Inert doublet model with U(1) Higgs symmetry

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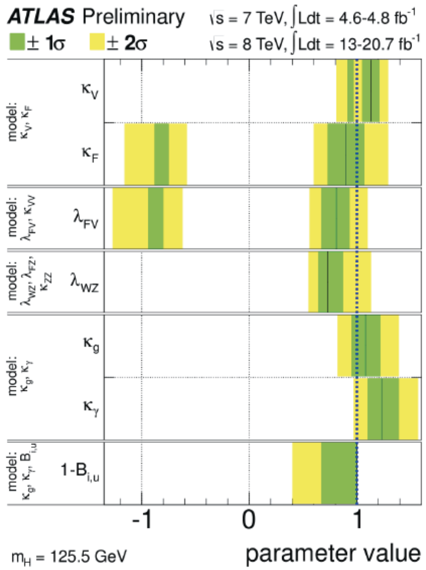
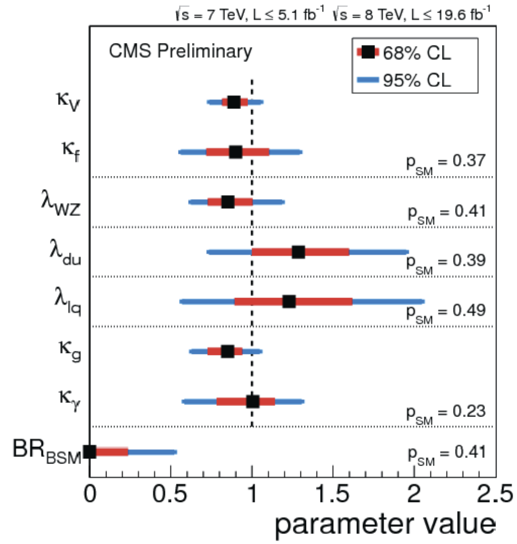
Based on JHEP 1401 (2014) 016;
work in preparation

Collaboration with P. Ko (KIAS) and Yuji Omura (TUM)

KIAS-NCTS Joint workshop on Particle Physics, String theory and Cosmology
High1 Resort, Korea, Feb 13, 2014

A Higgs boson discovered





- consistent with the SM Higgs couplings.
- nothing else seen yet.
- but, the new boson could be one of Higgs bosons in an extended model.
- decoupling or alignment?
  - e.g. in the 2HDM, $g_{hVV} = \sin(\beta - \alpha) \sim 1,\ g_{HVV} = \cos(\beta - \alpha) \sim 0.$

Two Higgs doublet model

• Many high-energy models predict extra Higgs doublets.

- SUSY, GUT, flavor symmetric models, etc.

• Two Higgs doublet model could be an effective theory of a high-energy theory.

• Two (or multi) Higgs doublet model itself is interesting.

- Higgs physics (heavy Higgs, pseudoscalar, charged Higgs physics)
- dark matter physics (one of Higgs scalar or extra fermions could be CDM.)
- can resolve experimental anomalies (top A_{FB} at Tevatron, $B \to D(*)\tau\nu$ at BABAR)
- neutrino mass generation
- baryon asymmetry of the Universe

2HDMwZ_2

- One of the simplest models to extend the SM Higgs sector.

- In general, the models with many Higgs fields suffer from Flavor changing process.

- strong constraints on the Flavor changing neutral current (FCNC).

- A simple way to avoid FCNC problem is to assign ad hoc Z_2 symmetry.

$$Z_2 : (H_1, H_2) \to (+H_1, -H_2)$$

Type	H_1	H_2	U_R	D_R	E_R	N_R	Q_L, L
I	+	−	+	+	+	+	+
II	+	−	+	−	−	+	+
X	+	−	+	+	−	−	+
Y	+	−	+	−	+	−	+

- Type I : $V_y = y_{ij}^U \overline{Q}_{Li} \tilde{H}_1 U_{Rj} + y_{ij}^D \overline{Q}_{Li} H_1 D_{Rj} + y_{ij}^E \overline{L}_i H_1 E_{Rj} + y_{ij}^N \overline{L}_i \tilde{H}_1 N_{Rj}$

Generic problems of 2HDM

• It is well known that discrete symmetry could generate a domain wall problem when it is spontaneously broken.

• Usually the Z_2 symmetry is assumed to be broken softly by a dim-2 operator, $H_1^\dagger H_2$ term.

The softly broken Z_2 symmetric 2HDM potential

$$V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - (m_{12}^2 H_1^\dagger H_2 + h.c.) + \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2$$
$$+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{1}{2}\lambda_5 [(H_1^\dagger H_2)^2 + h.c.]$$

• the origin of the softly breaking term?

We propose to replace the Z_2 symmetry in 2HDM by new $U(1)_H$ symmetry associated with Higgs flavors.

Type-I 2HDM

- Only one Higgs couples with fermions.

$$V_y = y_{ij}^{U} \overline{Q}_{Li} \tilde{H}_1 U_{Rj} + y_{ij}^{D} \overline{Q}_{Li} H_1 D_{Rj} + y_{ij}^{E} \overline{L}_i H_1 E_{Rj} + y_{ij}^{N} \overline{L}_i \tilde{H}_1 N_{Rj}$$

- anomaly free $U(1)_H$ without no extra fermions except RH neutrinos.

U_R	D_R	Q_L	L	E_R	N_R	H_1
u	d	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$\frac{(u-d)}{2}$

2 parameters

~Most general family-universal U(1) model

Type-I 2HDM

- Only one Higgs couples with fermions.

$$V_y = y_{ij}^U \overline{Q}_{Li} \tilde{H}_1 U_{Rj} + y_{ij}^D \overline{Q}_{Li} H_1 D_{Rj} + y_{ij}^E \overline{L}_i H_1 E_{Rj} + y_{ij}^N \overline{L}_i \tilde{H}_1 N_{Rj}$$

- anomaly free $U(1)_H$ without no extra fermions except RH neutrinos.

U_R	D_R	Q_R	L	E_R	N_R	H_1	Type
u	d	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$\frac{(u-d)}{2}$	
0	0	0	0	0	0	0	$h_2 \neq 0$
$1/3$	$1/3$	$1/3$	-1	-1	-1	0	$U(1)_{B-L}$
1	-1	0	0	-1	1	1	$U(1)_R$
$2/3$	$-1/3$	$1/6$	$-1/2$	-1	0	$1/2$	$U(1)_Y$

Ko,Omura,Yu, PLB717,202(2013)

- SM fermions are $U(1)_H$ singlets.
- Z_H is fermiophobic and Higgphilic.
- We discuss the fermiophobic case.

Higgs Potential

- in the ordinary 2HDM with Z_2 symmetry

$$V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - (m_{12}^2 H_1^\dagger H_2 + h.c.) + \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \frac{1}{2}\lambda_5 [(H_1^\dagger H_2)^2 + h.c.].$$

not invariant under $U(1)_H$

- in the case with Φ, $H_1^\dagger H_2 \Phi$ is gauge-invariant if $h_\phi = h_1 - h_2$.

$$\Delta V = m_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda_\Phi}{2}(\Phi^\dagger \Phi)^2 + (\mu H_1^\dagger H_2 \Phi + h.c.) + \mu_1 H_1^\dagger H_1 \Phi^\dagger \Phi + \mu_2 H_2^\dagger H_2 \Phi^\dagger \Phi,$$

Source of pseudo-scalar mass

- in the 2HDM with $U(1)_H$

$$V = \hat{m}_1^2(|\Phi|^2) H_1^\dagger H_1 + \hat{m}_2^2(|\Phi|^2) H_2^\dagger H_2 - \left(m_3^2(\Phi) H_1^\dagger H_2 + h.c. \right) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2 + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4.$$

no λ5 terms!

$$\hat{m}_i^2(|\Phi|^2) = m_i^2 + \widetilde{\lambda}_i |\Phi|^2 \qquad m_3^2(\Phi) = \mu \Phi^n, \text{ where } n = (q_{H_1} - q_{H_2})/q_\Phi$$

Higgs Potential

- VEVs and Higgs fields in the interaction eigenstates

$$H_i = \begin{pmatrix} \phi_i^+ \\ \frac{v_i}{\sqrt{2}} + \frac{1}{\sqrt{2}}(h_i + i\chi_i) \end{pmatrix}, \Phi = \frac{1}{\sqrt{2}}(v_\Phi + h_\Phi + i\chi_\Phi).$$

- charged Higgs

$$\begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} = \begin{pmatrix} \cos\beta \\ \sin\beta \end{pmatrix} G^+ + \begin{pmatrix} -\sin\beta \\ \cos\beta \end{pmatrix} H^+$$

- pseudoscalar Higgs

$$\begin{pmatrix} \chi_\Phi \\ \chi_1 \\ \chi_2 \end{pmatrix} = \begin{pmatrix} 0 \\ \cos\beta \\ \sin\beta \end{pmatrix} G_1 + \frac{v_\Phi}{\sqrt{v_\Phi^2 + (nv\cos\beta\sin\beta)^2}} \begin{pmatrix} 1 \\ \frac{nv}{v_\Phi}\cos\beta\sin^2\beta \\ -\frac{nv}{v_\Phi}\cos^2\beta\sin\beta \end{pmatrix} G_2$$
$$+ \frac{v_\Phi}{\sqrt{v_\Phi^2 + (nv\cos\beta\sin\beta)^2}} \begin{pmatrix} \frac{nv}{v_\Phi}\cos\beta\sin\beta \\ -\sin\beta \\ \cos\beta \end{pmatrix} A.$$

- neutral Higgs

$$\begin{pmatrix} h_\Phi \\ h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \cos\alpha_1 & 0 & -\sin\alpha_1 \\ 0 & 1 & 0 \\ \sin\alpha_1 & 0 & \cos\alpha_1 \end{pmatrix} \begin{pmatrix} \cos\alpha_2 & -\sin\alpha_2 & 0 \\ \sin\alpha_2 & \cos\alpha_2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \widetilde{h} \\ H \\ h \end{pmatrix}$$

- a pair of charged Higgs + 1 pseudoscalar Higgs + 3 neutral Higgs bosons

Constraints

- experimental and theoretical constraints

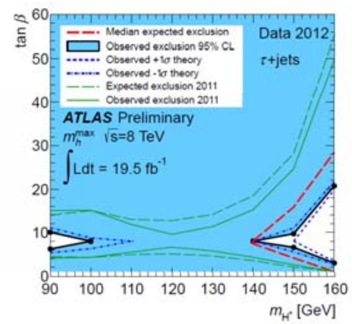
$m_h \sim 126$ GeV

$|m_{H^+} - m_A|$

$|m_{H^+} - m_H|$

$\sin(\beta - \alpha)$

EWPOs
small mass differences requied

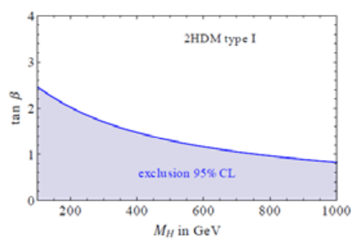


$\tan\beta$

m_{H^+}

Exotic top decay

$b \to s\gamma$



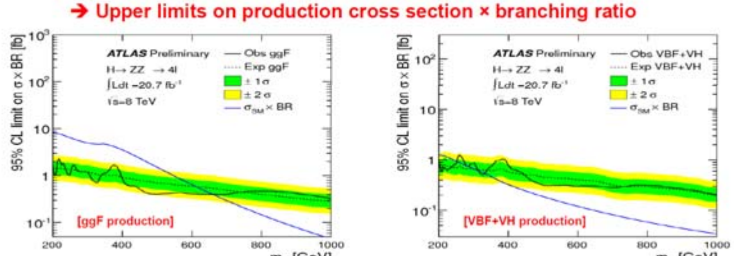
$\tan\beta \gtrsim 1$

Hermann,Misiak,Steinhauser, JHEP1211 (2012) 036

m_H

Heavy Higgs search at LHC

➔ Upper limits on production cross section × branching ratio



Constraints

- experimental and theoretical constraints

$m_h \sim 126$ GeV

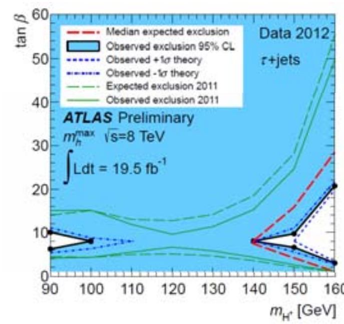
Perturbativity
Unitarity
Vacuum stability

$|m_{H^+} - m_A|$

$|m_{H^+} - m_H|$

$\sin(\beta - \alpha)$

EWPOs
small mass differences requied



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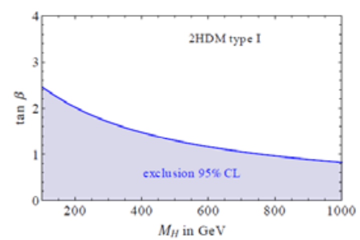

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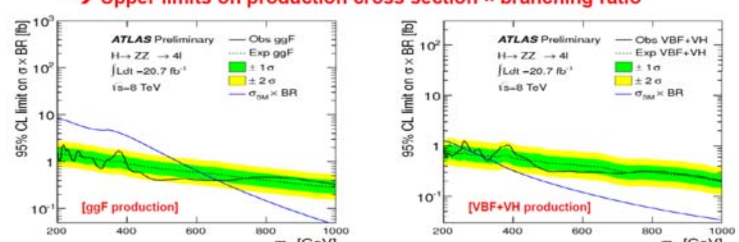


Constraints

- experimental and theoretical constraints

$m_h \sim 126\ \text{GeV}$

$|m_{H^+} - m_A|$

$|m_{H^+} - m_H|$

$\sin(\beta - \alpha)$

$\tan\beta$

m_{H^+}

SM-like Higgs

m_H

Perturbativity

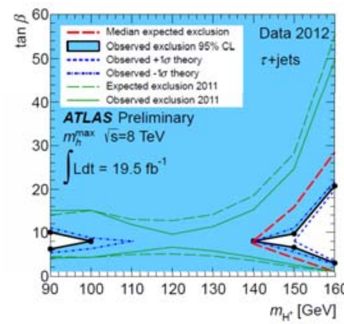
Unitarity

Vacuum stability

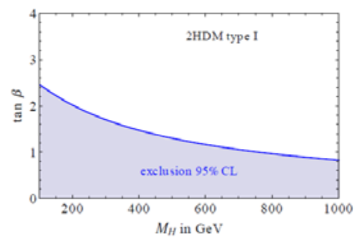
EWPOs

small mass differences requied

Exotic top decay



$b \to s\gamma$



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Heavy Higgs search at LHC

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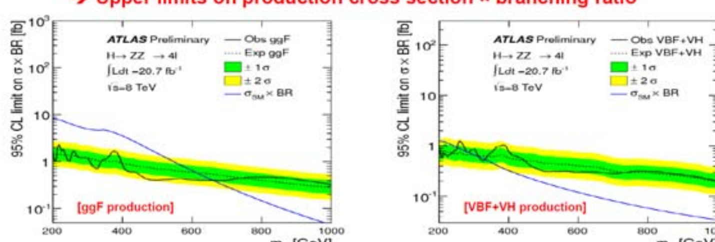


EWPOs in 2HDMwU(1)$_H$

- SM + extended Higgs sector + Z_H (+ extra fermions).
- oblique parameters : S,T,U

  - the dominant effects of new physics appear in self energies of gauge bosons.

$$S = 0.03 \pm 0.10,\ T = 0.05 \pm 0.12,\ U = 0.03 \pm 0.10,$$

Baak et al., EPJC 72, 2205 (2012)

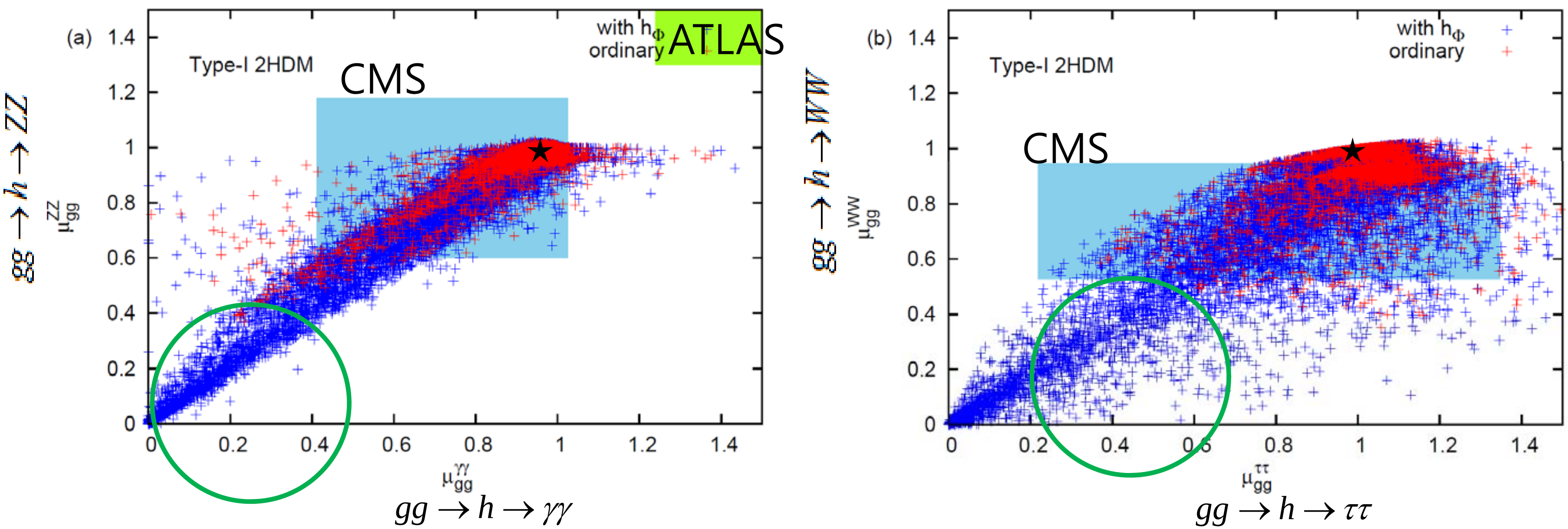
- consider two cases.

1. Z_H is decoupled in the limit of m_{Z_H}>>EW scale.
2. Z_H is fermiophobic for u=d=0.

Type-I 2HDM with h_Φ

- the gg fusion

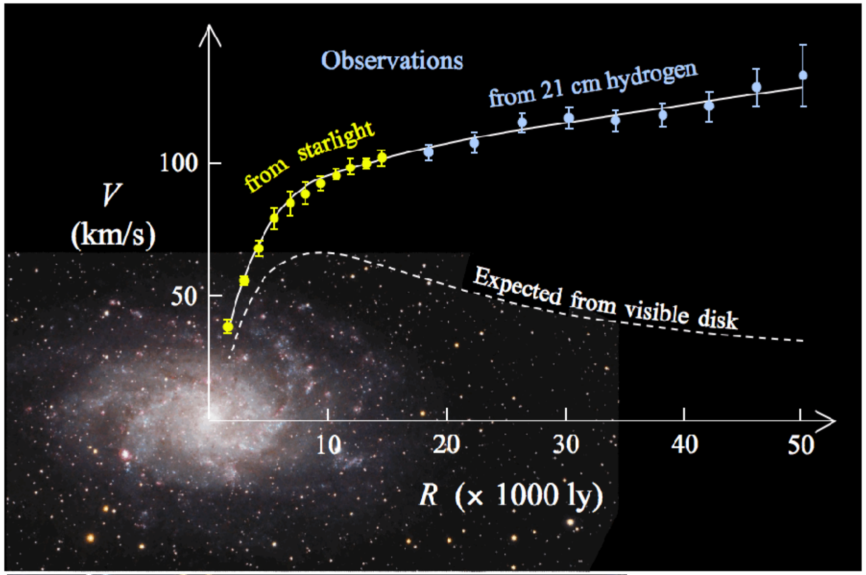
★ =SM

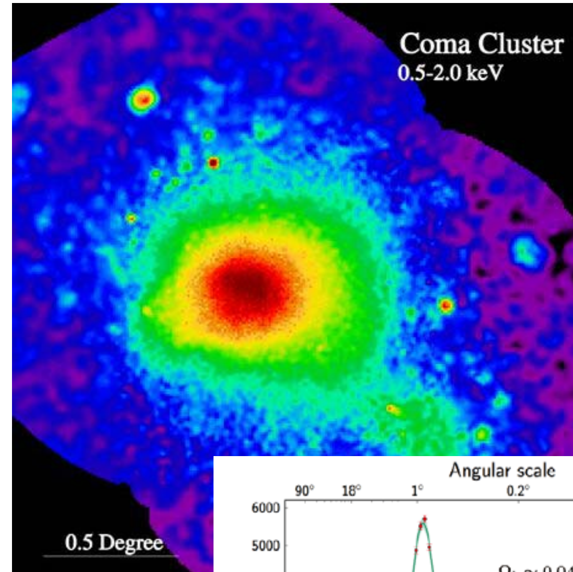


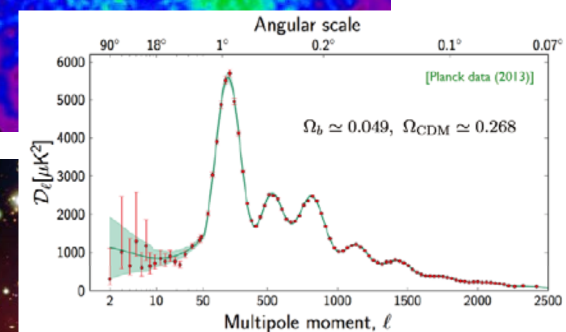
- consistent with CMS in the 1σ level while consistent with ATLAS in the 2σ.
- difficult to distinguish because the current experimental values are consistent with the SM prediction.
- essential to discover the extra scalar bosons and the new gauge boson.

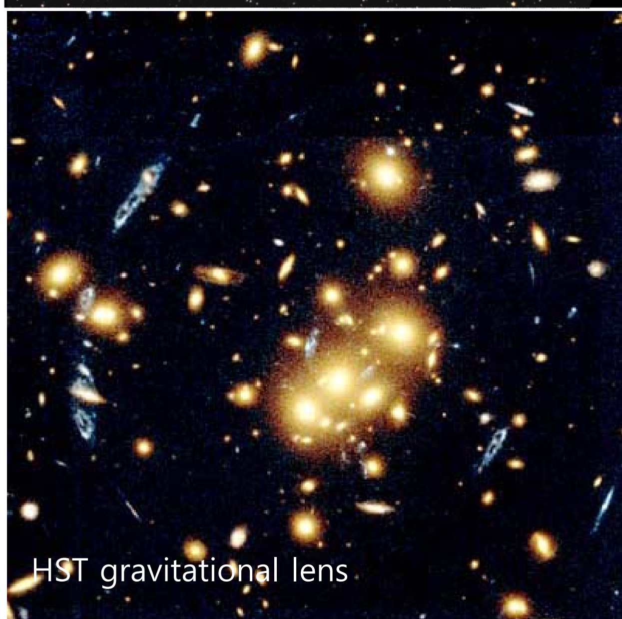
Ko,Omura,Yu, JHEP1401 (2014) 016

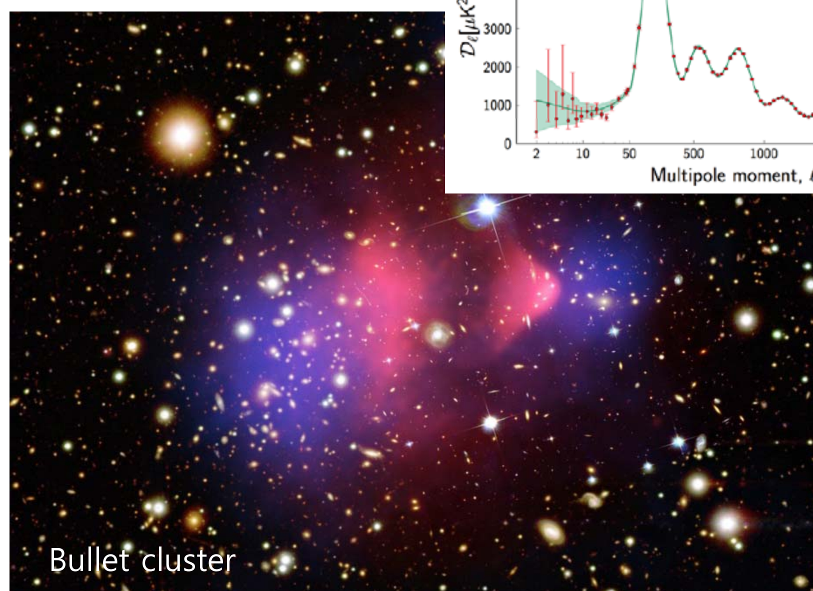
Dark Matter





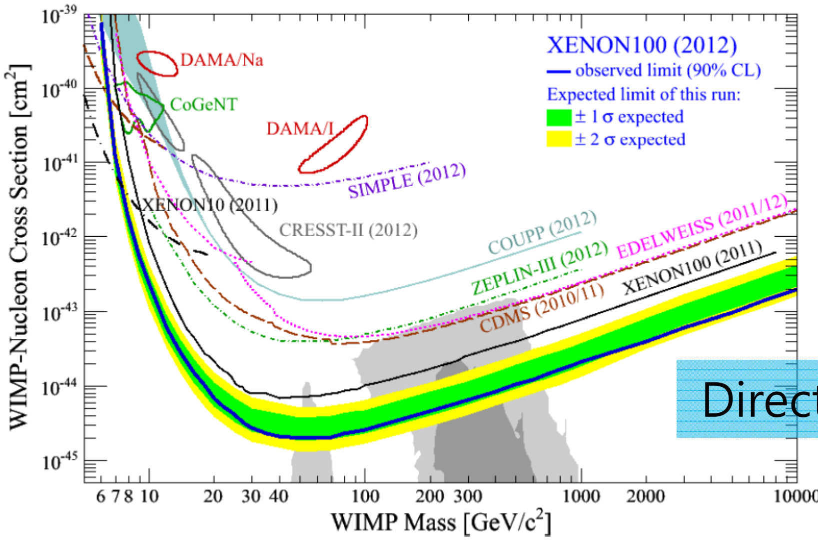


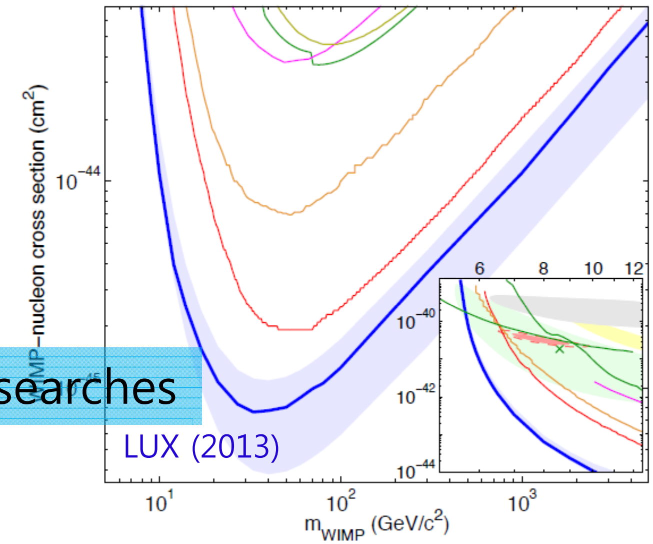




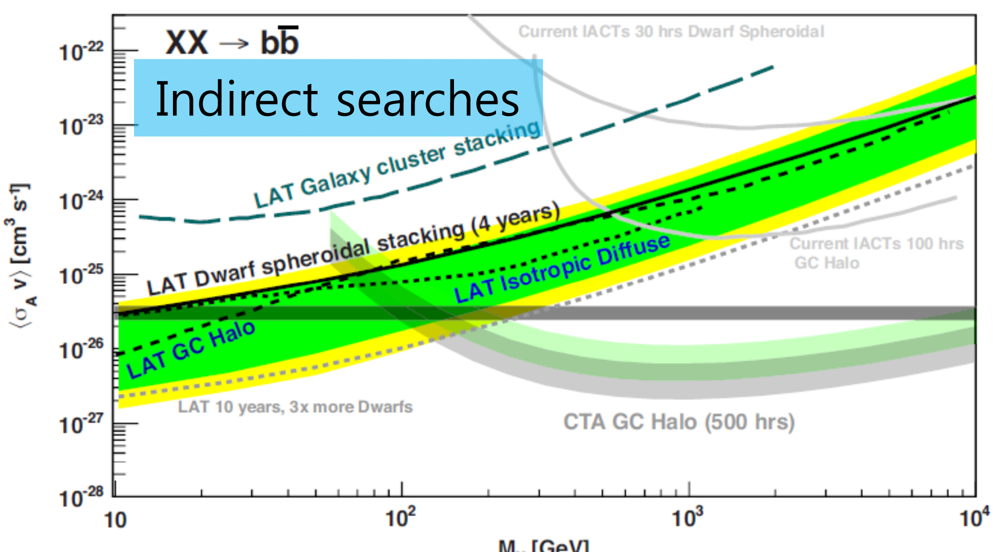
See the talks by C.ChenH.M.Lee, S.Baek, and W.I.Park

Constraints on DM

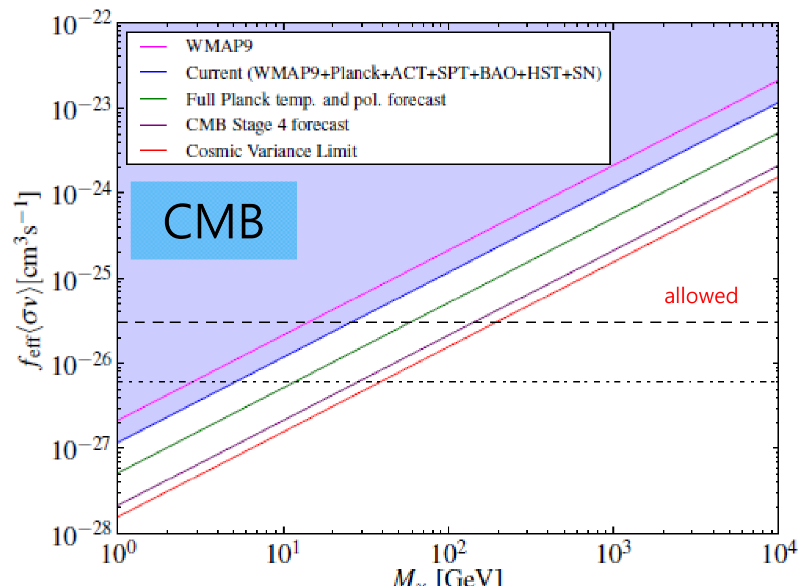




Direct searches



Indirect searches



CMB

See the talks by C.Chen,H.M.Lee, S.Baek, and W.I.Park

Inert Doublet Model (IDMwZ_2)

- one of Higgs doublets does not develop VEV and an exact Z_2 symmetry is imposed.

- Under the Z_2 symmetry, SM particles are even, but the new Higgs doublet is odd (type-I).

$$H_1 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}, \quad H_2 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}$$

DM candidates (H, A) SM-like Higgs (h)

forbidden by the Z_2 symmetry

$$V = \mu_1 (H_1^\dagger H_1) + \mu_2 (H_2^\dagger H_2) - \mu_{12} (H_1^\dagger H_2 + \text{h.c.}) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2$$
$$+ \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\{(H_1^\dagger H_2)^2 + h.c.\}.$$

IDMwU(1)$_H$

- IDM + SM-singlet Φ.

$$V = (m_1^2 + \tilde{\lambda}_1 |\Phi|^2)(H_1^\dagger H_1) + (m_2^2 + \tilde{\lambda}_2 |\Phi|^2)(H_2^\dagger H_2) - (m_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.})$$
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$
$$+ \frac{\lambda_5}{2}\{(H_1^\dagger H_2)^2 + h.c.\} + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4$$

- Without Φ, Z_H boson becomes massless.
- Only Φ breaks the $U(1)_H$ symmetry while only H_2 breaks the EW symmetry.

IDMwU(1)$_H$

- IDM + SM-singlet Φ.

forbidden by the Z_2 symmetry

$$V = (m_1^2 + \tilde{\lambda}_1 |\Phi|^2)(H_1^\dagger H_1) + (m_2^2 + \tilde{\lambda}_2 |\Phi|^2)(H_2^\dagger H_2) - (m_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.})$$
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$
$$+ \frac{\lambda_5}{2}\{(H_1^\dagger H_2)^2 + h.c.\} + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4$$

forbidden by the U(1)$_H$ symmetry ($q_{H_2}=0, q_{H_1} \neq 0$)

- Without Φ, Z_H boson becomes massless.
- Only Φ breaks the U(1)$_H$ symmetry while only H_2 breaks the EW symmetry.

IDMwU(1)$_H$

- IDM + SM-singlet Φ.

forbidden
by the Z_2 symmetry

$$V=(m_1^2+\tilde{\lambda}_1|\Phi|^2)(H_1^\dagger H_1)+(m_2^2+\tilde{\lambda}_2|\Phi|^2)(H_2^\dagger H_2)-(m_{12}^2 H_1^\dagger H_2+\mathrm{h.c.})$$

$$+\frac{\lambda_1}{2}(H_1^\dagger H_1)^2+\frac{\lambda_2}{2}(H_2^\dagger H_2)^2+\lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2)+\lambda_4|H_1^\dagger H_2|^2$$

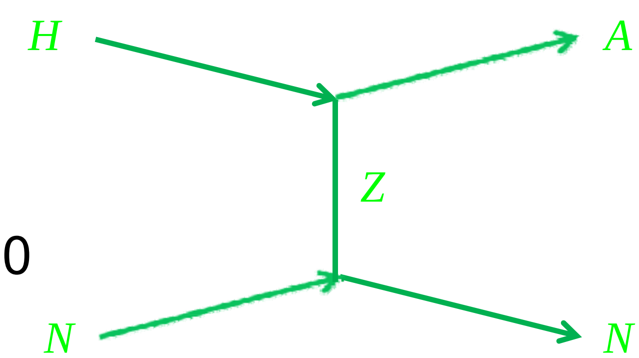
$$+\frac{\lambda_5}{2}\{(H_1^\dagger H_2)^2+h.c.\}+m_\Phi^2|\Phi|^2+\lambda_\Phi|\Phi|^4$$

forbidden by the U(1)$_H$ symmetry ($q_{H_2}=0, q_{H_1}\neq 0$)

- Without λ_5, A and H are degenerate.

$$m_A=\sqrt{m_H^2-\lambda_5 v^2}$$

- Direct searches for the DM at XENON100 and LUX exclude the degenerate case.



IDMwU(1)$_H$

- IDM + SM-singlet Φ.

forbidden
by the Z_2 symmetry

$$V = (m_1^2 + \tilde{\lambda}_1 |\Phi|^2)(H_1^\dagger H_1) + (m_2^2 + \tilde{\lambda}_2 |\Phi|^2)(H_2^\dagger H_2) - (m_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.})$$
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$
$$+ \{c_l \left(\frac{\Phi}{\Lambda}\right)^l (H_1^\dagger H_2)^2 + h.c.\} + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4$$

- include a higher-dimensional operator.

IDMwU(1)$_H$

- IDM + SM-singlet Φ.

forbidden
by the Z_2 symmetry

$$V = (m_1^2 + \tilde{\lambda}_1 |\Phi|^2)(H_1^\dagger H_1) + (m_2^2 + \tilde{\lambda}_2 |\Phi|^2)(H_2^\dagger H_2) - (m_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.})$$

$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$

$$+ \{c_l \left(\frac{\Phi}{\Lambda}\right)^l (H_1^\dagger H_2)^2 + h.c.\} + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4$$

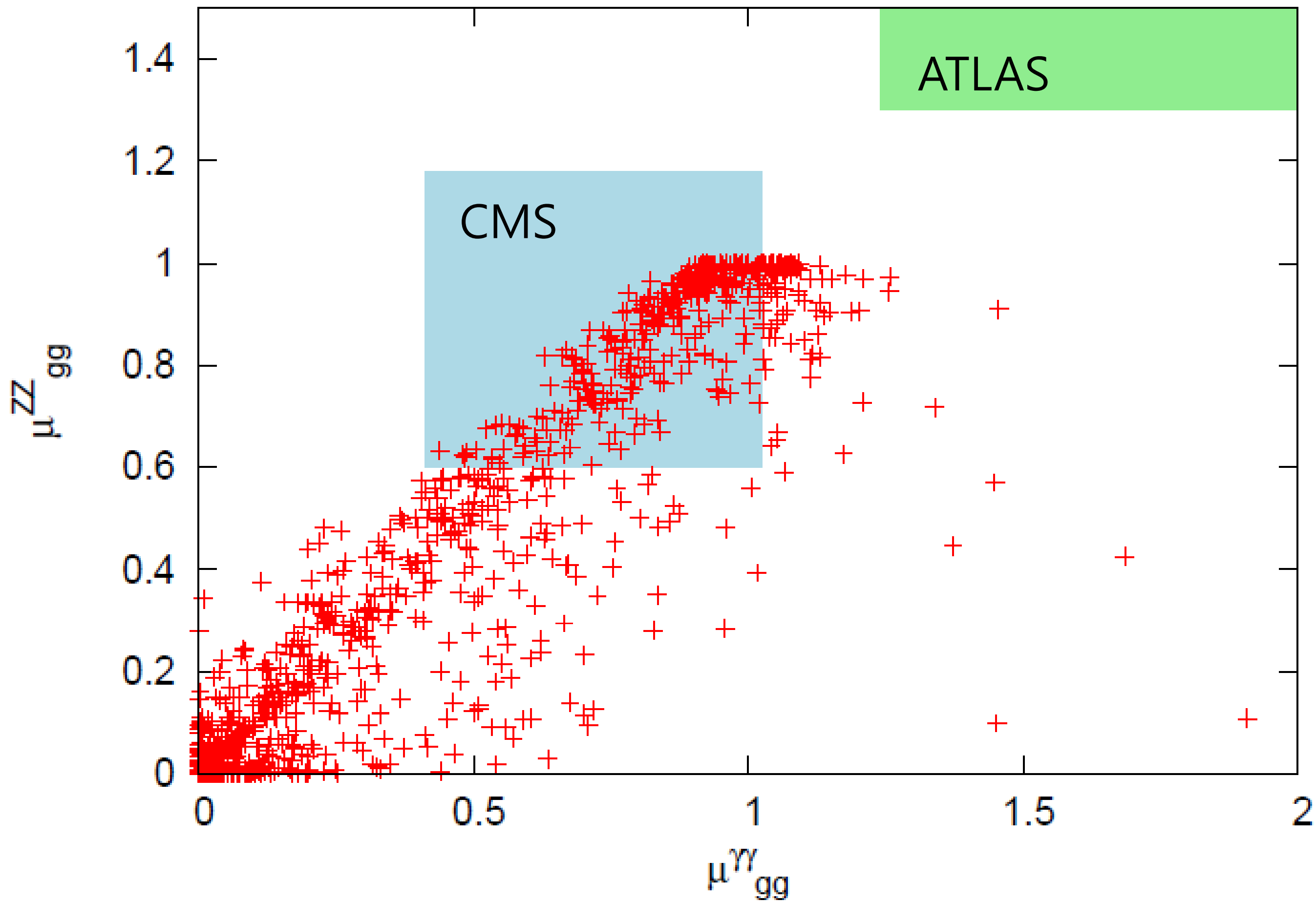
- include a higher-dimensional operator.

- It could be realized by introducing a singlet S charged under U(1)$_H$ with $q_S = q_{H_1}$.

$$V_\Phi(|\Phi|^2, |S|^2) + V_H(H_i, H_i^\dagger) + \lambda_S(\Phi) S^2 + \lambda_H(S) H_1^\dagger H_2 + h.c..$$

$$\lambda_H = \lambda_H^0 S \qquad \lambda_5 \sim \frac{(\lambda_H^0)^2}{2} \frac{\Delta m^2}{m_{Re(S)}^2 m_{Im(S)}^2},$$

Higgs production



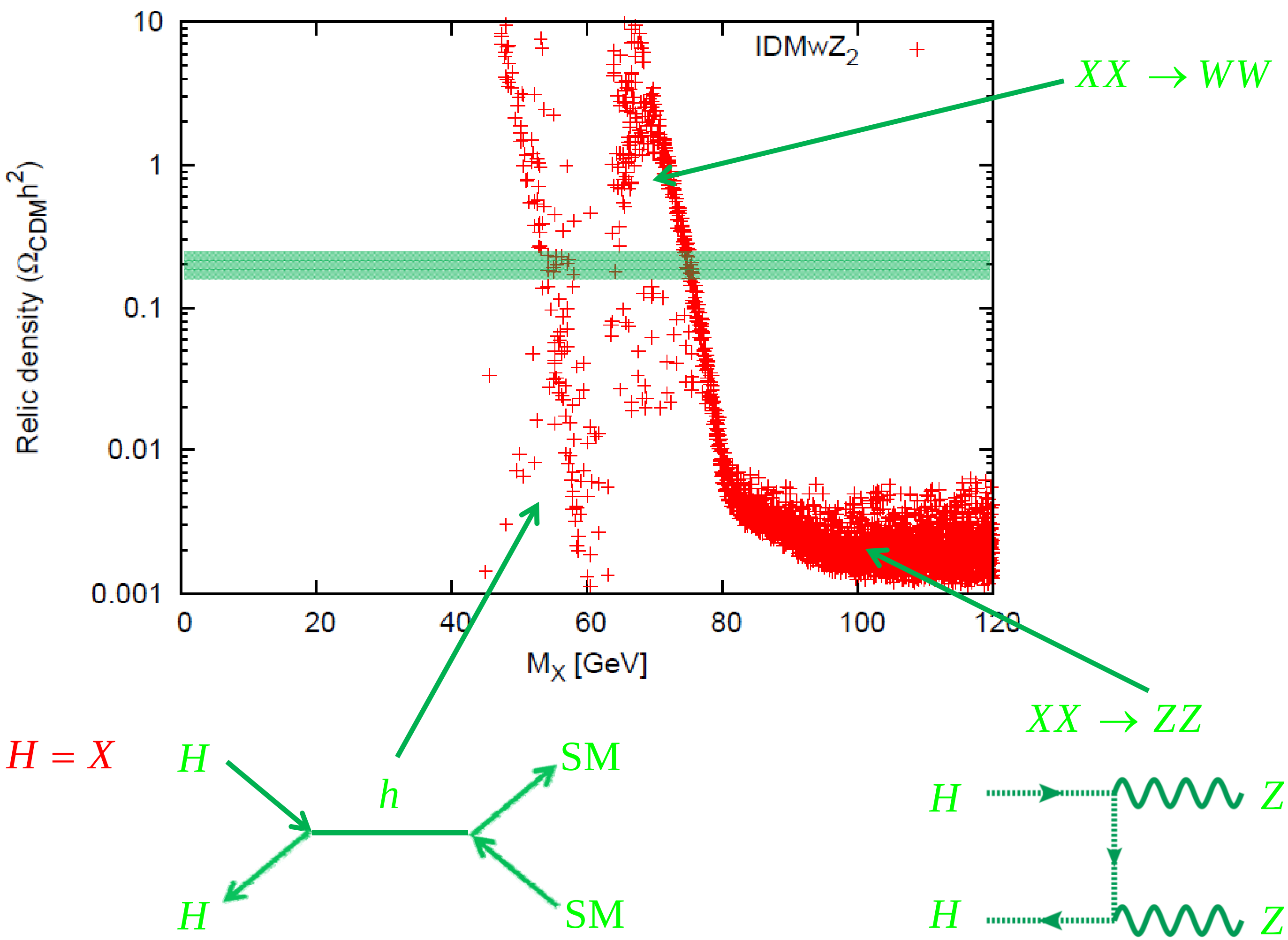
- a global fit for invisible Higgs decay $B(h \to \text{inv}) < 0.2$

Belanger, Dumont, Ellwanger, Gunion, Kraml; Espinosa, Grojean, Mühlleitner, Trott

Relic density

Preliminary

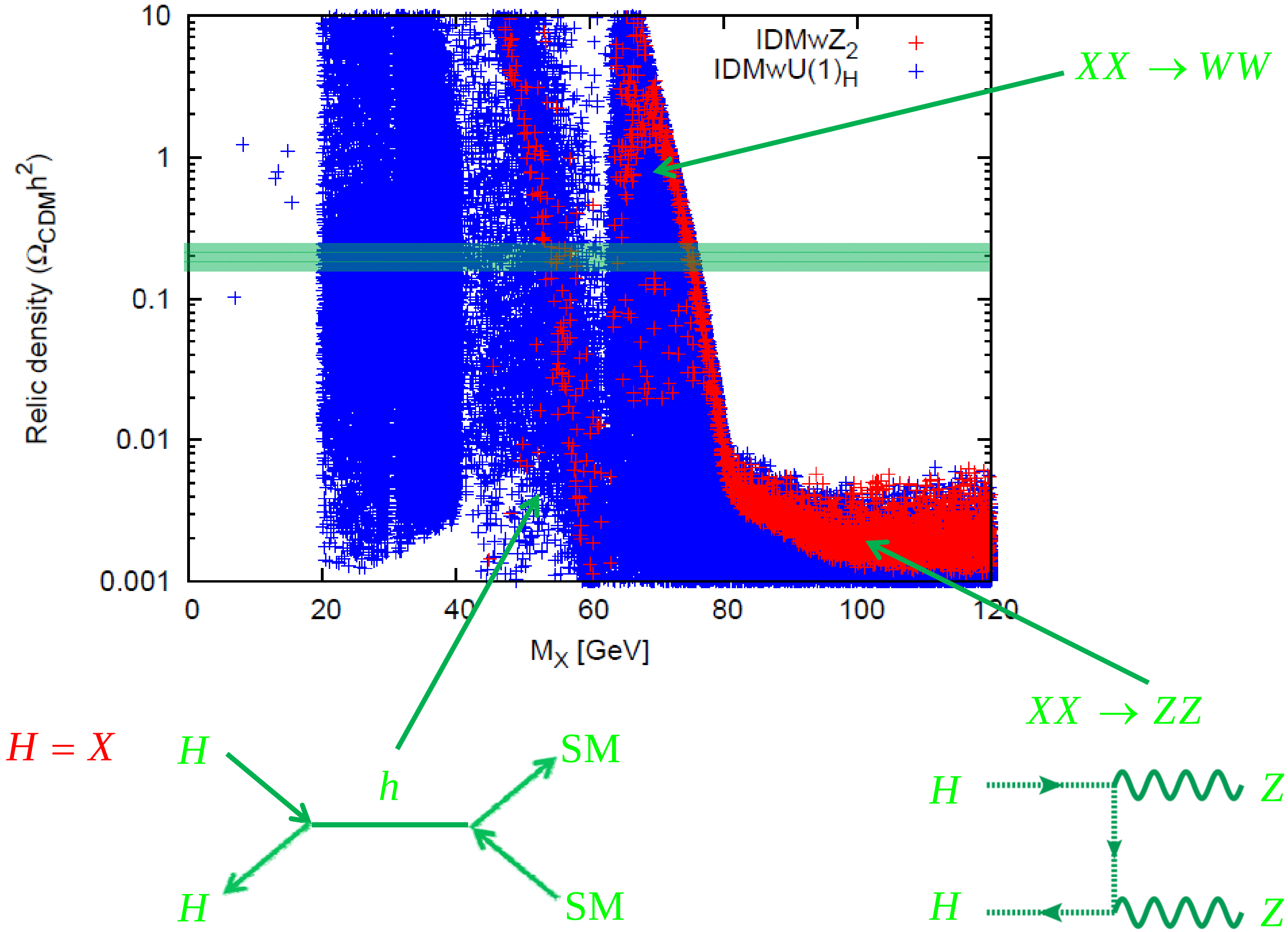
$$\Omega_{\rm CDM} h^2 = 0.1199 \pm 0.0027$$



Relic density

Preliminary

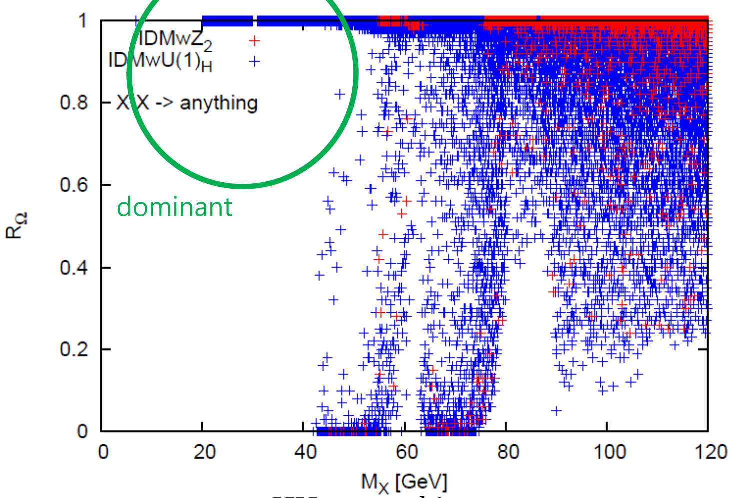
$$\Omega_{\rm CDM} h^2 = 0.1199 \pm 0.0027$$



Relic density

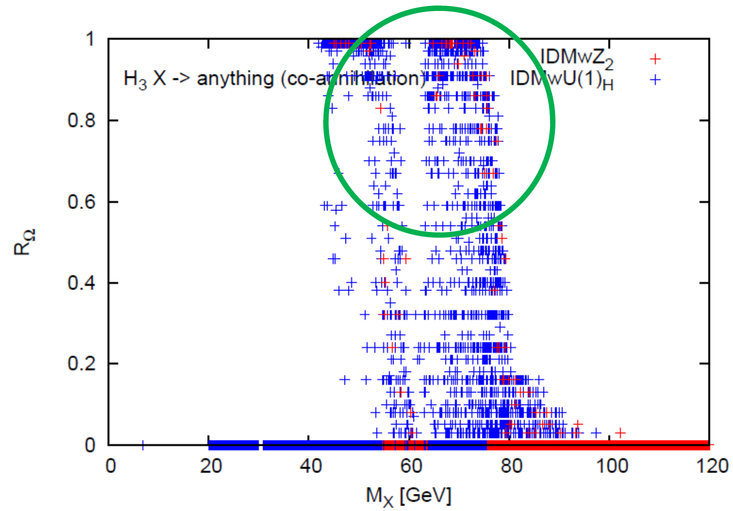
$$R_{\Omega}(ab \to cd) = \frac{\Omega(ab \to cd)}{\Omega_{\mathrm{CDM}}}$$

Preliminary

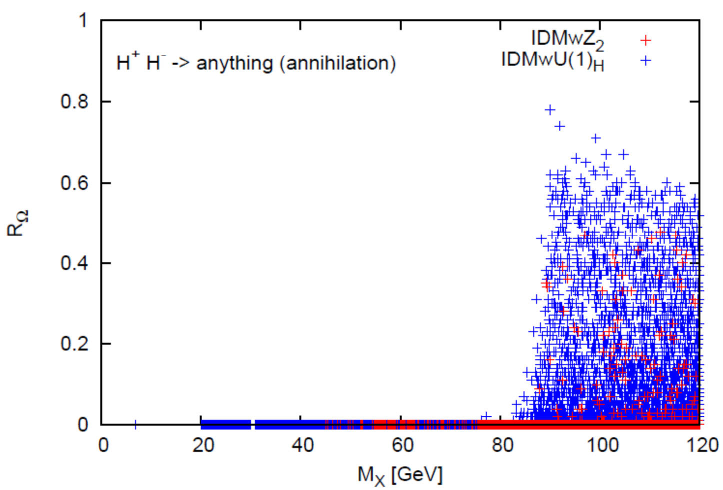


$HH \to$ anything

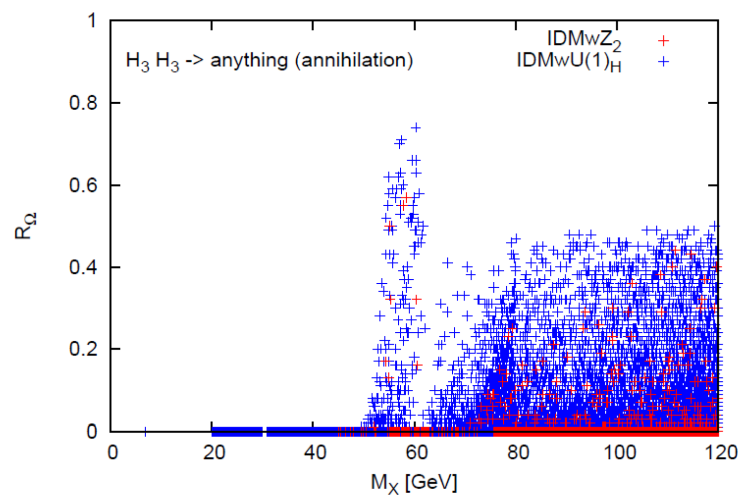
could be dominant



$HA \to$ anything



$H^{+}H^{-} \to$ anything

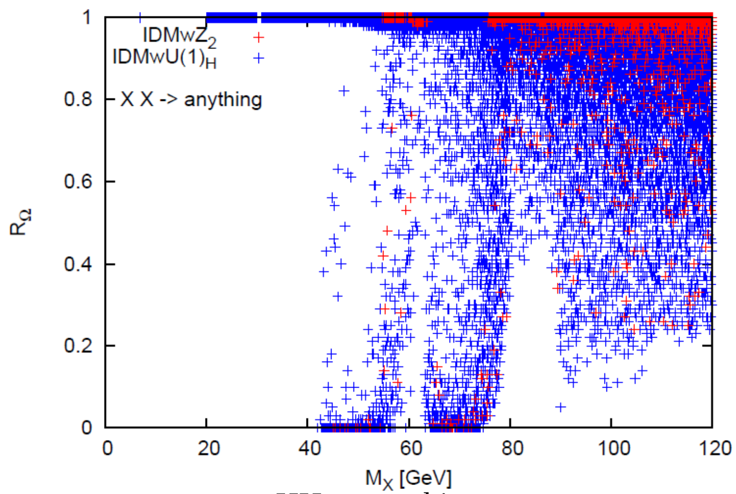


$AA \to$ anything

Relic density

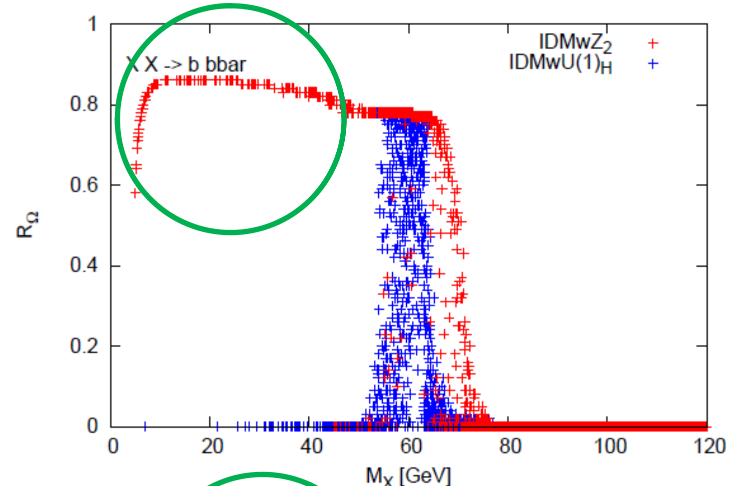
$$R_\Omega(ab \to cd) = \frac{\Omega(ab \to cd)}{\Omega_{CDM}}$$

Preliminary

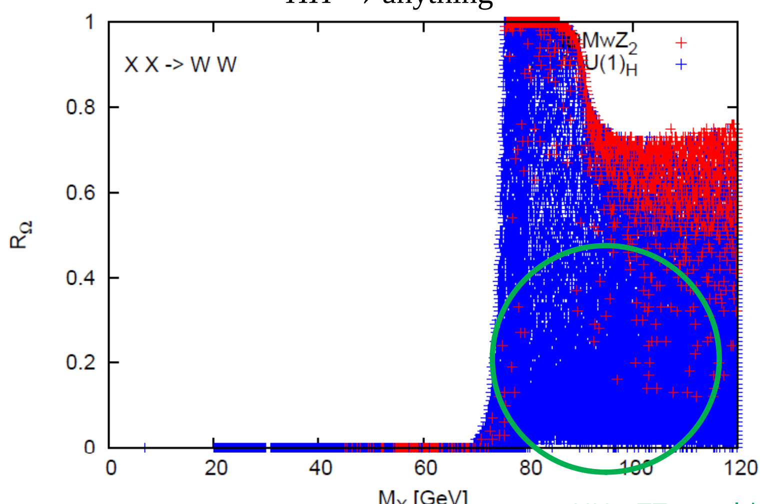


$HH \to$ anything

too small cross section

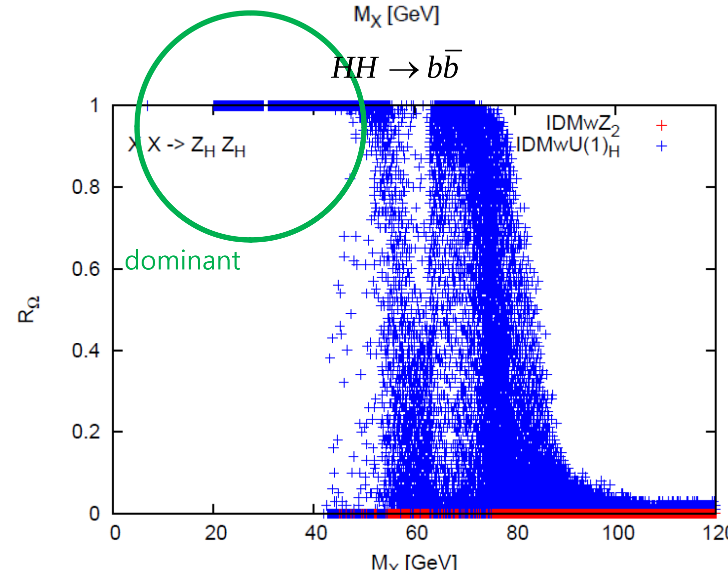


$HH \to b\bar{b}$



$HH \to W^+W^-$

HH→ZZ$_H$ could be dominant.

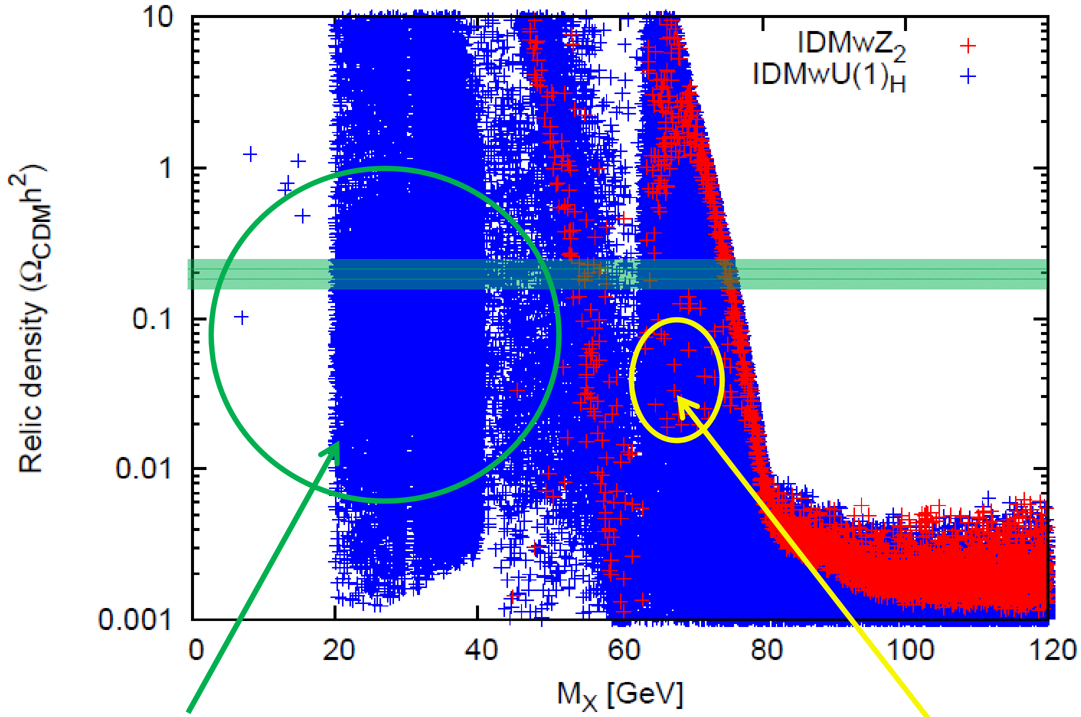


$HH \to Z_H Z_H$

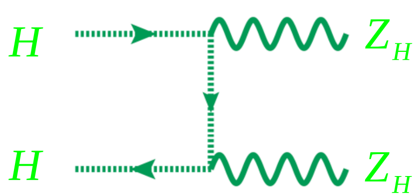
Relic density

Preliminary

$$\Omega_{\rm CDM} h^2 = 0.1199 \pm 0.0027$$



$XX \to Z_H Z_H$

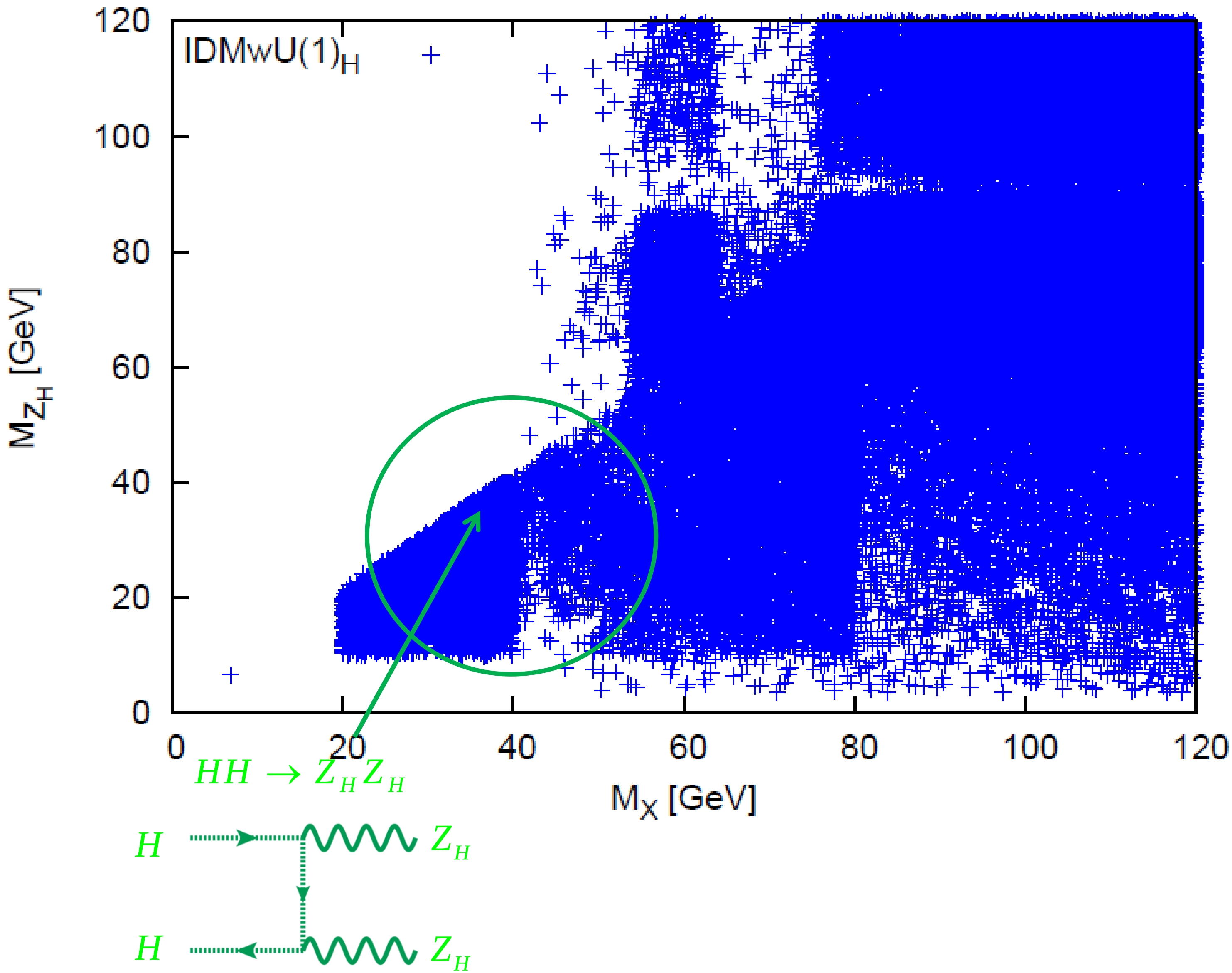


co-annihilation

$HA \to$ anything

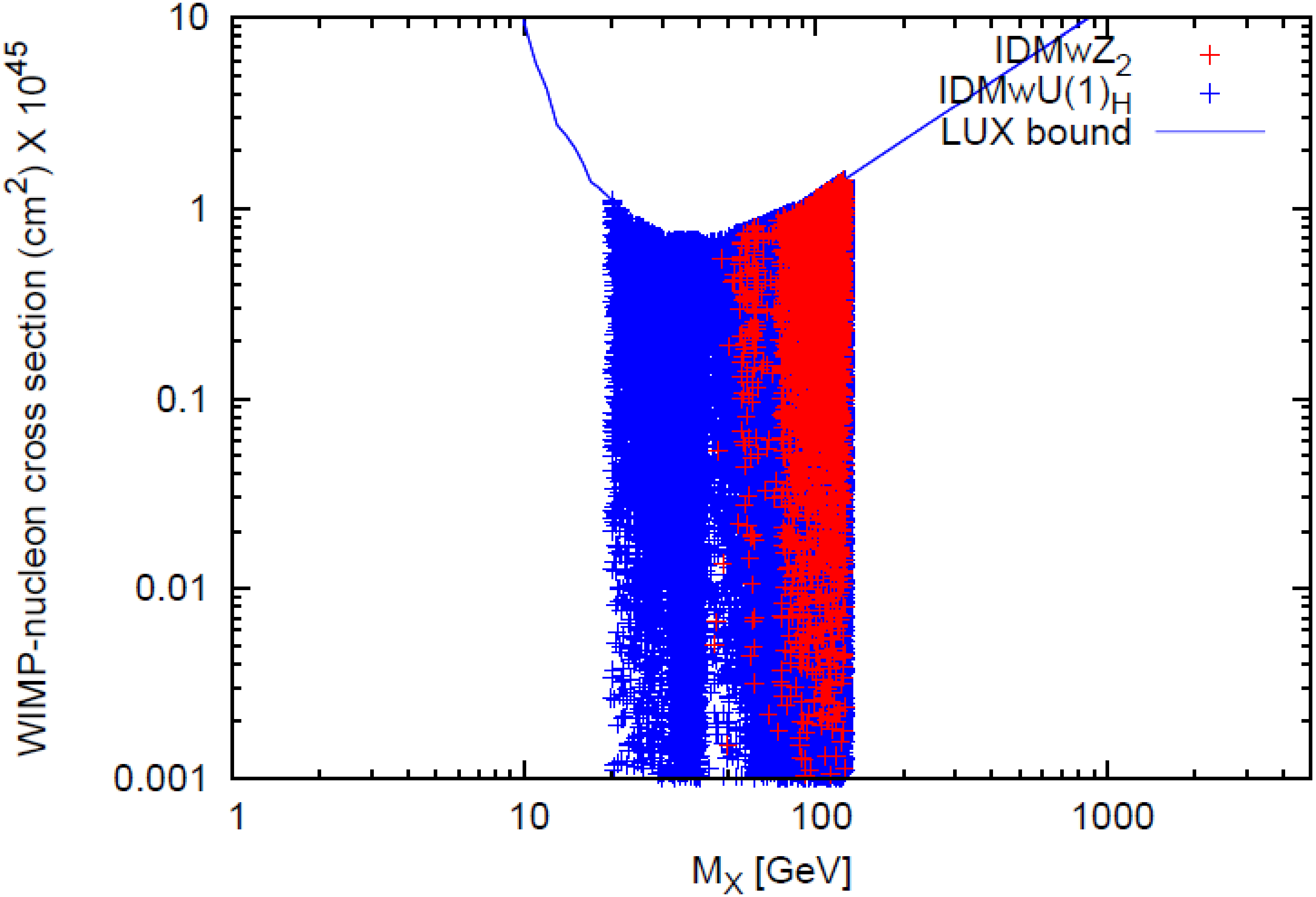
Z_H boson mass

Preliminary



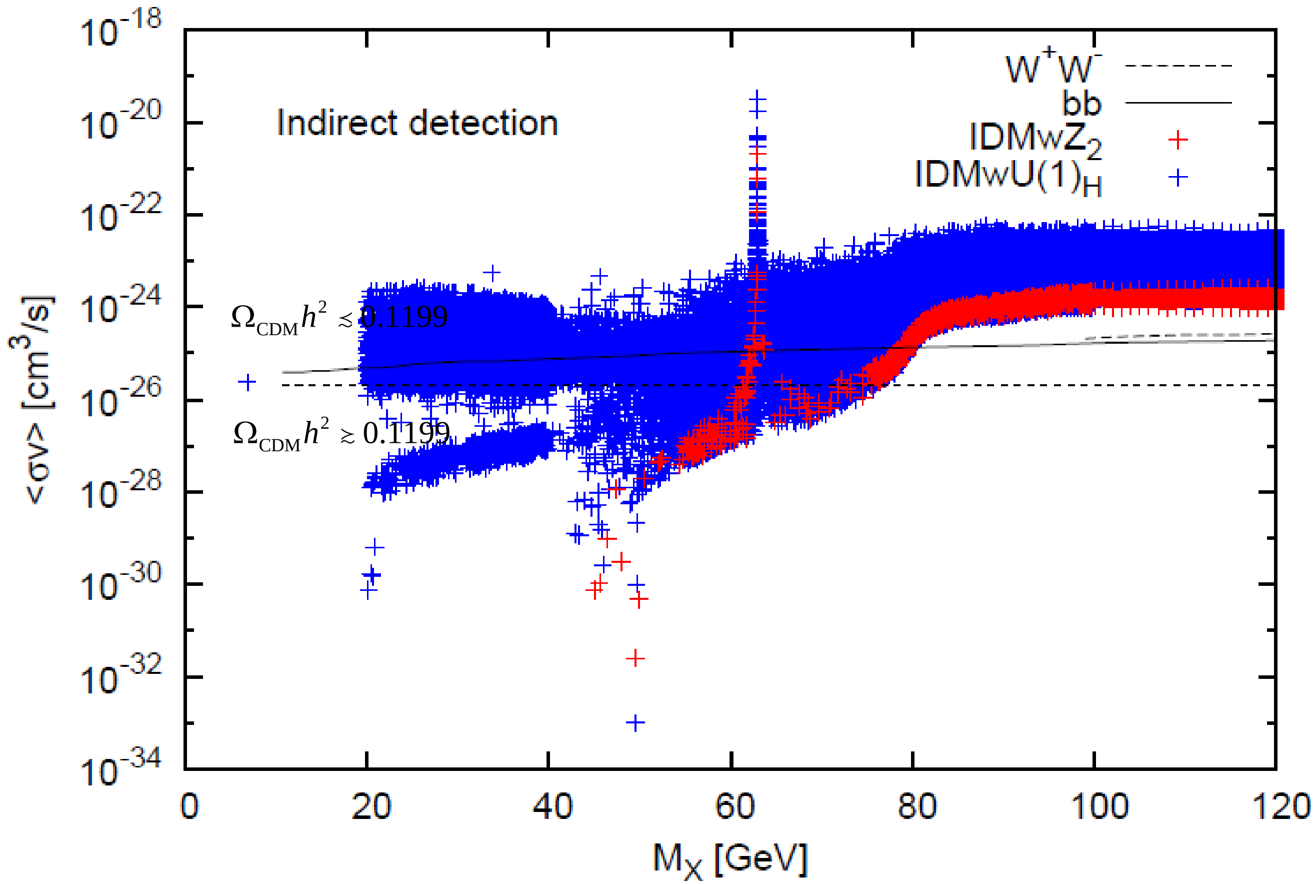
Direct searches

Preliminary



Indirect searches

Preliminary



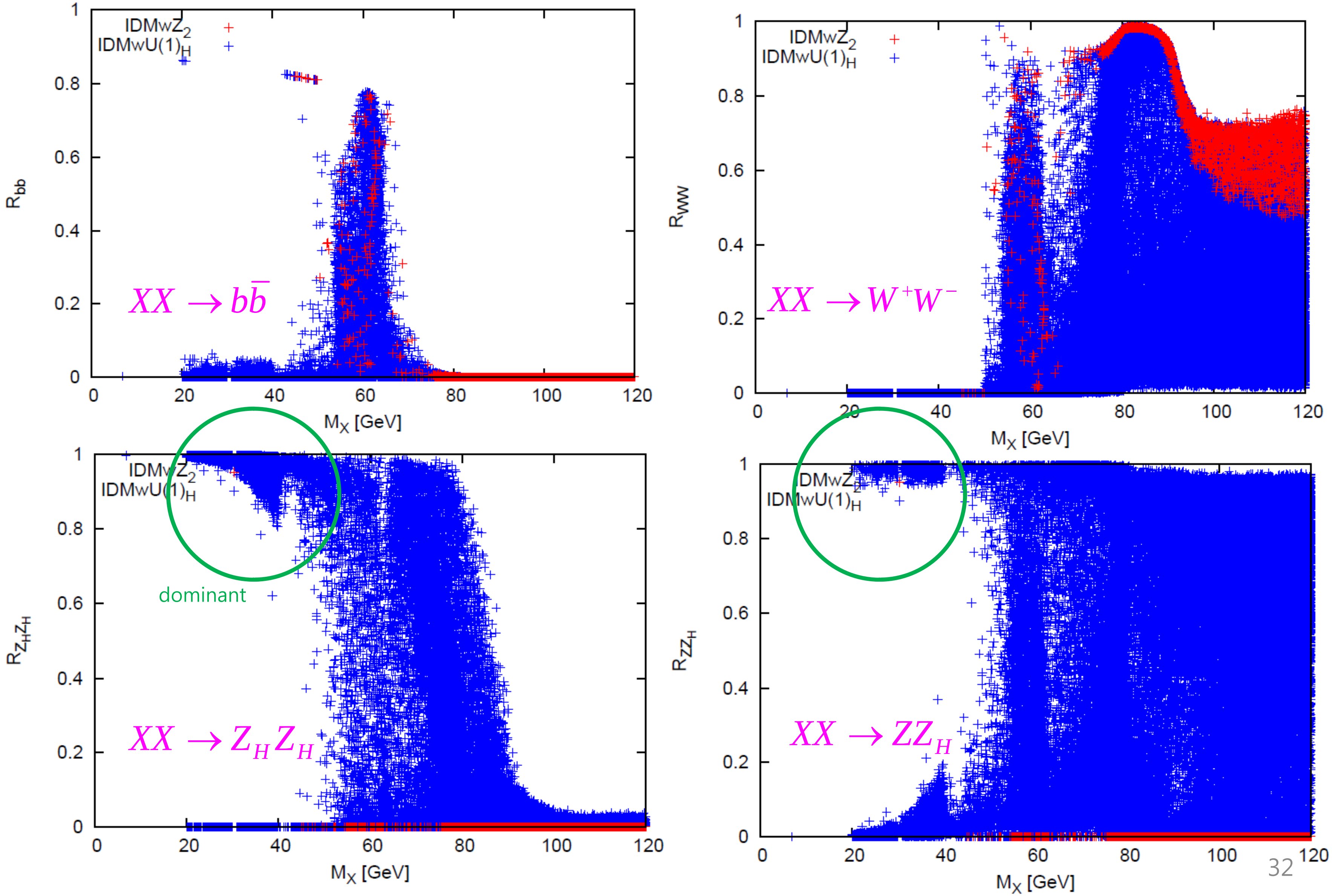
• Constraints on the DM annihilation cross section are derived from a combined analysis of 15 dwarf spheroidal galaxies (Fermi-LAT).

Fermi-LAT collaboration, arXiv:1310.0828

$$R_{ab} = \frac{\langle \sigma v \rangle (XX \to ab)}{\langle \sigma v \rangle (XX \to \text{anything})}$$

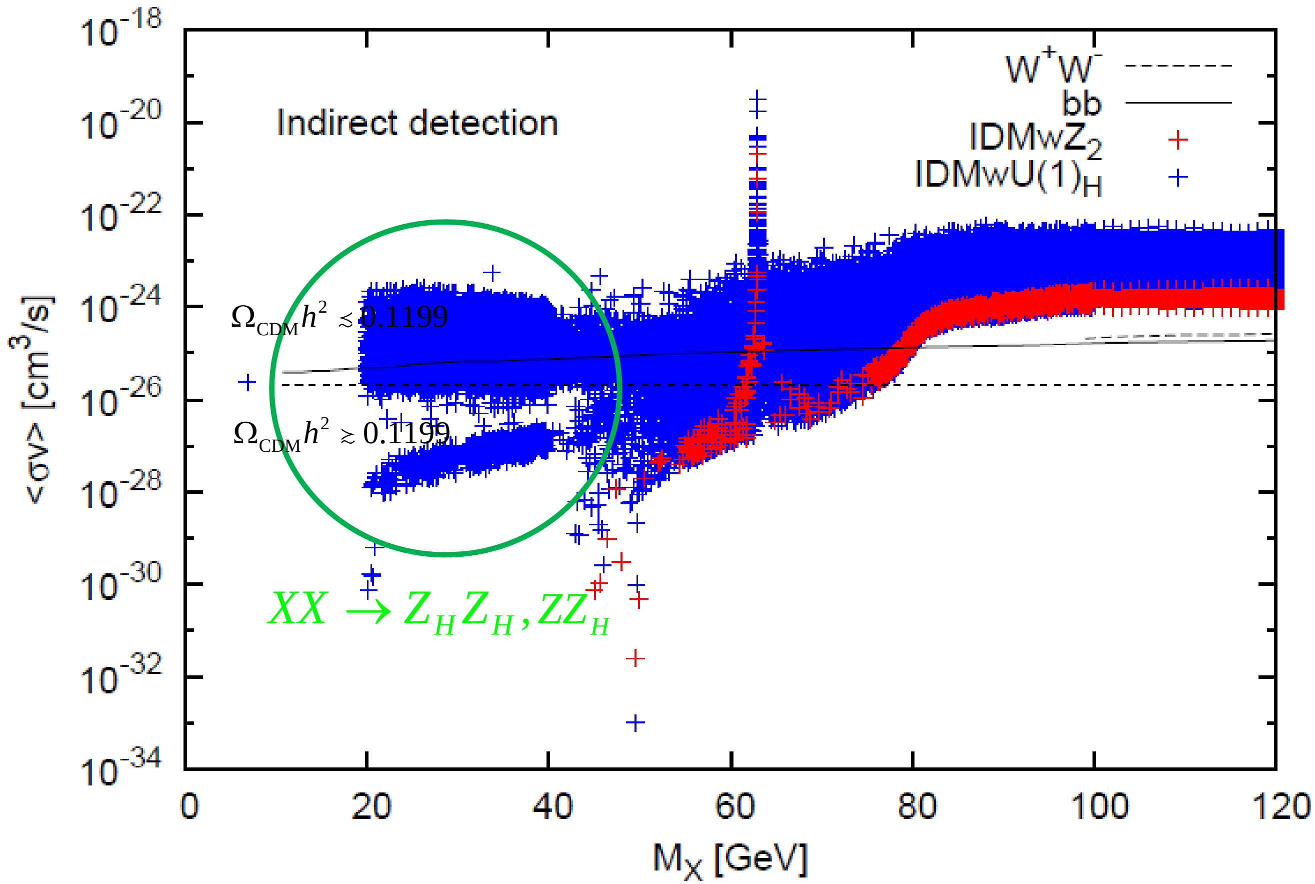
Indirect searches

Preliminary



Indirect searches

Preliminary



Gamma ray flux from DM annihilation

• Dwarf spheroidal galaxies are excellent targets to search for annihilating DM signatures because of DM-dominant nature without astrophysical backgrounds like hot gas.

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\Phi_{\rm PP}} \cdot \underbrace{\int_{\Delta\Omega}\left\{\int_{\rm l.o.s.}\rho^2(r){\rm d}l\right\}{\rm d}\Omega'}_{\rm J\text{-}factor} .$$

The final γ-ray spectrum.

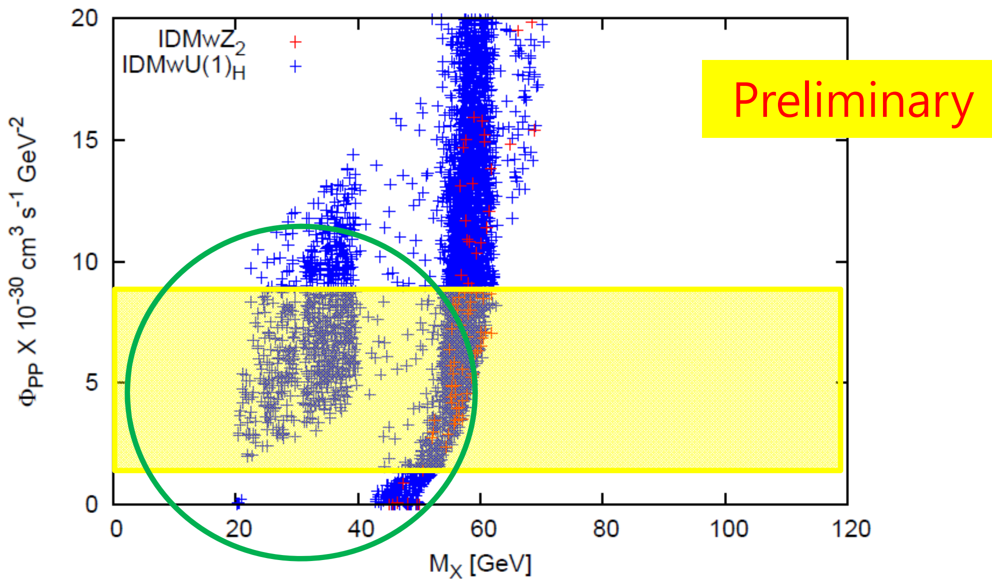
contains information about the distribution of DM.

Geringer−Sameth and Koushiappas, arxiv:1108.2914

7 Milky Way dwarfs + Pass 7 data from the Fermi Gamma-ray Space Telescope

A 95% upper bound is

$$\Phi_{PP} = 5.0^{+4.3}_{-4.5}\times 10^{-30}\,{\rm cm^3 s^{-1} GeV^{-2}}$$



Conclusions

• 2HDM may be an effective theory of a high-energy theory and useful to test the underlying theory.

• We proposed a new resoluton of the Higgs mediated FCNC problem in 2HDM by considering gauged $U(1)_H$.

• 2HDM has rich phenomenology : extra scalars, Z_H, dark matter, and extra fermions.

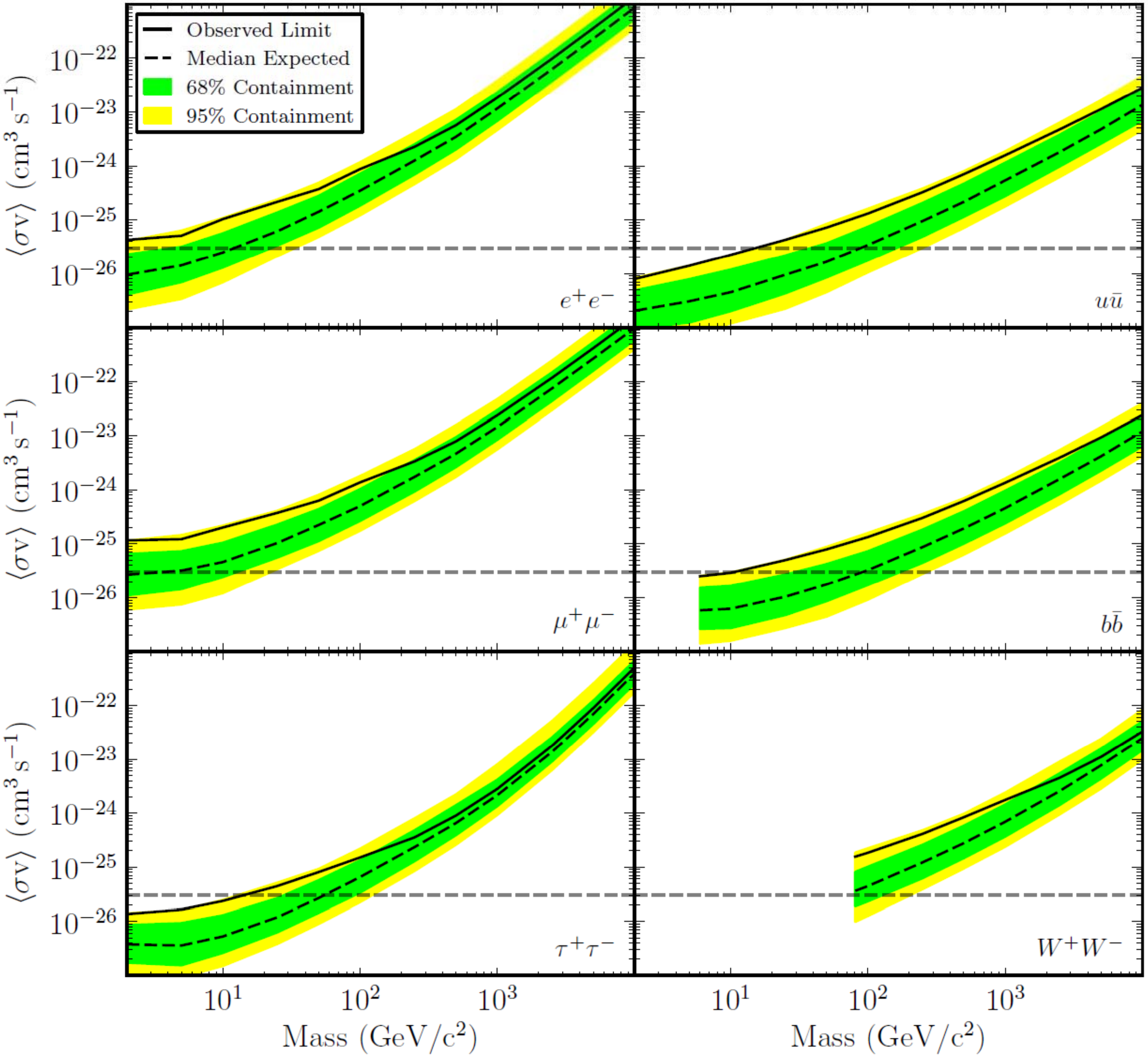
• The U(1) extension could introduce dark matter candidates whose stability are guaranteed by the remnant symmetry of $U(1)_H$.

• In type-I, a light CDM scenario is possible in the $IDMwU(1)_H$ and $h \to Z_H Z_H$ is predicted.

Thank you for your attention.

Back up

Indirect searches



- Constraints on the DM annihilation cross section are derived from a combined analysis of 15 dwarf spheroidal galaxies.

Fermi-LAT collaboration, arXiv:1310.0828

Z-Z_H mixing

- tree-level

$$\Delta M^2_{ZZ_H} = -\frac{\hat{M}_Z}{v} g_H \sum_{i=1}^{2} q_{H_i} v_i^2.$$

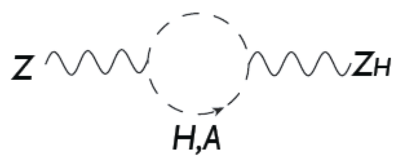
$$\frac{M_W^2}{M_Z^2 c_W^2} = \rho = 1 + \frac{\Delta M^2_{ZZ_H}}{M_Z^2}\xi + O(\xi^2)$$

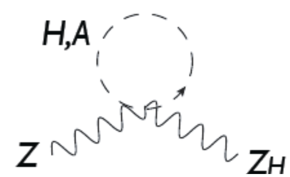
should be small

$\rho = 1.01051 \pm 0.00011$ in the SM

$$\tan 2\xi = \frac{2\Delta M^2_{ZZ_H}}{\hat{M}^2_{Z_H} - \hat{M}^2_Z}.$$

- loop-level





$$-\frac{\kappa_Z}{2} F_Z^{\mu\nu} F_{H\mu\nu} - \frac{\kappa_\gamma}{2} F_\gamma^{\mu\nu} F_{H\mu\nu} + \Delta M^2_{Z_H Z} \hat{Z}^\mu \hat{Z}_{H\mu}$$

Even if we assume $U(1)_Y \times U(1)_H$ kinetic mixing is negligible at MW, the mixing appears because of $SU(2)_L \times U(1)_Y$ breaking effects

$$\kappa_Z = \frac{q_H g_H e c_W}{16\pi^2 s_W} \left\{ \frac{1}{3} \ln\left(\frac{m_A^2}{m_{H+}^2}\right) - \frac{1}{6} \frac{m_A^2 - m_H^2}{m_A^2} \right\},$$

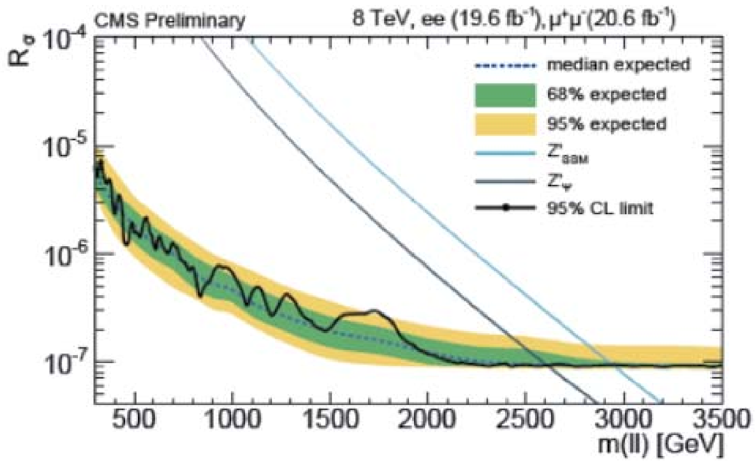
$$\kappa_\gamma = \frac{q_H g_H e}{16\pi^2} \left\{ \frac{1}{3} \ln\left(\frac{m_A^2}{m_{H+}^2}\right) - \frac{1}{6} \frac{m_A^2 - m_H^2}{m_A^2} \right\},$$

$$\Delta M^2_{Z_H Z} = -\frac{q_H g_H e}{32\pi^2 s_W c_W}(m_A^2 - m_H^2).$$

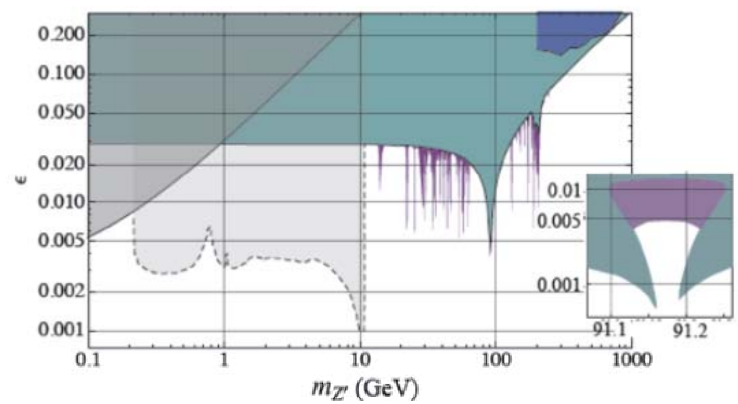
Degenerate masses make the mixings disappear.

Z' search

- collider bound depends on the U(1)' charge assignment.
- in the fermiophobic Z_H case, the Z_H boson can be produced through the Z-Z_H mixing.



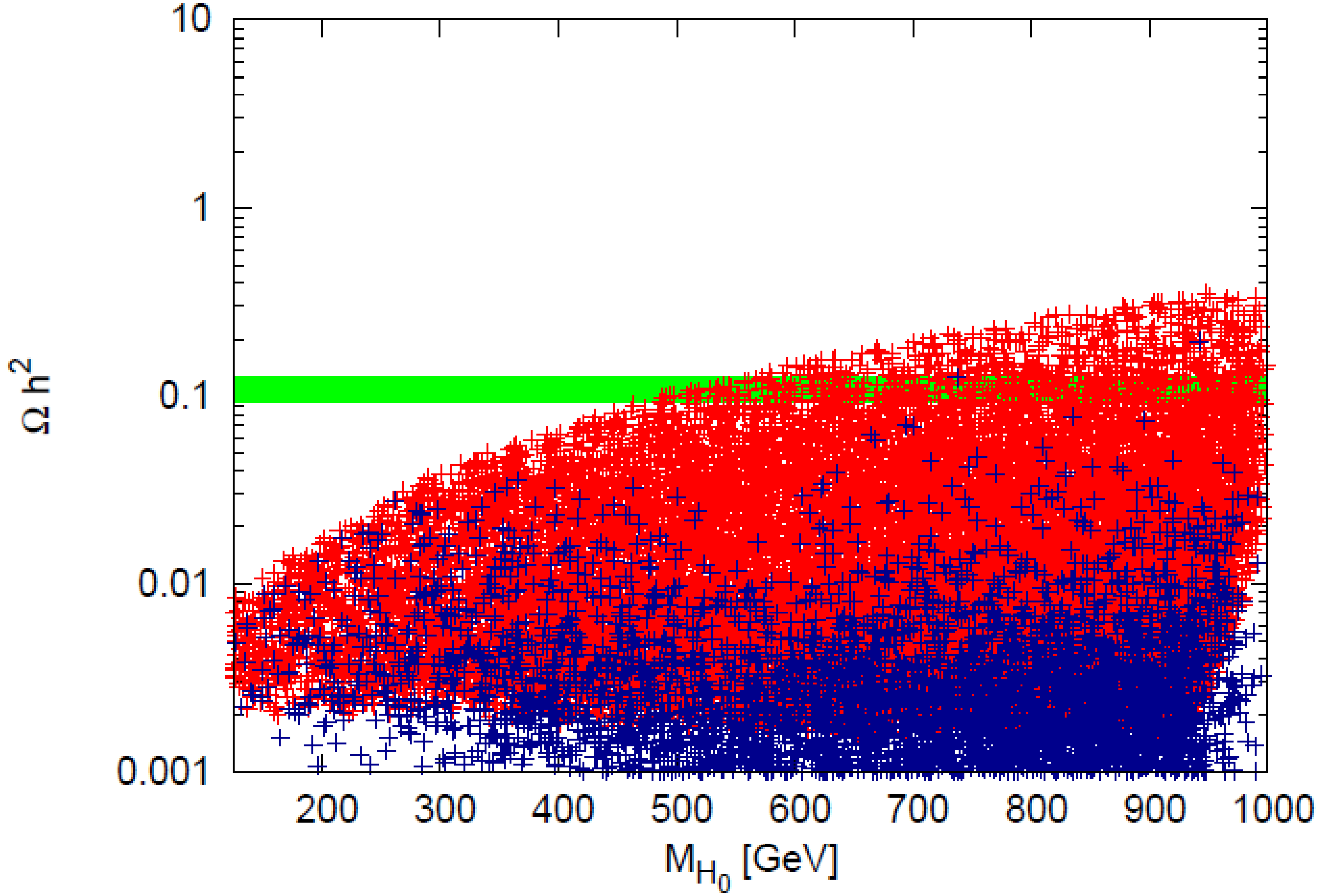
resonance search (CMS.25.2.2013)



Bound on U(1)×U(1)' kinetic mixing (Hook,Izaguirre,Wacher)

$$\sin\xi \lesssim O(10^{-2}) \sim O(10^{-3})$$

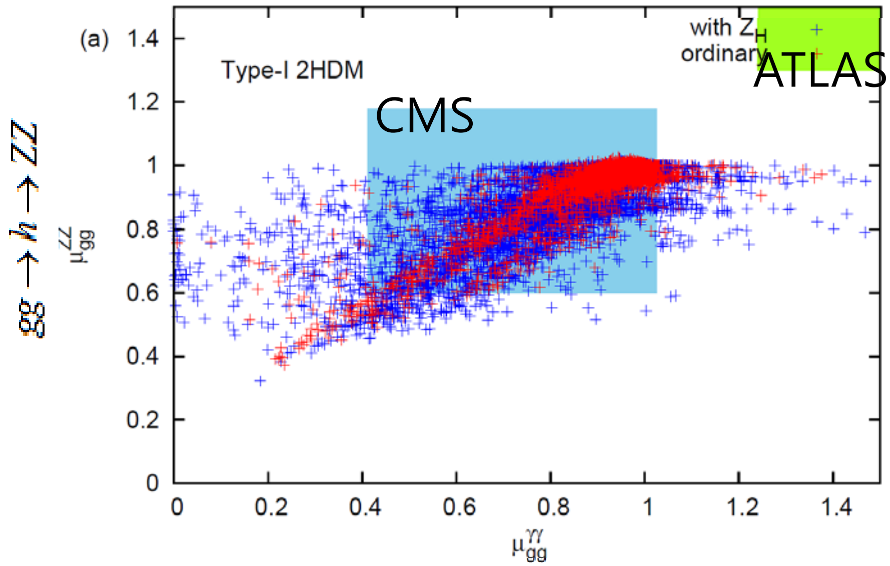
Heavy Higgs



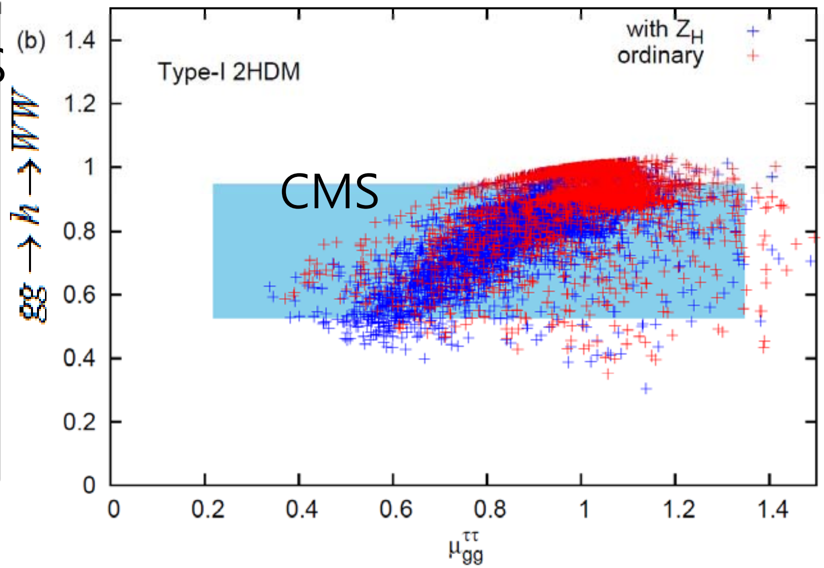
Type-I 2HDM with fermiophobic Z_H

- gg fusion

$(\alpha_1 = \alpha_2 = 0)$



$gg \rightarrow h \rightarrow \gamma\gamma$



$gg \rightarrow h \rightarrow \tau\tau$

2HDM with fermiophobic Z_H

- realized with u=d=0 and assume $\alpha_1 = \alpha_2 = 0$.

- Z_H can mix with the Z boson.

$$M^2 = \begin{pmatrix} g_Z^2 v^2 & -g_Z g_H (h_1 v_1^2 + h_2 v_2^2) \\ -g_Z g_H (h_1 v_1^2 + h_2 v_2^2) & g_H^2 (h_1^2 v_1^2 + h_2^2 v_2^2) \end{pmatrix}$$

- affects EWPOs and Drell-Yan process.

- requires that corrections to the most sensitive variables are within the errors of the SM prediction.

$$\rho_{\rm 2HDM}^{\rm tree} = 1 + \frac{\Delta M_{ZZ_H}^2}{M_{Z0}^2}\xi, \text{ where } \rho_{\rm SM} = 1.01051 \pm 0.00011.$$

$$\Gamma_Z = 2.4961 \pm 0.0010 \text{ GeV}.$$

- requires $\xi < 10^{-3}$, which is safe for the Drell-Yan process at LHC.

- impose the constraints on S,T,U at the one-loop level.

Type-II 2HDM

- H_1 couples to the up-type fermions, while H_2 couples to the down-type fermions.

$$V_y = y_{ij}^U \bar{Q}_{Li} \tilde{H}_1 U_{Rj} + y_{ij}^D \bar{Q}_{Li} H_2 D_{Rj} + y_{ij}^E \bar{L}_i H_2 E_{Rj} + y_{ij}^N \bar{L}_i \tilde{H}_1 N_{Rj}$$

U_R	D_R	Q_L	L	E_R	N_R	H_1	H_2
u	0	0	0	0	u	u	0

- Requires extra chiral fermions for cancellation of gauge anomaly.

for example, $E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\chi \times U(1)_\psi$.

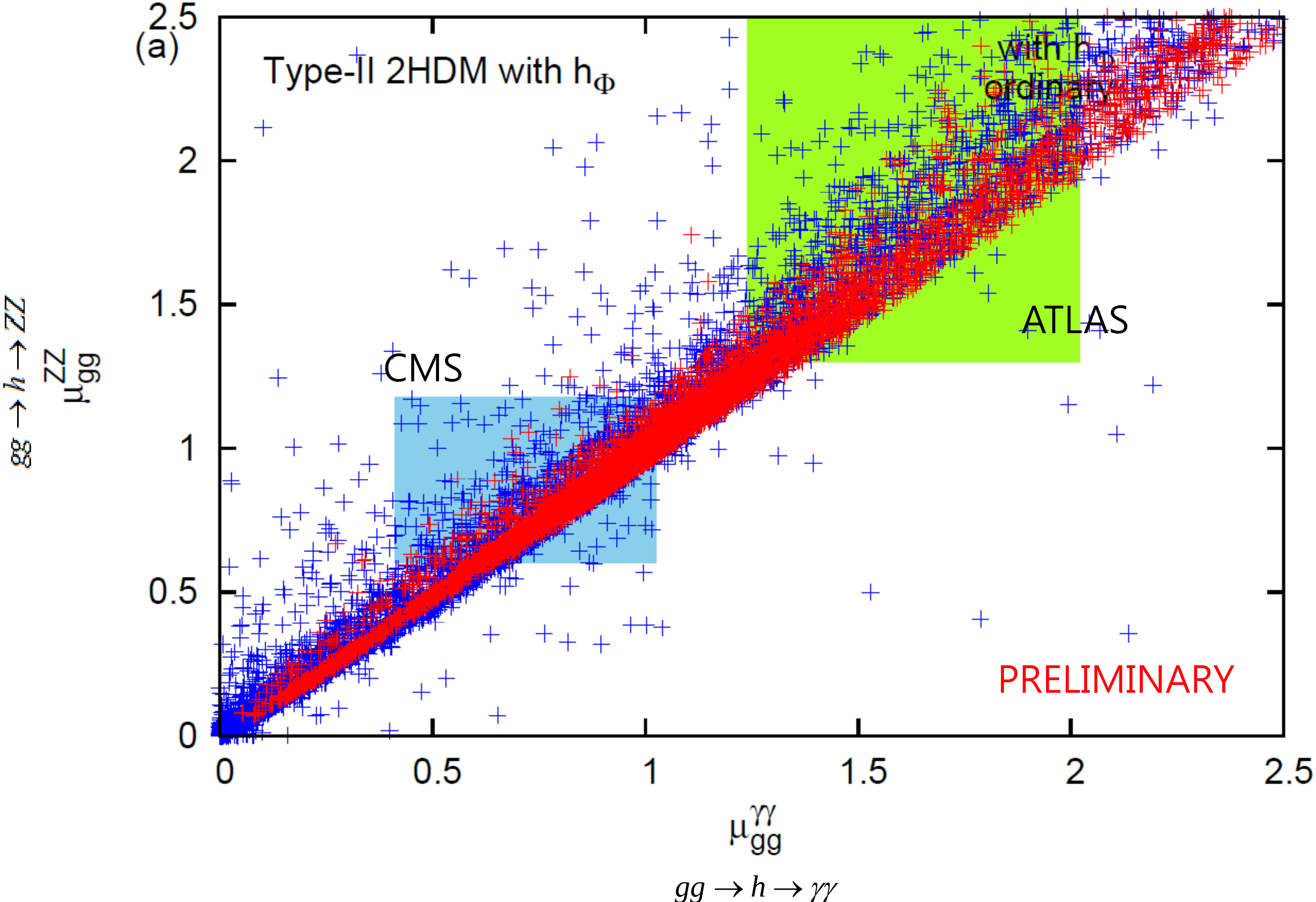
	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
Q^i	3	2	1/6	−1/3	1	−1	−2
U_R^i	3	1	2/3	2/3	−1	1	2
D_R^i	3	1	−1/3	−1/3	−1	−3	−1
L_i	1	2	−1/2	0	1	3	1
E_R^i	1	1	−1	0	−1	1	2
N_R^i	1	1	0	1	−1	5	5
H_1	1	2	1/2	0	2	2	−1
H_2	1	2	1/2	1	−2	2	4

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
q_L^i	3	1	−1/3	2/3	−2	2	4
q_R^i	3	1	−1/3	−1/3	2	2	−1
l_L^i	1	2	−1/2	0	−2	−2	1
l_R^i	1	2	−1/2	−1	2	−2	−4
n_L^i	1	1	0	−1	4	0	−5

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
Φ	1	1	0	1	−4	0	5

Type-II 2HDM with h_Φ

- gg fusion



Z_2 symmetry

- A simple way to avoid FCNC problem is to assign ad hoc Z_2 symmetry.

→ Natural Flavor Conservation (NFC). Glashow, Weinberg, PRD15, 1958 (1977)

Fermions of same electric charges get their masses from one Higgs VEV.

~ achieved by assigning new distinct charges to the two Higgs doublets as well as SM fermions.

$$Z_2 : (H_1, H_2) \to (+H_1, -H_2)$$

- Type II : $V_y = y_{ij}^U \bar{Q}_{Li} \tilde{H}_1 U_{Rj} + y_{ij}^D \bar{Q}_{Li} H_2 D_{Rj} + y_{ij}^E \bar{L}_i H_2 E_{Rj} + y_{ij}^N \bar{L}_i \tilde{H}_1 N_{Rj}$

Type	H_1	H_2	U_R	D_R	E_R	N_R	Q_L, L
I	+	−	+	+	+	+	+
II	+	−	+	−	−	+	+
X	+	−	+	+	−	−	+
Y	+	−	+	−	+	−	+