FLAVOR @MUON COLLIDER

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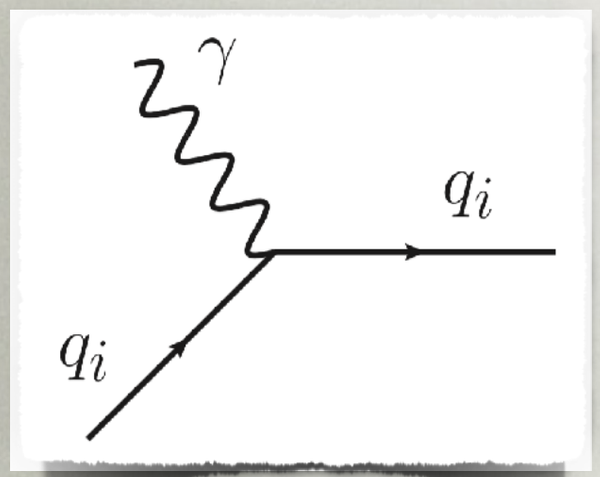
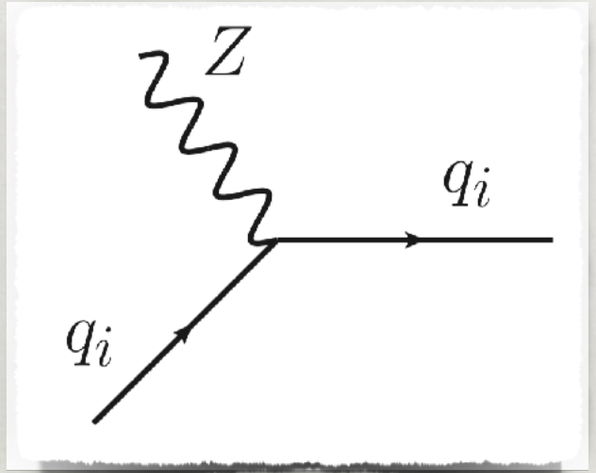
U. of Cincinnati

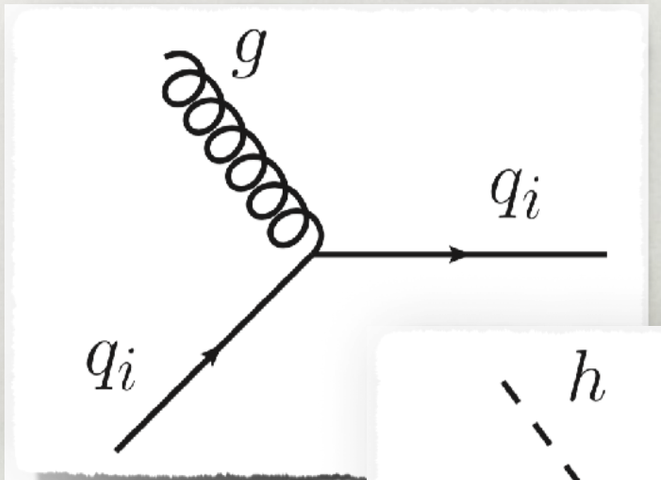
Inaugural US Muon Collider Meeting, Fermilab, Aug 8 2024

FLAVOR IN THE SM

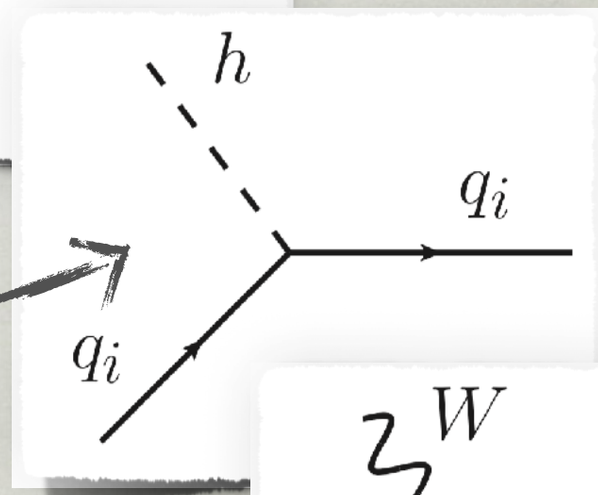
- neutral currents are flavor conserving (at tree level)
  - photon, gluon, *Z:* have *flavor (generation) universal* interactions



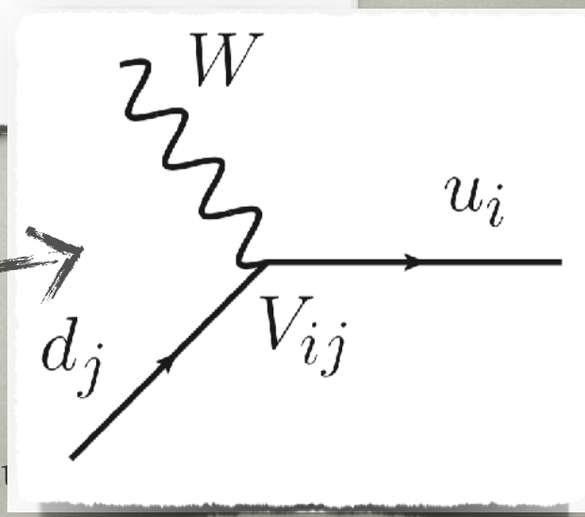




- Higgs has *flavor diagonal* interactions
  - proportional to quark mass



- charged currents are *flavor changing*
  - *W* couplings are flavor changing



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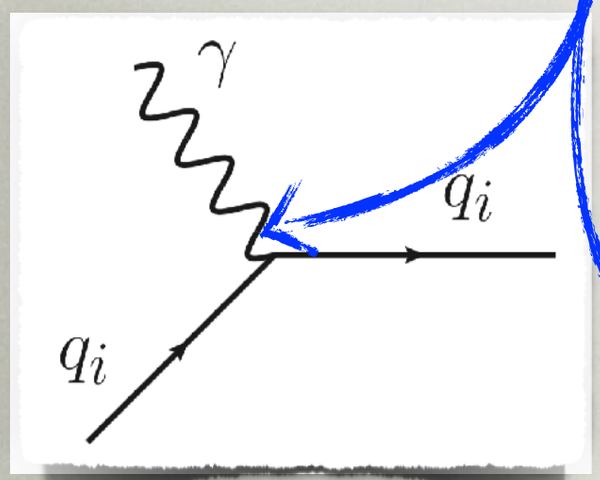

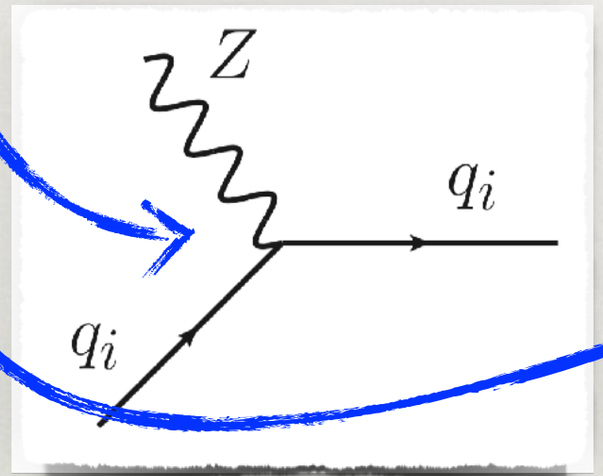

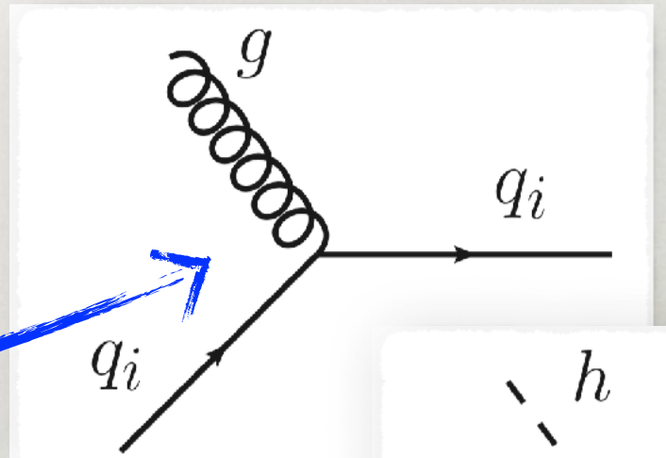

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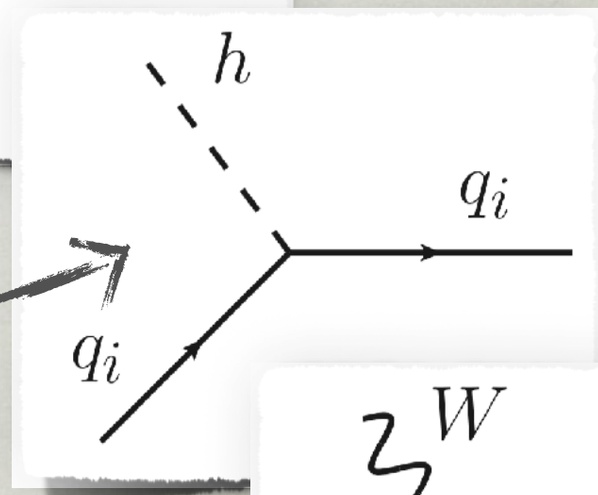

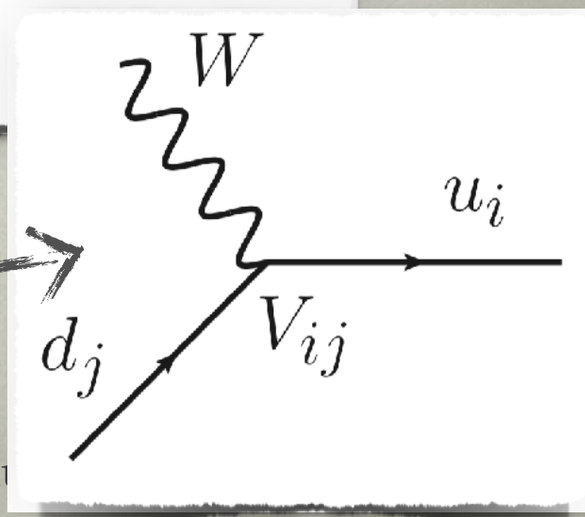

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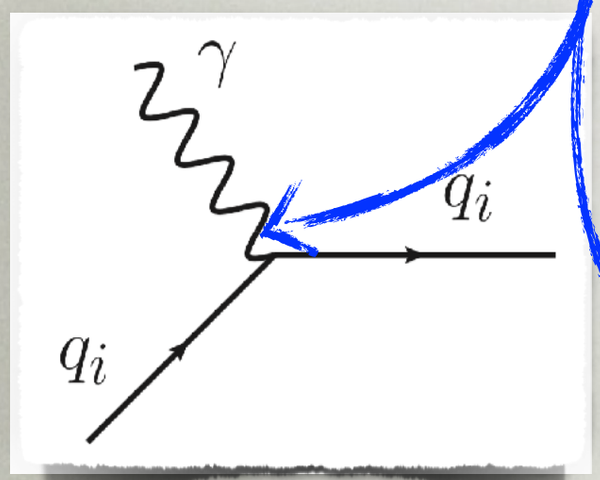

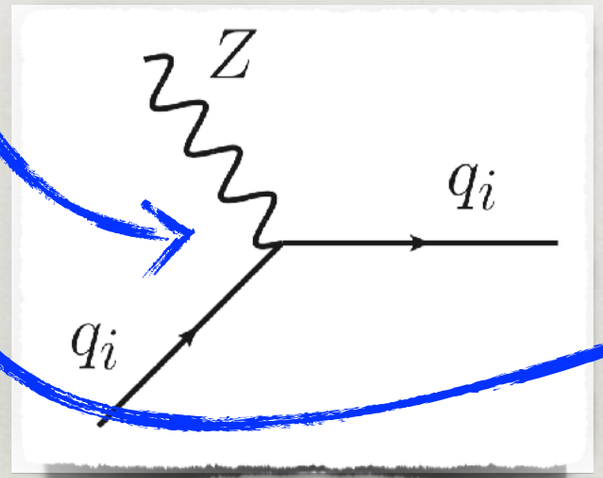

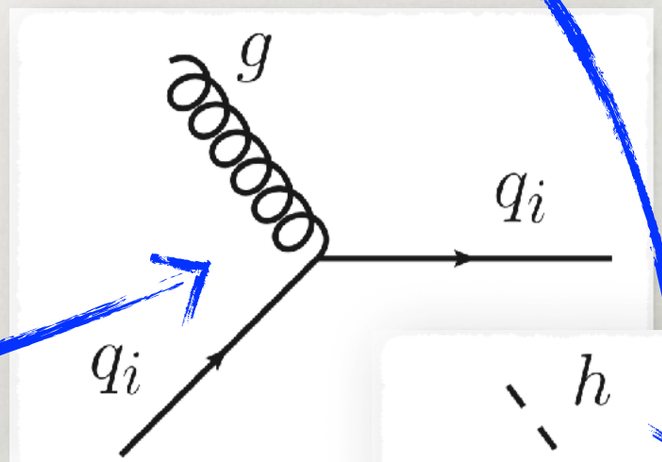

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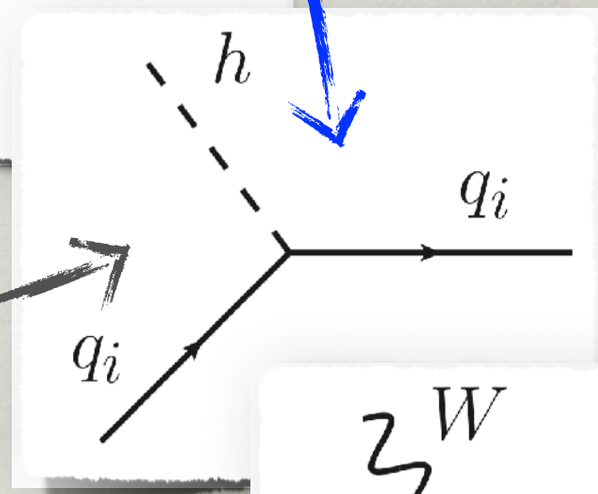

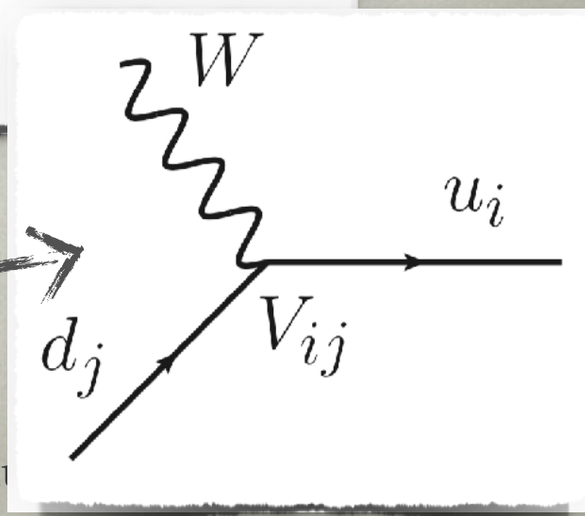

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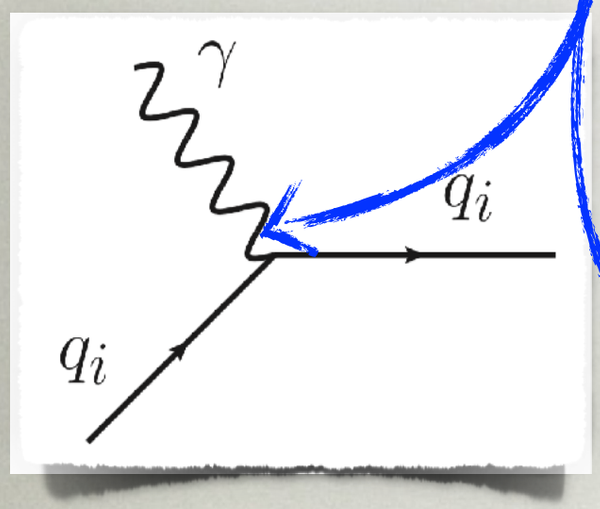

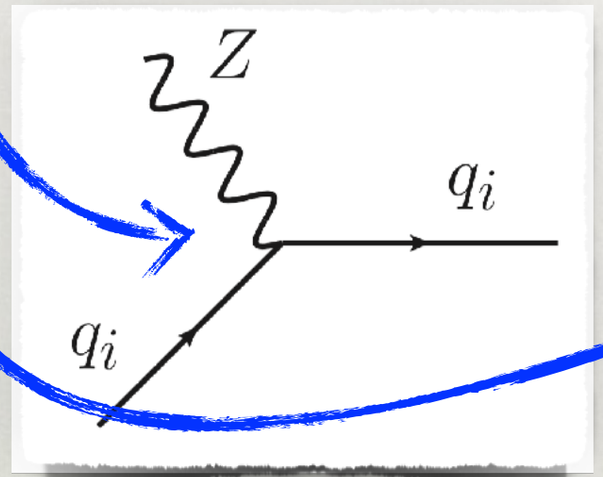

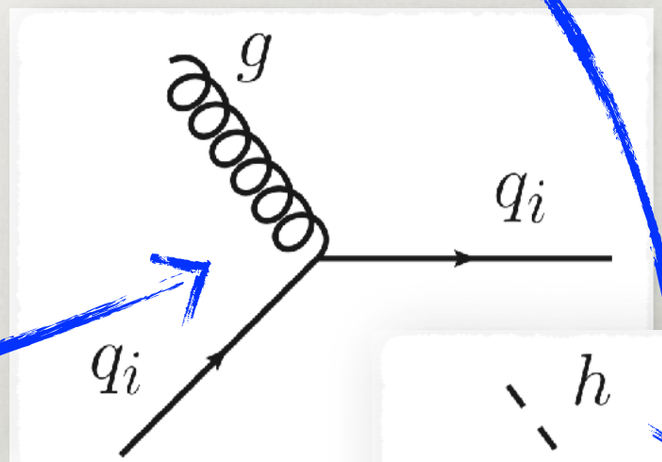

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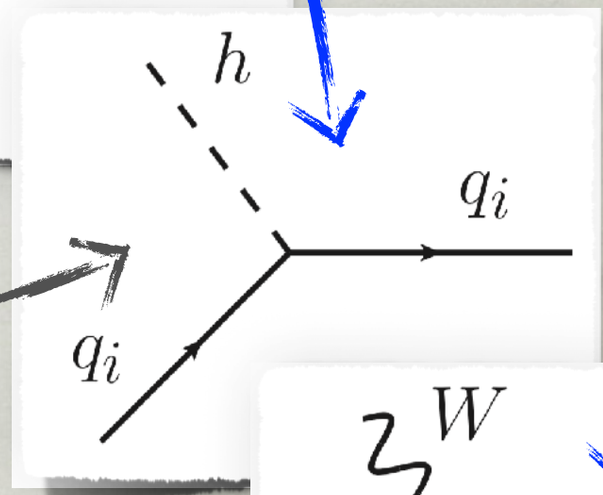
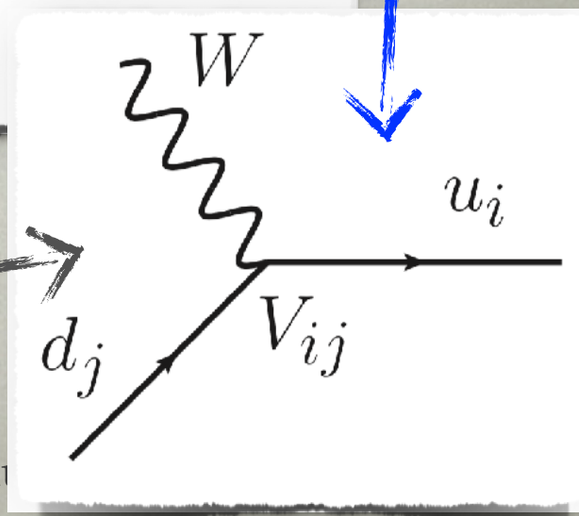
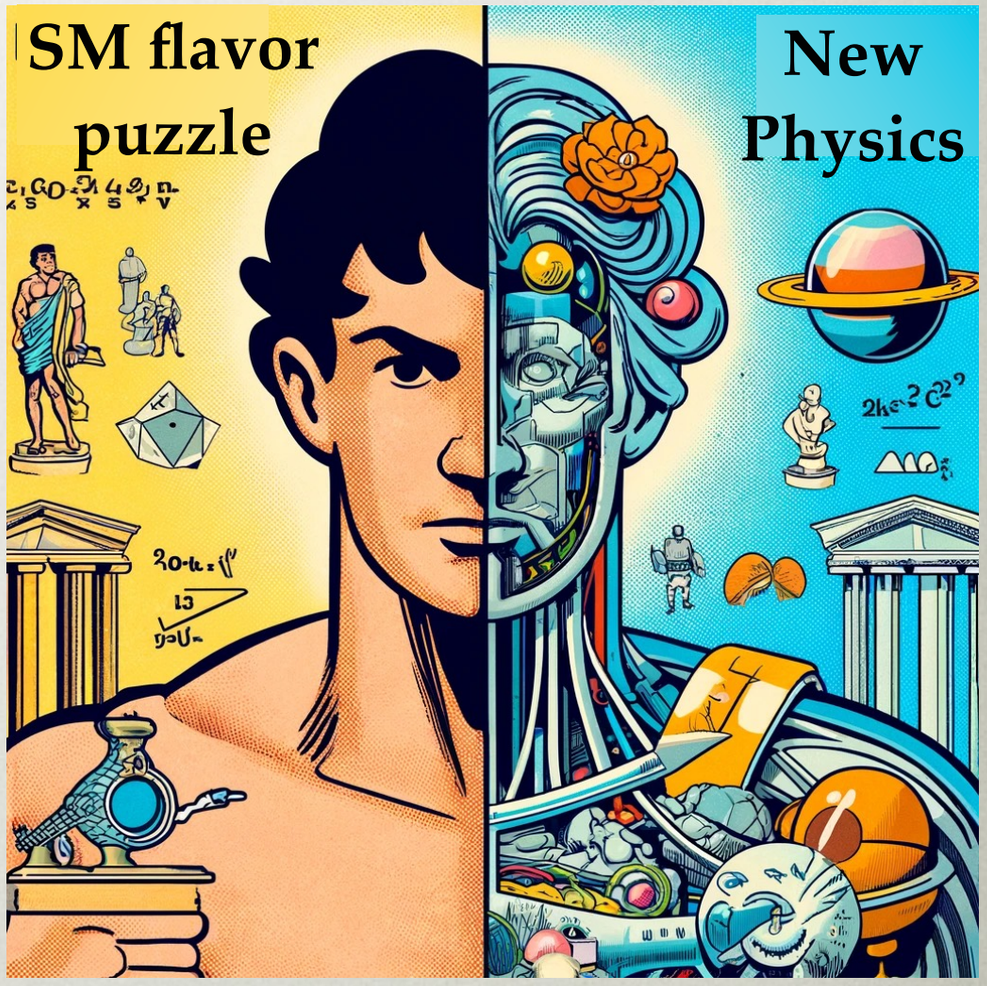




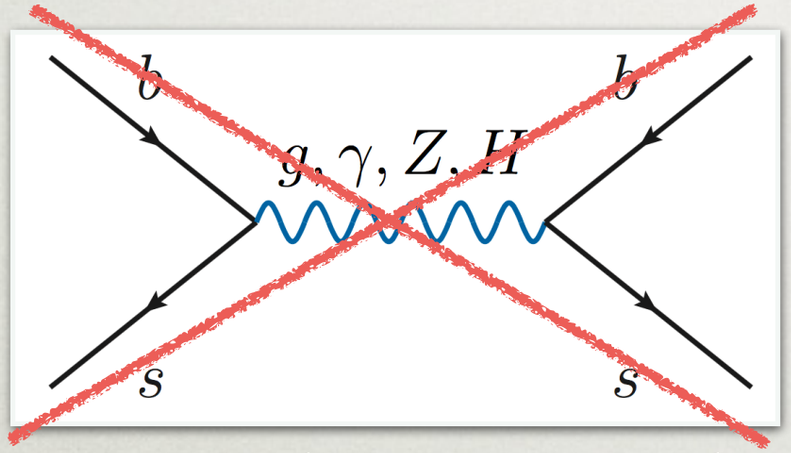
TWO FACES OF FLAVOR PHYSICS

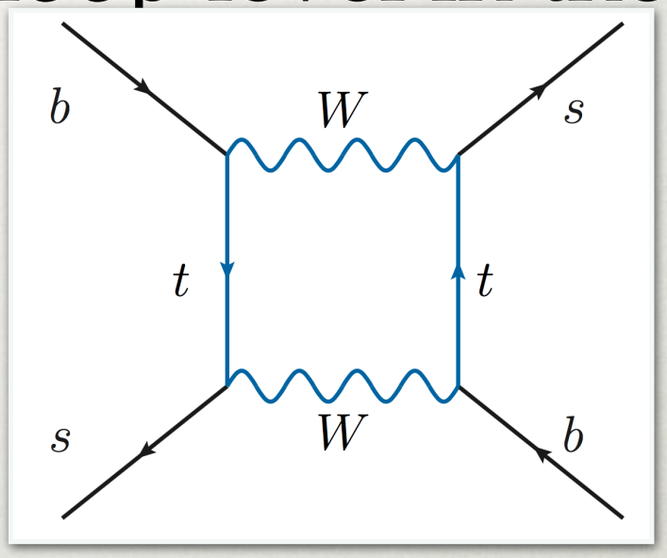
- no flavor changing neutral currents in the SM
  - ⇒ flavor transitions sensitive probes of new physics
- why the observed structure of quark and lepton masses and mixings?
  - ⇒ flavor model building



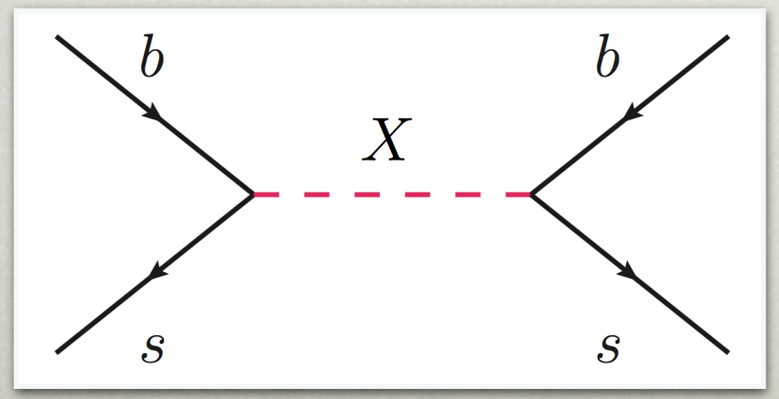
SEARCHING FOR OFF-SHELL NEW PHYSICS

- FCNC processes only at loop level in the SM





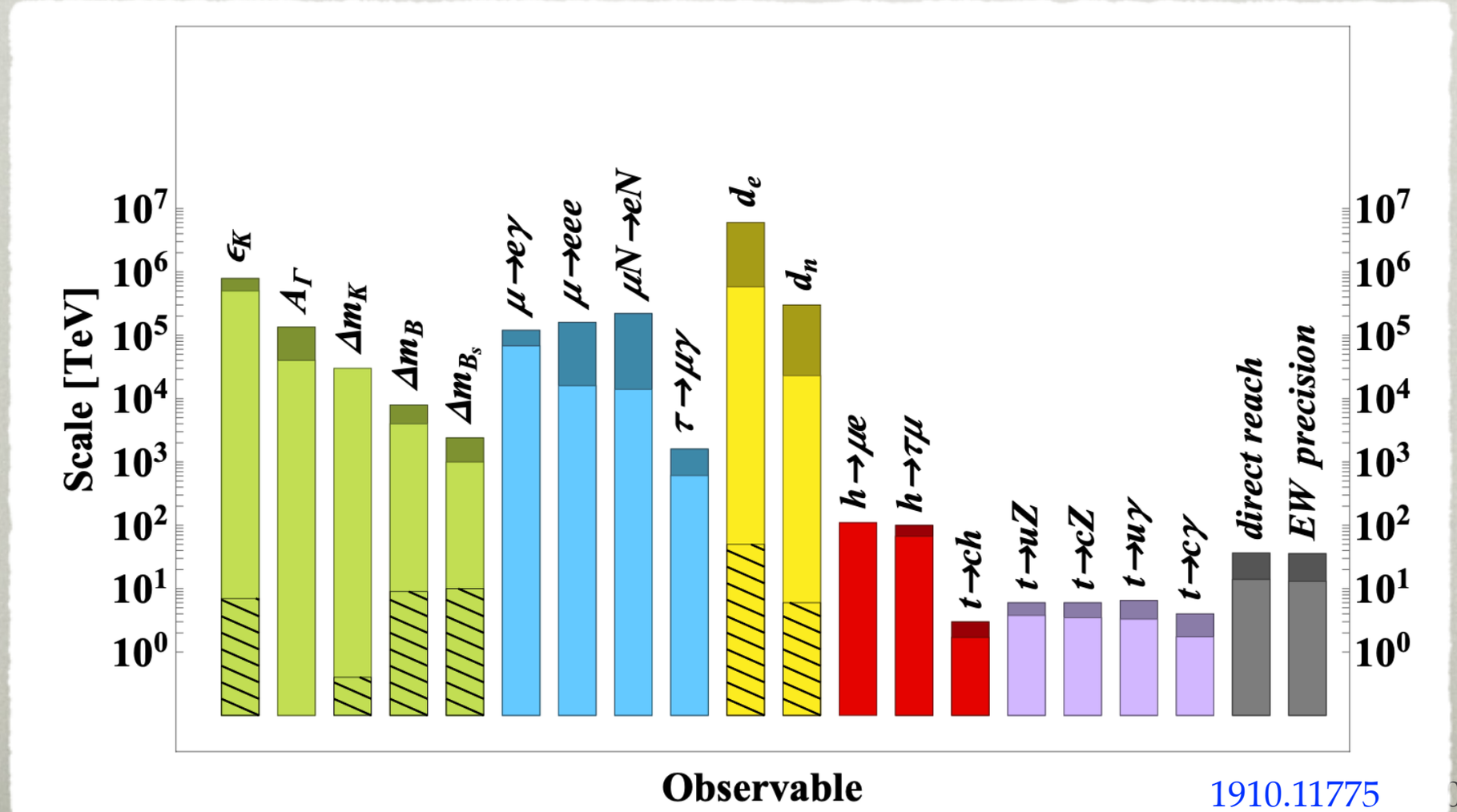
- can search for off-shell new physics



$$\delta C^{\rm NP} \propto \frac{g_{sb}^2}{M_{\rm NP}^2}$$

HEAVY NEW PHYSICS

- compare exp. and SM prediction
  - does it agree? ⇒ place bounds
  - for $g_{\rm NP} \sim \mathcal{O}(1)$ ⇒ probe high scales



1910.11775

Flavor @ Muon Collider

- searching for NP through precision probes
  - off-shell NP coupling to muons: $\mu^+\mu^- \to \tau\mu$
  - Higgs as a probe of flavor
    - $h \to \tau\mu, \tau e, \mu e$
    - $h \to bs, cu$
- production of new states
  - flavor structure of these ⇒ learn about the solution to the SM flavor puzzle?

PRECISION FLAVOR PROBES @MuC

$\tau \to 3\mu$

- assume NP is heavy ⇒ SMEFT
- focus on $\tau \to 3\mu$ couplings
  - dimension 6 operators

The Muon Smasher's Guide, 2103.14043

$$\mathcal{L} \supset V_{LL}^{\tau 3\mu}\left(\bar{\mu}\gamma^{\mu}P_L\mu\right)\left(\bar{\tau}\gamma_{\mu}P_L\mu\right) + V_{LR}^{\tau 3\mu}\left(\bar{\mu}\gamma^{\mu}P_L\mu\right)\left(\bar{\tau}\gamma_{\mu}P_R\mu\right) + \left(L \leftrightarrow R\right) + \text{h.c.}\,,$$

$$V_{LL}^{\tau 3\mu} = V_{LR}^{\tau 3\mu} = V_{RL}^{\tau 3\mu} = V_{RR}^{\tau 3\mu} = \frac{c^{\tau 3\mu}}{\Lambda^2}$$

- indirect probe from (Belle)
  $Br(\tau \to 3\mu) < 2.1 \times 10^{-8} \Rightarrow \Lambda \gtrsim 15\ \text{TeV}$
- gain for MuC: $\sigma(\mu\mu \to \tau\mu) \propto s/\Lambda^4$
  - can probe indirectly much higher scales than Belle II

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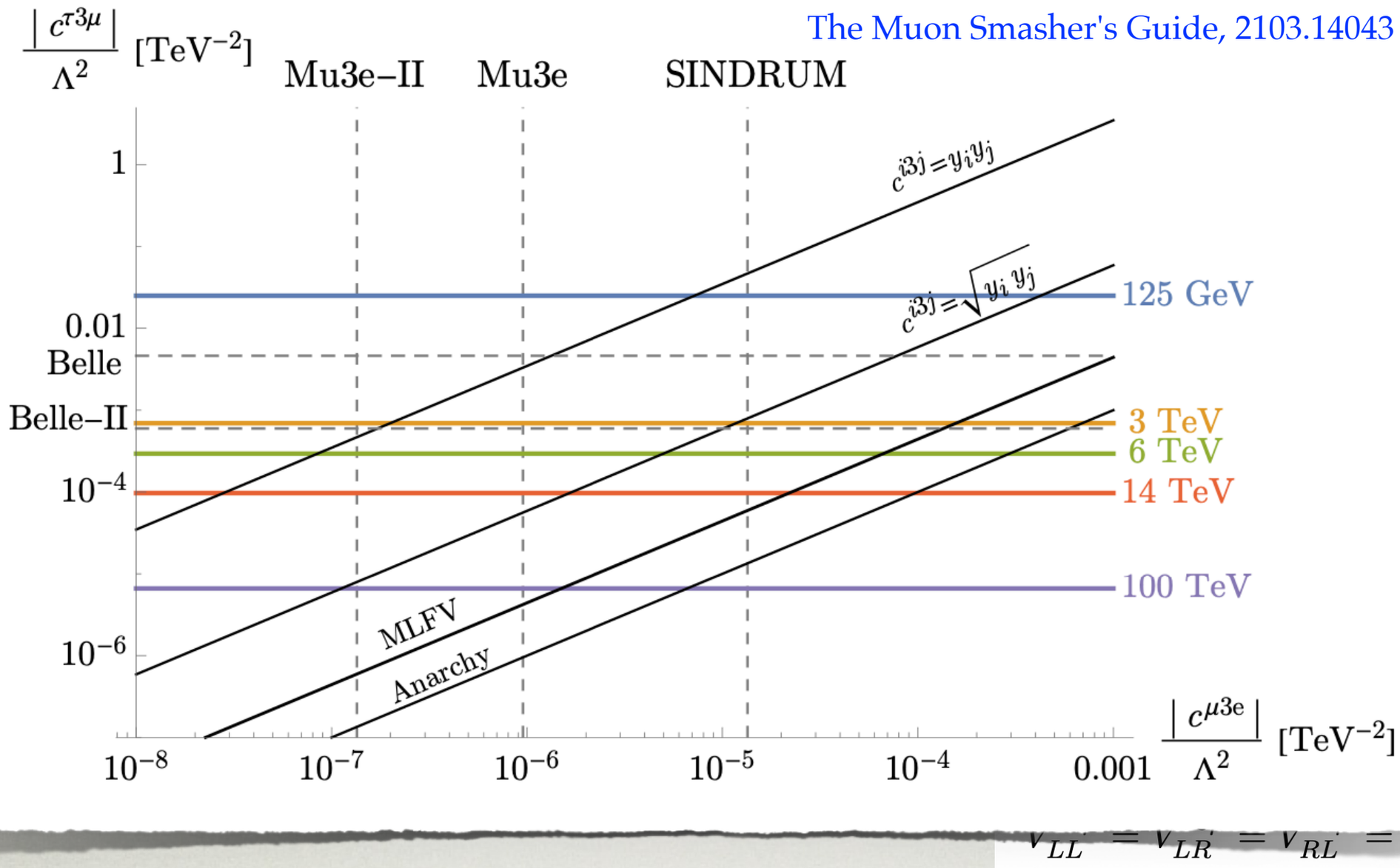

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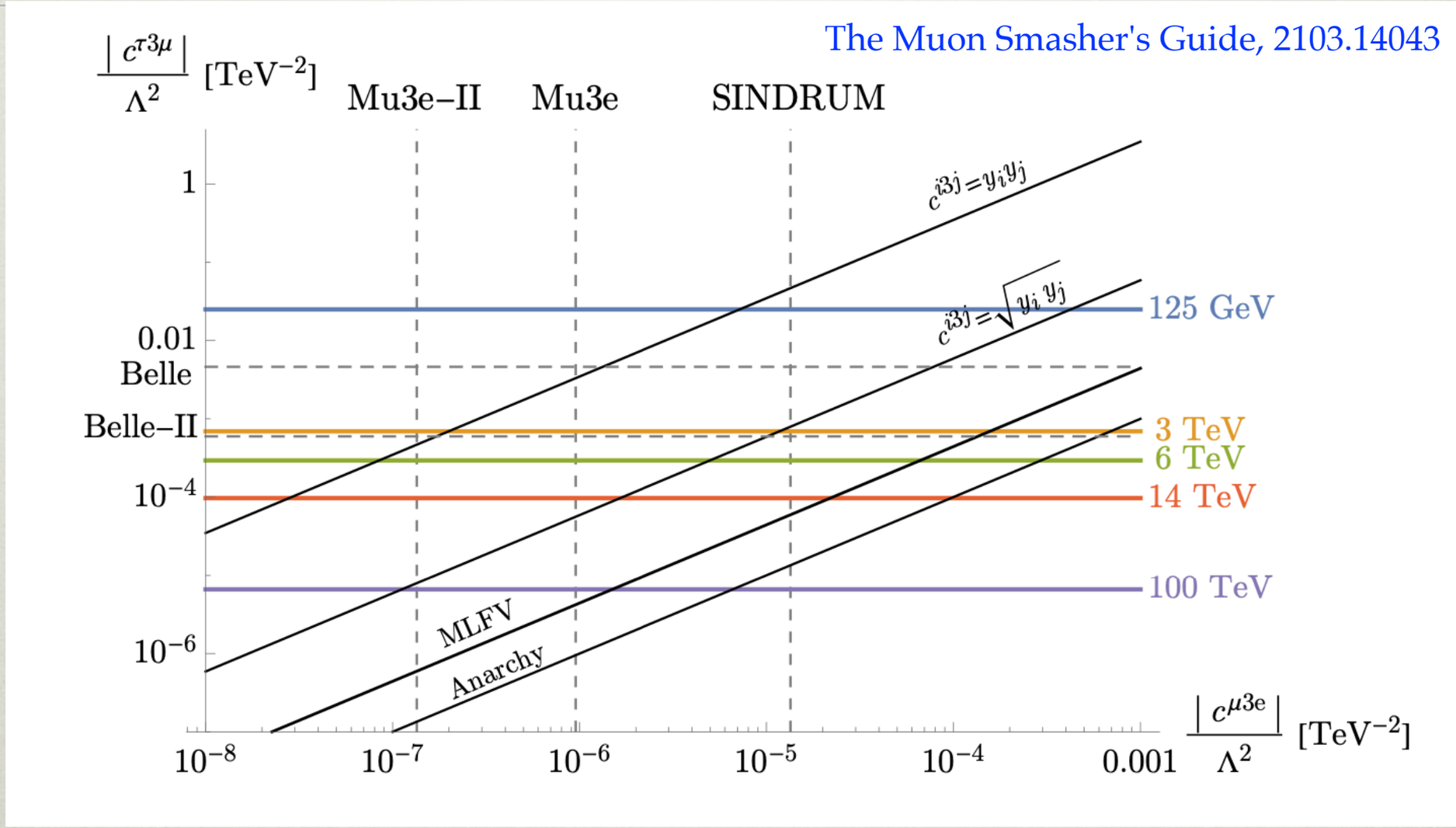
$\tau \to 3\mu$



- for $\mu\mu \to \mu e$ bounds from $\mu \to 3e$ much more stringent ($\Lambda \gtrsim 270$ TeV)
  - relation between $\tau \to 3\mu$ and $\mu \to 3e$ model dependent
- similar analysis for $\mu\mu \to \tau e$

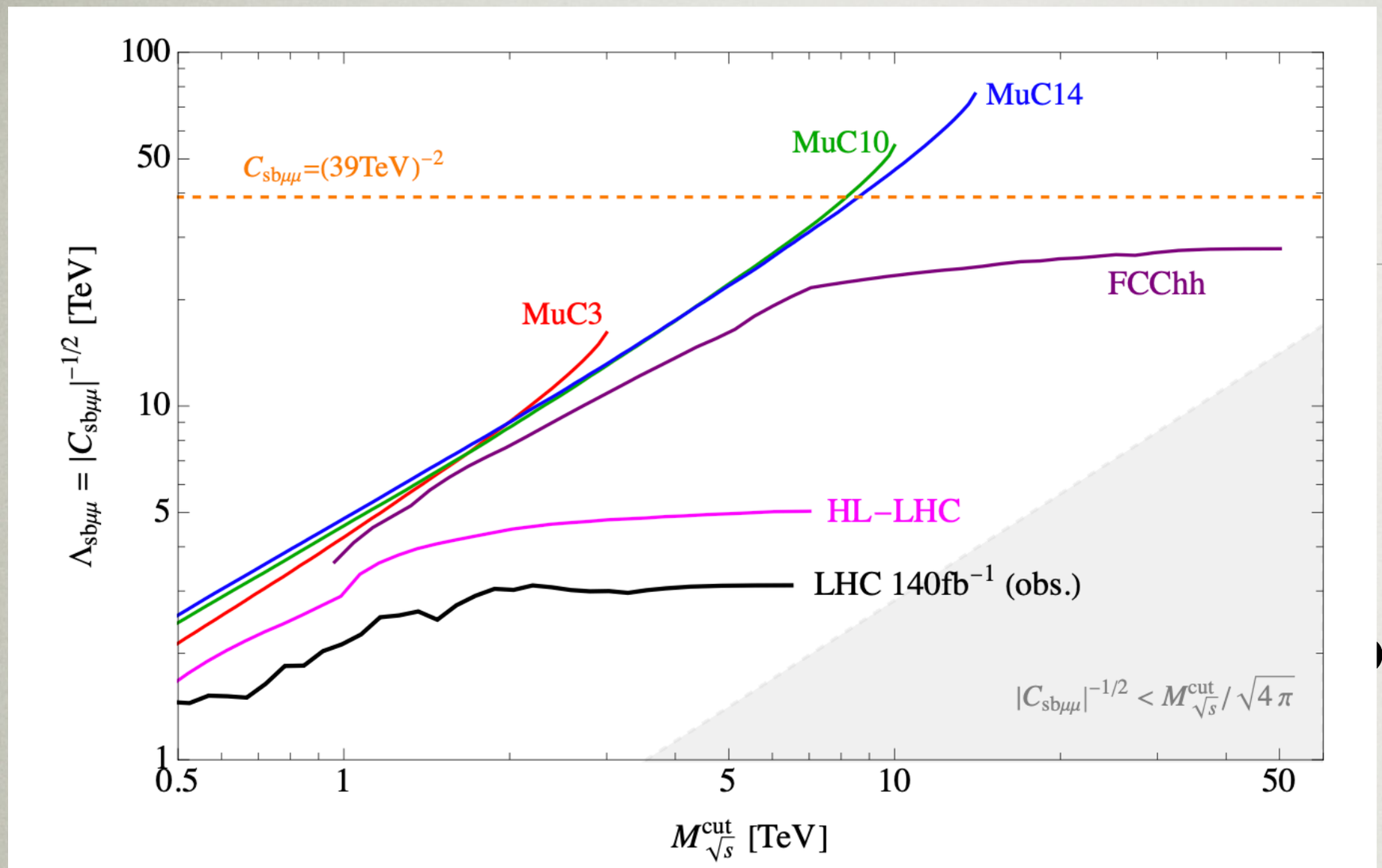
$\mu\mu \to bs$

Azatov et al, 2205.13552

- the $\mu^+\mu^- \to \bar{b}s + \bar{s}b$ a probe of $B \to K^{(*)}\mu\mu$ anomalies
  - assume that dim-6 EFT operator

$$(\bar{s}_L \gamma_\alpha b_L)(\bar{\mu}_L \gamma^\alpha \mu_L)$$

  - MuC could probe interesting parameter space
- other flavors could be explored as well $\mu\mu \to tc, tu, cu, bd, (sd?)$



Azatov et al, 2205.13552

$\to K^{(*)}\mu\mu$

or

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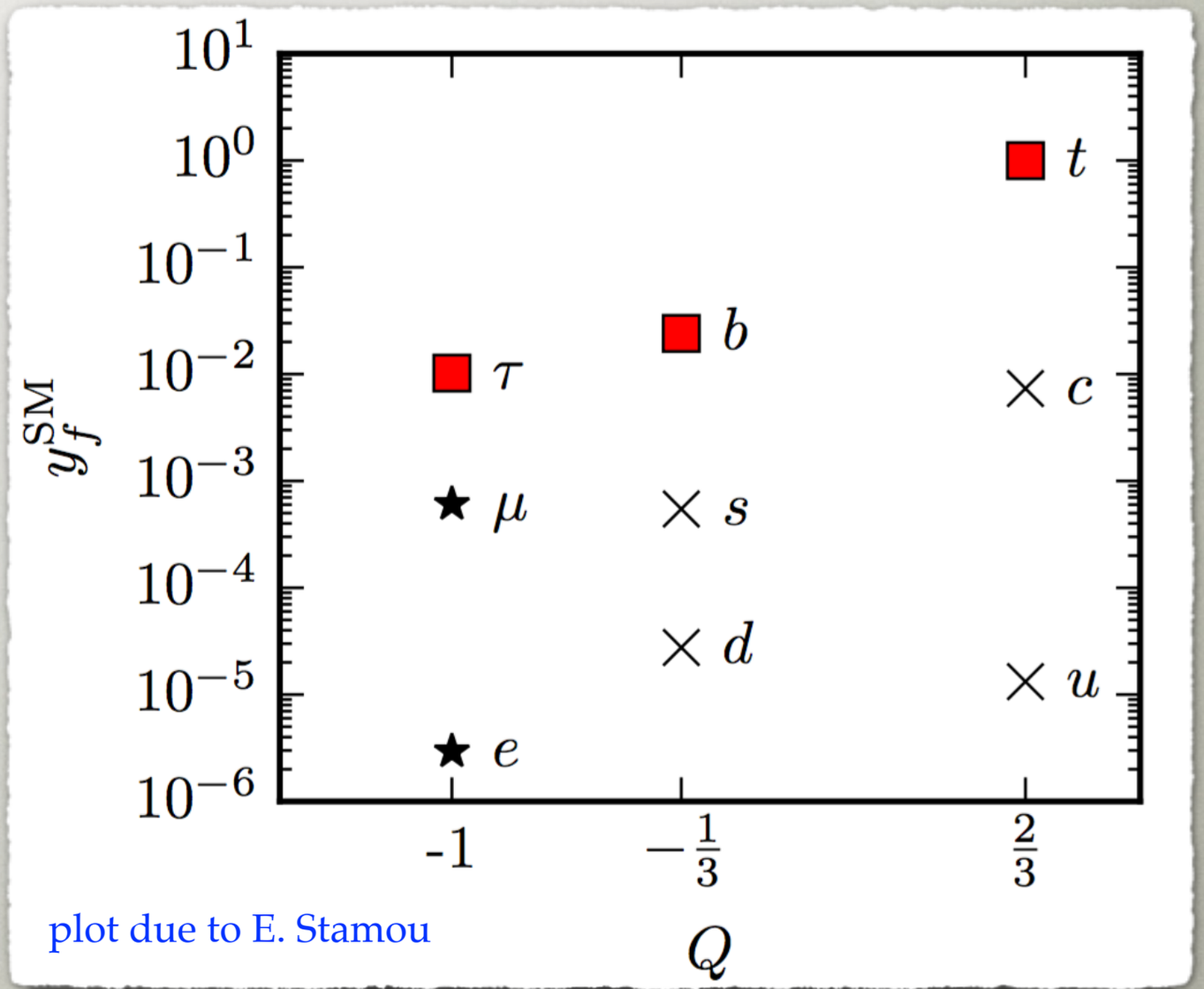
HIGGS AS A PROBE OF FLAVOR

HIGGS = NONTRIVIAL FLAVOR STRUCTURE

- generation of masses in the SM through the Higgs mechanism
- implies Higgs has hierarchical couplings to fermions
- in the SM

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

- we want to test this



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

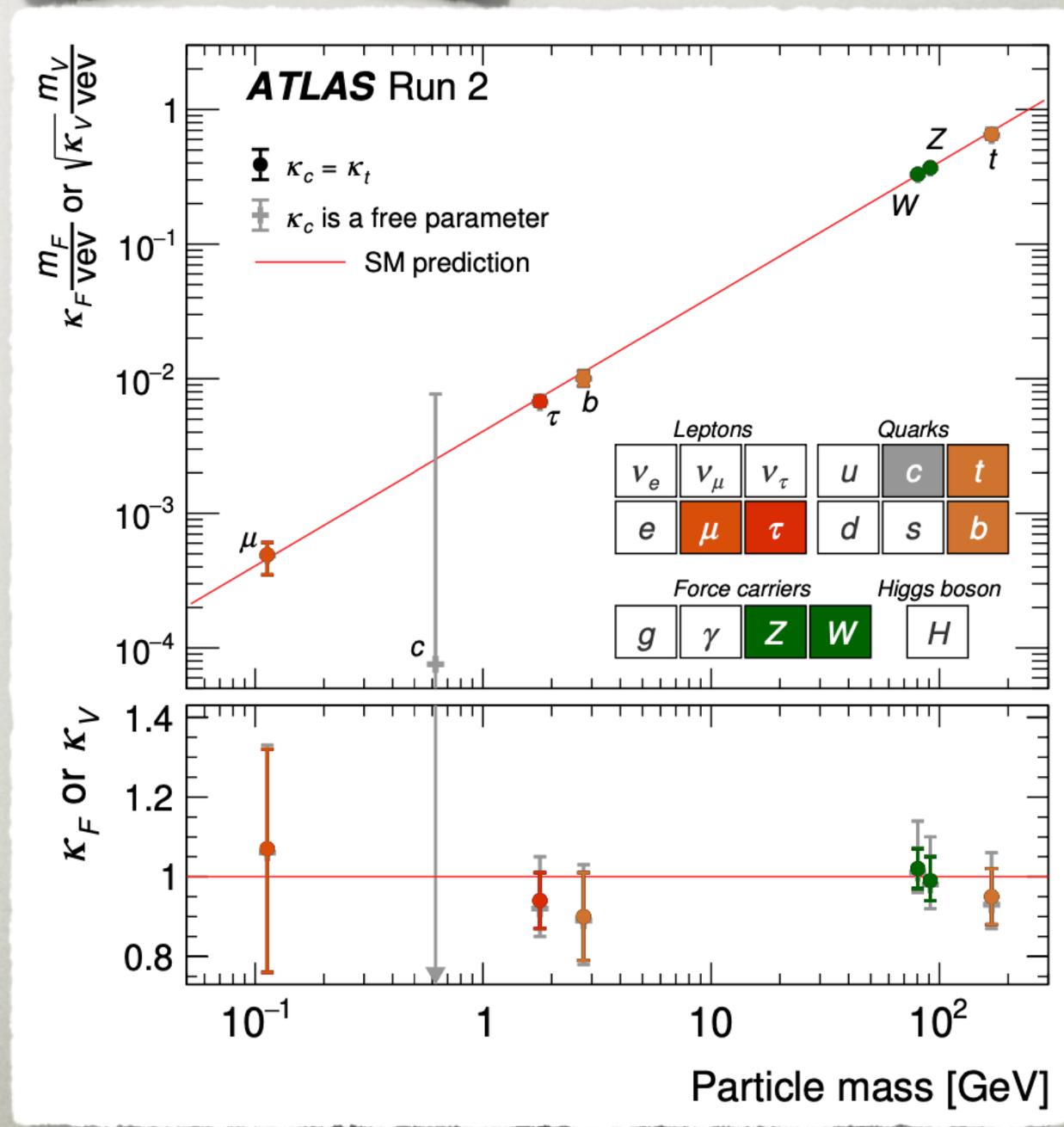
$$y_{ii}/m_i = \sqrt{2}/v$$

- diagonality

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

- reality

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



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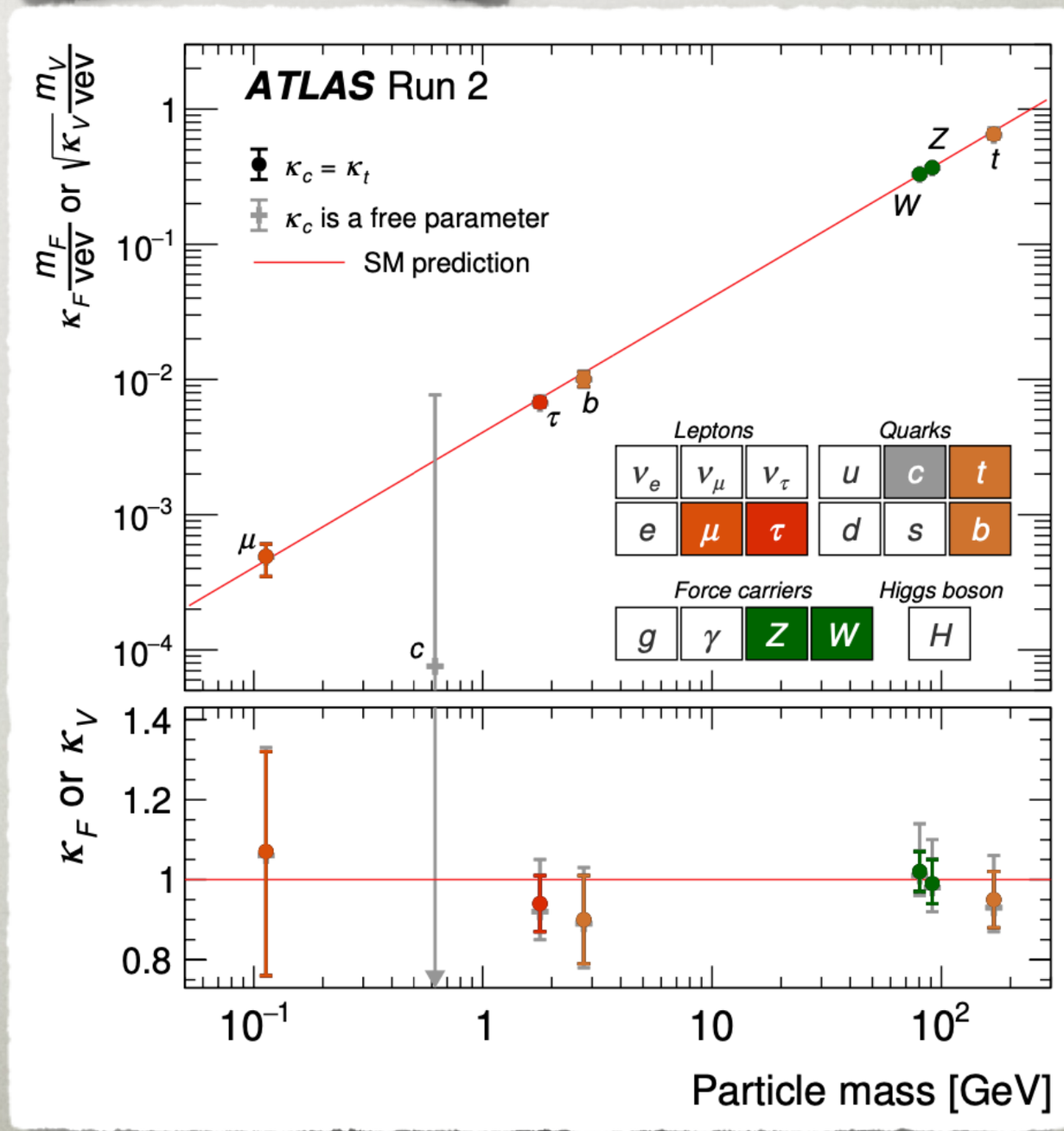

NEW PHYSICS CORRECTIONS TO HIGGS COUPLINGS

- in SMEFT, the Yukawas get corrected by higher dim. ops

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

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

  - there could be other sources of EWSB

- NP in general misaligns mass and Yukawa matrices

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

$$m = \left(\lambda + \frac{v^2}{2\Lambda^2}\lambda'\right)\frac{v}{\sqrt{2}} \qquad Y = \left(\lambda + 3\frac{v^2}{2\Lambda^2}\lambda'\right)\frac{1}{\sqrt{2}}$$

$$m = v\begin{pmatrix} * + *' & * + *' & * + *' \\ * + *' & * + *' & * + *' \\ * + *' & * + *' & * + *' \end{pmatrix} \qquad Y = \begin{pmatrix} * + *' & * + *' & * + *' \\ * + *' & * + *' & * + *' \\ * + *' & * + *' & * + *' \end{pmatrix}$$

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CPV and FV higgs couplings to SM fermions

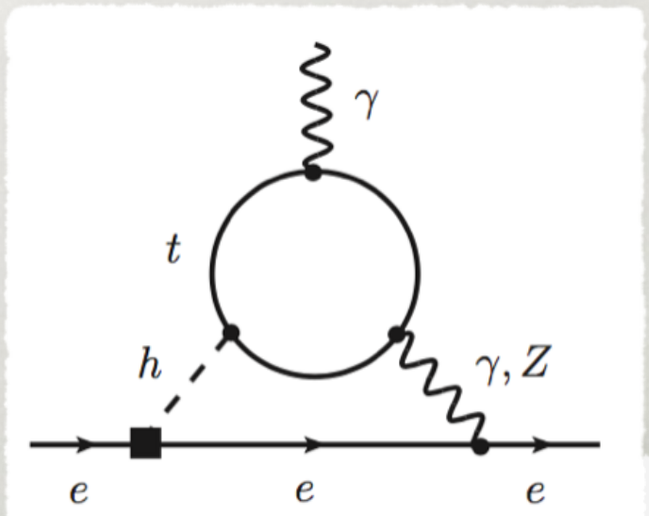
$$m = v \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & 0 & * \end{pmatrix} \qquad Y = \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix}$$

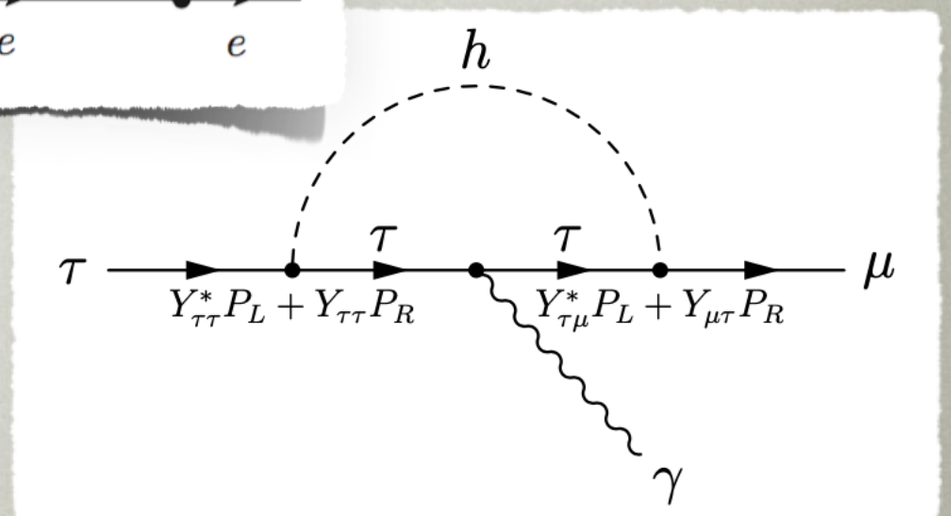
- NP contribs in general lead to
  - flavor violating Higgs decays
  - CPV Higgs decays
- different models lead to different patterns of flavor diagonal and flavor violating Yukawas
- note: large Yukawas for light fermions require significant tuning in contributions to fermion masses

Harnik, Kopp, JZ, 1209.1397
Blackenburg, Ellis, Isidori, 1202.5704

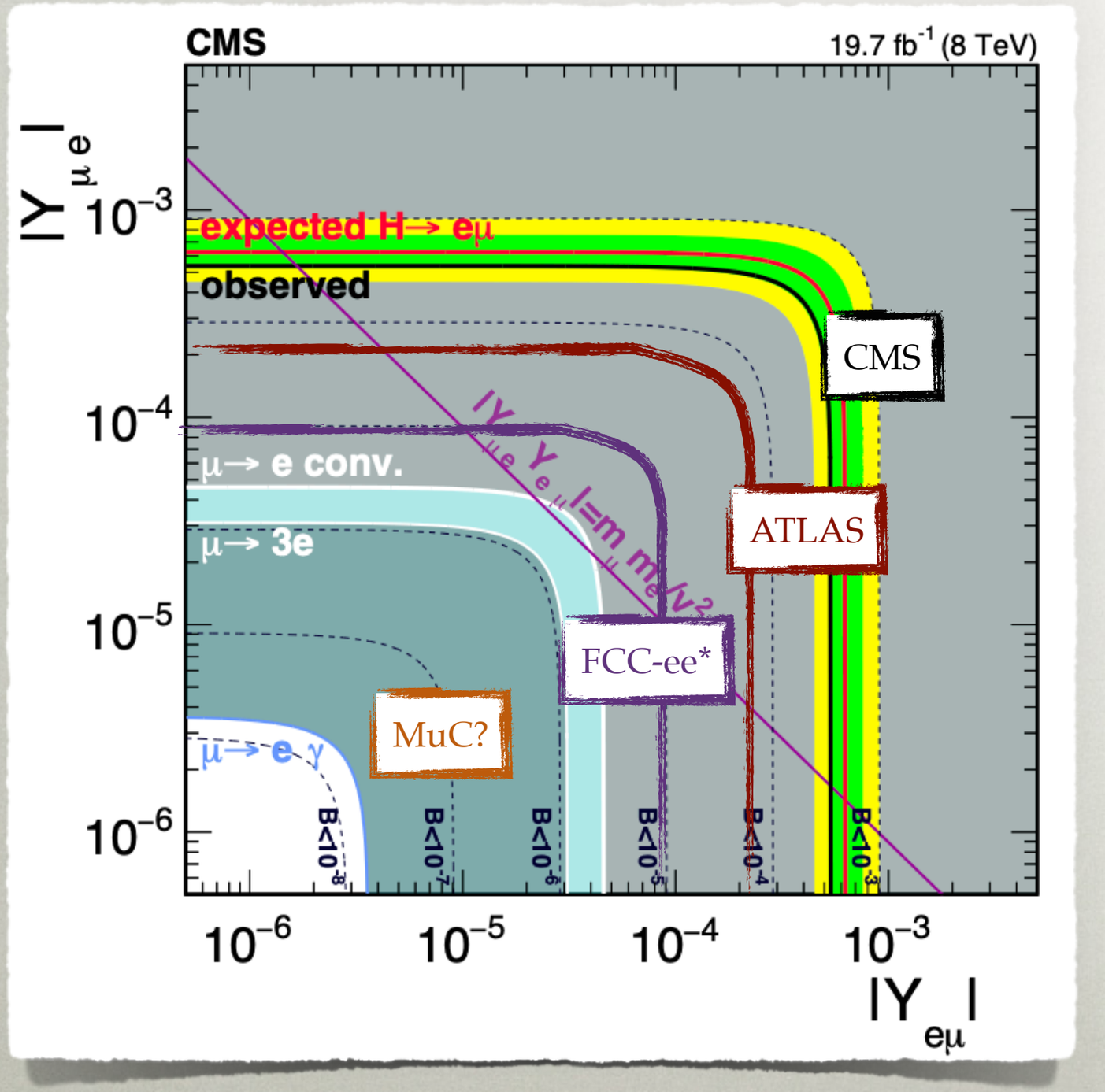
OTHER CONSTRAINTS

- both CPV and FV Higgs couplings face severe indirect constraints
  - CPV from EDM
  - FV from low energy FCNC processes
    - wide open for HL-LHC & future colliders: $h \to \tau\mu, \tau e$ and $t \to hc, hu$
    - $h \to bs, cu$ with some tuning





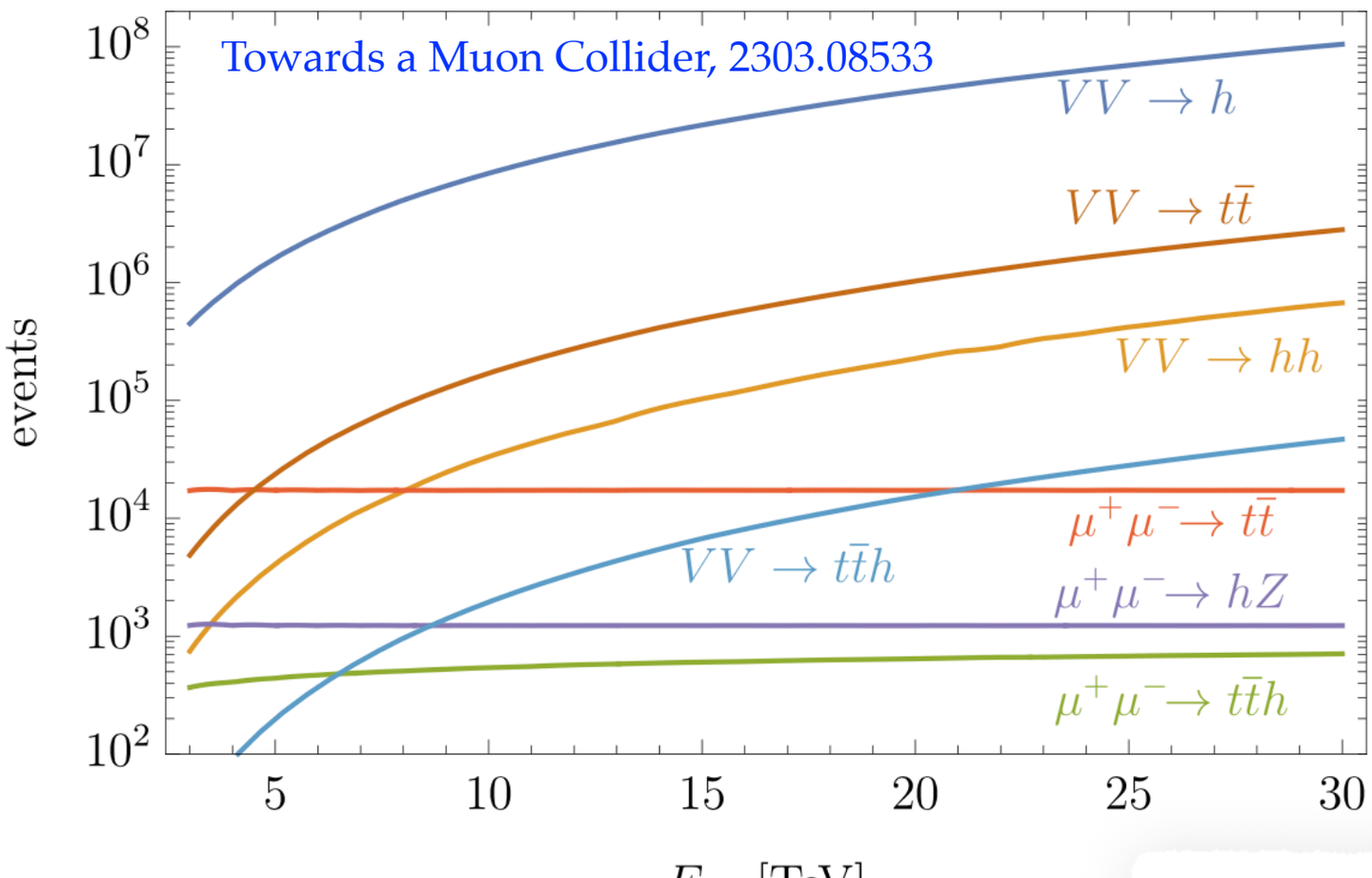
$Y_{\mu e}$ YUKAWA

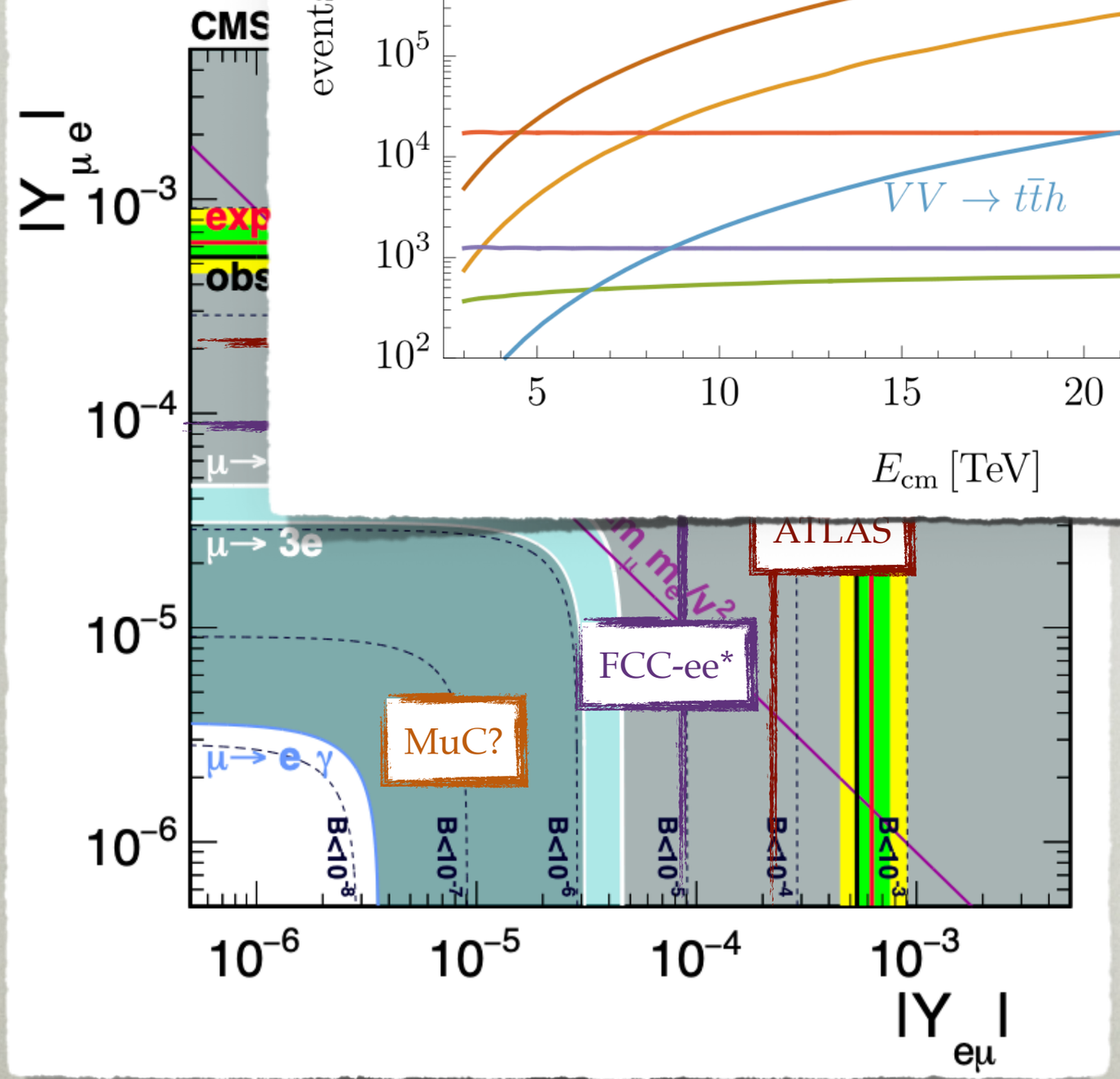


ATLAS, 1909.10235

CMS, 1607.03561

*from Qin et al, 1711.07243





ATLAS, 1909.10235

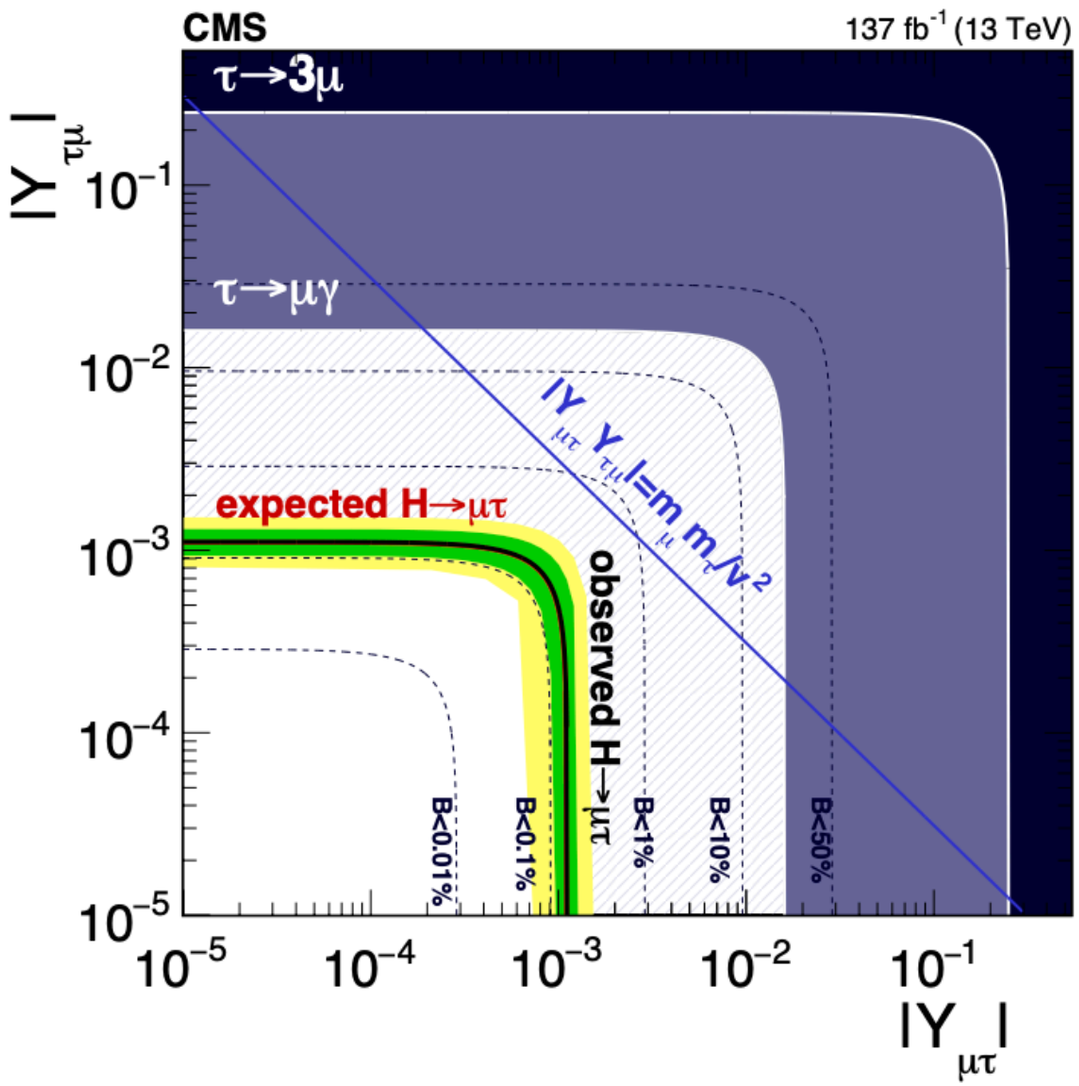
CMS, 1607.03561

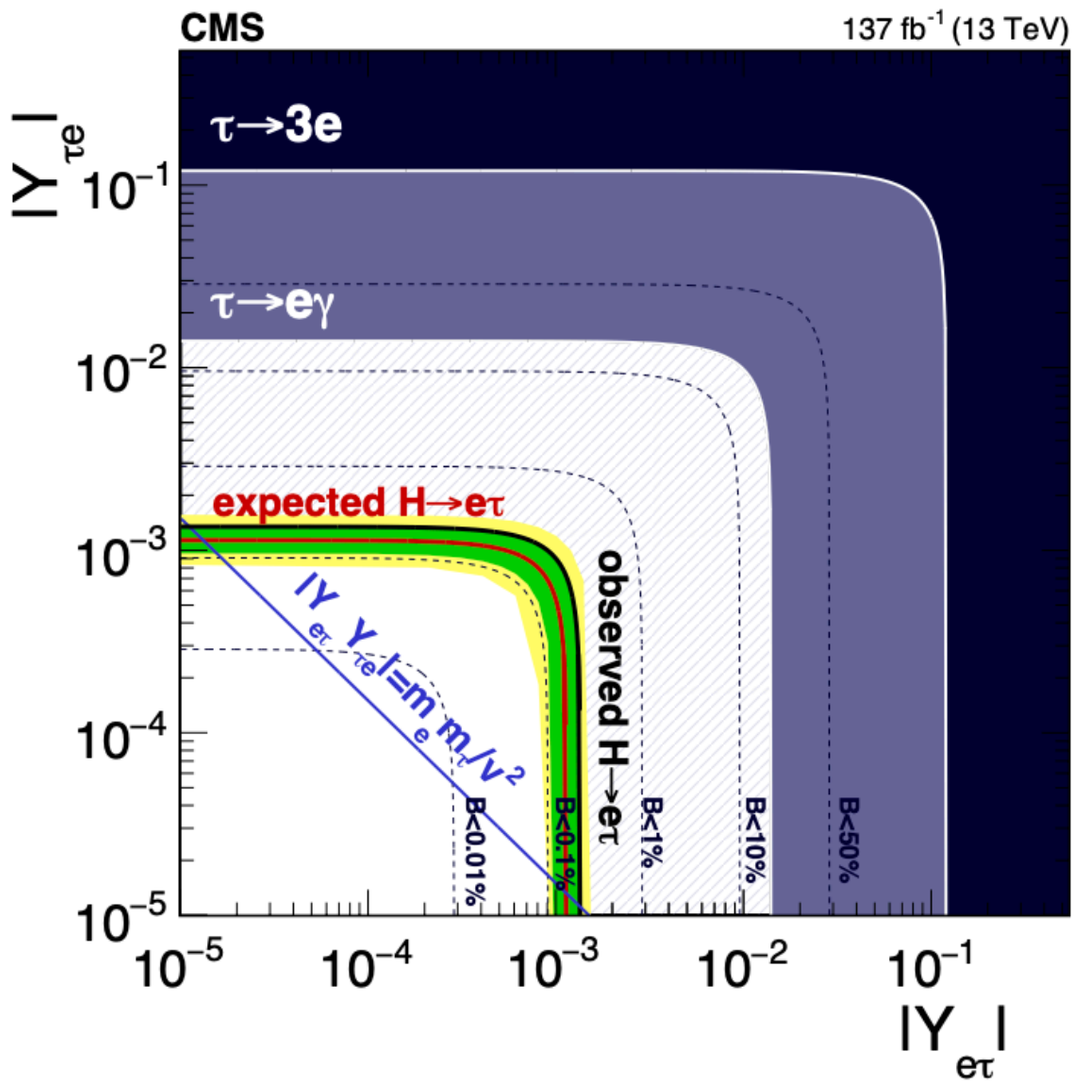
$$\mathfrak{L}_{\rm int} = 10\,{\rm ab}^{-1}\left(\frac{E_{\rm cm}}{10\,{\rm TeV}}\right)^2$$

*from Qin et al, 1711.07243

$Y_{\tau\mu}, Y_{\tau e}$ YUKAWAS

CMS, 2105.03007
ATLAS, 1907.06131

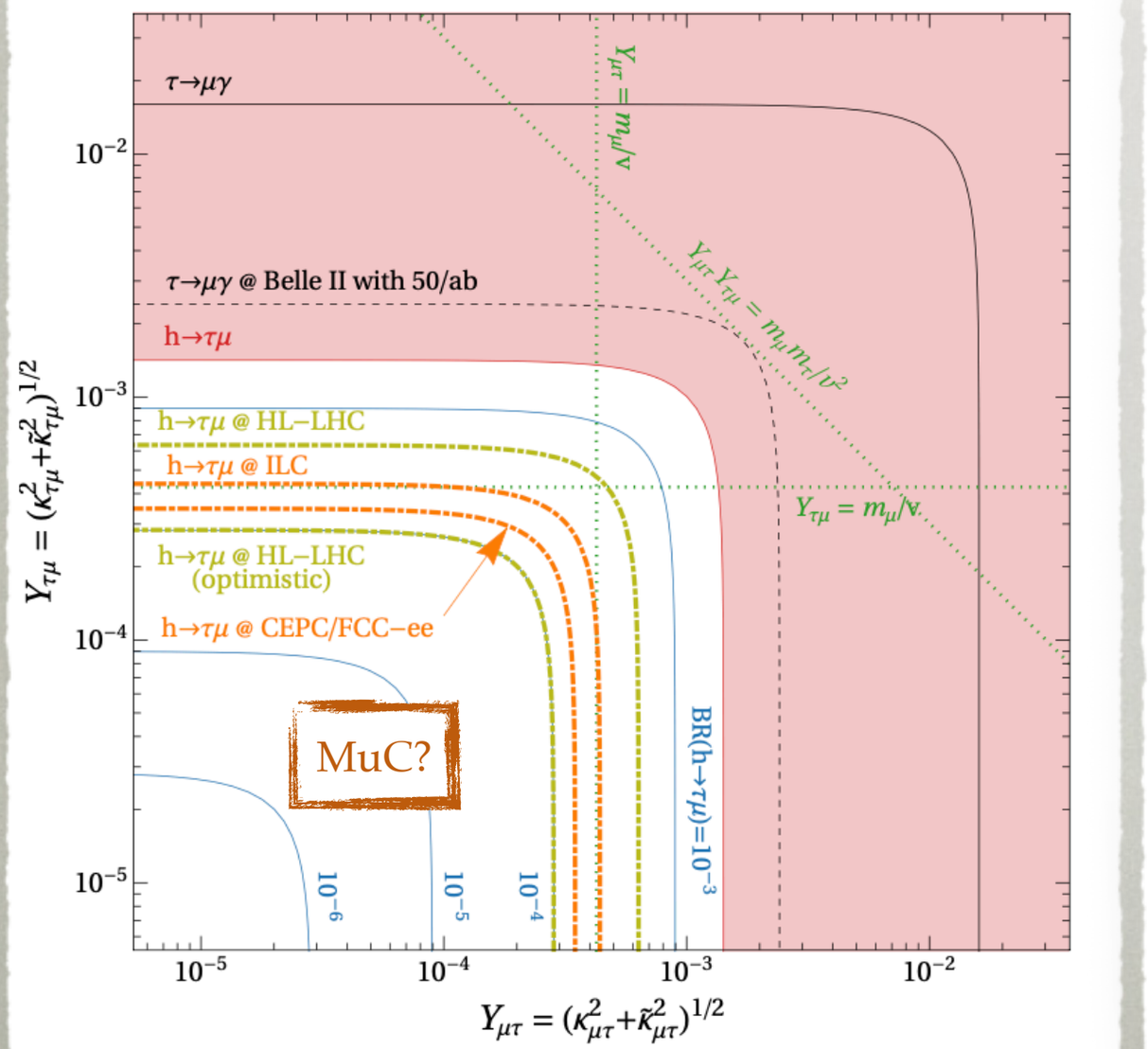


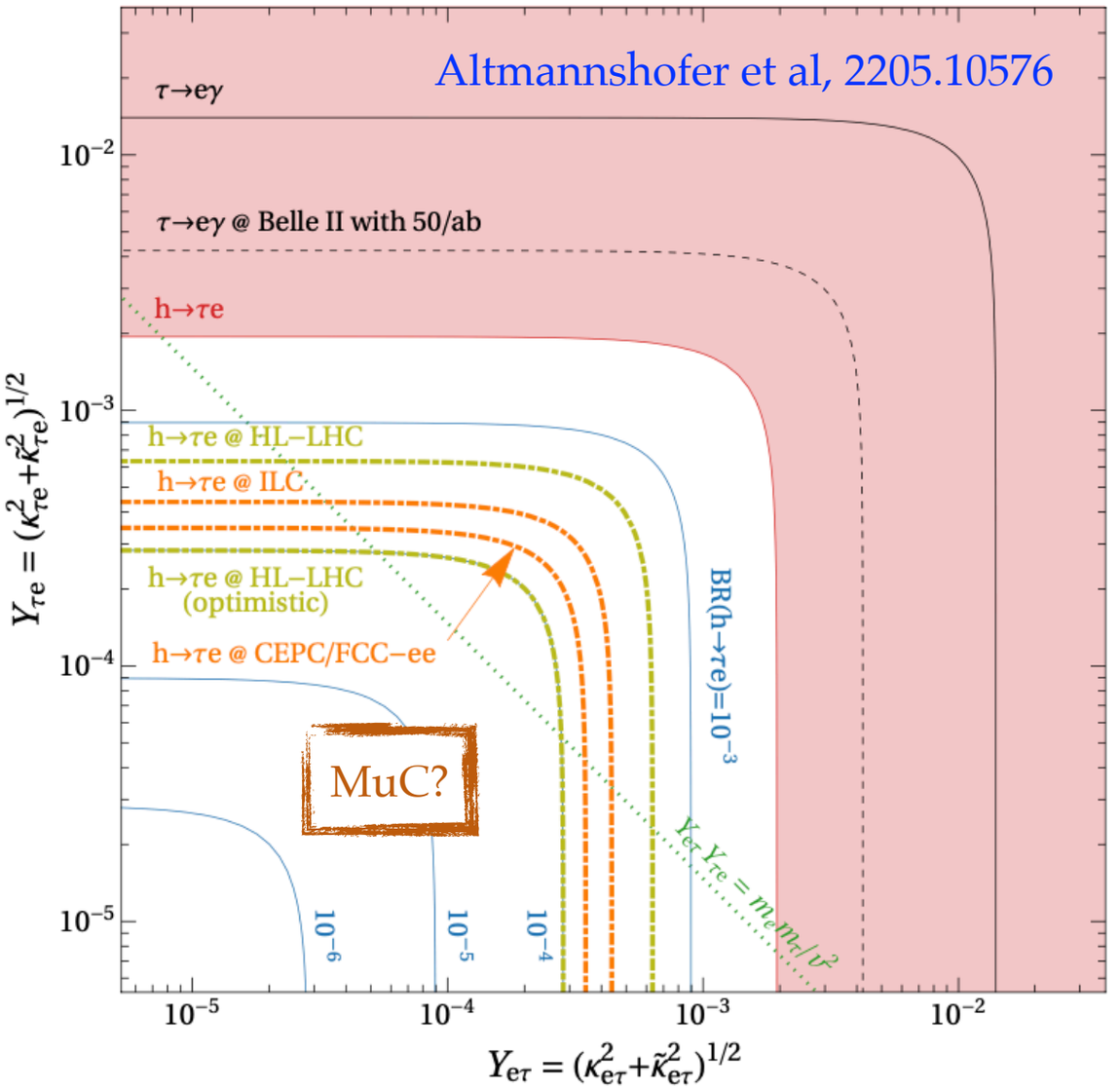


$Y_{\tau\mu}, Y_{\tau e}$ YUKAWAS - FUTURE

see also Qin et al, 1711.07243
Arroyo-Urena et al, 2002.04120

- $\text{Br} \lesssim \mathcal{O}(10^{-4}) \Rightarrow \Lambda \gtrsim 10\,\text{TeV}\ (C_{ij} = 1)$

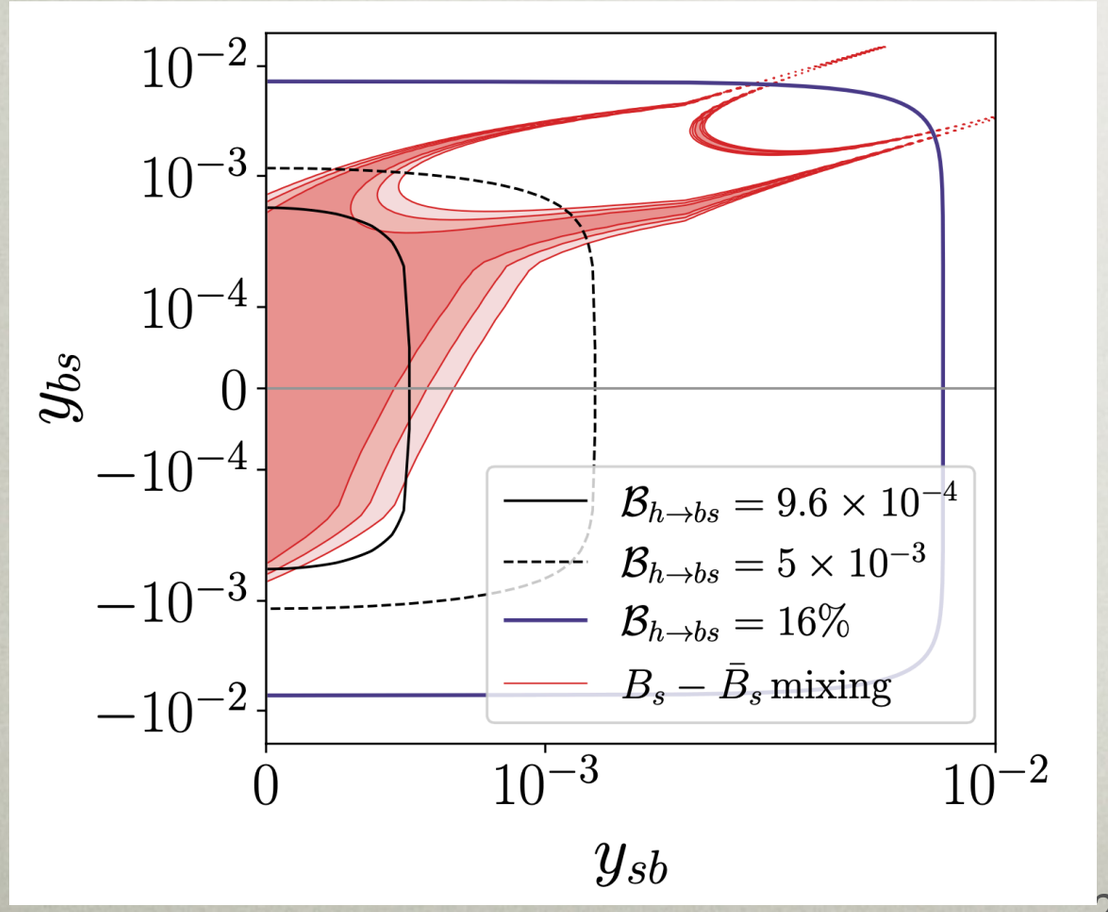


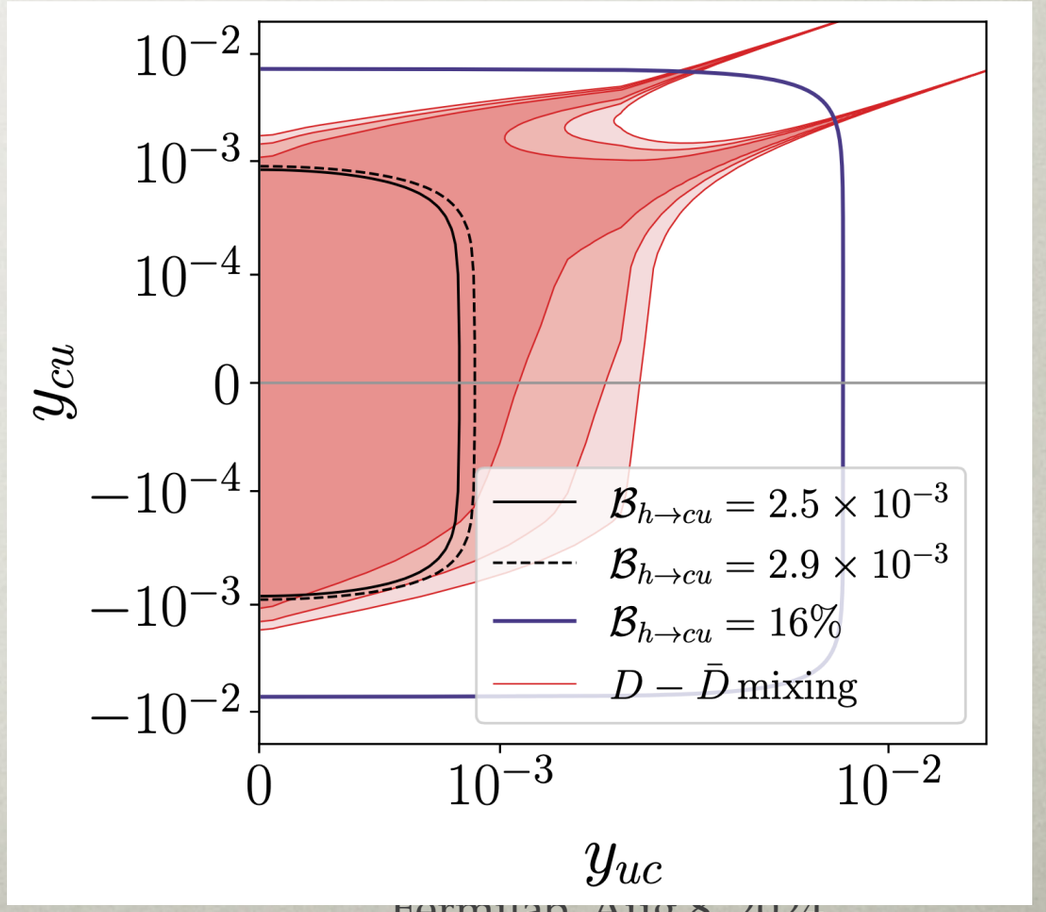


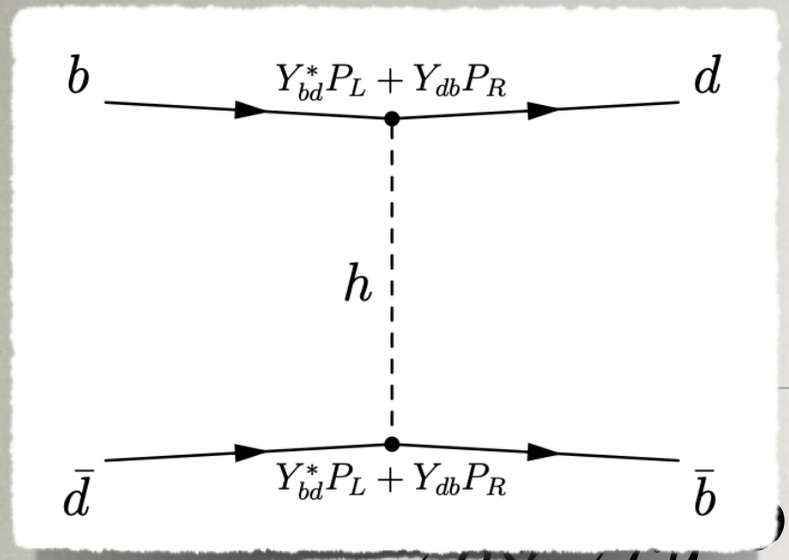
$h \to bs, cu$

- $y_{bs'}$ y_{cu} bounded from meson mixing
- for $Br(h \to qq') \sim 10^{-3}$ direct searches become more important

Kamenik et al, 2306.17520







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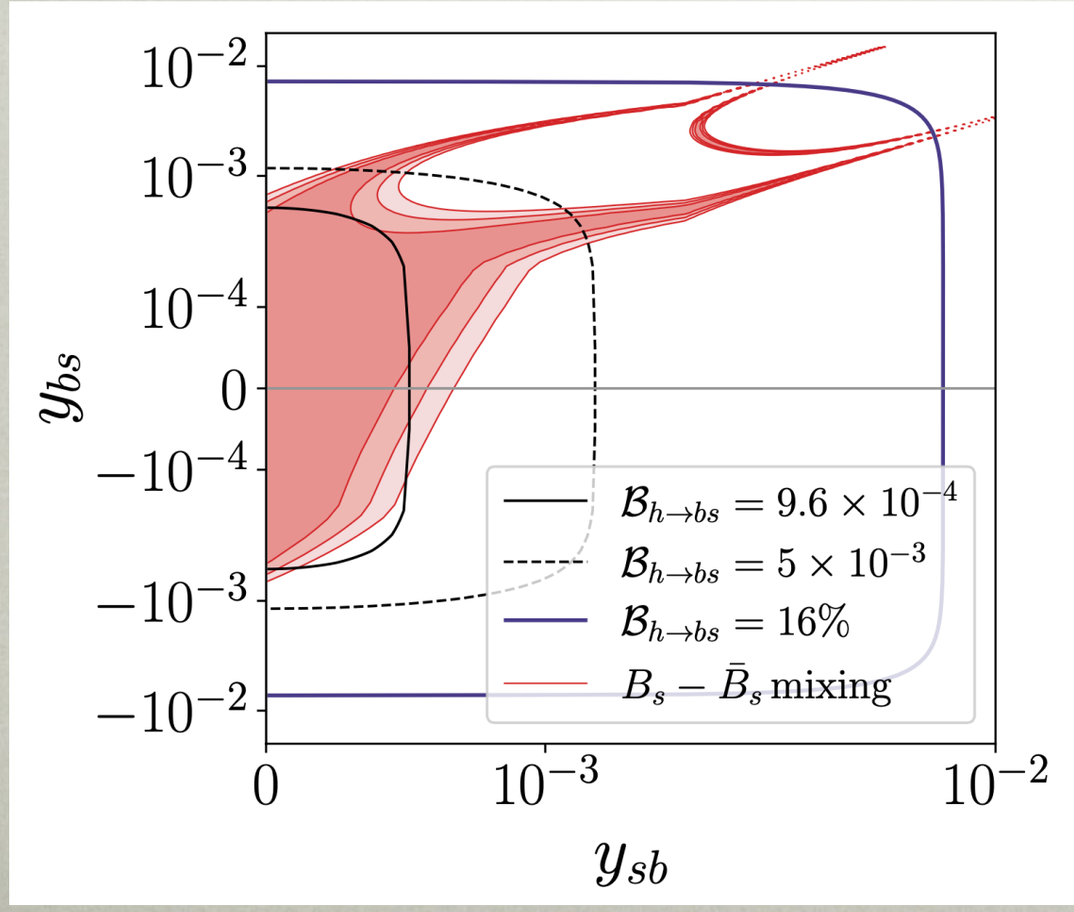
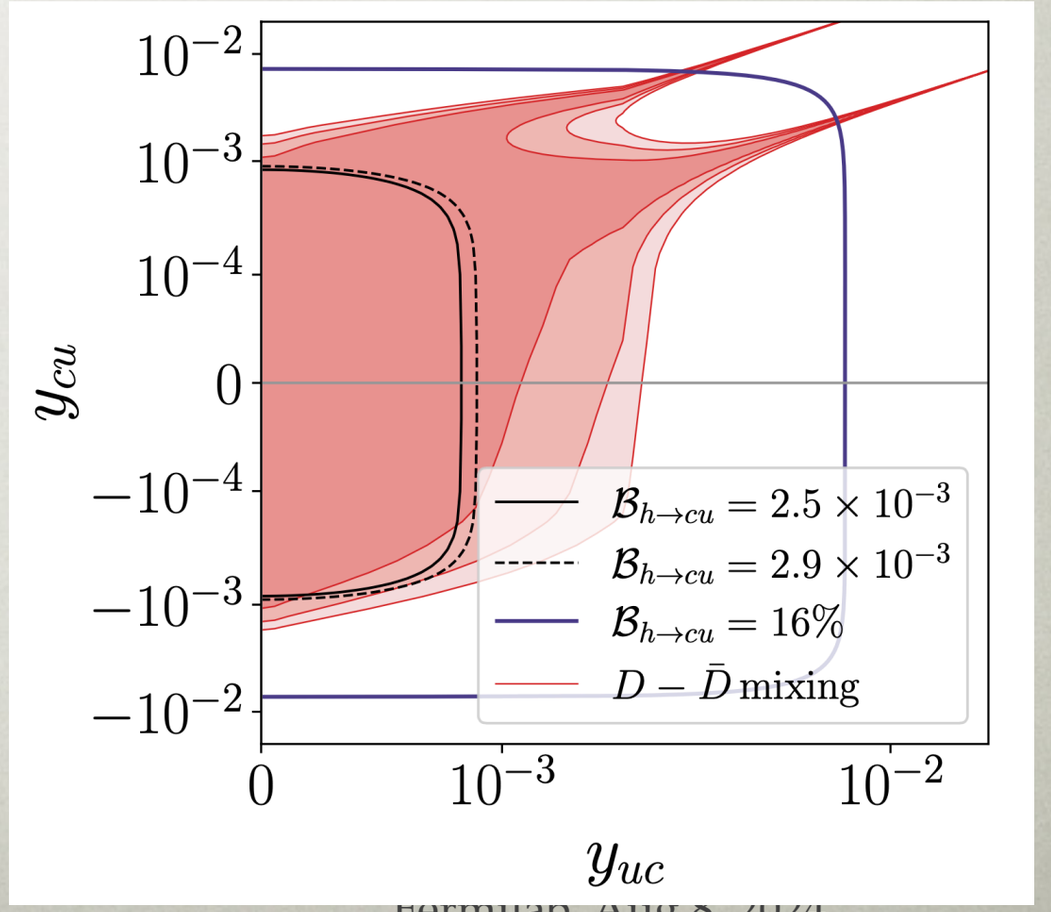


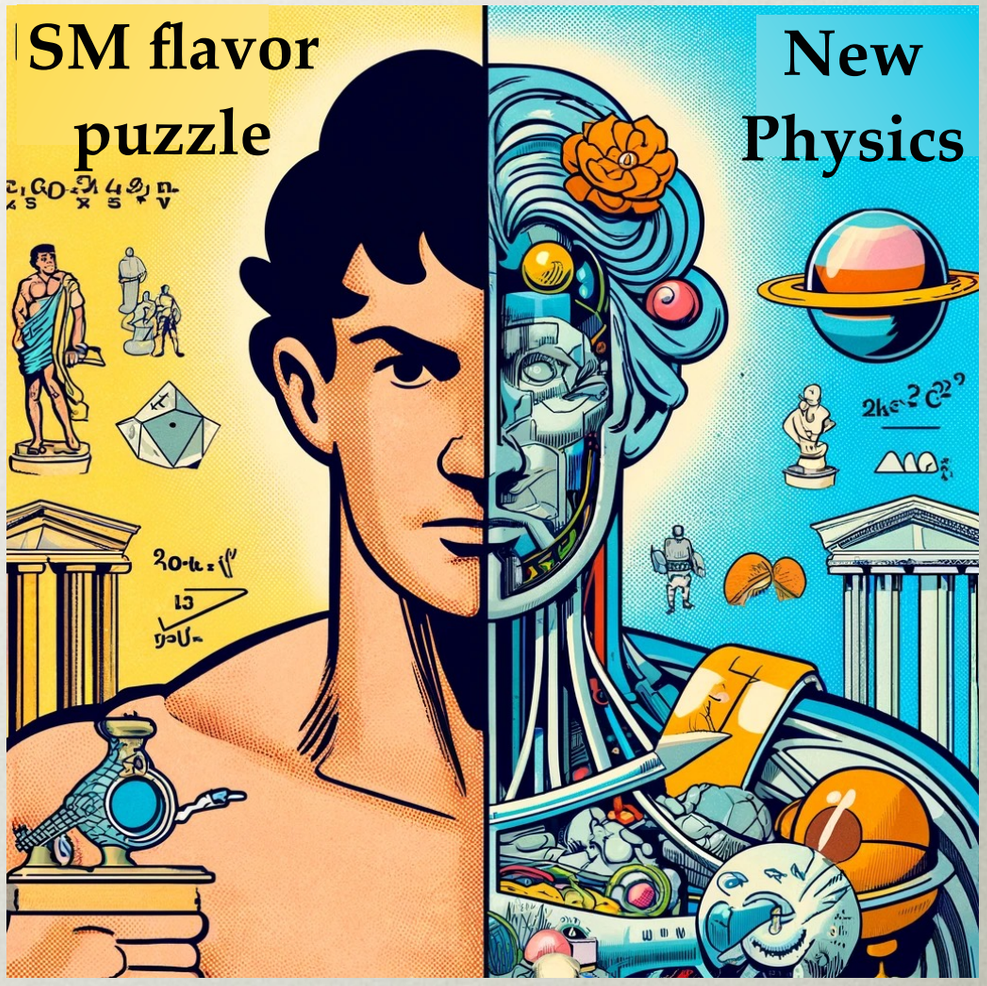


STANDARD MODEL FLAVOR PUZZLE

TWO FACES OF FLAVOR PHYSICS

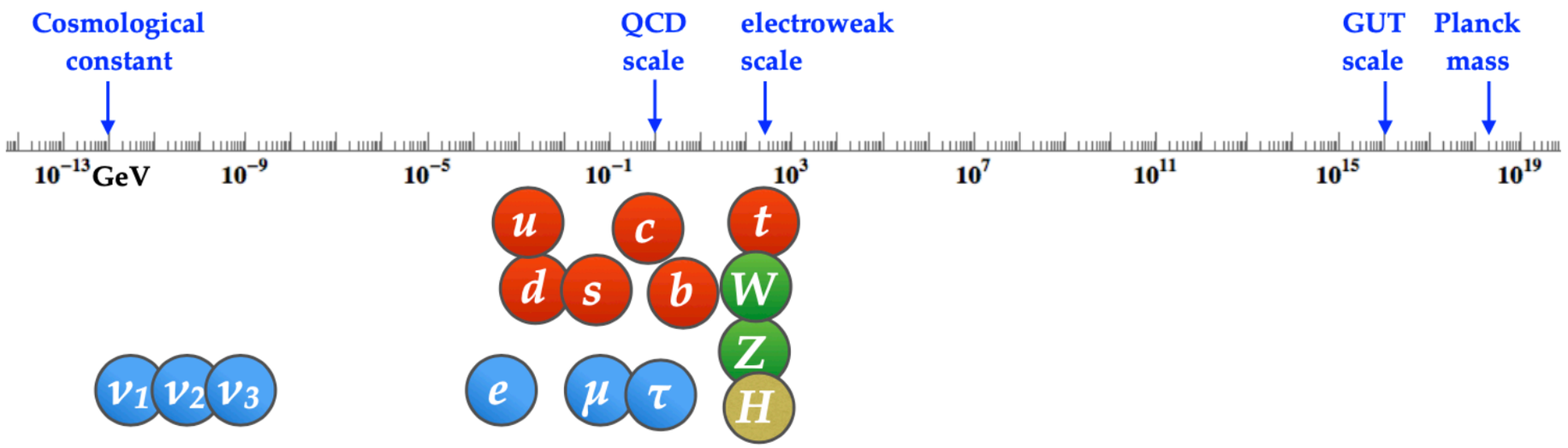
- no flavor changing neutral currents in the SM
  - ⇒ flavor transitions sensitive probes of new physics

- why the observed structure of quark and lepton masses and mixings?
  - ⇒ flavor model building



see, e.g., JZ, 1903.05062
Altmannshofer, JZ, 2203.07726

FLAVOR MODEL BUILDING



- dynamical explanations
  - horizontal flavor symmetries
  - warped extra dimensions
  - partial compositness
  - radiative fermion masses
- common to all: extra states, new sources of flavor violation
  - generically above the reach of MuC

SM flavor puzzle @MuC

- if SM flavor puzzle has a dynamical explanation
- ⇒ same dynamics would control flavor couplings of NP states
  - for instance, if squarks are produced
    - flavor violating decays $\tilde{q}_i \to q_j \tilde{\chi}^0$ in principle possible
    - (squark mass degeneracy would avoid indirect constraints from FCNCs)
- the NP spectrum and couplings carry more information
  - e.g., for squarks, mass terms are $\tilde{q}^*_{Li}\tilde{q}_{Lj}$ and $\tilde{q}^*_{Ri}\tilde{q}_{Rj}$ instead of $\bar{q}_{Li}q_{Rj}$ for SM quarks

MORE FLAVOR @MUC

- other examples/possibillities
  - other LFV SMEFT operators through $\mu Z \to \tau h$, $\mu\gamma \to \tau h$,... poster by H. Bagherian
  - CP violating $h \to \tau\tau$, $ht\bar{t}$ couplings
  - Y_{tc} coupling from $\mu^+\mu^- \to \bar{t}c + X$ or $\mu^+\mu^- \to \bar{t}ch + X$ similar to Y_{tt} in Liu et al, 2308.06323
  - probes of $(g-2)_\mu$ UV physics see, e.g., Buttazzo, Paradisi, 2012.02769
  - V_{cb}, V_{cs} from W decays (so far analysis only for FCC-ee) Marzocca, Szewc, Tammaro, 2405.08880
  - exotic Z decays
    - flavor violating $Z \to \tau\mu, \tau e, \mu e$ decays
    - Z decays that could gain from boosts, e.g., $Z \to \tau(\tau \to \mu a)$
  - TeV muon beams to produce flavor violating ALPs in $\mu A \to \tau A a$ Batell et al, 2407.15942
  - $Y_{e\mu}$ from $e^-\mu^+ \to h$ thanks to Zhen Liu
  - .....

CONCLUSIONS

- two ways flavor may become important for physics at Muon Collider
  - probe off-shell new physics from precision flavor probes
    - example: higgs FV decays
      $h \to \tau\mu, h \to \tau e, h \to \mu e$
      $h \to bs, h \to cu$
  - flavor structure of new physics states produced on-shell
    - extra heavy Higgses, SUSY partners, ...

BACKUP SLIDES

EDM CONSTRAINTS

Brod et al, 2203.03736

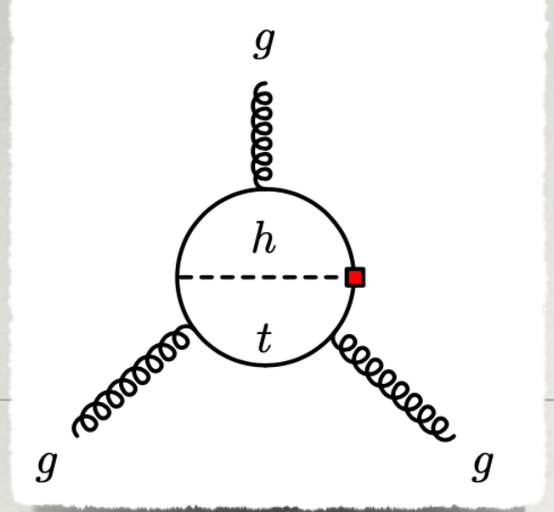
- CPV dim. 6 ops contribute to EDMs through loops

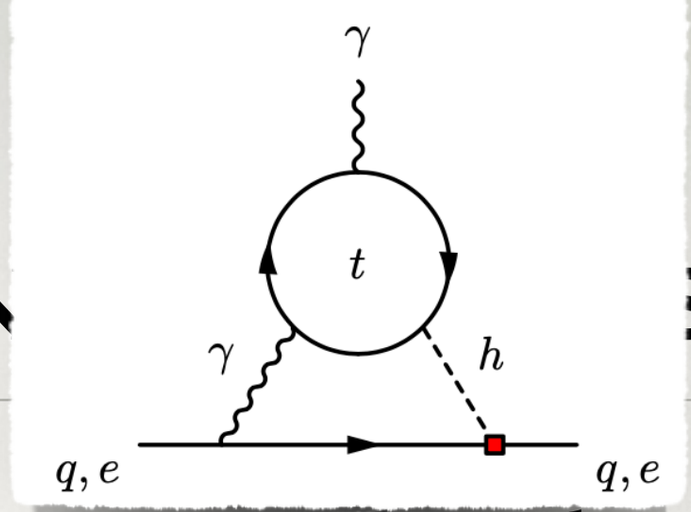
$$\mathscr{L}_h = -\sum_{f=u,d,\ell} \frac{h}{\sqrt{2}} \bar{f}_L \left(y_f^{\rm SM} - \frac{v^2}{\Lambda^2} C_{fH} \right) f_R + \text{h.c.},$$

$$C_{fH,ij} = C_{fH+,ij} + iC_{fH-,ij}$$

  - 2-loop electroweak mixing⇒large logs⇒ leading log QCD resummation

- if single flavor dominates ⇒ in general stringent constraints
  - two extreme cases: top and muon
- if more than one flavor important
  - cancellations in EDMs possible but not in LHC constr.
  - the parameter space for CPV couplings opens up ⇒FCC





Brod et al, 2203.03736

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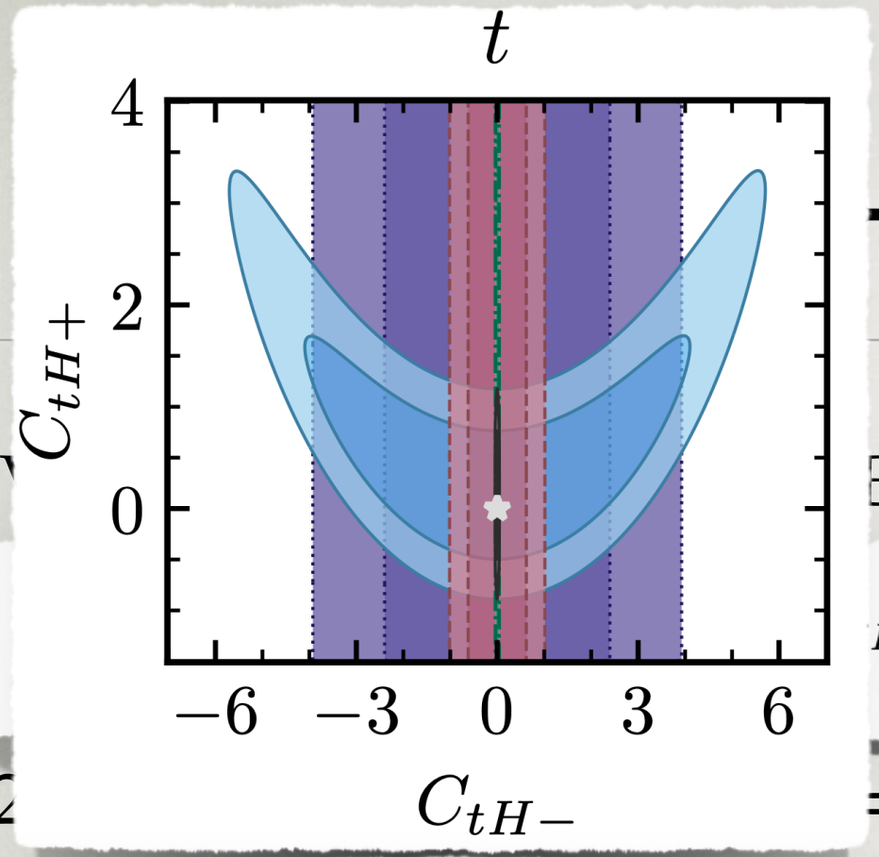
TRAINTS



Brod et al, 2203.03736

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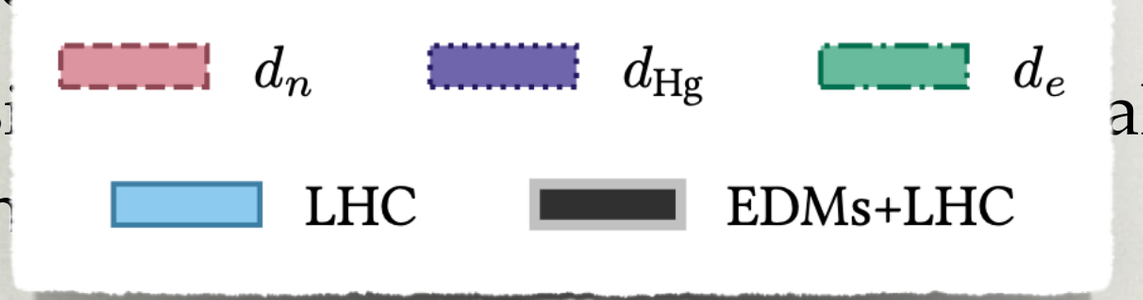

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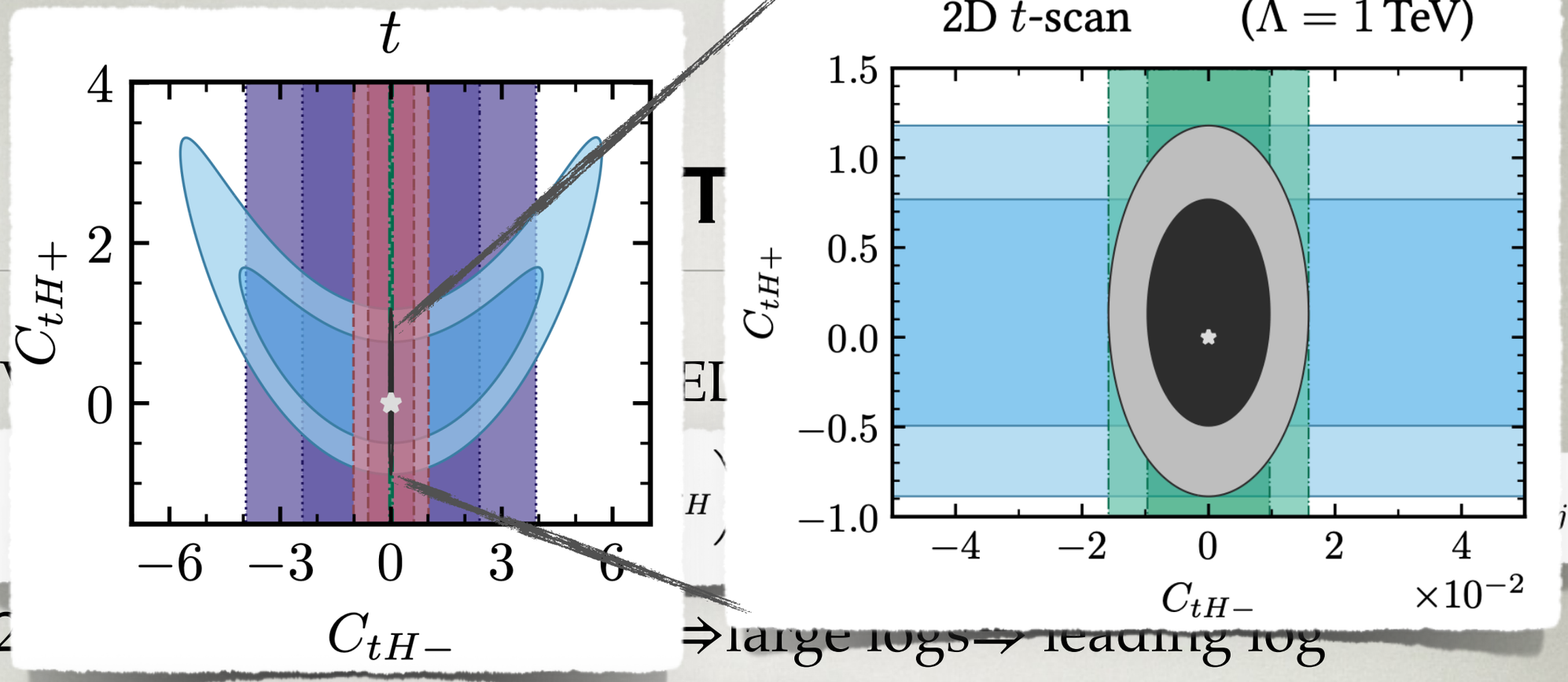

- CP

- 2 ⇒large logs⇒ leading log

QCD

- if si al stringent con

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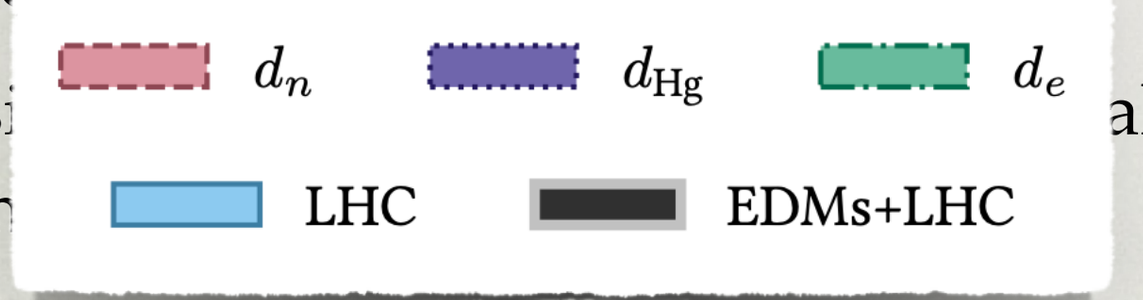

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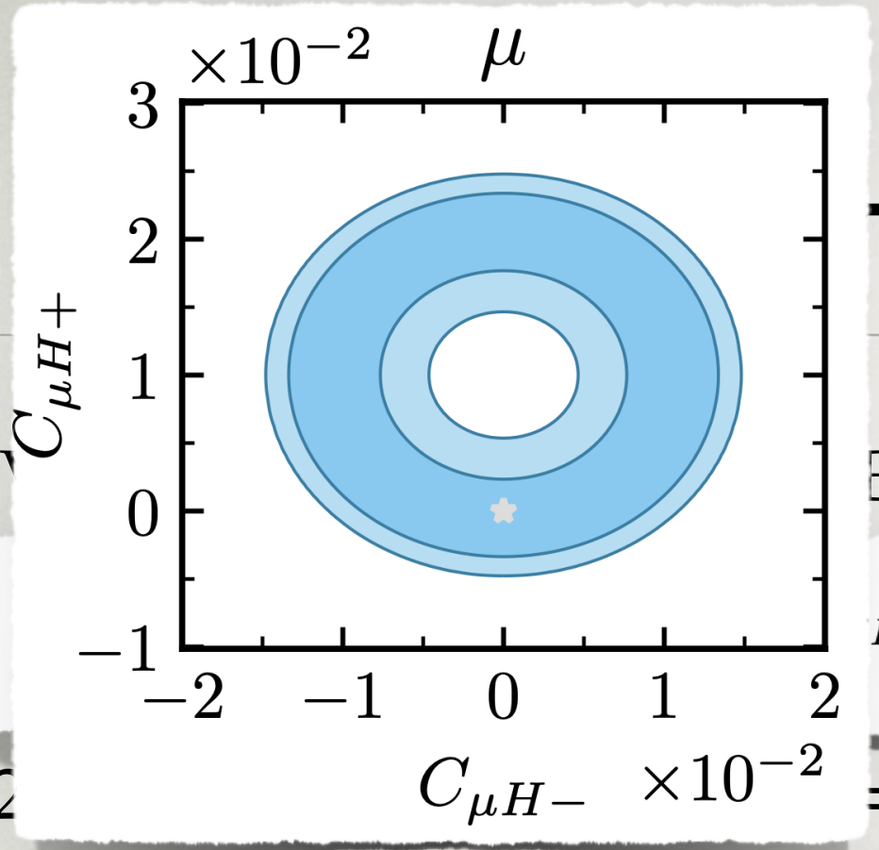

Brod et al, 2203.03736

- CP
- 2

EDMs through loops

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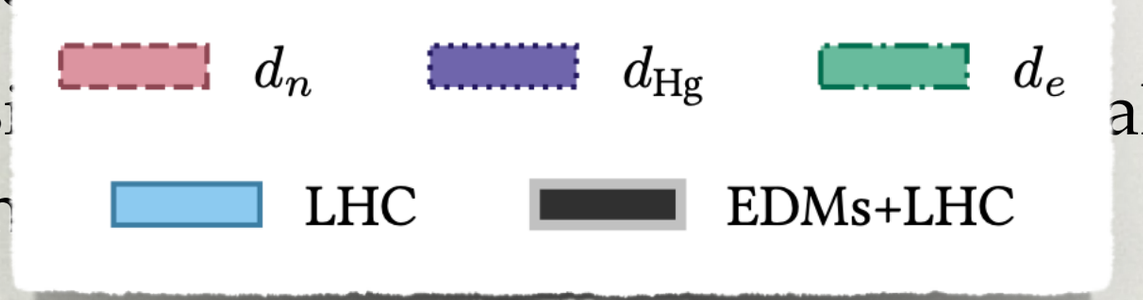
$$C_{fH,ij} = C_{fH+,ij} + iC_{fH-,ij}$$

⇒large logs⇒ leading log



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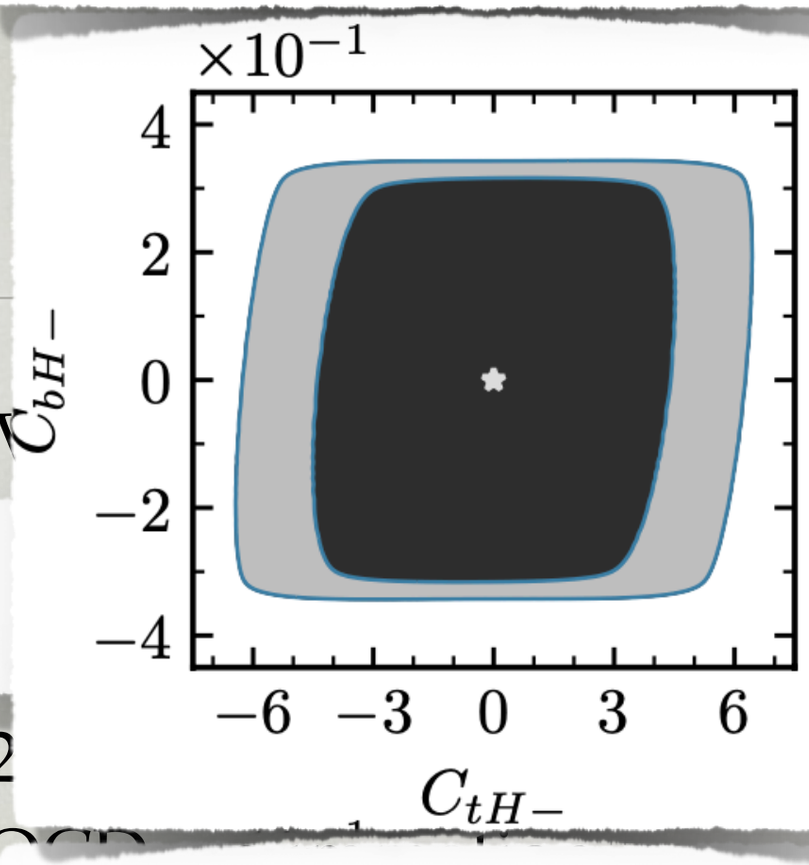
4D t, b LHC scan $(\Lambda = 1\,\text{TeV})$



TRAINTS

Brod et al, 2203.03736

- CPV EDMs through loops

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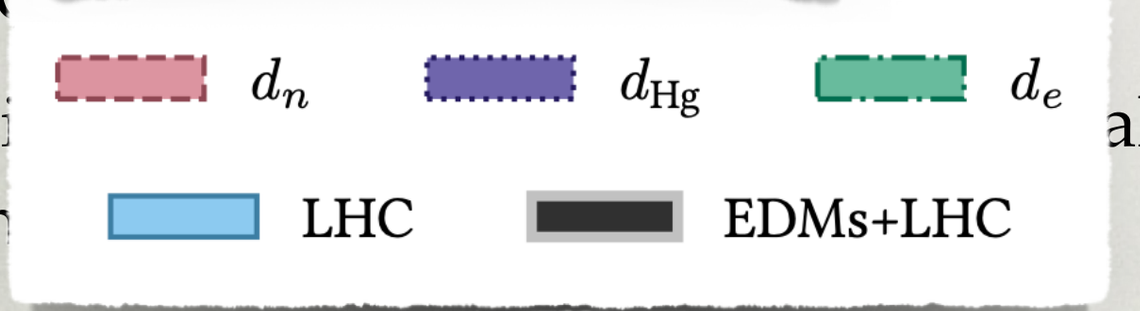
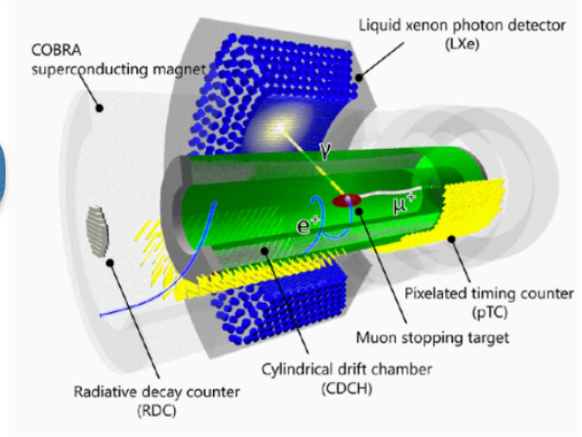


cLFV experiments in the world

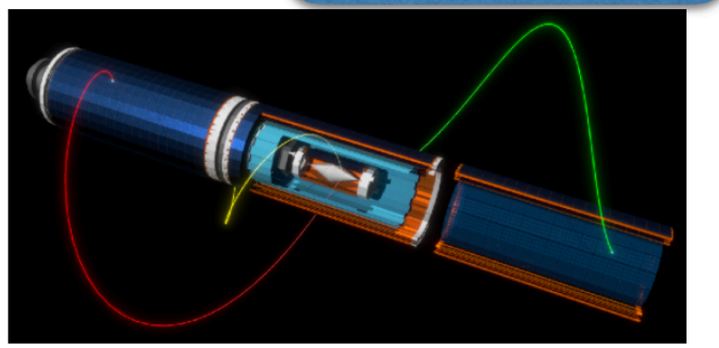
MEG II

$\mu^+ \rightarrow e^+\gamma$



Mu3e

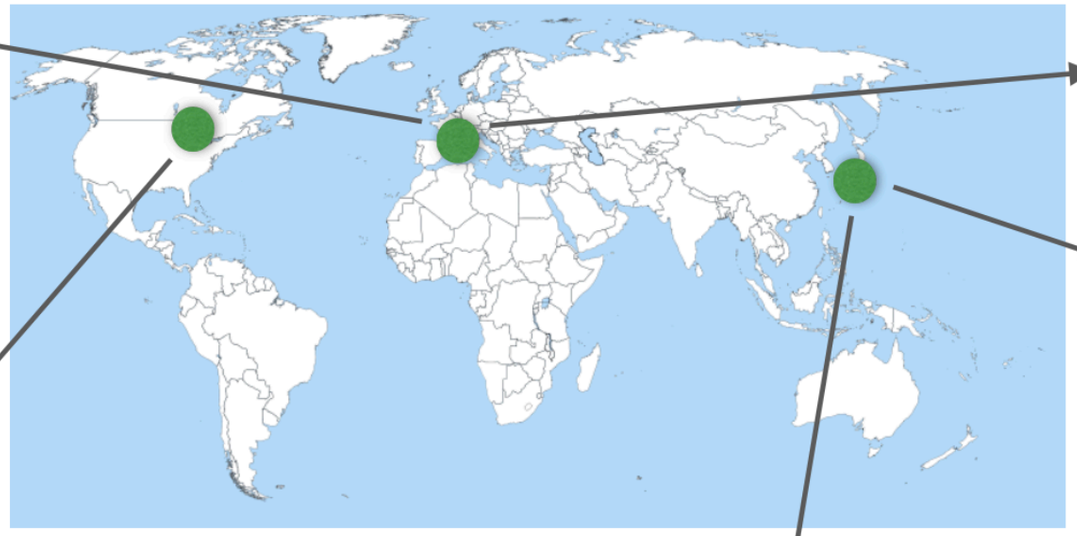
$\mu^+ \rightarrow e^+e^+e^-$



Coincidence measurement:
DC beam needed to minimize backgrounds from accidental coincidences

BKG $\propto$ (Rate)^2

PSI



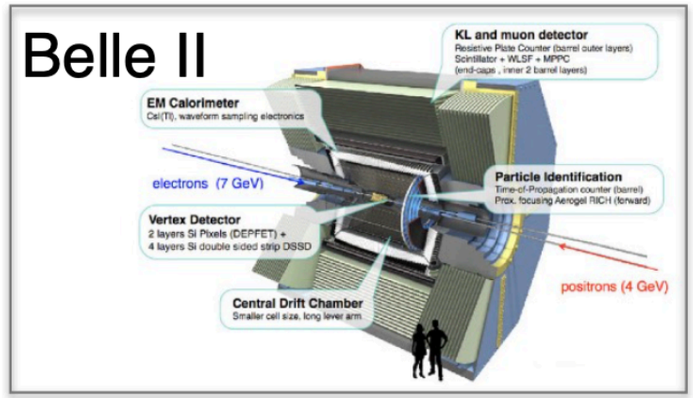
CERN

LHCb/ATLAS/CMS

$\tau \rightarrow 3\mu$, $\tau \rightarrow \mu\gamma$

KEK

Belle II

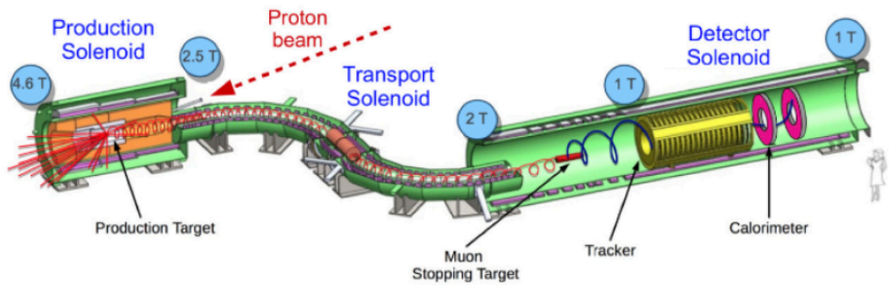


Fermilab

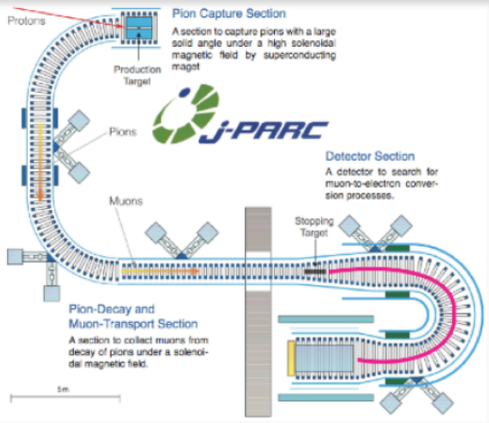
$\mu^-N \rightarrow e^-N$

J-PARC

Mu2e



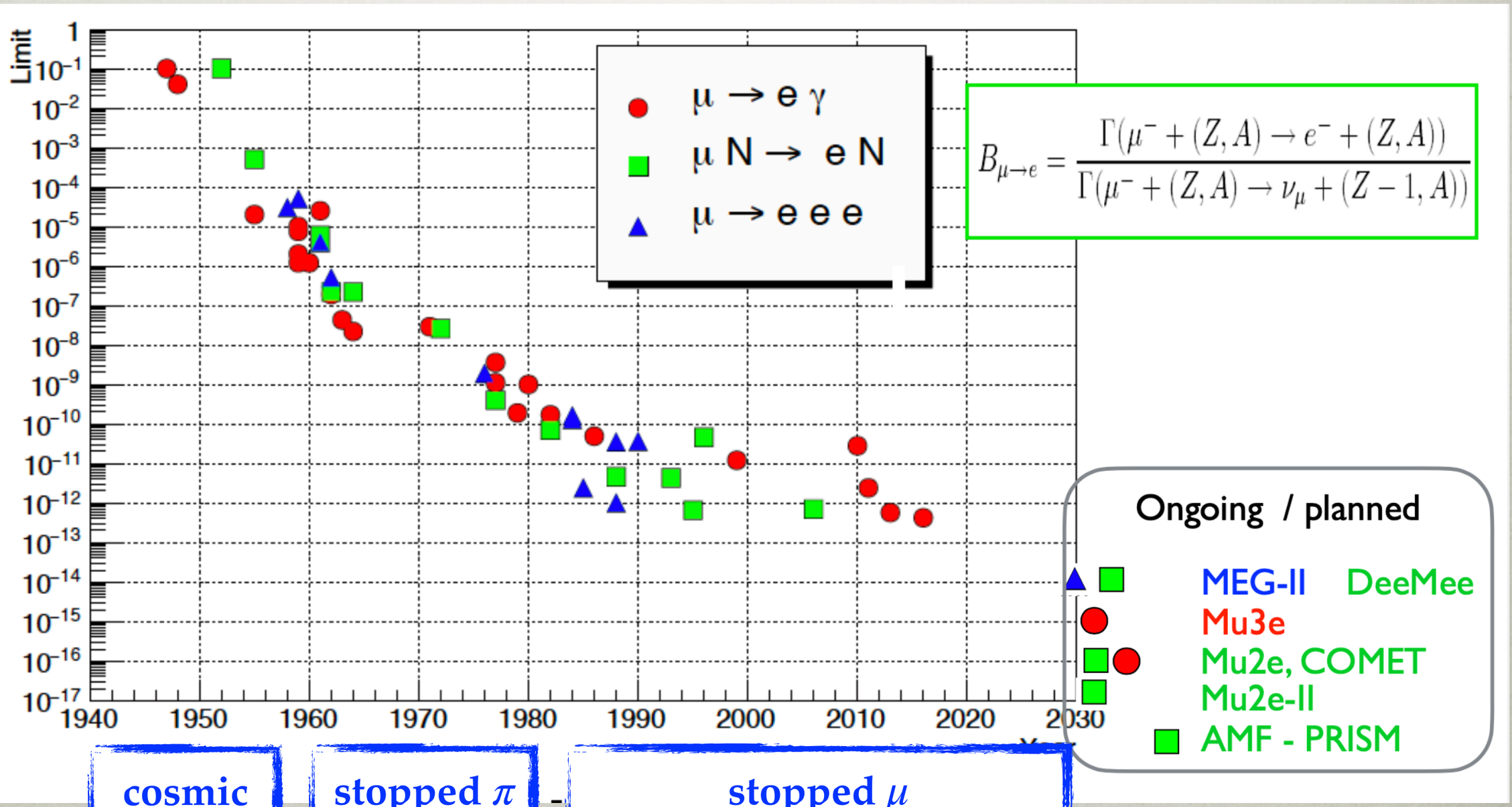
DeeMe, COMET



Single e$^-$ measurement:
pulsed beam needed
Many pion-induced backgrounds after proton pulse
wait it out with 26 ns lifetime

EXPERIMENTAL PROGRESS

- steady experimental progress since 1940s



CPV and FV higgs couplings to SM fermions

$$m = v \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & 0 & * \end{pmatrix} \qquad Y = \begin{pmatrix} * & * & * \\ * & * & * \\ * & * & * \end{pmatrix}$$

- NP contribs in general lead to
  - flavor violating Higgs decays
  - CPV Higgs decays
- different models lead to different patterns of flavor diagonal and flavor violating Yukawas
- note: large Yukawas for light fermions require significant tuning in contributions to fermion masses

Harnik, Kopp, JZ, 1209.1397
Blackenburg, Ellis, Isidori, 1202.5704

CPV and FV higgs

C

Bishara et al, 1504.04022

Model	$\kappa_{ct(tc)}/\kappa_t$	$\kappa_{ut(tu)}/\kappa_t$	$\kappa_{uc(cu)}/\kappa_t$
GL & GL2	$\epsilon(\epsilon^2)$	$\epsilon(\epsilon^2)$	ϵ^3
MFV	$\frac{\mathrm{Re}\left(c_u m_b^2 V_{cb}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(c)}}{v_W}$	$\frac{\mathrm{Re}\left(c_u m_b^2 V_{ub}^{(*)}\right)}{\Lambda^2}\frac{\sqrt{2}m_{t(u)}}{v_W}$	$\frac{\mathrm{Re}\left(c_u m_b^2 V_{ub(cb)} V_{cb(ub)}^*\right)}{\Lambda^2}\frac{\sqrt{2}m_{c(u)}}{v_W}$
RS	$\sim \lambda^{(-)2}\frac{m_{t(c)}}{v_W}\bar{Y}^2\frac{v_W^2}{m_{KK}^2}$	$\sim \lambda^{(-)3}\frac{m_{t(u)}}{v_W}\bar{Y}^2\frac{v_W^2}{m_{KK}^2}$	$\sim \lambda^{(-)1}\frac{m_{c(u)}}{v_W}\bar{Y}^2\frac{v_W^2}{m_{KK}^2}$
pNGB	$\mathcal{O}(y_*^2\frac{m_t}{v_W}\frac{\lambda_{L(R),2}\lambda_{L(R),3}m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2\frac{m_t}{v_W}\frac{\lambda_{L(R),1}\lambda_{L(R),3}m_W^2}{M_*^2})$	$\mathcal{O}(y_*^2\frac{m_c}{v_W}\frac{\lambda_{L(R),1}\lambda_{L(R),2}m_W^2}{M_*^2})$

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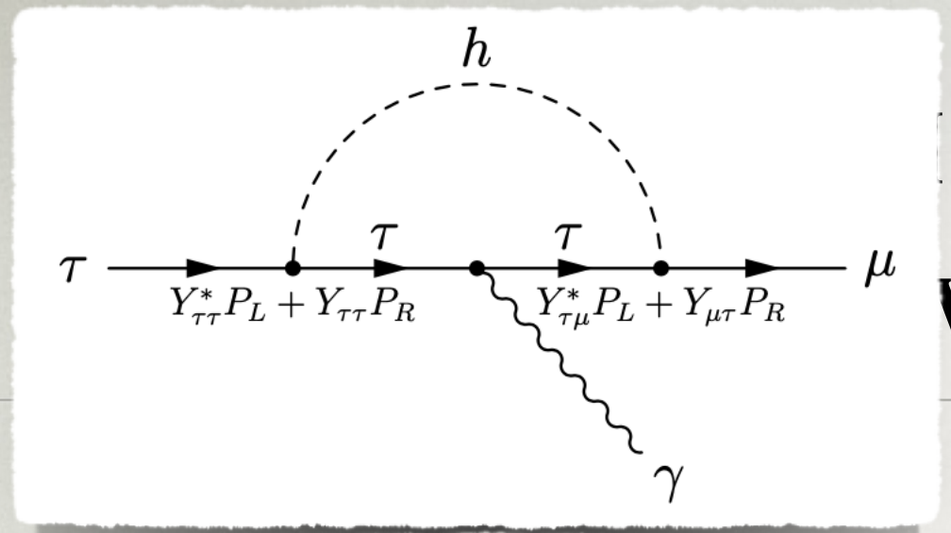
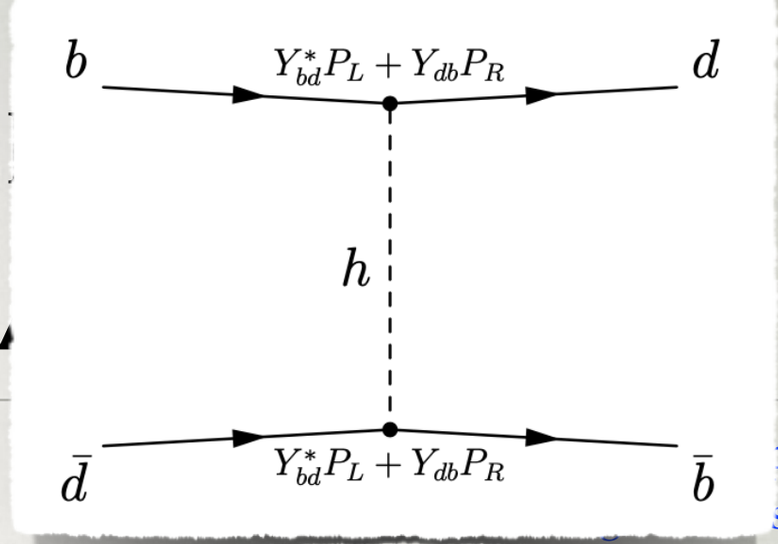
Harnik, Kopp, JZ, 1209.1397
Blackenburg, Ellis, Isidori, 1202.5704

FLAVOR VIOLATING YUKAWAS

Harnik, Kopp, JZ, 1209.1397
Blackenburg, Ellis, Isidori, 1202.5704

- FV Yukawas induce other FCNCs
  - D,B,B_s,K mixing ⇒ constrain FV quark Yukawas
    - these very poor for top ⇒Y_{tq} Yukawas from LHC, HL-LHC, future coll.
      - Y_{bs}, Y_{cu} maybe in reach of future coll
  - $\mu \to e\gamma, \mu \to 3e, \ldots$ ⇒ stringent constraints on $Y_{\mu e}$, less on $Y_{\tau e}, Y_{\tau\mu}$
- "model independent" ⇒ not easy to suppress in concrete models





op, JZ, 1209.1397
sidori, 1202.5704

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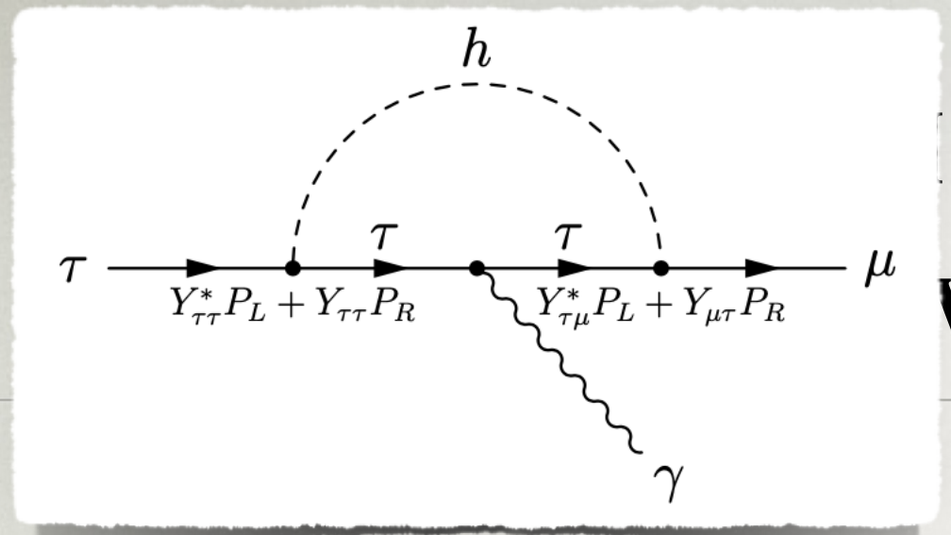

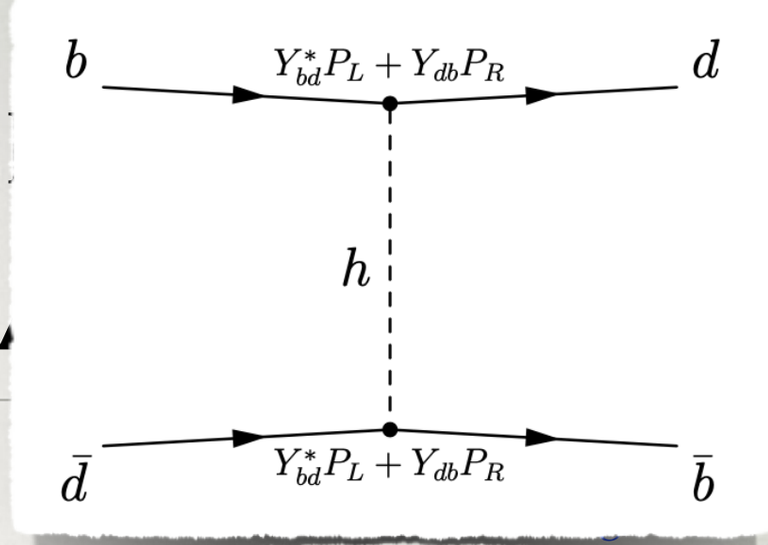

pp, JZ, 1209.1397
sidori, 1202.5704

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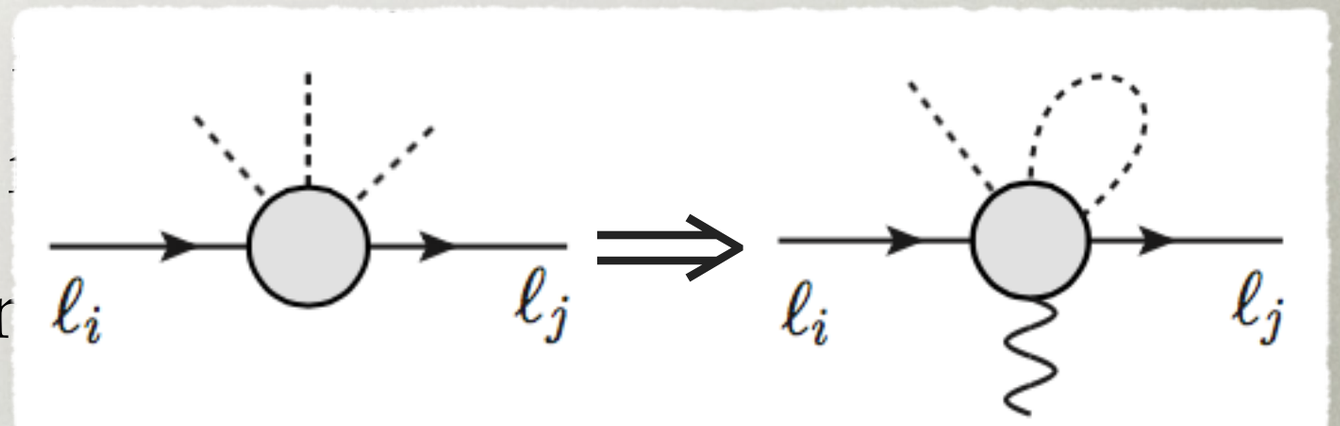

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