X Workshop ATLAS Italia

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Dip. Fisica and INFN - Milano, Italy

~ Dark

Hidden Sectors and all that…

… on the verge of LHC Run 2 start-up !

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Outline

- our starting point
- signature-based searches of BSM at LHC
- broad and (usual) strict definitions of Hidden (Dark) Sectors
- Hidden Sectors and the LHC
- (massive and massless) Hidden (Dark) Photons
- Hidden Sectors explaining Flavor hierarchy
- new Higgs signatures from Hidden Sectors
- Outlook

everywhere in my slides:
HS = Hidden Sector = Dark Sector
DP = Dark Photon = Hidden Photon
F (f) $\leftrightarrow$ Flavor index

where we stand today

(in one slide)

pp collisions: where we stand today

- LHC run at 7-8 TeV completed [$\int L \sim 5 + 20\ \mathrm{fb}^{-1}$/ exp]
  (just initial LHC phase !)
  amazing performance ➜ results well above expectations...
- SM tested at high accuracy in a new $\sqrt{s}$ range :
  QCD (many regimes), top physics, EW processes, flavor
- "direct" exploration of SM EWSB sector started up with observation of a (quite light) Higgs resonance !!!
- still a lot of room for a non-SM EWSB sector
- bounds on new heavy states predicted by many BSM models widely extended wrt pre-LHC era
- no real hint of BSM physics !
- SM Hierarchy-Problem solution getting harder...

SM-Lagrangian basics

SM gauge group :

$SU(3)_{QCD} \times SU(2)_L \times U(1)_B$

spontaneusly broken
via Higgs mechanism

$\rightarrow SU(3)_{QCD} \times U(1)_{em}$

Higgs Lagrangian :

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi^\dagger \phi) - \bar{\psi}_L \Gamma \psi_R \phi - \bar{\psi}_R \Gamma^\dagger \psi_L \phi^\dagger$$

masses fix all
Higgs interactions

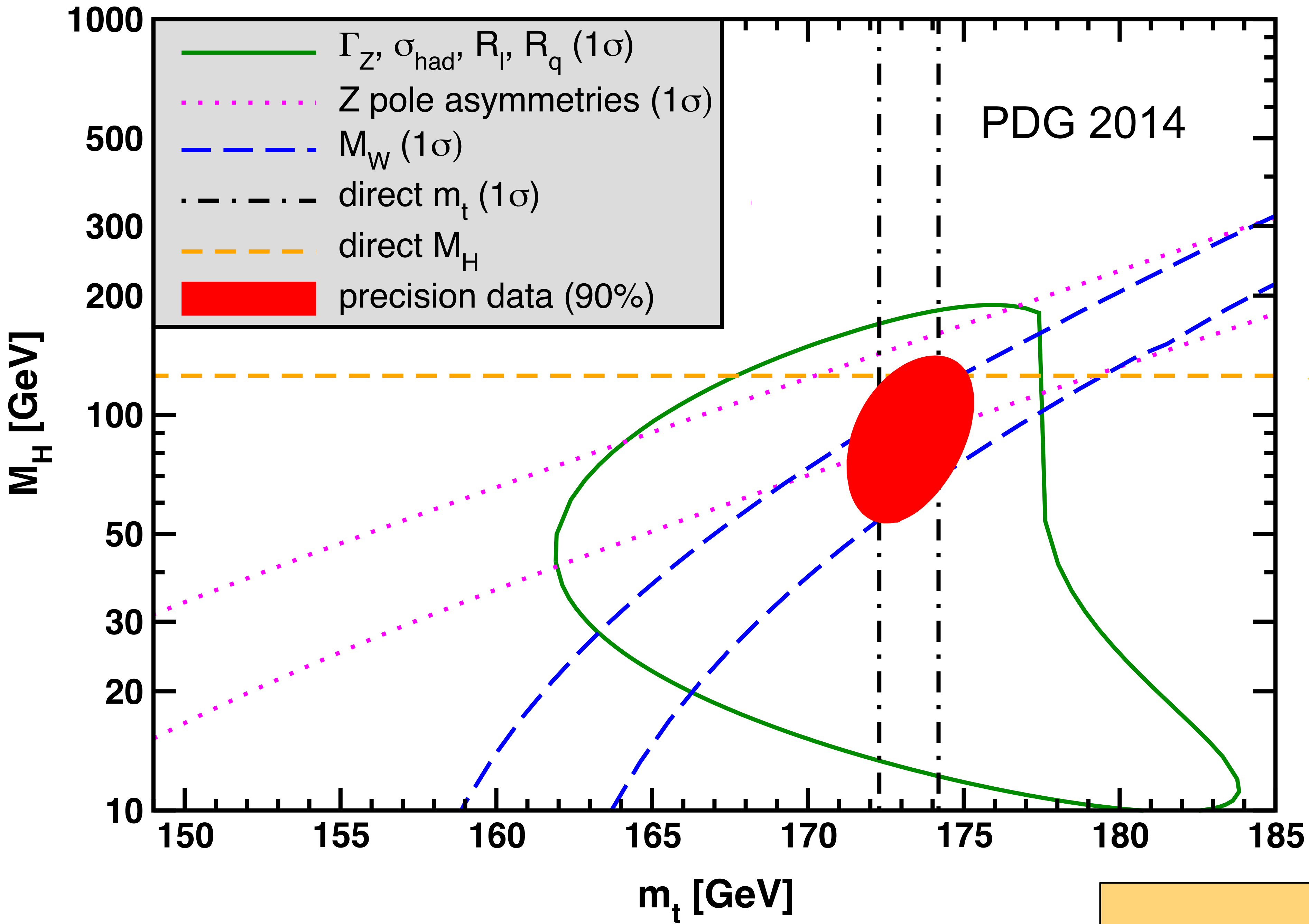
$$V(\phi^\dagger \phi) = \boxed{-\mu^2 \phi^\dagger \phi} + \frac{1}{2}\lambda(\phi^\dagger \phi)^2$$

$$m_H^2 = 2\mu^2 = 2\lambda v^2$$

built up just by imposing

- gauge invariance (L_{SM} singlet of SM group)
- renormalizability [D ≤4 operators]

Higgs observation ➜ triumph of SM (and LHC !)

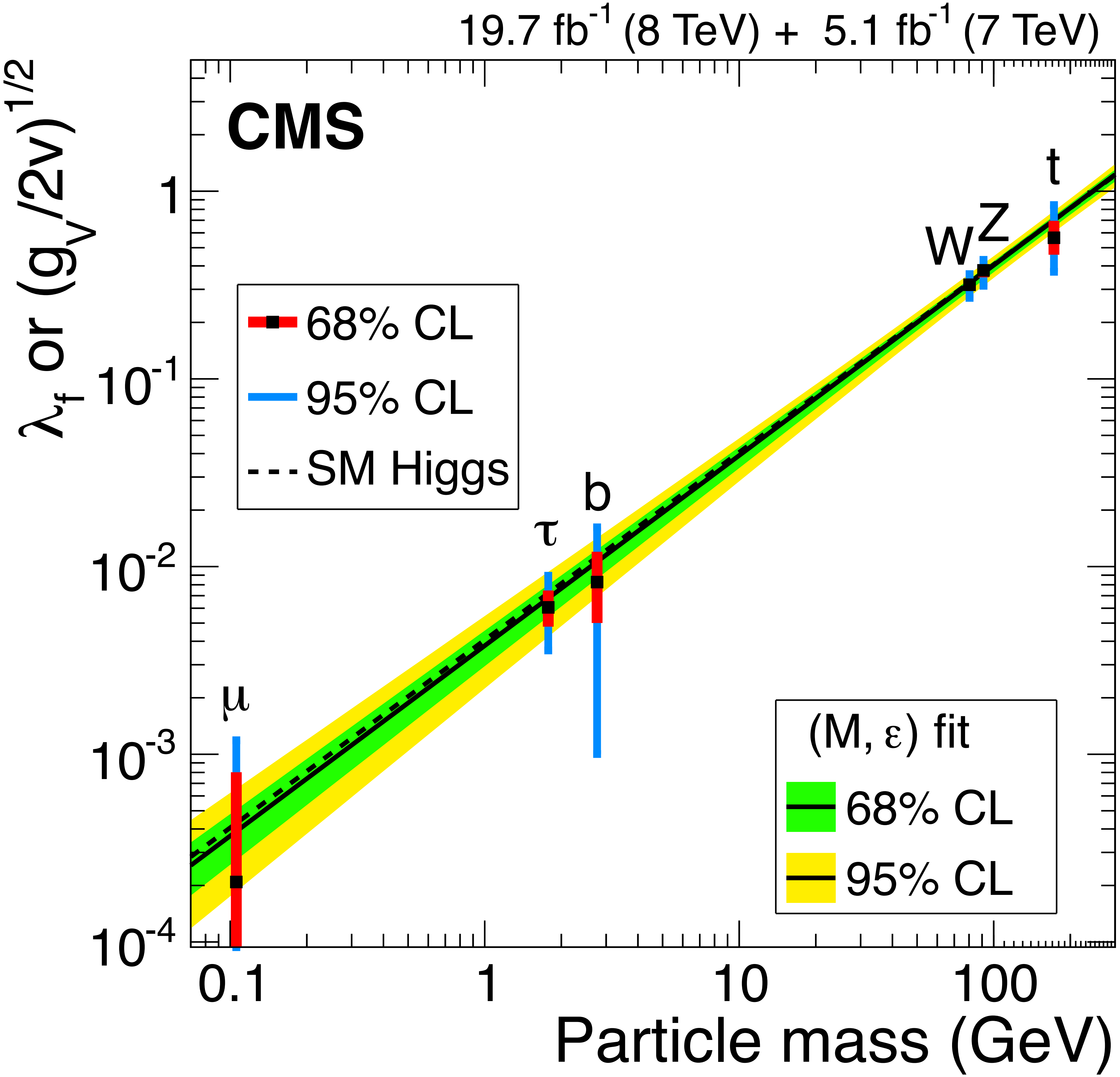


"invisible" width !
(m_H error band)

red area is 90% CL prediction from EWPTs

last missing SM state !

a clear SM footprint is emerging : $g_{HXX} \sim m_X^{(2)}$



it is not a generic scalar state!

SM pattern well matched within errors !

SM is not enough !

guiding principles to go BSM

- SM beautifully successful at $E < 1$ TeV,
but has some "messy features" (flavour sector...),
and does not explain a number of things
(strong CP, neutrino sector, baryogenesis, Dark Matter...)

- crucial issue for Collider Physics (and LHC !) :

what is the expected
Energy THReshold (E_{THR}) to go BSM ???

▷ quadratic divergences on fundamental-scalar mass

drive m_H to the next energy threshold E_{THR} !

→ to avoid Fine-Tuning of parameters, one expects roughly :

$$E_{THR} \sim m_H / g_{coupling} \sim o\ (1\ \text{TeV})$$

▷ this was (before LHC start-up), and STILL IS (after Run 1), a ROBUST statement !!!

WARNING !

the exact way E_{THR} materializes

(→ enters theory)

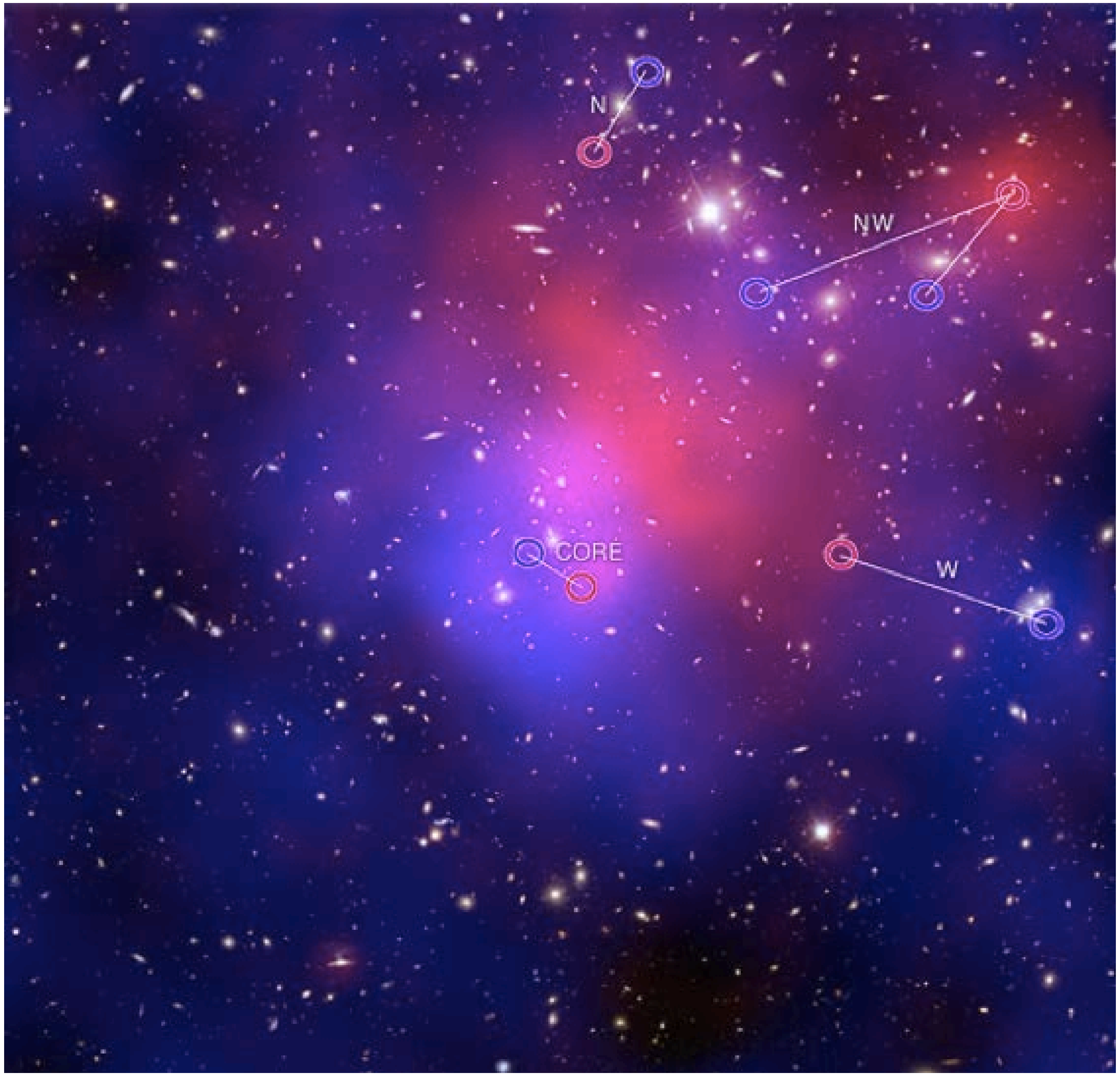
depends on the actual

(yet unknown !) SM extension

- after LHC Run I, Simplest Versions of "PROPOSED" Models look quite Fine-Tuned !

a ROBUST statement too !!!

25 % of matter in the Universe is DARK !
(non relativistic, non baryonic, non luminous)
➜ *WIMP interpretation of DM* *widens LHC potential for New Physics !*



collisions between galaxy clusters

Abell 2744:
Pandora's Cluster;
3.5 billion light years away;
5.9 million light years across;

Blue : mostly dark matter, via gravitational lensing (HST+VLT+Subaru)

Red: gas with T's of millions of degrees (Chandra X-ray)

ingredients to optimize BSM coverage at the LHC

- highest collision cm energy and luminosity to produce heavy states with moderate production coupling

- highest ability to separate S from B, in particular in high-p_T tails and m(i,j) distributions (revealing scattering exchange of new states)

- highest ability to cover stealthy kinematical configurations (mass degeneracies, soft final objects …)

- exploiting as much as possible signature-based searches!

most valuable activity in
BSM model building is suggesting
new kinds of signatures !
(help pushing LHC discovery potential in
a model-independent way …)

Hidden Sector models

chart the way

in devising

new kinds of signatures

to look for !

Hidden Sector

"LOOSE" definition :

"what is actually missing in the SM"

(apart from gravity)

SM ⟷ HS

(possibly quite interacting !)

in principle rich internal structure and interactions

"too heavy"

"too weakly coupled"

"undetected by exp.s"

(or combinations of)

Hidden Sector

("LOOSE DEF.")

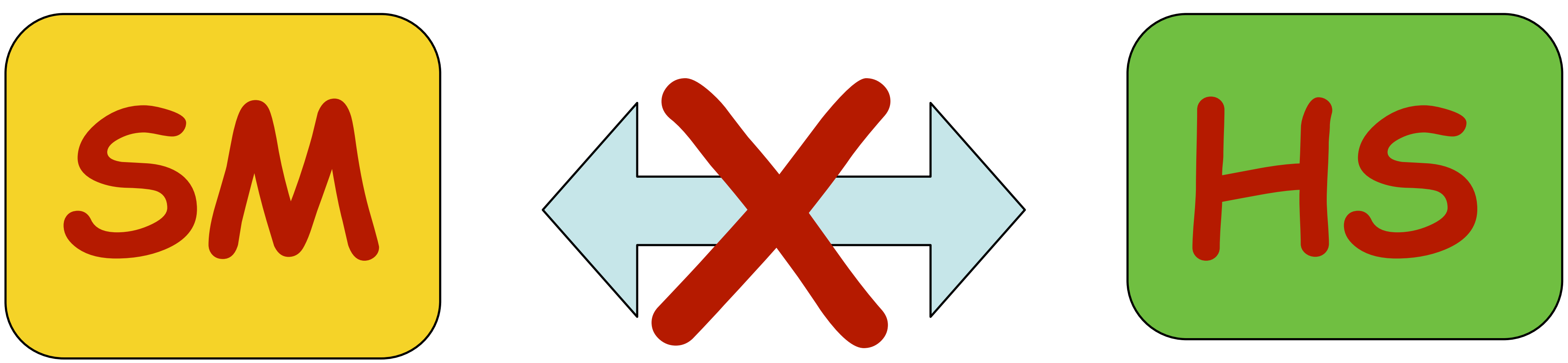
ex: SUSY partners could be presently in this class, Dark Matter is surely there !!!

"STRICTER" definition of HS :

(the usual one ...)

"Sector UNCHARGED (= singlet) under SM gauge group (and vice versa)"

at tree level in general :



but 4D terms $L \sim [SM]_{singlet} \times [HS]_{singlet}$

in Lagrangian possible in a few cases !

(see next slides → → →)

in principle rich internal structure and interactions

typically:

"more weakly coupled than SM"

(needs messengers)

Hidden Sector

("STRICT DEF.")

ex: SUSY partners are not in this class ,
DM might be there or not !

3 kinds of interactions connecting SM $\leftrightarrow$ HS

- Mixing of gauge neutral particles ➜ $U(1)_{SM} \leftrightarrow U(1)_{DP}$

  (photon $\leftrightarrow$ Dark Photon) [D=4, renormalizable ($m_{DP} \neq 0$)]

- new HS scalars ϕ interacting with SM Higgs

  ~ $\phi^\dagger \phi H^\dagger H$ (Higgs-portal type) [D=4, renormalizable]

- higher-dimensional [D > 4] operators :

  $$L \sim 1/[E]^{(D-4)} \quad [SM]_{singlet} \times [HS]_{singlet}$$

  [suppressed by large E scale (mediator masses ?)]

  many many possibilities (axion-like enters here) !

$$\boxed{\text{crucial parameters are (in principle unconstrained) HS masses, couplings, mixing angles !!!}}$$

HS phenomenology at LHC

- very rich phenomenology both at LHC and lower-energy experiments [if mass-scale/couplings at reach]
- weak couplings of HS to SM can give rise to stable or long-lived states
  on the length scale of LHC detectors !
- a quite weak point (!):

usually not a very predictive framework !

➜ long list of (~ implicit !) assumptions needed

➜ every study tends to be dependent on quite a few parameters …

FOCUS on Dark Photon (DP) from extra U(1)

- HS can contain light or massless gauge bosons (Dark Photons, DP) mediating long-range forces between Dark particles

- present studies mainly involving "massive" DP

- a massive DP interacts with SM matter mainly via "kinetic mixing" with SM hypercharge U(1)$_Y$ gauge boson :

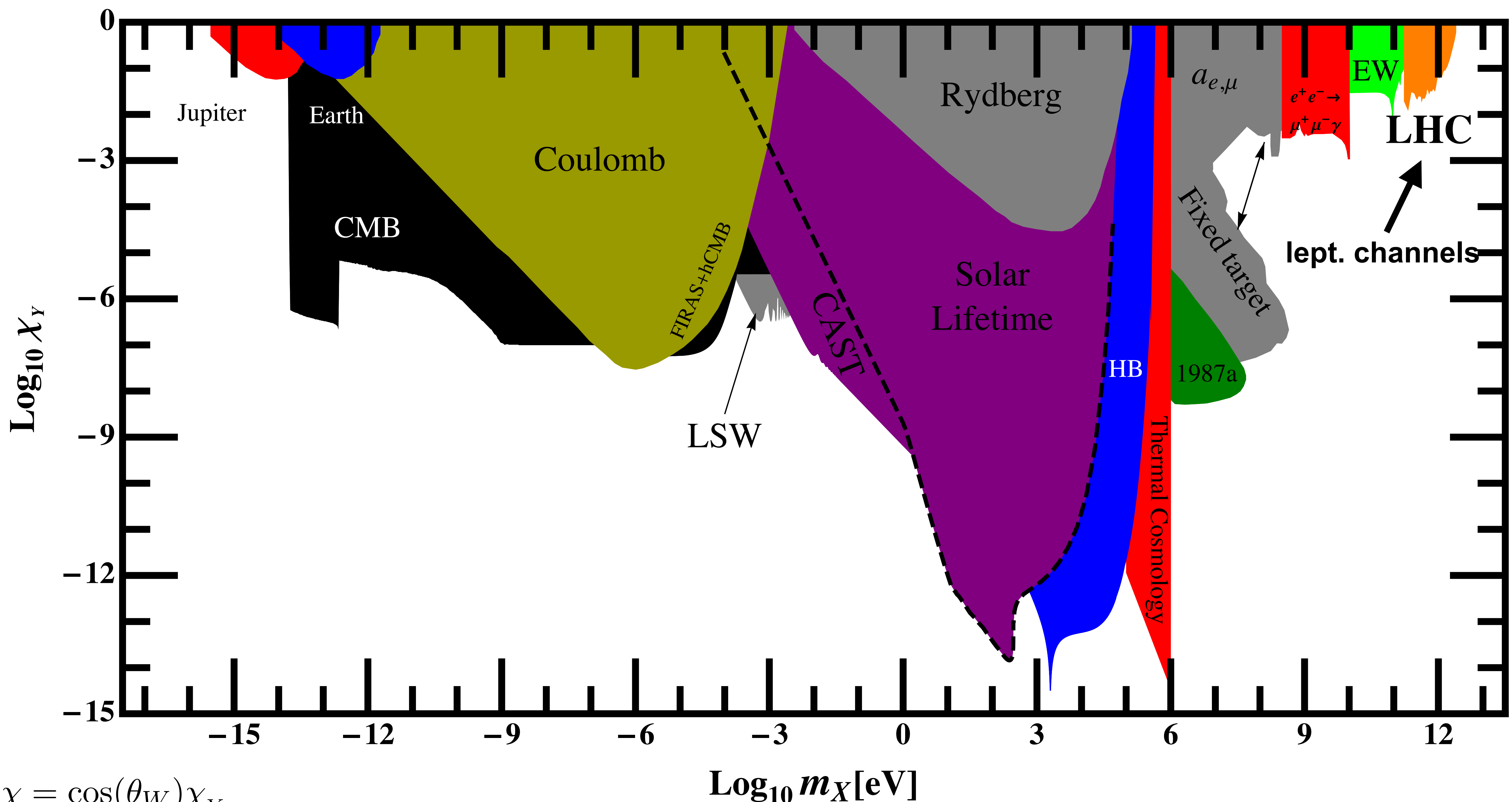
  $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ [U(1) gauge invariant]

4D interac. between field-strengths of two different U(1) allowed ➜ $\mathcal{L}_{mix} = \chi B_{\mu\nu} C^{\mu\nu}$

mixing param.

➜ DP couples to SM particles with strength $-\chi e Q_{el}$

exp bounds on massive DP (Z')



$$\chi = \cos(\theta_W)\chi_Y$$

$$m_X^2 \ll m_Z^2$$

in Field and String Theories wide range of kinetic-mixing parameters predicted : $\chi_Y \sim 10^{-12}$ to 10^{-3}

WARNING !

if $U(1)_F$ unbroken ($\rightarrow$ massless DP)

no such constraints !

(on-shell DP decoupled from SM)

(off-shell) massless DP can interact

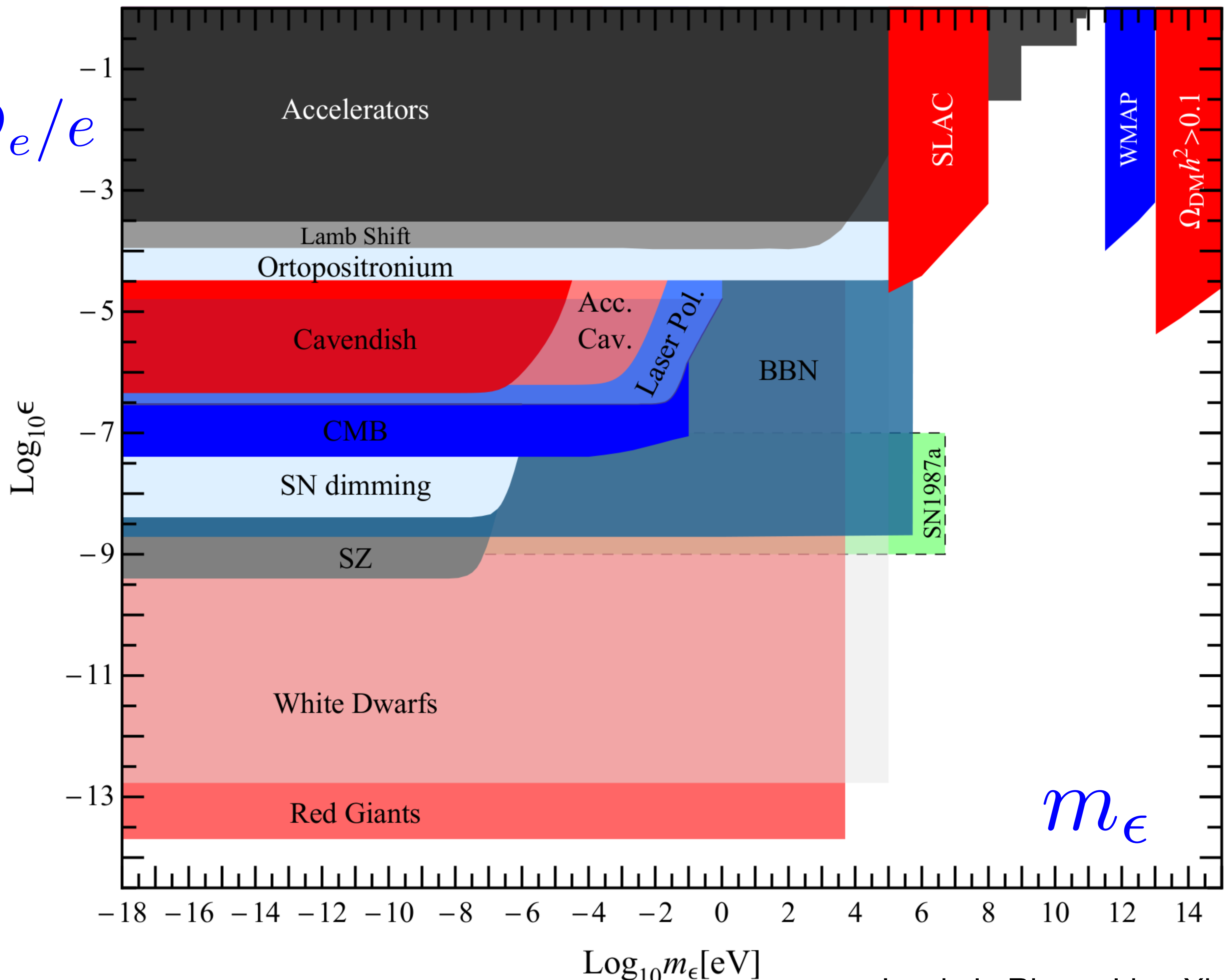
with SM sector only through

higher-dimensional (i.e. quite suppressed)

interactions !

HS matter charged under hidden U(1) can get small electric charge !

$$\epsilon = Q_e/e$$



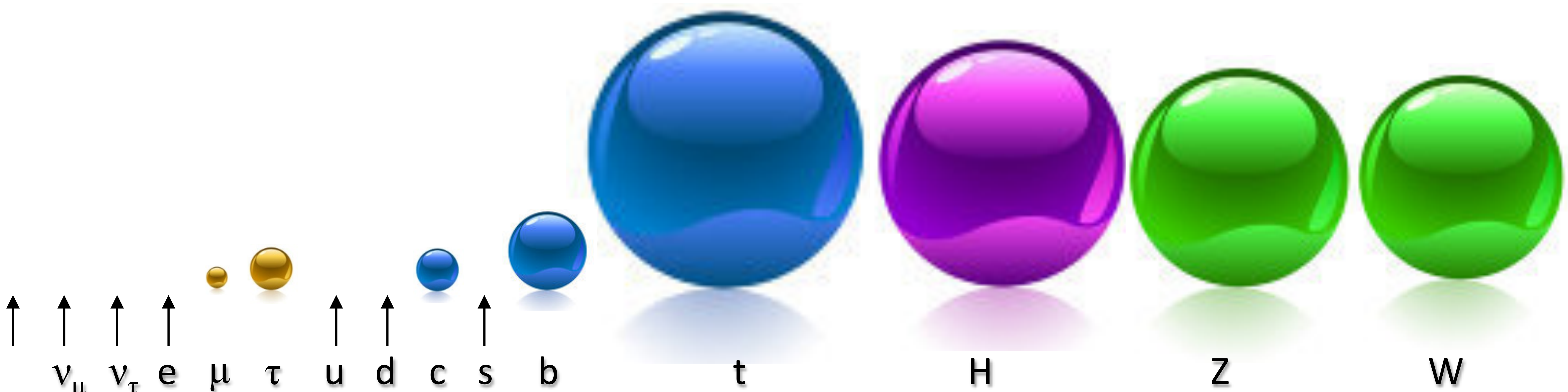
Summary of limits from cosmology, astrophysics, and laboratory-accelerator-fixed targets-experiments

Jaeckel, Ringwald, arXiv:1002.0329

Mystery in Hierarchy of SM Yukawa's

$$\mathcal{L}_{Y_f} \sim \boxed{m_f} \over v \; \bar{f} f \, H$$

m_f's span many orders of magnitudes…



courtesy of R. Chierici

origin of Flavor Symmetry Breaking ?

Explaining Y_f hierarchy via HS and extra $U(1)_F$

Gabrielli Raidal, arXiv:1310.1090; Ma, arXiv:1311.3213

- HS containing N_f heavy fermions (Dark Matter ?) charged under Dark unbroken $U(1)_F$ (→ massless DP $\bar{\gamma}$)
- Chiral Simmetry spont. broken in HS via non-perturbative effects (via higher-derivative in DP field ~ $1/\Lambda$ → Lee-Wick ghosts) Gabrielli arXiv:0712.2208

  → Dark fermions (Df) get M_{Df} mass depending on their $U(1)_F$ charge q_{Df} :

anom. dim.

$$M_{D_f} \sim \exp\left(-\frac{\kappa}{q_{D_f}^2 \bar{\alpha}}\right)$$

DP coupling

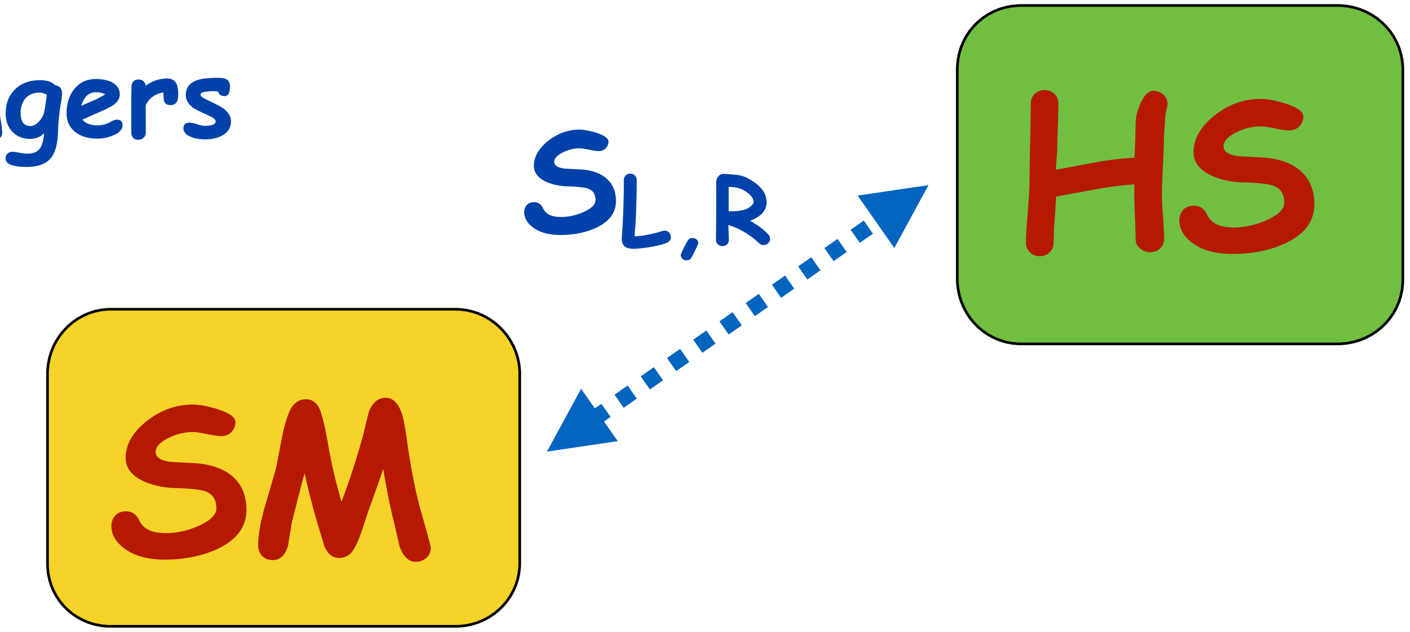
- ex: for integer q_{Df} sequence (q_{Df}=1, 2, 3, 4...)

  → exponential hierarchy in M_{Df}

Flavor and Chiral Symmetry Breaking in HS transferred to visible-sector Yukawa couplings at one-loop via squark/slepton-like scalar messangers !

heavy scalar messengers $S_{L,R}$

- heavy scalar messengers (squark/slepton-like) connecting SM states with HS states



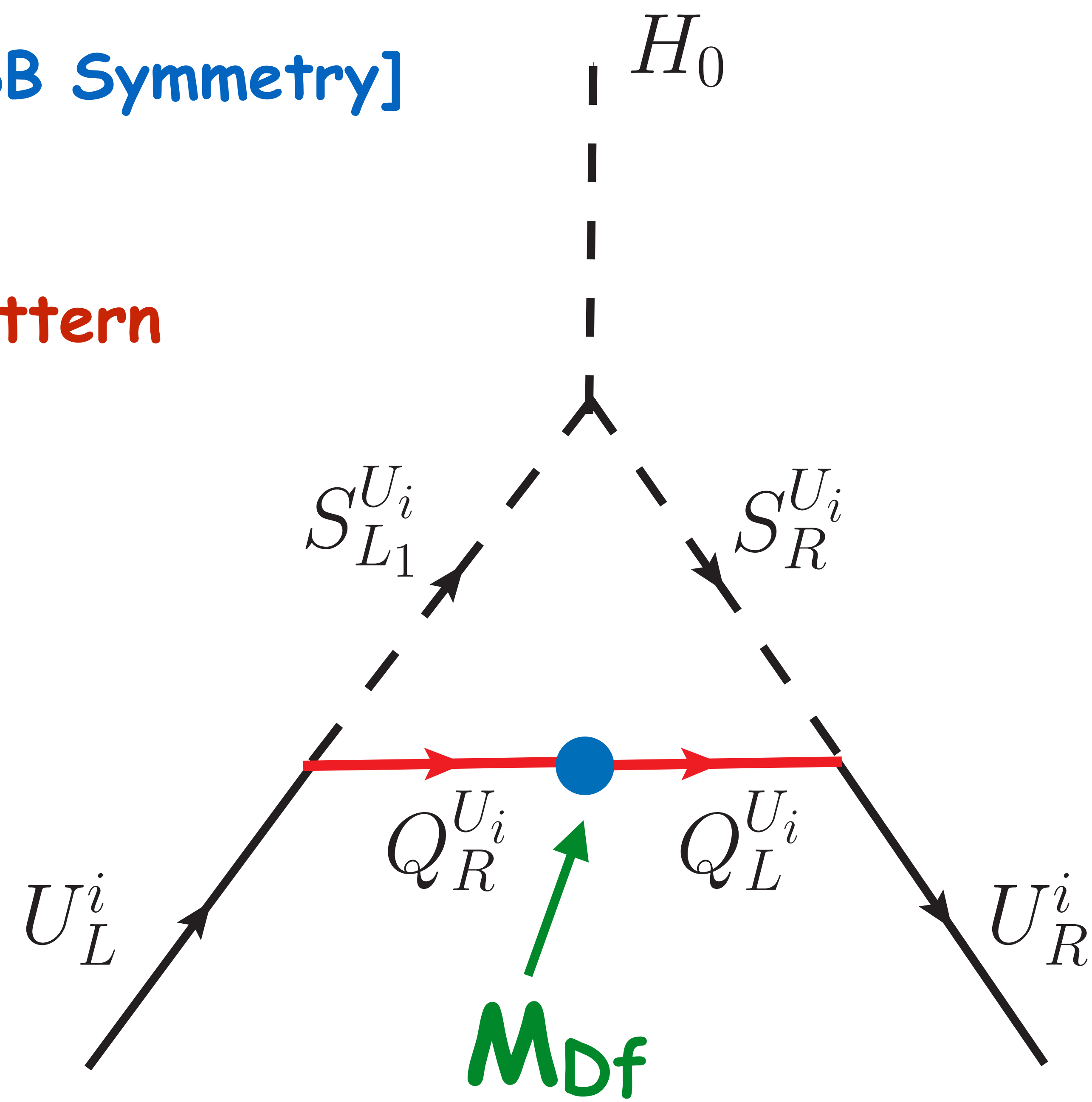
Messengers (Scalars): $\hat{S}_L^{D_i}$, $\hat{S}_L^{U_i}$, $S_R^{D_i}$, $S_R^{U_i}$

Dark Sector (Fermions+Scalar): Q^{D_i}, Q^{U_i}, S_0

Fields	Spin	$SU(2)_L$	$U(1)_Y$	$SU(3)_c$	$U(1)_F$
$\hat{S}_L^{D_i}$	0	1/2	1/3	3	$-q_{D_i}$
$\hat{S}_L^{U_i}$	0	1/2	1/3	3	$-q_{U_i}$
$S_R^{D_i}$	0	0	-2/3	3	$-q_{D_i}$
$S_R^{U_i}$	0	0	4/3	3	$-q_{U_i}$
Q^{D_i}	1/2	0	0	0	q_{D_i}
Q^{U_i}	1/2	0	0	0	q_{U_i}
S_0	0	0	0	0	0

radiative Yukawa coupl.s follow M_{Df} hierarchy !!!

- Y_f=0 at tree level [(H ↔ -H) SB Symmetry]
- Y_f's arise radiatively (via loop messenger-exchange) with same pattern of exponential hierarchy of Dark fermion (D_f) masses :



$$Y_f \sim M_{D_f} \sim \exp(-\frac{\kappa}{q^2_{D_f}\bar{\alpha}})$$

Flavor ⇔ Non-Universal q_{Df}

example : if

$$q_{D_e} = 4\,,\ q_{D_\mu} = 5\,,\ q_{D_\tau} = 6$$

➜ given m_e, m_μ as input $\Rightarrow m_\tau \simeq 1.9\ \mathrm{GeV}$

(and, for Dirac ν's, $q_{D_{\nu_\tau}} = 3 \Rightarrow m_{\nu_\tau} \sim 5\ \mathrm{eV}$)

- Df are lightest Dark particles, all stable [conserved $U(1)_F$ charge], potentially contributing to Dark Matter
- rich phenomenology at colliders if Df-mass scale accessible (yet to be explored...)

[colored-$S_{L,R}$ mass scale > 50 TeV] (vacuum stability)

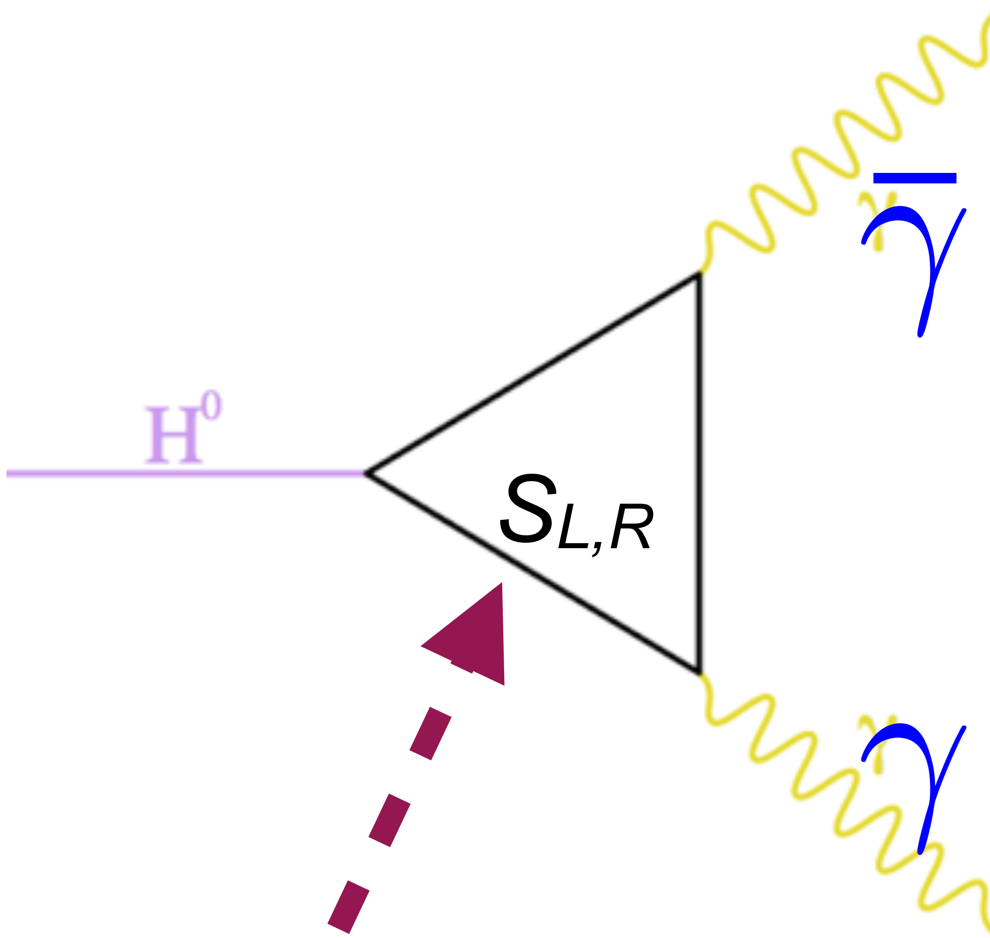
- in the meantime ...

one straightforward (nontrivial) new signature in Higgs decays...

mono-photon exotic Higgs signature

$$H \to \gamma\bar{\gamma}$$

Gabrielli et al, arXiv:1405.5196



massless (invisible) Dark Photon

(mediating long-range $U(1)_F$ force between Dark particles)

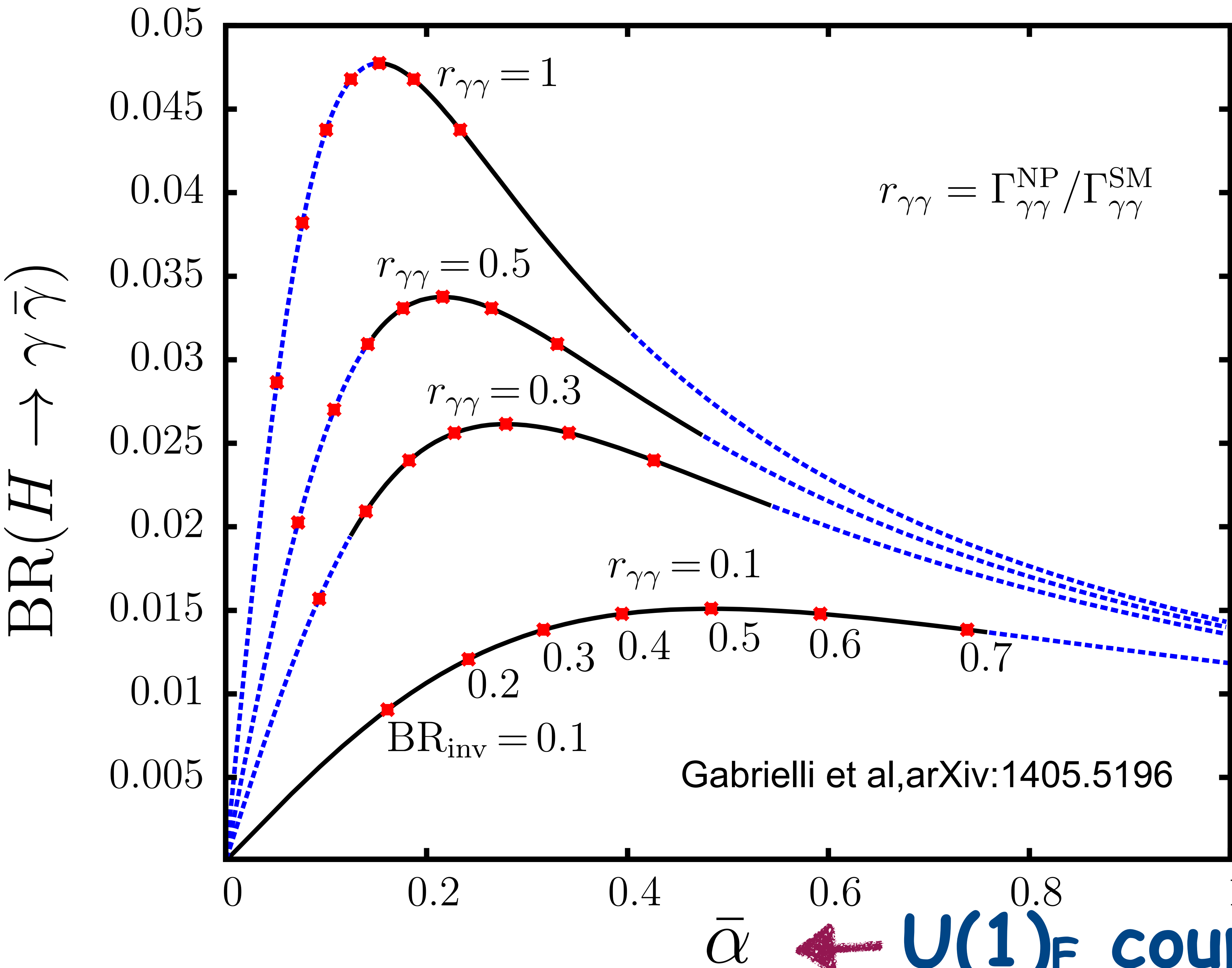
heavy scalar messengers (squark/slepton-like)

connecting SM to Dark-Fermion sector (Dark Matter?, Yukawa origin and hierarchy?)

H non-decoupling effects (just as in SM) possible:

$$\Gamma(H \to \gamma\bar{\gamma}) \sim \frac{1}{M^2_{Heavy}} \to \frac{1}{v^2}$$

$BR_H(\bar\gamma\gamma)$ prediction in minimal models



U(1)$_F$ coupling

similar loop effects contribute to :

$H \to \gamma\gamma$

$H \to \bar\gamma\bar\gamma$

affects BR$_{\rm inv}$:

solid lines corresponds to :

$$\mathrm{BR}^{\rm SM}_{\gamma\gamma}/2 \le \mathrm{BR}_{\gamma\gamma} \le 2\ \mathrm{BR}^{\rm SM}_{\gamma\gamma}$$

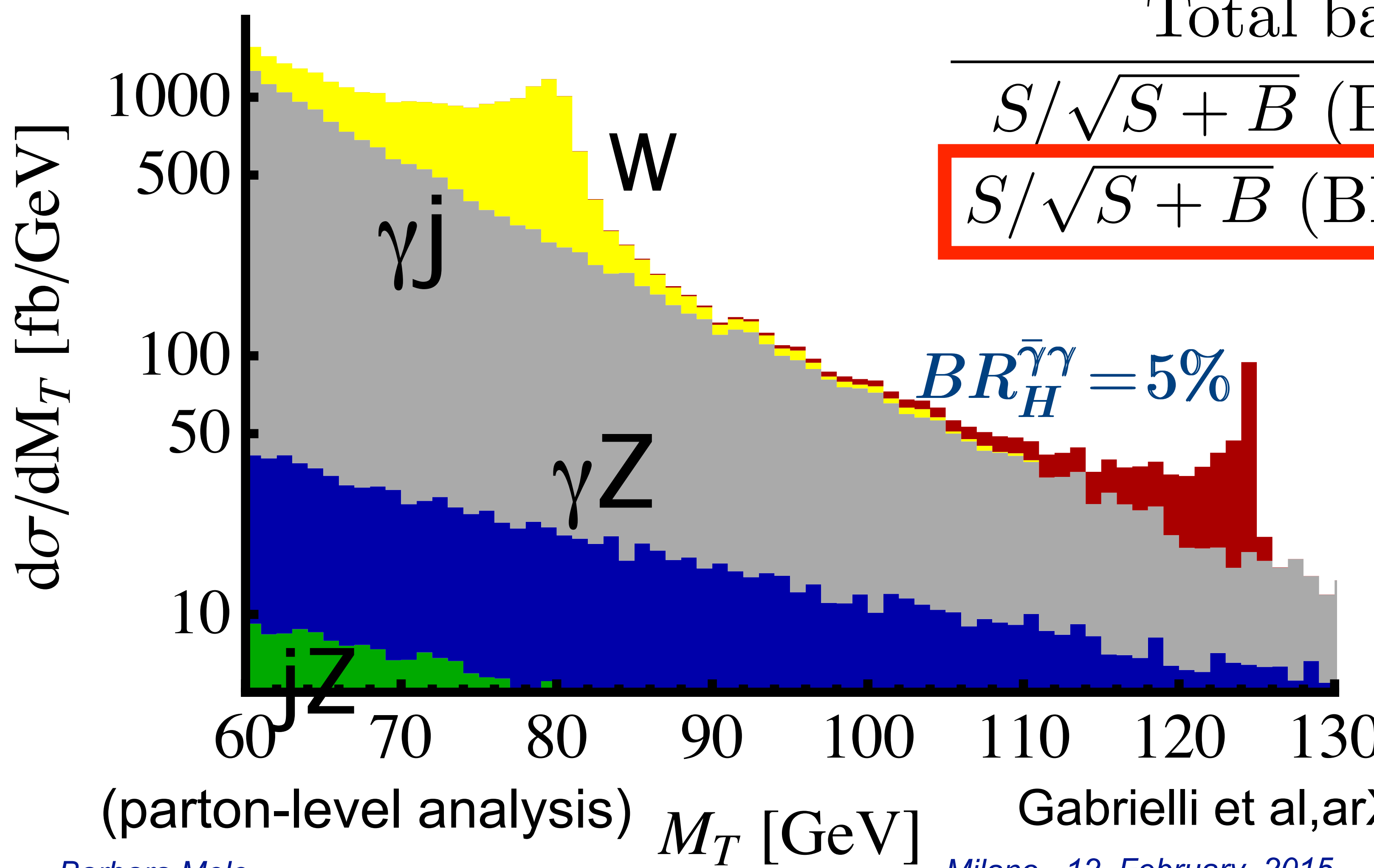
$\mathrm{BR}(H \to \gamma\bar\gamma)$ up to 5% !

resonant mono-photon signature

$$H \to \bar{\gamma}\gamma$$

$E_{miss} \sim E_\gamma \sim m_H/2$

$$M_T = \sqrt{2 p_T^\gamma \not{E}_T (1 - \cos\Delta\phi)}$$



(parton-level analysis)

(A_1) 50 GeV $< p_T^\gamma <$ 63 GeV (A_2) 60 GeV $< p_T^\gamma <$ 63 GeV

σ (fb)	$\sigma \times A_1$	$\sigma \times A_2$
Signal $BR_{H\to\gamma\bar{\gamma}} = 1\%$	65	34
γj	715	65
$\gamma Z \to \gamma\nu\bar{\nu}$	157	27
$jZ \to j\nu\bar{\nu}$	63	11
$W \to e\nu$	22	0
Total background	957	103
$S/\sqrt{S+B}$ $(BR_{H\to\gamma\bar{\gamma}} = 1\%)$	9.1	13.0
$S/\sqrt{S+B}$ $(BR_{H\to\gamma\bar{\gamma}} = 0.5\%)$	4.6	6.9

(8TeV/20fb^{-1})

model-independent measurement of BR_{DP}!

Gabrielli et al,arXiv:1405.5196

Outlook

- SM is not enough…
- Hidden Sectors fruitful (and theoretically-consistent) way to parametrize our ignorance about what is missing in SM
- sometimes theoretically motivated (i.e. solving SM drawbacks) (sometimes not so much …)
- useful for devising new kinds of exp. signatures to boost LHC potential for BSM discovery
- massless Dark Photon theoretically appealing (evading most of present experimental bounds on massive DP !)
- Higgs boson observation (and Higgs decoupling properties) opened up an entire new chapter of HS exploration
- worth looking to Higgs resonant single-photon signature as a probe of HS explaining Flavor Hierarchy (or other BSM…)
- many other non-SM signatures from HS's… (see next talks)