Beyond the Standard Model Physics

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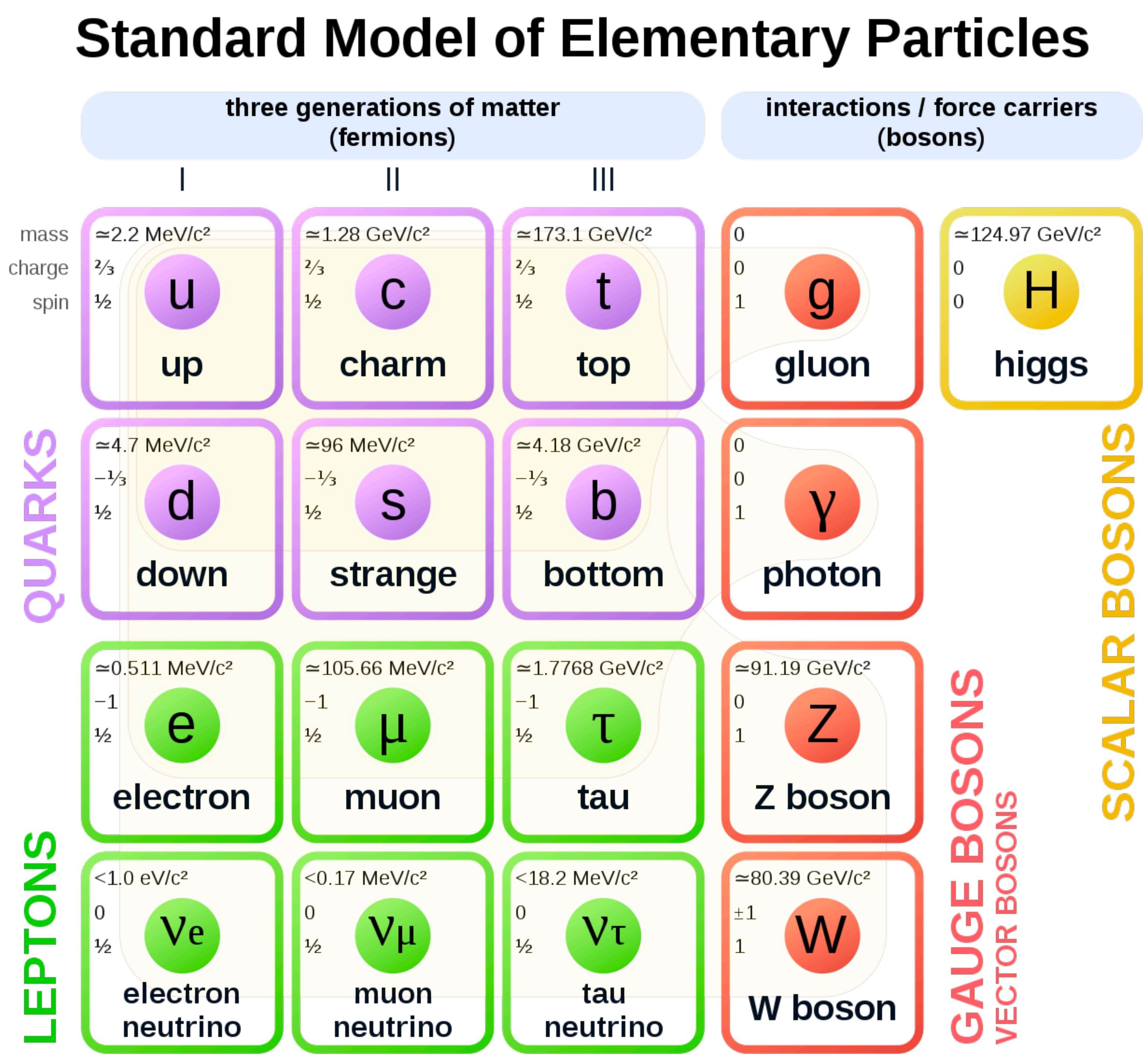
The 6th China LHC Physics Workshop (CLHCP2020)
11/08/2020

The Standard Model

- A unified story for strong, weak and electromagnetic interactions.



The unknown BSM world

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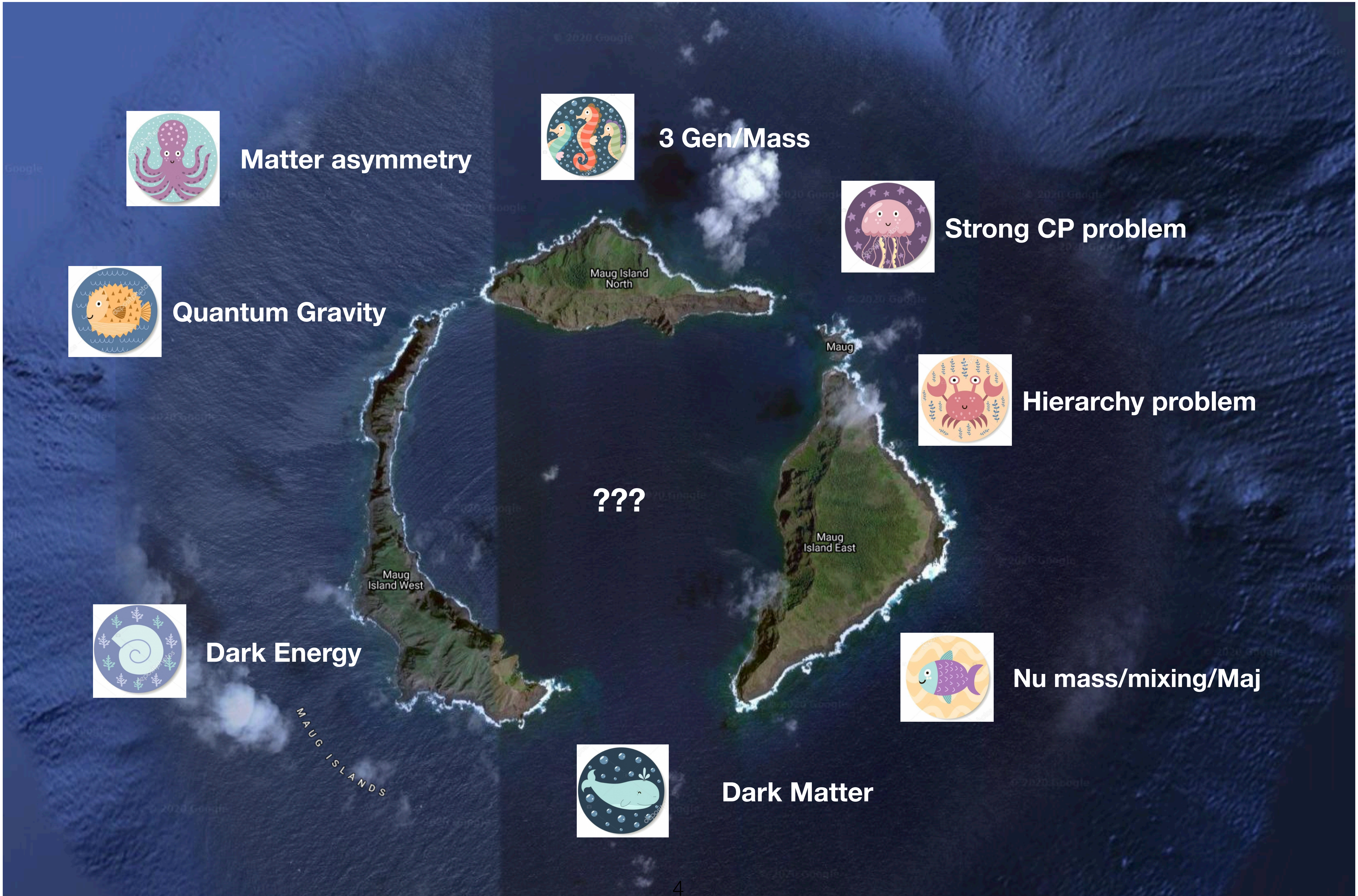
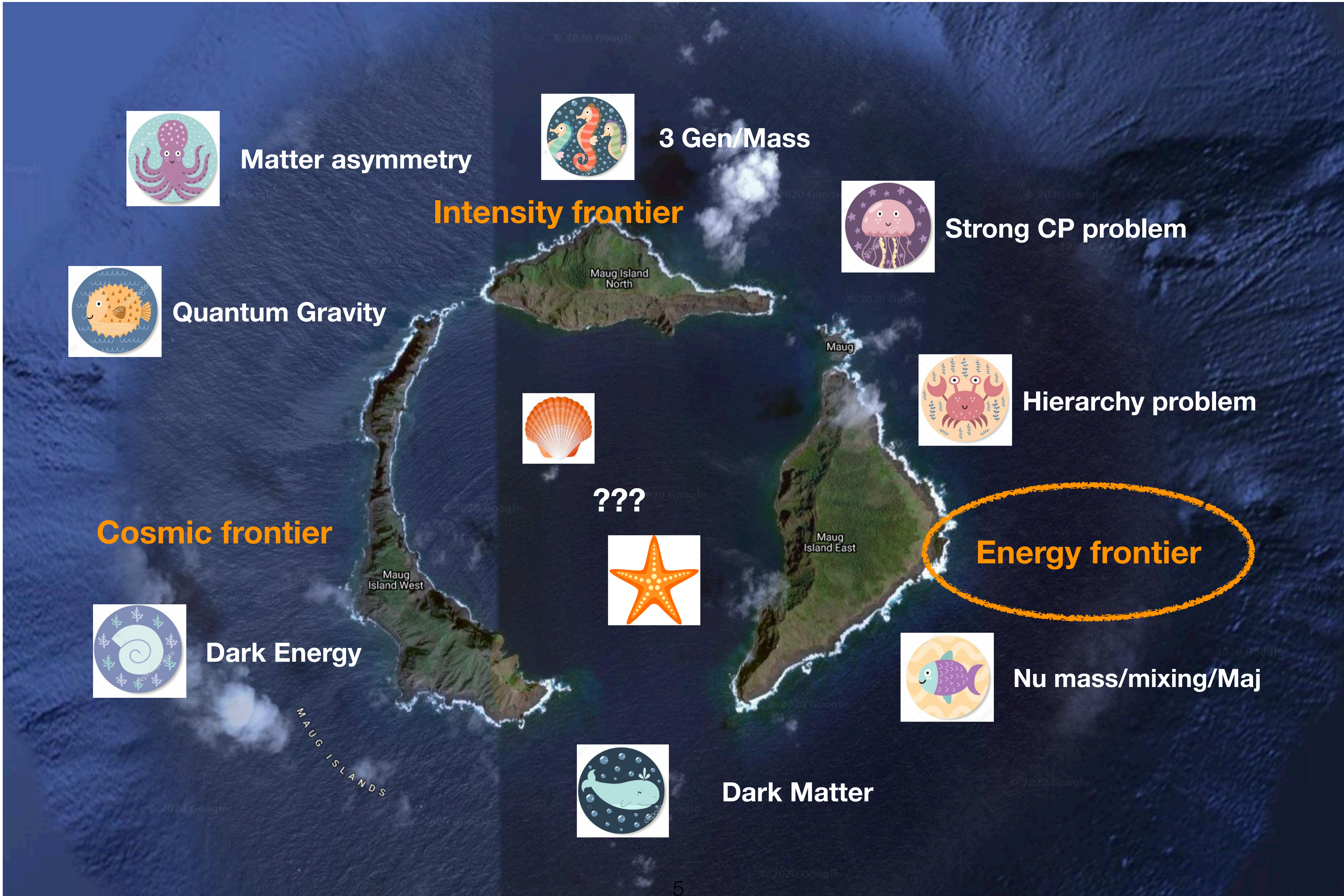
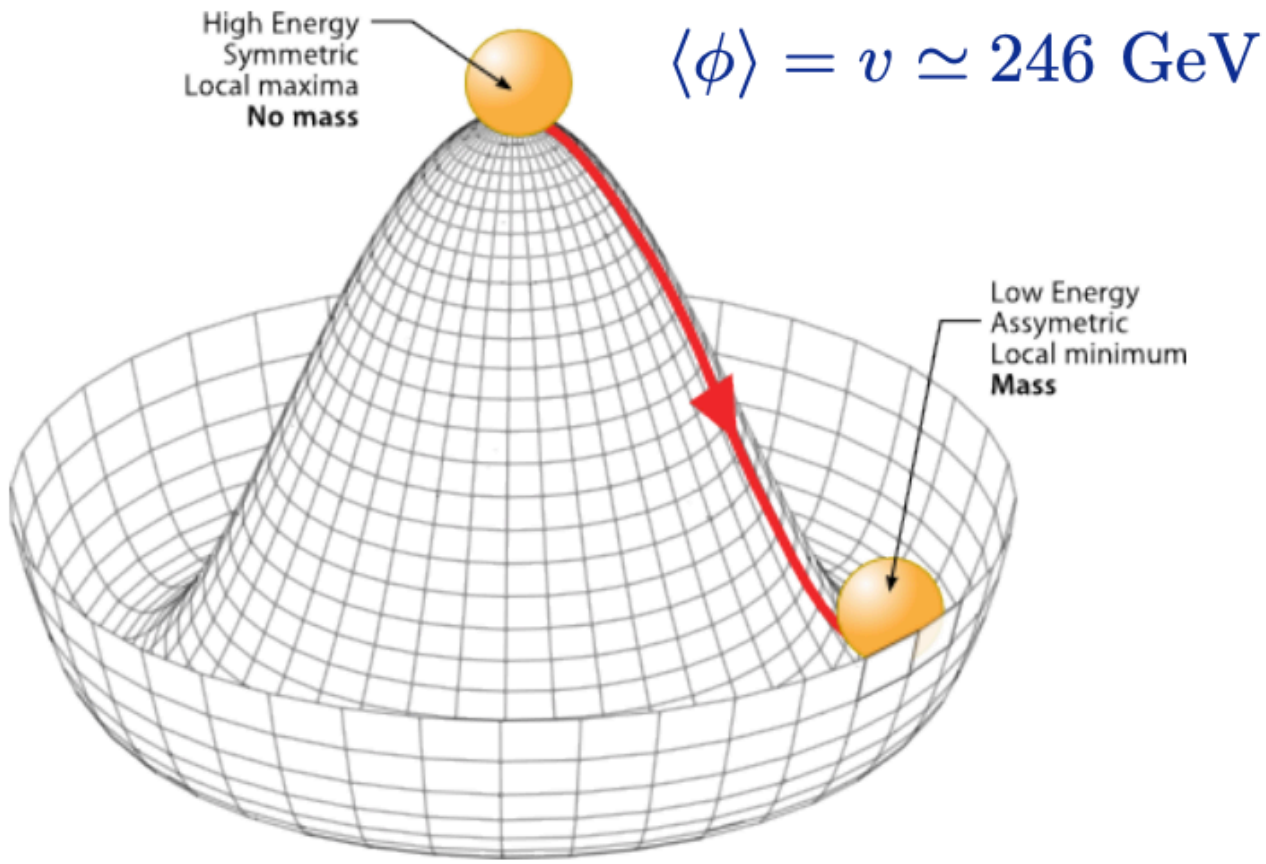


The unknown BSM world



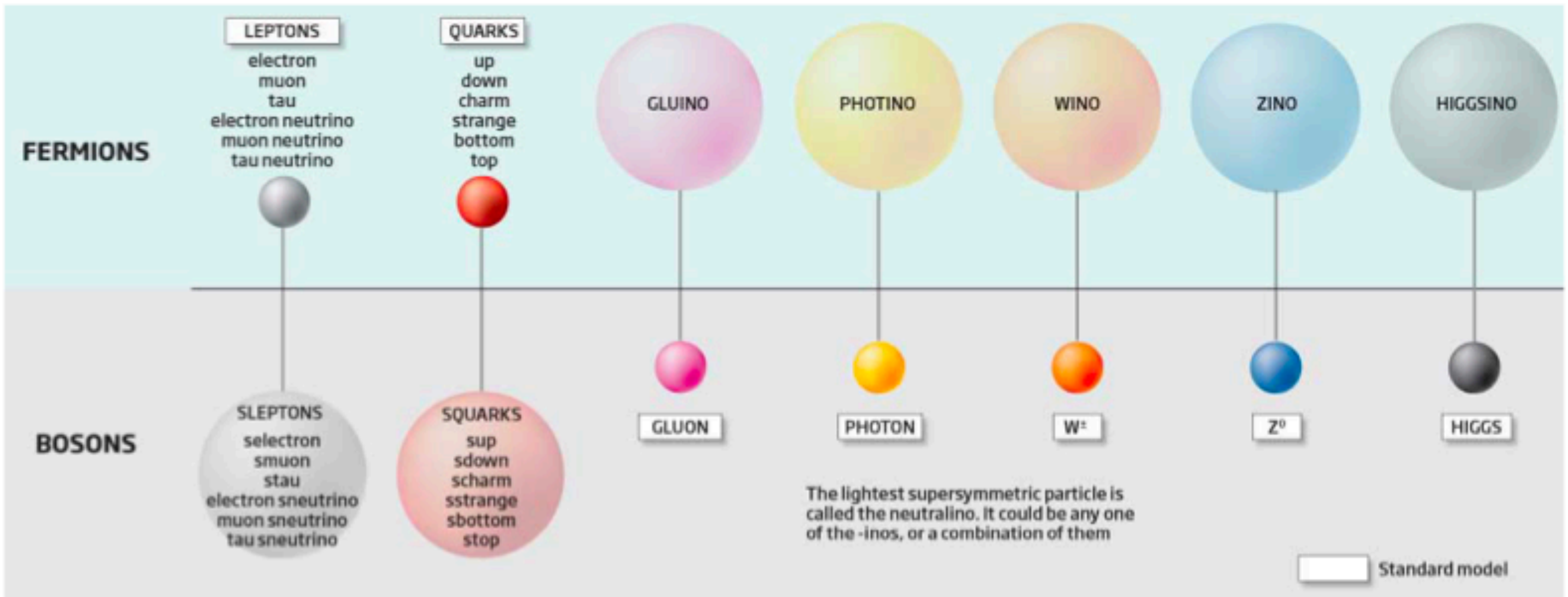
The hierarchy problem

- The EW scale << Planck scale
- A calculable Higgs mass



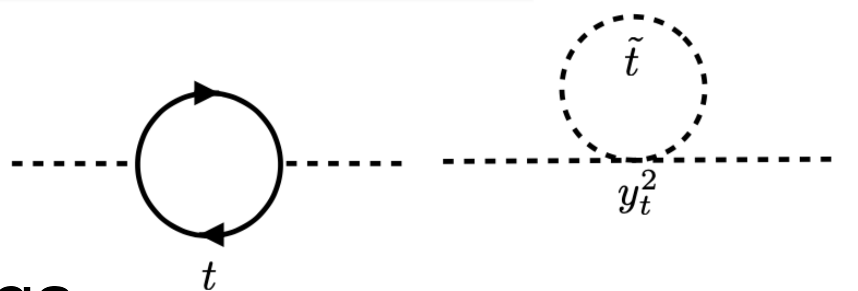
- Good candidate models
  - Supersymmetric models
  - Composite Higgs models
  - Extra dimension models …

Supersymmetric models



Credit:
New Scientist

- Stabilize the weak scale from Planck scale



- MSSM leads to unification of gauge couplings
- μ² is positive at high scale, EW breaking is induced radiatively
- Neutralino as an excellent candidate for cold dark matter

SUSY status

ATLAS SUSY Searches* - 95% CL Lower Limits
July 2020

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV

	Model	Signature			$\int \mathcal{L}\, dt$ [fb^{-1}]		Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{q}$	[10× Degen.] 1.9	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2019-040
		mono-jet	1-3 jets	E_T^{miss}	36.1	$\tilde{q}$	[1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	E_T^{miss}	139	$\tilde{g}$	2.35	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2019-040
						$\tilde{g}$	Forbidden 1.15-1.95	m($\tilde{\chi}_1^0$)=1000 GeV	ATLAS-CONF-2019-040
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}W\tilde{\chi}_1^0$	1 e,μ	2-6 jets		139	$\tilde{g}$	2.2	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2020-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee,\mu\mu$	2 jets	E_T^{miss}	36.1	$\tilde{g}$	1.2	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	E_T^{miss}	139	$\tilde{g}$	1.97	m($\tilde{\chi}_1^0$) <600 GeV	ATLAS-CONF-2020-002
		SS e,μ	6 jets		139	$\tilde{g}$	1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	1909.08457
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	E_T^{miss}	79.8	$\tilde{g}$	2.25	m($\tilde{\chi}_1^0$)<200 GeV	ATLAS-CONF-2018-041
		SS e,μ	6 jets		139	$\tilde{g}$	1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1909.08457
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$	Forbidden 0.9	m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		139	$\tilde{b}_1$	Forbidden 0.74	m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1909.08457
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_2^0 \to bh\tilde{\chi}_1^0$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$	Forbidden 0.23-1.35	Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	1908.03122
		2 τ	2 b	E_T^{miss}	139	$\tilde{b}_1$	0.13-0.85	Δm($\tilde{\chi}_2^0,\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2020-031
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{t}_1$	1.25	m($\tilde{\chi}_1^0$)=1 GeV	ATLAS-CONF-2020-003, 2004.14060
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	E_T^{miss}	139	$\tilde{t}_1$	0.44-0.59	m($\tilde{\chi}_1^0$)=400 GeV	ATLAS-CONF-2019-017
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to\tilde{\tau}_1 b\nu, \tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	E_T^{miss}	36.1	$\tilde{t}_1$	1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$	0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
						$\tilde{t}_1$	0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	36.1	$\tilde{t}_1$	0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_2^0, \tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$	1-2 e,μ	1-4 b	E_T^{miss}	139	$\tilde{t}_1$	0.067-1.18	m($\tilde{\chi}_2^0$)=500 GeV	SUSY-2018-09
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ	1 b	E_T^{miss}	139	$\tilde{t}_2$	Forbidden 0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	SUSY-2018-09
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	3 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.64	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2020-015
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	0.205	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	1911.12606
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	0.42	m($\tilde{\chi}_1^0$)=0	1908.08215
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	0-1 e,μ	2 b/2 γ	E_T^{miss}	139	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$	Forbidden 0.74	m($\tilde{\chi}_1^0$)=70 GeV	2004.10894, 1909.09226
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}_1^\pm$	1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1908.08215
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		E_T^{miss}	139	$\tilde{\tau}$	[$\tilde{\tau}_L$, $\tilde{\tau}_{R,L}$] 0.16-0.3 0.12-0.39	m($\tilde{\chi}_1^0$)=0	1911.06660
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$	0.7	m($\tilde{\chi}_1^0$)=0	1908.08215
		$ee,\mu\mu$	$\geq$ 1 jet	E_T^{miss}	139	$\tilde{\ell}$	0.256	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	$\geq$ 3 b	E_T^{miss}	36.1	$\tilde{H}$	0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0 \to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	139	$\tilde{H}$	0.55	BR($\tilde{\chi}_1^0 \to Z\tilde{G}$)=1	ATLAS-CONF-2020-040

See Jin Wang's SUSY talk

- For electroweakino, the exp constraints assumes 100% BR.
  - Pretty close in most cases, but could overestimate the constraints

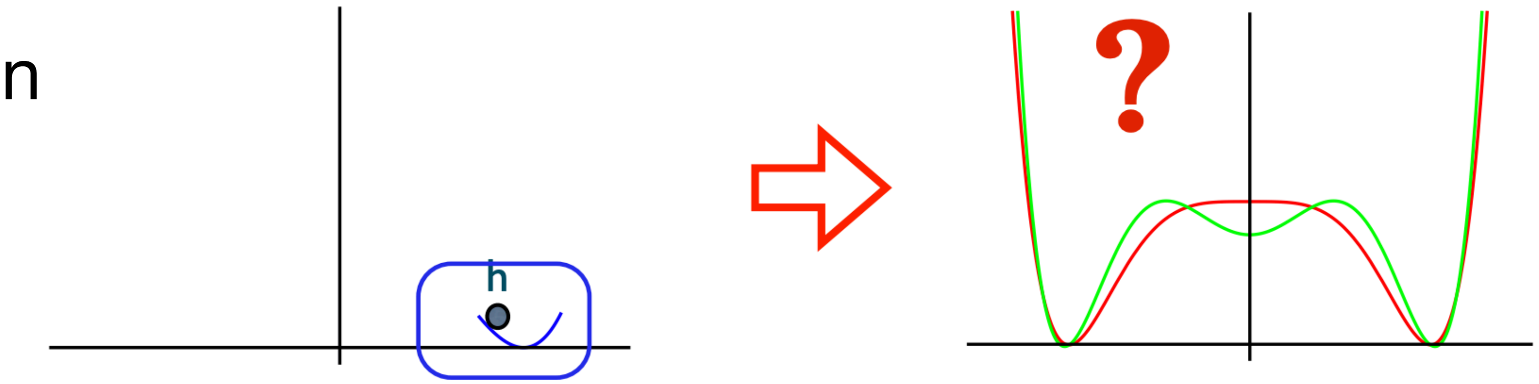
See JL, N. McGinnis, C. Wagner, X.P. Wang 2020

Composite Higgs models

- Pion in the QCD: no hierarchy problem, cut-off at Λ_{QCD}
- SM Higgs as pseudo-Nambu-Goldstone boson
  - Looking for resonance in strong sector
  - Looking for deviation in Higgs couplings

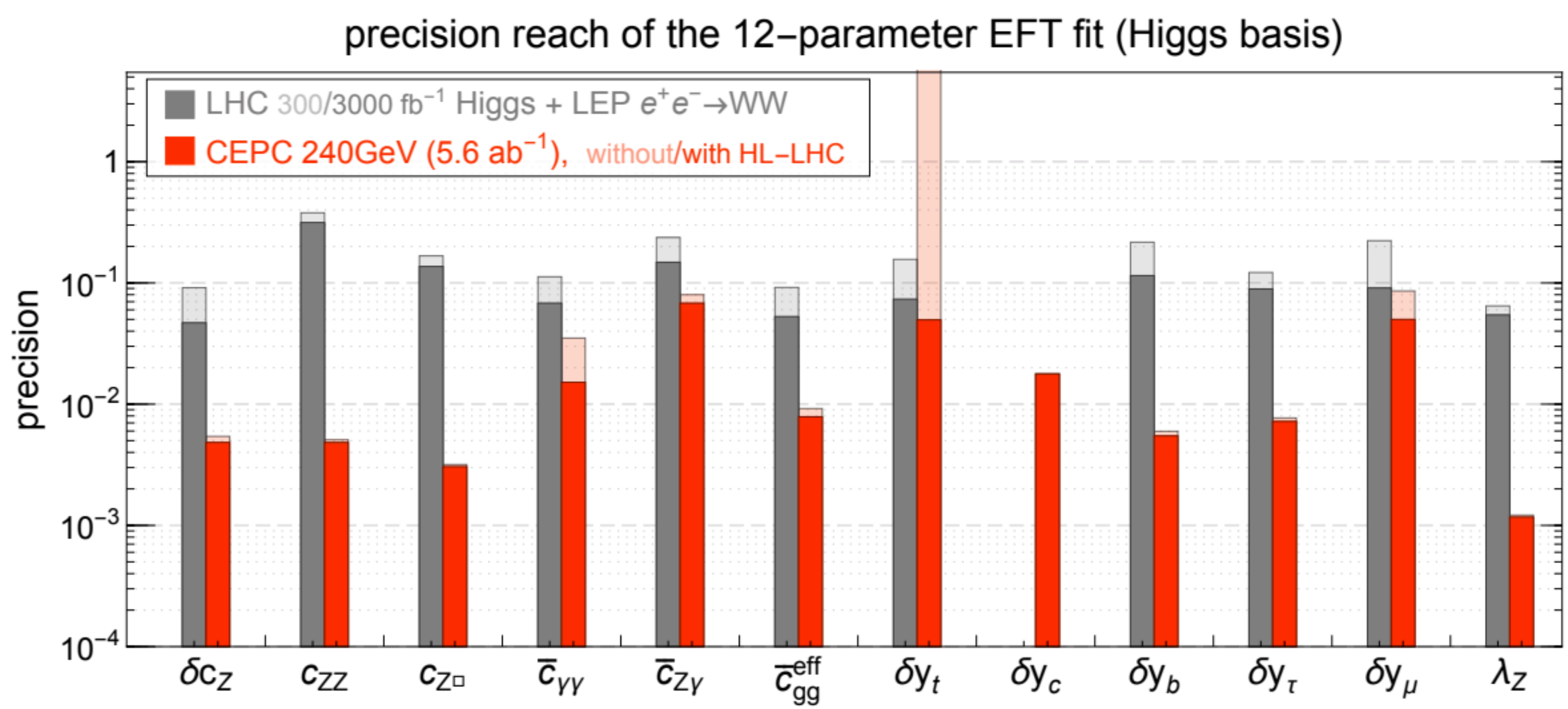
Higgs precision test

- NP models can modify Higgs coupling
- Electroweak phase transition



Precision Higgs Physics at the CEPC, CPC 2019

- Higgs factories: precision measurement is necessary



Flavor: 3 generation and masses

- SM Yukawa couplings and masses are free parameters
- Why 3 gen? $m_t/m_e \sim 3.4\text{x}10^5$?
- Any underline physics?

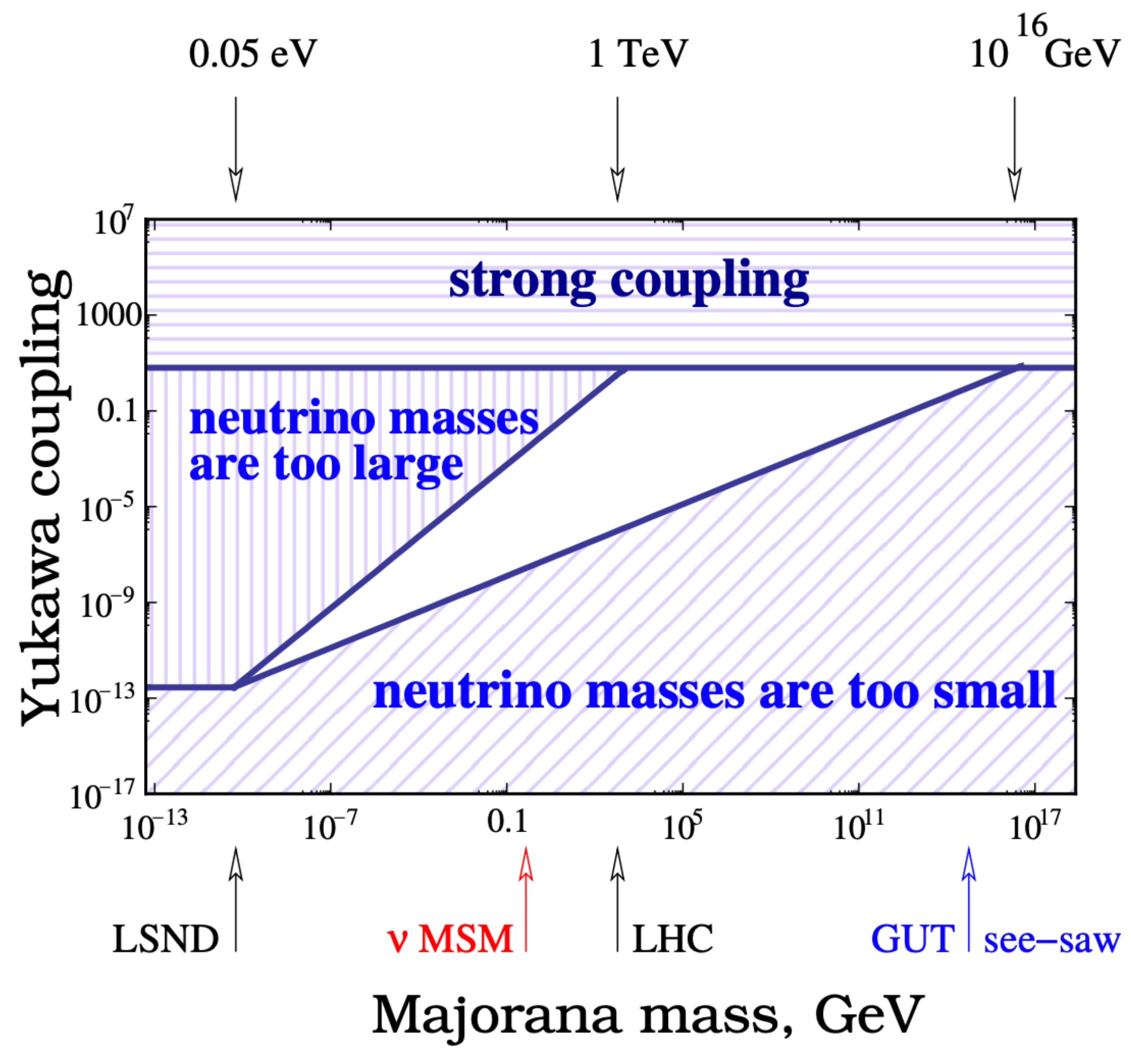
See Yuming Wang, Liming Zhang, Yanxi Zhang, Wenbin Qian's talk

- EFT as a good framework
- Looking for exotics in B, D, K mesons
  - E.g. lepton universality in B > K l+ l- decay
  - Synergy between hadron collider LHCb and electron collider BaBar, Belle-II and BES-III

Neutrino mass and mixing

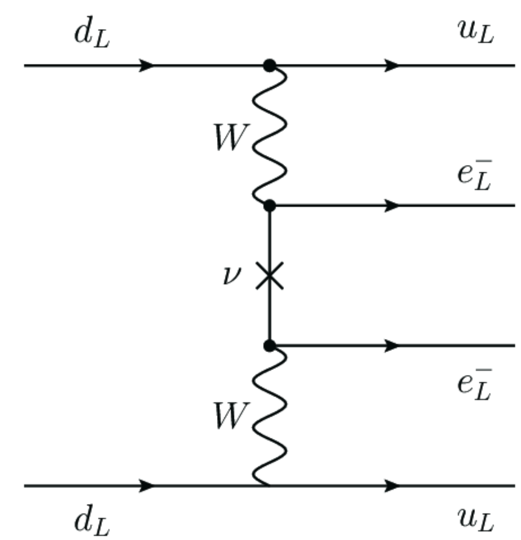
- Neutrino mass origin: the sub-eV scale
- Mixing pattern: flavor structure in lepton sector
- Dirac or Majorana?
- See-saw models
- More extended models
  - Inverse or linear seesaw
- EW scale ν_s searches at the LHC

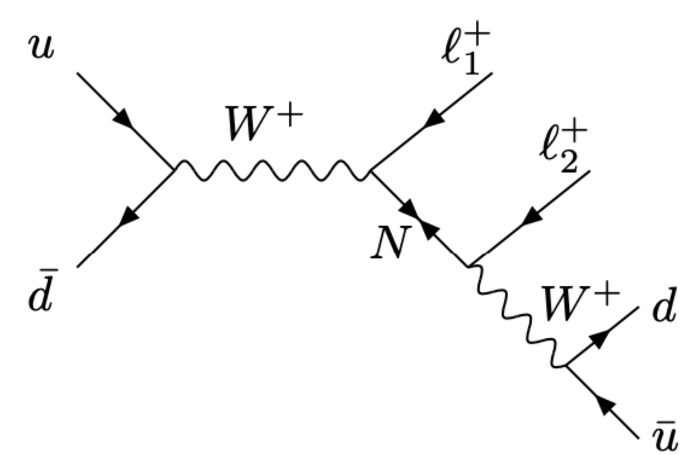
1204.5379



EW scale ν_s searches at the LHC

- Lepton number violation via Majorana neutrino
  - Same sign lepton searches
    - $0\nu\beta\beta$ type
    - Coherent production (on-shell)
    - Exotic meson/tau decays
      - $M^+ > l^+ \, l'^+ \, M'^-$
  - Displaced searches





T. Han, B. Zhang 2006, etc …

Helo, Hirsch, Kovalenko 2013; A. Maiezza, Nemevsek, Nesti 2015 … etc

EW scale ν_s searches at the LHC

$$\mathcal{L} = \frac{g\sin\theta}{\sqrt{2}}\left(W_\mu \bar{\ell}_L \gamma^\mu N + h.c.\right) - \frac{g\cos\theta\sin\theta}{2\cos\theta_w} Z_\mu \left(\bar{\nu}_L\gamma^\mu N + \bar{N}\gamma^\mu \nu_L\right) + \frac{g\sin^2\theta}{2\cos\theta_w} Z_\mu \bar{N}\gamma^\mu P_L N,$$

- Displaced searches: good for small mixing
  - Smaller mass m_N for large $c\tau$
  - $m_N < 10$ GeV is a good target

$$c\tau \simeq 12\ \mathrm{km} \times \left(\frac{10^{-12}}{\sin^2\theta}\right)\left(\frac{10\ \mathrm{GeV}}{m_N}\right)^5$$

EW scale vs displaced searches @LHC

$$\mathcal{L} = \frac{g\sin\theta}{\sqrt{2}}\left(W_\mu \bar{\ell}_L \gamma^\mu N + h.c.\right) - \frac{g\cos\theta\sin\theta}{2\cos\theta_w} Z_\mu\left(\bar{\nu}_L\gamma^\mu N + \bar{N}\gamma^\mu \nu_L\right) + \frac{g\sin^2\theta}{2\cos\theta_w} Z_\mu \bar{N}\gamma^\mu P_L N,$$

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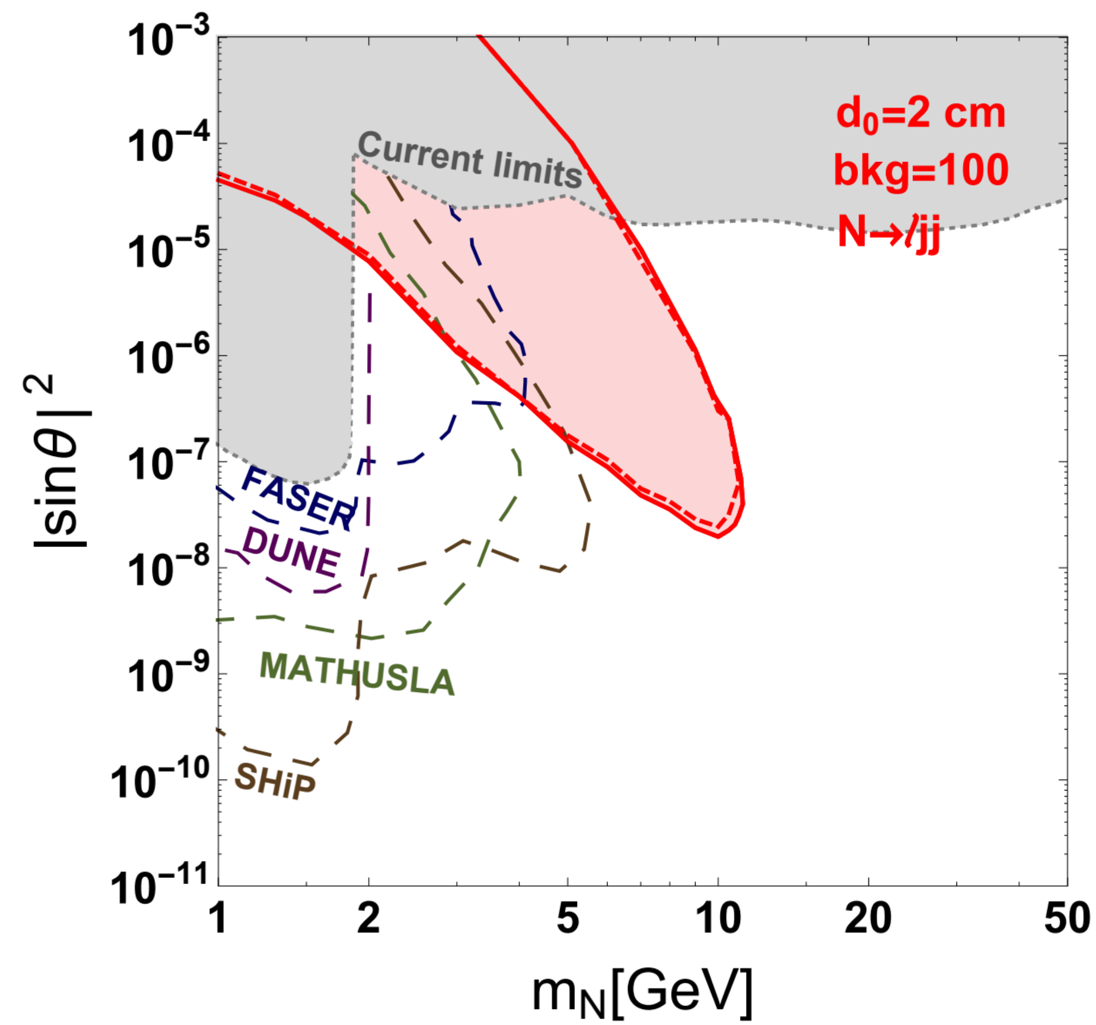
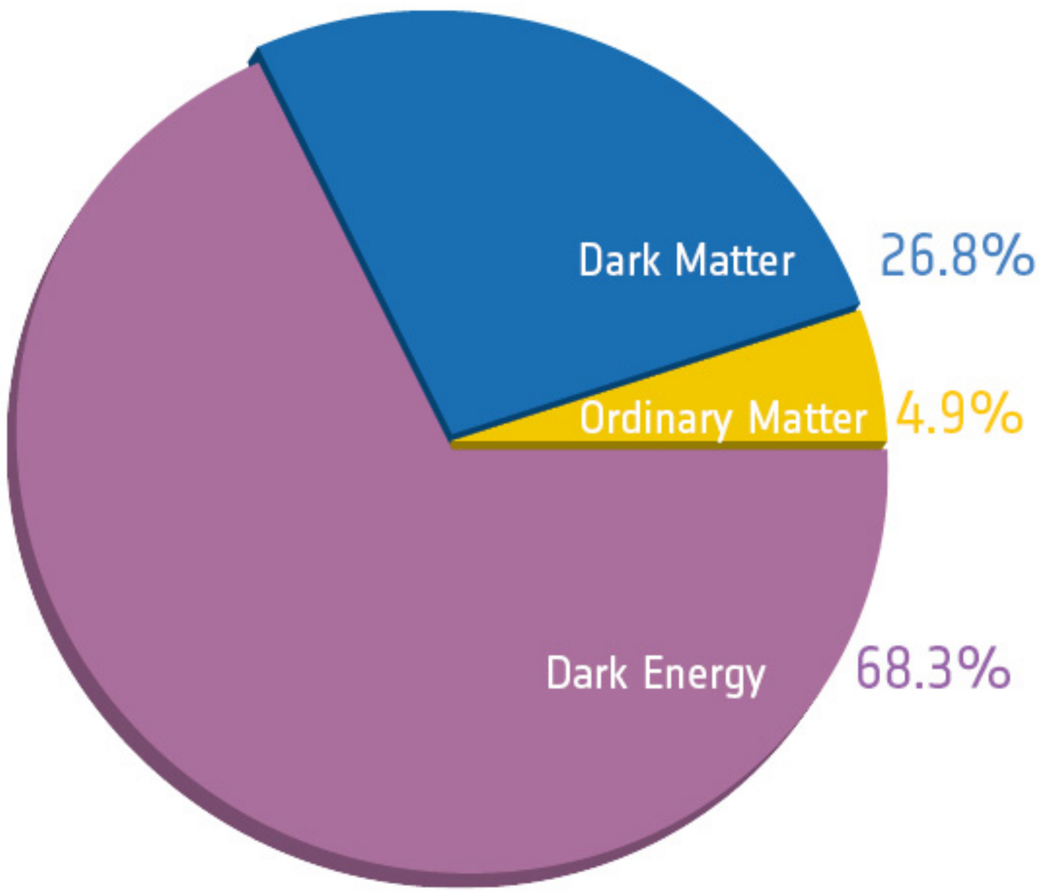
- Typical method: displaced vertex reconstruction and inv mass
  - Non-isolated leptons: bkg from SM mesons
  - Our method: displaced track search

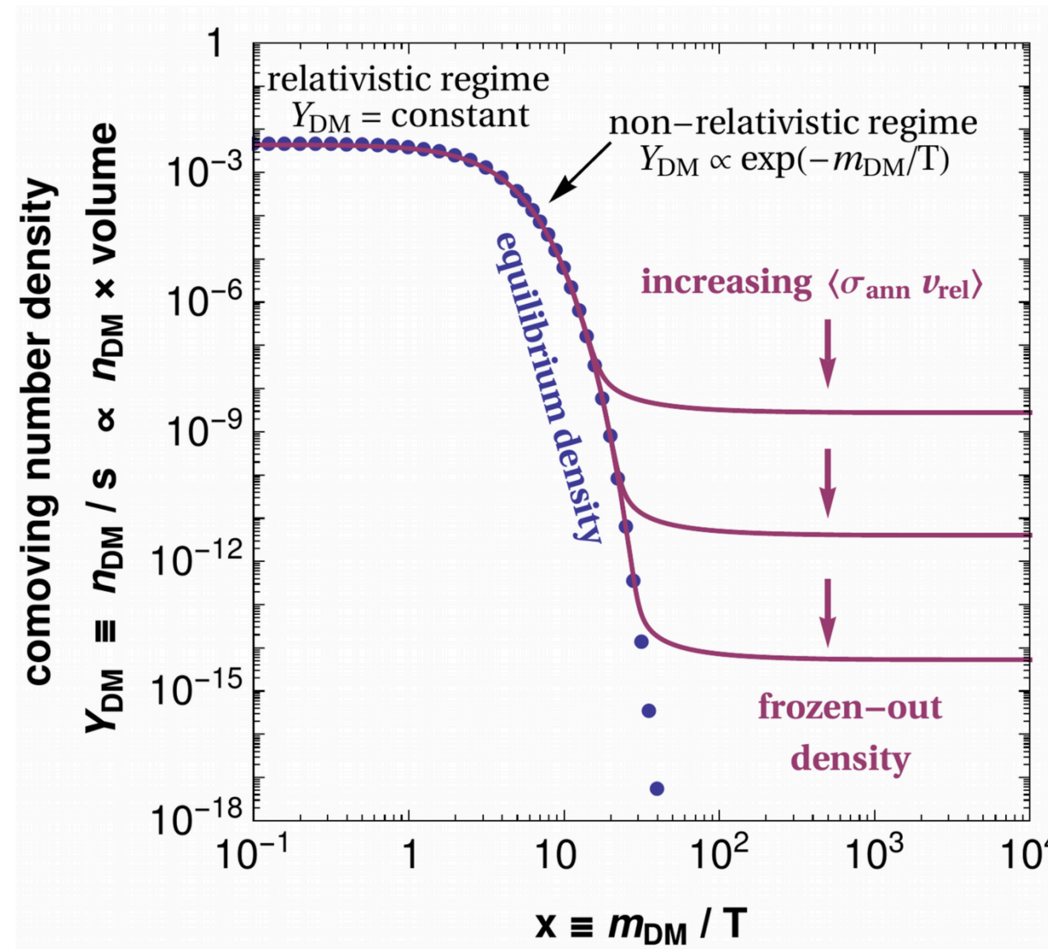
JL, Z. Liu, L.T. Wang, X.P Wang JHEP 2019



Dark matter at collider

Courtesy of Kalliopi Petraki





- What is the particle nature of the Dark Matter?
- Not a particle in SM!

$$\mathrm{DM} + \mathrm{DM} \rightarrow \mathrm{SM} + \mathrm{SM}$$

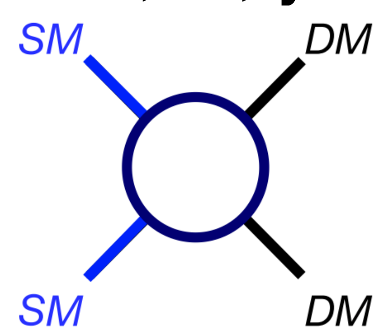
$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$
$$\sim \alpha^2/m_W^2$$

- The WIMP miracle!

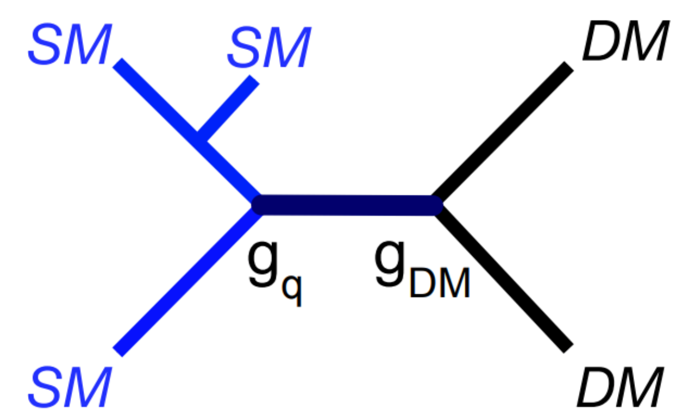
Dark matter at collider

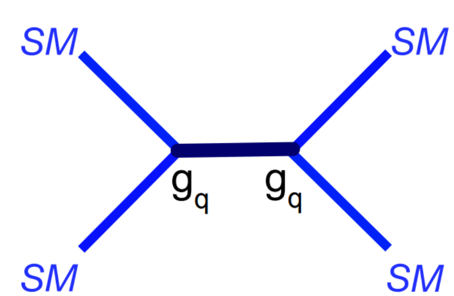
See Tongguang Chen's DM talk

- The DM pair can be produced at LHC
  - mono-X search: X = photon, Z, jet, Higgs …
  - EFT operators



  - Simplified models
    - Mediator searches



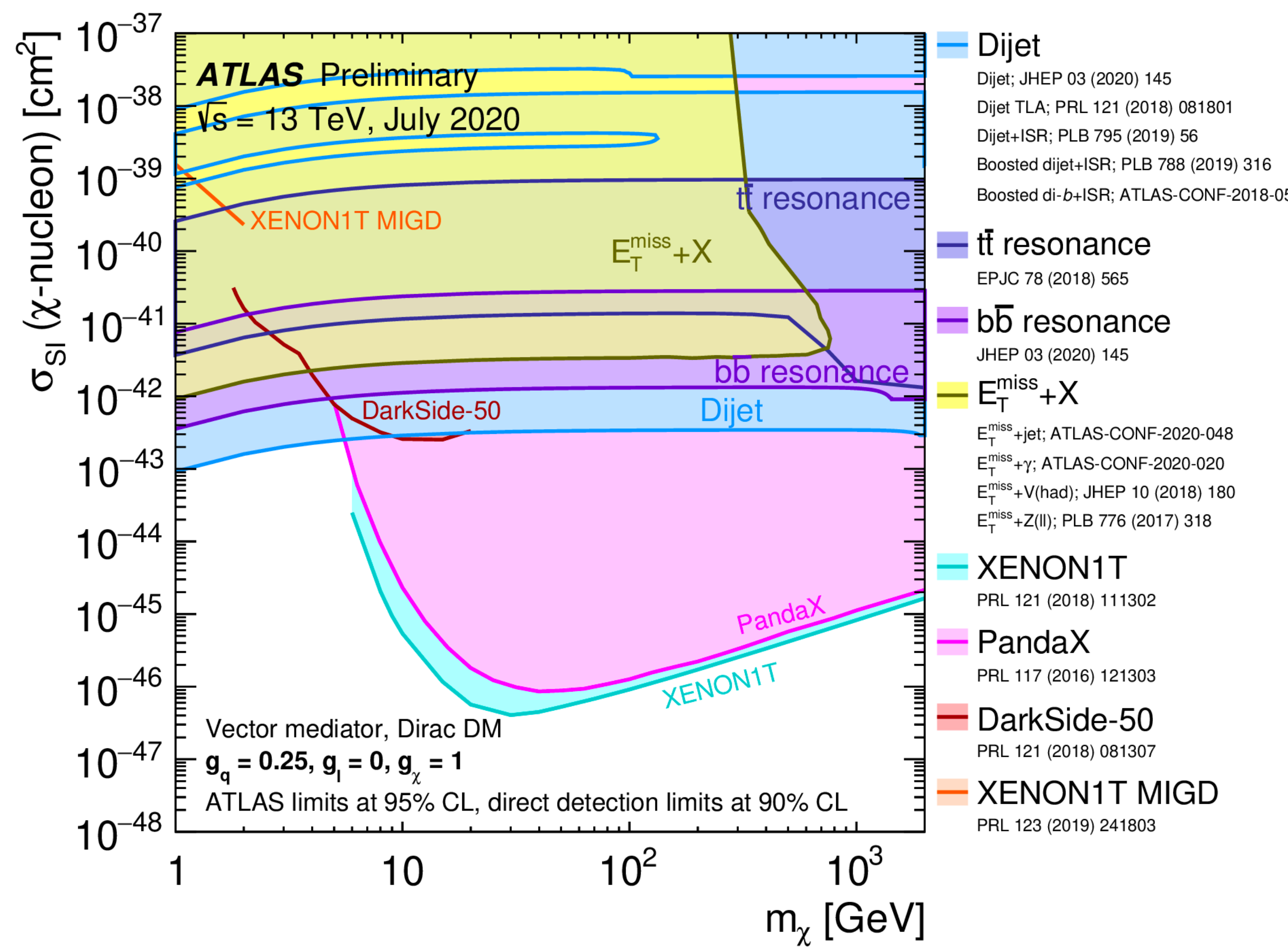


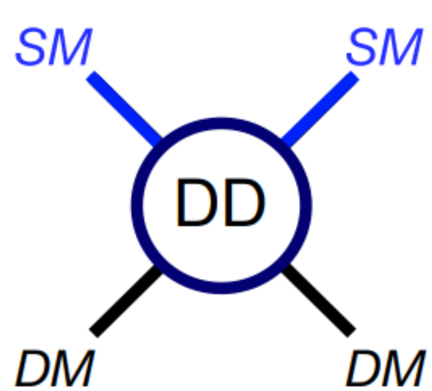
See Jun Guo's exotic searches talk

Dark matter at collider

See Tongguang Chen's talk

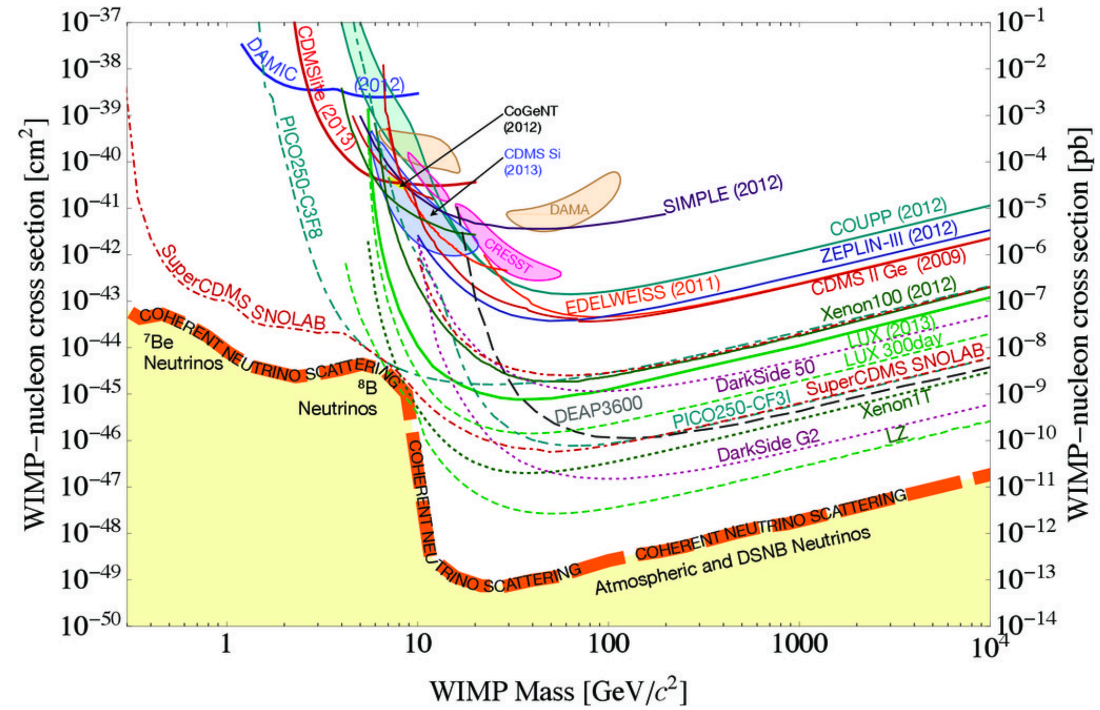
- The DM pair can be produced at LHC
  - mono-X search: X = photon, Z, jet, Higgs …
  - EFT operators
  - Simplified models
    - Mediator searches
- Direct synergy with DM direct detection

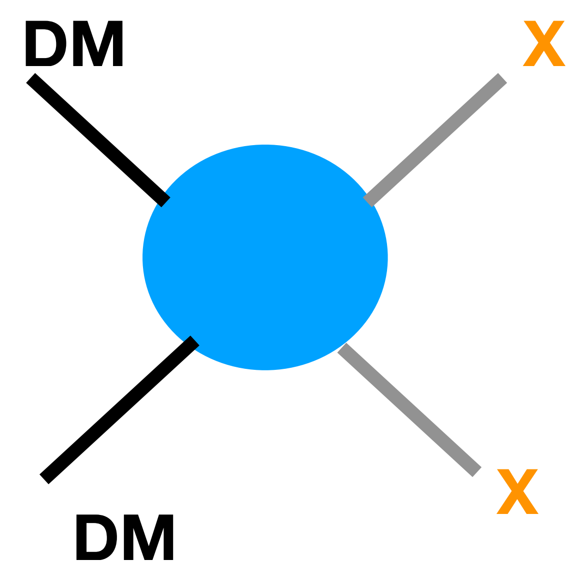


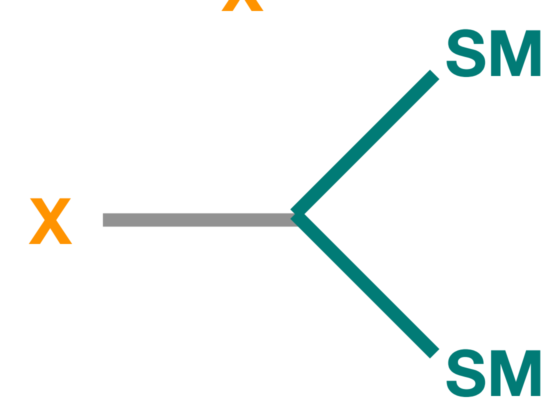


From dark matter to dark sector

- The existence of dark matter
  - do not interact with strong, weak, or electromagnetic forces
  - A zoo of similar particles in the dark sector as in the visible sector
- The null detection of dark matter
  - Secluded annihilation: DM + DM → X + X
  - X is light and very weakly coupled to visible sector







X can be long-lived!

Long-lived particle @ colliders

See also Chaochen Yuan and Mingxuan Du’s talks

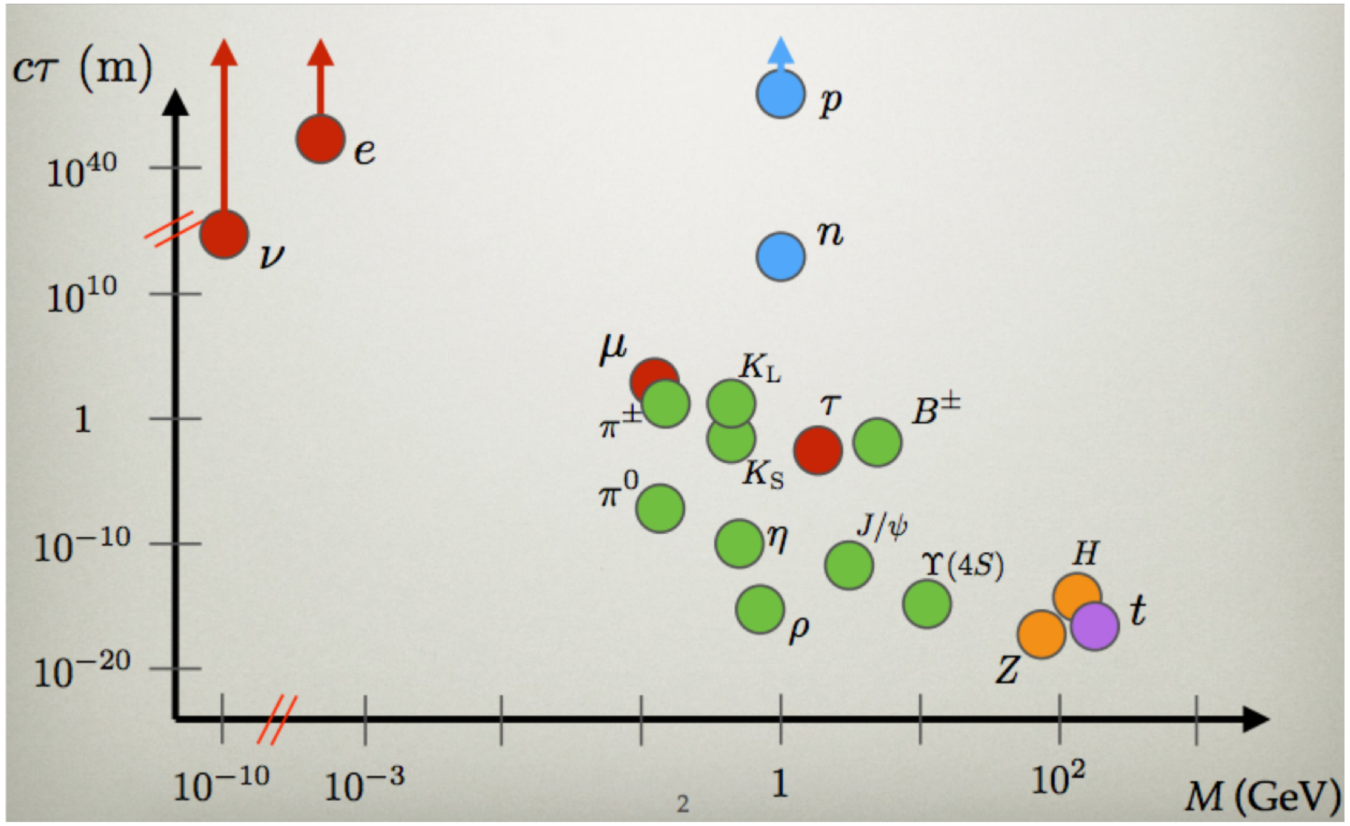
- Feeble couplings:
  Dark sector models, R-parity violating Supersymmetry, sterile neutrinos

- Suppression from heavy mass scale:
  muon/charged pion, gauge mediated spontaneous breaking Supersymmetry

- Near degenerate state:
  higgsino-like chargino/neutralino, or anomaly-mediated spontaneous breaking Supersymmetry

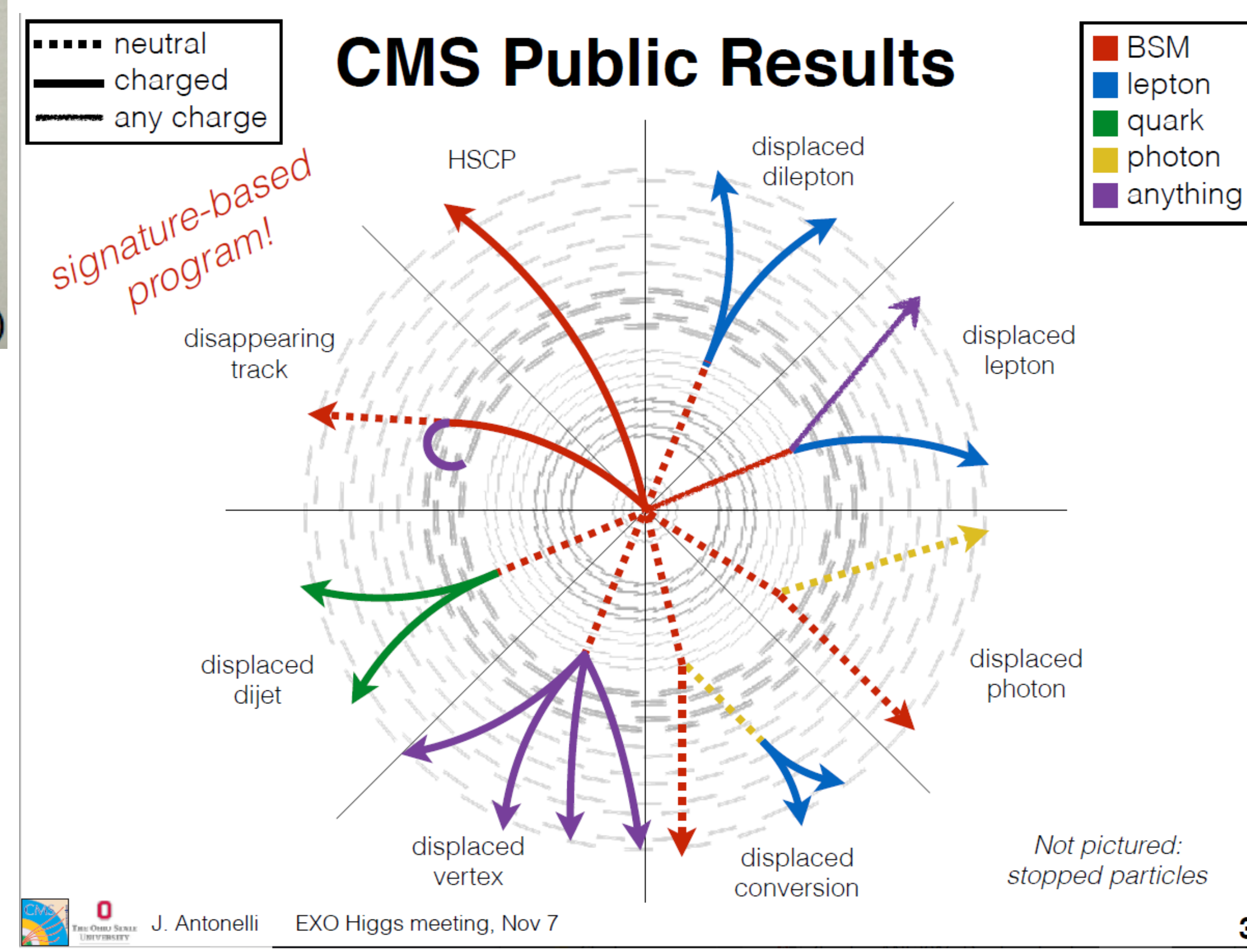
- Approximate symmetry:
  K_L to three pions (accidental PS suppression)

Long-lived particle signatures



Credit: B. Shuve

- Lifetime is a different of angle to think about NP



- Spatial discrimination: mostly related with displaced-vertex, and track-based

Time delay signature of LLP

- Long-lived particle X decay, X-> a b

$$\Delta t = \boxed{\frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a}} - \boxed{\frac{\ell_{\rm SM}}{\beta_{\rm SM}}}$$

Signal arrival time - SM bkg ref time

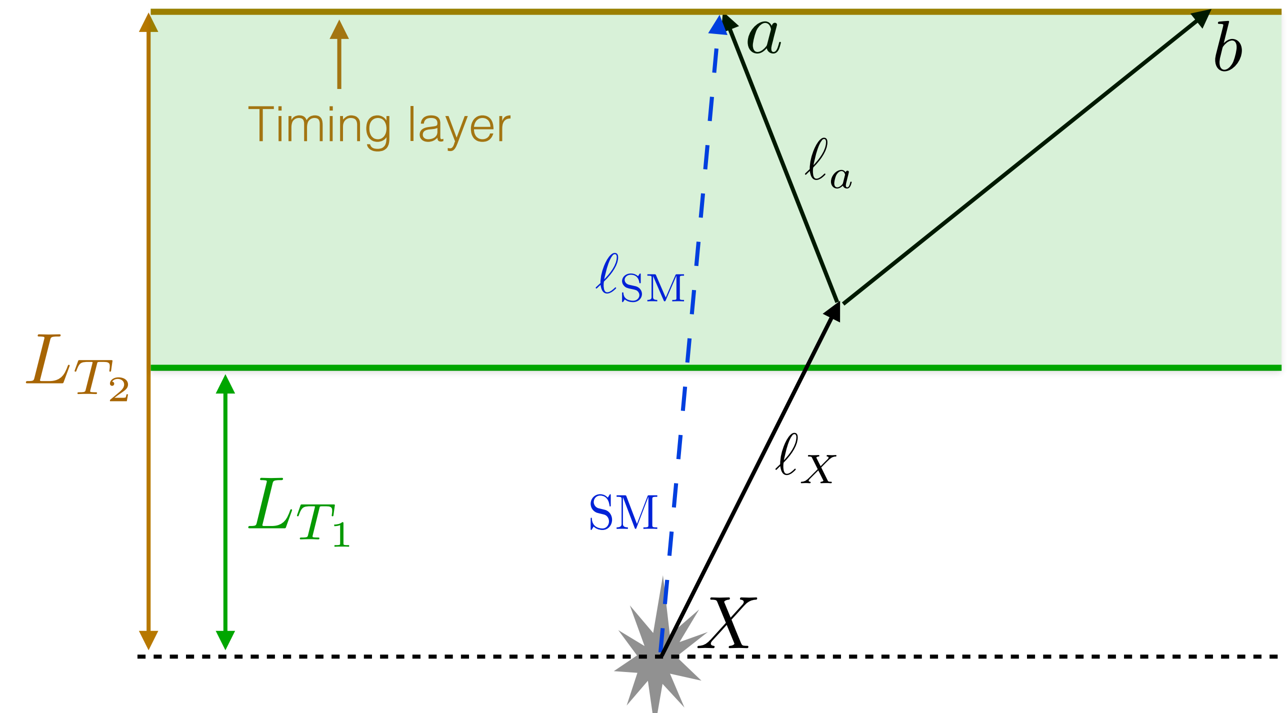
$$\beta_X \lesssim O(1) \qquad \beta_a \simeq \beta_{\rm SM} \simeq 1$$

- Lower bound from slow X

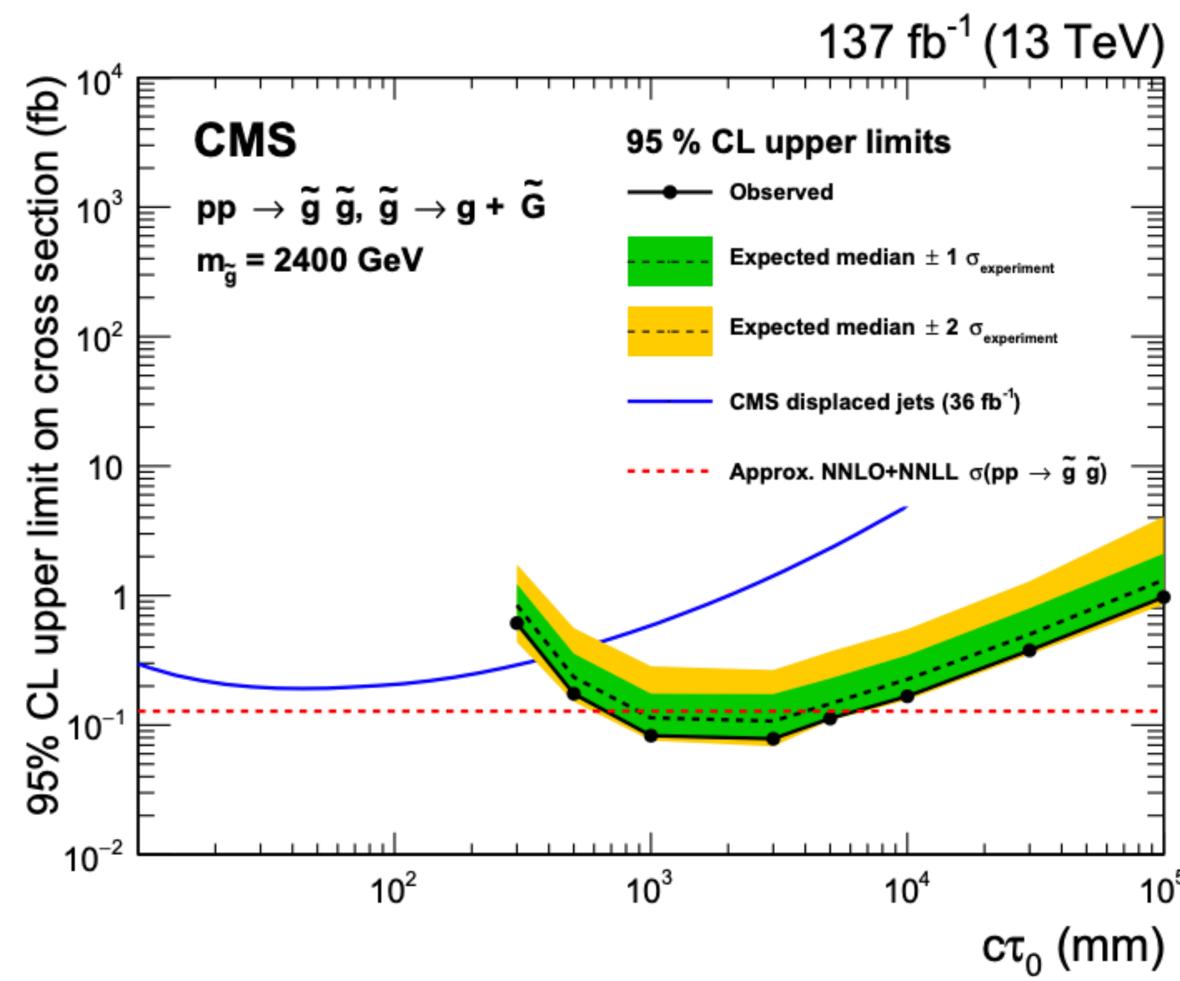
$$\Delta t \geq \frac{\ell_X}{\beta_X} - \frac{\ell_X}{1} = \ell_X(\beta_X^{-1} - 1)$$

- LLPs are significantly delayed comparing with SM backgrounds!

- Already applied by CMS collaboration
PLB 797 (2019) 134876



JL, Z. Liu, L.T. Wang, PRL 2019

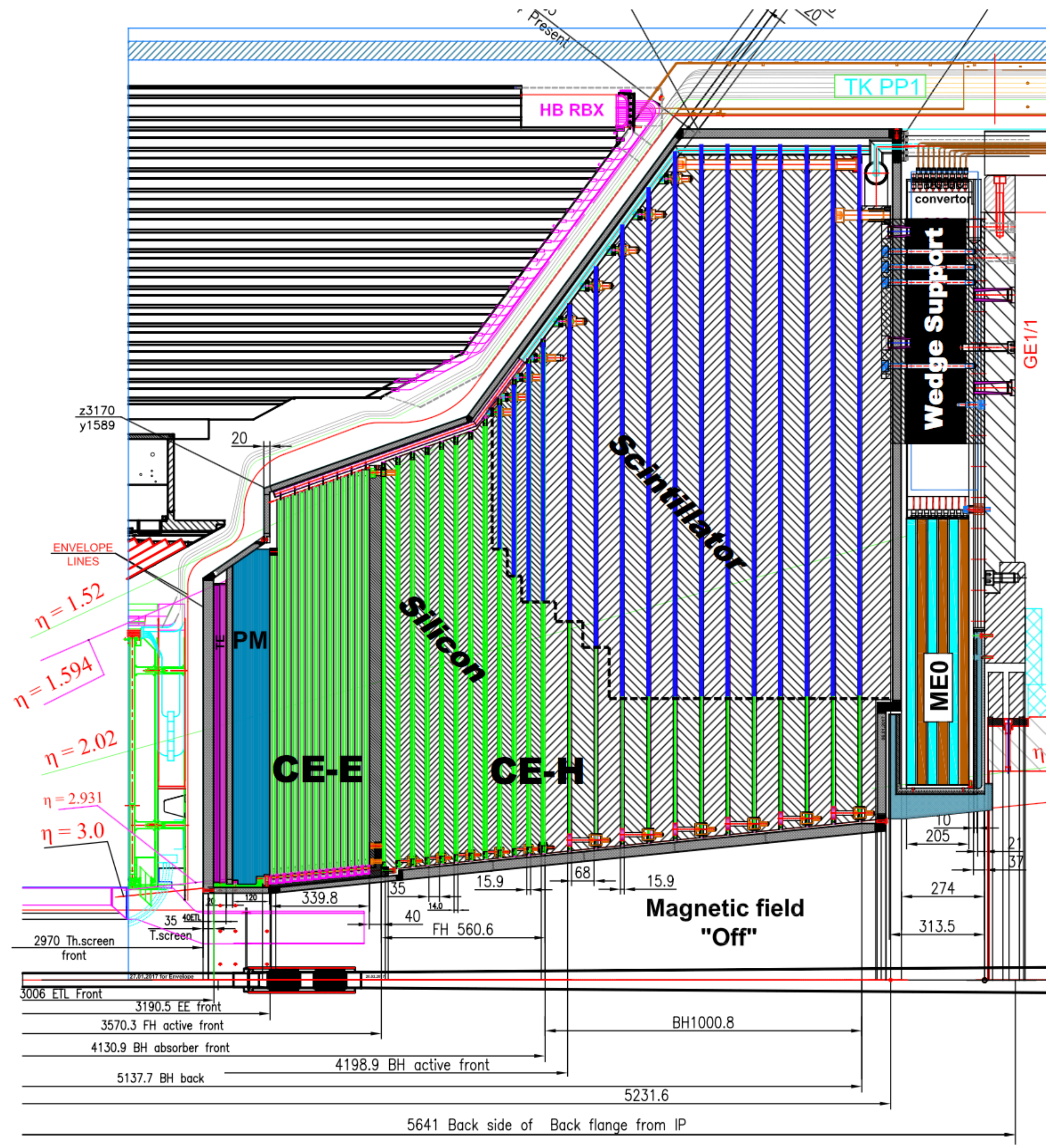


LLP motivation @ HGCAL

- Endcap replacement

See Zhen Lin, Yong Liu and Feng Wang's talks

- Pile-up suppression etc …



- Own triggers
- Tracker with silicon cell 0.5~1 cm^2 for EM and most HA calos
- Angular resolution of 5×10^{-3} rad stand-alone from high granularity (improvement by combining with ID trackers)
- Timing resolution ~ 25 ps from silicon sensor
- Semi-central coverage good for forward LLP
  Collinear enhancement
  Pt PS suppression

What is the HGCAL sensitivity for LLP?

LLP motivation @ HGCAL

- Endcap replacement
- Pile-up suppression etc …

- Own triggers
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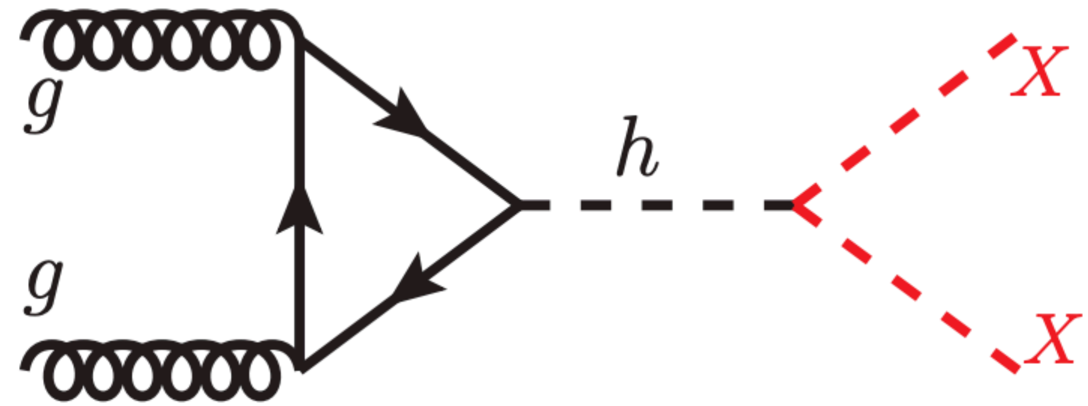
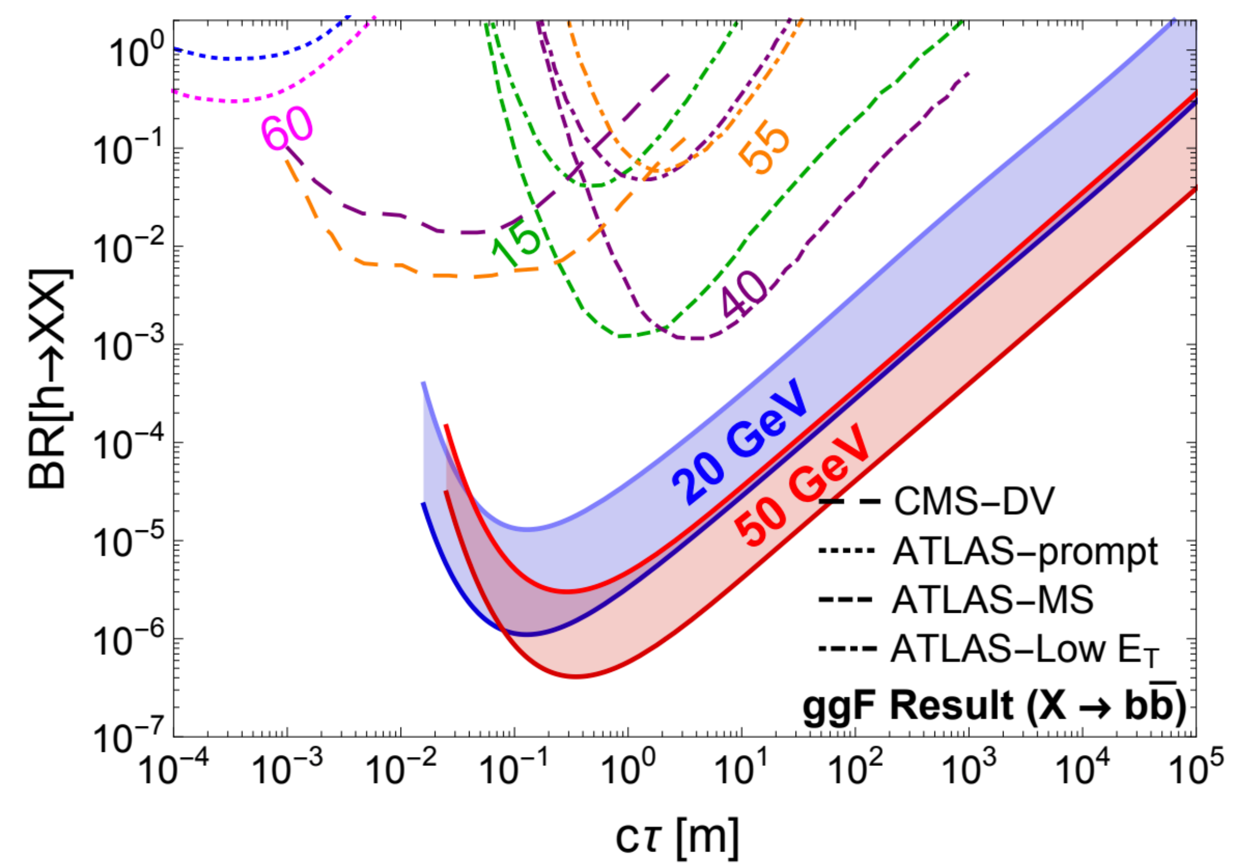
What is the HGCAL sensitivity for LLP?

- The first LLP study @HGCAL
- More NP proposals needed

JL, Z. Liu, L.T. Wang, X.P. Wang 2020

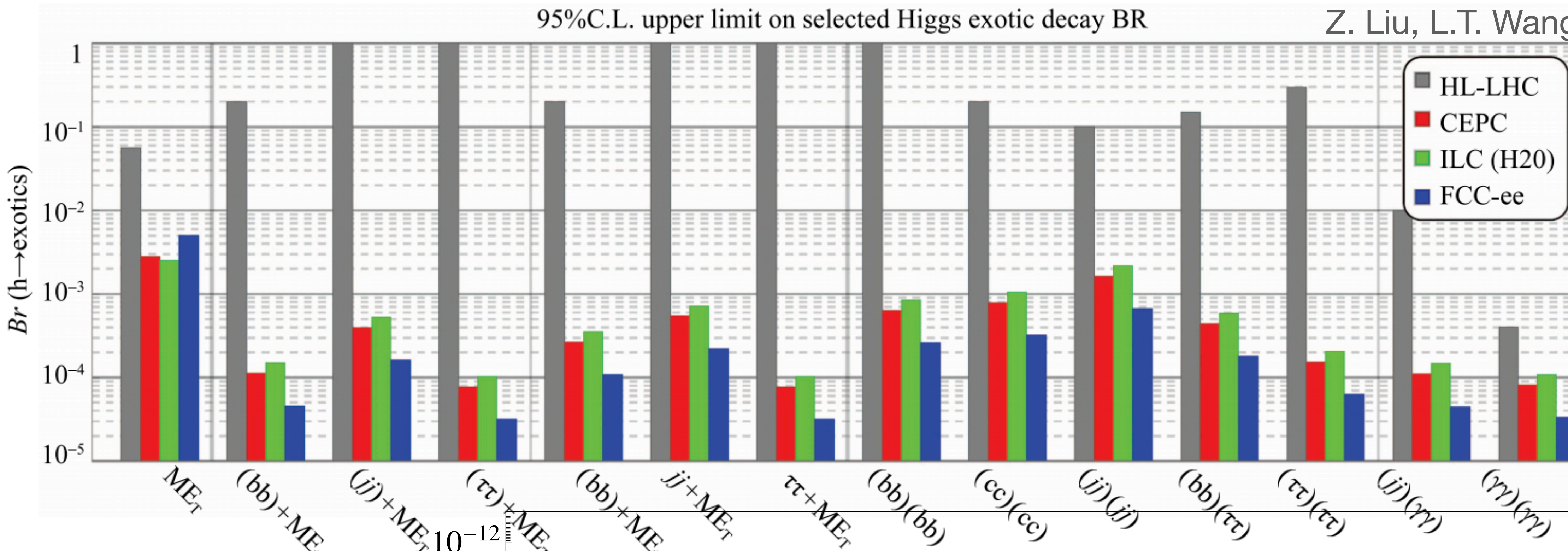




Dark sectors at colliders

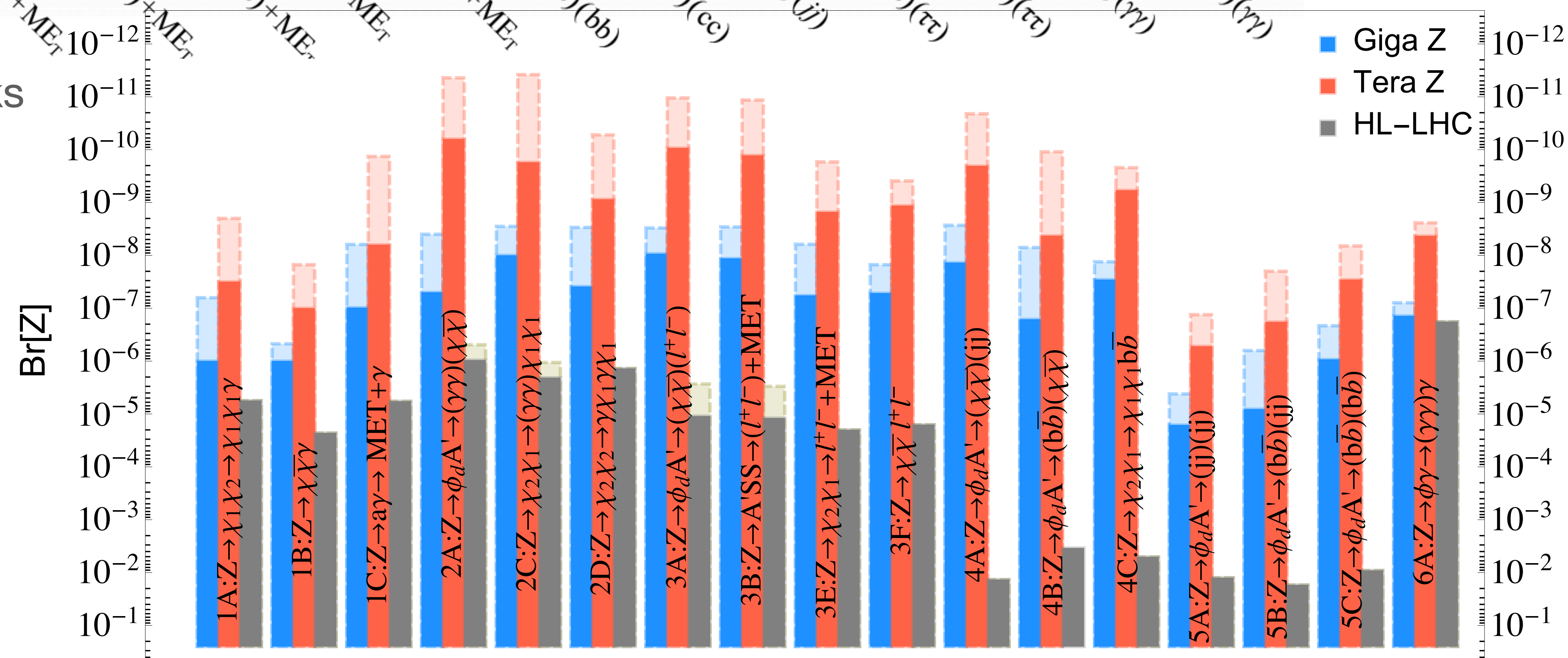
- The dark sector particles can couple to SM H and Z

Z. Liu, L.T. Wang, H. Zhang 2016



See Lianliang Ma's talks

JL, L.T. Wang, X.P. Wang, W. Xue 2017



Jia Liu

Summary

- We have a lot of open questions in BSM
- Theory motivated
- Experimental motivated
- Need to turn every stones to look for BSM
- Synergy between energy/intensity/cosmic frontiers
- Powerful discovery potential from complementary exp approaches!

Thank you!