Scalar DM from non-minimal CHMs

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1. CHMs

SM: very strong but cannot explain everything:

UV
↓ large corrections to m_H^2
EW scale

fine-tuning: $\frac{v^2}{f^2}$, need $f \sim$ TeV

solution: in CHMs, Higgs is a bound state

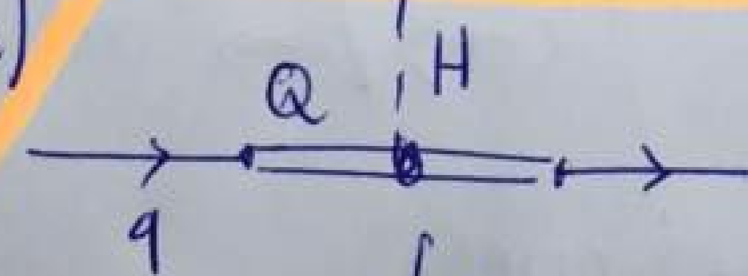
$f \sim$ TeV ——— G/H → H is pGoldstone ——— EW

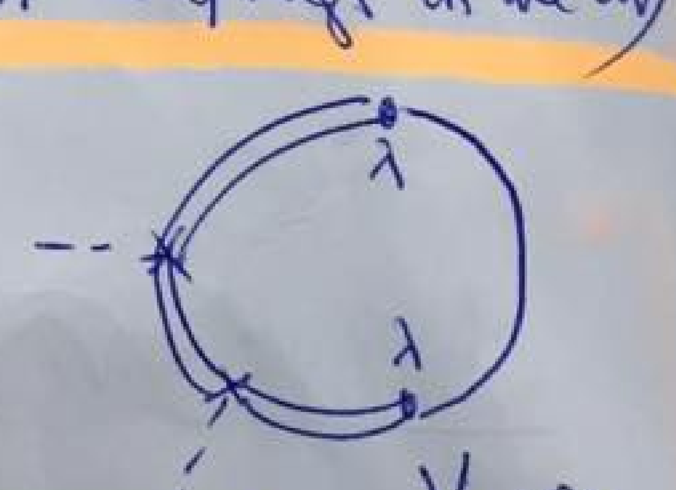
~ QCD-like: $SU(2)_L \times SU(2)_R$ ——— p, n (~1 GeV)
↓
$SU(2)_V$ ——— $\pi^0, \pi^\pm$ (~100 MeV)

only term that explicitly breaks symmetry: $\mathcal{L} \sim \lambda \bar{q}_i \mathcal{O}_F^i$ (strong sector condensate) $\to \lambda[\text{TeV}]\, \bar{q}_i Q^i$

(non-hierarchical coupling in the UV)

$y_q \sim \left(\frac{\lambda}{m_Q}\right)^2$





potential depends on this term ∴ depends on the quantum nrs of Q.

minimal model: $SO(5)/SO(4)$ (to preserve symme…

↓ beyond

NM CHMs

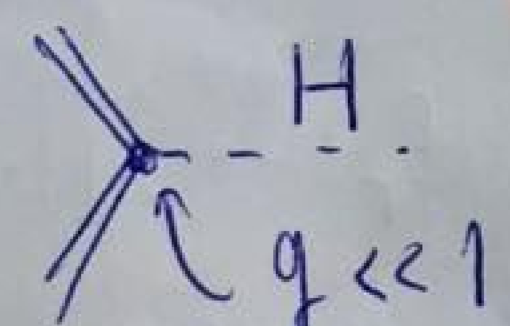
- more abundant
- better evade constraints
- 4-dim UV completions (smallest: $SO(6)/SO(5)$)
- lead to anomalies (access to UV)
- new pheno (FCNC, new decays of VLQs → allow smaller tuning)
- DM, EWB, ...

2. Composite DM

standard WIMP paradigm:

WIMP:
$$\Omega h^2 \sim \frac{330\,fb}{\langle \sigma v \rangle} \approx 0.1 \left(\frac{0.01}{g}\right)^2 \left(\frac{M}{100\,\text{keV}}\right)^2$$

DD
($M \gtrsim 10$ GeV)



$\langle \sigma v \rangle \downarrow \Rightarrow$ overproduce DM

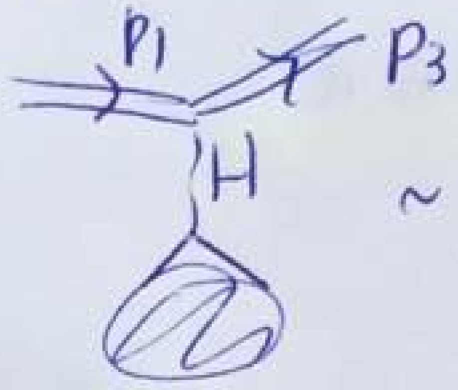
Motivations from CHMs
(with $\mathbb{Z}_2$ symmetry)

long-lived mediators: 1812.04628

① 1 mechanism to explain $\Lambda(DM) \sim EW$ (WIMP miracle) we can have $\lambda_{SM} \sim 0$

while new interactions $\frac{1}{f^2}(\partial\eta)^2 H^2 \sim \frac{m_\eta^2}{f^2}$

produce Ω^{obs} — negligible at such DD



$\sim \frac{t}{f^2}$

③ scalar sector is the one we know less;
most likely, there is new physics.
If DM is scalar, need to embed in
CHM or SUSY to avoid hierarchy problem.

④ $\mathbb{Z}_2$ symmetry:

in σ-model [symmetric cosets]

↳ need to choose specific representation (1 choice)

↓ then we can have automatically $\lambda_{\eta H} \sim 0$

$27 \oplus 1$, $\mathbb{Z}_2$ } ⇒ $\mu_\eta^2 > 0$, $\lambda_{\eta H}$ small

$\mu_\eta^2 > 0 \Rightarrow$ DM does not gain a VEV

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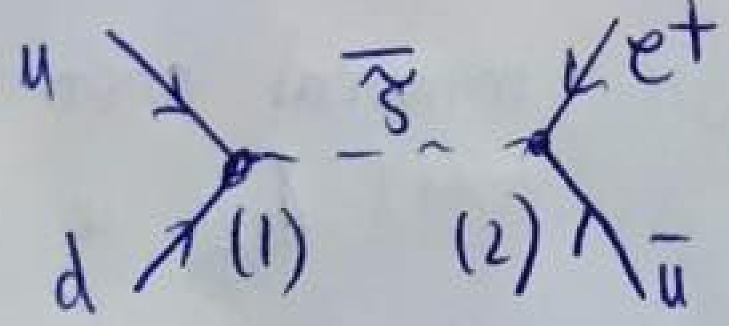
a comparison with R-parity:



↩ avoiding the proton decay

but can just avoid

(1): baryon parity

or (2): lepton parity

→ DM in SUSY does not really arise as a result of

→ as many, CDM provides a rationale for the WIMP to be @ EW

but | CHMs are much more predictive |

literature : SO(6)/SO(5) from 2012

: SO(7)/SO(6)

: SO(7)/G2

: ⋮

but, in all: ———

———

———

——— ← DM

no theoretical motivation: $\sim \lambda \bar{q}_i Q^i$

$$\frac{m_n}{m_i} \sim \frac{y_t}{y_b}$$

~~and~~ the complementary can be experimentally ~~prefe~~ preferred

3. Case of study: | SO(7) → SO(6) |

(new exotic | channels of annihilation)

· minimal anomaly-free CHM, not to spoil Z_2 in the UV.

$$\mathcal{L} = \frac{1}{f^2}\left[(\eta\partial_\mu\eta)(\partial^\mu|H|^2) + k\partial^\mu k) + (k\partial_\mu k)\partial^\mu|H|^2\right]$$

$$- \frac{\lambda_{\eta H}}{2}\eta^2|H|^2 - \frac{\lambda_{\eta k}}{4}\eta^2 k^2 - \frac{\lambda_{kh}}{2}k^2|H|^2$$

$$+ \left(c_\eta \frac{\eta^2}{2f^2} + c_k\frac{k}{f}\right)\sum_q y_q \bar{q} H q$$

Two Regimes

(I) composite resonance that couples to q_L transforms in 27 (symmetric) and " bRu in 1

$$V = \mu_H^2|H|^2 + \lambda_H|H|^4 + \lambda_H f^2\left[\frac{1-2\varepsilon}{3-\gamma^2}\right]\eta^2$$
$$+ \frac{1}{2}\lambda_H\eta^2|H|^2 + \lambda_H f^2\left[\frac{(1-2\varepsilon)(\gamma^2-1)}{\gamma^2-3}\right]k^2$$
$$+ \frac{1}{2}\lambda_H(1-\gamma^2)|H|^2 k^2$$

~~[illegible]~~ $\Rightarrow m_k < m_\eta$ for natural values $\gamma\in[0,1]$

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anyways, $\gamma<\sqrt{3}$, otherwise $\mu_\eta < 0$ & gains VEV and $\gamma\in[1,\sqrt{3}]$: $m_k > m_\eta$.

$\Rightarrow$ 2 unknown parameters $\rightarrow m_k, m_\eta$
$\rightarrow f(m_k, m_\eta)$

$\lambda_{H\eta} = \lambda_H$
$\lambda_{k\eta} = 0$.

(II) $q_L \oplus q_R = 7 \oplus 7$

un predictive, still:

$\# \eta^2$ and $\# \kappa^2 (1-\delta^2)$ so $m_\kappa < m_\eta$

$$V = c_1 [h^2 f^2 + \eta^2 f^2 + \kappa^2 (1-\delta^2) f^2] + \frac{c_2}{2} h^2 f^2$$

and
$$V = \mu_H^2 |H|^2 + \lambda_H |H|^4 + \frac{1}{2} m_\eta^2 \eta^2 + \frac{1}{2} m_\kappa^2 \kappa^2 + \frac{1}{2} \lambda_{\eta H} \eta^2 |H|^2 + \frac{1}{4} \lambda_{\eta\kappa} \eta^2 \kappa^2 + \frac{1}{2} \lambda_{\eta H} \left(\frac{m_\kappa}{m_\eta} \right)^2 \kappa^2 |H|^2$$

independent

can choose: $\lambda_{\eta H} = 0$, $\lambda_{\eta\kappa} = \lambda_H$, $f = 1, 2, \ldots$

note that: $\lambda_{\kappa H} \left(\frac{m_\kappa}{m_\eta} \right)^2 \sim \lambda_{\eta H}$

$\Gamma_H^{inv} \underset{\sim}{\Rightarrow} \lambda_{\eta H} < \lambda_H$ ✓ good

3.1) Relic Density

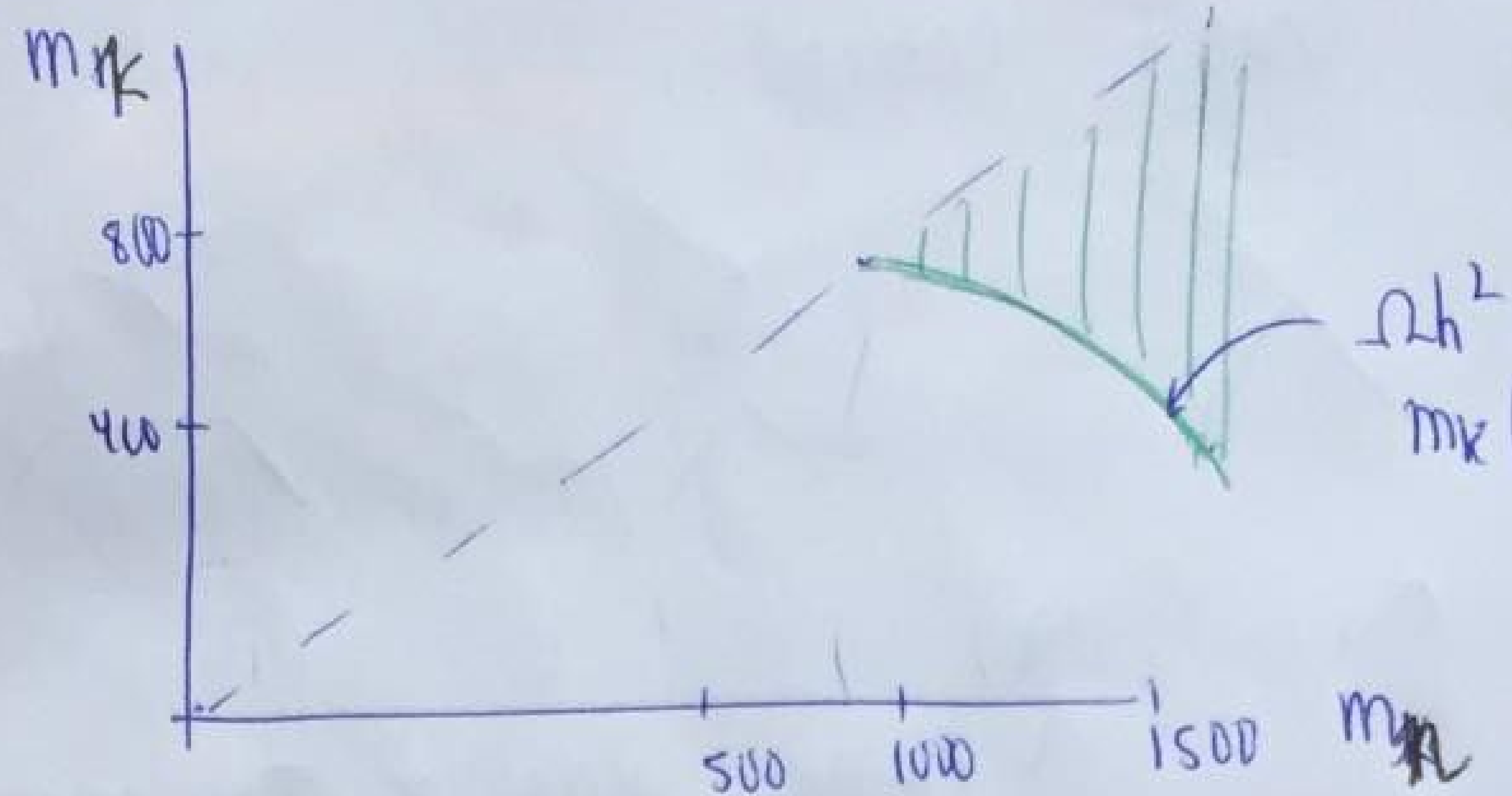
$v < 1$:

$$\sigma v (\eta\eta \to hh) \sim \frac{1}{64\pi m_\eta^2} \left[\lambda - \frac{4 m_\eta^2}{f^2} \right] \sqrt{1 - \frac{m_H^2}{m_\eta^2}}$$

as well as for EW bosons for $m_\eta \gg v$ [GET]

and $\eta\eta \to \kappa\kappa$

(I)



$\Omega h^2 = \Omega h^2_{obs}$
$m_K(m_\eta)$

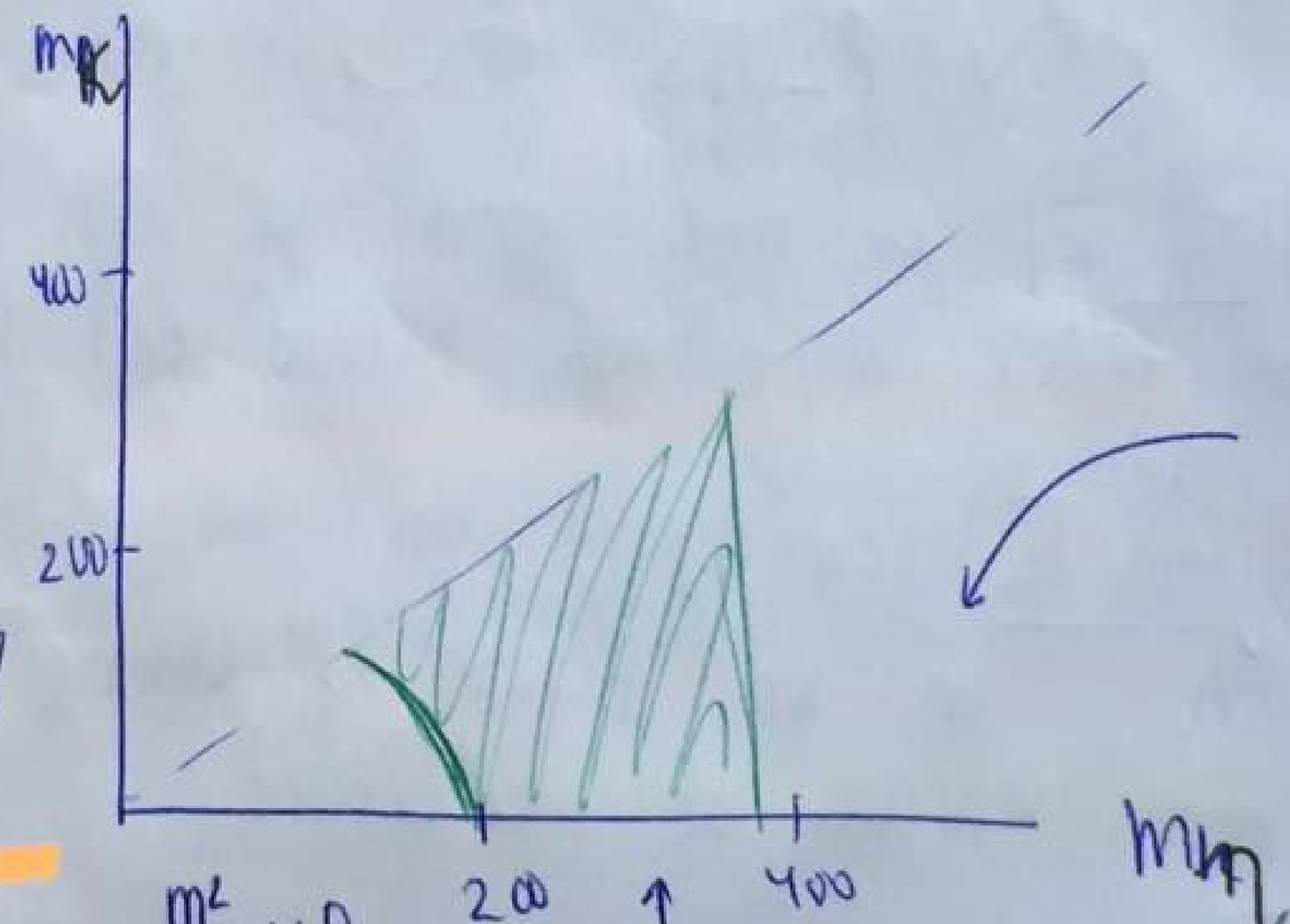
↑

$f \gtrsim 2$ TeV.

~~$2 \lesssim f \lesssim 4$ TeV~~

based on actual measure/

(II)



$\frac{m^2}{f^2}$ large

H

$\sim \frac{\lambda}{f^2}$

f = 2.5 TeV

$\frac{m^2}{f^2} \sim 0$

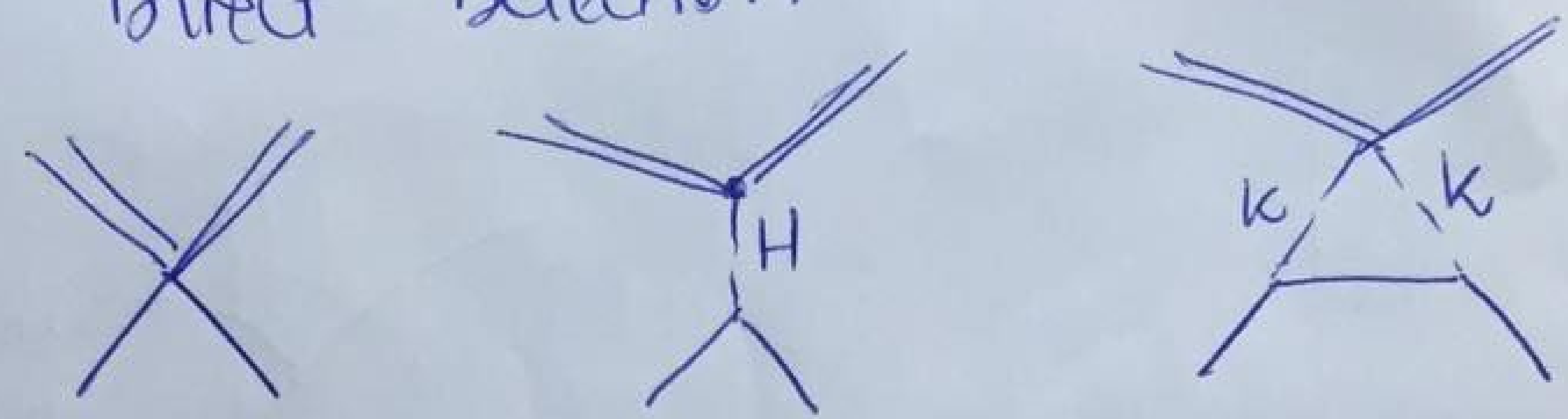
↑ interference

$\lambda_{\eta K} - \frac{m_\eta^2}{f^2} \Longrightarrow \downarrow \langle \sigma v \rangle \Longrightarrow \uparrow \Omega h^2$

f = 1 TeV : all white (still consider it for non-thermal relic)

[MICROMEGAS with CALCHEP and model from FEYNRULES]

4.2) Direct Detection



$\sigma_{SI}(\ldots, a_q)$

{ effective $\eta^2 q\bar{q}$ at low-energy

tree-level: c_η and $\lambda_{\eta H}$

if they vanish: dominant contribution from loops of exotic scalar

left: Reg I ~> PLOTS ~> right: reg II ($\lambda^{H}_{[illegible]}=0$)

red: exclusion

blue: total

$m_k = m_\eta + \text{fit}$

- Reg I is fine and we will be able to test it with future colliders

here, we show: $m_k = 20$ GeV, $f = 2.5$ TeV

- Reg II ($c_\eta = 0$): won't be able to test it even in the future → strong motivation for searches at colliders

($\uparrow f$ or $\uparrow m_k \Rightarrow$ less constrained)

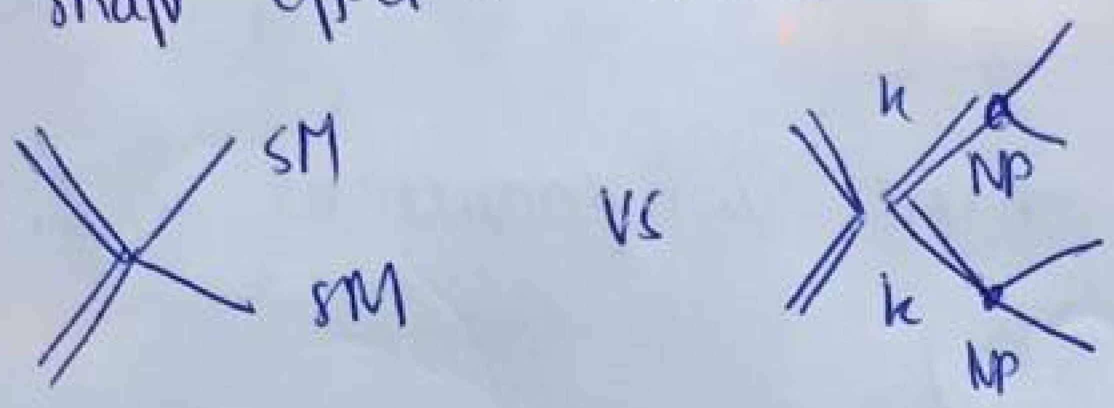
3) Indirect Detection

(focus on spectra of γ-rays) ↓ [MADDM v.3]
↑ obtained with MADDM v.3

(parton level: mg5; shower: pythia 8)

~ PLOTS ~

- shape effect: larger multiplicity → shift to left
(↓ nr high energy γ's)



(SM line: $0.5\, WW + 0.25\, HH + 0.25\, ZZ$
(cp absent))

- simulate the Fermi limits

MADDM includes the Fermi-LAT likelihoods of dwarf spheroidal galaxies (in Milky Way)

(combined analysis: no global excess [1611.03184])
↓
strong bounds

Good targets {
- proximity
- large DM density
- no observed evidence for non-thermal astrophysical processes that produce γ's

expected flux:

$$\phi(\Delta\Omega, E_{min}, E_{max}) \propto \frac{\langle \sigma v \rangle}{m_{DM}^2} \int_{E_{min}}^{E_{max}} \frac{dN_\gamma}{dE_\gamma} dE_\gamma \times J(\rho_{DM}, \Delta\Omega, \text{l.o.s.})$$

↳ for each point, contrast model with the observed flux.

· known dsphs have similar central DM densities:

J-factor $\sim D^{-2}$

· modelling: point-sources

(uncertainties included for NFW profile)

note: $\kappa \to$ leptons : very weak bounds

(in $\mathcal{L}_y$ no freedom for c_κ, but for $c_\kappa \sim (1-r^2)$ # ← can make it muonphilic)

4.4) Colliders signals

η, κ hard to produce at colliders (gauge singlets)

but can be produce in decay of heavy resonances (COMPOSITE NATURE)

e.g. B, T partners

lightest $m_* \sim f$

→ VLQs can be produced in pairs via QCD [model-independent]

- XS drops sharply with M
- also, $f \gtrsim 2$ TeV (to match to Ω^{obs})

↳ we do simulation for

all bounds can be rescaled { 100 TeV collider, $\mathcal{L} = 1\ ab^{-1}$

decay rates

$$27 = 1 + 6 + 20$$

(T) $\qquad + 1' + 1''$

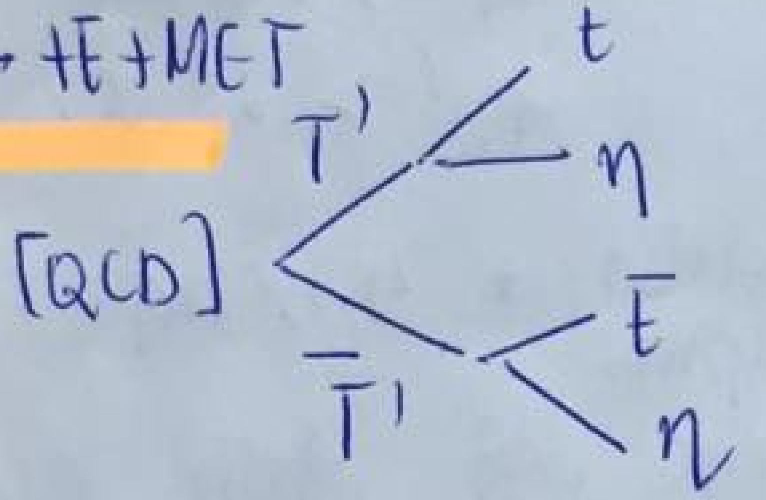
$\qquad (T') \quad (T'')$

$$\mathcal{L} = + \ldots + \left(f\, u^i u^j (\bar{Q}_L)_{ij}\, T_R \right) + h.c$$

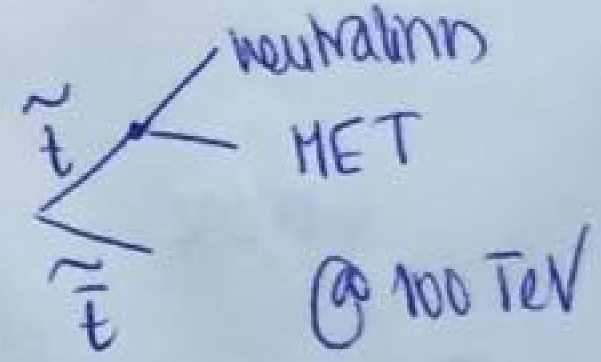
$$\rightarrow \quad = \ldots + \left[\frac{h}{\sqrt{2}} \bar{t}_L + i\, \gamma \frac{r}{f} k\, \bar{t}_L \right] T_R$$

analogously to B $\qquad \ldots + \frac{\eta^2}{f} \bar{t}_L T_R' + \ldots$

TT → tt + MET



recast



↓

$M \in [1, 9]$ TeV → $m_\eta \lesssim 2.5$ TeV excluded

only we this,
we cannot test non-minimality :
we need VLQ → k q (no analysis for 100 TeV collider)
(@LHC: 100 GeV ≲ m_k ≲ 400 GeV ↳ $b\bar{b}$)

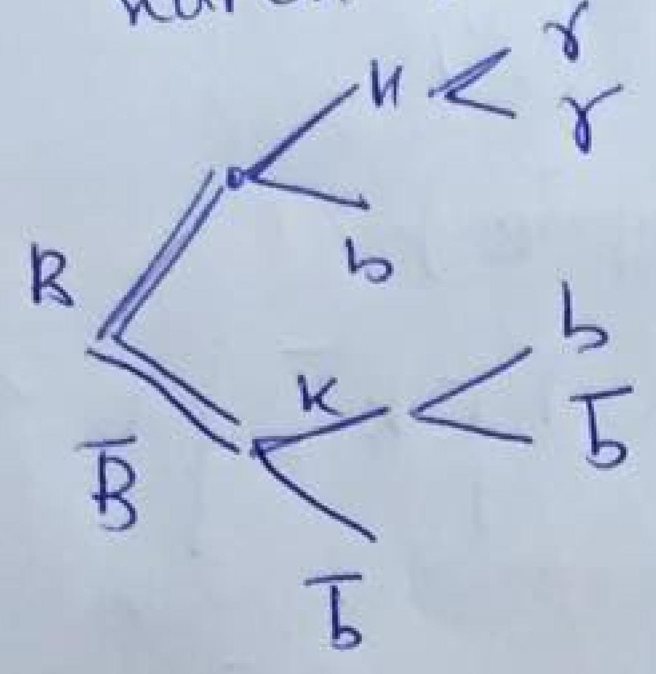
we develop dedicated searches
→ $pp \to BB \to kk\, b\bar{b}$ ~~(......)~~

further motivation: if T/B is light(st) resonance,
DM channel is absent

decay to k ↲
is only insight into composite structure

+ clean signature
+ adaptable to CHMs without DM

4.1 search for $\kappa\kappa \to \gamma\gamma b\bar{b}$



[shower: PYTHIA8 ;
routines: ROOT v5 &
FASTJET v3]

jets: anti-k_t with $R = 0.4$
$\varepsilon_{b\text{-tag}} = 0.7$

bkg: $pp \to b\bar{b}b\bar{b}\gamma\gamma$; $p_T^{b_1} > 500$ GeV
$p_T^{\gamma} > 20$ GeV

~~[crossed out]~~: require 2 isolated photons + 4 b-tags
veto all events with isolated leptons

reconstruction:

(1) $p_{\gamma_1}^{\mu} + p_{\gamma_2}^{\mu} \equiv p_{\kappa_1}^{\mu} \longrightarrow m_{\kappa_1}^{rec}$

(2) choose 2 b-tag jets with invariant mass $\sim m_{\kappa_1}^{rec}$
↳ $= m_{\kappa_2}^{rec}$

(3) to decide which b comes from each B, choose the combination that minimizes $|m_{B_1}^{rec} - m_{B_2}^{rec}|$
(m_{B_1}: 3-particle system)

~ PLOTS : $M = 5$ TeV, $m_K = 300$ GeV ~

really good discriminative power

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select events in:

$|m_{K_1}^{rec} - m_K| < 10$ GeV

$|m_{K_2}^{rec} - m_K| < 50$ GeV

$|m_{B_1}^{rec} - m_B| < 500$ GeV

$|m_{B_2}^{rec} - m_B| < 500$ GeV

we can get $S = \frac{s}{\sqrt{b}} > 2$ (can be probed with 95% CL)

4.2) search for $KK \to b\bar{b}b\bar{b}$

require no isolated leptons and at least 6 b-tagged jet

~~reconstruct 2 k's with the 4 b-tagged jets with smallest pT and choose~~

- b-tagged jets that reconstruct Ks are those minimizing $|m_{K_1}^{rec} - m_{K_2}^{rec}|$ among the 4 with smallest PT.

assign the other 2 to form the Bs,

- as before

⟹ is captured in this analysis