THE HIGGS AS A PORTAL TO NEW DYNAMICS

Roberto Contino
Scuola Normale Superiore, Pisa
INFN, Pisa

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DISCLAIMER

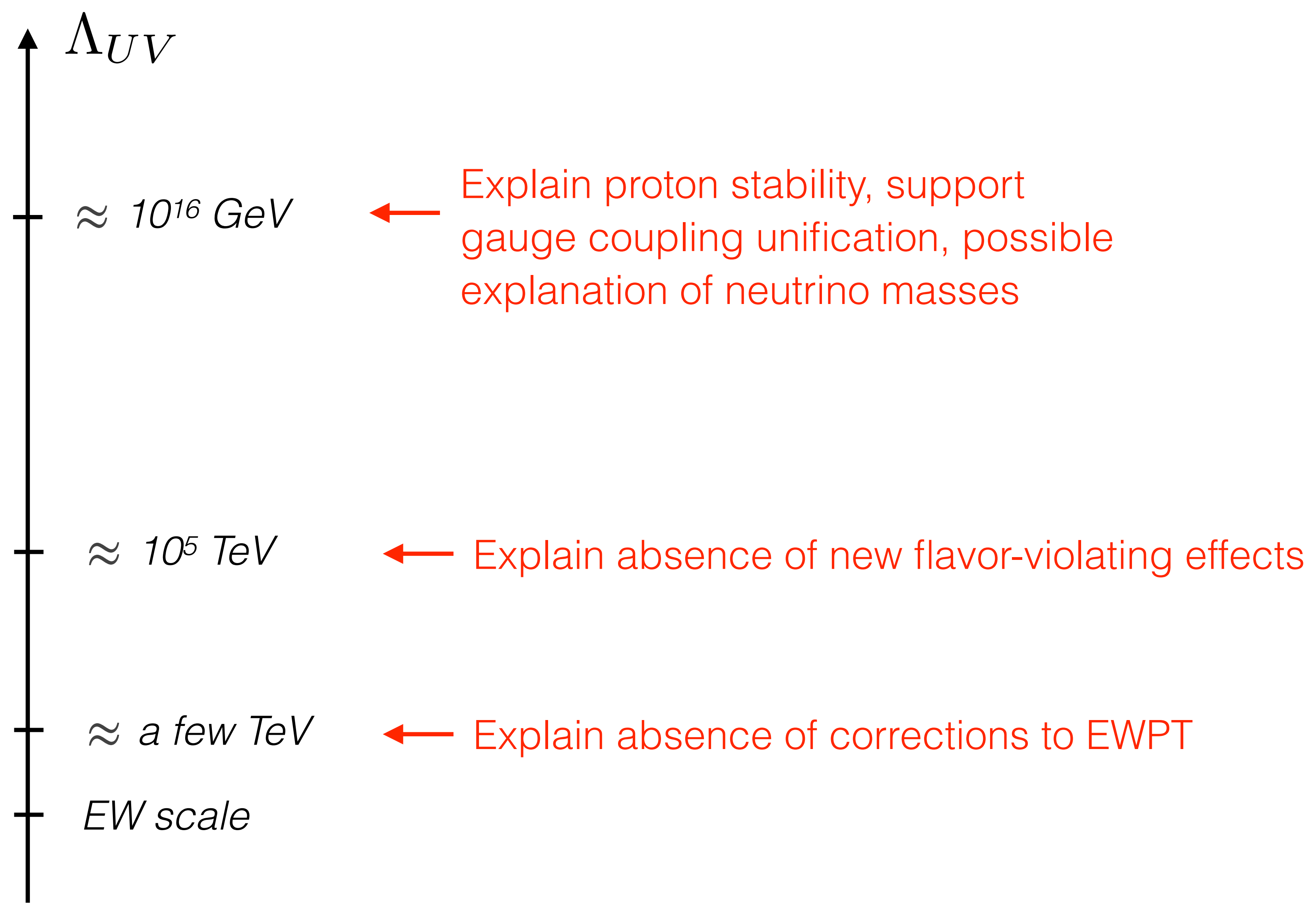
I will not talk about:

- Flavour (e.g. B-anomalies) → *see talk by S. Blasi*
- Dark Matter in natural models → *see talks by M.Ruhdorfer and G. Perez*
- cosmological solutions to the hierarchy problem (relaxation) → *see talk by G. Perez*
- Models of (EW) Baryogenesis → *see talk by A. Glioti*
- SUSY theories

The SM paradigm

1. Global symmetries are accidental

- Large hierarchy ⟶ (approximate) flavor, custodial, B and L_i symmetries emerge accidentally in the IR



The SM paradigm

1. Global symmetries are accidental

- Large hierarchy $\longrightarrow$ (approximate) flavor, custodial, B and L_i symmetries emerge accidentally in the IR

2. Fermions in complex representations of $SU(3)xSU(2)_L xU(1)_Y$

- Bare masses forbidden. Masses explained in terms of couplings
- Only naturally light fermion fields are observed

3. Apparent gauge coupling unification

- Fermions in complete GUT multiples
- Gauge couplings unify with ~20% accuracy at very high scale (~10^{16} GeV)

Feature that seems to undermine the SM paradigm:

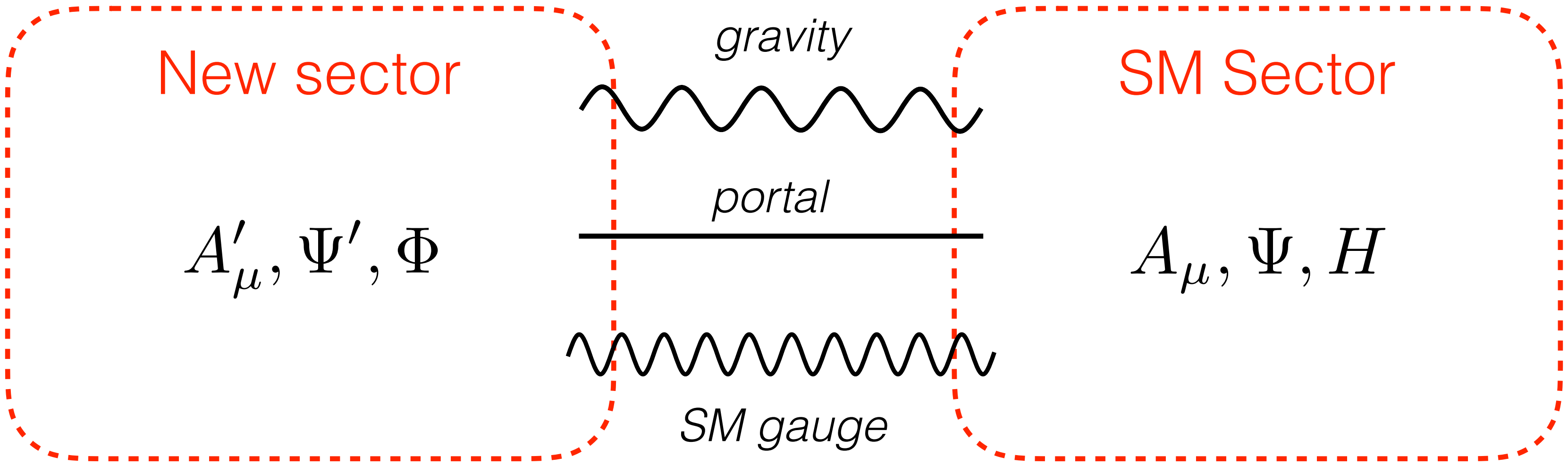
The SM contains one relevant operator with $d \simeq 2$: the Higgs mass term

- EW-GUT hierarchy destabilised
- value of EW scale set in by hand (not dynamically generated)

- SM successfully reproduces all data from laboratory experiments ✓

- QFT + GR can describe cosmological evolution of the Universe, but the SM itself fails to explain two basic features: Dark Matter and Baryogenesis ✗

Extending the SM



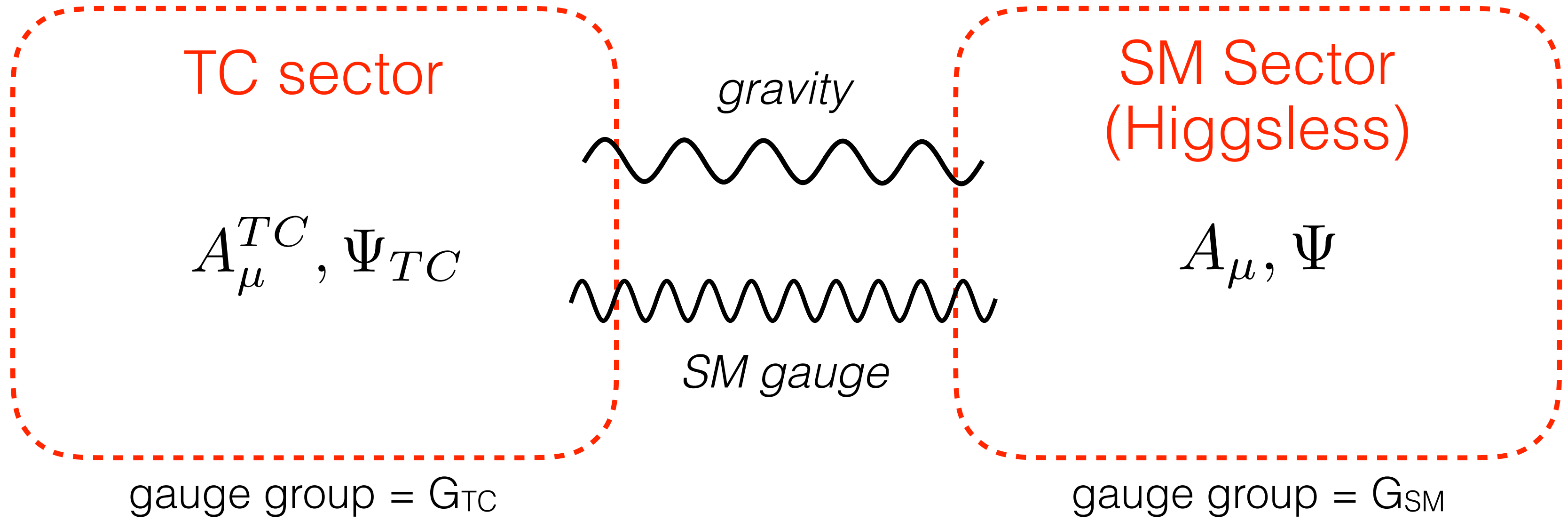
Postulate a new sector with new dynamics and/or new matter

Requirements: the new sector must

- Stabilise and generate dynamically the EW scale
- Achieve SM precision unification
- Explain DM
- Generate baryon asymmetry

Ex. #1: New sector to generate dynamically the EW scale (*Technicolor*)

[Weinberg, Susskind `70]



- Ψ_{TC} vectorlike under G_{TC}, but complex under $G_{TC} \times G_{SM}$

  ☞ TC condensate $\langle \bar{\Psi}_{TC} \Psi_{TC} \rangle$ not a full $G_{TC} \times G_{SM}$ singlet, breaks G_{SM}

Main prediction: *heavy* and *broad* composite Higgs boson

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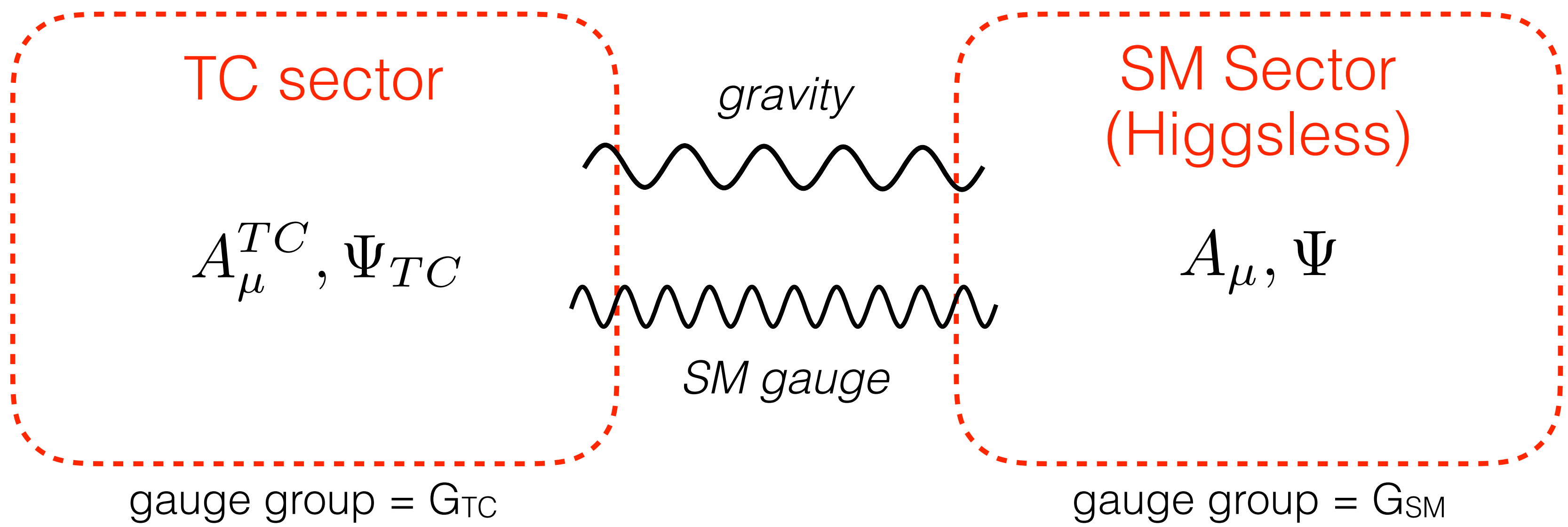

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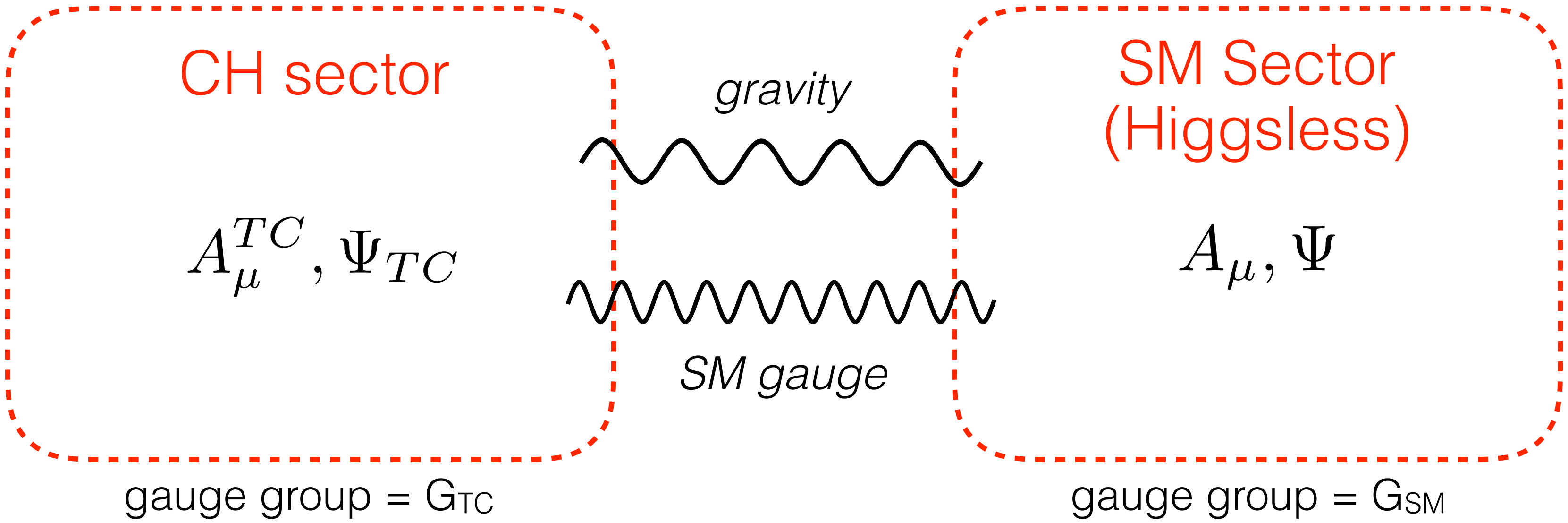
Ruled Out

Ex. #2: New sector to generate dynamically the EW scale (*Composite Higgs*)

[Georgi & Kaplan `80]



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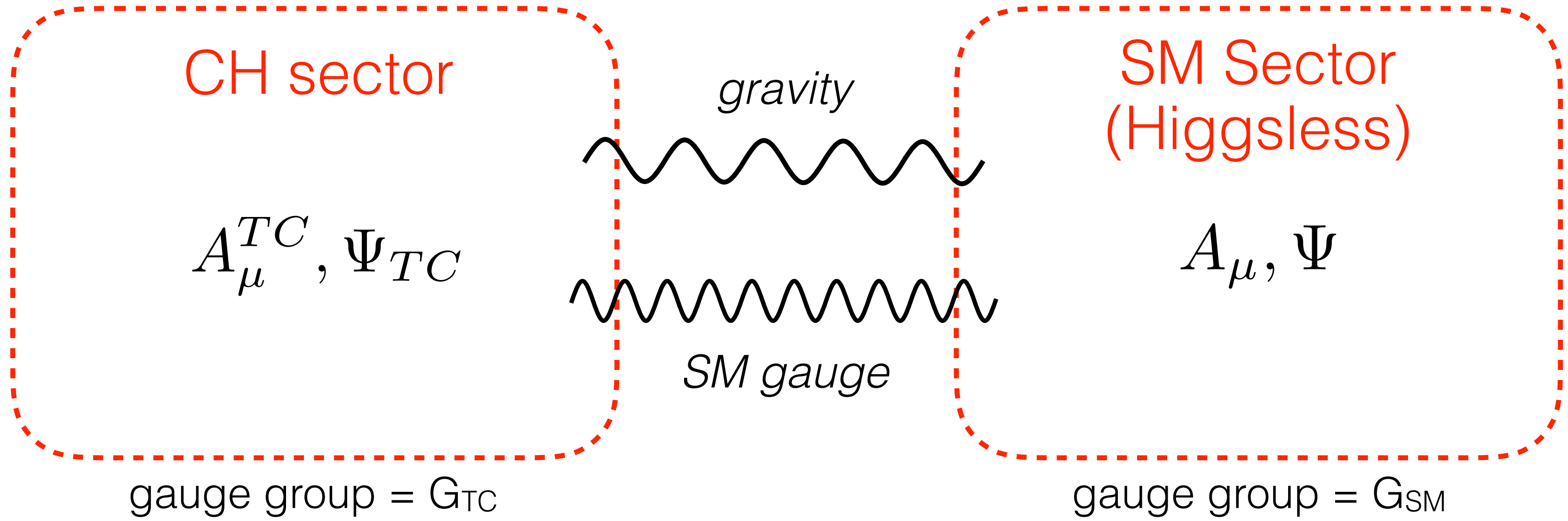

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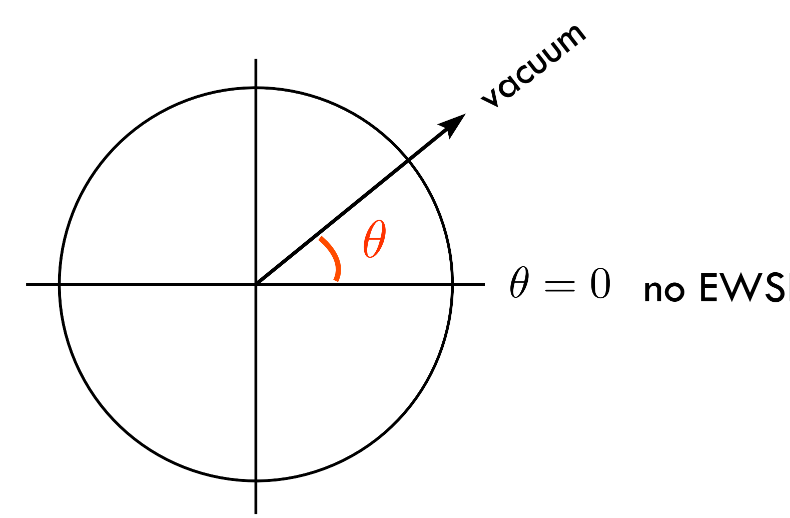
- Vacuum misalignment generated by weak pertubations triggers EWSB. Realistic if NGBs ⊃ $\mathbf{2}_{1/2}$ of $SU(2)_L \times U(1)_Y$



<u>Notice</u>: $\theta \sim \dfrac{v}{f} \ll 1$ requires tuning

General prediction: *light* and *narrow* composite Higgs boson with modified couplings

$$\delta g/g \sim O\big(v^2/f^2\big)$$

$$f^2 \left|\partial_\mu\, e^{i\pi/f}\right|^2 = |D_\mu H|^2 + \frac{c_H}{2f^2}\big[\partial_\mu(H^\dagger H)\big]^2 + \dots$$

- SM fermion masses generated by higher-dim operators

$$\mathcal{L} \supset c\,\bar\Psi\Psi O_H + \lambda_L\,\bar\Psi_L O_L + \lambda_R\,\bar\Psi_R O_R + h.c. \qquad O_H \sim \bar\Psi_{TC}\Psi_{TC}, \quad O_{L,R} \sim \bar\Psi_{TC}\Psi_{TC}\Psi_{TC}$$

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Tension between generating large enough quark masses and avoiding the hierarchy problem in theories with bilinear couplings

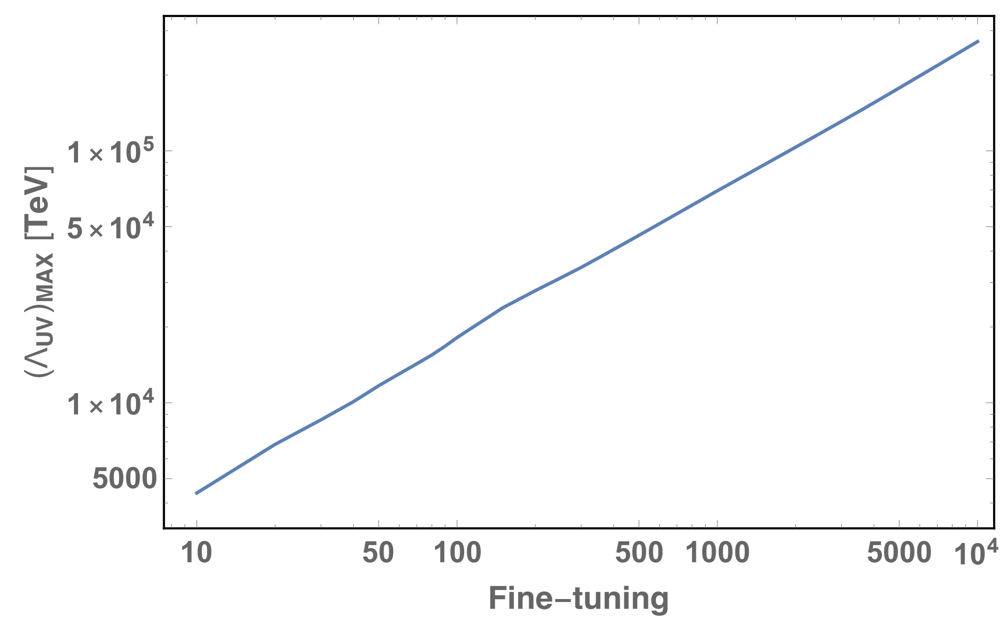
[Rattazzi, Rychkov, Tonni, Vichi JHEP 0812 (2008) 031]

$$[O_H] = d_H \qquad [O_H^2] = \Delta(d_H) \qquad \lim_{d_H \to 1} \Delta = 2$$

$$\frac{m_q}{v} \sim \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{d_H - 1} \qquad \mathrm{FT} \sim \left(\frac{\Lambda_{UV}}{\Lambda}\right)^{4-\Delta}$$

Upper bound on $\Delta(d_H)$ from bootstrap of CFTs gives lower bound on Λ_{UV}

[adapted from JHEP 1205 (2012) 110]



UV completion required at relatively low scales, must address flavor

[Poland, Simmons-Duffin, Vichi JHEP 1205 (2012) 110]

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Theories with linear couplings and partial compositeness can have a higher cutoff

$$[O_i] = d_i \qquad \lim_{d\to 3/2}[O^2] = 3 \qquad \frac{m_q}{v} \sim \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{d_L+d_R-5}$$

need $d_i \simeq 5/2$ $\longrightarrow$ one can safely have $[O^2] > 4$

Prediction: top partners (composite fermions χ) $\qquad \langle 0|O_i|\chi_i\rangle \neq 0$

- 4D Composite Higgs Theories with partial compositeness give non-minimal EW cosets.
(ex: SU(4)/Sp(4), SU(5)/SO(5), SU(4)xSU(4)/SU(4)) Ferretti, Karateev JHEP 03 (2014) 077

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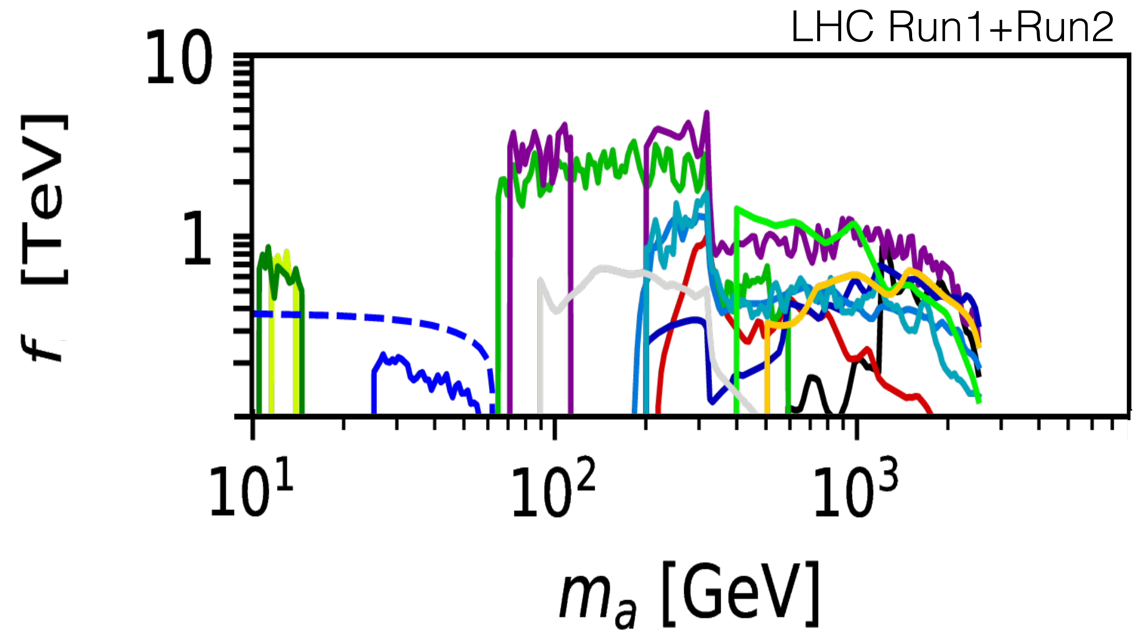
☞ Production at LHC via gluon fusion
Decay to $VV, \bar{\psi}\psi$



[Cacciapaglia et al. Front. Phys. 7 (2019) 22]

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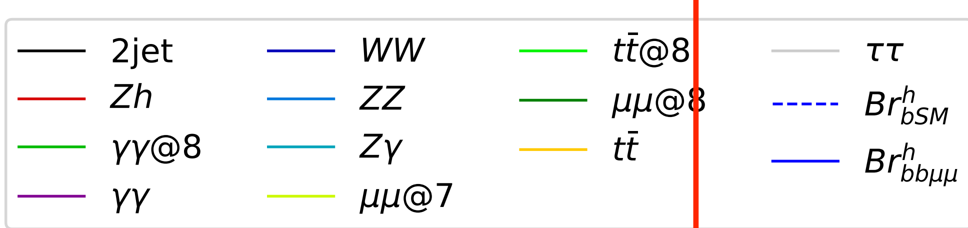

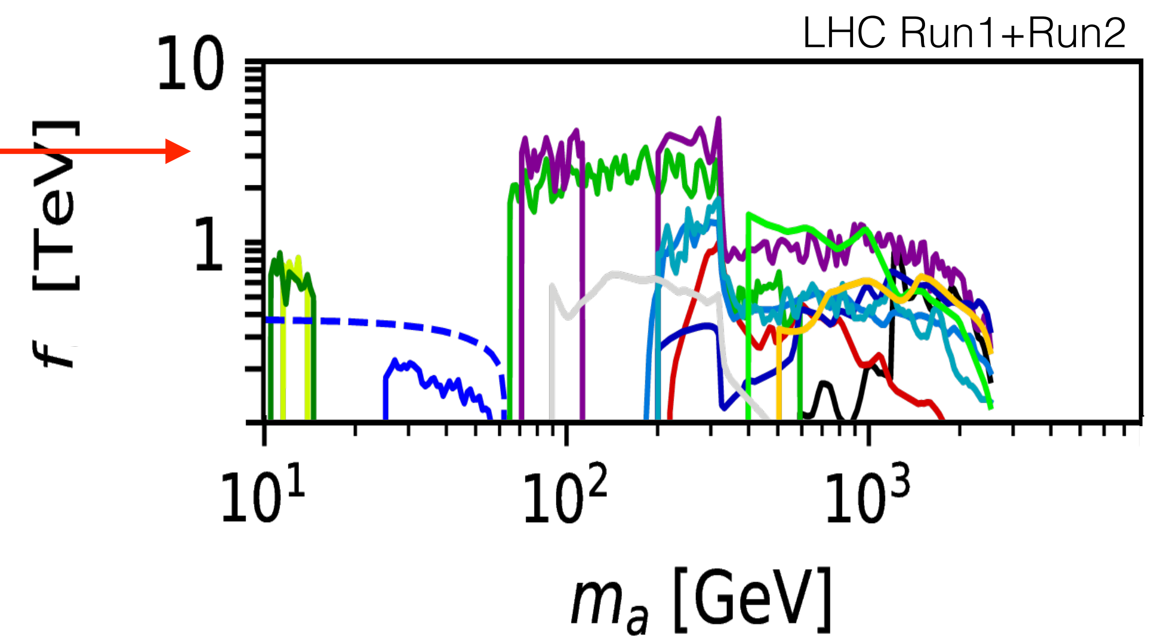

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Bounds **stronger** than those from

EWPT: $f \gtrsim 0.8 - 1.7\,\mathrm{TeV}$

Top partner searches: $f \gtrsim 300\,\mathrm{GeV}\left(\frac{3}{g_*}\right)$

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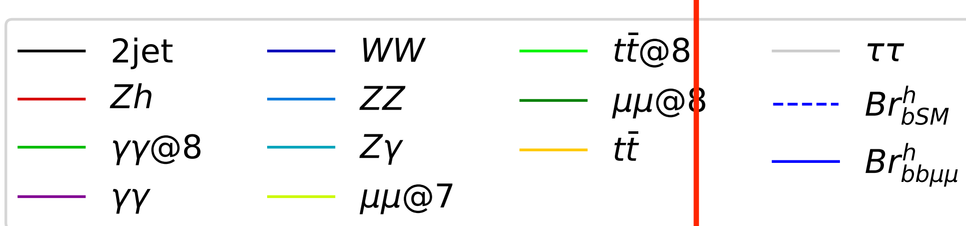

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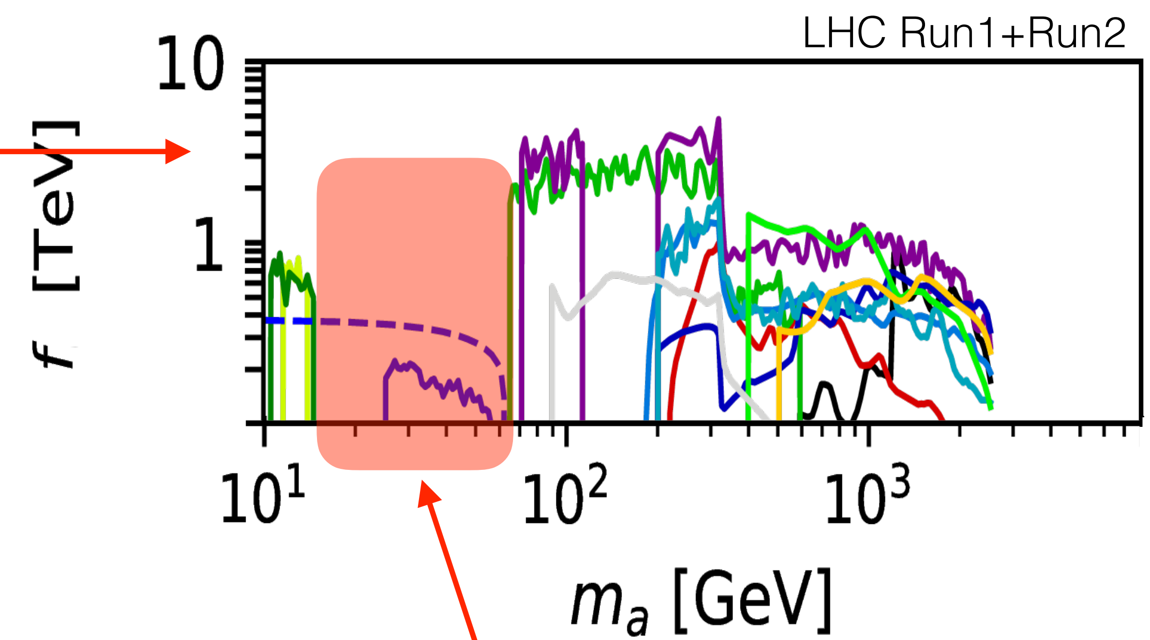

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Mass window $14\,\mathrm{GeV} \lesssim m_a \lesssim 65\,\mathrm{GeV}$ poorly constrained by current searches

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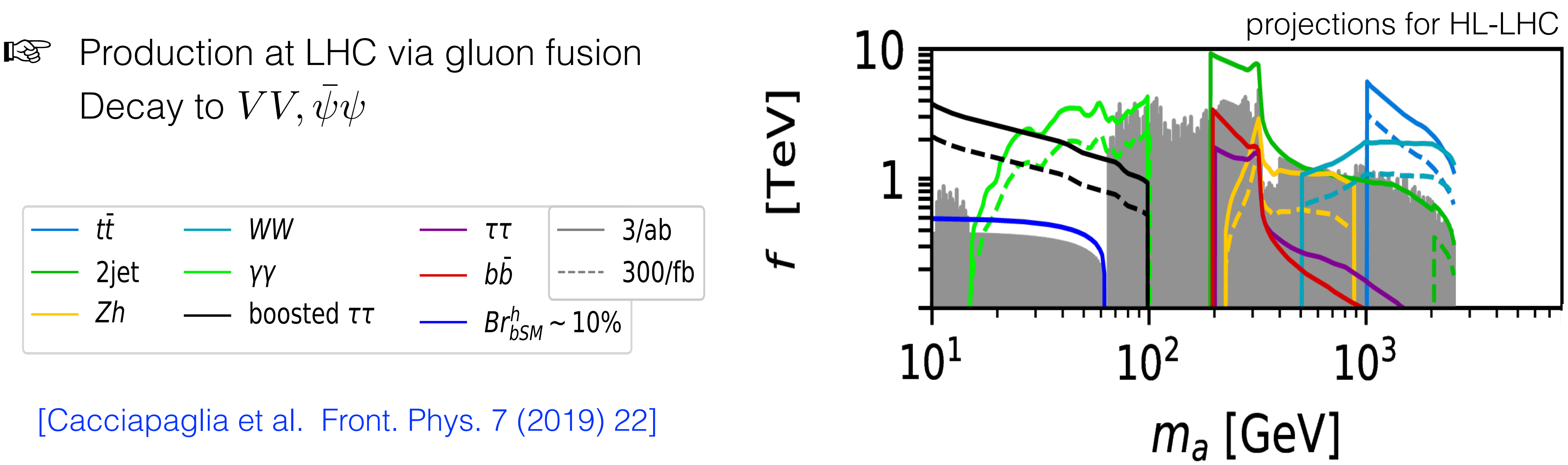

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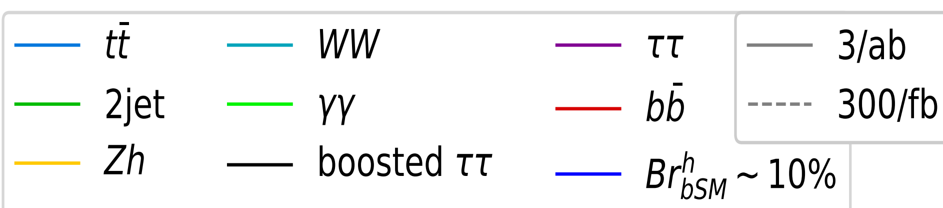

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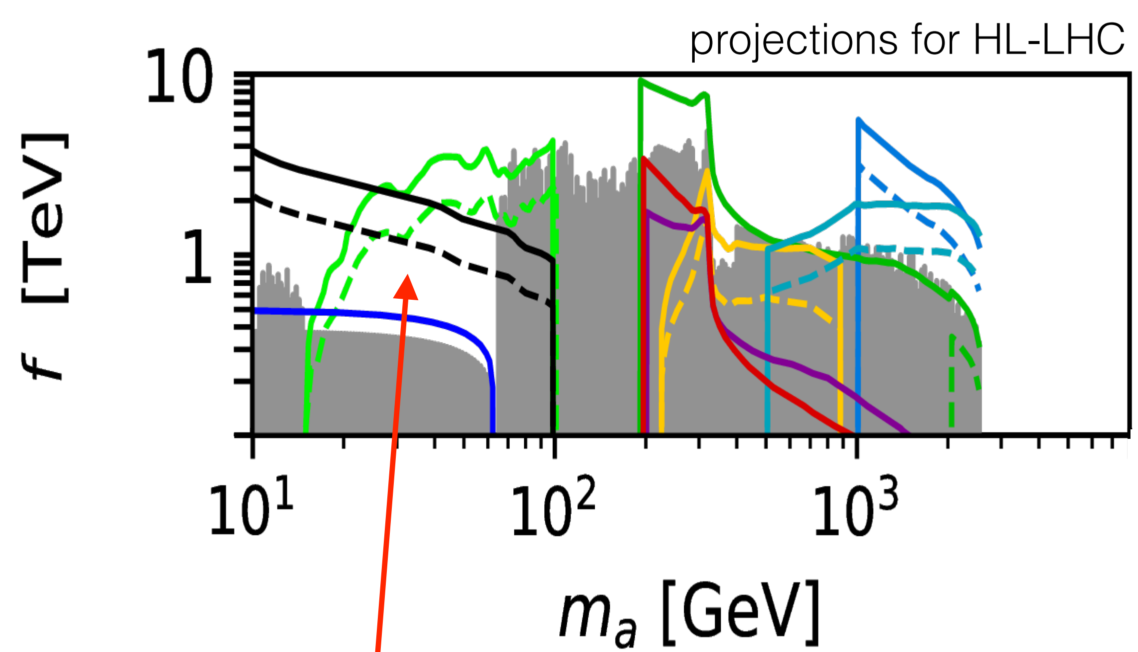

Proposed searches:

$a \to \tau\tau \to (e\nu\bar{\nu})(\mu\nu\bar{\nu})$ (boosted+ISR)

[Cacciapaglia et al. Eur.Phys.J. C78 (2018) 724]

$a \to \gamma\gamma$ (differential)

[Mariotti et al. PLB 783 (2018) 13]

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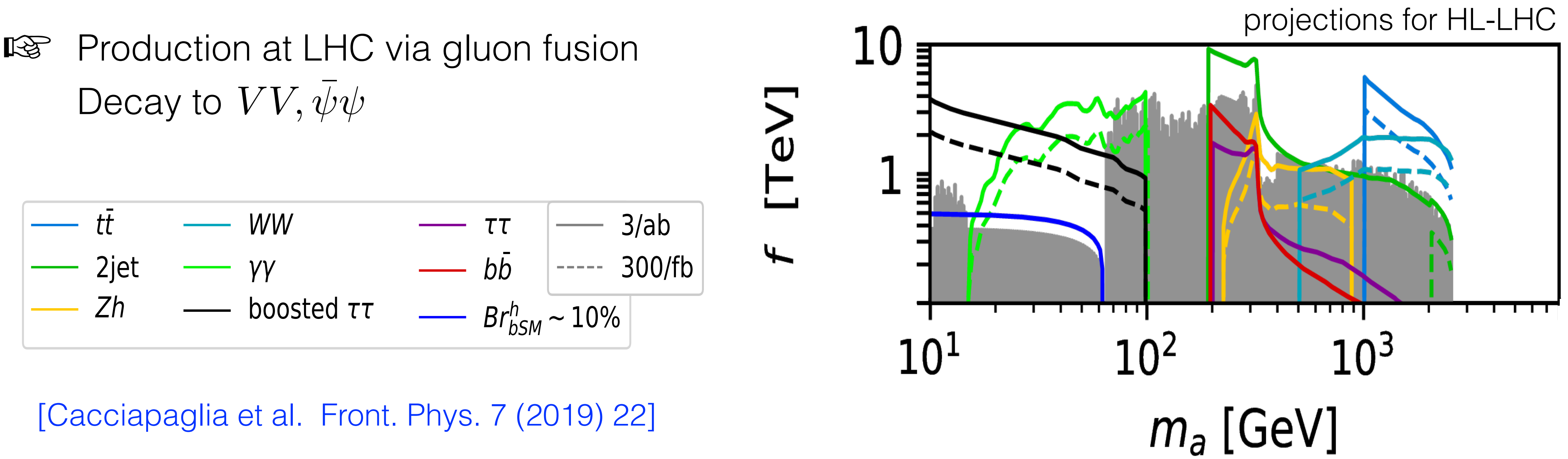

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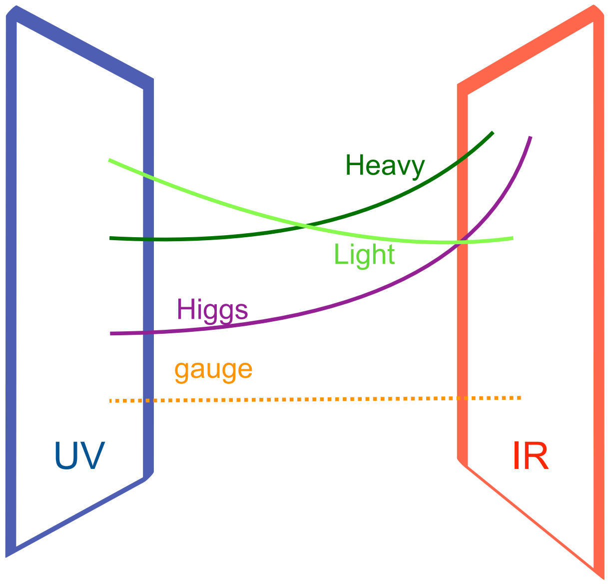
Warning: Only top/bottom are partial composite, lighter SM fermions must have bilinear couplings (cannot have too many new fermions since the theory has to confine)

Cutoff below 10^5 TeV, UV completion must address flavor

- Holographic Composite Higgs theories have partial compositeness built-in, minimal coset SO(5)/SO(4) and no ALPs. Cutoff can be at Planck scale.

[Agashe, RC, Pomarol (2005); RC, Da Rold, Pomarol (2007)]



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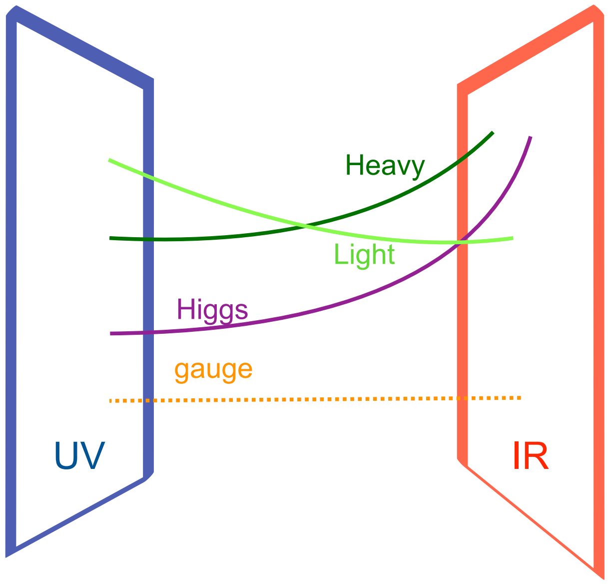

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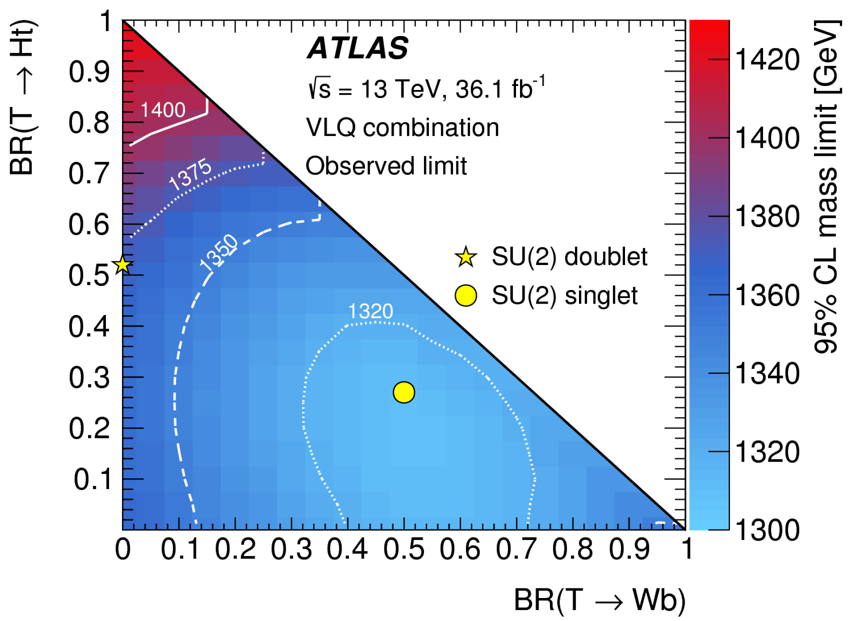
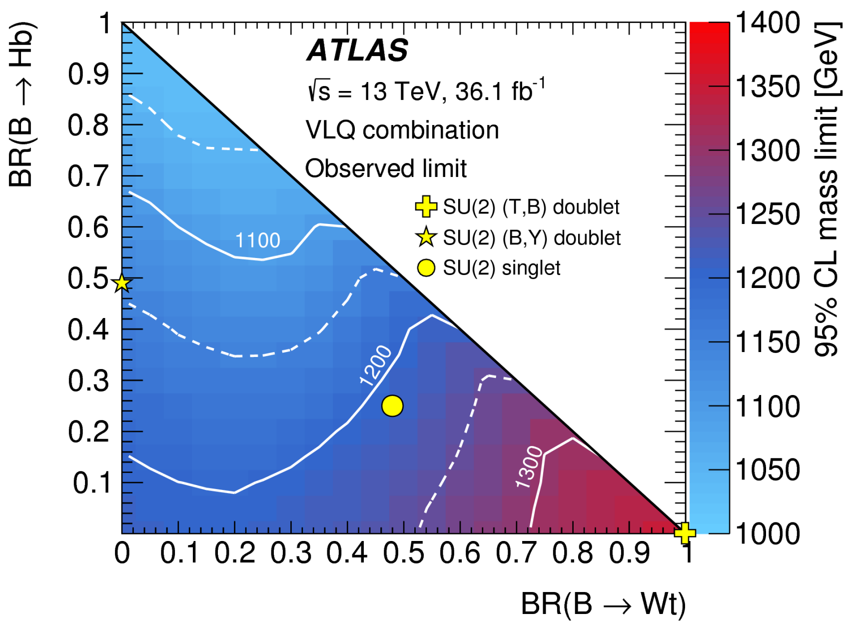




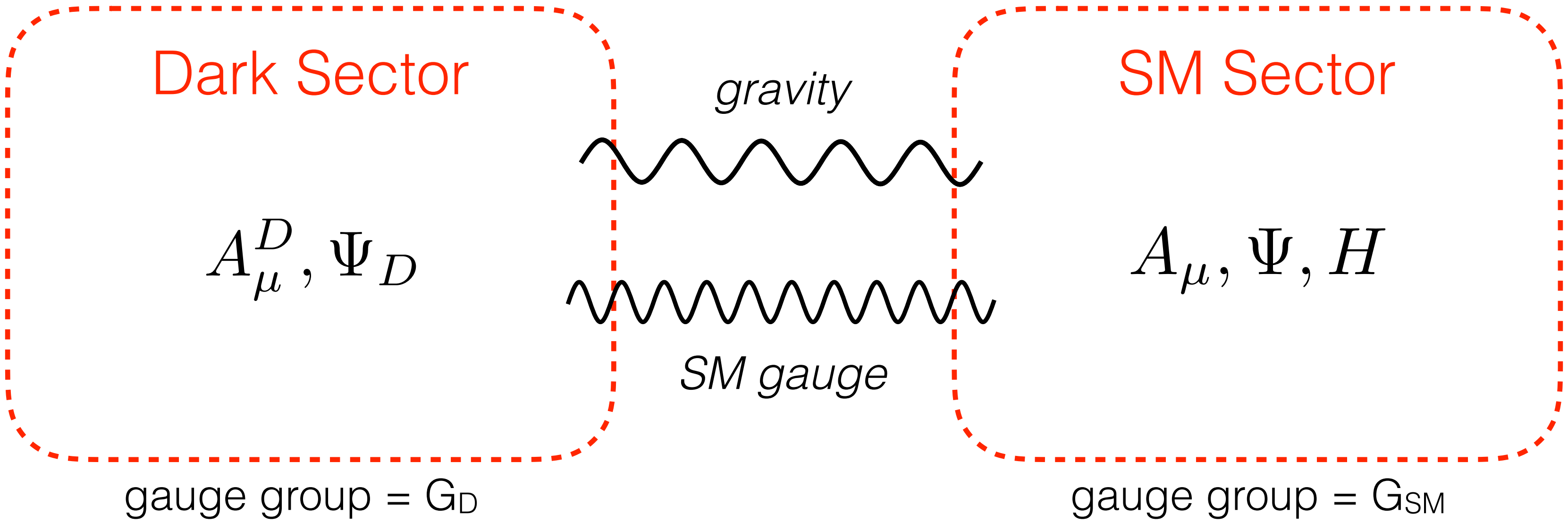
- ATLAS and CMS searches with 36fb^{-1} at 13TeV

- Lower bounds $M_T, M_B \gtrsim 1.1 - 1.3\,\mathrm{TeV}$

Associated fine tuning

$$\mathrm{FT} \approx \frac{3y_t^2}{4\pi^2}\frac{M^2}{m_h^2} \simeq \left(\frac{M}{0.45\,\mathrm{TeV}}\right)^2 \simeq 10$$

Ex. #3: New charged sector to give accidentally-stable DM candidate



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- Unbroken accidental symmetry $G_{global} \supset [U(1)_V]^{k-1} \otimes U(1)_{DB}$

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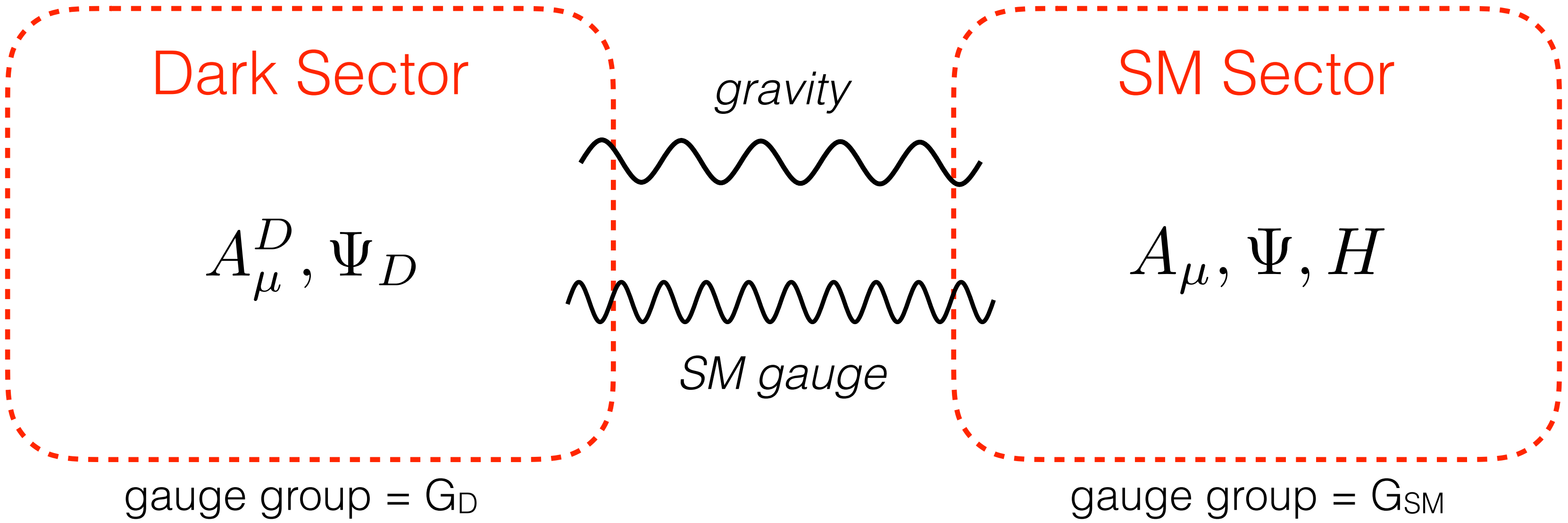

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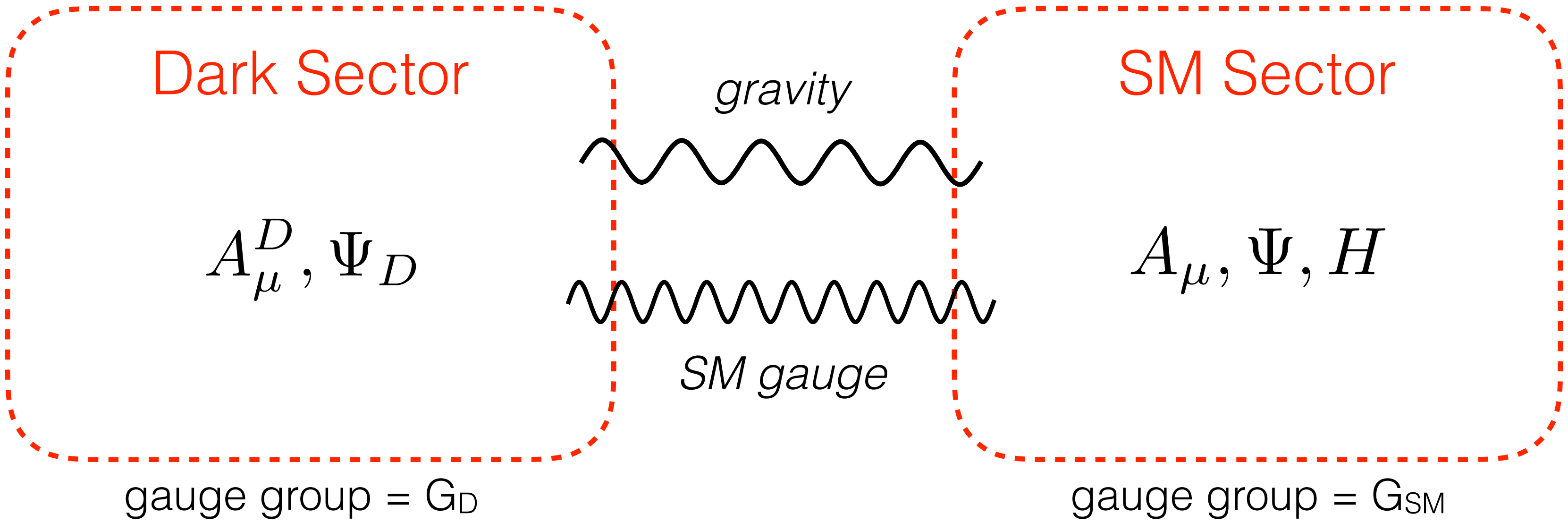

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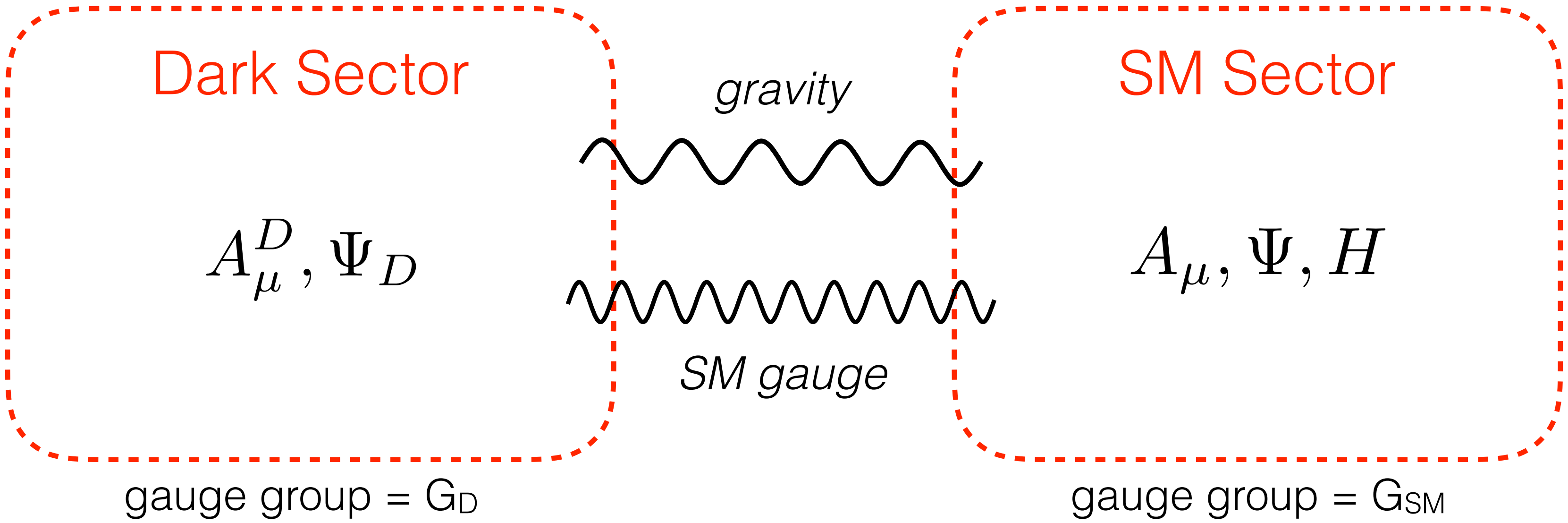

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species numbers dark baryon number

DM = Bound state stable due to an accidental symmetry

☞ Analogy: proton stable due to accidental baryon number

- Various types of accidental DM candidates

Dark baryons

Dark mesons (pions and quarkonia)

see recent classification in:
Antipin, Redi, Strumia and Vigiani JHEP 1507 (2015) 039
Mitridate, Redi, Smirnov, Strumia, JHEP 1710 (2017) 210

Gluequarks (Qg bound states with adjoint dark quarks)

R.C., Mitridate, Podo, Redi JHEP 1902 (2019) 187
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- Colliders probes: *production of dark resonances (pions, rho's, baryons,..) through their SM quantum numbers and anomaly couplings*

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$$\bar{\Psi}_D \Psi_D H \longrightarrow$$

After dark confinement, mixing between elementary H and dark pion $(\bar{\Psi}_D \Psi_D)$

Partial Higgs Compositeness

Georgi and Kaplan, Phys. Lett. 136B (1984) 183
Antipin and Redi, JHEP 1512 (2015) 031
Agugliaro et al. PRD 95 (2017) 035019
Galloway, Kagan, Martin PRD 95 (2017) 035038

Example: [Antipin and Redi, JHEP 1512 (2015) 031]

	$SU(N)_D$	$SU(2)_L$	$U(1)_Y$
L	$\square$	2	$+1/2$
$\bar{L}$	$\bar{\square}$	$\bar{2}$	$-1/2$
N	$\square$	1	0
$\bar{N}$	$\bar{\square}$	1	0

Dynamical symmetry breaking:

$SU(3)_L \times SU(3)_R \to SU(3)_V$ 8 NGBs

$$\mathcal{L}_{Yuk} = \bar{L}NH + \bar{N}LH^c + h.c.$$

$$\pi \sim \begin{cases} (\bar{N}L), (\bar{L}, N) = 2_{1/2} + \bar{2}_{-1/2} \\ (\bar{N}N), (\bar{L}L) = 1_0 + 3_0 \end{cases}$$

Example: [Antipin and Redi, JHEP 1512 (2015) 031]

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Dynamical symmetry breaking:

$SU(3)_L \times SU(3)_R \to SU(3)_V$ 8 NGBs

$$\mathcal{L}_{Yuk} = \bar{L}NH + \bar{N}LH^c + h.c.$$

$$\pi \sim \begin{cases} (\bar{N}L), (\bar{L}, N) = 2_{1/2} + \bar{2}_{-1/2} \\ (\bar{N}N), (\bar{L}L) = 1_0 + 3_0 \end{cases}$$

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$$\begin{pmatrix} H & \pi \end{pmatrix} \begin{pmatrix} m_H^2 & yf\Lambda \\ yf\Lambda & m_\pi^2 \end{pmatrix} \begin{pmatrix} H \\ \pi \end{pmatrix}$$

Induced EWSB: $\det(M^2) < 0$ **for** $m_H^2 < m_{crit}^2 = \frac{y^2 f^2 \Lambda^2}{m_\pi^2} \sim 16\pi^2 f^2 \frac{y^2}{g^2}$

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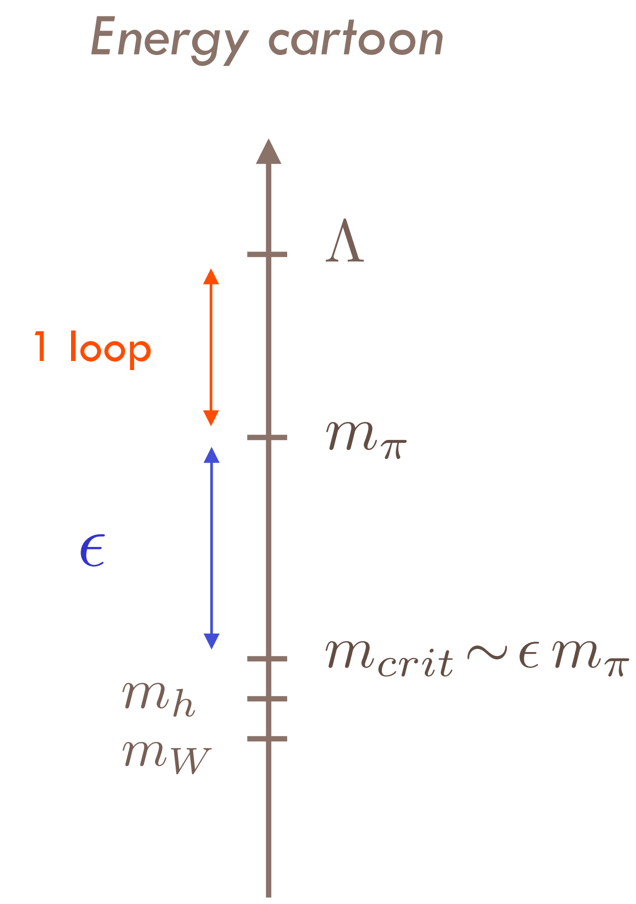

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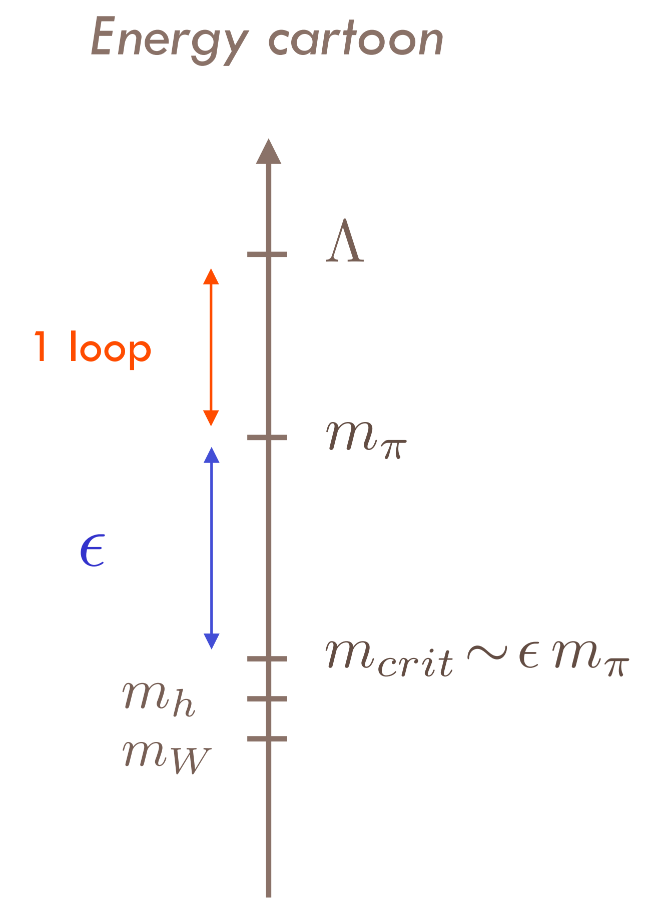

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- Modified Higgs couplings (as in Type-I 2HDM)

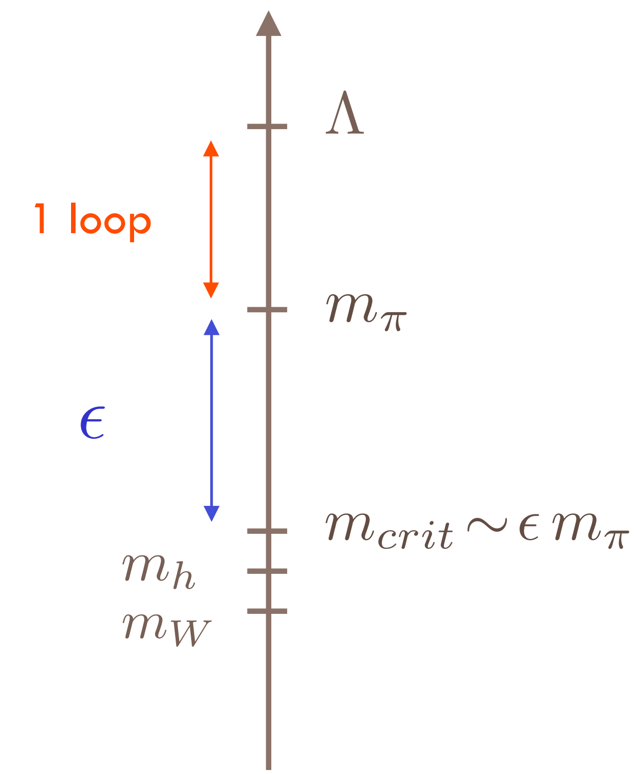
mixing between neutral states: $\tan 2\delta \approx \dfrac{2\epsilon\, m_h^2}{m_\pi^2 - m_h^2}$

$$\frac{g_{hVV}}{g_{hVV}^{SM}} = \cos\delta \approx 1 - \frac{\epsilon^2 m_h^4}{2(m_h^2 - m_\pi^2)^2}$$

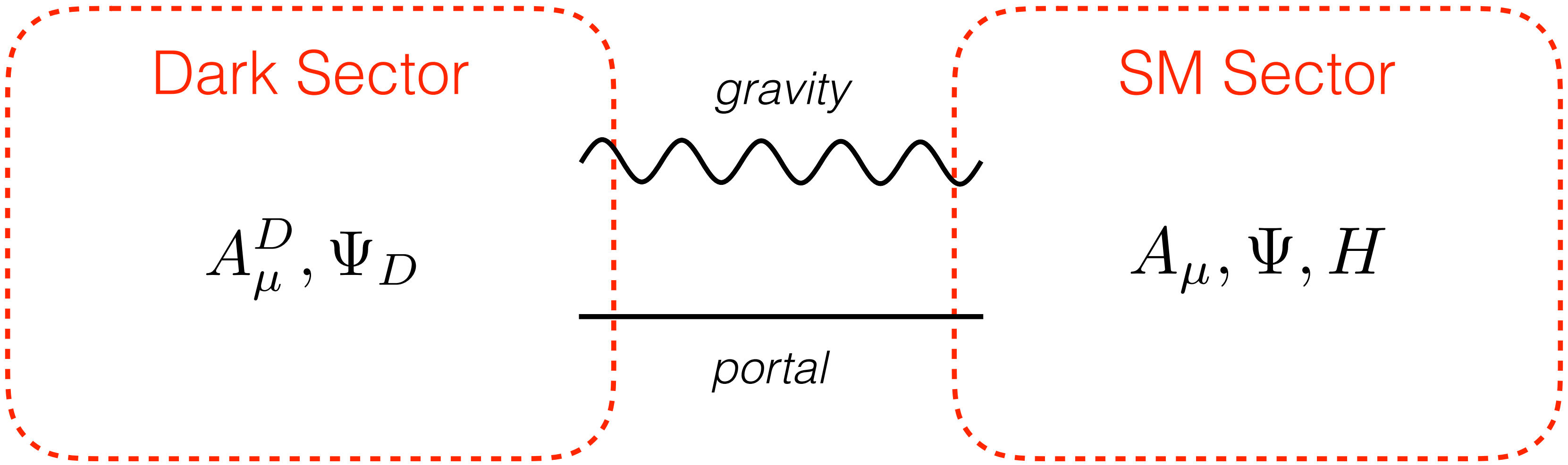
$$\frac{g_{h\psi\psi}}{g_{h\psi\psi}^{SM}} = \frac{\cos(\beta-\delta)}{\cos\delta} \approx 1 + \frac{\epsilon^2}{2}\frac{2m_h^2 m_\pi^2 - 3m_h^4}{(m_h^2 - m_\pi^2)^2}$$

[Antipin and Redi, JHEP 1512 (2015) 031]

Energy cartoon



Ex. #4: New neutral sector coupled through portal interactions



- Assumption: Dark sector characterized by a mass gap Λ_{IR} and a cutoff $\Lambda_{UV} \gg \Lambda_{IR}$, no other parametric energy scales

  ⇨ dark sector approximatively conformal for $\Lambda_{IR} \ll E \ll \Lambda_{UV}$

- Goal: Set general bounds on this scenario without specifying the details of the dark dynamics

[work in progress with K. Max and R. Mishra]

- Minimal set of lowest-dimensional operator characterising the dark CFT:

$T_{\mu\nu}$	*energy-momentum tensor*	$[T_{\mu\nu}] = 4$
$\mathcal{O}$	*scalar operator generating the hierarchy* $\Lambda_{UV} \gg \Lambda_{IR}$	$[\mathcal{O}] = 4 - \varepsilon$

Minimal portal interactions:

$$\mathcal{L}_{\rm portal} \supset g_* g_X \frac{T^{\rm SM}_{\mu\nu} T^{\mu\nu}_{\rm CFT}}{\Lambda^4_{UV}} + g_* g_Y \frac{\mathcal{O}\, H^\dagger H}{\Lambda^{d_\mathcal{O}-2}_{UV}} + g_* g_Z \frac{\mathcal{O}\, \mathcal{O}_{\rm 4SM}}{\Lambda^{d_\mathcal{O}}_{UV}}$$

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Higgs portal ⋯⋯▸ *see also talk by G. Perez*

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Higgs portal ⇢ *see also talk by G. Perez*

Examples:
- *pure Yang-Mills gauge theory*
- *Randall-Sundrum with only gravity + Goldberger-Wise scalar in the bulk*
- *free fermion*

- Setting constraints:
    - *(high-energy) collider searches*
    - *(low-energy) precision tests*
    - *astrophysical (stars, supernovae)*
    - *cosmological*

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1. *Compute rates conservatively by including only regime* $\Lambda_{IR}^2 \ll q^2 \ll \Lambda_{UV}^2$ *(where dark sector ~ CFT)*
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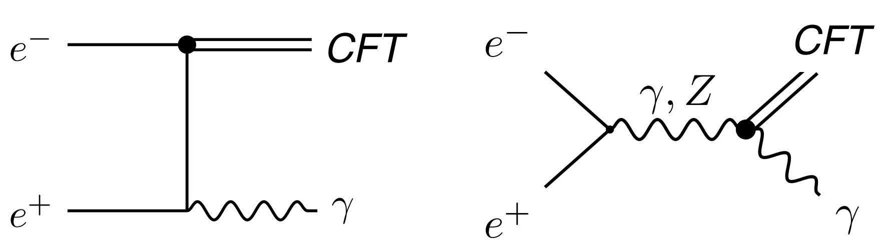
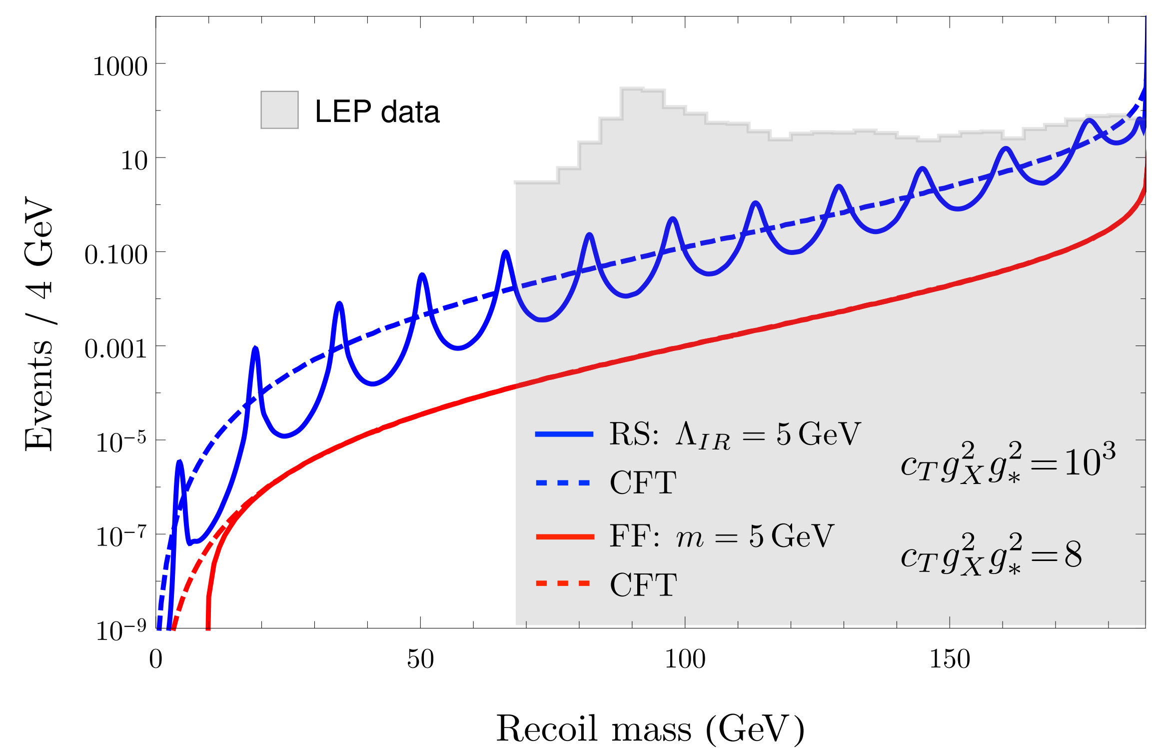
Bounds on dim-8 $T_{\mu\nu}^{\mathrm{SM}} T_{\mathrm{CFT}}^{\mu\nu}$ operator

1. Mono-X searches:

Ex: $e^+e^- \to \gamma + \not{p}$ at LEP2





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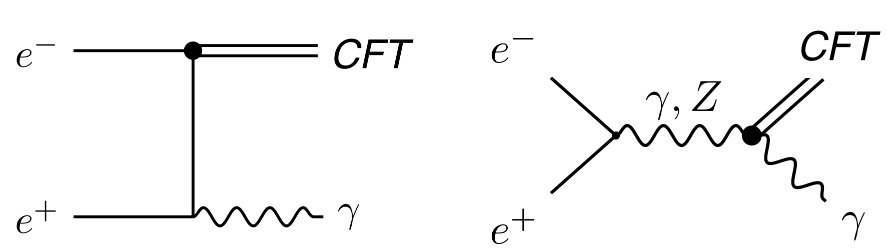
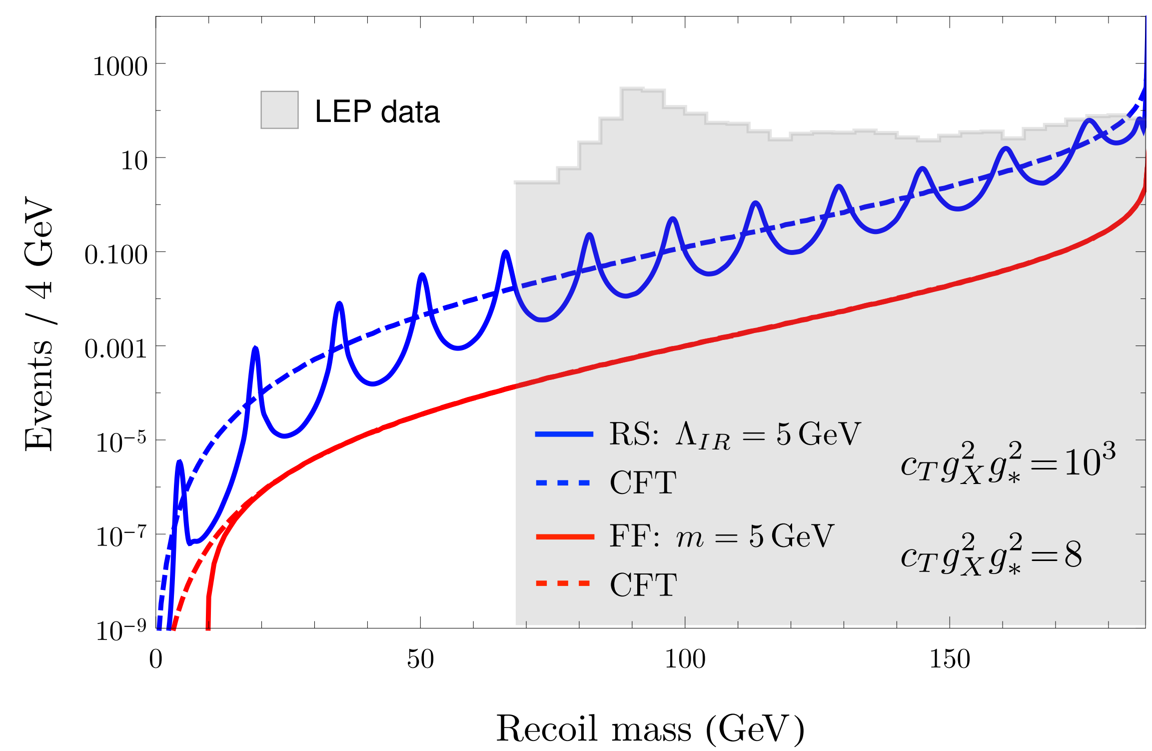
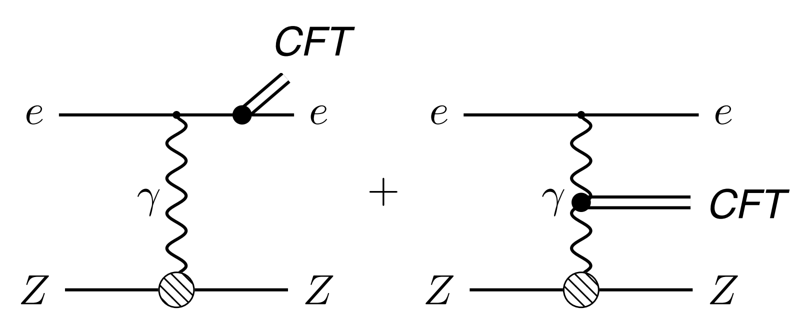




2. Fixed-target experiments:

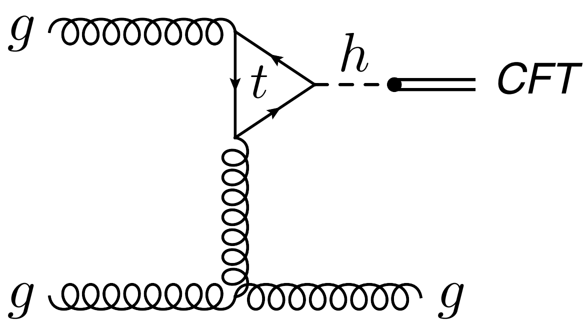
Ex: $e^- + (A,Z) \to e^- + (A,Z) + \not{E}$ at NA64



Bounds on dim-6 $\mathcal{O}H^\dagger H$ operator

1. Mono-X searches (CFT-SM coupling through the Higgs)

Ex: $pp \to j + \not{E}_T$ at the LHC



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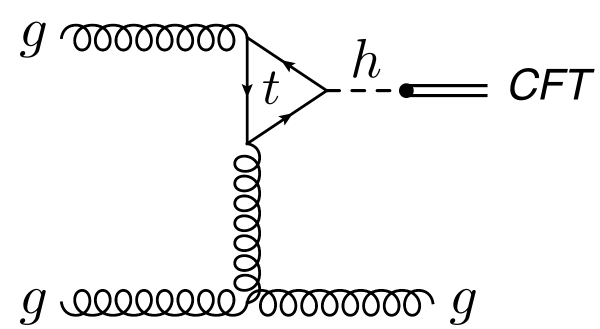
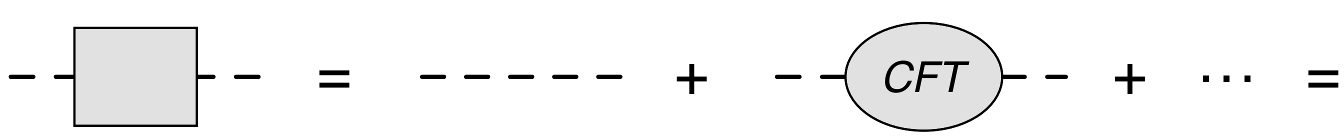


2. Modification of the Higgs propagator



$$= \frac{iZ}{q^2 - m^2 + i\,\Gamma m}$$

$$-i\Sigma(q^2) = v\frac{g_*^2 g_Y^2}{\Lambda_{UV}^4}\int d^4x\, e^{iqx}\langle \mathcal{O}(x)\mathcal{O}(0)\rangle$$

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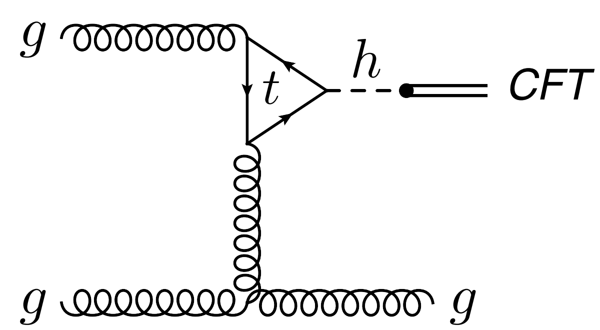

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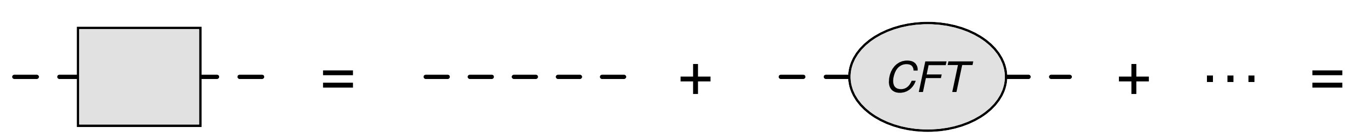

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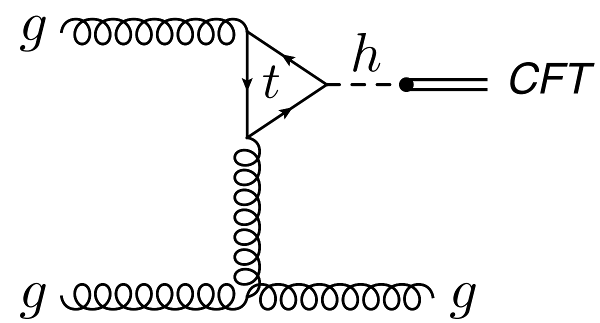

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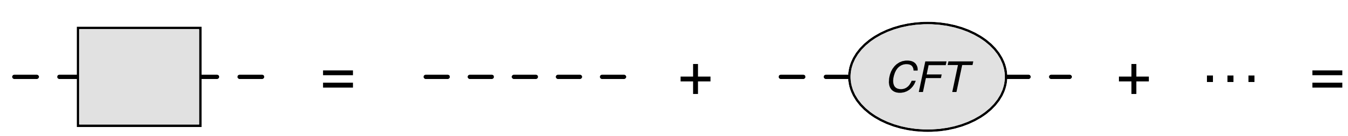

$$\frac{iZ}{q^2 - m^2 + i\,\Gamma m}$$

Higgs decay to CFT (for $m_h > \Lambda_{IR}$)

$$\Gamma_{h\to CFT} = -\frac{Z}{m} \mathrm{Im}(\Sigma(m^2))$$

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Electron (g-2)
Positronium decay

EWPT (LEP+SLD)
Higgs couplings (LHC)

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Astrophysical

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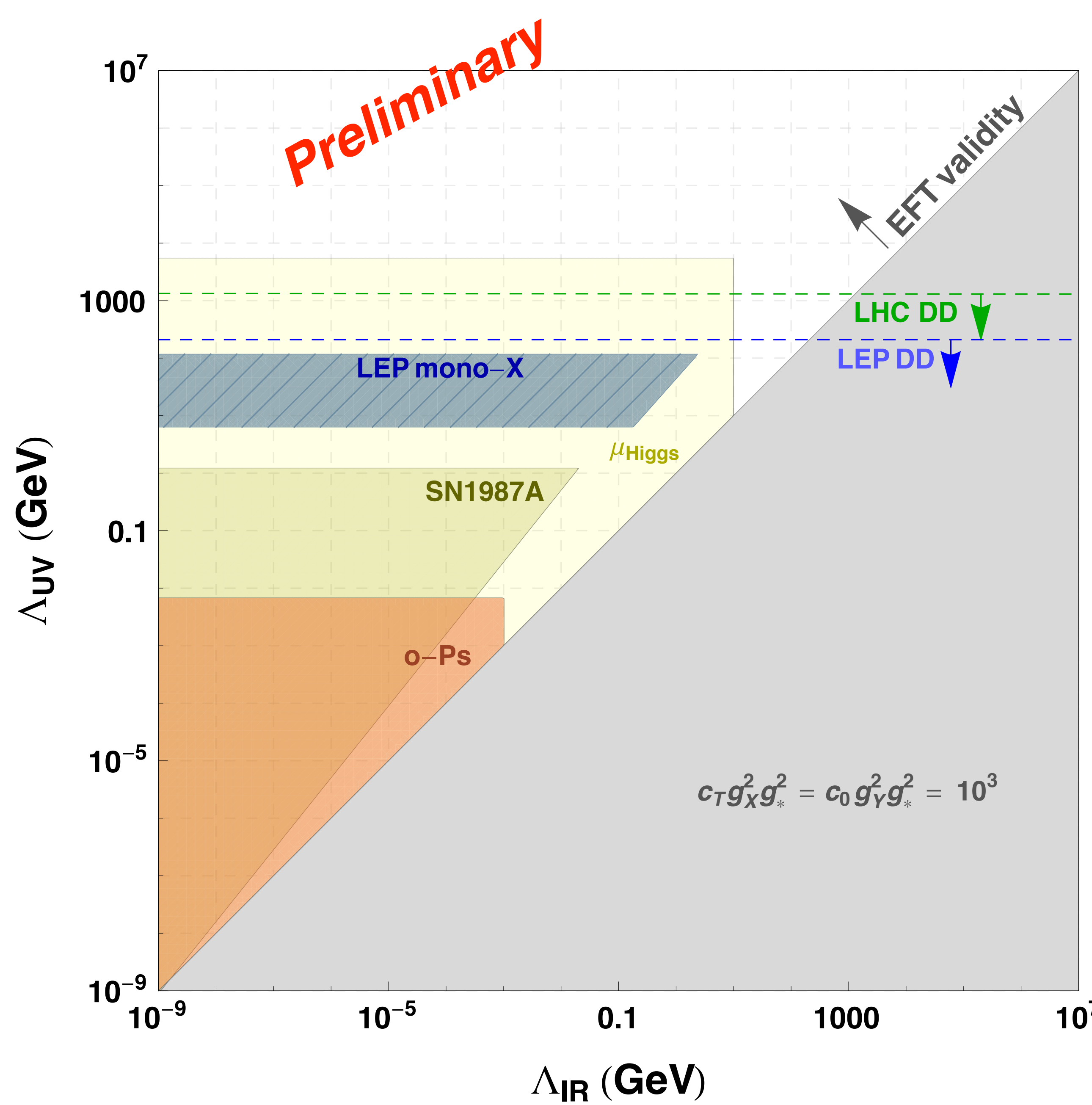
Terrestrial + Astrophysical Bounds



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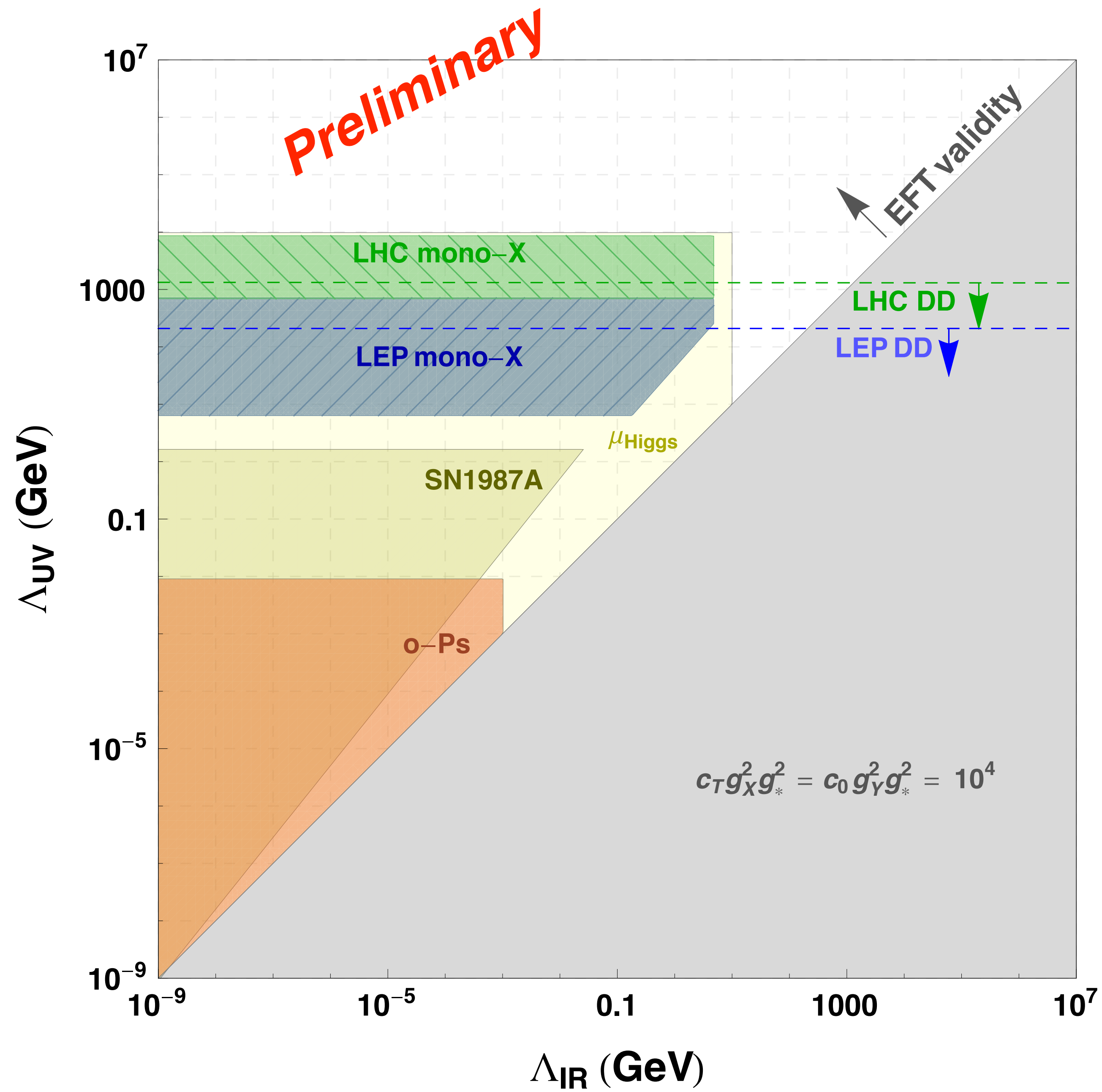

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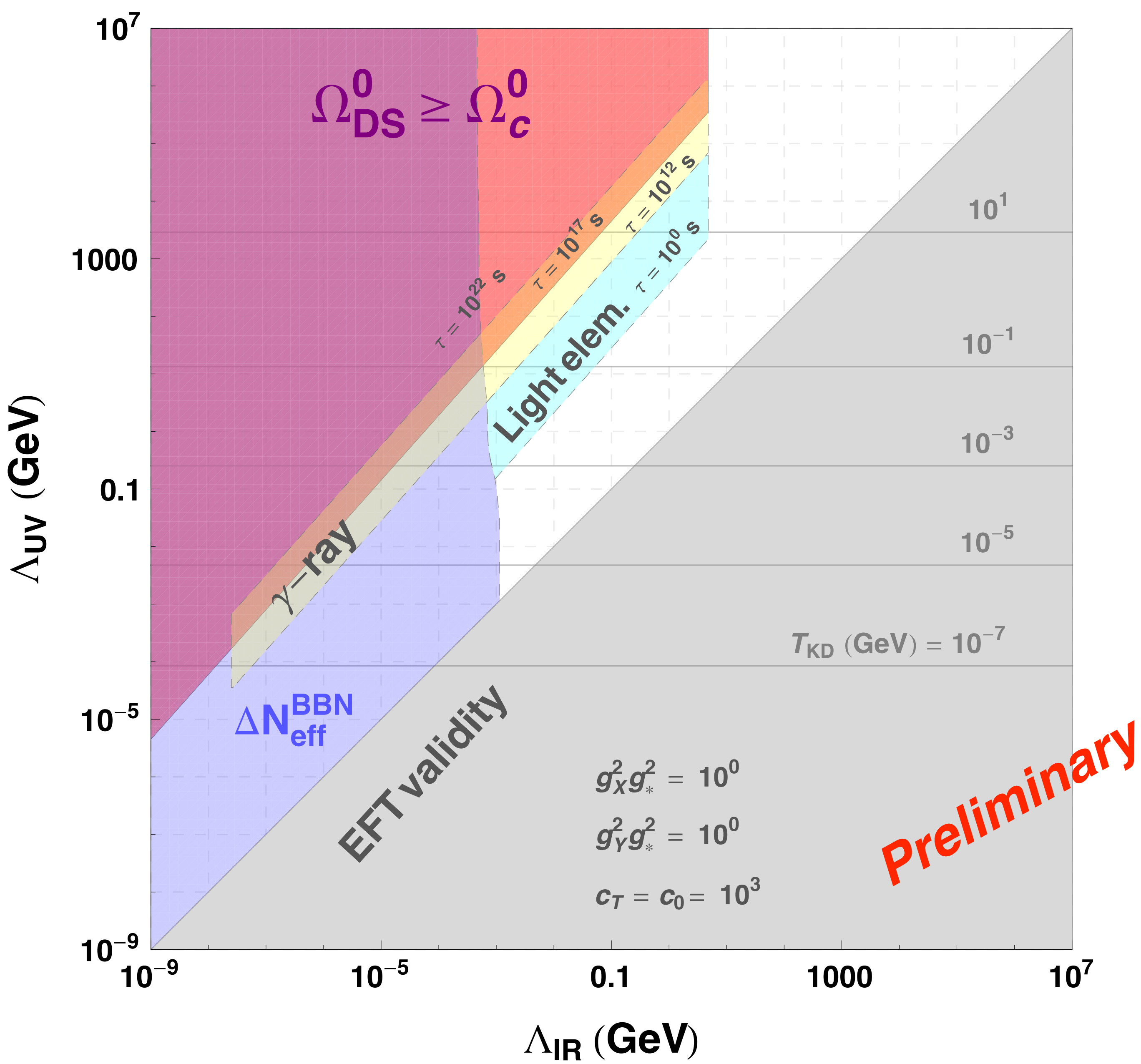

Relic density of a stable LDP ($\tau_{LDP} > 10^{17}\mathrm{s}$ *)*

Decay of the LDP

$1\,\mathrm{s} < \tau_{LDP} < 10^{12}\mathrm{s}$	*abundance of light elements*
$10^{12}\mathrm{s} < \tau_{LDP} < 3\times10^{22}\mathrm{s}$	*diffuse* $\boldsymbol{\gamma}$*-ray spectrum*

Number relativistic dof (at BBN, at time of last scattering)

LDP = Lightest Dark Particle

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- The Higgs can play a key role as a portal to new physics even if this is unnatural

  Example: theories with accidental (composite) Dark Matter