Non-SUSY BSM and Dark Matter

Shrihari Gopalakrishna

Institute of Mathematical Sciences (IMSc), Chennai, India

XXIII DAE-BRNS HEP Symposium

IIT Madras, Dec 2018

Talk Outline

- Non-SUSY BSM:
  - Composite-Higgs, Little Higgs Models of EWSB (4D/5D Duals)
  - LHC Limits on new vector-bosons, vector-like fermions (VLF), scalars
    - $G'_{\mu\nu}$, g'_{μ}, W'_{μ}, Z'_{μ}
    - $t'_{(2/3)}$, $b'_{(-1/3)}$, $\chi_{(5/3)}$ (Top-partners)
    - Singlet scalar, 2HDM
- Dark Matter (DM)
  - WIMP basics
  - Some DM candidates
    - Higgs-portal
  - Direct, Indirect detection limts, LHC Limits

General Idea of Composite Higgs

[Georgi, Kaplan 1984]

- Sector with global symmetry $\mathcal{G}$
  - Σ transforms under $\mathcal{G}$
- $\langle\Sigma\rangle \neq 0$ such that $\mathcal{G}$ broken to $\mathcal{H}$
  - **(massless) Goldstone Bosons (GB)** in coset $\mathcal{G}/\mathcal{H}$: π^a
    - π^a are $\{\phi^{1,2,3}, H, ...\}$
      ($\phi^{1,2,3}$ become $W^{\pm}_{longi}$, Z_{longi} after EWSB)
    - Note: **physical Higgs also a GB**
- Gauging $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ subgroup & writing Yukawa terms
  - explicitly breaks $\mathcal{G}$
    $\Longrightarrow$ **Higgs gets a mass (at loop level): Pseudo-GB (PGB)**
  - analogy: (light) Pions are PGB of $SU(3)_L \otimes SU(3)_R \to SU(3)$

General Idea of Composite Higgs

[Georgi, Kaplan 1984]

- Sector with global symmetry $\mathcal{G}$
  - Σ transforms under $\mathcal{G}$
- $\langle\Sigma\rangle \neq 0$ such that $\mathcal{G}$ broken to $\mathcal{H}$
  - **(massless) Goldstone Bosons (GB)** in coset $\mathcal{G}/\mathcal{H}$: π^a
    - π^a are $\{\phi^{1,2,3}, H, ...\}$
      ($\phi^{1,2,3}$ become $W^{\pm}_{longi}$, Z_{longi} after EWSB)
    - Note: **physical Higgs also a GB**
- Gauging $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ subgroup & writing Yukawa terms
  - explicitly breaks $\mathcal{G}$
    $\Longrightarrow$ **Higgs gets a mass (at loop level): Pseudo-GB (PGB)**
  - analogy: (light) Pions are PGB of $SU(3)_L \otimes SU(3)_R \to SU(3)$

General Idea of Composite Higgs

[Georgi, Kaplan 1984]

- Sector with global symmetry $\mathcal{G}$
  - Σ transforms under $\mathcal{G}$
- $\langle\Sigma\rangle \neq 0$ such that $\mathcal{G}$ broken to $\mathcal{H}$
  - **(massless) Goldstone Bosons (GB)** in coset $\mathcal{G}/\mathcal{H}$: π^a
    - π^a are $\{\phi^{1,2,3}, H, ...\}$
      ($\phi^{1,2,3}$ become $W^{\pm}_{longi}$, Z_{longi} after EWSB)
    - Note: **physical Higgs also a GB**
- Gauging $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ subgroup & writing Yukawa terms
  - explicitly breaks $\mathcal{G}$
    $\Longrightarrow$ **Higgs gets a mass (at loop level): Pseudo-GB (PGB)**
  - analogy: (light) Pions are PGB of $SU(3)_L \otimes SU(3)_R \to SU(3)$

4D model $\leftrightarrow$ Warped model Duality

[Maldacena, 1997] [Arkani-Hamed, Porrati, Randall, 2000; Rattazzi, Zaffaroni, 2001]

- Dual of Randall-Sundrum model **RS1 (SM on IR Brane)**
  - Planck brane $\Longrightarrow$ UV Cutoff; Dynamical gravity in the 4D CFT
  - TeV (IR) brane $\Longrightarrow$ IR Cutoff; Conformal invariance broken below a TeV
    - All SM fields are composites of the CFT
- Dual of Warped Models with **Bulk SM**
  - UV localized fields are elementary
  - IR localized fields (Higgs) are composite
    - 4D dual is Composite Higgs model [Georgi, Kaplan 1984]
    - Shares many features with Walking Extended Technicolor
  - Partial Compositeness
    - AdS dual is weakly coupled and hence calculable!
  - KK states are dual to composite resonances

AdS dual of MCHM and Higgs mass

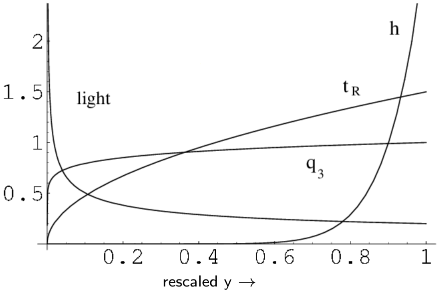
- AdS/CFT Corrsp : $\mathcal{G}$ global symm of CFT $\leftrightarrow$ AdS gauge symm
  - Bulk gauge group : $SO(5) \otimes U(1)_X$ $\qquad A_M = (A_\mu, A_5)$
  - Impose boundary condition (BC) to keep/break a symm:
- $A_5^{\hat{a}}(++)$ **dual of PNGB** $\pi^a = \{\phi^{1,2,3}, h\}$ [Contino, Nomura, Pomarol 2003]
  - **Gauge symmetry forbids tree-level mass**
  - **Mass at loop-level from gauge and top loops** [Hosotani 1983]
- Minimal Composite Higgs Model (MCHM) dual is [Agashe, Contino, Pomarol, 2004]

  Global Symm: $[SO(5) \otimes U(1)_X]/[SO(4) \otimes U(1)_X]$
  Gauge & Yukawa interactions break $SO(5)$
  - 1-loop effective potential gives: $m_h^2 \sim \frac{2N_c}{N} y_t^2 v^2$ [Coleman, Weinberg 1988]
- Resonances $m_{res} \sim g_{res}\, f$ $\qquad m_{res} \leftrightarrow m_{KK}$

Generating SM mass hierarchy

Bulk Fermions explain SM mass hierarchy [Gherghetta, Pomarol 00][Grossman, Neubert '00]

$$\mathcal{L}^{(5)}_{Yuk} \supset \sqrt{|g|}\,\left\{ c_L k\,\bar{\psi}_L\psi_L + c_R k\,\bar{\psi}_R\psi_R + \left(\lambda_5\,\bar{\psi}_R\psi_L H + h.c.\right)\right\}$$



FCNC largely under control, but still strong constraints

[Agashe, Perez, Soni, 2004]

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

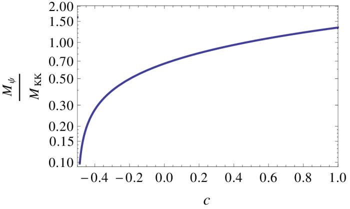
- Typical c_{t_R}, c_{t_L} : $(-,+)$ top-partners "light"

  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]

LSS Little Higgs Model

Implement collective symmetry breaking

- Higgs is a pseudo Goldstone boson
- no Λ^2 divergent contribution at 1-loop
  - Gauge sector & Yukawa couplings specially constructed

A case study: **Low, Skiba, Smith (LSS), 2002 :** $SU(6)/Sp(6)$

- Coset: $35 - 21 = 14$ $\rightarrow$PNGB (Higgs included)
- Gauge sector: $SU(2)_1 \otimes SU(2)_2 \otimes U(1)_1 \otimes U(1)_2 \rightarrow SU(2)_L \otimes U(1)_Y$
- Vector-like fermions
  - SU(2) doublet: $Q' = \begin{pmatrix} t' \\ b' \end{pmatrix}$; SU(2) singlets: t'', b''
- Higgs sector is a 2HDM

$$V \supset m_1^2 \left|\phi_1\right|^2 + m_2^2 \left|\phi_2\right|^2 + \left(b^2 \phi_1^T \cdot \phi_2 + h.c.\right) + \lambda_5' \left|\phi_1^T \cdot \phi_2\right|^2$$

$SU(6)/Sp(6)$ Little Higgs with 2HDM structure

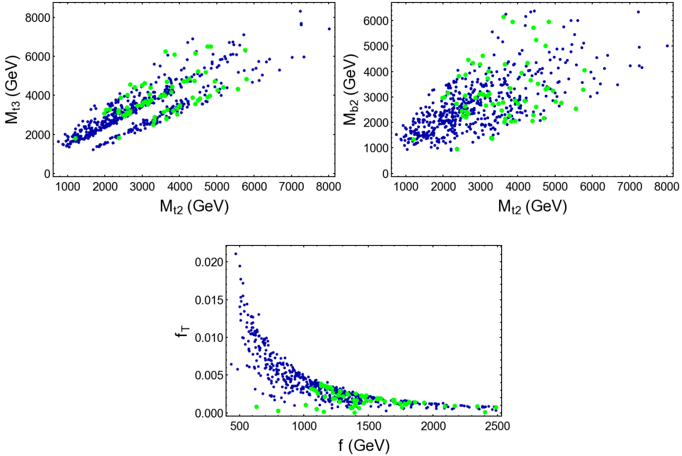
Scalars are: h, H, A, $H^{\pm}$; We focus on neutral scalars

- Seek hWW, hZZ SM like
  - Alignment limit: $(\beta - \alpha) \approx \frac{\pi}{2}$; [Gunion, Haber, 2002]
    - HWW, $HZZ \approx$ zero!
- Also seek htt SM like
- AWW, AZZ are zero at tree-level : $\mathcal{CP}$ inv

$$\langle \phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}; \quad \langle \phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_2 \\ 0 \end{pmatrix}; \quad \tan\beta = \frac{v_1}{v_2}$$

VLF properties and fine-tuning

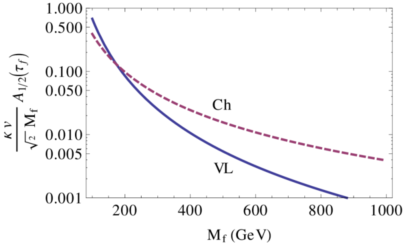
[SG, T. Mukherjee, S. Sadhukhan: PRD 94, 015034 (2016)]



f_T : fine-tuning measure

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 remain perturbative
    - As M increases, fine-tuning increases
  - Nice decoupling behavior : S, T, U, $h \to \gamma\gamma$, $gg \to h$, ...
    - For instance $h\gamma\gamma$, ggh couplings



Generic signatures

New particles

- Vector resonances
- Fermion resonances
- Bigger coset $\Longrightarrow$ extra (pNBG) scalars (can be "light")
  - Eg: $SU(6)/Sp(6) \Longrightarrow$ 2HDM

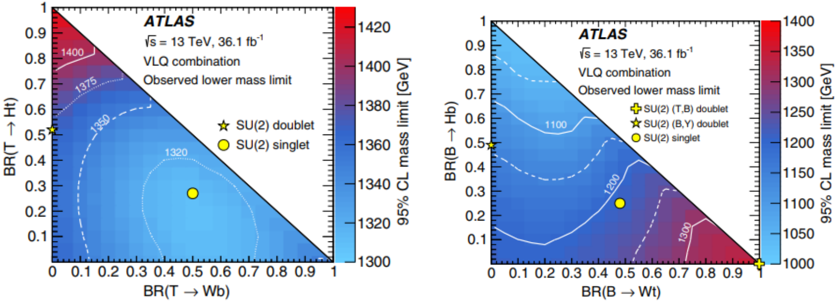
Observables

- Precision electroweak probes (tree-level!)
  - $S \approx 1.3\,(4\pi)\,(v/m_{KK})^2 \quad \Longrightarrow \quad m_{KK} \gtrsim 2\ TeV$
- LHC signals
  - Direct
  - Indirect Eg: hVV coupling shifts $\frac{hVV_{BSM}}{hVV_{SM}} \approx (1 - \kappa\, v^2/f^2)$
- FCNC probes

Decay Modes of t', b', χ

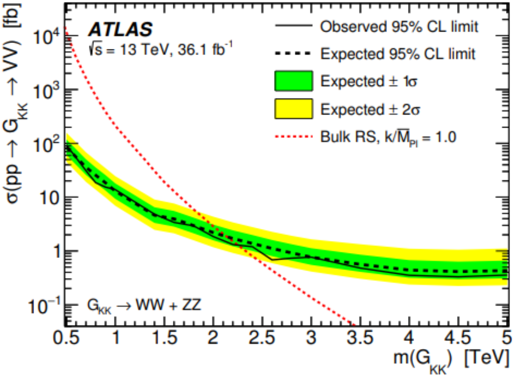
- VL Tree-level Decays
  - $b' \to tW$, $b' \to bZ$, $b' \to bh$
  - $t' \to bW$, $t' \to tZ$, $t' \to th$
  - $\chi \to tW$

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



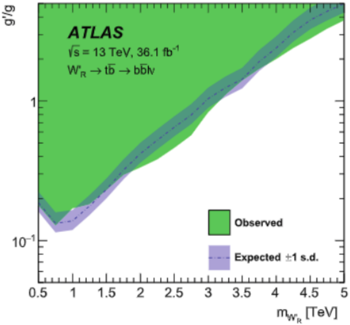
[ATLAS: 1808.02343; PRL 2018]

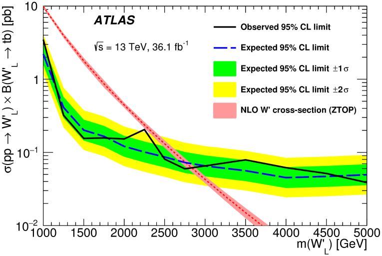
graviton$^{(1)}$ $\rightarrow WW, ZZ$ search



[ATLAS: 1808.02380; PRD 2018]

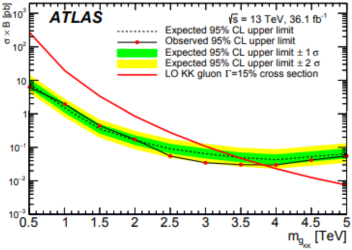
$W'_{R,L} \to t\bar{b}$ search

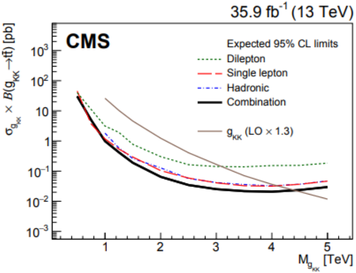




[ATLAS: 1807.10473; PLB 2018]

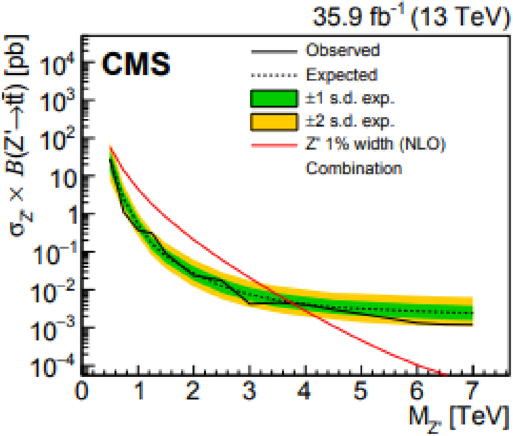
gluon$^{(1)}$ $\to t\bar{t}$ search





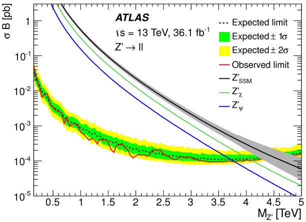
[ATLAS: 1804.10823] [CMS:1810.0590]

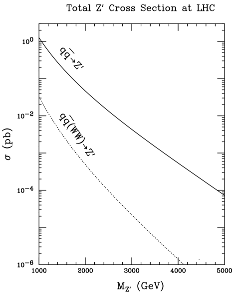
$Z' \to t\bar{t}$ search

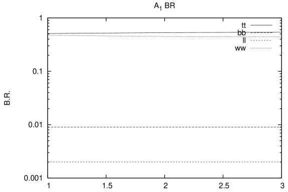


[CMS:1810.0590]

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







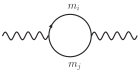
[Agashe, Davoudiasl, SG, Han, Huang, Perez, Si, Soni: 0709.0007 [hep-ph]]

VECTOR-LIKE FERMIONS IN ELECTROWEAK PRECISION & HIGGS OBSERVABLES

[S.Ellis, R.Godbole, SG, J.Wells; 1404.4398 [hep-ph], JHEP 09 (2014) 130]

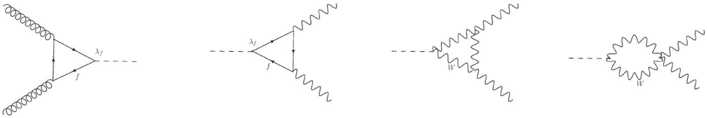
EWPrecision + Higgs Observables

Precision electroweak observables (S, T, U)



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

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



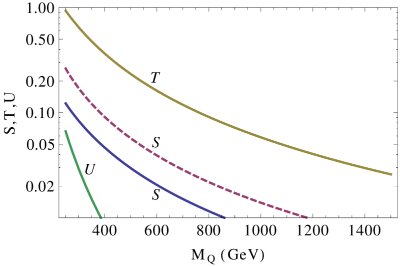
We compute ratios $\frac{\Gamma_{h\to gg}}{SM}$, $\frac{\Gamma_{h\to\gamma\gamma}}{SM}$ using leading-order expressions

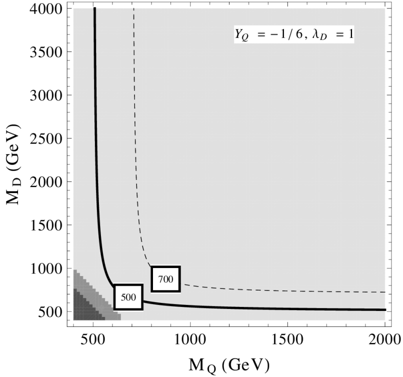
QCD corrections to ratios small: [Furlan '11] [Gori, Low '13]

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

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

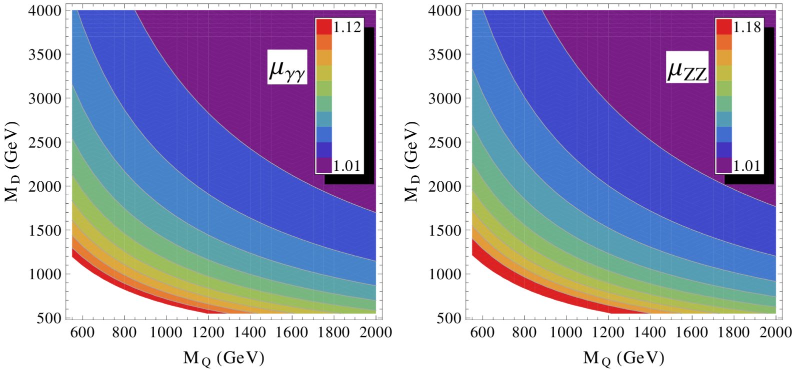
$Q + U$ model (ST Model like) : MVQD Model with $Y_\chi = -1/6$





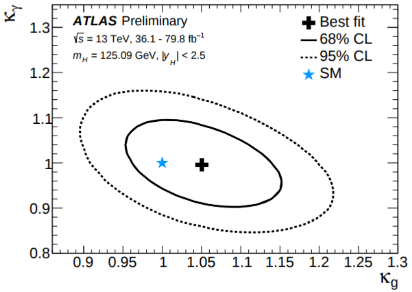
$\lambda_D = 1,\ M_D = M_Q,\ Y_Q = (1/6, -1/6)$ (solid, dashed)

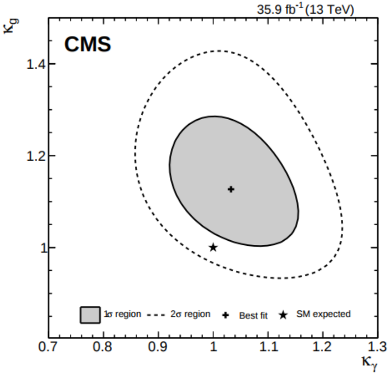
$Q + U$ model



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

LHC constraints on Higgs couplings





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

Particle Dark Matter

- Thermal Relic
  - In thermal equilibrium in early universe
  - Details of its origin do NOT matter
    - So most studied
- Nonthermal Relic
  - Never in thermal equilibrium
  - Details of its origin matter

Some Particle DM Candidates

- LSP - Lightest Supersymmetric Particle
  - $\tilde{\chi}_1^0$ Neutralino (SUSY partner of neutral gauge boson)
  - $\tilde{\nu}$ Sneutrino (SUSY partner of neutrino)
- Hidden sector DM
- LKP - Lightest Kaluza-Klein Particle - Extra space dimensions
- LTP - Lightest T-odd Particle - Little-higgs theory with Z_2
- SuperWIMP - Gravitino (SUSY partner of graviton)
- E-WIMP - Right-handed sneutrino (partner of neutrino)
- WIMPzilla - Extremely massive particle

- Your candidate here

Some Particle DM Candidates

- LSP - Lightest Supersymmetric Particle
  - $\tilde{\chi}_1^0$ Neutralino (SUSY partner of neutral gauge boson)
  - $\tilde{\nu}$ Sneutrino (SUSY partner of neutrino)
- Hidden sector DM
- LKP - Lightest Kaluza-Klein Particle - Extra space dimensions
- LTP - Lightest T-odd Particle - Little-higgs theory with Z_2
- SuperWIMP - Gravitino (SUSY partner of graviton)
- E-WIMP - Right-handed sneutrino (partner of neutrino)
- WIMPzilla - Extremely massive particle
- Your candidate here

Weakly Interacting Massive Particle (WIMP)

WIMP Cold dark matter - New particle

- Mass: $M \sim 100\,\text{GeV}$
- Interaction strength: $g \sim g_{EW}$

"WIMP Miracle"

$$\Omega_0 \equiv \frac{n_0 M}{\rho_c} \approx 4 \times 10^{-10} \left(\frac{\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \right)$$

- Precisely the scale being explored at colliders!
  - DM at present colliders? (LHC connection)

Weakly Interacting Massive Particle (WIMP)

WIMP Cold dark matter - New particle

- Mass: $M \sim 100\,\text{GeV}$
- Interaction strength: $g \sim g_{EW}$

$$\Omega_0 \equiv \frac{n_0 M}{\rho_c} \approx 4 \times 10^{-10} \left(\frac{\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \right)$$

"WIMP Miracle"

- Precisely the scale being explored at colliders!
    - DM at present colliders? (LHC connection)

Nonthermal $\tilde{\nu}_0$ DM

[de Gouvea, SG, Porod 2006]

If thermalization conditions not met $\Rightarrow$ Nonthermal $\tilde{\nu}_0$

Happens when :

- $Y_N \lesssim 10^{-6}$ i.e., $\tilde{\nu}_0$ is almost pure right-handed
- Low Reheat temp $T_{RH} < 100$ GeV ; Reheat into $\tilde{\nu}_0$ + SM

  No Relic-from-decay of heavier SUSY particles
  No $\tilde{\nu}_0$ thermalization from co-interaction with SUSY or Top

$\tilde{N}$ Relic density depends on Inflaton coupling to SM and $\tilde{N}$

Nonthermal $\tilde{\nu}_0$ DM

[de Gouvea, SG, Porod 2006]

If thermalization conditions not met $\Rightarrow$ Nonthermal $\tilde{\nu}_0$

Happens when :

- $Y_N \lesssim 10^{-6}$ i.e., $\tilde{\nu}_0$ is almost pure right-handed
- Low Reheat temp $T_{RH} < 100$ GeV ; Reheat into $\tilde{\nu}_0$ + SM

No Relic-from-decay of heavier SUSY particles
No $\tilde{\nu}_0$ thermalization from co-interaction with SUSY or Top

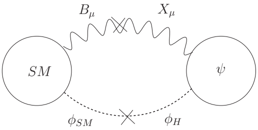
$\tilde{N}$ Relic density depends on Inflaton coupling to SM and $\tilde{N}$

Hidden sector DM ψ

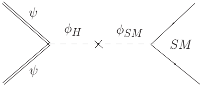
[SG, Lee, Wells 2009]

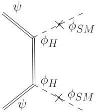
SM $\times U(1)_X$: $U(1)_X$ sector: X_μ, Φ_H, ψ

$$\mathcal{L} \supset -\alpha\, |\Phi_{SM}|^2 |\Phi_H|^2 + \frac{\eta}{2}\, X_{\mu\nu} B^{\mu\nu} - \kappa \phi_H \bar{\psi}\psi$$



Self-annihilation





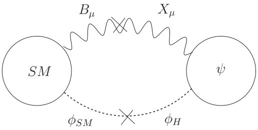
Channels $\psi\psi \to b\bar{b}, W^+W^-, ZZ, hh, t\bar{t}$

Hidden sector DM ψ

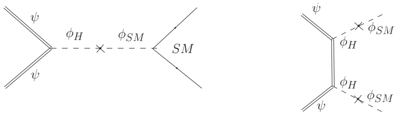
[SG, Lee, Wells 2009]

SM $\times U(1)_X$: $U(1)_X$ sector: X_μ, Φ_H, ψ

$$\mathcal{L} \supset -\alpha\ |\Phi_{SM}|^2|\Phi_H|^2 + \frac{\eta}{2}\ X_{\mu\nu}B^{\mu\nu} - \kappa\phi_H\bar{\psi}\psi$$

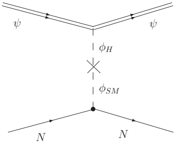


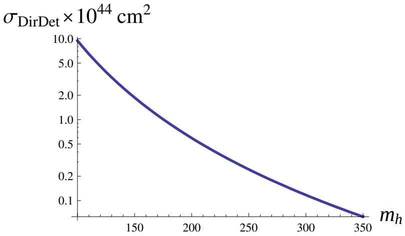
Self-annihilation



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

Direct Detection of Hidden sector





$M_\psi = 125\ GeV,\ \kappa_{11} = 1.5, s_h = 0.25$

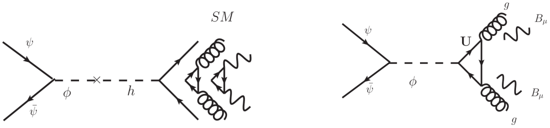
Effective $h\bar{N}N$ coupling $\approx 2 \times 10^{-3}$ [Shifman, Vainshtein, Zakharov (1973)]

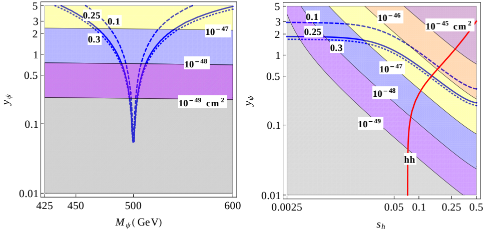
ψ- Nucleon c.s. :

$$\sigma(\psi N \to \psi N) \approx \frac{\kappa_{11}^2 s_h^2 c_h^2 \lambda_N^2}{8\pi v_{rel}} \frac{(|\mathbf{p}_\psi|^2 + m_N^2)}{(t - m_h^2)^2}$$

Singlet fermion DM with scalar mediator

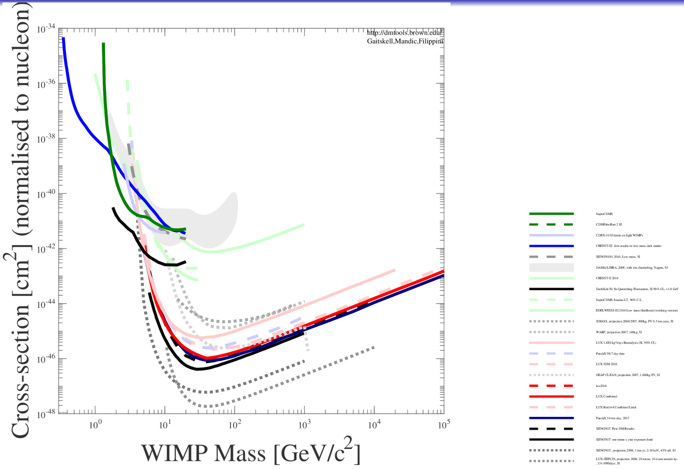
[SG. T.Mukherjee: AHEP 2017]



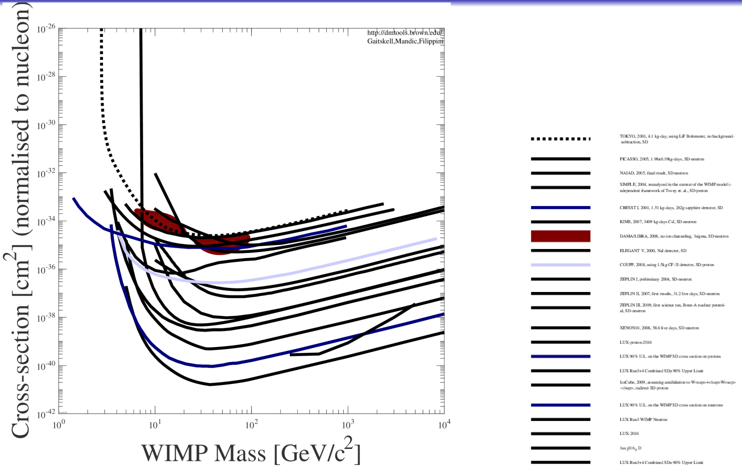


For $s_h \ll 1$, loop suppressed coupling can give correct relic density
direct-detection rate can be very small - experimentally very challenging

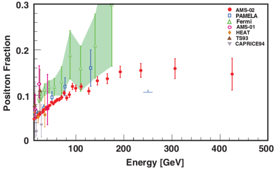
Direct Detection Experimental Limits

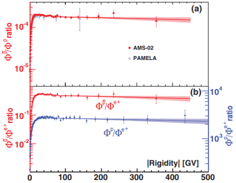


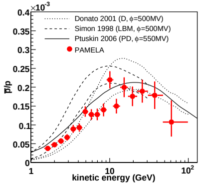
Direct Detection Spin Dependent Limits



e^+, $\bar{p}$ data



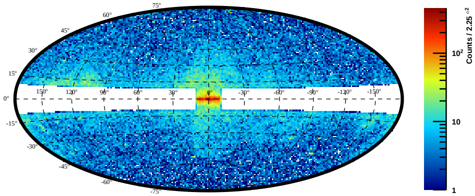


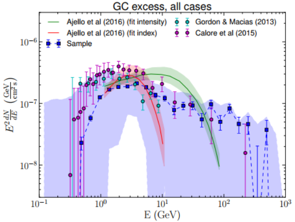


AMS02 e^+ [PRL113, 2014] [PRL117,2016]; PAMELA $\bar{p}$ [Nature 09]

Dark matter annihilations? .... or astro sources (pulsars) ? ... or other bkgnd?

Fermi-LAT γ





[Fermi-LAT Galactic Excess: 1704.03910]

Fermi-LAT DSph Limits

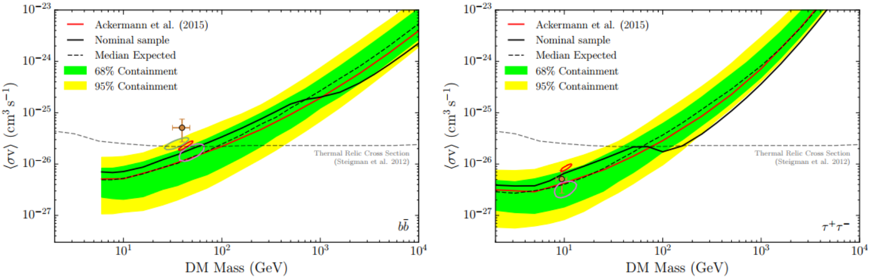


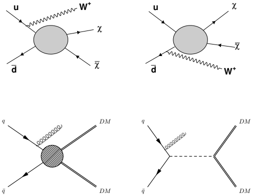
Figure 9. Upper limits (95% confidence level) on the DM annihilation cross section derived from a combined analysis of the nominal target sample for the $b\bar{b}$ (*left*) and $\tau^+\tau^-$ (*right*) channels. Bands for the expected sensitivity are calculated by repeating the same analysis on 300 randomly selected sets of high-Galactic-latitude blank fields in the LAT data. The dashed line shows the median expected sensitivity while the bands represent the 68% and 95% quantiles. Spectroscopically measured J-factors are used when available; otherwise, J-factors are predicted photometrically with an uncertainty of 0.6 dex (solid red line). The solid black line shows the observed limit from the combined analysis of 15 dSphs from Ackermann et al. (2015b). The closed contours and marker show the best-fit regions (at 2σ confidence) in cross-section and mass from several DM interpretations of the GCE: green contour (Gordon & Macias 2013), red contour (Daylan et al. 2016), orange data point (Abazajian et al. 2014), purple contour (Calore et al. 2015). The dashed gray curve corresponds to the thermal relic cross section from Steigman et al. (2012).

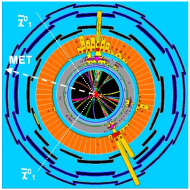
[Fermi-LAT: 1611.03184]

LHC DM signatures

DM leads to missing energy ($\not\!\!E_T$) events at the LHC

Look in $pp \to \quad \gamma + \not\!\!E_T,\, j + \not\!\!E_T,\, V_\mu + \not\!\!E_T,\, h + \not\!\!E_T,\, \ldots$





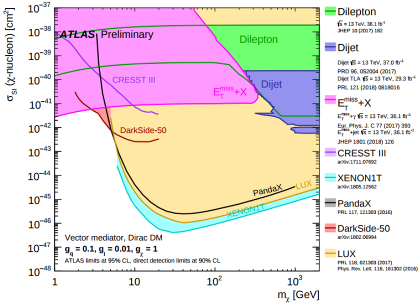
Effective Operators

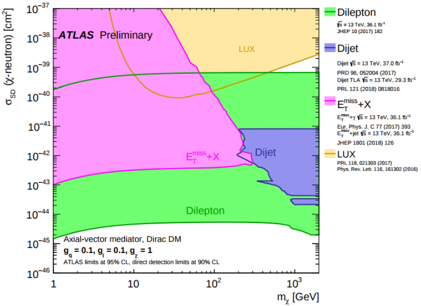
[Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu 1008.1783]

Name	Operator	Coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/M_*^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/M_*^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5 q$	im_q/M_*^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	m_q/M_*^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/M_*^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	$1/M_*^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu} q$	$1/M_*^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta} q$	i/M_*^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4M_*^3$

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\bar{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\bar{q}\gamma^5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\bar{q}\gamma^\mu\gamma^5 q$	$1/M_*^2$
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4M_*^2$
R1	$\chi^2\bar{q}q$	$m_q/2M_*^2$
R2	$\chi^2\bar{q}\gamma^5 q$	$im_q/2M_*^2$
R3	$\chi^2 G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/8M_*^2$
R4	$\chi^2 G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/8M_*^2$

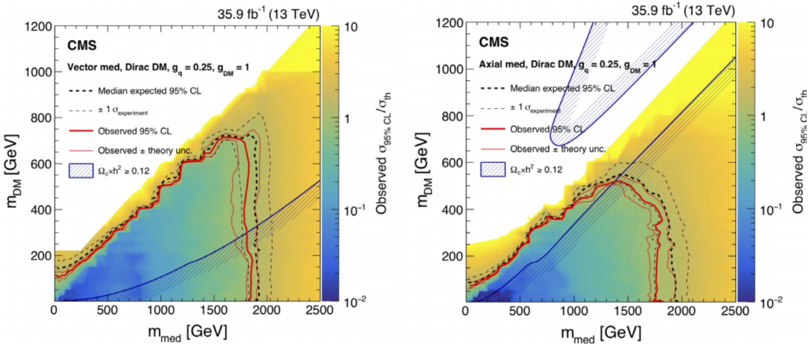
ATLAS DM Limits





[ATLAS-CONF-2018-051]

CMS DM Limits



[CMS: PRD 97, 2018]

Conclusions

- Many compelling arguments why standard model is not the full story
  - possible new physics that stabilize the Higgs sector include composite-Higgs, Little Higgs models
  - so far no definitive signals of BSM at LHC
    - direct searches probing interesting region now!
    - hgg, $h\gamma\gamma$ couplings may show deviations
- Strong evidence for Dark Matter. But what is it?
  - Many Candidates, Mass range 10^{-5}eV - 10^{12}GeV
    - Vigorous search underway - Direct, Indirect, Collider
  - We may discover DM particle soon

BACKUP SLIDES

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
    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''

EWSB region

[Contino, Da Rold, Pomarol 0612048]

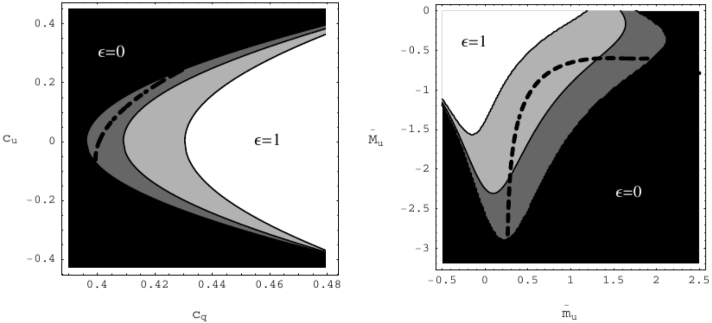
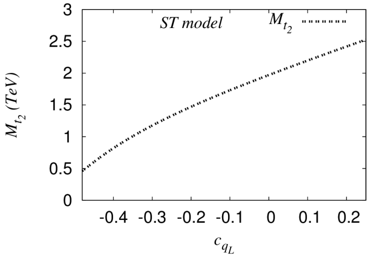
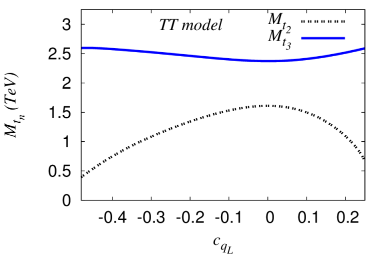


Figure 1: *Contour plots of ϵ in the plane (c_q, c_u) with $\widetilde{m}_u = 1$, $\widetilde{M}_u = -2$, $N = 8$ for the $MCHM_{10}$ (left plot), and in the plane $(\widetilde{m}_u, \widetilde{M}_u)$ with $c_q = 0.35$, $c_u = 0.45$, $N = 8$ for the $MCHM_5$ (right plot). The two gray areas correspond to the region with EWSB and non-zero fermion masses, $0 < \epsilon < 1$. The lighter gray area is excluded when the bound $S \lesssim 0.3$ is imposed. The dashed black line represents the curve with $m_t^{\overline{MS}}(2\,TeV) = 150\,GeV$, equivalent to $m_t^{pole} = 173\,GeV$.*

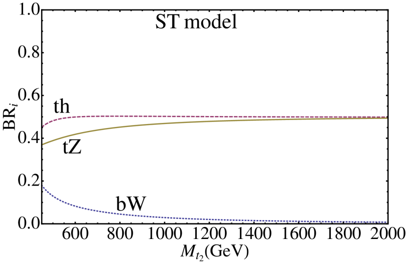
Warped model t' parameters

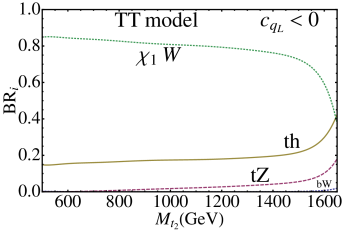
[SG, T.Mandal, S.Mitra, R.Tibrewala, arXiv:1107.4306] [SG, T.Mandal, S.Mitra, G.Moreau : arXiv:1306.2656]

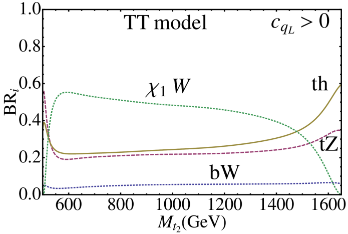




Warped model t' BR







Custodial protected MCHM (5,10 reps)

[Contino, Da Rold, Pomarol 0612048] [Pomarol, Riva 1205.6434]

$\mathcal{V}_{eff}(h) = \alpha s_h^2 - \beta s_h^2 c_h^2 \qquad s_h \equiv sin\left(\langle h \rangle / f\right)$

- α : gauge loops, q_L or q_R
- β : q_L and q_R

$\langle s_h \rangle = \epsilon = \sqrt{\frac{\beta - \alpha}{2\beta}}$ So ϵ is a measure of fine-tuning

$$m_h^2 \approx \frac{N_c m_t^2 \epsilon^2 \Lambda^2}{\pi^2 v^2}$$

$$S = \frac{3}{8}\frac{N}{\pi}\epsilon^2 \qquad S \lesssim 0.3 \quad \Longrightarrow \quad f \gtrsim v\sqrt{\frac{10}{8}\frac{N}{\pi}}$$

$$m_h^2 \gtrsim \frac{N_c}{\pi^2}\frac{m_t^2}{f^2} m_Q^2 \quad \Longrightarrow \quad m_Q \lesssim 1\,TeV \left(\frac{m_h}{125\,GeV}\right)\left(\frac{160\,GeV}{m_t}\right)\left(\frac{f}{750\,GeV}\right)$$

LSS model symmetry breaking, PNGB and VLF

$$\Sigma = \exp\left(\frac{i\pi^a X^a}{f}\right)\langle\Sigma\rangle\ ; \qquad \langle\Sigma\rangle = \begin{pmatrix} 0 & -\mathbb{1} \\ \mathbb{1} & 0 \end{pmatrix}$$

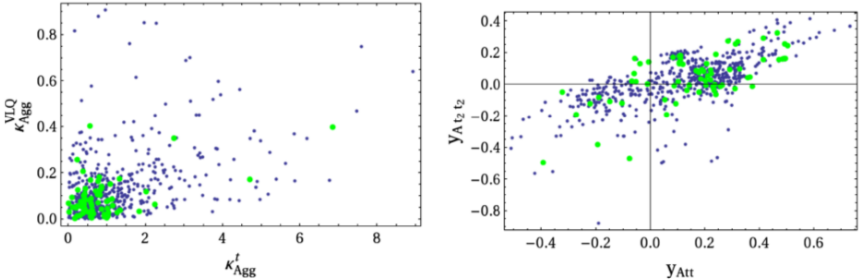
$$\pi^a X^a \supset \begin{pmatrix} \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \phi_2 & \begin{matrix} 0 & s \\ -s & 0 \end{matrix} & \phi_1 \\ \phi_2^\dagger & 0 & -\phi_1^T & 0 \\ \begin{matrix} 0 & -s^* \\ s^* & 0 \end{matrix} & -\phi_1^* & \begin{matrix} 0 & 0 \\ 0 & 0 \end{matrix} & \phi_2^* \\ \phi_1^\dagger & 0 & \phi_2^T & 0 \end{pmatrix}$$

Gauge group: $SU(2)_1 \otimes SU(2)_2 \otimes U(1)_1 \otimes U(1)_2$ with $Q_1^a = \begin{pmatrix} \sigma^a & 0 \\ 0 & 0 \end{pmatrix}$; $Q_2^a = \begin{pmatrix} 0 & 0 \\ 0 & \sigma^a \end{pmatrix}$

BSM vector-like fermions: 1 VL doublet (Q') + 2 VL singlets (t'', b'')

1-loop effective potential $\Longrightarrow$ potential for PNGB, EWSB

Effects from VLF on A, H



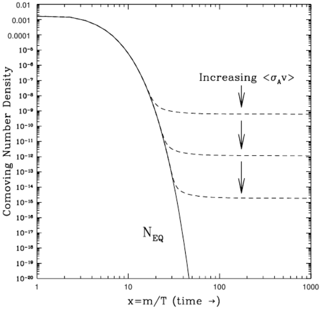
Computing Thermal DM Relic Density: Boltzmann Eqn

$$\frac{d}{dt}n = -3Hn - \langle\sigma v\rangle_{SI}\left(n^2 - n_{eq}^2\right) - \langle\sigma v\rangle_{CI}\left(nn_\phi - n_{eq}n_{\phi\, eq}\right) + C_\Gamma$$

Thermal equilibrium if : $\langle\sigma v\rangle_{SI}\, n_{\tilde{\nu}_0} > 3H$ OR $\langle\sigma v\rangle_{CI}\, n_\phi > 3H$

$$n_{eq} = \begin{cases} (\zeta(3)/\pi^2) g T^3 & T \gg M \\ g\left(\frac{MT}{2\pi}\right)^{3/2} e^{-(M-\mu)/T} & T \lesssim M \end{cases}$$

Freeze-out



[Kolb & Turner, Early Universe]

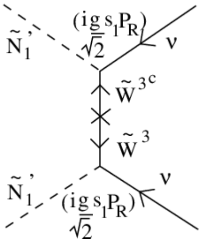
$$\Omega_0 h^2 \equiv \frac{n_0 M}{\rho_c} \approx 2 \times 10^{-10}\left(\frac{\mathrm{GeV}^{-2}}{\langle\sigma v\rangle}\right)$$

(h is H_0 in units of 100 $Km\, s^{-1} Mpc^{-1}$)

Planck 2015

$\Omega_0 = 0.308 \pm 0.012$

Thermal (Mixed) $\tilde{\nu}_0$ DM

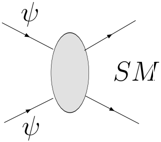


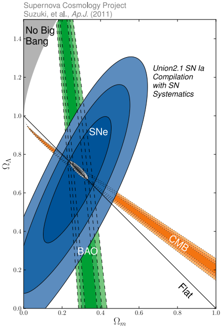
$$\Omega_0 h^2 = \frac{10^{-4}}{s_1^4}\left\{\left[g^2\left(\frac{100\ \mathrm{GeV}}{M_{\tilde{W}}}\right) + g'^2\left(\frac{100\ \mathrm{GeV}}{M_{\tilde{B}}}\right)\right]^2\right\}^{-1}$$

$\therefore s_1 \approx 0.2$ results in observed relic density

Thermal avg. c.s. $\langle \sigma v \rangle$

Self-annihilation





$$\sigma v_{rel} = a + b\ v_{rel}^2 + O(v_{rel}^4)$$

$$\langle \sigma v \rangle \approx a + (6b - 9a)/x_f \ ; \quad x_f \equiv M_\psi / T_f \approx 25$$

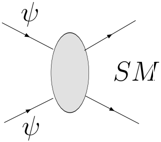
$$\Omega_0 = 0.308 \pm 0.012$$

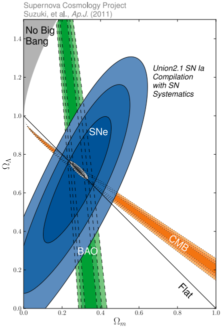
[Planck '15]

Co-annihilation and/or decays into DM may also be important

Thermal avg. c.s. $\langle \sigma v \rangle$

Self-annihilation





$$\sigma v_{rel} = a + b\ v_{rel}^2 + O(v_{rel}^4)$$

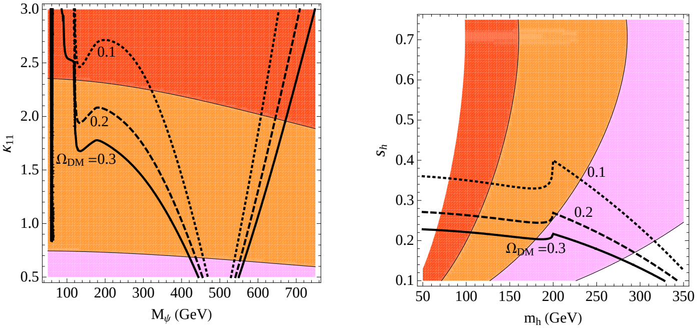
$$\langle \sigma v \rangle \approx a + (6b - 9a)/x_f \ ; \quad x_f \equiv M_\psi / T_f \approx 25$$

$$\Omega_0 = 0.308 \pm 0.012$$

[Planck '15]

Co-annihilation and/or decays into DM may also be important

ψ Relic Density + Direct Detection



[SG, S.Lee, J.Wells 2009]

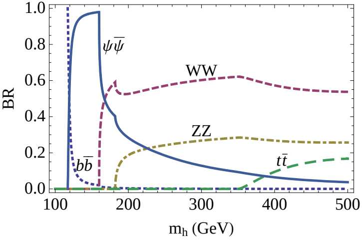
$M_\psi = 250\,GeV, m_h = 120\,GeV, \kappa_{11} = 2.0, s_h = 0.25, \kappa_{3\phi} = 1, m_H = 1\,TeV$

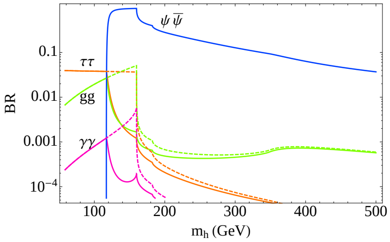
Shaded:

$\sigma_{Dir} \gtrsim 10^{-43}\ \mathrm{cm}^2$ (dark); $\gtrsim 10^{-44}\ \mathrm{cm}^2$ (medium); $\gtrsim 10^{-45}\ \mathrm{cm}^2$ (light)

Higgs decay to DM

- Higgs decay and BR
  - If $m_h > 2M_\psi$: $h \to \psi\overline{\psi}$ Invisible Decay!
    - Decay channels: $h \to \psi\bar{\psi}\,,\, b\bar{b}\,,\, WW\,,\, ZZ\,,\, t\bar{t}$

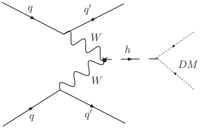




$$M_\psi \approx 59\,GeV, s_h = 0.25, \kappa_{11} = 2.0, \kappa_{3\phi} = 1.0, m_H = 1\,TeV$$

NB: Relic density not enforced

Hidden sector DM @ 14 TeV LHC



[O. J. P. Eboli and D. Zeppenfeld, 2000]

$$p_T^j > 40\ ,\ |\eta_j| < 5.0\ ,\ |\eta_{j_1} - \eta_{j_2}| > 4.4\ ,\ \eta_{j_1} \cdot \eta_{j_2} < 0\ ,$$
$$\not{p}_T > 100\ \mathrm{GeV}\ ,\ M_{jj} > 1200\ \mathrm{GeV}\ ,\ \phi_{jj} < 1\ .$$

For $s_h = 0.25$, $BR_{INV} = 0.25$:

m_h (GeV)	$\sigma_S BR_{inv}(fb)$	$\sigma_B(fb)$	$\mathcal{L}_{5\sigma}$ (fb^{-1})
120	22.7	167	8
200	18	167	12.8
300	13.2	167	23.7