BEYOND THE STANDARD MODEL WITH STRONG DYNAMICS

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The SM and its successful paradigm

- SM = EFT with very high cutoff
  - higher-dim operators become irrelevant in the IR
  - accidental symmetries in the IR (approximate flavor and custodial, B, L)

- Fermions in complex representations
  - only naturally light fields are observed

- Global symmetry group broken by Yukawas
  - massless particles implied by 't Hooft anomalies are lifted by Yukawas

  Exception: $[U(1)_{B-L}]^3$ 't Hooft anomaly would imply massless neutrinos,
  $U(1)_{B-L}$ explicitly broken by dim-5 LLHH operator

Not explained within the SM

- Experimental facts

  - Dark Matter

  - Baryogenesis

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- Suggestive hints

  - Fermion fields fill GUT multiplets + Gauge coupling unification
  - We live in a very special point in parameter space

Observed rich chemistry requires a delicate interplay among different SM parameters

Ex:

- m_u heavier by $\sim 1(10)\,\mathrm{MeV}$ $\longrightarrow$ free (bound) protons unstable
- m_d heavier by $\sim 1(10)\,\mathrm{MeV}$ $\longrightarrow$ deuterium (bound neutrons) unstable
- $m_e > m_n - m_d = 1.29\,\mathrm{MeV}$ $\longrightarrow$ hydrogen unstable

[for a review see Donoghue, arXiv:1601.05136]

Going beyond the SM

- Enlarge gauge dynamics to explain missing experimental facts
  but *maintain* the SM paradigm

Request: *unification of SM gauge couplings must not be spoiled by new physics*

Postulate new gauge symmetry G_{HC} (hyper color) with new fermions ψ in a representation $r(\psi)$

In this talk: *assume* ψ *charged under* G_{SM}

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In this talk: *assume* ψ *charged under* G_{SM}

☞ Theories can be classified according to whether $r(\psi)$ is real or complex under $G_{HC} \times G_{SM}$

In this talk:

real = { vector-like: $r + \bar{r}$, r complex; strictly real; pseudo-real }

- **Class I:** (G_{HC} real, $G_{HC} \times G_{SM}$ complex)

  i) Hyper fermions naturally light

  ii) Hyper fermion condensate ***necessarily*** *breaks* G_{SM} ➡ Technicolor

$$\langle \psi \psi \rangle \sim 1_{HC} \; \Sigma_{SM}$$

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Similar in spirit to Bosonic Technicolor

Two possibilities:

$\Lambda_{conf} \gtrsim \Lambda_{EW}$	*Standard TC* — Susskind PRD 20 (1979) 2619; Weinberg PRD 13 (1976) 974, PRD 19 (1979) 1277 *Strong dynamics main source of EWSB* Severely constrained by EW precision tests

or

$\Lambda_{conf} \ll \Lambda_{EW}$	Similar in spirit to 'Bosonic Technicolor' by Samuel, Dine, and Kagan See also 'Superconformal Technicolor' by: Azatov, Galloway, Luty PRL 108 (2012) 041802

- Class II: (G_{HC} complex, G_{SM} real)

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  ii) Hyper fermion condensate necessarily breaks G_{HC} (but it may preserve G_{SM})

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Presumably theory 'tumbles' to another gauge theory and eventually confines

[Raby, Dimopoulos, Susskind NPB 169 (1980) 373]

Example:

[Georgi NPB 156 (1979) 126]

$\psi = \bar{5} + 10$ of $SU(5)_{HC}$

condensates $\langle 10\,10\rangle, \langle 10\ \bar{5}\rangle$ break $SU(5)_{HC} \to SU(4)_{HC}$

$\bar{5} = \bar{4} + 1, \quad 10 = 6\,(\text{real}) + 4$

$4, \bar{4}, 6$ get mass and decouple, $SU(4)_{HC}$ theory confines

No fully controlled lattice simulations available for complex (i.e. chiral) gauge theories
IR behavior of this class of theories not rigorously known yet

- Class III: ($G_{HC} \times G_{SM}$ real)

i) Hyper fermion masses allowed and technically natural, but not explained by theory

ii) Hyper fermion condensate in general breaks $G \rightarrow H$ *and may preserve* G_{SM}

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1. $G \supset G_{SM}$ $H \not\supset G_{SM}$ Condensate necessarily breaks G_{SM} $\longrightarrow$ Technicolor

Example:

	$SU(N)_{HC}$	$SU(2)_L$	$U(1)_Y$
ψ	adj	2	0

Dynamical breaking

$SU(2) \to SO(2) \not\supset G_{SM}$

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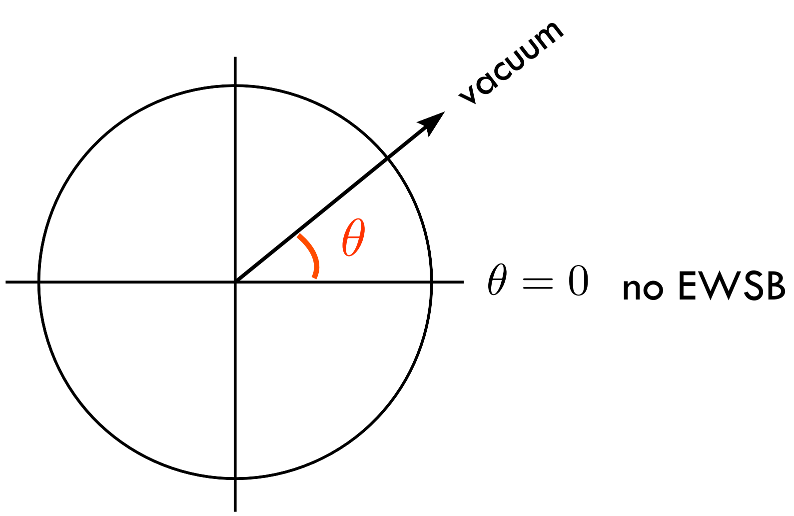
2. $G \to H \supset G_{SM}$

Vacuum alignment depends on weaker external interactions which can lift the degeneracy and trigger EWSB



Possibility #1: Composite Higgs Theories [Georgi and Kaplan `80]

- *G/H contains an $SU(2)_L$ doublet (composite Higgs)*
- *vacuum misalignment from fermion interactions*

Example:

[Luty, JHEP 0904 (2009) 050]

	$SU(2)_{HC}$	$SU(2)_L$	$U(1)_Y$
ψ	$\square$	2	0
$\tilde{\psi}_1$	$\square$	1	$+1/2$
$\tilde{\psi}_2$	$\square$	1	$-1/2$

Global symmetry breaking:

$$SU(4) \to Sp(4) \supset SU(2)_L \times U(1)_Y$$

$$\mathrm{NGBs} = 2_{1/2} + 1_0$$

Predictions:

i) *Modified Higgs couplings* $\delta g/g \sim O\big(v^2/f^2\big)$

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

ii) *Suppressed corrections to EWPO* $\delta O/O \sim O\big(v^2/f^2\big) \times \delta O/O|_{TC}$

Possibility #2: 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

- *G/H contains an $SU(2)_L$ doublet (composite Higgs)*
- *vacuum misalignment from mixing with an elementary Higgs*

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

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

Dynamical breaking from condensate :

$$SU(3)_L \times SU(3)_R \times U(1)_V \to SU(3)_V \times U(1)_V$$
$$\supset SU(2)_L \times U(1)_Y$$

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from Yukawas $y\, LHN^c$

$$(\phi\ \mathcal{H}) \begin{pmatrix} m_\phi^2 & yf\Lambda \\ yf\Lambda & m_\mathcal{H}^2 \end{pmatrix} \begin{pmatrix} \phi \\ \mathcal{H} \end{pmatrix}$$

from radiative corrections $m_\mathcal{H}^2 \sim \frac{g^2}{16\pi^2}\Lambda^2$

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

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Higgs compositeness controlled by the mixing

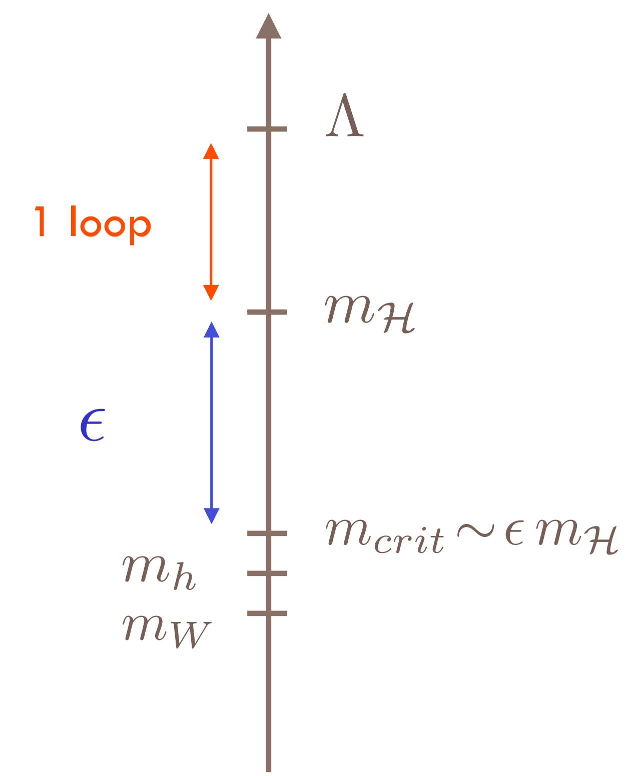
$$\epsilon \sim \frac{y f \Lambda}{m_{\mathcal{H}}^2}$$

Corrections to EWPO suppressed for small mixing:

$$\hat{T} \sim \frac{v^2}{f^2}\epsilon^4 \qquad \hat{S} \sim \frac{m_W^2}{m_\rho^2}\epsilon^2$$

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

Energy cartoon



☞ **See talk by Redi on Thursday**

Possibility #3: ‘Vector-like’ confinement [see for ex: Kilic, Okui, Sundrum, JHEP 1002 (2010) 018]

- no vacuum misalignment (ex: no Yukawas allowed)

- Elementary Higgs

- No large corrections to EWPT
- Scale of fermion masses arbitrary and not explained

  Theory could be the low-energy limit of one with complex representations (like QCD)
- Strong dynamics can lead to an <u>accidentally</u> stable DM candidate

  [See for ex: Antipin, Redi, Strumia, Vigiani, JHEP 1507 (2015) 039
  Kribs and Neil, Int.J.Mod.Phys. A31 (2016) no.22, 1643004]

Many models considered in the literature, rich and diverse IR phenomenology

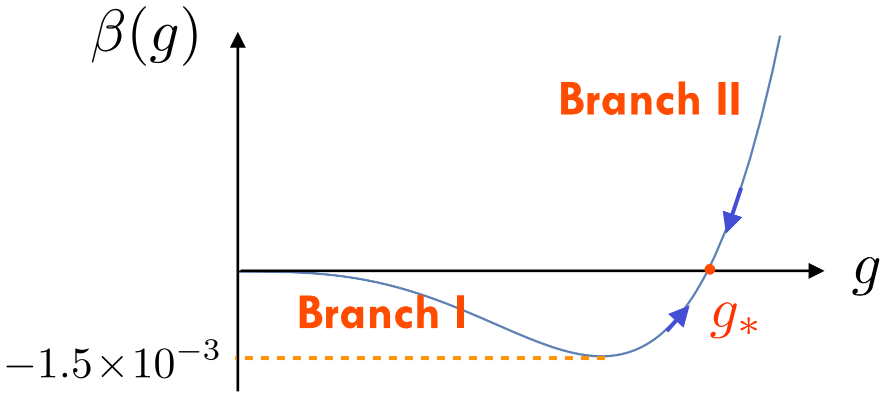
☞ **See talks on Thursday**

Example of a theory real under $G_{HC} \times G_{SM}$ with an IR fixed point

R.C., Mitridate, Podo, Redi, work in progress

	$SU(3)_{HC}$	$SU(2)_L$	$U(1)_Y$
V	adj	3	0
N_1	adj	1	0
N_2	adj	1	0

The beta-function of G_{HC} has a Banks-Zaks perturbative fixed point



$$g_* = 4\pi\sqrt{\frac{-b_0}{b_1}} = 1.07$$

$$b_0 = -1$$
$$b_1 = 138$$

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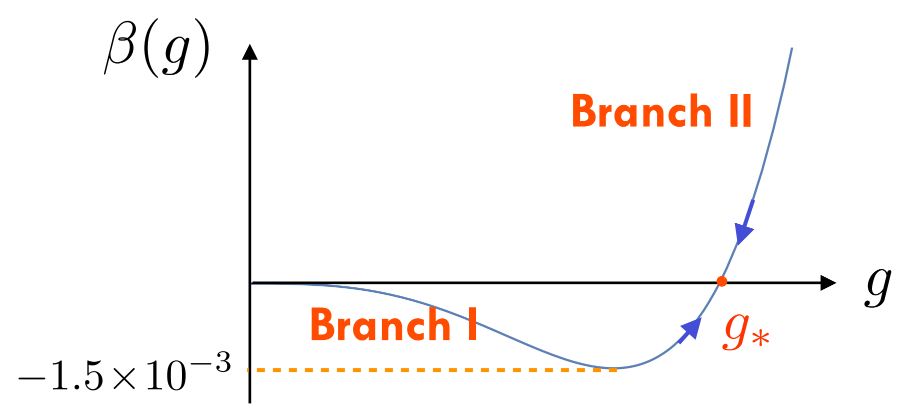

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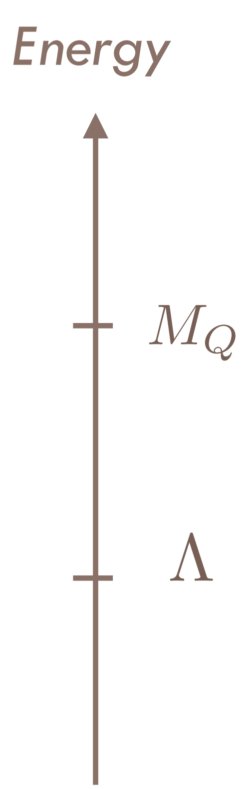

Theory slowly evolves until one reaches the scale of fermion masses below which it becomes a pure YM confining theory

☞ *Hierarchy between M_Q and Λ is fixed* [cf. Mitridate et al. arxXiv:1707.05380]

In Branch I: $\Lambda/M_Q \lesssim 10^{-3}$

In Branch II: *upper limit on Λ to avoid Landau pole below M_{Pl}*

- Accidental symmetries: three matter parities

$$Z_2^V: \quad V \to -V$$
$$Z_2^{N_1}: \quad N_1 \to -N_1$$
$$Z_2^{N_2}: \quad N_2 \to -N_2$$

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- Low-energy spectrum:

Even		*Odd*	
Φ	*glueball*	$\chi \sim \psi g$	*gluequark* ← DM candidate
$\psi\psi$	*'meson'*	$\psi\psi\psi$	
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$\vdots$		$\vdots$	

- Effect of higher-dimensional operators:

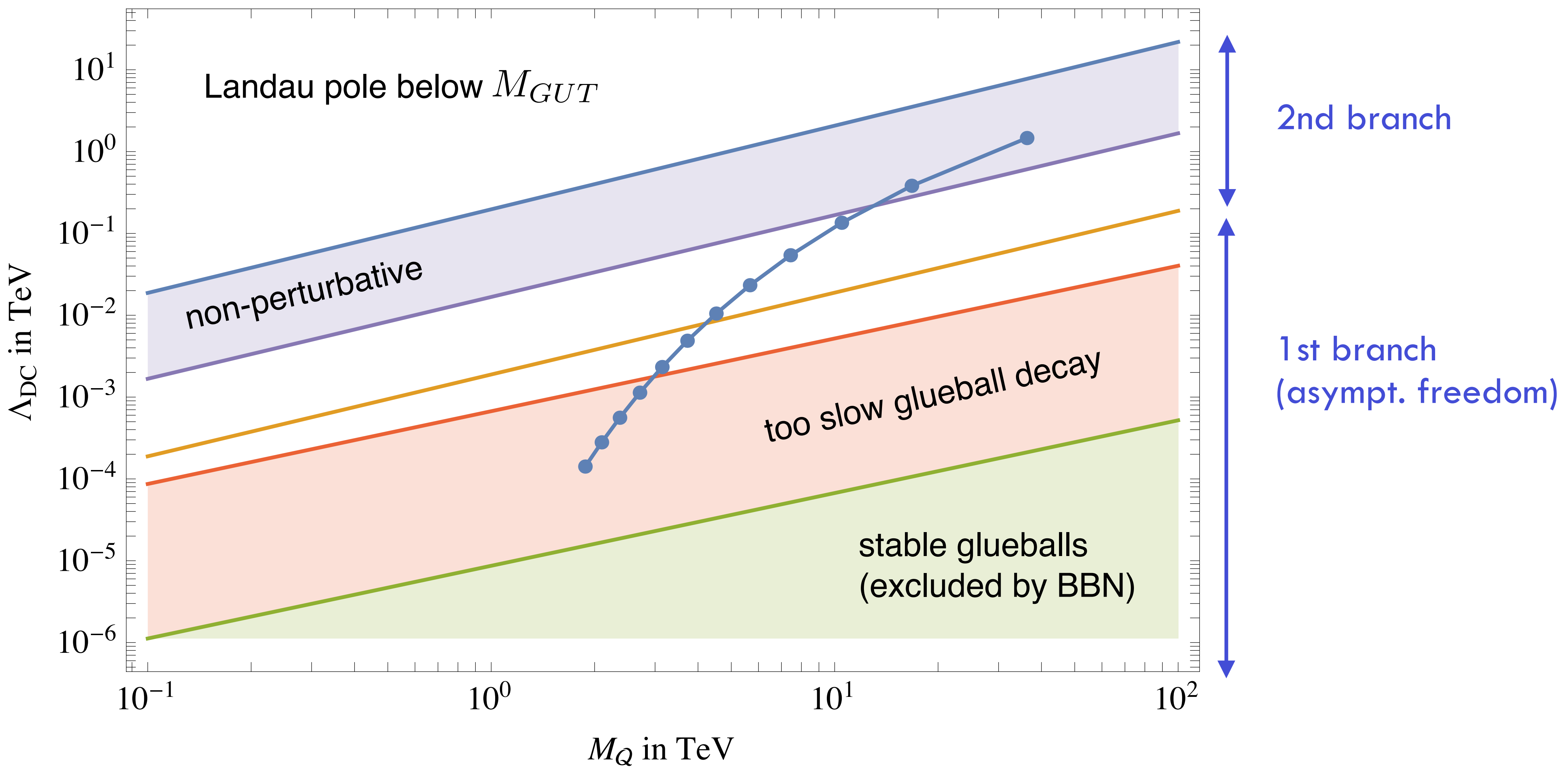
  - *gluequarks decay through dim-6 operators* $\frac{1}{\Lambda_{UV}^2} G_{\mu\nu}\sigma^{\mu\nu} V^i H \sigma^i L_L \qquad \frac{1}{\Lambda_{UV}^2} G_{\mu\nu} N H L_L$

$$\Gamma_\chi \sim \frac{1}{4\pi}\frac{v^2}{\Lambda_{\rm UV}^4} M_Q^3 \sim 10^{-50}\left(\frac{M_Q}{\rm TeV}\right)^3 \left(\frac{10^{15}\,\rm GeV}{\Lambda_{\rm UV}}\right)^4 \rm TeV$$

cosmologically stable

  - *glueballs decay through dim-8 operators* $\frac{1}{M_Q^4} G_{\mu\nu}^2 W_{\alpha\beta}^2$

Preliminary results



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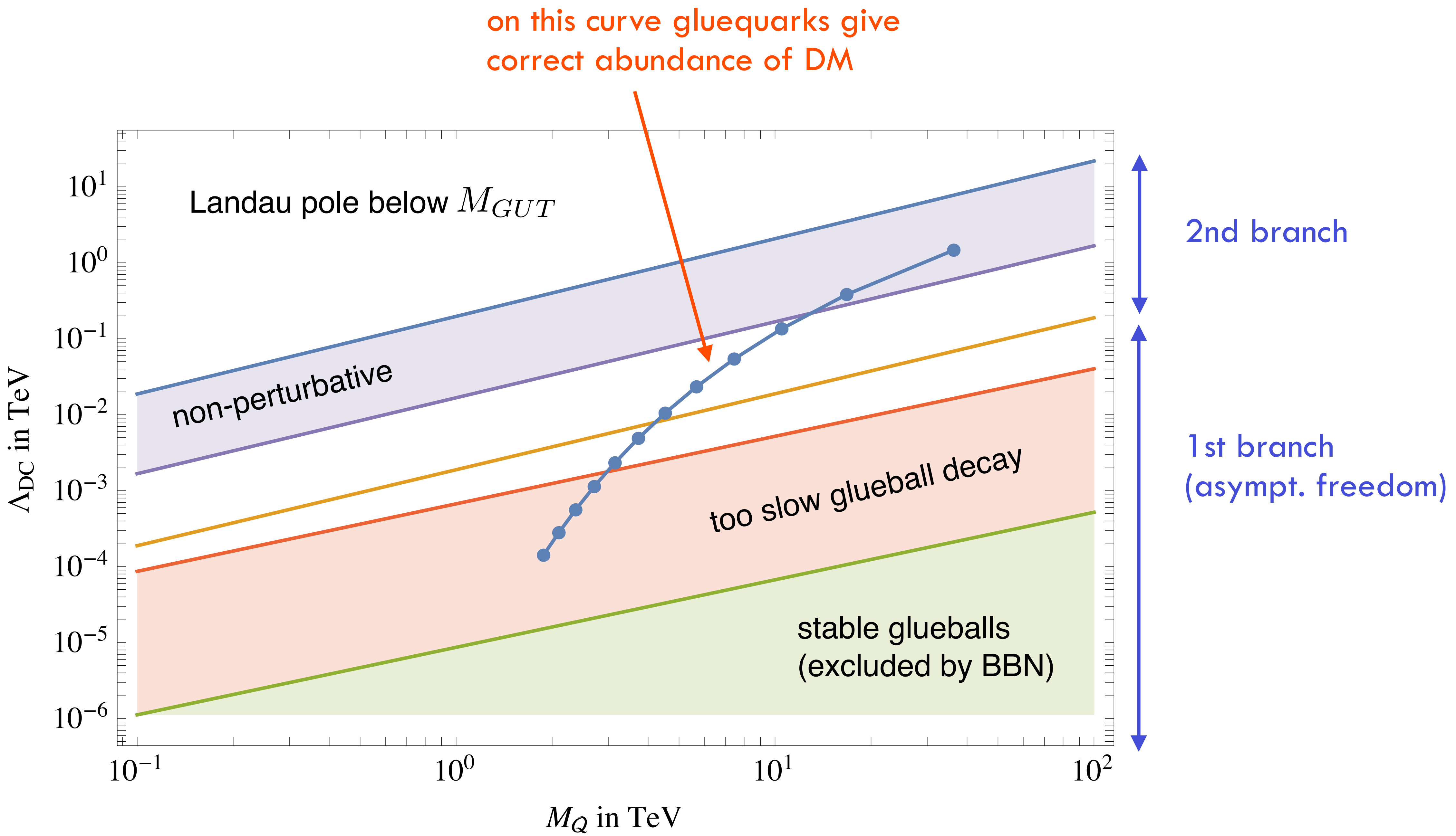

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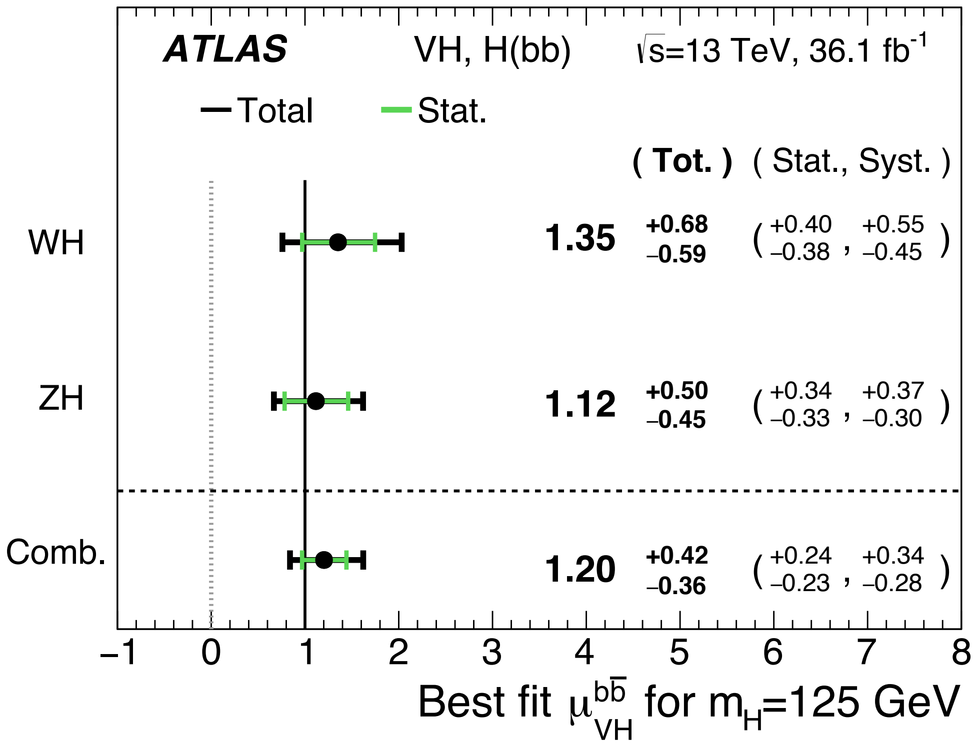

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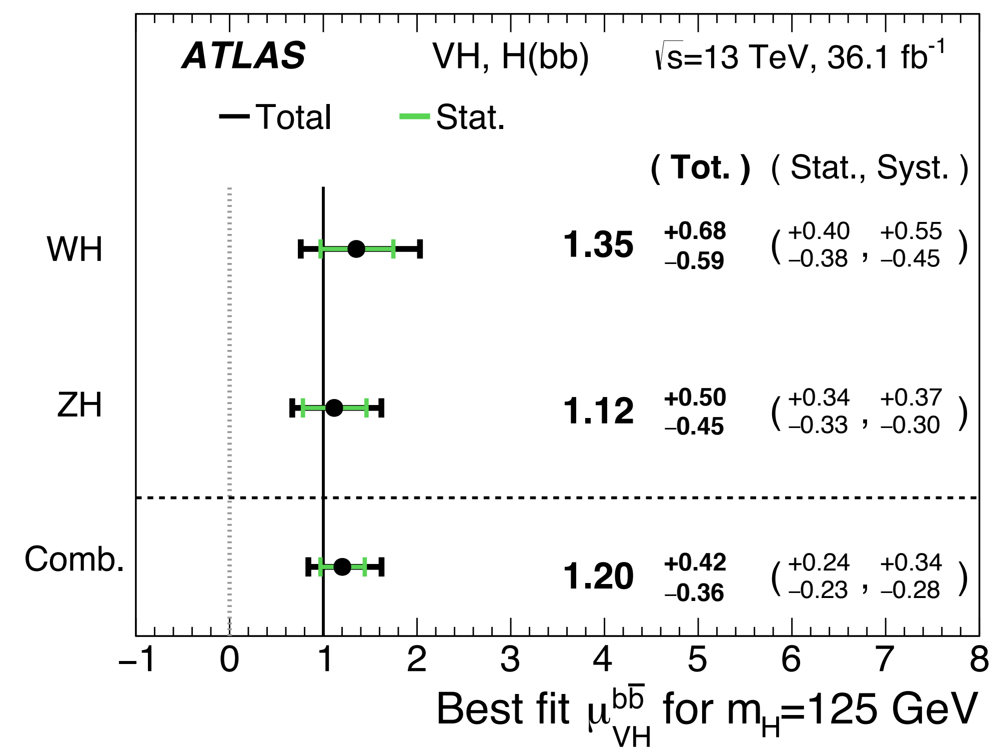

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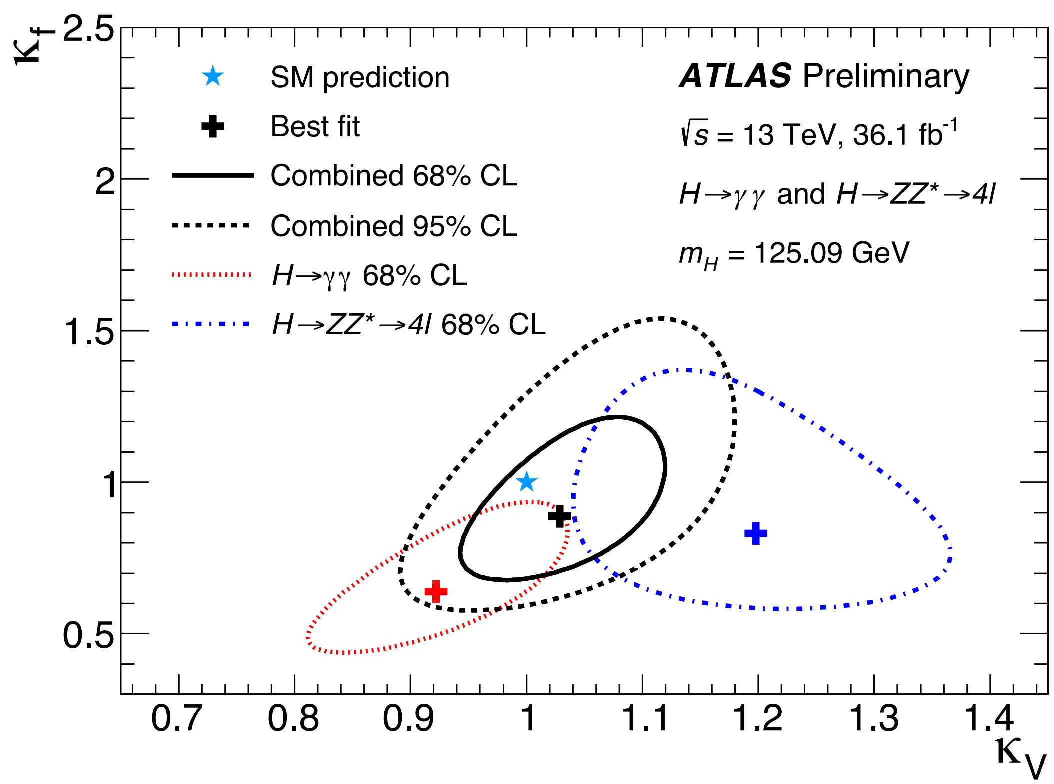
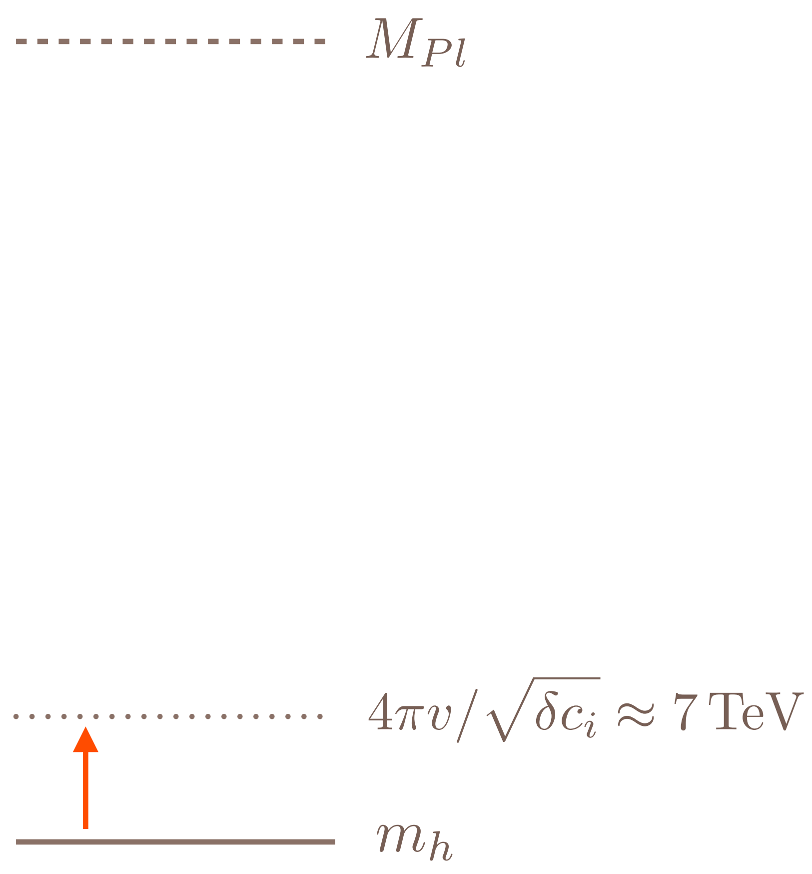
☞ In general, couplings still constrained at the ~20% level



How far can can we extrapolate our theory



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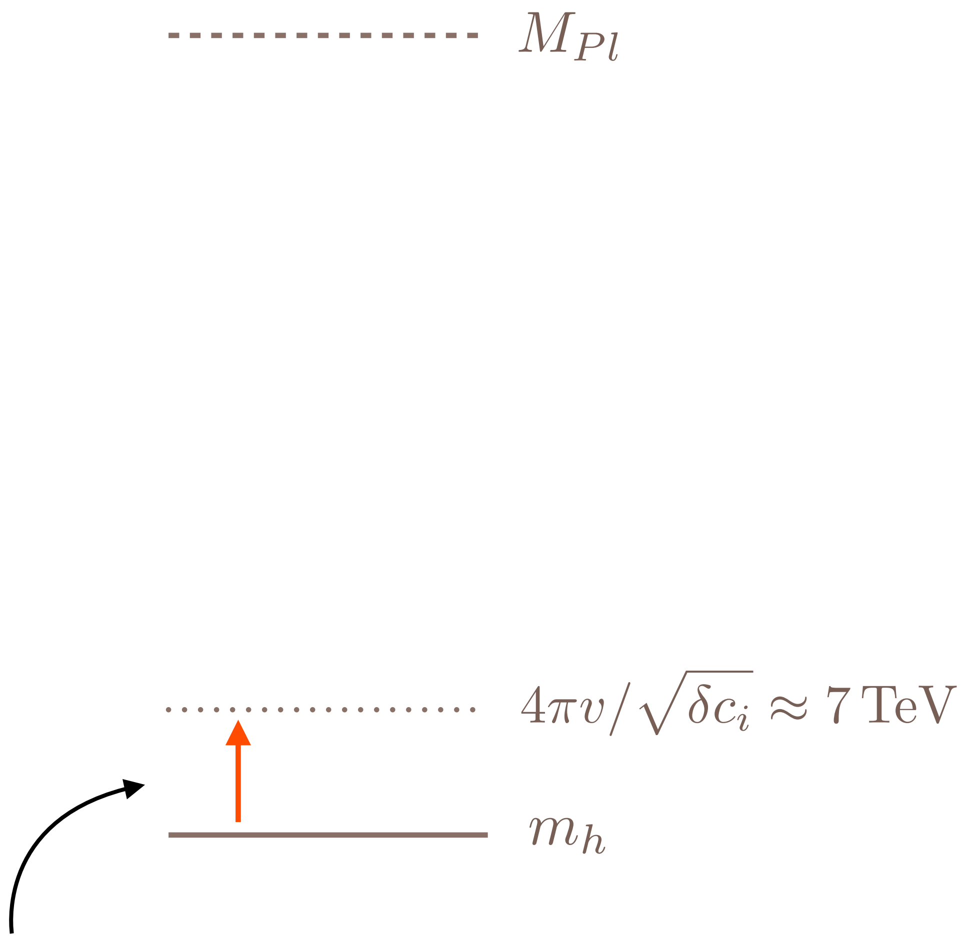

With current knowledge of the Higgs couplings ($\delta c_i \lesssim 0.2$) we can extrapolate so much

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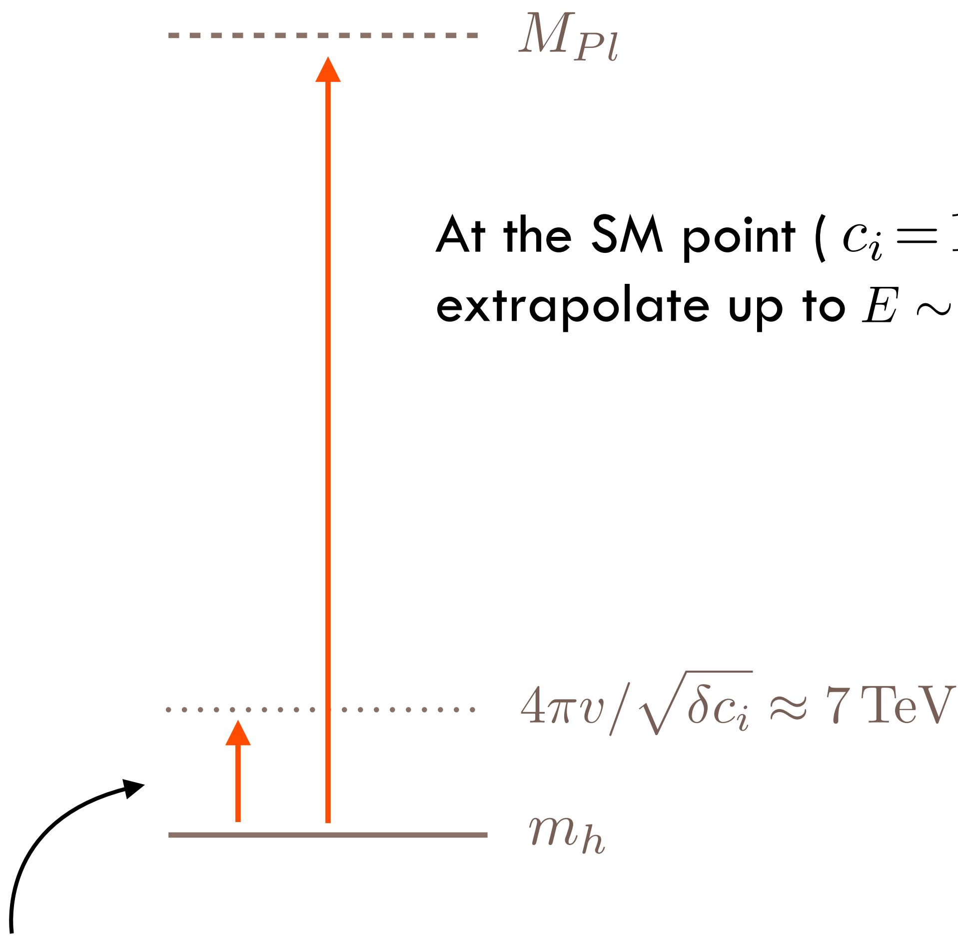
Residual $\log E$ dependence of gauge couplings and Higgs trilinear coupling

$$\frac{d\lambda_4}{d\log E} = \frac{\beta_\lambda}{16\pi^2}\lambda_4^2 + \frac{\beta_t}{16\pi^2}y_t^4 = \beta(\lambda_4, y_t)$$



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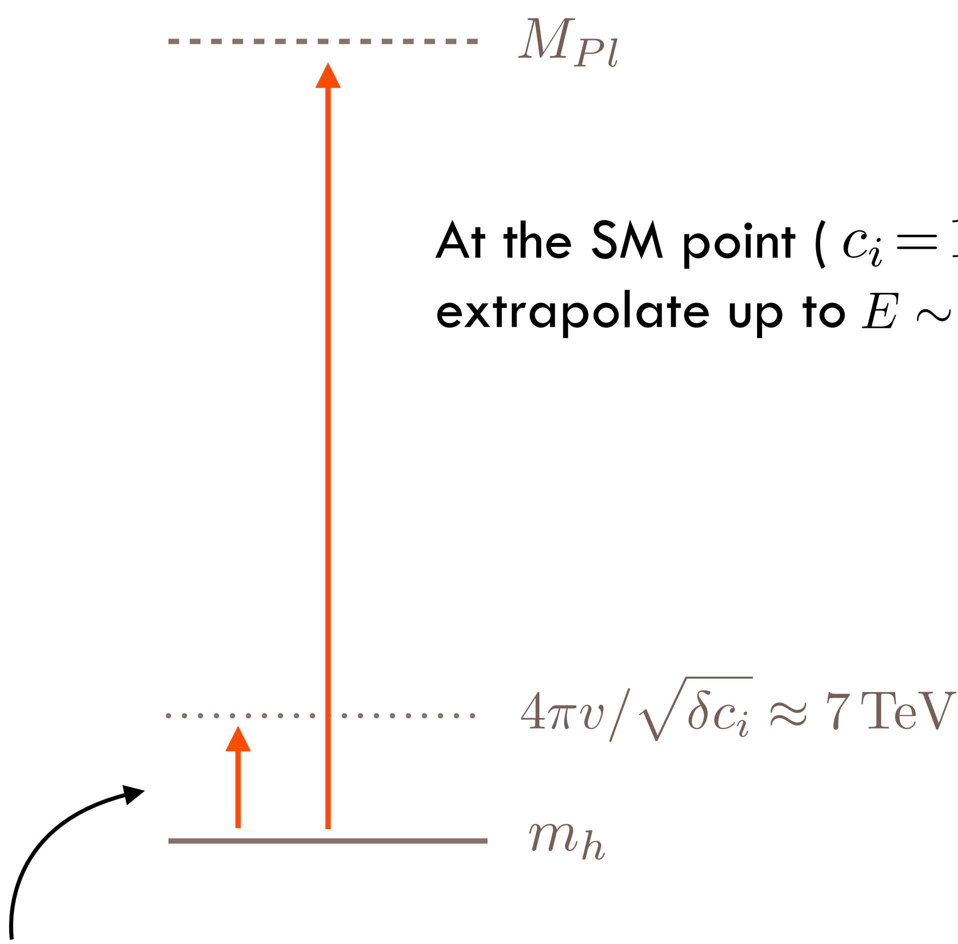

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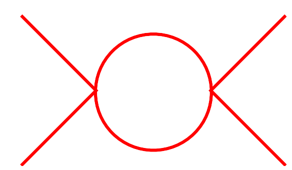

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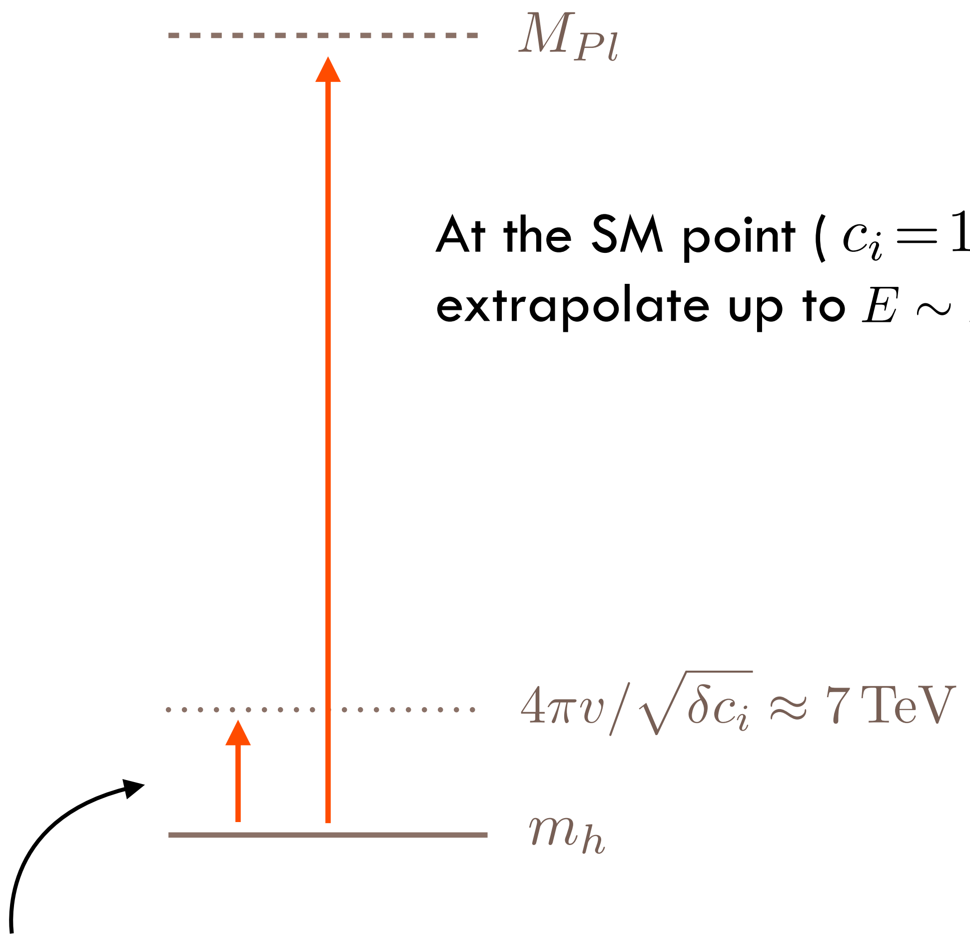

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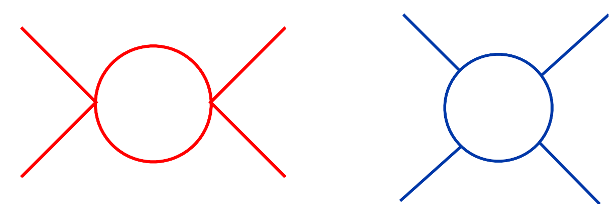

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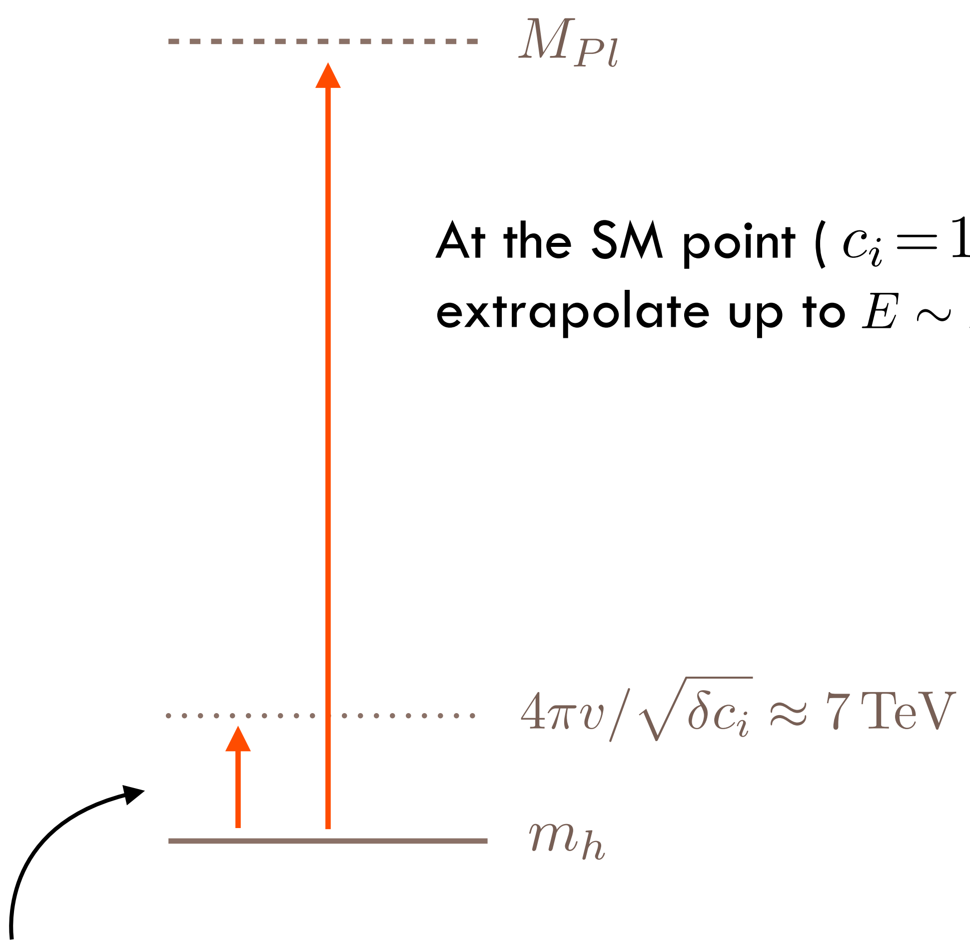

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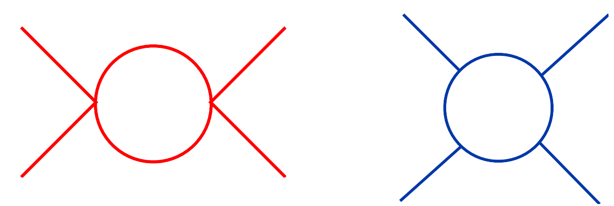
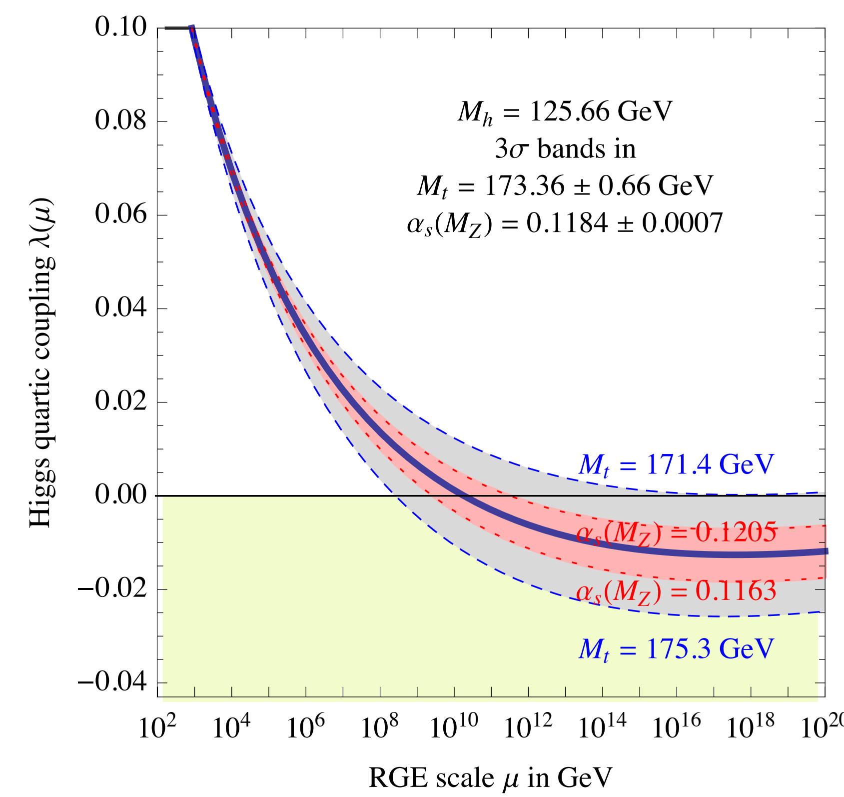


For $m_h = 125\,\mathrm{GeV}$ $\Longrightarrow$ λ_4 remains weak



from: G. Degrassi et al. JHEP 1208 (2012) 098

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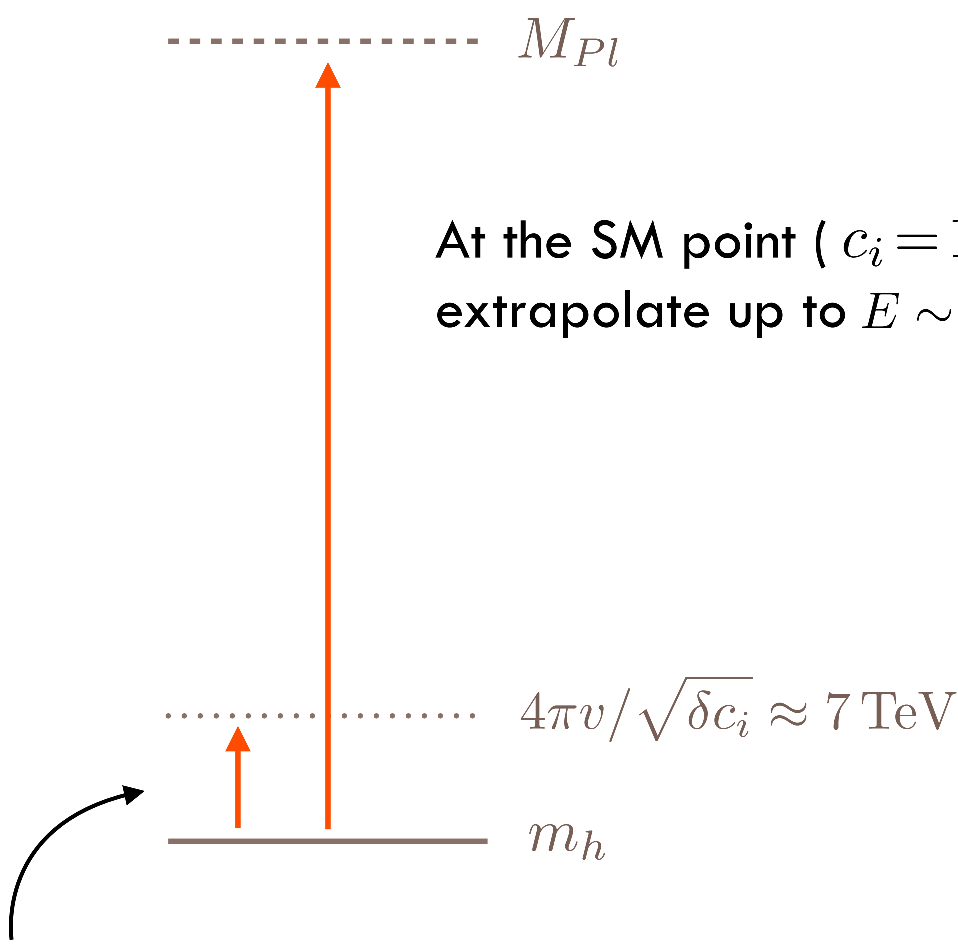

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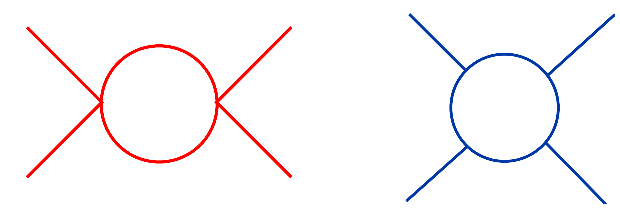

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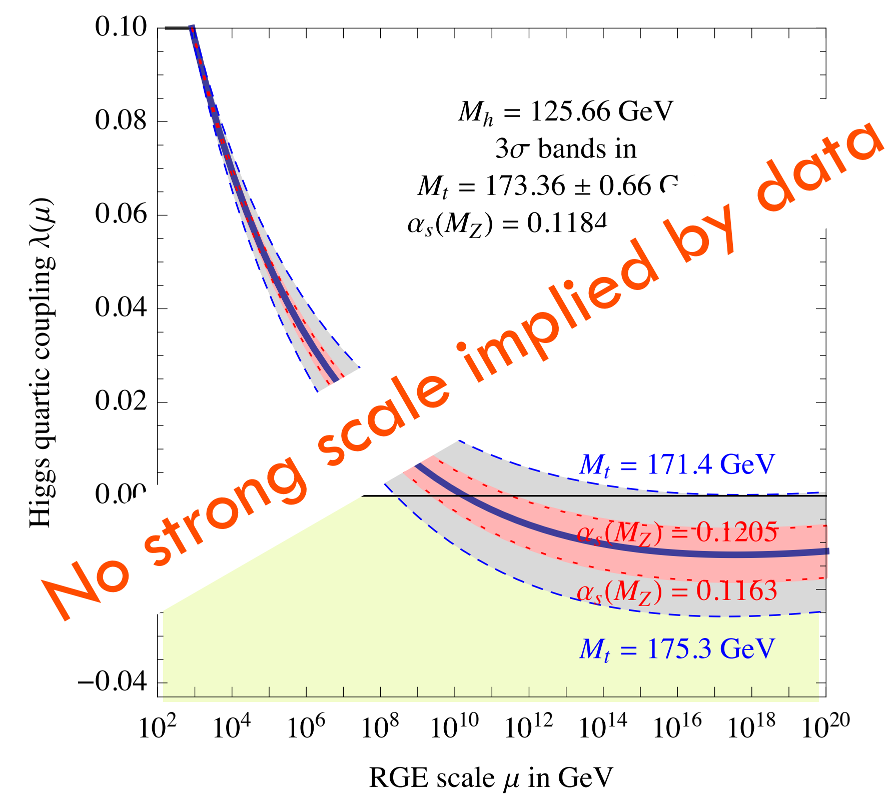

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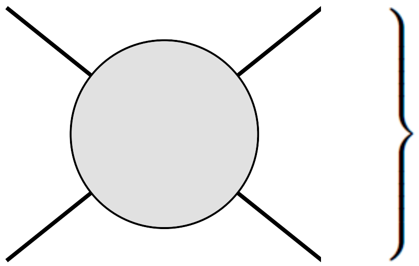
Future directions: probing directly strong dynamics through 2→2 scatterings

- On-shell single-Higgs production and decay give information at fixed scale $Q = m_h$ and constrain *indirectly* the strength of new dynamics

$$\frac{\delta c}{c} \sim \frac{g_*^2}{g_{SM}^2} \frac{m_h^2}{\Lambda^2}$$

- 2→2 scattering processes probe *directly* the strength of SSB dynamics at energies $E \gg m_h$



$E \gg m_h$

$$\frac{\delta \mathcal{A}}{\mathcal{A}} \sim \frac{g_*^2}{g_{SM}^2} \frac{E^2}{\Lambda^2}$$

Examples:
- $q\bar{q} \to WV\,(\mathrm{TGC}) + HV \qquad (V = W, Z)$
- Vector boson scattering $VV \to VV$
- Double Higgs production $gg \to HH$
- H+jet associated production

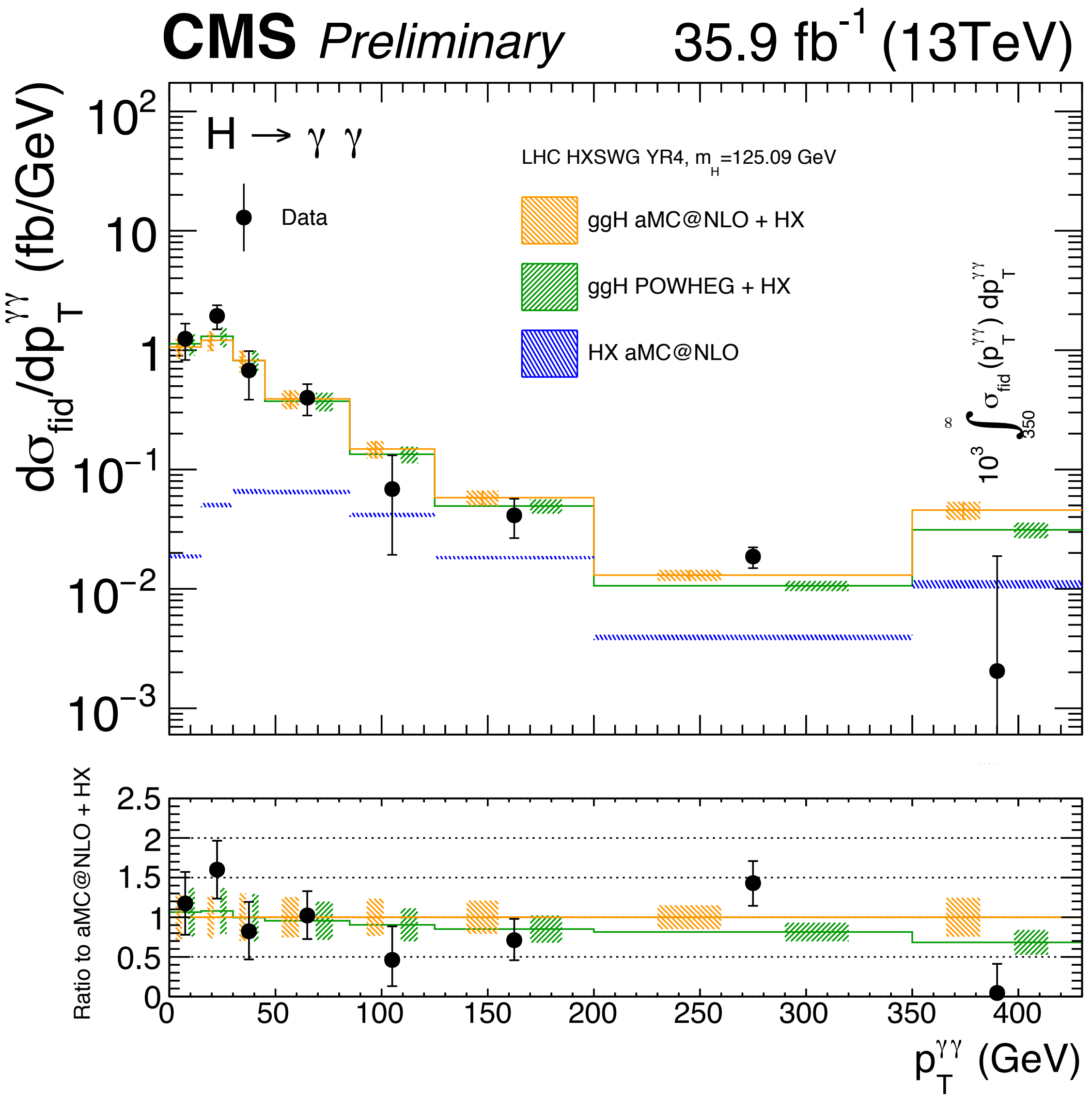
$\vdots$

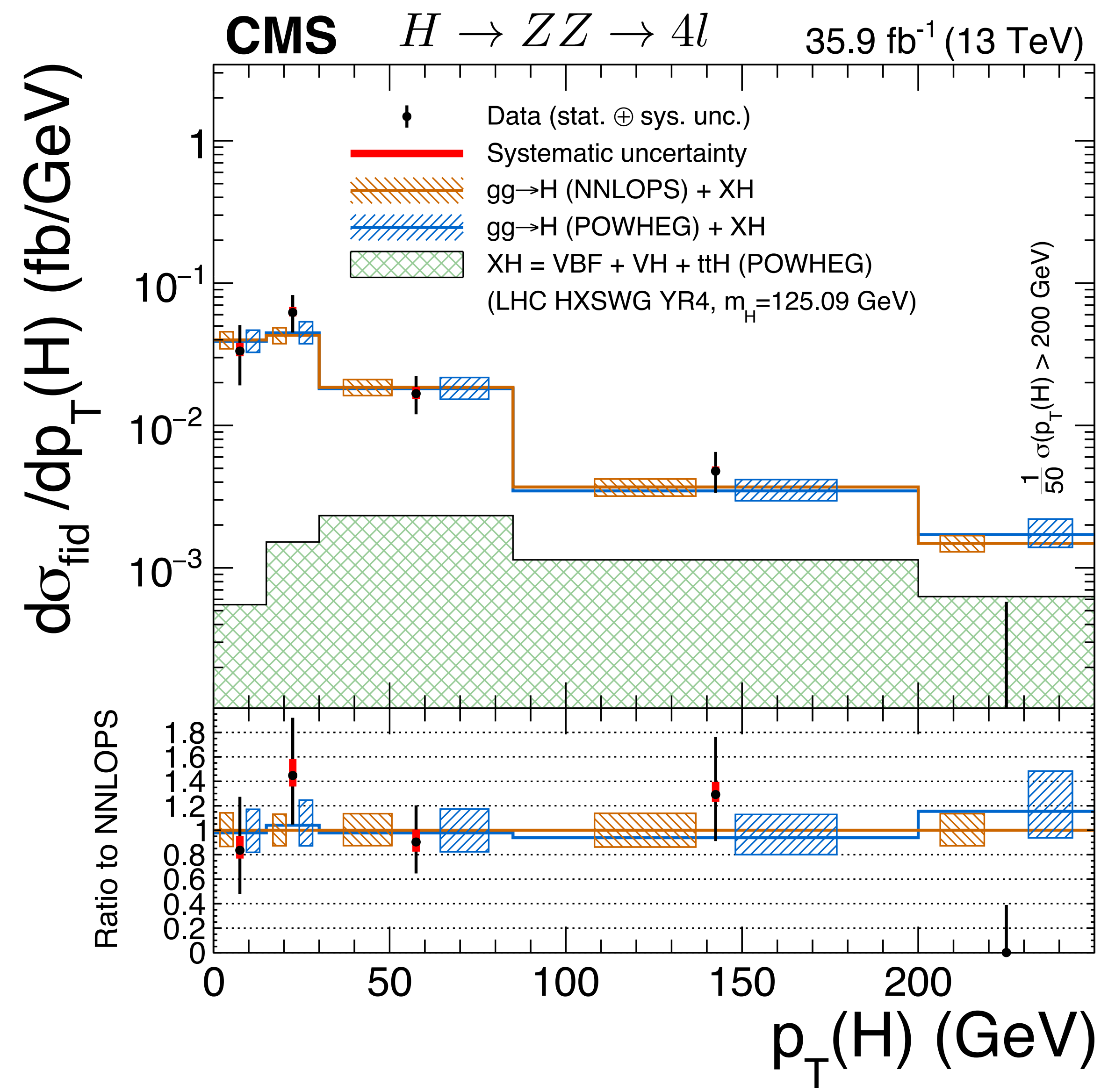
Sensitivity to NP maximized at large energy (tails of distributions)

☞ challenge for EFT validity

- First (quantitative) results in this direction have arrived from LHC Run2

Example: Higgs transverse momentum in $h \to \gamma\gamma, ZZ(\to 4l)$





Future directions: measuring the Higgs trilinear coupling

- Higgs self-interaction is the last elusive coupling to be measured, and could be our 'portal' to strong dynamics

  Ex: *shifts of O(1) in λ_3 still possible with underlying strong dynamics compatibly with small deviations in other couplings*

  see for ex: Azatov, R.C., Panico, Son, PRD92 (2015) 035001

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- Ultimate measurement of Higgs trilinear will require future machines

FCC 100TeV with L=30ab^{-1}

$pp \to hh \to \gamma\gamma bb$

systematic uncertainty on signal

background rescaling factor

$\Delta\lambda_3/\lambda_3$	$\Delta_S = 0.00$	$\Delta_S = 0.01$	$\Delta_S = 0.015$	$\Delta_S = 0.02$	$\Delta_S = 0.025$
$r_B = 0.5$	2.7%	3.4%	4.1%	4.9%	5.8%
$r_B = 1.0$	3.4%	3.9%	4.6%	5.3%	6.1%
$r_B = 1.5$	3.9%	4.4%	5.0%	5.7%	6.4%
$r_B = 2.0$	4.4%	4.8%	5.4%	6.0%	6.8%
$r_B = 3.0$	5.2%	5.6%	6.0%	6.6%	7.3%

from: R.Contino et al. '*Physics at a 100TeV pp collider: Higgs and EWSB studies*'

Conclusions

- Standard Model paradigm based on large energy gap and accidental symmetries has been surprisingly successful so far

- Maintaining its philosophy, even at the cost of renouncing to Naturalness could be the right strategy to go beyond the SM and account for unexplained experimental facts (DM, baryogenesis) and suggestive hints (ex: gauge coupling unification)

- Gauge theories characterized by simplicity in the UV and fascinating complexity in the IR. Many models and variants have been constructed, yet many other interesting ones can be still be identified

- Besides EWSB, strong dynamics can play a key role also in the description of Dark Matter

Extra slides

	com Energy	Precision	Process	Reference
ILC	$500\,\mathrm{GeV}$ $[L = 500\,\mathrm{fb}^{-1}]$	$\Delta c_3 \sim 104\%$	DHS	ILC TDR, Volume 2, arXiv:1306.6352
	$1\,\mathrm{TeV}$ $[L = 1\,\mathrm{ab}^{-1}]$	$\Delta c_3 \sim 28\%$	VBF	ILC TDR, Volume 2, arXiv:1306.6352
		$\Delta c_{2V} \sim 20\%$	DHS	RC, Grojean, Pappadopulo, Rattazzi and Thamm, JHEP 1402 (2014) 006
CLIC	$1.4\,\mathrm{TeV}$ $[L = 1.5\,\mathrm{ab}^{-1}]$	$\Delta c_3 \sim 24\%$	VBF	P. Roloff (CLICdp Coll.), talk at LCWS14
		$\Delta c_{2V} \sim 7\%$		
	$3\,\mathrm{TeV}$ $[L = 2\,\mathrm{ab}^{-1}]$	$\Delta c_3 \sim 12\%$		
		$\Delta c_{2V} \sim 3\%$		