2HDMs with U(1) gauge symmetry and phenomenology therein

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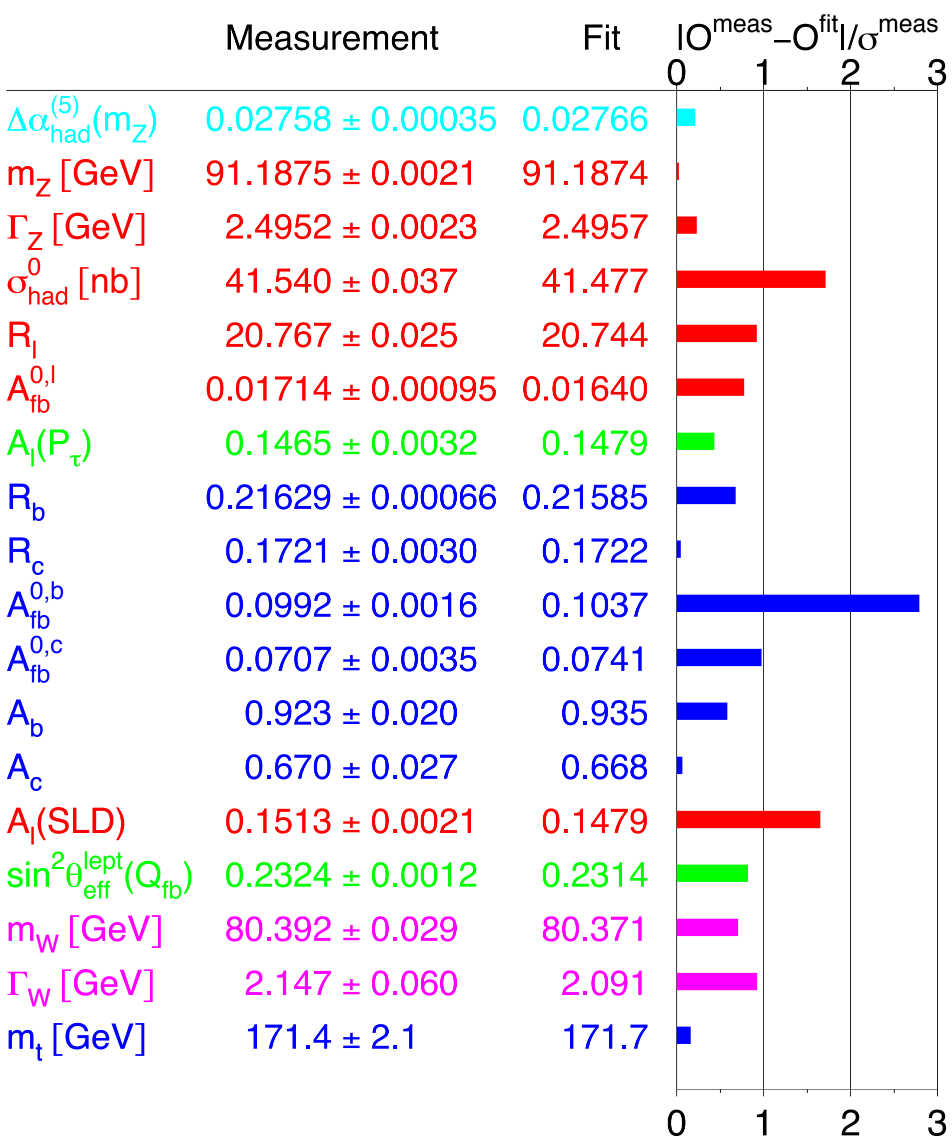
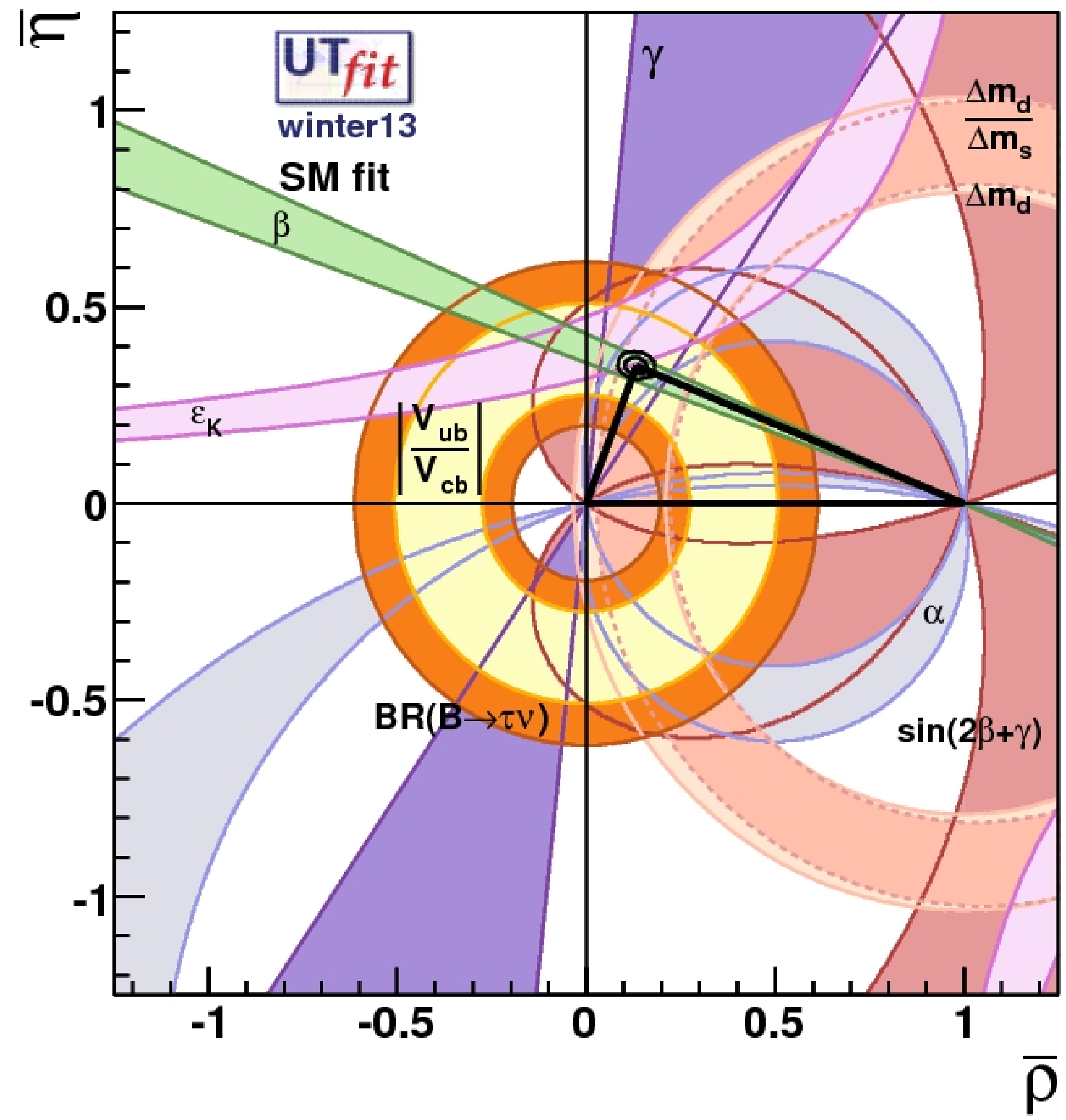
Workshop on Multi Higgs Models
@Lisbon, Portugal, Sep. 2-5 (2014)

EWPT & CKM





Almost Perfect !

SM Lagrangian

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

Based on local gauge principle

Only Higgs (~SM) and Nothing Else So Far at the LHC &

Local Gauge Principle Works !

Building Blocks of SM

- Lorentz/Poincare Symmetry
- Local Gauge Symmetry : Gauge Group + Matter Representations from Experiments
- Higgs mechanism for masses of weak gauge bosons and SM chiral fermions
- These principles lead to unsurpassed success of the SM in particle physics

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

New Physics Scale ?

- No theory for predicting new physics scale, if our renormalizable model predictions agree well with the data
- Only data can tell where the NP scales are
- Given models working up to some energy scale, we can tell new physics scale if Unitarity is violated, or Landau pole or Vacuum Instability appears
- Otherwise we don't know for sure where is new physics scale

Why extended H sector ?

- Thermal WIMP dark matter with dark gauge symmetry often calls for additional singlet scalar(s)
- Higgs sector of MSSM : 2HDMs
- Multi Higgs doublets in string inspired models
- New Higgs doublets needed if there is a new chiral gauge interactions for the SM fermions
- TeV seesaw with triplet Higgs, and so on

Contents

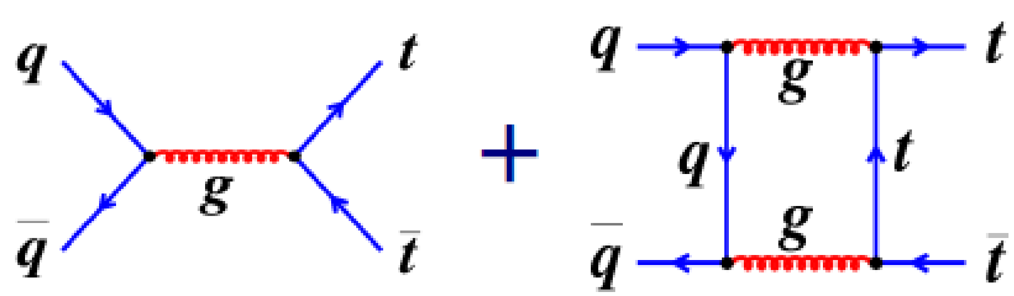
- Z' model for Top FBA and Flavor dependent U(1)' model with multi-Higgs Doublets
- 2HDMs with U(1) Higgs flavor symmetry
- Inert DM with local U(1) Higgs flavor

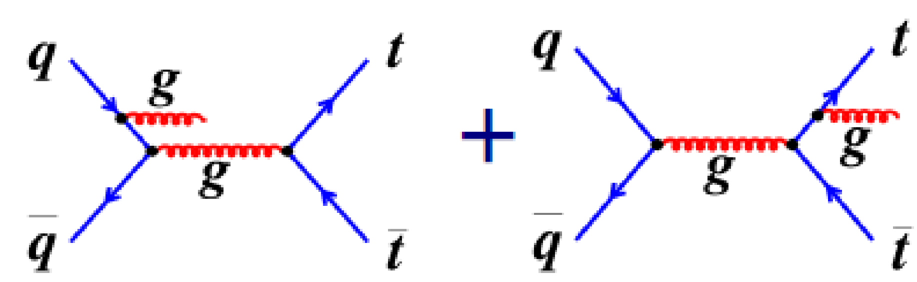
Z' model for Top FBA and Flavor dependent U(1)' model with multi-Higgs doublets

Top Charge Asym in QCD (Muller@ICHEP2012)

NLO QCD: interference of higher order diagrams leads to asymmetry for $t\bar{t}$ produced through $q\bar{q}$ annihilation:

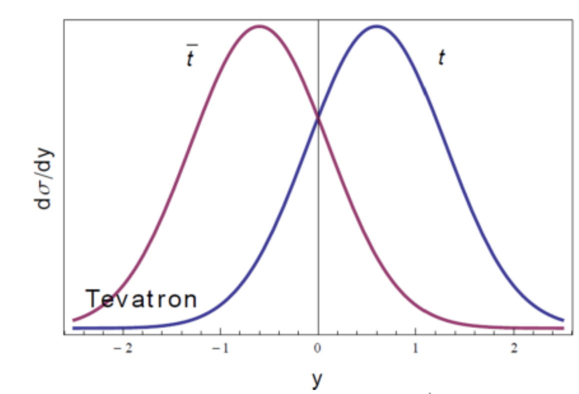
- Top quark is emitted preferentially in direction of the incoming quark
- Antitop quark opposite
- Production through new processes may lead to different asymmetries





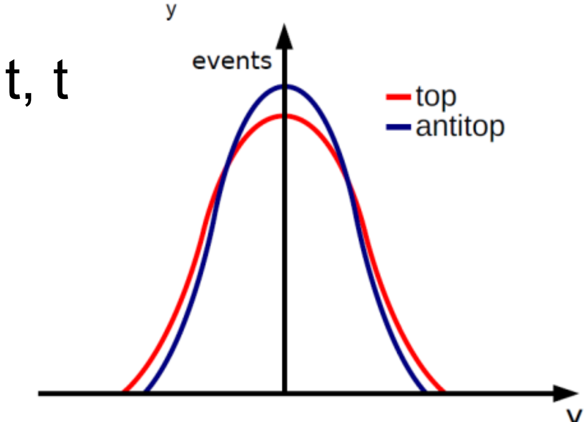
- At Tevatron: define forward-backward asymmetry

$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

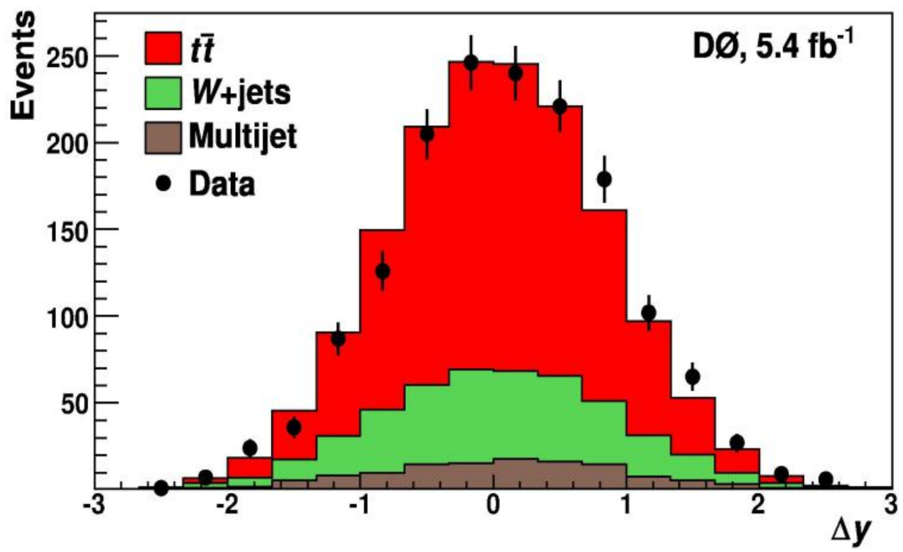


- At LHC: define asymmetry in the widths of rapidity distributions of t, $\bar{t}$

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \qquad \Delta|y| = |y_t| - |y_{\bar{t}}|$$



ICHEP 2012 : Top FBA (Muller's talk)



Δy in the lepton-jets channel

Measured asymmetry on detector level after bkg subtraction:

A_{FB} det = 0.092 ± 0.037 (stat+syst)

MC@NLO: A_{FB} det = 0.024 ± 0.007

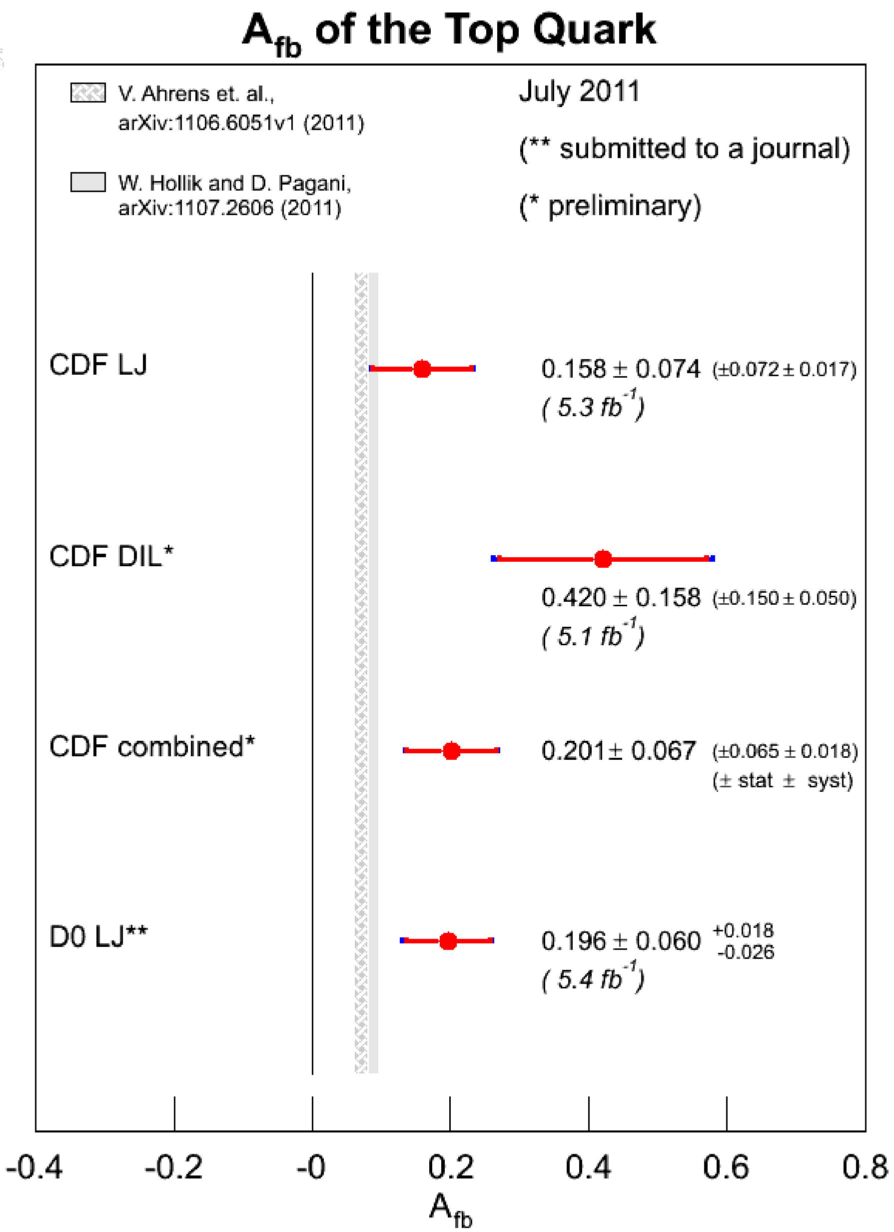
Measured asymmetry on parton level:

A_{FB} = 0.196 ± 0.065 (stat+syst)

D0 results in the di-lepton channel:

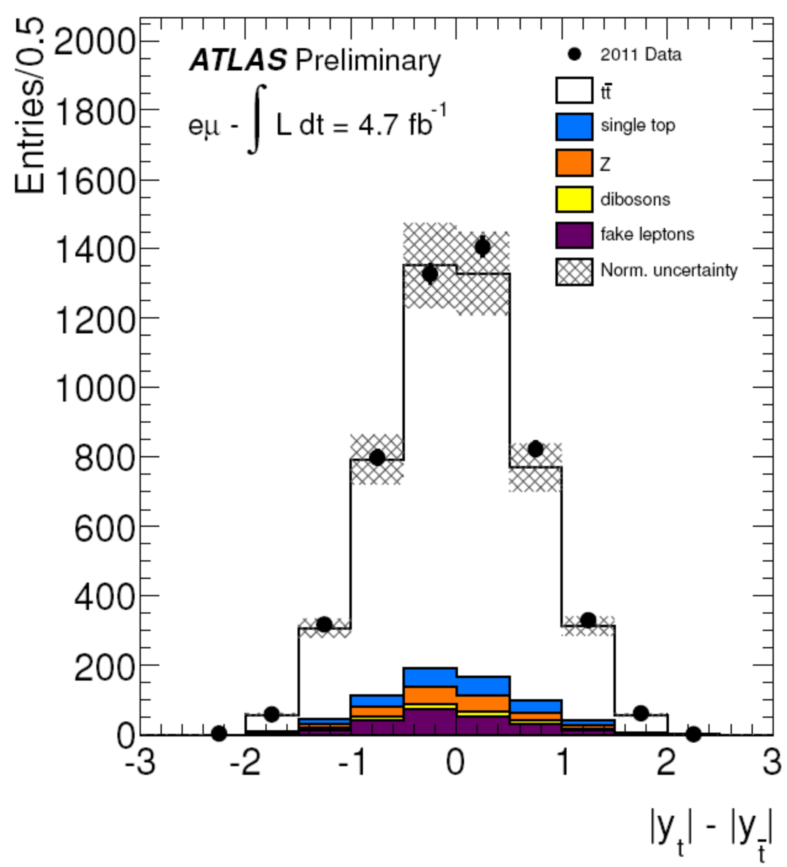
A_{FB} = 0.118 ± 0.032

Summary:

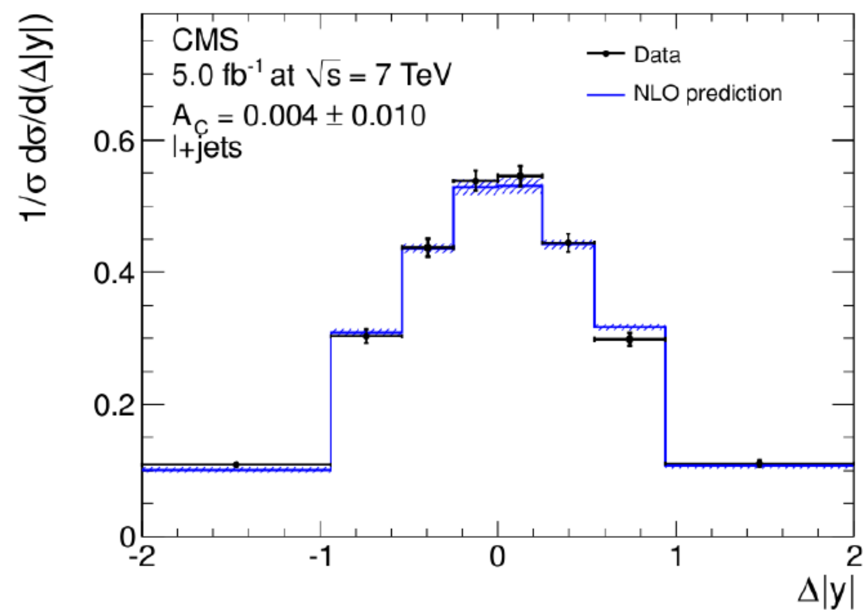


Both CDF and D0 see significant asymmetry in $t\bar{t}$ production in all channels with strong dependence on m_{tt}, in conflict with the SM

ICHEP 2012 : Top C Asym (Muller's talk)



ATLAS-CONF-2012-057

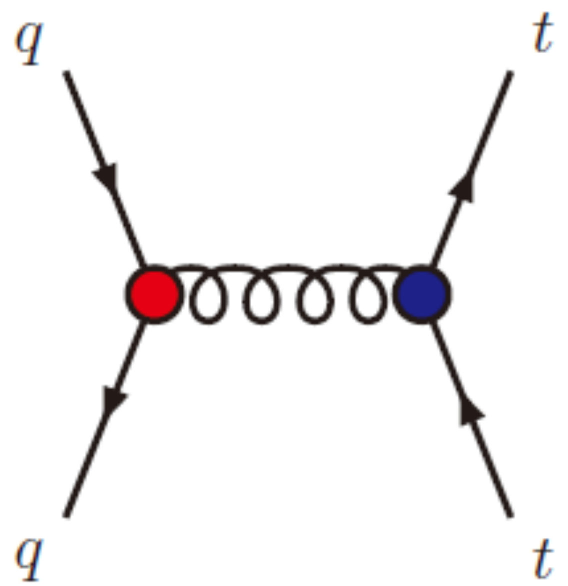


CMS PAPER TOP-11-030

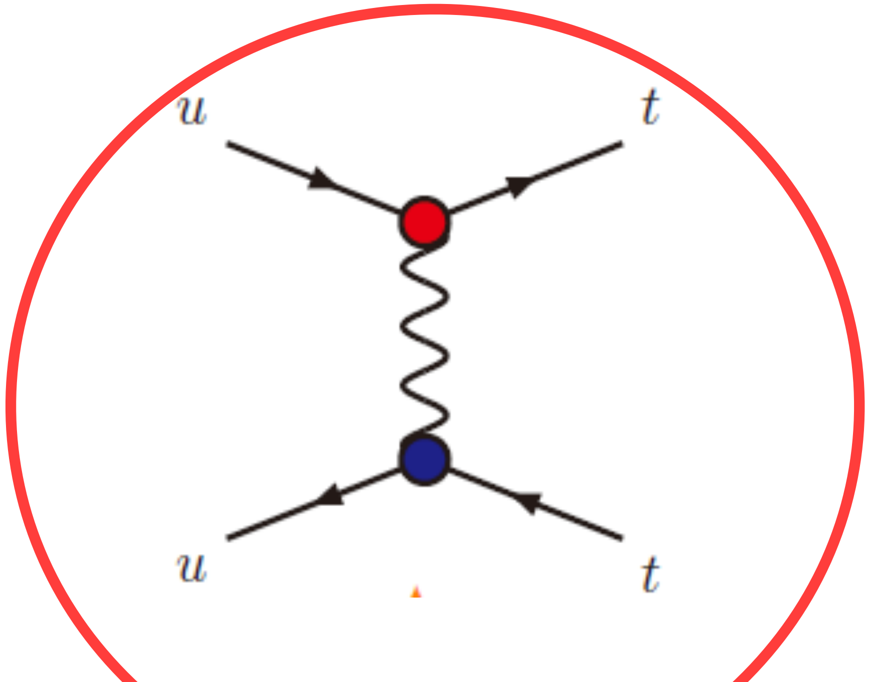
- ATLAS: A_C = 0.029 +- 0.018 (stat.) +- 0.014 (syst.)
- CMS: Corrected: A_C = 0.004 +- 0.010 (stat.) +- 0.011 (syst.)

- Theory (Kühn, Rodrigo): A_C = 0.0115 +- 0.0006

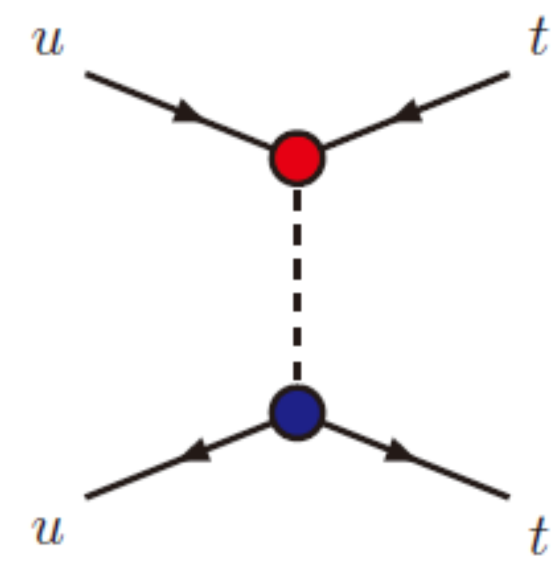
New physics models for top A_{FB}



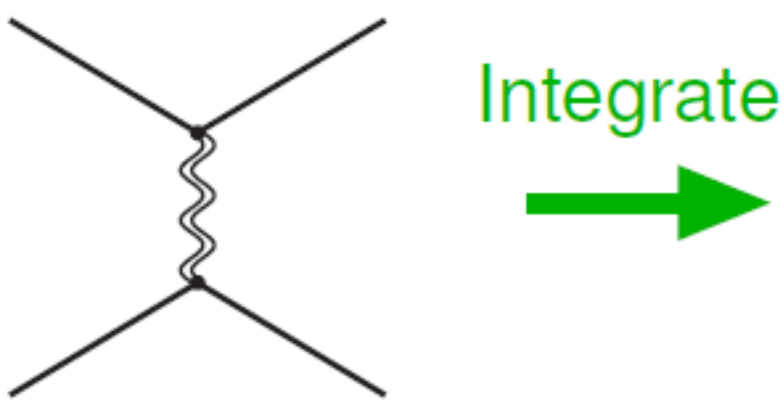
s-channel: coloured resonance $\mathcal{G}_\mu$



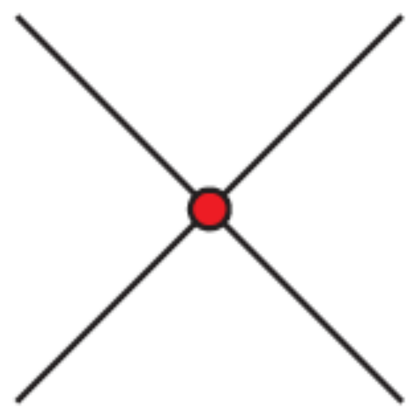
t-channel: Z', W', ϕ



u-channel: exotic scalars



(new) heavy VB

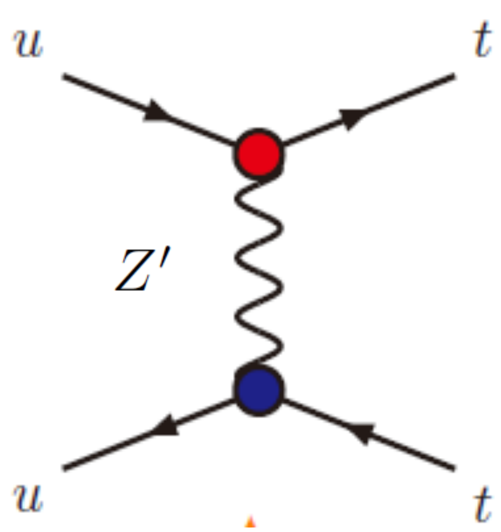


4-fermion interaction

Ko et al (2009), (2010);
Degrande et al (2010); etc.

- flavor dependent.
- challenging to construct a realistic model.
  - anomaly free, renormalizable, and realistic Yukawa couplings.

Z′ model

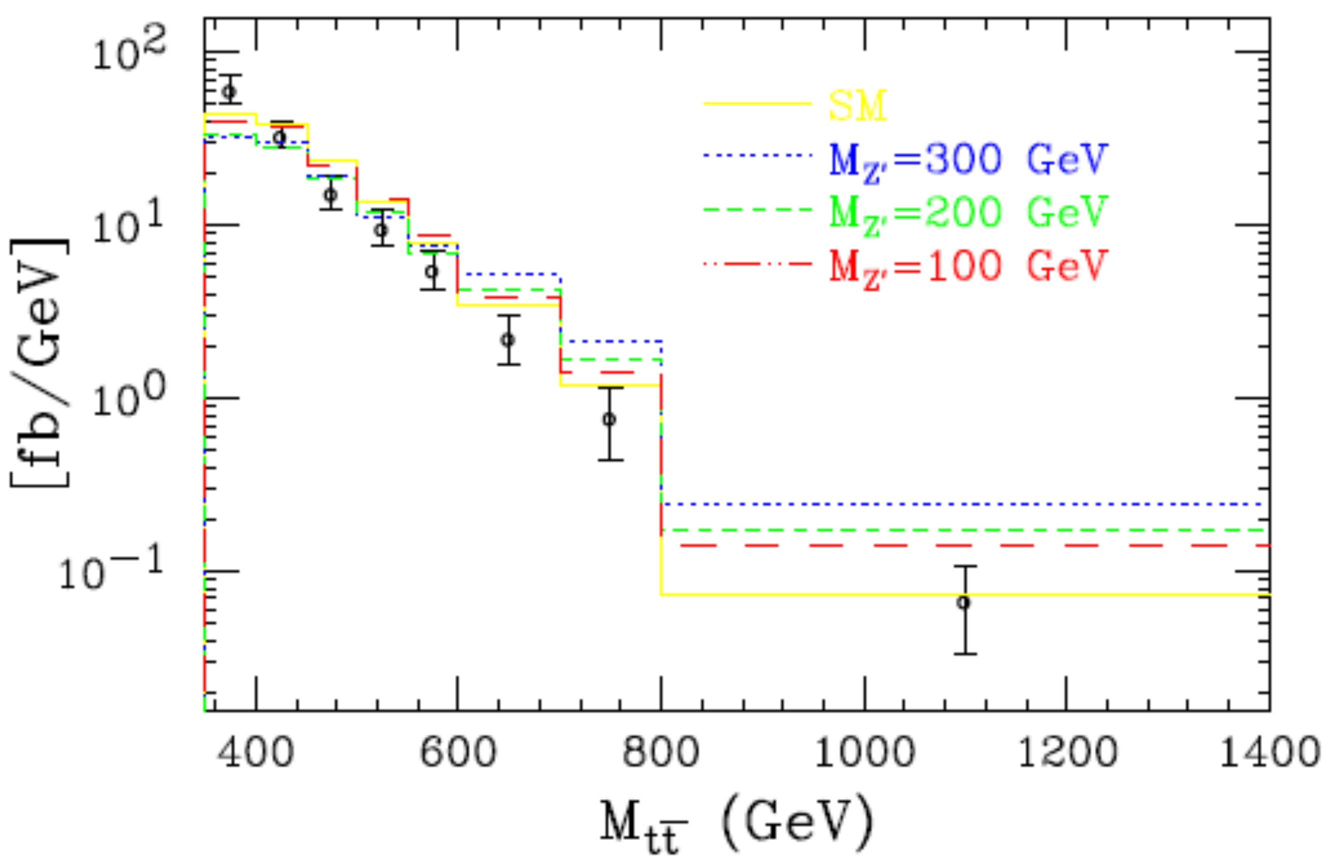


Jung, Murayama, Pierce, Wells, PRD81♪

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

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

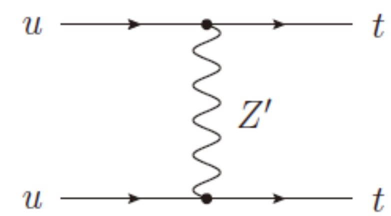
- In general, could have different couplings to the top and antitop quarks.



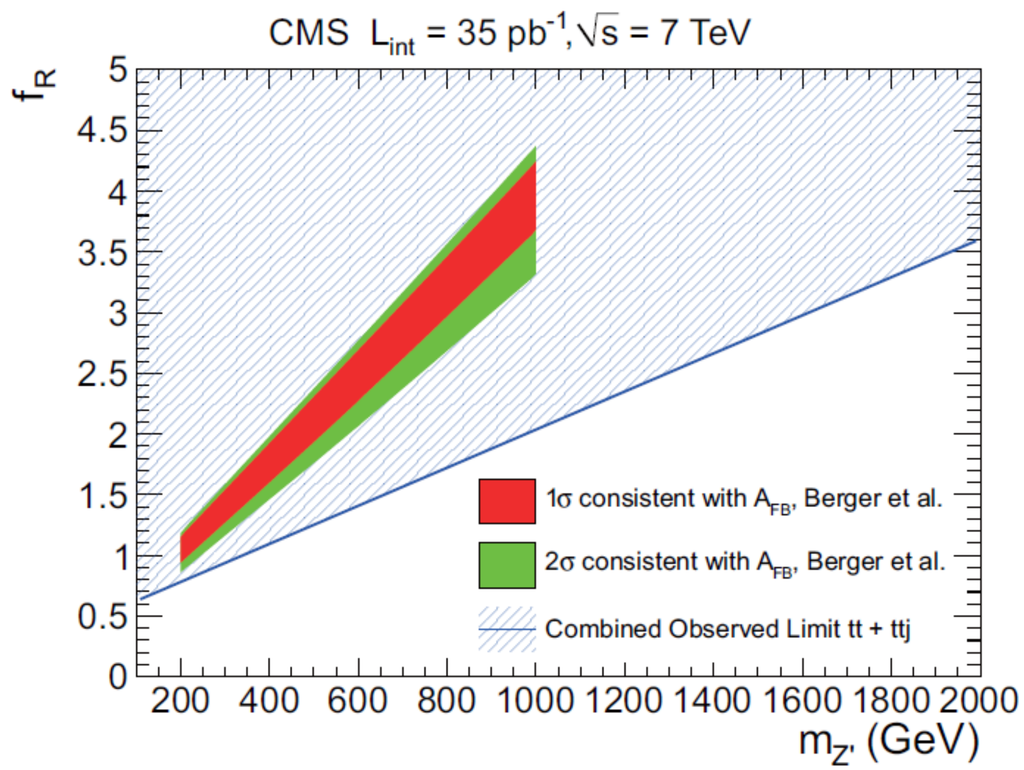
- light Z′ is favored from the M_{tt} distribution.

- severely constrained by the same sign top pair production.
  - the t-channel scalar exchange model has a similar constraint.

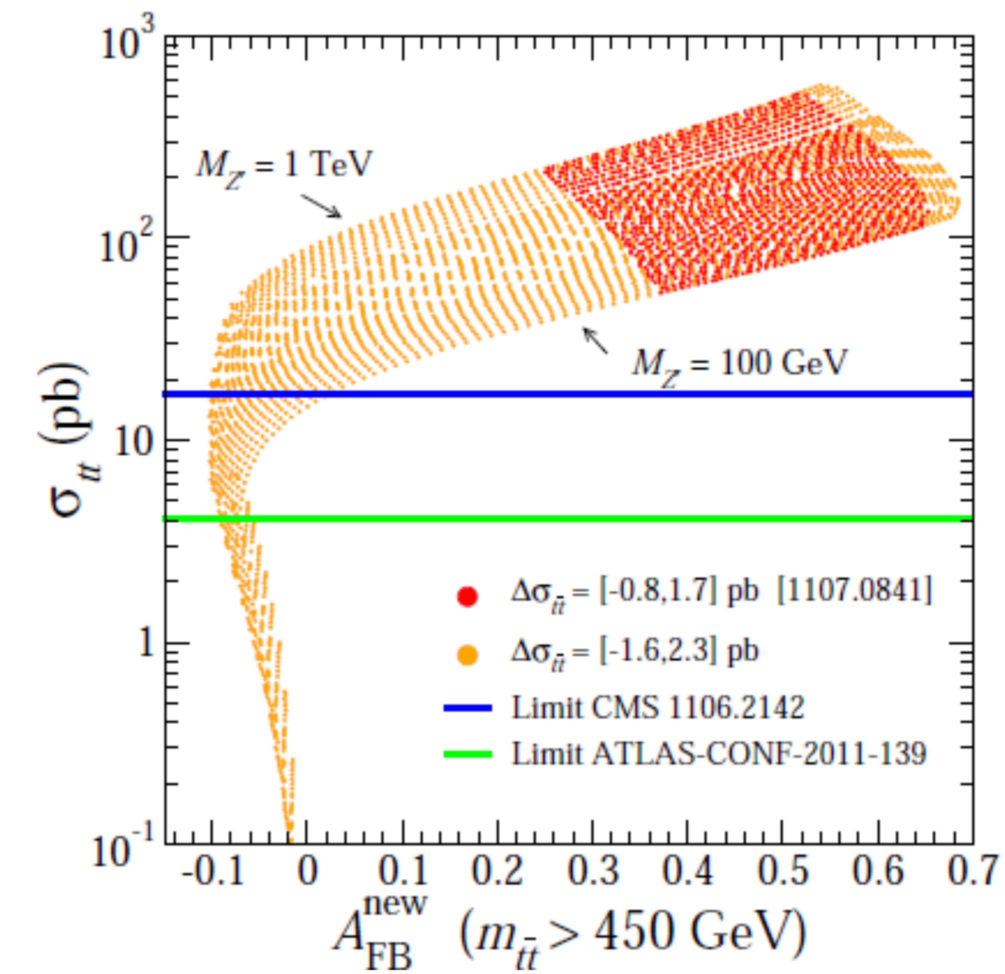
Same sign top pair production at LHC



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



General exclusion plot



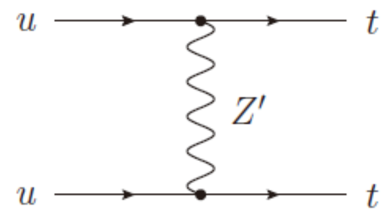
CMS: σ(pp→tt(j))<17 pb at 95C.L.
ATLAS: σ(pp→tt(j))<4 pb at 95C.L.

CMS, JHEP1108; ATLAS-CONF-2011-169♪

Aguilar-Saavedra, TOP2011♪

- the t-channel Z′ or scalar exchange models are excluded?

Same sign top pair production at LHC



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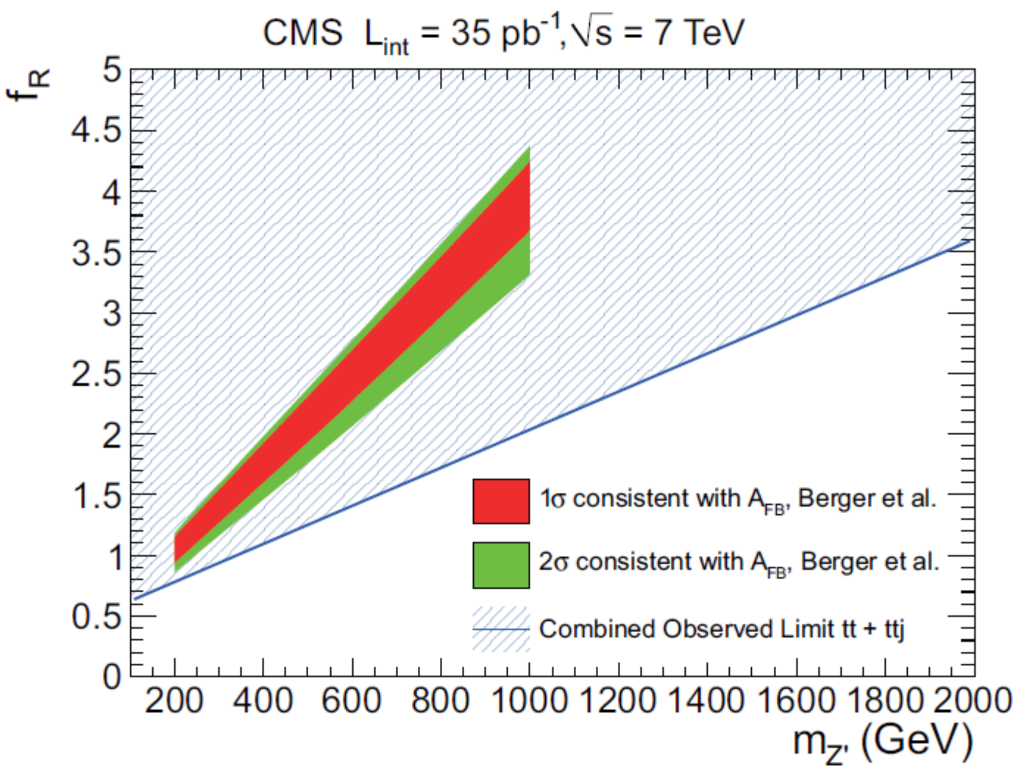

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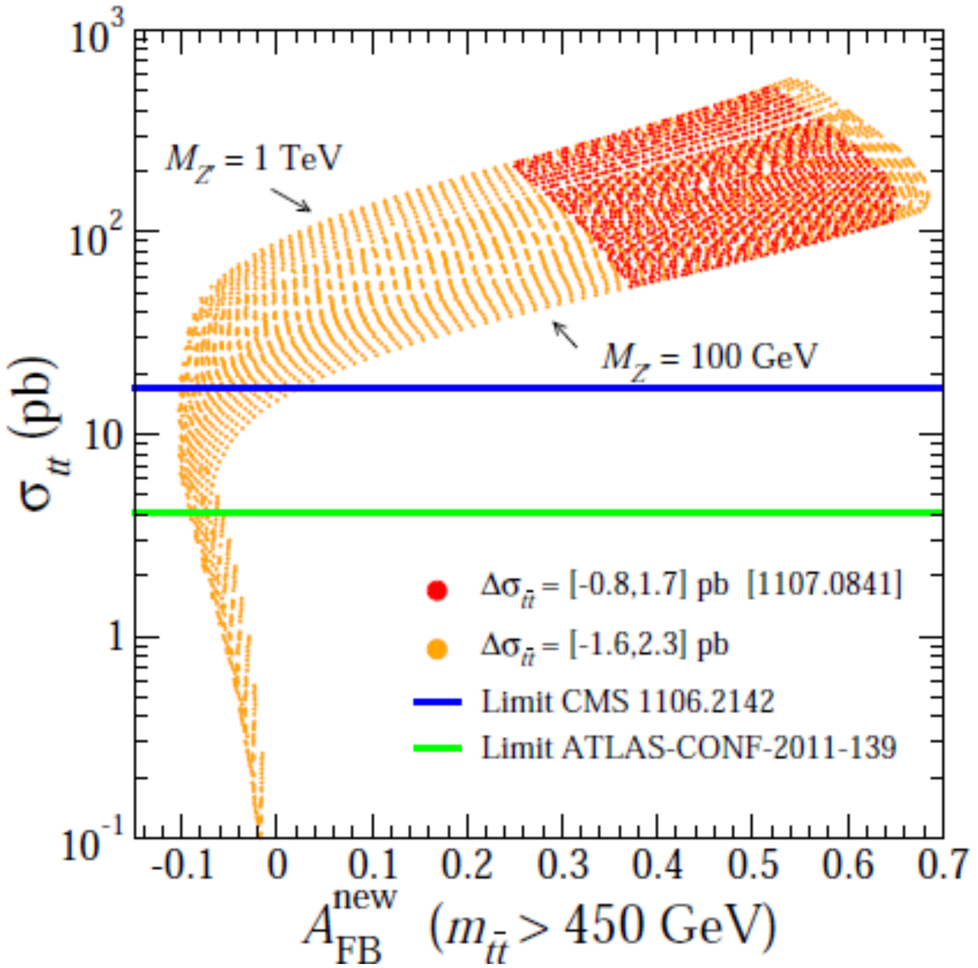


Aguilar-Saavedra, TOP2011

- the t-channel Z′ or scalar exchange models are excluded?
- the answer is NO.

Is the Z' model for top FB asym excluded by the same sign top pair production ?

Is the Z' model for top FB asym excluded by the same sign top pair production ?

NO !

NOT YET !

Life is not that 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, EPJC 73 (2013) 2269
(4) arXiv:1212.4607, JHEP 1303 (2013) 151

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 ?

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

Not gauge invariant

Gauge invariant : OK!

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

- Charge assignment : SM fermions

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)'$
Q_1	3	2	1/6	q_L
Q_2	3	2	1/6	q_L
Q_3	3	2	1/6	q_L
$\overline{D_1}$	$\overline{3}$	1	1/3	$-q_L$
$\overline{D_2}$	$\overline{3}$	1	1/3	$-q_L$
$\overline{D_3}$	$\overline{3}$	1	1/3	$-q_L$
$\overline{U_1}$	$\overline{3}$	1	$-2/3$	u_1
$\overline{U_2}$	$\overline{3}$	1	$-2/3$	u_2
$\overline{U_3}$	$\overline{3}$	1	$-2/3$	u_3
H	1	2	1/2	0

LH quarks and RH down-type quarks have universal couplings.

Flavor-dependent

Higgs

Flavor-dependent U(1)′ model

- Charge assignment : Higgs fields

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
H_1	1	2	1/2	$-q_L - u_1$
H_2	1	2	1/2	$-q_L - u_2$
H_3	1	2	1/2	$-q_L - u_3$
Φ	1	1	1	$-q_\Phi$

- introduce three Higgs doublets charged under U(1)′ in addition to the S M Higgs which is not charged under U(1)′.

$$\begin{aligned} V_y &= y^u_{i1} H_1 \overline{U_1} Q_i + y^u_{i2} H_2 \overline{U_2} Q_i + y^u_{i3} H_3 \overline{U_3} Q_i \\ &+ y^d_{ij} \overline{D_j} Q_i i\tau_2 H^\dagger \\ &+ y^e_{ij} \overline{E_j} L_i i\tau_2 H^\dagger + y^n_{ij} H \overline{N_j} L_i . \end{aligned}$$

- The U(1)′ is spontaneously broken by U(1)′ charged complex scalar Φ.

Anomaly Cancellation : Sol. I

- Anomaly cancelation requires extra fermions I: SU(2) doublets

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
Q'	3	2	1/6	$-(q_1+q_2+q_3)$
D'_R	3	1	−1/3	$-(d_1+d_2+d_3)$
U'_R	3	1	2/3	$-(u_1+u_2+u_3)$
L'	1	2	−1/2	0
E'	1	1	−1	0
l_{L1}	1	2	−1/2	Q_L
l_{R1}	1	2	−1/2	Q_R
l_{L2}	1	2	−1/2	$-Q_L$
l_{R2}	1	2	−1/2	$-Q_R$

one extra generation

$SU(2)_L{}^2 \cdot U(1)'$

vector-like pairs

$U(1)'^2 \cdot U(1)$

a candidate for CDM

Anomaly Cancellation : Sol. II

- Anomaly cancelation requires extra fermions II: $SU(3)_c$ triplets

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)'$
q_{L1}	3	1	$-1/3$	Q_L
q_{R1}	3	1	$-1/3$	Q_R
q_{L2}	3	1	$-1/3$	$-Q_L$
q_{R2}	3	1	$-1/3$	$-Q_R$

- introduce the singlet scalar X to the SM in order to allow the decay of th
e extra colored particles.

$$V_m = \lambda_i X^\dagger \overline{D_{Ri}} q_{L1} + \lambda_i X \overline{D_{Ri}} q_{L2}$$

a candidate for CDM

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

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

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

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

∝ 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

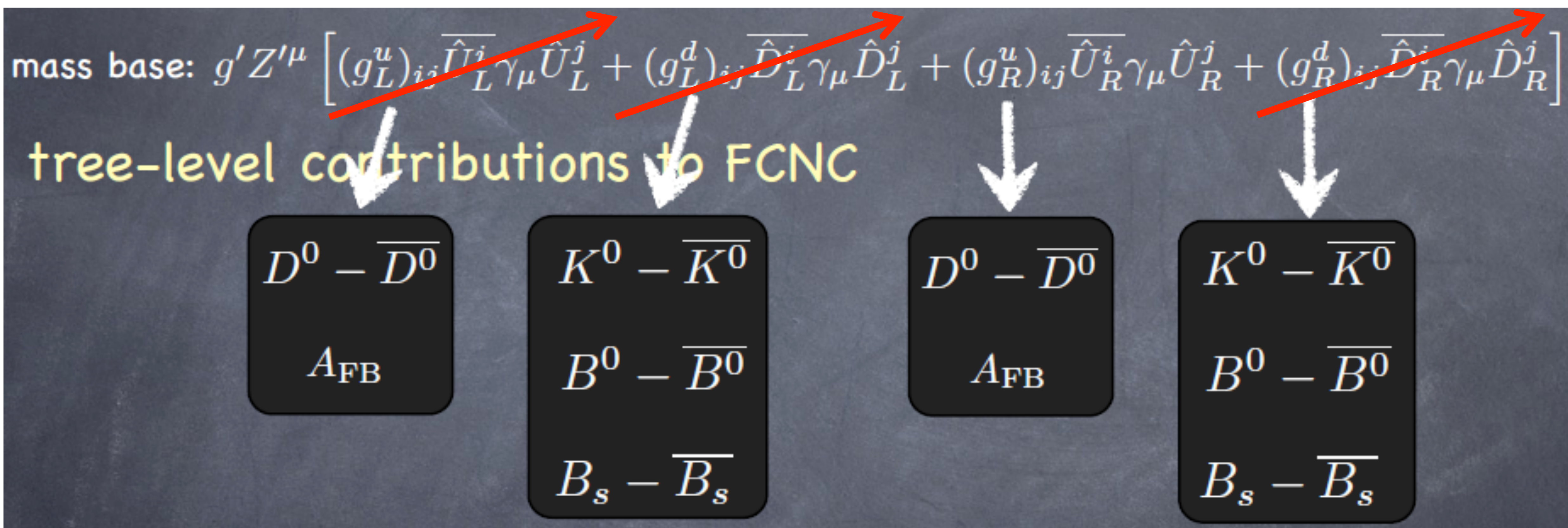
- Z′ interacts only with the right-handed up-type quarks

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

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

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

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

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

NonMFV from flavor dep U(1) interactions

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

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

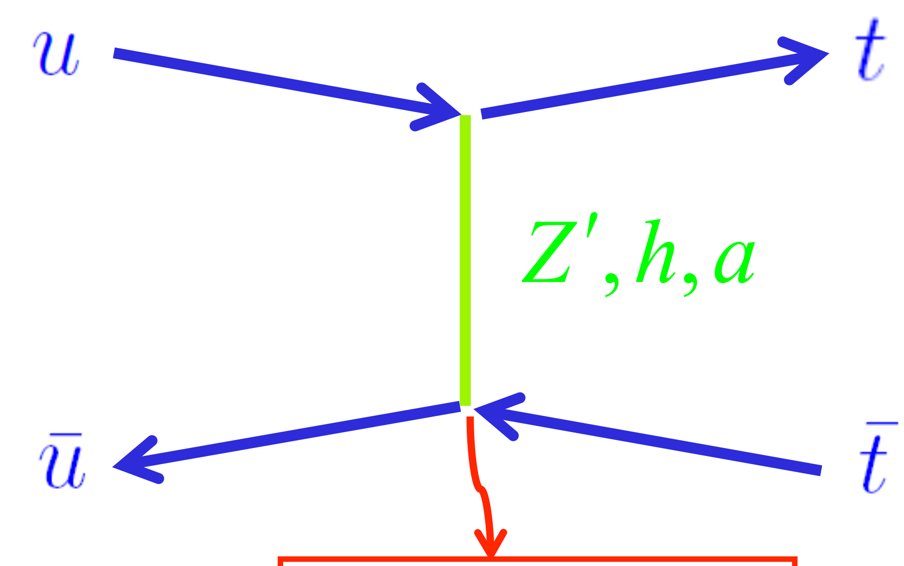
$$Y^{ad}_{ij} = \frac{m^d_i\tan\beta}{v}\delta_{ij},$$

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

Top-antitop pair production

1. Z′ dominant scenario

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



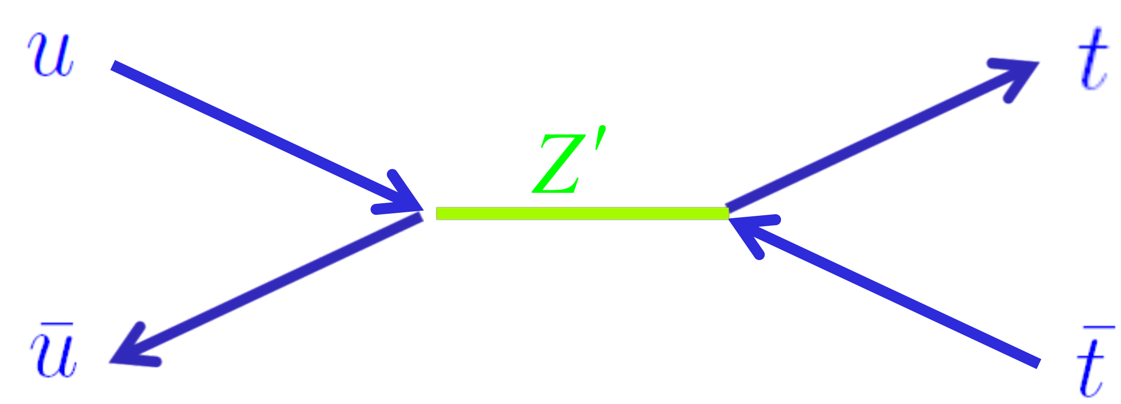
$$\alpha_X = \frac{(g' g^u_{Rut})^2}{4\pi}, Y_{tu}, Y^a_{tu}$$

2. Higgs dominant scenario

cf. Babu, Frank, Rai, PRL107(2011)♪

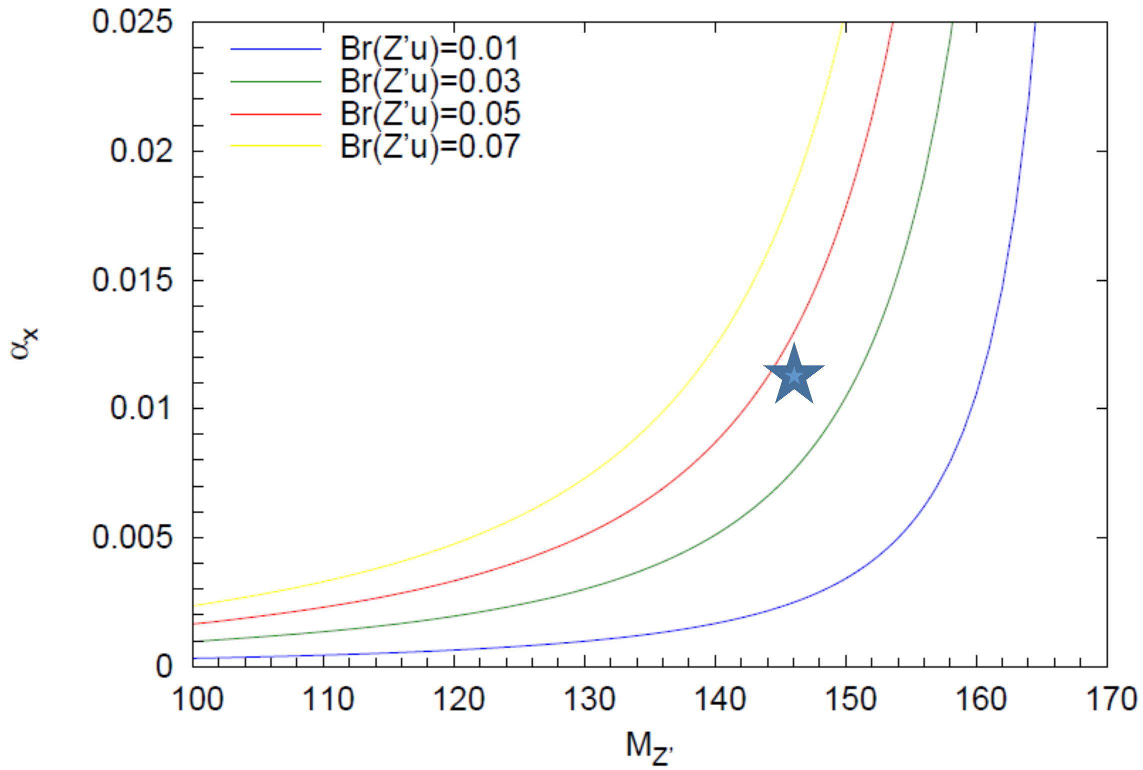
3. Mixed scenario

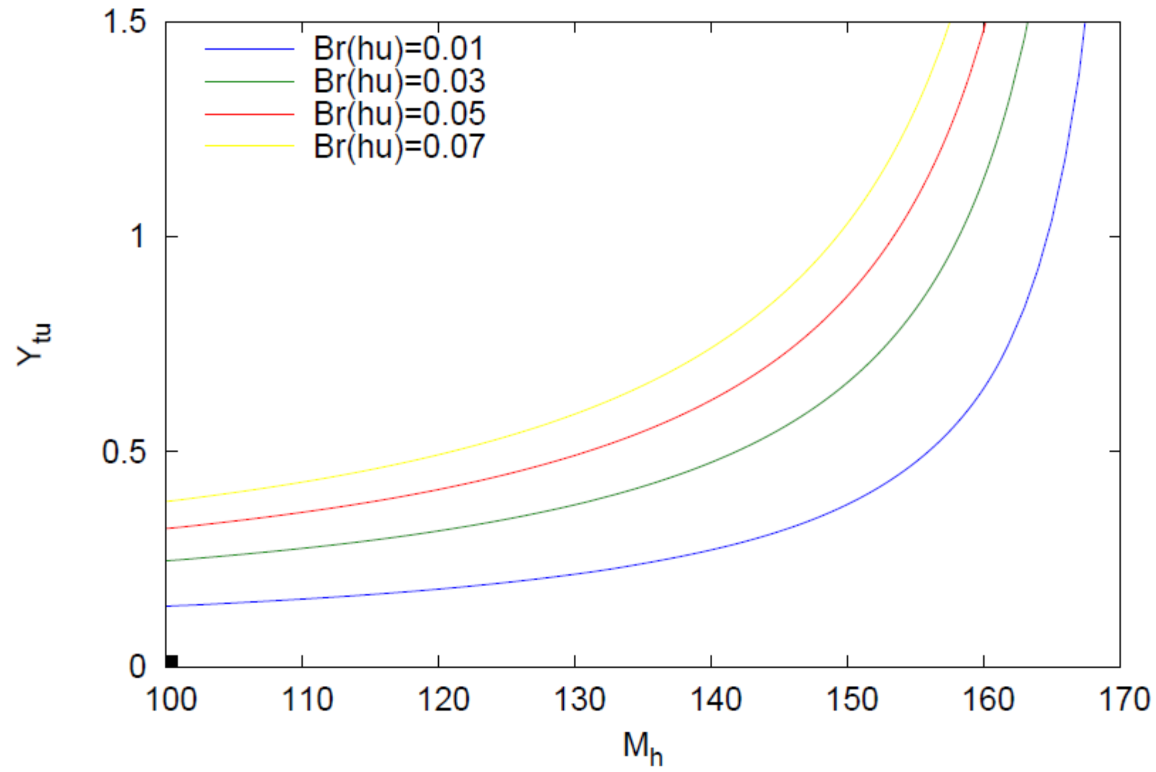
Destructive interference between Z' and h,a for the same sign pair production (Ko, Omura, Yu)



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 be changed.

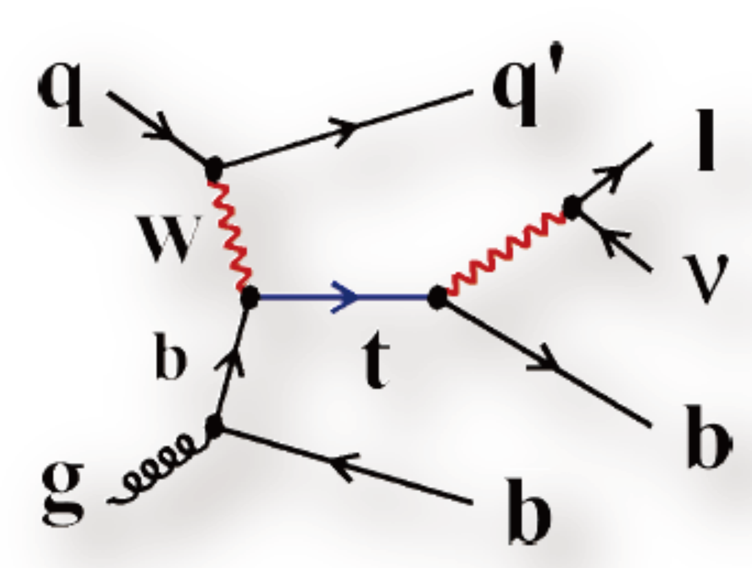




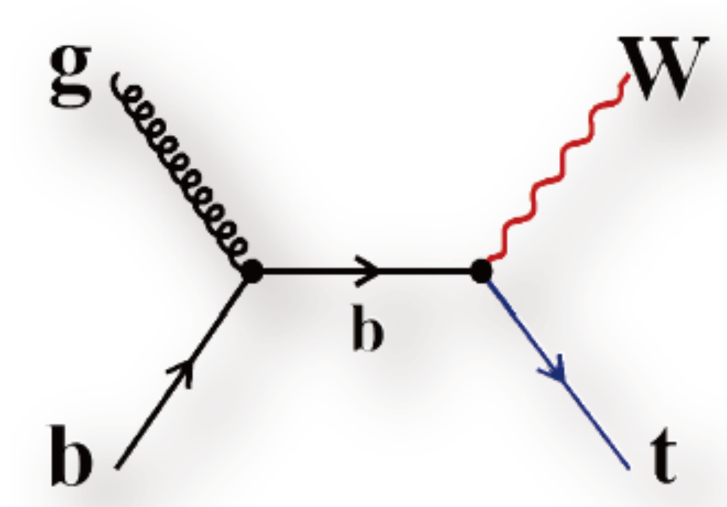
- requires Br(t →non-SM)<5% .
- choose either $m_{Z'} < m_t$ or $m_h < m_t$.

Single top quark production

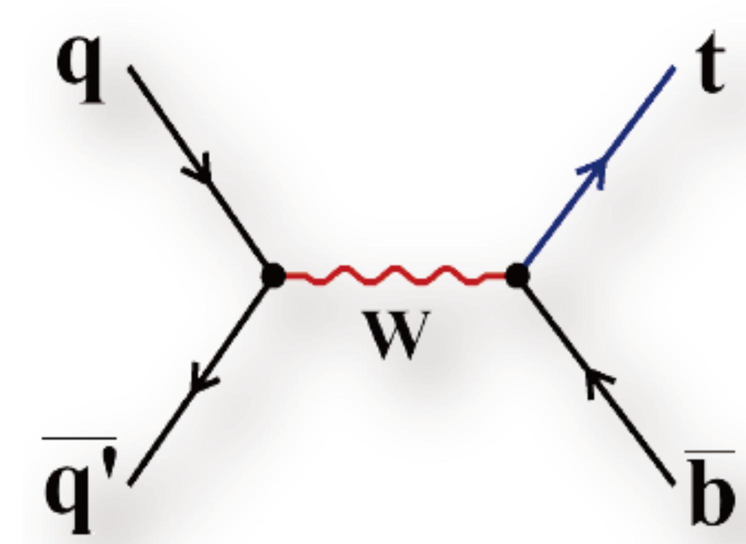
t channel



Wt channel



s channel



- D0 D0, 1105.2788

$$\sigma(p\bar{p} \to tbq) = 2.90 \pm 0.59 \text{ pb}$$

- CMS CMS, 1106.3052

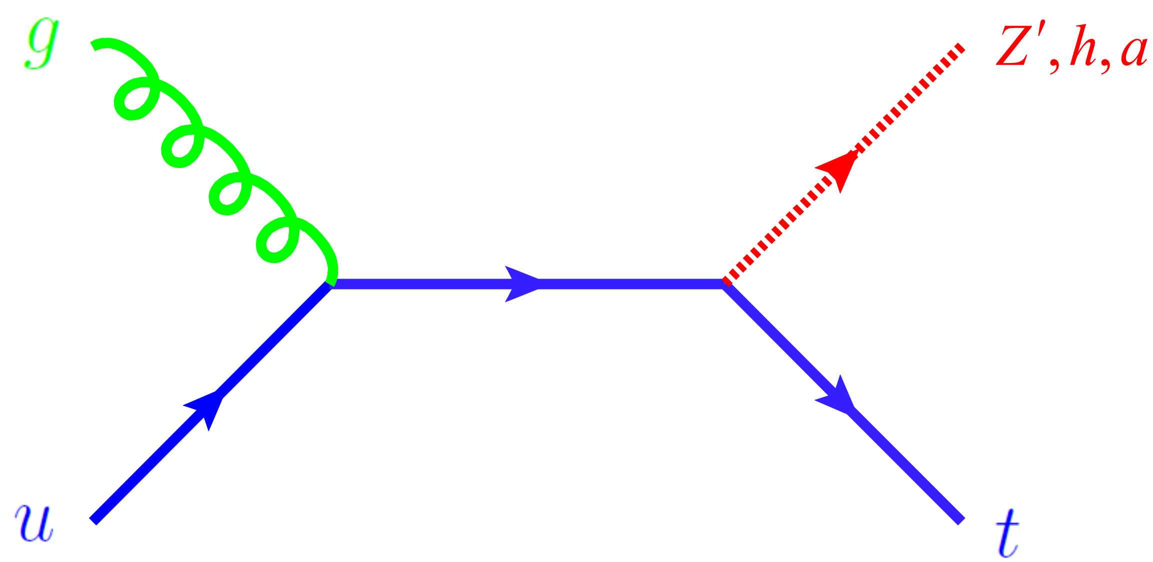
$$\sigma(pp \to tbq) = 83.6 \pm 29.8 \pm 3.3 \text{ pb}$$

In the SM,

$$\sigma(p\bar{p} \to tbq) = 2.26 \pm 0.12 \text{ pb}$$

$$\sigma(pp \to tbq) = 64.3^{+2.1+1.5}_{-0.7-1.7} \text{ pb}$$

Single top quark production



$\Rightarrow$ no b quark or W boson in the final state

- D0 D0, 1105.2788

$$\sigma(p\bar{p} \to tbq) = 2.90 \pm 0.59 \text{ pb}$$

In the SM,

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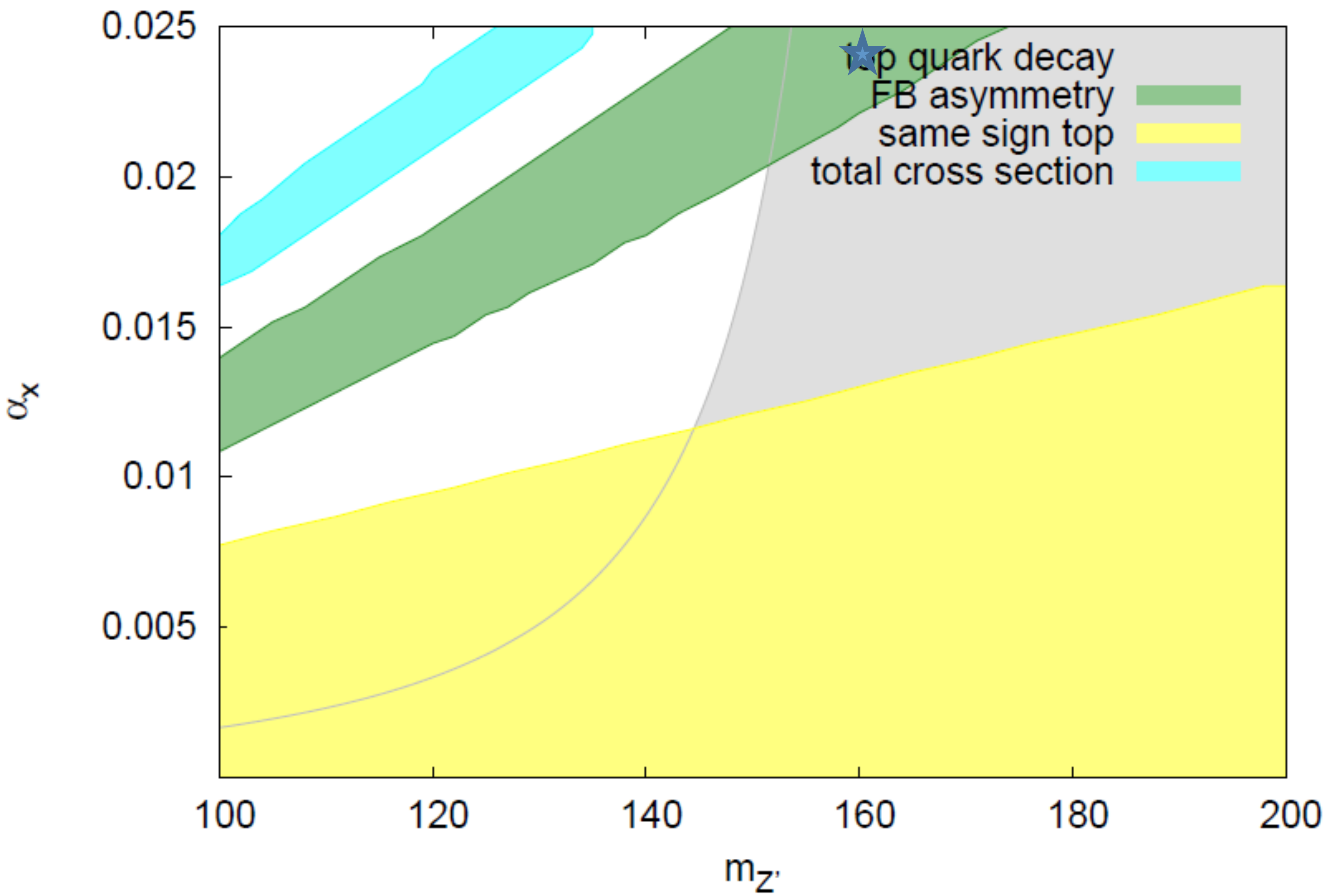
$$\sigma(pp \to tbq) = 64.3^{+2.1+1.5}_{-0.7-1.7} \text{ pb}$$

Favored region

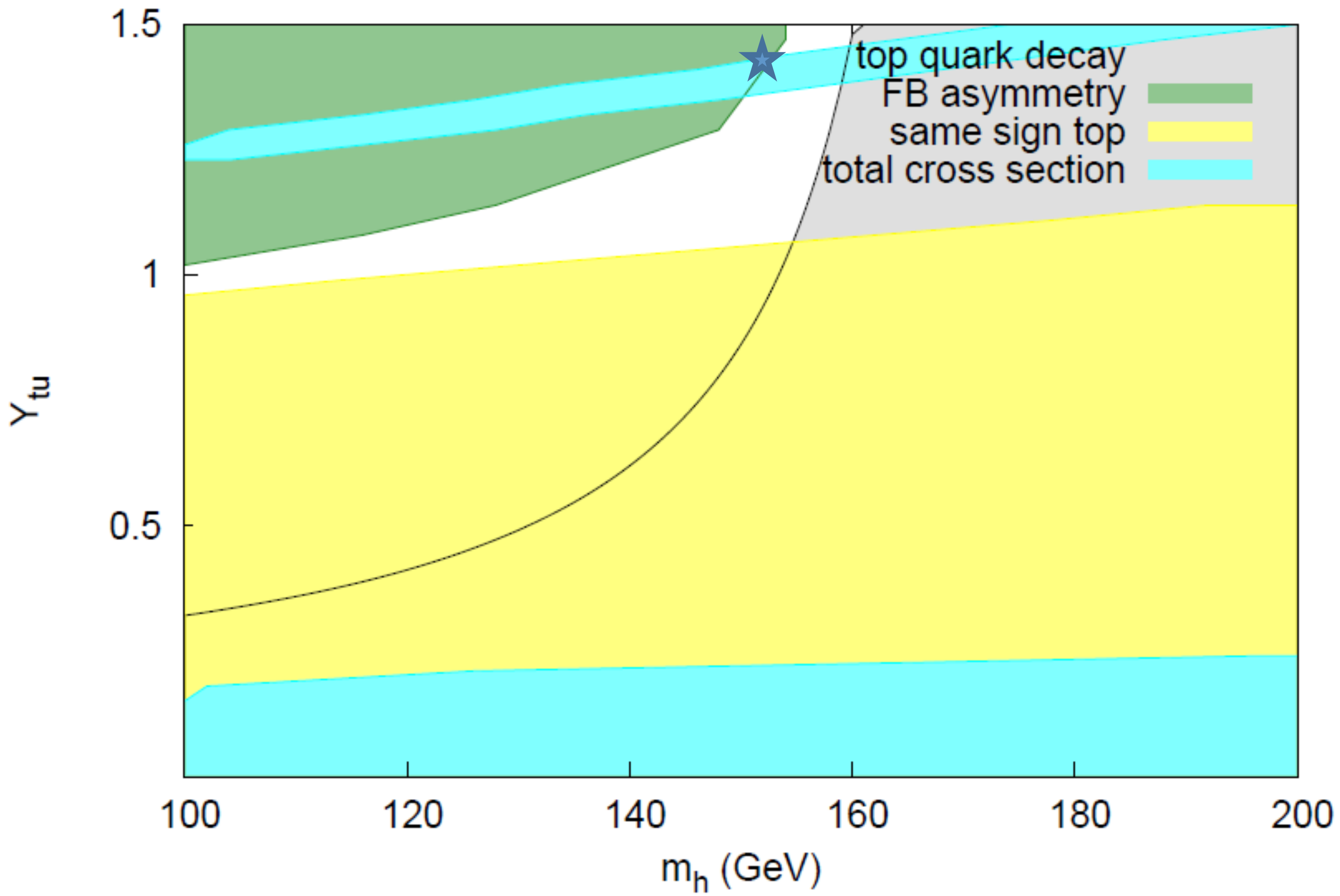
Z′ dominant case



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

Favored region

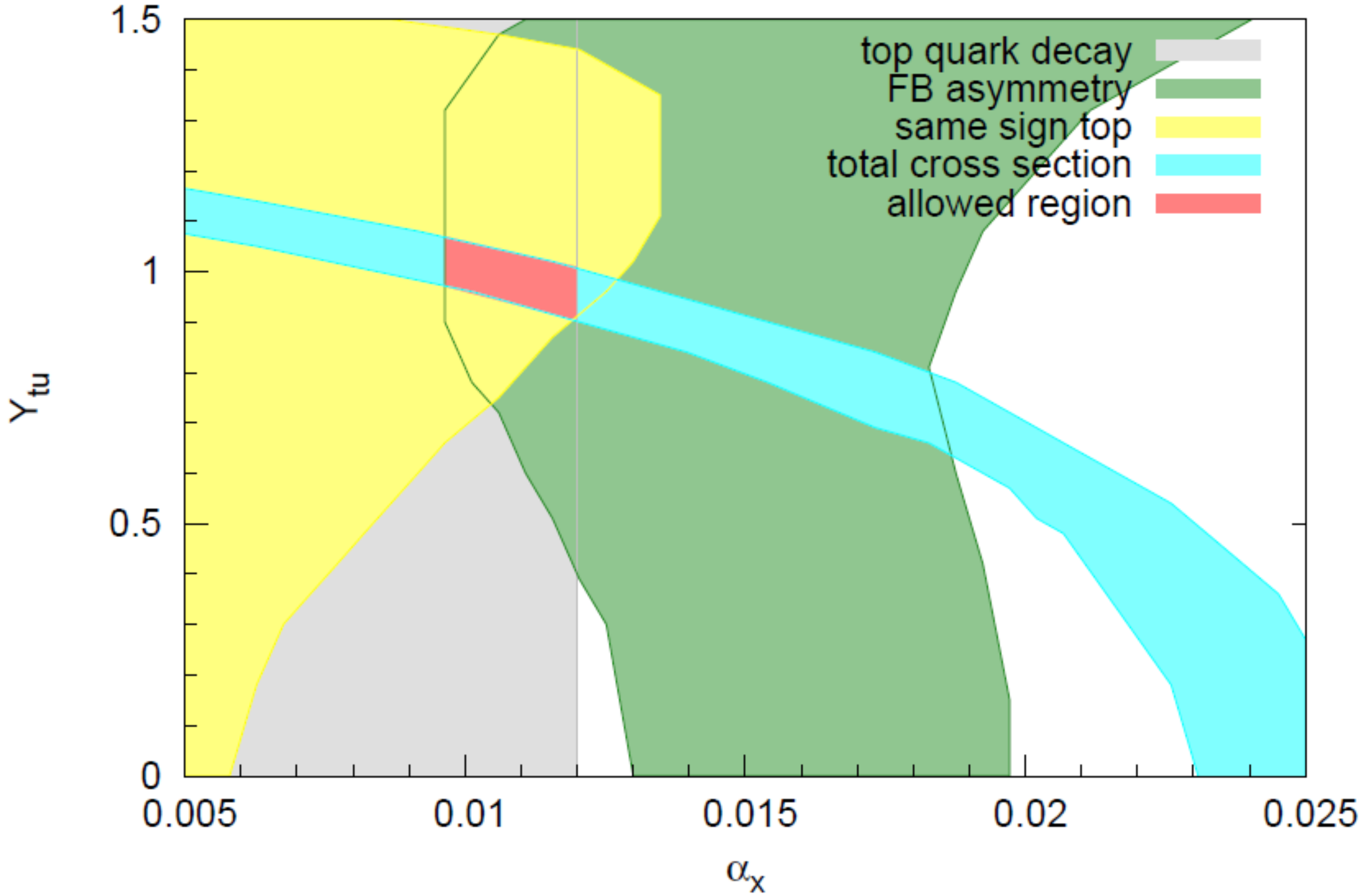
Scalar Higgs (h) dominant case



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

Favored region

Z′+h+a case



$m_{Z'} = 145$ GeV

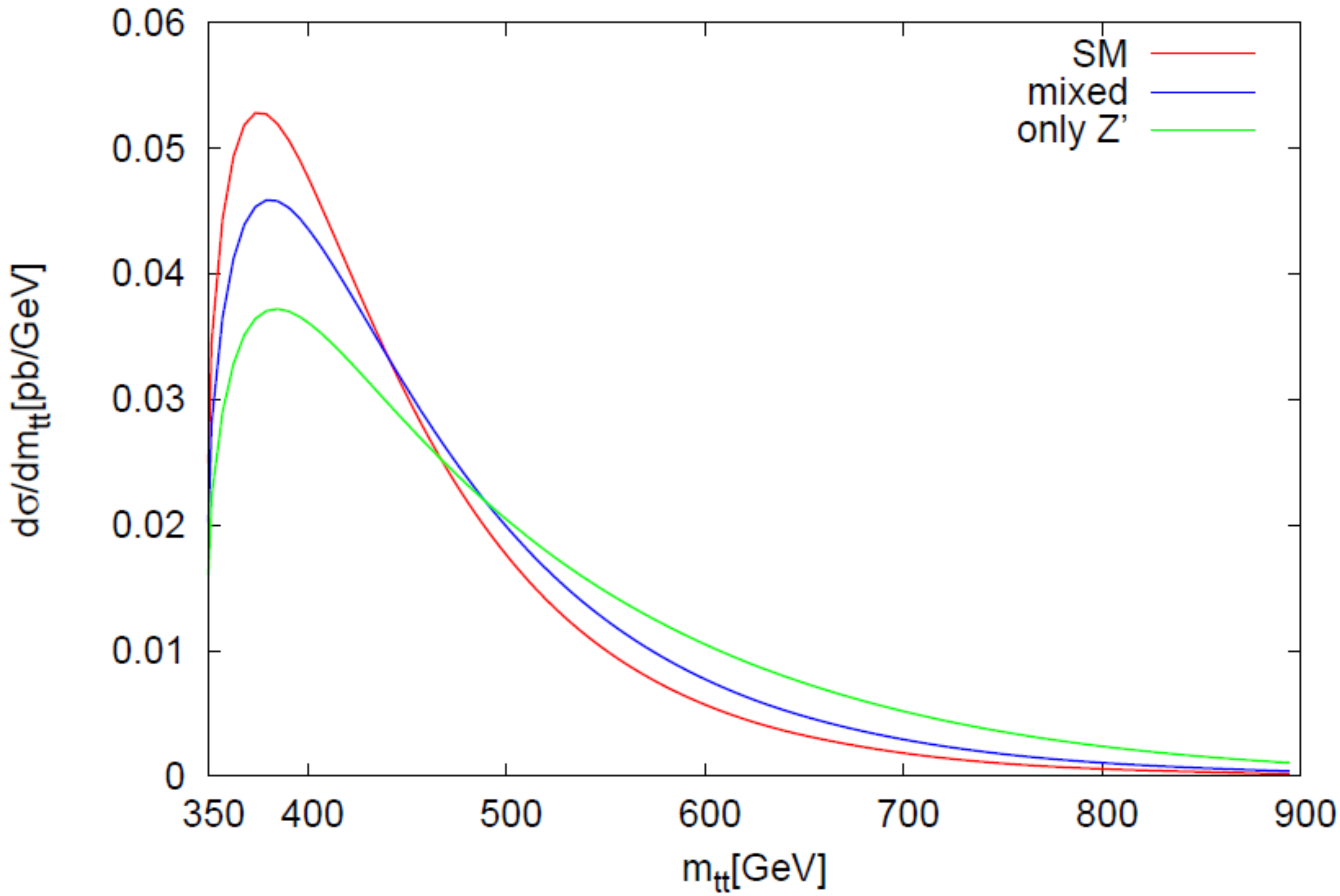
$m_h = 180$ GeV

$m_a = 300$ GeV

$Y_{tu}^a = 1.1$

- destructive interference between Z and Higgs bosons in the same signe top pair production.
- consistent with the CMS bound, but not with the ATLAS bound.

Invariant mass distribution



Only Z′ case

$m_{Z'} = 145$ GeV

$\alpha_x = 0.029$

mixed case

$m_{Z'} = 145$ GeV

$m_h = 180$ GeV

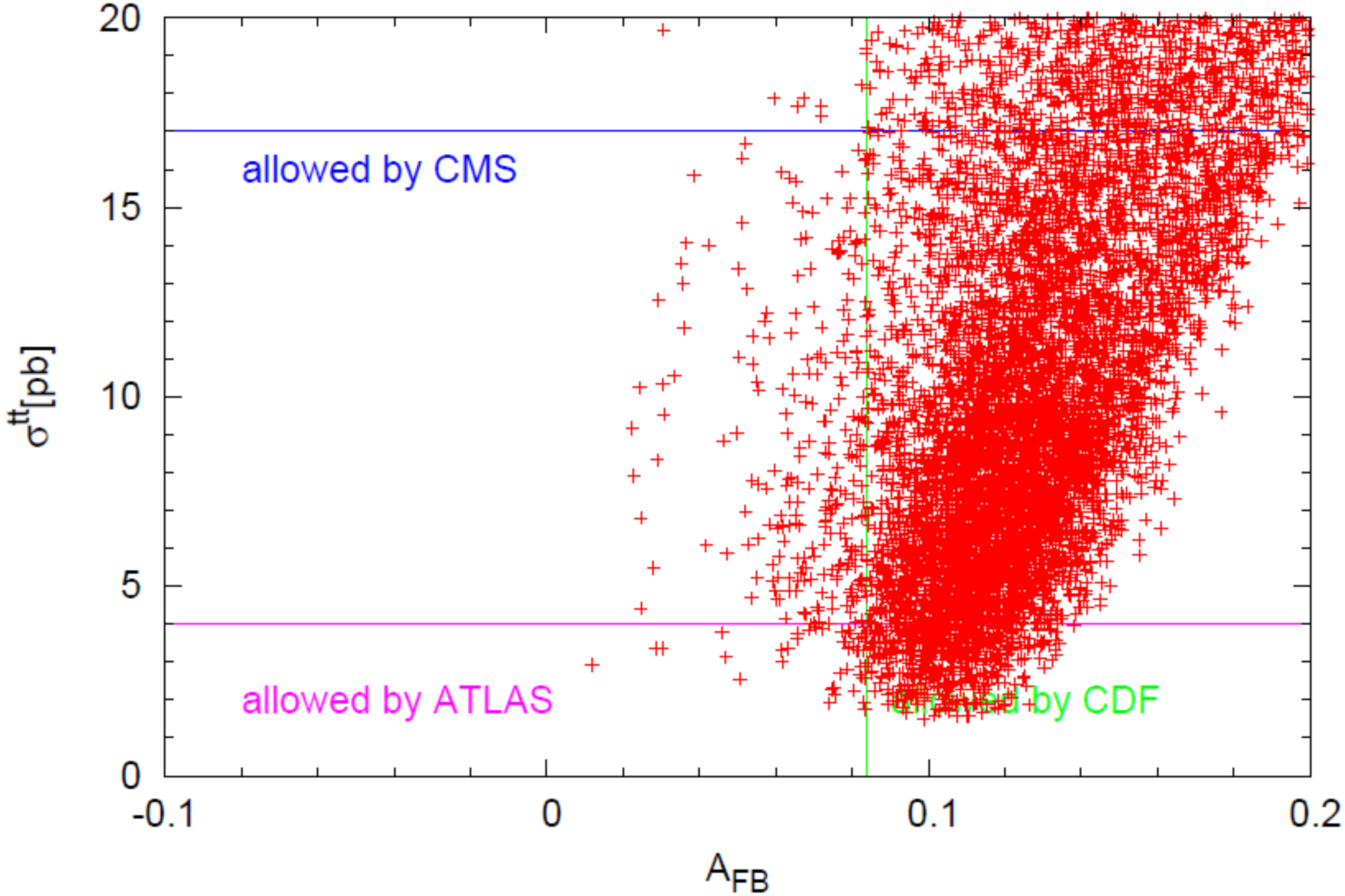
$m_a = 300$ GeV

$\alpha_x = 0.01$

$Y_{tu} = 1.0$

$Y_{tu}^a = 1.1$

A_{FB} versus σ_{tt}



$m_{Z'} = 145$ GeV

180 GeV$< m_h < 1$ TeV

180 GeV$< m_a < 1$ TeV

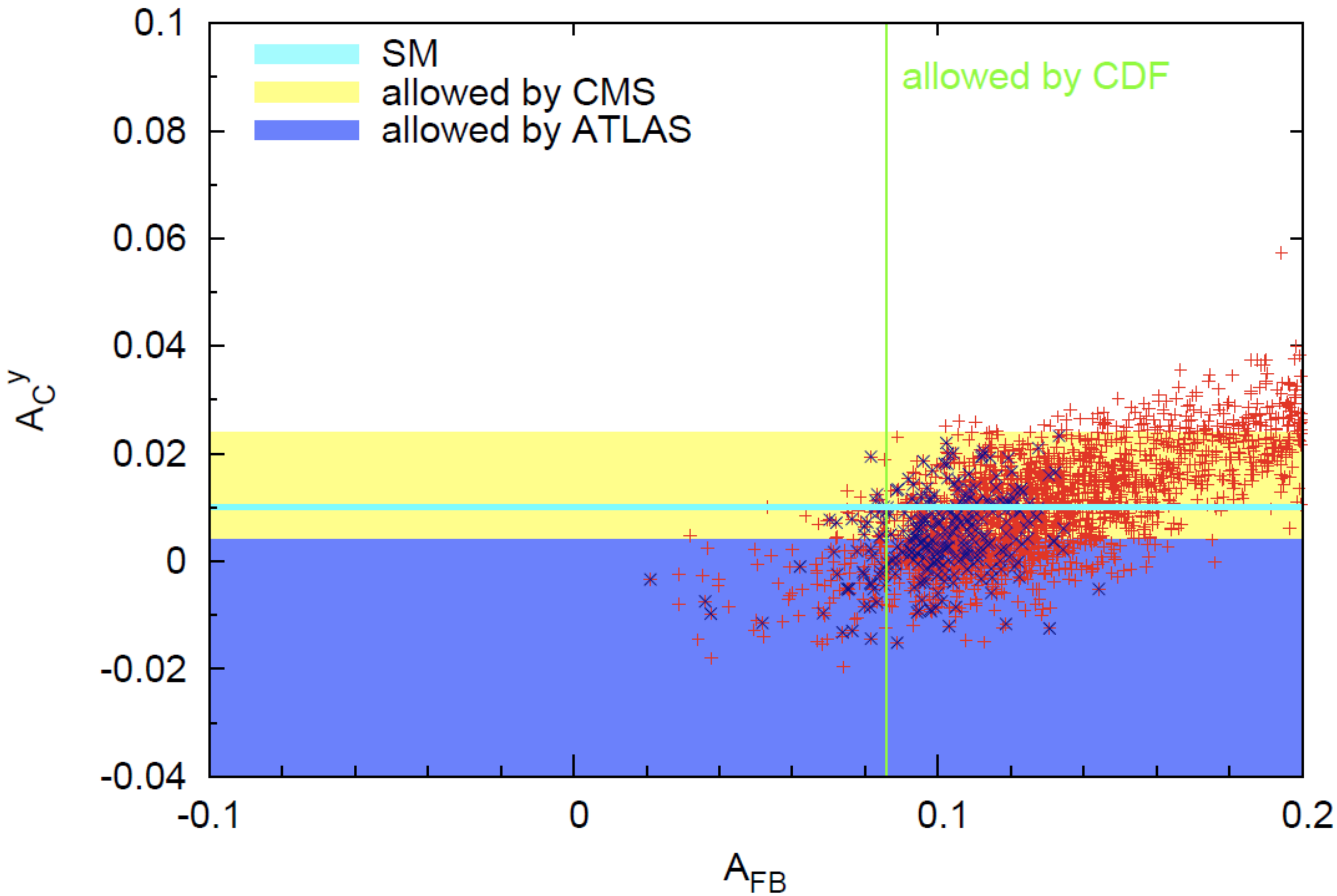
$0.005 < \alpha_X < 0.025$

$0.5 < Y_{tu} < 1.5$

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

Have a trouble with new CMS data < 0.39 pb

A_{FB} versus A_C^y



$m_{Z'} = 145$ GeV

180 GeV$< m_h < 1$ TeV

180 GeV$< m_a < 1$ TeV

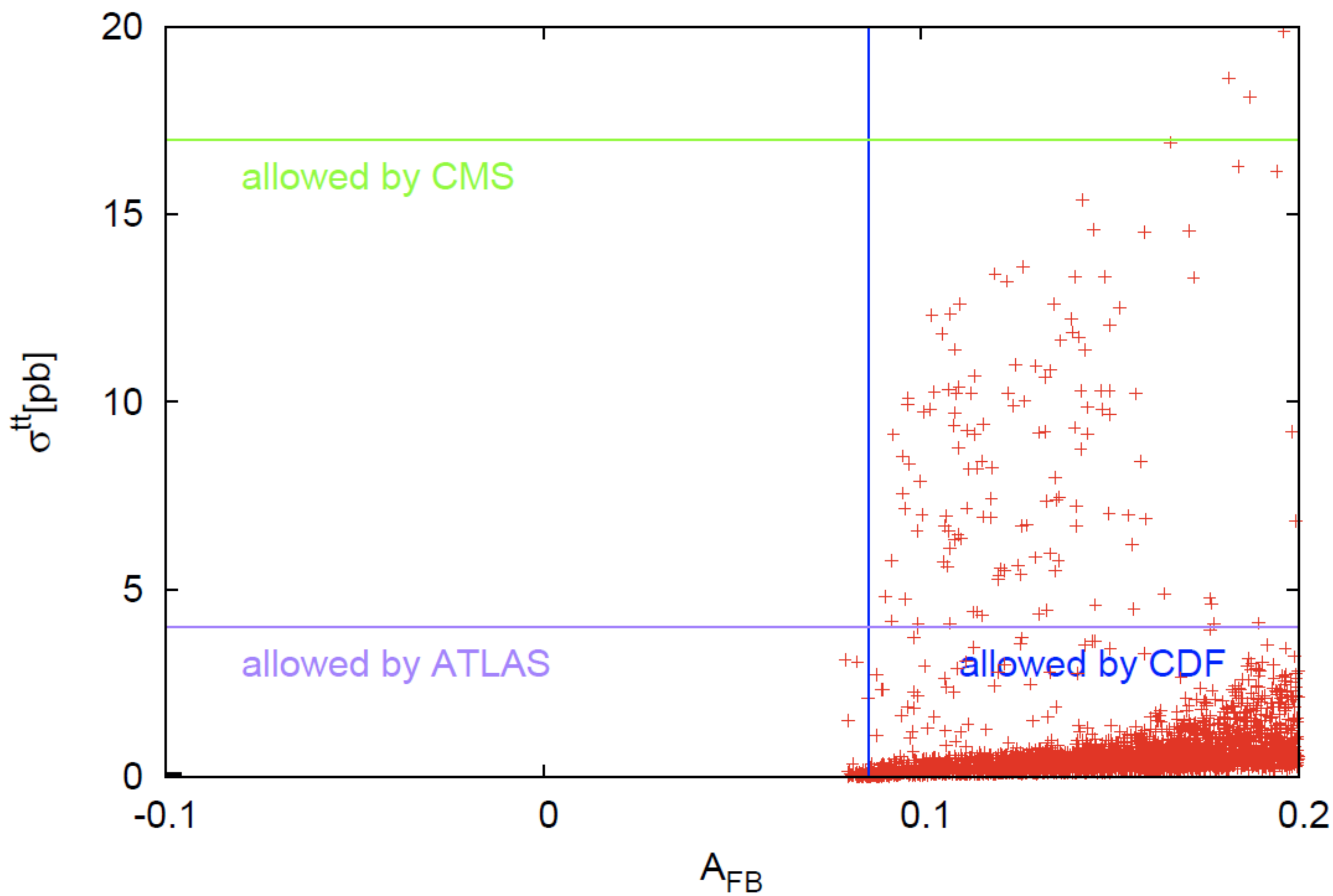
$0.005 < \alpha_X < 0.025$

$0.5 < Y_{tu} < 1.5$

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

Have a trouble with new CMS data < 0.39 pb

A_{FB} versus σ_{tt}



$m_h = 126$ GeV

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

180 GeV $< m_a < 1$ TeV

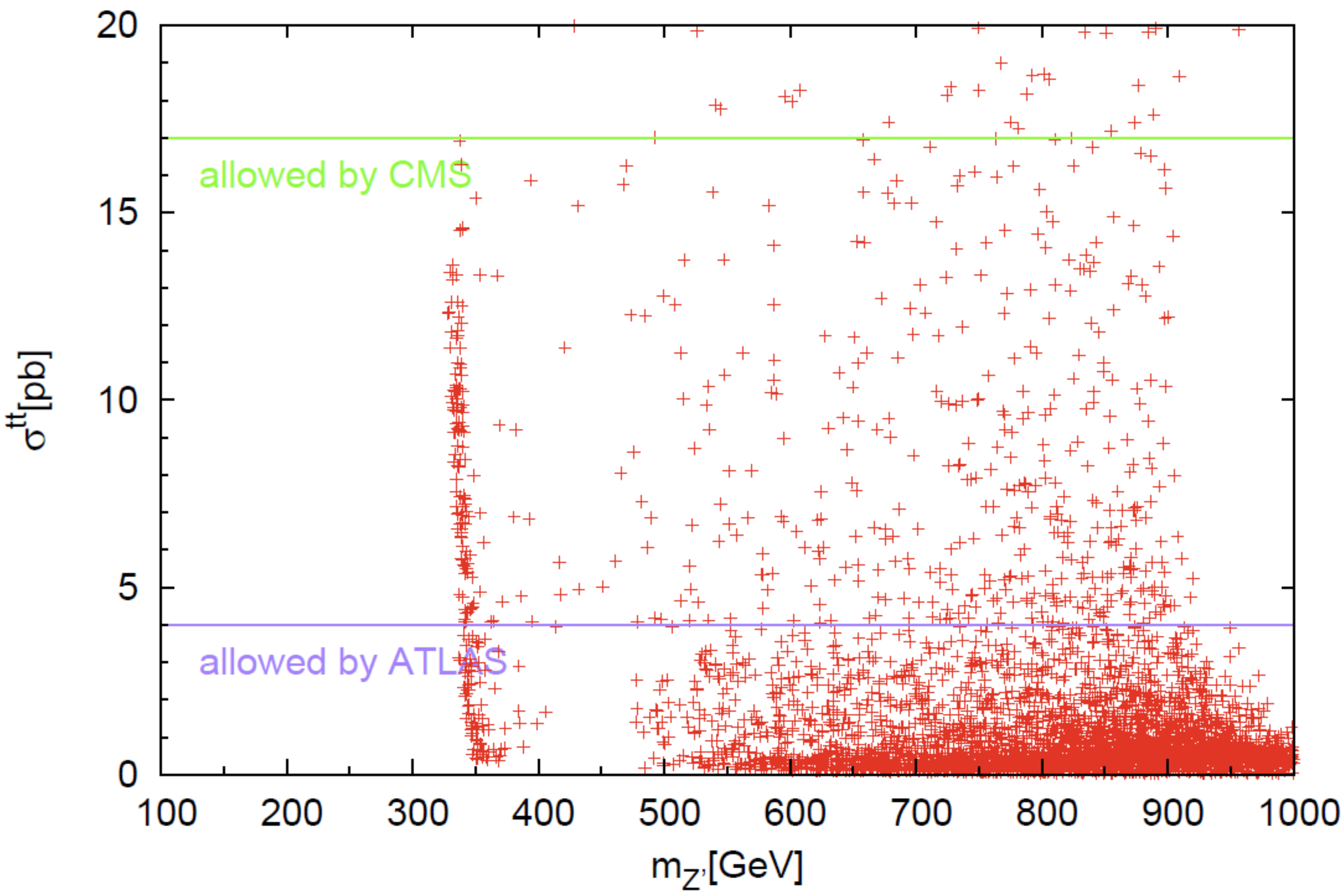
$0.005 < \alpha_X < 0.025$

$0.1 < Y_{tu} < 0.5$

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

Still OK with new CMS data < 0.39 pb

$m_{Z'}$ versus σ_{tt}



$m_h = 126$ GeV

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

180 GeV$< m_a < 1$ TeV

$0.005 < \alpha_X < 0.025$

$0.1 < Y_{tu} < 0.5$

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

Still OK with new CMS data < 0.39 pb

Conclusions

- We constructed realistic Z' models with additional Higgs doublets that are cahrged under U(1)' : Based on local gauge symmetry, renormalizable, anomaly free and realistic Yukawa
- New spin-one boson (Z') with chiral couplings to the SM fermion requires a new Higgs doublet that couples to the new Z'
- This is also true for axigluon, flavor SU(3)_R, W', etc.
- Our model can accommodate the top FB Asym @ Tevatron, the same sign top pair production, and the top CA@LHC

- Meaningless to say "The Z' model is excluded by the same sign top pair production."
- Important to consider a minimal consistent (renormalizable, realistic, anomaly free) in order to do phenomenology
- B->D(*) tau nu puzzle can be accommodated in this model (w/ Yuji Omura and C. Yu)
- Top longitudinal pol (which is zero in QCD because of Parity) could be another important tool for resolving the issue (Ko et al, Godbole et al, Degrande et al, etc)

2HDMs with U(1) Higgs flavor symmetry

Based on

arXiv:1204.4588 (PLB)
arXiv:1309.7156 (JHEP)
arXiv:1405.2138 (JHEP under review)
work in preparation for Type II, X, Y etc

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♪

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

However

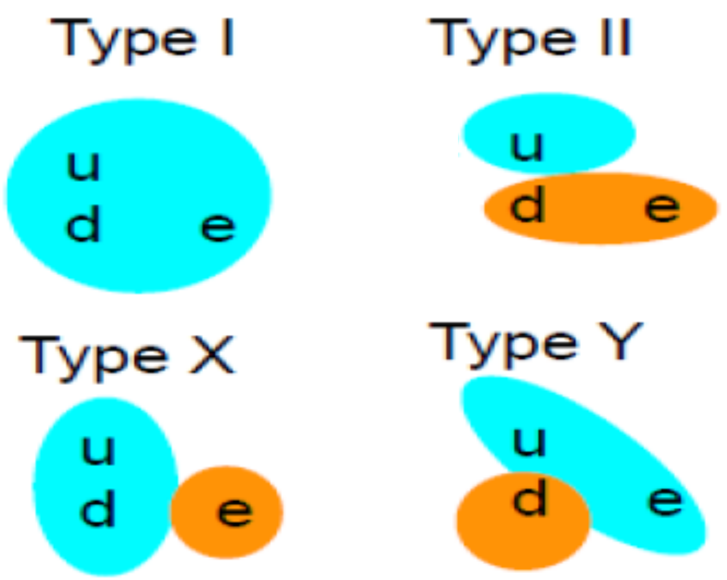
- The discrete Z_2 seems to be rather ad hoc, and its origin and the reason for its soft breaking are not clear
- We implement the discrete Z_2 into a continuos local U(1) Higgs flavor sym under which H_1 and H_2 are charged differently [Ko, Omura, Yu PLB (2012)]
- This simple idea opens a new window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

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.

Z2 : 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.

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 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

- In general, extra fermions are required in order to cancel gauge anomal y.

→ one of extra fermions can be a candidate for the cold dark matter.

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.

Type-II 2HDM

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

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

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.

$U(1)_H^3$

$U(1)_Y U(1)_H^2$

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$
q_{Li}	3	1	2/3	$\hat{Q}_L = u + \hat{Q}_R$
q_{Ri}	3	1	2/3	$\hat{Q}_R$
n_{Li}	1	1	0	$\hat{n}_L = u + \hat{n}_R$
n_{Ri}	1	1	0	$\hat{n}_R$

+ Two vector-like pairs of SU (2)$_L$

Mixing between new chiral fermions and SM fermions is prohibited by U(1)$_H$ c harge assignment.

One of extra fermions could be a candidate for CDM.

Constraints

- experimental and theoretical constraints

$m_h \sim 126$ GeV

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

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

$\sin(\beta - \alpha)$

$\tan\beta$

m_{H^+}

SM-like Higgs

m_H

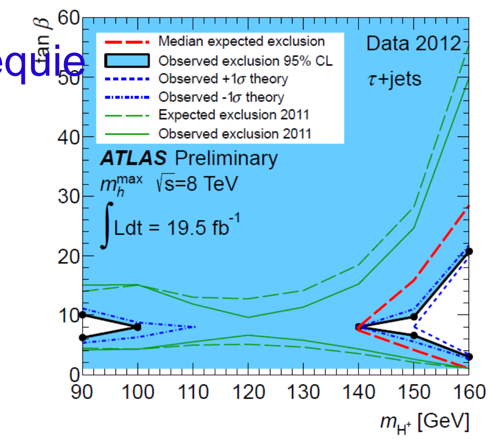
Perturbativity

Unitarity

Vacuum stability

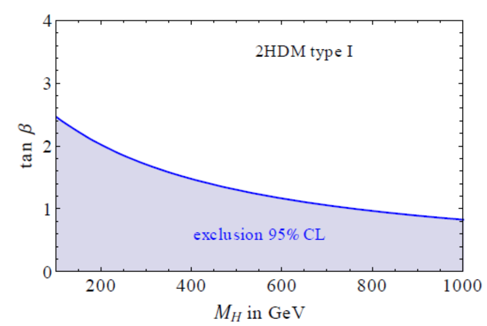
EWPOs

small mass differences requie d



Exotic top decay

$b \to s\gamma$

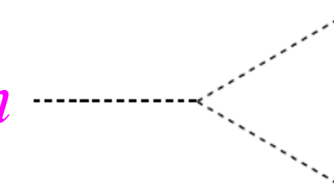


tanβ t 1

Hermann,Misiak,Steinhauser, JHEP1211 (2012) 036♪

Invisible Higgs decay

h

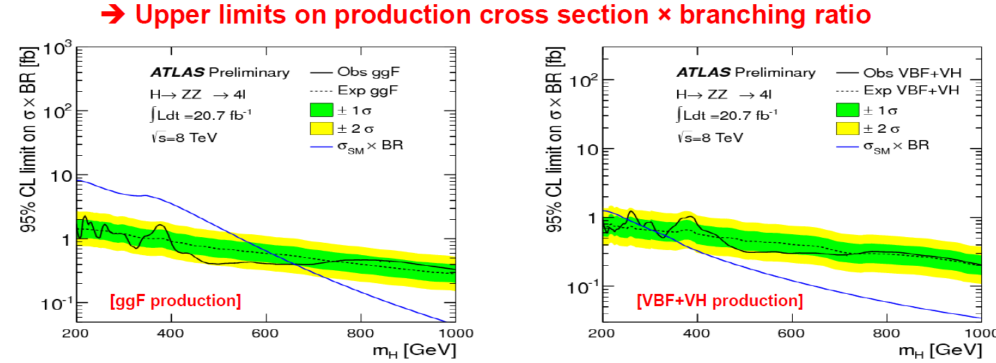


non-SM

non-SM

Heavy Higgs search at LHC

➔ Upper limits on production cross section × branching ratio

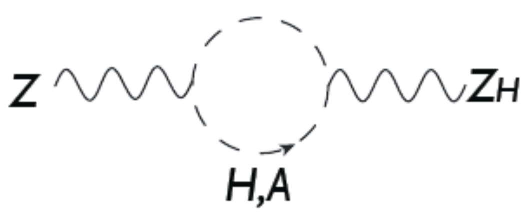


Z-Z_H mixing

- tree-level mixing ($v_i \neq 0$)

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

- loop-level mixing ($v_1=0$, $v_2 \neq 0$)



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

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

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

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

The mixing can appear because of $SU(2)_L \times U(1)_Y$ breaking effects.

- collider bound depends on the $U(1)_H$ charge assignment.

- In the fermiophobic Z_H case, the Z_H boson can be produced through the Z-Z_H mixing and the bound for the mixing angle is

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

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

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

DM candidates

SM-like Higgs

Inert Doublet Model (IDMwZ_2)

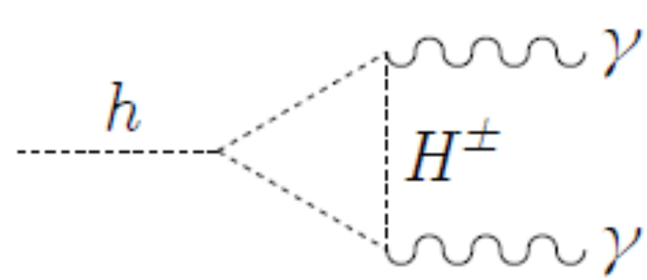
• CP-conserving potential

forbidden by the Z_2 symmetry

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

• 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,$H^\pm$ ~ 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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$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$

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

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

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

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

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- Without Φ, Z_H boson becomes massless.

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 ($q_{H_2}=0, q_{H_1} \neq 0$)

- 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

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

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

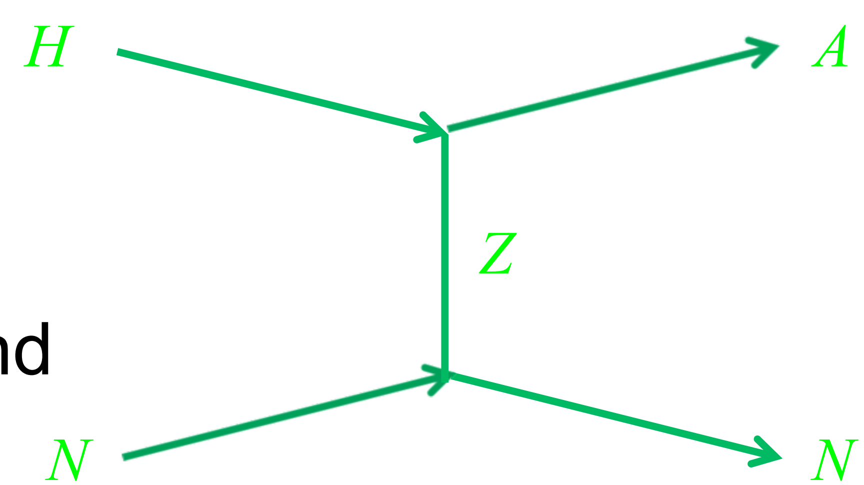
$$+ \frac{\lambda_5}{2}\{(H_1^\dagger H_2)^2 + h.c.\} + m_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4$$

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

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

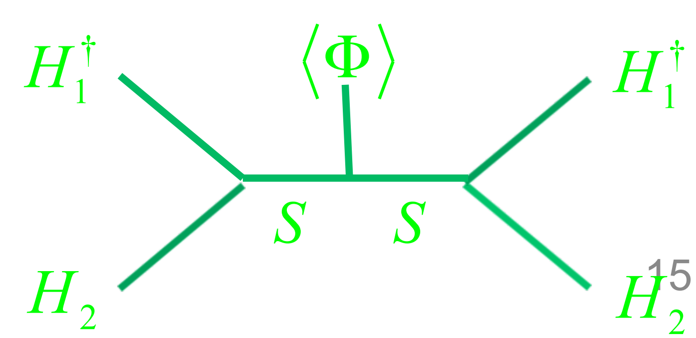
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 |H_1^\dagger H_2|^2$$

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

- 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 $q_S = q_{H_1}$.

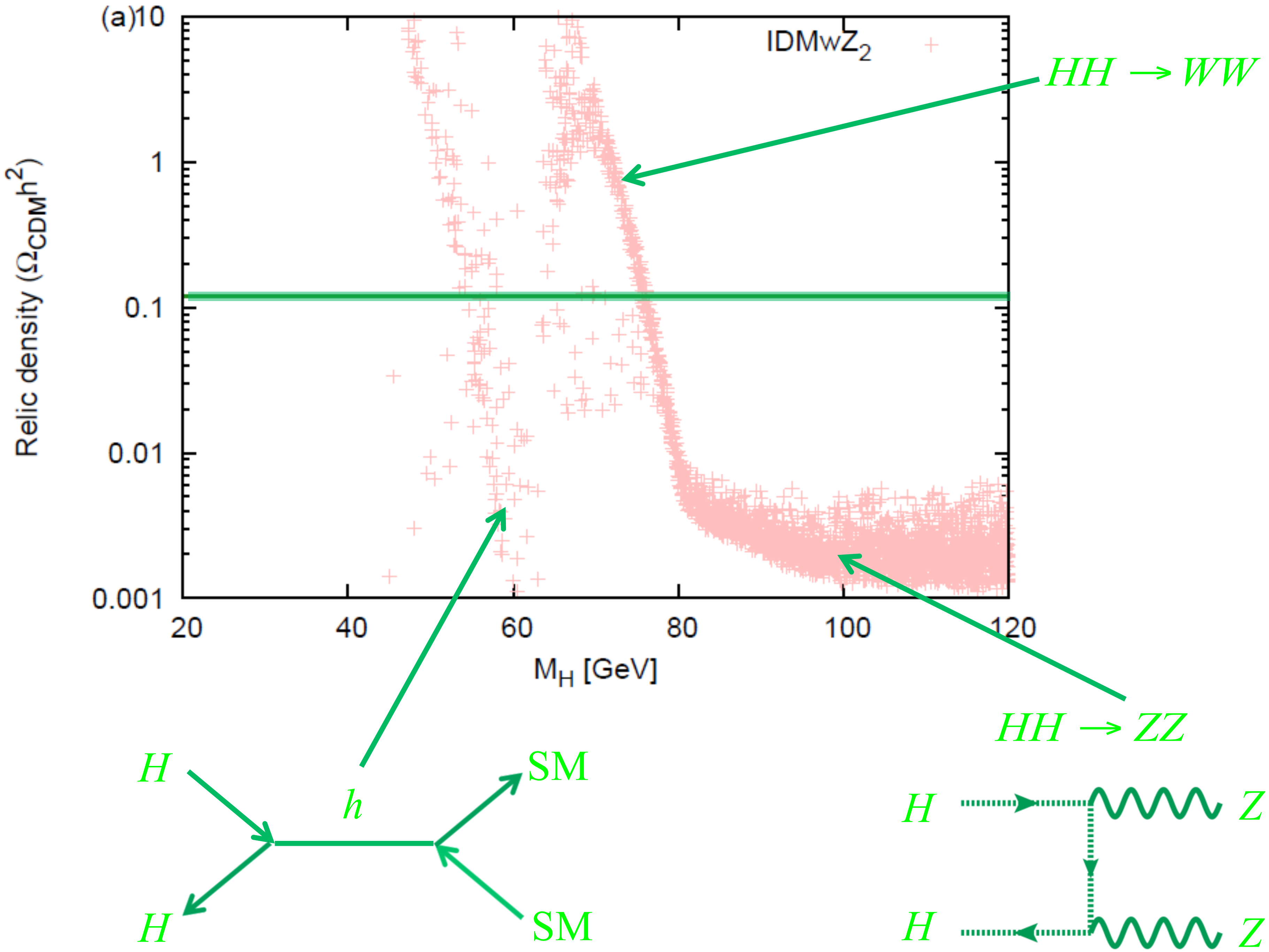
$$V_\Phi(|\Phi|^2, |S|^2) + V_H(H_i, H_i^\dagger) + \lambda_S(\Phi) S^2 + \lambda_H(S) H_1^\dagger H_2 + h.c..$$

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



Relic density (low mass)

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

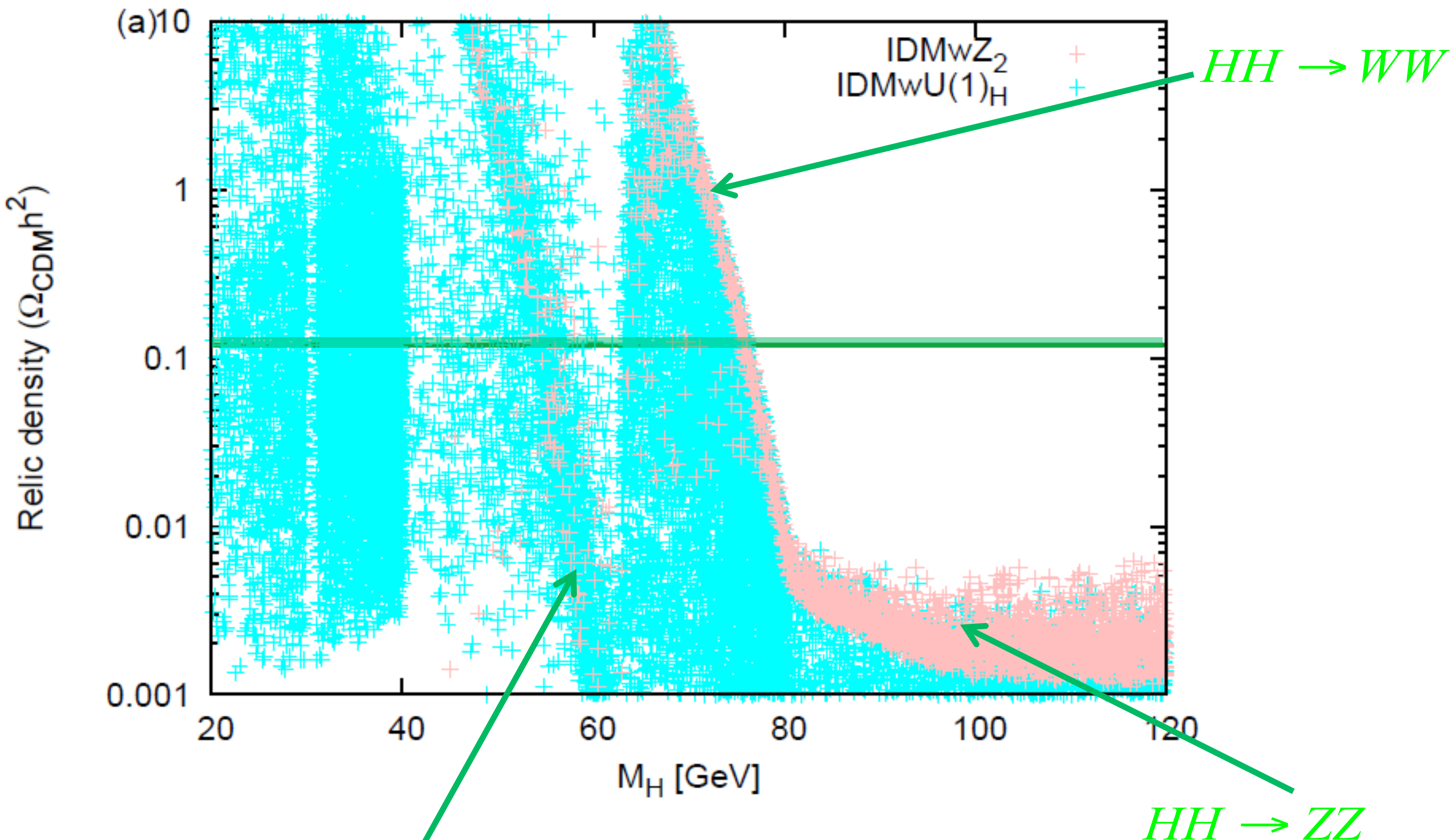


+ IDMwZ$_2$

LUX bound is satisfied.

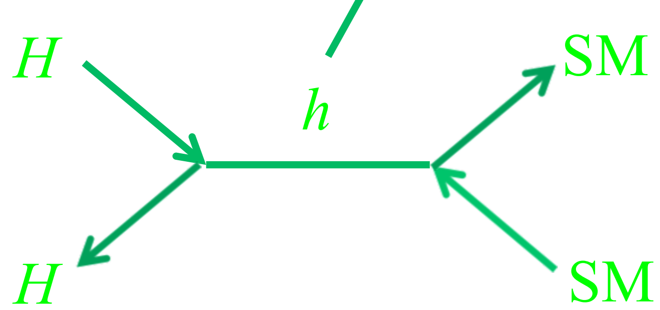
Relic density (low mass)

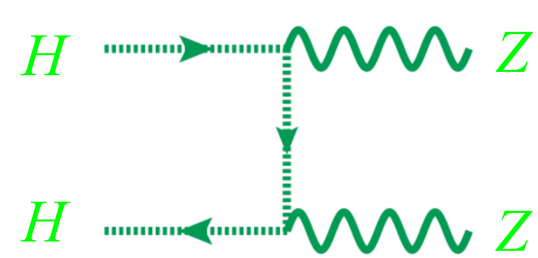
$$\Omega_{\rm CDM} h^2 = 0.1199 \pm 0.0027$$



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

LUX bound is satisfied.





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+ IDMwZ$_2$
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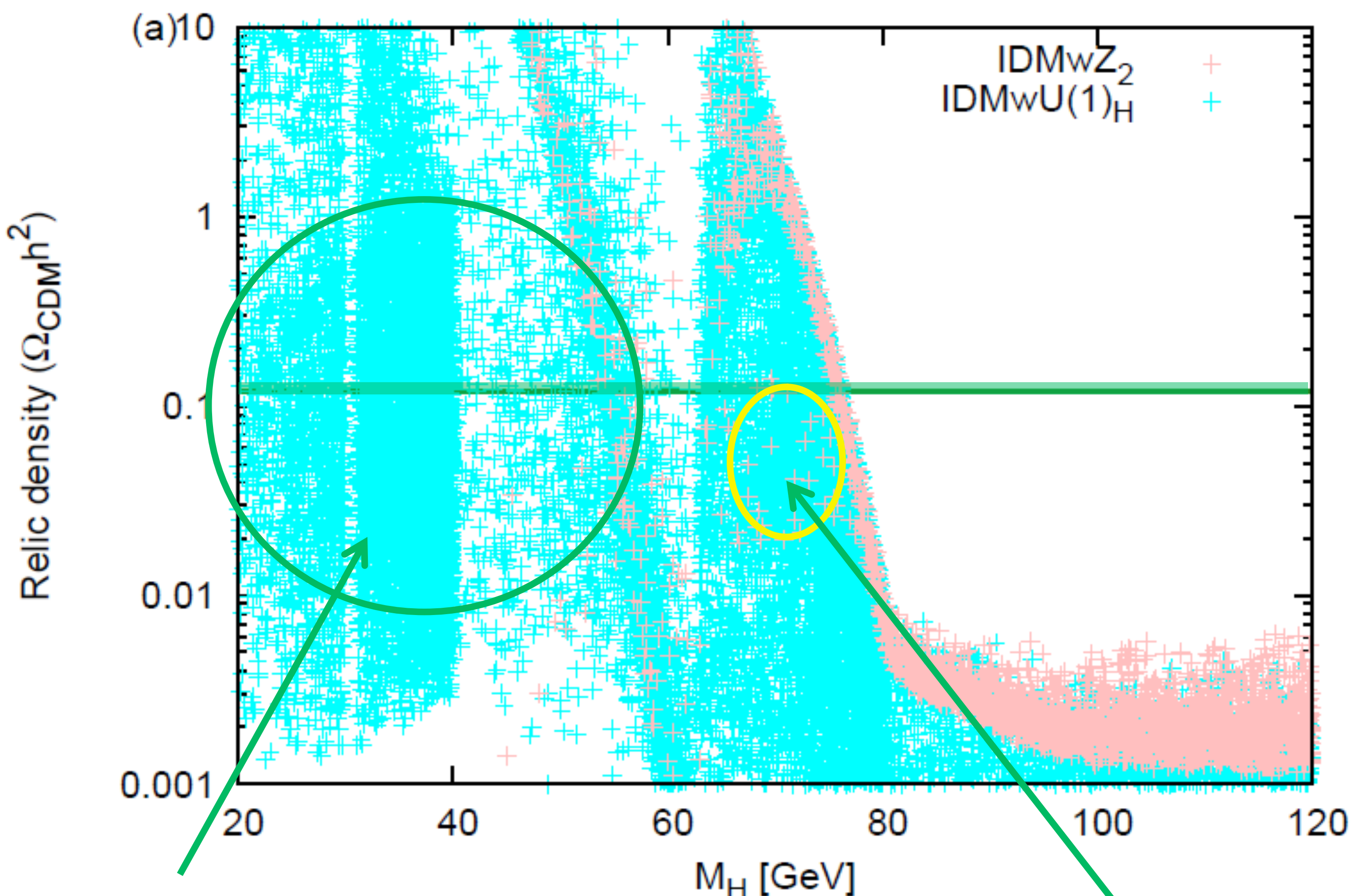
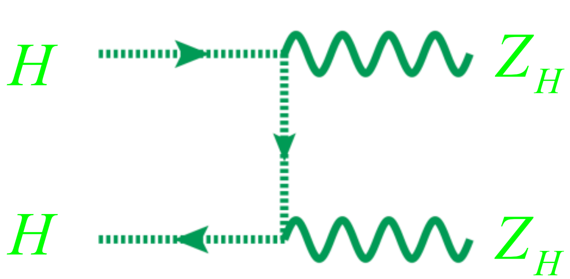
LUX bound is satisfied.



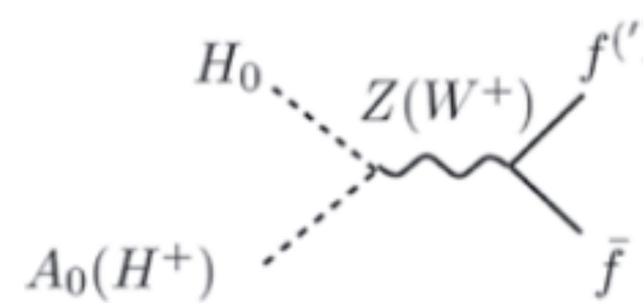
$$HH \to Z_H Z_H, ZZ_H$$



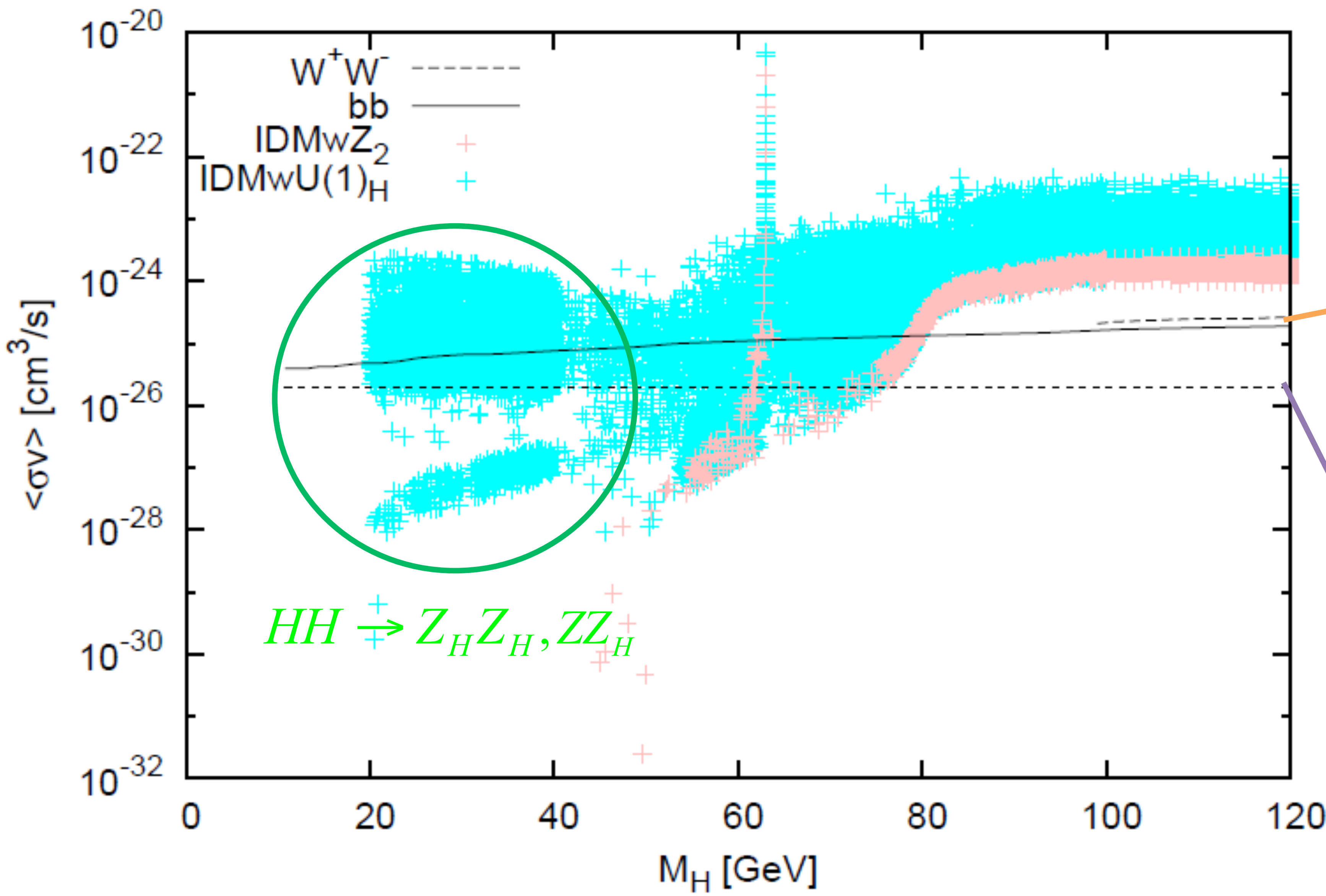
$$HA, HH^{\pm} \to \mathrm{SM} + \mathrm{SM}^{(\prime)}$$

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

Co-annihilation



Indirect searches (low mass)



+ IDMwZ_2
+ IDMwU$(1)_H$

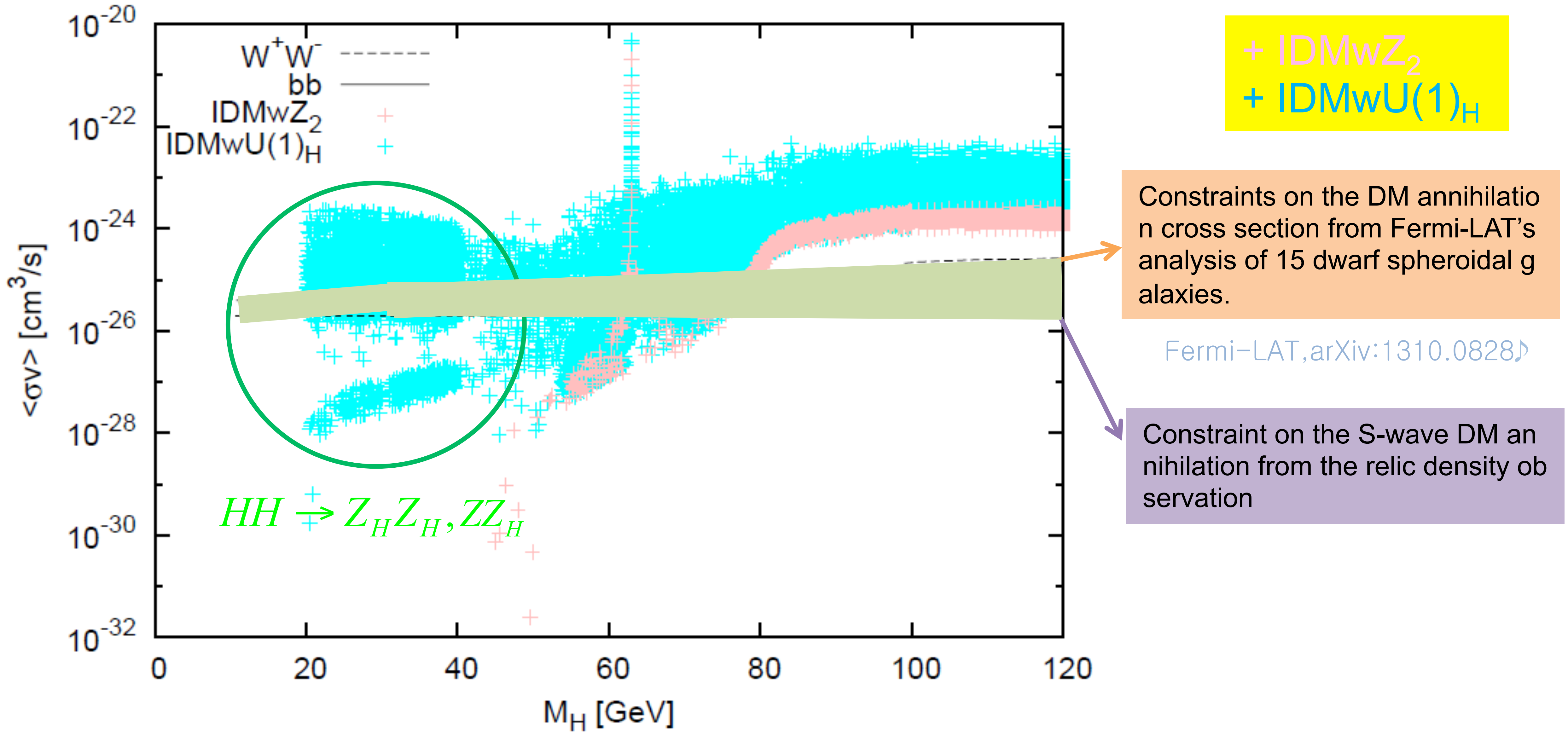
Constraints on the DM annihilation cross section from Fermi-LAT's analysis of 15 dwarf spheroidal galaxies.

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)



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

Gamma ray flux from DM annihilation

• Dwarf spheroidal galaxies are excellent targets to search for annihilatin g DM signatures because of DM-dominant nature without astrophysical b ackgrounds like hot gas.

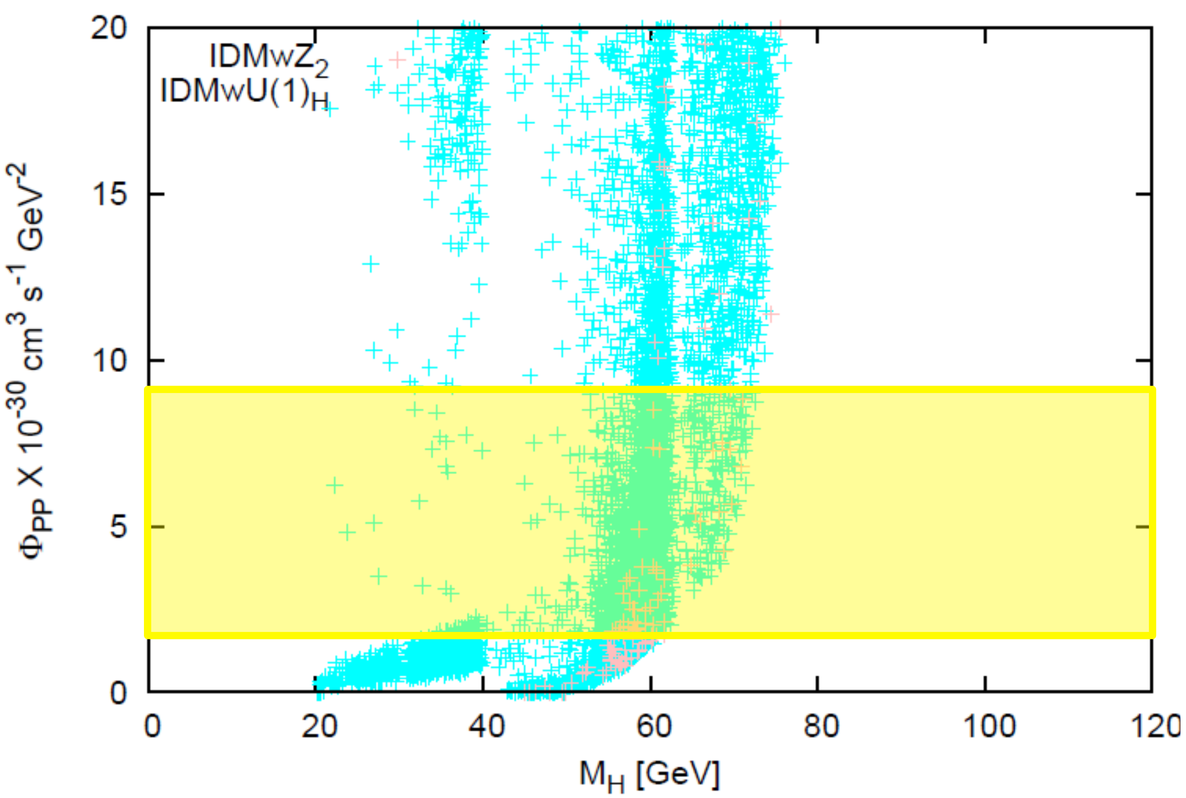
$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\Phi_{\rm PP}} \cdot \underbrace{\int_{\Delta\Omega}\left\{\int_{\rm l.o.s.}\rho^2(r){\rm d}l\right\}{\rm d}\Omega'}_{\text{J-factor}}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

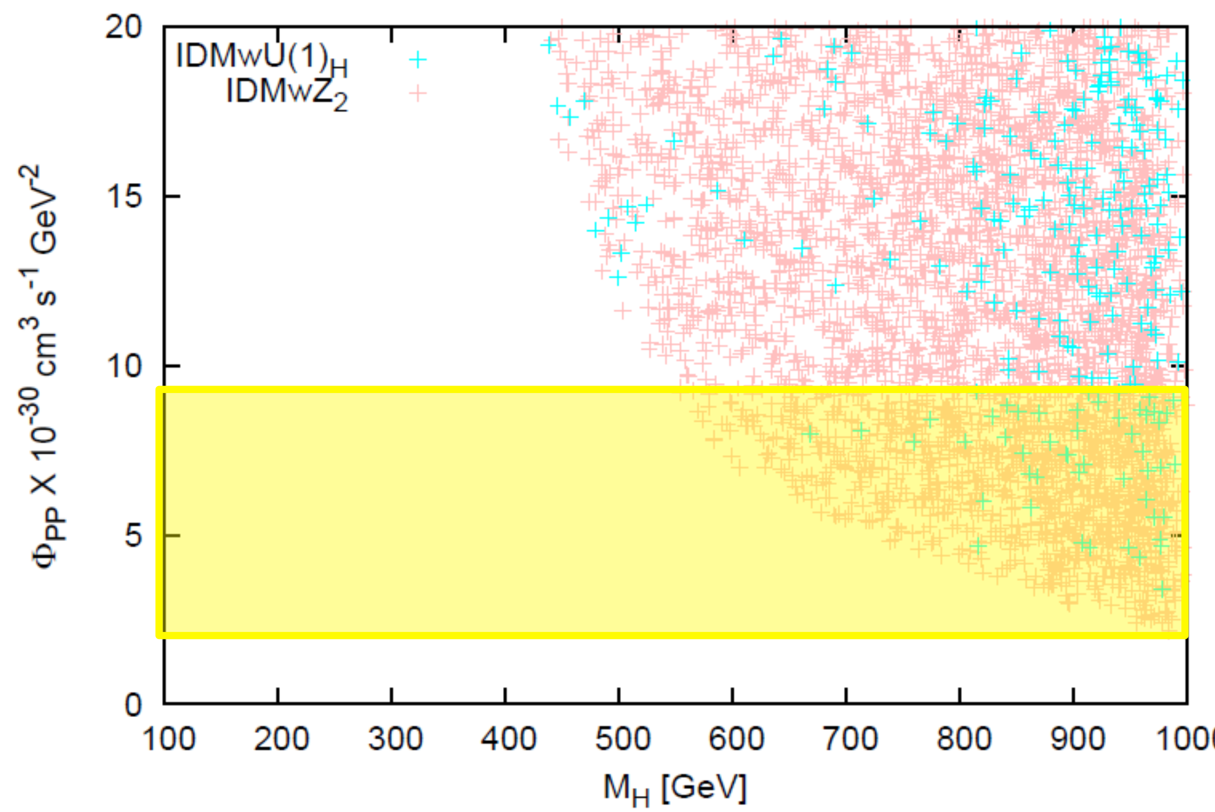
The final γ-ray spectrum.

contains information about the distribution of DM.

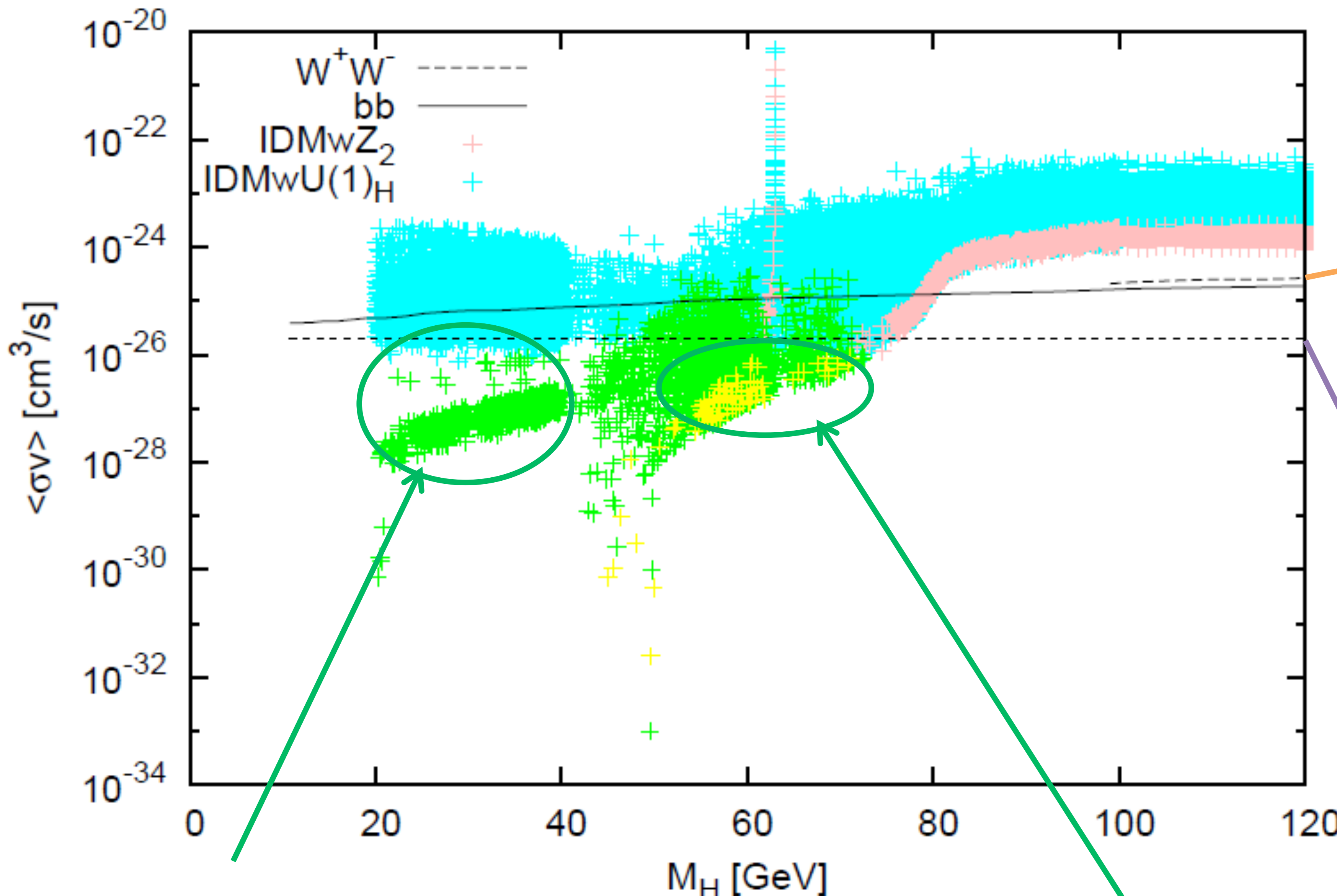
A 95% upper bound is $\Phi_{\rm PP} = 5.0^{+4.3}_{-4.5}\times 10^{-30}\,{\rm cm}^3{\rm s}^{-1}{\rm GeV}^{-2}$

Geringer-Sameth,Koushiappas, PRL107♪





Indirect searches (low mass)



$m_H \sim m_{Z_H}$

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

Constraints on the DM annihilatio n cross section from Fermi-LAT's analysis of 15 dwarf spheroidal g alaxies.

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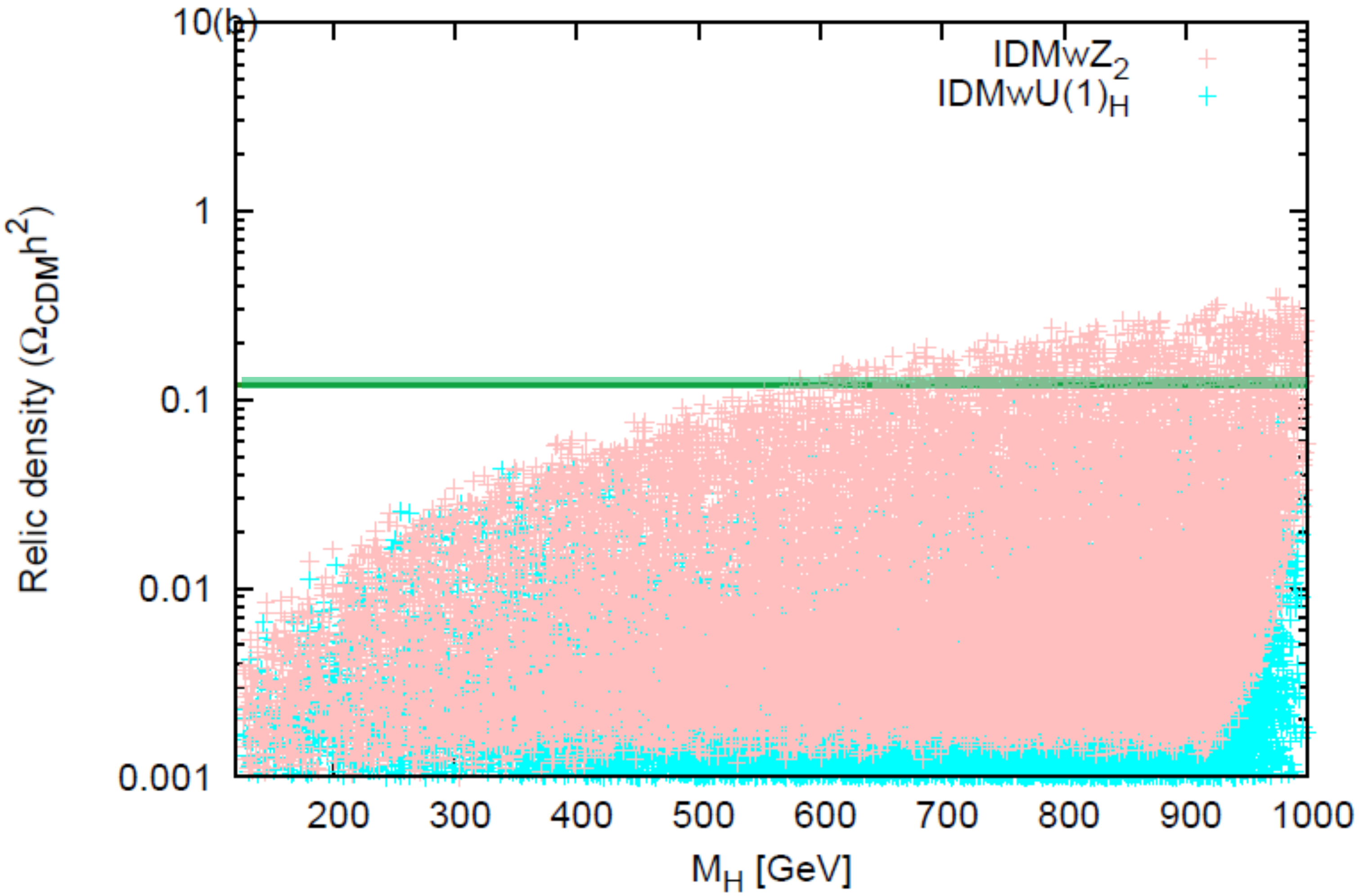
Constraint on the S-wave DM an nihilation from the relic density ob servation

Co-annihilation

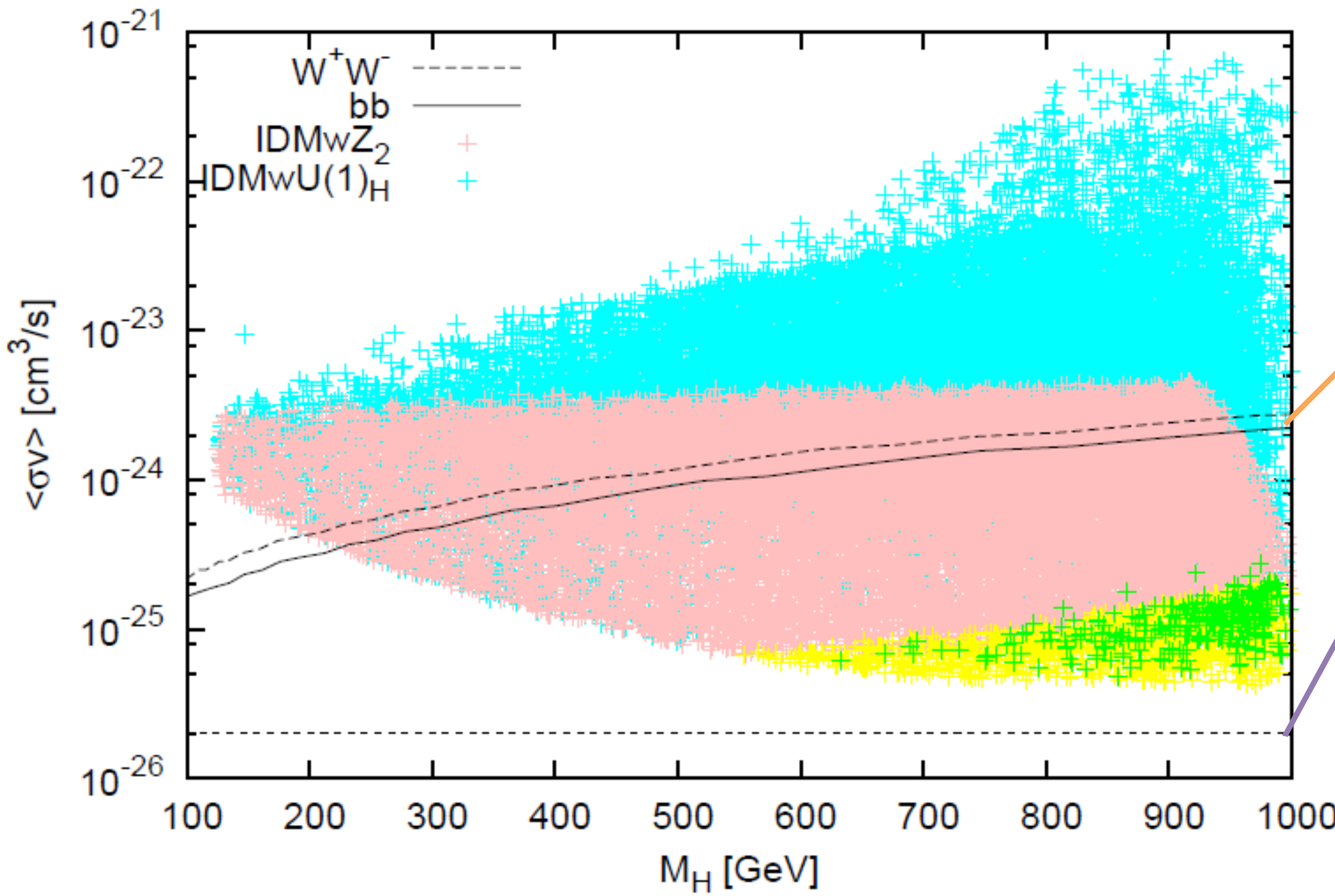
Relic density (high mass)

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



+ 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 (work in progress)
- 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

Scalar DM with Local Z3

P, Ko, Y.Tang, arXiv:1402.6449, JCAP (2014)

Scalar DM with local Z_3 sym

P, Ko, YTang, arXiv:1402.6449 (JCAP)

Consider $U(1)_X$ dark gauge symmetry, with scalar DM X and dark Higgs phi_X with charges 1 and 3, respectively.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon \tilde{X}_{\mu\nu}\tilde{B}^{\mu\nu} + D_\mu\phi_X^\dagger D^\mu\phi_X + D_\mu X^\dagger D^\mu X - V$$

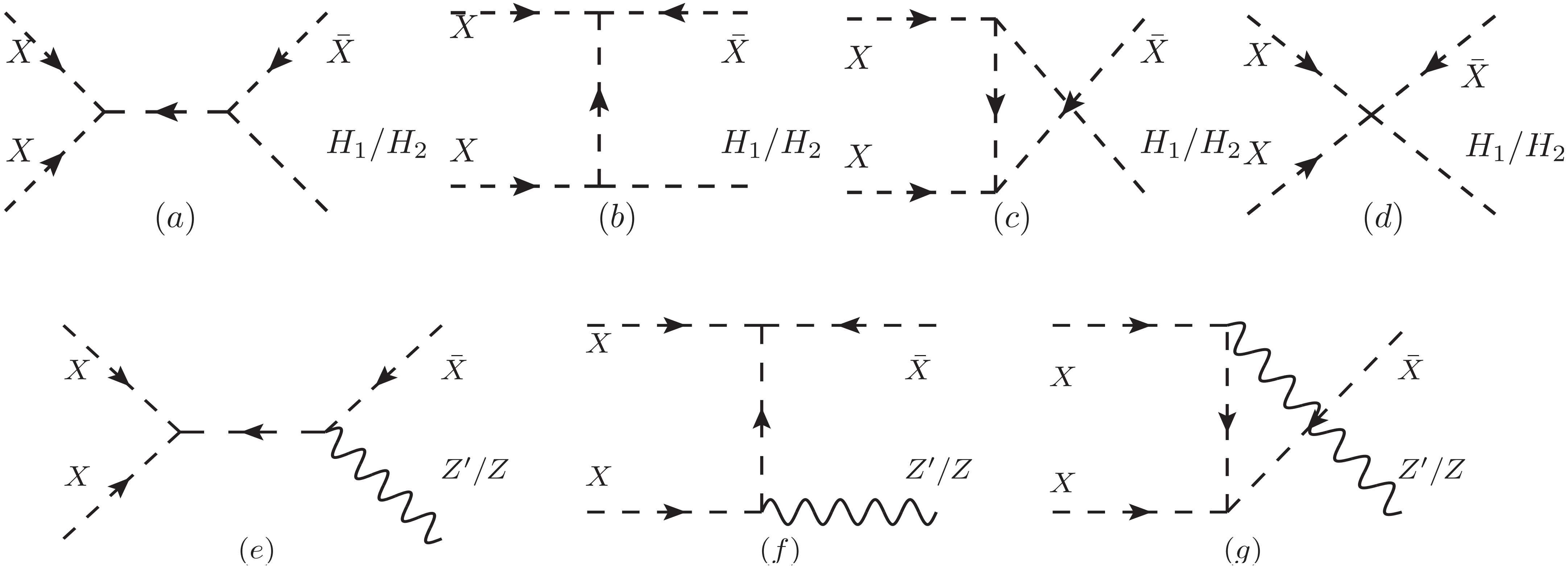
$$V = -\mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 - \mu_\phi^2\phi_X^\dagger\phi_X + \lambda_\phi\left(\phi_X^\dagger\phi_X\right)^2 + \mu_X^2 X^\dagger X + \lambda_X \left(X^\dagger X\right)^2$$
$$+ \lambda_{\phi H}\phi_X^\dagger\phi_X H^\dagger H + \lambda_{\phi X} X^\dagger X\phi_X^\dagger\phi_X + \lambda_{HX} X^\dagger X H^\dagger H + \left(\lambda_3 X^3\phi_X^\dagger + H.c.\right)$$

Global Z3 model by Belanger et al arXiv:1211.1014 (JCAP)

v_X

without phi and Z'

Semi-annihilation



$$\frac{dn_X}{dt} = -v\sigma^{XX^*\to YY}\left(n_X^2 - n_{X\,\mathrm{eq}}^2\right) - \frac{1}{2}v\sigma^{XX\to X^*Y}\left(n_X^2 - n_X n_{X\,\mathrm{eq}}\right) - 3Hn_X,$$

$$r \equiv \frac{1}{2}\frac{v\sigma^{XX\to X^*Y}}{v\sigma^{XX^*\to YY} + \frac{1}{2}v\sigma^{XX\to X^*Y}}.$$

micrOMEGAs

Comparison with global Z3

$$V_{\text{eff}} \simeq -\mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 + \mu_X^2 X^\dagger X + \lambda_X \left(X^\dagger X\right)^2 + \lambda_{HX} X^\dagger X H^\dagger H + \mu_3 X^3$$
$$+ \text{higher order terms} + H.c,$$

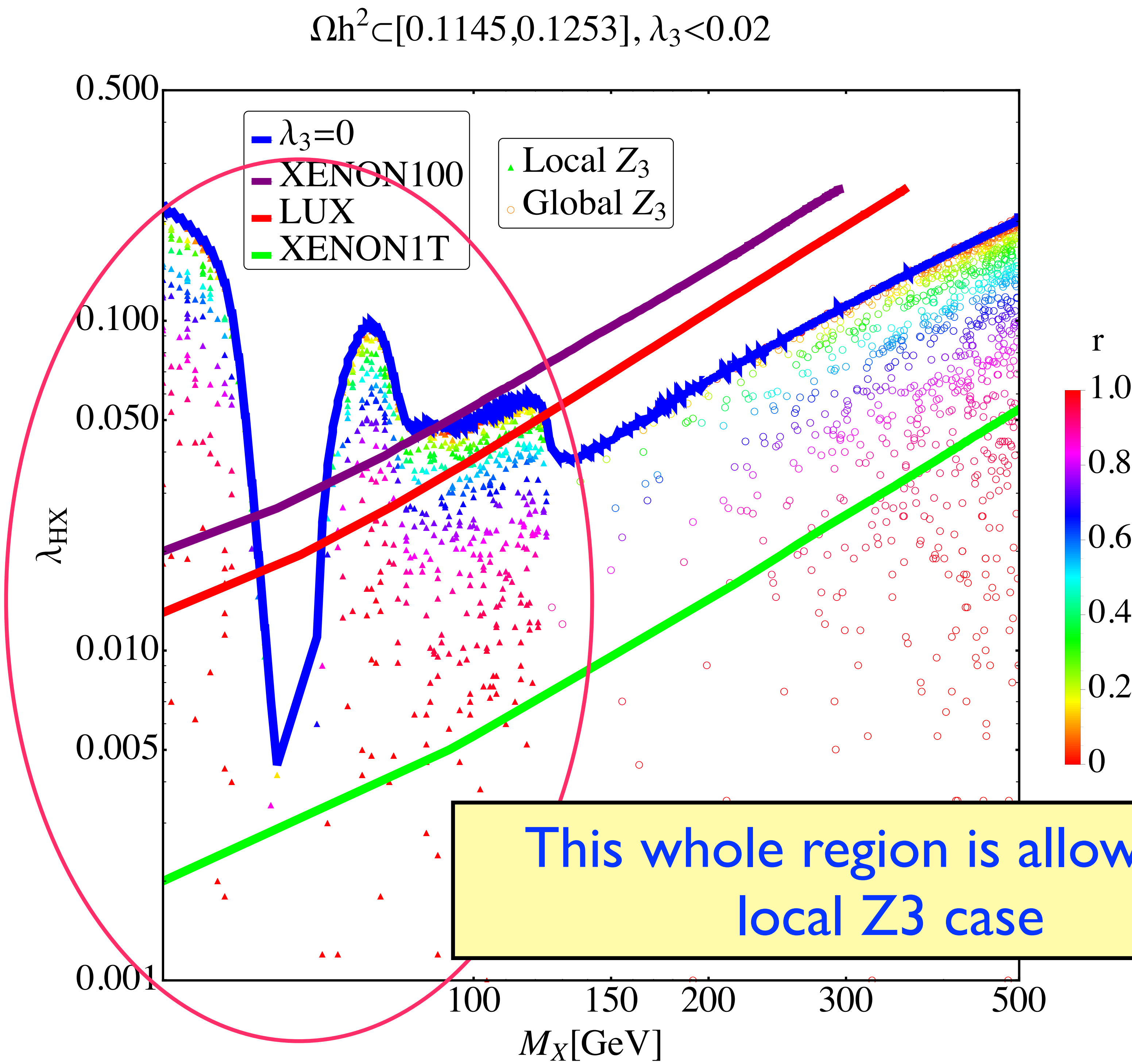
- However global symmetry can be broken by gravity induced nonrenormalizable op's:

$$\frac{1}{\Lambda} X F_{\mu\nu} F^{\mu\nu}$$

Global Z_3 "X" with EW scale mass will decay immediately and can not be a DM

- Also particle contents different : Z' and H_2
- DM & H phenomenology change a lot

Relic density and Direct Search



This whole region is allowed in local Z3 case

- Blue band marks the upper bound,
- All points are allowed in our local Z3 model, 1402.6449
- only circles are allowed in global Z3 model,1211.1014

$$r \equiv \frac{1}{2} \frac{v\sigma^{XX \to X^* Y}}{v\sigma^{XX^* \to YY} + \frac{1}{2} v\sigma^{XX \to X^* Y}}.$$

Comparison with EFT

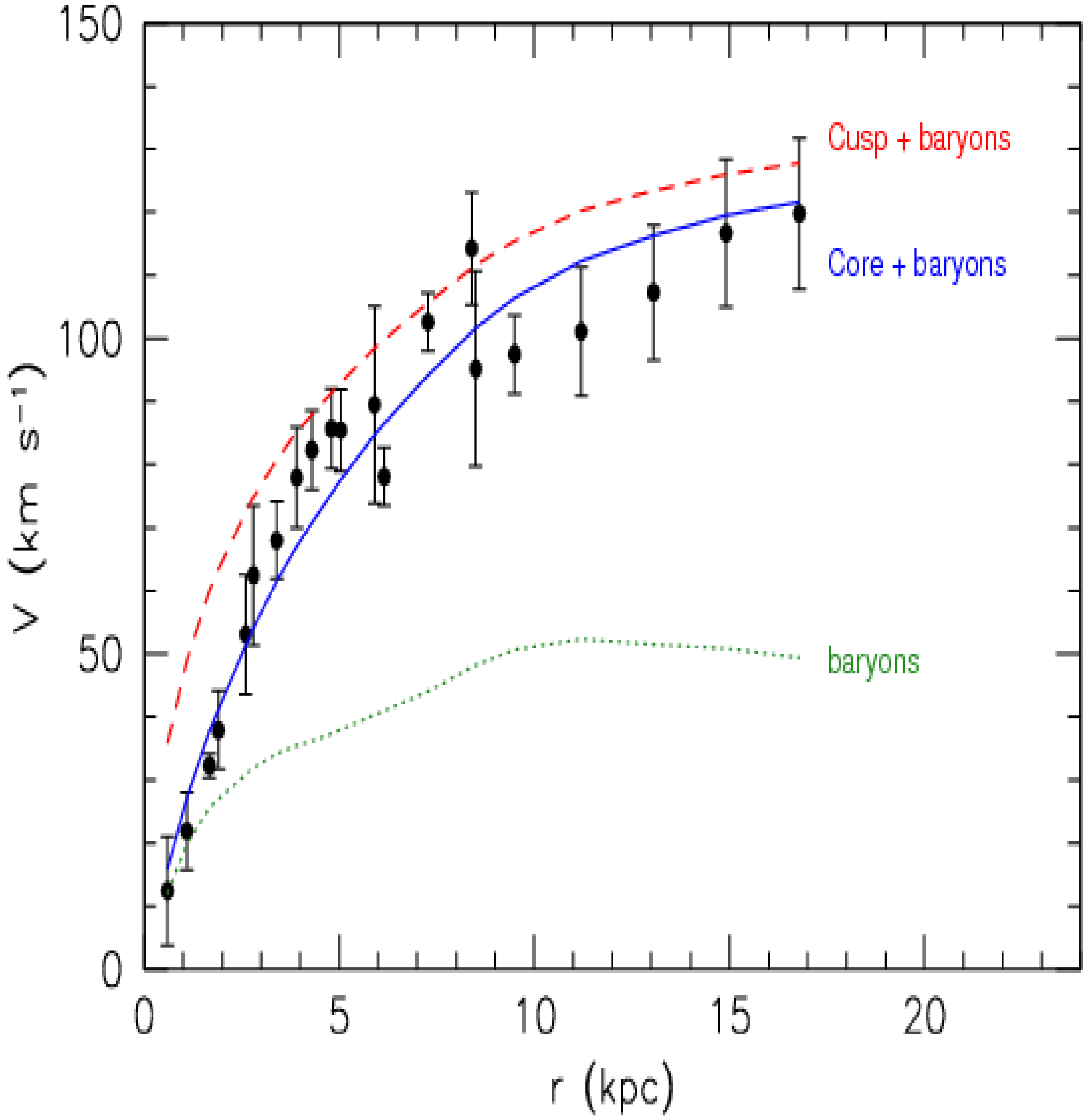
$$U(1)_X \text{ sym}: \quad X^\dagger X H^\dagger H, \ \frac{1}{\Lambda^2}\left(X^\dagger D_\mu X\right)\left(H^\dagger D^\mu H\right), \ \frac{1}{\Lambda^2}\left(X^\dagger D_\mu X\right)\left(\overline{f}\gamma^\mu f\right), \ etc. \quad (4.3)$$

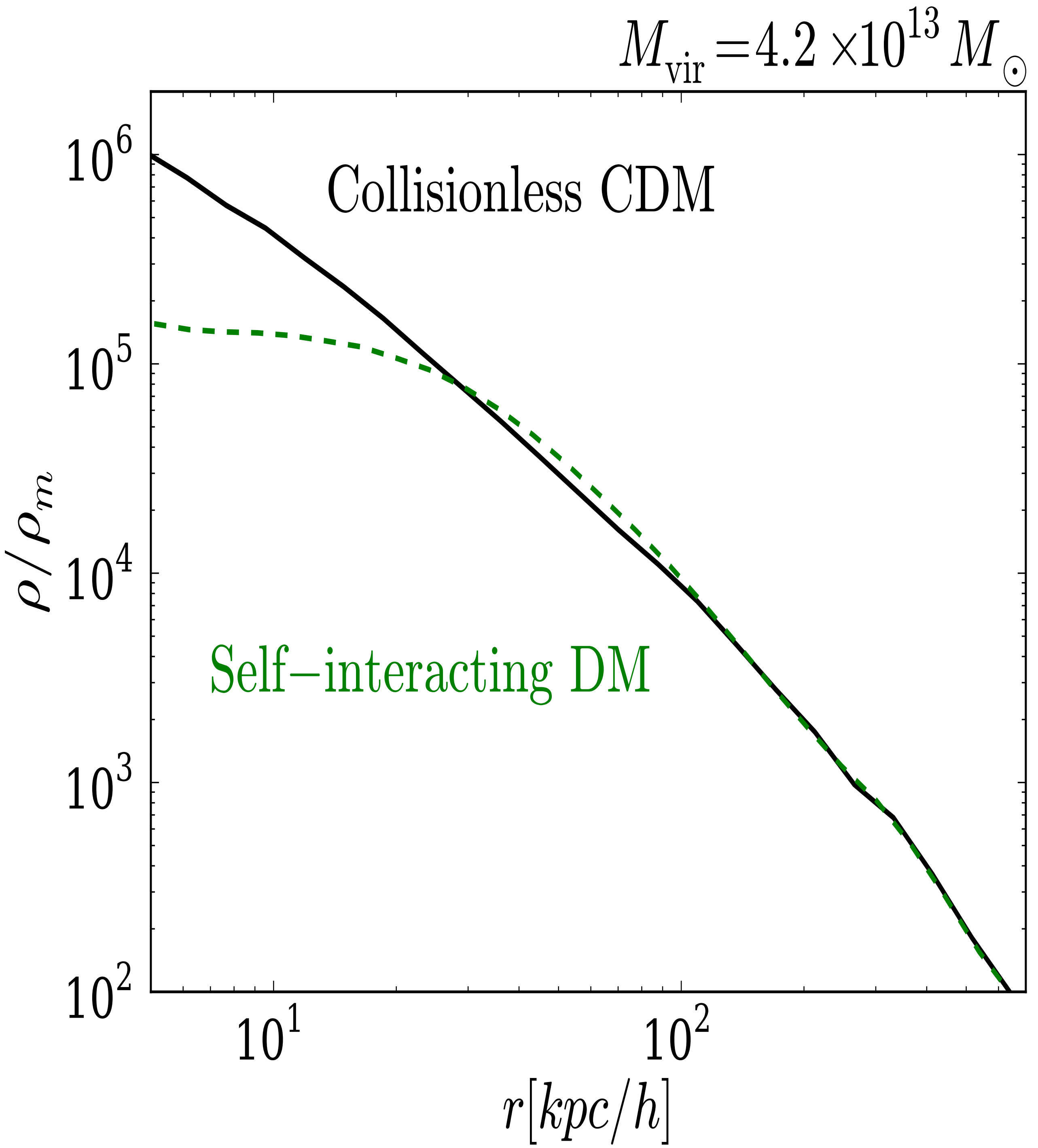
$$Z_3 \text{ sym}: \quad \frac{1}{\Lambda} X^3 H^\dagger H, \quad \frac{1}{\Lambda^2} X^3 \overline{f} f, \ etc. \quad (4.4)$$

$$\left(\text{or } \frac{1}{\Lambda^3} X^3 \overline{f_L} H f_R, \text{if we imposed the full SM gauge symmetry}\right) \quad (4.5)$$

- There is no Z’, H2 in the EFT, and so indirect detection or thermal relic density calculations can be completely different
- Complementarity breaks down : (4.3) cannot capture semi-annihilation

Cusp vs. Core


150
100
50
0
0
5
10
15
20
V (km s⁻¹)
r (kpc)
Cusp + baryons
Core + baryons
baryons


$M_{\rm vir} = 4.2 \times 10^{13} M_\odot$
10^6
10^5
10^4
10^3
10^2
10^1
10^2
ρ/ρ_m
$r[kpc/h]$
Collisionless CDM
Self–interacting DM

Possible solutions

- Baryonic physics:
  gas cooling, star formation,
  supernova feedback,…

- Dark Matter:
  warm dark matter
  Self-Interacting CDM

Spergel et al, Sigurdson et al,
Boehm et al, Kaplinghat et al,
Loeb et al, Tulin et al,
van de Aarseen et al,
….

What is SIDM?

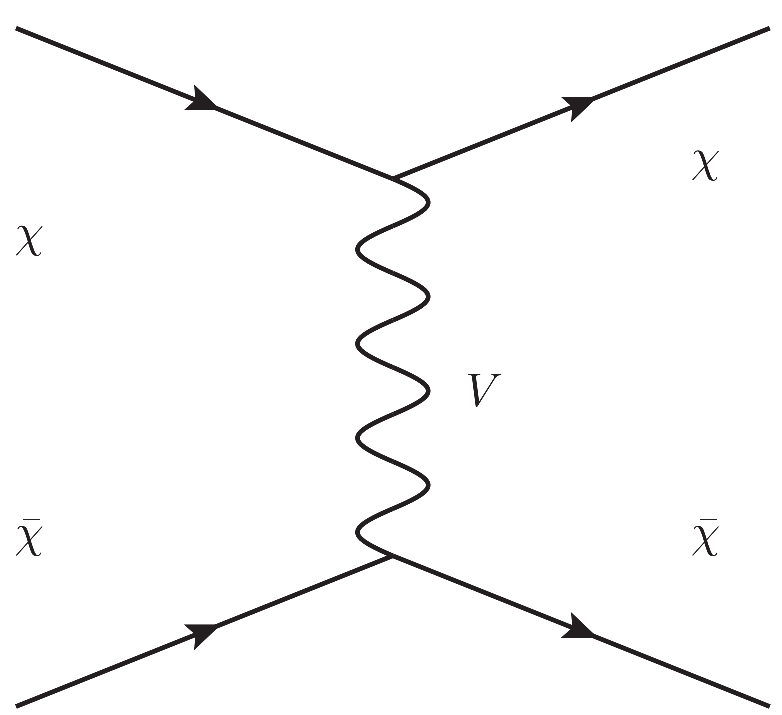
- DM-DM scattering cross section is around

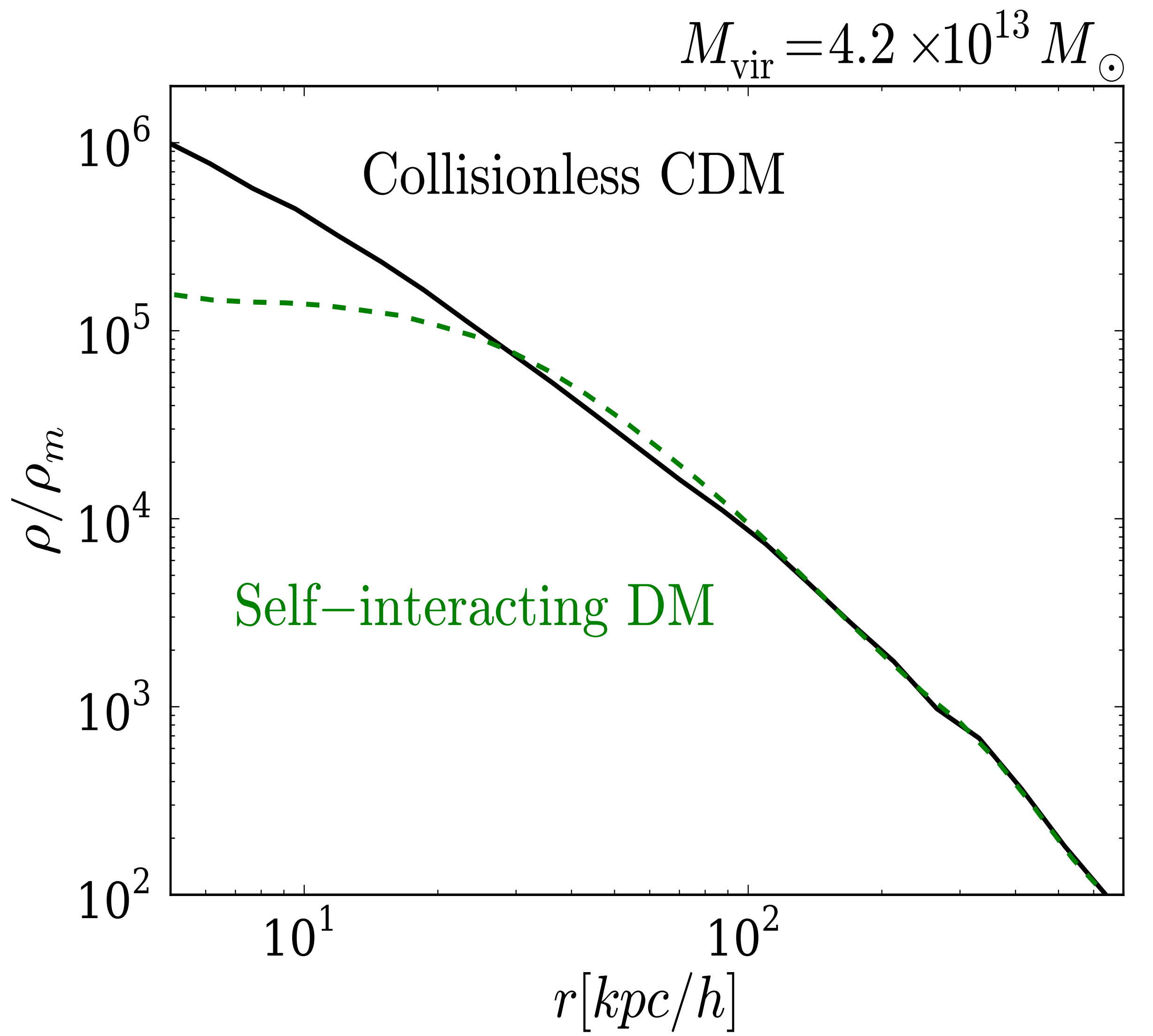
$$\frac{\sigma}{M_X} \sim \mathrm{cm}^2/\mathrm{g} \sim \mathrm{barn}/\mathrm{GeV}$$

- It can flatten the halo centre, solving the “cups-core” and “too-big-to-fail” problems.
- Interaction with relativistic particles can induce a cut-off in the matter power spectrum by collisional damping, solving the “missing satellites” problem.

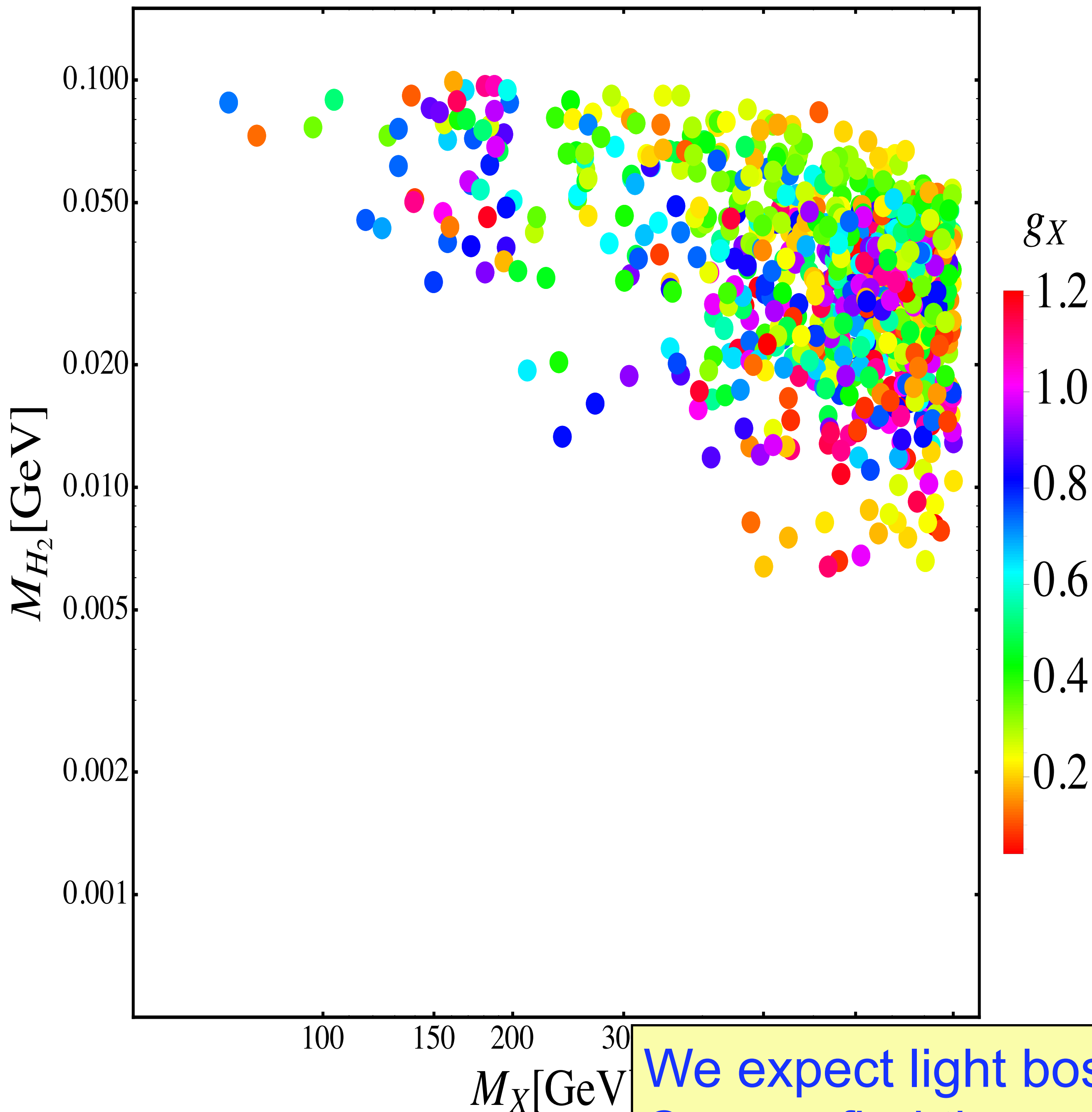
How?

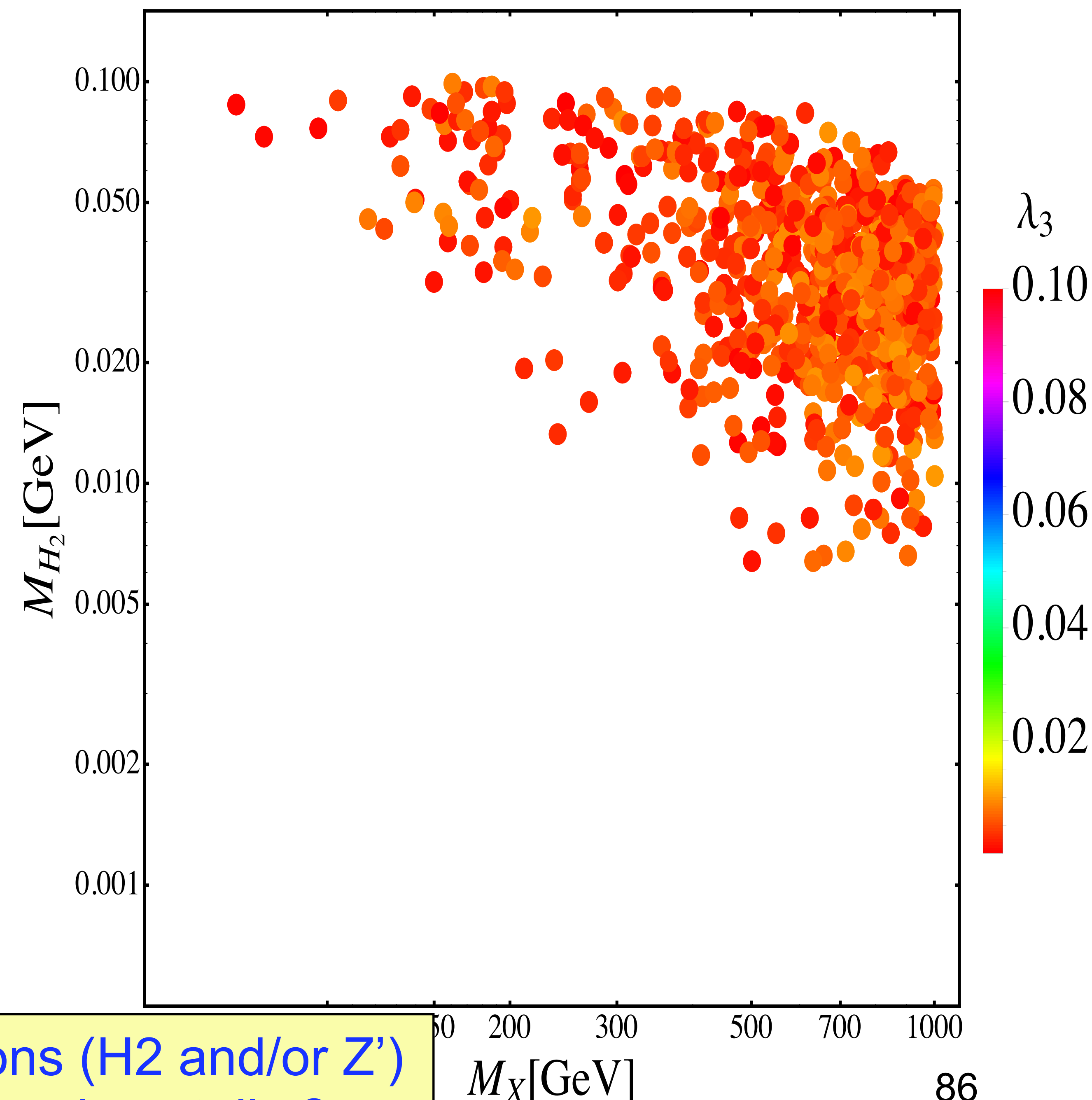
- MeV mediator can provide the right elastic scattering cross section for TeV dark matter,





Strong DM self interaction from Light Mediators





We expect light bosons (H2 and/or Z')
Can we find them experimentally ?

Global Z3 (Belanger, Pukhov et al)	Local Z3 (Ko, Yong Tang)
- SM + X - DD & thermal relic >> m_X > 120 GeV - Vacuum stability >> DD cross section within Xenon1T experiment - No light mediators	- SM + X , phi , Z' - Additional annihilation channels open - DD constraints relaxed - Light m_X allowed - Light mediator phi : strong self interactions of X's

Gamma ray excess from GC

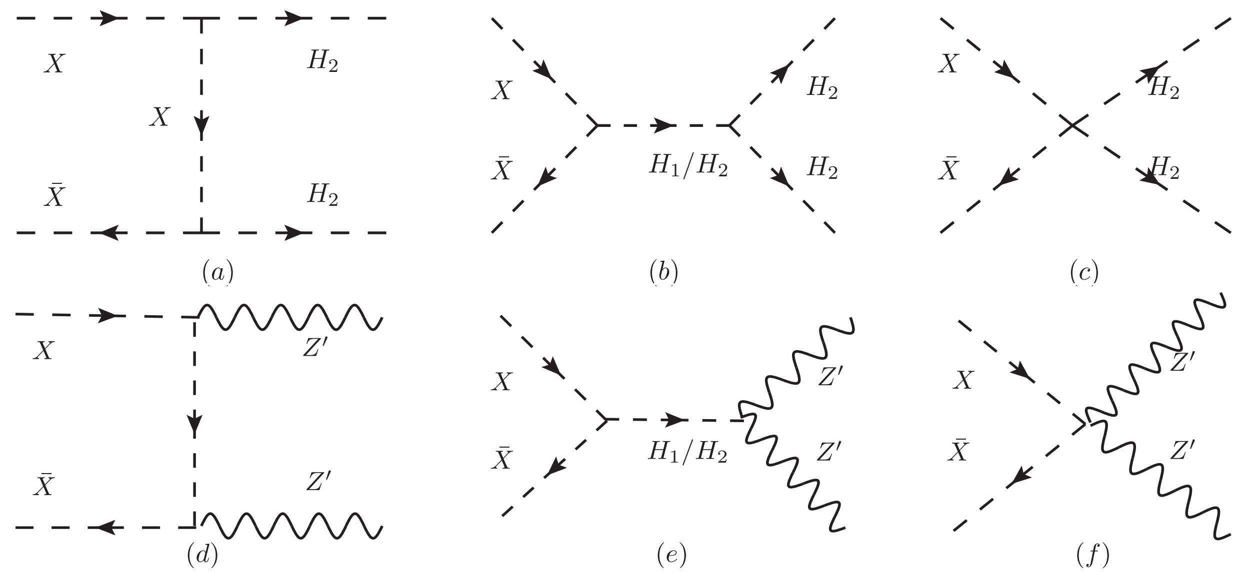


FIG. 1: Feynman diagrams for $X\bar{X}$ annihilation into H_2 and Z'.

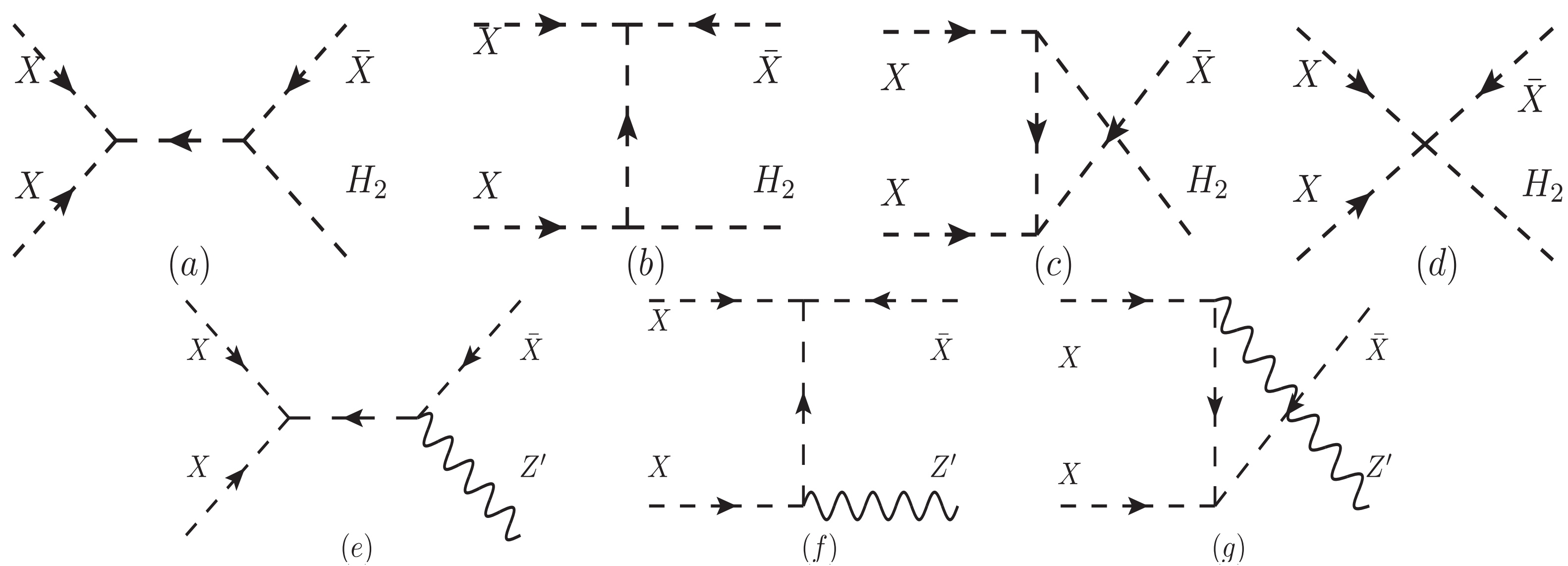


FIG. 2: Feynman diagrams for XX semi-annihilation into H_2 and Z'.

(arXiv:1407.5492 with Yong Tang)

Gamma ray excess from GC

(arXiv:1407.5492 with Yong Tang)

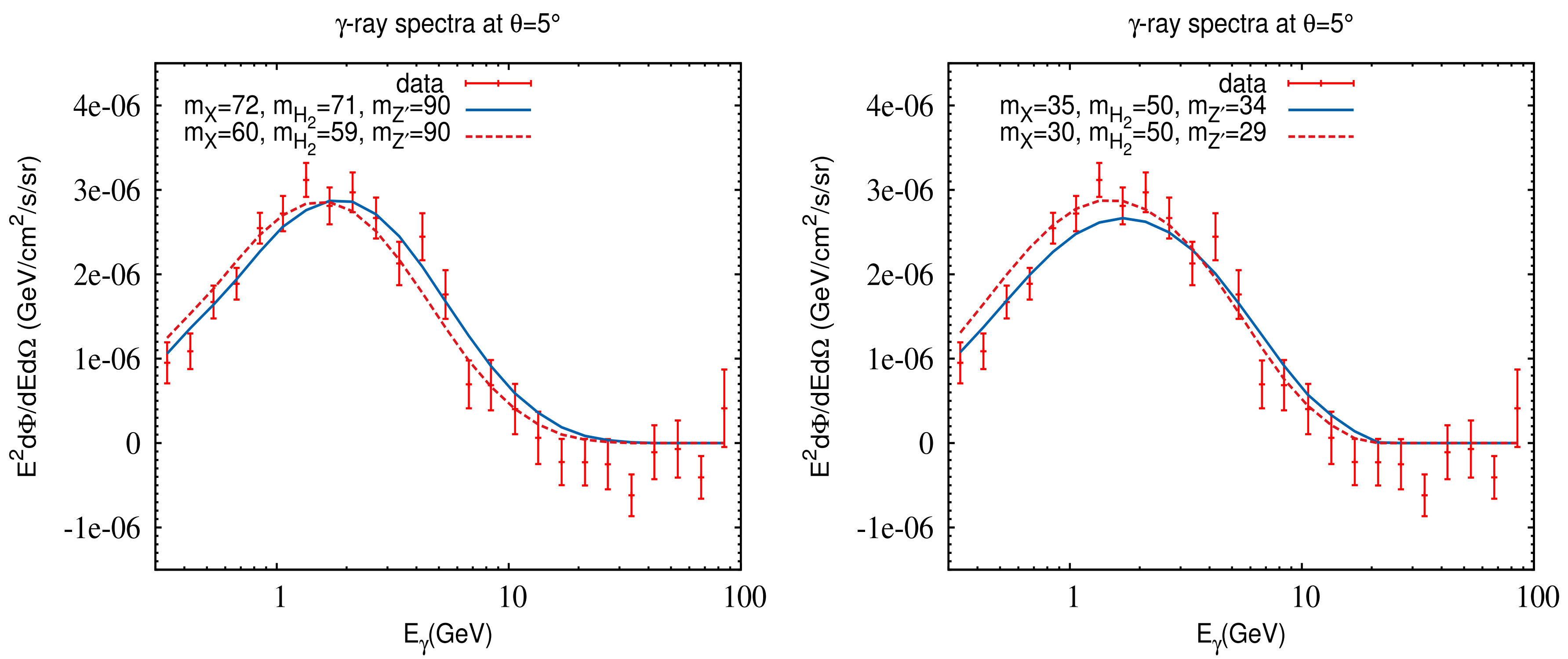


FIG. 4: γ-ray spectra from dark matter (semi-)annihilation with H_2(left) and Z'(right) as final states. In each case, mass of H_2 or Z' is chosen to be close to m_X to avoid large lorentz boost. Masses are in GeV unit. Data points at $\theta = 5$ degree are extracted from [1].

Possible only in local Z3, not in global Z3

Antiproton and positron

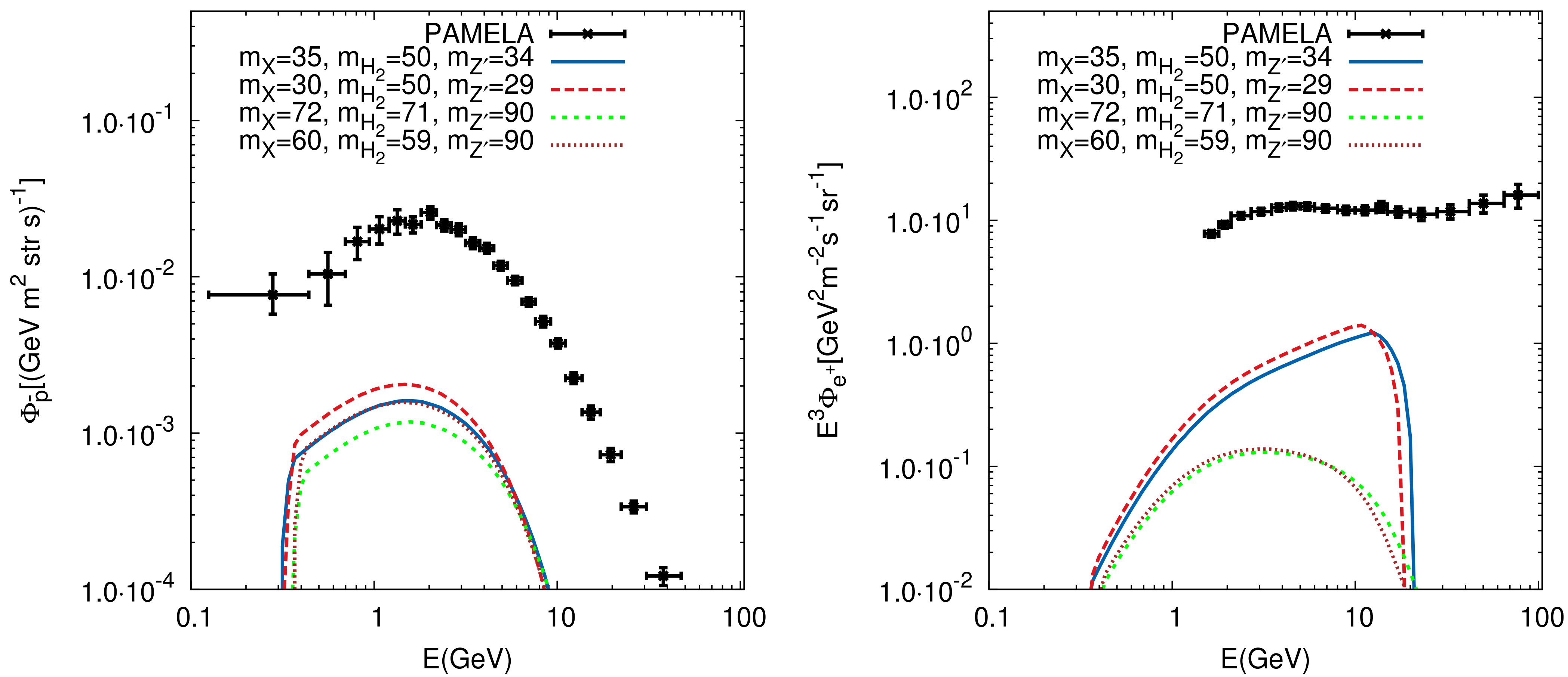


FIG. 5: $\bar{p}$ and e^+ spectra from dark matter (semi-)annihilation with H_2(left) and Z'(right) as final states. In each case, mass of H_2 or Z' is chosen to be close to m_X to avoid large lorentz boost. Masses are in GeV unit. $\langle\sigma v\rangle_{\rm ann} \simeq 6.8(4.4)\times 10^{-26}{\rm cm}^3/{\rm s}$ for $H_2(Z')$ final states are assumed. Data point are taken from [53] for anti-proton and [54] for positron fluxes, using the database [55].

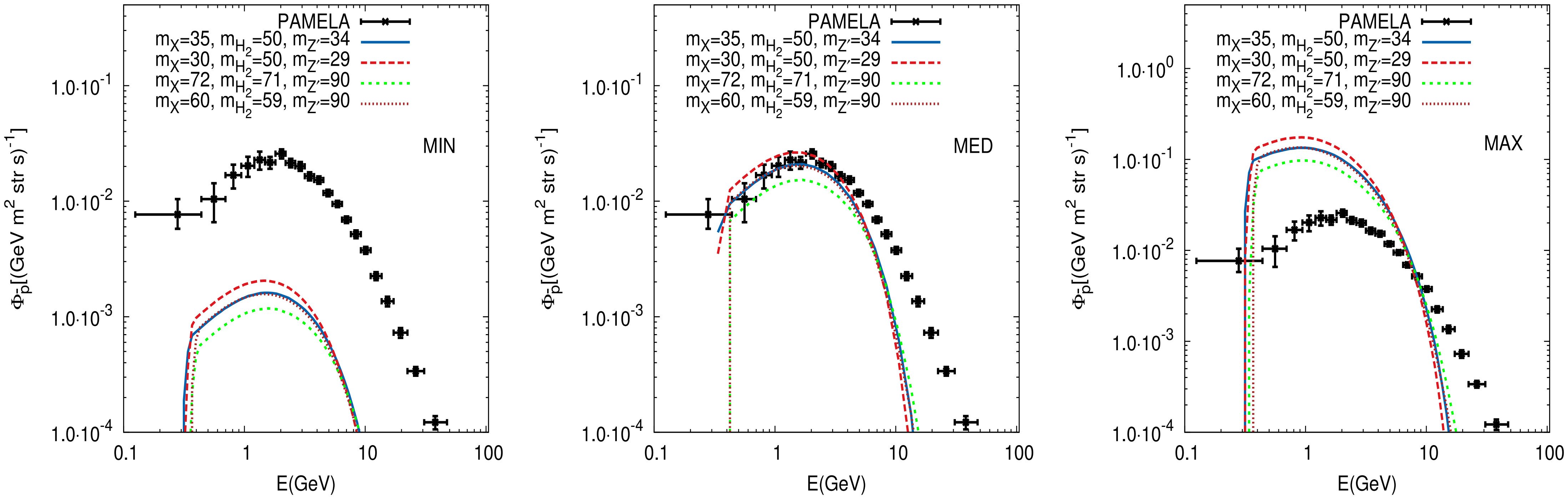


FIG. 6: Antiproton flux dependence on astrophysical parameters. From left to right, MIN, MED and MAX models are used respectively. See table. I for model parameters.

Conclusions

- U(1) Higgs gauge symmetry may be a useful concept in multi Higgs doublet models for evading the Higgs-mediated FCNCs
- Usually taken as low energy EFT of MSSM
- Could be a signature of new chiral U(1) gauge interactions (in order to have realistic Yukawa interactions)
- It remains to be seen whether there exists an extended Higgs sector or not

- When applied to the inert DM model, a new range for DM mass is open due to newly open channels involving Z_H's

- Possible to accommodate the gamma ray excess from the GC in the IDM with local U(1) Higgs gauge symmetry, in sharp contrast with the usual IDM where this is impossible

- Likewise local dark gauge symmetries can play an important role in DM physics