Flavor Physics at Colliders

Jure Zupan
u. of cincinnati & CERN

SLAC Summer Institute, Aug 25, 2016

FLAVOR AT COLLIDERS

- constraints on NP models from "low energy" precision observables

see talks by V. Cirigliano, M. Sokoloff, H. Jawahery

  - B physics programs at LHCb, ATLAS, CMS
  - examples: B_s mixing, rare B decays, etc
- high p_T physics at ATLAS and CMS
  - nontrivial flavor structure modifies signatures
    - example: stop searches, $\tilde{t} \to c\chi^0$ instead of $\tilde{t} \to t\chi^0$
    - example: searches for vector-like quarks $B' \to tW$ vs. $B' \to uW$

see presentation by Team 3 in the afternoon

  - Higgs flavor structure (e.g., $h \to \tau\mu$)

LOW ENERGY PRECISION FLAVOR

HISTORIC VIEW

- most of on-shell discoveries in particle physics in the last ~50 years anticipated through a combination of
  - theoretical arguments
  - indirect experimental information
- GIM cancellation ⇒ NP@~GeV (charm quark)
- unitarization of Fermi theory ⇒ NP@~100GeV *(W,Z)*
- *B&L* accidental in the SM+ solar neutrino deficit ⇒ neutrino masses
- CPV in kaon sector ⇒ 3rd generation
- *B* mixing, EW fits ⇒ top quark@~170 GeV
- EW fits (WW unitarization) ⇒ Higgs@~100 GeV (NP <1TeV)

FACING THE FUTURE

- a number of open questions
  - origin/nature of dark matter
  - baryon asymmetry
  - cosmological constant
  - hierarchy problem (origin of EW scale)
  - strong CP problem
- unlike some of the historic examples none of the above uniquely fixes NP scale
  - B physics (flavor physics in general) can probe high NP scales

SENSITIVITY TO NEW PHYSICS

- sensitivity to NP from virtual corrections
  - e.g. $b \to s l^+ l^-$
- NP contribs. scale as

$$\boxed{\delta C^{\rm NP} \propto \frac{\sin\theta_i \sin\theta_j}{M_{\rm NP}^2}}$$

- need to know mix. angles and NP masses

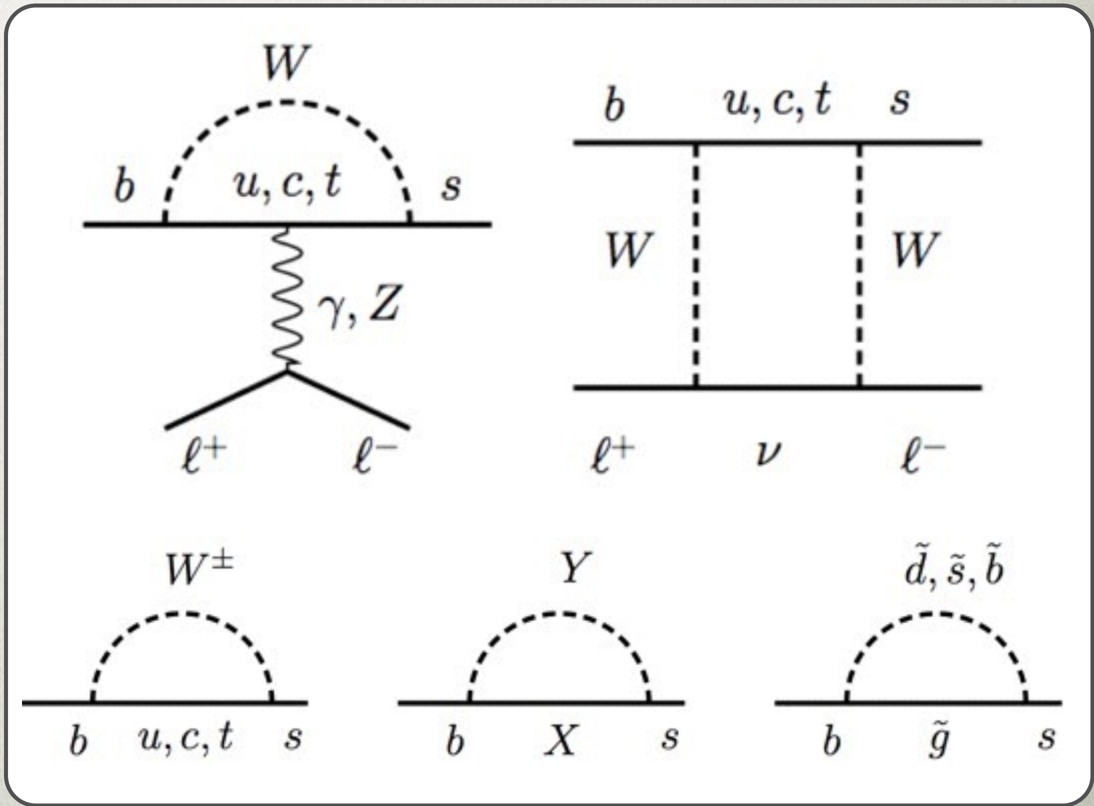


fig. from talk by G. Hiller at The First Three years of LHC, Mainz, Mar 2013

SEARCHING FOR THE TAIL

- from observing the tail can deduce the existence of a whale

- in *B* (flavor) physics many observables
  - can reconstruct many features of the NP (whale)

SEARCHING FOR THE TAIL

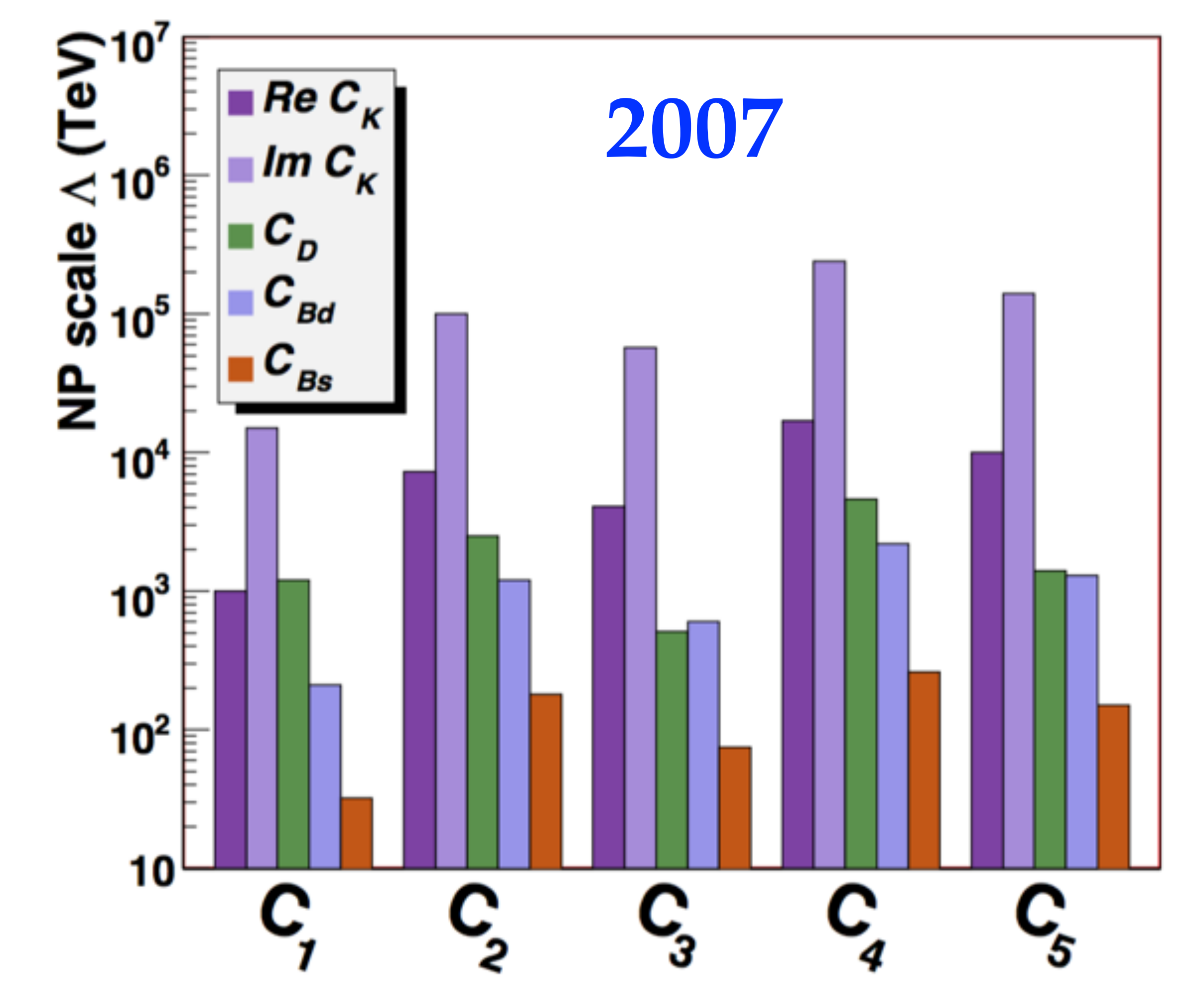
- from observing the tail can deduce the existence of a whale

- in B (flavor) physics many observables
  - can reconstruct many features of the NP (whale)

LOW ENERGY PRECISION BOUNDS

UTFit 0707.0636, 1411.7233

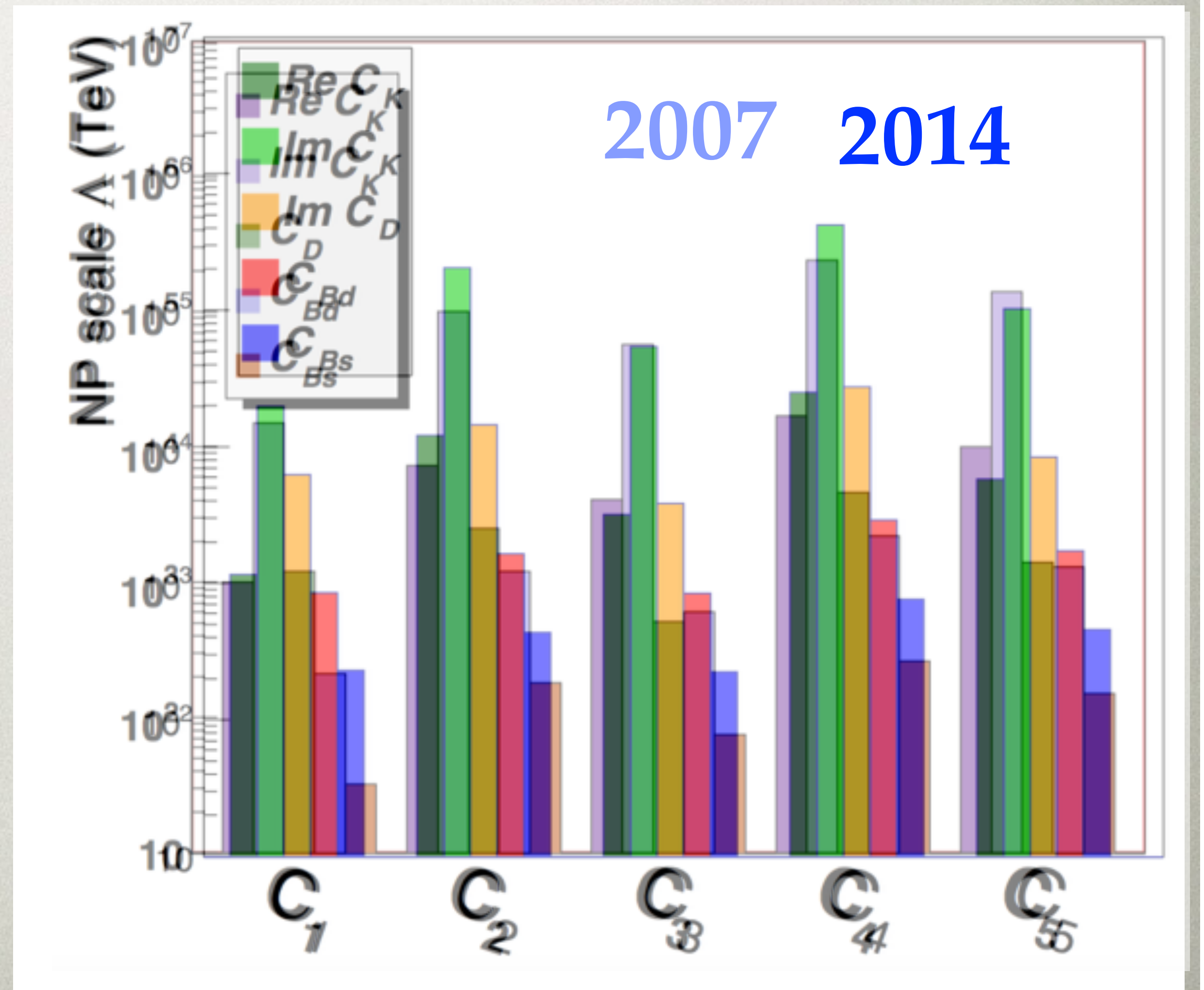
- an impressive progress on flavor bounds in last 10 years
- in D, B_s mixing
- also ~2x on NP scale from ε_K



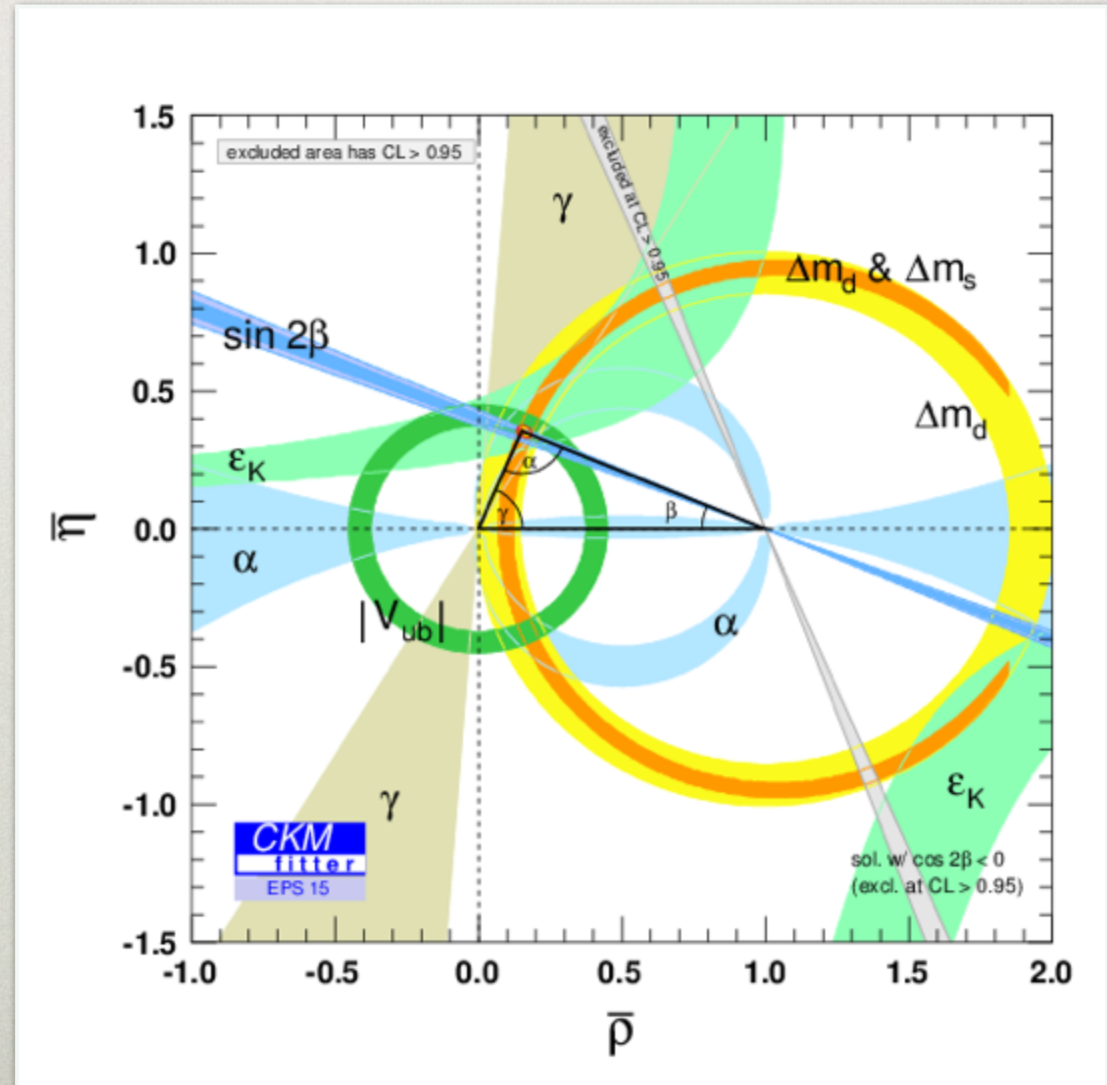
LOW ENERGY PRECISION BOUNDS

UTFit 0707.0636, 1411.7233

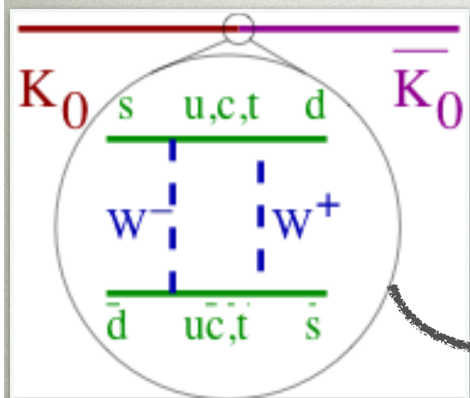
- an impressive progress on flavor bounds in last 10 years
- in D, B_s mixing
- also ~2x on NP scale from ε_K

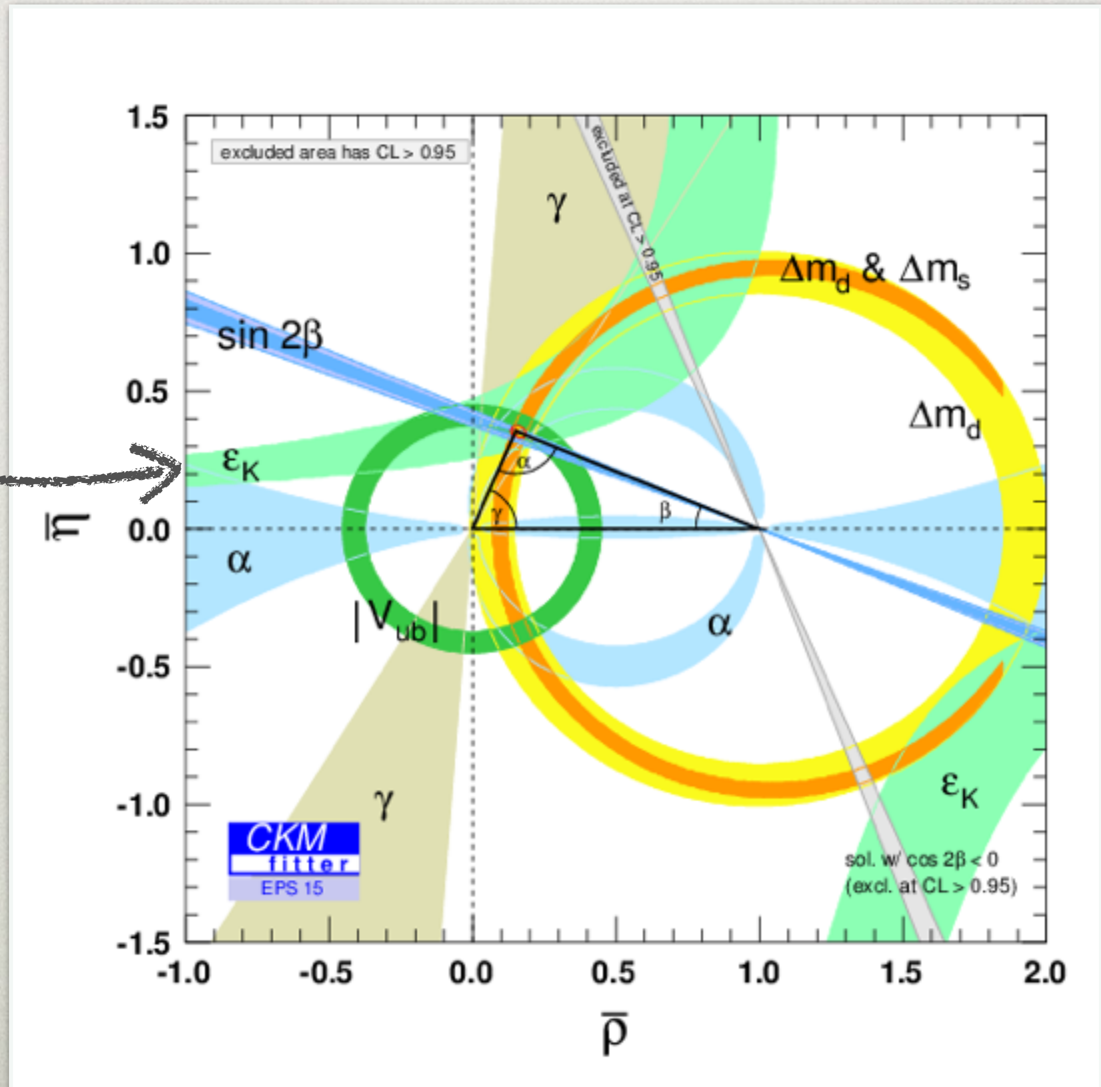


CKM TRIANGLE

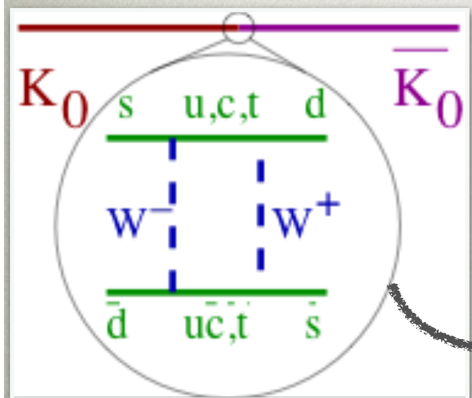


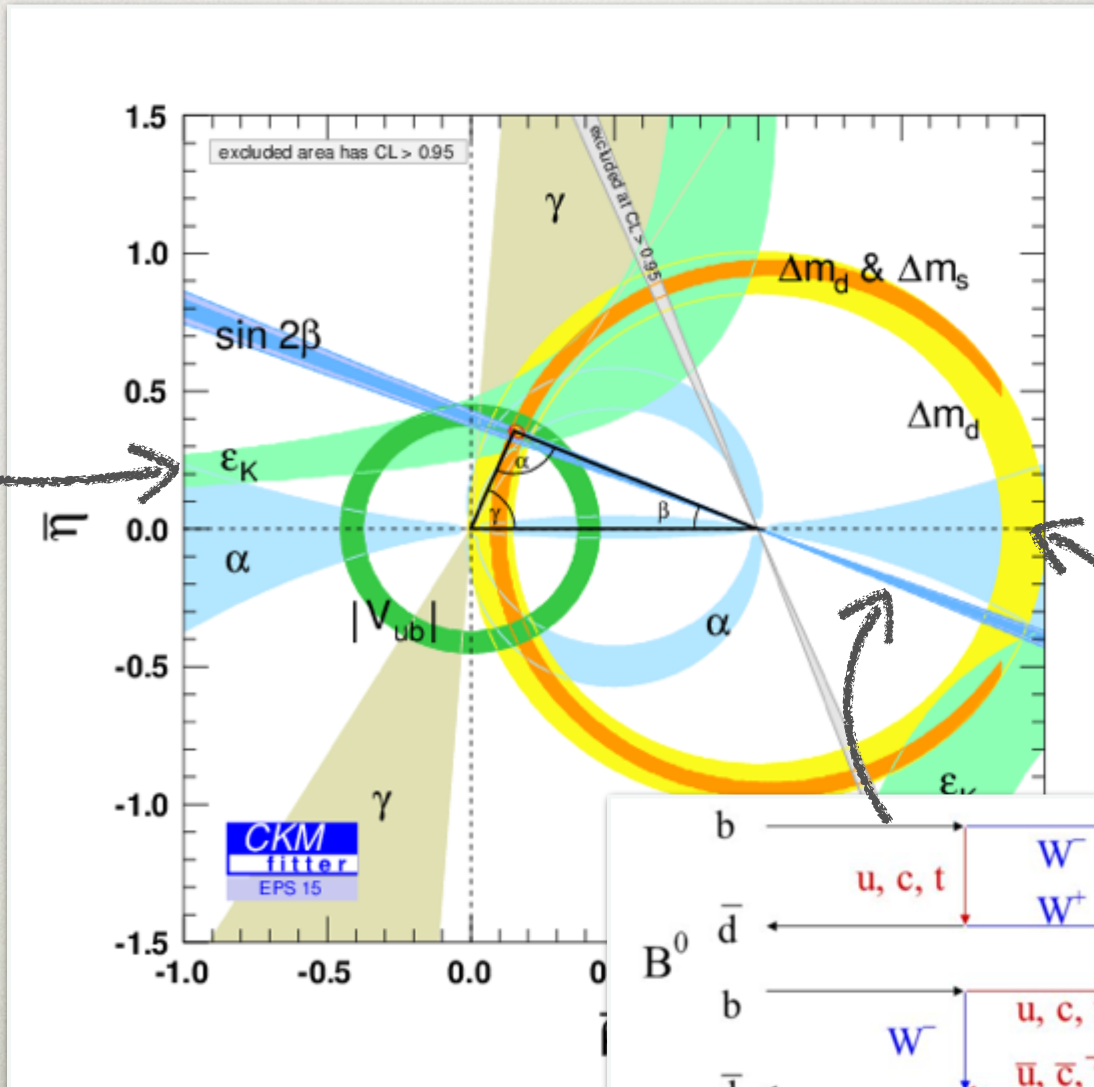
CKM TRIANGLE

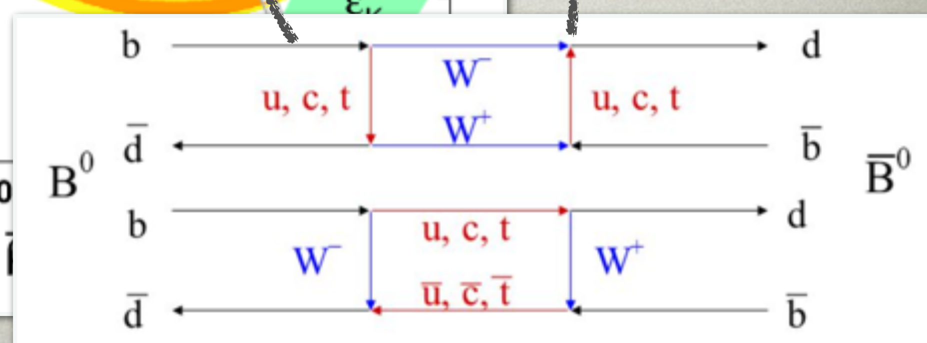




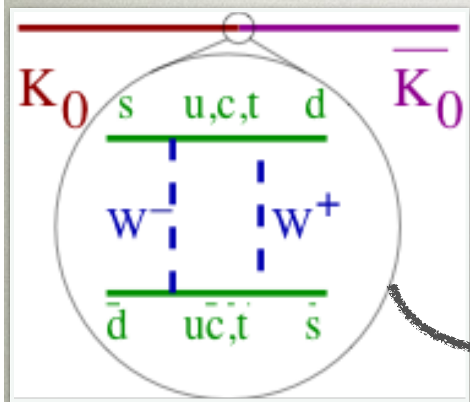
CKM TRIANGLE



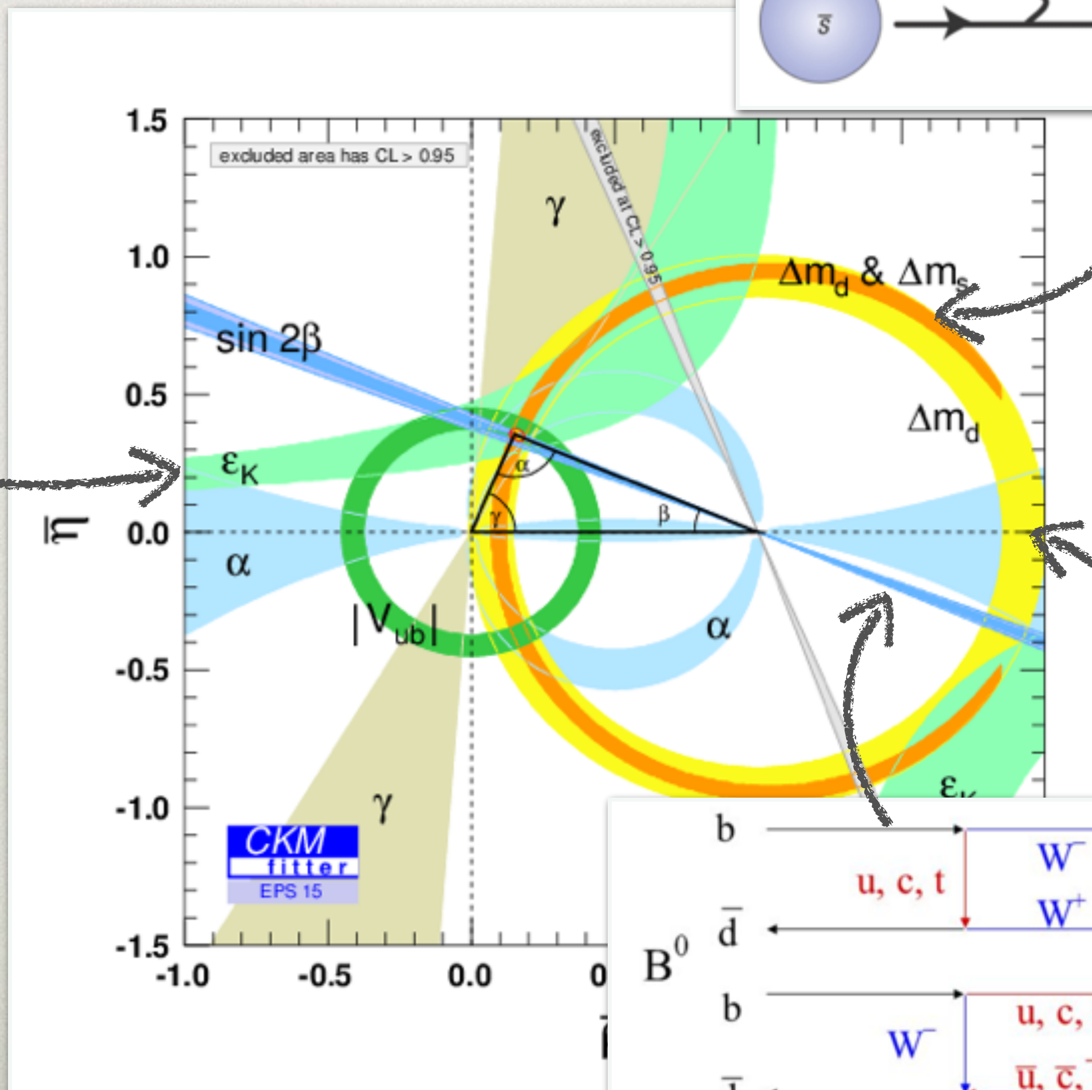




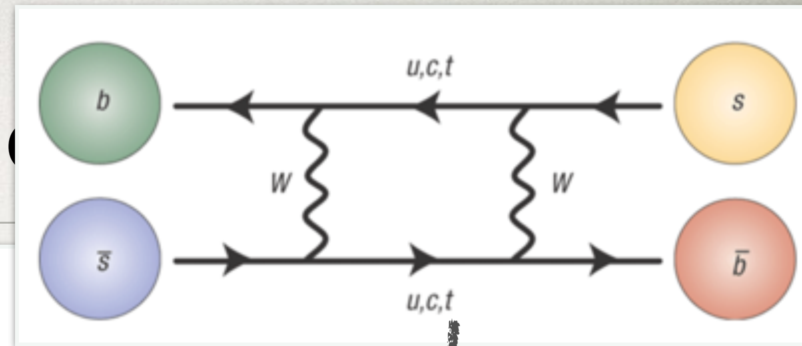
CKM TRIANG



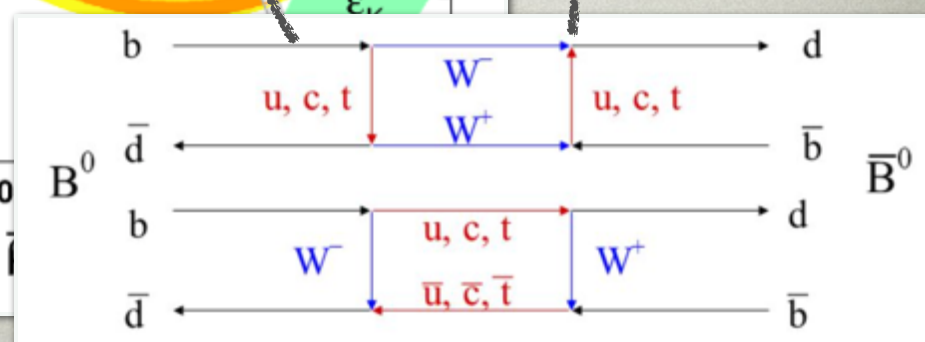
K_0
$\overline{K}_0$
s u,c,t d
W^- W^+
$\bar{d}$ $\bar{u}\bar{c},\bar{t}$ $\bar{s}$



excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
Δm_d
sin 2β
ε_K
α
$|V_{ub}|$
β
CKM fitter
EPS 15
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
$\bar{\eta}$

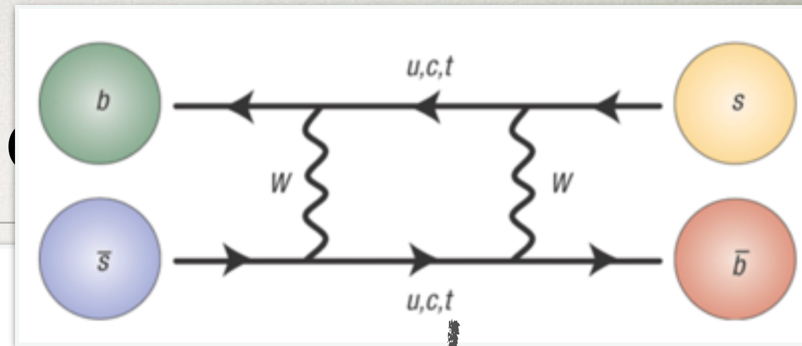


b
$\bar{s}$
u,c,t
W
W
s
$\bar{b}$

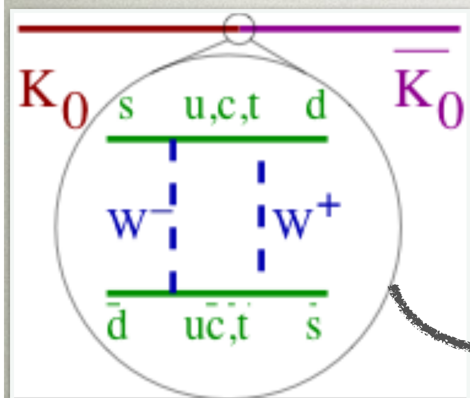


B^0
$\overline{B}^0$
b
$\bar{d}$
d
$\bar{b}$
u, c, t
W^-
W^+
$\bar{u}, \bar{c}, \bar{t}$

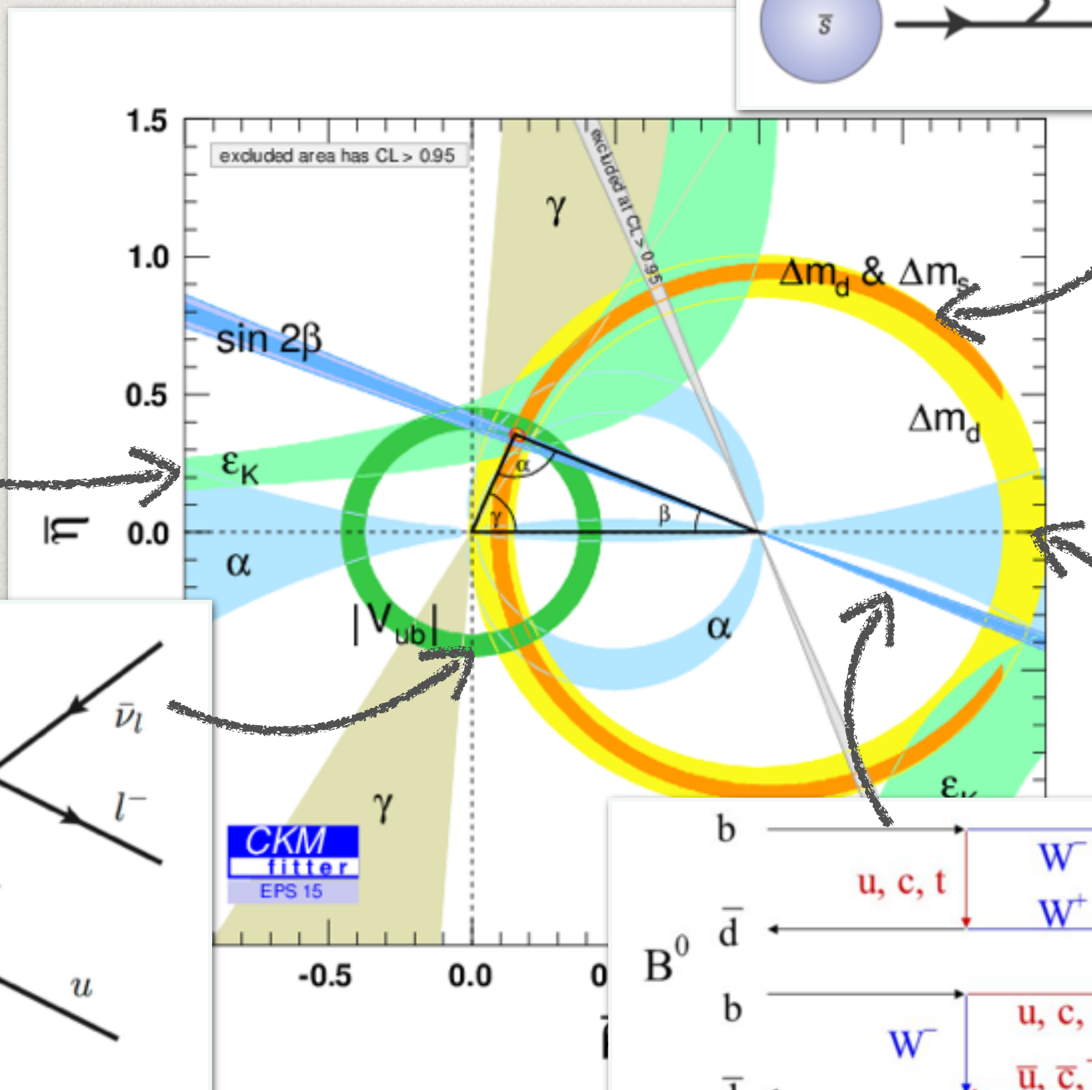
CKM TRIANG



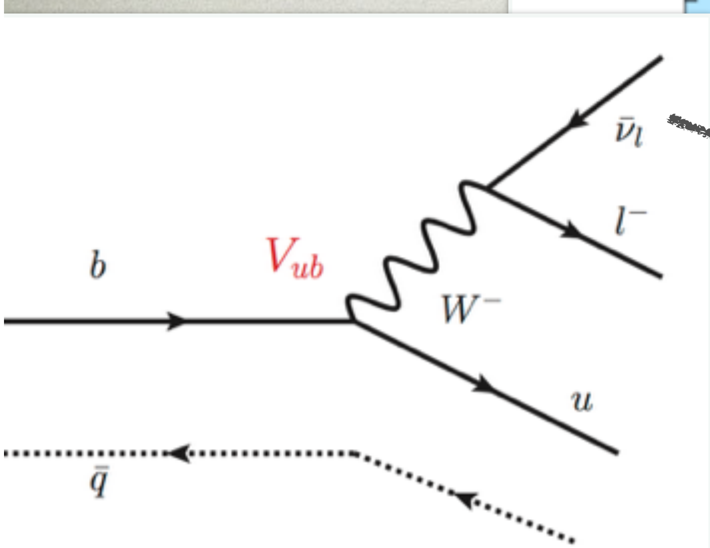
b
s
$\bar{s}$
$\bar{b}$
u,c,t
W
W
u,c,t



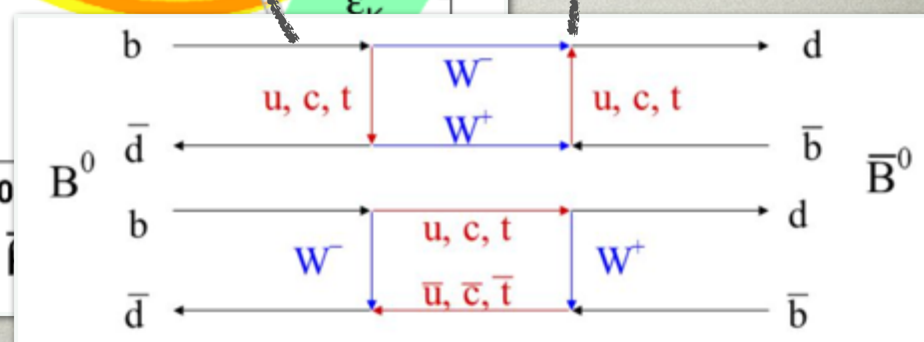
K_0
$\overline{K}_0$
s u,c,t d
W^-
W^+
$\bar{d}$ $\bar{u}\bar{c},\bar{t}$ $\bar{s}$



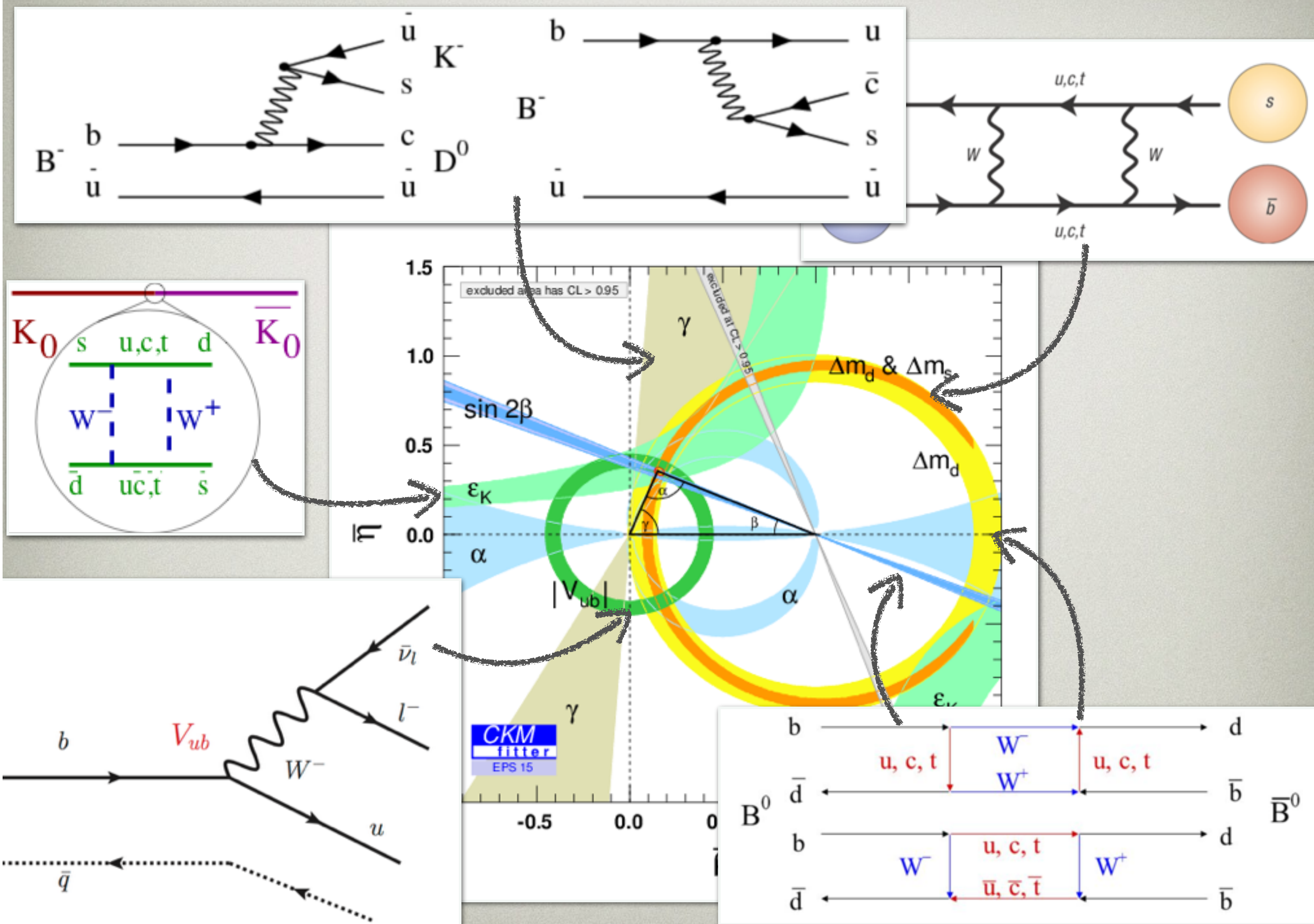
excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
$\bar{\eta}$
α
$|V_{ub}|$
α
γ
1.5
1.0
0.5
0.0
-0.5
0.0
CKM fitter
EPS 15



$\bar{\nu}_l$
l^-
b
V_{ub}
W^-
u
$\bar{q}$

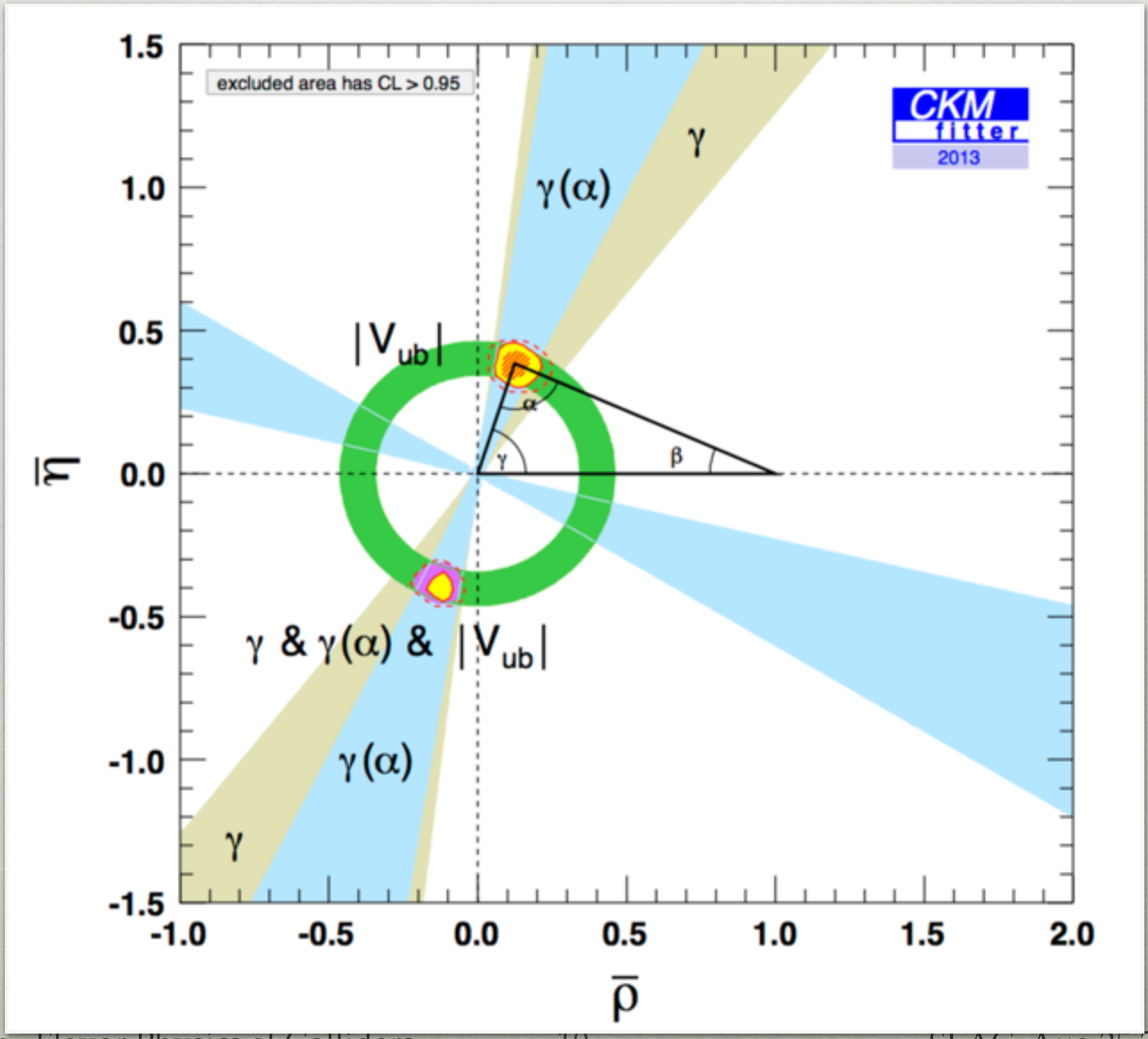


b
d
W^-
u, c, t
u, c, t
W^+
$\bar{d}$
$\bar{b}$
B^0
$\bar{B}^0$
b
d
u, c, t
W^-
W^+
$\bar{u}, \bar{c}, \bar{t}$
$\bar{d}$
$\bar{b}$


B⁻
b
ū
u
K⁻
s
c
D⁰
u
c̄
s
u,c,t
W
s
b̄
K0
K̄0
s
u,c,t
d
W⁻
W⁺
d̄
ū c̄,t̄
s̄
excluded area has CL > 0.95
excluded at CL > 0.95
1.5
1.0
0.5
0.0
-0.5
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
|V_ub|
CKM fitter
EPS 15
b
V_ub
W⁻
ν̄_l
l⁻
u
q̄
B⁰
B̄⁰
d
d̄
b̄
u, c, t
ū, c̄, t̄
W⁻
W⁺

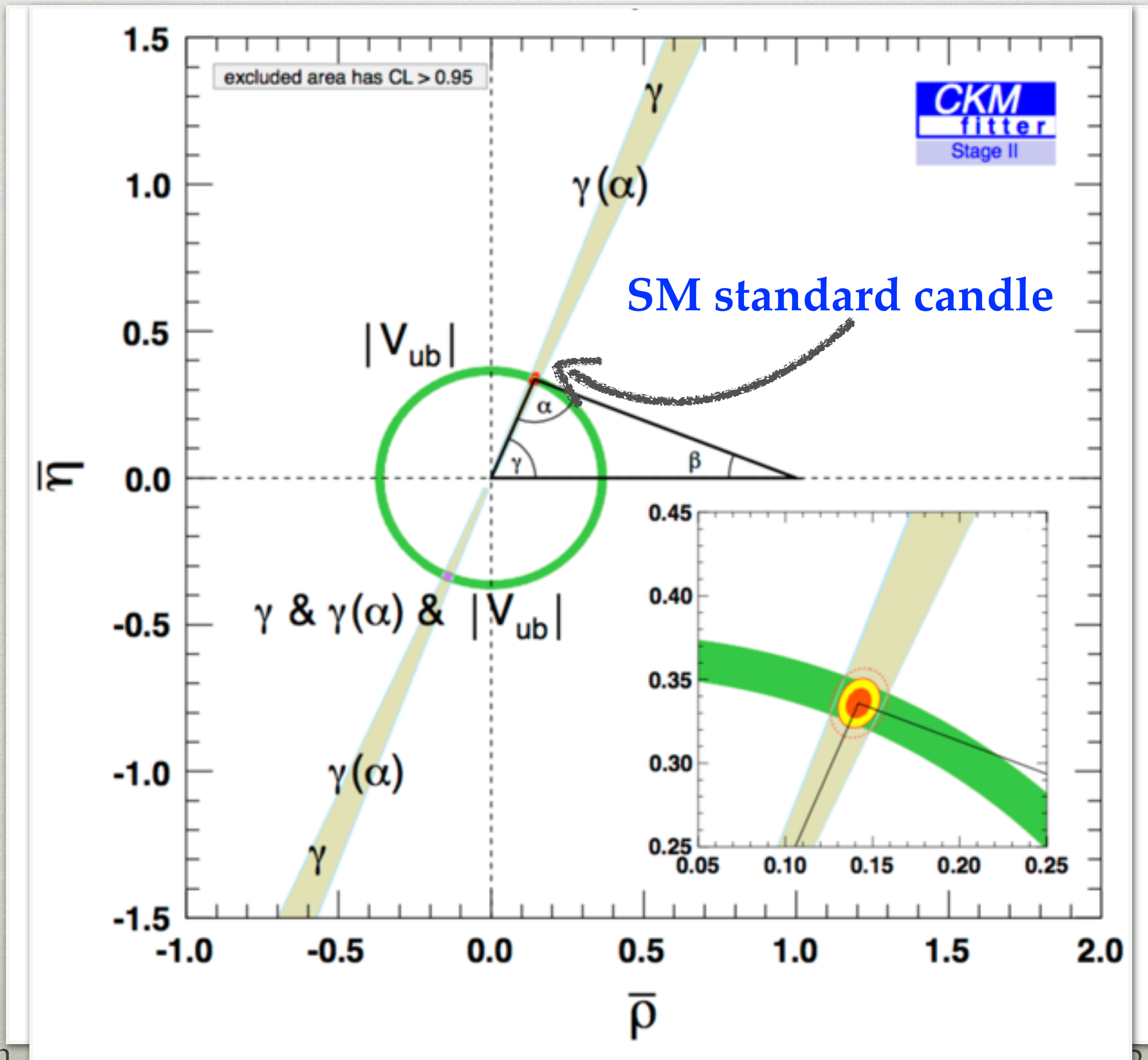
THE FUTURE: TREE PROCESSES @ BELLE 2

Charles et al, 1309.2293



THE FUTURE: TREE PROCESSES @ BELLE 2

Charles et al, 1309.2293



BELLE 2 RULE OF THUMB

- if NP gives dim-6 operators at low eng.
  - *Br* scale as ~Λ_{NP}^{-4}

$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$

- keeping NP couplings the same
  - increasing luminosity
    - $1ab^{-1} \rightarrow 50ab^{-1}$ corresponds to an increase in energy scale by ~2.7x
  - like going from 8TeV LHC to 21TeV LHC

HIGGS AND FLAVOR

HIGGS BOSON IN THE STANDARD MODEL

- the Higgs has a dual role in the SM
  - breaks EW symmetry and generates *W*, Z masses

$$D_\mu \phi = \left(\partial_\mu \phi - i g T^a W_\mu^a - i g' Y B_\mu\right)\phi$$

$$\mathcal{L}_\phi = |D_\mu \phi|^2 + \mu^2 \phi^\dagger \phi - \lambda\left(\phi^\dagger \phi\right)^2$$

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h \end{pmatrix} \qquad v = 246 \text{ GeV}$$

$$\mathcal{L}_\phi \supset \frac{1}{2}\left(\partial_\mu h\right)^2 + \left[m_W^2 W^{\mu +} W_\mu^- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right]\left(1 + 2\frac{h}{v} + \frac{h^2}{v^2}\right)$$

  - gives SM fermions their masses

FERMION MASS GENERATION IN THE STANDARD MODEL

- in the SM fermion masses from Yukawa interactions with the Higgs

$$\mathcal{L}_{\rm Yuk} = -\big(Y_d\big)_{ij}\bar{Q}_{L,i}d_{R,j}\phi - \big(Y_u\big)_{ij}\bar{Q}_{L,i}u_{R,j}\phi^c - \big(Y_\ell\big)_{ij}\bar{L}_{L,i}\ell_{R,j}\phi + \text{h.c.}$$

$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix} \quad v = 246 \text{ GeV}$$

$$\mathcal{L}_f = -m_f\bar{f}f\Big(1+\frac{h}{v}\Big) = m_f\bar{f}f - \frac{y_f}{\sqrt{2}}\bar{f}fh$$

$$y_f = \sqrt{2}m_f/v$$

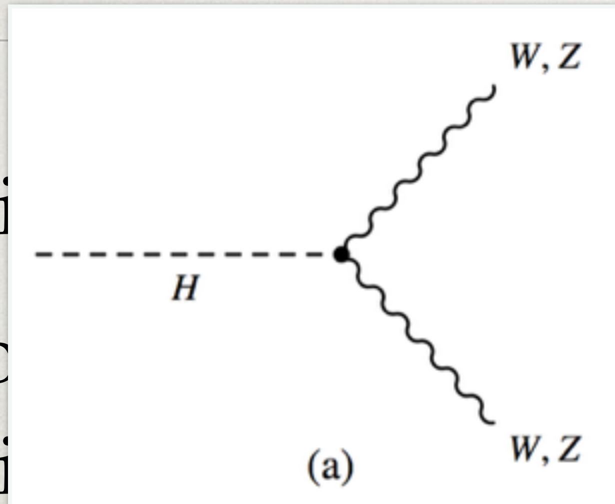
- Higgs Yukawa couplings proportional to masses
- masses and Yukawas diagonal in the same basis

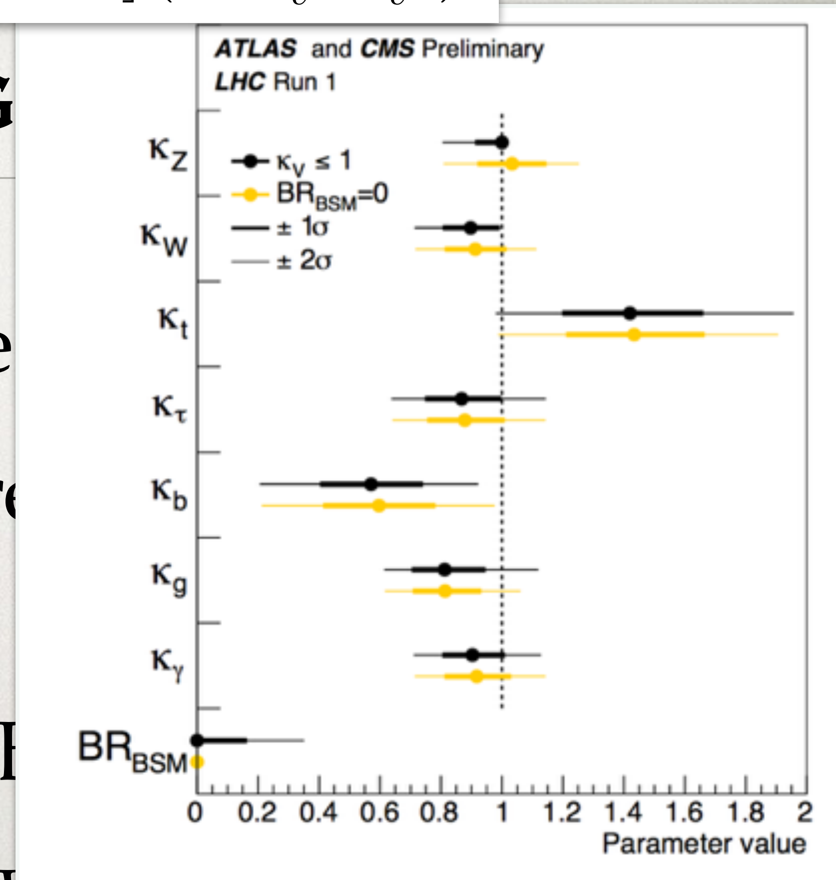
SM HIGGS?

- Higgs boson discovery July 2012
- how closely does it resemble the SM Higgs?
- responsible for EWSB?
  - from couplings to $W,Z \Rightarrow$ yes, most of it
- fermion mass generation
  - does it couple to fermions?

$$\mathcal{L}_\phi \supset \frac{1}{2}(\partial_\mu h)^2 + \left[\kappa_W m_W^2 W^{\mu+} W_\mu^- + \frac{\kappa_Z}{2} m_Z^2 Z^\mu Z_\mu\right]\left(1 + 2\frac{h}{v} + \frac{h^2}{v^2}\right)$$

SM HIG





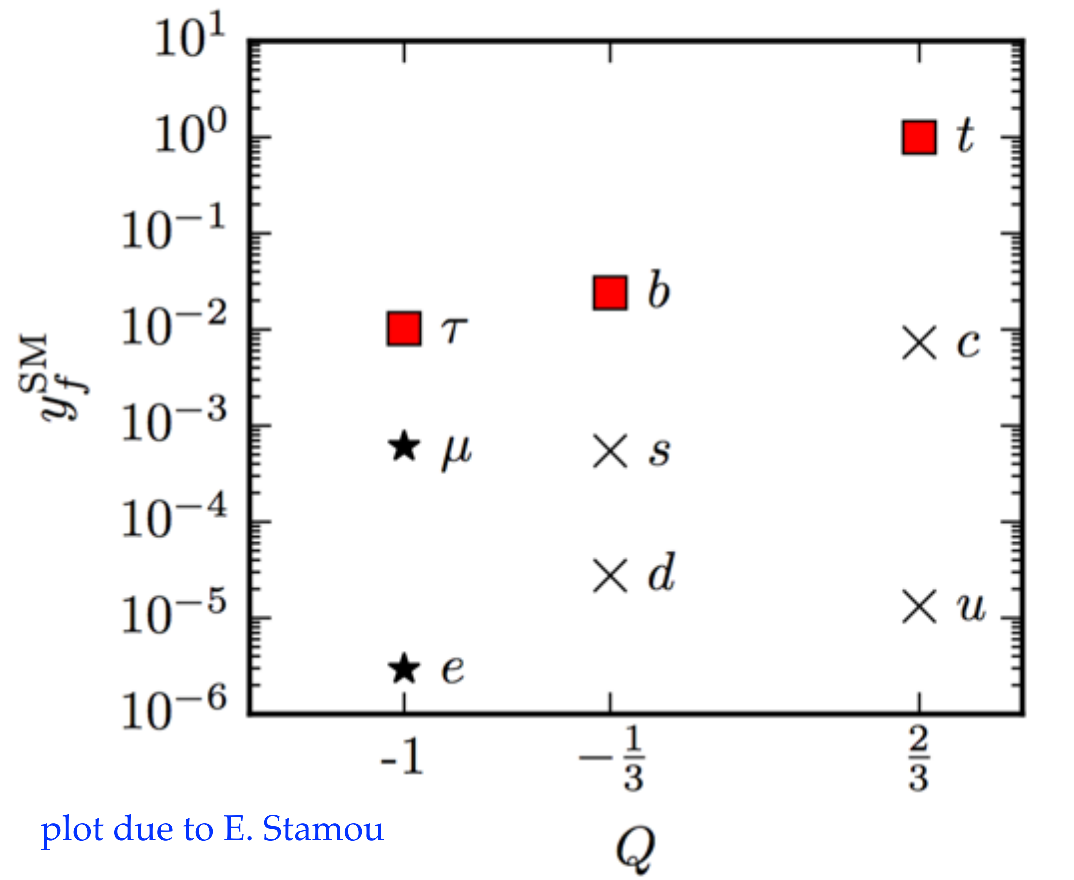
- Hi ve
- ho t re Hi
- responsible for EWSI
  - from couplings to $W,Z \Rightarrow$ yes, most of it
- fermion mass generation
  - does it couple to fermions?

YUKAWA COUPLINGS : NONTRIVIAL FLAVOR STRUCTURE

- fermion masses are very hierarchical
- what is the origin of this?
  - this is the **SM flavor puzzle**
- in the SM

$$y_f = \sqrt{2} m_f / v$$

- implies Higgs has very hierarchical couplings to fermions
- how well have we tested this?



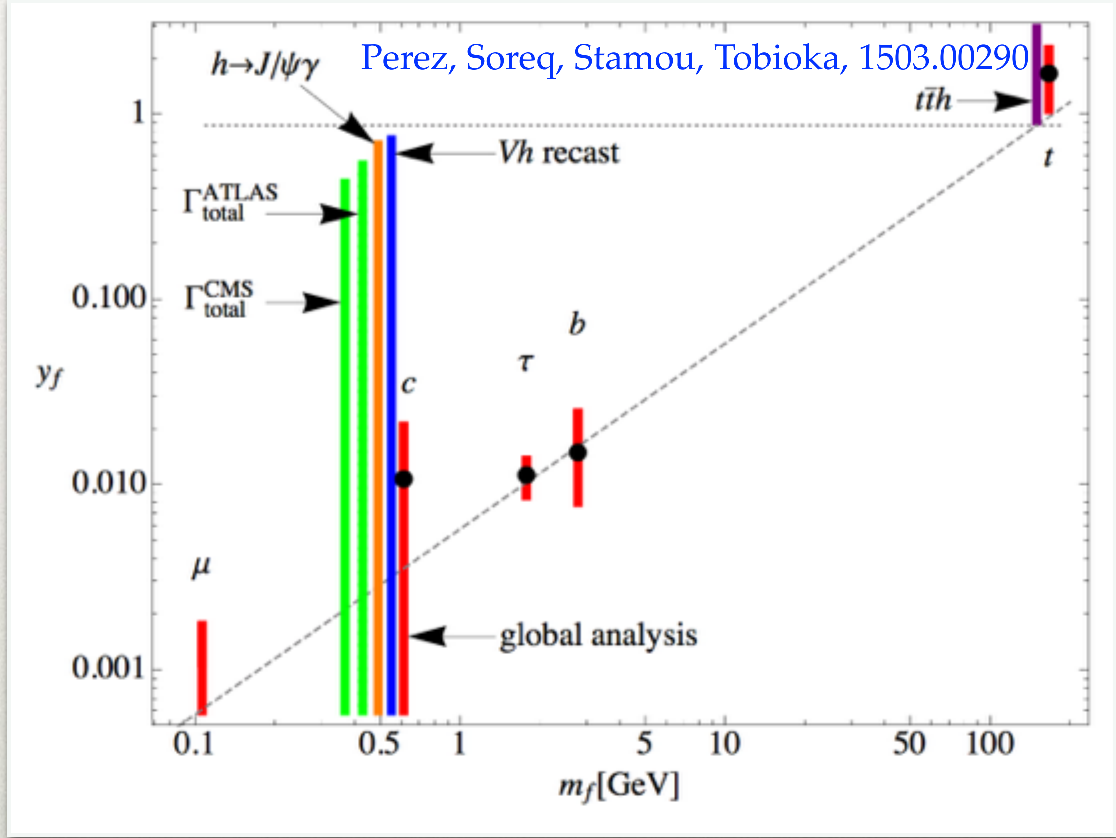
plot due to E. Stamou

TESTING THE FLAVOR OF THE HIGGS

Nir, 1605.00433

- several questions
  - proportionality
    $$y_{ii} \propto m_i$$
  - factor of proportionality
    $$y_{ii}/m_i = \sqrt{2}/v$$
- diagonality (flavor violation)
  $$y_{ij} = 0, \quad i \neq j$$
- reality (CP violation)
  $$\mathrm{Im}(y_{ij}) = 0$$

$$y_f^{\rm SM} = \sqrt{2} m_f / v$$

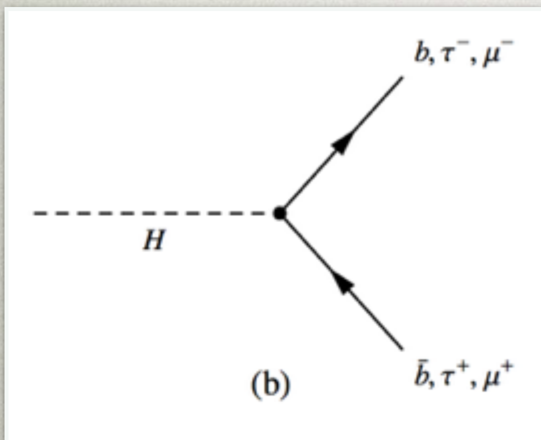


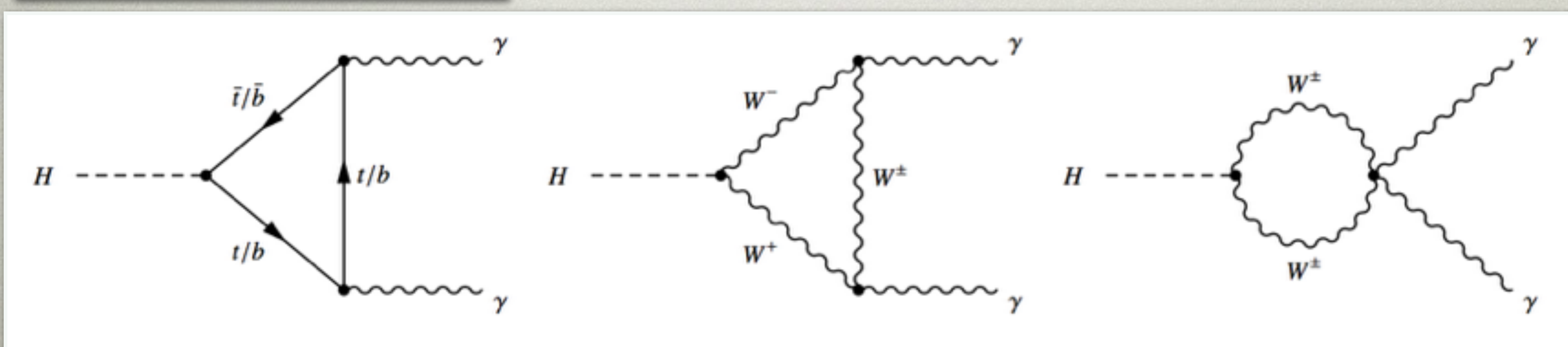
PROPORTIONALITY

- "proportionality" and "factor of proportionality"

$$\boxed{y_{ii} \propto m_i} \qquad \boxed{y_{ii}/m_i = \sqrt{2}/v}$$

- tested for 3rd generation fermions



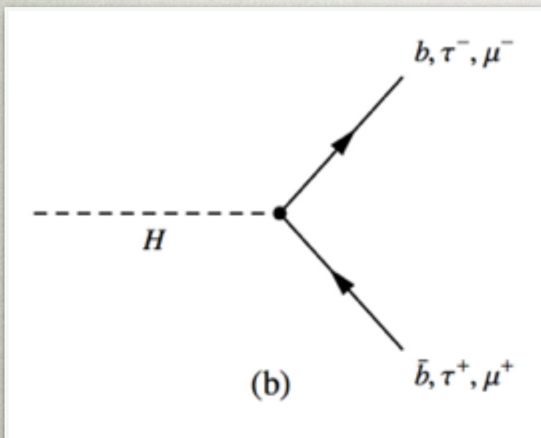


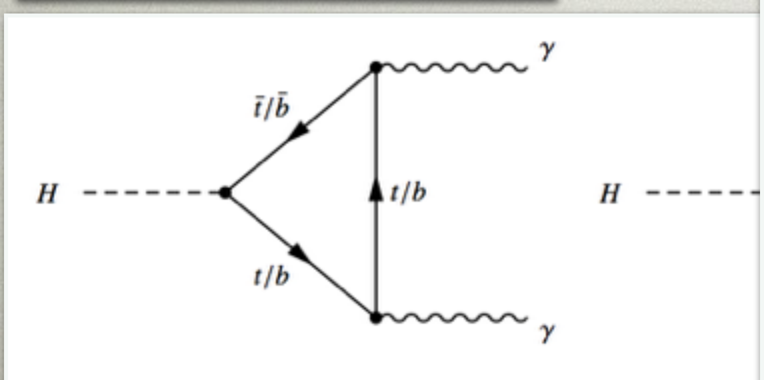
PROPORTIONALITY

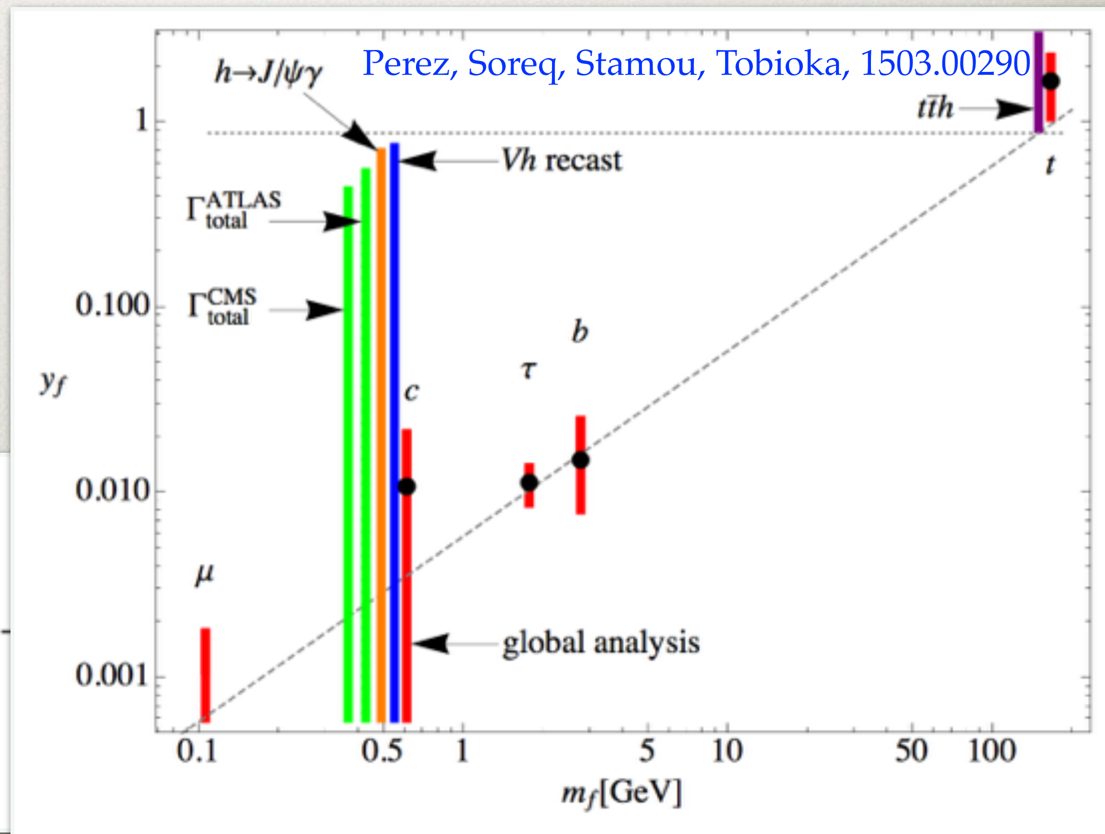
- "proportionality" and "factor of proportionality"

$$y_{ii} \propto m_i \qquad\qquad y_{ii}/m_i = \sqrt{2}/v$$

- tested for 3rd generation fermions







HIERARCHICAL COUPLINGS?

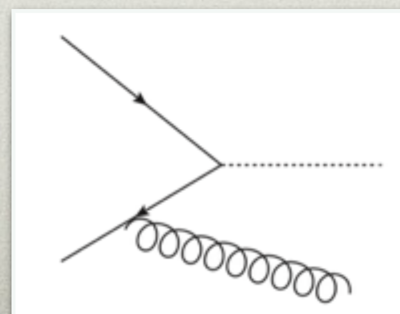
- does Higgs couple to the first two generations?
  - tough: couplings are small
- more modest question: can we show that the couplings are hierarchical?
  - already known for charged leptons and up-quarks

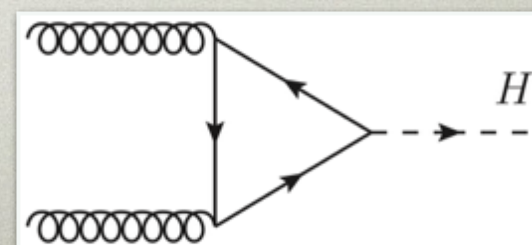
direct measurements

$$\frac{y_{e(\mu)}^{\rm exp}}{y_\tau^{\rm exp}} < 0.22(0.28)\,, \qquad \frac{y_{u(c)}^{\rm exp}}{y_t^{\rm exp}} < 0.036\,, \qquad \frac{y_{d(s)}^{\rm exp}}{y_b^{\rm exp}} < 5.6\,.$$

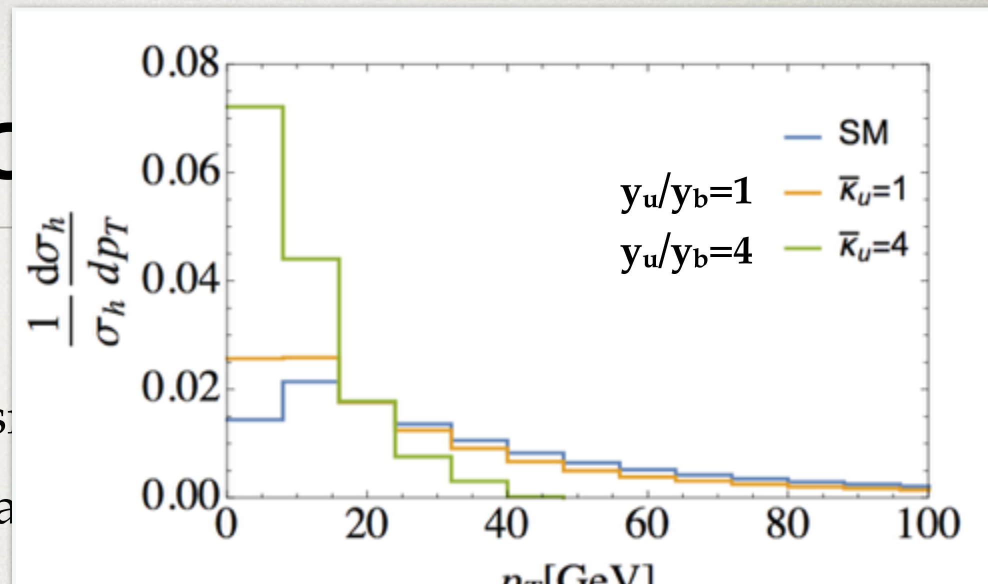
global fit

  - can we establish this for down quarks?
- seems possible to establish $y_d < y_b$ at high luminosity LHC (~300 fb^{-1})
  - from Higgs + jet p_T distributions





HIERARCHIC



Soreq et al., 1606.09621

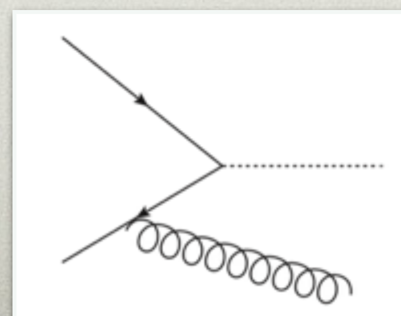
- does Higgs couple to the
  - tough: couplings are s
- more modest question: ca hierarchical?
  - already known for charged leptons and up-quarks

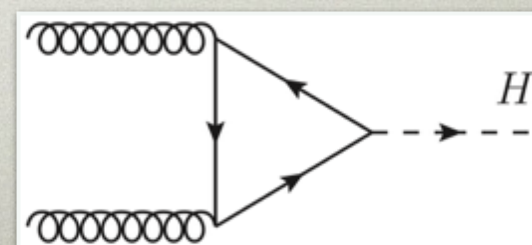
$$\frac{y_{e(\mu)}^{\rm exp}}{y_\tau^{\rm exp}} < 0.22(0.28)\,, \qquad \frac{y_{u(c)}^{\rm exp}}{y_t^{\rm exp}} < 0.036\,, \qquad \frac{y_{d(s)}^{\rm exp}}{y_b^{\rm exp}} < 5.6\,.$$

direct measurements

global fit

  - can we establish this for down quarks?
- seems possible to establish $y_d<y_b$ at high luminosity LHC (~300 fb^{-1})
  - from Higgs + jet p_T distributions





CPV AND FV HIGGS COUPLINGS TO SM FERMIONS

- flavor violating couplings?

$$\boxed{y_{ij} = 0, \quad i \neq j}$$

  - very sensitive indirect probes (from precise bounds on FCNCs, such at $\tau \to \mu\gamma$)
  - from Higgs decays (e.g. $h \to \tau\mu$)

- CP violating couplings?

$$\boxed{\mathrm{Im}(y_{ij}) = 0}$$

  - severe bounds from precision measurements of CP violating observables (such as electric dipole moments, EDMs)

see talk by V. Cirigliano

PROBE OF NEW PHYSICS?

- discovery of a FV or CPV Higgs Yukawa coupling would mean New Physics
- how sensitive are these to New Physics?
- how precise are the experimental measurements?

see e.g., Falkowski, Straub, Vicente, 1312.5329

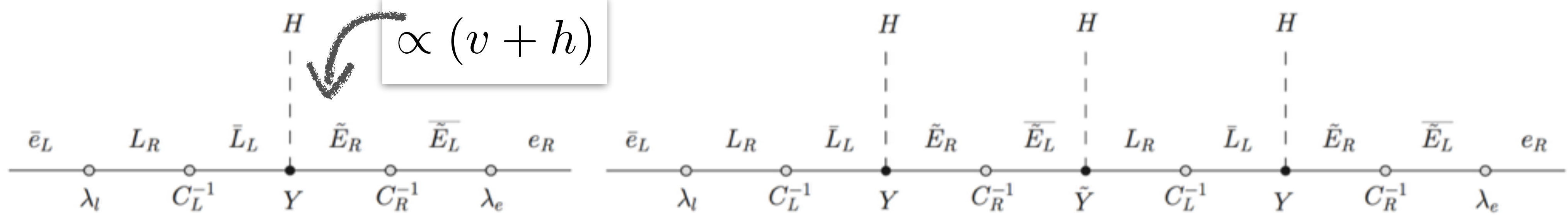
THE EFFECTS OF NEW PHYSICS

- an example: SM + 3 gen. of vectorlike leptons $L_i = (N_i, E_i)$, $\tilde{E}_i$

$$\mathcal{L}_{F,c} = -M\left(\bar{L}C_L L + \bar{E}C_R E\right) - \left(\bar{L}_L Y \tilde{E}_R H + \bar{L}_R \tilde{Y} \tilde{E}_L H + \text{h.c.}\right).$$

$$\mathcal{L}_{\text{mix}} = M\left(\bar{l}_L \lambda_l L_R + \overline{\tilde{E}}_L \lambda_e e_R\right) + \text{h.c.}$$

- imagine that the Higgs only couples to these but not the SM fermions



$\propto (v + h)$

$\propto (v^3 + 3v^2 h + \cdots)$

- the two contribs. have different flavor structure in general
- the Yukawas misaligned from the masses by $1/M^2$

$$y_f = \frac{\sqrt{2}}{v} m_f + \frac{v^2}{M^2} \lambda_\ell C_L^{-1} Y C_R^{-1} \tilde{Y} C_L^{-1} Y C_R^{-1} \lambda_e$$

EFFECTIVE FIELD THEORY DESCRIPTION

- this result is general - integrate heavy NP and obtain EFT description

$$\mathcal{L}_{\rm Yuk} = -\left(Y_f\right)_{ij}\left(\bar{f}^i_L f^j_R\right)\phi + \text{h.c.}$$

$$\Delta\mathcal{L}_{\rm Yuk} = -\frac{\lambda'_{ij}}{\Lambda^2}\left(\bar{f}^i_L f^j_R\right)\phi\left(\phi^\dagger\phi\right) + \text{h.c.} + \cdots$$

$$\sqrt{2}m_f = V_L\left(Y_f + \frac{v^2}{2\Lambda^2}\lambda'\right)V_R^\dagger v$$

$$y_f = V_L\left(Y_f + 3\frac{v^2}{2\Lambda^2}\lambda'\right)V_R^\dagger$$

$$\left(y_f\right)_{ij} = \sqrt{2}\frac{m_i}{v}\delta_{ij} + \frac{v^2}{\Lambda^2}\left(V_L\lambda' V_R^\dagger\right)_{ij}$$

- important: SM Yukawa couplings small for the first two generations
  - Λ can be large but still have an effect for *λ'~ O(1)*
- the effects different in different NP models of flavor
  - can learn about these from measured patterns

HOW LARGE?

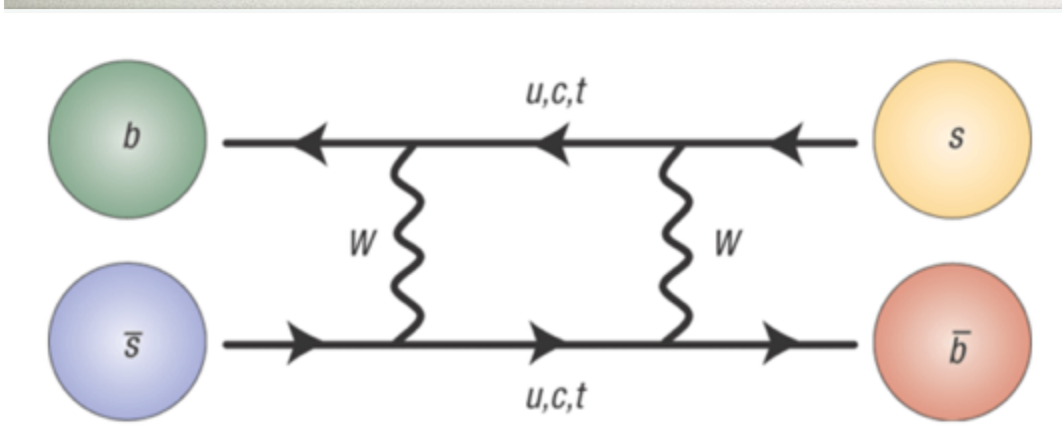
- a useful rule of thumb for maximal FV
  - do not want fine-tuned cancelations when diagonalizing mass matrix

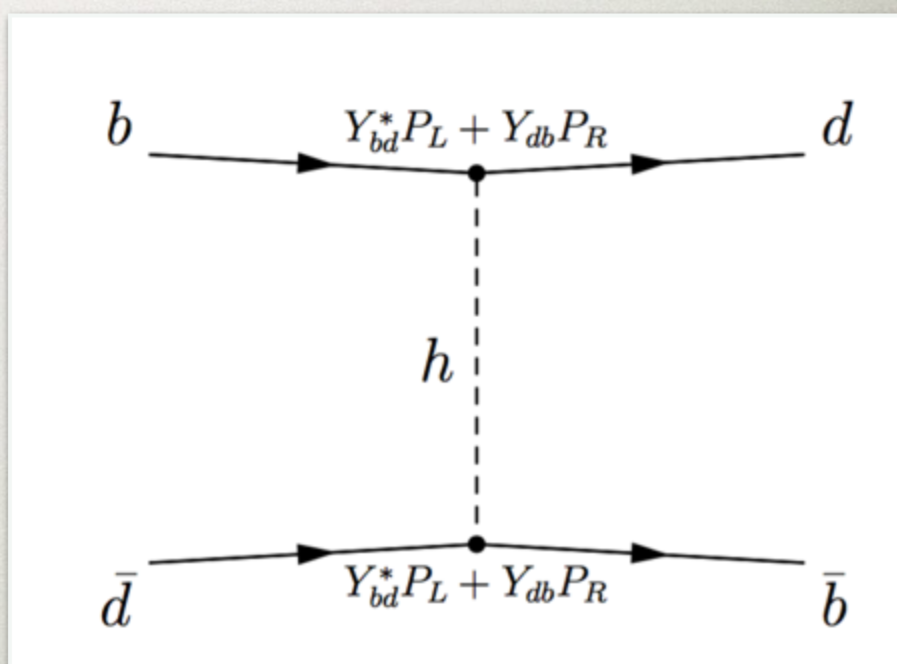
$$y_{\tau\mu} y_{\mu\tau} \lesssim 2\frac{m_\tau m_\mu}{v^2}$$

  - also what we would expect for $\Lambda \gtrsim v$

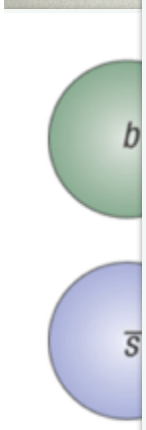
MESON MIXING

- in K^0-$\bar{K}^0$, B_d-$\bar{B}_d$, B_s-$\bar{B}_s$, D^0-$\bar{D}^0$ small mass splitting due to FV interactions

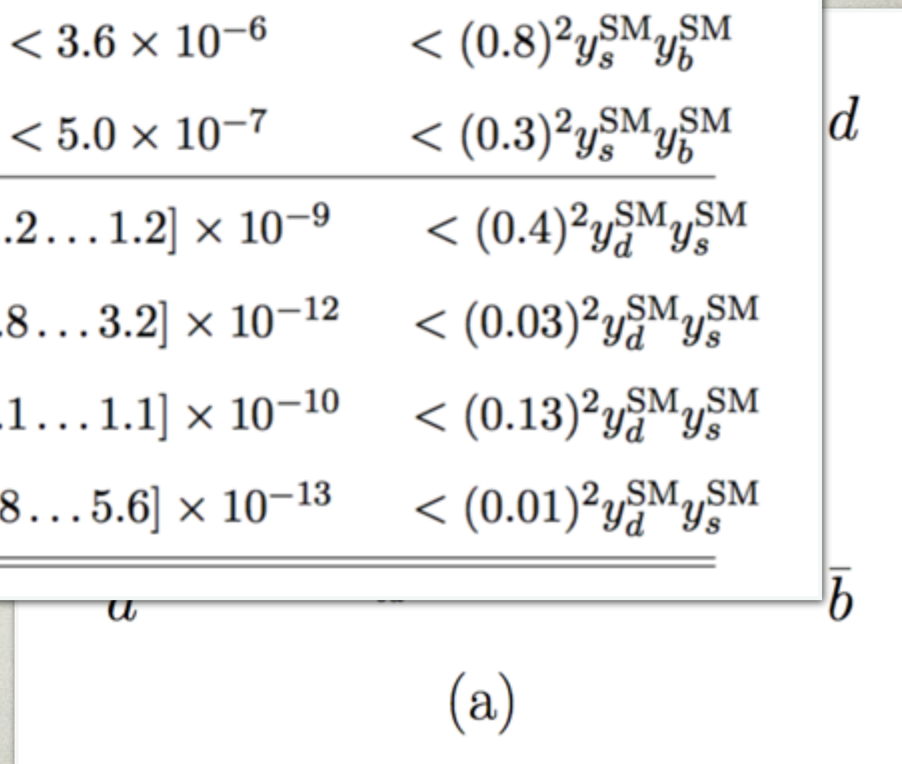




(a)



Technique	Coupling	Constraint	Norm. Constr.
D^0 oscill. [48]	$\lvert y_{uc}\rvert^2, \lvert y_{cu}\rvert^2$	$< 1.0 \times 10^{-8}$	$< (0.5)^2 y_u^{\rm SM} y_c^{\rm SM}$
	$\lvert y_{uc} y_{cu}\rvert$	$< 1.5 \times 10^{-9}$	$< (0.2)^2 y_u^{\rm SM} y_c^{\rm SM}$
B_d^0 oscill. [48]	$\lvert y_{db}\rvert^2, \lvert y_{bd}\rvert^2$	$< 4.6 \times 10^{-8}$	$< (0.4)^2 y_d^{\rm SM} y_b^{\rm SM}$
	$\lvert y_{db} y_{bd}\rvert$	$< 6.6 \times 10^{-9}$	$< (0.15)^2 y_d^{\rm SM} y_b^{\rm SM}$
B_s^0 oscill. [48]	$\lvert y_{sb}\rvert^2, \lvert y_{bs}\rvert^2$	$< 3.6 \times 10^{-6}$	$< (0.8)^2 y_s^{\rm SM} y_b^{\rm SM}$
	$\lvert y_{sb} y_{bs}\rvert$	$< 5.0 \times 10^{-7}$	$< (0.3)^2 y_s^{\rm SM} y_b^{\rm SM}$
K^0 oscill. [48]	${\rm Re}(y_{ds}^2), {\rm Re}(y_{sd}^2)$	$[-1.2 \ldots 1.2] \times 10^{-9}$	$< (0.4)^2 y_d^{\rm SM} y_s^{\rm SM}$
	${\rm Im}(y_{ds}^2), {\rm Im}(y_{sd}^2)$	$[-5.8 \ldots 3.2] \times 10^{-12}$	$< (0.03)^2 y_d^{\rm SM} y_s^{\rm SM}$
	${\rm Re}(y_{ds}^* y_{sd})$	$[-1.1 \ldots 1.1] \times 10^{-10}$	$< (0.13)^2 y_d^{\rm SM} y_s^{\rm SM}$
	${\rm Im}(y_{ds}^* y_{sd})$	$[-2.8 \ldots 5.6] \times 10^{-13}$	$< (0.01)^2 y_d^{\rm SM} y_s^{\rm SM}$



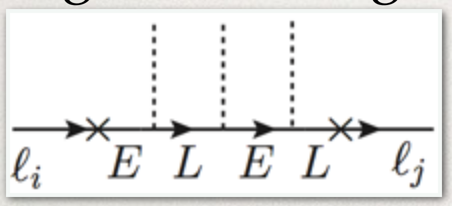
(a)

DIPOLE TRANSITIONS

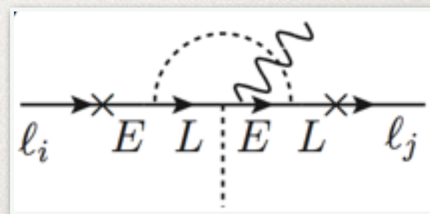
- severe exp. bounds on dipole transitions BaBar, 0908.2381 MEG, 1605.05081

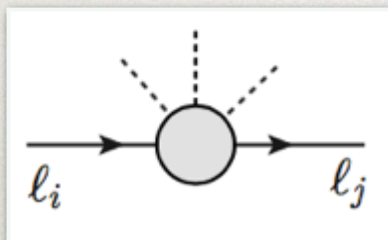
$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \cdot 10^{-8} \qquad \mathrm{Br}(\tau \to e\gamma) < 3.3 \cdot 10^{-8} \qquad \mathrm{Br}(\mu \to e\gamma) < 4.2 \cdot 10^{-13}$$

- same NP diagrams that give $h\to\tau\mu$ generically also give $\tau\to\mu\gamma$ at 1-loop

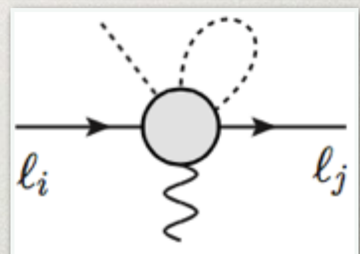


$\Longrightarrow$





$\Longrightarrow$



- NDA estimate for the EM dipole operators

$$y_{\tau\mu} \sim \frac{v^2}{\Lambda^2}\lambda'_{\tau\mu}$$

$$c_{L,R} \sim \frac{v}{m_\tau \Lambda^2}\lambda'_{\tau\mu,\mu\tau} \sim \frac{1}{m_\tau v} y_{\tau\mu,\mu\tau}$$

$$\mathcal{L}_{\rm eff} = c_{L,R}\, m_\tau \frac{e}{8\pi^2}\left(\bar\mu_{R,L}\sigma^{\mu\nu}\tau_{L,R}\right)F_{\mu\nu}$$

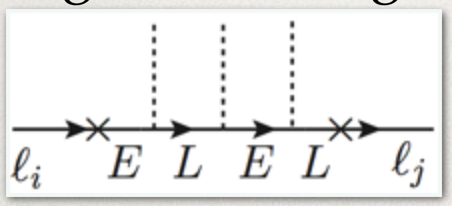
$y_{\tau\mu} \lesssim 3 \cdot 10^{-5}$ $\quad$ $y_{\tau e} \lesssim 3 \cdot 10^{-5}$ $\quad$ $y_{\mu e} \lesssim 4 \cdot 10^{-8}$

$\sqrt{y_\mu^{\rm SM} y_\tau^{\rm SM}} = 2.5 \cdot 10^{-3}$ $\quad$ $\sqrt{y_e^{\rm SM} y_\tau^{\rm SM}} = 1.7 \cdot 10^{-4}$ $\quad$ $\sqrt{y_e^{\rm SM} y_\mu^{\rm SM}} = 4.2 \cdot 10^{-5}$

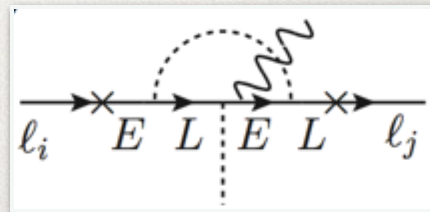
- severe exp. bounds on dipole transitions BaBar, 0908.2381 MEG, 1605.05081

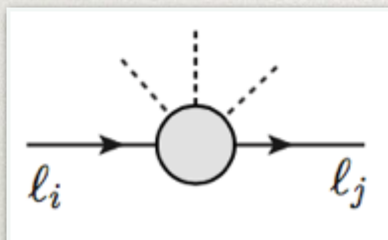
$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \cdot 10^{-8}$ $\quad$ $\mathrm{Br}(\tau \to e\gamma) < 3.3 \cdot 10^{-8}$ $\quad$ $\mathrm{Br}(\mu \to e\gamma) < 4.2 \cdot 10^{-13}$

- same NP diagrams that give $h \to \tau\mu$ generically also give $\tau \to \mu\gamma$ at 1-loop

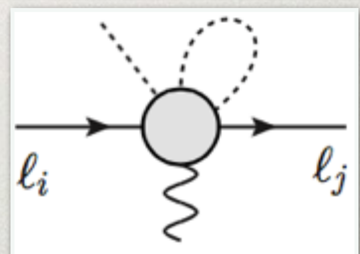


$\Longrightarrow$





$\Longrightarrow$



- NDA estimate for the EM dipole operators

$$y_{\tau\mu} \sim \frac{v^2}{\Lambda^2} \lambda'_{\tau\mu}$$

$$c_{L,R} \sim \frac{v}{m_\tau \Lambda^2} \lambda'_{\tau\mu,\mu\tau} \sim \frac{1}{m_\tau v} y_{\tau\mu,\mu\tau}$$

$$\mathcal{L}_{\rm eff} = c_{L,R}\, m_\tau \frac{e}{8\pi^2} (\bar\mu_{R,L} \sigma^{\mu\nu} \tau_{L,R}) F_{\mu\nu}$$

$h \to \tau\mu$ exp. info

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

  CMS-HIG-14-005

  - CMS: $Br(h \to \tau\mu) = (0.89 \pm 0.39)\%$
  - ATLAS: $Br(h \to \mu\tau) = (0.53 \pm 0.51)\%$

  ATLAS, 1508.03372; 1604.07730

- first 13 TeV result

  CMS-PAS-HIG-16-005

  - CMS @ 13 TeV, 2.3 fb^{-1}: no excess, $Br(H \to \tau\mu) < 1.20\%$ (1.62% expected)

EXCLUDED?

- if Higgs the only* source of ferm. mass $\Rightarrow Br(\tau\to\mu\gamma)$ too large by <u>4 orders</u> of magnitude
  - *and no tunings   for tuned MSSM example see e.g., Aloni, Nir, Stamou, 1511.00979
- alternatively one could do EFT analysis of low energy constraints with the Lagrangian after EWSB

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

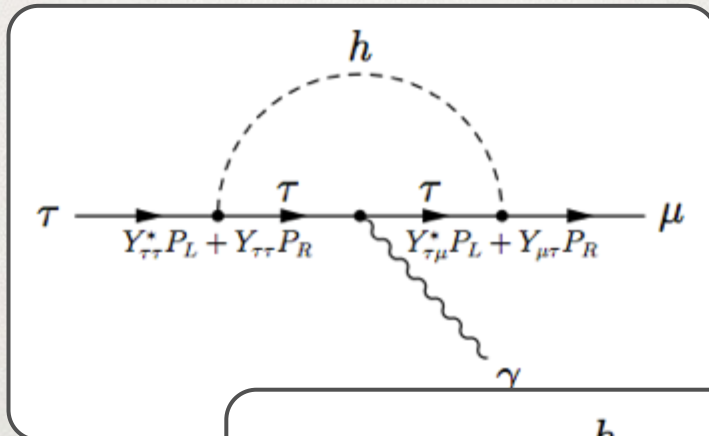
  - does not care whether Higgs is part of a doublet
  - or if there are other EWSB sources

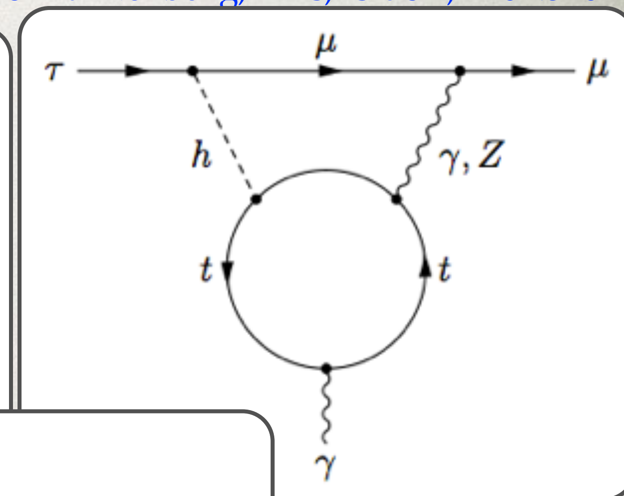
$h \to \tau\mu$

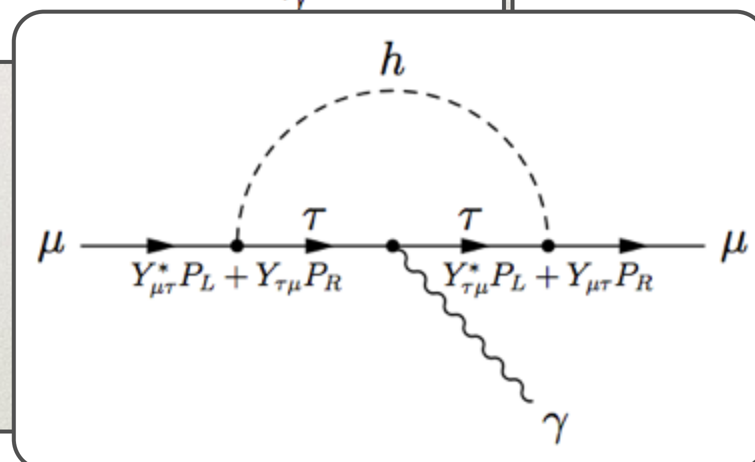
Harnik, Kopp, JZ, 1209.1397

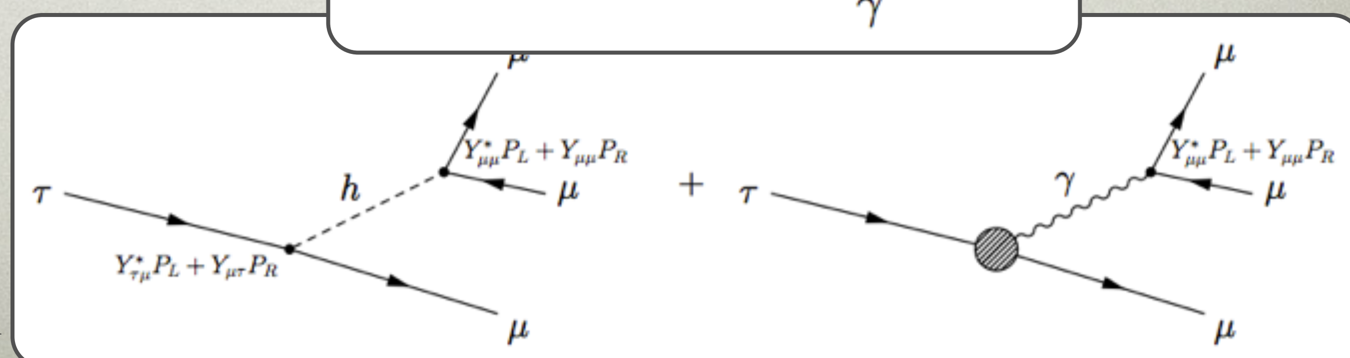
see also Blankenburg, Ellis, Isidori, 1202.5704

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



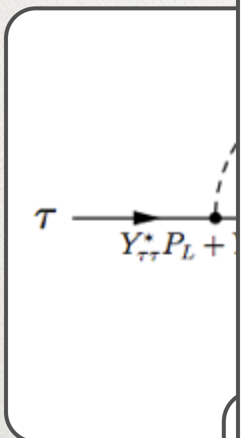


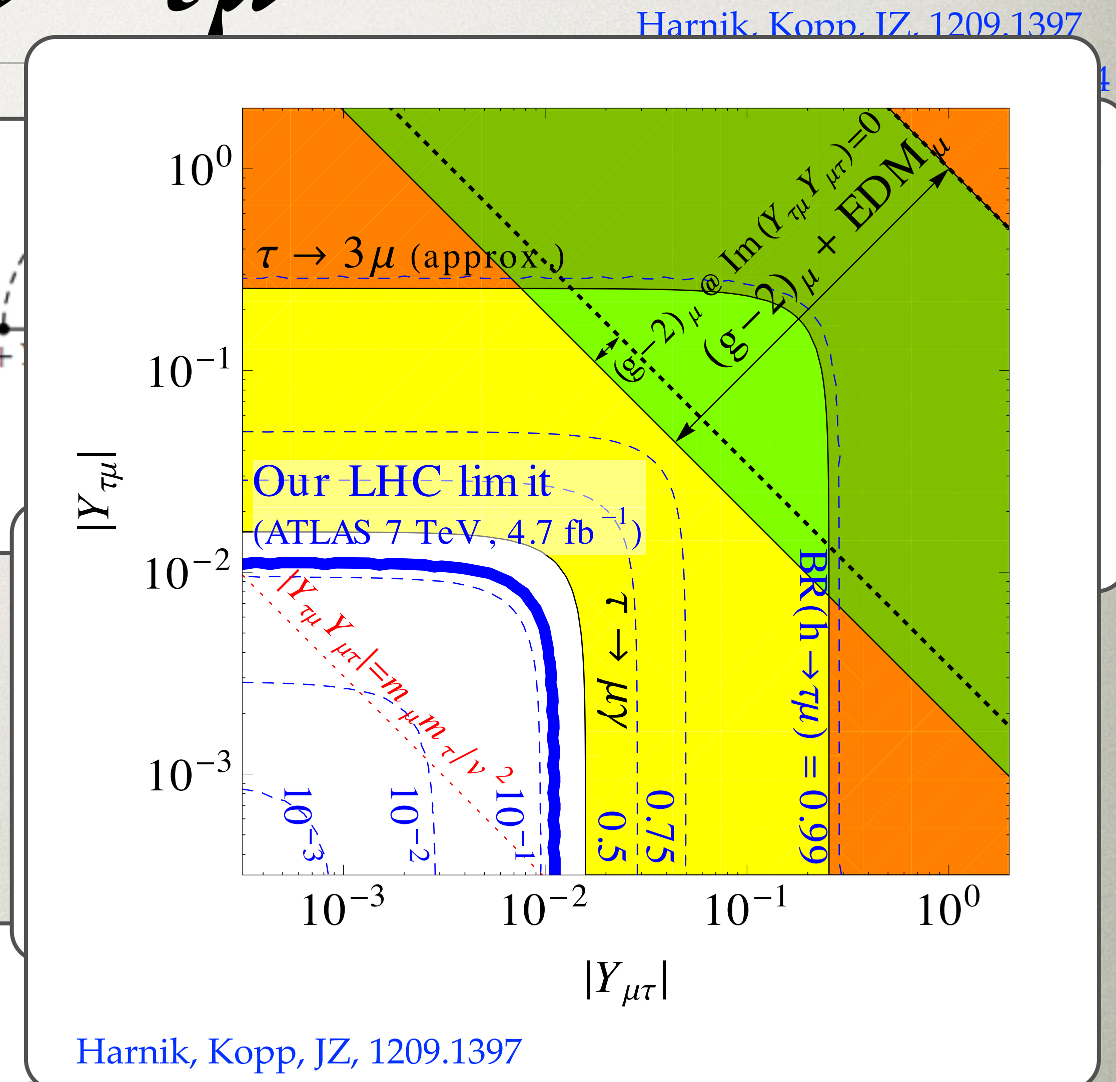


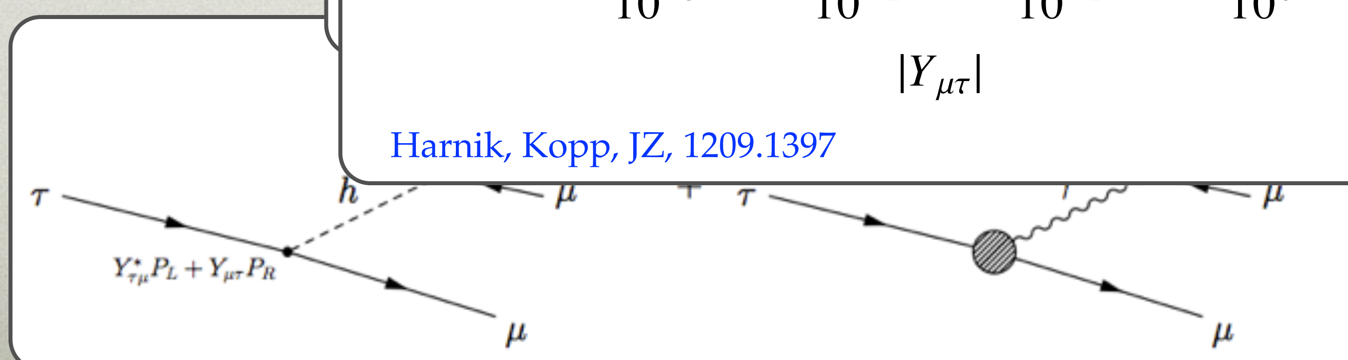


$h \to \tau\mu$

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

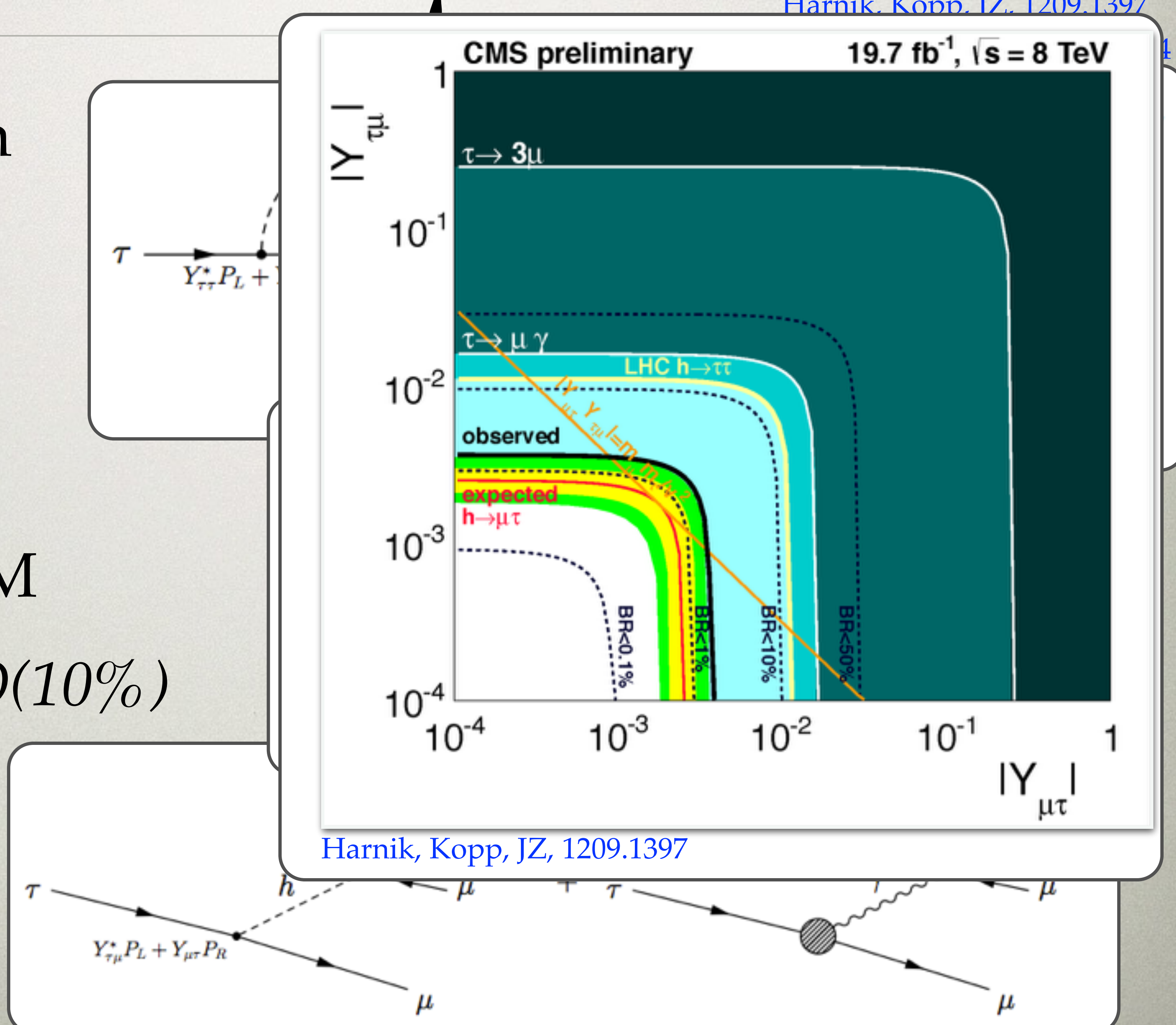






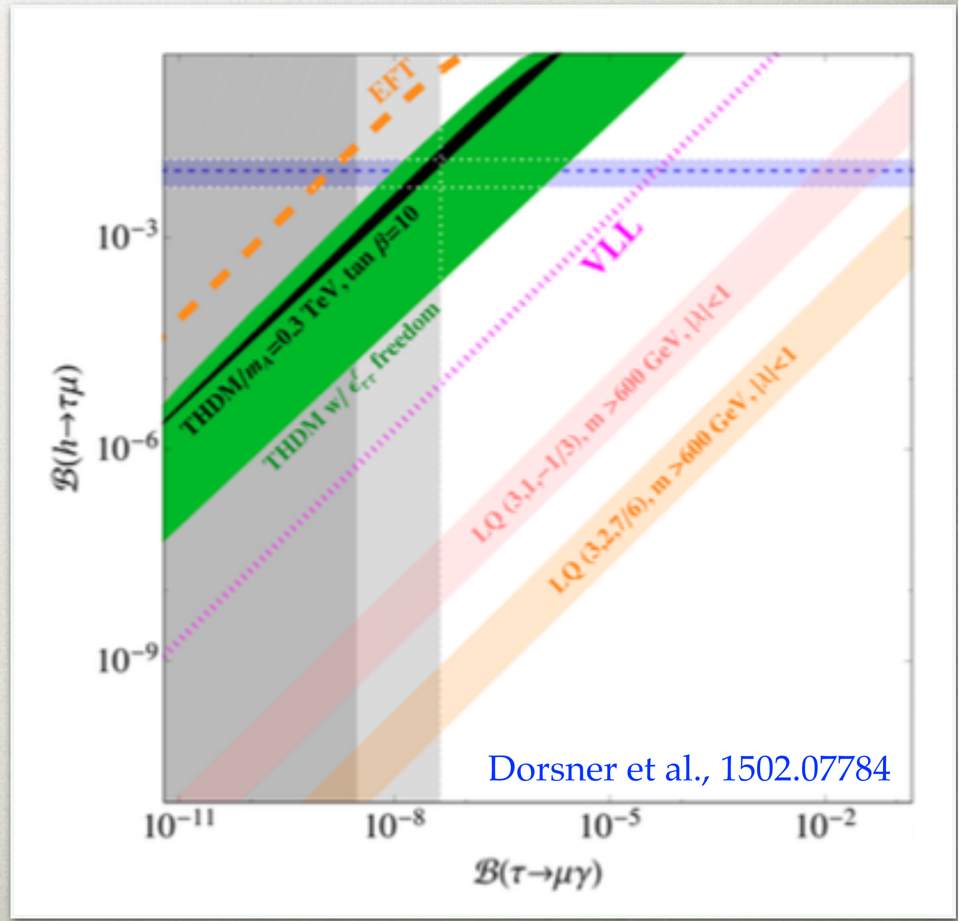
$h \to \tau\mu$

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



LARGE FV HIGGS DECAYS?

- Can one have large flavor violating Higgs decays in reasonable NP models?
- What is so special about type III 2HDM?



VIABLE MODELS: SEQUESTERED MASS GENERATION

Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

- a family of viable new physics models
  - lepton mass matrix of the form

$$\mathcal{M}^\ell = \underbrace{\mathcal{M}_0^\ell}_{\text{rank 1 matrix, from } \phi} + \underbrace{\Delta\mathcal{M}^\ell}_{\text{rank 2 or 3 matrix}},$$

  - scalar ϕ the primary component of the Higgs
    - accounts for the bulk of m_τ
  - ΔM_l due to an additional source of EWSB
    - accounts for m_e and m_μ

2HDM

- two Higgs doublets, neutral compts: ϕ, ϕ', vevs v, v'
  - ϕ couples to 3rd family, ϕ' to all three

$$\tan\beta = v/v'$$

$$M^l = \begin{pmatrix} \mathbf{x} & \mathbf{x} & \mathbf{x} \\ \mathbf{x} & \mathbf{x} & \mathbf{x} \\ \mathbf{x} & \mathbf{x} & \mathbf{x} \end{pmatrix}$$

ϕ'

ϕ **and** ϕ'

  - a hierarchy of vevs $v \gg v'$ can explain $m_\tau \gg m_\mu$
- can saturate $Br(h \to \tau\mu)$
- $Br(\tau \to \mu\gamma)$ parametrically suppressed (there is an extra y_τ insertion)
- predicts modified phenomenology of heavy Higgses

CONCLUSIONS

- flavor physics can probe NP scales well above LHC
- flavor violating Higgs decays a window to fermion mass generation

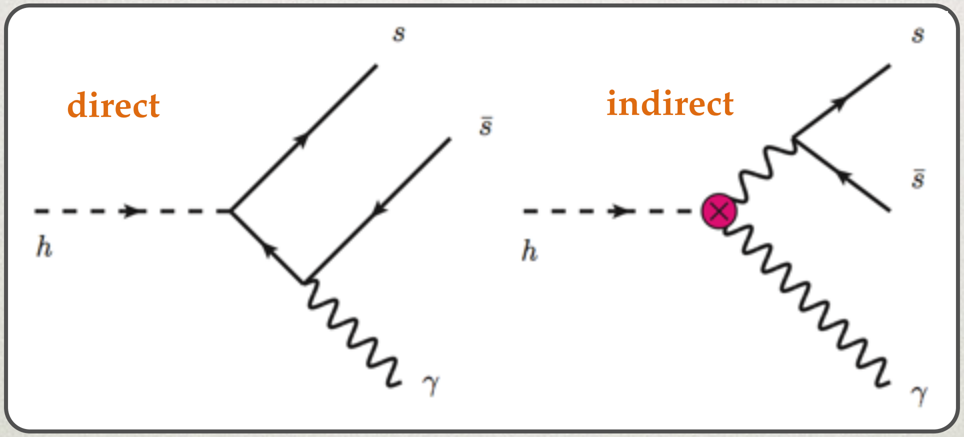
BACKUP SLIDES

DIFFERENT PROBES

- several probes of 1st and 2nd generation Higgs yukawas proposed
  - using charm tagging for $h \to c\bar{c}$ inclusive decays
    Perez, Soreq, Stamou, Tobioka, 1503.00290
  - exclusive decays: $h \to \Upsilon\gamma$ (y_b), $h \to J/\psi\gamma$ (y_c), $h \to \phi\gamma$ (y_s)
    Bodwin, Petriello, Stoynev, Velasco, 1306.5770
    Konig, Neubert, 1505.03870
    Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722
  - isotopic shift measurements
    Delaunay, Ozeri, Perez, Soreq, 1601.05087
  - Higgs p_T distributions
    Bishara, Haisch, Monni, Re, 1606.09253
    Soreq, Zhu, JZ, 1606.09621

$h \to \phi\gamma$

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



- prediction at NLO

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(2.3\pm0.1)\kappa_\gamma - 0.43\bar{\kappa}_s\right]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2}$$

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

Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722
Konig, Neubert, 1505.03870

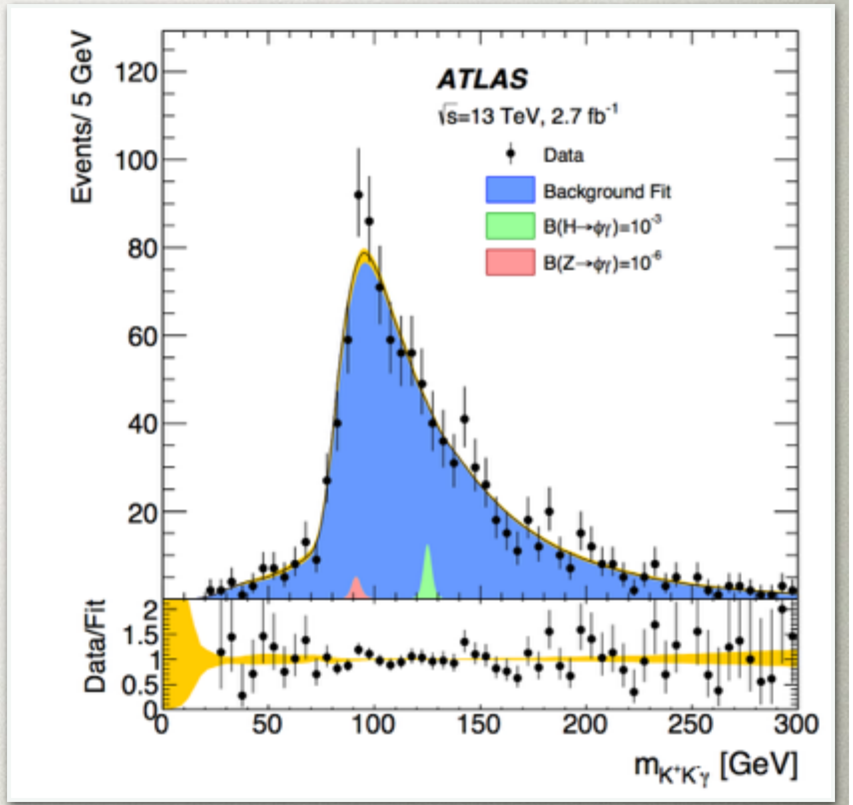
ATLAS MEASUREMENT

ATLAS, 1607.03400

- first bound on *Br(h→φγ)* by ATLAS

Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)$ [10^{-3}]	$1.5^{+0.7}_{-0.4}$	1.4

$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma[(2.3\pm0.1)\kappa_\gamma - 0.43\bar{\kappa}_s]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2}$$



- projecting to 100 TeV, 2x3ab^{-1}, same S/B

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

$$\mathrm{BR}_{h\to\phi\gamma} < 7\cdot 10^{-6}$$

$$\bar{\kappa}_s < 12$$

CHARM YUKAWA

- similarly Y_c from $h \to J/\psi\gamma$

Bodwin, Petriello, Stoynev, Velasco, 1306.5770

Konig, Neubert, 1505.03870

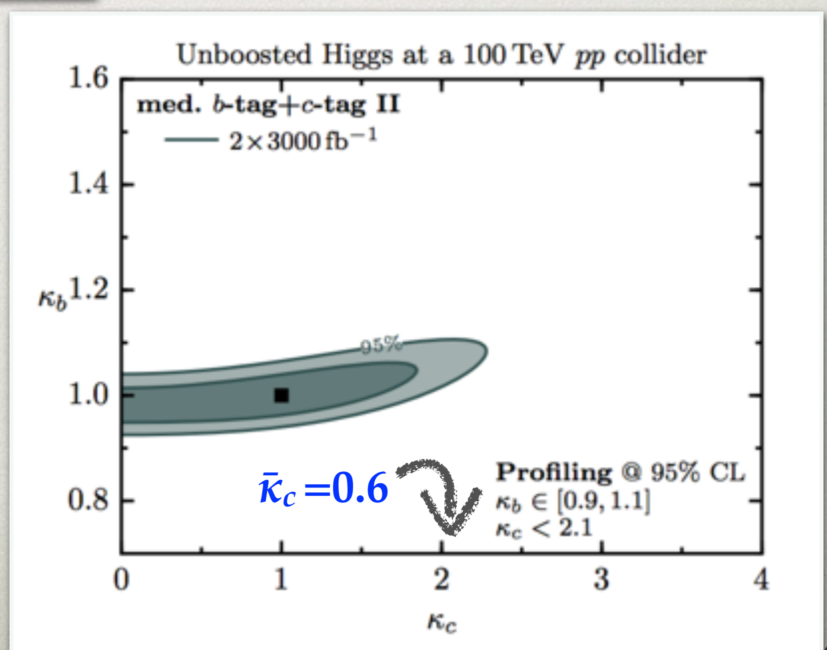
$$\frac{\mathrm{BR}_{h\to J/\psi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma[(3.0\pm 0.15)\kappa_\gamma - 0.56\bar{\kappa}_c]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2}$$

ATLAS, 1501.03276

- projecting the ATLAS bound to 100TeV, 2x3ab^{-1}, same S/B: $\boxed{\bar{\kappa}_c < 4}$

Perez, Soreq, Stamou, Tobioka, 1505.06689

- from inclusive, using charm tagging

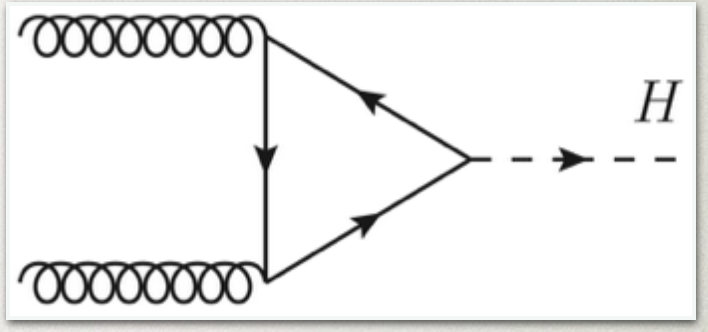


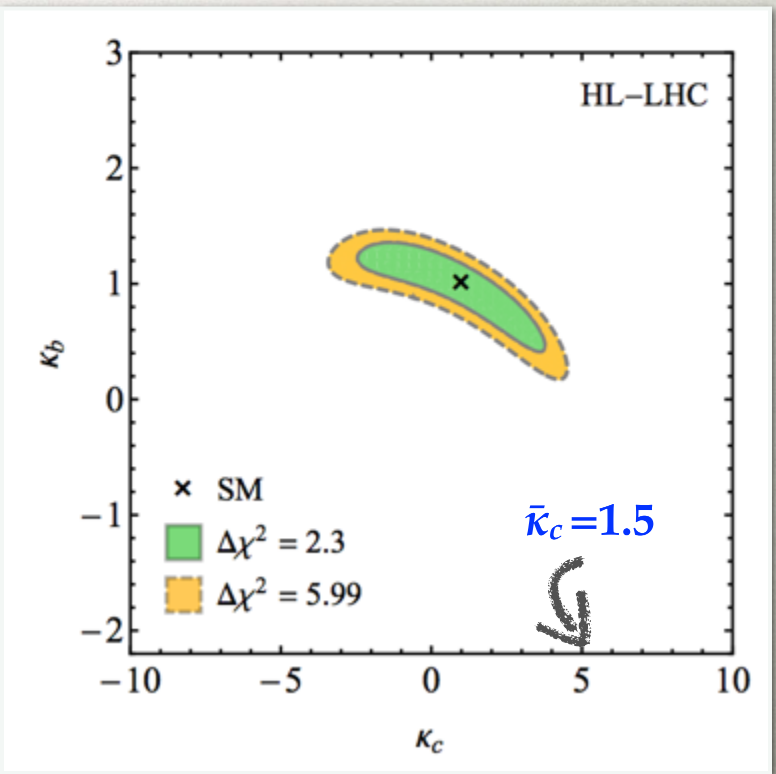
CHARM QUARK

Bishara, Haisch, Monni, Re, 1606.09253

- Higgs p_T also sensitive to charm quark, if enhanced Yukawa
- sensitivity from the charm loop in gluon fusion
- log enhanced

$$\kappa_Q \frac{m_Q^2}{m_h^2} \ln^2\left(\frac{p_\perp^2}{m_Q^2}\right)$$





DIAGONAL YUKAWAS

- scanning over mass matrix entries and imposing
  - that m_μ, m_τ are eigenvalues
  - the heavy Higgs xsec bounds

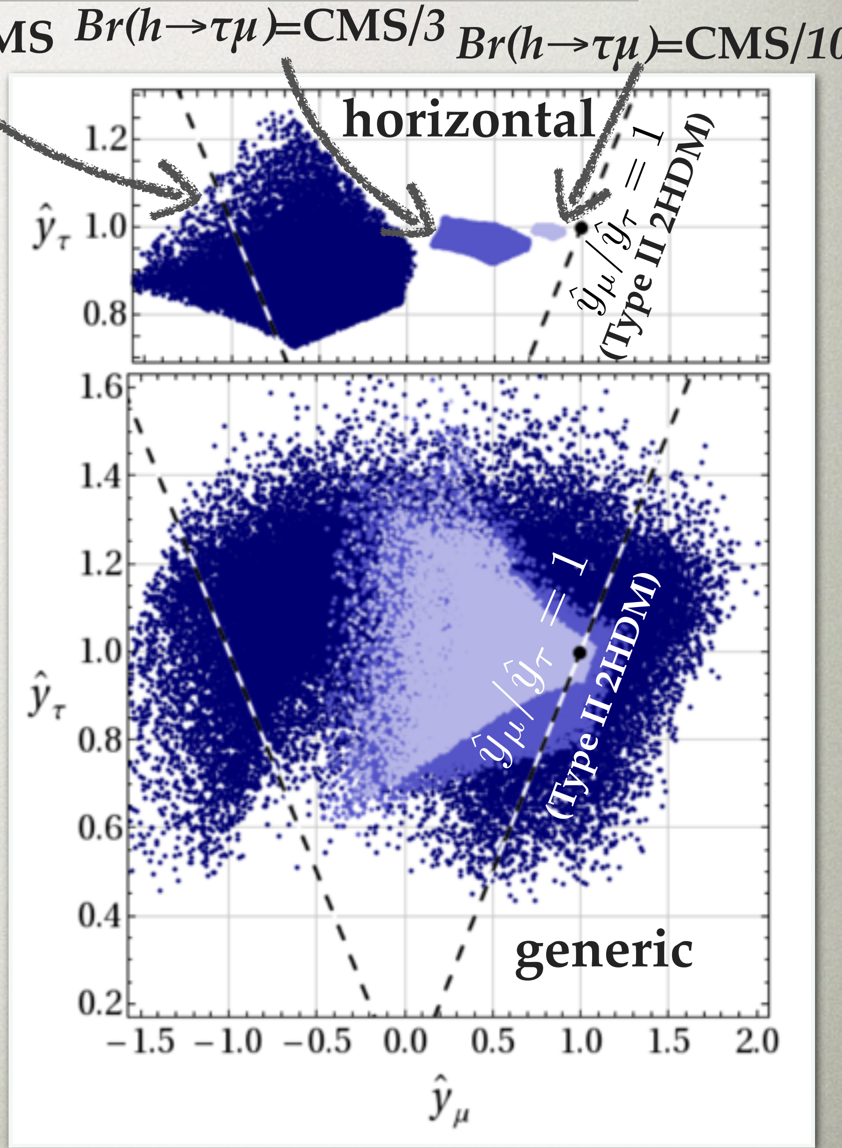
$$1/5 < |m'_{32}/m'_{23}| < 5$$

$$\lambda_{3,4} \leq 2,\ m_A \geq 400\,\mathrm{GeV}$$

$$|(\Delta\mathcal{M}^\ell)_{ij}| < 5m_\mu$$

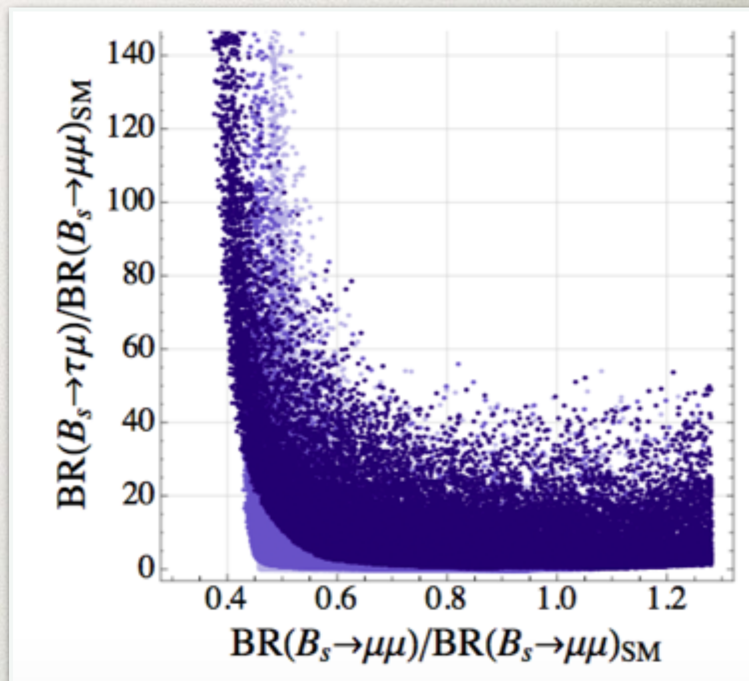
$$|\delta g_{hVV}/g_{hVV}^{\mathrm{SM}}| \leq 20\%$$

- deviations larger in generic case
- ratios $|\hat{y}_\mu| < 1$ and $|\hat{y}_\mu/\hat{y}_\tau| < 1$ favored



PHENOMENOLOGICAL IMPLICATIONS

- $B_s \to \mu\mu$ can be modified by $O(1)$
- sizable $B_s \to \tau\mu$, $B \to K\tau\mu$, $B \to K^*\tau\mu$
- anomalies could be seen in B_s mixing, $\tau \to \mu\gamma$, $b \to s\gamma$
- leptonic heavy Higgs (H) decays to $\mu\mu$ dominate over $\tau\tau$
  - opposite to Type-II 2HDMs
- $t \to hc$ potentially sizable
- a general sum rule



$$\hat{y}_\mu \hat{y}_\tau - \hat{y}_{\tau\mu}\hat{y}_{\mu\tau} = \hat{y}_{t,b}(\hat{y}_\mu + \hat{y}_\tau - \hat{y}_{t,b})$$

$$\hat{y}_{ij} \equiv Y_{ij}/Y_{ii}^{\rm SM}$$

  - valid to the extent that both ΔM^l and ΔM_0 are rank 1
  - is explicitly true in our TC example

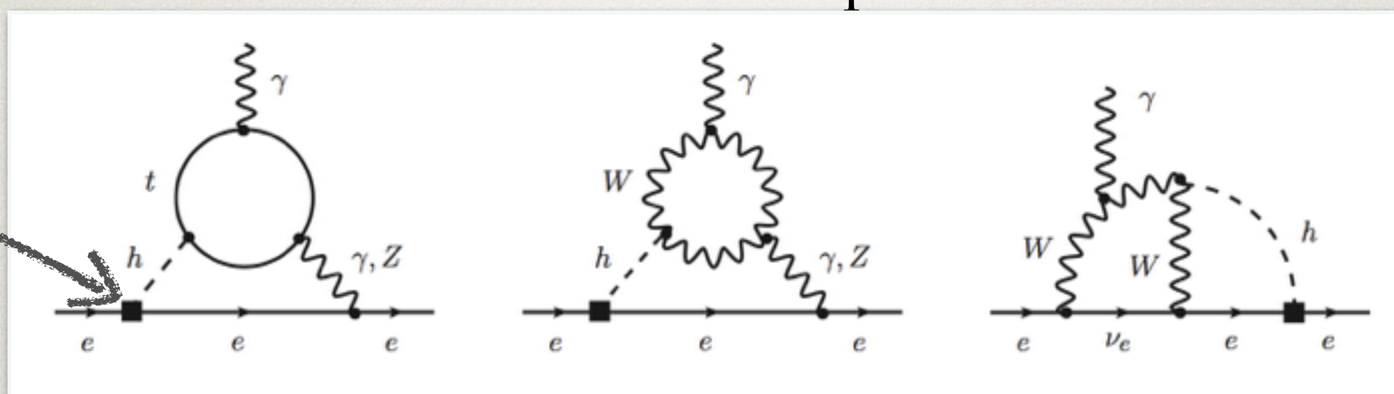
ELECTRON YUKAWA

- $\tilde{\kappa}_e \neq 0$ induces electron EDM

Altmannshofer, Brod, Schmaltz, 1503.04830

- dominant contributions at 2-loop

CPV



- analytic results with an internal Z boson are new
- experimental bound

ACME coll., 1310.7534

$$\left|\frac{d_e}{e}\right|_{\rm exp} < 8.7 \times 10^{-29}\ \text{cm} \quad @\ 90\%\ \text{C.L.}\,,$$

$$|\tilde{\kappa}_e| < 1.7 \times 10^{-2}$$

SUMMARY OF MODELS

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

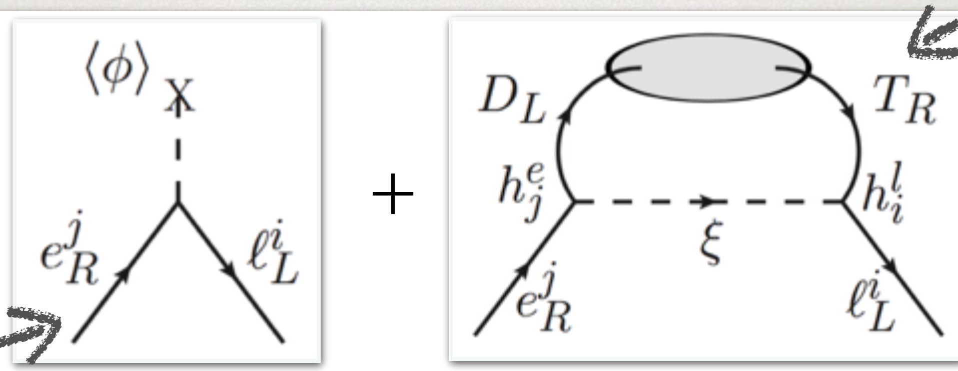
adapted from Dery, Efrati, Hochberg, Nir, 1302.3229 and extended;
see also Bishara, Brod, Uttayarat, JZ, 1504.04022

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	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\|U_{23}\|^2 v^4/\Lambda^4)$
GL	9	25/9	$\mathcal{O}(\hat{\mu}_{\mu\mu}/\hat{\mu}_{\tau\tau})$
RS (i)	$1+\mathcal{O}(\bar{Y}^2 v^2/m_{KK}^2)$	$1+\mathcal{O}(\bar{Y}^2 v^2/m_{KK}^2)$	$\mathcal{O}(\bar{Y}^2 v^2/m_{KK}^2)\sqrt{m_\tau/m_\mu}$
RS (ii)	$1+\mathcal{O}(\bar{Y}^2 v^2/m_{KK}^2)$	$1+\mathcal{O}(\bar{Y}^2 v^2/m_{KK}^2)$	$\mathcal{O}(\bar{Y}^2 v^2/m_{KK}^2)$
PGB (1 rep.)	$1-v^2/f^2$	1	0

TECHNICOLOR EXAMPLE

- ΔM_l due to technicolor strong dynamics
  - UV completion is bosonic TC
- Higgs: elementary ϕ + composite heavy scalar σ_{TC}
- ΔM^l from TC condensate, rank 1

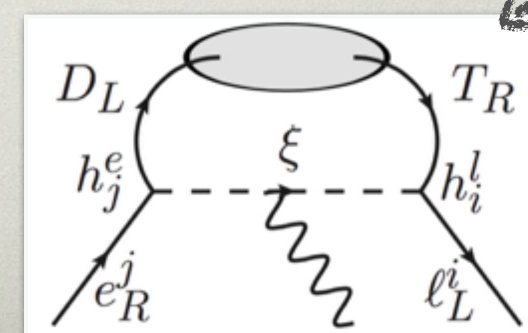
$M^l=$



$\Delta M^l \propto 1/m_\xi^2$

M^l_0

  - misalignment gives $h\to\tau\mu$
- the $\tau\to\mu\gamma$ is further parametrically suppressed
  - $m_\xi \gtrsim O(10\text{TeV})$



$\Delta M^l \propto 1/m_\xi^4$