From EFT's to Simplified Models to UV Completions: DM and top as examples

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Lectures at Yonsei U, HEP Group
Feb. 11 and 25 (2022)

Contents

- Repraisal of the SM
- Motivations for the BSM : phenomenological vs. theoretical (with comments on the hierarch problem)
- Flavor anomalies
- Dark Matter : Dark photon vs. dark Higgs
- Takehome Messages

Repraisal of SM

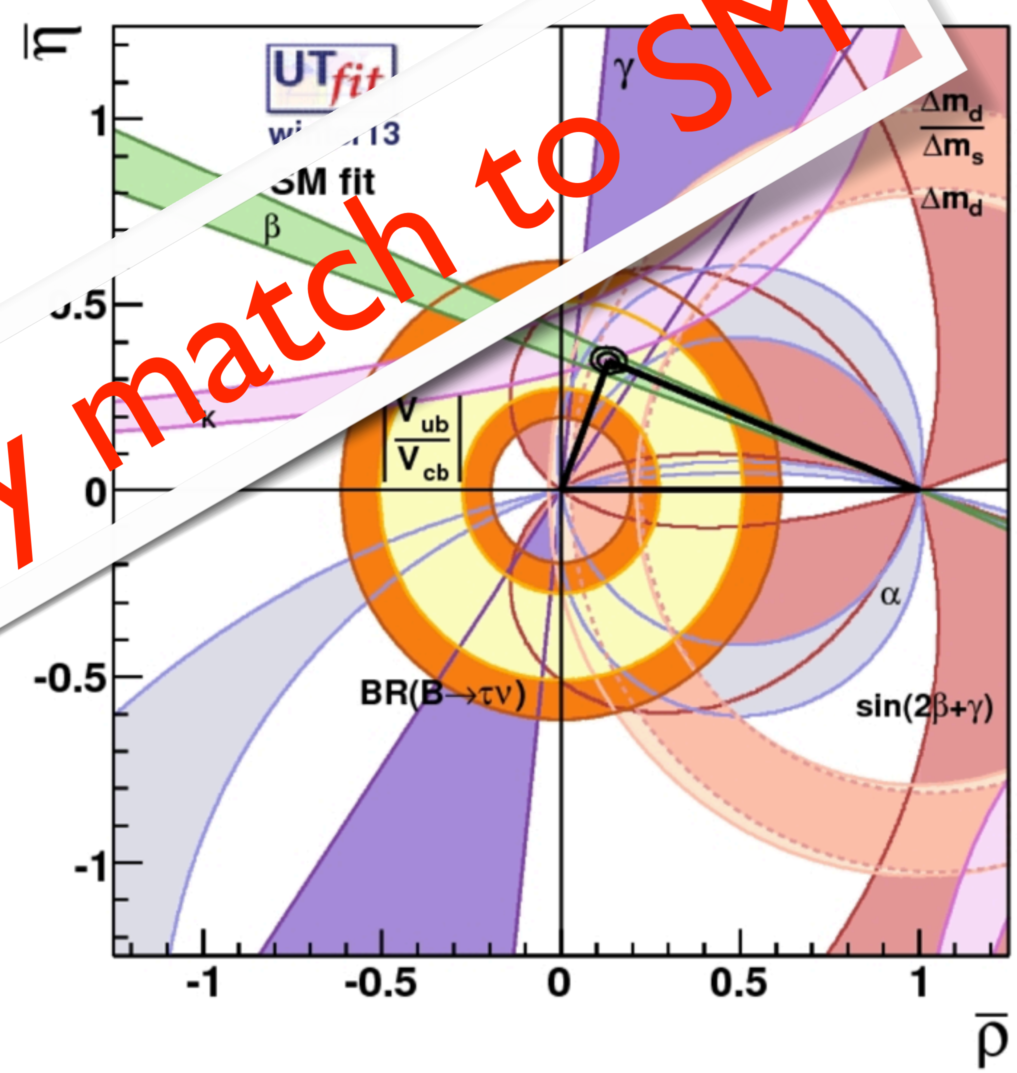
For subatomic world

- SM has been so successful

EWPT

[LEPEWWG, Mar 2012]

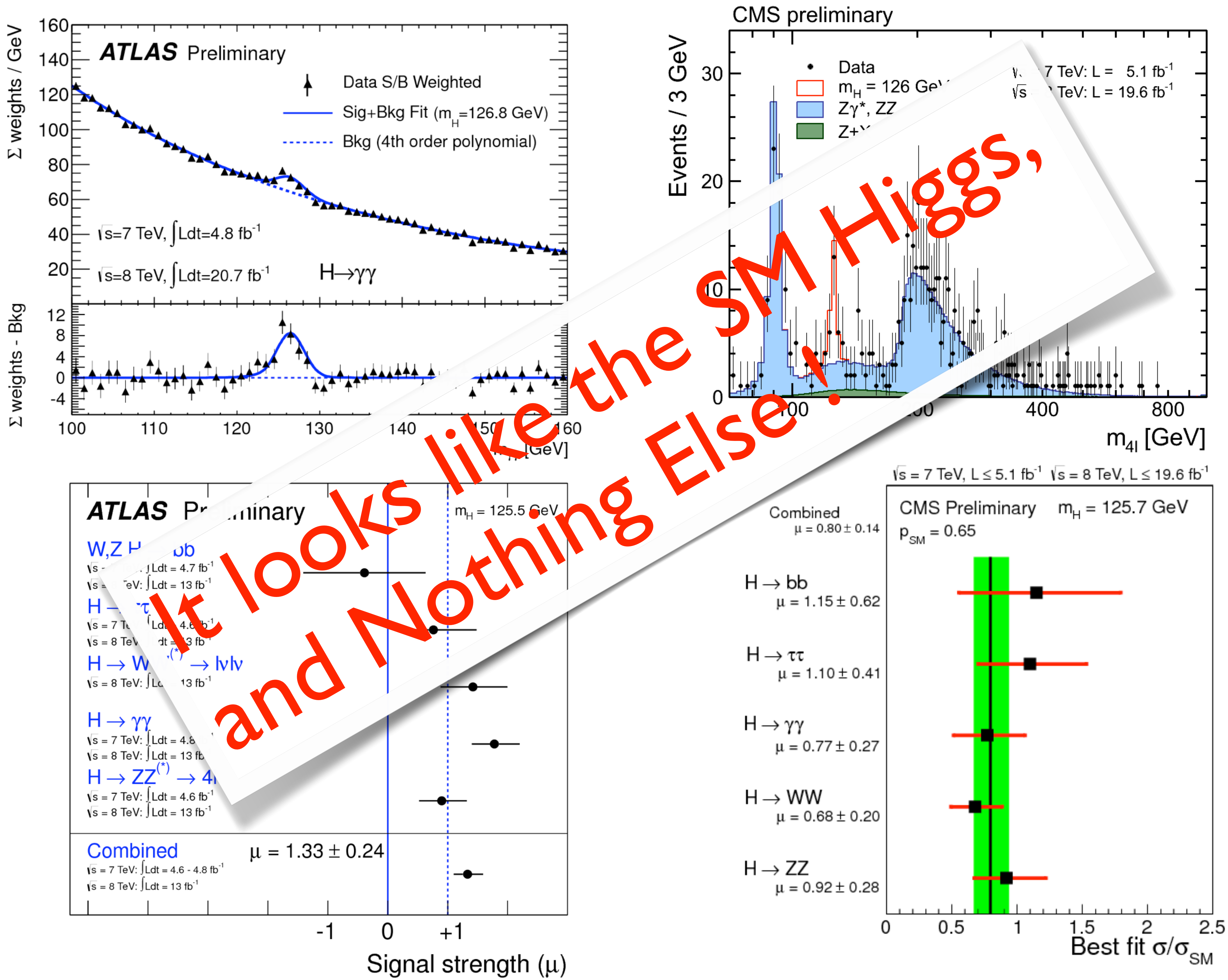
CKM



[Unitary Triangle fit]

Almost perfectly match to SM

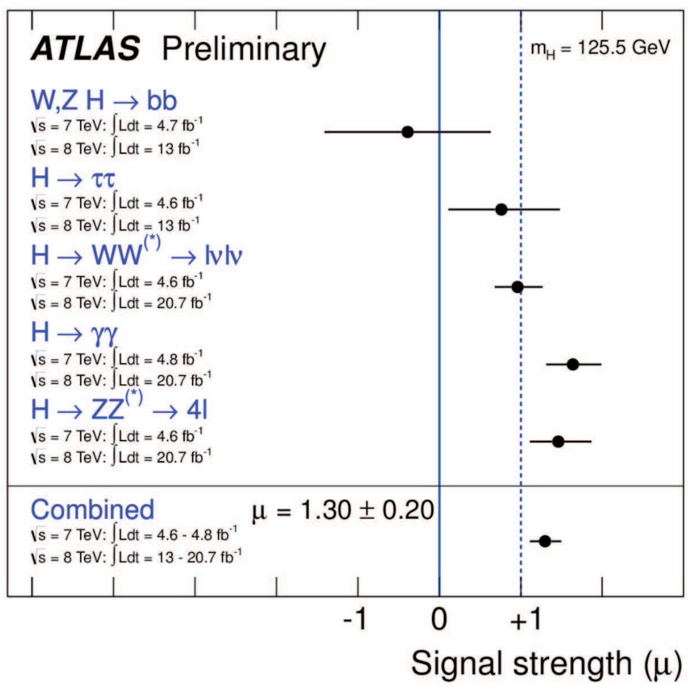
- The last SM chapter also looks correct

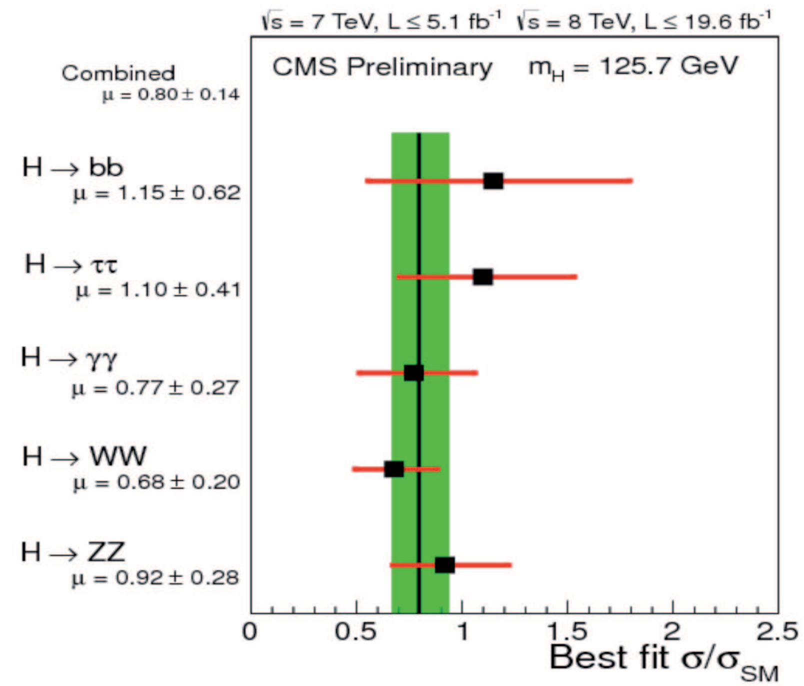


Updates@LHCP

Signal Strengths

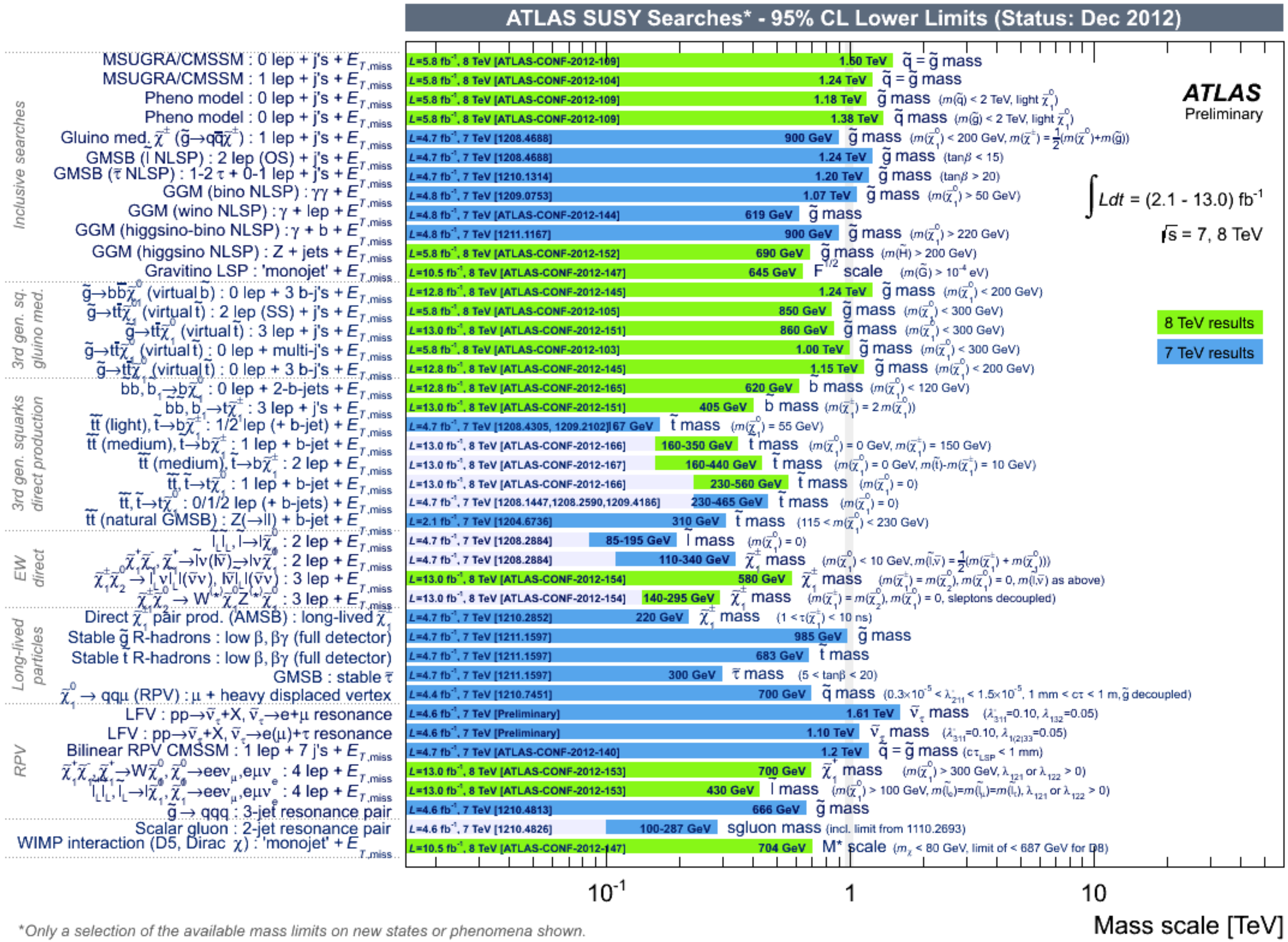
$$\mu \equiv \frac{\sigma \cdot \mathrm{Br}}{\sigma_{\mathrm{SM}} \cdot \mathrm{Br}_{\mathrm{SM}}}$$





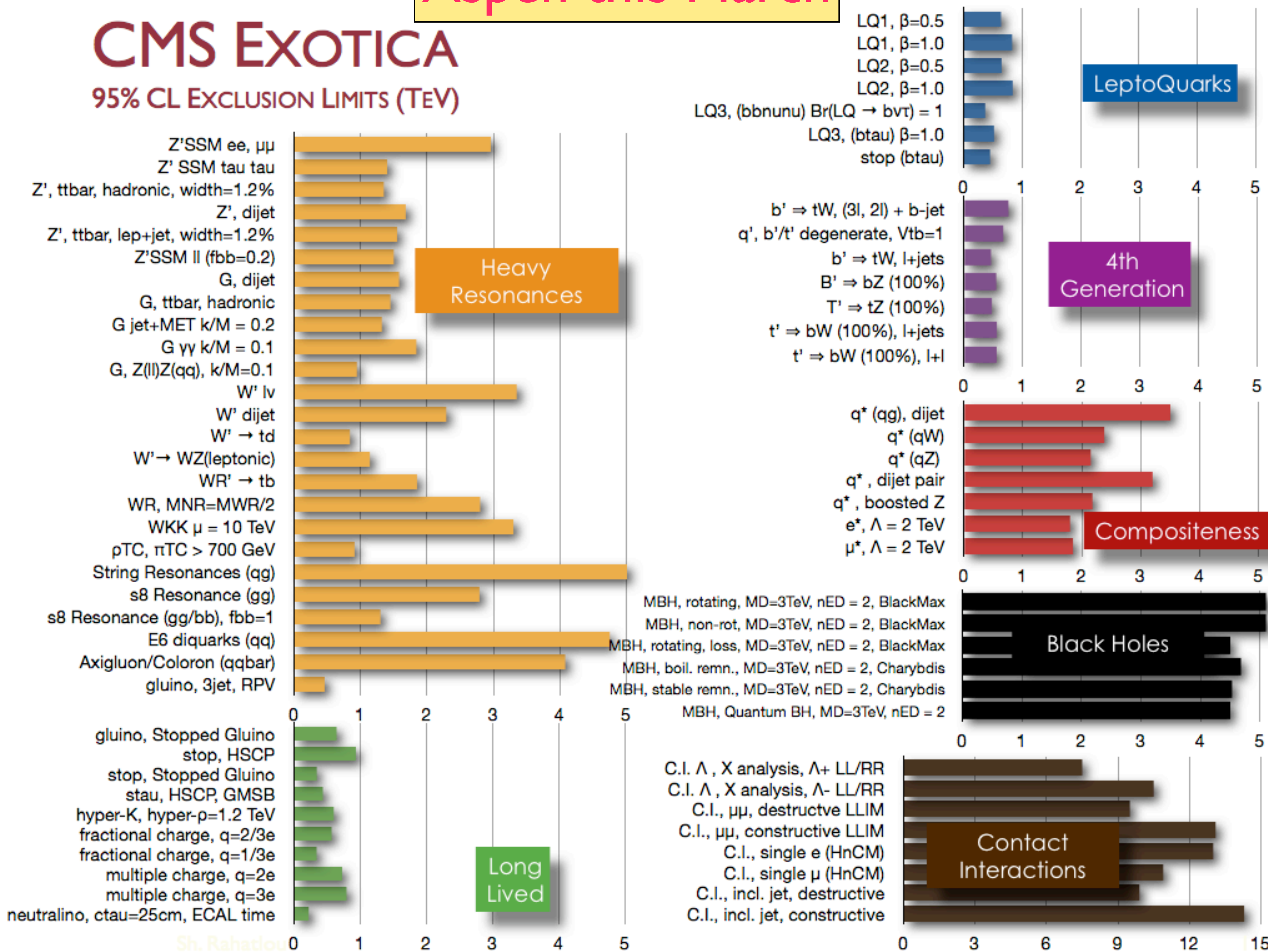
Decay Mode	ATLAS ($M_H = 125.5$ GeV)	CMS ($M_H = 125.7$ GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

$$\langle \mu \rangle = \mathbf{0.96 \pm 0.12}$$



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Aspen this March



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

$(3,2,1)$ or $SU(3)_C \times U(1)_{\rm em}$?

- Well below the EW sym breaking scale, it may be fine to impose $SU(3)_C \times U(1)_{\rm em}$
- At EW scale, better to impose (3,2,1) which gives better description in general after all
- Majorana neutrino mass is a good example
- For example, in the Higgs + dilaton (radion) system, and you get different resultsSinglet mixing with SM Higgs

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
  - 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,..)

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 ? 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.

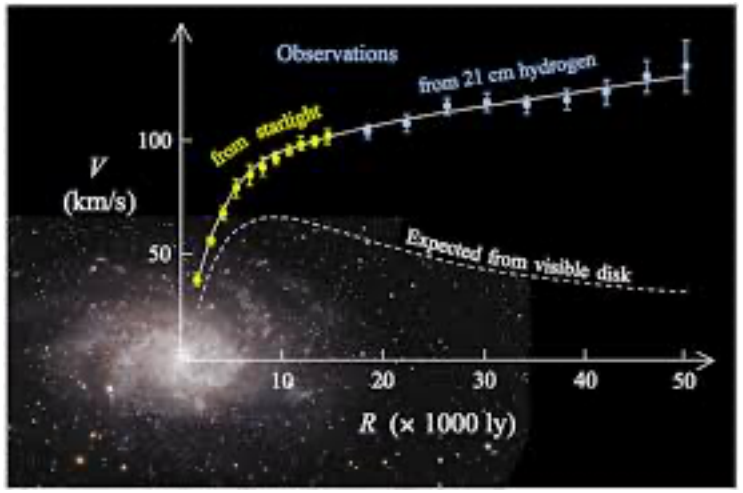
- In any case, search for New Physics without any theoretical prejudice is most important (SUSY, MSW with the large mixing for the solar neutrino problem, etc.)

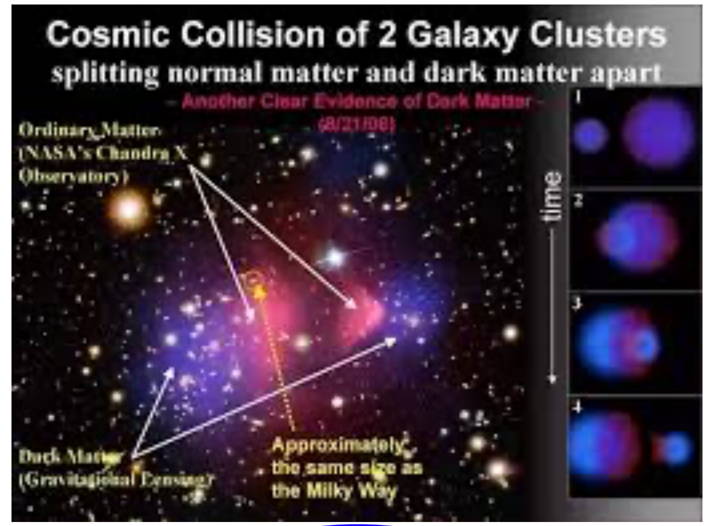
My personal favorites

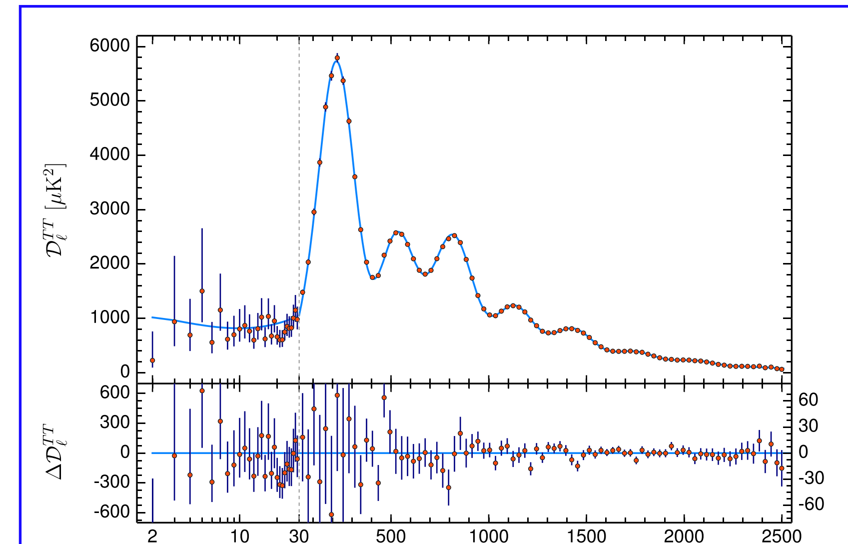
- So far, all the observed fermions are chiral, and charged under some gauge symmetries (not completely neutral)
- All the matters are fundamental representations of the gauge group. No higher dim rep.'s have been found yet
- Dark photon, dark Higgs (~singlet scalar) if DM mass ~ EW scale
- Vectorlike fermions which are chiral under new gauge sym
- New confining (dark) forces

Dark Matter :
Dark photon vs. dark Higgs

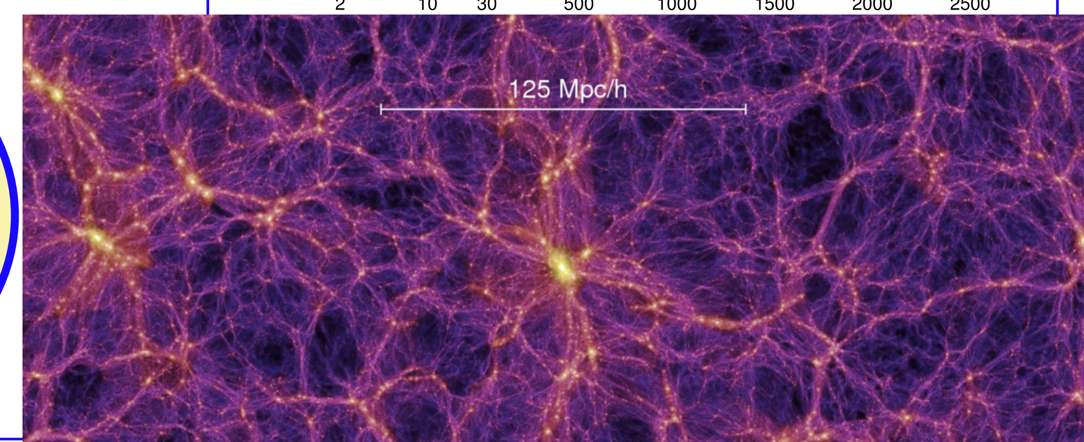
Evidences for DM

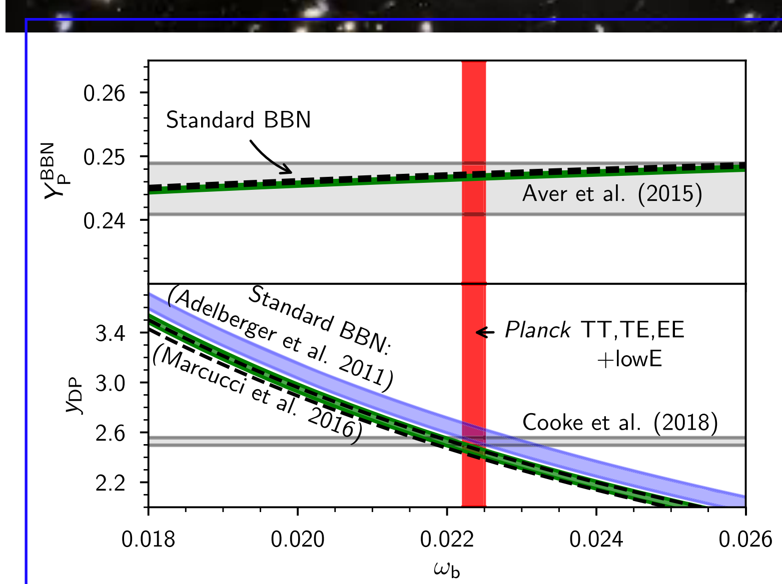


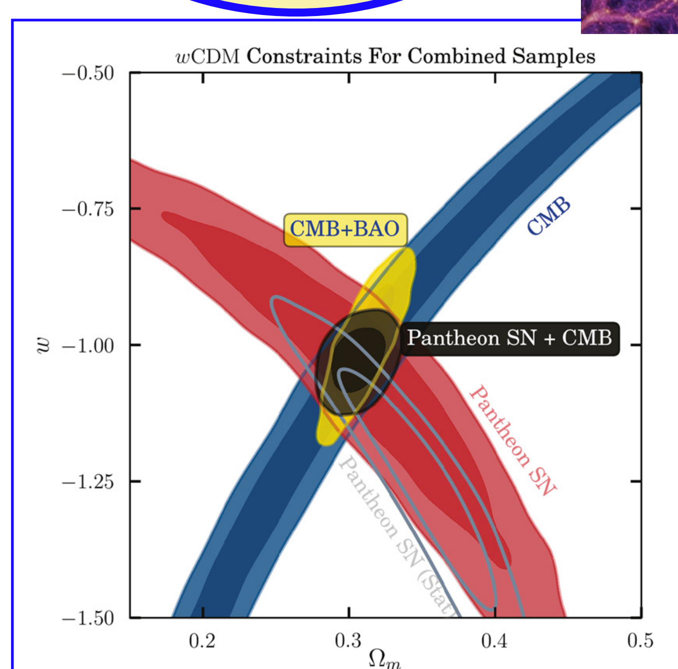


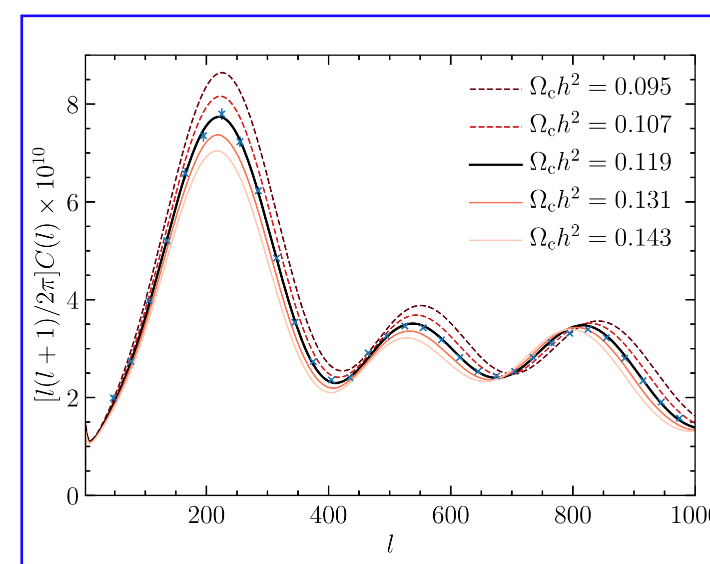


GRAVITY

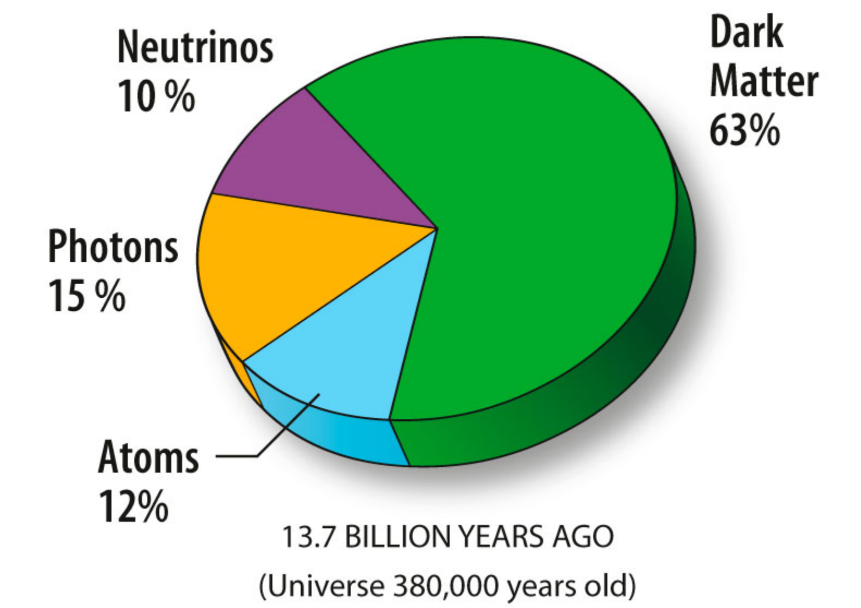


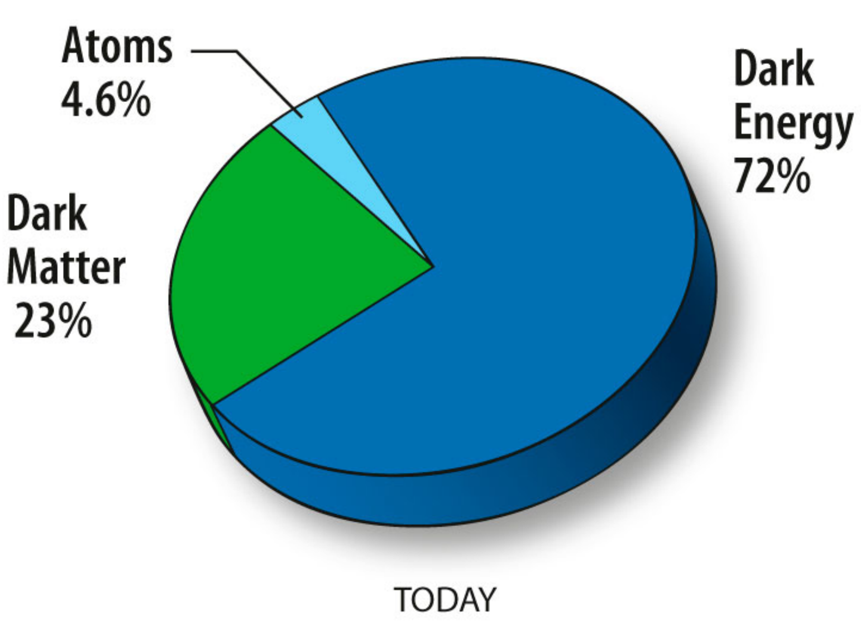


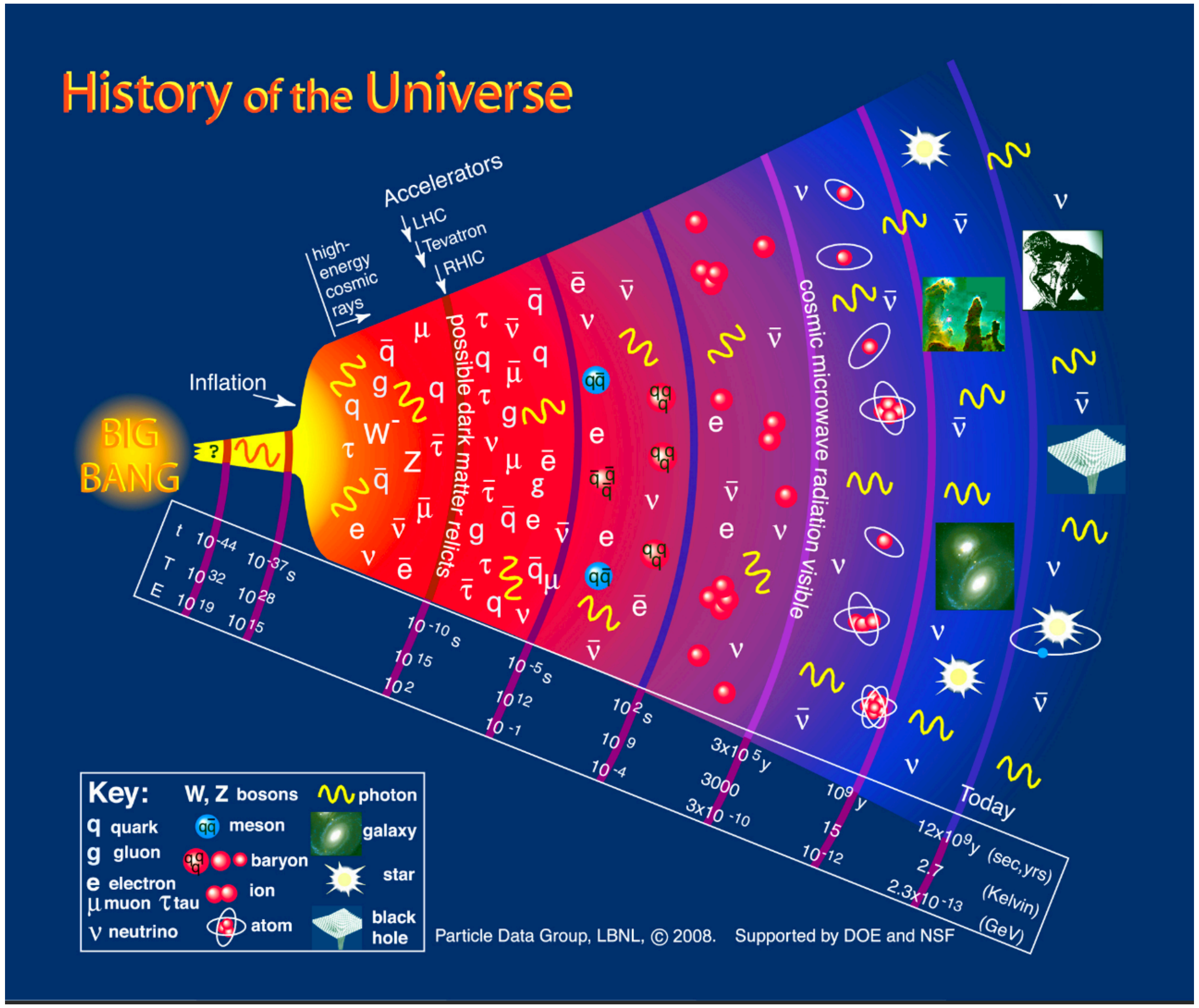




Cos. Concordance Model







KNOWNS

- Feels Gravity > Currently evidences come only thru this
- Its lifetime >> Age of Universe
- $\rho(\simeq m) \gg \ p(\simeq 0)$ (Nonrel.)
- $\Omega_{\rm DM} \sim 5\ \Omega_{\rm Baryon}$
- $\rho_{\rm local} \sim 0.3 {\rm GeV/cm^3}$
- 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

- Charge/color neutral : no renormalizable int's w/ γ, g
- Eq of State : $\rho \simeq 0 \ (i.e. \, p \simeq 0)$
- $\tau_{\rm DM} \gg \tau$ (Age of the Universe) or ∞

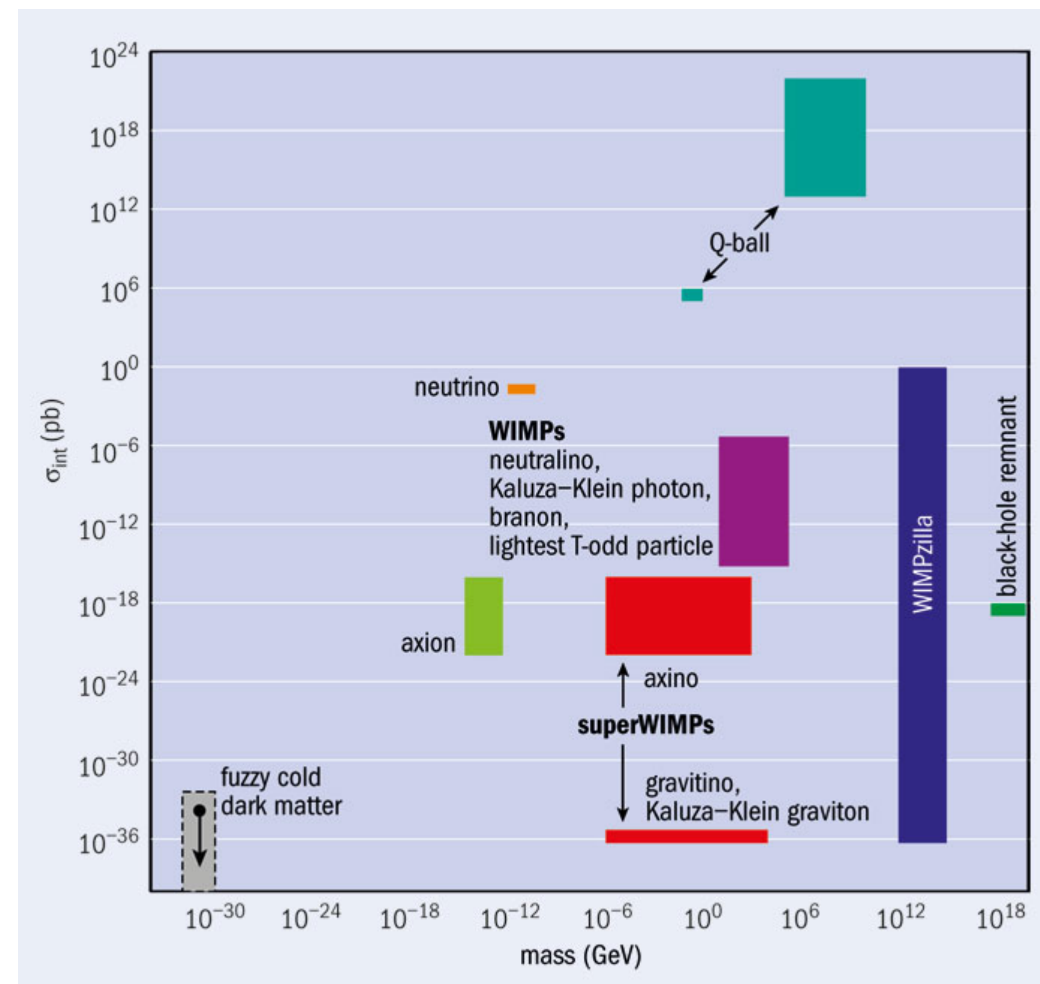
What is the DM mass ?

- If very light, DM is long lived for the kinematical reason
- Axion and light sterile ν's are good examples

- If not, reasonable to assume some conserved quantum #, either exactly or approximately conserved
- Local or global Dark Sym

DM models in the market : Mass & Couplings ?

- WIMP, SIMP, ELDERS,…
- Axion (axino), gravitino, sterile ν
- PBH (Primordial Blackhole)
- Fuzzy DM (Scalar Field DM)
- Topological objects
- Some DM models also solve another particle physics problems (🏌🐦🐦 ??)
- More than Baskin Robbins 31…



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
- So on & on & on …
- <u>Eventually "Portal" is what we observe in the experiments</u>

ϕ : Dark Scalars

X_μ : Dark photon

ψ : Dark fermion
~ Sterile ν

Portals to DM

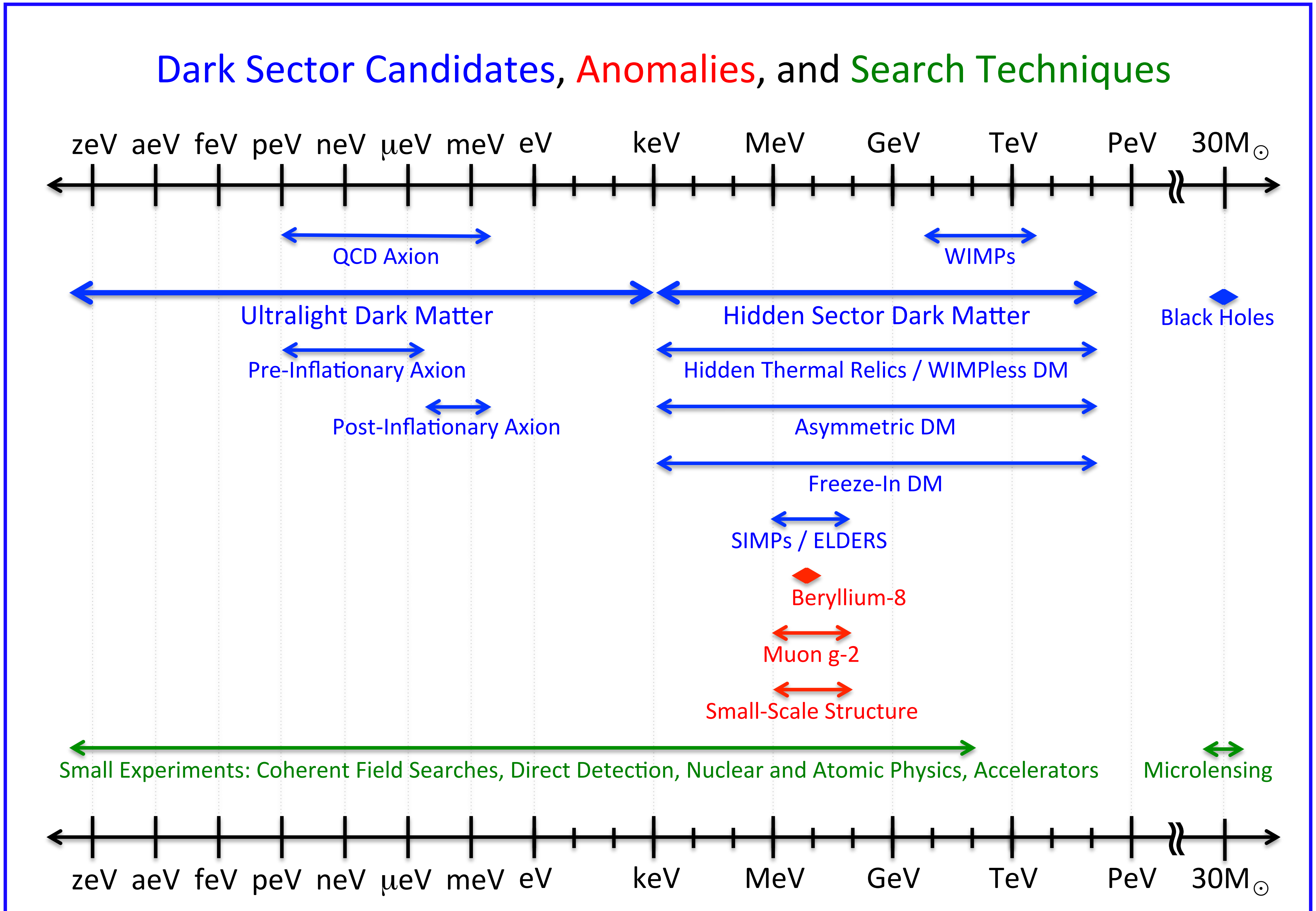
- Higgs portal : $H^\dagger HS,\ H^\dagger HS^2,\ H^\dagger H\phi^\dagger\phi$
- U(1) Vector porta
- Neutrino portal : $\overline{N_R}(\widetilde{H} l_L +$
- (Dark) Axion portal (HSLee
- So on, & on & on , …
- Eventually "Portal" is what we observe in experiments

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 sym

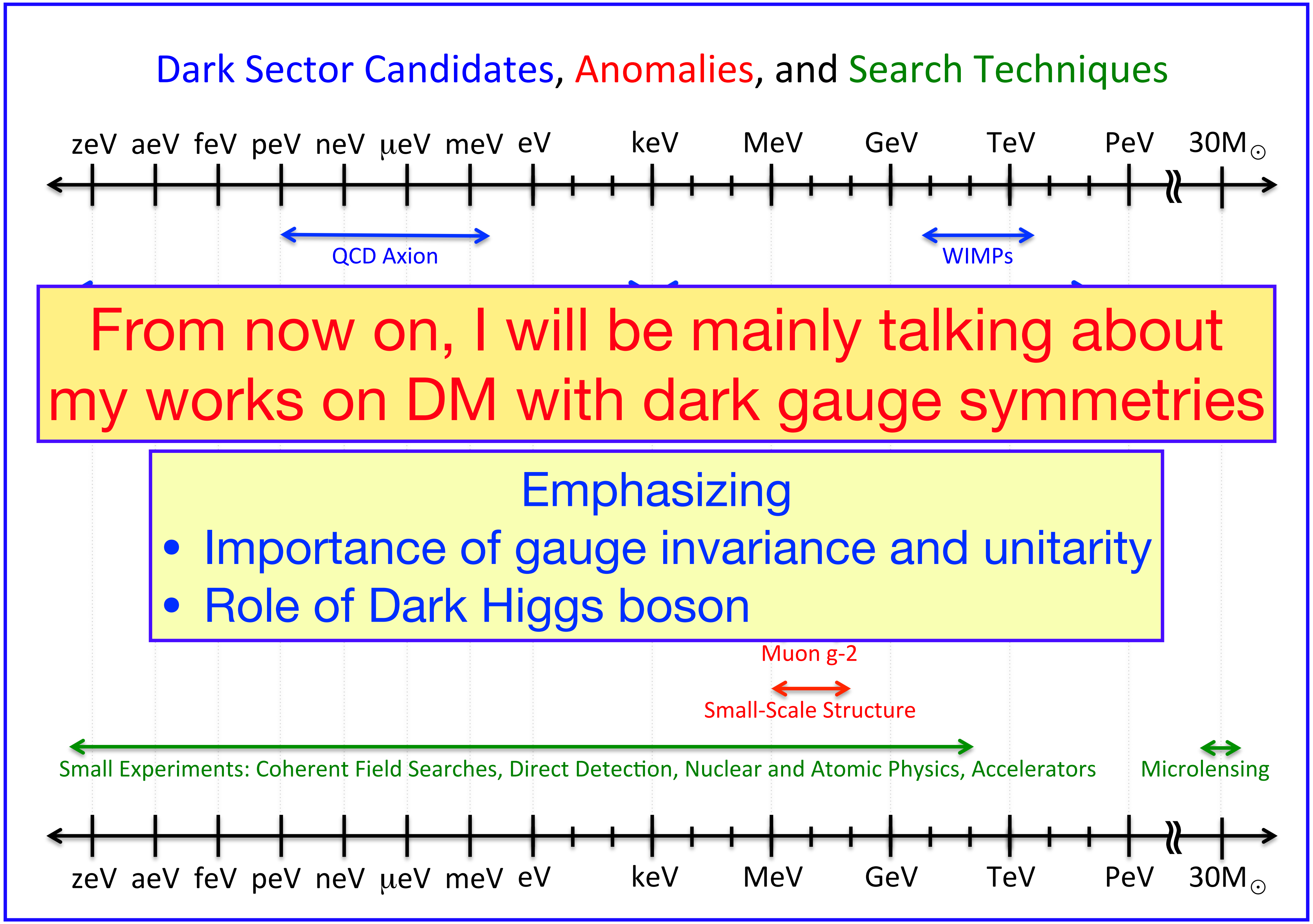
Domestic Activities (Th)

[US Cosmic Visions:…., arXiv:1707.04591]



Domestic Activities (Th)

[US Cosmic Visions:...., arXiv:1707.04591]



From now on, I will be mainly talking about my works on DM with dark gauge symmetries

Emphasizing

- Importance of gauge invariance and unitarity
- Role of Dark Higgs boson

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

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 : $\frac{1}{M_{\text{Planck}}} S O_{\text{SM}}^{(4)}$

- 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

$X_R \to X_I \gamma_h^*$ 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)

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,

- DM could be absolutely stable due to unbroken local gauge symmetry (DM with local Z_2, Z_3 etc.) or topology (hidden sector monopole + vector DM + dark radiation)
- Longevity of DM could be due to some accidental symmetries (hidden sector pions and baryons) or kinematical reasons (very light axion or sterile neutrinos)
- I will focus on the roles of (light) dark Higgs boson

HP DM @ LHC

2 more relevant parameters

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

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

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

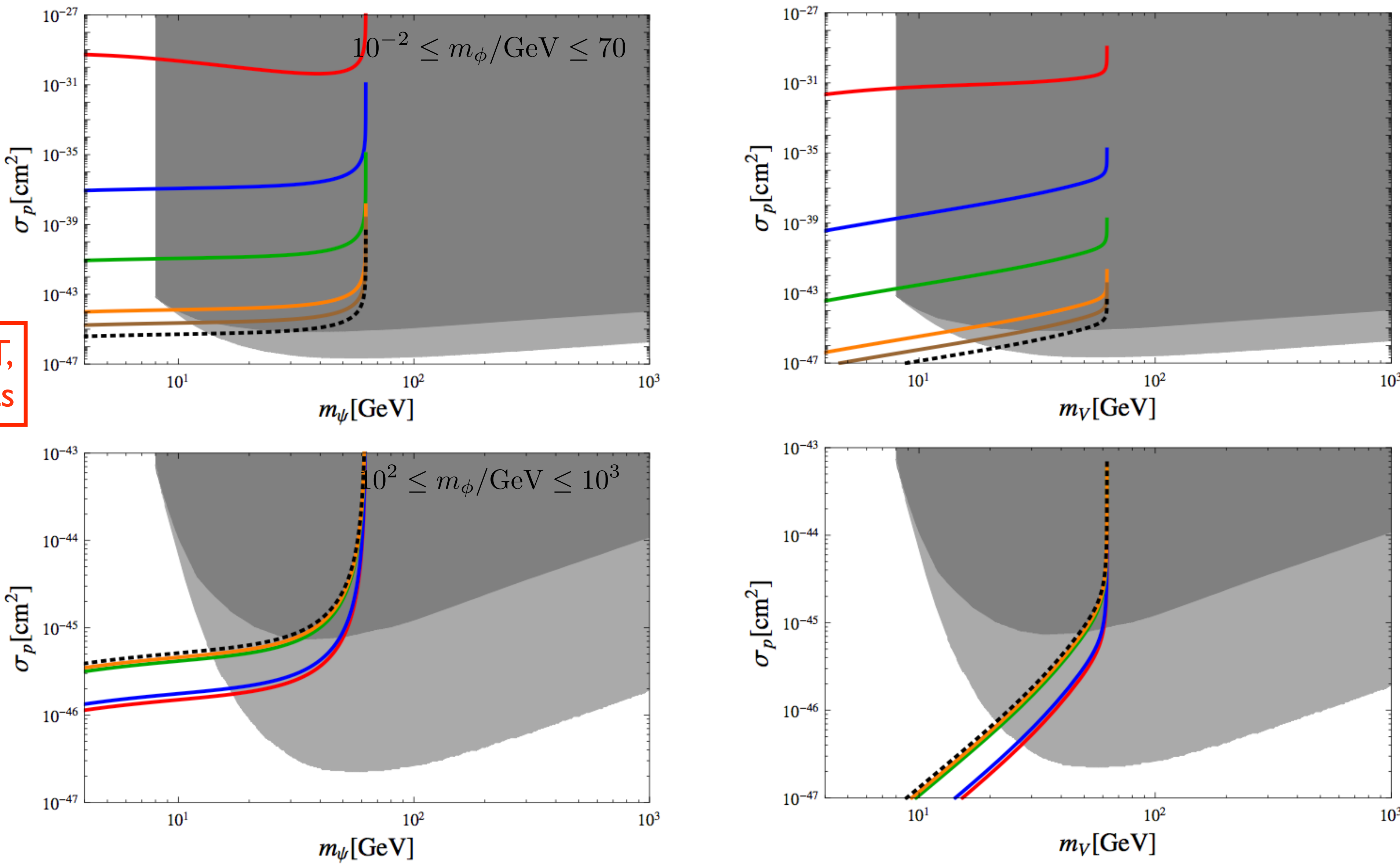
$$\mathcal{L}_{\rm vector} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV}H^\dagger H V_\mu V^\mu.$$

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 (under review now) 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

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).

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

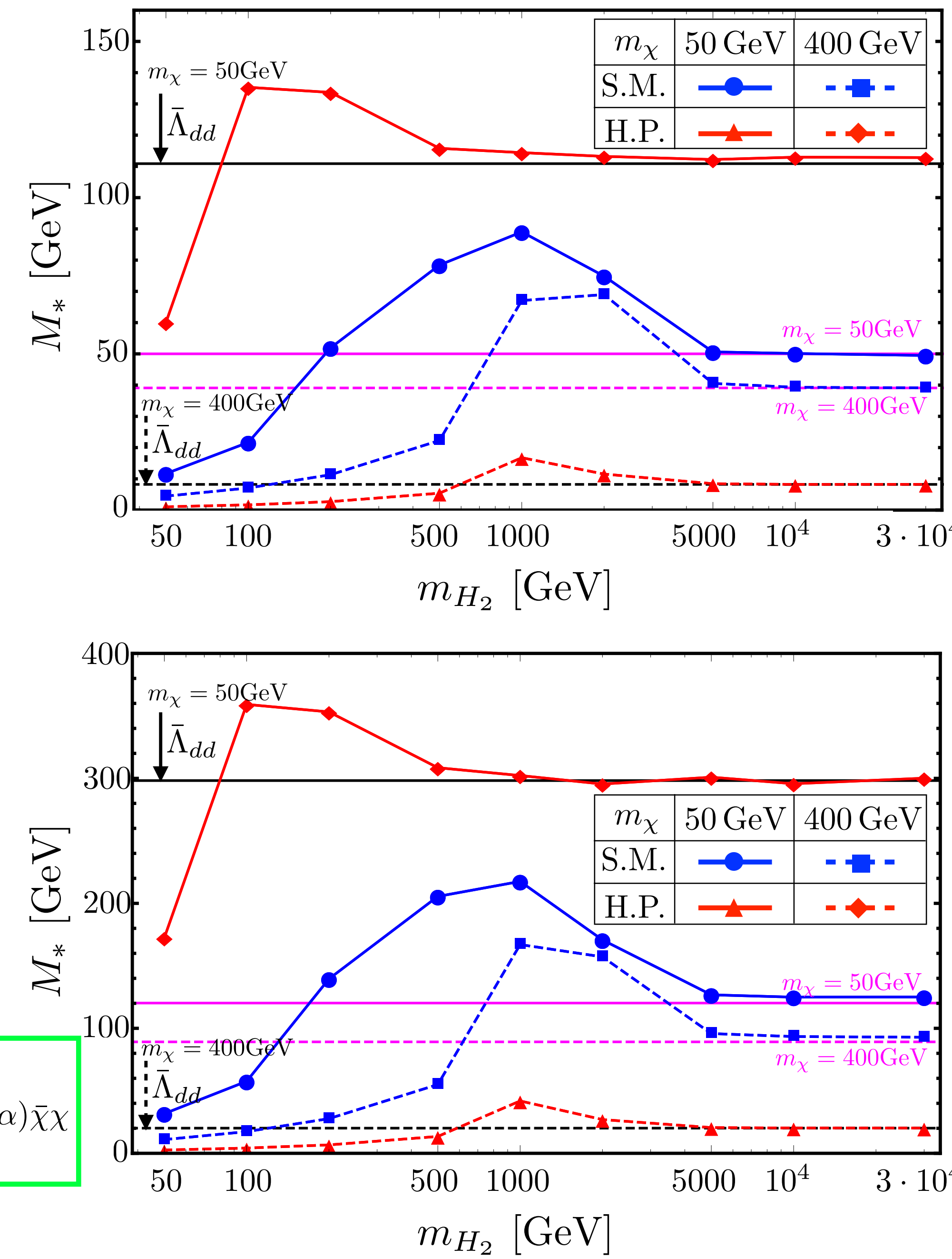


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t} + \not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of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

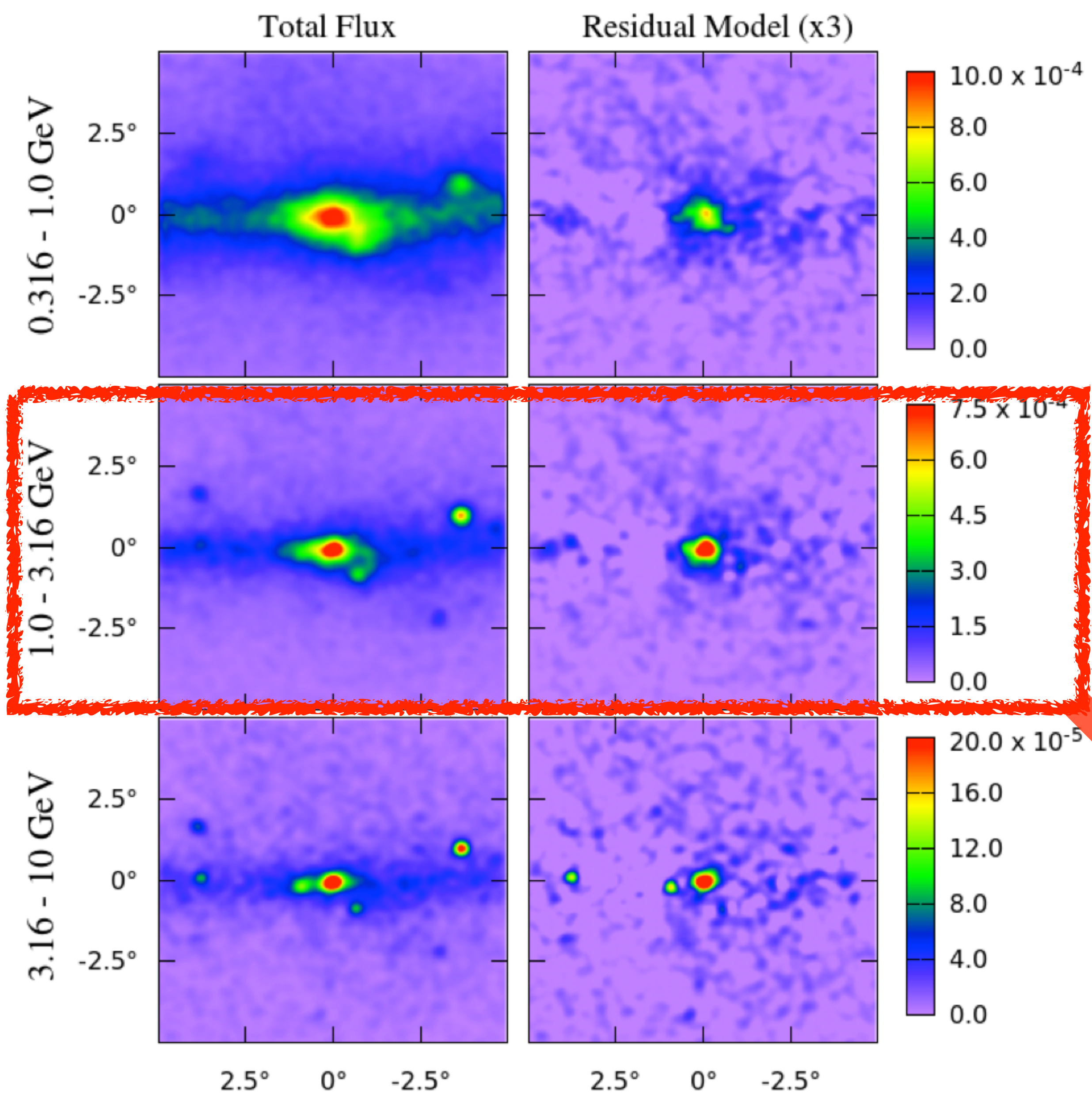
$$\text{H.P.} \xrightarrow[m_{H_2}^2 \gg \hat{s}]{} \text{H.M.},$$

$$\text{S.M.} \xrightarrow[m_S^2 \gg \hat{s}]{} \text{EFT},$$

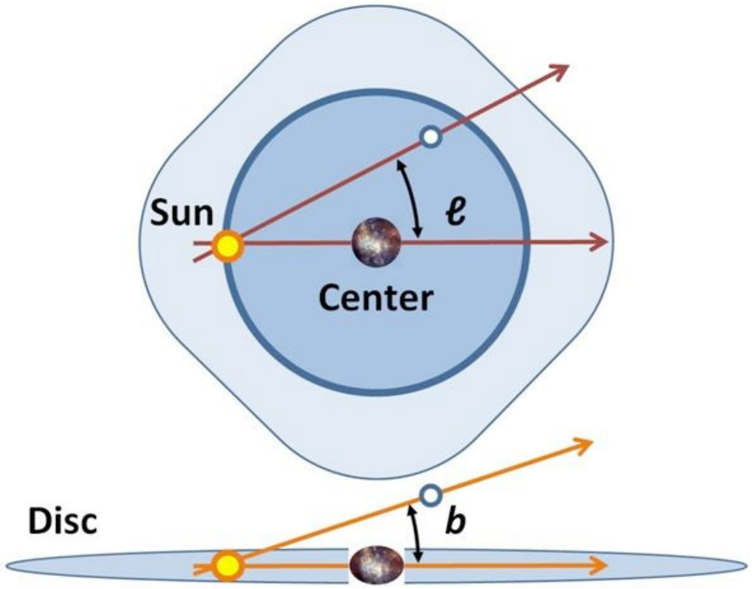
$$\text{H.M.} \neq \text{EFT}\,.$$

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.]

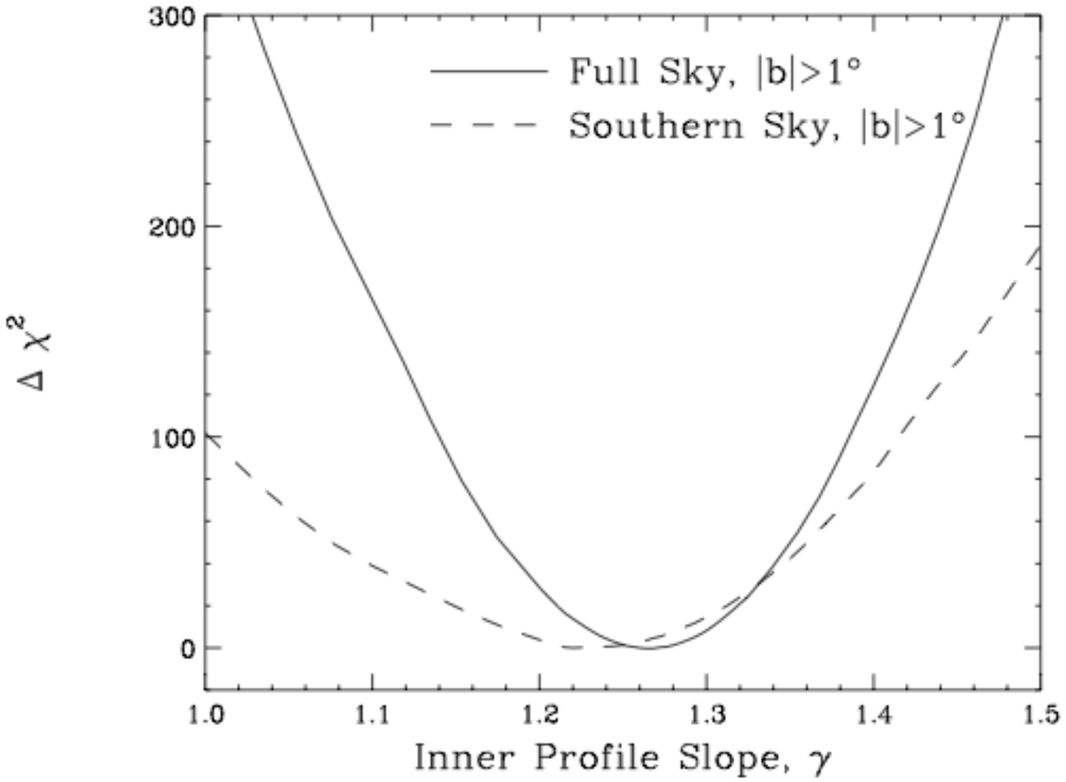


$$\mathrm{GC} : b \sim l \lesssim 0.1^\circ$$

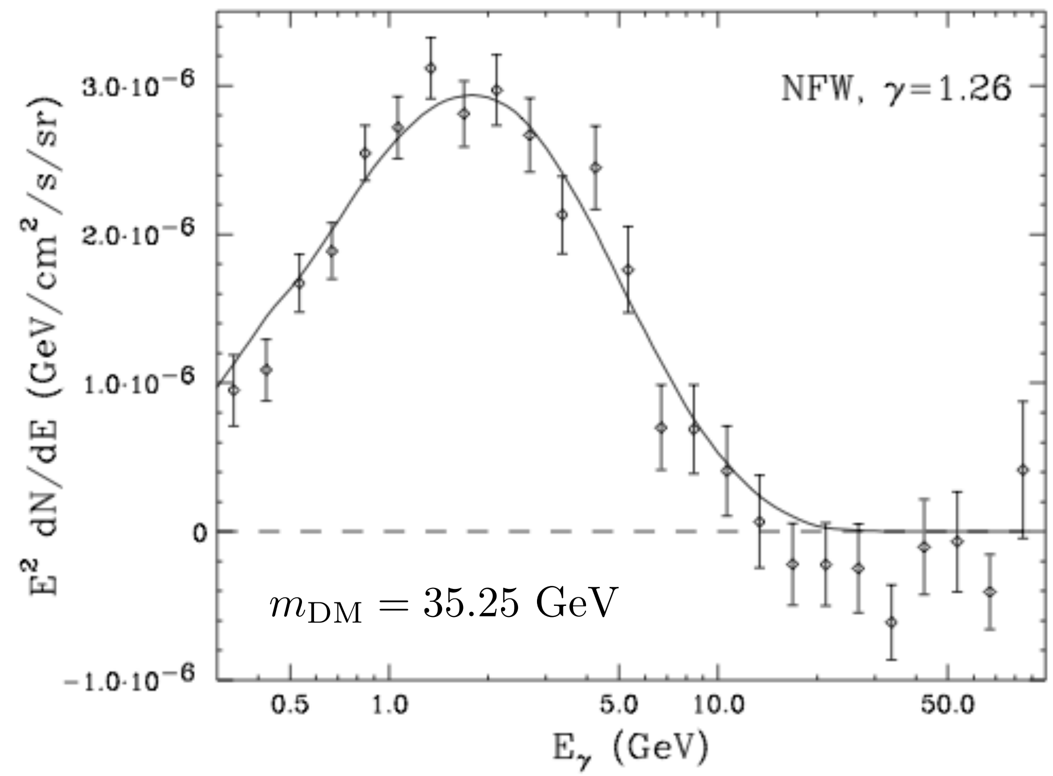
extended

GeV scale excess!

• A DM interpretation



$\mathrm{DM} + \mathrm{DM} \to b\bar{b}$ 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)

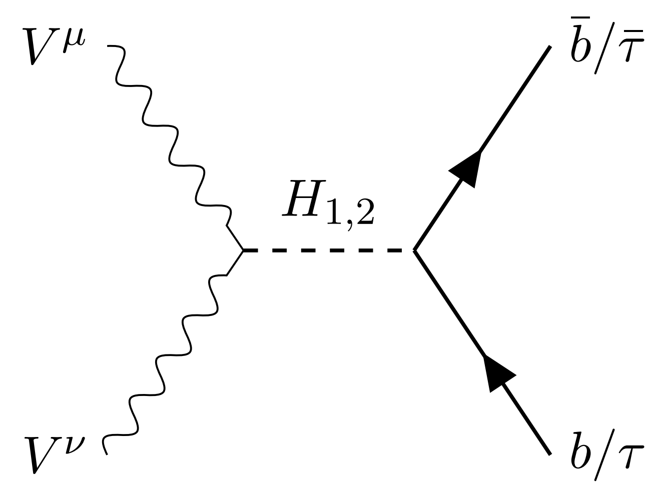
It may or may not be the main source, depending on

- 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



H2 : 125 GeV Higgs
H1 : absent in EFT

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

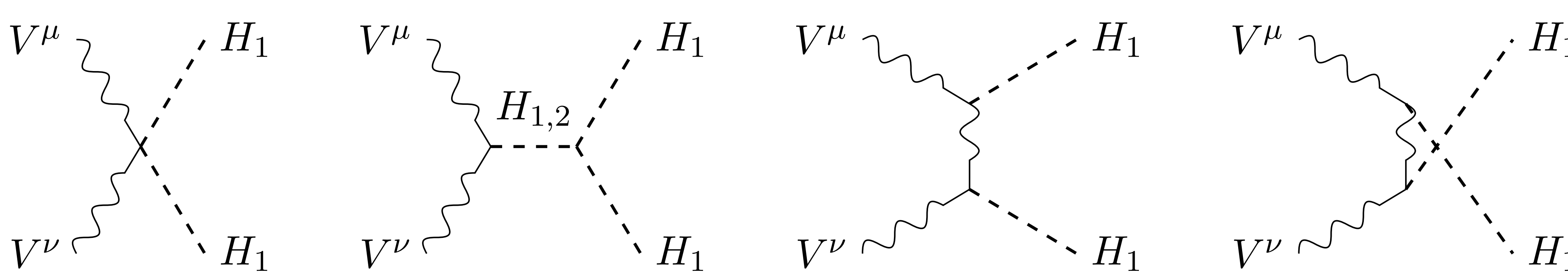


Figure 3. Dominant s/t-channel production of H_1s that decay dominantly to $b+\bar{b}$

Importance of HP VDM with Dark Higgs Boson

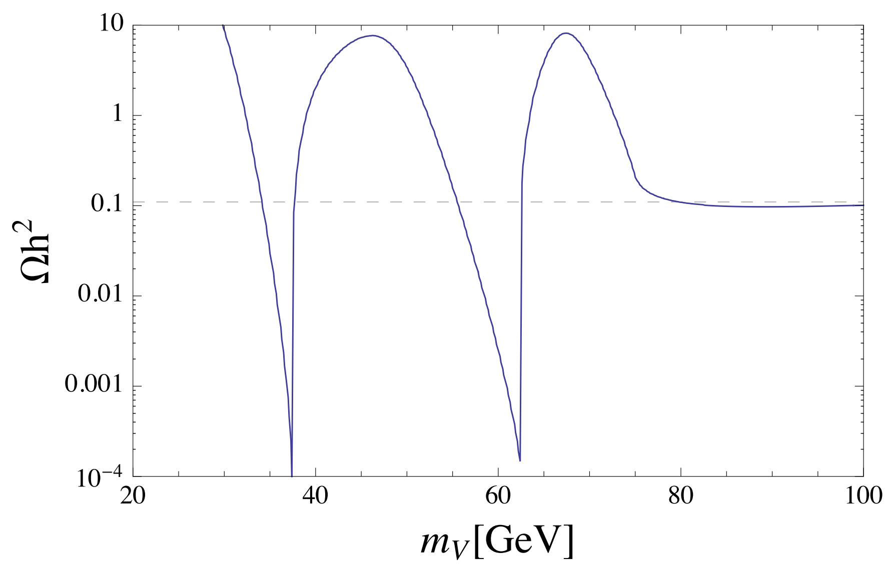


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75\,\text{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

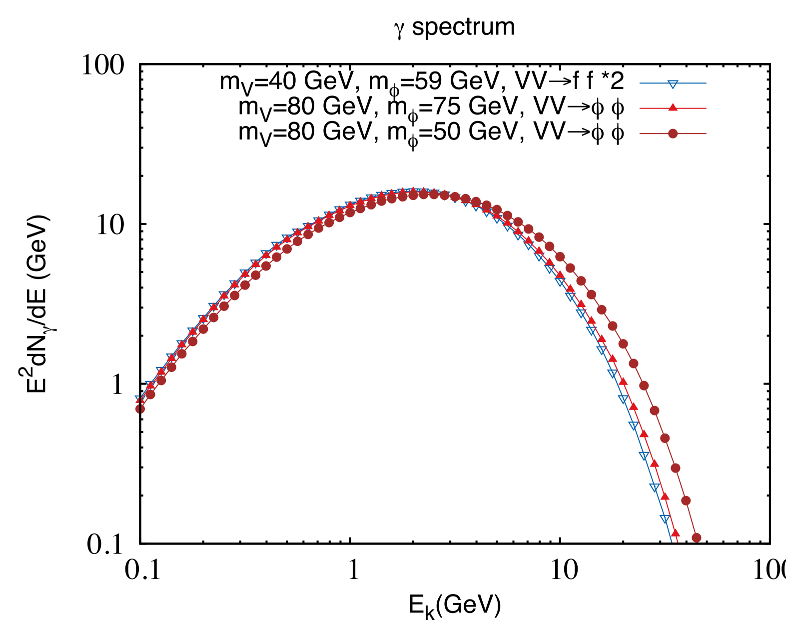
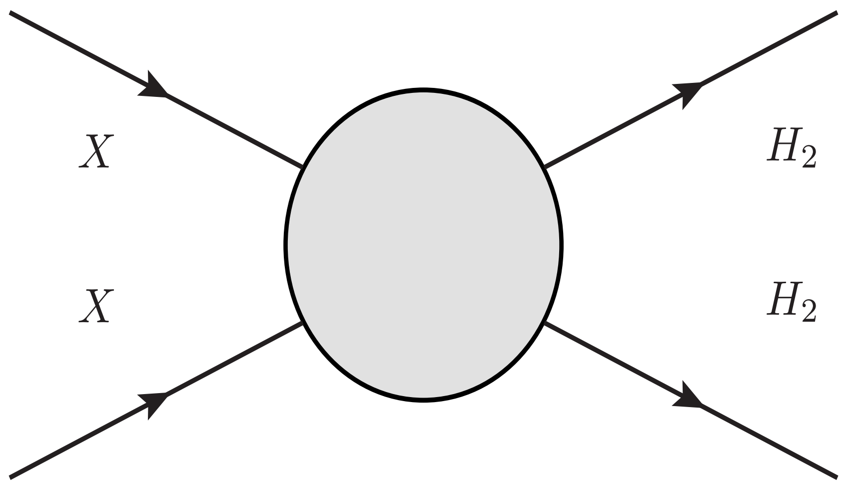


Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

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

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



P.Ko, Yong Tang.
arXiv:1504.03908

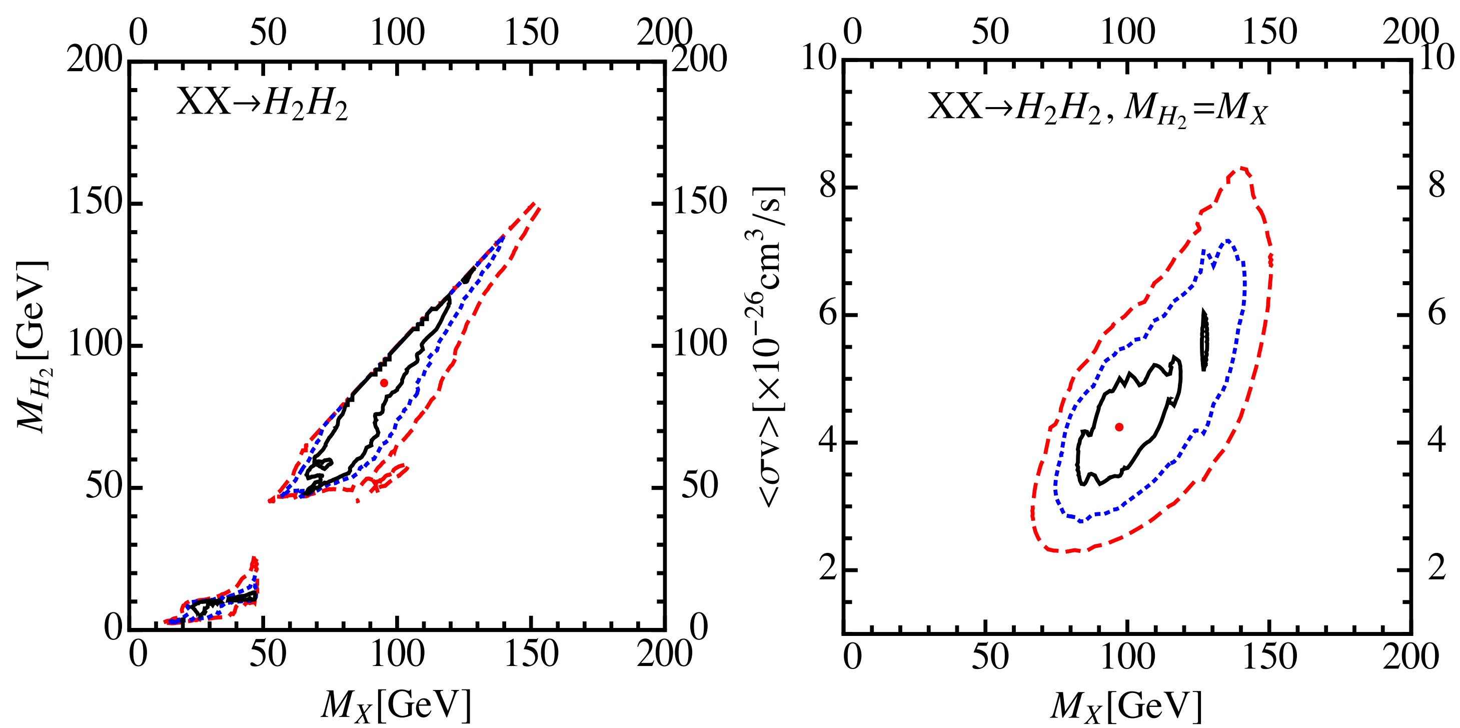


FIG. 3: The regions inside solid(black), dashed(blue) and long-dashed(red) contours correspond to 1σ, 2σ and 3σ, respectively. The red dots inside 1σ contours are the best-fit points. In the left panel, we vary freely M_X, M_{H_2} and $\langle\sigma v\rangle$. While in the right panel, we fix the mass of H_2, $M_{H_2} \simeq M_X$.

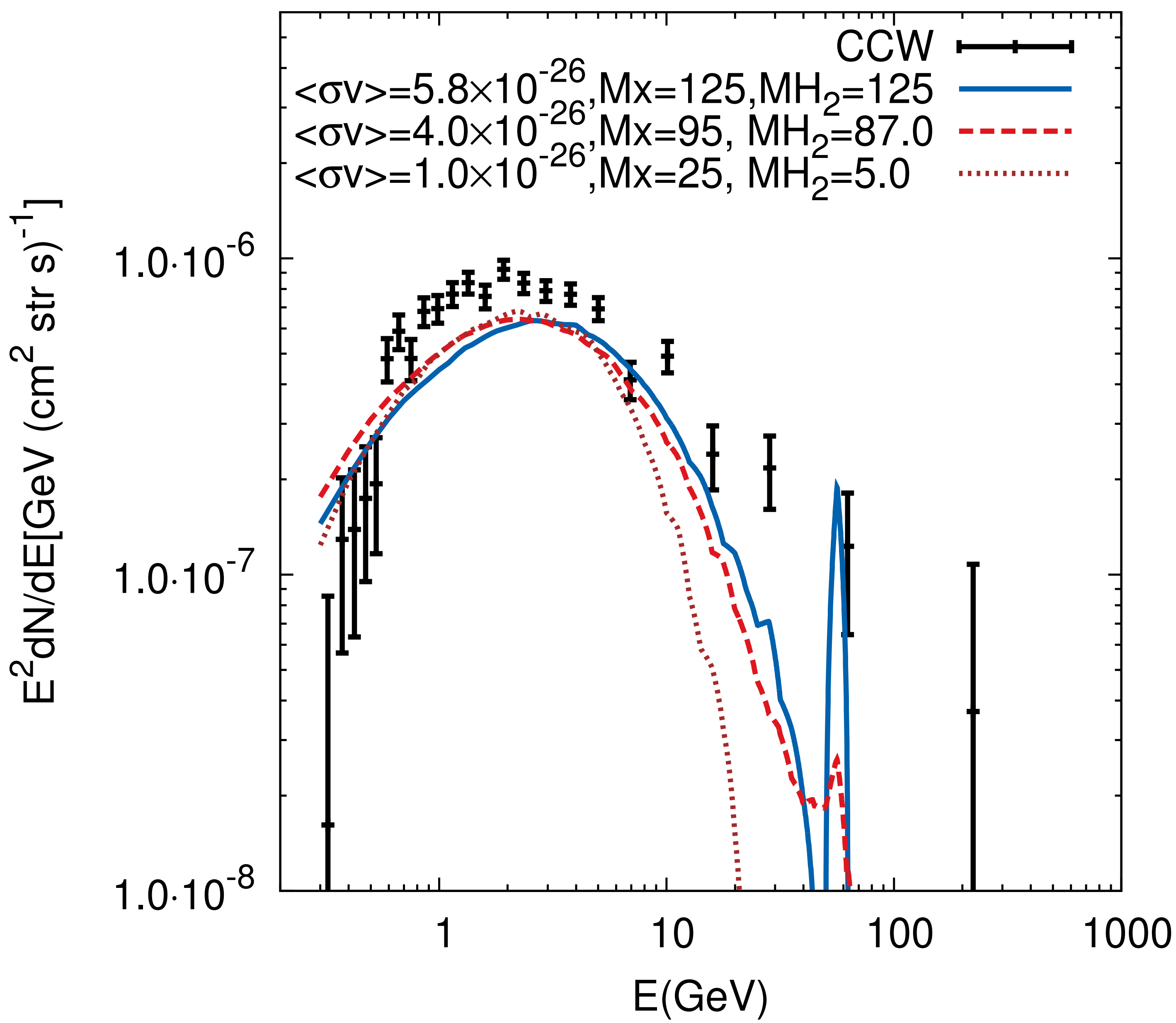


FIG. 2: Three illustrative cases for gamma-ray spectra in contrast with CCW data points [11]. All masses are in GeV unit and σv with cm^3/s. Line shape around $E \simeq M_{H_2}/2$ is due to decay modes, $H_2 \to \gamma\gamma, Z\gamma$.

This would have never been possible within the DM EFT

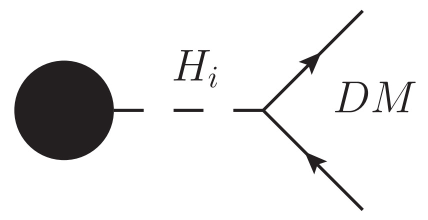
P.Ko, Yong Tang.
arXiv:1504.03908

Channels	Best-fit parameters	$\chi^2_{\rm min}/{\rm d.o.f.}$	p-value
$XX \to H_2H_2$ (with $M_{H_2} \neq M_X$)	$M_X \simeq 95.0{\rm GeV}, M_{H_2} \simeq 86.7{\rm GeV}$ $\langle\sigma v\rangle \simeq 4.0 \times 10^{-26}{\rm cm}^3/{\rm s}$	$22.0/21$	0.40
$XX \to H_2H_2$ (with $M_{H_2} = M_X$)	$M_X \simeq 97.1{\rm GeV}$ $\langle\sigma v\rangle \simeq 4.2 \times 10^{-26}{\rm cm}^3/{\rm s}$	$22.5/22$	0.43
$XX \to H_1H_1$ (with $M_{H_1} = 125{\rm GeV}$)	$M_X \simeq 125{\rm GeV}$ $\langle\sigma v\rangle \simeq 5.5 \times 10^{-26}{\rm cm}^3/{\rm s}$	$24.8/22$	0.30
$XX \to b\bar{b}$	$M_X \simeq 49.4{\rm GeV}$ $\langle\sigma v\rangle \simeq 1.75 \times 10^{-26}{\rm cm}^3/{\rm s}$	$24.4/22$	0.34

TABLE I: Summary table for the best fits with three different assumptions.

DM Production @ ILC

P Ko, H Yokoya, arXiv:1603.08802, JHEP



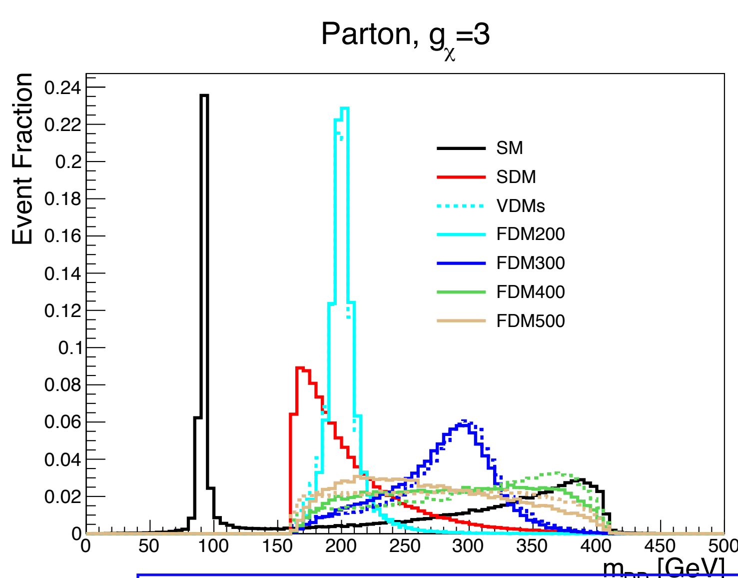
, $\quad t \equiv m_{DD}^2$

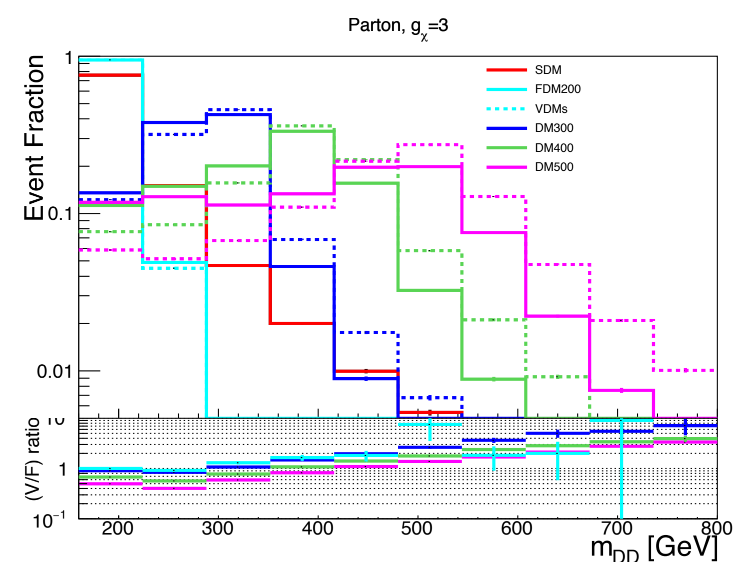
We consider $e^+e^- \to Z^* \to ZH_{i=1,2}$ followed by $H_i \to \bar{\chi}\chi$

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

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

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





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)

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

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

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

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

Unitarity is violated in EFT!

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).

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

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

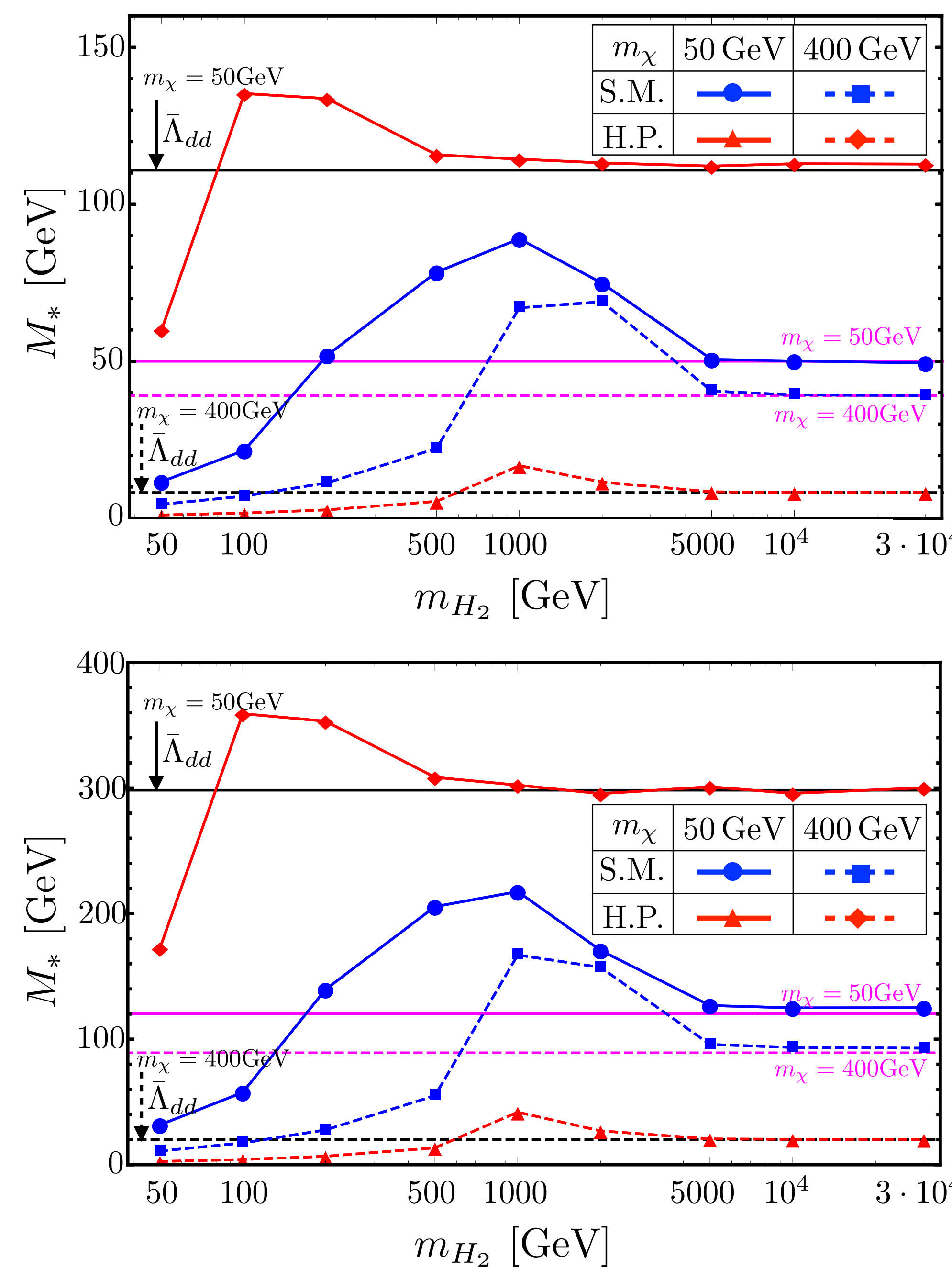


FIG. 3: The experimental bounds on M_* at 90% C.L. as a function of m_{H_2} (m_S in S.M. case) in the monojet+$\not{E}_T$ search (upper) and $t\bar{t} + \not{E}_T$ search (lower). Each line corresponds to the EFT approach (magenta), S.M. (blue), H.M. (black), and H.P. (red), respectively. The bound of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

Inelastic DM for XENON1T excess

S. Baek, Jongkuk Kim, P. Ko,
arXiv:2006.16876, PLB

Motivations for XDM

- In the usual real scalar DM with Z_2 symmetry, DM stability is not guaranteed in the presence of high dim op's induced by gravity effects

- Better to have local gauge symmetry for absolutely stable DM (Baek,Ko,Park,arXiv:1303.4280)

- Then XDM appears quite naturally $U(1) \to Z_2$ for both scalar and fermion DM cases

- NB : complex scalar DM for $U(1) \to Z_3$ [Ko, Tang, hep-ph:1402.6449, JCAP ; hep-ph:1407.5492, JCAP]

Motivations for XDM

- XDM : phenomenologically interesting possibility, used for interpretation of DAMA, 511 keV γ-ray & PAMELA e^+ excesses, and XENON1T excess, muon (g-2), etc

- Constraints from DD and Colliders are different

- Co-annihilation could be important for relic density calculations

- Usually the mass difference btw XDM & DM is put in by hand, by dim-2 for scalar and dim-3 for fermions DM cases, and dark photon is introduced

- However such theories are mathematically inconsistent and unitarity will be violated in some channels, when (X)DM couples to dark photon

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 : Current is not conserved

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

Similarly for the fermion DM case

$\Delta\ \overline{\psi^C}\psi$: **breaks U(1) explicitly**

Without dark Higgs

P.Ko, T.Matsui, Yi-Lei Tang, arXiv:1910.04311, Appendix A

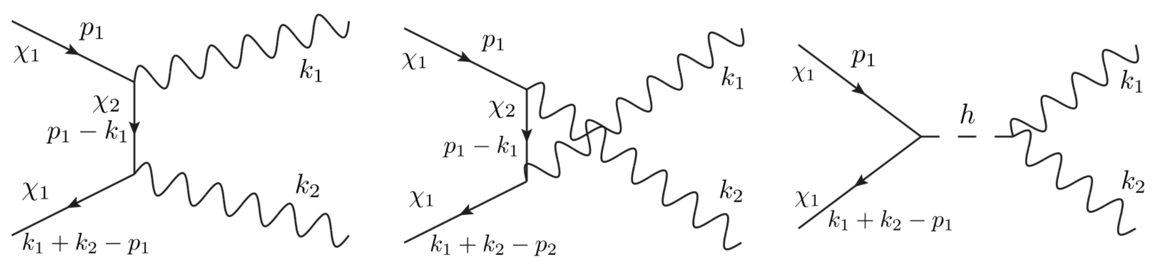


Figure 9: $\chi_1\chi_1 \to \gamma'\gamma'$ diagrams. Compared with the Higgsless soft-breaking model, the third diagram arises in our model

- Only the first two diagrams if the mass gap is given by hand
- The third diagram if the mass gap is generated by dark Higgs mechanism
- Without the last diagram, the amplitude violates unitarity at large $E_{\gamma'}$

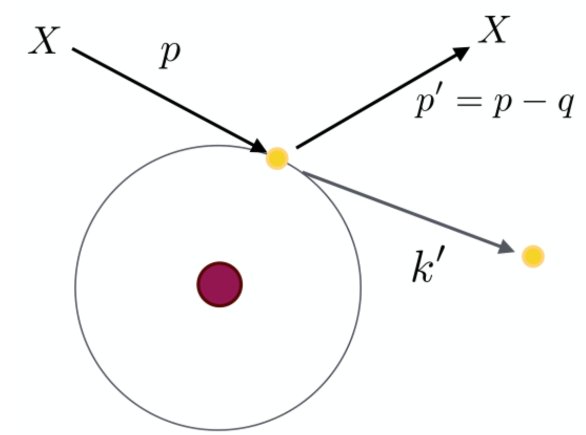
XENON1T Excess

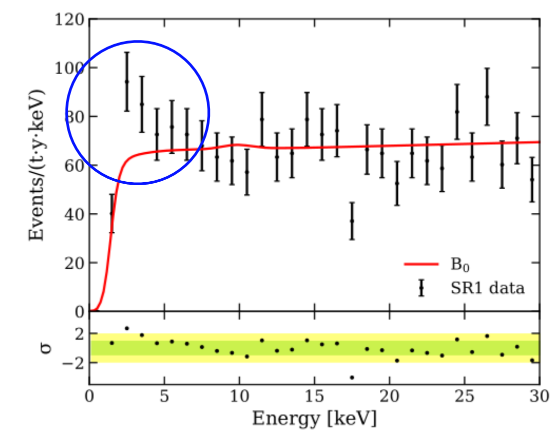
(Scalar XDM, Fermion XDM)

XENON1T Excess

- Excess between 1-7 keV
  - Expectated : 232 ± 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



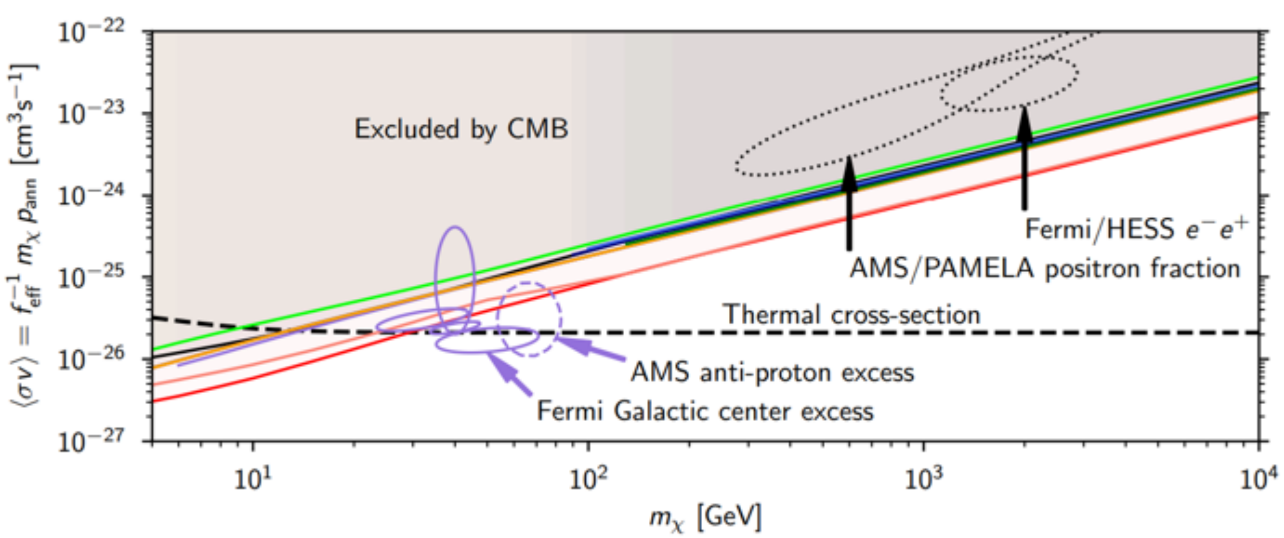


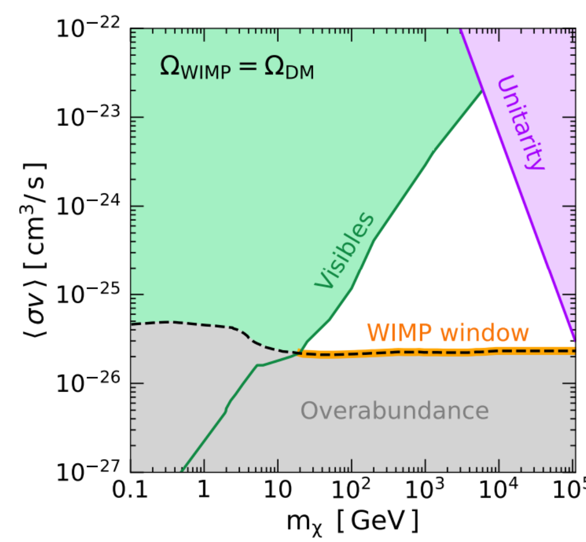
DD/CMB Constraints

- 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 $\langle \sigma v \rangle \sim \cancel{a} + b v^2$

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 !

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

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

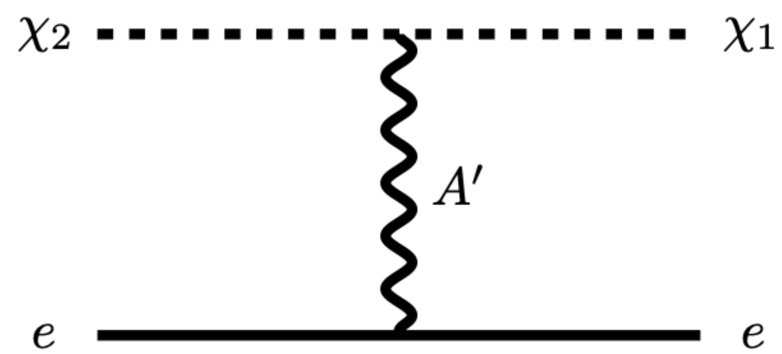


FIG. 1. Inelastic scattering of the heavier DM particle χ_2 off the electron e into the lighter particle χ_1, mediated by the dark photon A'.

- 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

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

(P-wave annihilation)

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

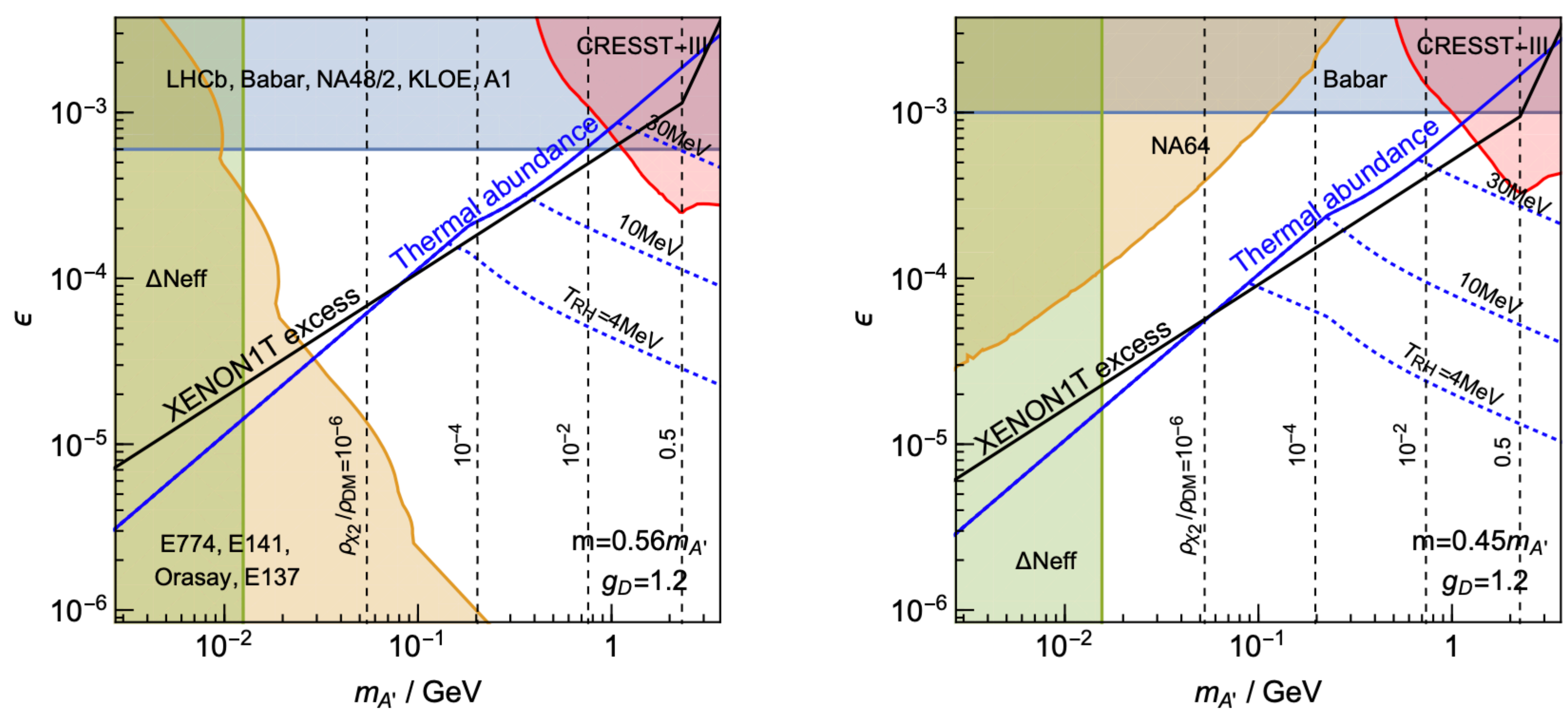


FIG. 4. The required value of ϵ to explain the observed excess of events at XENON1T in terms of the dark photon mass $m_{A'}$ (black solid lines). The left and right panels correspond to the cases of $m > m_{A'}/2$ and $m < m_{A'}/2$ respectively. We assume $g_D = 1.2$ in both cases. The blue lines denote 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.

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 $v_\phi \neq 0 : X \to -X$

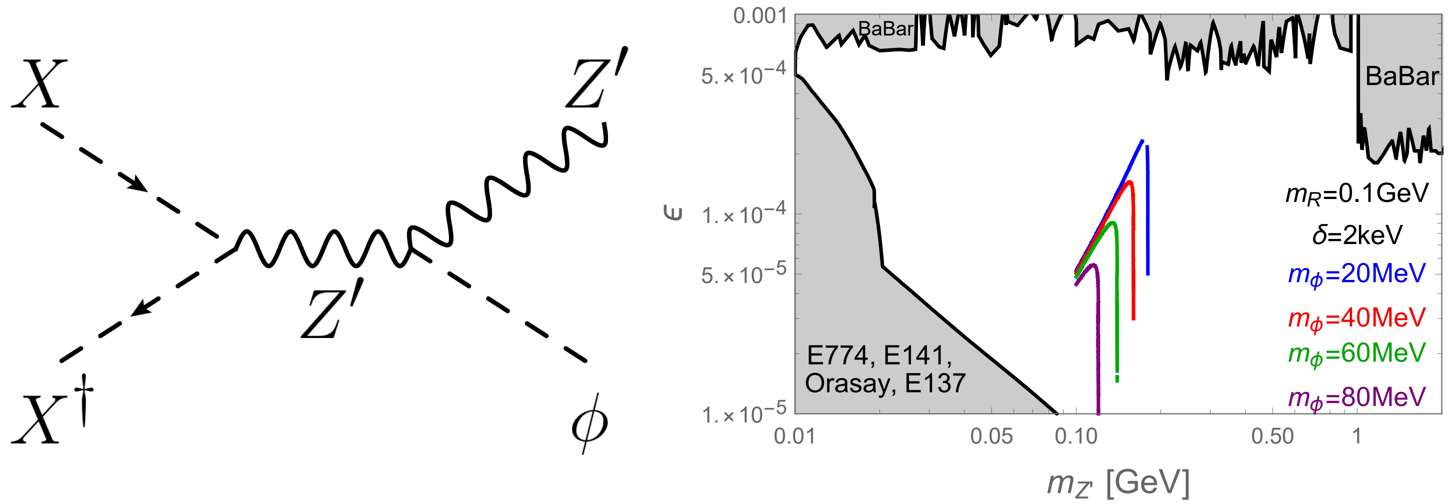


FIG. 1: (*left*) Feynman diagrams relevant for thermal relic density of DM: $XX^\dagger \to Z'\phi$ and (*right*) the region in the $(m_{Z'}, \epsilon)$ plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for scalar DM case for $\delta = 2$ keV : (a) $m_{\rm DM} = 0.1$ 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 : $XX^{\dagger} \to Z^{\prime *} \to Z^{\prime}\phi$

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

Fermion XDM (χ_R & χ_I)

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

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

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

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

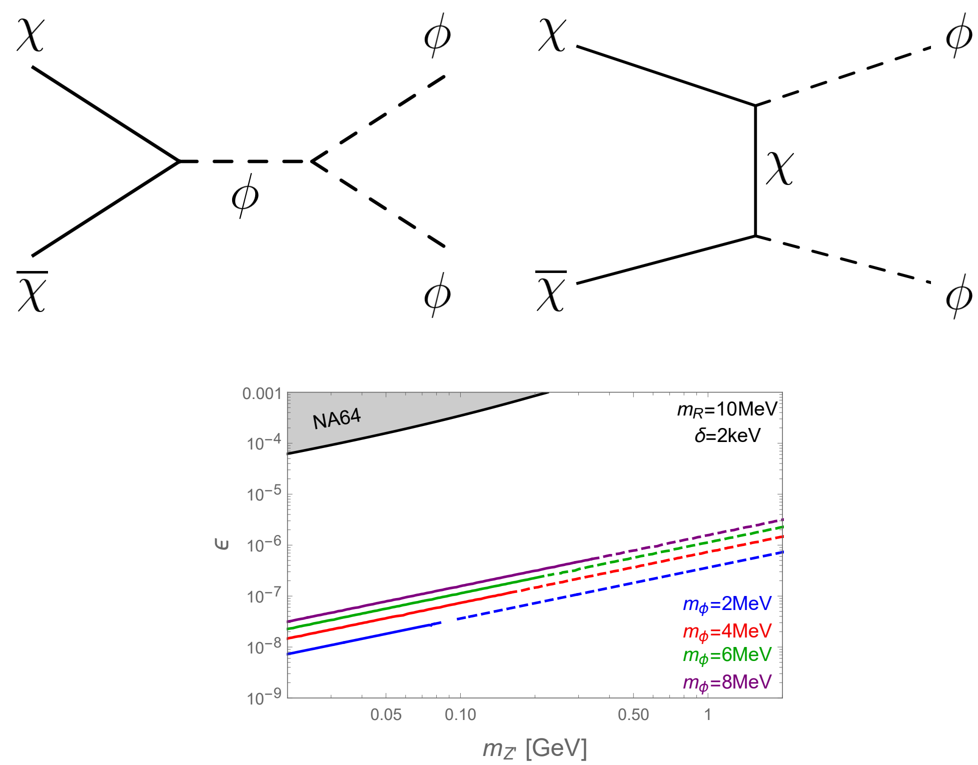


FIG. 2: (*top*) Feyman diagrams for $\chi\bar{\chi} \to \phi\phi$. (*bottom*) the region in the $(m_{Z'}, \epsilon)$ plane that is allowed for the XENON1T electron recoil excess and the correct thermal relic density for fermion DM case for $\delta = 2$ keV and the fermion DM mass to be $m_R = 10$ MeV. 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 : $XX^\dagger \to Z'^* \to Z'\phi$

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

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

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

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

Takehome Messages

- Assuming a single operator can explain everything is an oversimplified assumption (could produce wrong results)

- Huge number of data from (astro)particle physics and cosmology

- Better to construct a mathematically consistent minimal (Occam's razor) model before doing phenomenology

- Depending on the numerical values of parameters (masses, couplings), one can test the model using both particle physics and cosmology (e.g., DM + H_0 + σ_8)

- Get along well with EFT approaches vs. UV completions