BSM discovery in flavor physics and rare decays

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FCC week, Ma 26 2015, Washington DC

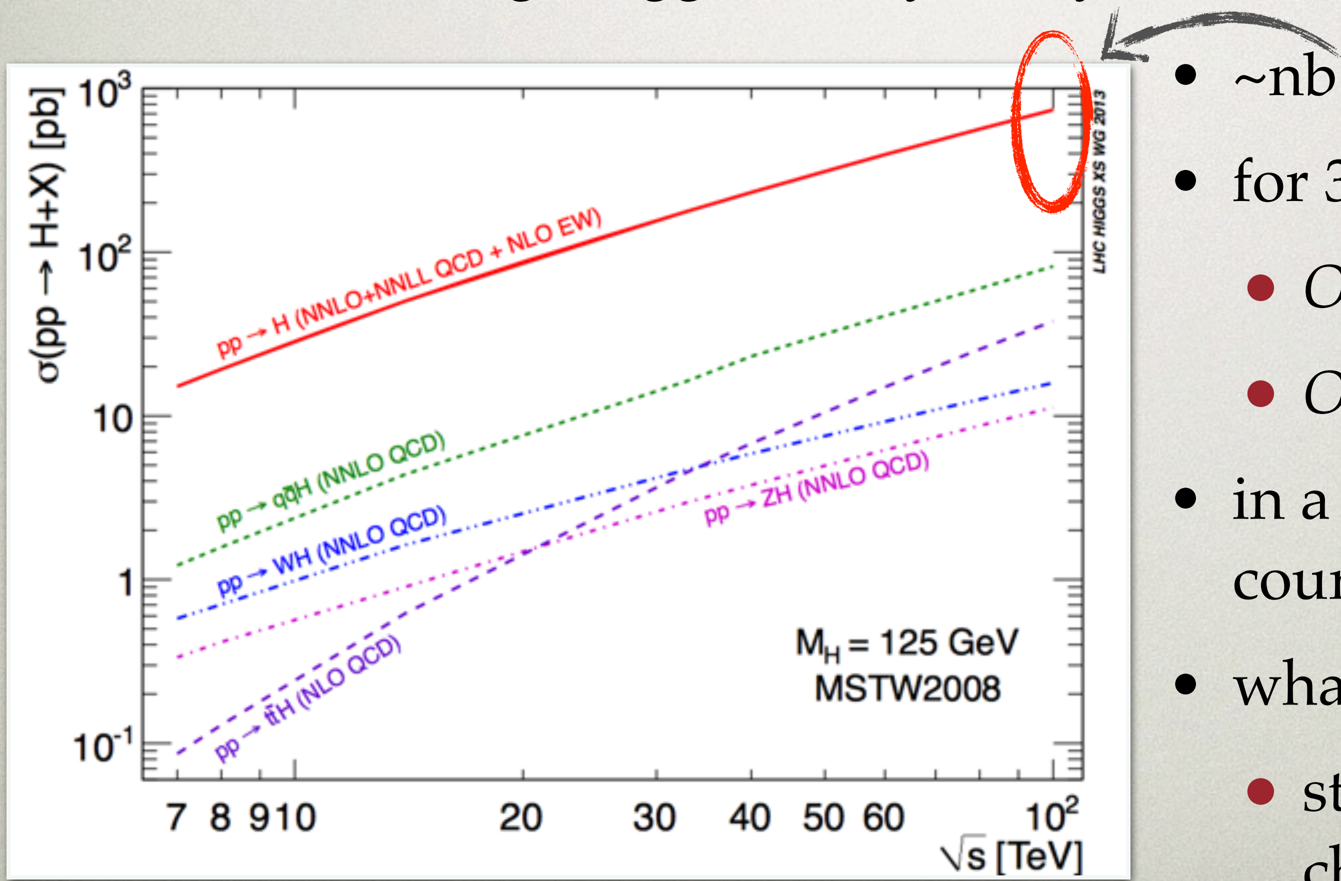
OUTLINE

- rare decays
  - Higgs
  - B mesons
  - Z, W, etc

RARE HIGGS DECAYS

SUBSTANTIAL # OF HIGGSES

- FCC-ee=MegaHiggs factory (clean)
- FCC-hh=GigaHiggs factory (dirty)



- ~nb xsec!
- for 3ab
  - $O(2x10^9)$ *h* from ggh
  - $O(2x10^8)$ *h* from VBF
- in a dirty environment of course
- what can we use it for?
  - statistically limited channels

RARE HIGGS DECAYS

- several probes
  - flavor violating Higgs decays
  - CP violating Higgs decays
  - probing light Yukawa couplings
  - exotic Higgs decays

RARE HIGGS DECAYS

- several probes
  - flavor violating Higgs decays
  - CP violating Higgs decays
  - probing light Yukawa couplings
  - exotic Higgs decays

This talk

FV higgs couplings to SM fermions

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

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

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

  - decouples mass terms from yukawas

$$\mathcal{L}_Y = -m_i \bar{f}^i_L f^i_R - Y_{ij}(\bar{f}^i_L f^j_R)h + h.c. + \cdots ,$$

  - 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

FLAVOR VIOLATION IN DIFFERENT NP MODELS

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

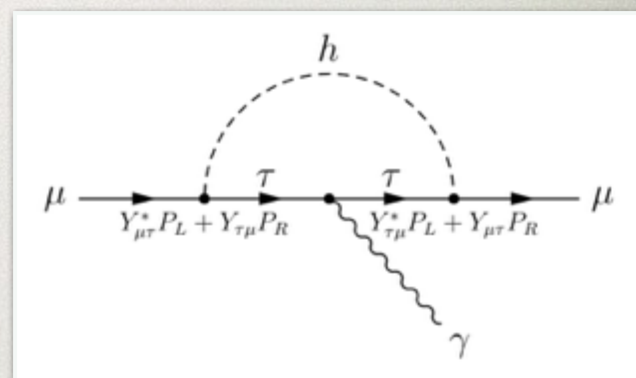
adapted from Dery, Efrati, Hochberg, Nir, 1302.3229 and extended

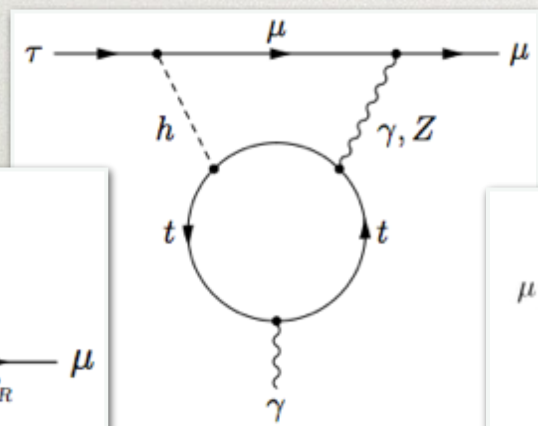
Model	$\hat{\mu}_{\tau\tau}$	$(\hat{\mu}_{\mu\mu}/\hat{\mu}_{\tau\tau})/(m_\mu^2/m_\tau^2)$	$\hat{\mu}_{\mu\tau}/\hat{\mu}_{\tau\tau}$
SM	1	1	0
NFC	$(V_{h\ell}^* v/v_\ell)^2$	1	0
MSSM	$(\sin\alpha/\cos\beta)^2$	1	0
MFV	$1+2av^2/\Lambda^2$	$1-4bm_\tau^2/\Lambda^2$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\lvert U_{23}\rvert^2 v^4/\Lambda^4)$
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

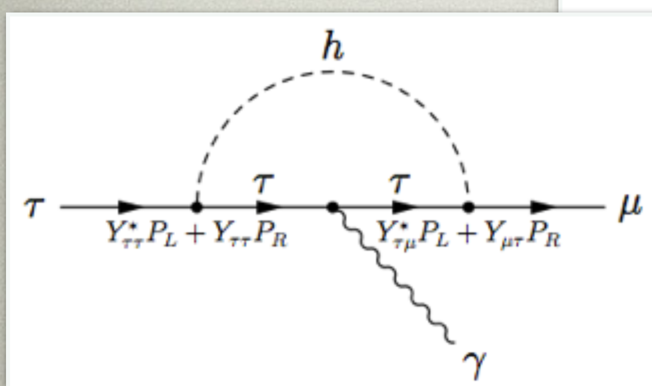
LOW ENERGY CONSTRAINTS

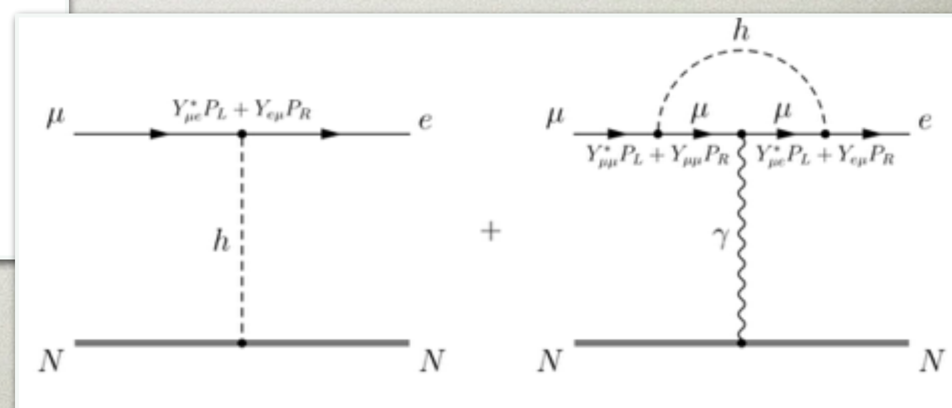
Harnik, Kopp, JZ, 1209.1397
Blankenburg, Ellis, Isidori, 1202.5704
Goudelis, Lebedev, Park, 1111.1715

- already constraints from low energy probes
- e.g, for $h\to\mu e$: $\mu\to e\gamma$, $\mu\to e$ conversion, $\mu\to 3e$, muon g-2, muon EDM,
- for $h\to\tau\mu$: $\tau\to\mu\gamma$, $\tau\to 3\mu$, muon g-2, muon EDM



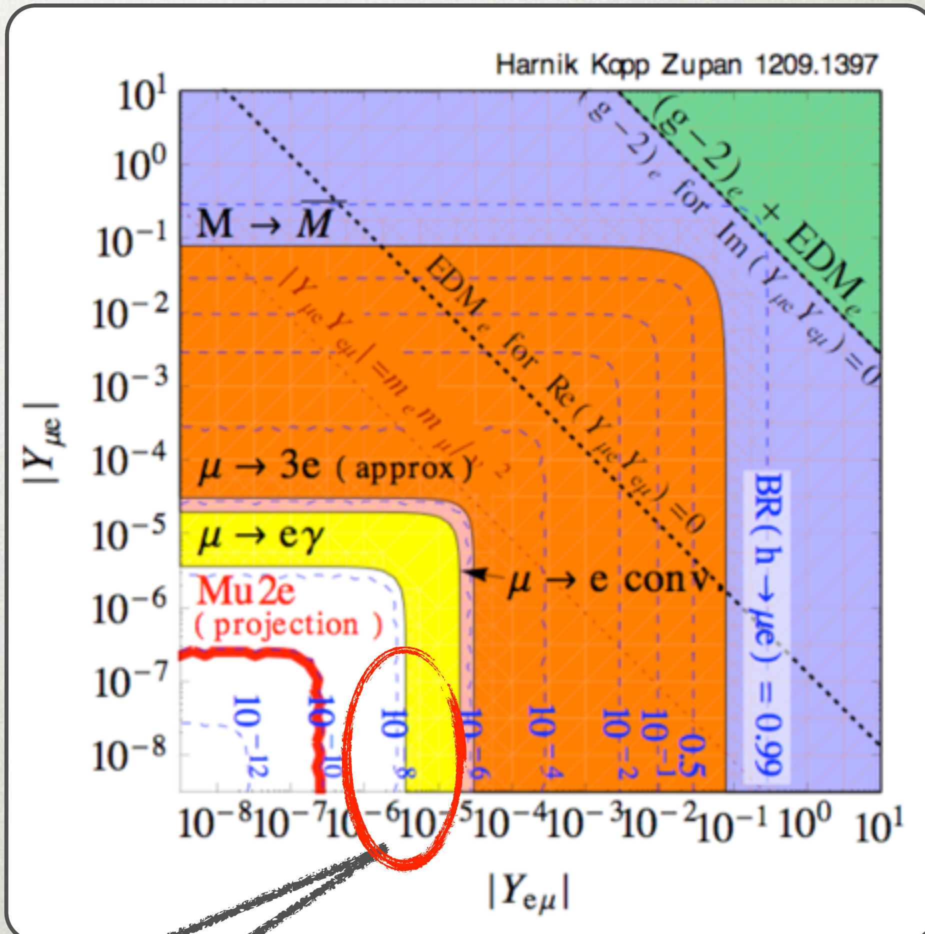






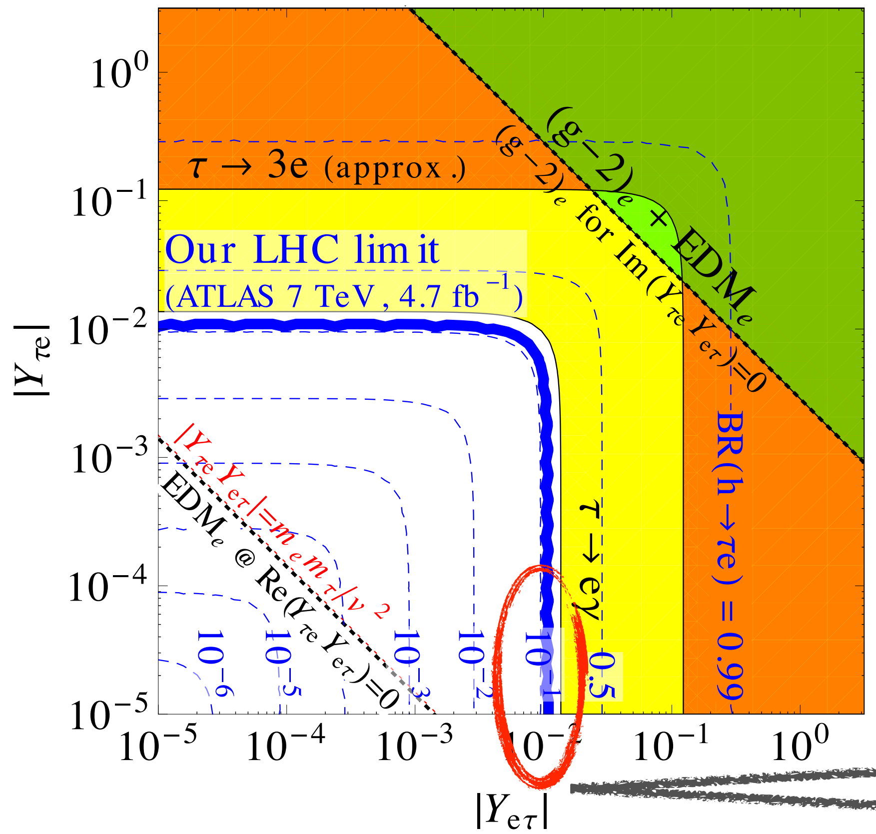
$h \to \mu e$

- indirect bounds better than LHC
- $h \to \mu e$ very clean channel



- what can one do with 10^9 Higgses @100TeV?

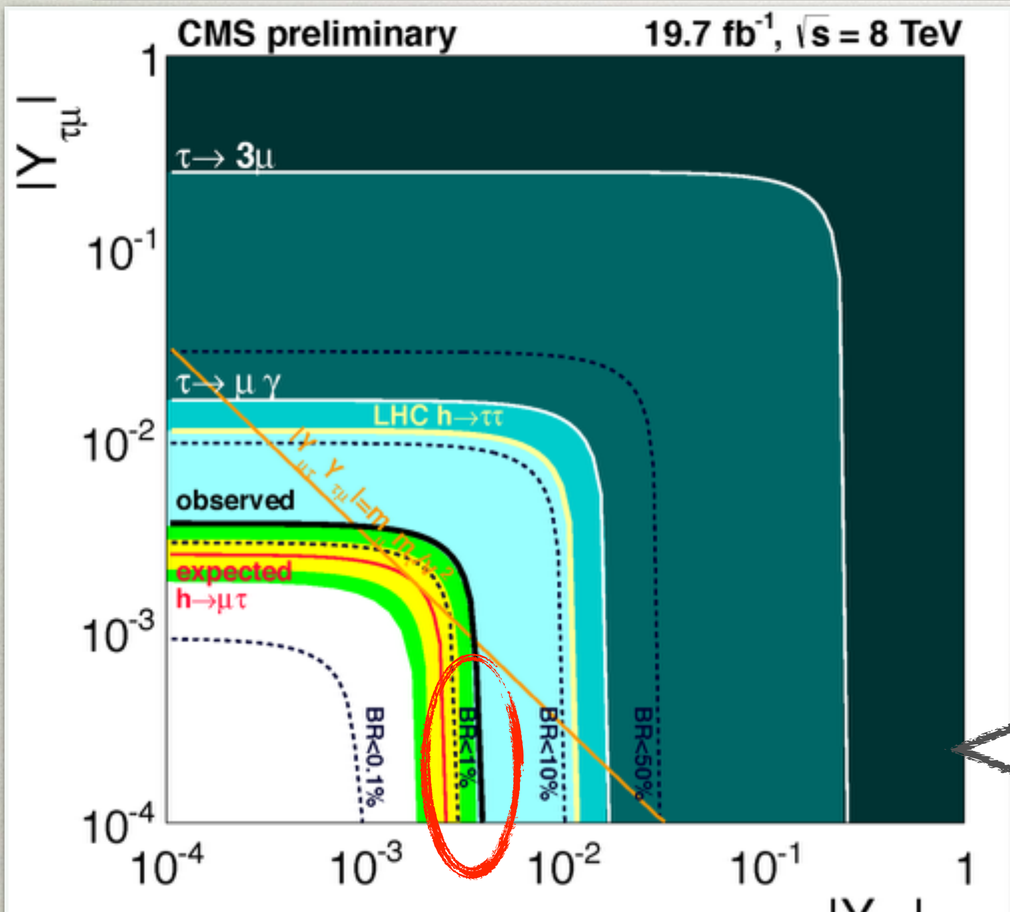
$h \to \tau e$



Harnik, Kopp, JZ, 1209.1397

- how well can LHC do?
- reach @100TeV, FCC-ee?

$h \to \tau\mu$



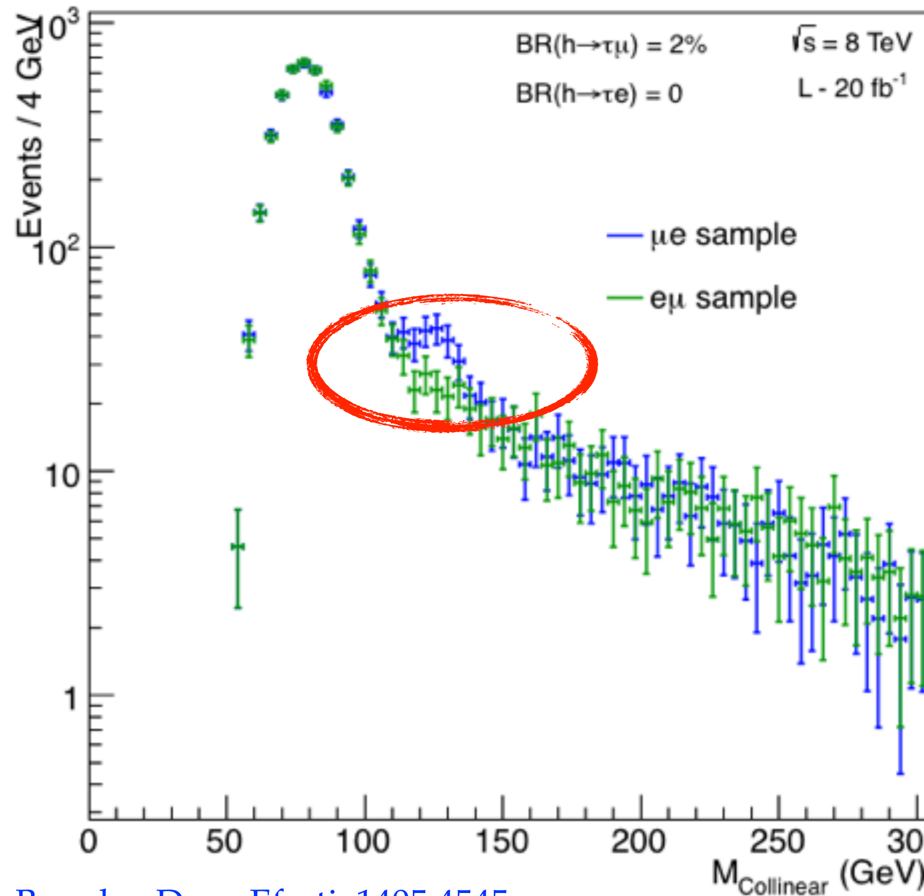
CMS-HIG-14-005

- right now: 2j channel statistics limited, 0j+1j not
- how about with $\sim 10^9$ *h?* ***LHC8*** $\Rightarrow$ ***100 TeV 3 ab^{-1}***
- assume same scaling for signal and bckg
  - $Br \sim 10^{-2} \Rightarrow Br \sim 10^{-4}$
  - $\Lambda \sim 0.2\ TeV \Rightarrow \Lambda \sim 2 TeV$
- if bckg free
  - $Br \sim 10^{-2} \Rightarrow Br \sim 10^{-6}$
  - $\Lambda \sim 0.2\ TeV \Rightarrow \Lambda \sim 20 TeV$ $(Y_{\mu\tau}\, Y_{\tau\mu} = m_\mu m_\tau / \Lambda^2)$

REDUCING BACKGROUNDS

Bressler, Dery, Efrati, 1405.4545

- novel technique to reduce systematics
- leptonic tau decays: $h \to \tau_e \mu$
  - not $\mu \leftrightarrow e$ symmetric
  - the bckg. is symmetric
  - promising for hadronic machine
- still probably hard to beat FCC-ee/ILC/CepC



Bressler, Dery, Efrati, 1405.4545

NEW PHYSICS IN $h \to \tau\mu$?

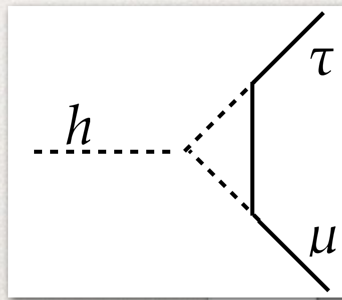
Dorsner et al., 1502.07784 Sierra, Vicente, 1409.7690

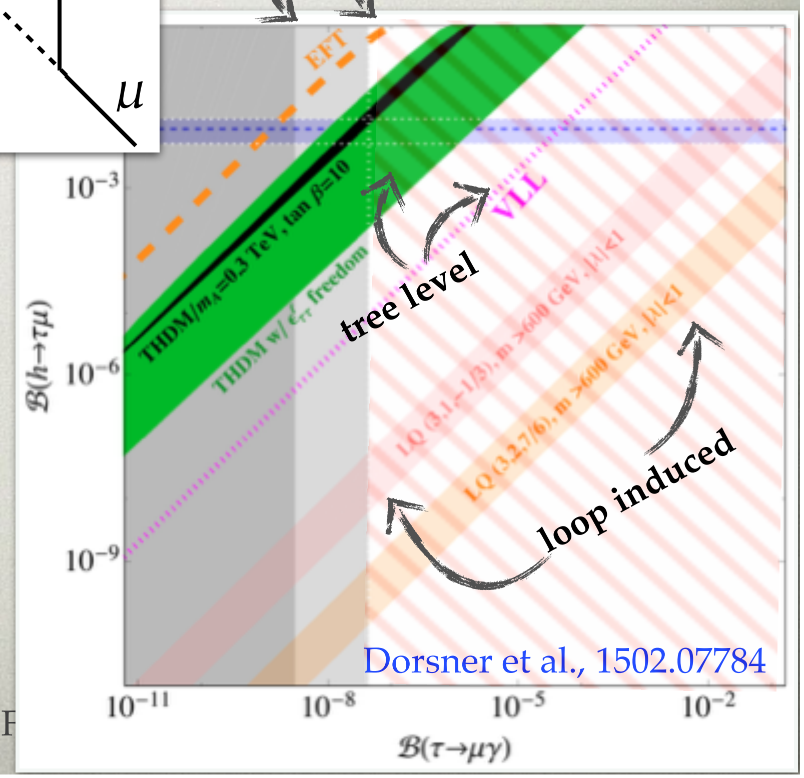
- CMS bound interpreted as hint of a signal in $h \to \tau\mu$

CMS-HIG-14-005

$$\mathcal{B}(h \to \tau\mu) = (0.89^{+0.40}_{-0.37})\ \%$$

- if real, what type of NP?
- if $h \to \tau\mu$ due to 1-loop
  - 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

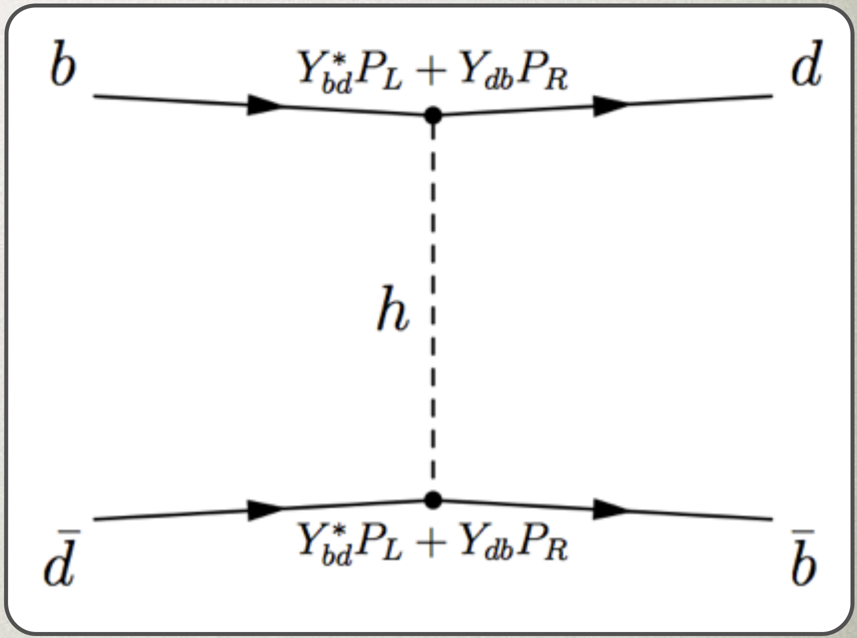




QUARK COUPLINGS

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



QUARK COUPLINGS

1209.1397

Technique	Coupling	Constraint	$Br(h \to q\bar{q}') + Br(h \to q'\bar{q})$
D^0 oscillations [48]	$\|Y_{uc}\|^2, \|Y_{cu}\|^2$	$< 5.0 \times 10^{-9}$	$< 2.1 \times 10^{-6}$
	$\|Y_{uc}Y_{cu}\|$	$< 7.5 \times 10^{-10}$	–
B_d^0 oscillations [48]	$\|Y_{db}\|^2, \|Y_{bd}\|^2$	$< 2.3 \times 10^{-8}$	$< 9.5 \times 10^{-6}$
	$\|Y_{db}Y_{bd}\|$	$< 3.3 \times 10^{-9}$	–
B_s^0 oscillations [48]	$\|Y_{sb}\|^2, \|Y_{bs}\|^2$	$< 1.8 \times 10^{-6}$	$< 7.4 \times 10^{-4}$
	$\|Y_{sb}Y_{bs}\|$	$< 2.5 \times 10^{-7}$	–
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2), \mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$	$< 2.4 \times 10^{-7}$
	$\mathrm{Im}(Y_{ds}^2), \mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$	$< 1.2 \times 10^{-8}$
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$	–
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$	–

- strong constraints

- can one look for $h \to bs$ (i.e. $h \to b + jet$) at 100TeV?
- *Br* large enough for FCC-ee

PROBING LIGHT YUKAWAS?

- can one bound *u,d,s* quark Yukawas?
- the problem with light quark Yukawas is that they are very small

$m_s/m_b \simeq 0.020$ $m_d/m_b \simeq 1.0 \cdot 10^{-3}$ $m_u/m_b \simeq 4.7 \cdot 10^{-4}$

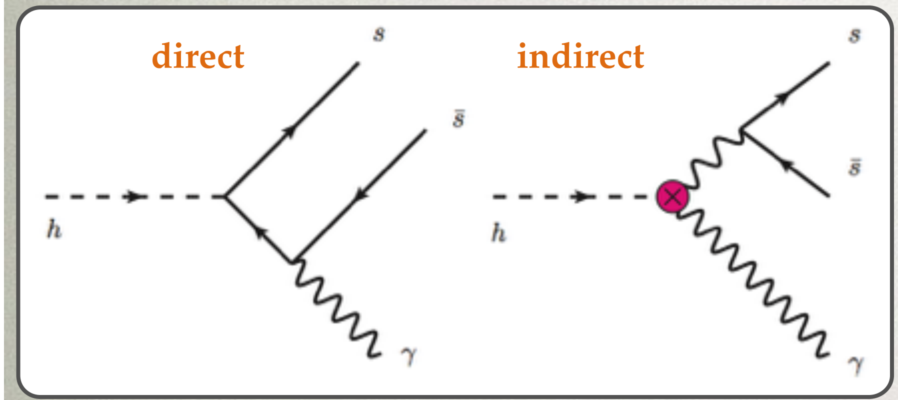
- in low energy processes this means that the Higgs exchange is a subdominant contribution
- if no FV then Higgs decays are the only way
  - statistics will always be a problem to reach the SM
  - a nontrivial challenge is even to find a channel where measurement at least in principle is possible

EXCLUSIVE DECAYS

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

- use exclusive decays $h \to \phi\gamma$, $h \to \rho\gamma$, $h \to \omega\gamma$

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



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

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

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

  - interference with the indirect term essential

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

FUTURE EXPERIMENTAL PROSPECTS

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

- focus on $h \to \phi\gamma$, with $\phi \to K^+K^-$ (49%)
  - assume $\kappa_\gamma = 1$, negligible background, 3σ reach

no theory error

two detectors

one detector

$\sqrt{s}$ [TeV]	$\int \mathcal{L}\, dt$ [fb^{-1}]	# of events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\text{stat.}} > (<)$
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

- compare this with ILC *1TeV 2.5ab*$^{-1}$ estimate

Peskin, 1312.4974

  - $\Delta Br(h\to gg)/Br(h\to gg)=1.2\%$
  - 3σ correspond to 3.5x SM strange Yukawa

ELECTRON YUKAWA COUPLING

Altmannshofer, Brod, Schmaltz, 1503.04830

- electron Yukawa the smallest of the charged fermions

$$\mathrm{Br}(h \to e^+e^-)_{\mathrm{SM}} \simeq 5.1 \times 10^{-9}$$

  - CMS upper bound

$$\mathrm{Br}(h \to e^+e^-) < 0.0019 \quad @\ 95\%\ \mathrm{C.L.} \qquad |\kappa_e| < 611$$

CMS, 1410.6679

  - could potentially be sensitive to NP
- reach at 100 TeV 3 ab^{-1}: $|\kappa_e| \sim 75$
- at FCC-ee on h resonance

$$e^+e^- \to h \to b\bar{b}$$

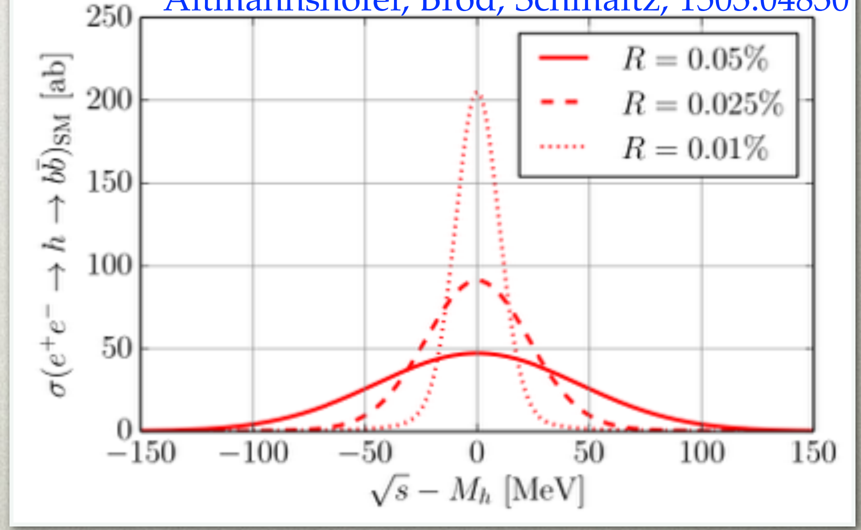
  - is subleading to γ,Z exchange

$$e^+e^- \to \gamma, Z \to f\bar{f}$$

  - the beam eng. resolution is important, taking R=0.05%

$$|\kappa_e| \lesssim 15 \text{ for } 100/\mathrm{fb}$$

Altmannshofer, Brod, Schmaltz, 1503.04830



RARE B MESON DECAYS

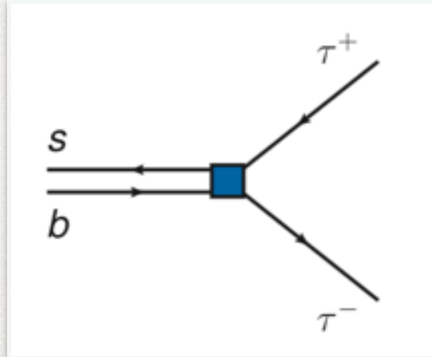
B, D flavor program

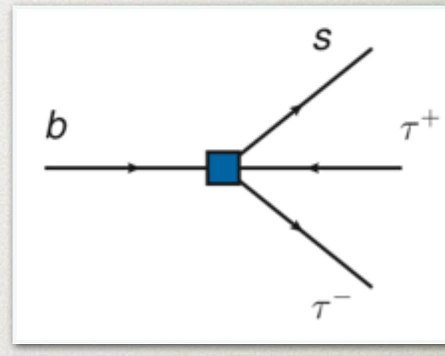
- $\sim 10^{12}$ Z at FCC-ee $\Rightarrow$ $\sim 10^{11}$ *b,c* quarks
- comparable # of *B* and *D* at end of Belle2, less than HL LHCb
  - Belle2: detailed B_d,B_u program
  - LHCb: all *b* hadrons, less efficient for modes with *e*, τ, neutrals, missing energy, hadronic multibody decays
- focus on modes that difficult for Belle2&LHCb
  - $B_{d,s} \to ee, \mu\mu, \tau\tau$
  - V_{ub} from excl. semileptonic decays (e.g., $\Lambda_b \to p l \nu$)
  - modes involving neutrals: $B_s \to \gamma\gamma$, $B_s \to K_S K_S$, $B_s \to X \nu\nu$
  - multi-body decays: γ from $B_s \to D_s^{\pm} K^{\mp}$

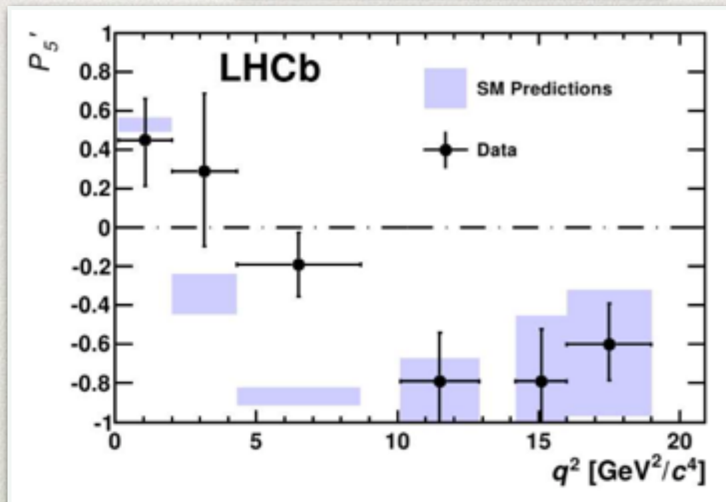
see talk by Altmannshofer at Flavor and Top Physics @ 100 TeV Workshop, Mar 2015

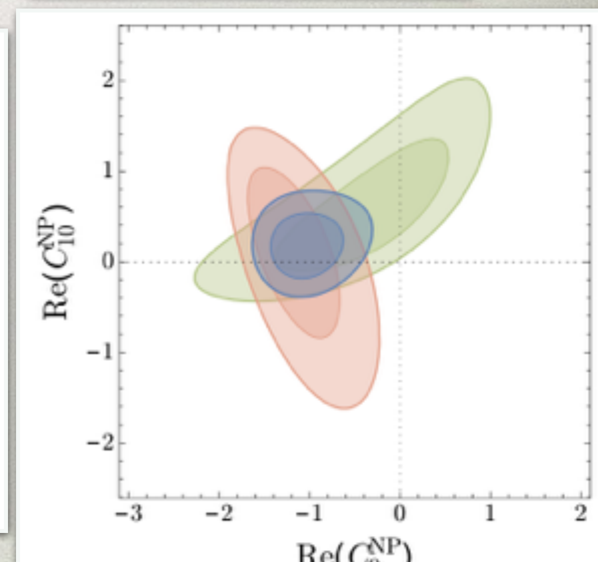
$b \to s\tau^+\tau^-$

- $B_s \to \tau^+\tau^-$ and $B \to K^{(*)}\tau^+\tau^-, B_s \to \phi\tau^+\tau^-$, $B \to X_s\tau^+\tau^-$
- especially interesting in view
  - of the LHCb $B \to K^*\mu^+\mu^-$ anomaly
  - indications of non-universality in $B \to K l^+ l^-$









Altmannshofer, Straub, 1503.06199

$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\mathrm{BR}(B \to K e^+ e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036\,, \quad R_K^{\mathrm{SM}} \simeq 1.00$$

see talk by Straub at EW Moriond 2015

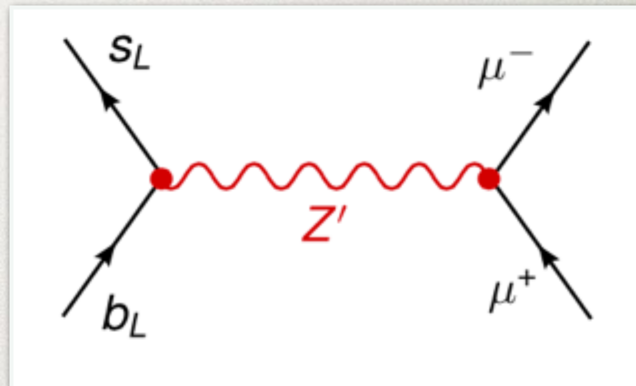
$$C_9^{(\prime)}(\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\tau}\gamma^\mu \tau)$$

$$C_{10}^{(\prime)}(\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\tau}\gamma^\mu\gamma_5 \tau)$$

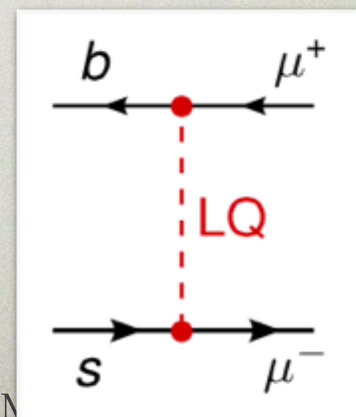
WHAT TYPE OF NEW PHYSICS

see talk by Straub at EW Moriond 2015

- if new physics:
- *s*-channel Z' boson
    - has to be FV to quarks: bsZ′
    - non-universal to leptons
        - gauged L_μ-L_τ Altmannshofer et al., 1403.1269
        - composite Higgs with part. composite muons Niehoffetal, 1503.03865
        - Z′ with couplings to 3rd gen. in flavor basis Glashow et al. 1411.0565



- *t*-channel leptoquarks (vector or scalar) Buras et al., 1409.4557; Varzielas, Hiller, 1503.01084
    - can have any flavor structure in principle



RARE Z DECAYS

RARE Z DECAYS

- 10^{12} Z ⇒ improve bounds on FV Z decays decays
- present bounds

ATLAS, 1408.5774

$$\mathrm{BR}(Z \to e^{\mp}\mu^{\pm}) < 7.5 \times 10^{-7}$$

$$\mathrm{BR}(Z \to e^{\mp}\tau^{\pm}) < 9.8 \times 10^{-6}$$

L3 1993, OPAL 1995

$$\mathrm{BR}(Z \to \mu^{\mp}\tau^{\pm}) < 1.2 \times 10^{-5}$$

DELPHI 1995, OPAL 1997

- any signal would mean BSM
- at FCC-ee (naive extrapolation)

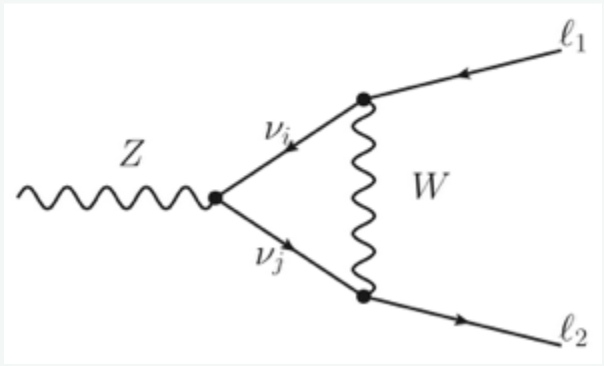
$$Br(Z \to \tau\ell) < \mathcal{O}(10^{-10} - 10^{-11})$$

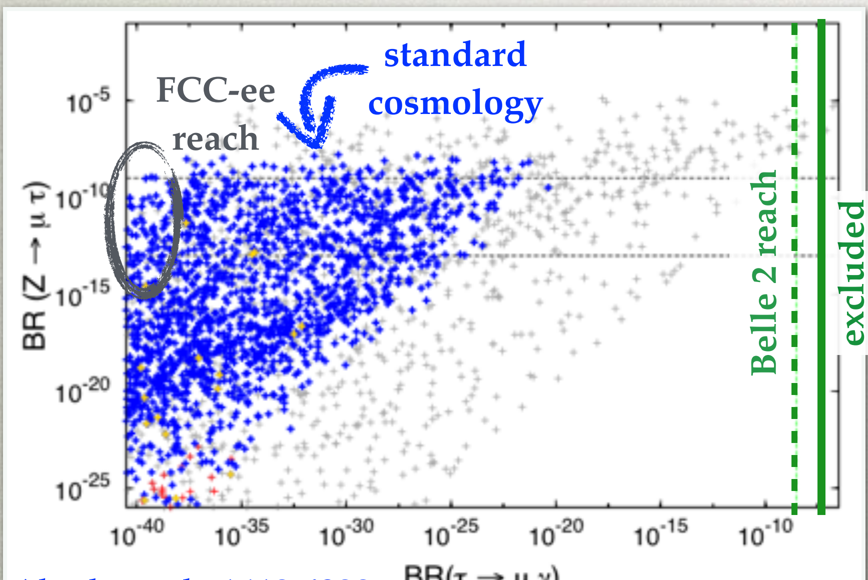
$$Br(Z \to \mu e) < \mathcal{O}(10^{-12})$$

TESTING NEUTRINO MODELS

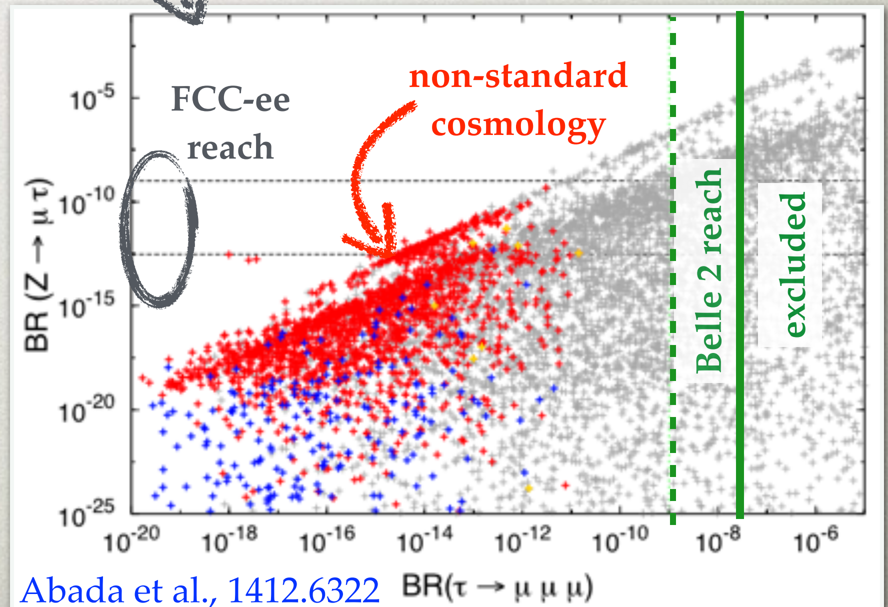
Abada et al., 1412.6322

- could test some of the neutrino mass models
- two examples
  - one extra sterile neutrino
  - inverse see-saw model





Abada et al., 1412.6322



Abada et al., 1412.6322

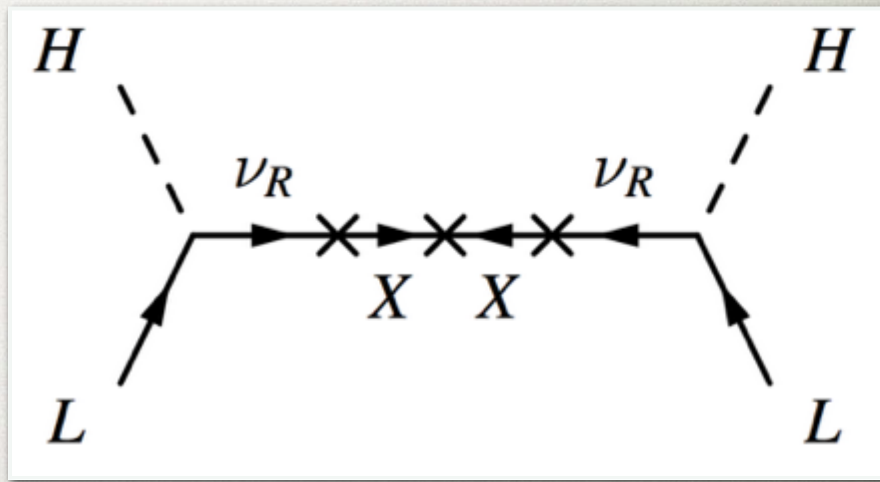
CONCLUSIONS

- covered several rare decays as probes of new physics @ FCC-ee or FCC-hh
  - flavor violating Higgs decays, Higgs decays to light fermions
  - B decays
  - flavor violating Z decays
  - many more possible signals (!)

BACKUP SLIDES

INVERSE SEE-SAW

$$M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$$



$$0.01 \text{ eV} \lesssim (\mu_X)_{ij} \lesssim 1 \text{ MeV}$$

$$0.1 \text{ MeV} \lesssim (M_R)_i \lesssim 10^6 \text{ GeV}$$

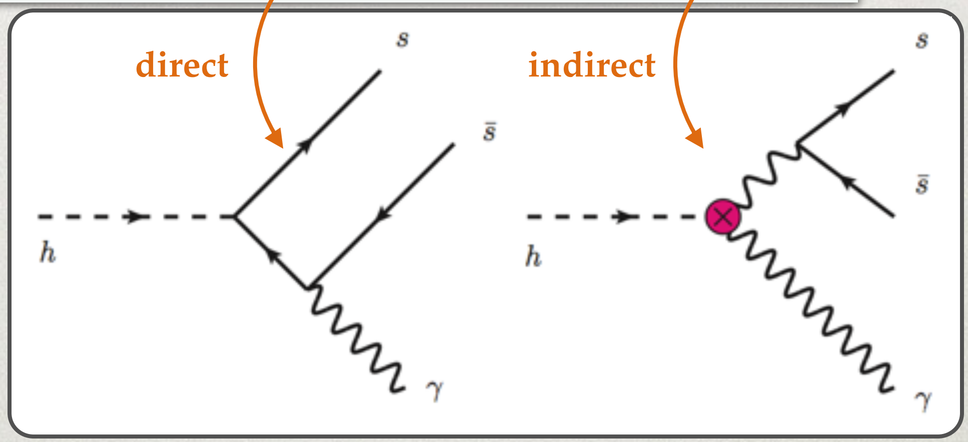
Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722

$h \to \phi\gamma$

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

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

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



- hadronic matrix elements are
  - ϕ decay constant

from experiment, $\phi \to e^+e^-$

$$\langle \phi | J_{\rm EM}^{\mu}(0)|0\rangle = f_\phi m_\phi \epsilon_\phi^{\mu}$$

$$J_{\rm EM}^{\mu} = \sum_f Q_f \bar{f}\gamma^\mu f$$

  - inverse moment of the leading twist chiral odd LCDA

from lattice QCD

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

from lattice QCD

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

FUTURE EXPERIMENTAL PROSPECTS

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

- focus on $h \to \phi\gamma$, use **`Pythia 8.1`**
  - main decay modes: $\phi \to K^+K^-(49\%)$, $K_L K_S\,(34\%)$, $\pi^+\pi^-\pi^0(15\%)$
  - 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

$\sqrt{s}$ [TeV]	$\int \mathcal{L}\, dt$ [fb^{-1}]	# of events (SM)	$\bar{\kappa}_s > (<)$	$\bar{\kappa}_s^{\text{stat.}} > (<)$
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)

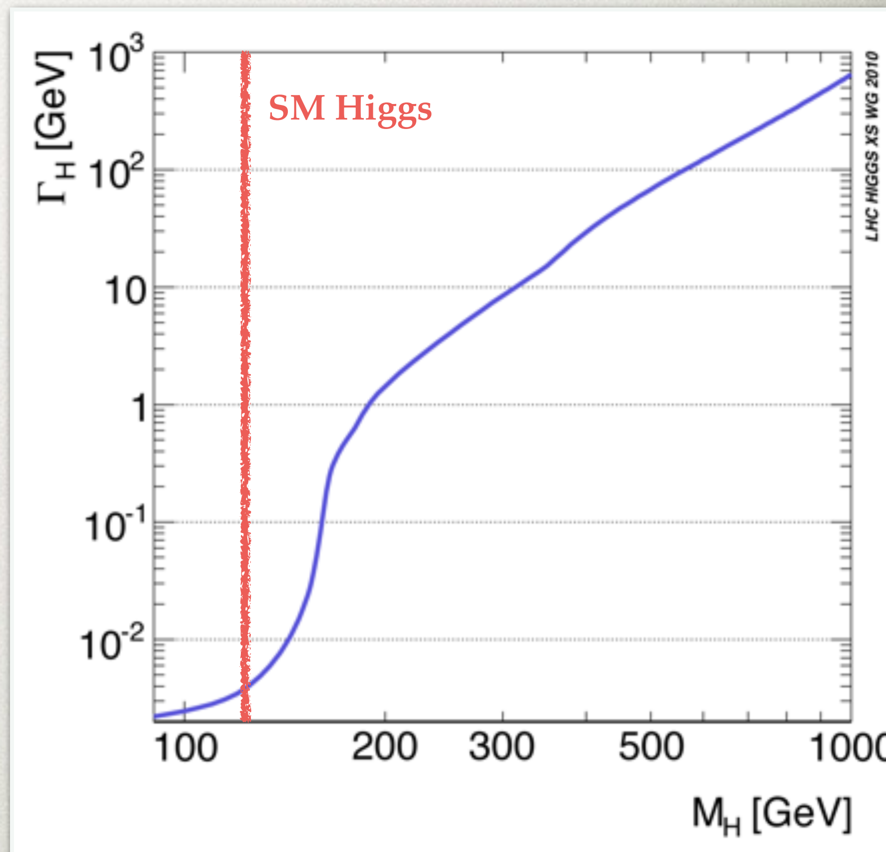
two detectors

one detector

6x SM strange Yukawa

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

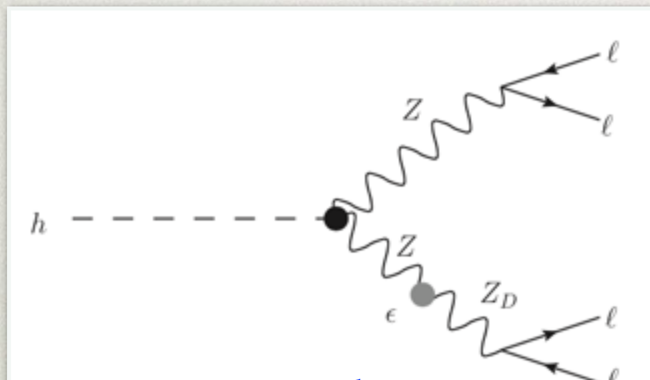


EXOTIC DECAYS

- 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



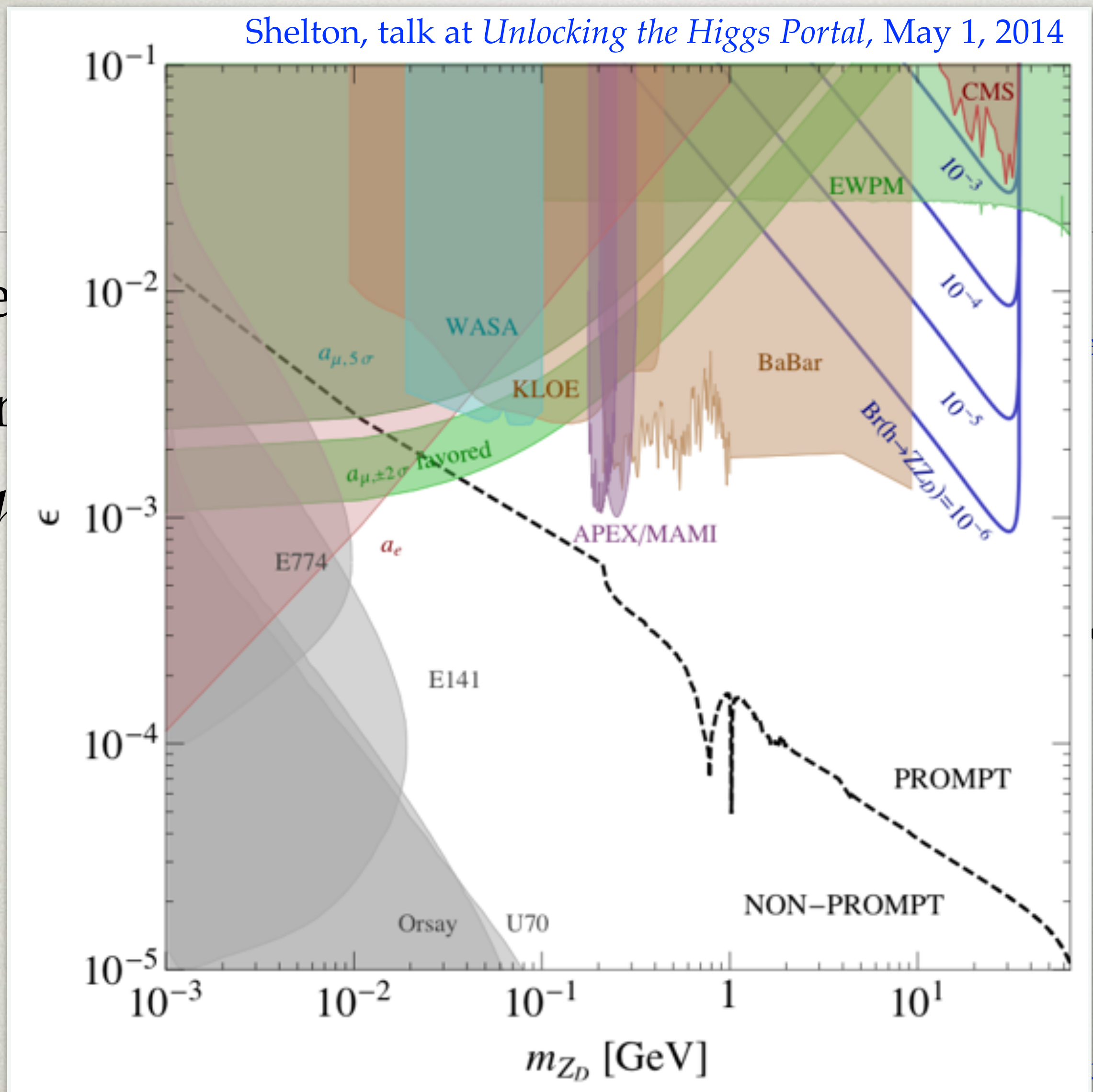
Curtin, Essig, Gori, Shelton, 1412.0018

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

- the sector
  erman, Volansky, JZ, 1002.2952
  Curtin et al, 1312.4992
  +many refs.
  - r
  - *h*
- an king



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

owski, Vega-Morales, 1405.1095

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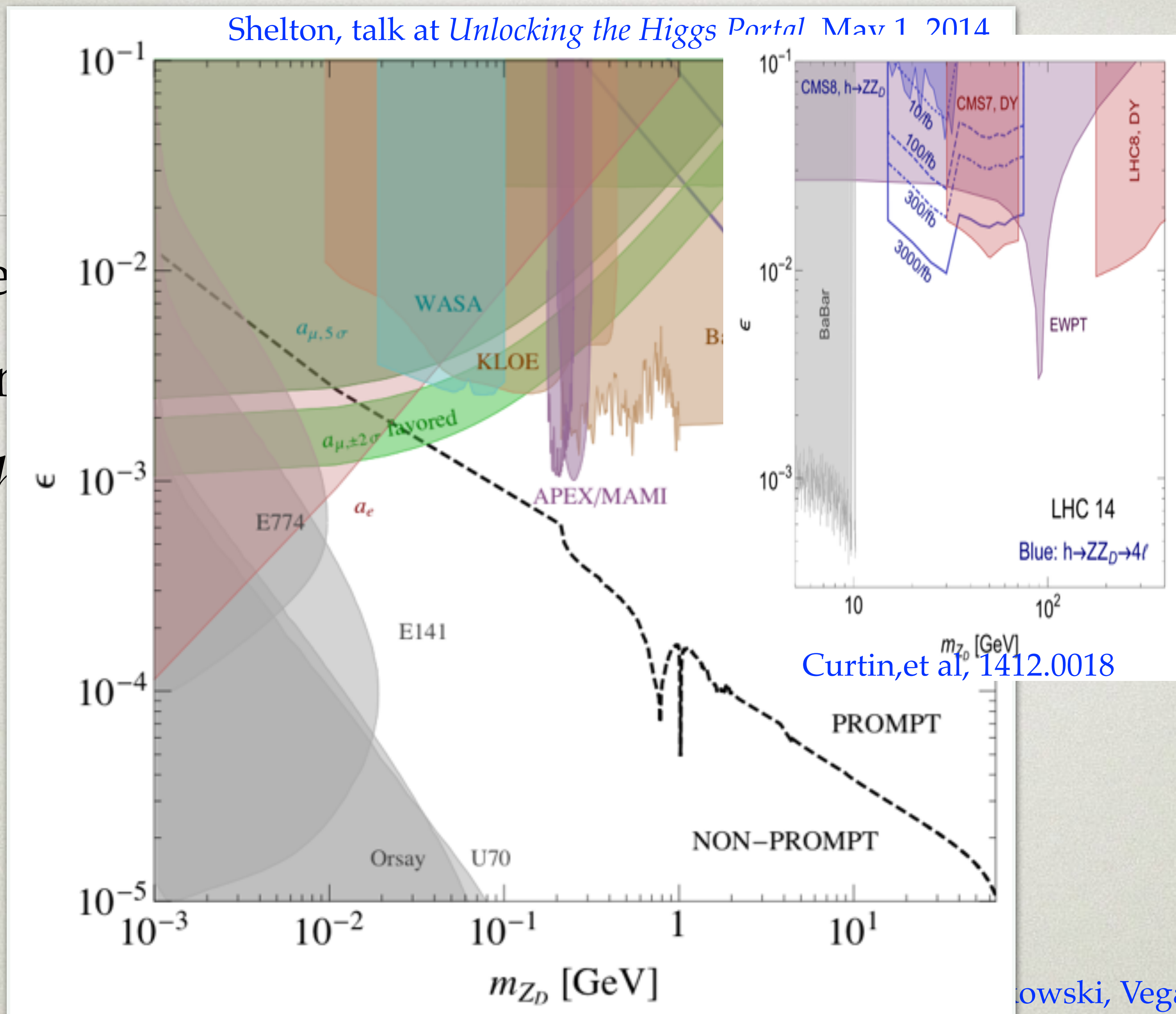
Gonzalez-Alonso, Greljo, Isidori, Marzocca, 1412.6038

- the
  - r
  - h
- an



Curtin,et al, 1412.0018

nsky, JZ, 1002.2952

rtin et al, 1312.4992

+many refs.

owski, Vega-Morales, 1405.1095

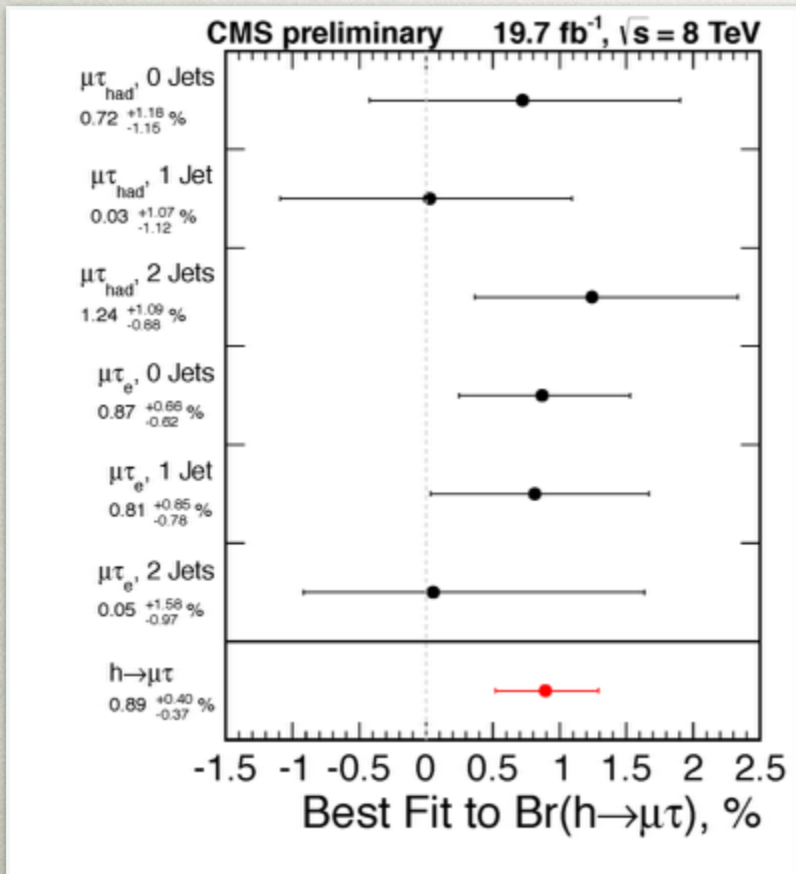
  - the final state is *h→4l*
  - could use pseudo-observables for general searches

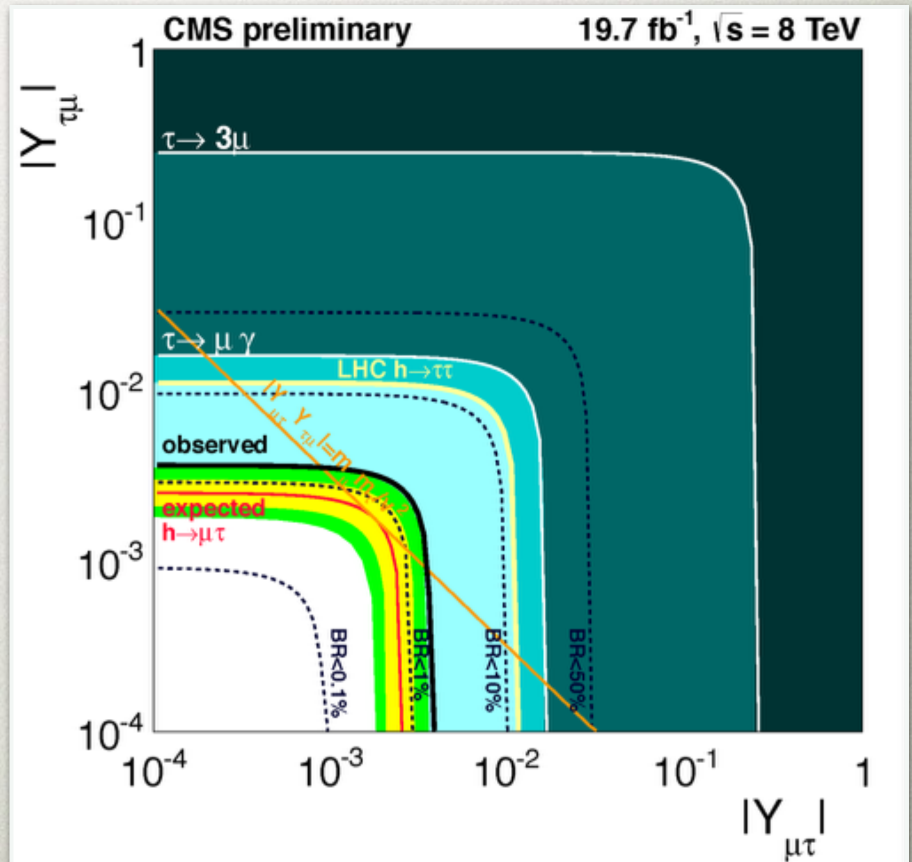
Gonzalez-Alonso, Greljo, Isidori, Marzocca, 1412.6038

$h \to \tau\mu$ from CMS

CMS-HIG-14-005

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





Process	√s = 14 TeV	√s = 33 TeV	√s = 40 TeV	√s = 60 TeV	√s = 80 TeV	√s = 100 TeV
ggF [a]	50.35 pb	178.3 pb (3.5)	231.9 pb (4.6)	394.4 pb (7.8)	565.1 pb (11.2)	740.3 pb (14.7)
VBF [b]	4.40 pb	16.5 pb (3.8)	23.1 pb (5.2)	40.8 pb (9.3)	60.0 pb (13.6)	82.0 pb (18.6)
WH [c]	1.63 pb	4.71 pb (2.9)	5.88 pb (3.6)	9.23 pb (5.7)	12.60 pb (7.7)	15.90 pb (9.7)
ZH [c]	0.904 pb	2.97 pb (3.3)	3.78 pb (4.2)	6.19 pb (6.8)	8.71 pb (9.6)	11.26 pb (12.5)
ttH [d]	0.623 pb	4.56 pb (7.3)	6.79 pb (11)	15.0 pb (24)	25.5 pb (41)	37.9 pb (61)
$gg \to HH$[e]$(\lambda=1)$	33.8 fb	207 fb (6.1)	298 fb (8.8)	609 fb (18)	980 fb (29)	1.42 pb (42)

Patrick Janot, CERN-TH Seminar CERN, 16 Oct 2013

	Lumi / 5 yrs / 4 IPs	# of HZ events	# of WW→H events
TLEP 240	10 ab^{-1}	2,000,000	50,000
TLEP 350	2.6 ab^{-1}	325,000	65,000