Part - II

Varying fundamental constants and particle physics

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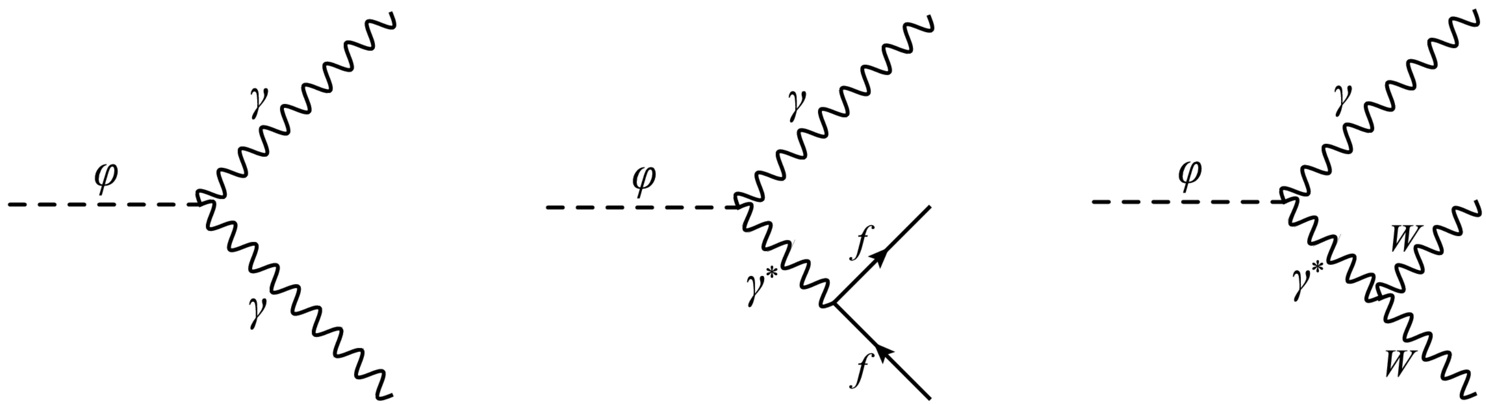
Based on 1601.00624 & 1612.01192

Effective Lagrangian

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}{M_\phi}^2\phi^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2\Lambda}\phi F_{\mu\nu}F^{\mu\nu}$$

- Very economical & predictive model. Two free parameters.
- Other than a scalar, no new particle is present
- This scalar does not couple to *gg*, photon-Z, ZZ or WW

Decay modes

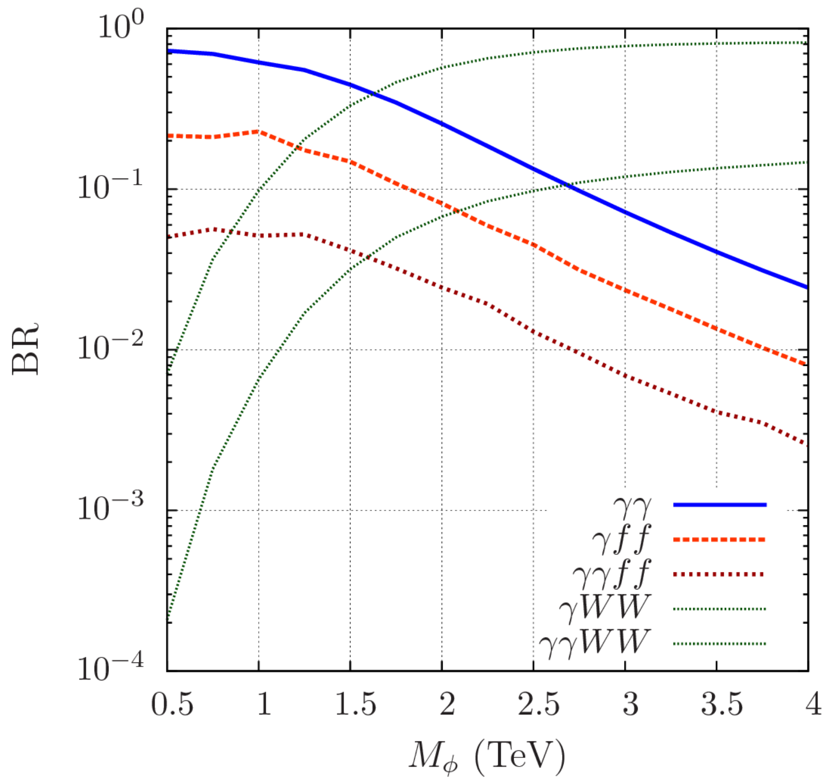


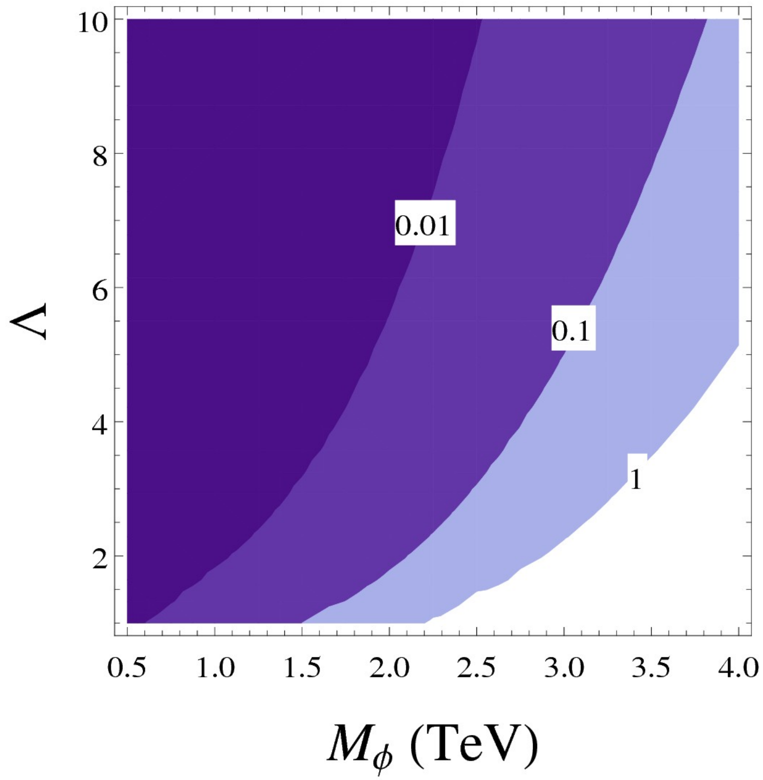
Decay Mode	$\phi \to \gamma\gamma$	$\phi \to \gamma f f (jj)$	$\phi \to \gamma W W$	Total
Width (GeV)	5.0	1.9 (0.86)	0.79	7.6
BR (%)	65	25 (11)	10	-

$$M_\phi = 1 \text{ TeV}; \quad \Lambda = 2 \text{ TeV}$$

- BRs are independent of scale, only depends on mass
- Diphoton BR is as large as 65% (a photophilic scalar)

Branching ratios and total width

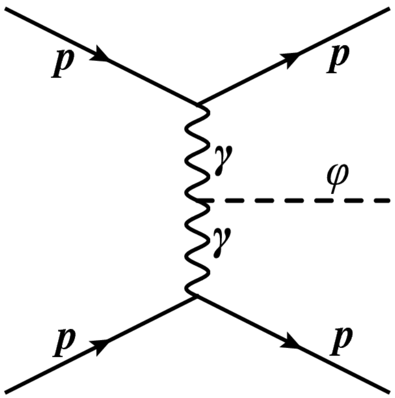




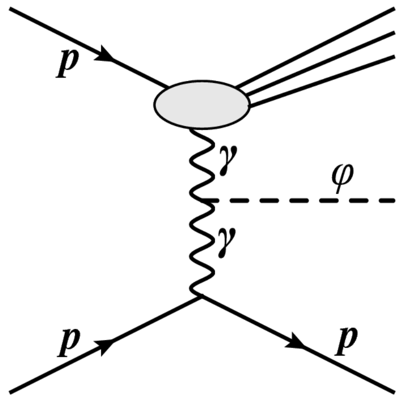
Total width increases very fast due to longitudinal-W contribution

New physics to control rapid growth – perturbativity & unitarity

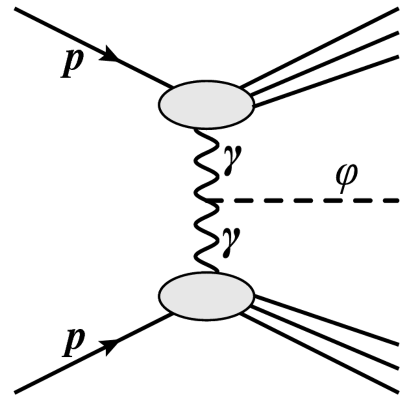
Production at the LHC



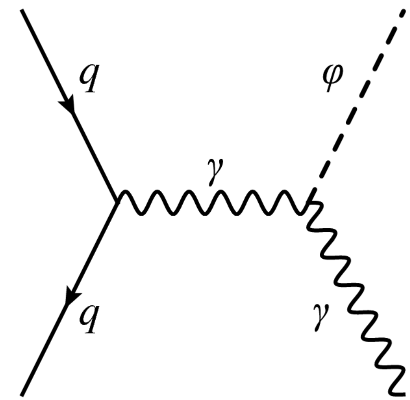
Central exclusive production



Semi-elastic production



VBF: inelastic production



Associated production

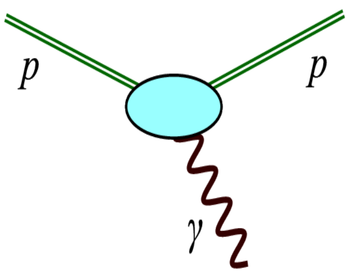
Production mode	$\gamma\gamma \to \phi$	$\gamma p \to \phi j$	$pp \to \phi jj$	$pp \to \phi\gamma$	$pp \to \phi\gamma j$	$pp \to \phi\gamma jj$
CS@8TeV (fb)	32.18	7.841	0.451	0.182	0.095	0.043
CS@13TeV (fb)	110.5	29.94	1.846	1.116	0.711	0.396

$$M_\phi = 1\ \text{TeV}; \quad \Lambda = 2\ \text{TeV}$$

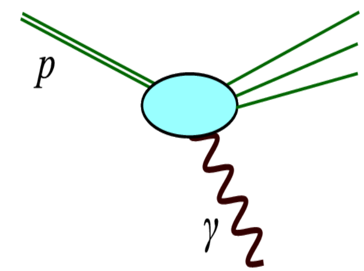
Different from most "solutions" to the 750 GeV dead-excess in that it is Produced in photon-photon or quark-quark initial states

Uncertainties in photon-flux

Photon-fusion contribution can be very large due to IR enhancement in the collinear limit (equivalent / Weizsacker-Williams photon approximation)



Various uncertainties



Elastic photon-flux

Inelastic photon-flux

Cross section crucially depends on the proton form-factors

In the forward limit, IR singularities are cutoff by the finite size of the proton

Leading order computation is not a good approximation and one should take into account the large collinear logarithms properly for robust predictions

Examples from literature

C. Csaki, J. Hubisz, S. Lombardo, J. Terning [1601.00638]

$$\sigma_{13\ \mathrm{TeV}} = 10.8\ \mathrm{pb} \left(\frac{\Gamma}{45\ \mathrm{GeV}} \right) \mathrm{BR}^2(R \to \gamma\gamma)$$

$$\sigma_{8\ \mathrm{TeV}} = 5.5\ \mathrm{pb} \left(\frac{\Gamma}{45\ \mathrm{GeV}} \right) \mathrm{BR}^2(R \to \gamma\gamma)$$

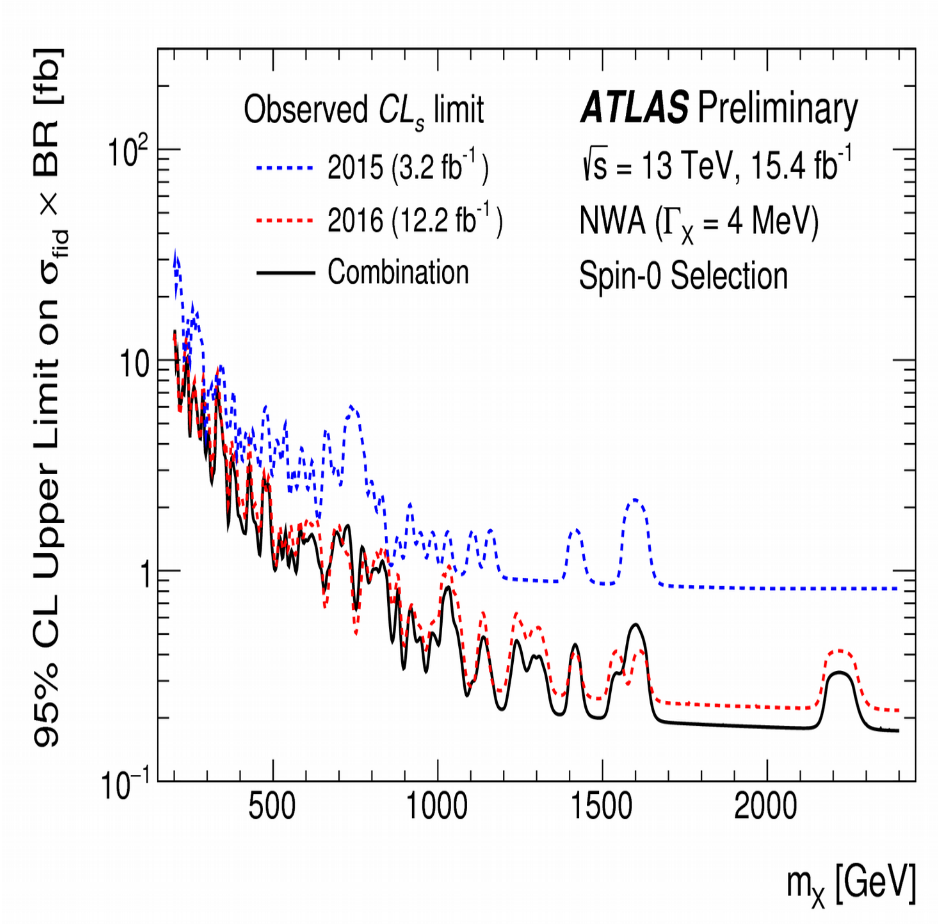
M. Ababekri, S. Dulat, J. Isaacson, C. Schmidt, C. P. Yuan [1603.04874]

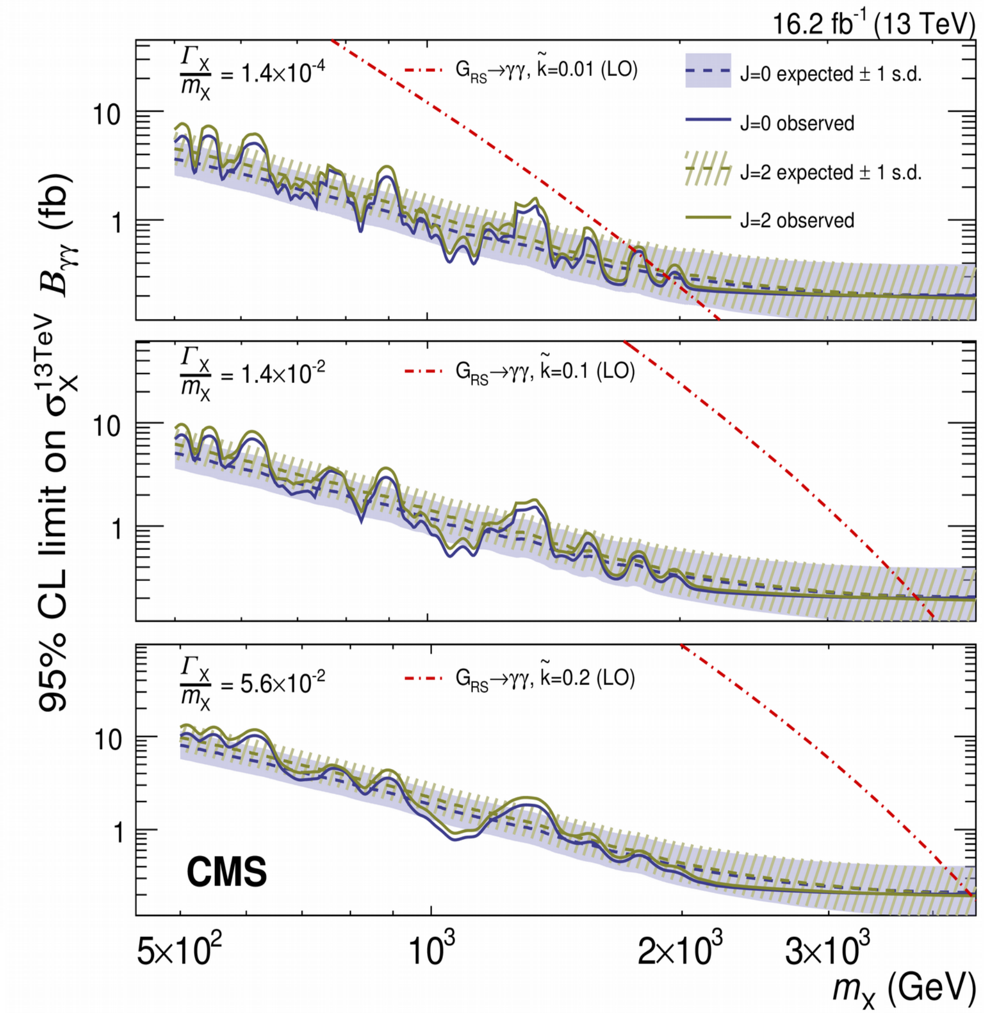
$$\sigma_{13\ \mathrm{TeV}} = [1.7\ \mathrm{pb} - 3.6\ \mathrm{pb}] \left(\frac{\Gamma}{45\ \mathrm{GeV}} \right) \mathrm{BR}^2(R \to \gamma\gamma)$$

$$\sigma_{8\ \mathrm{TeV}} = [0.5\ \mathrm{pb} - 1.3\ \mathrm{pb}] \left(\frac{\Gamma}{45\ \mathrm{GeV}} \right) \mathrm{BR}^2(R \to \gamma\gamma)$$

Why so different? Need to understand various issues in the photon-flux

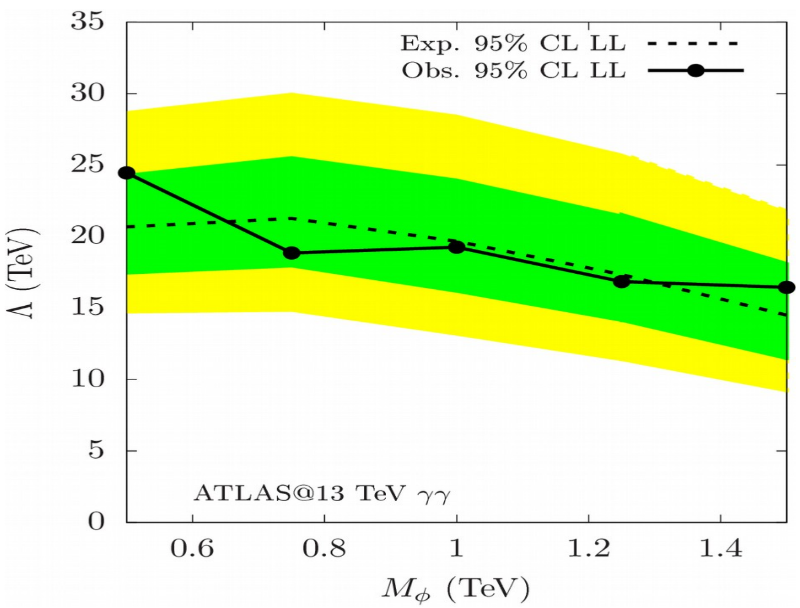
Cross section upper limits

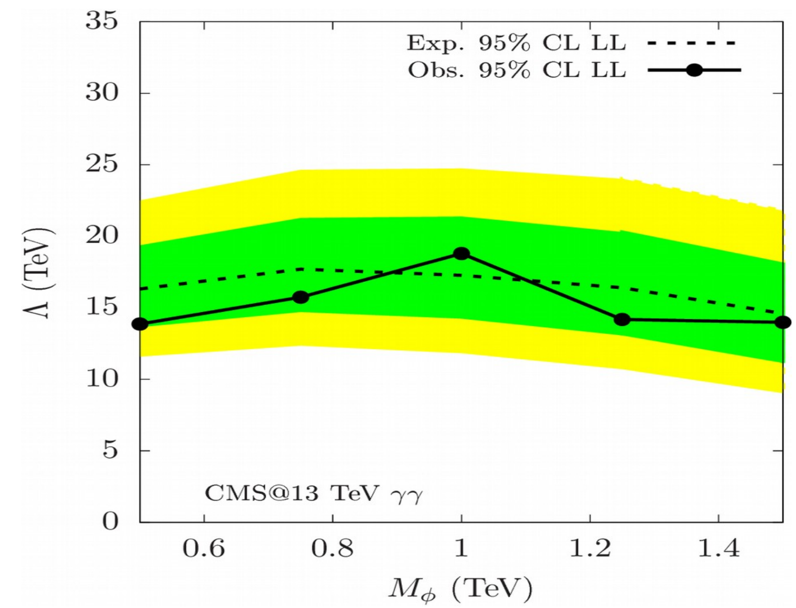




Assumption: gluon-gluon fusion

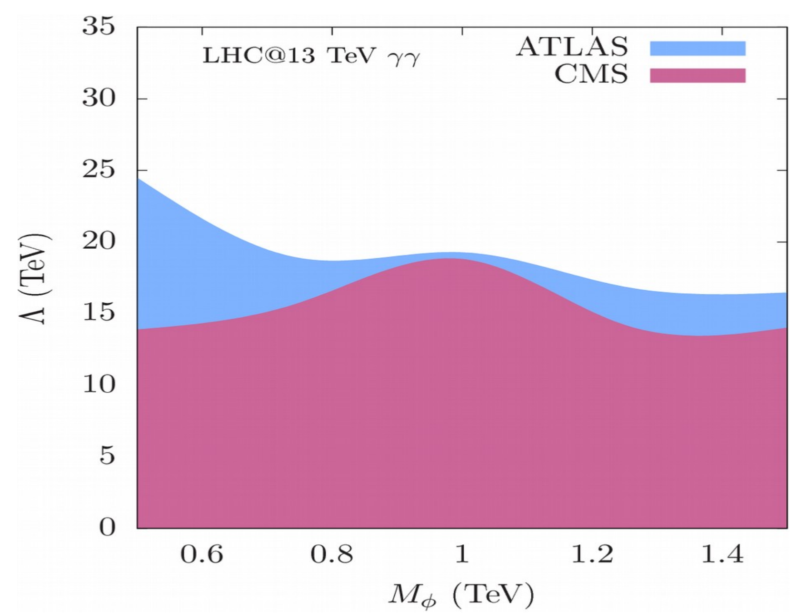
Exclusion limits from diphoton data





Recast limit

$$\mathcal{N}_s = \sigma_s \times \varepsilon_s \times \mathcal{L} = \left(\sum_i \sigma_i \times \varepsilon_i \right) \times \mathcal{L}$$



Varying electroweak theory

$$SU(2)_L \otimes U(1)_Y$$

$$g_2(x) = g_2^0 e^{S_2/\Lambda_2} \qquad\qquad g_1(x) = g_1^0 e^{S_1/\Lambda_1}$$

$$\mathcal{L} \supset -\frac{1}{4} e^{2S_1/\Lambda_1} B_{\mu\nu}^2 - \frac{1}{4} e^{2S_2/\Lambda_2} W_{\mu\nu}^2$$

$$\mathcal{L} \supset -\frac{1}{4} W_{\mu\nu}^2 - \frac{1}{4} B_{\mu\nu}^2 - \frac{1}{2\Lambda_1} S_1 B_{\mu\nu}^2 - \frac{1}{2\Lambda_2} S_2 W_{\mu\nu}^2$$

$$M_\gamma = 0 \qquad M_W = \frac{v}{\sqrt{2}} g_2 = \frac{v}{\sqrt{2}} g_2^0 e^{S_2/\Lambda_2}$$

$$M_Z = \frac{v}{\sqrt{2}} \sqrt{(g_1^0 e^{S_1/\Lambda_1})^2 + (g_2^0 e^{S_2/\Lambda_2})^2}$$

$$\tan\theta_w = \frac{g_2^0}{g_1^0} e^{(S_2/\Lambda_2 - S_1/\Lambda_1)}$$

W and Z masses will vary
and also Weinberg angle

Varying electroweak theory

Replacing: $B_\mu = c_w A_\mu - s_w Z_\mu \quad W^3_\mu = s_w A_\mu + c_w Z_\mu$

$$\mathcal{L} \supset \frac{1}{2}\left(c_w^2 \frac{S_1}{\Lambda_1} + s_w^2 \frac{S_2}{\Lambda_2}\right) F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\left(s_w^2 \frac{S_1}{\Lambda_1} + c_w^2 \frac{S_2}{\Lambda_2}\right) Z_{\mu\nu}Z^{\mu\nu}$$
$$- s_w c_w \left(\frac{S_1}{\Lambda_1} - \frac{S_2}{\Lambda_2}\right) F_{\mu\nu}Z^{\mu\nu} + \frac{1}{\Lambda_2} S_2 W^+_{\mu\nu} W^{-\mu\nu} \ .$$

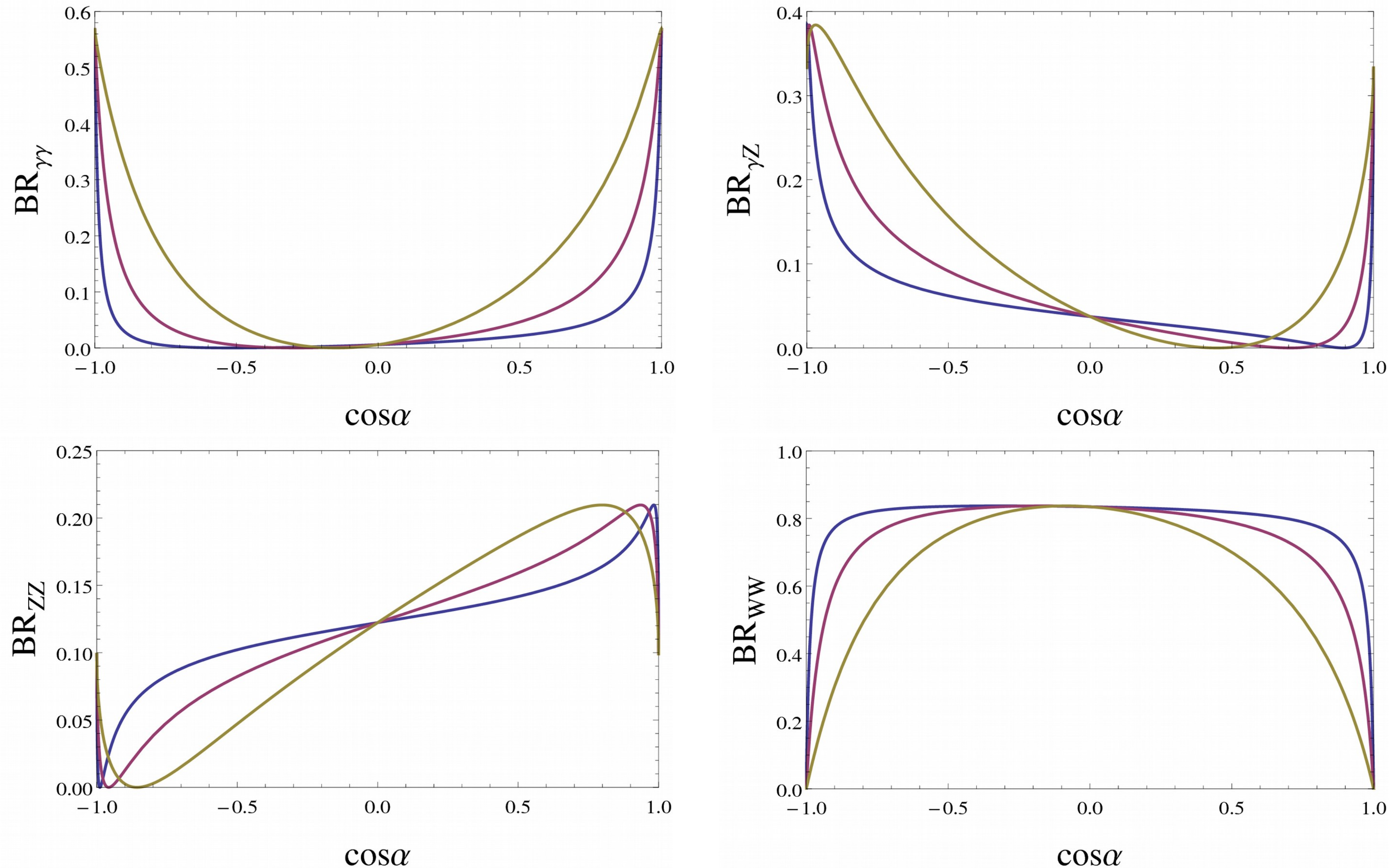
Mass eigenstates: $\phi_1 = \cos\alpha S_1 + \sin\alpha S_2; \quad \phi_2 = -\sin\alpha S_1 + \cos\alpha S_2$

$$\mathcal{L}_{\phi_1} \supset \frac{1}{2}\left(\frac{c_\alpha c_w^2}{\Lambda_1} + \frac{s_\alpha s_w^2}{\Lambda_2}\right) \phi_1 F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\left(\frac{c_\alpha s_w^2}{\Lambda_1} + \frac{s_\alpha c_w^2}{\Lambda_2}\right) \phi_1 Z_{\mu\nu}Z^{\mu\nu}$$
$$- s_w c_w \left(\frac{c_\alpha}{\Lambda_1} - \frac{s_\alpha}{\Lambda_2}\right) \phi_1 F_{\mu\nu}Z^{\mu\nu} + \frac{s_\alpha}{\Lambda_2} \phi_1 W^+_{\mu\nu} W^{-\mu\nu} \ .$$

$$\mathcal{L}_{\phi_2} \supset -\frac{1}{2}\left(\frac{s_\alpha c_w^2}{\Lambda_1} - \frac{c_\alpha s_w^2}{\Lambda_2}\right) \phi_2 F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\left(\frac{s_\alpha s_w^2}{\Lambda_1} - \frac{c_\alpha c_w^2}{\Lambda_2}\right) \phi_2 Z_{\mu\nu}Z^{\mu\nu}$$
$$+ s_w c_w \left(\frac{s_\alpha}{\Lambda_1} + \frac{c_\alpha}{\Lambda_2}\right) \phi_2 F_{\mu\nu}Z^{\mu\nu} + \frac{c_\alpha}{\Lambda_2} \phi_2 W^+_{\mu\nu} W^{-\mu\nu} \ .$$

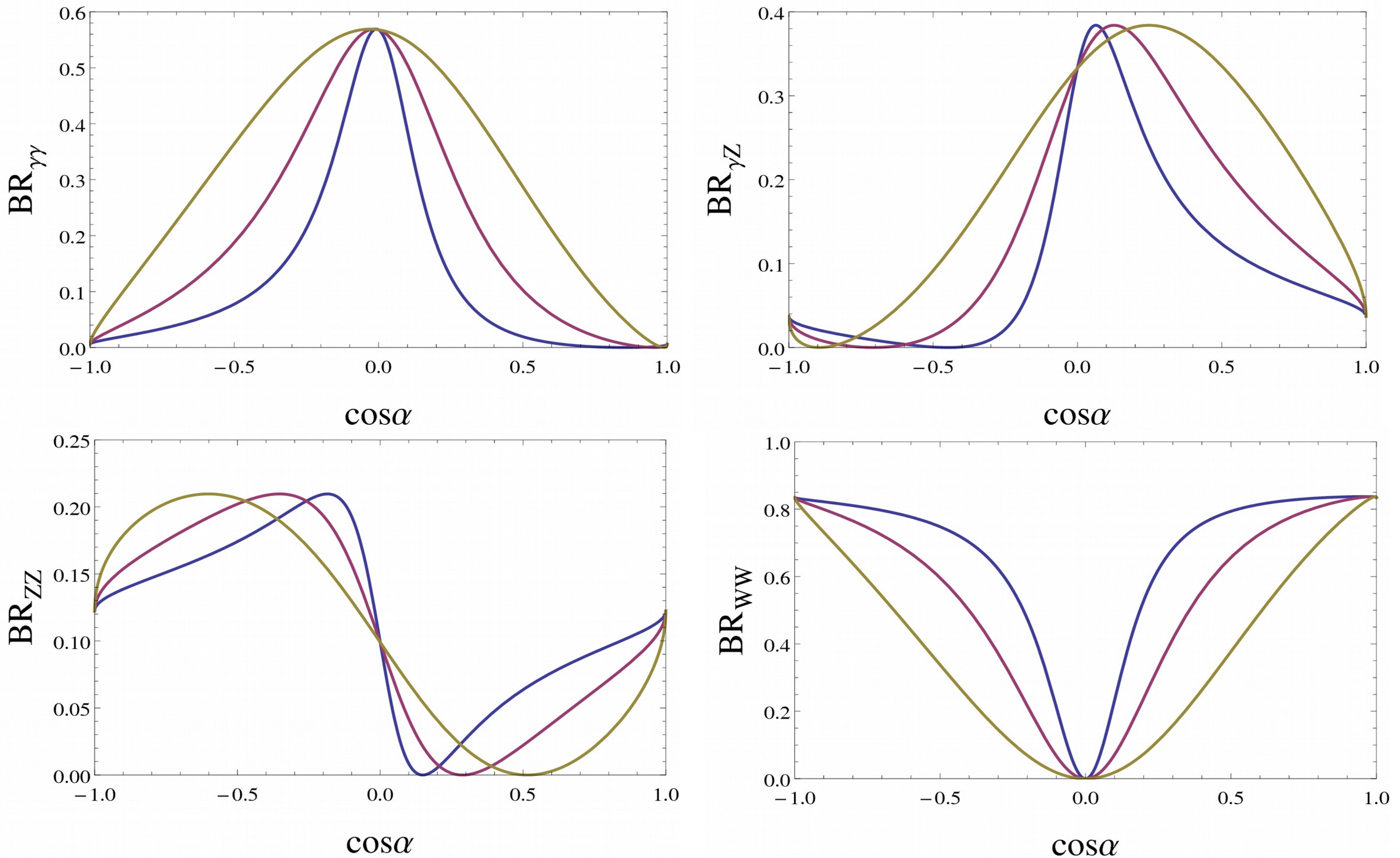
Assuming $\Lambda_2 \gg \Lambda_1 \quad \mathrm{BR}_{\gamma\gamma} : \mathrm{BR}_{\gamma Z} : \mathrm{BR}_{ZZ} \approx \frac{1}{2} c_w^4 : s_w^2 c_w^2 : \frac{1}{2} s_w^4 \approx 60\% : 35\% : 5\%$

Varying EW: branching ratio



For $M_{\phi_1} = 1$ TeV; $\Lambda_2/\Lambda_1 = 0.5, 1, 2$

Varying EW: branching ratio



For $M_{\phi_2} = 1$ TeV; $\Lambda_2/\Lambda_1 = 0.5, 1, 2$

Varying all gauge couplings

- The SU(3) scalar will similarly couple to gluons
- For SU(2) and U(1) there is mixing due to the Weinberg angle and from the scalar potential
- But for SU(3): only mixing from scalar potential
- Possible signature of SU(3) scalar: resonance in dijets channel at LHC
- Mixing parameters should be determined from the scalar potential
- We take the approach that mixings are our phenomenological parameters
- These scalars are real, neutral and are not charged under the gauge groups

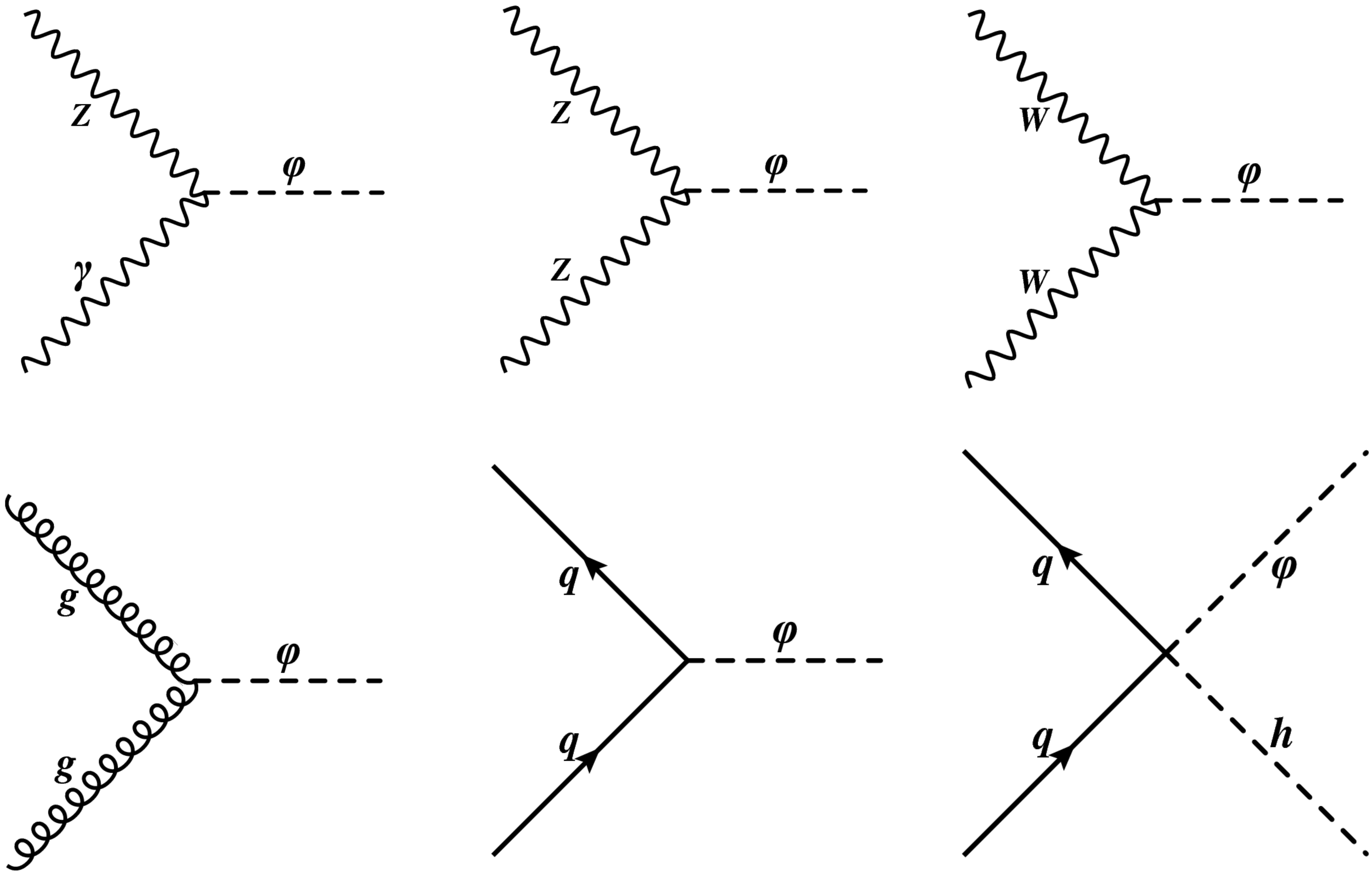
Varying Yukawa couplings

- In a varying gauge couplings theory, fermion masses are constant
- In most general setup, one can consider all Yukawa couplings are also varying
- Tree level fermion masses will vary but at low energy they are constant unless we excite the associated scalar fields

Typical new interactions: $$y_q \left(\frac{v}{\Lambda} \phi \bar{q} q + \frac{h}{\Lambda} \phi \bar{q} q \right)$$

Similar idea: Flavon models - Yukawa interactions are generated through higher dimensional operators. Similar interactions and can generate LFV interactions

Varying all couplings: signatures

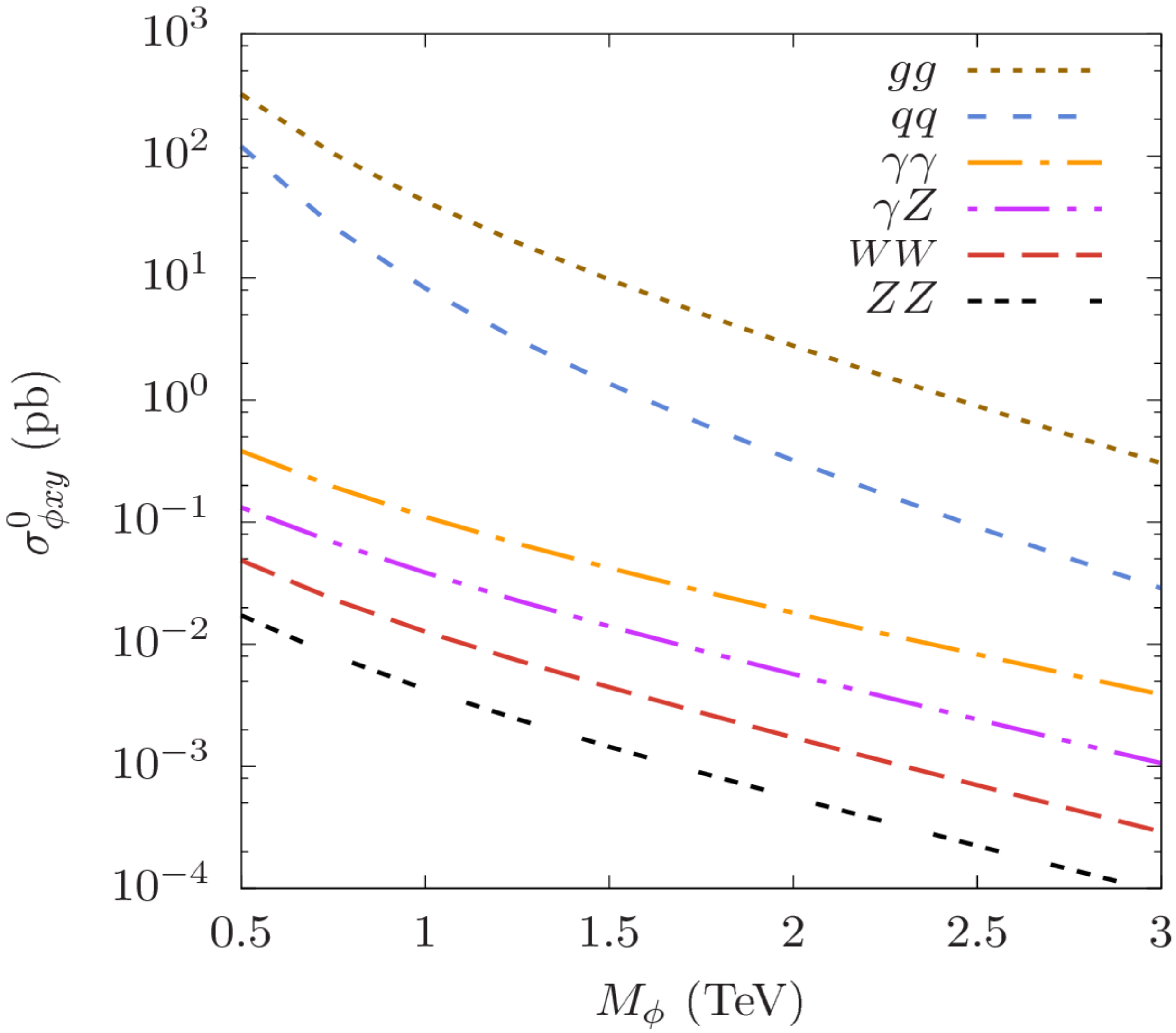


Generic effective Lagrangian

$$\mathcal{L} \supset -\frac{\kappa_{gg}}{4\Lambda}\,\phi G^{a}_{\mu\nu}G^{a;\mu\nu} - \frac{\kappa_{\gamma\gamma}}{4\Lambda}\,\phi A_{\mu\nu}A^{\mu\nu} - \frac{\kappa_{ZZ}}{4\Lambda}\,\phi Z_{\mu\nu}Z^{\mu\nu} - \frac{\kappa_{\gamma Z}}{2\Lambda}\,\phi A_{\mu\nu}Z^{\mu\nu}$$
$$- \frac{\kappa_{WW}}{2\Lambda}\,\phi (W^{+})_{\mu\nu}(W^{-})^{\mu\nu} - \sum_{q}\frac{\kappa_{qq}}{\Lambda}\,\left(v\phi\bar{q}q + h\phi\bar{q}q\right)$$

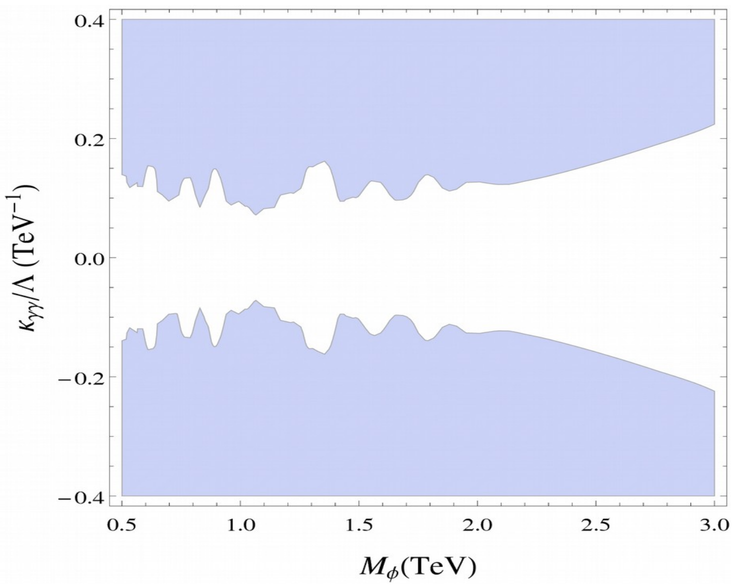
Many free parameters. Difficult to work with this.

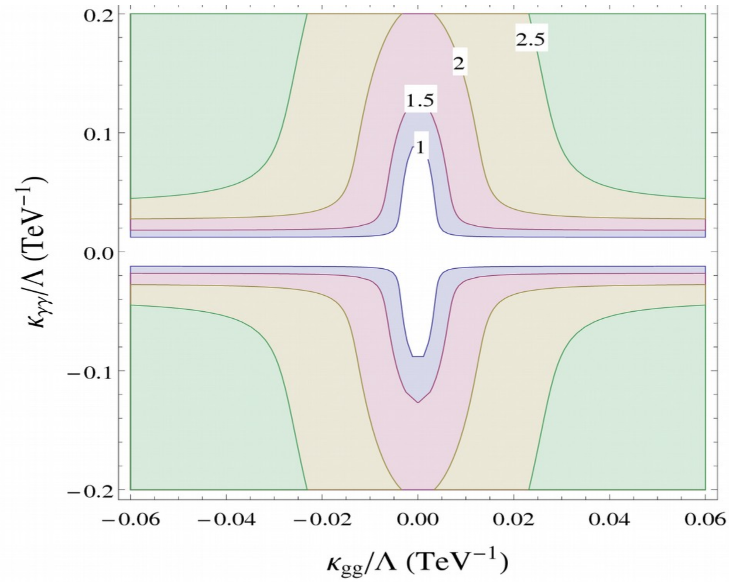
Production cross sections @13 TeV

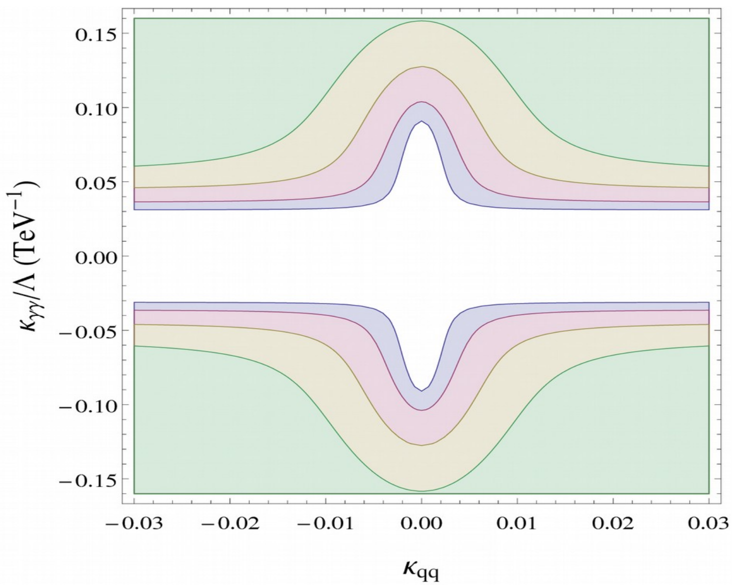


$$\kappa_{xy} = 1; \quad \Lambda = 1 \text{ TeV}$$

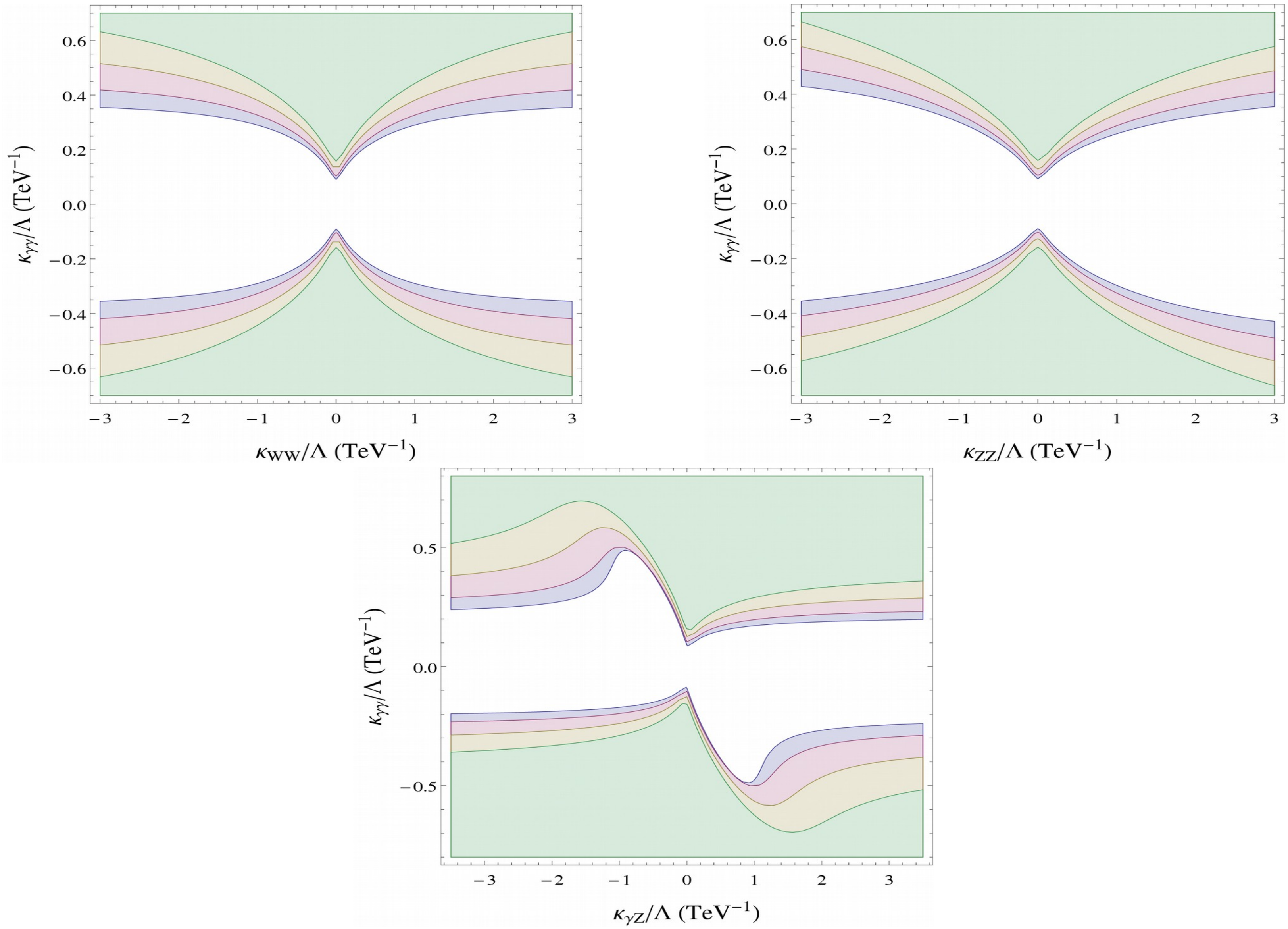
Exclusion from diphoton data





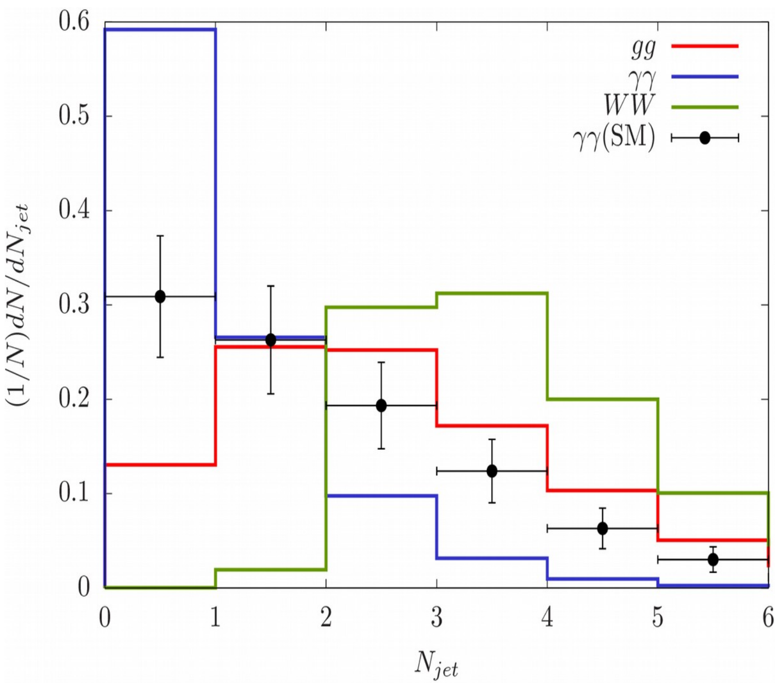


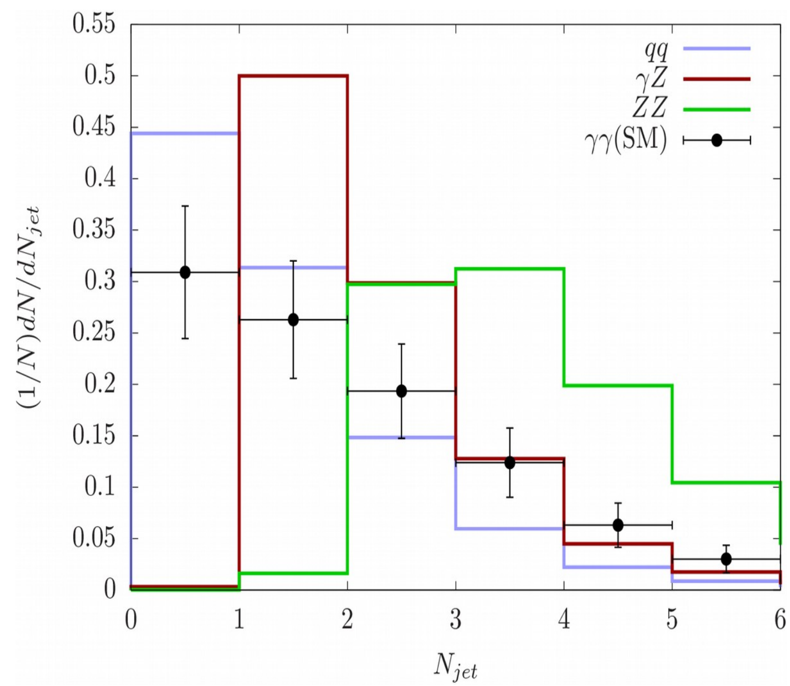
Exclusion from diphoton data



Distinguishing production modes

N-jet distributions @ 13 TeV





Uncertainty: statistical (50 1/fb) + 20% systematic

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{N_i^{obs} - N_i^{th}}{\Delta N} \right)^2$$

function to distinguish two distributions

Jet multiplicity

$gg \to \phi$	$qq \to \phi$	$\gamma\gamma \to \phi$	$\gamma Z \to \phi$	$WW \to \phi$	$ZZ \to \phi$	$\gamma\gamma$ SM
1.94	0.92	0.61	1.75	2.85	2.87	1.42

TABLE I. Average jet multiplicity for different production modes of ϕ at the 13 TeV LHC with $\mathcal{L} = 50$ fb^{-1}. Average jet multiplicity is defined by the sum, $\sum_i (BH)_i N_i$ where BH_i represents the bin height of the i-th bin of the normalized N_{jet} distribution and $N_i = i - 1$ is the number of jets associated with the i-th bin.

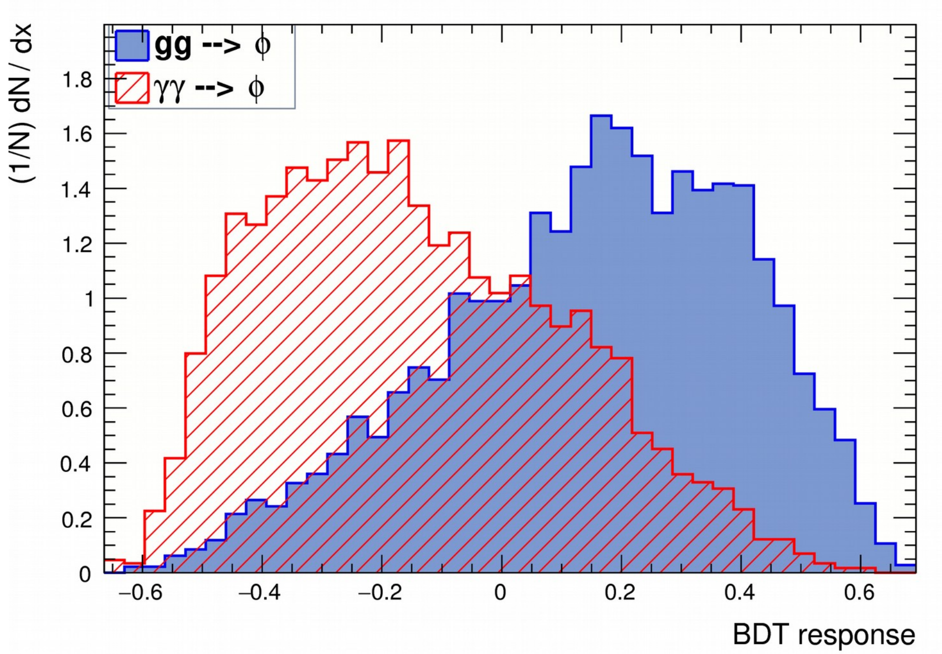
Mode:	$gg \to \phi$	$qq \to \phi$	$\gamma\gamma \to \phi$	$\gamma Z \to \phi$	$WW \to \phi$	$ZZ \to \phi$
$S \gg B$	3.6	3.4	8.9	10.0	30.4	30.3
$S = B$	0.9	0.8	2.2	2.5	7.6	7.6

TABLE II. The χ^2/dof values for the different production modes for two cases *viz.* $S \gg B$ and $S = B$. These are computed by considering up to $N_{jet} = 4$ for $M_\phi = 1$ TeV at the 13 TeV LHC with $\mathcal{L} = 50$ fb^{-1}.

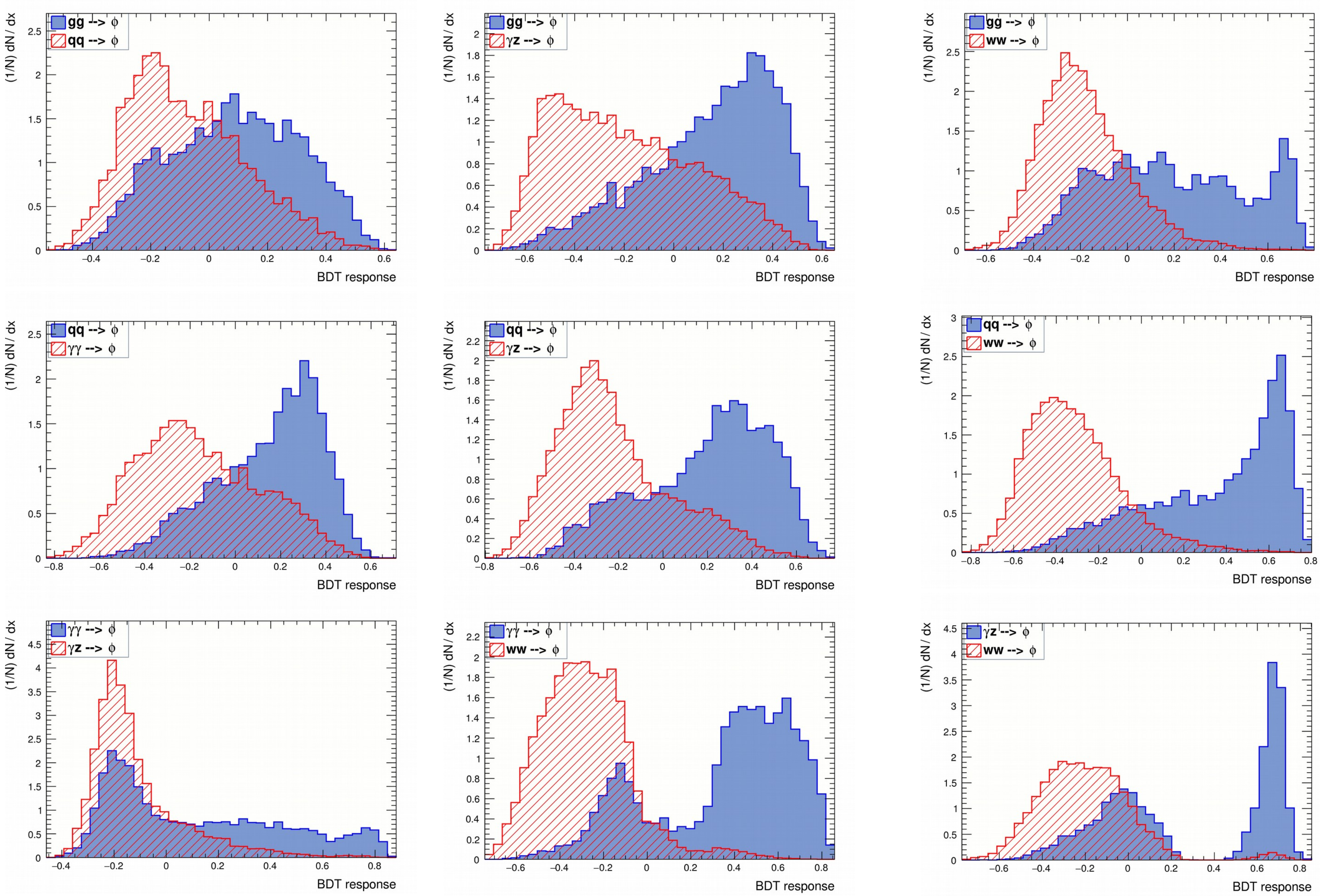
Fun with multivariate analysis

Variable	Importance	Variable	Importance	Variable	Importance	Variable	Importance
N_{jet}	1.77×10^{-1}	$p_T(\gamma_1)$	4.87×10^{-2}	$\eta(\gamma_1)$	7.50×10^{-2}	$\Delta R(\gamma_1, \gamma_2)$	6.68×10^{-2}
H_T	4.48×10^{-2}	$p_T(\gamma_2)$	5.98×10^{-2}	$\eta(\gamma_2)$	6.21×10^{-2}	$\Delta R(\gamma_1, j_1)$	9.94×10^{-2}
$\Delta\eta(\phi, j_1)$	8.11×10^{-2}	$p_T(j_1)$	9.14×10^{-2}	$\eta(j_1)$	9.40×10^{-2}	$\Delta R(\gamma_2, j_1)$	1.00×10^{-1}

TABLE III. Input variables used for MVA to separate gg and $\gamma\gamma$ production modes and their relative importance.



BDT response



Summary and outlook

- "Varying couplings" - natural in string theory
- Interesting to search for at colliders like the LHC
- First time connected VC theories to collider experiments
- Varying Yukawa couplings can generate LFV interactions
- Scalars in this theory could be responsible for inflation
- If unification is true and only vary the unification scale – leads to gauge coupling variations at low energy
- These variations are correlated and can be tested
- Many things can be done - cosmological, collider stuffs...

Thank you