Rare Higgs decays

Jure Zupan
u. of cincinnati

Jefferson Lab, Mar 2 2015

OUTLINE

- general introduction
- new physics searches and Higgs couplings
  - flavor violating Higgs decays
  - CP violating Higgs decays
  - Higgs couplings to light quarks

THE DISCOVERY

- July 4th 2012 a discovery announced at CERN
  - a new particle with mass ~125 GeV
  - a year after: to *O(1)* behaves as the SM Higgs boson

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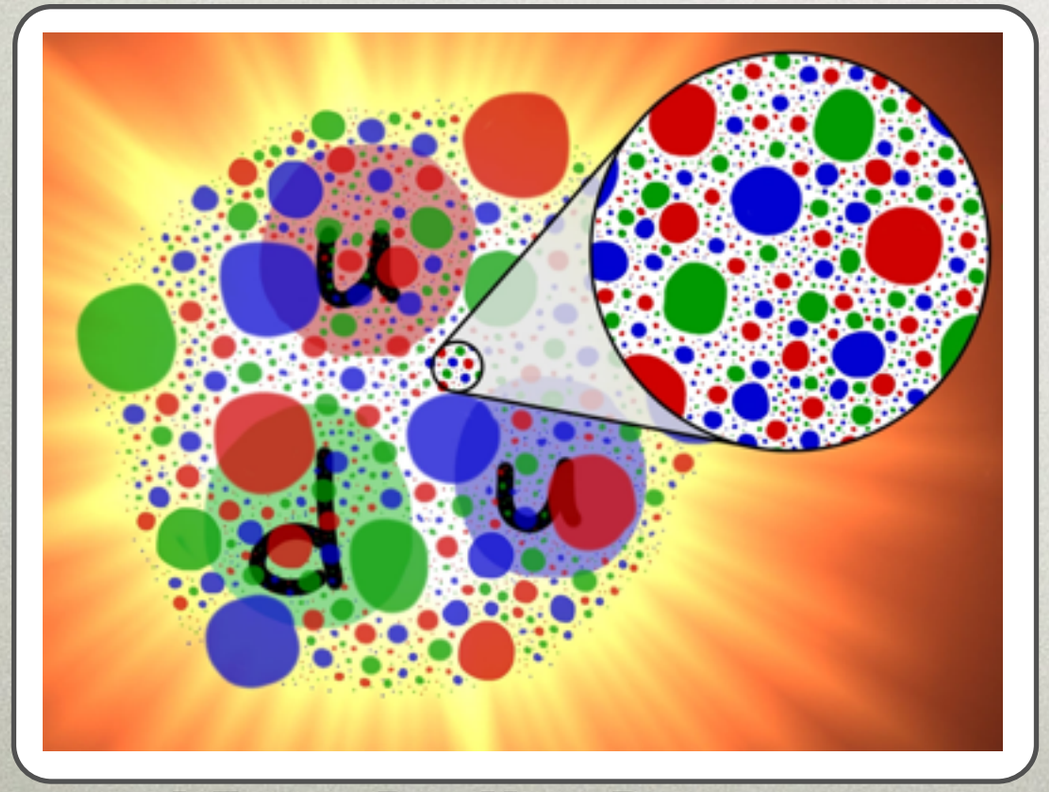
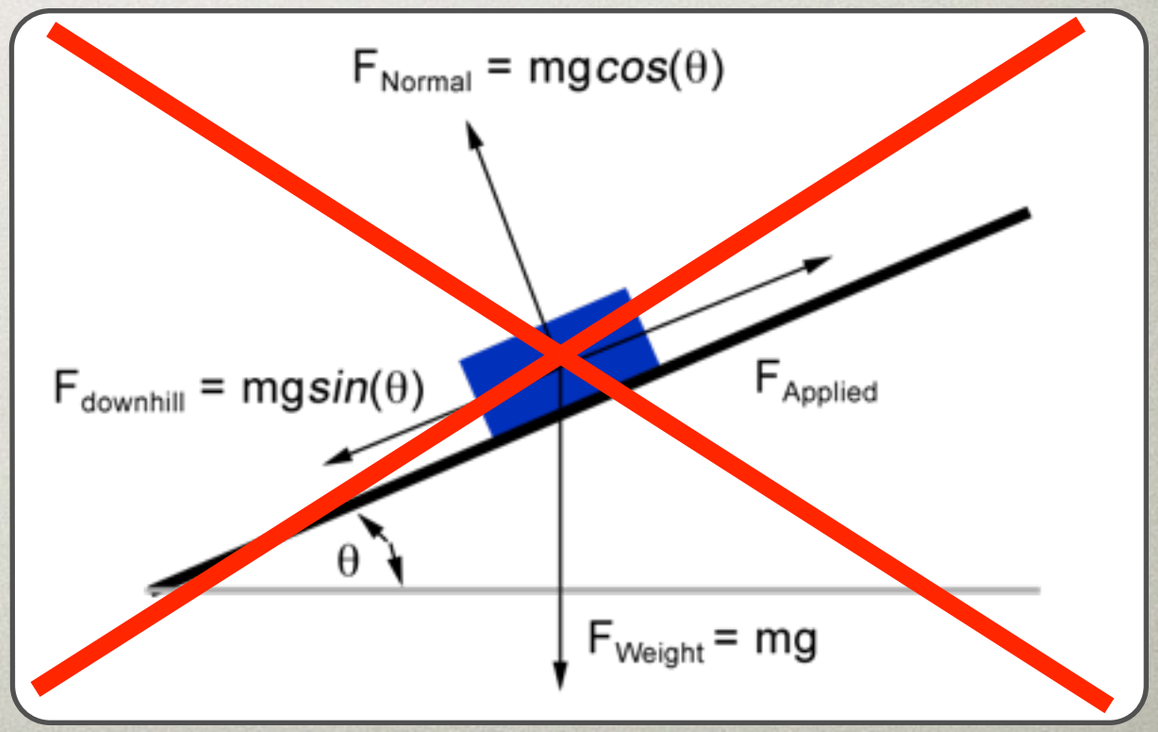
THE DUAL ROLE OF THE HIGGS

- dual role of the Higgs in the SM
  - breaks electroweak symmetry
  - gives a mass to elementary particles
- a disclaimer: most of "our" mass comes from QCD energy
  - Higgs thus has more to do with chemistry/nucl. structure than with the mass of the ordinary matter

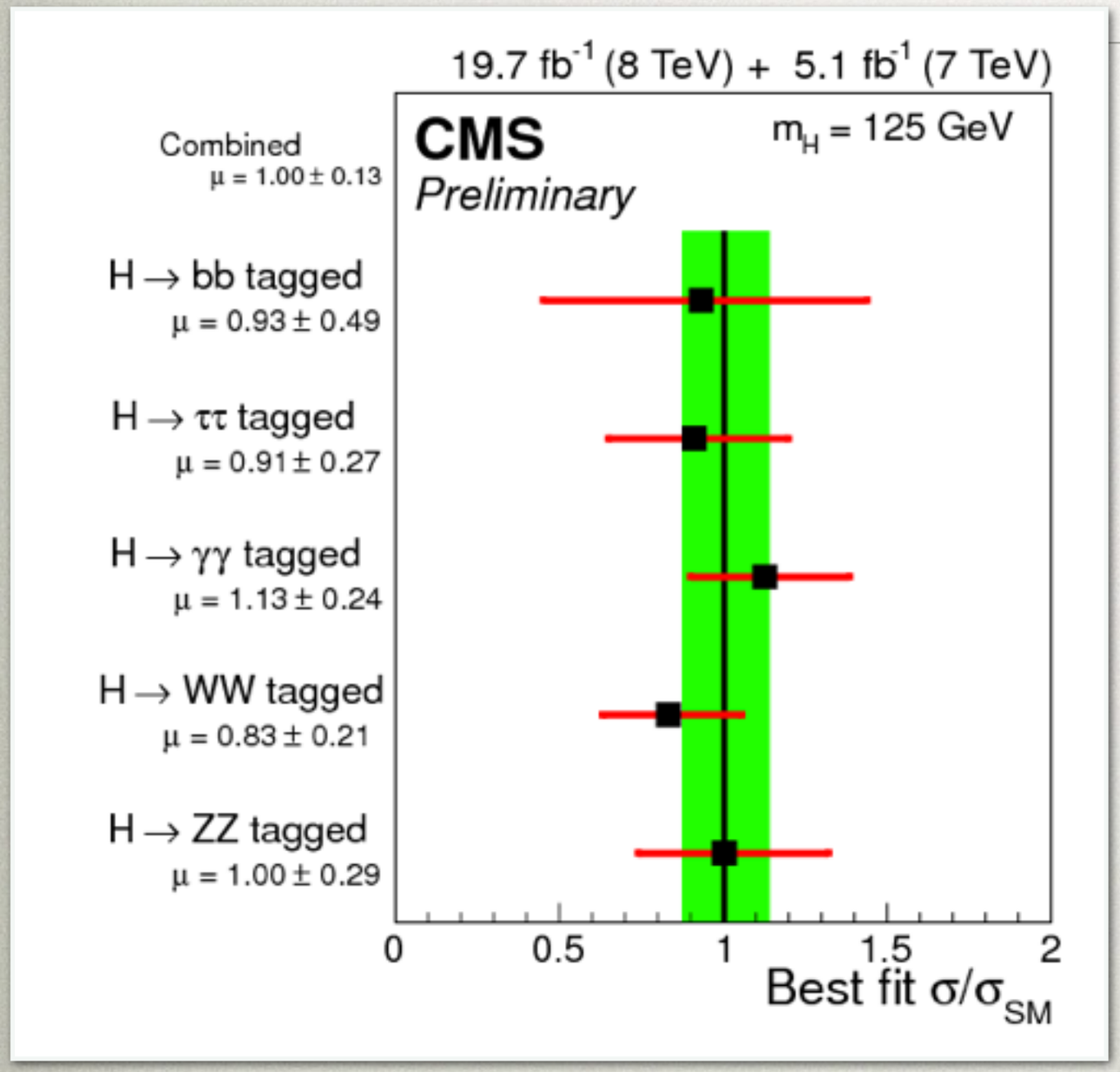


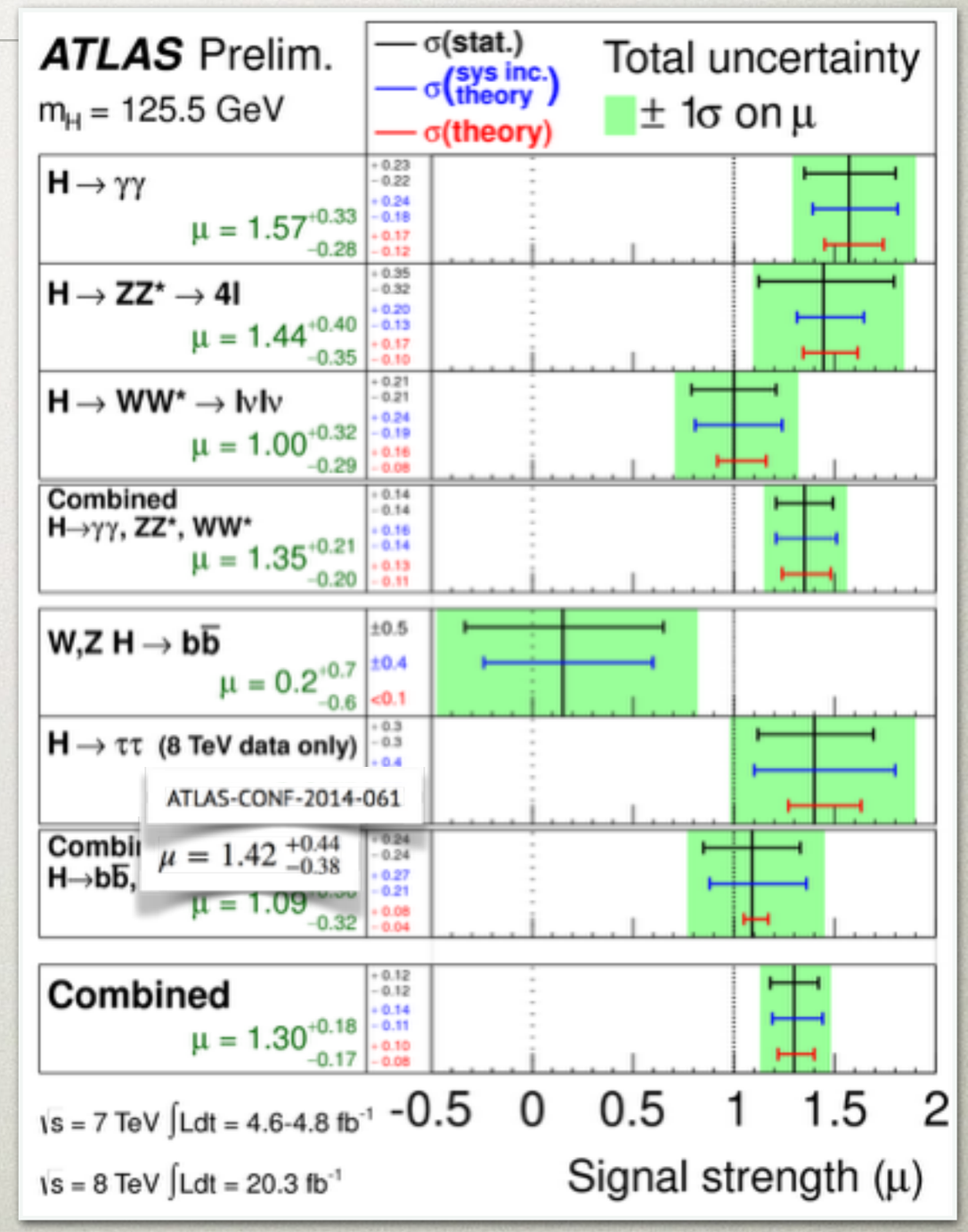


SM HIGGS?

- how closely does it resemble the SM Higgs?
  - EWSB: - does it couple to *W,Z*?
  - fermion mass generation: does it couple to fermions?

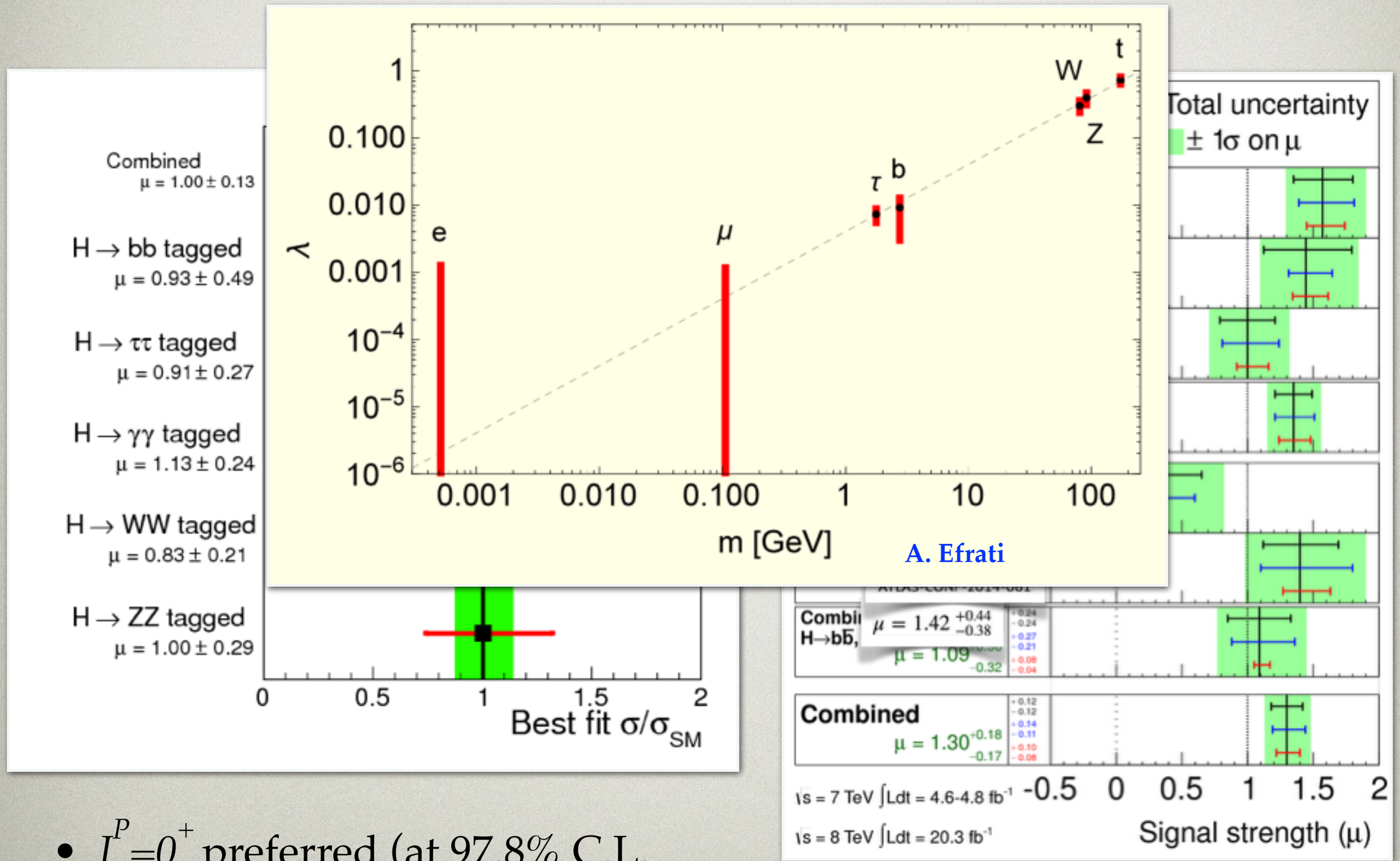
MEASUREMENTS





- $J^P = 0^+$ preferred (at 97.8% C.L. over 0^-)

ATLAS-CONF-2013-013;
CMS PAS-HIG-13-002



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ATLAS-CONF-2013-013;
CMS PAS-HIG-13-002

TO RECAPITULATE

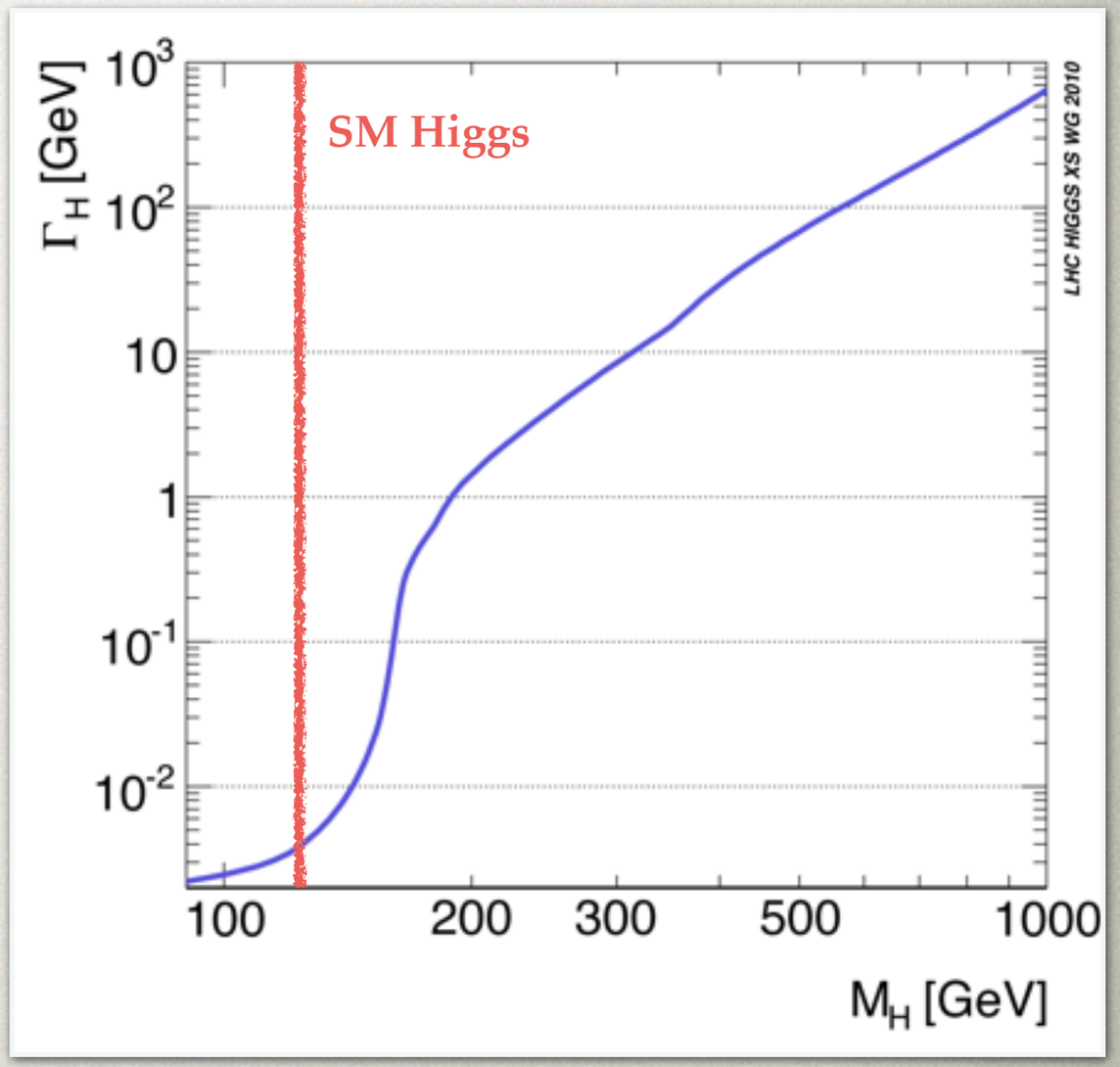
- the 125GeV state resembles the SM Higgs at the ~O(few10%) level
- for many problems can now think of the SM as a good low energy approximation
  - i.e. can use EFT
- among the SM fields H stands out
  - it forms one of only two dim2 gauge invariant operators: $H^\dagger H$ and $B_{\mu\nu}$

SENSITIVITY TO NEW PHYSICS

- is a blessing and a curse
  - naturally $\Lambda^2 H^\dagger H$, where Λ is a scale of physics that couples to the SM (e.g. M_{Pl})
  - if $\Lambda \gg v_{EW} \Rightarrow$ hierarchy problem
  - one of the reasons for new physics at TeV
- the flip side: $H^\dagger H$ can couple to NP
  - if NP contains scalars the interact. are dim-4 (unsuppressed in NDA), $H^\dagger H \, \phi^\dagger \phi$
  - in general the lowest suppression
- next best thing to producing these states on-shell in colliders

HIGGS - A WINDOW TO NEW PHYSICS

- the 125GeV scalar resembles the SM Higgs at the ~O(few10%) level for measured couplings
- Higgs decay width small
  - in the SM Γ_H=*4.1 MeV*
- this enhances sensitivity to NP in decays
  - exotic decays, i.e., not present in the SM
  - modified *Br* for the SM channels

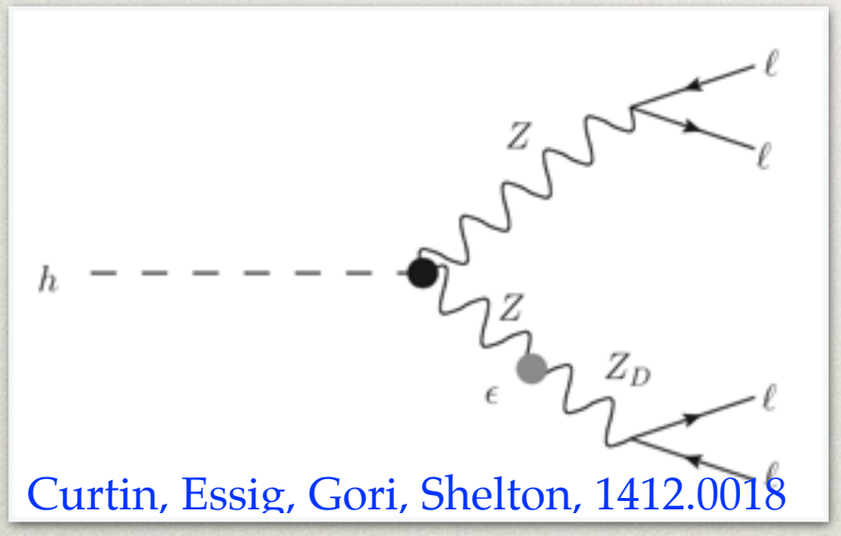


EXOTIC DECAYS

- the Higgs could decay to completely new sector

Falkowski, Ruderman, Volansky, JZ, 1002.2952
Curtin et al, 1312.4992
+many refs.

  - many signatures, model dependent
  - $h \to inv.$, $4b$, $2b\ 2\tau$, …
- an example: dark photon from kinetic mixing



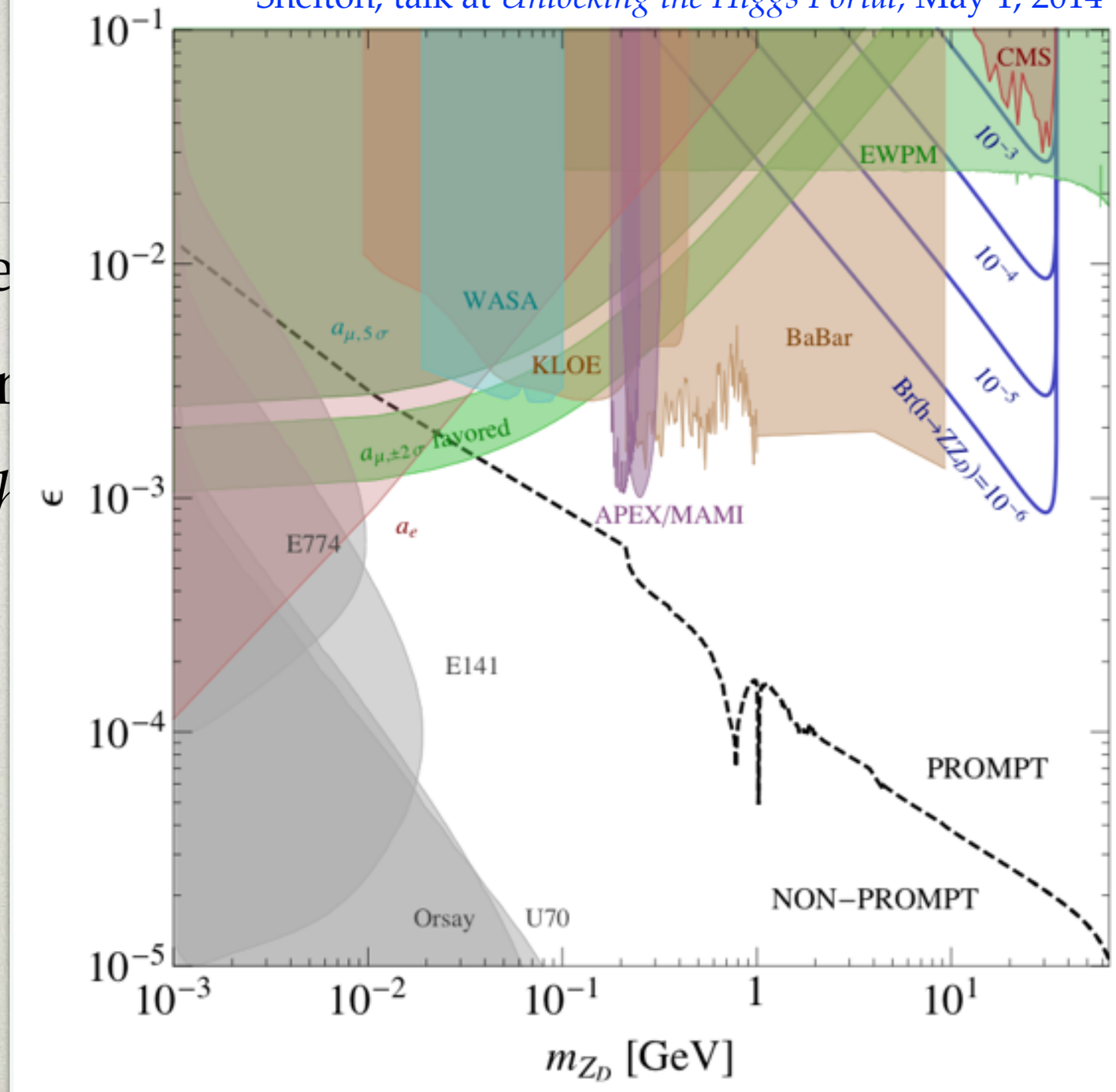
Curtin, Essig, Gori, Shelton, 1412.0018

see also Falkowski, Vega-Morales, 1405.1095

  - the final state is $h \to 4l$
  - could use pseudo-observables for general searches

Gonzalez-Alonso, Greljo, Isidori, Marzocca, 1412.6038

Shelton, talk at *Unlocking the Higgs Portal*, May 1, 2014



- the sector
  - r
  - *h*
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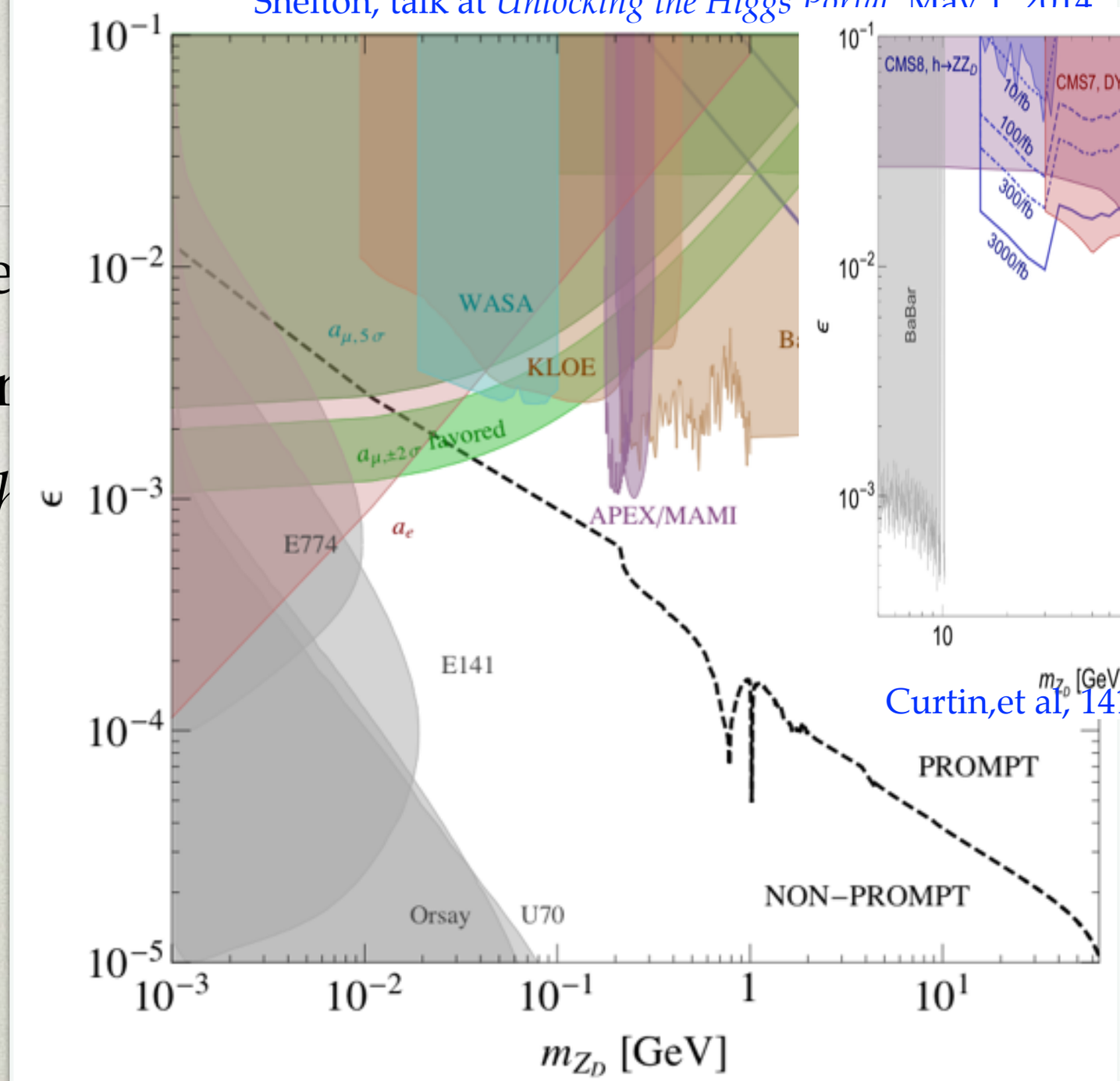

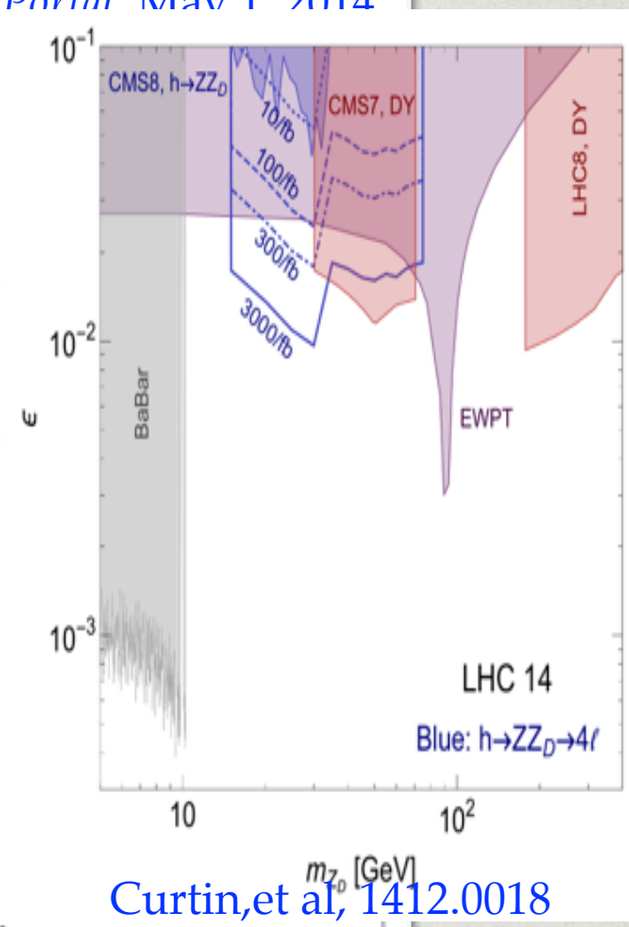

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FOCUS OF THIS TALK

- focus on two-body rare decays of the Higgs to SM particles
- many couplings very small or zero in the SM
  - no flavor violating couplings to quarks
  - couplings to the first two generation quarks
  - no CP violating couplings
- can be used to search for the NP

CPV and FV Higgs couplings to SM fermions

- if SM an EFT, the Yukawas get corrected by higher dim. ops

$$\mathcal{L}_{SM} = -\left[\lambda_{ij}(\bar{f}_L^i f_R^j)H + h.c.\right]$$

$$\Delta\mathcal{L}_Y = -\frac{\lambda'_{ij}}{\Lambda^2}(\bar{f}_L^i f_R^j)H(H^\dagger H) + h.c. + \cdots$$

  - decouples mass terms from yukawas

$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}(\bar{f}_L^i f_R^j)h + h.c. + \cdots ,$$

  - can lead to flavor violating Higgs decays
  - can lead to CPV Higgs decays

- different models lead to different patterns of flavor diagonal and flavor violating Yukawas

SUMMARY OF MODELS

- an example: higgs couplings to 2nd&3rd gen. charged leptons

adapted from Dery, Efrati, Hochberg, Nir, 1302.3229 and extended

Model	$\hat{\mu}_{\tau\tau}$	$(\hat{\mu}_{\mu\mu}/\hat{\mu}_{\tau\tau})/(m_\mu^2/m_\tau^2)$	$\hat{\mu}_{\mu\tau}/\hat{\mu}_{\tau\tau}$
SM	1	1	0
NFC	$(V_{h\ell}^* v/v_\ell)^2$	1	0
MSSM	$(\sin\alpha/\cos\beta)^2$	1	0
MFV	$1+2av^2/\Lambda^2$	$1-4bm_\tau^2/\Lambda^2$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\lvert U_{23}\rvert^2 v^4/\Lambda^4)$
GL	9	25/9	$\mathcal{O}(\hat{\mu}_{\mu\mu}/\hat{\mu}_{\tau\tau})$
RS (i)	$1+\mathcal{O}(\bar{Y}^2v^2/m_{KK}^2)$	$1+\mathcal{O}(\bar{Y}^2v^2/m_{KK}^2)$	$\mathcal{O}(\bar{Y}^2v^2/m_{KK}^2)\sqrt{m_\tau/m_\mu}$
RS (ii)	$1+\mathcal{O}(\bar{Y}^2v^2/m_{KK}^2)$	$1+\mathcal{O}(\bar{Y}^2v^2/m_{KK}^2)$	$\mathcal{O}(\bar{Y}^2v^2/m_{KK}^2)$
PGB (1 rep.)	$1-v^2/f^2$	1	0

Flavor violating Higgs couplings

A GENERAL BENCHMARK

- what is a reasonable aim for precision on Y_{ij}?
  - if off-diagonals are large ⇒ spectrum in general not hierarchical
  - no tuning, if

$$|Y_{\tau\mu}Y_{\mu\tau}| \lesssim \frac{m_\mu m_\tau}{v^2}$$

Cheng, Sher, 1987

  - in concrete models it will be typically further suppressed parametrically

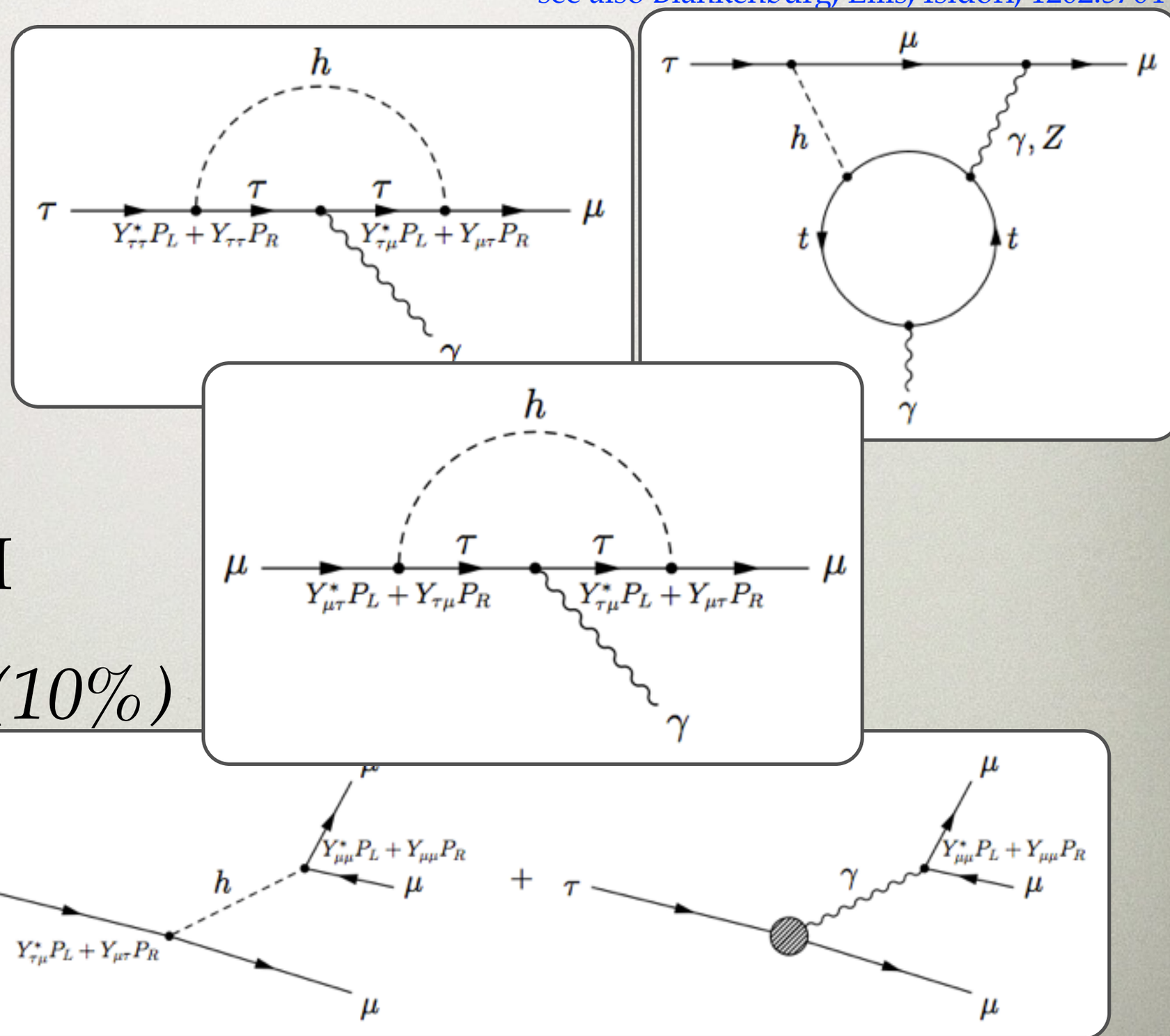
see e.g, Dery, Efrati, Nir, Soreq, Susic, 1408.1371; Dery, Efrati, Hochberg, Nir, 1302.3229; Arhrib, Cheng, Kong, 1208.4669

$h \to \tau\mu$

Harnik, Kopp, JZ, 1209.1397

see also Blankenburg, Ellis, Isidori, 1202.5704

- bounds from
  - $\tau \to \mu\gamma$
  - $\tau \to 3\mu$
  - muon g-2
  - muon EDM
- $Br(h \to \tau\mu) \sim O(10\%)$ allowed



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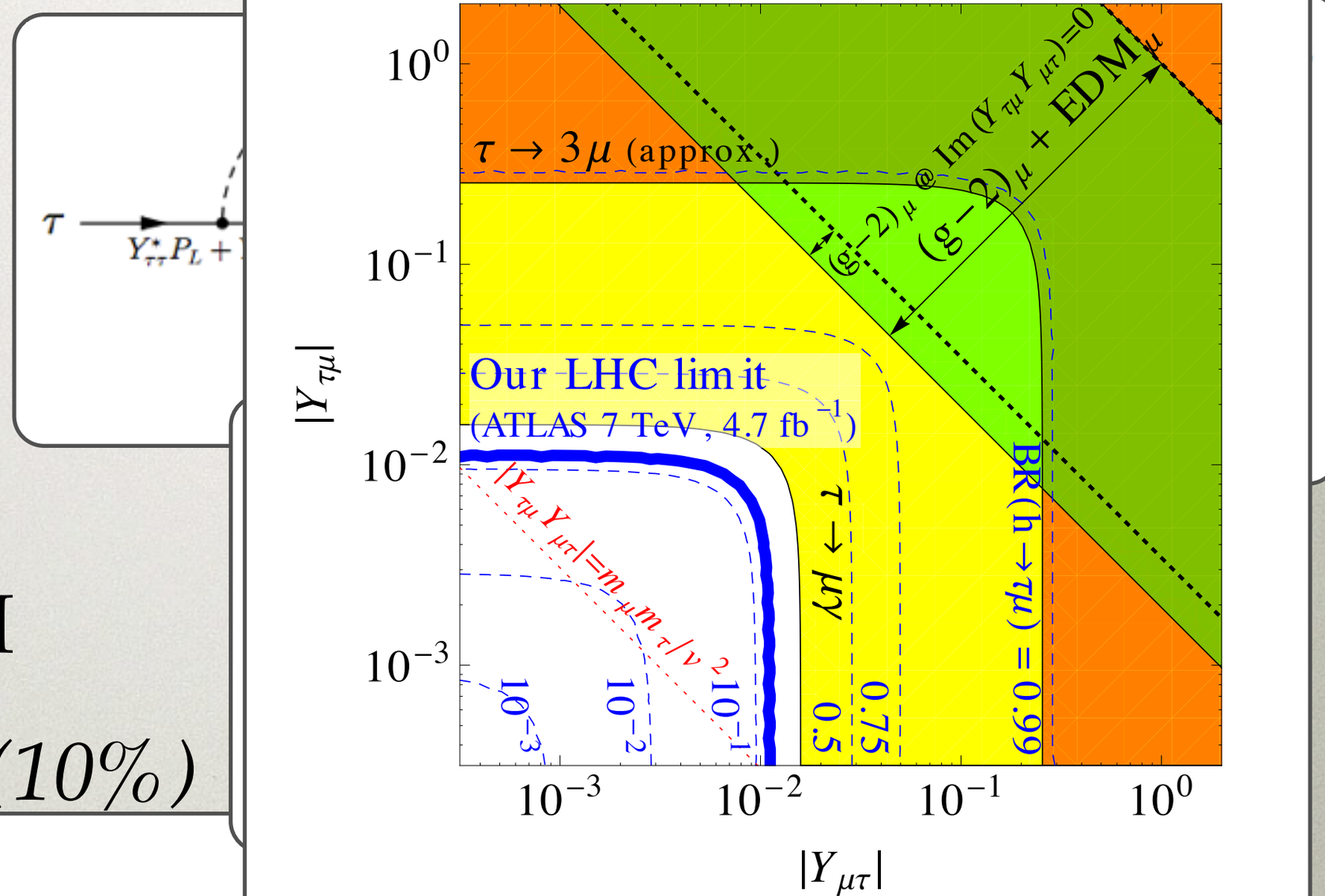
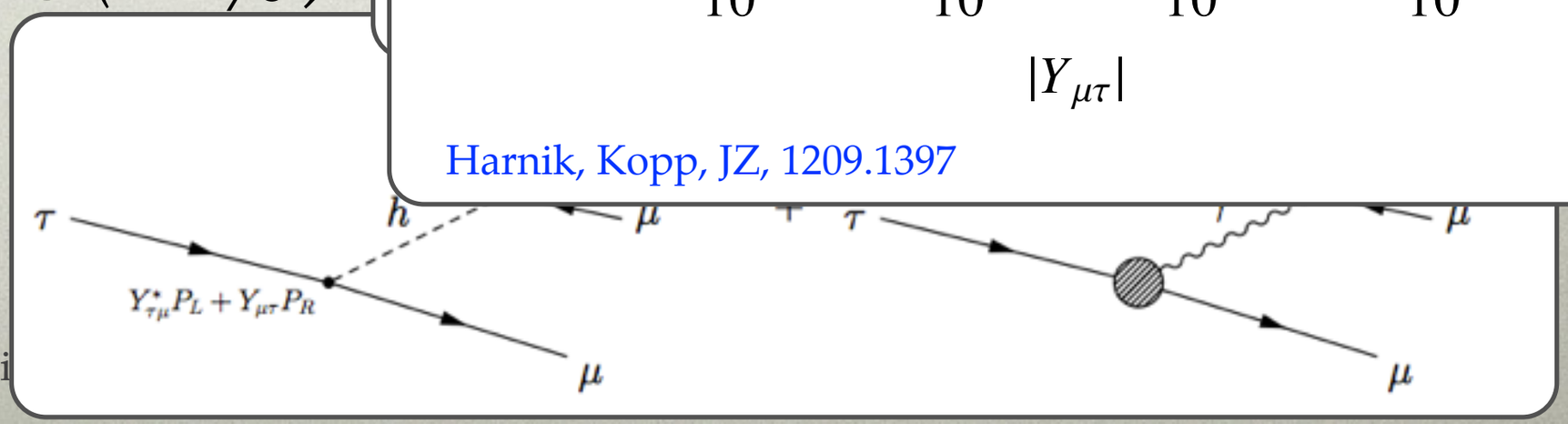


Harnik, Kopp, JZ, 1209.1397



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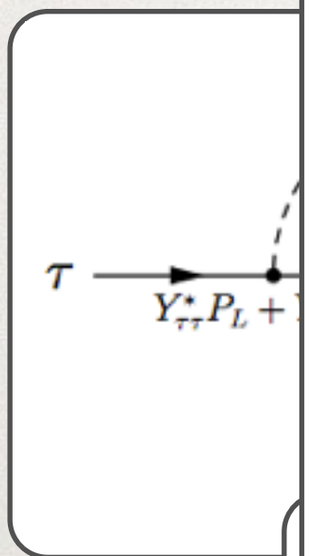

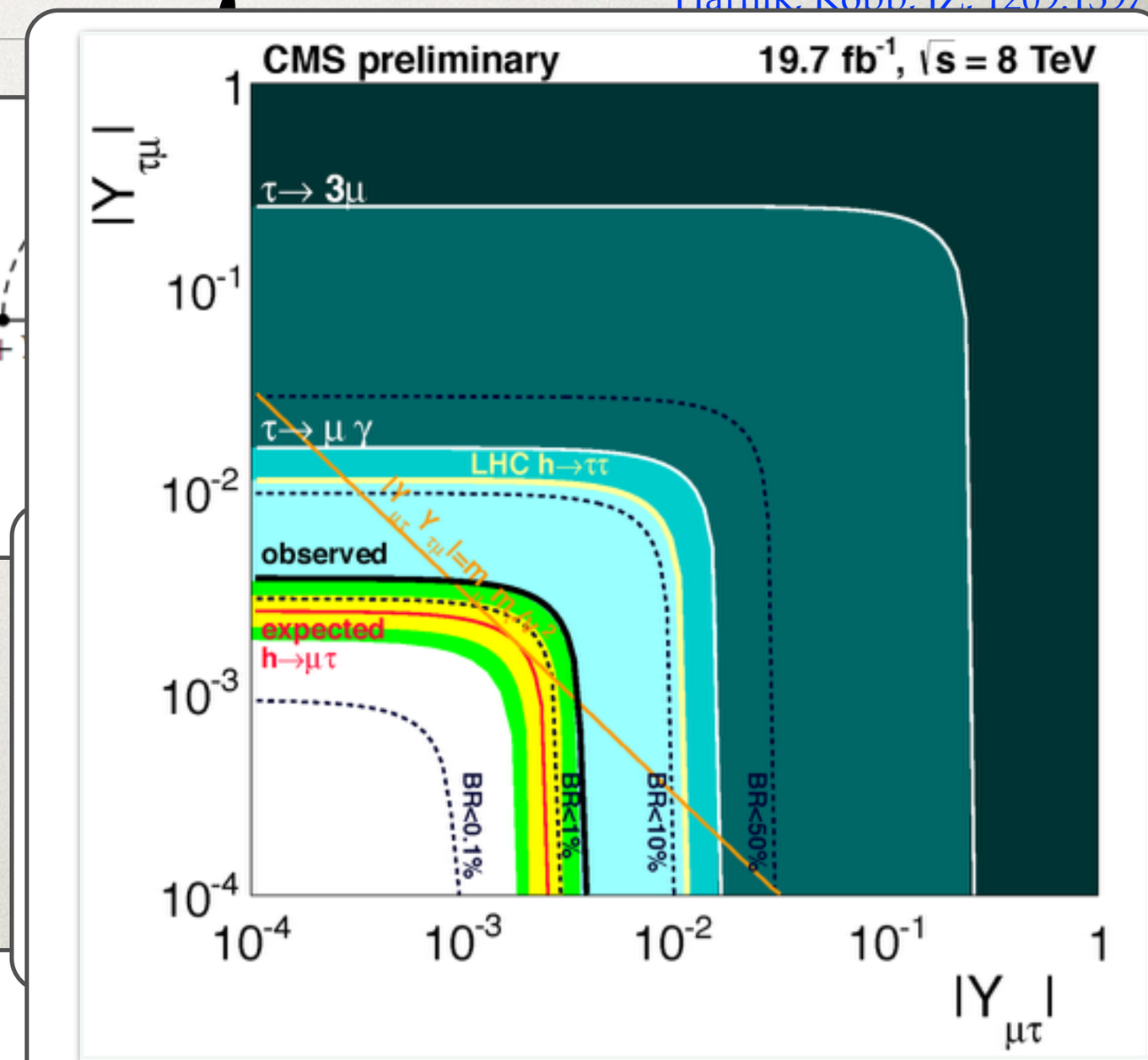

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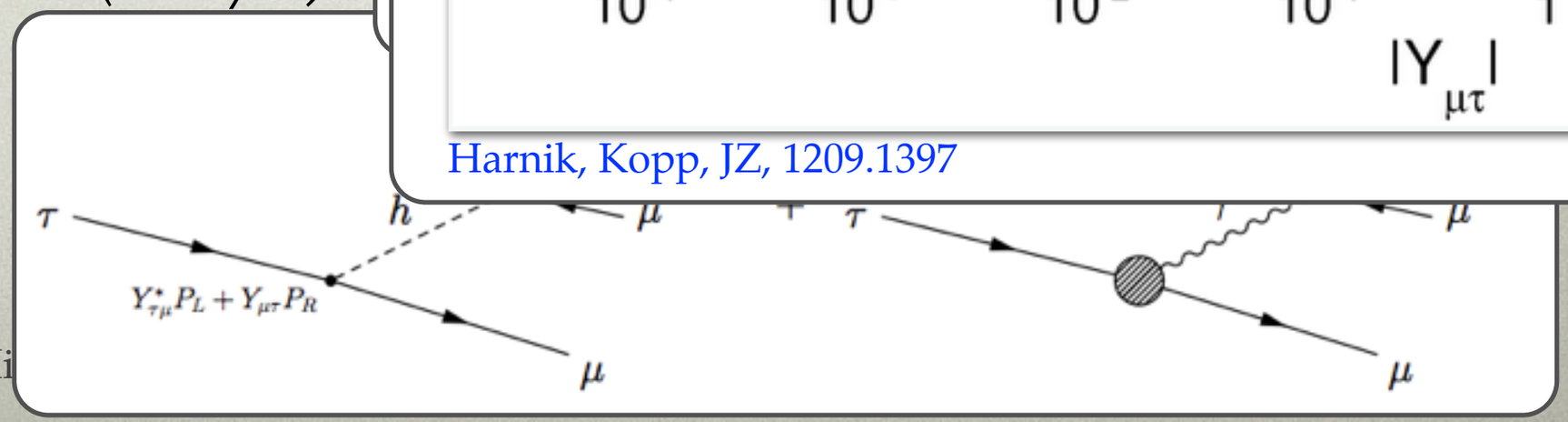
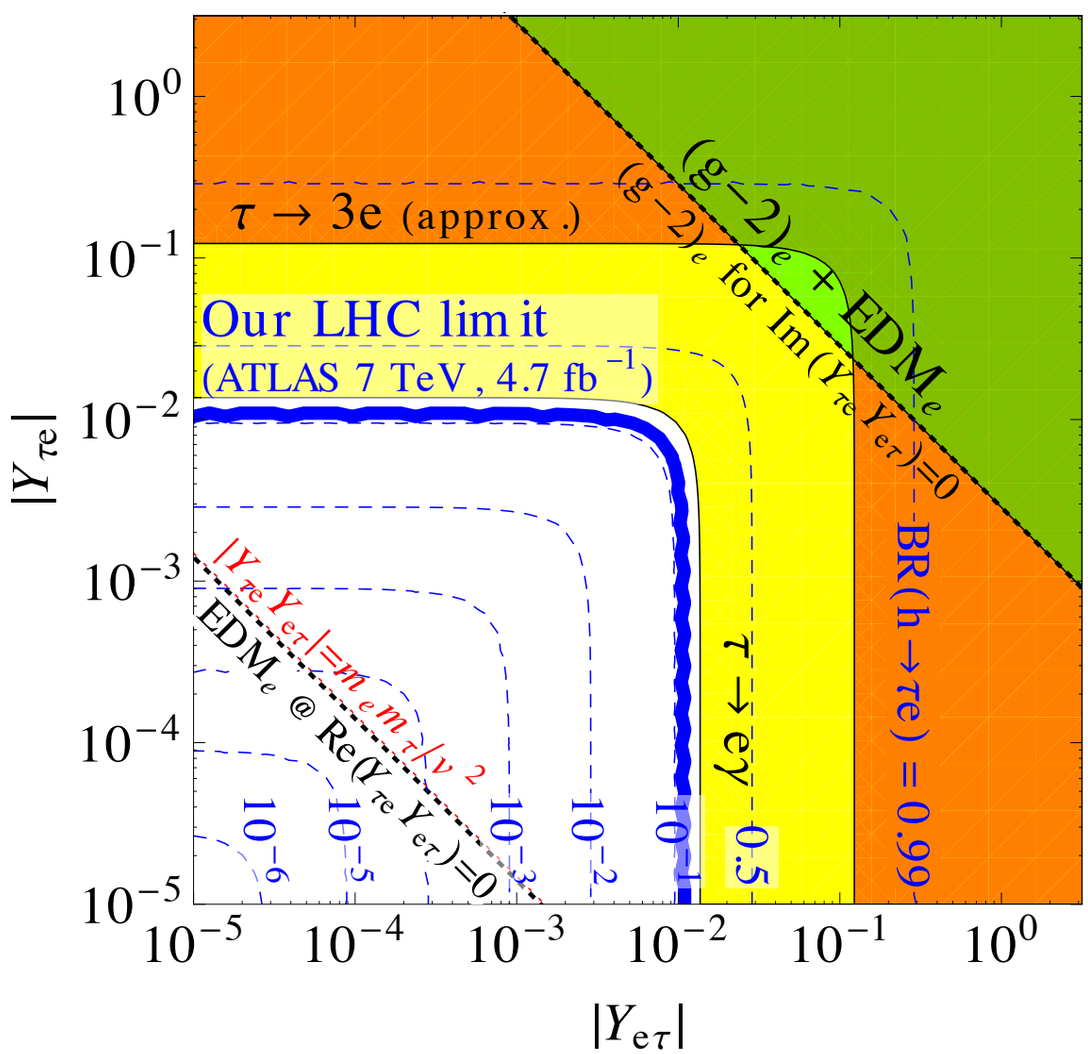


$h \to \tau e$ and $h \to \mu e$



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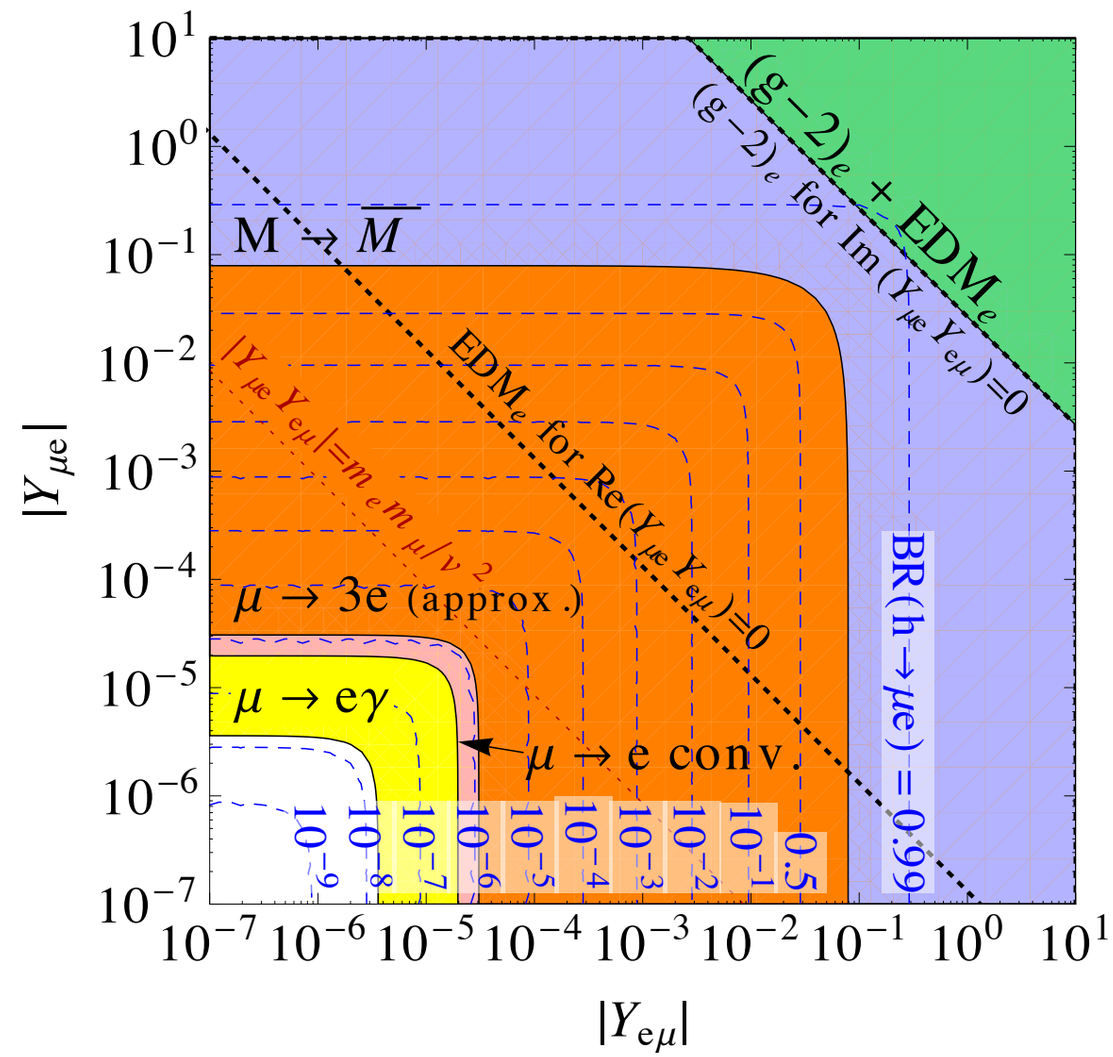
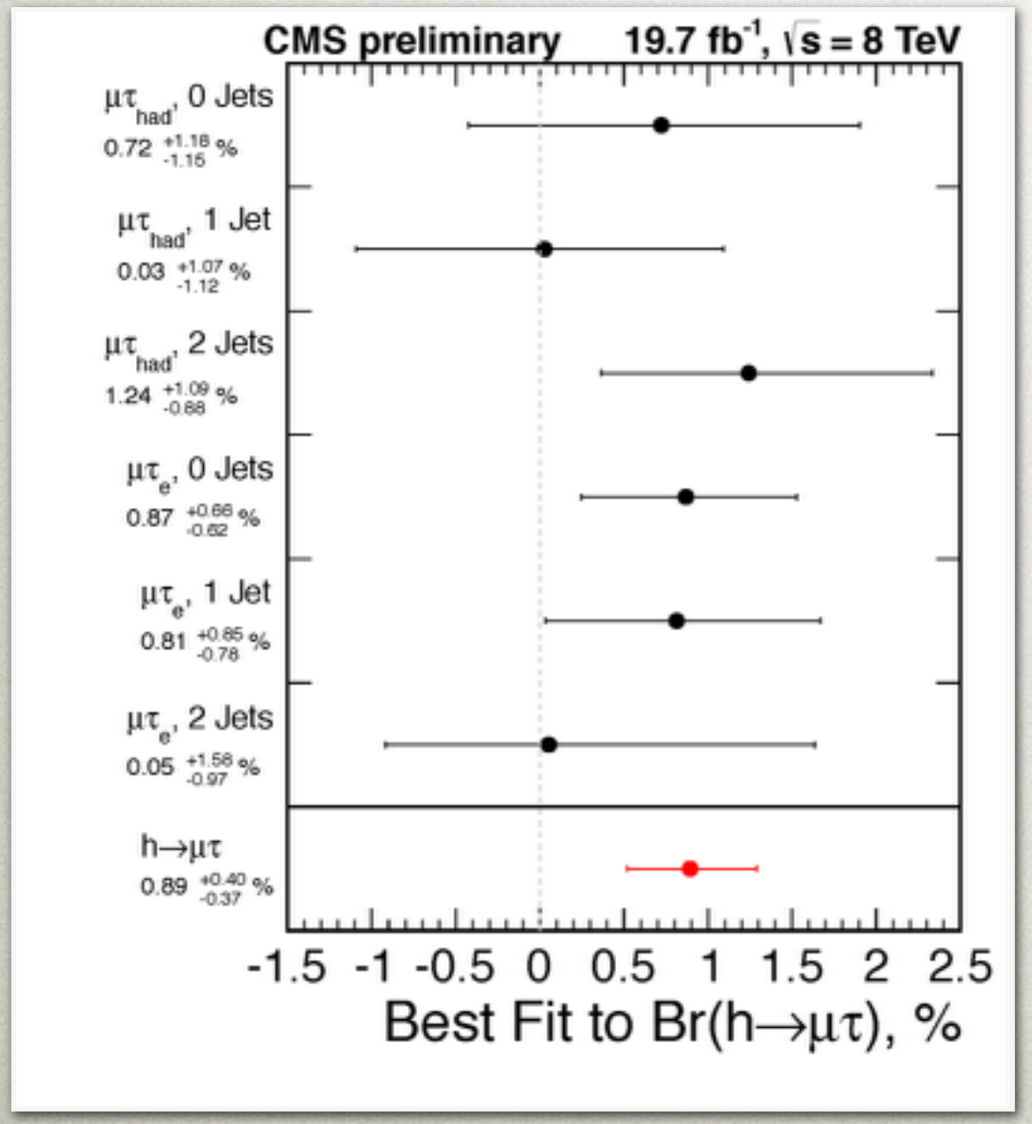


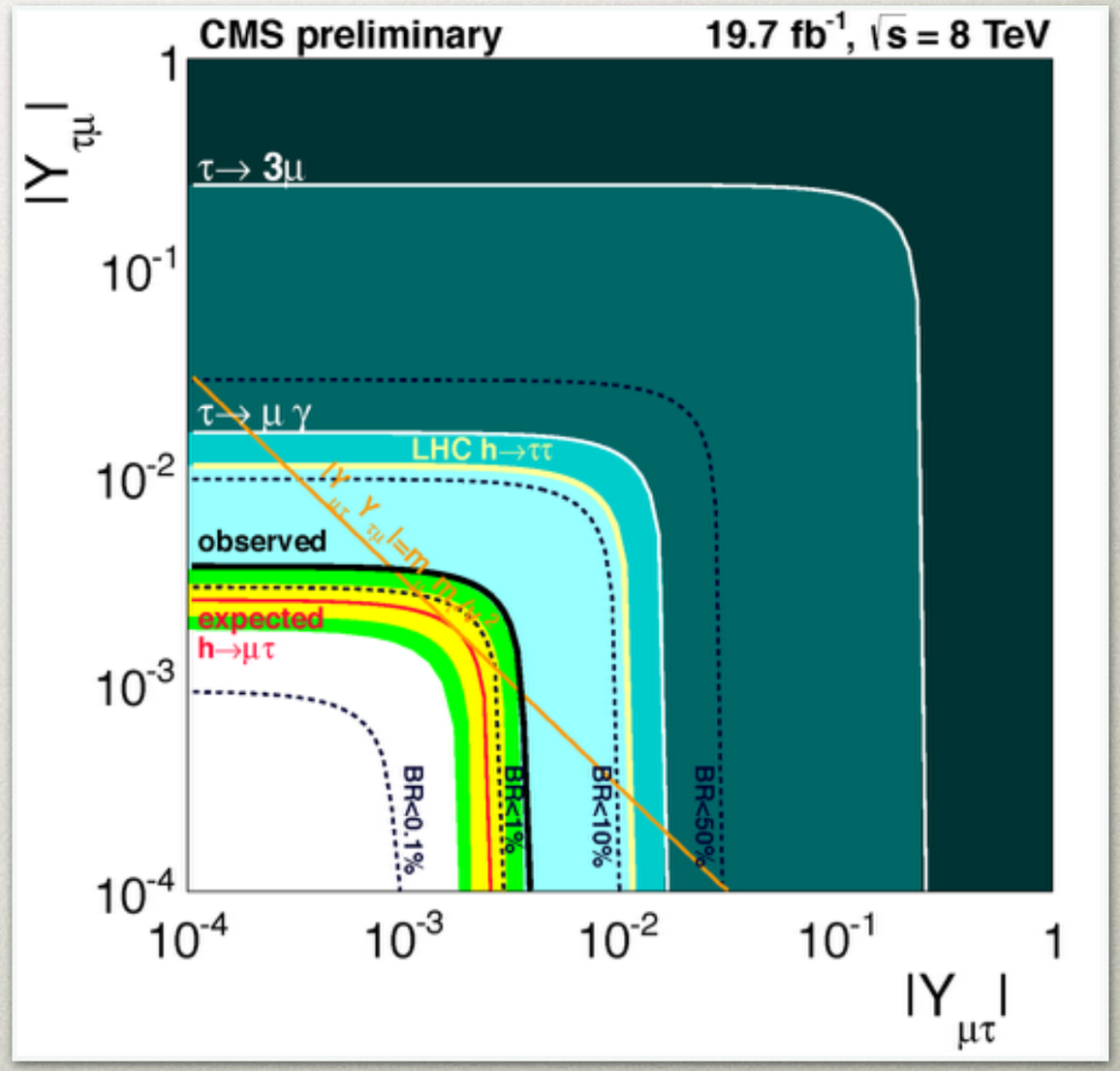
Harnik, Kopp, JZ, 1209.1397

$h \to \tau\mu$ from CMS

CMS-HIG-14-005

- hint of a signal in $h \to \tau\mu$?

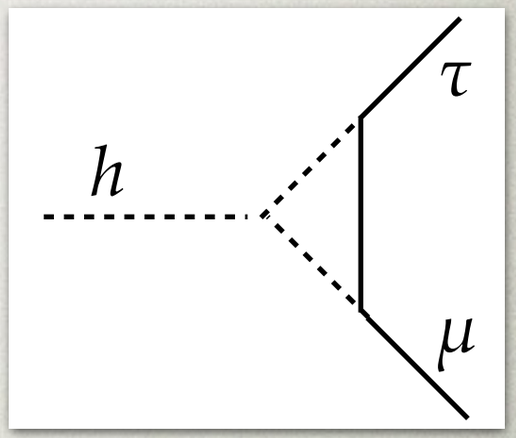




NEW PHYSICS INTERPRETATION

Dorsner et al, 1502.07784

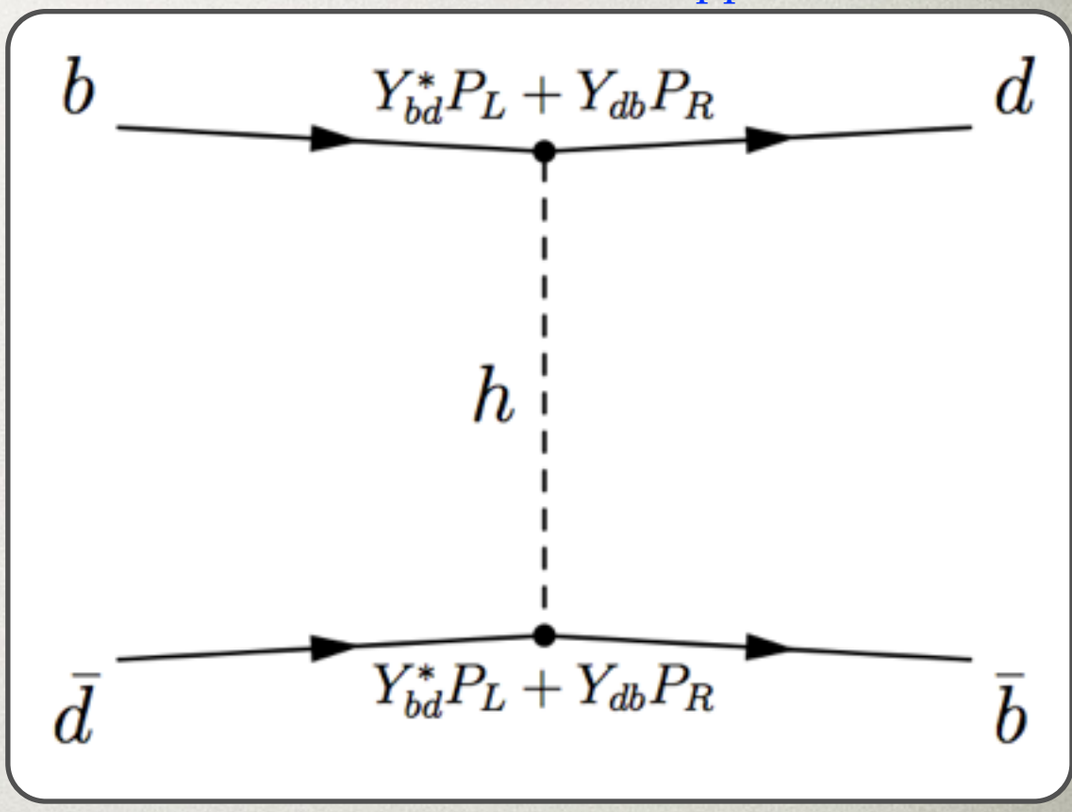
- if real, what type of NP?
- if $h \to \tau\mu$ due to 1-loop correction
  - extra charged particles necessary
  - $\tau \to \mu\gamma$ typically too large



- $h \to \tau\mu$ possible to explain if extra scalar doublet
  - 2HDM of type III
  - slightly above Cheng-Sher naturalness criterion

QUARK COUPLINGS

Harnik, Kopp, JZ, 1209.1397



- constraints from
  - D, B, B_s,K oscillations
  - bounds on Y_{uc}, Y_{uc}, Y_{db}, Y_{bd}, Y_{sb}, Y_{bs}, Y_{sd}, Y_{ds}
  - strong constraints
  - O(0.1)-O(0.01) of Cheng-Sher ansatz
- improvements on these couplings will come from exp&theory improvements in meson mixing

QUARK C

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  - D, B, B_s, K oscillations
  - bounds on Y_{uc}, Y_{uc}, Y_{db}, Y_{bd}, Y_{sb}, Y_{bs}, Y_{sd}, Y_{ds}
  - strong constraints
  - O(0.1)-O(0.01) of Cheng
- improvements on these couplings will come from exp&theory improvements in meson mixing

Technique	Coupling	Constraint
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2$, $\lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$
	$\lvert Y_{uc}Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2$, $\lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$
	$\lvert Y_{db}Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2$, $\lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$
	$\lvert Y_{sb}Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2)$, $\mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$
	$\mathrm{Im}(Y_{ds}^2)$, $\mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$
single-top production [49]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 3.7
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 1.6
$t \to hj$ [50]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	<0.10
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	<0.10
D^0 oscillations [48]	$\lvert Y_{ut}Y_{ct}\rvert$, $\lvert Y_{tu}Y_{tc}\rvert$	$< 7.6 \times 10^{-3}$
	$\lvert Y_{tu}Y_{ct}\rvert$, $\lvert Y_{ut}Y_{tc}\rvert$	$< 2.2 \times 10^{-3}$
	$\lvert Y_{ut}Y_{tu}Y_{ct}Y_{tc}\rvert^{1/2}$	$< 0.9 \times 10^{-3}$
neutron EDM [37]	$\mathrm{Im}(Y_{ut}Y_{tu})$	$< 4.4 \times 10^{-8}$

HIG-13-034

CPV in Higgs couplings

CPV Higgs couplings

- couplings of Higgs to other SM fields can be CPV
- CPV for Higgs couplings to gauge bosons from on shell production

  F. Bishara, Y. Grossman, R. Harnik, D. Robinson, J. Shu, JZ, 1312.2955

  - e.g., $h \to \gamma\gamma$ potentially from Bethe-Heitler photon conversion, or from $h \to \gamma\gamma \to 4l$ (this also CPV in $h \to ZZ$)

    Chen, Roni Harnik, Roberto Vega-Morales, 1404.1336

  - CPV in $h \to gg$ from $h+2j$ production

    Anderson et al., 1309.4819
    Delaunay, Perez, de Sandes, Skiba, 1308.4930

  - CPV in $h \to WW$ from hW associated production
- focus on CP violating Higgs couplings to fermions

  Brod, Haisch, JZ, 1310.1385

  - the notation

$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}} \left(\kappa_f \, \bar{f} f + i \tilde{\kappa}_f \, \bar{f} \gamma_5 f \right) h$$

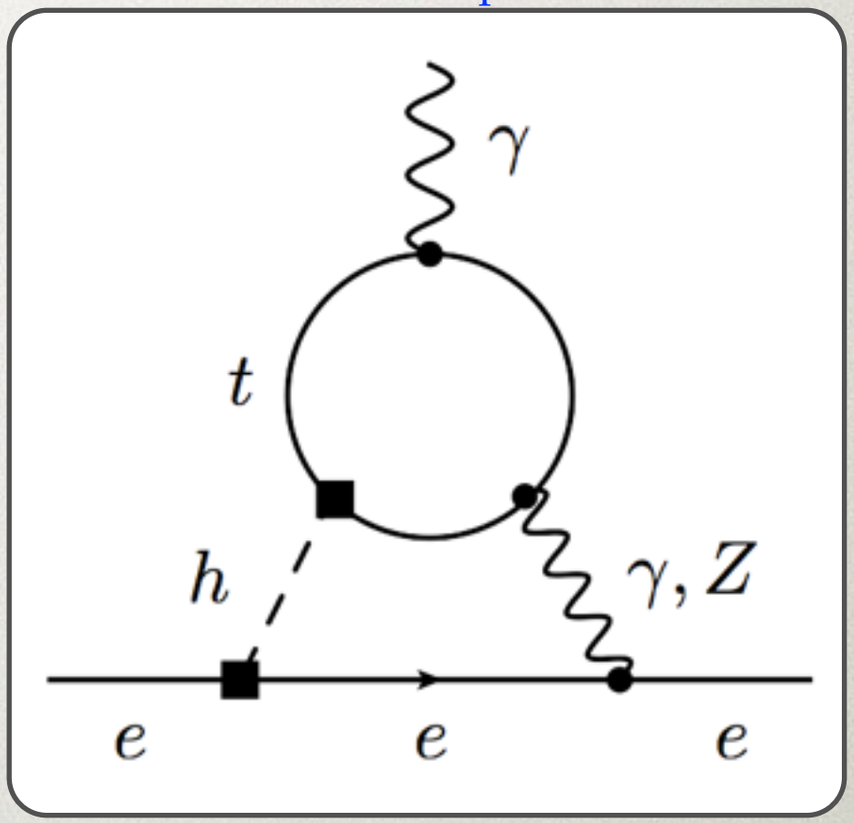
- can probe CPV couplings to 3rd generation, so $f=t,b,\tau$

HIGGS-TOP CPV COUPLING

Brod, Haisch, JZ, 1310.1385, updated to ACME 1310.7534

- electron EDM: dominant contribution from 2-loop Barr-Zee type diagram

$$\mathcal{L}_{\text{eff}} = -d_e \frac{i}{2} \bar{e} \sigma^{\mu\nu} \gamma_5 e F_{\mu\nu}$$



- depends on electron yukawa
  - setting $y_e=1$ is then quite constraining

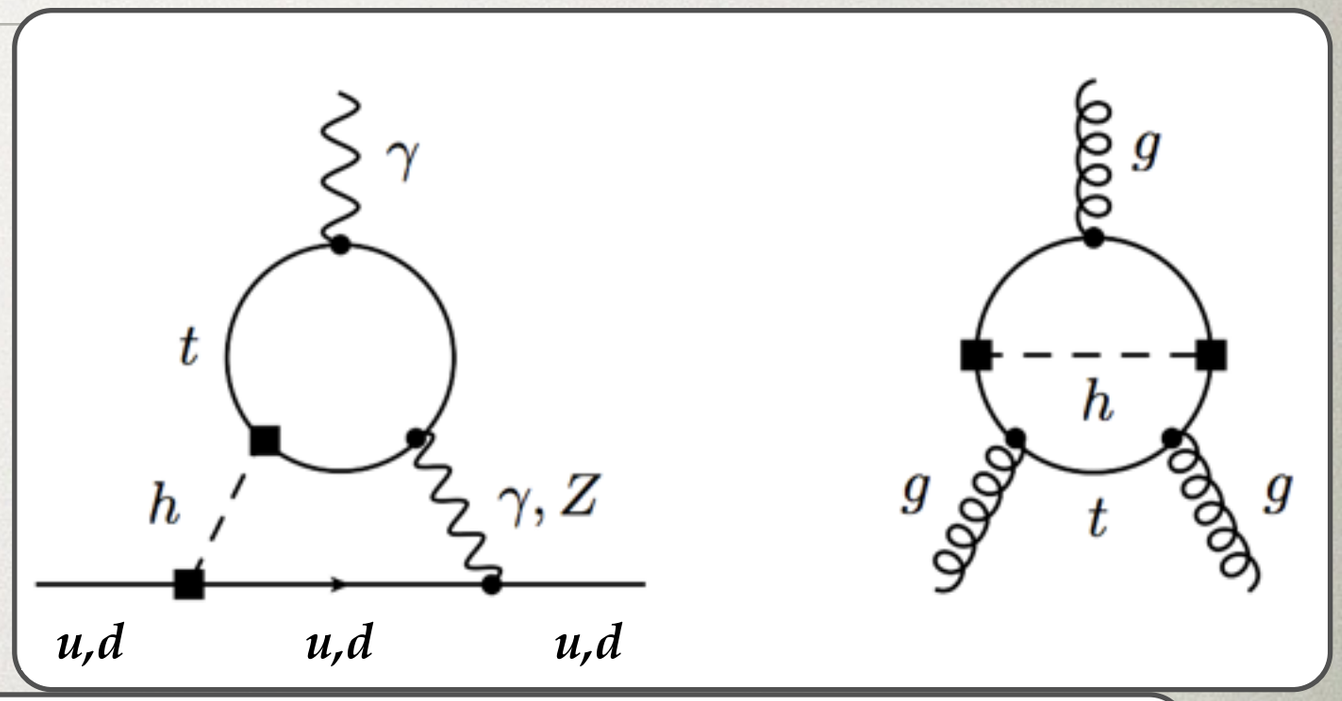
$$|\tilde{\kappa}_t| < 0.01$$

  - the constraint vanishes, if the Higgs does not couple to electrons
- if it only couples to the 3rd gen. still a constraint from neutron EDM
  - relevant in the future (at a permit level), now ~O(1) allowed

NEUTRON AND MERCURY EDM

Brod, Haisch, JZ, 1310.1385

- neutron and Hg EDM also dominated by Barr-Zee type diagrams (SM-like couplngs. of the Higgs to light quarks)



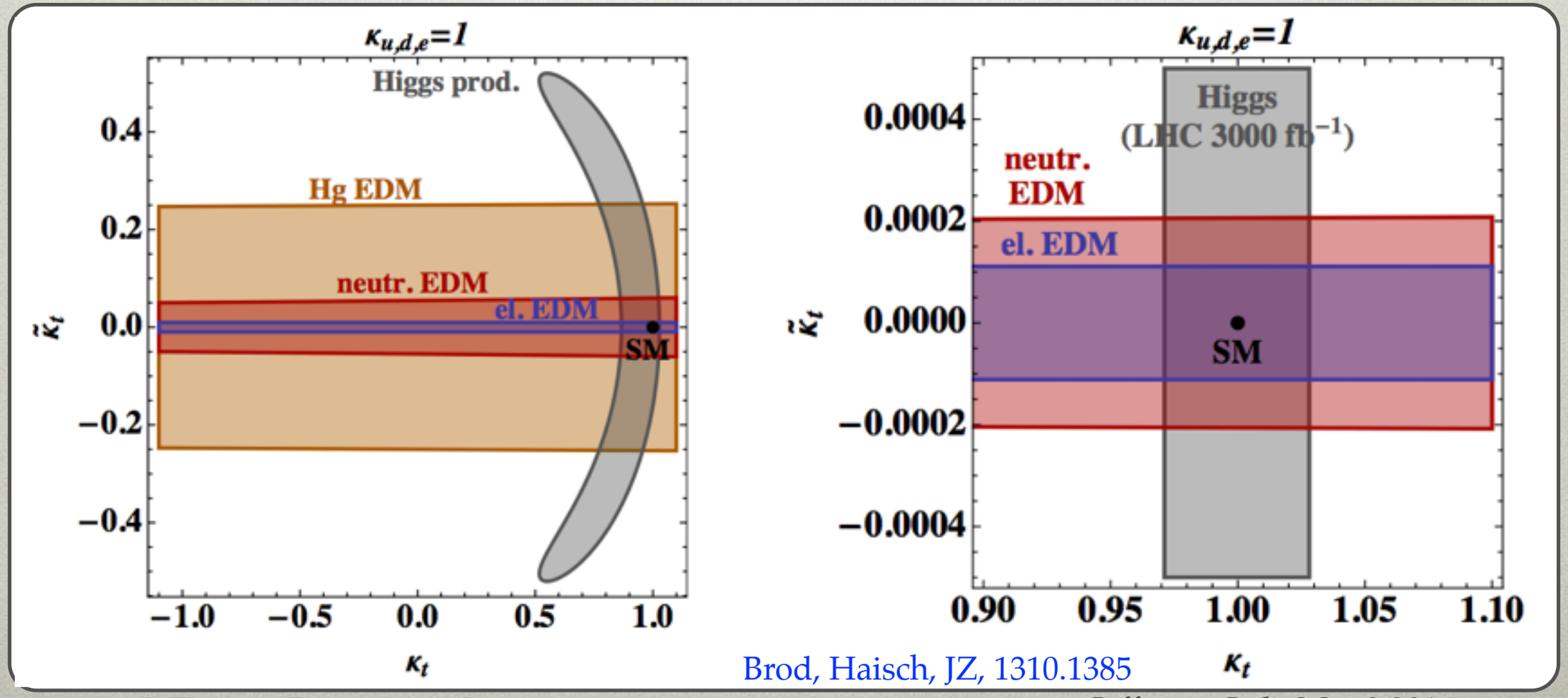
$$\mathcal{L}_{\rm eff} = -d_q \frac{i}{2} \bar{q}\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu} - \tilde{d}_q \frac{i g_s}{2} \bar{q}\sigma^{\mu\nu} T^a \gamma_5 q\, G^a_{\mu\nu} - w \frac{1}{3} f^{abc} G^a_{\mu\sigma} G^{b,\sigma}_{\nu} \widetilde{G}^{c,\mu\nu}$$

- an important difference: at 2-loop also Weinberg operator is generated
  - is nonzero even, if CPV <u>is only</u> in the Higgs couplings to the 3rd gen. quarks!

CPV coupling to top

Brod, Haisch, JZ, 1310.1385

- comparing with the LHC reach
  - assuming that no CPV measurements at the LHC
- for 1st gen. Yukawas **equal to the SM**

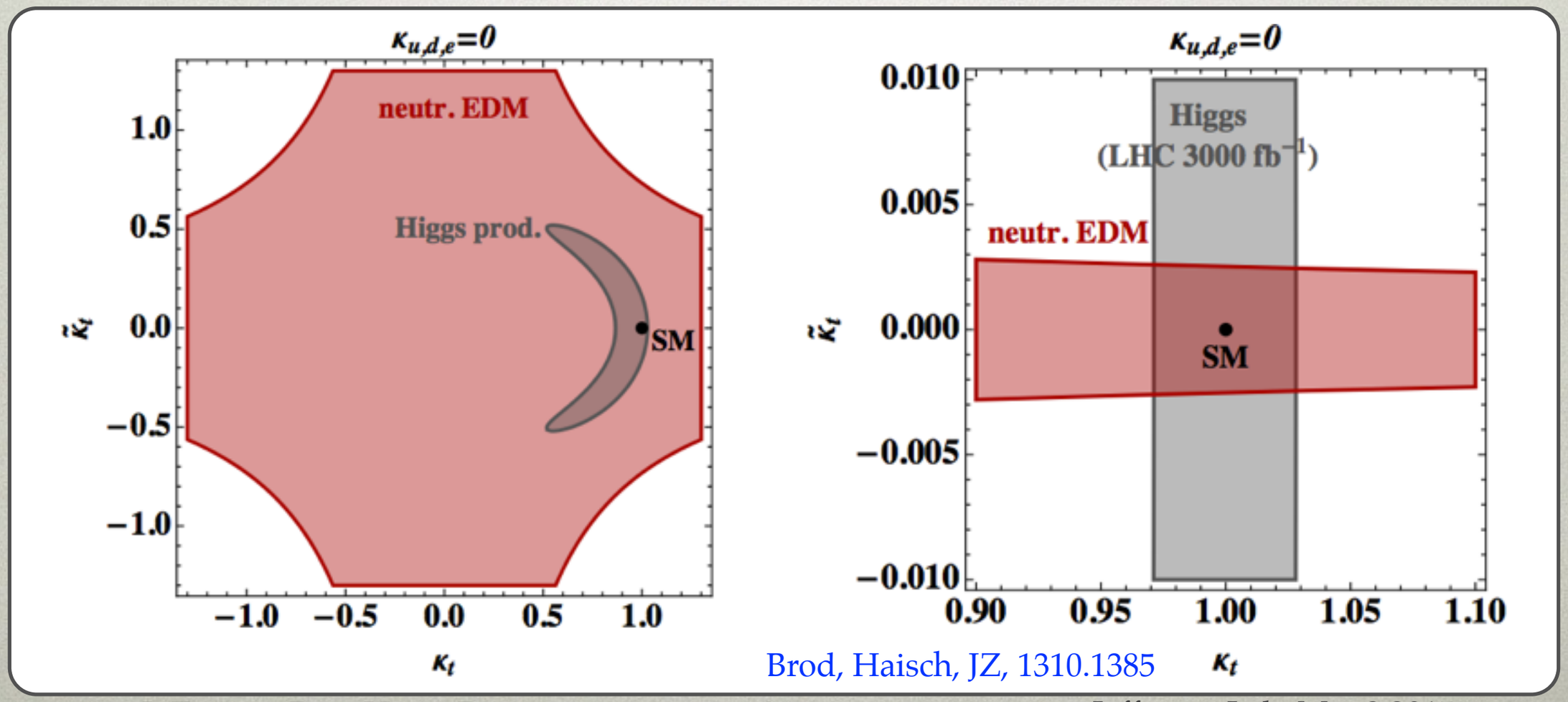


Brod, Haisch, JZ, 1310.1385

CPV coupling to top

Brod, Haisch, JZ, 1310.1385

- comparing with the LHC reach
  - assuming that no CPV measurements at the LHC
- 1st gen. Yukawas **set to zero**



Brod, Haisch, JZ, 1310.1385

ON SHELL SEARCHES

Ellis, Hwang, Sakurai, Takeuchi, 1312.5736
Harnik, Martin, Okui, Primulando, 1308.1094

- CPV couplings $h\bar{t}t$ and $h\bar{\tau}\tau$ can be searched for on-shell

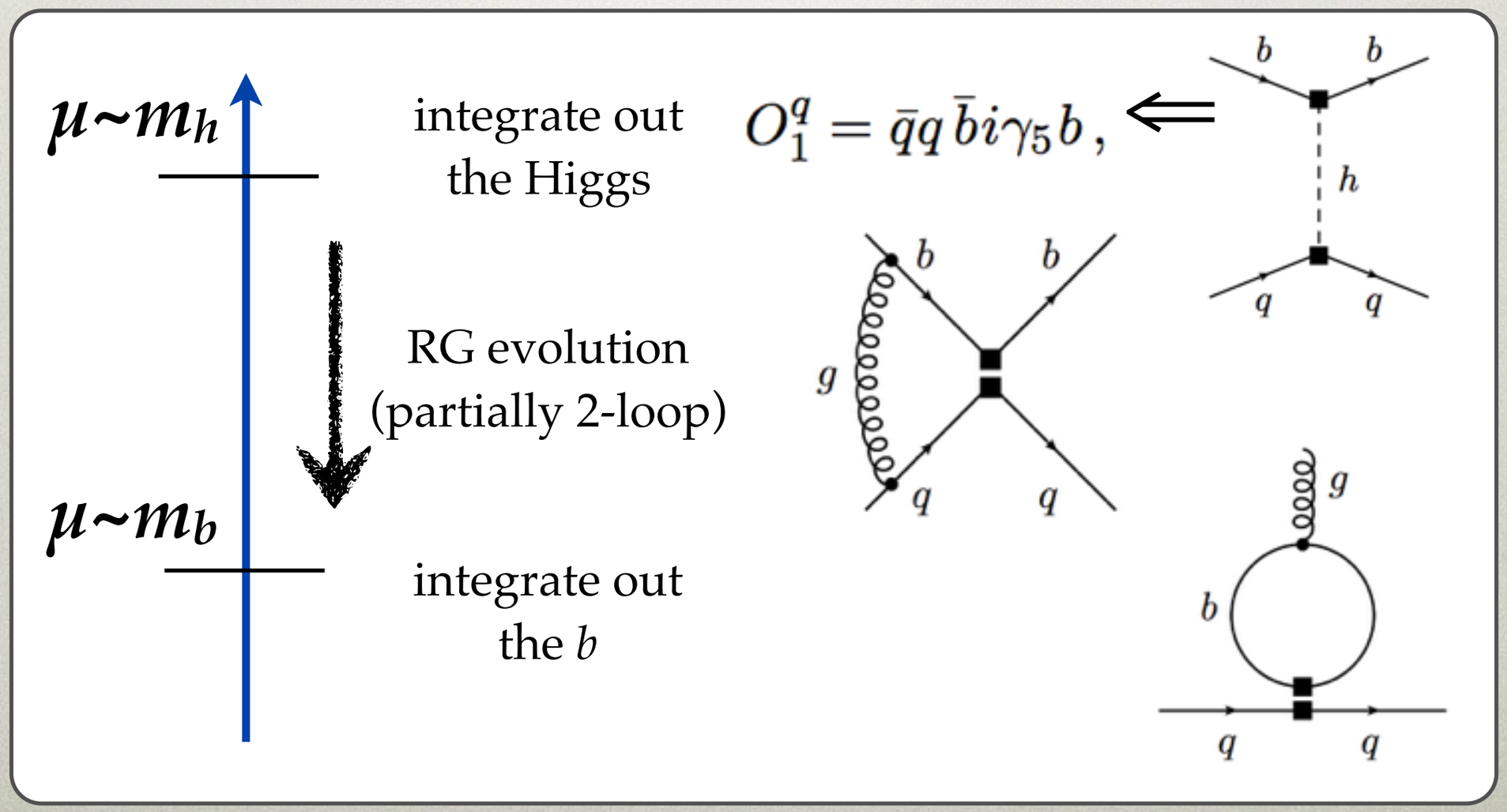
Galanti, Giammanco, Grossman, Kats, Stamou, JZ, to appear

- CPV $h\bar{b}b$ very hard to probe on shell
  - in principles possible through Λ_b polarization in the jet
  - however requires large statistics
  - off-shell thus probably the only probe

CPV coupling to b quark

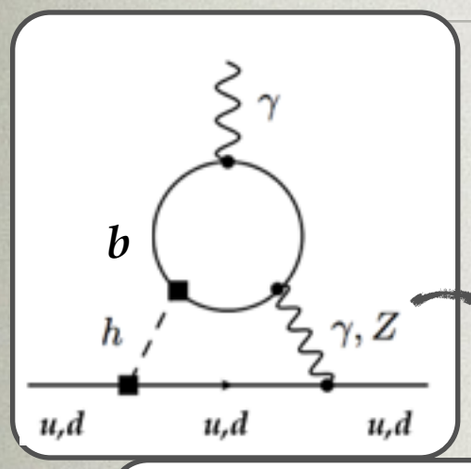
Brod, Haisch, JZ, 1310.1385

- now have an extra scale $m_b \ll m_h$
  - need to re-sum $\alpha_s log(x_{b/h})$ (here $x_{b/h}=m_b^2/m_h^2$)



RESUMMATION

Brod, Haisch, JZ, 1310.1385



- only one relevant entry of anomalous dimension not known previously, $\gamma_{5,11}^{(1)}$

$$O_5^q = -\frac{i}{2} e Q_b \frac{m_b}{g_s^2} \bar{q}\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu}\,,$$

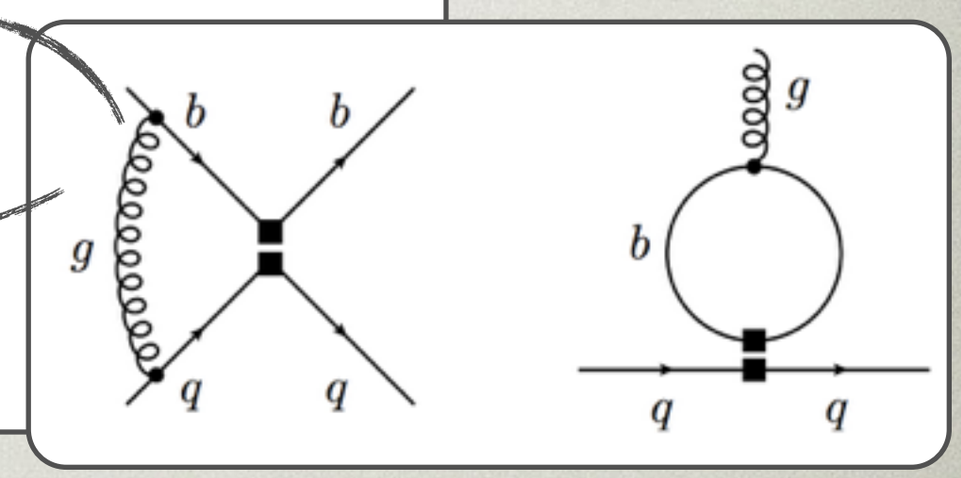
$$O_6^q = -\frac{i}{2} \frac{m_b}{g_s} \bar{q}\sigma^{\mu\nu} T^a \gamma_5 q\, G^a_{\mu\nu}\,,$$

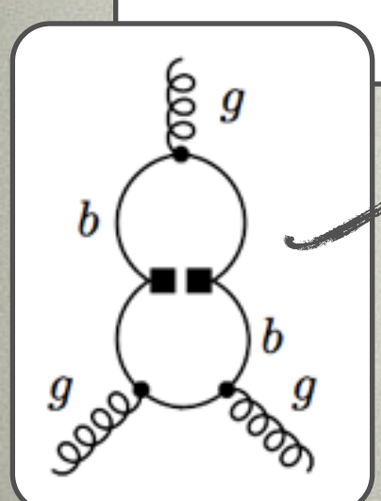
$$O_7 = -\frac{1}{3g_s} f^{abc} G^a_{\mu\sigma} G^{b,\sigma}_{\nu} \widetilde{G}^{c,\mu\nu}\,,$$

$$C_5^q(\mu_b) \simeq -4\,\frac{\alpha\alpha_s}{(4\pi)^2} Q_q \ln^2 x_{b/h} + \left(\frac{\alpha_s}{4\pi}\right)^3 \frac{\gamma_{14}^{(0)}\gamma_{48}^{(0)}\gamma_{87}^{(0)}}{48} \ln^3 x_{b/h} + \mathcal{O}(\alpha_s^4)$$

$$C_6^q(\mu_b) \simeq \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\gamma_{14}^{(0)}\gamma_{48}^{(0)}}{8} \ln^2 x_{b/h} + \mathcal{O}(\alpha_s^3)$$

$$C_7(\mu_b) \simeq \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\gamma_{5,11}^{(1)}}{2} \ln x_{b/h} + \mathcal{O}(\alpha_s^3)$$





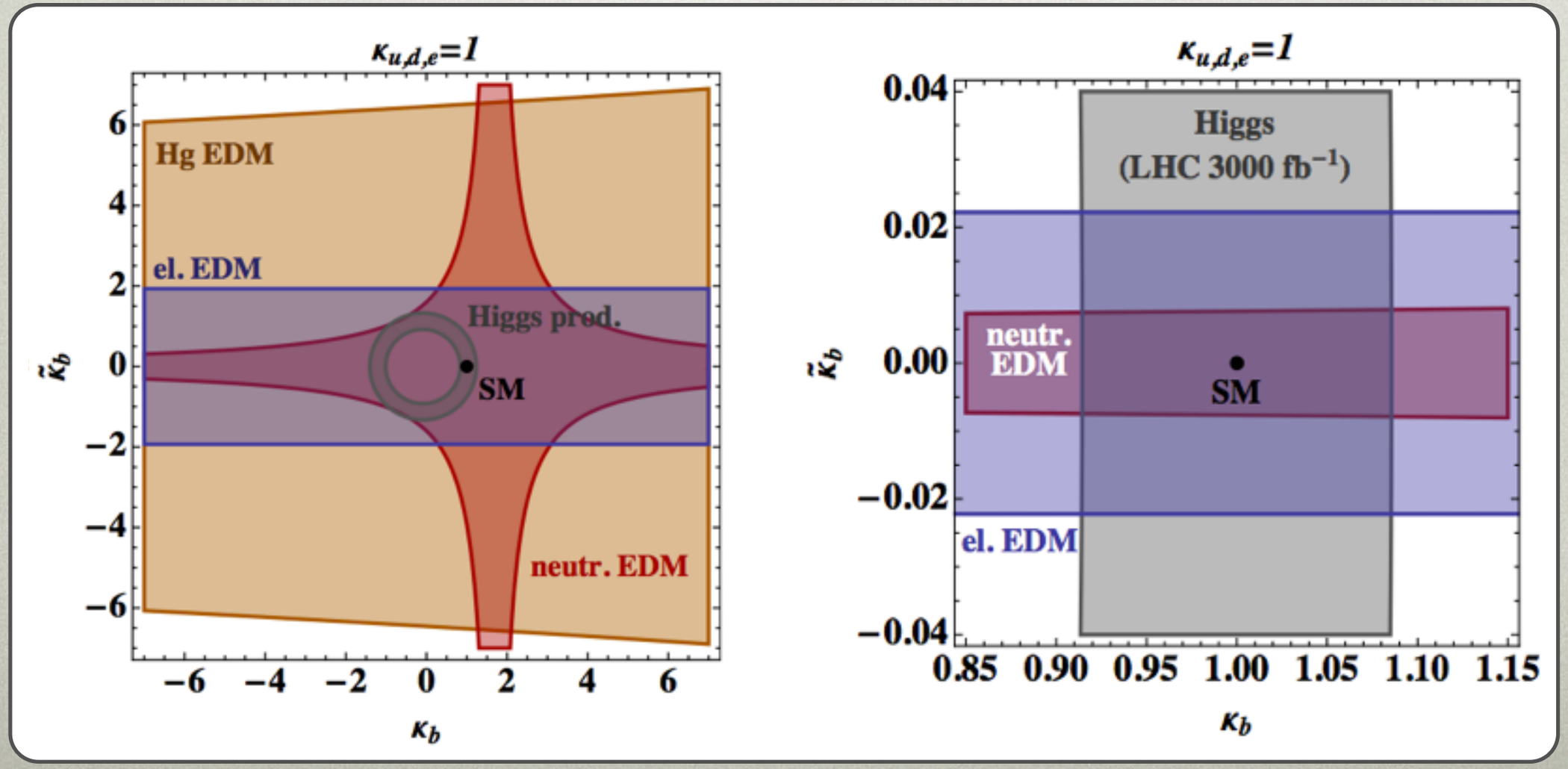
- resummation numerically important
  - without it a factor of ~3 ambiguity in nEDM

CPV coupling to b quark

- the EDM constraints on CPV Higgs coupling to b quark are weaker than the LHC data

Brod, Haisch, JZ, 1310.1385

  - this can change in the future
  - EDMs scale linearly with $\tilde{\kappa}_b$



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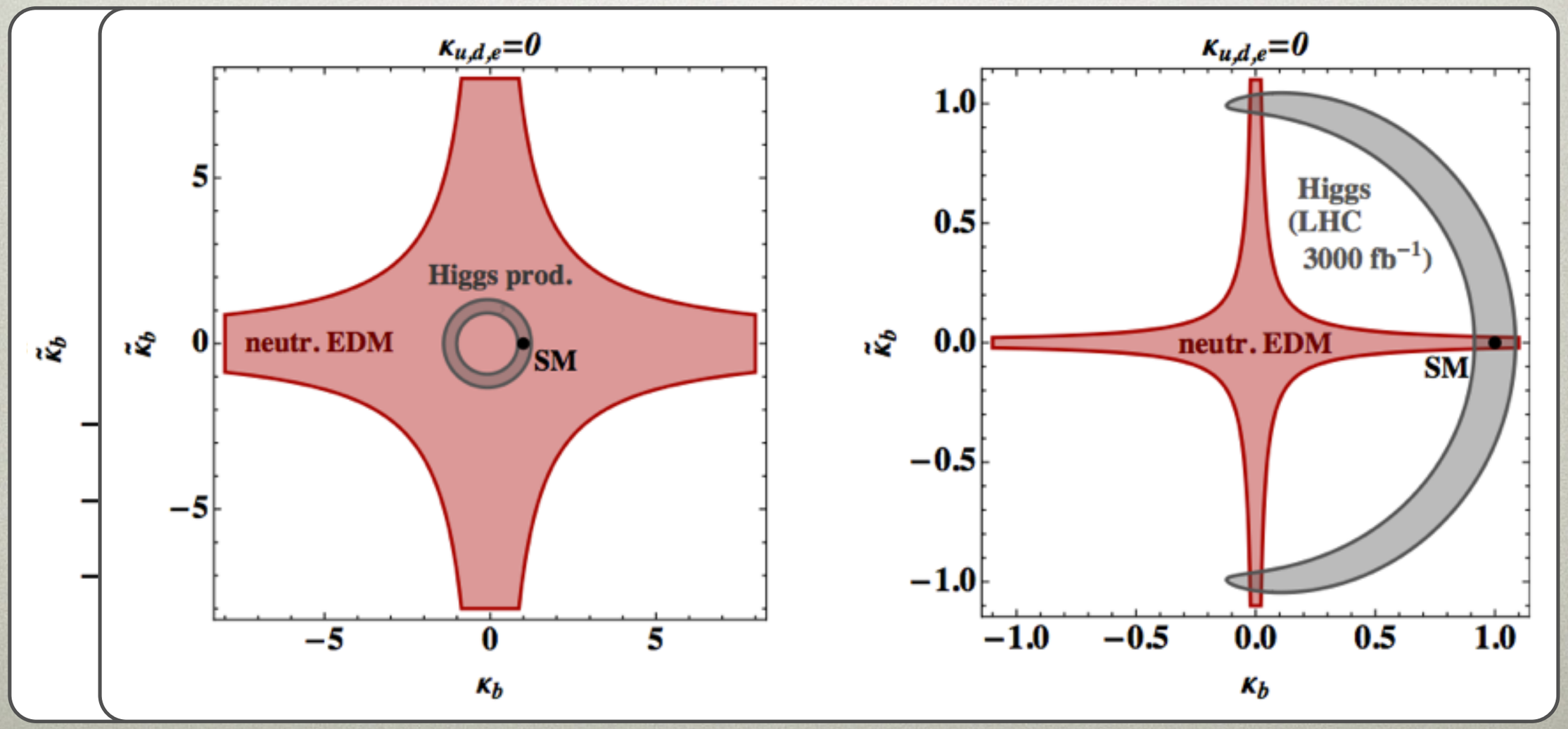


HIGGS COUPLINGS TO LIGHT FERMIONS

BOUNDS ON LIGHT QUARK YUKAWAS

Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722

- the higgs couplings to light quarks assumed to be negligible in the global fits (as in the SM)
- varying $\kappa_u, \kappa_d, \kappa_s$
  - total width modified
  - sublead.: $gg \to h$, $h \to \gamma\gamma$ modified, $u\bar{u} \to h$, $d\bar{d} \to h$, $s\bar{s} \to h$ prod.
- varying only one at the time (95%CL, and normalized to $y_{b,SM}$)

$$|\bar{\kappa}_u| < 0.98\,, \quad |\bar{\kappa}_d| < 0.93\,, \quad |\bar{\kappa}_s| < 0.70$$

- varying all of the higgs couplings

$$|\bar{\kappa}_u| < 1.3\,, \quad |\bar{\kappa}_d| < 1.4\,, \quad |\bar{\kappa}_s| < 1.4$$

- for FV Yukawas (varying only one at the time)

$$|\bar{\kappa}_{qq'}| < 0.6\,(1) \qquad \text{for } q, q' \in u, d, s, c, b \text{ and } q \neq q'$$

  - from FCNCs stronger (model dep.) constr, e.g., $|\bar{\kappa}_{bs}| < 8 \cdot 10^{-2}$

Harnik, Kopp, JZ, 1209.1397; see also Blankenburg, Ellis, Isidori, 1202.5704; Goertz, 1406.0102

PROBING LIGHT YUKAWAS?

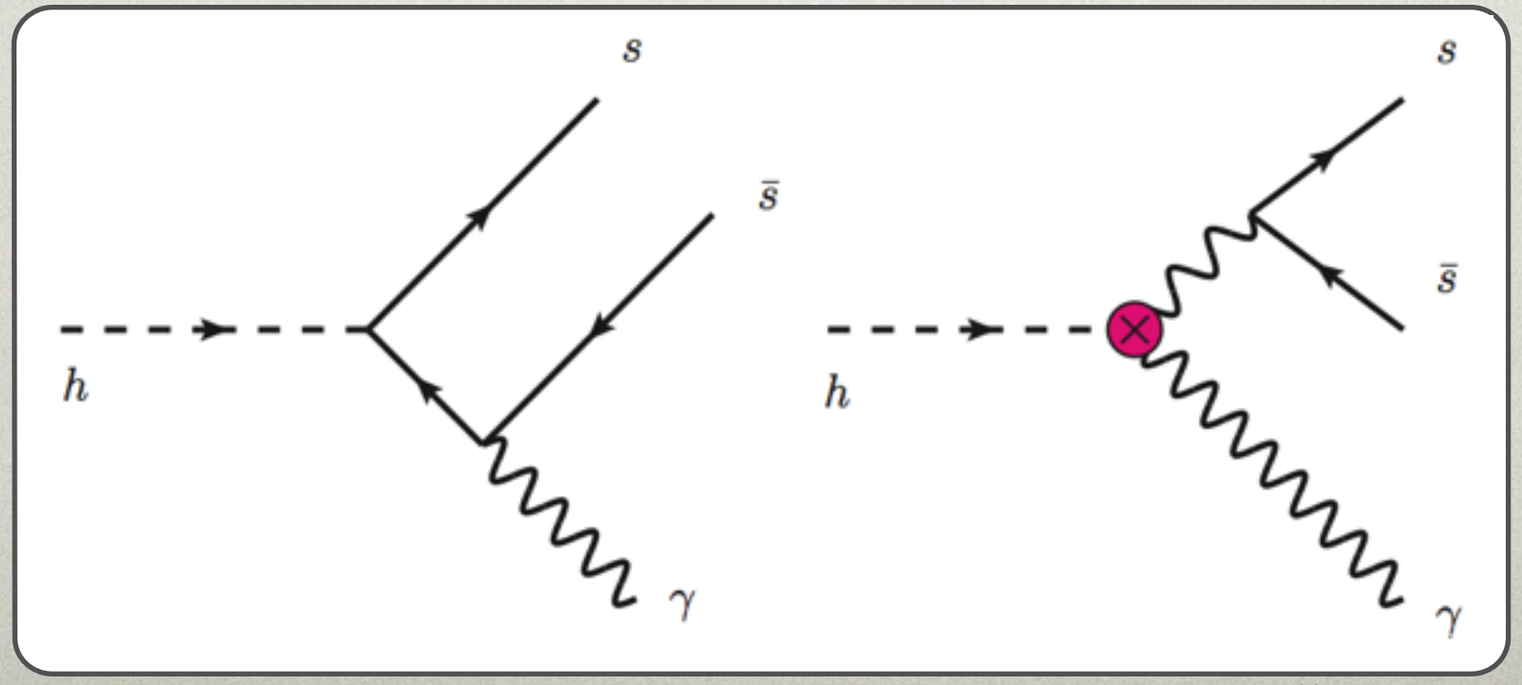
- the problem with light quark Yukawas is that they are very small
- in low energy processes this means that the Higgs exchange is a subdominant contribution
- if no FV then Higgs decays are the only way
  - statistics will always be a problem to reach the SM
  - a nontrivial challenge is even to find a channel where measurement at least in principle is possible

HIGGS COUPLINGS TO LIGHT QUARKS

Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722

- can one directly measure (bound) h-$d\bar{d}$, h-$u\bar{u}$, h-$s\bar{s}$ couplings?
- the topic of this talk:
  - potentially possible through exclusive higgs decays $h \to MV$ ($V=\gamma,Z,W$)
  - direct and indirect amplitude
- similar idea as $h \to J/\Psi\gamma$ for h-$c\bar{c}$

Bodwin, Petriello, Stoynev, Velasco, 1306.5770



MODIFIED EFFECTIVE LAGRANGIAN

- in principle sensitive to diagonal and off-diagonal couplings
- a (slight) change of notation: Yukawa coupl. normalized to y_b

$$\mathcal{L}_{\rm eff} = -\sum_{q=u,d,s} \bar{\kappa}_q \frac{m_b}{v} h \bar{q}_L q_R - \sum_{q\neq q'} \bar{\kappa}_{qq'} \frac{m_b}{v} h \bar{q}_L q'_R + h.c.$$
$$+ \kappa_Z m_Z^2 \frac{h}{v} Z_\mu Z^\mu + 2\kappa_W m_W^2 \frac{h}{v} W_\mu W^\mu$$
$$+ \kappa_\gamma A_\gamma \frac{\alpha}{\pi} \frac{h}{v} F^{\mu\nu} F_{\mu\nu} \,, \qquad (1)$$

- assume CP conserv. $\bar{\kappa}_{qq'} = \bar{\kappa}^*_{q'q}$
- SM limit: $\kappa_\gamma = \kappa_V = 1$

$$\bar{\kappa}_s = m_s/m_b \simeq 0.020$$
$$\bar{\kappa}_d = m_d/m_b \simeq 1.0 \cdot 10^{-3}$$
$$\bar{\kappa}_u = m_u/m_b \simeq 4.7 \cdot 10^{-4}$$

THE MODES

- many exclusive modes
- for diagonal couplings
  - $h \to \phi\gamma$, $h \to \rho\gamma$, $h \to \omega\gamma$, $h \to \phi Z$, $h \to \rho^0 Z$, $h \to \omega Z$, $h \to \pi^0 Z$, $h \to \eta Z$, $h \to \eta' Z$
- for FV couplings
  - $h \to \bar{B}^{0*}\gamma$, $h \to \bar{B}^{0*}\gamma$, $h \to K^{0*}\gamma$, $h \to D^{0*}\gamma$, $h \to K^{*-}W^+$, $h \to \rho^- W^+$, $h \to K^- W^+$, $h \to \pi^- W^+$, $h \to B^{*-}W^+$, $h \to B_c^{*-}W^+$, $h \to D^{*+}W^-$, $h \to D_s^{*+}W^-$, $h \to B^- W^+$, $h \to B_c^- W^+$, $h \to D^+ W^-$, $h \to D_s^+ W^-$, $h \to \bar{B}^{*0} Z$, $h \to \bar{B}_s^{*0} Z$, $h \to D^{*0} Z$, $h \to \bar{B}^0 Z$, $h \to \bar{B}_s^0 Z$, $h \to D^{*0} Z$, $h \to \bar{K}^0 Z$

THE MODES

- many exclusive modes
- for diagonal couplings
  - $h \to \phi\gamma$, $h \to \rho\gamma$, $h \to \omega\gamma$, $h \to \phi Z$, $h \to \rho^0 Z$, $h \to \omega Z$, $h \to \pi^0 Z$, $h \to \eta Z$, $h \to \eta' Z$
- for FV couplings
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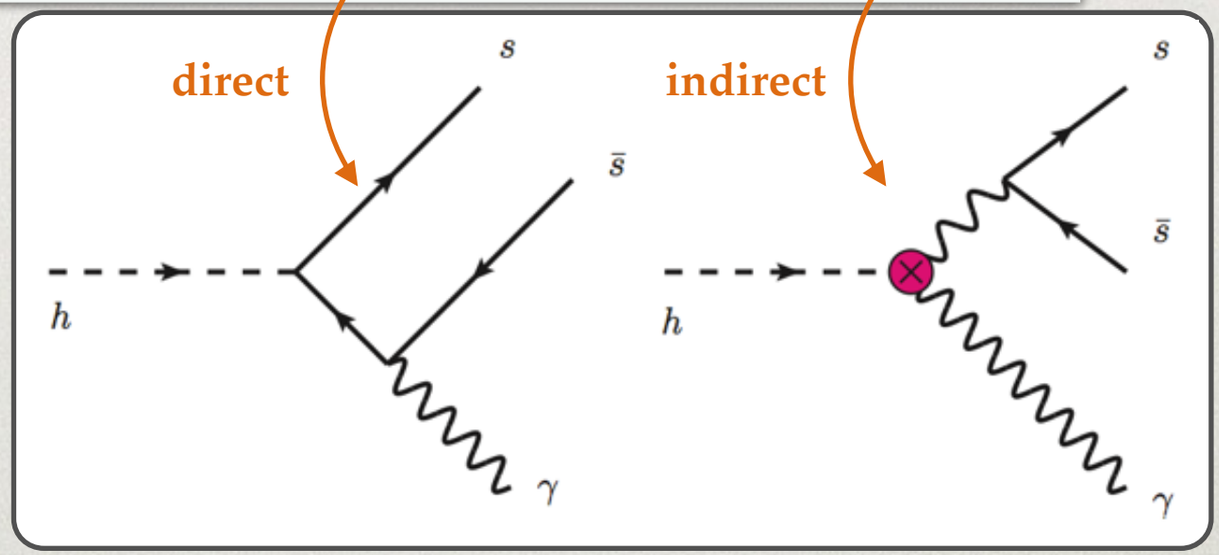
Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722

$h \to \phi\gamma$

- for s Yukawa $h \to \phi\gamma$ (where $\phi \sim \bar{s}s$; $J^{PC}=1^{--}$; $m_\phi=1.02$GeV)

$$M^\phi_{ss} = \frac{Q_s e_0}{2}\epsilon^\phi \cdot \epsilon^\gamma \left(Y_{ss} f^\phi_\perp \langle 1/u\bar{u}\rangle_{\phi,\perp} + \frac{4\alpha}{\pi v}\kappa_\gamma A_\gamma \frac{f_\phi m_h^2}{m_\phi}\right)$$

$$Y_{ss} = \bar{\kappa}_s m_b/v$$



- hadronic matrix elements are
  - ϕ decay constant $\langle\phi|J^\mu_{\rm EM}(0)|0\rangle = f_\phi m_\phi \epsilon^\mu_\phi$ from experiment, $\phi \to e^+e^-$ $\quad J^\mu_{\rm EM} = \sum_f Q_f \bar{f}\gamma^\mu f$
  - inverse moment of the leading twist chiral odd LCDA

from lattice QCD $\langle 1/u\bar{u}\rangle^\phi_\perp = \int_0^1 du \frac{\phi^\phi_\perp(u)}{u(1-u)}$

$$\langle\phi(p,\varepsilon_\perp)|\bar{s}(x)\sigma_{\mu\nu}s(0)|0\rangle = -if^\phi_\perp \int_0^1 du e^{iup\cdot x}(\varepsilon_{\perp\mu}p_\nu - \varepsilon_{\perp\nu}p_\mu)\phi^\phi_\perp(u)$$

from lattice QCD

NONPERTURBATIVE PARAMETERS

Dimou, Lyon, Zwicky, 1212.2242

- in numerical predictions
  - LCDA Gegenbauer polynomial expansion truncated at second order

$$\phi_\perp(u) = 6u(1-u)\sum_{n=0}^{\infty} a_n^\perp C_n^{3/2}(2u-1)$$

$$a_0^{\perp,\phi} = 1 \qquad a_1^{\perp,\phi} = 0 \qquad a_2^{\perp,\phi} = 0.14(7)$$

RBC-UKQCD LC sum rules

  - decay constants

$$f_\phi = 0.235(5)\ \text{GeV} \qquad f_\perp^\phi = 0.191(28)\ \text{GeV}$$

from experiment, $\phi \to e^+e^-$ RBC-UKQCD varying $\mu \in [0.5, 10]$GeV

  - improvable precision: lattice QCD, measurements
  - higher Fock states negligible

COUPLINGS TO LIGHT QUARKS

Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722

- similar analysis for $h \to \rho\gamma$, $h \to \omega\gamma$

$$\frac{Br_{h\to\phi\gamma}}{Br_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(3.0\pm 0.13)\kappa_\gamma - 0.78\bar{\kappa}_s\right]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2},$$

$$\frac{Br_{h\to\rho\gamma}}{Br_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm 0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]\cdot 10^{-5}}{0.57\bar{\kappa}_b^2},$$

$$\frac{Br_{h\to\omega\gamma}}{Br_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.6\pm 0.17)\kappa_\gamma - 0.59\bar{\kappa}_u - 0.29\bar{\kappa}_d\right]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2},$$

  - interference with the indirect term essential
  - direct (SM) amplitude only $\Rightarrow Br \sim O(10^{-11})$

- indirect bound (varying all $\bar{\kappa}_i, \kappa_i$)

$$|\bar{\kappa}_u| < 1.29\,, \quad |\bar{\kappa}_d| < 1.42\,, \quad |\bar{\kappa}_s| < 1.39$$

- similar idea also for h-$c\bar{c}$ from $h \to J/\Psi\gamma$ Bodwin, Petriello, Stoynev, Velasco, 1306.5770

COUPLINGS TO LIGHT QUARKS

Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722

- similar analysis for $h \to \rho\gamma$

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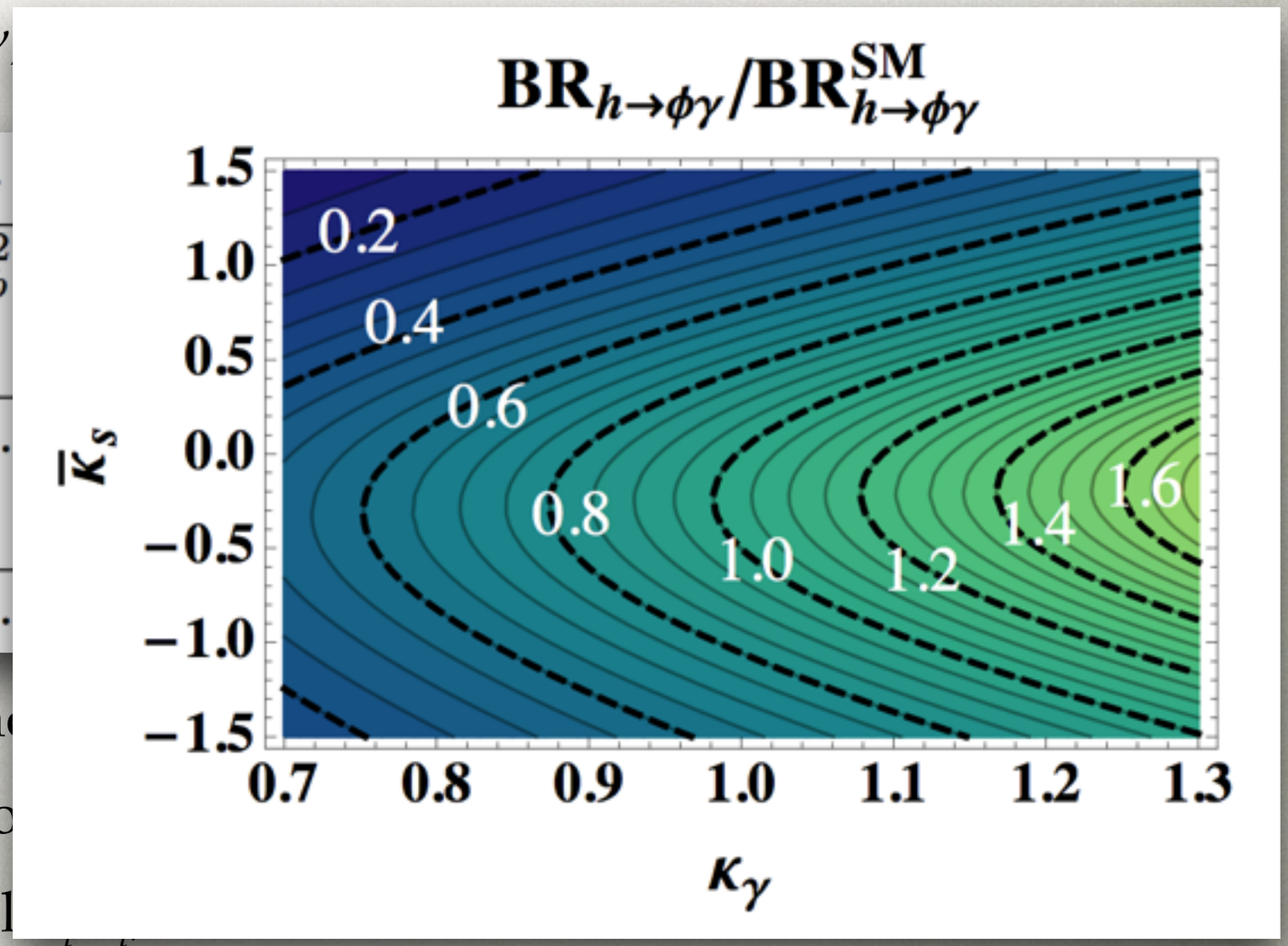
$$\frac{Br_{h\to\rho\gamma}}{Br_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm 0.15)\kappa_\gamma -\right.}{0.}$$

$$\frac{Br_{h\to\omega\gamma}}{Br_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.6\pm 0.17)\kappa_\gamma -\right.}{0.}$$



- interference with the in
- direct (SM) amplitude c

- indirect bound (varying all

$$|\bar{\kappa}_u| < 1.29\,, \quad |\bar{\kappa}_d| < 1.42\,, \quad |\bar{\kappa}_s| < 1.39$$

- similar idea also for h-$c\bar{c}$ from $h \to J/\Psi\gamma$ Bodwin, Petriello, Stoynev, Velasco, 1306.5770

FUTURE EXPERIMENTAL PROSPECTS

- focus on $h \to \phi\gamma$, use **`Pythia 8.1`** Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722
  - main decay modes: $\phi \to K^+K^-(49\%)$, $K_LK_S(34\%)$, $\pi^+\pi^-\pi^\circ(15\%)$
  - for $pp \to h \to \phi\gamma$ at 14TeV LHC in 70 to 75% cases the kaons/pions and the prompt photon have $|\eta| < 2.4$
    - within the minimal fiducial volume of the ATLAS and CMS experiments
  - adopt the geometrical acceptance factor $Ag = 0.75$
    - do not include other efficiency or trigger factors
- assume $\kappa_\gamma = 1$, negligible background, 3σ reach

no theory error

two detectors

one detector

$\sqrt{s}$ [TeV]	$\int \mathcal{L}\, dt\, [\mathrm{fb}^{-1}]$	# of events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\mathrm{stat.}} > (<)$
14	3000	770	0.39 (−0.97)	0.27 (−0.81)
33	3000	1380	0.36 (−0.94)	0.22 (−0.75)
100	3000	5920	0.34 (−0.90)	0.13 (−0.63)

6x SM strange Yukawa

$\tau \to \mu\pi\pi$

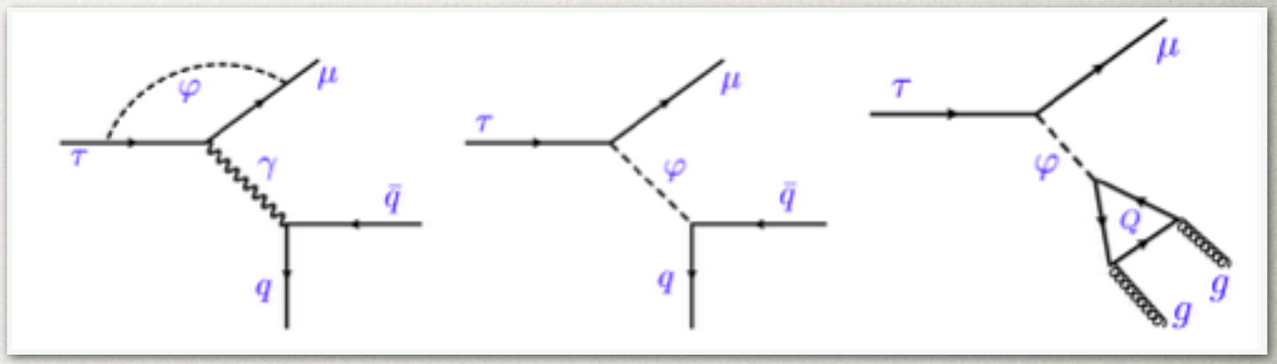
reinterpreting Celis, Cirigliano, Passemar, 1309.3564;
see also Petrov, Zhuridov, 1308.6561

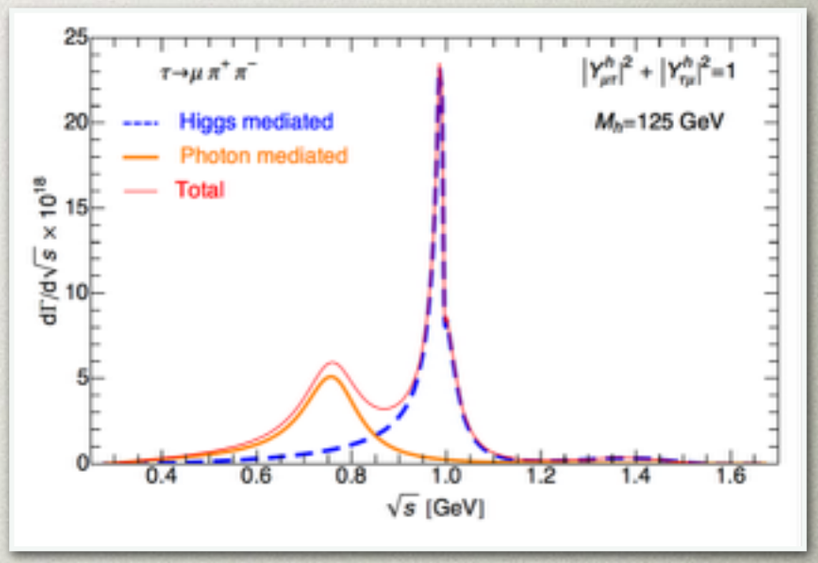
- hadronic tau decays $\tau \to \mu\pi+\pi-, \tau \to \mu\pi 0\pi 0$
  - sensitive to both $Y_{\tau\mu', \mu\tau}$ and light quark yukawas $Y_{u,d,s}$
  - $Y_{u,d,s}$ poorly bounded $\sim O(Y_b)$
- for $Y_{u,d,s}$ at their SM values then

$$Br(\tau \to \mu\pi^+\pi^-) < 1.6 \times 10^{-11}, Br(\tau \to \mu\pi^0\pi^0) < 4.6 \times 10^{-12}$$
$$Br(\tau \to e\pi^+\pi^-) < 2.3 \times 10^{-10}, Br(\tau \to e\pi^0\pi^0) < 6.9 \times 10^{-11}$$

- for $Y_{u,d,s}$ at their present upper bounds

$$Br(\tau \to \mu\pi^+\pi^-) < 3.0 \times 10^{-8}, Br(\tau \to \mu\pi^0\pi^0) < 1.5 \times 10^{-8}$$
$$Br(\tau \to e\pi^+\pi^-) < 4.3 \times 10^{-7}, Br(\tau \to e\pi^0\pi^0) < 2.1 \times 10^{-7}$$





- $Br(\tau \to \mu\pi+\pi-)$ below present exp. limit, if discovered would (among other things) imply upper limit on $Y_{u,d}$
- similarly pseudoscalar Higgses can be bounded from $\tau \to \mu\pi(\eta,\eta')$, $\tau \to e\pi(\eta,\eta')$
  - can saturate present experimental limits

CONCLUSIONS

- Higgs is a unique probe of new physics
- have discussed modified Higgs couplings
  - $h \to \tau\mu$, $h \to \tau e$ being probed at the LHC
  - strong constraints on CPV couplings from EDMs
  - some potential to probe light quark Yukawas

BACKUP SLIDES