Theory News Higgs

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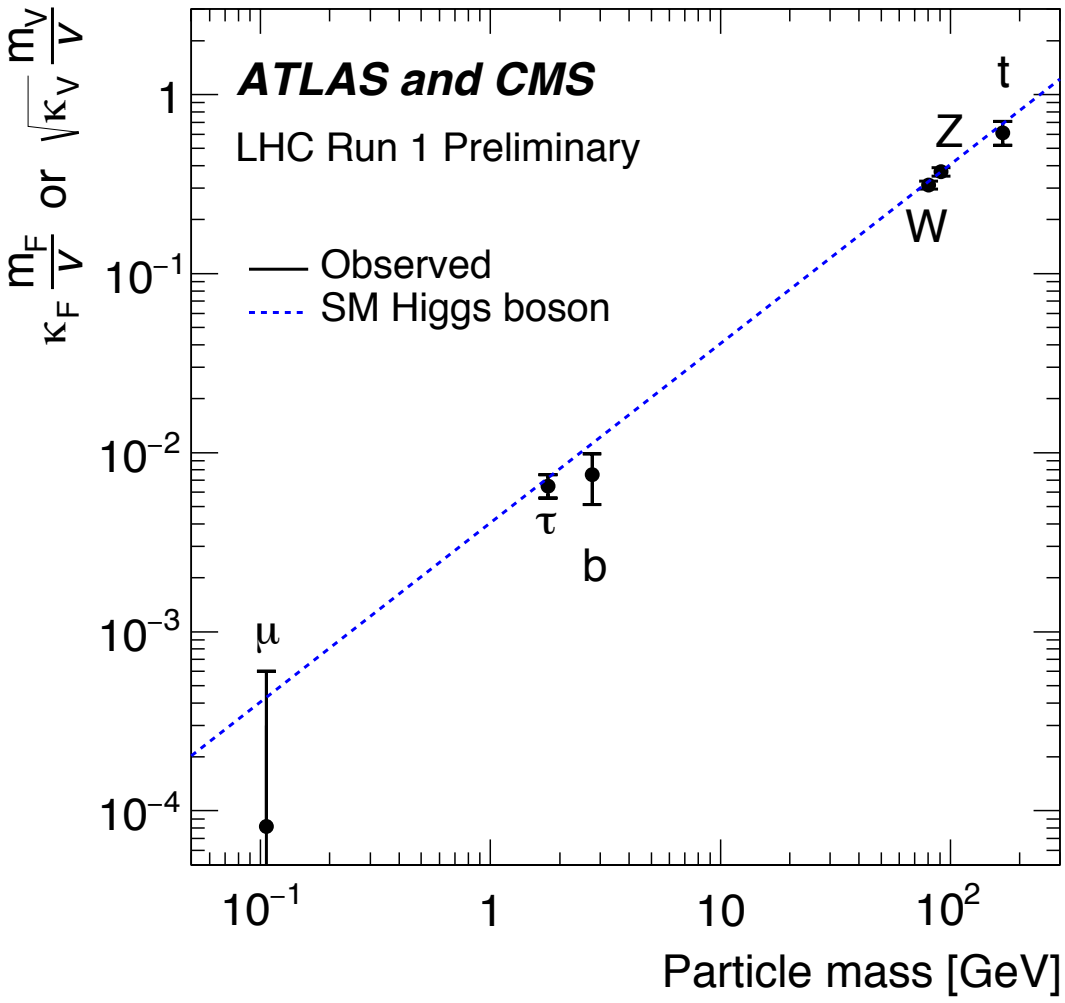
The Higgs in the SM

- Gauge sector:
  - Gauge-boson masses
  - Unitarization of gauge-boson scattering in the UV
- Yukawa sector:
  - Fermion masses
  - Yukawa interactions
- Higgs couplings completely determined in the SM
- SM Yukawas are
  - flavor-diagonal
  - real (CP-conserving)
- Experimentally, we know very little about the light-fermion Yukawas

Higgs Couplings

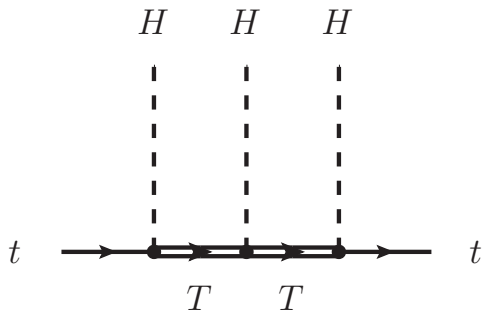


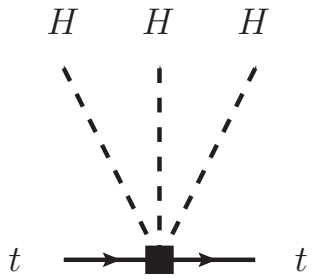
[ATLAS/CMS 2015]

How can we change the Higgs couplings?

Operator	Mass term	Higgs-fermion coupling
$y_t(\bar{Q}_L t_R H^c) + \text{h.c.}$	$m_t = \frac{y_t v}{\sqrt{2}}$	$\frac{y_t}{\sqrt{2}}$
$\frac{H^\dagger H}{\Lambda^2}(\bar{Q}_L t_R H^c) + \text{h.c.}$	$\delta m_t \propto \frac{(v/\sqrt{2})^3}{\Lambda^2}$	$\delta y_t \propto 3\frac{(v/\sqrt{2})^2}{\Lambda^2}$

- Mass and Yukawa term become independent
- Relative complexe phase $\rightarrow$ CP violation
- Misalignment $\rightarrow$ Flavor violation





We write

$$y_f/y_f^{\mathrm{SM}} \equiv \kappa_f$$

[and – apologies! – sometimes $\kappa_f = \mathrm{Re}(y_f/y_f^{\mathrm{SM}}), \tilde{\kappa}_f = \mathrm{Im}(y_f/y_f^{\mathrm{SM}})$]

Plan of this talk

- Size of Yukawa couplings
- Beyond the SM
  - CP Violation
  - Flavor Violation
- New Ideas

How to measure the Yukawas

Changing the Yukawa Couplings

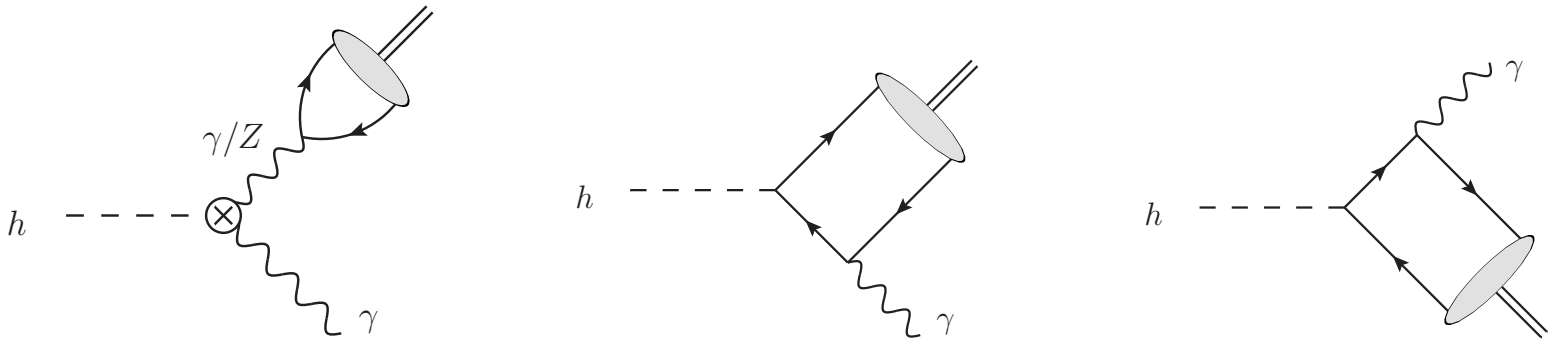
- Higgs-dependent Yukawa couplings [Guidice et al. 0804.1753]

$$Y_{ij}^{u,d}(H) = c_{ij}^{u,d} \left(\frac{H^\dagger H}{M^2} \right)^{n_{ij}^{u,d}}$$

  - $\epsilon = m_b/m_t \simeq 1/60$
  - Predicts $\kappa_b \simeq 3$ – excluded by $h \to b\bar{b}$
  - Modify by using two Higgs doublets $\Rightarrow \kappa_b \simeq -\sin\alpha/\cos\beta$
    [Bishara et al. 1504.04022; see also Bauer et al. 1506.01719]
  - Enhance light Yukawas up to factor $\kappa_q \sim 10$
- Yukawa-less light generations – $\kappa_q = 0$
  [Ghosh et al. 1508.01501]
- Look also for new states! (H, $H^\pm$, $A^0 \ldots$)

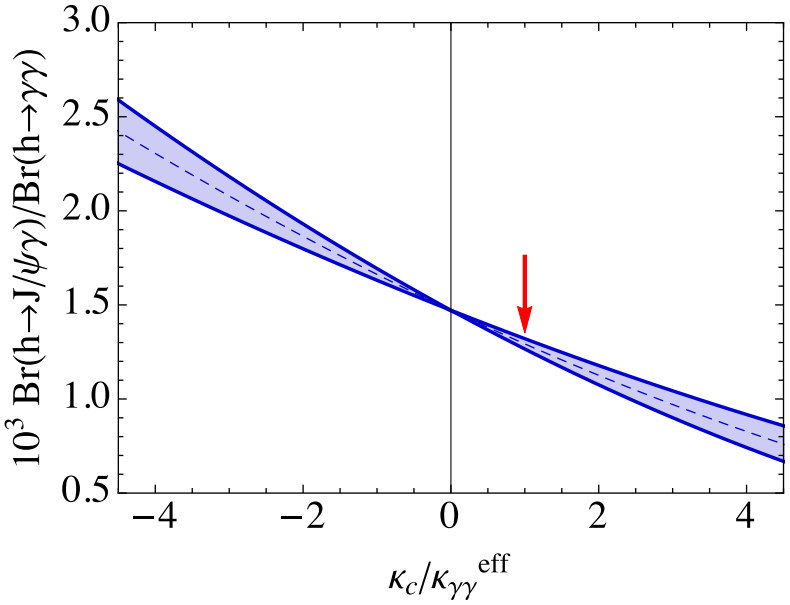
Exclusive Higgs Decays

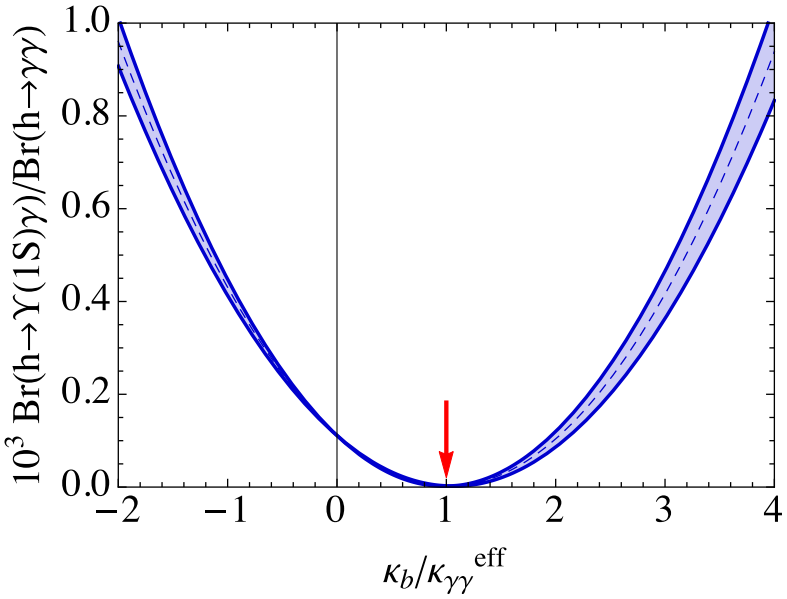
- Processes with off-shell Higgs and external SM particles difficult:
  - Scalar Higgs current competes with neutral currents induced by g, γ, Z
- Use on-shell Higgs decays [Isidori et al. 1305.0663; Bodwin et al. 1407.6695; Kagan et al. 1406.1722; König et al. 1505.03870]



$\mathrm{Br}(h \to \phi\gamma)$	$(2.31 \pm 0.11) \times 10^{-6}$
$\mathrm{Br}(h \to J/\Psi\gamma)$	$(2.95 \pm 0.17) \times 10^{-6}$
$\mathrm{Br}(h \to \Upsilon(1S)\gamma)$	$(4.61^{+1.76}_{-1.23}) \times 10^{-9}$

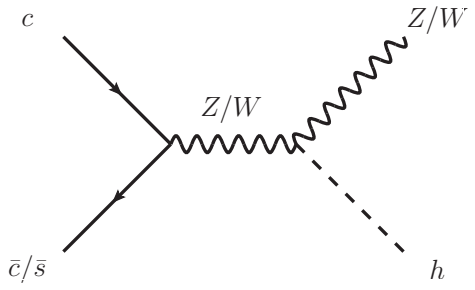
Exclusive Higgs Decays – Charms vs. Bottom

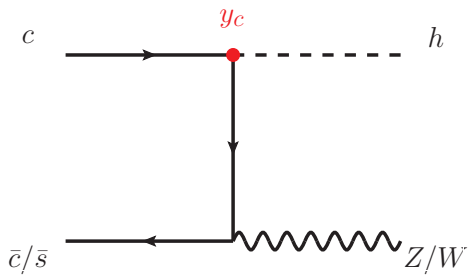




Charm Yukawa

- Several ways to constrain charm Yukawa
  [Perez et al. 1503.00290, 1505.06689]
  - Total width
  - Global fit
  - Exclusive decays (e.g. $h \to J/\Psi\gamma$)
  - Charm tagging

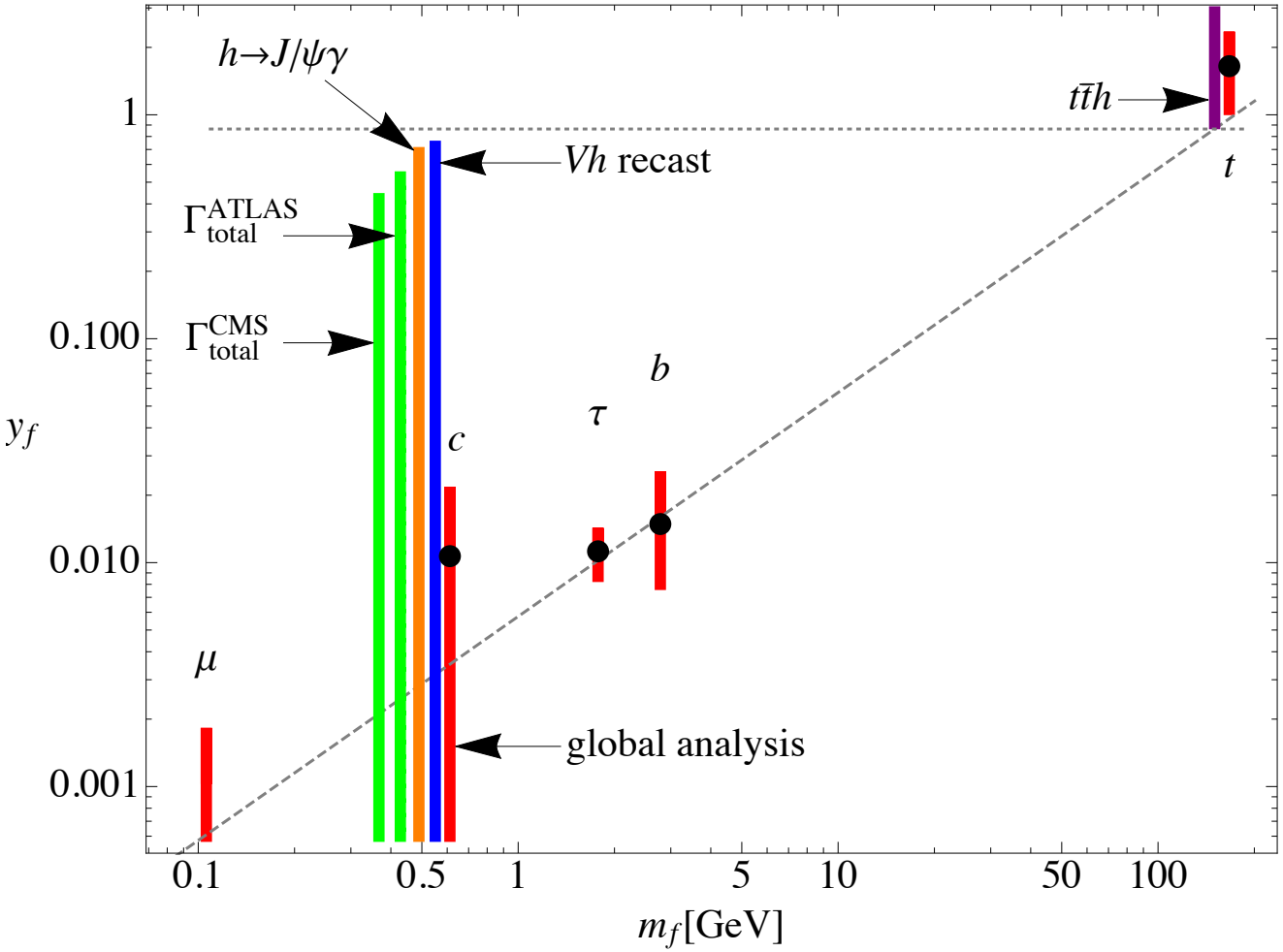




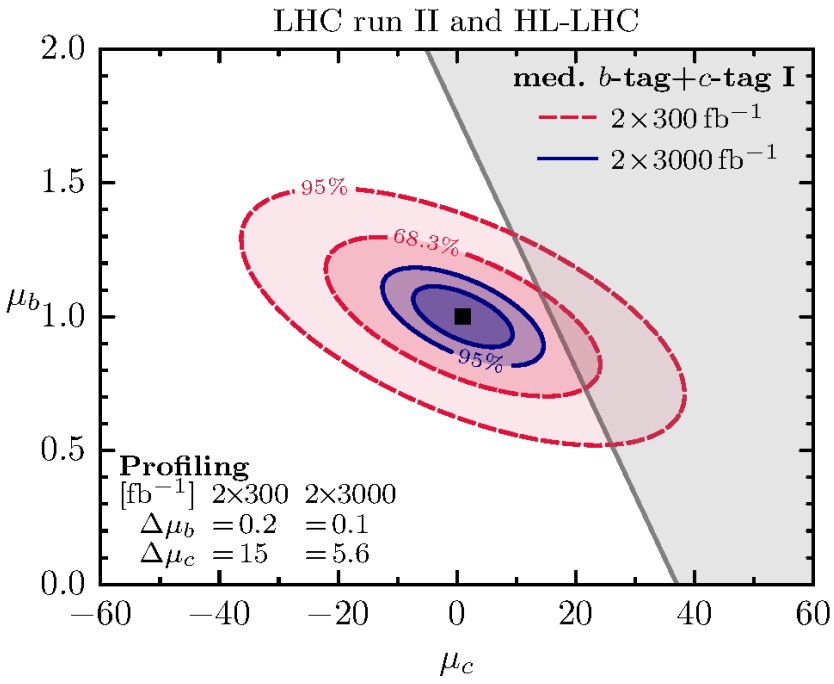
$$\mu_f \equiv \frac{\sigma_h \mathrm{BR}_{ff}}{\sigma_h^{\mathrm{SM}} \mathrm{BR}_{ff}^{\mathrm{SM}}}$$

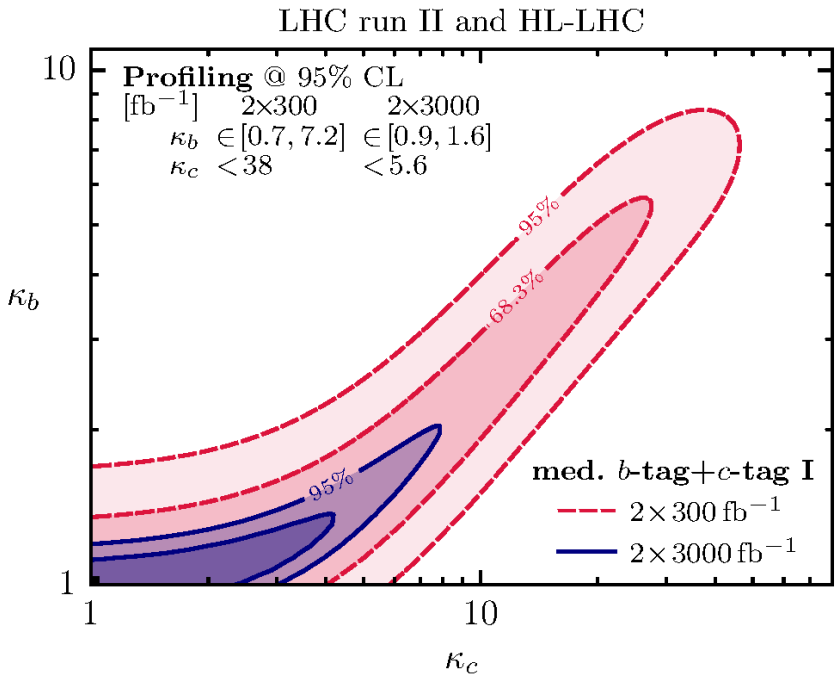
$$\mu_b \to \frac{\sigma_h \mathrm{BR}_{bb} \epsilon_{b_1} \epsilon_{b_2} + \sigma_h \mathrm{BR}_{cc} \epsilon_{c_1} \epsilon_{c_2}}{\sigma_h^{\mathrm{SM}} \mathrm{BR}_{bb}^{\mathrm{SM}} \epsilon_{b_1} \epsilon_{b_2} + \sigma_h^{\mathrm{SM}} \mathrm{BR}_{cc}^{\mathrm{SM}} \epsilon_{c_1} \epsilon_{c_2}} \propto \left(\mu_b + \frac{\mathrm{BR}_{cc}^{\mathrm{SM}} \epsilon_{c_1} \epsilon_{c_2}}{\mathrm{BR}_{bb}^{\mathrm{SM}} \epsilon_{b_1} \epsilon_{b_2}} \mu_c \right)$$

Charm Yukawa – Summary



Charm – Future Sensitivity



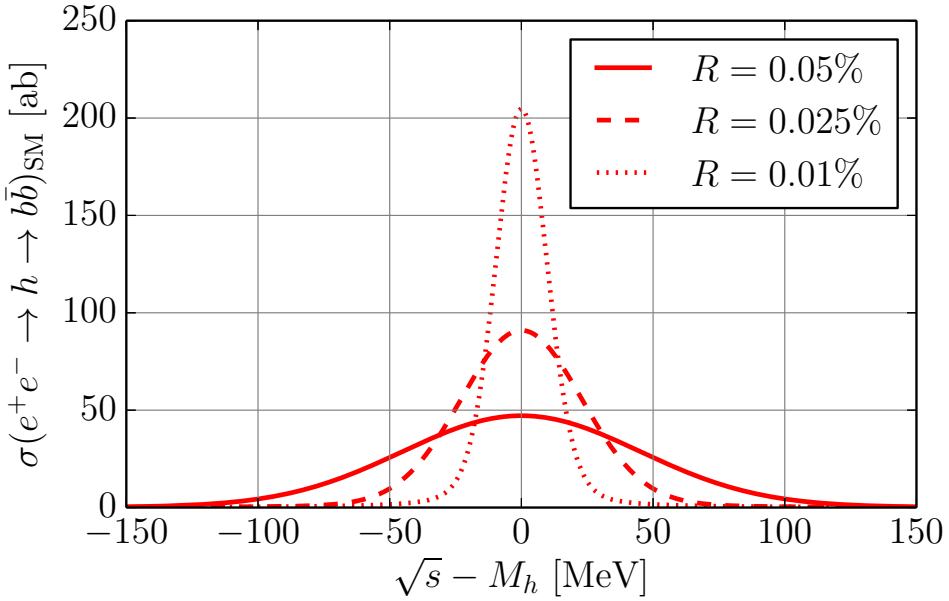


Electron Yukawa: Hadron Colliders

$$\mathrm{Br}(h \to e^+e^-) = \frac{|\kappa_e|^2 \mathrm{Br}(h \to e^+e^-)_{\mathrm{SM}}}{1 + \left(|\kappa_e|^2 - 1\right)\mathrm{Br}(h \to e^+e^-)_{\mathrm{SM}}}$$

- CMS limit $\mathrm{Br}(h \to e^+e^-) < 0.0019$ [CMS, 1410.6679]
  leads to $|\kappa_e| < 611$ [Altmannshofer et al. 1503.04830]
- Estimated future sensitivities at hadron colliders:
  - 14 TeV LHC with 3000/fb: $|\kappa_e| \sim 150$
  - 100 TeV collider with 3000/fb: $|\kappa_e| \sim 75$

Electron Yukawa: e^+e^- machines



- A future e^+e^- machine...
  - collecting 100 fb^{-1} on the Higgs resonance
  - assuming 0.05% beam-energy spread
- ...would be sensitive to $|\kappa_e| \sim 15$ [Altmannshofer et al. 1503.04830]

Electron Yukawa: Indirect bounds

- Usually, the measurement of $a_e \equiv (g-2)_e/2$ is used to extract α
- Using independent α measurement, can make a prediction for a_e [cf. Giudice et al., 1208.6583]
- With
  - $\alpha = 1/137.035999037(91)$ [Bouchendira et al., 1012.3627]
  - $a_e = 11596521807.3(2.8) \times 10^{-13}$ [Gabrielse et al. 1009.4831]
- ...we find $|\kappa_e| \lesssim 3000$ [Altmannshofer et al. 1503.04830]
- Bound expected to improve by a factor of 10 in the next few years

Beyond the SM – CP Violation

Electroweak Baryogenesis

- Sakharov conditions:
  - Baryon number non-conservation
  - P, CP violation
  - Thermal non-equilibrium
- A minimal setup:

$$\mathcal{L} = \frac{1}{\Lambda^2}(H^\dagger H)^3 + \frac{Z_t}{\Lambda^2}(H^\dagger H)\bar{Q}_3 H^c t_R$$

- Can we test it?

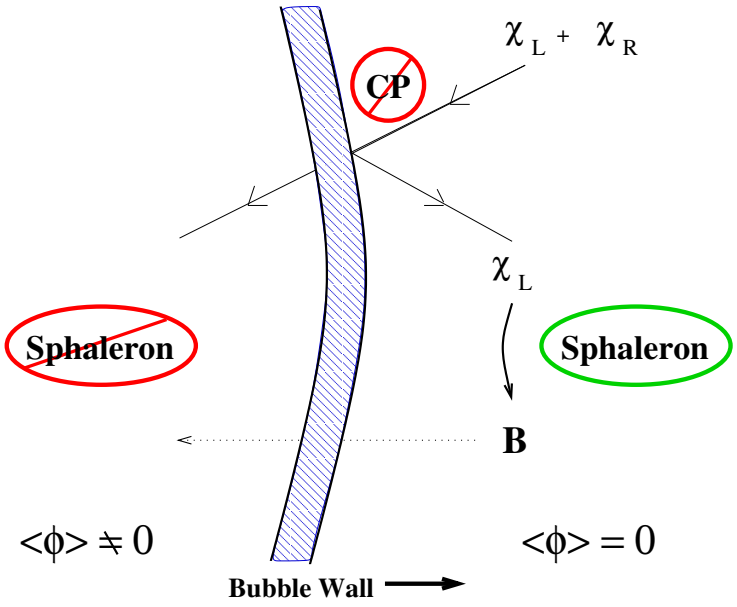
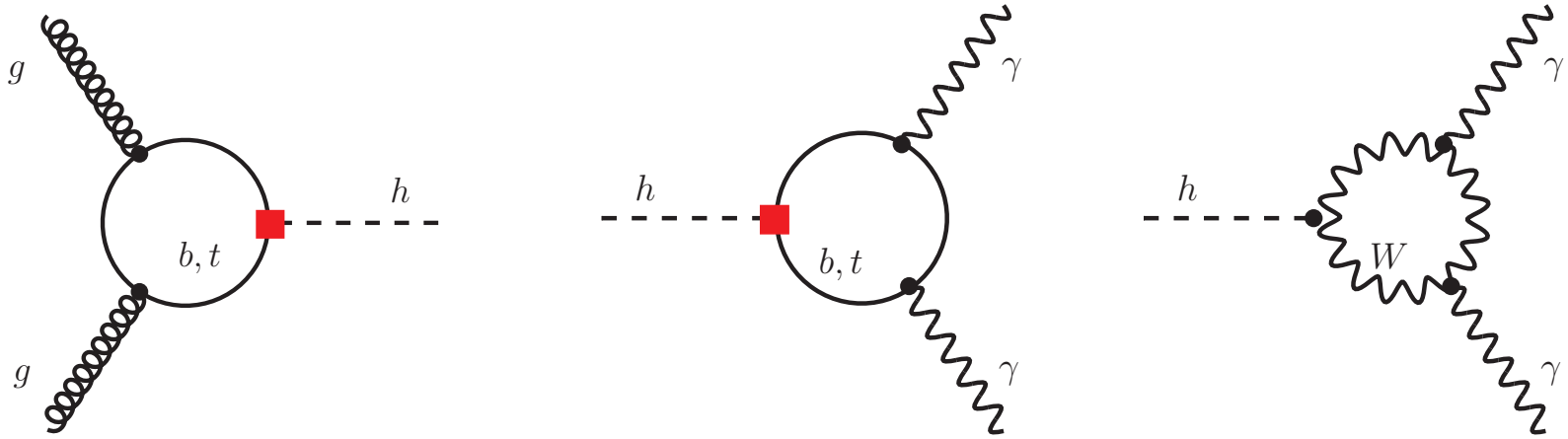
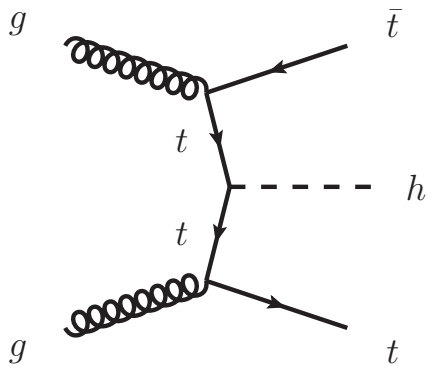


Image Credit: D. Morrisey et al.

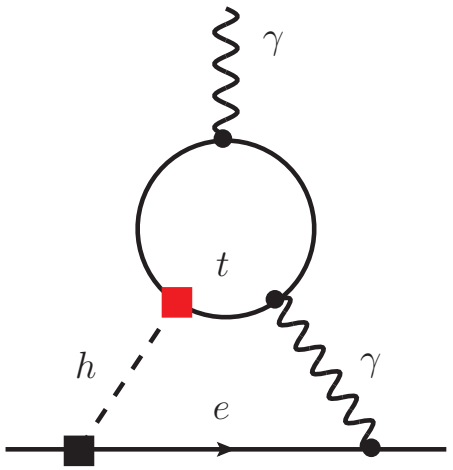
Top Yukawa – Higgs Production and decay



- Modified top Yukawa will change Higgs production and $h \to \gamma\gamma$ decay
- $t\bar{t}h$ production also sensitive, but need very high statistics

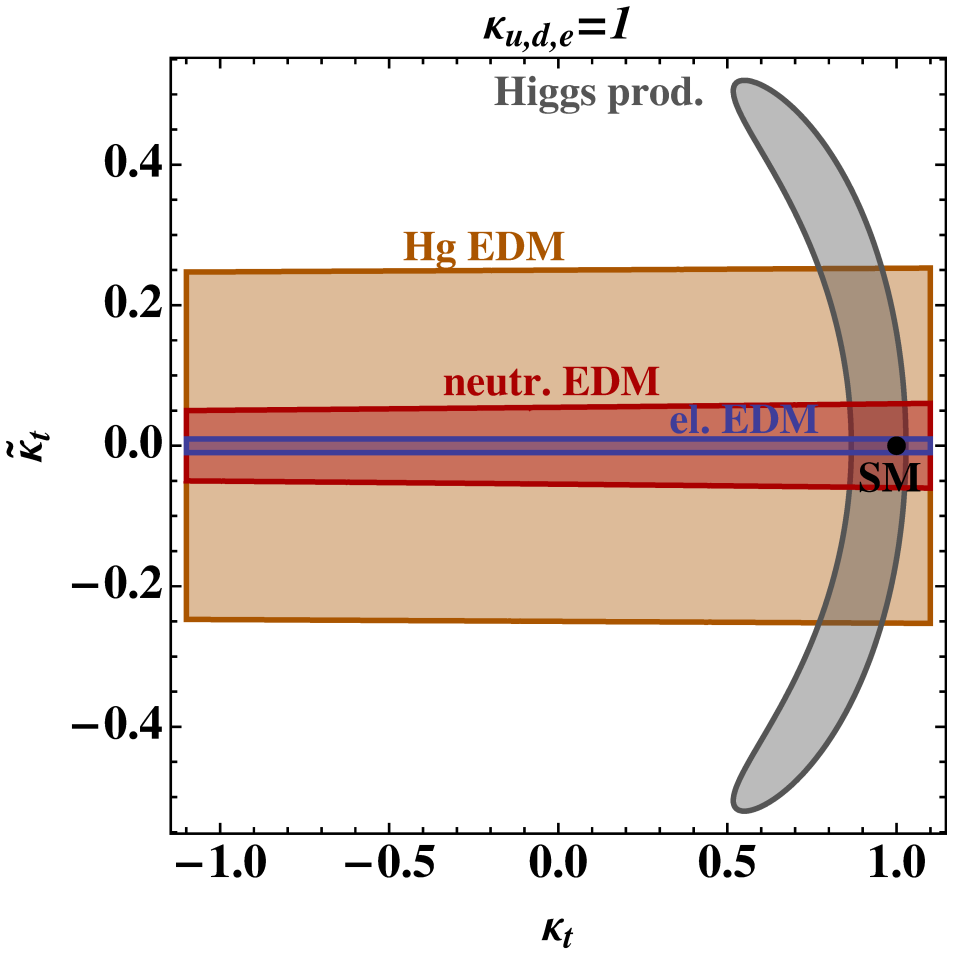


Top Yukawa – Constraints from EDMs



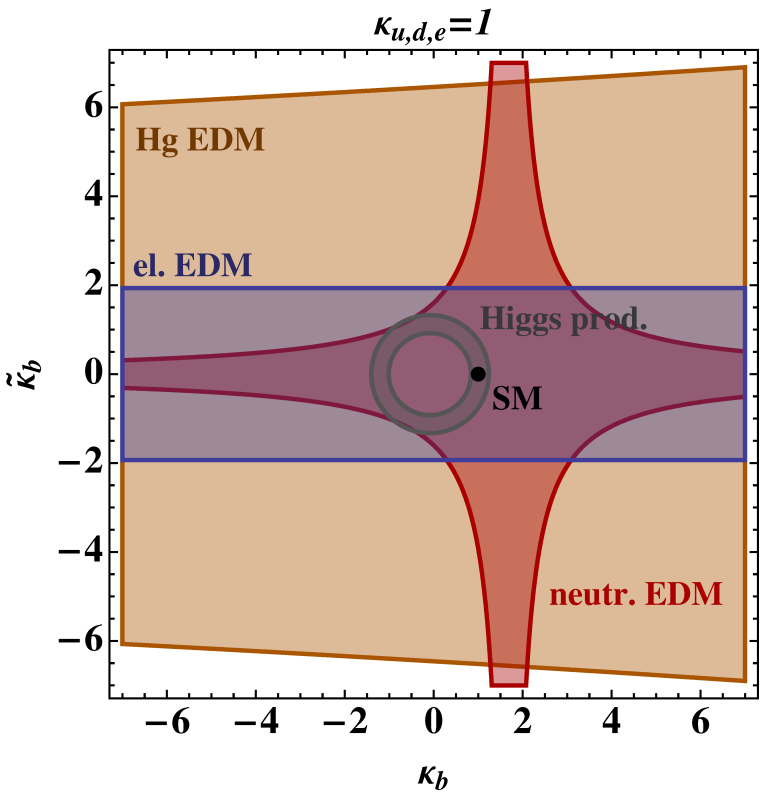
- EDM induced via "Barr-Zee" diagrams [Weinberg 1989, Barr & Zee 1990]
- $|d_e/e| < 8.7 \times 10^{-29}$ cm (90% CL) [ACME 2013, 1310.7534] with ThO molecules leads to $|\tilde{\kappa}_t| \lesssim 0.01$
- Plus further constraints from mercury EDM, neutron EDM [Brod et al. 1310.1385]
- See also [Jung et al. 1308.6283; Chien et al. 1510.00725] for comprehensive analysis of theory uncertainties

Top Yukawa – Summary



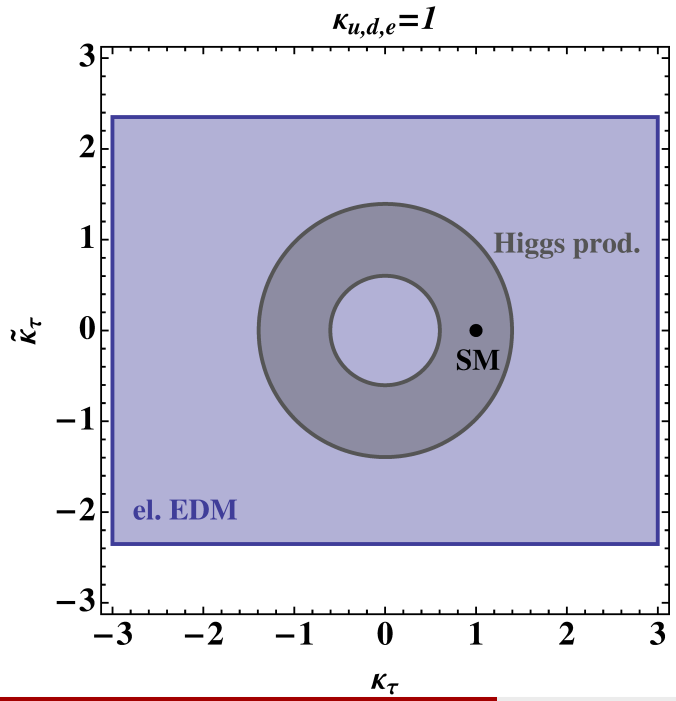
CP Violation – Bottom Yukawa

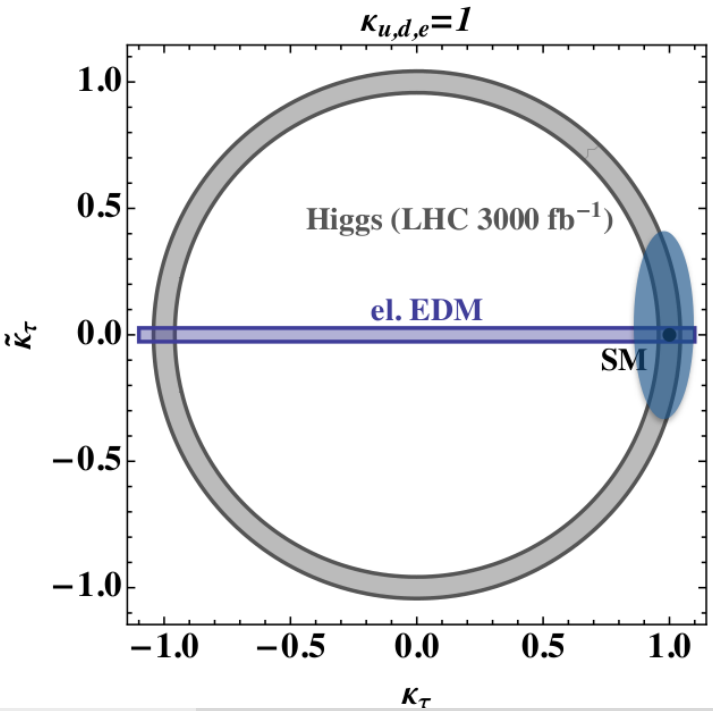
- $h \to b\bar{b}$ dominant SM decay channel
- $\kappa_b \neq 1$ will modify all branching ratios
- EDMs lead to comparable constraints [Brod et al. 1310.1385]
- Fragmentation to baryons retains spin information [Galanti et al. 1505.02771]



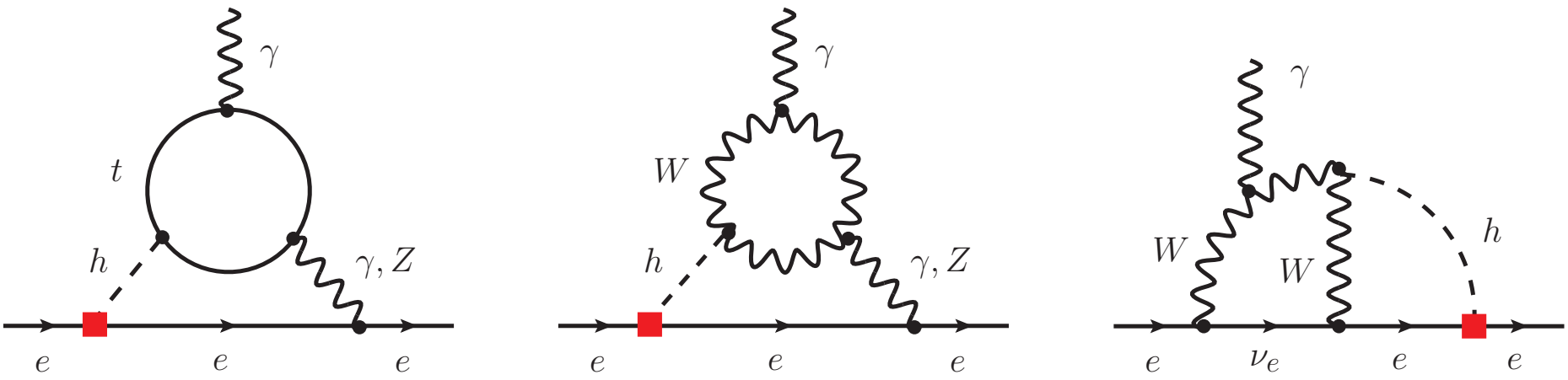
CP Violation – τ Yukawa

- $\kappa_\tau \neq 1$ will modify branching ratios
- Electron EDM gives indirect constraint
- $\tau^+ - \tau^-$ spin correlation sensitive to the CP phase
- Use momentum distribution for decay $\tau^\pm \to (\rho^\pm \to \pi^\pm \pi^0)\nu$
  [Harnik et al. 1308.1094]



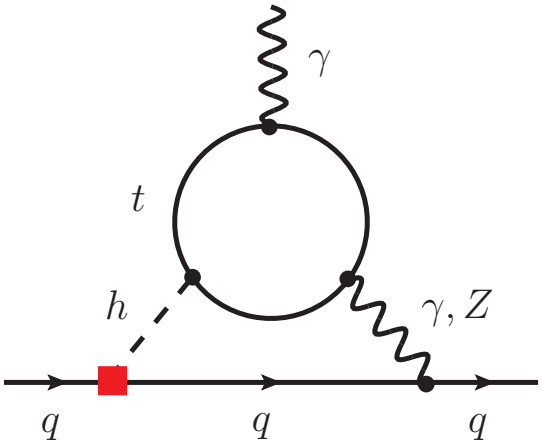


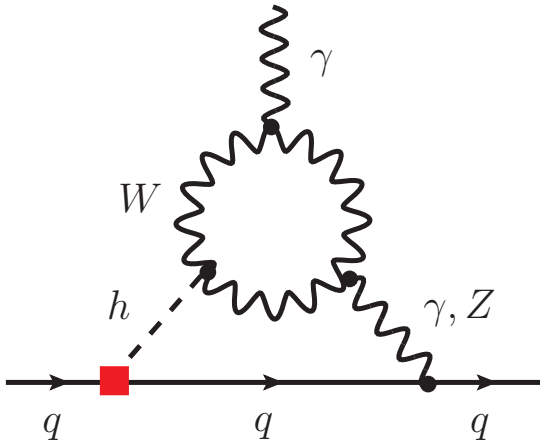
CP Violation – electron Yukawa

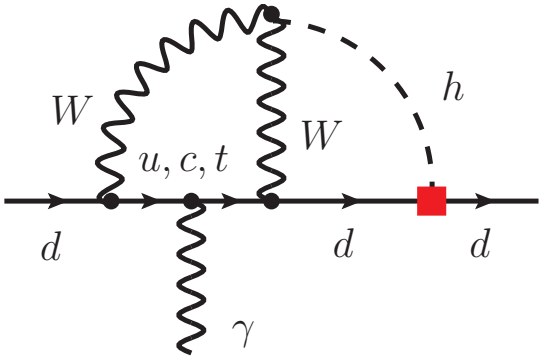


- . . . + 117 more two-loop diagrams
- Complete analytic result [Altmannshofer et al. 1503.04830]
- $|d_e/e| < 8.7 \times 10^{-29}$ cm (90% CL) [ACME 2013, 1310.7534]
- . . . leads to $|\tilde{\kappa}_e| < 0.017$

CP Violation: 1st generation quark Yukawas







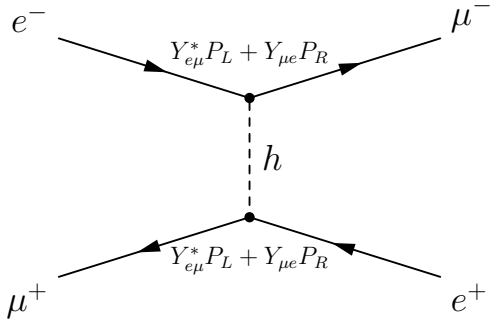
- Complete analytic result [work in progress]
- PRELIMINARY results:

$$\frac{d_n}{e} = (1.0 \pm 0.5)\,[0.36\,\tilde{\kappa}_u + 1.70\,\tilde{\kappa}_d]\,\kappa_t \times 10^{-25}\,\mathrm{cm}\,.$$

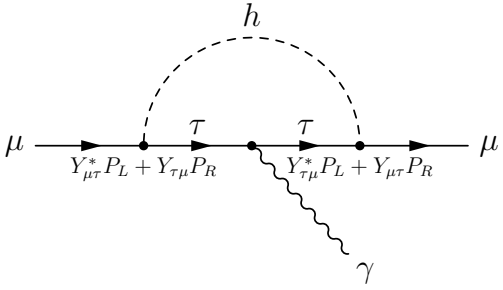
- $\Rightarrow |\tilde{\kappa}_u| \lesssim 0.8\,, \quad |\tilde{\kappa}_d| \lesssim 0.2$

Beyond the SM – (Lepton) Flavor Violation

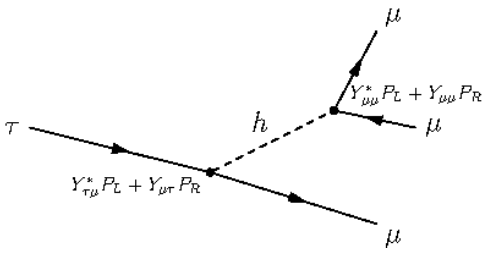
Low-Energy Constraints on Lepton Flavor Violation



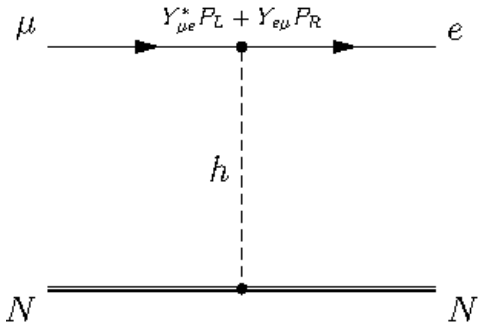
$M - \bar{M}$ oscillations



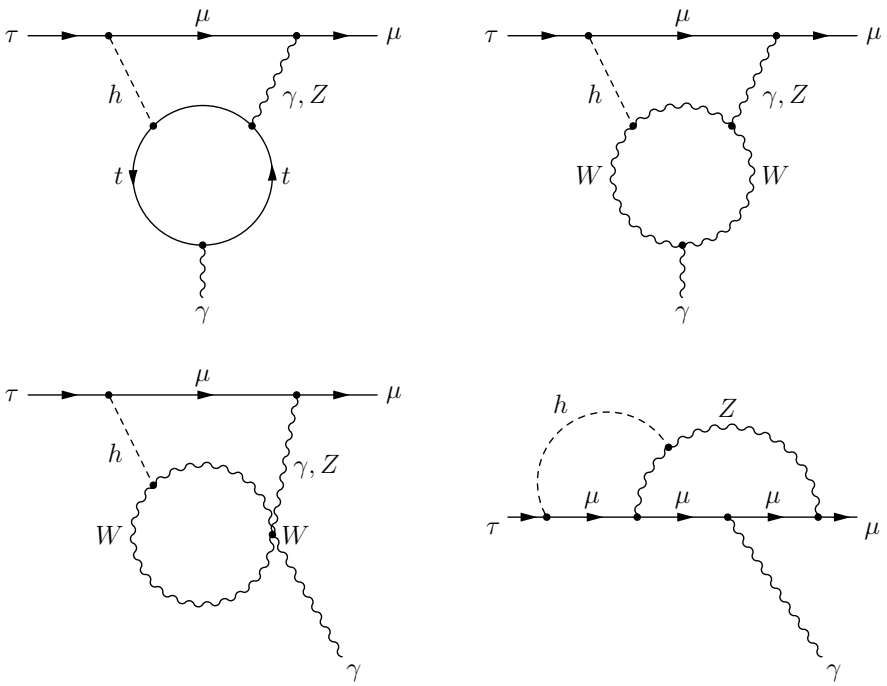
$g - 2$, EDMs



$\tau \to 3\mu$, $\mu \to 3e$



$\mu - e$ conversion

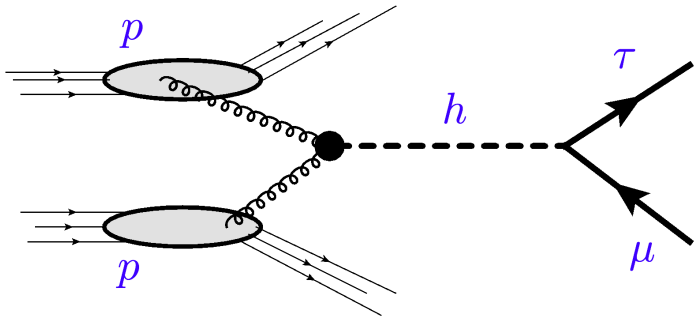


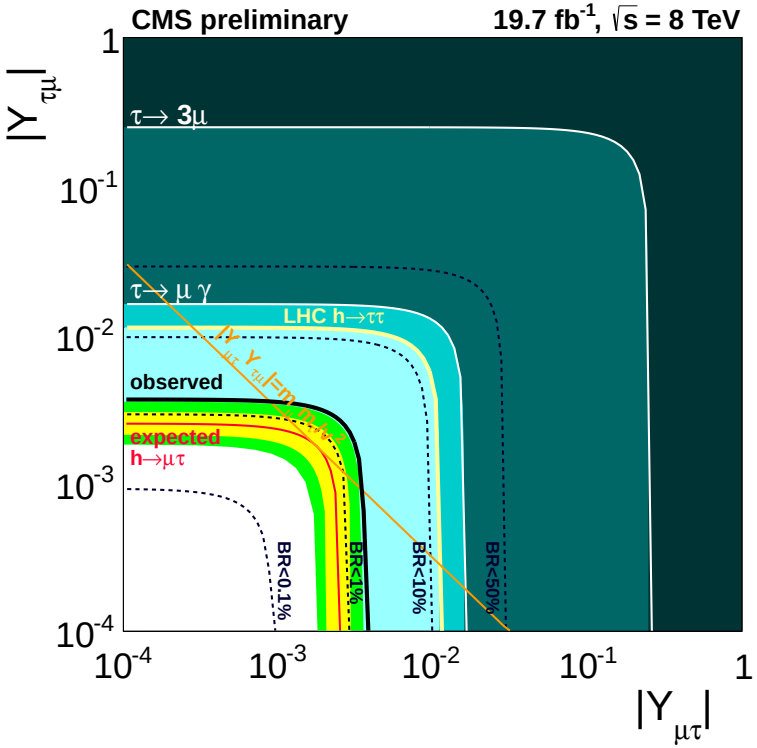
$\tau \to \mu\gamma$, $\mu \to e\gamma$

$h \to \tau\mu$ at CMS

- $\tau \to \mu\gamma$, $\tau \to 3\mu$, $(g-2)_\mu$, μEDM allow for $\mathrm{BR}(h \to \tau\mu) = \mathcal{O}(10\%)$

  [Harnik et al. 1209.1397]



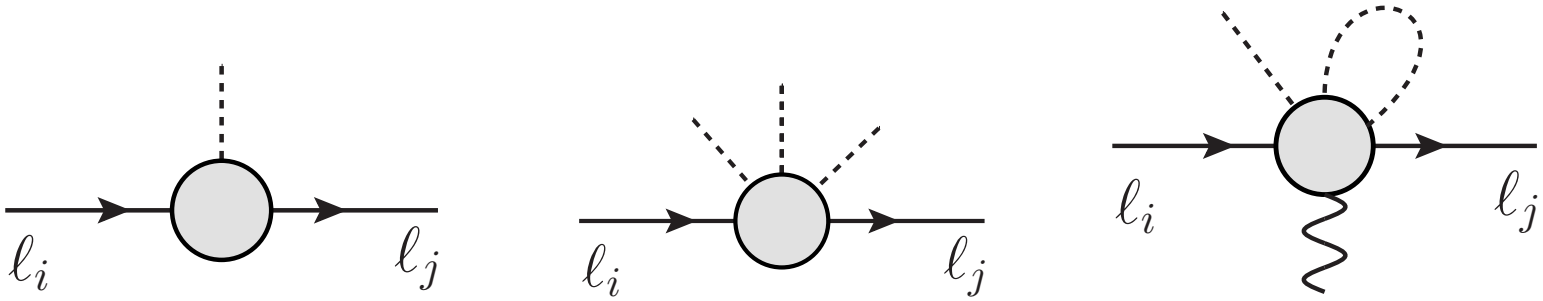


- $\mathrm{BR}(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$

  $\Rightarrow \sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} = (2.6 \pm 0.6) \times 10^{-3}$

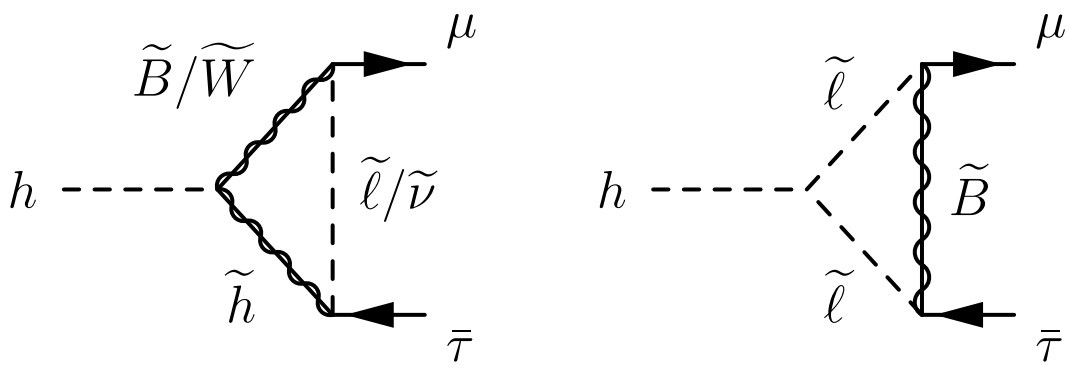
  [Altmannshofer et al. 1507.07927]

$h \to \tau\mu$ – General Considerations



- Assume large $h \to \tau\mu$ branching ratio
- At least one particle in loop has to be charged
- $\Rightarrow$ large dipole operator
- Either need fine tuning, or second source of EWSB
  [Altmannshofer et al., 1507.07927]
- 2HDM [E.g. Crivellin et al., 1501.00993; Altmannshofer et al., 1604.08221; Bizot et al. 1512.08508]
  Leptoquarks [Cheung et al. 1508.01897; Dorsner et al. 1502.07784]
  Strong interactions [Altmannshofer et al. 1507.07927]

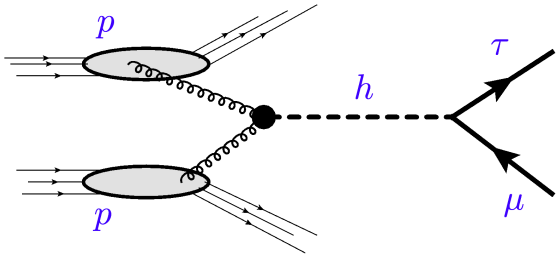
Large BR($h \to \tau\mu$) in the MSSM?

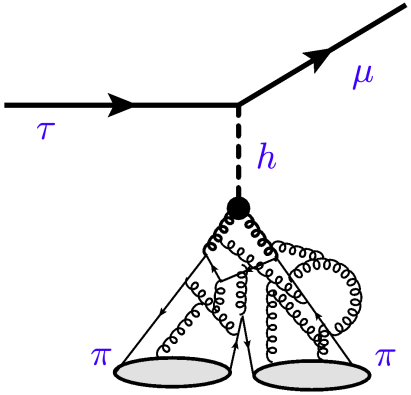


- Consider the MSSM with R parity
- Soft SUSY-breaking terms violate lepton flavor at tree level
- Possible to get observed BR($h \to \tau\mu$) consistent with precision, but needs large fine tuning!
- However, all these solution ruled out by charge breaking vacua
- If BR($h \to \tau\mu$) $\gtrsim \mathcal{O}(1\%)$, the MSSM is ruled out
  [Aloni et al., 1511.00979]

$h \to \tau\mu$ at Belle II

- "Most direct" indirect constraint: $\tau \to \mu\pi\pi$
  [Celis et al. 1309.3564]
- CMS result implies
  $\mathrm{BR}(\tau \to \mu\pi^+\pi^-) < 1.6 \times 10^{-11}$
- $\mathrm{BR}(\tau \to \mu\pi^+\pi^-) \lesssim \text{few} \times 10^{-8}$
  [Belle 1206.5595]
- $\mathrm{BR}(\tau \to \mu\pi^0\pi^0) < 1.4 \times 10^{-5}$
  [Cleo hep-ex/9704010]
- Measure at Belle II?





New Ideas

Probing the atomic Higgs force

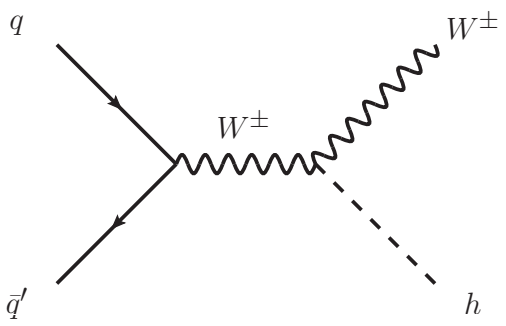
- Measure $\kappa_e \times \kappa_q$ in "atomic clock transitions"
  [Delaunay et al. 1601.05087]
- Characteristic $\Delta E \sim \Delta\nu$ in atomic transition
- Higgs force: Point-like, attractive – small change in frequency
- Can't switch off Higgs force – isotope shifts
- "Difference of differences" to eliminate nuclear uncertainties
- King's relation (1963):

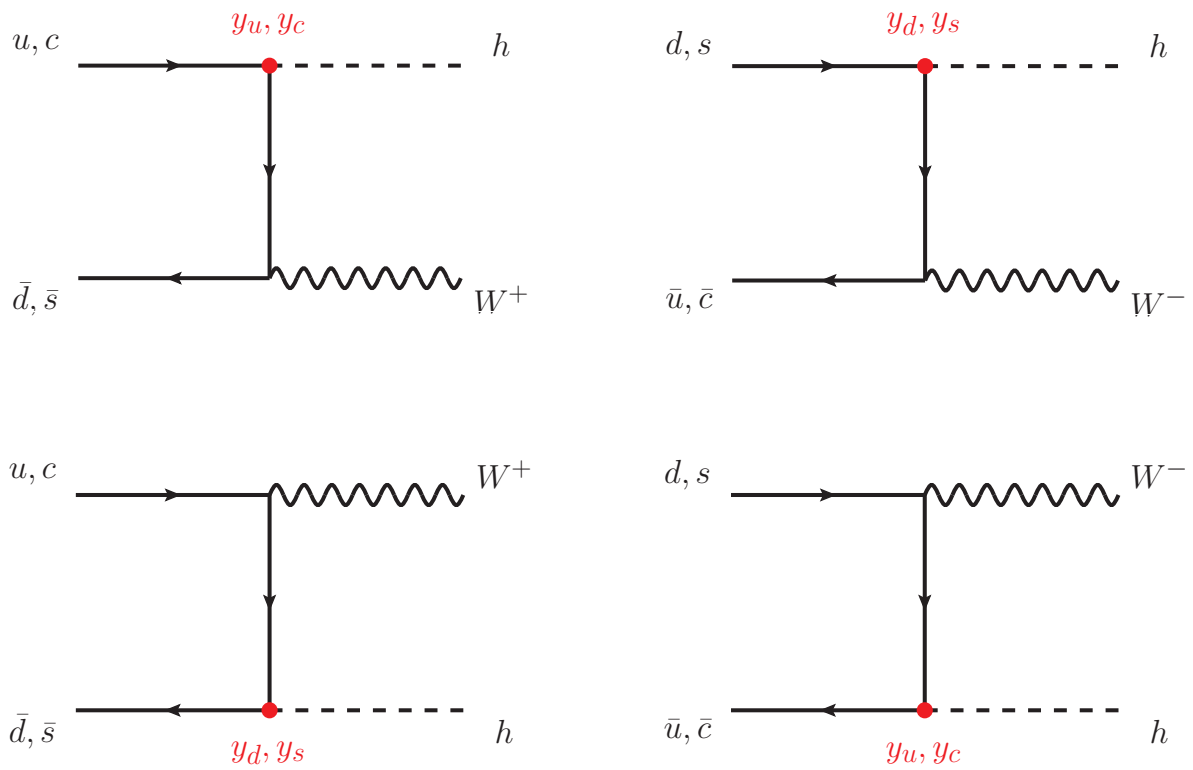
$$m\delta\nu^2_{AA'} = F_{21}\delta\nu^1_{AA'} + K_{21} + \text{non-linear Higgs contr.}$$

- Measure transitions in several isotopes (e.g., Yb^+ ion)
- Probe Yukawas with current LHC sensitivity or better

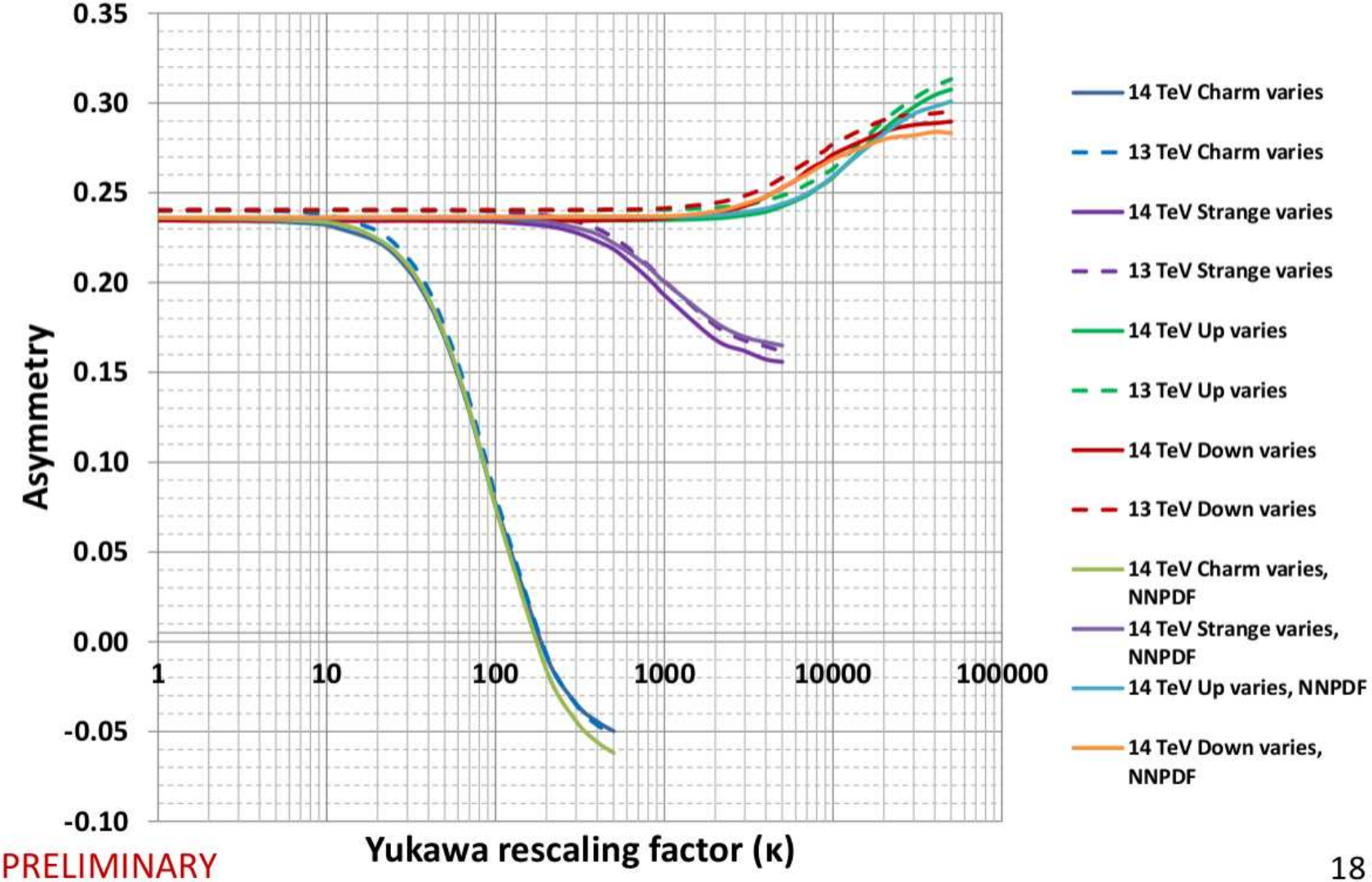
Charge asymmetries

- $hW^{\pm} \to (\ell^{\pm}\nu)(\ell^{\pm}\nu jj)$ charge asymmetry [Felix Yu, work in progress]





Charge asymmetries



PRELIMINARY

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Summary

- Higgs couplings completely determined in the SM
- That's why we need to measure them!
  - CP violation, flavor violation
- Interesting interplay between precision and collider probes
- Exciting experimental results and exciting new theoretical ideas