CHASING NATURALNESS @LHC

– a personal summary of the workshop

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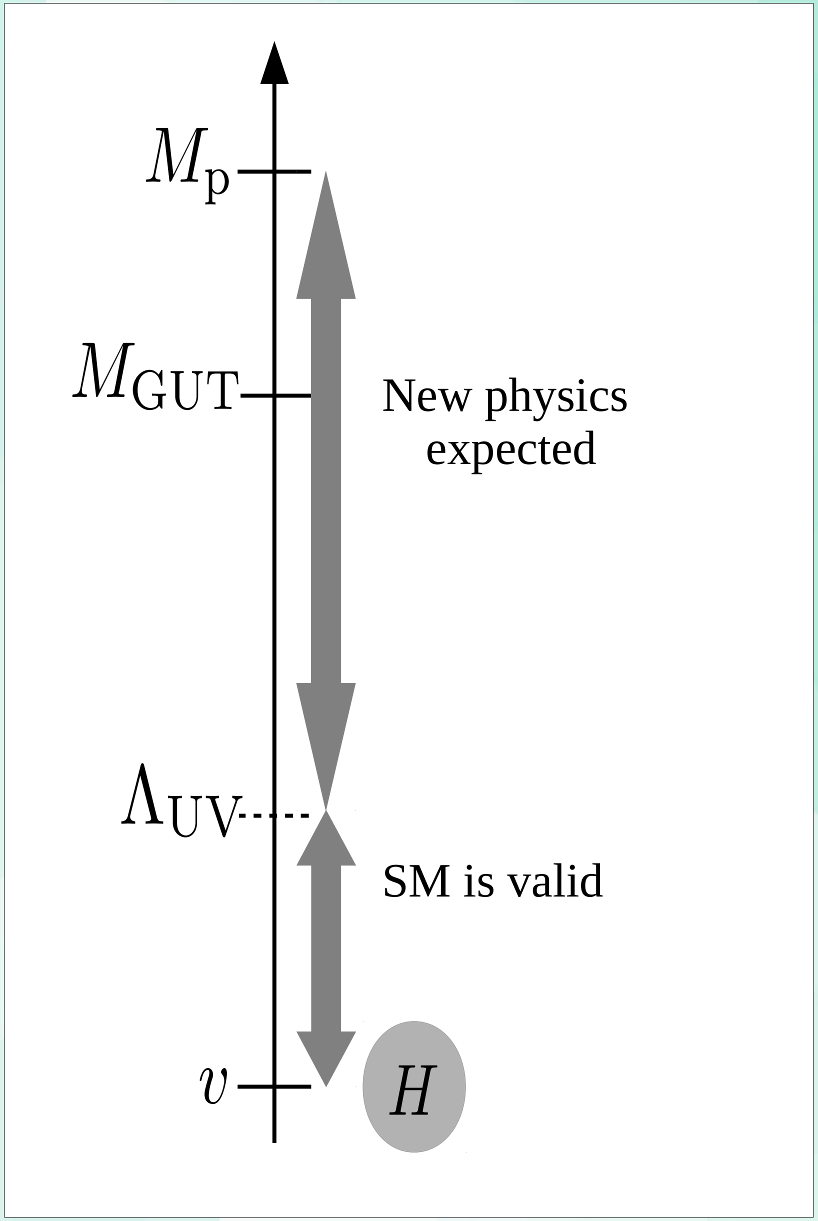
Nordita Workshop
Is there still room for naturalness?
28.04.2022

NORDITA
The Nordic Institute for Theoretical Physics

CHALMERS
UNIVERSITY OF TECHNOLOGY

Naturalness / Hierarchy problem



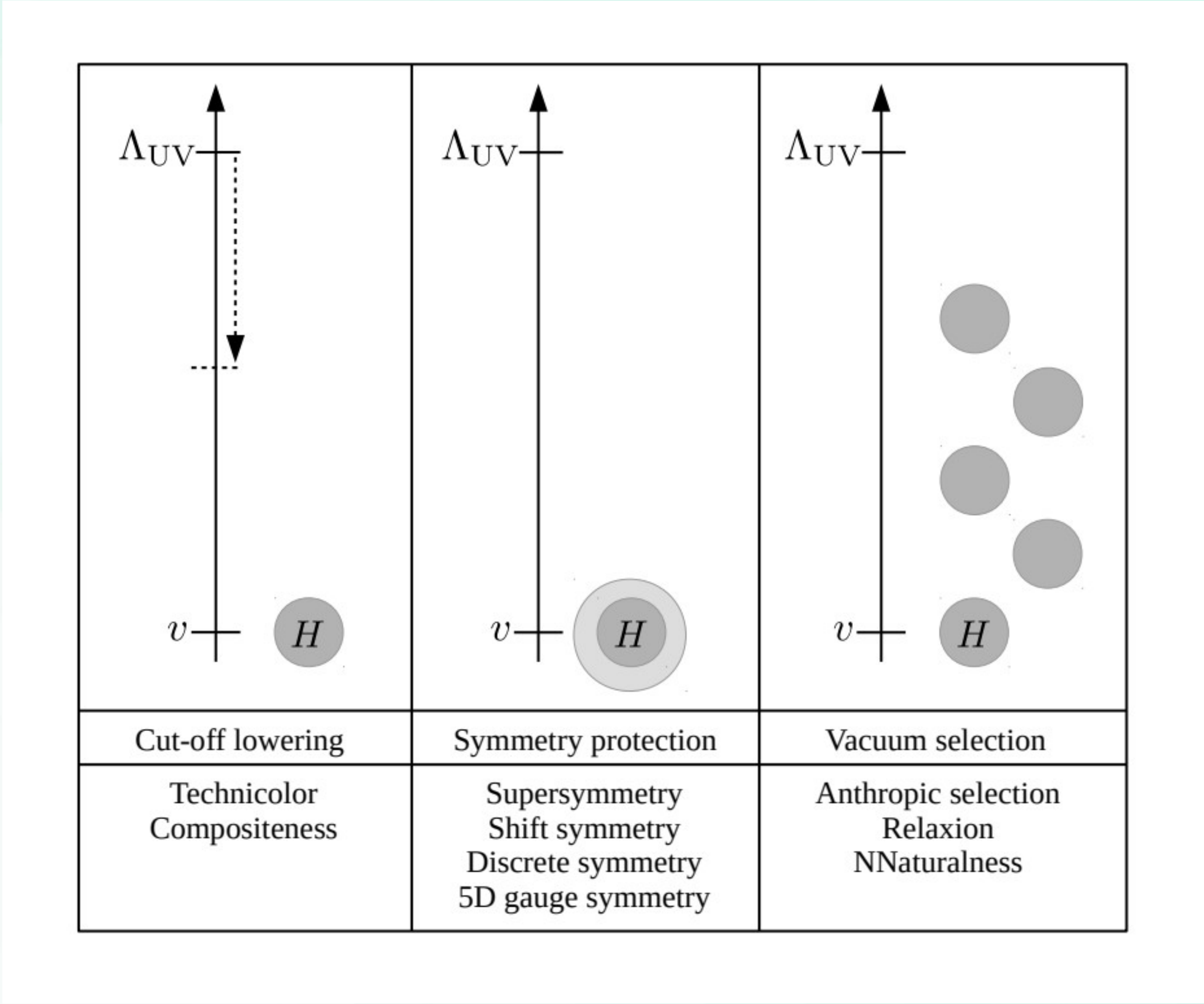
$$\delta m_h^2 \simeq \frac{\lambda_i}{16\pi^2}\Lambda_{UV}^2$$

"Technically unnatural":
Unstable under quantum corrections

- **SM isolated from other scales is natural**
- **However, any scale above the weak scale may potentially change the physics at the weak Scale, contrary to our intuition from other branches of physics**
- **SM has a hierarchy problem**

Talks by James Wells, Gia Dvali

Category of Solutions

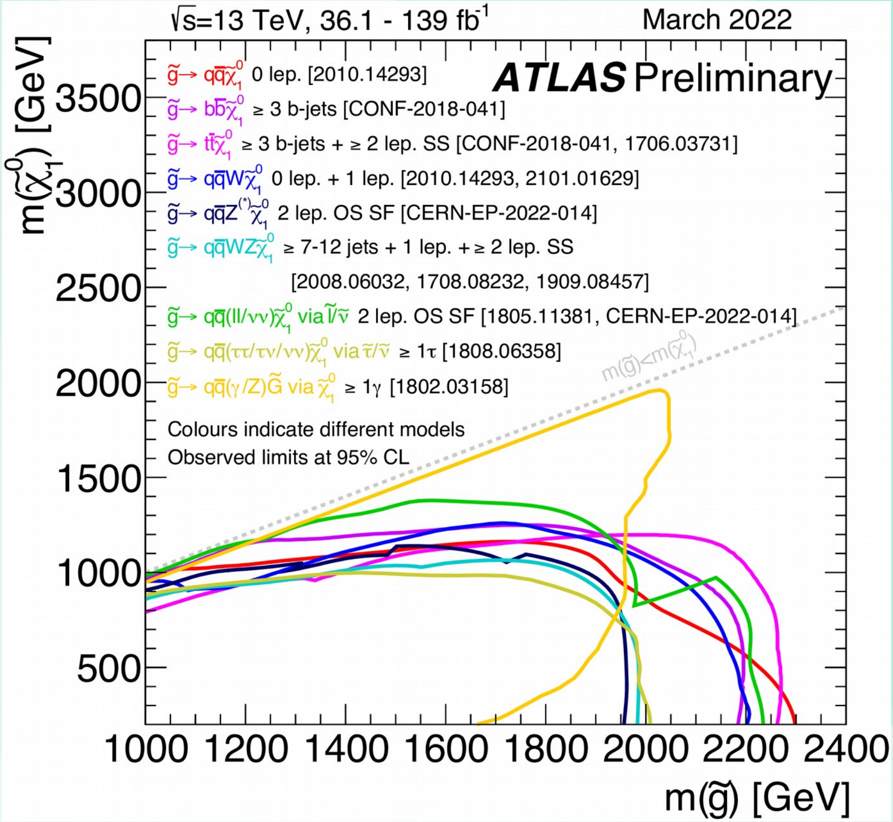


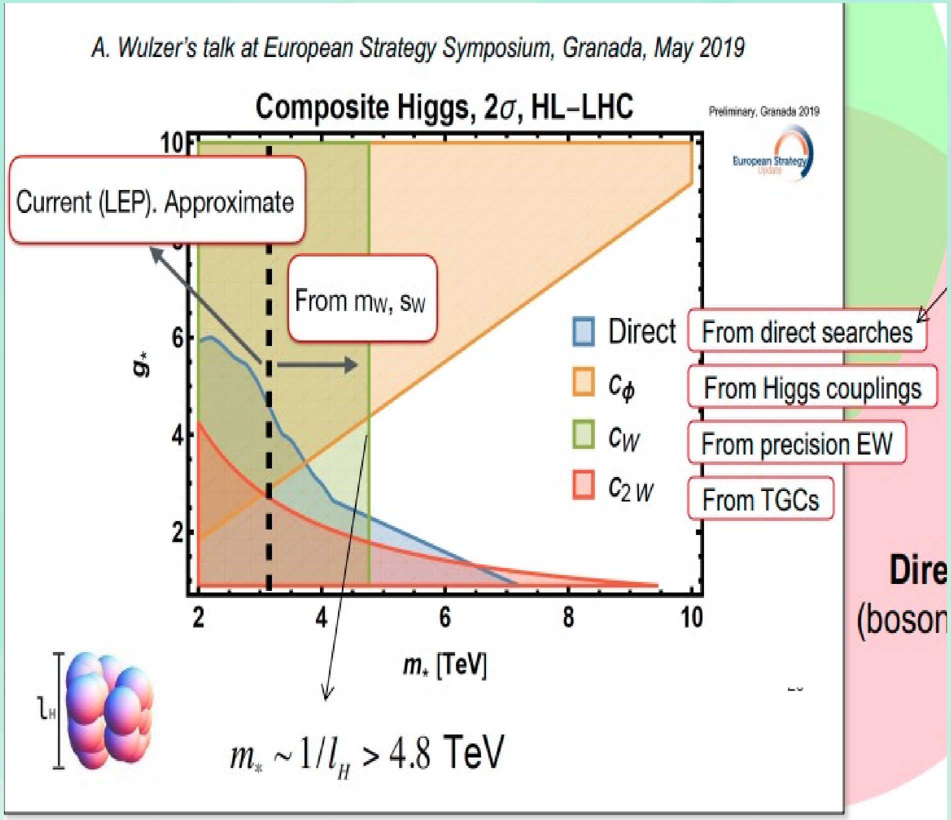
and many exciting new ideas... (talk by Nathaniel Craig)

Supersymmetry vs Composite Higgs

- Higgs mass protected by Supersymmetry
- Higgs mass protected by the joint effect of lowered cutoff and approx. shift symmetry of pNGB Higgs
- Higgs is too heavy to by supersymmetric
- Scalar top-partners, opposite statistics cancellation
- Higgs is too light to be composite
- Fermionic top-partners, same statistics cancellation

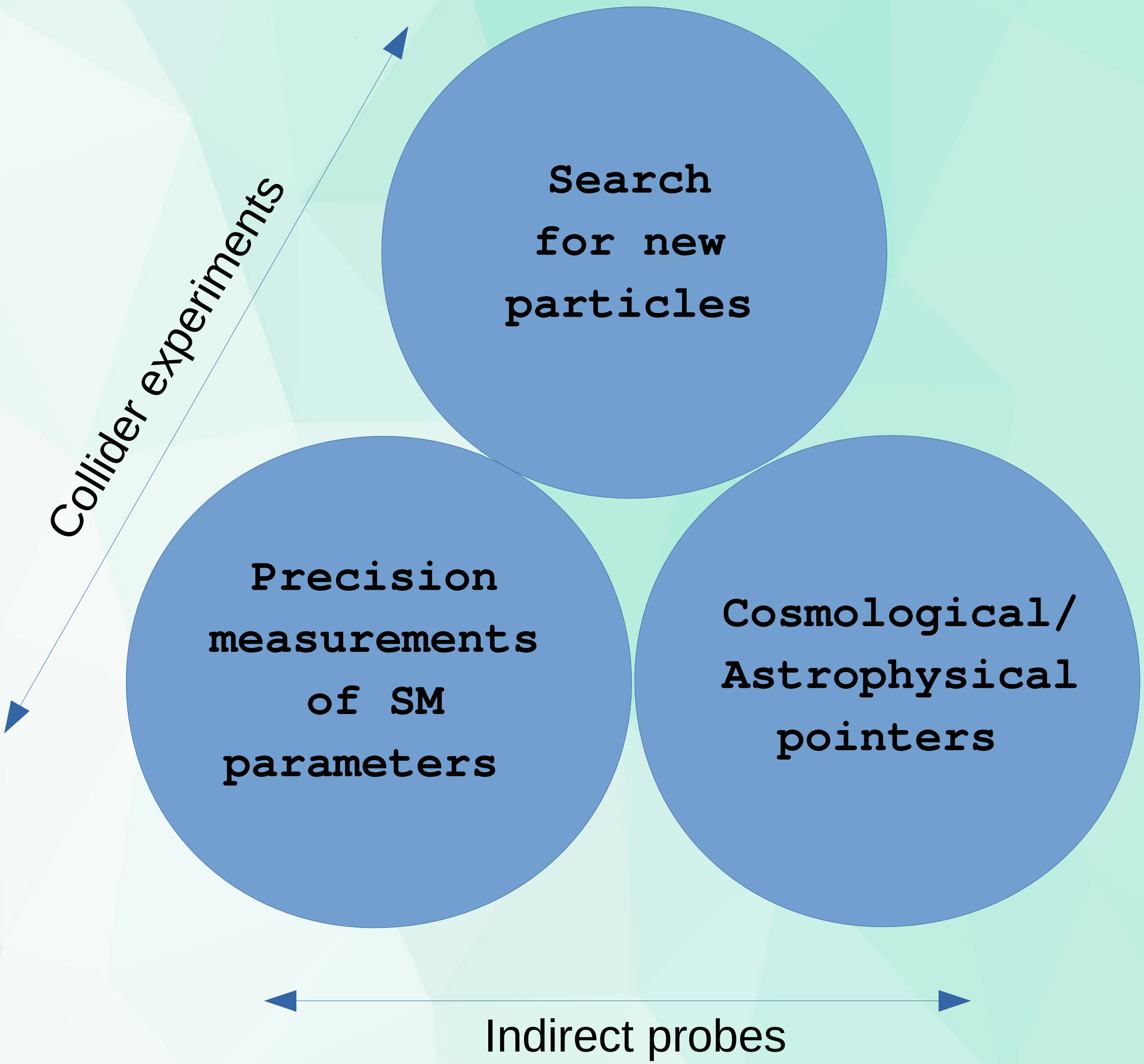
Supersymmetry vs Composite Higgs



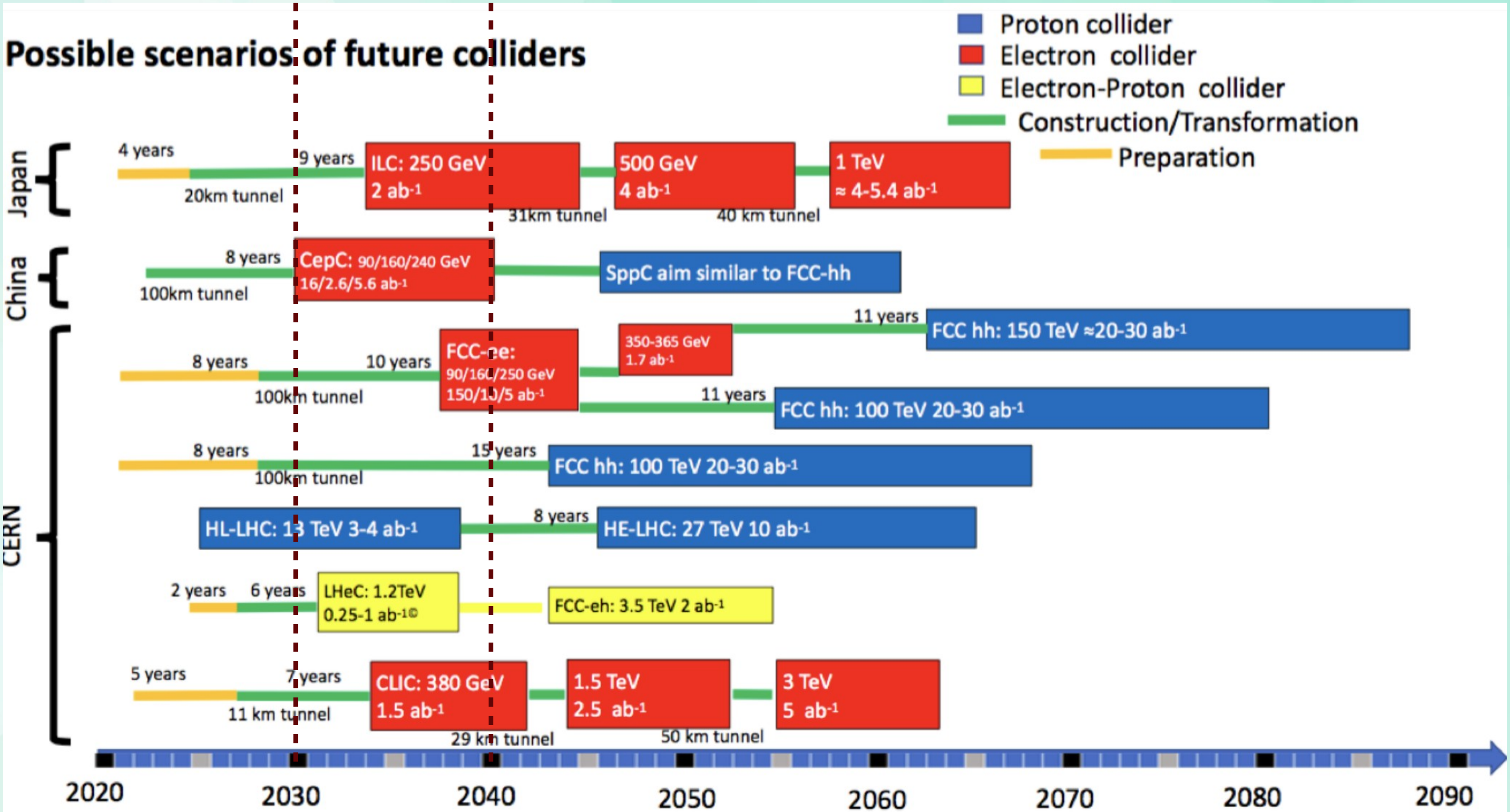


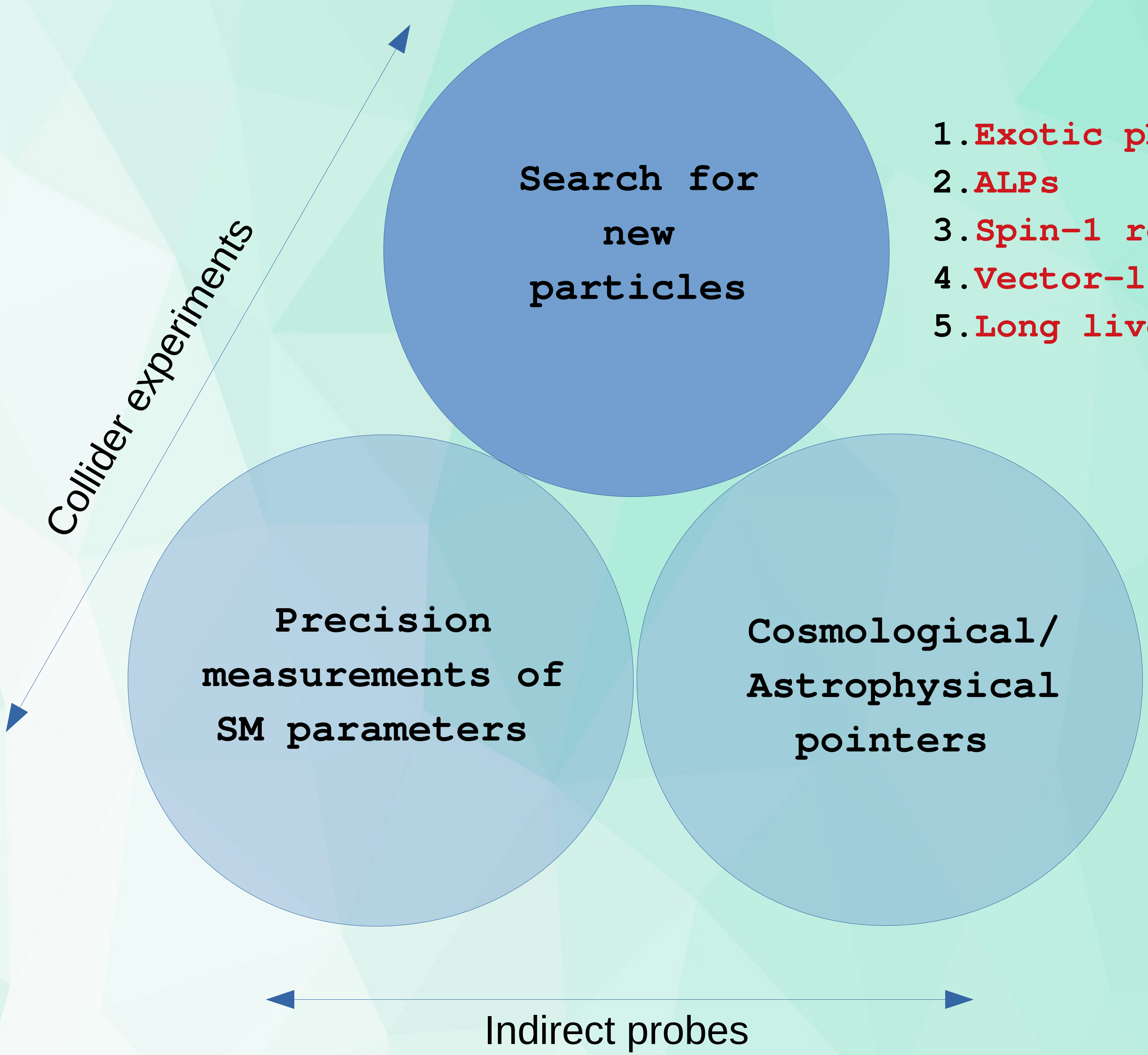
Taken from talk by Aurelio Juste

Experimental Frontiers



Collider calender

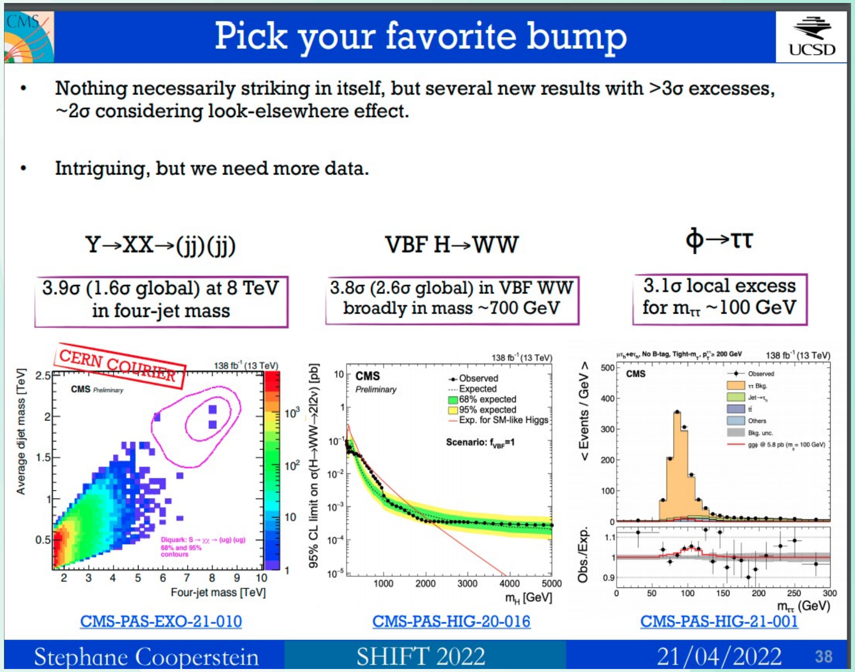




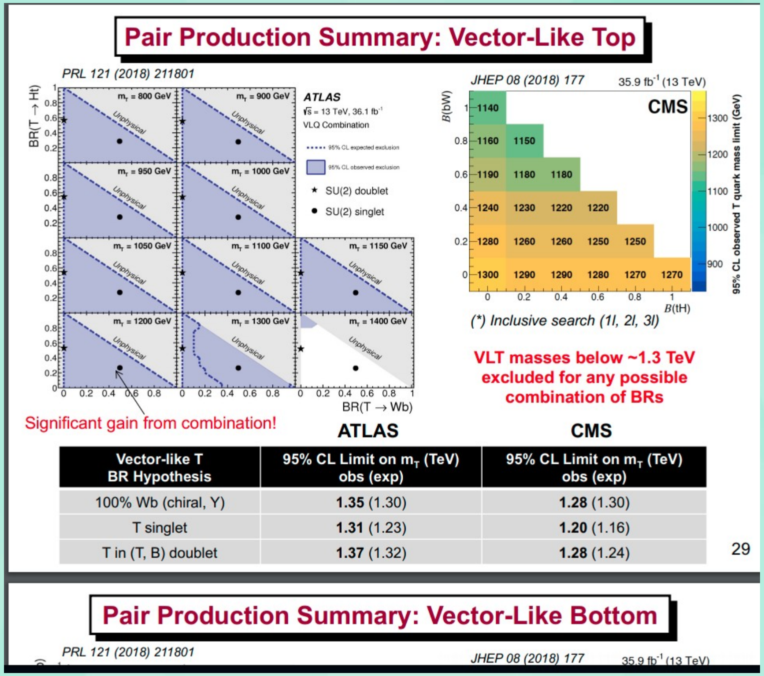
1. Exotic pNGBs
2. ALPs
3. Spin-1 resonances
4. Vector-like quarks
5. Long lived particles

Talk by Binxuang Liu, Stephane Cooperstein, Carlos V Sierra, Aurelio Juste, Stefano Morretti, Werner Porod, Kaustubh Agashe

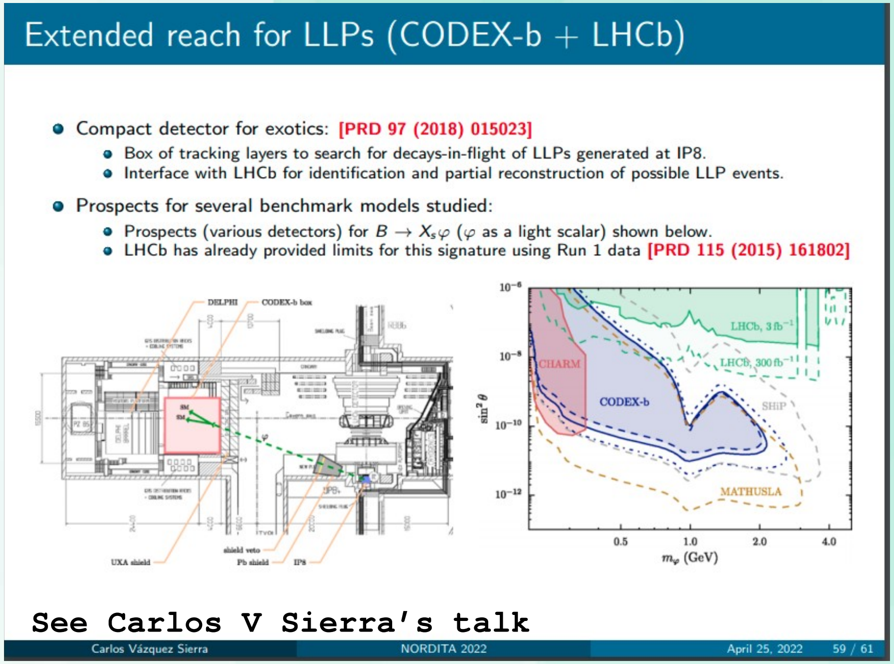
Exciting results and prospects



See Stephane Cooperstein's talk

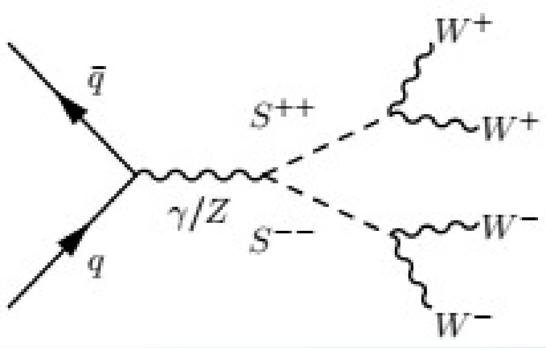


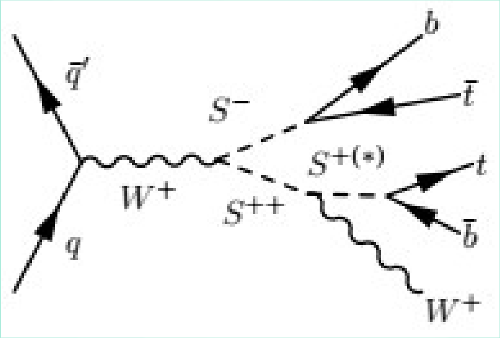
See Aurelio Juste's talk

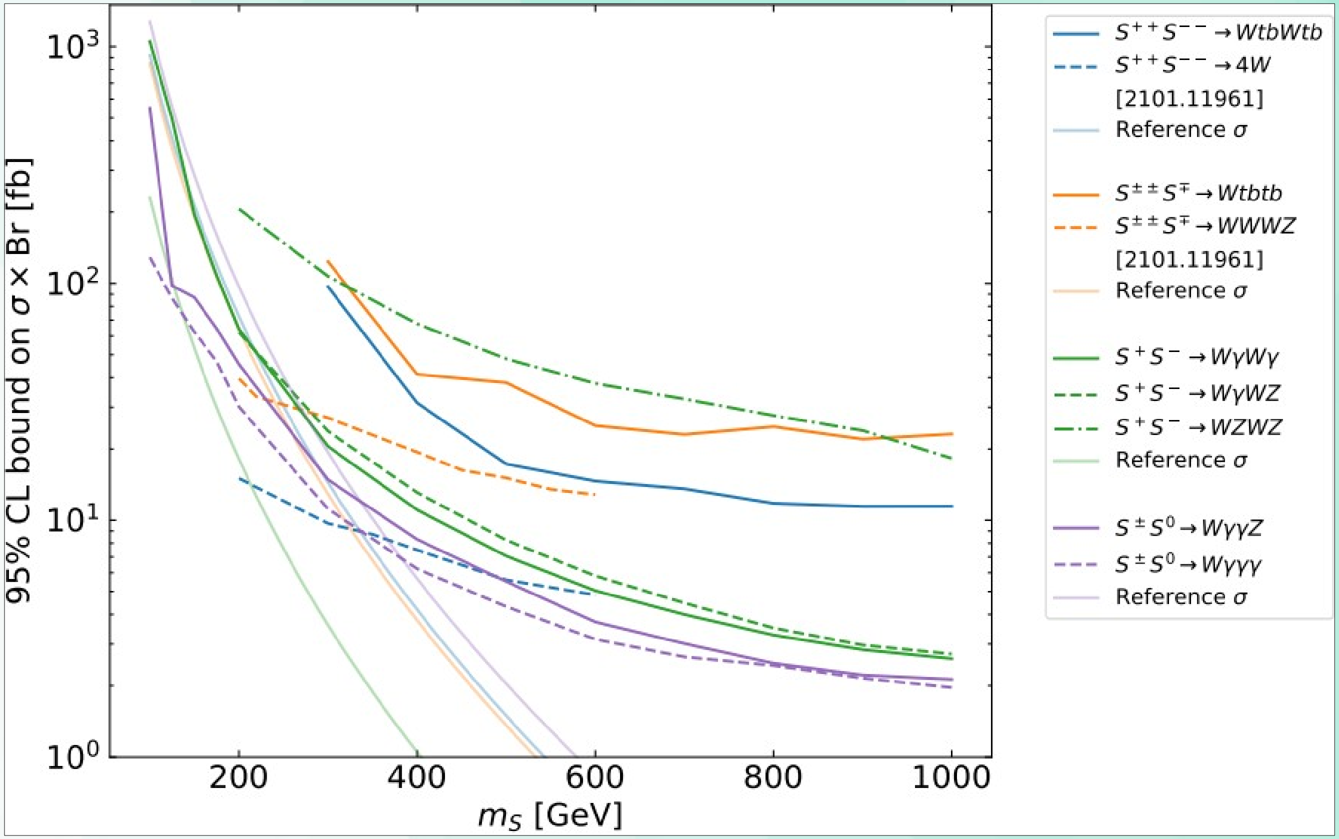


See Carlos V Sierra's talk

Search for exotic pNGBs







AB, D B Franzosi, G Cacciapaglia et. al.[2203.07270]

See also talk by Werner Porod

Top mass in partial compositeness

$$m_t \propto \frac{f y_L y_R v}{\sqrt{M^2 + y^2 f^2}}$$

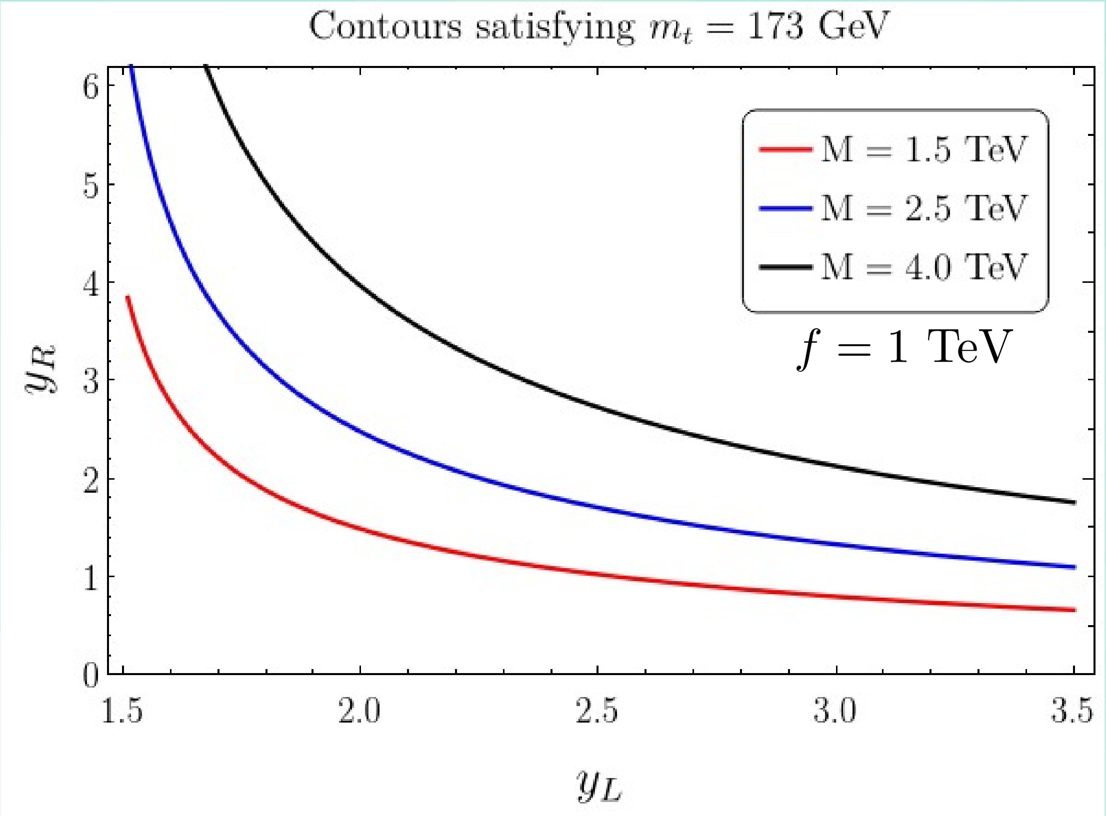
$$\mathcal{L}_{\mathrm{P.C.}} = -M\bar{\Psi}\Psi + y_L f \bar{q}_L \Sigma \Psi_R + y_R f \bar{\Psi}_L \Sigma t_R$$

$$\mathcal{M}_{2/3} = \left(\begin{array}{c|c} 0 & y_L f_L^t(v)^T \\ \hline y_R f_R^t(v) & M\mathbb{I}_{n-1} \end{array}\right)$$

- **(n-3) degenerate states with mass M**
- **One state shifted by ~ y^2v^2**
- **Others shifted by ~ y^2f^2**

$$\mathcal{M}_{-1/3} = \left(\begin{array}{c|c} y_b v & y_L f_L^b(v)^T \\ \hline 0_{n-1\times 1} & M\mathbb{I}_{n-1} \end{array}\right)$$

- **(n-2) degenerate states with mass M**

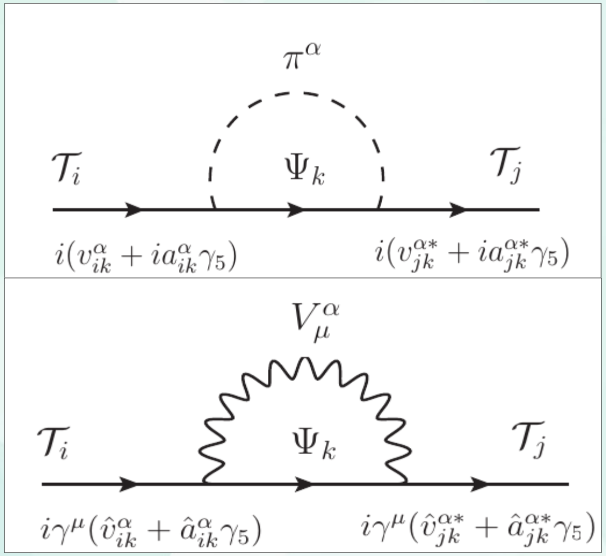


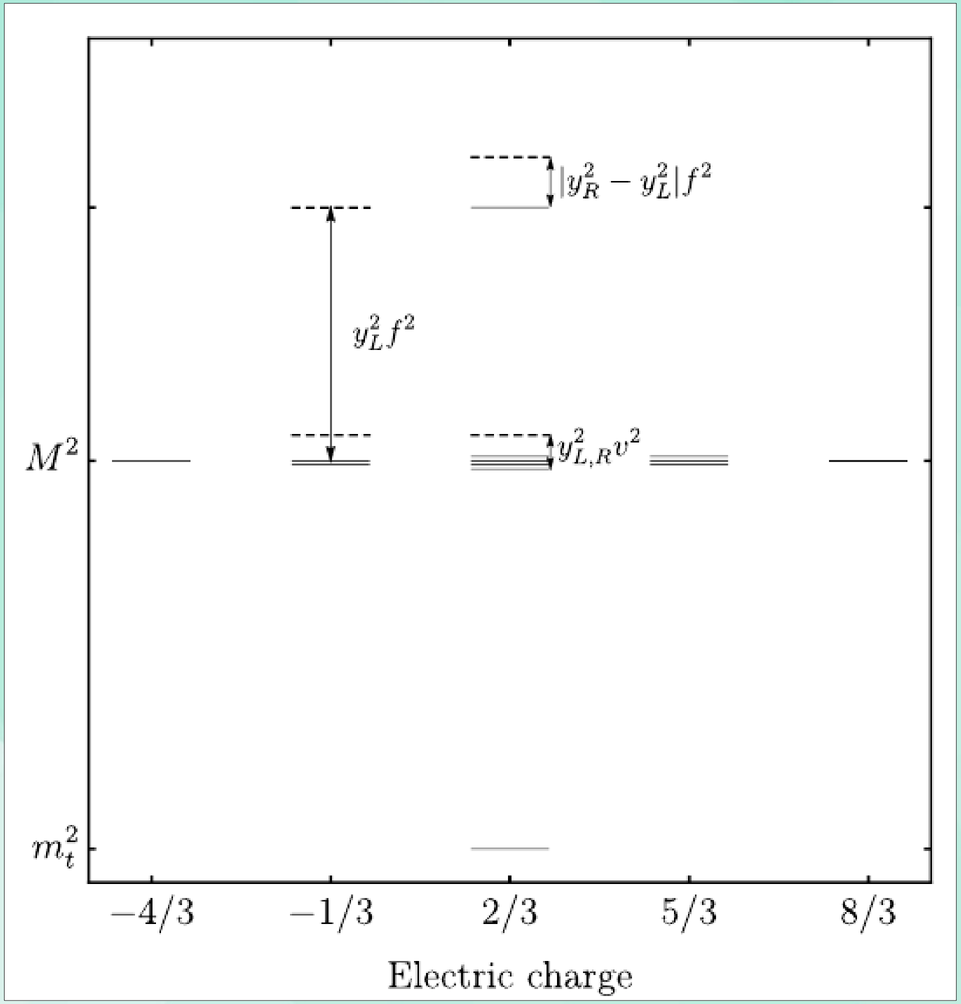
Light top-partners are usually required to reproduce correct top mass

Top-partner spectrum

$$\mathcal{M}_{2/3} = \left(\begin{array}{c|c} 0 & y_L f_L^t(v)^T \\ \hline y_R f_R^t(v) & M\mathbb{I}_{n-1} \end{array}\right)$$

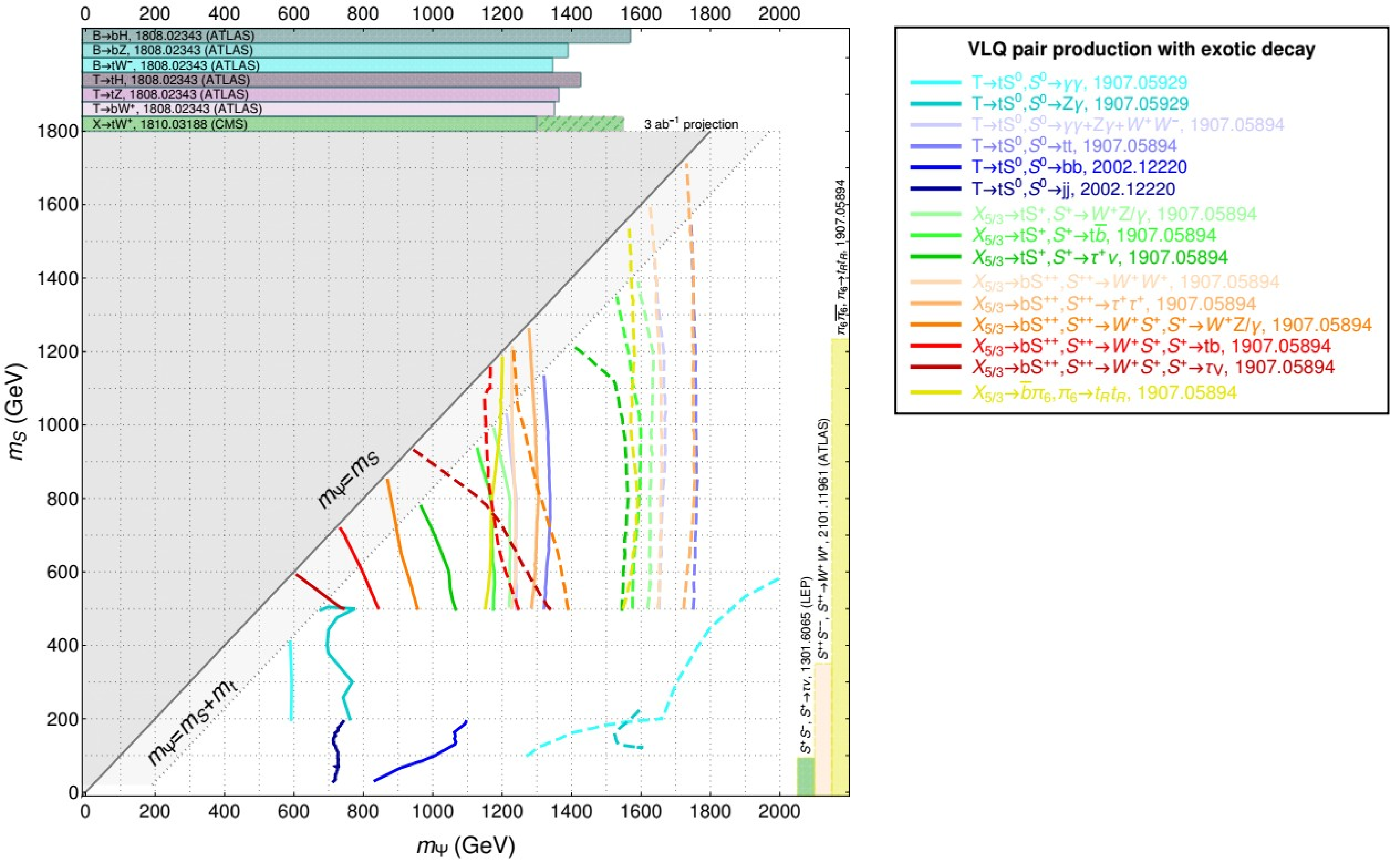
- Generic spectrum
- Degenerate states at tree level, loop corrections break degeneracy





AB, D B Franzosi, G Ferretti [2202.00037]

Summary plot for VLQ search

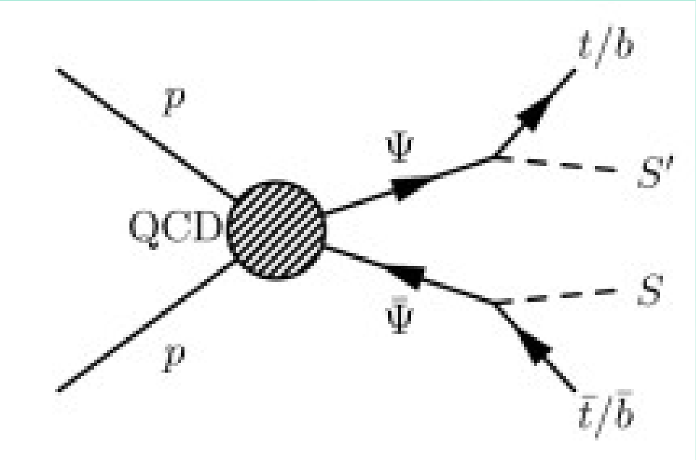


AB, D B Franzosi, G Cacciapaglia et. al.[2203.07270]

Diphoton signal

SU(5)/SO(5) coset

(see talk by Werner Porod)



Relevant for leptonically decaying top, so that top and anti-top can be distinguished

$$\Longrightarrow \; \sigma\left(pp \to (t\gamma\gamma) + X\right) \sim 1 \text{ fb}$$

For 1.5 TeV VLQ mass

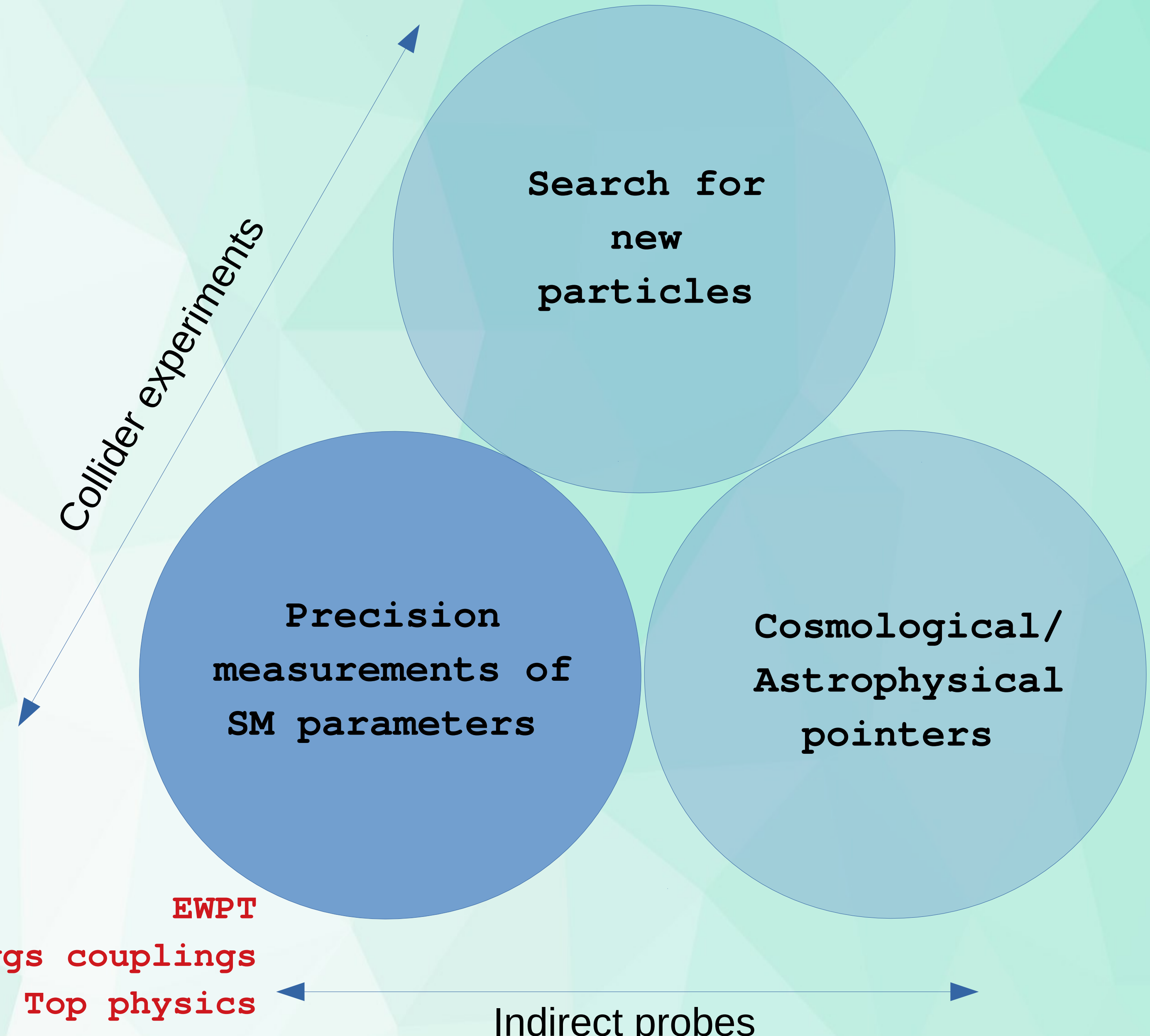
Relevant for hadronically decaying top:

$$\Longrightarrow \; \sigma\left(pp \to (t/\bar{t}\gamma\gamma) + X\right) \sim 2.5 \text{ fb}$$

More inclusive diphoton cross-sections ~ 5 fb

These numbers are in the ballpark region of interest for VLQ searches by ATLAS and CMS collaborations

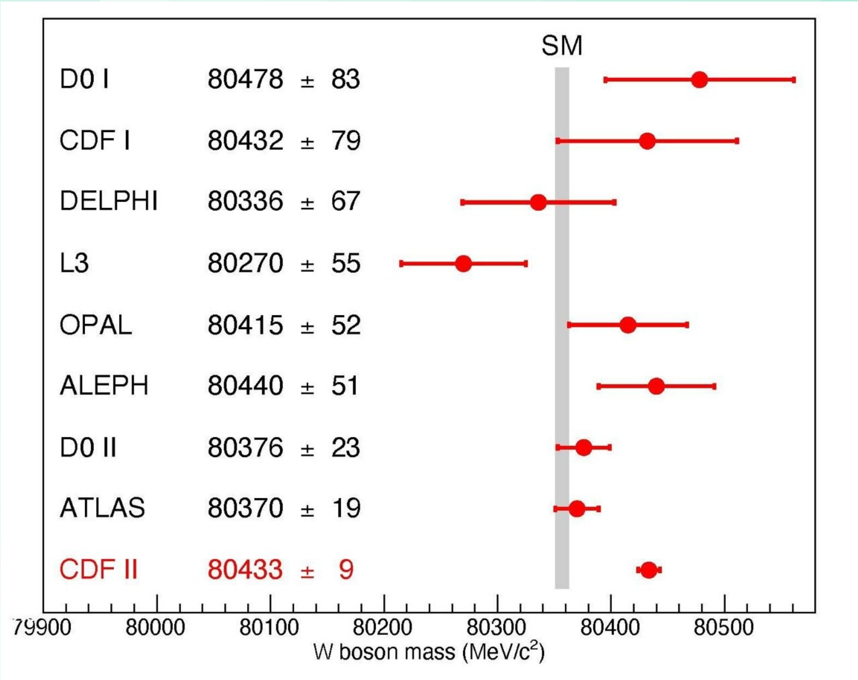
AB, D B Franzosi, G Ferretti [2202.00037]



EWPT
Higgs couplings
Top physics
Differential distributions

Talks by Chris Hays, Sebastian Bruggisser, Riccardo Torre,

CDF W mass measurement

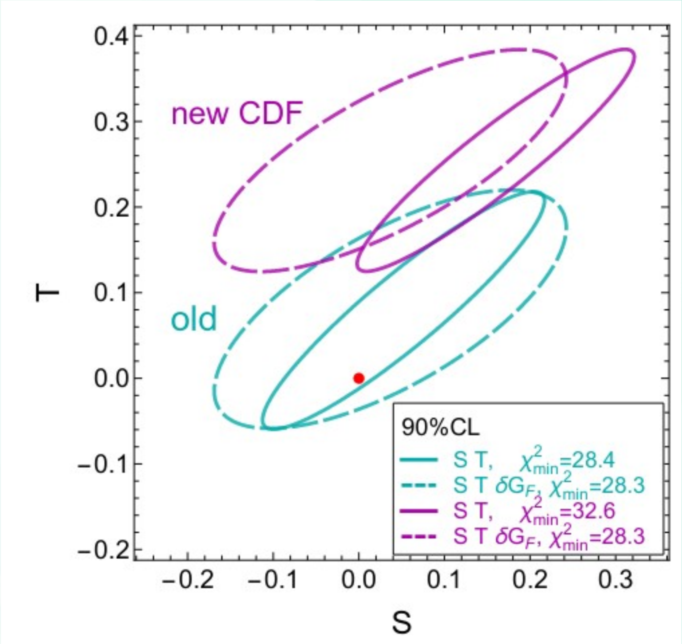


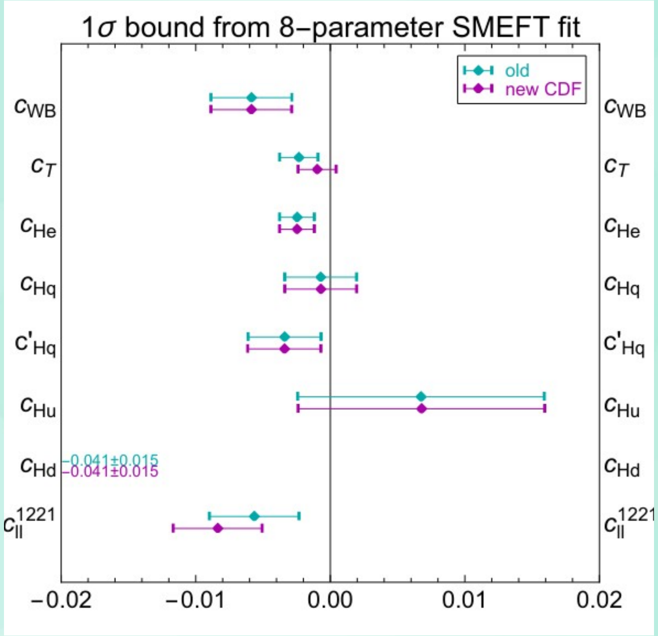
A closer look on the uncertainties in the PDF sets is necessary!

See talk by Chris Hays

Impact of the new measurement:

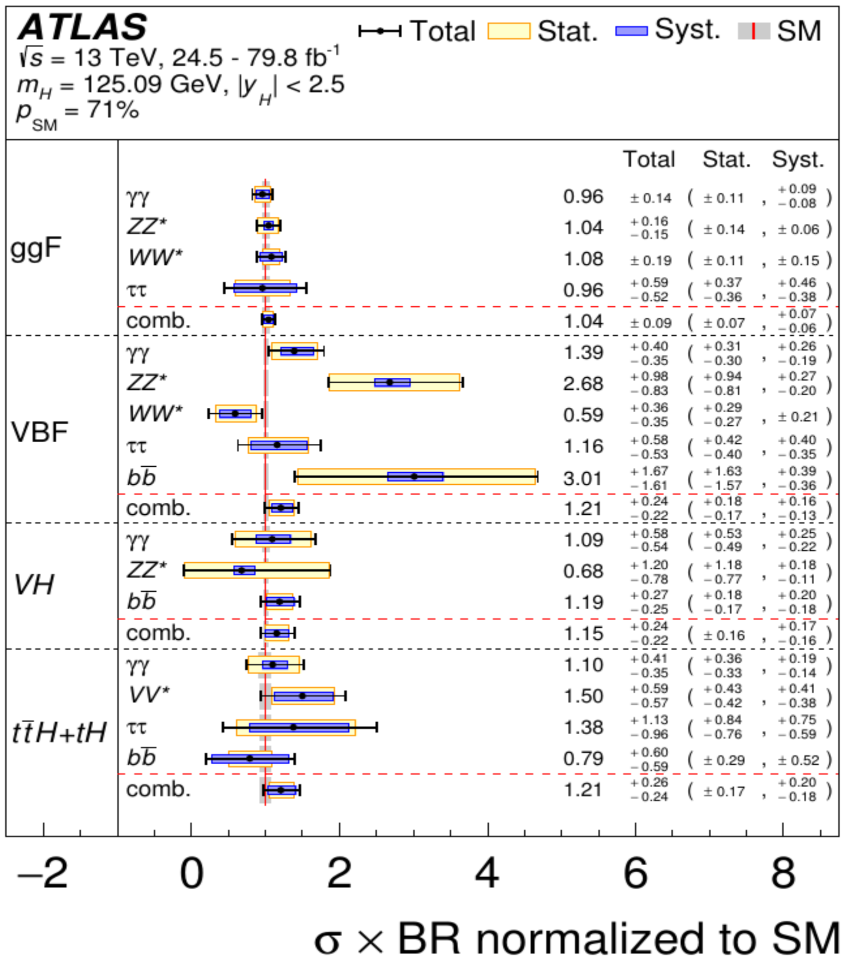
(plots taken from 2204.05296)



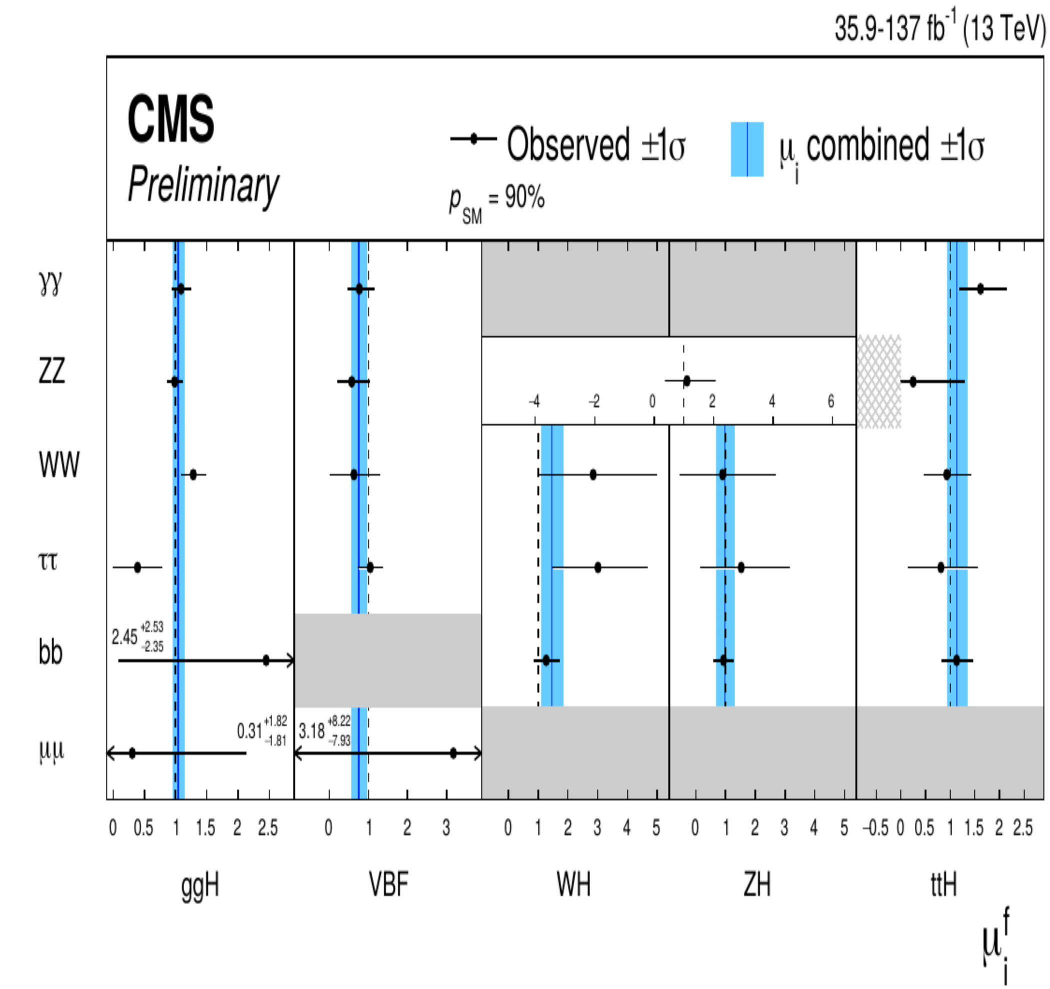


Higgs data @Run 2

1909.02845



CMS-PAS-HIG-19-005



Modification of Higgs couplings

- **Mixing with other spin-0 bosons,**

  Examples: models with additional SU(2)×U(1) multiplets.

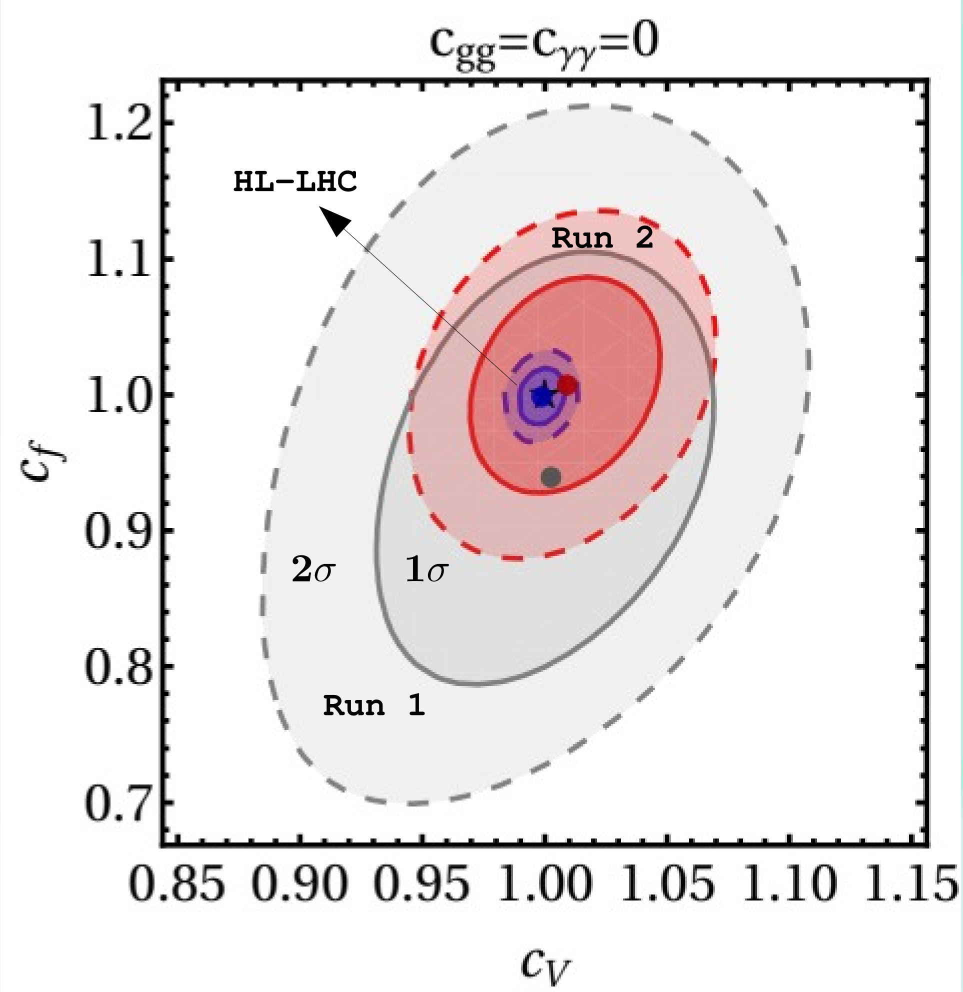
- **Higher dimensional operators, obtained by integrating out heavy degrees of freedom,**

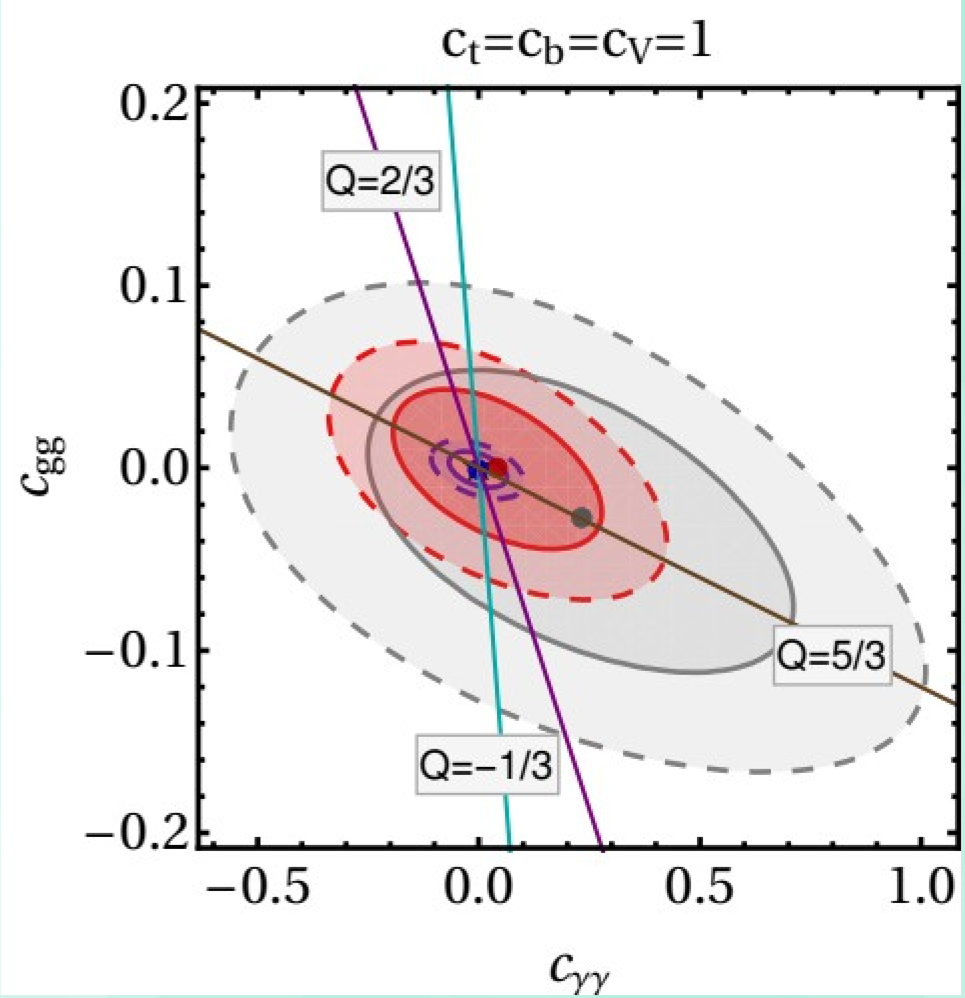
  Example: Composite Higgs scenario

$$\mathcal{L}_{(0)} = \frac{h}{v}\left[c_V\left(2M_W^2 W_\mu^\dagger W^\mu + M_Z^2 Z_\mu Z^\mu\right) - \sum_f c_f m_f \bar{f} f\right]$$

$$\mathcal{L}_{(2)} = -\frac{h}{4\pi v}\left[\alpha_e c_{\gamma\gamma} F_{\mu\nu} F^{\mu\nu} + \alpha_e c_{Z\gamma} Z_{\mu\nu} F^{\mu\nu} - \frac{\alpha_s}{2} c_{gg} G^a_{\mu\nu} G^{a\mu\nu}\right]$$

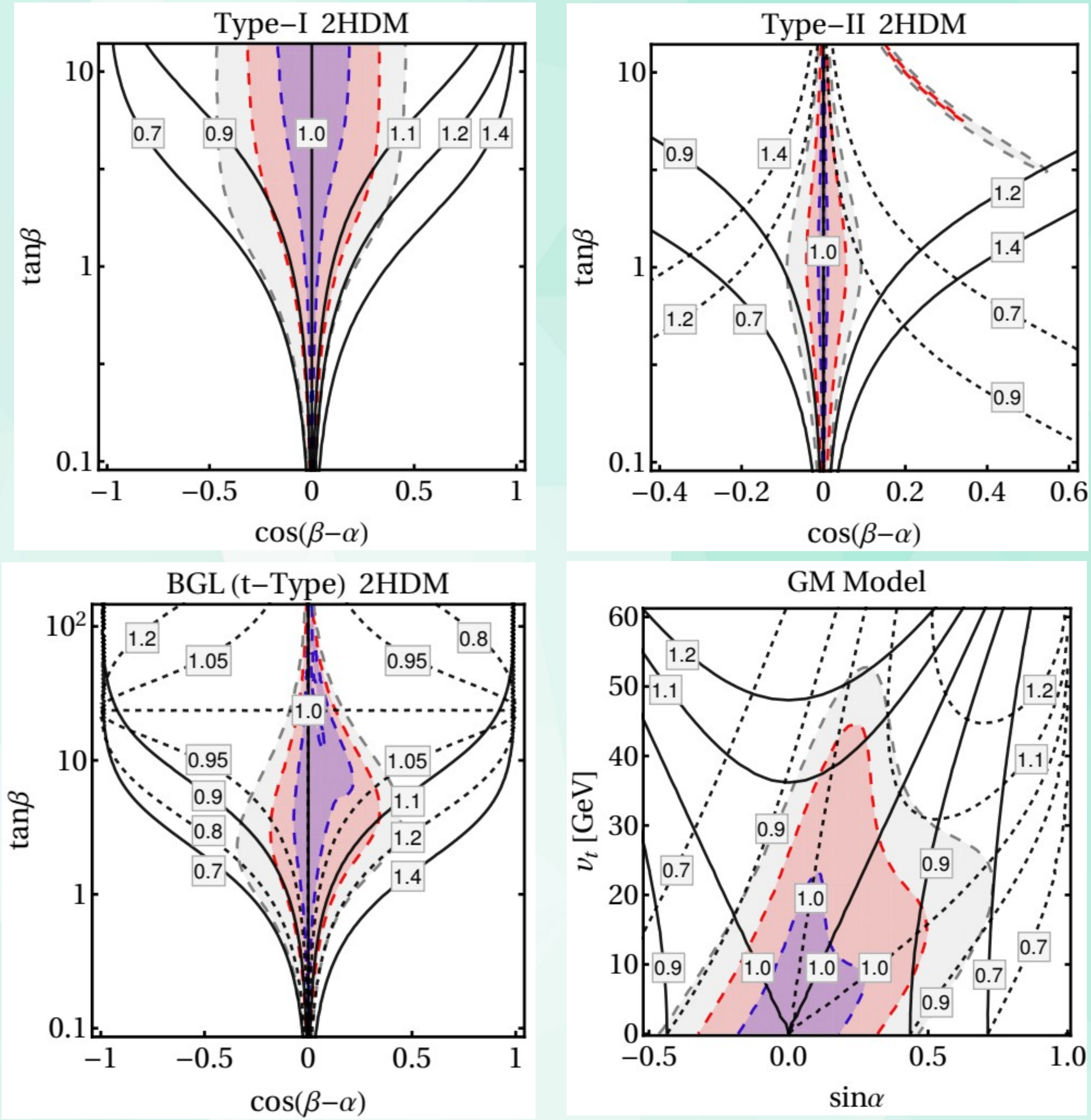
LHC Run 2 limits





AB, G Bhattacharyya [2006.01164]

Interpretation in extended Higgs models

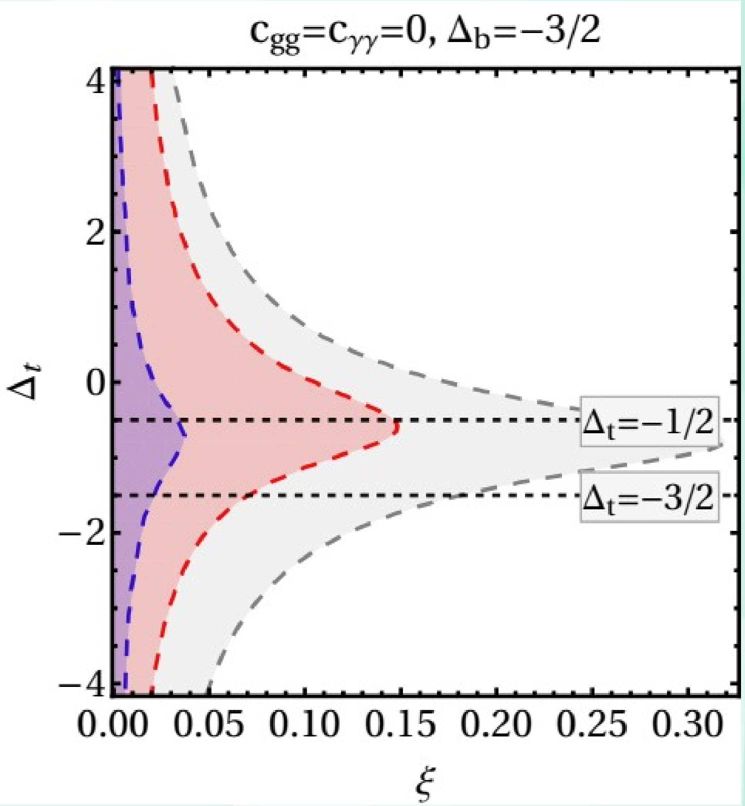


- Alignment limit is preferred in Type-II 2HDM
- In composite 2HDM additional suppression in couplings due to pNGB nature of Higgs

(see Stefano Moretti's talk)

AB, G Bhattacharyya [2006.01164]

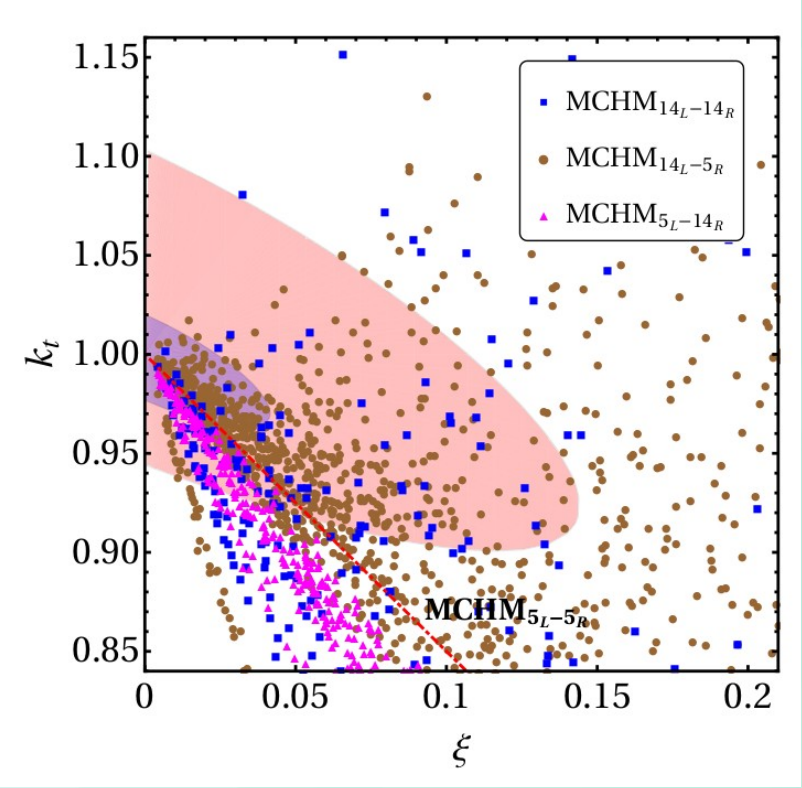
Interpretation in composite Higgs



- **Higher dimensional operators from pNGB nature of Higgs**
- **Momentum dependence captured through form factors**

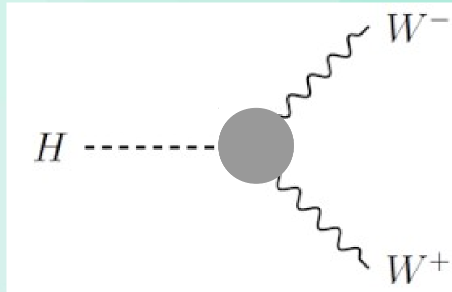
$$c_V = \sqrt{1-\xi}$$
$$c_f = 1 - \Delta_f \xi$$

f > 1 TeV



AB, G Bhattacharyya, N Kumar, T S Ray [1712.07494]

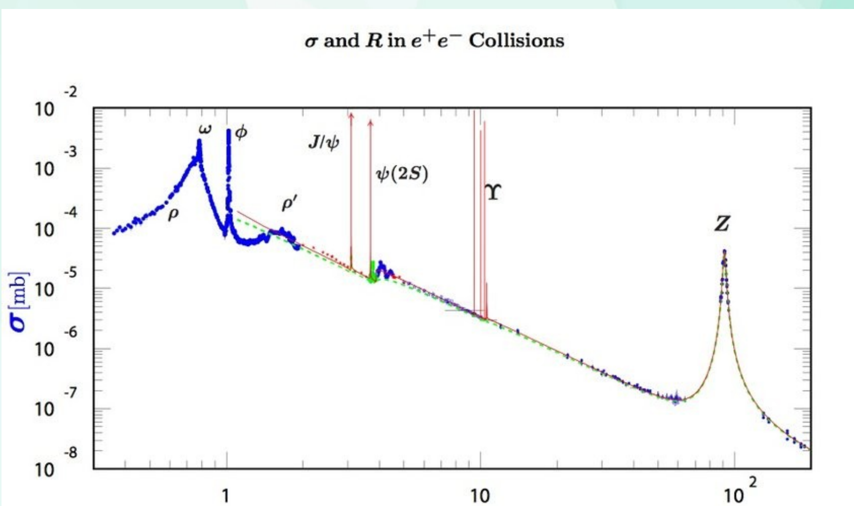
Momentum dependent form factors

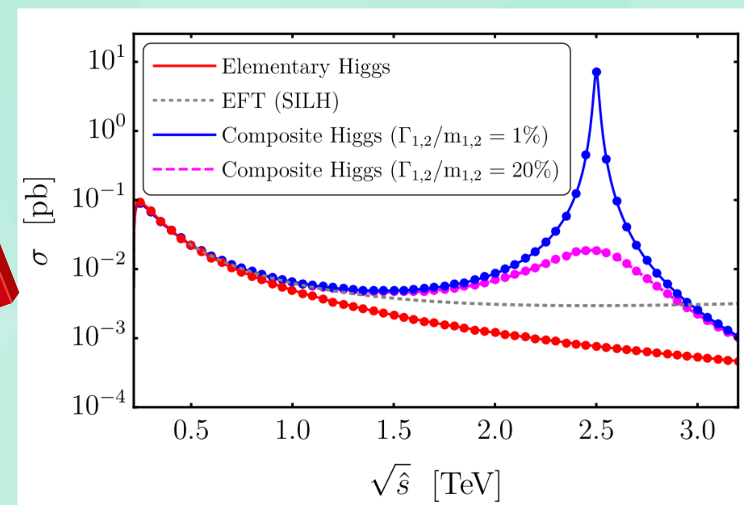


$$g_V^{\rm SM}\frac{\Pi_V^{\mu\nu}(p_1,p_2)}{f^2}hV_\mu(p_1)V_\nu(p_2)$$

$$\Pi_V^{\mu\nu} \simeq \frac{f^2m^4}{(p_1^2-m^2+im\Gamma)(p_2^2-m^2+im\Gamma)}\left[\sqrt{1-\xi}\eta^{\mu\nu}+\frac{1}{m^2}\{c_2^V\,(\eta^{\mu\nu}p_1.p_2-p_2^\mu p_1^\nu)+c_3^V\,p_1^\mu p_2^\nu+c_4^V\,p_1^\mu p_1^\nu+c_5^V\,p_2^\mu p_2^\nu\}\right]$$

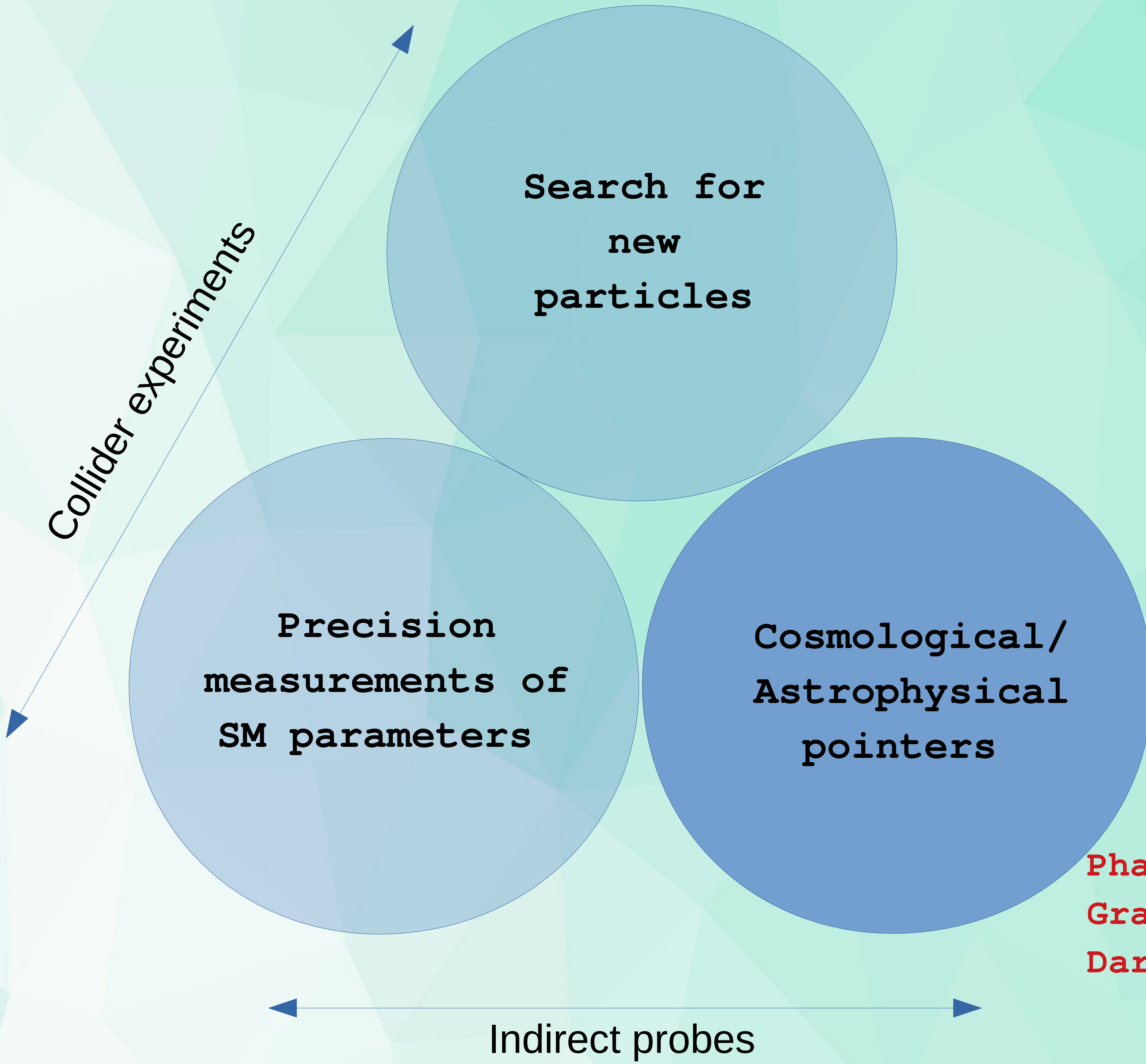
Form factors parametrize the information of strong dynamics





If the compositeness scale is just beyond the reach of LHC...
fineprints in differential distributions?

AB, S Dasgupta, T S Ray [2105.01093]

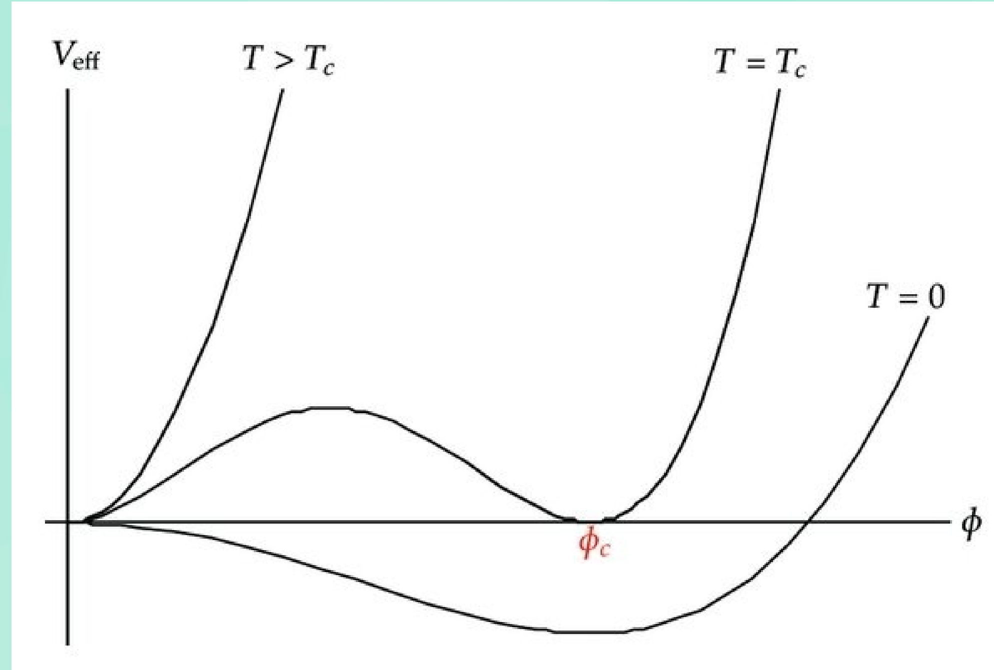


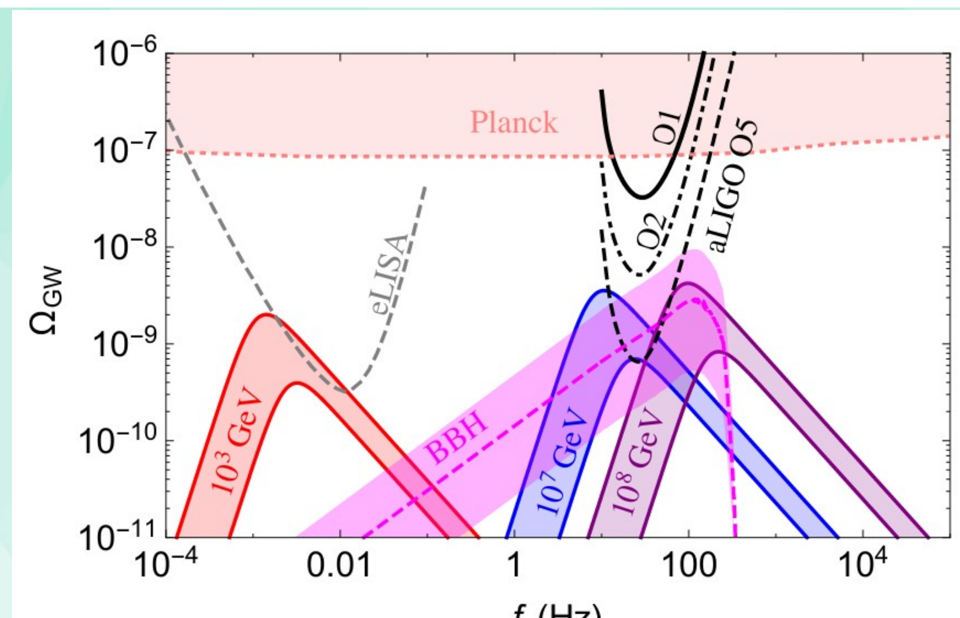
Phase transitions
Gravitaional wave
Dark matter

Talk by Elliel Camargo-molina

Electroweak phase transitions

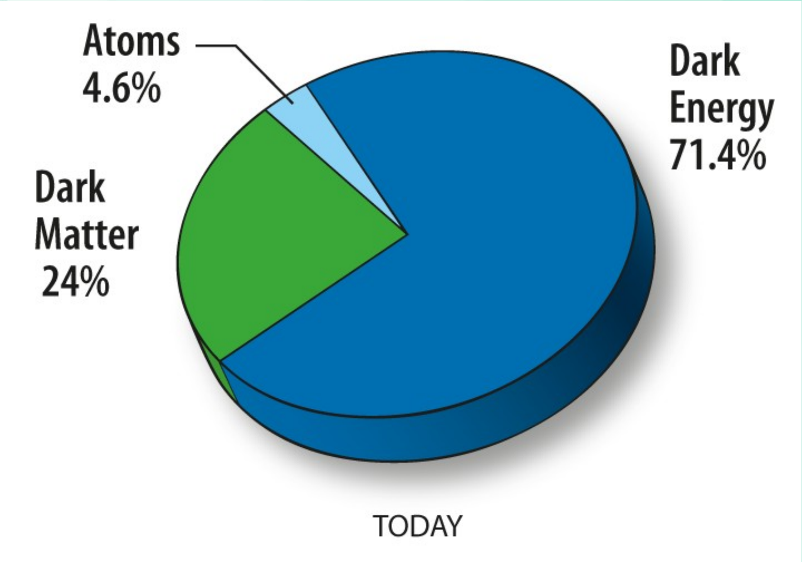
- Closely related to the structure of Higgs potential
- Presence of **|H|⁶ operator** is crucial
- Modification of Higgs self-coupling => **di-Higgs production** is the key to probe
- **Gravitational waves?**

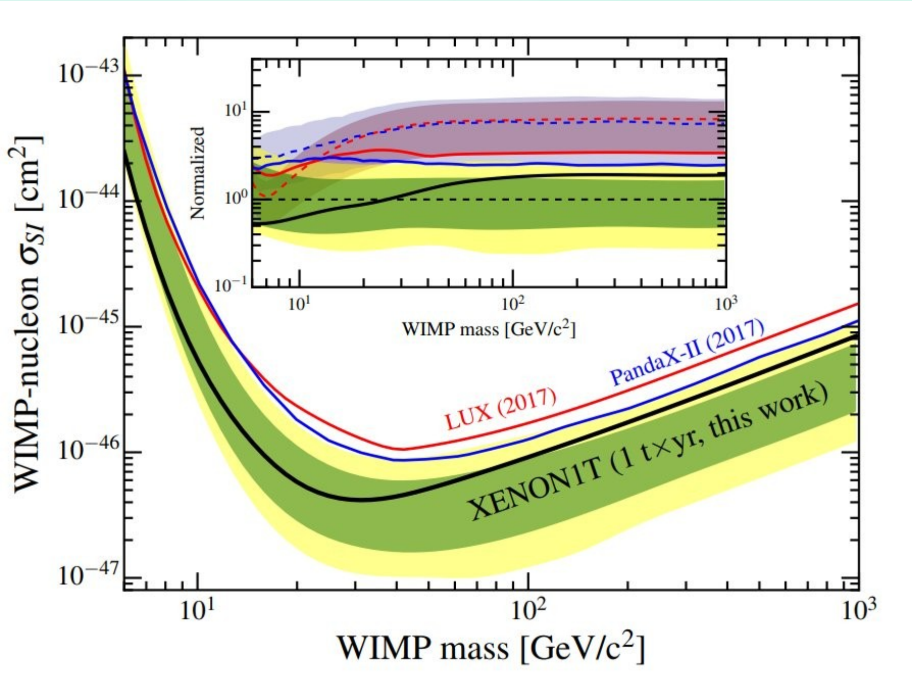


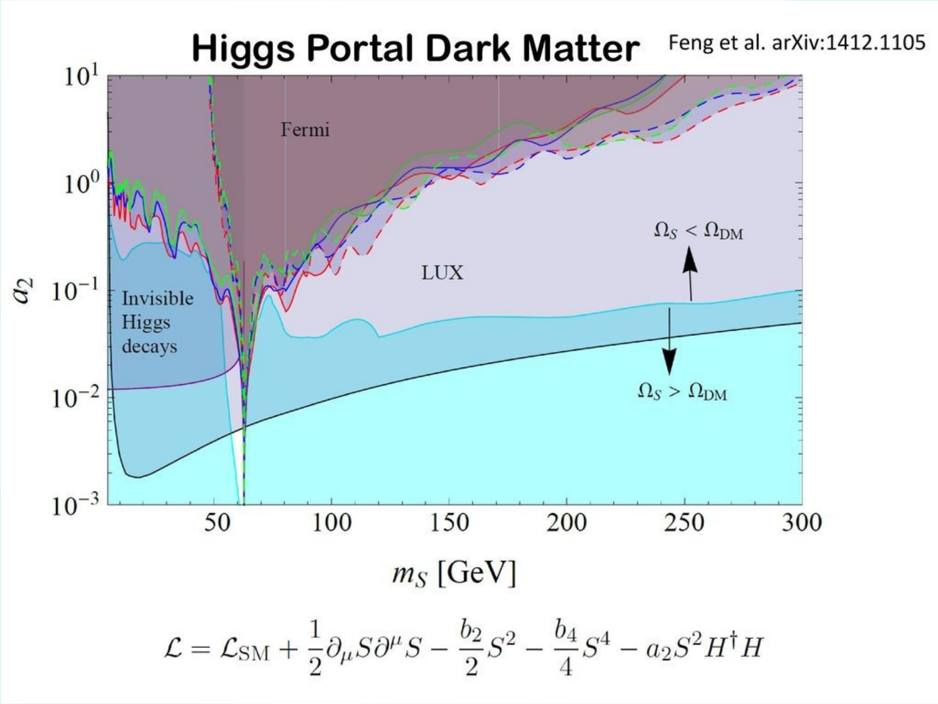


[1602.04203]

Dark matter: Is there still room for WIMP?





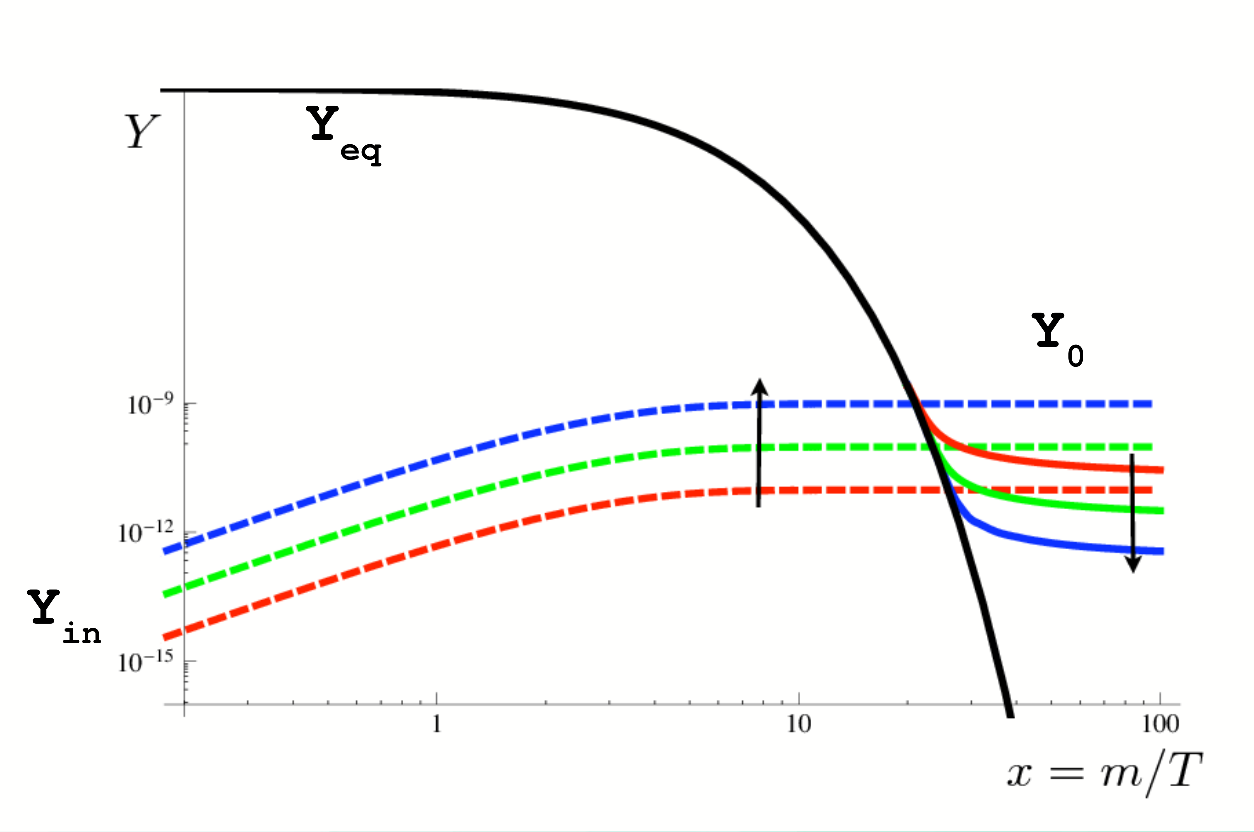


No longer a miracle?

Alternatives: Feebly interacting massive particles (FIMP)?

DM-SM in thermal equilibrium

Freeze-out due to expansion



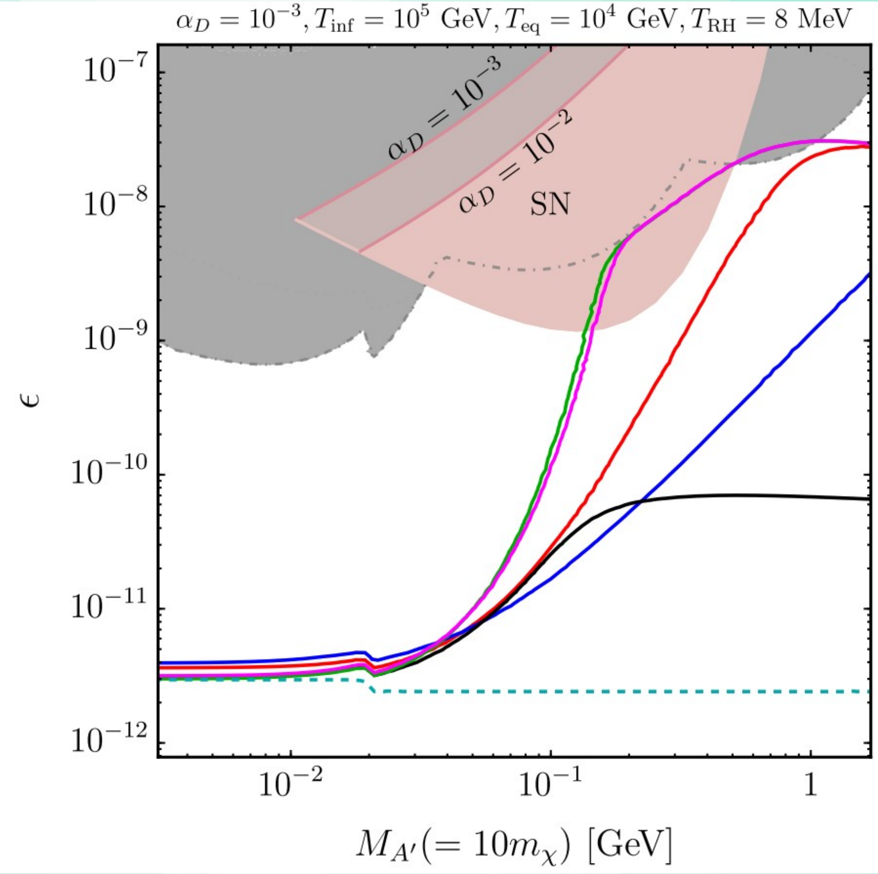
DM-SM coupling is small

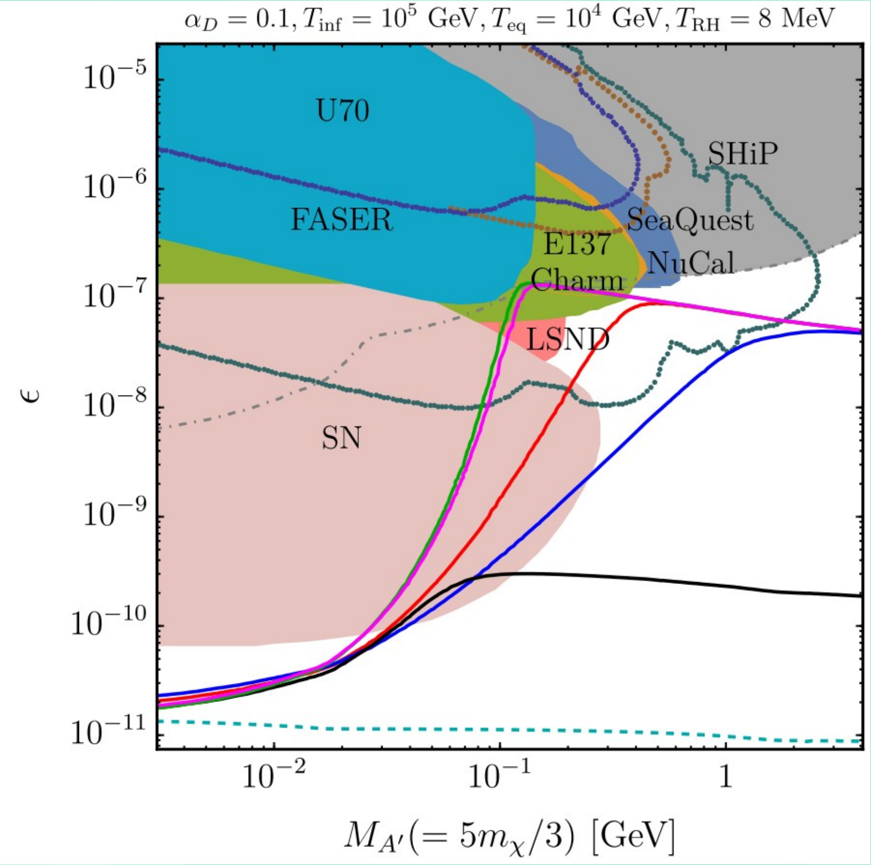
DM not in thermal equilibrium

Freeze-in production from negligible initial abandunce

Fingerprints of FIMP

A dark photon portal to fermionic FIMP dark matter in early matter dominated universe





Can be interesting for CODEX-b

AB, D Chowdhury [2204.03670]

Conclusions

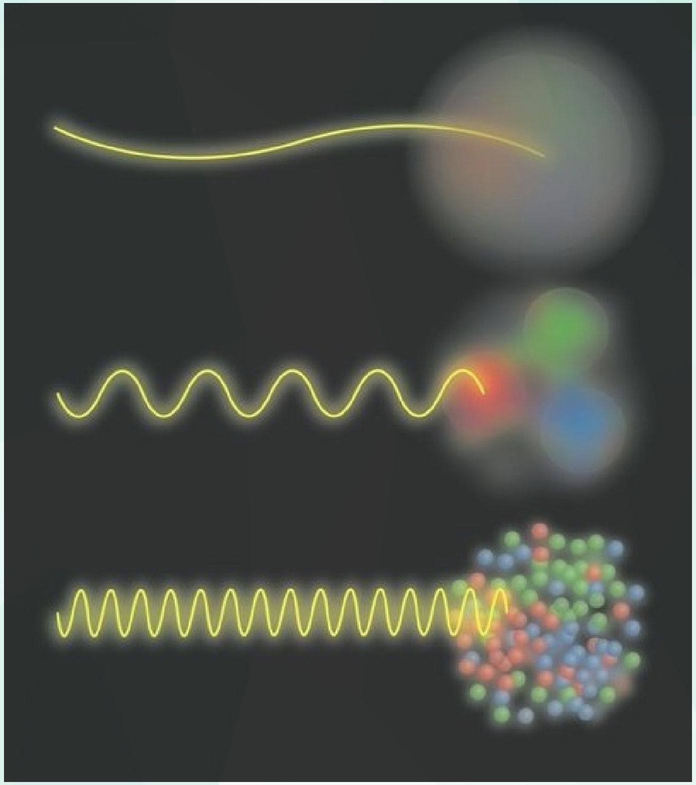
- ✓ Naturalness: is there a real issue? SM has Hierarchy problem
- ✓ Lots of effort on theoretical grounds: 20+ ways to address, concrete models to brand new ideas
- ✓ Experimental frontier: Direct search of new particles (pNGB, VLQ, spin-1,ALP,LLP... ...)
- ✓ Precision measurements: EFT frameworks and challenges therein
- ✓ Cosmology: Still futuristic, but it is time to think about it
- ✓ Is there still room for naturalness? Yes!
- ✓ Other related questions: Dark matter, Strong CP?

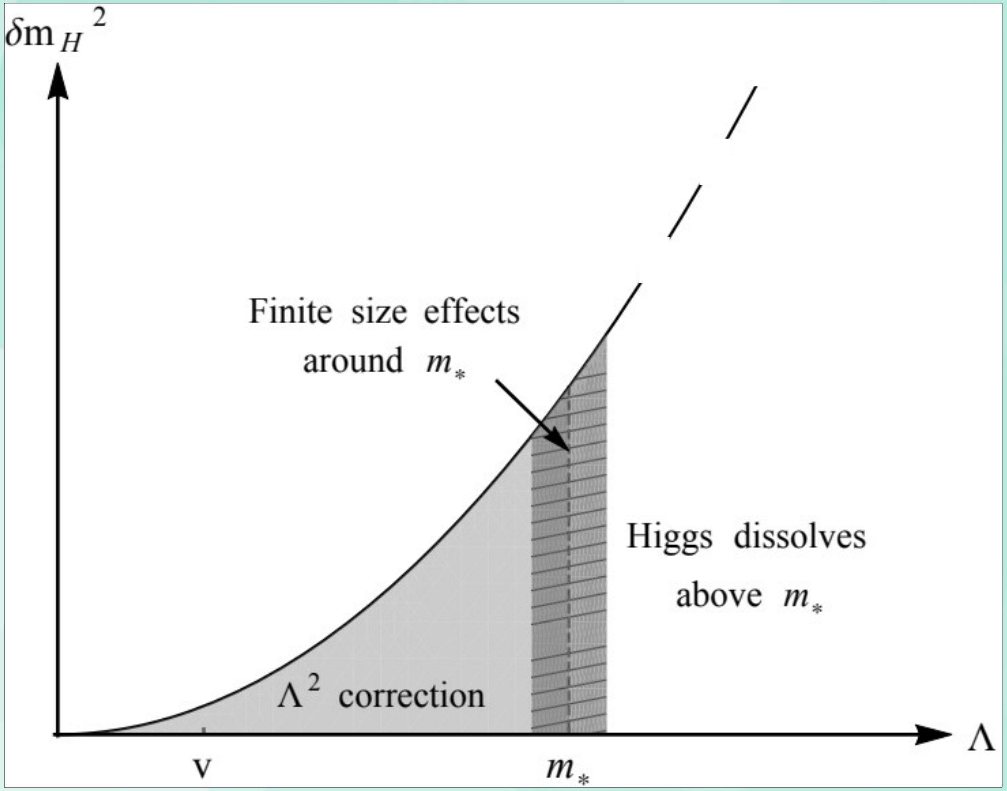
Thank you!

Backup

Composite pNGB Higgs

- **Higgs is a composite bound state of a strongly interacting sector**
- **Higgs emerges as a pseudo Nambu-Goldstone boson (pNGB)**





Compare with QCD

Properties	QCD	Composite Higgs
Confining gauge group	$\mathrm{SU}(3)_\mathrm{c}$	Hypercolor $\mathrm{SU(n)},\ \mathrm{Sp(n)},\ \mathrm{SO(n)}$
Fundamental dof	Quarks & Gluons	Hyperquarks & Hypergluons
Global symmetry	$\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R}/\mathrm{SU}(2)_\mathrm{D}$	G/H
pNGBS $\langle\bar{\psi}\psi\rangle$	Pions	Higgs + BSM pNGBs
$\langle\bar{\psi}\gamma^\mu\psi\rangle$	Rho-mesons	Spin-1 vector resonances
$\langle\bar{\psi}\psi\psi\rangle$	Baryons	Top-partners(VLQ)
Vacuum misalignment	No	Yes (triggers EWSB)

Partial compositeness

Examples

Main requirements:

1. Atleast one Higgs doublet among the pNGBs

2. Custodial $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R}$ should remain unbroken

Three minimal cosets:

Taken from Gabriele's talk

$4\ (\psi_\alpha, \tilde{\psi}_\alpha)$ Complex	$SU(4) \times SU(4)'/SU(4)_D$
$4\ \psi_\alpha$ Pseudoreal	$SU(4)/Sp(4)$
$5\ \psi_\alpha$ Real	$SU(5)/SO(5)$

[Barnard et al. 1311.6562, Ferretti et al. 1312.5330, 1404.7137]

Top-partners

$$\mathcal{L}_{\rm mix} \simeq \frac{\lambda_L}{\Lambda_{\rm UV}^{d_L-5/2}} \bar{q}_L \mathcal{O}_R + \frac{\lambda_R}{\Lambda_{\rm UV}^{d_R-5/2}} \bar{u}_R \mathcal{O}_L + {\rm h.c.}$$

$$\mathcal{O} \sim \psi\chi\chi\,,\ \chi\psi\chi$$

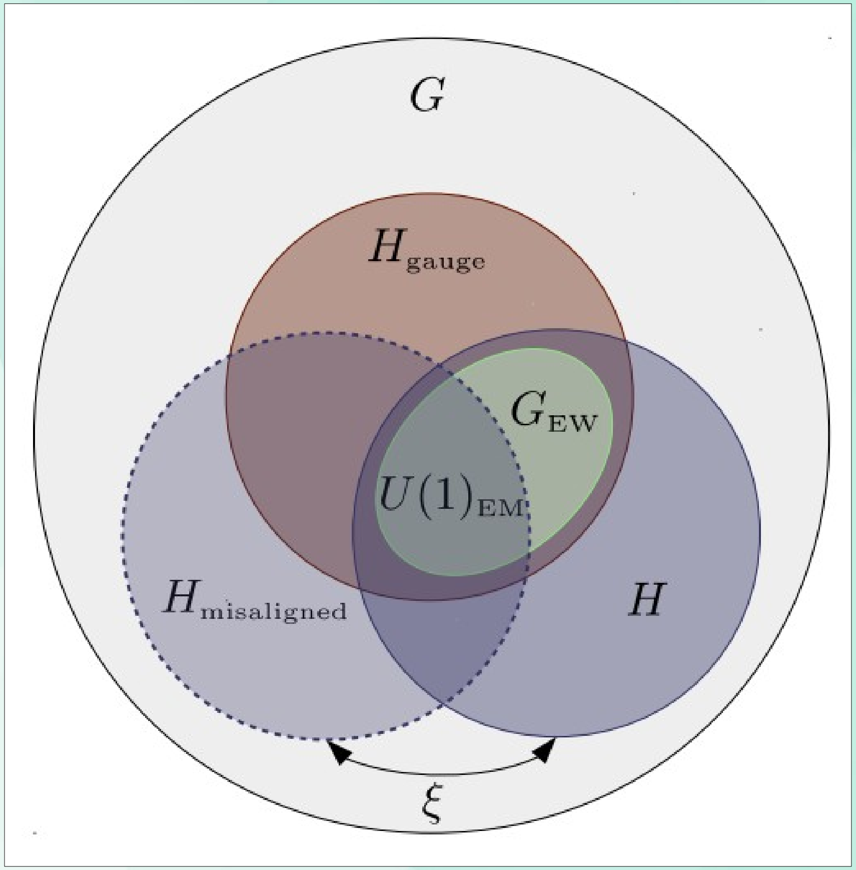
Trilinear fermionic operators give rise to vector-like fermionic bound states (top-partners) below the confinement scale

χ **carries the SU(3) color quantum numbers,** ψ **does not.**

Since we want to obtain the top partners, we also need to embed the color group SU(3)c into the global symmetry

$3\ (\chi_\alpha, \tilde{\chi}_\alpha)$ Complex	$SU(3) \times SU(3)' \to SU(3)_D \equiv SU(3)_c$
$6\ \chi_\alpha$ Pseudoreal	$SU(6) \to Sp(6) \supset SU(3)_c$
$6\ \chi_\alpha$ Real	$SU(6) \to SO(6) \supset SU(3)_c$

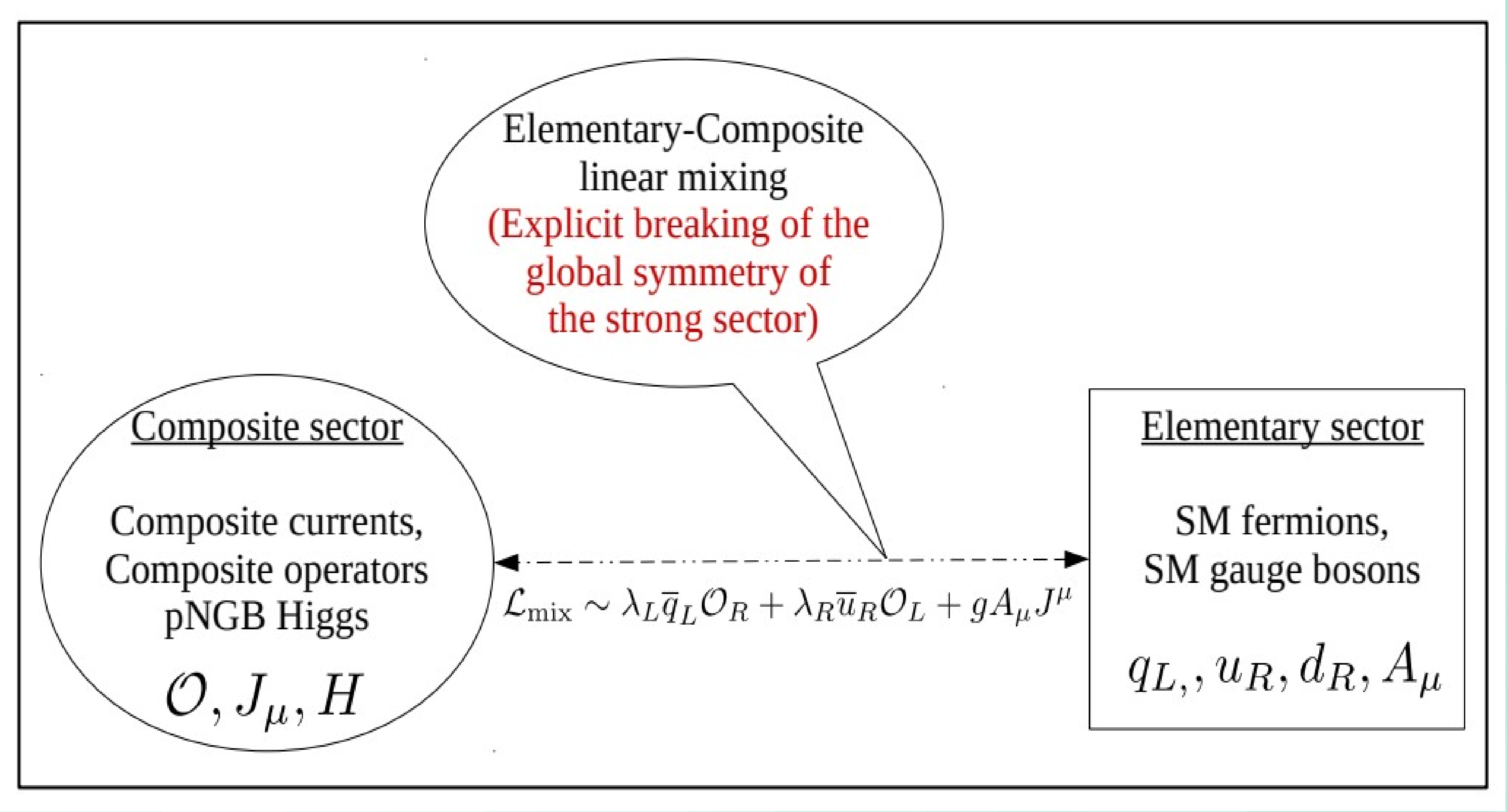
Vacuum misalignment



$$\xi = \frac{v^2}{f^2} \ll 1$$

- **Explicit breaking of global symmetry leads to 1-loop potential for the pNGBs**
- **Contribution from top quark is essential to trigger electroweak symmetry breaking**

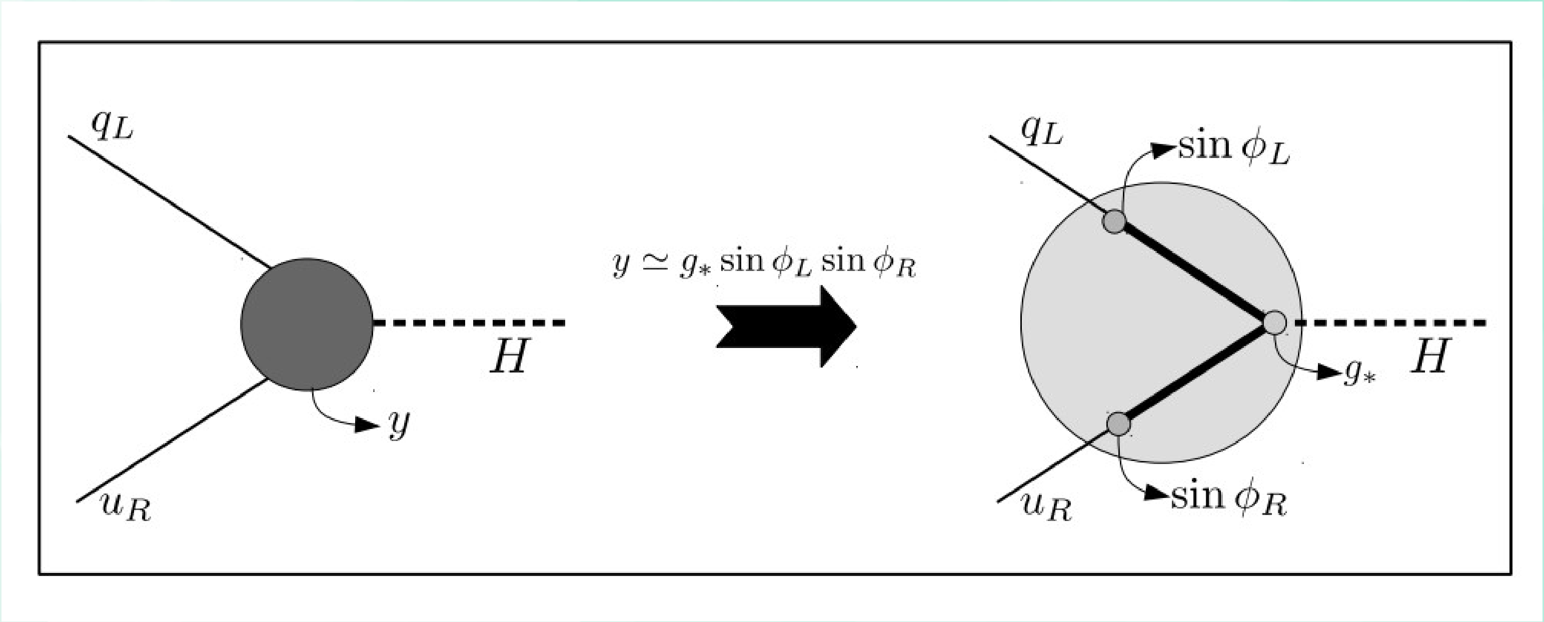
Partial compositeness



Physical states are linear combination of elementary and composite states

$$|\mathrm{SM}\rangle = \cos\phi|\mathrm{elem}\rangle + \sin\phi|\mathrm{comp}\rangle$$

Yukawa couplings and top-partners



- **Trilinear fermionic operators give rise to vector-like quarks (top-partners) below the confinement scale**

- **SM fermions mix with the top-partners, receive mass after electroweak breaking, interaction with Higgs via composite resonances**

- **Top can be substantially composite, while other light quarks are mostly elementary**

Vector-like quarks: defining features

Left-handed and right-handed chiralities transform identically under a gauge group

e.g. SM quarks are vector-like under QCD and EM, but chiral under the electroweak group

Example: Charged current $\mathcal{L} = \frac{g}{\sqrt{2}} j^\mu W_\mu^+ + \mathrm{h.c.}$

Chiral quarks:

$$j^\mu = j_L^\mu + j_R^\mu = \bar{f}_L \gamma^\mu f'_L = \bar{f} \gamma^\mu (1 - \gamma_5) f'$$ V-A structure

Vector-like quarks:

$$j^\mu = j_L^\mu + j_R^\mu = \bar{f}_L \gamma^\mu f'_L + \bar{f}_R \gamma^\mu f'_R = \bar{f} \gamma^\mu f'$$ V structure

Distinguishing Features:

1. Gauge invariant Dirac mass term exists without Higgs insertion
2. Axial anomalies are automatically absent

Specific example: SU(5)/SO(5)

- **pNGBs: 14 pNGBs,** only the doublet Higgs receives vev

$$\mathbf{14} \overset{\mathrm{SU(2)_L \times SU(2)_R}}{\rightarrow} (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1}) \overset{\mathrm{SU(2)_L \times U(1)_Y}}{\rightarrow} \mathbf{3}_0(\Phi_0) + \mathbf{3}_{\pm 1}(\Phi_\pm) + \mathbf{2}_{\pm 1/2}(H) + \mathbf{1}_0(\eta)$$

- **Vector-like quarks: transform under unbroken SO(5)**

$\mathrm{SU(2)_L \times U(1)_Y}$ multiplets			
$\mathbf{2}_{\frac{1}{6}}: \begin{pmatrix} T_{\frac{2}{3}} \\ B_{-\frac{1}{3}} \end{pmatrix}$	$\mathbf{2}_{\frac{7}{6}}: \begin{pmatrix} X_{\frac{5}{3}} \\ X_{\frac{2}{3}} \end{pmatrix}$		
$\mathbf{3}_{\frac{2}{3}}: \begin{pmatrix} Y_{\frac{5}{3}} \\ Y_{\frac{2}{3}} \\ Y_{-\frac{1}{3}} \end{pmatrix}$	$\mathbf{1}_{\frac{5}{3}}: \tilde{X}_{\frac{5}{3}}$	$\mathbf{1}_{\frac{2}{3}}: \tilde{T}_{\frac{2}{3}}$	$\mathbf{1}_{-\frac{1}{3}}: \tilde{B}_{-\frac{1}{3}}$

- **SM quark embedding:** no corrections to Zbb

$$\hat{q}_L = t_L D^1_{t_L} + b_L D^1_{b_L} \in \mathbf{24}, \quad \hat{t}_R = t_R D^2_{t_R} \in \mathbf{24}$$

Lagrangian @TeV scale

$$\mathcal{L}_{\Psi^2} = \mathrm{tr}\left[\bar{\Psi} i D \Psi\right] - M \mathrm{tr}\left[\bar{\Psi}\Psi\right] + \kappa \mathrm{tr}\left[\bar{\Psi}\partial\Sigma\Psi\right]$$

$$\mathcal{L}_{\text{elem.}} = \bar{q}_L i \not{D} q_L + \bar{t}_R i \not{D} t_R + \bar{b}_R i \not{D} b_R$$

$$\mathcal{L}_{\text{P.C.}} = y_L f \bar{q}_L \Sigma \Psi_R + y_R f \bar{\Psi}_L \Sigma t_R$$

$$\mathcal{L} = \mathcal{L}_{\text{pNGB}} + \mathcal{L}_{\text{anom.}} + \mathcal{L}_{\text{elem.}} + \mathcal{L}_{\Psi^2} + \mathcal{L}_{\text{P.C.}} - V_{\text{pot.}}$$

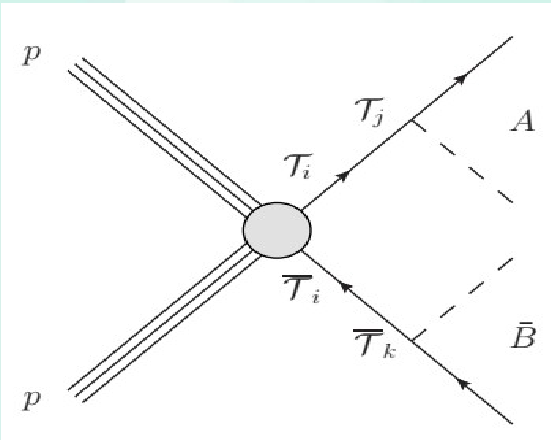
$$\mathcal{L}_{\text{pNGB}} = \frac{f^2}{2} \mathrm{tr}\left[(D_\mu \Sigma)^\dagger (D^\mu \Sigma)\right]$$

$$V_{\text{pot.}} = \frac{1}{2} m_h^2 h^2 + \frac{1}{2} m_i^2 \pi_i^2 + \mathcal{O}(\pi^3, \pi^4)$$

$$\begin{aligned} \mathcal{L}_{WZW} = \pi_i^0 &\left[c_{\gamma\gamma} F\tilde{F} + c_{ZZ} Z\tilde{Z} + c_{Z\gamma} F\tilde{Z} + c_{WW} W^+\tilde{W}^-\right] \\ &+ \pi_i^+ \left[c_{ZW} Z\tilde{W}^- + c_{\gamma W} F\tilde{W}^-\right] + \pi_i^{++}\left[c_{W^-W^-} W^-\tilde{W}^-\right] \end{aligned}$$

AB, D B Franzosi, G Ferretti [2202.00037]

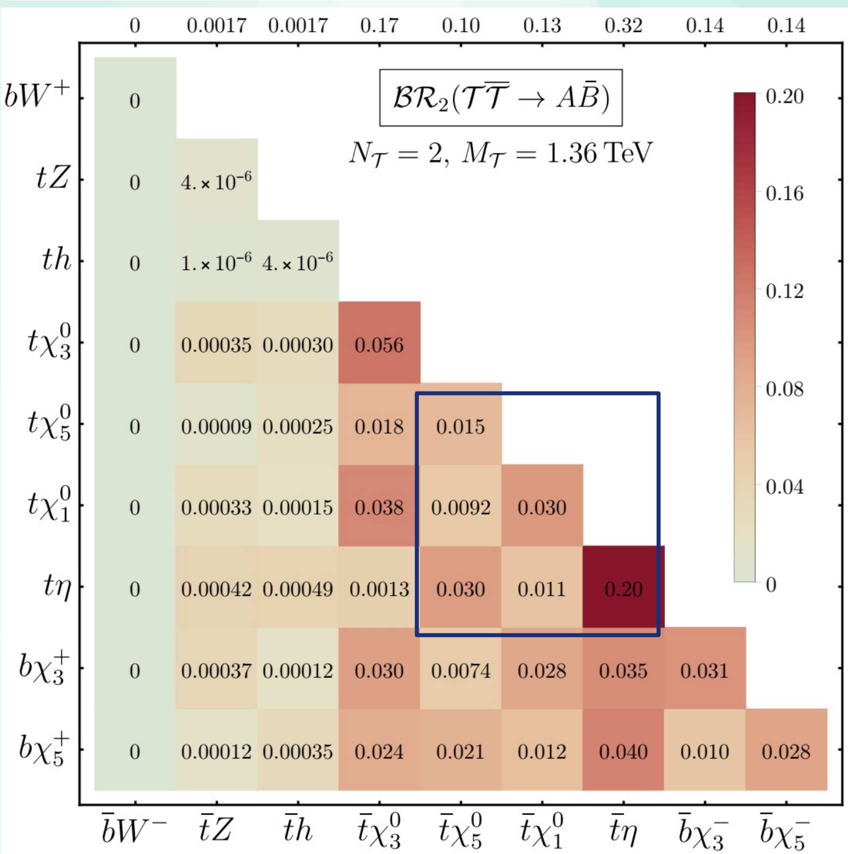
Decays of nearly degenerate states



- **Theoretical Challenges:**

$$\left[\frac{i(\not{p}+M_{\mathcal{T}})}{(p^2-M_{\mathcal{T}}^2)\mathbb{1}+iM_{\mathcal{T}}(\Gamma_{\mathcal{T}}+2i\delta M)}\right]_{ij}$$

- ✓ **Deal with the nearly degenerate states**
- ✓ **One-loop self energy is off-diagonal**
- ✓ **Consider matrix Breit-Wigner propagators**



$$\sigma(pp \to \mathcal{T}\overline{\mathcal{T}} \to A\bar{B}) \overset{\text{NWA}}{=} N_{\mathcal{T}}\sigma(pp \to \mathcal{T}\overline{\mathcal{T}})\mathcal{BR}_2(\mathcal{T}\overline{\mathcal{T}} \to A\bar{B})$$

$$\mathcal{BR}(\mathcal{T} \to A) = \sum_{\bar{B}} \mathcal{BR}_2(\mathcal{T}\overline{\mathcal{T}} \to A\bar{B}) \qquad \sum_{A} \mathcal{BR}(\mathcal{T} \to A) = 1$$

$$\mathcal{BR}_2(\mathcal{T}\overline{\mathcal{T}} \to A\bar{B}) \neq \mathcal{BR}(\mathcal{T} \to A)\mathcal{BR}(\bar{\mathcal{T}} \to \bar{B})$$

AB, D B Franzosi, G Ferretti [2202.00037]

Building blocks for IR theory

Three basic ingredients to construct the IR Lagrangian of VLQs and pNGBs

- pNGB matrix (fixed by the choice of coset G/H)

$$\Sigma = \Omega(\xi) \exp\left(\frac{i\pi_a \hat{T}^a}{f}\right), \qquad \Sigma \to g\Sigma h^{-1}(\pi)$$

- Irrep of the vector-like partners under unbroken H

$$\Psi_N \to \Psi_N, \quad \Psi_F \to h\Psi_F, \quad \Psi_{A/S} \to h\Psi_{A/S}h^T, \quad \Psi_D \to h\Psi_D h^\dagger$$

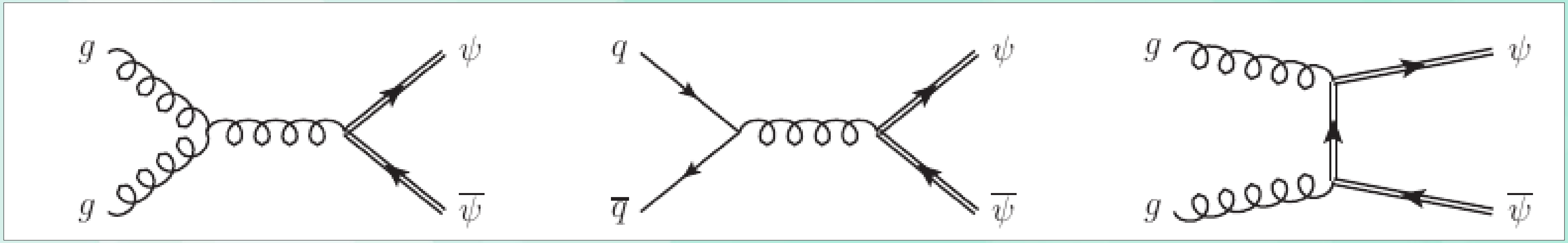
- Spurion embedding of SM quarks in the global symmetry G

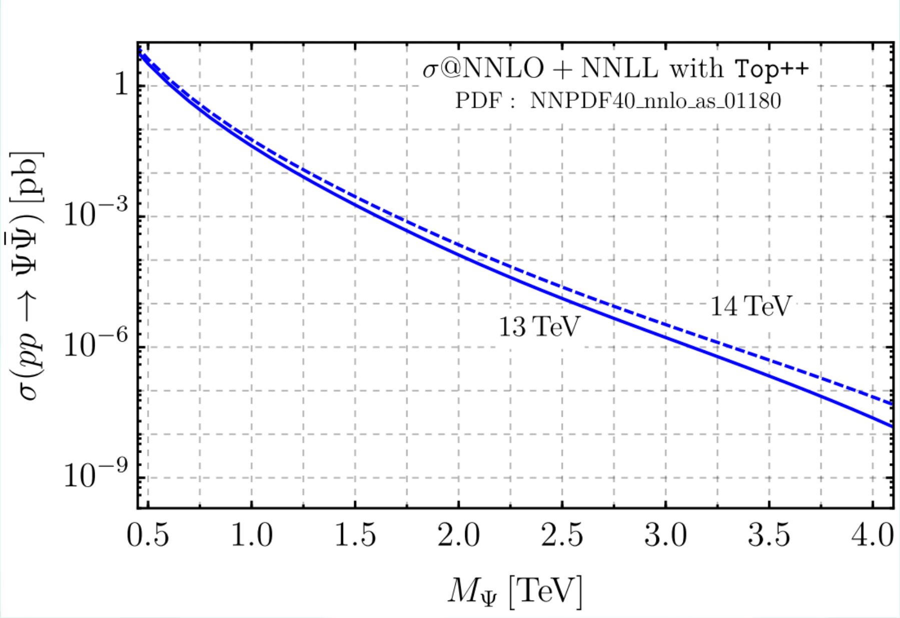
$$q_L \to t_L S_{t_L} + b_L S_{b_L}, \qquad t_R \to t_R S_{t_R} \qquad b_R \to b_R S_{b_R}$$

$$N \to N, \quad F \to gF, \quad A \to gAg^T, \quad S \to gSg^T, \quad D \to gDg^\dagger$$

Production and decays of VLQs

- **Pair production of VLQs at LHC: depends only on VLQ mass**





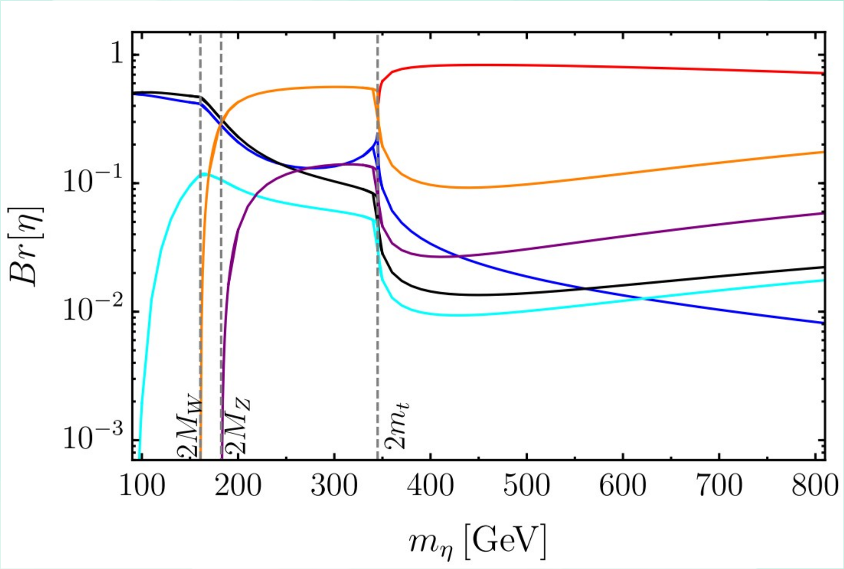
- **Possible decay channels**

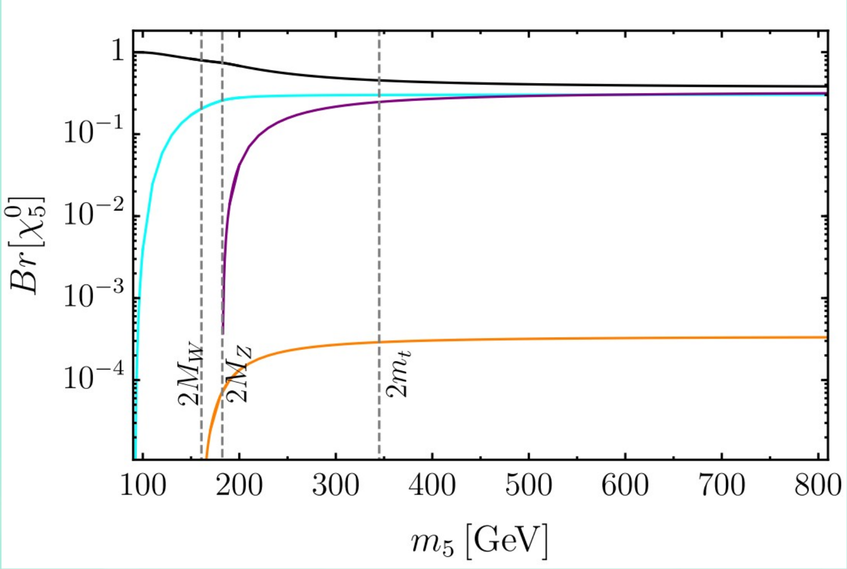
Top-partner	Decays to SM final states	Decays to BSM final states
$T_{\frac{2}{3}}, X_{\frac{2}{3}}, Y_{\frac{2}{3}}, \tilde{T}_{\frac{2}{3}}$	$th,\ tZ,\ bW^+$	$t\chi^0_{1,3,5},\ t\eta,\ b\chi^+_{3,5}$
$B_{-\frac{1}{3}}, Y_{-\frac{1}{3}}, \tilde{B}_{-\frac{1}{3}}$	$tW^-,\ bh,\ bZ$	$t\chi^-_{3,5},\ b\chi^0_{1,3,5}\ ,\ b\eta$
$X_{\frac{5}{3}}, Y_{\frac{5}{3}}, \tilde{X}_{\frac{5}{3}}$	tW^+	$t\chi^+_{3,5},\ b\chi^{++}_5$

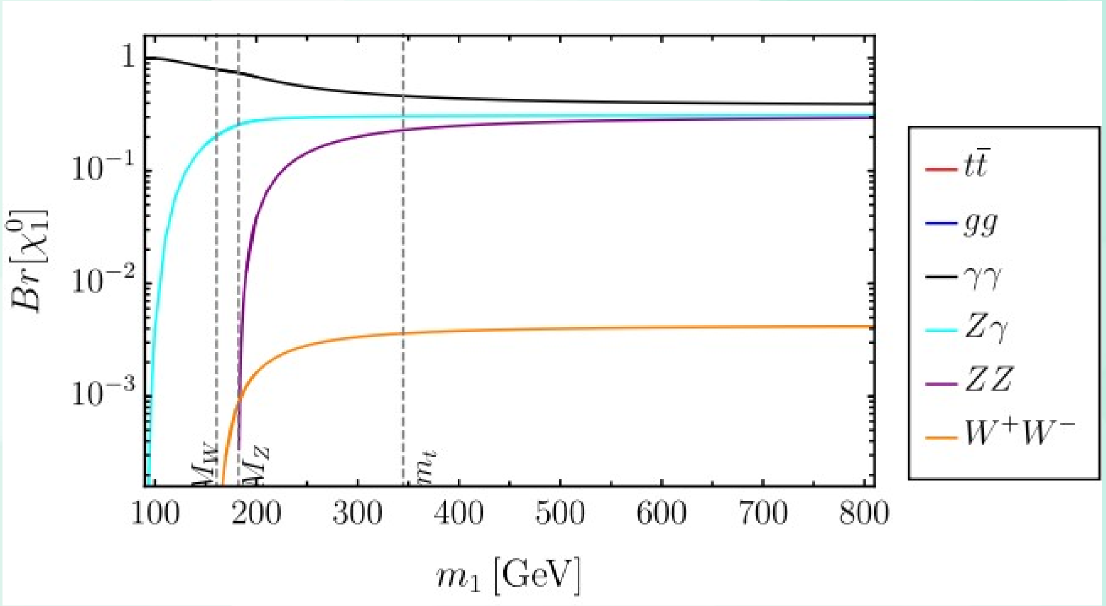
f	M	m_3	m_5	m_1	m_η	y_L	y_R	κ
1000	1500	330	315	335	290	1.80	1.87	0.50

- **Single production: Typically model dependent**

Branching ratios of pNGBs



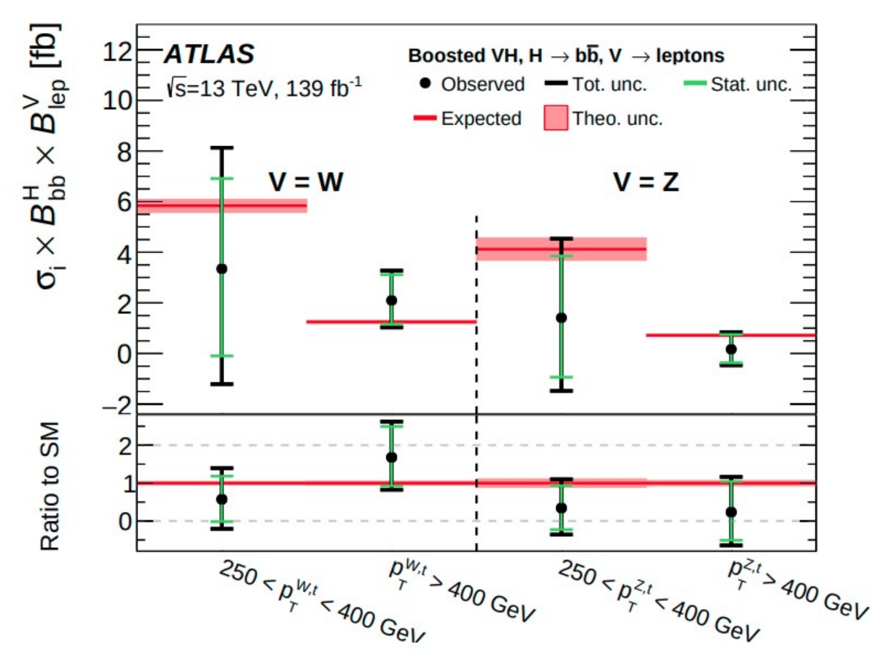


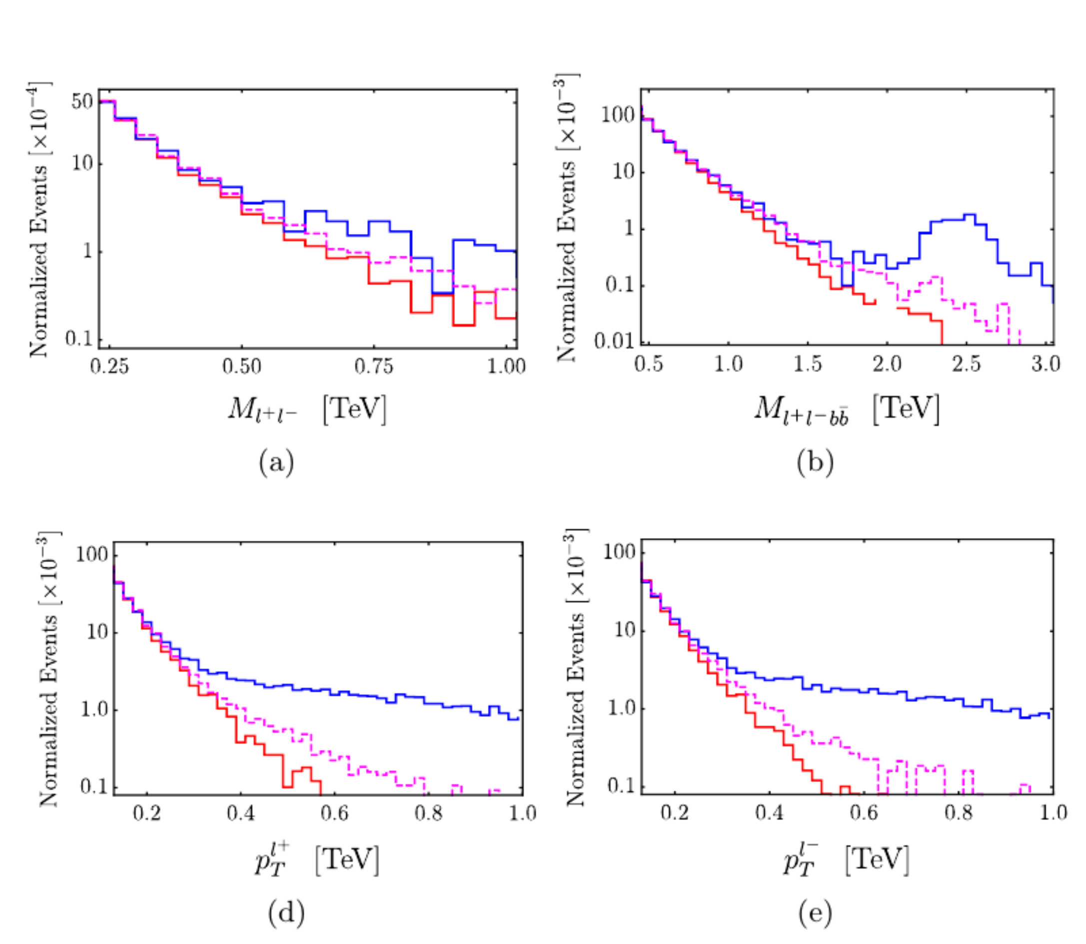


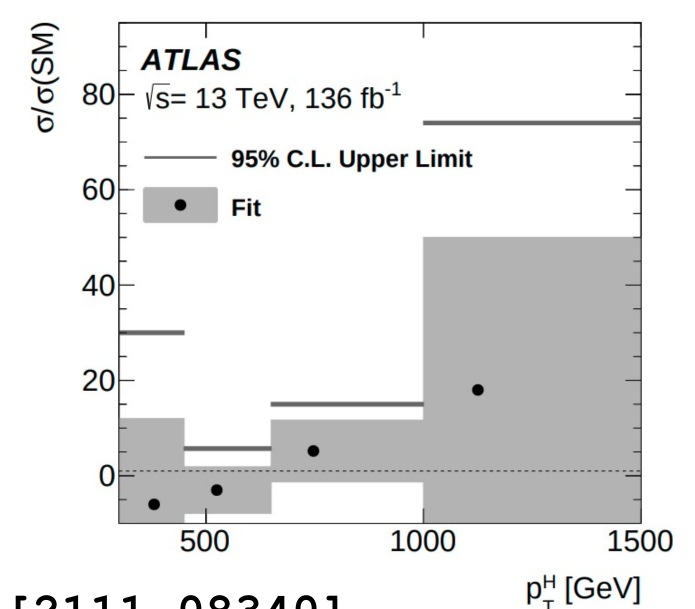
- **Decays into diboson are mainly driven by anomaly terms**
- χ_5^0 **and** χ_1^0 **are fermiophobic**
- η **decays to gg through top loop**

Higgstrahlung

[2008.02508]







[2111.08340]

Coleman-Weinberg Higgs potential

$$V_{\mathrm{top}}(h) = -2N_c \int \frac{d^4 q_E}{(2\pi)^4} \log\left[-q_E^2\left(\Pi_0^L + \frac{\Pi_1^L}{2} s_h^2\right)\left(\Pi_0^R + \Pi_1^R c_h^2\right) - \frac{|\Pi_1^{LR}|^2}{2} s_h^2 c_h^2\right]$$

$$V_{\mathrm{gauge}}(h) = \frac{9}{2}\int \frac{d^4 q_E}{(2\pi)^4} \log\left[1 + \frac{\Pi_1(-q_E^2)}{4\Pi_0(-q_E^2)} s_h^2\right]$$

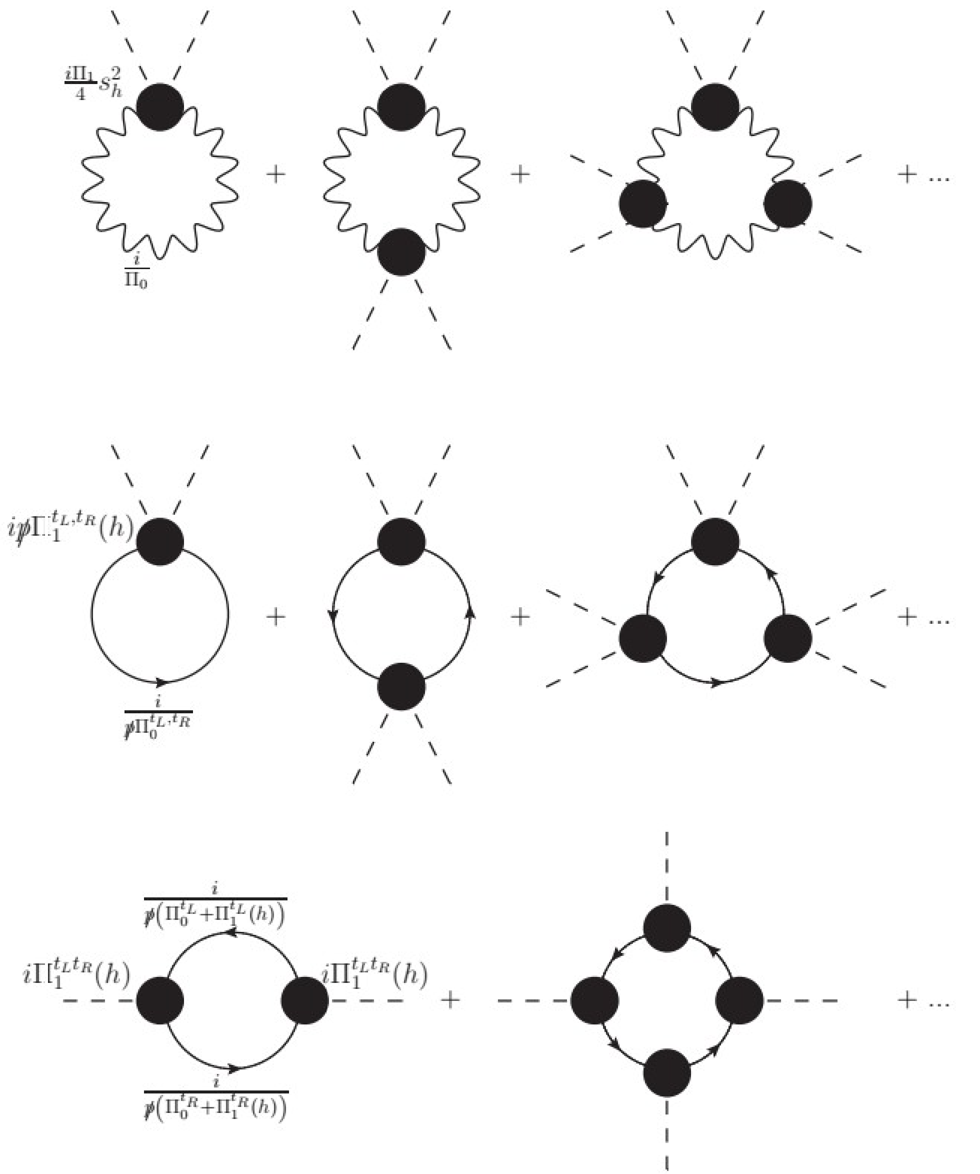
$$\simeq \frac{9}{2}\int \frac{d^4 q_E}{(2\pi)^4}\left[\frac{\Pi_1}{4\Pi_0} s_h^2 - \frac{\Pi_1^2}{32\Pi_0^2} s_h^4\right]$$

$$V_{\mathrm{eff}} = \alpha s_h^2 + \beta s_h^4$$

$\alpha_g > 0$ **Gauge contribution can not misalign the vacuum**

$\alpha_t < 0$ **Top contribution essential for EWSB**

$$\xi \equiv \langle s_h \rangle^2 = \frac{\alpha}{2\beta} \qquad m_h^2 = \frac{8}{f^2}\xi(1-\xi)\beta$$



Custodial symmetry

- **Custodial symmetry** ➡ $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{SU}(2)_\mathrm{R} \to \mathrm{SU}(2)_\mathrm{V}$

$$\rho_{\text{tree}} = \frac{M_W^2}{M_Z^2 \cos\theta_w^2} = \frac{\sum_i v_i^2 \left[4T_i(T_i+1) - Y_i^2\right]}{\sum_i 2v_i^2 Y_i^2}$$

One doublet

One doublet + singlets

Multi doublets

$$\rho_{\text{tree}} = 1$$

$$\rho_{\text{exp}} = 1.00039 \pm 0.00019$$

One doublet + one triplet

$$\rho_{\text{tree}} \simeq 1 \pm \frac{2v_t^2}{v_d^2} \implies v_t < 1\ \text{GeV}$$

Georgi-Machacek model

- **Doublet + one triplet ➡ Custodial symmetry violation**

$$\rho_{\rm tree} = \frac{M_W^2}{M_Z^2 \cos\theta_w^2} \simeq 1 \pm \frac{2v_t^2}{v_d^2} \quad \Longrightarrow \quad v_t \lesssim 1\mathrm{GeV}$$

- **Restore custodial symmetry: bidoublet + bitriplet**

$$\mathrm{SU(2)_L} \times \mathrm{SU(2)_R} \quad \to \quad \mathrm{SU(2)_V}$$

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -\phi^- & \phi^0 \end{pmatrix} \quad (\mathbf{2},\mathbf{2}) \quad \to \quad \mathbf{1} + \mathbf{3}$$

$$\Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^- & \xi^0 & \chi^+ \\ \chi^{--} & -\xi^- & \chi^0 \end{pmatrix} (\mathbf{3},\mathbf{3}) \quad \to \quad \mathbf{1} + \mathbf{3} + \mathbf{5}$$

$$\begin{pmatrix} h \\ H \end{pmatrix} \quad \begin{pmatrix} G^\pm \\ G^0 \end{pmatrix} \begin{pmatrix} H_3^\pm \\ H_3^0 \end{pmatrix} \quad \begin{pmatrix} H_5^{\pm\pm} \\ H_5^\pm \\ H_5^0 \end{pmatrix}$$

$$\rho_{\rm tree} = \frac{2\langle\xi^0\rangle^2 + 2\langle\chi^0\rangle^2 + \langle\phi^0\rangle^2}{4\langle\chi^0\rangle^2 + \langle\phi^0\rangle^2} = 1$$

Georgi-Machacek model