Searches for BSM

Shrihari Gopalakrishna

Institute of Mathematical Sciences (IMSc), Chennai

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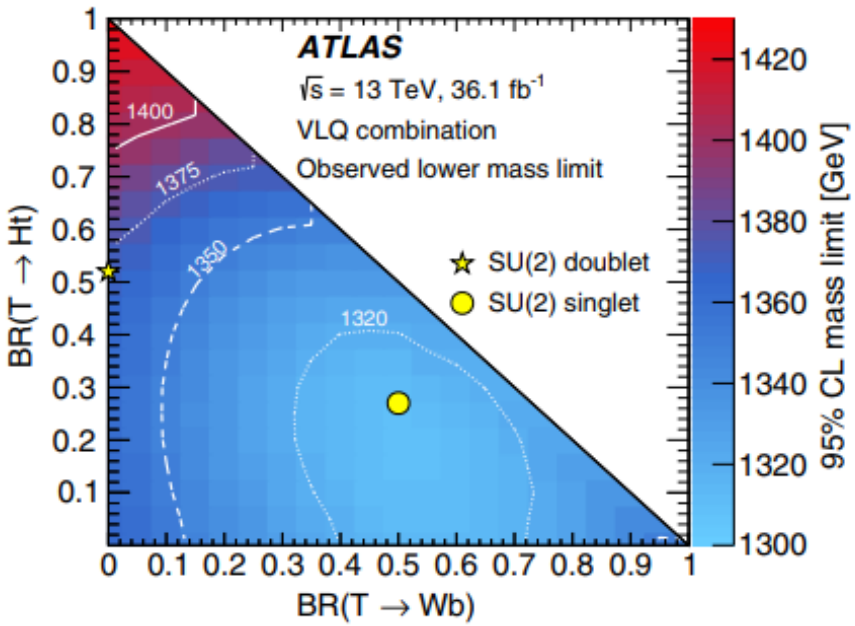
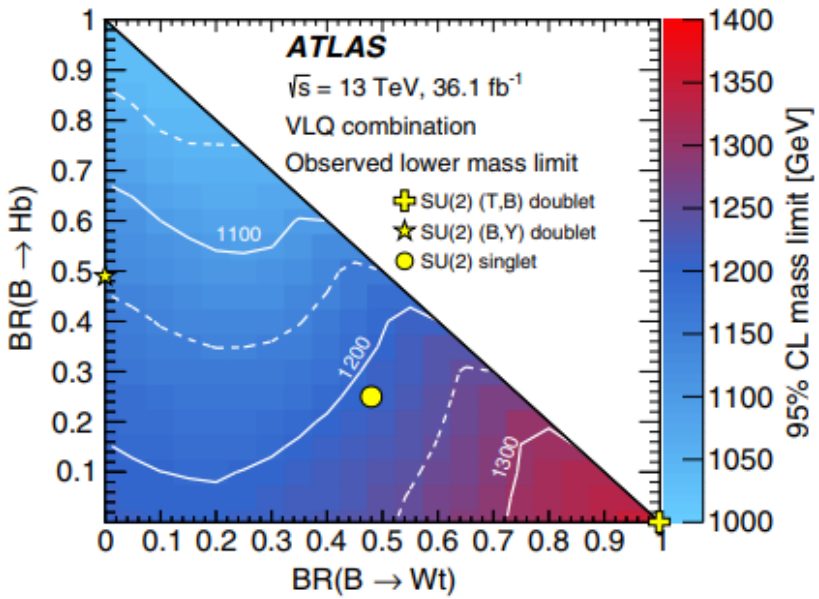
Talk Outline

- General aspects of searches for BSM

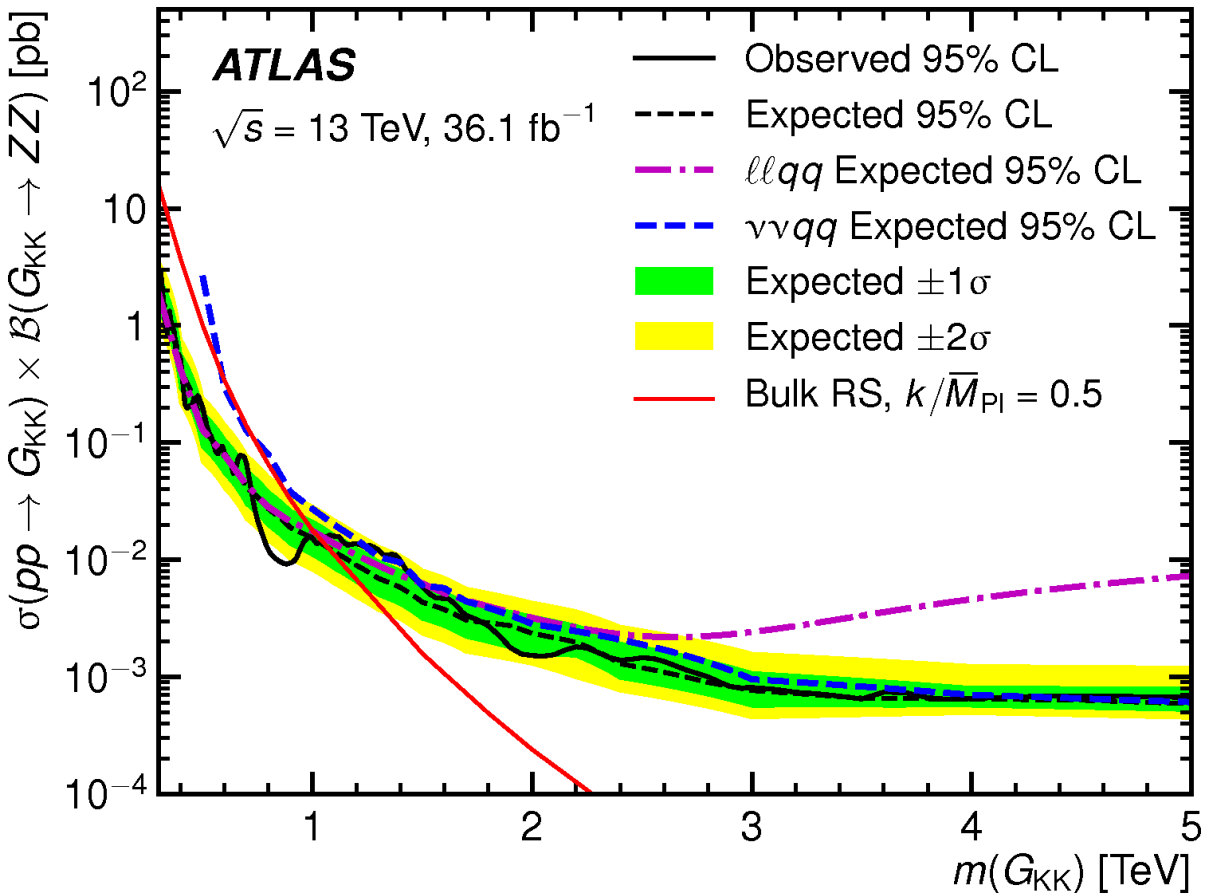
Vector-like fermion (t', b') search



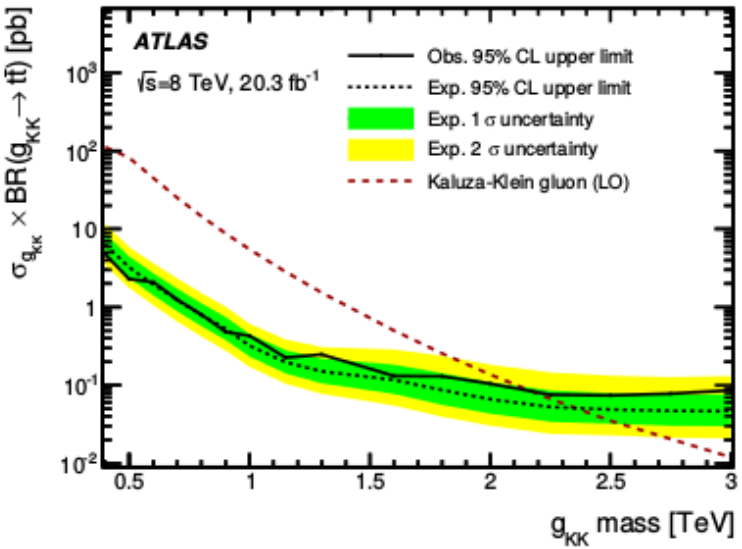


[ATLAS: 1808.02343; PRL 2018]

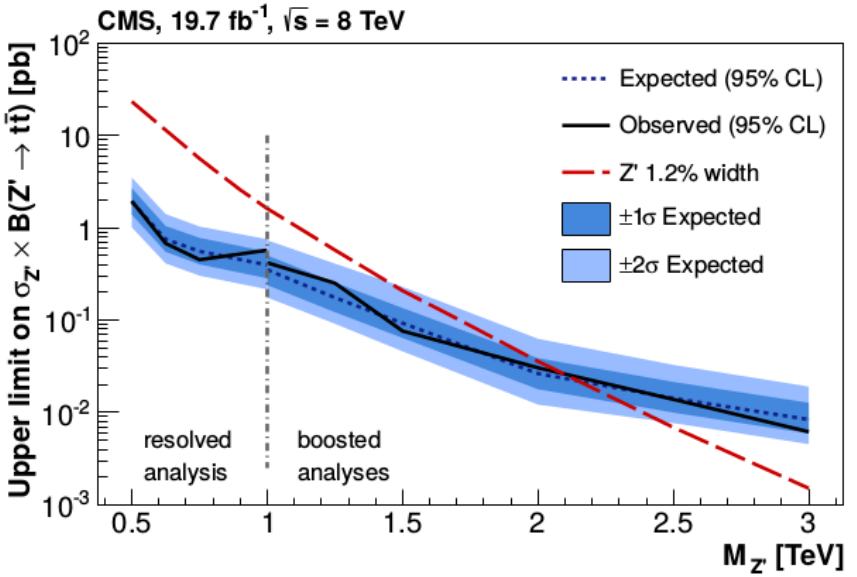
graviton$^{(1)} \rightarrow ZZ$ search



gluon$^{(1)} \to t\bar{t}$ search (8TeV)



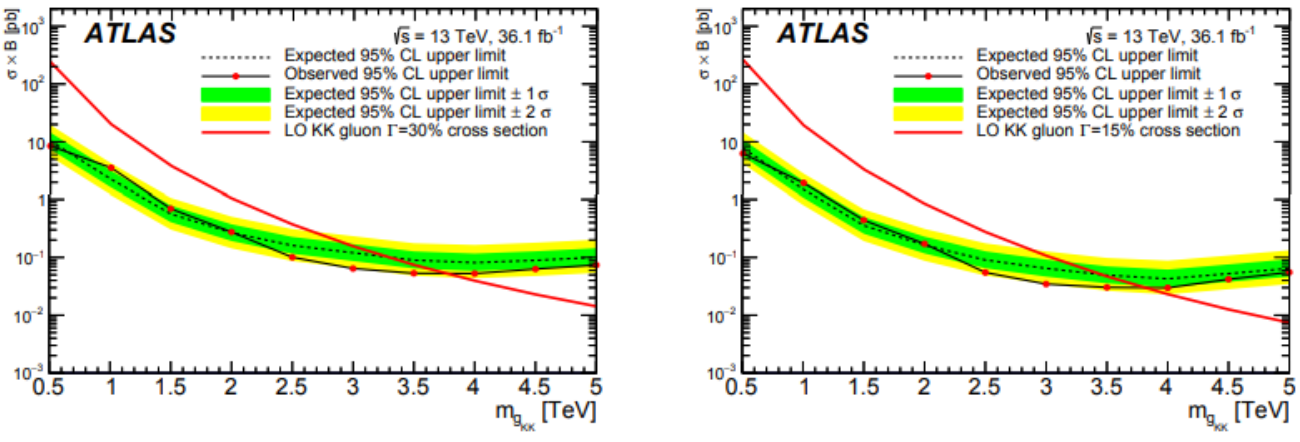
(b) g_{KK}, resolved and boosted combination.



Limit: $M_{KK} > 2.2\ TeV$ @ 95% CL

[ATLAS 1505.07018; CMS 1309.2030]

gluon$^{(1)} \to t\bar{t}$ search (13TeV)

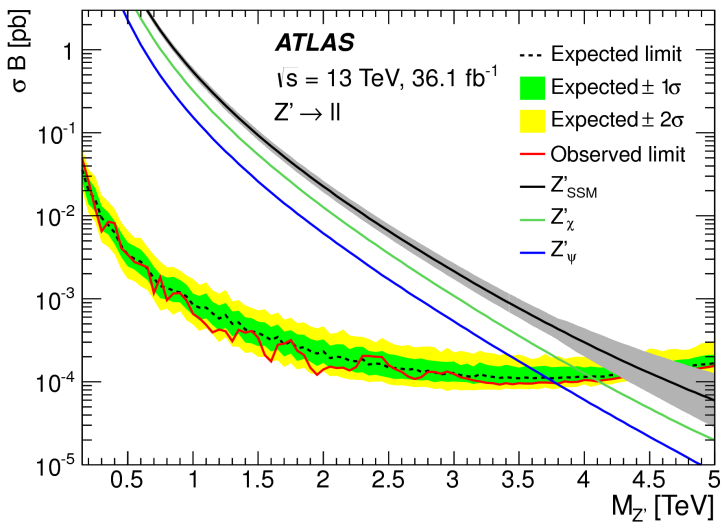


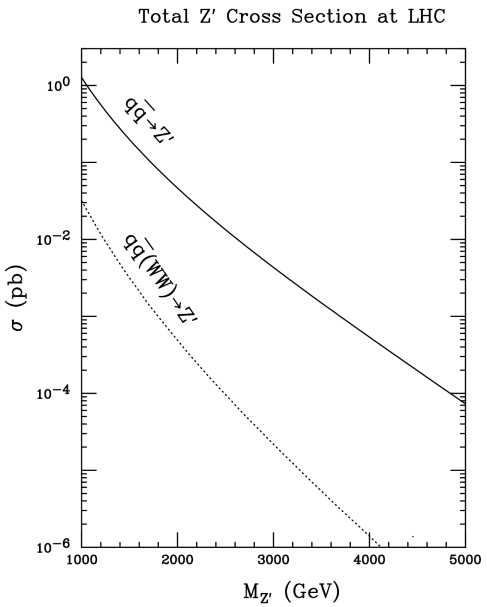
(a) 30% width (b) 15% width

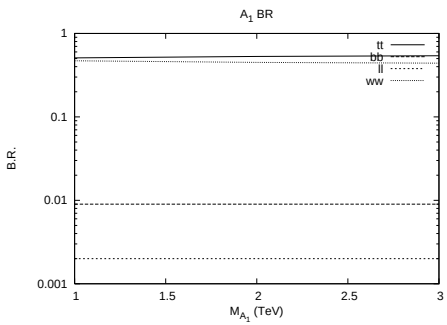
Figure 17: The observed and expected cross-section 95% CL upper limits on the g_{KK} signal for resonance widths of (a) 30% and (b) 15%. The theoretical predictions for the production cross-section times branching ratio of $g_{KK} \to t\bar{t}$ at the corresponding masses are also shown.

[ATLAS 1804.10823 [hep-ex]]

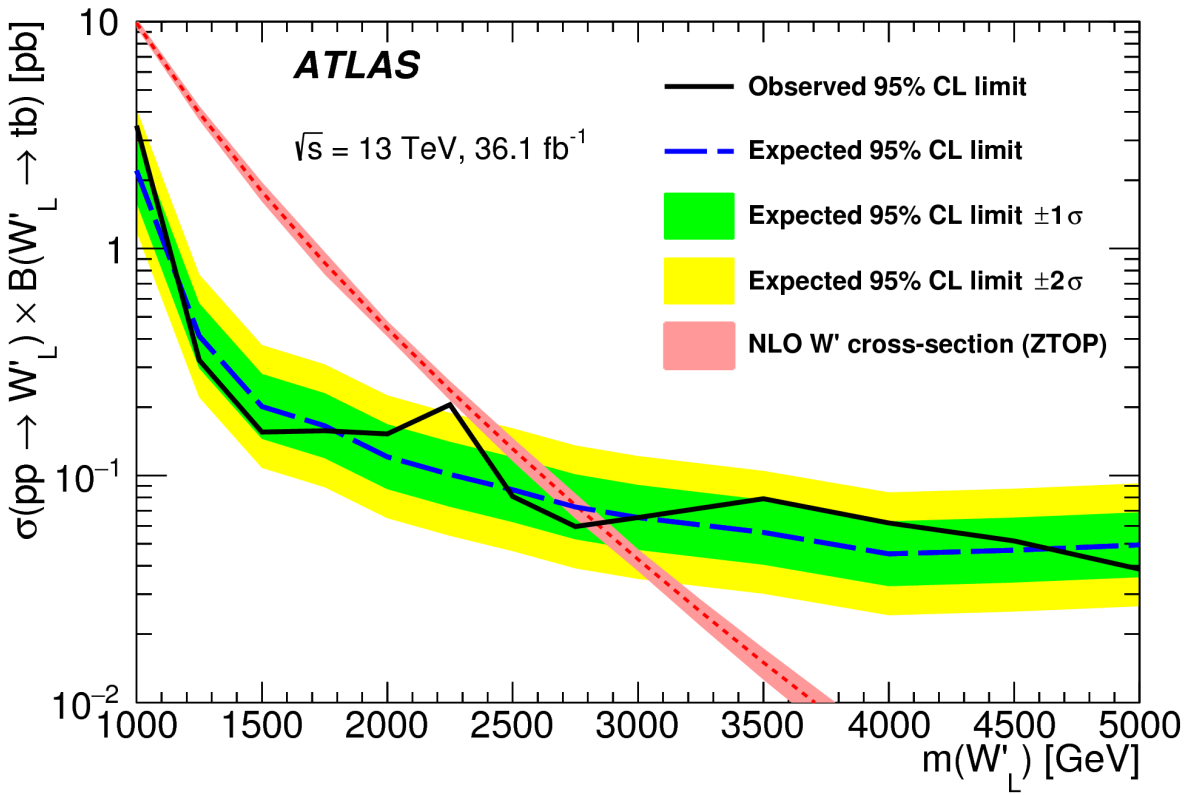
$Z' \to \ell^+\ell^-$





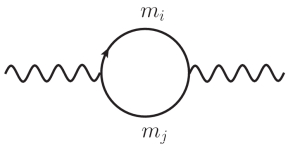


[Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni - 0709.0007 [hep-ph]]


ATLAS
√s = 13 TeV, 36.1 fb-1
Observed 95% CL limit
Expected 95% CL limit
Expected 95% CL limit ±1σ
Expected 95% CL limit ±2σ
NLO W' cross-section (ZTOP)
σ(pp → W'L) × B(W'L → tb) [pb]
m(W'L) [GeV]
10
1
10−1
10−2
1000
1500
2000
2500
3000
3500
4000
4500
5000

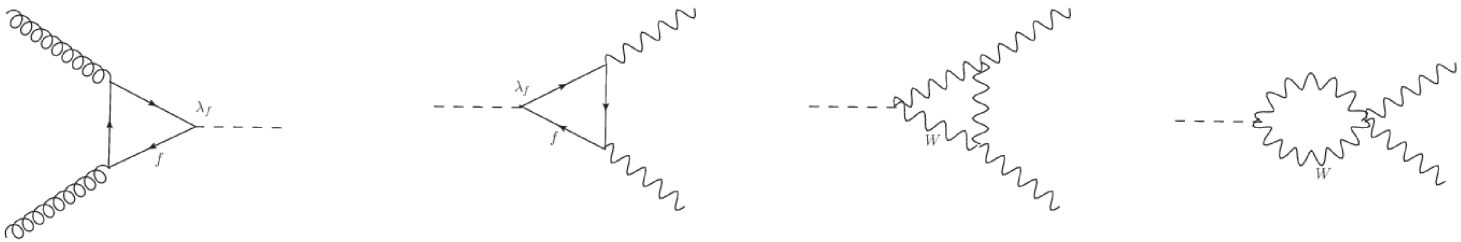
EWPrecision + Higgs Observables

Precision electroweak observables (S, T, U)



Modifications to hgg, $h\gamma\gamma$ couplings:

$\sigma(gg \to h)$ $\qquad$ $\Gamma(h \to \gamma\gamma)$



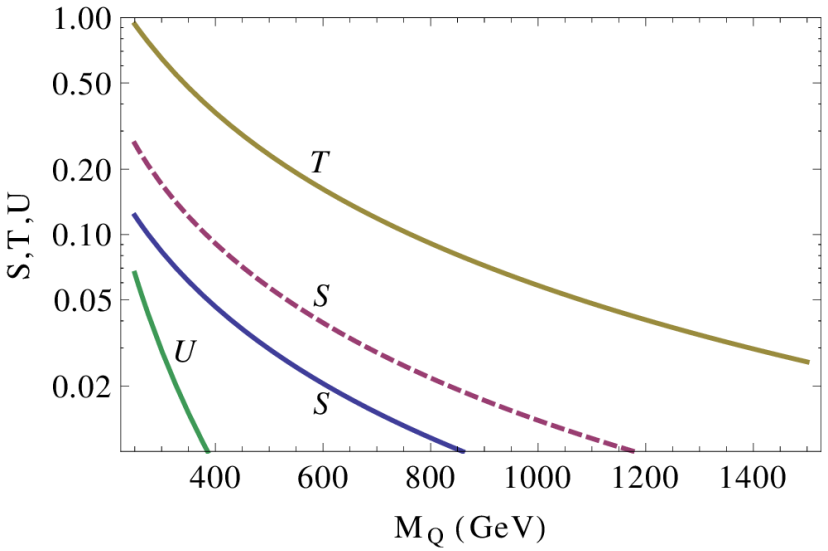
We compute ratios $\frac{\Gamma_{h\to gg}}{SM}$, $\frac{\Gamma_{h\to\gamma\gamma}}{SM}$ using leading-order expressions

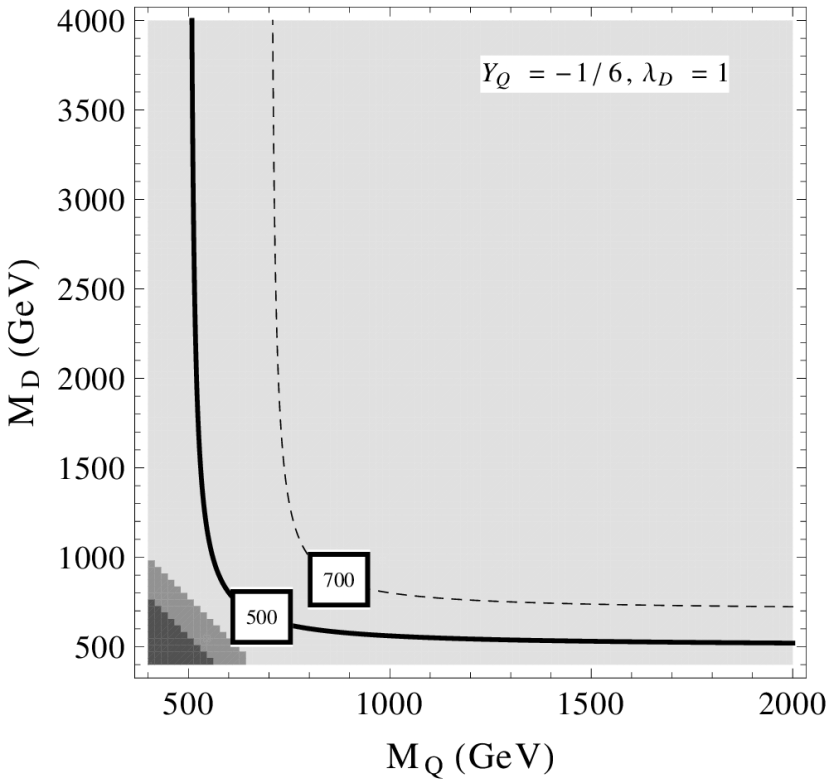
QCD corrections to ratios small: [Furlan '11] [Gori, Low '13]

$$\mu^{VBF}_{\gamma\gamma} \approx \frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} \; ; \quad \mu^{ggh}_{ZZ} \approx \frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} \; ; \quad \mu^{ggh}_{\gamma\gamma} \approx \frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} \frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} \; ; \quad \frac{\mu^{ggh}_{\gamma\gamma}}{\mu^{ggh}_{ZZ}} \approx \frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} \approx \mu^{VBF}_{\gamma\gamma}$$

$2\bar{2} + 1\bar{1}$ model

$Q + U$ model (ST Model like) : MVQD Model with $Y_\chi = -1/6$

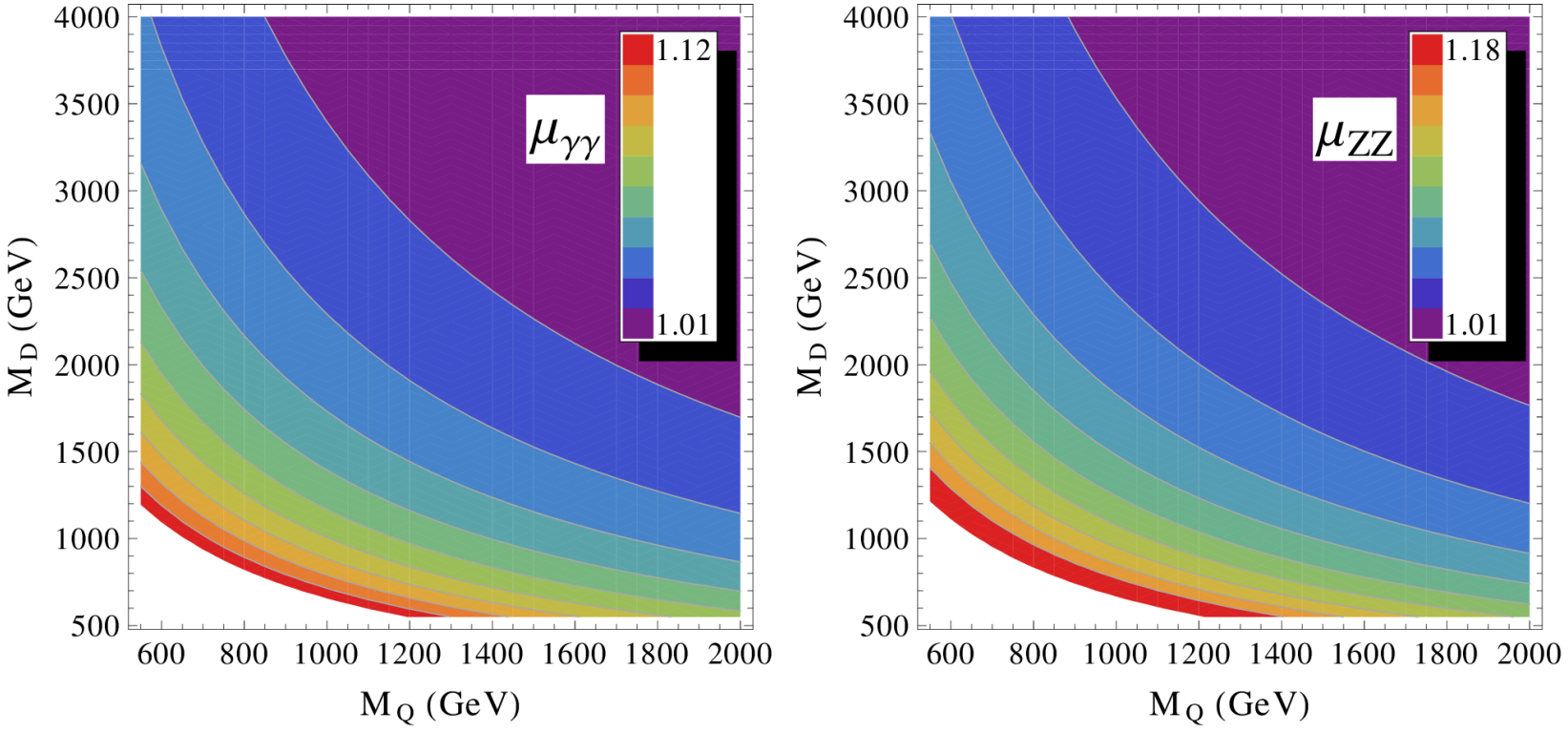




$\lambda_D = 1$, $M_D = M_Q$, $Y_Q = (1/6, -1/6)$ (solid, dashed)

[S.Ellis, R.Godbole, SG, J.Wells; 1404.4398, JHEP 2014]

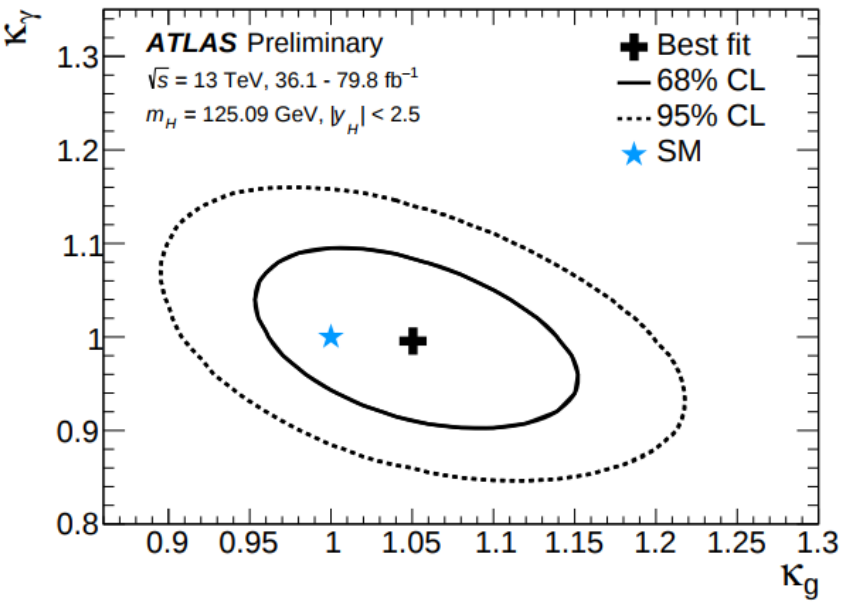
$Q + U$ model

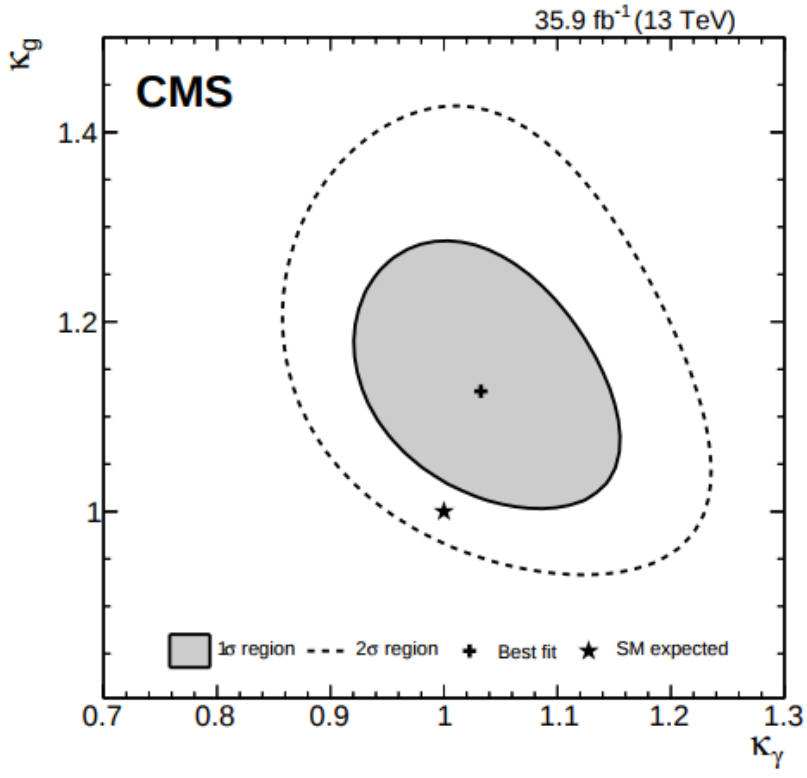


[Q+U model from MVQD model with $Y_\chi = -1/6$]

[S.Ellis, R.Godbole, SG, J.Wells; 1404.4398, JHEP 2014]

LHC constraints on Higgs couplings





[ATLAS-CONF-2018-31] [CMS-HIG-17-031]

BACKUP SLIDES

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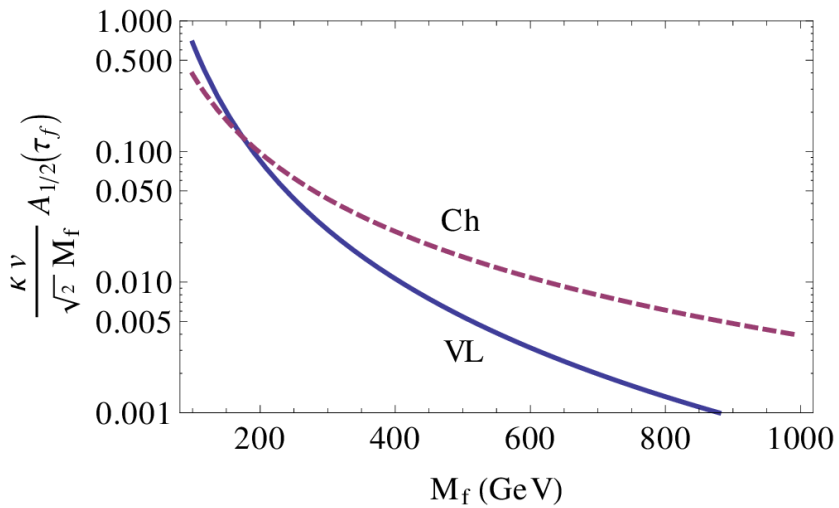
BSM Vector-like Fermions (VLF)

Vector-like fermions have both L and R chiralities charged under a gauge-group.
This allows a bare mass term.

- VLFs appear in many BSM extensions
  (Eg: composite-Higgs theories, Extra-dimensional theories)
  - they are sometimes the lightest BSM states
- We study VLF effects on Higgs vacuum stability
  - constraint on parameter space
    - but any other new states will alter conclusions!

Vector-like fermion (VLF) decoupling

- VLF has independent source of mass M (not given by $m = \lambda v$)
  - Can make M arbitrarily large
    - Yukawa coupling can be small; so perturbative
  - Nice decoupling behavior : S, T, U, $h \to \gamma\gamma$, $gg \to h$, ...
    - For instance $h\gamma\gamma$, ggh couplings



VLF signatures

Observables

- Precision Electroweak Probes
- LHC signals
  - Direct: $b' \to tW$,bZ; $t' \to bW, tZ, th$; $\chi \to tW$
  - Indirect: Higgs coupling modifications
- FCNC probes
- Vacuum stability implications

Precision Electroweak Constraints

Precision Electroweak Constraints (S, T, $Zb\bar{b}$)
(perturbatively calculable on the warped side)

- Bulk gauge symm - $SU(2)_L \times U(1)$ (SM ψ, H on TeV Brane)
- T parameter $\sim (\frac{v}{M_{KK}})^2 (k\pi R)$ [Csaki, Erlich, Terning 02]
  - S parameter also $(k\pi R)$ enhanced
- AdS bulk gauge symm $SU(2)_R \Leftrightarrow$ CFT Custodial Symm

  [Agashe, Delgado, May, Sundrum 03]
  - T parameter - Protected; S parameter - $\frac{1}{k\pi R}$ for light bulk fermions
  - Implies heavy vector bosons: W'_μ, Z'_μ, ...
  - Problem: $Zb\bar{b}$ shifted
- 3rd gen quarks (2,2) [Agashe, Contino, DaRold, Pomarol 06]
  - $Zb\bar{b}$ coupling - Protected
  - Precision EW constraints $\Rightarrow M_{KK} \gtrsim 1.5 - 2.5$ TeV
  - Implies top partners: t', b', χ, ...

[Carena, Ponton, Santiago, Wagner 06,07]

Warped Fermions

- SM fermions : $(+,+)$ BC $\rightarrow$ zero-mode
- "Exotic" fermions : $(-,+)$ BC $\rightarrow$ No zero-mode
  - 1^{st} KK vectorlike fermion

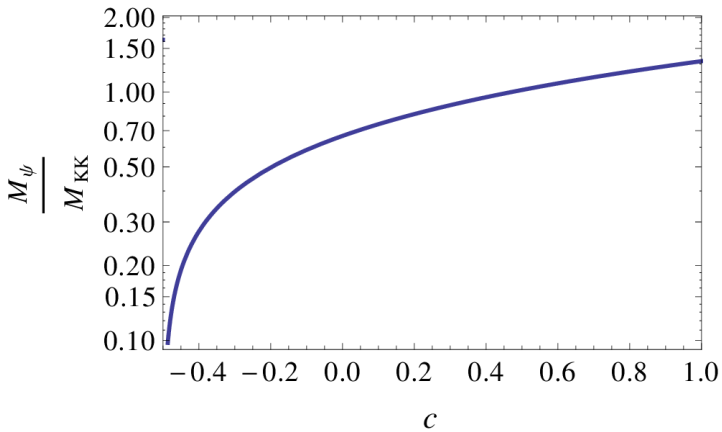
- Typical c_{t_R}, c_{t_L} : $(-,+)$ top-partners "light"

  c : Fermion bulk mass parameter

  [Choi, Kim, 2002] [Agashe, Delgado, May, Sundrum, 03]

  [Agashe, Perez, Soni, 04] [Agashe, Servant 04]

  - Look for it at the LHC



[Dennis et al, '07] [Carena et al, '07] [Contino, Servant, '08]
[Atre et al, '09, '11] [Aguilar-Saavedra, '09] [Mrazek, Wulzer, '09]
[SG, Moreau, Singh, '10] [SG, Mandal, Mitra, Tibrewala, '11] [SG, Mandal, Mitra, Moreau : '13]

Fermion rep : $Zb\bar{b}$ not protected (DT model)

[Agashe, Delgado, May, Sundrum '03]

- Complete $SU(2)_R$ multiplet
  - $Q_L \equiv (\mathbf{2},\mathbf{1})_{1/6} = (t_L, b_L)$
    $\psi_{t_R} \equiv (\mathbf{1},\mathbf{2})_{1/6} = (t_R, b')$
    $\psi_{b_R} \equiv (\mathbf{1},\mathbf{2})_{1/6} = (T, b_R)$
    - "Project-out" b', T zero-modes by $(-,+)$ B.C.
    - New ψ_{VL} : b', T
- $b \leftrightarrow b'$ mixing
  - $Zb\bar{b}$ coupling shifted
    - So LEP constraint quite severe

Fermion rep : $Zb\bar{b}$ protected (ST & TT models)

- $Q_L = (2,2)_{2/3} = \begin{pmatrix} t_L & \chi \\ b_L & T \end{pmatrix}$ [Agashe, Contino, DaRold, Pomarol '06]
  - $Zb_L\overline{b_L}$ protected by custodial $SU(2)_{L+R} \otimes P_{LR}$ invariance
    Wt_Lb_L, Zt_Lt_L not protected, so shifts

Two t_R possibilities:

1. Singlet t_R (ST Model) : $(1,1)_{2/3} = t_R$ New ψ_{VL} : χ, T
2. Triplet t_R (TT Model) :

$$(1,3)_{2/3} \oplus (3,1)_{2/3} = \psi'_{t_R} \oplus \psi''_{t_R} = \begin{pmatrix} \frac{t_R}{\sqrt{2}} & \chi' \\ b' & -\frac{t_R}{\sqrt{2}} \end{pmatrix} \oplus \begin{pmatrix} \frac{t''}{\sqrt{2}} & \chi'' \\ b'' & -\frac{t''}{\sqrt{2}} \end{pmatrix}$$

New ψ_{VL} : χ, T, χ', b', χ'', t'', b''

Fermion rep : $Zb\bar{b}$ protected (ST & TT models)

- $Q_L = (2,2)_{2/3} = \begin{pmatrix} t_L & \chi \\ b_L & T \end{pmatrix}$ [Agashe, Contino, DaRold, Pomarol '06]
  - $Zb_L\overline{b_L}$ protected by custodial $SU(2)_{L+R} \otimes P_{LR}$ invariance
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Two t_R possibilities:

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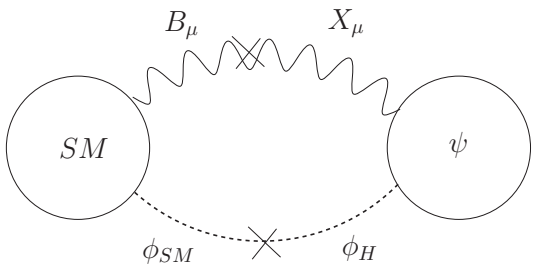
New ψ_{VL} : χ, T, χ', b', χ'', t'', b''

Hidden sector DM ψ

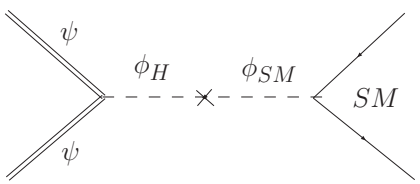
[SG, Lee, Wells 2009]

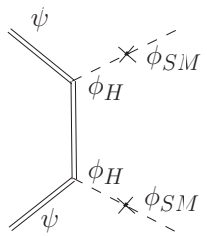
SM $\times U(1)_X$: $U(1)_X$ sector: X_μ, Φ_{hid}, ψ

$$\mathcal{L} \supset -\alpha\ |H|^2 |\Phi_{hid}|^2 + \frac{\eta}{2}\ X_{\mu\nu} B^{\mu\nu} - \kappa \phi_{hid} \bar{\psi}\psi$$



Higgs portal DM: Self-annihilation





Channels $\psi\psi \to b\bar{b}, W^+W^-, ZZ, hh, t\bar{t}$

Hidden sector DM ψ

[SG, Lee, Wells 2009]

SM $\times U(1)_X$: $U(1)_X$ sector: X_μ, Φ_{hid}, ψ

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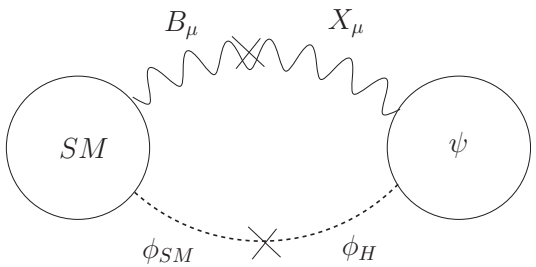

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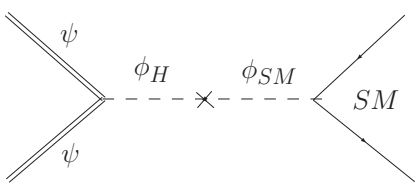
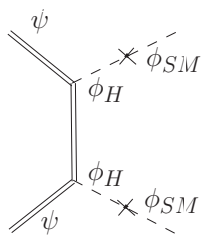
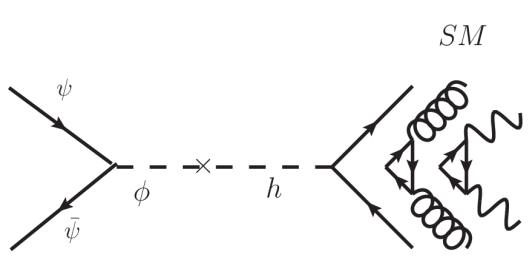


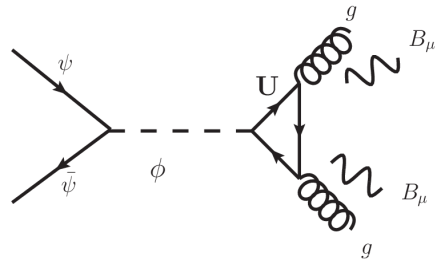


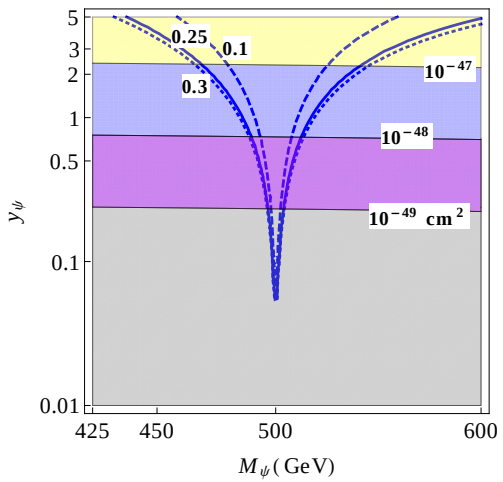
Channels $\psi\psi \to b\bar{b}, W^+W^-, ZZ, hh, t\bar{t}$

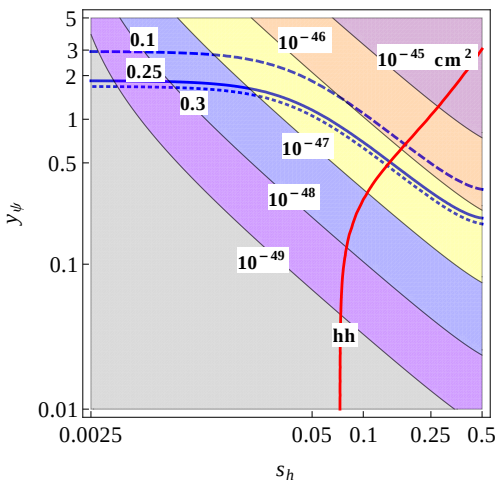
Aside: Application to Higgs Portal DM (VLL)

Can also apply to Higgs portal DM case: [SG, T.Mukherjee: AHEP 2017]









Constraint requires $s_h \ll 1$, so vacuum stability constraint is with VLL (DM) effectively coupling with $\tilde{y} \equiv y_\psi s_h \ll 1$