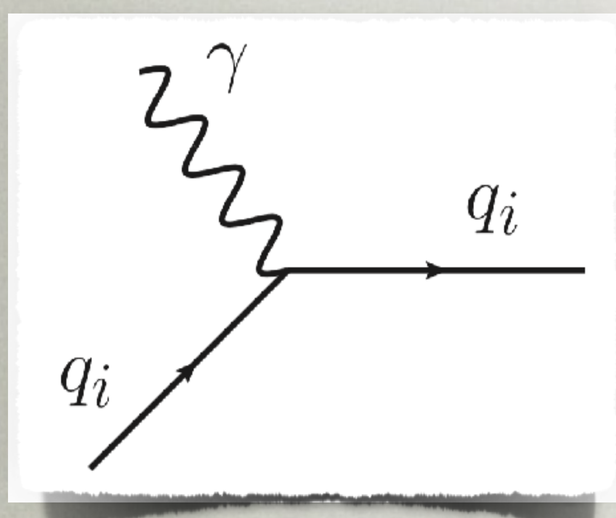
FLAVOR THEORY

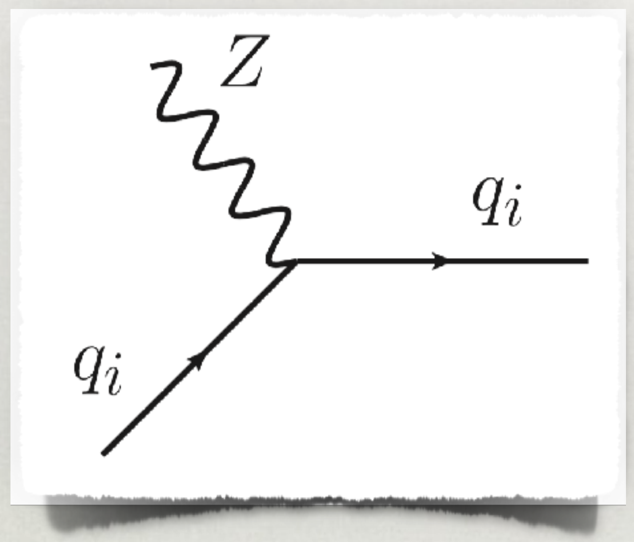
Jure Zupan
U. of Cincinnati

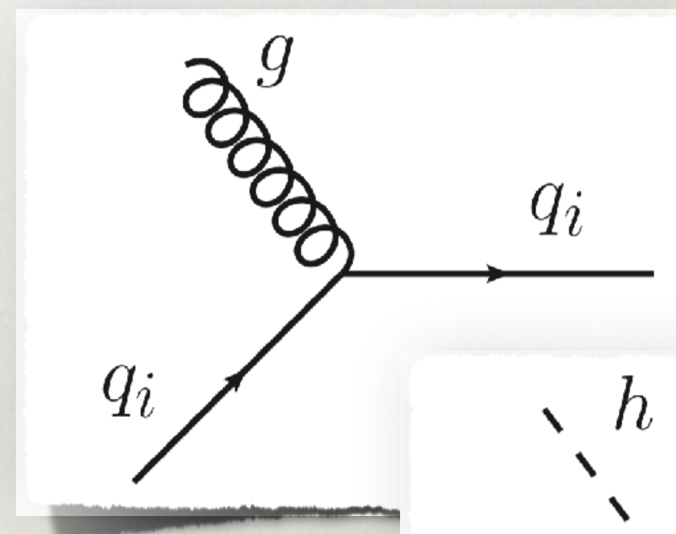
DPF-Pheno 2024, May 17 2024

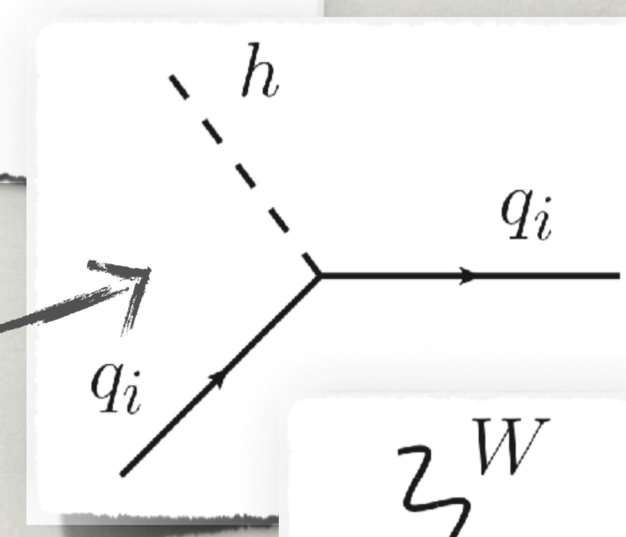
FLAVOR IN THE SM

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

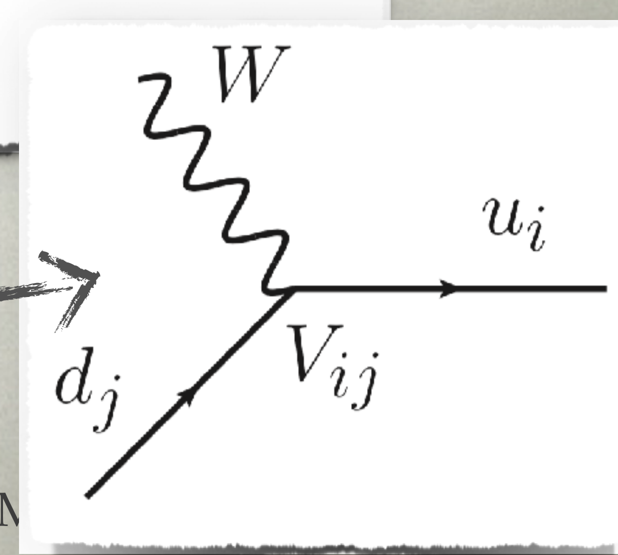


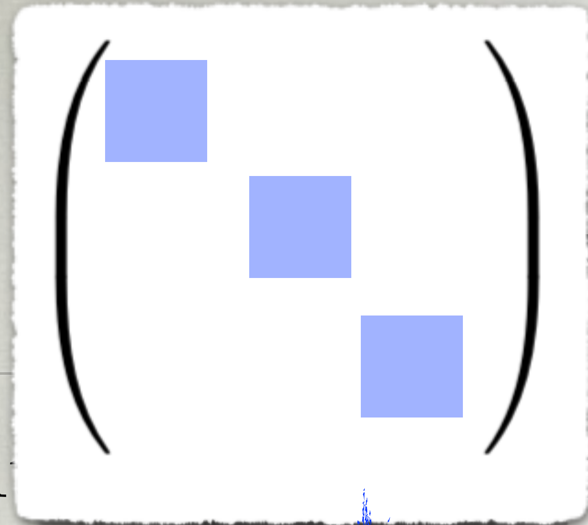






- Higgs has *flavor diagonal* interactions
    - proportional to quark mass
- charged currents are *flavor changing*
    - *W* couplings are flavor changing





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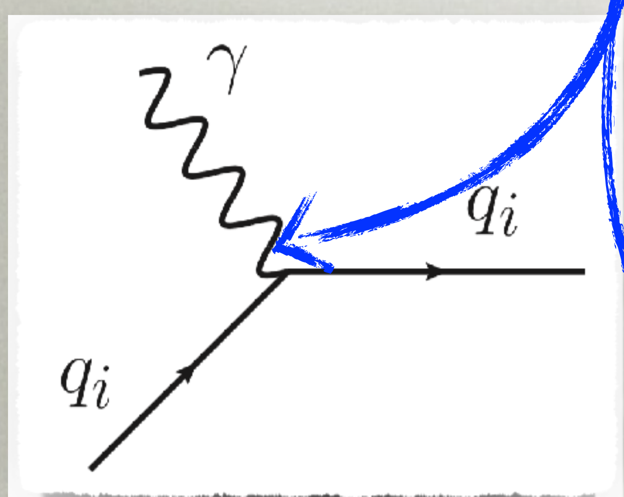

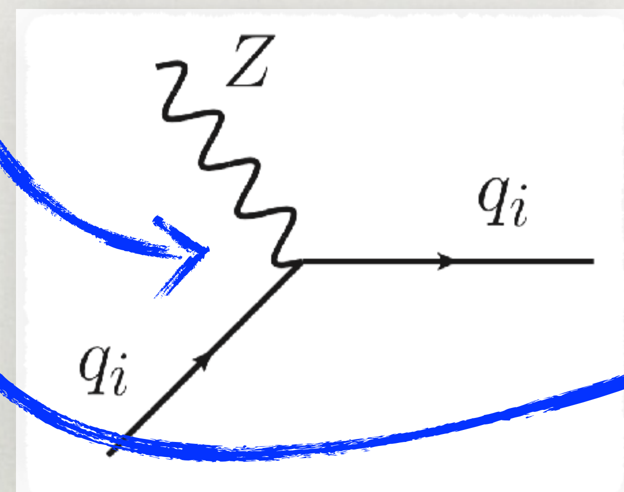

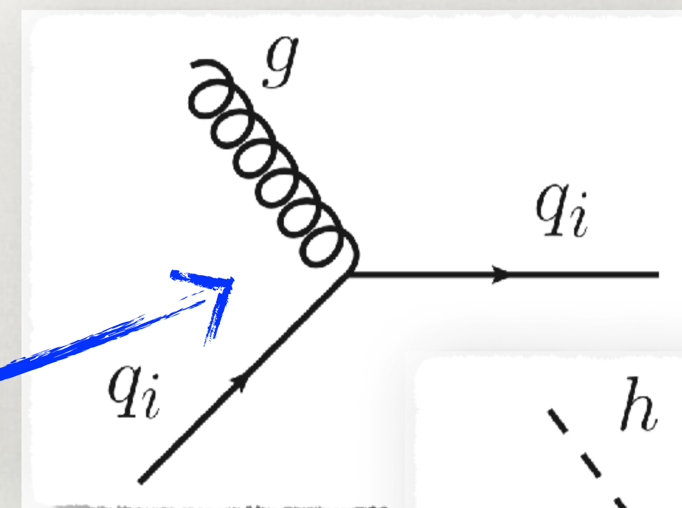

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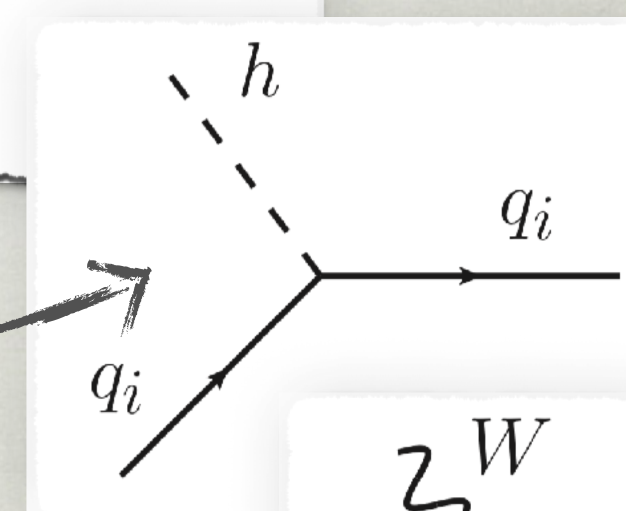

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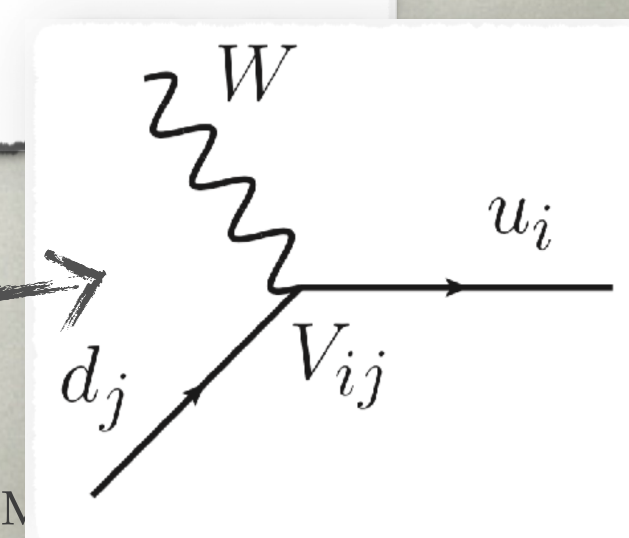

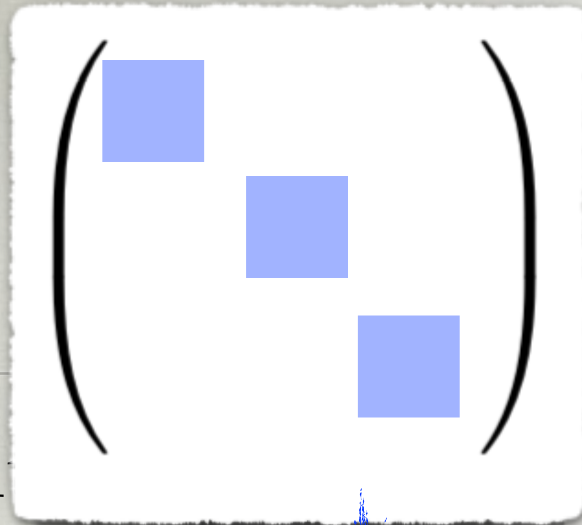

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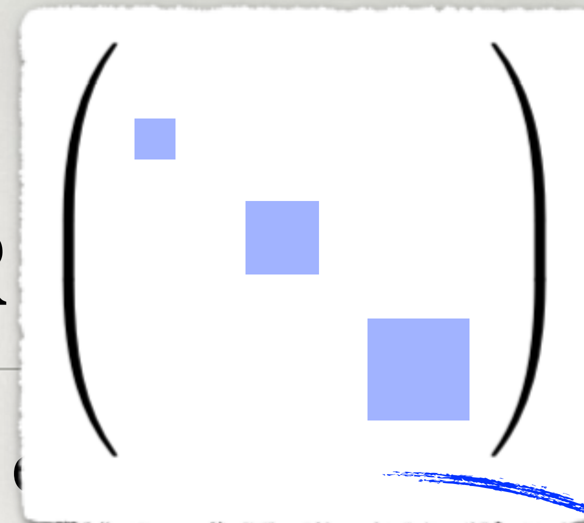

SM

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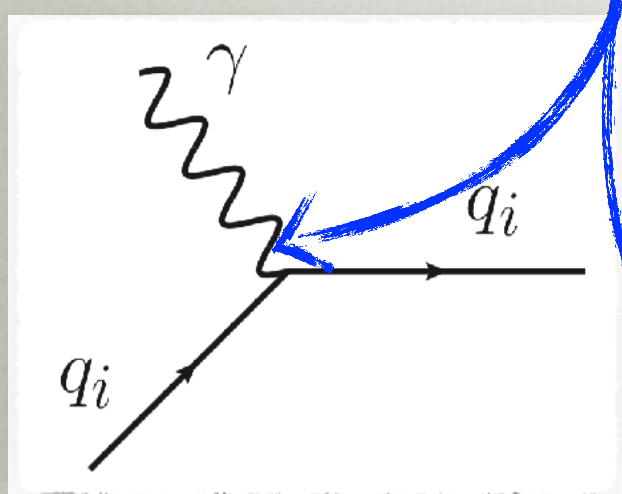

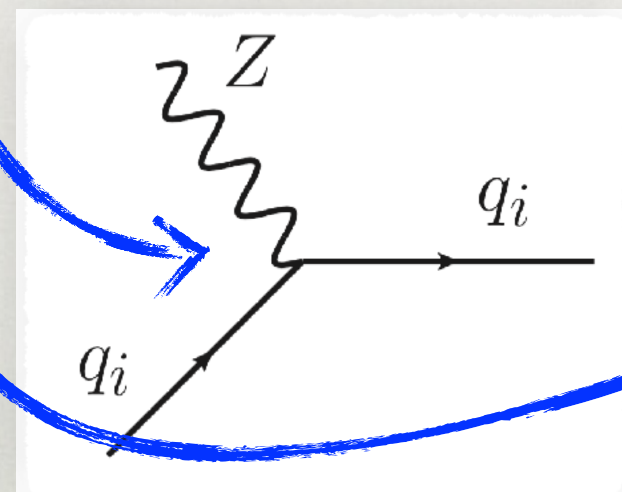

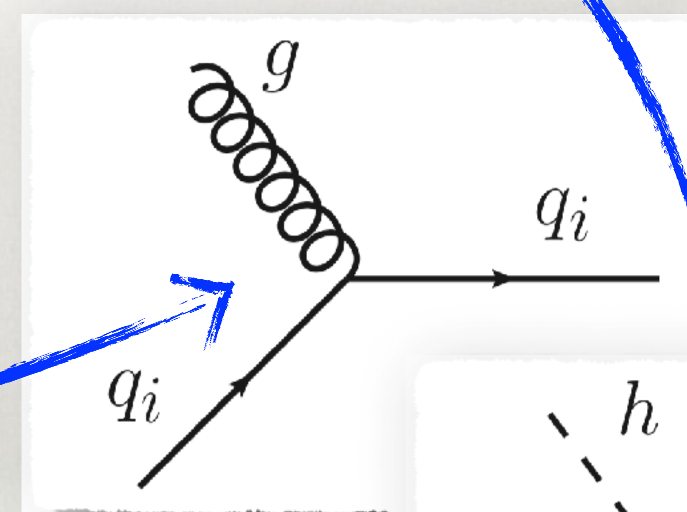

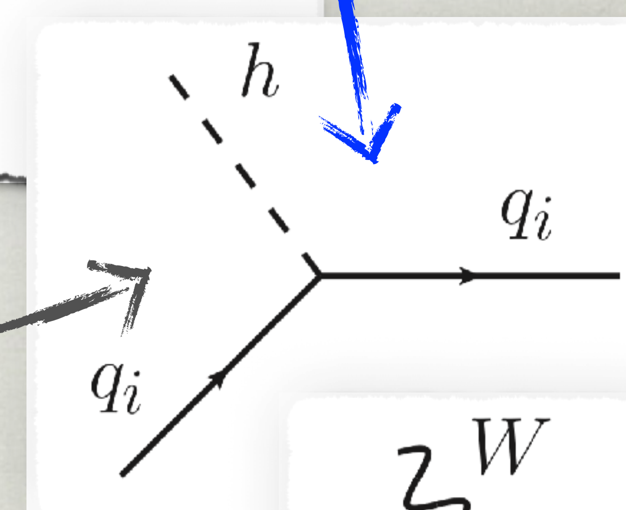

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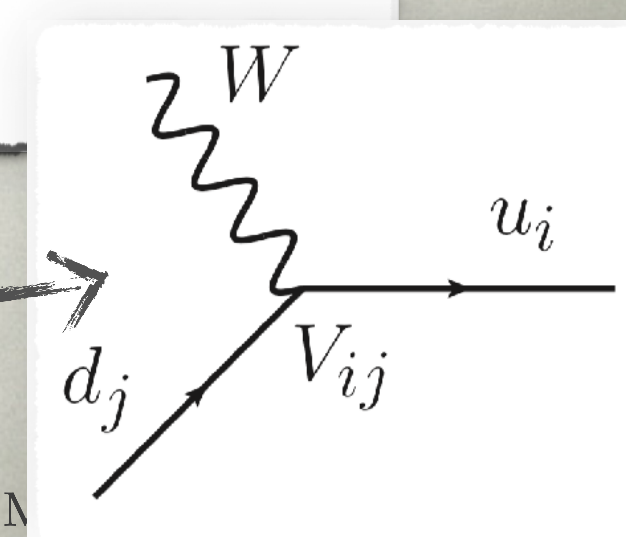

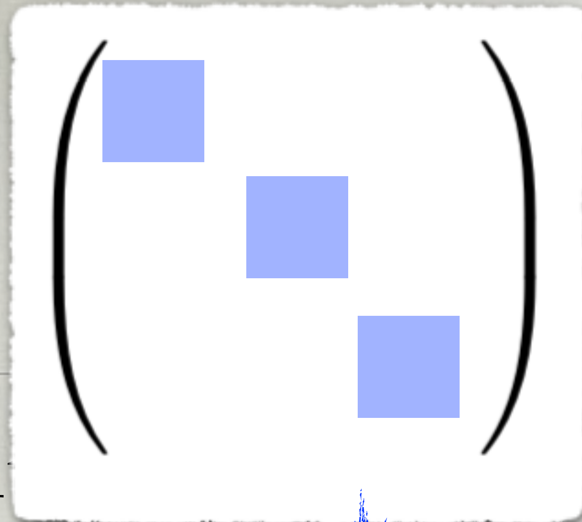

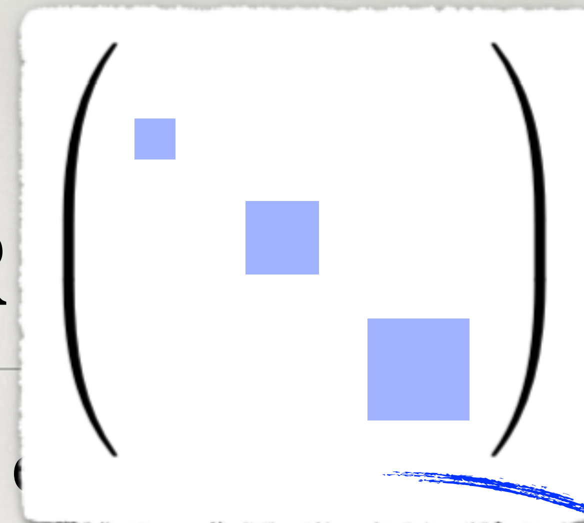

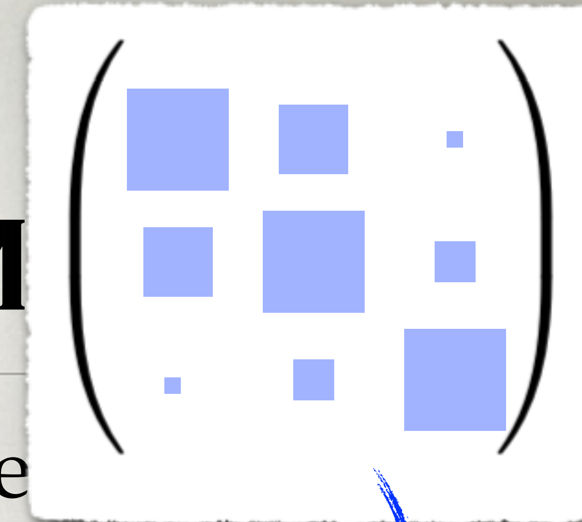

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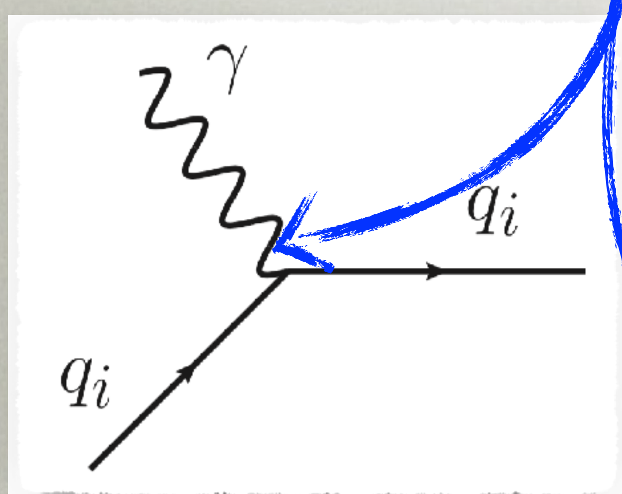

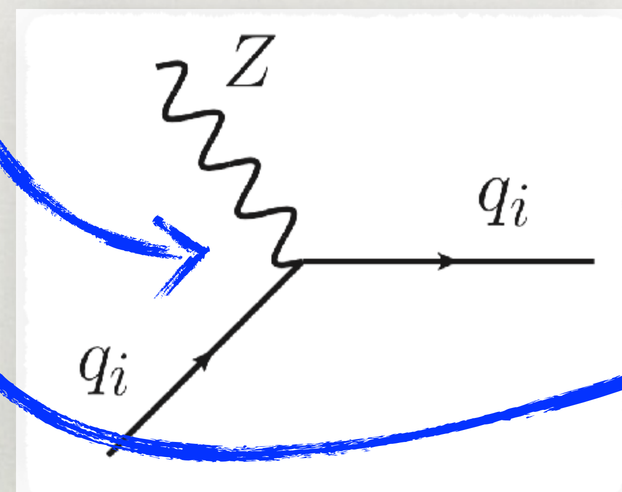

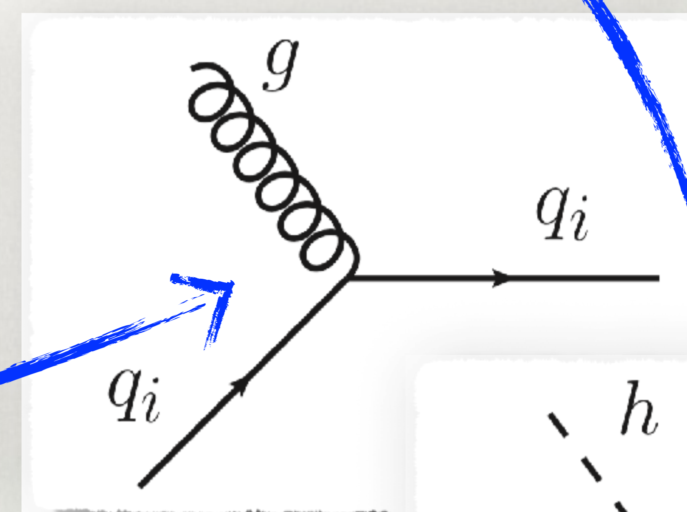

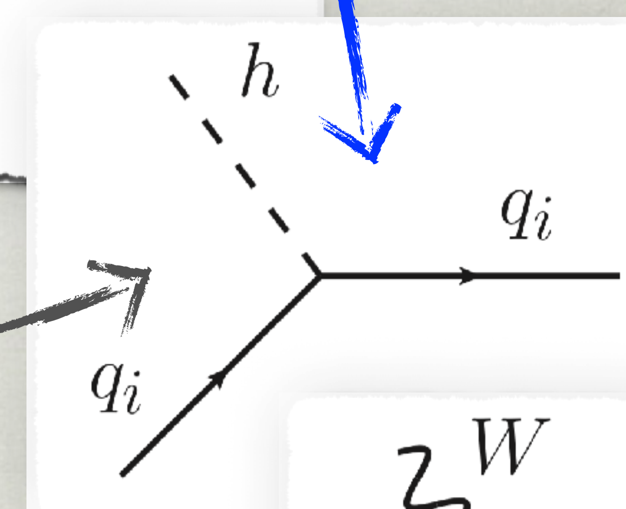

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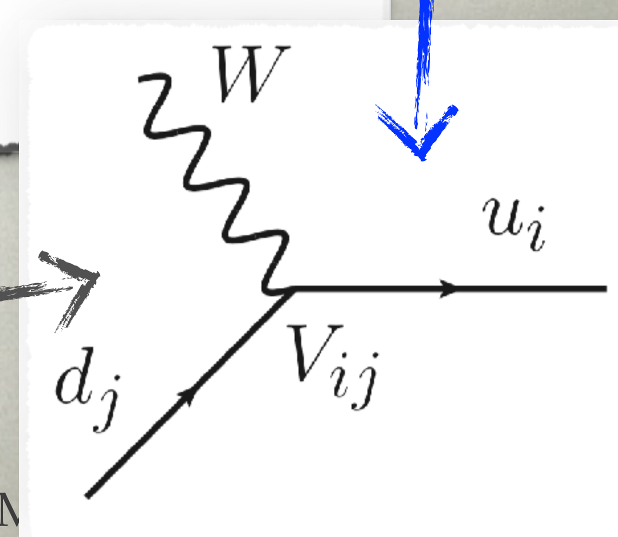
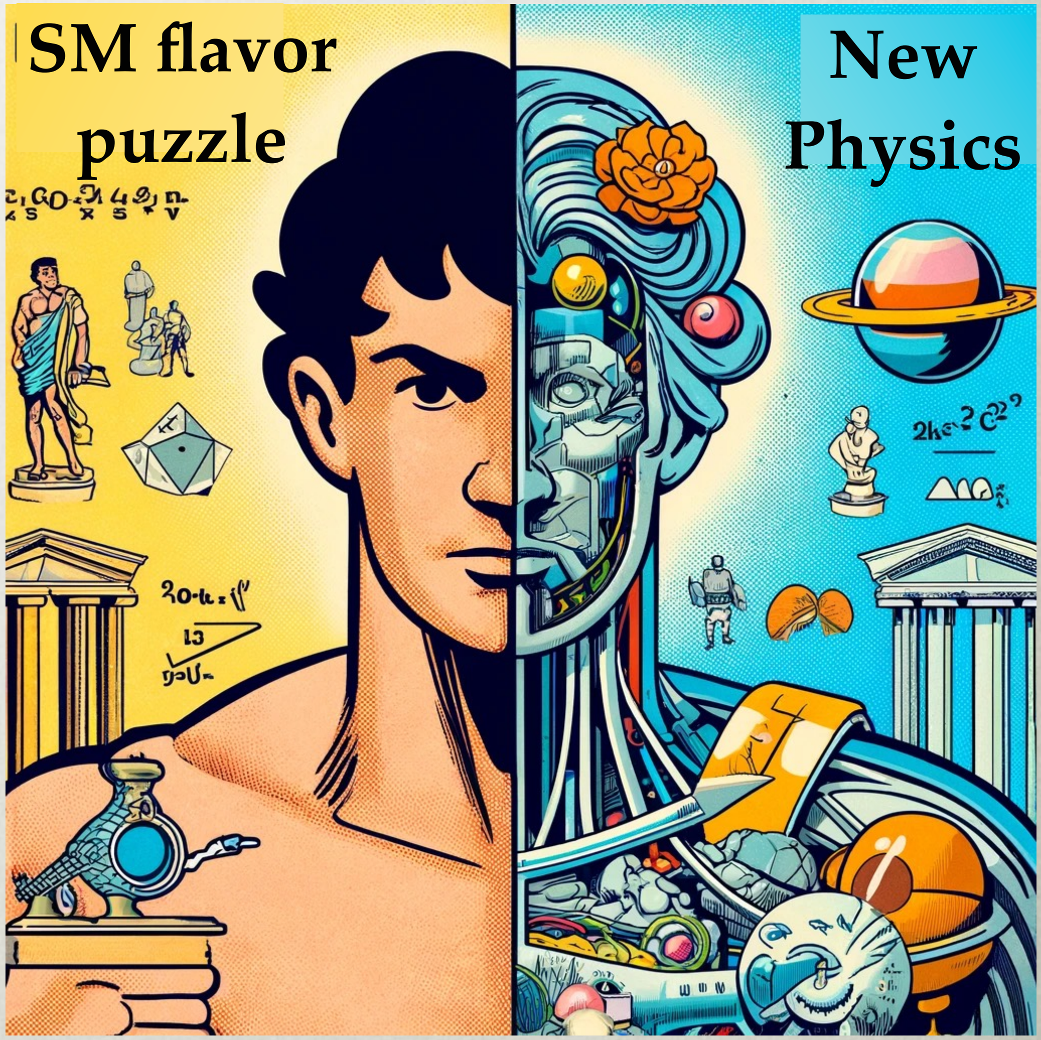


TWO FACES OF FLAVOR PHYSICS

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



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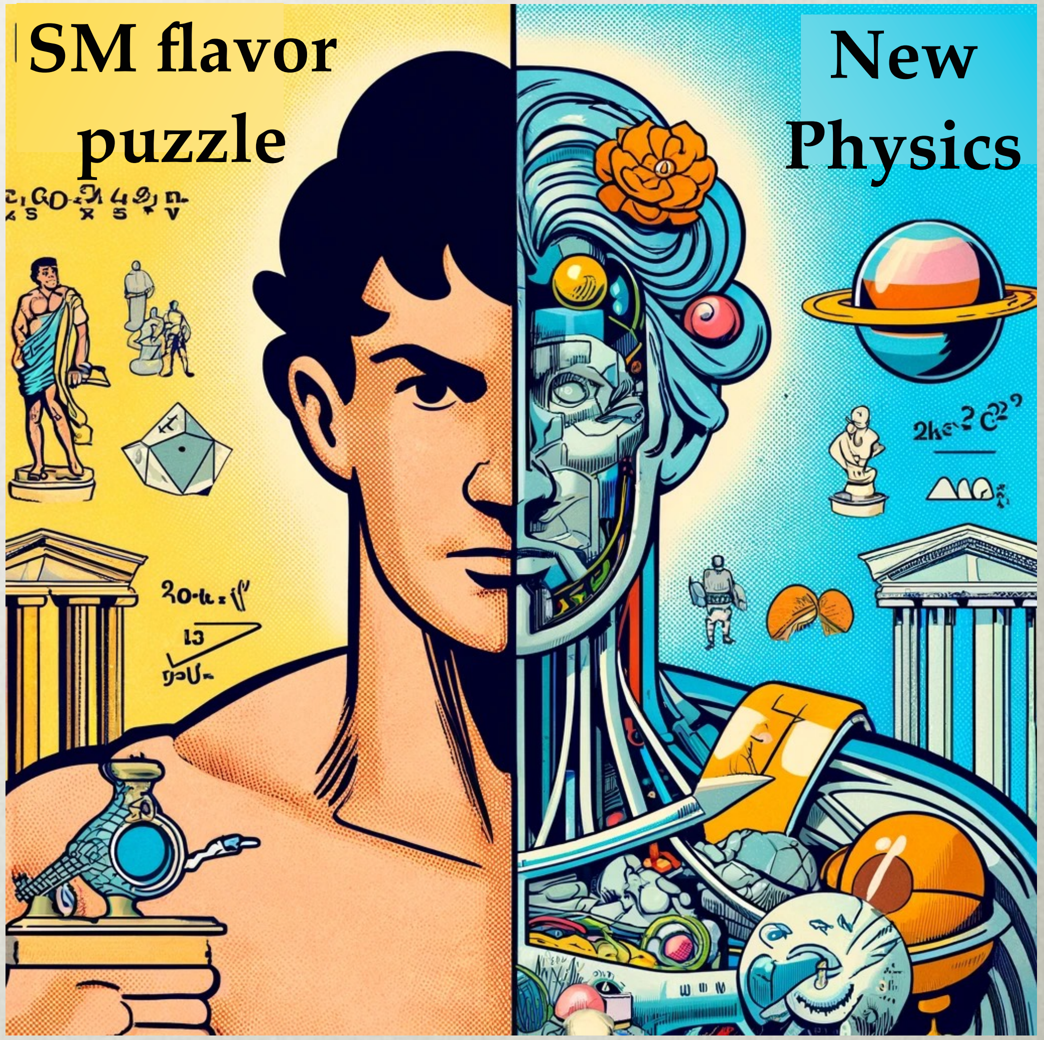
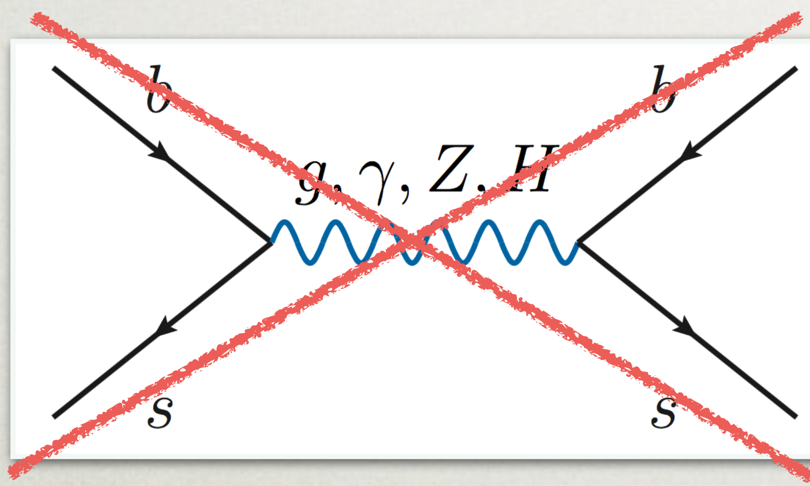
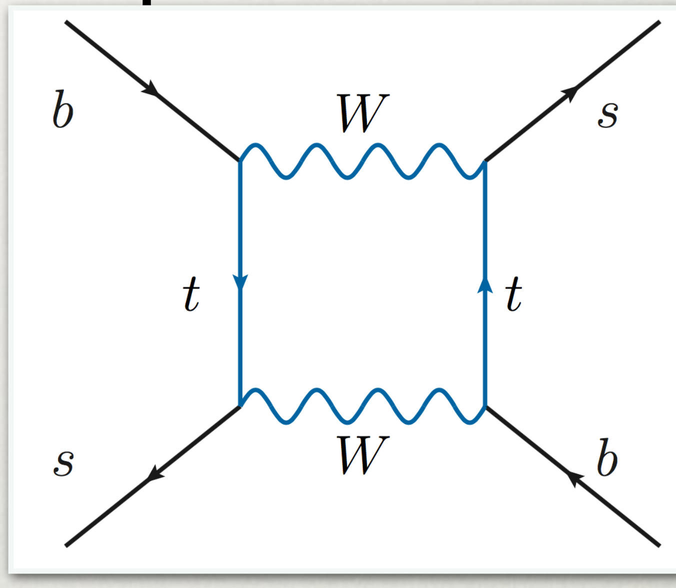


SEARCHING FOR NEW PHYSICS

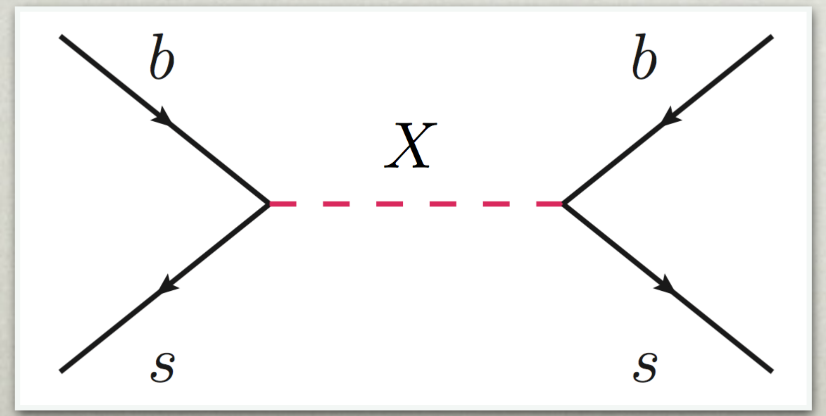
SEARCHING FOR OFF-SHELL NEW PHYSICS

- FCNC processes only at loop level in the SM





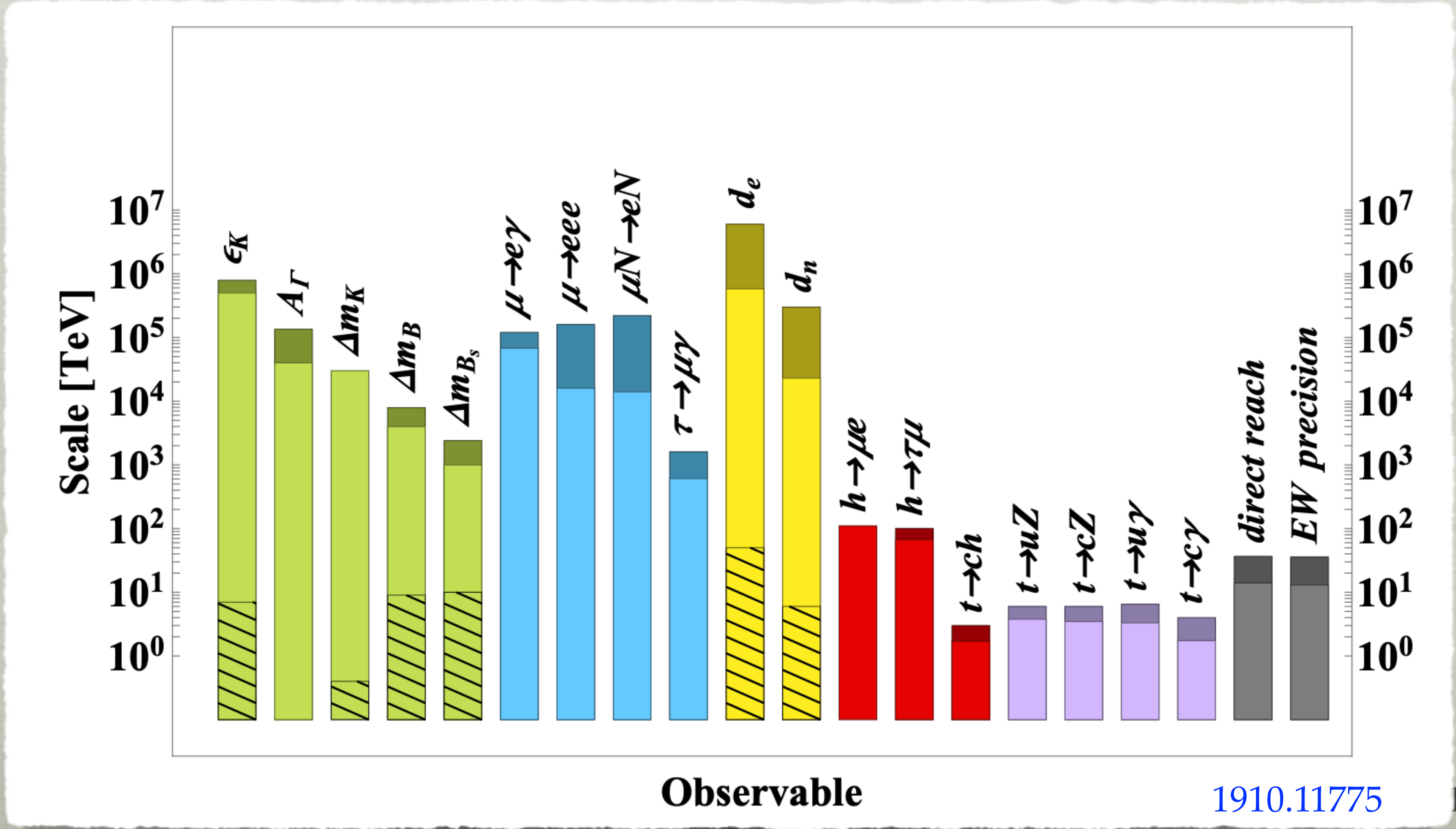
- can search for off-shell new physics



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

HEAVY NEW PHYSICS

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



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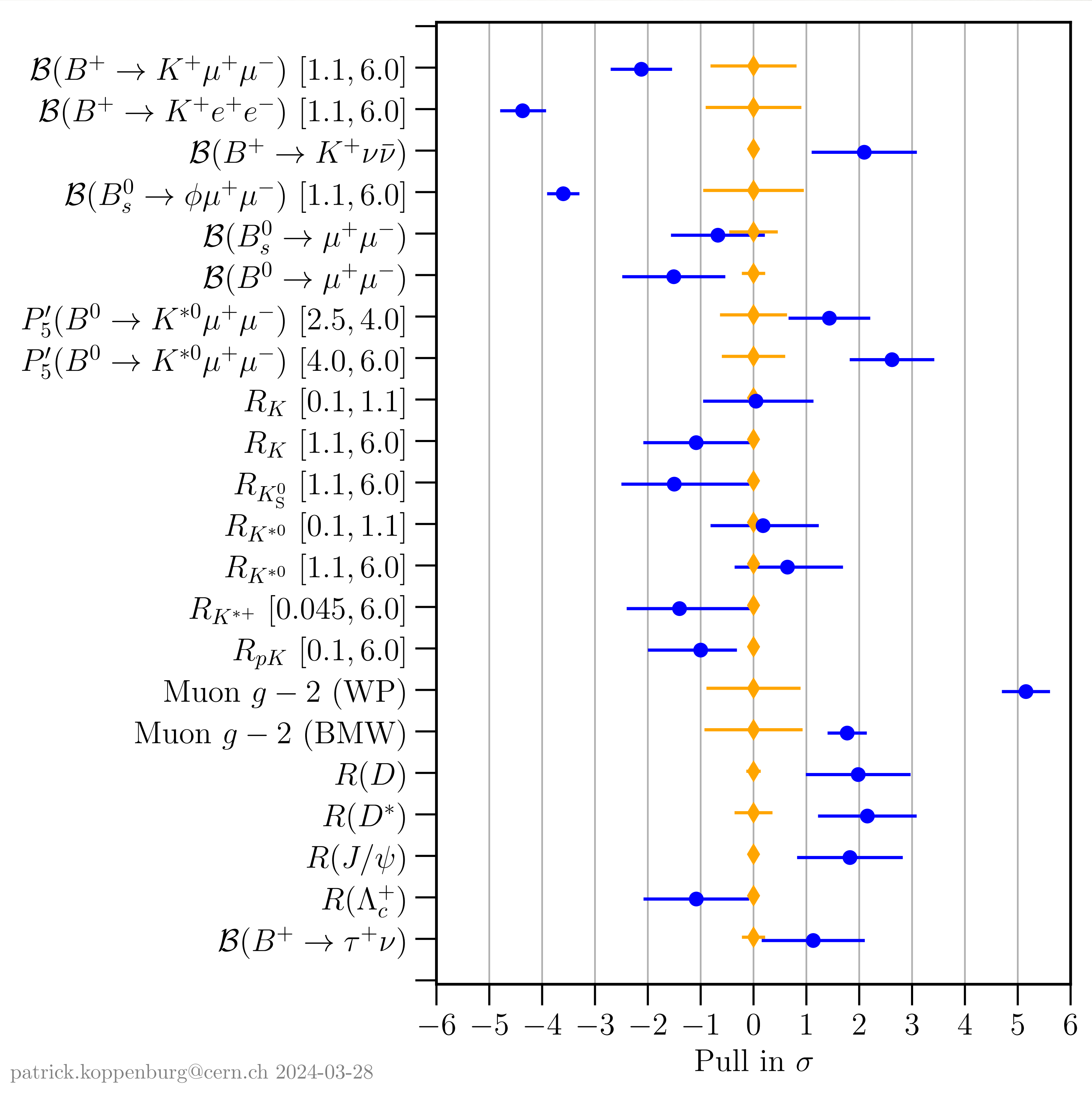
NEXT FEW SLIDES...

see also talks by Y. Zhang on Mon,
M. Sokhashvili on Tue,
A. Fernez on Thu,
G. Hou on Tue,
A. Jean on Thu,
A. Gadam on Thu
M. Gavrilova on Thu

- *B* physics
  - anomalies + active exp. program at LHCb, Belle 2, ATLAS, CMS
- rare muon decays
  - new generation of experiments coming soon: Mu2e, Mu3e,...

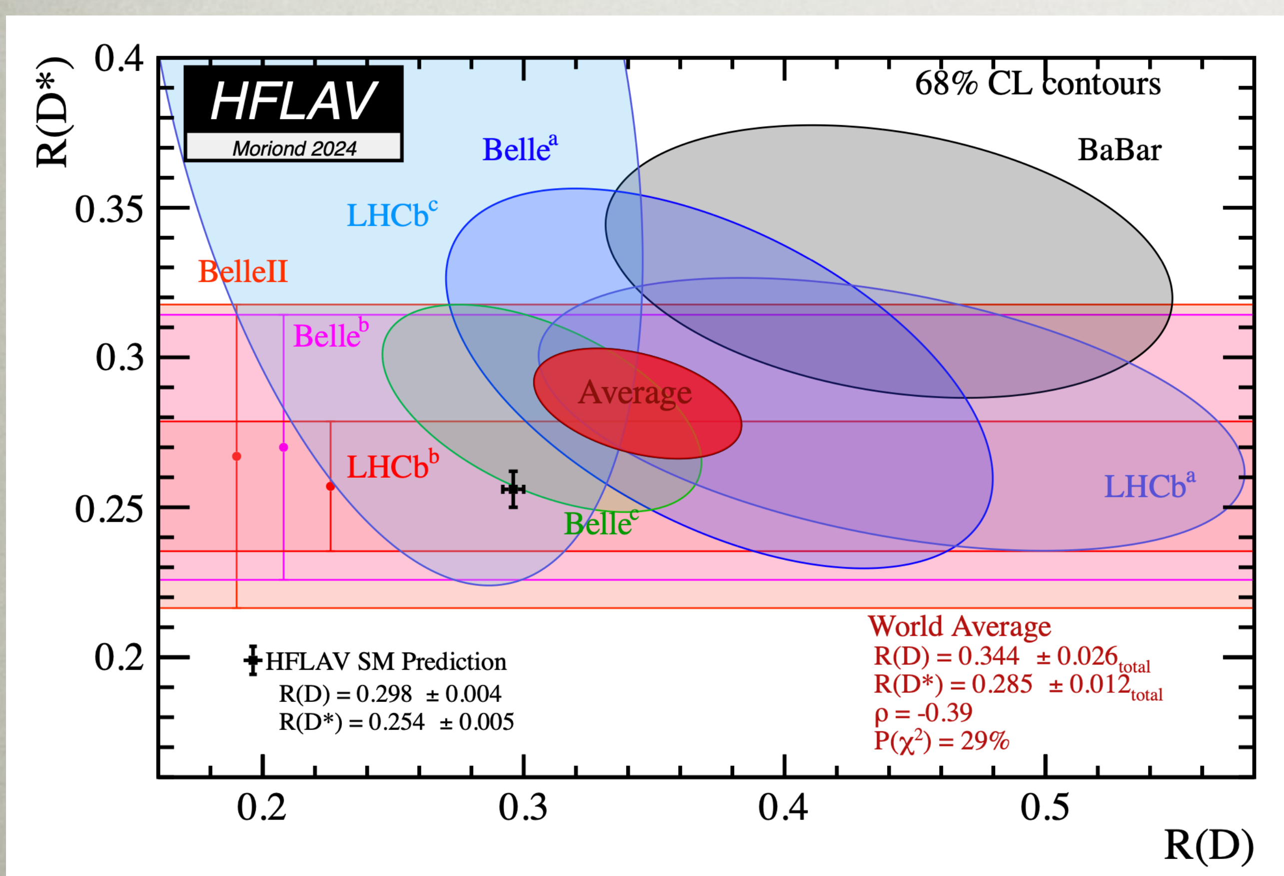
ANOMALIES

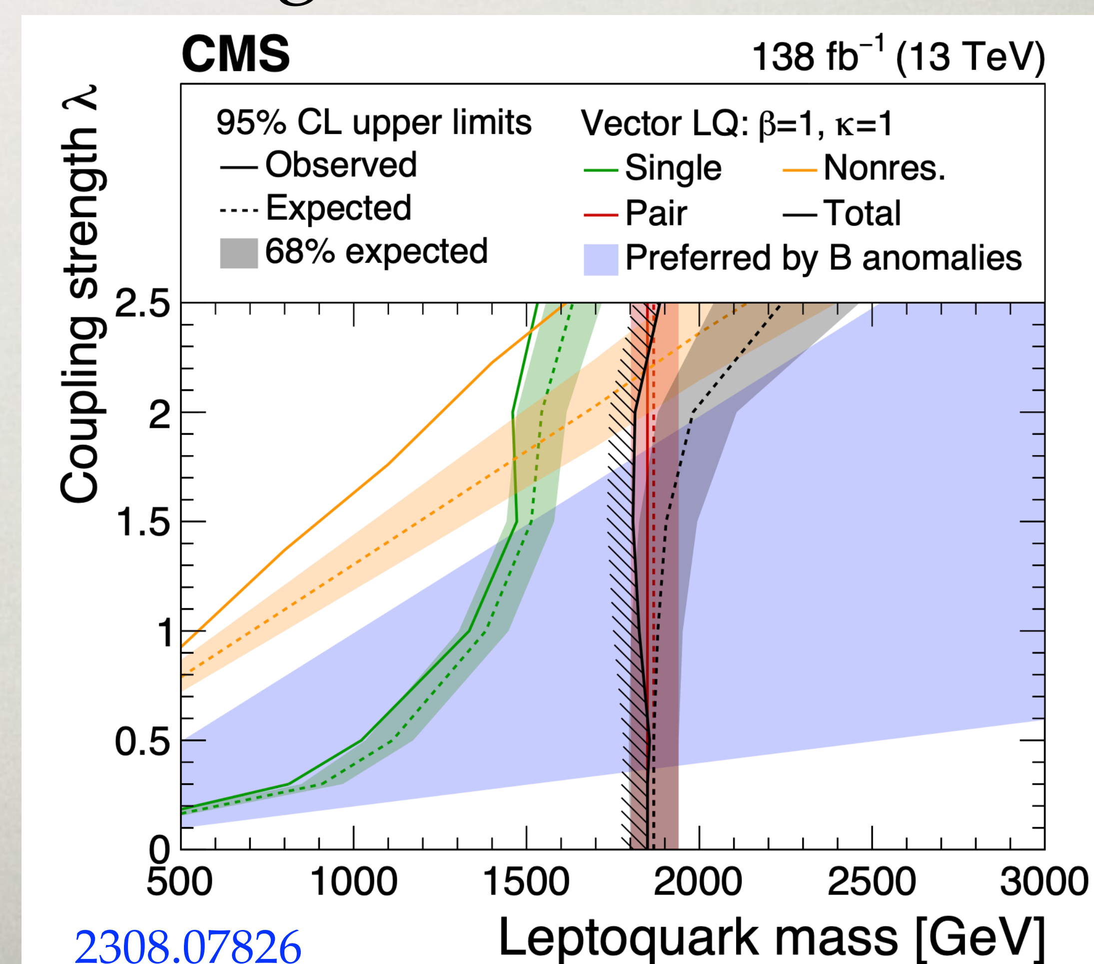
- a number of disagreements
  - $(g-2)_\mu$ see Ethan Neil's talk
  - $b \to s\nu\nu$ see Peter Lewis's talk
  - $b \to s\ell\ell$
  - $b \to c\tau\nu$



$b \to c\tau\nu$

- $b \to c\tau\nu$
  - SM theory under very good control
  - if not NP it has to be an experimental issue
  - NP at tree level, mass in TeV regime





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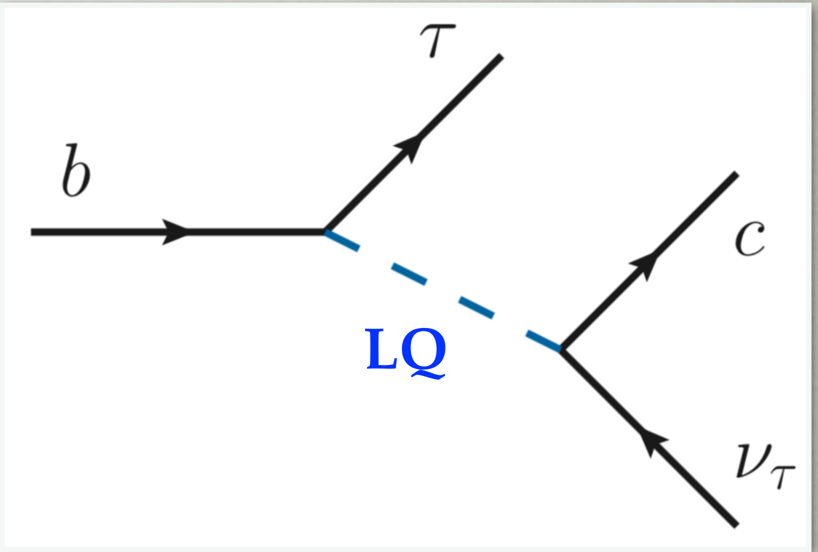

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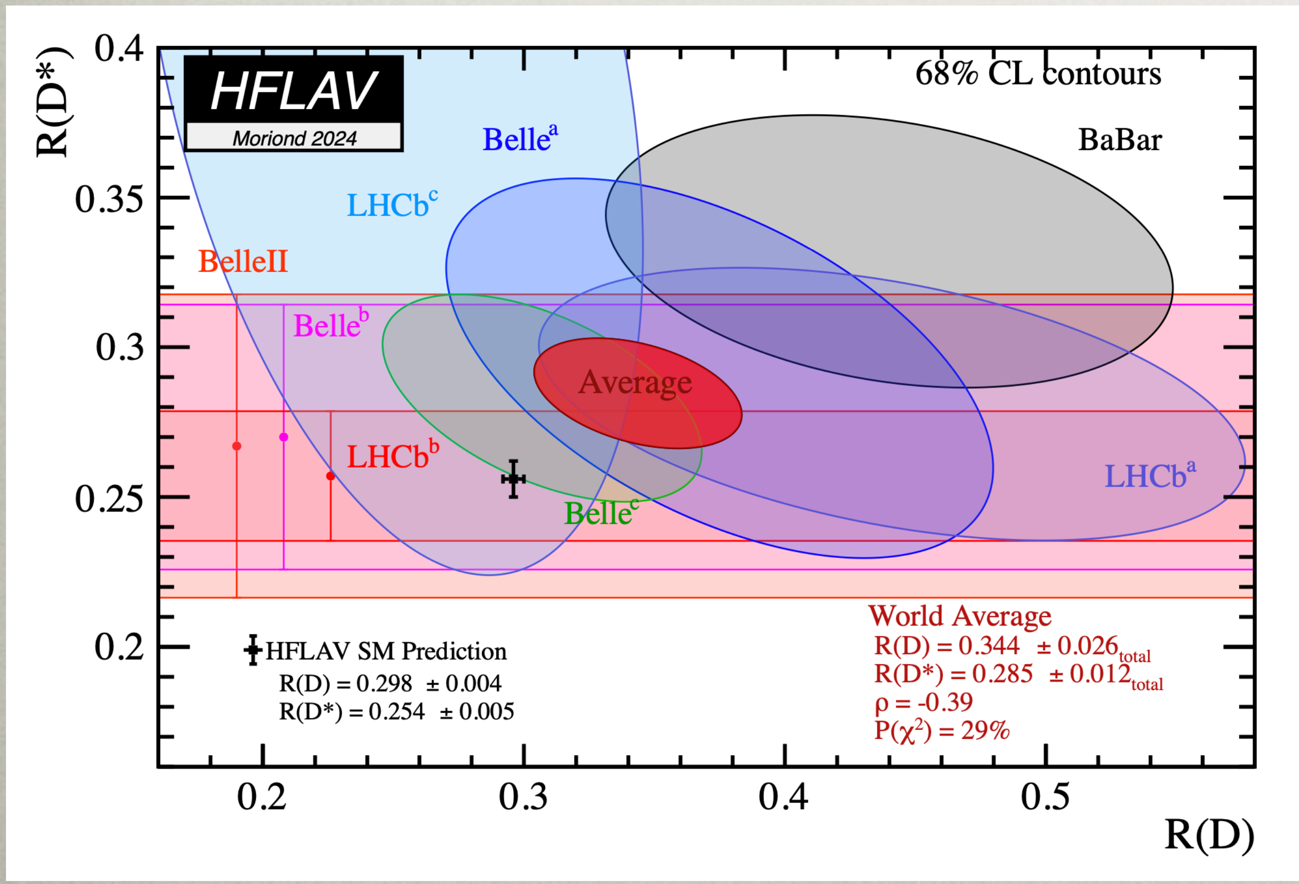

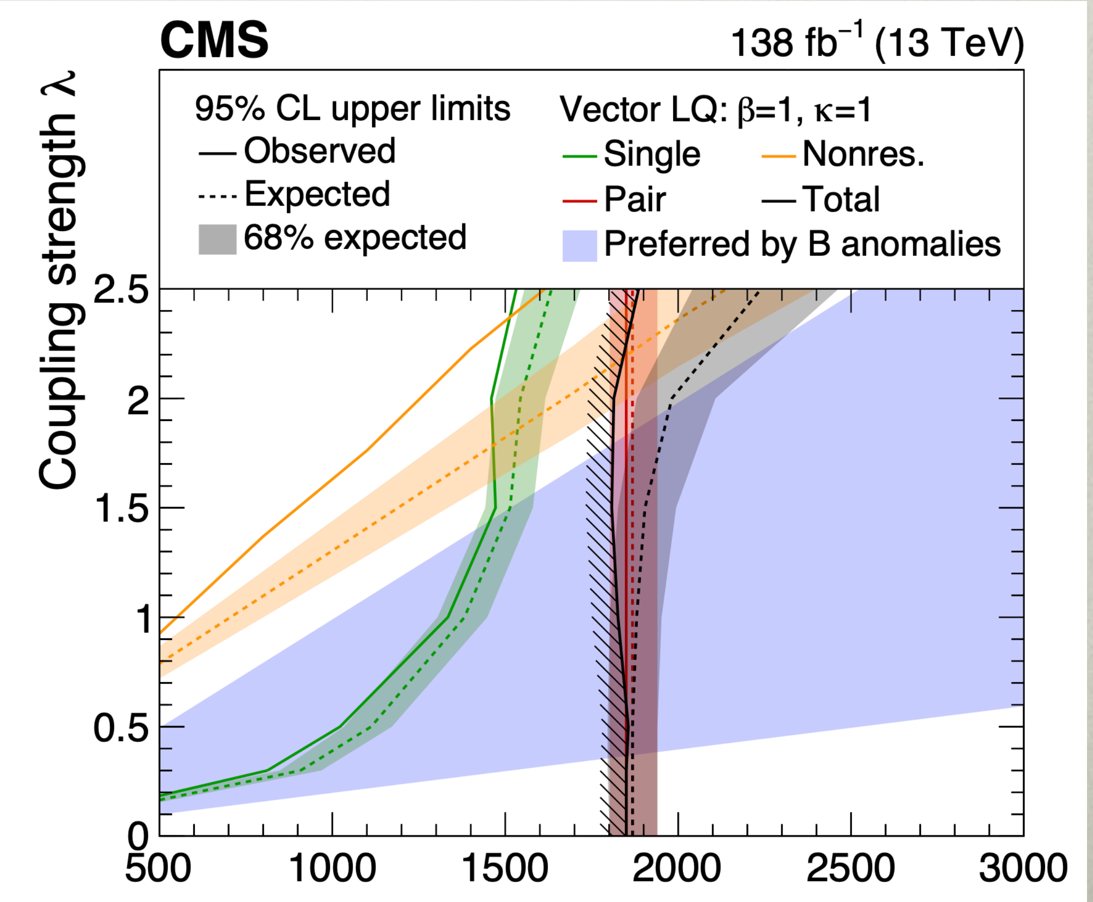

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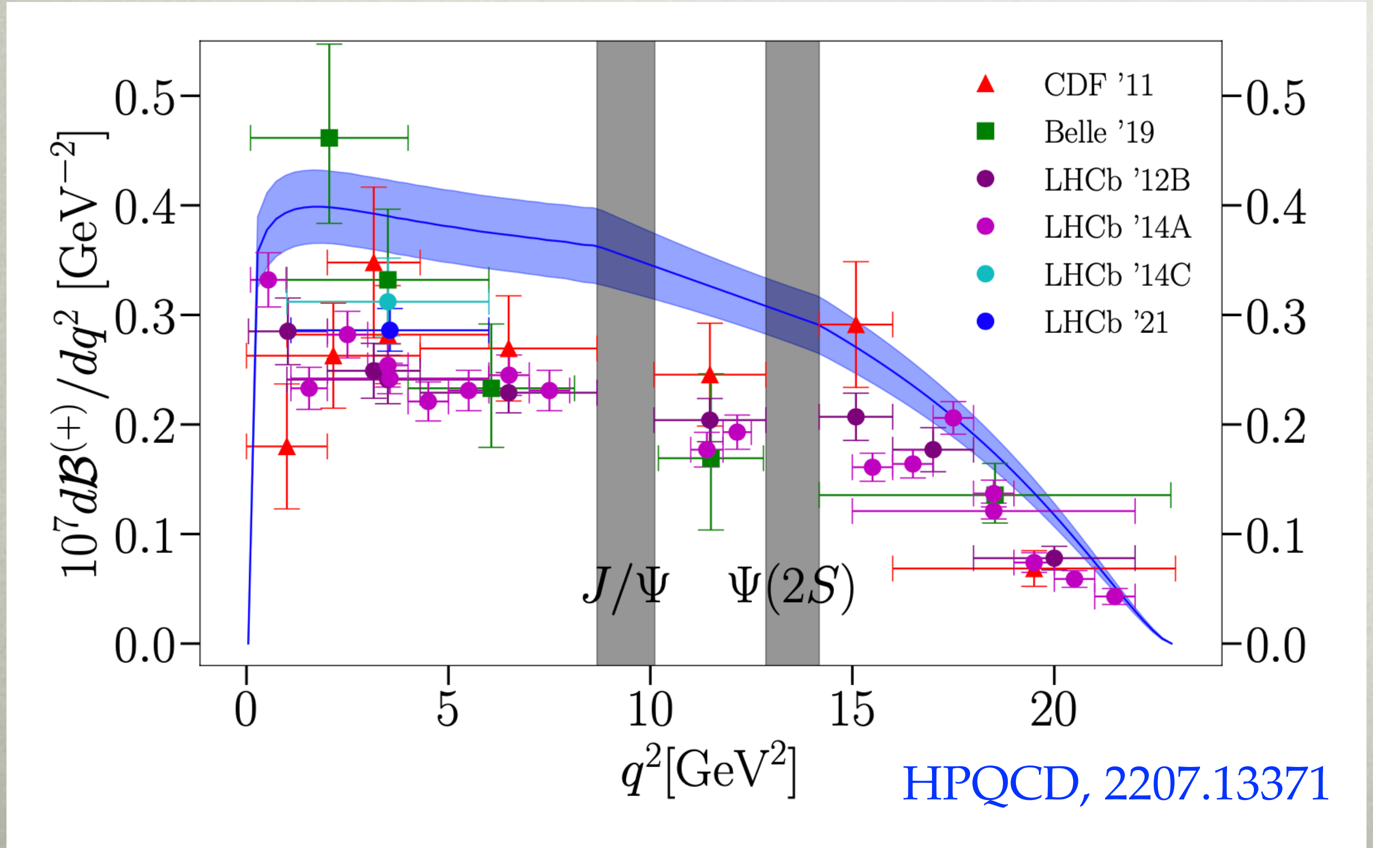
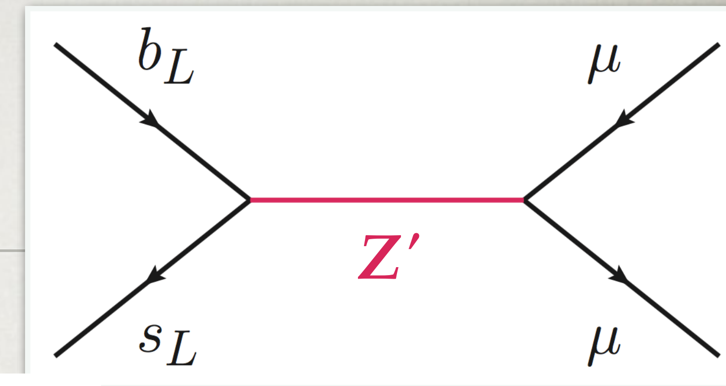
$b \to s\ell\ell$

- $b \to s\ell\ell$
  - discrepancies mainly in observables limited by theory (branching ratios)
  - at least some of these accessible on lattice
    - e.g., low recoil (large q^2) $Br(B \to K\ell^+\ell^-)$



HPQCD, 2207.13371

$b \to s\ell\ell$



- $b \to s\ell\ell$

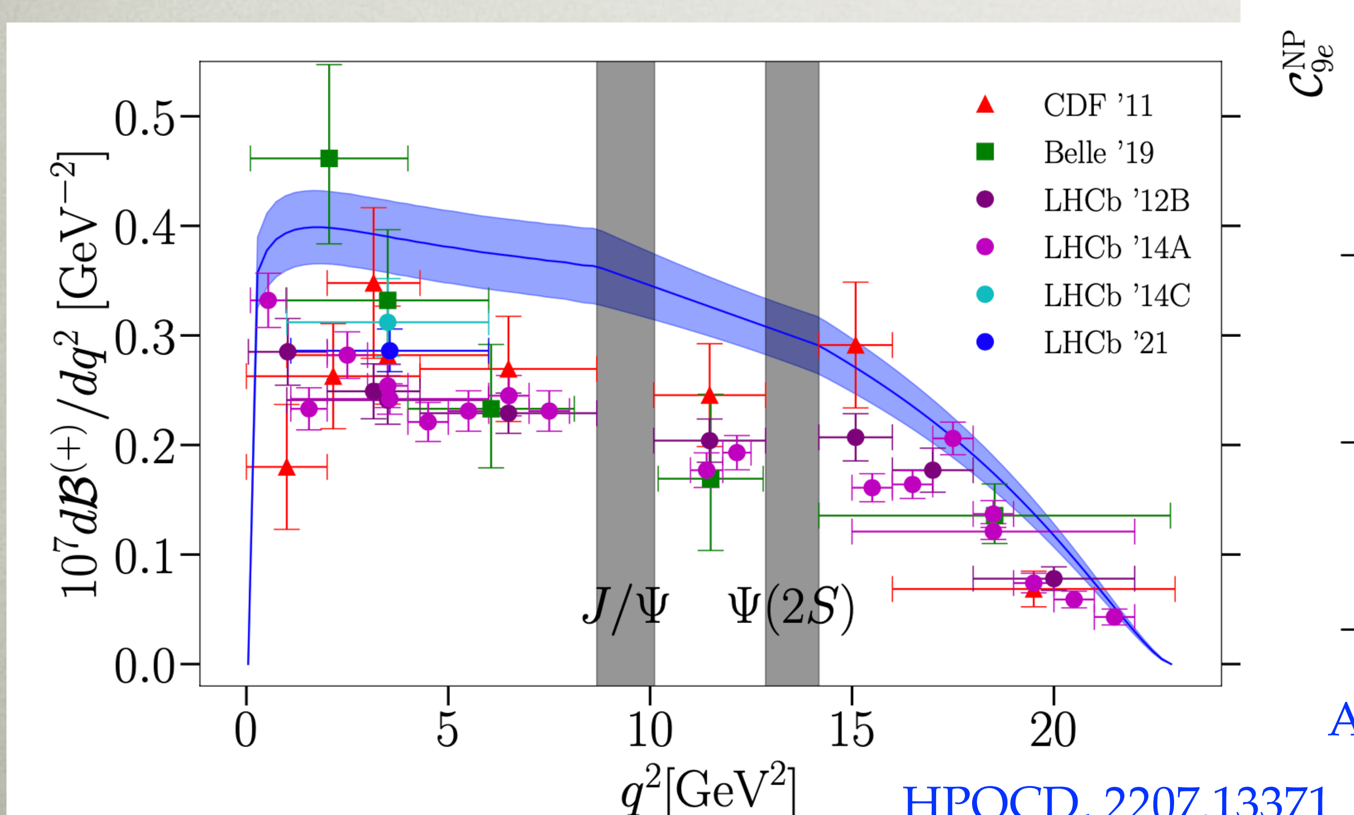
Wilson coefficients

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum (C_i \mathcal{O}_i + C_i' \mathcal{O}_i') + \text{h.c.}$$

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$
$$\mathcal{O}_9' = (\bar{s}\gamma_\mu P_R b)(\ell\gamma^\mu \ell)$$

theory (branching ra

- at least some of these
  - e.g., low recoil (lar



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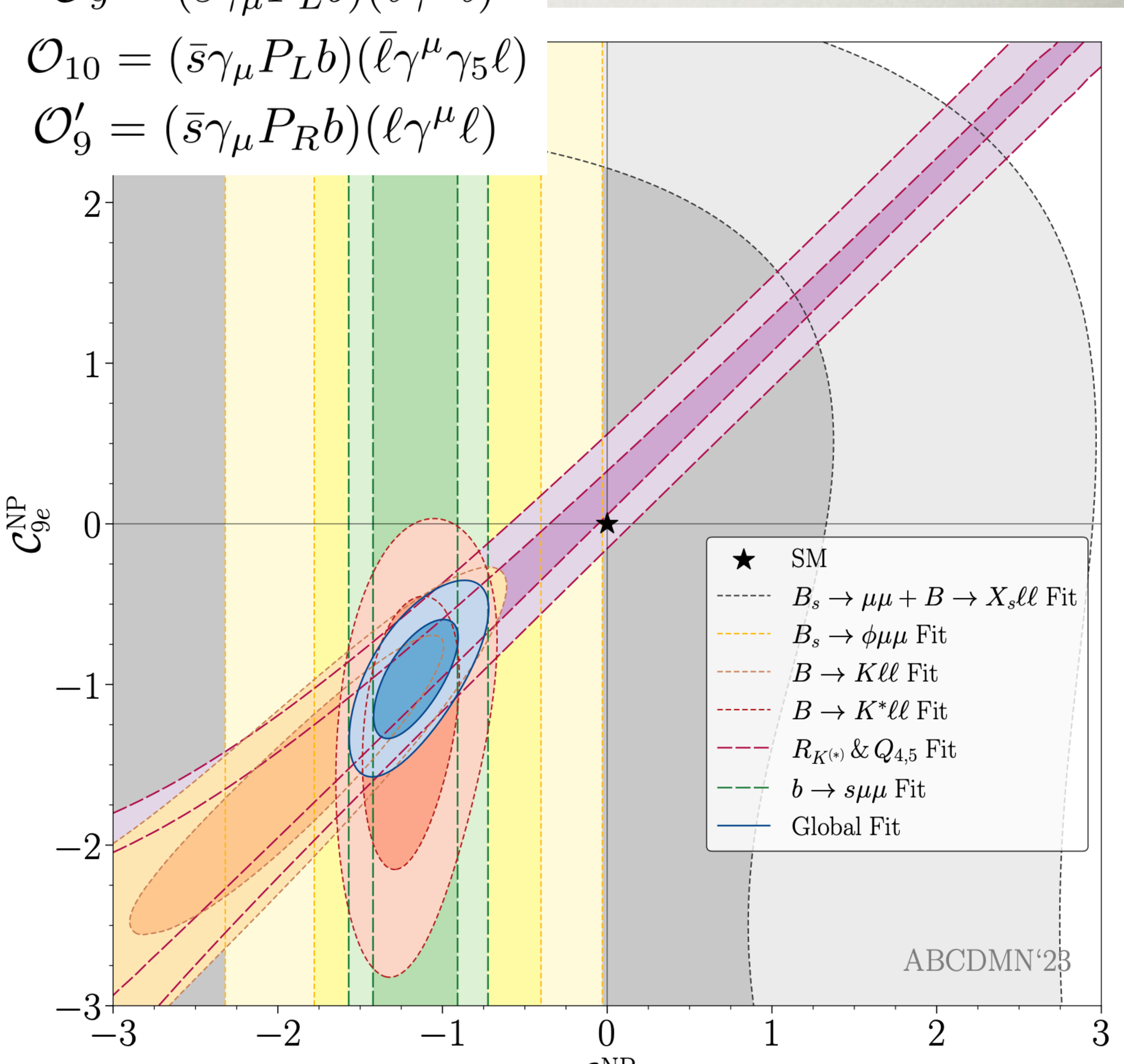
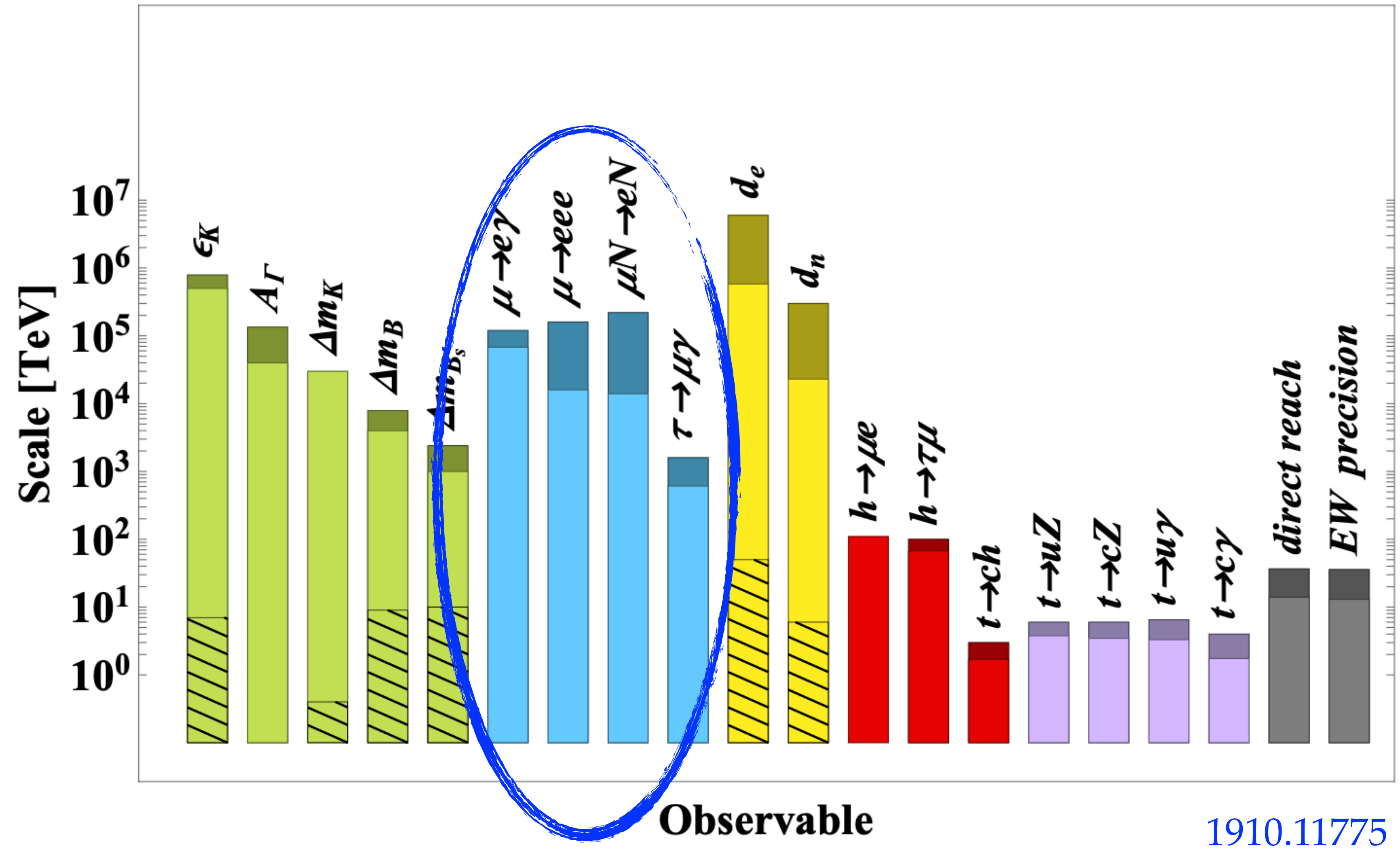


Alguero et al, 2304.07330

RARE MUON TRANSITIONS

see also talks by S. Banerjee on Mon,
S. Grant on Mon,
M. Mackenzie on Mon,
G. Pezzullo on Mon,
G. Papiri on Thu,
T. Gao on Thu



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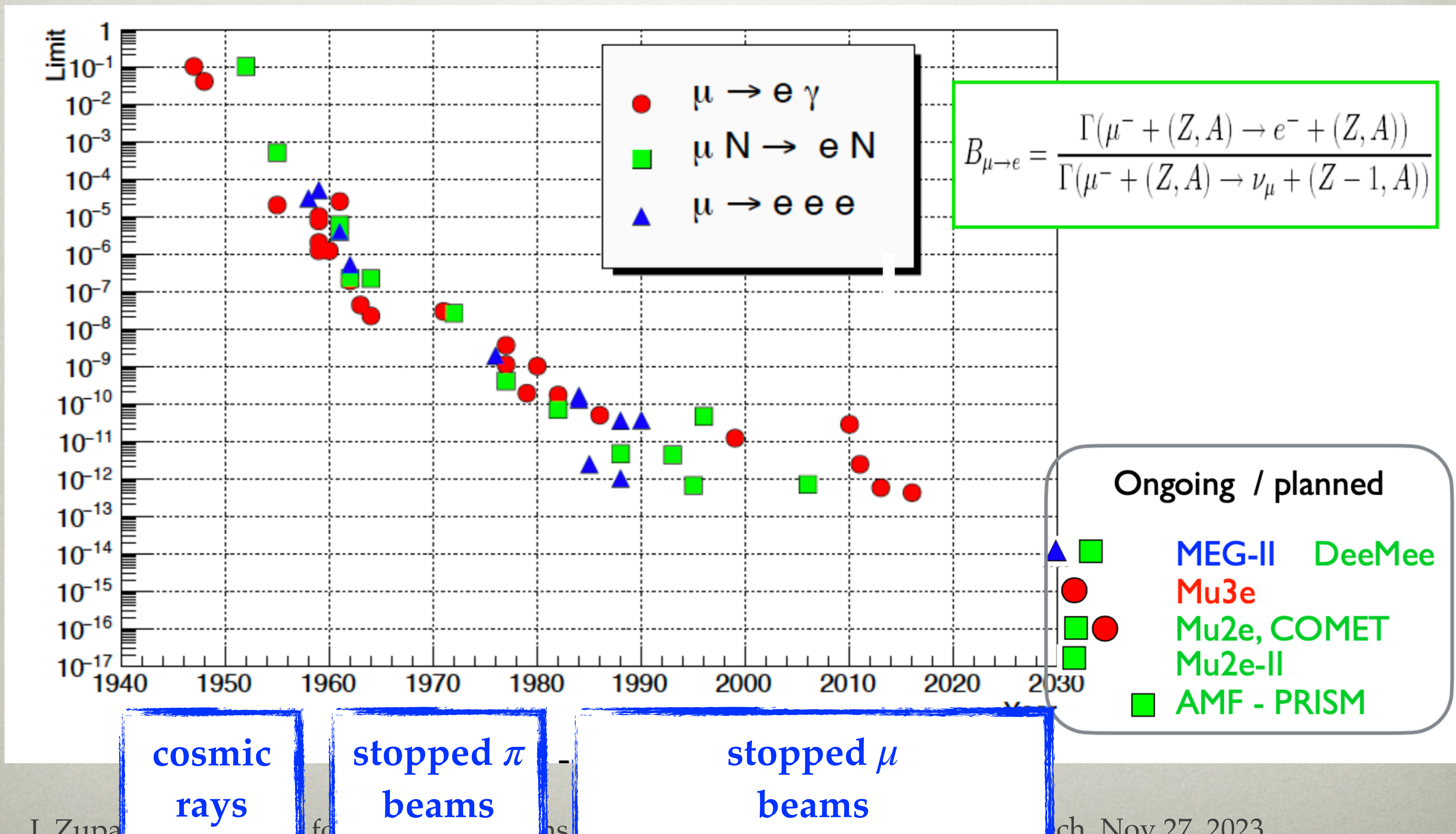
EXPERIMENTAL PROGRESS

- steady experimental progress since 1940s

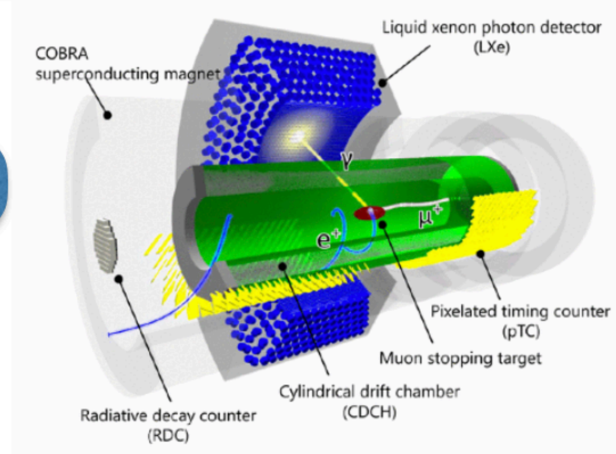


talk by Toshiyuki Iwamoto @ FPCP2020

cLFV experiments in the world

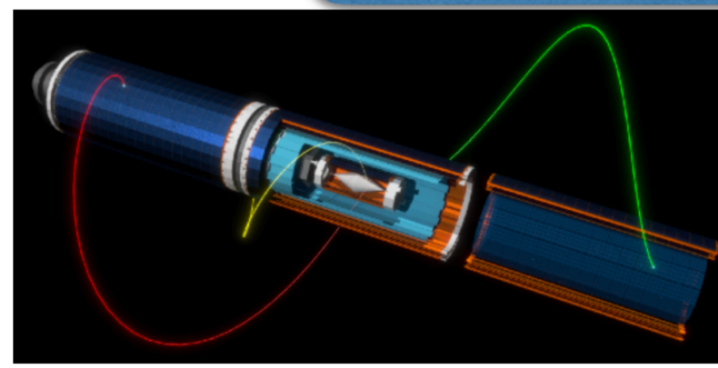
MEG II

$\mu^+ \to e^+\gamma$



Mu3e

$\mu^+ \to e^+e^+e^-$



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

BKG $\propto$ (Rate)^2

PSI

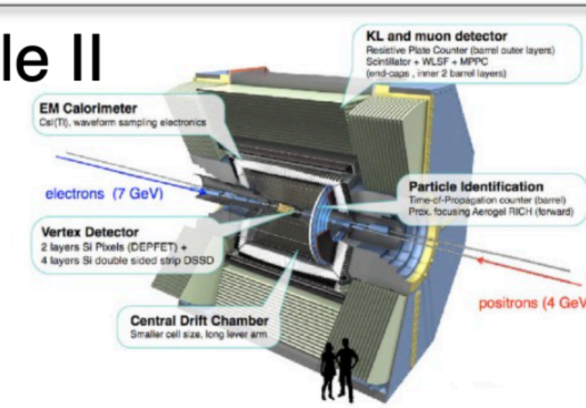
CERN

LHCb/ATLAS/CMS

$\tau \to 3\mu$, $\tau \to \mu\gamma$

KEK

Belle II

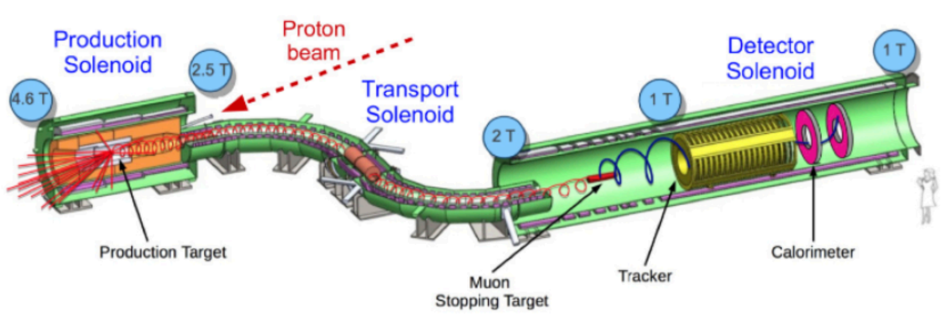


Fermilab

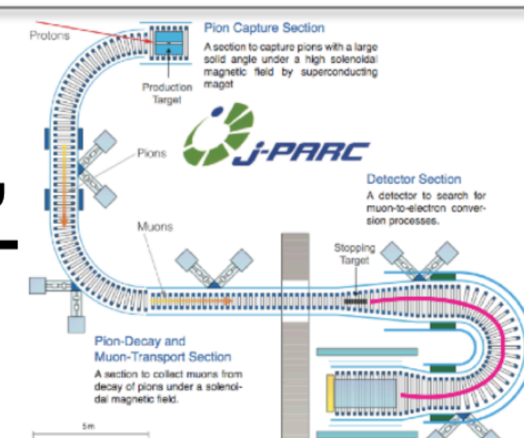
$\mu^- N \to e^- N$

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

COMPLEMENTARY PROBES

- complete list of dim 6 CLFV operators

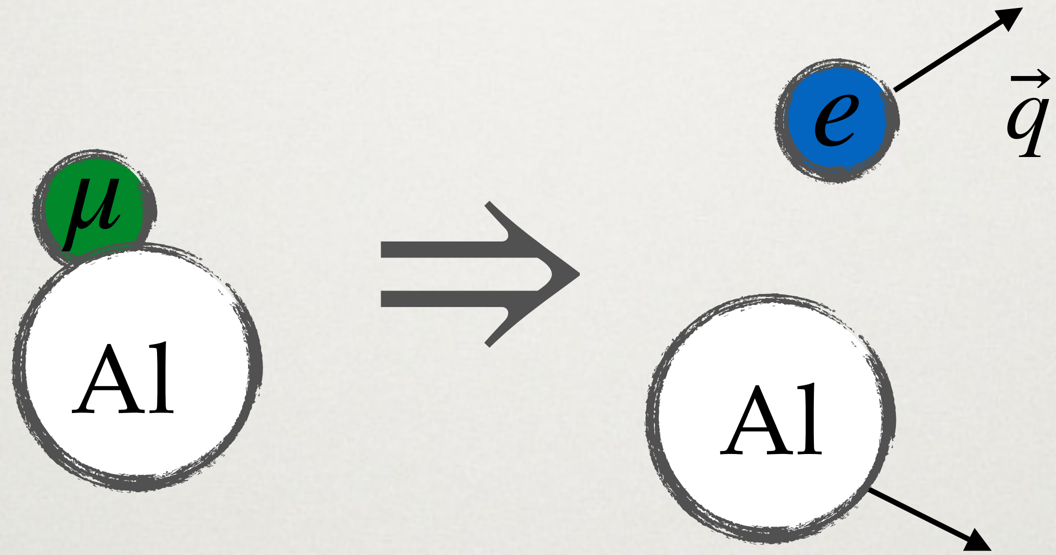
	4-leptons operators		Dipole operators
$Q_{\ell\ell}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$	Q_{eW}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\tau_I\Phi W^I_{\mu\nu}$
Q_{ee}	$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$	Q_{eB}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$
$Q_{\ell e}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{e}_R\gamma^\mu e_R)$		
	2-lepton 2-quark operators		
$Q^{(1)}_{\ell q}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$
$Q^{(3)}_{\ell q}$	$(\bar{L}_L\gamma_\mu\tau_I L_L)(\bar{Q}_L\gamma^\mu\tau_I Q_L)$	Q_{eu}	$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$
Q_{eq}	$(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar{L}^a_L e_R)(\bar{d}_R Q^a_L)$
$Q_{\ell d}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(1)}_{\ell equ}$	$(\bar{L}^a_L e_R)\epsilon_{ab}(\bar{Q}^b_L u_R)$
Q_{ed}	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(3)}_{\ell equ}$	$(\bar{L}^a_i\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}^b_L\sigma^{\mu\nu}u_R)$
	Lepton-Higgs operators		
$Q^{(1)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_L\gamma^\mu L_L)$	$Q^{(3)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{L}_L\tau_I\gamma^\mu L_L)$
$Q_{\Phi e}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_R\gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar{L}_L e_R\Phi)(\Phi^\dagger\Phi)$

probed by
$\mu \to e\gamma$
$\mu \to 3e$
$\mu \to e$

J. Z

$\mu \to e$ conversion

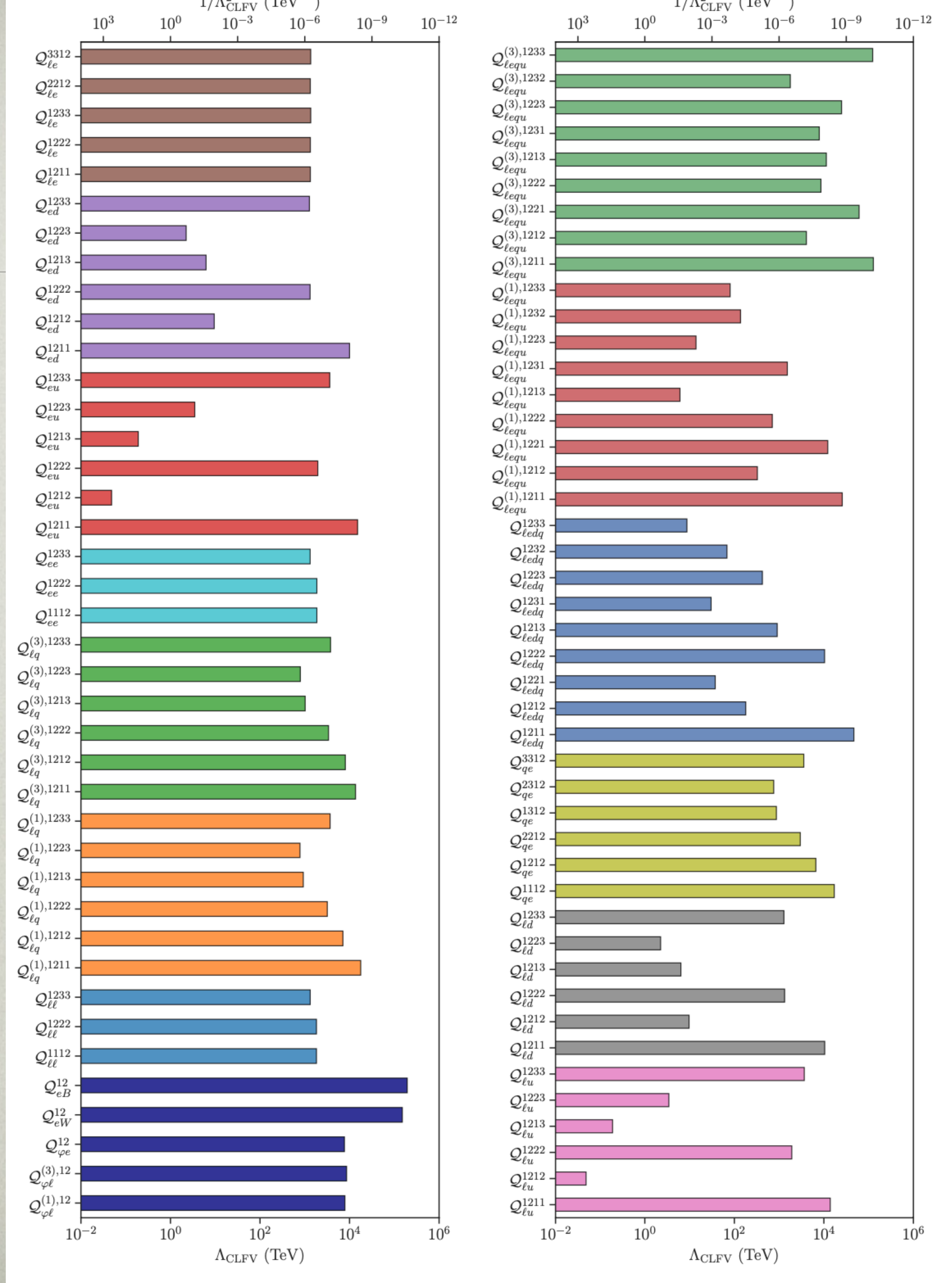
- initial state: μ^- in 1s orbital



- a theory challenge: predictions require nuclear physics
- there is a small parameter $|\vec{q}| \sim \mathcal{O}(100\,\mathrm{MeV}) \ll m_N$
  - can use EFT techniques (non-relativistic EFT / chiral EFT)
  - **MuonBridge** code

see talk by T. Menzo on Tue

Haxton, McElvain, Menzo, Rule, JZ, 2405.nnnn



ION

$\vec{q}$

e nuclear physics

0 MeV) $\ll m_N$

istic EFT / chiral EFT)

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, McElvain, Menzo, Rule, JZ, 2405.nnnn

SEARCHING FOR LIGHT NEW PHYSICS

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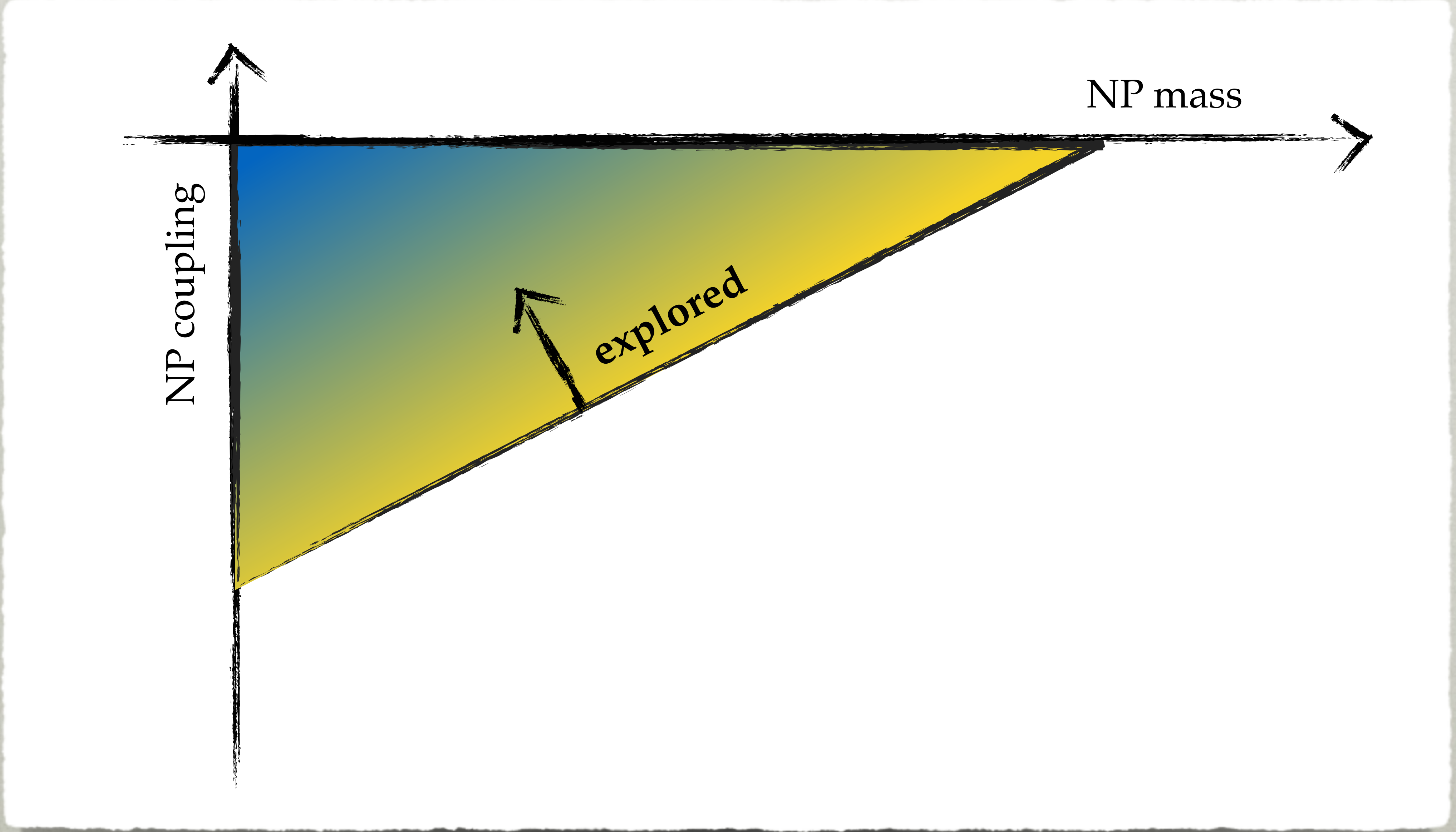
- heavy new physics only part of the NP parameter space
- light particles: a window to high UV dynamics



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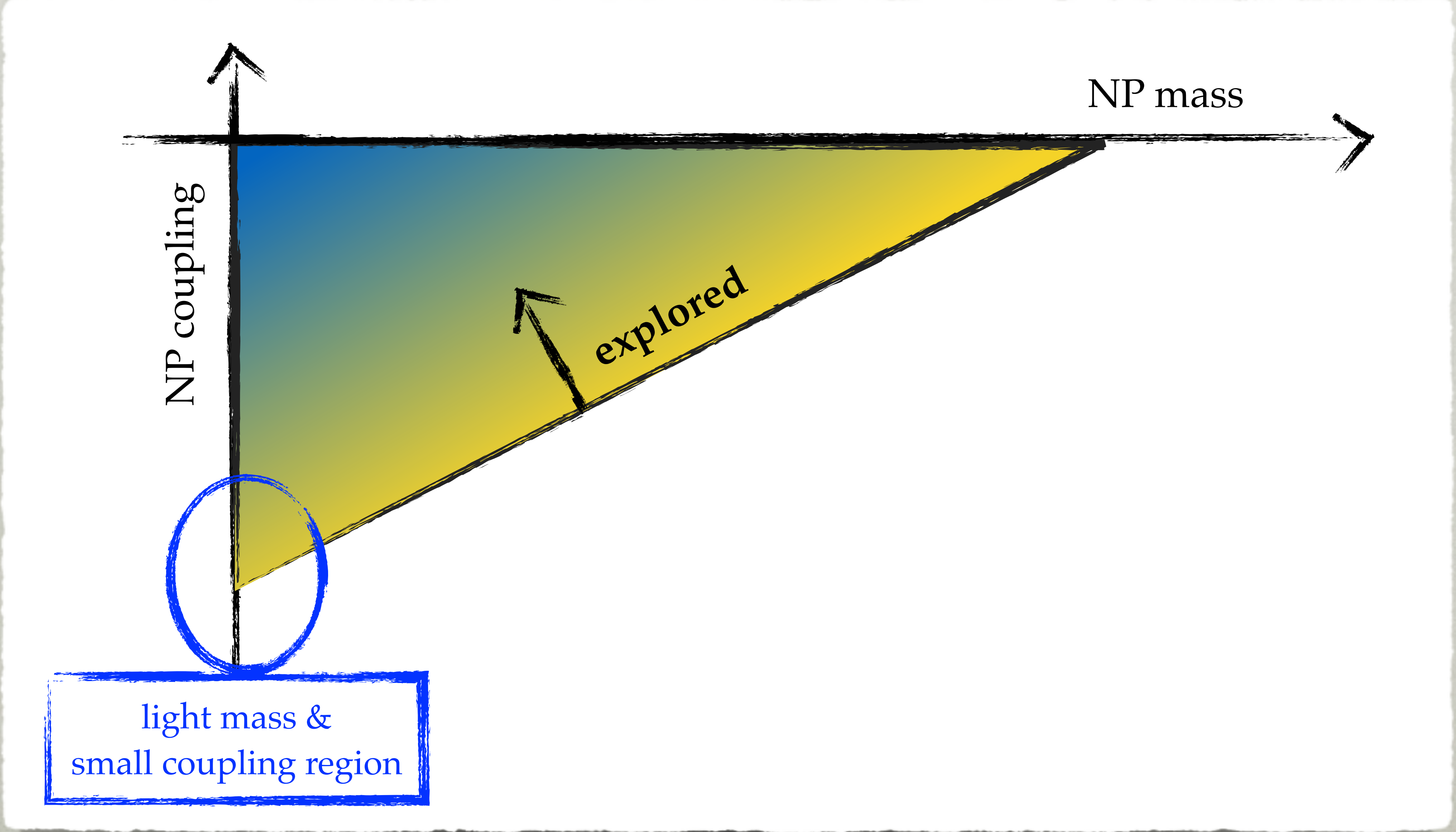

SEARCHING FOR LIGHT NEW PHYSICS

- heavy new physics only part of the NP parameter space
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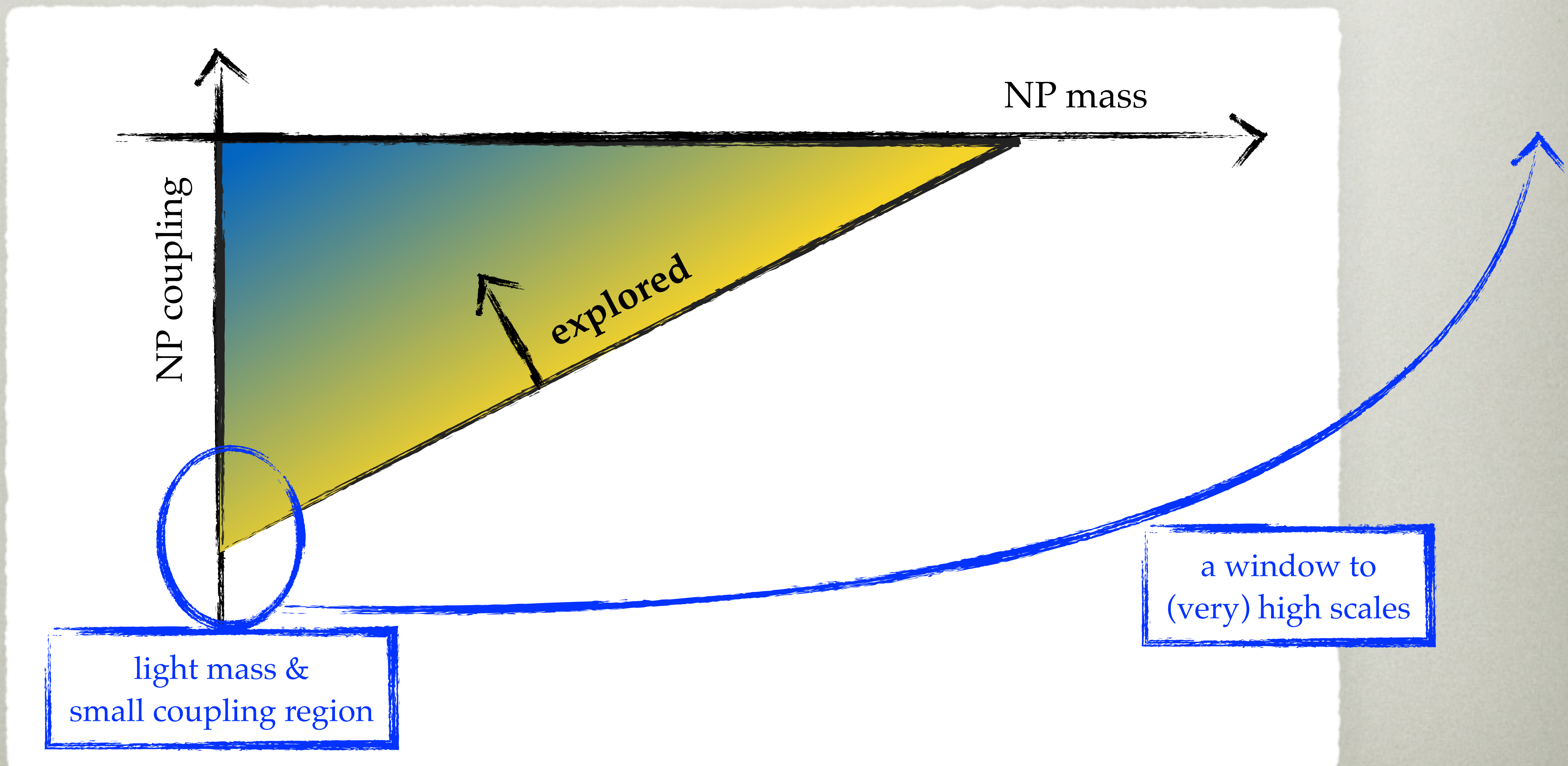
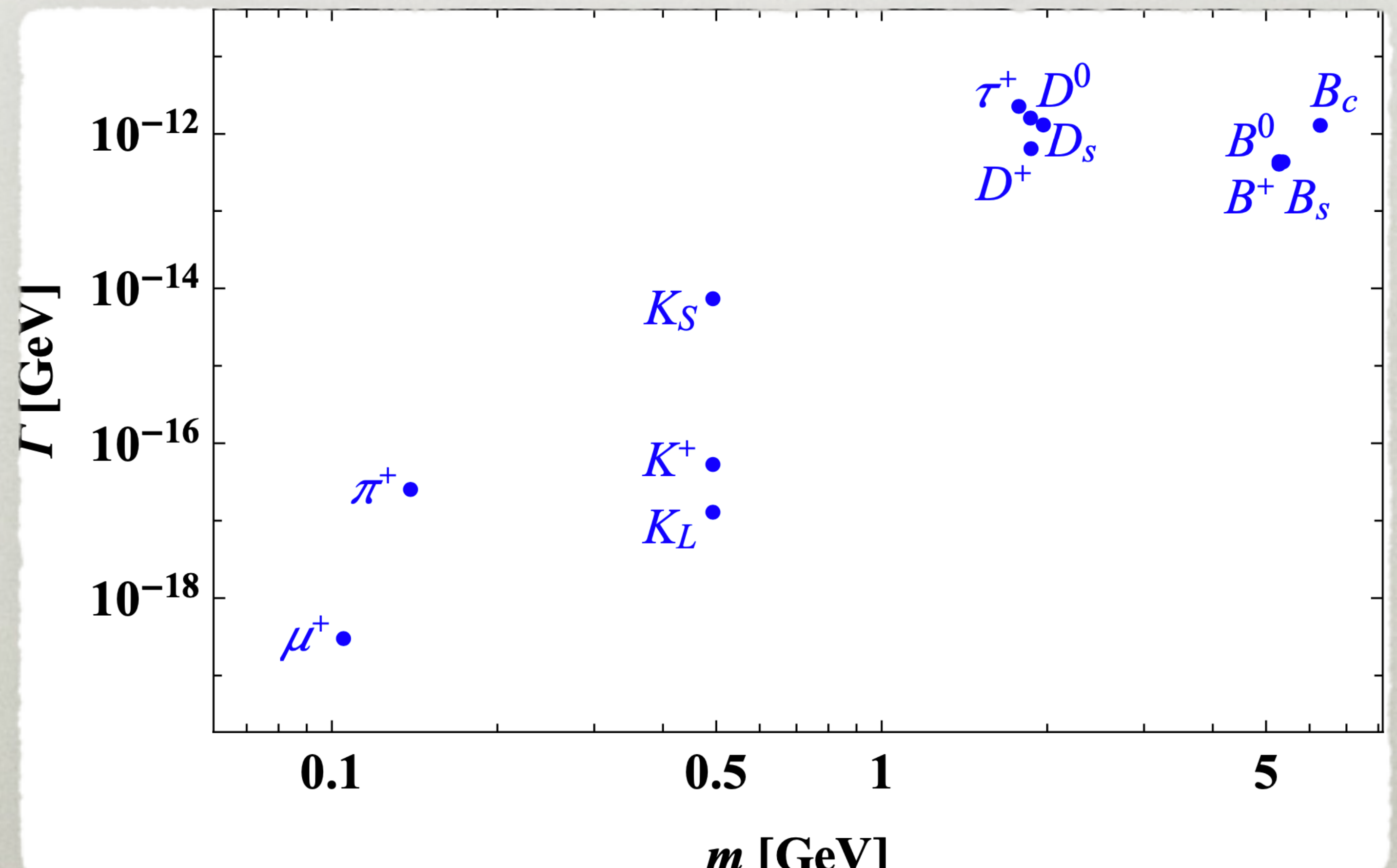


FLAVOR PORTAL

- example of a flavor portal: dim 5 op. $\partial_\alpha\varphi(\bar{e}\gamma^\alpha\gamma_5\mu)/f_a \Rightarrow$ $Br(\mu \to e\varphi) \propto (m_W^2/f_a m_\mu)^2$
- searching for $K \to \pi X$, $\mu \to eX$, $\pi \to X$ decays expect to reach very high UV scales

see also talks by Lingfeng Li on Wed,
A. Rashed on Thu,
S. Roy on Thu



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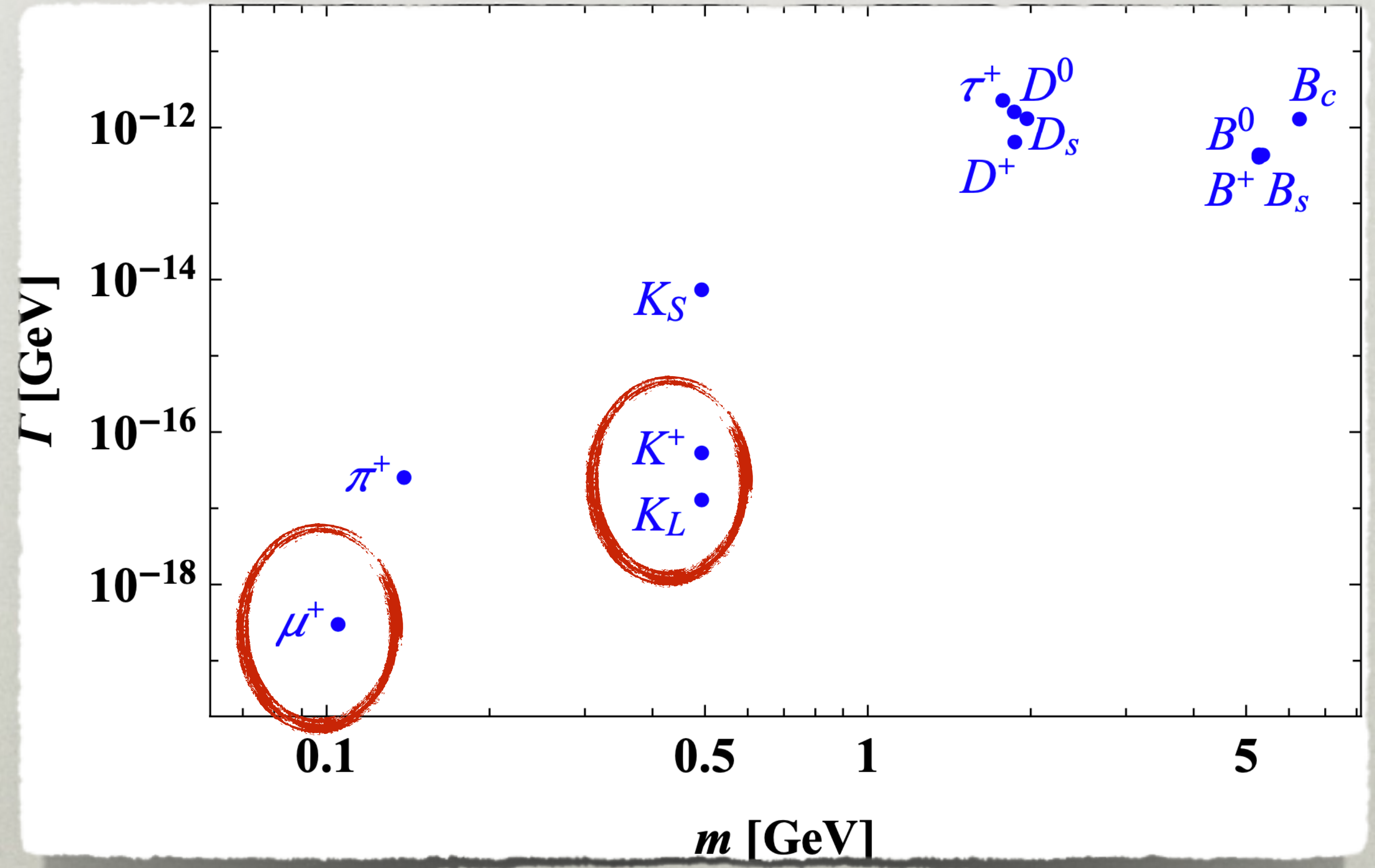
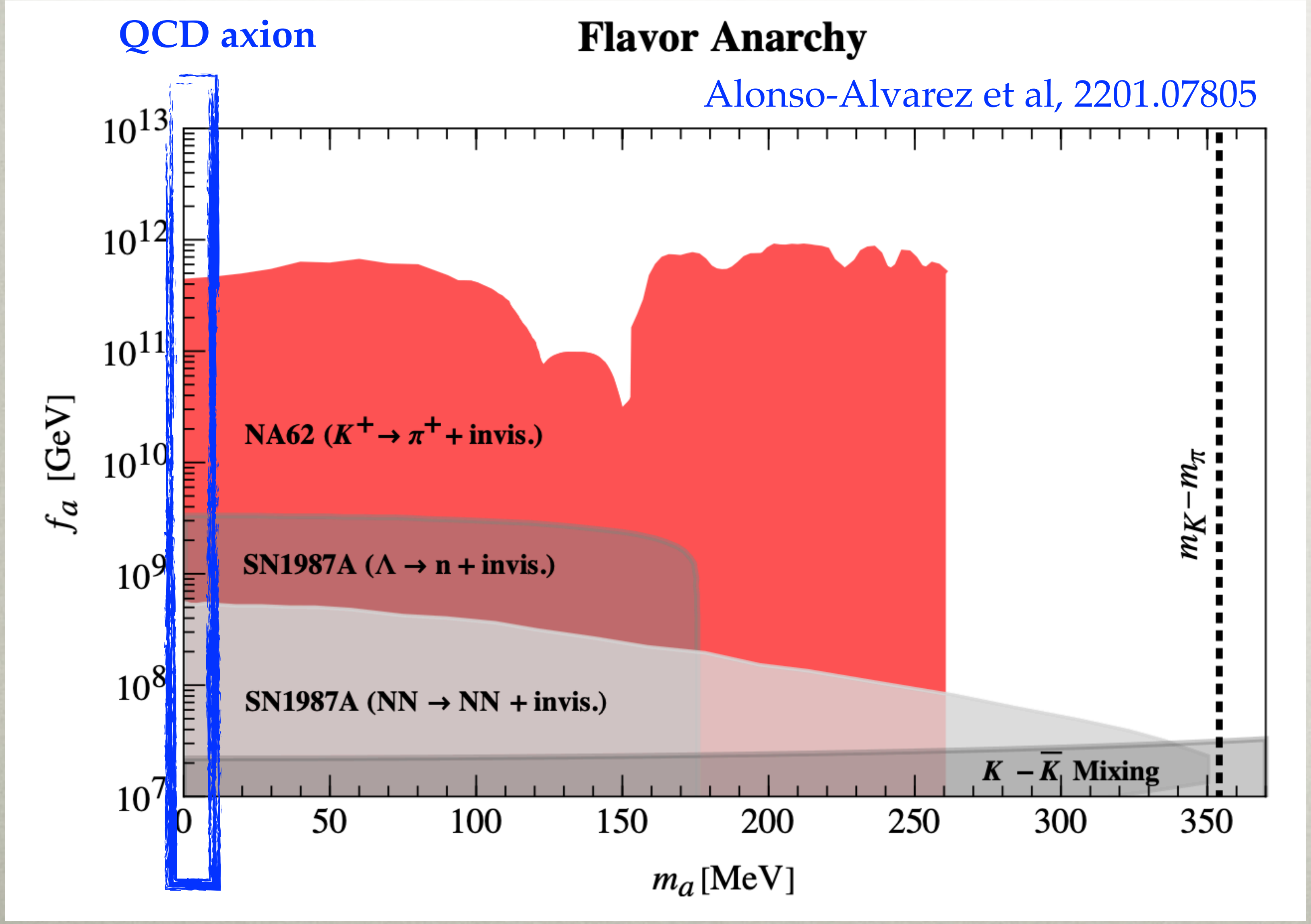


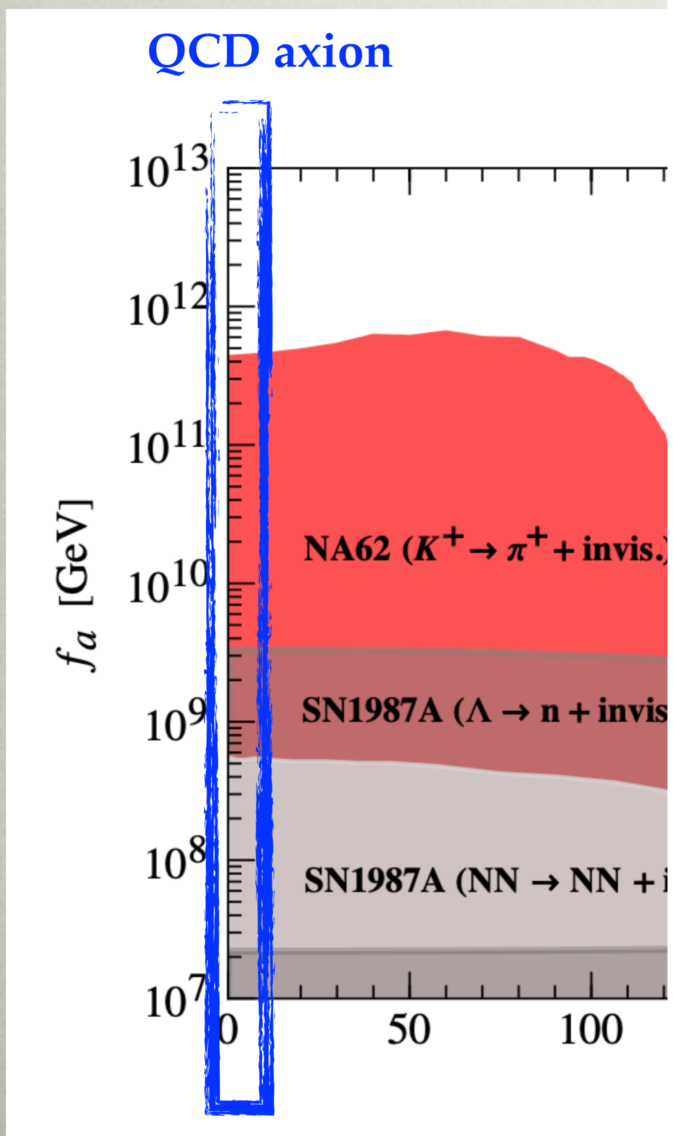
FLAVORFUL QCD AXION

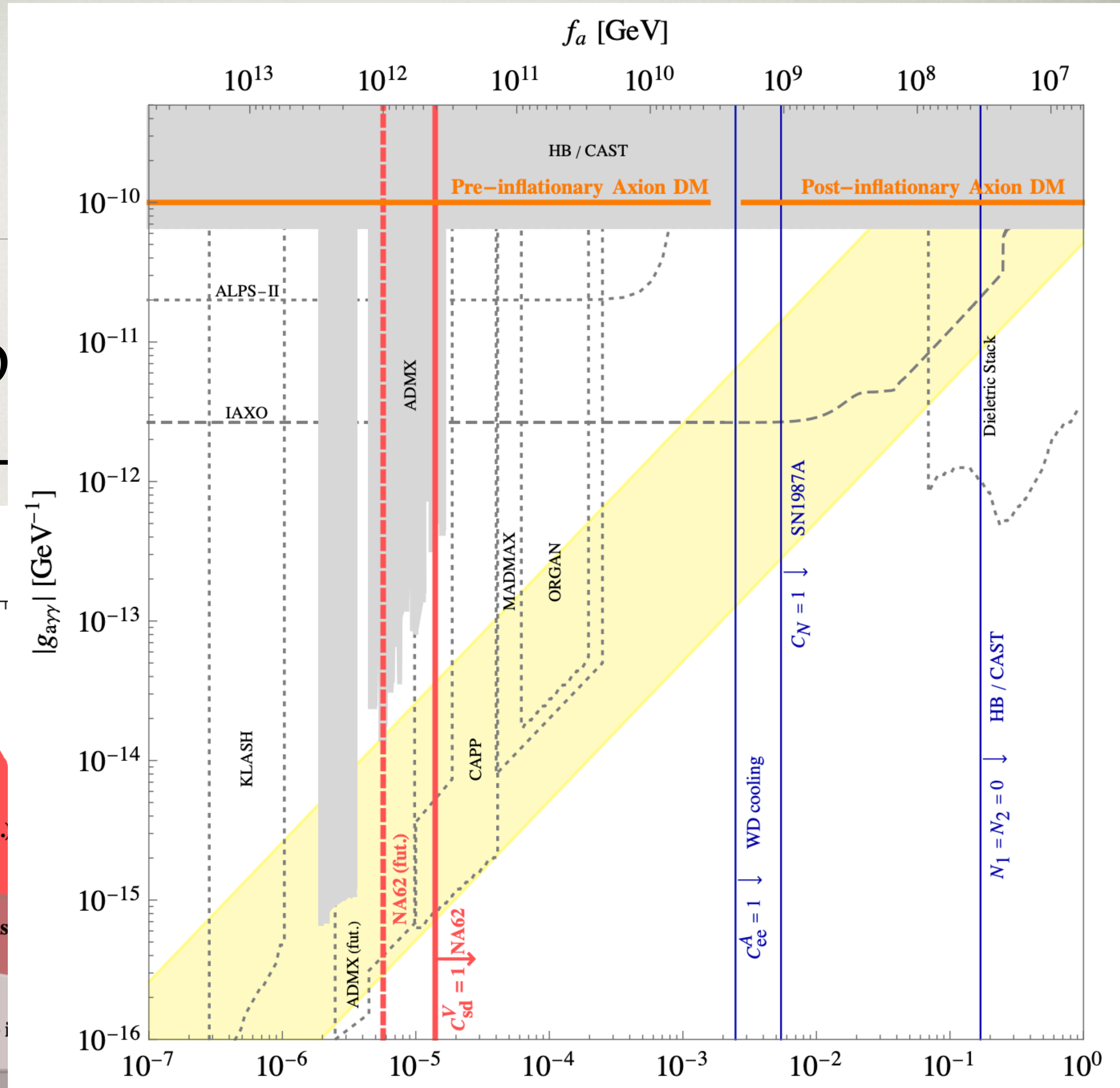
- if QCD axion has $\partial_\mu a(\bar{d}\gamma^\mu\gamma_5 s)/f_a$ coupling $\Rightarrow K^+ \to \pi^+ a$ decay a very sensitive probe



- if QCD

$\Rightarrow K^+$ -





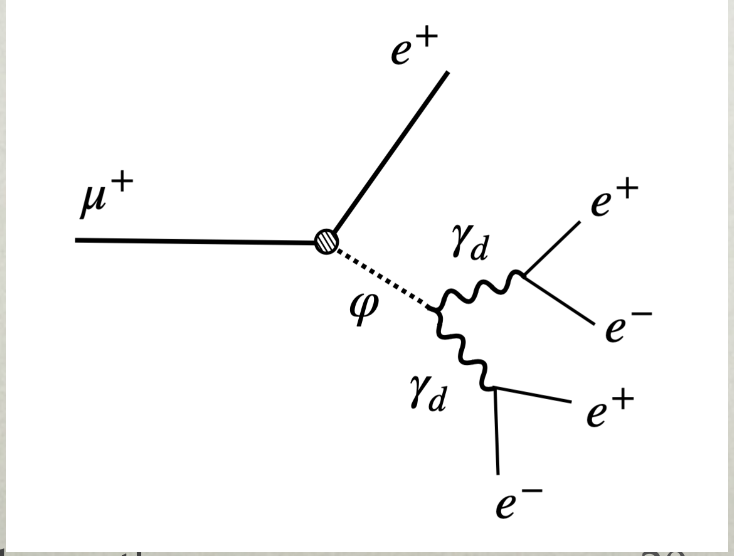
Alonso-Alvarez et al, 2201.07805

$\mu \to 5e$

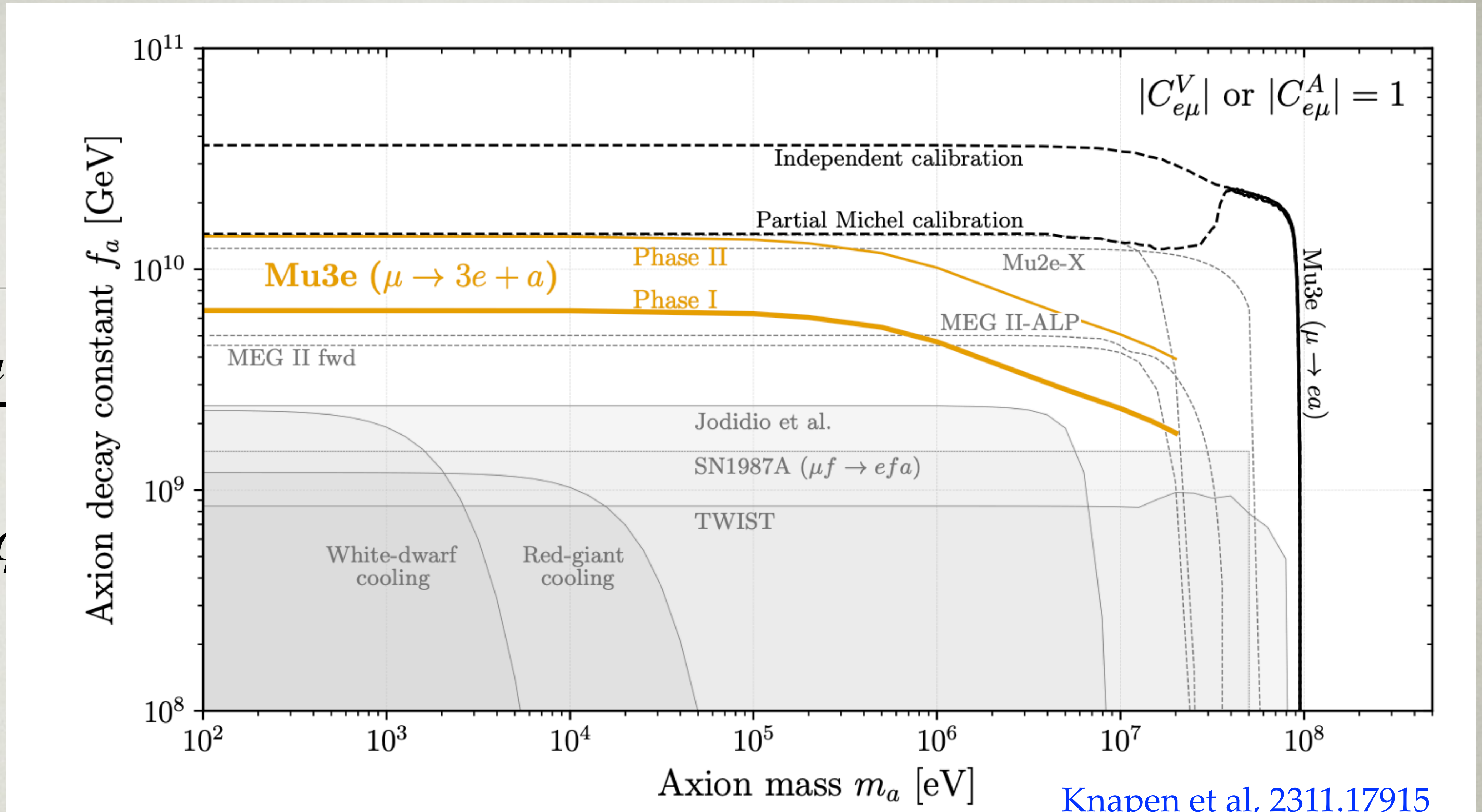
see also a talk by K. Langhoff on Mon

- if $\frac{m_\mu}{\Lambda}\phi(\bar{e}\mu)$ coupling $\Rightarrow$ mediates $\mu \to e\varphi$
  - if φ QCD axion $\Rightarrow$ escapes the detector $\mu \to e + \text{inv}$
    - MEG-II, Mu3e, Mu2e-X, COMET-X can search for it
  - if φ can decay $\Rightarrow$ sensitivity to even higher scales
    - example: $\mu \to 5e$ can probe $f_a \gtrsim 10^{13}$GeV

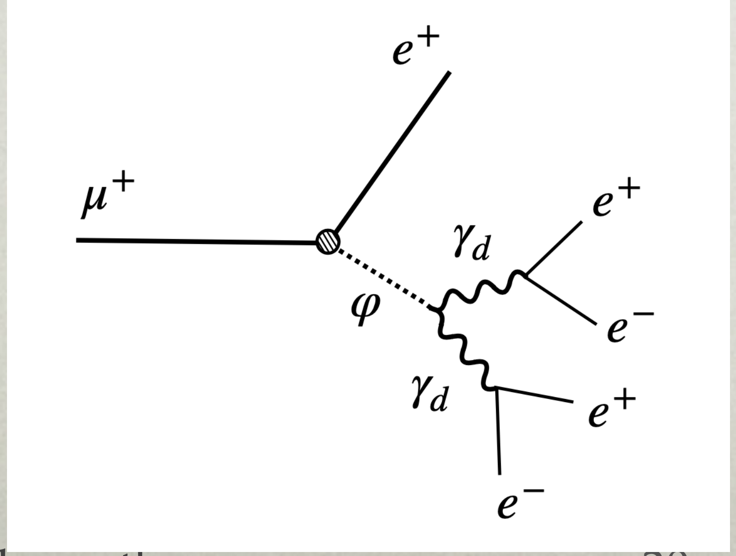
Hostert, Menzo, Pospelov, JZ, 2306.15631



- if $\frac{m_\mu}{\Lambda}$
  - if φ
    -
  - if φ can decay → sensitivity to even higher scales
    - example: $\mu \to 5e$ can probe $f_a \gtrsim 10^{13}$GeV



Knapen et al, 2311.17915



Hostert, Menzo, Pospelov, JZ, 2306.15631

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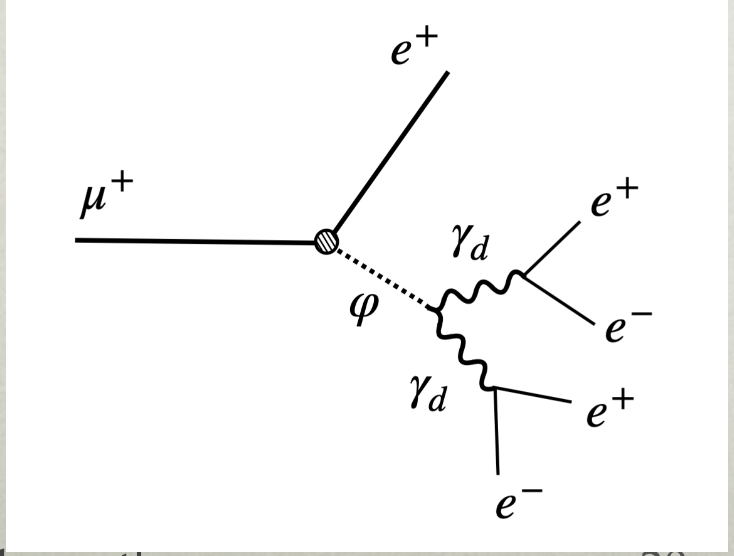
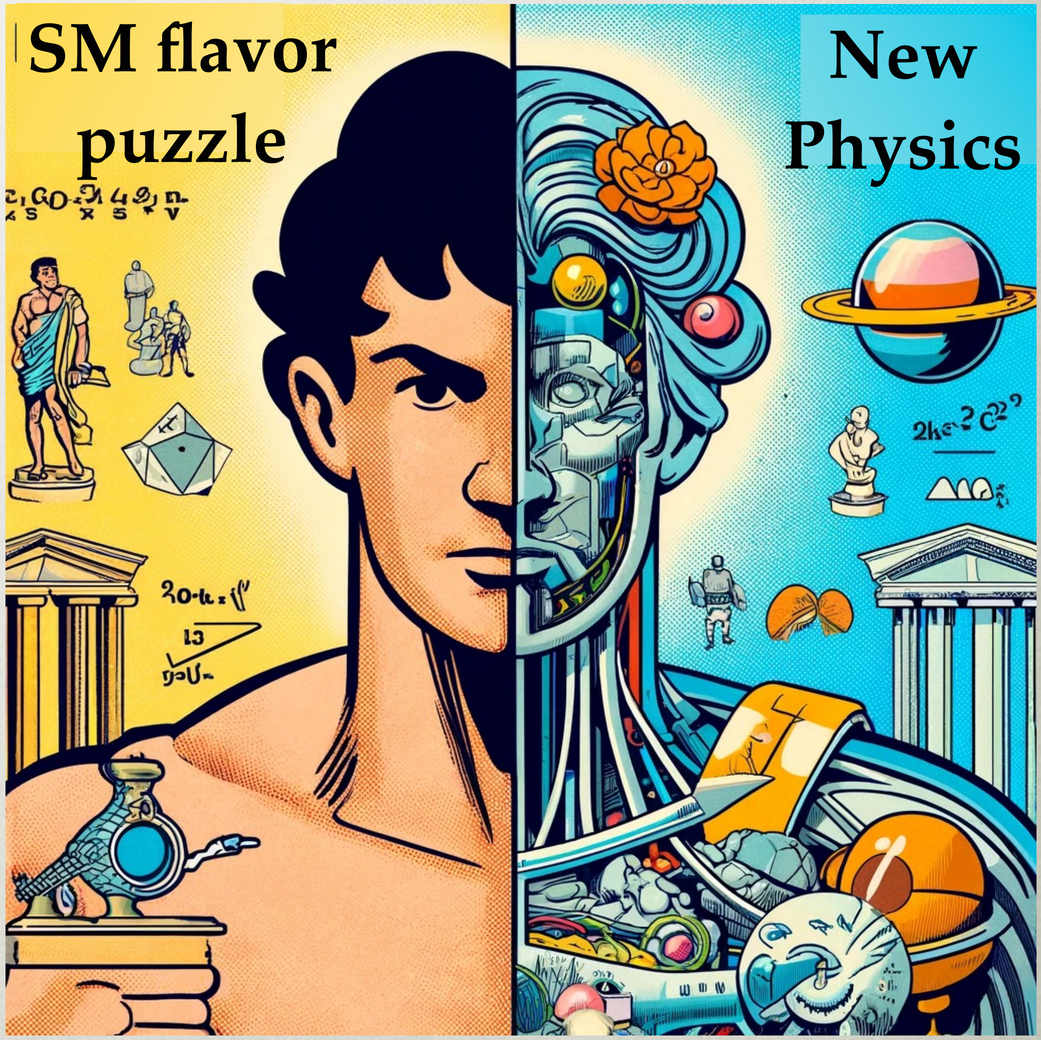


Hostert, Menzo, Pospelov, JZ, 2306.15631

STANDARD MODEL FLAVOR PUZZLE

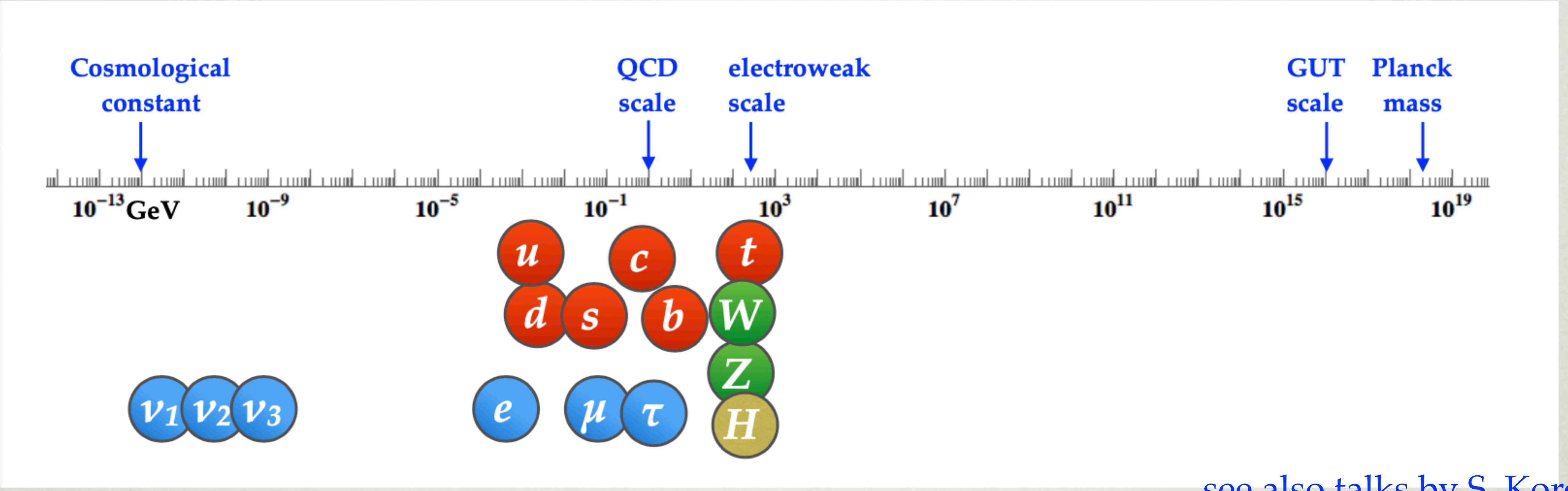
TWO FACES OF FLAVOR PHYSICS

- no flavor changing neutral currents in the SM
  - ⇒ flavor transitions sentive 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



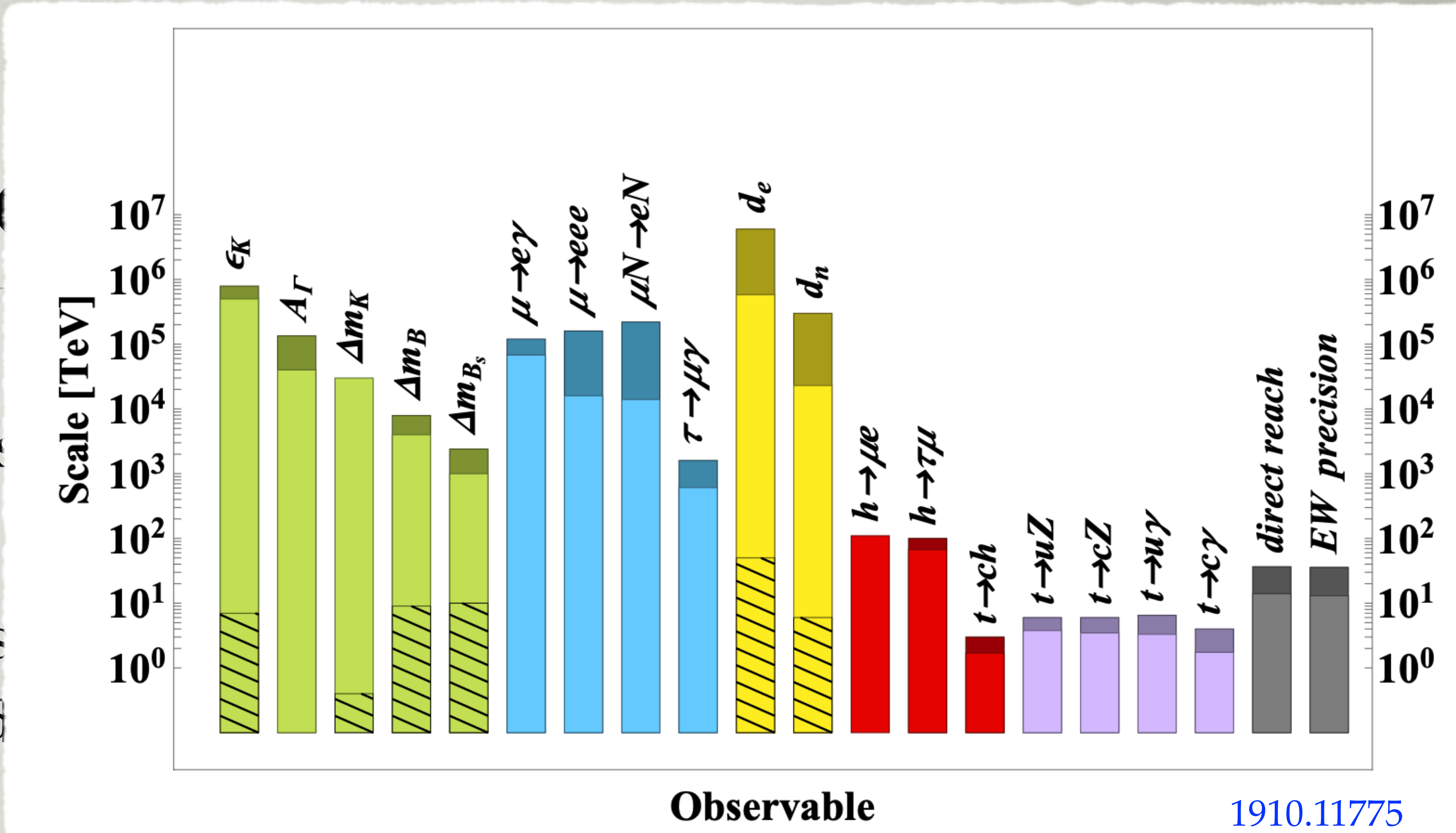
see also talks by S. Koren on Thu,
M. Mellors on Tue,
J. Goldman on Mon,
M.-S. Liu on Tue,
Y. Georis on Tue

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

FLAVOR MODEL BUILDING

- new states predicted: flavons, KK modes, vector-like quarks...
  - bounds on these range from TeV to 10^7TeV, depending on FV structure
  - how to search for these ?
- directly at HL-LHC, FCC-ee, CEPC,... see talk by M. Szewc on Thu
- indirectly
  - using FCNC probes, EDMs
  - also through gravitational waves, if strong first order phase transitions or changed cosmology

FLAV



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  quarks...
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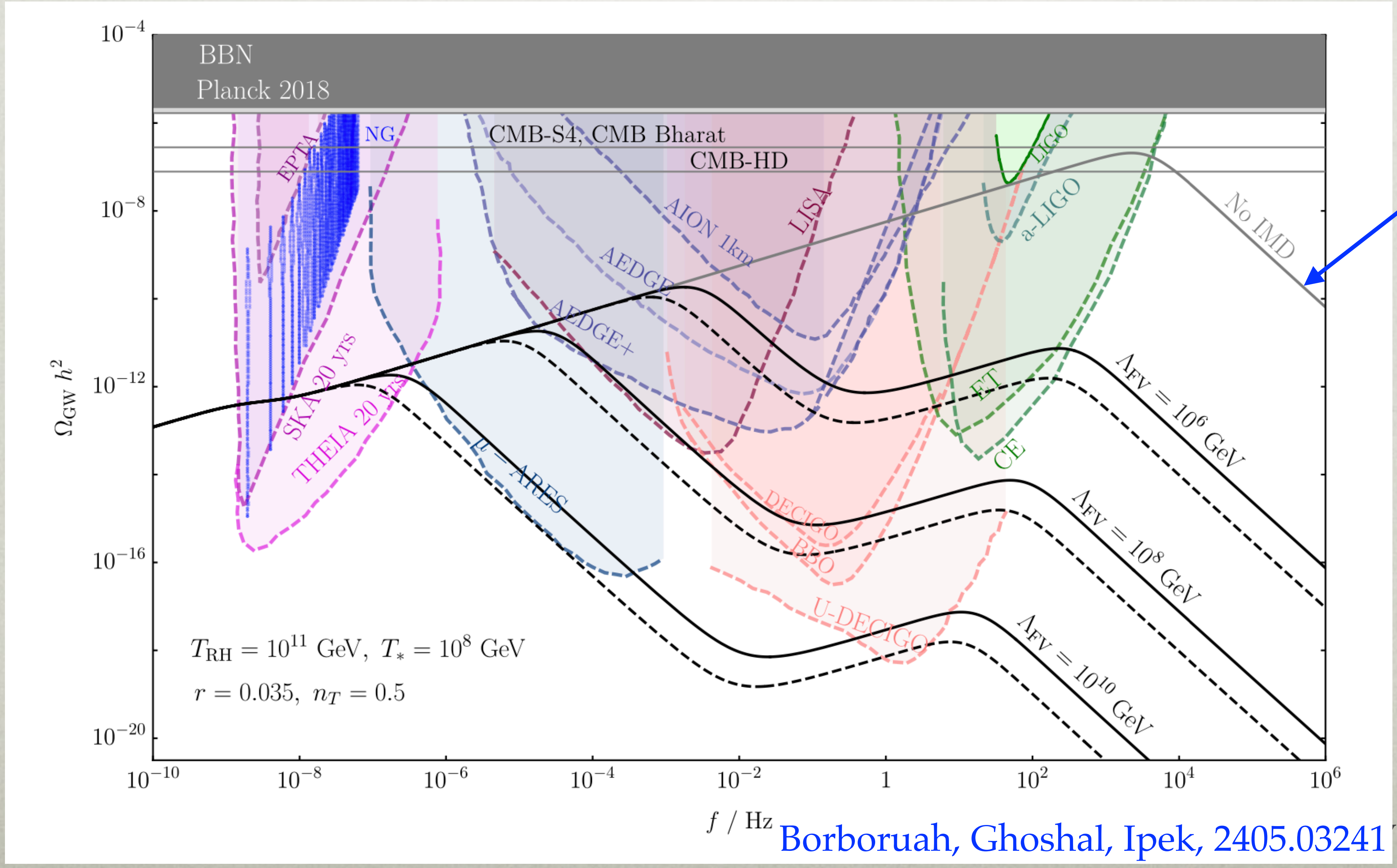
FLAVOR PHYSICS AND GRAVITATIONAL WAVE PHYSICS

- example no. 1: suppression of GW due to era of flavon domination

$$\mathcal{L} \supset \left(\frac{v_S + S}{\Lambda_{\rm FV}}\right)^{n_i} \bar{e}^i_R \phi^* \ell^i_L + \text{h.c.}\,,$$

see talk by Borboruah on Wed



no flavon

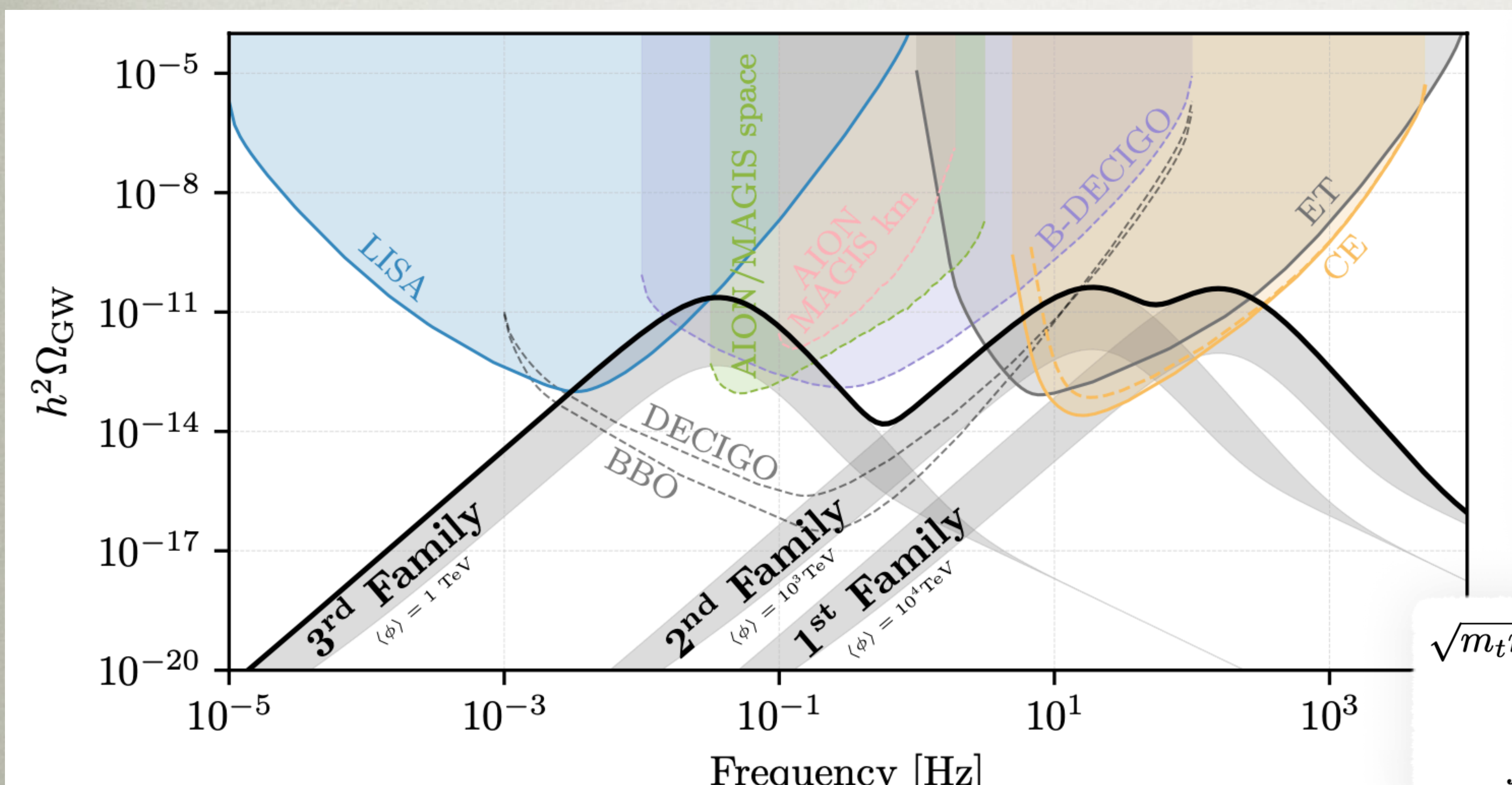
m_S = 2 TeV

m_S = 1 TeV

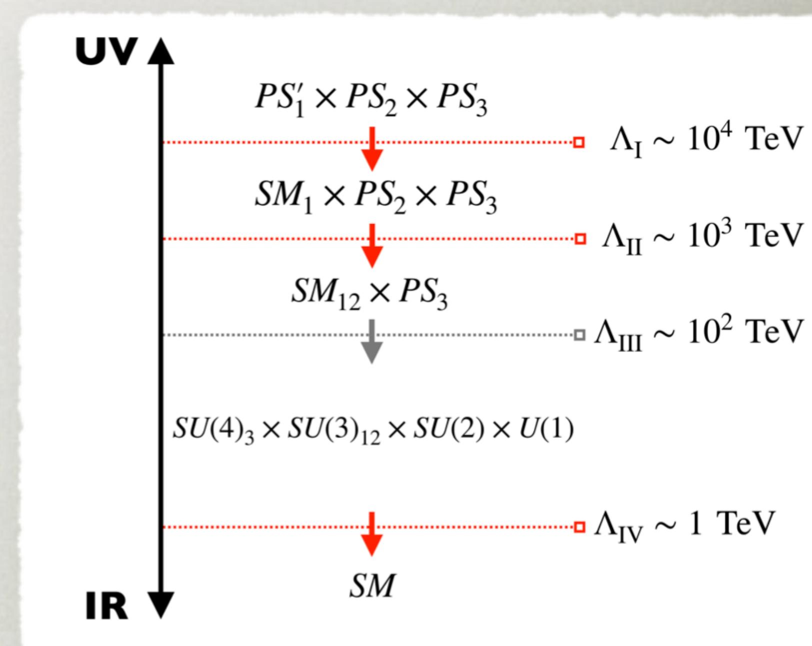
Borboruah, Ghoshal, Ipek, 2405.03241

FLAVOR PHYSICS AND GRAVITATIONAL WAVE PHYSICS

- example no. 2: the Triglav* signature from a hierarchy of spontaneous symmetry breakings



Greljo, Opferkuch, Stefanek, 1910.02014



$$\begin{array}{ccccc} \sqrt{m_t m_b} & : & \sqrt{m_s m_c} & : & \sqrt{m_u m_d} \\ 1 & : & 10^{-2} & : & 10^{-4} \\ f_{\rm LISA}^{-1} & : & \dots & : & f_{\rm ET}^{-1}\,. \end{array}$$

*Triglav = "Three heads" is the highest mountain in Slovenia, and has three peaks

CONCLUSIONS

- flavor physics a sensitive probe of UV physics
  - parametrically enhanced sensitivity if decays to light states: can probe QCD axion
- expected experimental and theoretical progress on current anomalies

BACKUP SLIDES

LIGHT NEW PHYSICS ⇒ PROBE OF HIGH SCALES

- rare decays into a light state, X, e.g., K → πX or μ → eX,
  - exquisite probes of UV physics
- parametric gains compared to probing NP through dim-6 ops
  - the reason is that the SM decay widths are power suppressed $\Gamma_\ell \propto m_\ell^5/m_W^4$
- if light NP couples through dim 4 op with mixing angle $\theta \Rightarrow$ $\Gamma(K \to \pi\varphi) \propto \theta^2 m_K \Rightarrow Br(K \to \pi\varphi) \propto \theta^2 (m_W/m_K)^4$
- if through dim 5 op. suppressed by $1/f_a \Rightarrow$ $Br(\mu \to e\varphi) \propto (m_W^2/f_a m_\mu)^2$
- no such $1/m_\mu$ or $1/m_K$ enhancement for dimension 6 couplings $Br(\mu \to 3e) \propto (m_W/\Lambda)^4$

TOWER OF EFTs FOR $\mu \to e$