ANOMALY FREE FROGGATT-NIELSEN MODELS OF FLAVOR

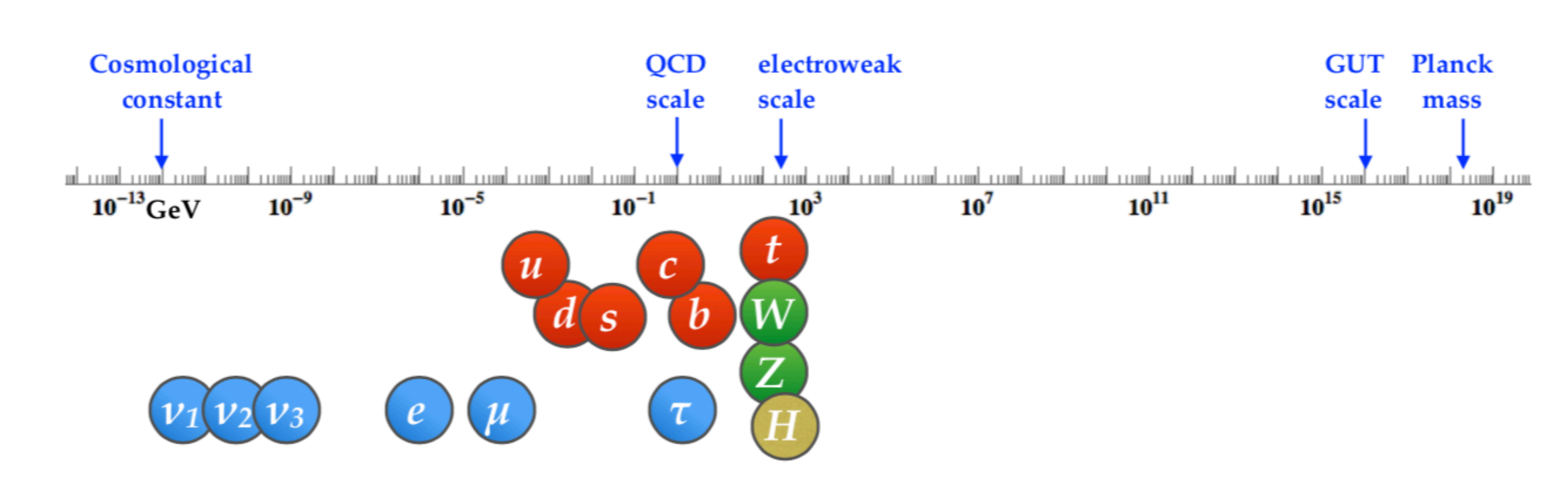
Jure Zupan
u. of cincinnati

based on Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040
Alonso, Carmona, Dillon, Kamenik, Martin Camalich, JZ, 1807.09792
Smolkovic, Tammaro, JZ, 1907.10063

HEP seminar, BNL, Feb 26 2020

STANDARD MODEL FLAVOR PUZZLE

- why are fermion masses so hierarchical?
- an explanation of mixing patterns?



SM flavor puzzle

- several solutions to the SM flavor puzzle
  - Froggatt-Nielsen models
  - extra dimensional RS models
  - partial compositness
- in all cases important constraints from flavor observables
- some predict states at ~TeV

IN THIS TALK

- anomaly free FN models
  - gauged, pheno of $Z's$
  - not gauged + flavons irrelevant
    - "clockwork flavor" model
- traditional FN models
  - axiflavon

TRADITIONAL FN MODELS

TRADITIONAL FN SOLUTION TO THE FLAVOR PUZZLE

Froggatt, Nielsen, NPB 147, 277 (1979),...

- Large hierarchies in quark + lepton masses and in CKM matrix
  - can be addressed via horizontal $U(1)_{FN}$ symmetry
  - SM LH and RH fermions have different $U(1)_{FN}$ charges
  - hierarhical Higgs Yukawas after $U(1)_{FN}$ broken via vev of scalar field, the flavon Φ

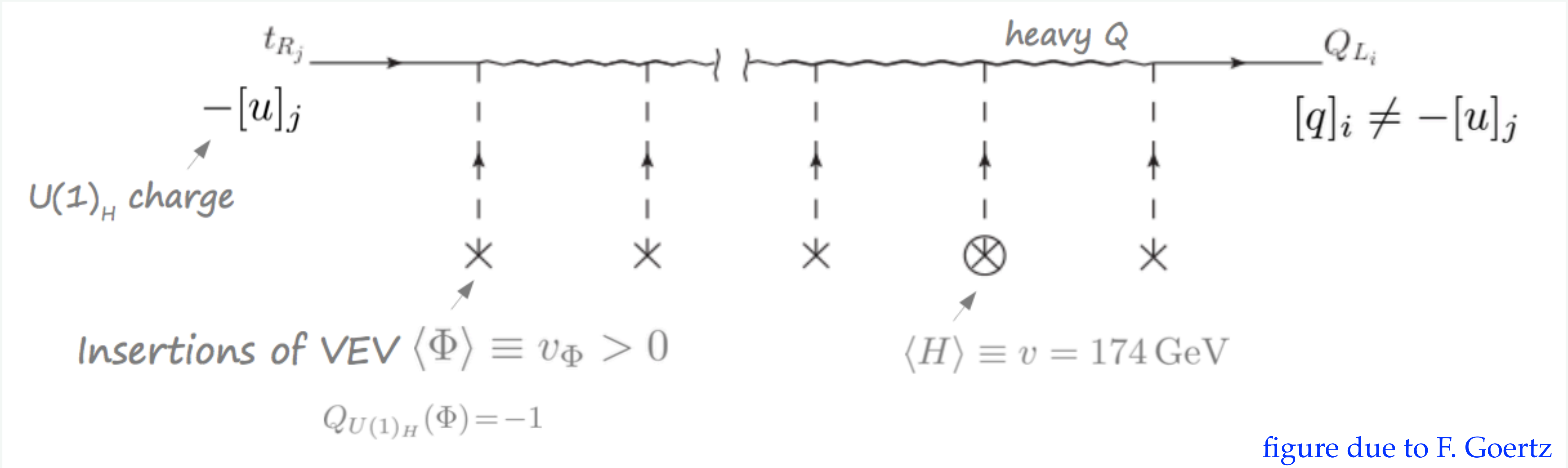
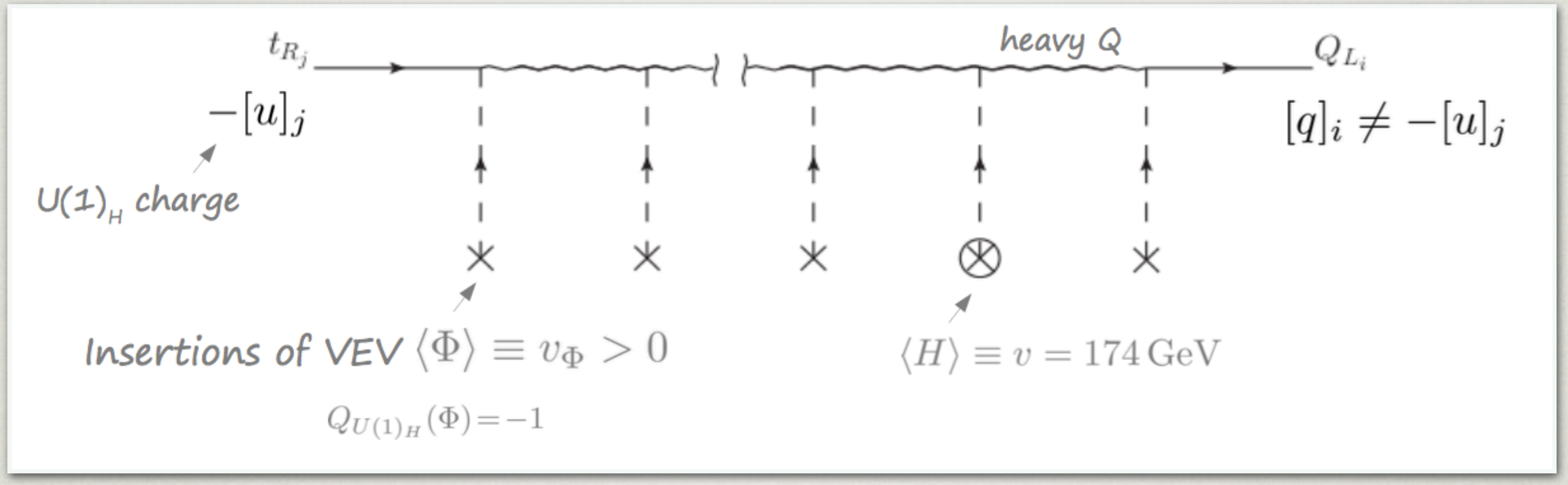


figure due to F. Goertz

SPURION ANALYSIS



- effective Yukawas governed by flavon insertions (so that invariant under flavor symm.)

$$\mathcal{L}_{eff} \sim \left(\frac{\phi}{\Lambda_F}\right)^{x_{ij}} h\,\overline{q}_i u_j \qquad \epsilon \equiv \frac{\phi}{\Lambda_F}$$

  - hierarchy from powers of small parameter ε
- FN mechanism involves
  - vector-like fermions + scalar flavon fields (no anomaly)
  - chiral fields at the end of the chains: in general anomalous $U(1)_{FN}$

ANOMALY FREE FN MODELS

THE UPSHOT

- there are two limits of Froggatt-Nielsen models that lead to hierarchical fermion masses

Smolkovic, Tammaro, JZ, 1907.nnnnn

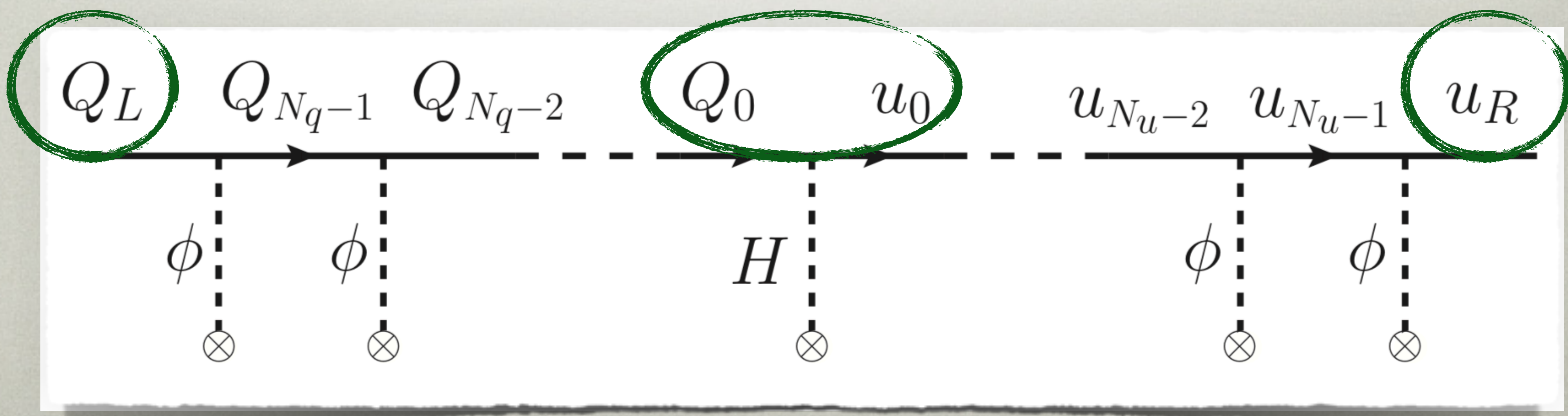
Alonso, Carmona, Dillon, Kamenik, Camalich, JZ, 1807.09792

- traditional FN: $$(Y_u^{\rm SM})_{ij} \sim \left(\frac{\langle\phi\rangle}{\Lambda}\right)^{N_{Q(i)}+N_{u(j)}}$$
- inverted FN: $$(Y_u^{\rm SM})_{ij} \sim \left(\frac{\Lambda}{\langle\phi^*\rangle}\right)^{N_{Q(i)}+N_{u(j)}}$$

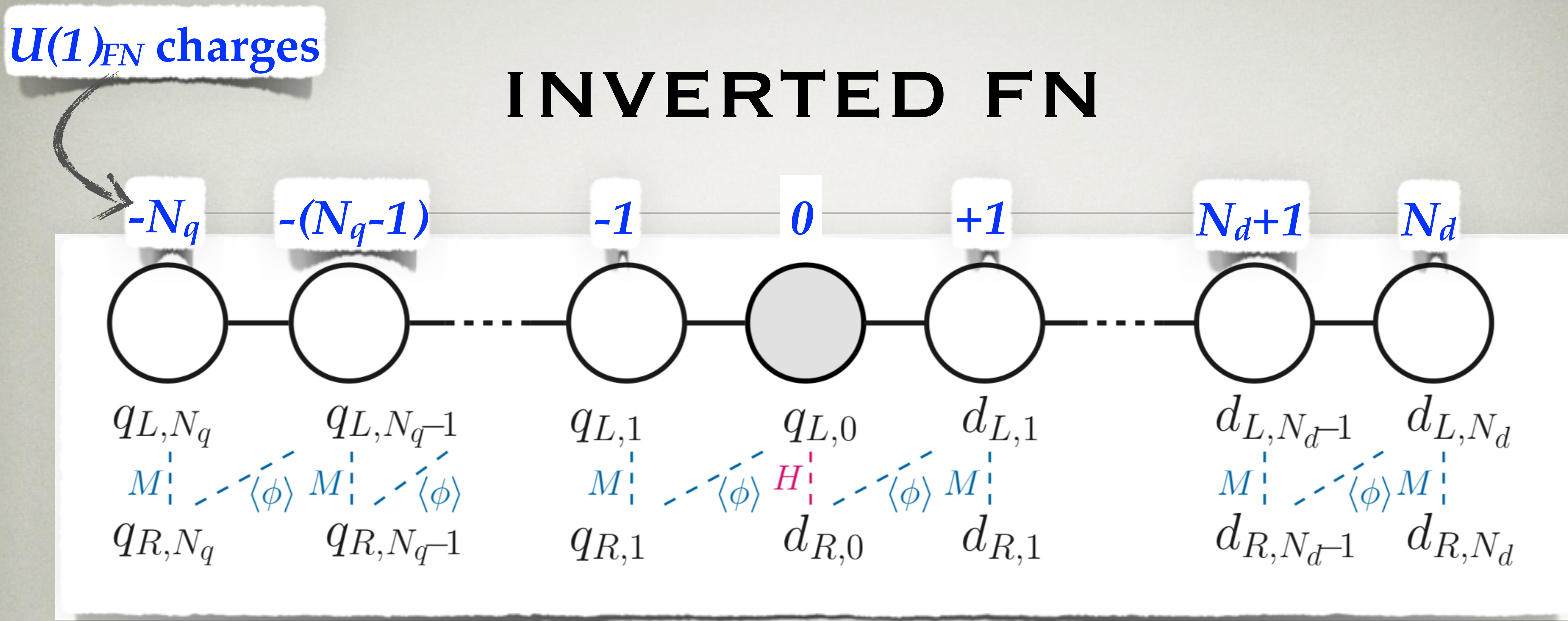
anomaly free models

inv. FN: vectorlike | **chiral** | **vectorlike**

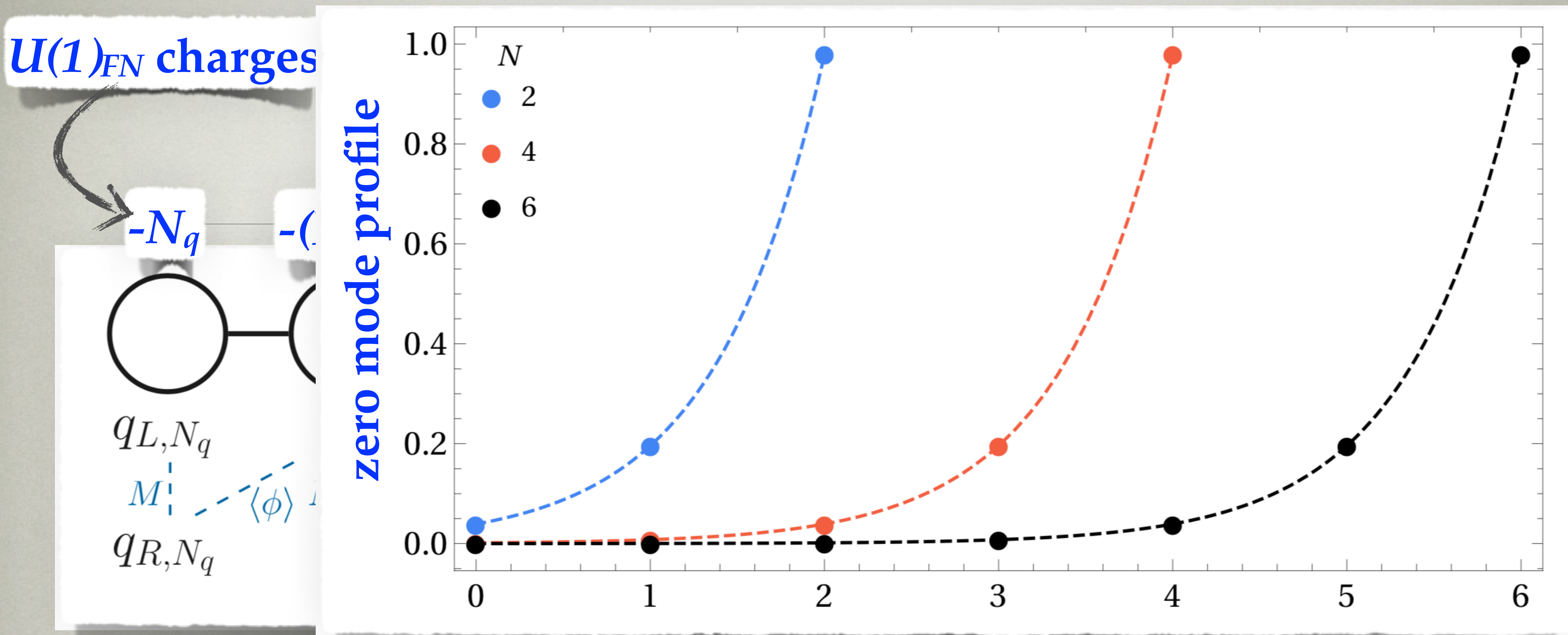
trad.FN: chiral | **vector-like** | **chiral**



INVERTED FN



- example: a single generation, Higgs not charged under $U(1)_{FN}$
  - a chain of vector-like fermions
  - chiral fields uncharged under $U(1)_{FN}$, couple to the Higgs
  - for $\langle\phi\rangle \gg M$ the zero modes located near the ends of the chains
- crucial ingredient: flavons appear only as ϕ not ϕ^*
  - natural if embedded in SUSY from holomophicity



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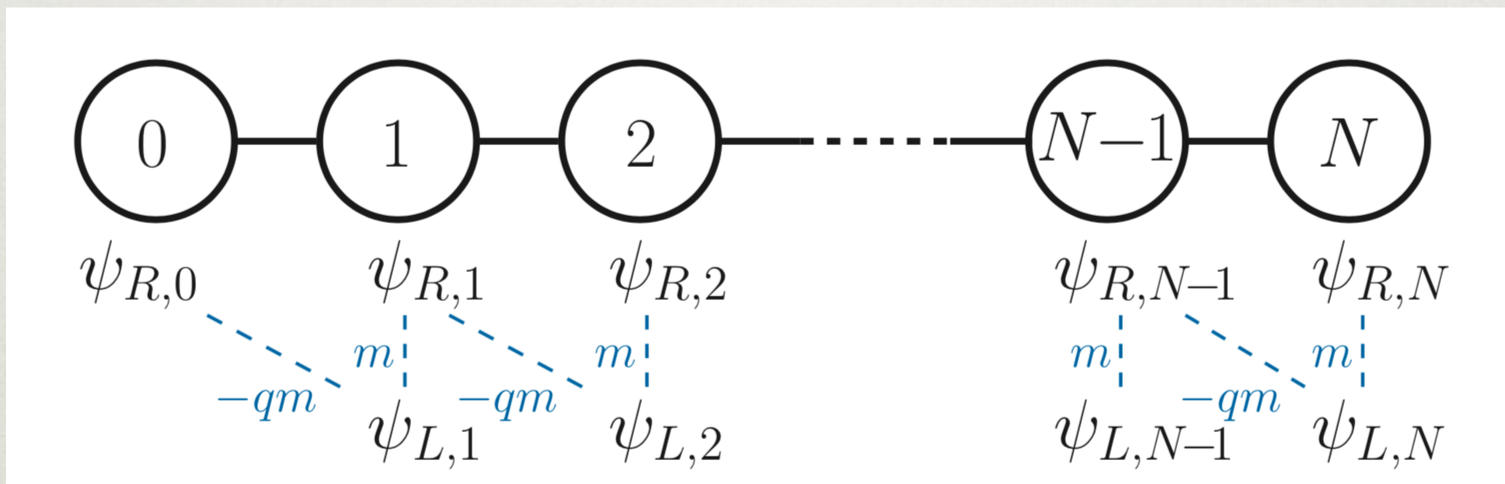
CLOCKWORKING

- taking all yukawas, $Y_a=1$

Choi, Im, 1511.00132 ; Kaplan, Rattazzi, 1511.01827
Giudice, McCullough, 1610.07962

  - a realization of the clockwork ``mechanism''



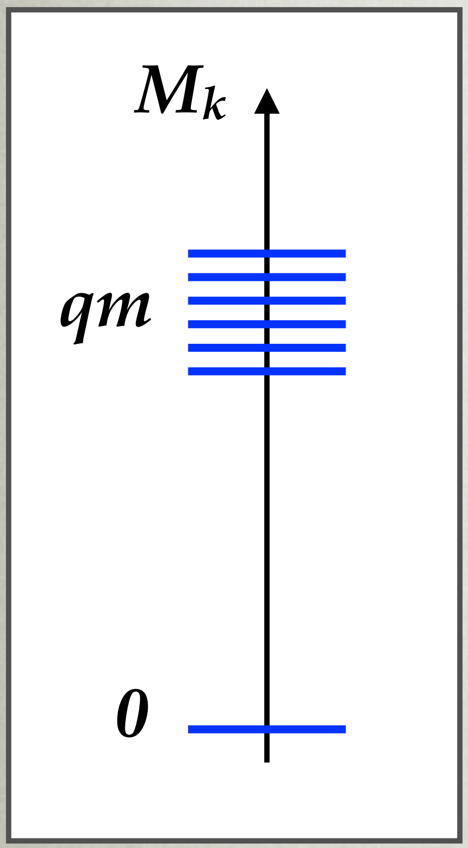
$$\mathcal{L}_{\psi_R} = i\sum_{j=0}^{N} \bar{\psi}_{R,j} \not{D}\psi_{R,j} + i\sum_{j=1}^{N} \bar{\psi}_{L,j}\not{D}\psi_{L,j} - m\sum_{j=1}^{N}\left(\bar{\psi}_{L,j}\psi_{R,j} - q\bar{\psi}_{L,j}\psi_{R,j-1}\right) + \text{h.c.},$$

- a special form of the $N \times (N+1)$ mass matrix

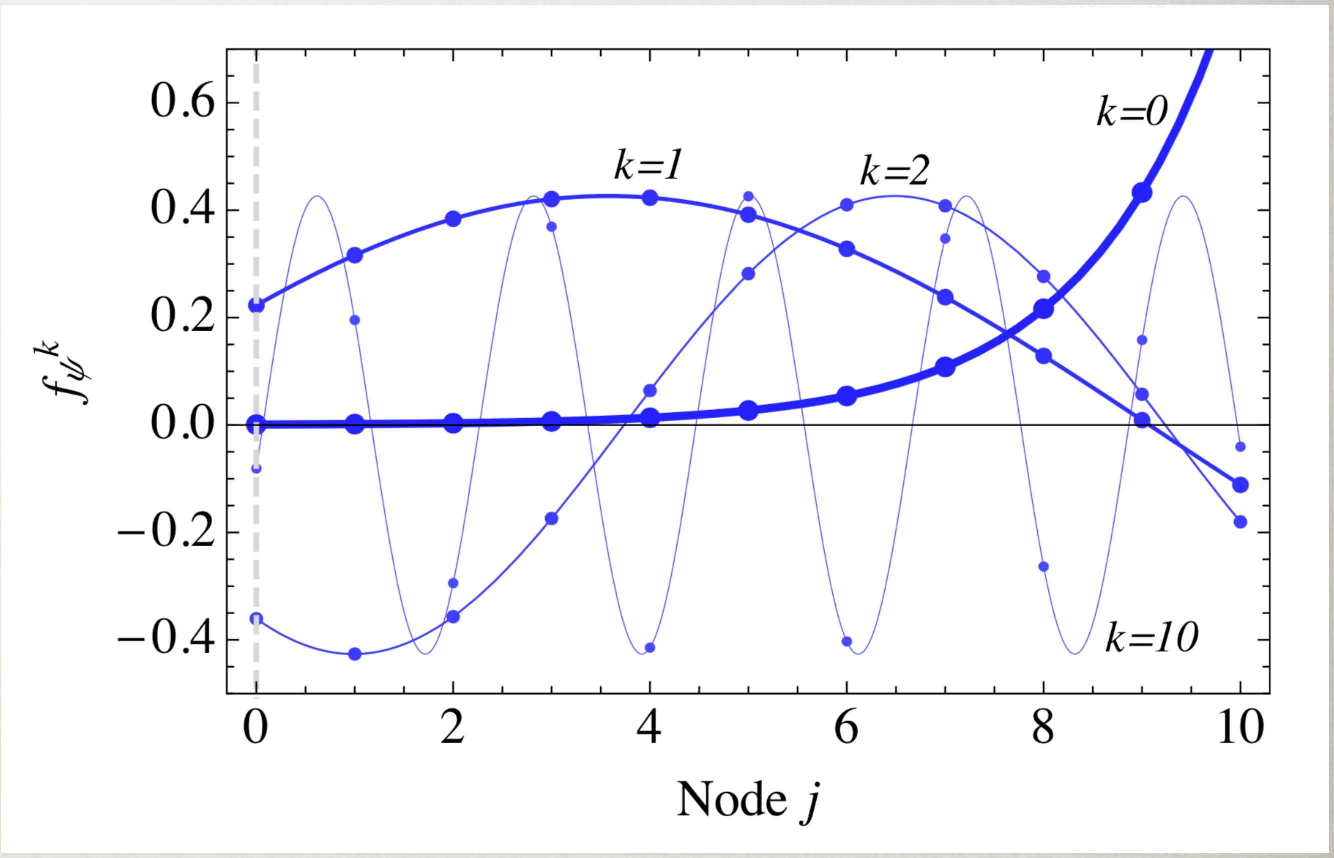
$$\mathcal{M}_\psi = m\begin{pmatrix} -q & 1 & 0 & \dots & 0 \\ 0 & -q & 1 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & -q & 1 \end{pmatrix},$$

for us: $q \leftrightarrow \langle\phi\rangle/M$
$m \leftrightarrow M$

CLOCKWORKING



- one zero mode
- N massive modes
  - for $q \gg 1$ have masses $M_k \sim mq$
  - there is a mass gap



- zero mode overlap with 0-th node exponentially suppressed

$$f_\psi \sim 1/q^N$$

- if Higgs on 0-th node → hierarchical masses

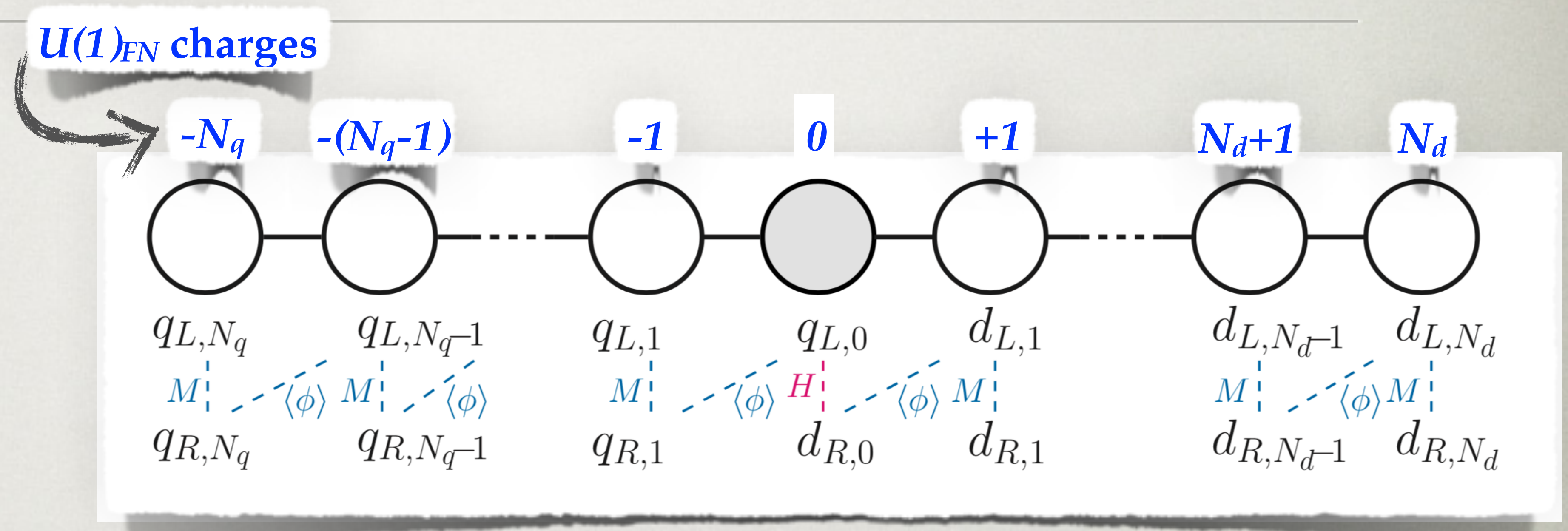
Alonso, Carmona, Dillon, Kamenik, Camalich, JZ, 1807.09792

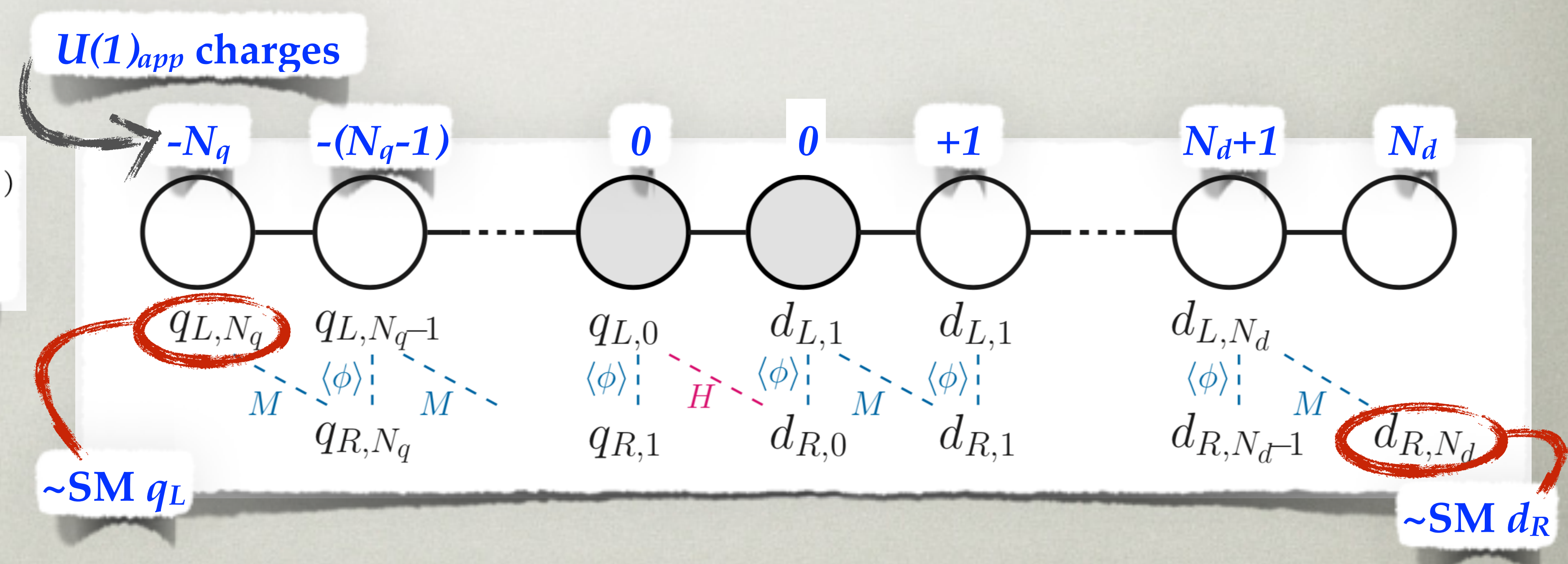
SPURION ANALYSIS

- at low energies an emergent $U(1)_{app}$
  - simple relabeling of fields
  - broken by M
- taking the limit of heavy flavon
- spurion analysis then gives

$$(Y_u^{SM})_{ij} \sim \left(\frac{M}{\langle \phi^* \rangle}\right)^{N_{Q(i)}+N_{u(j)}}$$

- from low eng. looks like traditional FN
  - but M and ϕ flipped



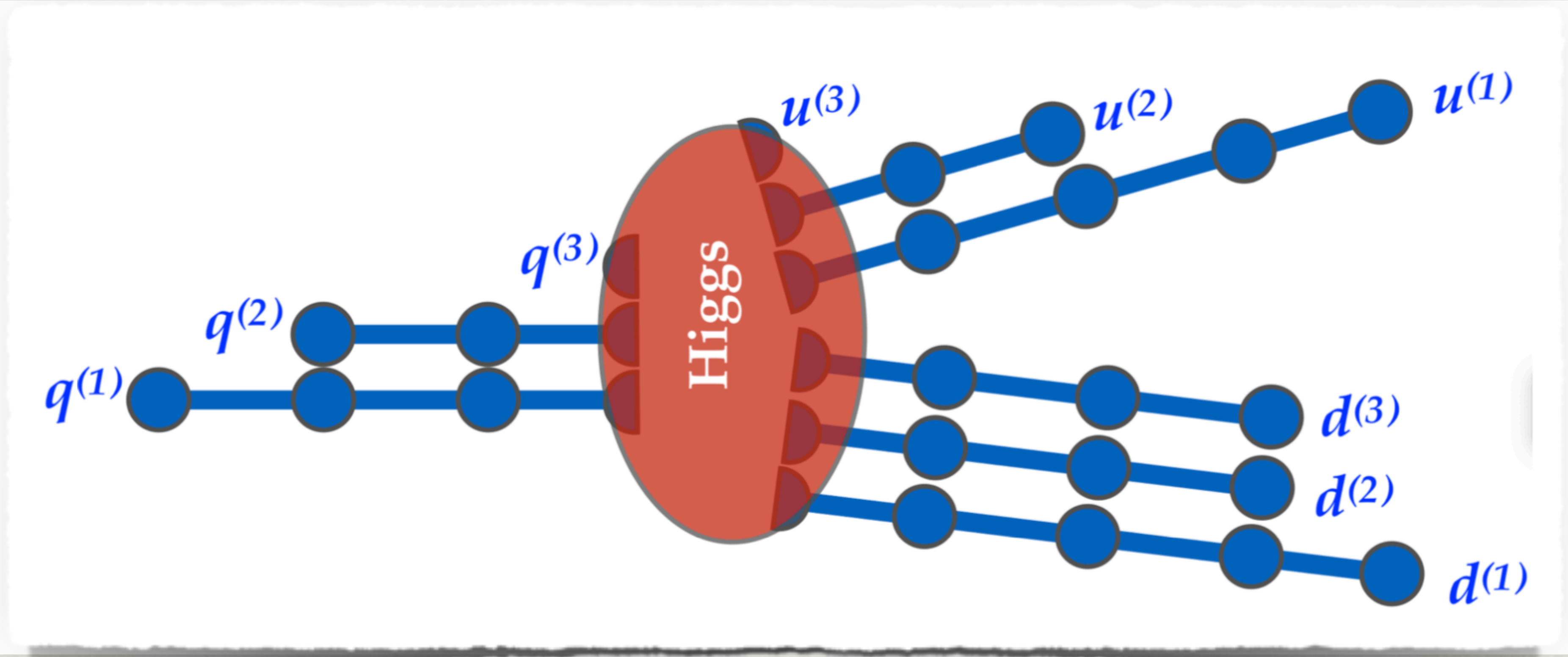


FURTHER COMMENTS

- if flavon field heavy and $U(1)_{FN}$ not gauged, the inv. FN and trad. FN completely equivalent
  - just relabeling of the fields
- differences arise from couplings of flavons and $U(1)_{FN}$ gauge boson
- for 3 generations several choices for the horizontal group
  - $G_{FN}=U(1)^3$ gives decoupled FN chains
  - $G_{FN}=U(1)$ leads to coupled FN chains

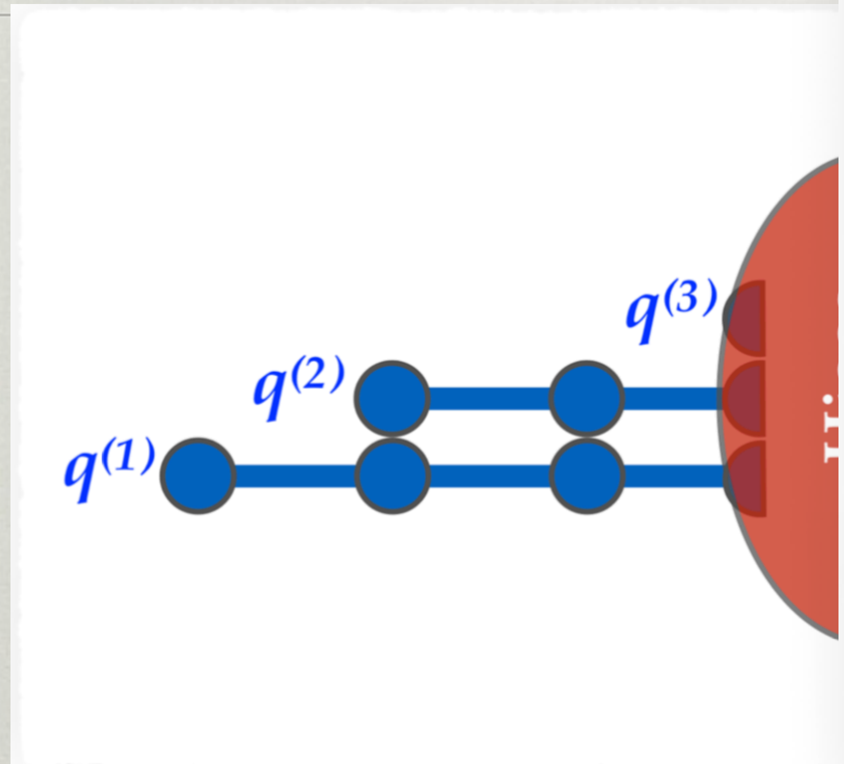
Smolkovic, Tammaro, JZ, 1907.10063

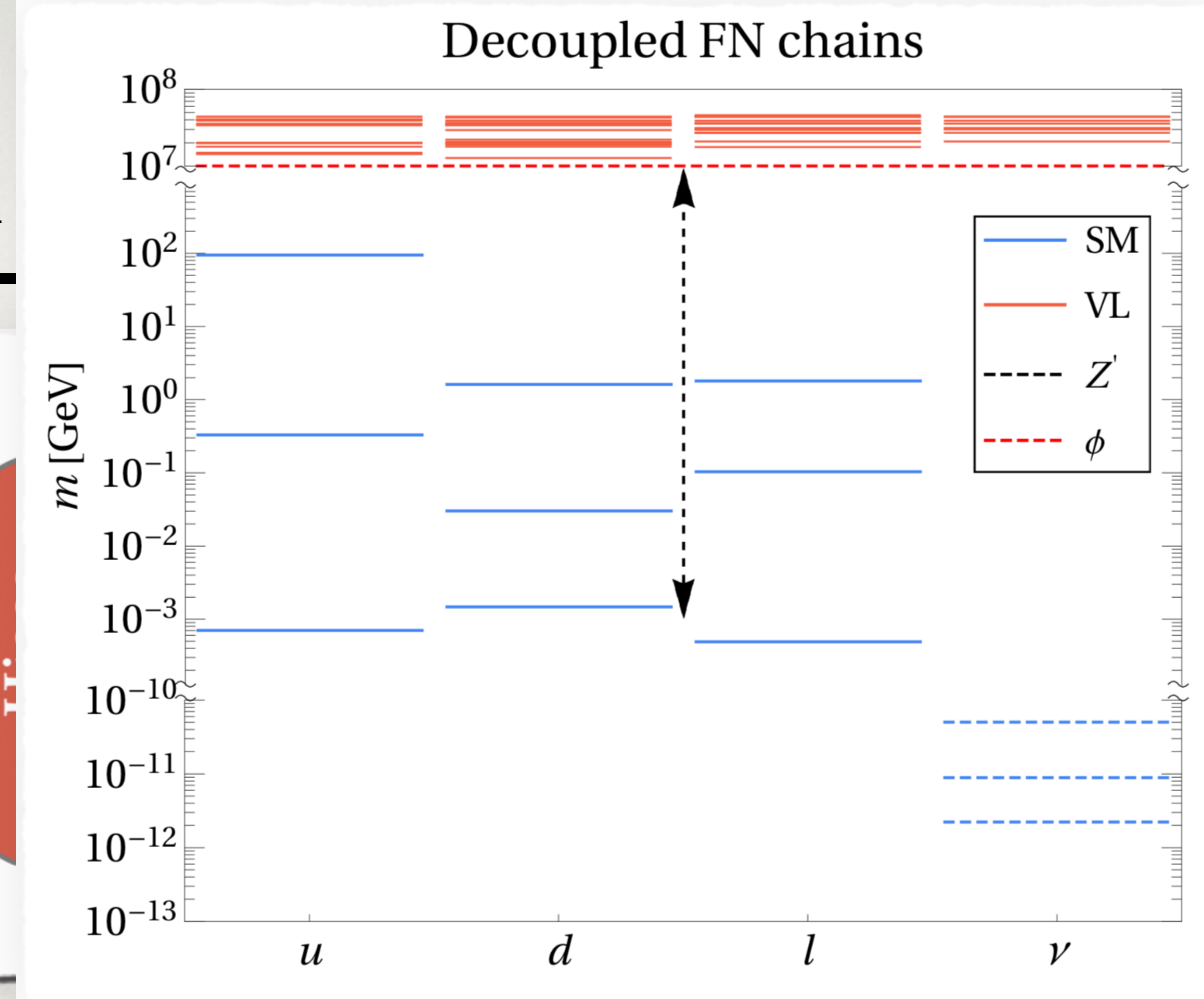
DECOUPLED CHAINS



- different *U(1)* for each generation: $G_{FN}=U(1)_1\times U(1)_2\times U(1)_3$
- only mixing between generations is through couplings to the Higgs
- set $\frac{\Lambda_1}{\langle\phi_1\rangle}=\frac{\Lambda_2}{\langle\phi_2\rangle}=\frac{\Lambda_3}{\langle\phi_3\rangle}=\frac{1}{q}\simeq\lambda=0.2$

DECOUPL





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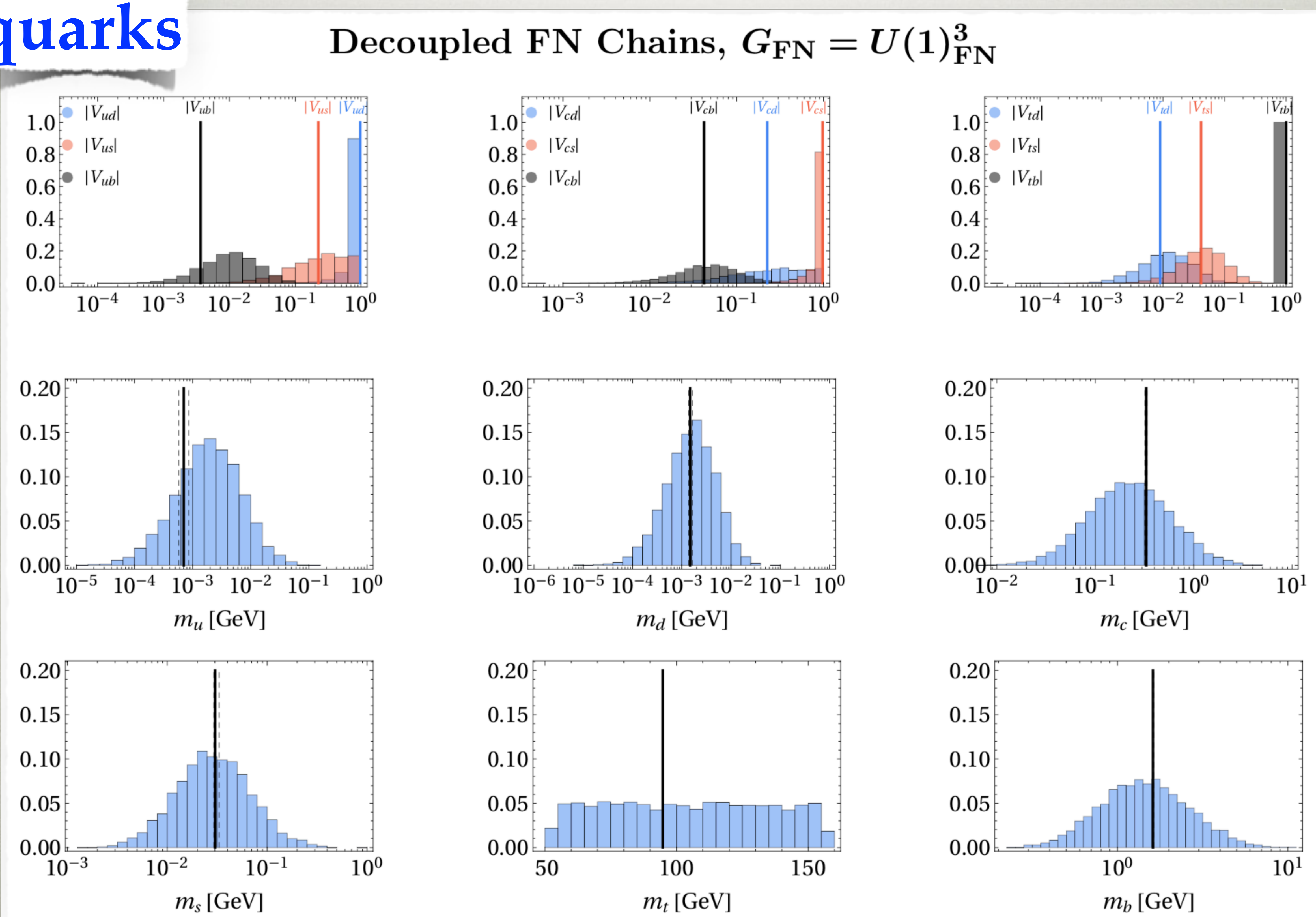
SCAN FOR DECOUPLED CHAINS

- perform a scan:
  - fix $q=5$, $\langle\phi\rangle=10^7$ GeV
  - vary Yukawas in range [0.3, 0.9]
  - vectorlike masses in range $[0.3, 0.9]\langle\phi\rangle/q$
  - arbitrary phases
- compare to SM quark masses and CKM elements at $\mu=10^7$GeV

SCAN "PREDICTIONS"

quarks



SCAN "PRED

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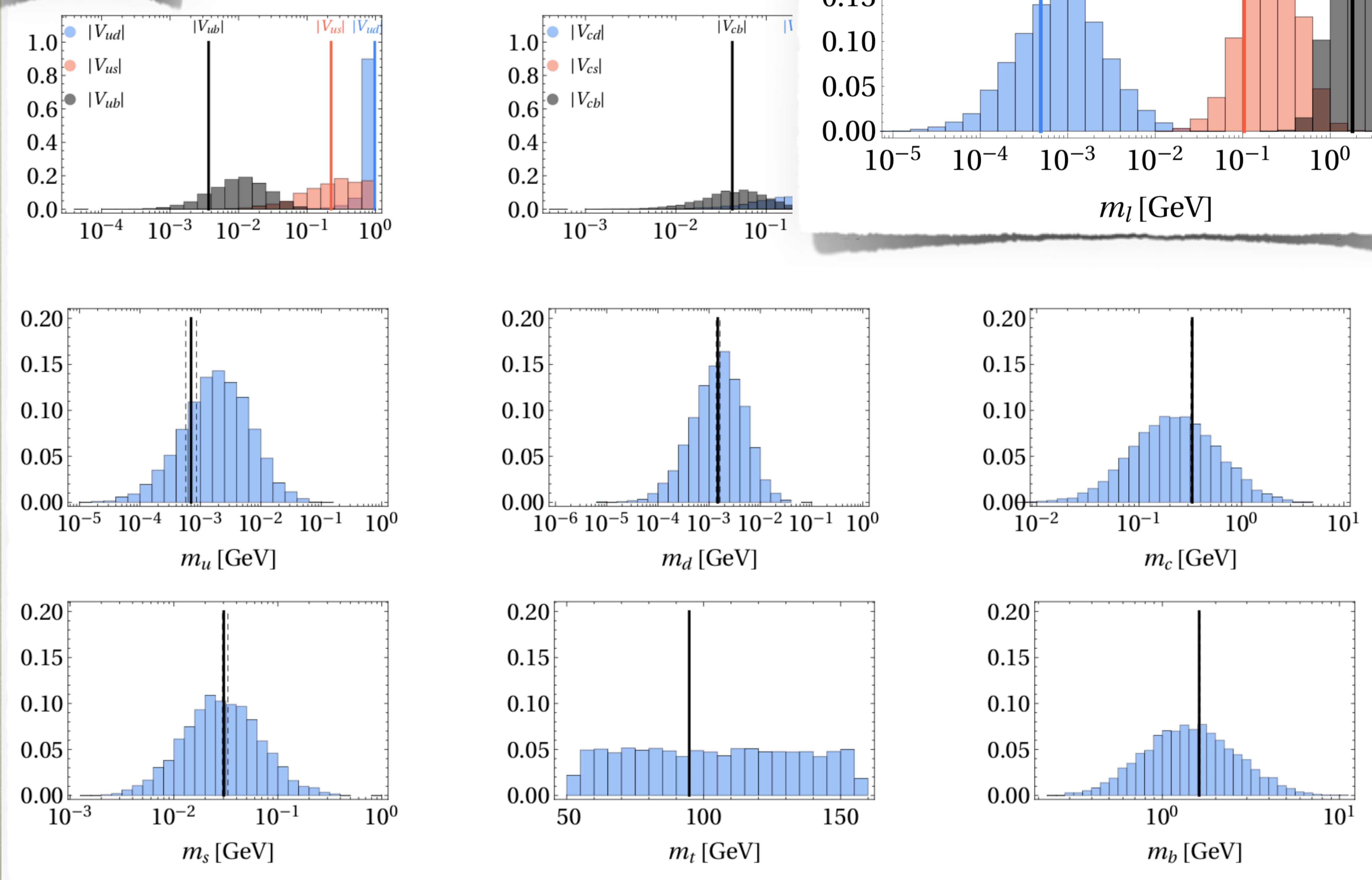
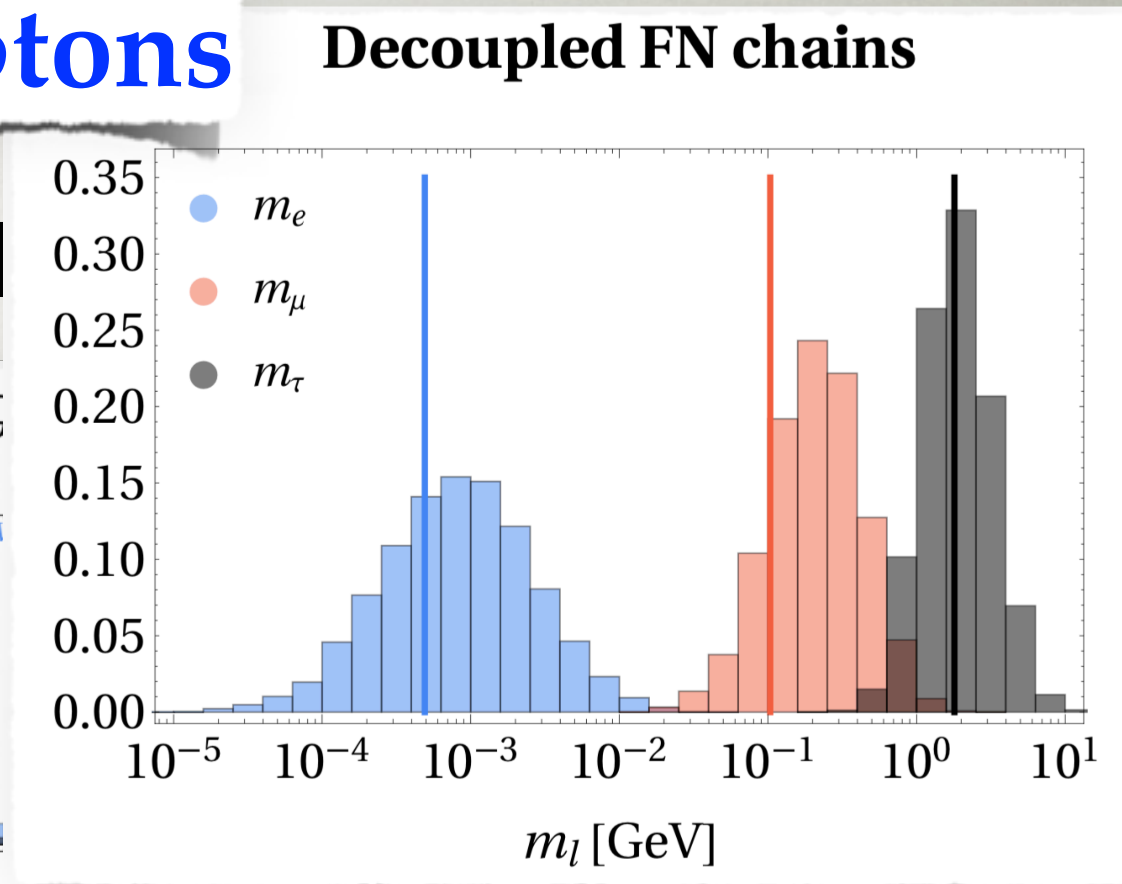


leptons



NEUTRINOS

- quite some freedom regarding neutrinos
  - assume to be Majorana, neutrino mass matrix from dim 5 Weinberg op.

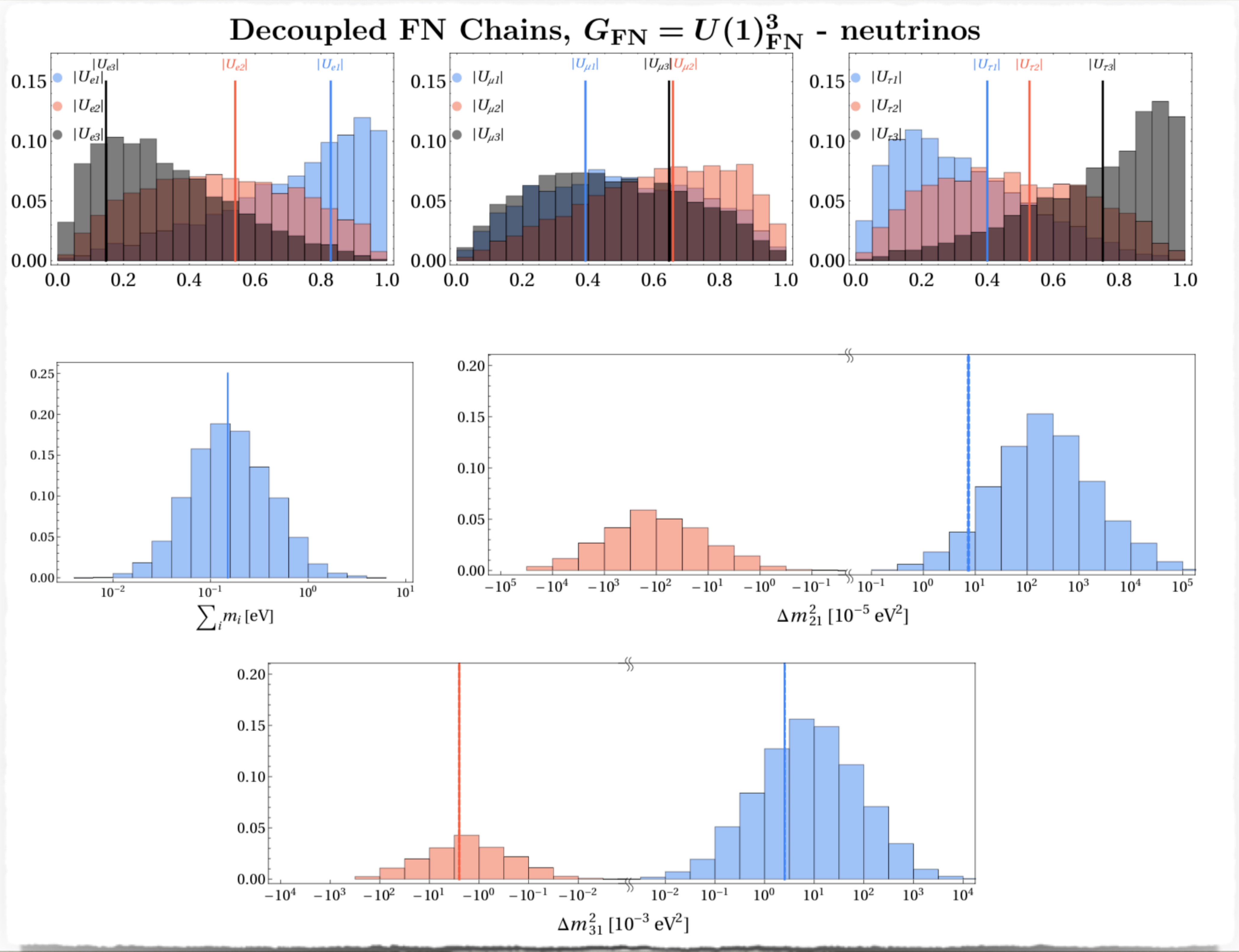
$$m_{ij}^{\nu} \sim \frac{v^2}{\Lambda_{\rm LN}} \left(\frac{M}{\langle\phi\rangle}\right)^{N_{L(i)}+N_{L(j)}}$$

  - take it to be anarchical, which means $N_{L(1)} = N_{L(2)} = N_{L(3)}$
- charged leptons, still several choices for $N_{e(i)}$

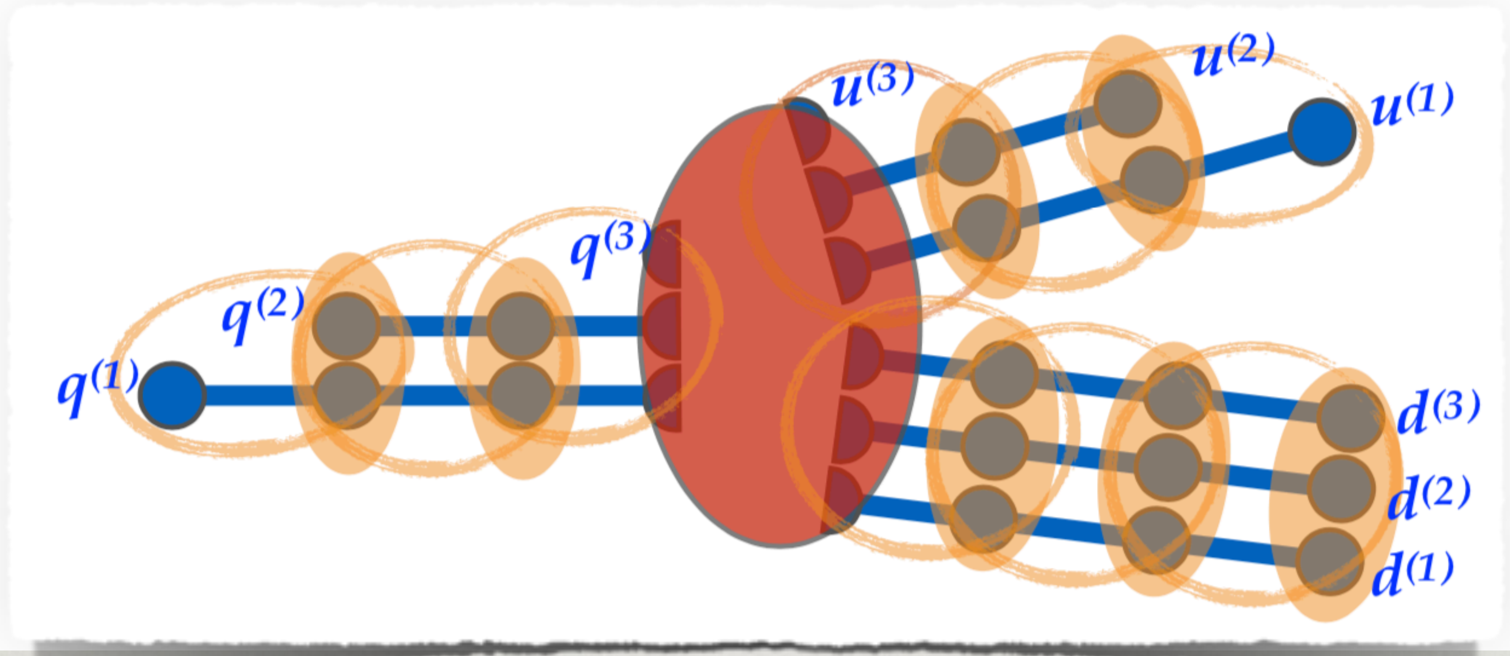
$$m_{ij}^{e} \sim v \left(\frac{M}{\langle\phi\rangle}\right)^{N_{L(i)}+N_{e(j)}}$$

$$N_{L(1)} = N_{L(2)} = N_{L(3)} = 3, \qquad N_{e(1)} = 4, \qquad N_{e(2)} = 1, \qquad N_{e(3)} = 0.$$

ANARCHIC NEUTRINOS



COUPLED CHAINS

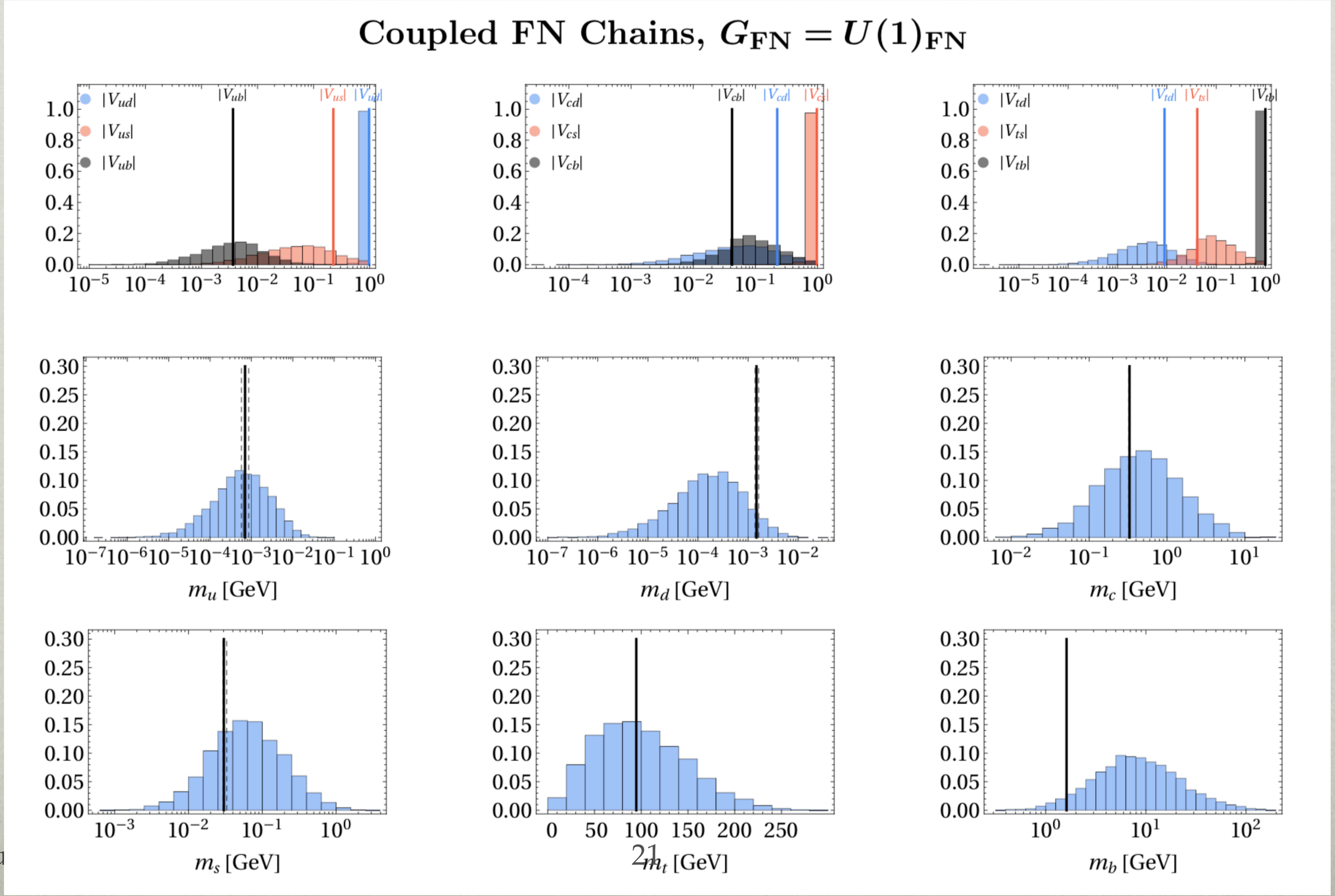


- the same *U(1)* for all generations: $G_{FN}=U(1)_{FN}$
- now on each node the Yukawas mix different generations
- required lengths for the vectorlike chains differ from the decoupled case

$$N_{q(1)} = 3, \quad N_{q(2)} = 2, \quad N_{q(3)} = 0,$$
$$N_{u(1)} = 3, \quad N_{u(2)} = 2, \quad N_{u(3)} = 0,$$
$$N_{d(1)} = 3, \quad N_{d(2)} = 3, \quad N_{d(3)} = 3,$$

COUPLED CHAINS SCAN

- distributions wider, but still well reproduces the hierarchies



COUPLED CHAI

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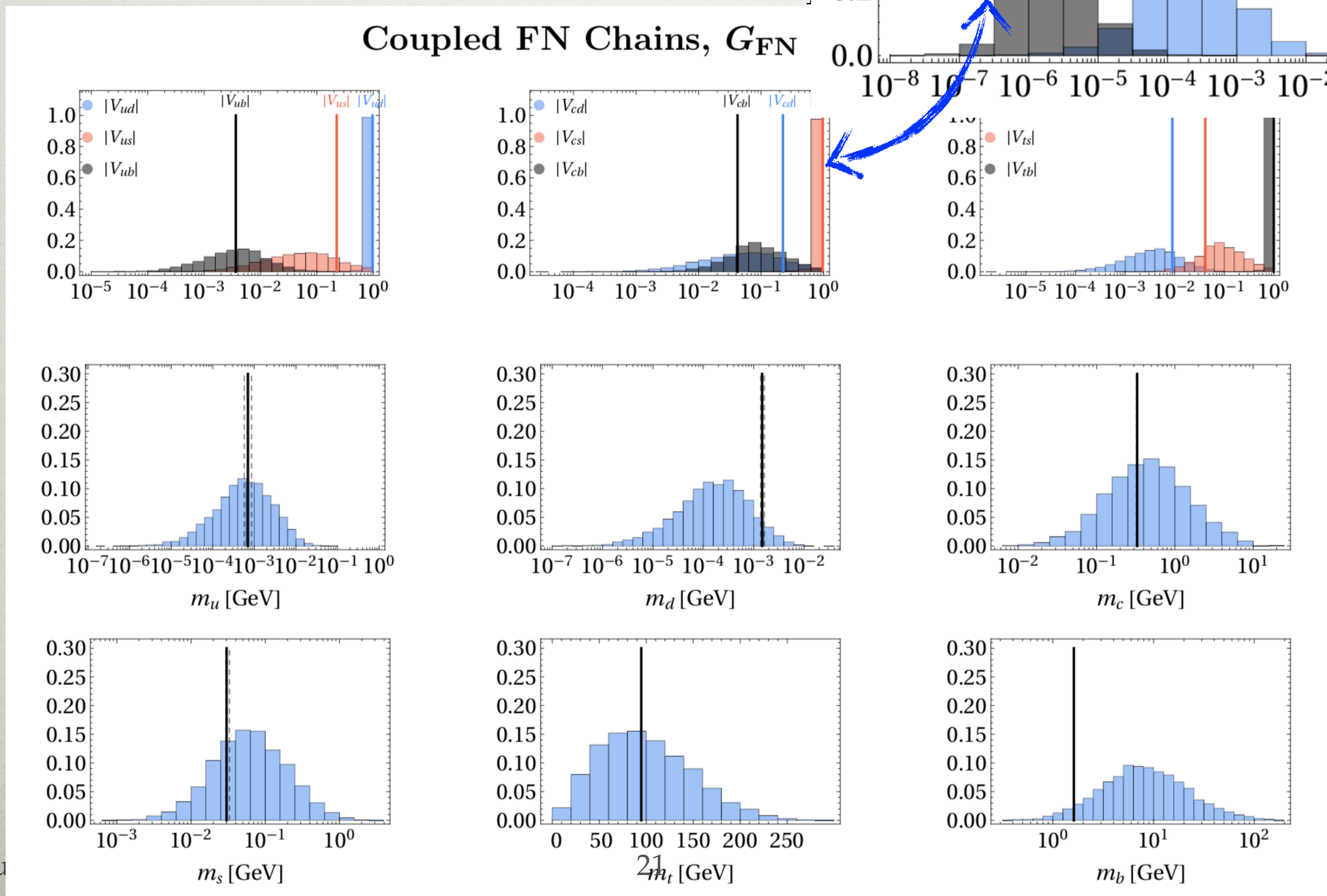
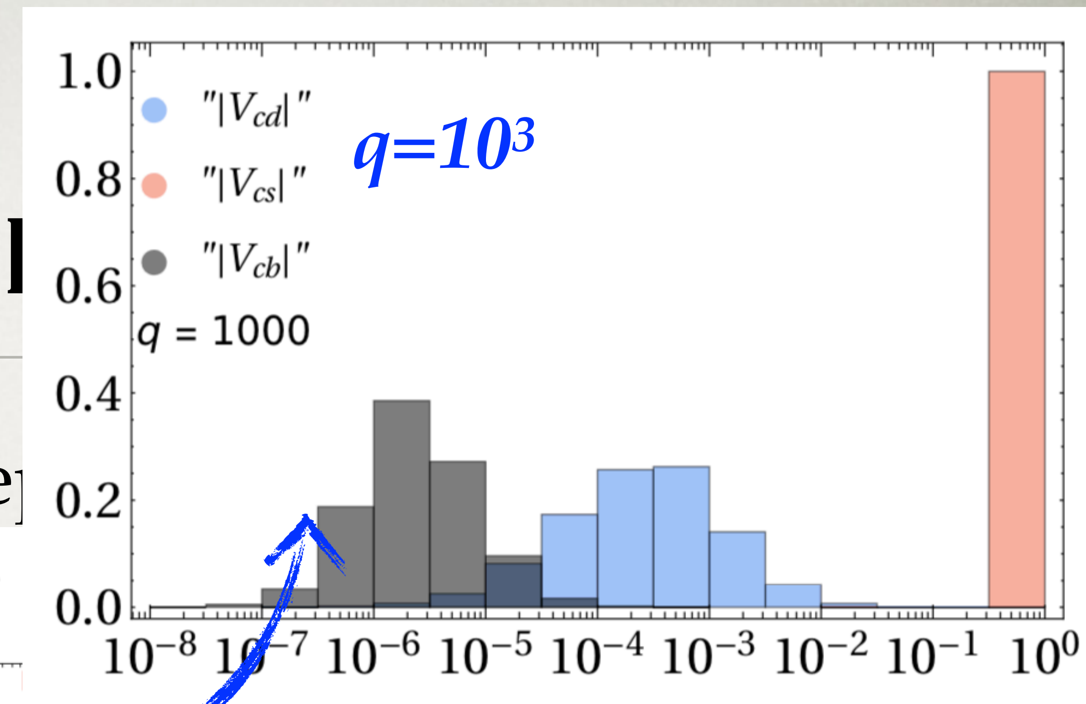
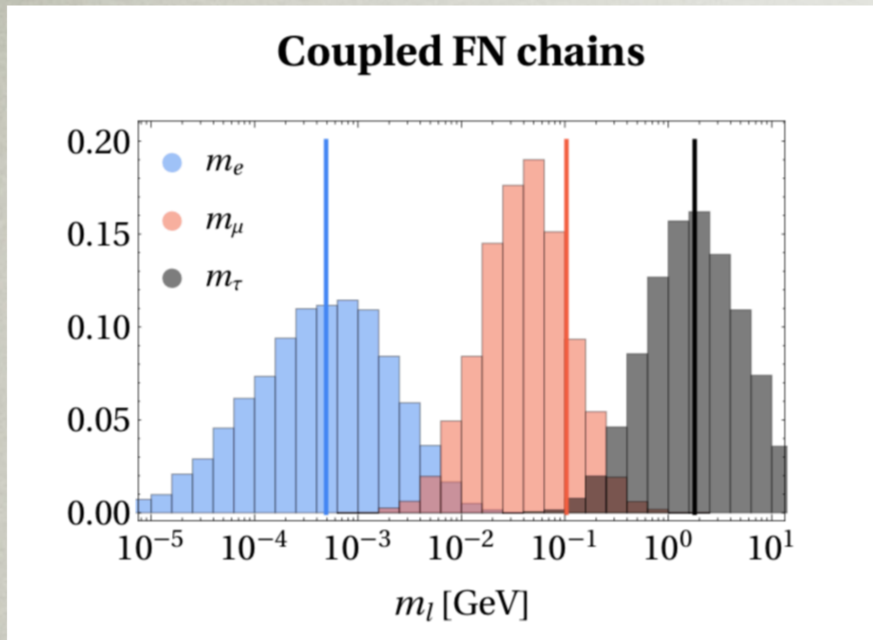


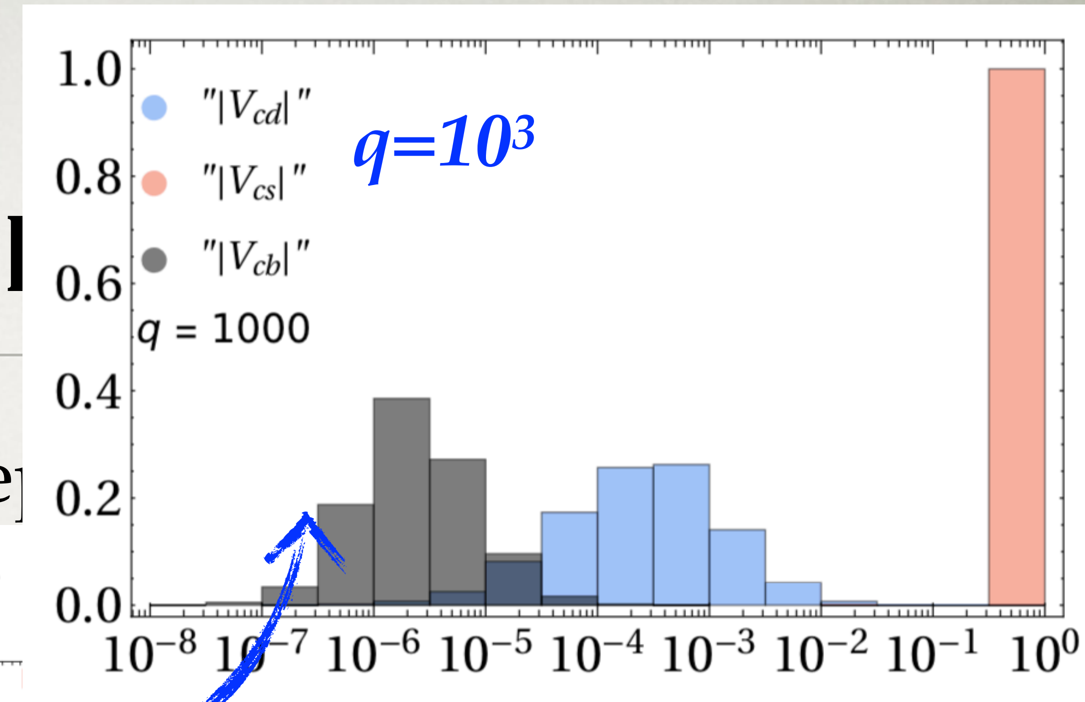


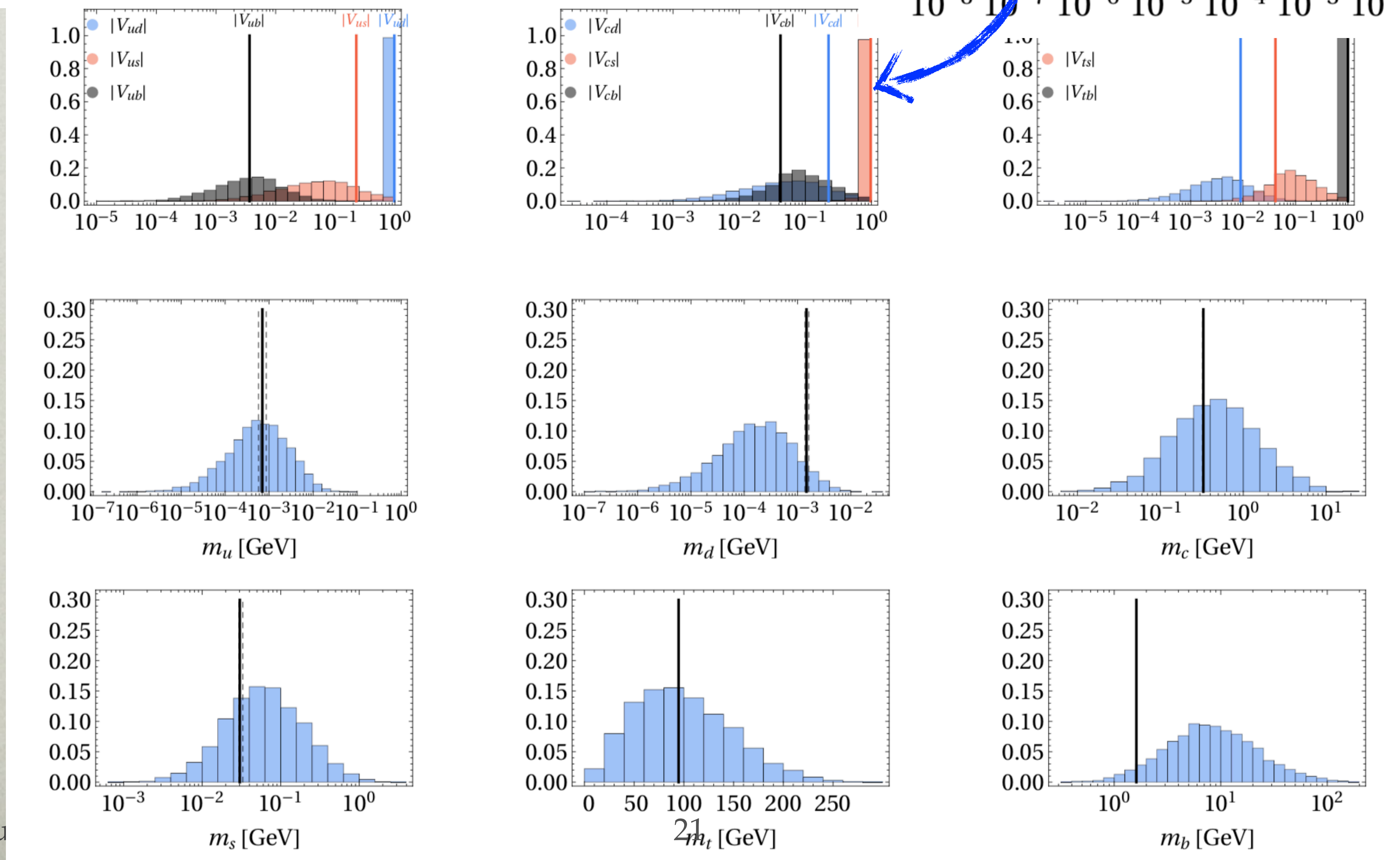
ED CHAI

der, but still well re

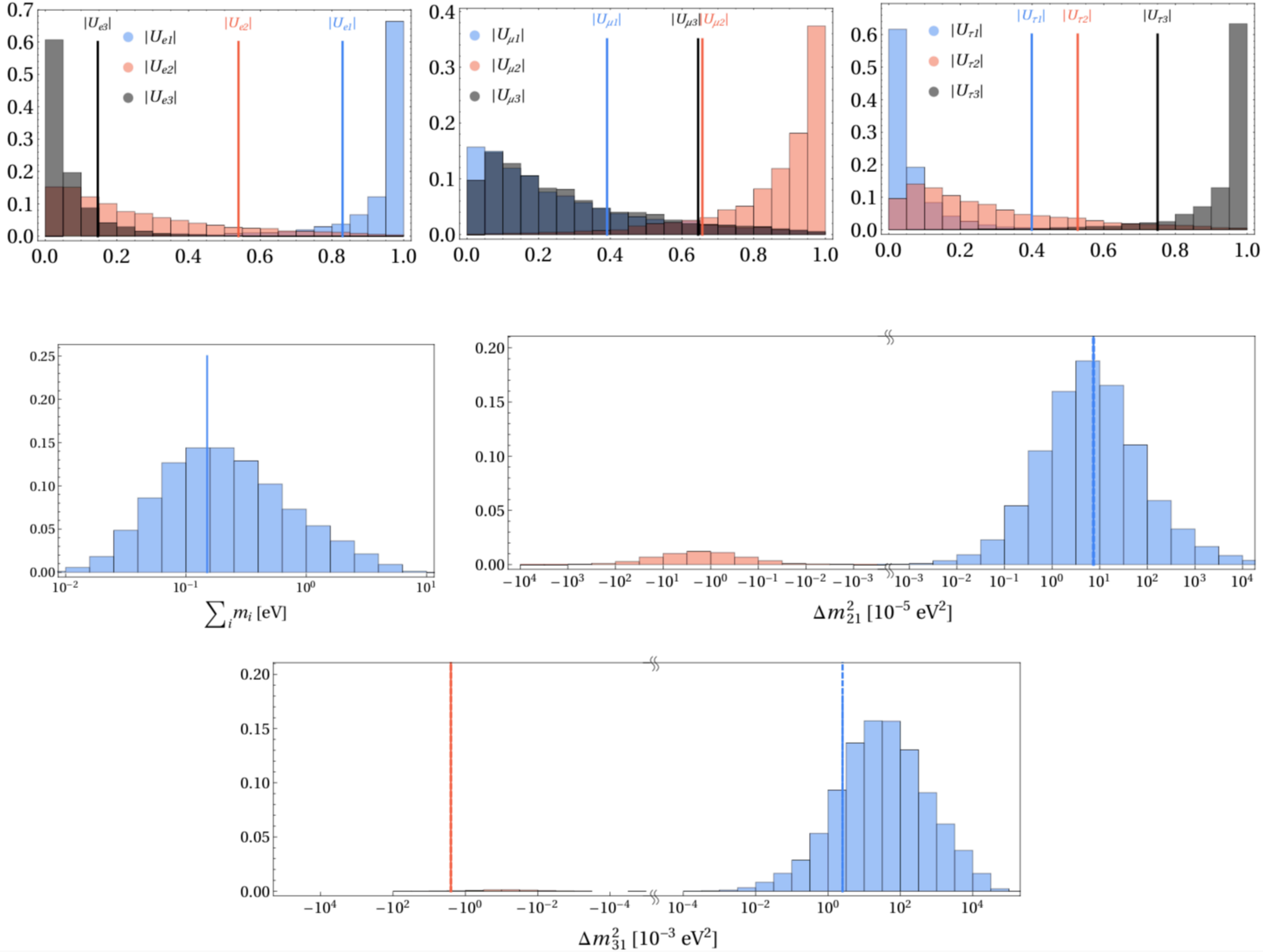
upled FN Chains, G_{FN}







Coupled FN Chains, $G_{\mathbf{FN}} = U(1)_{\mathbf{FN}}$ - neutrinos



EXPERIMENTAL SEARCHES

- how to observe experimentally?
- immediate answer: search in FCNCs
  - K-$\bar{K}$, B-$\bar{B}$ mixing, etc.
  - exchanges of flavons, heavy vector-like fermions, flavorful Z's
  - for $O(1)$ couplings masses$\gtrsim 10^7$GeV
- for small $U(1)_{FN}$ gauge couplings Z' can be light
  - can also search for it directly: beam dumps, e^+e^- colliders, astrophysics

Smolkovic, Tammaro, JZ, 1907.10063

FLAVORED Z'

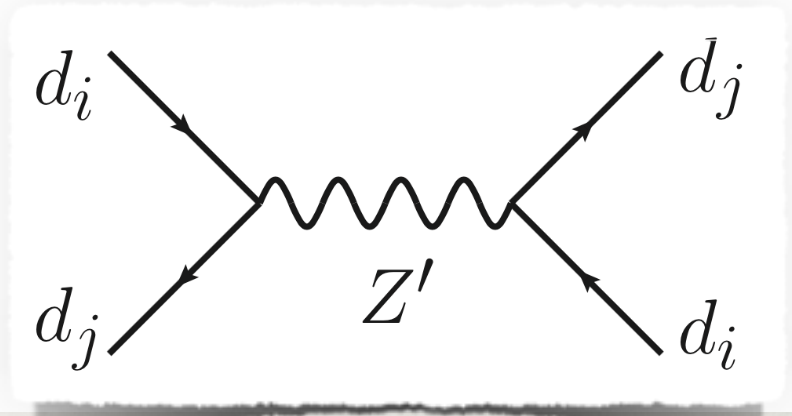
- focus on $G_{FN}=U(1)$ case

$$J^\mu_{\rm FN} = g' \sum_{i,j=1}^{3} c'^{q_L}_{ij} \left(\bar{q}_L^{(i)} \gamma^\mu q_L^{(j)}\right) + \cdots$$

$$\mathcal{L} \supset -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} - \frac{\epsilon}{2} B_{\mu\nu} Z'^{\mu\nu} + B_\mu J^\mu_Y + W^a_\mu J^\mu_{W^a} + Z'_\mu J^\mu_{\rm FN}$$

- the couplings of Z' to fermions is not flavor conserving
  - on each node a different FN charge
  - leads to flavor violation after mass diagonalization of zero modes
- two regimes
  - kinetic mixing dominates, $\varepsilon \gg g'$
    - standard dark photon phenomenology, flavor violation irrelevant
  - kinetic mixing is negligible, $\varepsilon \ll g'$
    - genuinely new regime, flavor violation important
    - couplings are mostly axial vector

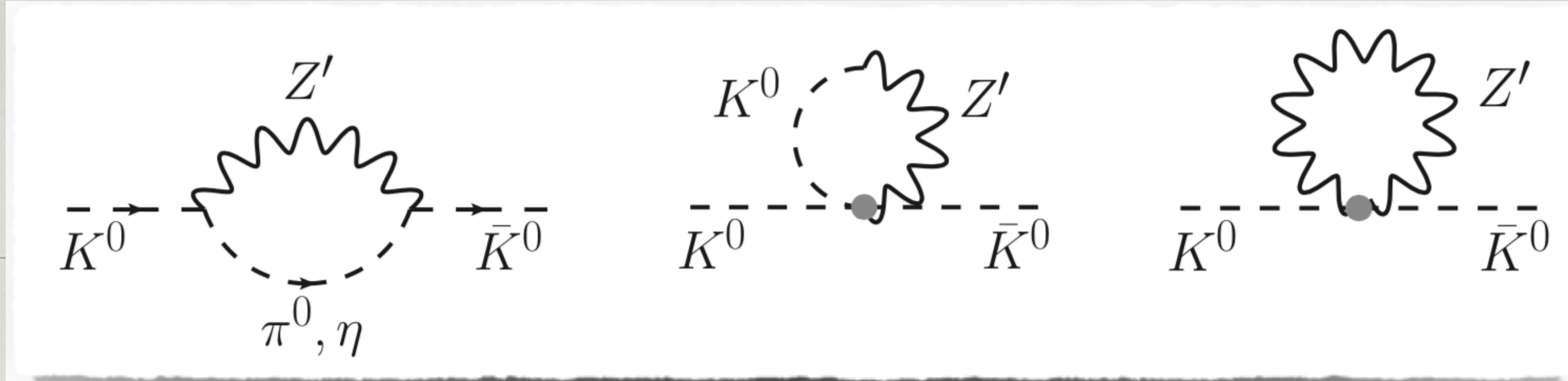
FLAVOR CONSTRAINTS

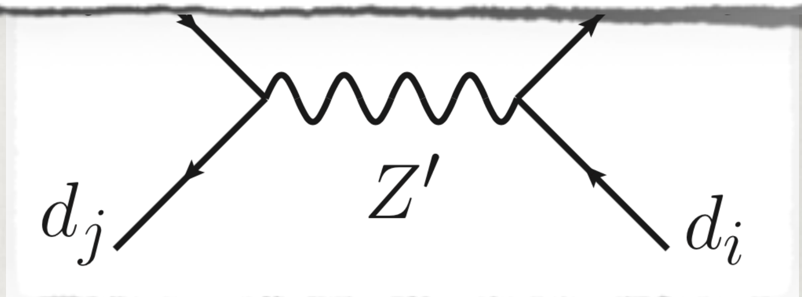


- from now on set *ε=0*
- important constraints from meson mixing
  - both for light Z', $m_{Z'} \ll m_{K,B}$, and heavy Z', $m_{Z'} \gg m_{K,B}$, the NP amplitude scales as

$$M_{12}^{\rm NP} \propto \frac{g'^2}{m_{Z'}^2} \propto \frac{1}{\langle\phi\rangle^2} \quad \Longrightarrow \quad \langle\phi\rangle \gtrsim 10^7 GeV$$

- for heavy Z', the usual EFT matching by integrating out the Z'
- for light Z' for K-$\bar{K}$ use ChPT at LO and NLO
- for light Z' for B-$\bar{B}$ use OPE





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LIGHT Z'

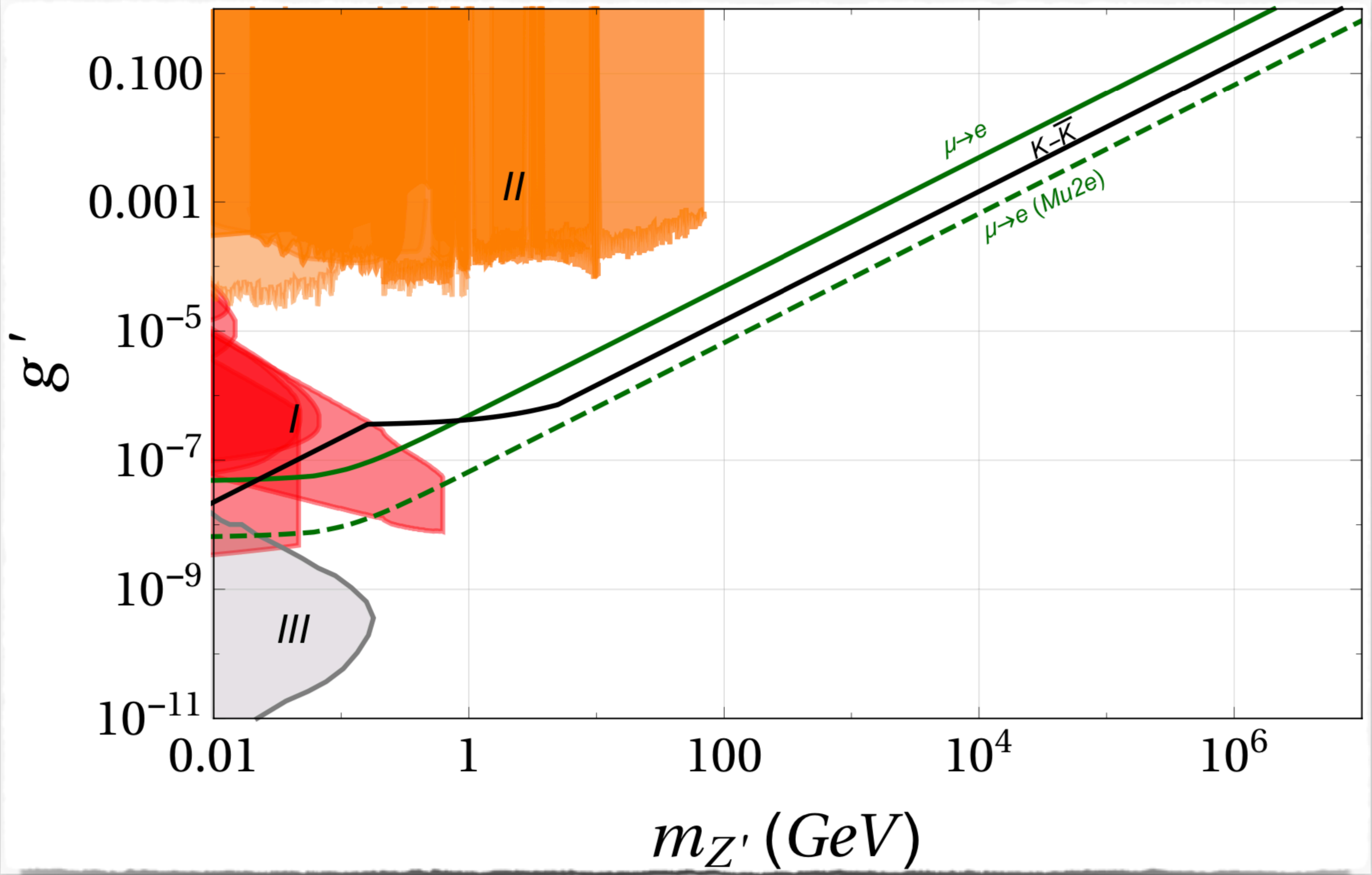
- for light Z' pheno. important how it couples to leptons
  - beam dump experiments, $\mu \to e\gamma$, $\mu \to 3e$, ...
- FN charge assignments depend crucially on what one assumes for the netrino masses
  - we assumed to be Majorana, from dim 5 Weinberg op.

$$m^{\nu}_{ij} \sim \frac{v^2}{\Lambda_{\rm LN}}\left(\frac{M}{\langle\phi\rangle}\right)^{N_{L(i)}+N_{L(j)}}$$

  - take it to be anarchical, which means $N_{L(1)} = N_{L(2)} = N_{L(3)}$
- show constraints for our particular benchmarks

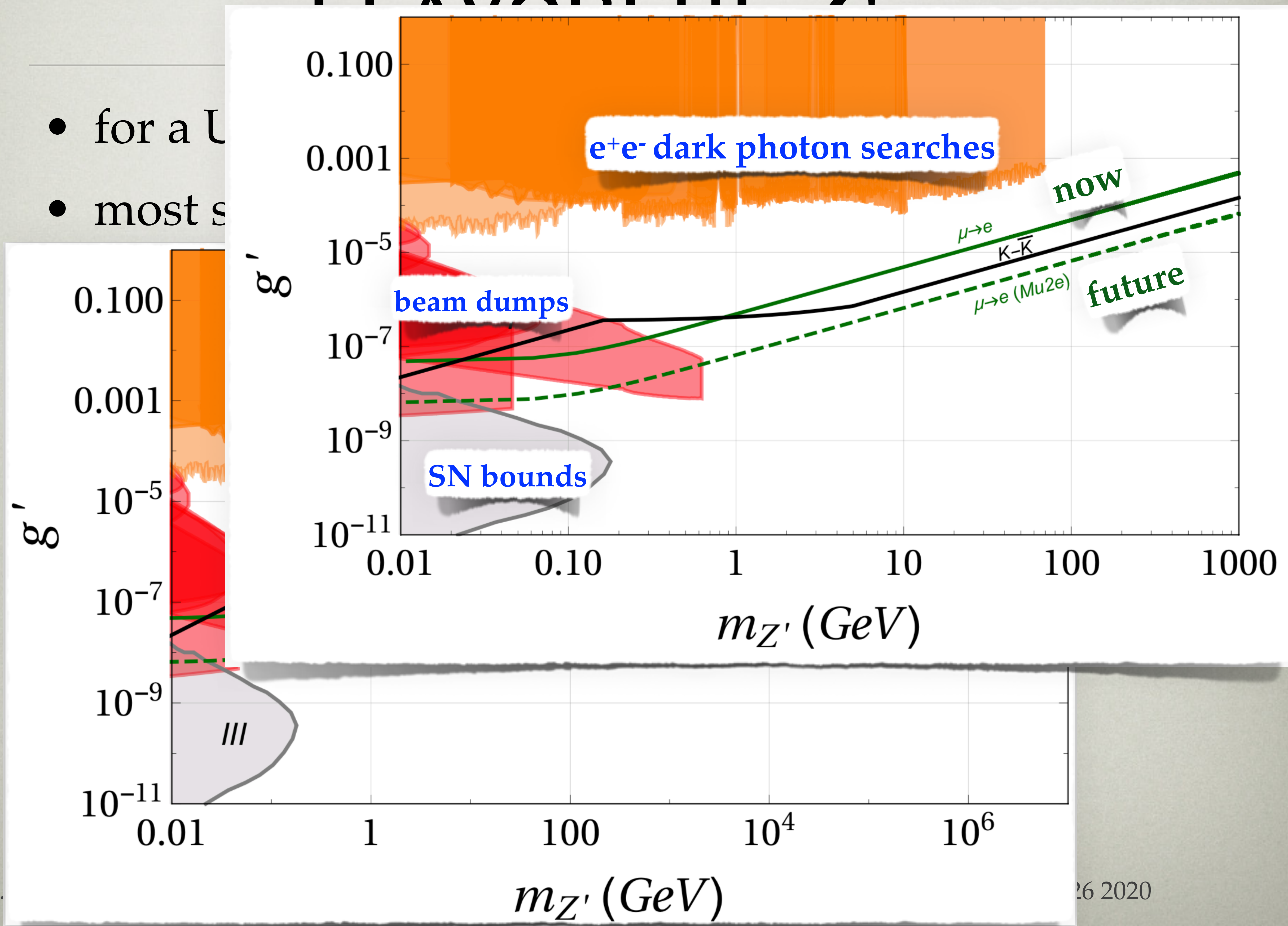
FLAVORFUL Z'

- for a $U(1)_{FN}$ benchmark
- most stringent bounds



FLAVORFUL Z'

- for a U
- most s



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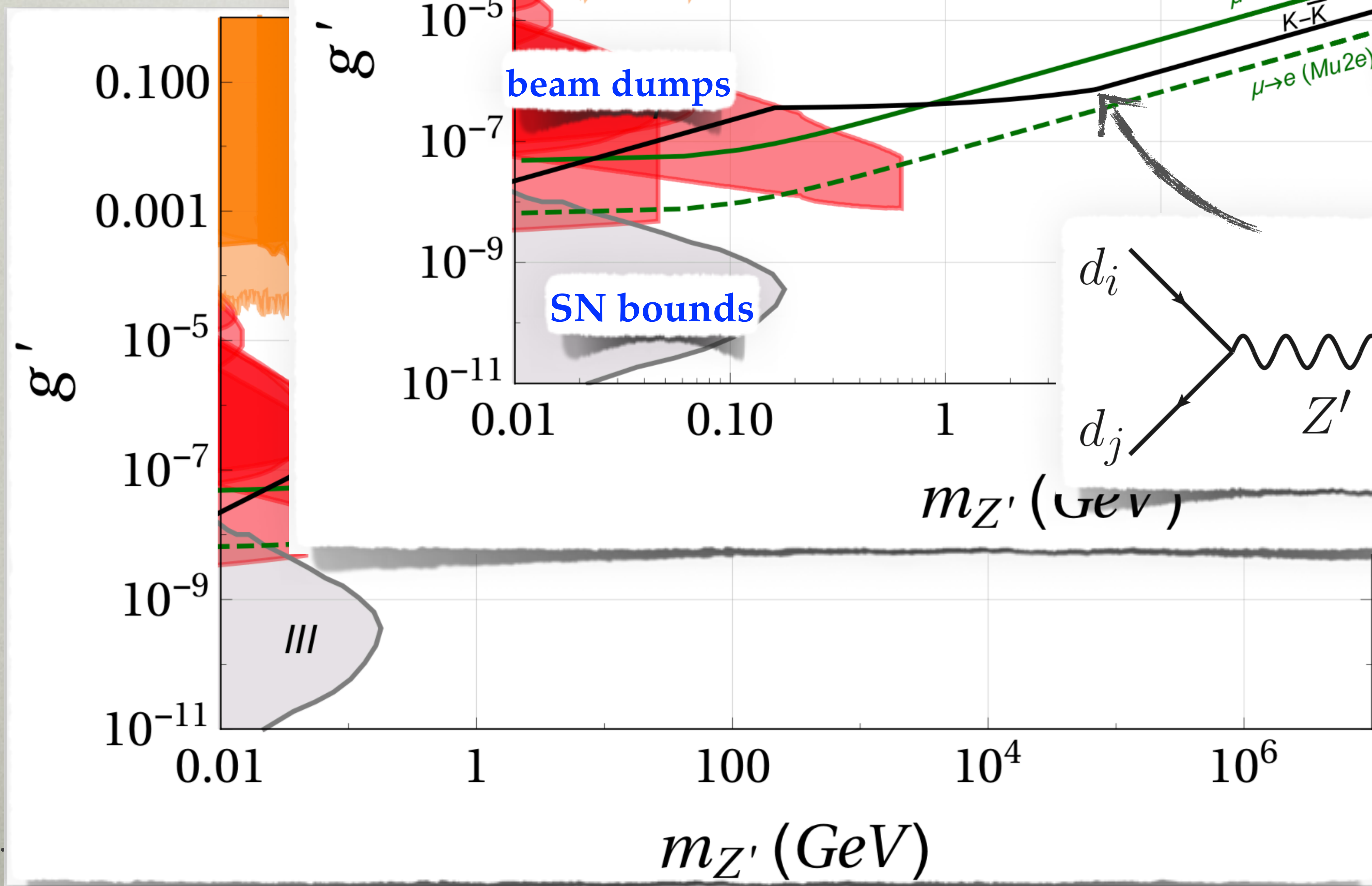

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10^4
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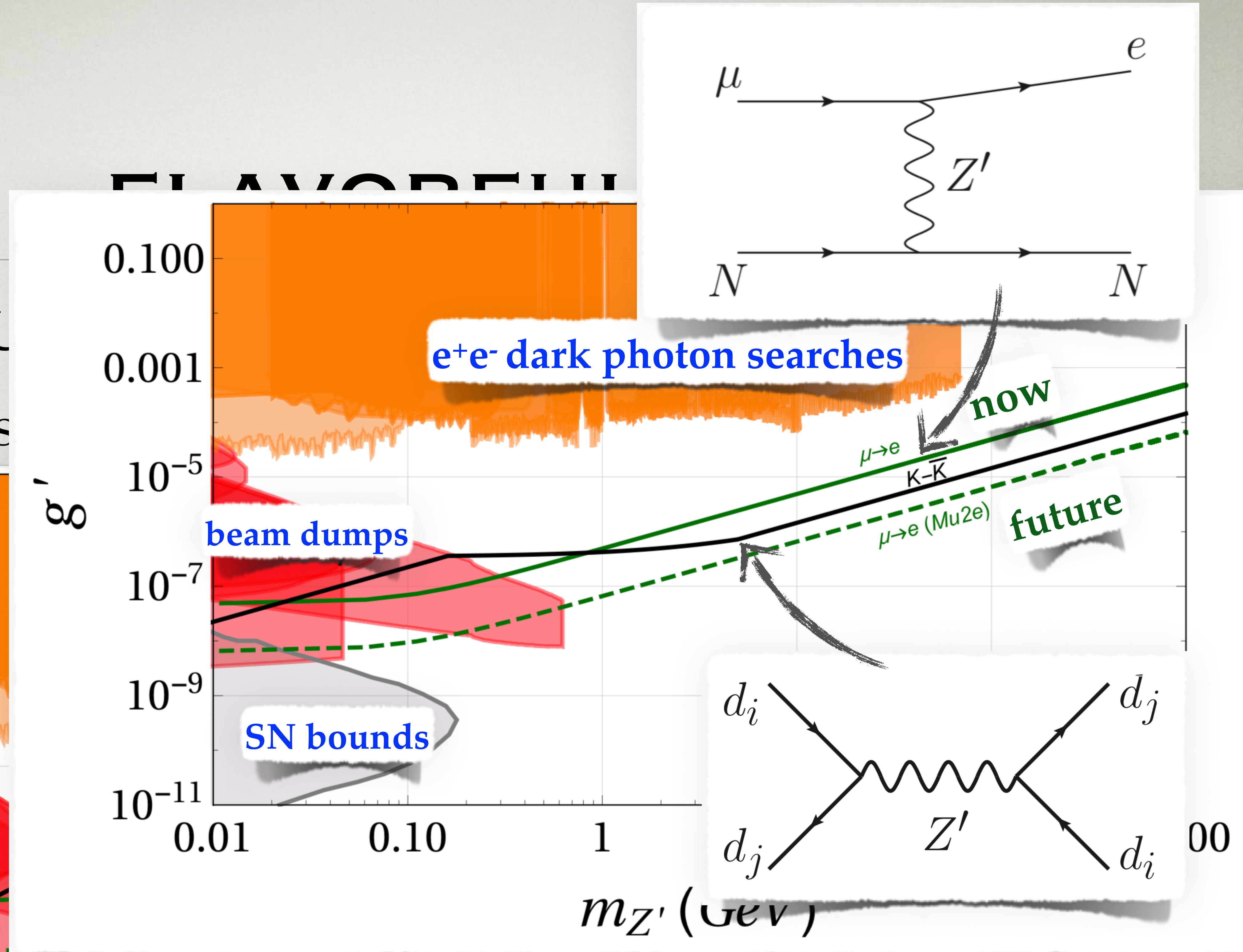
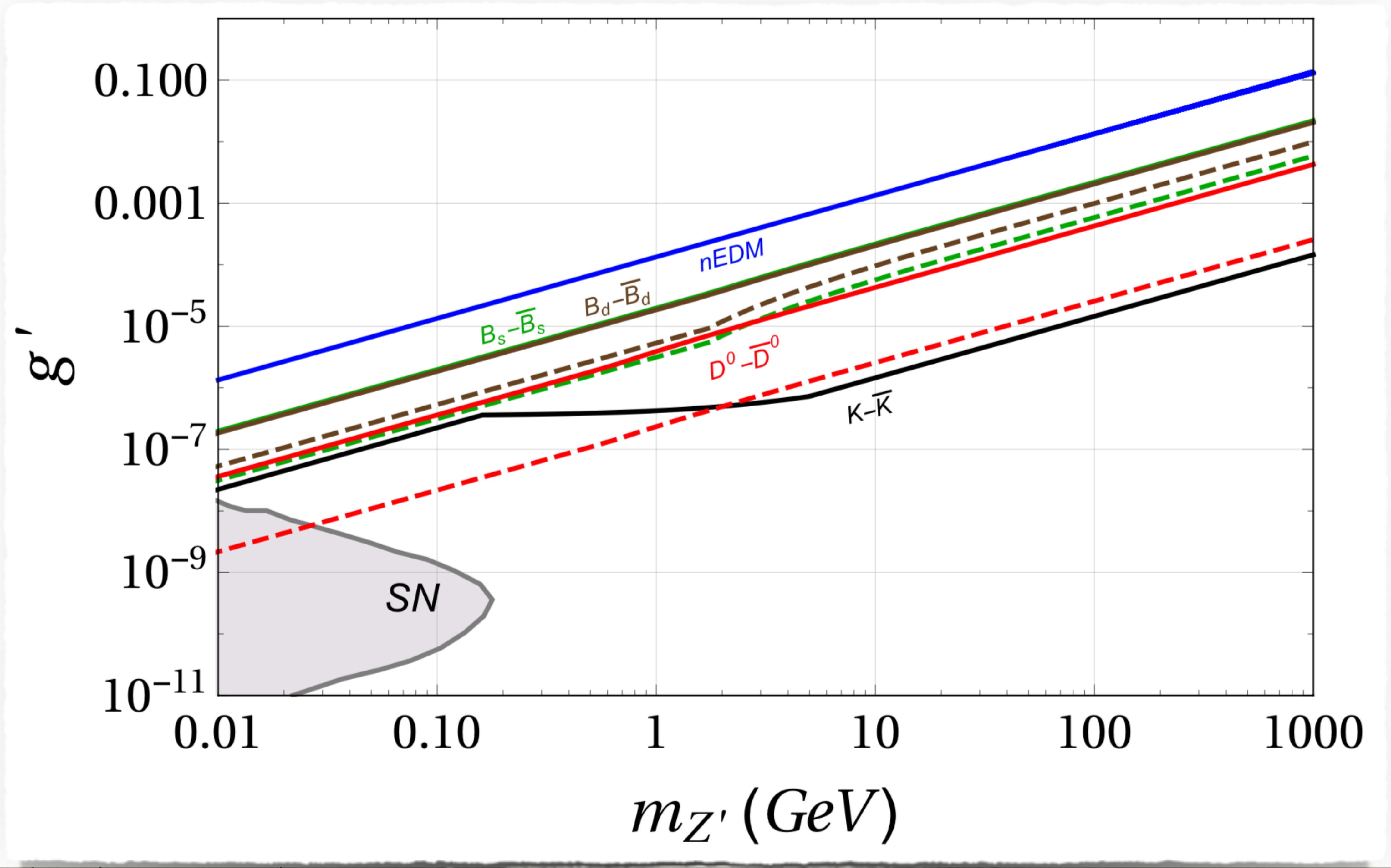
$m_{Z'}$ (GeV)



μ
e
Z'
N
N
e⁺e⁻ dark photon searches
now
$\mu \to e$
K–K̄
future
$\mu \to e$ (Mu2e)
beam dumps
SN bounds
d_i
d_j
d_j
d_i
Z'
0.100
0.001
10^{-5}
10^{-7}
10^{-9}
10^{-11}
g'
0.01
0.10
1
$m_{Z'}$

VARIANTS

- if only couplings to quarks



VARIANTS

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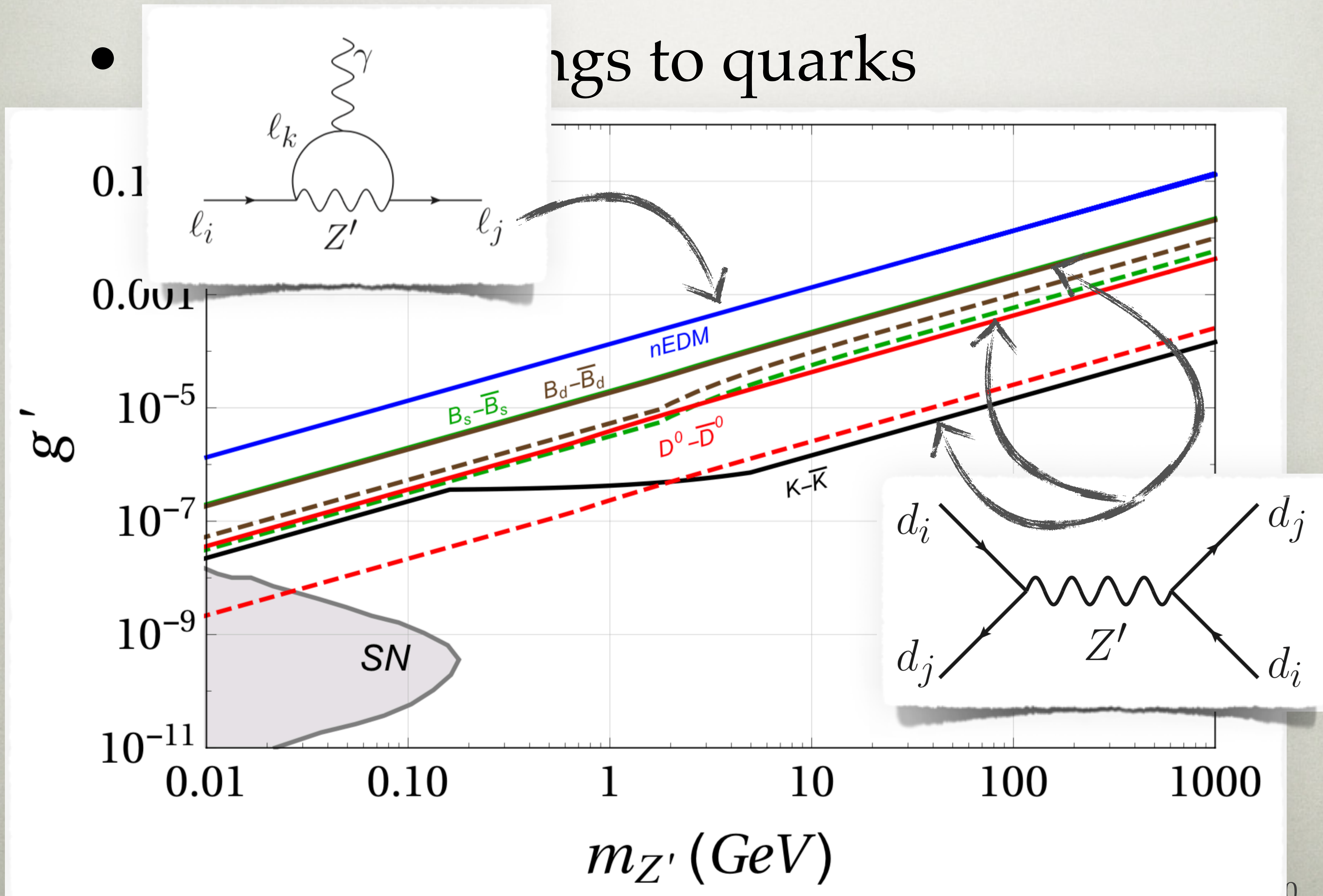
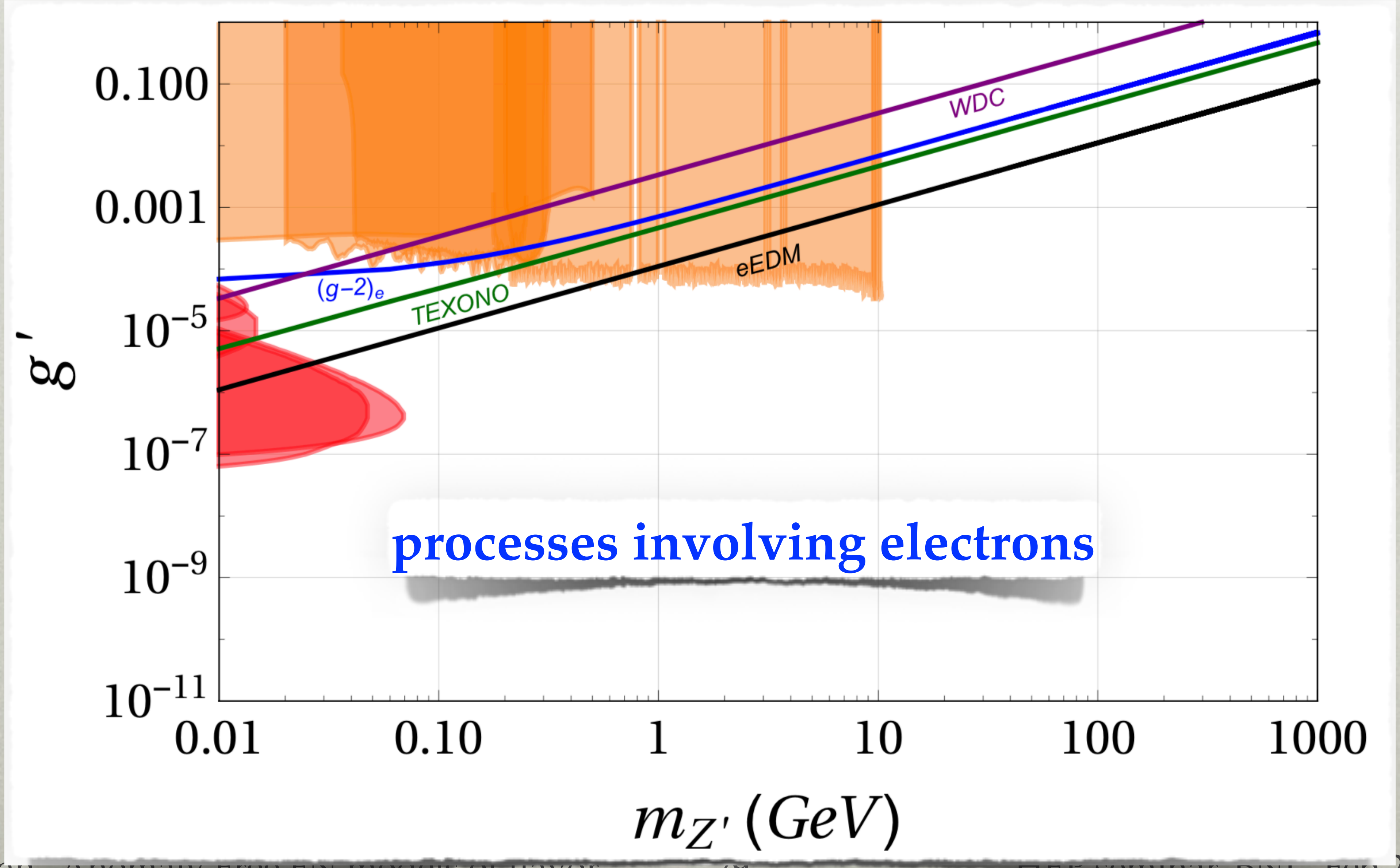


VARIANTS

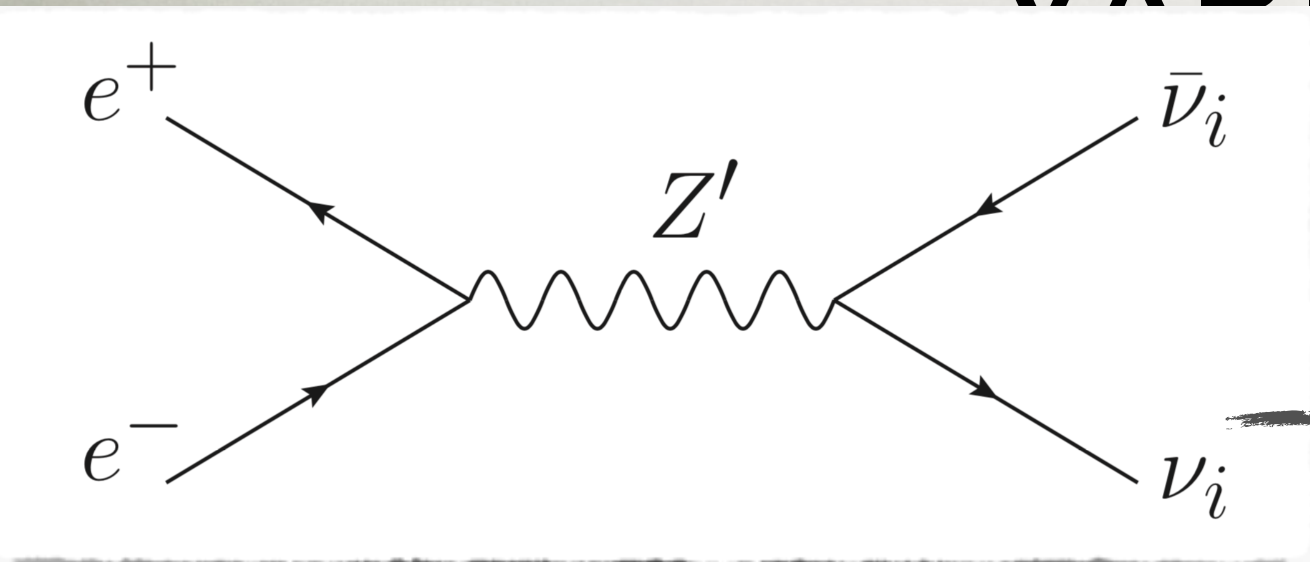
- same benchmark, highligting bounds from couplings to leptons

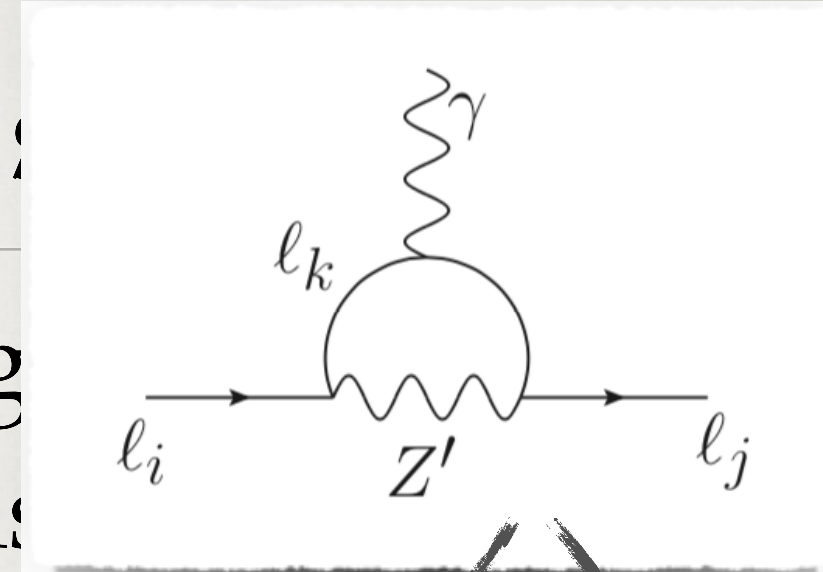


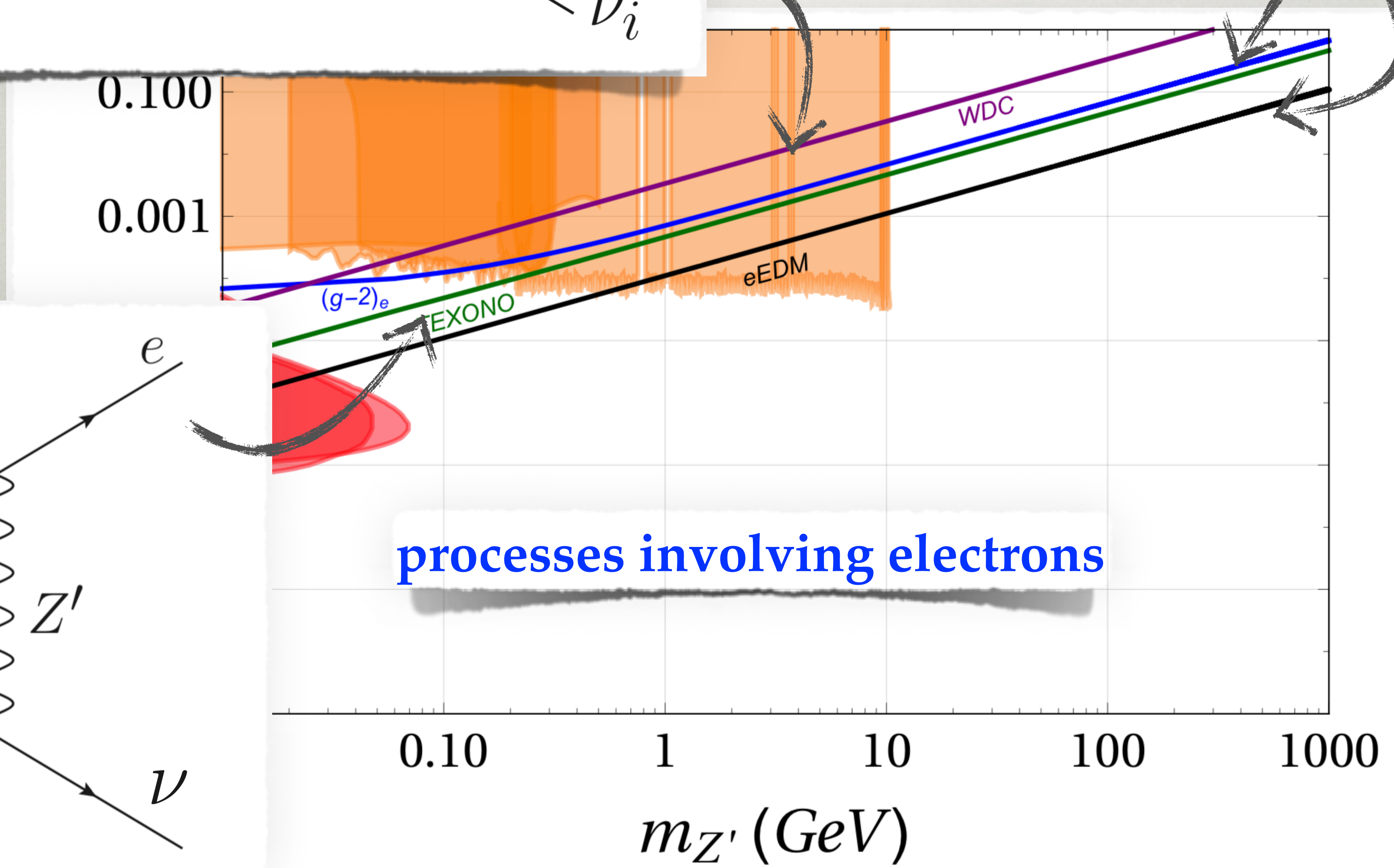
VARIANTS

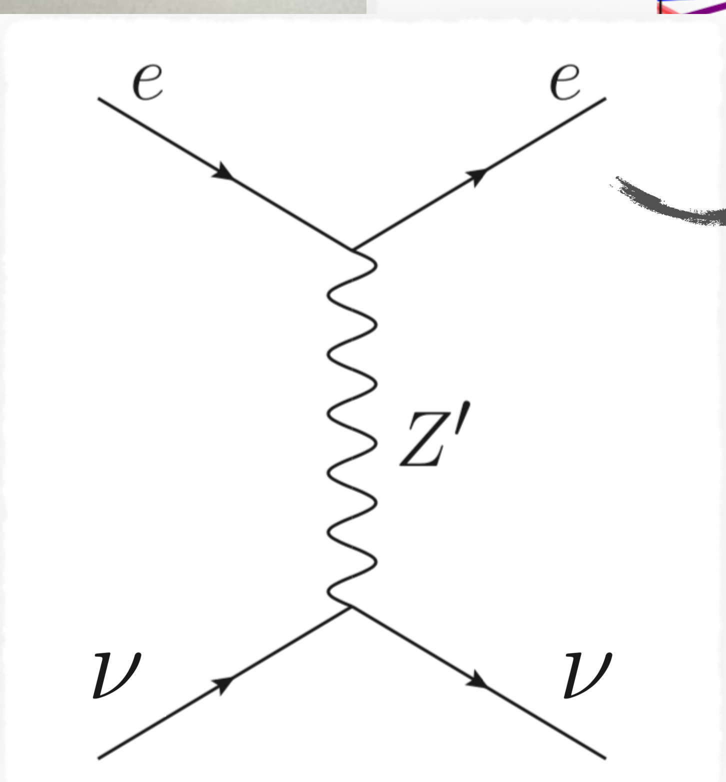
highlig

leptons









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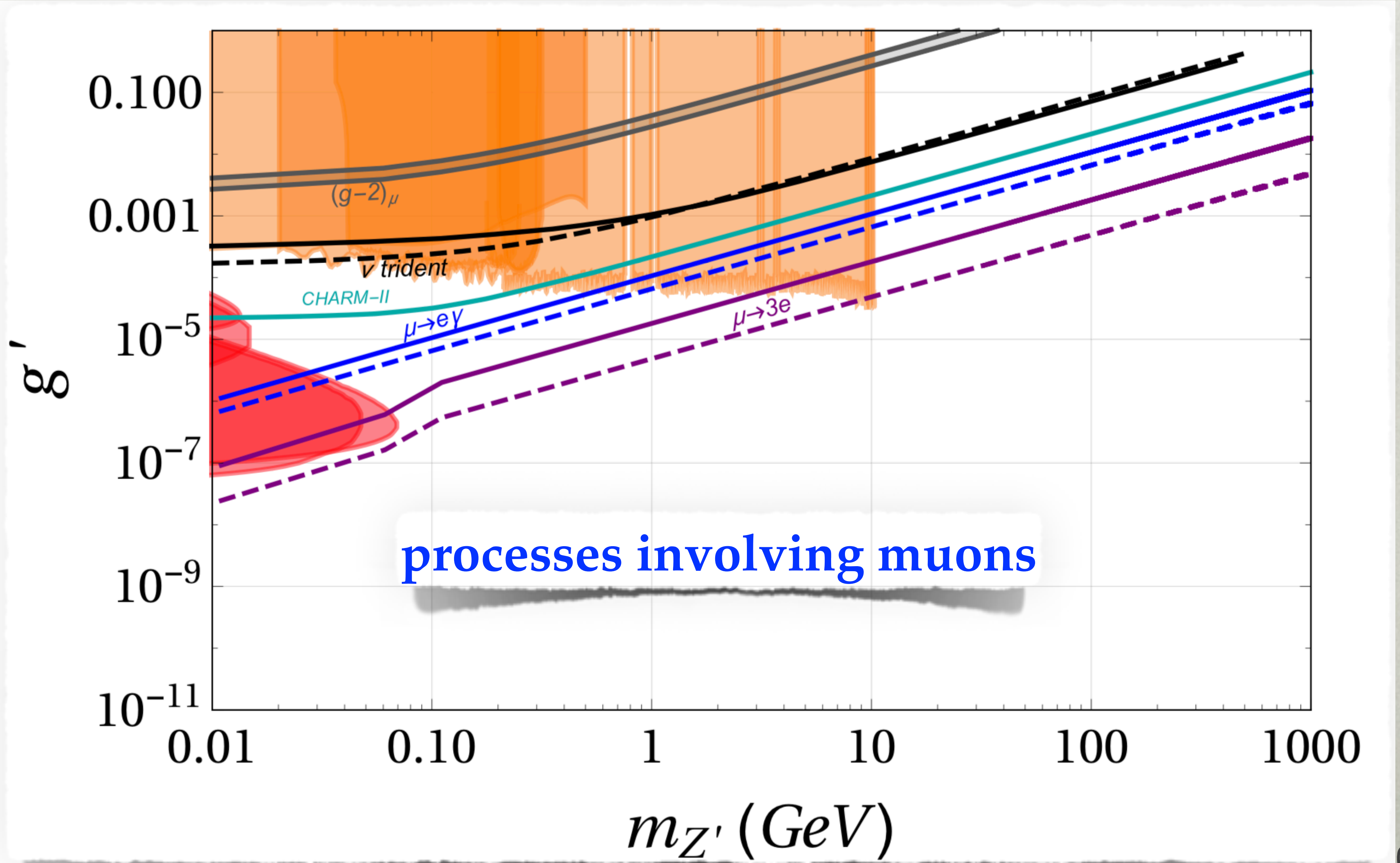

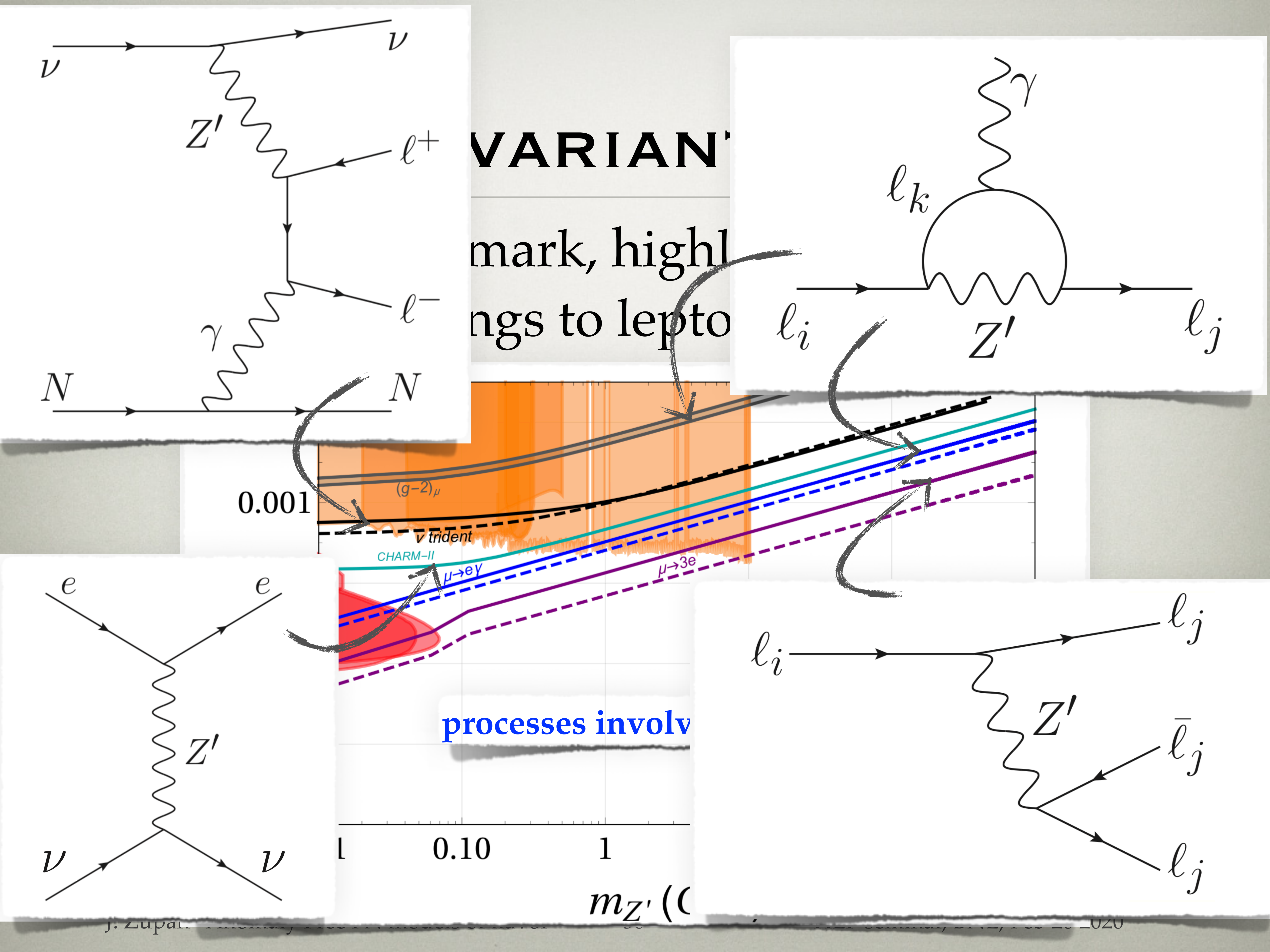

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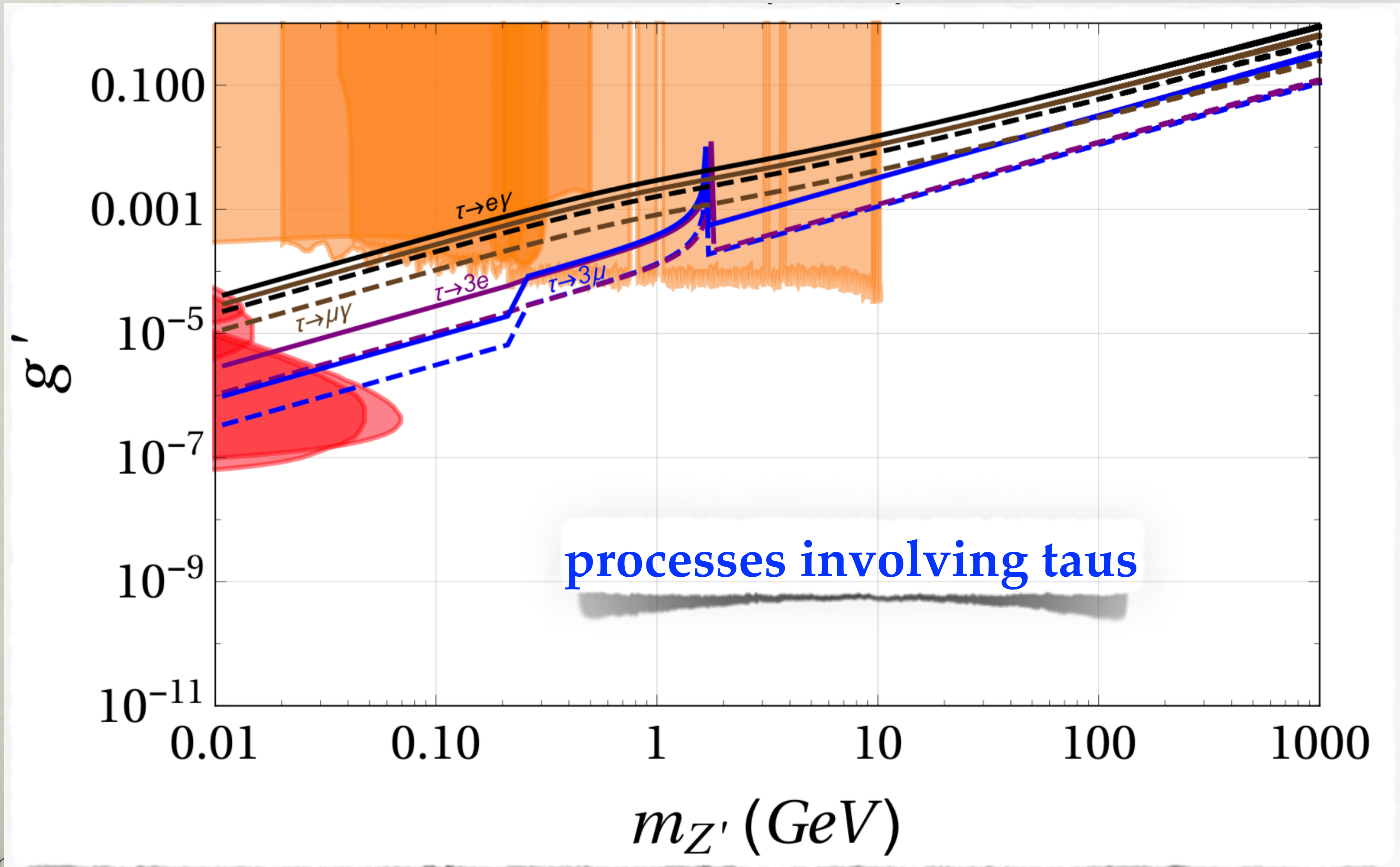
VARIANTS

- same benchmark, highligting bounds from couplings to leptons



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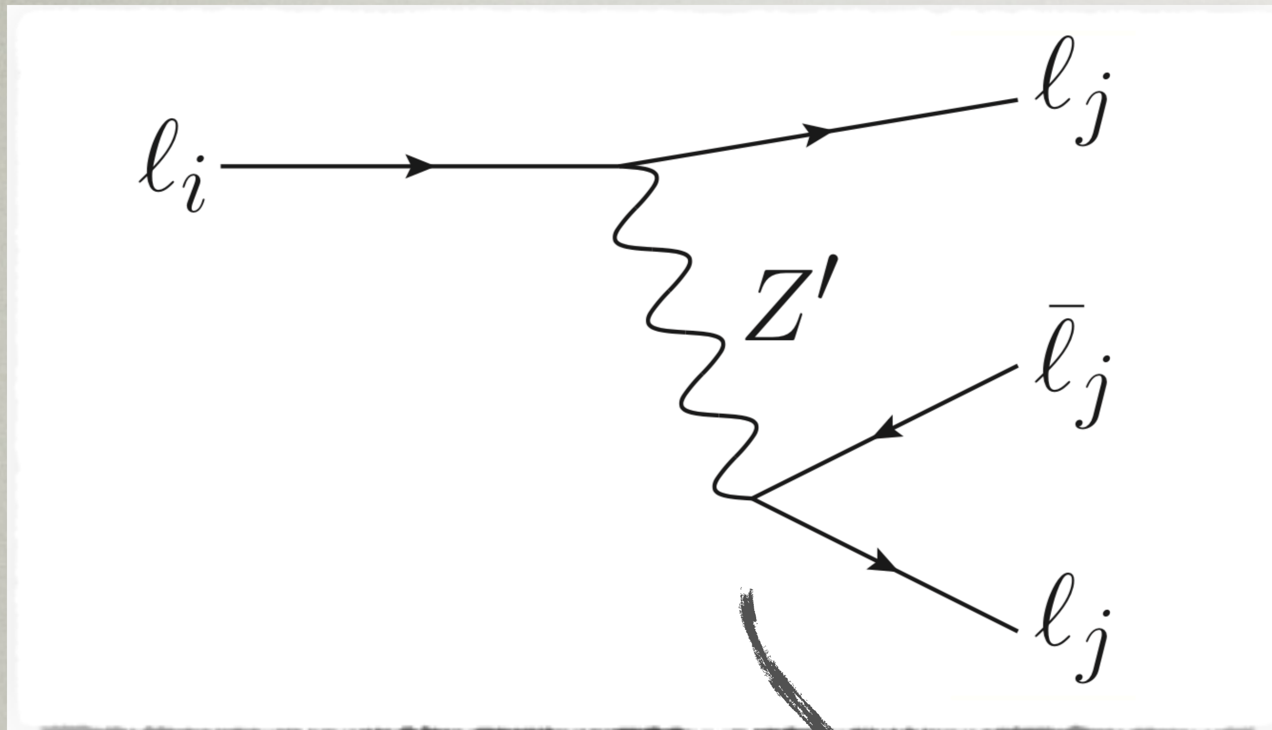
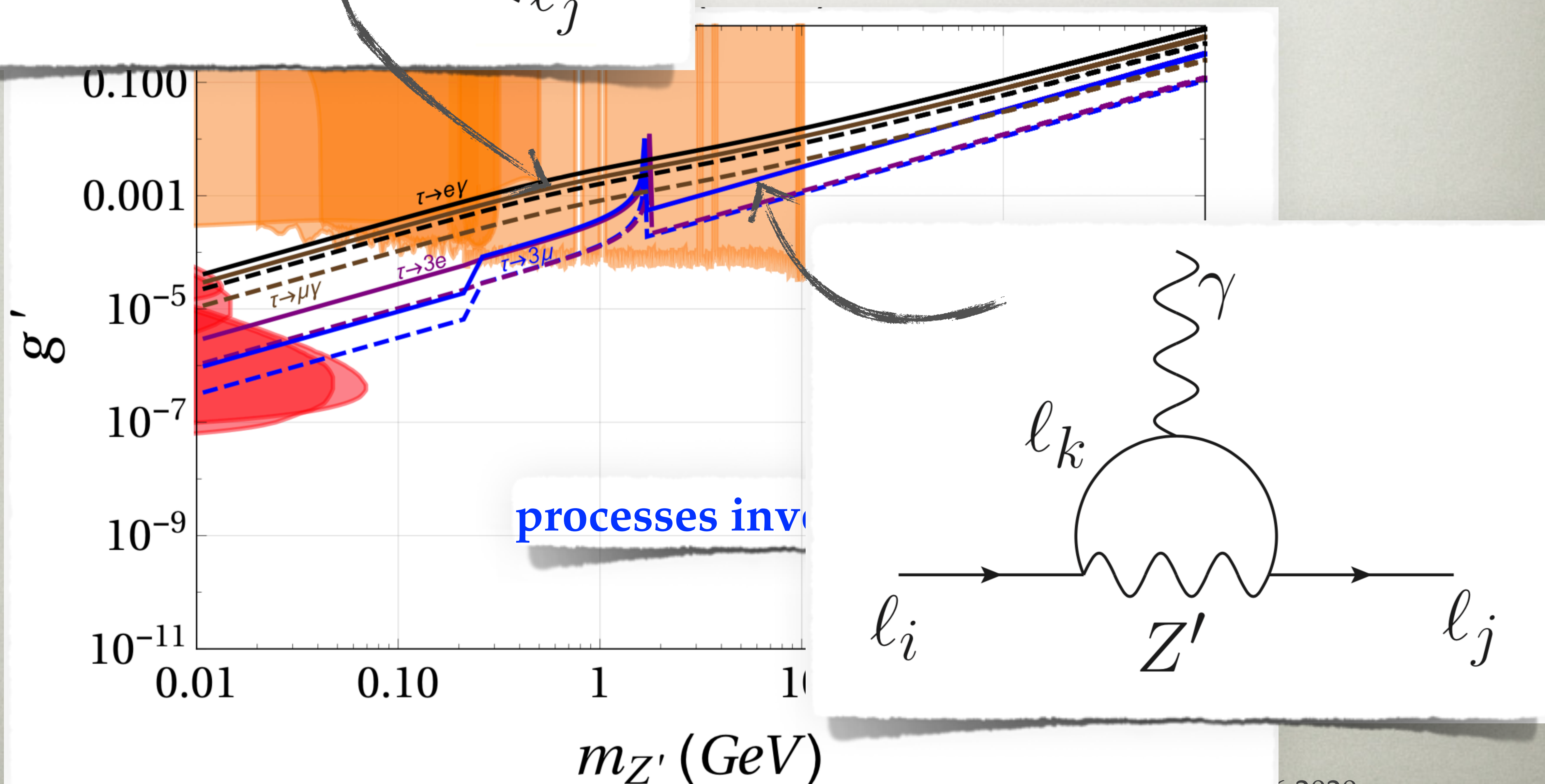
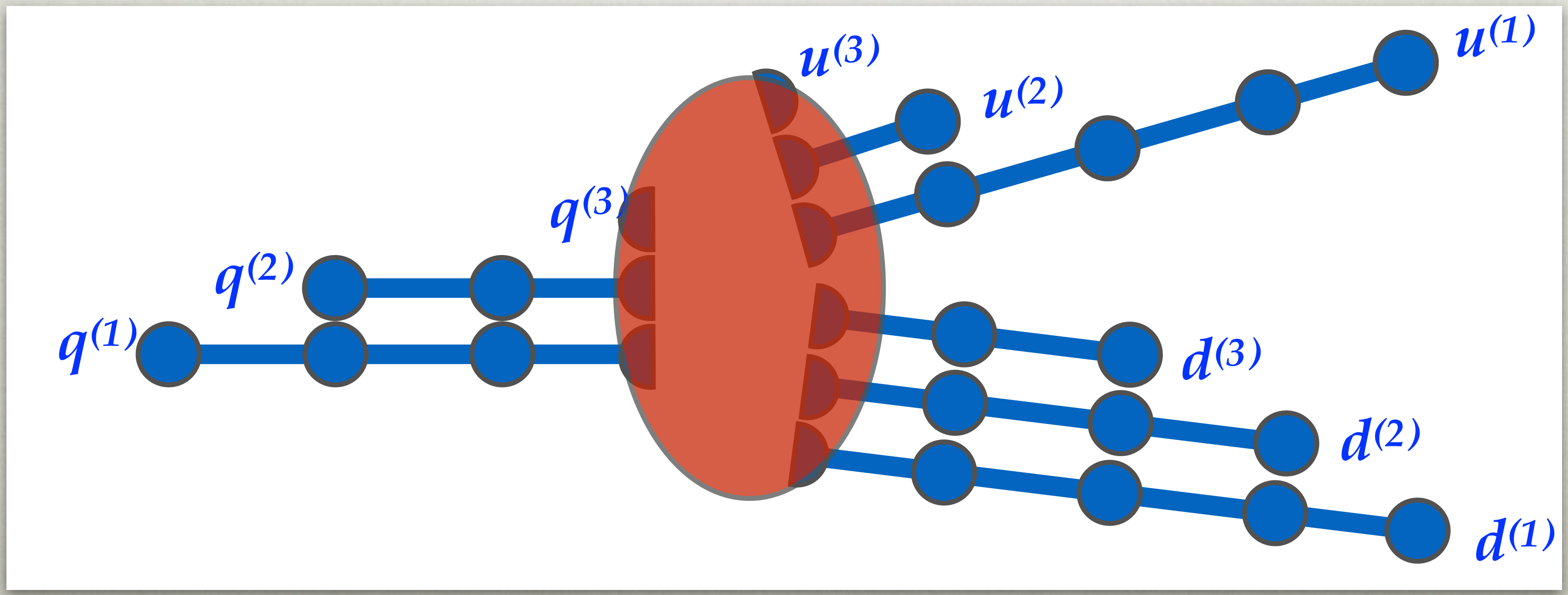




CLOCKWORK FLAVOR

CLOCKWORK FLAVOR

- "clockwork flavor"= inverted FN model in which
  - all the vectorlike Yukawas set to 1
  - the $U(1)^3$ symmetry is a global one
  - flavons are taken to be (more than) a loop factor heavier, so irrelevant
- the bare bones model for generating flavor hierarchies
  - minimal field content: only SM fermions + vectorlike fermions



LANDAU POLE

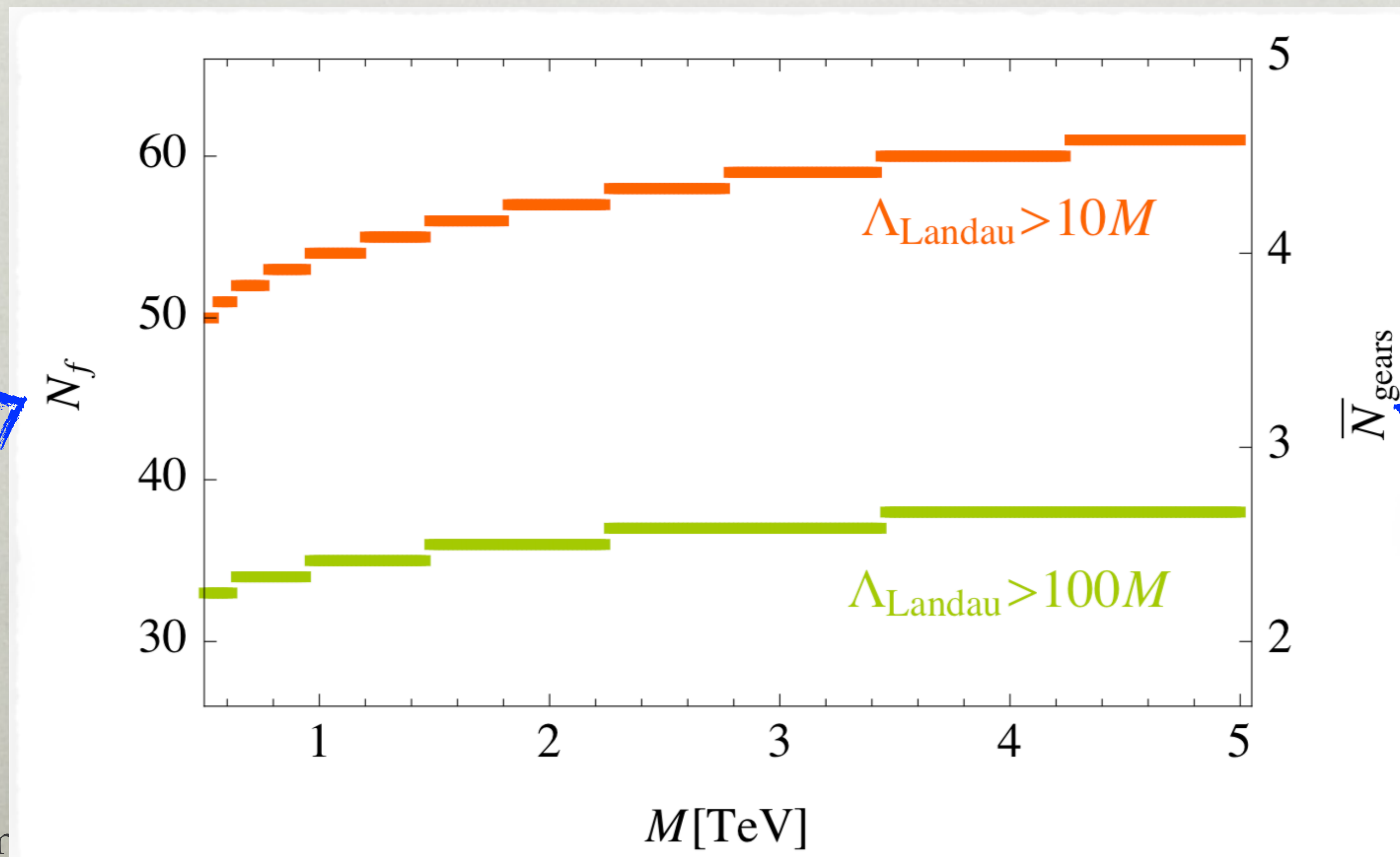
- many new colored fermions
- lead to Landau pole in α_S

$$\frac{d\alpha_s}{d\ln\mu} = -2\beta_0\frac{\alpha_s^2}{4\pi}, \quad \beta_0 = \frac{11N_c - 2N_f}{3},$$

- limits the number of gears

# of colored Dirac fermions

$$N_f = 6 + N_{\rm gears}$$

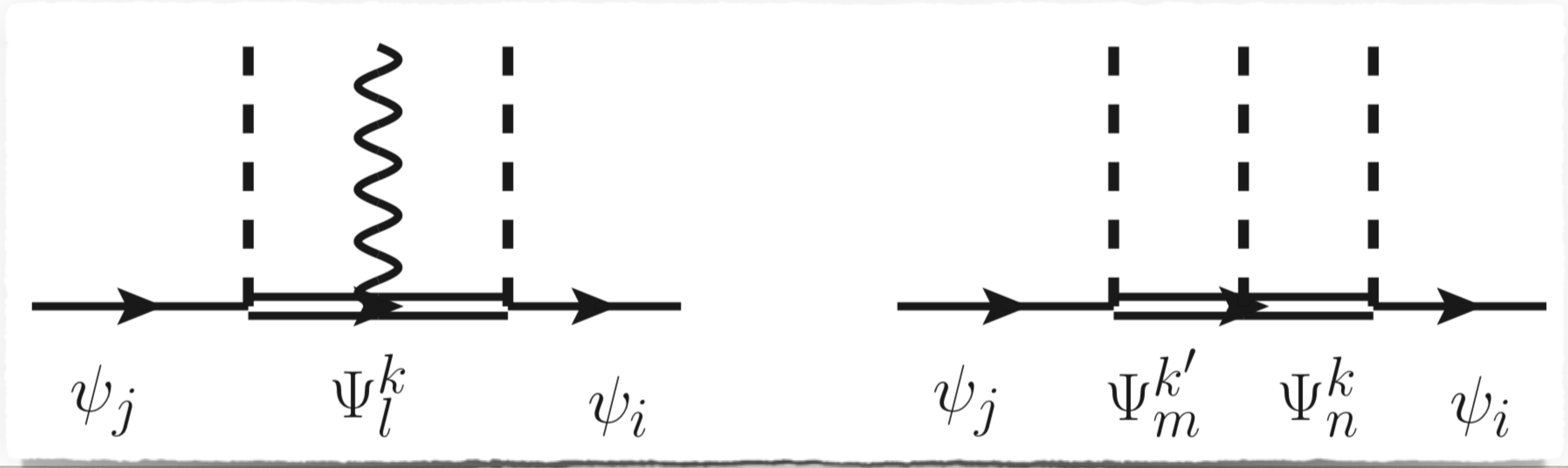


effective # of gears per quark flavor

$$\bar{N}_{\rm gears} \equiv N_{\rm gears}/12$$

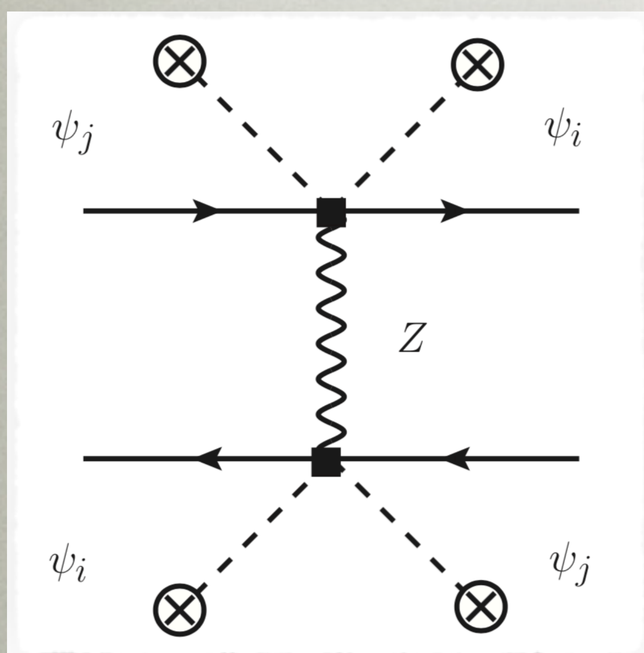
FLAVOR CONSTRAINTS

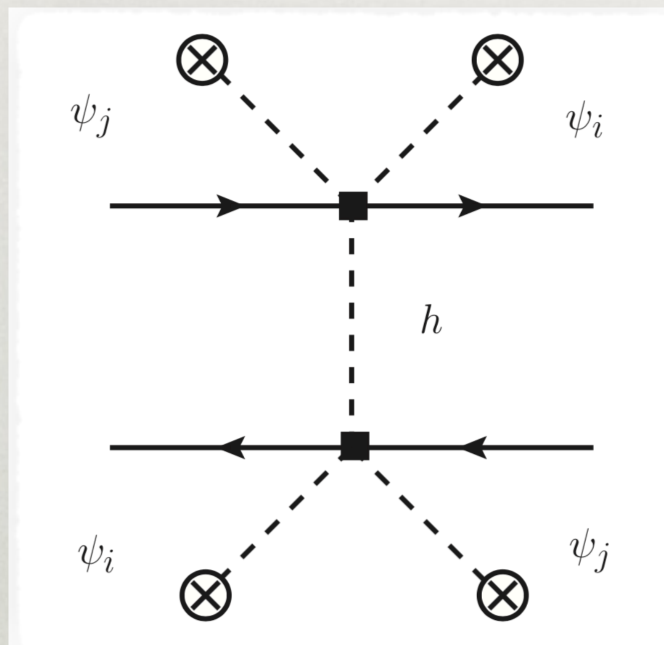
- all flavor violation from couplings to the Higgs
- induces FV couplings of Z and H
  - suppressed by $f_{\psi(i)}\, f_{\psi(j)}\, v^2/M^2$
  - $Z \to \bar{b}_L b_L$ most important bound on d-type gears

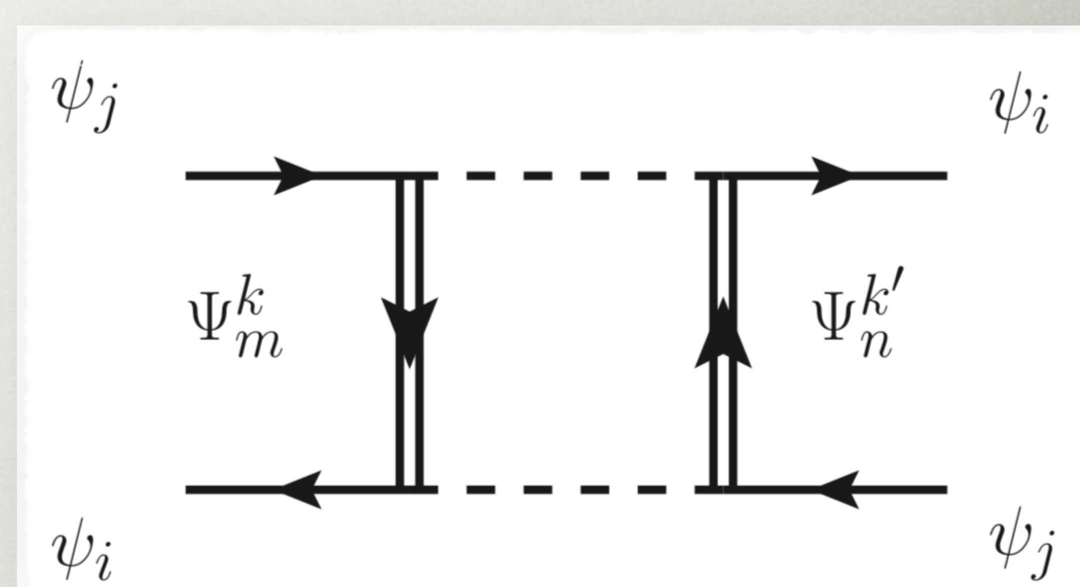


FLAVOR CONSTRAINTS

- B_s-$\bar{B}_s$, B_d-$\bar{B}_d$ mixing obs., ε_K most important bounds on *u*-type gears







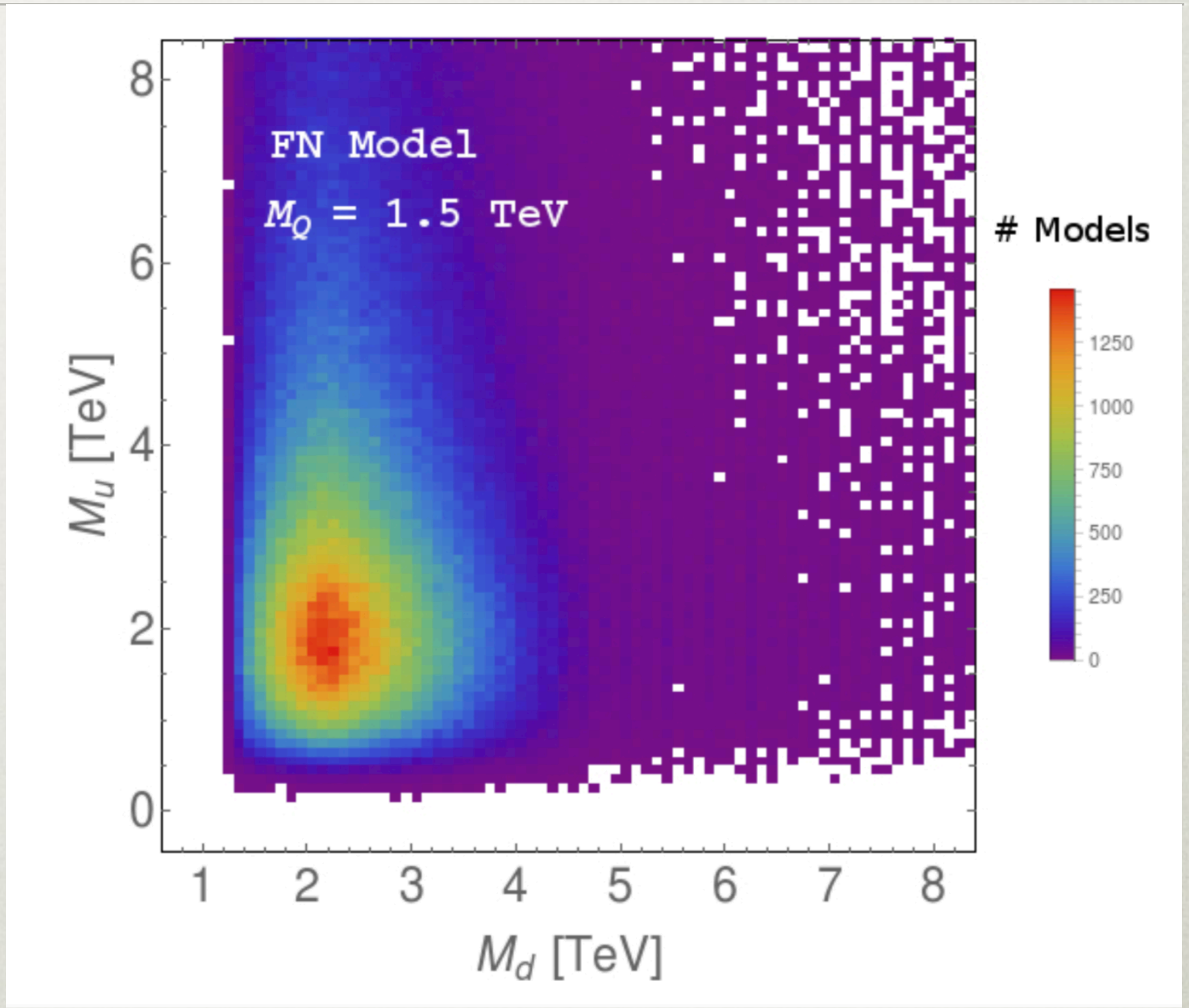
$\mathcal{O}(v^4/M^4)$

$(4\pi)^{-2} \times \mathcal{O}(v^2/M^2)$

- for *q*-type gears direct searches the most important

ALL FLAVOR CONSTRAINTS

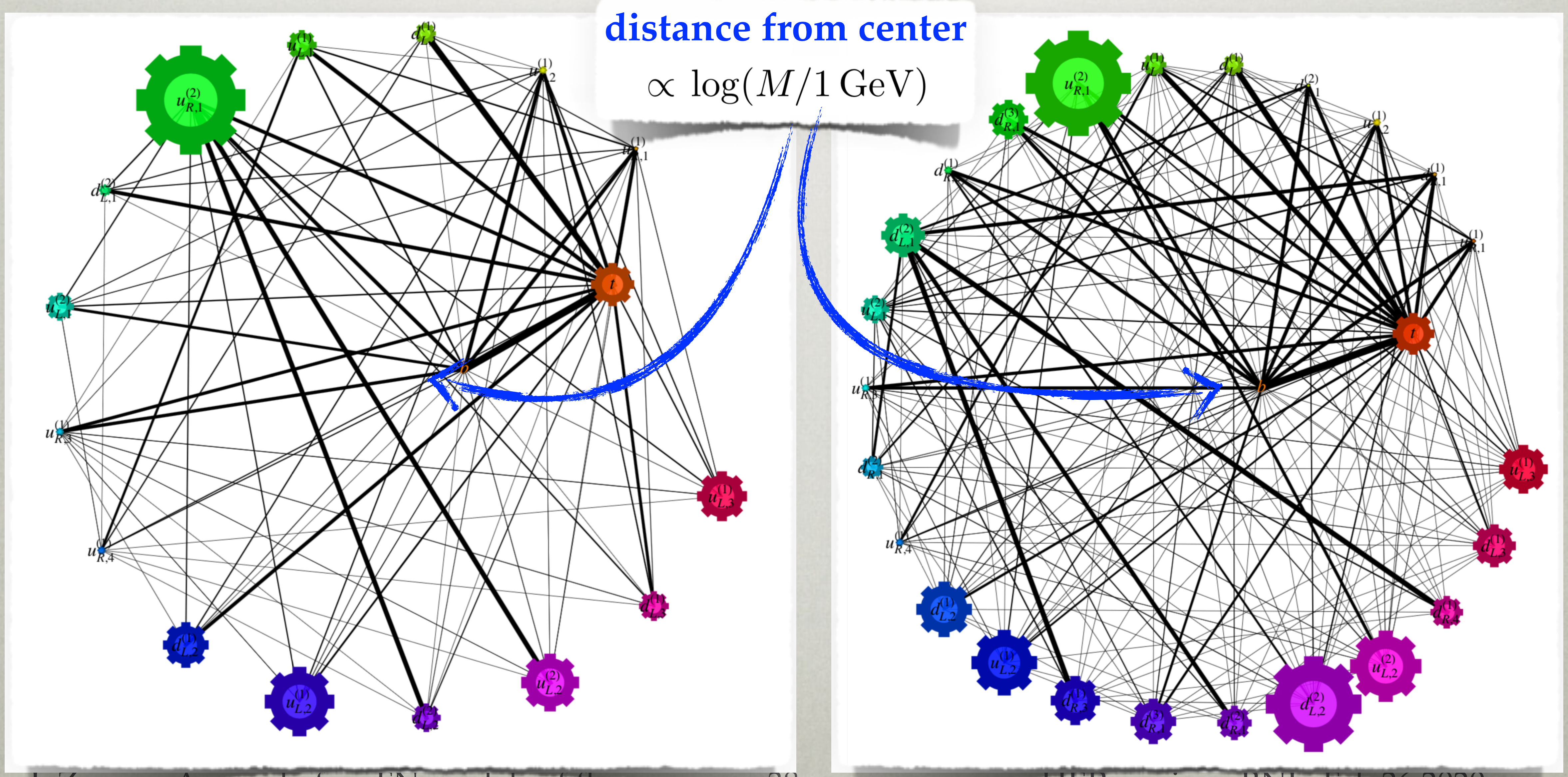
- perform a scan, fixing M_Q=1.5TeV



- choose 2 benchmarks
  - benchmark 1: $M_Q^{(1)}$ = 1.50 TeV,..., $M_U^{(1)}$ = 1.33 TeV,.., $M_D \to \infty$
  - benchmark 2: $M_Q^{(1)}$ = 1.50 TeV,..., $M_U^{(1)}$ = 1.33 TeV,.., $M_D \to$1.52 TeV

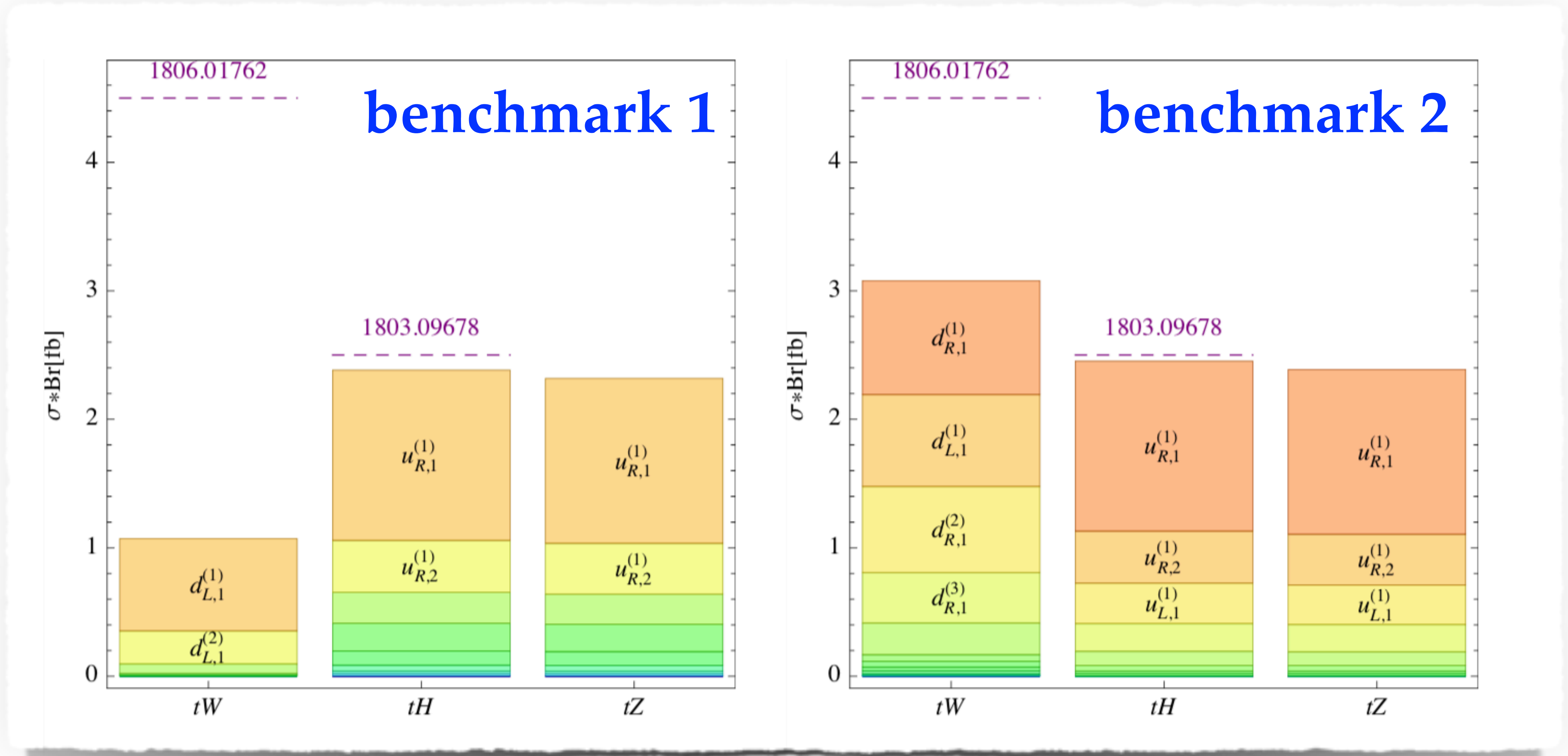
DECAY PATTERNS

- many gears accessible at the LHC
- relatively complicated decay patterns
  - for instance $u_{L,i}^{(n)} \to u_{R,i}^{(n')} H,\ u_{L,i}^{(n')} Z,\ d_{L,i}^{(n')} W$



LHC production

- gears pair produced at the LHC
- most sensitive searches $d_{L,i}{}^{(n)} \to tW+X$, $u_{L/R,i}{}^{(n)} \to tH+X$, $tZ+X$
- can recast leptoquark searches by ATLAS
- many gears contribute to total cross sections

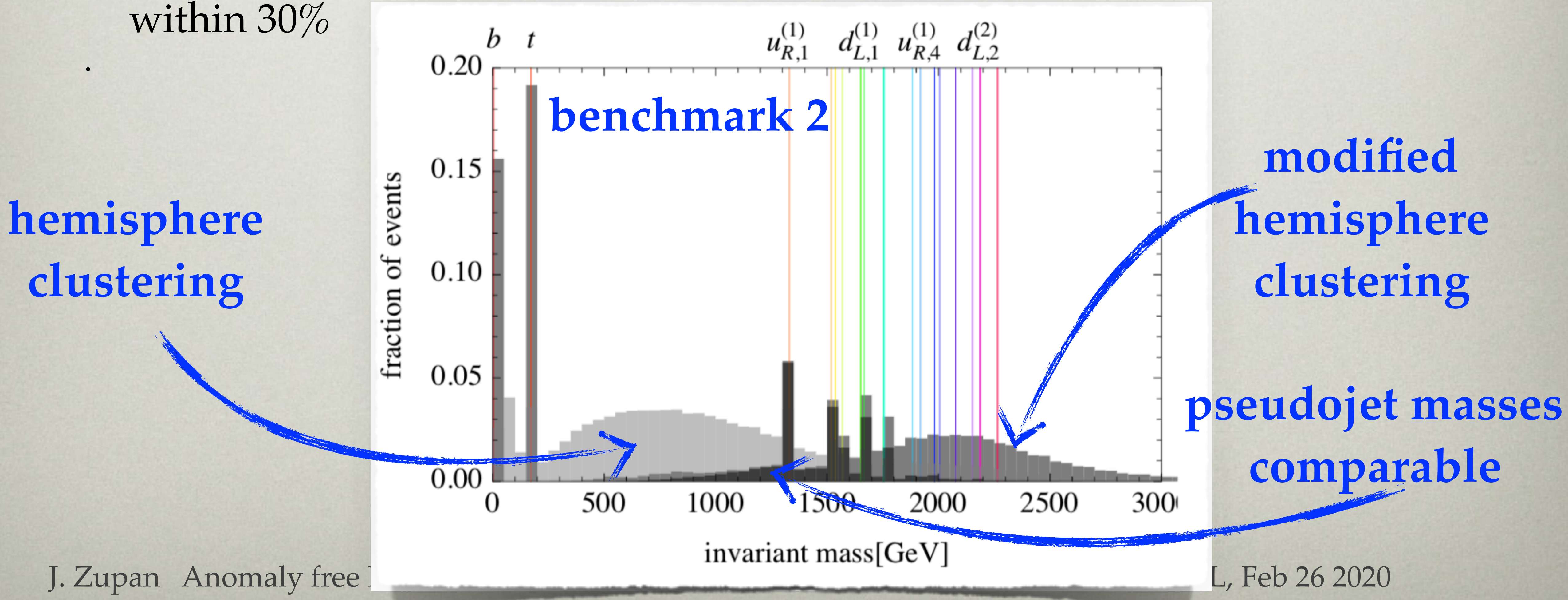


HOW TO SEARCH FOR GEARS AT THE LHC?

Alonso, Carmona, Dillon, Kamenik, Camalich, JZ, 1807.09792

- modified hemisphere clustering could reveal individual gears
    - hemisphere clustering: all objects clustered into exactly two pseudojets, seeds have the largest combined invariant mass
    - modified hemisphere clustering: seeds are the two t and/or b jets
- keep only events where invariant masses of the two pseudojets are within 30%

.



AXIFLAVON AND TRADITIONAL FN MODELS

STRONG CP PROBLEM

- Lorentz and gauge invariance allow a CP violating term in QCD

$$\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{a,\mu\nu} = \theta \frac{\alpha_s}{16\pi} \epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}$$

    - physically observable is the combination

$$\bar{\theta} \equiv \theta + \arg\det(\mathcal{M}_u \mathcal{M}_d)$$

- experimentally :

$$d_n \approx 4 \times 10^{-16} \bar{\theta}\, e\,\mathrm{cm} \quad \longleftrightarrow \quad |d_n|_{\rm exp} < 3 \times 10^{-26}\, e\,\mathrm{cm}$$

- why $\bar{\theta}$ so small?

$$\bar{\theta} < 10^{-10}$$

    - very puzzling given large CPV phase in the CKM

AXION

Peccei, Quinn, PRL 38, 1440 (1977)
Weinberg, PRL 40, 223, (1978)
Wilczek, PRL 46, 279 (1978)
Vafa, Witten, PRL 53, 535 (1984)

- if $\bar{\theta}(x)$ a dynamical field and couples only to $\bar{\theta} G\tilde{G} \Rightarrow$ potential min. at $\bar{\theta}(x) = 0$
  - new ultra-light particle - axion

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F} + \frac{\partial_\mu a}{2f_a}\,\bar{f}_i\gamma^\mu(C^V_{f_i f_j} + C^A_{f_i f_j}\gamma_5)f_j$$

  - obtains mass from QCD anomaly

$$m_a = 5.70(7)\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

  - viable cold dark matter candidate for

$$10^{-8}\,\text{eV} \lesssim m_a \lesssim 10^{-3}\,\text{eV}$$

AXIFLAVON

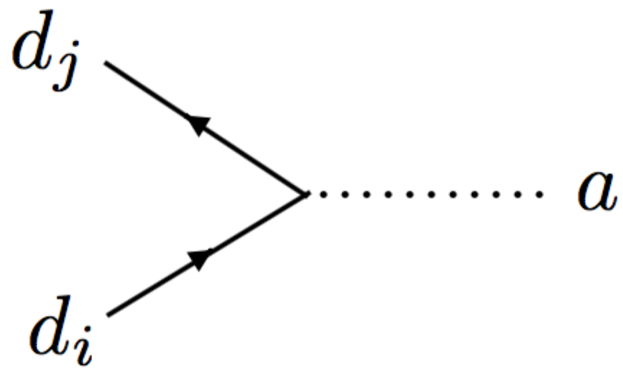
- ingredients for axion mechanism
  - need a global PQ symmetry that is spontaneously broken $\Rightarrow$ Goldstone boson is the axion
  - global symmetry needs to be anomalous under QCD
- flavor symmetries that explain Yukawa hierarchies have a QCD anomaly
- axiflavon mechanism: identify PQ symmetry with FN $U(1)_H$
  - the phase of the flavon is the QCD axion = axiflavon

$$\Phi = \frac{f + \phi(x)}{\sqrt{2}} e^{ia(x)/f}$$

Wilczek, PRL 49, 1549 (1982)
Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040
Ema, Hamaguchi, Moroi, Nakayama, 1612.05492

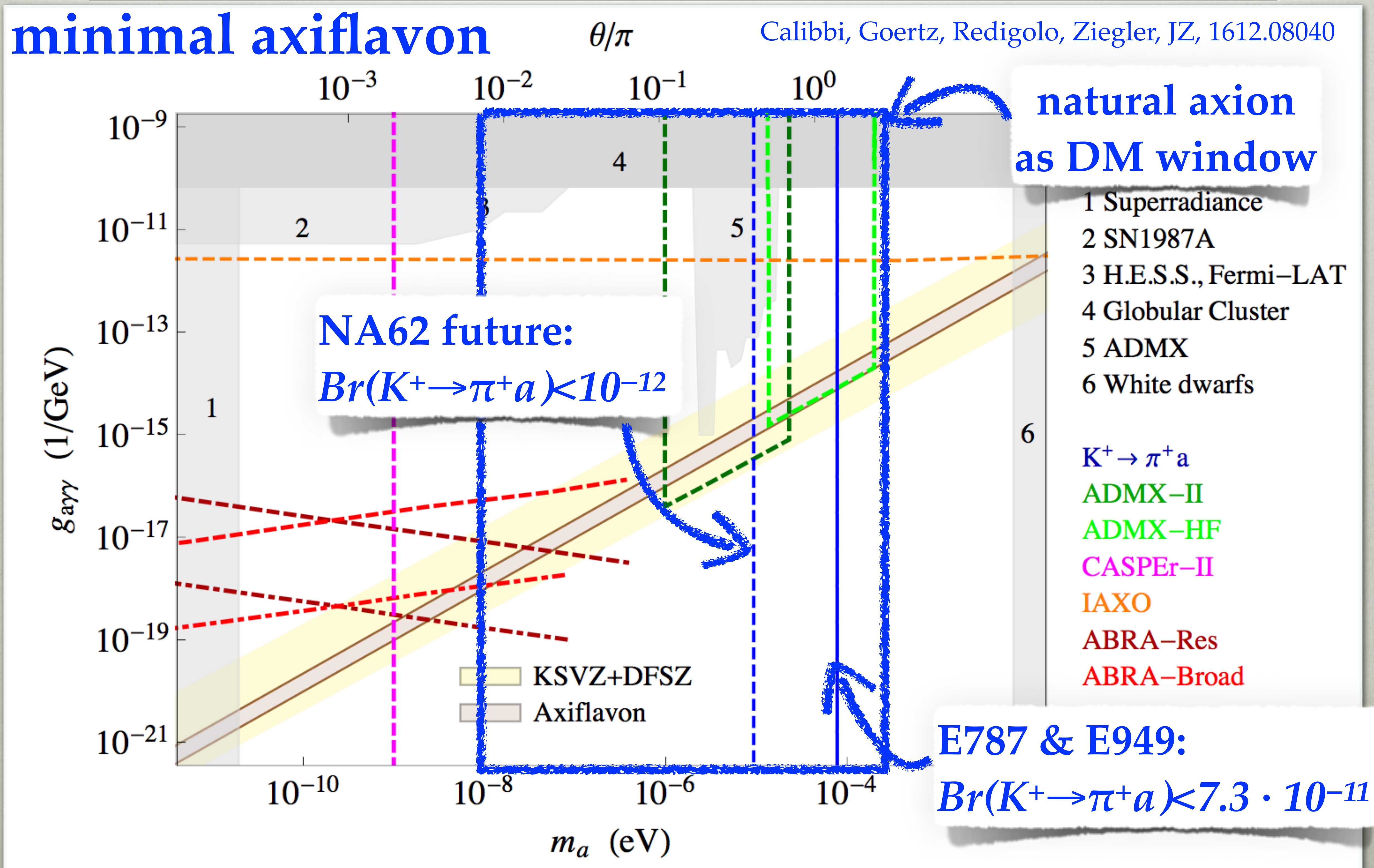
SEARCHING FOR AXIONS/ AXIFLAVONS

- axion searches use
  - couplings to photons (haloscopos, helioscopes,...)
  - couplings to gluons (CASPEr)
  - flavor diagonal couplings to electrons, nucleons (astrophysical bounds)
- axiflavon
  - in additon flavor violating couplings to fermions
  - in the minimal FN axiflavon model



$$\sim \frac{\sqrt{m_i m_j}}{f_a} \sim \frac{m_a}{\mu\mathrm{eV}} \frac{\sqrt{m_i m_j}}{10^{12}\mathrm{GeV}}$$

SEARCHING FOR AXIONS/ AXIFLAVONS



CONCLUSIONS

- identified a new class of Froggatt-Nielsen models of flavor
  - expansion in $M/\langle\phi\rangle$
- connection to clockwork when flavon is parametrically heavier than vectorlike fermions
- could be searched for using FCNCs
- a wider set of experiments sensitive if Z's light: FCNCs, beam dumps, e^+e^- collisions, astrophysics

BACKUP SLIDES