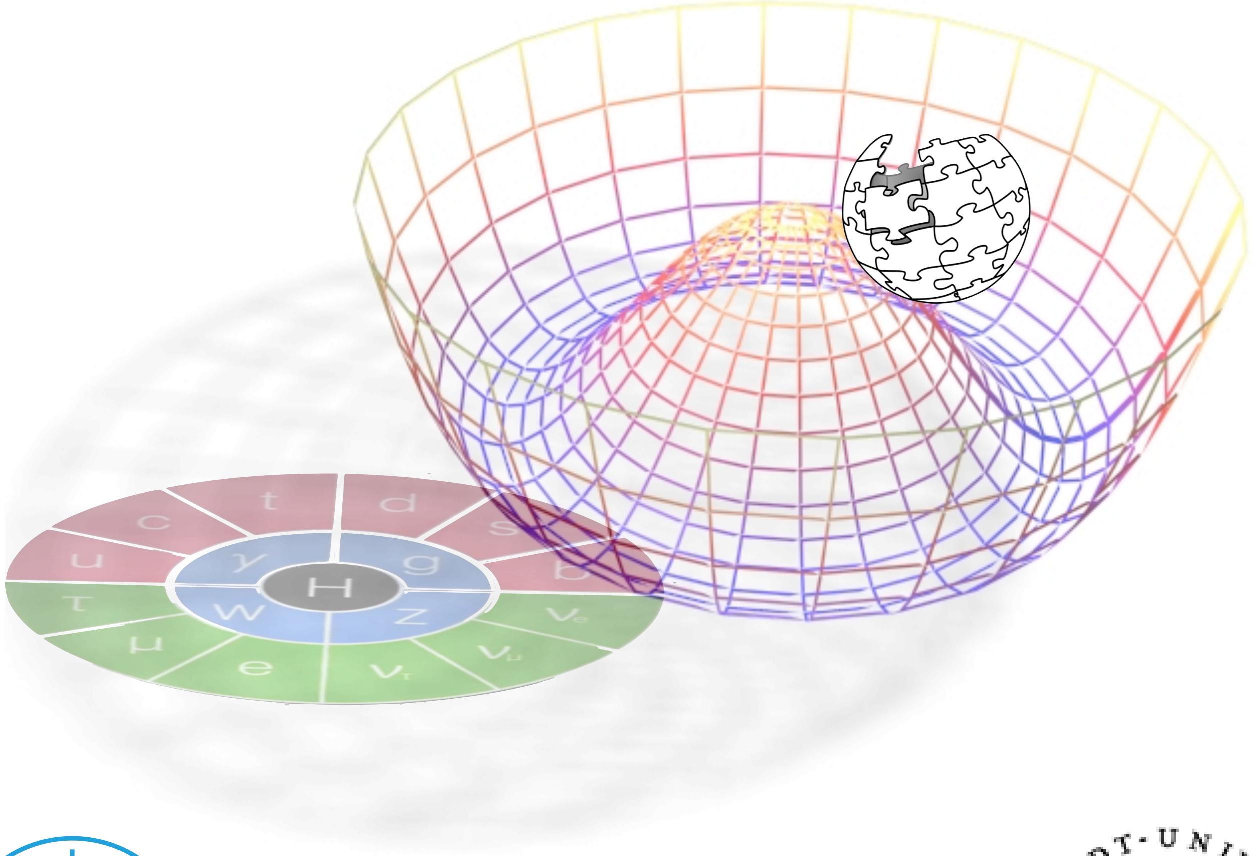
BSM Landscape

Present and Future

CMS B2G Spring Workshop
UHH, May 23, 2018



Christophe Grojean
DESY (Hamburg)
Humboldt University (Berlin)

(christophe.grojean@desy.de)

What is physics beyond the Standard Model?

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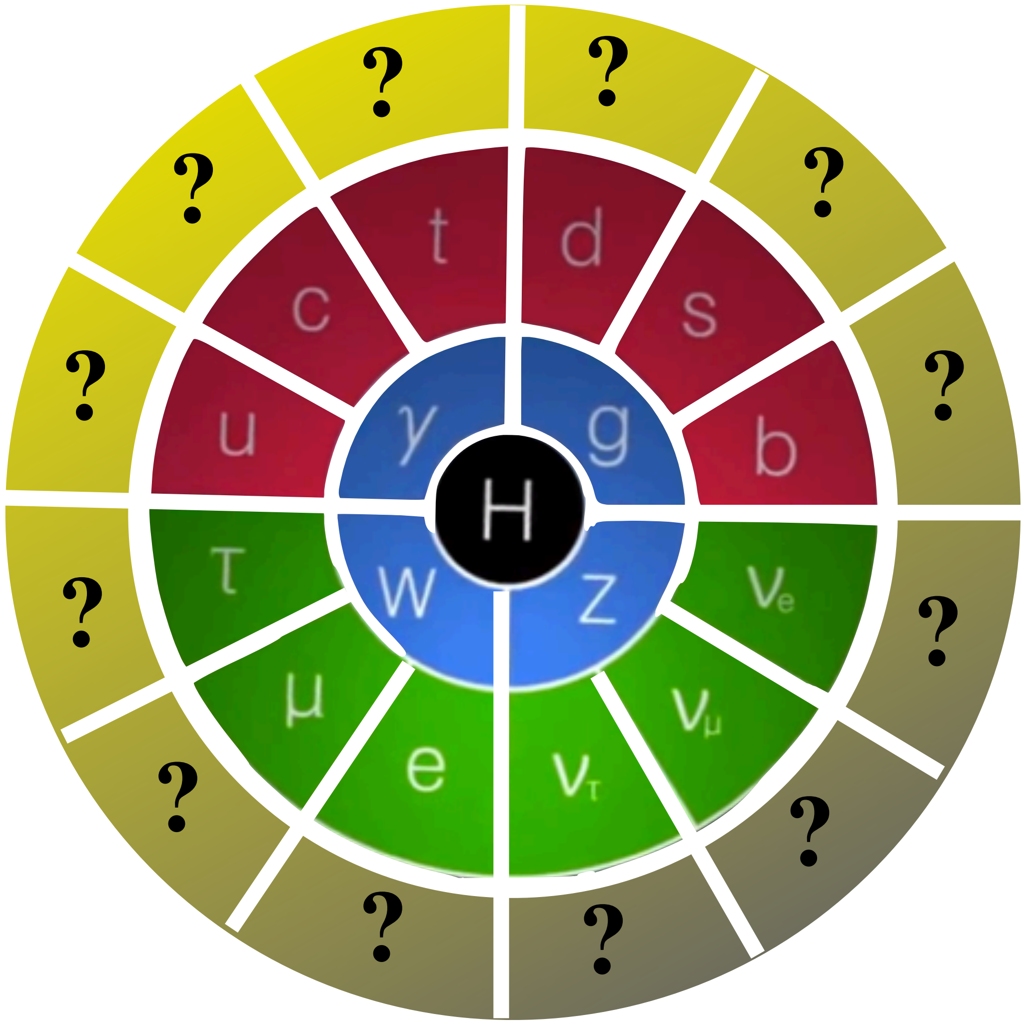

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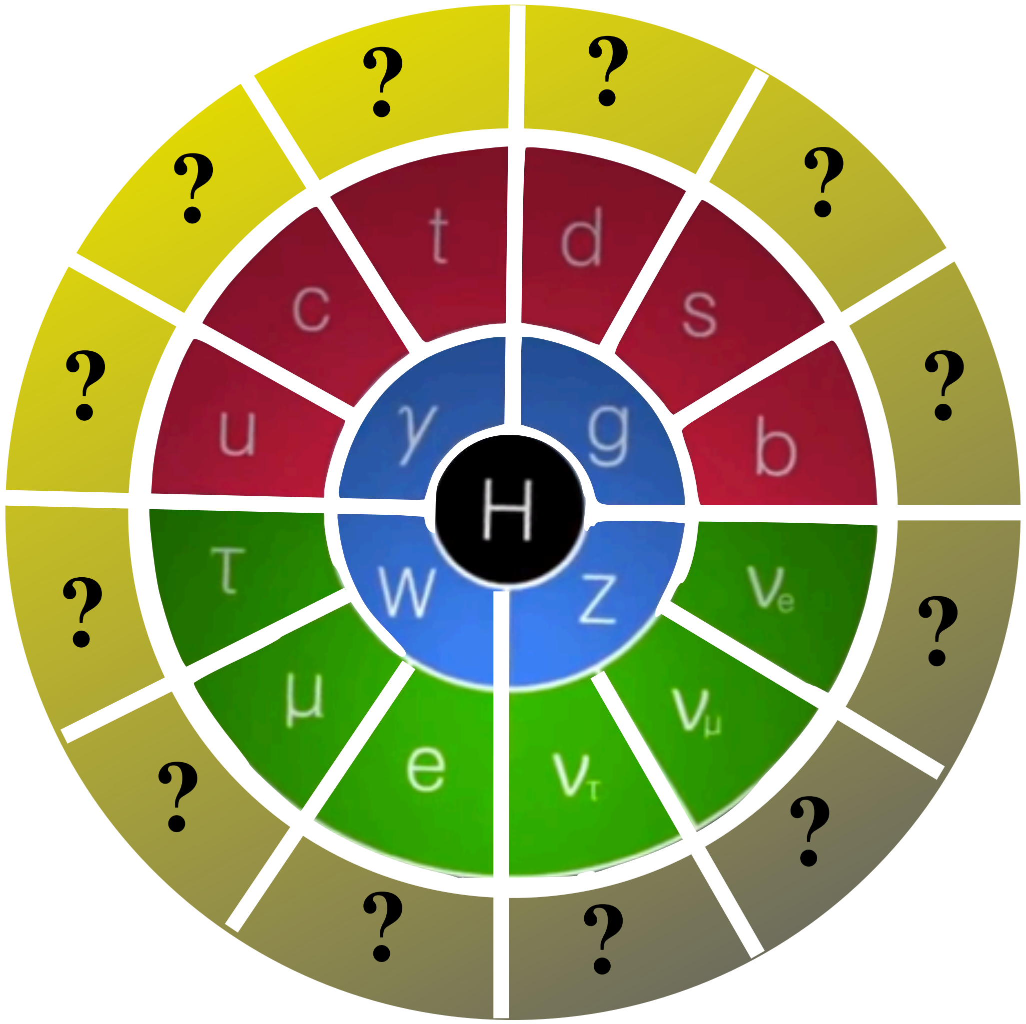

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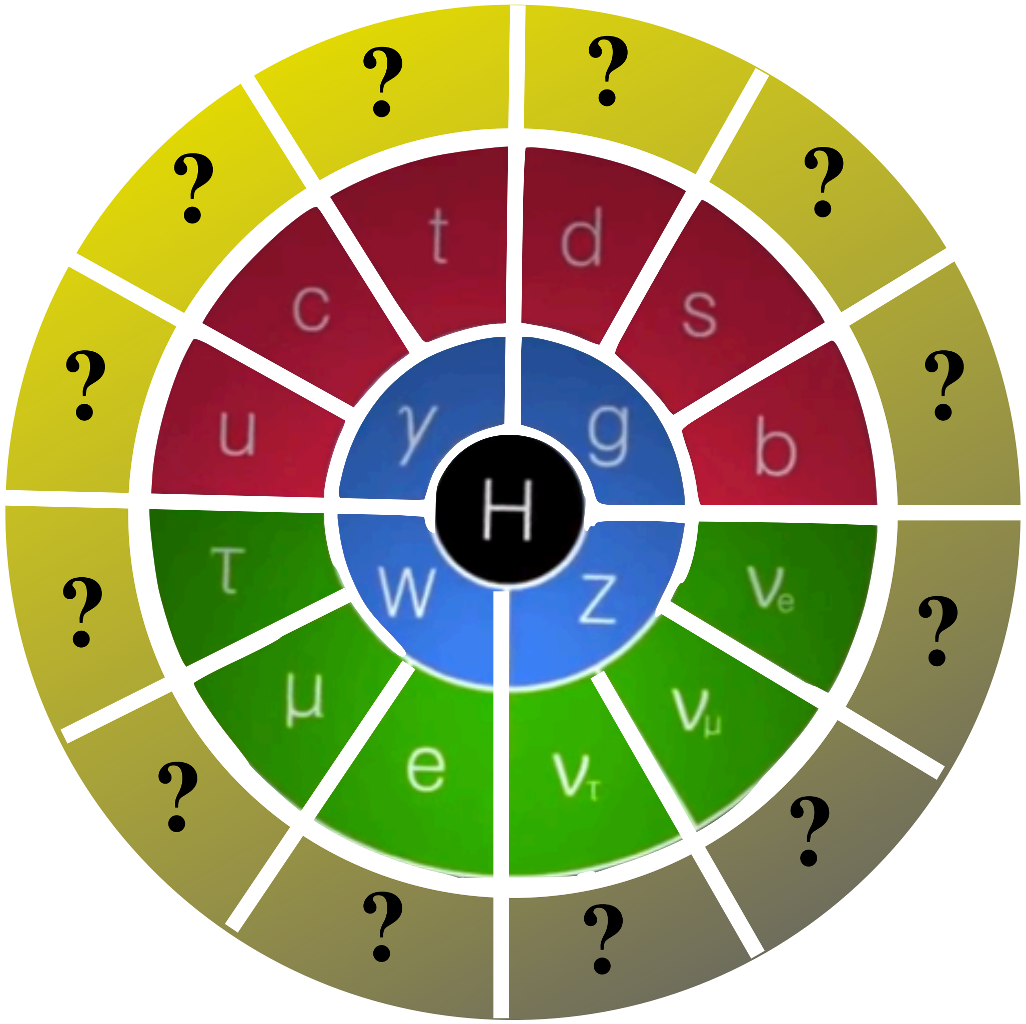

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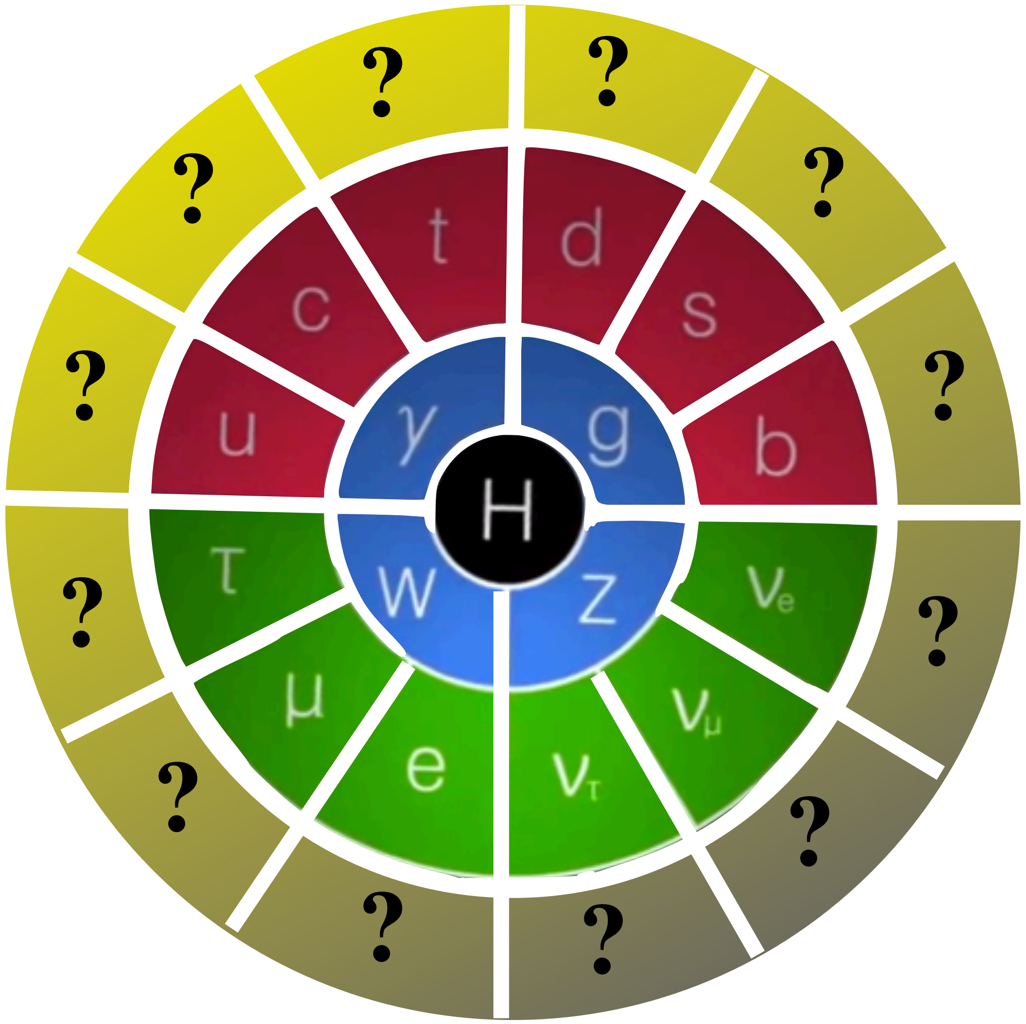

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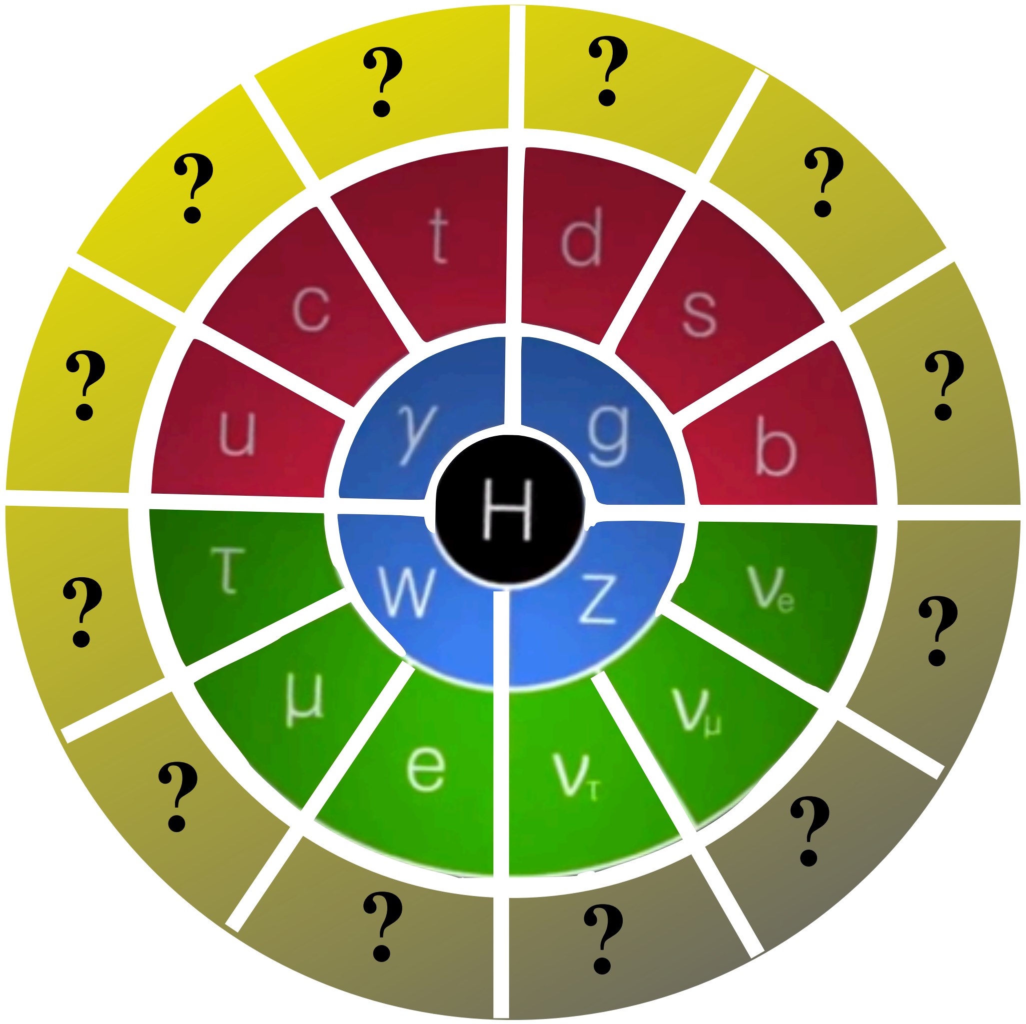

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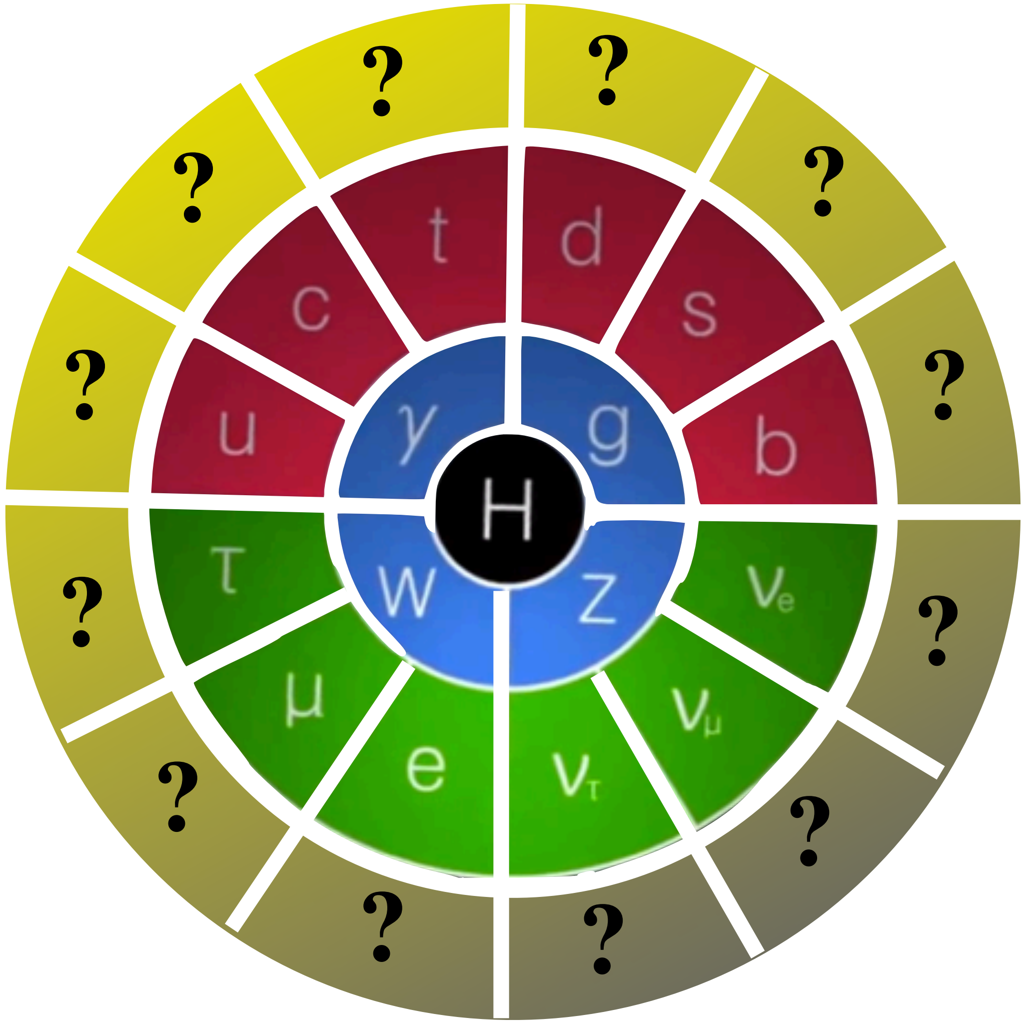

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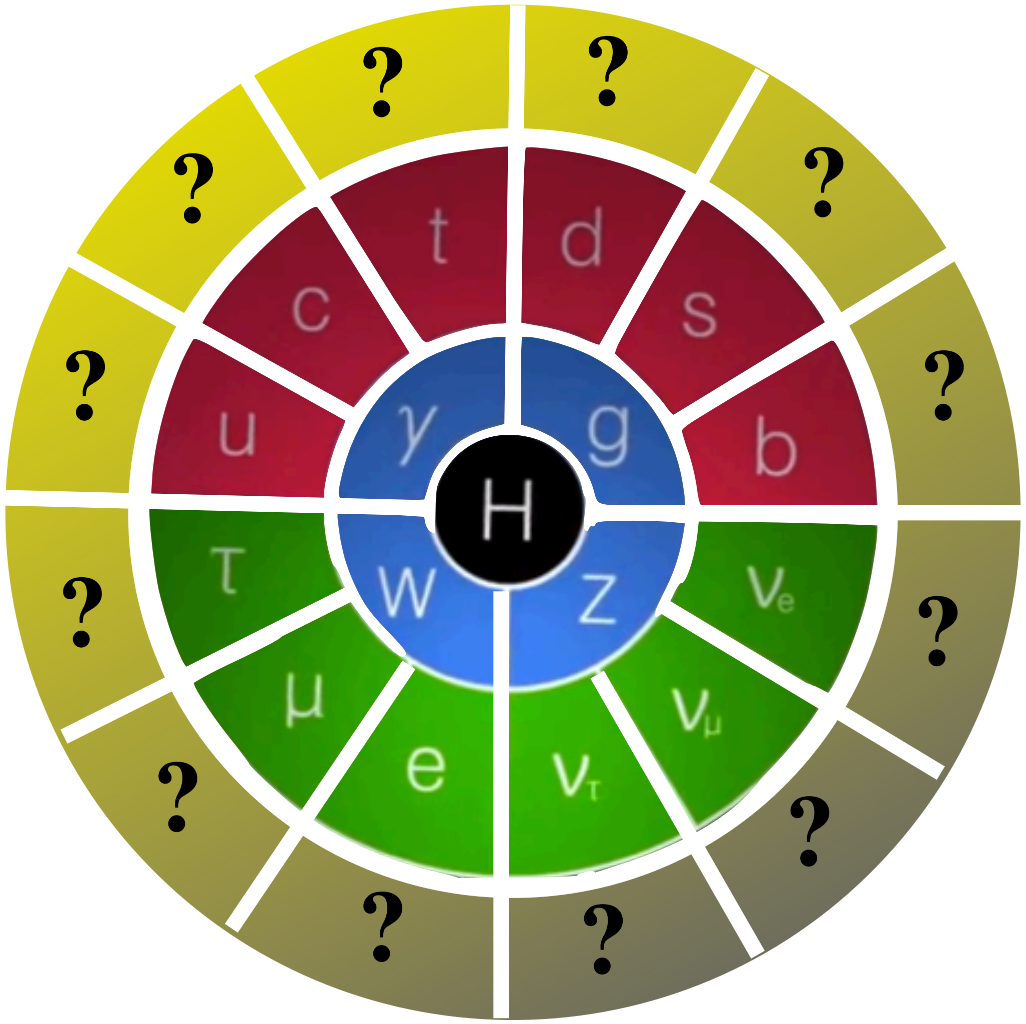

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" Looking and not finding is different than not looking"

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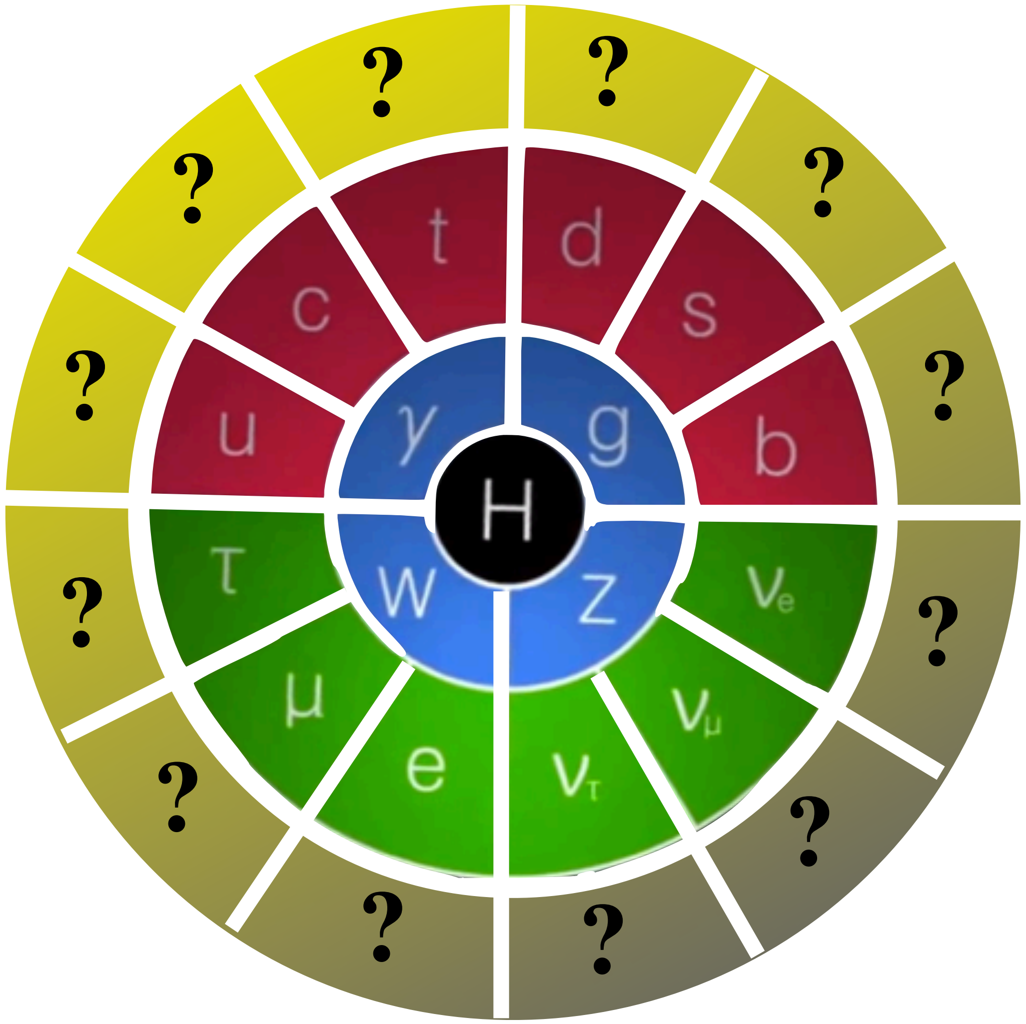

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" Looking and not finding is different than not looking "

" A negative search teaches us something about Nature "

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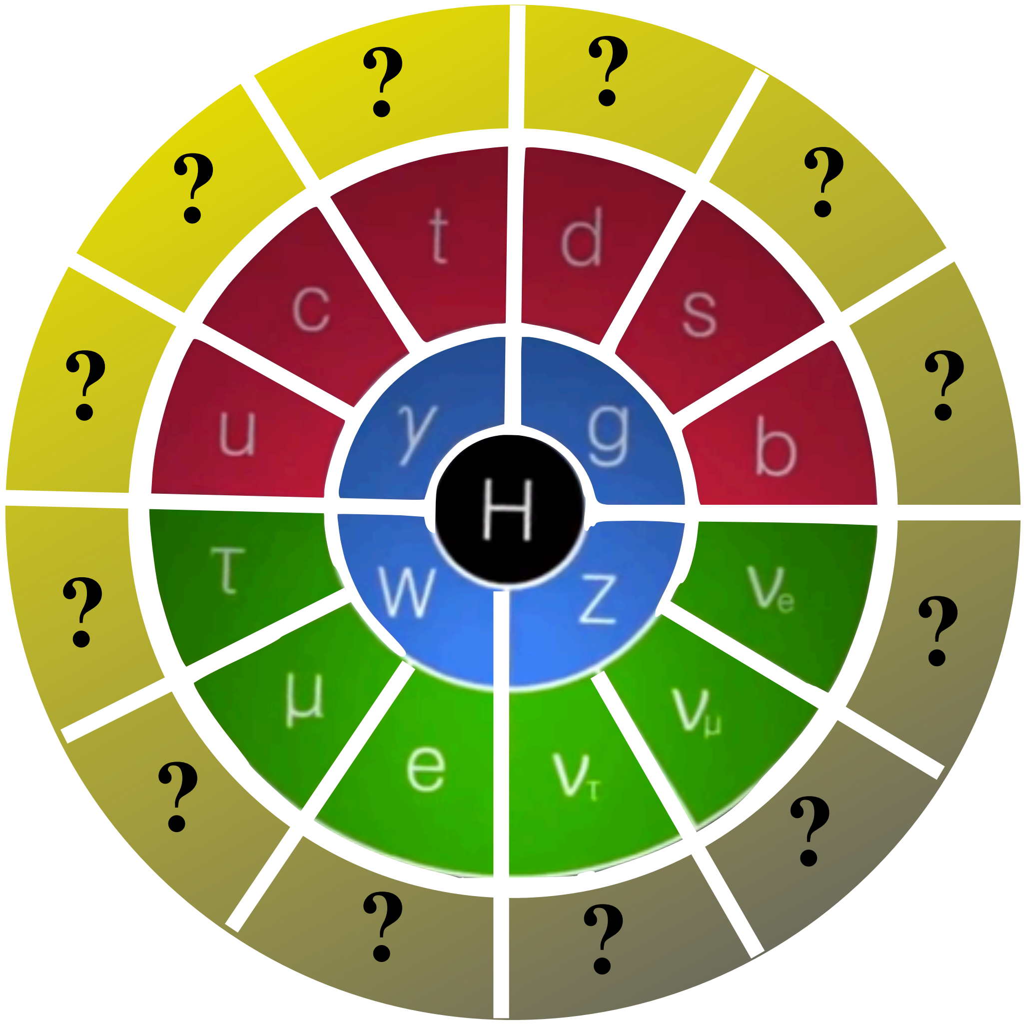

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What is the probability that BSM seats B2G?

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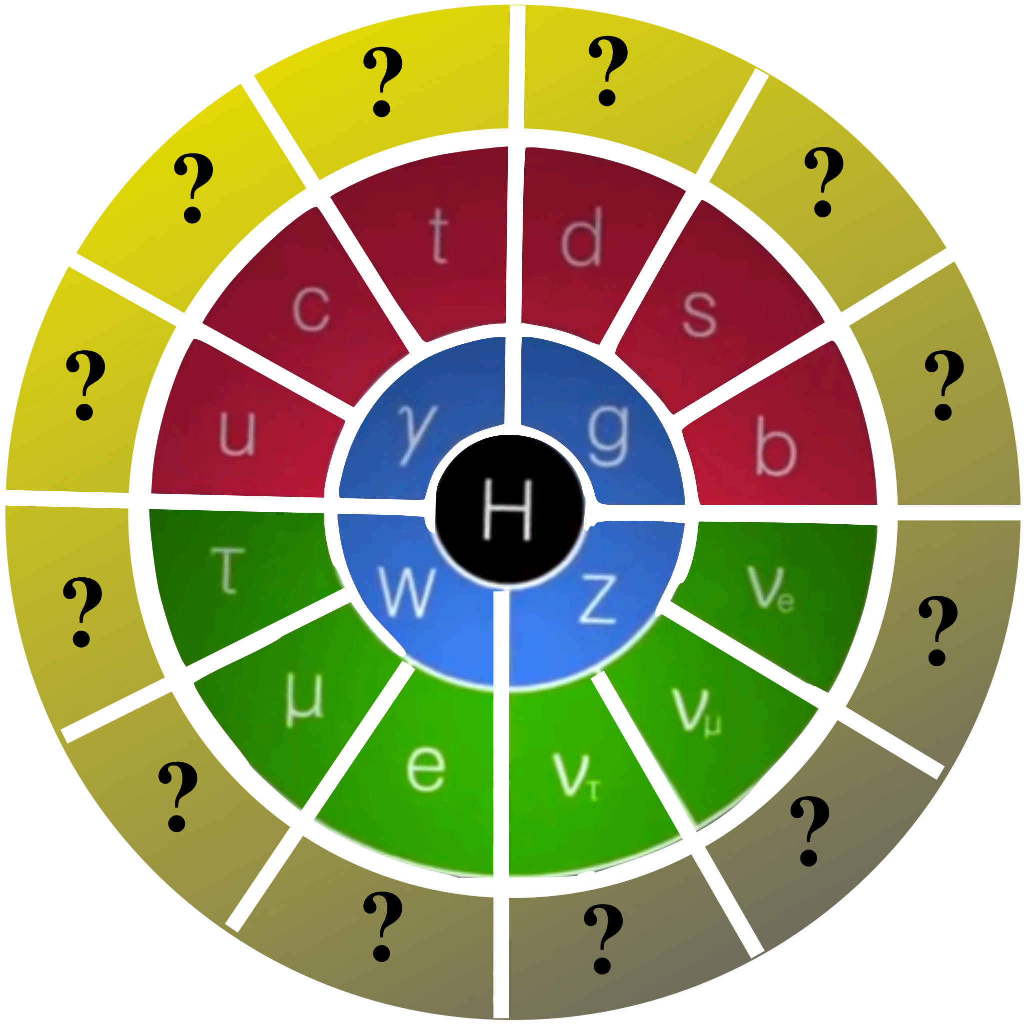

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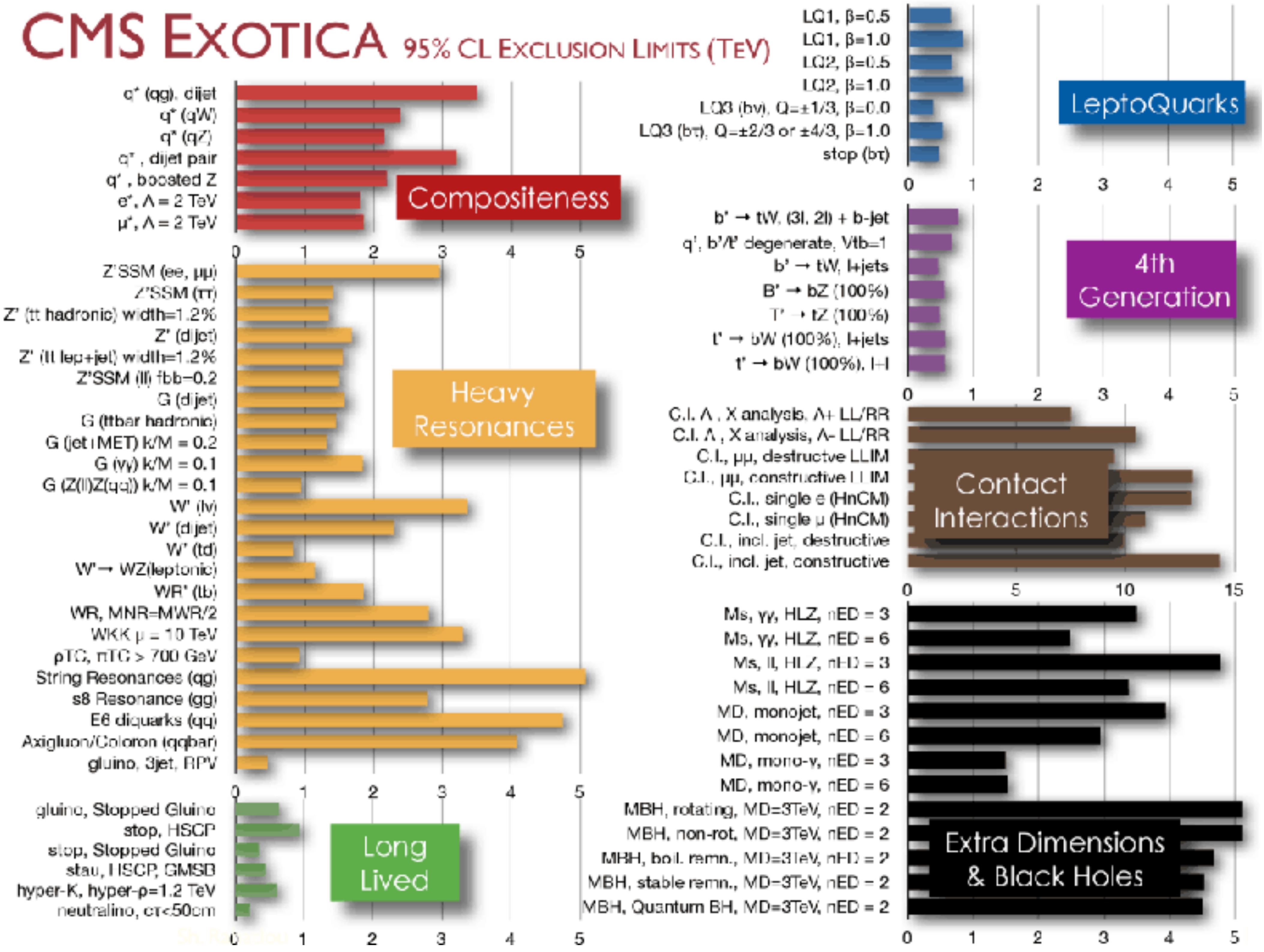
What is the probability that BSM seats B2G?

As usual the conservative and honest answer is 50%

Current status of BSM searches



Current status of BSM searches

lost in translation: Babel tower!

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the ultimate goal

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lost in translation: Babel tower!

the ultimate goal

theorists and experimentalists also need
to start speaking a common language

What is the scale of New Physics?

High Scale Wishes

small FCNC: $\dfrac{gF_{\mu\nu}\bar{\psi}H\sigma^{\mu\nu}\psi}{M_{\rm NP}^2}$

tiny neutrino masses: $\dfrac{(LH)^2}{M_{\rm NP}}$

slow proton decay: $\dfrac{UUDE}{M_{\rm NP}^2}$

Low Scale Wishes

small EDMs: $\mathrm{arg det Y} \leq 10^{-10}$

⤷ axion?

tiny vacuum energy: $\Lambda \approx M_{\rm NP}^4 \gg \left(10^{-3}\mathrm{eV}\right)^4$

⤷ ?

light Higgs boson: $m_H^2 \approx M_{\rm NP}^2 \gg (125\mathrm{GeV})^2$

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$$10^{-22}\,\text{eV} < m_{DM} < 10^{20}\,\text{GeV}$$

(ALPs) (Wimpzillas, Q-balls)

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(ALPs) (Wimpzillas, Q-balls)

$$0.1\,\mathrm{eV} < m_{\nu_R} < 10^{14}\,\mathrm{GeV}$$

$$90\,\mathrm{GeV} < m_{\tilde{t}} < \mathcal{O}(\mathrm{few\ TeV})$$

was considered for a long time a robust prediction but it is being reconsidered now

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Where is everyone?

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Where is everyone?

even new physics at few hundreds of GeV might be difficult to see and could escape our detection

- **compressed spectra**
- **displaced vertices**
- **no MET, soft decay products, long decay chains**
- **uncoloured new physics**

$\not{R}$-susy ◂

Neutral naturalness
(twin Higgs, folded susy) ◂

Relaxion ◂

What is the scale of New Physics?

High Scale Wishes

Low Scale Wishes

Quantum Gravity

Naturalness

EW-B.Gen

D.M.

Dark Sectors

Flavour

ν-Mass

Strong CP

?

A. Wulzer [FCC week]

Particle or not Particle?

- Nima: “*If you do particle physics with the goal of discovering a new particle, better you think what to do with your life now.”* (in the context of “direct discovery” vs “indirect/precision physics” at future colliders)

LHCP ‘2017

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it could also mean new dynamics.
And it could reveal through precision measurements

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$$m_* = g_* f_*$$

g_* weak:

resonances before interactions

g_* strong:

interactions before resonances

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energy helps accuracy

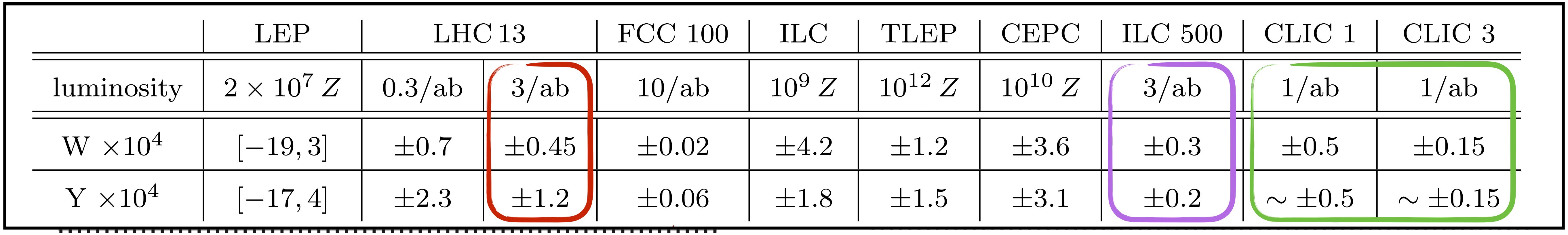
Farina et al '16

$\frac{\Delta \mathcal{O}}{\mathcal{O}} \propto E^2$ ⇔ precision of 0.1% @ 100GeV ≈ precision of 10% @ 1TeV
same sensitivity to new physics

at high energy, you can be sensitive without having to be precise

Particle or not Particle?

e.g. measurement of p^4 EW oblique parameters



	LEP	LHC 13		FCC 100	ILC	TLEP	CEPC	ILC 500	CLIC 1	CLIC 3
luminosity	$2 \times 10^7\ Z$	0.3/ab	3/ab	10/ab	$10^9\ Z$	$10^{12}\ Z$	$10^{10}\ Z$	3/ab	1/ab	1/ab
W $\times 10^4$	$[-19, 3]$	± 0.7	± 0.45	± 0.02	± 4.2	± 1.2	± 3.6	± 0.3	± 0.5	± 0.15
Y $\times 10^4$	$[-17, 4]$	± 2.3	± 1.2	± 0.06	± 1.8	± 1.5	± 3.1	± 0.2	$\sim \pm 0.5$	$\sim \pm 0.15$

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Composite Higgs

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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S-parameter : [De Blas et. al.] (LEP: 10^{-3})

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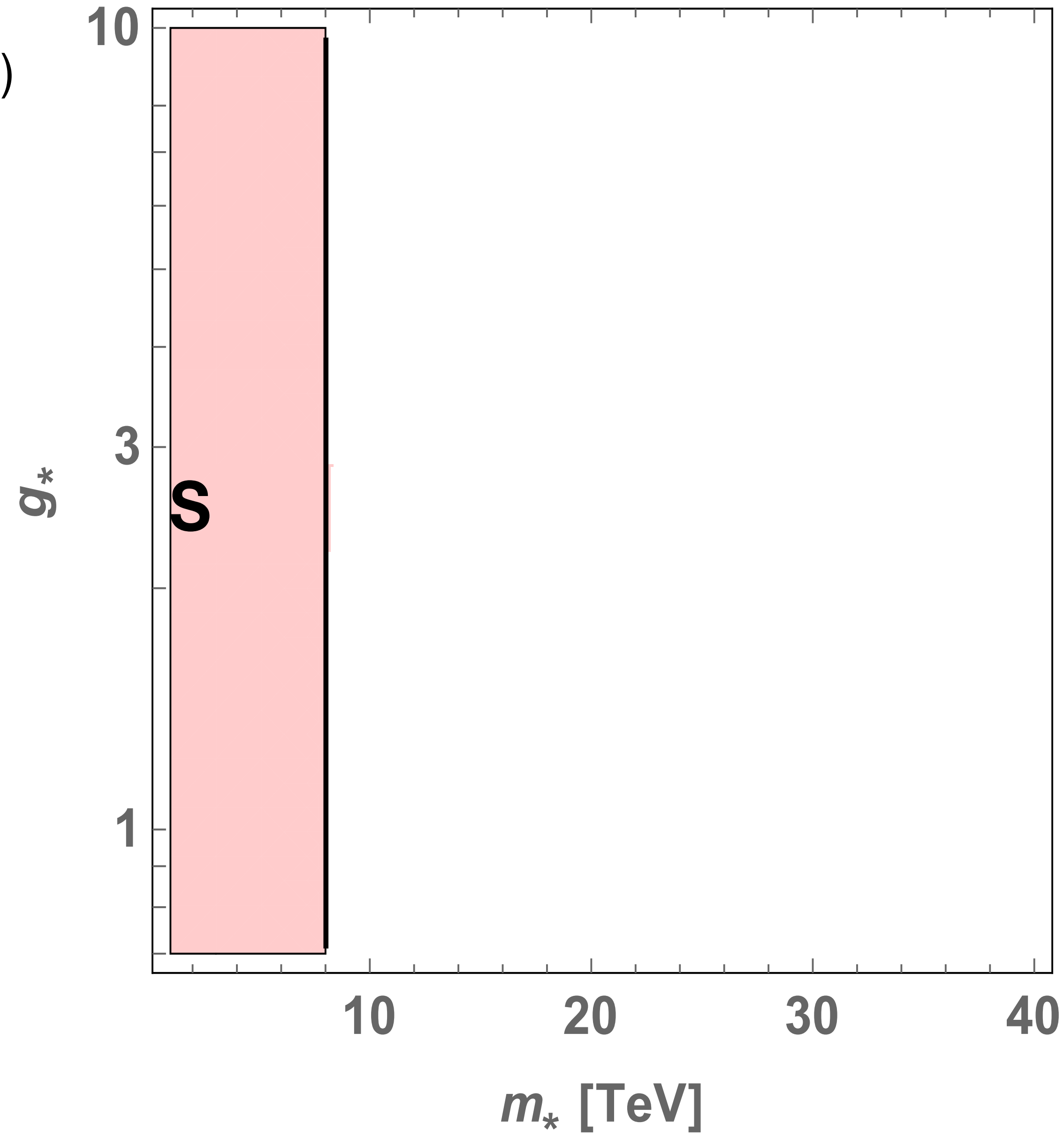

Grojean-Wulzer @ FCC physics week ’17

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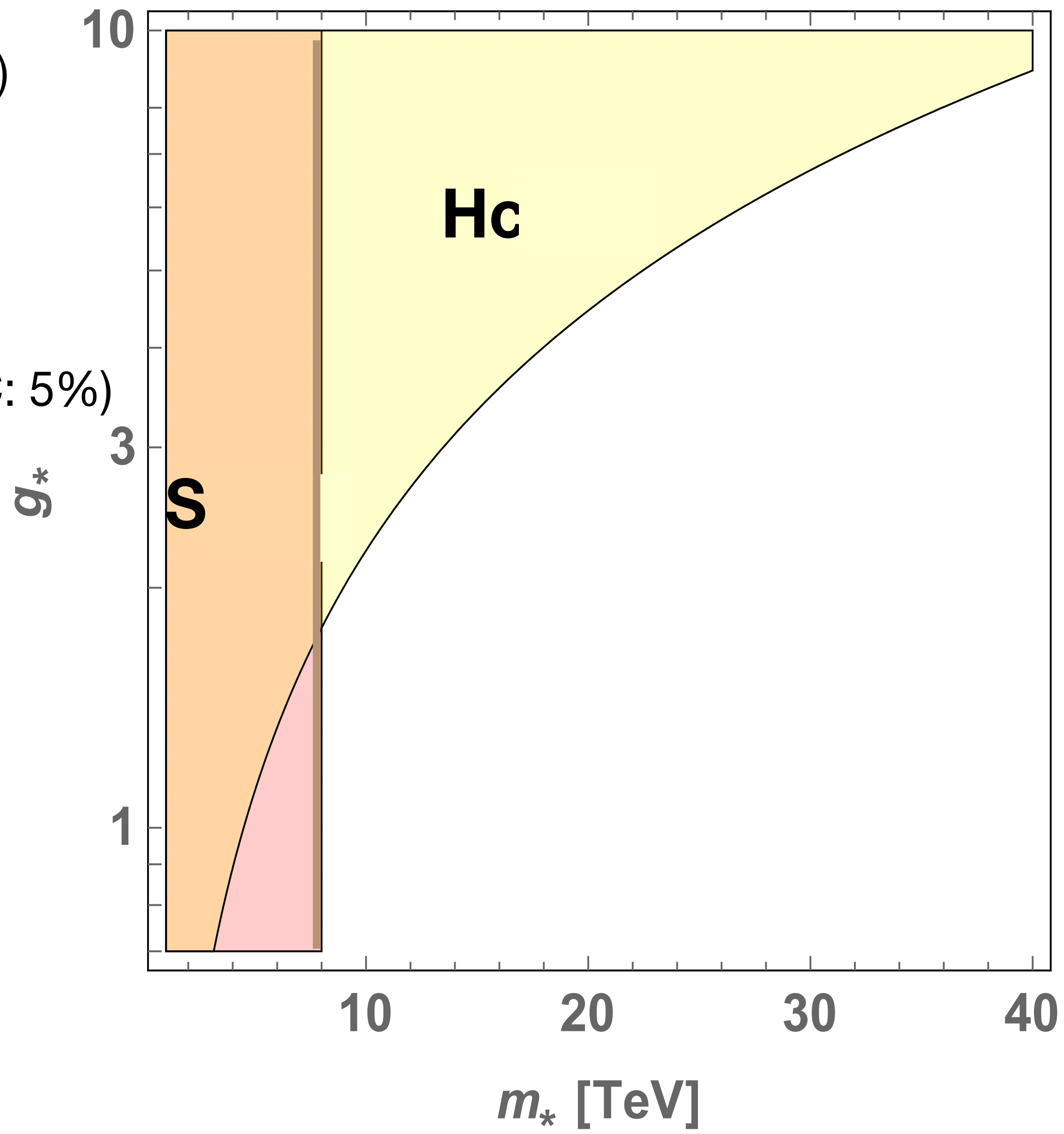
Higgs Couplings : [ee Report] (HL-LHC: 5%)

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



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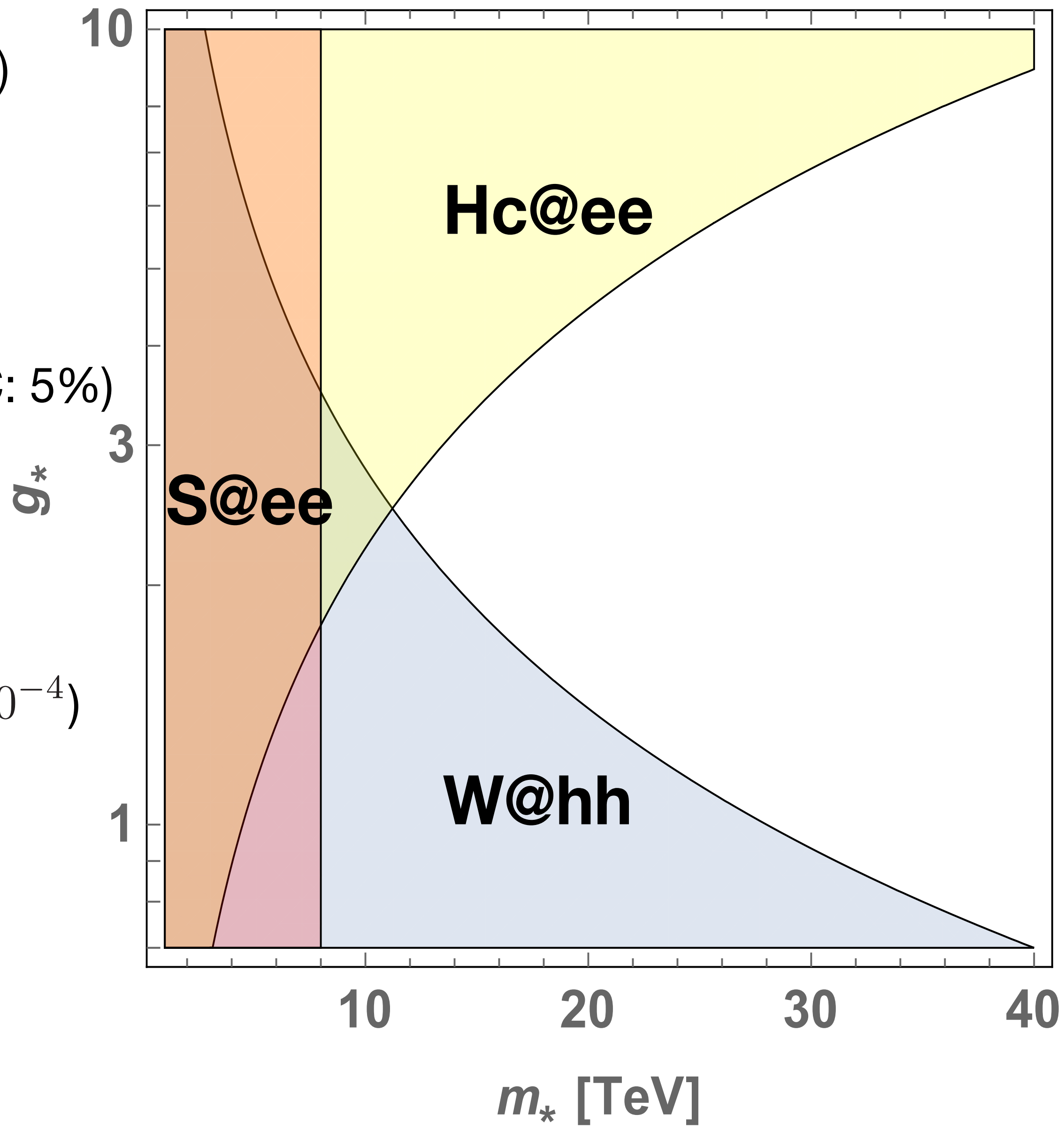
W @hh: (energy + accuracy) (HL-LHC<10^{-4})

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



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Composite tR, comp. Higgs, **elementary tL** and gauge

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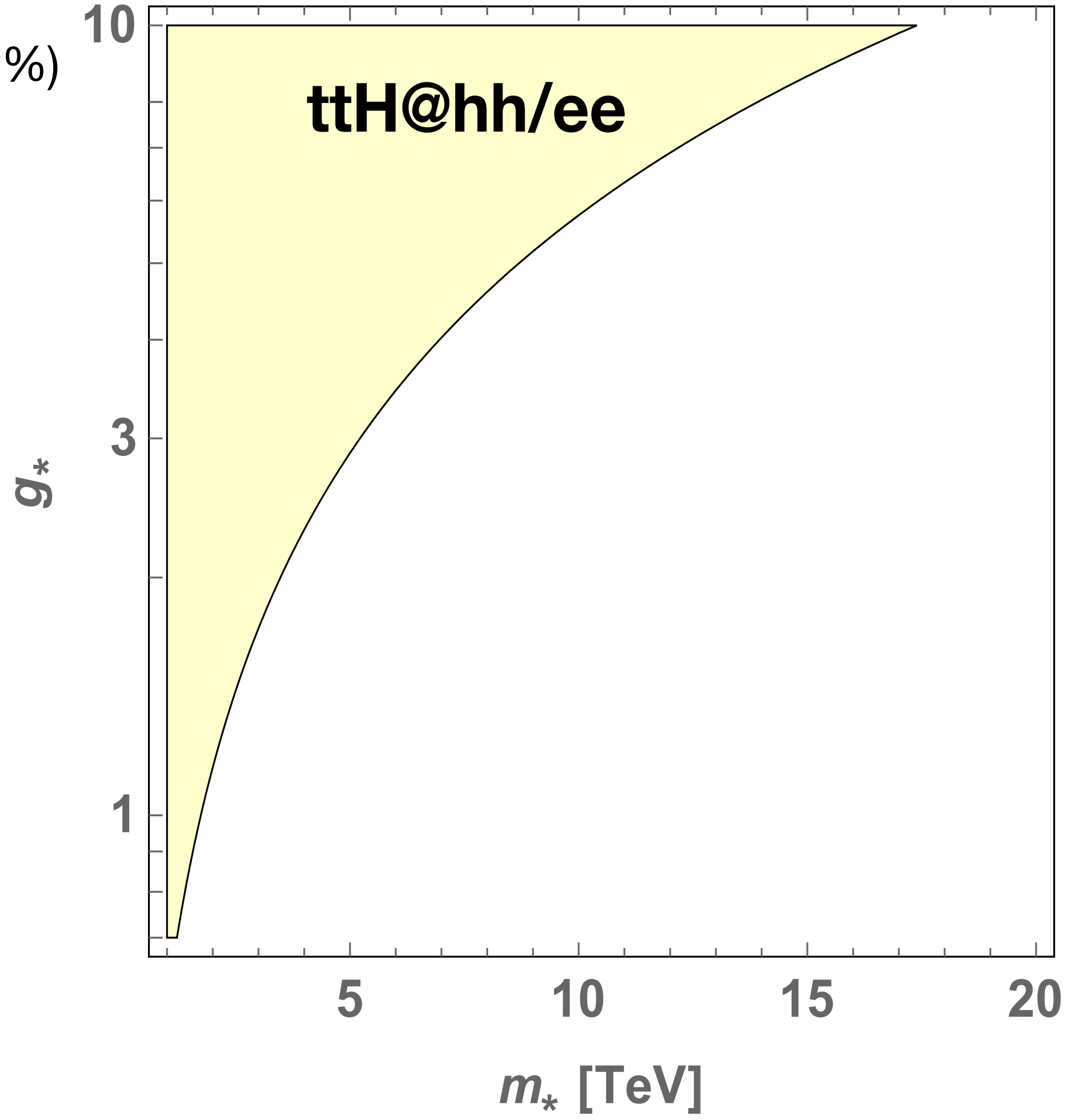
Diff. oper.s comb. in ee and hh!!



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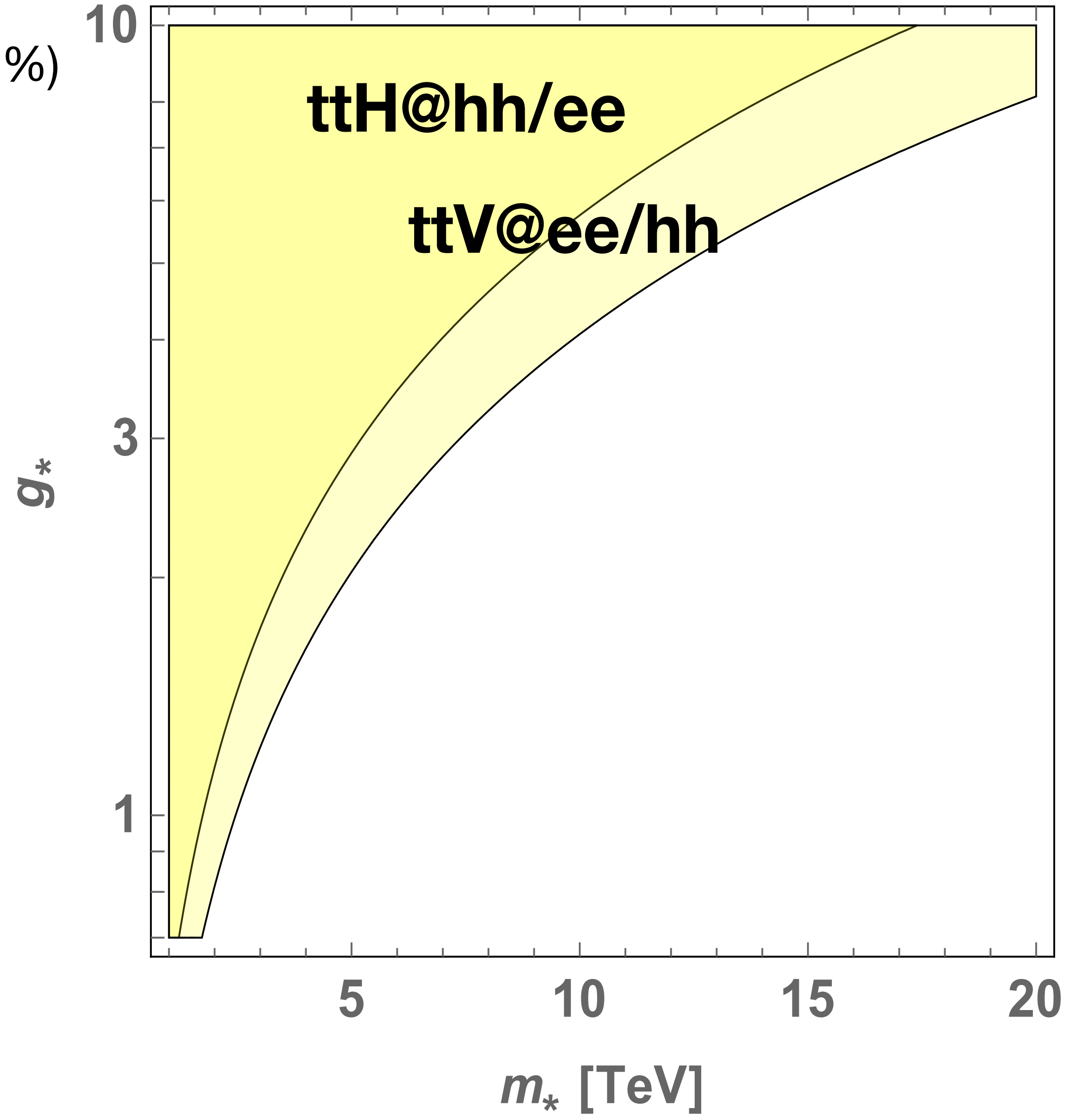
ttV coupling @ee/hh: [Janot / Farina et.al.]

$$\frac{g_*^2}{m_*^2} H^\dagger \overleftrightarrow{D}_\mu H\, \bar{t}_R \gamma^\mu t_R \Rightarrow \frac{\delta g_{tV}}{g_{tV}} = \frac{g_*^2 v^2}{m_*^2} < 10^{-2}$$

Same hh reach from en. + acc.?



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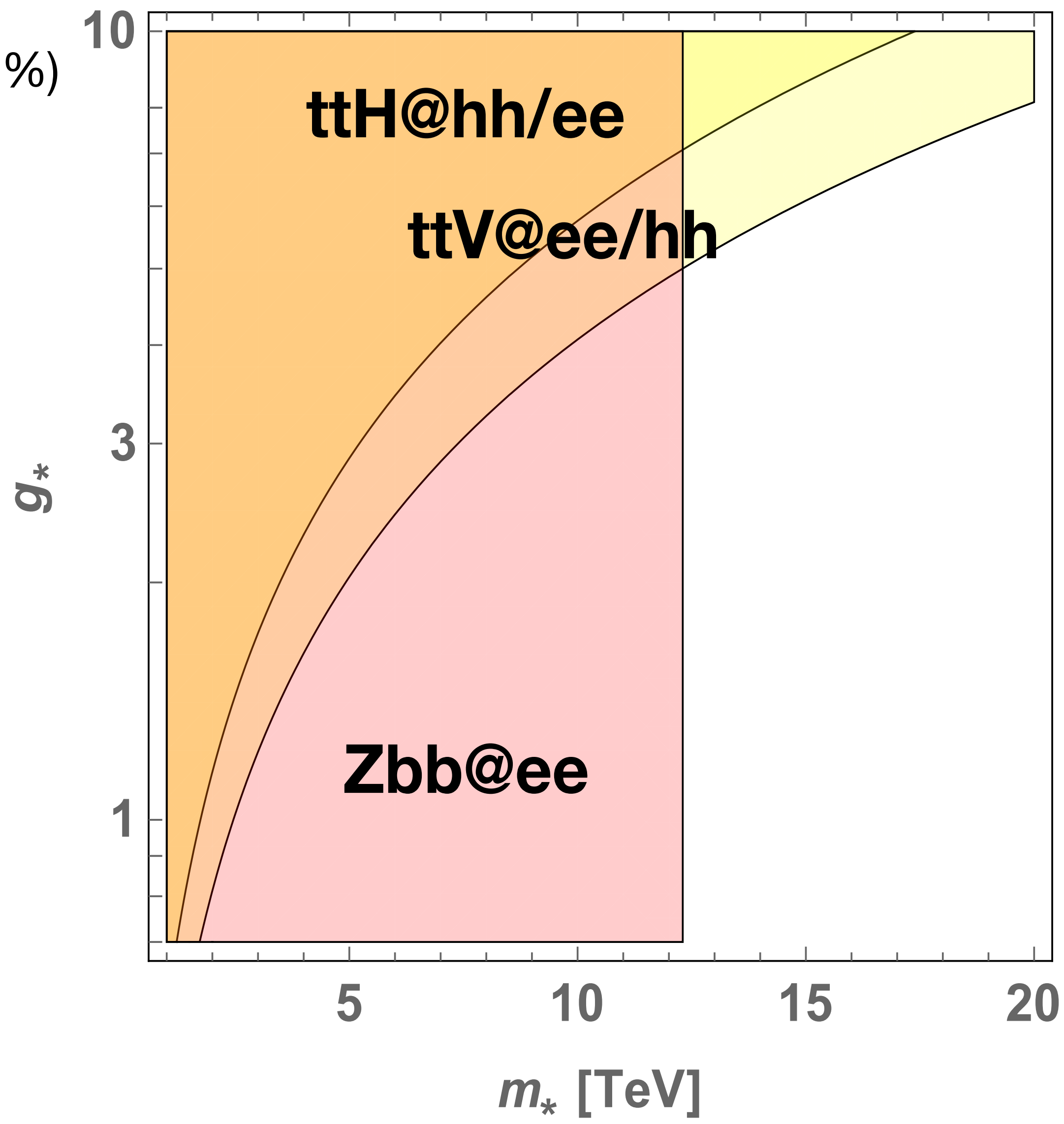
Zbb coupling @ee: [ee Report] (LEP:10^{-3})

$$\frac{y_t^2}{m_*^2}H^\dagger \overleftrightarrow{D}_\mu H\,\bar{q}_L\gamma^\mu q_L + .. \Rightarrow \frac{\delta g_b}{g_b} = \frac{m_t^2}{m_*^2} < 2\,10^{-4}$$



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4-top contact interactions @hh:

$$\frac{g_*^2}{m_*^2}(\bar{t}_R\gamma_\mu t_R)^2 \Rightarrow \frac{g_*^2}{m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

$$\frac{y_t^2}{m_*^2}(\bar{q}_L\gamma_\mu q_L)(\bar{t}_R\gamma_\mu t_R) \Rightarrow \frac{y_t^2}{m_*^2} < \frac{1}{\Lambda_{4t}^2}$$

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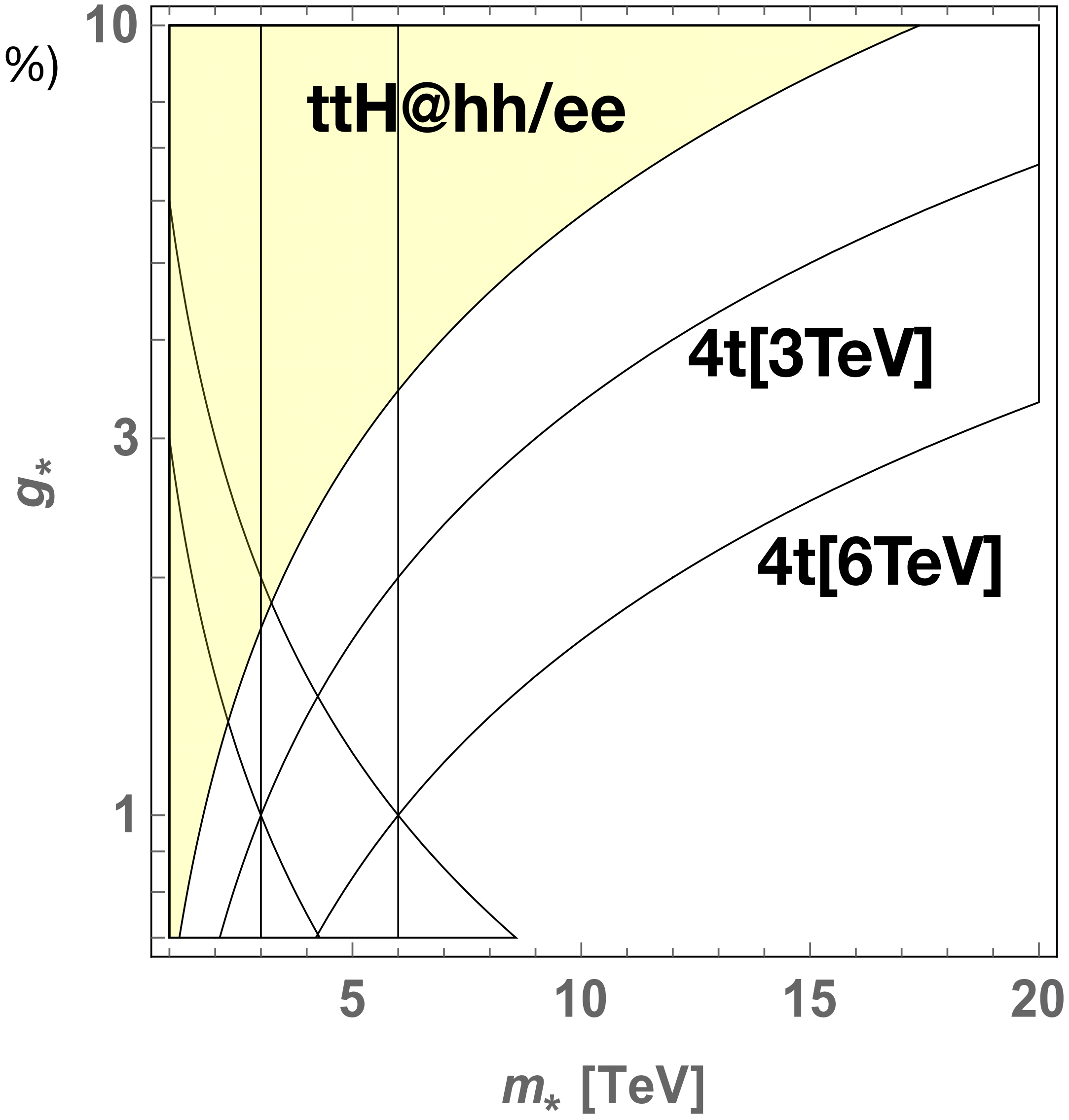
No study available (?)



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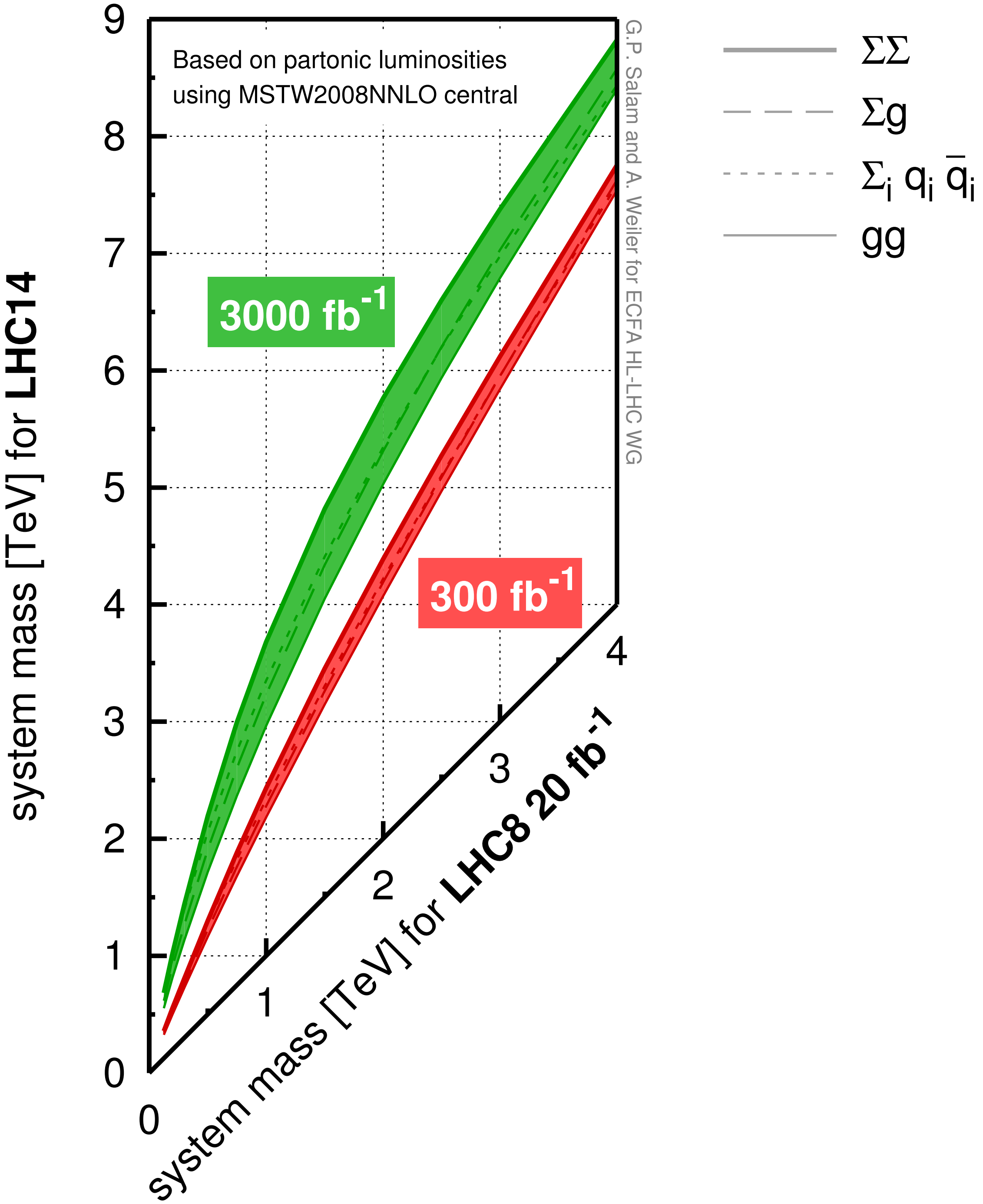
Exploration potential

New Physics

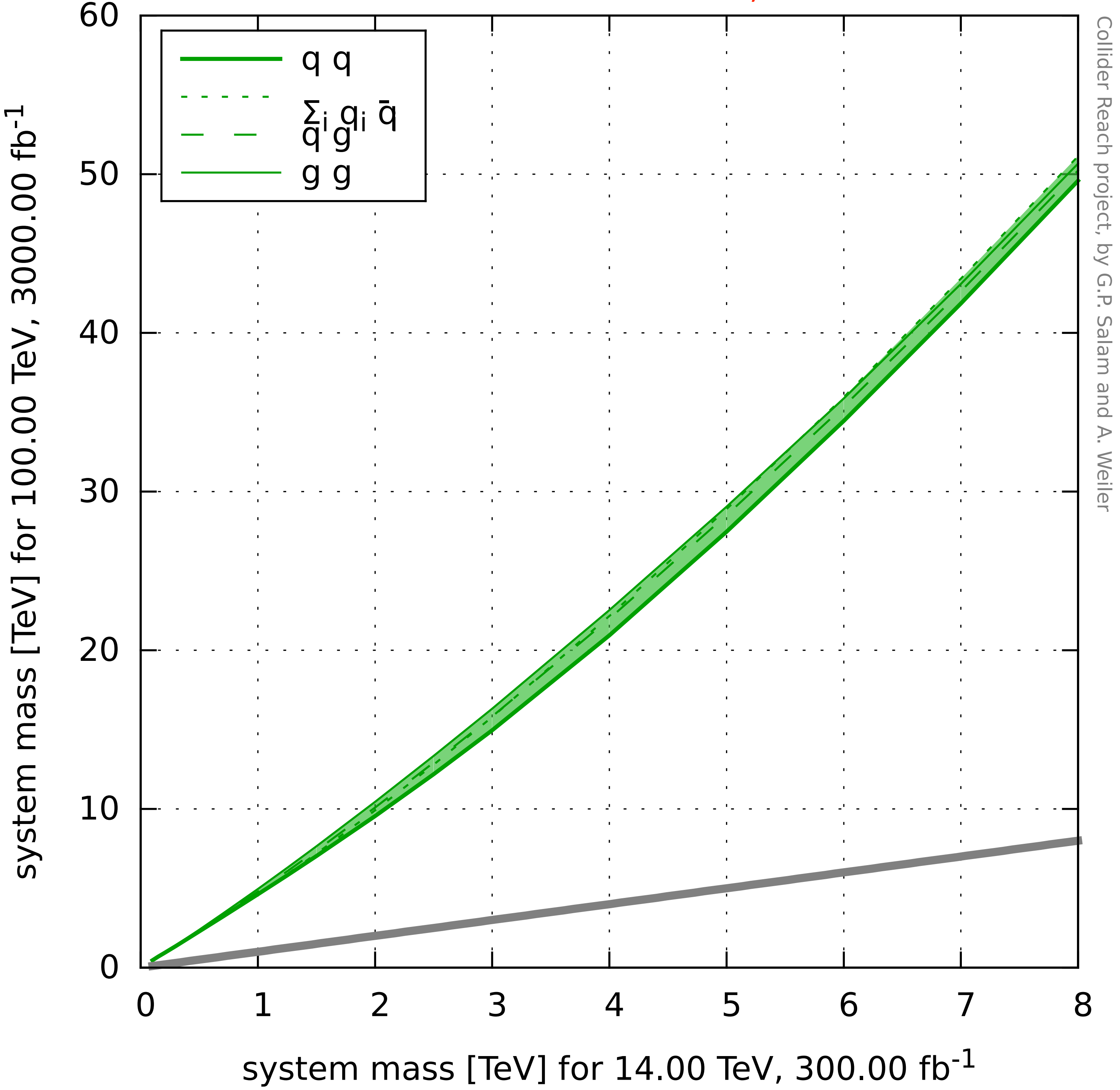
e.g. susy searches, vector resonances, extended Higgs sectors, searches for new interactions

The power of PDF

Direct exploration of an unexplored energy territory



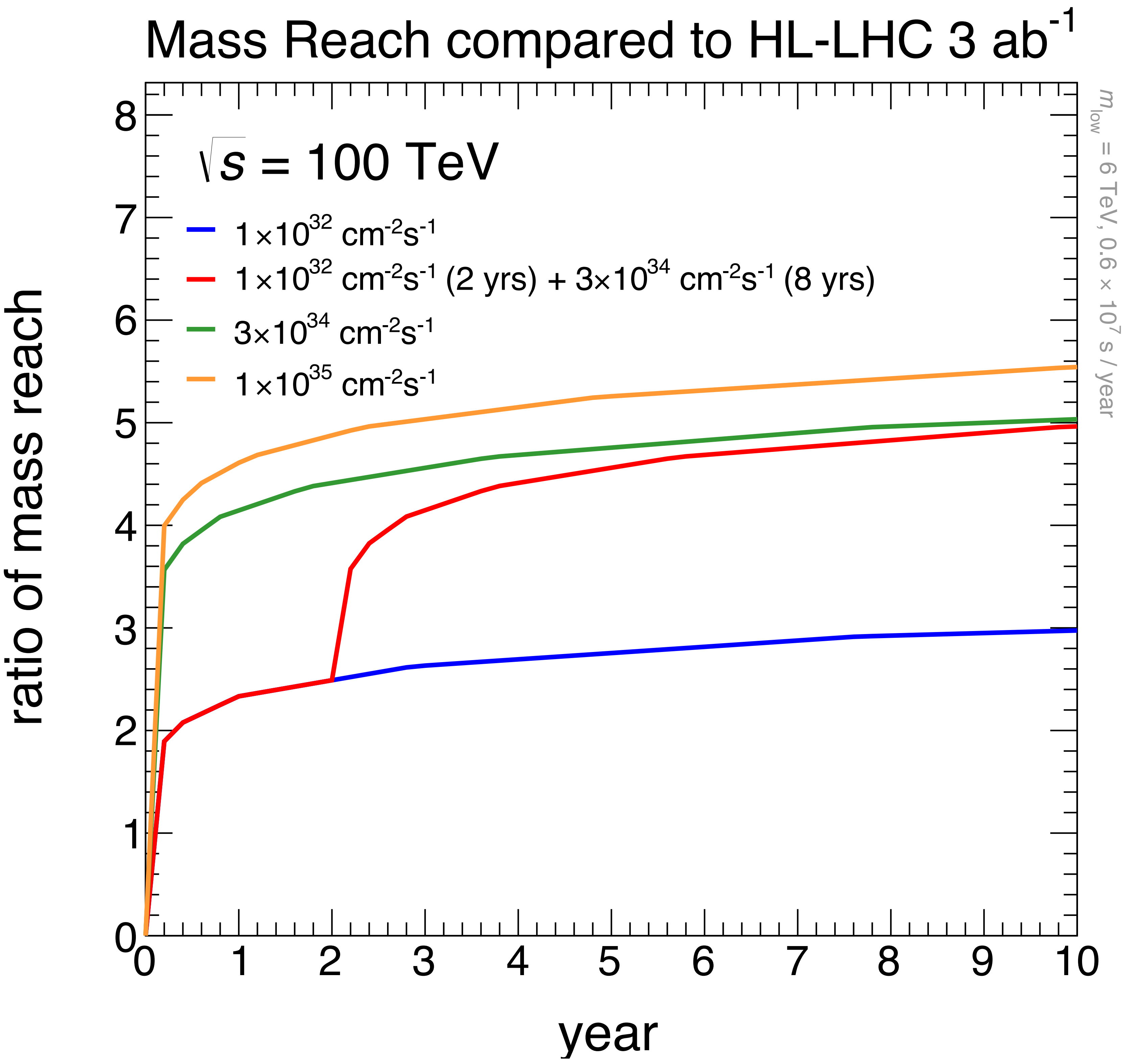
Salam & Weiler "cern.ch/collider-reach" '14



LHC$_{14}$/LHC$_8$:
mass reach x O(2)

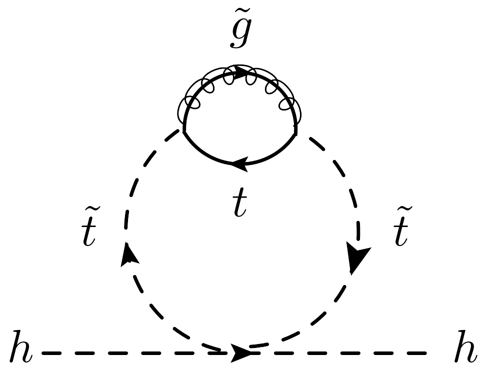
VHE-LHC$_{100}$/LHC$_{14}$:
mass reach x O(5)

The power of PDF

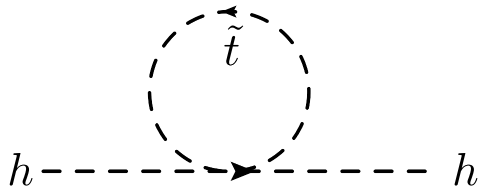


Hinchliffe, Kotwal, Mangano, Quigg, Wang ’15

I. Probing natural SUSY

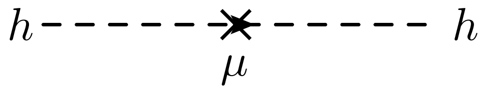


$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi} m_{gluino}^2 \left(\log\frac{\Lambda}{m_{gluino}}\right)^2$$



$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m_{stop}^2 \log\frac{\Lambda}{m_{stop}}$$

well tested @ LHC
but most questionable predictions
(RG effects)



$$\delta m_H^2 \sim |\mu|^2$$

light Higgsinos!
very low sensitivity @ LHC
ILC needed to probe the other side

I. Probing natural SUSY

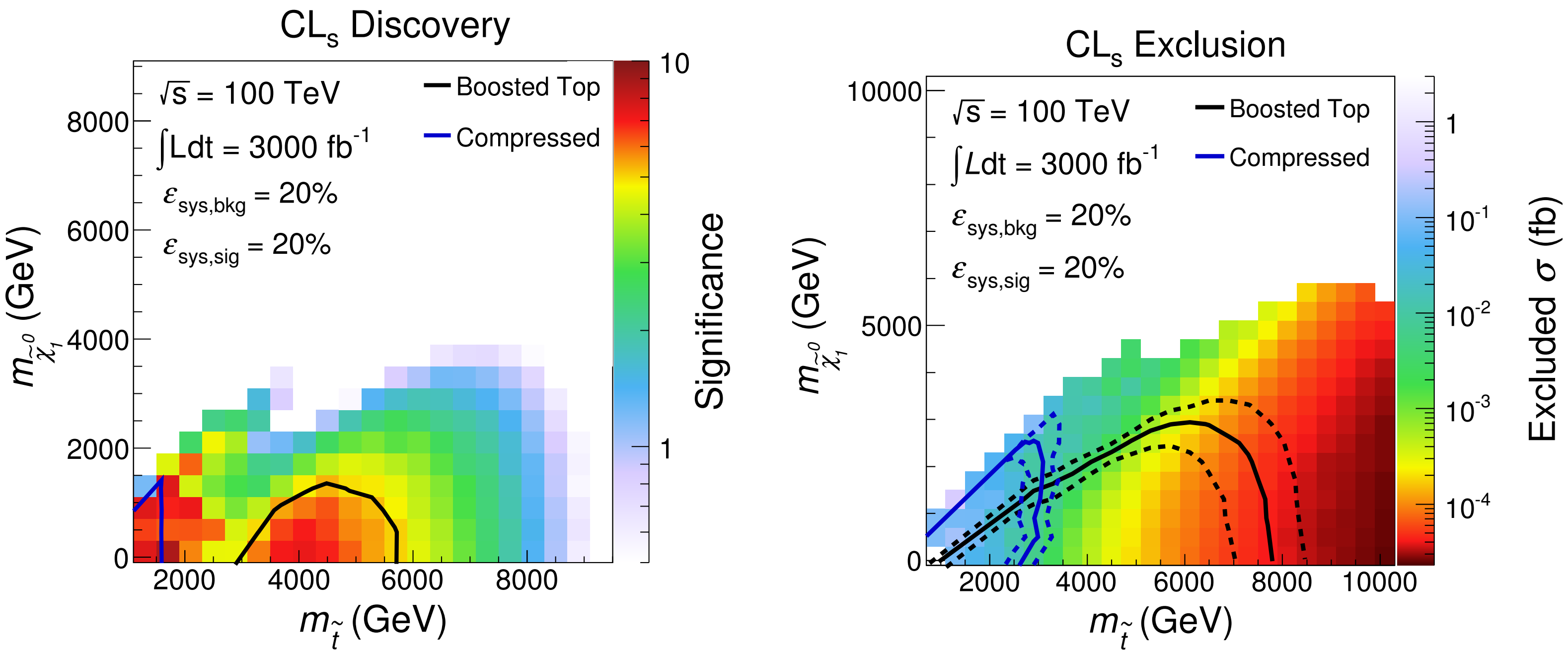


Fig. 12: Left: Discovery potential and Right: Projected exclusion limits for 3000 fb^{-1} of total integrated luminosity at $\sqrt{s} = 100$ TeV. The solid lines show the expected discovery or exclusion obtained from the boosted top (black) and compressed spectra (blue) searches. In the boosted regime we use the $\not{E}_T$ cut that gives the strongest exclusion for each point in the plane. The dotted lines in the left panel show the $\pm 1\sigma$ uncertainty band around the expected exclusion.

Collider	Energy	Luminosity	Cross Section	Mass
LHC8	8 TeV	20.5 fb^{-1}	10 fb	650 GeV
LHC	14 TeV	300 fb^{-1}	3.5 fb	1.0 TeV
HL LHC	14 TeV	3 ab^{-1}	1.1 fb	1.2 TeV
HE LHC	33 TeV	3 ab^{-1}	91 ab	3.0 TeV
FCC-hh	100 TeV	1 ab^{-1}	200 ab	5.7 TeV

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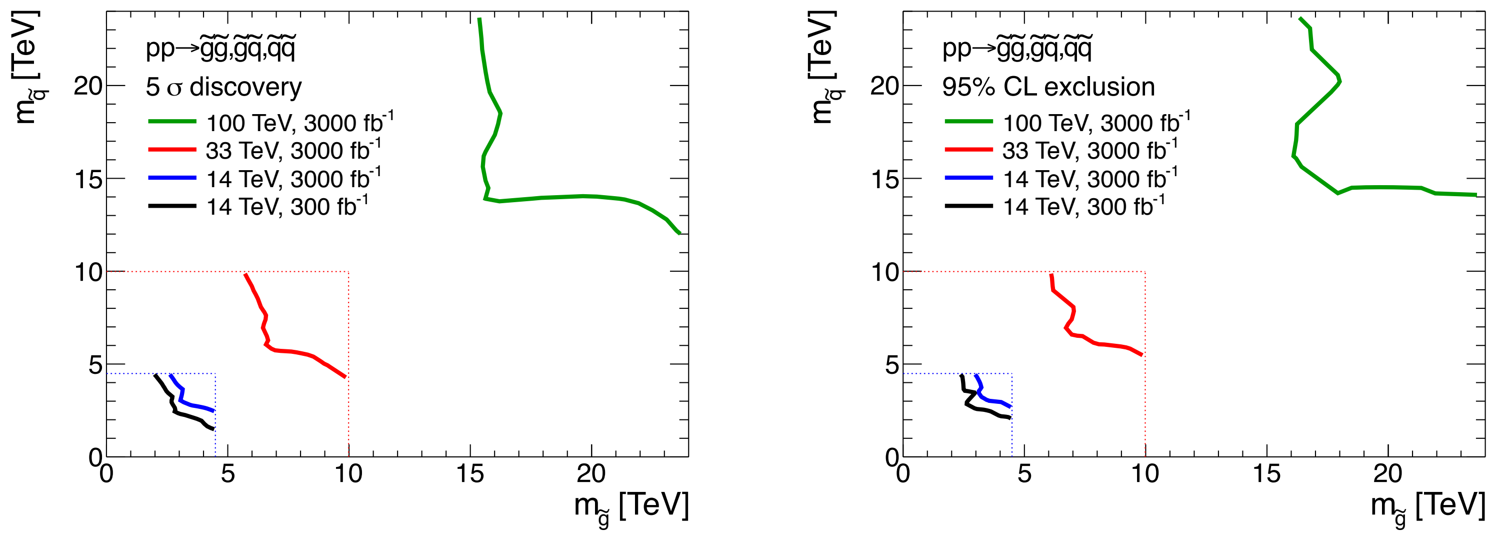
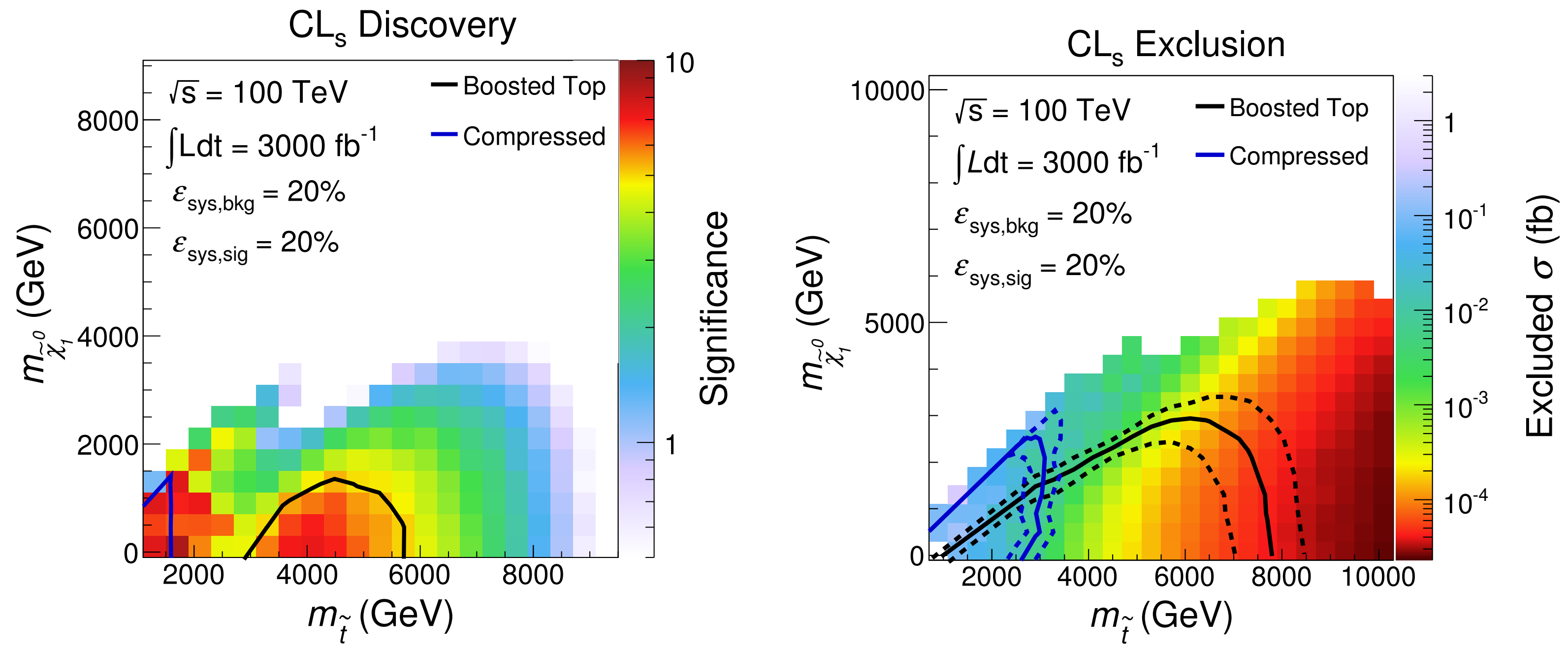


Fig. 16: Results for the gluino-squark-neutralino model. The neutralino mass is taken to be 1 GeV. The left [right] panel shows the $5\,\sigma$ discovery reach [95% CL exclusion] for the four collider scenarios studied here. A 20% systematic uncertainty is assumed and pile-up is not included.



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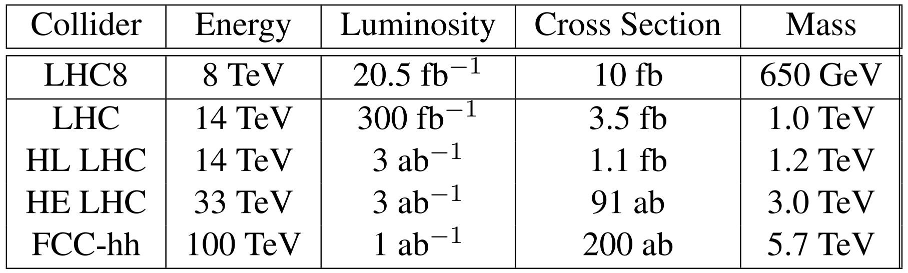

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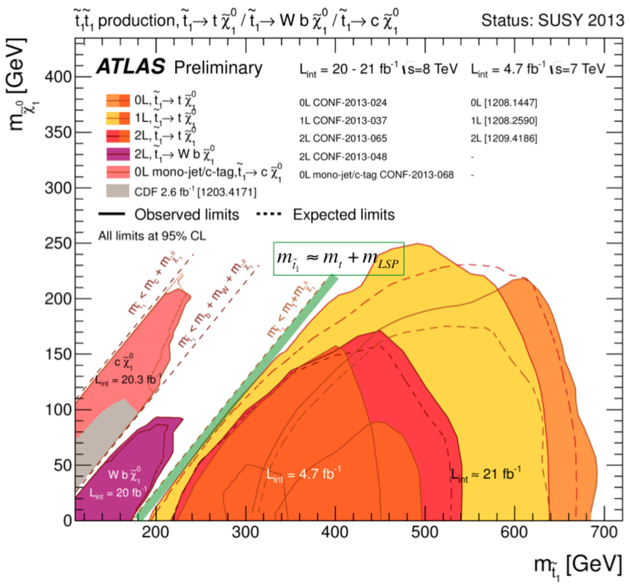
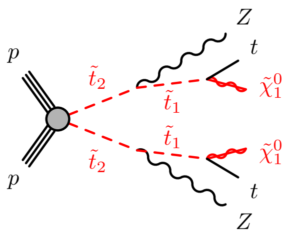
I. Natural SUSY: beyond standard searches

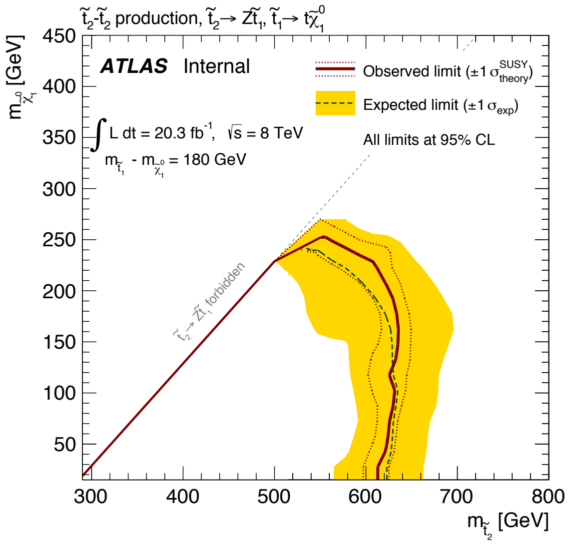
Searching for light stop from heavy stop decay

~ RUN 1 ~



- 2012 (20 fb^{-1}): stops searches based on $\tilde{t}_1\tilde{t}_1$ production, with $\tilde{t}_1 \to t\tilde{\chi}_1^0$ or $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$
- No sensitivity for $\tilde{t}_1 \to t\tilde{\chi}_1^0$ with $m_{\tilde{t}_1} \gtrsim m_{\tilde{\chi}_1^0} + m_t$: very similar to SM $t\bar{t}$
- **[New at the LHC]** Production of the heavier stop mass eigenstate ($\tilde{t}_2$) relying on the $\tilde{t}_2 \to Z\tilde{t}_1$ decay to reduce $t\bar{t}$ → Signature: $Z(\ell^+\ell^-)+\ell+b+E_T^{\rm miss}$
- Eur. Phys. J. C **74** (2014) 2883 (20 fb^{-1})

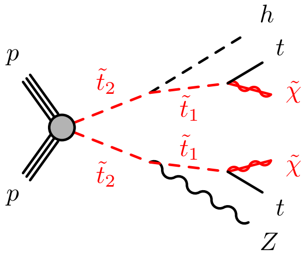


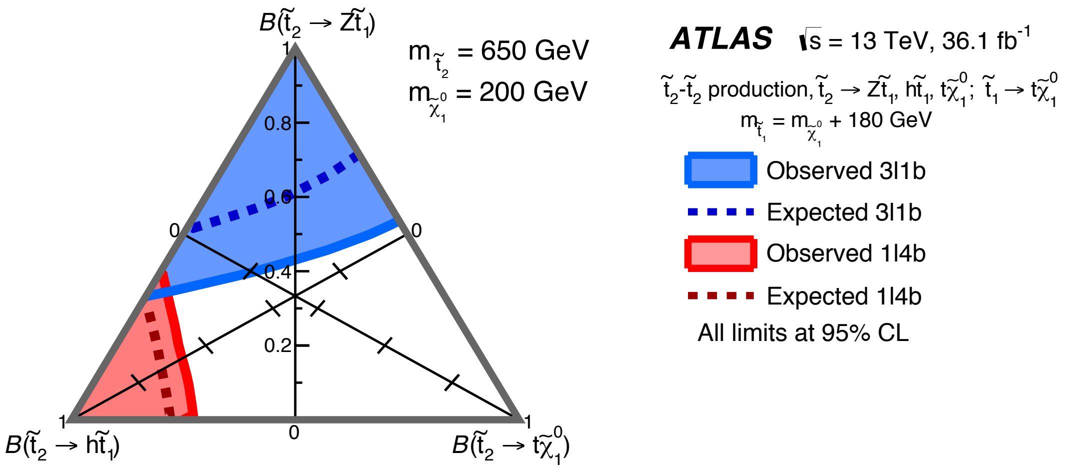


X. Poveda @ DESY'17

~ RUN 2 ~

- ATLAS-CONF-2016-038 (13 fb^{-1}): explore $\tilde{t}_2 \to Z\tilde{t}_1$ with $\boxed{3\ell+b+E_T^{\rm miss}}$
- JHEP **1708** (2017) 006 (36 fb^{-1}): analysis extended to $\tilde{t}_2 \to h\tilde{t}_1$ with $\boxed{1\ell+4b+E_T^{\rm miss}}$
- Interpretations for varying BRs in $\tilde{t}_2 \to h\tilde{t}_1/Z\tilde{t}_1$ and also for $\tilde{t}_1 \to t\chi_2^0$, $\chi_2^0 \to h/Z\tilde{\chi}_1^0$





II. Probing Compositeness: fermions

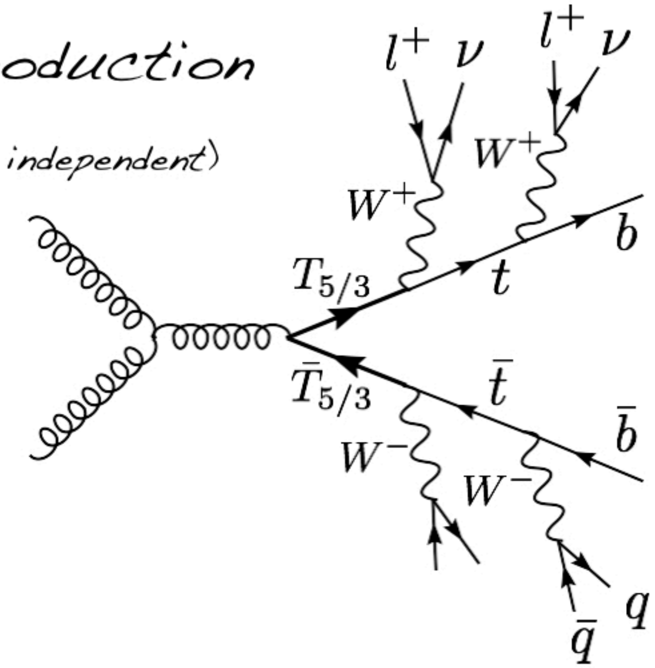
(aka vector-like quarks)

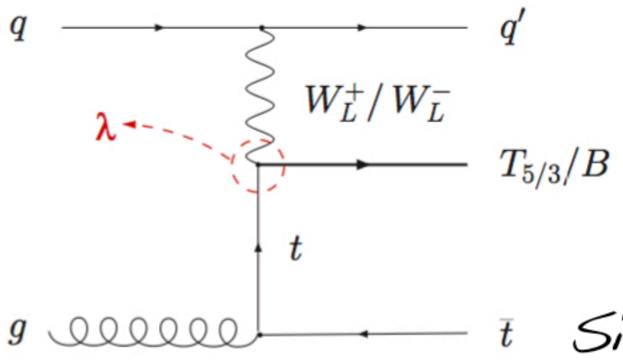
Search in same-sign dilepton events

- $t\bar{t}$+jets is not a background [except for charge mis-ID and fake e^-]
- the resonant (tW) invariant mass can be reconstructed

Pair production

(model independent)

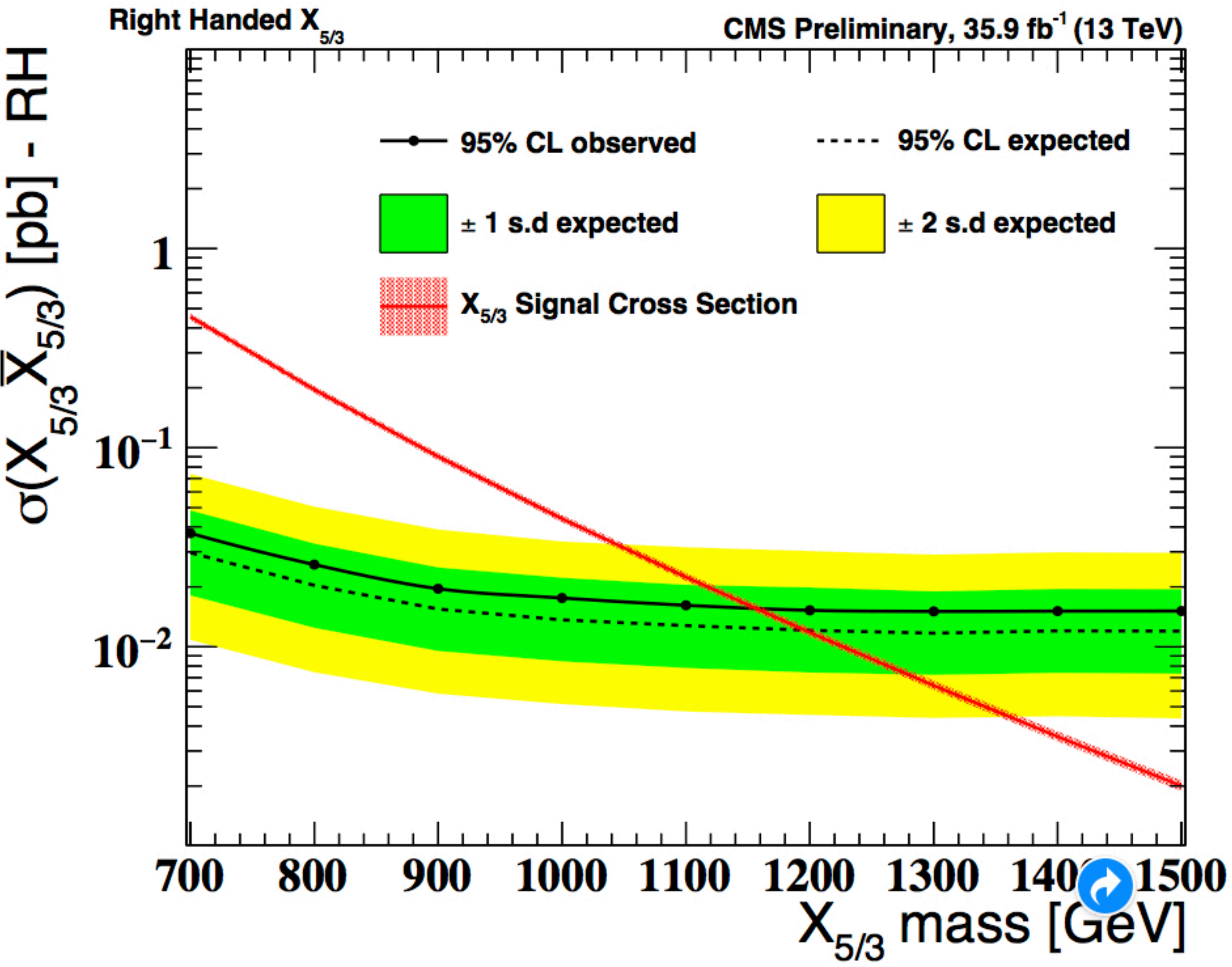




Single production

(model dependent)

Moriond'17 bound: 1160 GeV



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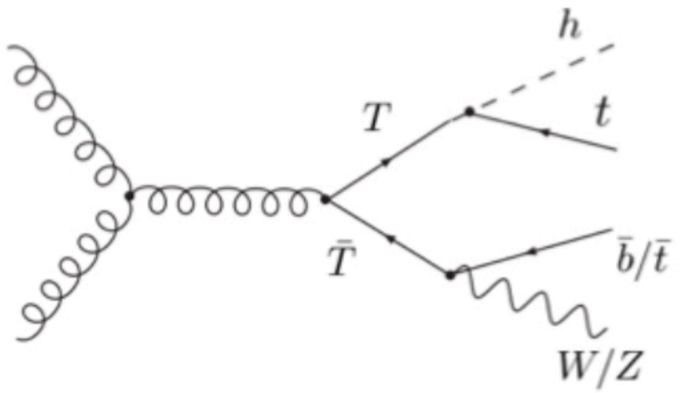


- $\ell^\pm$ + 4b final state Aguilar-Saavedra '09

  $T\bar T \to HtW^-\bar b \to HW^+bW^-\bar b$ $\quad H\to b\bar b, WW\to \ell\nu q\bar q'$,

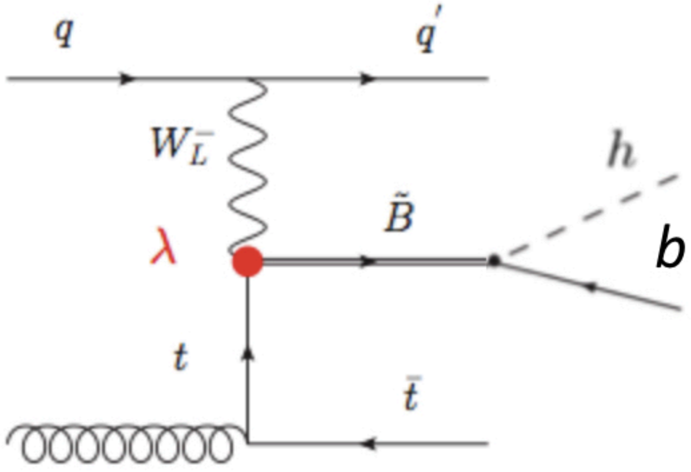
  $T\bar T \to HtV\bar t \to HW^+bVW^-\bar b$ $\quad H\to b\bar b, WW\to \ell\nu q\bar q', V\to q\bar q/\nu\bar\nu$

- $\ell^\pm$ + 6b final state Aguilar-Saavedra '09

  $T\bar T \to HtH\bar t \to HW^+bHW^-\bar b$ $\quad H\to b\bar b, WW\to \ell\nu q\bar q'$

- $\gamma\gamma$ final state Azatov et al '12

  $thbW/thtZ/thth,\ h\to\gamma\gamma$

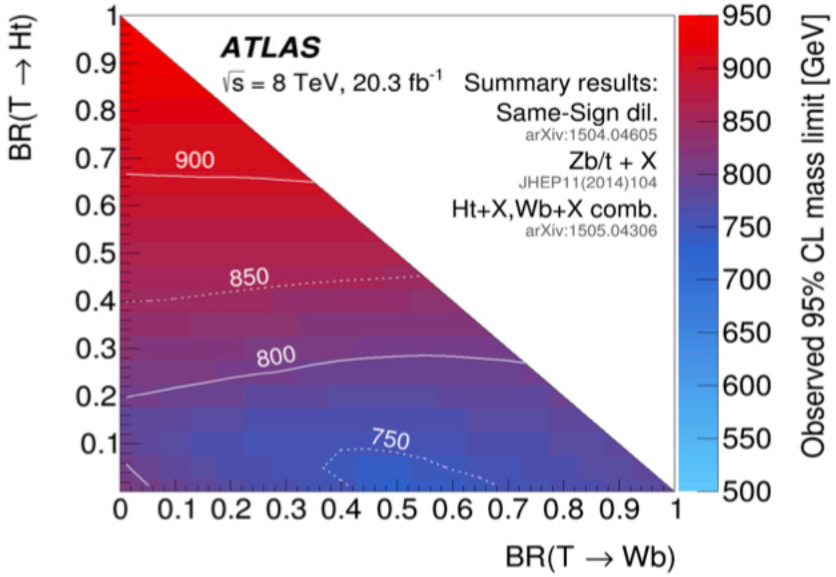


- $\ell^\pm$ + 4b final state Vignaroli '12

  $pp\to(\tilde B\to(h\to bb)b)t+X$

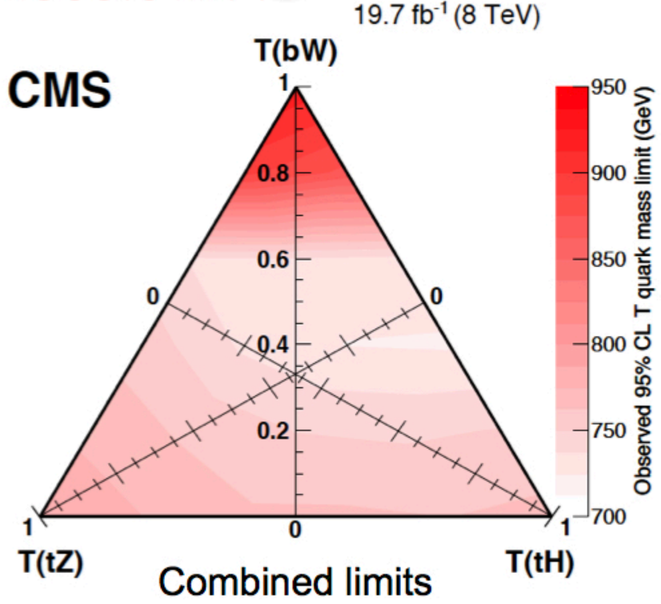
Moriond'17 update
bounds above 1 TeV!

1505.04306



(*) Not a combination. Only most restrictive individual bounds shown.

1509.04177

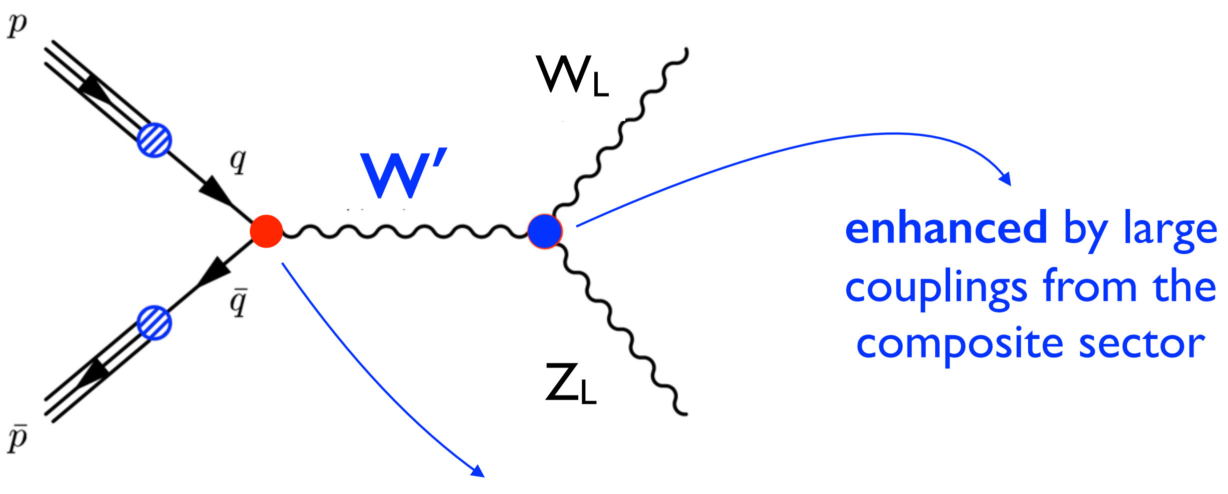


Combined limits

II. Probing Compositeness: vectors

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Torre, Thamm, Wulzer '15

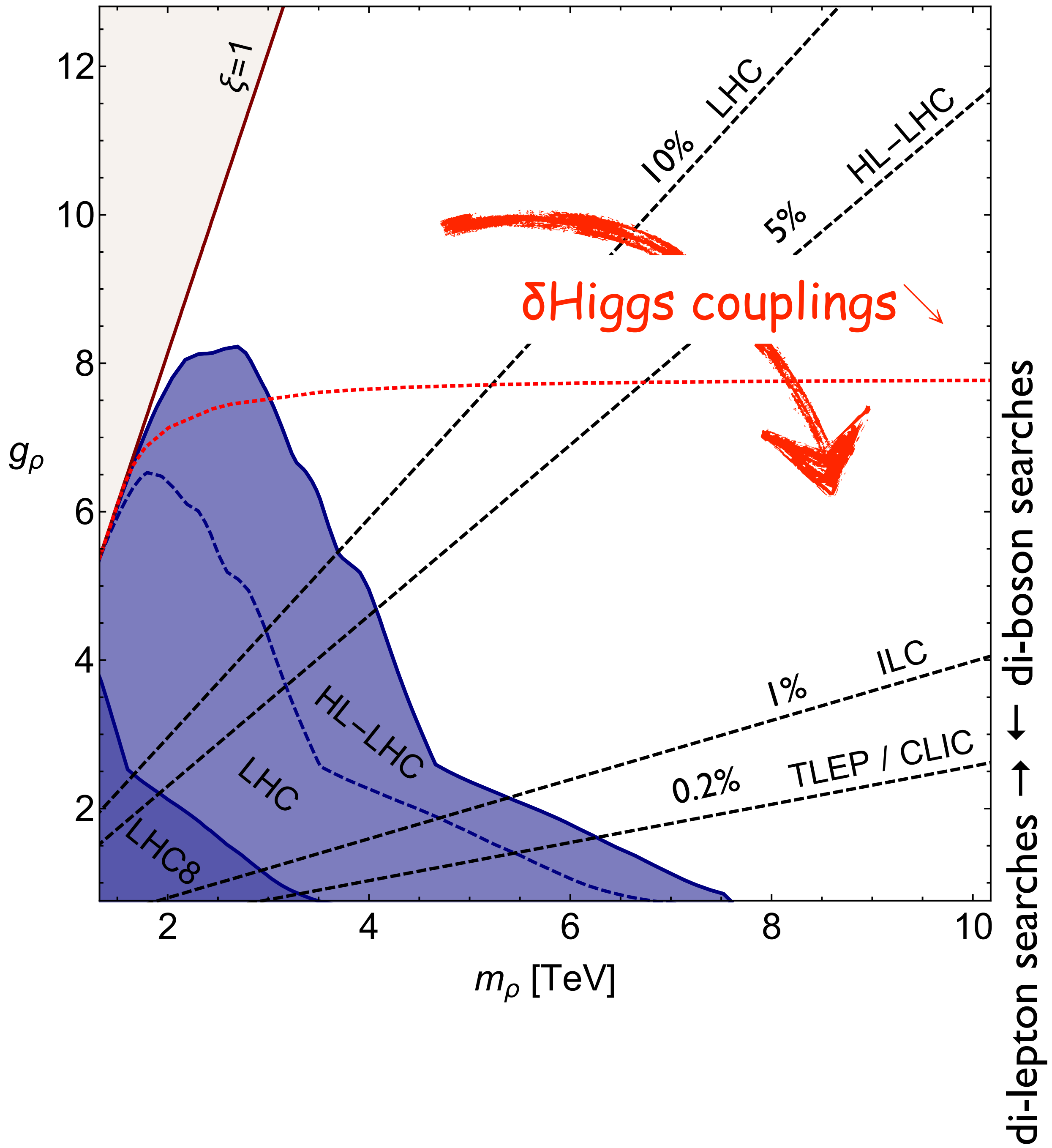


enhanced by large couplings from the composite sector

suppressed by large couplings from the composite sector

W' couples to SM fermions via its mixing to W: $\dfrac{g_{SM}^2}{g_\rho}$

DY production xs of resonances decreases as $1/g_\rho^2$



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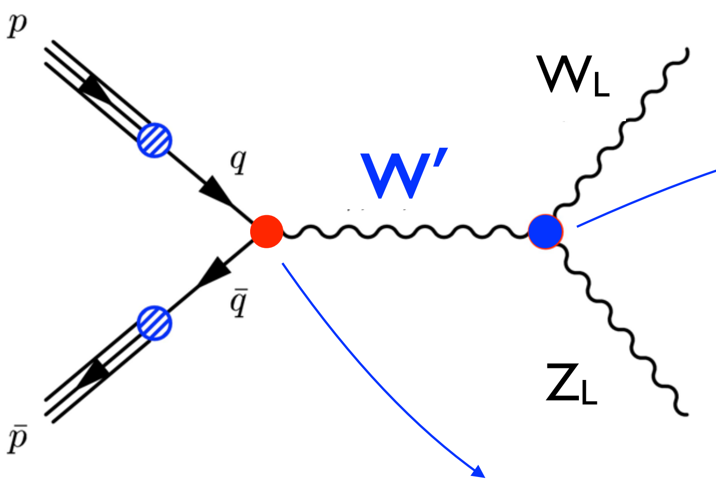

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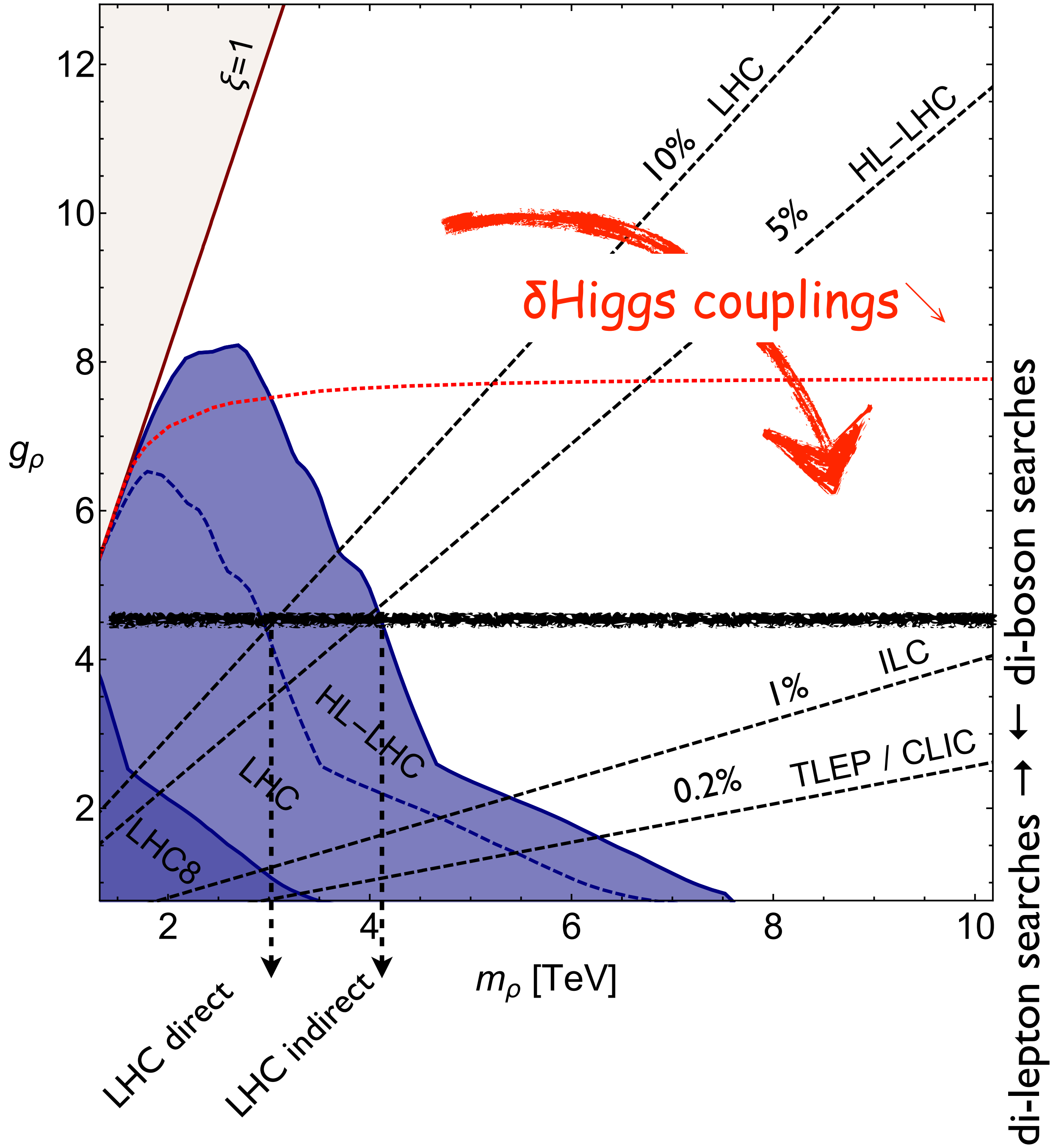

- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

e.g.
indirect searches at LHC over-perform direct searches for g > 4.5
indirect searches at ILC over-perform direct searches at HL-LHC for g > 2

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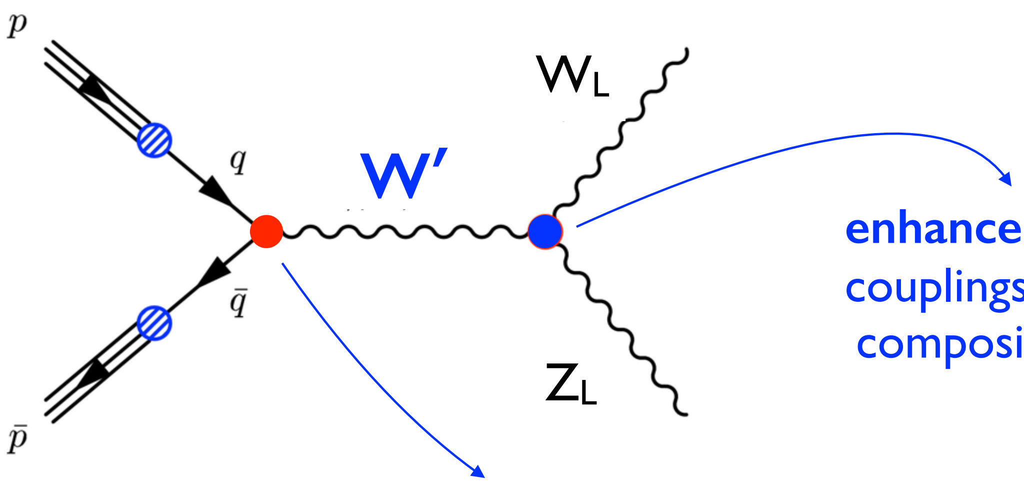

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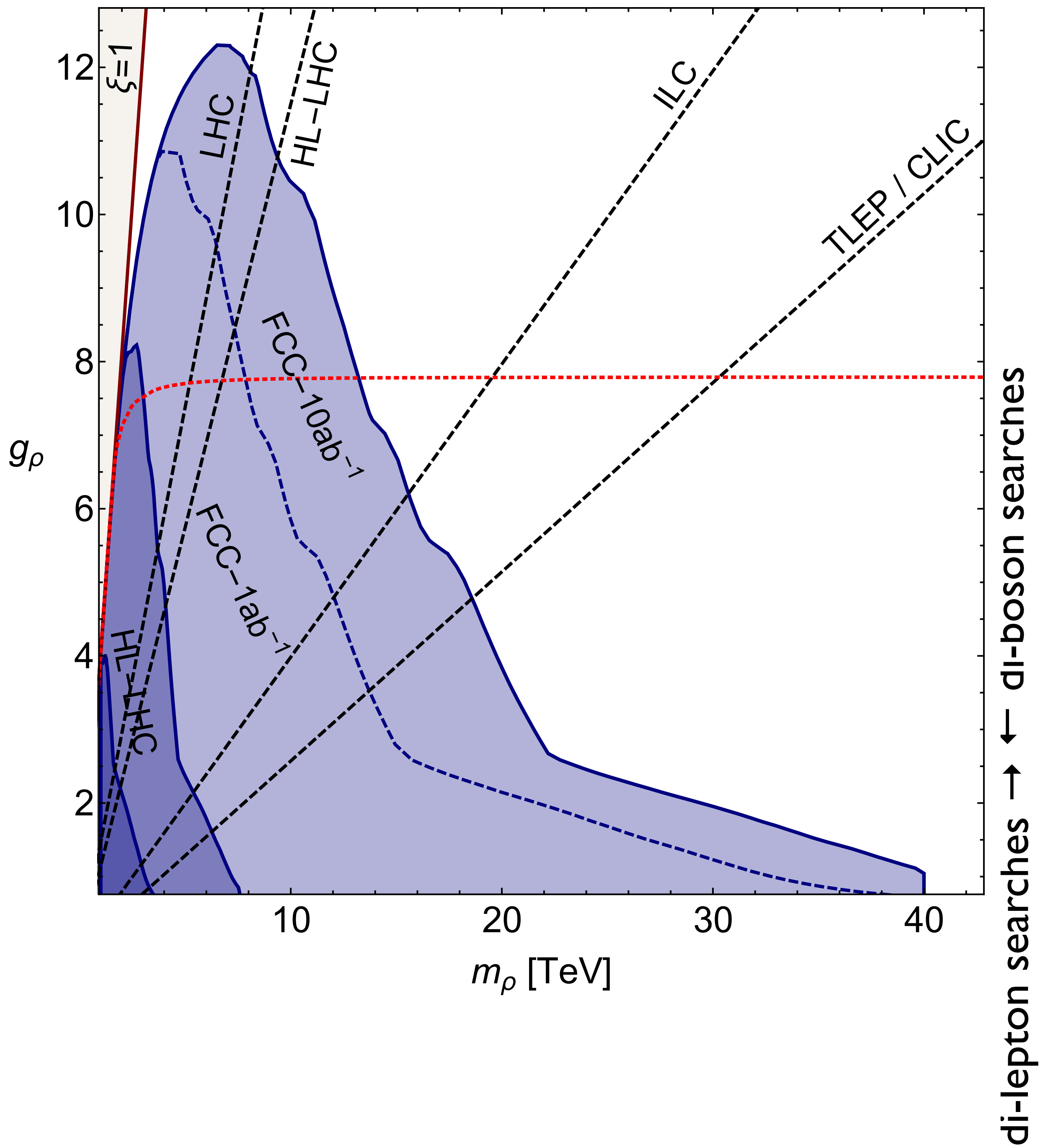

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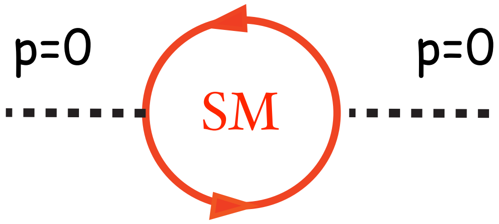
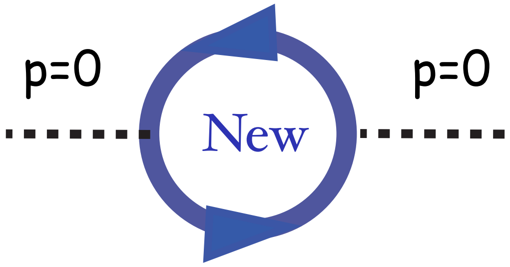
III. Other Naturalness

$$-(125\ \text{GeV})^2\left(\frac{\Lambda}{600\ \text{GeV}}\right)^2 \qquad\qquad \frac{g_*^2}{16\pi^2}\Lambda^2$$

$\delta m_H^2 =$



$+$



$\sim m_H^2$

generically

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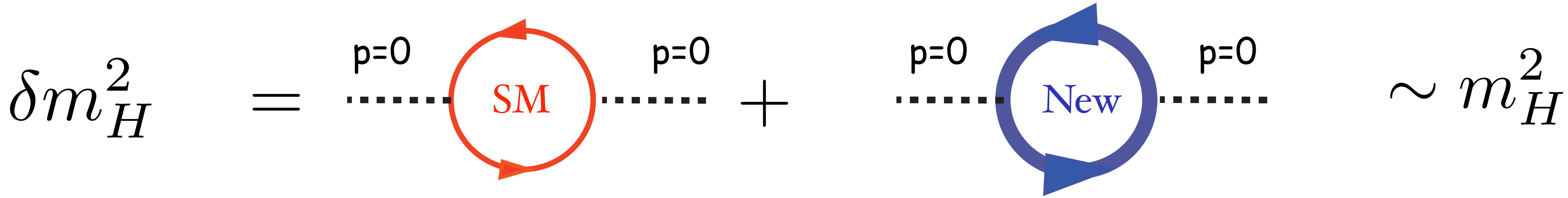
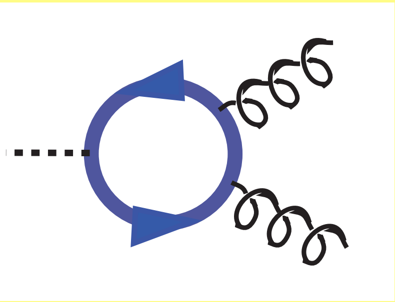


charged particles

generically



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad\qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\mathrm{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$

Colorful naturalness probed @ LHC

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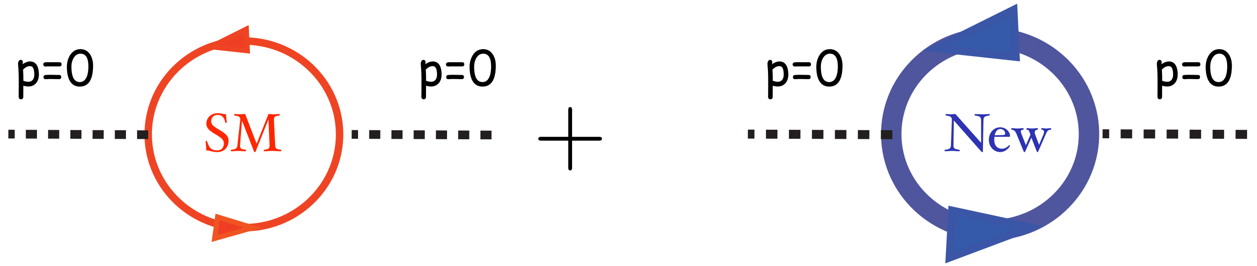
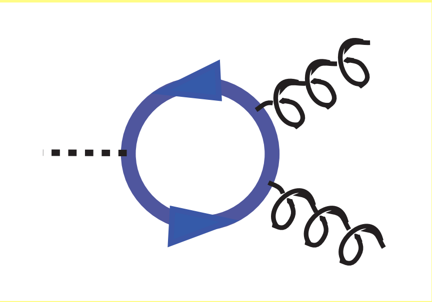


$\sim m_H^2$

charged particles

generically

neutral particles



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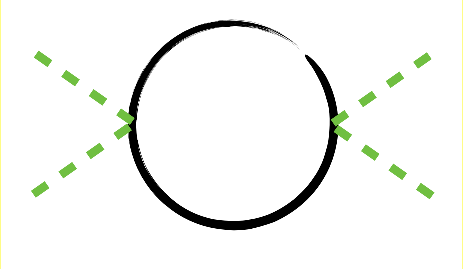

$$\frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

$$BR(h\to ii) = BR_{\text{SM}} \qquad \Gamma = \left(1-\frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

$$\delta\sigma_{Zh} = -\frac{g_\star^2}{8\pi^2}\frac{v^2}{m_\star^2}$$

nice to be able to measure Zh & Γ

Colorful naturalness probed @ LHC

Neutral naturalness (invisible?) @ LHC

aka twin Higgs

III. Other Naturalness

" Looking and not finding is different than not looking "

giving the null search results, the top partners should either be

- **heavy** (harder to produce because of phase space)
- **stealthy** (easy to produce but hard to distinguish from background, e.g. $m_{stop} \sim m_{top}$)
- **colorless** (hard to produce, unusual decay)

need to go beyond traditional searches

	Scalar Top Partner	Fermion Top Partner
All SM Charges	SUSY	pNGB/RS
EW Charges	Folded SUSY	Quirky Little Higgs
No SM Charges	???	Twin Higgs

only little corner
of theory/model space
has been explored so far

require **hidden QCD**
with a higher confining scale:

⇒ 1) hidden glueball (0^{++}) that can mix with Higgs
$h \rightarrow G_0 G_0 \rightarrow 4l$ with displaced vertices

Curtin, Verhaaren '15

⇒ 2) emerging jets

Schwaller, Stolarski, Weiler '15

(C. Verhaaren@NKPI'16)

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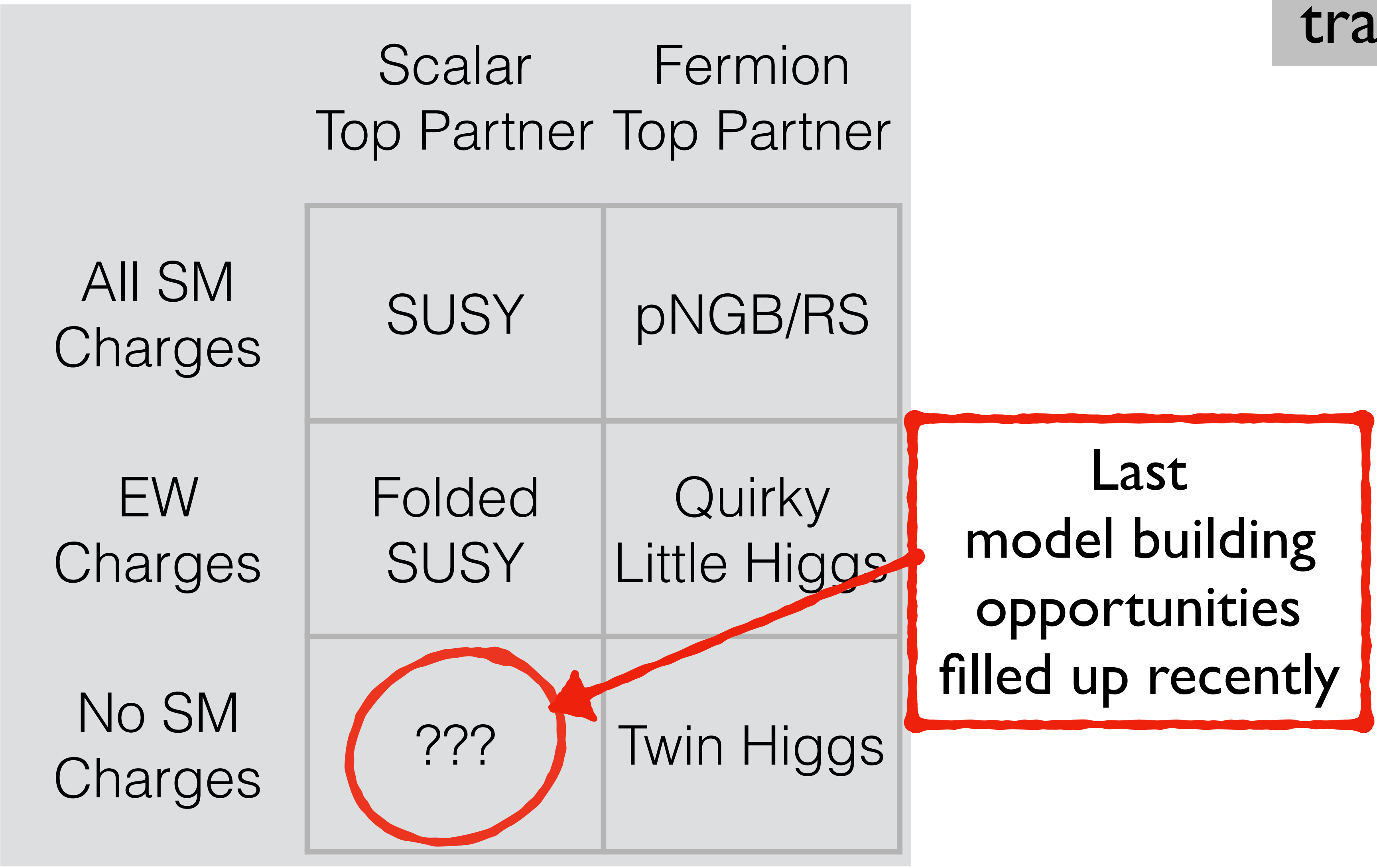
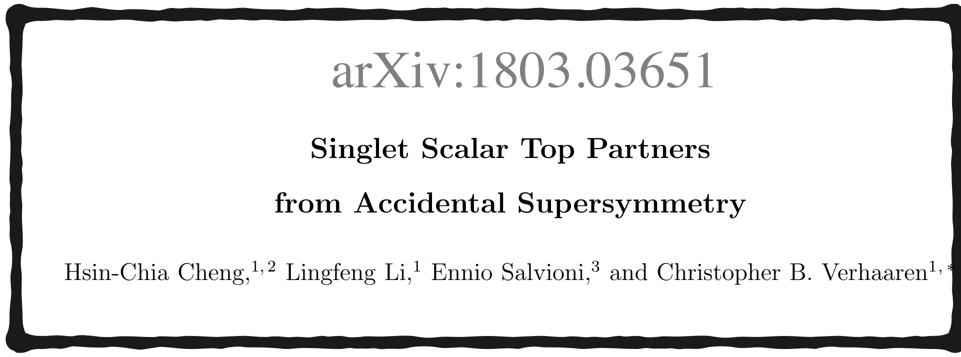
(C. Verhaaren)



	Scalar Top Partner	Fermion Top Partner
All SM Charges	SUSY	pNGB/RS
EW Charges	Folded SUSY	Quirky Little Higgs
No SM Charges	???	Twin Higgs

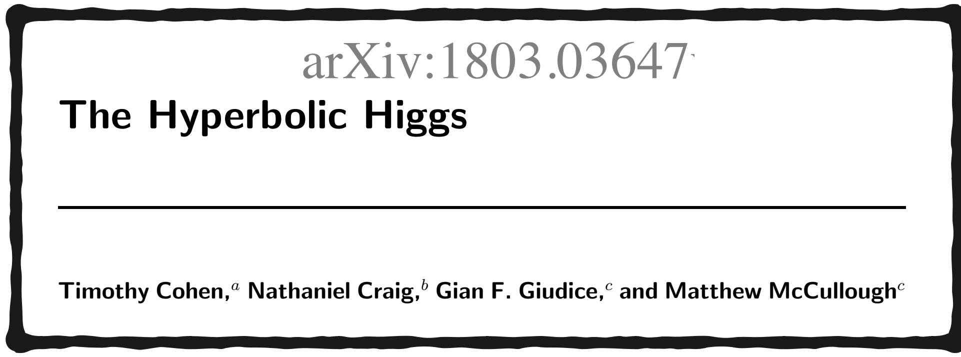
Last model building opportunities filled up recently



arXiv:1803.03651

Singlet Scalar Top Partners from Accidental Supersymmetry

Hsin-Chia Cheng,[1,2] Lingfeng Li,[1] Ennio Salvioni,[3] and Christopher B. Verhaaren[1,*]

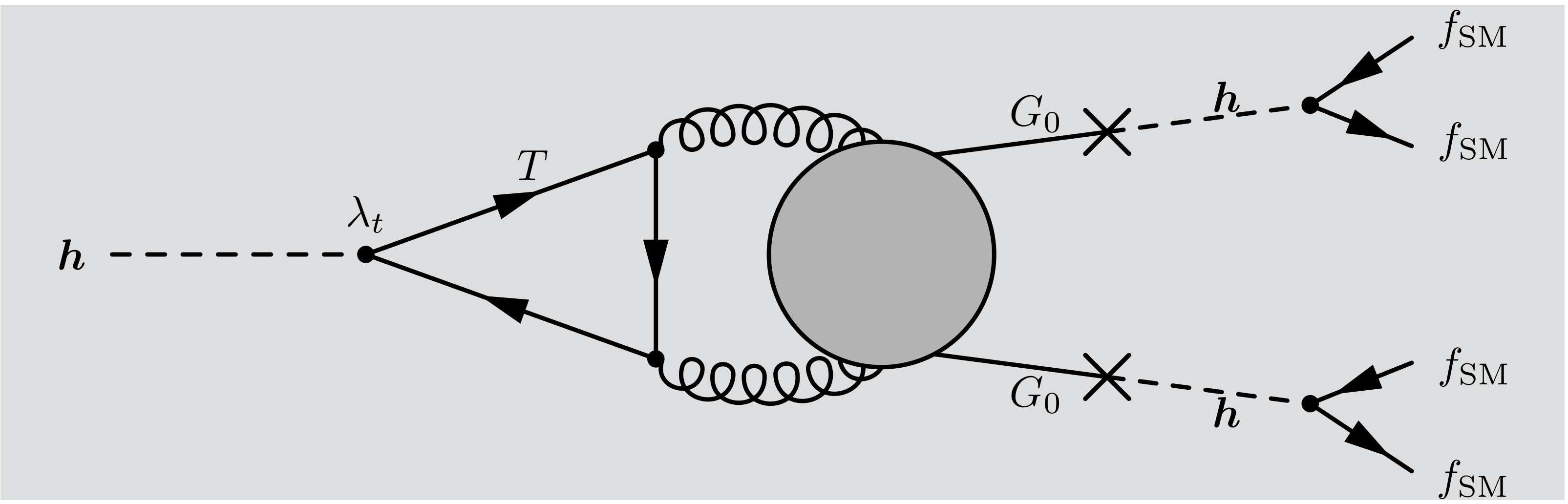


arXiv:1803.03647

The Hyperbolic Higgs

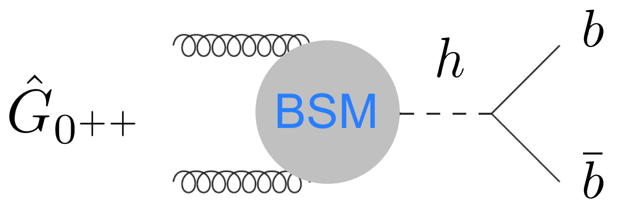
Timothy Cohen,[a] Nathaniel Craig,[b] Gian F. Giudice,[c] and Matthew McCullough[c]

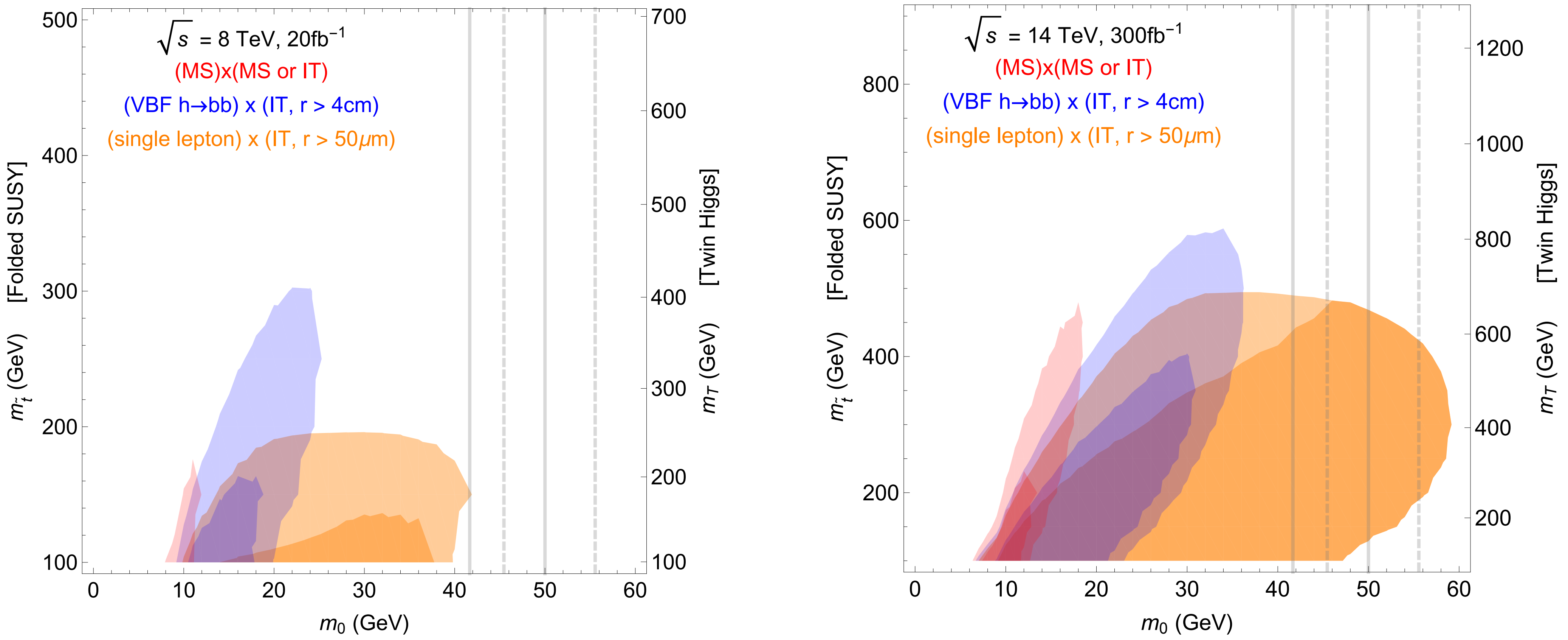
III. Neutral Naturalness



top parters are EW charged: m>100GeV (LEP)
Lightest hidden states are glueballs of QCD'
that can mix with the Higgs boson

Exotic Higgs decays with displaced vertices

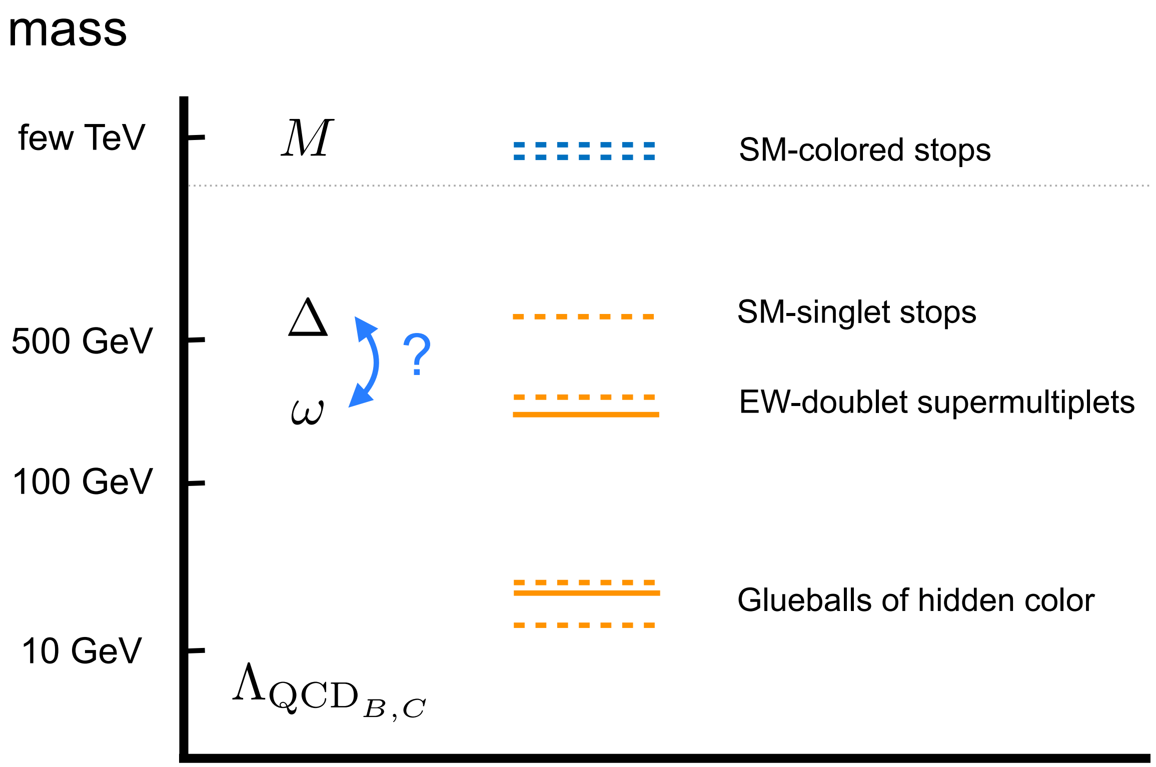




Curtin, Verhaaren '15

III. Singlet scalar top partners

Cheng, Li, Savlioni, Verhaaren ’18

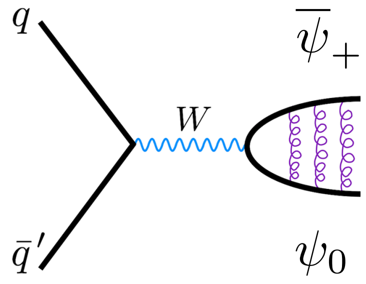


Rich opportunities for B2G

Same pheno as twin Higgs/folded susy

Fermions have larger Drell-Yan production than scalars,

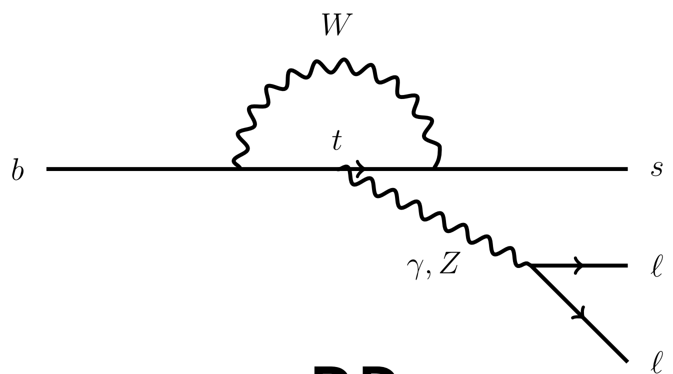
$$Q_{B,C} \sim \mathbf{2}_{-1/2} \sim \begin{pmatrix}\psi_0\\ \psi_-\end{pmatrix}$$



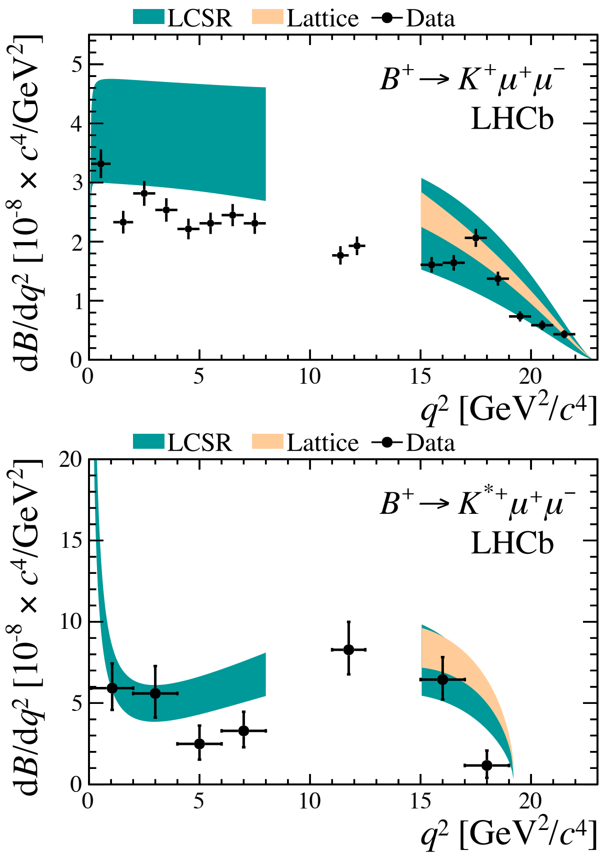
“quirky” bound state

de-excites down to ground state via emission of **soft photons**

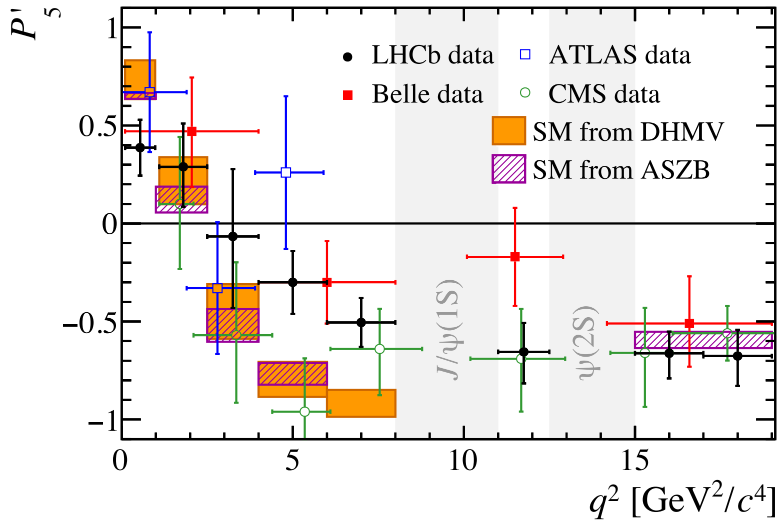
IV. New Physics hints from Flavour



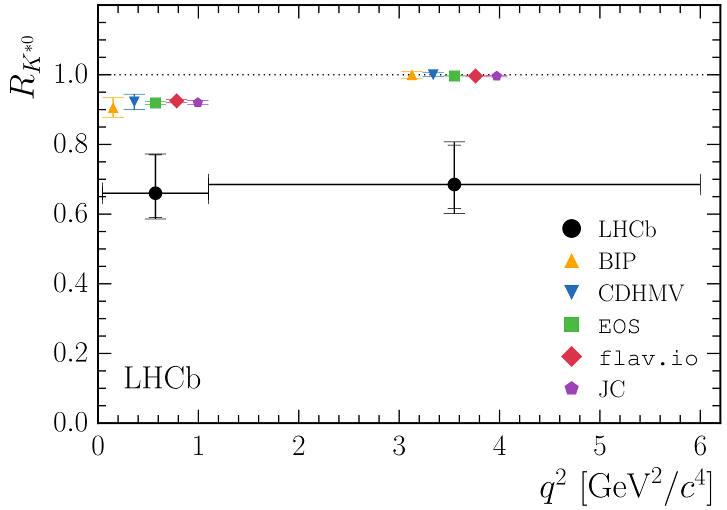
BR

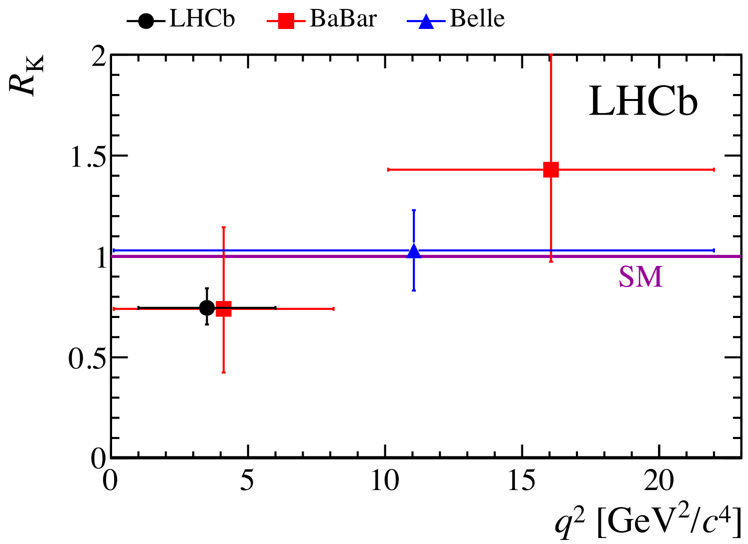


Angular distributions



LFU violation





Deviations from the SM appeared in the last years in observables in $b \to s\ell^+\ell^-$ and semileptonic decays in LHCb.

They were confirmed by measurements from other experiments.

The deviations show a consistent pattern and in combination (might) become significant (see Sebastian's talk on Thursday).

M. De Cian @ SM@LHC'18

IV. New Physics hints from Flavour

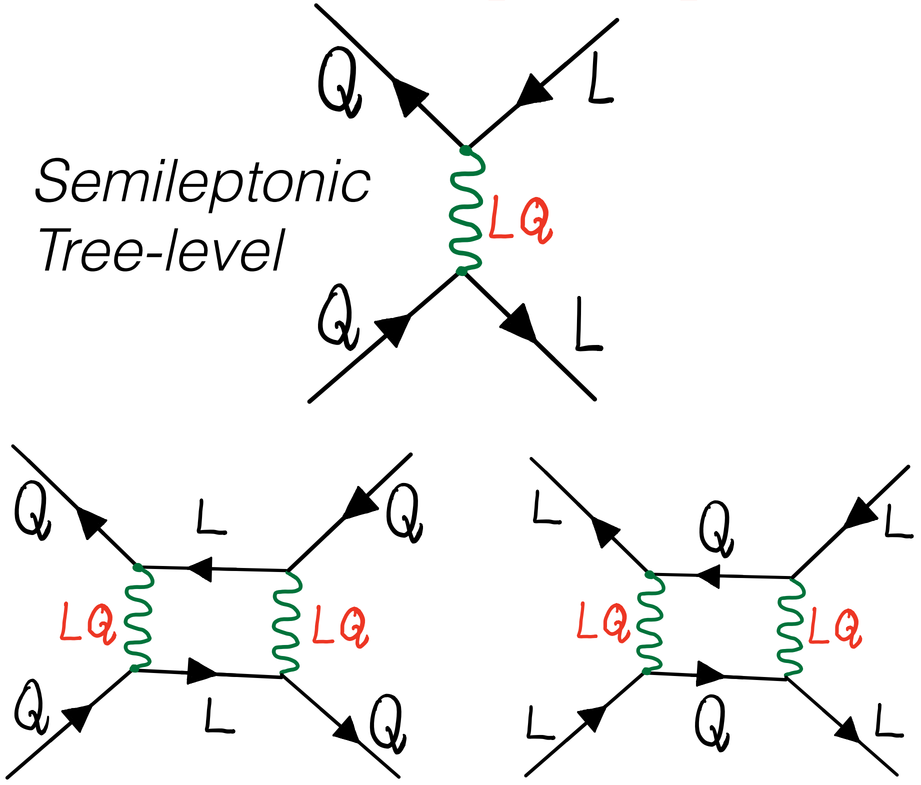
A. Greljo @ Zurich WS '18

Essentials of (most) models

$$\mathscr{L}^{\text{SMEFT}} \supset$$
$$\frac{c^{(3)}_{Q_{ij}L_{kl}}}{\Lambda^2}(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}_k\gamma^\mu\sigma_a L_l)+\frac{c^{(1)}_{Q_{ij}L_{kl}}}{\Lambda^2}(\bar{Q}_i\gamma_\mu Q_j)(\bar{L}_k\gamma^\mu L_l)$$

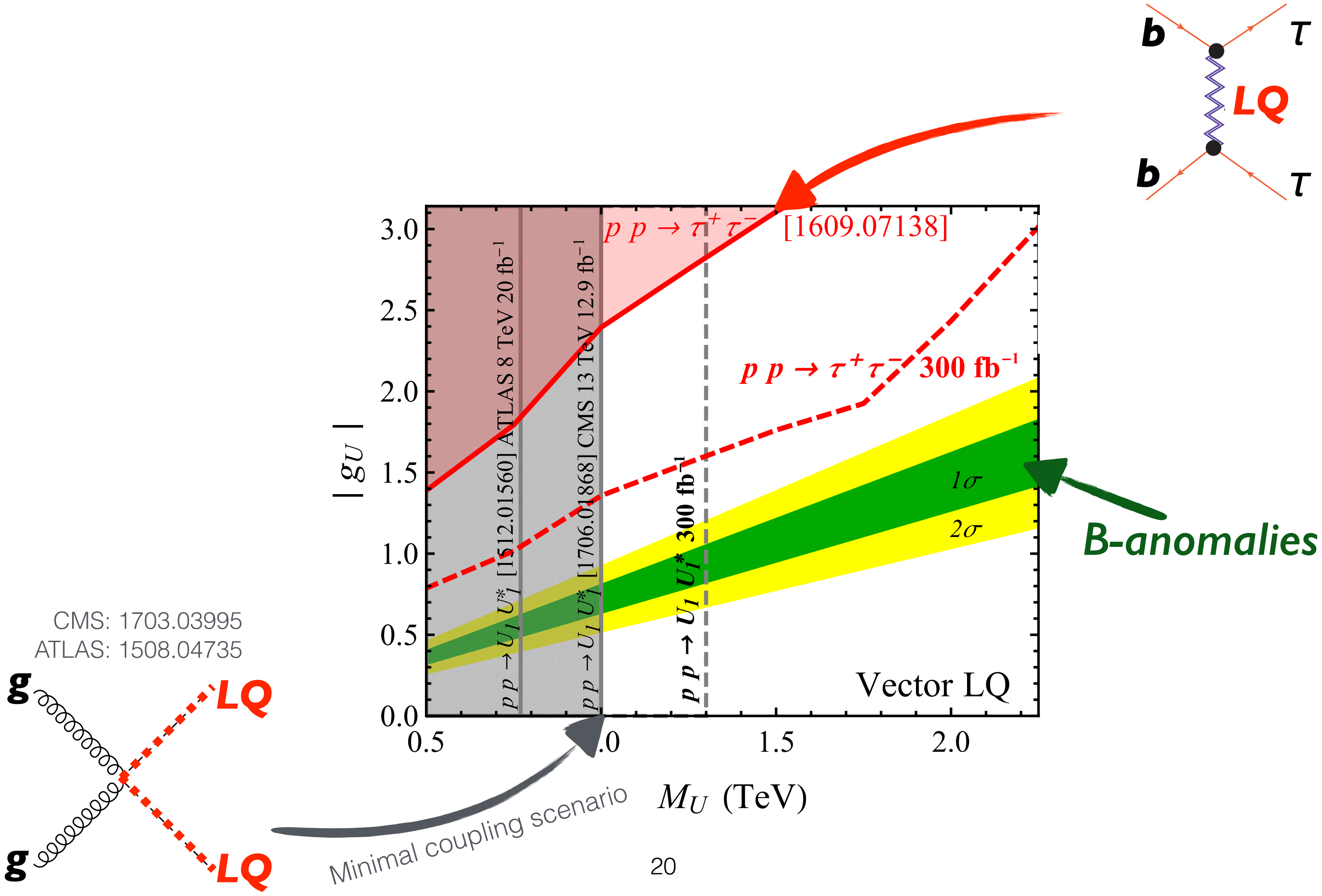
$$Q_i = (V^*_{ji}u^j_L, d^i_L)^T$$
$$L_i = (\nu^i_L, \ell^i_L)^T$$

Example: **Leptoquark**



Semileptonic
Tree-level

Suppression in 4Q and 4L operators



CMS: 1703.03995
ATLAS: 1508.04735

IV. New Physics hints from Flavour

Essentials of (most) models

A. Greljo @ Zurich WS '18

$$\mathscr{L}^{\rm SMEFT} \supset$$

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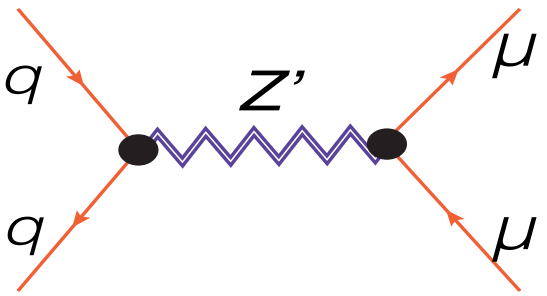
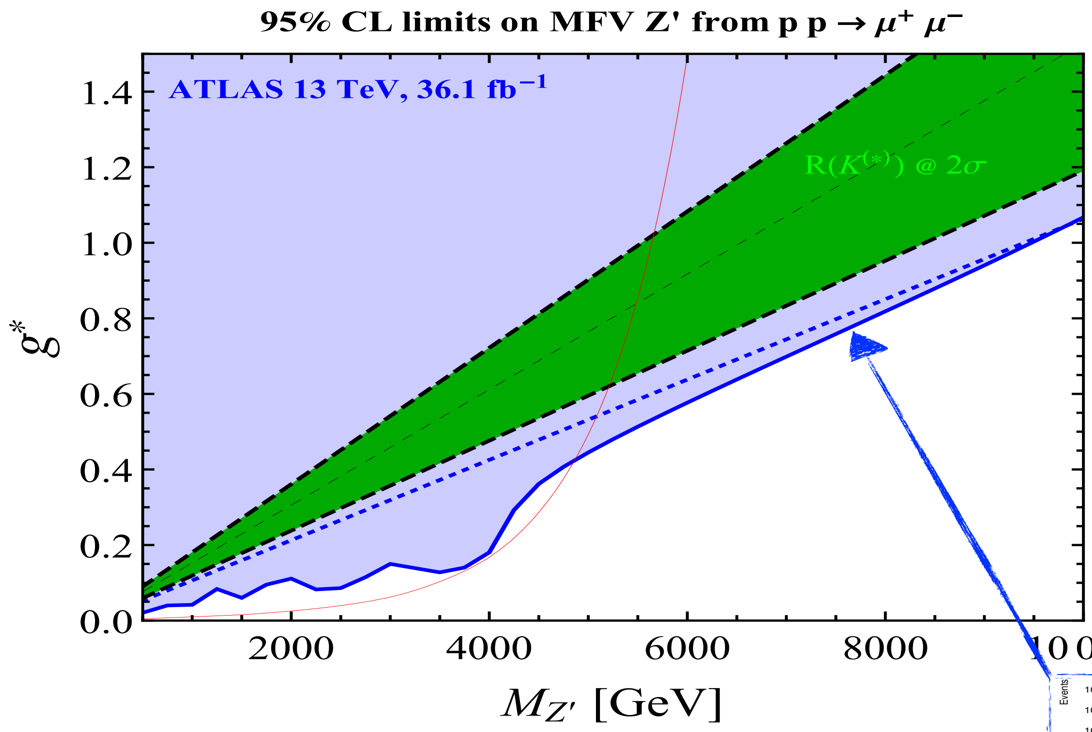
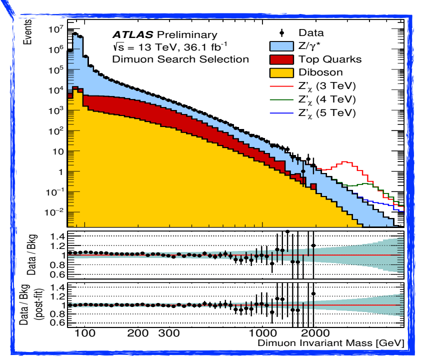
$$\begin{aligned} Q_i &= (V^*_{ji}u^j_L, d^i_L)^T \\ L_i &= (\nu^i_L, \ell^i_L)^T \end{aligned}$$





Correct limit
(from the tail)



Conclusions: breaking the HEP frontiers

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LHC crisis: strong bounds and no new discovery where it was anticipated

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no lack of theoretical motivations
& plenty of physics issues outside the SM frame

from deep QFT questions ~~ to pressing phenomenological puzzles

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* don’t listen too much to theorists: there are 10^{500} vacua so the theory predictions always come with great prejudice that vary with time.