New viewpoints about 2HDM's

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After the Higgs boson discovery, we are deeply depressed

- What would be the next ?

- Let me experiment with new ideas (not on SUSY, RS, (partially) composite Higgs boson, etc..), while waiting for exciting news from various experiments/observations

- Personal favorite : (chiral) gauge principle, (local) scale invariance for gravity (Weyl quadratic gravity) in particle physics and cosmology

- Note that local gauge principle, general covariance and Equivalent principle are extremely well tested in many different circumstances

Contents

Ingredients of the extremely successful SM

SM Lagrangian

$$
\begin{aligned}
\mathcal{L}_{MSM} = & -\frac{1}{2g_s^2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu} \\
& -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} + i\frac{\theta}{16\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + M_{Pl}^2 R \\
& +|D_\mu H|^2 + \bar{Q}_i i\not{D} Q_i + \bar{U}_i i\not{D} U_i + \bar{D}_i i\not{D} D_i \\
& +\bar{L}_i i\not{D} L_i + \bar{E}_i i\not{D} E_i - \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2 \\
& -\left(h_u^{ij} Q_i U_j \tilde{H} + h_d^{ij} Q_i D_j H + h_l^{ij} L_i E_j H + c.c.\right) . (1)
\end{aligned}
$$

Based on local gauge principle

- Only Higgs (~SM) and Nothing Else so far at the LHC (No SUSY, KK, etc..)
- Our perception for the fine tuning problem is to be modified (revised) ???
- Nature is surely described by Local Gauge Theories and QFT works
- All the observed particles carry some gauge charges (no gauge singlets observed so far)
- And no higher dim representations for matter fields (gauge fields~adj)

Phenomonological Motivations for BSM

- Neutrino masses and mixings
- Baryogenesis — Leptogenesis & many other ways
- Inflation (inflaton) — Starobinsky ? Higgs Inflations
- Nonbaryonic DM — Many candidates for CDM
- Origin of EWSB and Cosmological Const ?

Can we attack these problems ?

Ingredients of the SM

- Success of the Standard Model of Particle Physics lies in Poincare sym + “local gauge symmetry” without imposing any internal global symmetries
- electron stability : U(1)em gauge invariance, electric charge conservation
- proton longevity : baryon # is an accidental sym; proton composite
- No gauge singlets in the SM ; all the SM fermions chiral
- Only fundamental rep’s

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P, C invariance of low energy QED, QCD : accidental sym of the SM

SM vs. DM models

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- electron stability : U(1)em gauge invariance, electric charge conservation
- proton longevity : baryon # is an accidental sym; proton composite
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- Dark sector with (excited) dark matter, dark radiation and force mediators might have the same structure as the SM
- “Chiral dark gauge theories without any global sym”
- Origin of DM stability/ longevity from dark gauge sym, and not from dark global symmetries, as in the SM
- Just like the SM (conservative)

In QFT

- DM could be absolutely stable due to unbroken local gauge symmetry (DM with local Z_2, Z_3 etc.) or topology (hidden sector monopole + vector DM + dark radiation)
- Longevity of DM could be due to some accidental symmetries (hidden sector pions and baryons)
- In any case, DM models with local dark gauge symmetry ~ the success of the SM

Examples of importance of gauge symmetry in DM physics

WIMP with ad hoc Z2 sym

- Global sym. is not enough since

$$-\mathcal{L}_{\rm int} = \begin{cases} \lambda \frac{\phi}{M_{\rm P}} F_{\mu\nu} F \mu\nu & \text{for boson} \\ \lambda \frac{1}{M_{\rm P}} \bar{\psi} \gamma^{\mu} D_{\mu} \ell_{Li} H^{\dagger} & \text{for fermion} \end{cases}$$

Observation requires [M.Ackermann et al. (LAT Collaboration), PRD 86, 022002 (2012)]

$$\tau_{\rm DM} \gtrsim 10^{26-30} {\rm sec} \Rightarrow \begin{cases} m_{\phi} \lesssim \mathcal{O}(10){\rm keV} \\ m_{\psi} \lesssim \mathcal{O}(1){\rm GeV} \end{cases}$$

$\Rightarrow$ WIMP is unlikely to be stable

- SM is guided by gauge principle

It looks natural and may need to consider a gauge symmetry in dark sector, too.

Why Dark Symmetry ?

- Is DM absolutely stable or very long lived ?
- If DM is absolutely stable, one can assume it carries a new conserved dark charge, associated with unbroken dark gauge sym
- DM can be long lived (lower bound on DM lifetime is much weaker than that on proton lifetime) if dark sym is spontaneously broken

Higgs is harmful to weak scale DM stability

Z_2 sym Scalar DM

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_S}{4!} S^4 - \frac{\lambda_{SH}}{2} S^2 H^\dagger H.$$

- Very popular alternative to SUSY LSP
- Simplest in terms of the # of new dof's
- But, where does this Z2 symmetry come from ?
- Is it Global or Local ?

Fate of CDM with Z_2 sym

- Global Z_2 cannot save EW scale DM from decay with long enough lifetime

Consider Z_2 breaking operators such as

$$\frac{1}{M_{\text{Planck}}} S O_{\text{SM}}$$

keeping dim-4 SM operators only

The lifetime of the Z_2 symmetric scalar CDM S is roughly given by

$$\Gamma(S) \sim \frac{m_S^3}{M_{\text{Planck}}^2} \sim \left(\frac{m_S}{100\text{GeV}}\right)^3 10^{-37} GeV$$

The lifetime is too short for ~100 GeV DM

Fate of CDM with Z2 sym

Spontaneously broken local U(1)X can do the job to some extent, but there is still a problem

Let us assume a local $U(1)_X$ is spontaneously broken by $\langle \phi_X \rangle \neq 0$ with

$$Q_X(\phi_X) = Q_X(X) = 1$$

Then, there are two types of dangerous operators:

$\phi_X^\dagger X H^\dagger H,$ and $\phi_X^\dagger X O_{\rm SM}^{(dim-4)}$

Problematic !

Perfectly fine !

- These arguments will apply to DM models based on ad hoc symmetries (Z_2,Z_3 etc.)
- One way out is to implement Z_2 symmetry as local U(1) symmetry (arXiv:1407.6588 with Seungwon Baek and Wan-Il Park);
- See a paper by Ko and Tang on local Z_3 scalar DM, and another by Ko, Omura and Yu on inert 2HDM with local $U(1)_H$
- DM phenomenology richer and DM stability/ longevity on much solider ground

arXiv:1407.6588 w/ WIPark and SBaek

$$Q_X(\phi) = 2, \quad Q_X(X) = 1$$

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} + -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\epsilon X_{\mu\nu}B^{\mu\nu} + D_\mu\phi_X^\dagger D^\mu\phi_X - \frac{\lambda_X}{4}\left(\phi_X^\dagger\phi_X - v_\phi^2\right)^2 + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X \\ &- \frac{\lambda_X}{4}\left(X^\dagger X\right)^2 - \left(\mu X^2\phi^\dagger + H.c.\right) - \frac{\lambda_{XH}}{4}X^\dagger X H^\dagger H - \frac{\lambda_{\phi_X H}}{4}\phi_X^\dagger\phi_X H^\dagger H - \frac{\lambda_{XH}}{4}X^\dagger X\phi_X^\dagger\phi_X\end{aligned}$$

The lagrangian is invariant under $X \to -X$ even after $U(1)_X$ symmetry breaking.

Unbroken Local Z2 symmetry

Gauge models for excited DM

$$X_R \to X_I\gamma_h^* \quad \text{followed by} \quad \gamma_h^* \to \gamma \to e^+e^-$$ etc.

The heavier state decays into the lighter state

The local Z2 model is not that simple as the usual Z2 scalar DM model (also for the fermion CDM)

Model Lagrangian

$$q_X(X, \phi) = (1, 2)$$

[1407.6588, Seungwon Baek, P. Ko & WIP]

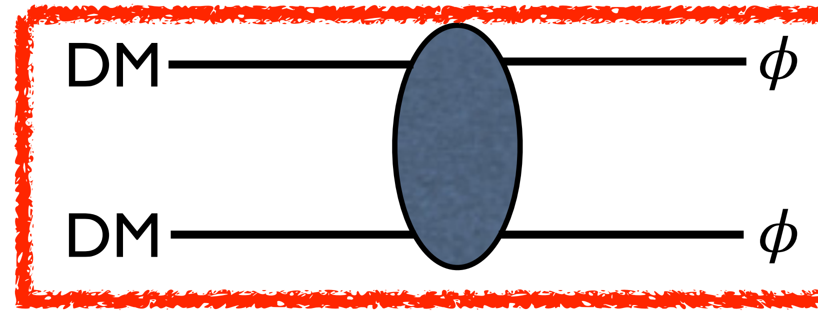
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon \hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D_\mu\phi D^\mu\phi + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X + m_\phi^2 \phi^\dagger\phi$$
$$-\lambda_\phi \left(\phi^\dagger\phi\right)^2 - \lambda_X \left(X^\dagger X\right)^2 - \lambda_{\phi X} X^\dagger X \phi^\dagger\phi - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H - \lambda_{HX} X^\dagger X H^\dagger H - \mu\left(X^2\phi^\dagger + H.c.\right).$$

- X : scalar DM (XI and XR, excited DM)
- phi : Dark Higgs
- X_mu : Dark photon
- 3 more fields than Z2 scalar DM model
- Z2 Fermion DM can be worked out too

- Some DM models with Higgs portal

  - ➢ Vector DM with Z2 [1404.5257, P. Ko, WIP & Y. Tang]

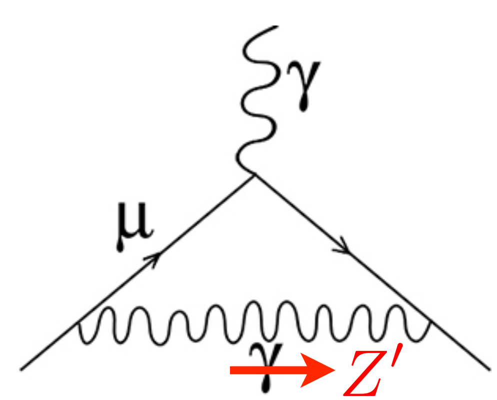
$$\mathcal{L}_{VDM} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \lambda_\Phi\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right),$$



  - ➢ Scalar DM with local Z2 [1407.6588, Seungwon Baek, P. Ko & WIP]

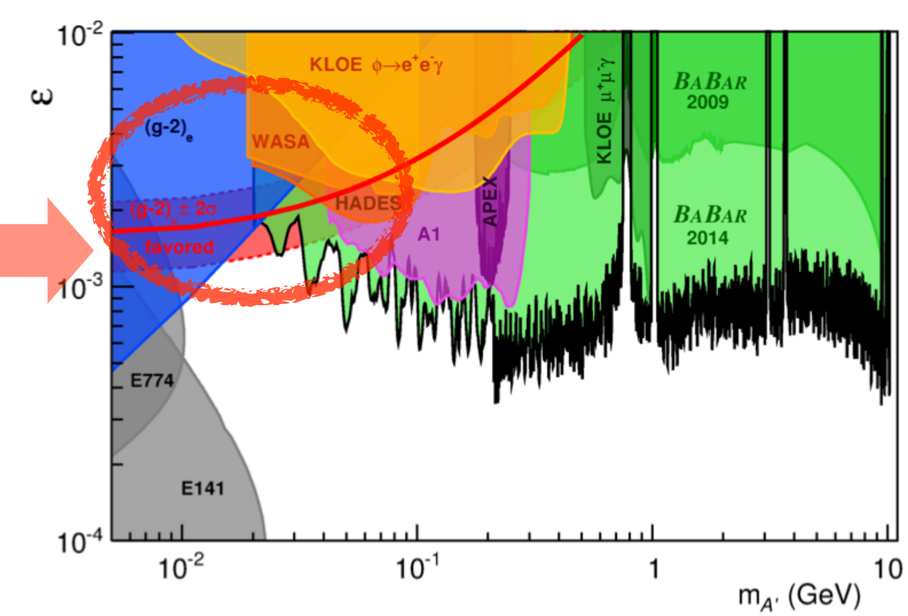
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D_\mu\phi D^\mu\phi + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X + m_\phi^2\phi^\dagger\phi - \lambda_\phi\left(\phi^\dagger\phi\right)^2 - \lambda_X\left(X^\dagger X\right)^2 - \lambda_{\phi X}X^\dagger X\phi^\dagger\phi - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H - \lambda_{HX}X^\dagger X H^\dagger H - \mu\left(X^2\phi^\dagger + H.c.\right)$$

    - muon (g-2) as well as GeV scale gamma-ray excess explained
    - natural realization of excited state of DM
    - free from direct detection constraint even for a light Z'



$$\Delta a_\mu \approx \frac{\alpha_{\rm em}\epsilon^2}{2\pi\cos\theta_W^2}$$

(for $m_{Z'} \lesssim m_\mu$)



[1406.2980, BaBar collaboration]

Gauge symmetries for (Stable) Vector Dark Matter

- Phenomenological models : Lebedev, Lee, Mambrini (2012) VDM + Higgs portal (EFT); Farzan and Akbarieh (2012), Baek, Ko, Park, Senaha (2012), Duch, Grzadkowski, McGarrie (2015), renormalizable models for VDM

- Completely broken dark gauge symmetries : Hambye (2009) dark SU(2); Gross, Lebedev, Mambrini (2015) completely broken SU(2), SU(3) [VDM decays because of dim>=5 op's]

- Dark gauge sym with unbroken subgroups : Baek, Ko, Park (2013) SO(3) broken to SO(2)~U(1), hidden sector (or dark monopole) + stable VDM ; Ko and Tang (2016), SU(3) broken to SU(2), stable VDM + Non-Abelian DR

Higgs portal Vector DM

$$\mathcal{L} = -m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{4} H^\dagger H V_\mu V^\mu - \frac{\lambda_V}{4}(V_\mu V^\mu)^2$$

- Although this model looks renormalizable, it is not really renormalizable, since there is no agency for vector boson mass generation
- Need to a new Higgs that gives mass to VDM
- A complete model should be something like this:

$$\mathcal{L}_{VDM} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \frac{\lambda_\Phi}{4}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{H\Phi}\left(H^\dagger H - \frac{v_H^2}{2}\right)\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right) ,$$

$$\langle 0|\phi_X|0\rangle = v_X + h_X(x)$$

$X_\mu \equiv V_\mu$ here

- There appear a new singlet scalar h_X from phi_X , which mixes with the SM Higgs boson through Higgs portal
- The effects must be similar to the singlet scalar in the fermion CDM model, and generically true in the DM with dark gauge sym
- Important to consider a minimal renormalizable and unitary model to discuss physics correctly [Baek, Ko, Park and Senaha, arXiv:1212.2131 (JHEP)]
- Can accommodate GeV scale gamma ray excess from GC

New scalar improves EW vacuum stability

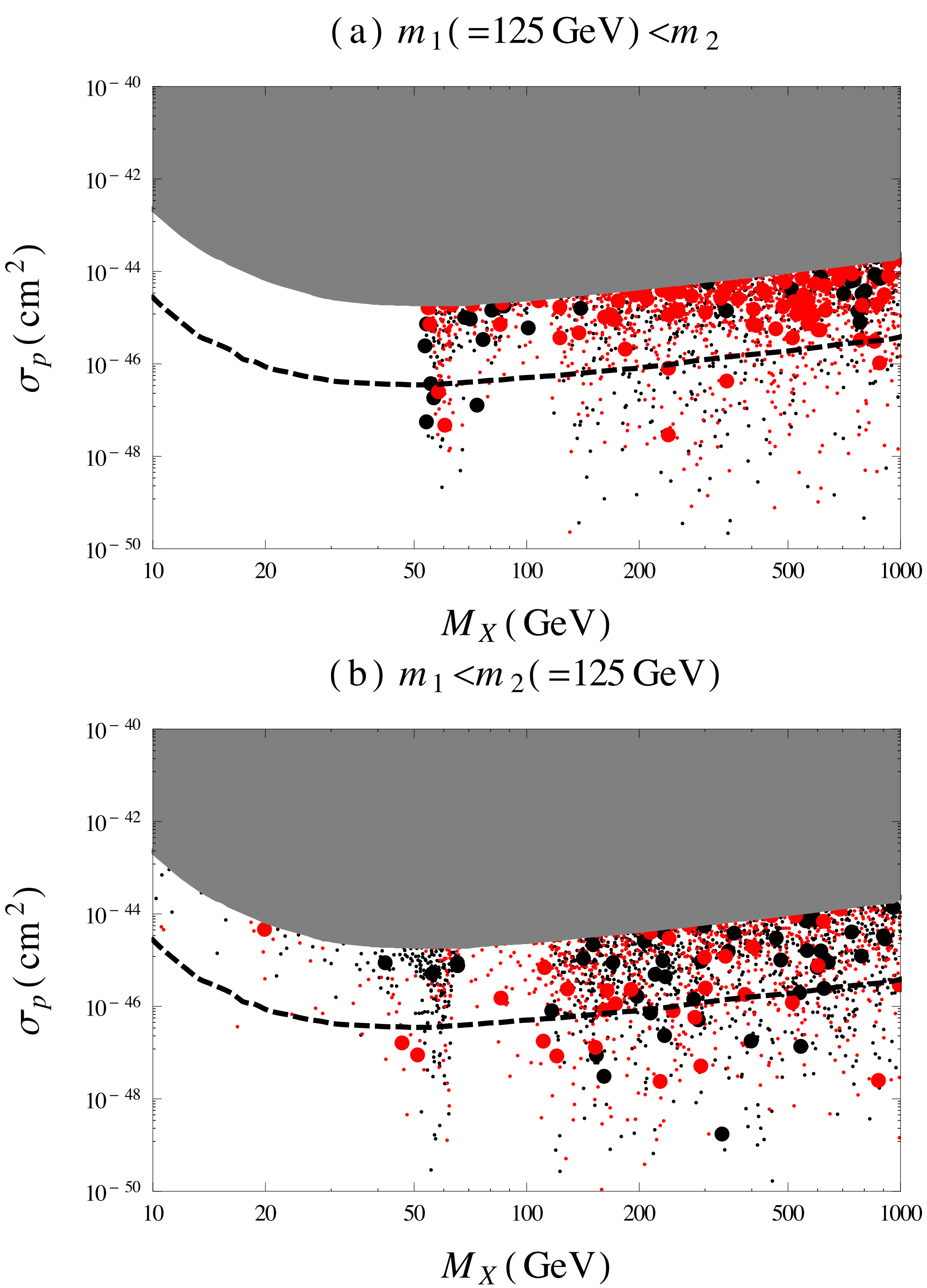


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7 (r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity of the next XENON experiment, XENON1T.

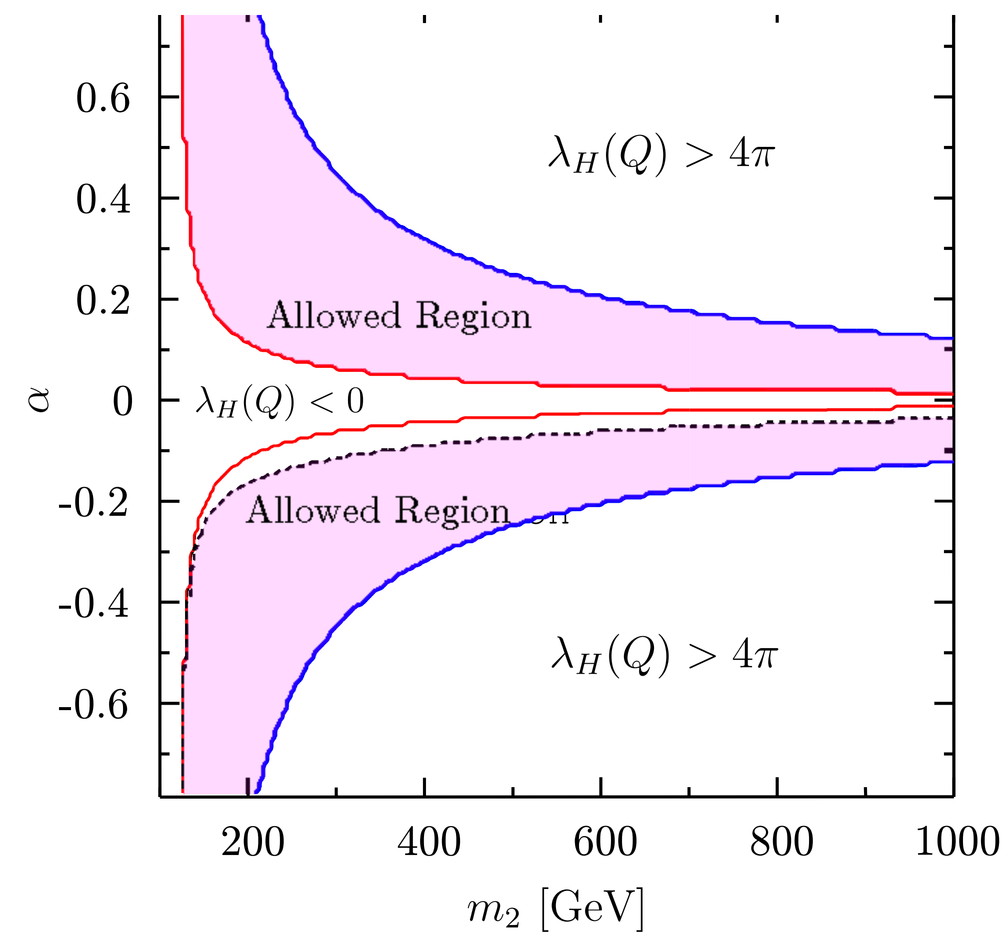


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

Higgs portal (EFT) no good

$$\mathcal{L}_{\text{scalar}} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4$$

$$\mathcal{L}_{\text{fermion}} = \overline{\psi}\left[i\gamma \cdot \partial - m_\psi\right]\psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \, \overline{\psi}\psi$$

$$\mathcal{L}_{\text{vector}} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu .$$

All invariant under ad hoc Z2 symmetry

arXiv:1112.3299, … 1402.6287, etc.

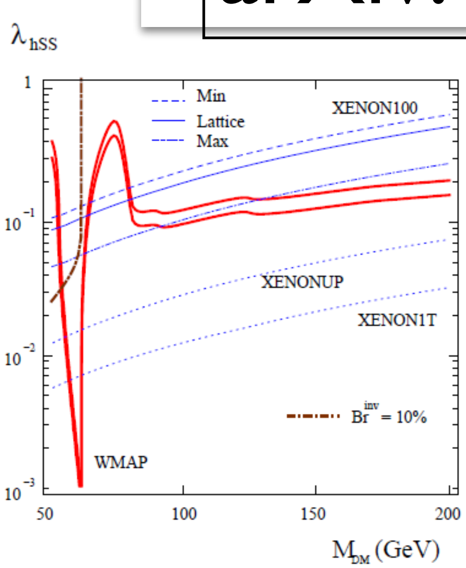


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

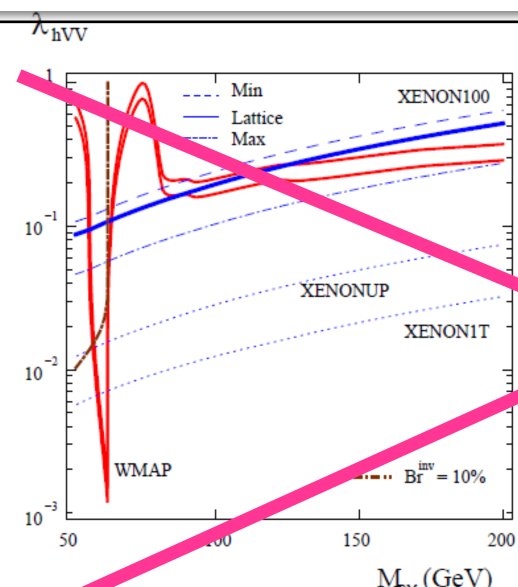


FIG. 2. Same as Fig. 1 for vector DM particles.

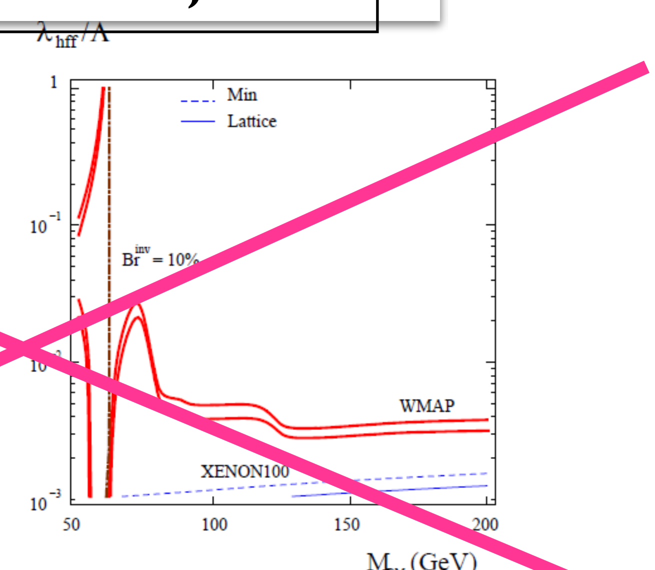


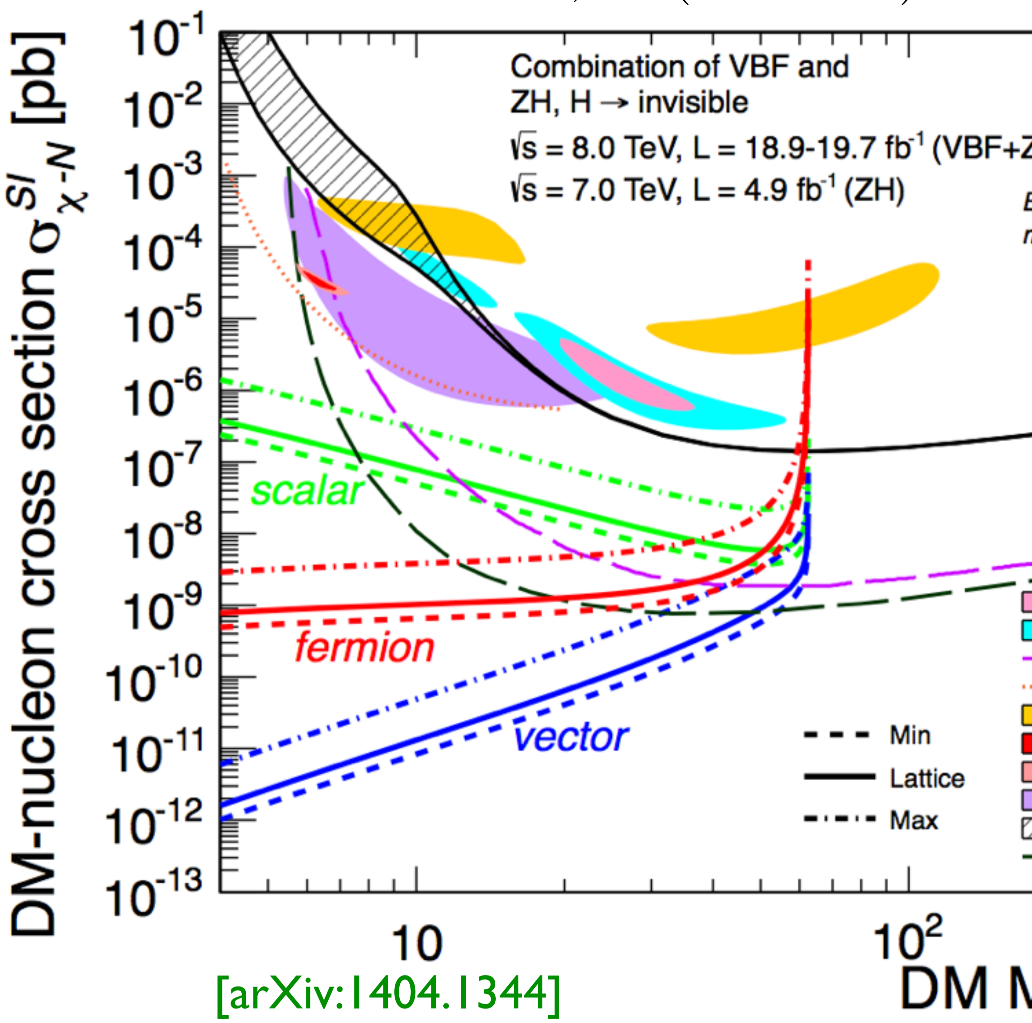
FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Is this any useful and/or important in phenomenology ?

YES !

Collider Implications

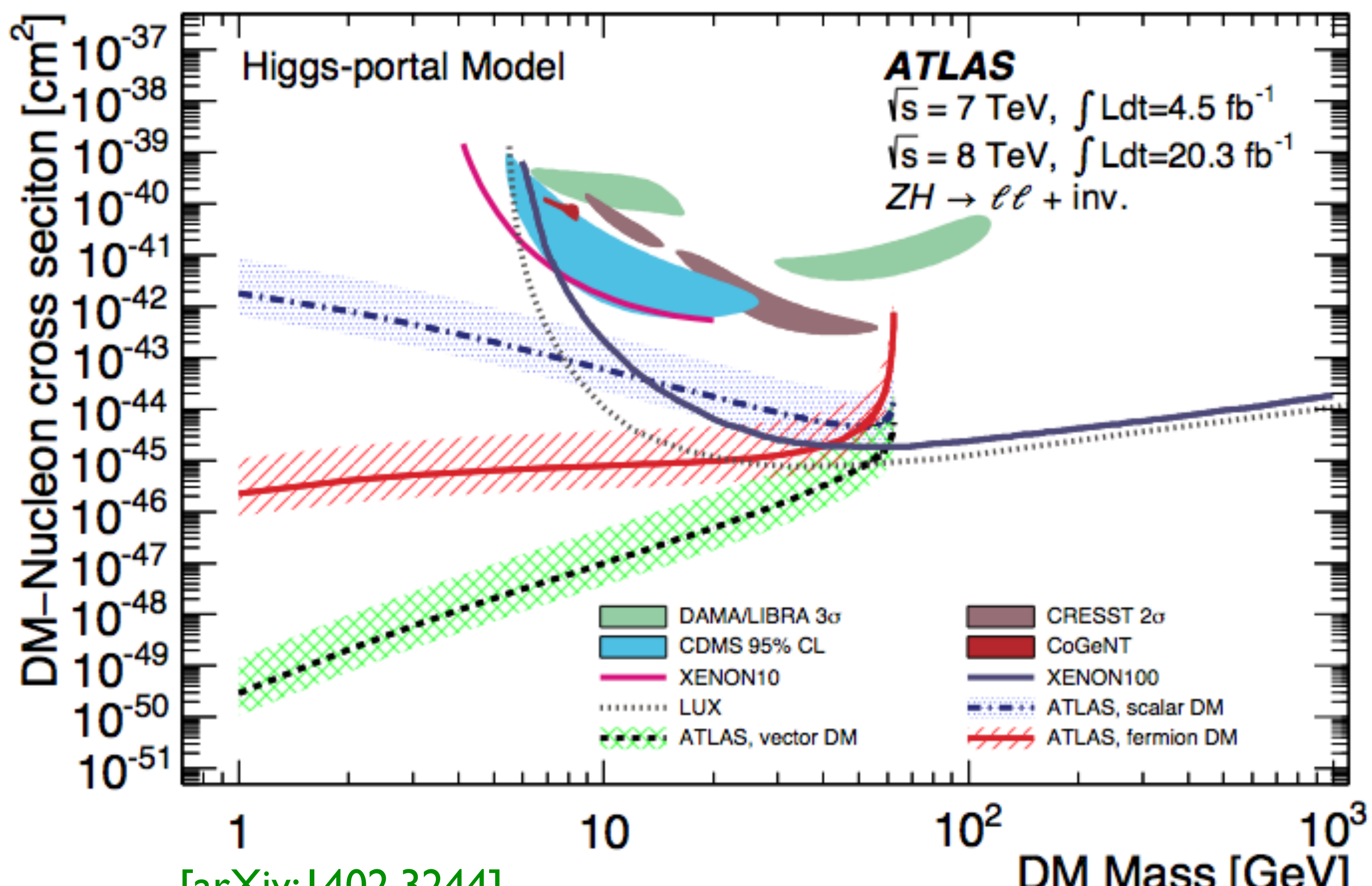
$m_h = 125\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.51 \text{ at } 90\% \text{ CL}$



[arXiv:1404.1344]

Based on EFTs

$m_h = 125.5\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.52 \text{ at } 90\% \text{ CL}$



[arXiv:1402.3244]

- However, in renormalizable unitary models of Higgs portals, **2 more relevant parameters**

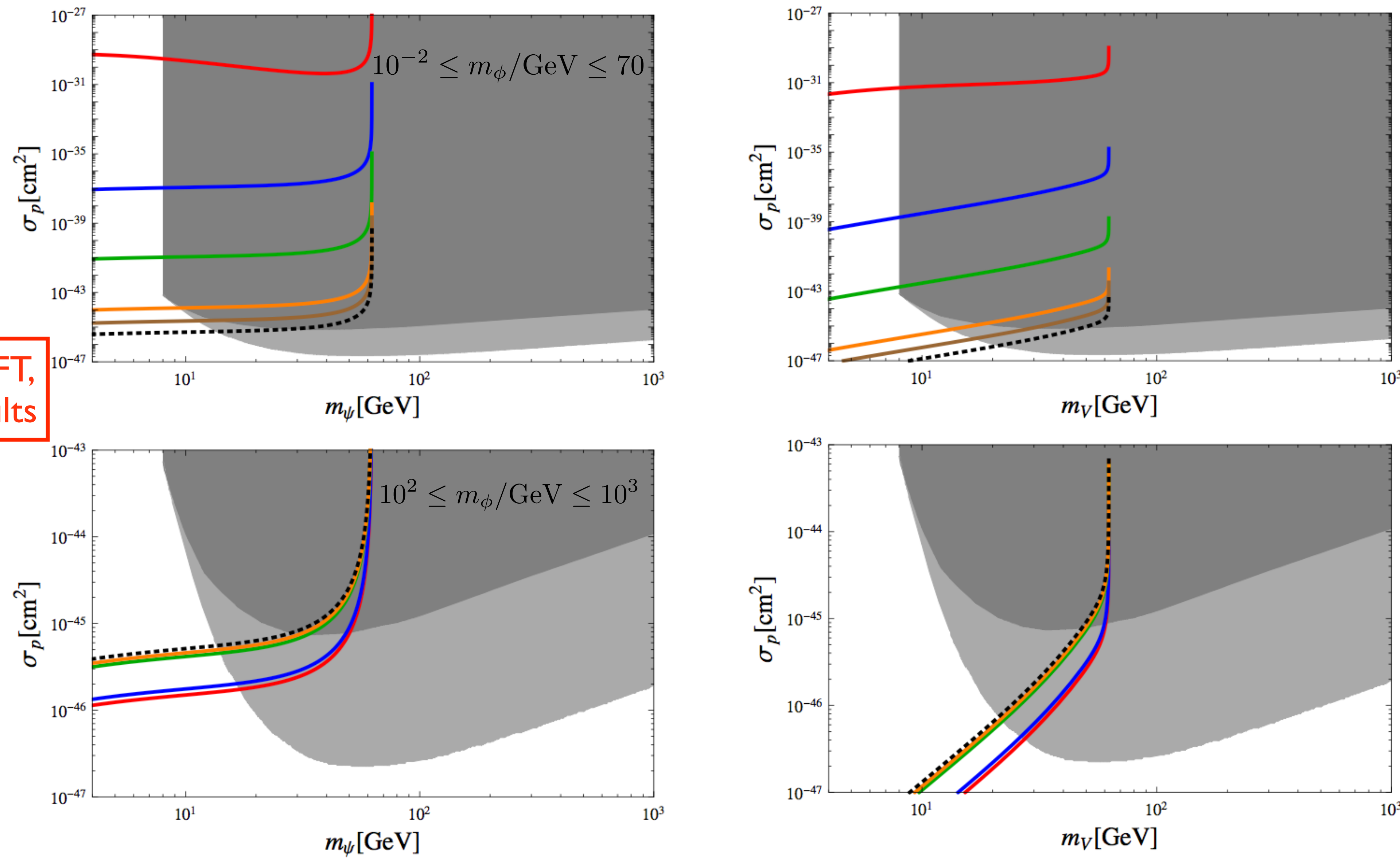
[arXiv: 1405.3530, S. Baek, P. Ko & WIPark, PRD]

$$\mathcal{L}_{\rm SFDM} = \overline{\psi}\left(i\partial - m_\psi - \lambda_\psi S\right) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu_S'}{3} S^3 - \frac{\lambda_S}{4} S^4.$$

$$\sigma_p^{\rm SI} = (\sigma_p^{\rm SI})_{\rm EFT}\, c_\alpha^4 m_h^4 \mathcal{F}(m_{\rm DM}, \{m_i\}, v) \simeq (\sigma_p^{\rm SI})_{\rm EFT}\, c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2$$

$$\mathcal{L}_{\rm VDM} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right)$$

Dashed curves:EFT, ATLAS,CMS results

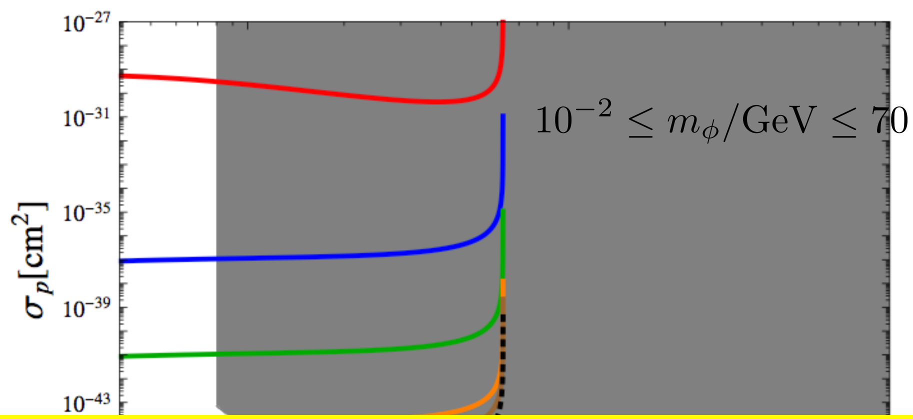


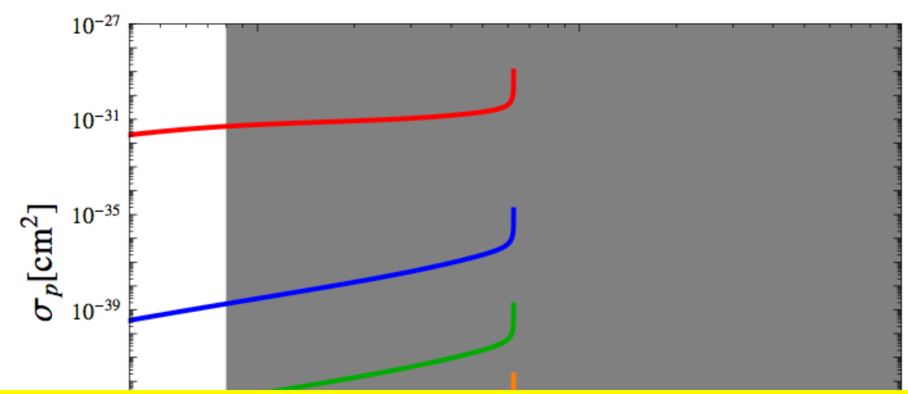
- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

$$\mathcal{L}_{\rm SFDM} = \overline{\psi}\left(i\partial - m_\psi - \lambda_\psi S\right) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu_S^3 S - \frac{\mu_S^{'}}{3} S^3 - \frac{\lambda_S}{4} S^4.$$

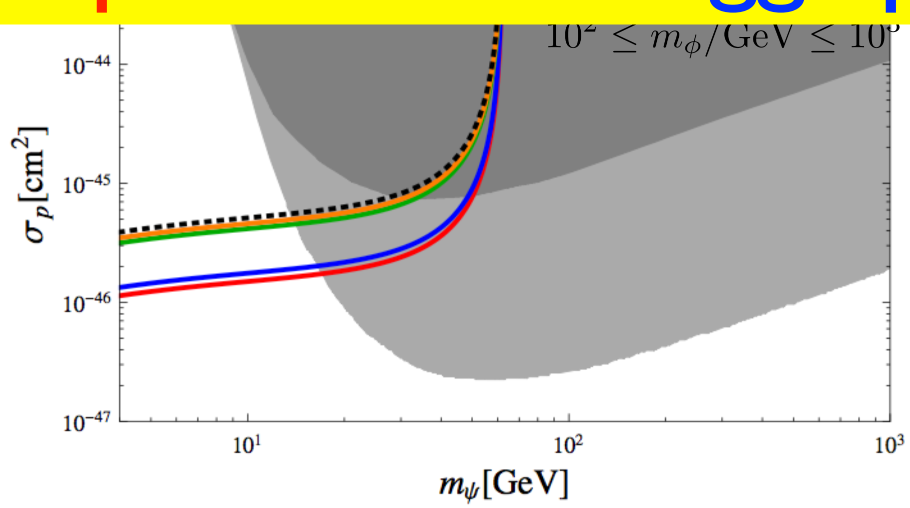
$$\sigma_p^{\rm SI} = (\sigma_p^{\rm SI})_{\rm EFT}\ c_\alpha^4 m_h^4 \mathcal{F}(m_{\rm DM}, \{m_i\}, v) \simeq (\sigma_p^{\rm SI})_{\rm EFT}\ c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2$$

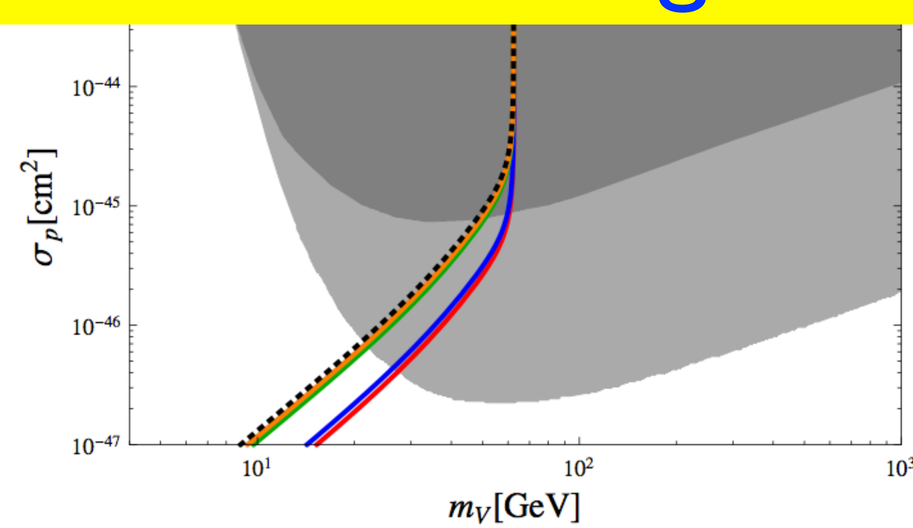
$$\mathcal{L}_{\rm VDM} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right)$$





Interpretation of collider data is quite model-dependent in Higgs portal DMs and in general





Invisible H decay into a pair of VDM

[arXiv: 1405.3530, S. Baek, P. Ko & WIPark, PRD]

$$(\Gamma_h^{\rm inv})_{\rm EFT} = \frac{\lambda_{VH}^2}{128\pi}\frac{v_H^2 m_h^3}{m_V^4} \times \left(1-\frac{4m_V^2}{m_h^2}+12\frac{m_V^4}{m_h^4}\right)\left(1-\frac{4m_V^2}{m_h^2}\right)^{1/2} \quad (23)$$

$m_V \propto g_x Q_\Phi v_\Phi$

$$\frac{g_X^2}{m_V^2} = \frac{g_X^2}{g_X^2 Q_\Phi^2 v_\Phi^2} \to \frac{1}{v_\Phi^2} = \text{finite}$$

VS.

$$\Gamma_i^{\rm inv} = \frac{g_X^2}{32\pi}\frac{m_i^3}{m_V^2}\left(1-\frac{4m_V^2}{m_i^2}+12\frac{m_V^4}{m_i^4}\right)\left(1-\frac{4m_V^2}{m_i^2}\right)^{1/2}\sin^2\alpha \quad (22)$$

Invisible H decay width : finite for small mV in unitary/renormalizable model

DM searches @ colliders : Beyond the EFT and simplified DM models

- S. Baek, P. Ko, M. Park, WIPark, C. Yu, arXiv:1506.06556, PLB (2016)
- P. Ko and Hiroshi Yokoya, arXiv:1603.04737, JHEP (2016)
- P. Ko, A. Natale, M. Park, H. Yokoya, arXiv:1605.07058, JHEP(2017)
- P. Ko and Jinmian Li, arXiv:1610.03997, PLB (2017)
- P. Ko, Gang Li, and Jinmian Li, arXiv:1807.06697, PRD (2018)

Why is it broken down in DM EFT ?

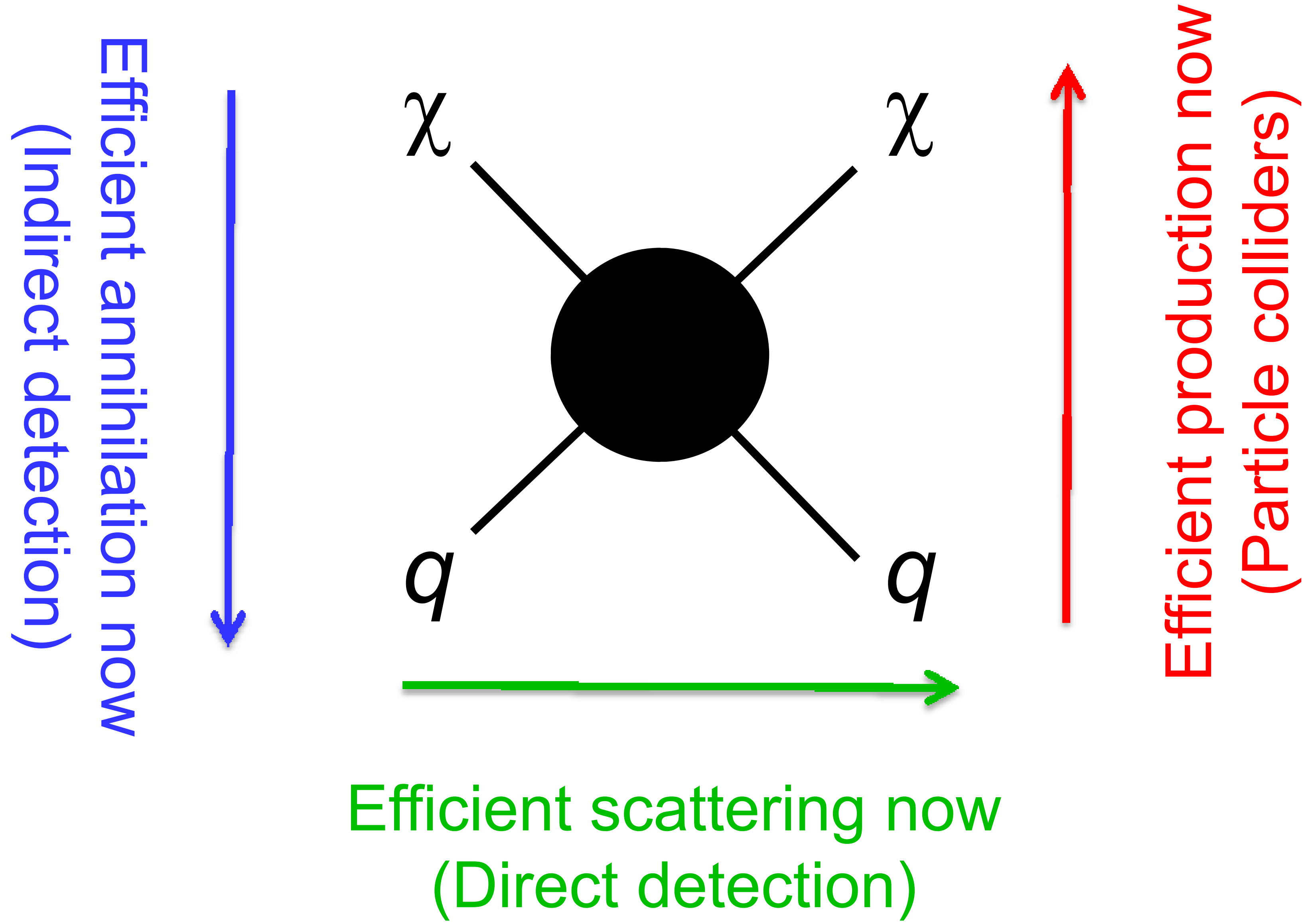
The most nontrivial example is the (scalar)x(scalar) operator for DM-N scattering

$$\mathcal{L}_{SS} \equiv \frac{1}{\Lambda_{dd}^2}\bar{q}q\bar{\chi}\chi \quad \text{or} \quad \frac{m_q}{\Lambda_{dd}^3}\bar{q}q\bar{\chi}\chi$$

This operator clearly violates the SM gauge symmetry, and we have to fix this problem

Crossing & WIMP detection

Correct relic density → Efficient annihilation then



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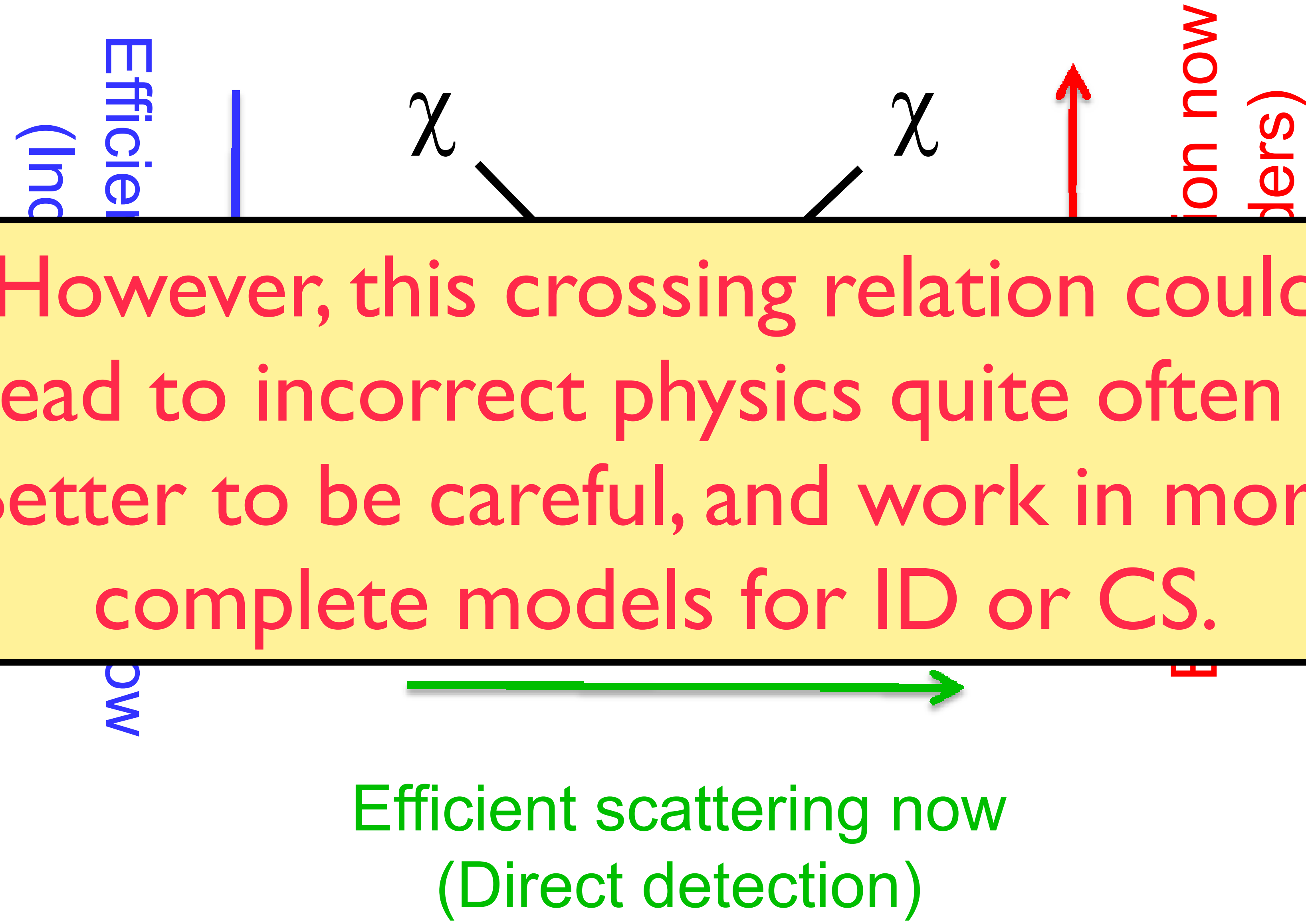


However, this crossing relation could lead to incorrect physics quite often ! Better to be careful, and work in more complete models for ID or CS.

Limitation and Proposal

- EFT is good for direct detection, but not for indirect or collider searches as well as thermal relic density calculations in general
- Issues : Violation of Unitarity and SM gauge invariance, Identifying the relevant dynamical fields at energy scale we are interested in, Symmetry stabilizing DM etc.

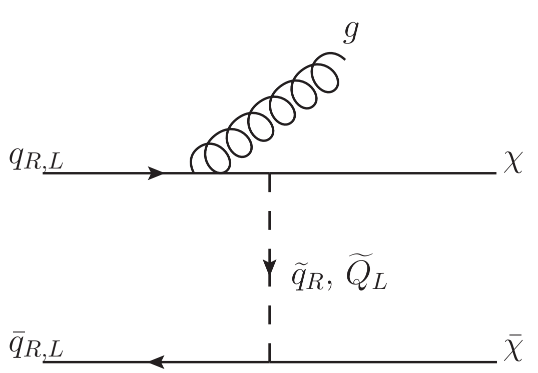
$$\frac{1}{\Lambda_i^2}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi \rightarrow \frac{g_q g_\chi}{m_\phi^2 - s}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi$$

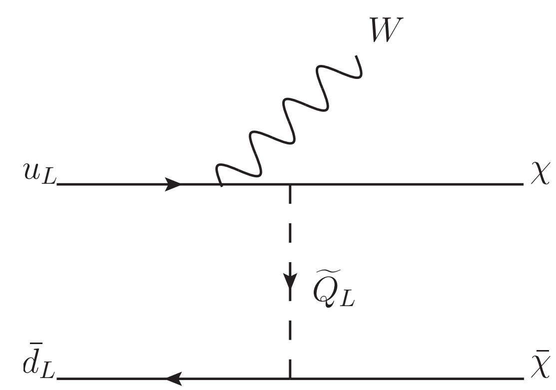
- Usually effective operator is replaced by a single propagator in simplified DM models
- This is not good enough, since we have to respect the full SM gauge symmetry (Bell et al for W+missing ET)
- In general we need two propagators, not one propagator, because there are two independent chiral fermions in 4-dim spacetime

arXiv:1605.07058 (with A. Natale, M.Park, H.Yokoya)

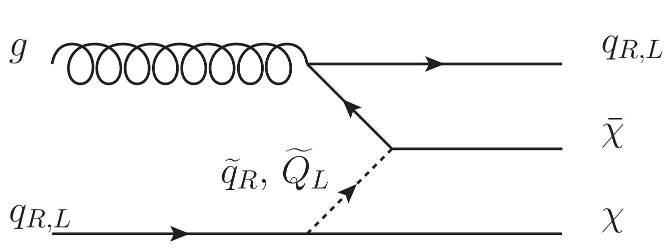
for t-channel mediator

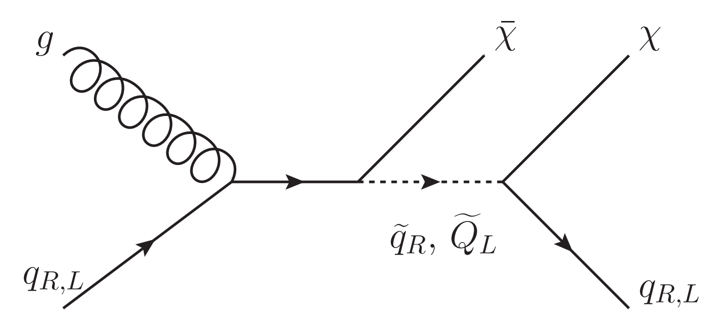
Our Model: a 'simplified model' of colored t-channel, spin-0, mediators which produce various mono-x + missing energy signatures (mono-Jet, mono-W, mono-Z, etc.):





W+missing ET : special





$$\frac{1}{\Lambda_i^2}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi \to \frac{g_q g_\chi}{m_\phi^2 - s}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi$$

- This is good only for W+missing ET, and not for other signatures
- The same is also true for (scalar)x(scalar) operator, and lots of confusion on this operator in literature
- Therefore let me concentrate on this case in detail in this talk

$$\overline{Q}_L H d_R \quad \text{or} \quad \overline{Q}_L \widetilde{H} u_R,$$ OK

$$h\bar{\chi}\chi, \qquad\qquad s\bar{q}q$$

Both break SM gauge

$$\mathcal{L} = \frac{1}{2}m_S^2 S^2 - \lambda_{s\chi} s\bar{\chi}\chi - \lambda_{sq} s\bar{q}q$$
$$\mathcal{L} = -\lambda_{h\chi} h\bar{\chi}\chi - \lambda_{hq} h\bar{q}q$$

Therefore these Lagragians often used in the literature are not good enough

$$s\bar{\chi}\chi \times h\bar{q}q \to \frac{1}{m_s^2}\bar{\chi}\chi\bar{q}q$$

Need the mixing between s and h

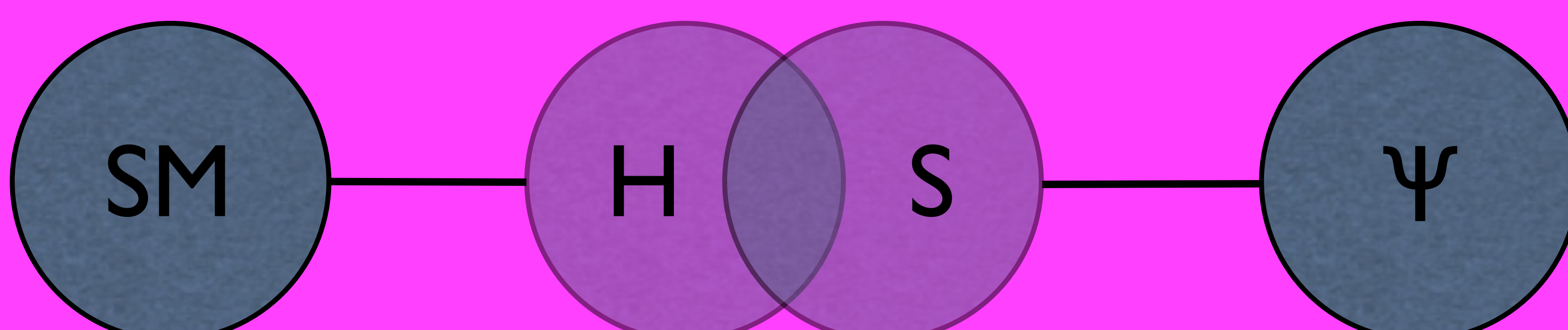
Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

$$
\begin{aligned}
\mathcal{L} \;=\; & \mathcal{L}_{\rm SM} - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\
& + \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \mu_S^3 S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4 \\
& + \overline{\psi}(i \not\partial - m_{\psi_0})\psi - \lambda S \overline{\psi}\psi
\end{aligned}
$$

mixing

invisible decay



Production and decay rates are suppressed relative to SM.

This simple model has not been studied properly !!

Full Theory Calculation

$$\chi(p) + q(k) \to \chi(p') + q(k')$$

$$\begin{aligned}
\mathcal{M} &= \overline{u(p')}u(p)\overline{u(q')}u(q)\ \frac{m_q}{v}\lambda_s \sin\alpha\cos\alpha\ \left[\frac{1}{t - m_{125}^2 + i m_{125}\Gamma_{125}} - \frac{1}{t - m_2^2 + i m_s \Gamma_2}\right] \\
&\to \overline{u(p')}u(p)\overline{u(q')}u(q)\ \frac{m_q}{2v}\lambda_s \sin 2\alpha \left[\frac{1}{m_{125}^2} - \frac{1}{m_2^2}\right] \\
&\to \overline{u(p')}u(p)\overline{u(q')}u(q)\ \frac{m_q}{2v}\lambda_s \sin 2\alpha \frac{1}{m_{125}^2} \equiv \frac{m_q}{\Lambda_{dd}^3}\overline{u(p')}u(p)\overline{u(q')}u(q)
\end{aligned}$$

$$\begin{aligned}
\Lambda_{dd}^3 &\equiv \frac{2 m_{125}^2 v}{\lambda_s \sin 2\alpha}\left(1 - \frac{m_{125}^2}{m_2^2}\right)^{-1} \\
\bar{\Lambda}_{dd}^3 &\equiv \frac{2 m_{125}^2 v}{\lambda_s \sin 2\alpha}
\end{aligned}$$

Monojet+missing ET

Can be obtained by crossing : s <>t

$$\frac{1}{\Lambda_{dd}^3} \to \frac{1}{\Lambda_{dd}^3}\left[\frac{m_{125}^2}{s-m_{125}^2+im_{125}\Gamma_{125}} - \frac{m_{125}^2}{s-m_2^2+im_2\Gamma_2}\right] \equiv \frac{1}{\Lambda_{col}^3(s)}$$

There is no single scale you can define
for collider search for missing ET

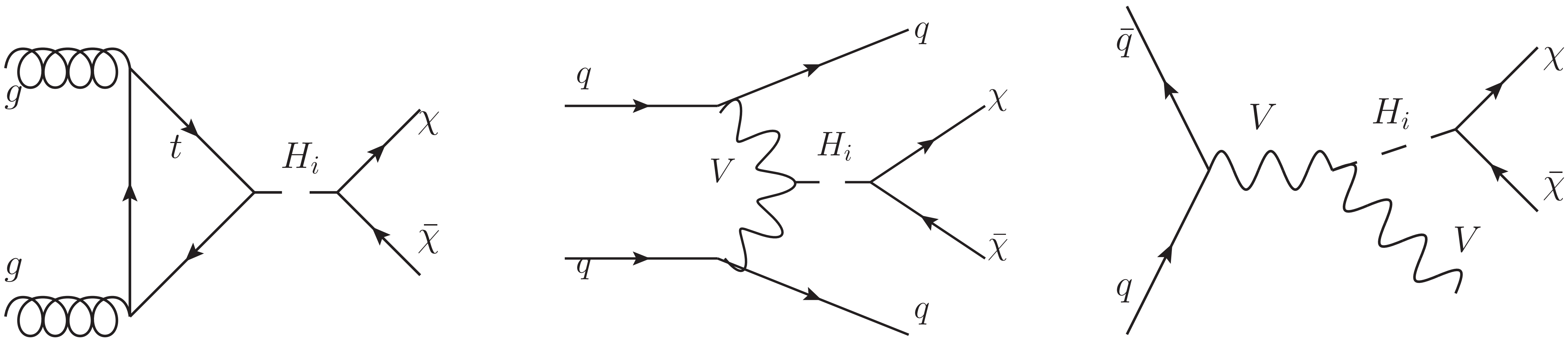


Figure 1: The dominant DM production processes at LHC.

Interference between 2 scalar bosons could be important in certain parameter regions

$$\frac{d\sigma_i}{dm_{\chi\chi}} \propto \left| \frac{\sin 2\alpha \; g_\chi}{m_{\chi\chi}^2 - m_{H_1}^2 + i m_{H_1}\Gamma_{H_1}} - \frac{\sin 2\alpha \; g_\chi}{m_{\chi\chi}^2 - m_{H_2}^2 + i m_{H_2}\Gamma_{H_2}} \right|^2$$

$$\boxed{\sin\alpha = 0.2, g_\chi = 1, m_\chi = 80\mathrm{GeV}}$$

Interference effects

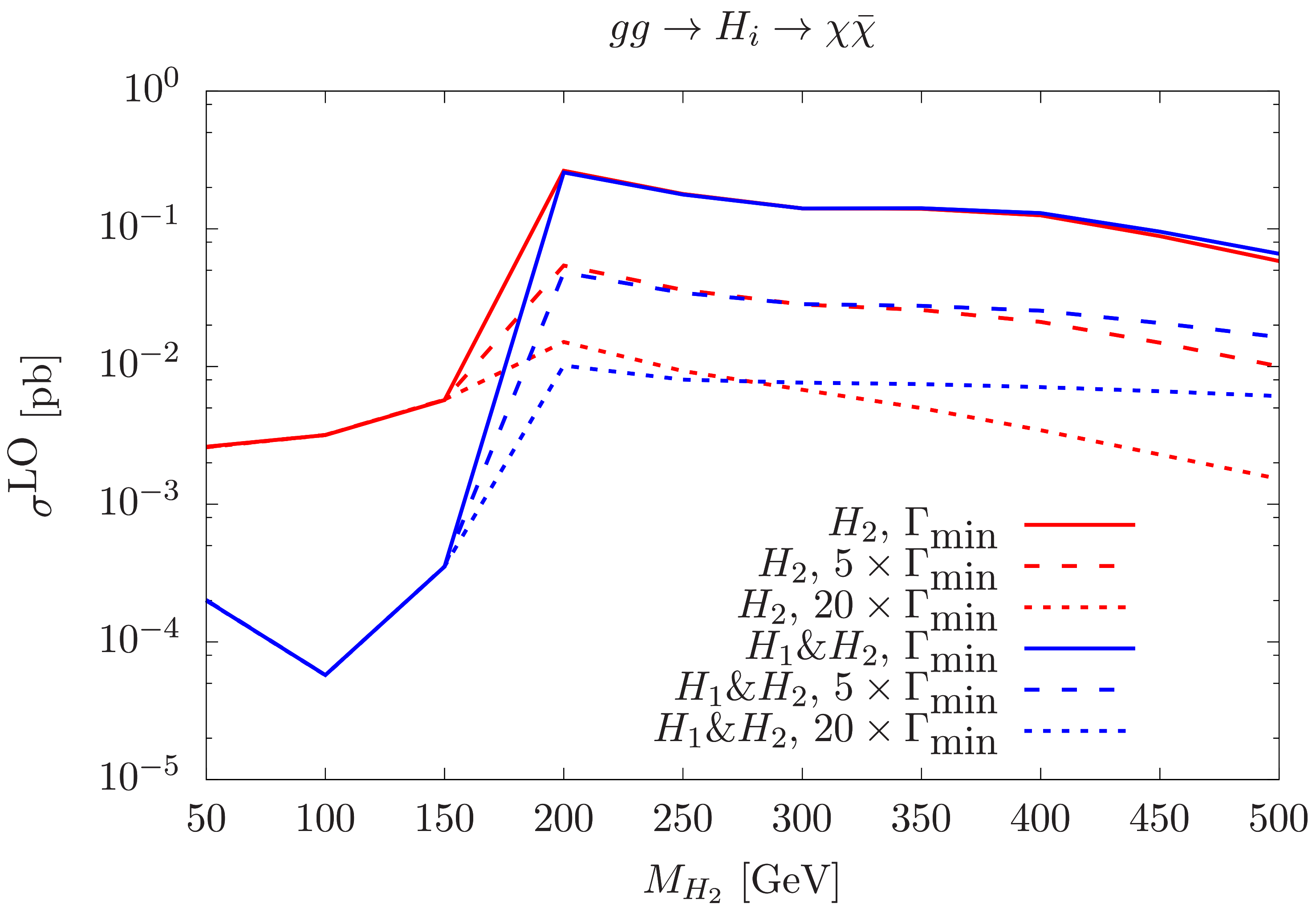


Figure 2: The LO cross section for gluon-gluon fusion process at 13 TeV LHC. The meanings of the different line types are explained in the text and the similar strategy will be used in all figures.

Exclusion limits with interference effects

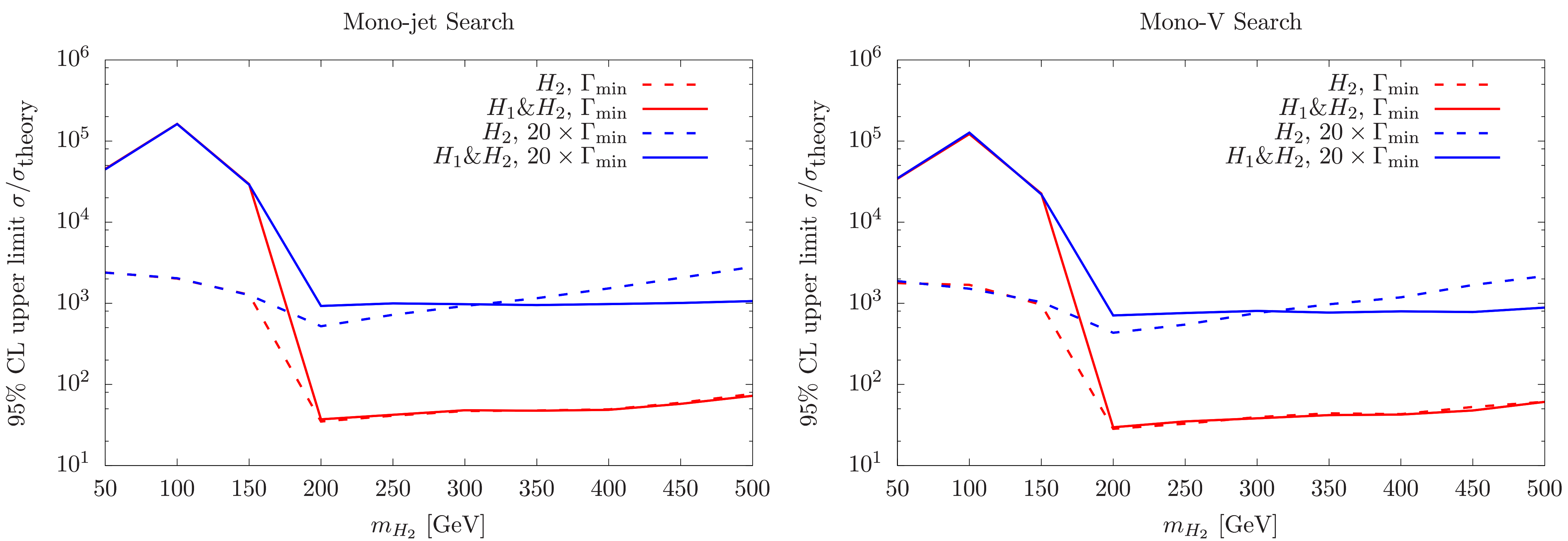


Figure 8: The CMS exclusion limits on our simplified models. Left: upper limit from mono-jet search. Right: upper limit from mono-V search.

- P. Ko and Jinmian Li, 1610.03997, PLB (2017)
- S. Baek, P. Ko and Jinmian Li, 1701.04131

- EFT : Effective operator $\mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}^3}\bar{q}q\bar{\chi}\chi$
- S.M.: Simple scalar mediator S of
  $\mathcal{L}_{int} = \left(\frac{m_q}{v_H}\sin\alpha\right) S\bar{q}q - \lambda_s \cos\alpha S\bar{\chi}\chi$
- H.M.: A case where a Higgs is a mediator
  $\mathcal{L}_{int} = -\left(\frac{m_q}{v_H}\cos\alpha\right) H\bar{q}q - \lambda_s \sin\alpha H\bar{\chi}\chi$
- H.P.: Higgs portal model as in eq. (2).

$$\text{H.P.} \underset{m_{H_2}^2 \gg \hat{s}}{\longrightarrow} \text{H.M.},$$
$$\text{S.M.} \underset{m_S^2 \gg \hat{s}}{\longrightarrow} \text{EFT},$$
$$\text{H.M.} \neq \text{EFT}\,.$$

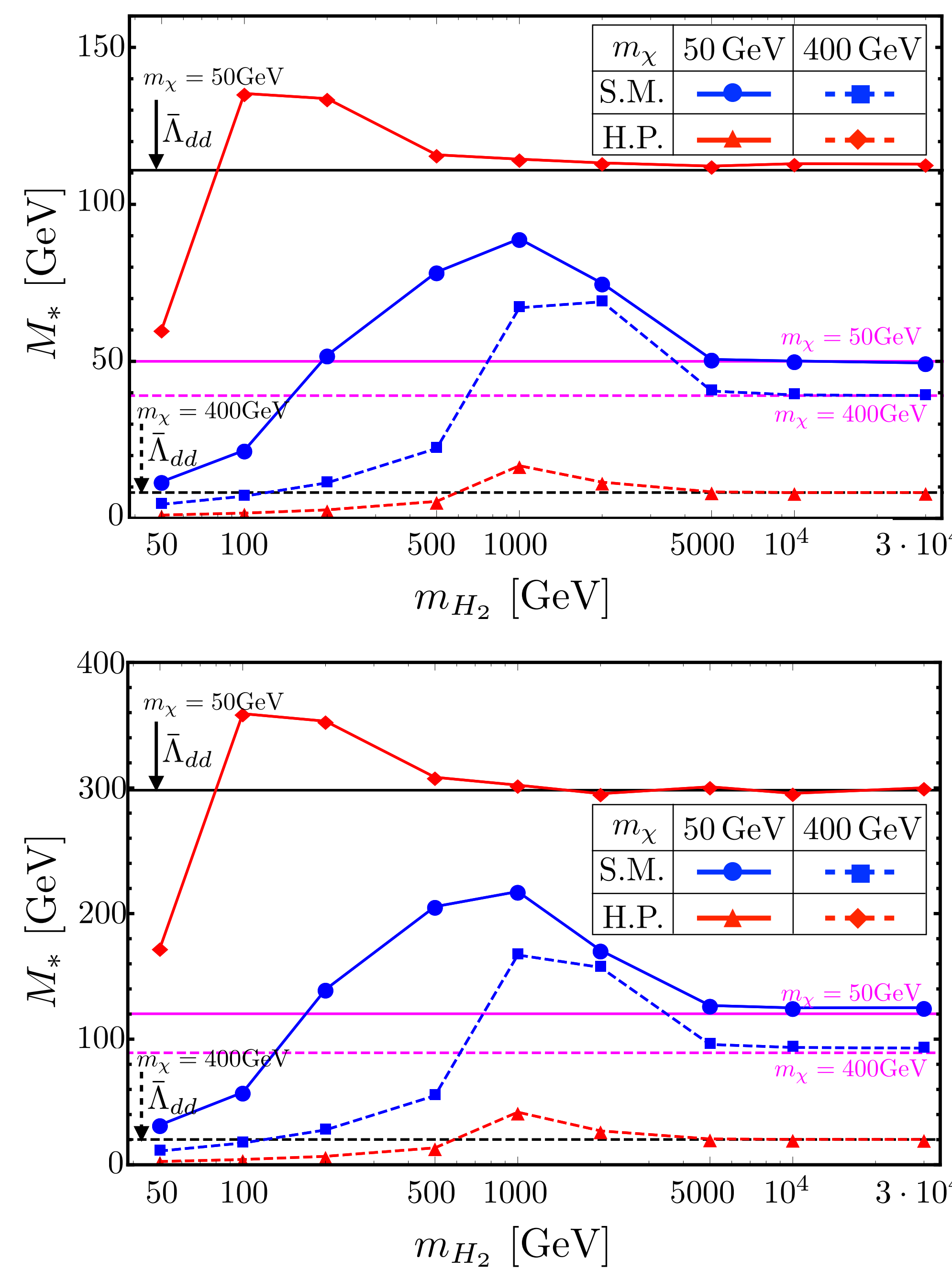


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t} + \not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of S.M., H.M., and H.P., are expressed in terms of the effective mass M_* through the Eq.(16)-(20). The solid and dashed lines correspond to $m_\chi = 50$ GeV and 400 GeV in each model, respectively.

Higgs Strahlung

$$e^+(p_1) + e^-(p_2) \to h^*(q) + Z(p_Z) \to S(k_1) + S(k_2) + Z(p_Z)$$

arXiv:1603.04737
w/ H. Yokoya

Differential cross section

$$\frac{d\sigma_{SD}}{dt} = \frac{1}{2\pi}\sigma_{h^*Z}(s,t) \cdot F_S(t)$$

$$\lambda_F = y_F \sin\alpha\cos\alpha.$$

$$\mu_V = \lambda_V m_D = 2m_D^2/v_\phi \cdot \sin\alpha\cos\alpha$$

$$F_S(t) = C_S \frac{\beta_D}{8\pi}\left|\frac{2\lambda_{HS}v}{t - m_h^2 + i m_h\Gamma_h}\right|^2$$

$$F_F(t) = C_F \lambda_F^2 \cdot \frac{\beta_D^3}{8\pi} \cdot 2t \cdot \left|\frac{1}{t - m_1^2 + i m_1\Gamma_1} - \frac{1}{t - m_2^2 + i m_2\Gamma_2}\right|^2$$

$$F_V(t) = C_V \frac{\beta_D}{8\pi} \cdot \frac{\mu_V^2 t^2}{4m_D^4}\left(1 - \frac{4m_D^2}{t} + \frac{12 m_D^4}{t^2}\right) \cdot \left|\frac{1}{t - m_1^2 + i m_1\Gamma_1} - \frac{1}{t - m_2^2 + i m_2\Gamma_2}\right|^2$$

General Comments

- One can calculate the collider signatures at high energy scale, since the amplitudes were obtained in renormalizable and unitary models for singlet fermion DM and VDM
- There are two scalar propagators for SFDM and VDM, because of the SM gauge sym, unitarity and renormalizability
- EFT results can be obtained only if H2 is much heavier than the ILC CM energy

Asymtotic behavior in the full theory

$$\text{ScalarDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \tag{5.7}$$

$$\text{SFDM}: \quad G(t) \sim \left|\frac{1}{t-m_1^2+im_1\Gamma_1} - \frac{1}{t-m_2^2+im_2\Gamma_2}\right|^2 \left(t-4m_\chi^2\right) \tag{5.8}$$

$$\to |\frac{1}{t^2}|^2 \times t \sim \frac{1}{t^3} \ (\text{as } t \to \infty) \tag{5.9}$$

$$\text{VDM}: \quad G(t) \sim \left|\frac{1}{t-m_1^2+im_1\Gamma_1} - \frac{1}{t-m_2^2+im_2\Gamma_2}\right|^2 \left[2 + \frac{(t-2m_V^2)^2}{4m_V^4}\right] \tag{5.10}$$

$$\to |\frac{1}{t^2}|^2 \times t^2 \sim \frac{1}{t^2} \ (\text{as } t \to \infty) \tag{5.11}$$

Asymptotic behavior w/o the 2nd Higgs (EFT)

$$\text{SFDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \left(t-4m_\chi^2\right)$$

$$\to \frac{1}{t} \ (\text{as } t \to \infty)$$

$$\text{VDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \left[2 + \frac{(t-2m_V^2)^2}{4m_V^4}\right]$$

$$\to \text{constant} \ (\text{as } t \to \infty)$$

Unitarity violated !

Asymtotic behavior in the full theory

$$\text{ScalarDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \tag{5.7}$$

$$\text{SFDM}: \quad G(t) \sim \left| \frac{1}{t - m_1^2 + i m_1 \Gamma_1} - \frac{1}{t - m_2^2 + i m_2 \Gamma_2} \right|^2 \left(t - 4m_\chi^2\right) \tag{5.8}$$

$$\to |\frac{1}{t^2}|^2 \times t \sim \frac{1}{t^3} \ (\text{as } t \to \infty) \tag{5.9}$$

$$\text{VDM}: \quad G(t) \sim \left| \frac{1}{t - m_1^2 + i m_1 \Gamma_1} - \frac{1}{t - m_2^2 + i m_2 \Gamma_2} \right|^2 \left[2 + \frac{(t - 2m_V^2)^2}{4m_V^4}\right] \tag{5.10}$$

$$\to |\frac{1}{t^2}|^2 \times t^2 \sim \frac{1}{t^2} \ (\text{as } t \to \infty) \tag{5.11}$$

Asym... (EFT)

For pseudo Goldstone boson DM, the form factors are different and so are high energy behaviors

$$\text{SFDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \left(t - 4m_\chi^2\right)$$

$$\to \frac{1}{t} \ (\text{as } t \to \infty)$$

$$\text{VDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \left[2 + \frac{(t - 2m_V^2)^2}{4m_V^4}\right]$$

$$\to \text{constant} \ (\text{as } t \to \infty)$$

Unitarity violated !

Motivations for U(1)H extensions of 2HDM

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 t heory.

- 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.)
    Ma,PRD73;Barbieri,Hall,Rychkov,PRD74♪
  - baryon asymmetry of the Universe Shu,Zhang,PRL111♪
  - neutrino mass generation Kanemura,Matsui,Sugiyama,PLB727♪
  - can resolve experimental anomalies (top A_{FB} at Tevatron, $B \to D(*)\tau\nu$ at BA BAR) Ko,Omura,Yu,EPJC73;JHEP1303♪

Motivations

- Generic 2HDM suffer from neutral Higgs mediated FCNC
- Glashow-Weinberg criterion :
- Impose Z_2 symmetry under which both H_1 and H_2 are charged differently; the SM fermions are also charged appropriately to allow realistic Yukawa interactions (Type-I, II, X, Y)
- This Z_2 symmetry is softly broken by dim-2 operator

Natural Flavor Conservation
(Glashow and Weinberg, 1977)

- Fermions of the same electric charge get their masses from the same Higgs doublet [Glashow and Weinberg, PRD (1977)]
- The usual way to achieve this is to impose a discrete Z_2 sym under which two Higgs doublets H_1 and H_2 are charged differently
- This Z_2 is softly broken to avoid the domain wall problem and massless Goldstone boson

However

- The discrete Z_2 seems to be rather ad hoc, and its origin and the reason for its soft breaking are not clear
- We implement the discrete Z_2 into a continuous local U(1) Higgs flavor sym under which H_1 and H_2 are charged differently [Ko, Omura, Yu PLB (2012)]
- This simple idea opens a new window for the multi-Higgs doublet models, which was not considered before

2HDMs with U(1) Higgs gauge symmetry

Based on works with
Yuji Omura and Chaehyun Yu
arXiv:1204.4588 (PLB)
arXiv:1309.7156 (JHEP)
arXiv:1405.2138 (JHEP), etc..

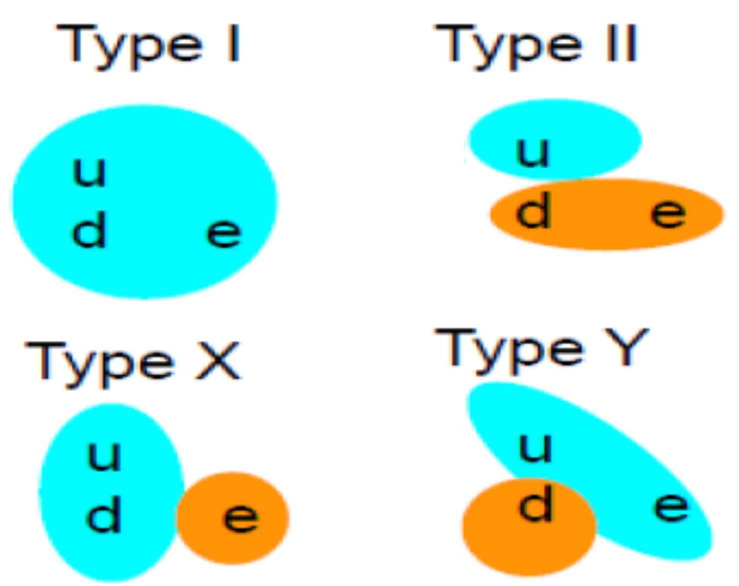
Also talk by TCYuan on $SU(2)_H$ extensions

2HDM with Z_2 symmetry (2HDMwZ_2)

- One of the simplest models to extend the SM Higgs sector.
- In general, flavor changing neutral currents (FCNCs) appear.
- A simple way to avoid the FCNC problem is to assign ad hoc Z_2 symmetry.

Z_2 : Chiral

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



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

$$\mathcal{L} = \bar{L}_i (y^E_{1ij} H_1 + \cancel{y^E_{2ij} H_2}) E_{Rj} + \mathrm{H.c.}$$

or vice versa

NO FCNC at tree level.

Generic problems of 2HDM

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

• Usually the Z_2 symmetry is assumed to be broken softly by a dim-2 oper ator, $H_1^\dagger H_2$ 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?

Z_2 symmetry in 2HDM can be replaced by new $U(1)_H$ symmetry associated with Higgs flavors.

Setup of 2HDM with U(1)H

Type I

Only one Higgs couples with fermion

$$V_y = y^U_{ij}\overline{Q_{Li}}\widetilde{H_1}U_{Rj} + y^D_{ij}\overline{Q_{Li}}H_1 D_{Rj} + y^E_{ij}\overline{L_i}H_1 E_{Rj} + y^N_{ij}\overline{L_i}\widetilde{H_1}N_{Rj}.$$

Anomaly free U(1)H with RH neutrino

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

Setup of 2HDM with $U(1)_H$

Type I

Only one Higgs couples with fermion

$$V_y = y^U_{ij}\overline{Q_{Li}}\widetilde{H_1}U_{Rj} + y^D_{ij}\overline{Q_{Li}}H_1 D_{Rj} + y^E_{ij}\overline{L_i}H_1 E_{Rj} + y^N_{ij}\overline{L_i}\widetilde{H_1}N_{Rj}.$$

Anomaly free U(1)H with RH neutrino

H-Z-Z_H coupling

U_R	D_R	Q_L	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	$1/2$	$U(1)_Y$

Drell-Yan

Anomaly free U(1)H with extra chiral fermion

$U(1)_B$, $U(1)_L$, and so on.

Setup of 2HDM with U(1)$_H$

Type II

two Higgs couples with fermion

$$V_y = y^U_{ij}\overline{Q_{Li}}\widetilde{H_1}U_{Rj} + y^D_{ij}\overline{Q_{Li}}H_2 D_{Rj} + y^E_{ij}\overline{L_i}H_2 E_{Rj} + y^N_{ij}\overline{L_i}\widetilde{H_1}N_{Rj}.$$

U_R	D_R	Q_L	L	E_R	N_R	H_1	H_2
$+1$	0	0	0	0	$+1$	0	1

Require extra chiral fermions. (q_L, q_R)

Extra fermion may cause FCNC.

Suppress FCNC ⟷ Decouple with SM (Yukawa int.) ⟷ Stable charged (colored) particle

$\lambda_i \overline{Q^i_L}\widetilde{H}_1 q_R$

$\lambda_i \to 0$

"safe" mixing required

Type II   one way for anomaly free

"E6" Model (leptophobic)   by Rosner, London, etc.

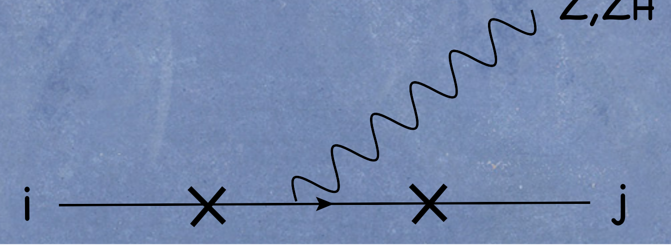
U_R	D_R	Q_L	L	E_R	N_R	H_1	H_2
$2/3$	$-1/3$	$-1/3$	0	0	1	1	0

Extra fields for anomaly free

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$
q_{Li}	3	1	$-1/3$	$2/3$
q_{Ri}	3	1	$-1/3$	$-1/3$
l_{Li}	1	2	$-1/2$	0
l_{Ri}	1	2	$-1/2$	-1
n_{Li}	1	1	0	-1

tree-level mixing

$$V_m = Y_{ij}^{q}\overline{Q_{Li}}H_2 q_{Rj} + Y_{ij}^{E}\overline{l_{Li}}H_2 E_{Rj} + Y_{ij}^{N}\overline{l_{Li}}\widetilde{H_1}N_{Rj} + \ldots$$



J.L. Rosner, hep-ph/9607207 (PLB)

Table 1: Assignment of quantum numbers to left-handed members of the **27**-plet of E_6.

(SO(10), SU(5))	Q_η	State	Q	I_{3L}	I_{3R}	Y_L	Y_R	Q'
$(\mathbf{16}, \mathbf{5}^*)$	1	d^c	1/3	0	1/2	0	−1/3	1/3
		e^-	−1	−1/2	0	−1/3	−2/3	0
		ν_e	0	1/2	0	−1/3	−2/3	0
$(\mathbf{16}, \mathbf{10})$	−2	u	2/3	1/2	0	1/3	0	−1/3
		d	−1/3	1/2	0	1/3	0	−1/3
		u^c	−2/3	0	−1/2	0	−1/3	−2/3
		e^+	1	0	1/2	2/3	1/3	0
$(\mathbf{16}, \mathbf{1})$	−5	N_e^c	0	0	−1/2	2/3	1/3	−1
$(\mathbf{10}, \mathbf{5}^*)$	1	h^c	1/3	0	0	0	2/3	1/3
		E^-	−1	−1/2	−1/2	−1/3	1/3	0
		ν_E	0	1/2	−1/2	−1/3	1/3	0
$(\mathbf{10}, \mathbf{5})$	4	h	−1/3	0	0	−2/3	0	2/3
		E^+	1	1/2	1/2	−1/3	1/3	1
		ν_E^c	0	−1/2	1/2	−1/3	1/3	1
$(\mathbf{1}, \mathbf{1})$	−5	n	0	0	0	2/3	−2/3	−1

$$Q' = (Q_\eta + Y_W)/5 = I_{3R} - Y_L + (1/2)Y_R$$

$$A_{FB} = \frac{3}{4}\,\frac{[Q(u)^2 - Q(u^c)^2][Q(f)^2 - Q(f^c)^2]}{[Q(u)^2 + Q(u^c)^2][Q(f)^2 + Q(f^c)^2]}$$

Table 2: Branching ratios for a Z' coupling to the charge Q' into various members of a single family in the **27**-plet of E_6.

State f	Squared charge	Branching ratio	Branching ratio/3 (%)	$A_{FB}(u\bar{u} \to Z' \to f\bar{f})$
d	$(1+1)/3$	$1/12$	2.8	0
u	$(1+4)/3$	$5/24$	6.9	0.27
N_e^c	1	$1/8$	4.2	0.45
h	$(4+1)/3$	$5/24$	6.9	-0.27
E	$0+1$	$1/8$	4.2	0.45
ν_E	$0+1$	$1/8$	4.2	0.45
n	1	$1/8$	4.2	-0.45
Total	8	1	33.3	

Inert Doublet Model (IDMwZ_2)

- a 2HDM ~ one of the simplest extension

- One of Higgs doublets does not develop VEV and exact Z_2 sy mmetry is imposed.

- The new Higgs doublet does not participate in the EW sym metry breaking.

- Under the Z_2 symmetry, SM particles are even, but the new Higgs do ublet is odd.

- Viable DM candidate

We don't have to impose extra dark gauge sym to ensure DM longevity. The SM gauge sym just does the job.

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

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

Inert Doublet Model (IDMwZ_2)

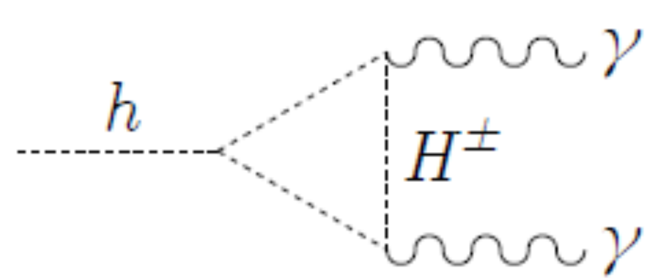
- CP-conserving potential

forbidden by the Z_2 symmetry

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

- Type-I Yukawa interactions ~ only H_2 couples to the SM fermions.

- The h decay to two photons receives additional contribution through charg ed Higgs loop.



- H,A,H± ~ do not couple to SM fermions at tree level.

Inert Double Model (IDMwU(1)$_H$)

- We replace the Z_2 symmetry by U(1) gauge symmetry.
- A SM-singlet Φ has to be added.
- Without Φ, Z_H boson becomes massless.

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

- Φ breaks the U(1)$_H$ symmetry while H_2 breaks the EW symmetry.
- The remnant symmetry of U(1)$_H$ is the origin of the exact Z_2 symmetry.

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

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

- Φ breaks the U(1)$_H$ symmetry while H_2 breaks the EW symmetry.
- The remnant symmetry of U(1)$_H$ is the origin of the exact Z_2 symmetry.

Inert Double Model (IDMwU$(1)_H$)

- IDM + SM-singlet .

forbidden
by the Z_2 symmetry

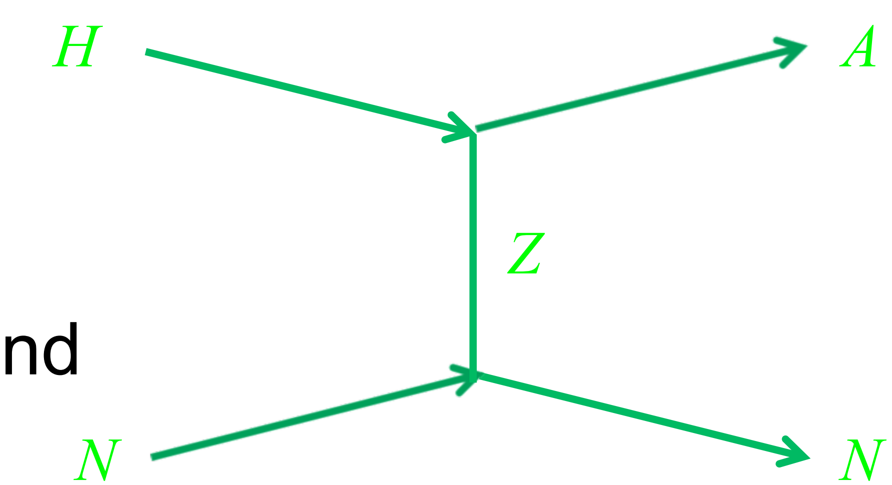
$$V = (m_1^2 + \tilde{\lambda}_1 |\Phi|^2)(H_1^\dagger H_1) + (m_2^2 + \tilde{\lambda}_2 |\Phi|^2)(H_2^\dagger H_2) - (m_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.})$$
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4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

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

- Without λ_5, H and A are degenerate.

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

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



Inert Double Model (IDMwU$(1)_H$)

- IDM + SM-singlet Φ.

forbidden
by the Z_2 symmetry

$$V = (m_1^2 + \tilde{\lambda}_1^0 |\Phi|^2)(H_1^\dagger H_1) + (m_2^2 + \tilde{\lambda}_2^0 |\Phi|^2)(H_2^\dagger H_2) - (m_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.})$$

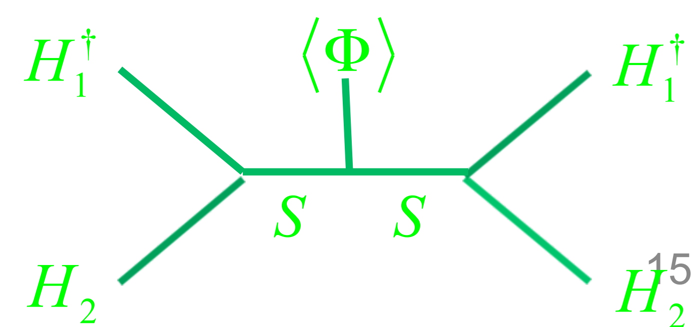
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$

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

- The λ_5 term can effectively be generated by a higher-dimensional operator.
- It could be realized by introducing a singlet S charged under U$(1)_H$ with $q_S = q_{H_1}$.

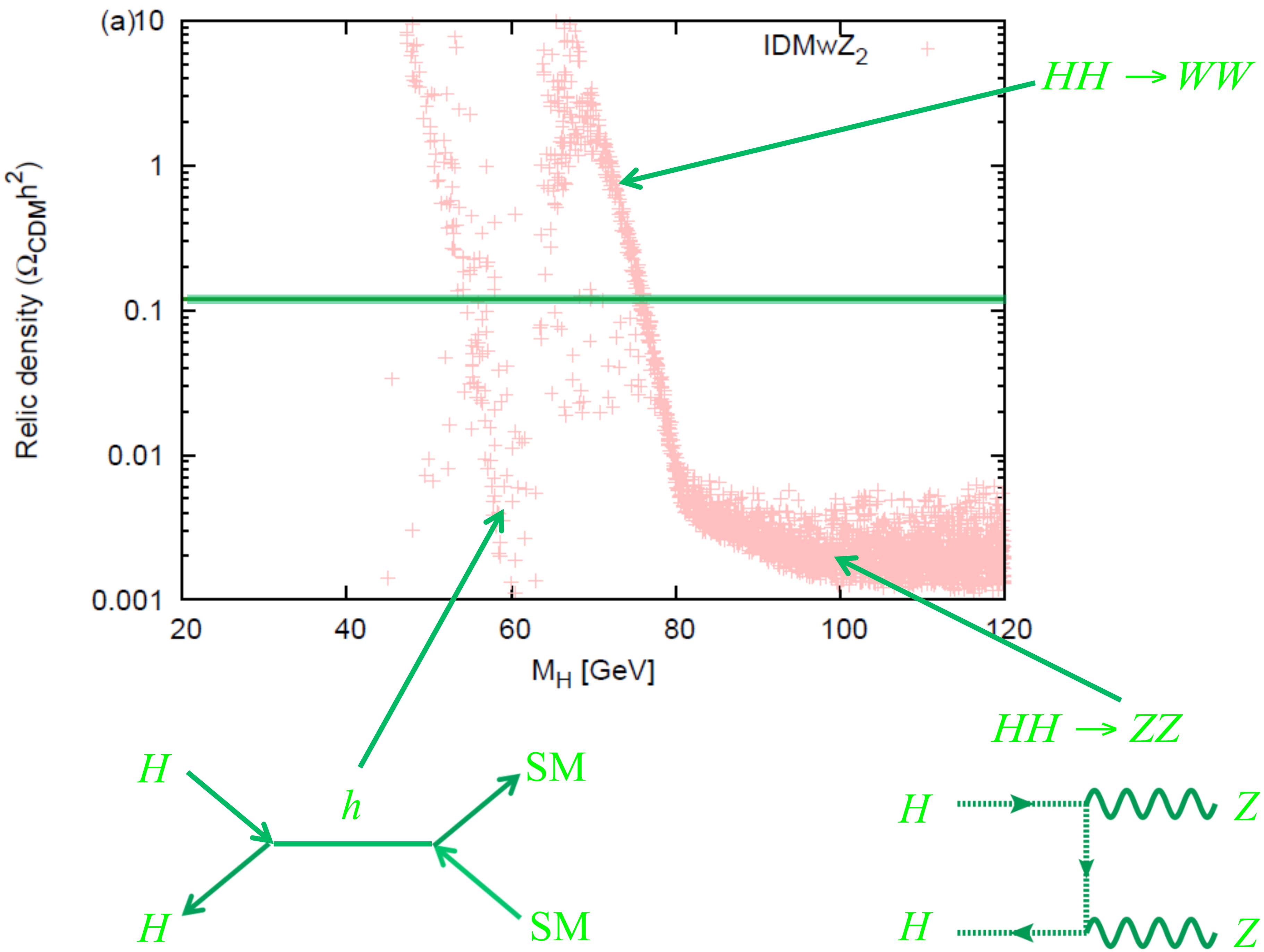
$$V_\Phi(|\Phi|^2, |S|^2) + V_H(H_i, H_i^\dagger) + \lambda_S(\Phi) S^2 + \lambda_H(S) H_1^\dagger H_2 + h.c..$$

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



Relic density (low mass)

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

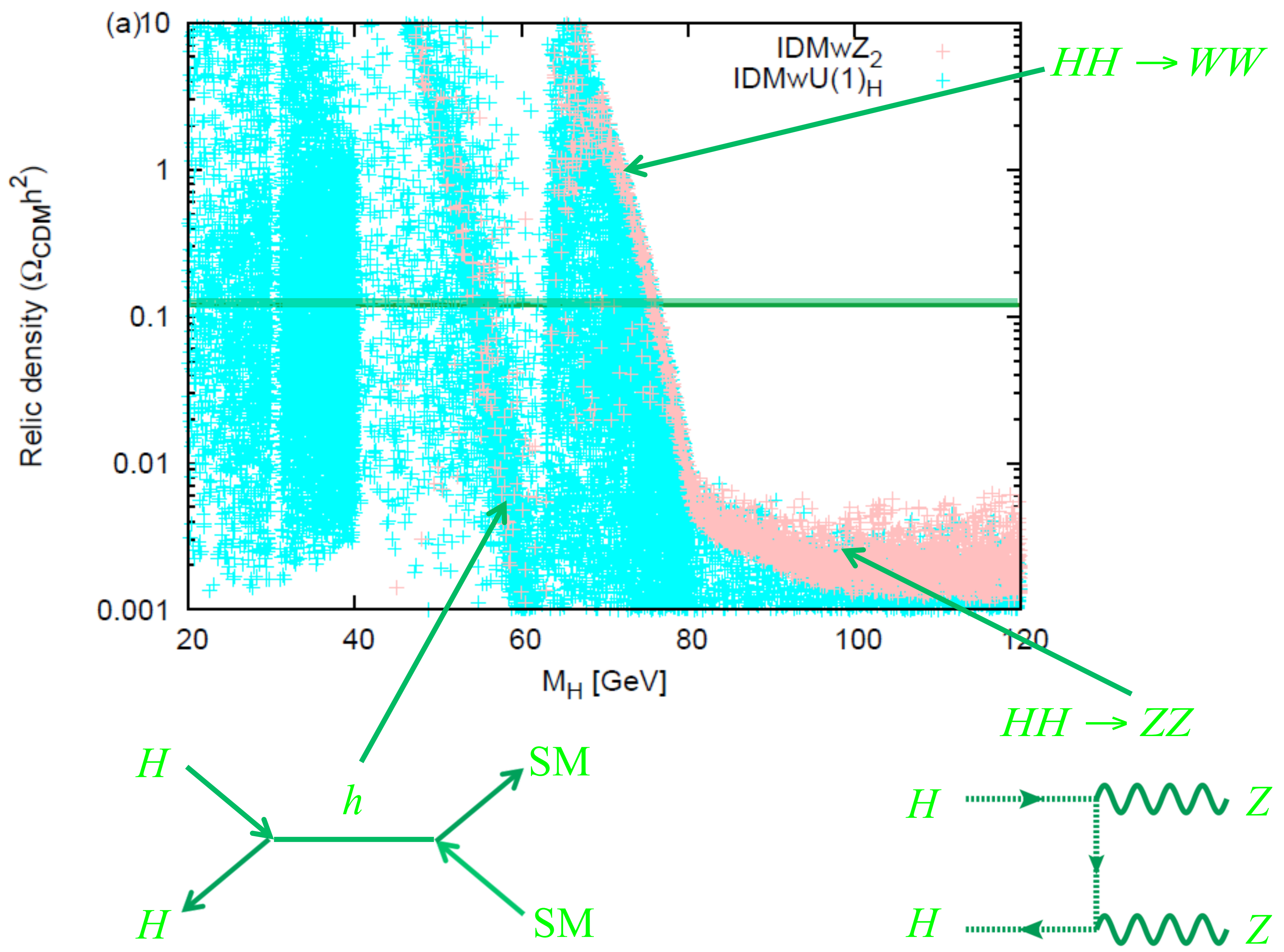


+ IDMwZ$_2$

LUX bound is satisfied.

Relic density (low mass)

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



+ IDMwZ$_2$
+ IDMwU(1)$_H$

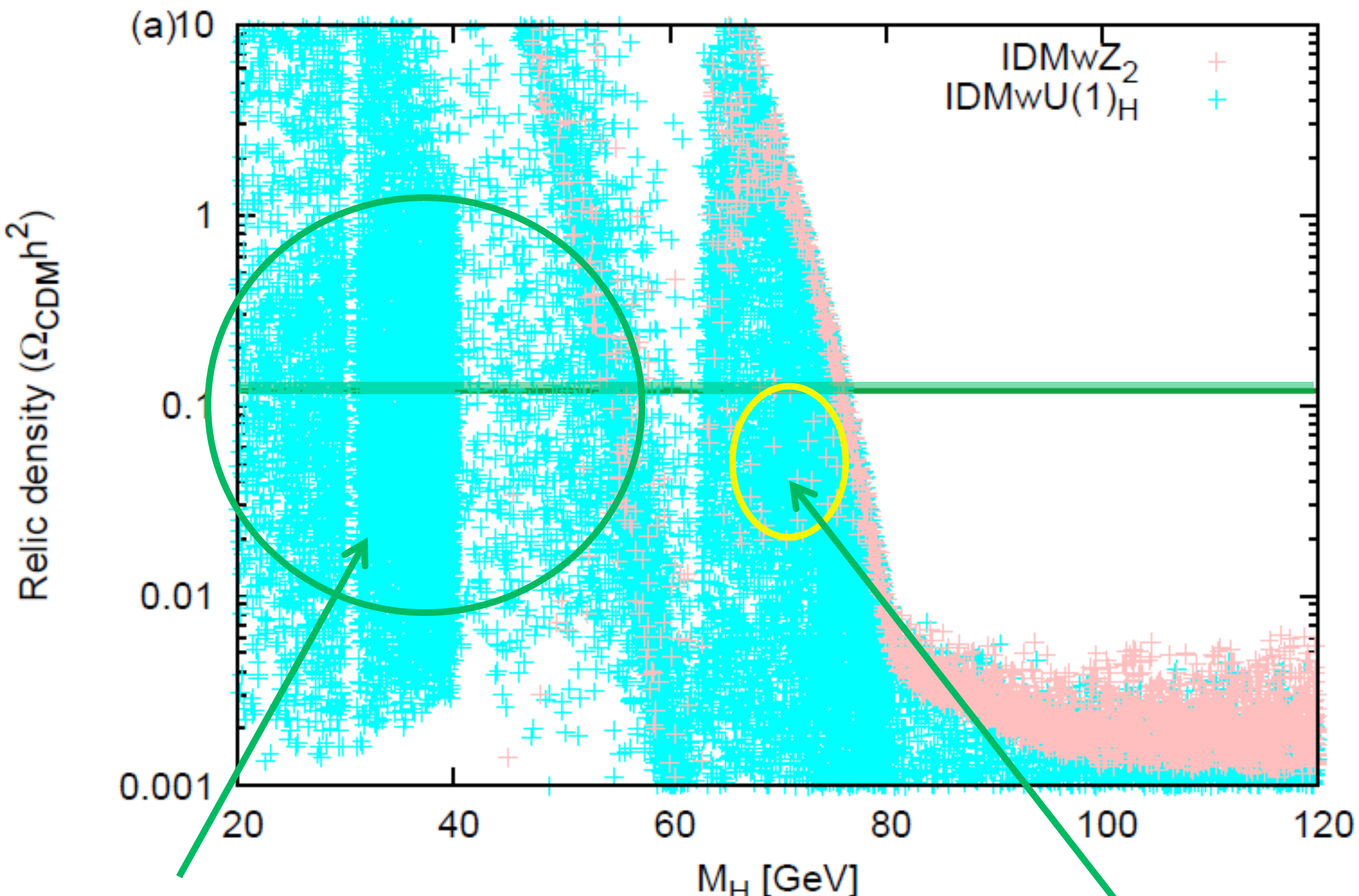
LUX bound is satisfied.

Relic density (low mass)

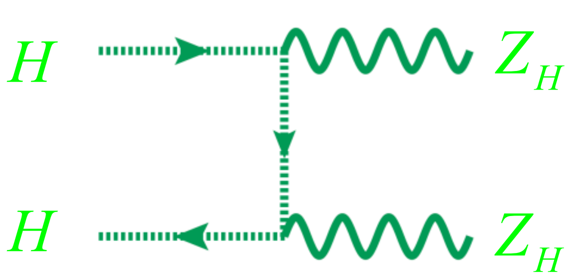
$$\Omega_{\rm CDM}h^2 = 0.1199 \pm 0.0027$$

+ $\mathrm{IDMwZ_2}$
+ $\mathrm{IDMwU(1)_H}$

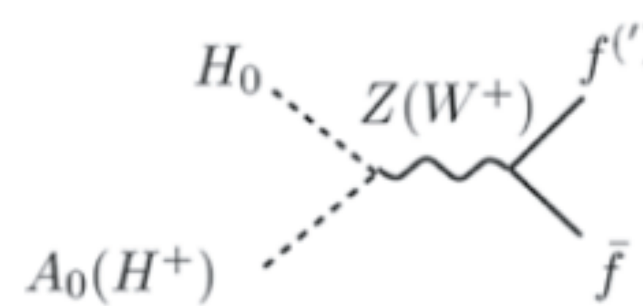
LUX bound is satisfied.



$HH \to Z_H Z_H, ZZ_H$



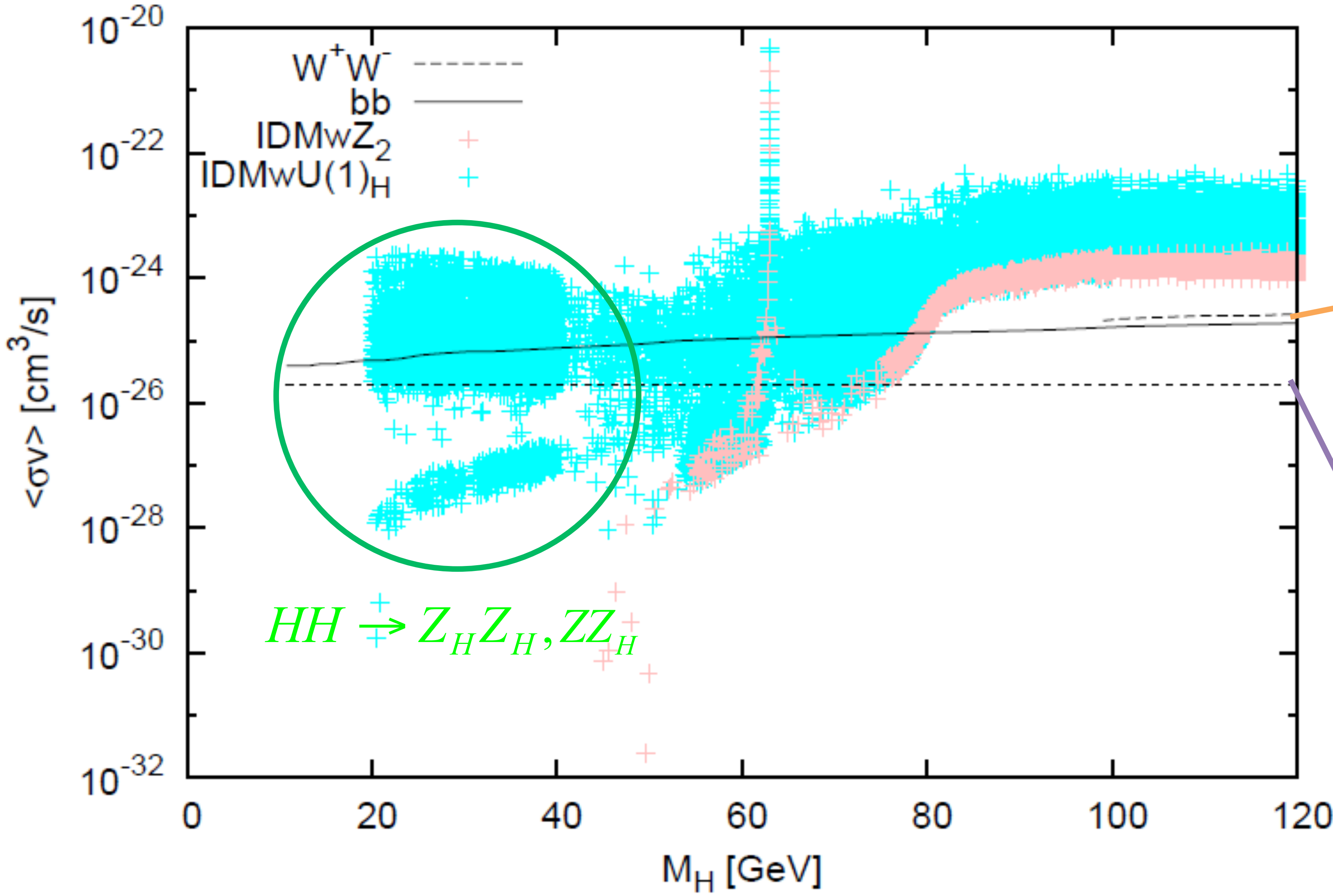
Co-annihilation



$HA, HH^\pm \to \mathrm{SM}+\mathrm{SM}^{(\prime)}$

$H^+H^- \to A + Z_H, Z + Z_H, \ldots$

Indirect searches (low mass)



+ $IDMwZ_2$
+ $IDMwU(1)_H$

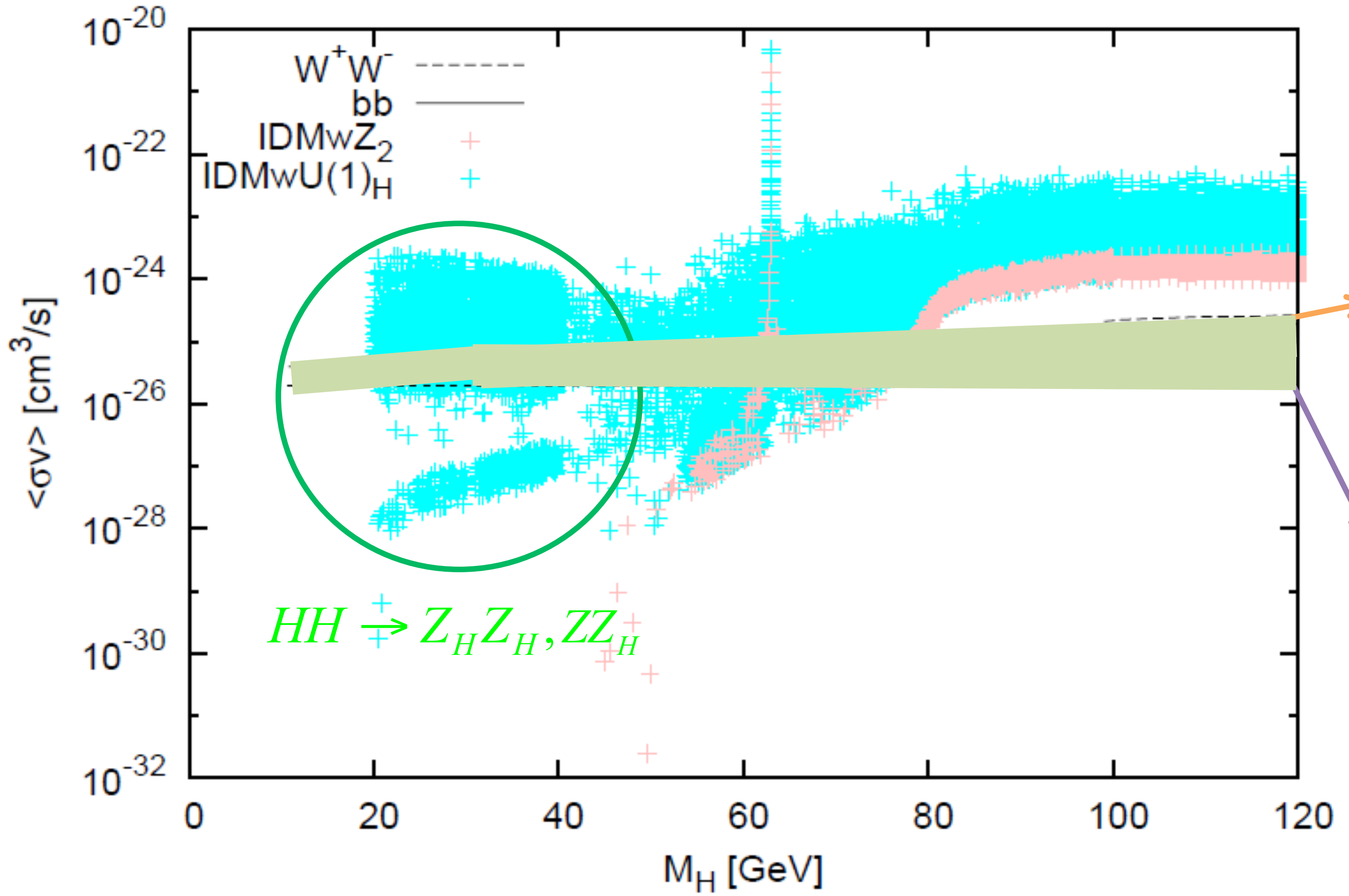
Constraints on the DM annihilation cross section from Fermi-LAT's analysis of 15 dwarf spheroidal galaxies.

Fermi−LAT,arXiv:1310.0828)

Constraint on the S-wave DM annihilation from the relic density observation

- All points satisfy constraints from the relic density observation and LUX experiments.

Indirect searches (low mass)



+ IDMwZ_2
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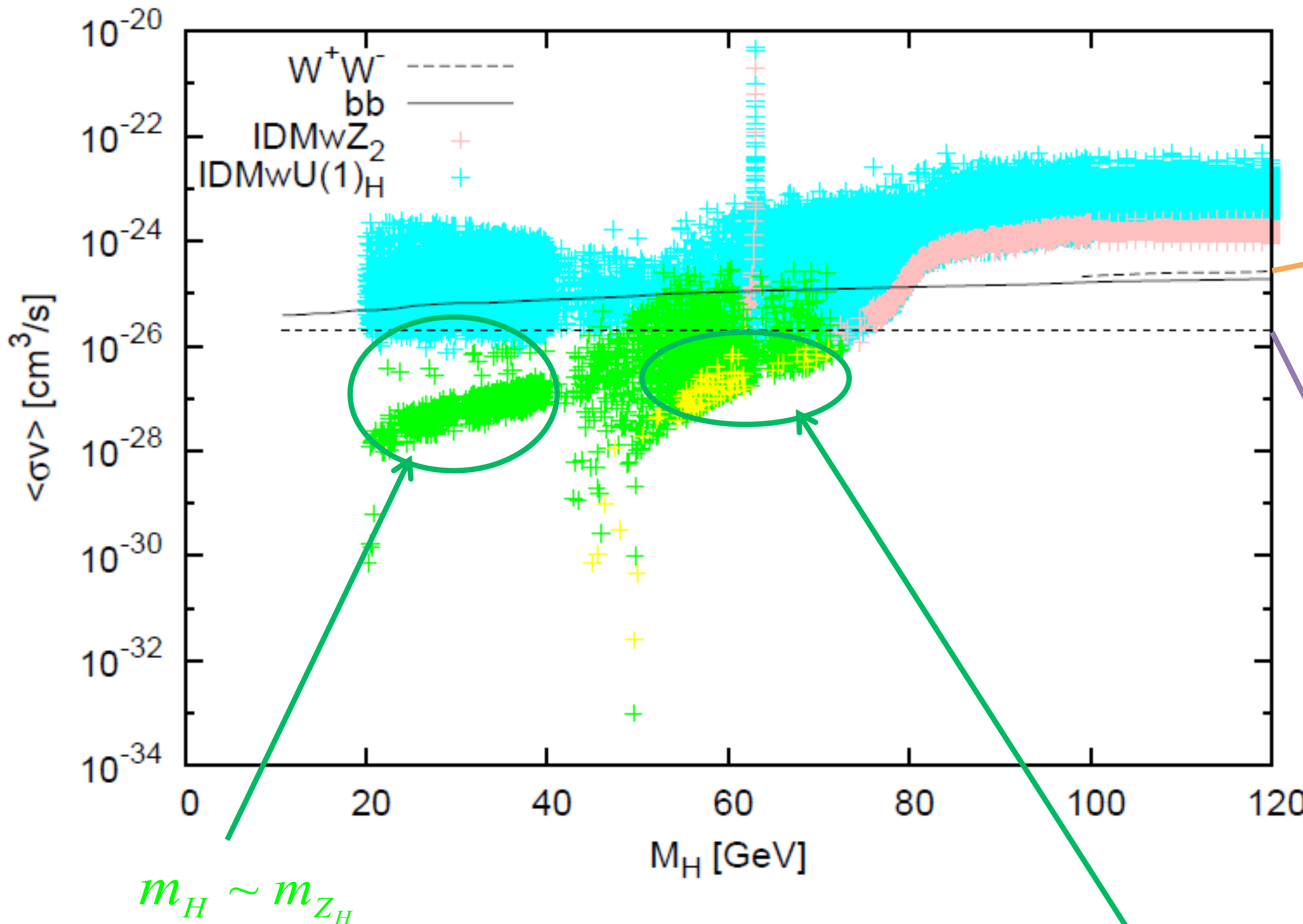
Constraints on the DM annihilation cross section from Fermi-LAT's analysis of 15 dwarf spheroidal galaxies.

Fermi-LAT,arXiv:1310.0828

Constraint on the S-wave DM annihilation from the relic density observation

- But, indirect DM signals depend on the decay patterns of produced particles from annihilation or decay of DMs.

Indirect searches (low mass)



+ $IDMwZ_2$
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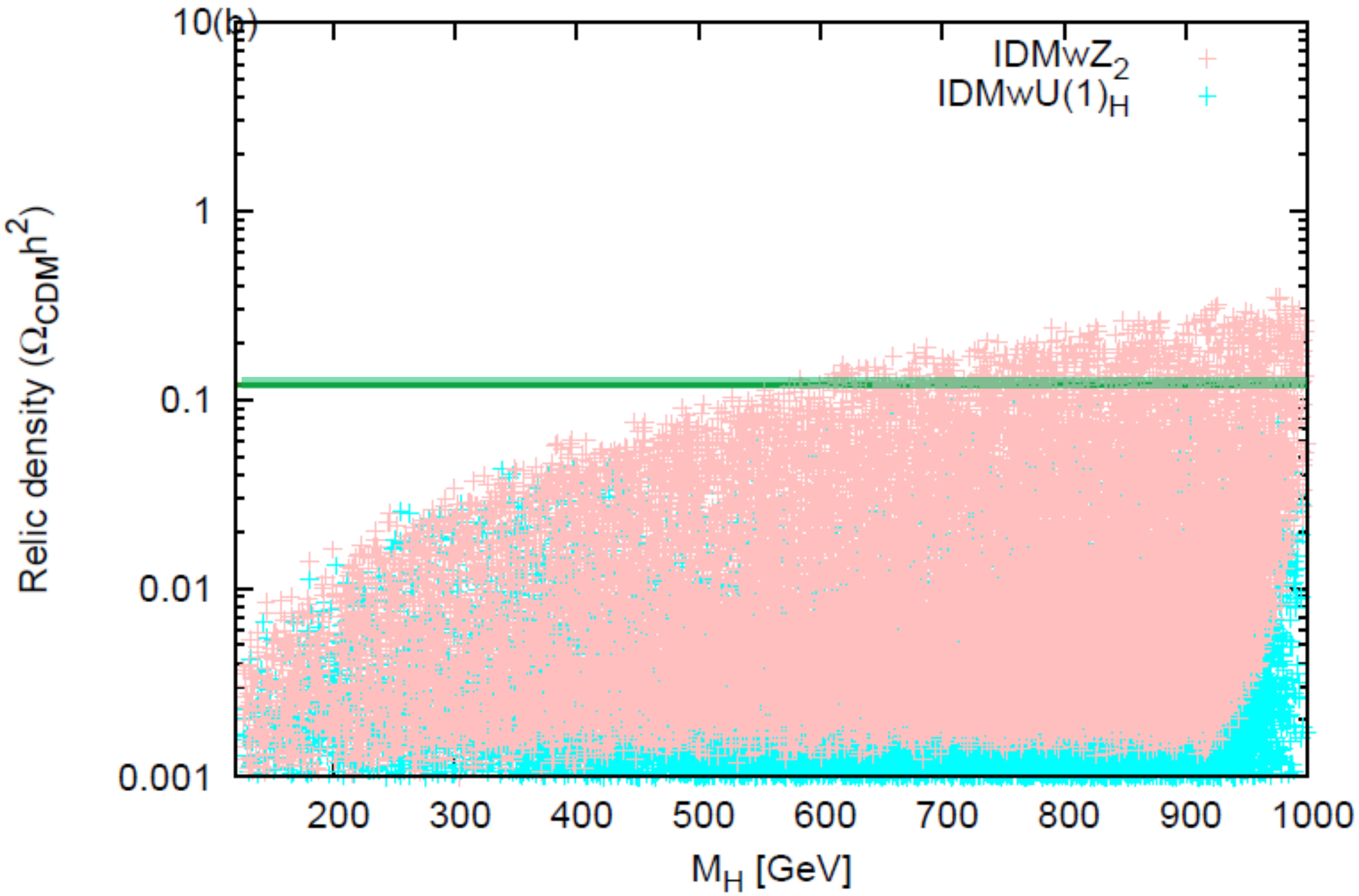
Fermi−LAT,arXiv:1310.0828♪

Constraint on the S-wave DM an nihilation from the relic density ob servation

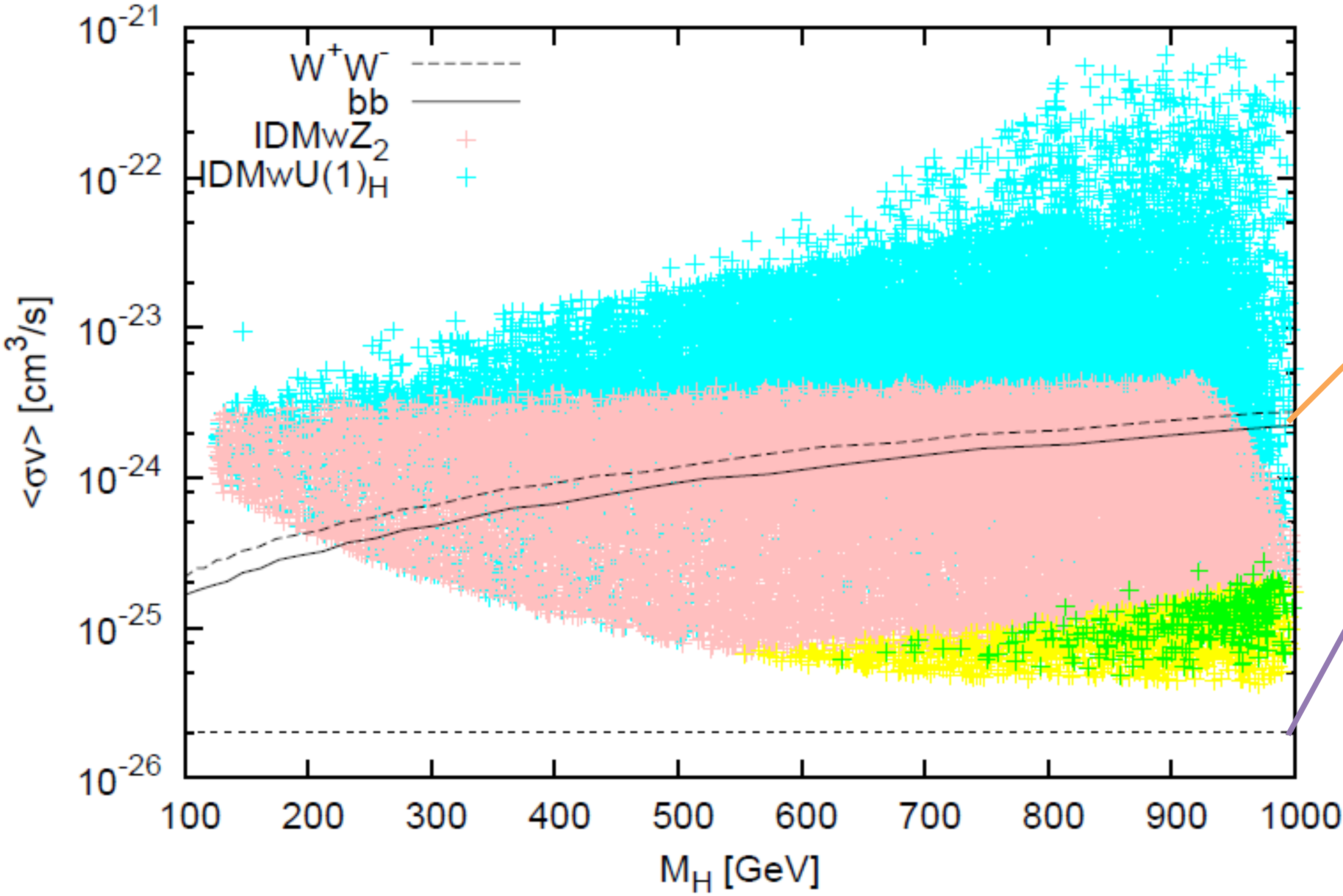
Relic density (high mass)

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



+ $IDMwZ_2$
+ $IDMwU(1)_H$

Indirect searches (high mass)



+ $IDMwZ_2$

+ $IDMwU(1)_H$

Constraints on the DM annihilation cross section from Fermi-LAT's analysis of 15 dwarf spheroidal galaxies.

Fermi−LAT,arXiv:1310.0828♪

Constraint on the S-wave DM annihilation from the relic density observation

Gamma flux from GC

- DM with mass 30-40 GeV with pair annihilating into Z_H Z_H should be able to accommodate the gamma ray excess from the galactic center
- This DM mass range is impossible within the usual IDM
- Becomes possible in IDM with local U(1)H because of new channels involving Z_H s

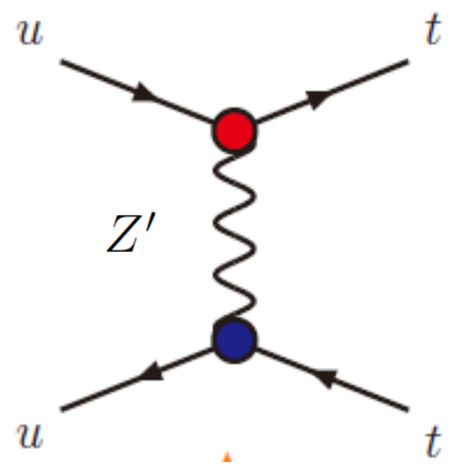
New chiral gauge symmetry requires more Higgs doublets

New chiral gauge sym

- If we introduce a new chiral gauge symmetry, we have to introduce more Higgs doublets in order that we can write down realistic Yukawa matrices for the SM fermions
- Interference between gauge boson and additional Higgs boson contributions can be important (especially for the 3rd generation fermions)
- Examples in the top FBA, B physics anomalies, etc..
- If additional charged/neutral Higgs bosons are discovered, that may indicate the existence of a new chiral gauge symmetry, and not of weak scale SUSY

Z′ model

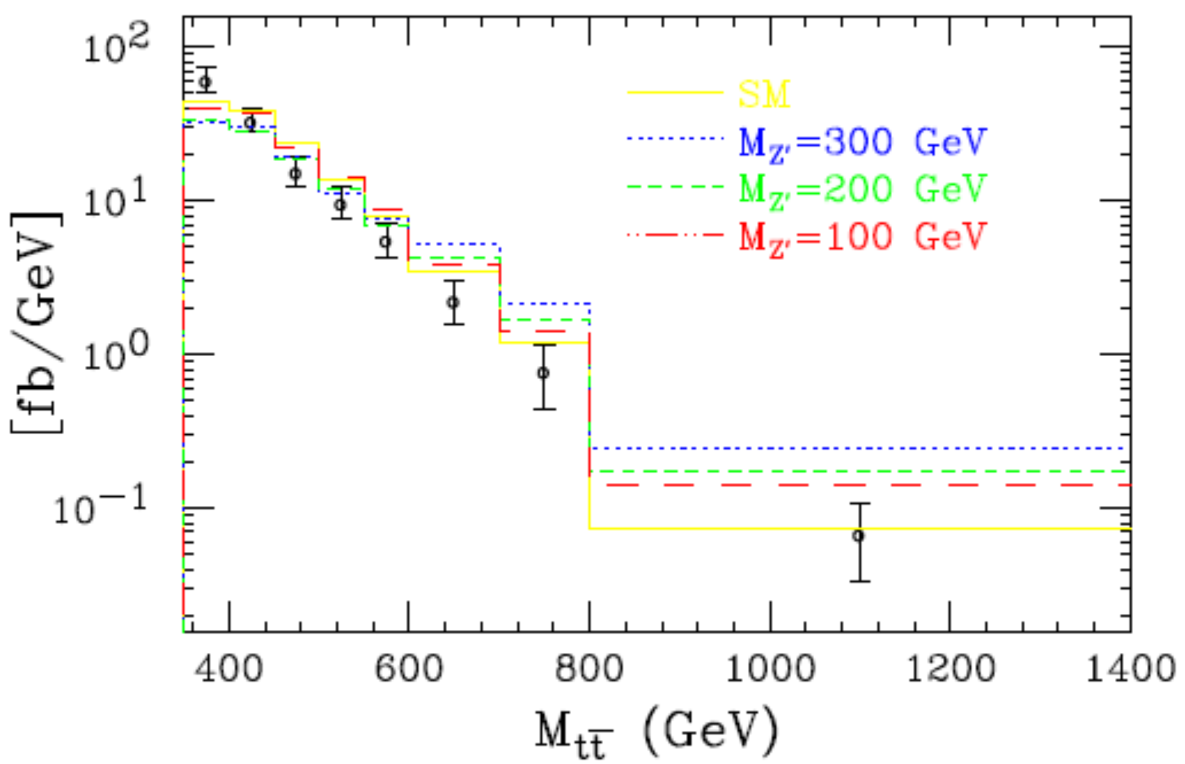
Jung, Murayama, Pierce, Wells, PRD81♪



• assume large flavor-offdiagonal coupling and small diagonal couplings.

$$\mathcal{L} \ni g_X Z'_\mu \bar{u}\gamma^\mu P_R t + h.c.$$

• In general, could have different couplings to t he top and antitop quarks.

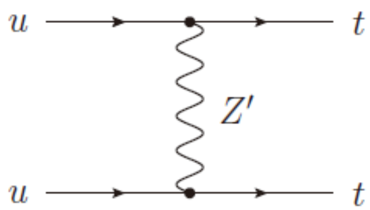


• light Z′ is favored from the M_{tt} dis tribution.

• severely constrained by the sa me sign top pair production.

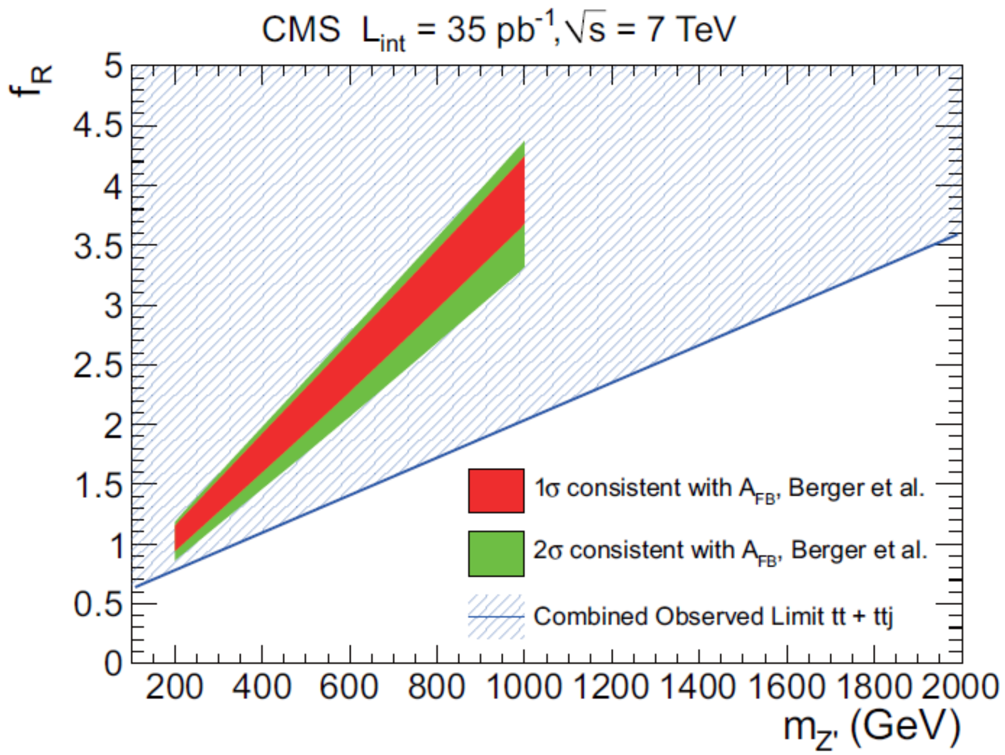
- the t-channel scalar exchange model has a similar constraint.

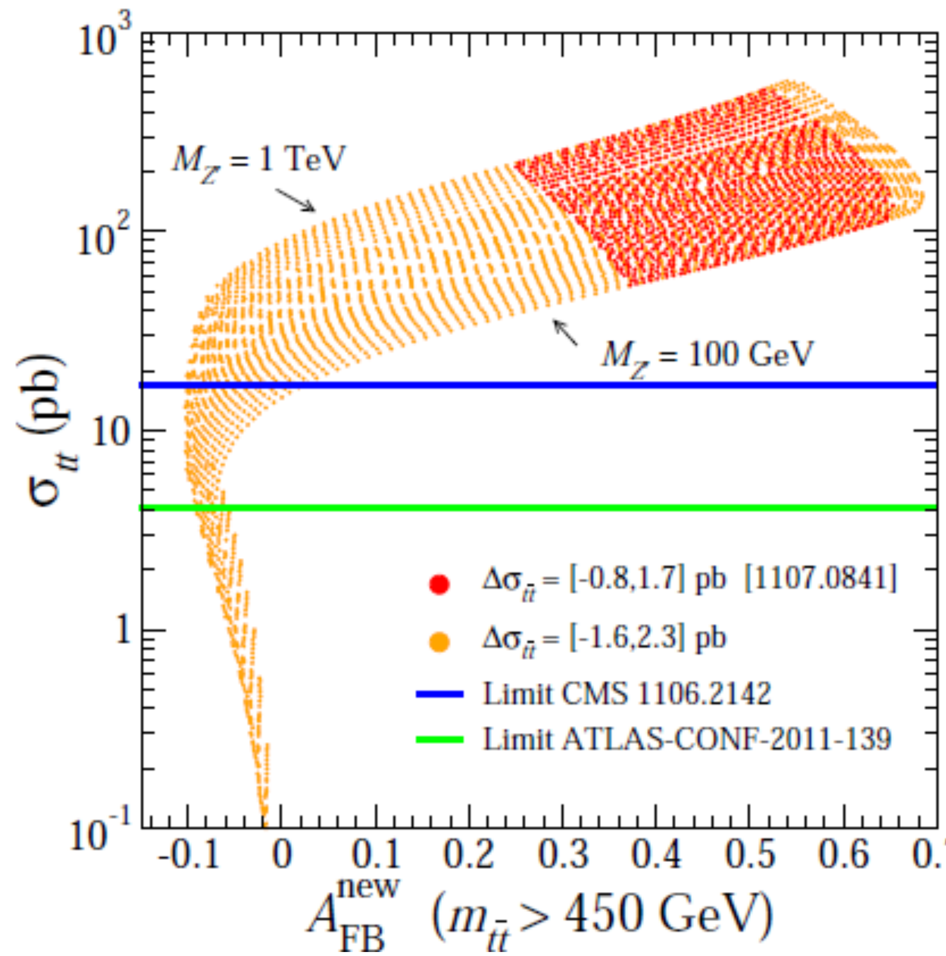
Same sign top pair production at LHC



$$\mathcal{L} = g_W \bar{u} \gamma^\mu (f_L P_L + f_R P_R) t Z'_\mu + \text{h.c.},$$

General exclusion plot





CMS: σ(pp→tt(j))<17 pb at 95C.L.
ATLAS: σ(pp→tt(j))<4 pb at 95C.L.

CMS, JHEP1108; ATLAS-CONF-2011-169♪

Aguilar-Saavedra, TOP2011♪

- the t-channel Z′ or scalar exchange models are excluded? – No.

Flavor-dependent U(1)′ model

- many studies for a relatively light Z′ gauge boson with mass ~ 150 GeV.

- the Z′ is associated with some U(1)′ gauge symmetry.

- better be leptophobic to avoid the LEP II and Drell-Yan bounds.

- approximately lighter than 200 GeV from the dijet production in the UA2 , Tevatron, LHC experiments and has flavor-dependent couplings.

- difficult to assign flavor-dependent charges to down-type quarks due to the strong constraints from FCNC experiments → assign U(1)′ charges o nly to right-handed up-type quarks.

- Yukawa interactions : additional Higgs fields are inevitable.

- a flavor-dependent leptophobic U(1)′ : anomalous.
  - introduce additional fermions to cancel the gauge anomalies.

- Both Z′ and Higgs fields affect the top A_{FB} and charge asymmetry.

However, the story is not so simple for models with vector bosons that have chiral couplings with the SM fermions !

Chiral U(1)' model (Ko, Omura, Yu)

(1) arXiv:1108.0350, PRD (2012)
(2) arXiv:1108.4005, JHEP 1201 (2012) 147
(3) arXiv:1205.0407, under review

What is the problem of the original Z' model ?

- Z' couples to the RH up type quarks : leptophbic and chiral : ANOMALY ?
- No Yukawa couplings for up-type quarks : MASSLESS TOP QUARK ?
- Origin of Z' mass
- Origin of flavor changing couplings of Z'

What is the problem of the original Z' model ?

$$\mathcal{L}_Y = -Y_{ij}^U \overline{Q_{Li}} \tilde{H} U_{Rj} - Y_{ij}^D \overline{Q_{Li}} H D_{Rj} + H.c.$$

Not gauge invariant

Gauge invariant : OK!

No Yukawa's for up quarks !

How to cure this problem ?

Answer : Extend Higgs sector

$$\mathcal{L}_Y = -Y^U_{ij}\overline{Q_{Li}}\tilde{H}U_{Rj} - Y^D_{ij}\overline{Q_{Li}}HD_{Rj} + H.c.$$

Not gauge invariant

Gauge invariant : OK!

$$\mathcal{L}_Y = -Y^U_{ijk}\overline{Q_{Li}}\tilde{H}_k U_{Rj} - Y^D_{ij}\overline{Q_{Li}}HD_{Rj} + H.c.$$

$H_k : U(1)$ charged

Mandatory to extend Higgs sector!
Z' only model does not exist!

# of U(1)'-charged new Higgs doublets depend on U(1)' charge assigments to the RH up quarks

Flavor-dependent U(1)′ model

- 2 Higgs doublet model : $(u_1, u_2, u_3) = (0, 0, 1)$

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H	1	2	1/2	0
H_3	1	2	1/2	1
Φ	1	1	1	q_Φ

$$\begin{aligned} V_y &= y^u_{i1}\overline{Q_i}\widetilde{H}U_{R1} + y^u_{i2}\overline{Q_i}\widetilde{H}U_{Rj} + y^u_{i3}\overline{Q_i}\widetilde{H_3}U_{Rj} \\ &\quad + y^d_{ij}\overline{Q_i}HD_{Rj} + y^e_{ij}\overline{L_i}H\overline{E_j} + y^n_{ij}\overline{L_i}\widetilde{H}N_j. \end{aligned}$$

$$V_h = Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}\hat{h}_0 + Y^d_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}\hat{h}_0,$$

$$\begin{aligned} Y^u_{ij} &= \frac{m^u_i \cos\alpha}{v\cos\beta}\delta_{ij} + \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij}\sin(\alpha-\beta), \\ Y^d_{ij} &= \frac{m^d_i \cos\alpha}{v\cos\beta}\delta_{ij}, \end{aligned}$$

$\propto$ the fermion mass

Flavor-dependent U(1)′ model

- 3 Higgs doublet model: $(u_1, u_2, u_3) = (-q, 0, q)$

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)'$
H_1	1	2	1/2	q
H_2	1	2	1/2	0
H_3	1	2	1/2	$-q$
Φ	1	1	0	-1

$$\begin{aligned}\mathcal{L}_{\rm Y} &= y^u_{i1} H_1 \overline{U_1} Q_i + y^u_{i2} H_2 \overline{U_2} Q_i + y^u_{i3} H_3 \overline{U_3} Q_i \\ &+ y^d_{ij} H_2^\dagger \overline{D_j} Q_i + y^e_{ij} H_2^\dagger \overline{E_j} L_i + y^n_{ij} H_2 \overline{N_j} L_i .\end{aligned}$$

Flavor-dependent U(1)′ model

- Gauge coupling in the mass base

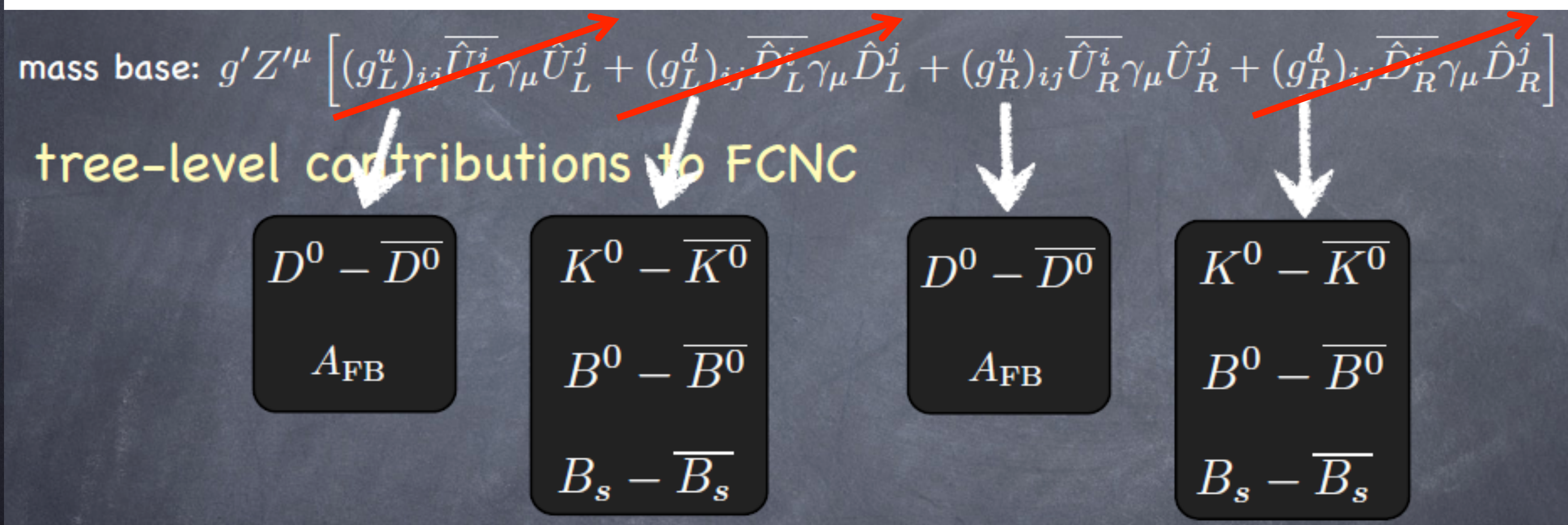
- Z′ interacts only with the right-handed up-type quarks

$$g' Z'^{\mu} \sum_{i,j=1,2,3} (g_R^u)_{ij} \overline{U_R}^i \gamma_\mu U_R^j$$

- The 3 X 3 coupling matrix g_R^u is defined by

$$(g_R^u)_{ij} = (U_R^u)_{ik} u_k (U_R^u)^\dagger_{kj}$$

biunitary matrix diagonalizing the up-type quark mass matrix



Flavor-dependent U(1)′ model

- Yukawa coupling in the mass base (2HDM)

- lightest Higgs h: $V_h = Y^u_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}h + Y^d_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}h + Y^e_{ij}\overline{\hat{E}_{Li}}\hat{E}_{Rj}h + h.c.,$

$$Y^u_{ij} = \frac{m^u_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi \delta_{ij} + \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij}\sin(\alpha-\beta)\cos\alpha_\Phi,$$

$$Y^d_{ij} = \frac{m^d_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi \delta_{ij},$$

$$Y^e_{ij} = \frac{m^l_i \cos\alpha}{v\cos\beta}\cos\alpha_\Phi \delta_{ij},$$

- lightest charged Higgs h^+: $V_{h^\pm} = -Y^{u-}_{ij}\overline{\hat{D}_{Li}}\hat{U}_{Rj}h^- + Y^{d+}_{ij}\overline{\hat{U}_{Li}}\hat{D}_{Rj}h^+ + h.c.,$

$$Y^{u-}_{ij} = \sum_l (V_{\rm CKM})^*_{li}\left\{\frac{\sqrt{2}m^u_l\tan\beta}{v}\delta_{lj} - \frac{2\sqrt{2}m^u_l}{v\sin 2\beta}(g^u_R)_{lj}\right\},$$

$$Y^{d+}_{ij} = (V_{\rm CKM})_{ij}\frac{\sqrt{2}m^d_j\tan\beta}{v},$$

- lightest pseudoscalar Higgs a: $V_a = -iY^{au}_{ij}\overline{\hat{U}_{Li}}\hat{U}_{Rj}a + iY^{ad}_{ij}\overline{\hat{D}_{Li}}\hat{D}_{Rj}a + iY^{ae}_{ij}\overline{\hat{E}_{Li}}\hat{E}_{Rj}a + h.c.,$

$$Y^{au}_{ij} = \frac{m^u_i\tan\beta}{v}\delta_{ij} - \frac{2m^u_i}{v\sin 2\beta}(g^u_R)_{ij},$$

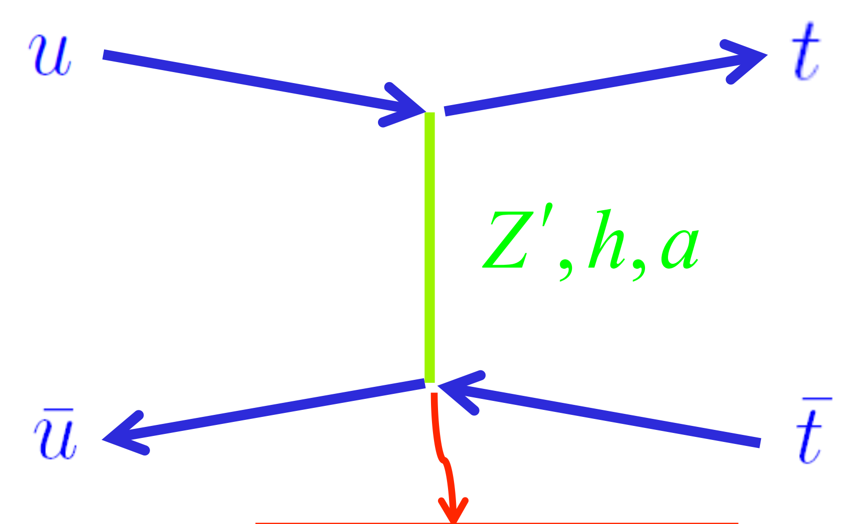
$$Y^{ad}_{ij} = \frac{m^d_i\tan\beta}{v}\delta_{ij},$$

$$Y^{ae}_{ij} = \frac{m^l_i\tan\beta}{v}\delta_{ij}.$$

Top-antitop pair production

1. Z′ dominant scenario

cf. Jung, Murayama, Pierce, Wells, PRD81(2010)♪

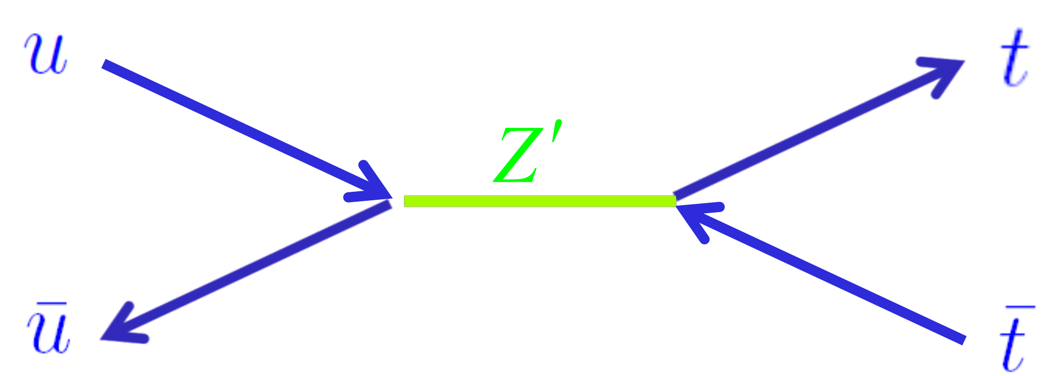


$$\alpha_X = \frac{(g' g^u_{Rut})^2}{4\pi}, Y_{tu}, Y^a_{tu}$$

2. Higgs dominant scenario

cf. Babu, Frank, Rai, PRL107(2011)♪

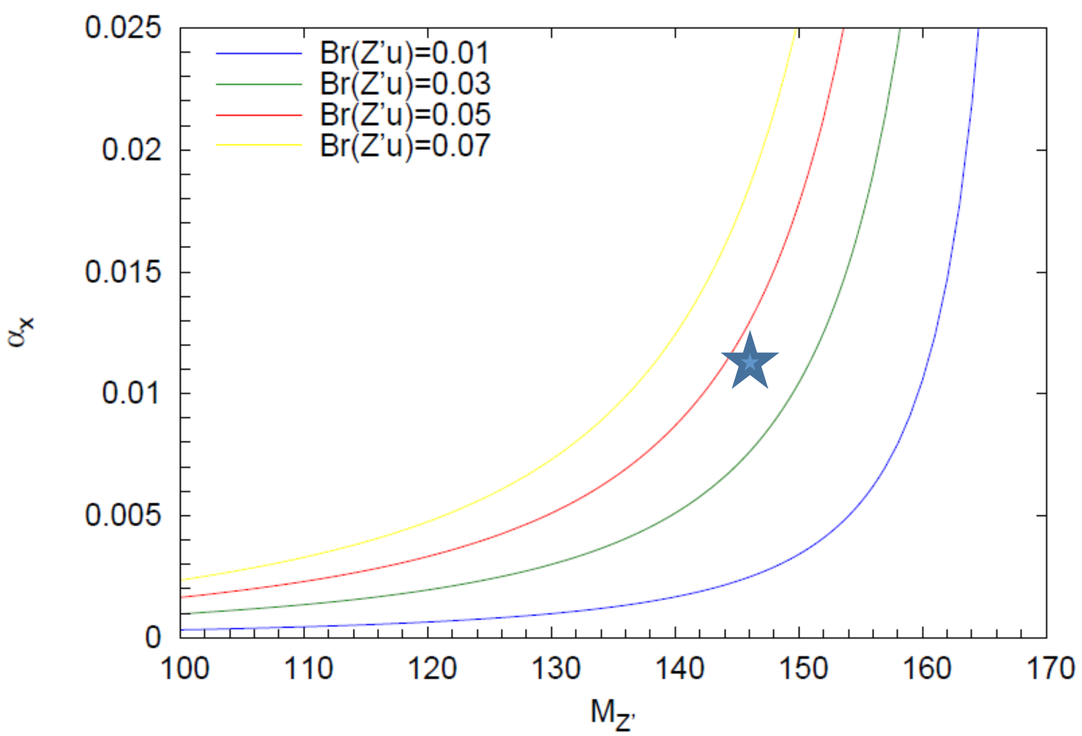
3. Mixed scenario

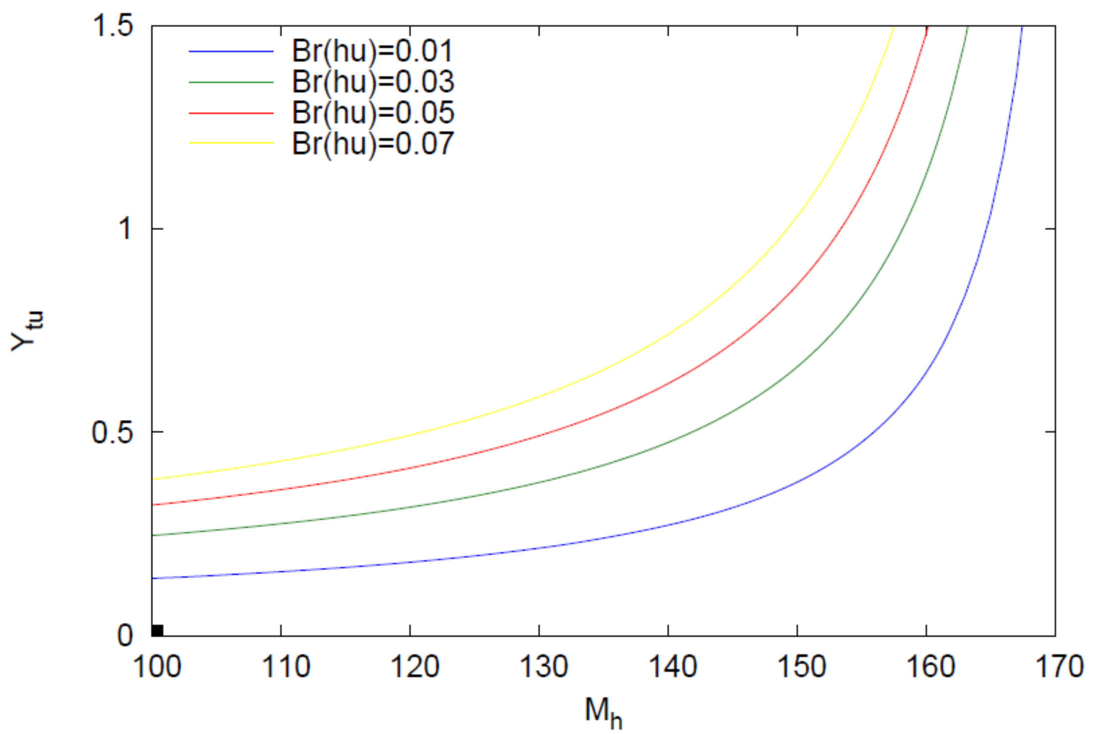


Top quark decay

- decay into W+b in SM : Br(t→Wb)~100%.

- If the top quark decays to $Z'+u$ or $h+u$, Br(t→Wb) might significantly b e changed.



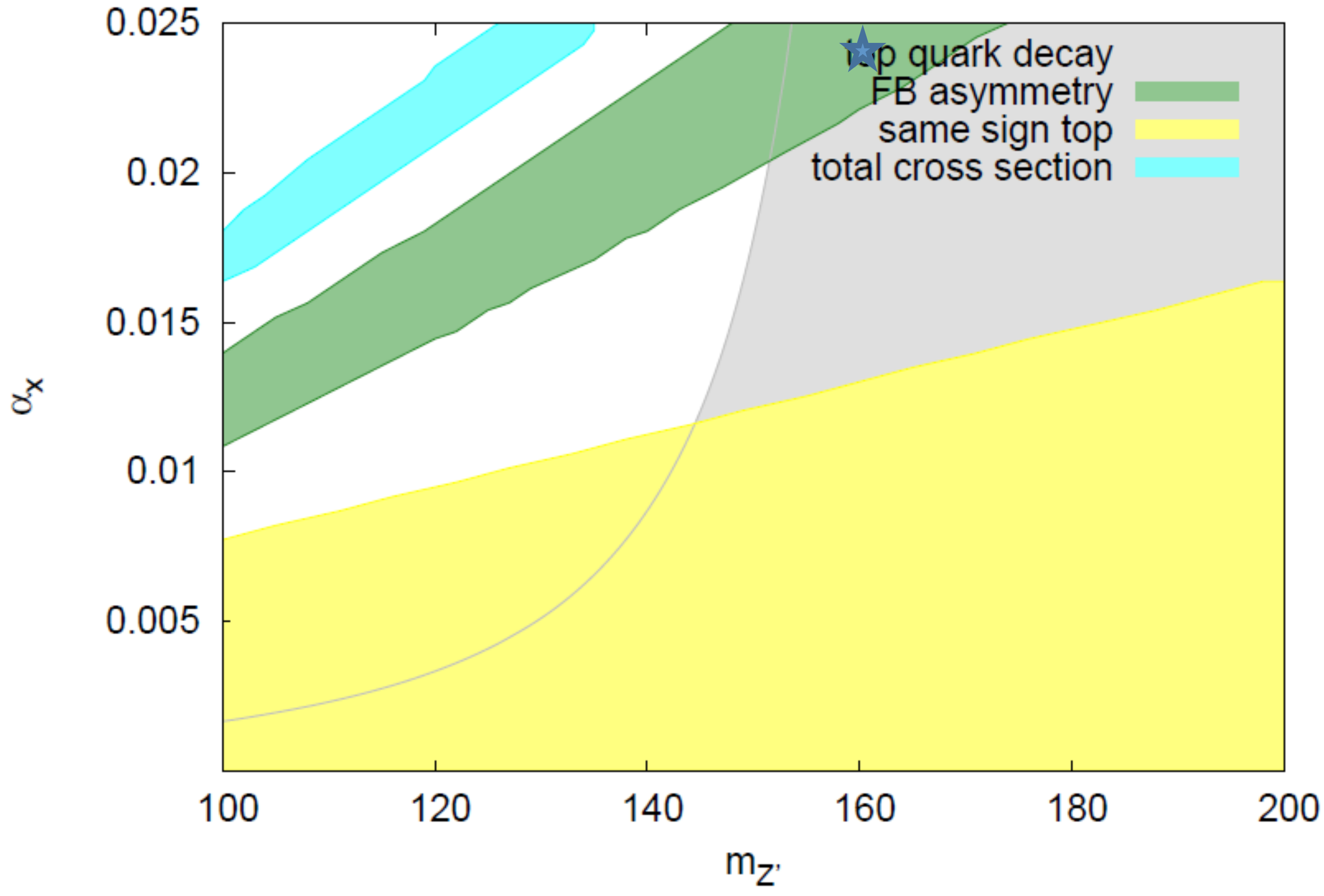


- assume Br(t →non-SM)<5% .

- choose either $m_{Z'} < m_t$ or $m_h < m_t$.

Favored region

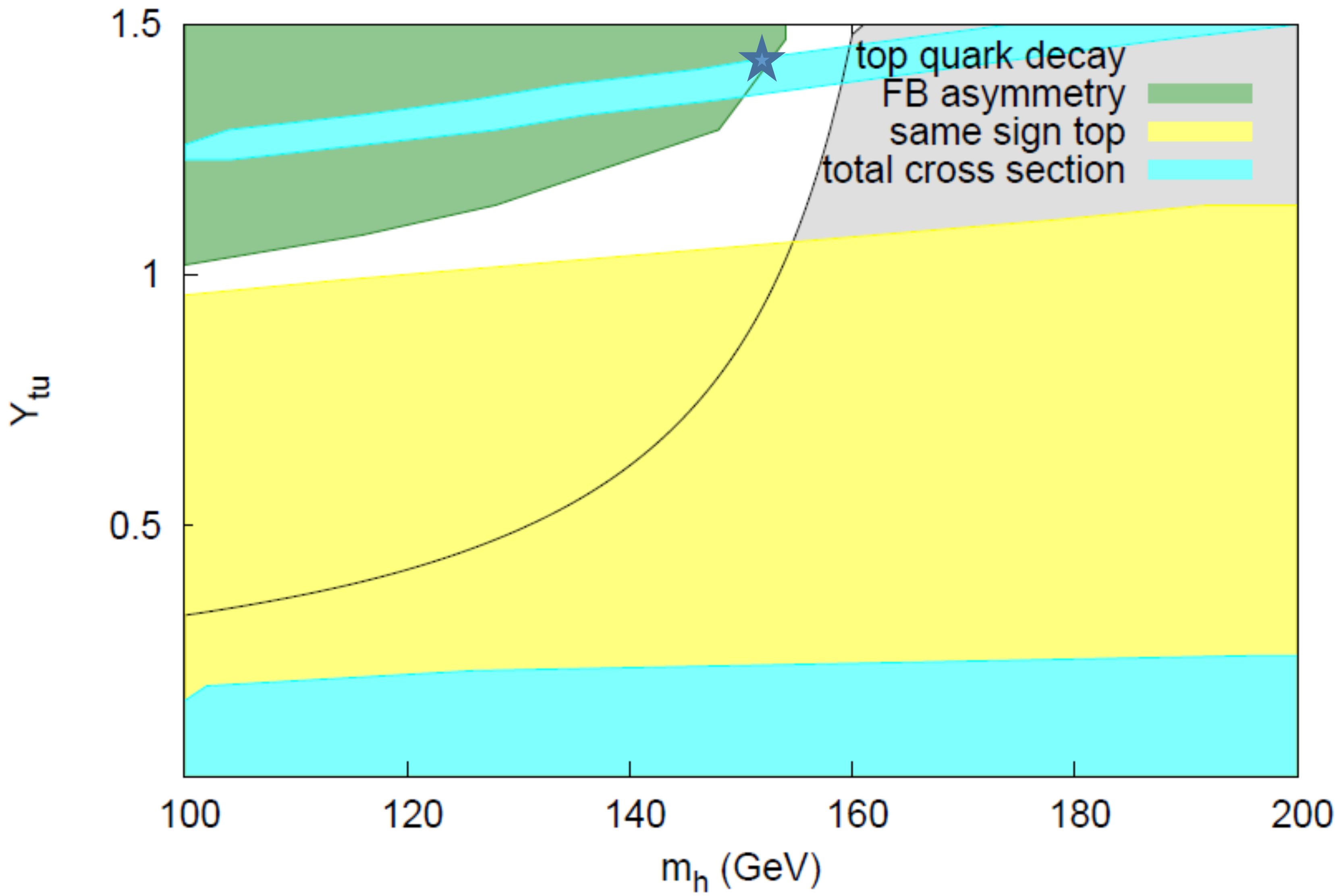
Z′ dominant case



★ = similar to Jung, Murayama, Pierce, Wells' model (PRD81)

Favored region

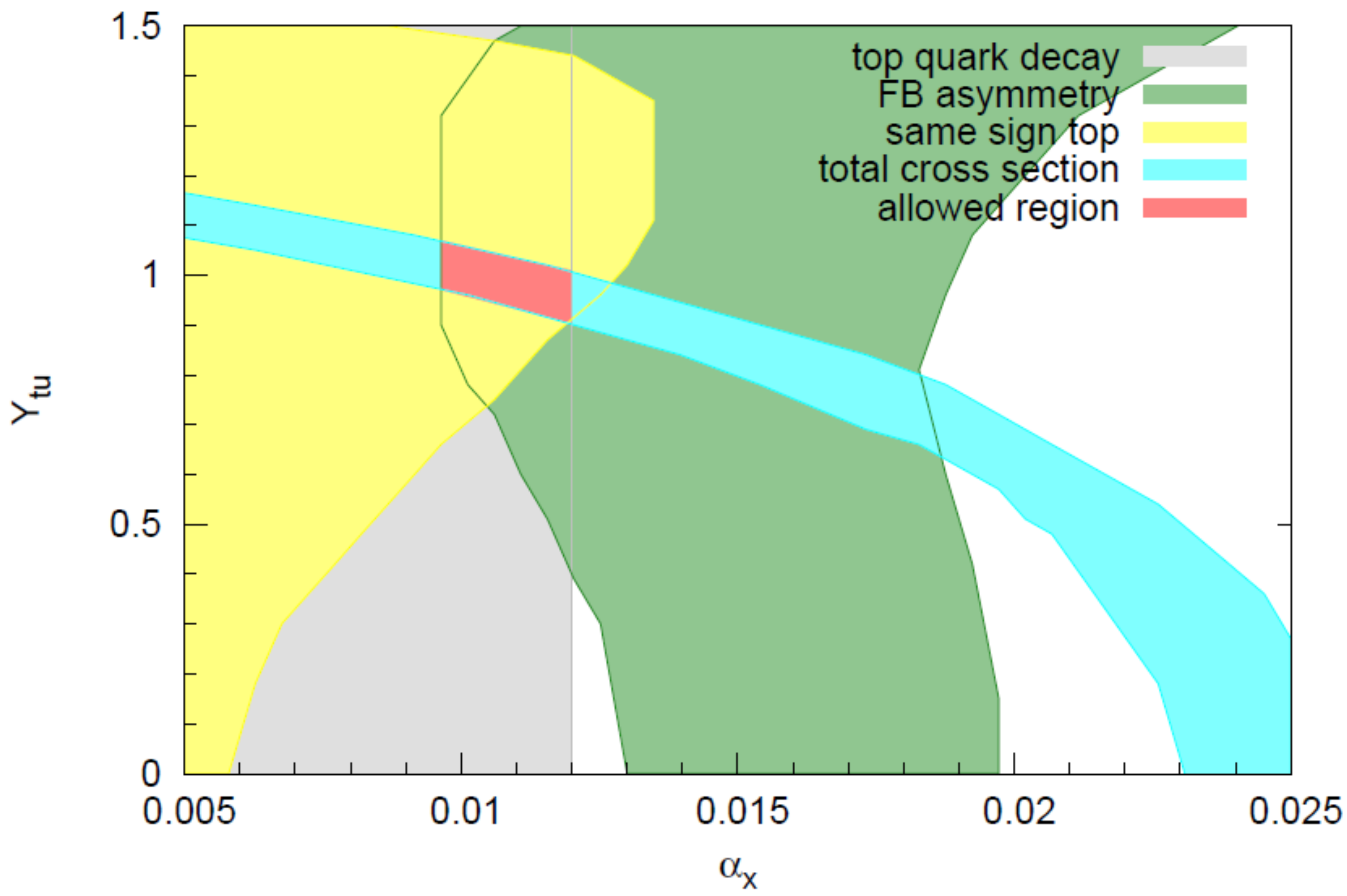
Scalar Higgs (h) dominant case



★ = similar to Babu, Frank, Rai's model (PRL107)

Favored region

Z′+h+a case



$m_{Z'} = 145$ GeV

$m_h = 180$ GeV

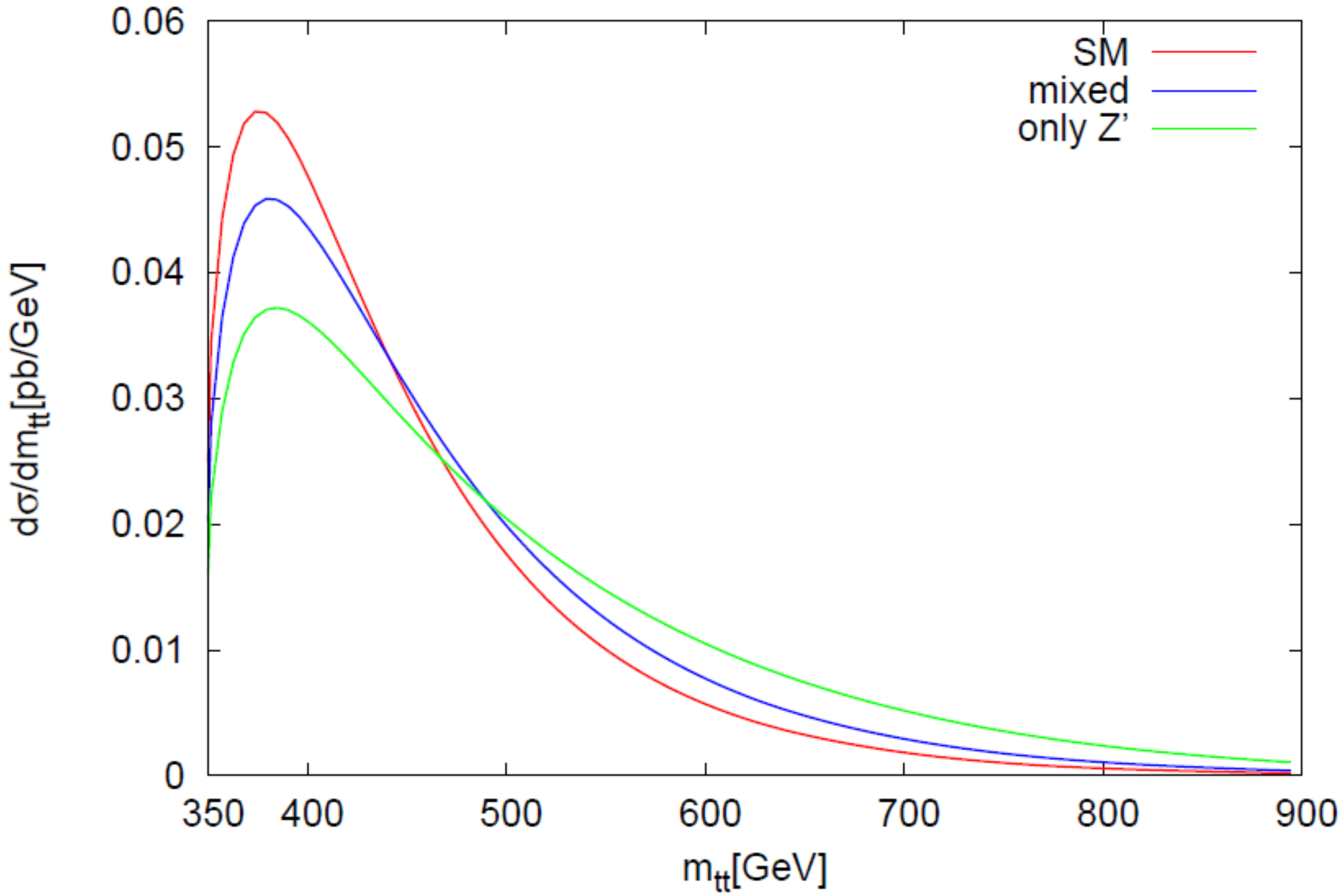
$m_a = 300$ GeV

$Y^a_{tu} = 1.1$

$A_{FB} = 0.084 \sim 0.12$

consistent with CMS data, but not with ATLAS data.

Invariant mass distribution



Only Z′ case

$m_{Z'} = 145 \text{ GeV}$

$\alpha_x = 0.029$

mixed case

$m_{Z'} = 145 \text{ GeV}$

$m_h = 180 \text{ GeV}$

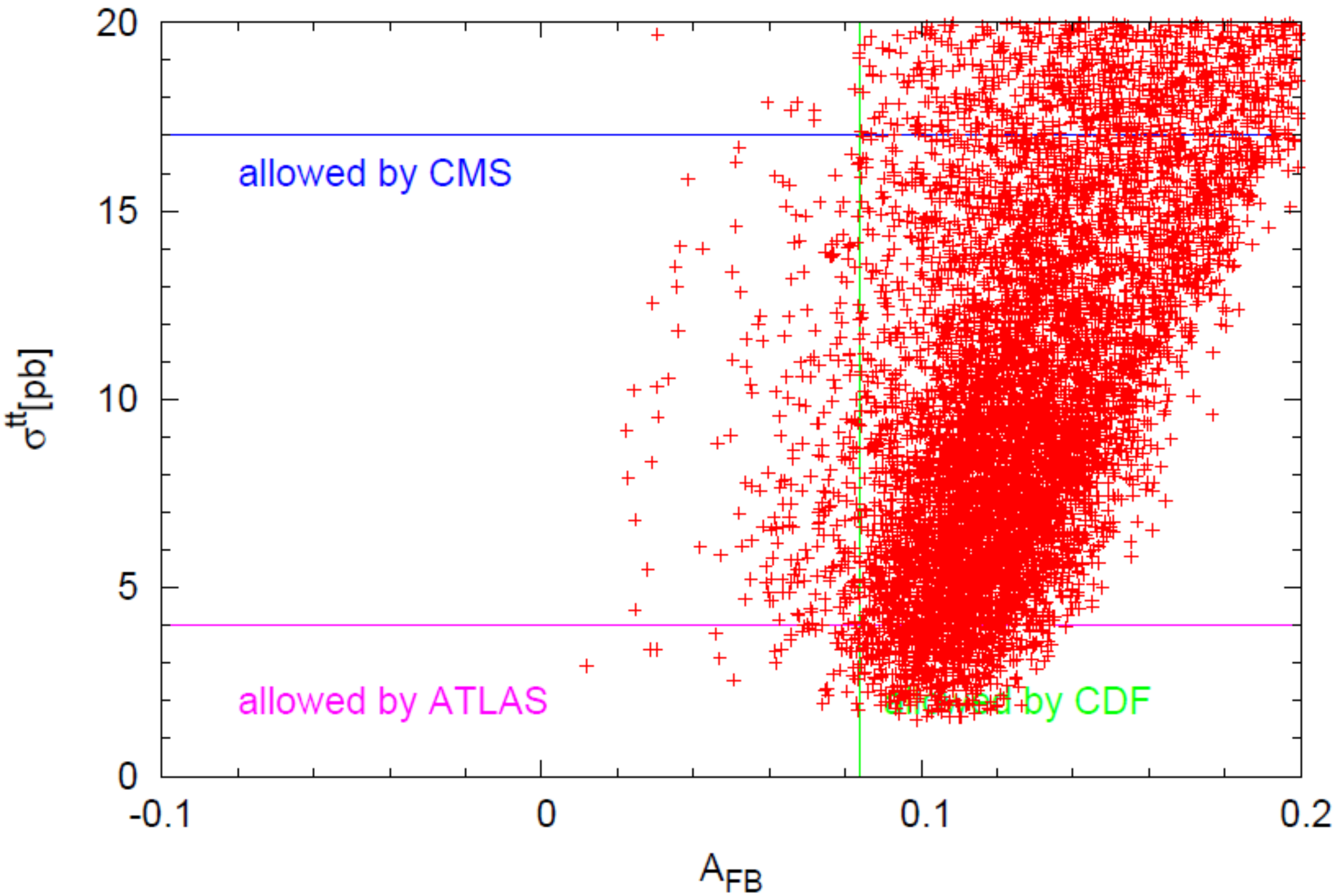
$m_a = 300 \text{ GeV}$

$\alpha_x = 0.01$

$Y_{tu} = 1.0$

$Y_{tu}^a = 1.1$

A_{FB} versus σ_{tt}



$m_{Z'} = 145$ GeV

180 GeV $< m_h < 1$ TeV

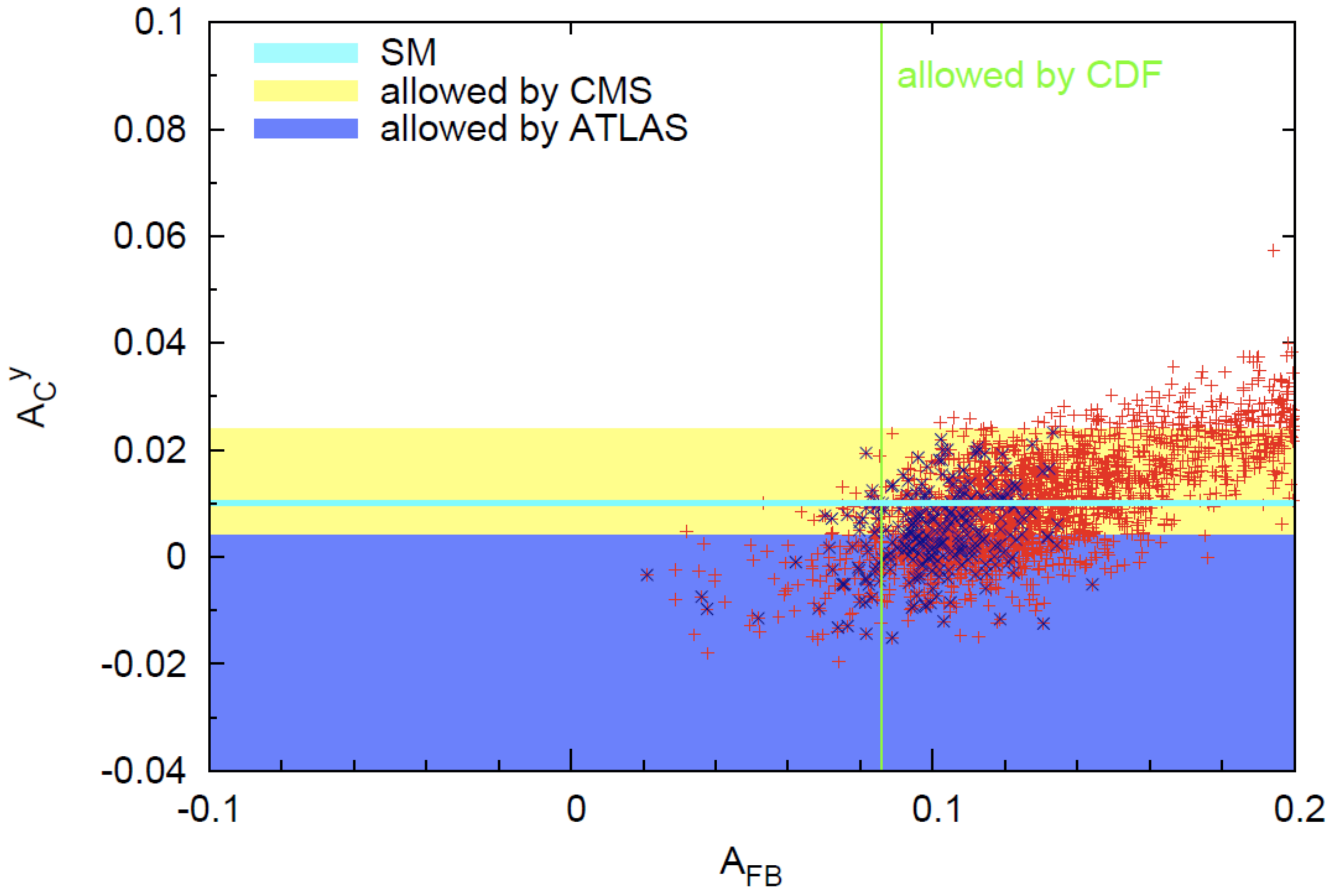
180 GeV $< m_a < 1$ TeV

$0.005 < \alpha_X < 0.025$

$0.5 < Y_{tu} < 1.5$

$0.5 < Y_{tu}^{a} < 1.5$

A_{FB} versus A_C^y



$m_{Z'} = 145$ GeV

180 GeV$< m_h < 1$ TeV

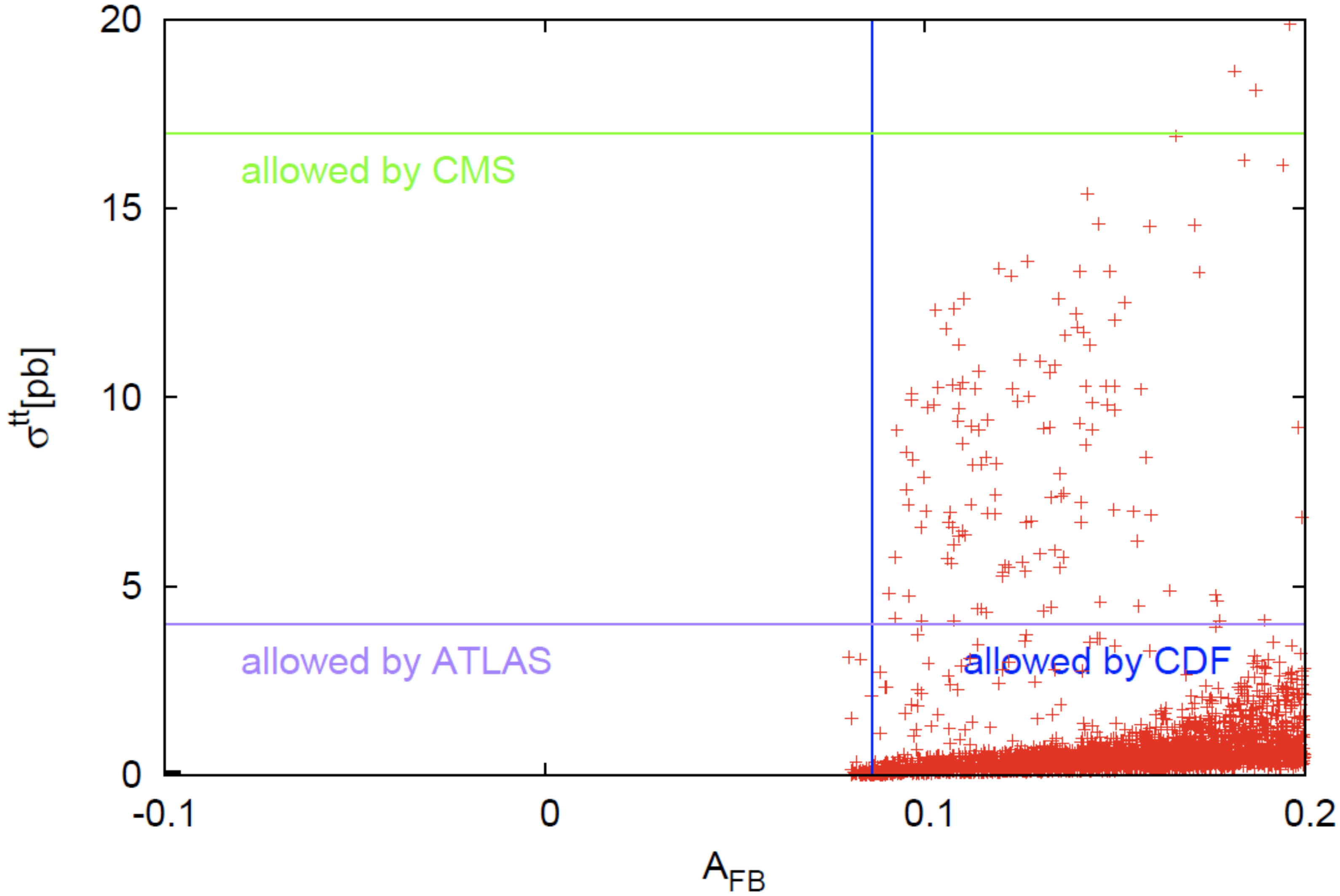
180 GeV$< m_a < 1$ TeV

$0.005 < \alpha_X < 0.025$

$0.5 < Y_{tu} < 1.5$

$0.5 < Y_{tu}^a < 1.5$

A_{FB} versus σ_{tt}



$m_h = 126$ GeV

180 GeV$< m_{Z'} < 1.5$ TeV

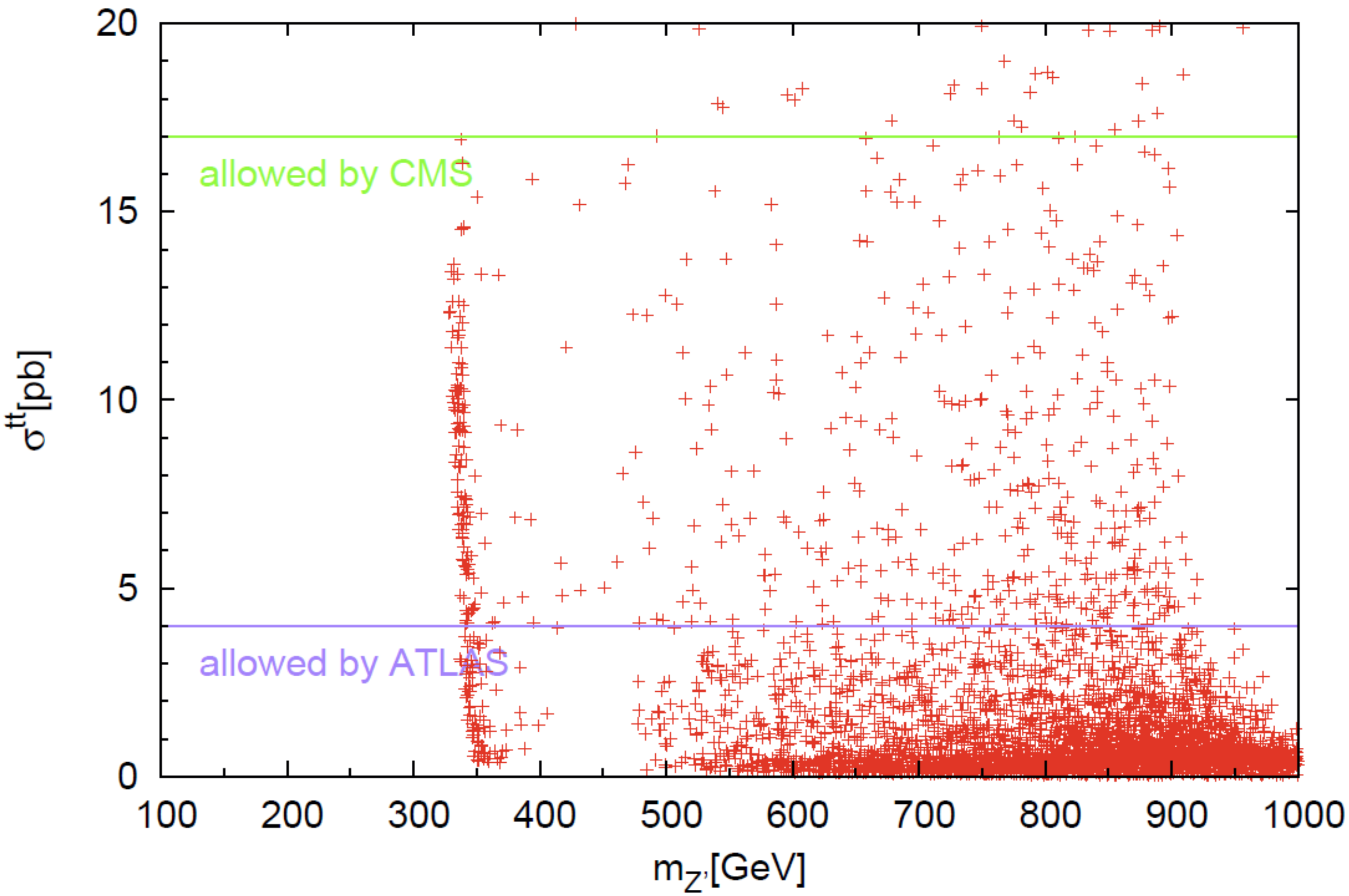
180 GeV$< m_a < 1$ TeV

$0.005 < \alpha_X < 0.025$

$0.1 < Y_{tu} < 0.5$

$0.1 < Y_{tu}^a < 1.5$

$m_{Z'}$ versus σ_{tt}



$m_h = 126$ GeV

180 GeV$< m_{Z'} < 1.5$ TeV

180 GeV$< m_a < 1$ TeV

$0.005 < \alpha_X < 0.025$

$0.1 < Y_{tu} < 0.5$

$0.1 < Y_{tu}{}^a < 1.5$

Conclusions

- Top A_{FB} is the only signal for new physics in the top sector.
- It has motivated brilliant ideas of new physics, but many of them are rather phenomenological.
- We constructed a compete U(1)′ model where only the right-handed up-type quarks in the standard model are charged.
- requires extra Higgs doublets charged under U(1)′ for a realistic model.
- requires extra chiral fermions for anomaly cancellation → CDM.
- Destructive interferences between Z', h, and a reduce the rate for the sa me sign top pair production.

Conclusions

- Simple models would be excluded by the measurements for the charge asymmetry , same sign top pair production, the large tail behavior of the m_{tt} distribution at the LHC.

- In order to confirm new physics models, anticipate the direct production of new particles in new physics models.

- The most important lesson of our study : It is mandatory to extend the Higgs sector, if there are new vector bosons with chiral couplings to the SM fermions. This is necessary in order that we can write a realistic Yukawa couplings for the SM fermions. Without extended Higgs sector, it is meaningless to do phenomenology.

- This is true for all models with W’, axigluons, flavor SU(3)_{RHU}, most of them introduce chiral couplings with the SM fermions. One can do the extensions for these models, similar to our works presented at this talk.

Further Tests

- $t \to c + H$ and $t \to u + H$
- $pp \to t + H$
- $pp \to Z^{'} \to t\bar{u} + u\bar{t}$
- $Z^{'} \to H^{\pm}W^{\mp}$

The 1st two modes are clean tests, since we know the Higgs mass

Lessons for Model Building

- Specify local gauge sym, matter contents and their representations under local gauge group
- Write down all the operators upto dim-4
- Check anomaly cancellation
- Consider accidental global symmetries
- Look for nonrenormalizable operators that break/conserve the accidental symmetries of the model

- If there are spin-1 particles, extra care should be paid : need an agency which provides mass to the spin-1 object
- Check if you can write Yukawa couplings to the observed fermion
- One may have to introduce additional Higgs doublets with new gauge interaction if you consider new chiral gauge symmetry (Ko, Omura, Yu on chiral U(1)' model for top FB asymmetry)
- Impose various constraints and study phenomenology

Conclusions

- Local gauge symmetries play a key role in the unsurpassed successful SM
- It may play the same role in DM physics ; many evidences that they really do
- $U(1)_H$ extensions of 2HDM (and multi Higgs doublet models) can be interesting possibilities to consider ; Inert 2HDM with $U(1)_H$ is a good example ; Top FBA and B anomalies
- A lot of possibilities for new ways to look at Physics of Higgs, Flavor, DM, EW phase transitions, Neutrinos (one can consider CSI as well)