Massive Dark Photon: w/o & w/ Dark Higgs Boson

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- Massive Vector Boson (MVB) : common in many BSM models
- Very often, origin of MVB mass is neglected assuming Proca or Stueckelberg mechanism, and consider $V_\mu V^\mu H^\dagger H, R g^{\mu\nu} V_\mu V_\nu, R^{\mu\nu} V_\mu V_\nu,$ etc
- Higgs Portal VDM : $\Gamma(h \rightarrow VV) \rightarrow \infty$ for $m_V \rightarrow 0$. Problematic! What's going on ?
- I will show that physics depends crucially on origin of MVB (and SM fermion) mass
- If mass origin is neglected, you can sometimes get misleading/wrong results

Main themes and Key Words

- Unitarity, Gauge Invariance (renorm.) Math / Th Consistency
- Proca, Stueckelberg vs. (Dark) Higgs for the case of massive vector boson (dark photon) : several pheno examples in this talk
- Theoretical issues (including gravity): in preparation

Lessons I learned from Bygone Anomalies

- Large FCNC ~ FCCC Weak Interactions
- Muon g-2, ATOMKI, MiniBooNE, ….
- CDF Wjj, Top FBA, 750 GeV diphoton,
- DM related ones: 511 keV γ ray excess, PAMELA e^+ excess, Galactic Center γ ray excess, XENON1T, ….

Reappraisal of SM

Current Status of SM

- Only Higgs (~SM) and Nothing Else so far at the LHC
- Yukawa & Higgs self couplings to be measured and tested
- Nature is described by Quantum Local Gauge Theories
- Unitarity and gauge invariance played key roles in development of the SM

Building Blocks of SM

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

Accidental Sym's of SM

- Renormalizable parts of the SM Lagrangian conserve baryon #, lepton # : broken only by dim-6 and dim-5 op's $\longrightarrow$"longevity of proton" and "lightness of neutrinos" becoming Natural Consequences of the SM (with conserved color in QCD)

- QCD and QED at low energy conserve P and C, and flavors

- In retrospect, it is strange that P and C are good symmetries of QCD and QED at low energy, since the LH and the RH fermions in the SM are independent objects

- What is the correct question ? "P and C to be conserved or not ?" Or "LR sym or not ?"

How to do Model Building

- Specify local gauge sym, matter contents and their representations w/o any global sym
- 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
- You 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

Motivations for BSM

Pheno'cal Motivations

- Neutrino masses and mixings
- Baryogenesis
- Inflation (inflaton)
- Nonbaryonic DM
- Origin of EWSB and Cosmological Const ?

Leptogenesis

Starobinsky & Higgs Inflations

?

Many candidates

Can we attack these problems ?

Theoretical Motivations

- Fine tuning problem of Higgs mass parameter : SUSY, RS, ADD, etc.
- Critical comments in the Les Houches Lecture by Aneesh Manohar (arXiv:1804.05863)
- Standard arguments :
  - Electron self-energy in classical E&M vs. QED
  - Δm_K without/with charm quark
  - $\Delta m^2 = m_{\pi^\pm}^2 - m_{\pi^0}^2$ without/with ρ mesons
  - They are simply wrong !

No-lose theorem for LHC

- Before the Higgs boson discovery, rigorous arguments for LHC due to the No-Lose theorem
- W/o Higgs boson, $W_L W_L \rightarrow W_L W_L$ scattering violates unitarity, which is one of the cornerstones of QFT
- Unitarity will be restored by
  - Elementary Higgs boson
  - Infinite tower of new resonances (KK tower)
  - New resonances for strongly interacting EWSB sector
  - Higgs is there, but not observable if it decays into DM (2007,2011,..)

My Personal Viewpoints

- Traditionally, Fine Tuning or Naturalness problem was the driving force for many BSM, and predicted many signatures @ LHC
- No signatures @ LHC means that the traditional motivation is not that well motivated
- Mathematical and Theoretical Consistency : more important for BSM model buildings
- Unitarity is one of the Holy Grails in EFT approach

Contents

- Anomaly free : before/after GIM mechanism
- Extra spin-1 requires extensions of the Higgs sector : top FB asymmetry
- DM : Unitarity and DM stability/longevity important
- Dark Higgs for massive dark photon (Jongkuk's talk on Wednesday)

Anomaly Free : before/after GIM

Before GIM (1970)

- Weinberg Model for u,d,s :
  $(u_L, d_L \cos\theta_c + s_L \sin\theta_c)^T$, $u_R, d_R, s_R,$

- Predicts FCNC ~ FCCC :
  $\Gamma(K^+ \to \mu^+\nu_\mu) \sim \Gamma(K^0 \to \mu^+\mu^-)$, in contradiction to the exp data. What is going on ?

- Where is another combination,
  $(-d_L \sin\theta_c + s_L \cos\theta_c)$?

GIM (1970)

- GIM proposed to introduce the 4th quark, “charm”, as the SU(2) partner of the 2nd combination
- FCNC=0 @ tree level, and induced at loops
- $m_c \sim 1.5$ GeV explains Δm_K (Gaillard, Lee, Rossner, 1974), and confirmed by discovery of J/ψ in 1974 !
- In retrospect, large FCNC is a wrong prediction of anomalous gauge theory for 3 quark flavors, which is not a healthy theory [ABJ anomaly in 1969]

Extra spin-1 requires extensions of the Higgs sector : Top FBA as an example

Top FBA@Tevatron & Top CA@LHC in chiral U(1)' models with flavored Higgs fields

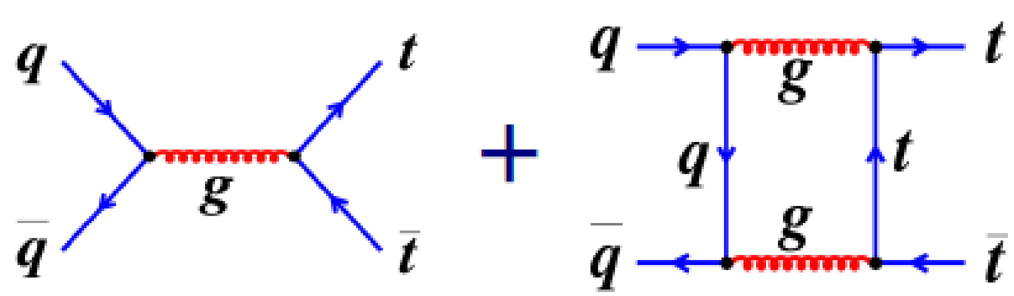
Contents

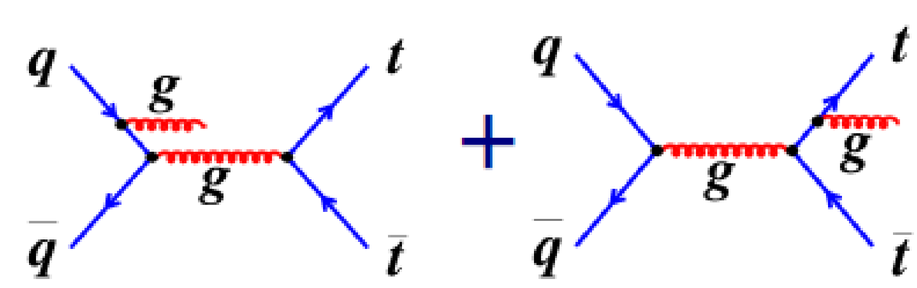
- SM Prediction vs. Data
- Z' model for Top FBA
- Flavor dependent U(1)' model
- Conclusion & General Remarks

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:

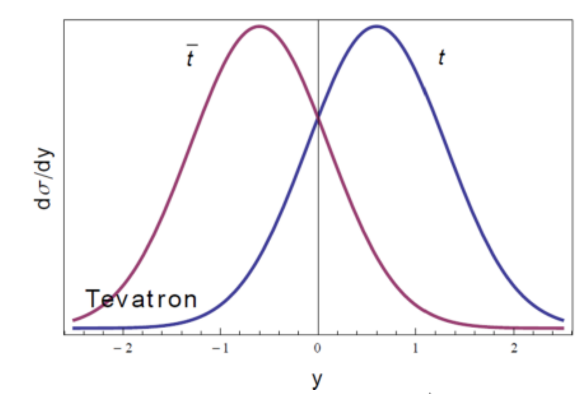
- Top quark is emitted preferentially in direction of the incoming quark
- Antitop quark opposite
- Production through new processes may lead to different asymmetries





- At Tevatron: define forward-backward asymmetry

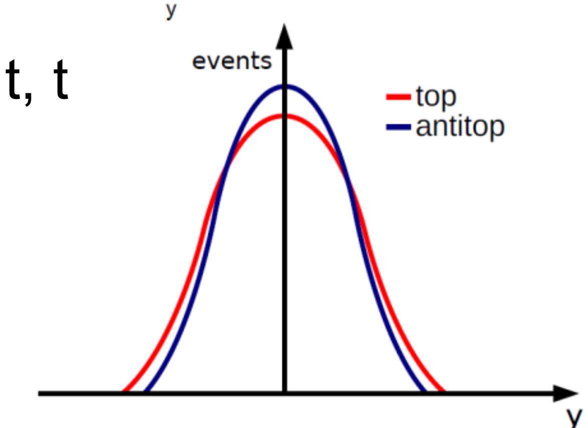
$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$



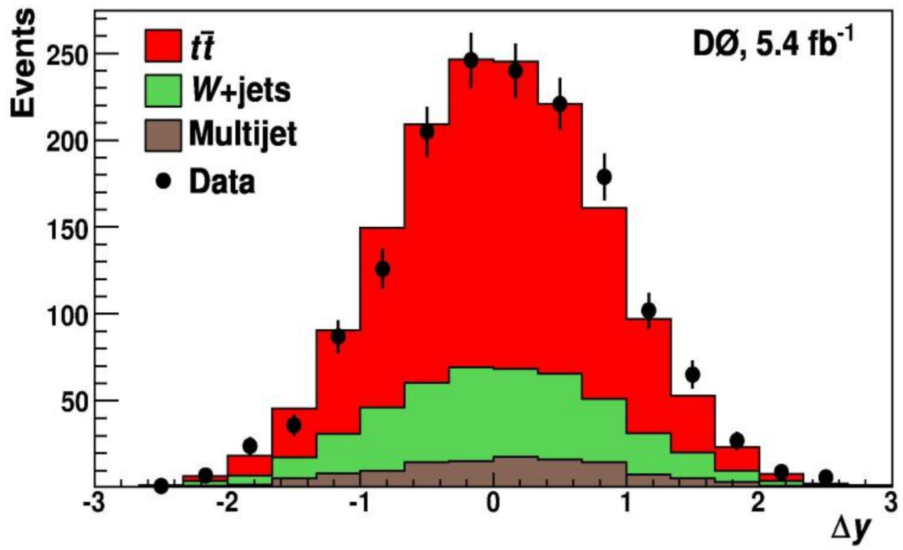
- At LHC: define asymmetry in the widths of rapidity distributions of t, t

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$



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

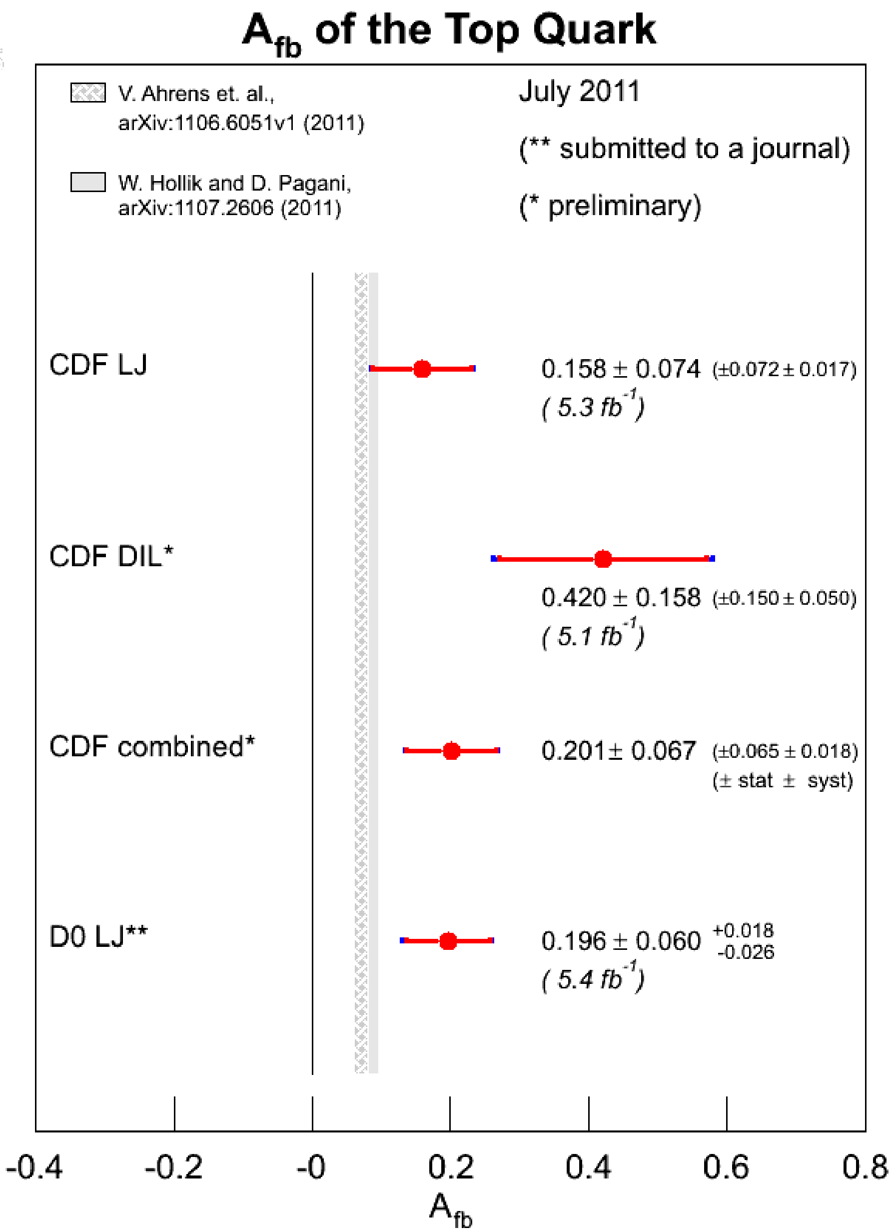
Measured asymmetry on parton level:

A_{FB} = 0.196 ± 0.065 (stat+syst)

D0 results in the di-lepton channel:

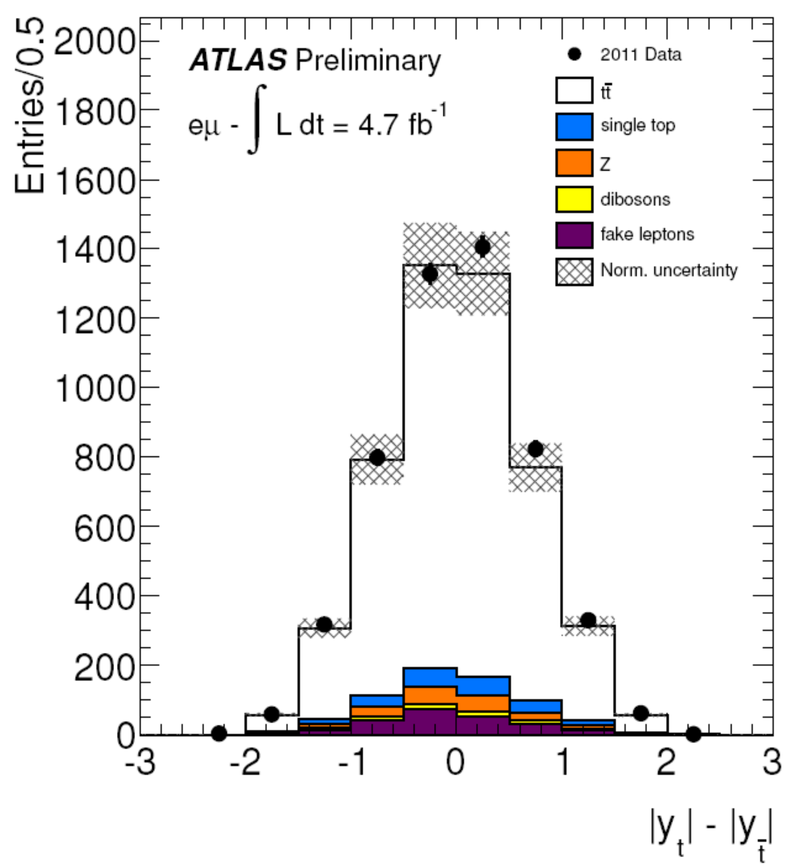
A_{FB} = 0.118 ± 0.032

Summary:

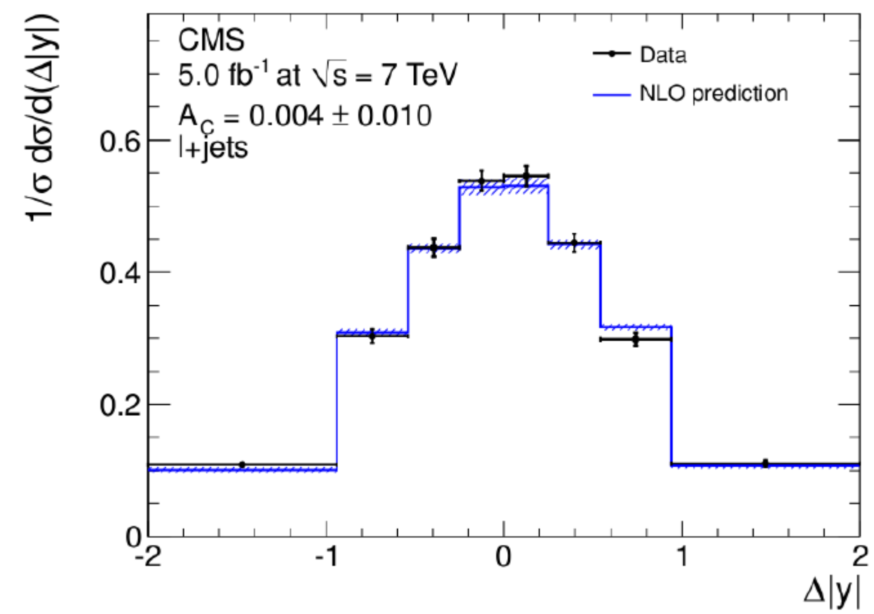


Both CDF and D0 see significant asymmetry in $t\bar{t}$ production in all channels with strong dependence on m_{tt}, in conflict with the SM

ICHEP 2012 : Top C Asym



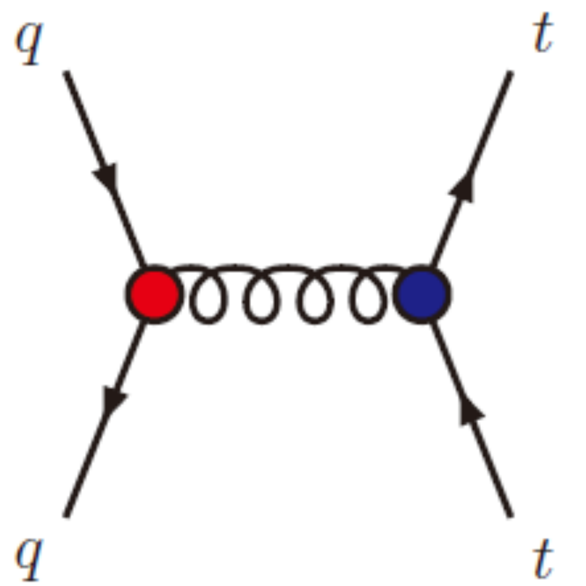
ATLAS-CONF-2012-057



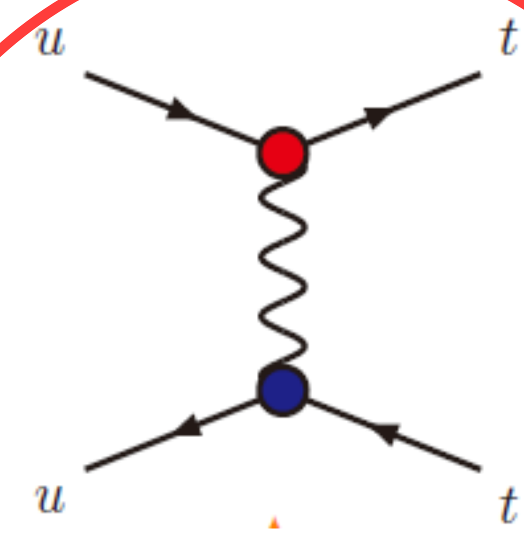
CMS PAPER TOP-11-030

- 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

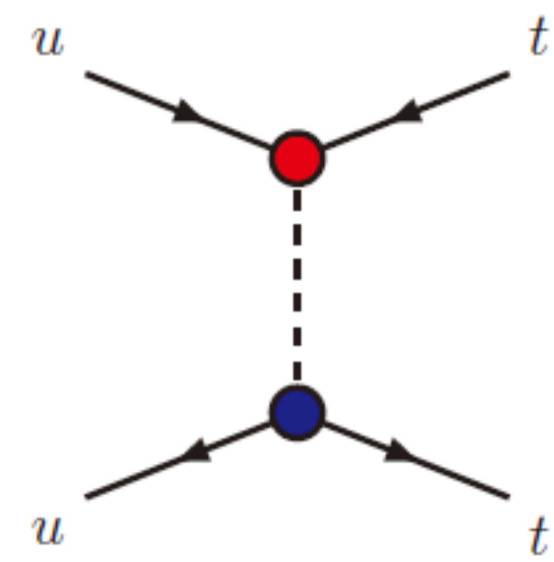
New physics models for top A_{FB}



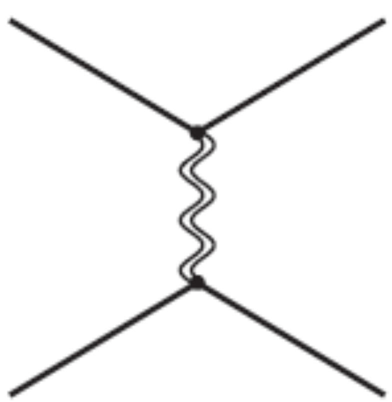
s-channel: coloured resonance $\mathcal{G}_\mu$



t-channel: Z', W', ϕ

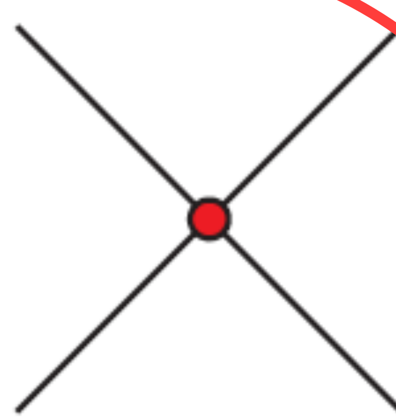


u-channel: exotic scalars



(new) heavy VB

Integrate



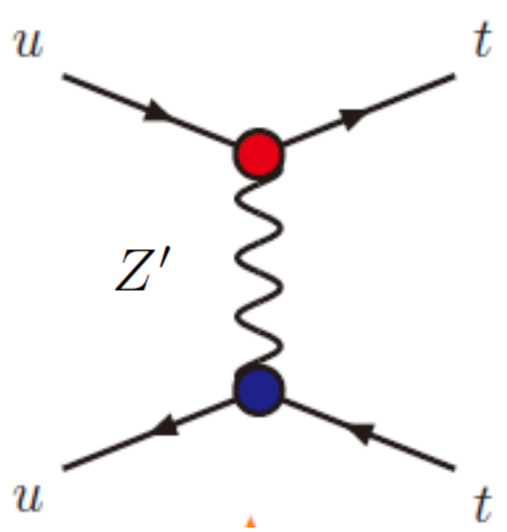
4-fermion interaction

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

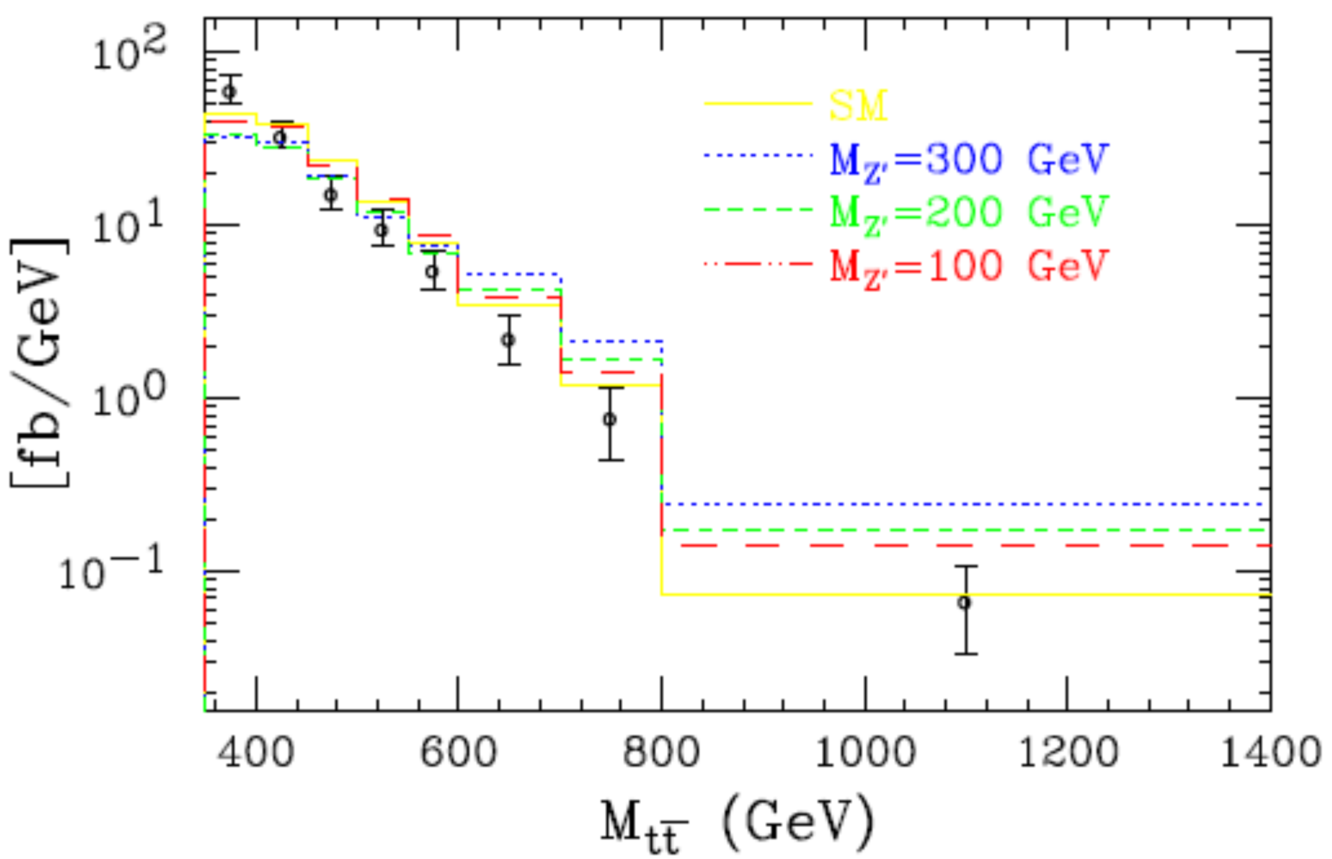
Jung, Murayama, Pierce, Wells, PRD81♪



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

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

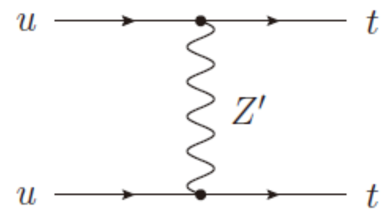
- In general, could have different couplings to the top and antitop quarks.



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

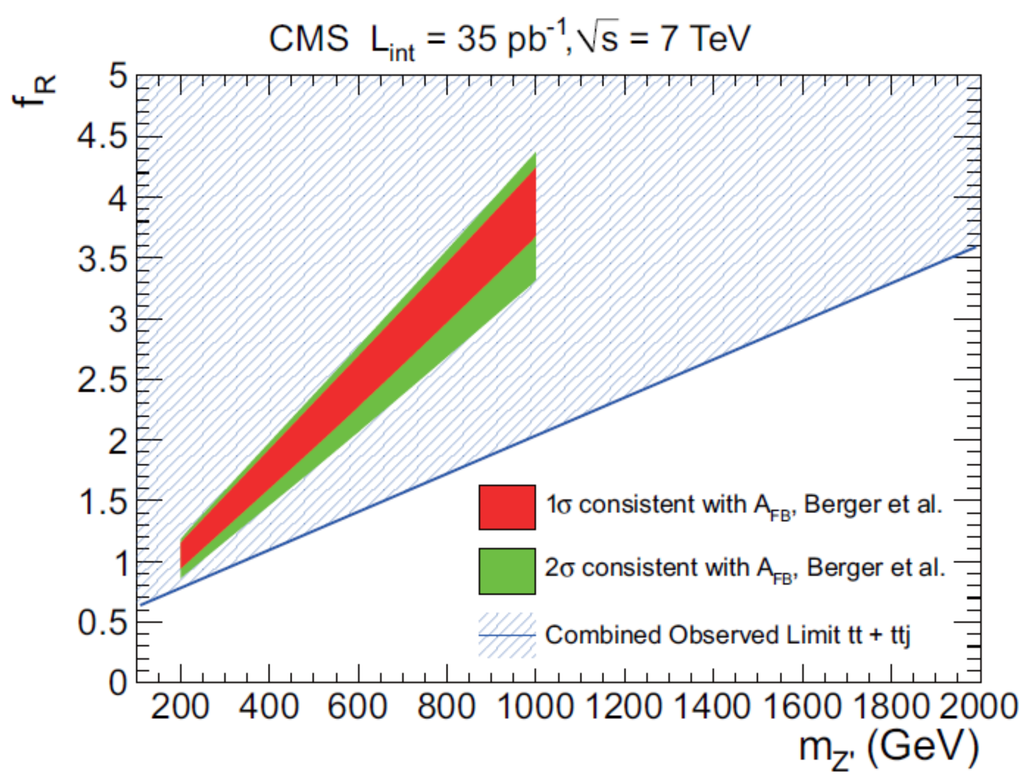
- severely constrained by the same sign top pair production.
  - the t-channel scalar exchange model has a similar constraint.

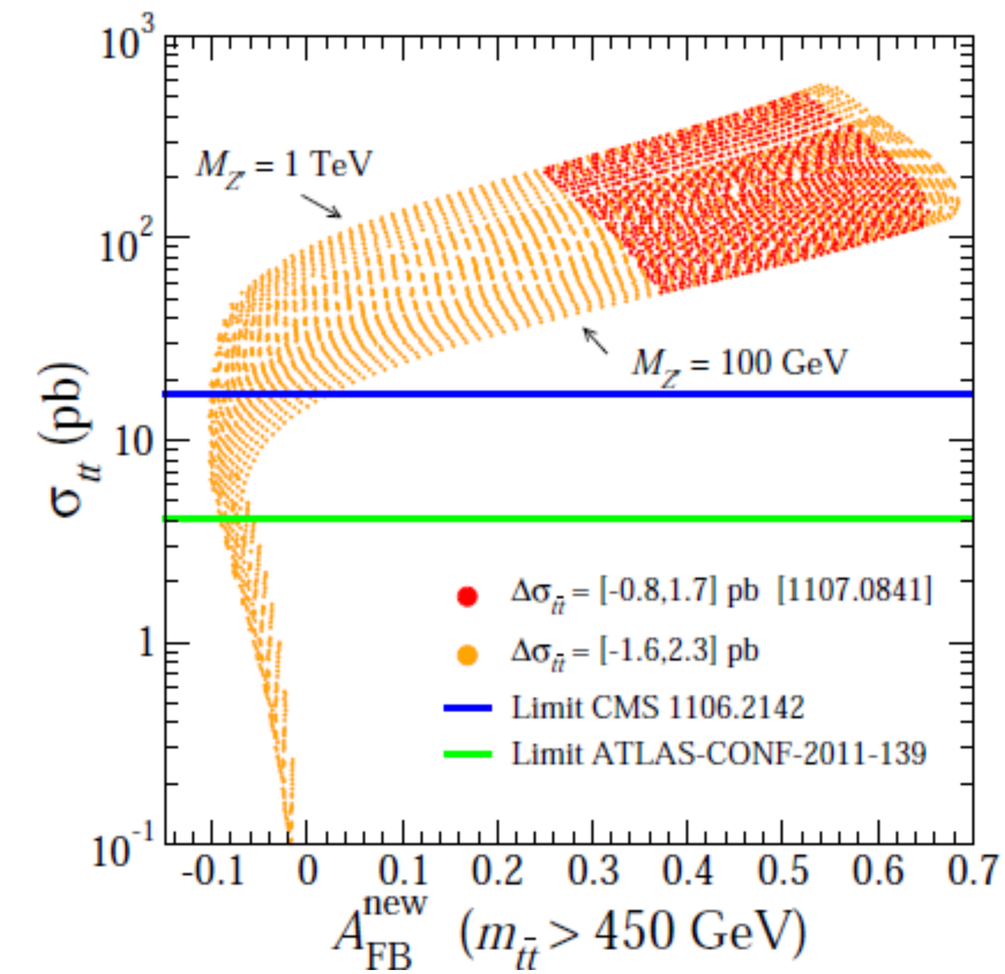
Same sign top pair production at LHC



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

General exclusion plot





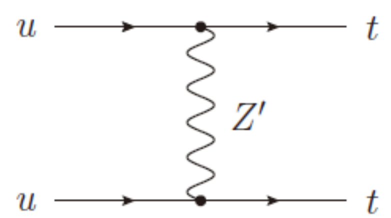
CMS: σ(pp→tt(j))<17 pb at 95C.L.
ATLAS: σ(pp→tt(j))<4 pb at 95C.L.

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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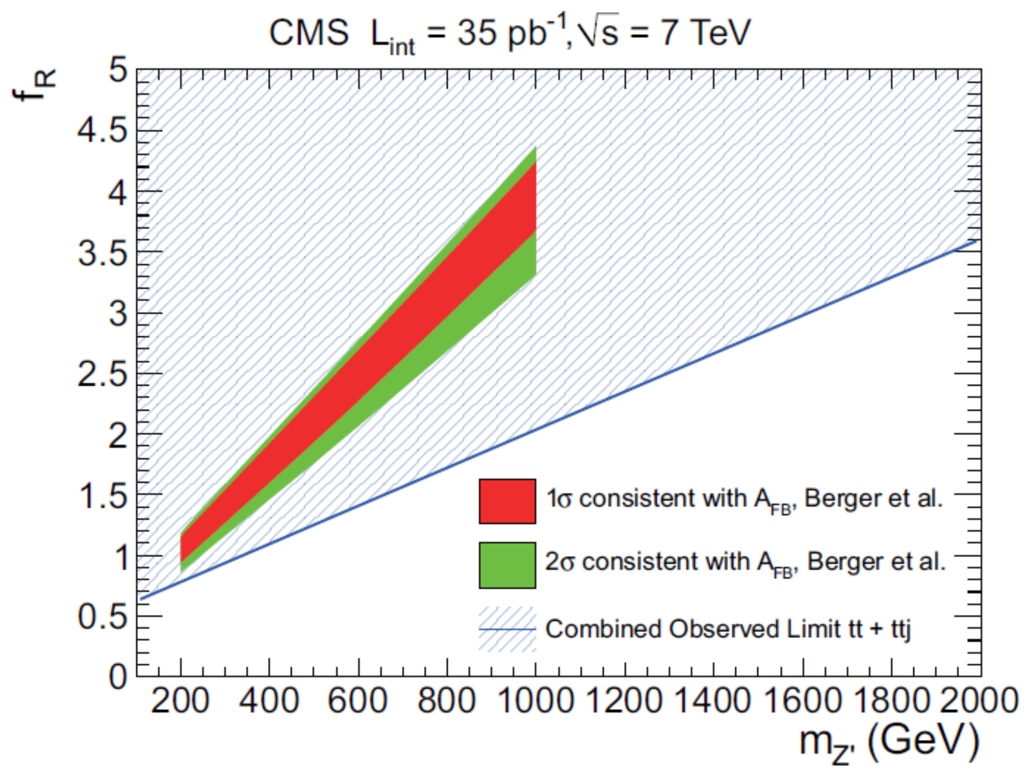

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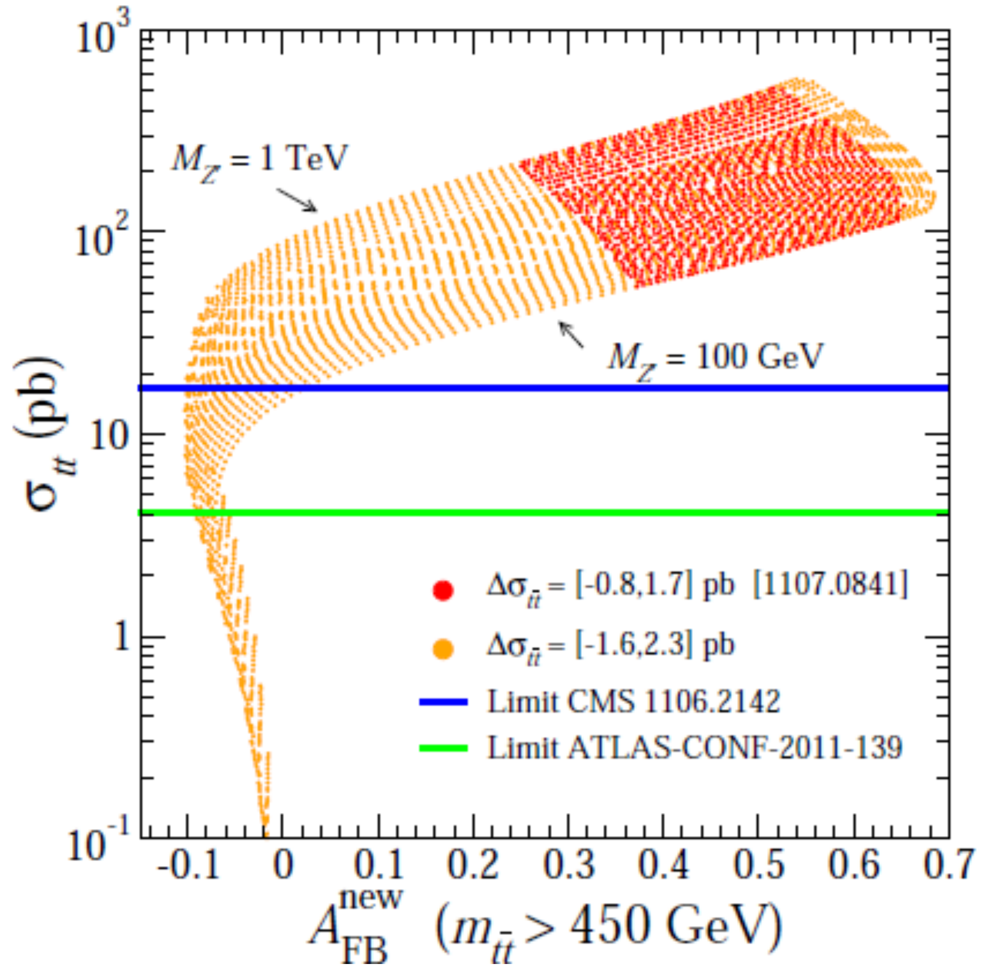
General exclusion plot



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 !

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, 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 : leptophobic 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-type quarks:
MASSLESS TOP QUARK !

How to cure this problem ?

This problem is independent of top FCNC

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

- Gauge coupling in the mass base

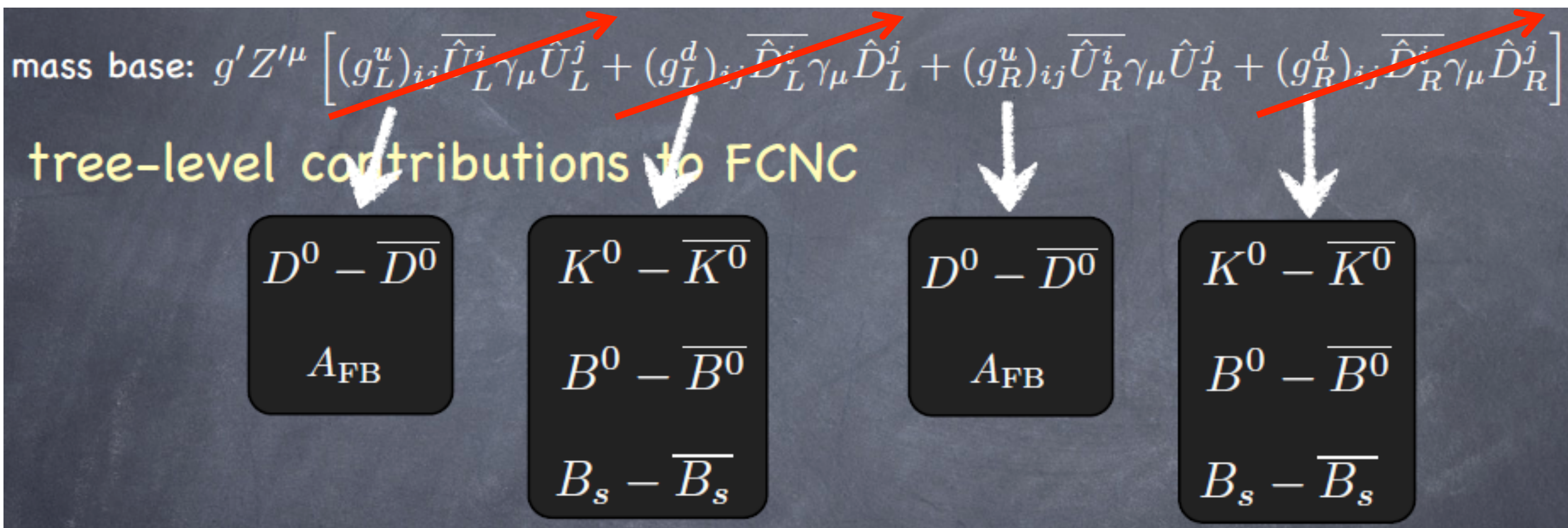
- Z′ interacts only with the right-handed up-type quarks

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

- 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

- 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

$$\begin{aligned} \mathcal{L}_{\rm Y} &= y^u_{i1} H_1 \overline{U_1} Q_i + y^u_{i2} H_2 \overline{U_2} Q_i + y^u_{i3} H_3 \overline{U_3} Q_i \\ &+ y^d_{ij} H^\dagger_2 \overline{D_j} Q_i + y^e_{ij} H^\dagger_2 \overline{E_j} L_i + y^n_{ij} H_2 \overline{N_j} L_i . \end{aligned}$$

Flavor-dependent U(1)′ model

- Yukawa coupling in the mass base (2HDM)

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

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

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

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

Higgs-mediated FCNC controlled by flavor dependent U(1) gauge int.

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

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

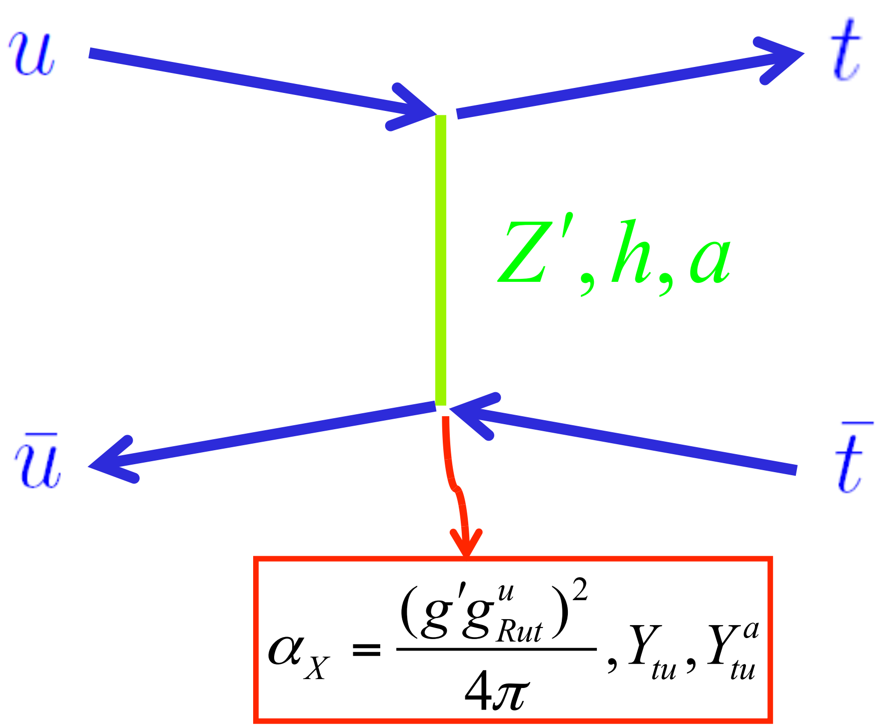
$$Y^{ad}_{ij} = \frac{m^d_i\tan\beta}{v}\delta_{ij},$$

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

Top-antitop pair production

1. Z′ dominant scenario

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

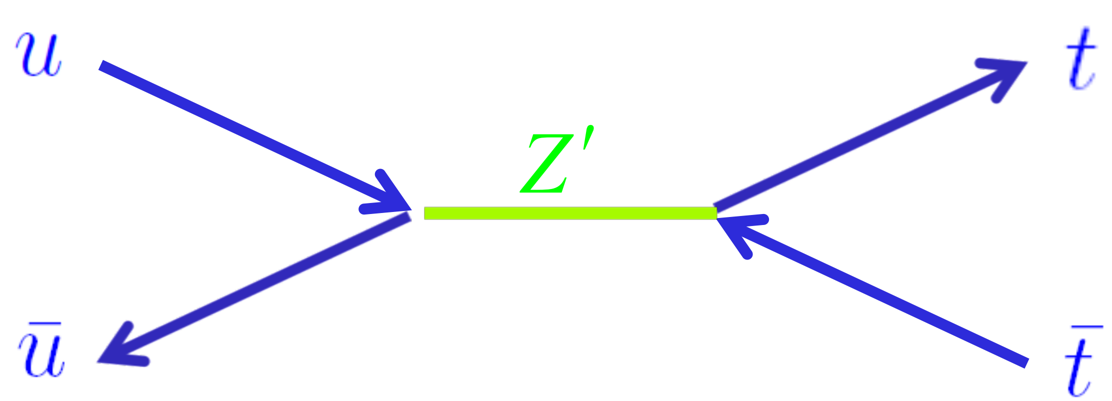


2. Higgs dominant scenario

cf. Babu, Frank, Rai, PRL107(2011)♪

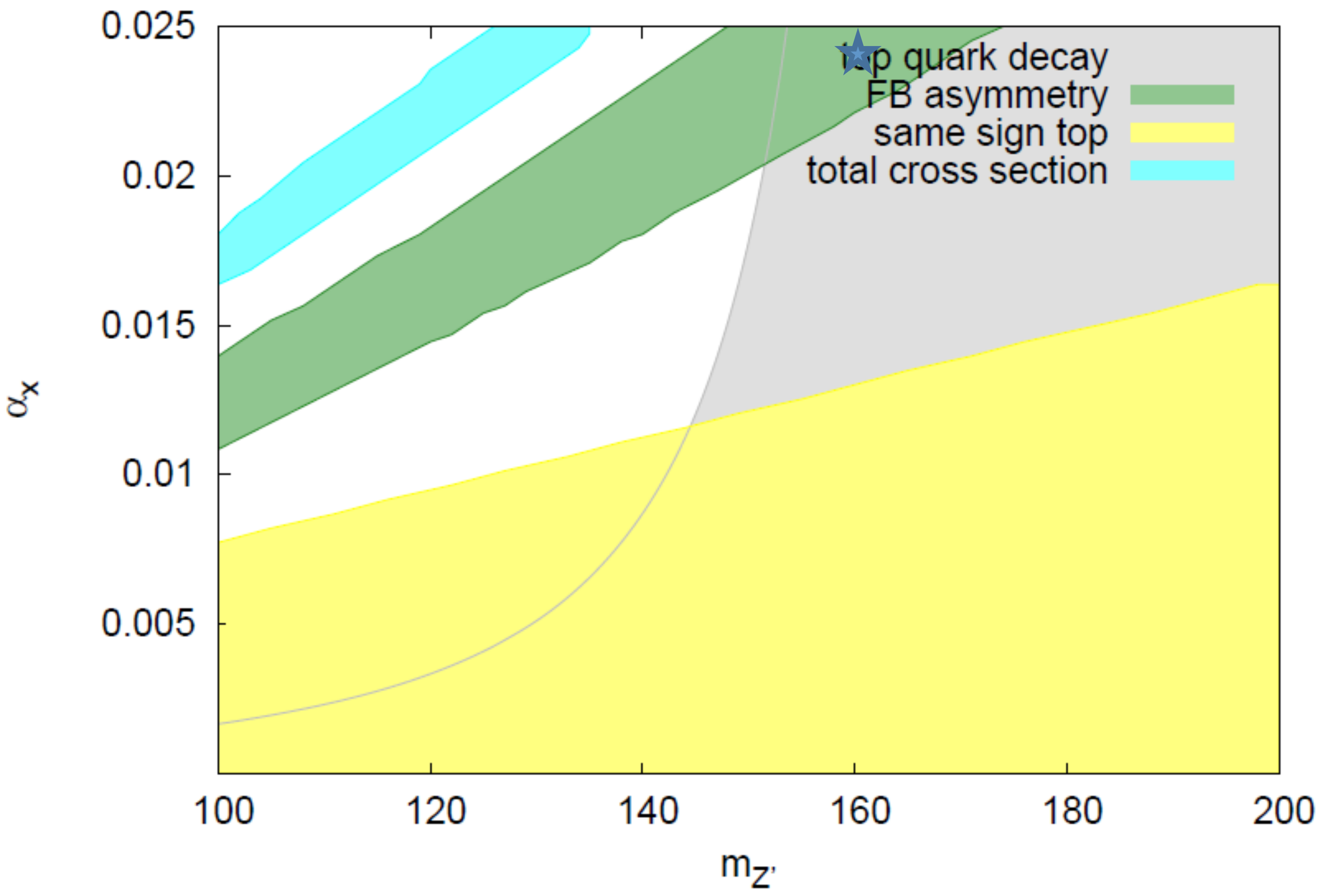
3. Mixed scenario

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



Favored region

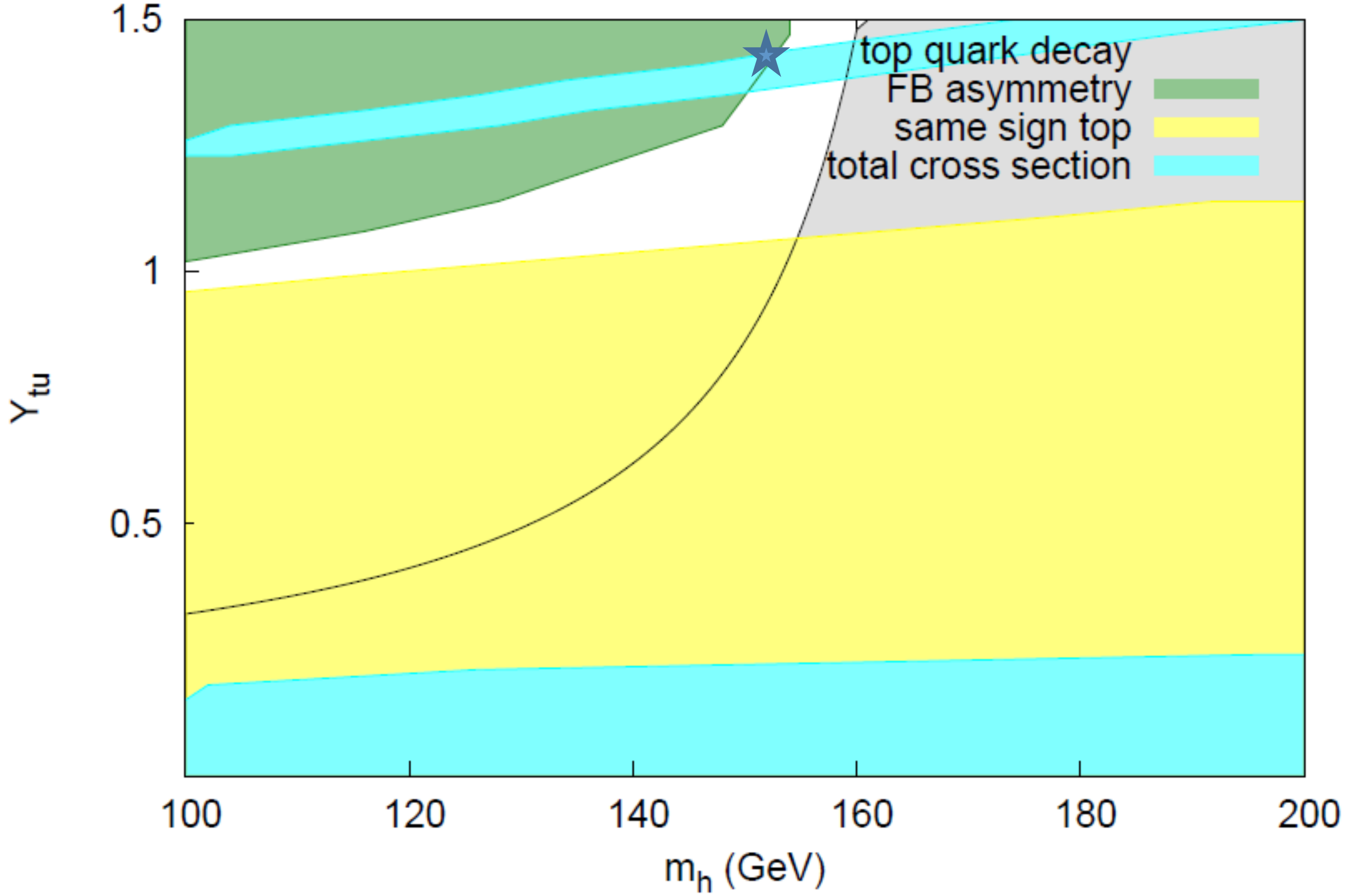
Z′ dominant case



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

Favored region

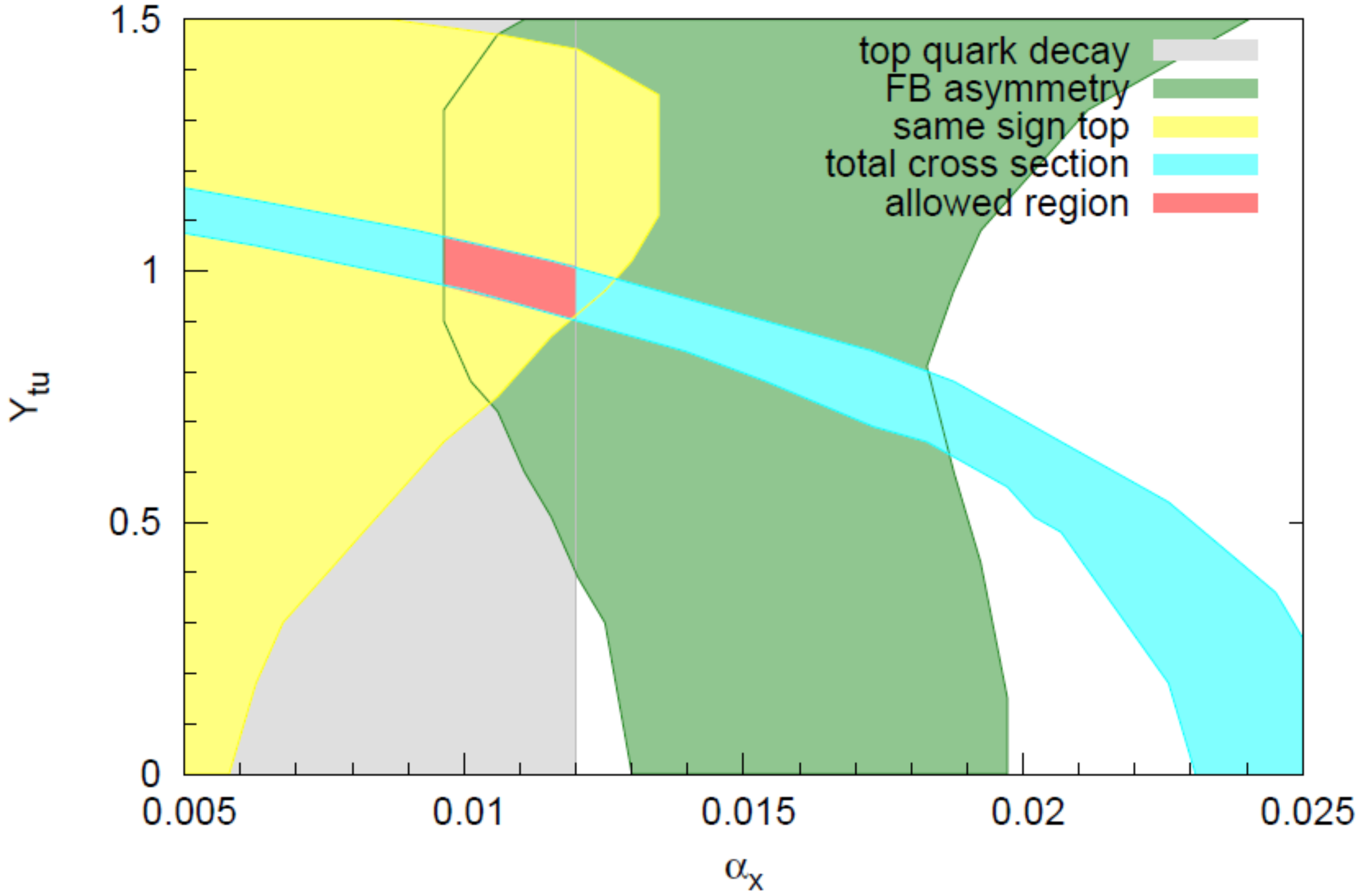
Scalar Higgs (h) dominant case



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

Favored region

Z′+h+a case



$m_{Z'} = 145$ GeV

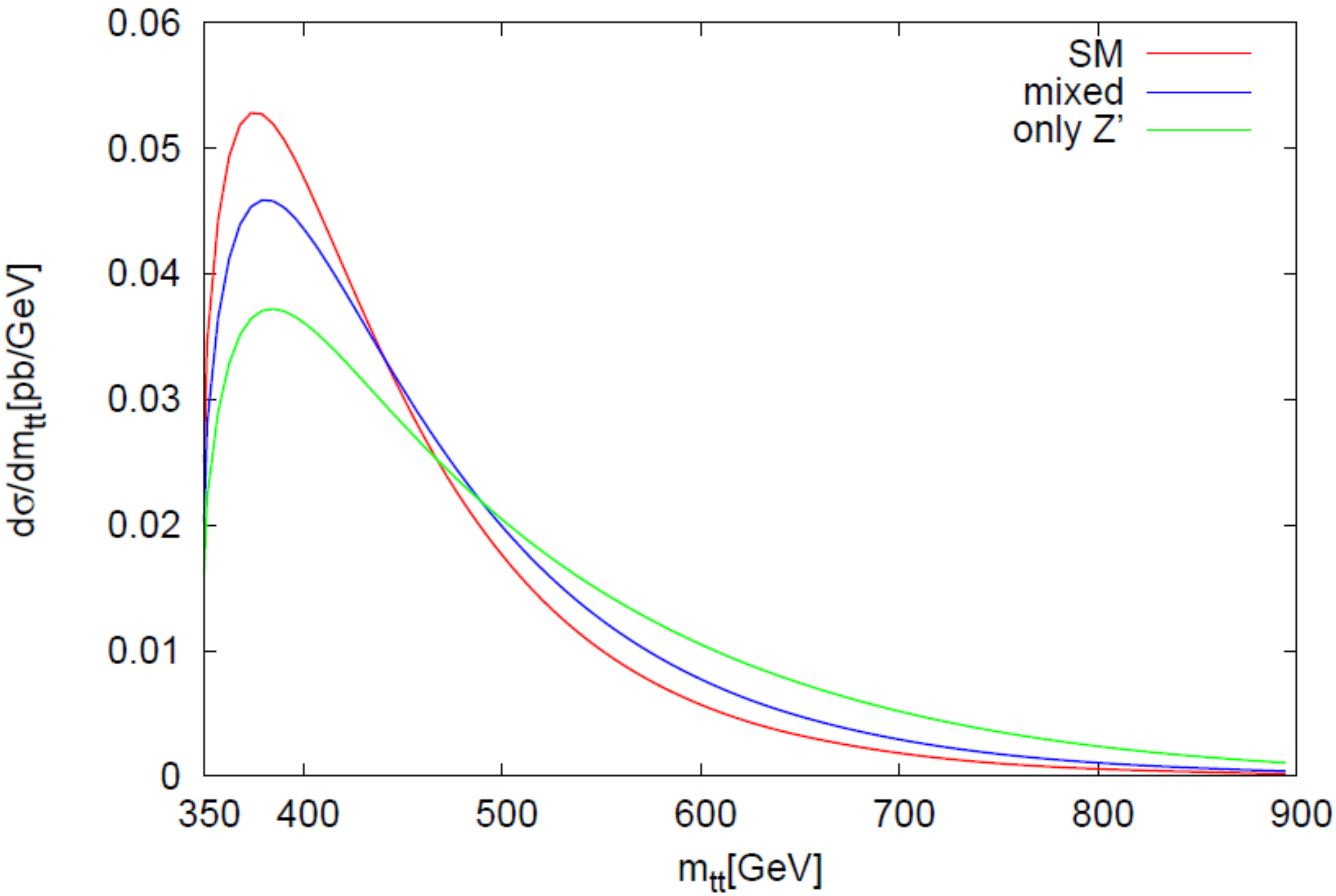
$m_h = 180$ GeV

$m_a = 300$ 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

$\alpha_x = 0.01$

$Y_{tu} = 1.0$

$Y_{tu}^a = 1.1$

Conclusions

- We constructed realistic Z' models with additional Higgs doublets that are charged 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
- Flavor issues in B and charm systems were also studied (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)

$B \to D^{(*)}\tau\nu$ and $B \to \tau\nu$ in chiral $U(1)'$ models with flavored multi Higgs doublets

Ko, Omura, Yu, arXiv:1212.4607, JHEP(2013)

Not covered in this talk

General Remarks

- Model independent study or simplified models are useful only if the stuffs put away under the rug (such as gauge invariance, renormalizability, unitarity, anomaly cancellation, realistic Yukawa's, etc.) do not affect the physical observables we study
- Very often you don't know a priori if this assumption is true or not
- When some simple model can/cannot explain some phenomena, it is important to work out various UV completions and study the detailed phenomenology
- More examples in DM physics later

DM: EFT vs. UV Completions

KNOWNS

- Feels Gravity > Currently evidences come only thru this
- Its lifetime >> Age of Universe
- $\rho(\simeq m) \gg \; p(\simeq 0)$ (Nonrel.)
- $\Omega_{\mathrm{DM}} \sim 5 \; \Omega_{\mathrm{Baryon}}$
- $\rho_{\mathrm{local}} \sim 0.3 \mathrm{GeV/cm}^3$
- It forms a halo, not a disk

UNKNOWNS

- Mass, Spin ?
- How many species ?
- Any internal quantum #'s ?
- Any internal structures ?
- Interactions w/ SM particles ?
- DM self int. ? ($\sigma_{\chi\chi}/m_\chi \lesssim 1 g/cm^2$)
- Almost nothing known about particle physics nature of DM

Local dark gauge symmetry

- Better to use local gauge symmetry for DM stability
  (Baek,Ko,Park,arXiv:1303.4280)

- Success of the Standard Model of Particle Physics lies in “local gauge symmetry” without imposing any internal global symmetries
- Electron stability : U(1)em gauge invariance, electric charge conservation, massless photon
- Proton longevity : baryon # is an accidental sym of the SM
- No gauge singlets in the SM ; all the SM fermions chiral

- 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 (I)

- Kinematically long-lived if DM is very light (axion, sterile ν_s ,...) : not considered here
- DM could be absolutely stable due to unbroken local gauge symmetry
    - DM with local Z2 (inelastic), Z3 (semi-annihilation)
    - $SU(3)_D \to SU(2)_D$ (and 2 more works) for H_0, σ_8 (2016)

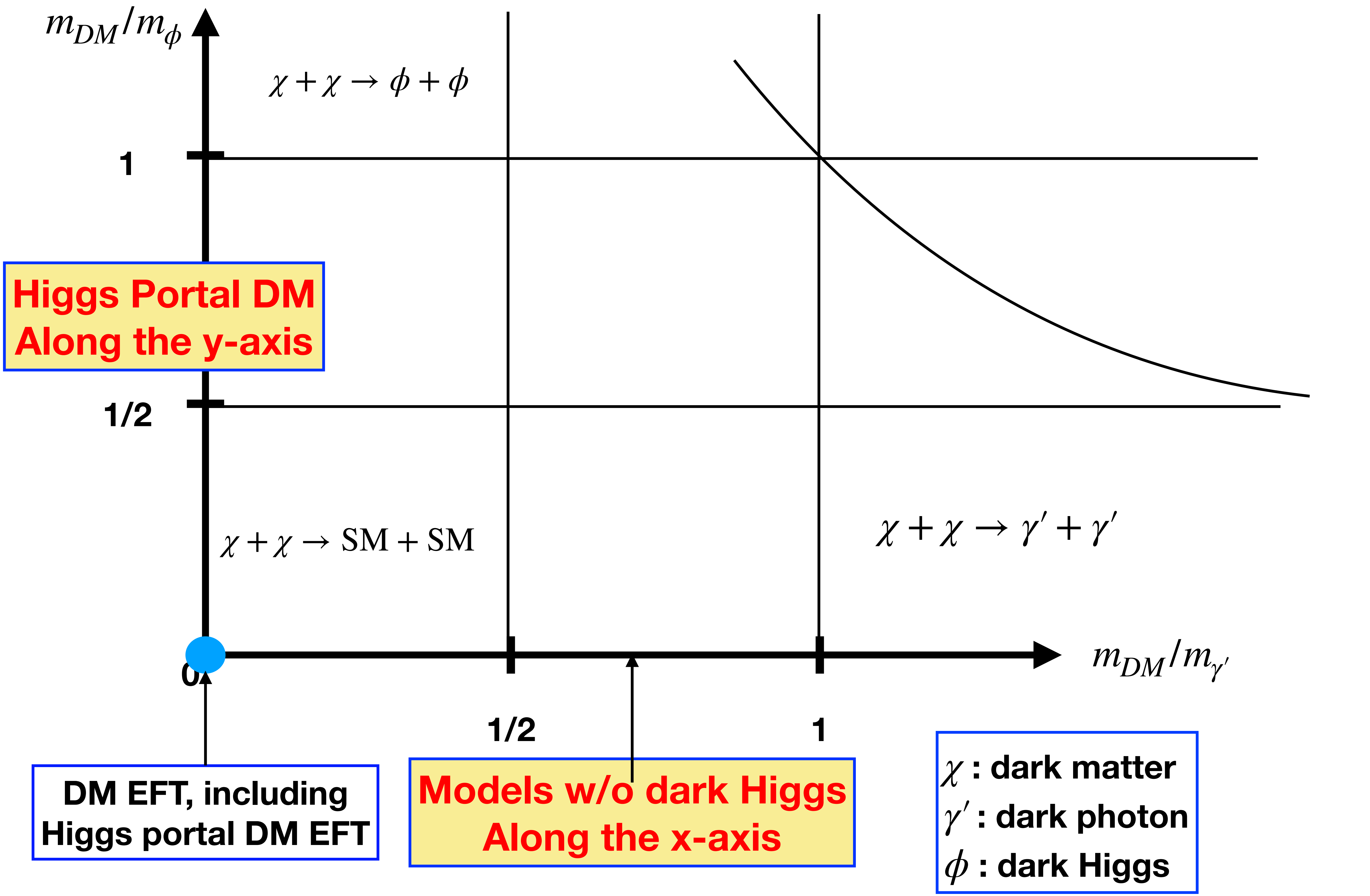
In QFT (II)

- DM could be stable because of topology (hidden sector monopole + VDM+DR)
- Longevity of DM could be due to some accidental symmetries of unbroken/broken dark gauge symmetries
  - EWSB and CDM from hQCD, and scale invariant extensions : dark pions and dark baryons : Hur, Ko et al (2007)
  - Dark gauge sym completely broken

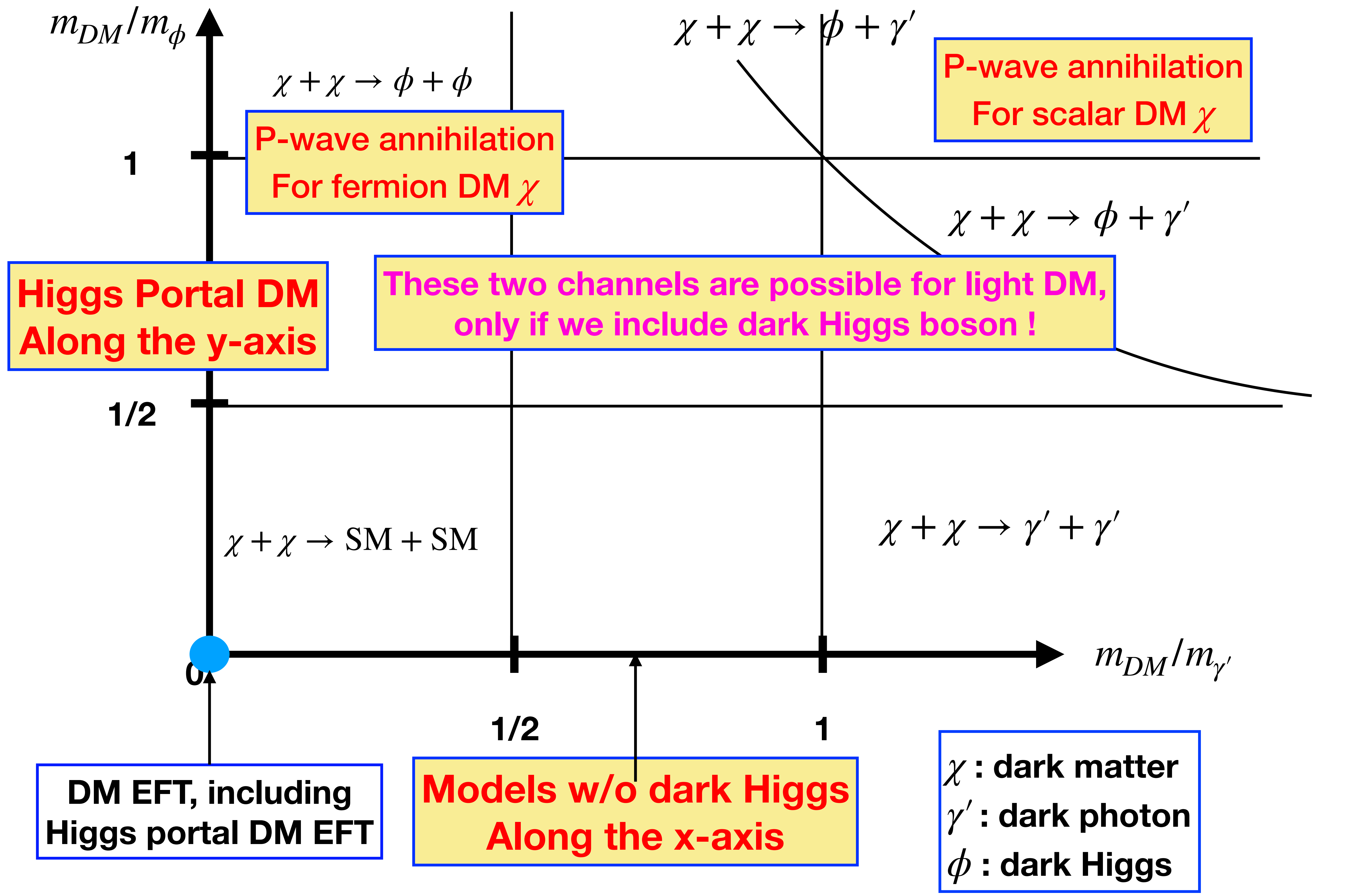
Landscape of dark sector

- DM EFT : DM + SM (unitarity violation in most cases)
- (Improved) Simplified Model for DM : DM + SM + Mediators (without full SM gauge symmetry) Full SM gauge symmetry was imposed by P Ko, A Natale, MH Park, H Yokoya (2016)
- DM stabilized by global symmetry can not protect DM to decay fast from dim-5 operators from gravity : Need to introduce dark gauge symmetry [S Baek, P Ko, WI Park (2013)] : Now called as a “dark sector”
- (Excited) DM, DR, (Light) Mediators with dark gauge symmetry
- Only questions: mass scales and couplings (various mechanisms)

Dark sector parameter space for a fixed m_{DM}



Dark sector parameter space for a fixed m_{DM}



Portals to DM

- Higgs portal : $H^\dagger HS,\ H^\dagger HS^2,\ H^\dagger H\phi^\dagger\phi$
- U(1) Vector portal : $\epsilon B_{\mu\nu}X^{\mu\nu}$
- Neutrino portal : $\overline{N_R}(\widetilde{H}\, l_L + \phi^\dagger\psi)$
- (Dark) Axion portal (HSLee et al)
- So on & on & on …
- Eventually "Portal" is what we observe in the experiments

ϕ : Dark Scalars

X_μ : Dark photon

ψ : Dark fermion
~ Sterile ν

Portals to DM

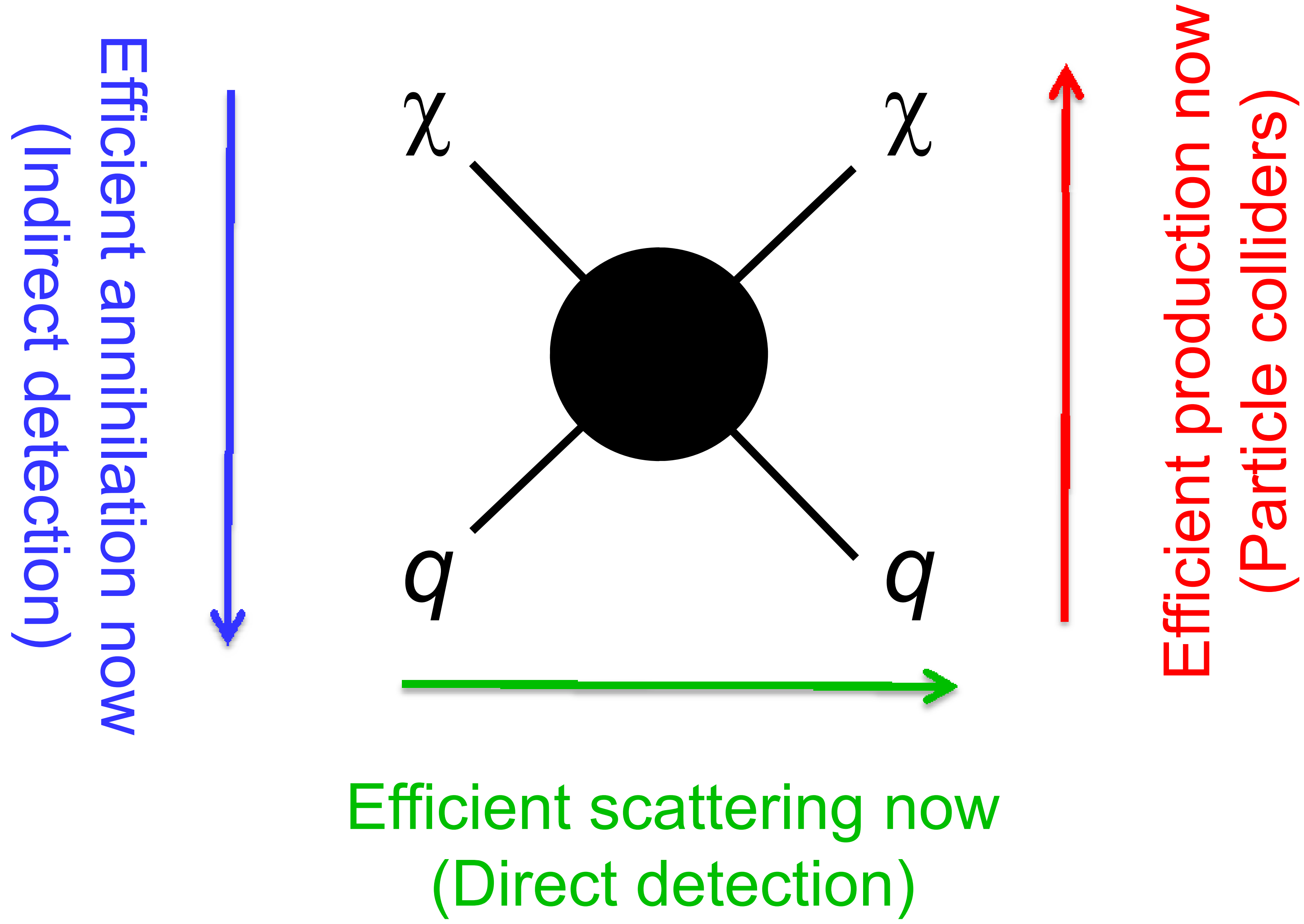
- Higgs portal : $H^\dagger HS,\ H^\dagger HS^2,\ H^\dagger H\phi^\dagger\phi$
- U(1) Vector porta
- Neutrino portal : $\overline{N_R}(\widetilde{H} l_L +$
- (Dark) Axion portal (HSLee
- So on, & on & on , …
- Eventually "Portal" is what we observe in experiments

Singlet Portals to Dark sector w/ local dark gauge sym
(Baek, Park, Ko, arXiv:1303.4280 [hep-ph])

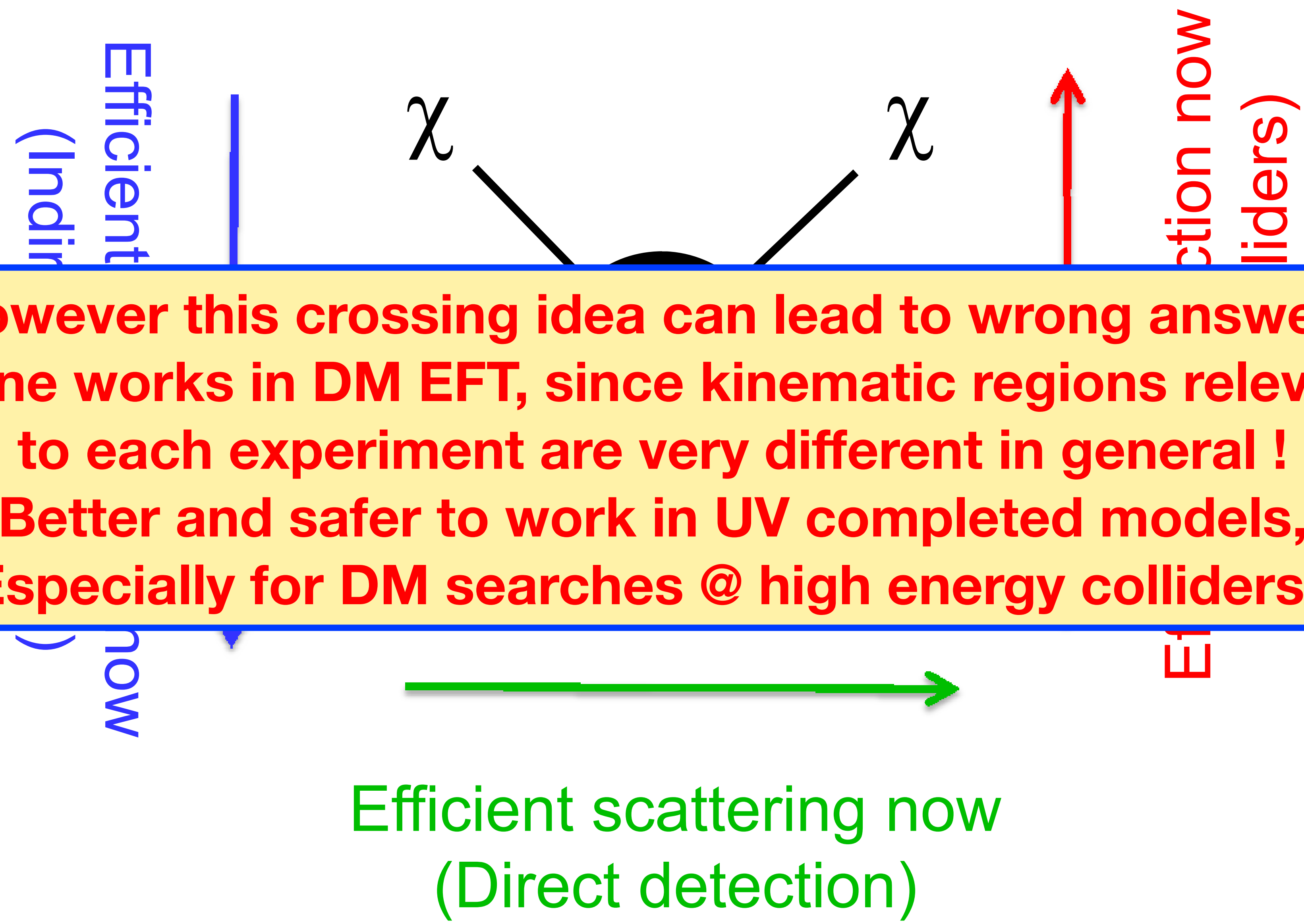
DM stability is guaranteed by
Local gauge symmetry
OR
DM longevity is guaranteed by
accidental global symmetries

Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Furthermore one can consider on-shell mediators, dark radiation and inelastic DM, etc..



However this crossing idea can lead to wrong answers if one works in DM EFT, since kinematic regions relevant to each experiment are very different in general !
Better and safer to work in UV completed models, Especially for DM searches @ high energy colliders !

Dark Gauge Symmetry

Z2 real scalar DM

- Simplest DM model with Z2 symmetry : $S \to -S$

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

- Global Z2 could be broken by gravity effects (higher dim operators)

- e.g. consider Z2 breaking dim-5 op : $\dfrac{1}{M_{\text{Planck}}} S O_{\text{SM}}^{(4)}$

- Lifetime of EW scale mass "S" is too short to be a DM

- Similarly for singlet fermion DM

Fate of CDM with Z2 sym

(Baek,Ko,Park,arXiv:1303.4280)

Consider Z_2 breaking operators such as

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

keeping dim-4 SM operators only

3 3

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

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

- Global Z2 cannot save EW scale DM from decay with long enough lifetime

The lifetime is too short for ~100 GeV DM

NB: For very light “S”, its lifetime can be very long by kinematic reasons

Fate of CDM with Z_2 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:

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

Problematic ! Perfectly fine !

Higgs is not good for DM stability/longvity

- 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

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

arXiv:1407.6588 w/ WIPark and SBaek

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

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

Unbroken Local Z2 symmetry
Gauge models for excited DM

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

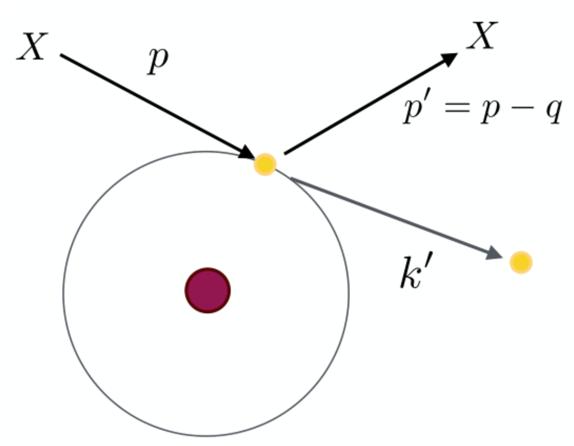
XENON1T Excess

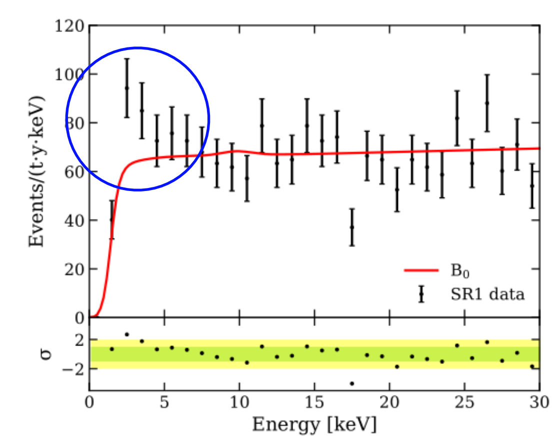
(Scalar XDM, Fermion XDM)

XENON1T Excess

- Excess between 1-7 keV
  - Expectated : 232 $\pm$ 15 , Observed : 285
  - Deviation ~ 3.5 σ
- Tritium contamination
  - Long half lifetime (12.3 years)
  - Abundant in atmosphere and cosmogenically produced in Xenon
- Solar axion
  - Produced in the Sun
  - Favored over bkgd @ 3.5 σ
- Neutrino magnetic dipole moment
  - Favored @ 3.2 σ

Electron recoil

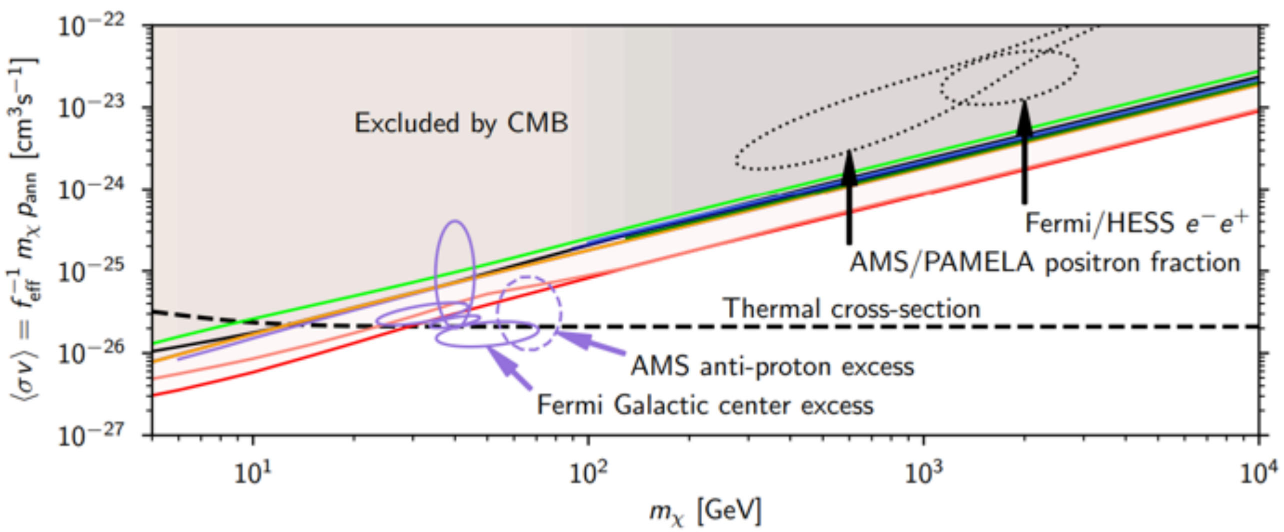


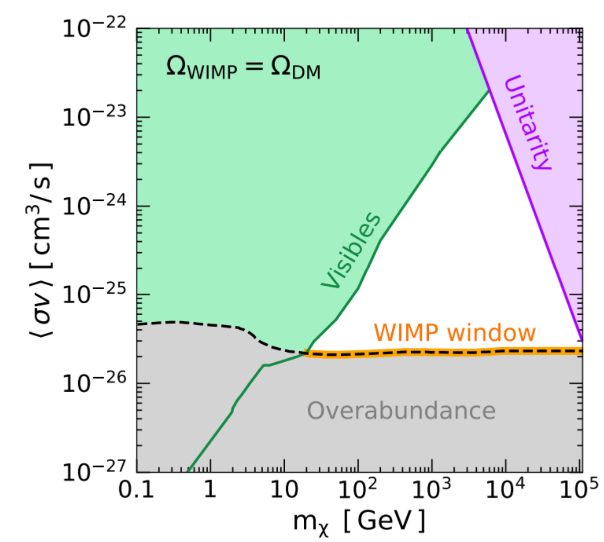


DD/CMB Constraints

- To evade stringent bounds from direct detection expt's : sub GeV DM
- CMB bound excludes thermal DM freeze-out determined by S-wave annihilation : DM annihiliation should be mainly in P-wave $\langle \sigma v \rangle \sim a + b v^2$

Planck 2018
R.K.Leane 35 al, PRD2018





Exothermic DM

- Inelastic exothermic scattering of XDM
- $XDM + e_{\text{atomic}} \to DM + e_{\text{free}}$ by dark photon exchange + kinetic mixing
- Excess is determined by $E_R \sim \delta = m_{XDM} - m_{DM}$
- Most works are based on effective/toy models where δ is put in by hand, or ignored dark Higgs
- dim-2 op for scalar DM and dim-3 op for fermion DM : soft and explicit breaking of local gauge symmetry), and include massive dark photon as well → theoretically inconsistent !

Usual Approaches

For example, Harigaya, Nagai, Suzuki, arXiv:2006.11938

$$V(\phi) = m^2|\phi|^2 + \Delta^2\left(\phi^2 + \phi^{*2}\right), \qquad (1)$$

This term is problematic

$$\mathcal{L} = g_D A'^{\mu}\left(\chi_1 \partial_\mu \chi_2 - \chi_2 \partial_\mu \chi_1\right) + \epsilon e A'_\mu J^\mu_{\rm EM},$$

Similarly for the fermion DM case

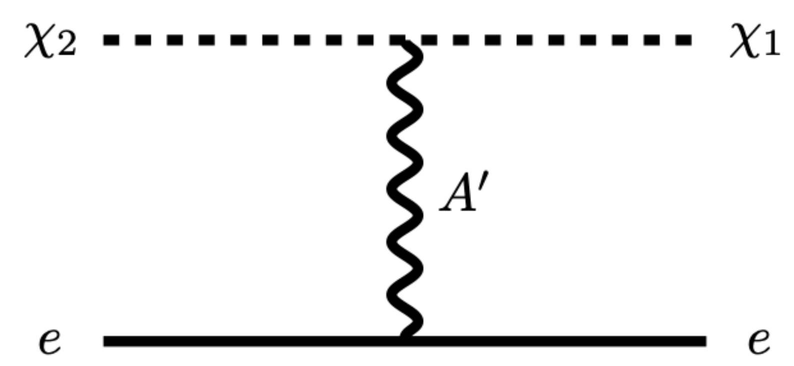


FIG. 1. Inelastic scattering of the heavier DM particle χ_2 off the electron e into the lighter particle χ_1, mediated by the dark photon A'.

- The model is not mathematically consistent, since there is no conserved current a dark photon can couple to in the massless limit
- The second term with Δ^2 breaks $U(1)_X$ explicitly, although softly

Relic Density from

$$XX^{\dagger} \to Z^{\prime\,*} \to f\bar{f}$$

(P-wave annihilation)

For example, Harigaya, Nagai, Suzuki, arXiv:2006.11938

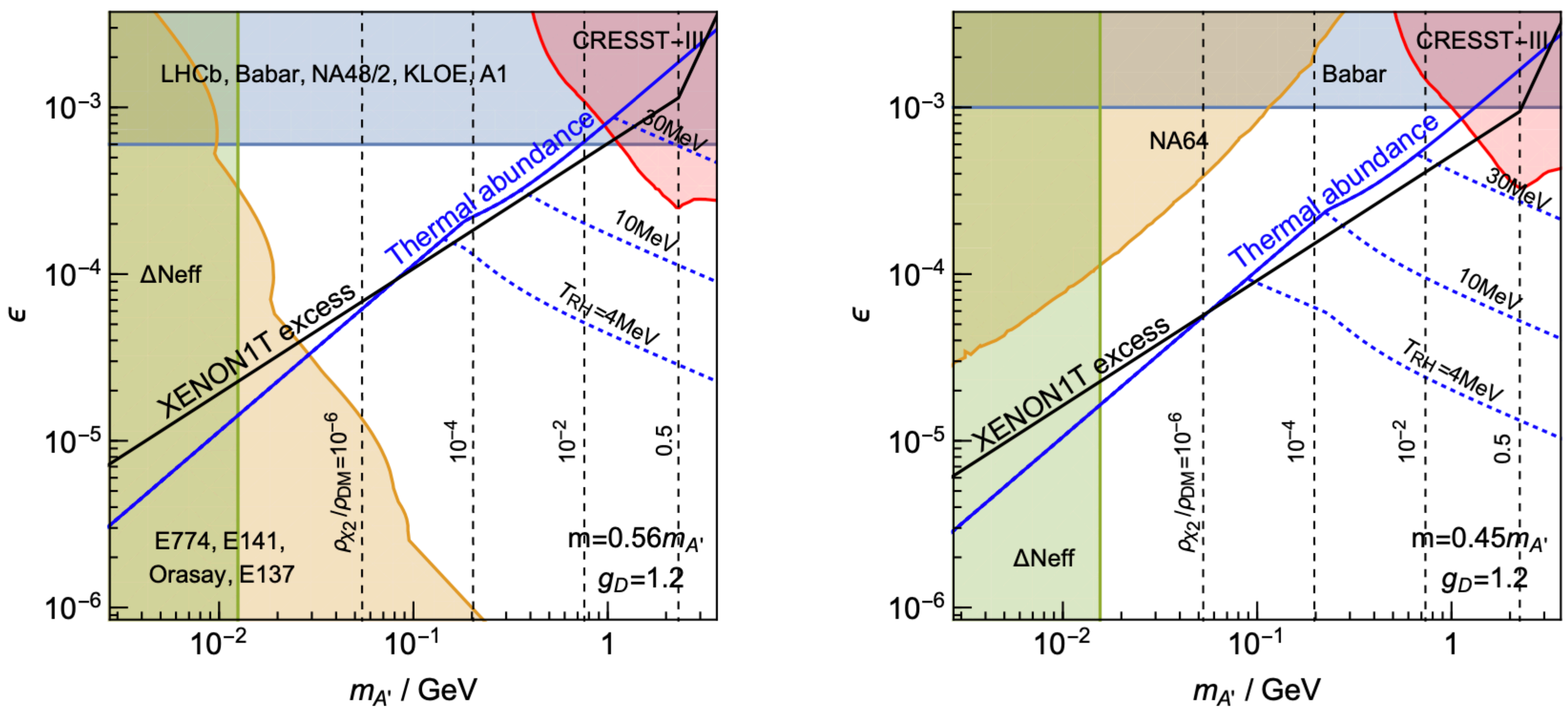


FIG. 4. The required value of ϵ to explain the observed excess of events at XENON1T in terms of the dark photon mass $m_{A'}$ (black solid lines). The left and right panels correspond to the cases of $m > m_{A'}/2$ and $m < m_{A'}/2$ respectively. We assume $g_D = 1.2$ in both cases. The blue lines denote the required value of ϵ to obtain the observed DM abundance by the thermal freeze-out process, discussed in Sec. IV. The solid lines correspond to the case without any entropy production. The dashed lines assume freeze-out during a matter dominated era and the subsequent reheating at $T_{\rm RH}$, which suppresses the DM abundance by a factor of $(T_{\rm RH}/T_{\rm FO})^3$. The black dashed lines denote the mass density of χ_2 normalized by the total DM density. The shaded regions show the constraints from dark radiation and various searches for the dark photon A' which are discussed in Sec. V.

Z_2 DM models with dark Higgs

- We solve this inconsistency and unitarity issue with Krauss-Wilczek mechanism
- By introducing a dark Higgs, we have many advantages:
  - Dark photon gets massive
  - Mass gap δ is generated by dark Higgs mechanism
  - We can have DM pair annihilation in P-wave involving dark Higgs in the final states, unlike in other works

Scalar XDM (X_R & X_I)

Field	ϕ	X	χ
U(1) charge	2	1	1

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

$$X = \frac{1}{\sqrt{2}}(X_R + iX_I),$$

$$H = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v_H + h_H)\end{pmatrix}, \quad \phi = \frac{1}{\sqrt{2}}(v_\phi + h_\phi),$$

$$\mathcal{L} \supset \epsilon g_X s_W Z^\mu(X_R\partial_\mu X_I - X_I\partial_\mu X_R) - \frac{g_Z}{2}Z_\mu\overline{\nu}_L\gamma^\mu\nu_L.$$

$$\mathcal{L} \supset g_X Z'^\mu(X_R\partial_\mu X_I - X_I\partial_\mu X_R) - \epsilon\, e c_W Z'_\mu\overline{e}\gamma^\mu e,$$

$U(1) \to Z_2$ by $v_\phi \neq 0 : X \to -X$

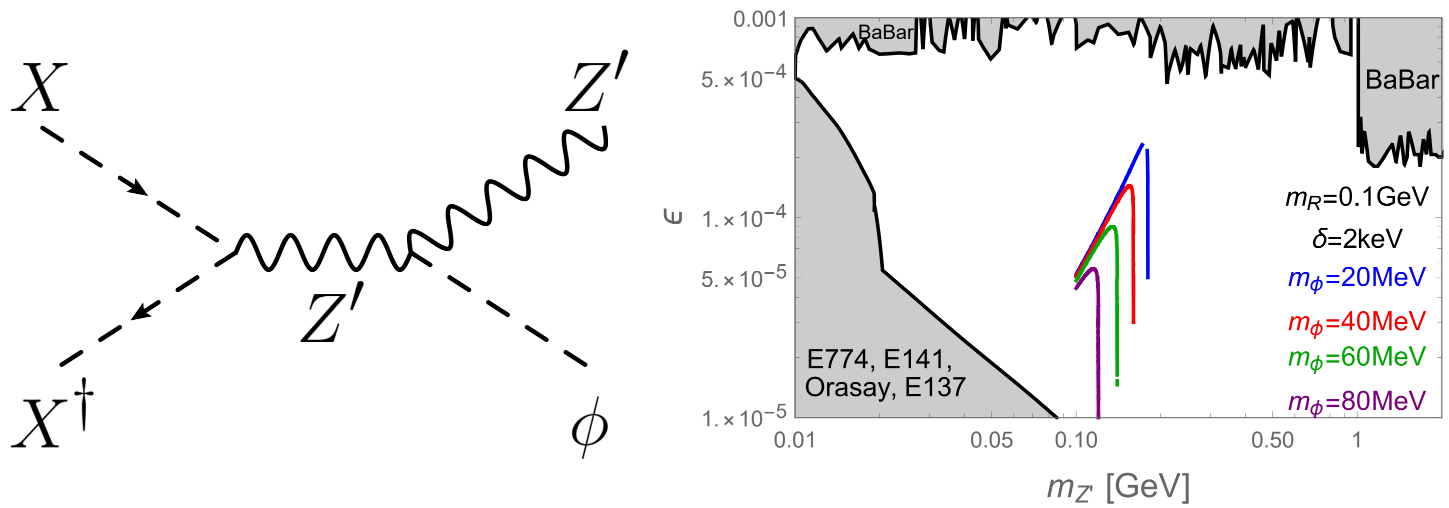


FIG. 1: (*left*) Feynman diagrams relevant for thermal relic density of DM: $XX^\dagger \to Z'\phi$ and (*right*) the region in the $(m_{Z'}, \epsilon)$ plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for scalar DM case for $\delta = 2$ keV : (a) $m_{\rm DM} = 0.1$ GeV. Different colors represents $m_\phi = 20, 40, 60, 80$ MeV. The gray areas are excluded by various experiments, from BaBar [61], E774 [62], E141 [63], Orasay [64], and E137 [65], assuming $Z' \to X_R X_I$ is kinematically forbidden.

P-wave annihilation x-sections

Scalar DM : $XX^\dagger \to Z'^* \to Z'\phi$

$$\sigma v \simeq \frac{g_X^4 v^2}{384\pi\, m_X^4 (4m_X^2 - m_{Z'}^2)^2} \left(16m_X^4 + m_{Z'}^4 + m_\phi^4 + 40m_X^2 m_{Z'}^2 - 8m_X^2 m_\phi^2 - 2m_{Z'}^2 m_\phi^2\right)$$
$$\times \left[\left\{4m_X^2 - (m_{Z'} + m_\phi)^2\right\} \left\{4m_X^2 - (m_{Z'} - m_\phi)^2\right\} \right]^{1/2} + \mathcal{O}(v^4), \tag{10}$$

Fermion XDM (χ_R & χ_I)

$$\mathcal{L} = -\frac{1}{4}\hat{X}^{\mu\nu}\hat{X}_{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}B^{\mu\nu} + \overline{\chi}\left(i\not{D} - m_\chi\right)\chi + D_\mu\phi^\dagger D^\mu\phi - \mu^2\phi^\dagger\phi - \lambda_\phi|\phi|^4 - \frac{1}{\sqrt{2}}\left(y\phi^\dagger\overline{\chi^C}\chi + \text{h.c.}\right) - \lambda_{\phi H}\phi^\dagger\phi H^\dagger H$$

$$\chi = \frac{1}{\sqrt{2}}(\chi_R + i\chi_I),$$
$$\chi^c = \frac{1}{\sqrt{2}}(\chi_R - i\chi_I),$$
$$\chi_R^c = \chi_R, \quad \chi_I^c = \chi_I,$$

$$\mathcal{L} = \frac{1}{2}\sum_{i=R,I}\overline{\chi_i}\left(i\not{\partial} - m_i\right)\chi_i - i\frac{g_X}{2}(Z'_\mu + \epsilon s_W Z_\mu)\left(\overline{\chi_R}\gamma^\mu\chi_I - \overline{\chi_I}\gamma^\mu\chi_R\right) - \frac{1}{2}yh_\phi\left(\overline{\chi_R}\chi_R - \overline{\chi_I}\chi_I\right),$$

$U(1) \to Z_2$ by $v_\phi \neq 0 : \chi \to -\chi$

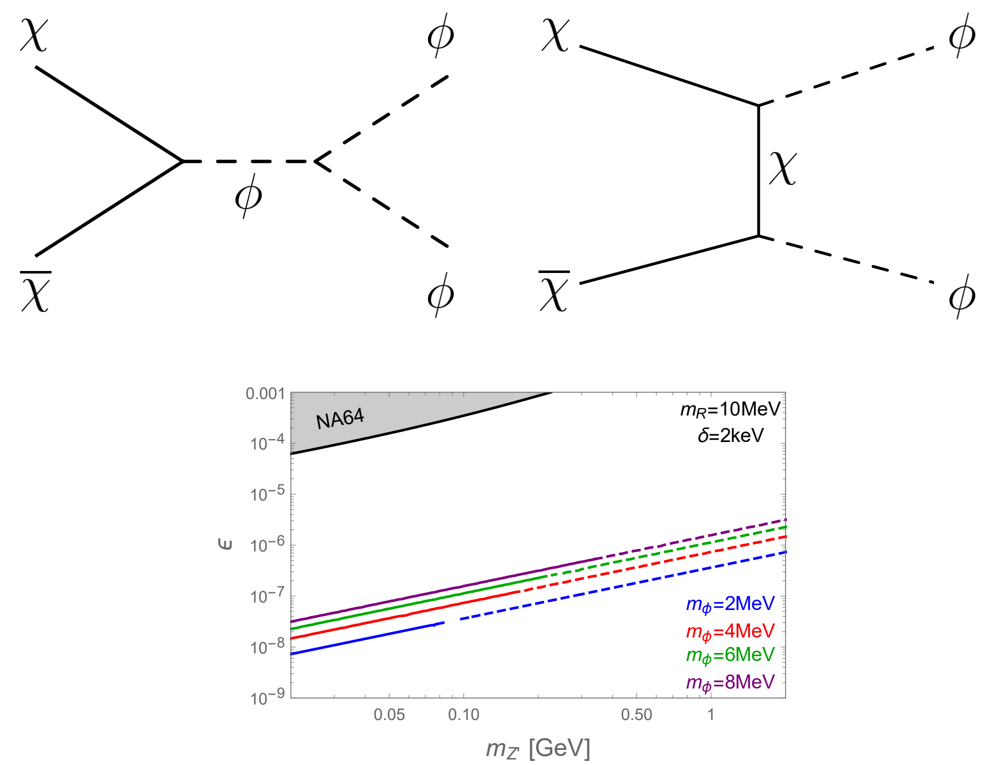


FIG. 2: (*top*) Feyman diagrams for $\chi\bar{\chi} \to \phi\phi$. (*bottom*) the region in the $(m_{Z'}, \epsilon)$ plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for fermion DM case for $\delta = 2$ keV and the fermion DM mass to be $m_R = 10$ MeV. Different colors represents $m_\phi = 2, 4, 6, 8$ MeV. The gray areas are excluded by various experiments, assuming $Z' \to \chi_R \chi_I$ is kinematically allowed, and the experimental constraint is weaker in the ϵ we are interested in, compared with the scalar DM case in Fig. 1 (right). We also show the current experimental bounds by NA64 [66].

P-wave annihilation x-sections

Scalar DM : $XX^{\dagger} \to Z'^{*} \to Z'\phi$

$$\sigma v \simeq \frac{g_X^4 v^2}{384\pi\, m_X^4 (4m_X^2 - m_{Z'}^2)^2} \left(16m_X^4 + m_{Z'}^4 + m_\phi^4 + 40m_X^2 m_{Z'}^2 - 8m_X^2 m_\phi^2 - 2m_{Z'}^2 m_\phi^2\right) \times \left[\left\{4m_X^2 - (m_{Z'} + m_\phi)^2\right\}\left\{4m_X^2 - (m_{Z'} - m_\phi)^2\right\}\right]^{1/2} + \mathcal{O}(v^4), \tag{10}$$

Fermion DM : $\chi\bar{\chi} \to \phi\phi$

$$\sigma v = \frac{y^2 v^2 \sqrt{m_\chi^2 - m_\phi^2}}{96\pi m_\chi}\left[\frac{27\lambda_\phi^2 v_\phi^2}{(4m_\chi^2 - m_\phi^2)^2} + \frac{4y^2 m_\chi^2 (9m_\chi^4 - 8m_\chi^2 m_\phi^2 + 2m_\phi^4)}{(2m_\chi^2 - m_\phi^2)^4}\right] + \mathcal{O}(v^4), \tag{28}$$

Crucial to include “dark Higgs” to have sub-GeV DM pair annihilation in P-wave

Local dark gauge symmetry

- Better to use local gauge symmetry for DM stability in the presence of gravity (Baek,Ko,Park,arXiv:1303.4280)

- Success of the Standard Model of Particle Physics lies in “local gauge symmetry” without imposing any internal global symmetries
- Electron stability : U(1)em gauge invariance, electric charge conservation, massless photon
- Proton longevity : baryon # is an accidental sym of the SM
- No gauge singlets in the SM ; all the SM fermions chiral

- 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)

Higgs portal DM models

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

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

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

All invariant under ad hoc Z2 symmetry

arXiv:1112.3299, … 1402.6287, etc.

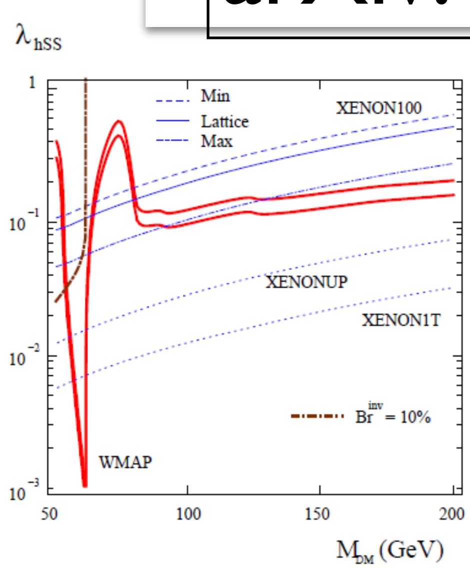


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $\mathrm{BR}^{\rm inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

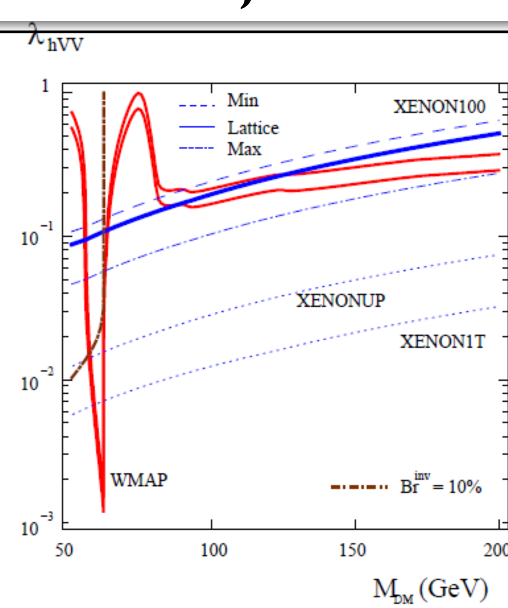


FIG. 2. Same as Fig. 1 for vector DM particles.

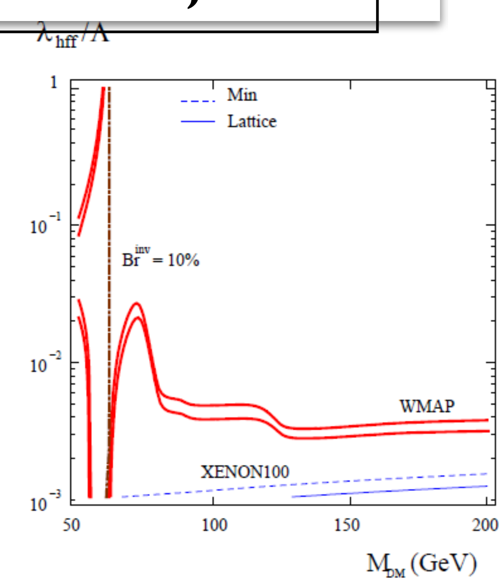


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Higgs portal DM as examples

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

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

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

All invariant under ad hoc Z2 symmetry

arXiv:1112.3299, … 1402.6287, etc.

We need to include dark Higgs or singlet scalar to get renormalizable/unitary models for Higgs portal singlet fermion or vector DM

[NB: UV Completions : Not unique]

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}.

Models for HP SFDM & VDM

UV Completion of HP Singlet Fermion DM (SFDM)

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

UV Completion of HP VDM

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

- **The simplest UV completions in terms of # of new d.o.f.**
- **At least, 2 more parameters, (m_ϕ , $\sin\alpha$) for DM physics**

HP DM @ LHC

2 more relevant parameters

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

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

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

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

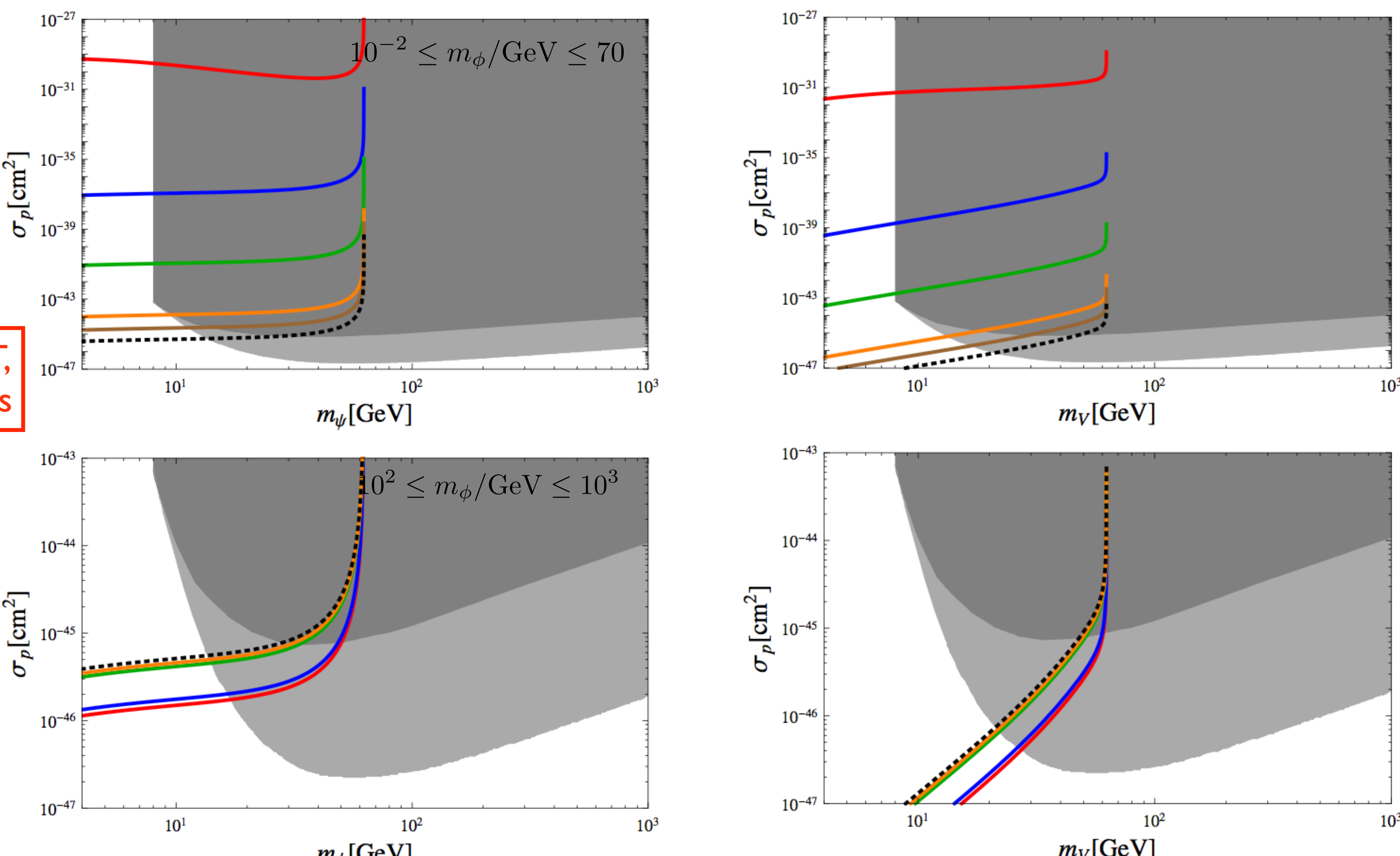
EFT

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

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

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

Dashed curves:EFT, ATLAS,CMS results



Invisible H decay into a pair of VDM

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

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

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

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

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 $m_V \rightarrow 0$
in unitary/renormalizable model
NB: it is infinite in the effective VDM model

Two Limits for $m_V \to 0$

Also see the addendum:
by S Baek, P Ko, WI Park

- $m_V = g_X Q_\Phi v_\Phi$ in the UV completion with dark Higgs boson

- Case I : $g_X \to 0$ with finite $v_\Phi \neq 0$

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

$$\left(\Gamma_h^{\rm inv}\right)_{\rm UV} = \frac{1}{32\pi}\frac{m_h^3}{v_\Phi^2}\sin^2\alpha = \Gamma(h \to a_\Phi a_\Phi)$$

with a_Φ being the NG boson for spontaneously broken global $U(1)_X$

- Case II : $v_\Phi \to 0$ with finite $g_X \neq 0$

$$\alpha \xrightarrow{v_\Phi \to 0^+} \frac{2\lambda_{H\Phi} v_\Phi}{\lambda_H v_H}$$

$$\frac{g_X^2 Q_\Phi^2}{m_V^2}\sin^2\alpha \xrightarrow{v_\Phi \to 0^+} \frac{4\lambda_{H\Phi}^2}{\lambda_H^2 v_H^2} = \frac{2\lambda_{H\Phi}^2}{\lambda_H m_h^2} = \text{finite,}$$

$$\left(\Gamma_h^{\rm inv}\right)_{\rm UV} \xrightarrow{v_\Phi \to 0^+} \frac{1}{16\pi}\frac{\lambda_{H\Phi}^2 m_h}{\lambda_H}$$

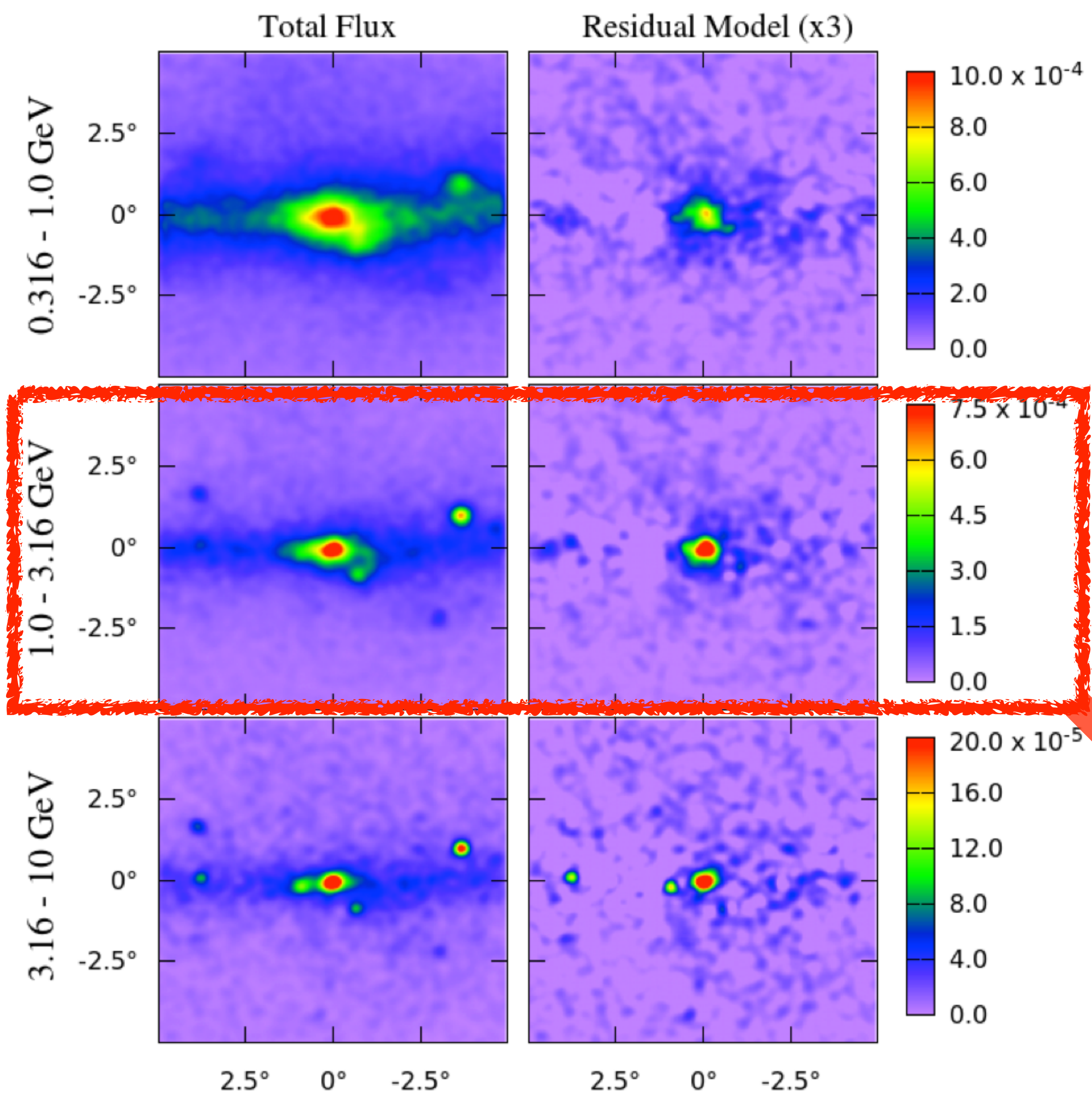
Therefore $\Gamma(h \to VV)$ is finite when $m_V \to 0$ in the UV completions

What if $m_V \to 0$?

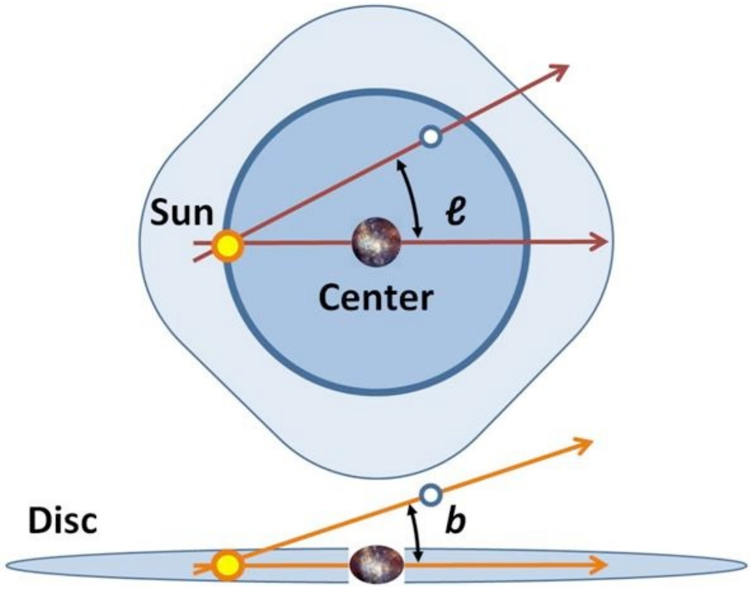
- In this limit, $\epsilon_L^\mu \sim (\frac{p}{m_V}, 0, 0, \frac{E}{m_V})$ blows up, unless it couples to a conserved current. This is the origin of the problem of Higgs Portal VDM without dark Higgs boson : $V_\mu V^\mu H^\dagger H$
- Unitarity is violated when (i) $E \to \infty$ for a fixed m_V , or equivalently (ii) $m_V \to 0$ for a fixed E
- There is a lower cutoff on m_V , below which unitarity is violated (work in progress)
- No such problem if we include dark Higgs boson for m_V

Fermi-LAT GC γ-ray

see arXiv:1612.05687 for a recent overview by C.Karwin, S. Murgia, T. Tait, T.A.Porter, P. Tanedo



[1402.6703, T. Daylan et.al.]

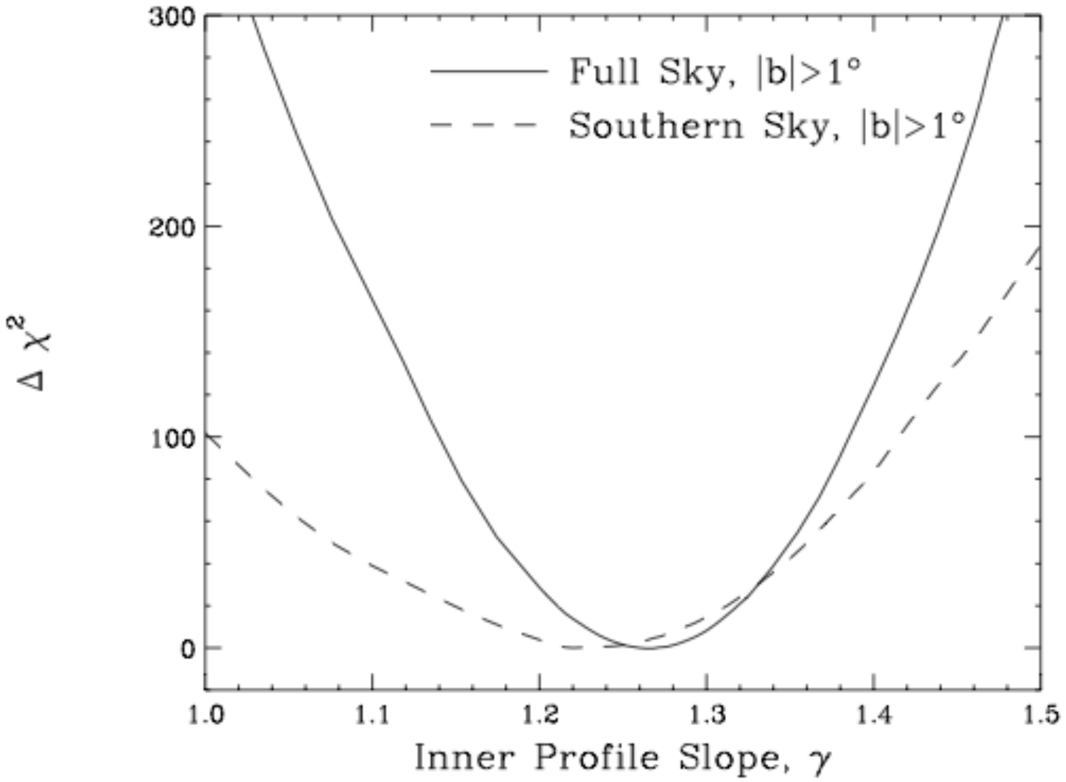


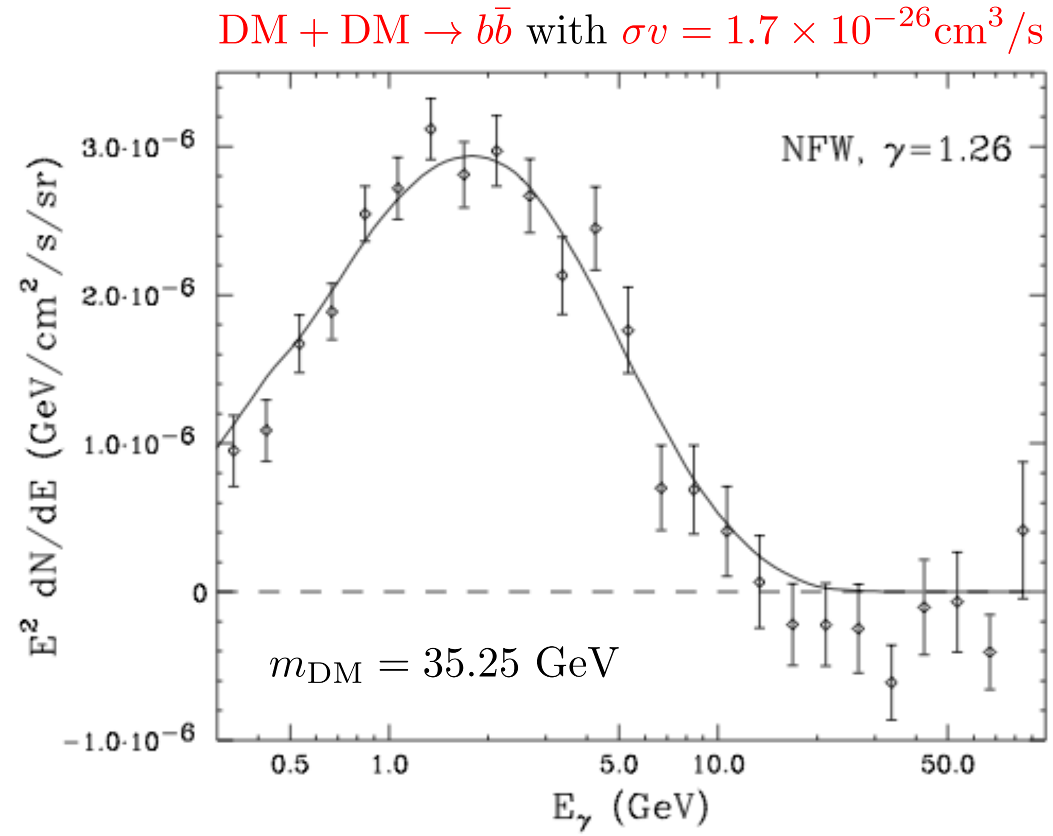
$$\mathrm{GC} : b \sim l \lesssim 0.1^\circ$$

extended

GeV scale excess!

• A DM interpretation





* See "1402.6703, T. Daylan et.al." for other possible channels

• Millisecond Pulars (astrophysical alternative)

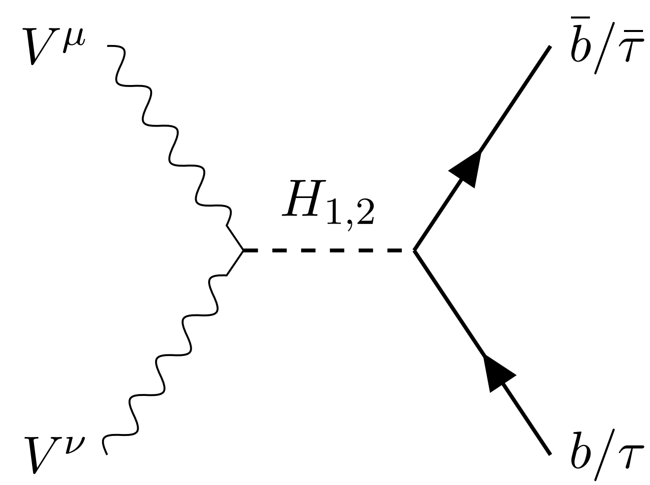
It may or may not be the main source, depending on

- luminosity func.
- bulge population
- distribution of bulge population

* See "1404.2318, Q. Yuan & B. Zhang" and "1407.5625, I. Cholis, D. Hooper & T. Linden"

GC gamma ray in HP VDM

P. Ko, WI Park, Y. Tang. arXiv:1404.5257, JCAP



H2 : 125 GeV Higgs
H1 : absent in EFT

Figure 2. Dominant s channel $b + \bar{b}$ (and $\tau + \bar{\tau}$) production

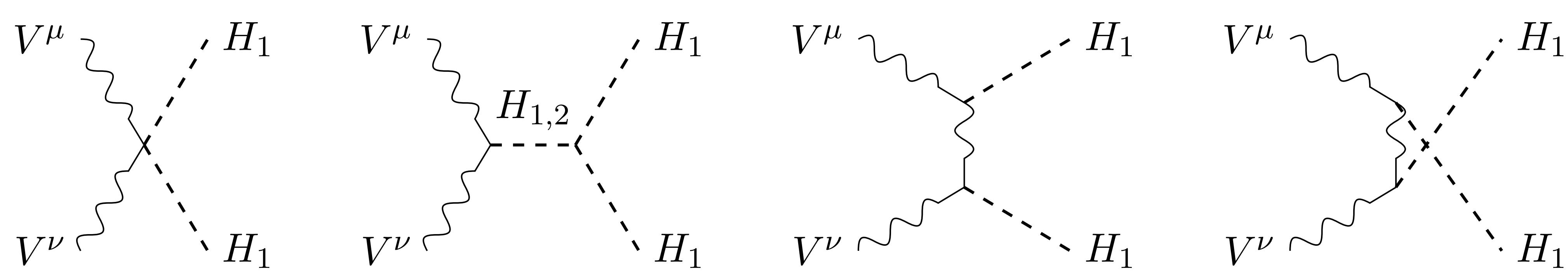


Figure 3. Dominant s/t-channel production of H_1s that decay dominantly to $b + \bar{b}$

Importance of HP VDM with Dark Higgs Boson

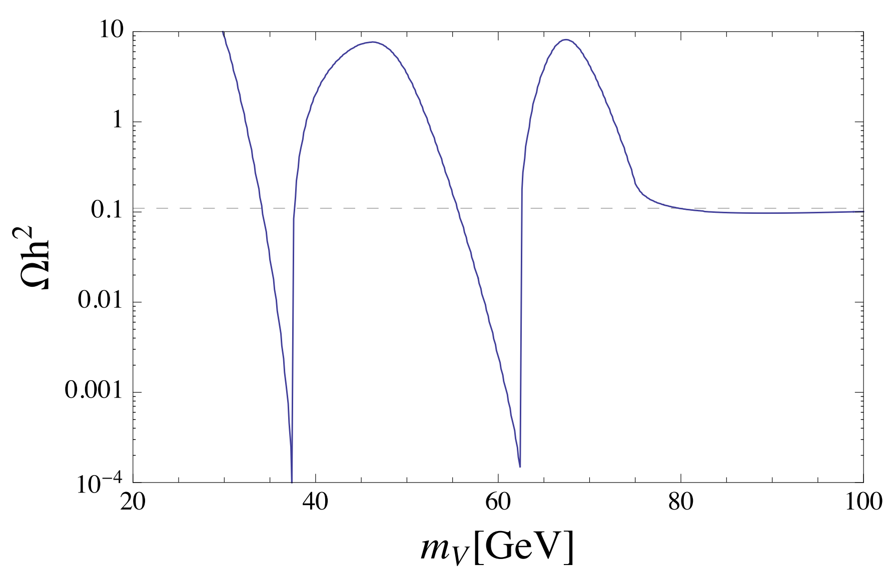


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75\,\text{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

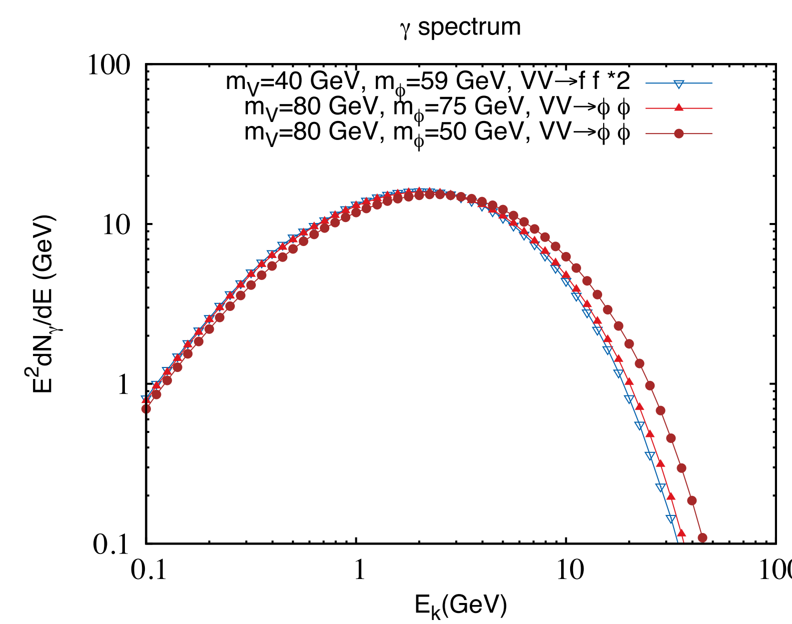


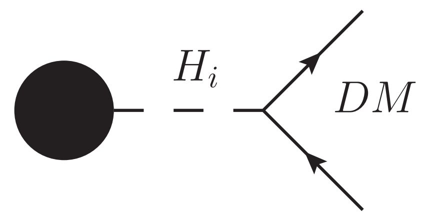
Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

This mass range of VDM would have been impossible in the VDM model (EFT)

And No 2nd neutral scalar (Dark Higgs) in EFT

DM Production @ ILC

P Ko, H Yokoya, arXiv:1603.08802, JHEP



,

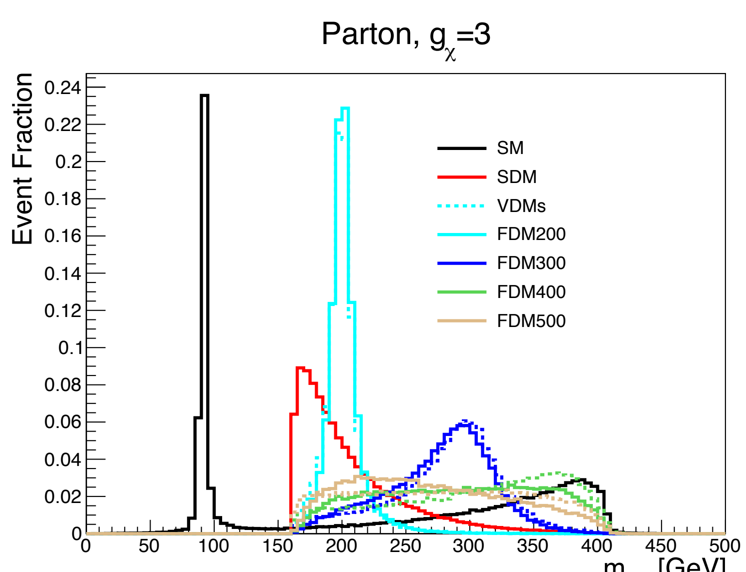
$$t \equiv m_{DD}^2$$

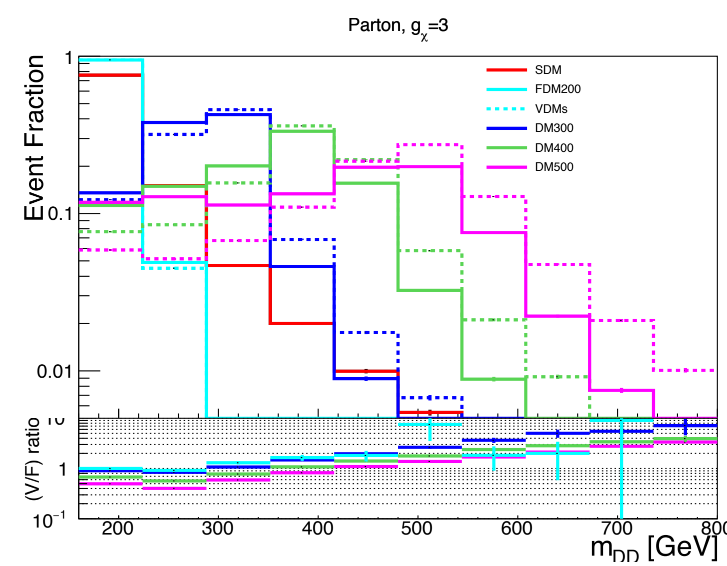
We consider $e^+e^- \to Z^* \to ZH_{i=1,2}$ followed by $H_i \to \bar{\chi}\chi$

$$\frac{d\sigma_{\rm SDM}}{dt} \propto \sigma^{h^*}_{\rm SDM} \times |\frac{1}{t - m_h^2 + i m_h \Gamma_h}|^2,$$

$$\frac{d\sigma_{\rm FDM}}{dt} \propto \sigma^{h^*}_{\rm FDM} \times |\frac{1}{t - m_{H_1}^2 + i m_{H_1}\Gamma_{H_1}} - \frac{1}{t - m_{H_2}^2 + i m_{H_2}\Gamma_{H_2}}|^2 \cdot \left(2t - 8m_\chi^2\right),$$

$$\frac{d\sigma_{\rm VDM}}{dt} \propto \sigma^{h^*}_{\rm VDM} \times |\frac{1}{t - m_{H_1}^2 + i m_{H_1}\Gamma_{H_1}} - \frac{1}{t - m_{H_2}^2 + i m_{H_2}\Gamma_{H_2}}|^2 \cdot \left(2 + \frac{(t - 2m_D^2)^2}{4m_V^4}\right).$$





Fix DM mass = 80 GeV, sin(alpha) = 0.3, and vary H2 mass (200,300,400,500) GeV

Asymptotic behavior in the full theory ($t \equiv m_{\chi\chi}^2$)

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

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

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

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

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

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

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

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

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

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

Unitarity is violated in EFT!

Baek, Ko, MHPark,WIPark, CHYu
arXiv:1506.06556 [hep-ph]

- 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).

$$\mathcal{L}_{\rm int} = -(H_1\cos\alpha + H_2\sin\alpha)\left[\sum_f \frac{m_f}{v_H}\bar{f}f - \frac{2m_W^2}{v_H}W_\mu^+W^{-\mu} - \frac{m_Z^2}{v_H}Z_\mu Z^\mu\right] + \lambda(H_1\sin\alpha - H_2\cos\alpha)\bar{\chi}\chi$$

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

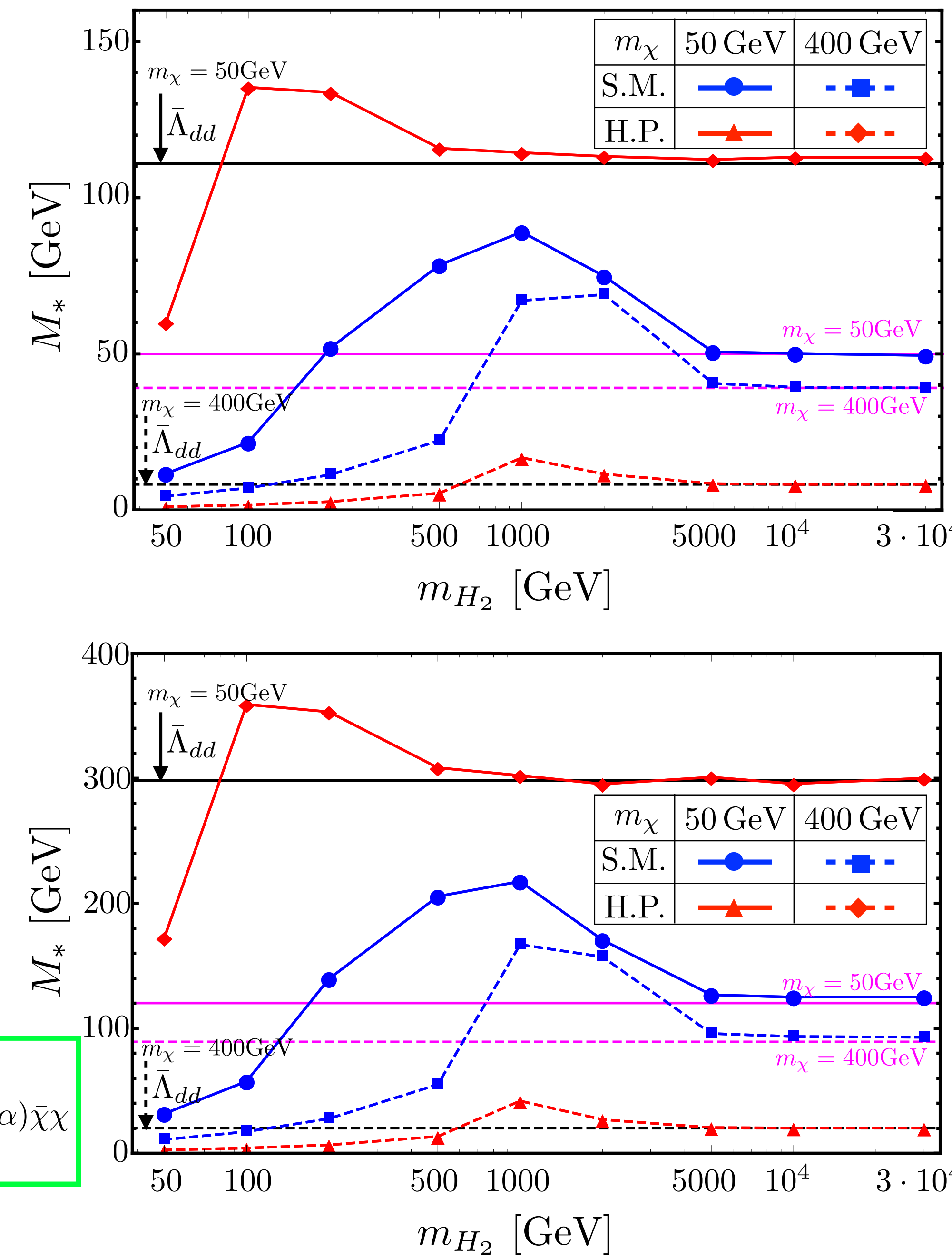


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t}+\not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of 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.

Summary

- Phenomenology of HP VDM and Singlet FDM presented within EFT vs. UV completed models

- EFT approach has a number of drawbacks : non-renormalizable, unitarity violation at high energy colliders, and it applies only if $m_{DM}, m_{\rm SM} \ll m_\phi$ [But we don't know mass scales of dark particles !]

- In particular, one has $\Gamma_{\rm EFT}(H_{125} \to VV) \to \infty$, as $m_V \to 0$, whereas it is finite in UV completed models [Importance of gauge invariance, unitarity and renormalizability]

- The dark Higgs ϕ can play crucial roles in interpreting the DM signatures at colliders, explaining the GC γ-ray excess ($VV \to \phi\phi$), improving vacuum stability up to Planck scale, modifying the Higgs inflation [ϕ should be actively searched for !]

EWSB and CDM from Strongly Interacting Hidden Sector

All the masses (including CDM mass) from hidden sector strong dynamics, and CDM long lived by accidental sym

Hur, Jung, Ko, Lee : 0709.1218, PLB (2011)
Hur, Ko : arXiv:1103.2517,PRL (2011)
Proceedings for workshops/conferences during 2007-2011 (DSU,ICFP,ICHEP etc.)

Talks by Felix Karlhoefer, Suchita Kulkarni

Nicety of QCD

- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations : accidental symmetries of QCD (pion is stable if we switch off EW interaction; proton is stable or very long lived)

h-pion & h-baryon DMs

- In most WIMP DM models, DM is stable due to some ad hoc Z2 symmetry
- If the hidden sector gauge symmetry is confining like ordinary QCD, the lightest mesons and the baryons could be stable or long-lived >> Good CDM candidates
- If chiral sym breaking in the hidden sector, light h-pions can be described by chiral Lagrangian in the low energy limit

(arXiv:0709.1218 with T.Hur, D.W.Jung and J.Y.Lee)

Basic Picture

SM
Quarks
Leptons
Gauge Bosons
Higgs boson

Hidden Sector
Quarks Q_h
Gluons g_h
Others

Similar to ordinary QCD

Key Observation

- If we switch off gauge interactions of the SM, then we find
- Higgs sector ~ Gell-Mann-Levy's linear sigma model which is the EFT for QCD describing dynamics of pion, sigma and nucleons
- One Higgs doublet in 2HDM could be replaced by the GML linear sigma model for hidden sector QCD

- Potential for H_1 and H_2

$$V(H_1, H_2) = -\mu_1^2(H_1^\dagger H_1) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \mu_2^2(H_2^\dagger H_2)$$
$$+\frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \frac{a v_2^3}{2}\sigma_h$$

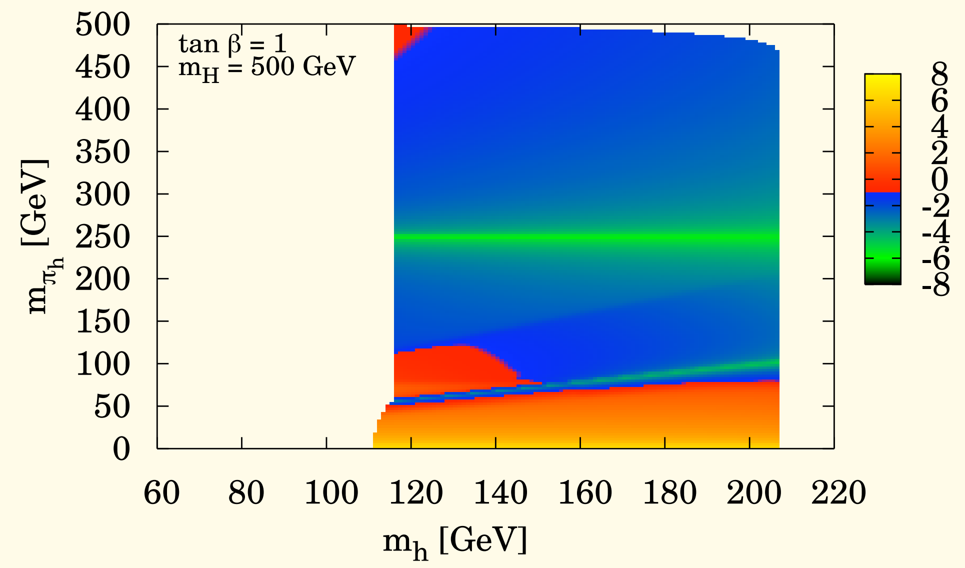
Not present in the two-Higgs Doublet model

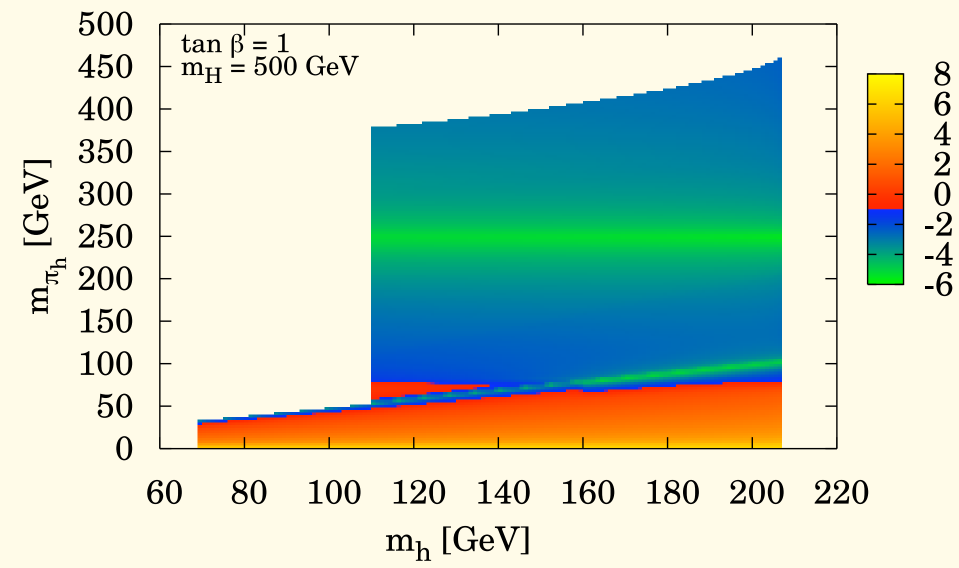
- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

$$H_1 = \begin{pmatrix} 0 \\ \frac{v_1 + h_{\rm SM}}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} \pi_h^+ \\ \frac{v_2 + \sigma_h + i\pi_h^0}{\sqrt{2}} \end{pmatrix}$$

- Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1 \lambda_2' > \lambda_3^2$

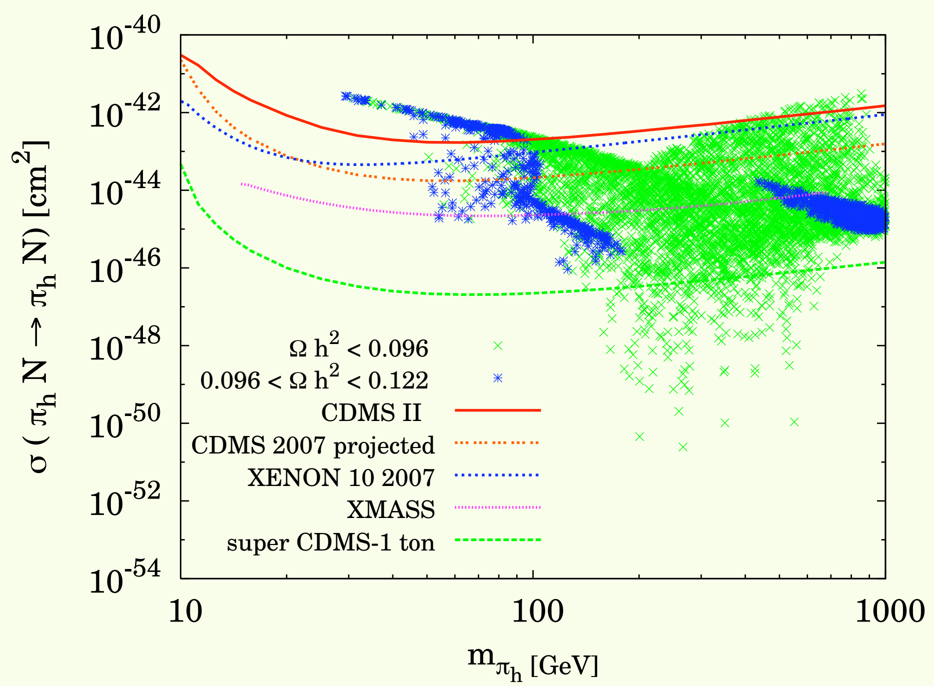
Relic Density

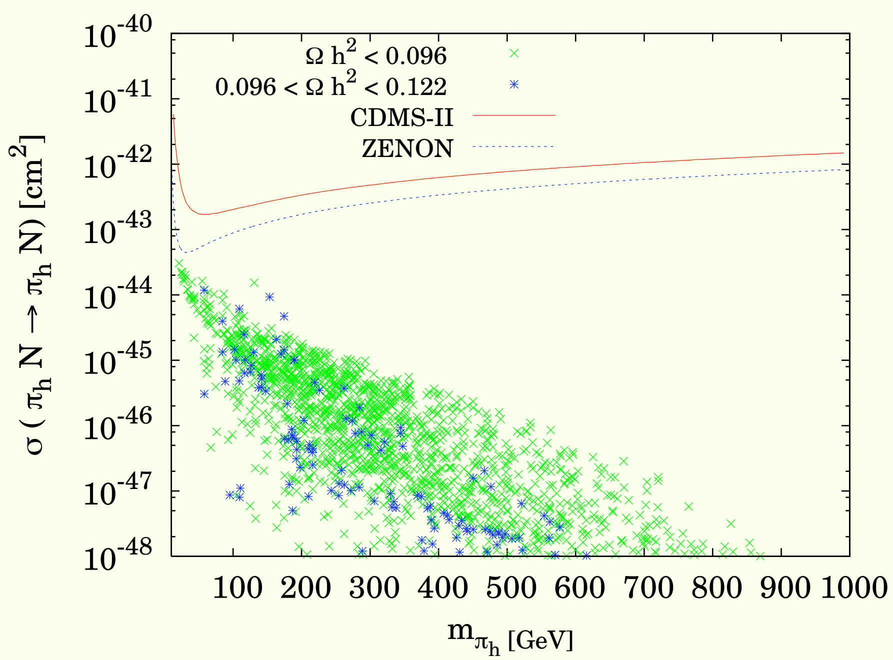




- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

Direct detection rate

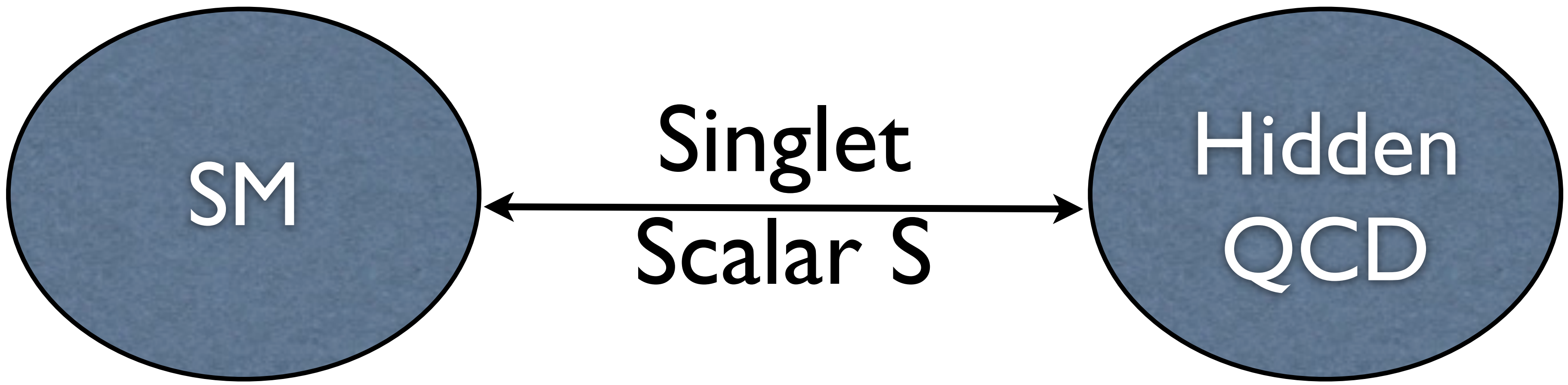




- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be probed to some extent at Super CDMS

Model I (Scalar Messenger)

Hur, Ko, PRL (2011)



- SM - Messenger - Hidden Sector QCD
- Assume classically scale invariant lagrangian --> No mass scale in the beginning
- Chiral Symmetry Breaking in the hQCD generates a mass scale, which is injected to the SM by "S"

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

$$\begin{aligned}\mathcal{L}_{\rm SM} &= \mathcal{L}_{\rm kin} - \frac{\lambda_H}{4}\,(H^\dagger H)^2 - \frac{\lambda_{SH}}{2}\,S^2\,H^\dagger H - \frac{\lambda_S}{4}\,S^4 \\ &+ \Big(\overline{Q}^i H Y_{ij}^D D^j + \overline{Q}^i \tilde{H} Y_{ij}^U U^j + \overline{L}^i H Y_{ij}^E E^j \\ &+ \overline{L}^i \tilde{H} Y_{ij}^N N^j + S N^{iT} C Y_{ij}^M N^j + h.c.\Big)\end{aligned}$$

Hidden sector lagrangian with new strong interaction

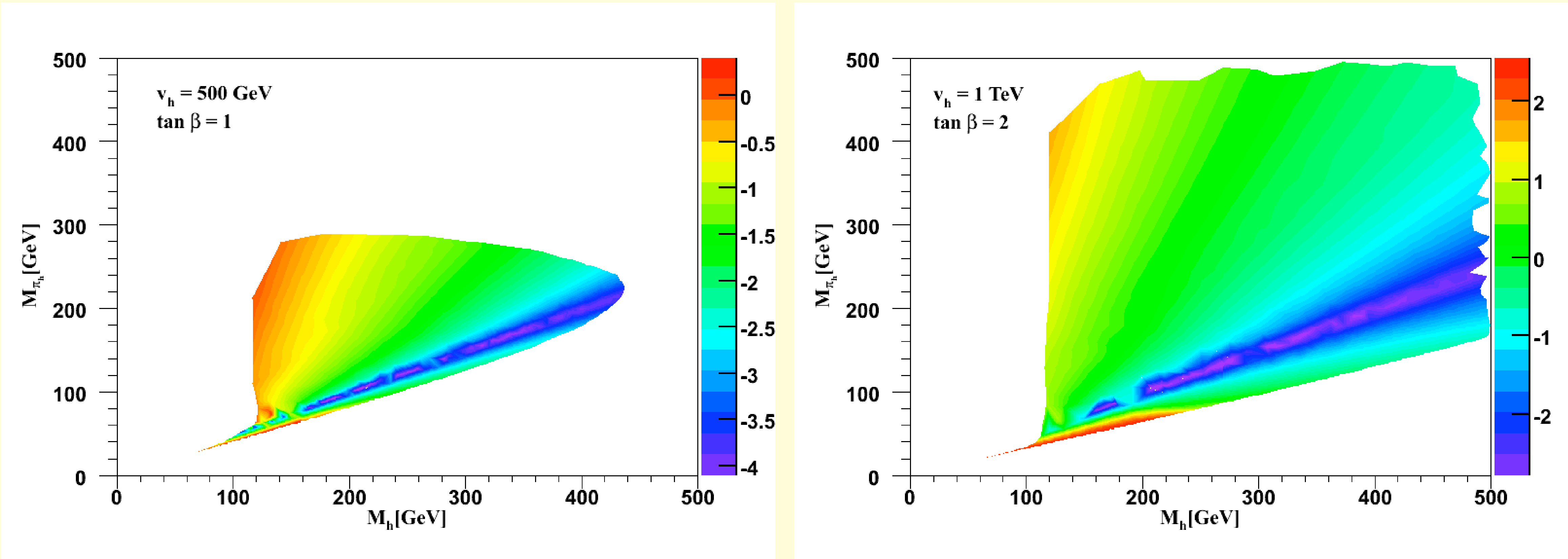
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

3 neutral scalars : h, S and hidden sigma meson
Assume h-sigma is heavy enough for simplicity

Effective lagrangian far below $\Lambda_{h,\chi} \approx 4\pi\Lambda_h$

$$
\begin{aligned}
\mathcal{L}_{\rm full} &= \mathcal{L}^{\rm eff}_{\rm hidden} + \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm mixing} \\
\mathcal{L}^{\rm eff}_{\rm hidden} &= \frac{v_h^2}{4}{\rm Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2}{\rm Tr}[\lambda S \mu_h (\Sigma_h + \Sigma_h^\dagger)] \\
\mathcal{L}_{\rm SM} &= -\frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 - \frac{\lambda_S}{8} S^4 \\
\mathcal{L}_{\rm mixing} &= -v_h^2 \Lambda_h^2 \left[\kappa_H \frac{H_1^\dagger H_1}{\Lambda_h^2} + \kappa_S \frac{S^2}{\Lambda_h^2} + \kappa_S' \frac{S}{\Lambda_h} \right. \\
&+ \left. O(\frac{S H_1^\dagger H_1}{\Lambda_h^3}, \frac{S^3}{\Lambda_h^3}) \right] \\
&\approx -v_h^2 \left[\kappa_H H_1^\dagger H_1 + \kappa_S S^2 + \Lambda_h \kappa_S' S \right]
\end{aligned}
$$

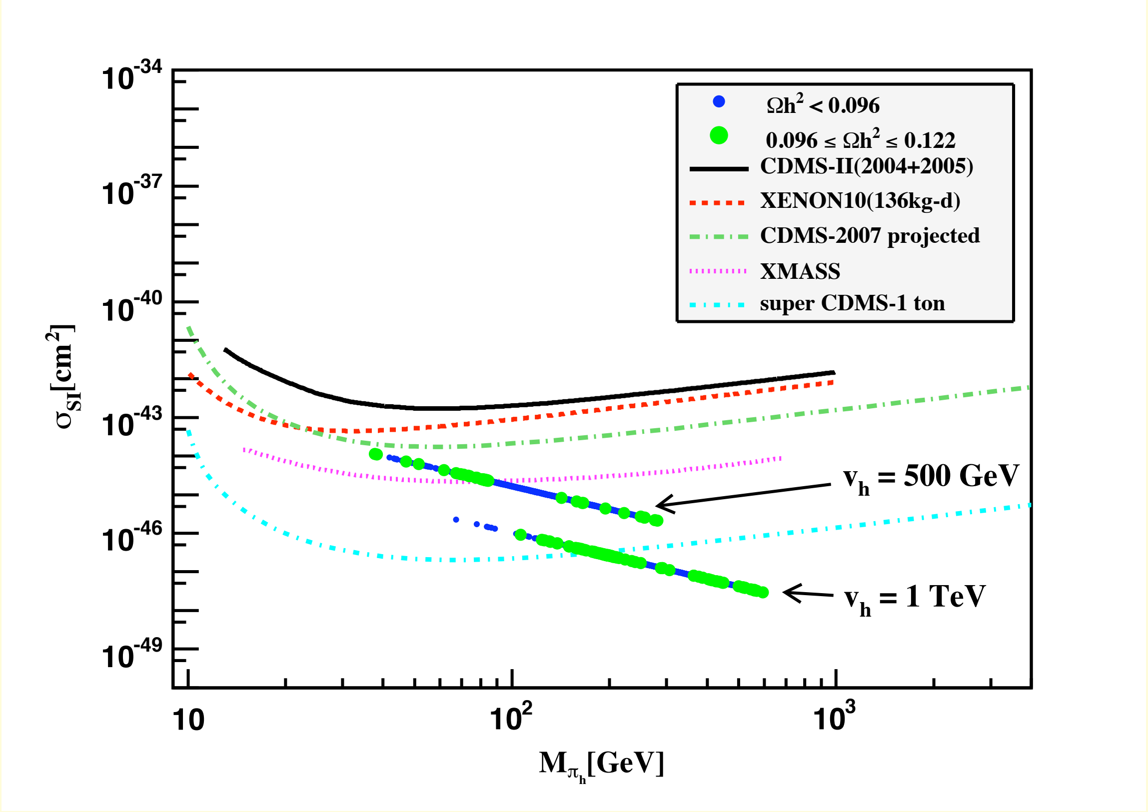
Relic density



$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for
(a) $v_h = 500$ GeV and $\tan\beta = 1$,

(b) $v_h = 1$ TeV and $\tan\beta = 2$.

Direct Detection Rate



$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.

the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

the lower one: $v_h = 1$ TeV and $\tan\beta = 2$.

Low energy pheno.

- Universal suppression of collider SM signals

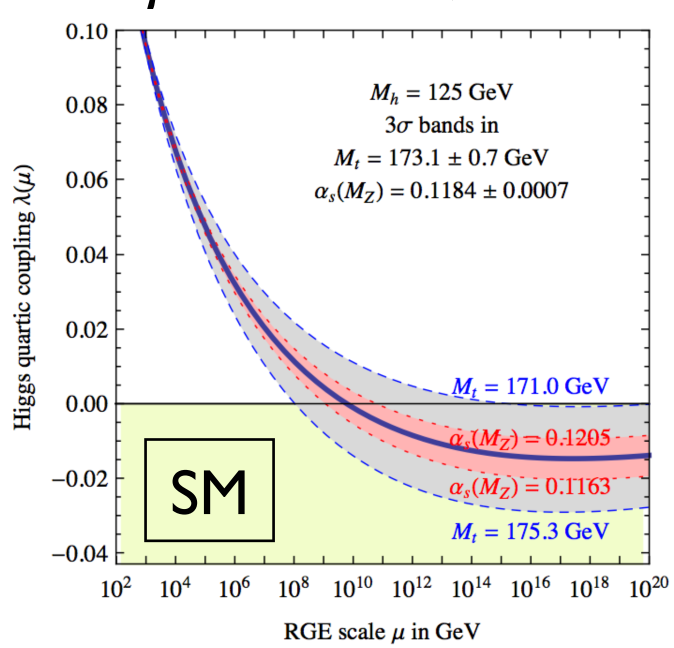
[See 1112.1847, Seungwon Baek, P. Ko & WIP]

- If "$m_h > 2\, m_\phi$", non-SM Higgs decay!

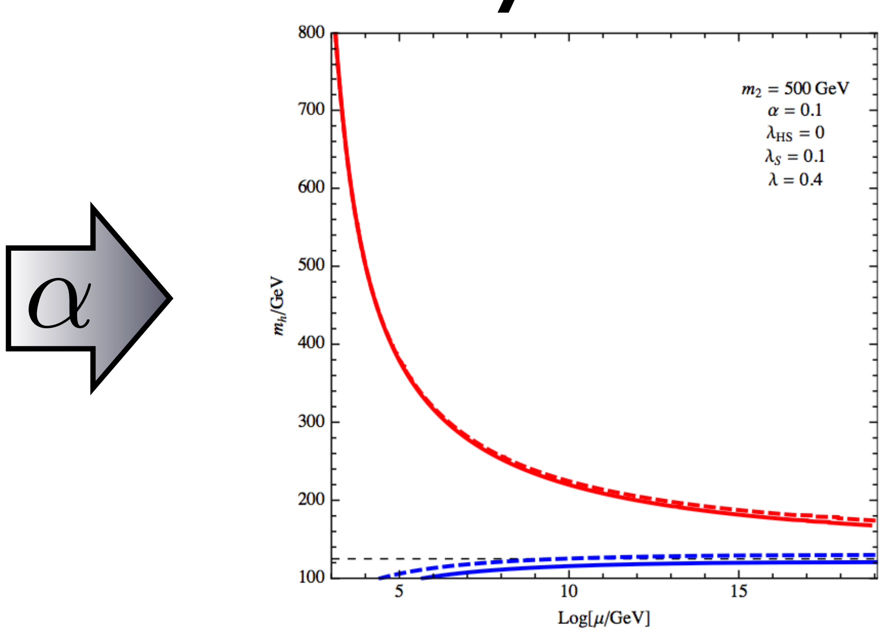
- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)

$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1\right)\sin^2\alpha\right]\lambda_H^{\rm SM}$$

➡ If "$m_\phi > m_h$", vacuum instability can be cured.



[G. Degrassi et al., 1205.6497]



[S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

Comparison w/ other model

- Dark gauge symmetry is unbroken (DM is long-lived because of accidental flavor symmetry), but confining like QCD (No long range dark force and no Dark Radiation)
- DM : composite hidden hadrons (mesons and baryons)
- All masses including CDM masses from dynamical sym breaking in the hidden sector
- Singlet scalar is necessary to connect the hidden sector and the visible sector
- Higgs Signal strengths : universally reduced from one

- Similar to the massless QCD with the physical proton mass without fine tuning problem
- Similar to the BCS mechanism for SC, or Technicolor idea
- "S" helps the Higgs inflation [Higgs-portal assisted Higgs inflation, Kim,Ko,Park, arXiv:1405.1635]
- Eventually we would wish to understand the origin of DM and RH neutrino masses, and this model is one possible example

More issues to study

- DM : strongly interacting composite hadrons in the hidden sector >> self-interacting DM >> can solve the small scale problem of DM halo
- TeV scale seesaw : TeV scale leptogenesis, or baryogenesis from neutrino oscillations
- Wess-Zumino term: 3 > 2 possible (e.g. Hochberg, Kuflik, Murayam, Volansky, Wacker for Sp(N) case)
- Another approach for hQCD ? (For example, Kubo, Lindner et al use NJL approach; and AdS/QCD approach with H.Hatanaka, D.W.Jung@KIAS)

SIMP Scenario in Dark QCD

SIMP paradigm

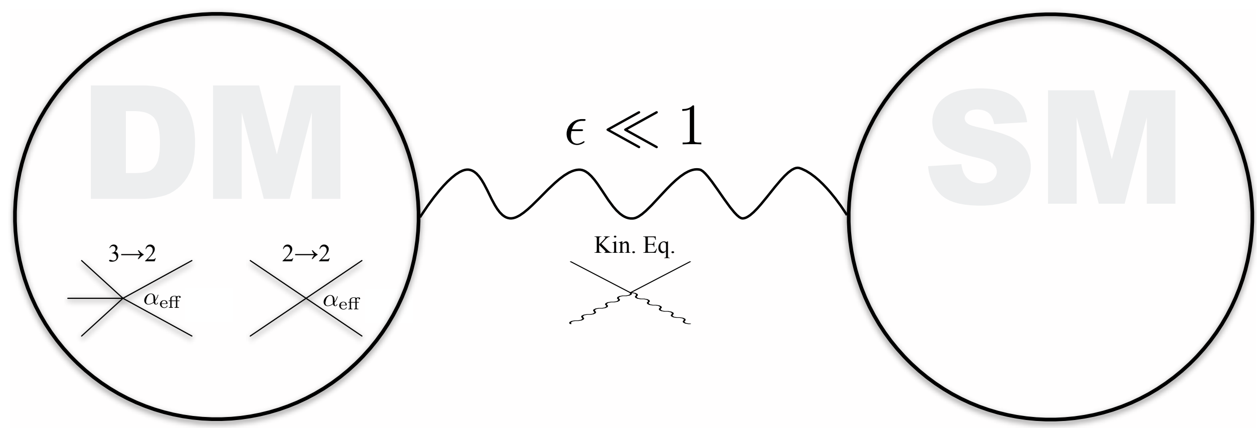


FIG. 1: A schematic description of the SIMP paradigm. The dark sector consists of DM which annihilates via a $3 \to 2$ process. Small couplings to the visible sector allow for thermalization of the two sectors, thereby allowing heat to flow from the dark sector to the visible one. DM self interactions are naturally predicted to explain small scale structure anomalies while the couplings to the visible sector predict measurable consequences.

Hochberg, Kuflik, Tolansky, Wacker, arXiv:1402.5143
Phys. Rev. Lett. 113, 171301 (2014)

SIMP Conditions

Freeze-out :

$$\Gamma_{3\to 2} = n_{DM}^2 \langle \sigma v^2 \rangle_{3\to 2} \sim H(T_F)$$

$$\langle \sigma v^2 \rangle_{3\to 2} = \frac{\alpha_{\mathrm{eff}}^3}{m_{\mathrm{DM}}^5}$$

$$\alpha_{\mathrm{eff}} = 1 - 30 \to m_{\mathrm{DM}} \sim 10\mathrm{MeV} - 1\mathrm{GeV}$$

2->2 Self scattering :

$$\frac{\sigma_{\mathrm{scatter}}}{m_{\mathrm{DM}}} = \frac{a^2 \alpha_{\mathrm{eff}}^2}{m_{\mathrm{DM}}^3}$$

with a~O(1)

$$\frac{\sigma_{\mathrm{scatter}}}{m_{\mathrm{DM}}} \lesssim 1 \ \mathrm{cm}^2/\mathrm{g}$$

Dark QCD + WZW

- Dark flavor symmetry $G=SU(N_f)_L \times SU(N_f)_R$ is SSB into diagonal $H=SU(N_f)_V$ by dark QCD condensation
- Effective Lagrangian for NG bosons (dark pions) contain 5-point self interaction : WZW term for $\pi_5(G/H) = Z$ ($N_f > 2$)

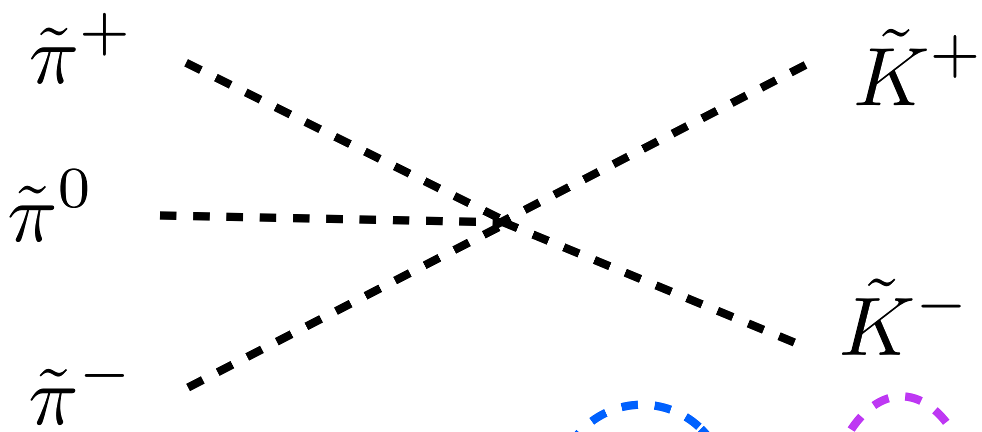
$$\Gamma_{\mathrm{WZ}} = C \int_{M^5} d^5x \ \mathrm{Tr}(\alpha^5) \qquad \text{with} \quad \alpha = dUU^\dagger.$$

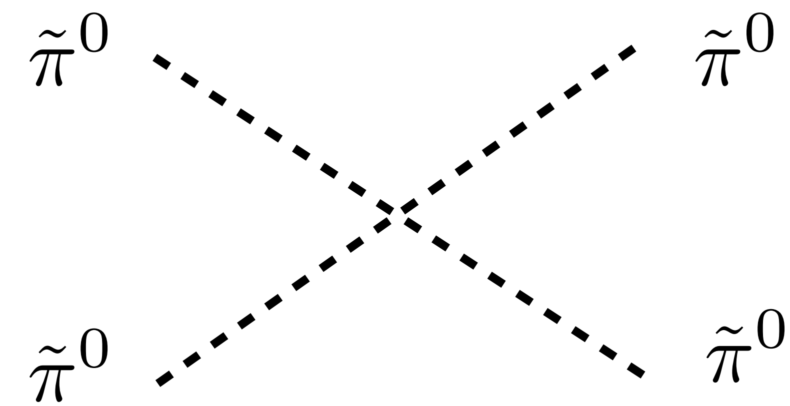
$$U = e^{2i\pi/F}$$

$$C = -i\frac{N_c}{240\pi^2}$$

in the absence of external gauge fields

SIMP Dark Mesons





~const

$$\langle \sigma v^2 \rangle_{3\to2} = \frac{5\sqrt{5}N_c^2 m_\pi^5}{2\pi^5 F^{10}} \frac{t^2}{N_\pi^3} \left(\frac{T_F}{m_\pi}\right)^2,$$

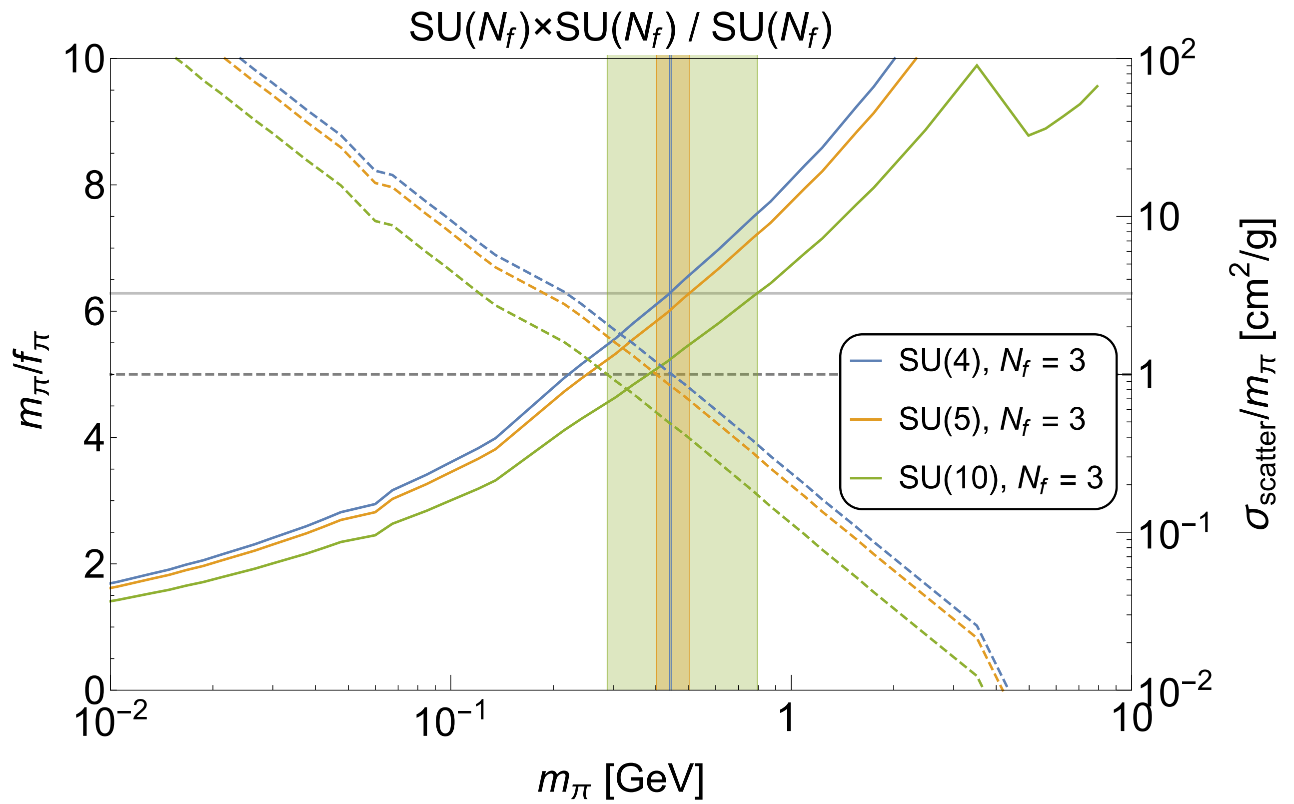
$$\sigma_{\rm self} = \frac{m_\pi^2}{32\pi F^4} \frac{a^2}{N_\pi^2}$$

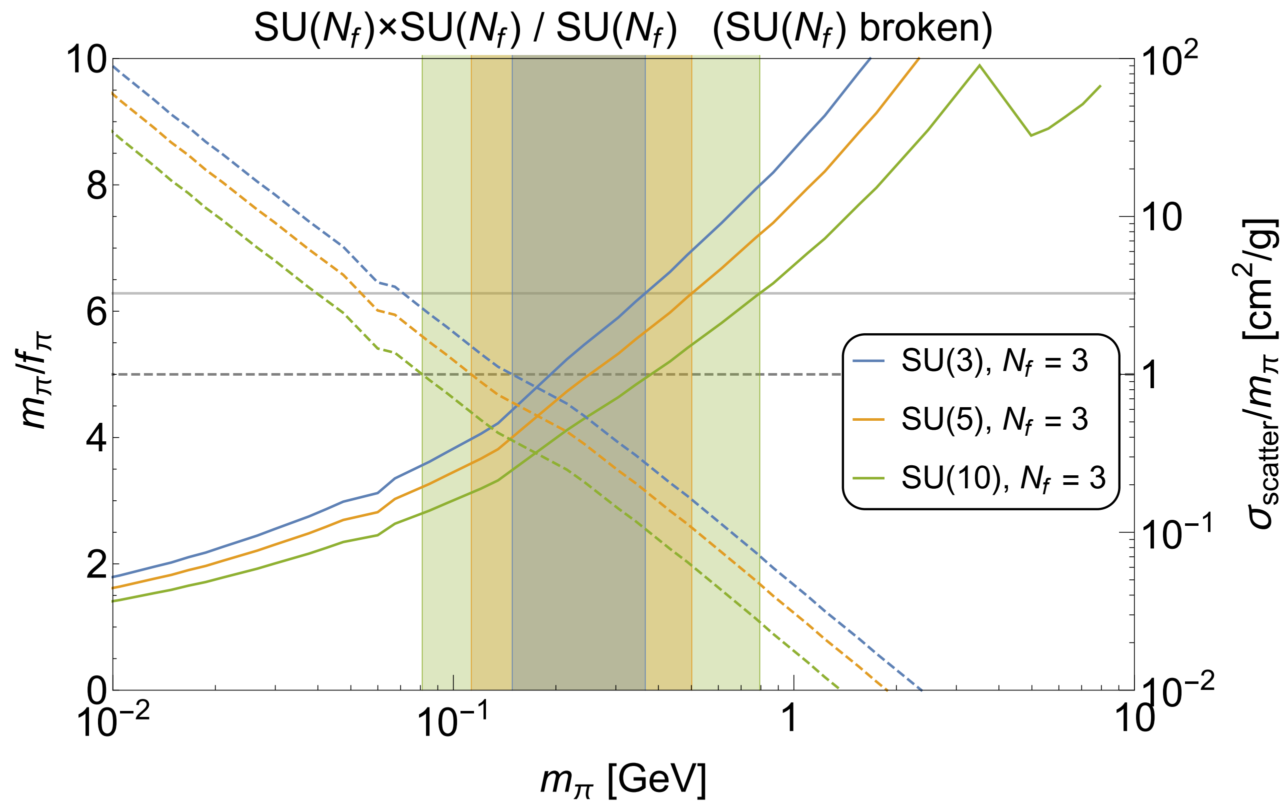
~const

G_c	G_f/H	N_π	t^2	$N_f^2 a^2$
$SU(N_c)$	$\frac{SU(N_f)\times SU(N_f)}{SU(N_f)}$ $(N_f \geq 3)$	$N_f^2 - 1$	$\frac{4}{3}N_f(N_f^2-1)(N_f^2-4)$	$8(N_f-1)(N_f+1)(3N_f^4-2N_f^2+6)$
$SO(N_c)$	$SU(N_f)/SO(N_f)$ $(N_f \geq 3)$	$\frac{1}{2}(N_f+2)(N_f-1)$	$\frac{1}{12}N_f(N_f^2-1)(N_f^2-4)$	$(N_f-1)(N_f+2)(3N_f^4+7N_f^3-2N_f^2-12N_f+24)$
$Sp(N_c)$	$SU(2N_f)/Sp(2N_f)$ $(N_f \geq 2)$	$(2N_f+1)(N_f-1)$	$\frac{2}{3}N_f(N_f^2-1)(4N_f^2-1)$	$4(N_f-1)(2N_f+1)(6N_f^4-7N_f^3-N_f^2+3N_f+3)$

[Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727, PRL (2015)]

SIMP Parameter Space





Hochberg, Kuflik, Murayama, Volansky, Wacker, 1411.3727, PRL

- DM self scattering : $\sigma_{\rm self}/m_{\rm DM} < 1\,{\rm cm}^2/{\rm g}$

Large Nc > 3

- Validity of ChPT : $m_\pi/f_\pi < 2\pi$

More serious in NNLO ChPT
Sannino et al, 1507.01590

Issues in the SIMP w/ hQCD

- Dark flavor sym is not good enough to stabilize dark pion (We have to assume dim-5 operator is highly suppressed)

- Dark baryons can make additional contribution to DM of the universe (It could produce additional diagrams for SIMP)

- Validity region of ChPT : need to include resonances (dark rho meson, dark sigma meson, etc.)

- How to achieve Kinetic equilibrium with the SM ? (Dark sigma meson or adding singlet scalar S may help. Or lifting the mass degeneracy of dark pions can help.)

SIMP + DVM

With Soo Min Choi, Hyun Min Lee, Alexander Natale,
arXiv:1801.07726, PRD (2018)

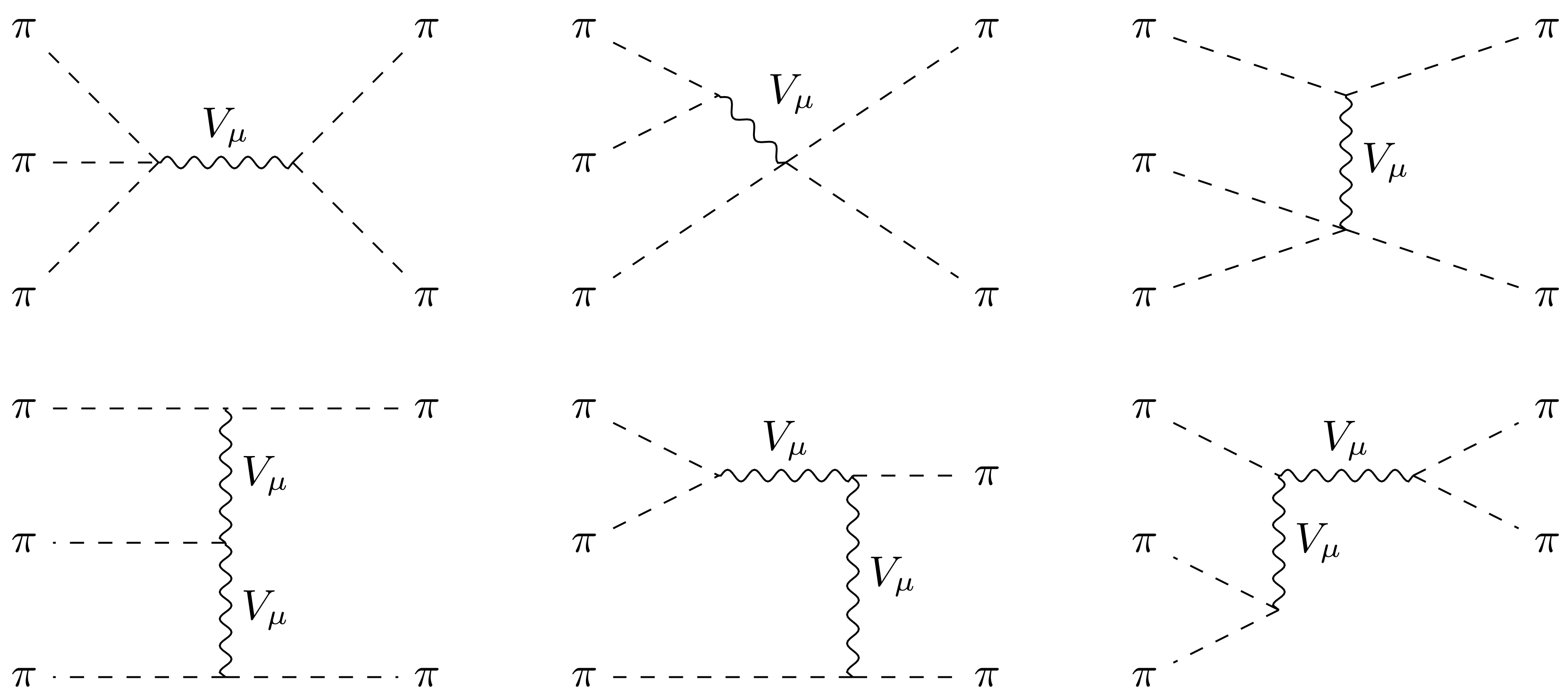


FIG. 1: Feynman diagrams contributing to $3 \to 2$ processes for the dark pions with the vector meson interactions.

Including light DVM improves unitarity !

SIMP + DVM

New diagrams involving dark vector mesons

$$\pi^+\pi^-\pi^0 \to \omega \to K^+K^-(K^0\overline{K^0})$$

$$\gamma = \frac{m_V\Gamma}{9m_\pi^2}, \text{ and } \epsilon = \frac{m_V^2-9m_\pi^2}{9m_\pi^2}$$ **(for 3 pi resonance case)**

**We choose a small epsilon [say, 0.1 (near resonance)]
and a small gamma (NWA)**

Results

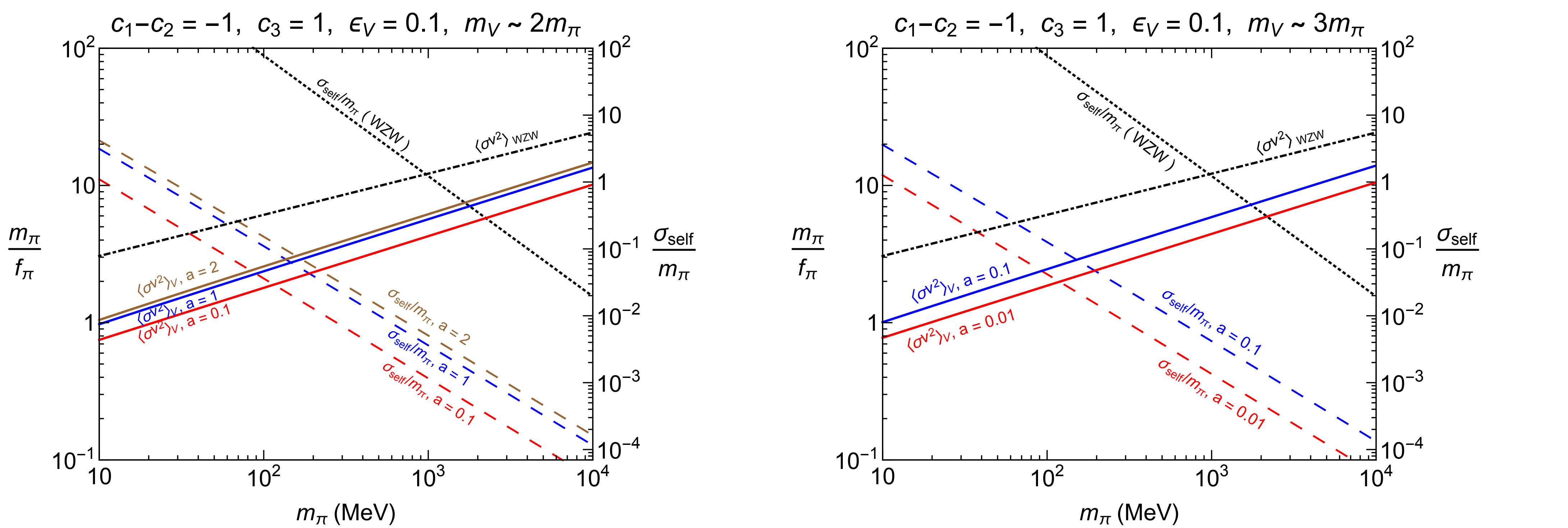


FIG. 2: Contours of relic density ($\Omega h^2 \approx 0.119$) for m_π and m_π/f_π and self-scattering cross section per DM mass in cm^2/g as a function of m_π. The case without and with vector mesons are shown in black lines and colored lines respectively. We have imposed the relic density condition for obtaining the contours of self-scattering cross section. Vector meson masses are taken near the resonances with $m_V = 2(3)m_\pi\sqrt{1+\epsilon_V}$ on left(right) plots. In both plots, $c_1 - c_2 = -1$ and $\epsilon_V = 0.1$ are taken.

- The allowed parameter space is in a better shape now, especially for 2 pi resonance case

Conclusion

- Hidden (dark) QCD models make an interesting possibility to study the origin of EWSB, (C)DM

- WIMP scenario is still viable, and will be tested to some extent by precise measurements of the Higgs signal strength and by discovery of the singlet scalar, which is however a formidable task unless we are very lucky

- SIMP scenario using 3->2 scattering via WZW term is interesting, but there are a few issues which ask for further study (dark resonance could play an important role for thermal relic and kinetic contact with the SM sector)

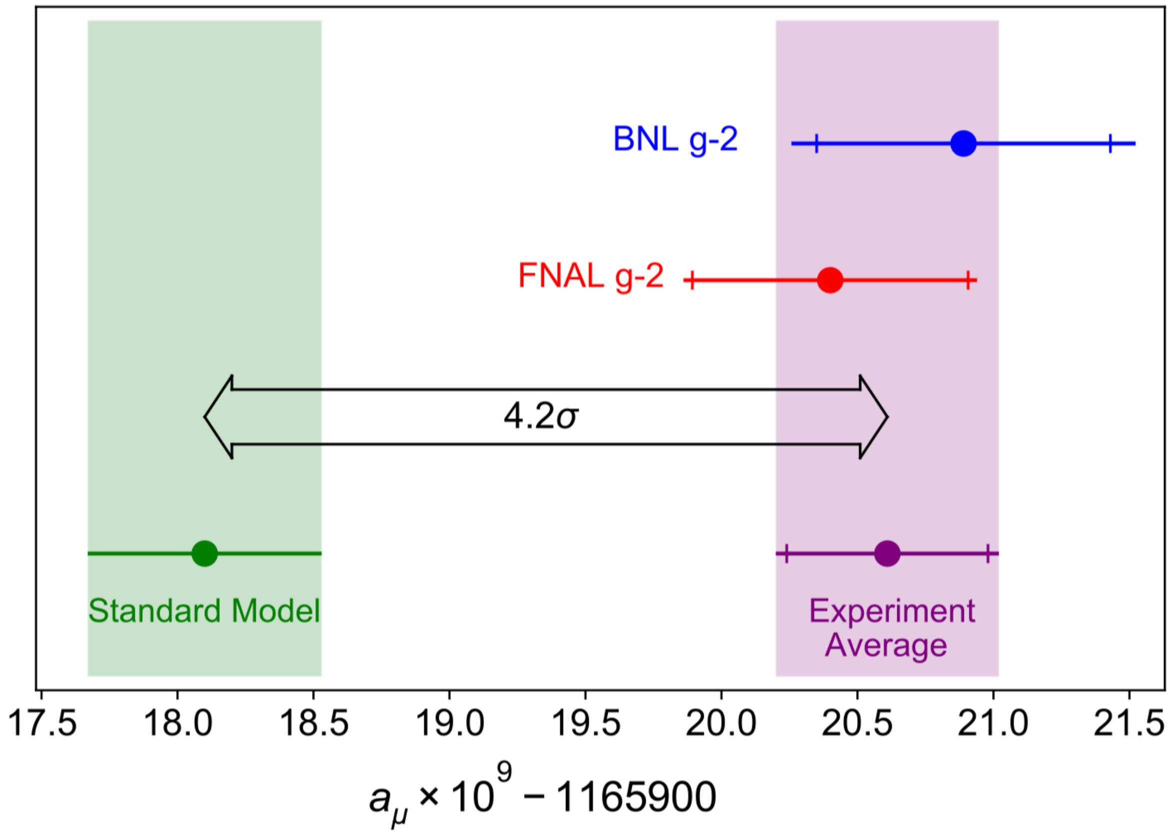
$U(1)_{L_\mu - L_\tau}$ -charged DM
: Z' only vs. $Z' + \phi$

arXiv:2204.04889 [hep-ph]
With Seungwon Baek, Jongkuk Kim

SM+$U(1)_{L_\mu - L_\tau}$ gauge sym

- He, Josh, Lew, Volkas, PRD 43, 22; PRD 44, 2118 (1991)
- One of the anomaly free gauge groups without extension of fermion contents
- The simplest anomaly free U(1) extensions that couple to the SM fermions directly
- Can affect the muon g-2, PAMELA e^+ excess, (and B anomalies with extra fermions : Not covered in this talk)

Muon g-2



The Muon g-2 Collaboration, 2104.03281

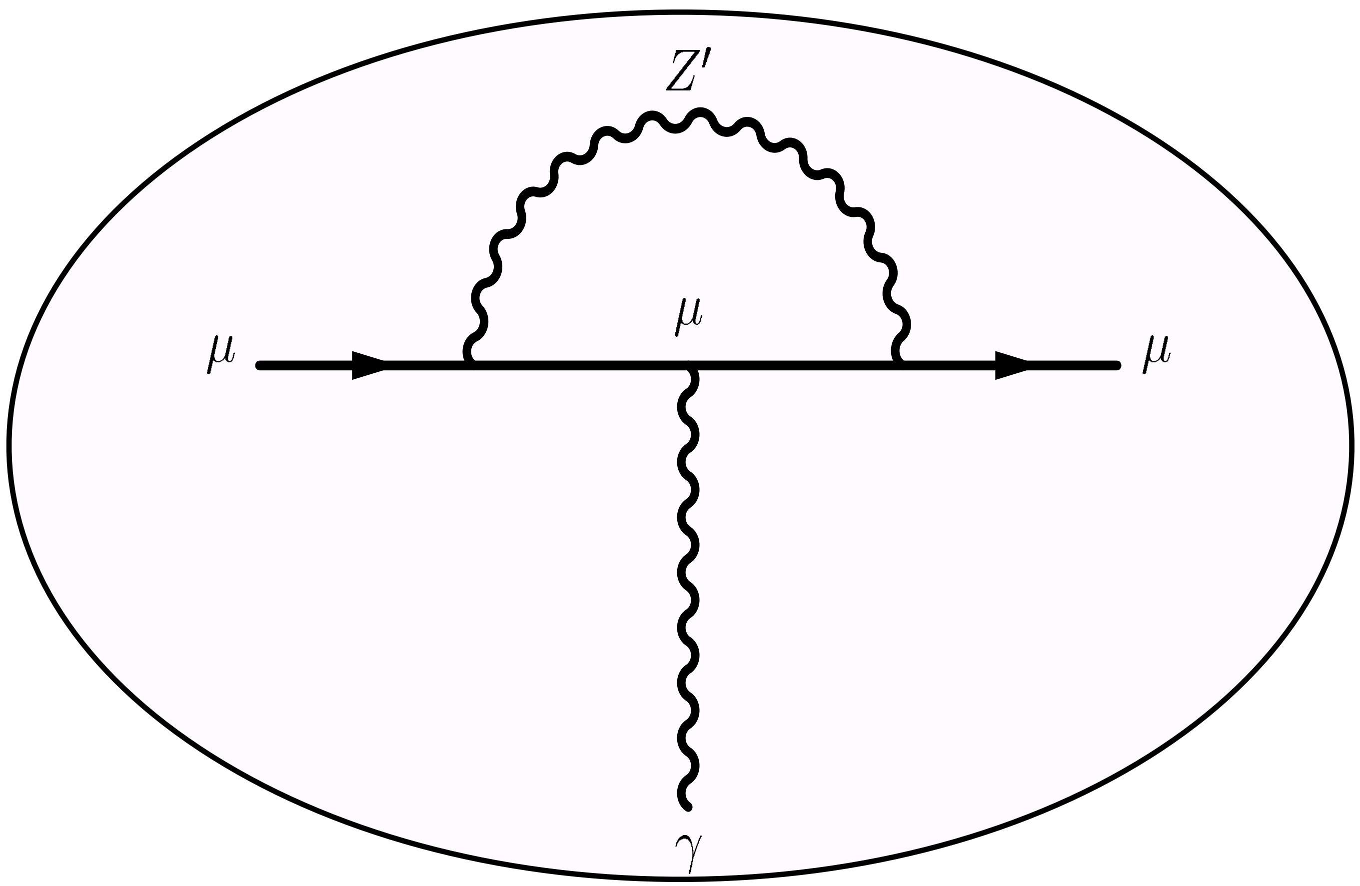
Excellent example for graduate students

- Relativistic E&M (spinning particle in EM fields)
- Special relativity (time dilation)
- (V-A) structure of charged weak interaction

Muon (g-2)

Baek, Deshpande, He, Ko : hep-ph/0104141
Baek, Ko : arXiv:0811.1646 [hep-ph]

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (302 \pm 88) \times 10^{-11}.$$



$$\Delta a_\mu = \frac{\alpha'}{2\pi} \int_0^1 dx \frac{2m_\mu^2 x^2 (1-x)}{x^2 m_\mu^2 + (1-x) M_{Z'}^2} \approx \frac{\alpha'}{2\pi} \frac{2m_\mu^2}{3M_{Z'}^2}$$

Baek and Ko, arXiv:0811.1646, for PAMELA e^+ excess

$$\mathcal{L}_{\rm Model} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm New}$$
$$\mathcal{L}_{\rm New} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \overline{\psi_D} i D \cdot \gamma \psi_D - M_{\psi_D} \overline{\psi_D} \psi_D + D_\mu \phi^* D^\mu \phi$$
$$-\lambda_\phi (\phi^* \phi)^2 - \mu_\phi^2 \phi^* \phi - \lambda_{H\phi} \phi^* \phi H^\dagger H.$$

Here we ignored kinetic mixing for simplicity

$$D_\mu = \partial_\mu + ieQA_\mu + i\frac{e}{s_W c_S}(I_3 - s_W^2 Q) Z_\mu + i g' Y' Z'_\mu$$

muon g-2, Leptophilc DM, Collider Signature

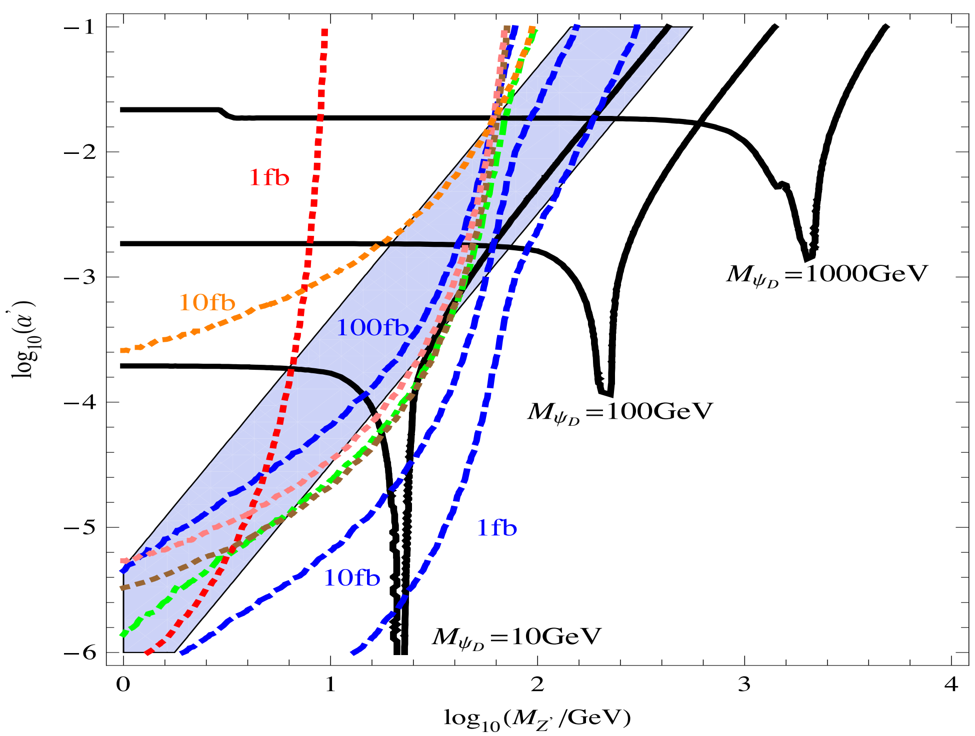


Figure 1: The relic density of CDM (black), the muon $(g-2)_\mu$ (blue band), the production cross section at B factories (1 fb, red dotted), Tevatron (10 fb, green dotdashed), LEP (10 fb, pink dotted), LEP2 (10 fb, orange dotted), LHC (1 fb, 10 fb, 100 fb, blue dashed) and the Z^0 decay width (2.5×10^{-6} GeV, brown dotted) in the $(\log_{10}\alpha', \log_{10} M_{Z'})$ plane. For the relic density, we show three contours with $\Omega h^2 = 0.106$ for $M_{\psi_D} = 10$ GeV, 100 GeV and 1000 GeV. The blue band is allowed by $\Delta a_\mu = (302 \pm 88) \times 10^{-11}$ within 3 σ.

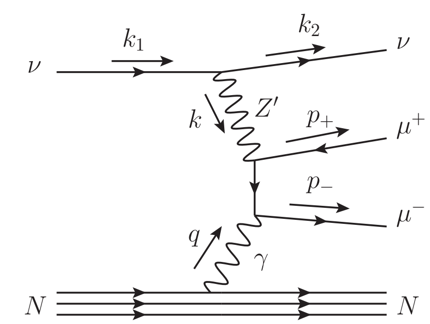


FIG. 1. The leading order contribution of the Z′ to neutrino trident production (another diagram with μ^+ and μ^- reversed i ... in g'

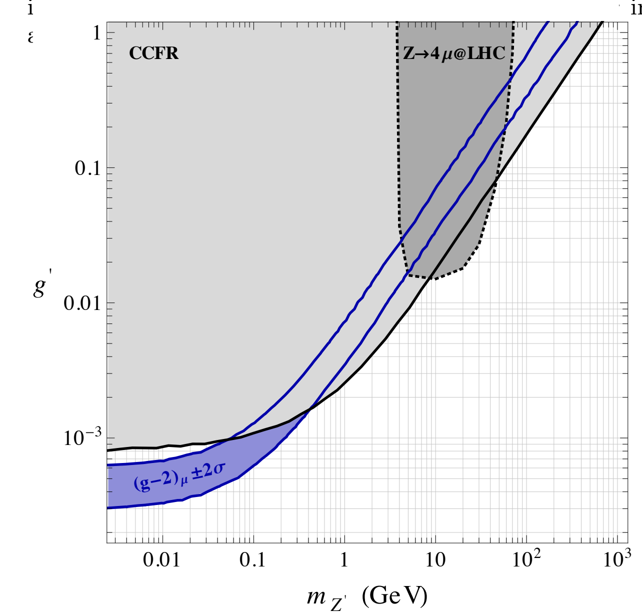


FIG. 2. Parameter space for the Z′ gauge boson. The light-grey area is excluded at 95% C.L. by the CCFR measurement of the neutrino trident cross-section. The grey region with the dotted contour is excluded by measurements of the SM

Seungwon Baek, Pyungwon Ko, arXiv:0811.1646, JCAP(2009) about PAMELA e^+ excess

Altmannshofer et al. arXiv:1406.2332 [hep-ph]

Neutrino trident puts strong constraints on this model

One can evade the neutrino trident constraint, if one introduces New fermions and generate muon g-2 at loop level w/ new fermions !

Z’ Only

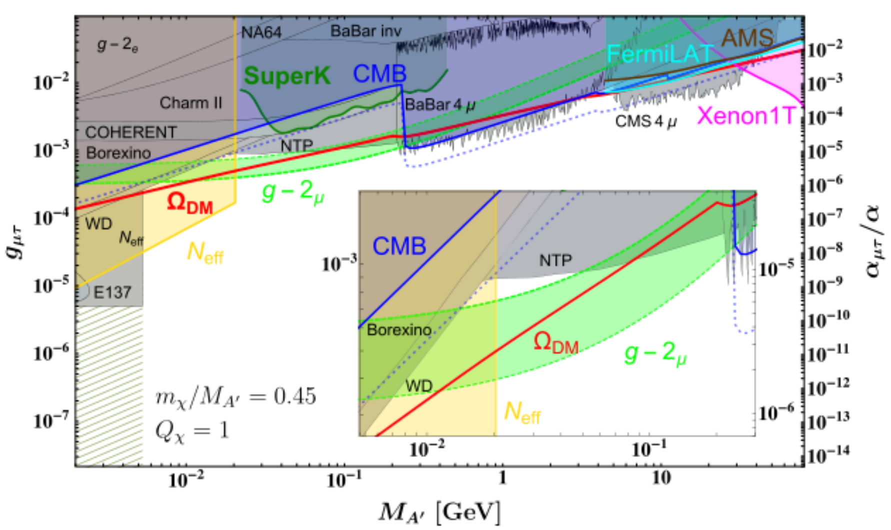
- Consider light Z’ and $g_X \sim (\text{a few}) \times 10^{-4}$ for the muon g-2. Then
- $\chi\bar{\chi} \to Z'^{*} \to f_{\rm SM}\bar{f}_{\rm SM}$: dominant annihilation channel
- $g_X \sim 10^{-4}$ is too small for $\chi\bar{\chi} \to Z'Z'$ to be effective for $\Omega_\chi h^2$
- $m_{Z'} \sim 2m_{\rm DM}$ with the s-channel Z' resonance for the correct relic density
- Many recent studies on this case:

- Asai, Okawa, Tsumura, 2011.03165
- Holst, Hooper, Krnjaic, 2107.09067
- Drees and Zhao, arXiv:2107.14528
- And some earlier papers

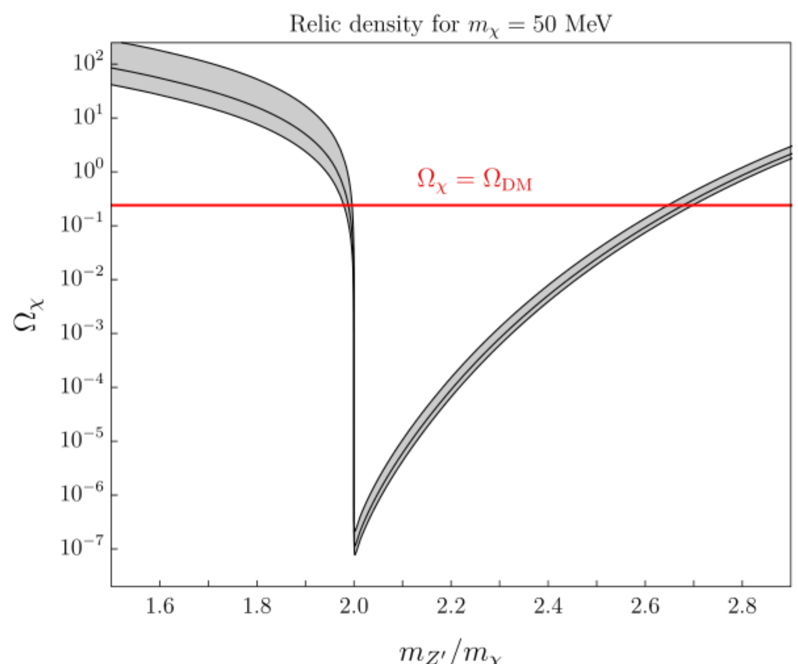
Leptophilic Z' model + DM

- $\chi\bar{\chi}(X\bar{X}) \to Z'^{*} \to \nu\bar{\nu}$: dominant annihilation channels
  - $M_{Z'} \sim 2M_{\chi}$ with the **s-channel Z' resonance** only gives the correct relic density

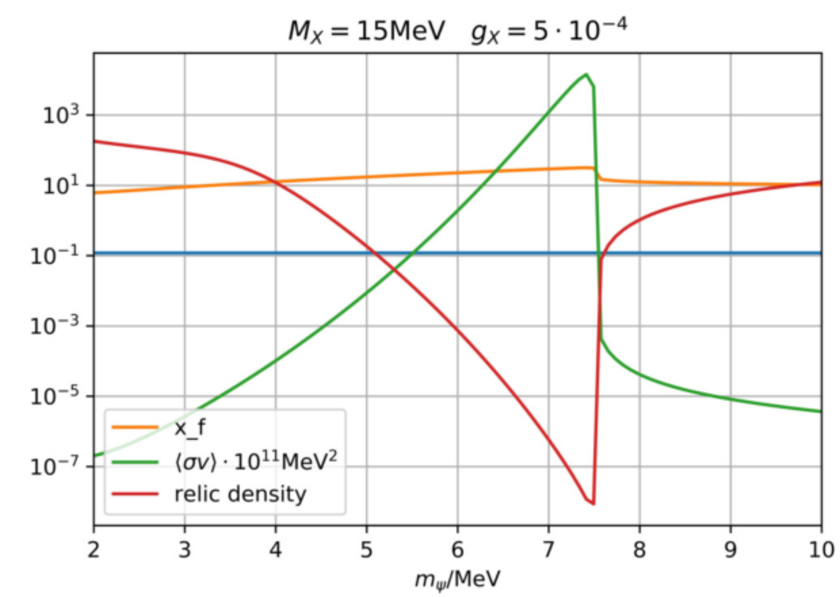
P. Foldenauer, PRD 2019



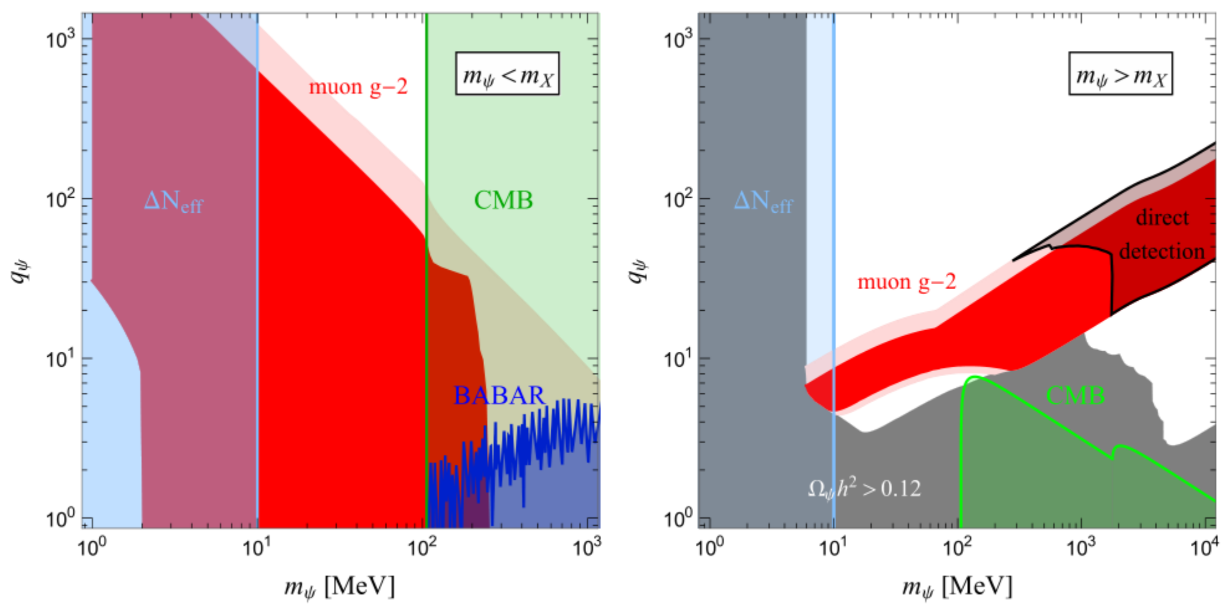
I. Holst. D. Hooper, G. Krnjaic, PRL 2022

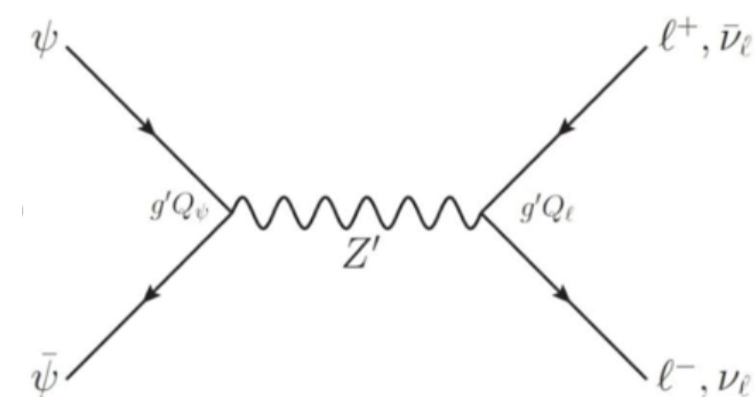


M. Drees, W. Zhao, PLB 2022



Asai, Okawa, Tsumura, JHEP 2021





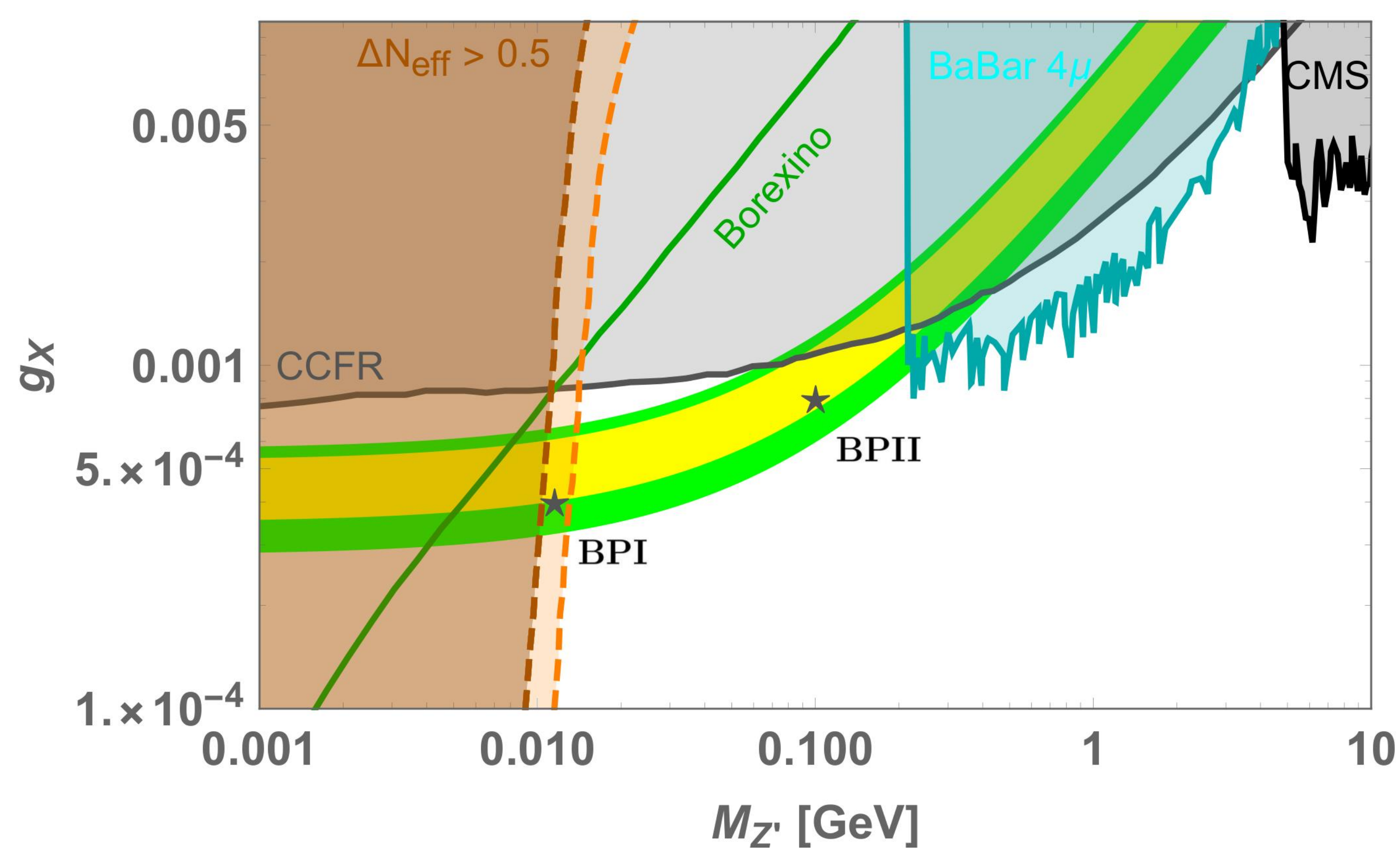


FIG. 1. Regions inside the yellow and Green shaded areas by the Δa_μ are allowed at 1σ and 2σ C.L.. Cyan, black, and orange regions are excluded by other experimental bounds. Above green solid line is ruled out by the Borexino experiment. Region inside the orange area can resolve the Hubble tension. We take two Benchmark Points (BP) $(M_{Z'}, g_X)$ as **BPI** $=(11.5\,\text{MeV}, 4\times10^{-4})$ and **BPII** $= (100\,\text{MeV}, 8\times10^{-4})$.

Models with Φ

TABLE I: $U(1)$ charge assignments of newly introduced particles and SM particles. The other SM particles are singlet.

Field	Z'_μ	$X(\chi)$	Φ	$L_\mu = (\nu_{L\mu}, \mu_L), \mu_R$	$L_\tau = (\nu_{L\tau}, \tau_L), \tau_R$
spin	1	0 (1/2)	0	1/2	1/2
$U(1)$ charge	0	$Q_X(Q_\chi)$	Q_Φ	+1	-1

We Consider Both Complex Scalar (X) and Dirac Fermion DM (χ)

- Physics depends on Q_Φ , Q_X and Q_χ
- $Q_\Phi = 2Q_{X(\chi)}$ and $3Q_X$ need special cares, since there are extra gauge invariant op's that break $U(1) \to Z_2$, Z_3 after $U(1)$ is spontaneously broken by nonzero VEV of Φ

Complex Scalar DM (generic with $Q_\Phi \neq Q_X, etc$)

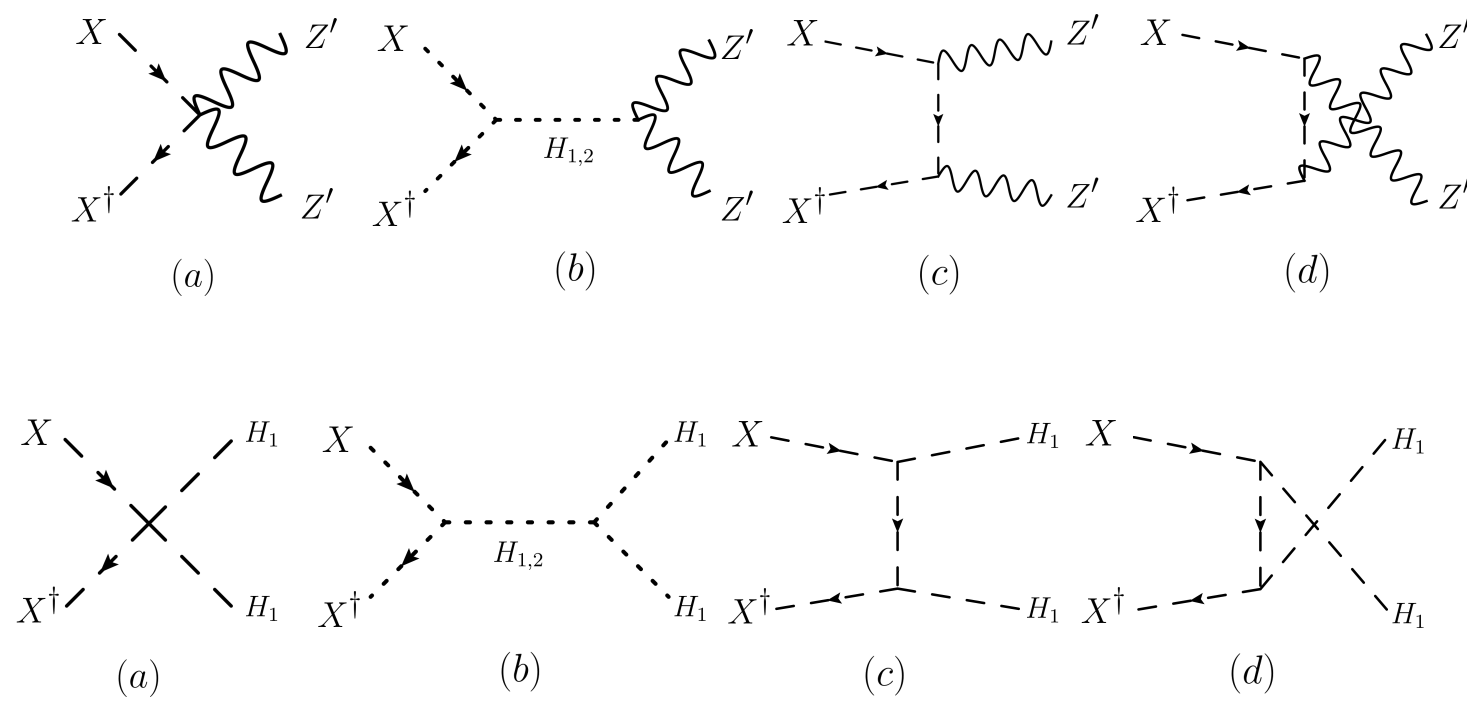


FIG. 2. (*Top*) Feynman diagrams for Complex scalar DM annihilating to a pair of Z' bosons. (*Bottom*) Feynman diagrams for Complex scalar DM annihilating to a pair of H_1 bosons.

$H_2 \simeq H_{125}$ and $H_1 \simeq \phi$ (dark Higgs)

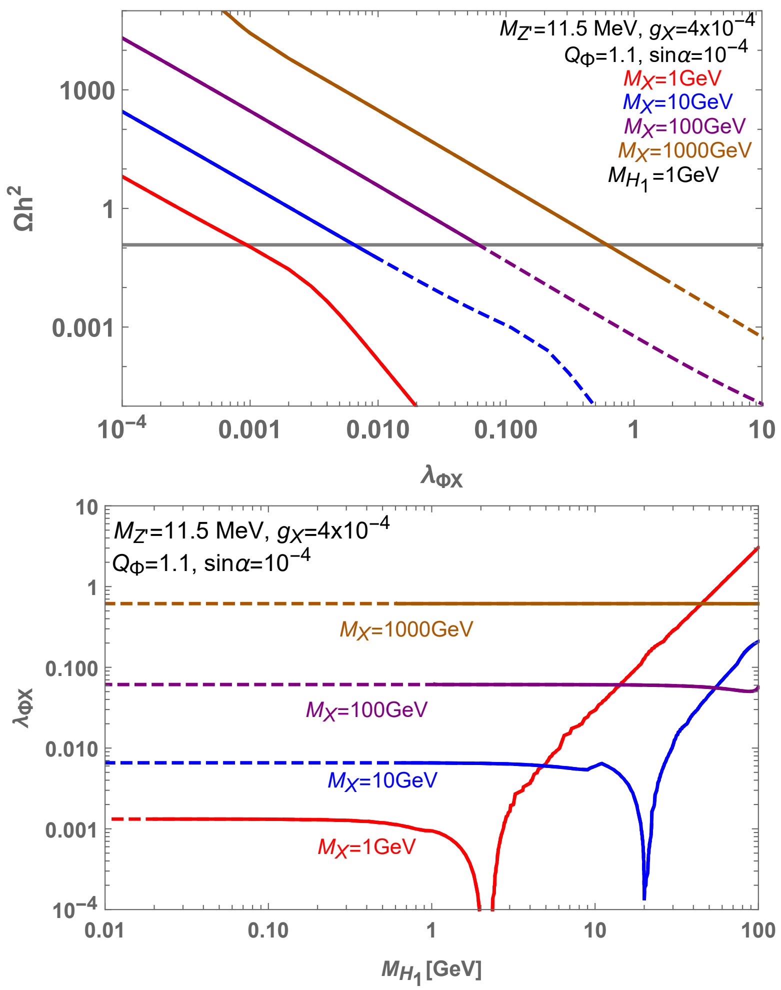


FIG. 3. *Top*: relic abundance of complex scalar DM as functions of $\lambda_{\Phi X}$ for [**BPI**] for $M_X = 1,\ 10, 100,\ 1000$GeV, respectively. We assumed $Q_\Phi = 1.1$, $M_{H_1} = 1$GeV, and $\sin\alpha = 10^{-4}$. Solid (Dashed) lines represent the region where bounds on DM direct detection are satisfied (ruled out). *Bottom*: the preferred parameter space in the $(M_{H_1}, \lambda_{\Phi X})$ plane for $\lambda_{HX} = 0$.

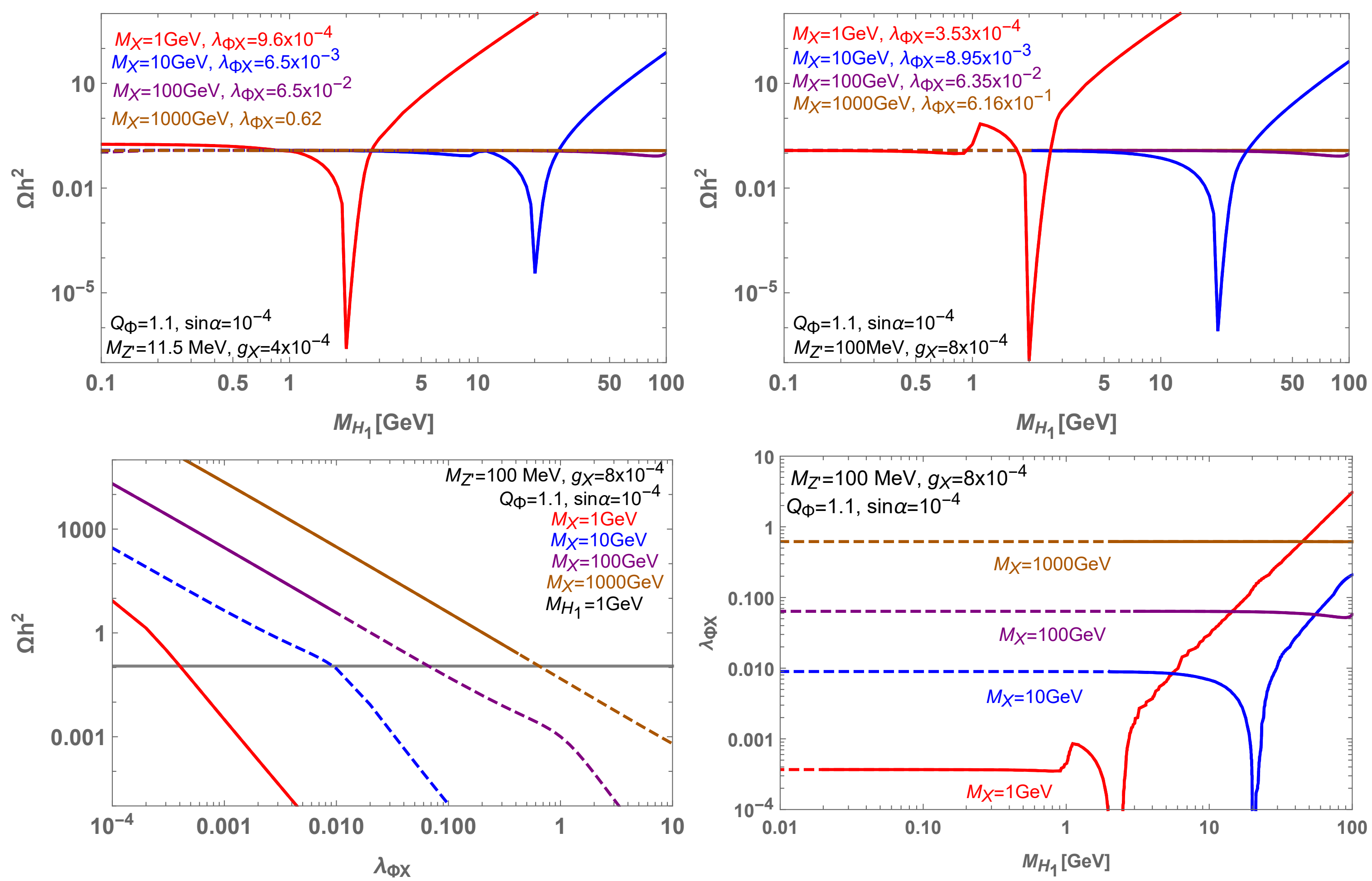


FIG. 7. The (*Top*) plots show the relic abundance of complex scalar DM for $Q_\Phi = 1.1$ as functions of dark Higgs mass M_{H_1} for [**BPI**] (*Left*) and [**BPII**] (*Right*). The (*Bottom*) plots show the relic density as functions of $\lambda_{\Phi X}$ (*Left*) and the preferred parameter space in the $(M_{H_1}, \lambda_{\Phi X})$ plane for $\lambda_{HX} = 0$ (*Right*) for [**BPII**] . We take four different DM masses, $M_X = 1,\ 10, 100,\ 1000$GeV, respectively. Solid (Dashed) lines represent the region where bounds on DM direct detection are satisfied (ruled out).

DM mass : much wider range than $m_{Z'} \sim 2m_{\rm DM}$
due to dark Higgs boson contributions

Complex Scalar DM: $U(1)_{L_\mu - L_\tau} \to Z_2\ (Q_\Phi = 2Q_X)$

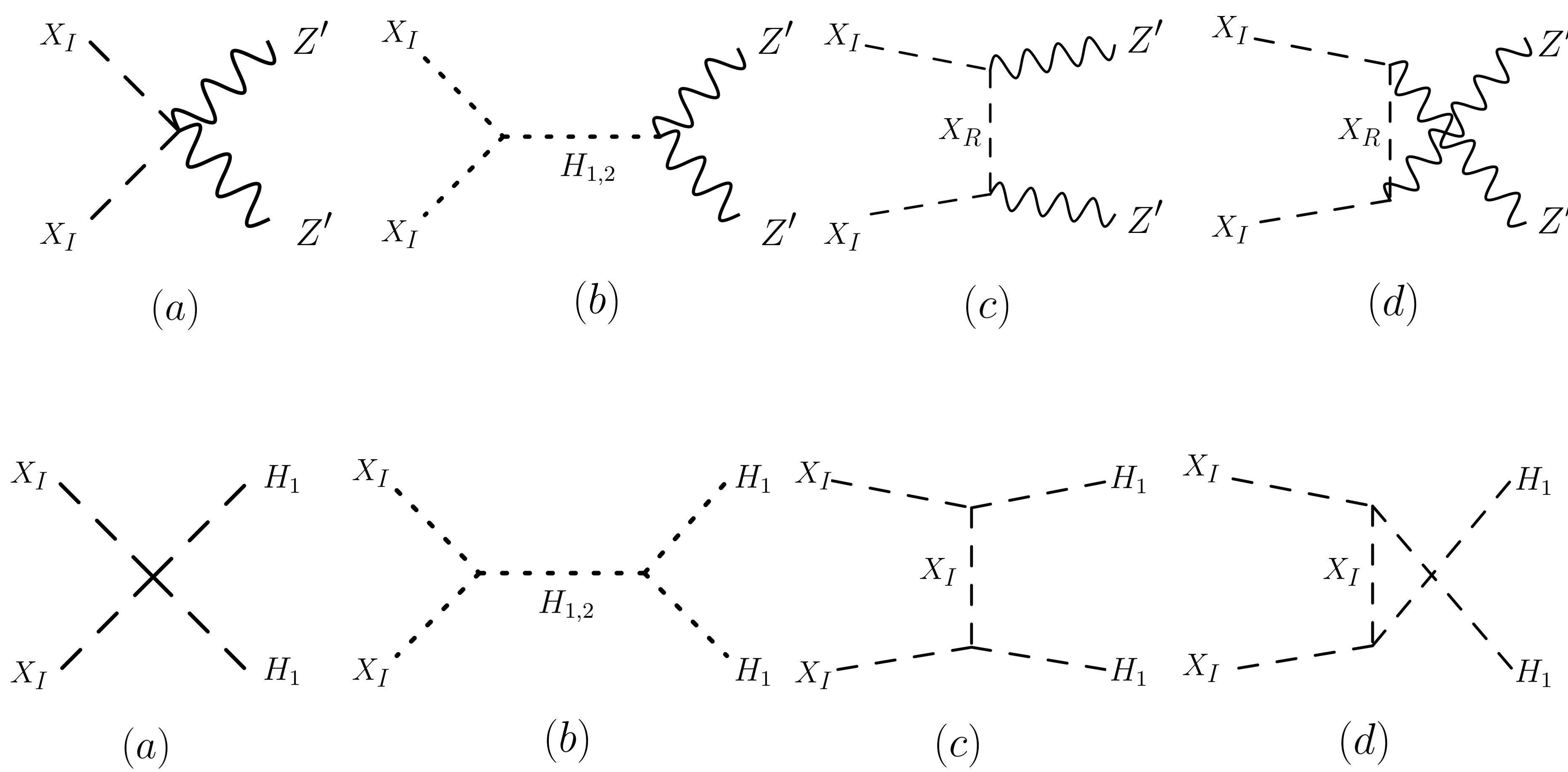


FIG. 8. (*Top*) Feynman diagrams for local Z_2 scalar DM annihilatiing to a pair of Z' bosons. (*Bottom*) Feynman diagrams for local Z_2 scalar DM annihilatiing to a pair of H_1 bosons, which is mostly dark Higgs-like.

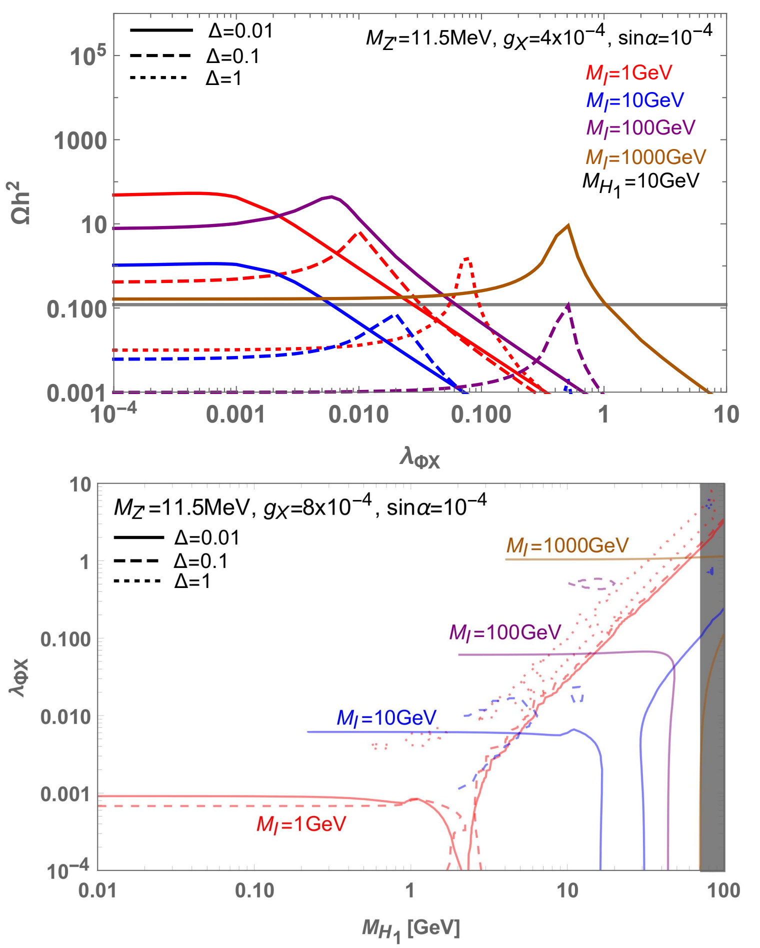


FIG. 4. *Top*: Relic abundance of local Z_2 scalar DM as functions of $\lambda_{\Phi X}$ for [**BPI**] and different values of mass splittings (Δ). We take $\lambda_{HX} = 0$, $M_{H_1} = 10\text{GeV}$, and $s_\alpha = 10^{-4}$. All the curves satisfy the DM direct detection bound. *Bottom*: The preferred parameter space in the $(M_{H_1}, \lambda_{\Phi X})$ plane for different values of Δ. The gray area is excluded by the perturbative condition.

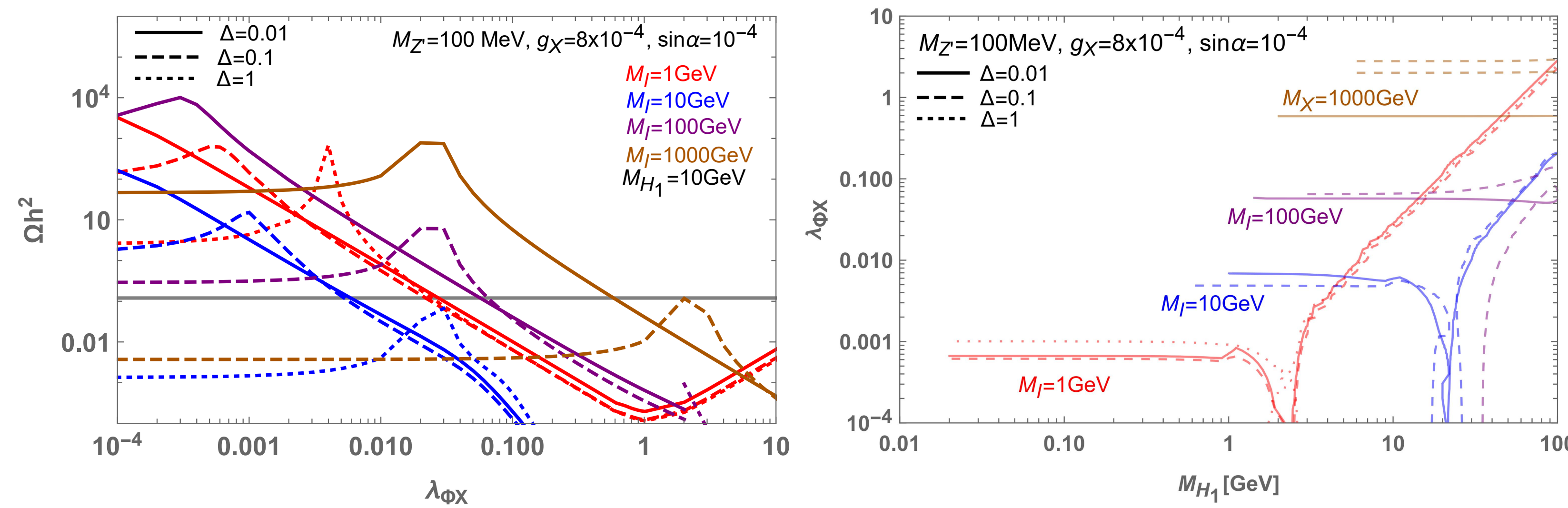


FIG. 9. (*Left*) Relic abundance of local Z_2 scalar DM in case of [**BPII**]. We take $\lambda_{HX} = 0$, $M_{H_1} = 10\text{GeV}$, and $s_\alpha = 10^{-4}$. All the lines satisfy the DM direct detection bound. (*Right*) Relic abundance of local Z_2 scalar DM in the $(M_{H_1}, \lambda_{\Phi X})$ plane.

DM mass : much wider range than $m_{Z'} \sim 2m_{\text{DM}}$
due to dark Higgs boson contributions

Dirac fermion DM: $U(1)_{L_\mu - L_\tau} \to Z_2 \; (Q_\Phi = 2Q_\chi)$

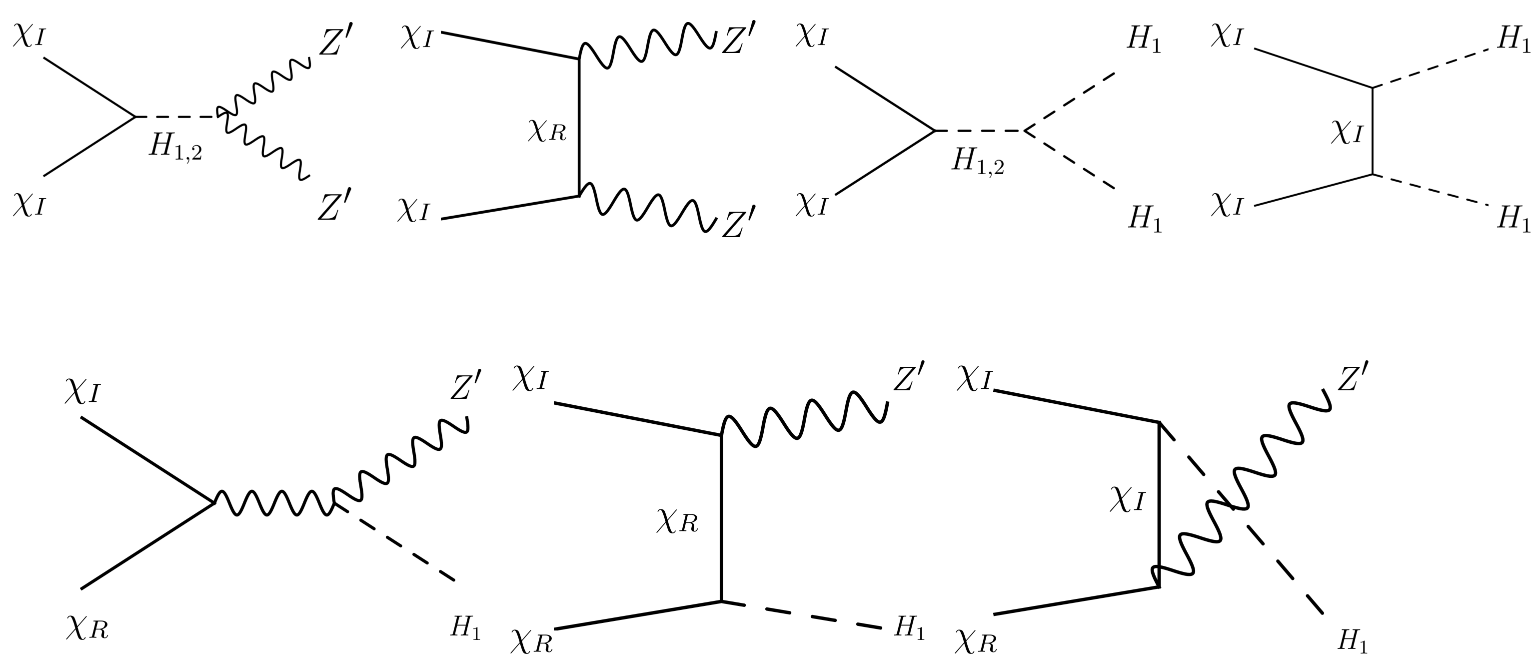


FIG. 5. Feynman diagrams of local Z_2 fermion DM (co-)annihilating into a pair of Z' bosons and H_1 bosons (*Top*), and $Z' + H_1$ (*Bottom*).

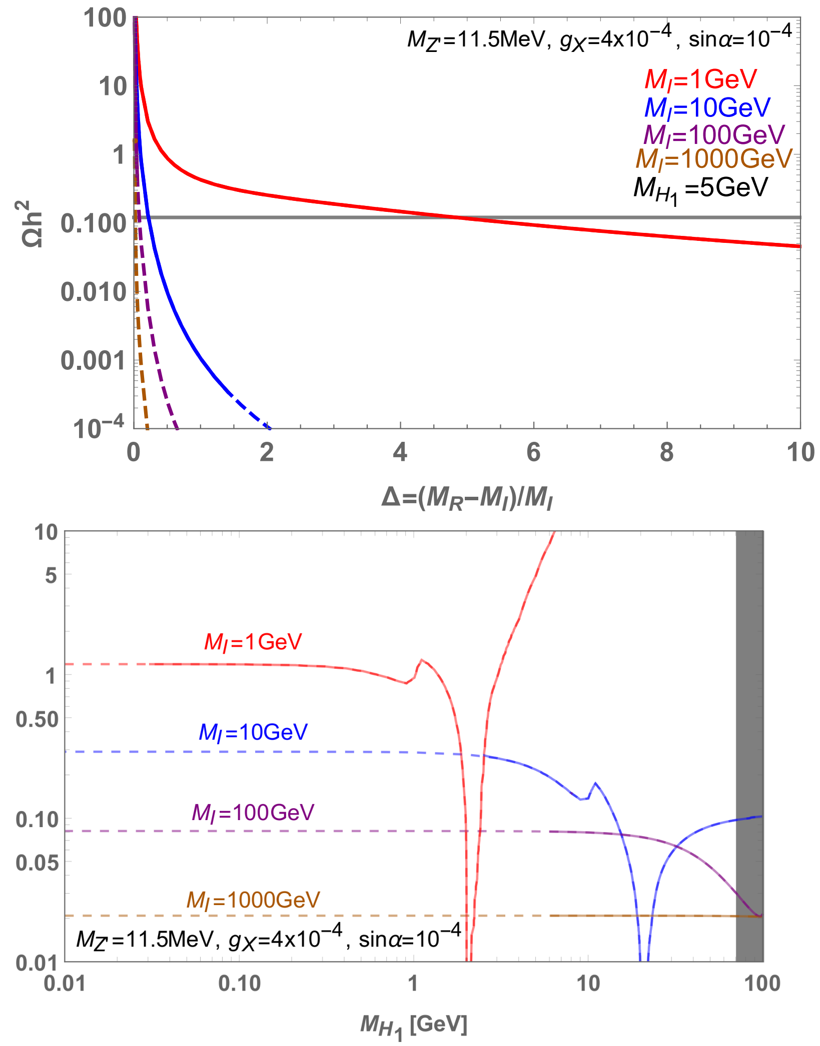


FIG. 6. *Top*: Dark matter relic density as functions of mass splitting Δ for [**BPI**] and for different values of DM mass, $M_I = 1, 10, 100, 1000$GeV. Solid (Dashed) lines denote the region where bounds on DM direct detection are satisfied (ruled out). *Bottom*: Preferred parameter space in the (M_{H_1}, Δ) plane for different DM masses. The gray region is ruled out by the perturbativity condition on λ_Φ.

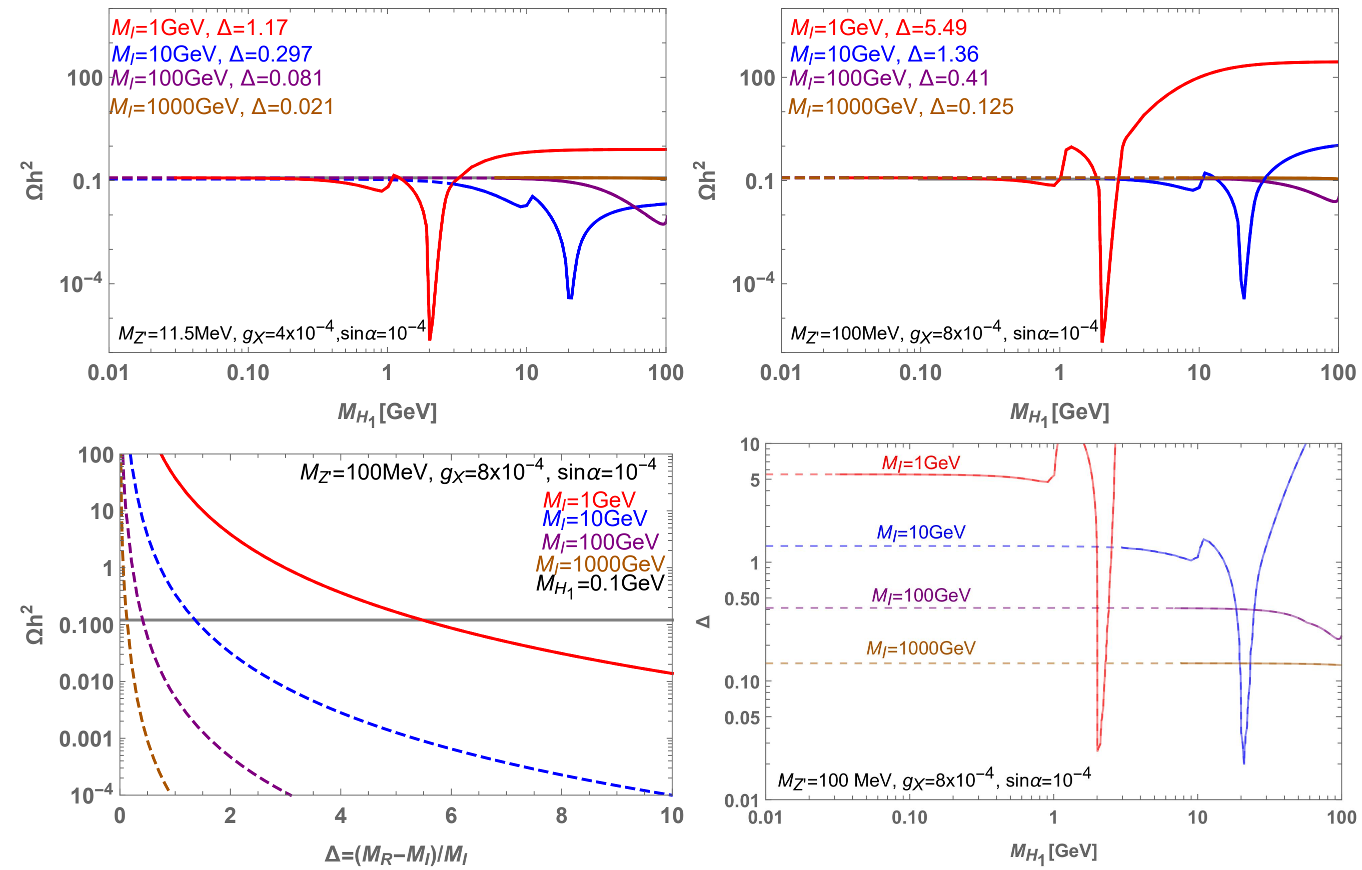


FIG. 11. (*Top*) Dark matter relic density as functions of dark Higgs mass M_{H_1} for [**BPI**] (*Left*) and [**BPII**] (*Right*) (*Bottom-Left*) Dark matter relic density as functions of Δ for [**BPII**], and *(Bottom-right)* Preferred parameter region in the (Δ, M_{H_1}) plane. Solid (Dashed) lines denote the region where bounds on DM direct detection are satisfied (ruled out).

DM mass : much wider range than $m_{Z'} \sim 2m_{\rm DM}$ due to dark Higgs boson contributions

Conclusion

- DM physics with massive dark photon can not be complete without including dark gauge symmetry breaking mechanism, e.g. dark Higgs field ϕ, which have been largely ignored by DM community (or some ways other than dark Higgs to provide dark photon mass)

- Many examples show the importance of ϕ in DM phenomenology, astroparticle physics and cosmology

- Once ϕ is included, can accommodate the muon g-2 and thermal DM without the s-channel resonance condition $m_{Z'} \sim 2m_{\rm DM}$

- $m_{\rm DM}$: essentially free, whereas $m_{Z'} \sim O(10-100)$ MeV and $g_X \sim O(10^{-4})$ can explain the muon (g-2)

Conclusion

- If there is massive vector boson, one has to specify (i) the origin of its mass, (ii) anomaly cancellation, and (iii) check if one can write down Yukawa interactions for the SM fermions, before delving into phenomenology.
- Otherwise results can be misleading/wrong.
- If you consider MVB in Proca or Stueckelberg, there could be a lower bound on m_V , unless it couples to a conserved current