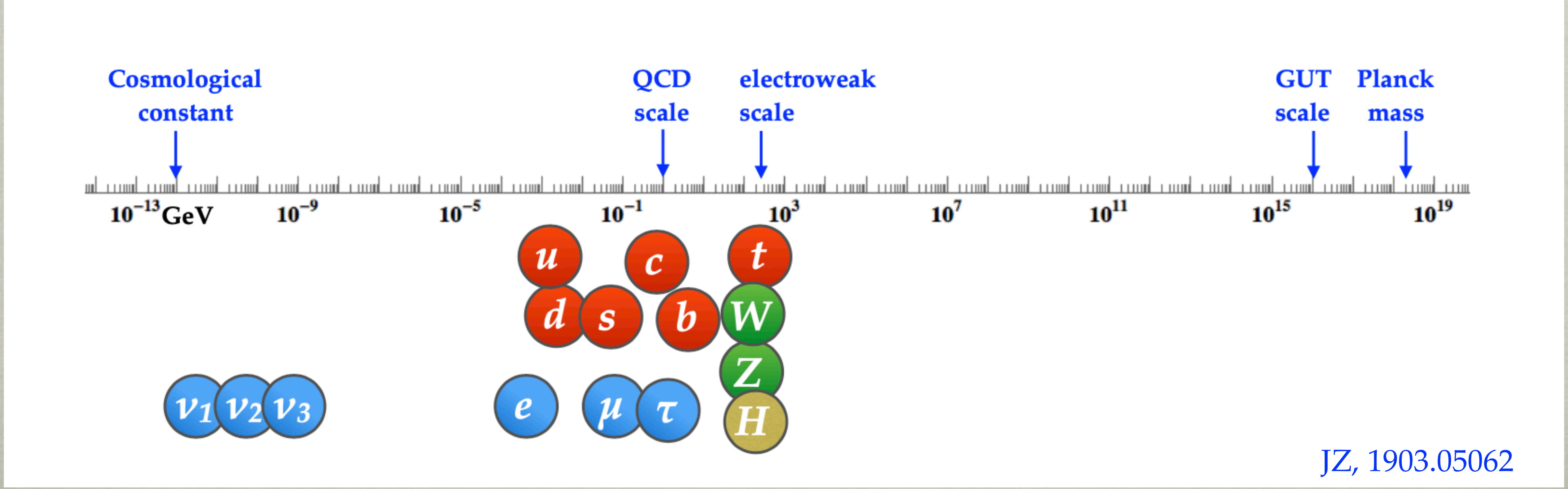
HIGGS AND FLAVOR

Jure Zupan
U. of Cincinnati

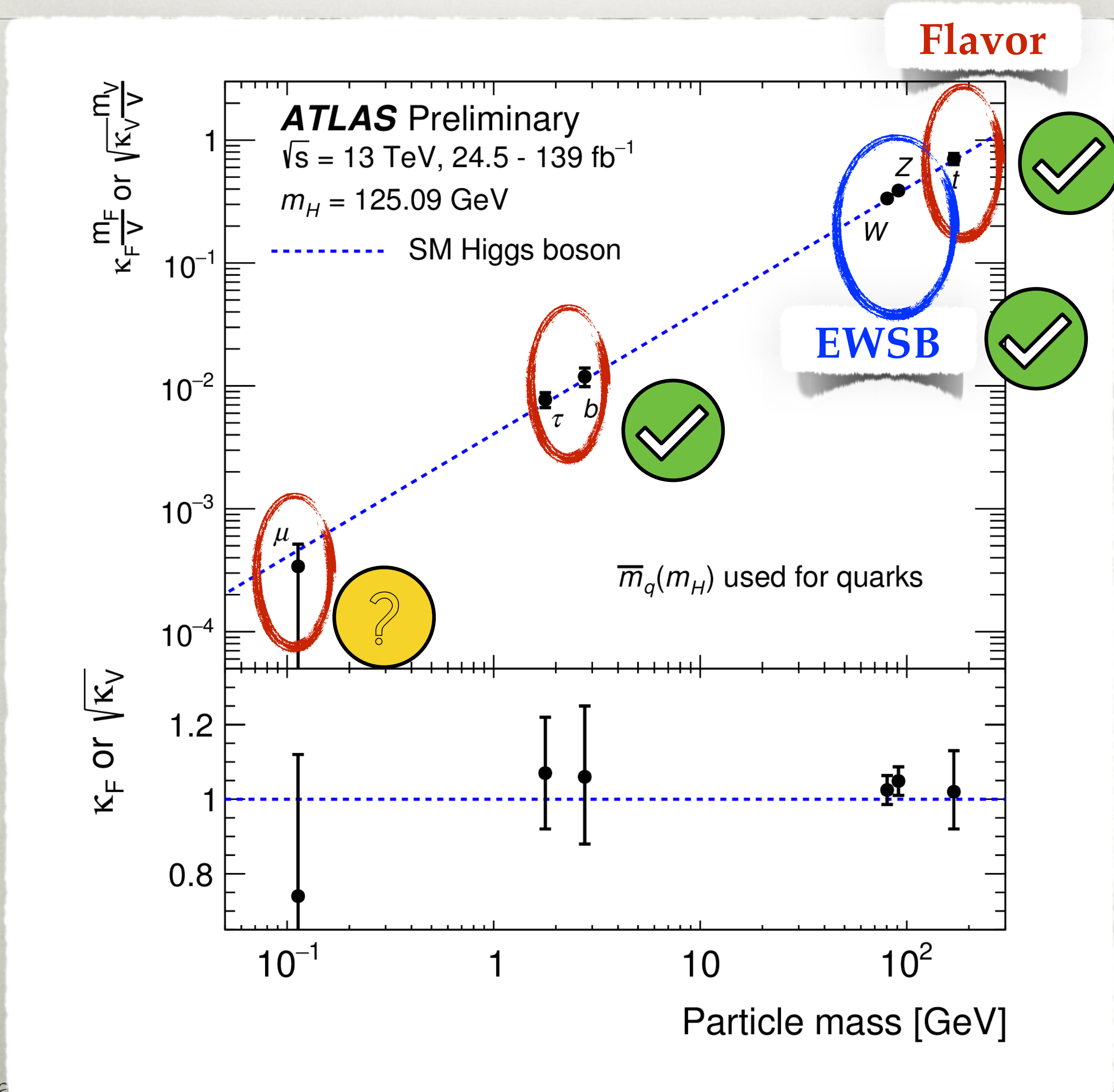
CRC meeting, Oct 6 2020

DUAL ROLE

- in the SM Higgs has a dual role
  - breaks electroweak symmetry and gives the masses to W, Z gauge bosons
  - same EWSB source gives the masses to the SM fermions
- how well have we tested this?



DUAL ROLE OF THE HIGGS



see, e.g., Cohen, Craig, Lu, Sutherland, 2008.08597

SMEFT and HEFT

- no sign of new physics at the LHC
  - assume it is heavy ⇒ integrate out, obtain EFTs
- SMEFT - uses EW symmetric phase, Higgs assumed to be EW doublet

$$\mathcal{L} \supset \lambda_{ij}(\bar{f}_L^i f_R^j)H - \frac{\lambda'_{ij}}{\Lambda^2}(\bar{f}_L^i f_R^j)H(H^\dagger H) + \cdots$$

- HEFT - uses EW broken phase
  - κ framework: dim4 HEFT in unitary gauge

$$\mathcal{L} \supset - m_i \bar{f}_L^i f_R^i - Y_{ij}(\bar{f}_L^i f_R^j)h + \cdots$$

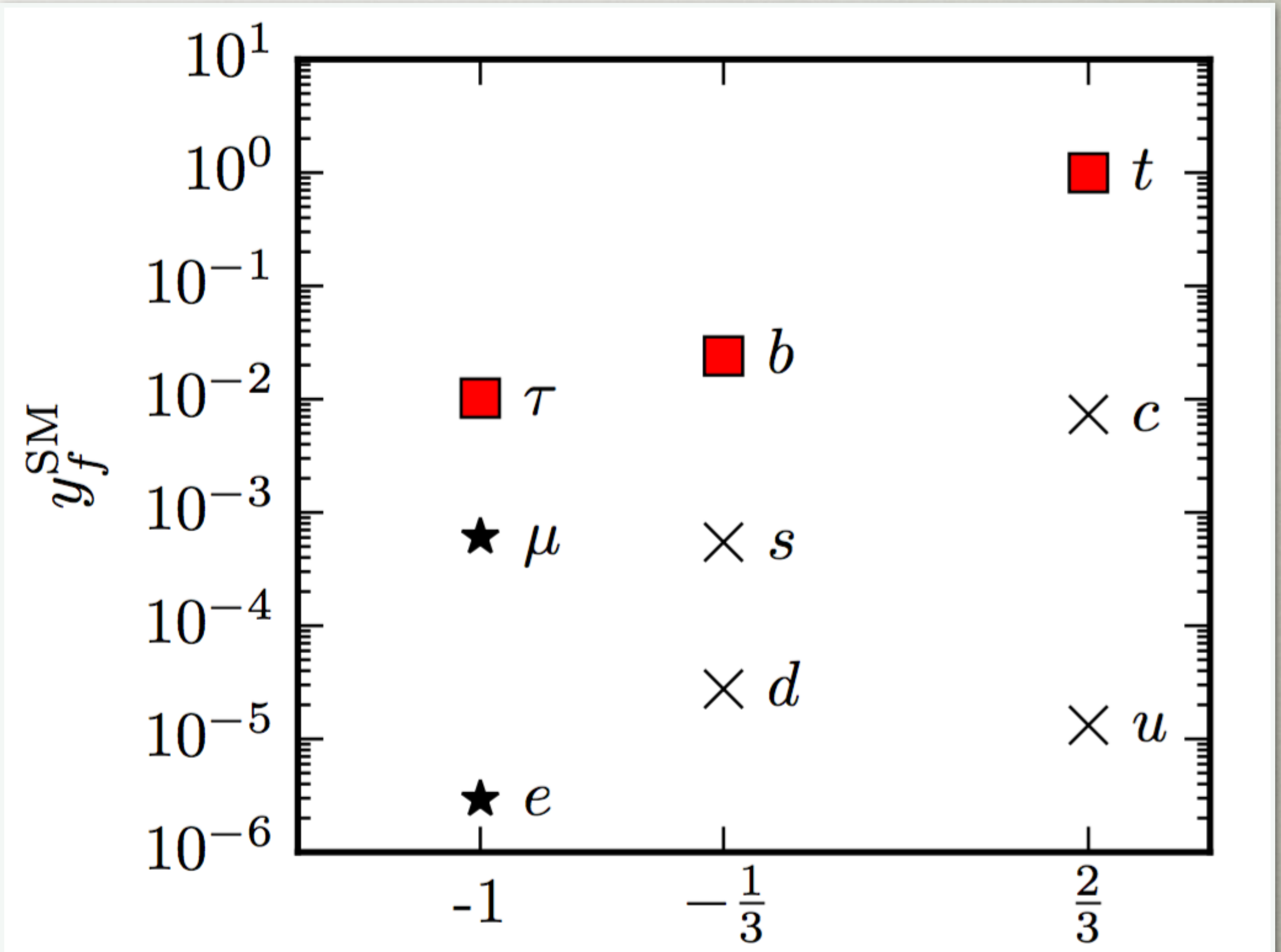
$$\mathcal{L}_{\rm eff,q} = -\kappa_q \frac{m_q}{v_W}\bar{q}qh - i\tilde{\kappa}_q \frac{m_q}{v_W}\bar{q}\gamma_5 qh - \Big[\big(\kappa_{qq'} + i\tilde{\kappa}_{qq'}\big)\bar{q}_L q'_R h + \text{h.c.}\Big],$$

HIGGS - A PROBE OF FLAVOR

- in the SM all flavor structure due to the Higgs Yukawa couplings

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

- implies Higgs has very hierarchical couplings to fermions
- clear experimental prediction



plot due to E. Stamou

TESTING THE FLAVOR OF THE HIGGS

Nir, 1605.00433; JZ, 1903.05062

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

- several questions
  - proportionality

    $$y_{ii} \propto m_i$$

  - factor of proportionality

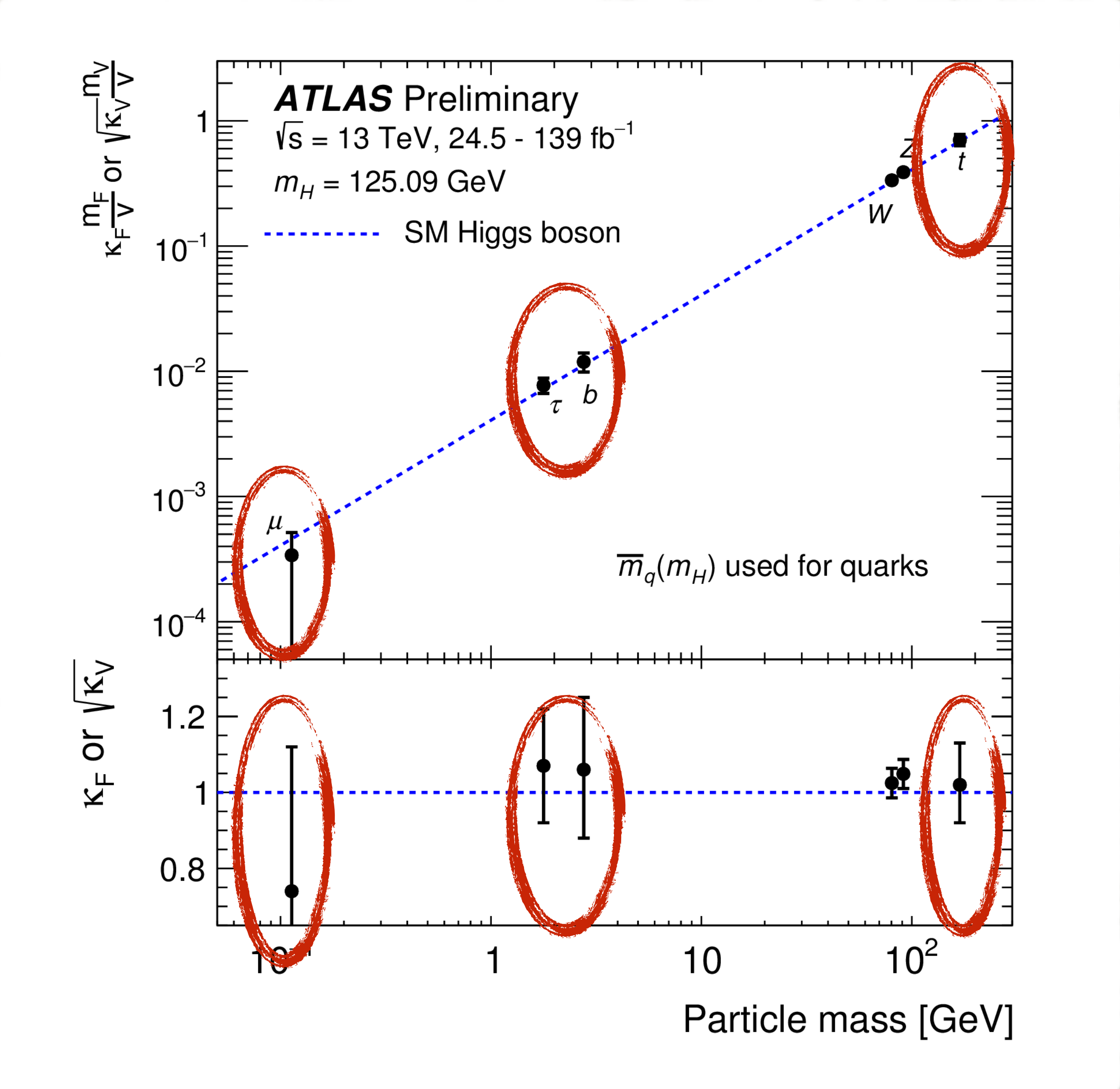
    $$y_{ii}/m_i = \sqrt{2}/v$$

  - diagonality (flavor violation)

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

  - reality (CP violation)

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

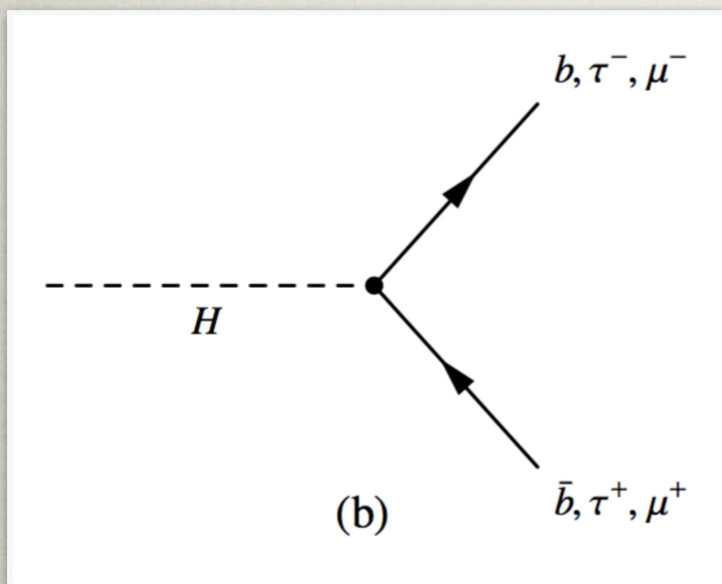


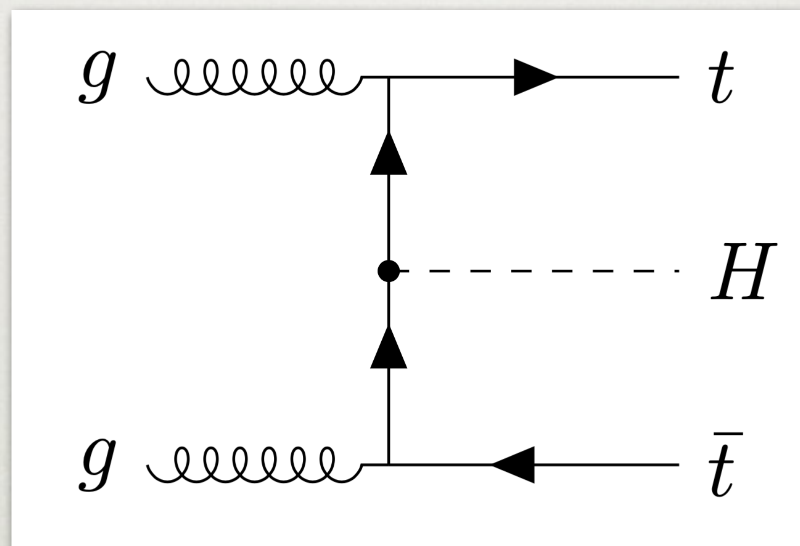
PROPORTIONALITY

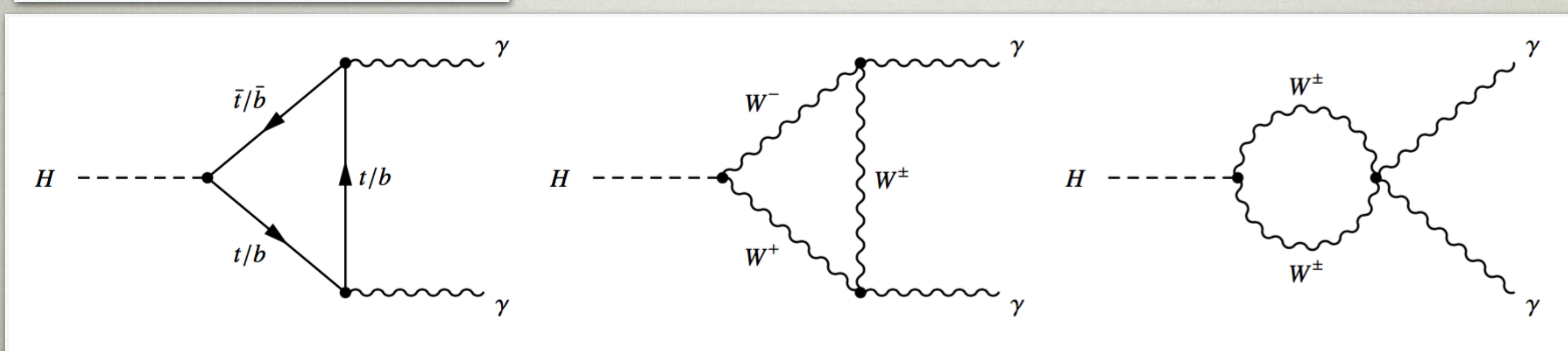
- “proportionality” and “factor of proportionality”

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

- reasonably well tested for 3rd generation fermions







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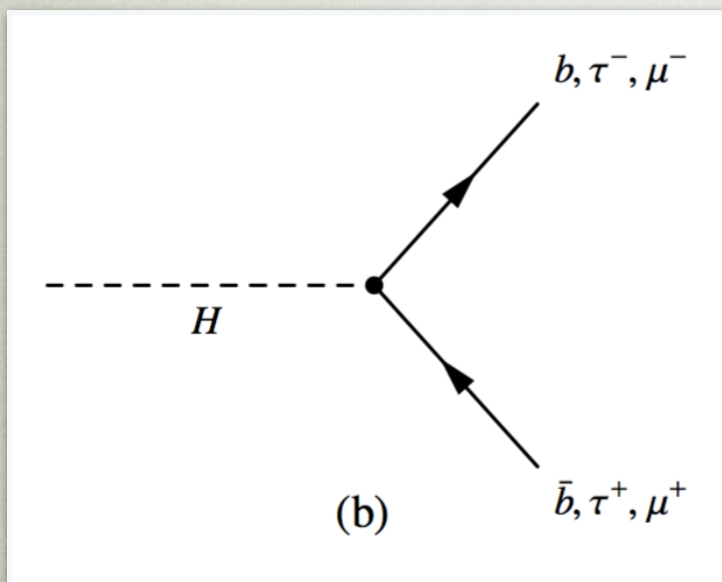

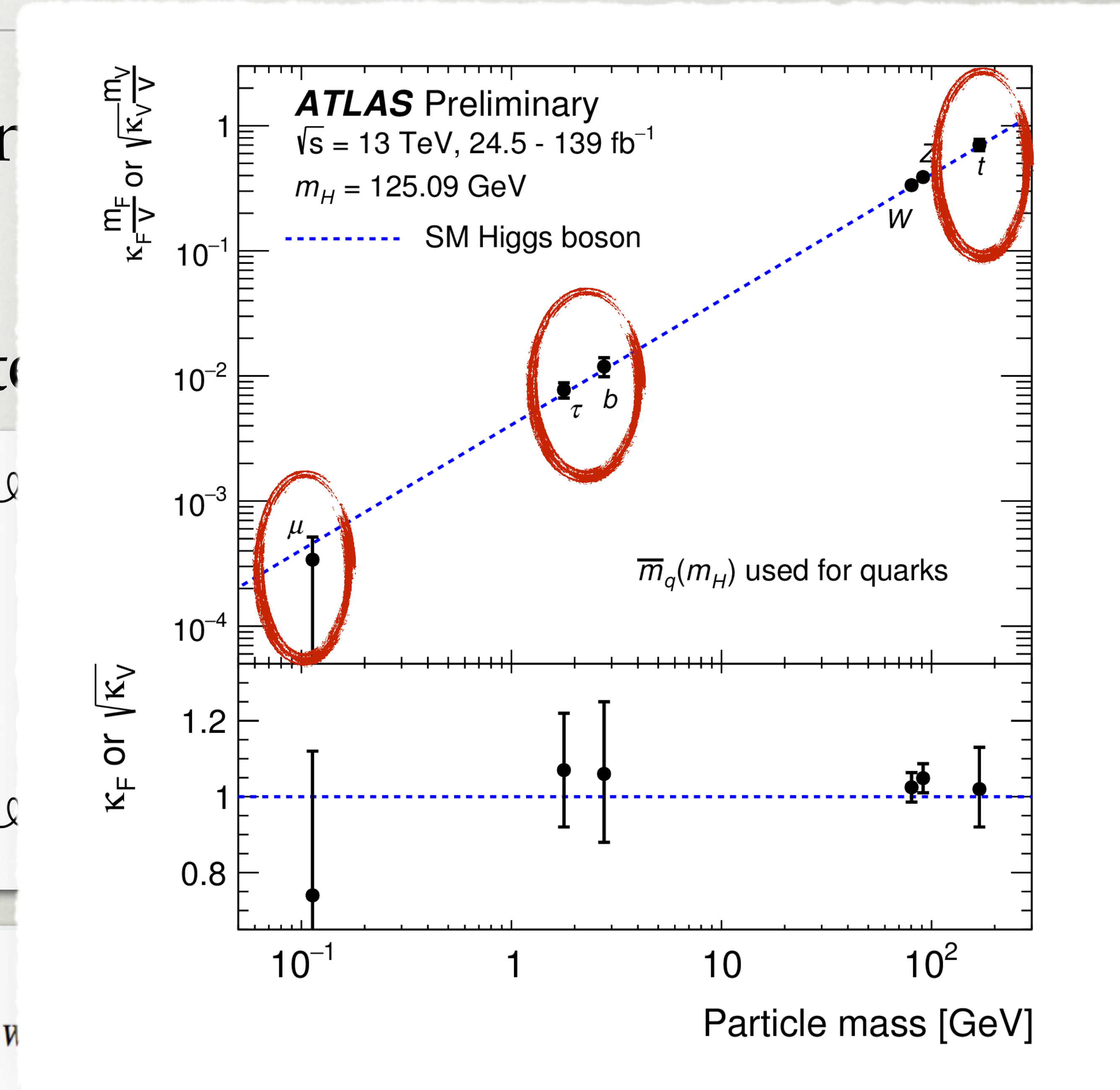

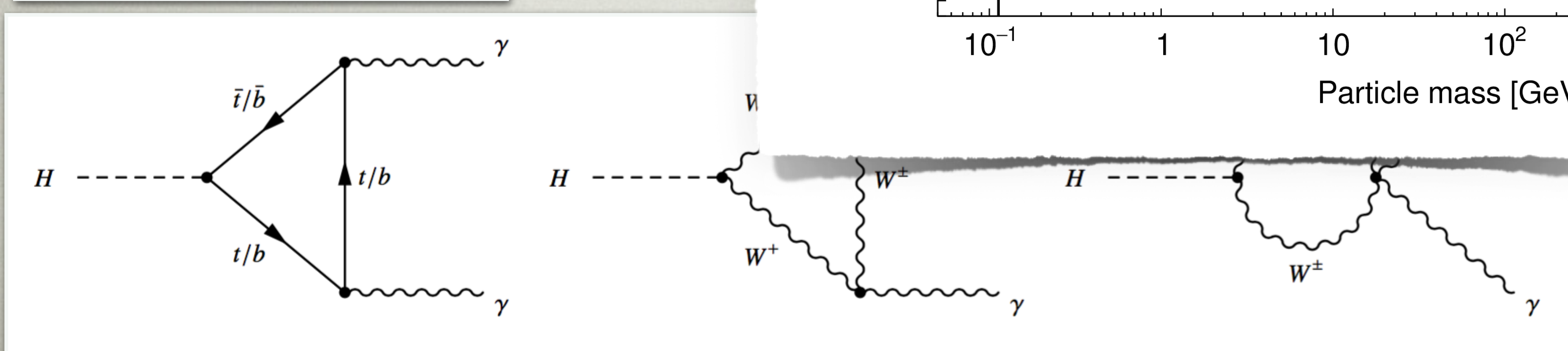

MUON YUKAWA

CMS, 2009.04363; ATLAS, 2007.07830

- CMS: evidence for nonzero SM muon Yukawa

$$\hat{\mu}_\mu|_{\text{CMS}} = 1.19 \pm 0.43, \quad \hat{\mu}_\mu|_{\text{ATLAS}} = 1.2 \pm 0.6$$

$$\Rightarrow \kappa_\mu = 1.09 \pm 0.16$$

- a qualitative change:
  - implies that Higgs Yukawas span many orders of magnitudes
  - before: 2HDM would allow for $\mathcal{O}(1)$ 3rd generation Yukawas
    - 2nd generation could be from a completely new sector EWSB with O(1) Yukawa
    - note: EWSB vev required for m_μ is only ~100MeV
    - caveat: still possible this is the case within present exp. errors

MUON

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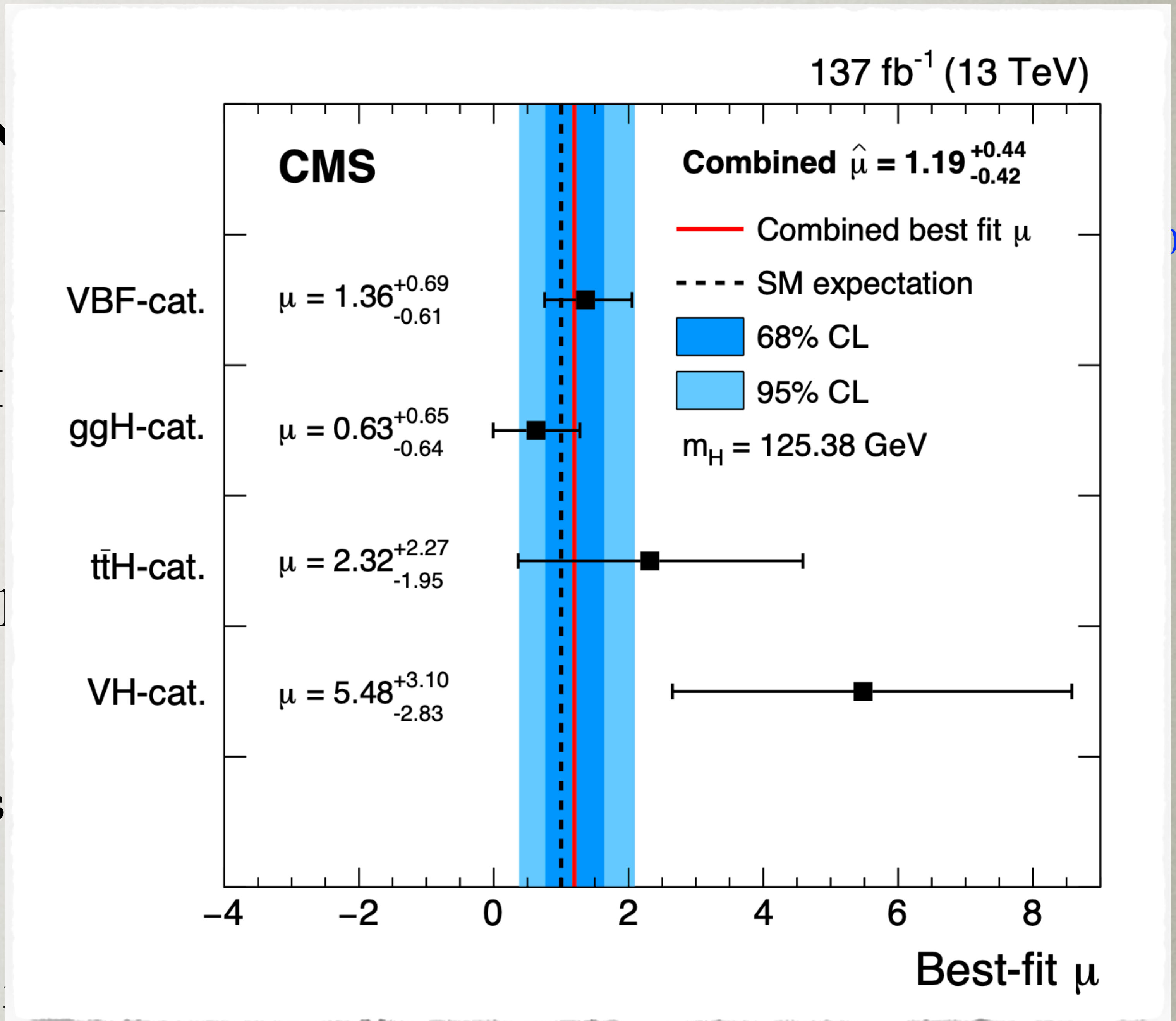

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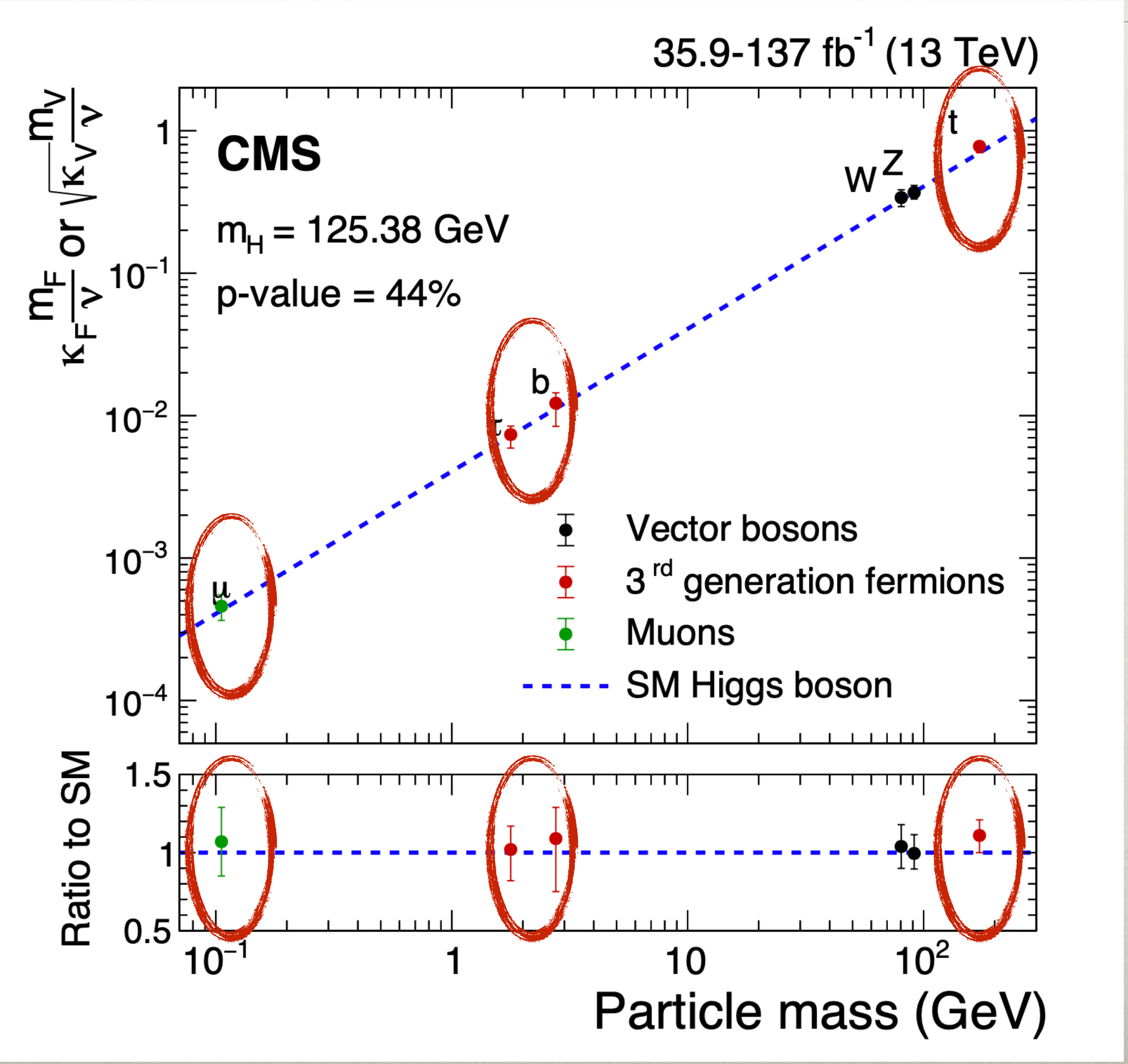
TESTING FLAVOR OF THE HIGGS

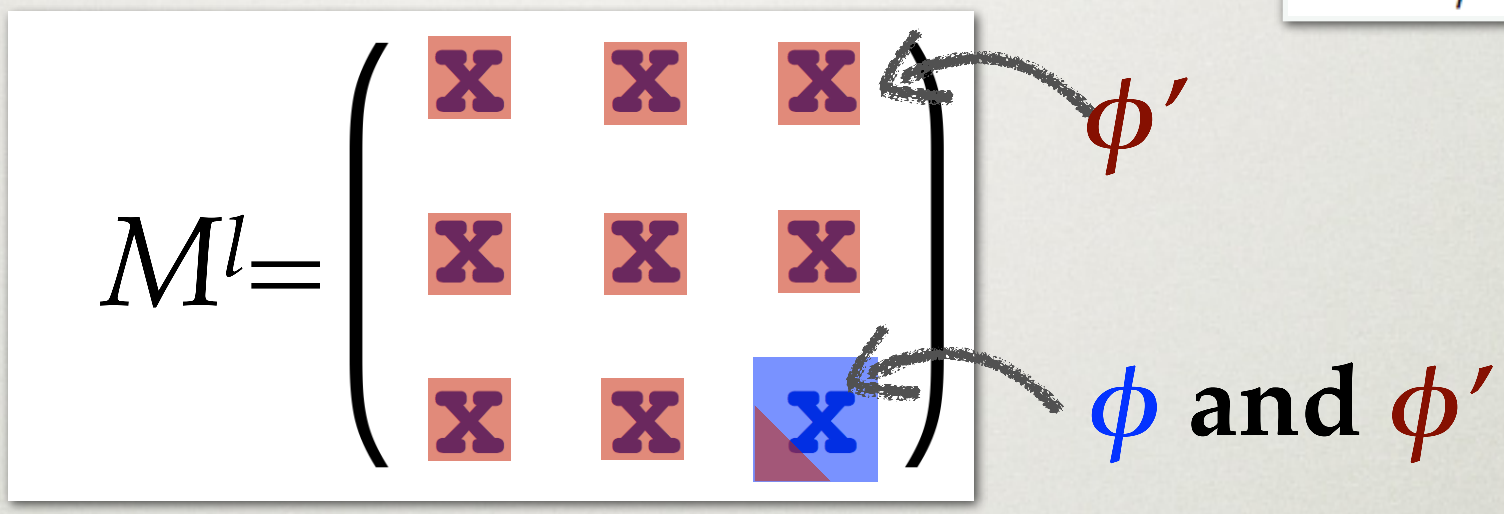


Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

2HDM EXAMPLE: SEQUESTERED MASS GENERATION

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

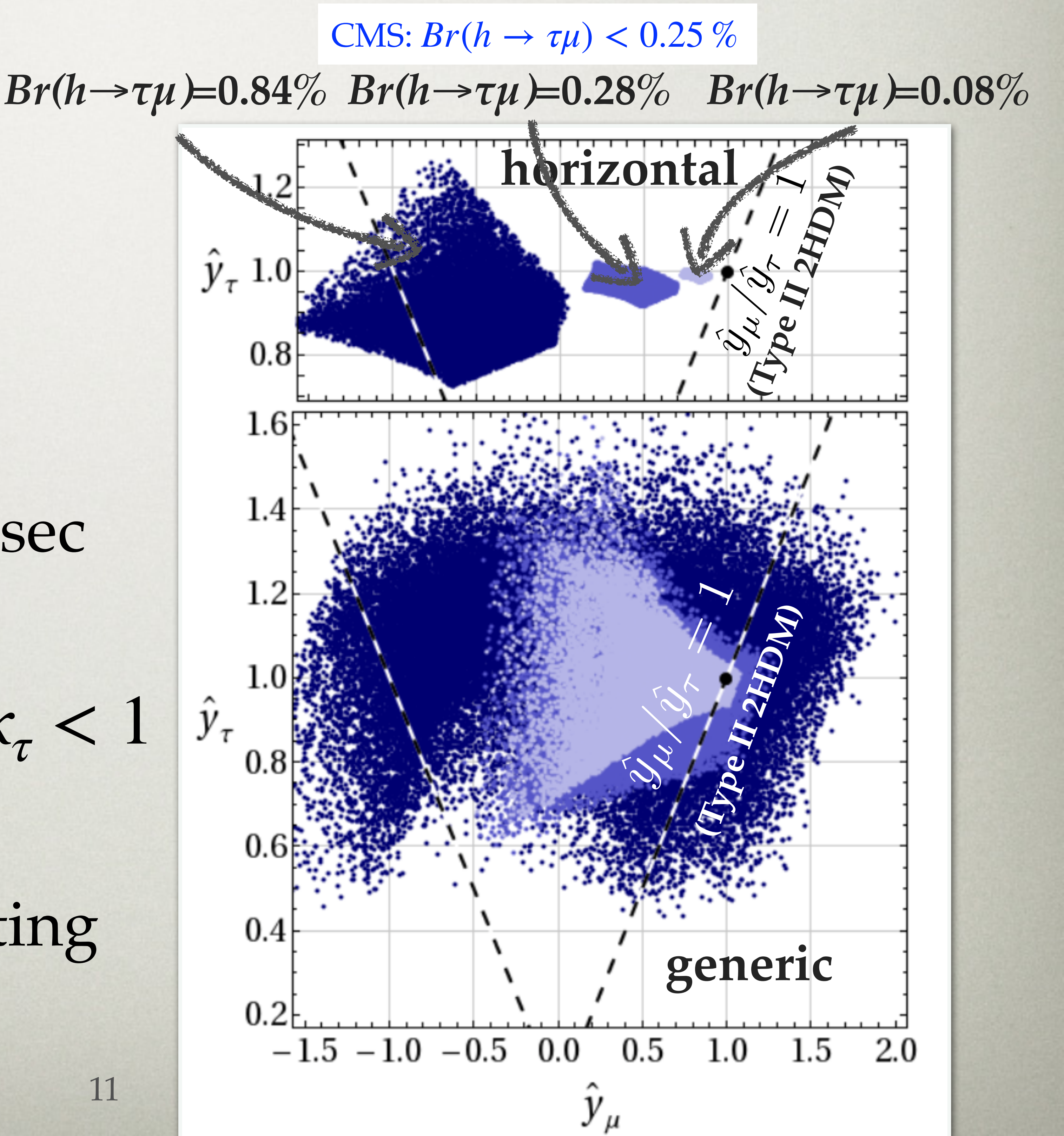
$$\tan\beta = v/v'$$



  - a hierarchy of vevs $v \gg v'$ can explain $m_\tau \gg m_\mu$
- consider two flavor structures for ϕ' contribs. to M^l
  - *"horizontal"*: only off-diagonal entries nonzero
  - *"generic"*: all m_{ij}' nonzero

DIAGONAL YUKAWAS

- scanning over mass matrix entries and imposing:
  - that m_μ, m_τ are eigenvalues
  - the heavy Higgs xsec bounds
- ratios $\kappa_\mu < 1$ and $\kappa_\mu/\kappa_\tau < 1$ favored
- sizeable flavor violating $Br(h \to \tau\mu)$



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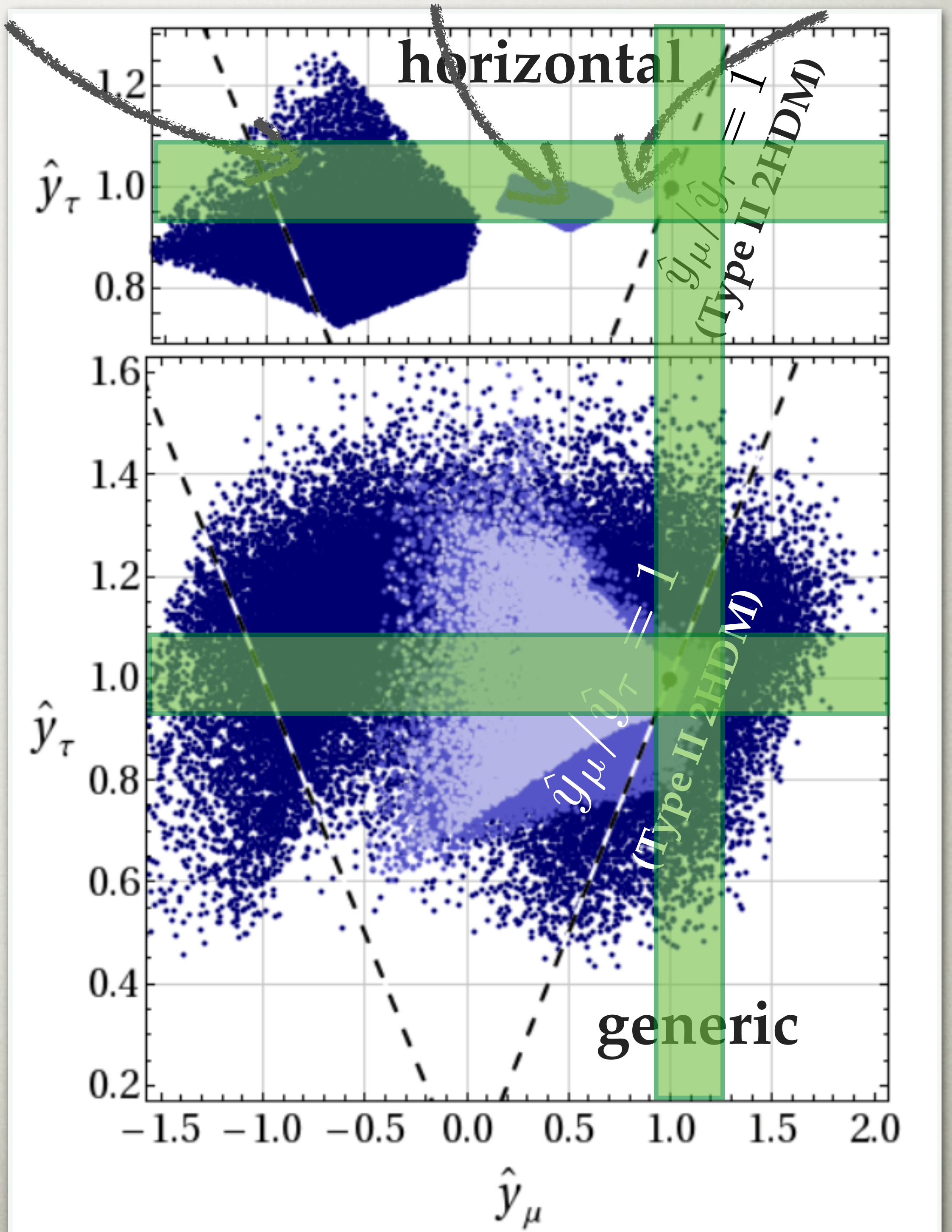


LIGHT QUARK YUKAWAS?

- does Higgs couple to the first two generations?
  - yes for muons
- how about quark Yukawas?
- more modest question: can we show that the quark Yukawa couplings are hierarchical?
  - yes, with some assumptions
    - from global fits:

Soreq, Zhu, JZ, 1606.0962

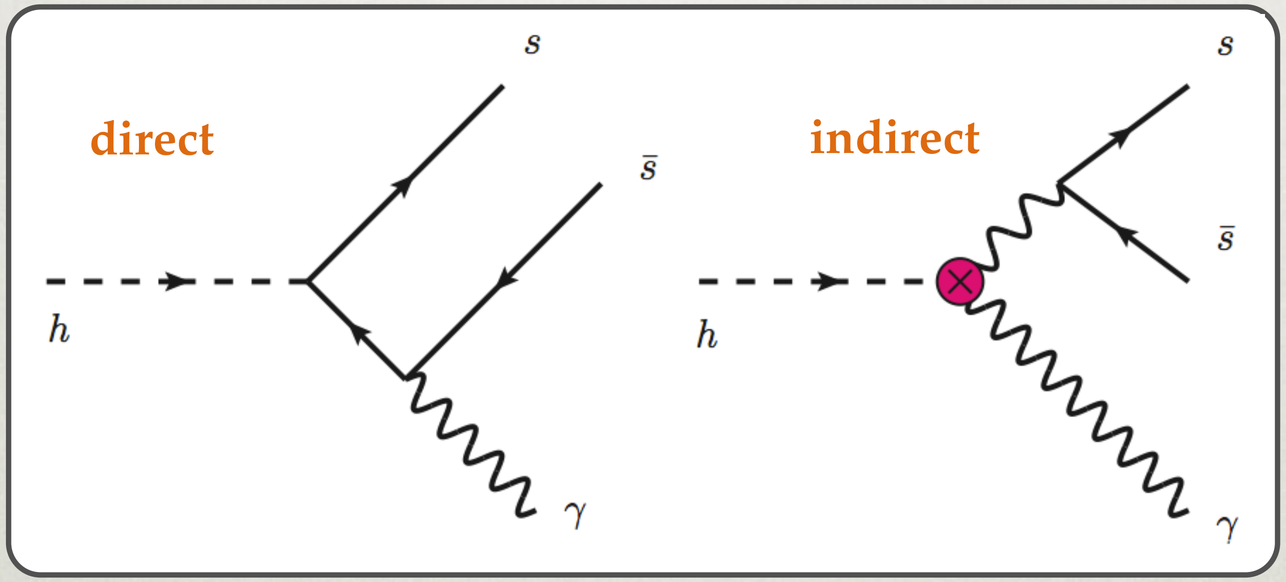
$$\frac{y_{u(c)}^{\rm exp}}{y_t^{\rm exp}} < 0.036\,, \qquad \frac{y_{d(s)}^{\rm exp}}{y_b^{\rm exp}} < 5.6$$

DIFFERENT PROBES

- several probes of 1st and 2nd generation Higgs quark 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
    Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722
    Konig, Neubert, 1505.03870
  - Higgs p_T distributions
    Bishara, Haisch, Monni, Re, 1606.09253
    Soreq, Zhu, JZ, 1606.09621
  - h+c associated production
    Brivio, Goertz, Isidori, 1507.02916
  - inclusive $h + \gamma$ production
    Aguilar-Saavedra, Cano, No, 2008.12538
  - strangeness tagging for future e^+e^- Higgs factory
    Duarte-Campderros, Perez, Schlaffer, Soffer, 1811.09636

$h \to \phi\gamma$

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



- prediction at NLO

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

$$\bar{\kappa}_s = y_s/y_b^{\mathrm{SM}}$$

Kagan, Perez, Petriello, Soreq, Stoynev, JZ, 1406.1722
Konig, Neubert, 1505.03870, 1609.06310

MEASUREMENTS

- first bound on $Br(h\to\phi\gamma)$ by ATLAS

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

ATLAS, 1607.03400, 1712.02758

$\mathcal{B}(H\to\phi\gamma) < 4.8\times10^{-4}$ → $|\bar{\kappa}_s| \lesssim 110$

- $h\to\phi Z$ for transverse polarization

$$\frac{Br_{h\to\phi_\perp Z_\perp}}{Br_{h\to b\bar{b}}} = \frac{[7.7-0.06\bar{\kappa}_s]\cdot 10^{-7}}{0.57\bar{\kappa}_b^2}$$

CMS, 2007.05122

$Br(h\to\phi_\perp Z_\perp) < 4\times10^{-3}$ → $|\bar{\kappa}_s| \lesssim 2400$

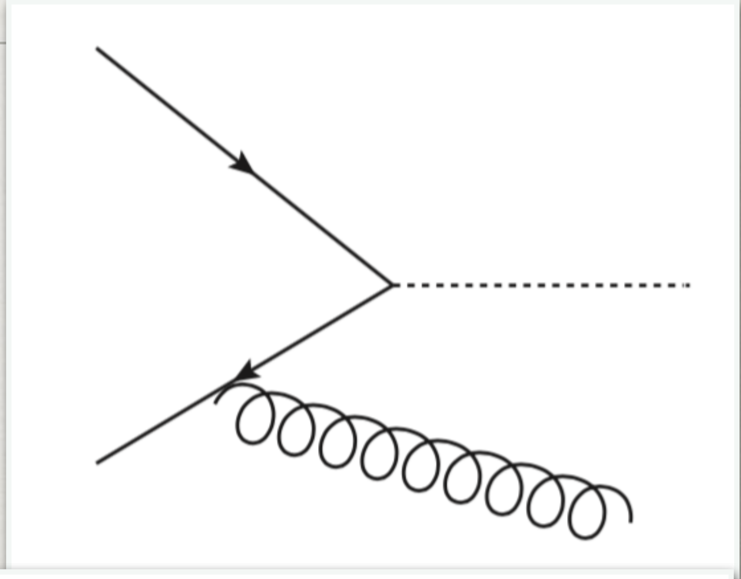
- projecting to 100 TeV FCC-hh, 2x15ab^{-1}, same S/B

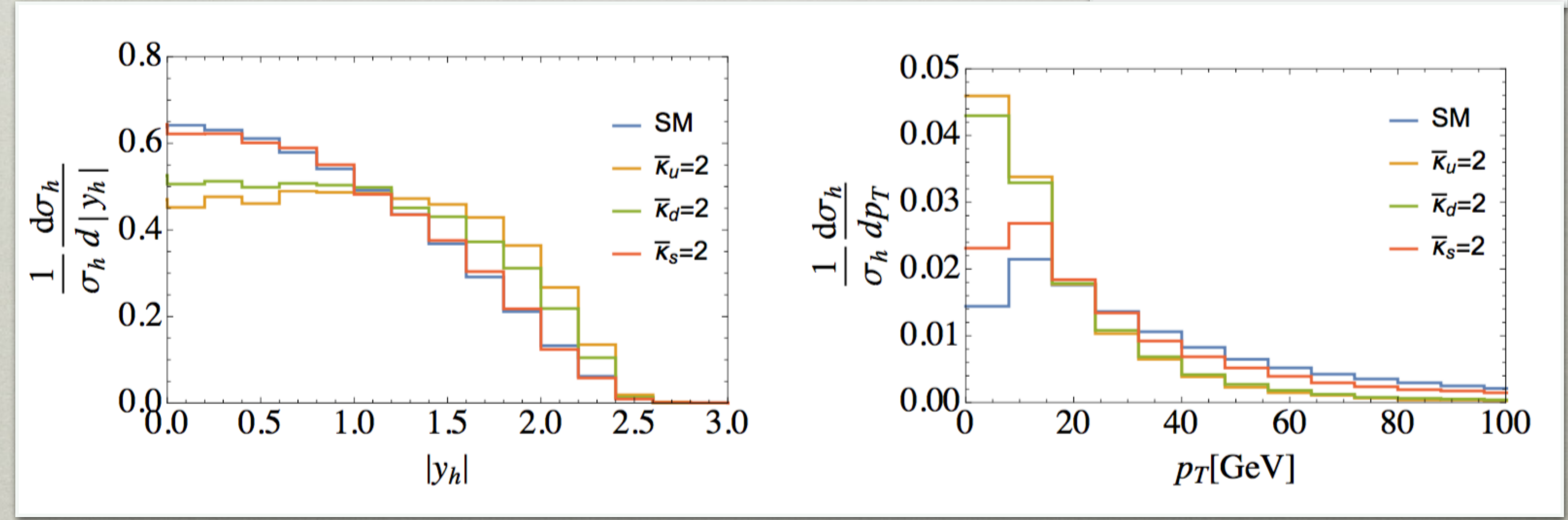
$Br(h\to\phi\gamma) < 4\times10^{-6}$ → $-3 < \bar{\kappa}_s < 18$

Soreq, Zhu, JZ, 1606.09621

HIGGS KINEMATICS

- light quarks in the initial state, change the Higgs p_T, or rapidity distribs.





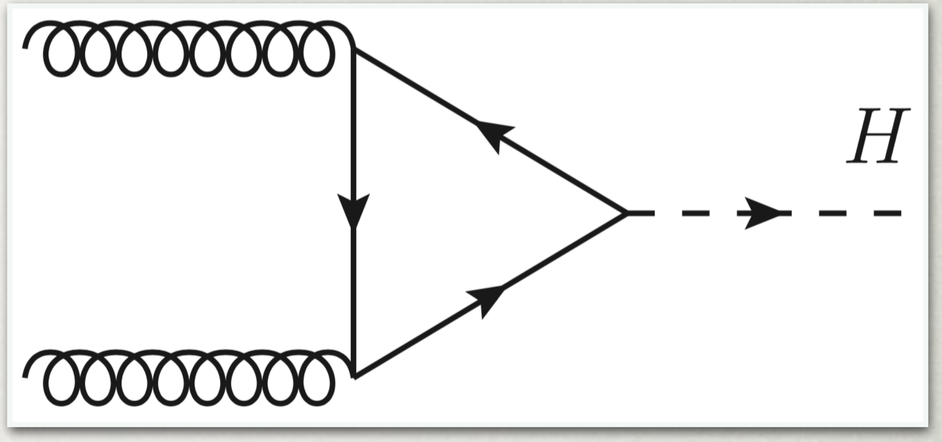
- end of HL-LHC, can expect $|\bar{\kappa}_s| \lesssim 0.5$

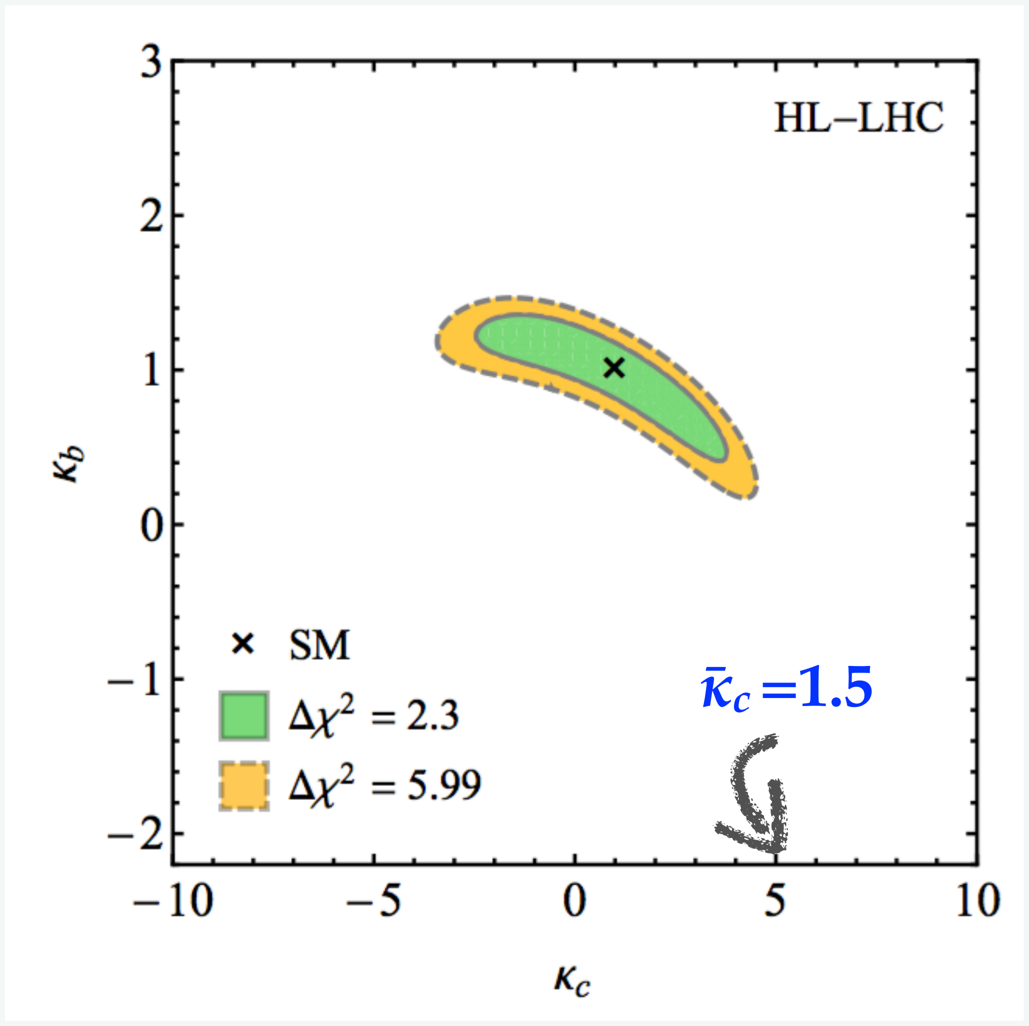
CHARM YUKAWA FROM HIGGS KINEMATICS

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

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





CHARM YUKAWA

- κ_c from $h \to J/\psi\gamma$

Bodwin, Petriello, Stoynev, Velasco, 1306.5770
Konig, Neubert, 1505.03870

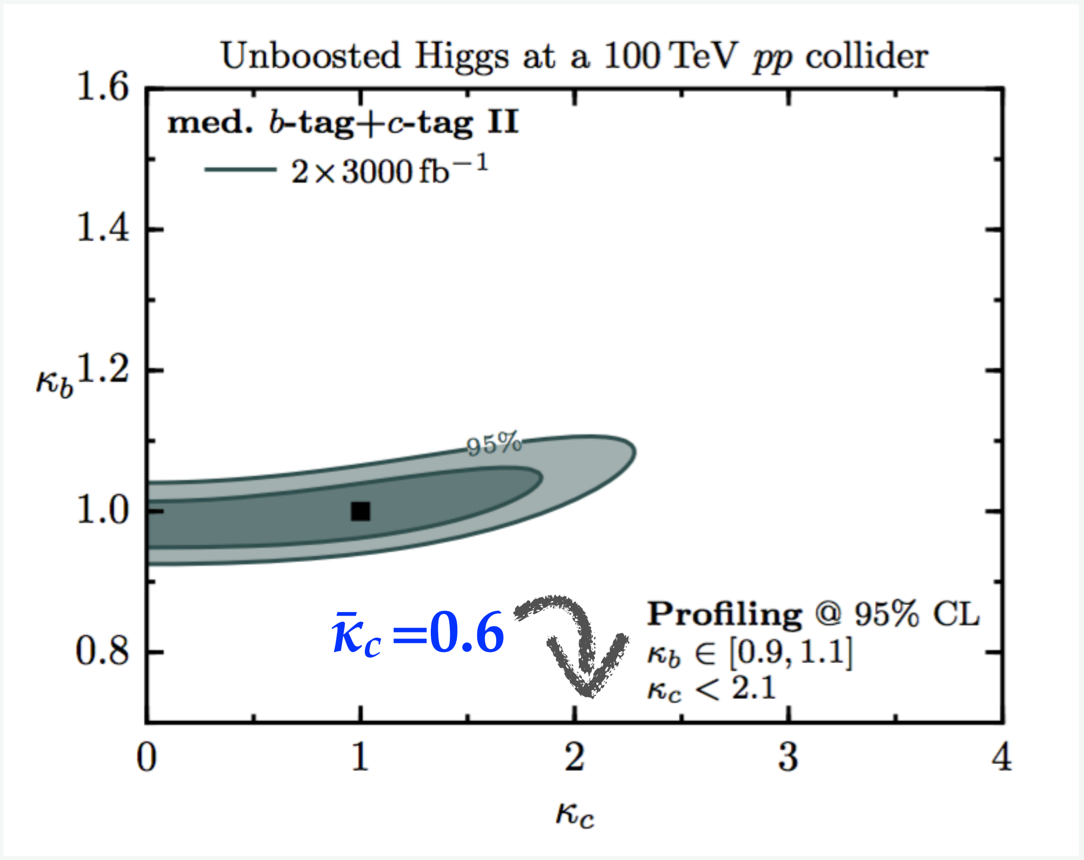
$$\frac{\mathrm{BR}_{h\to J/\psi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma[(3.0\pm 0.15)\kappa_\gamma - 0.56\bar{\kappa}_c]\cdot 10^{-6}}{0.57\bar{\kappa}_b^2}$$

ATLAS, 1501.03276

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

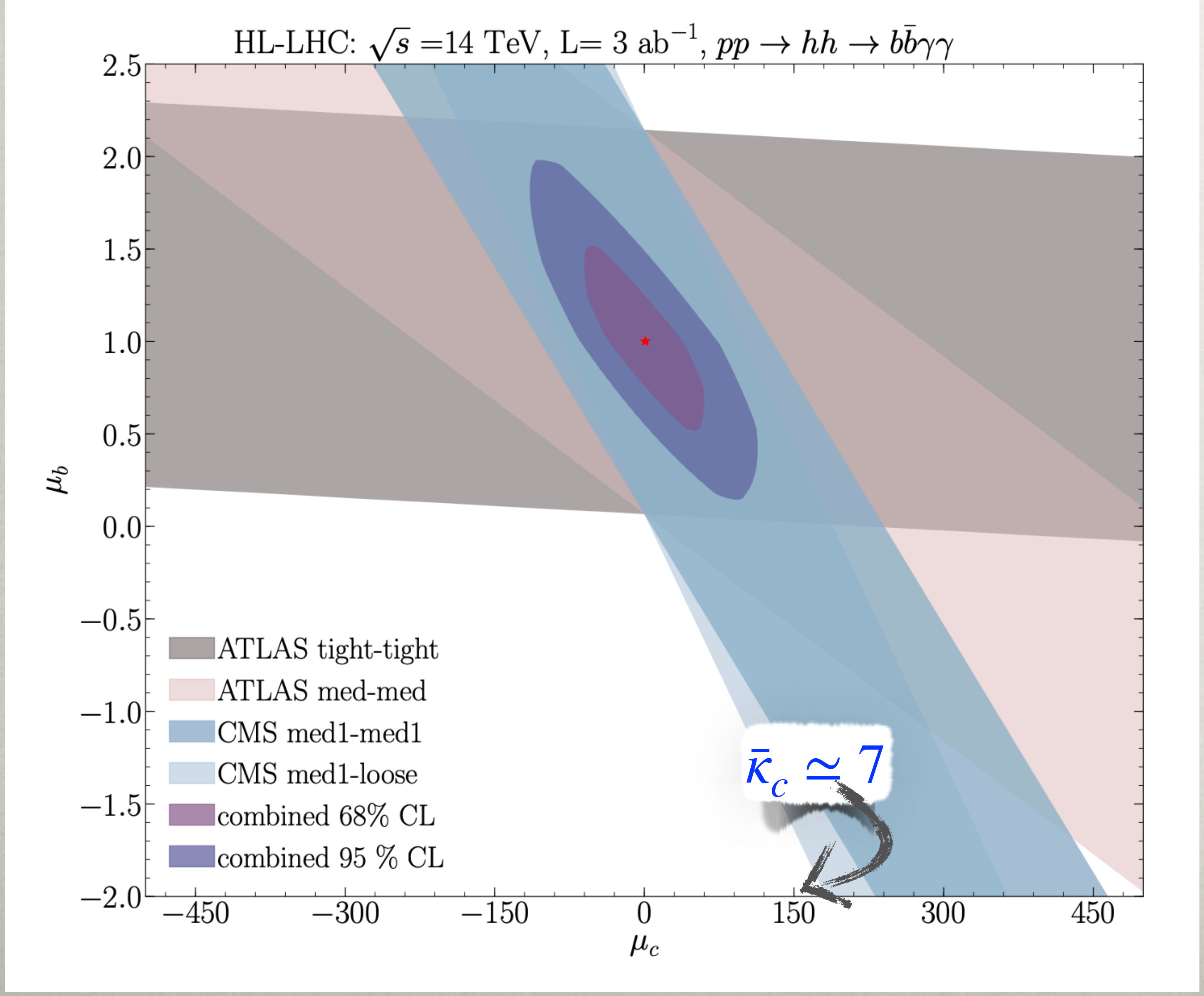
Perez, Soreq, Stamou, Tobioka, 1505.06689
see also Coyle, Wagner, Wei, 1905.09360

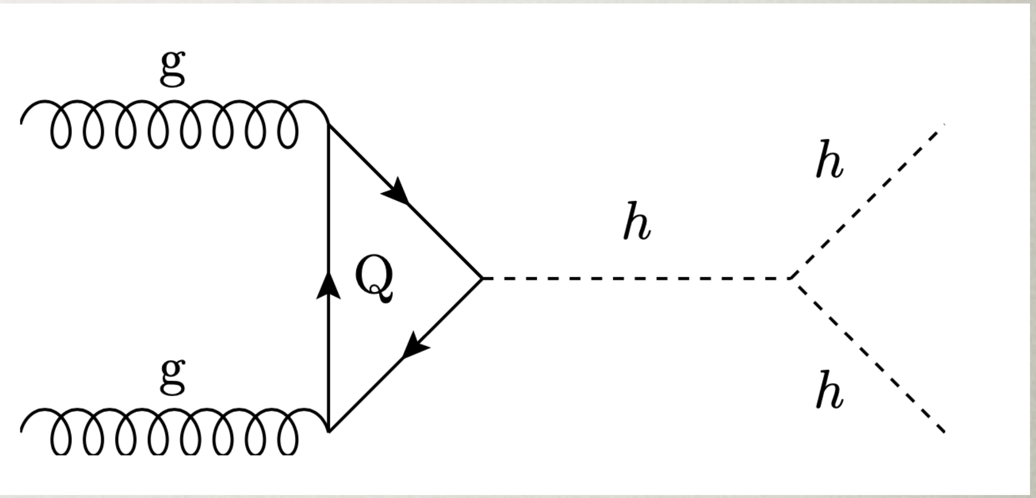
- from inclusive, using charm tagging

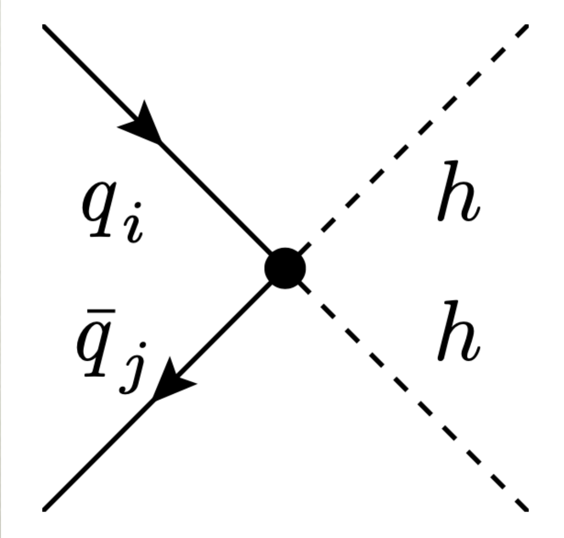


CHARM FROM DI-HIGGS PRODUCTION

- using that in SMEFT $\kappa_c \neq 1$ arises from dim 6 $(\bar{Q}_L c_R H)(H^\dagger H)$ operator
- $\Rightarrow$ sensitivity from di-Higgs production







CHARM YUKAWA FROM INCLUSIVE $h \to c\bar{c}$

- using charm tagging in $h \to c\bar{c}$

  M. Williams at Elba Phase 2workshop, 2017

  - LHCb@300fb^{-1} naive projected reach $\kappa_c \sim \mathcal{O}(2-3)$ from $pp \to hZ, hW$
  - rescaling naively ATLAS@36.1fb^{-1} to ATLAS+CMS 3ab^{-1} gives reach $\kappa_c < 3.6$

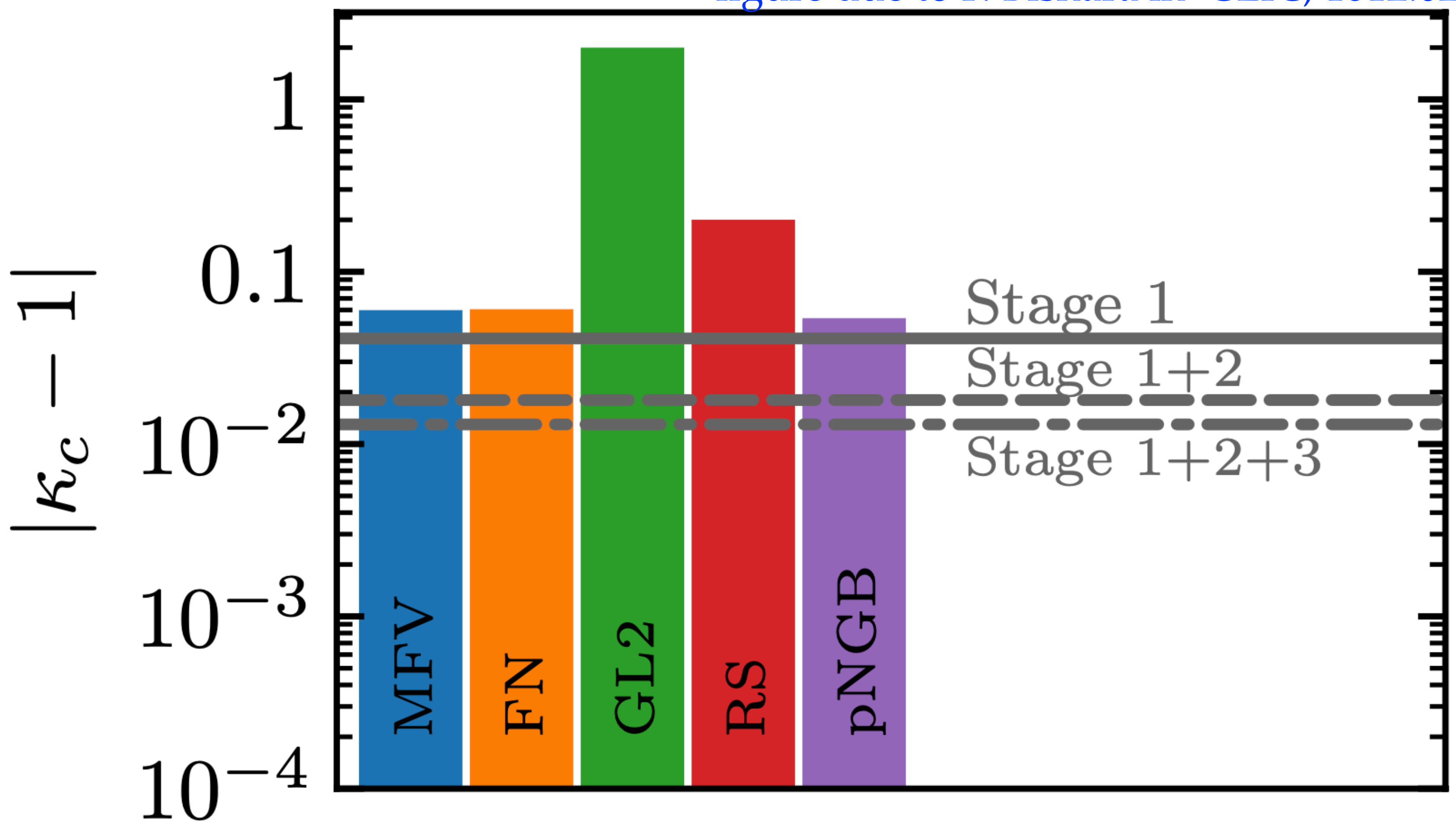
ATLAS, 1802.04329

see also Lenz, Spannowsky, Tetlalmatzi-Xolocotzi, 1708.03517

REACH AT CLIC

- at e^+e^- a completely different ballpark

figure due to F. Bishara in CLIC, 1812.02093



- strangeness tagging, expected reach $\kappa_s \lesssim 3.7(2.6)$ for $5(20)\text{ab}^{-1}$ at FCC-ee

Duarte-Campderros, Perez, Schlaffer, Soffer, 1811.09636

CP VIOLATING COUPLINGS

CLV HIGGS AND EDMS

- the notation

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

  - strong constraints from eEDM
  - also from nEDM once all hadronic matrix elements available from Lattice QCD
  - linear scaling with improvement on EDMs
  - connections with baryogenesis

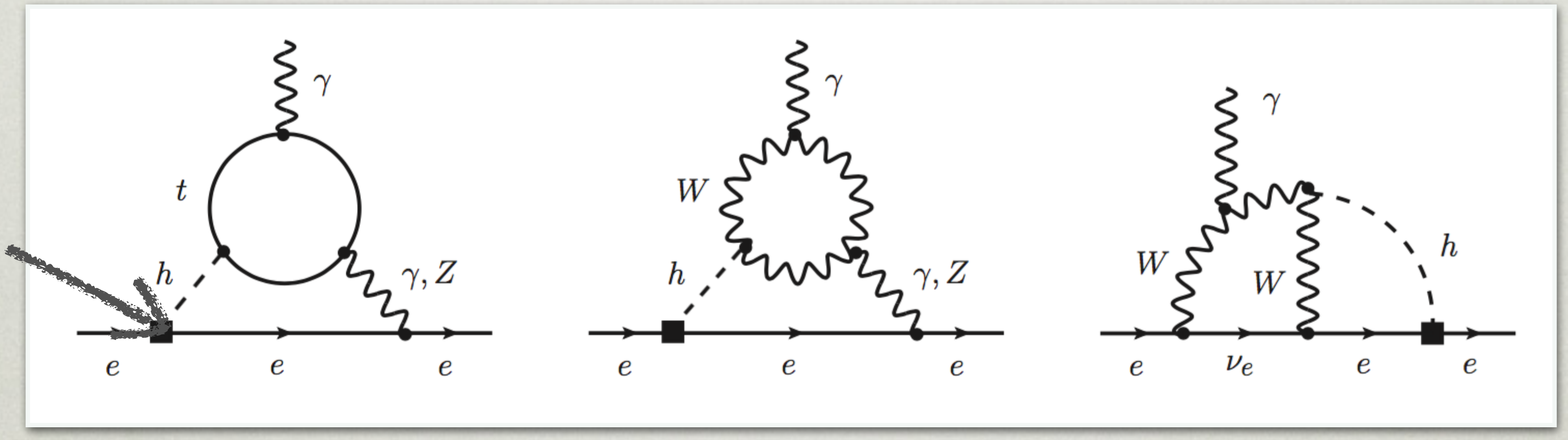
ELECTRON YUKAWA

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

Altmannshofer, Brod, Schmaltz, 1503.04830

- dominant contributions at 2-loop

CPV



- experimental bound ACME coll., 2018

$$\left|\frac{d_e}{e}\right|_{\text{exp}} < 1.1 \times 10^{-29}\ \text{cm} \quad @ 90\,\%\,\text{C.L.}$$

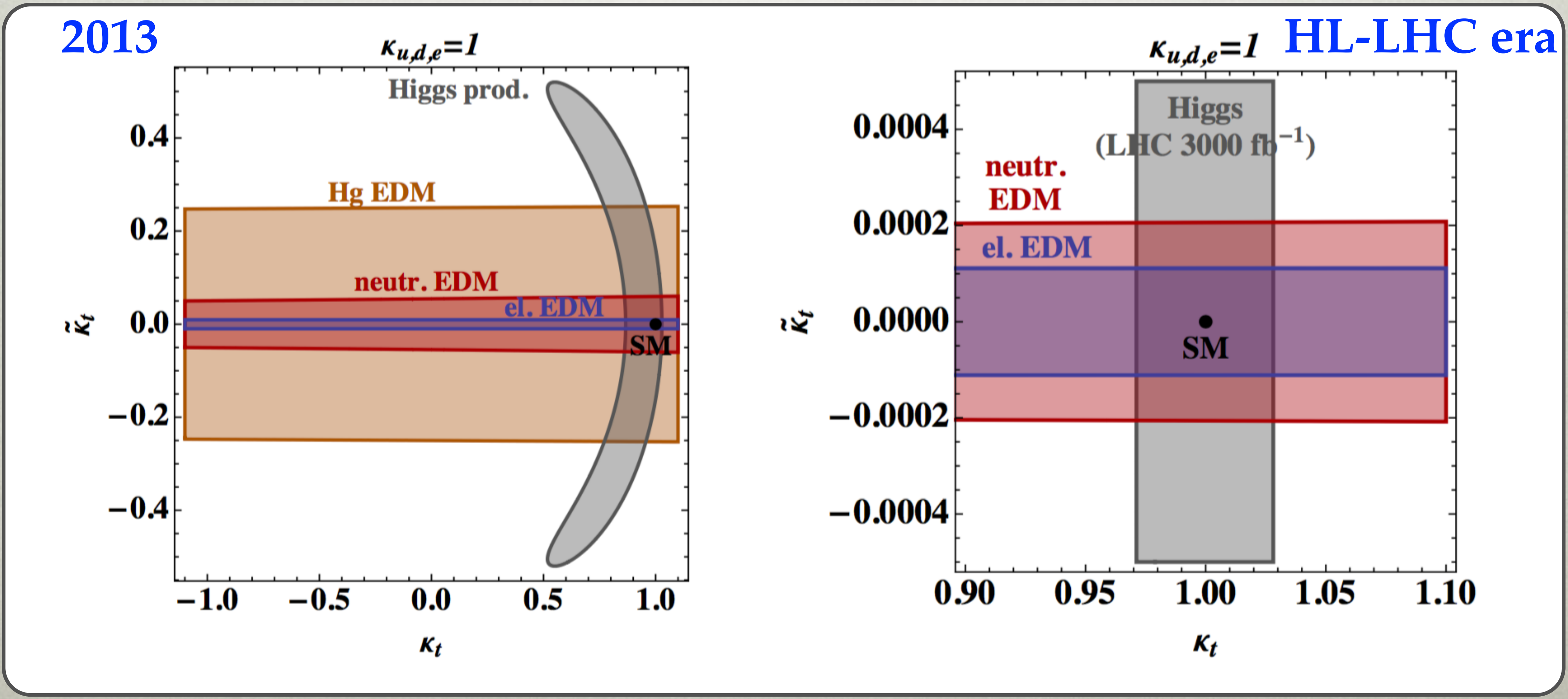
$$|\tilde{\kappa}_e| < 0.6 \cdot 10^{-2}$$

Brod, Haisch, JZ, 1310.1385 see also Cirigliano, de Vries, Dekens, Mereghetti, 1603.03049, 1605.04311

CPV coupling to top

- comparing with the LHC reach
  - assuming that no CPV measurements at the LHC
  - central values only for hadronic matrix elements
- for 1st gen. Yukawas **equal to the SM**

Pospelov-Ritz hep-ph/0504231



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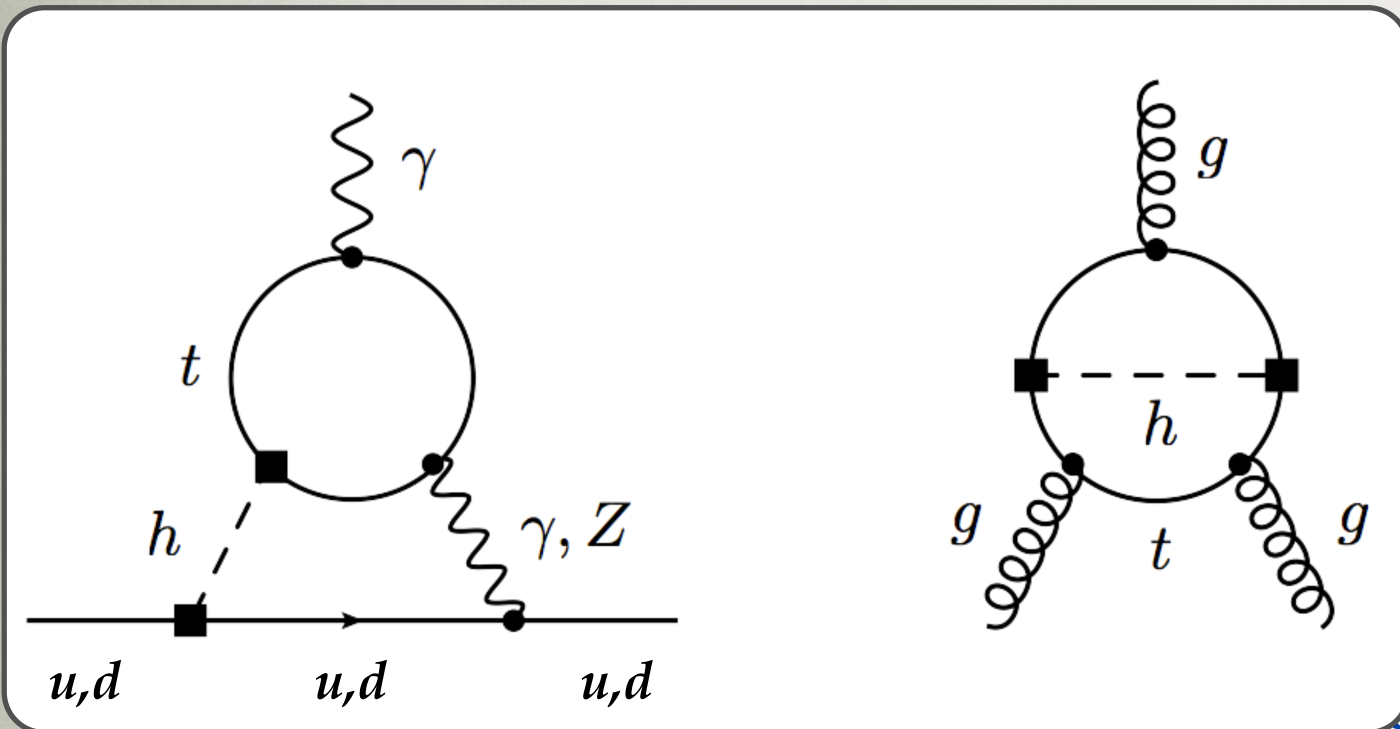

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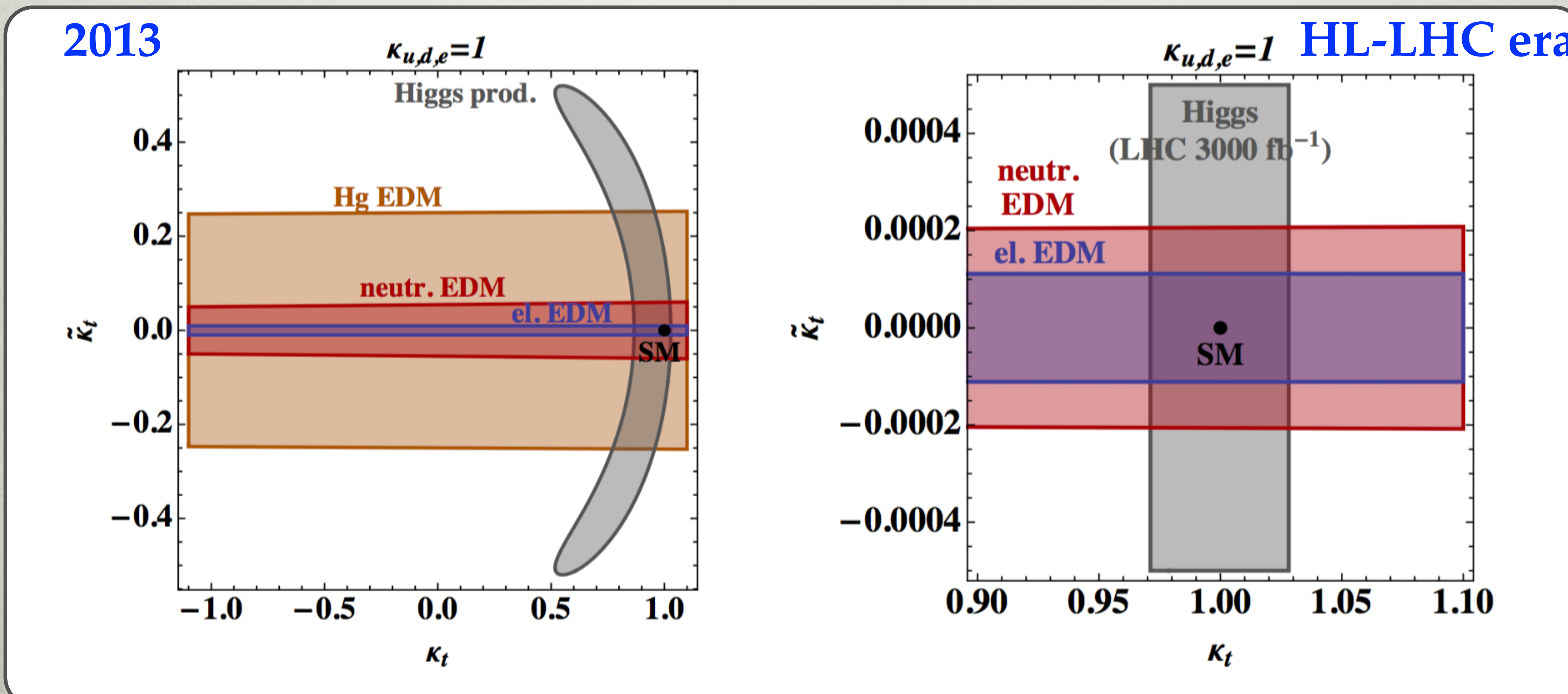
asurements at the LHC

dronic matrix elements

Pospelov-Ritz hep-ph/0504231

the SM



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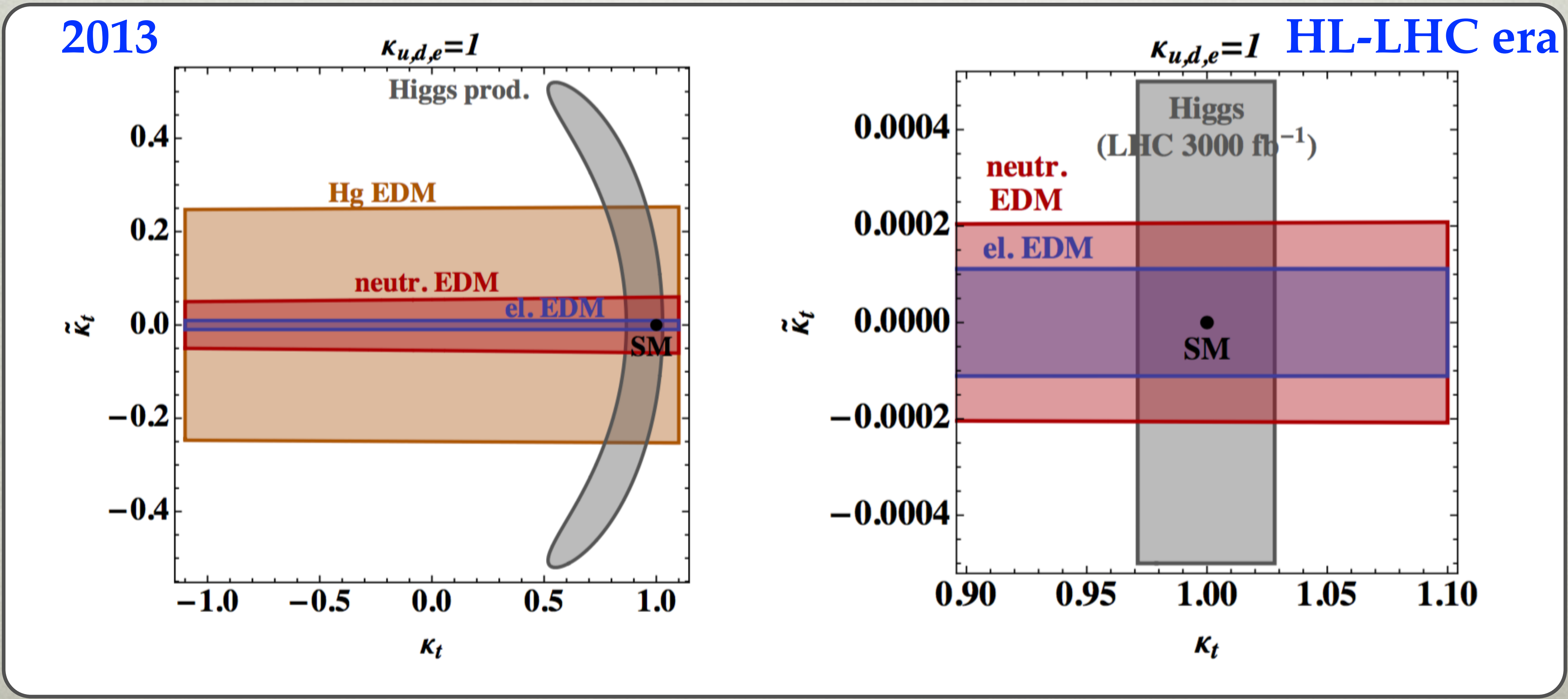
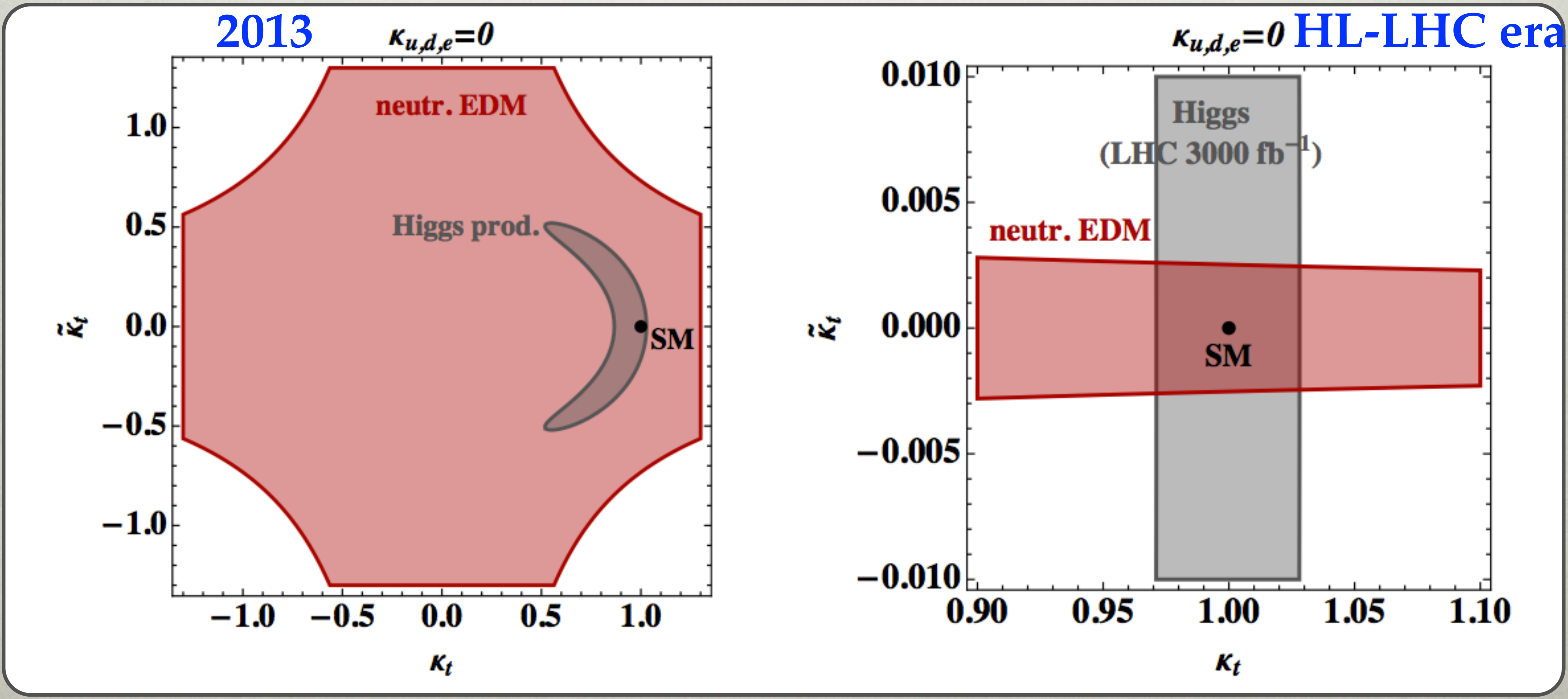


CPV coupling to top

- comparing with the LHC reach
  - assuming that no CPV measurements at the LHC
  - central values only for hadronic matrix elements
- 1st gen. Yukawas **set to zero**

Brod, Haisch, JZ, 1310.1385

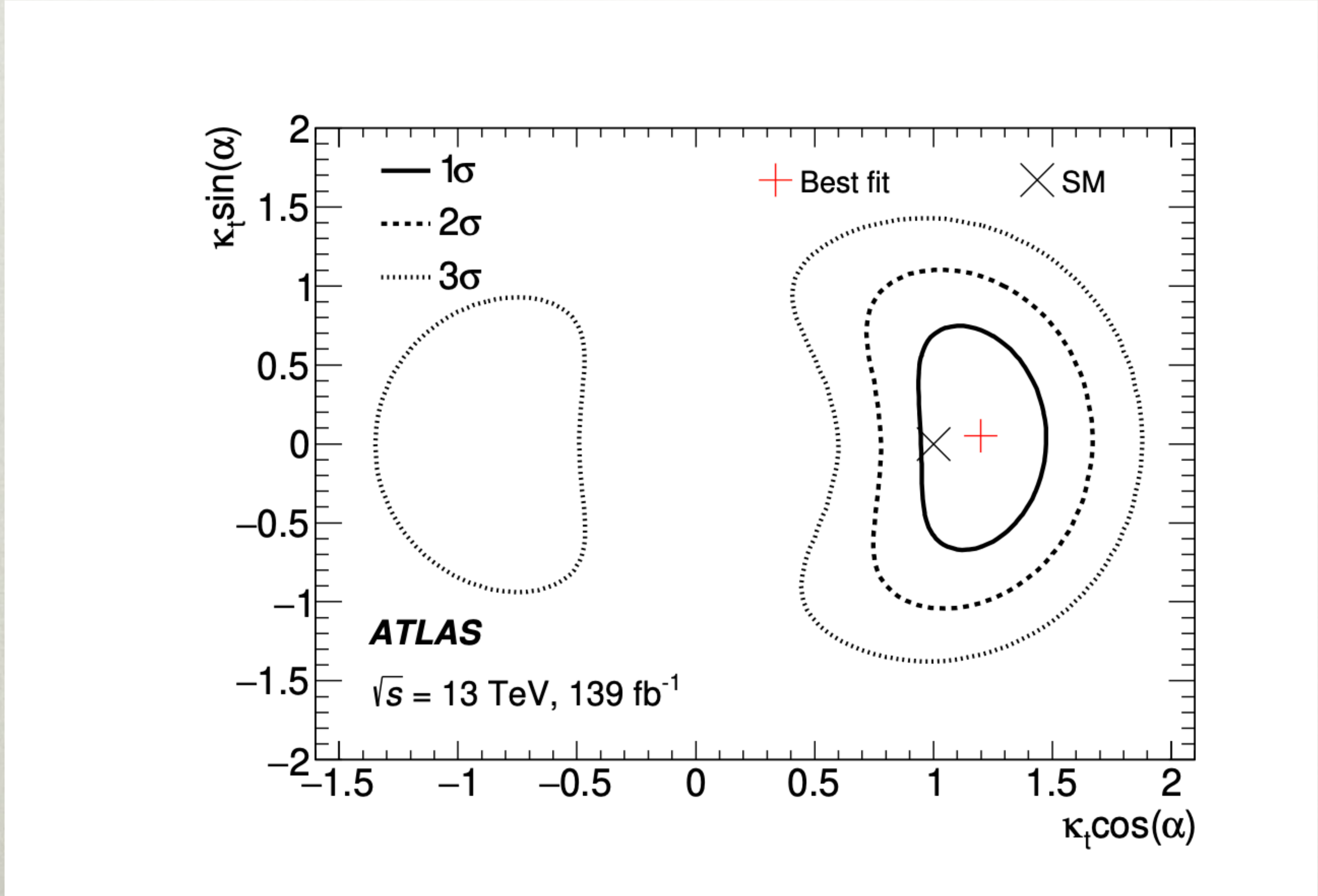
see also Haisch, Hala, 1909.09373, 1909.08955



HIGGS TOP COUPLINGS

- higgs top couplings - present

ATLAS, 2004.04545

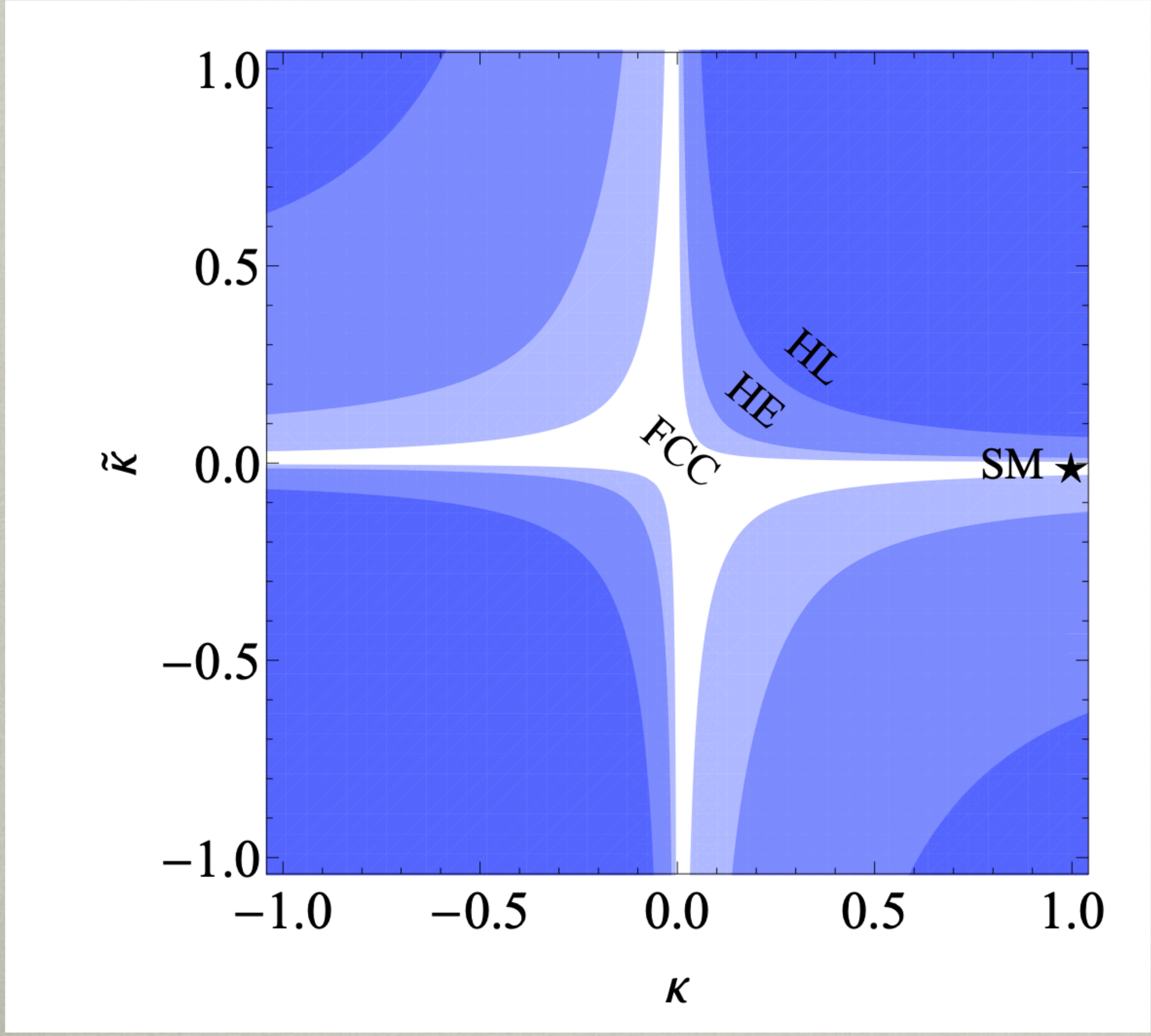


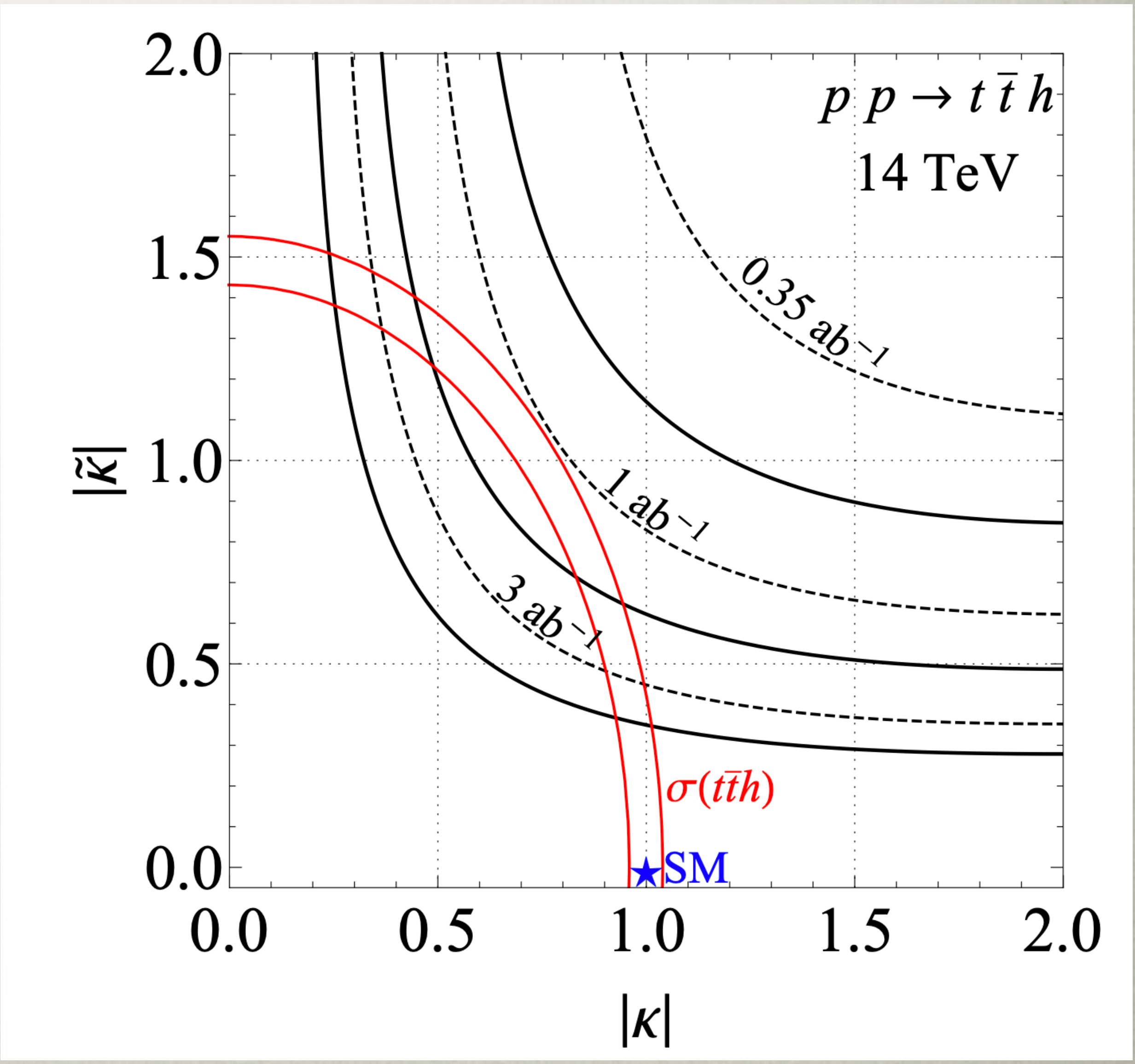
HIGGS TOP COUPLINGS

- Higgs top couplings - future

Bortolato, Kamenik, Kosnik, Smolkovic, 2006.13110

  - from ttH, ML optimized variables





CONNECTION TO BARYOGENESIS

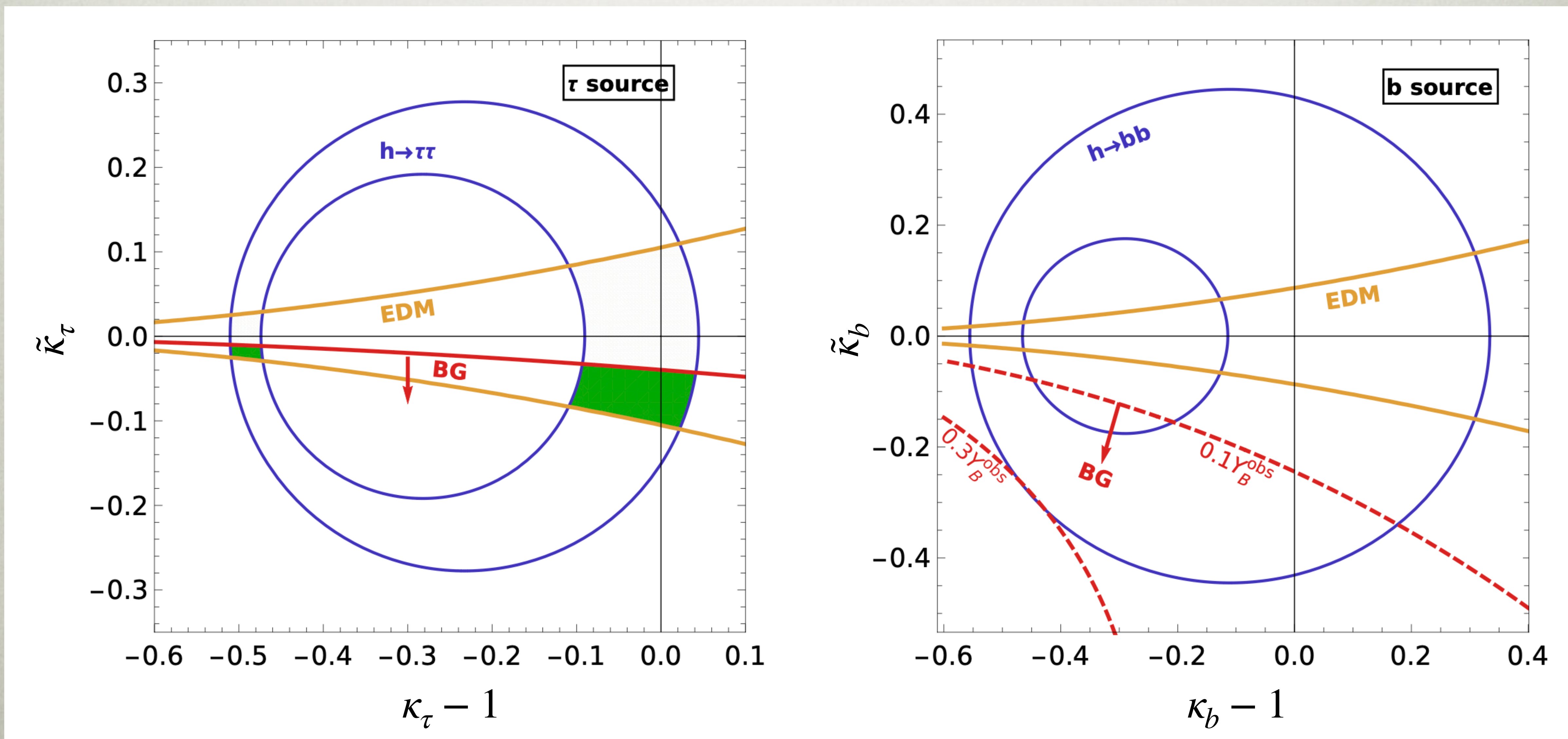
Fuchs, Losada, Nir, Viernik, 1911.08495, 2003.00099

- if EW baryogenesis assumed to be dominated by dim 6 Yukawas
  - $\Rightarrow$ lower limit on CPV Yukawas, κ_f
- additional assumptions:
  - there are additional d.o.f.s that give strongly first-order EWPT
  - these do not change SM fermion interact. in the bubble wall
  - no other (relevant) sources of CPV
- tau $\tilde{\kappa}_\tau \neq 0$ can explain EWBG, but not top or bottom
  - reduced wash-out since no strong sphalerons for tau lepton
  - large lepton diffusion coeffs. lead to efficient diffusion of baryon assmymetry intto the broke phase
  - overcompensate the smaller τ-Yukawa coupling

CONNECTION TO BARYOGENESIS

Fuchs, Losada, Nir, Viernik, 2003.00099

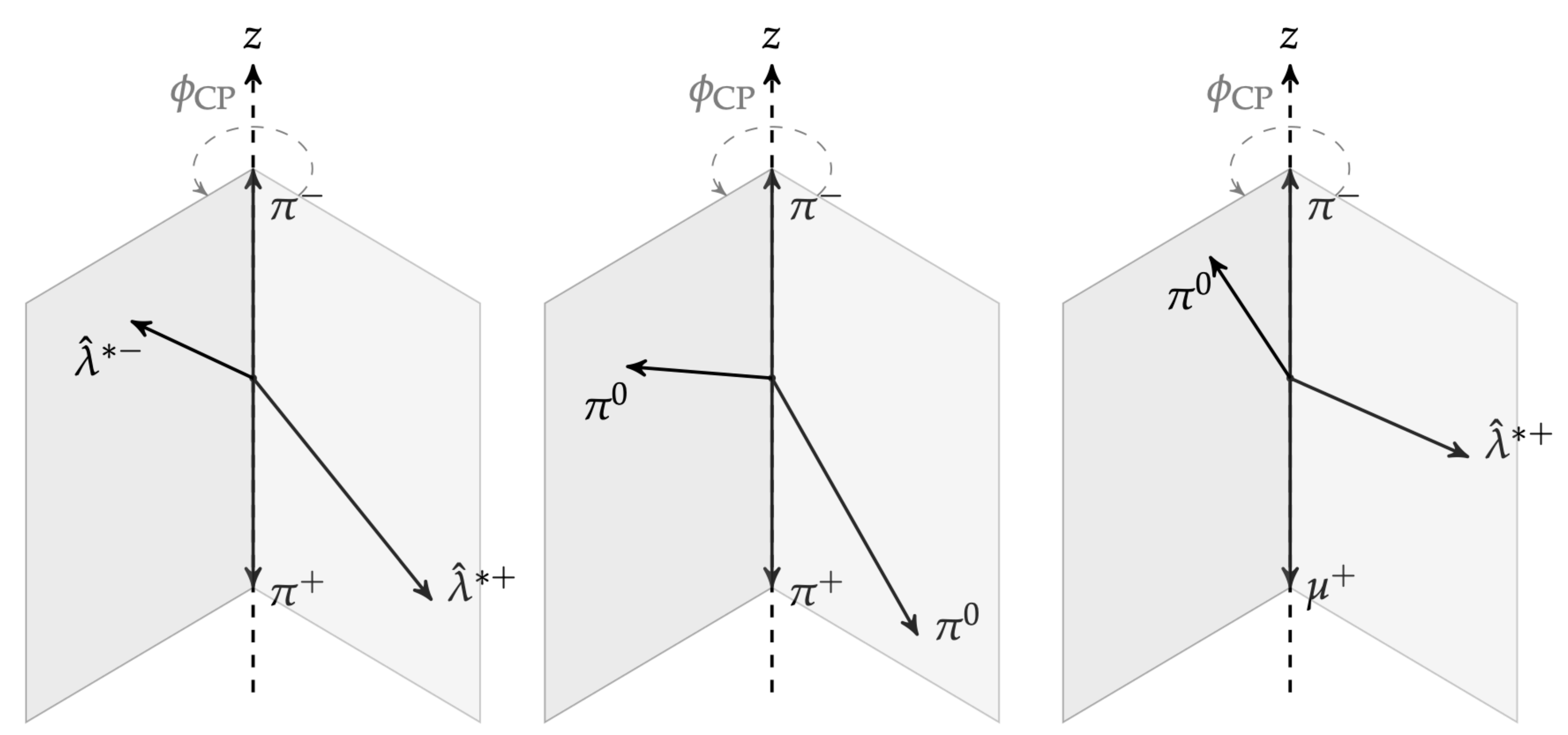
- $\tilde{\kappa}_\tau \sim 0.01 - 0.1$ required for successful EWBG
- corresponds to $\Lambda/\sqrt{\lambda'_{\tau\tau}} \lesssim 18\ \text{TeV}\sqrt{0.01/\tilde{\kappa}_\tau}$



HL-LHC implications

- at HL-LHC potential to measure CPV $h \to \tau\tau$ coupling
- for different tau decay modes define appropriate decay planes
    - such that the angle $\phi_{\tau\tau}$ between them is CP violating

Mode	$\mu^\pm$	$\pi^\pm$	$\rho^\pm \to \pi^\pm\pi^0$	$a_1{}^\pm \to \pi^\pm\pi^0\pi^0$	$a_1{}^\pm \to \pi^\pm\pi^\mp\pi^\pm$
$\mathcal{B}(\%)$	17.4	11.5	25.9	9.5	9.8

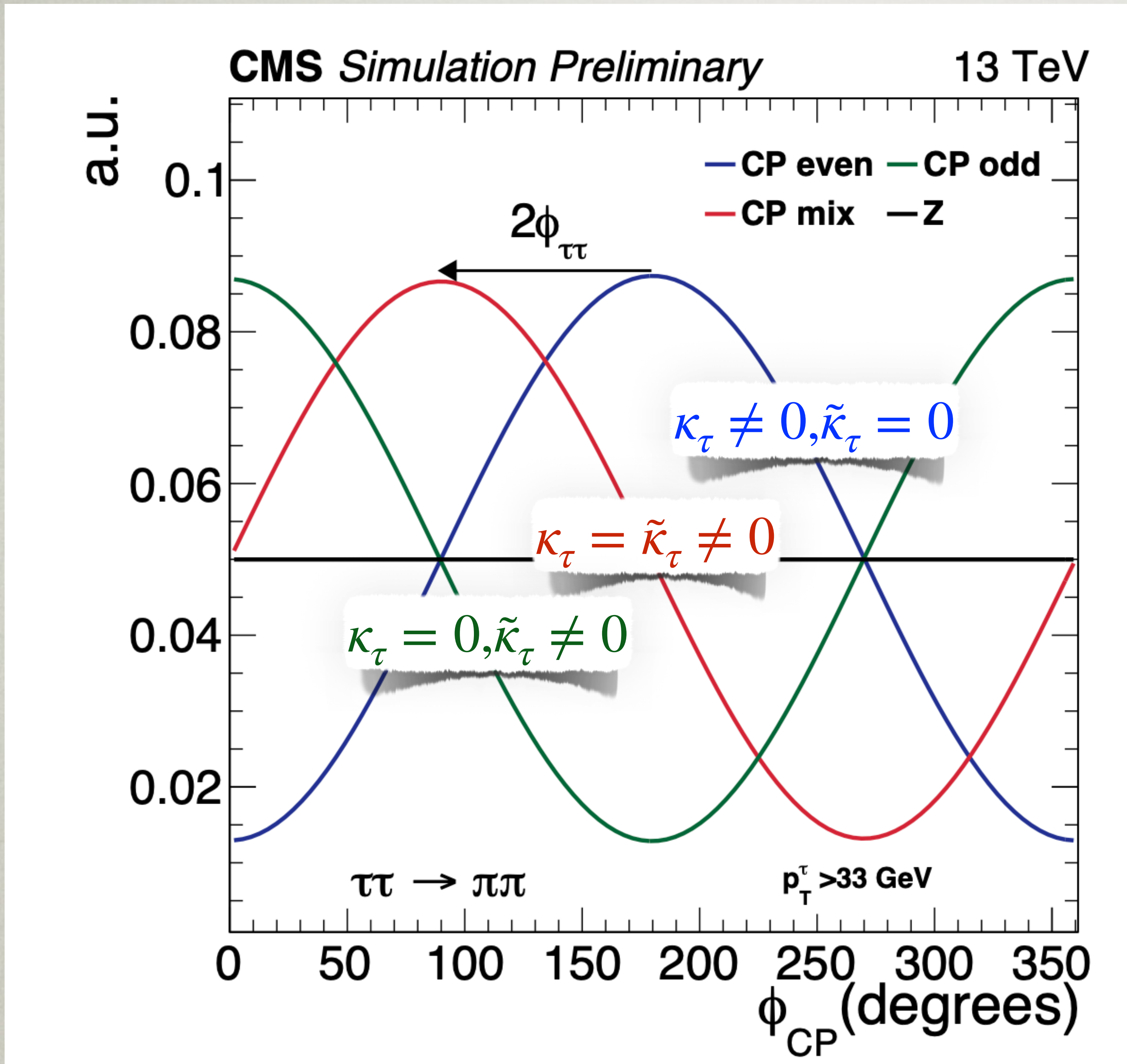


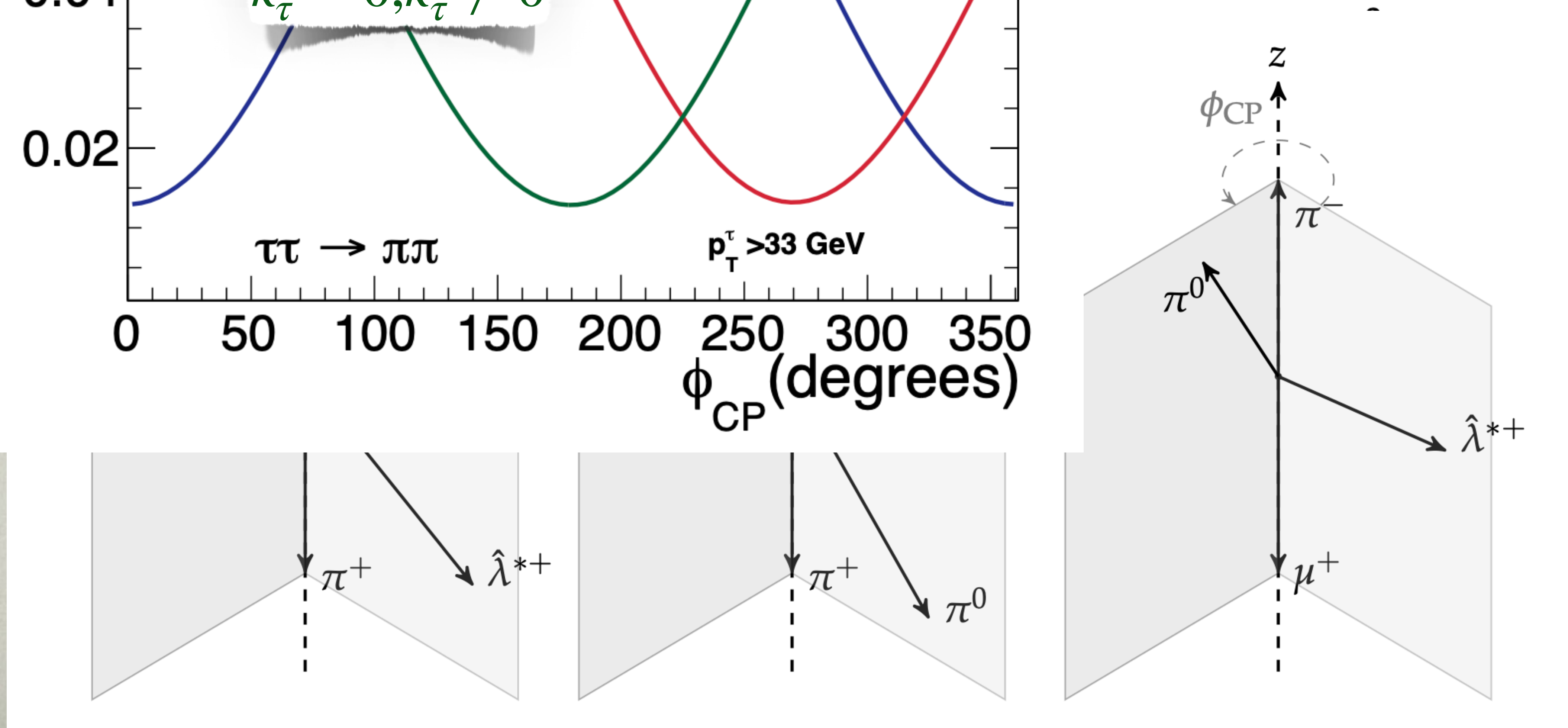
Harnik, Martin, Okui, Primulando, Yu, 1308.1094
CMS Coll., CMS-PAS-HIG-20-006

TIONS

- $\to \tau\tau$ coupling
- propriate decay planes
- is CP violating

π^0	$a_1^\pm \to \pi^\pm\pi^\mp\pi^\pm$
	9.8

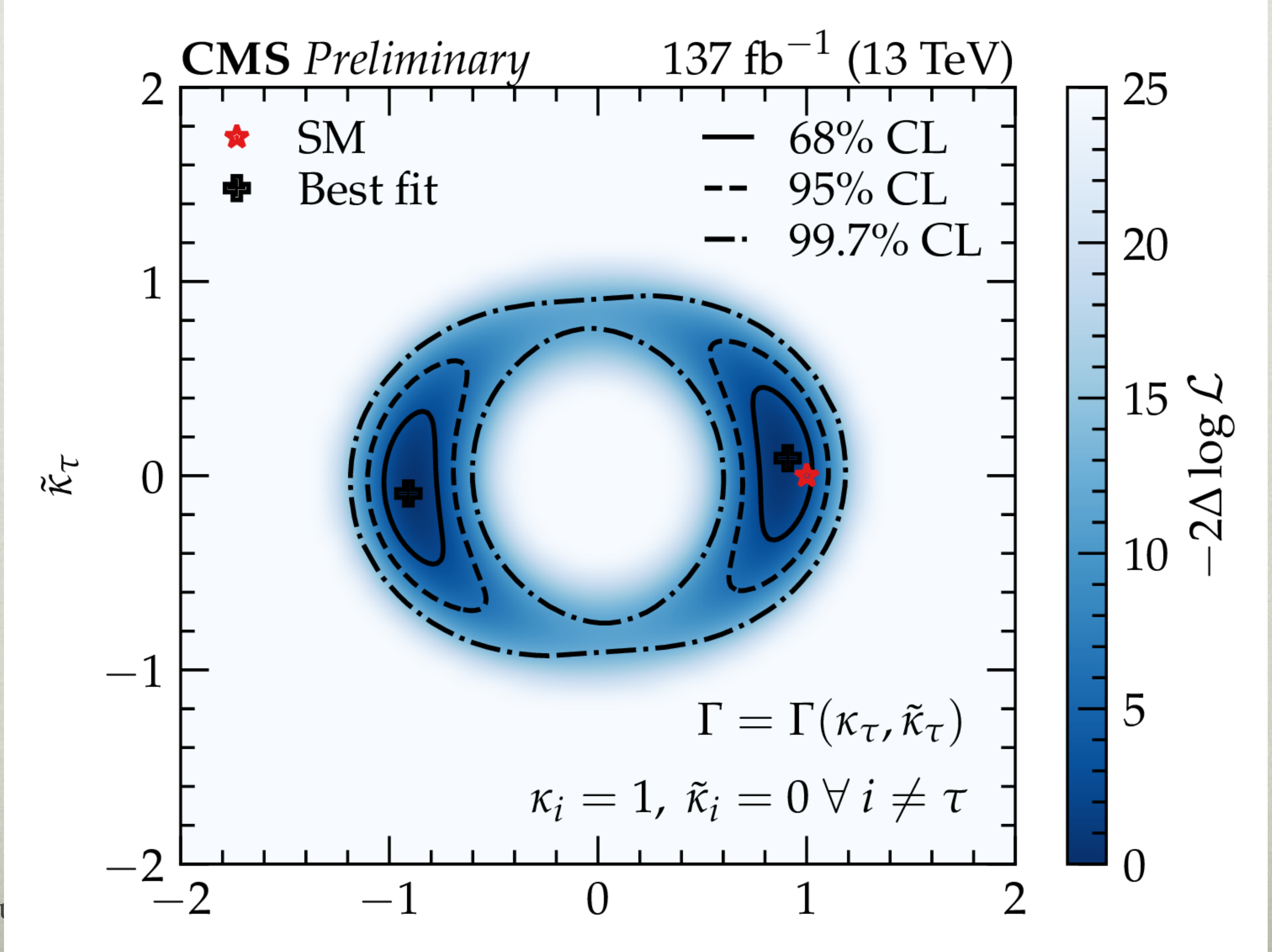




CMS Coll., CMS-PAS-HIG-20-006

PRESENT CONSTRAINT

- CMS with 137 fb^{-1}



FUTURE REACH

- future reach borders on the EWBG region
  - any possible improvements in the measurement strategy?

$$\mathcal{L}_{\rm CPV}^{hff} = -\bar{\kappa}_f m_f \frac{h}{v} \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f\,,$$

Cepeda et al, 1905.03764

Cepeda et al, 1902.00134

ILC, 1903.01629

Name	α_τ
HL-LHC	8°
HE-LHC	–
CEPC	–
FCC-ee$_{240}$	10°
ILC$_{250}$	4°

$\tilde{\kappa}_\tau < 0.14$ (HL-LHC)

$\tilde{\kappa}_\tau < 0.17$ (FCC-ee$_{240}$)

$\tilde{\kappa}_\tau < 0.07$ (ILC$_{250}$)

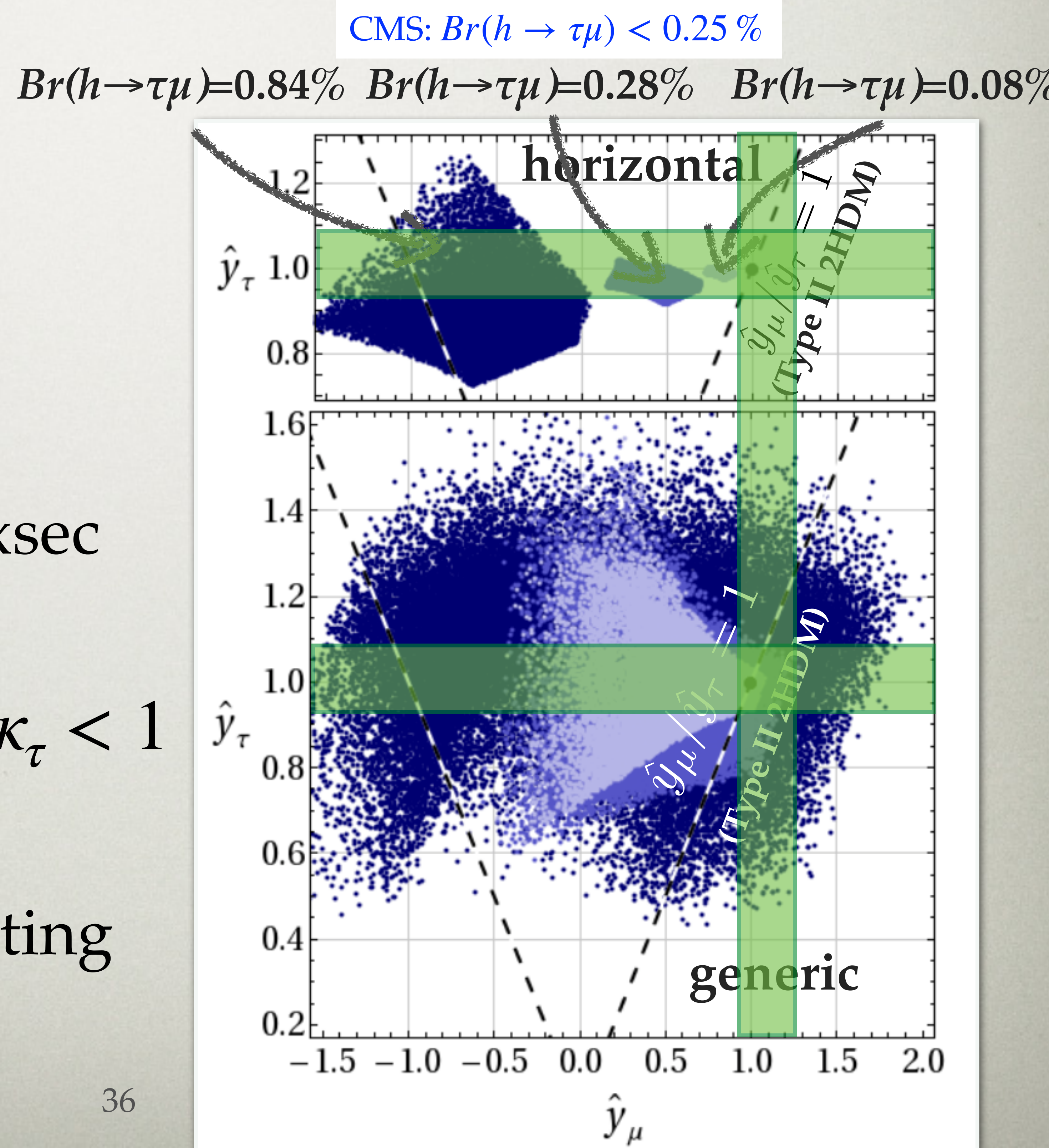
FLAVOR VIOLATING COUPLINGS

- discovery that Higgs couples to muons exacerbates the SM flavor puzzle
- dynamical explanations of small Yukawas?
    - could be at very high scales, i.e. if flavor and EWSB completely factorize
    - if new flavor structures at ~TeV $\Rightarrow$ expect off-diagonal Yukawas

Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

2HDM example: sequestered Yukawas

- scanning over mass matrix entries and imposing:
  - that m_μ, m_τ are eigenvalues
  - the heavy Higgs xsec bounds
- ratios $\kappa_\mu < 1$ and $\kappa_\mu/\kappa_\tau < 1$ favored
- sizeable flavor violating $Br(h \to \tau\mu)$

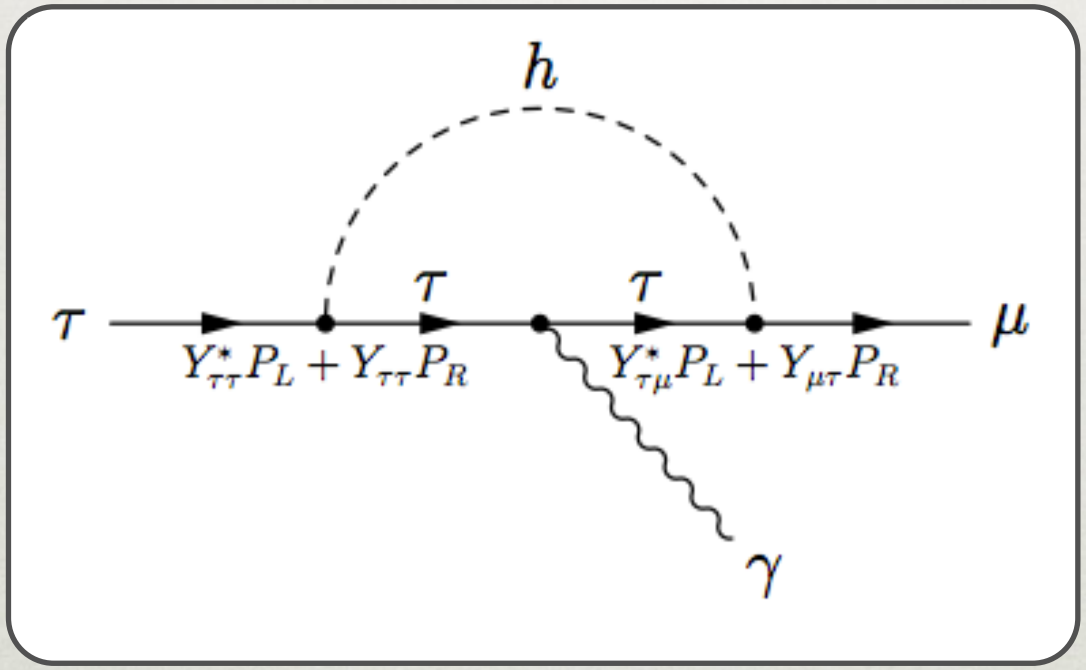


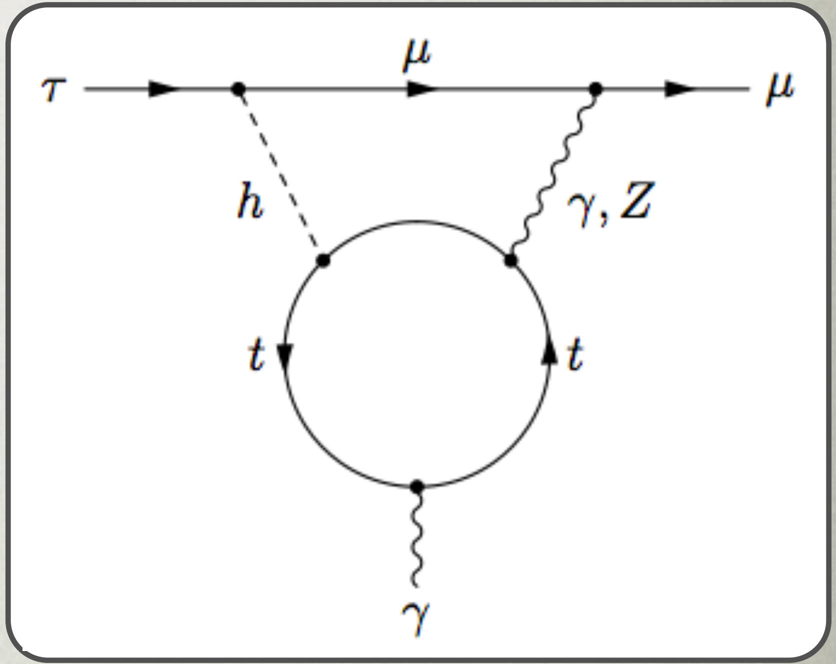
INDIRECT BOUNDS ON $h\to\tau\mu$

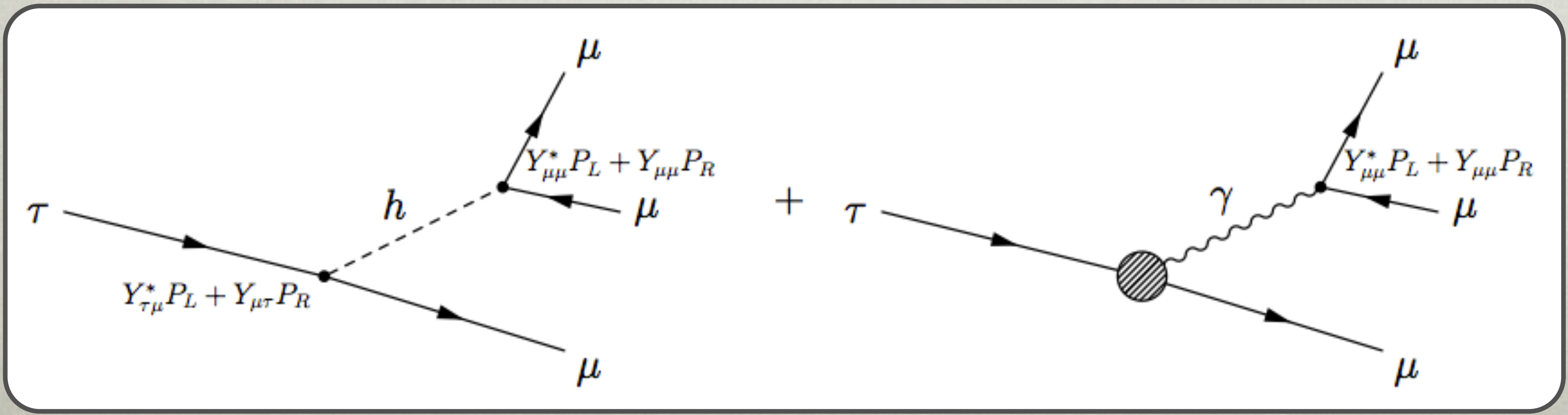
Harnik, Kopp, JZ, 1209.1397

see also Blankenburg, Ellis, Isidori, 1202.5704

- also indirect bounds from charged lepton FCNC transitions
    - $\tau\to\mu\gamma$
    - $\tau\to 3\mu$

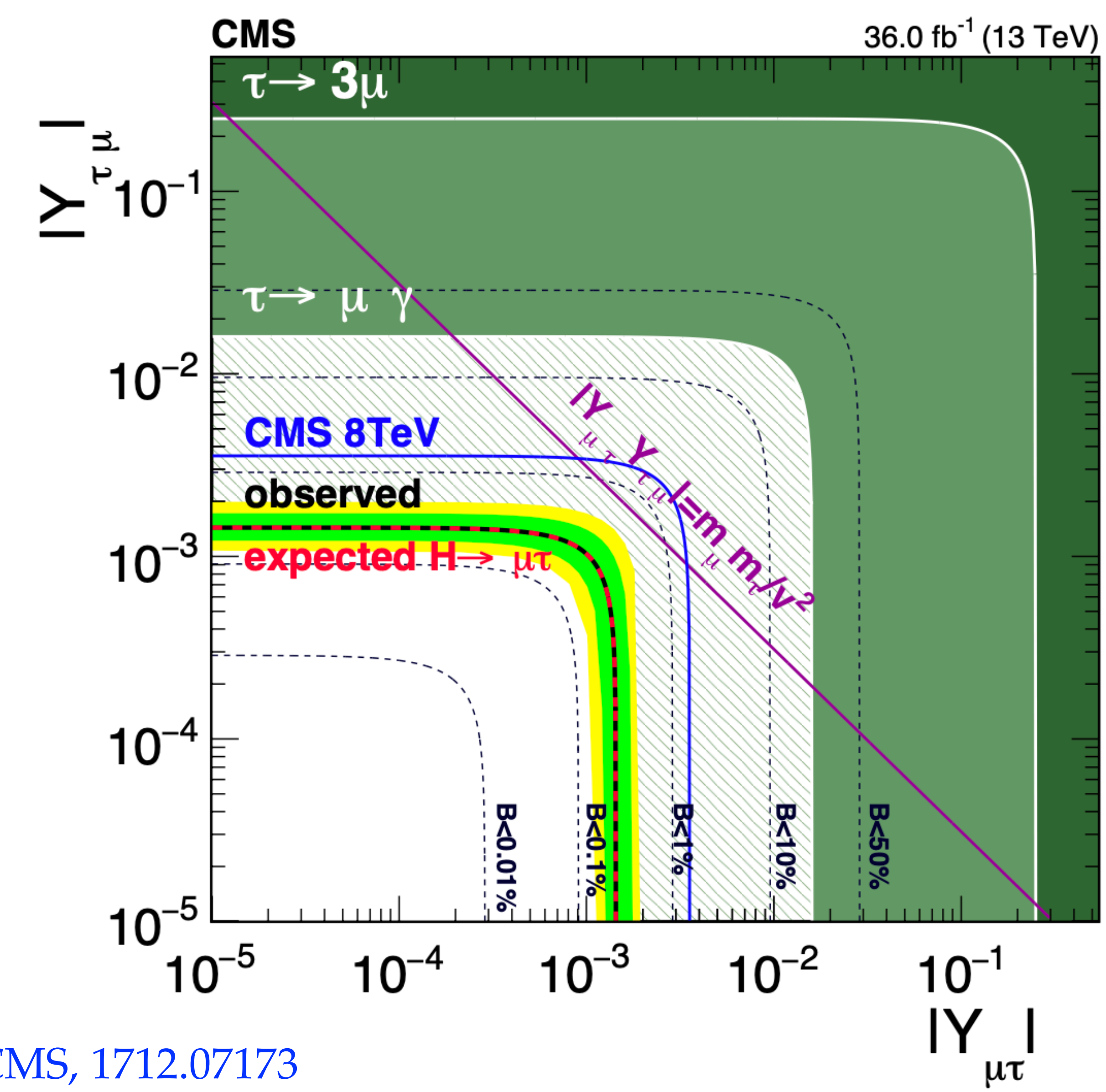




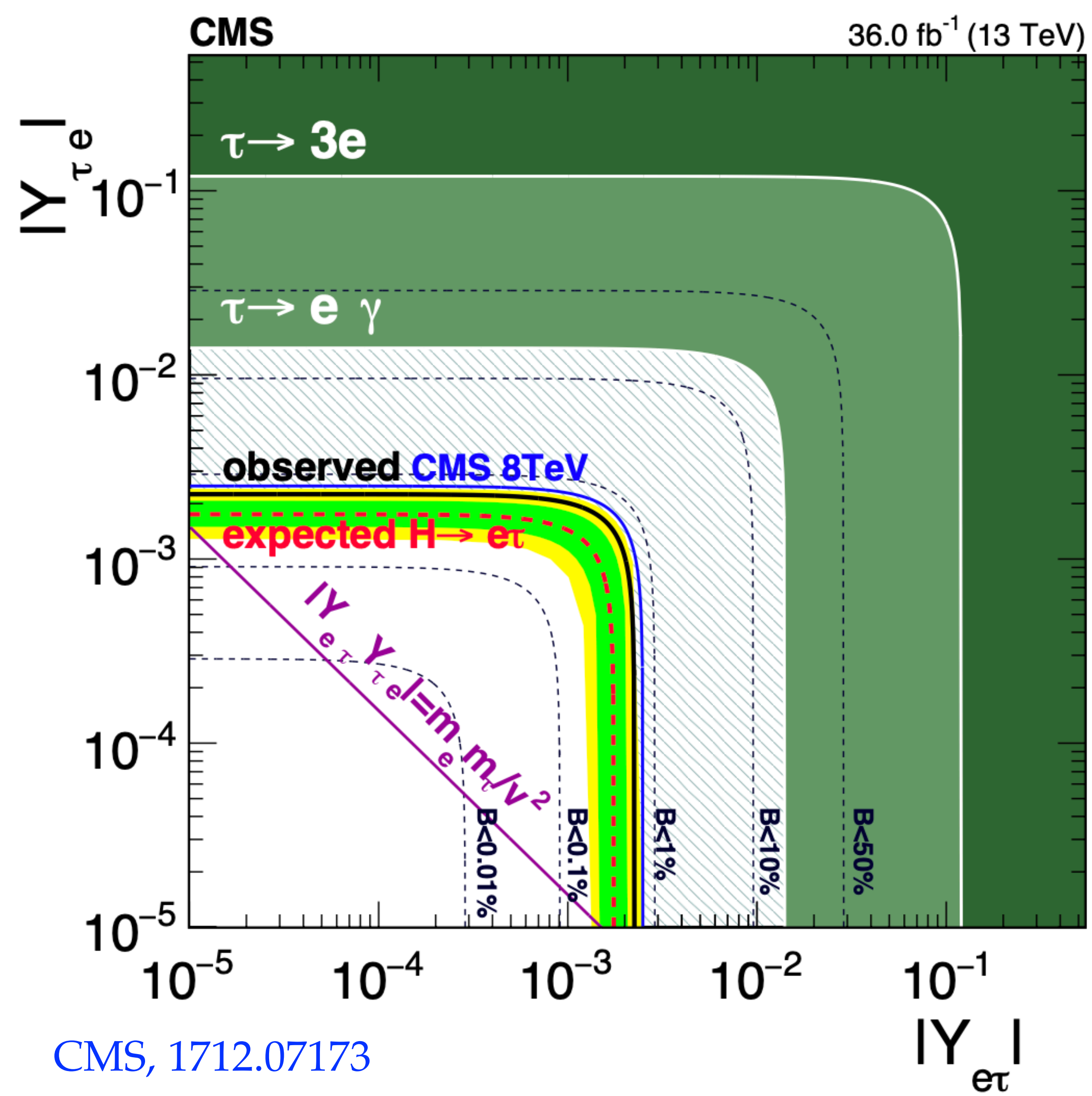


see also ATLAS 1907.06131

FLAVOR VIOLATING COUPLINGS



CMS, 1712.07173



CMS, 1712.07173

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

$$\Lambda_{\mu\tau} > 5.5 \text{ TeV}$$

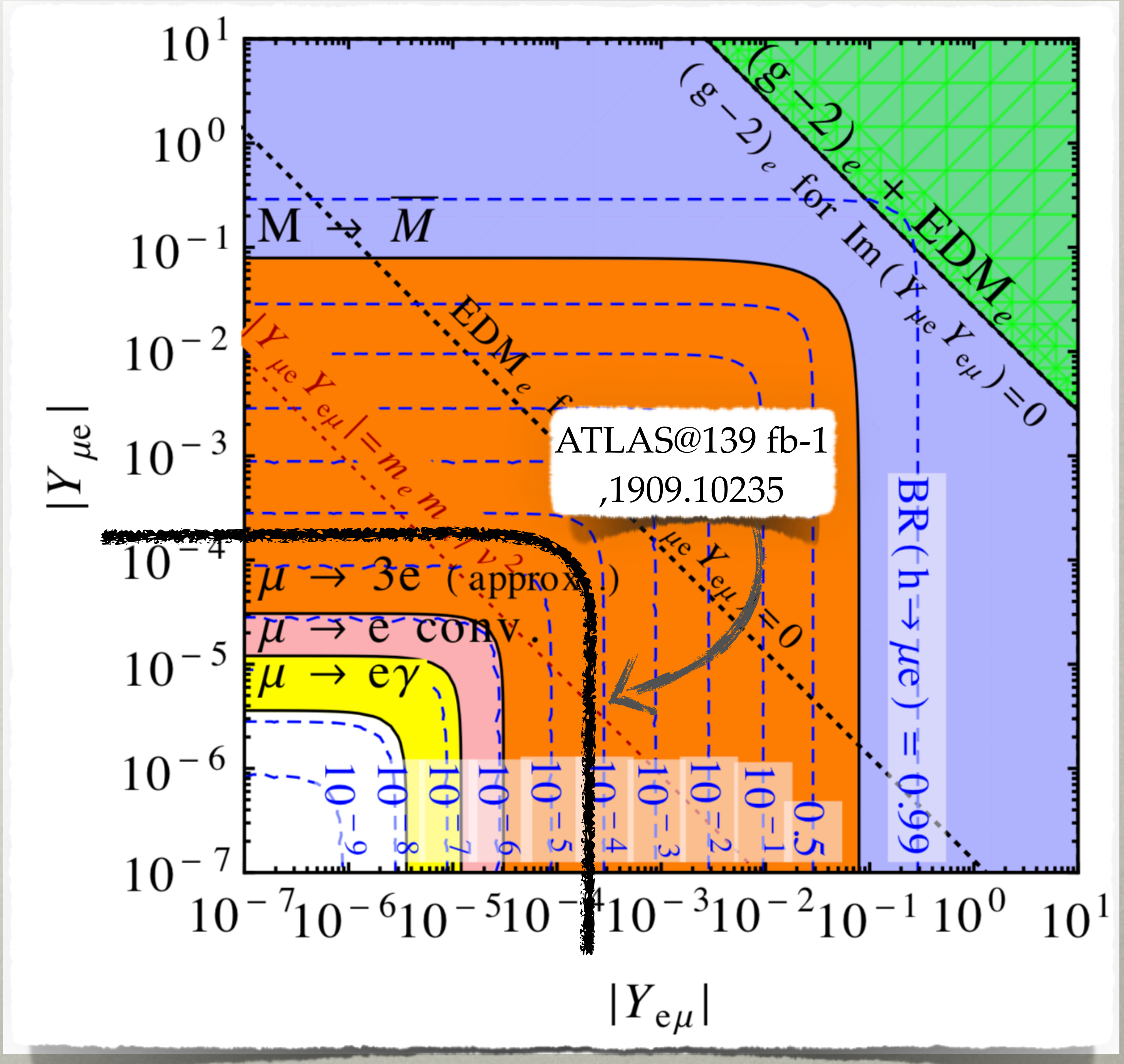
$$\Lambda_{e\tau} > 4.4 \text{ TeV}$$

for $\hat{\lambda}_{ij} = 1$

INDIRECT BOUNDS ON $h \to e\mu$

Harnik, Kopp, JZ, 1209.1397

- indirect bounds especially severe for $h \to e\mu$
- $Br(h \to e\mu) < 10^{-8}$ required to surpass the bound from $Br(\mu \to e\gamma)$
- caveat: could be cancellations in the loop

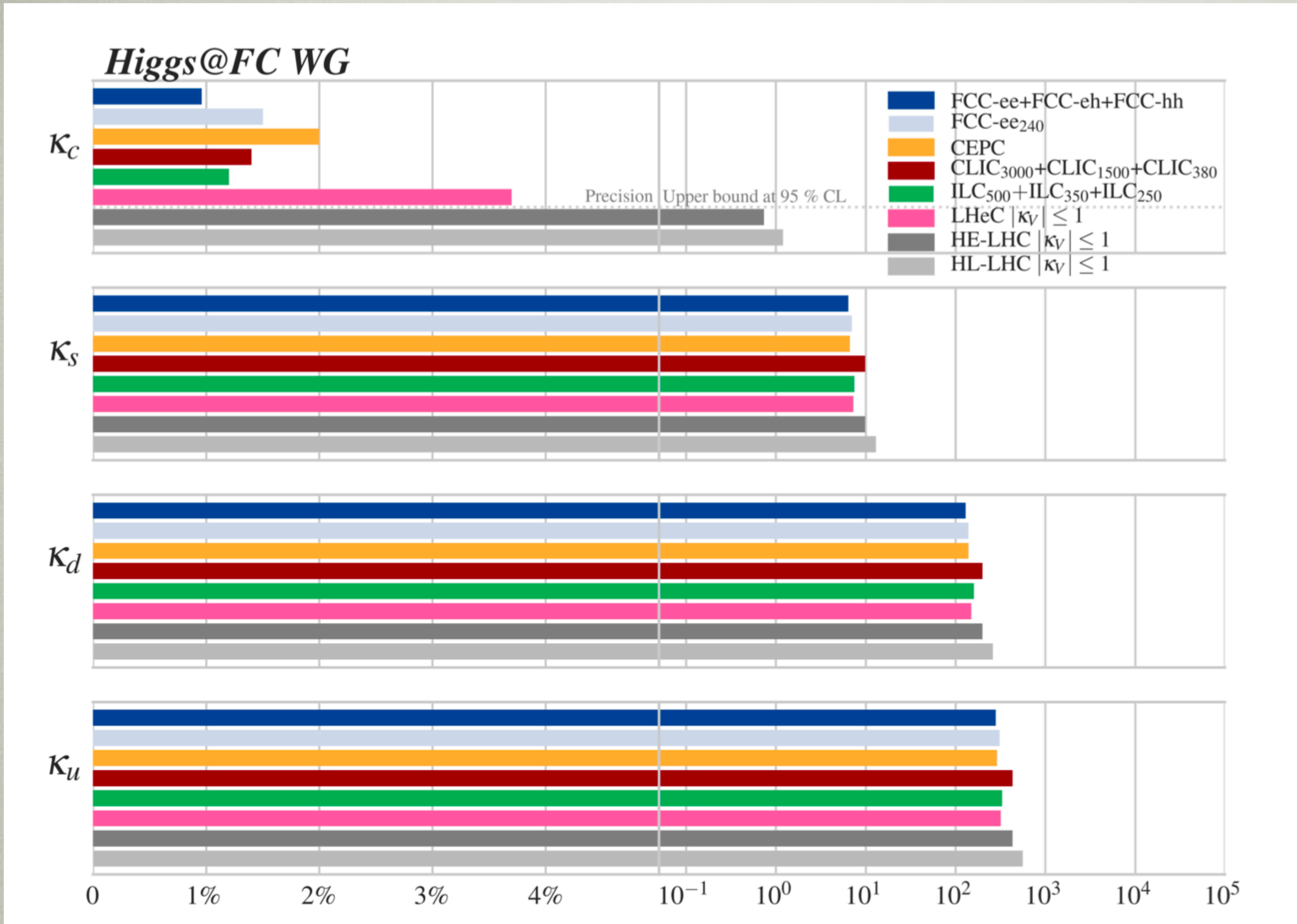


CONCLUSIONS

- observation of higgs coupling to muons implies hierarchical Yukawas (up to caveats)
    - measurements of diagonal and flavor violating Higgs couplings to leptons crucial
- nonzero CP violating tau Yukawas could drive EW baryogenesis

BACKUP SLIDES

Cepeda et al, 1905.03764



	HL-LHC	+LHeC	+HE-LHC	+ILC$_{500}$	+CLIC$_{3000}$	+CEPC	+FCC-ee$_{240}$	+FCC-ee/eh/hh
κ_u	560.	320.	430.	330.	430.	290.	310.	280.
κ_d	260.	150.	200.	160.	200.	140.	140.	130.
κ_s	13.	7.3	9.9	7.5	9.9	6.7	7.	6.4
κ_c	1.2		0.87	measured directly				