The CLIC Physics Potential

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Ideology

HEP before the LHC

HEP before the F.C.

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Naturalness
EW-B.Gen
D.M.
Dark Sectors
Flavour
ν-Mass
Strong CP
Quantum Gravity

?

Ideology

HEP before the LHC

HEP before the F.C.

Particle physics is not **validation** anymore, rather it is **exploration of unknown territories ***

* Not necessarily a bad thing. Columbus left for his trip just because he had no idea of where he was going !!

Indirect Exploration

Measuring and comparing with SM predictions is a **systematic, BSM-independent exploration strategy**

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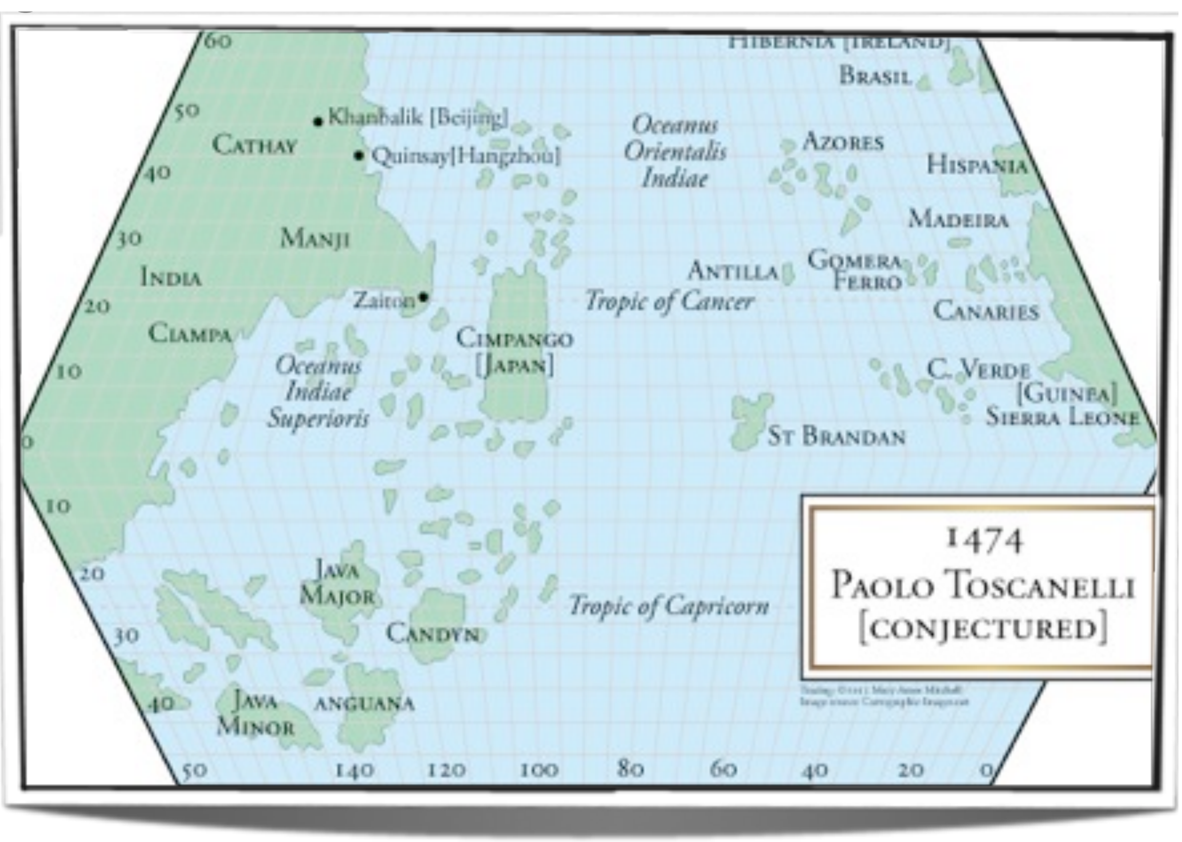

Columbus had Toscanelli's map.

It was terribly **wrong**, but **served the purpose**

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If N.P. is heavy, **EFT map:**

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{BSM}}^{d=6}$$

operator estimate from structural BSM assumptions. **Different assumptions produce different maps**

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operator estimate from structural BSM assumptions. **Different assumptions produce different maps**

The **Ideal Map:**

N.P **mass:** m_*
N.P **coupling:** g_*

The EFT Map

Dimension-6 operators classified:

Universal

BSM only coupled to SM bosons, negligible direct coupling to fermions

$\mathcal{O}_W = \frac{ig}{2}(\varphi^\dagger \tau^a \overleftrightarrow{D}_\mu \varphi) D^\nu W^a_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{g}{6}\varepsilon^{abc} W_\mu^{a\,\nu} W_\nu^{b\,\rho} W_\rho^{c\,\mu}$
$\mathcal{O}_B = \frac{ig'}{2}(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi) \partial^\nu B_{\mu\nu}$	$\mathcal{O}_T = \frac{1}{2}(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)^2$
$\mathcal{O}_{HW} = ig(D^\mu\varphi)^\dagger \tau^a (D^\nu \varphi) W^a_{\mu\nu}$	$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert\varphi\rvert^2)^2$
$\mathcal{O}_{HB} = ig'(D^\mu\varphi)^\dagger (D^\nu \varphi) B_{\mu\nu}$	$\mathcal{O}_6 = \lambda \lvert\varphi\rvert^6$
$\mathcal{O}_{BB} = g'^2 \lvert\varphi\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_r = \lvert\varphi\rvert^2 \lvert D_\mu \varphi\rvert^2$
$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$	$\mathcal{O}_{K4} = \lvert D^2 \varphi\rvert^2$
$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$	

[Recent discussion in Wells, Zhang, 2015]

The EFT Map

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Top-philic

direct BSM coupling to top. Motivated by Naturalness and flavour.

$Q_{\varphi t} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$
$\mathcal{N}_{tB} = (\bar{t}\gamma^\mu t)(\bar{e}\gamma_\mu e + \frac{1}{2}\bar{l}\gamma_\mu l)$
$Q_{t\varphi} = (\varphi^\dagger \varphi)(\bar{q}\, t\, \widetilde{\varphi})$
$Q_{tB} = (\bar{q}\sigma^{\mu\nu} t)\widetilde{\varphi} B_{\mu\nu}$
$Q^{(1)}_{\varphi q} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q)$
$Q^{(3)}_{\varphi q} = (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}\, \tau^I \gamma^\mu q)$
$Q_{tW} = (\bar{q}\sigma^{\mu\nu} t)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$
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direct BSM coupling to top. Motivated by Naturalness and flavour.

Flavour-breaking
light fermion couplings in BSM, such that not excluded by flavour physics.
To be studied by examples, or on the basis of motivated flavour models

The Energy and Accuracy Frontier

EFT

$\mathcal{L}^{d=6}$

Low-Energy: $\Delta\mathcal{O}/\mathcal{O} \sim m_{\mathrm{EW}}^2/\Lambda^2$

High-Energy: $\Delta\mathcal{O}/\mathcal{O} \sim E^2/\Lambda^2$

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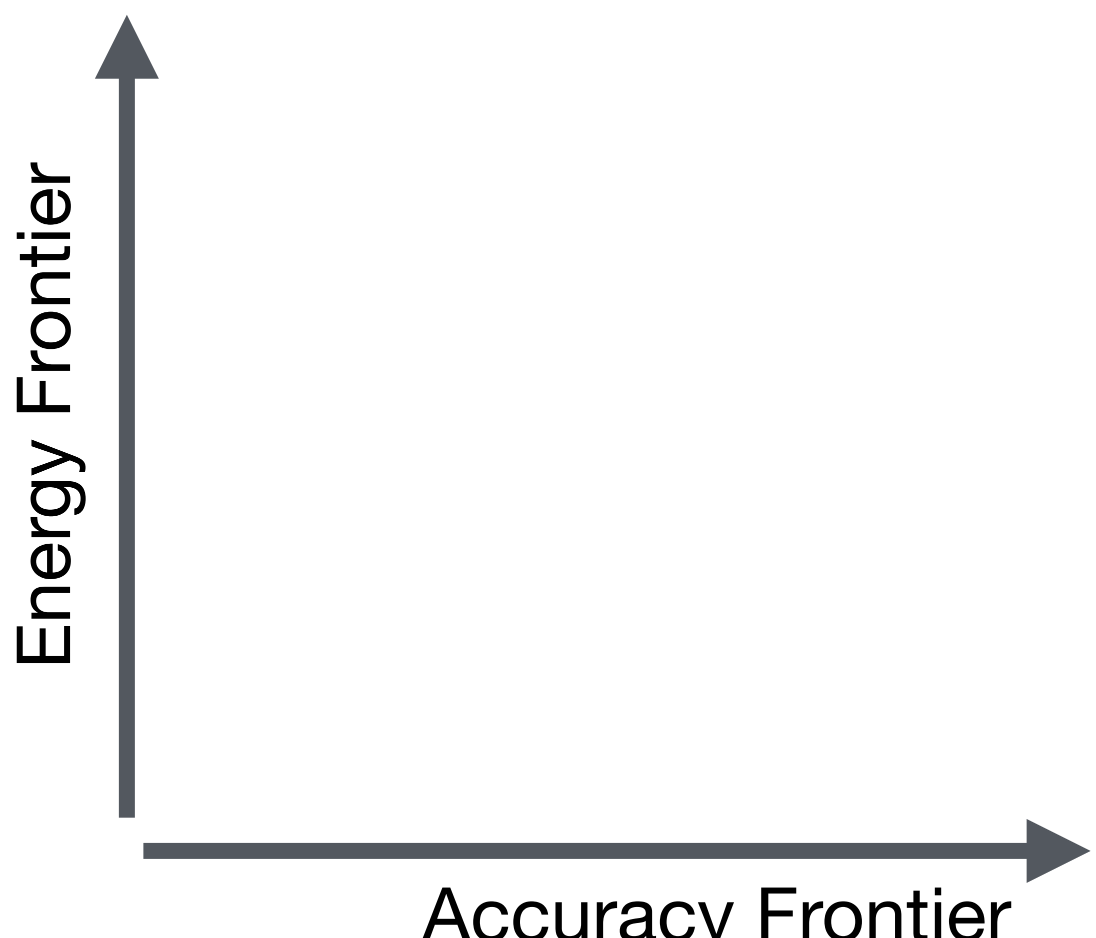

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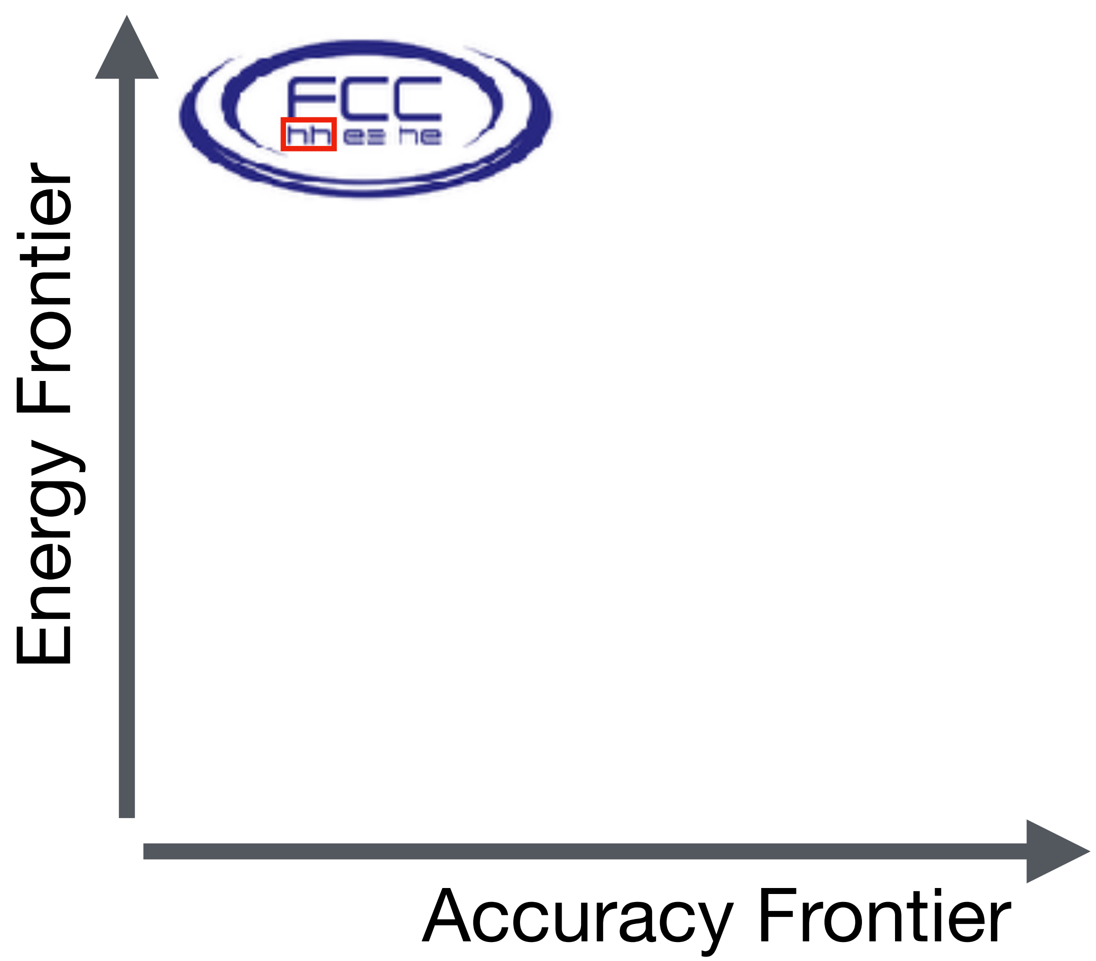

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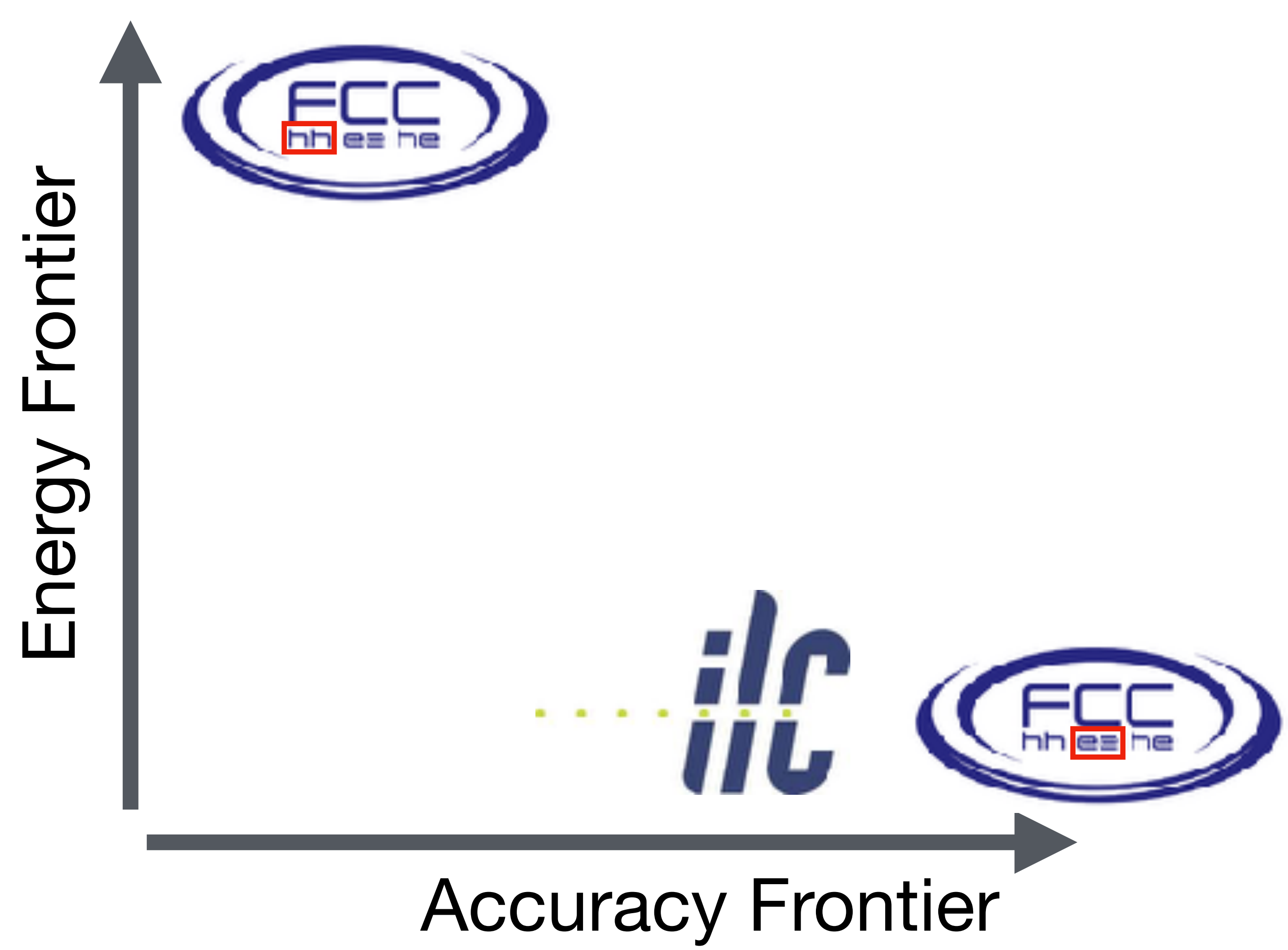

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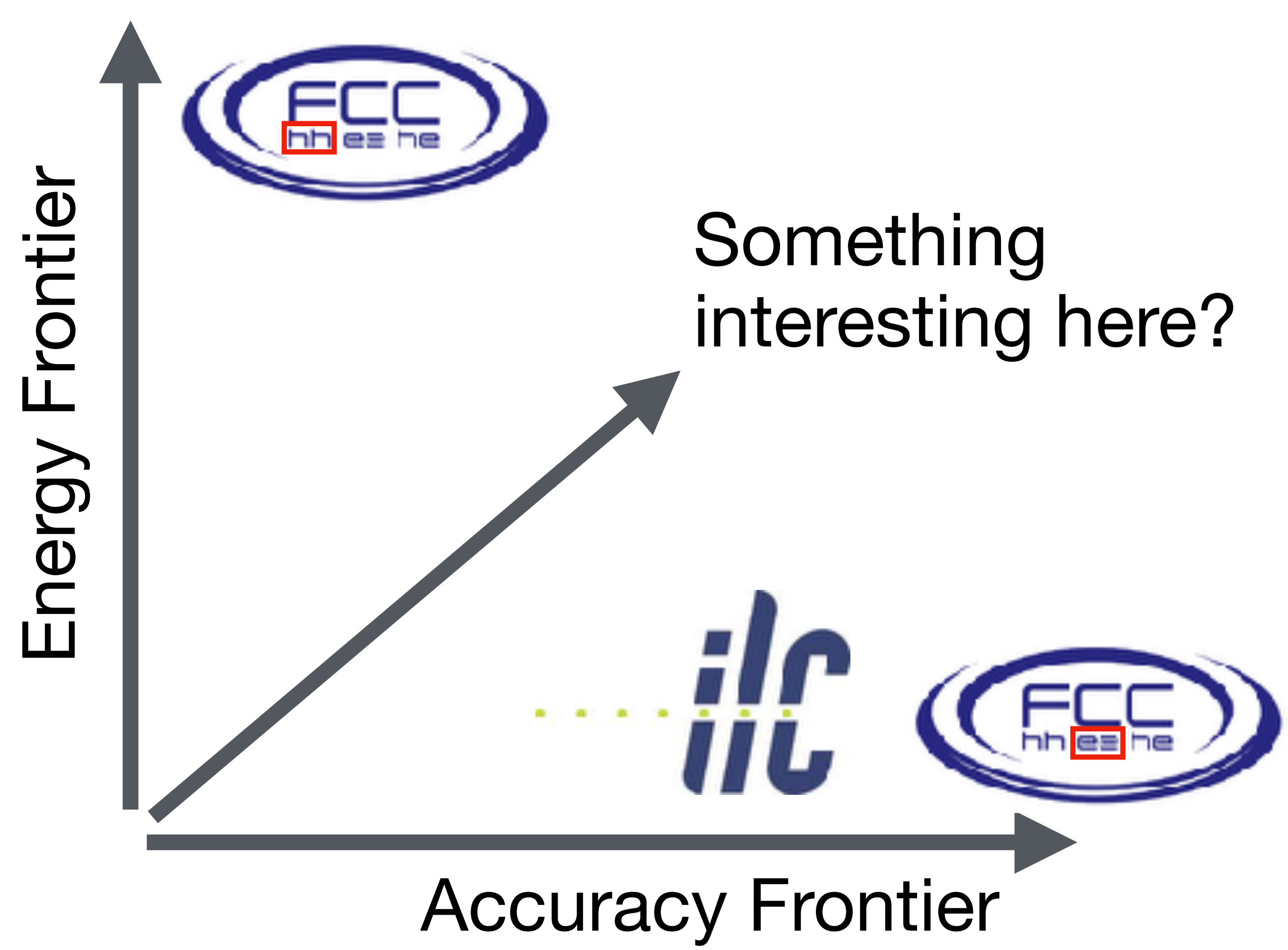

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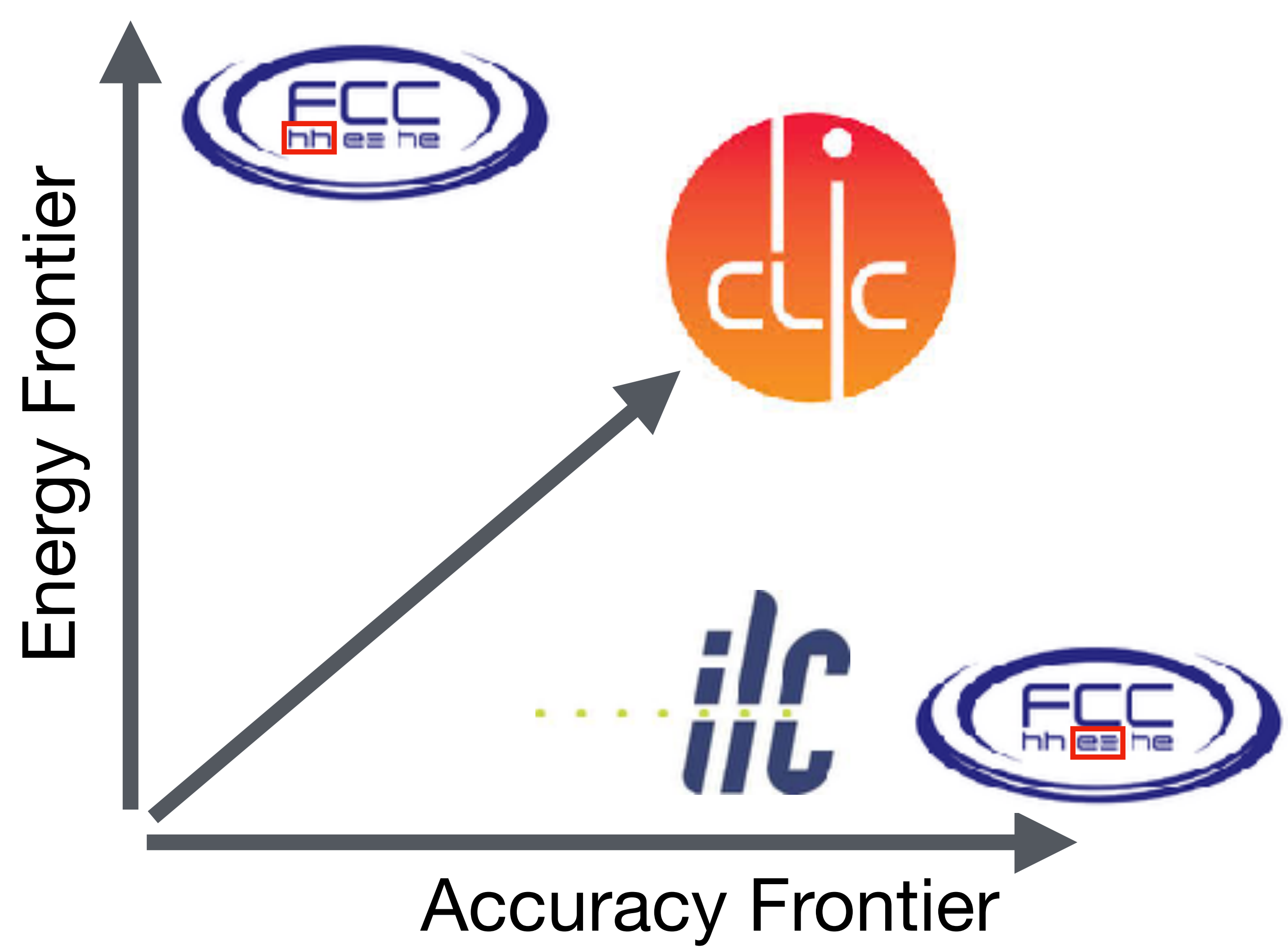

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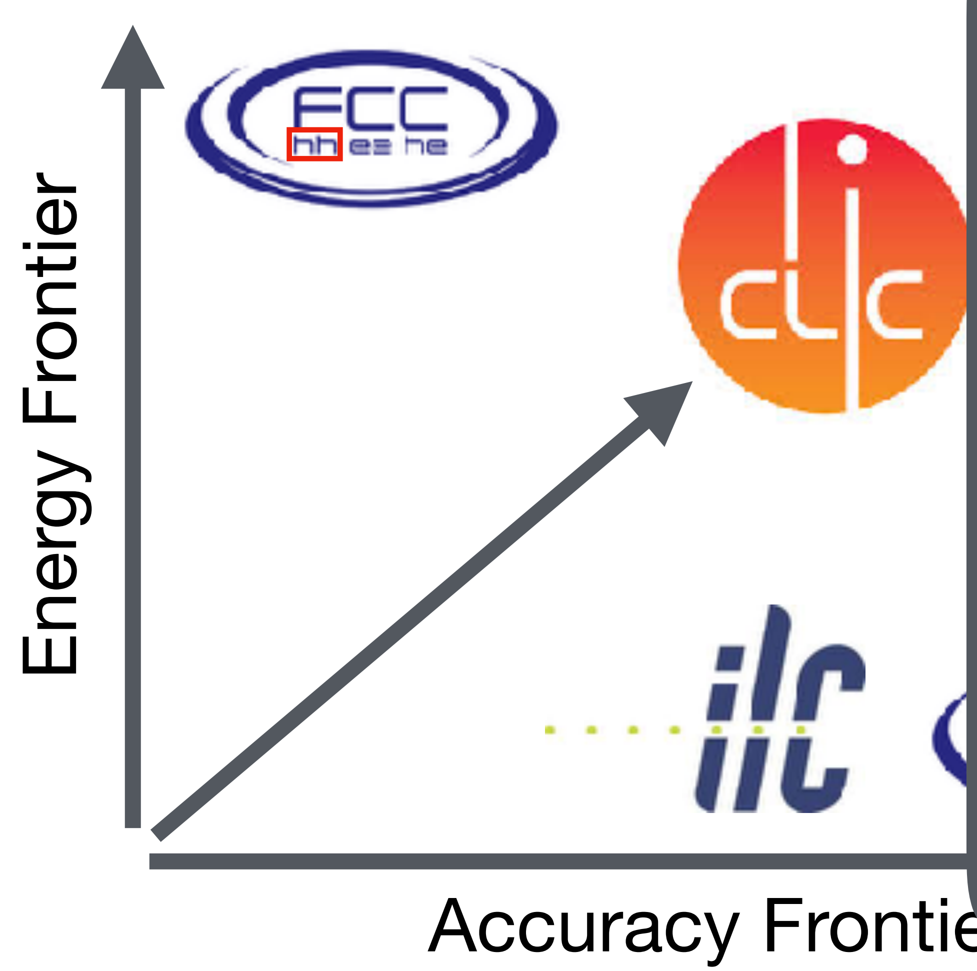


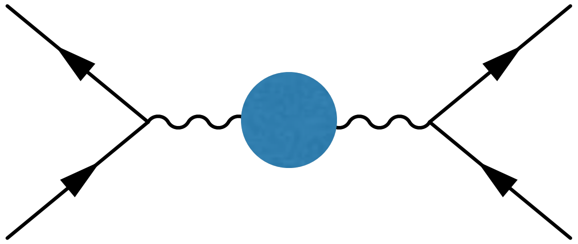
NOTICE THAT

H-E probes are **unique** of CLIC, but CLIC also **effective** on **L-E** ones

For instance:

- Higgs couplings at few ‰
- Higgs 3-linear at 10%
- Top mass at 0.5 ‰
- Top EW couplings < %
- ……

High-Energy Drell—Yan



Simplest EW process: Drell-Yan (l+l- or qq)

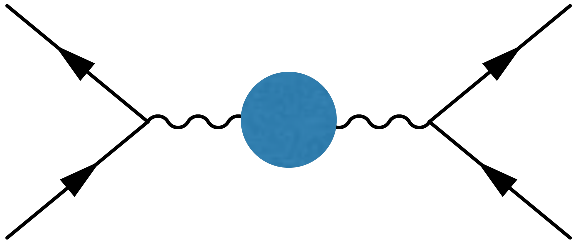
Simplest BSM effects: Oblique corrections (Universal d=6)

$$P_N = \begin{bmatrix} \frac{1}{q^2} - \frac{t^2 \mathrm{W} + \mathrm{Y}}{m_Z^2} & \frac{t\left(\left(\mathrm{Y}+\hat{\mathrm{T}}\right)c^2 + s^2\mathrm{W} - \hat{\mathrm{S}}\right)}{(c^2-s^2)\left(q^2-m_Z^2\right)} + \frac{t(\mathrm{Y}-\mathrm{W})}{m_Z^2} \\ \star & \frac{1+\hat{\mathrm{T}}-\mathrm{W}-t^2\mathrm{Y}}{q^2-m_Z^2} - \frac{t^2\mathrm{Y}+\mathrm{W}}{m_Z^2} \end{bmatrix}$$

$\hat{\mathrm{S}}$ and $\hat{\mathrm{T}}$: only affect pole residues, no energy growth in this process.
Best studied on Z-pole (LEP did ‰)

W and Y: produce constant terms.
Quadratically enhanced at high mass.

High-Energy Drell—Yan



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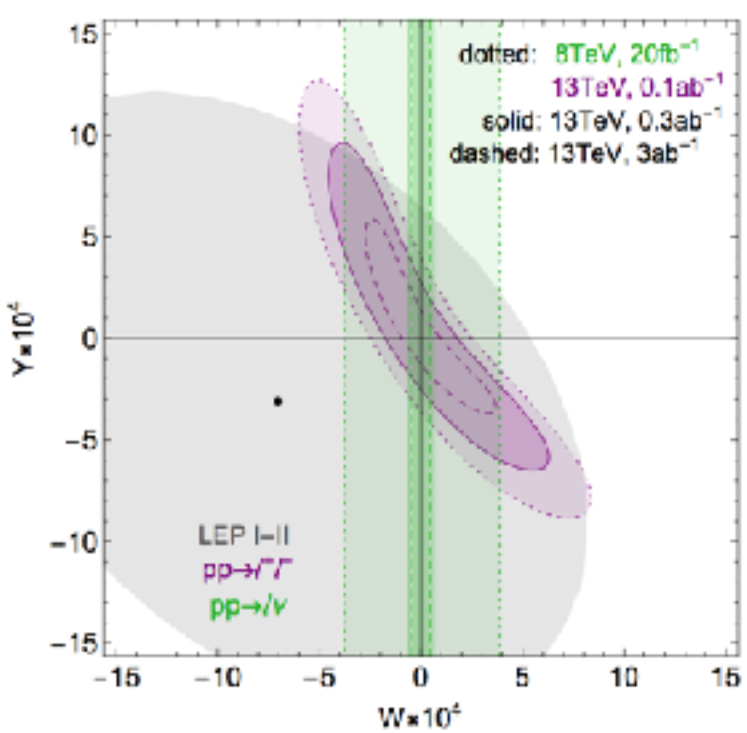

HL-LHC reach: $\begin{cases} Y \times 10^4 = \pm 1.2 \\ W \times 10^4 = \pm 0.45 \end{cases}$

CLIC reach: $\begin{cases} Y \times 10^4 = \pm 0.1 \\ W \times 10^4 = \pm 0.1 \end{cases}$

Could probe **~20 TeV BSM scale**

High-Energy Dibosons

W/Y limits **easily evaded** (e.g., by strongly-coupled SILH):

$$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \quad -\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2 \qquad \sim \quad \frac{g_W^2}{g_*^2}\cdot\frac{1}{m_*^2}$$

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Some un-suppressed Universal operators: $\sim 1/m_*^2$ (SILH-basis coefficient)

$$\begin{aligned}
\mathcal{O}_W &= \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}\\
\mathcal{O}_B &= \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}\\
\mathcal{O}_{HW} &= ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}\\
\mathcal{O}_{HB} &= ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}
\end{aligned}$$

SILH basis

$$\begin{aligned}
\mathcal{O}_L^{(3)} &= (\bar{Q}_L\sigma^a\gamma^\mu Q_L)(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)\\
\mathcal{O}_L &= (\bar{Q}_L\gamma^\mu Q_L)(iH^\dagger \overleftrightarrow{D}_\mu H)\\
\mathcal{O}_R^u &= (\bar{u}_R\gamma^\mu u_R)(iH^\dagger \overleftrightarrow{D}_\mu H)\\
\mathcal{O}_R^d &= (\bar{d}_R\gamma^\mu d_R)(iH^\dagger \overleftrightarrow{D}_\mu H)
\end{aligned}$$

Warsaw basis

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SILH basis		Warsaw basis
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$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$ $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$		$\mathcal{O}_R^u = (\bar{u}_R\gamma^\mu u_R)(iH^\dagger \overleftrightarrow{D}_\mu H)$ $\mathcal{O}_R^d = (\bar{d}_R\gamma^\mu d_R)(iH^\dagger \overleftrightarrow{D}_\mu H)$

$\Downarrow$

Growing-with-energy longitudinal diboson and boson plus Higgs prod.

High-Energy Dibosons

Three growing-with-energy effects (operators).[Franceschini, Panico, Pomarol, Riva, AW]

Amplitude	High-energy primaries	Deviations from SM couplings
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2}\frac{g^2\Lambda^2}{4m_W^2}\left[c_{\theta_W}(\boldsymbol{\delta g_{uL}^Z} - \boldsymbol{\delta g_{dL}^Z})/g - c_{\theta_W}^2 \boldsymbol{\delta g_1^Z}\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{g^2\Lambda^2}{2m_W^2}\left[Y_L t_{\theta_W}^2 \boldsymbol{\delta\kappa_\gamma} + T_Z^{u_L}\boldsymbol{\delta g_1^Z} + c_{\theta_W}\boldsymbol{\delta g_{dL}^Z}/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{g^2\Lambda^2}{2m_W^2}\left[Y_L t_{\theta_W}^2 \boldsymbol{\delta\kappa_\gamma} + T_Z^{d_L}\boldsymbol{\delta g_1^Z} + c_{\theta_W}\boldsymbol{\delta g_{uL}^Z}/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{g^2\Lambda^2}{2m_W^2}\left[Y_{f_R} t_{\theta_W}^2 \boldsymbol{\delta\kappa_\gamma} + T_Z^{f_R}\boldsymbol{\delta g_1^Z} + c_{\theta_W}\boldsymbol{\delta g_{fR}^Z}/g\right]$

Two of which independent (and same for q and l) for Universal theories

HL-LHC has some sensitivity to one of them:

$$a_q^{(3)} \sim \pm 5 \times 10^{-2}\mathrm{TeV}^{-2}$$

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$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{g^2\Lambda^2}{2m_W^2}\left[Y_{f_R} t^2_{\theta_W}\boldsymbol{\delta\kappa_\gamma} + T_Z^{f_R}\boldsymbol{\delta g^Z_1} + c_{\theta_W}\boldsymbol{\delta g^Z_{fR}}/g\right]$

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CLIC with **polarised beams** sensitive to **all of them:**

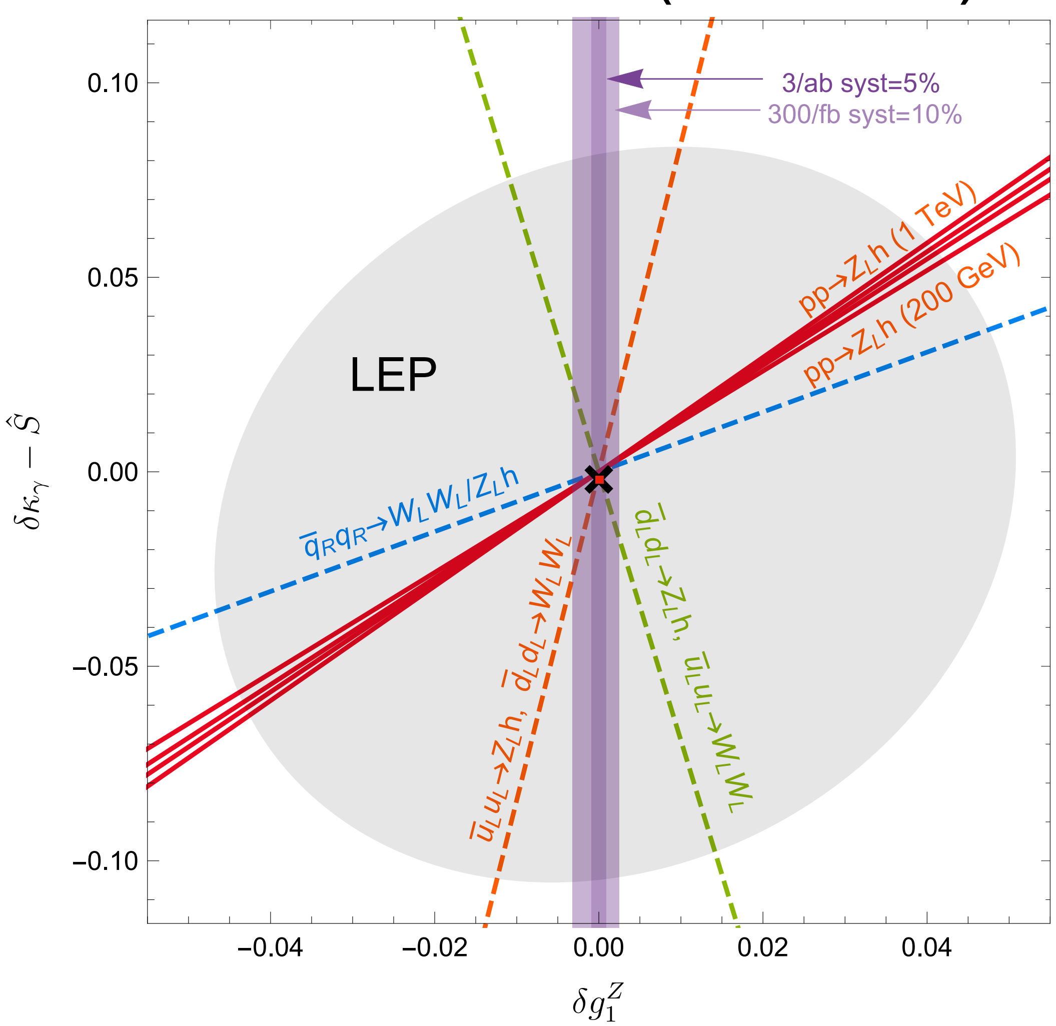
[from Ellis, Roloff, Sanz, You, 2017]

$$a \sim \pm 3 \times 10^{-3}\,\mathrm{TeV}^{-2}$$

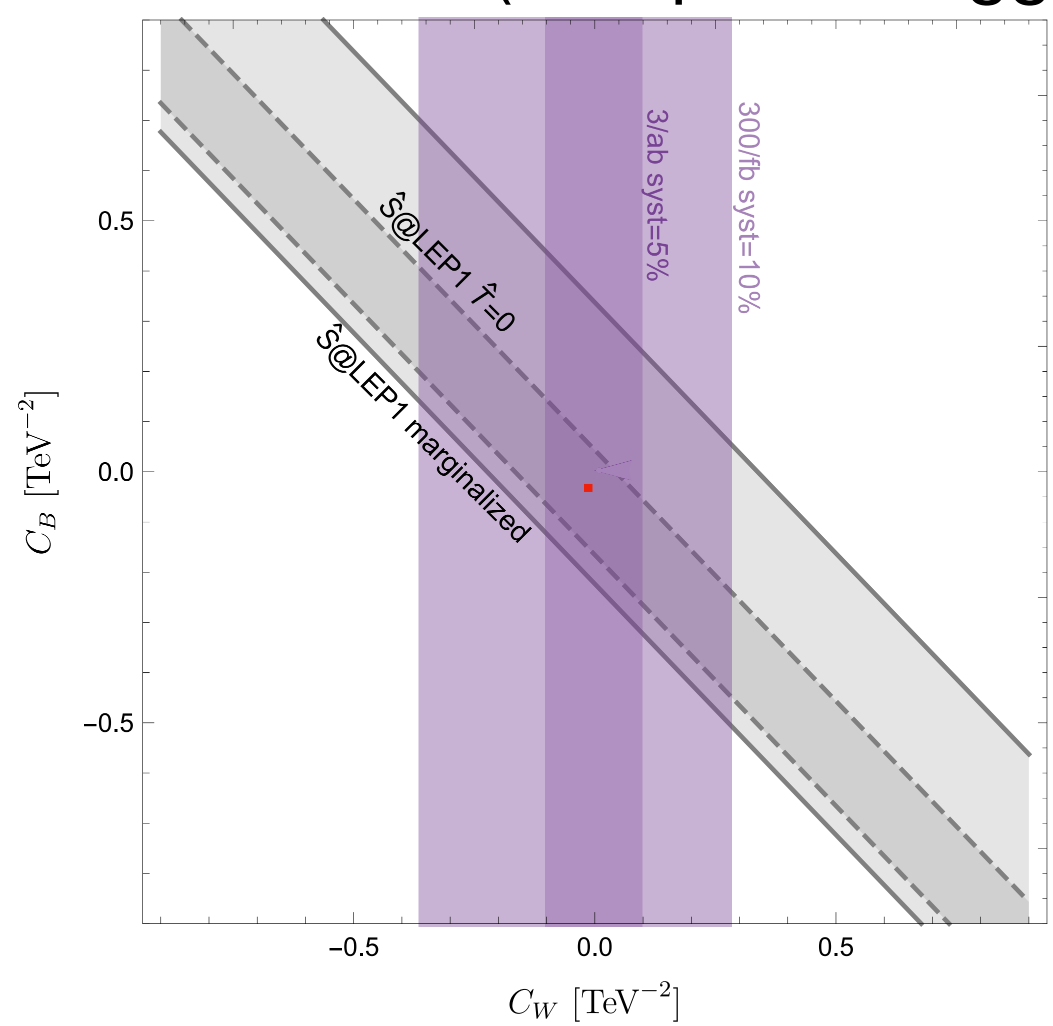
High-Energy Dibosons

BSM Implications: [CLIC is red point in the middle of the plots]

LHC vs LEP (Univ. Th.)



LHC vs LEP (Composite Higgs)



Imposing strong W/Y bounds

$$a_q^{(3)} = -\frac{g^2\Lambda^2}{4m_W^2}\left(c_{\theta_W}^2\delta g_1^Z + \cancel{W}\right)$$

$$a_q^{(1)} = \frac{g^2\Lambda^2}{12m_W^2}t_{\theta_W}^2\left(\widehat{S} - \delta\kappa_\gamma + c_{\theta_W}^2\delta g_1^Z - \cancel{Y}\right)$$

Power-counting + loop suppression

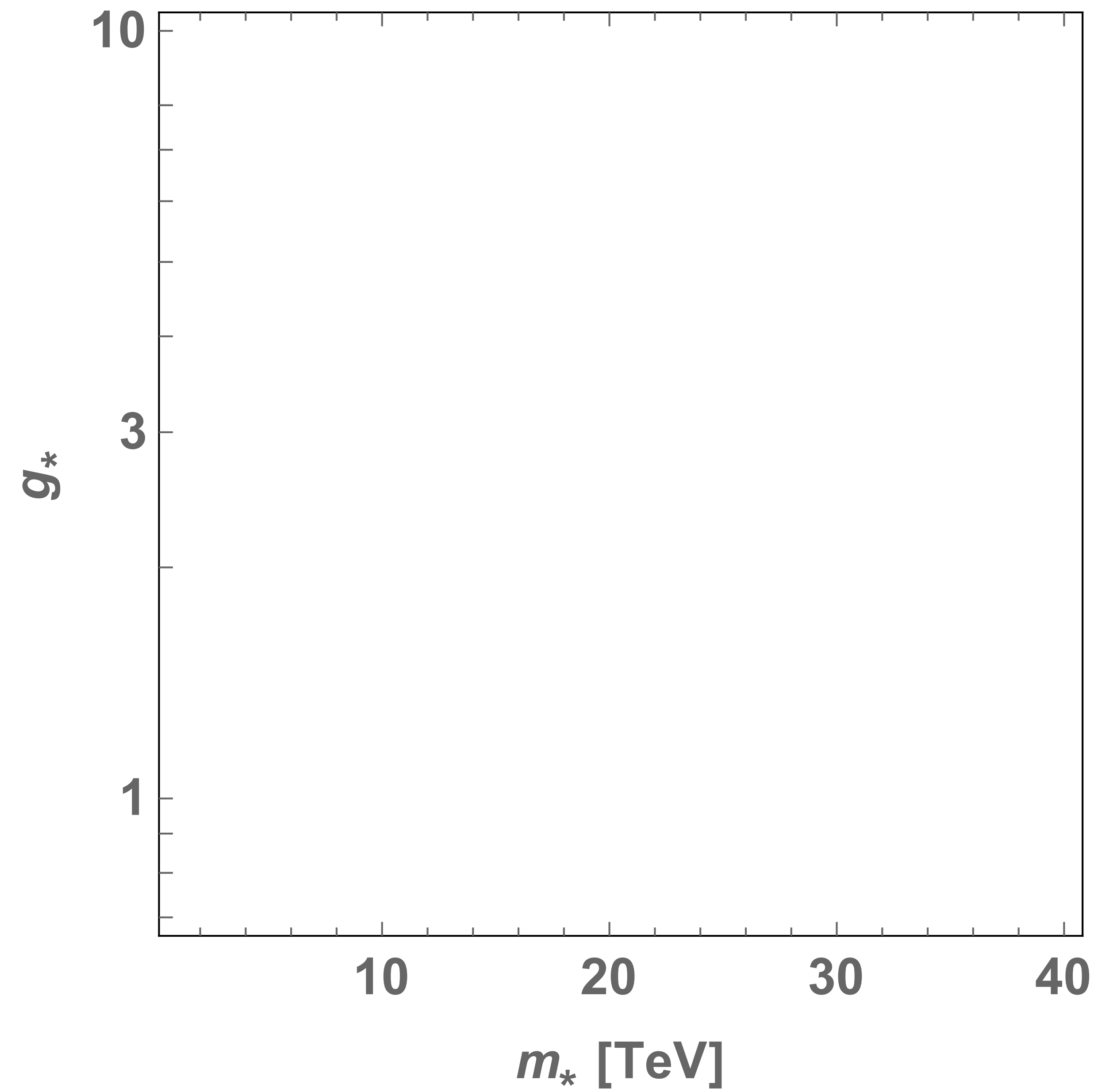
$$a_q^{(3)} = \frac{g^2}{4}\left(c_W + \cancel{c_{HW}} - \cancel{c_{2W}}\right)$$

$$\widehat{S} = (c_W + c_B)\frac{m_W^2}{\Lambda^2}$$

Universal EFT Summarised

Assuming **composite** Higgs, **elementary** gauge bos.:

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* H, g_w V_\mu, \partial_\mu]$$



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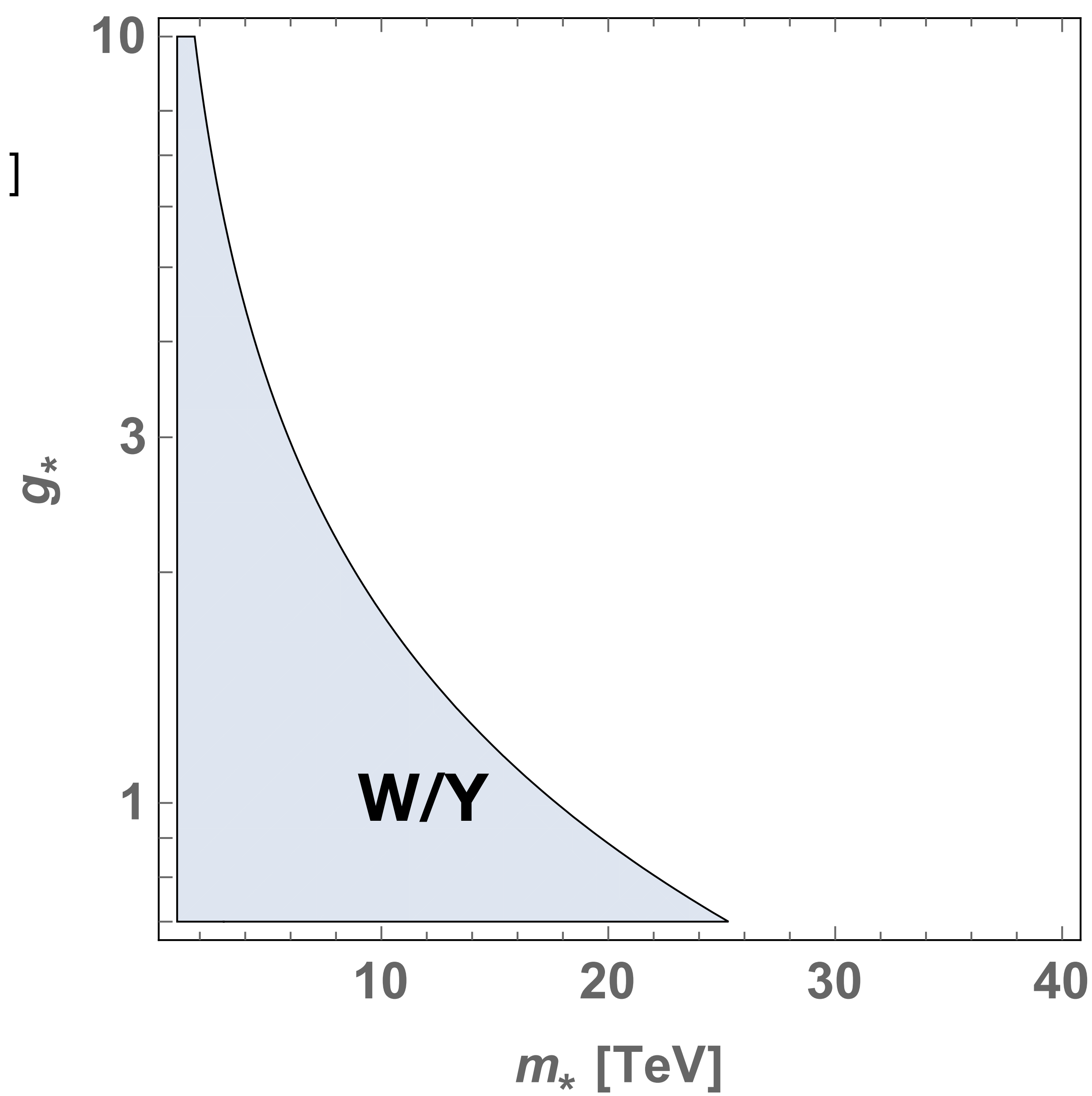
W/Y: (high energy probe) [HL-LHC < 10^{-4}]

$$\frac{g_w^2}{g_*^2 m_*^2}(D_\mu W_{\nu\rho})^2 \;\Rightarrow\; W = \frac{g_W^2 m_W^2}{g_*^2 m_*^2} < 10^{-5}$$



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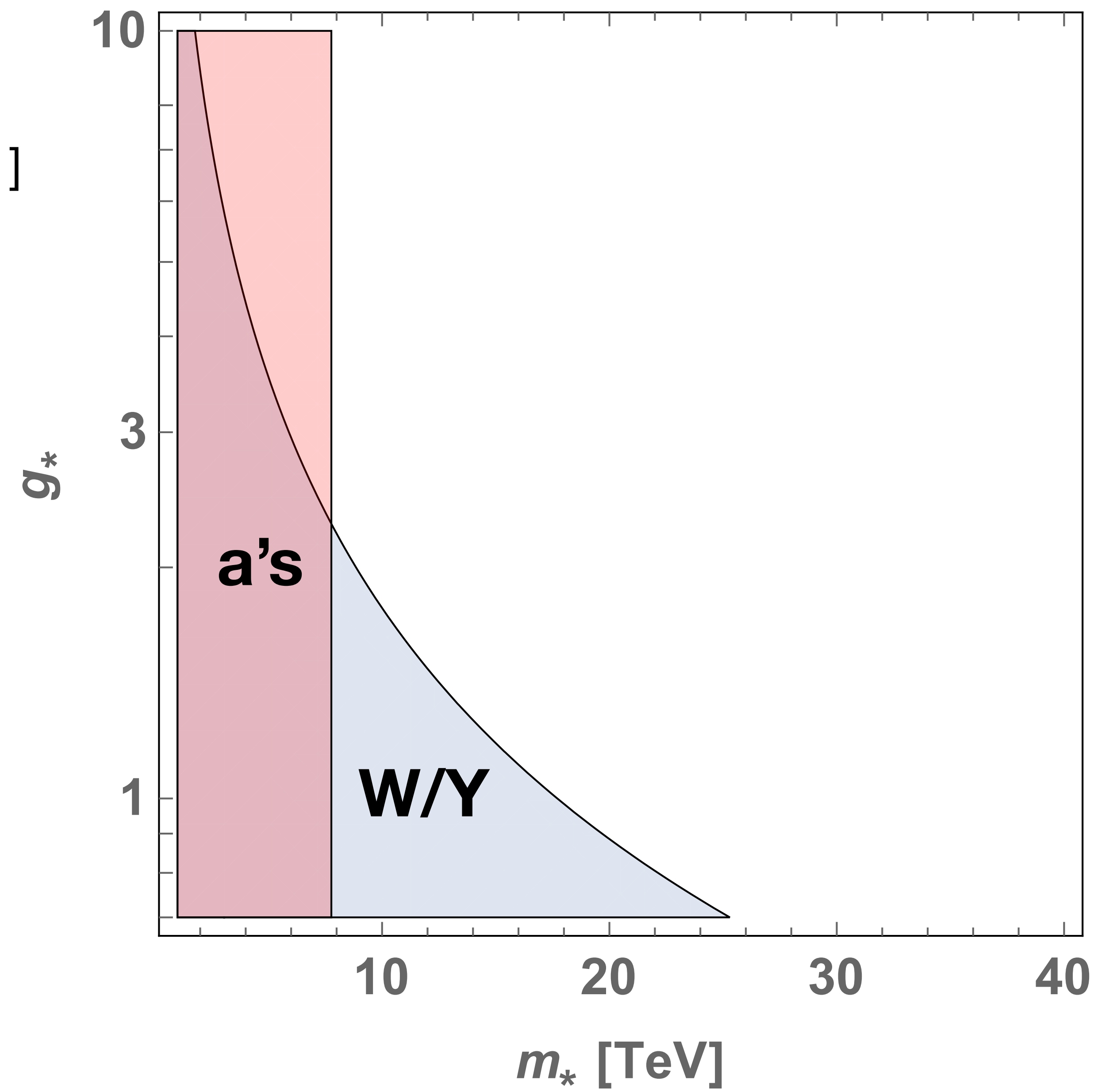
a's: (high energy probe) [LEP $< 10^{-3}$]

$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \;\Rightarrow\; \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$



Universal EFT Summarised

Assuming **composite** Higgs, **elementary** gauge bos.:

$$\mathcal{L}^{d=6}_{\rm BSM} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* H, g_w V_\mu, \partial_\mu]$$

W/Y: (high energy probe) [HL-LHC < 10^{-4}]

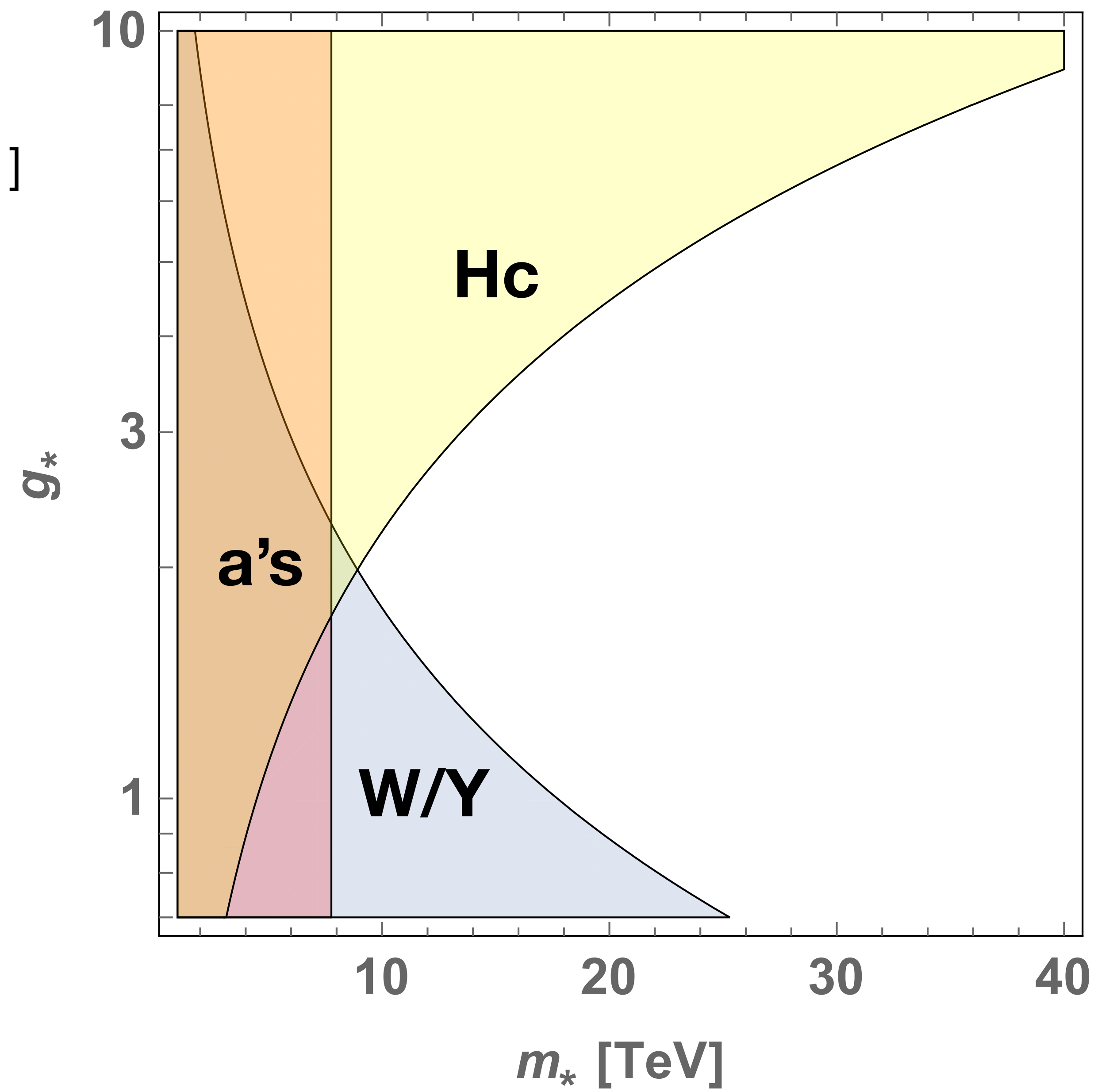
$$\frac{g_w^2}{g_*^2 m_*^2}(D_\mu W_{\nu\rho})^2 \quad \Rightarrow \quad W = \frac{g_W^2 m_W^2}{g_*^2 m_*^2} < 10^{-5}$$

a's: (high energy probe) [LEP < 10^{-3}]

$$\frac{g_w g'}{m_*^2} H^\dagger \sigma_a H W^a_{\mu\nu} B^{\mu\nu} \quad \Rightarrow \quad \hat{S} = \frac{m_w^2}{m_*^2} < 10^{-4}$$

Higgs Couplings: (low energy probe)

$$\frac{g_*^2}{m_*^2}\partial_\mu |H|^2 \partial^\mu |H|^2 \quad \Rightarrow \quad \delta\kappa_{V,F} = \frac{g_*^2 v^2}{m_*^2} < 3\,10^{-3}$$



High-Energy Tops

Growing-with-Energy in **ee->tt**:

[Durieux, Perelló, Vos, C.Zhang]

$$Q_{\varphi t} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$$

$$\boxed{\mathcal{N}_{tB} = (\bar{t}\gamma^\mu t)(\bar{e}\gamma_\mu e + \tfrac{1}{2}\bar{l}\gamma_\mu l)}$$

$$Q_{t\varphi} = (\varphi^\dagger \varphi)(\bar{q}\, t\, \tilde{\varphi})$$

$$\boxed{Q_{tB} = (\bar{q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}}$$

$$Q^{(1)}_{\varphi q} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q)$$

$$Q^{(3)}_{\varphi q} = (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}\,\tau^I \gamma^\mu q)$$

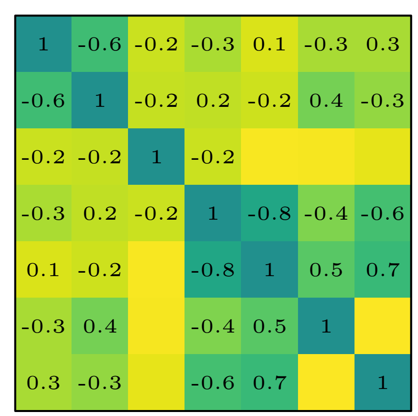
$$\boxed{Q_{tW} = (\bar{q}\sigma^{\mu\nu} t)\tau^I \tilde{\varphi} W^I_{\mu\nu}}$$

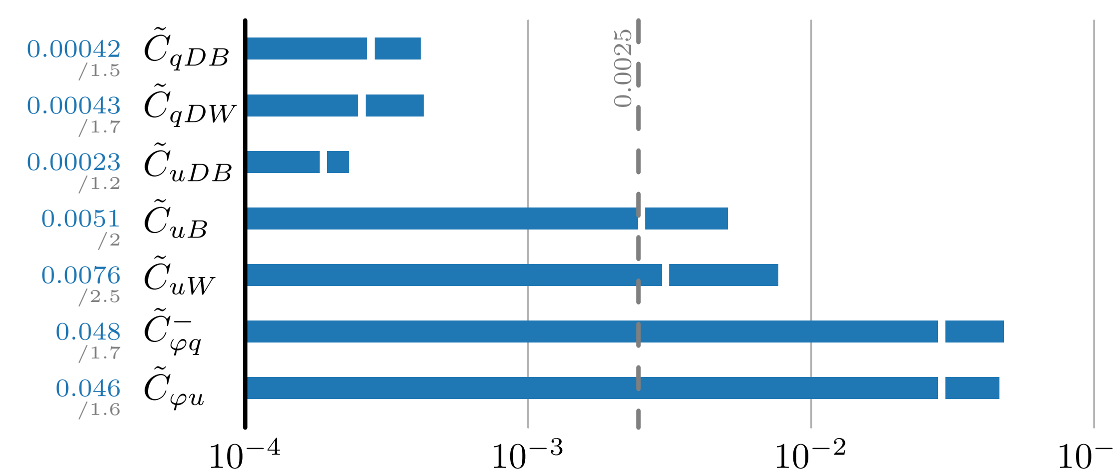
$$\boxed{\mathcal{N}_{qB} = (\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e + \tfrac{1}{2}\bar{l}\gamma_\mu l)}$$

$$\boxed{\mathcal{N}_{qW} = (\bar{q}\tau^I \gamma^\mu q)(\bar{l}\tau^I \gamma_\mu l)}$$

quadratic growth

linear growth
(and diff. top decay dist needed)





High-Energy Tops

Growing-with-Energy in **WW->tt**:

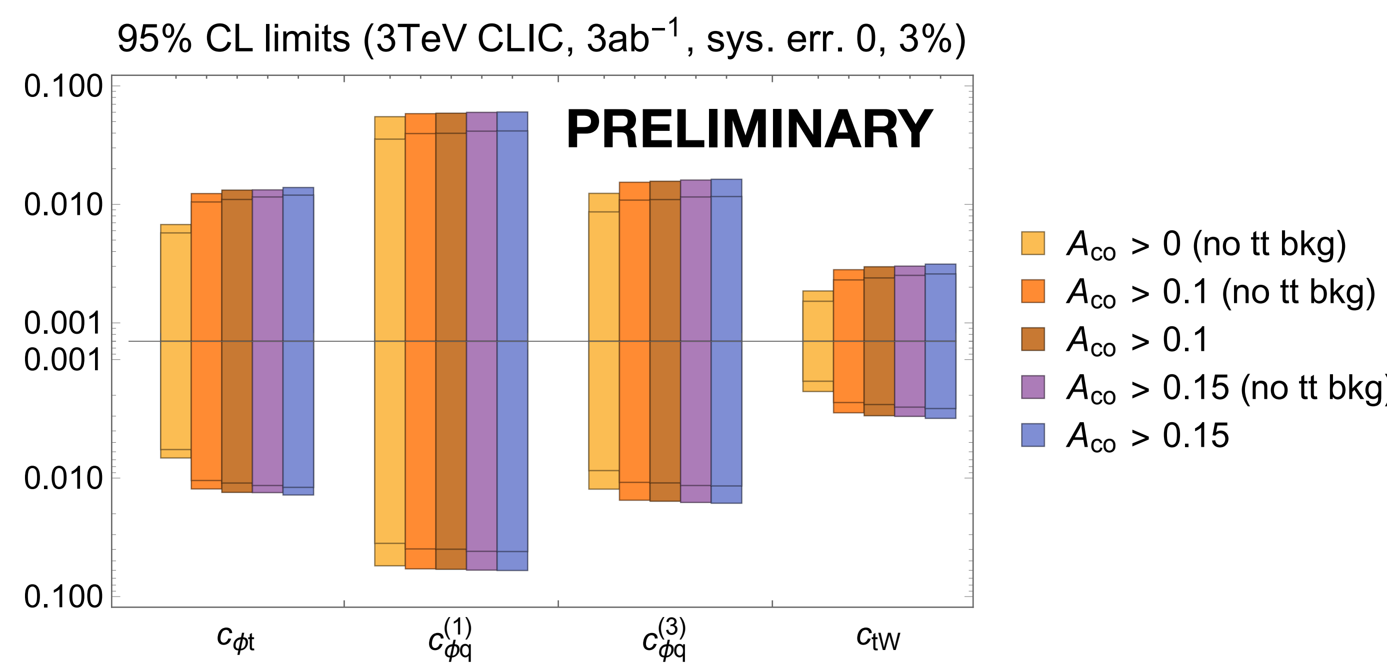
[Grojean, You, AW, Z.Zhang]

$Q_{\varphi t} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$
$\mathcal{N}_{tB} = (\bar{t}\gamma^\mu t)(\bar{e}\gamma_\mu e + \frac{1}{2}\bar{l}\gamma_\mu l)$
$Q_{t\varphi} = (\varphi^\dagger \varphi)(\bar{q}\, t\, \widetilde{\varphi})$
$Q_{tB} = (\bar{q}\sigma^{\mu\nu} t)\widetilde{\varphi} B_{\mu\nu}$
$Q^{(1)}_{\varphi q} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}\gamma^\mu q)$
$Q^{(3)}_{\varphi q} = (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}\,\tau^I \gamma^\mu q)$
$Q_{tW} = (\bar{q}\sigma^{\mu\nu} t)\tau^I \widetilde{\varphi} W^I_{\mu\nu}$
$\mathcal{N}_{qB} = (\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e + \frac{1}{2}\bar{l}\gamma_\mu l)$
$\mathcal{N}_{qW} = (\bar{q}\tau^I \gamma^\mu q)(\bar{l}\tau^I \gamma_\mu l)$

quadratic growth

linear growth
(and diff. top decay dist needed)

H-E probe of y_t? (no result yet)

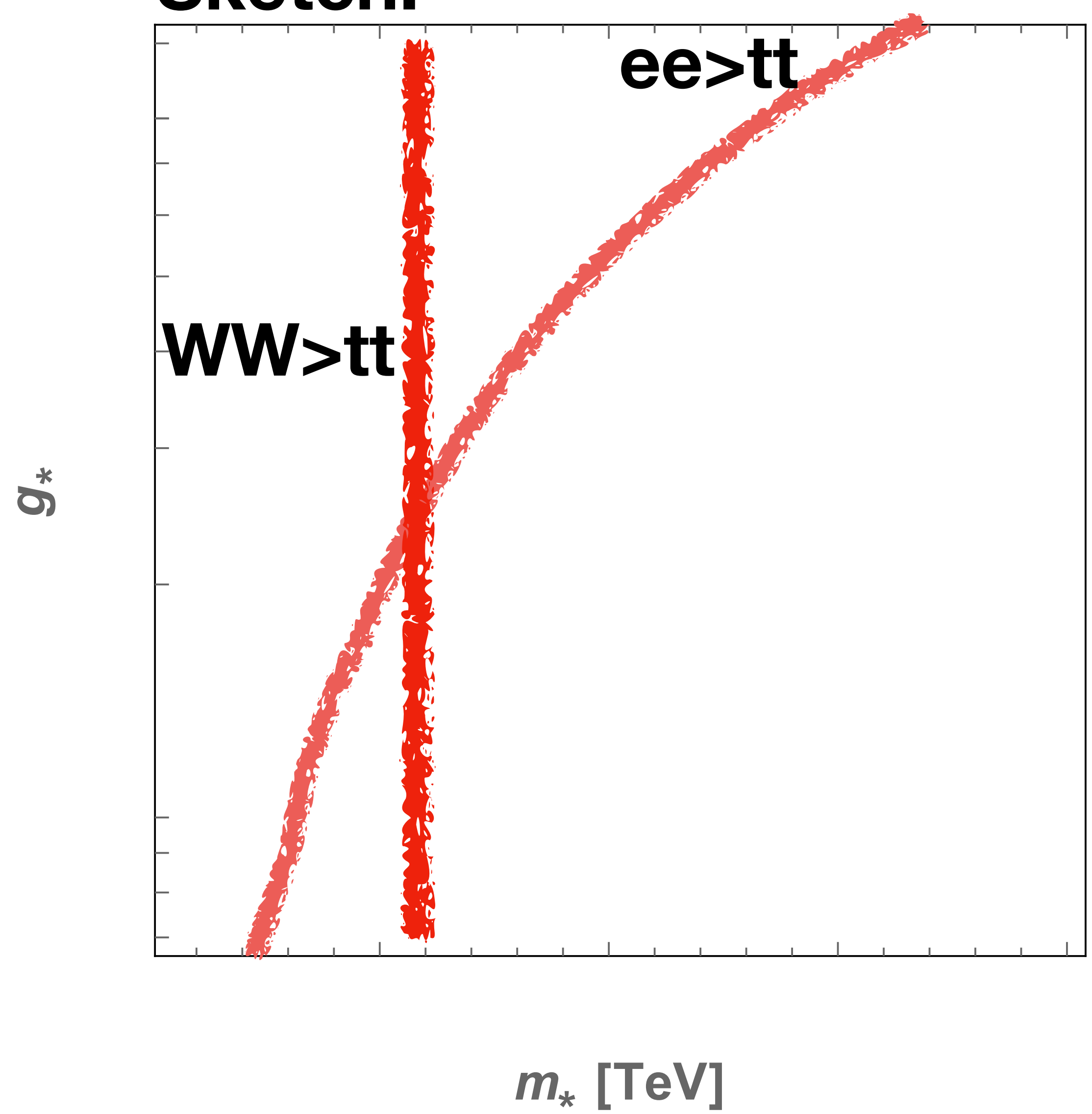


Top-philic EFT

Assuming **composite** t_R and H, **elementary** t_L and gauge

$$\mathcal{L}_{\rm BSM}^{d=6} = \frac{1}{m_*^2}\frac{1}{g_*^2}\,\widehat{\mathcal{L}}[g_* t_R, y_t q_L, g_* H, g_w V_\mu, \partial_\mu]$$

Sketch:



More Maps

High Energy FCNC: [ee > τ μ, ee > t q, …]
can compete with flavour phys. and/or exotic top dec?

Light quark Yukawa determination:
assessing BSM impact

EW-Charged Particles: [Higgsino/EW-ikno, Minimal DM]
Opportunity: **Millicharged Minimal DM at 1.5 TeV**

Exploring Holes in SUSY parameter space.

Extra Singlets Production: [for EWBG? related to H^3?]

…

Summary

- Indirect BSM probes of heavy new physics through growing-with-energy effects, exploring the **Energy and Accuracy Frontier**, are very effective at CLIC.
- Several groups are further exploring CLIC potential in this direction, and assessing BSM implications of the program.
- This adds to, and **complements**, well-studied L-E probes
- Direct search program also to be updated with new ideas, in reaction to LHC non-discovery.
- Discussing Yellow Report report summary by this year.