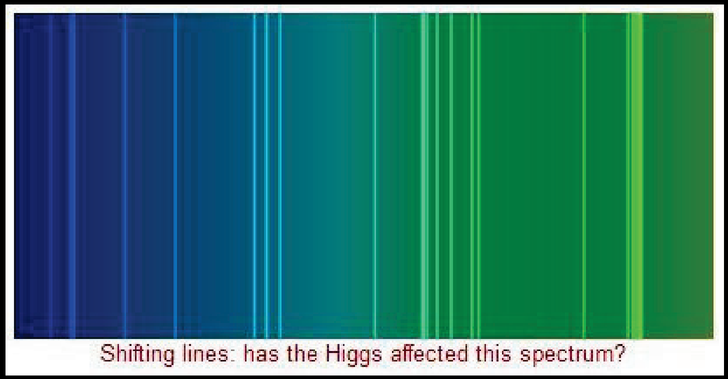
Probing the Atomic Higgs force



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hep-ph: 1601.05087 + in progress
CD, Y. Soreq hep-ph:1602.04838

LAL Seminar
1-04-2016 | Orsay

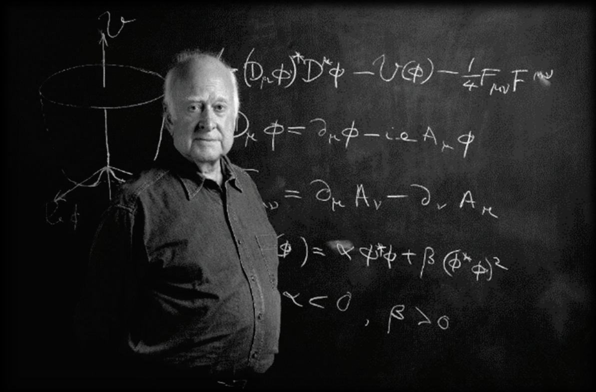
Outline

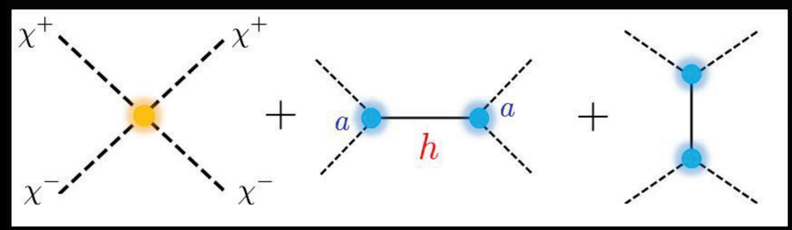
1. The Higgs Mechanism and the Flavor Puzzle
2. Higgs Force in Atoms
3. Probing Higgs Couplings with Isotope Shift
4. The Weak Force and New Physics

The Higgs Mechanism
and the Flavor Puzzle

The Higgs Mechanism

- breaks EW symmetry: $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to U(1)_{\mathrm{QED}}$





$$\propto \frac{E^2}{v^2}(1-a^2)$$

ATLAS+CMS: $|a-1| \lesssim \mathcal{O}(10\%)$

ATLAS-CONF-2015-044

- provides charged fermion masses:

in the SM: $$m_f = y_f \times v$$

The flavor Puzzle

- Charged fermion masses are highly hierarchical:

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- The origin of this hierarchy is unknown, despite a host of precision flavor measurements.

- Within the SM, it is ***assumed*** to originate from hierarchical Higgs-to-fermion couplings:

$$y_f^{\rm SM} \propto m_f$$

How well can we test?

Alternative Approaches

- Froggat-Nielsen like: lighter fermions couple to higher powers of the Higgs

Giudice-Lebedev ’08
Bauer-Carena-Gemmler ‘15

$$\frac{m_f}{v} \propto \frac{v^{n_f}}{\Lambda^{n_f}} \qquad y_f \propto (1+n_f)\frac{m_f}{v}$$

solving the flavor puzzle: $n_f \sim \log(m_f/v)$

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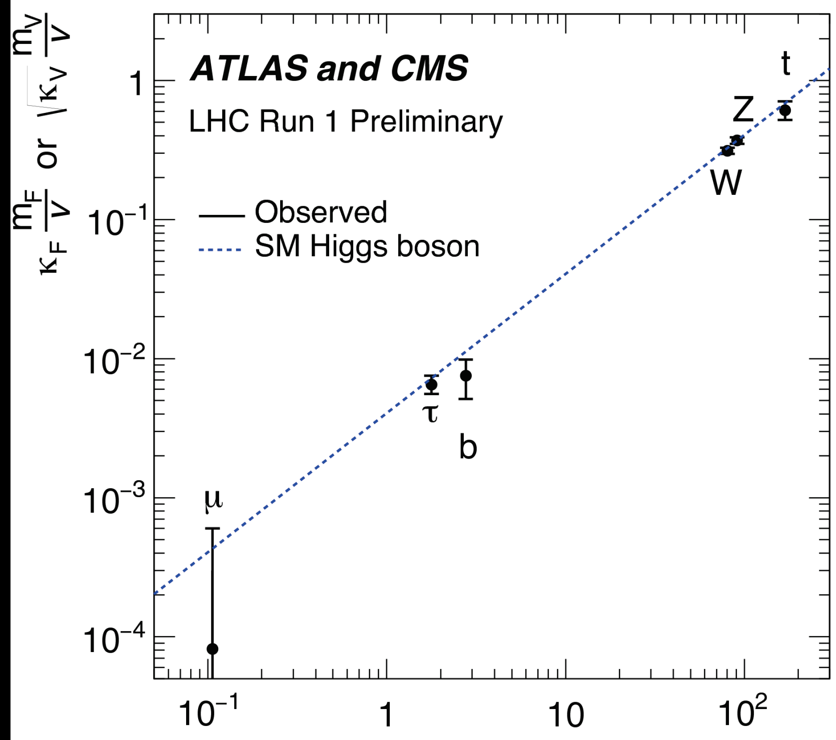
solving the flavor puzzle: $n_f \sim \log(m_f/v)$

- First two generation masses do not come from the Higgs mechanism at all! (technicolor?)

Ghosh-Gupta-Perez '15
Altmannshofer-Gori-Kagan-Silvestrini-Zupan '15

The Flavor Puzzle at LHC



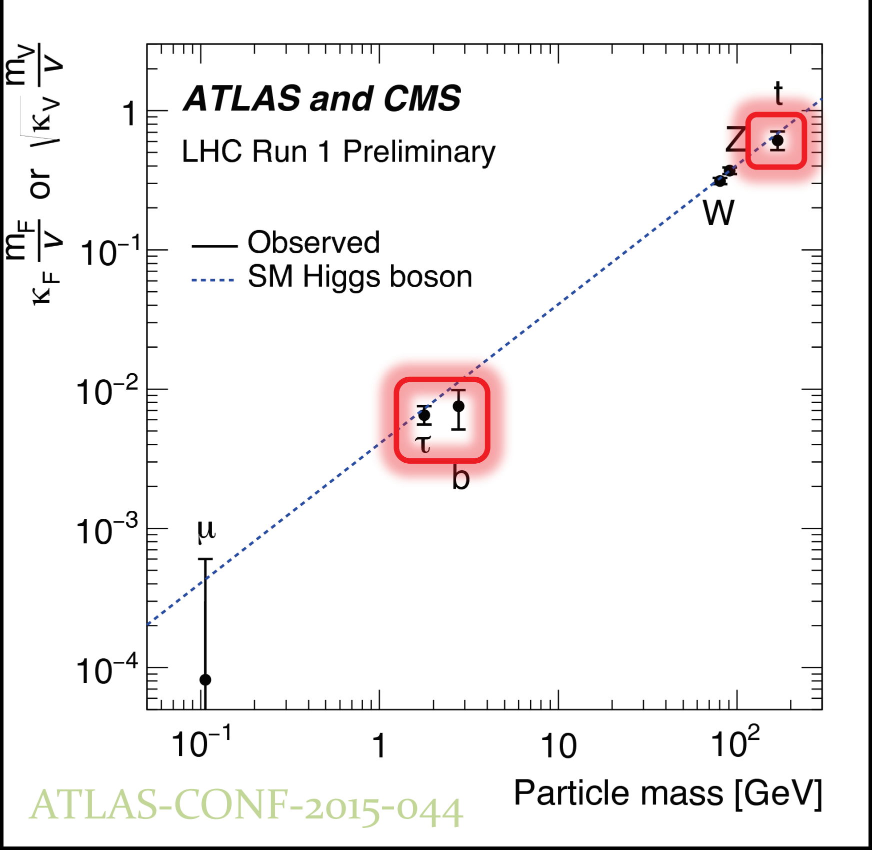
ATLAS-CONF-2015-044

The Flavor Puzzle at LHC

ATLAS+CMS
Higgs-signal/SM:

$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$

μ_{ttH}	$2.3^{+0.7}_{-0.6}$



→ the Higgs mechanism is likely to be the dominant source of 3rd generation masses

The Flavor Puzzle at LHC

There is an opportunity to probe c-coupling directly, thanks to charm-tagging:

in VH production

Perez-Soreq-Stamou-Tobioka '15

in Hc production

Isidori-Goertz '15

Other probes exist:

- $h \to J/\psi\gamma$

Perez-Soreq-Stamou-Tobioka '15

- global fits

CD-Golling-Perez-Soreq '13

- $\Gamma_h \leq 1.7\,\mathrm{GeV}$

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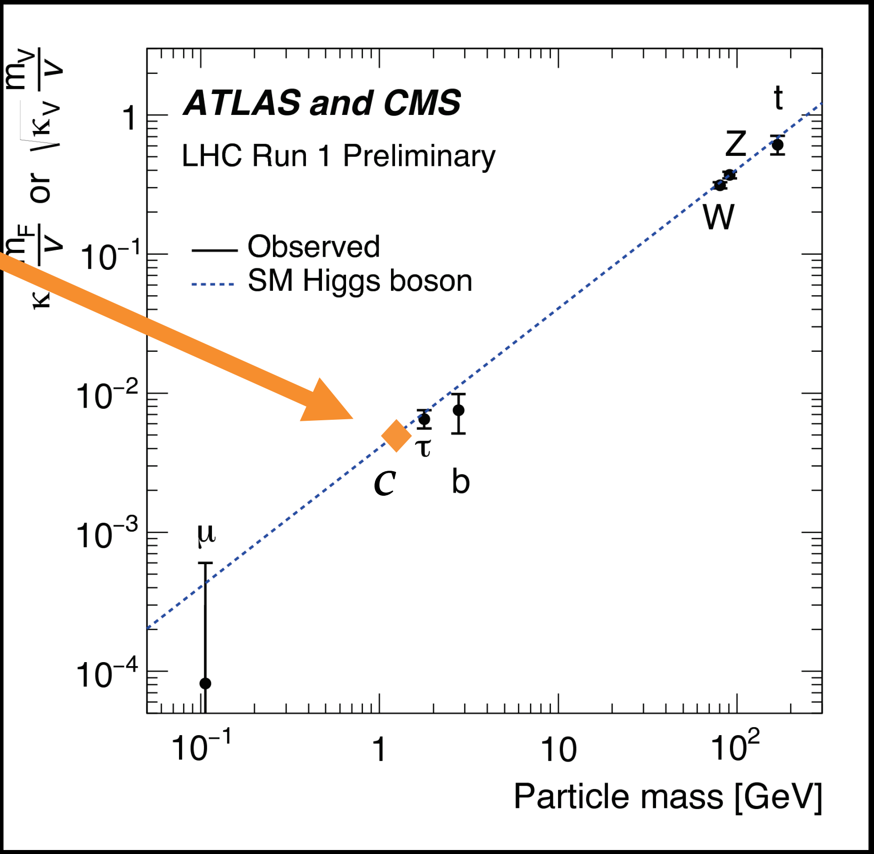

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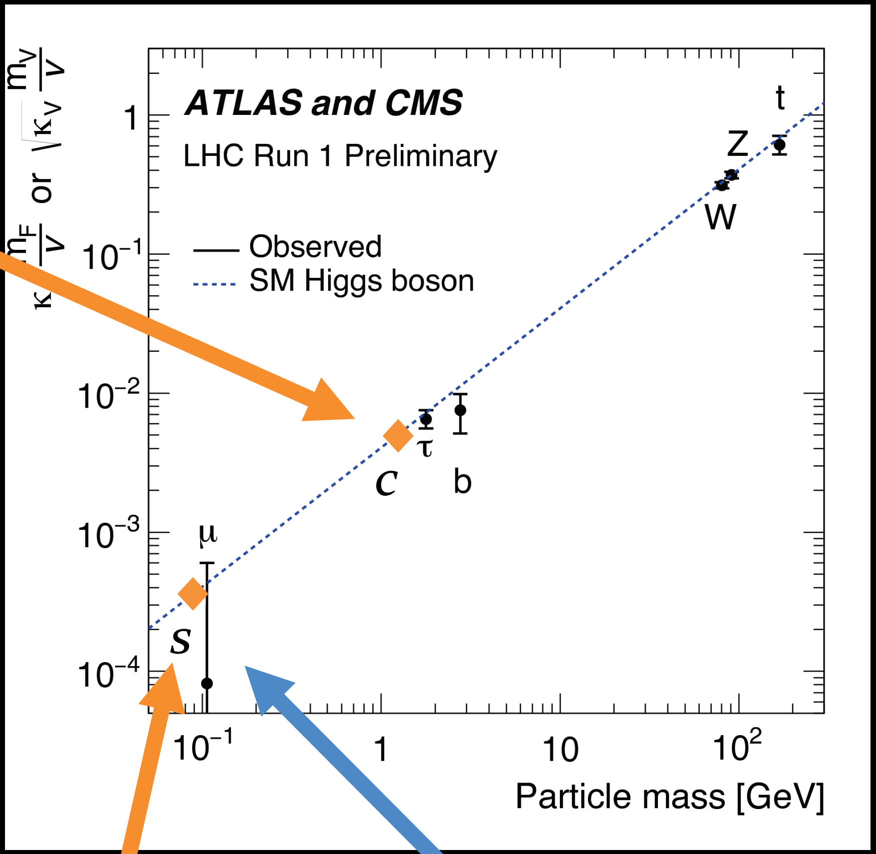

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$h \to \phi\gamma$?

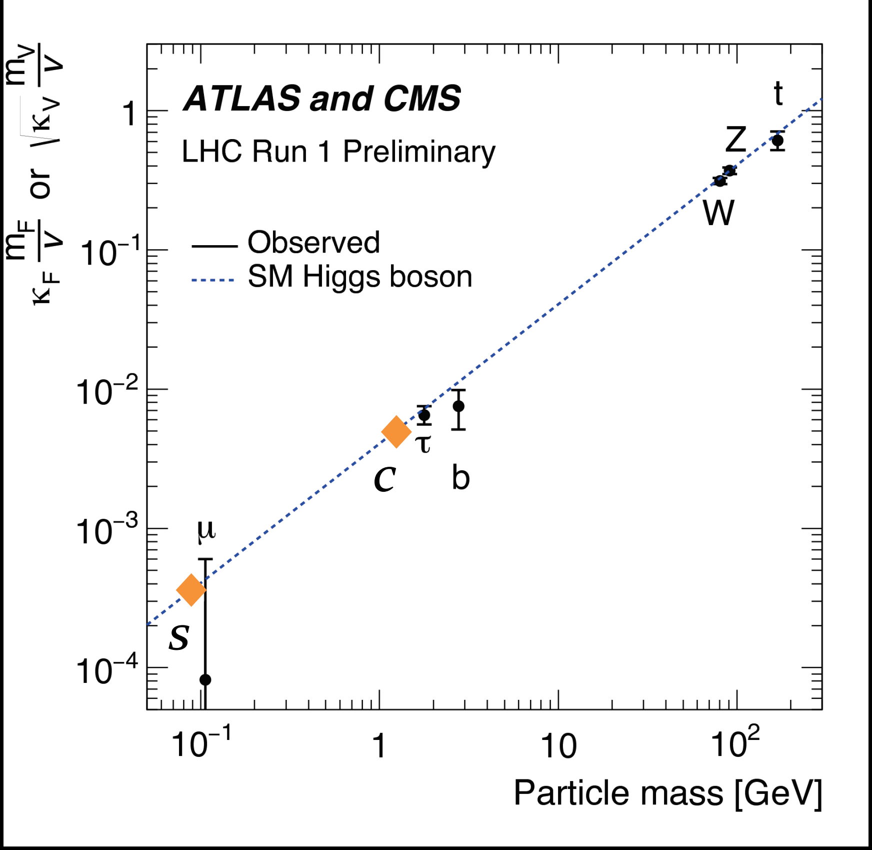
Kagan et al. '14

Sensitivity to muon-coupling, with high-enough luminosity

ATL-PHYS-PUB-2014-016

The Flavor Puzzle at LHC

What about e, u, d?



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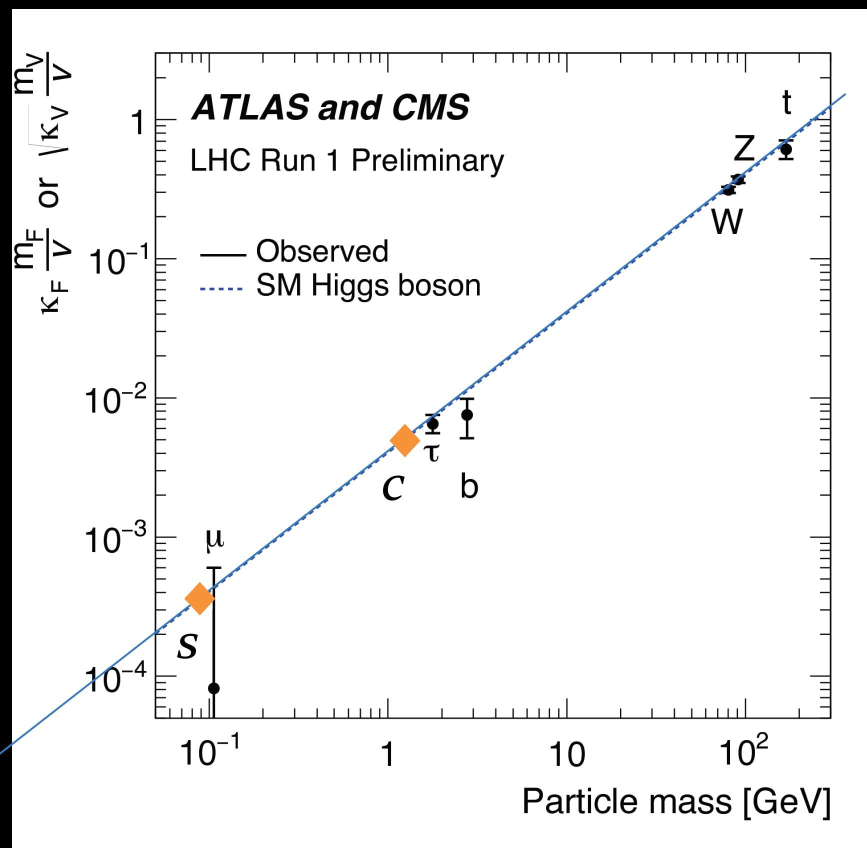

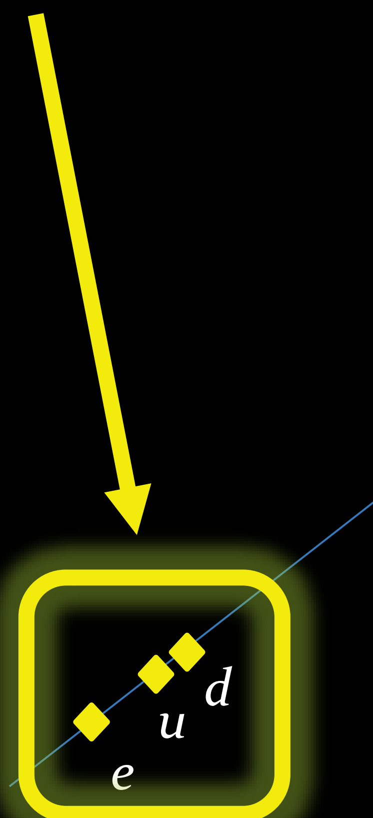

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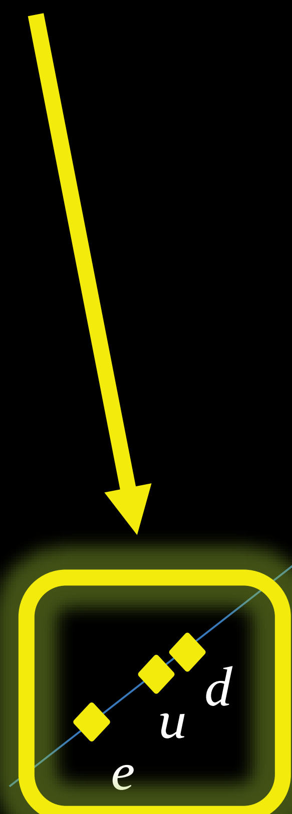

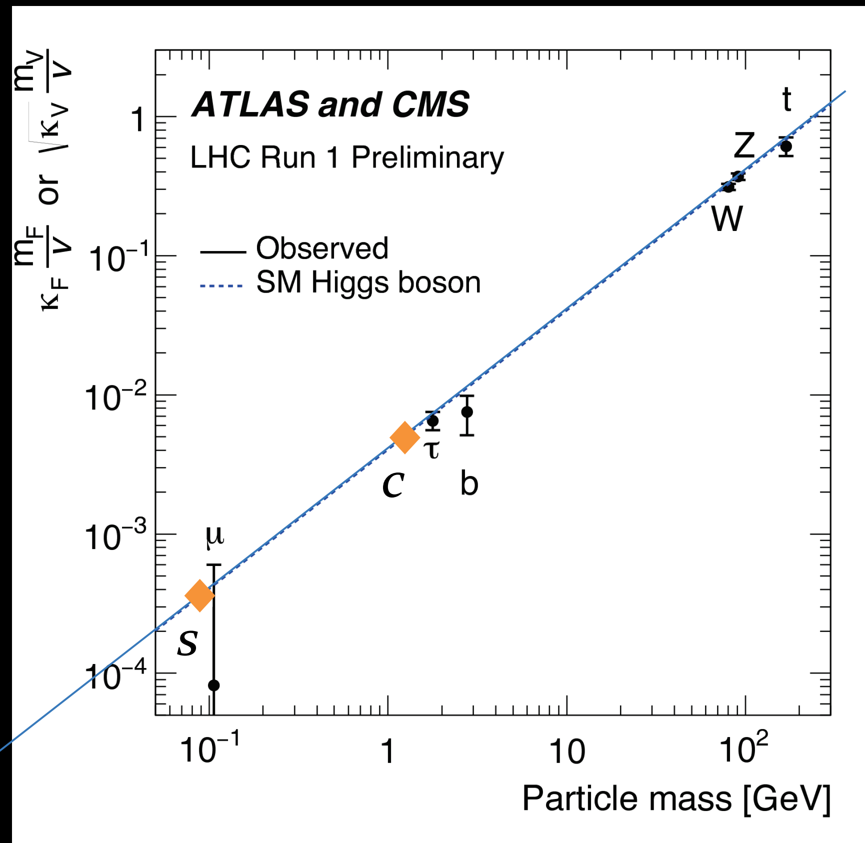

[stable nuclei]
[chemistry]

Probing the couplings to the building blocks of matter is an important test of the Higgs mechanism

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$h \to ee$

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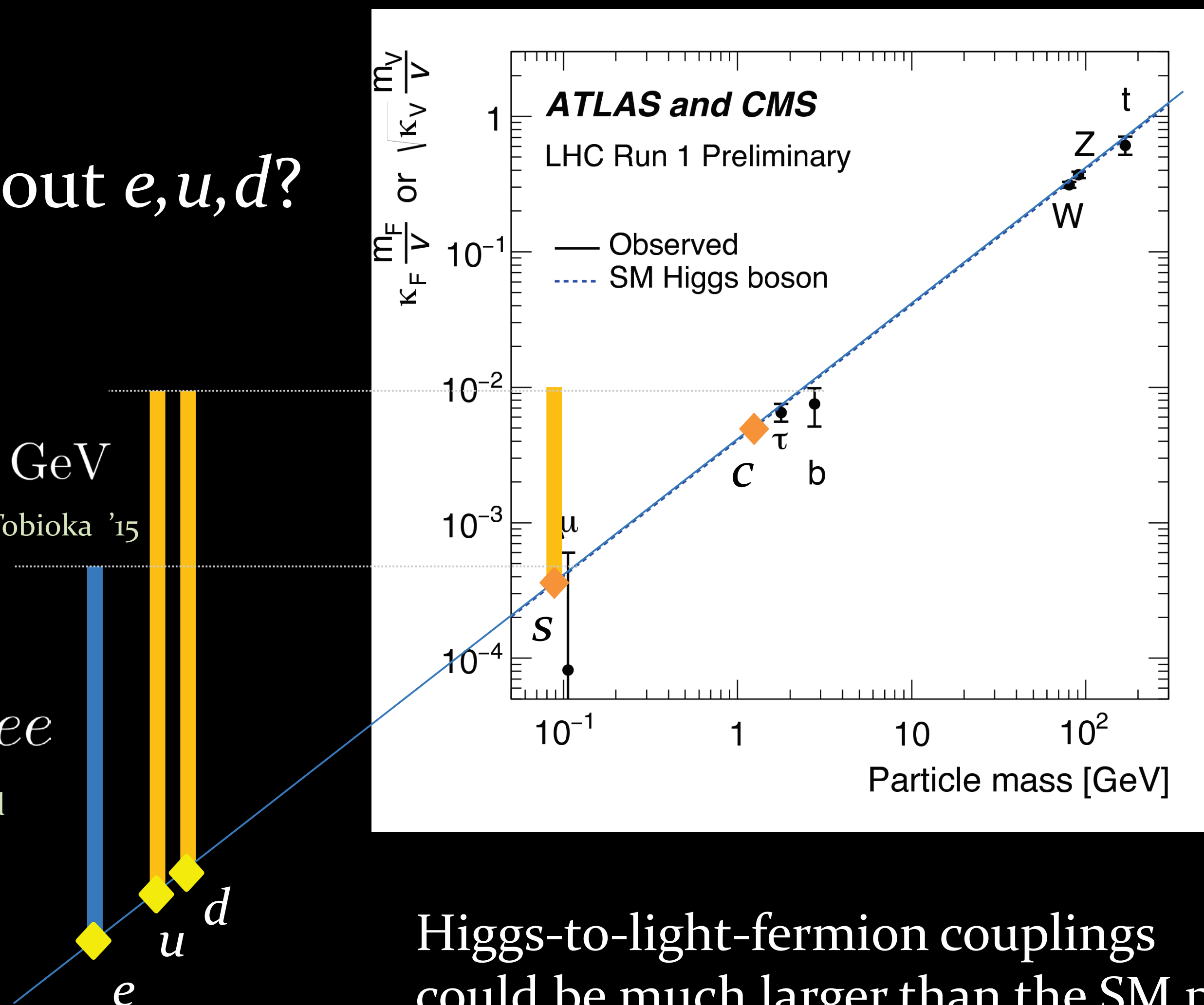

Higgs-to-light-fermion couplings
could be much larger than the SM prediction.
LHC is and will remain weak in bounding them.

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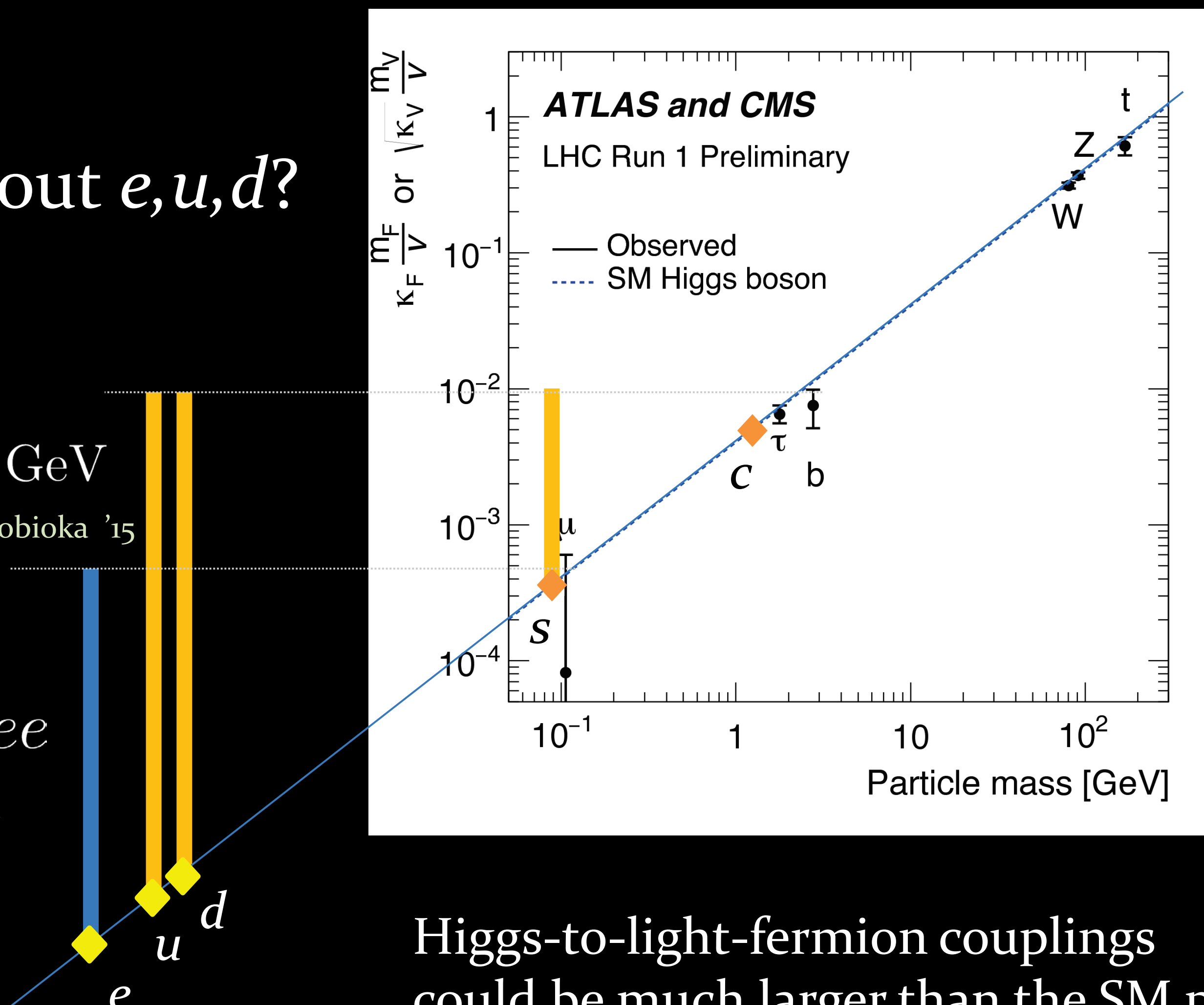

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The Higgs force
in Optical Clock Transitions

The Atomic Higgs Force

- The Higgs results in an attractive force between nuclei and their bound electrons (à la Yukawa):

$$V_{\text{Higgs}}(r) = -\frac{y_e y_A}{4\pi}\frac{e^{-m_h r}}{r} \approx -\frac{y_e y_A}{4\pi m_h^2}\frac{\delta(r)}{r^2}$$

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- $y_A = Z y_p + (A-Z) y_n$ with:

Shifman-Vainshtein-Zakharov '78
+ nuclear data, see *e.g.* micrOmegas

$$y_n \approx 7.7 y_u + 9.4 y_d + 0.75 y_s + 2.6 \times 10^{-4} c_g$$
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$\mathcal{O}(10-20\%)$ uncertainties in matching

- c_g constrained by LHC, weaker sensitivity to s-coupling

Higgs Force Strength

- Under current LHC constraints:

Higgs width (direct)

$$y_{n,p} \lesssim 3 \ (0.2) \qquad \text{and} \qquad y_e \lesssim 1.3 \times 10^{-3}$$

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- This shifts transition frequencies by:

electron-density at the nucleus

$$\Delta\nu^{\text{Higgs}}_{nS \to n'D,F} \approx 1\,\text{Hz} \times A \frac{y_e y_{n,p}}{0.004} \frac{|\psi(0)|^2}{4n^3 a_0^{-3}}$$

Bohr radius $(\alpha m_r)^{-1}$

Electron Density in Nuclei

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ion charge

See *e.g.* Budker-Kimball-DeMille: Atomic Physics

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- Using non-relativistic hydrogen-like wavefunction:

$$|\psi(0)|^2 \simeq \frac{4.2Z}{a_0^3}(1+n_e)^2$$

Optical Atomic Clocks

- State-of-the-art accuracy at the 10^{-18} level

Bloom et al., Nature 506, 71-76 (2014)

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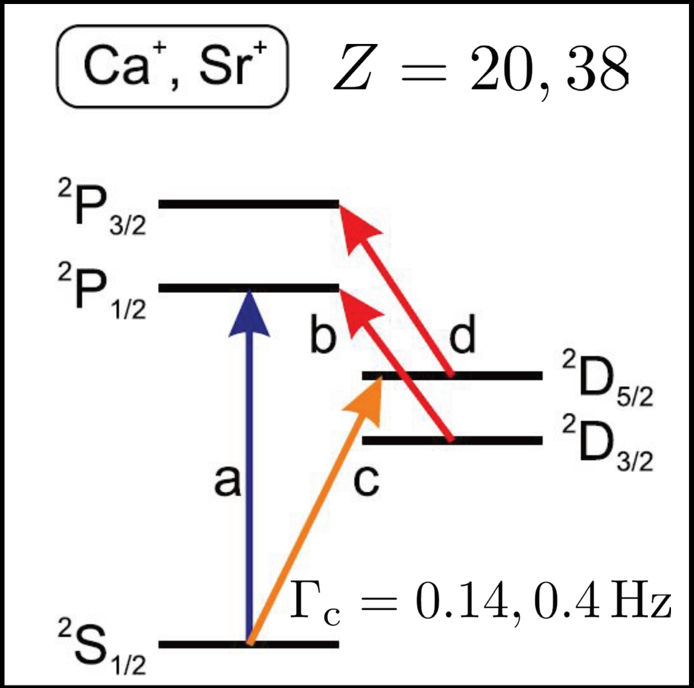
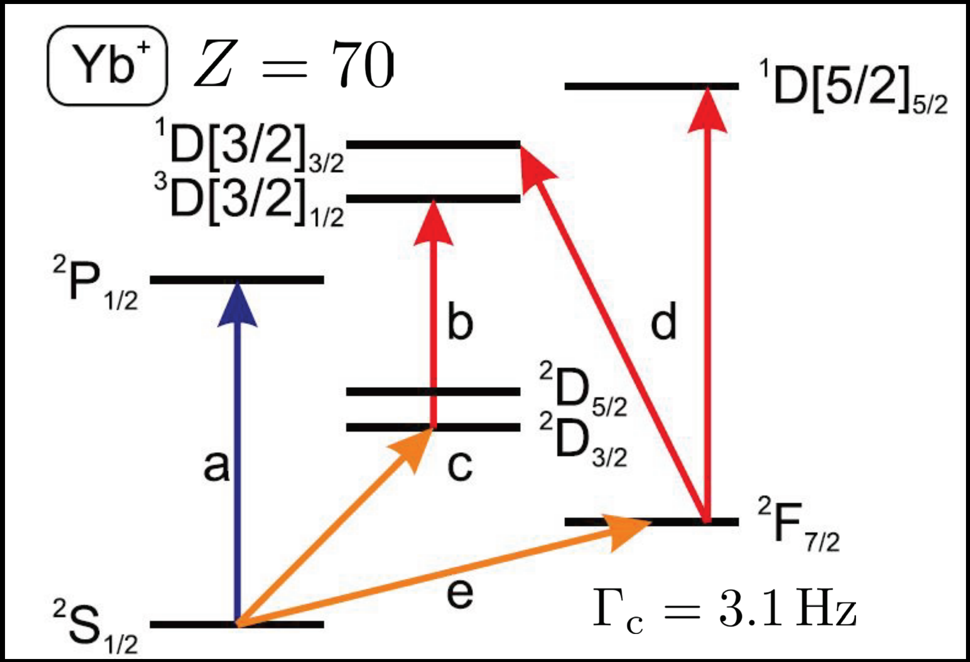
- Narrow transitions with S-wave are needed:

Ludlow-Boyd-Ye, Rev. Mod. Phys. 87 (2015)





$\Gamma_e = 10^{-9}\,\mathrm{Hz}$

Frequency Comparisons

- Experimental accuracy in $^{40}\mathrm{Ca}^{+}$, $^{88}\mathrm{Sr}^{+}$ is $\sim \mathrm{Hz}$

Dube et al., Phys. Rev. A87 (2013)
Chwalla et al., PRL 102 (2009)

$$\nu_{E2}^{\mathrm{Ca}^+} = 411\ 042\ 129\ 776\ 393.2(1.0)\mathrm{Hz}$$

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$$\sim 10^{15}\mathrm{Hz}$$

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sensitivity to the Higgs force →

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- Theory side is however much less promising:

  electron-electron correlations, nuclear finite-size, relativistic corrections, QED...

  are not accounted for at the 10^{-15} level...

Isotope Shifts
and King plots

Isotope Shift

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(consider $A' - A = 2, 4, \ldots$ *to avoid influence of nuclear spin)*

- The Higgs force however scales like the nuclear mass A, so there is still a net shift between isotopes!

Isotope Shift Sources

- There are yet non-trivial IS from changes in:
  - the reduced mass: $m_r = \frac{m_e m_A}{m_e + m_A} \simeq m_e(1 - m_e/m_A)$
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$$\delta\nu^i_{AA'} = K_i \mu_{AA'} + F_i \delta\langle r^2 \rangle_{AA'} + H_i(A - A')$$

$\mu_{AA'} \equiv m_A^{-1} - m_{A'}^{-1}$

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mass shift | field shift | Higgs shift

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- MS/FS effects are typically in the GHz range $\gg$ HS

The King Plot

W. H. King,
J. Opt. Soc. Am. 53, 638 (1963)

- First, define modified IS as $m\delta\nu^i_{AA'} \equiv \delta\nu^i_{AA'}/\mu_{AA'}$

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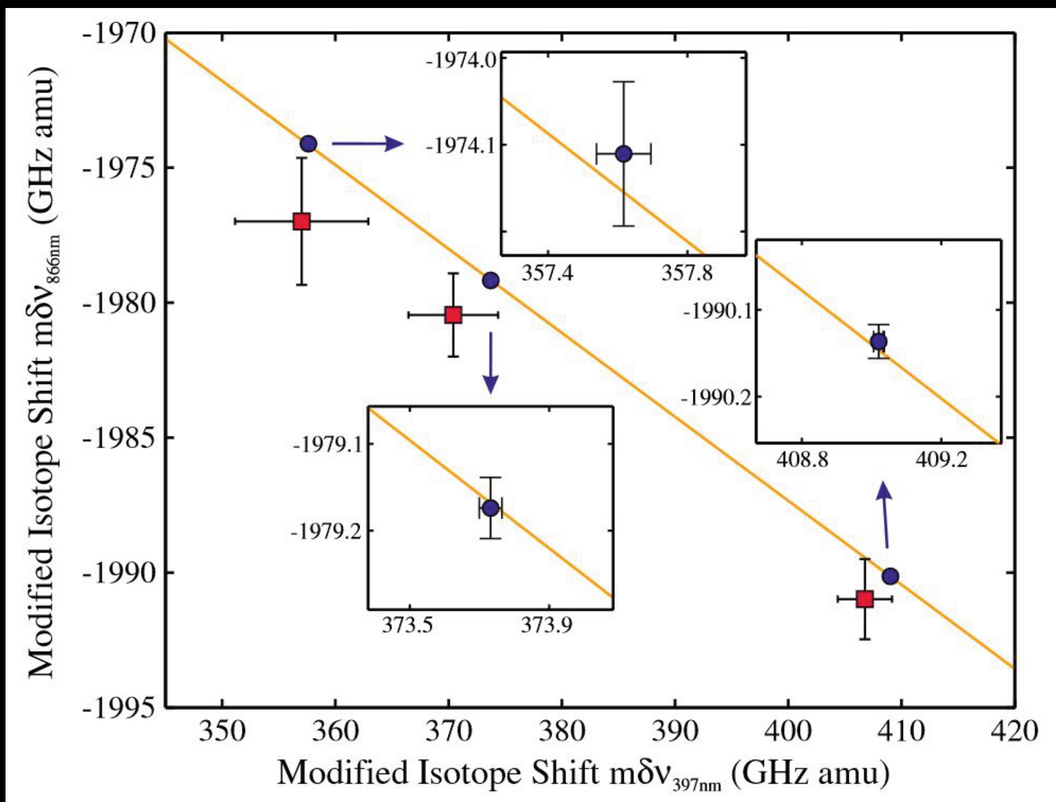
- Plot $m\delta\nu^1_{AA'}$ vs. $m\delta\nu^2_{AA'}$ along the isotopic chain and as long as linearity is observed, H_{21} can be bounded (unless accidentally $m\delta\nu \propto A'$)

Proof of Concept in Ca^+

Gebert et al. PRL 115 (2015)

$$A = 40, A' = 42, 44, 48$$

$4S \rightarrow 3D_{5/2}$



$4S \rightarrow 4P_{1/2}$ (not-clock)

IS ~ 1 GHz

error ~ 100 kHz

$y_e y_n \lesssim 40$

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- This is ~10 times better than (comparable to) LHC8 direct (indirect) bounds, with good/better prospect for improvements!

Higher-Order Corrections

- Need to control King's linearity at least down to:

Higgs force →

$$\frac{\mathrm{Hz}}{\mathrm{GHz}} \sim 10^{-9}$$

total IS →

- Higher-order corrections are not trivial to compute, many-body, relativistic simulations are needed [in progress]
- Yet, IS are controlled by two small parameters:

$$\varepsilon_\mu = m_e \mu_{AA'} \sim (A - A')10^{-8}$$
$$\varepsilon_r = \delta\langle r^2\rangle_{AA}/a_0^2 \sim (A - A')10^{-11}$$

- So, we can entertain NDA...

Field Shift

- Perturbation theory: Seltzer '69 Blundell et al. '87

nuclear charge distribution

$$\delta\nu^{\mathrm{FS}}_{AA'} = -e\int d^3r_e|\psi(r_e)|^2\delta V(r_e)\,, \qquad \delta V(r_e) = \frac{Ze}{4\pi}\int d^3r_N\frac{\delta\rho(r_N)}{|\vec{r}_e-\vec{r}_N|}$$

electron density

nuclear potential

- LO: $\propto |\psi(0)|^2\delta\langle r^2\rangle_{AA'} \sim \mathcal{O}(\varepsilon_r)$
- NLO/LO: $\sim \mathcal{O}(\varepsilon_\mu^2, \varepsilon_r^2, \varepsilon_\mu\varepsilon_r)/\varepsilon_r \sim 10^{-7}$
- NLO is linear up to overlap with the nucleus $\sim \mathcal{O}(\varepsilon_r)$
- Hence, non-linearities are only of $\mathcal{O}(\varepsilon_\mu^2) \sim 10^{-14}$

Specific Mass Shift

- MS arises from:
  - « rescaling » Rydberg constant (normal MS)
  - electron-electron correlation, relativistic… (specific MS)

- at LO, both scale like $m_e \mu_{AA'} \sim \mathcal{O}(\varepsilon_\mu)$
- NLO correction is parametrically: Palmer '87

$$\sim \alpha^2 m_e^2 (m_A^{-2} - m_{A'}^{-2})$$

- Hence, NLO/LO $\sim \mathcal{O}(\alpha^2 \varepsilon_r) \sim 10^{-10}$

Probing EW
and BSM Physics

The Weak Force

$$V_{\text{weak}}(r) = -\frac{8G_{\text{F}}m_Z^2}{\sqrt{2}}\frac{g_e g_A}{4\pi}\frac{e^{-m_Z r}}{r}$$

- Z-to-electron couplings known at 10^{-3} level

LEPEWWG

The Weak Force

$$V_{\text{weak}}(r) = -\frac{8G_F m_Z^2}{\sqrt{2}} \frac{g_e g_A}{4\pi} \frac{e^{-m_Z r}}{r}$$

- Z-to-electron couplings known at 10^{-3} level

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- Yet, the coupling to first-generation quarks (especially d_R) are poorly known from LEP

Efrati-Falkowski-Soreq '14

$$[\delta g_L^{Zu}]_{ii} = \begin{pmatrix} -0.8 \pm 3.1 \\ -0.16 \pm 0.36 \\ -0.28 \pm 3.8 \end{pmatrix} \times 10^{-2}, \quad [\delta g_R^{Zu}]_{ii} = \begin{pmatrix} 1.3 \pm 5.1 \\ -0.38 \pm 0.51 \\ \times \end{pmatrix} \times 10^{-2},$$

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- IS improved bounds: $|\delta g_V^{Zu} + 2\delta g_V^{Zd}| \lesssim 0.018$
- still weaker than APV in Cs: $|\delta g_V^{Zu} + 2\delta g_V^{Zd}| \lesssim 10^{-3}$

Effective Field Theory

- Relevant operators:

$$\mathcal{O}^V_{eq} = (\bar{e}\gamma^\mu e)(\bar{q}\gamma_\mu q) \quad q = u, d$$

$$\mathcal{O}^S_{eq} = (\bar{e}e)(\bar{q}q) \quad q = u, d, s, c, b, t$$

$$\mathcal{O}_{eg} = \alpha_s(\bar{e}e)G^2_{\mu\nu}$$

operator $\mathcal{O}_i$	Upper bound on $\lvert c_i\rvert$ ($\Lambda = 1\,\mathrm{TeV}$)	Lower bound on Λ_i [TeV] ($c = 1$)	LEP2
$\mathcal{O}^V_{eu}$	2.3×10^{-2}	6.6	$3.4 \vert 4.5$
$\mathcal{O}^V_{ed}$	1.1×10^{-2}	9.3	$3.0 \vert 2.5$
$\mathcal{O}^S_{eu}$	2.6×10^{-3}	20	
$\mathcal{O}^S_{ed}$	2.1×10^{-3}	22	$\sim 1-2$
$\mathcal{O}^S_{es}$	2.7×10^{-2}	6.1	
$\mathcal{O}^S_{ec}$	0.20	2.3	
$\mathcal{O}^S_{eb}$	0.87	1.1	
$\mathcal{O}^S_{et}$	56	0.13	
$\mathcal{O}_{eg}$	9.6	0.47	

CD-Soreq *to appear*

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sensitive to scalar operators up to 20TeV!

* to be confirmed

750GeV Resonance*

- LHC established its coupling to hadrons
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750GeV Resonance*

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- What if it further couples to electrons?
- Assuming a scalar resonance S :

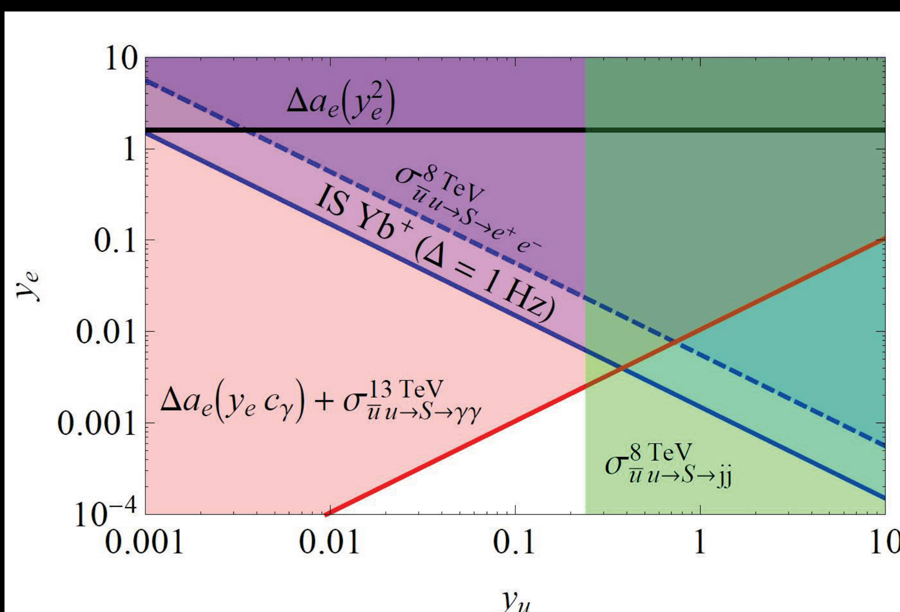
Unless it's produced through gluon or heavy quark fusion, IS has more sensitivity to S couplings than LHC searches in e^+e^-

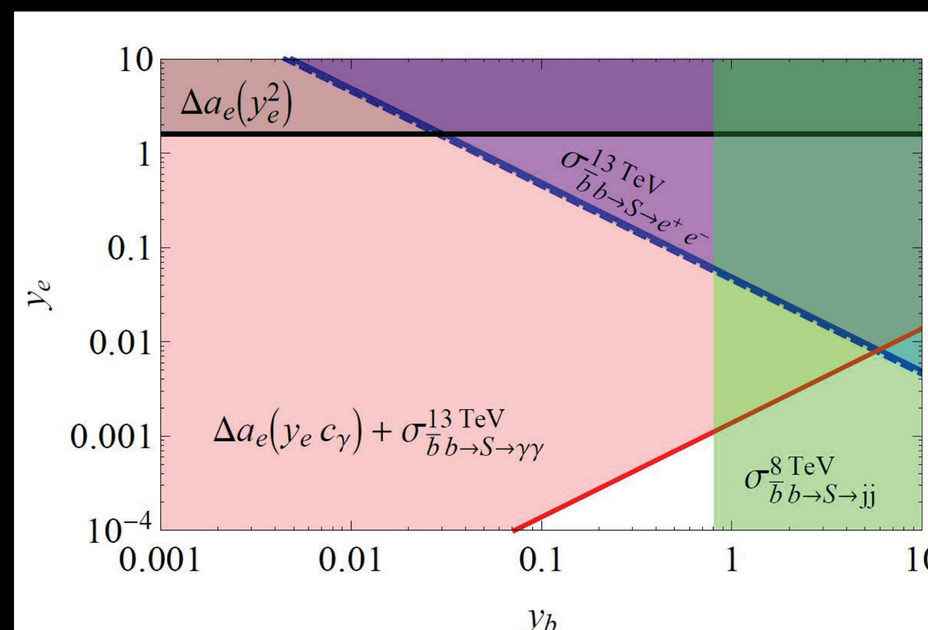
S couplings ($\mu = 750\,\text{GeV}$)	LHC (8, 13) bound [33, 37] ($\Gamma_S = 45\,\text{GeV}$)	IS projection ($\Delta = 1\,\text{Hz}$)
$\lvert y_e y_u \rvert$	$(5.6,\ 6.0) \times 10^{-3}$	1.5×10^{-3}
$\lvert y_e y_d \rvert$	$(7.3,\ 7.8) \times 10^{-3}$	1.2×10^{-3}
$\lvert y_e y_s \rvert$	$(2.9,\ 2.5) \times 10^{-2}$	1.5×10^{-2}
$\lvert y_e y_c \rvert$	$(3.6,\ 3.0) \times 10^{-2}$	9.6×10^{-2}
$\lvert y_e y_b \rvert$	$(5.6,\ 4.5) \times 10^{-2}$	0.49
$\lvert y_e y_t \rvert$	$(0.19,\ 0.16)$	32
$\lvert y_e c_g \rvert$	$(0.72,\ 0.60)$	150

* to be confirmed

750GeV Resonance*

- $\gamma\gamma$ signal + $g_e - 2$ bounds the $S\bar{e}e$ coupling
- Assuming *e.g.* $u\bar{u}$ or $b\bar{b}$ production:





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- Measurements in Yb+ are already underway!
- Other possibilities envisaged: Ca/Ca+, Sr/Sr+, Dy