Personal Viewpoints on the future direction of HEP

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Round Table Workshop on
“Exploring the future direction of HEP”

Feb 26-28 (2023)

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

- Neutrino masses/mixings
- Baryogenesis
- Nonbaryonic DM
- Inflation
- Quantum gravity
- ……

- Hierarchy problems (Λ , m_H^2)
- Various fine tuning problems
- Unification of all known forces
- Electric charge quantization
- Flavor problems
- ……

Key Questions

- What CM Energy ($\sqrt{s}$) for future colliders, and $\mathscr{L}$?
- Which questions can we address with such a machine ?
- Or vice versa

- Our stance on astro (particle) physics and cosmology ?
- Can we attract young people and create enough jobs (especially permanent positions) ?

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
  - Both of them 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, $W_L W_L \to W_L W_L$ 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 favorites

- So far, all the observed fermions are charged under some gauge symmetries, and chiral
- All the matters are fundamental representations of the gauge group. No higher dim rep.'s have been found yet
- Dark photon, dark Higgs (~singlet scalar) if DM mass ~ EW scale
- Vectorlike fermions which are chiral under new gauge sym
- New confining (dark) forces

Personal Viewpoints

- Higher energy colliders can produce heavier particles and probe shorter distance : $E = Mc^2$, $\Delta x \Delta p \gtrsim \hbar$
- No rigorous arguments to set new energy scales, unlike before the Higgs boson discovery
- Unexplored territory of the SM : Nonperturbative aspects such as QCD instanton, EW sphaleron
- Can we set a new energy scale for pp colliders so that we can measure the Higgs aquatic coupling within certain accuracy ?

- Model independent approach based on SMEFT ? However it could be misleading if used for high energy colliders

- Many UV completions for a given EFT operator in general

- Model dependent approaches motivated by the current anomalies, such as muon g-2, RK(*), RD(*), neutrino masses and mixings, dark matter, etc.

- Some interesting channels: DY + missing ET, Multi leptons (+ missing ET), $t\bar{t}$ + missing ET, etc.

- In any case, search for New Physics without any theoretical prejudice is most important (SUSY, MSW with the large mixing for the solar neutrino problem, etc.)

Definition of HEP ?

- Conventional particle physics (cosmic rays) [Based on QFT (+formal field theory, string theory ?)]

- Astroparticle physics, Cosmology, (Quantum) Gravity

- Data Science (ML, DL)

- Quantum Computing

- Snowmass Reports

High Energy (Particle) Physics $\rightarrow$ Fundamental Physics ?

- 3 known forces + gravity ?
- Nature of DM, DE ?
- Gravity : GR + …. ?
- New observational data: H_0 , σ_8 , $\Delta N_{\rm eff}$ (DM-DR interaction)
- Theoretical tools : various EFT's (ChPT, NRQCD, HQET, HQE, SCET, SMEFT, HEFT, EFT for inflation and LSS, etc.) and SUSY/SUGRA for more theory oriented minds

Some recollections

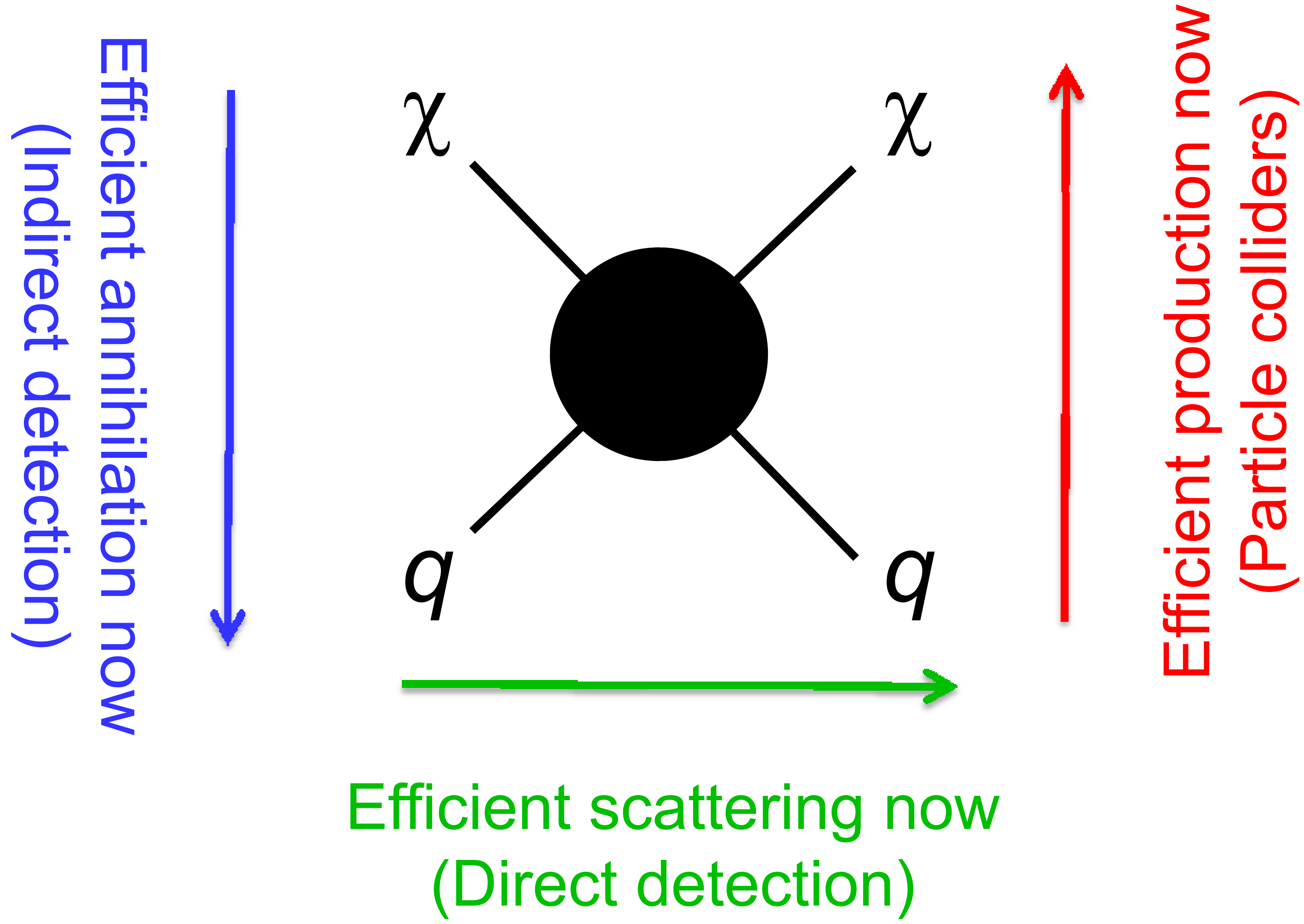
- $B \to J/\psi\pi\pi$ for D-wave charmonium $\to X(3872)$ (1997)
- $U(1)_{\mu-\tau}$ for the muon $(g-2)$ (2001) and PAMELA e^+ excess (2009) , and the muon (g-2) and WIMP DM
- Invisible Higgs decay into DM pair in the hidden valley scenario (2007, 2011)
- Double heavy quarkonia productions @ LHC (2010)
- Higgs invisible decay in Higgs portal DM (2007,2011,2014)
- SM Higgs + singlet scalar (2013) (w/ Suyong Choi, Sunghoon Jung)
- Beyond EFT/Simplified Model for DM @LHC (2015) (w/ MH Park et al.)
- $t-$channel mediated DM search at colliders (2017) (w/ MH Park et al.)
- $R(D^{(*)})$ and top FCNC in LQ models (2018) (w/ Tae Jeong Kim et al.)

Search for WIMP

- Direct Detections
- Indirect Detections (Current Universe, Early Universe)
- Collider Searches
- Quantum Force and search for the 5th force
- DM EFT/Simplified model : Not good for collider searches
  $\longrightarrow$ Dark Higgs is important !
- Theoretical consistency (unitarity, gauge invariance, renornalizabiyity) important for DM model buildings

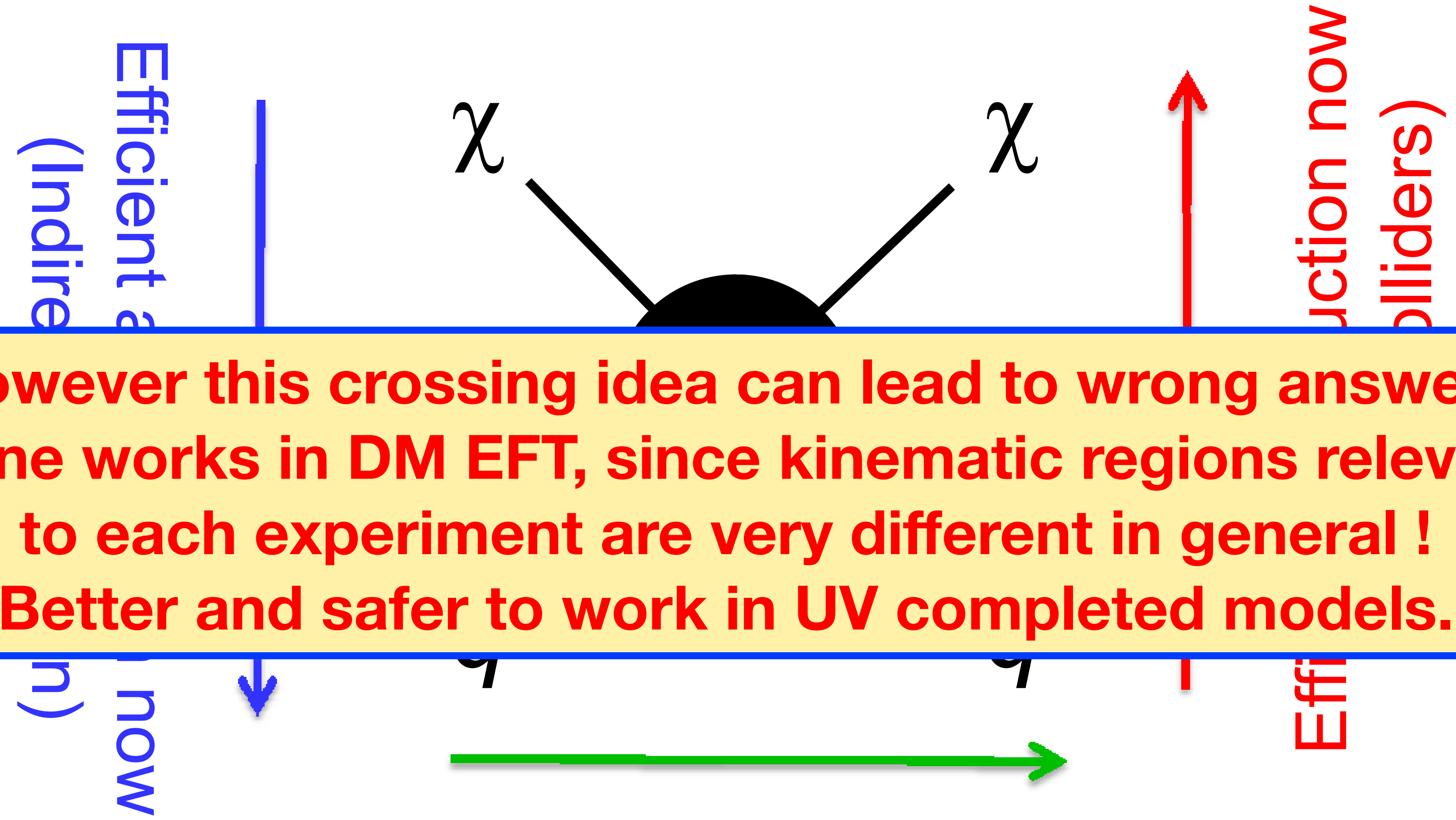
Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Crossing & WIMP detection

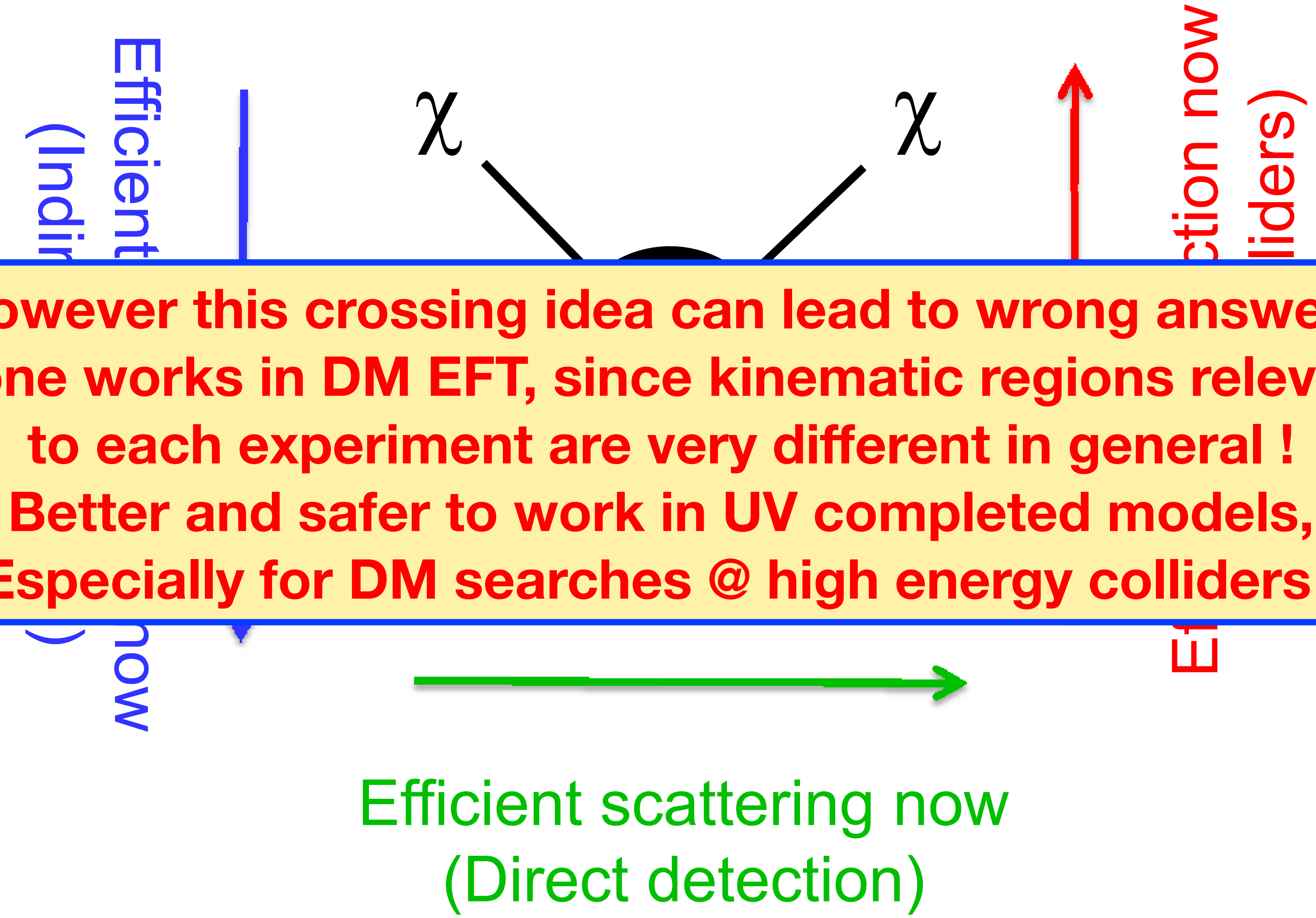
Correct relic density → Efficient annihilation then



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.

Efficient scattering now
(Direct detection)

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 !

Limitation and Proposal

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

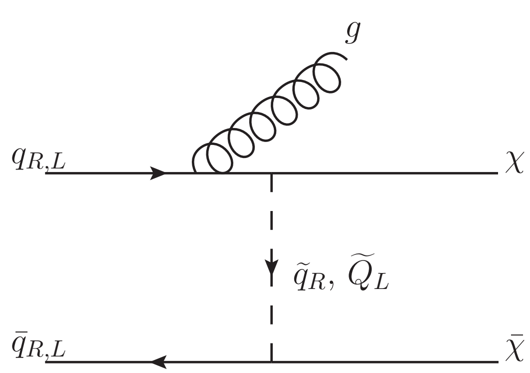
$$\frac{1}{\Lambda_i^2}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi \rightarrow \frac{g_q g_\chi}{m_\phi^2 - s}\ \bar{q}\Gamma_i q\ \bar{\chi}\Gamma_i\chi$$

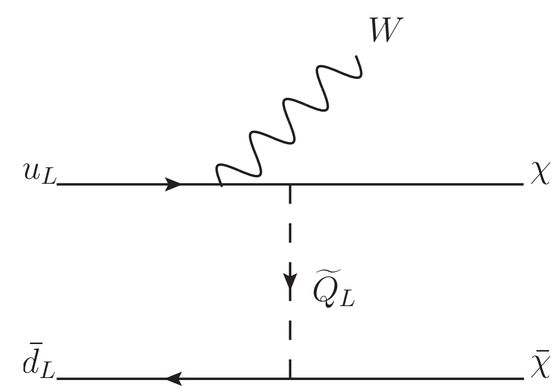
- Usually effective operator is replaced by a single propagator in simplified DM models
- This is not good enough, since we have to respect the full SM gauge symmetry (Bell et al for W+missing ET)
- In general we need two propagators, not one propagator, because there are two independent chiral fermions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

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

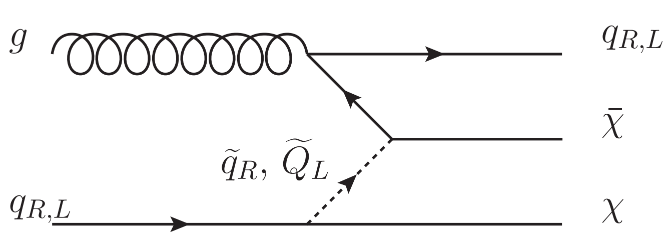
for t-channel mediator (w/ MH Park et al)

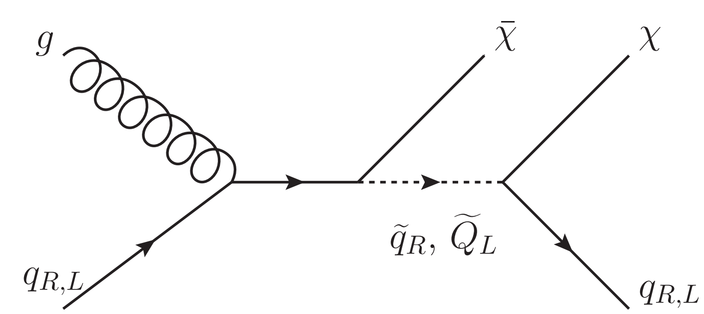
Our Model: a 'simplified model' of colored t-channel, spin-0, mediators which produce various mono-x + missing energy signatures (mono-Jet, mono-W, mono-Z, etc.):





W+missing ET : special





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

- This is good only for W+missing ET, and not for other singatures
- The same is also true for (scalar)x(scalar) operator, and lots of confusion on this operator in literature
- See a series of my works on this issue

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

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

Both break SM gauge

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

Therefore these Lagragians are not good enough

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

Need the mixing between s and h

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.

And Revived recent papers

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**

Interaction Lagrangians

Scalar DM

$$\mathcal{L}^{\rm int}_{\rm SDM} = -h\,\left(\frac{2m_W^2}{v_h}W^+_\mu W^{-\mu} + \frac{m_Z^2}{v_h}Z_\mu Z^\mu\right) - \lambda_{HS} v_h\; hS^2.$$

Singlet FDM

$$\mathcal{L}^{\rm int}_{\rm FDM} = -\left(H_1\cos\alpha + H_2\sin\alpha\right)\left(\sum_f \frac{m_f}{v_h}\bar{f}f - \frac{2m_W^2}{v_h}W^+_\mu W^{-\mu} - \frac{m_Z^2}{v_h}Z_\mu Z^\mu\right)$$
$$+\, g_\chi\left(H_1\sin\alpha - H_2\cos\alpha\right)\;\bar{\chi}\chi\;.$$

Vector DM

$$\mathcal{L}^{\rm int}_{\rm VDM} = -\left(H_1\cos\alpha + H_2\sin\alpha\right)\left(\sum_f \frac{m_f}{v_h}\bar{f}f - \frac{2m_W^2}{v_h}W^+_\mu W^{-\mu} - \frac{m_Z^2}{v_h}Z_\mu Z^\mu\right)$$
$$-\,\frac{1}{2}g_V m_V\left(H_1\sin\alpha - H_2\cos\alpha\right)\;V_\mu V^\mu\;.$$

NB: One can not simply ignore 125 GeV Higgs Boson or singlet scalar by hand, since it would violate gauge invariance and unitarity !

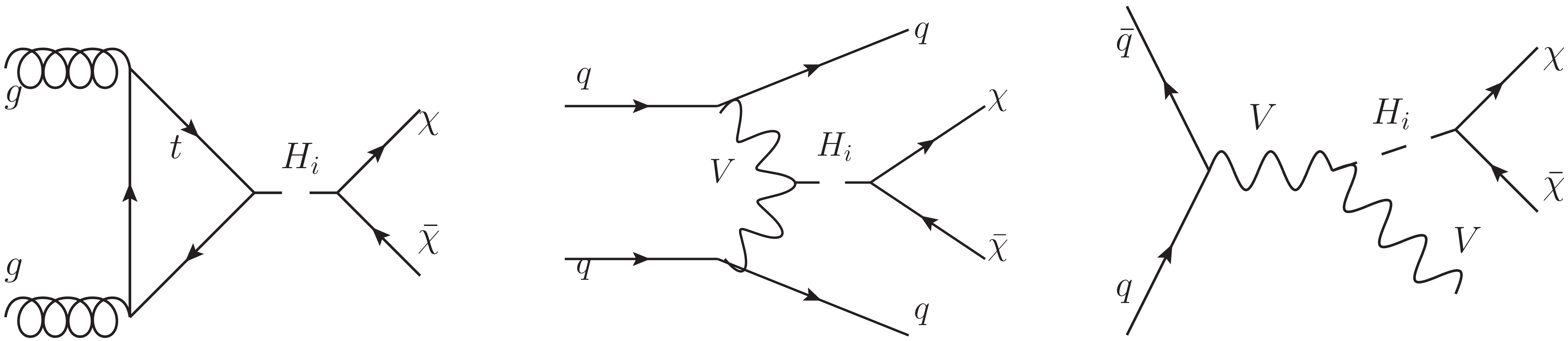


Figure 1: The dominant DM production processes at LHC.

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

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

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

S. Baek, P. Ko, M. Park, WIPark, C.Yu, arXiv:1506.06556, PLB (2016)

- 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).

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

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

$$\text{S.M.} \underset{m_S^2 \gg \hat{s}}{\longrightarrow} \text{EFT},$$

$$\text{H.M.} \neq \text{EFT}\,.$$

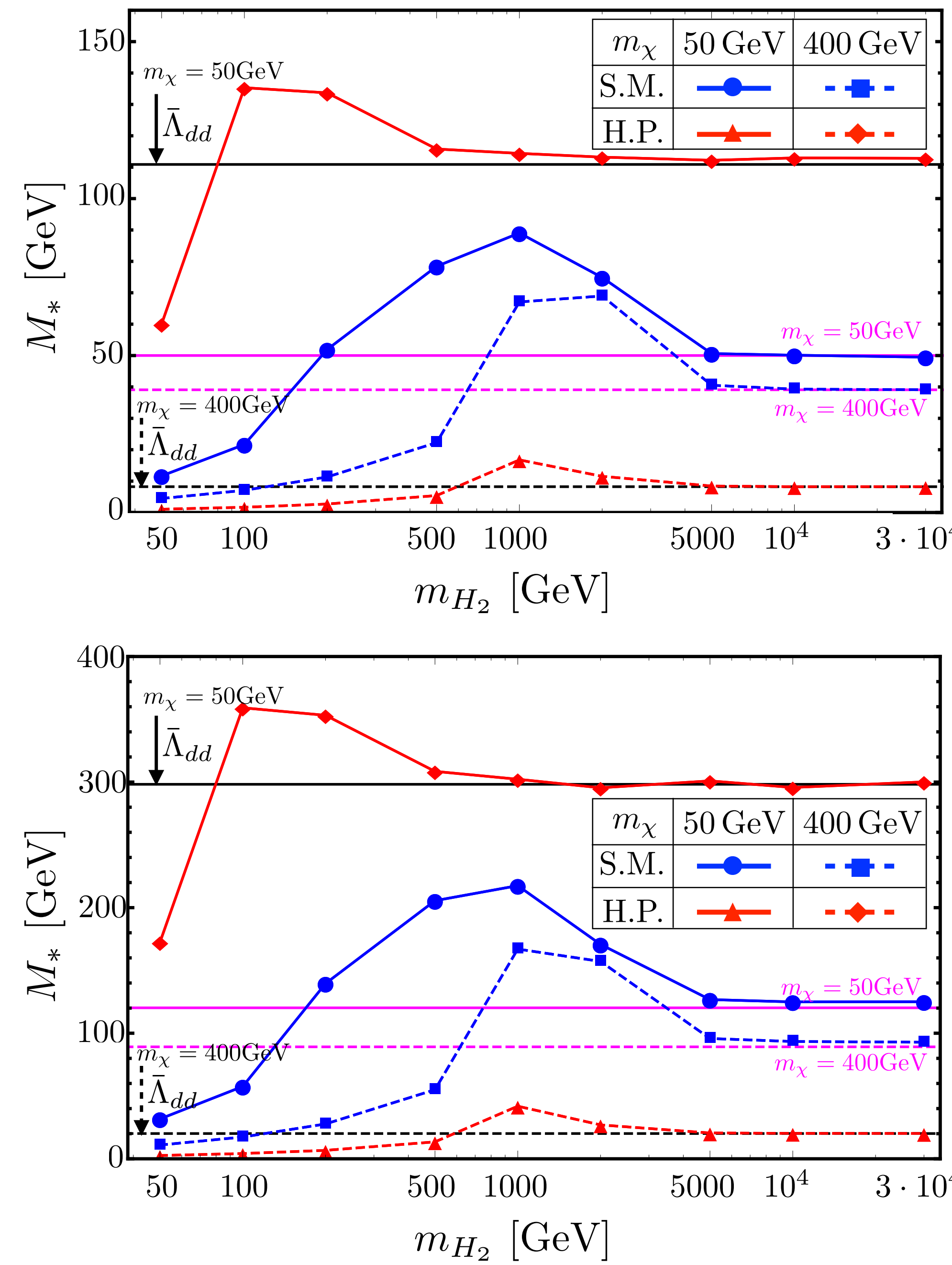
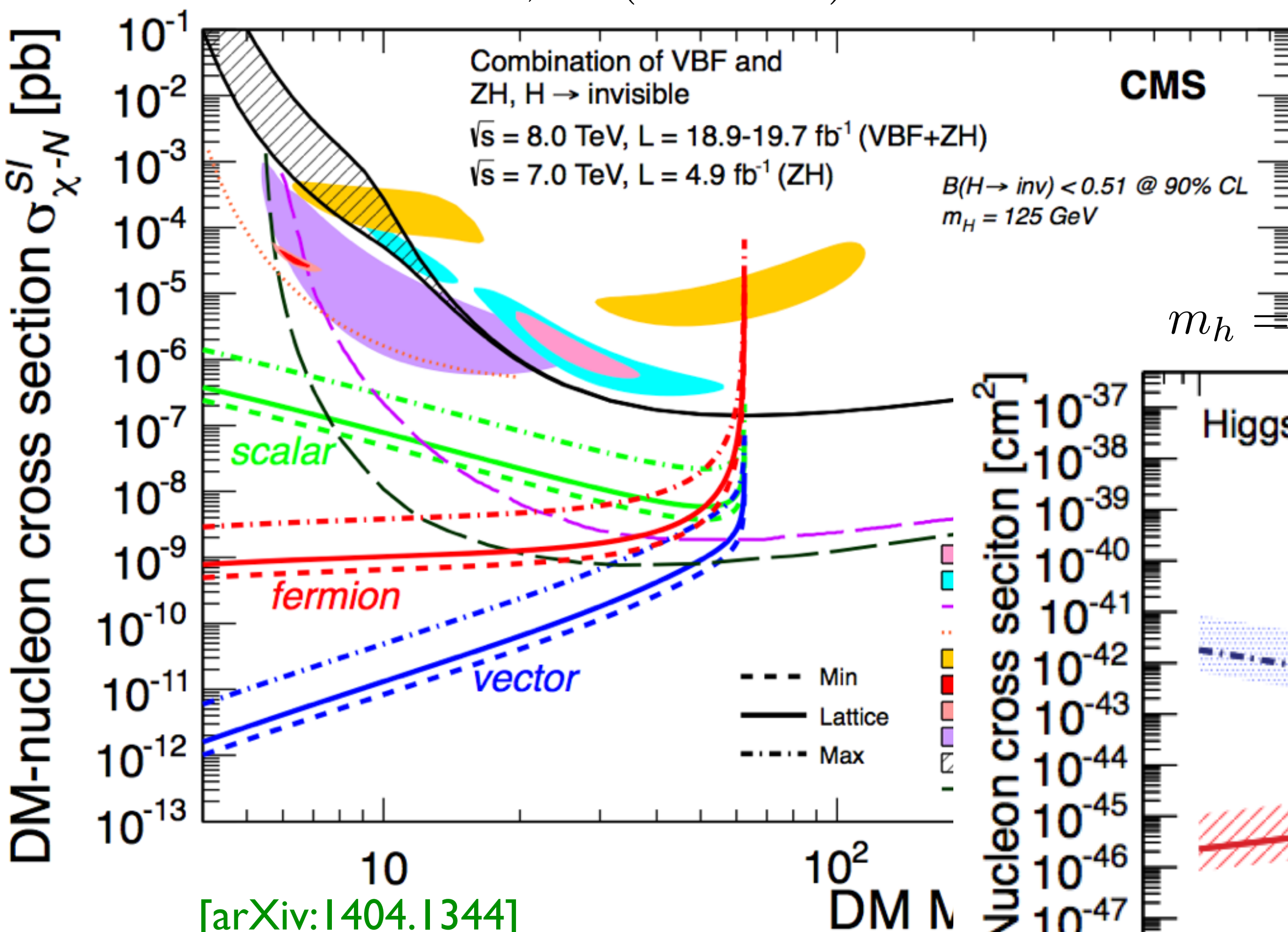


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t} + \not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of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

Collider Implications

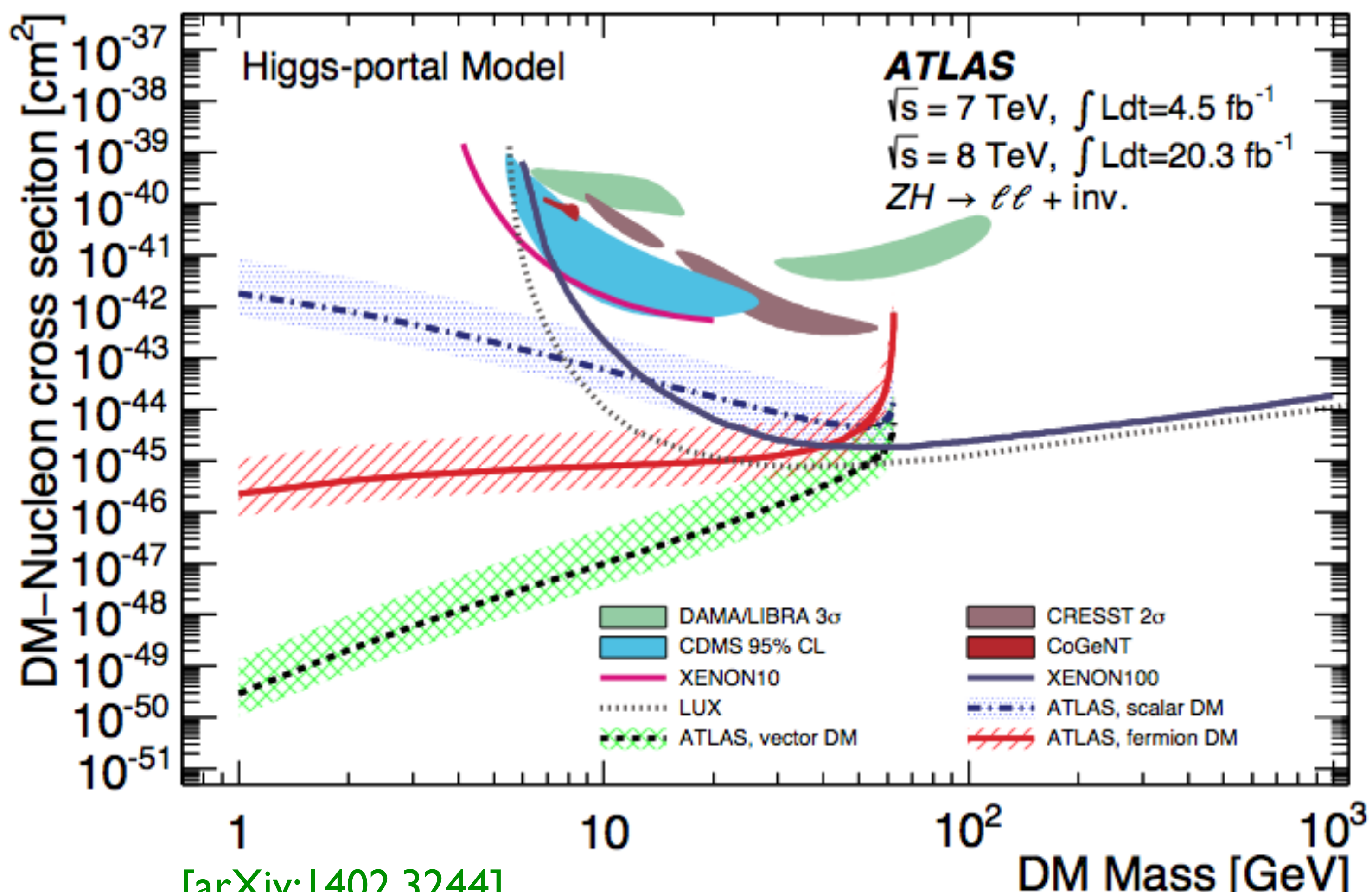
$m_h = 125\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.51 \text{ at } 90\%\text{ CL}$



[arXiv:1404.1344]

Based on EFTs

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



[arXiv:1402.3244]

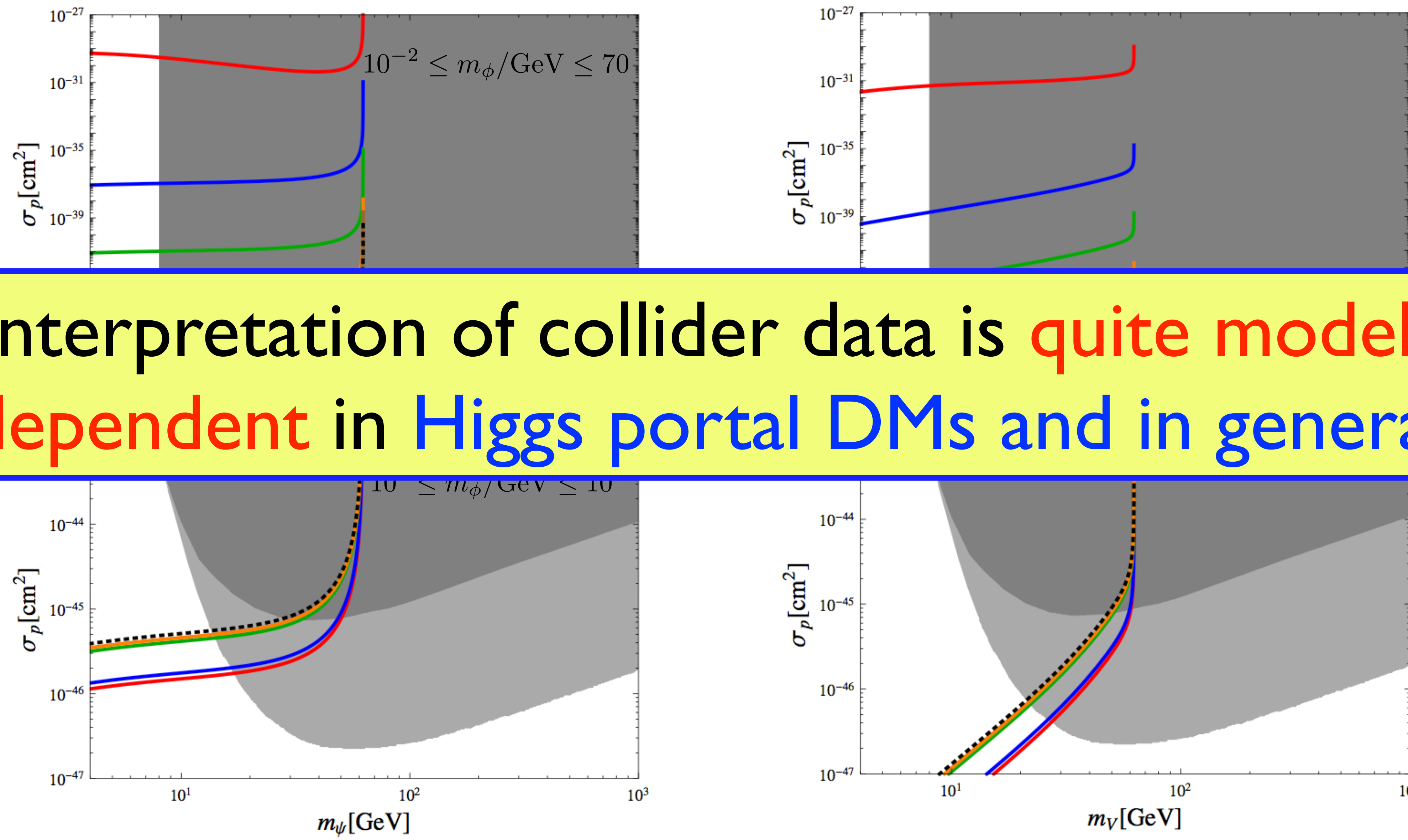
- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters !

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

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

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

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



Dashed curve
ATLAS,CMS

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

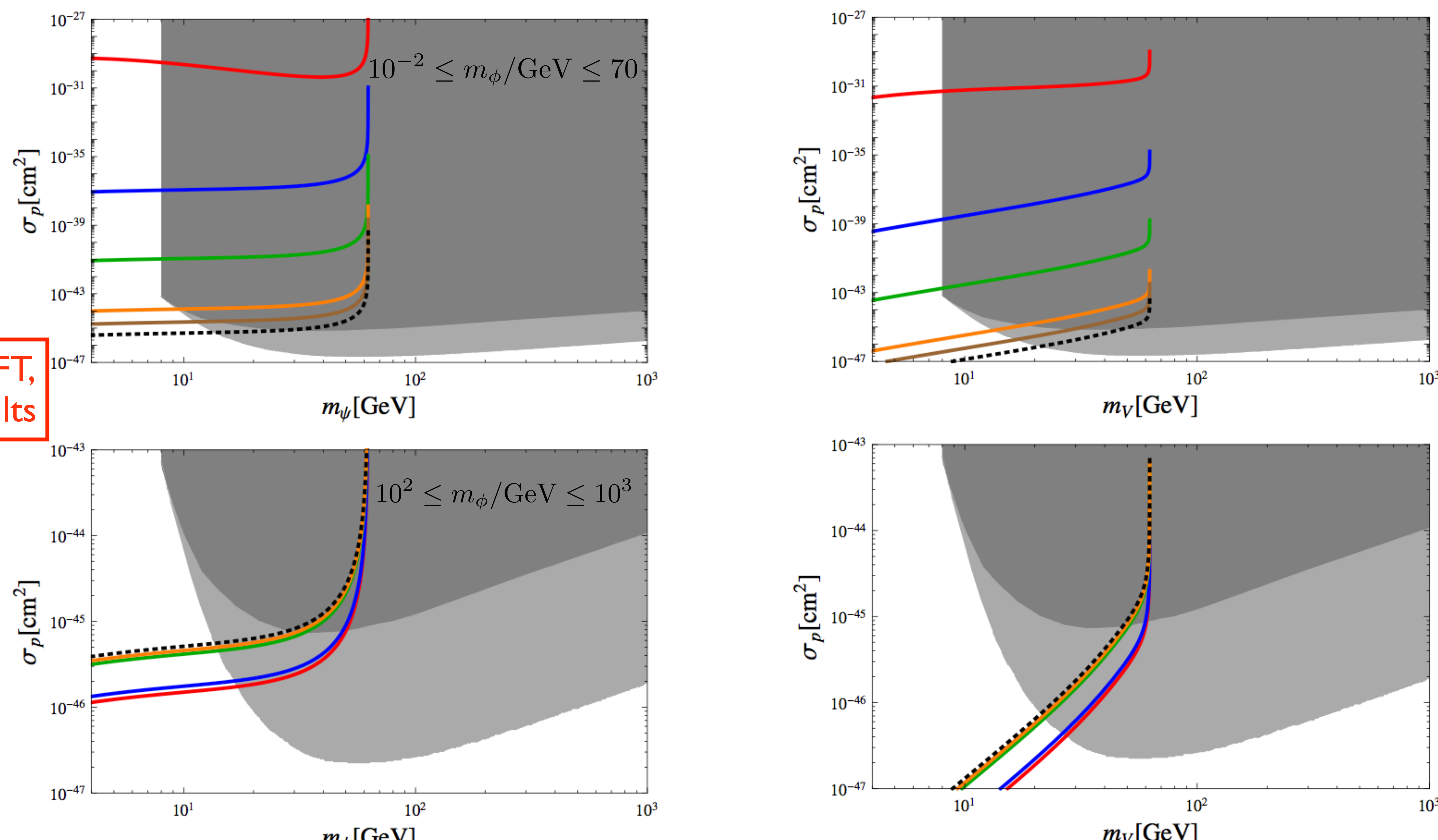
- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters !

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

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

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

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

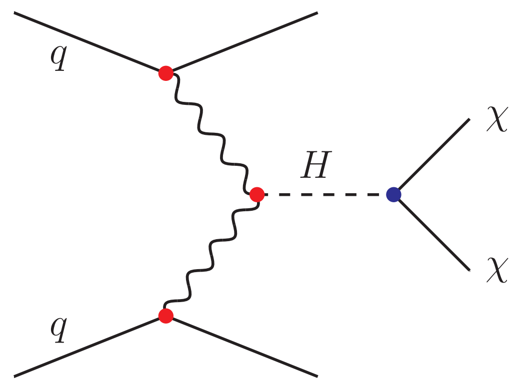


Dashed curves:EFT, ATLAS,CMS results

Search for H→ Dark matter (invisible)

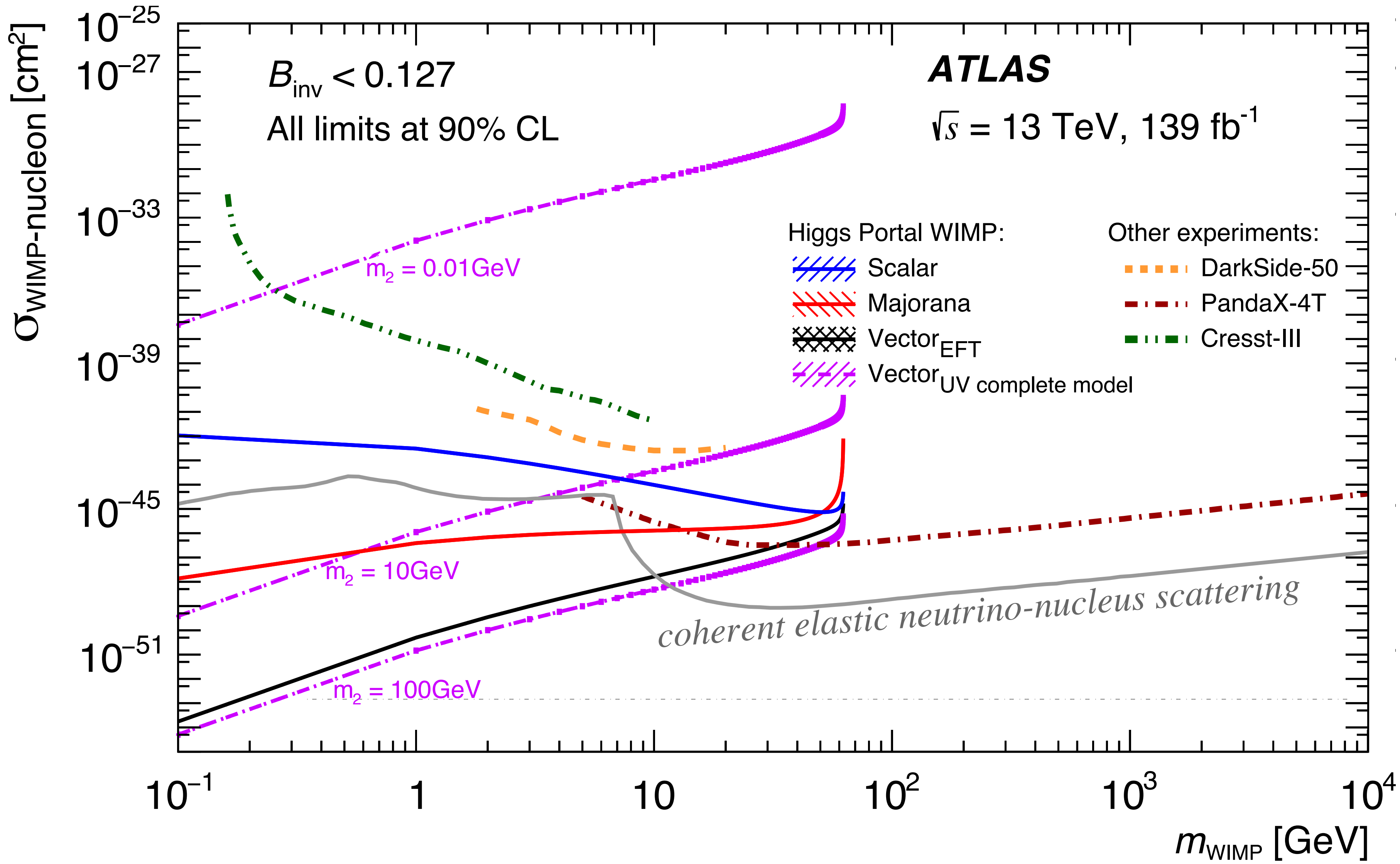
BR(H→invisible) < 14.5% (obs)   (10.3% exp.)
from search with VBF topology
(13% limit when combined with Higgs coupling measurements)

ATLAS Highlight talks
By G.Unal @ICHEP2022, and
By M. Cristinziani @ CORFU2022



Now implemented in the ATLAS results,
But only for VDM, and not for SFDM

arXiv:2202.07953



Invisible H decay into a pair of VDM

[arXiv: 1405.3530, 2112.11983, S. Baek, P. Ko & WIPark, PRD]

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

Diverge when $m_V \to 0$!!

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

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

VS.

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

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

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 $v_\Phi \neq 0$

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

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

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

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

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

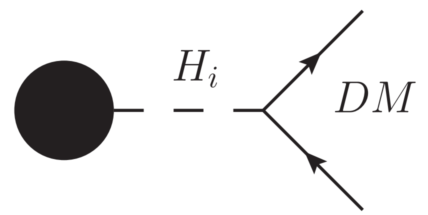
$$\frac{g_X^2 Q_\Phi^2}{m_V^2} \sin^2\alpha \xrightarrow{v_\Phi \to 0^+} \frac{4\lambda_{H\Phi}^2}{\lambda_H^2 v_H^2} = \frac{2\lambda_{H\Phi}^2}{\lambda_H m_h^2} = \text{finite,}$$

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

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

DM Production @ ILC

P Ko, H Yokoya, arXiv:1603.08802, JHEP



,

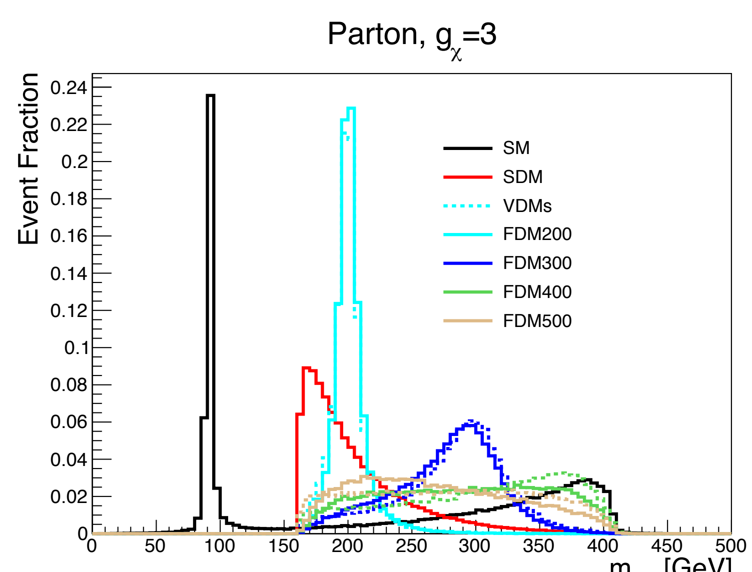
$$t \equiv m_{DD}^2$$

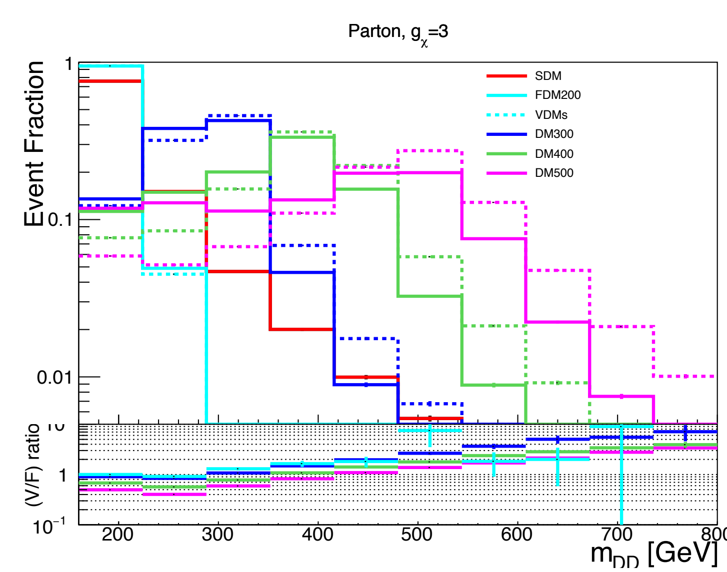
We consider $e^+e^- \to Z^* \to ZH_{i=1,2}$ followed by $H_i \to \bar{\chi}\chi$

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

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

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





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

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

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

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

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

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

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

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

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

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

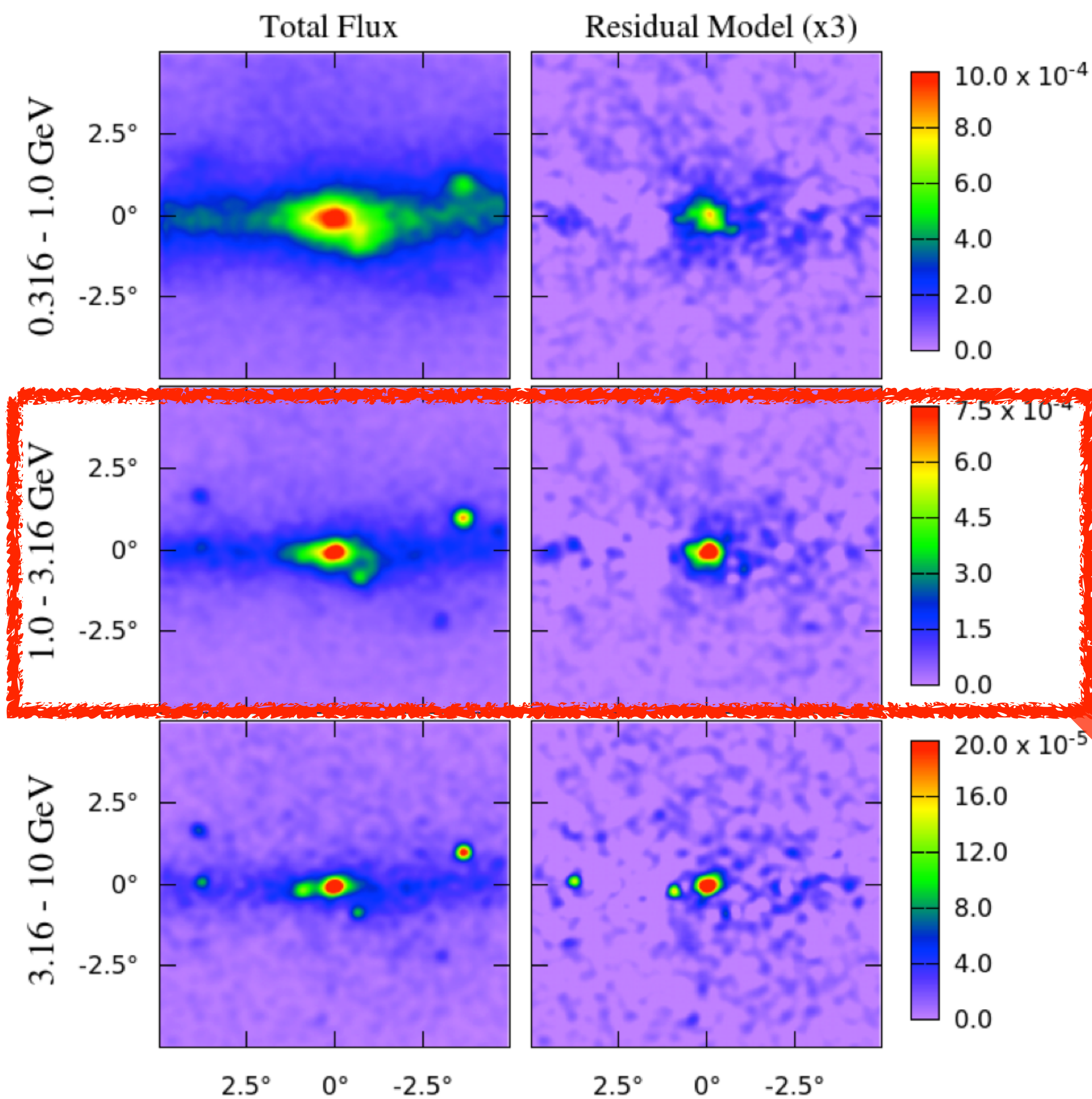
$$\text{VDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \left[2 + \frac{(t-2m_V^2)^2}{4m_V^4}\right]$$

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

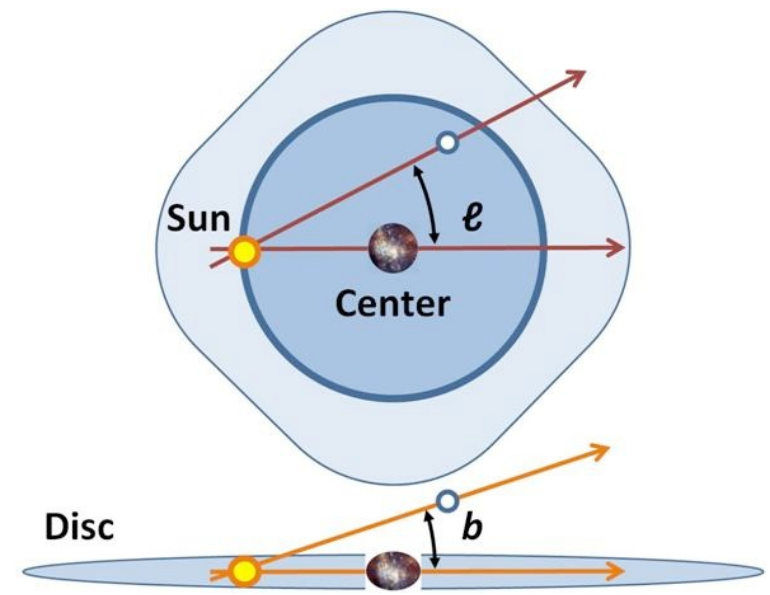
Unitarity is violated in EFT!

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



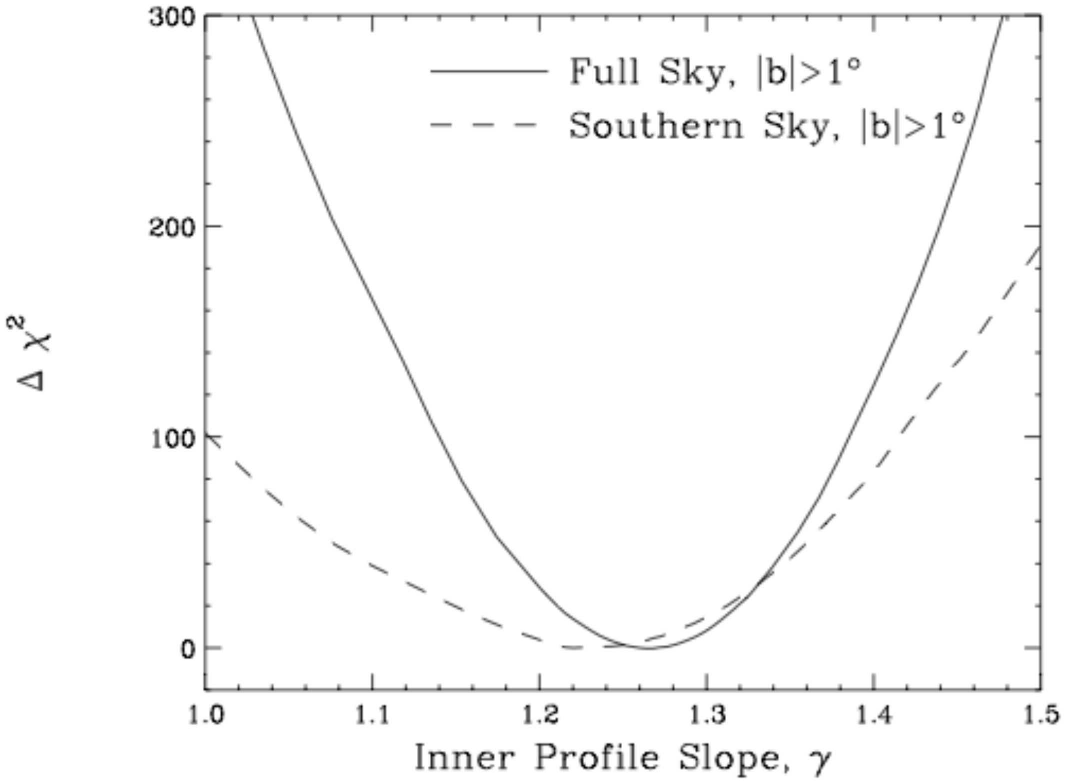
[1402.6703, T. Daylan et.al.]



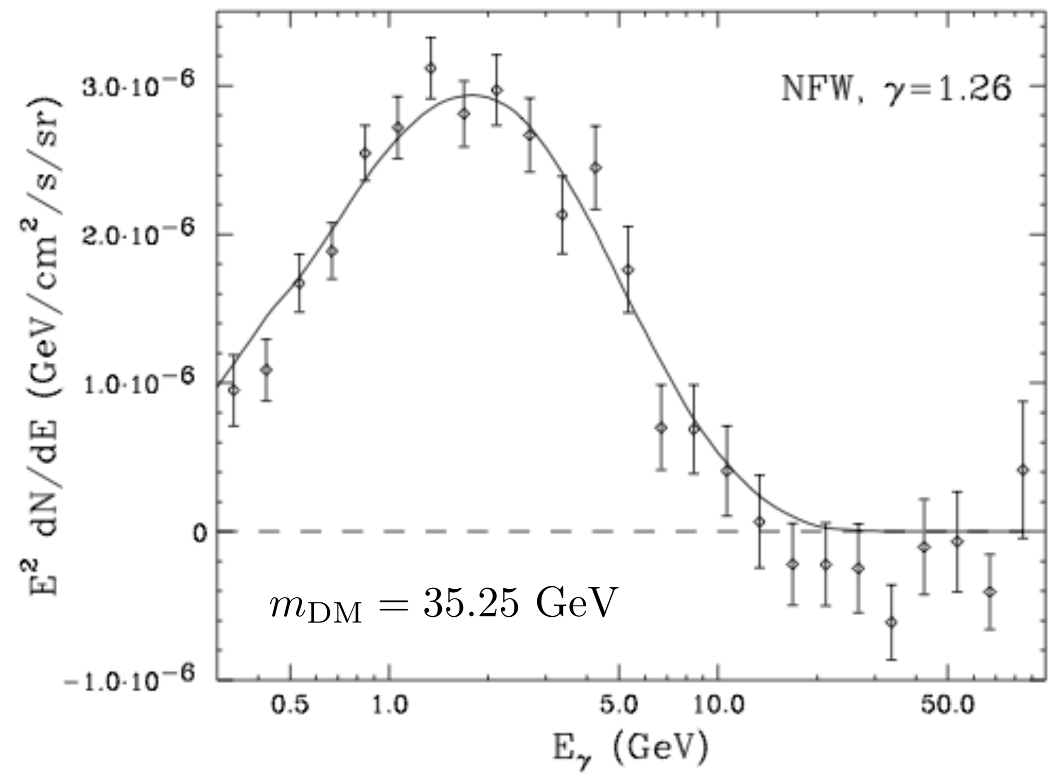
$$\mathrm{GC} : b \sim l \lesssim 0.1^\circ$$

extended
GeV scale excess!

• A DM interpretation



$\mathrm{DM} + \mathrm{DM} \rightarrow b\bar{b}$ with $\sigma v = 1.7 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$



* 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

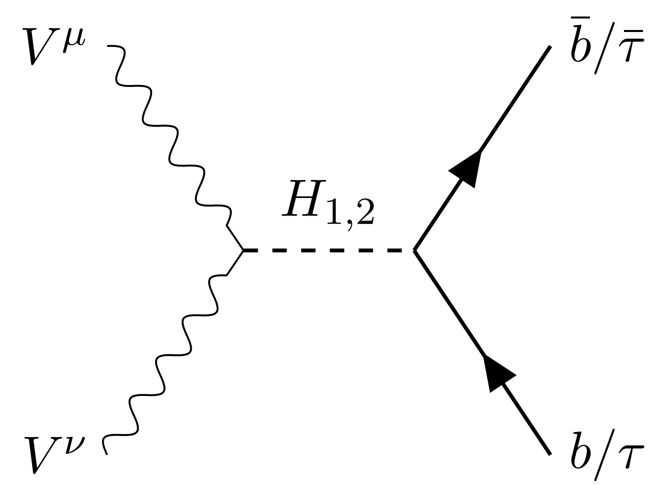


Figure 2. Dominant s channel $b + \bar{b}$ (and $\tau + \bar{\tau}$) production

H2 : 125 GeV Higgs
H1 : absent in EFT

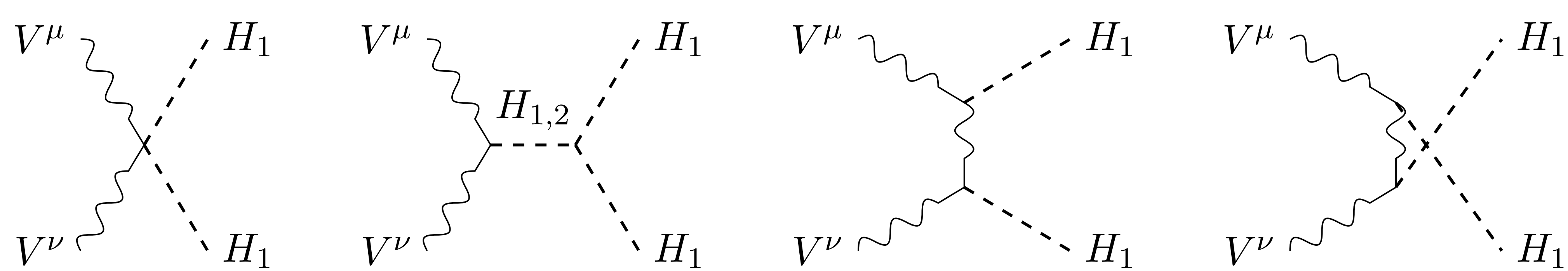


Figure 3. Dominant s/t-channel production of H_1s that decay dominantly to $b + \bar{b}$

Importance of HP VDM with Dark Higgs Boson

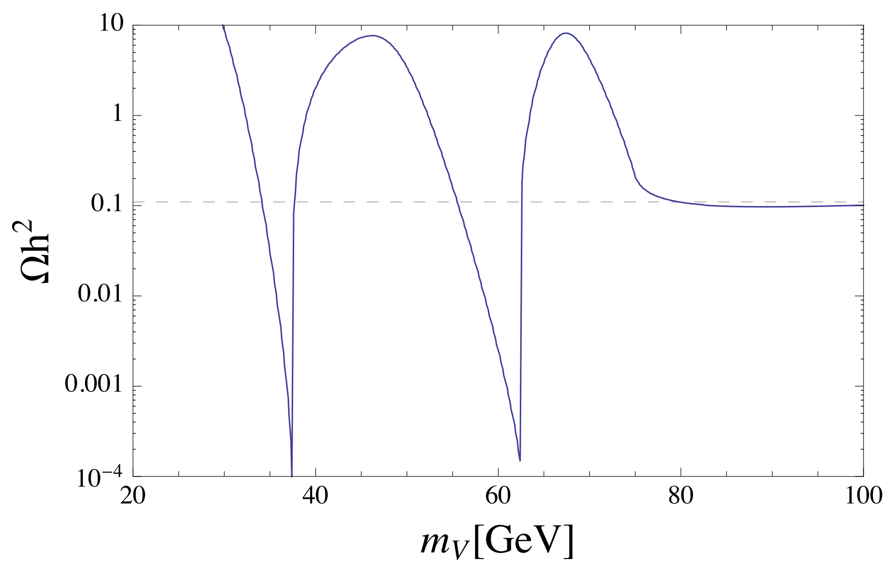


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75\,\text{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

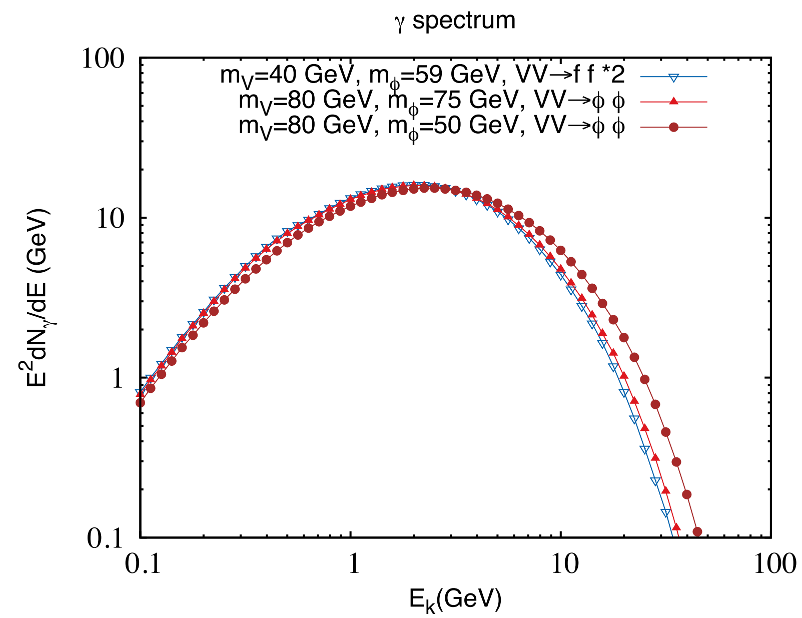
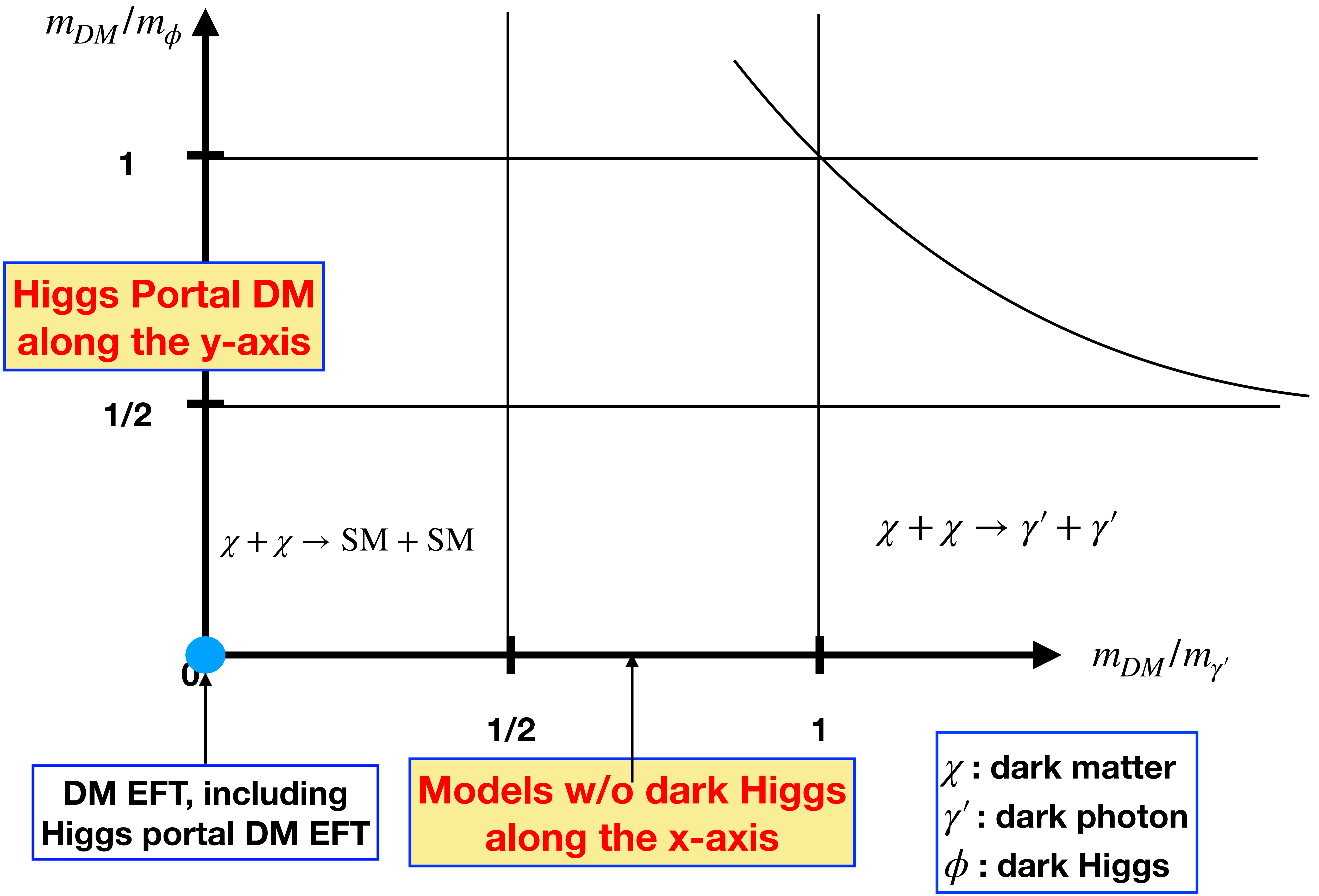


Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

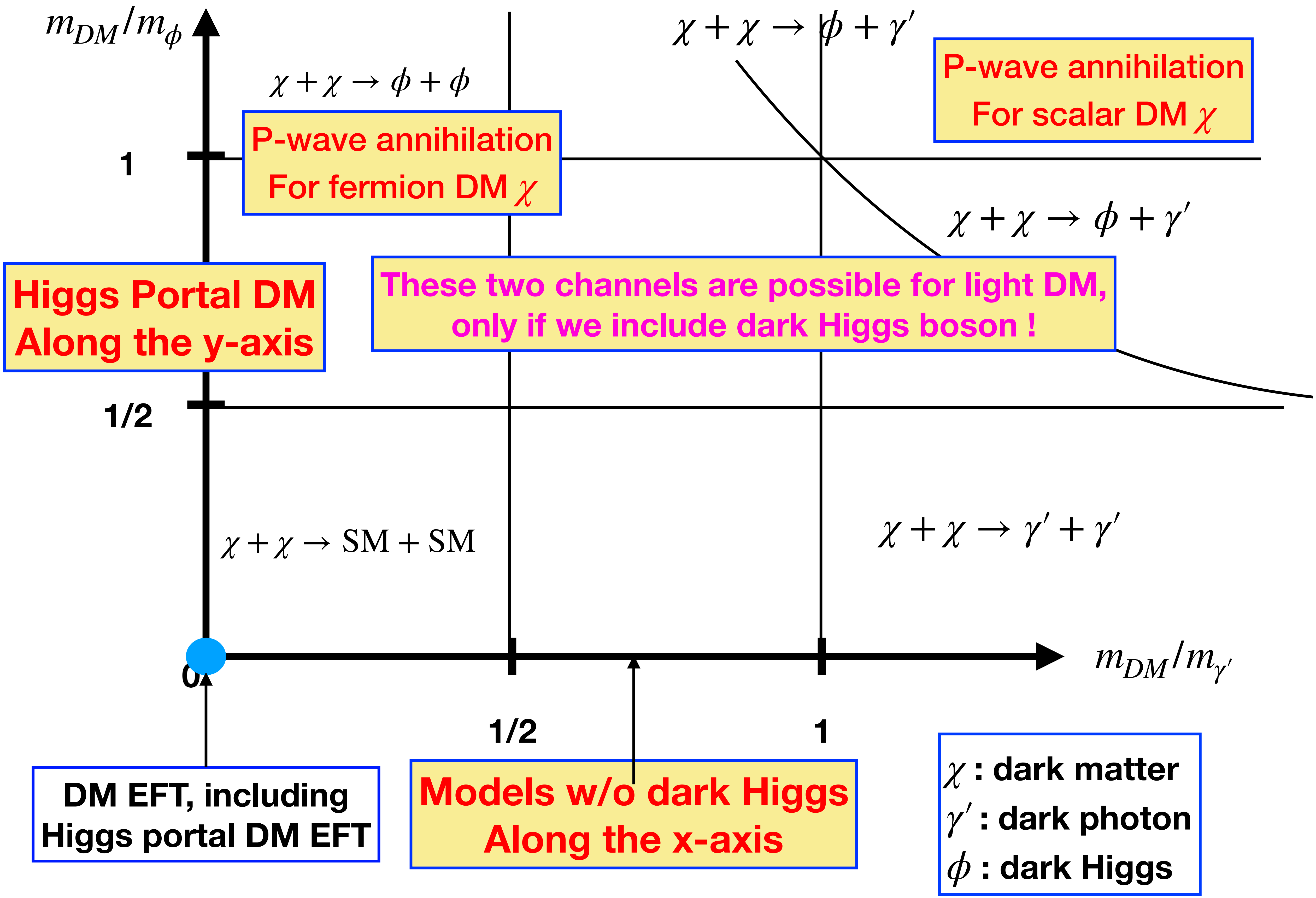
This mass range of VDM would have been impossible in the VDM model (EFT)

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

Dark sector parameter space for a fixed m_{DM}



Dark sector parameter space for a fixed m_{DM}



Top-philic Scalar DM

(W/ Seungwon Baek, Pei-wen Wu, 1606.00072,1709.00697)

- Null results from DM direct detection experiments could be due to the top-philic (or heavy-quark-phiilc) nature of DM
- Consider top-philic real scalar DM with RH vectorlike top partner
- Signature: $t\bar{t}$+missing E_T . One can recast the stop searches

Model Lagrangian

$$\begin{aligned}
\mathcal{L}_{\rm new} &= \mathcal{L}_{\rm fermion} + \mathcal{L}_{\rm scalar} + \mathcal{L}_{\rm Yukawa}, \\
\mathcal{L}_{\rm fermion} &= \bar{\psi}(i\not{D} - m_\psi)\psi, \\
\mathcal{L}_{\rm scalar} &= \frac{1}{2}\partial^\mu S \partial_\mu S - \frac{1}{2}m_S^2 S^2 - \frac{1}{4!}\lambda_S S^4 - \frac{1}{2}\lambda_{SH} S^2 H^2, \\
\mathcal{L}_{\rm Yukawa} &= -y_1 S\overline{\psi_L} u_R - y_2 S\overline{\psi_L} c_R - y_3 S\overline{\psi_L} t_R + h.c.,
\end{aligned}$$

S **: real scalar DM**

ψ **: a vectorlike force mediator** $\sim u_R, c_R, t_R,$

Both carry $Z_2 = -1$ **dark parity**

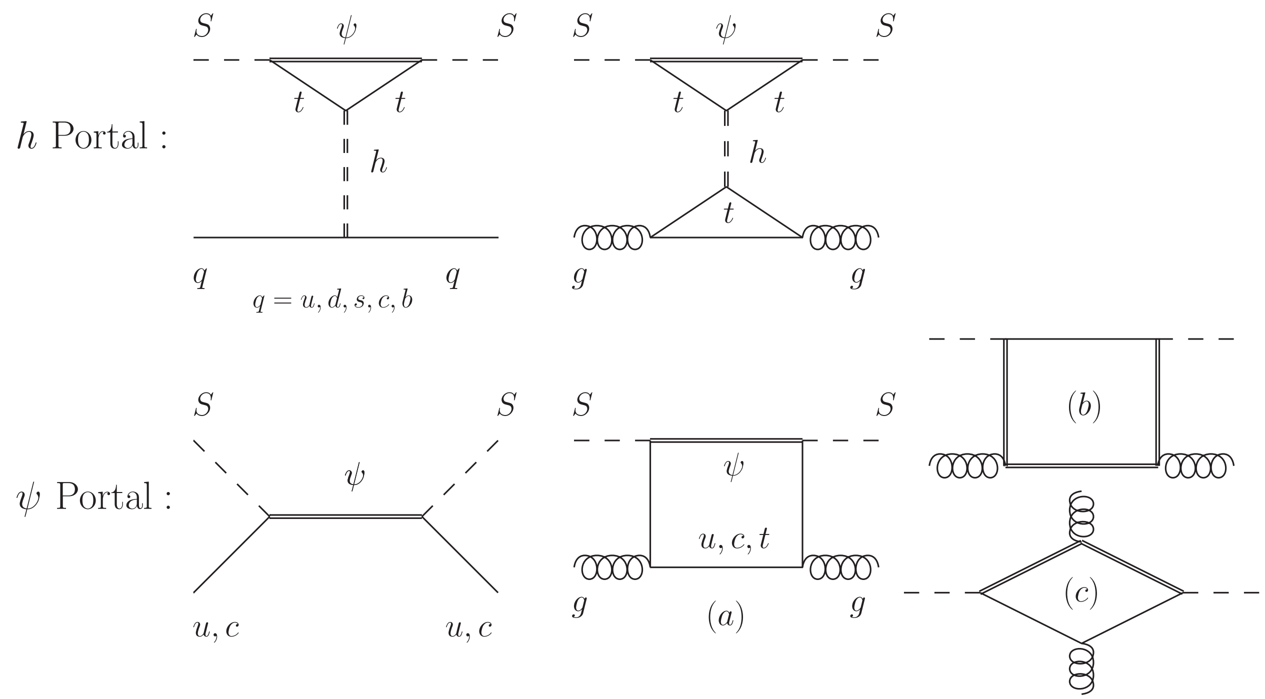


Figure 1. Feynman diagrams used for calculating the Wilson coefficients, at the order of $\mathcal{O}(y_i^2)$, of the effective operators in Eq.(3.1) when choosing $\mu_{\rm EFT} = m_Z$. We refer to diagrams mediated by the SM Higgs h as Higgs portal, while denoting others as vector-like ψ portal.

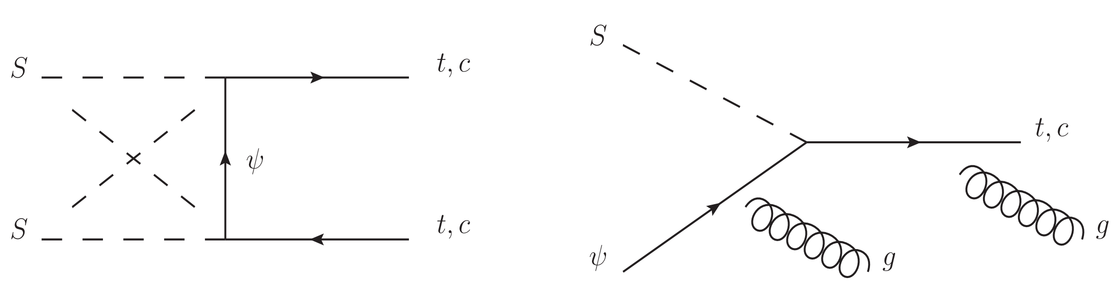


Figure 3. Most relevant DM annihilation channels in this work.

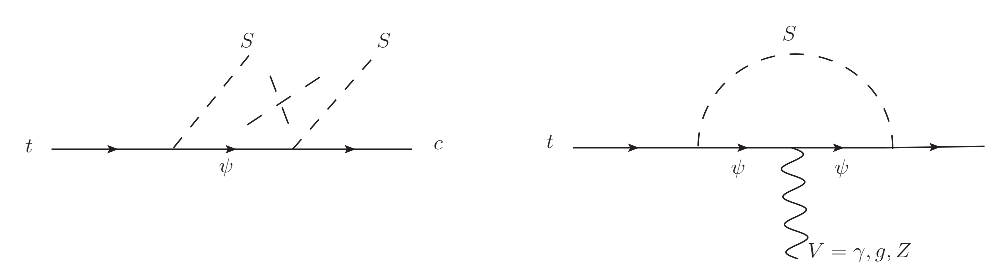


Figure 7. FCNC processes of top quark in this model.

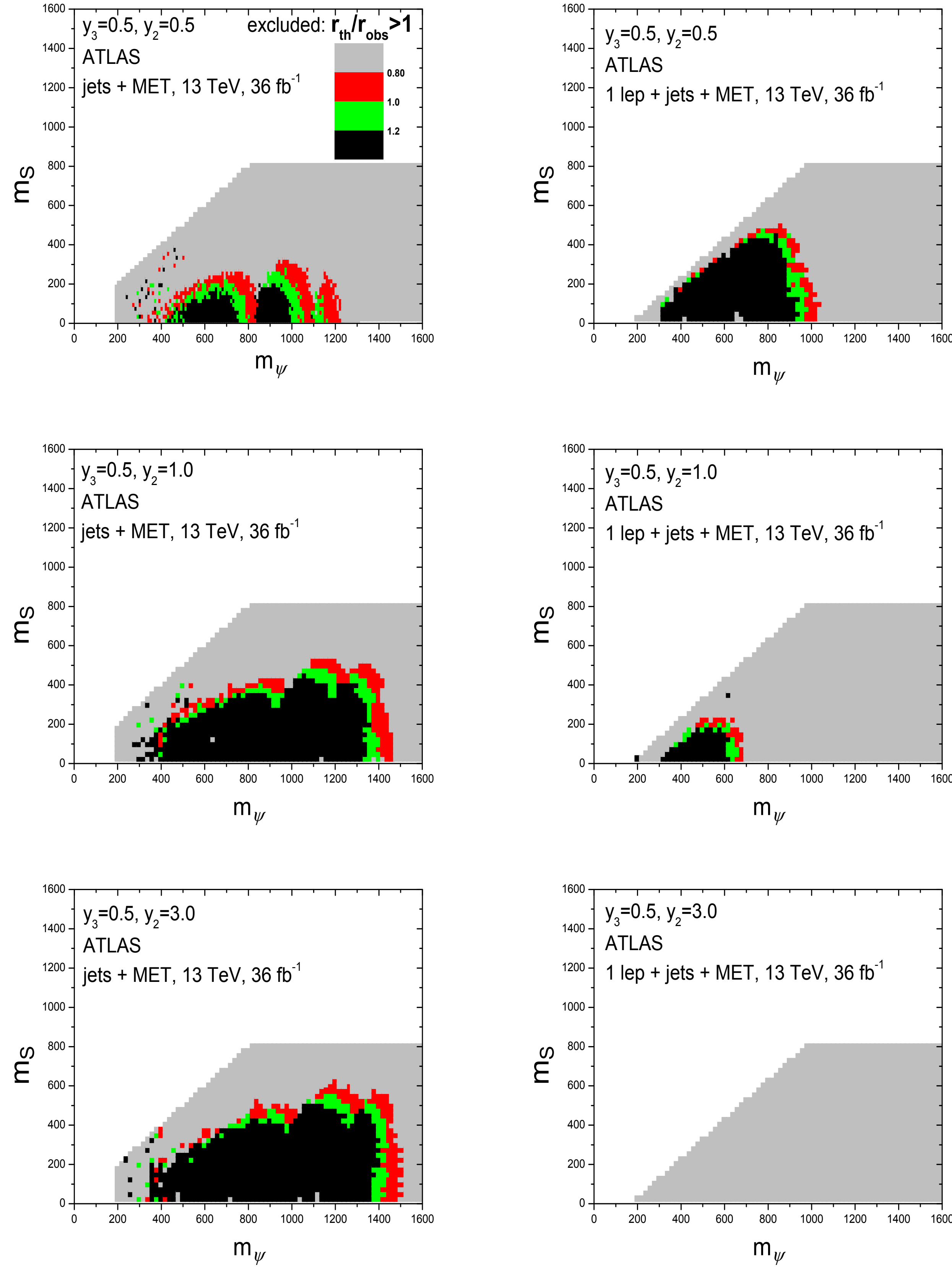


Figure 10. ATLAS bounds on the model of this work using 36 fb^{-1} data at 13 TeV. **Left**: $jets + \not{E}_T$ signal; **Right**: $1\ell + jets + \not{E}_T$ signal. Rows from top to bottom correspond to $y_2 = 0.5, 1, 3$ with common $y_3 = 0.5$. All masses are in unit of GeV.

1709.00697

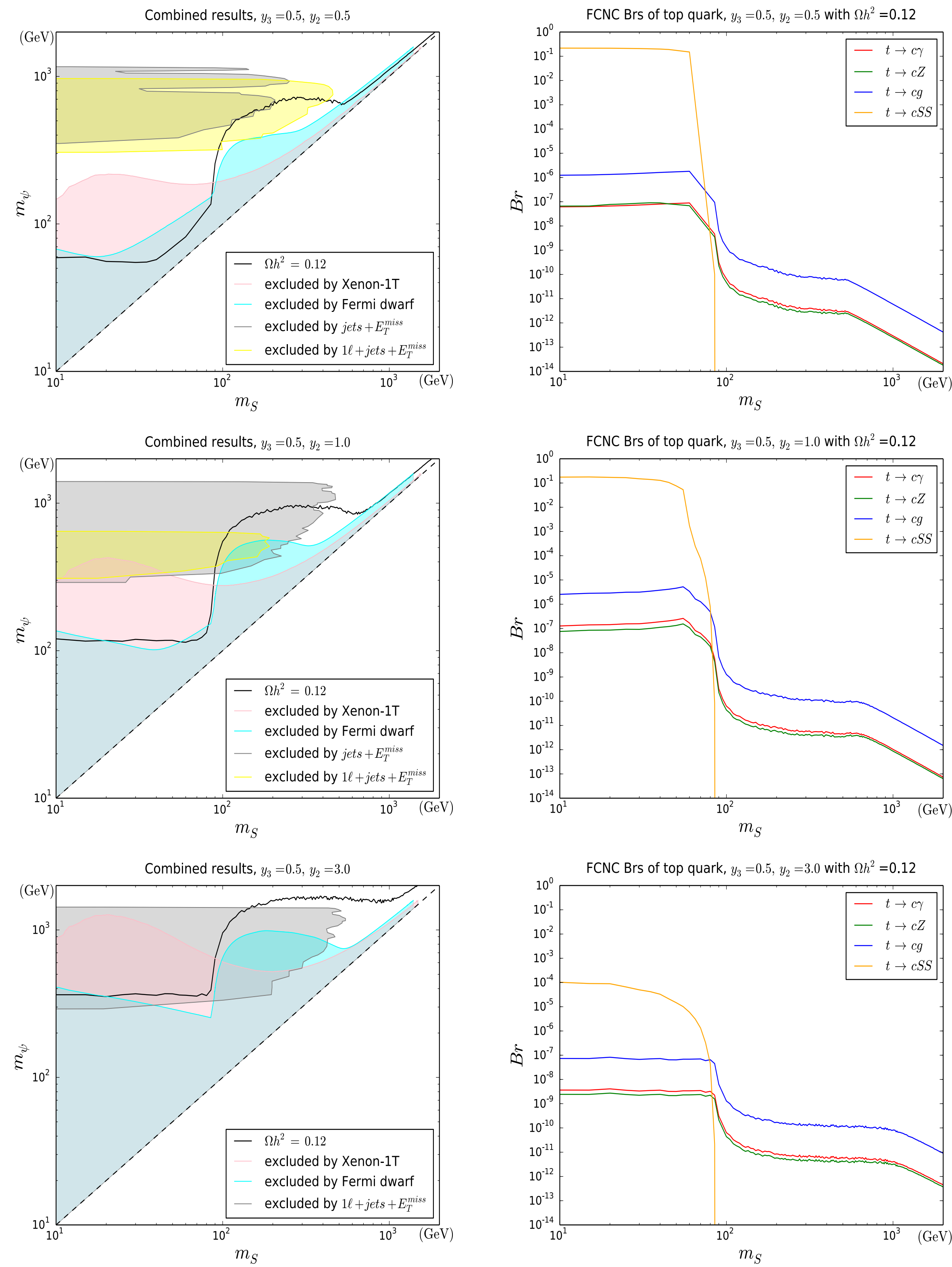


Figure 11. Combined results. **Left:** mass relations required by observed relic abundance confronting the excluded region by direct/indirect detection and 13 TeV LHC data; **Right:** predicted top FCNC branching fractions when satisfying $\Omega_{\rm DM} h^2 \simeq 0.12$. Rows from top to bottom correspond to $y_2 = 0.5, 1, 3$ with common $y_3 = 0.5$, respectively.

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