New physics and precision: the roads ahead.

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"New physics from precision at high energies", KITP at UCSB. March 11, 2021

From gravity to the Higgs we're still waiting for new physics

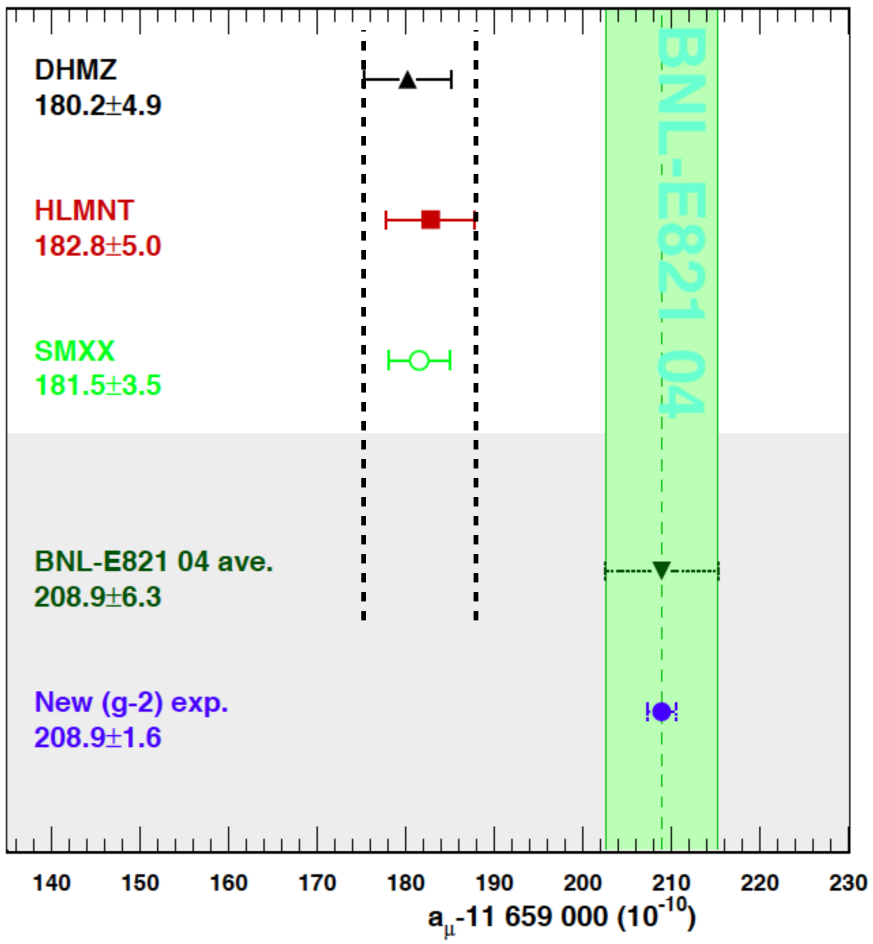
Guardian

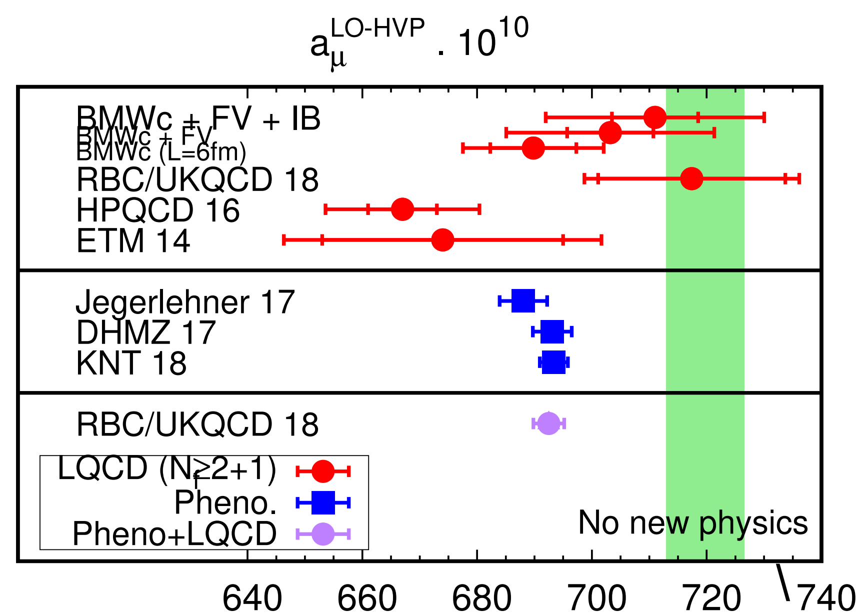
Annual physics jamboree Rencontres de Moriond has a history of revealing exciting results from colliders, and this year new theories and evidence abound

What's next?

Perhaps?

T. Blum et al. (arXiv:1311.2198)



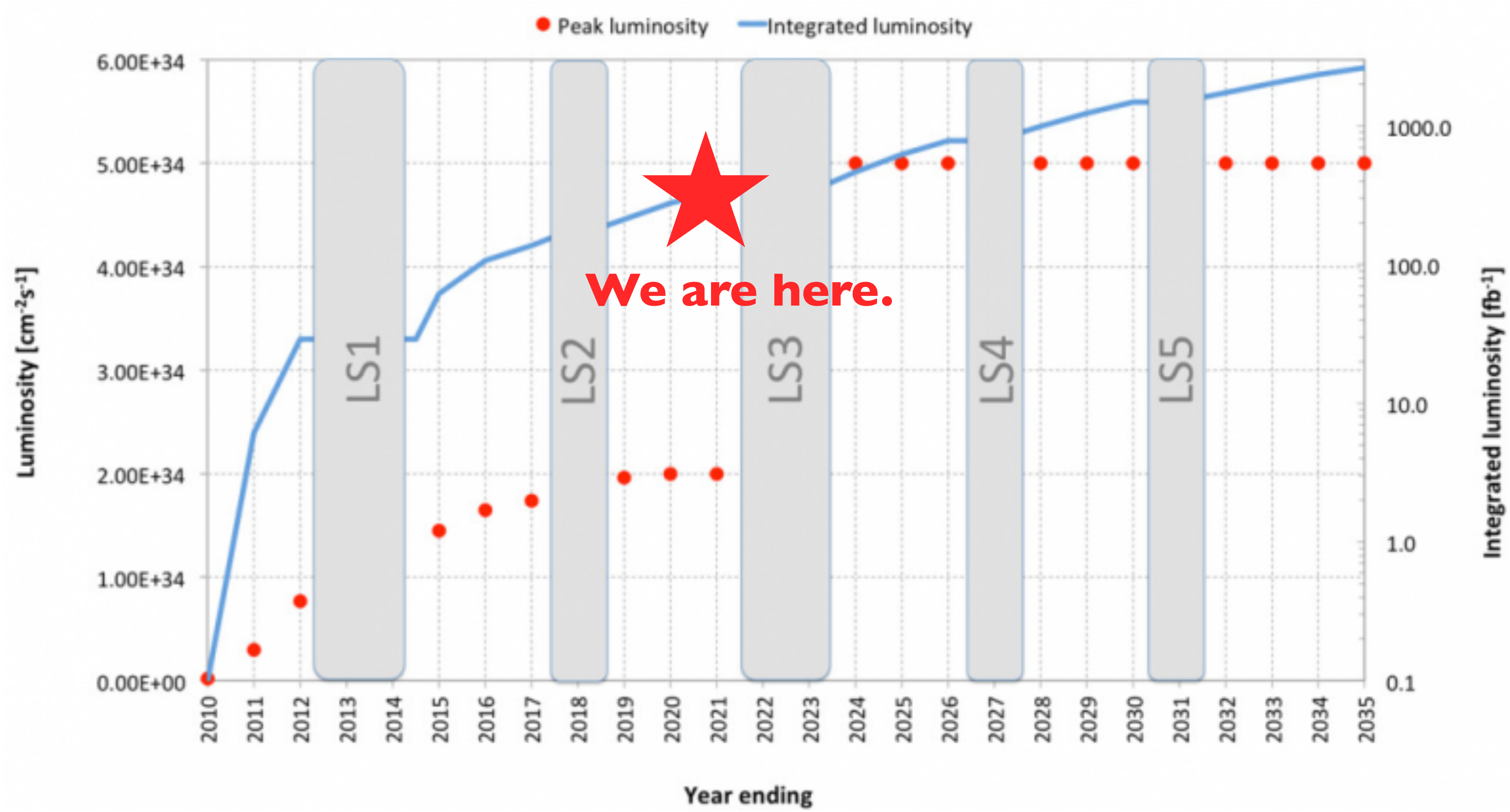


After a long wait, new results from Fermilab soon!

From: Deborah Sebastian <debseb@fnal.gov>
Subject: Special seminar on April 7: First results from the Muon g-2 experiment at Fermilab
Date: March 10, 2021 at 1:32:55 PM CST
To: fermi_scientists <fermi_scientists@fnal.gov>, engineers_all <engineers_all@fnal.gov>, SCIENTIST-EMERITI

Personal note: my first ambulance chasing paper, 2001

Coming back from dreamland

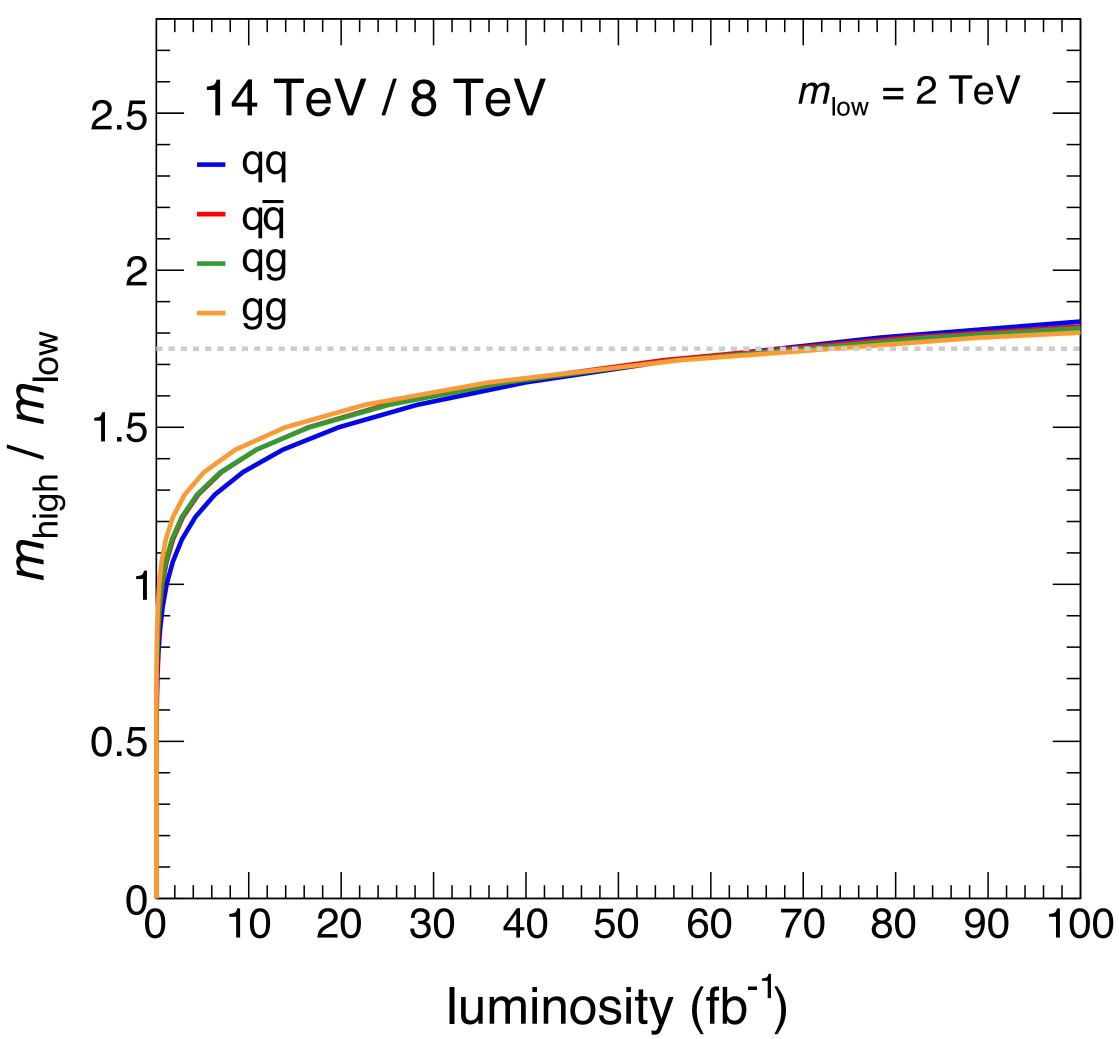


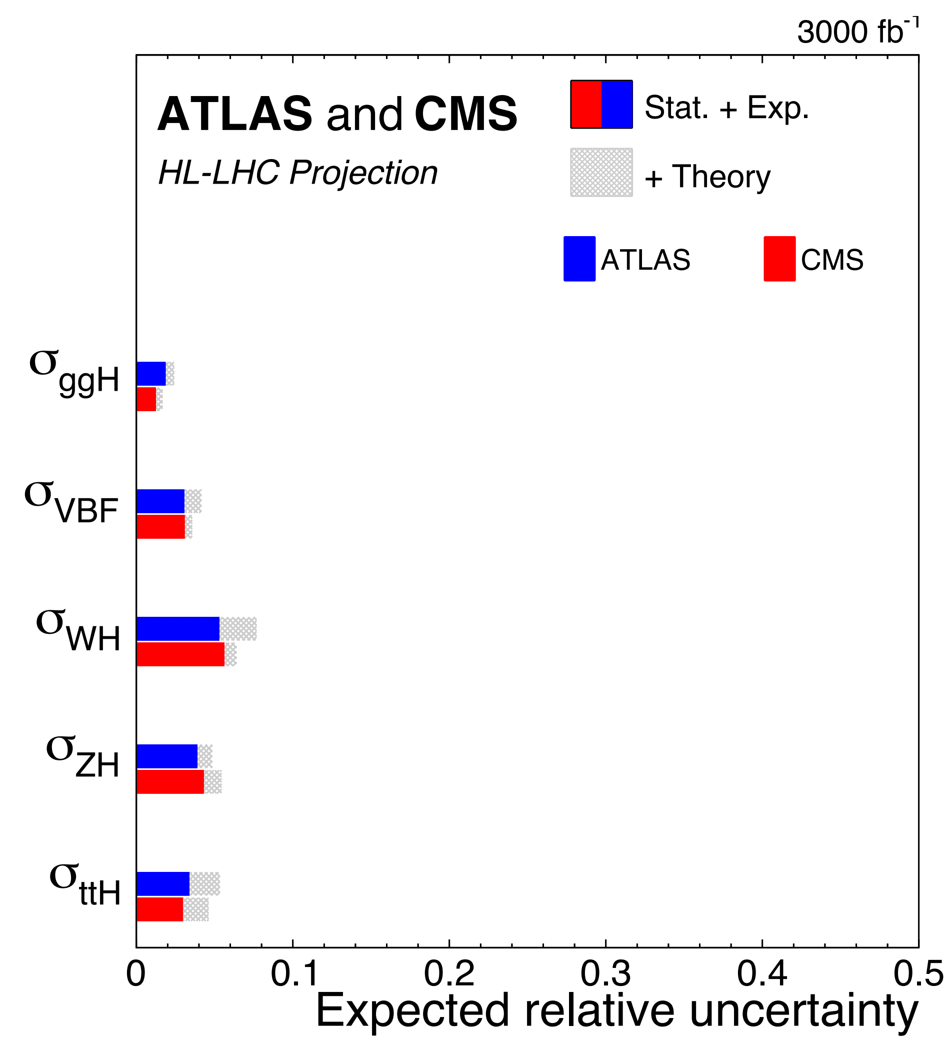
Still about 10 times amount of data to come.

Most immediate question:
How to fully realize the potential of the LHC?

As data accumulates

8 TeV limit 2 TeV, e.g. pair of 1 TeV gluino.



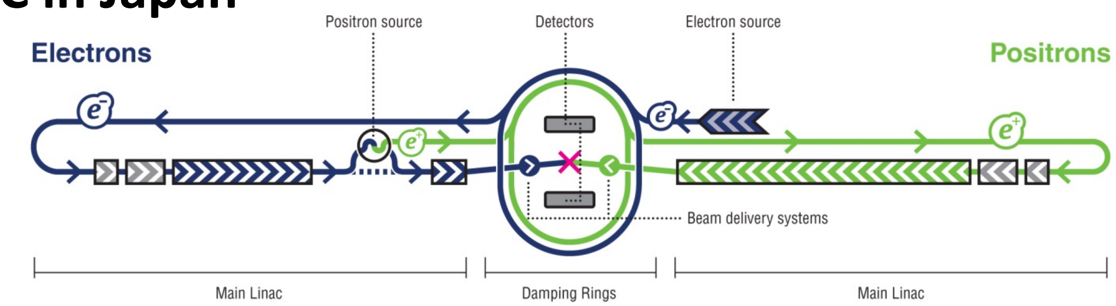


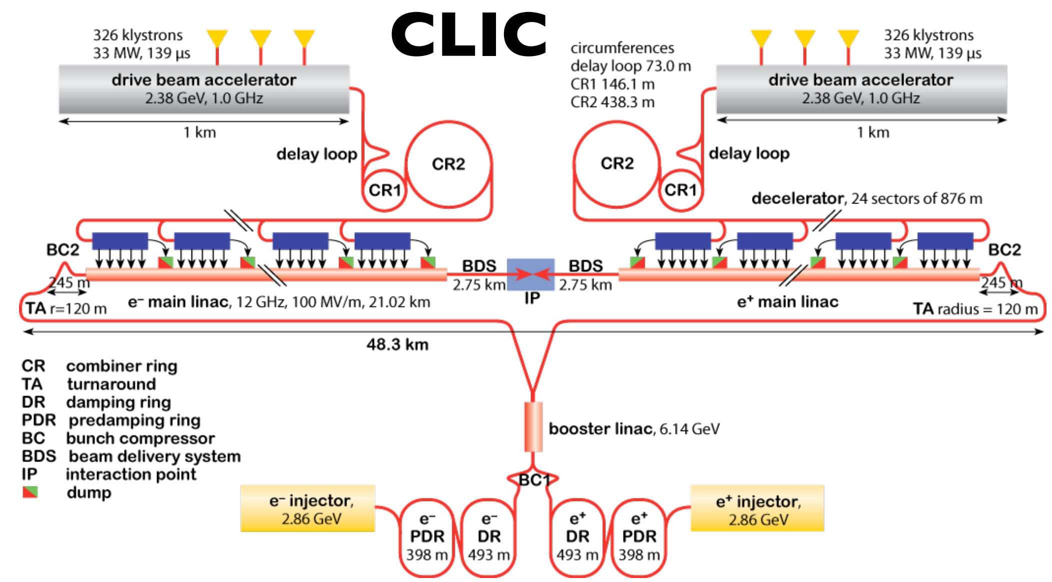
Progress on direct search will become slower, harder

At the same time, great potential for precision physics!

Future Colliders

ILC in Japan





pp collider ~100 TeV

FCC-hh (CERN), SppC(China)

e^-e^+ Higgs Factory 250 GeV

FCC-ee (CERN), CEPC(China)

Likely to get a precision machine first!

For the coming couple of decades:

Most of the progresses at the colliders will be made on precision measurements.

This talk:

- Brief summary of current approaches with implications to new physics searches.

- More focus on some promising future directions (personal perspective)

Importance of precision measurement

- New physics are needed to address Standard Model's open questions: such as origin of EWSB, flavor, CP, etc.
- Even though we have a lot of ideas, we likely don't have the right one. No confirmation of any of the proposed models.
- We need experiment!
- Great window for new physics: important players in the EWSB, flavor of SM, such as W/Z/Higgs and top.

What to measure?

- Precision measurement = coupling measurement
  - Yes, but too narrow.
- Kinematical distributions, especially on the tails.
- Rare decays.
  - Also important part of the properties of known particles.

What to measure?

- Precision measurement = coupling measurement
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  - Also important part of the properties of known particles.

Both can benefit a lot from large statistics

Precision from coupling measurement

- In new physics searches from precision measurement, we are going after deviations of the form

$$\delta \simeq c \frac{v^2}{M_{\rm NP}^2}$$

M_{NP} : mass of new physics
c: $O(1)$ coefficient

- Take the Higgs coupling.
  - LHC precision: ≈5% ⇒ sensitive to M_{NP} ≈ TeV
  - M_{NP} < TeV will also be covered by direct NP searches at the LHC. Precision measurements are complementary.
  - Beyond the LHC, 1% or less precision can be achieved.

Precision from high energies at LHC

Measurement limited by: $$\frac{\delta\sigma}{\sigma} < \delta_{\text{systematic}} \oplus \frac{1}{\sqrt{N}}$$

- Coupling measurement at low energy have significant systematic error.

$$\frac{\delta\sigma}{\sigma} \sim \frac{v^2}{\Lambda^2} \sim \delta_{\text{systematic}}$$

- Effect of new physics grow with energy.
  - Beneficial to measure at higher energy $E > m_{Z,W,h}$ if systematics does not grow as fast

$$\frac{\delta\sigma}{\sigma} \sim \frac{E^2}{\Lambda^2} \sim \delta_{\text{systematic}}$$

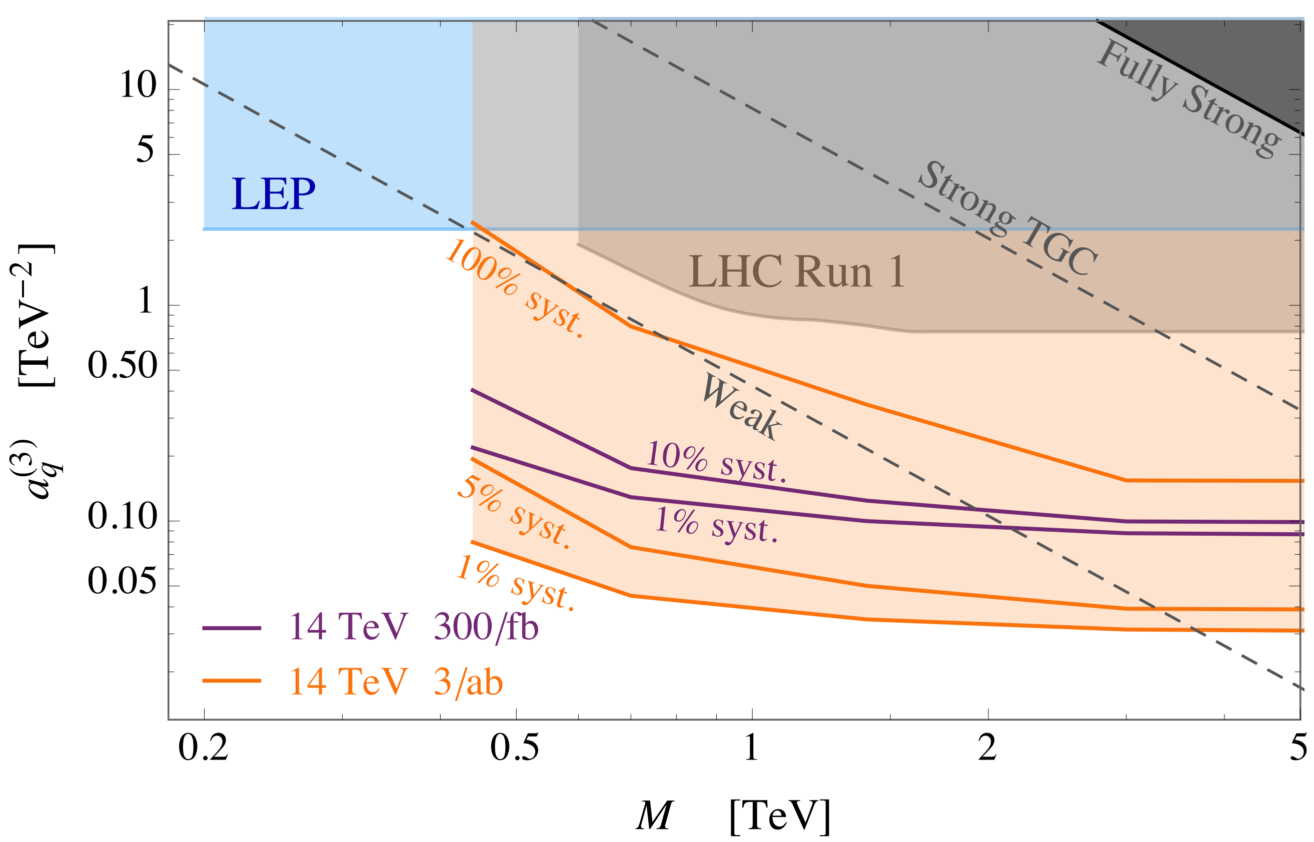
⇨ probing higher NP scales Λ

Examples of high energy → precision

LEP precision tests probe NP about 2 TeV

$$\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{m_W^2}{\Lambda^2} \sim 2\times 10^{-3} \quad \to \Lambda \geq 2 \text{ TeV}$$

At LHC, $\frac{\delta\sigma}{\sigma_{\rm SM}} \sim \frac{E^2}{\Lambda^2} \sim 0.25 \qquad E \sim 1 \text{ TeV},\ \Lambda \sim 2 \text{ TeV}$



$W_L\ Z_L$ at high energies

Franceschini, Panico, Pomarol, Riva, Wulzer. 1712.01310

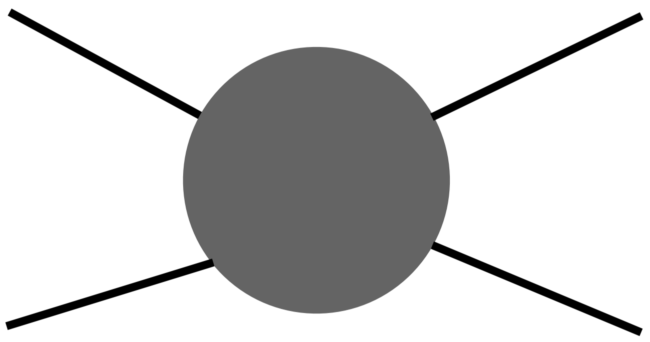
See also: Farina, Panico, Pappadopulo, Ruderman, Torre. 1609.08157; D. Liu, LTW. 1804.08688

EFT ≠ everything

- EFT is a great tool, applying broadly to cases where heavy new physics can be integrated out.
- However, it is important to keep in mind the there are cases where EFT does not cover.
- Obviously, not applicable in direct production of new physics particles.
- Even in the cases of precision measurements, there are important exceptions.

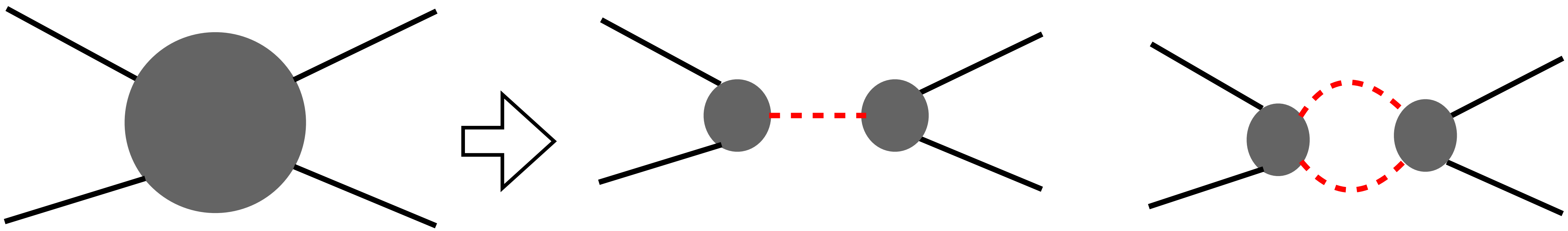
EFT ≠ everything

Focus on scattering with SM external states



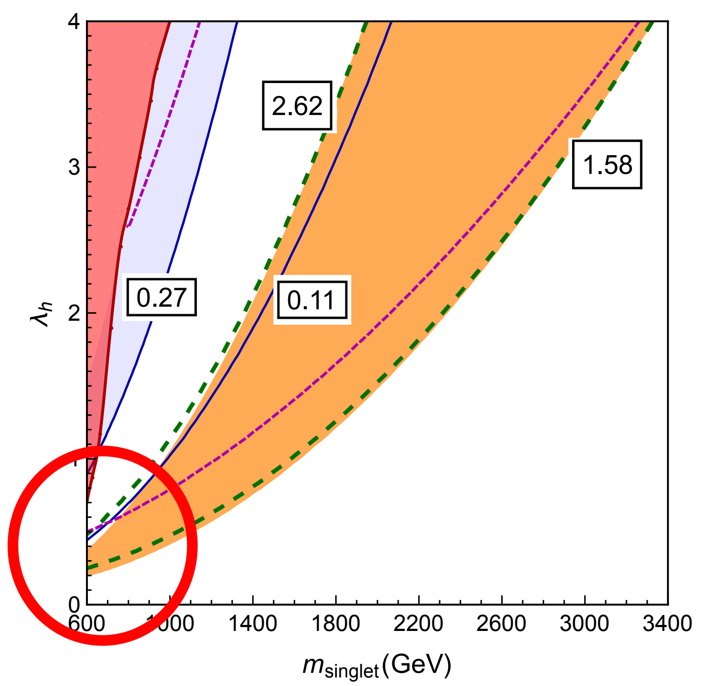
- Modeled with an EFT operator: $M \propto E^n$, n=1, 2...
- However, there can be important exceptions.

EFT ≠ everything



- Light particle

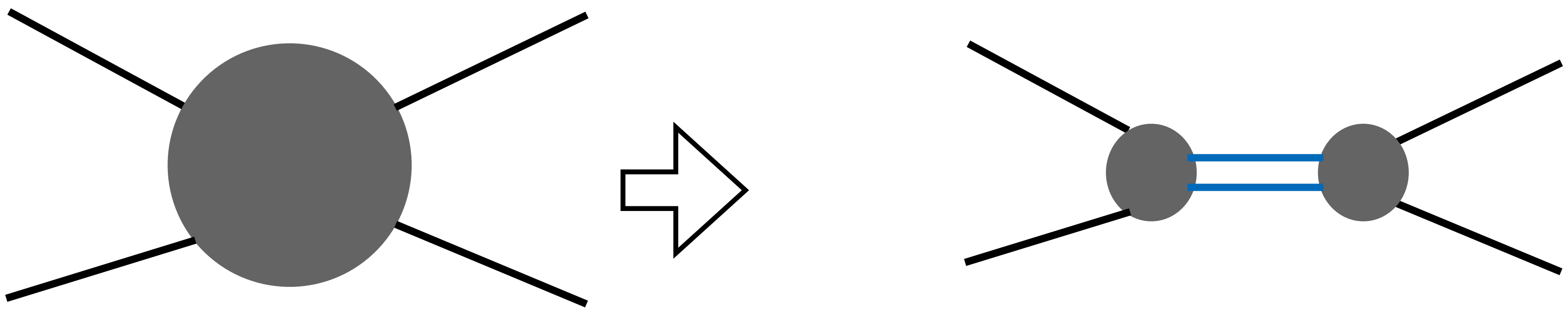
Amplitude will deviate (soften) from the prediction of the contact EFT operator.



For example: light singlet scalar for first order EW phase transition.

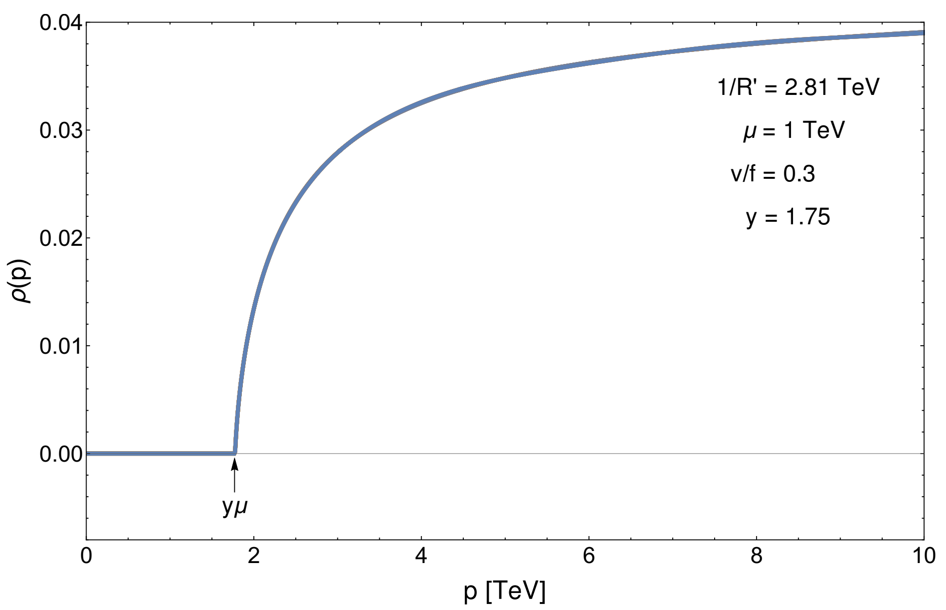
Huang, Joglekar, Li, Wagner, 1512.00068

EFT ≠ everything



- Strongly coupled, broad resonance, continuum, ...

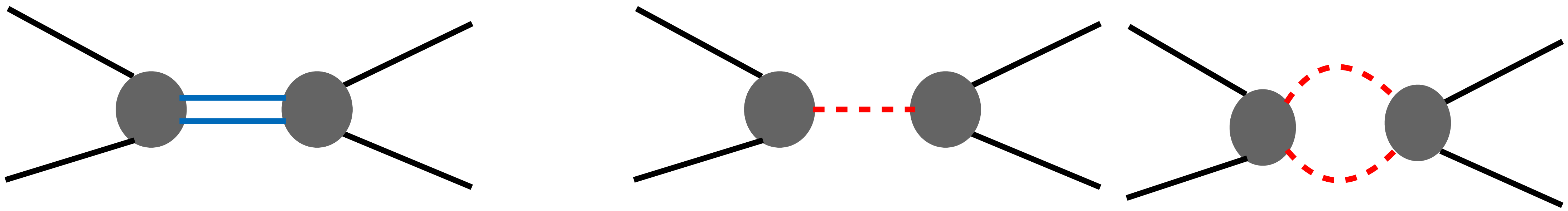
In this case, the amplitude can be a general form factor: $f(q^2)$



e.g.: top partner as a continuum

Csaki, G. Lee, S. Lee, Lombardo, Telem, 1811.06019

Bottom line:



- These new physics may not be easy to discover directly. Precision measurement could be the main (only) window.

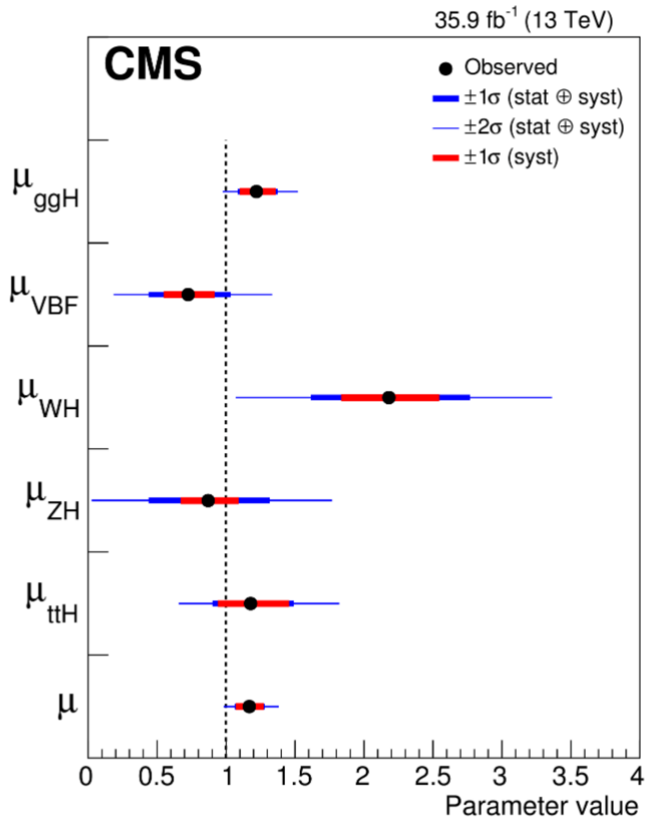
- In addition to energy dependence, we need to measure as a broad range of kinematical distribution as possible.

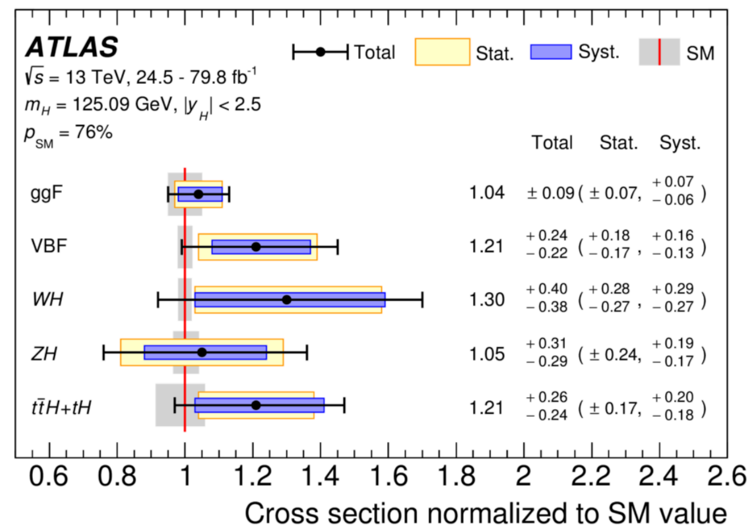
Where to look?

- Dynamics of the Standard Model: Electroweak
  - W, Z, h, top
  - Here, I focus on some examples for h and top.
- Approximate symmetries:
  - Flavor, CP. Examples with h and top.
- Sum rules, positivity.
  - Brief overview.

Higgs

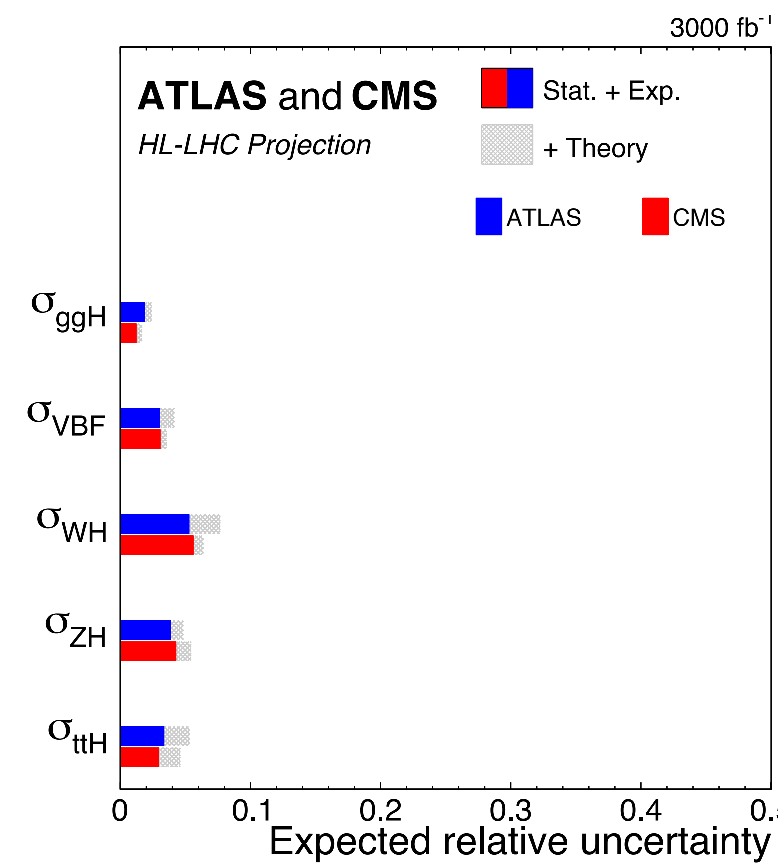
All eyes are on the Higgs





Current precision: 10(s)%

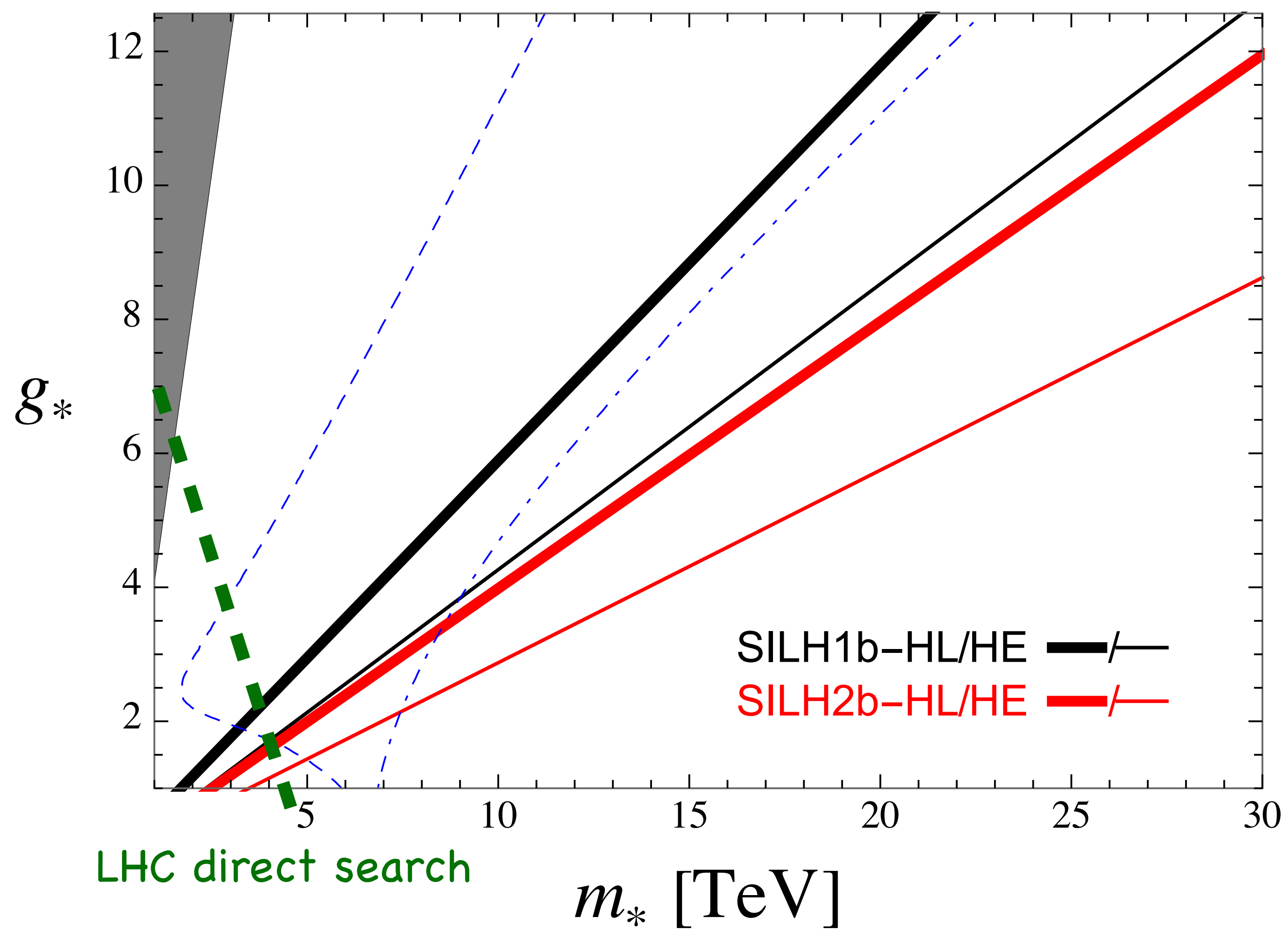
A few Percent by the end of the LHC



1902.00134

Implications of Higgs coupling measurement

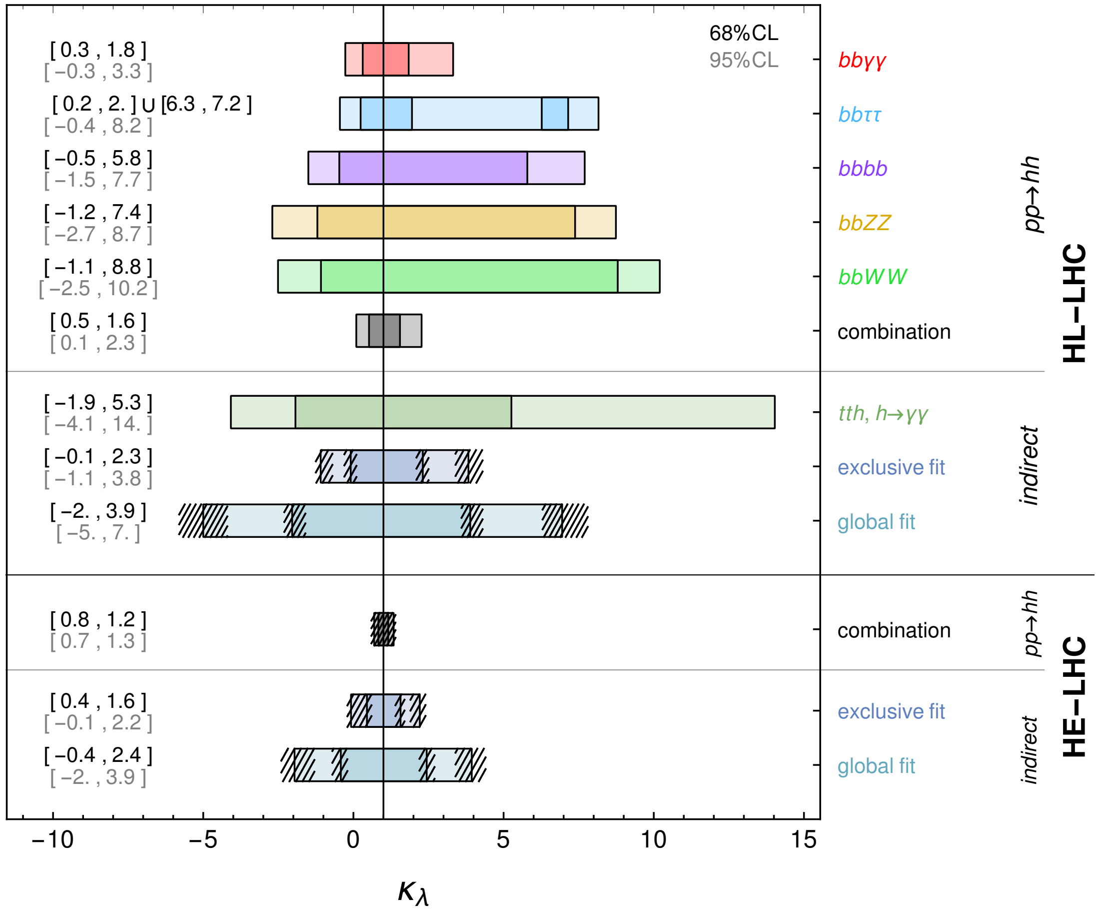
Composite Higgs



Coupling deviation:

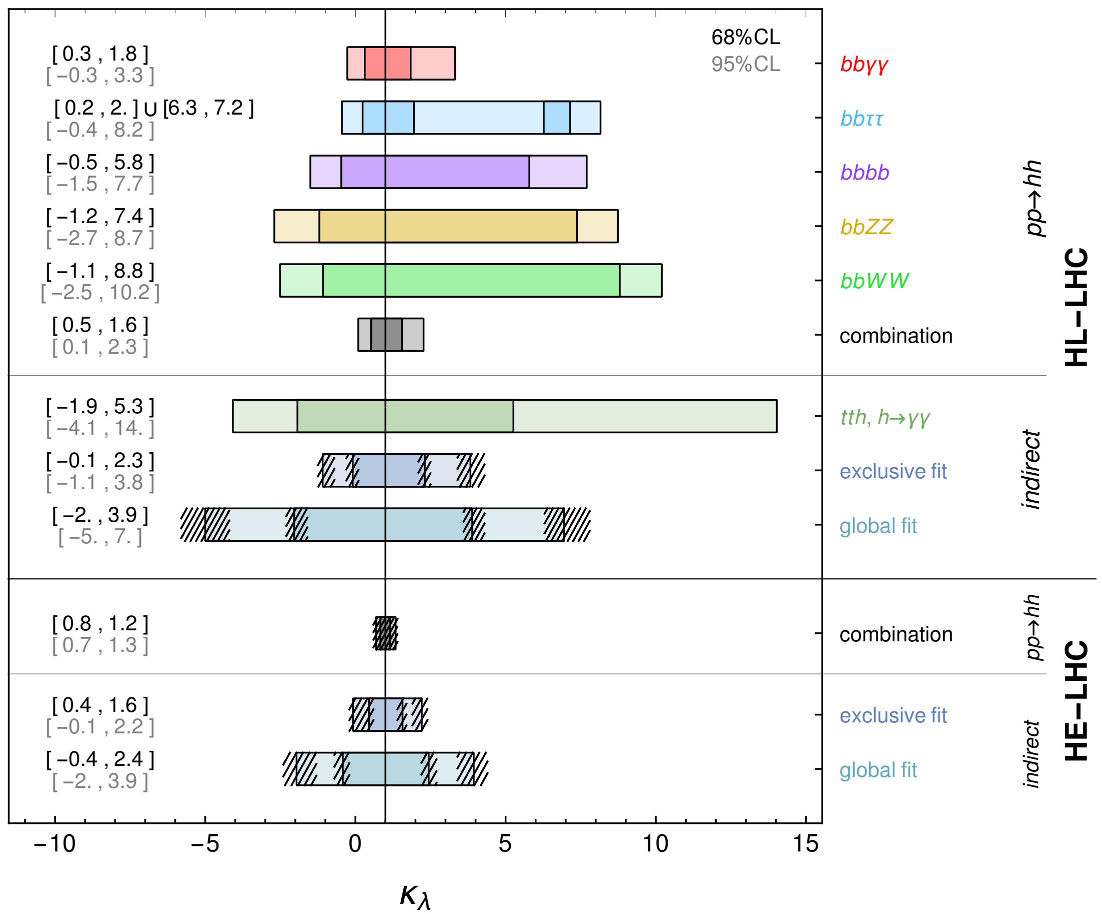
$$\delta \simeq \frac{g_*^2}{m_*^2} v^2$$

Higgs self-coupling

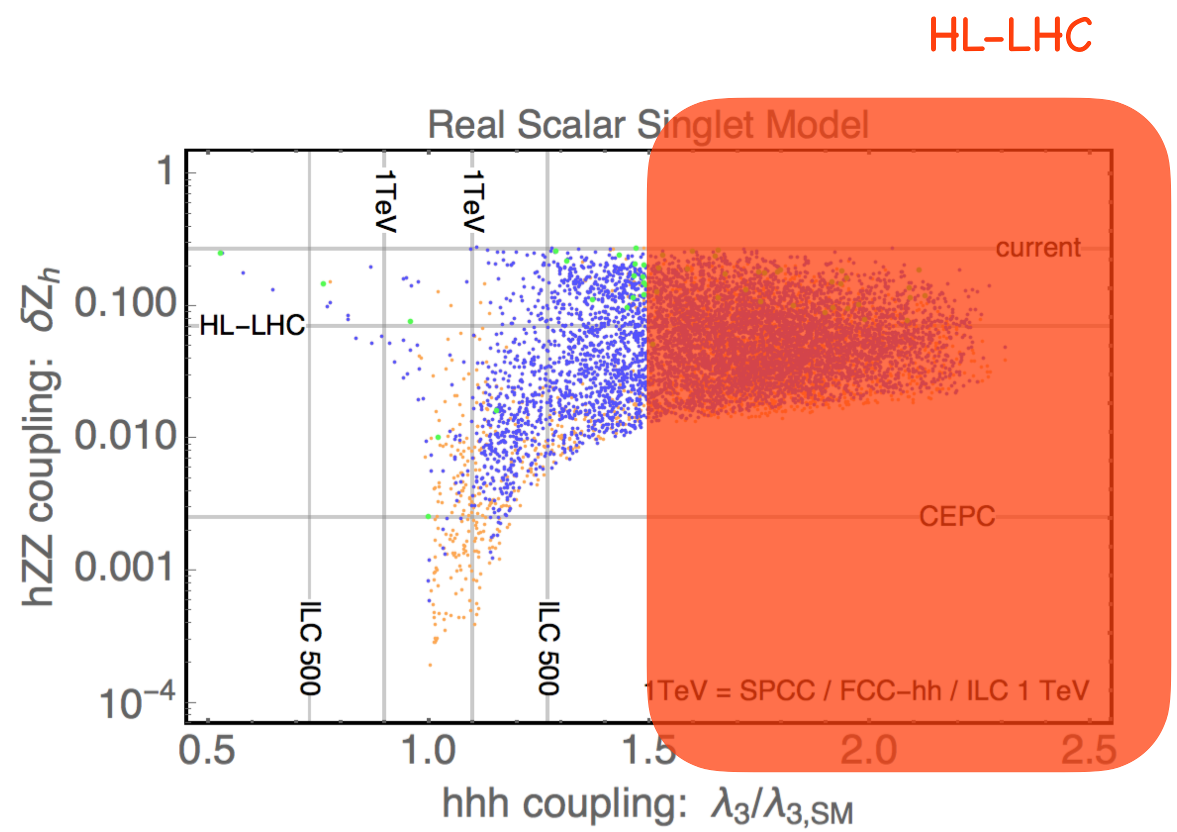


50% level measurement at HL-LHC

Higgs self-coupling



50% level measurement at HL-LHC



Huang, Long, LTW, 1608.06619

Singlet model with 1st order EW phase transition

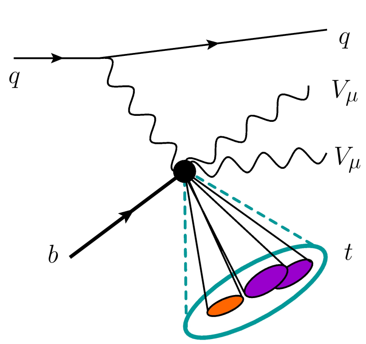
"Higgs without Higgs"

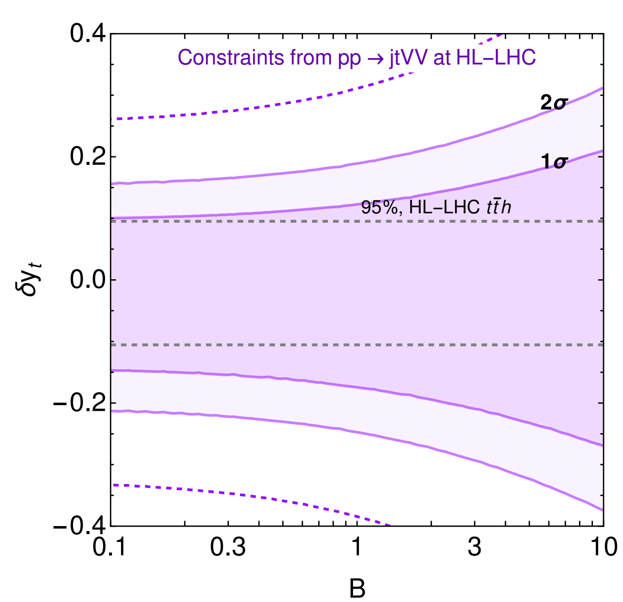
Henning, Lombardo, Riembau, Riva, 1812.09299

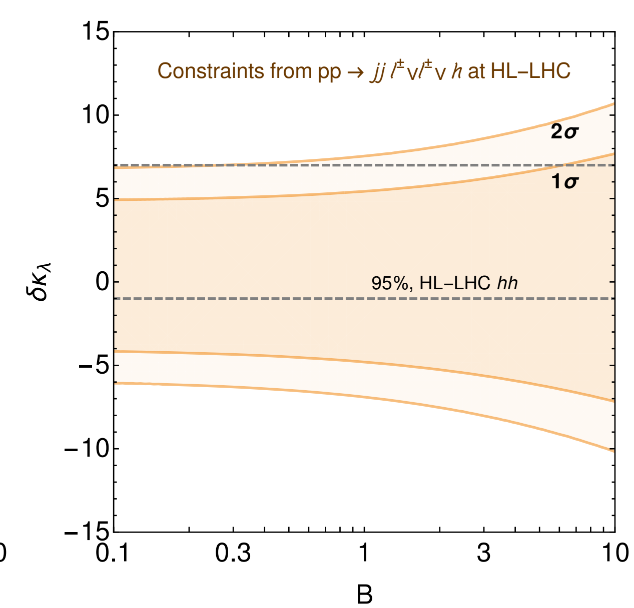
Deviation of the Higgs coupling parameterized by EFT operators.

$$\mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R \qquad \mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu} \qquad \text{etc.}$$

This leads to high energy excesses: $\propto E^1$ or E^2





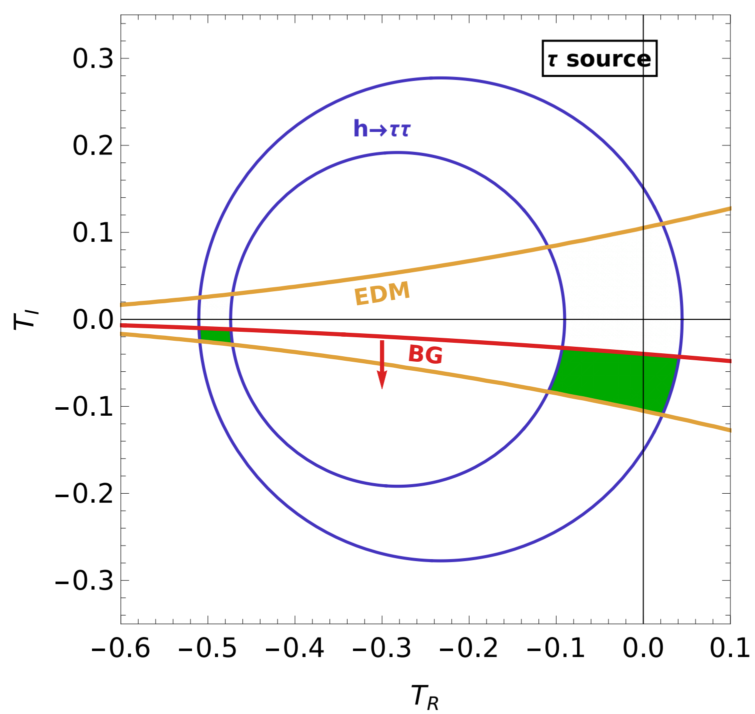


Complementary to the "standard" Higgs coupling measurement, could be competitive.

CP violation

$$\mathcal{L}_{\rm Yuk} = y_f \overline{F_L} F_R H + \frac{1}{\Lambda^2}(X_R^f + i X_I^f)|H|^2 \overline{F_L} F_R H + {\rm h.c.}$$

$$T_R^f \equiv \frac{v^2}{2\Lambda^2}\frac{X_R^f}{y_f}, \quad T_I^f \equiv \frac{v^2}{2\Lambda^2}\frac{X_I^f}{y_f}$$

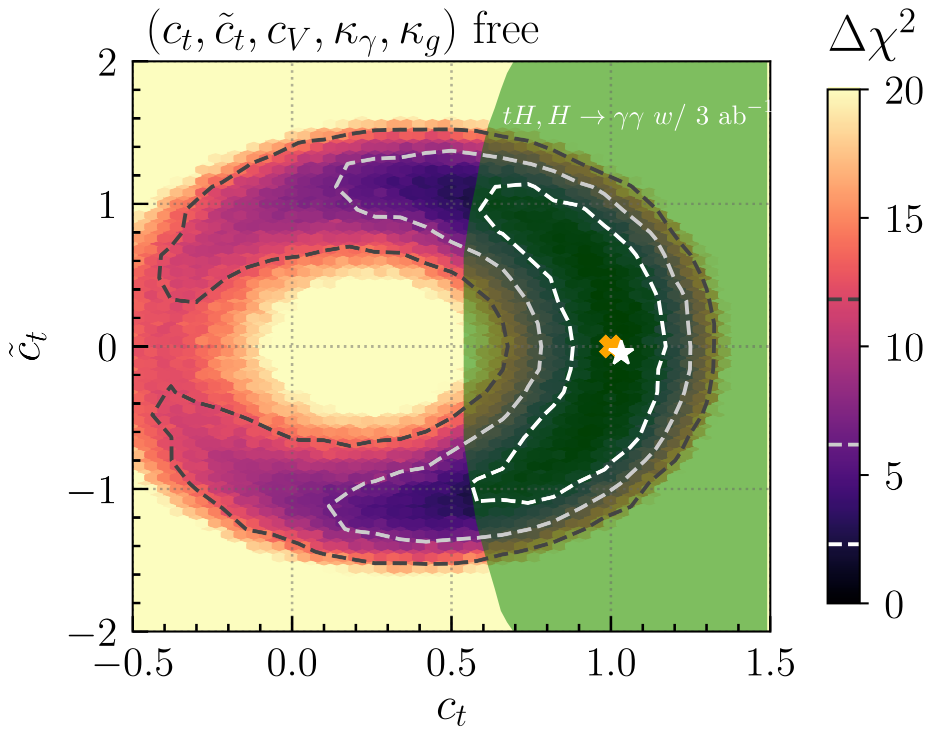


Tau as source of CP violation.

Combined constraints from Higgs measurement, EDM, and the requirement of electroweak baryogengesis.

With current LHC data. HL-LHC will improve.

$$\mathcal{L}_{\rm yuk} = -\frac{y_t^{\rm SM}}{\sqrt{2}}\bar{t}\,(c_t + i\gamma_5 \tilde{c}_t)\,tH$$



Top as source of CP violation.

Floating a set of other parameters.

Fuchs, Losada, Nir, Viernik, 2003.00099

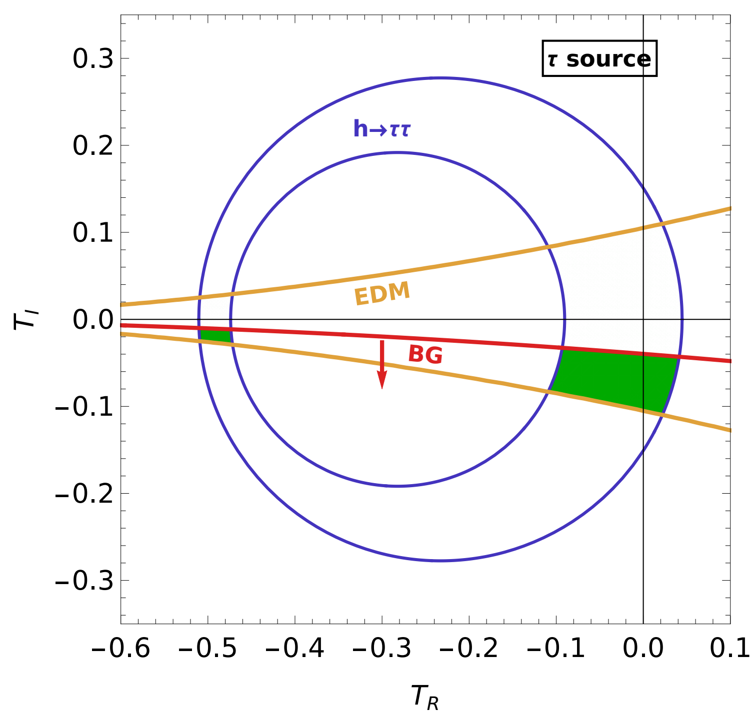
Bahl, Bechtle, Heinemeyer, Katzy, Klingl, Peters, Saimpert, Stefaniak, Weiglein, 2007.08542

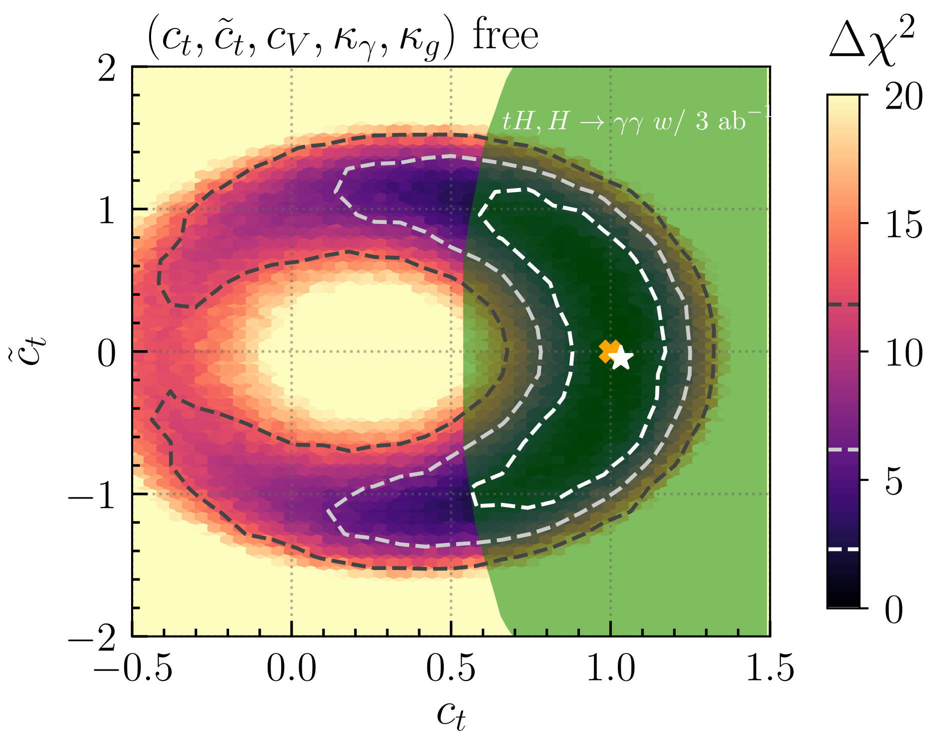
CP violation

$$\mathcal{L}_{\rm Yuk} = y_f \overline{F_L} F_R H + \frac{1}{\Lambda^2}(X_R^f + i X_I^f)|H|^2 \overline{F_L} F_R H + \text{h.c.}$$

$$T_R^f \equiv \frac{v^2}{2\Lambda^2}\frac{X_R^f}{y_f}, \quad T_I^f \equiv \frac{v^2}{2\Lambda^2}\frac{X_I^f}{y_f}$$

$$\mathcal{L}_{\rm yuk} = -\frac{y_t^{\rm SM}}{\sqrt{2}}\bar{t}\,(c_t + i\gamma_5 \tilde{c}_t)\,tH$$





So far, this relies mostly on rates and other non-CP violating observables.

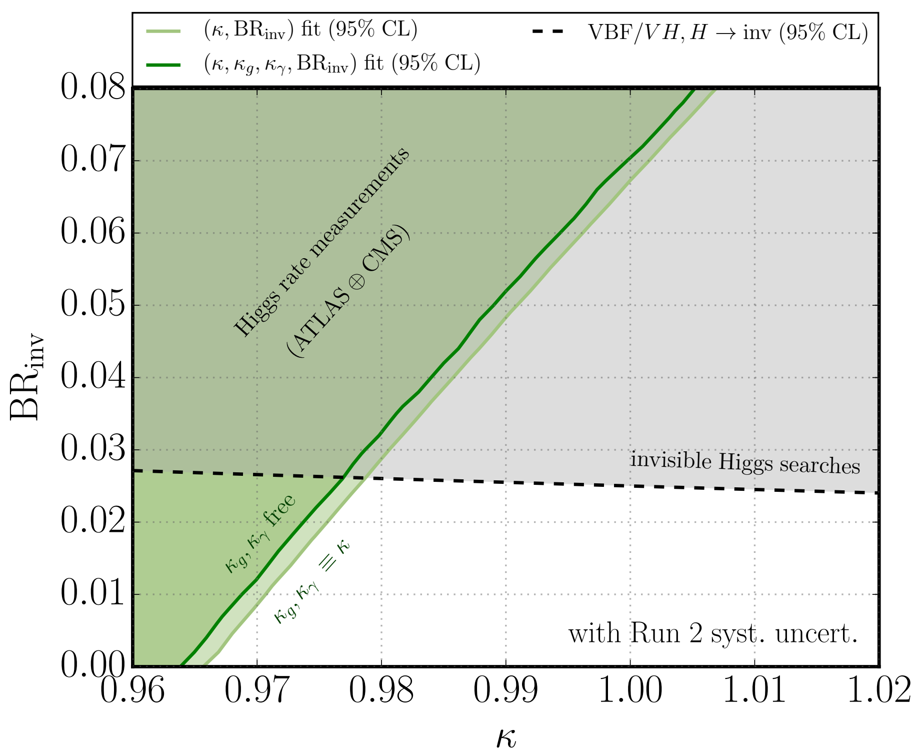
CP violating kinematics limited by statistics, should be pursued at HL-LHC.

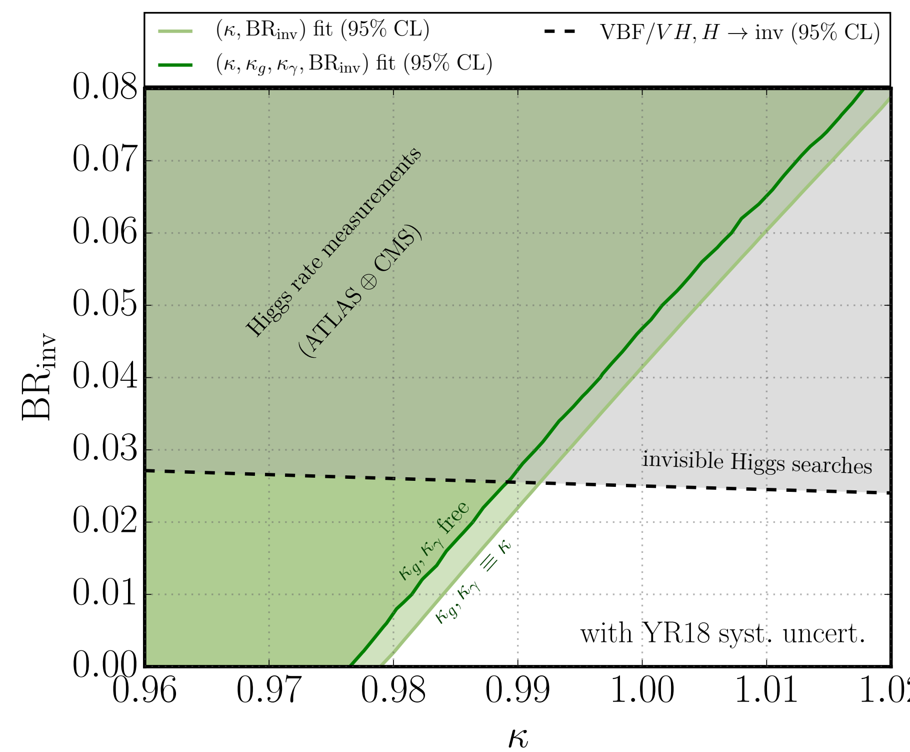
Fuchs, Losada, Nir, Viernik, 2003.00099

Bahl, Bechtle, Heinemeyer, Katzy, Klingl, Peters, Saimpert, Stefaniak, Weiglein, 2007.08542

Higgs exotic decay

- Going through Higgs portal. $\lambda H^\dagger H \mathcal{O}_{\rm exotic}$



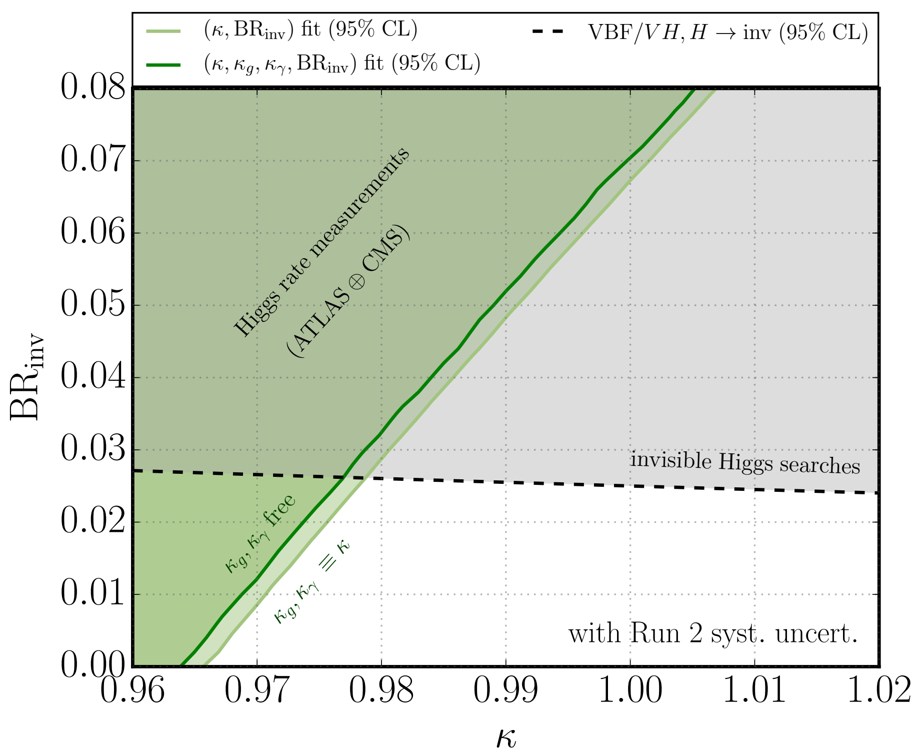


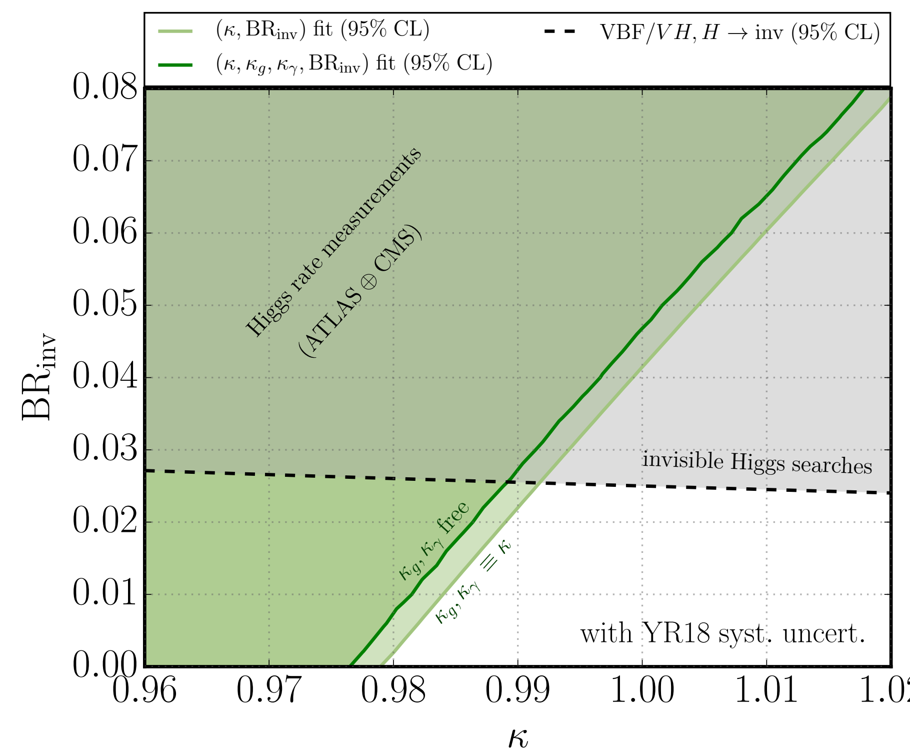
Invisible width etc will constrain the Higgs $\mathrm{BR}_{\rm exotic}$ to be less than a few percent

Still leave plenty of room to exotic decays.

Higgs exotic decay

- Higgs portal. $\lambda H^\dagger H \mathcal{O}_{\text{exotic}}$

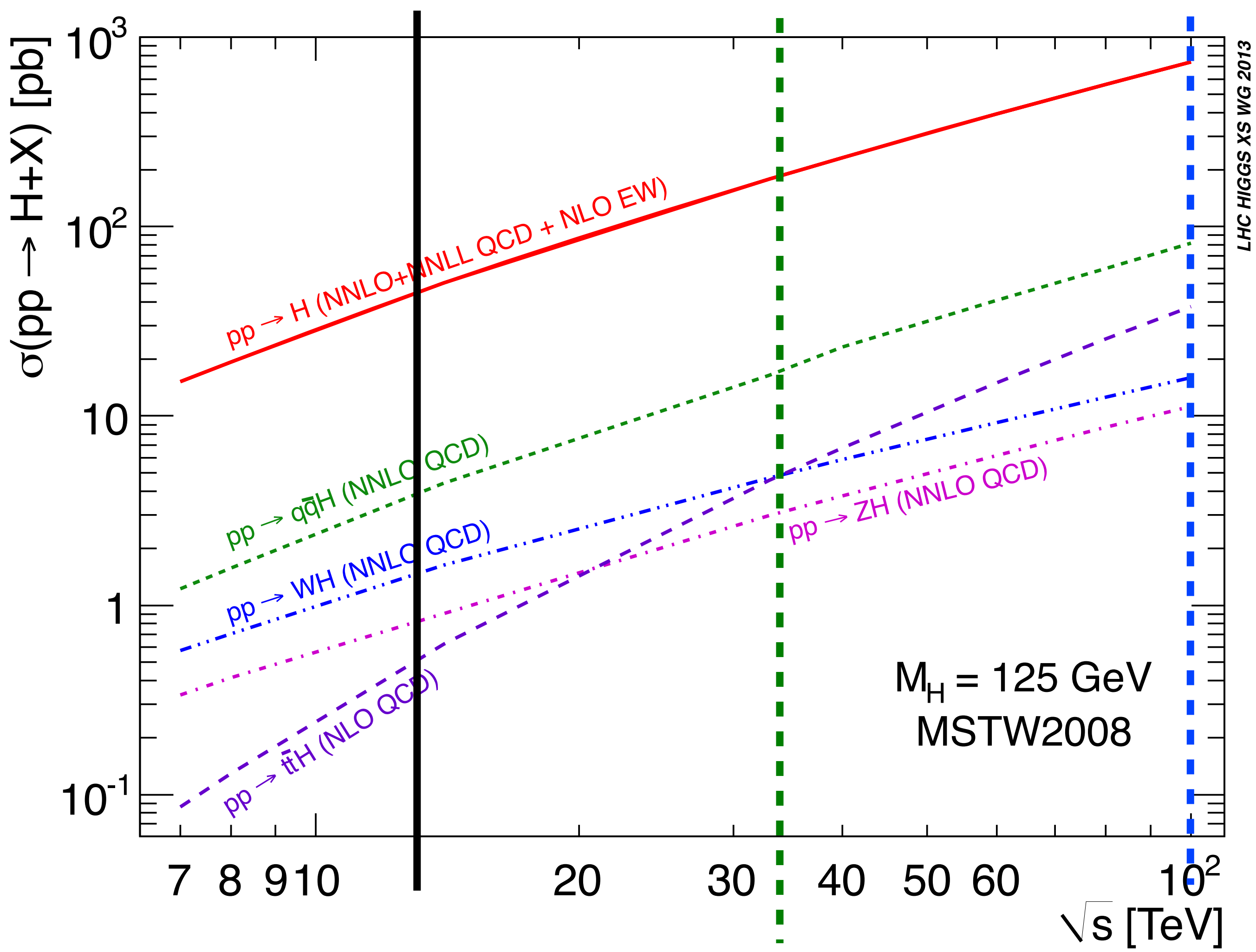




We do need a small coupling, which can come from integrating out new physics at around 10 - 100 TeV. Plausible!

Hadron collider

- The "ultimate" Higgs factories



# of Higgses in 3 ab^{-1}

14 TeV > 150 million

33 TeV > 500 million

100 TeV > 2 billion

In comparison, O(million) Higgs at ee Higgs factories

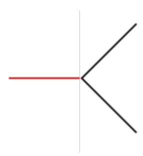
Hadron collider good for rare but clean signal

In principle, can be sensitive to BR ≈ 10^{-7}

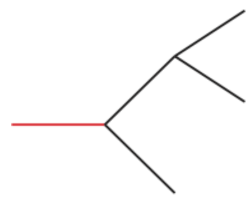
Higgs exotic decay scenarios

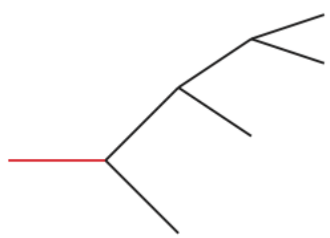
- Flavor changing decays (especially leptonic)
- ALPS
- Extended Higgs sector
- Dark sector, long lived particles (LLP)
- ...

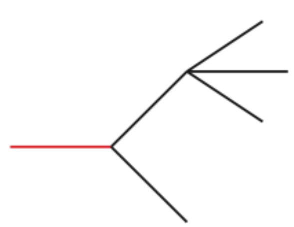
Some possible channels



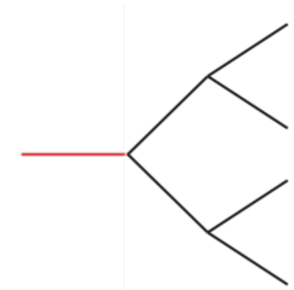
Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$

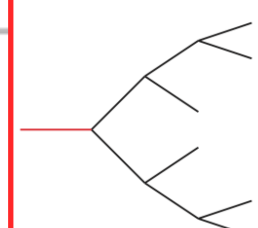


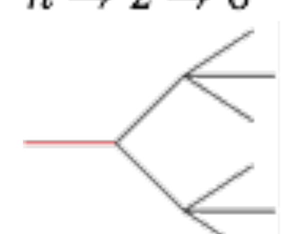




Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$	$h \to (b\bar{b})(b\bar{b})$
	$h \to (b\bar{b})(\tau^+\tau^-)$
	$h \to (b\bar{b})(\mu^+\mu^-)$
	$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
	$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
	$h \to (jj)(jj)$
	$h \to (jj)(\gamma\gamma)$
	$h \to (jj)(\mu^+\mu^-)$
	$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
	$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
	$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
	$h \to (\gamma\gamma)(\gamma\gamma)$
	$h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T + X$





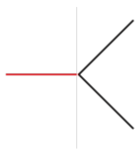
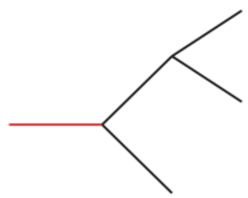
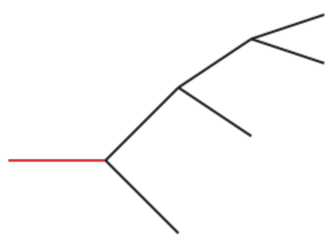
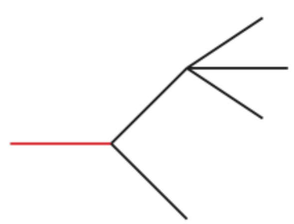


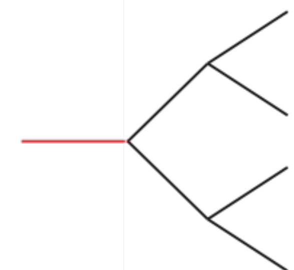
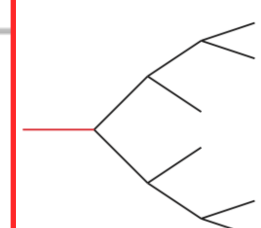
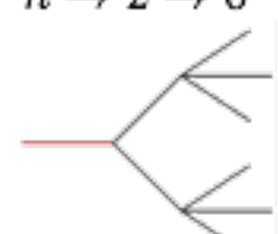
Simple, Great sensitivity from the LHC

With MET, less lepton

More hadronic

Some possible channels

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$ 	$h \to \not{E}_T$
$h \to 2 \to 3$ 	$h \to \gamma + \not{E}_T$ $h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$ 	$h \to (b\bar{b}) + \not{E}_T$ $h \to (jj) + \not{E}_T$ $h \to (\tau^+\tau^-) + \not{E}_T$ $h \to (\gamma\gamma) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T$ $h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$ 	$h \to b\bar{b} + \not{E}_T$ $h \to jj + \not{E}_T$ $h \to \tau^+\tau^- + \not{E}_T$ $h \to \gamma\gamma + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T$

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2 \to 4$ 	$h \to (b\bar{b})(b\bar{b})$ $h \to (b\bar{b})(\tau^+\tau^-)$ $h \to (b\bar{b})(\mu^+\mu^-)$ $h \to (\tau^+\tau^-)(\tau^+\tau^-)$ $h \to (\tau^+\tau^-)(\mu^+\mu^-)$ $h \to (jj)(jj)$ $h \to (jj)(\gamma\gamma)$ $h \to (jj)(\mu^+\mu^-)$ $h \to (\ell^+\ell^-)(\ell^+\ell^-)$ $h \to (\ell^+\ell^-)(\mu^+\mu^-)$ $h \to (\mu^+\mu^-)(\mu^+\mu^-)$ $h \to (\gamma\gamma)(\gamma\gamma)$ $h \to \gamma\gamma + \not{E}_T$
$h \to 2 \to 4 \to 6$ 	$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$ $h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to 2 \to 6$ 	$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$ $h \to \ell^+\ell^- + \not{E}_T + X$

Simple, Great sensitivity from the LHC

With MET, less lepton

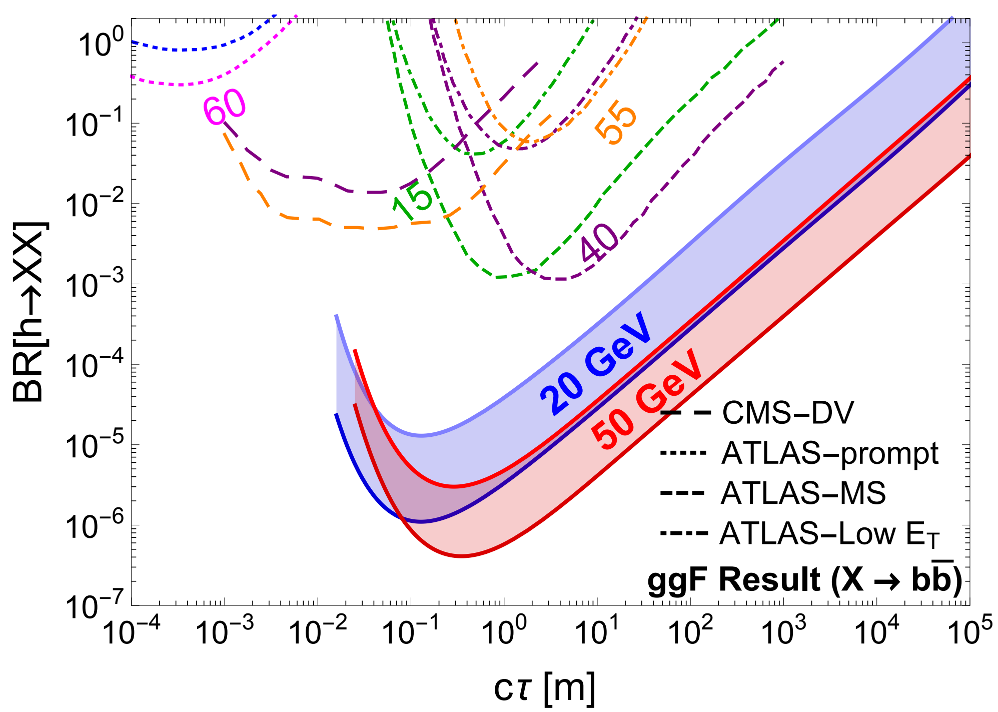
More hadronic

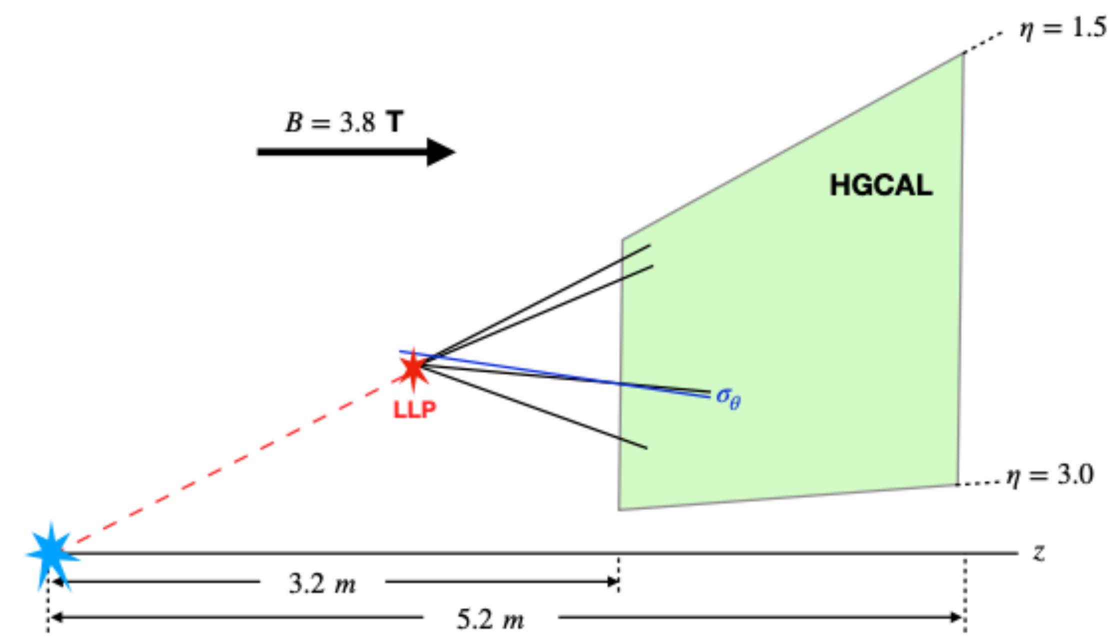
More challenging, but worth pursuing!

LLP

- h →XX, X long-lived

J. Liu, Z. Liu, XP Wang, LTW 2005.10836





Using the pointing capability of CMS HGCAL

Best sensitivity ≈ 10^{-7}, can reach cτ ≈ 10^3 m with BR ≈ 10^{-3}

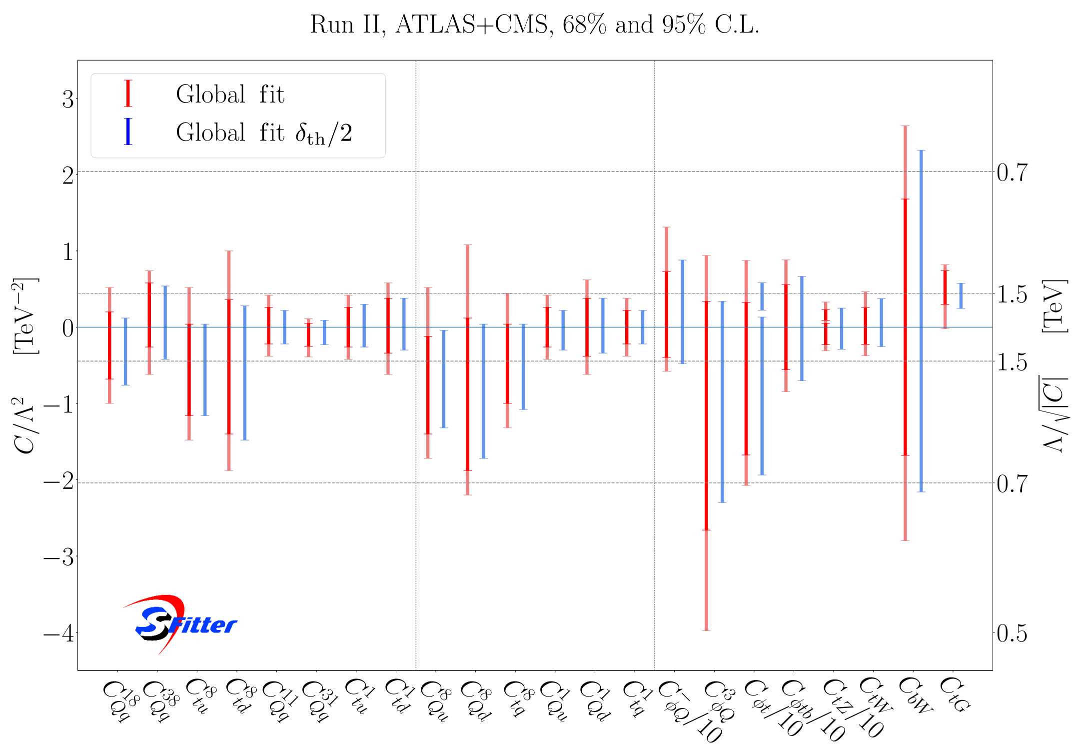
In addition, precise timing could also help.

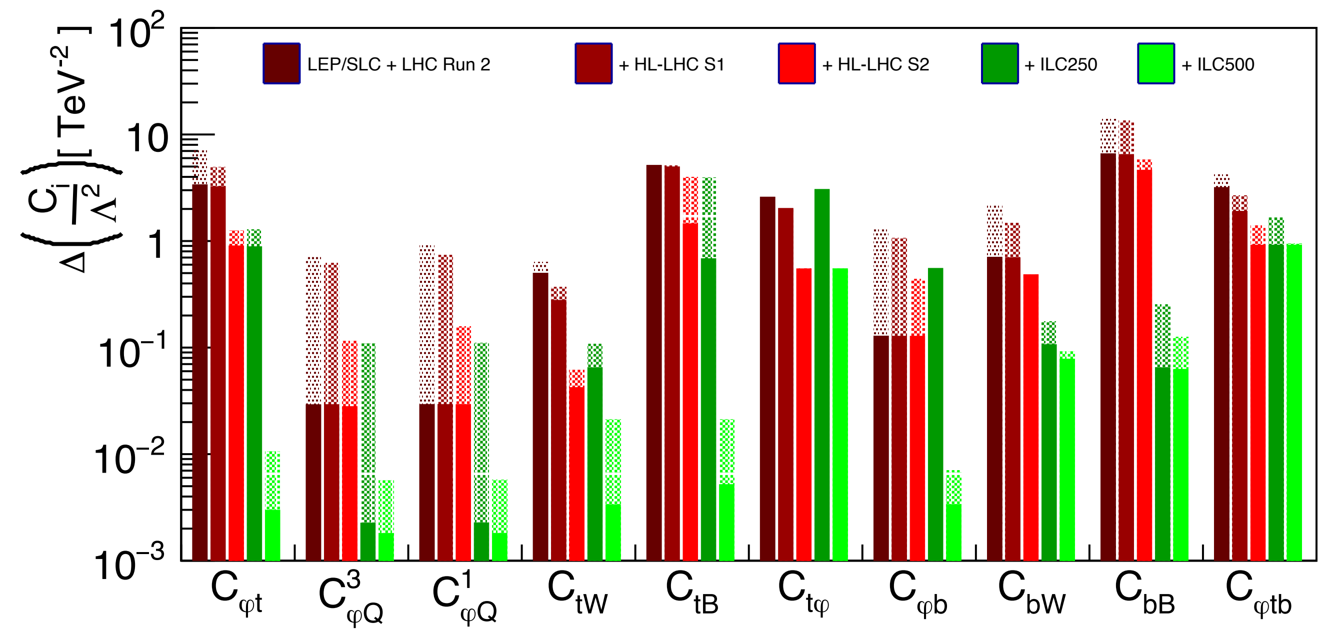
Of course, great to have dedicated detectors such as MATHUSLA.

Top quark

Top quark

Constraints on dim-6 top quark related operators





Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff, Zhang, 1910.03606

Durieux, Irles, Miralles, Penuelas, Perello, Poschl, Vos, 1907.10619

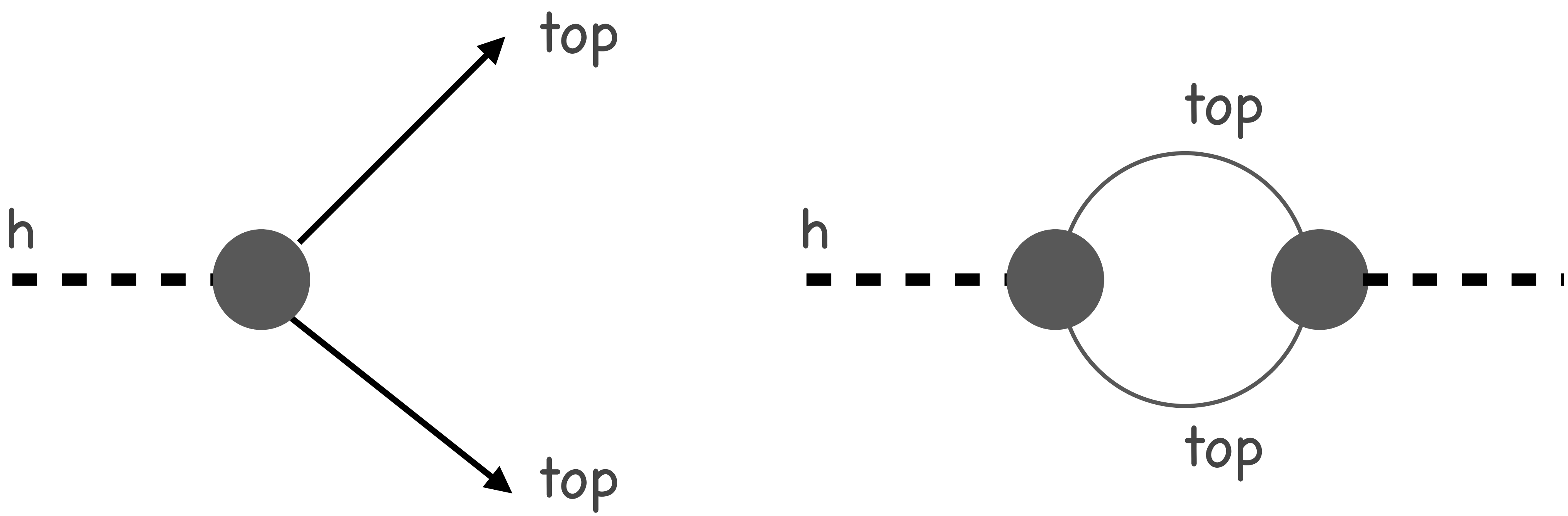
Based on the full suite top quark measurements

$$t\bar{t}, tW/tZ, t\bar{t}W, t\bar{t}Z, \ldots$$

Using inclusive rates as well as differential information

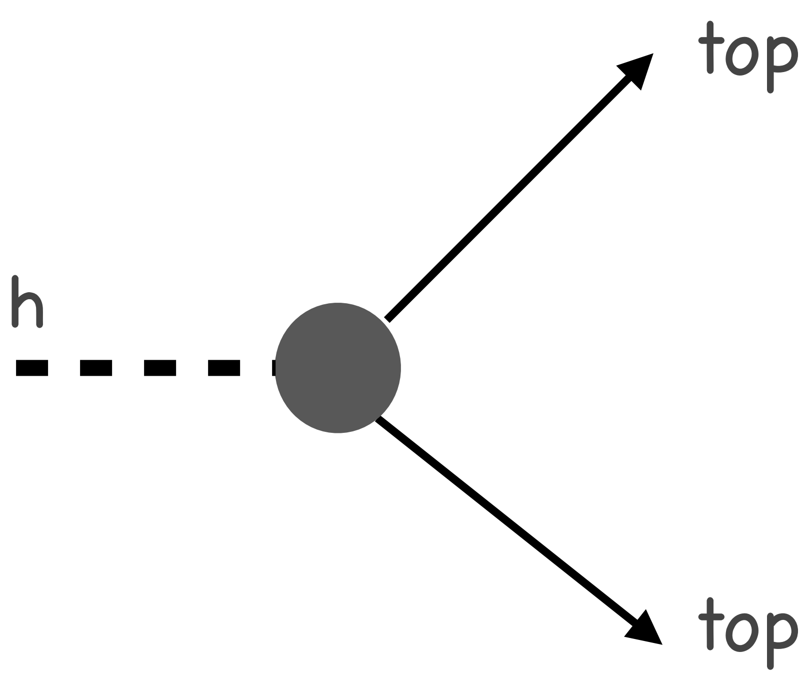
Impressive reach at HL-LHC, a factor of a few improvement beyond Run 2

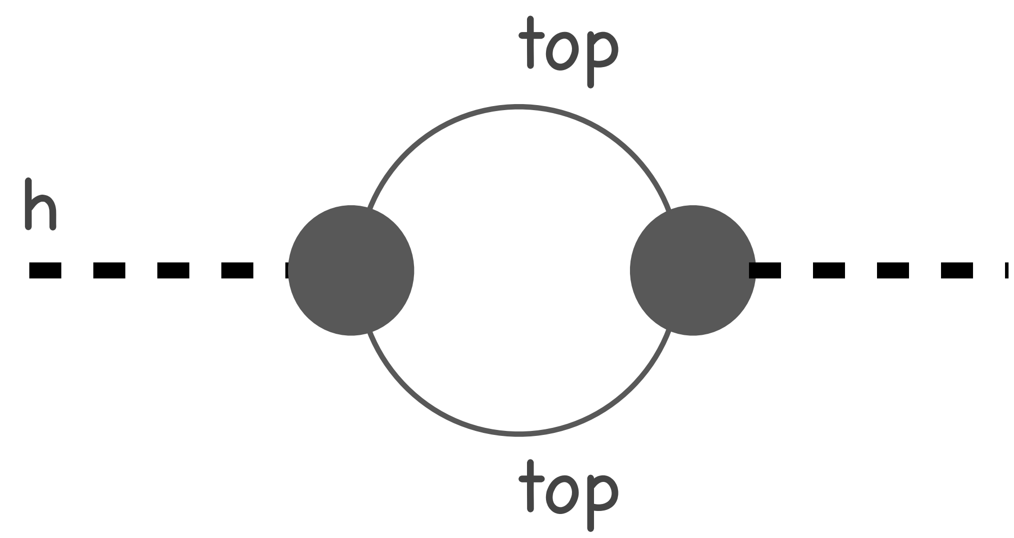
Top and Higgs



- Strongest coupling to EWSB.
- Root of the naturalness problem.
  - NP model frequently has top partners. Regulate the UV behavior of the top loop.

Top and Higgs





Coupling measured (mostly) on-shell.

New physics can in principle be very strange, not even particles.

For a model independent search:
poke around anyway we can, putting top/Higgs off-shell.

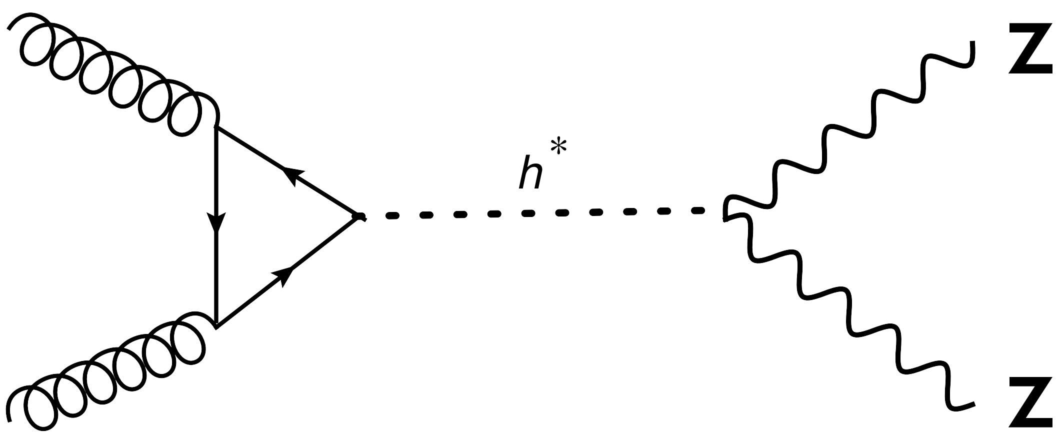
N. Arkani-Hamed

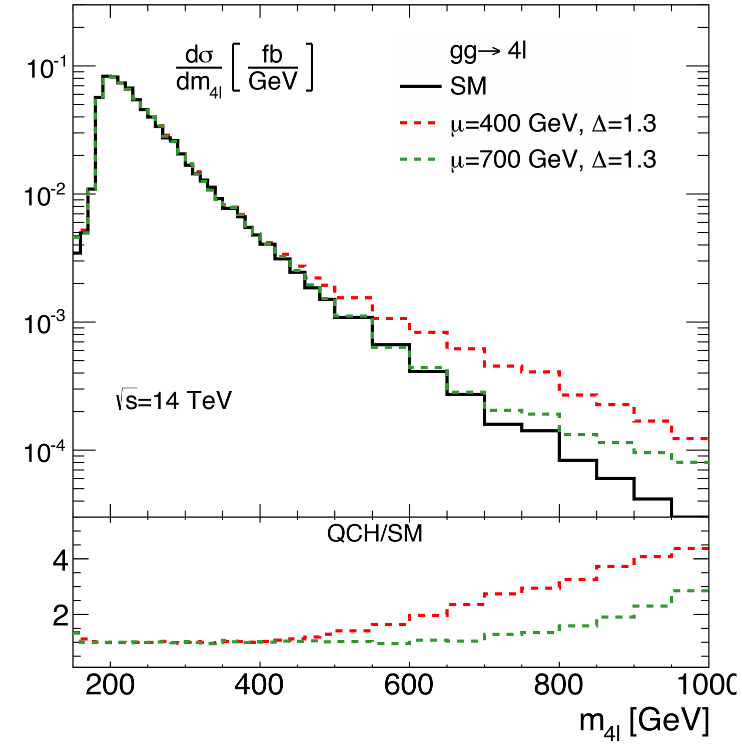
For example:

$h \to \gamma\gamma,\ gg$ Top off shell, should have some sensitivity

At higher energies

Goncalves, Han, 2018

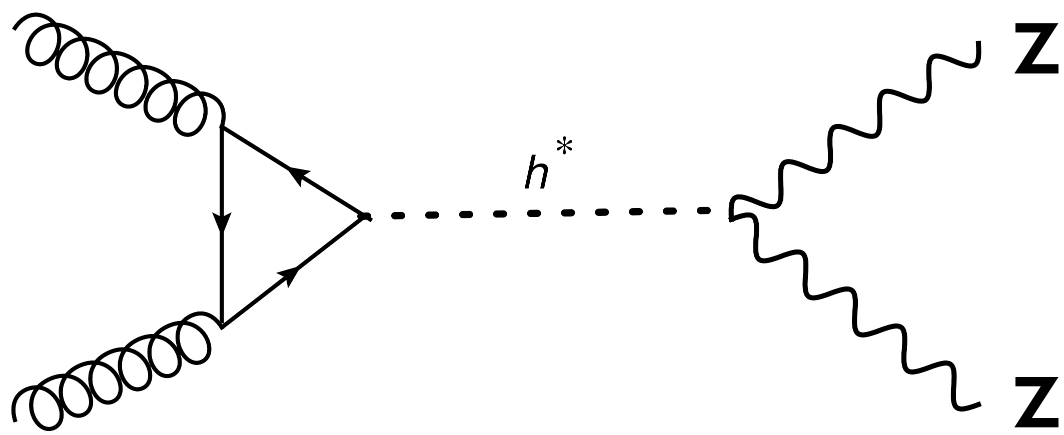




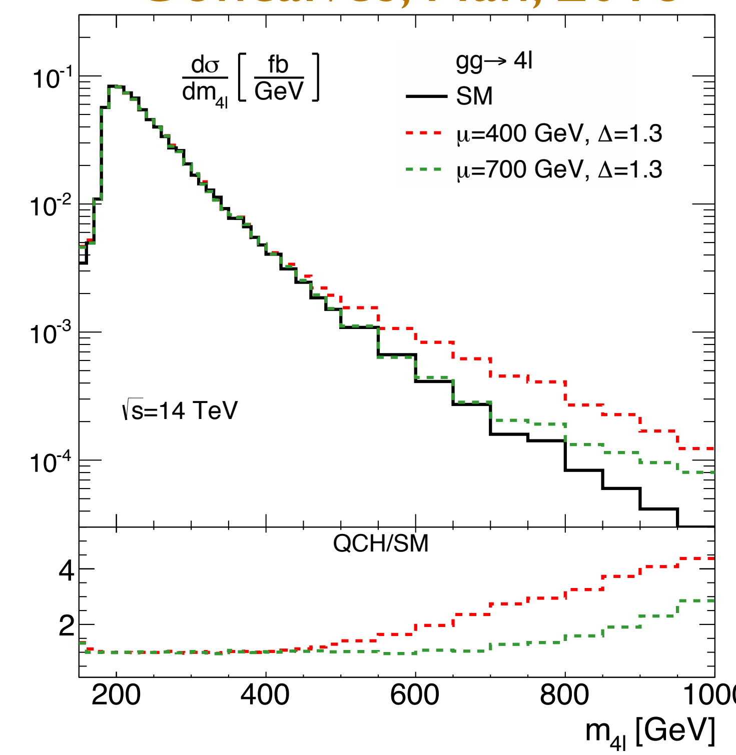
Off-shell Higgs.

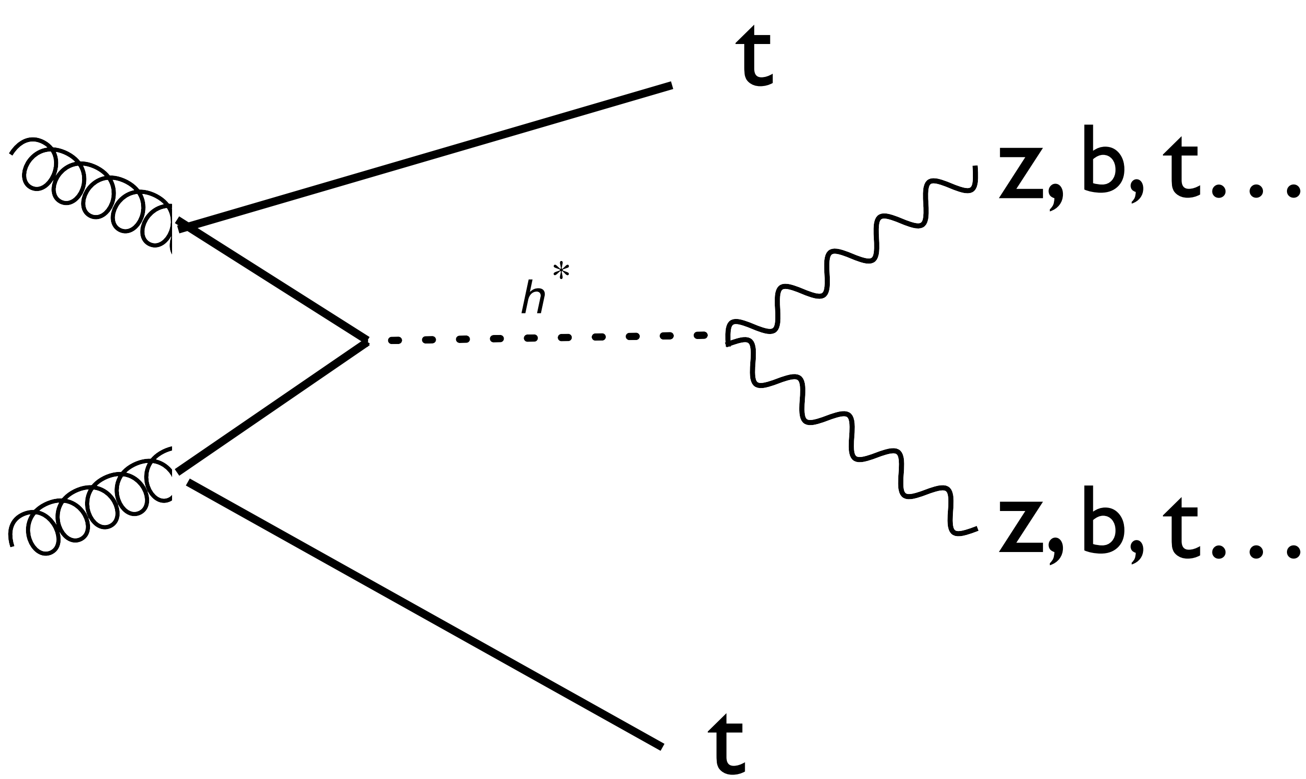
Modification of Higgs propagator and top Higgs coupling, parameterized by μ and Δ.

At higher energies



Goncalves, Han, 2018



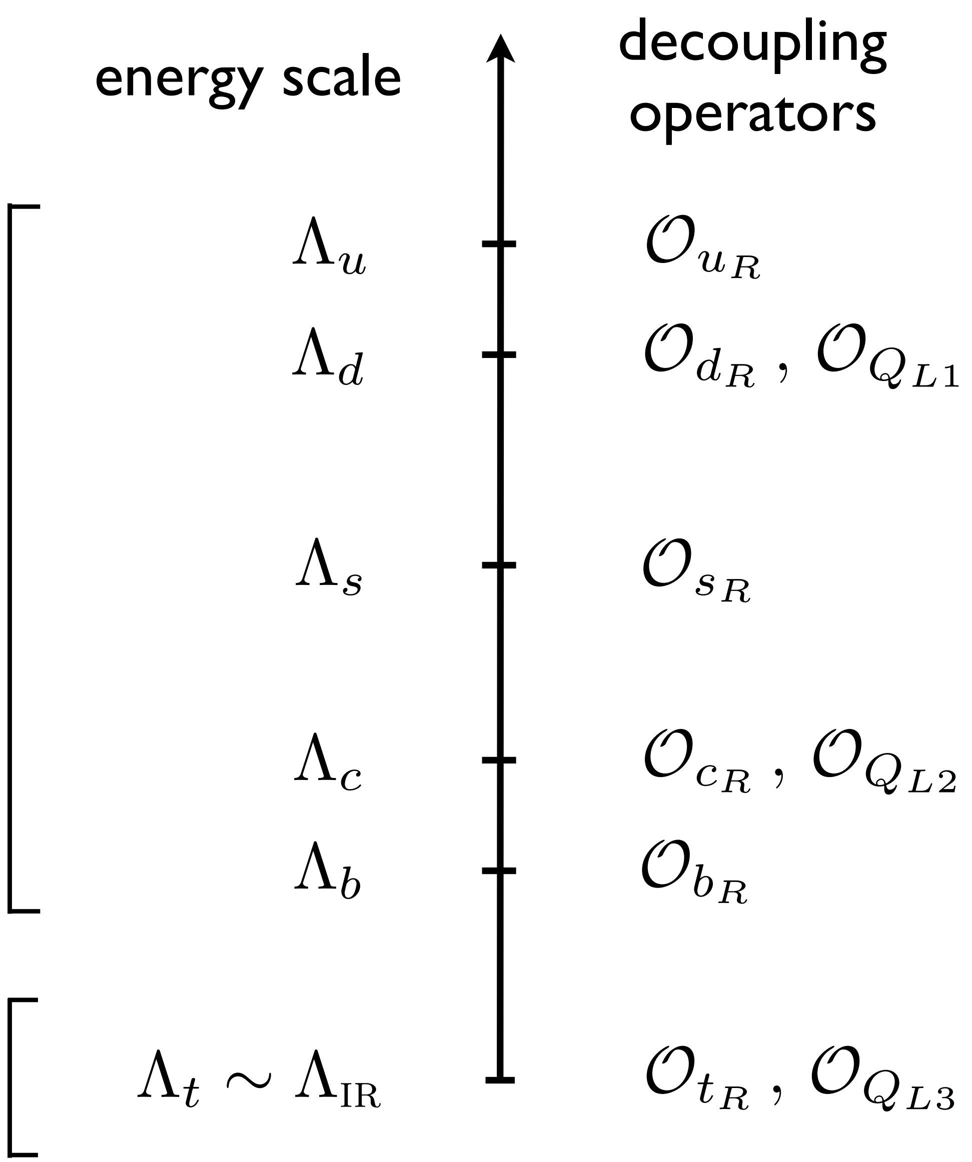


Potentially interesting:

Probing different kinematical regions of top and Higgs.

Top FCNC: e.g. from compositness

Panico and Pomarol, 1603.06609



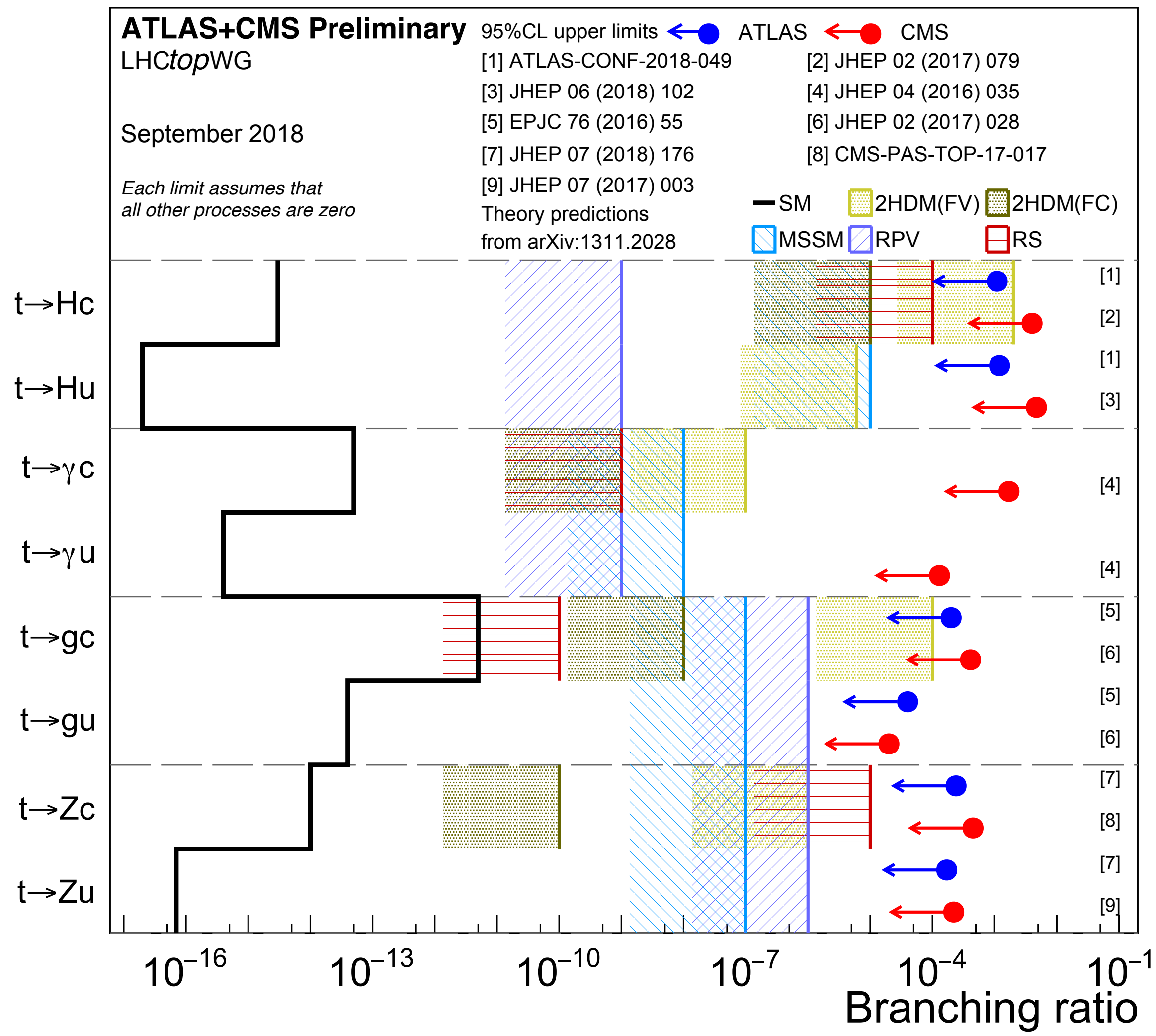
For example:

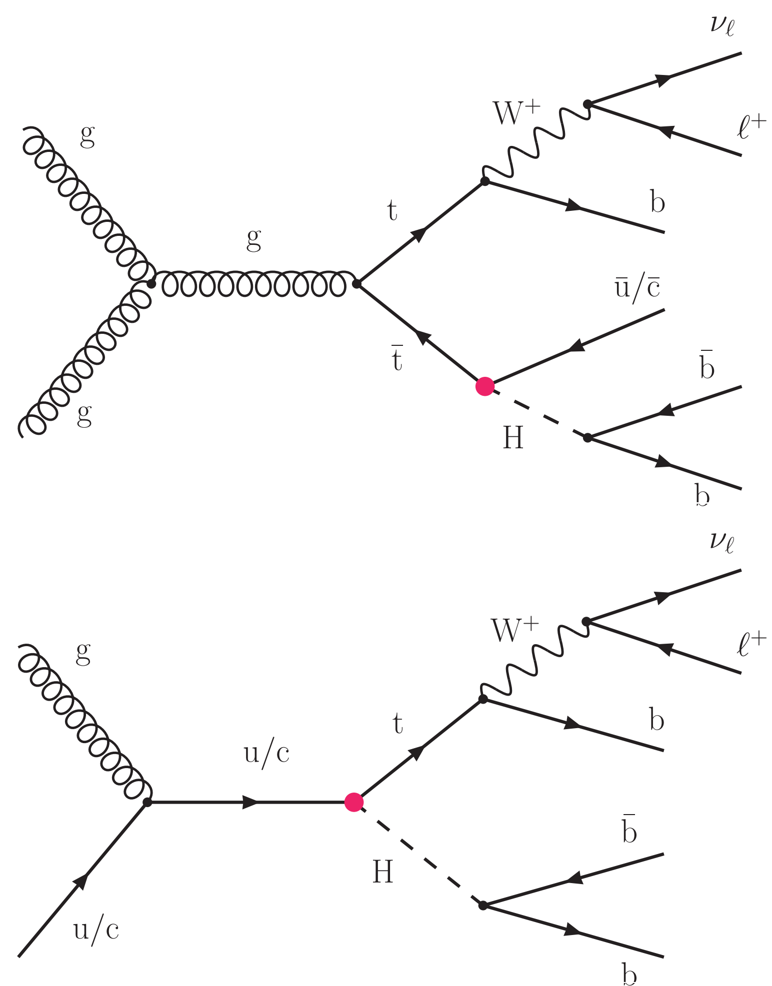
$$\frac{g_* y_t}{\Lambda_{\rm IR}} \bar{Q}_{3R} \gamma^\mu Q_{3R} H^\dagger D_\mu H$$

$$\Downarrow$$

$$t \to hq(q = u, c)$$

Top FCNC

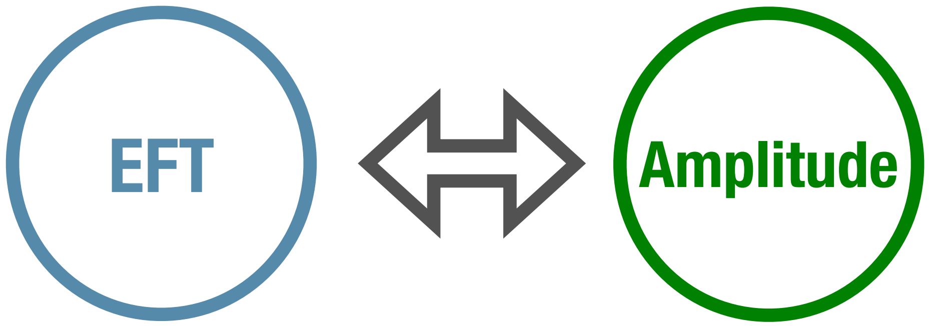




- Not quite in the interesting region for many models yet.
- But, certainly worth keep-going

Testing sum rules, positivity

EFT, amplitude, dispersion

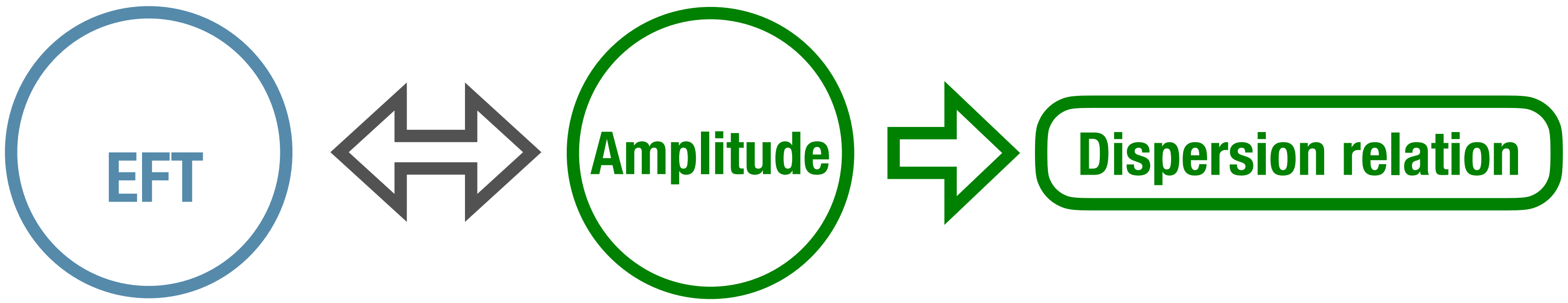


Alternative representation.

More direct connection with observables.

Many works in recent years:
Shadmi, Weiss. 1809.09644
Ma, Shu, Xiao. 1902.06752
Aoude, Machado. 1905.11433
Durieux, Kitahara, Shadmi, Weiss. 1909.10511
Franken, Schwinn. 1910.13407
Falkowski. 1912.07865
Durieux, Machado. 1912.08827
Bachu, Yellespur. 1912.04334
Durieux, Kitahara, Machado, Shadmi, Weiss. 2008.09652

EFT, amplitude, dispersion



Follows from general principles of QFT.

Leading to sum rules, positivity bounds.

Connection between IR measurement and UV completion

Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi, 2006
+ a lot of recent activities

Sum rules, positivity...

Schematically

$$\delta g \propto \frac{c}{M_{1,2}^{2n}} = \frac{d^n A(s,t=0)}{ds^n}\bigg|_{s=0} \simeq \int_0^\infty \frac{ds}{\pi}\frac{1}{s^n}\Big(\sigma(ab\to X_1) + (-)^n\sigma(a\bar{b}\to X_2)\Big) + \dots$$

δg shift in low energy coupling

$X_{1,2}$ NP particles with masses $M_{1,2}$

$n=1$, dim-6 $\rightarrow$ sum rules

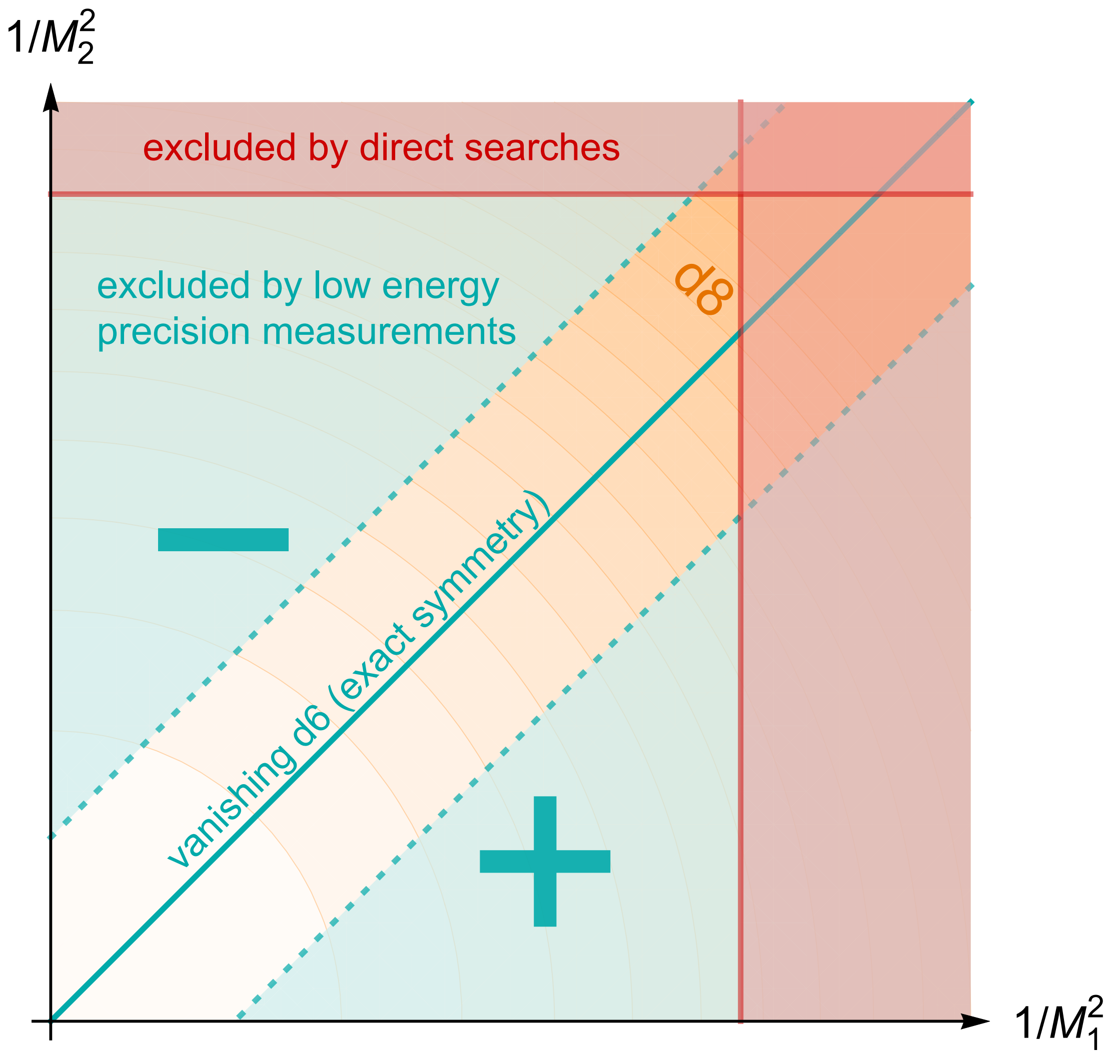
$n=2$, dim-8 $\rightarrow$ positivity

More relations
(also include $t \neq 0$)

Remmen, Rodd 2010.04723
Bellazzini, Miro, Rattazzi, Riembau, Riva, 2011.00037
Arkani-Hamed, Huang, Huang, 2012.15849
...

Precision vs direct search

J. Gu, LTW, 2008.07551

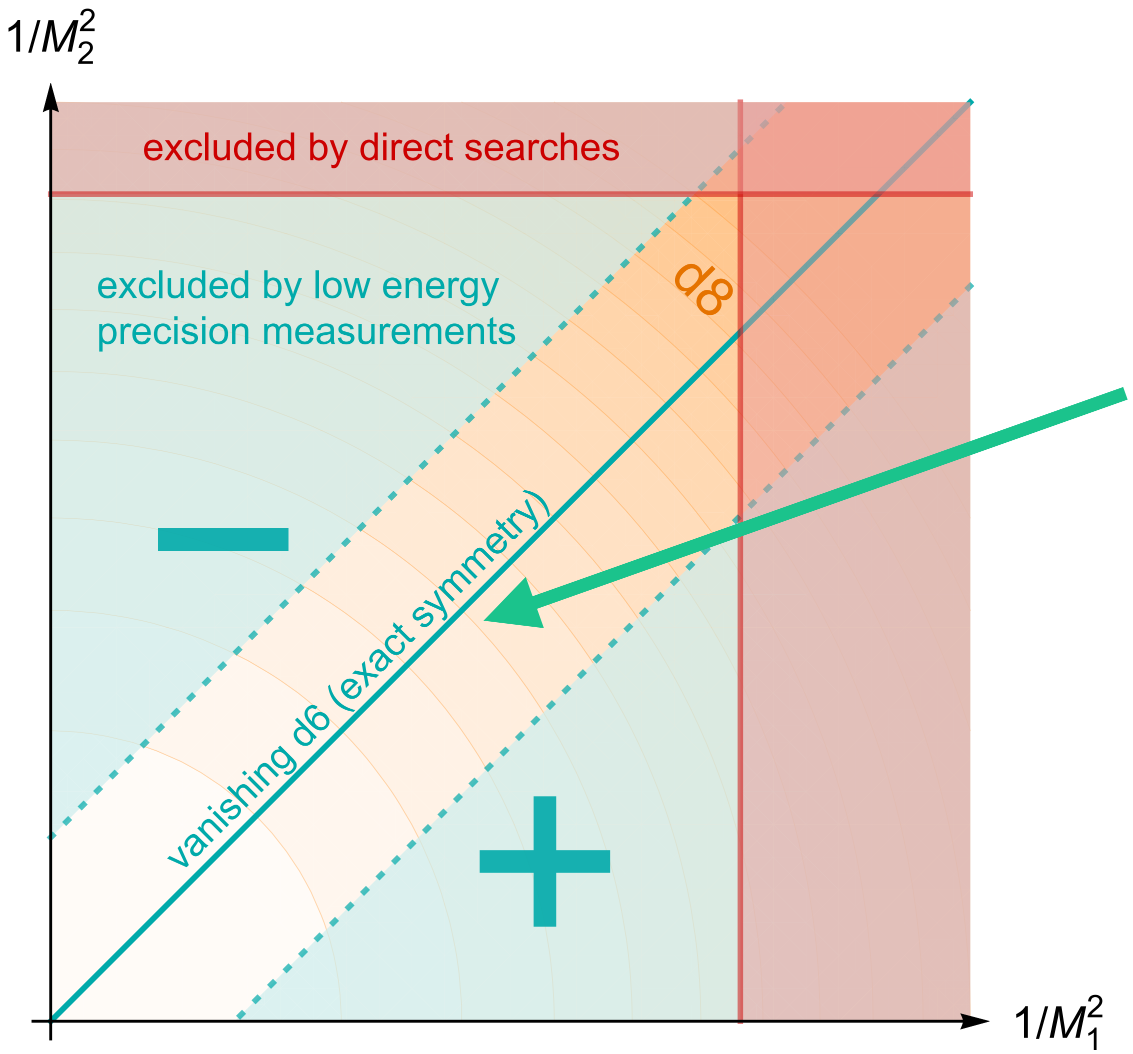


$$\delta g \propto \frac{c}{M_{1,2}^2} = \frac{dA}{ds}\bigg|_{s=0} = \int_0^\infty \frac{ds}{s\pi}\left(\sigma(ab \to X_1) - \sigma(a\bar{b} \to X_2)\right)$$

$X_{1,2}$ mass: $M_{1,2}$

Precision vs direct search

J. Gu, LTW, 2008.07551



Cancellation can occur for dim-6 contribution. Possible to implement a symmetry.

Cancellation not possible for dim-8. due to positivity.

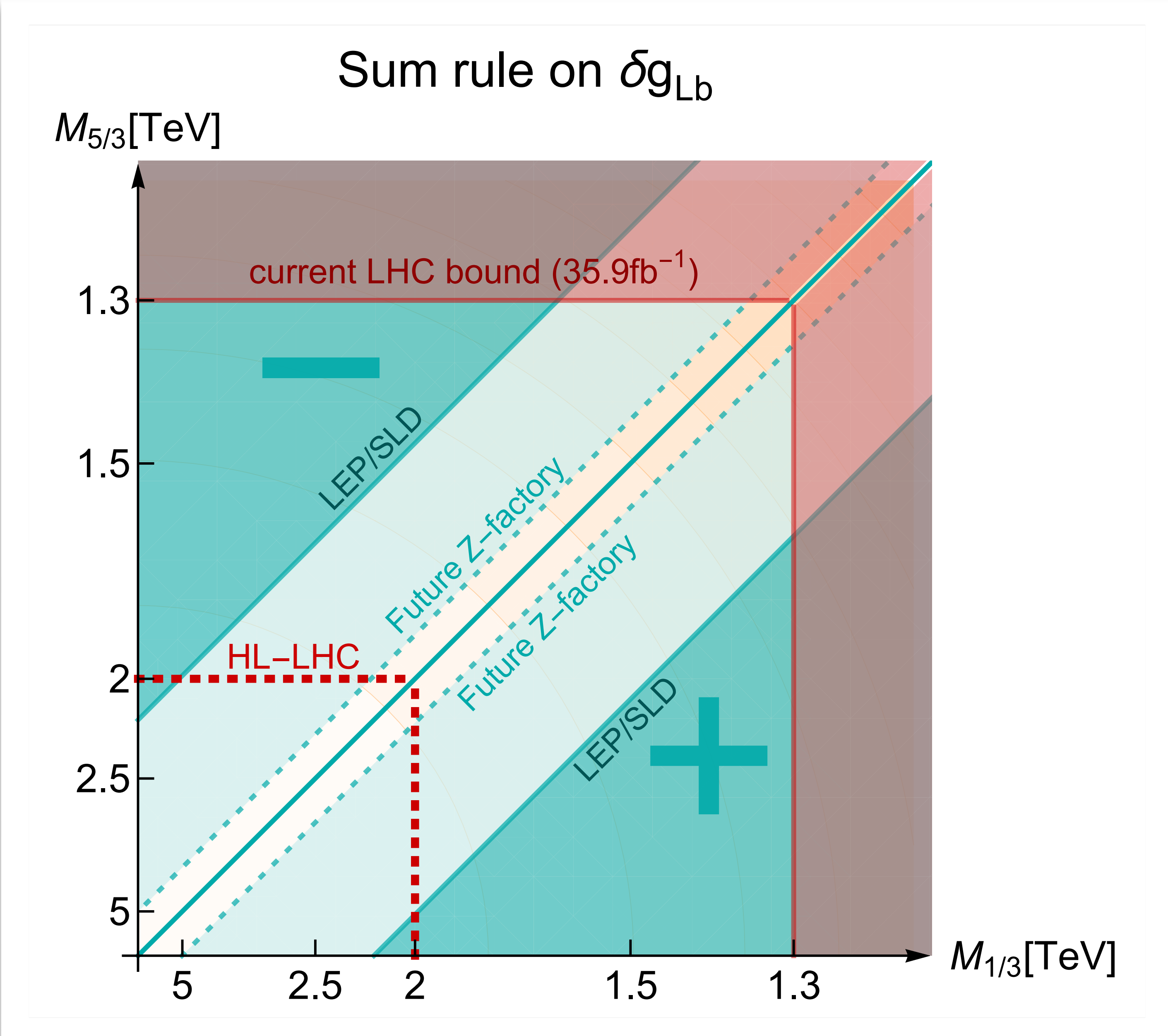
Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi, 2006

$$\delta g \propto \frac{c}{M_{1,2}^2} = \frac{dA}{ds}\bigg|_{s=0} = \int_0^\infty \frac{ds}{s\pi}\left(\sigma(ab \to X_1) - \sigma(a\bar{b} \to X_2)\right)$$

$X_{1,2}$ mass: $M_{1,2}$

Precision vs direct search

J. Gu, LTW, 2008.07551



New fermions with charge 5/3 and 1/3

Agashe, Contino, Da Rold, Pomarol, hep-ph/0605341

Probing dim-8?

Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi, 2006. + many.

- Dim-8 operators have positivity bound.
  - Stronger limit on the parameter space.
  - Could be a cleaner test of general properties (Unitarity, locality, analyticity) of UV completion.
- Unfortunately, typically, dim-6 will dominate a process. Hard to see the effect of dim-8.

Seeing dim-8

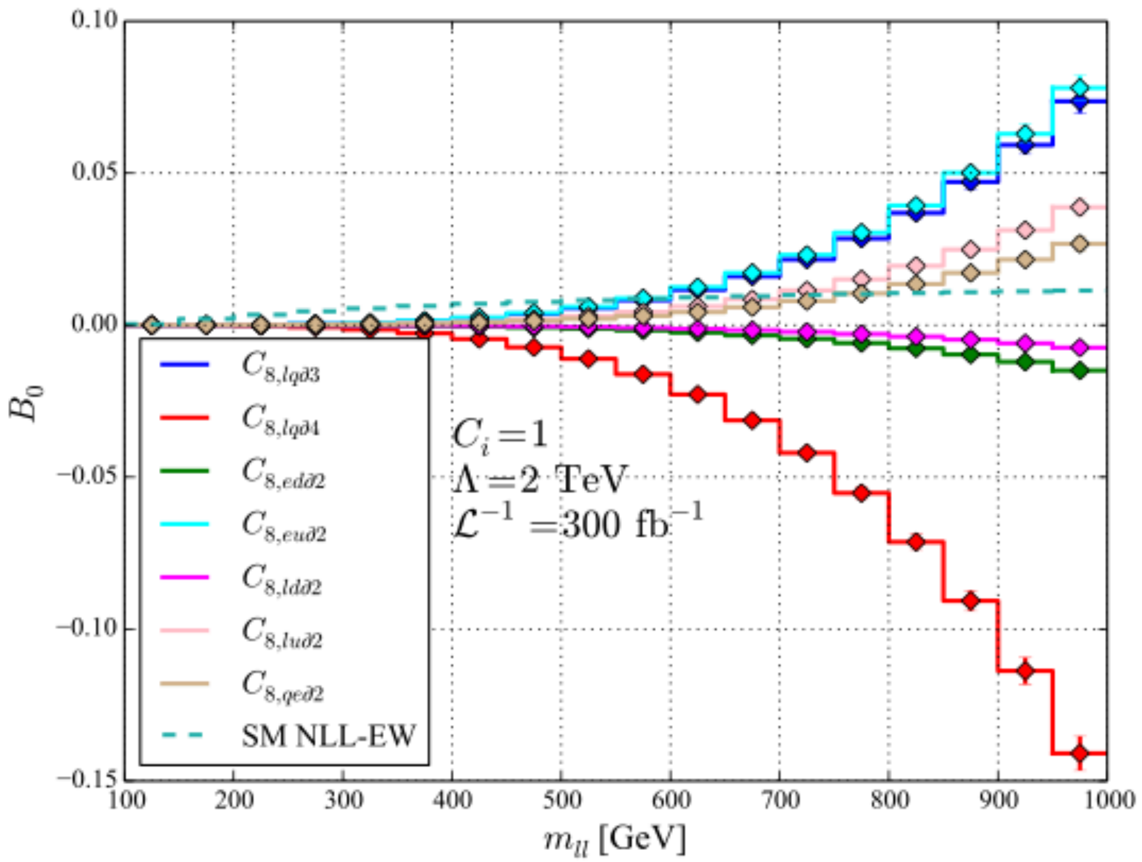
- Dim-6 =0
  - Could be symmetry or some accidental cancellation.
  - Unlikely to work for the generic case.
  - Need to identify special channels (an example later).

Seeing dim-8

- Dim-6 =0
- Different growth with energy
  - dim-6: E^2 vs dim-8: E^4
  - Be mindful that E^4 piece is $(E/\Lambda)^2$ smaller.
  - Also need to disentangle the $(\text{dim-6})^2$
  - Still, possible in some cases, useful to pursue.

Seeing dim-8

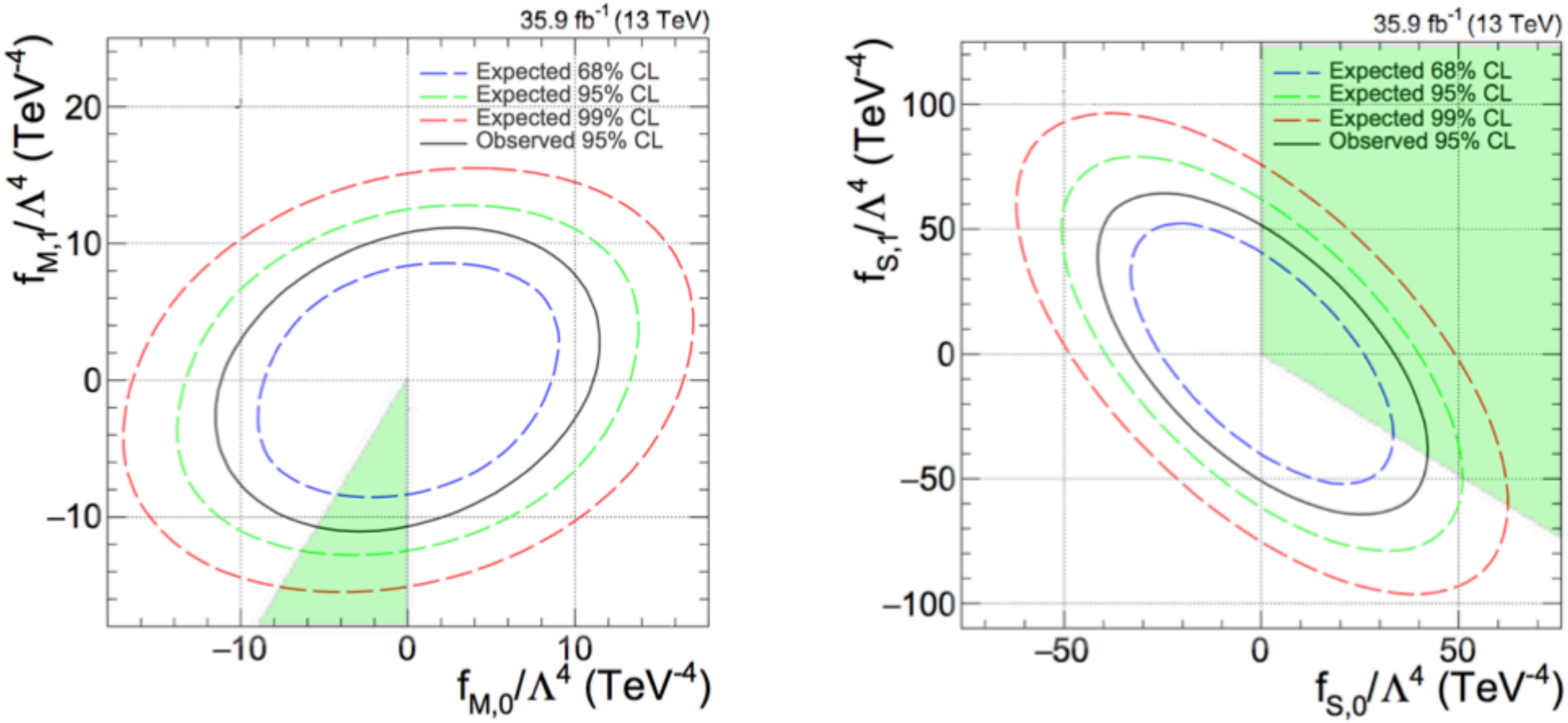
- Dim-6 =0
- E^2 vs E^4
- Different kin. Distribution:



Some dim-8 operators can give l=2 partial wave amplitudes

Alioli, Boughezal, Mereghetti, Petriello, 2003.11615

Tests at the LHC



Experimental bound assumes dim-8 dominates.

Green region from theoretical bounds on the coefficients of the operators.

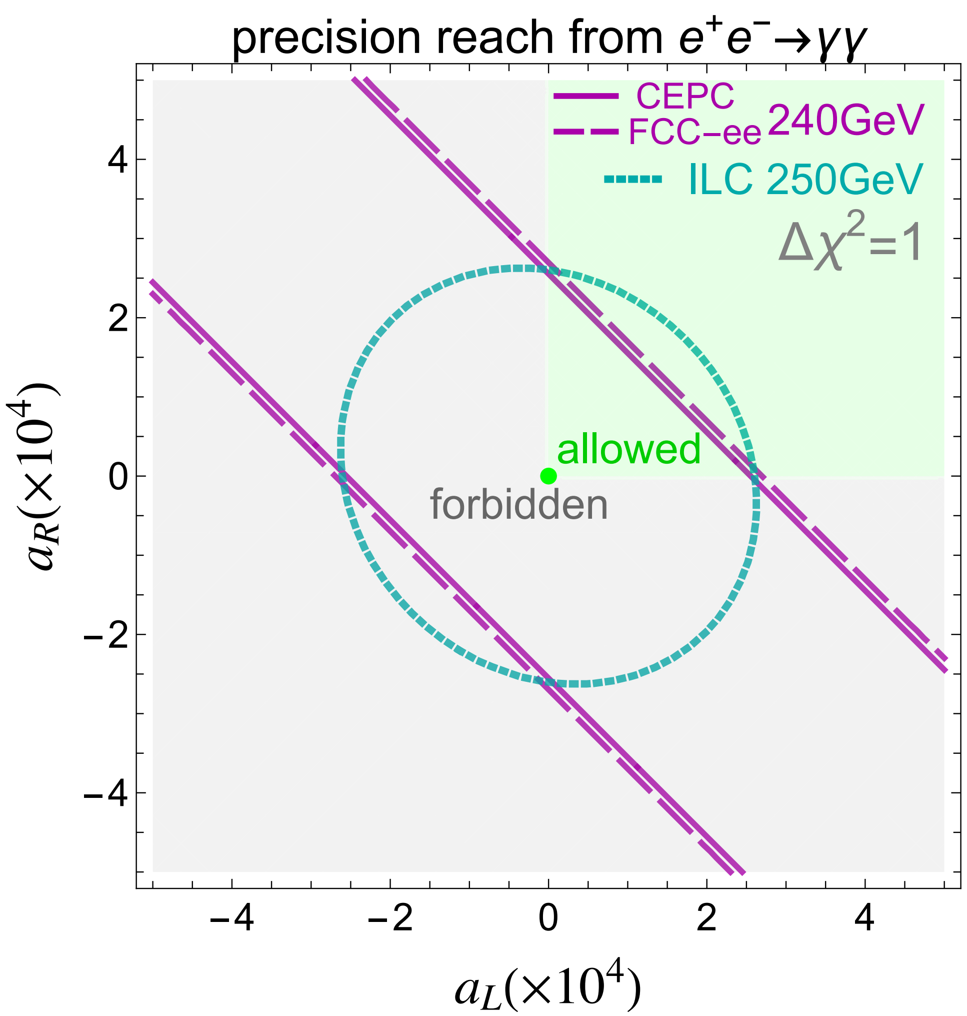
Bi, Zhang, Zhou, 1902.08977
Exp limit based on CMS PAS SMP-001

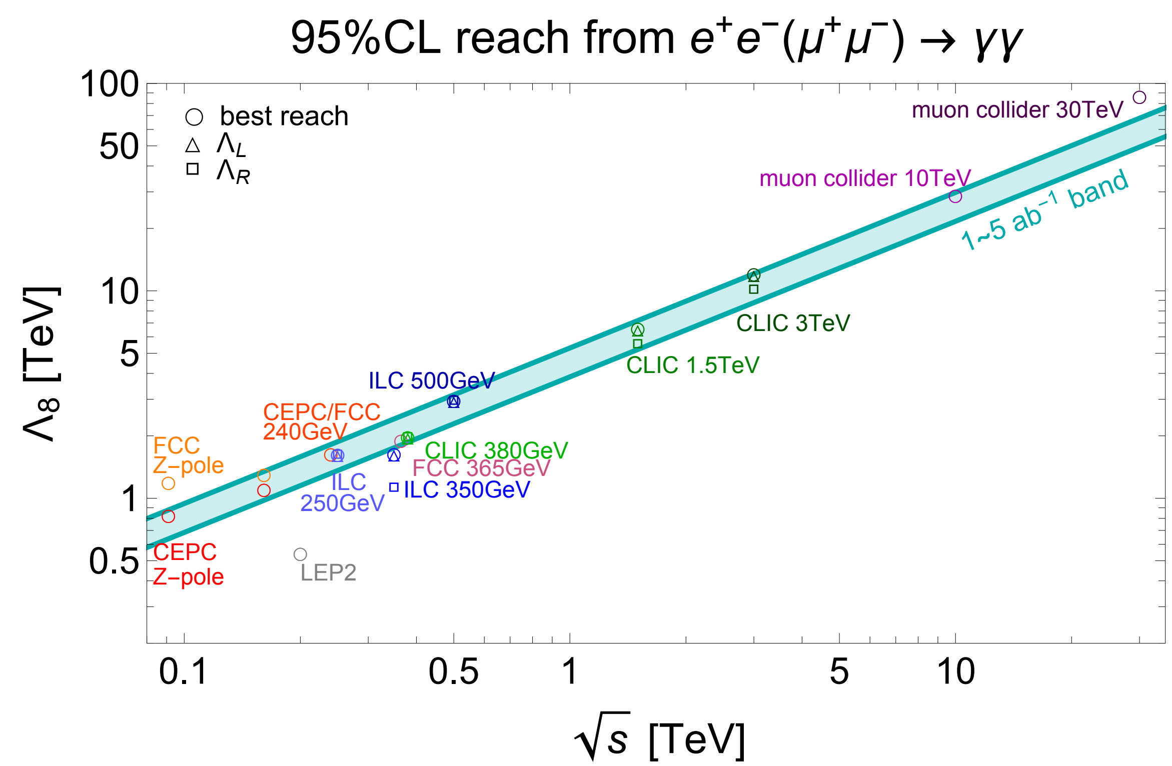
The ff $\rightarrow\gamma\gamma$ channel

J. Gu, C. Zhang, LTW, 2011.03055

- Effect from dim-6 operator either vanishing or suppressed.
  - Due to the nature of the amplitude and the experimental constraints.
- SM $\times$ dim-8 interference is the leading channel.
- Positivity bound on dim-8 leads to prediction

$$\sigma(e^+e^- \rightarrow \gamma\gamma) > \sigma_{\rm SM}(e^+e^- \rightarrow \gamma\gamma)$$





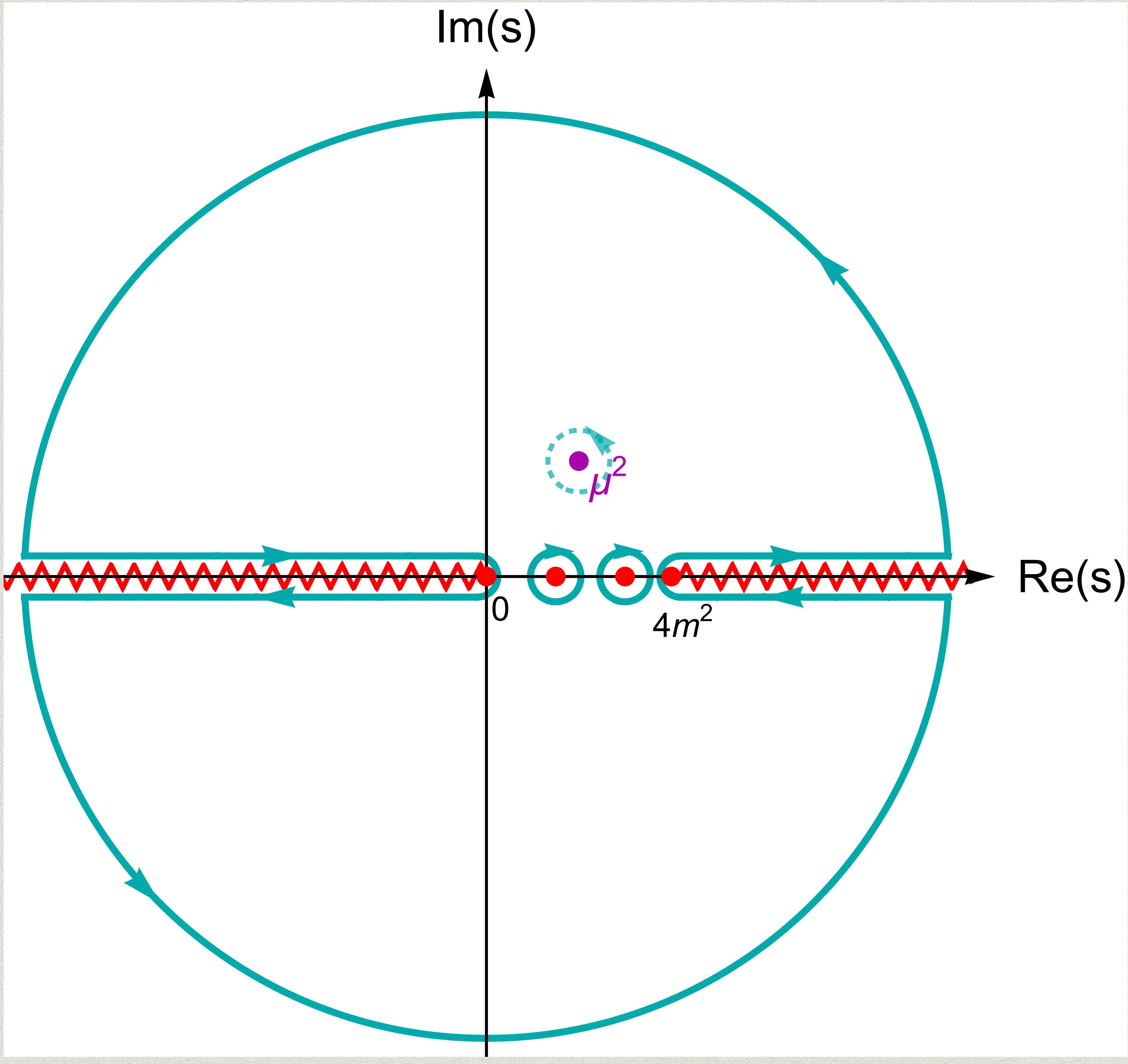
At hadron collider, harder, but in principle possible.

More work needed!

Conclusion

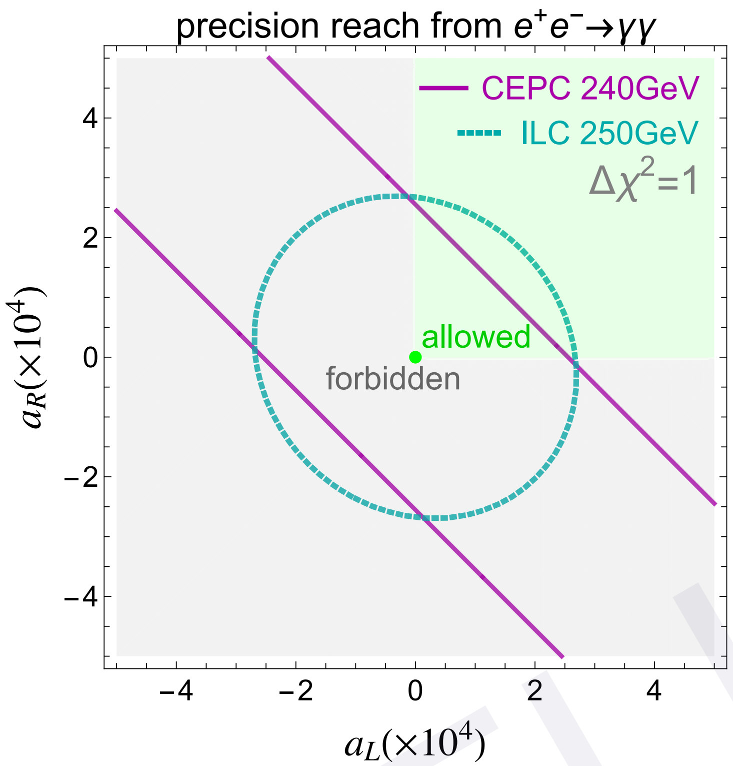
- The next stage of the LHC will make great progress in precision measurement, opening new windows to new physics.
  - Higgs, top, W/Z, flavor and CP violation.
- I emphasized
  - Detailed measurement of all kinematical distribution, high energy tails + others.
  - Huge potential in rare decays.
  - New non-trivial tests: such as positivity and other relations.

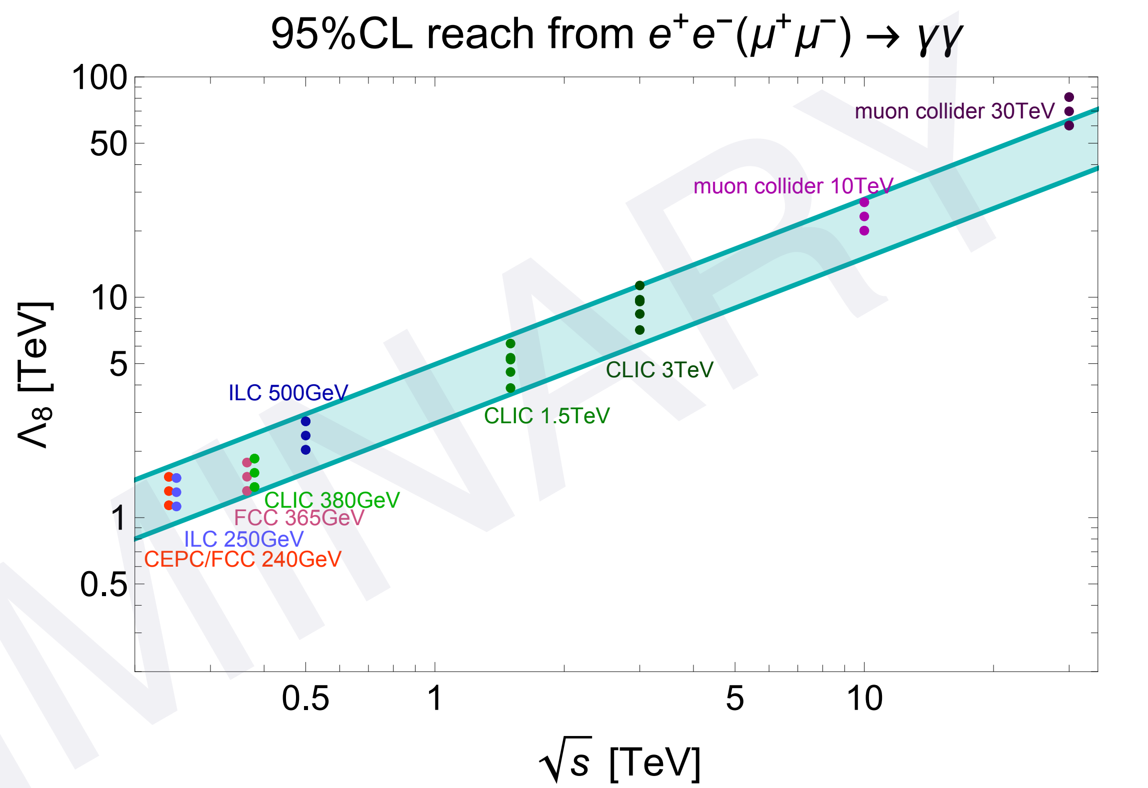
Extra



Im(s)
μ^2
Re(s)
0
$4m^2$

Dimension 8 operators? (current work, JG, C. Zhang and L.-T. Wang)





- Positivity bounds resolve the flat direction between a_L and a_R for unpolarized beams.
- Best reach still from high energy colliders.

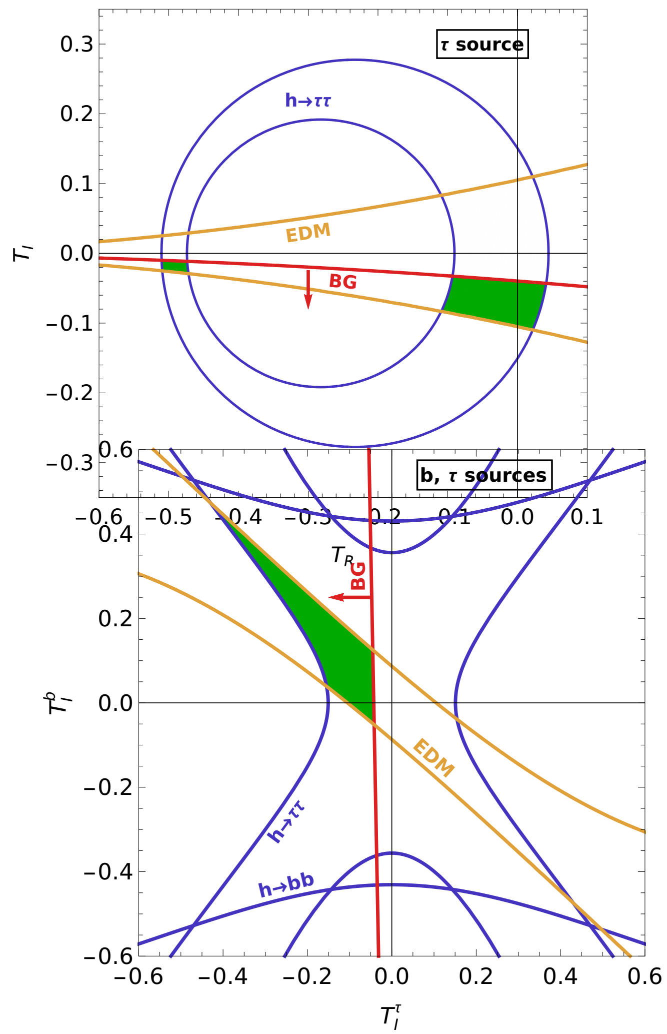
$$
\begin{aligned}
\mathcal{O}^{(8)}_{\ell B} &= -\frac{1}{4}(i\bar{\ell}_L\gamma^{\{\rho}D^{\nu\}}\ell_L + \text{h.c.})B_{\mu\nu}B^{\mu}{}_{\rho}\,,\\
\mathcal{O}^{(8)}_{eB} &= -\frac{1}{4}(i\bar{e}_R\gamma^{\{\rho}D^{\nu\}}e_R + \text{h.c.})B_{\mu\nu}B^{\mu}{}_{\rho}\,,\\
\mathcal{O}^{(8)}_{\ell W} &= -\frac{1}{4}(i\bar{\ell}_L\gamma^{\{\rho}D^{\nu\}}\ell_L + \text{h.c.})W^a_{\mu\nu}W^{a\mu}{}_{\rho}\,,\\
\mathcal{O}^{(8)}_{eW} &= -\frac{1}{4}(i\bar{e}_R\gamma^{\{\rho}D^{\nu\}}e_R + \text{h.c.})W^a_{\mu\nu}W^{a\mu}{}_{\rho}\,,\\
\mathcal{O}^{(8)}_{\ell BW} &= -\frac{1}{4}(i\bar{\ell}_L\sigma^a\gamma^{\{\rho}D^{\nu\}}\ell_L + \text{h.c.})B_{\mu\nu}W^{a\mu}{}_{\rho}\,,
\end{aligned}
$$

$$
\begin{aligned}
a_L &= \frac{v^4}{\Lambda^4}\left(\cos^2\theta_W\, c^{(8)}_{\ell B} - \cos\theta_W \sin\theta_W\, c^{(8)}_{\ell BW} + \sin^2\theta_W\, c^{(8)}_{\ell W}\right)\,,\\
a_R &= \frac{v^4}{\Lambda^4}\left(\cos^2\theta_W\, c^{(8)}_{eB} + \sin^2\theta_W\, c^{(8)}_{eW}\right)\,,
\end{aligned}
$$

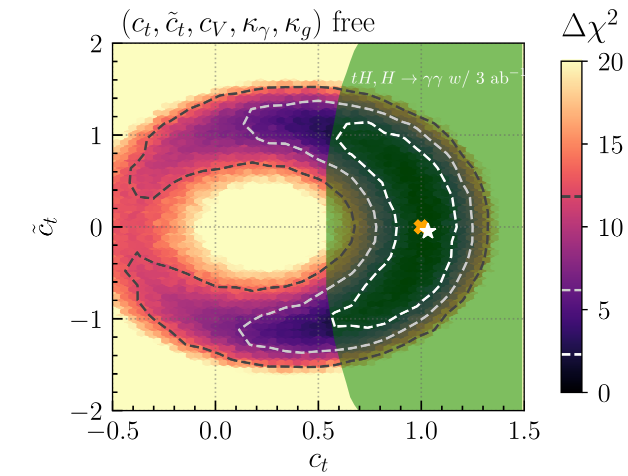
CP violation

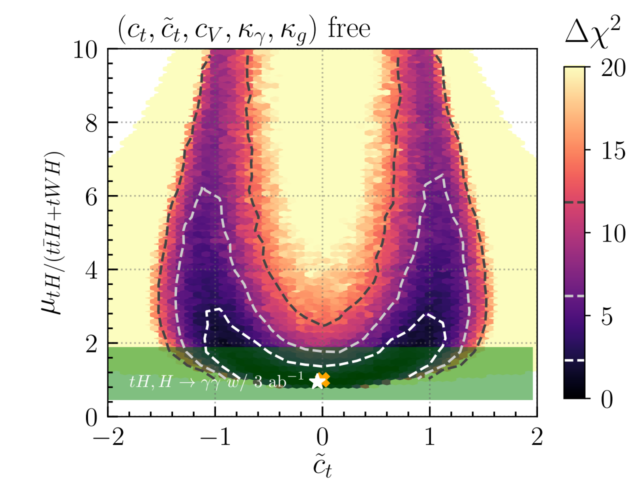
$$\mathcal{L}_{\rm Yuk} = y_f \overline{F_L} F_R H + \frac{1}{\Lambda^2}(X_R^f + i X_I^f)|H|^2 \overline{F_L} F_R H + \text{h.c.}$$

$$T_R^f \equiv \frac{v^2}{2\Lambda^2}\frac{X_R^f}{y_f}, \quad T_I^f \equiv \frac{v^2}{2\Lambda^2}\frac{X_I^f}{y_f}$$



Fuchs, Losada, Nir, Viernik, 2003.00099

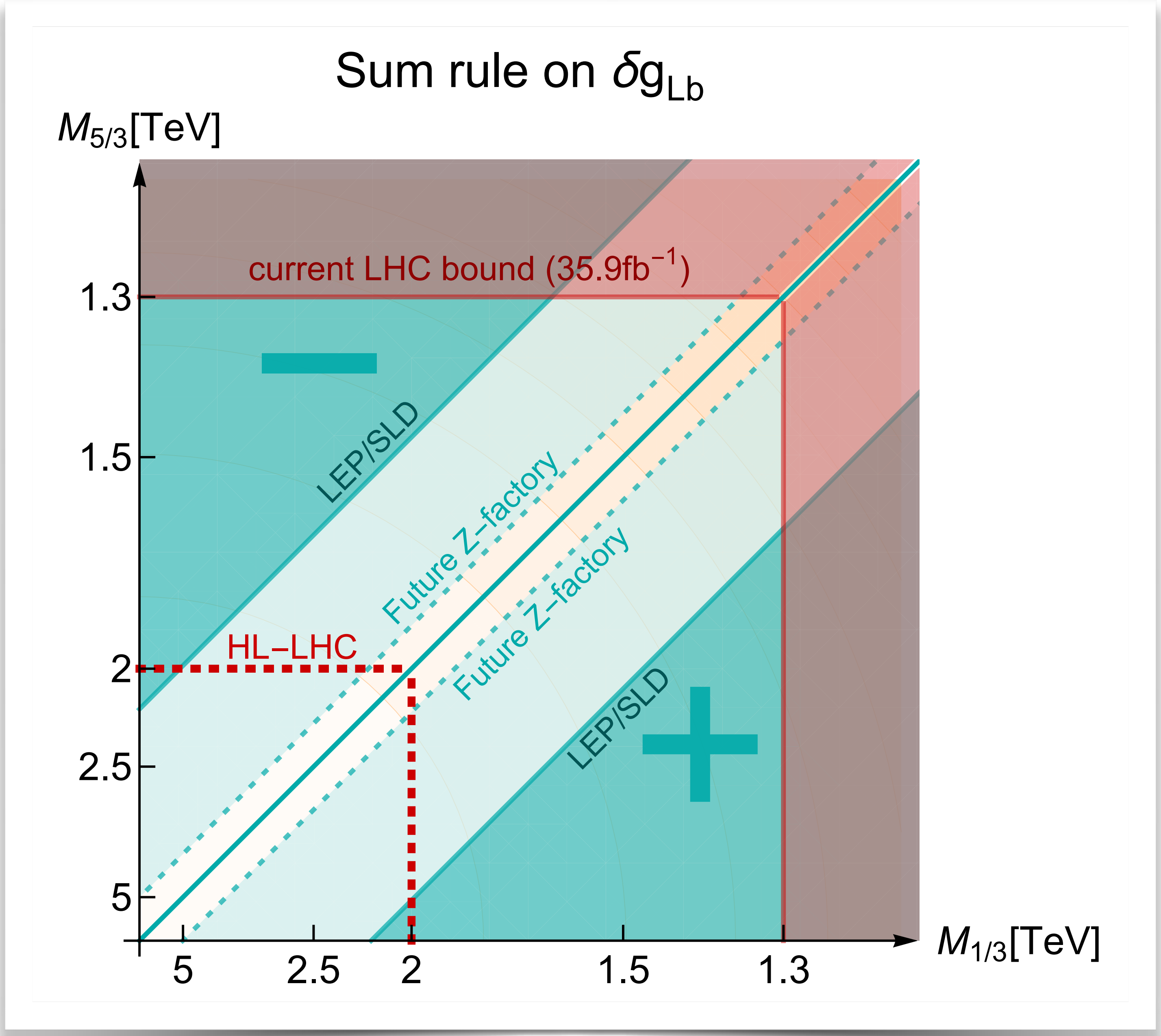




$$\mathcal{L}_{\rm yuk} = -\frac{y_t^{\rm SM}}{\sqrt{2}}\bar{t}\,(c_t + i\gamma_5 \tilde{c}_t)\, tH$$

Bahl, Bechtle, Heinemeyer, Katzy, Klingl, Peters, Saimpert, Stefaniak, Weiglein, 2007.08542

Precision vs direct search



Flavor violating Higgs decay

Model	$\kappa_{ct(tc)}/\kappa_t$	$\kappa_{ut(tu)}/\kappa_t$	$\kappa_{uc(cu)}/\kappa_t$
MFV	$\frac{\Re\left(c_u m_b^2 V_{cb}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(c)}}{v}$	$\frac{\Re\left(c_u m_b^2 V_{ub}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(u)}}{v}$	$\frac{\Re\left(c_u m_b^2 V_{ub(cb)} V_{cb(ub)}^{*}\right)}{\Lambda^2}\frac{\sqrt{2}m_{c(u)}}{v}$
F2HDM	$\mathcal{O}\left(\frac{m_c}{m_t}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m_u}{m_t}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m_c m_u}{m_t^2}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$
FN	$\mathcal{O}\left(\frac{v m_{t(c)}}{\Lambda^2}\lvert V_{cb}\rvert^{\pm 1}\right)$	$\mathcal{O}\left(\frac{v m_{t(u)}}{\Lambda^2}\lvert V_{ub}\rvert^{\pm 1}\right)$	$\mathcal{O}\left(\frac{v m_{c(u)}}{\Lambda^2}\lvert V_{us}\rvert^{\pm 1}\right)$
GL2	$\epsilon(\epsilon^2)$	$\epsilon(\epsilon^2)$	ϵ^3
RS	$\sim \lambda^{(-)2}\frac{m_{t(c)}}{v}\bar{Y}^2\frac{v^2}{m_{KK}^2}$	$\sim \lambda^{(-)3}\frac{m_{t(u)}}{v}\bar{Y}^2\frac{v^2}{m_{KK}^2}$	$\sim \lambda^{(-)1}\frac{m_{c(u)}}{v}\bar{Y}^2\frac{v^2}{m_{KK}^2}$
pNGB	$\mathcal{O}(y_*^2\frac{m_t}{v}\frac{\lambda_{L(R),2}\lambda_{L(R),3}m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2\frac{m_t}{v}\frac{\lambda_{L(R),1}\lambda_{L(R),3}m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2\frac{m_c}{v}\frac{\lambda_{L(R),1}\lambda_{L(R),2}m_W^2}{M_*^2})$

Model	$\kappa_{\tau\mu(\mu\tau)}/\kappa_\tau$	$\kappa_{\tau e(e\tau)}/\kappa_\tau$	$\kappa_{\mu e(e\mu)}/\kappa_\tau$
F2HDM	$\mathcal{O}\left(\frac{m_\mu}{m_\tau}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m_e}{m_\tau}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$	$\mathcal{O}\left(\frac{m_\mu m_e}{m_\tau^2}\frac{\cos(\beta-\alpha)}{\cos\alpha\cos\beta}\right)$
FN	$\mathcal{O}\left(\frac{v m_{\mu(\tau)}}{\Lambda^2}\lvert U_{23}\rvert^{\mp 1}\right)$	$\mathcal{O}\left(\frac{v m_{e(\tau)}}{\Lambda^2}\lvert U_{13}\rvert^{\mp 1}\right)$	$\mathcal{O}\left(\frac{v m_{e(\mu)}}{\Lambda^2}\lvert U_{12}\rvert^{\mp 1}\right)$
GL2	$\epsilon^2(\epsilon)$	ϵ	$\epsilon^2(\epsilon^3)$
RS	$\sim\sqrt{\frac{m_{\mu(\tau)}}{m_{\tau(\mu)}}}\bar{Y}^2\frac{v^2}{m_{KK}^2}$	$\sim\sqrt{\frac{m_{e(\tau)}}{m_{\tau(e)}}}\bar{Y}^2\frac{v^2}{m_{KK}^2}$	$\sim\sqrt{\frac{m_{e(\mu)}}{m_{\mu(e)}}}\bar{Y}^2\frac{v^2}{m_{KK}^2}$

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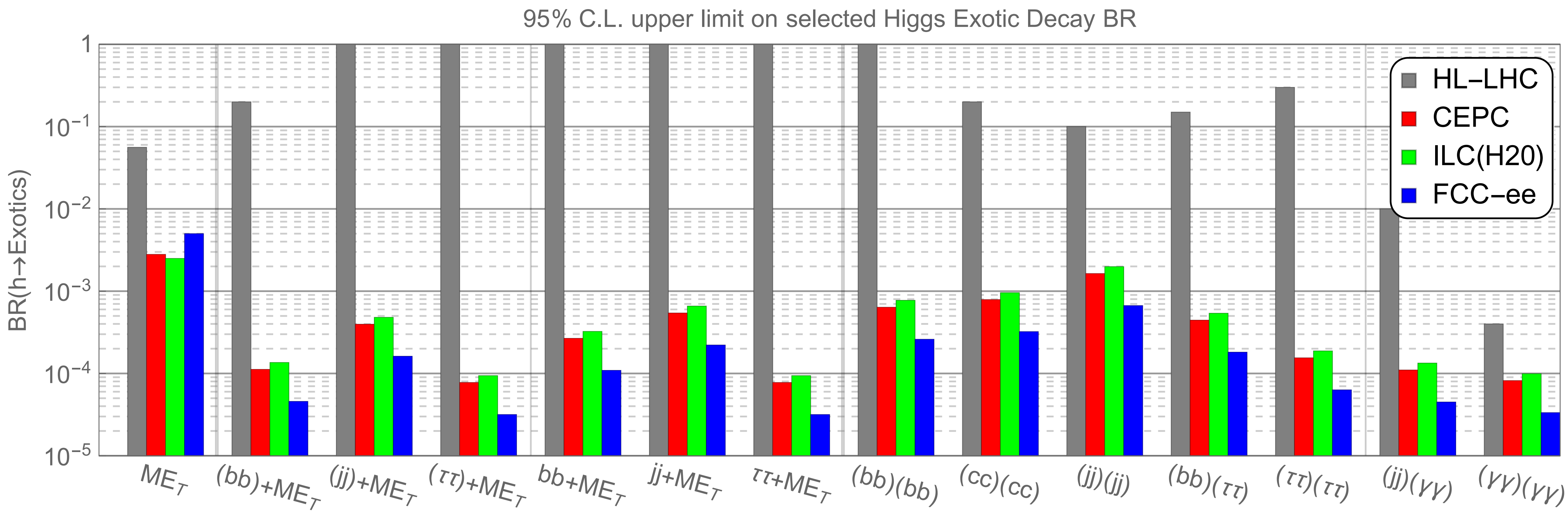
Many (all?) new physics models predict deviations, both flavor diagonal and flavor off-diagonal, in Higgs Yukawa couplings.

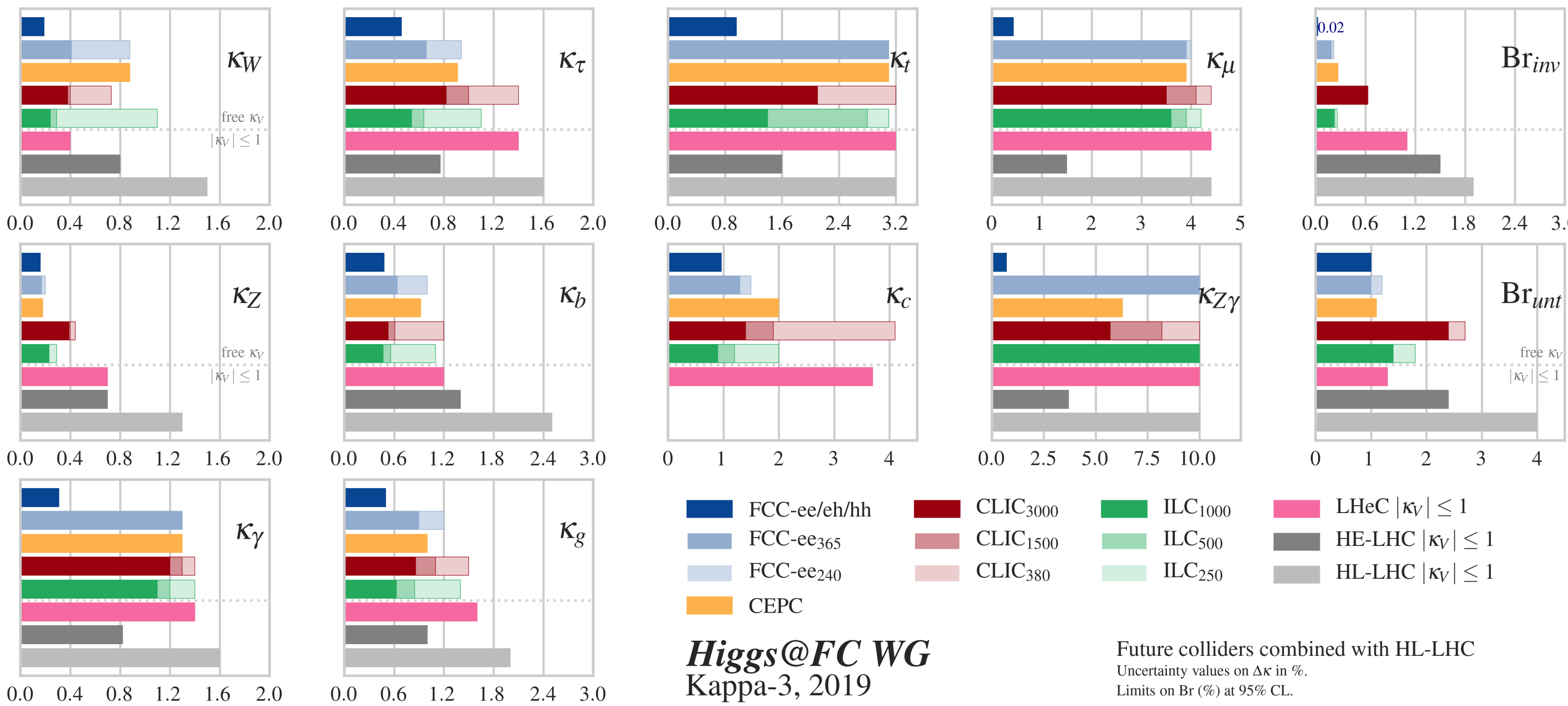
They can show up in light flavor-Higgs coupling, lepton flavor violating decay …

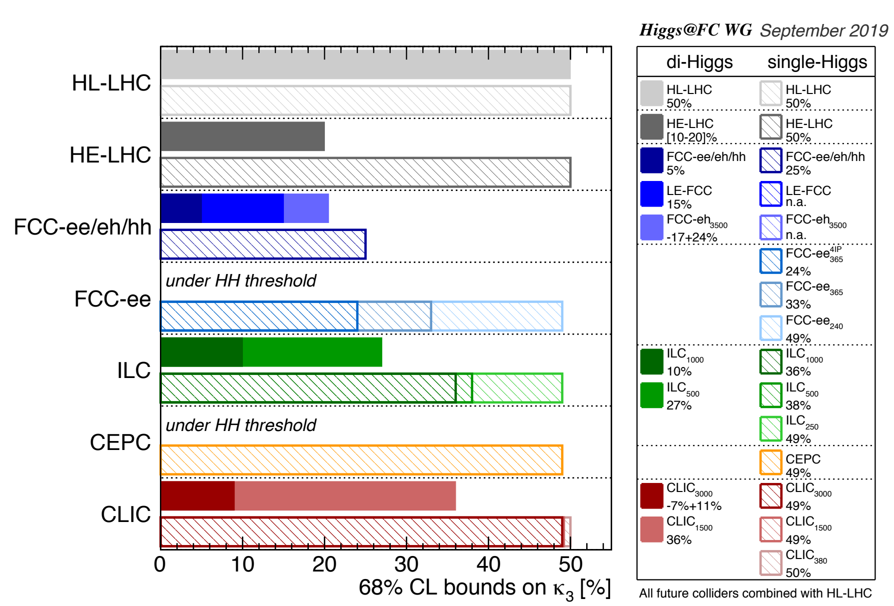
Summary



- Higgs factories can push these BR to 10^{-4}. Impressive reach and complementarity with HL-LHC

All eyes are on the Higgs

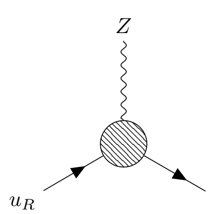




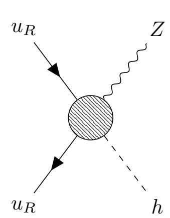
CP

Flavor non-universal effect

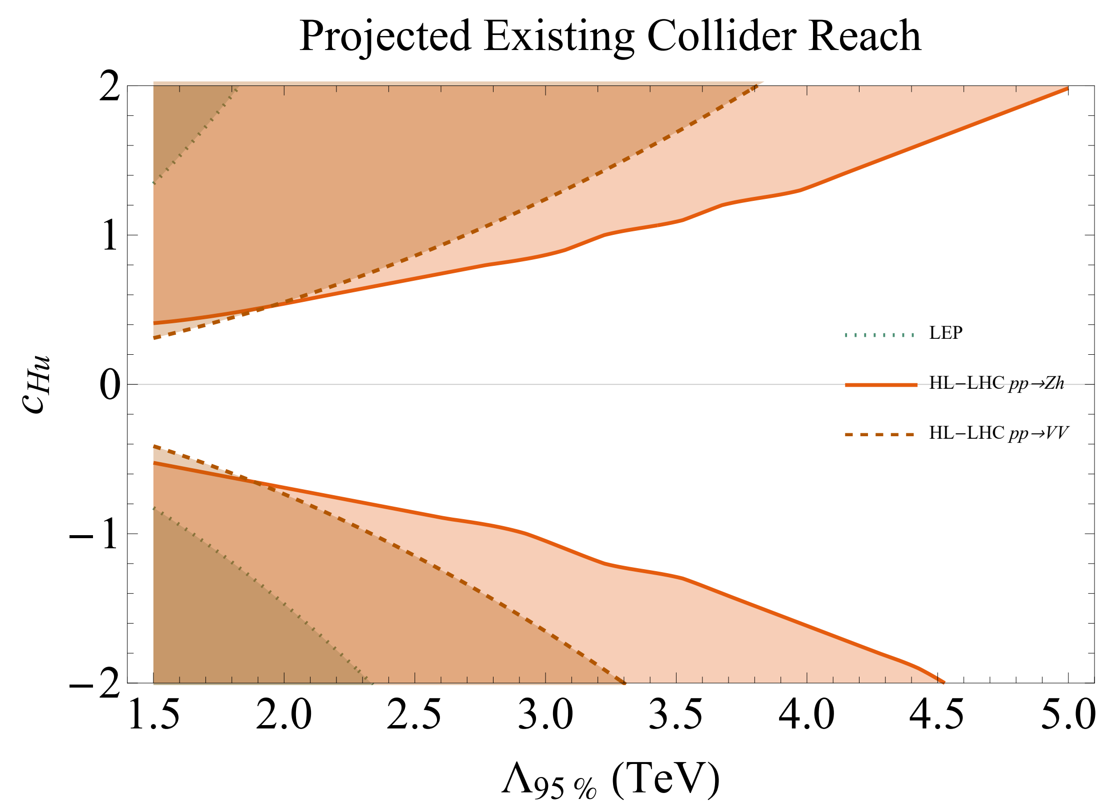
Operators
$\mathcal{O}_{Hu} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$
$\mathcal{O}_{Hd} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$
$\mathcal{O}_{HQ}^{(1)} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q} \gamma^\mu Q)$
$\mathcal{O}_{HQ}^{(3)} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q} \gamma^\mu \sigma^a Q)$

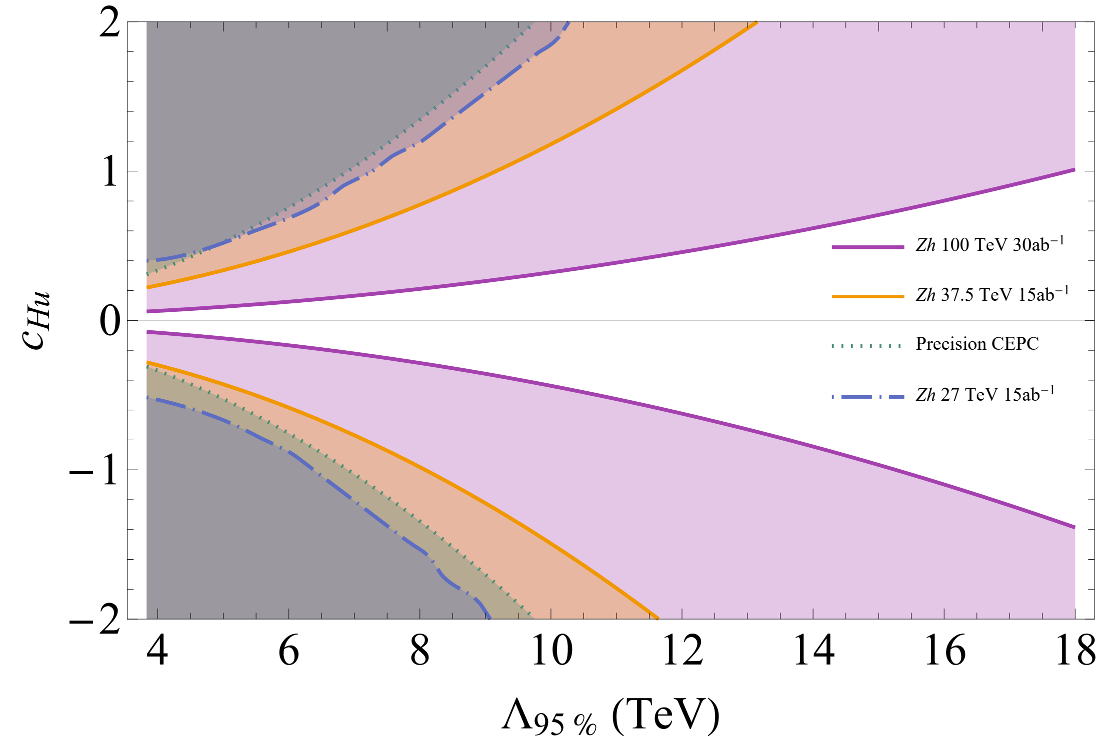


$$= -i \frac{g v^2}{2 c_w} \frac{c_{Hu}}{\Lambda^2}$$



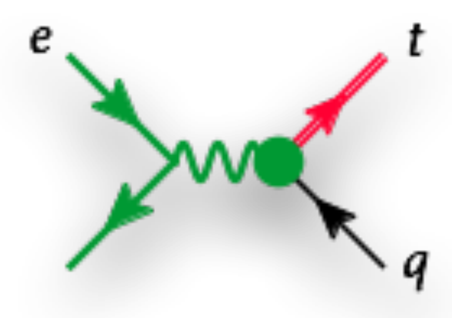
$$= -i \frac{g v}{c_w} \frac{c_{Hu}}{\Lambda^2}$$

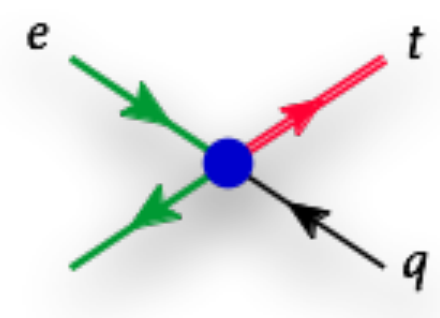




Higgs-top couplings: FCNC

Cen Zhang



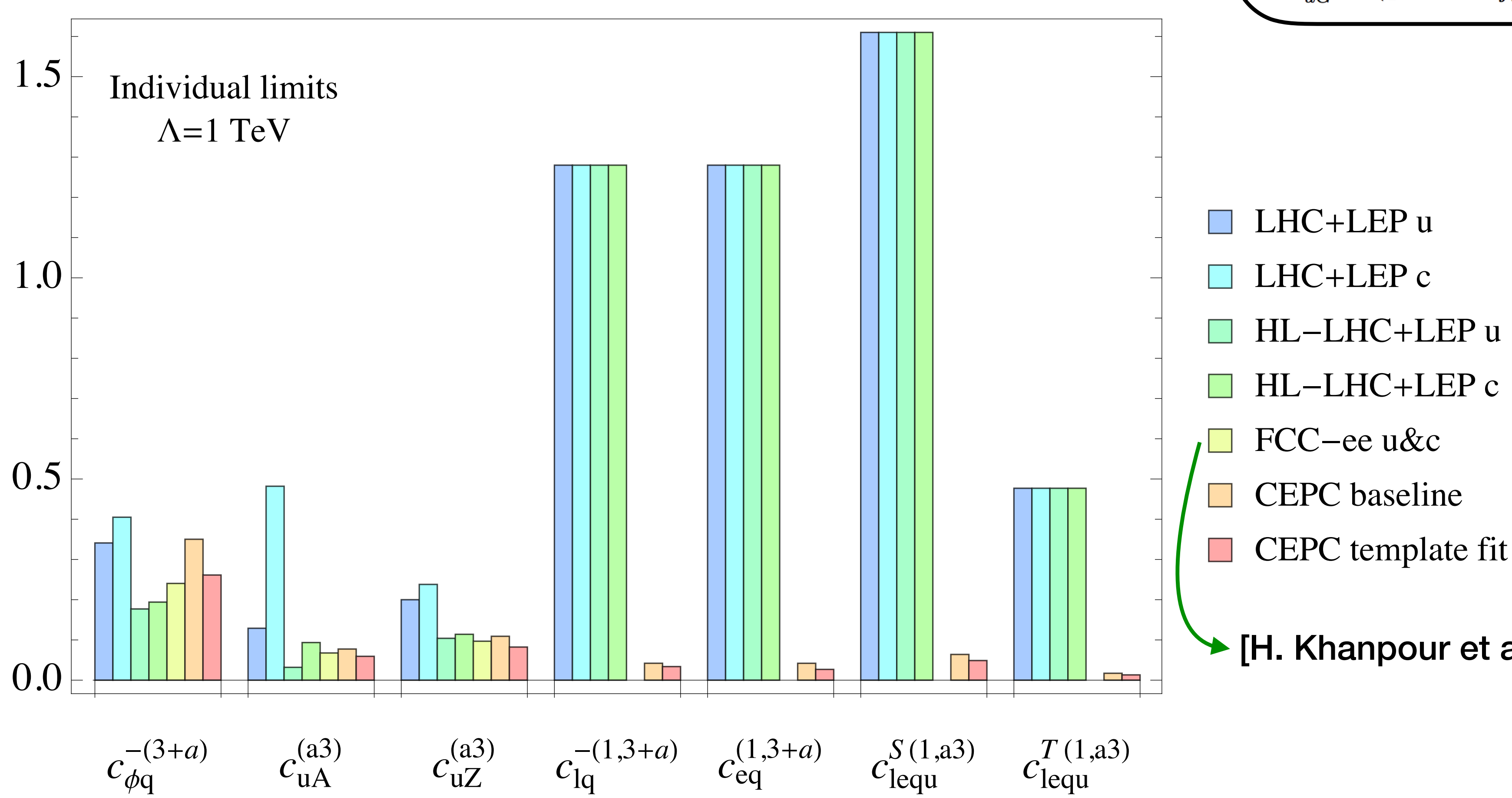


Warsaw basis operators

[B. Grzadkowski et al. 10]

$$O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{H}\,(H^\dagger H),$$
$$O_{\varphi q}^{1(ij)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_i\gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_i\gamma^\mu\tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_i\gamma^\mu u_j),$$
$$O_{\varphi ud}^{(ij)} = (\tilde{H}^\dagger iD_\mu H)(\bar{u}_i\gamma^\mu d_j),$$
$$O_{uW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I u_j)\,\tilde{H}W^I_{\mu\nu}$$
$$O_{dW}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}\tau^I d_j)\,HW^I_{\mu\nu},$$
$$O_{uB}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}u_j)\tilde{H}B_{\mu\nu},$$
$$O_{uG}^{(ij)} = (\bar{q}_i\sigma^{\mu\nu}T^A u_j)\,\tilde{H}G^A_{\mu\nu}.$$

$$O_{lq}^{1(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{lq}^{3(ijkl)} = (\bar{l}_i\gamma^\mu\tau^I l_j)(\bar{q}_k\gamma^\mu\tau^I q_l),$$
$$O_{lu}^{(ijkl)} = (\bar{l}_i\gamma^\mu l_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{eq}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{q}_k\gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_i\gamma^\mu e_j)(\bar{u}_k\gamma^\mu u_l),$$
$$O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\,\varepsilon\,(\bar{q}_k u_l),$$
$$O_{lequ}^{3(ijkl)} = (\bar{l}_i\sigma^{\mu\nu} e_j)\,\varepsilon\,(\bar{q}_k\sigma_{\mu\nu} u_l),$$
$$O_{ledq}^{(ijkl)} = (\bar{l}_i e_j(\bar{d}_k q_l)(\bar{u}_k\gamma^\mu u_l),$$



[H. Khanpour et al. '14]