Interpretation of the diphoton resonance in effective field theory

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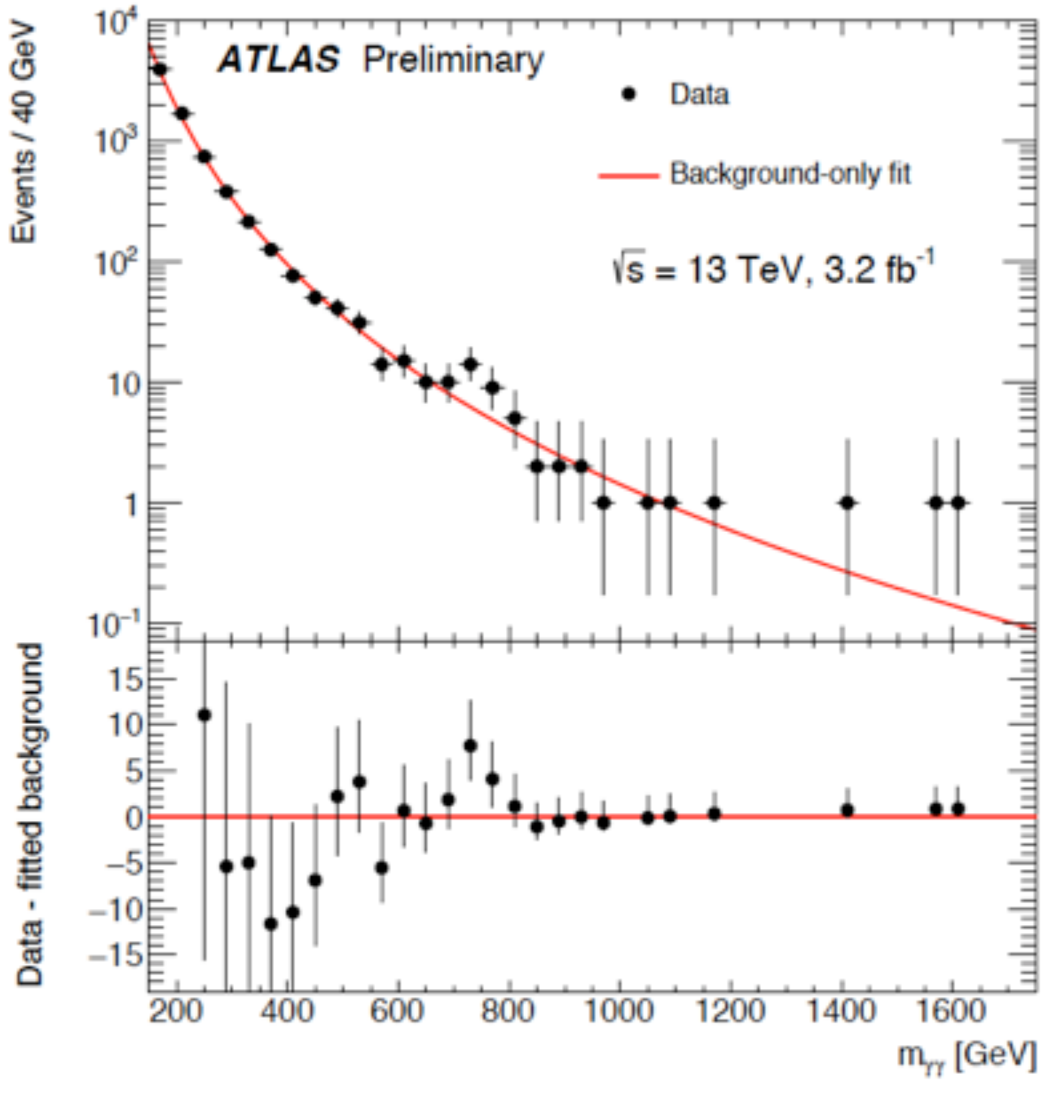
In collaboration with C. Han, M. Park, V. Sanz,
1512.06376 [hep-ph].

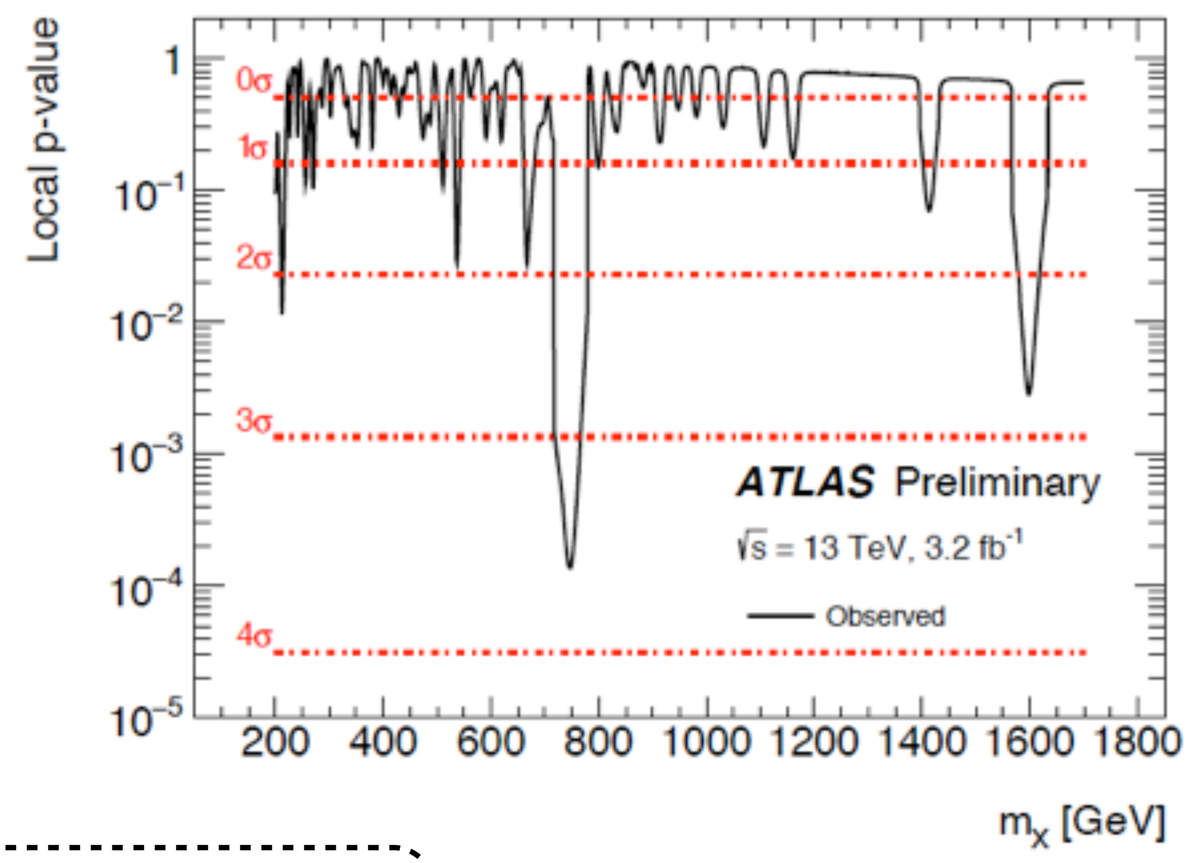
Overview on the recent diphoton excess at the LHC Run-2
IBS-CTPU, Jan 8, 2015

Outline

- Diphoton resonance
- Effective field theory for diphoton
- Diphoton as KK graviton
- KK graviton as DM mediator
- Spin determination
- Conclusions

Diphoton excesses





"cuts"

$|\eta^\gamma| < 2.37$

$E_T^\gamma > 25\,\mathrm{GeV}$

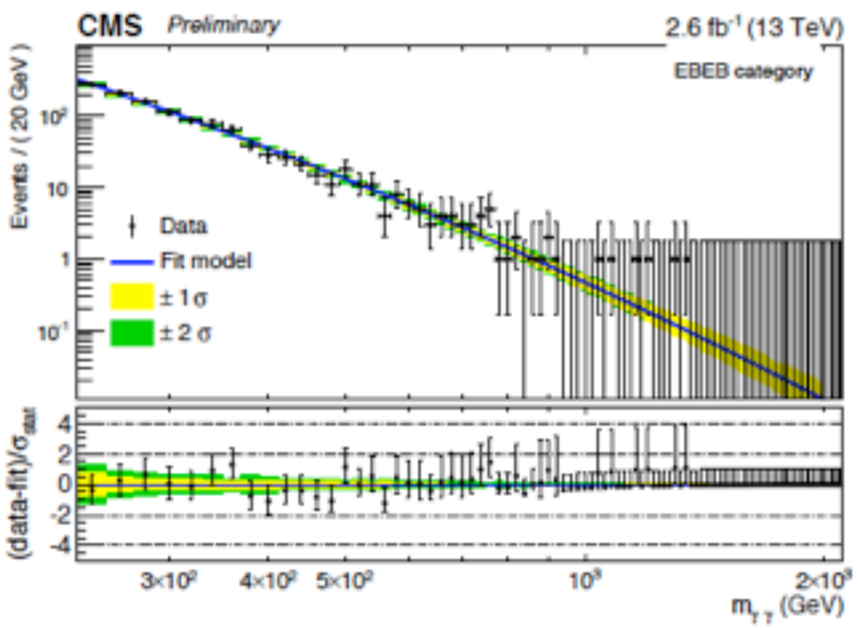
$E_T^{\gamma_{1(2)}}/m_{\gamma\gamma} > 0.4(0.3)$

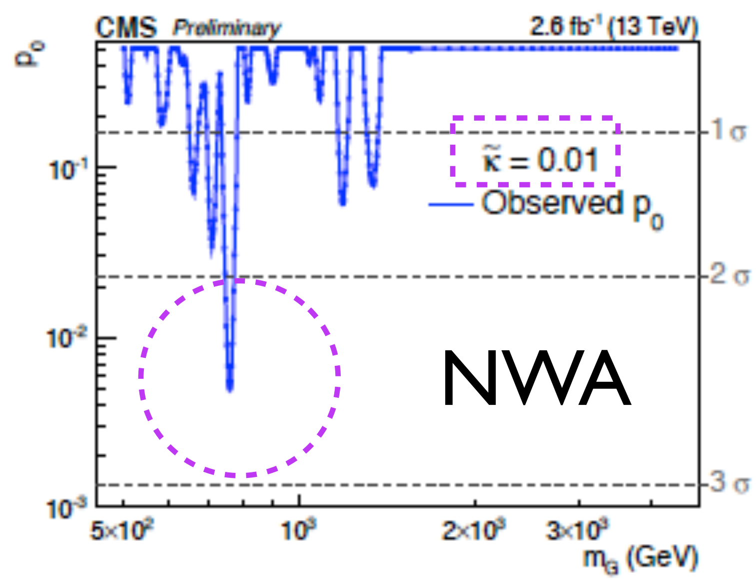
+NWA hypothesis

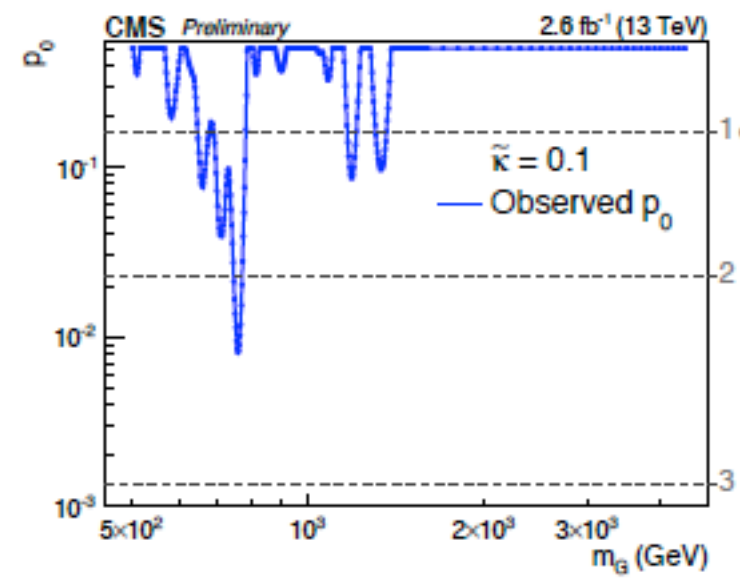
- Diphoton invariant mass in ATLAS in Run 2 shows 3.6σ (2.0σ) excesses at about 750GeV under NWA.

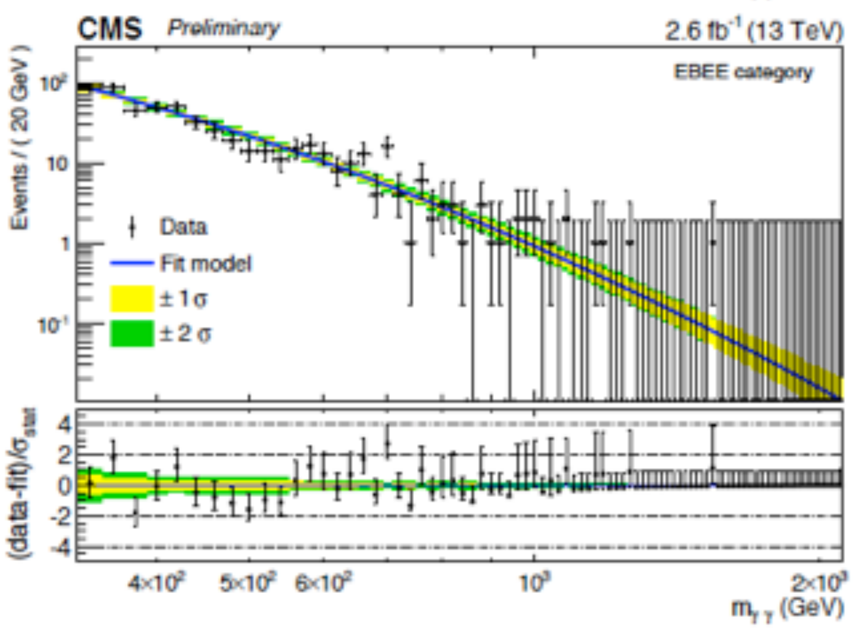
Large width: $\Gamma = 45\,\mathrm{GeV}$ → 3.9σ (2.3σ) excesses

What about CMS ?









$p_T^{\gamma} > 75\,\mathrm{GeV}$

"cuts"

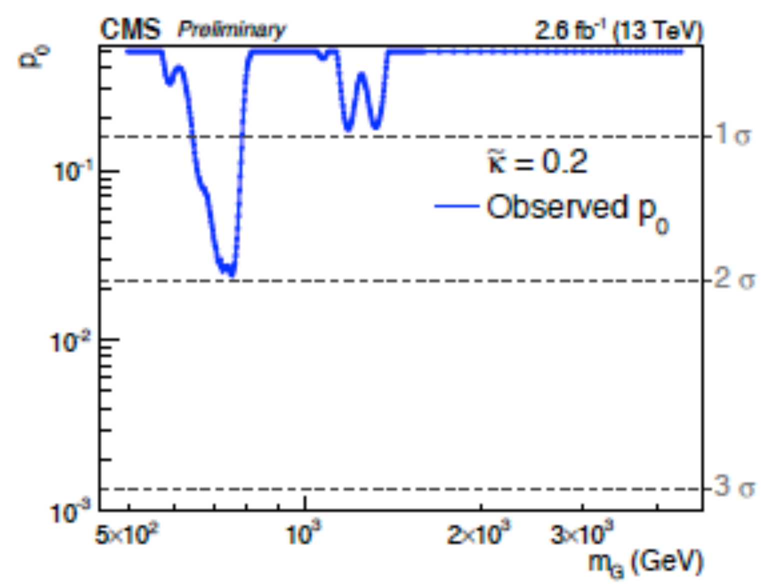
$|\eta^{\gamma}| < 1.44,$

or $1.57 < |\eta^{\gamma}| < 2.5$

$|\eta^{\gamma_1}| < 1.44$ (no EEEE)

$m_{\gamma\gamma} > 230\,\mathrm{GeV}$

$(\mathrm{EBEE}:\ 320\,\mathrm{GeV})$



$$\frac{\Gamma_G}{m_G} \sim \tilde{\kappa}^2$$

- CMS in Run 2 shows 2.6σ excess at 760GeV from EBEE category under NWA. (EBEB and EBEE only.)

Diphoton cross section

- Required diphoton cross sections are

$$\sigma(pp \to \gamma\gamma)_{\rm ATLAS} = (10 \pm 3)\,{\rm fb},$$
$$\sigma(pp \to \gamma\gamma)_{\rm CMS} = (6 \pm 3)\,{\rm fb}.$$

- ATLAS data fit favors a large width ~45GeV, which leads to smaller significance in CMS data.

cf. Bin size: ATLAS~50GeV, CMS~20GeV)

Width information is not settled!

Diphoton @ 8TeV vs 13TeV

- pp cross section: ~ pdf^2/s (e.g. ggF)

$$\sigma(pp \to X \to \gamma\gamma) = (2J+1)\,\frac{C_{gg}K_{gg}}{M_X s}\,\Gamma(X \to gg)\cdot \mathrm{BR}(X \to \gamma\gamma),$$

$$C_{gg} = \frac{\pi^2}{8}\int_{\tau_X}^{1}\frac{dx}{x}\,g(x)g(\frac{\tau_X}{x}), \quad \tau_X = \frac{M_X^2}{s}; \qquad K_{gg}: \text{ K-factor.}$$

- Parton-luminosity ratio: $r \equiv \frac{\sigma_{13\,\mathrm{TeV}}}{\sigma_{8\,\mathrm{TeV}}} = \frac{(C_{gg}/s)_{13\,\mathrm{TeV}}}{(C_{gg}/s)_{8\,\mathrm{TeV}}}.$

$\sqrt{s}$	$C_{b\bar b}$	$C_{c\bar c}$	$C_{s\bar s}$	$C_{d\bar d}$	$C_{u\bar u}$	C_{gg}
8 TeV	1.07	2.7	7.2	89	158	174
13 TeV	15.3	36	83	627	1054	2137

$r_{b\bar b}$	$r_{c\bar c}$	$r_{s\bar s}$	$r_{d\bar d}$	$r_{u\bar u}$	r_{gg}
5.4	5.1	4.3	2.7	2.5	4.7

[Franceschini et al, 1512.04933]

CMS Run 1 limit:
0.5~2 fb for 700-800GeV

Translated to
2.4~9.4 fb in Run 2:
Consistent with
diphoton excess .

cf. J. Ellis et al: true with
background increase, 1512.05327

Other searches

- ggF production necessarily leads to dijet production.
- Diphoton resonance could also decay into other particles in electroweak sector by gauge invariance so it is constrained by Run 1 searches.

final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[6,7]	$< 0.8\ (r/5)$
$e^+e^- + \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[8]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	15 fb	[9]	$< 6\ (r/5)$
$Z\gamma$	< 4.0 fb	< 3.4 fb	[10]	$< 2\ (r/5)$
ZZ	< 12 fb	< 20 fb	[11]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[12]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[13]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[14,15]	$< 20\ (r/5)$
$t\bar{t}$	< 550 fb	-	[16]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[17]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[18]	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	[5]	$< 1300\ (r/5)$

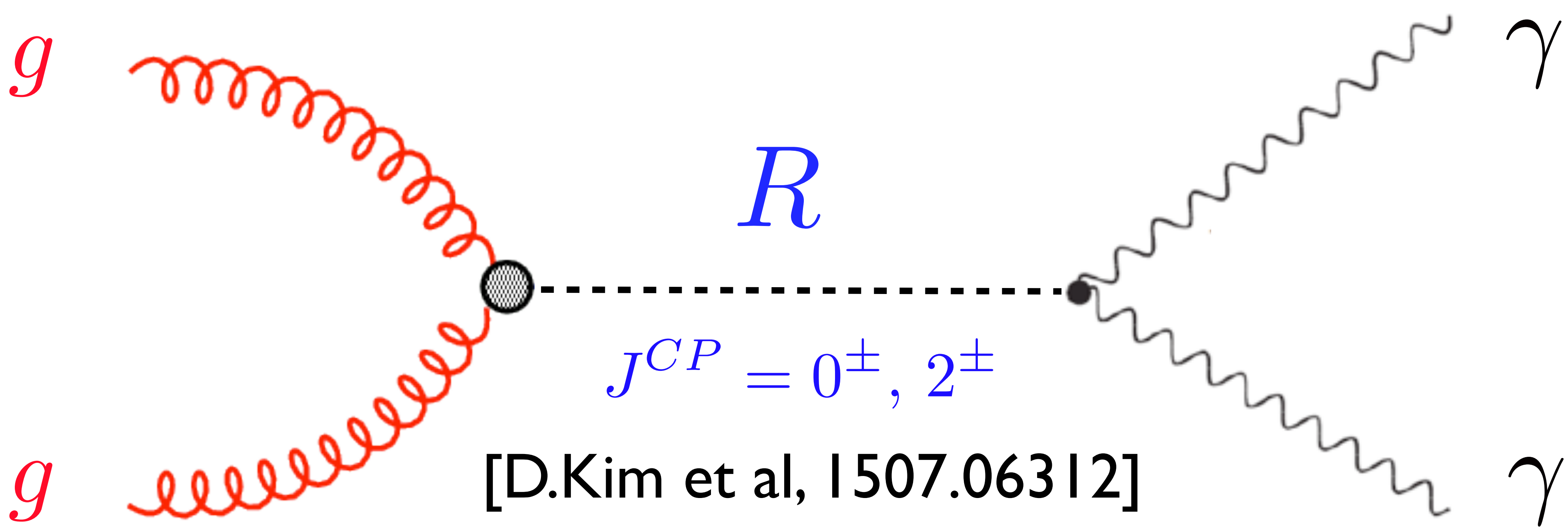
Rescaled Run I limits

[Franceschini et al, 1512.04933]

Diphoton from EFT

- Parton-luminosity ratio favors gluon fusion production.
- Landau-Yang theorem forbids on-shell massive spin-1 field from decaying into a photon pair.

spin-0 or spin-2 resonances with gluon and photon couplings in EFT.



[D.Kim et al, 1507.06312]

cf. Other interpretation: photon fusion, cascade decays, non-resonant production, MET+photons, etc.

Conditions on resonances

- Both CP states for spin-0 are possible; only CP-even state for spin-2 is possible.

  cf. On-shell CP-odd spin-2 can be produced only by VBF.

  [D.Kim et al, 1507.06312]

- Diphoton production cross section leads to a model-independent constraint on decay rates:

$$(2J+1)\Gamma(X \to gg) \times \mathrm{BR}(X \to \gamma\gamma) = 6.2 \times 10^{-4}\,\mathrm{GeV}\left(\frac{\sigma_{pp\to\gamma\gamma}}{6\,\mathrm{fb}}\right)$$

or

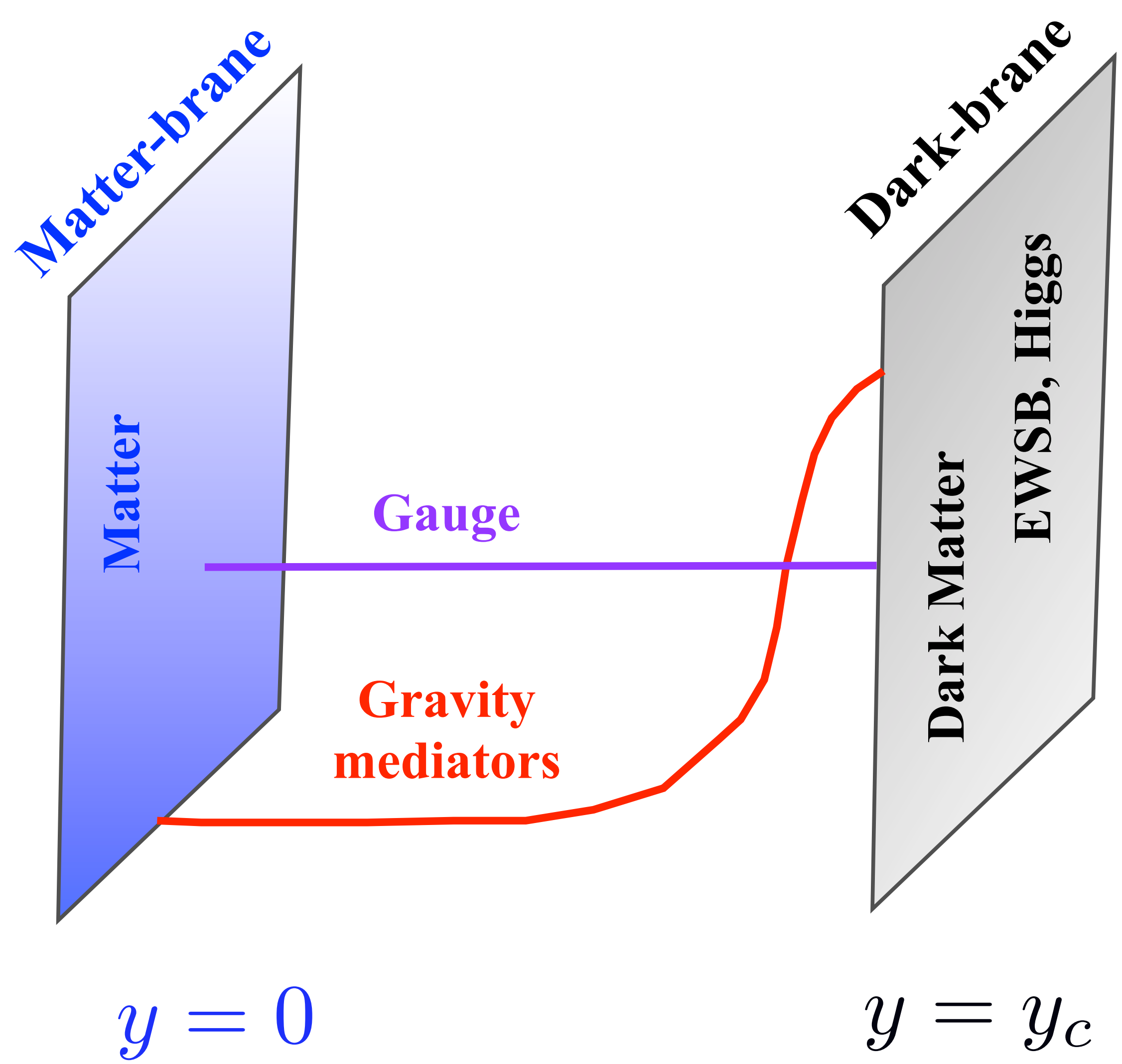
$$(2J+1)\Gamma(X \to gg) \times \Gamma(X \to \gamma\gamma) = 2.8 \times 10^{-2}\mathrm{GeV}^2\left(\frac{\Gamma_X/M_X}{0.06}\right)\left(\frac{\sigma_{pp\to\gamma\gamma}}{6\,\mathrm{fb}}\right).$$

CP-even spin-0 in P. Ko's talk, etc;
CP-odd spin-0 in KS Jeong, JC Park, etc;
CP-even spin-2 is the topic of this talk.

Diphoton as KK graviton

Bulk-RS model (A)

- Higgs and dark matter on IR brane;
- SM fermions on UV brane (for flavor problem/proton stability).



$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

$$M_P^2 = \frac{M^3}{k}(1 - e^{-2ky_c}),$$

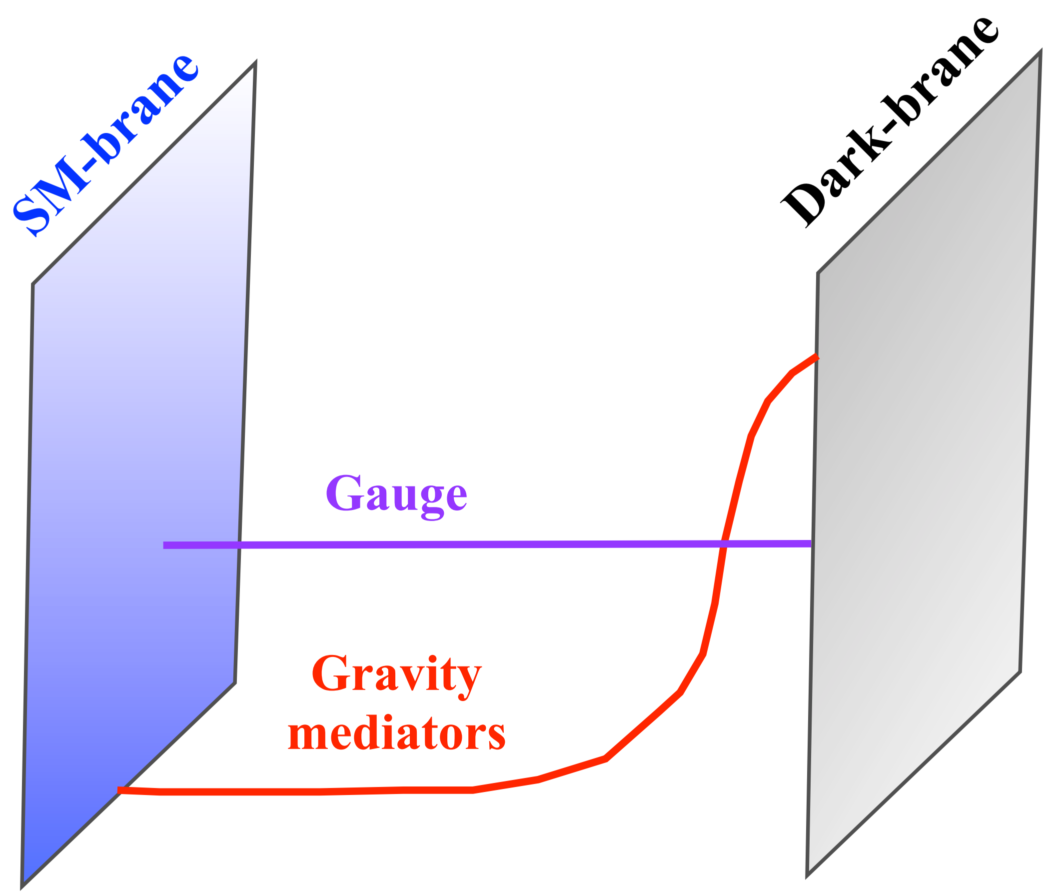
$$\frac{m_H}{M_P}, \frac{m_X}{M_P} \sim e^{-ky_c} \ll 1.$$

KK graviton strongly couples to Higgs doublet and dark matter, as well as bulk gauge bosons.

Dark-brane model (B)

[HML, M.Park, V. Sanz, 2013, 2014]

- DM on IR brane;
- All the SM particles on UV brane, except gauge bosons in bulk.



$$\frac{m_X}{M_P} \sim e^{-ky_c} \ll 1.$$

KK graviton strongly couples to dark matter and bulk (transverse) gauge bosons, depending on localization.

Focus for diphoton resonance!

Couplings of KK graviton

- KK graviton mass controlled by warp factor:

$$\frac{m_G}{\Lambda} = x_G \tilde{\kappa}: \;\; \Gamma(G \to gg) = \frac{x_G^2 \tilde{\kappa}^2}{10\pi} m_G.$$

e.g. in RS, $\tilde{\kappa} \equiv \frac{k}{M_P}, \;\; \Lambda = e^{-ky_c} M_P, \;\; x_G = 3.83.$

- Couplings to dark matter of spin 0, 1/2 or 1, and SM gauge bosons, are parametrized by c's:

$$\mathcal{L}_{\rm KK} \;\; = \;\; -\frac{1}{\Lambda} G^{\mu\nu} \left[T^{\rm DM}_{\mu\nu} + \sum_{a=1}^{3} c_a \left(\frac{1}{4} g_{\mu\nu} F^{\lambda\rho}_a F_{\lambda\rho,a} - F_{\mu\lambda,a} F^{\lambda}{}_{\nu,a} \right) \right]$$

couplings to physical gauge bosons:

$$\begin{aligned} \mathcal{L}^V_{\rm KK} \;\; = \;\; & -\frac{1}{\Lambda} G^{\mu\nu} \left[c_{\gamma\gamma} \left(\frac{1}{4} g_{\mu\nu} A^{\lambda\rho} A_{\lambda\rho} - A_{\mu\lambda} A^{\lambda}{}_{\nu} \right) + c_{Z\gamma} \left(\frac{1}{4} g_{\mu\nu} A^{\lambda\rho} Z_{\lambda\rho} - A_{\mu\lambda} Z^{\lambda}{}_{\nu} \right) \right. \\ & + c_{ZZ} \left(\frac{1}{4} g_{\mu\nu} Z^{\lambda\rho} Z_{\lambda\rho} - Z_{\mu\lambda} Z^{\lambda}{}_{\nu} \right) + c_{WW} \left(\frac{1}{4} g_{\mu\nu} W^{\lambda\rho} W_{\lambda\rho} - W_{\mu\lambda} W^{\lambda}{}_{\nu} \right) \\ & \left. + c_{gg} \left(\frac{1}{4} g_{\mu\nu} G^{\lambda\rho} G_{\lambda\rho} - G_{\mu\lambda} G^{\lambda}{}_{\nu} \right) \right] \end{aligned}$$

$$\begin{aligned} c_{\gamma\gamma} &= c_1 \cos^2\theta_W + c_2 \sin^2\theta_W, \\ c_{Z\gamma} &= (c_2 - c_1)\sin(2\theta_W), \\ c_{ZZ} &= c_1 \sin^2\theta_W + c_2 \cos^2\theta_W, \\ c_{WW} &= 2c_2, \\ c_{gg} &= c_3. \end{aligned}$$

Production/decay of KK graviton

- Production cross section for gg→G

$\sqrt{s}$=8 TeV	$\sqrt{s}$=13 TeV	$\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}}$	$\Gamma_{G\to gg}$
105 fb	465 fb	4.4	0.015 GeV

Λ=3 TeV and $c_3 = 0.1$

- Visible decay rates

$$
\begin{aligned}
\Gamma(\gamma\gamma) &= \frac{c_{\gamma\gamma}^2 m_G^3}{80\pi\Lambda^2}, \\
\Gamma(Z\gamma) &= \frac{c_{Z\gamma}^2 m_G^3}{160\pi\Lambda^2}\left(1-\frac{m_Z^2}{m_G^2}\right)^3\left(1+\frac{m_Z^2}{2m_G^2}+\frac{m_Z^4}{6m_G^4}\right), \\
\Gamma(ZZ) &= \frac{c_{ZZ}^2 m_G^3}{80\pi\Lambda^2}\left(1-\frac{4m_Z^2}{m_G^2}\right)^{\frac{1}{2}}\left(1-\frac{3m_Z^2}{m_G^2}+\frac{6m_Z^4}{m_G^4}\right), \\
\Gamma(WW) &= \frac{c_{WW}^2 m_G^3}{160\pi\Lambda^2}\left(1-\frac{4m_W^2}{m_G^2}\right)^{\frac{1}{2}}\left(1-\frac{3m_W^2}{m_G^2}+\frac{6m_W^4}{m_G^4}\right), \\
\Gamma(gg) &= \frac{c_{gg}^2 m_G^3}{10\pi\Lambda^2}.
\end{aligned}
$$

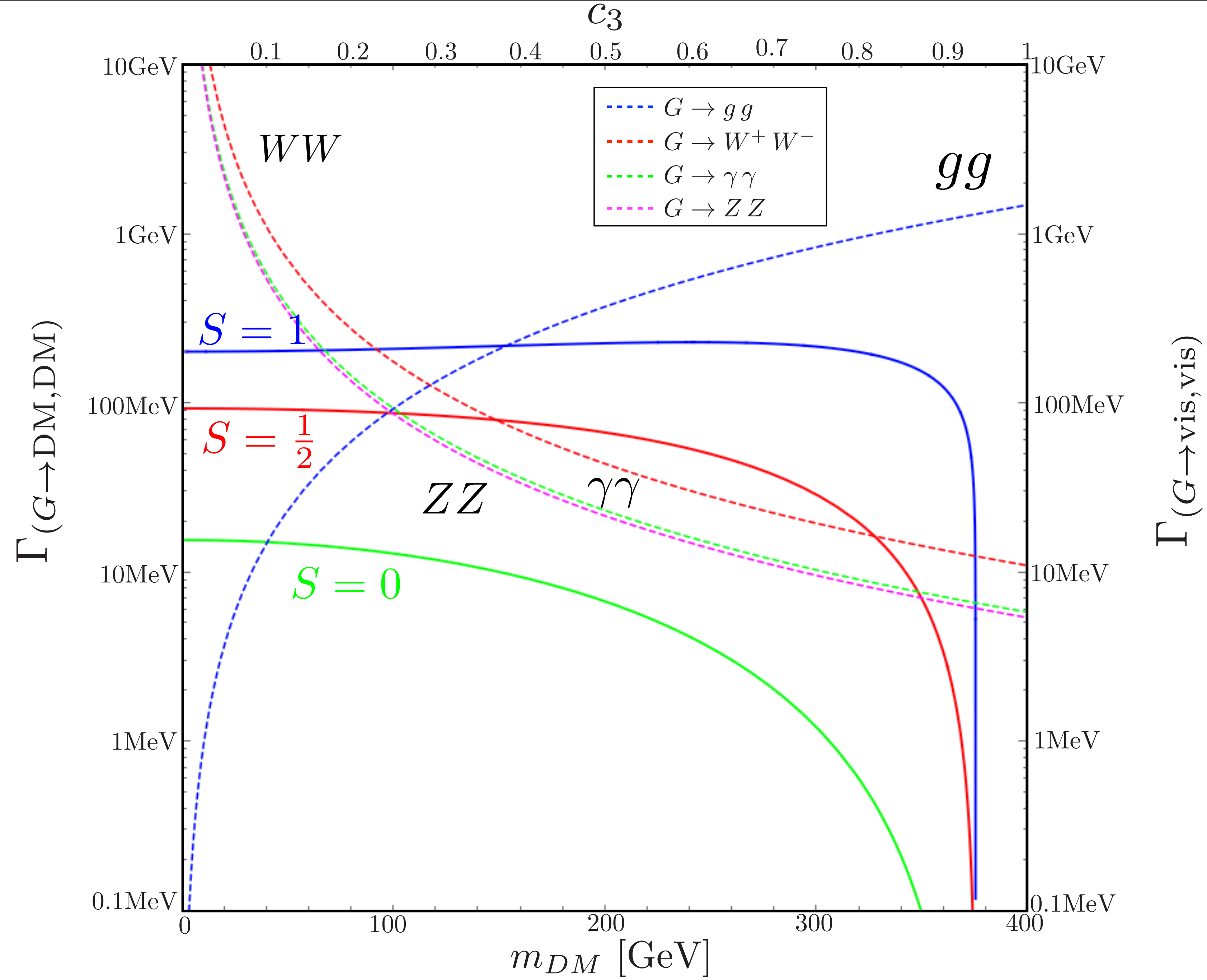
- Invisible decay rates

phase space suppressed

$$
\begin{aligned}
\Gamma(SS) &= \frac{N_f c_S^2 m_G^3}{960\pi\Lambda^2}\left(1-\frac{4m_S^2}{m_G^2}\right)^{\frac{5}{2}}, \\
\Gamma(\chi\bar{\chi}) &= \frac{N_f c_\chi^2 m_G^3}{160\pi\Lambda^2}\left(1-\frac{4m_\chi^2}{m_G^2}\right)^{\frac{3}{2}}\left(1+\frac{8}{3}\frac{m_\chi^2}{m_G^2}\right), \\
\Gamma(XX) &= \frac{N_f c_X^2 m_G^3}{960\pi\Lambda^2}\left(1-\frac{4m_X^2}{m_G^2}\right)^{\frac{1}{2}}\left(13+\frac{56m_X^2}{m_G^2}+\frac{48m_X^4}{m_G^4}\right).
\end{aligned}
$$

Henceforth, $c_1 = c_2$: no Zγ decay.

(discussion generalized otherwise.)



$\Gamma_G = 45\,\mathrm{GeV}$, diphoton signal rates imposed;

$$\Lambda = 3\,\mathrm{TeV},\ m_G = 750\,\mathrm{GeV}$$

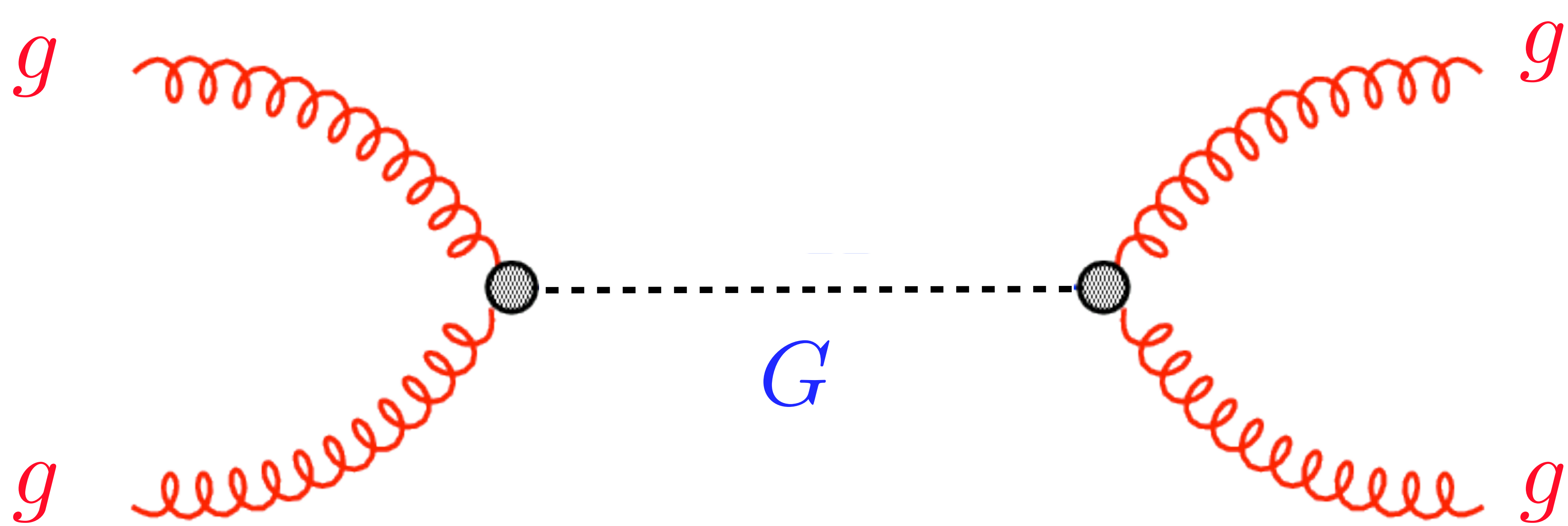
$c_X = 1:$ Invisible decay rate is subdominant.

Vector DM is the largest.

Bounds on KK graviton

- Null results in searches for KK graviton in Run I & II set limits on other channels.

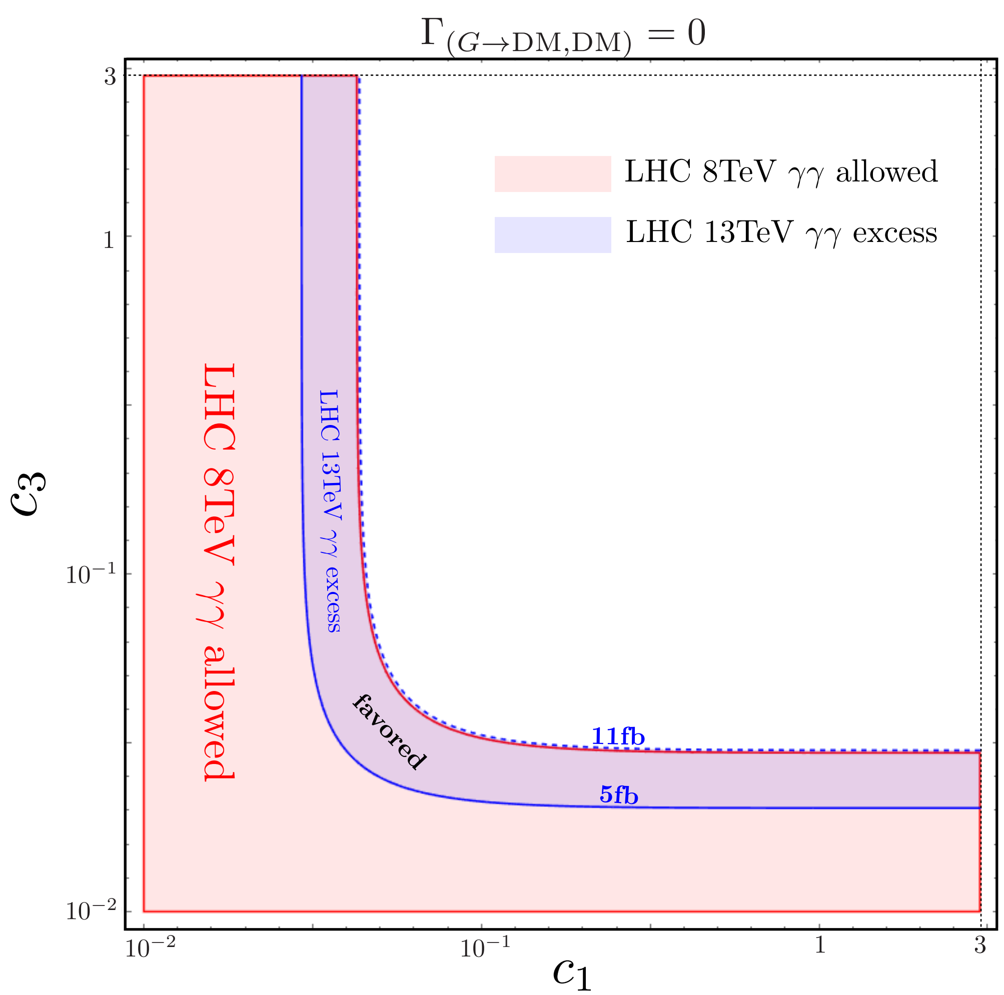
Channels	$\sqrt{s}$=8 TeV	$\sqrt{s}$=13 TeV
$WW(l\nu jj)$	$\lesssim$ 68 fb [10]	$\lesssim$ 259 fb [11]
$ZZ(lljj)$	$\lesssim$ 37 fb [12]	$\lesssim$ 151 fb [13]
$\gamma\gamma$	$\lesssim$ 2.4 fb [14]	$\lesssim$ 11 fb
dijet	14 pb[1] [15]	-
Monojet	$\lesssim$ 270 fb [16]	-



Diphoton = KK graviton

- Diphoton production cross section constrains KK graviton couplings to

$$c_{gg} \times c_{\gamma\gamma} = 0.16 \left(\frac{\sigma_{pp\to\gamma\gamma}}{8\,\mathrm{fb}}\right)^{1/2} \left(\frac{\Lambda}{3\,\mathrm{TeV}}\right)^{2} \left(\frac{45\,\mathrm{GeV}}{\Gamma_G}\right)^{1/2}.$$



No invisible decay

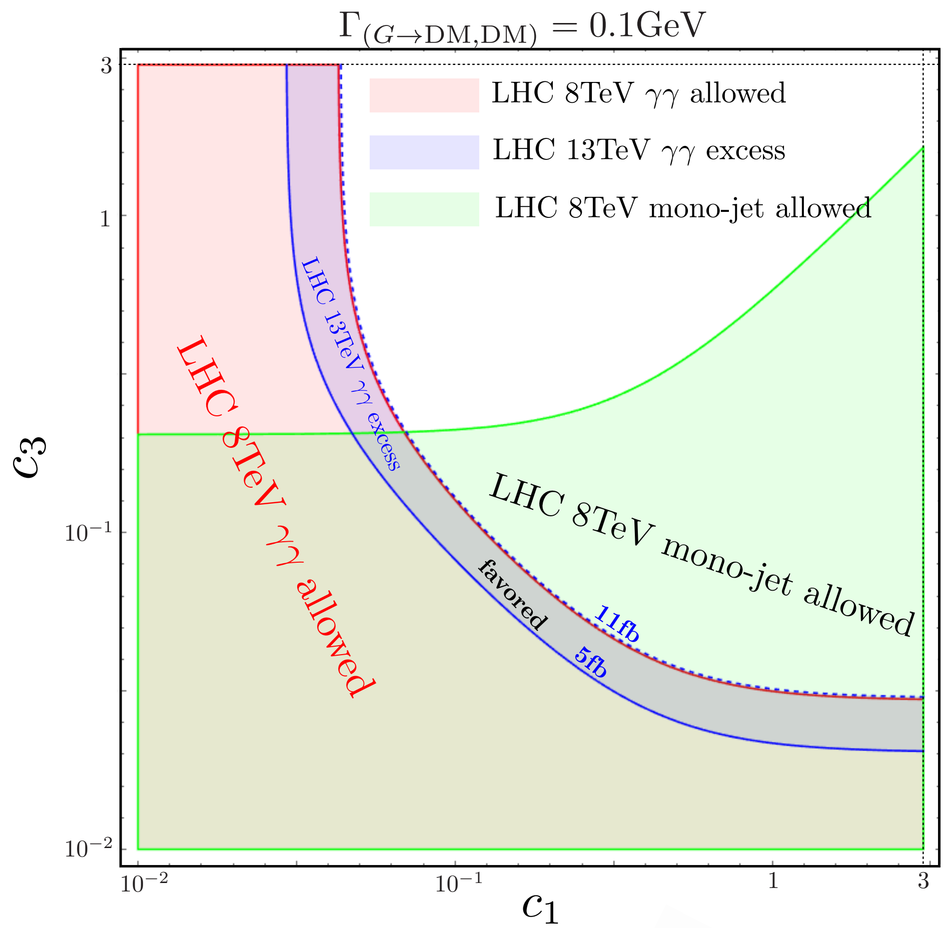
$$\Lambda = 3\,\mathrm{TeV},\ m_G = 750\,\mathrm{GeV}$$

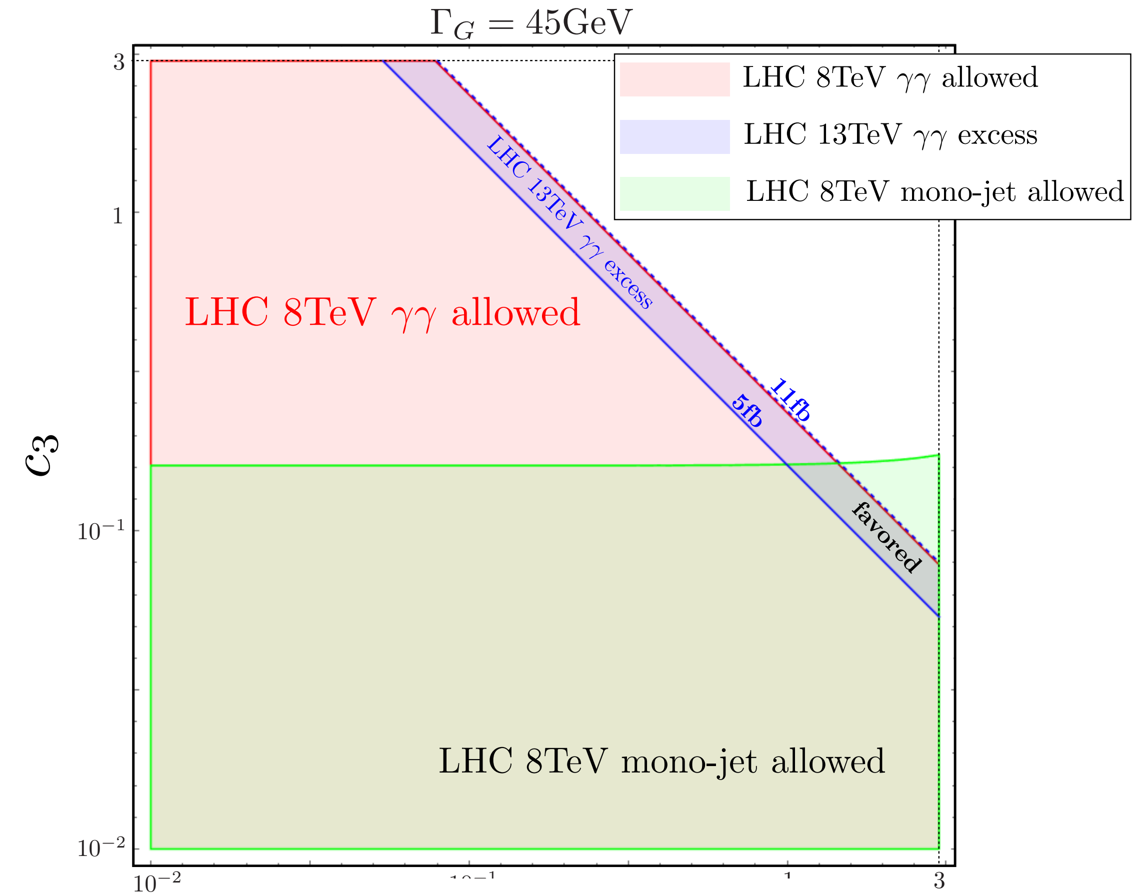
Dijet bound:

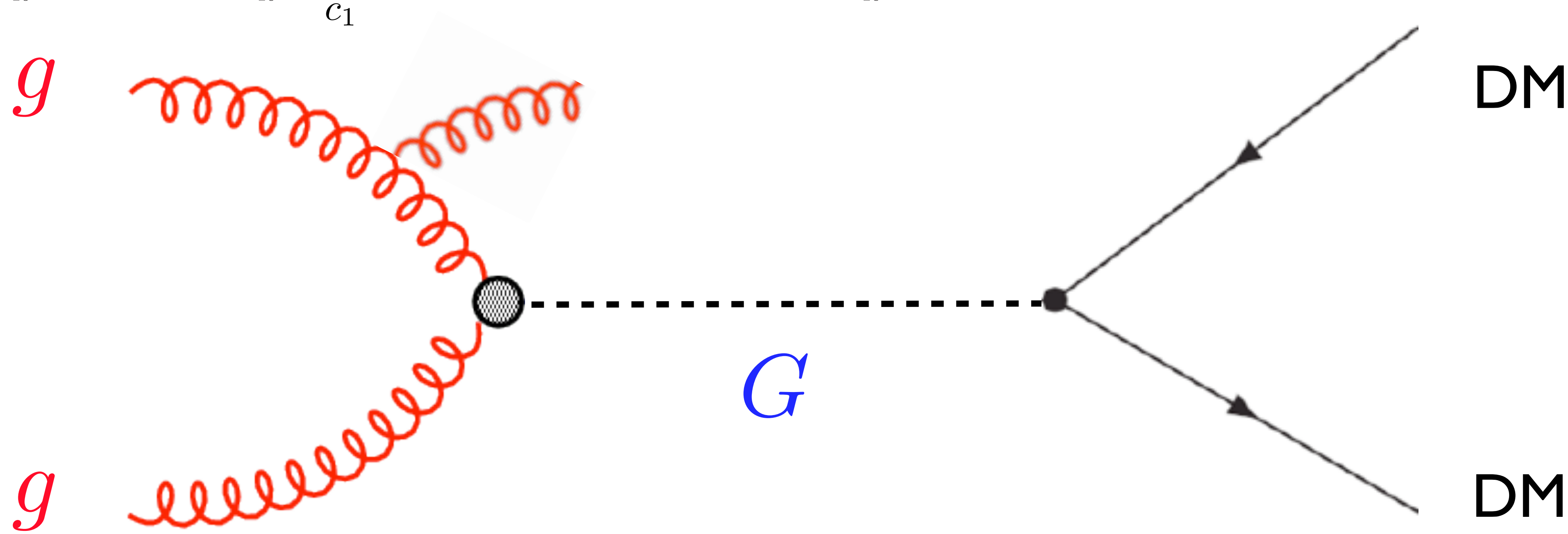
$$|c_3| \lesssim 1.5$$

Invisible decay & mono-jet

Allow large coupling to DM: Large invisible decay





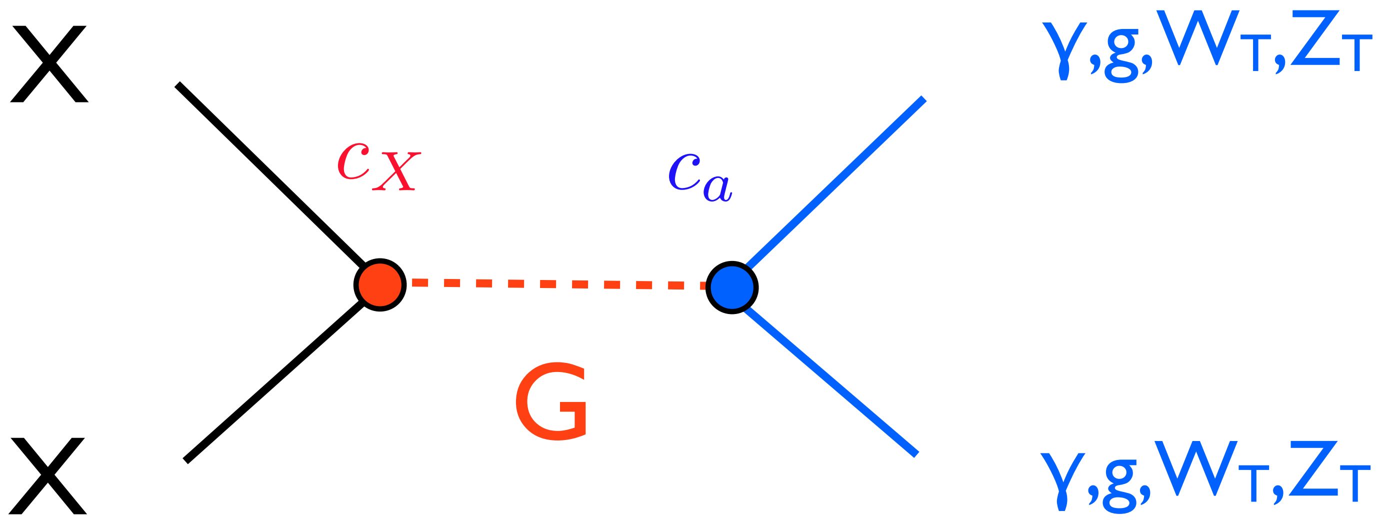


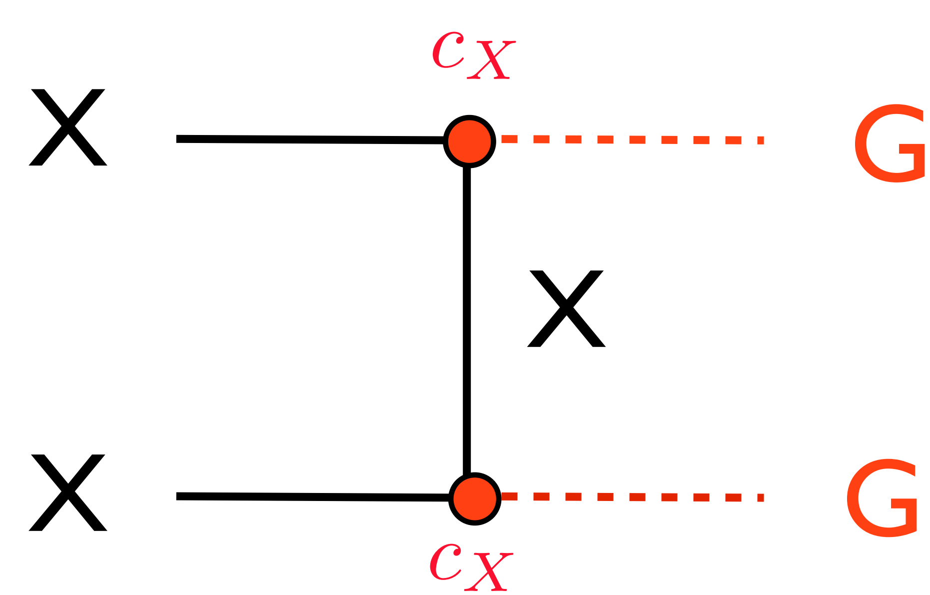
KK graviton as DM mediator

DM annihilation

[HML, M.Park, V. Sanz, 2013, 2014]

- DM annihilates via KK graviton exchanges, depending on the spin of dark matter.



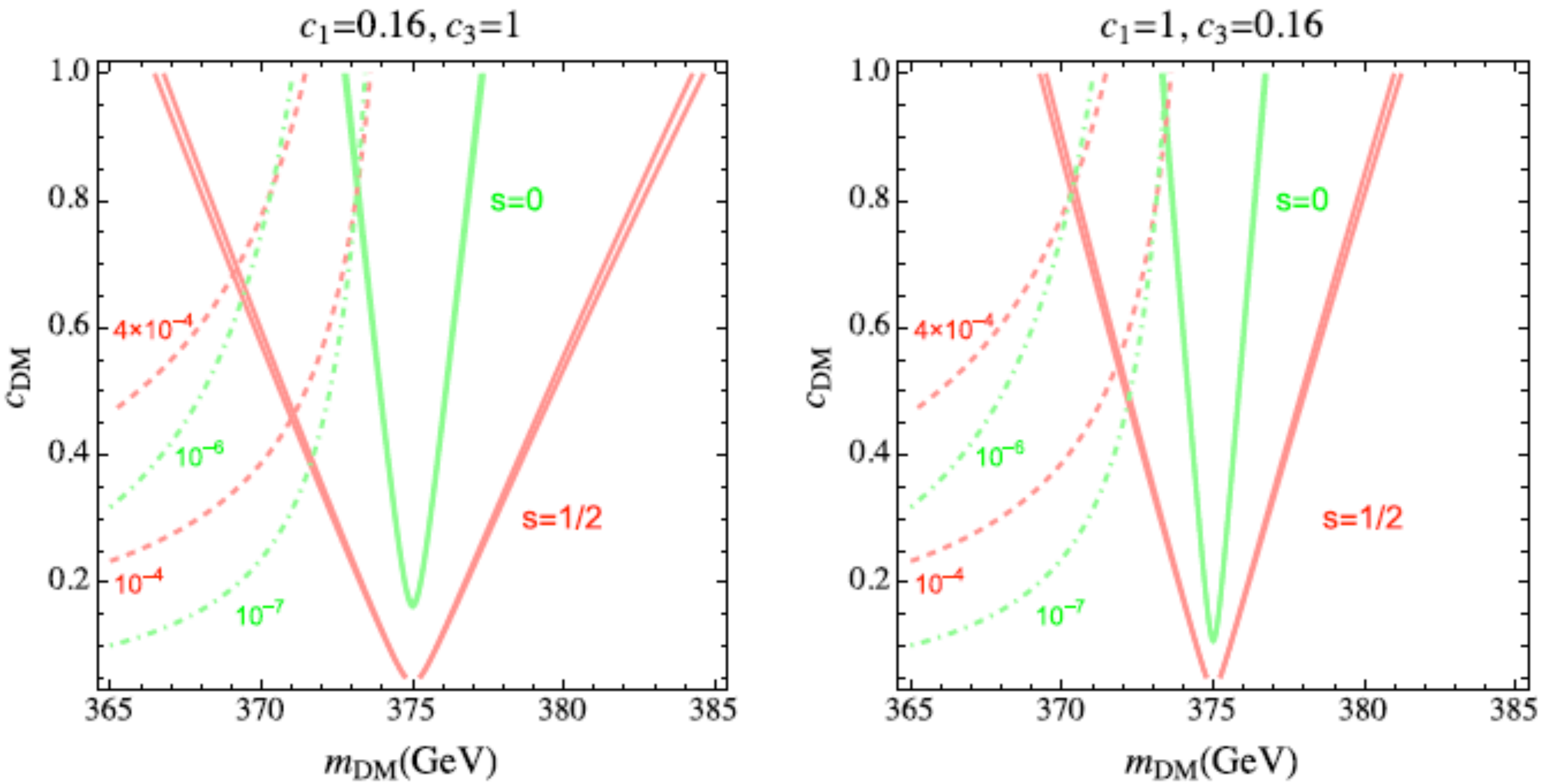


$$(\sigma v)_s \sim v^n \frac{c_X^2 c_a^2 m_X^2}{\Lambda^4}\left(\frac{m_X}{m_G}\right)^4$$

$$(\sigma v)_t \sim \frac{c_X^4 m_X^2}{\Lambda^4}\left(\frac{m_X}{m_G}\right)^8$$

channels	DM mass	X (s=0)	X (s=1/2)	X (s=1)
s-channel	$m_{DM} < m_W$	d-wave	p-wave	s-wave
s-channel	$m_{DM} > m_W$	s-wave	p-wave	s-wave
t-channel	$m_{DM} > m_G$	s-wave	s-wave	s-wave

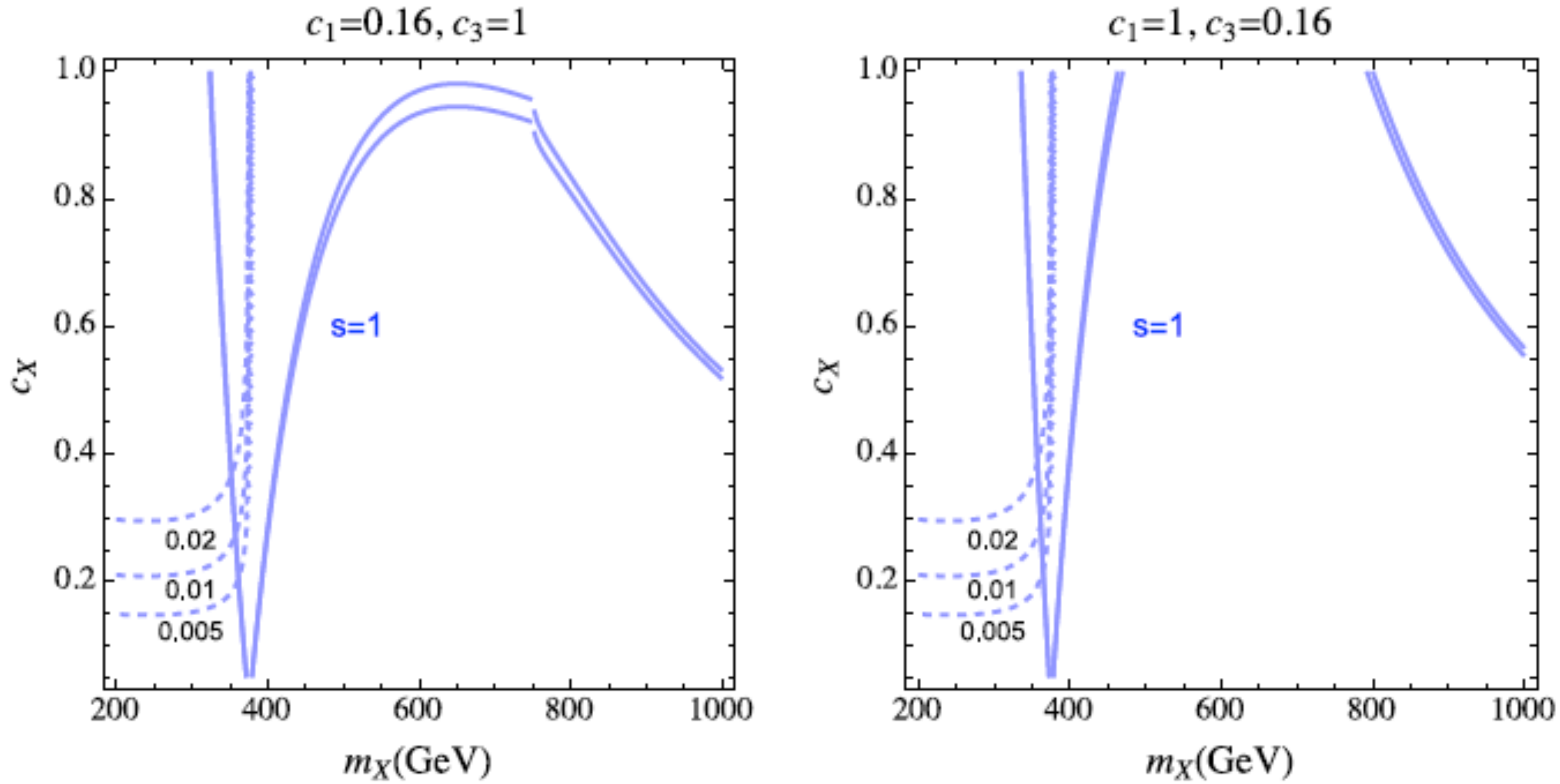
Scalar and fermion DM



$\Lambda = 3\,\mathrm{TeV}$ and $m_G = 750\,\mathrm{GeV}$

- Correct relic density is obtained near resonance, due to velocity-suppressed annihilation.
- Invisible decay rates (given in unit of GeV) are small in the region of correct relic density.

Vector DM



$\Lambda = 3\,\mathrm{TeV}$ and $m_G = 750\,\mathrm{GeV}$

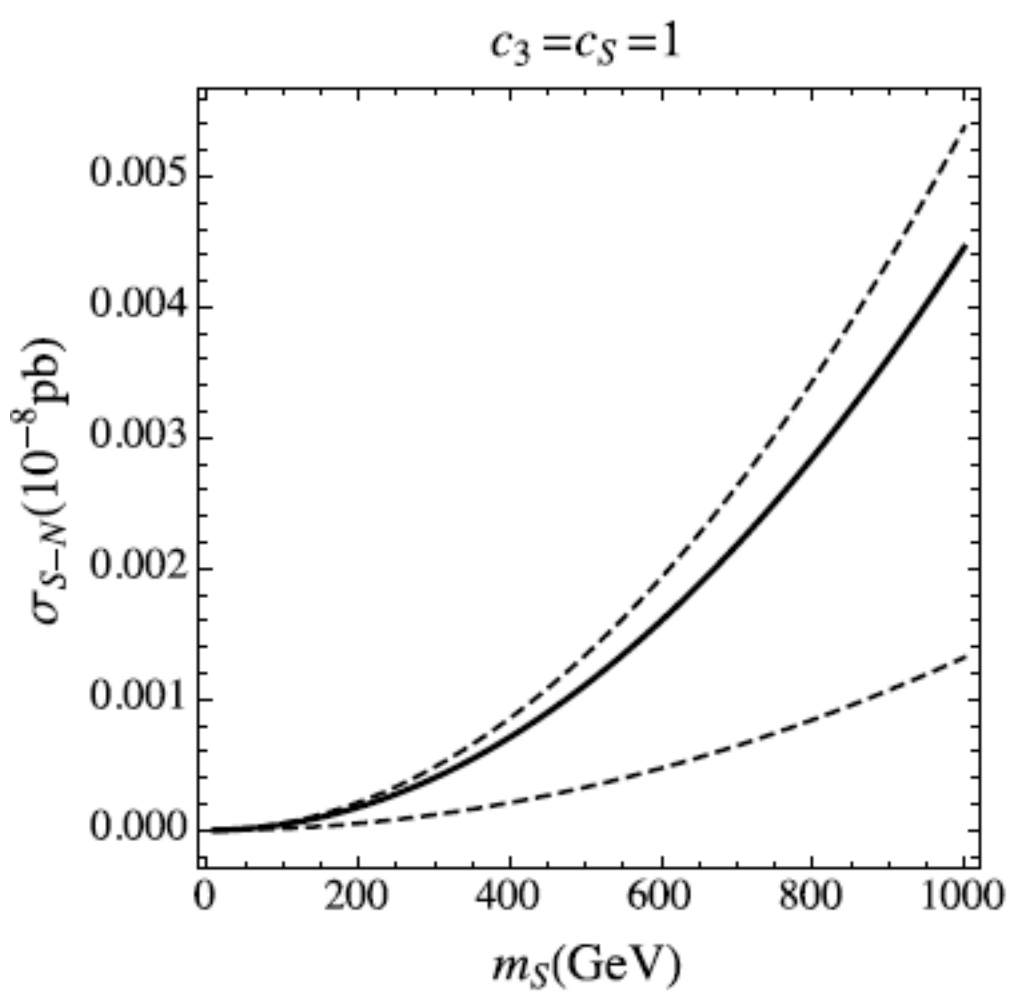
- Correct relic density can be obtained even away from resonance, due to s-wave annihilation.
- Invisible decay rate is larger than the cases with other spins, but is still small.

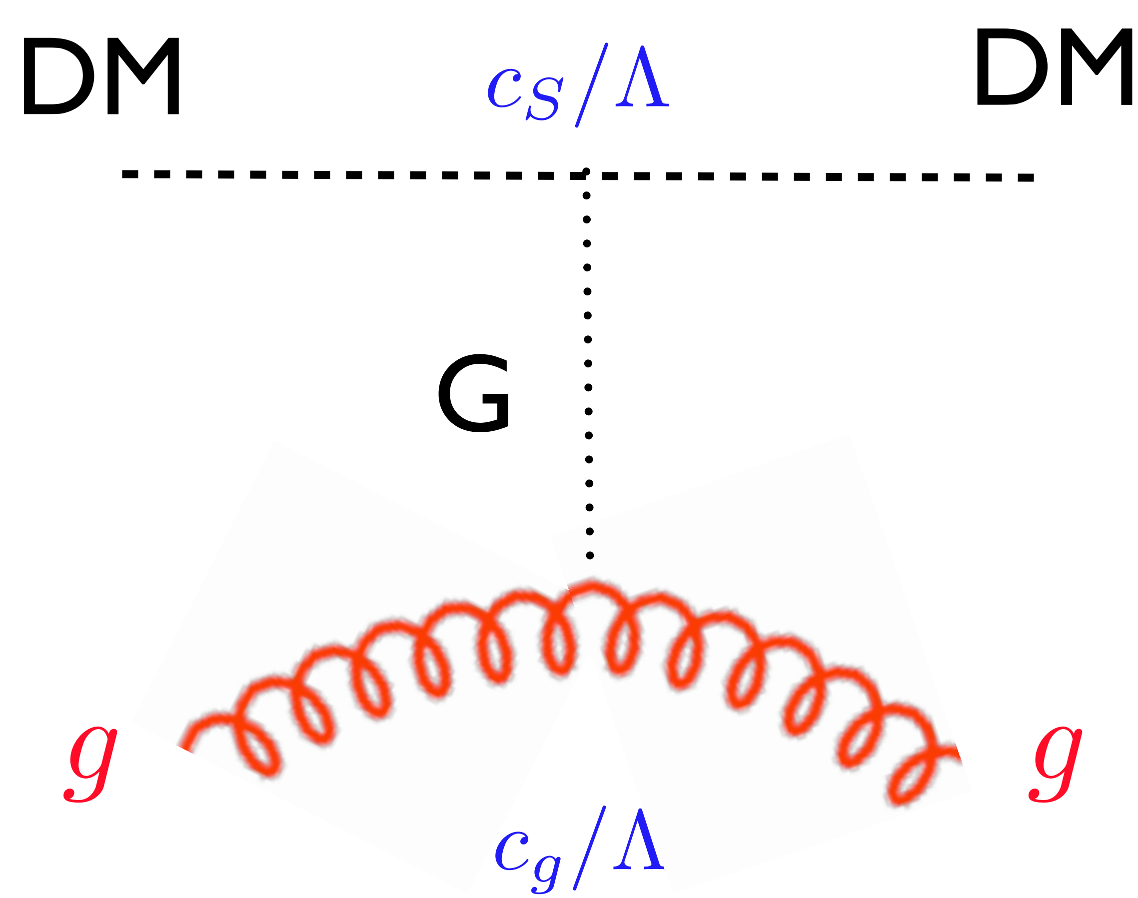
Direct detection

- Gluon coupling is unconstrained by direct detection.

$$\mathcal{L}_{S-N} = \xi_g S^2 G_{\mu\nu} G^{\mu\nu}, \ \xi_g = \frac{c_S c_g}{6\Lambda^2} \frac{m_S^2}{m_G^2},$$

$$\boxed{\sigma_{S-N} = \frac{\mu^2}{\pi m_S^2}\left(\frac{8\pi}{9\alpha_S}\right)^2 m_N^2 \xi_g^2 f_{TG}^2, \quad f_{TG} = \frac{1}{m_N}\langle N|\frac{-9\alpha_S}{8\pi} G_{\mu\nu}G^{\mu\nu}|N\rangle = 0.472 - 0.952(\mathrm{MILC}).}$$



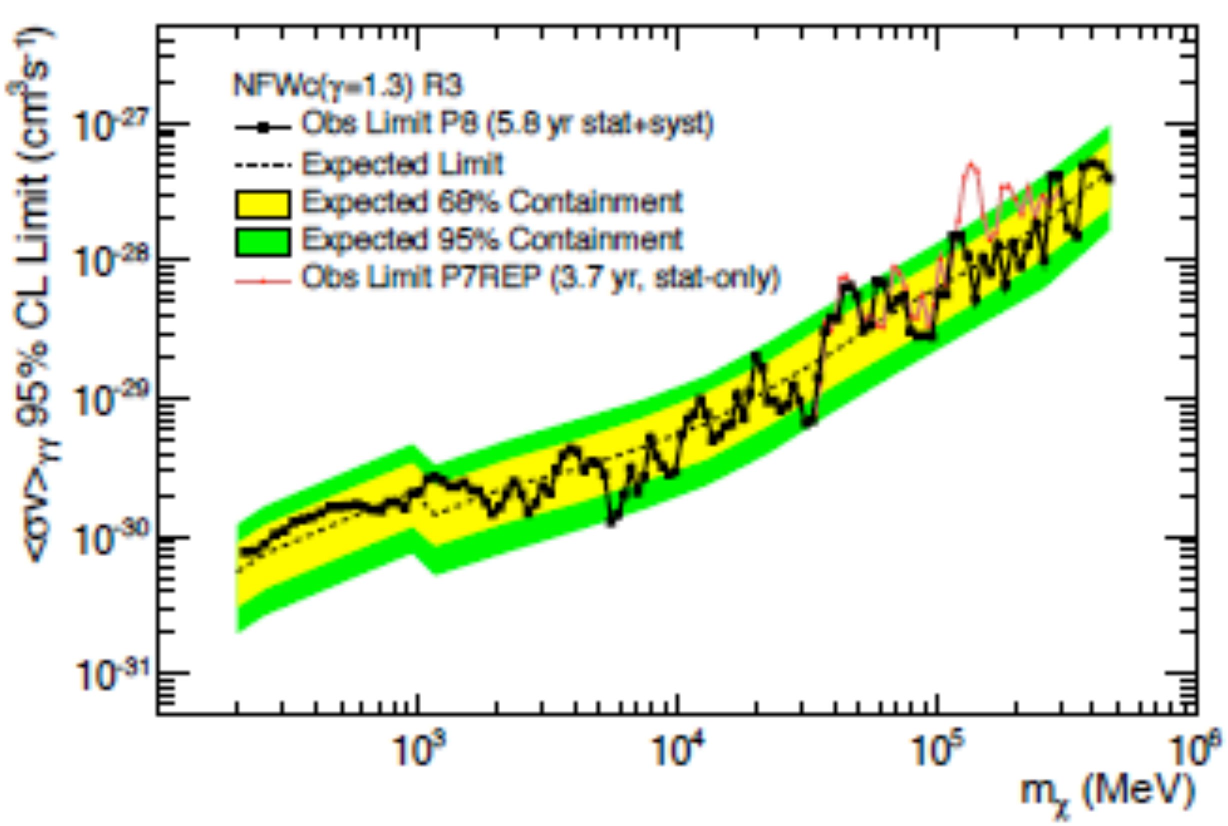


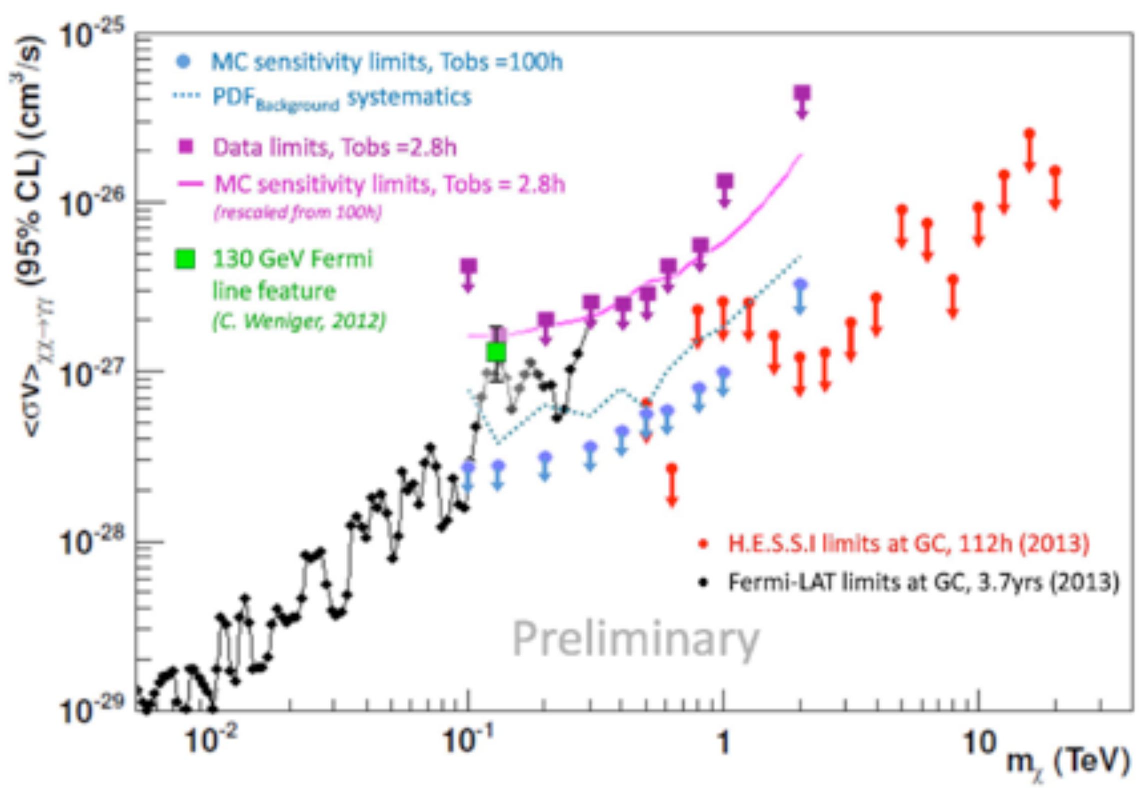
Indirect detection - lines

- Spectral gamma-ray line (Fermi-LAT, HESS, CTA, etc):

  $\gamma\gamma$, GG$\rightarrow$ $\gamma\gamma\gamma\gamma$ channels (vector DM)

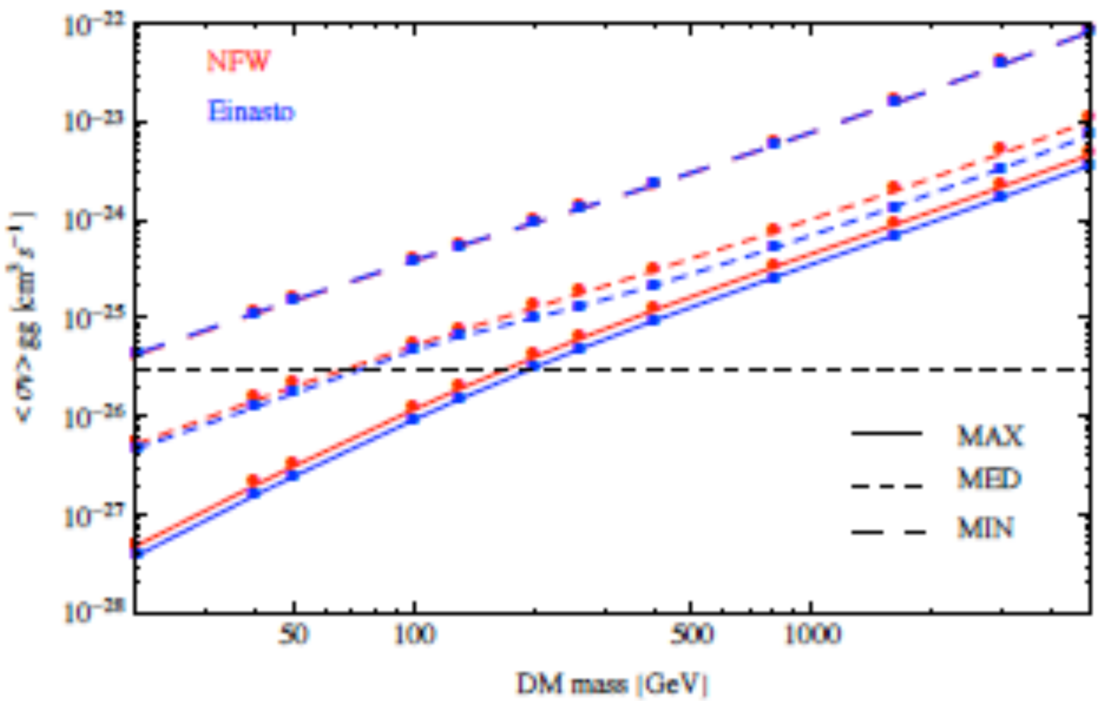
- BR of DM annihilation into a photon pair less than 1% of thermal cross section for DM mass ~ a few 100GeV.

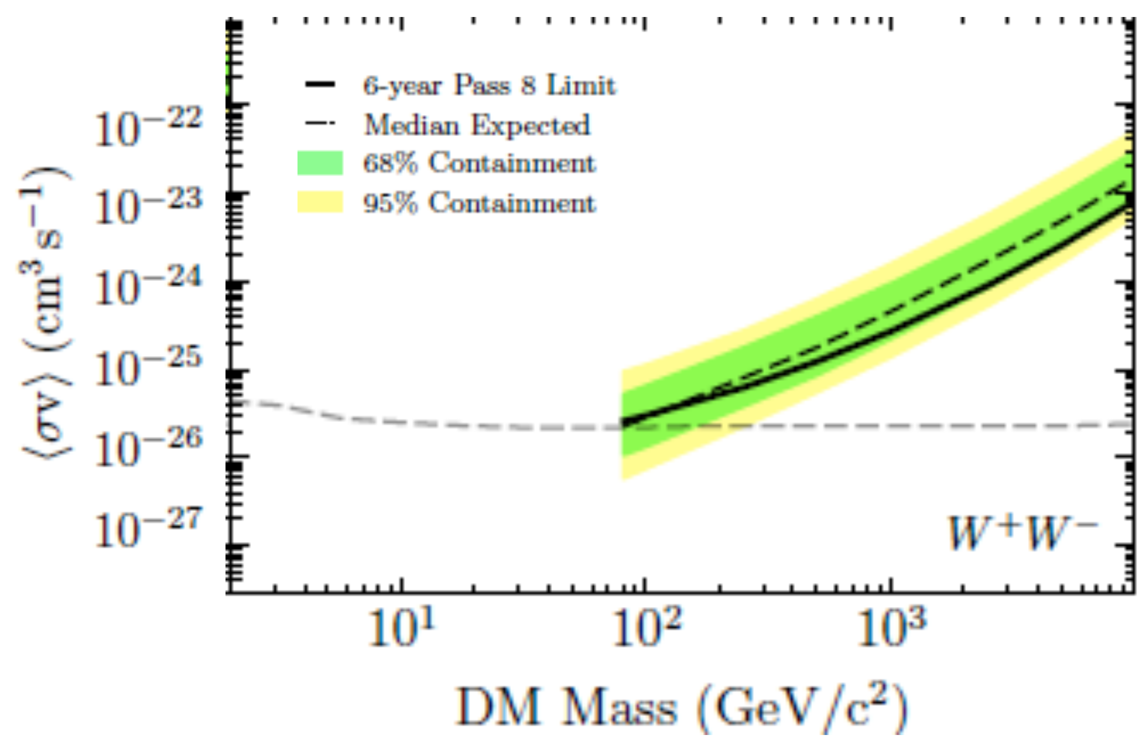




Indirect detection - continuum

- Continuum gamma-ray (Fermi-LAT dwarf galaxies): WW, ZZ channels (scalar & vector DM)
- Anti-proton (PAMELA, AMS-02): gg channel (vector DM)
- Bounds from Anti-proton & Fermi dwarf galaxies constrain thermal cross section for gg & WW.





[Chu, Hambye, Scarna, Tytgat, 2012]

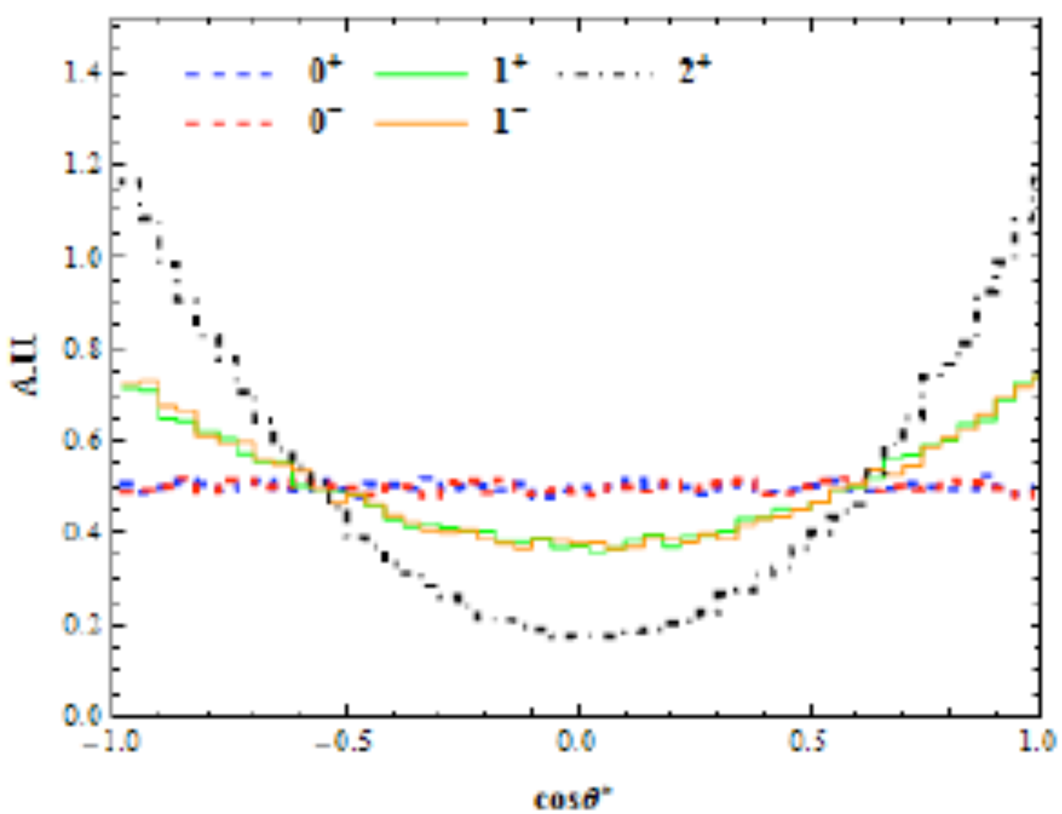
Spin determination

Spin/CP of resonances

- Angular correlations between decay products depend on spin/CP of the resonance particle.

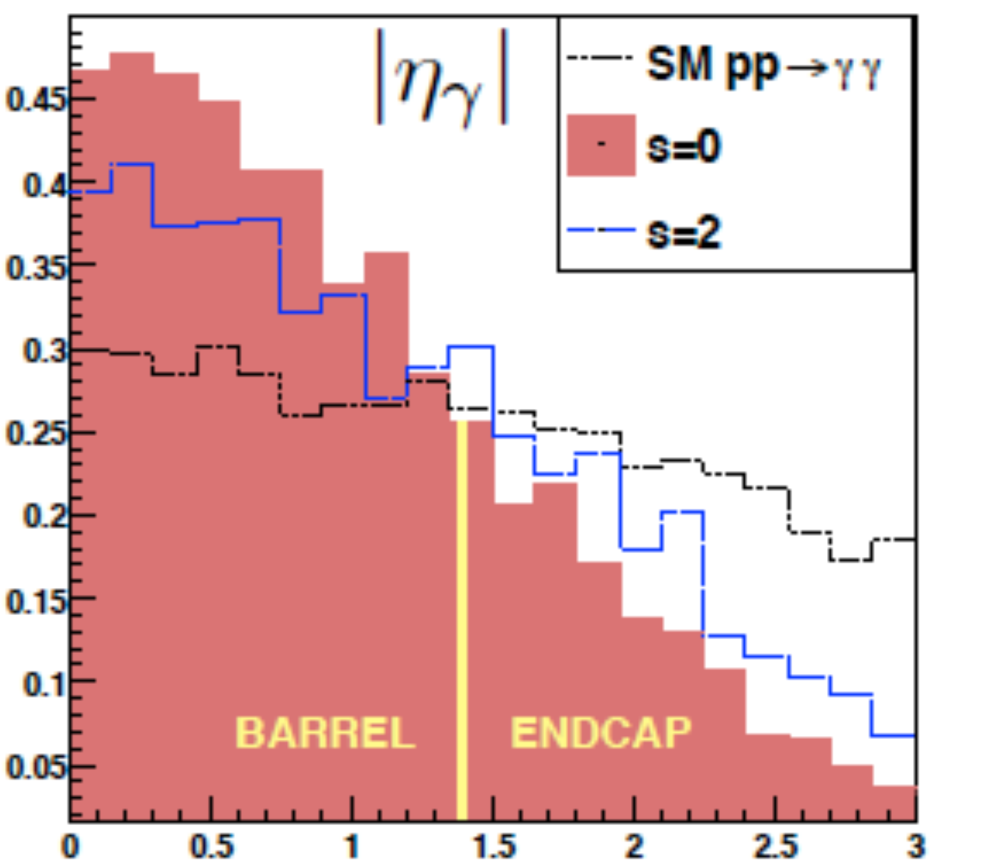
e.g. diboson resonance [D.Kim et al, 1507.06312]

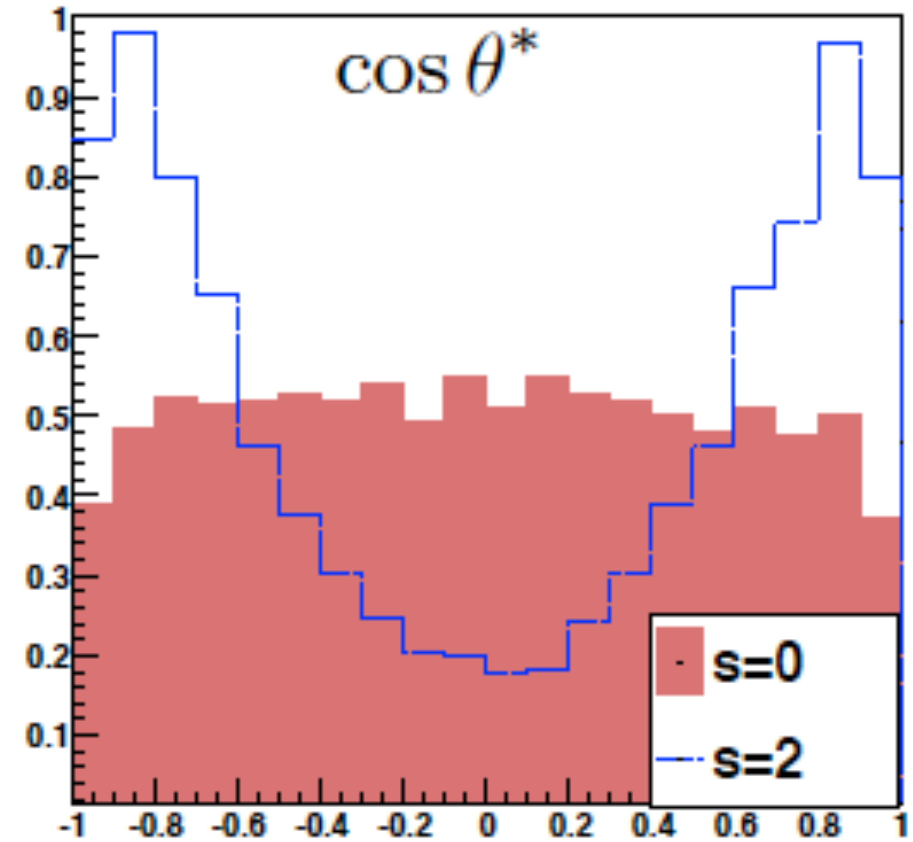
$$\frac{d\sigma}{d\cos\theta^*} \sim \begin{cases} 1\,, & \text{for } gg \to 0^+\,, 0^- \to W^+W^- \\ 1+\cos^2\theta^*\,, & \text{for } q\bar{q} \to 1^+\,, 1^- \to W^+W^- \\ 1+6\cos^2\theta^* + \cos^4\theta^*\,, & \text{for } gg \to \quad 2^+ \quad \to W^+W^- \end{cases} .$$



θ^* : the angle of decay product wrt the beam direction in C.M. of decaying particle.

Diphoton distribution





"rapidity" $m_{\gamma\gamma} = 750 \pm 50 \text{ GeV}$

- More events of spin-2 in end-cap region than spin-0 case. (CMS 2.6σ excess comes from EBEE.)
- Angular distribution distinguishes spin:
  spin-0 ~ symmetric, spin-2 ~ boosted decay.

Conclusions

- We considered the interpretation of the diphoton resonance in EFT.
- We presented a concrete example for spin-2 resonance where KK graviton plays a role of dark matter mediator.
- Gluon coupling can be constrained by mono-jet and dijet searches.
- Invisible decay rate is small in the region of correct DM relic density.
- Gluon or photon coupling can be constrained by indirect detection for scalar or vector DM.