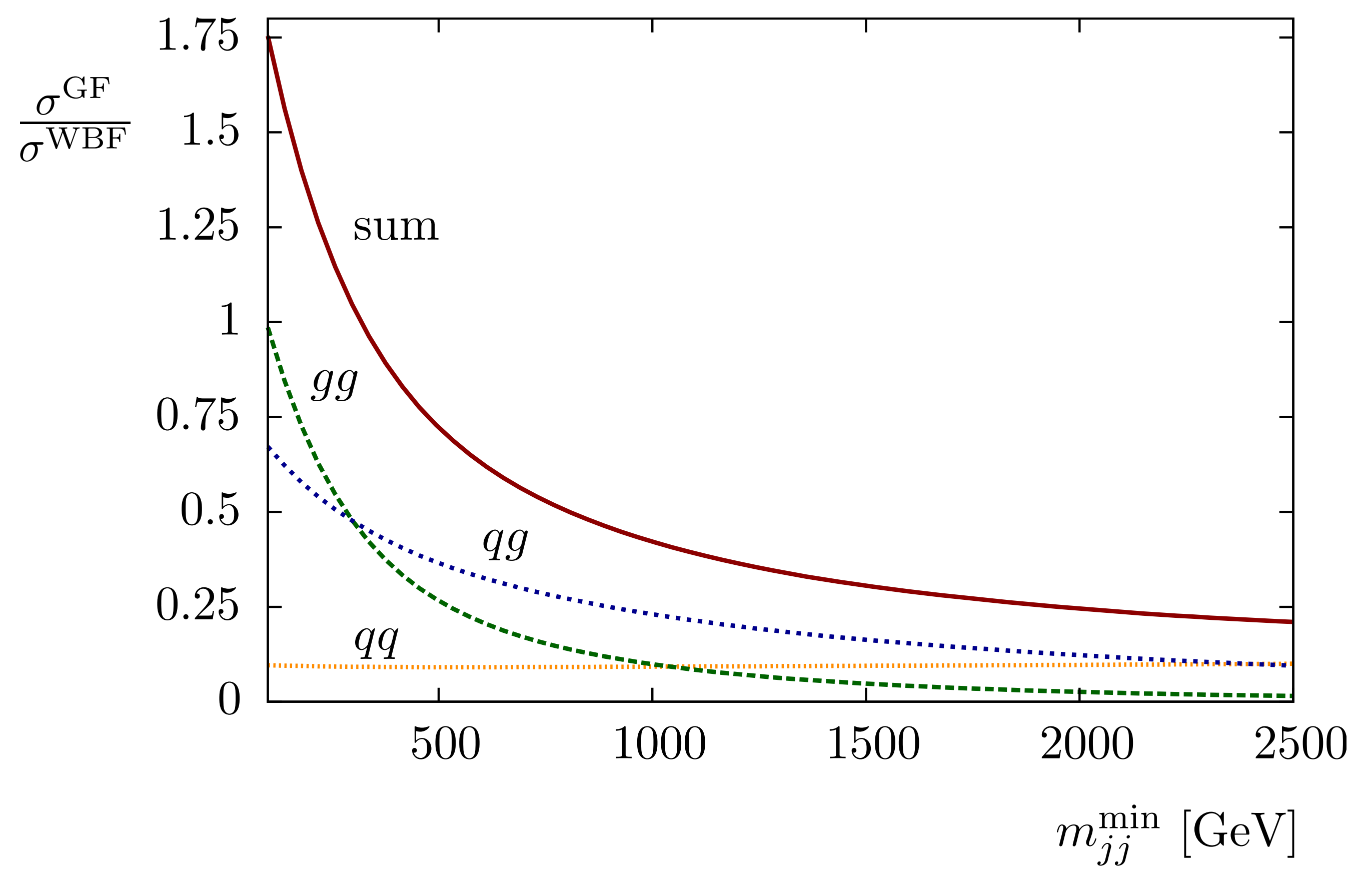
Tagging jet kinematics



- Central X production
- Spin-0 forward tagging jets
- Spin-2 central tagging jets
- Spin-2 PT go beyond the TeV scale. Consistent models will include a form factor to cut this tail

Contaminating sub-process for WBF

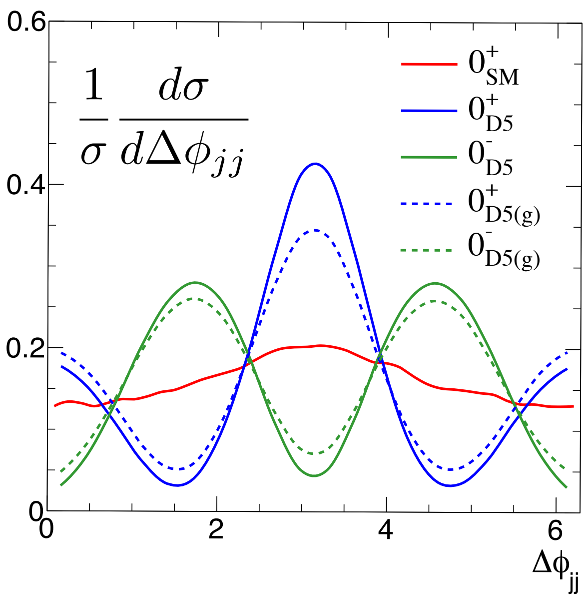




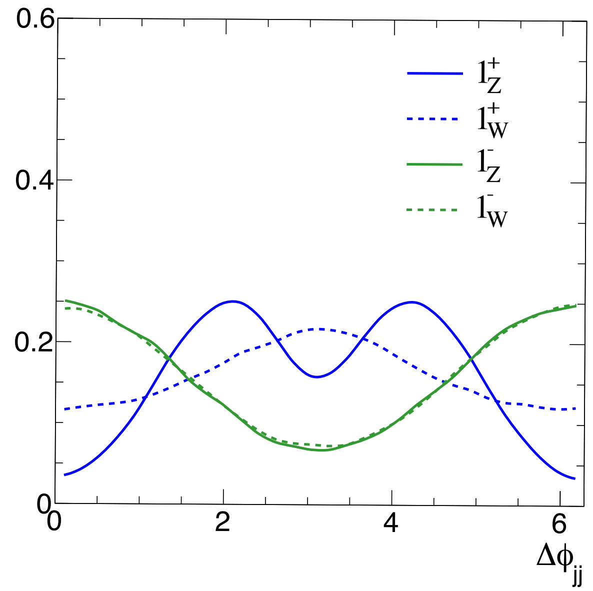
- $m_{jj} > 600\,\text{GeV}$ Gluon fusion is suppressed to 50%
- Jet veto reduces it to 10%

Tagging jet kinematics

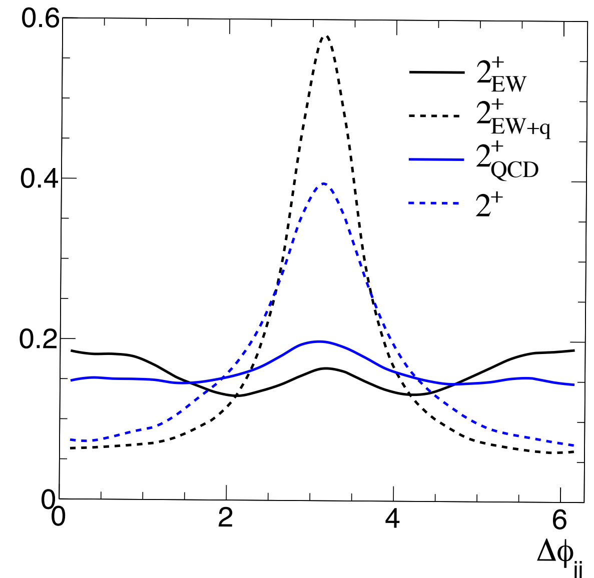
spin-0



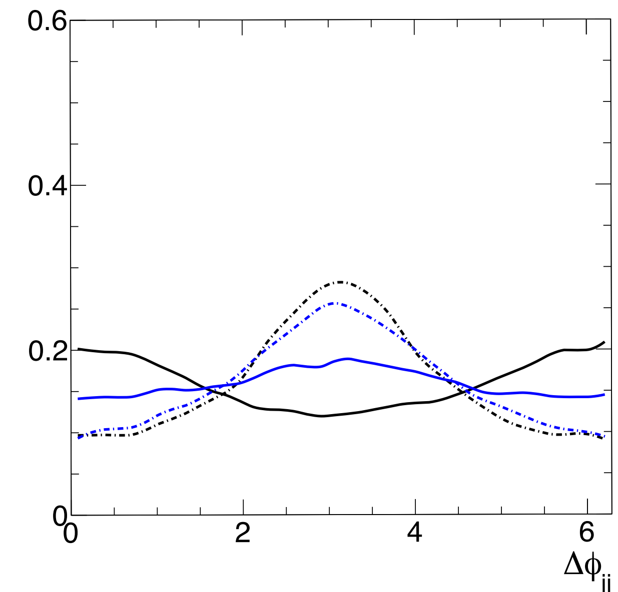
spin-1



spin-2



spin-2 PTj>100GeV



$$\frac{d\sigma}{d\Delta\phi_{jj}} \sim constant$$

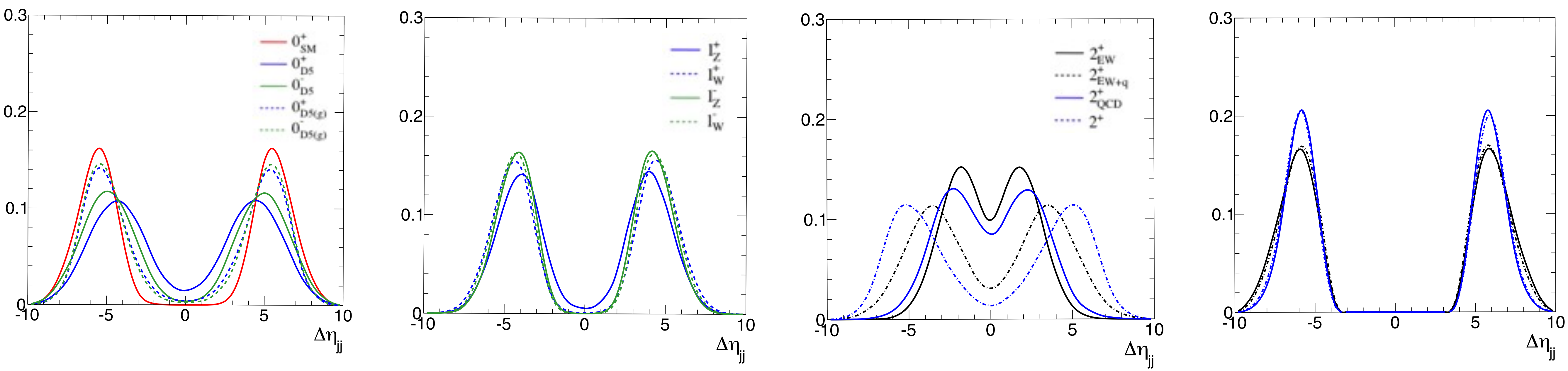
$$\frac{d\sigma}{d\Delta\phi_{jj}} \sim cos2\Delta\phi_{jj}$$

$$\frac{d\sigma}{d\Delta\phi_{jj}} \sim -cos2\Delta\phi_{jj}$$

Plehn, Rainwater, Zeppenfeld (2002)

Tagging jet kinematics

spin-0 spin-1 spin-2 spin-2 PTj>100GeV



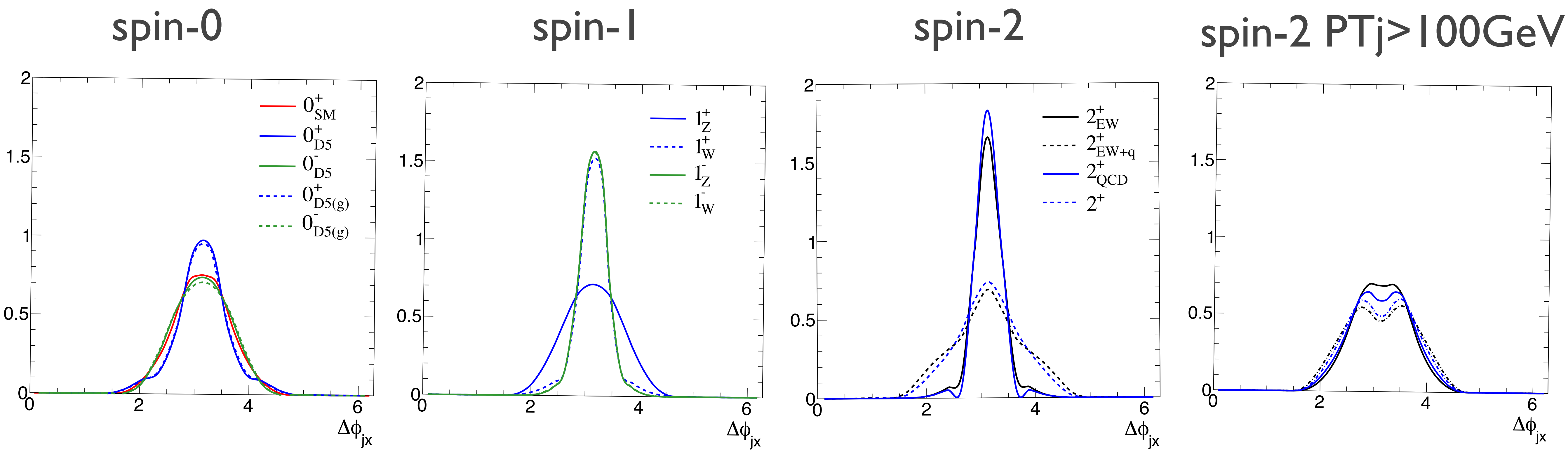
- In our analysis we avoid the standard WBF cut $\Delta\eta_{jj} > 4.2$

  This makes our set of observables more powerful to distinguish the hypothesis

- Spin-2, in contrary to the spin-0, does not present a large rapidity gap

- The cut $P_{T_{j1}} > 100\,\mathrm{GeV}$ selects the same helicity state as the spin-0

Higgs-jet correlations



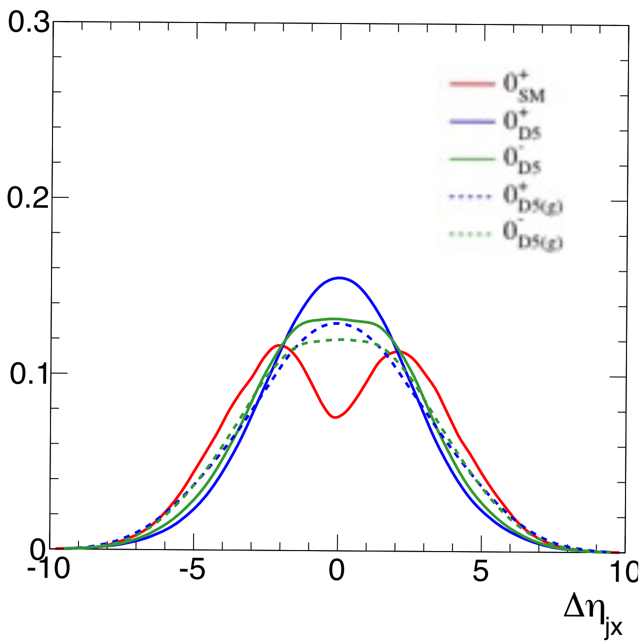
- Requires reconstruction of the heavy resonance:

  $X \to \gamma\gamma$ most promising channel

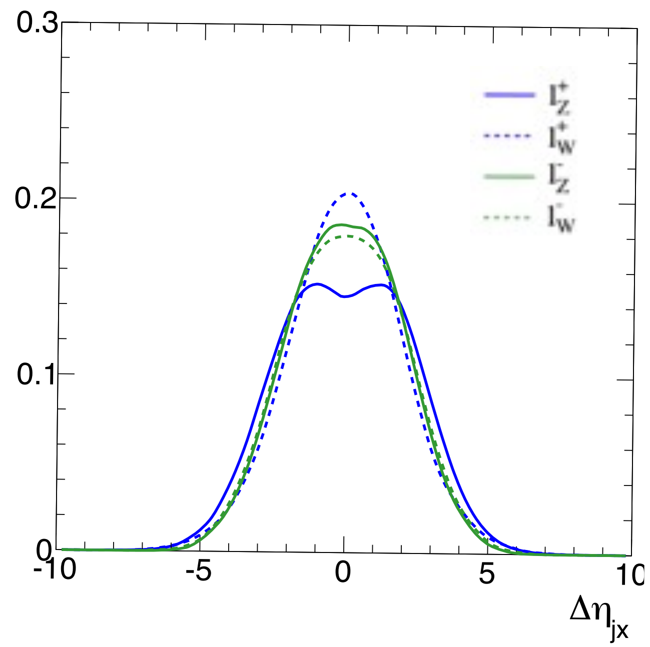
  $X \to \tau\tau$ approximate reconstruction

Higgs-jet correlations

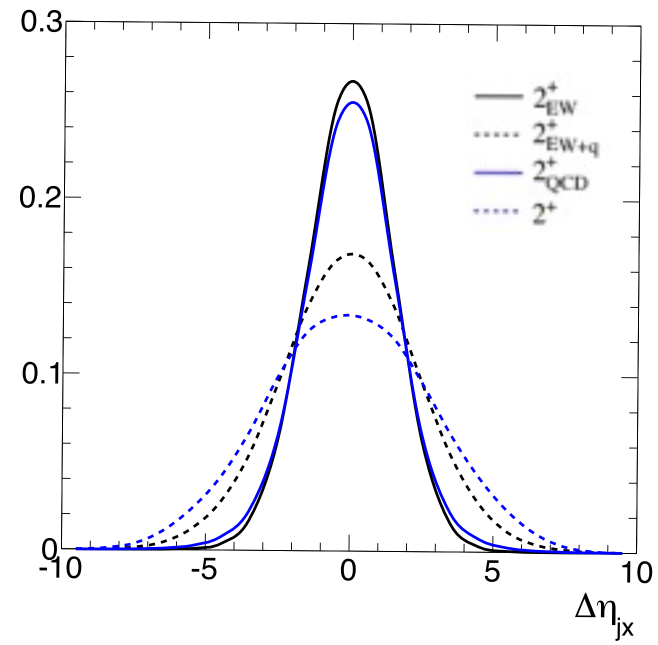
spin-0



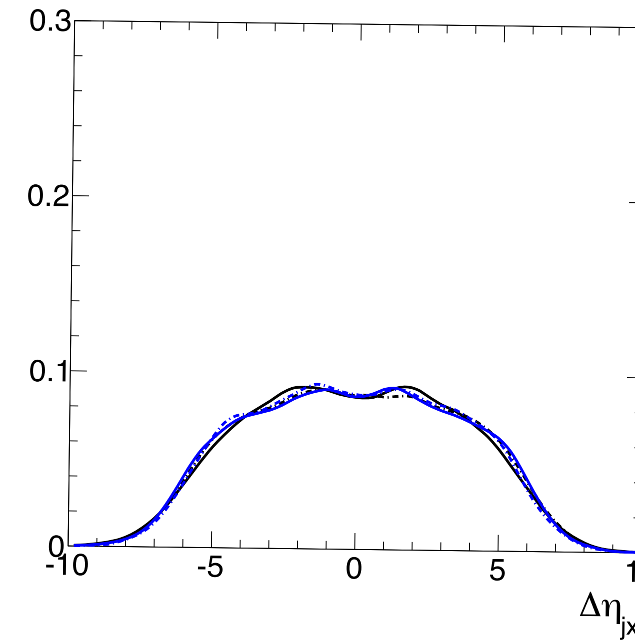
spin-1



spin-2



spin-2 PTj>100GeV



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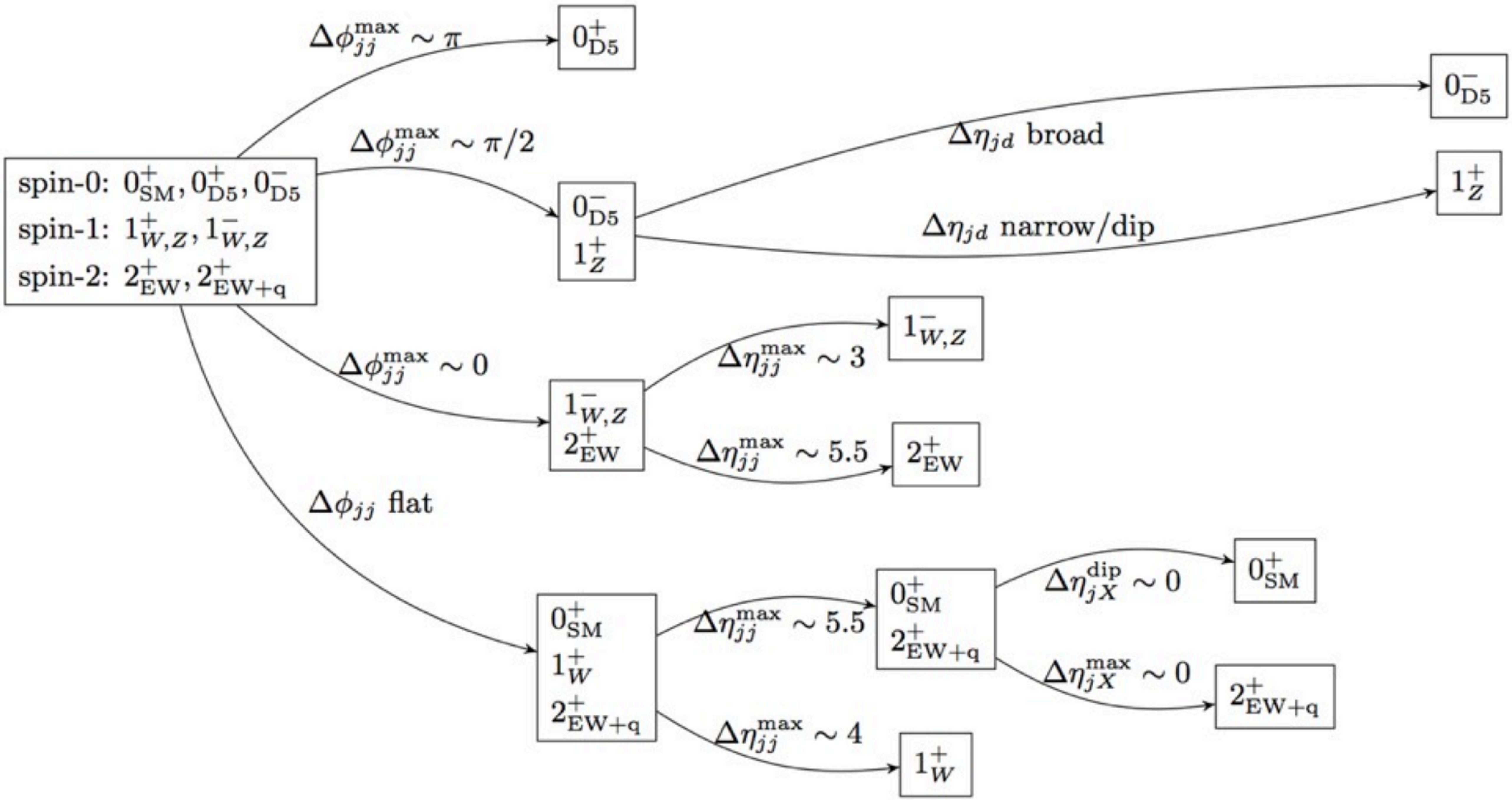
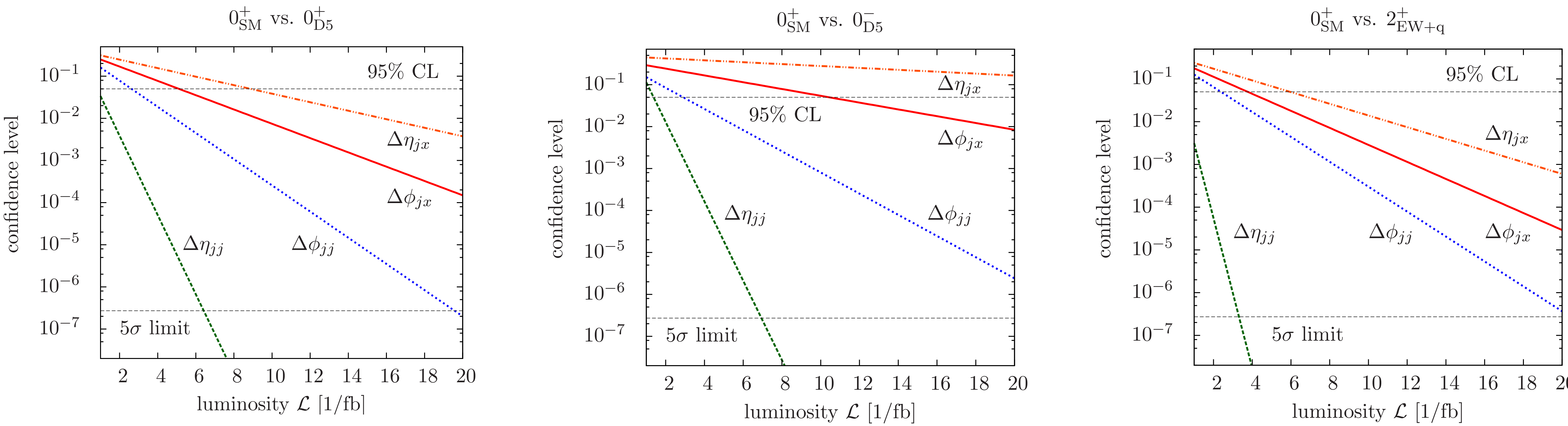
Basic strategy



Comparison of observables

- Confidence level for distinction from the SM hypothesis.



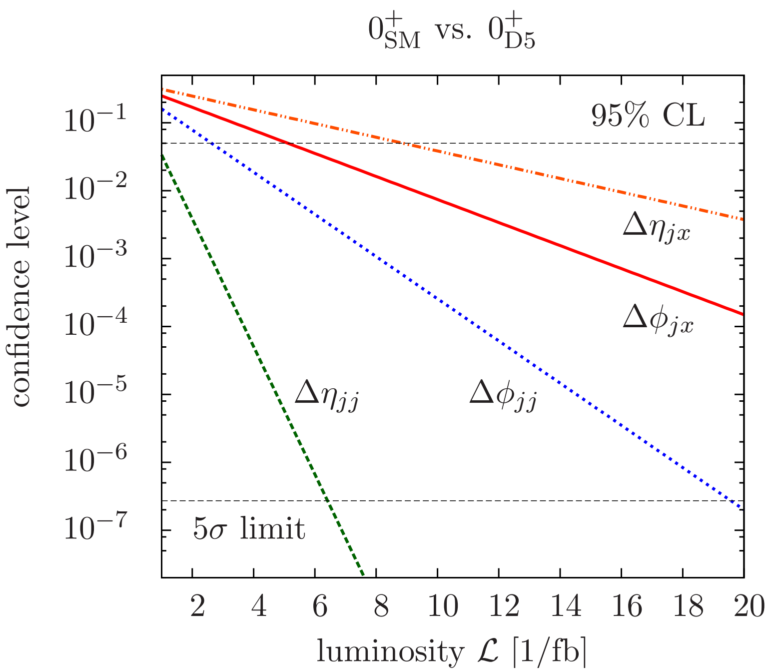
➡ Makes the analysis competitive with the standard $X \to ZZ$

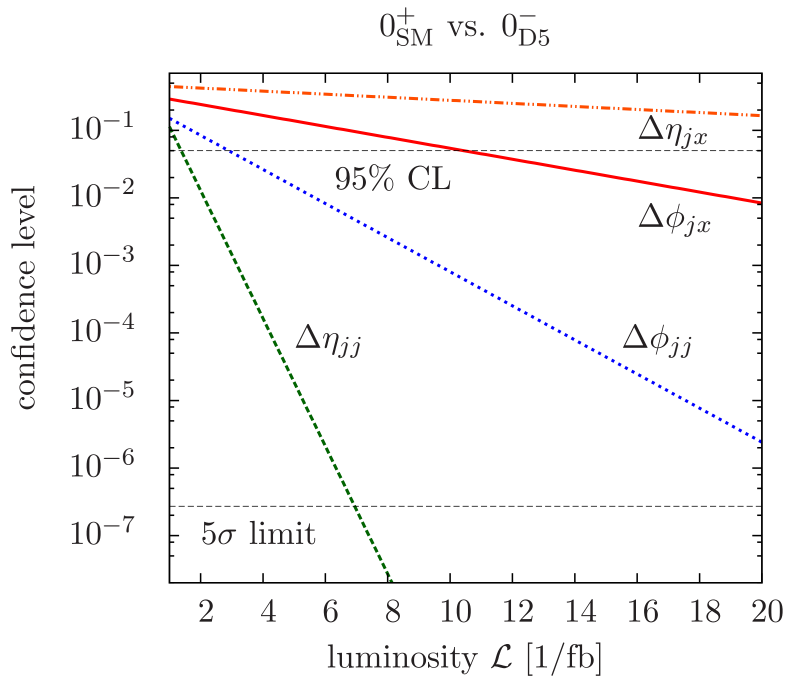
➡ Most powerful observables: $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$

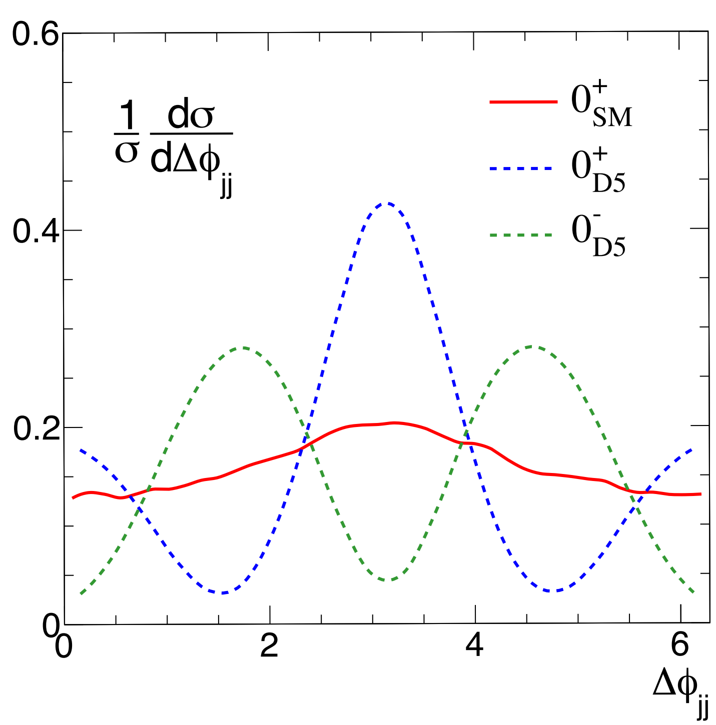
➡ It is essential avoiding the standard rapidity gap cut for WBF in this analysis

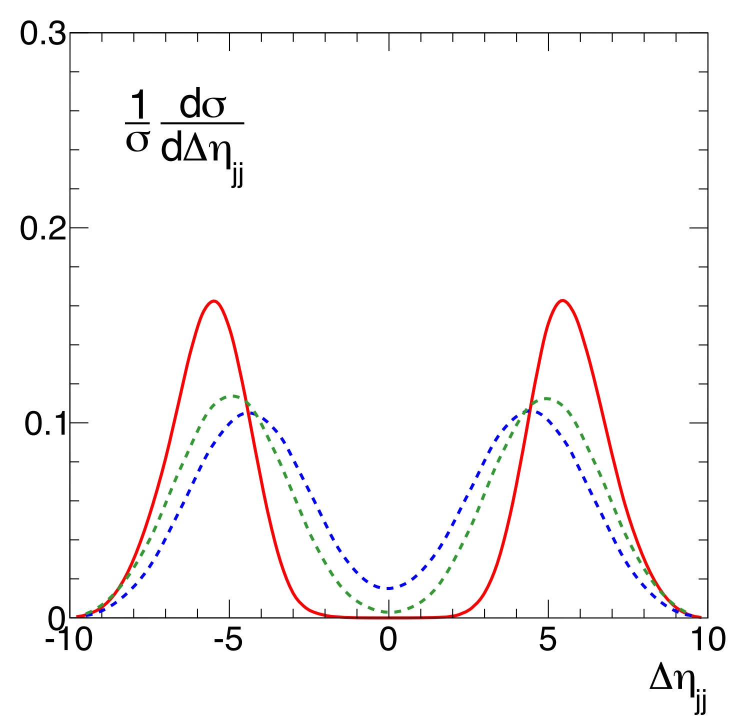
Comparison of observables

- Confidence level for distinction from the SM hypothesis.







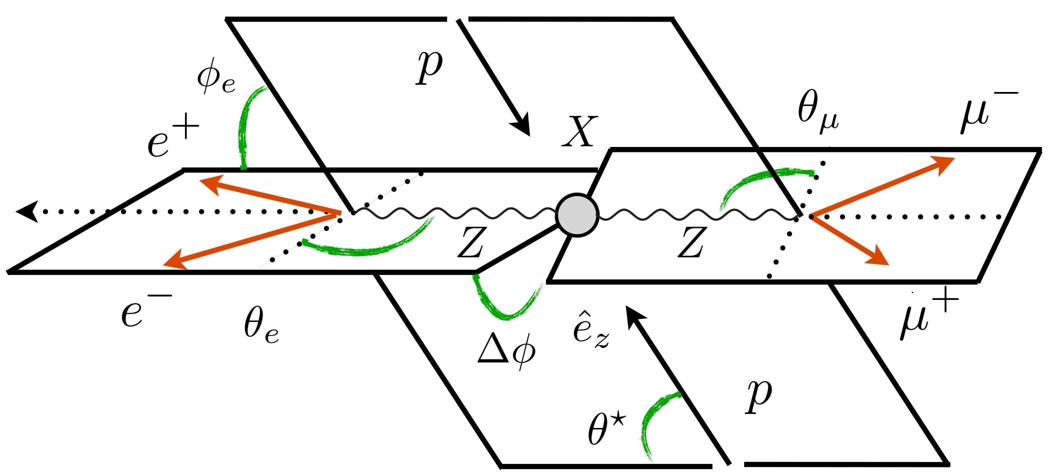


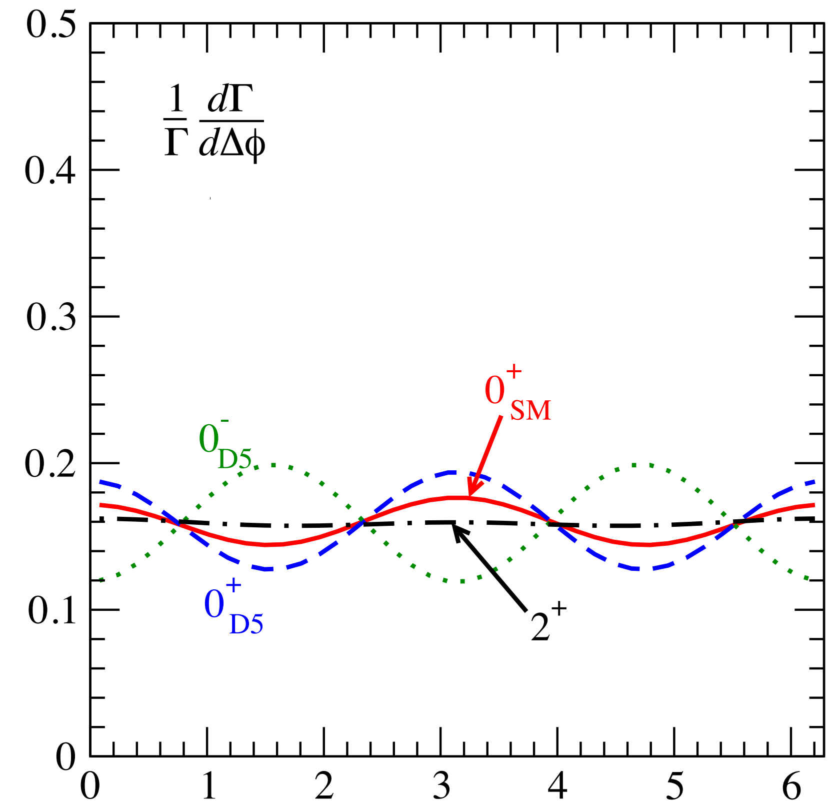
Summary

- After the 'Higgs' discovery the main challenge is to confirm its Lagrangian
  - We present a comprehensive study of the determination of it in WBF
  - Most powerful observables: $\Delta\eta_{jj}$ and $\Delta\phi_{jj}$
  - It is required very low luminosity to distinguish the hypothesis $\sim 10 fb^{-1}$
  - The analysis is competitive with the standard $X \to ZZ$

Nelson angles

- $X \to ZZ \to 4l$





- Nelson angles (standard approach):

$$\cos\theta_e = \hat{p}_{e^-} \cdot \hat{p}_{Z_\mu}\Big|_{Z_e} \qquad \cos\theta_\mu = \hat{p}_{\mu^-} \cdot \hat{p}_{Z_e}\Big|_{Z_\mu} \qquad \cos\theta^* = \hat{p}_{Z_e} \cdot \hat{p}_{\mathrm{beam}}\Big|_X$$

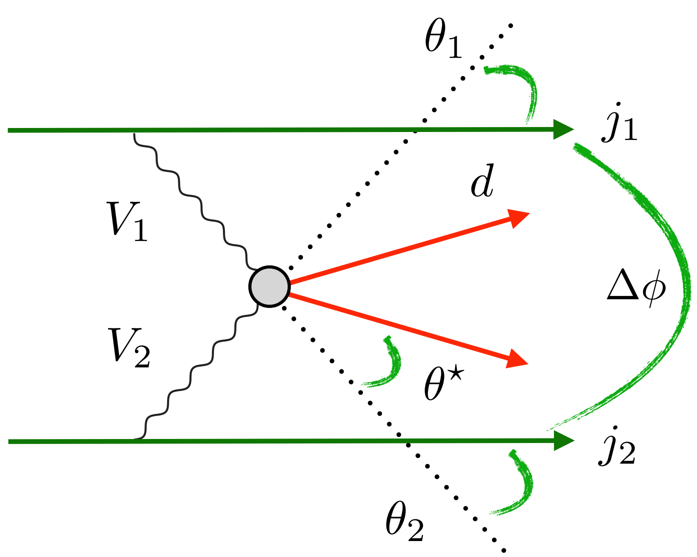
$$\cos\phi_e = (\hat{p}_{\mathrm{beam}} \times \hat{p}_{Z_\mu}) \cdot (\hat{p}_{Z_\mu} \times \hat{p}_{e^-})\Big|_{Z_e} \qquad \cos\Delta\phi = (\hat{p}_{e^-} \times \hat{p}_{e^+}) \cdot (\hat{p}_{\mu^-} \times \hat{p}_{\mu^+})\Big|_X .$$

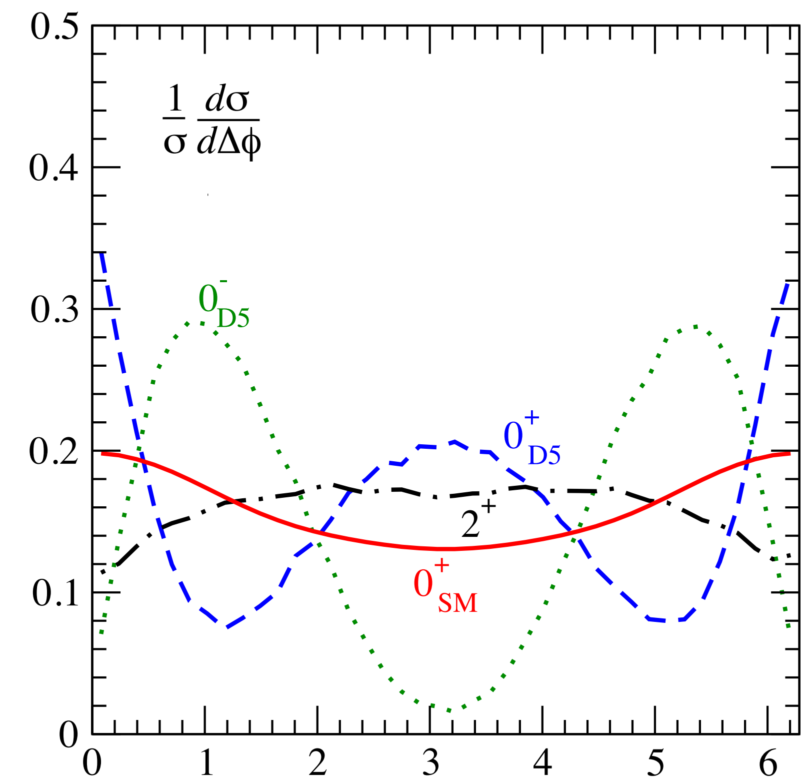
S.Y.Choi, Miller, Muhlleitner, Zerwas, PLB(2003)

Y. Gao, A. Gritsan, Z. Guo, K. Melnikov, M. Schulze, N. Tran (2010)

Flipped Nelson

- $VBF : q_1 q_2 \to j_1 j_2 \left(X \to d\bar{d}\right)$





- Flipped Nelson angles:

$$\cos\theta_1 = \hat{p}_{j_1}\cdot\hat{p}_{V_2}\Big|_{V_1\,\mathrm{Breit}} \qquad \cos\theta_2 = \hat{p}_{j_2}\cdot\hat{p}_{V_1}\Big|_{V_2\,\mathrm{Breit}} \qquad \cos\theta^* = \hat{p}_{V_1}\cdot\hat{p}_{d}\Big|_{X}$$

$$\cos\phi_1 = \left(\hat{p}_{V_2}\times\hat{p}_d\right)\cdot\left(\hat{p}_{V_2}\times\hat{p}_{j_1}\right)\Big|_{V_1\,\mathrm{Breit}} \qquad \cos\Delta\phi = \left(\hat{p}_{q_1}\times\hat{p}_{j_1}\right)\cdot\left(\hat{p}_{q_2}\times\hat{p}_{j_2}\right)\Big|_{X}\,.$$

➡ It assumes the completely reconstruction of the hard process
Not well suited for dealing with QCD effects at a Hadron Collider