To 350 GeV, and Beyond: Physics Case for High Energy e+e- Collisions

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Higgs and Top, Together

- ~350 GeV is the minimum energy required to pair-produce top quarks in e+e- collisions

- Top is special in the SM, due to its large Yukawa coupling to the Higgs:

$$\mathcal{L} = -\mu^2|H|^2 + \lambda|H|^4 + y_t Q_3 H t_R + \ldots$$

90 GeV — 0.13 — 1.0 — "small corrections"

- Understanding electroweak (-breaking) sector of the SM requires a precision top program, complementary to (and of equal importance with) precision Higgs.

Standard Model Breakdown?

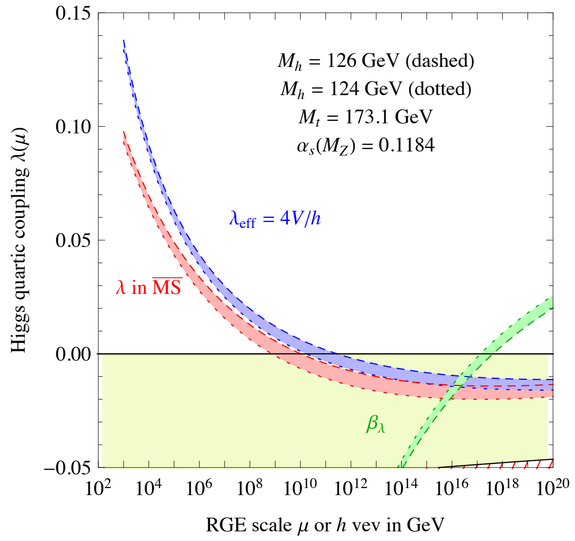
- Key parts of the SM were constructed by noticing and fixing theoretical inconsistencies in predictions of earlier theories at energies >> experiment at the time

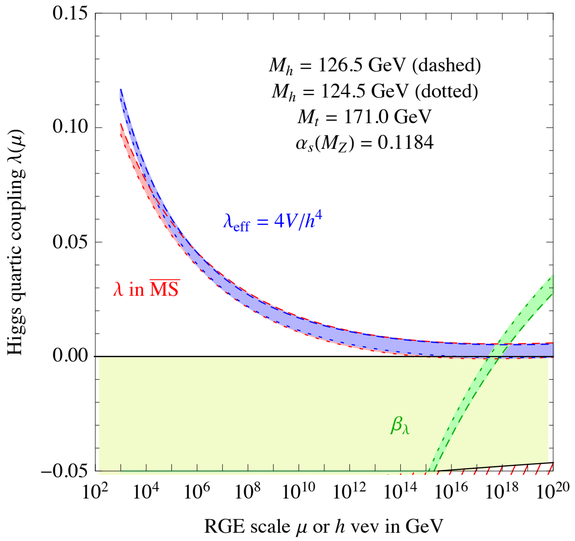
- SM itself might have a similar inconsistency:

$$\frac{d\lambda}{d\mu^2} = \frac{1}{16\pi^2}\left(12\lambda^2 + 6\lambda y_t^2 - 3y_t^4 + \ldots\right) < 0$$

unbounded negative energy if quartic < 0!

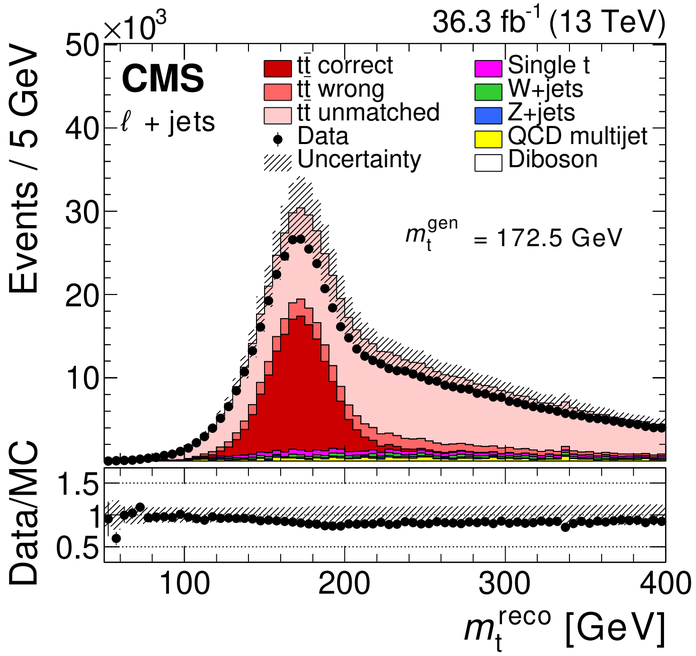
- However, this high-energy behavior depends very sensitively on the value of top Yukawa!

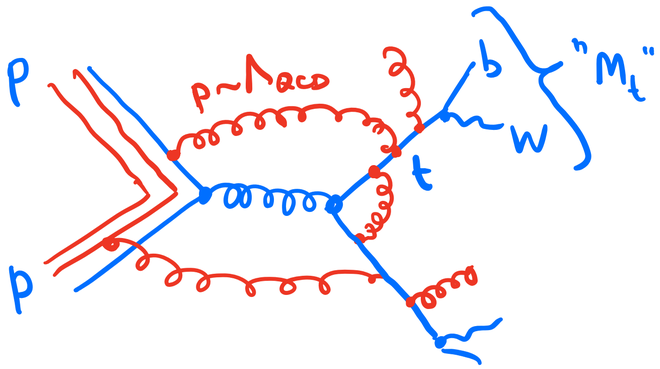




Top Mass: LHC

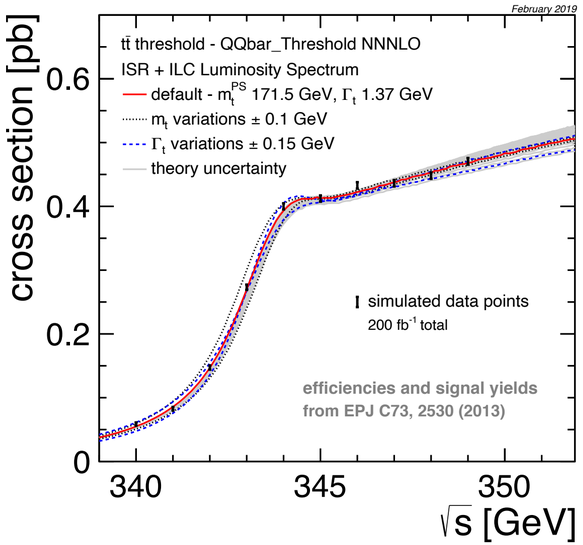
- Direct measurement of top Yukawa to required precision (<10^-3) appears out of reach
- Within SM: $m_t = y_t v$ ➡ precision top mass measures Yukawa
- LHC: reconstruct “kinematic” top mass from decay products. Need to model soft-gluon radiation/exchanges to relate it to “Lagrangian” mass
- Challenging: non-perturbative effects
- Not clear how/if required level of precision can be reached

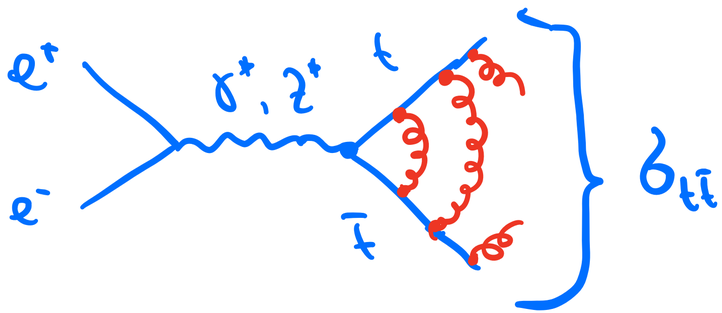




Top Mass: e+e- Threshold Scan

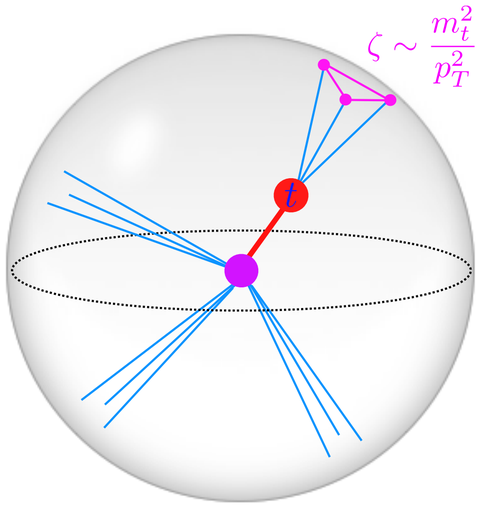
- Threshold scan in e+e- collisions provides a theoretically clean, precision observable: cross section
- State-of-the-art: NNNLO+NNLL resummation
- Expect $\Delta m_{\rm stat} \approx 20\ {\rm MeV}, \quad \Delta m_{\rm syst} \approx 50\ {\rm MeV}$
- This is sufficient to resolve the issue of possible SM inconsistency, and if it is present, to determine the required scale of new physics
- May control the fate of the universe: instability implies that our vacuum is unstable

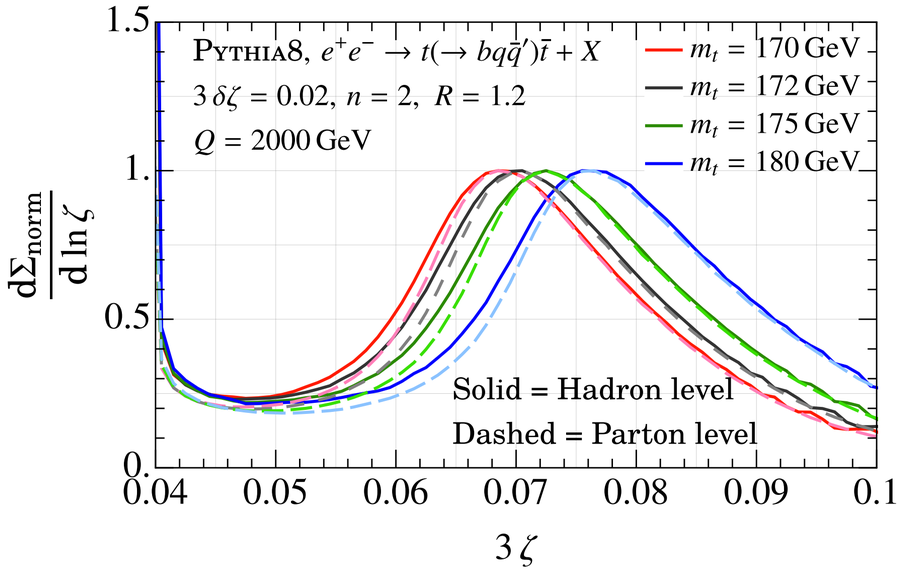




Top Mass with Energy Correlators

- A new alternative approach in QCD theory is to study energy correlation functions, rather than S-matrix for quarks and gluons
- Similar to temperature correlations in cosmic microwave background!
- 3-pt correlation fn. in boosted top jets is very sensitive to top mass, clean
- e+e- collisions at 500-1000 GeV will produce a large, clean sample of boosted tops

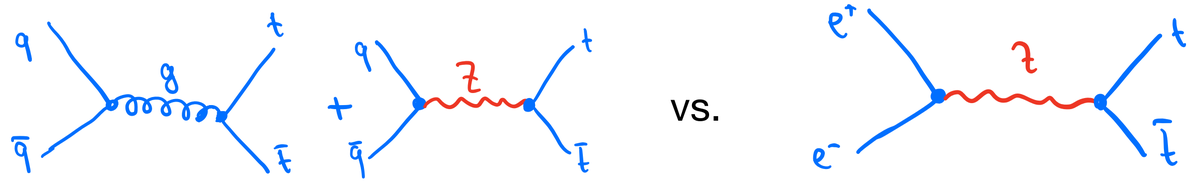




[Holguin, Moult, Pathak, Procura]

Top Couplings

- At 500 GeV and above, e+e- colliders provide a uniquely precise measurement of top electroweak couplings, especially to the Z

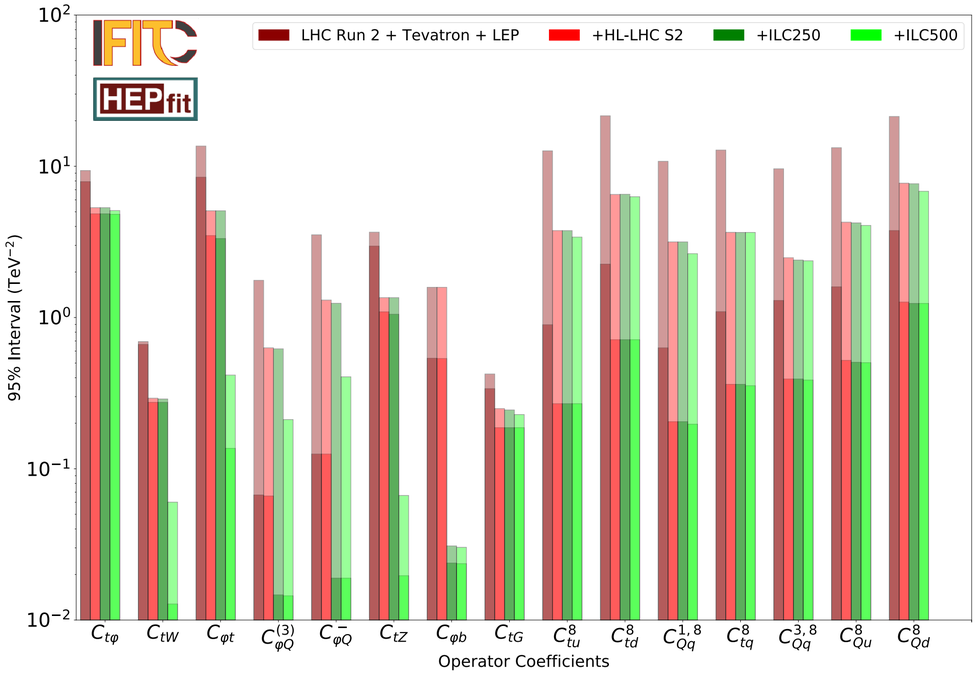


- Coupling deviations can be parametrized by effective contact operators - “SMEFT”

- Global fits demonstrate e+e- sensitivity 10-100 times above HL-LHC for some operators

$$
\begin{aligned}
O^1_{\varphi q} &\equiv \frac{y_t^2}{2}\ \bar{q}\gamma^\mu q\ \ \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi, & O_{uG} &\equiv y_t g_s\ \ \bar{q}T^A\sigma^{\mu\nu}u\ \ \epsilon\varphi^* G^A_{\mu\nu},\\
O^3_{\varphi q} &\equiv \frac{y_t^2}{2}\ \bar{q}\tau^I\gamma^\mu q\ \ \varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi, & O_{uW} &\equiv y_t g_W\ \ \bar{q}\tau^I\sigma^{\mu\nu}u\ \ \epsilon\varphi^* W^I_{\mu\nu},\\
O_{\varphi u} &\equiv \frac{y_t^2}{2}\ \bar{u}\gamma^\mu u\ \ \varphi^\dagger i\overleftrightarrow{D}_\mu\varphi, & O_{dW} &\equiv y_t g_W\ \ \bar{q}\tau^I\sigma^{\mu\nu}d\ \ \epsilon\varphi^* W^I_{\mu\nu},\\
O_{\varphi ud} &\equiv \frac{y_t^2}{2}\ \bar{u}\gamma^\mu d\ \ \varphi^T\epsilon\, iD_\mu\varphi, & O_{uB} &\equiv y_t g_Y\ \ \bar{q}\sigma^{\mu\nu}u\ \ \epsilon\varphi^* B_{\mu\nu},
\end{aligned}
\qquad O_{u\varphi} \equiv y_t^3\ \bar{q}u\ \epsilon\varphi^*\ \varphi^\dagger\varphi,
$$

$$
\begin{aligned}
O^1_{lq} &\equiv \frac{1}{2}\ \bar{q}\gamma_\mu q\ \ \bar{l}\gamma^\mu l, & O_{lu} &\equiv \frac{1}{2}\ \bar{u}\gamma_\mu u\ \ \bar{l}\gamma^\mu l, & O^S_{lequ} &\equiv \bar{q}u\ \epsilon\,\bar{l}e,\\
O^3_{lq} &\equiv \frac{1}{2}\ \bar{q}\tau^I\gamma_\mu q\ \ \bar{l}\tau^I\gamma^\mu l, & O_{eq} &\equiv \frac{1}{2}\ \bar{q}\gamma_\mu q\ \ \bar{e}\gamma^\mu e, & O_{ledq} &\equiv \bar{d}q\ \ \bar{l}e.\\
& & O_{eu} &\equiv \frac{1}{2}\ \bar{u}\gamma_\mu u\ \ \bar{e}\gamma^\mu e,
\end{aligned}
$$



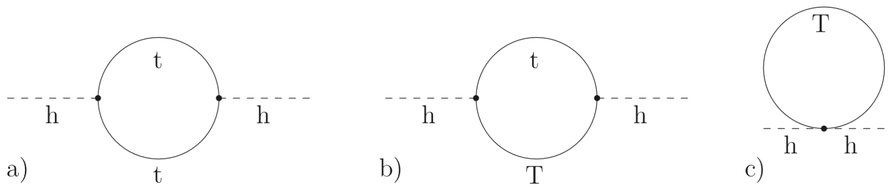
Example: Little Higgs

[Arkani-Hamed, Cohen, Katz, Nelson]

- As a benchmark model, consider “Little Higgs” theory:

$$\mathcal{L} = -f\,(\lambda_1 u_R + \lambda_2 U_R)^\dagger U_L - \lambda_1 u_R^\dagger \tilde{H} Q_L + \frac{\lambda_1}{2f}(H^\dagger H) u_R^\dagger U_L + \text{ h.c. } + \ldots$$

SM BSM SM

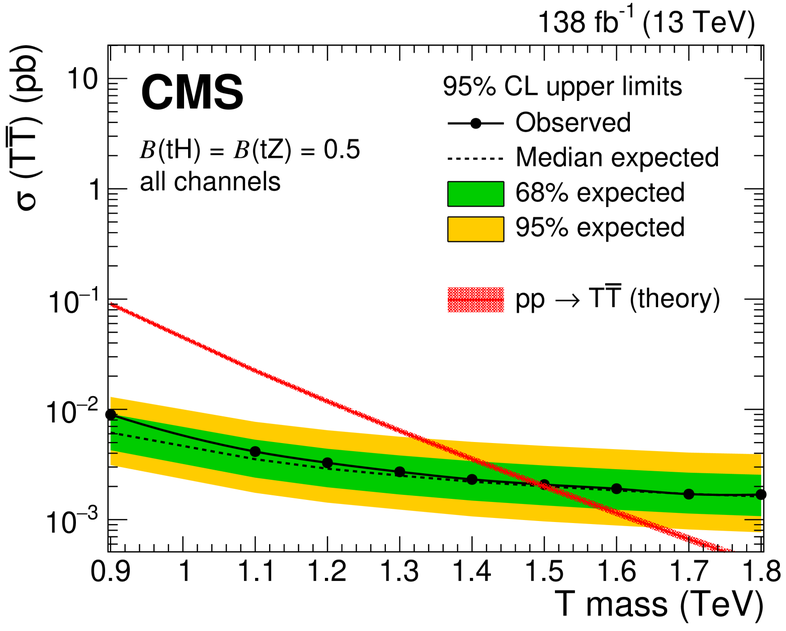


- At tree level, Higgs is a massless Goldstone boson

- At loop level, top + top partner loops generate a negative Higgs mass^2, triggering EWSB (i.e. EWSB is predicted, as opposed to the SM!)

- Direct searches for top partners at the LHC:

$$T \to Wb, tZ, th$$



Example: Little Higgs

- After EWSB, “our” top quark is an admixture of states with different SU(2)xU(1) quantum numbers

- This results in shifts in this particle’s couplings to gauge bosons:

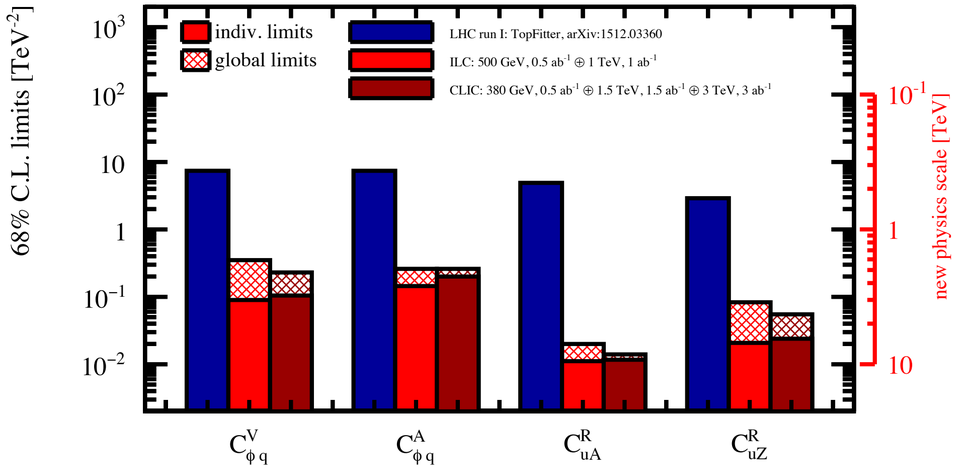
$$g_{ttL} = \frac{e}{c_w s_w}\left(\frac{\cos^2\beta}{2} - \frac{2s_w^2}{3}\right); \quad g_{ttR} = -\frac{2es_w}{3c_w}; \qquad \sin\beta \approx \tan\alpha\,\frac{m_t}{m_T}\,.$$

- These shifts can also be expressed as dim-6 SMEFT operators generated by integrating out the top partner:

$$O^1_{\varphi q} \equiv \frac{y_t^2}{2}\;\bar{q}\gamma^\mu q\;\;\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi, \qquad \frac{C^1_{\varphi q}}{\Lambda^2} = \frac{\lambda^2 y_t^{-2}}{4M_U^2}, \qquad \frac{C^3_{\varphi q}}{\Lambda^2} = -\frac{\lambda^2 y_t^{-2}}{4M_U^2}.$$

$$O^3_{\varphi q} \equiv \frac{y_t^2}{2}\;\bar{q}\tau^I\gamma^\mu q\;\;\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi,$$

- Precision top program in e+e- probes regions in parameter space inaccessible to the HL-LHC via either precision-top or direct top-partner searches



	existing		expected at high luminosity					expected at e^+e^-		
	TopFitter	Ref. [74]	Ref. [74]	$t\bar{t}V$ [14, 75]	$t\bar{t}V$ 10%	$t\bar{t}V$ 3%	tZj [76]	CC	ILC	CLIC
$C^1_{\varphi q}$	$[-12, 13]$			$[-1.3, 1.0]$	$[-2.0, 2.0]$	$[-0.6, 0.6]$	$[-17, 17]$	0.14	0.076	0.098
$C^3_{\varphi q}$	$[-5.3, 3.1]$			$[-1.0, 1.3]$	$[-2.0, 2.0]$	$[-0.6, 0.6]$	$[-2.8, 1.5]$	0.14	0.076	0.089
$C_{\varphi u}$	$[-20, 17]$			$[-1.3, 3.0]$	$[-3.4, 2.8]$	$[-0.8, 1.0]$	$[-26, 20]$	0.29	0.15	0.18
$C_{\varphi ud}$		$[-11, 14]$	$[-8.4, 11]$				$[-8.4, 8.4]$			
C_{uB}	$[-20, 14]$			$[-4.8, 4.8]$	$[-12, 12]$	$[-6.6, 4.0]$	$[-12, 11]$	0.022	0.022	0.024
C_{uW}	$[-2.0, 2.8]$	$[-2.7, 1.6]$	$[-1.3, 1.3]$	$[-1.4, 1.4]$	$[-3.6, 3.8]$	$[-2.2, 2.2]$	$[-1.3, 1.3]$	0.015	0.014	0.016
C_{dW}		$[-3.4, 3.6]$	$[-2.9, 3.1]$							

[Durieux, Perello, Vos, Zhang]

Composite Higgs/Top

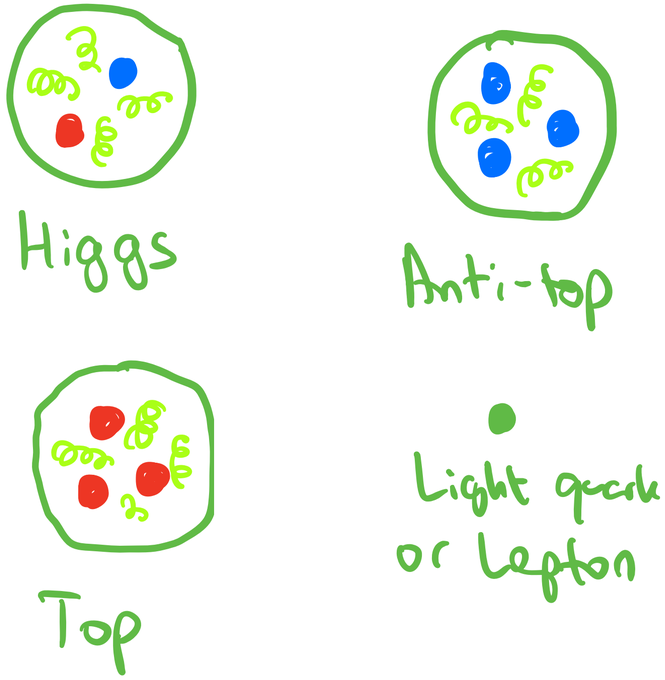
- Elementary scalar fields generically have masses of order the highest physical scale in the theory: $m \sim \max M_i$

- But $m_h \ll M_{\rm Pl}$ - “hierarchy problem”

- A possible resolution is for the Higgs to be a bound state, like a meson

- Top may be another bound state of the same constituents, like a baryon

- If other quarks are NOT composite, it would explain why the top Yukawa is >> all other Yukawas



Higgs/Top in Extra Dimension

[Randall, Sundrum, …]

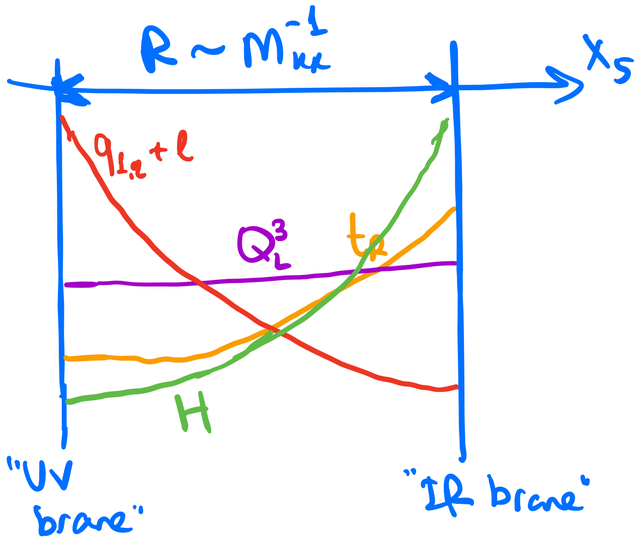
- Some of such composite models are “dual” (i.e. equivalent in some respects) to models with extra dimensions

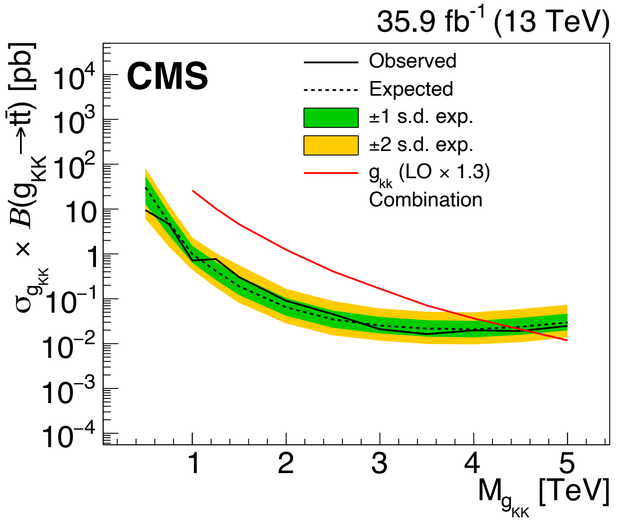
- All SM particles have “doubles” at Kaluza-Klein mass ~ size of extra dimension ~ compositeness scale

- Contact operators=form-factors are generated by integrating out KK excitations of Z, photon

$$\frac{C_{lq}^{-}}{\Lambda^2} = \frac{-0.022}{m_{KK}^2}, \qquad \frac{C_{lu}}{\Lambda^2} = \frac{-0.032}{m_{KK}^2}, \qquad \frac{C_{eq}}{\Lambda^2} = \frac{-0.004}{m_{KK}^2}, \qquad \frac{C_{eu}}{\Lambda^2} = \frac{-0.064}{m_{KK}^2}.$$

- Sensitivity up to 5-15 TeV KK mass can be reached in e+e- colliders

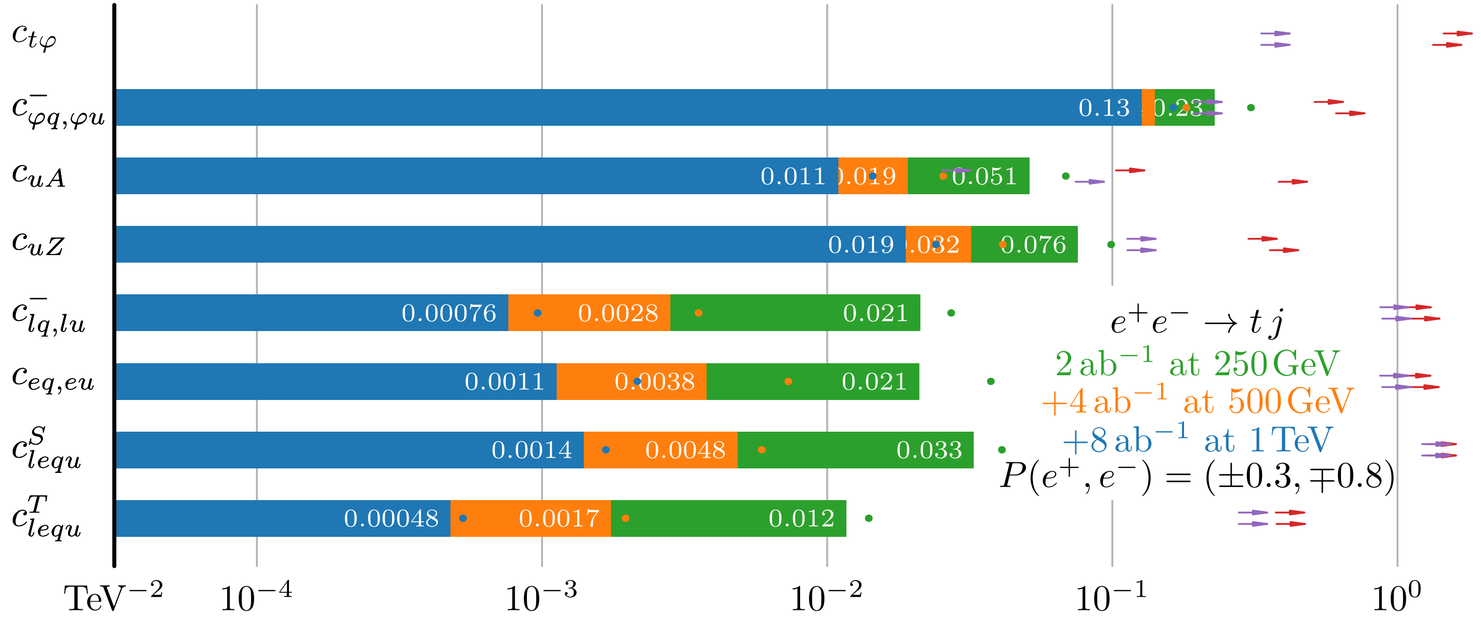




FCNC Top Couplings

- Flavor-non-diagonal operators can also be induced in new physics models, possibly inducing FCNC's that are negligible in the SM

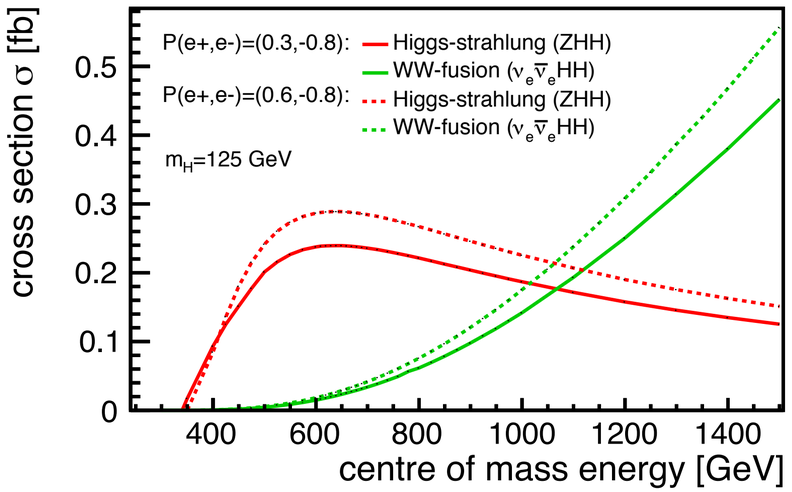
- e+e- colliders improve HL-LHC sensitivity by up to 3 orders of magnitude for some FCNC operators (such as 4-fermion llqq)

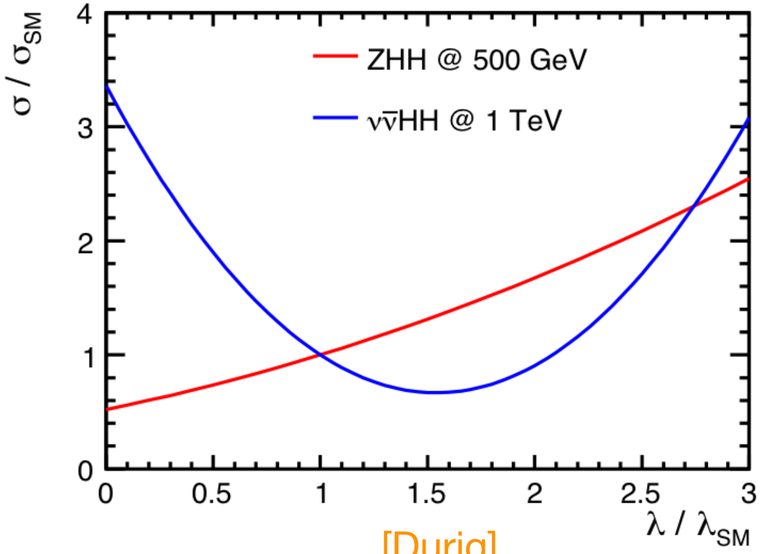


[de Blas et.al.]

Higgs Self-Coupling

- At 500 GeV, e+e- collisions allow a direct measurement of Higgs cubic self-coupling through ZHH production (~25% precision)
- At 1 TeV, the same coupling can be measured through HH production in WW fusion (~10% precision)
- SM makes an unambiguous prediction for h^3 once Higgs vev and mass are measured ➡ excellent test of new physics in the Higgs sector!





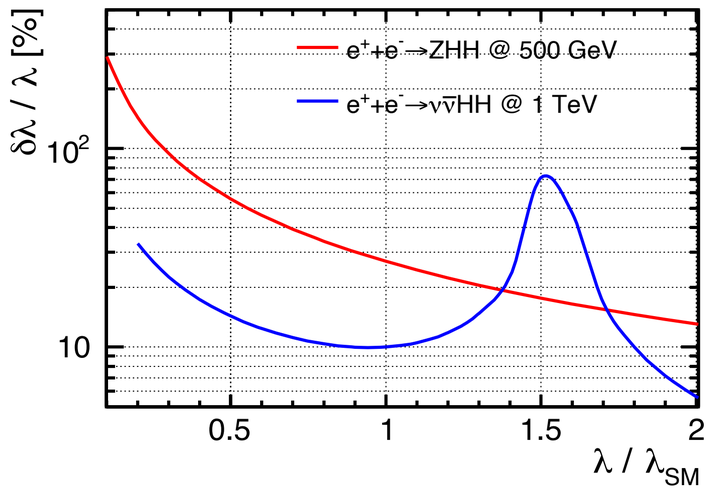
[Durig]

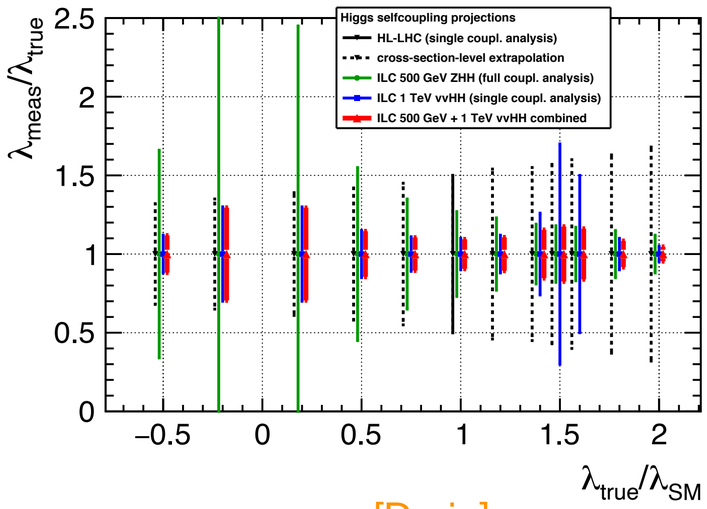
Higgs Self-Coupling

- The two cross sections have opposite behavior as h^3 coupling deviates from the SM: constructive interference in ZHH, destructive in WW fusion

- Combining the two measurements allows for a <20% precision in h^3, even if deviates from the SM by 50-100%!

- At LHC, gluon fusion has destructive interference - suffers for enhanced h^3

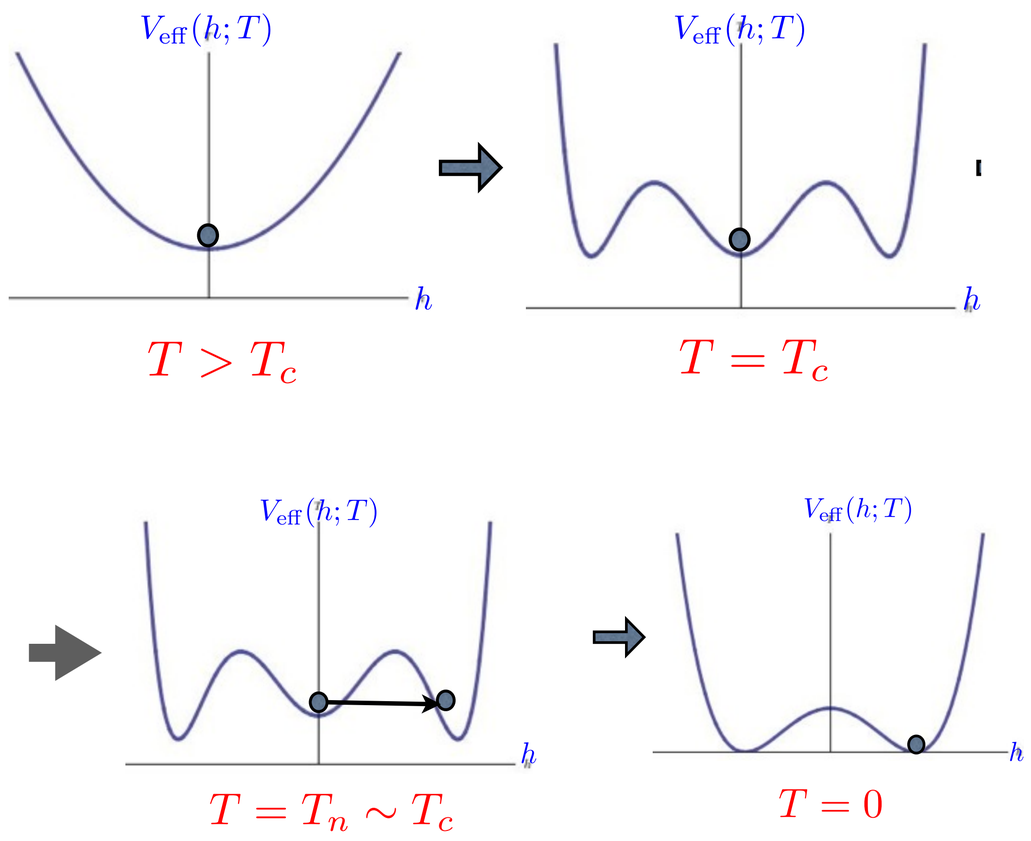




[Durig]

Electroweak Phase Transition

- In the early universe, electroweak symmetry is restored
- Higgs “plasma mass” decreases with temperature, resulting in EW-breaking phase transition at T ~ weak scale (t ~ nsec)
- SM predicts a gradual, adiabatic transition (“crossover”), but in BSM theories a first-order transition may occur
- First-order EWPT can generate matter-antimatter asymmetry (“electroweak baryogengesis”), create gravity waves



First-Order PT and Higgs Couplings

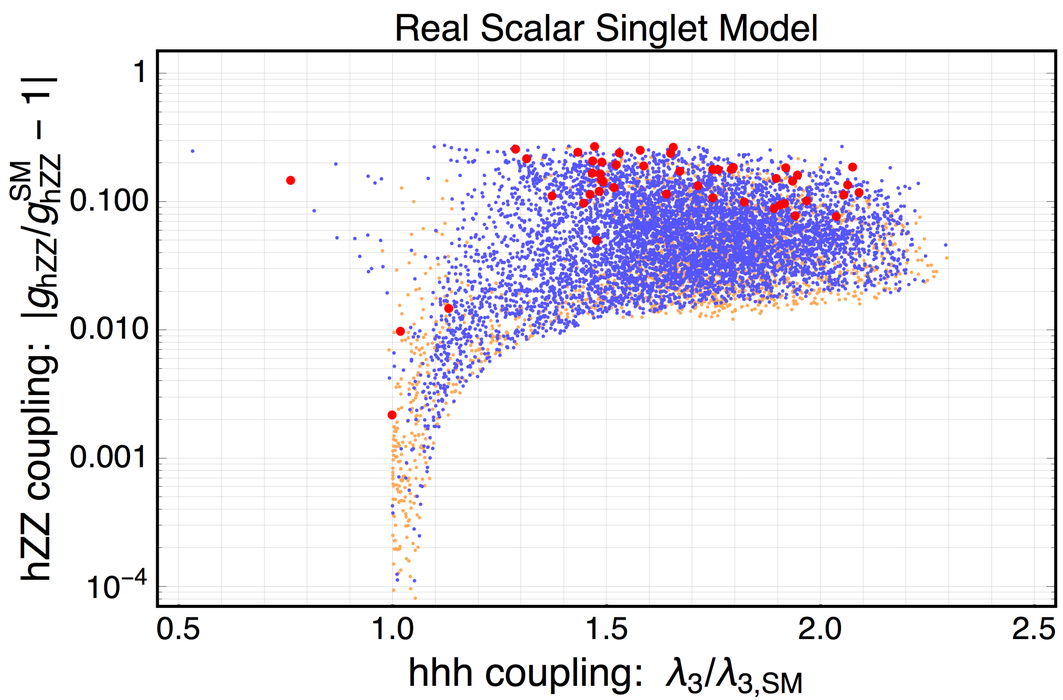
- First-order EWPT requires BSM fields, with significant coupling to Higgs and mass ~ weak scale

- A singlet scalar is the simplest benchmark:

$$V = m_S^2 S^2 + \frac{\kappa}{2} S^2 |H|^2$$

- Invisible to the LHC as long as $m_S > m_h/2$

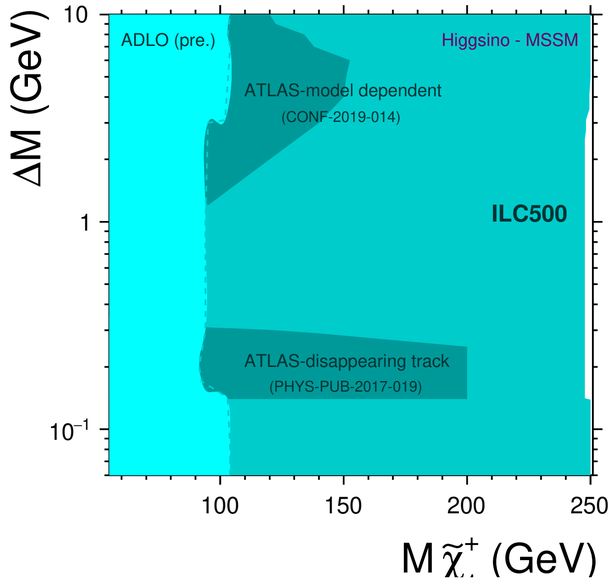
- Models with first-order EWPT typically predict ~20-120% enhancement in h^3

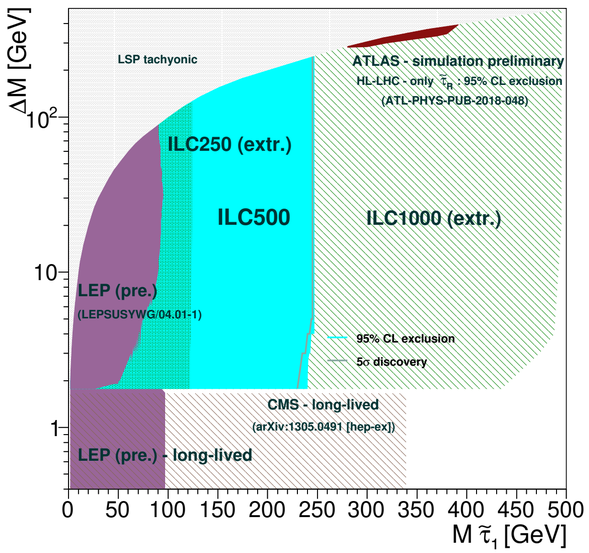


[Huang, Long, L-T. Wang]

New Physics: Supersymmetry

- LHC has put srong constraints on SUSY models with superpartners below TeV
- Loopholes remain: electroweak couplings, small splittings (e.g. Higgsino) are difficult to constrain
- For example, recent muon g-2 anomaly was interpreted in terms of SUSY models with such features
- e+e- collisions provide robust, model-independent sensitivity for such scenarios, probing SUSY masses up to kinematic threshold



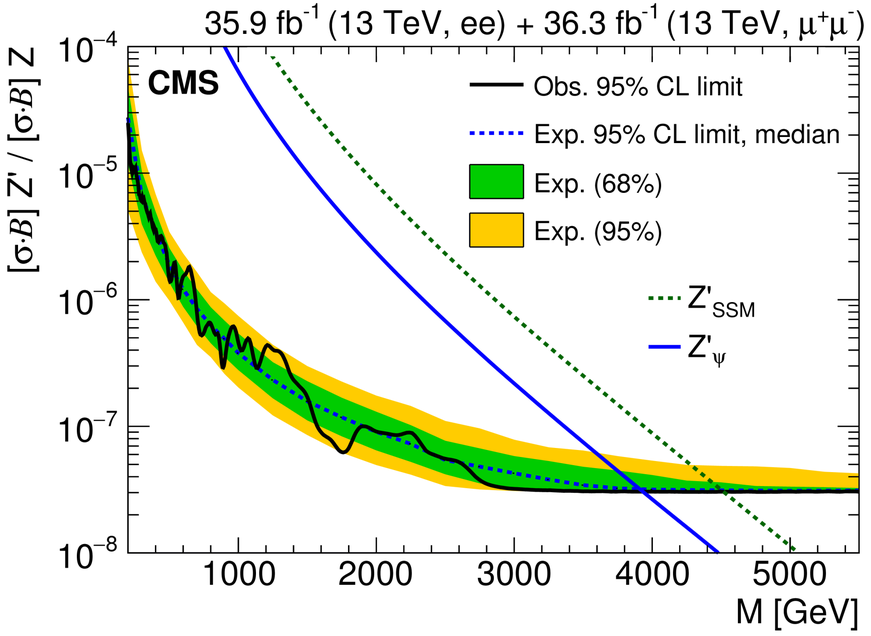


New Physics: Extra Gauge Bosons

- Extra U(1) gauge groups are ubiquitous in BSM physics: grand unification, string-inspired models, …
- Predict Z' bosons, with specific pattern of couplings to SM fermions depending on the model
- Study of e+e- -> fermions at 500 GeV/1 TeV provides a window into Z' far above the LHC reach

	250 GeV, 2 ab^{-1}		500 GeV, 4 ab^{-1}		1 TeV, 8 ab^{-1}	
Model	excl.	disc.	excl.	disc.	excl.	disc.
SSM	7.7	4.9	13	8.3	22	14
ALR	9.4	5.9	16	10	25	18
χ	7.0	4.4	12	7.7	21	13
ψ	3.7	2.3	6.3	4.0	11	6.7
η	4.1	2.6	7.2	4.6	12	7.8

[Suehara]

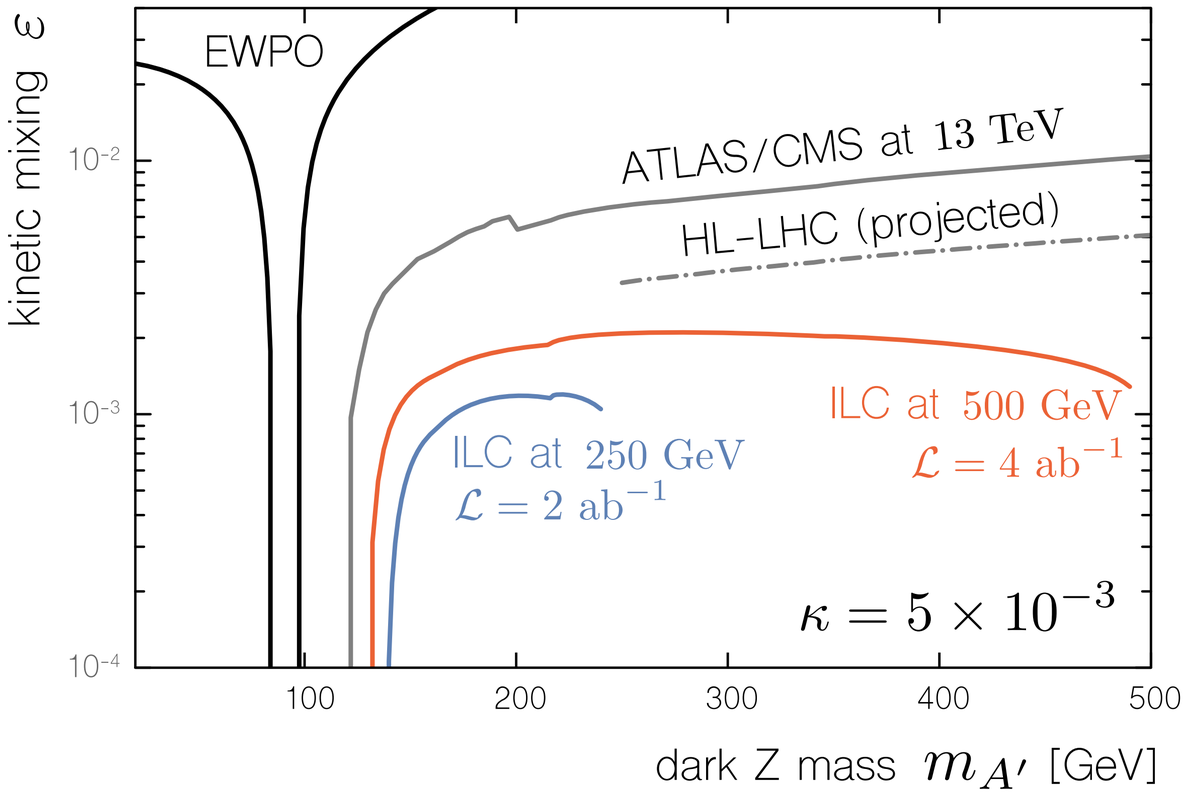


New Physics: Dark Photon/Z

- An alternative possibility is a U(1) symmetry that no SM field is charged under
- Could be part of "dark sector" along with dark matter particles
- Dominant coupling to SM is via kinetic mixing, typically a loop effect

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{\varepsilon}{2c_W}B_{\mu\nu}A'^{\mu\nu} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu}$$

- Sub-GeV DP is interesting [see next talk by Y. Sakaki] but could be much heavier - "dark Z"

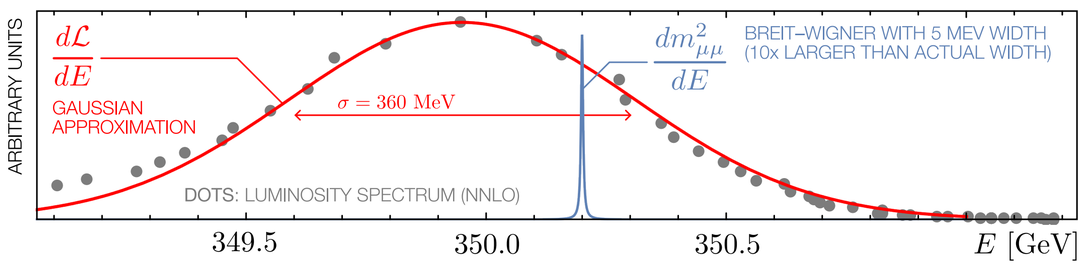


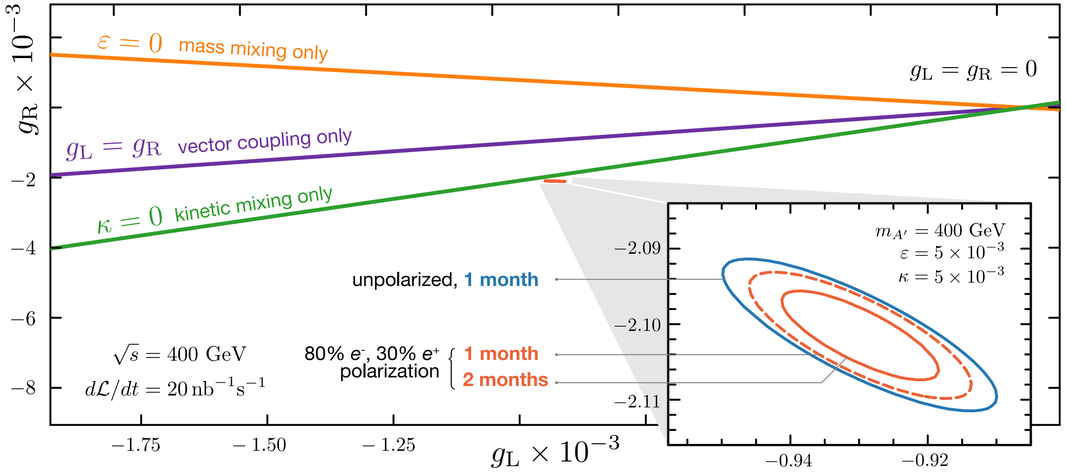
If Dark Z is within kinematic reach of an e+e- collider, regions inaccessible at the HL-LHC can be probed

[San, Tanedo, MP]

Dark Z Couplings

- If a dark Z is discovered, e+e- collider can be turned into a "dark Z factory" by running on resonance
- Similar to LEP-1, but dark Z is very narrow (< MeV width)
- Mass can be pinpointed accurately with an "inverse line-shape" scan
- Dark Z couplings can then be determined, model discrimination, …





[San, Tanedo, MP]

Highlights

- Understanding EWSB requires precision measurements of top mass and couplings, due to large top Yukawa coupling

- e+e- collisions at threshold (~350 GeV) and at 500 GeV provide unique sensitivity to top mass and couplings

- Higgs cubic coupling can be measured for the first time in e+e- collisions at 500-1000 GeV, deviations predicted by models with first-order electroweak phase transitions can be probed

- High precision in e+e- collisions provides indirect sensitivity to new physics far above the LHC reach, e.g. Z' bosons

- New physics can be within kinematic reach of e+e- collisions at 500-1000 GeV and escape LHC detection (e.g. Higgsinos, dark Z, …) - discovery potential