

# NLO QCD predictions for DM production at the LHC

in the FeynRules/MadGraph5\_aMC@NLO framework



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- ▶ “DM production through **loop-induced** processes at the LHC: **mono-X**”  
Mattelaer, Vryonidou [1508.00564]
- ▶ “**Higher-order QCD** predictions for DM production at the LHC in simplified models:  
**mono-j** and **tt+MET**”  
Backovic, Kramer, Maltoni, Martini, Mawatari, Pellen [1508.05327]
- ▶ “**Higher-order QCD** predictions for DM production in **mono-Z** searches at the LHC”  
Neubert, Wang, Zhang [1509.05785]

FeynRules DMsimp model: <http://feynrules.irmp.ucl.ac.be/wiki/DMsimp>  
MadGraph5\_aMC@NLO: <https://launchpad.net/mg5amcnlo>

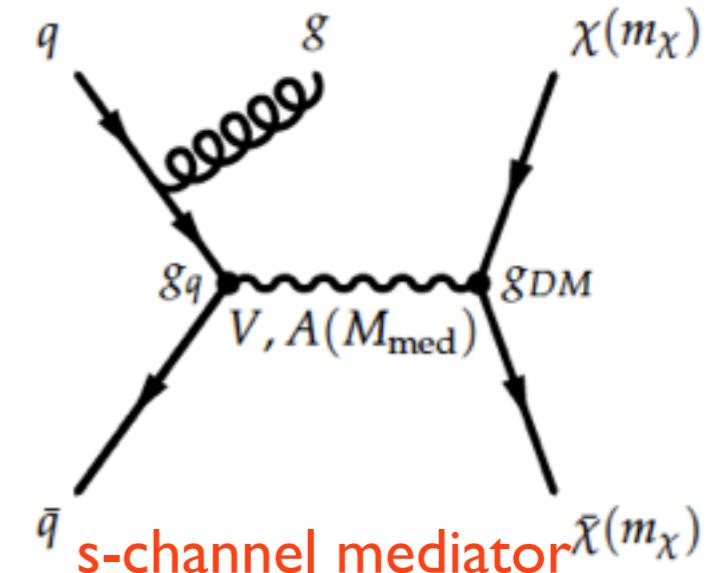
# Mono-X DM searches at the LHC Run-II

LHC DM WG I 507.00966

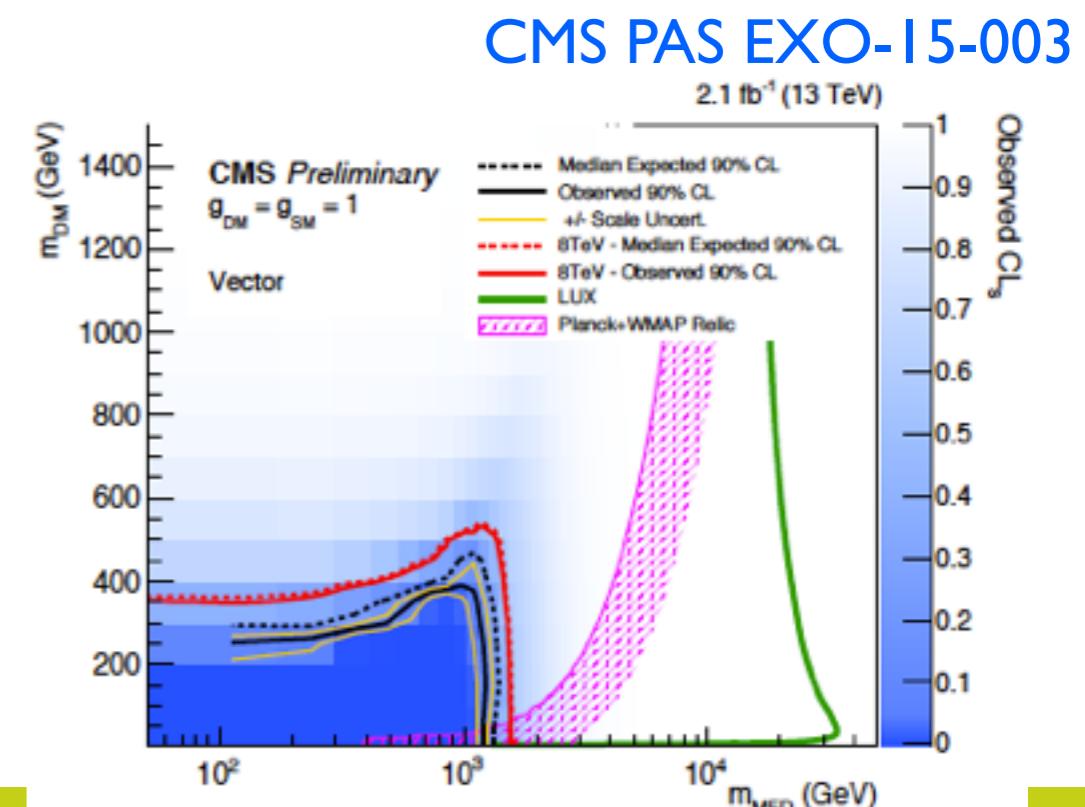
- employing simplified DM models (cf. EFT at Run-I).

- $$\mathcal{L}_{\text{vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \chi$$

$$\mathcal{L}_{\text{axial-vector}} = g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q} \gamma^\mu \gamma^5 q + g_\chi Z'_\mu \bar{\chi} \gamma^\mu \gamma^5 \chi$$



- The signal is determined by the mediator type, the DM and mediator masses, and the two couplings.



# I-min MadGraph5\_aMC@NLO tutorial

```
./bin/mg5_aMC  
>import model DMSimp_s_spin1  
>generate p p > xd xd~ j [QCD]  
>output  
>launch
```

- ☞ Start the MG5\_aMC shell
- ☞ Import the model
- ☞ Generate the process
- ☞ Write the code (including html)
- ☞ Generate the LO/NLO events

```
#####
## INFORMATION FOR DMINPUTS
#####
Block dminputs
 1 0.000000e+00 # gVXc
 2 1.000000e+00 # gVXd
 3 0.000000e+00 # gAXd
 4 2.500000e-01 # gVd11
 5 2.500000e-01 # gVu11
 6 2.500000e-01 # gVd22
 7 2.500000e-01 # gVu22
 8 2.500000e-01 # gVd33
 9 2.500000e-01 # gVu33
10 0.000000e+00 # gAd11
11 0.000000e+00 # gAu11
12 0.000000e+00 # gAd22
13 0.000000e+00 # gAu22
14 0.000000e+00 # gAd33
15 0.000000e+00 # gAu33

$$\mathcal{L}_{X_D}^{Y_1} = \bar{X}_D \gamma_\mu (g_{X_D}^V + g_{X_D}^A \gamma_5) X_D Y_1^\mu$$


$$\mathcal{L}_{SM}^{Y_1} = \sum_{i,j} \left[ \bar{q}_i \gamma_\mu (g_{q_{ij}}^V + g_{q_{ij}}^A \gamma_5) q_j \right] Y_1^\mu$$

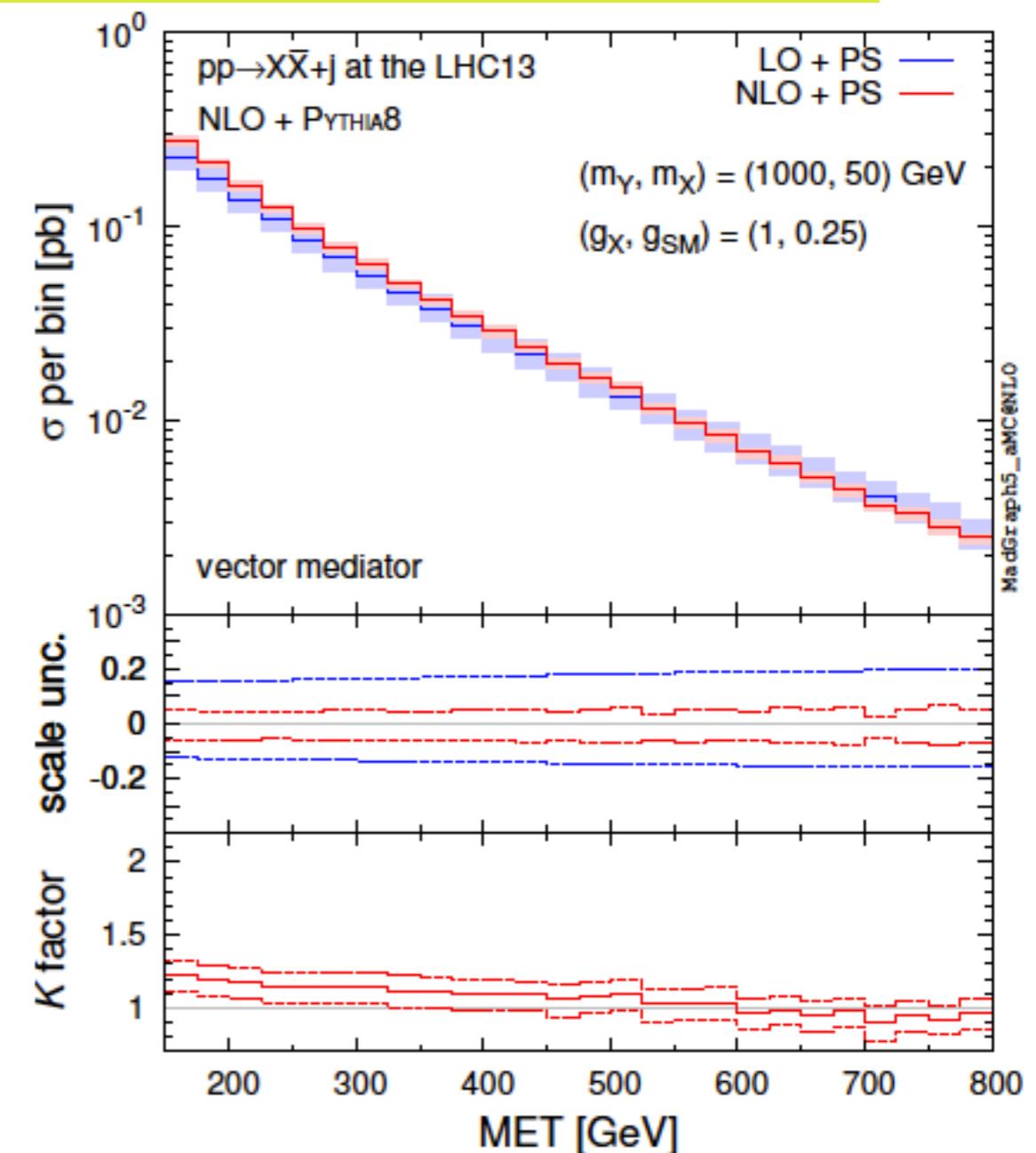
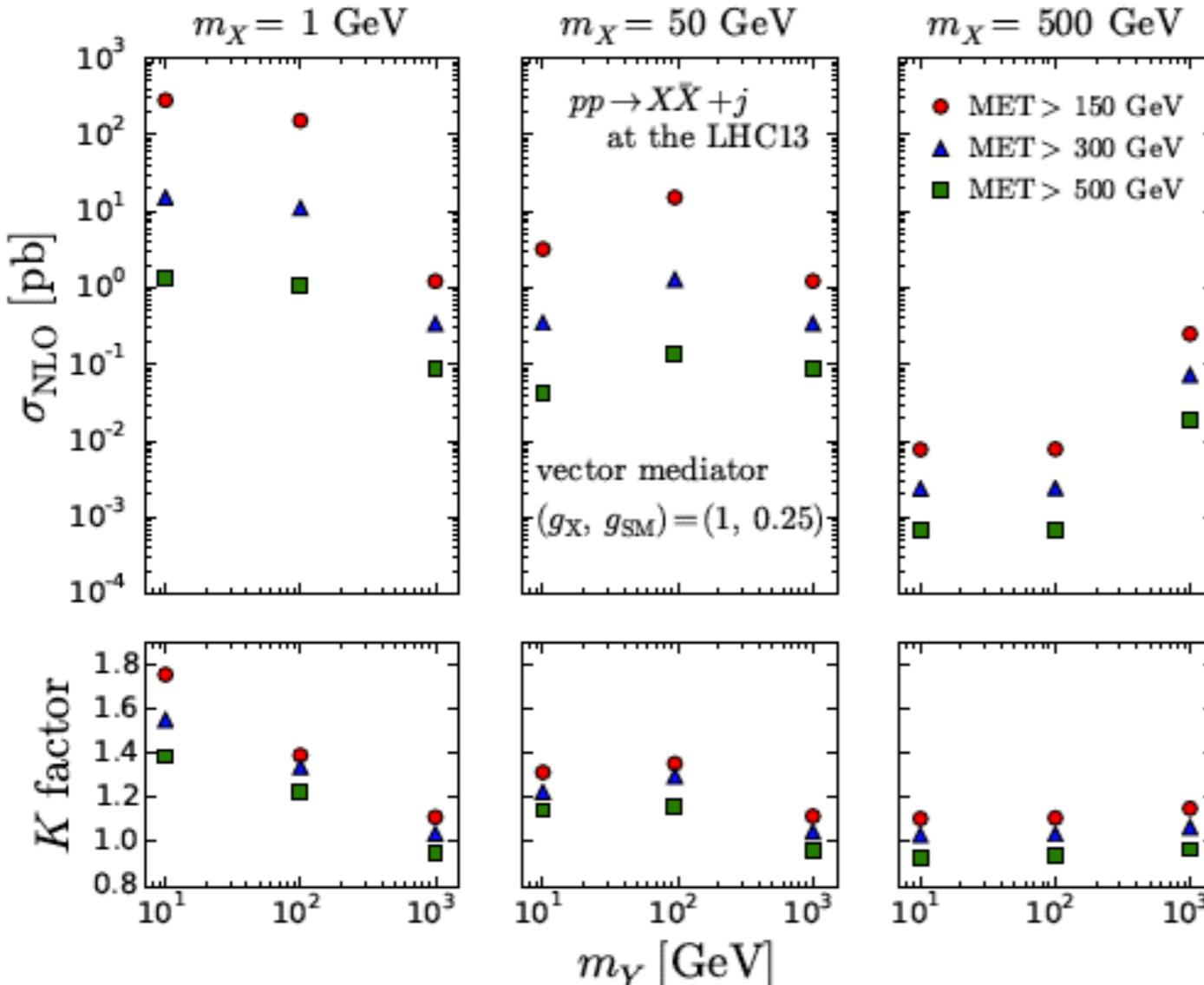
#####
## INFORMATION FOR MASS
#####
Block mass
 6 1.720000e+02 # MT
15 1.777000e+00 # MTA
23 9.118760e+01 # MZ
25 1.250000e+02 # MH
51 1.000000e+01 # MXc
52 1.000000e+01 # MXd
55 1.000000e+03 # MY1
5000001 1.000000e+01 # MXr
```

param\_card.dat

run\_card.dat

```
#####
# Collider type and energy
#####
 1 = lpp1 ! beam 1 type (0 = no PDF)
 1 = lpp2 ! beam 2 type (0 = no PDF)
 6500 = ebeam1 ! beam 1 energy in GeV
 6500 = ebeam2 ! beam 2 energy in GeV
#####
# PDF choice: this automatically fixes also alpha_s(MZ) and its evol.
#####
 nn23nlo = pdlabel ! PDF set
 230000 = lhaid ! if pdlabel=lhapdf, this is the lhapdf number
#####
# Include the NLO Monte Carlo subtr. terms for the following parton
# shower (HERWIG6 | HERWIGPP | PYTHIA6Q | PYTHIA6PT | PYTHIA8)
# WARNING: PYTHIA6PT works only for processes without FSR!!!!
#####
 HERWIG6 = parton_shower
```

# Importance of NLO corrections



- strong dependence on the mass spectrum and the kinematical regions.
- sizably reduction of the scale and PDF uncertainties.

# Backup

# CMS found a 750GeV spin-2 resonance ?!

CMS PAS EXO-15-004

The Randall-Sundrum (RS)  
effective coupling

$$\tilde{\kappa} = \sqrt{8\pi\kappa/m_{Pl}}$$

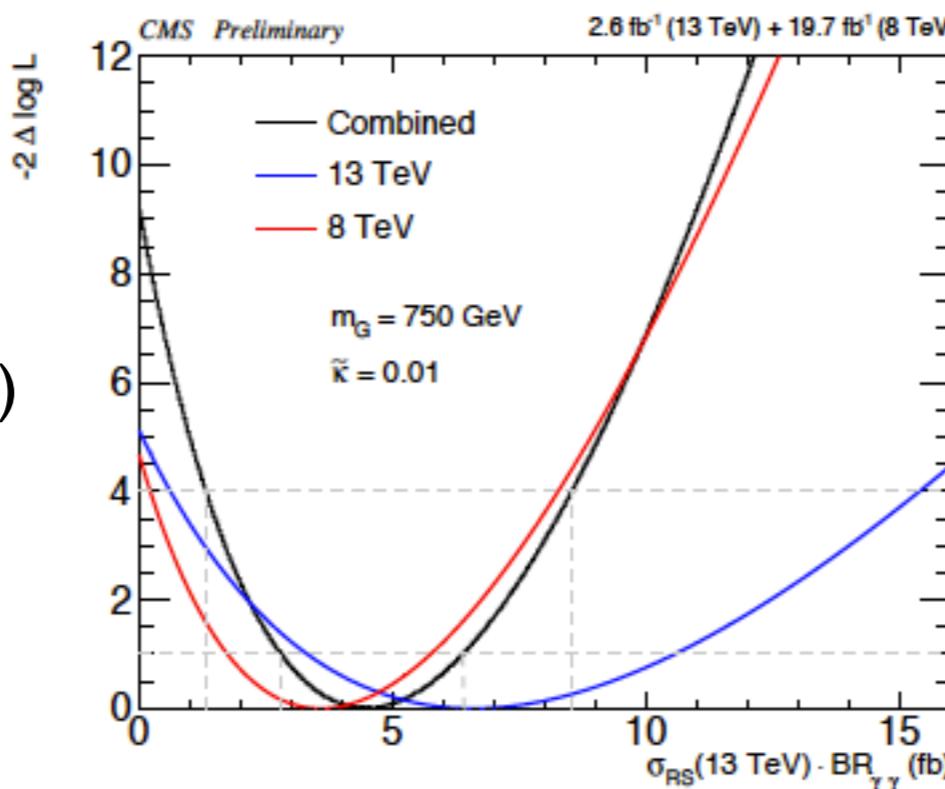


Figure 11: Likelihood scan for the cross section corresponding to the largest excess in the combined analysis of the 8 and 13 TeV datasets. The 8 TeV results are scaled by the expected ratio of cross sections predicted for an RS graviton resonance.

# HELAS and MadGraph/MadEvent with spin-2 particles

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**Abstract** Fortran subroutines to calculate helicity amplitudes with massive spin-2 particles (massive gravitons), which couple to the standard model particles via the energy momentum tensor, are added to the HELAS (HELicity Amplitude Subroutines) library. They are coded in such a way that arbitrary scattering amplitudes with one graviton production and its decays can be generated automatically by MadGraph and MadEvent, after slight modifications. All the codes have been tested carefully by making use of the invariance of the helicity amplitudes under the gauge and general coordinate transformations.

## 1 Introduction

In both classes of extra dimension models, there appear Kaluza-Klein (KK) towers of massive spin-2 gravitons, which can interact with the standard model (SM) fields. The effective interaction Lagrangian is given by [6, 7]

$$\mathcal{L}_{\text{int}} = -\frac{1}{\Lambda} \sum_{\vec{n}} T^{(\vec{n})\mu\nu} T_{\mu\nu}, \quad (1)$$

where  $T^{(\vec{n})\mu\nu}$  is the  $\vec{n}$ -th graviton KK modes, and  $\Lambda$  is the relevant coupling scale. In the ADD model we have

$$\Lambda = \overline{M}_{\text{Pl}} \equiv M_{\text{Pl}}/\sqrt{8\pi} \sim 2.4 \times 10^{18} \text{ GeV}, \quad (2)$$

where  $\overline{M}_{\text{Pl}}$  is the 4-dimensional reduced Planck scale, and in the RS model

# Diphoton excess

## in phenomenological spin-2 resonance scenarios



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1601.05729 (21 Jan 2016) with A. Martini (UC Louvain) and D. Sengupta (LPSC)

$$\mathcal{L}_{\text{eff}} = -\frac{1}{\Lambda} [\kappa_\gamma T_{\mu\nu}^\gamma + \kappa_g T_{\mu\nu}^g + \kappa_q T_{\mu\nu}^q] X_2^{\mu\nu}$$

theory scale parameter  
(=10TeV in this study)

energy-momentum tensor

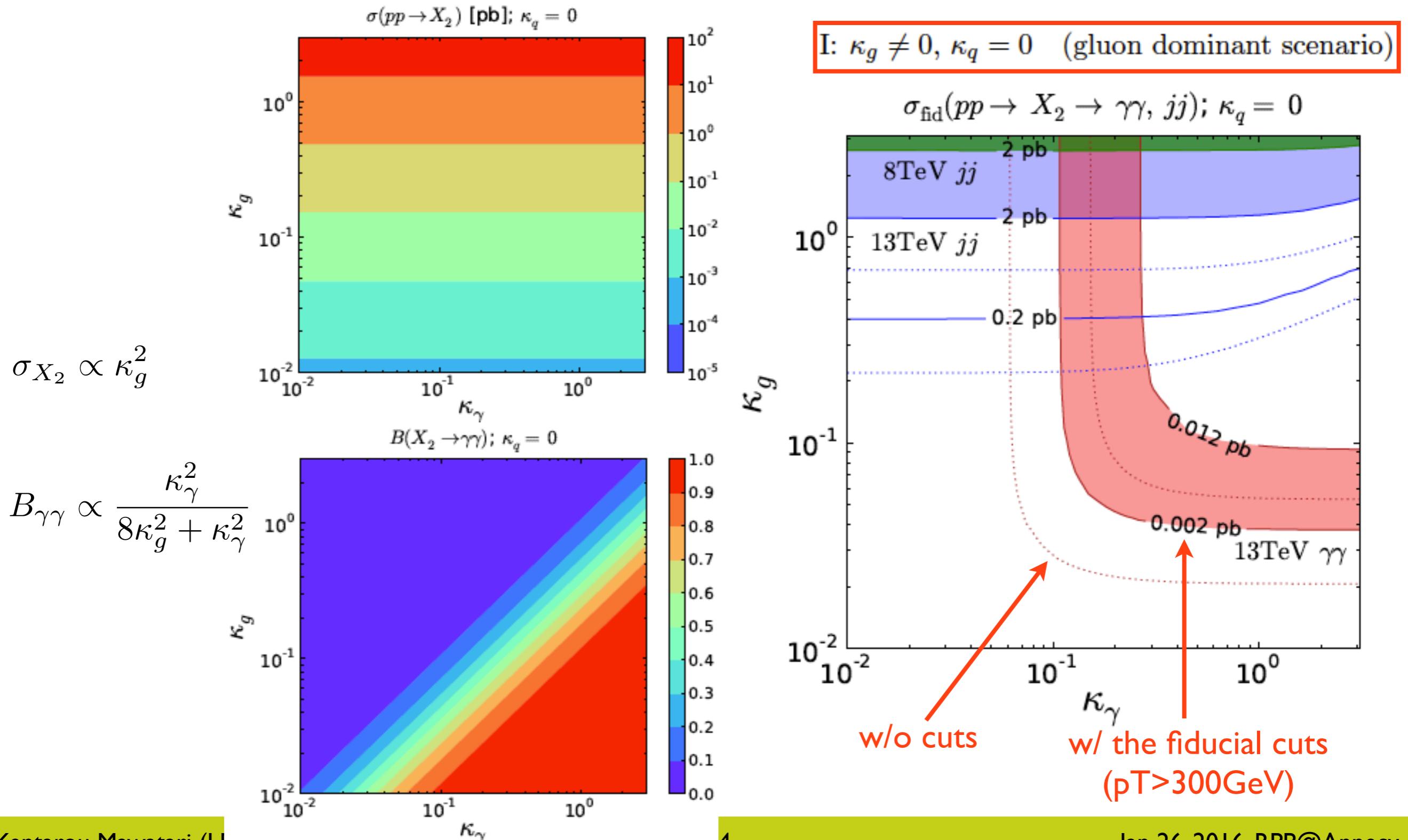
non-universal coupling parameters

spin-2 particle

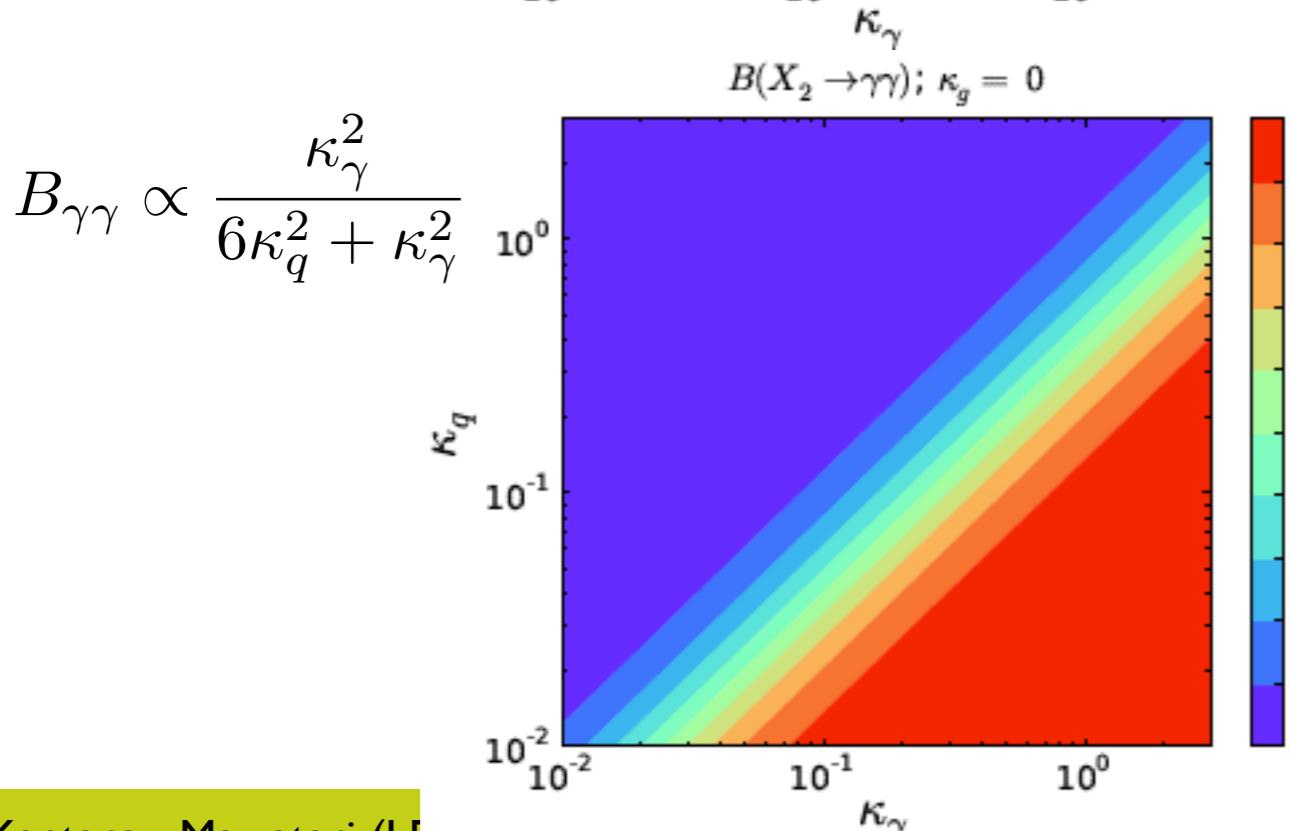
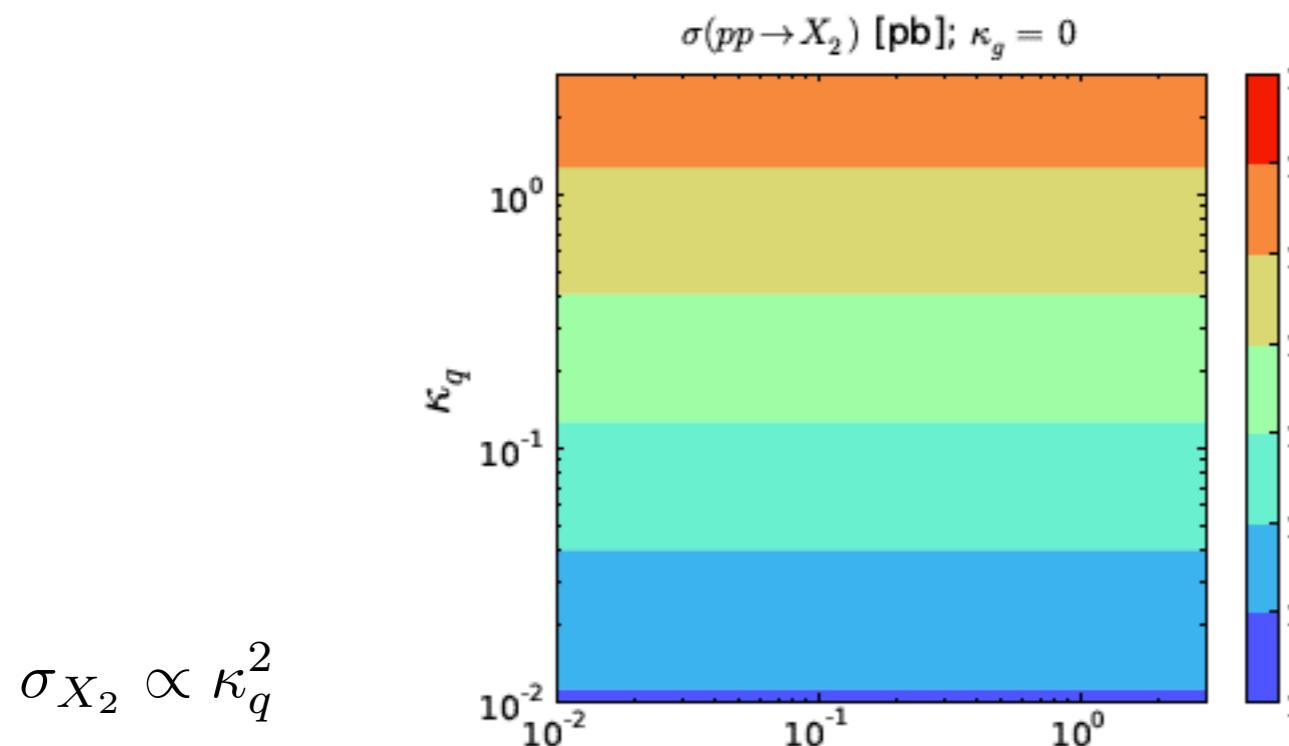
The diagram shows the effective Lagrangian  $\mathcal{L}_{\text{eff}}$  as a sum of three terms. Each term is a product of a non-universal coupling parameter ( $\kappa_\gamma$ ,  $\kappa_g$ , or  $\kappa_q$ ) and an energy-momentum tensor ( $T_{\mu\nu}^\gamma$ ,  $T_{\mu\nu}^g$ , or  $T_{\mu\nu}^q$ ). The tensors are labeled with arrows pointing to their respective components:  $T_{\mu\nu}^\gamma$  points to the  $\gamma$  field,  $T_{\mu\nu}^g$  points to the graviton field, and  $T_{\mu\nu}^q$  points to the spin-2 particle field. The coupling parameters are circled in red. The theory scale parameter  $\Lambda$  is circled in pink.

FeynRules HC model: <http://feynrules.irmp.ucl.ac.be/wiki/HiggsCharacterisation>  
MadGraph5\_aMC@NLO: <https://launchpad.net/mg5amcnlo>

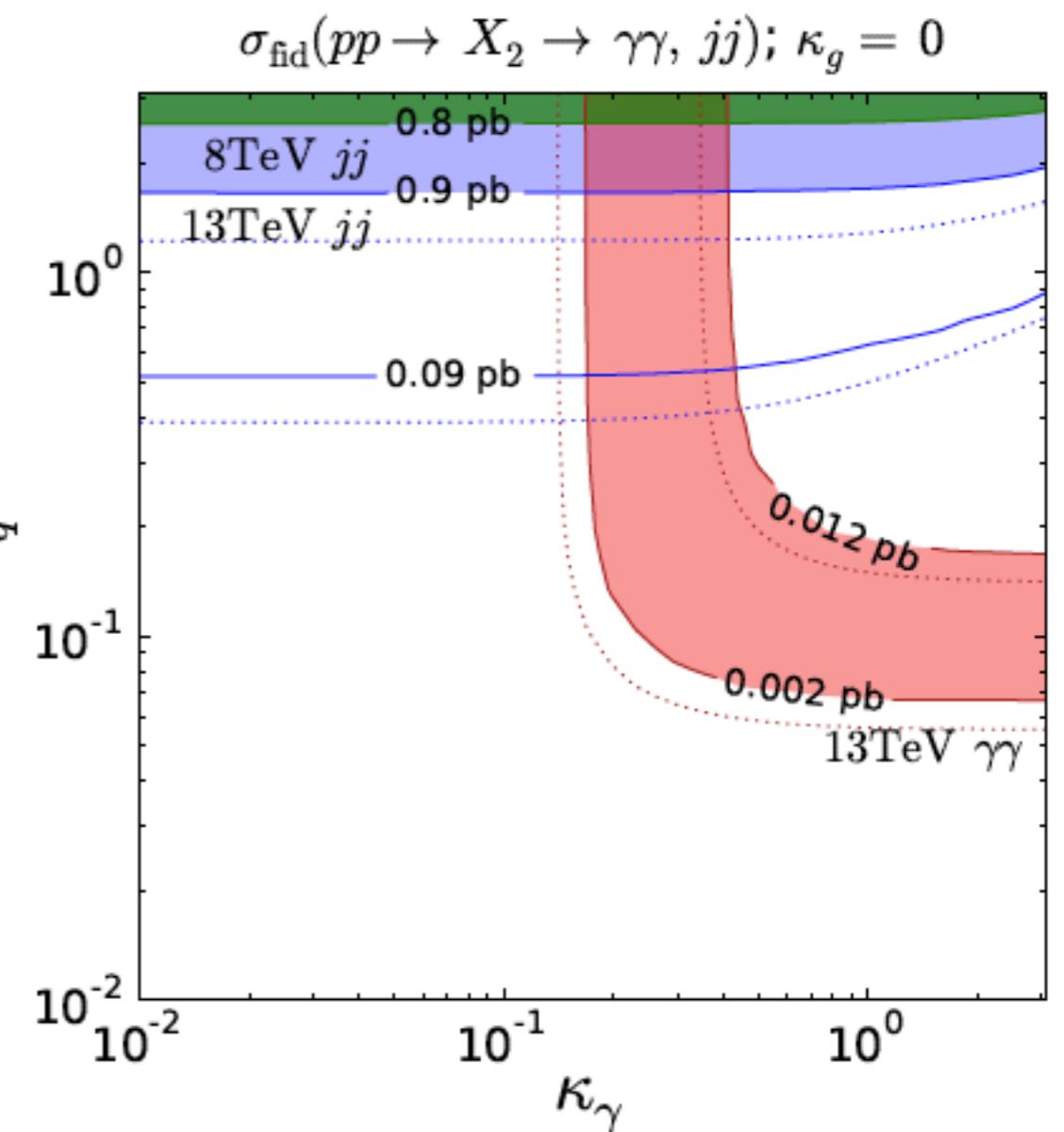
# diphoton excess vs. dijet constraint (I)



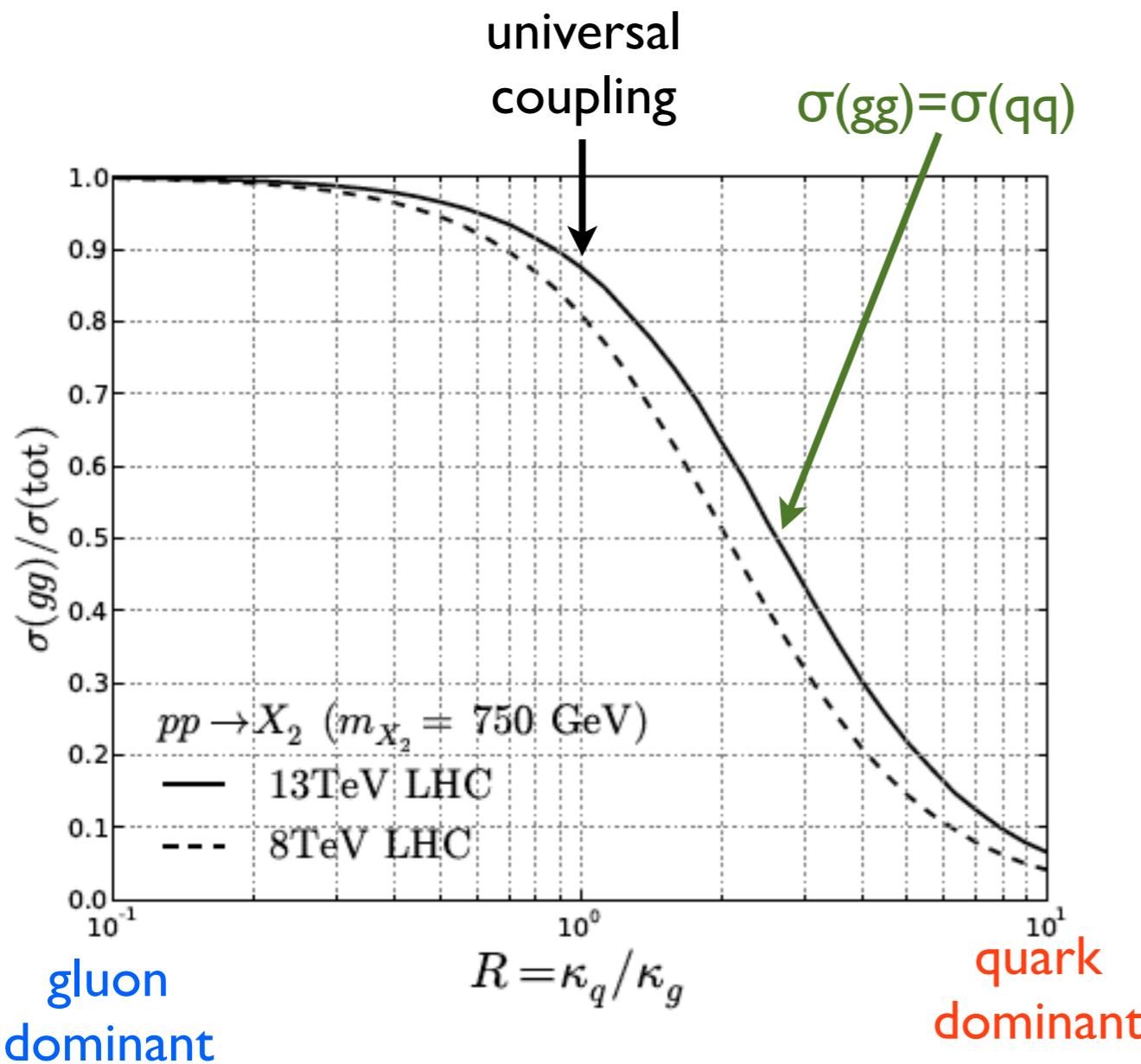
# diphoton excess vs. dijet constraint (II)



II:  $\kappa_g = 0, \kappa_q \neq 0$  (quark dominant scenario)



# gg vs. qq in diphoton events



750GeV spin-2 resonance ??

