Flavor and CP violation in the dark sectors

Jure Zupan
U. of Cincinnati

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MAIN IDEAS / THEMES

- flavor physics could be instrumental in searches for dark sector*/dark matter
  - if light, dark sector particles can be produced in FV rare decays
    - axiflavon
    - heavy neutral leptons
    - light scalar mixing with the higgs
    - dark photon
  - sensitivity to dark sectors through off-shell mediators
    - loops: DM+mediators, example: $(g\text{-}2)_\mu$
    - tree: mediators, example: Z' from a gauged flavor group
  - baryogenesis/leptogenesis assisted by dark sectors
  - stability of dark matter could be due to flavor symmetries

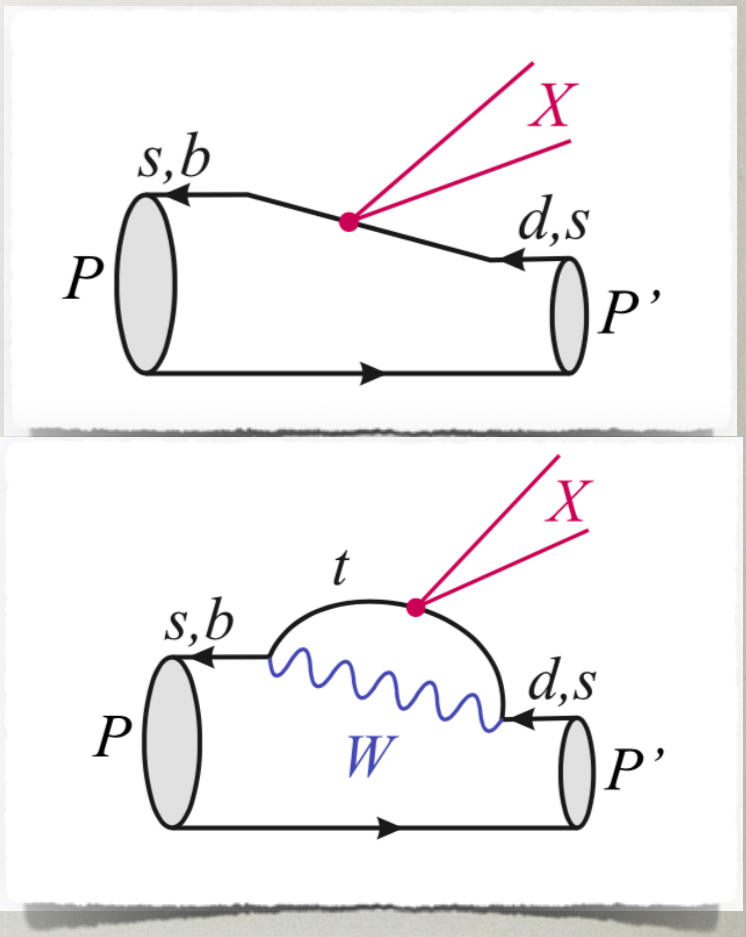
*here dark sector: any sector feebly coupled to the SM that can act as a portal to DM

DARK MATTER IN RARE DECAYS

DARK MATTER IN RARE DECAYS

see, e.g., Bird et al, hep-ph/0401195; Kamenik, Smith, 1111.6402

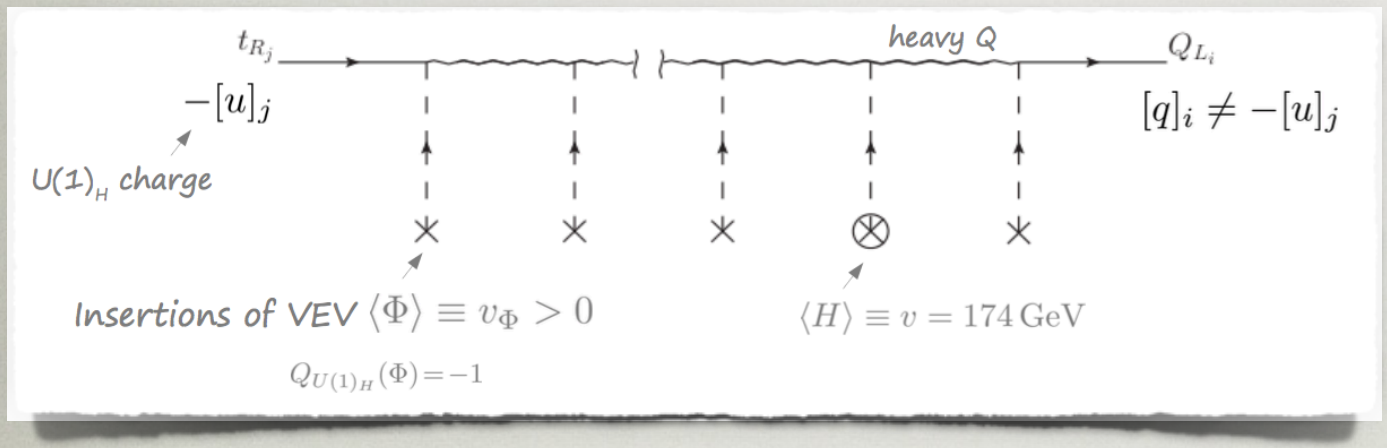
- DM could be produced at tree level, if FV couplings
- for flavor diagonal couplings DM can be produced at 1 loop
- X can be (pseudo-)scalar, (axial-) vector mediator
  - can decay to DM or visible



AXIFLAVON

- flavor symmetries that explain Yukawa hierarchies have a QCD anomaly
  - example FN models of flavor

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



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

$$\epsilon \equiv \frac{\phi}{\Lambda_F}$$

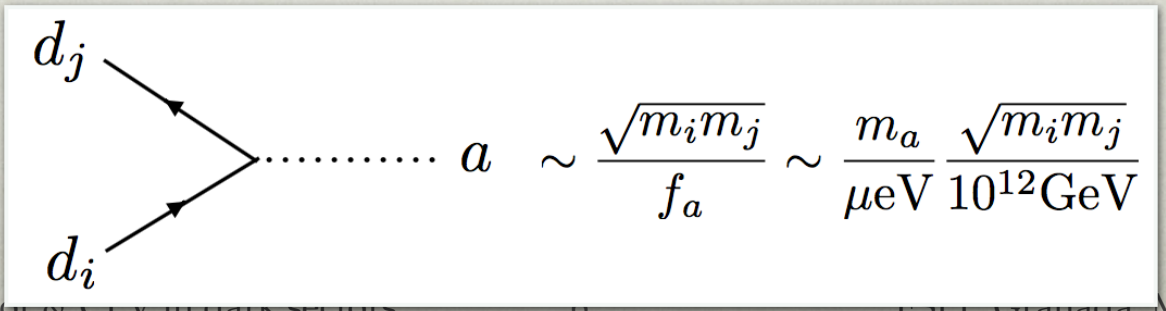
- axiflavon mechanism: identify PQ symmetry with FN $U(1)_H$
  - the phase of the flavon is the QCD axion = axiflavon

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

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

SEARCHING FOR AXIONS/ AXIFLAVONS

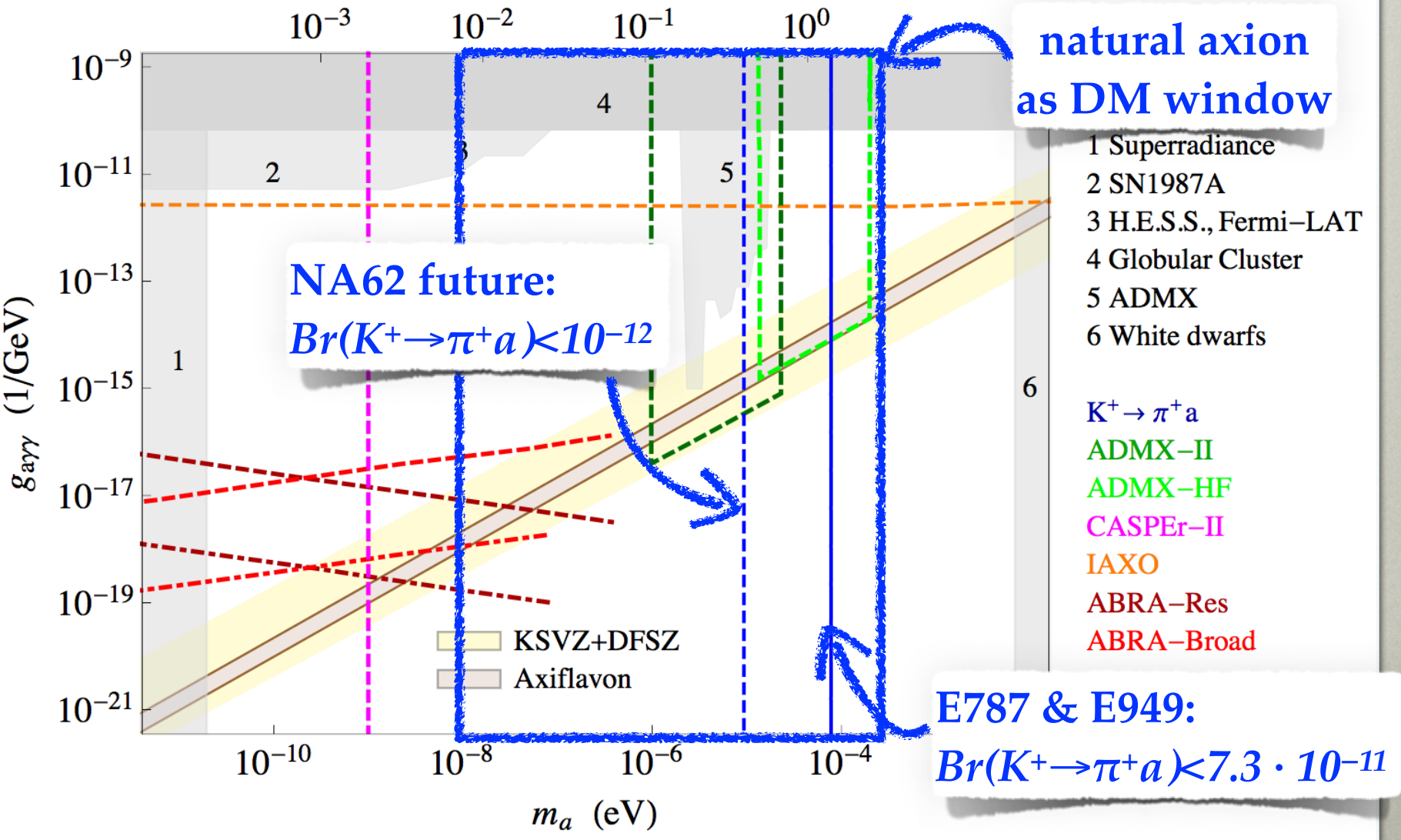
- axion searches use
  - couplings to photons (haloscopos, helioscopes,...)
  - couplings to gluons (CASPEr)
  - flavor diagonal couplings to electrons, nucleons (astrophysical bounds)
- axiflavon
  - in additon flavor violating couplings to fermions
  - in the minimal FN axiflavon model



SEARCHING FOR AXIONS/ AXIFLAVONS

minimal axiflavon

Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040

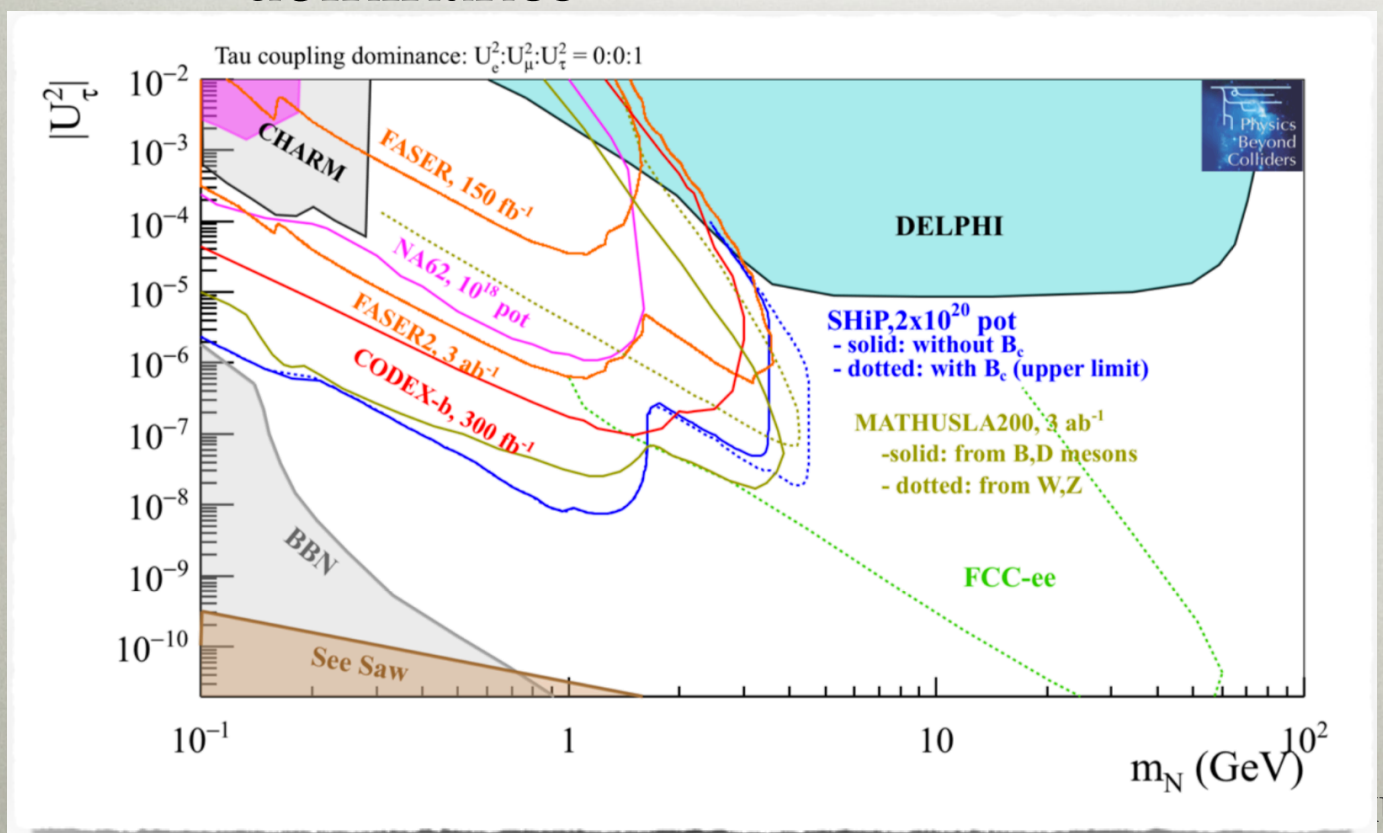


HEAVY NEUTRAL LEPTONS

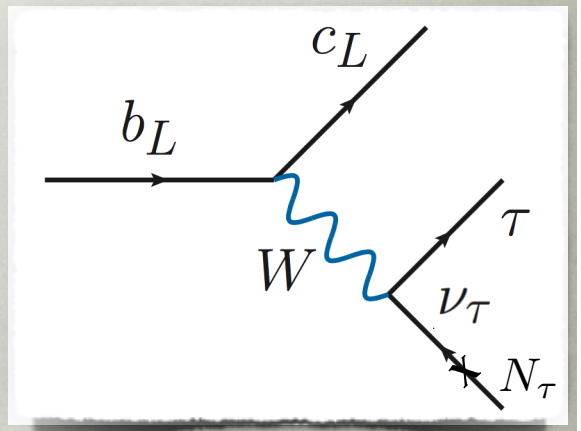
- neutrino portal

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \sum F_{\alpha I}(\bar{L}_\alpha H) N_I$$

- reach depends on flavor structure, example: tau dominance



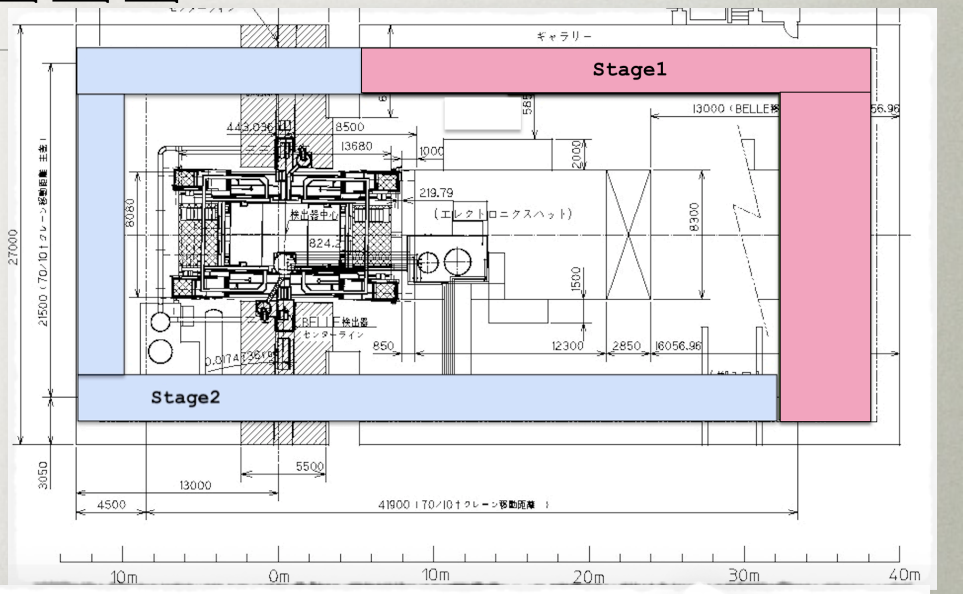
sample diagram for heavy N_τ



GAZELLE

Evans, Tammaro, Trabelsi, JZ, to appear

- a new proposal for long lived particle searches at superKEKB
- stage1: 50ab^{-1}, two walls in Tsukuba Hall instrumented
- stage2: 250ab^{-1}, all the walls and the ceiling instrumented
  - scintillating fibers, scintillators or MRPCs



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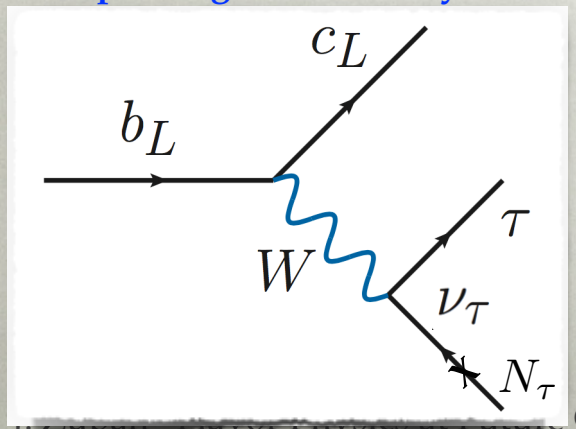
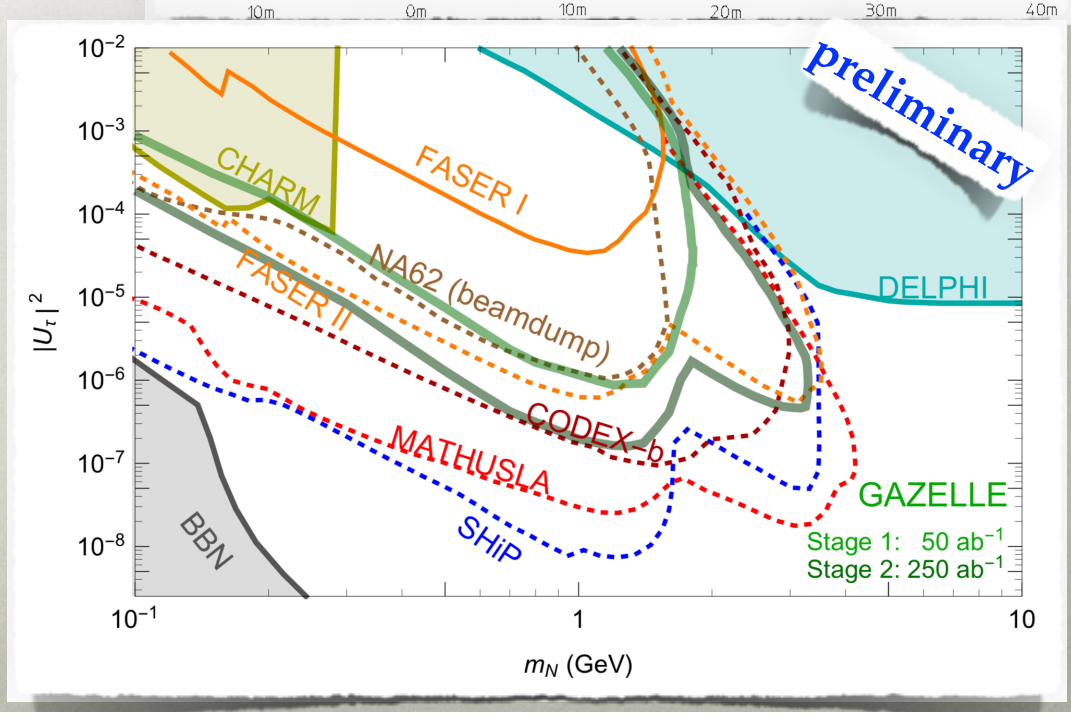




Colliders

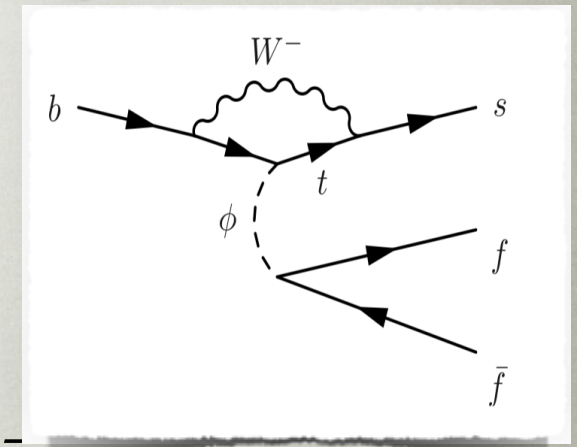
MIXING WITH THE HIGGS

see, e.g., O'Connell et al, hep-ph/0611014; Battell et al, 0911.4938; Winkler, 1809.01876

- another example: a mediator is a light scalar mixing with the Higgs

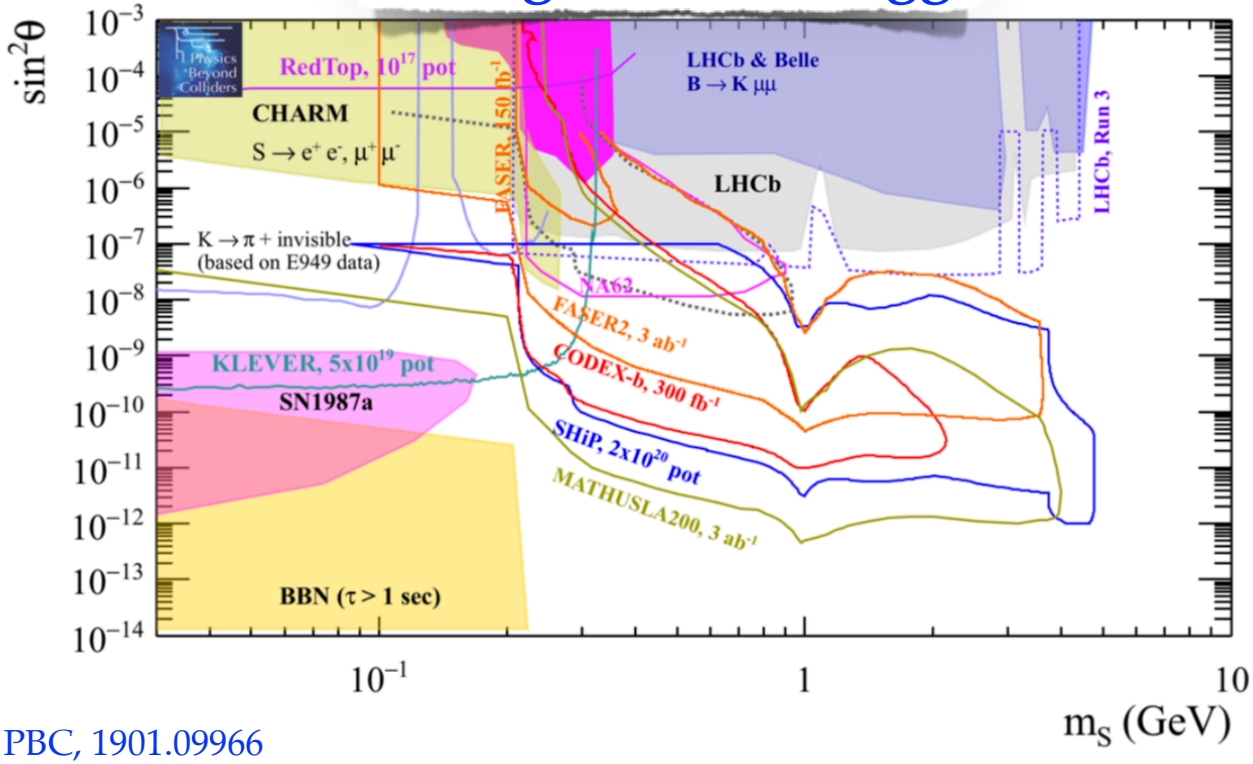
$$\mathcal{L}_{int} = -\mu S H^\dagger H \qquad \theta \simeq \mu v / m_h^2$$

- at 1 loop FCNC transitions: $B \to K^{(*)} S$, $D \to \pi S$, $K \to \pi S$, etc
- can be searched for
  - as a missing mass peak in $B \to K^{(*)} \nu\bar{\nu}$
  - from decays to the SM, e.g., $S \to \mu^+\mu^-$



MIXING WITH THE HIGGS

mixing with the Higgs



PBC, 1901.09966

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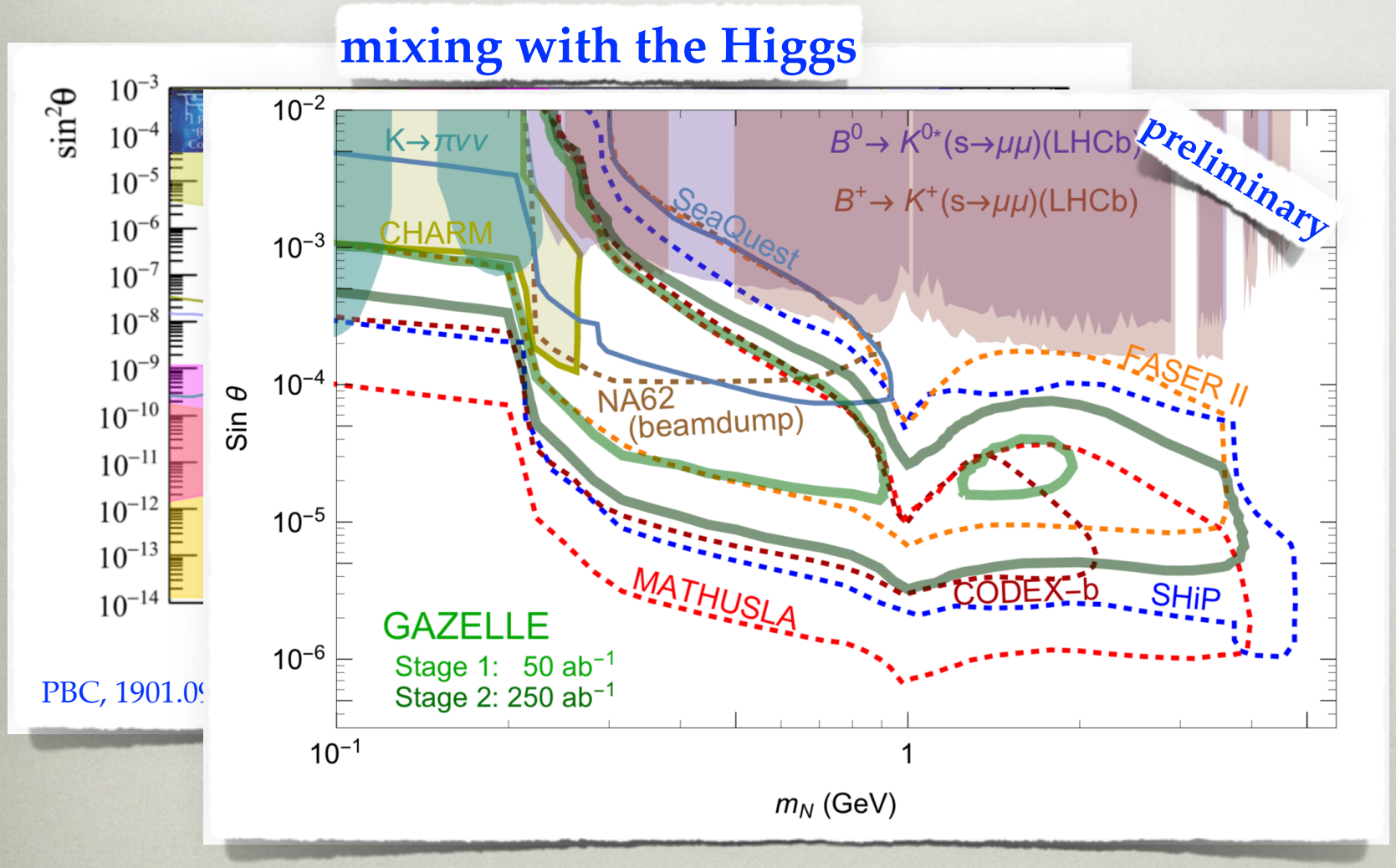

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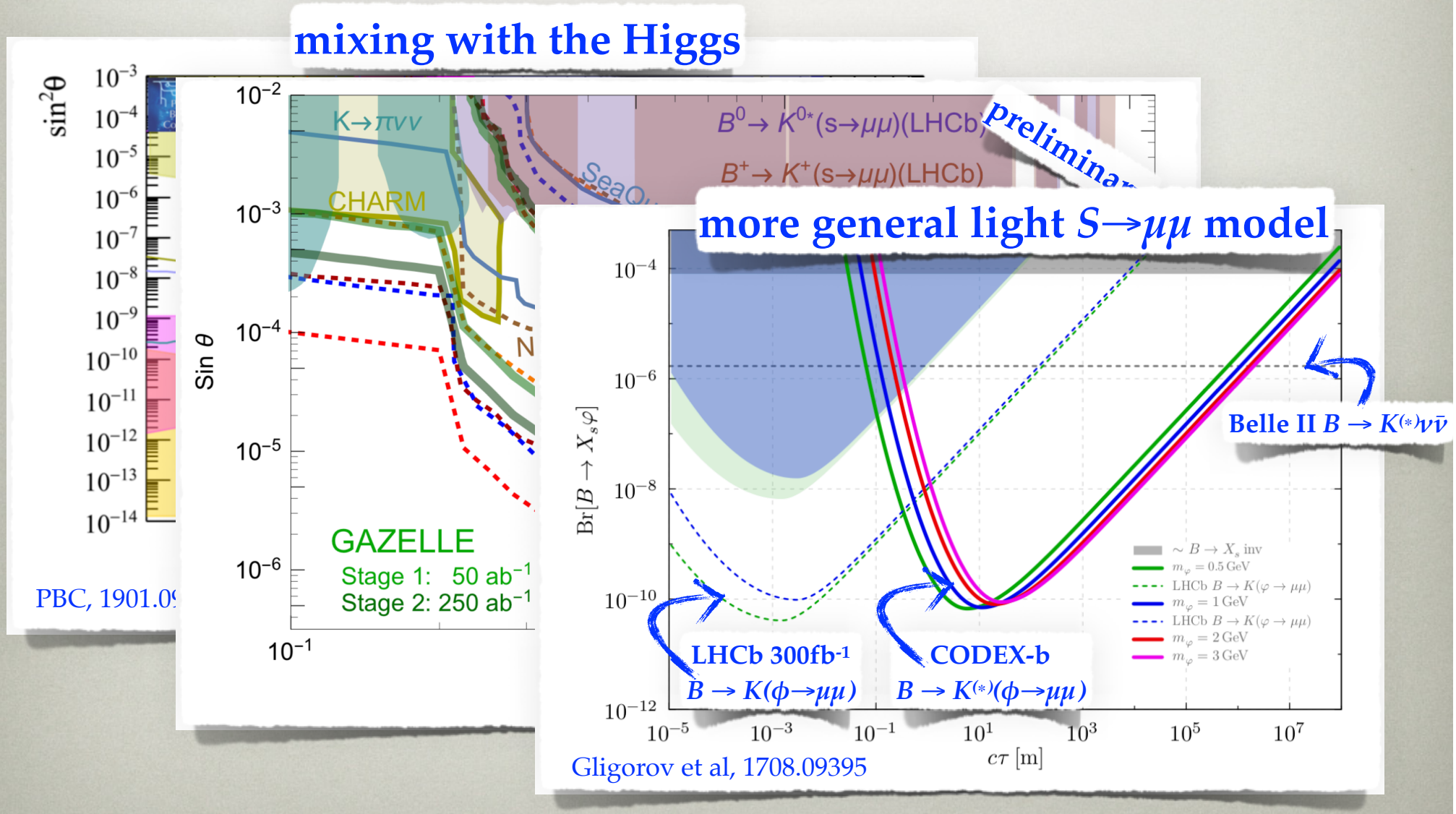
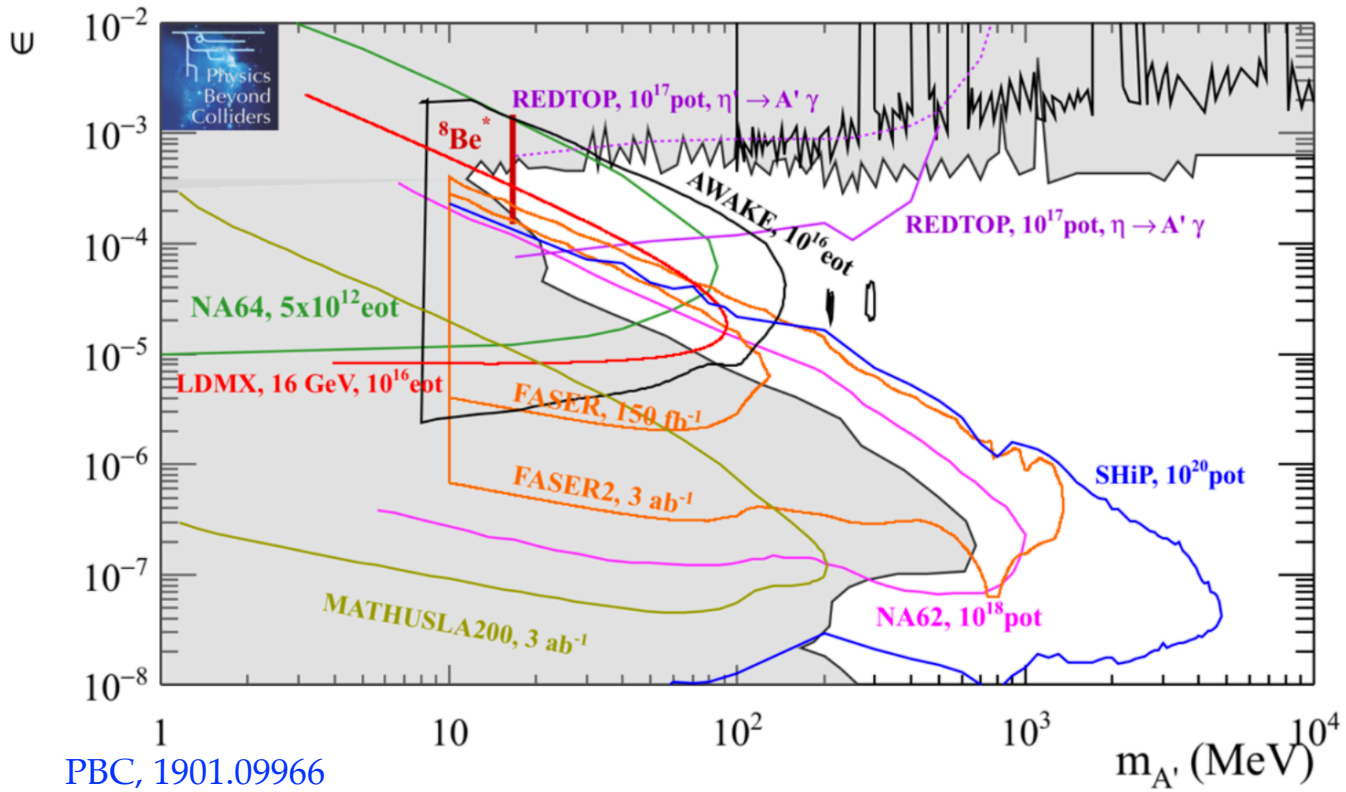


DARK PHOTON

- $U(1)_D$ can have kinetic mixing with hypercharge

$$\mathcal{L}_{\rm vector} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DS} - \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B_{\mu\nu},$$

- induces couplings of dark photon to the SM, prop.to charge



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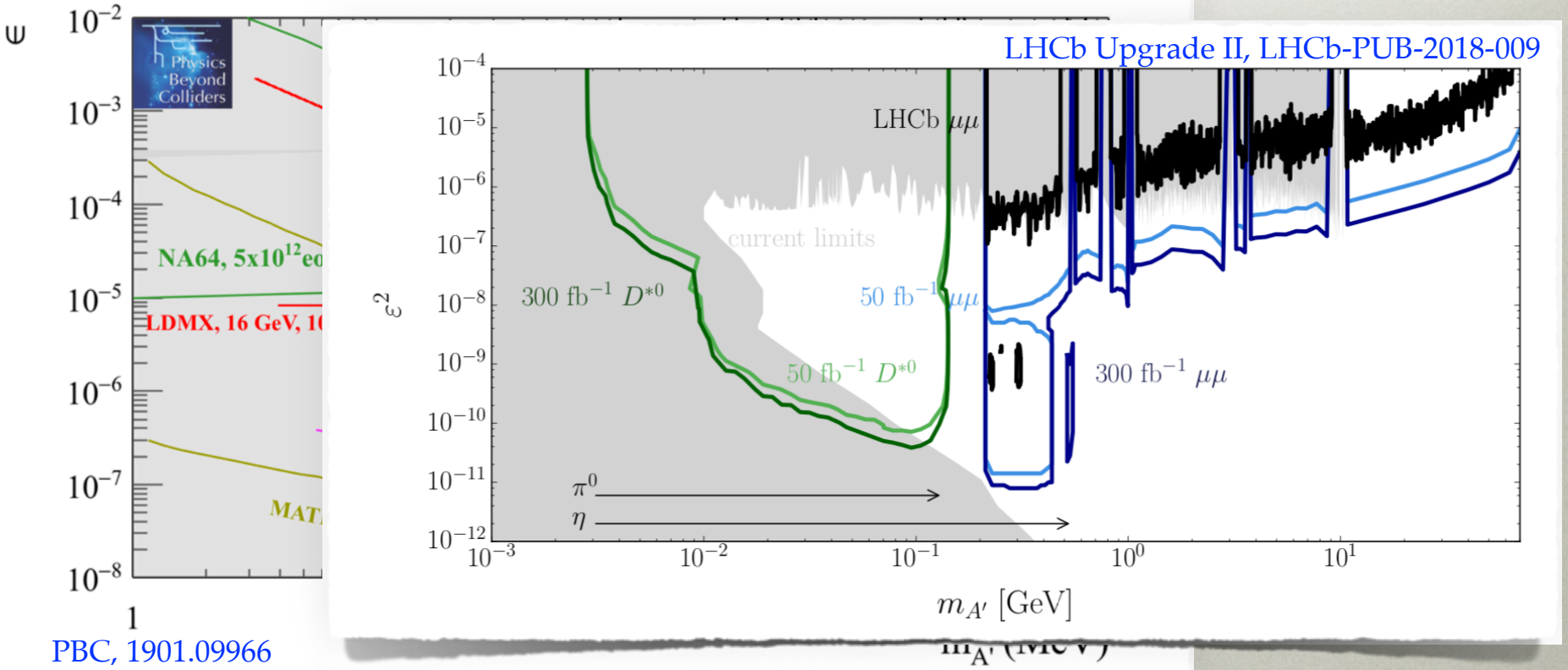


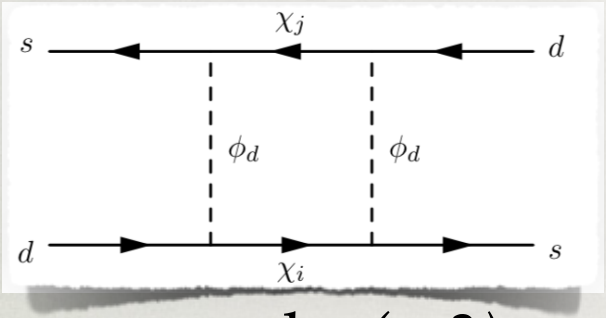
PBC, 1901.09966

DARK MATTER
IN LOOP CORRECTIONS

DM IN THE LOOPS

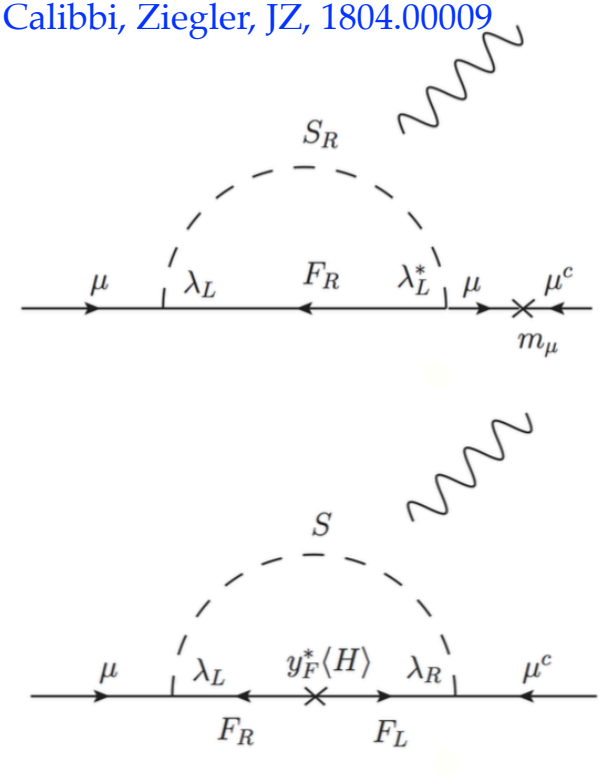
- DM + Z_2 odd partner can run in the loop
- e.g., can induce $B_{(s)}$, D, K mixing

see, e.g., Blanke, Das, Kast, 1711.10493



- another example: $(g\text{-}2)_\mu$
  - chirality flip can be on the NP fermion leg
  - NP/DM can be at TeV
  - if FV present ⇒ induces $\mu \to e\gamma$

Calibbi, Ziegler, JZ, 1804.00009



DM IN TH

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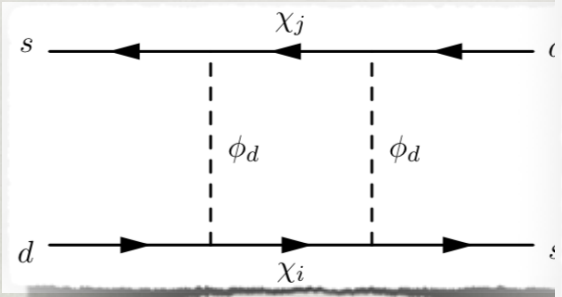

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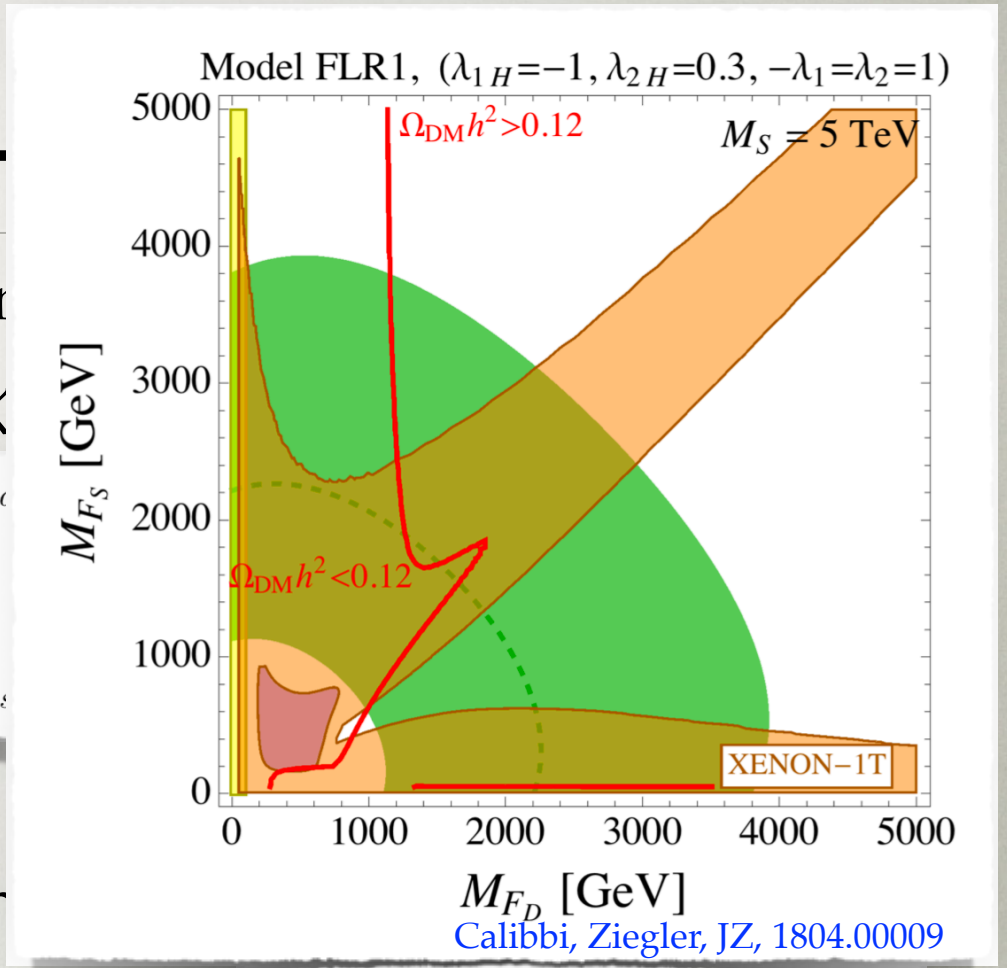

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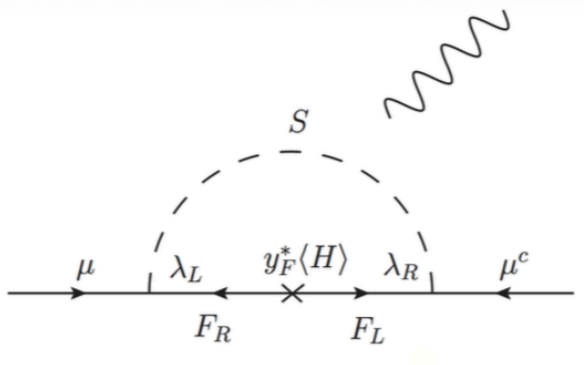


inputs #8, #25, #38, #123

FLAVORFUL Z'

- anomaly free formulation of Froggatt-Nielsen *U(1)* motivated by clockwork

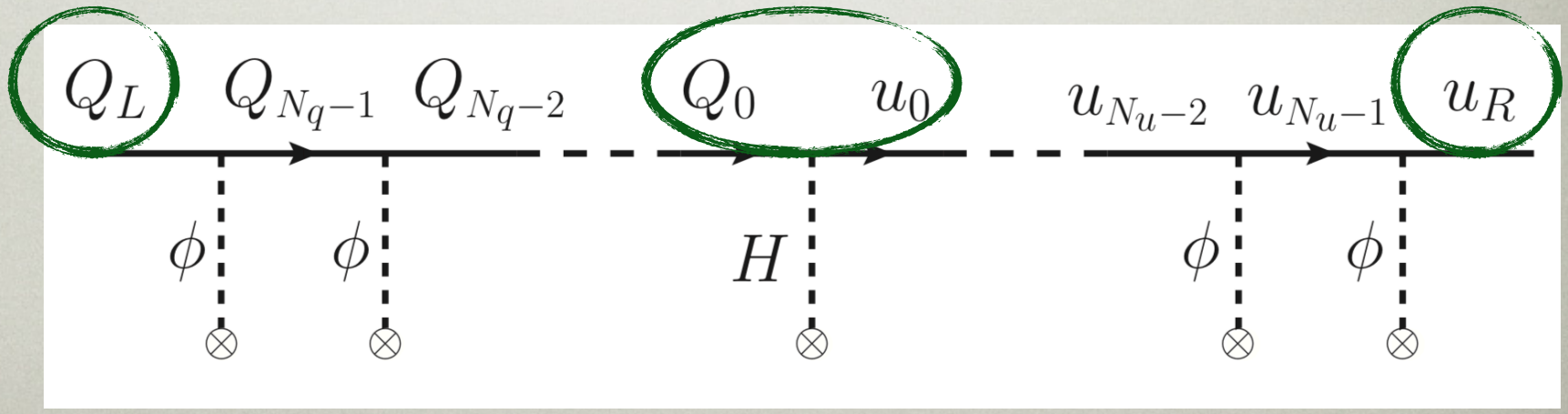
  Smolkovic, Tammaro, JZ, to appear

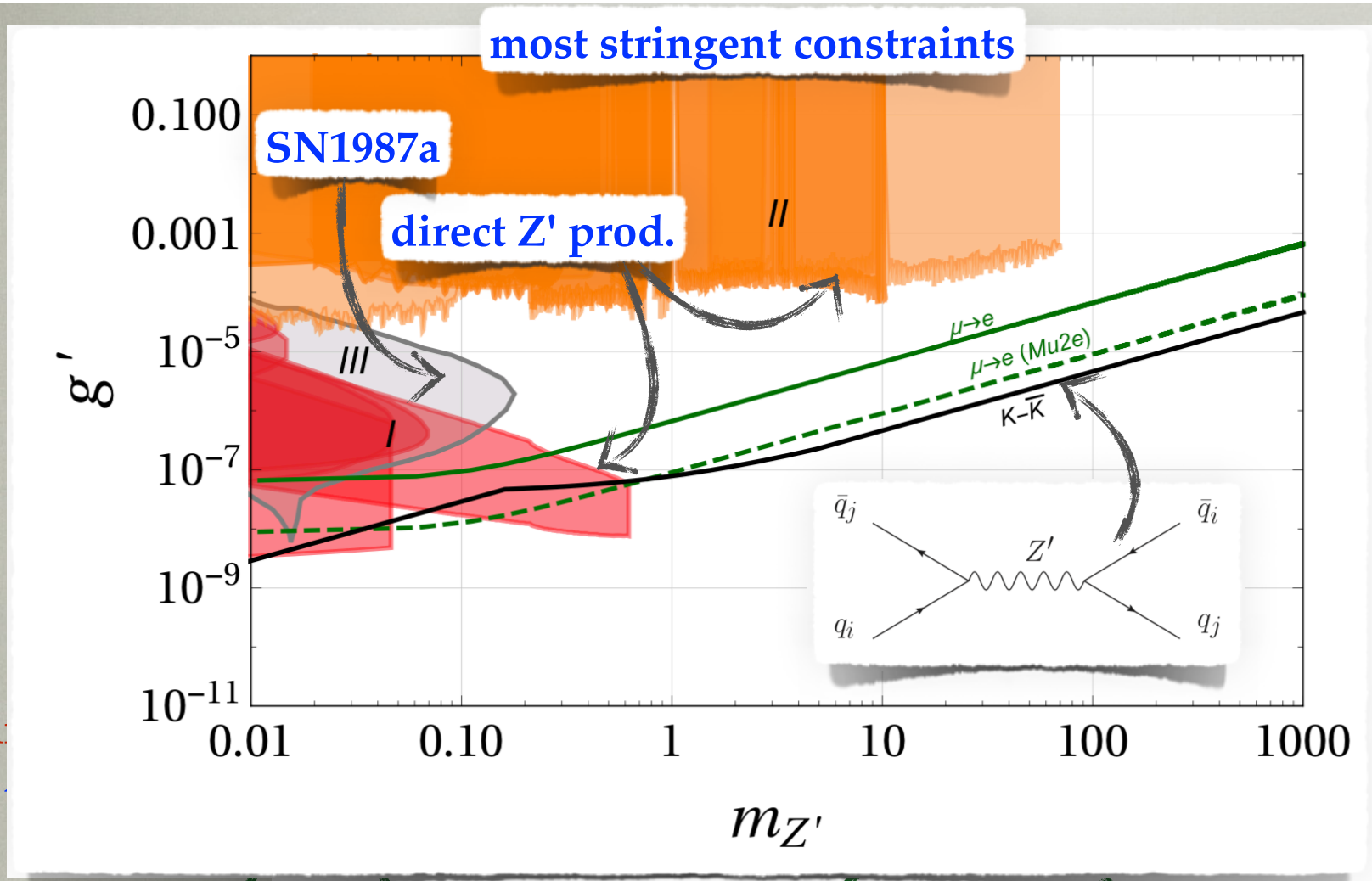
  Alonso, Carmona, Dillon, Kamenik, Camalich, JZ, 1807.09792

  - in traditional FN: $\lambda=\langle\phi\rangle/m\sim 0.2$
  - in anomaly free FN: $\lambda=m/\langle\phi\rangle\sim 0.2$
- anomaly free FN can be gauged flavorful Z'
  - could be light, a portal to dark sector

anom. free FN: vectorlike **chiral** **vectorlike**

tradition. FN: chiral **vector-like** **chiral**





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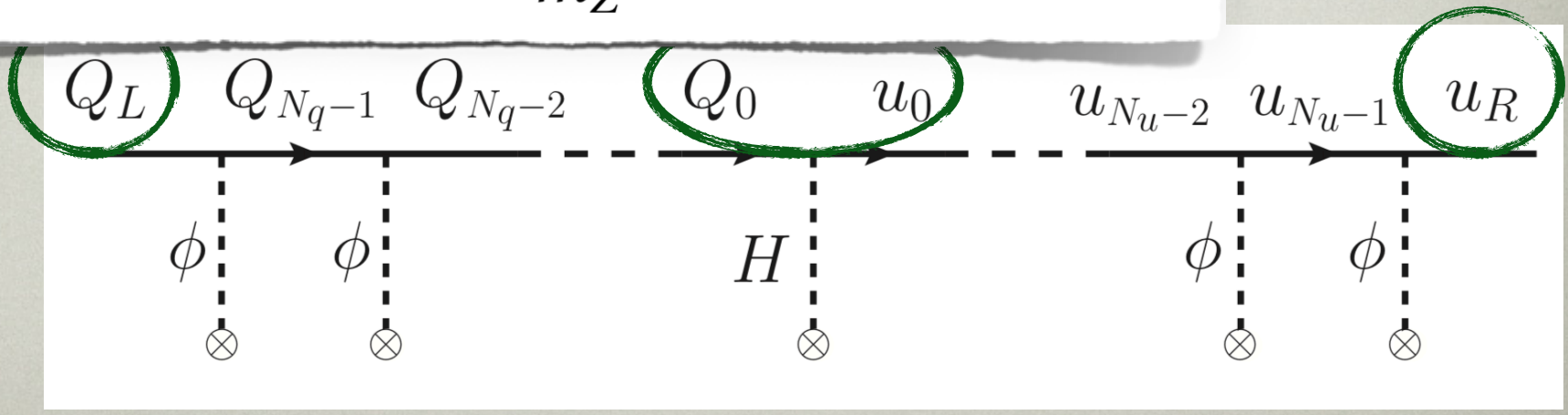
malich, JZ, 1807.09792

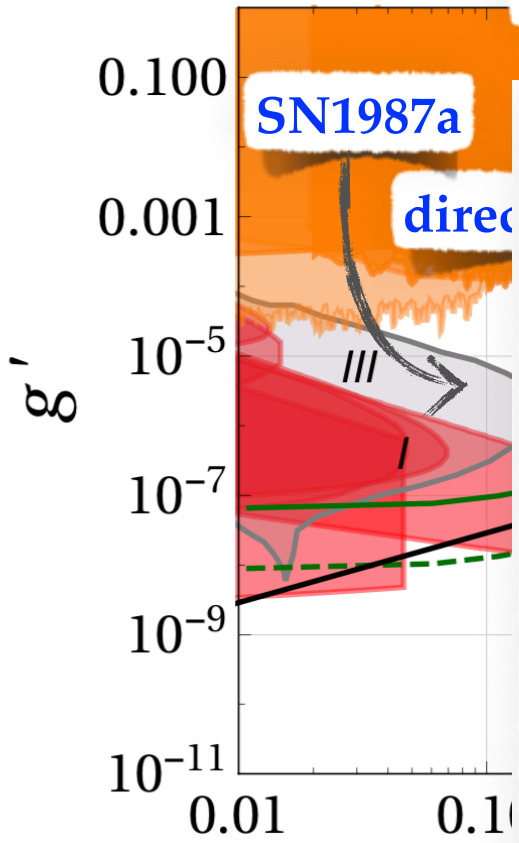
a

vectorlike

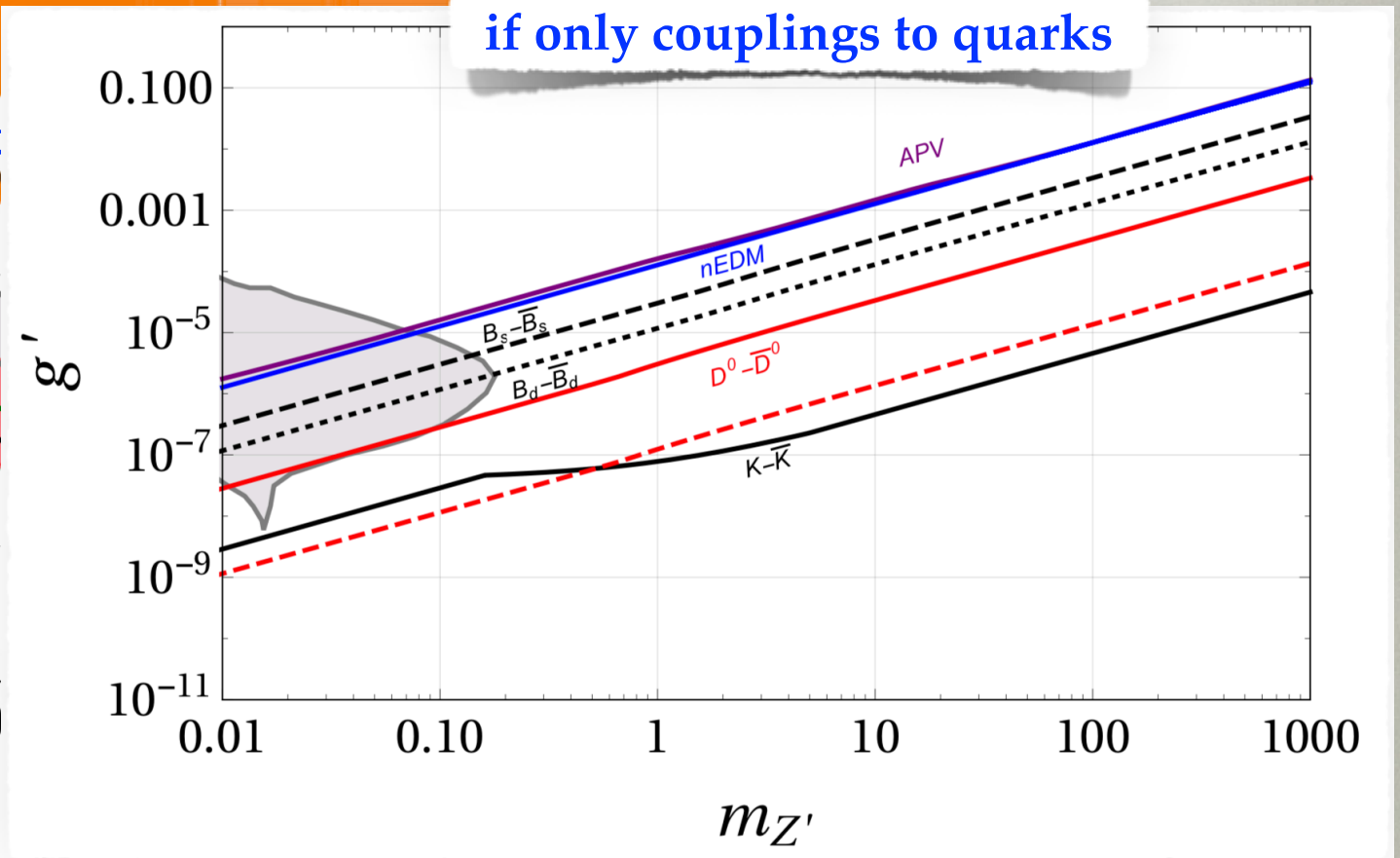
chiral

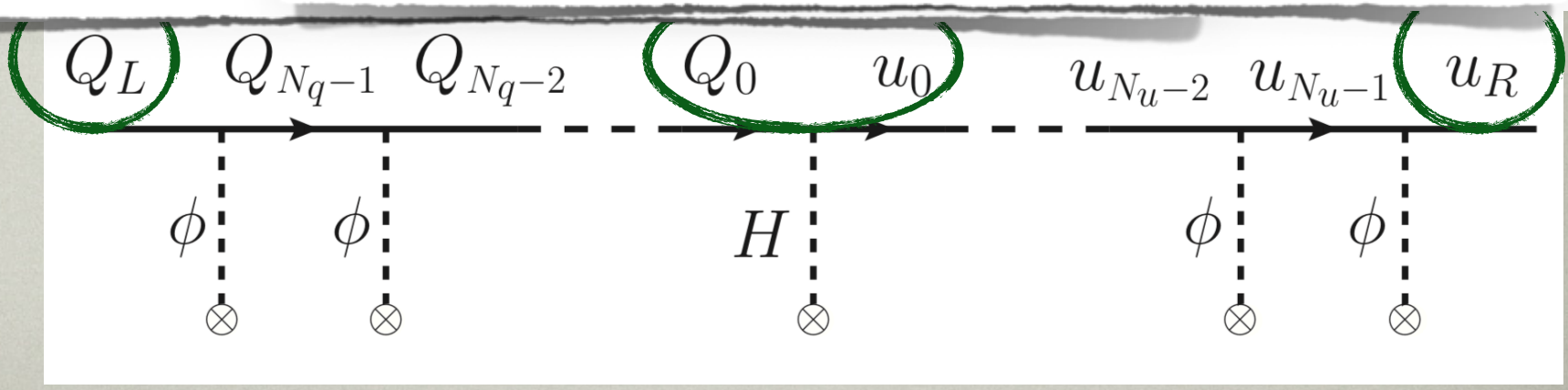


most stringent constraints



if only couplings to quarks





DARK MATTER AND BARYOGENESIS

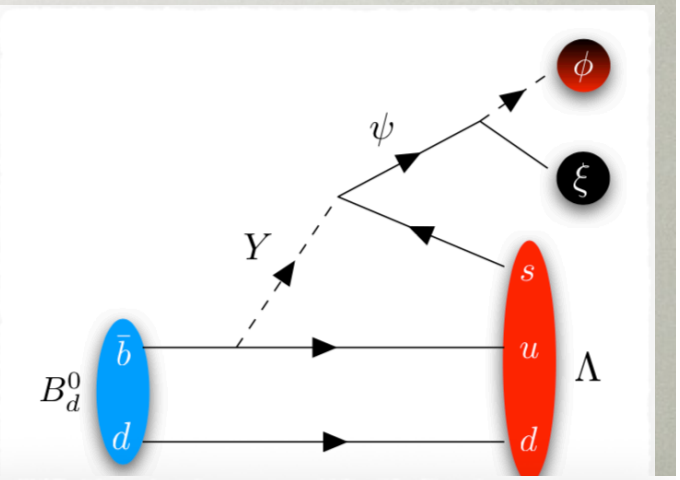
GENERAL COMMENTS

- electroweak/low scale baryogenesis usually requires
  - extra sources of CPV
  - baryon # violation
  - extra NP particles to generate 1st order phase transition or out-of equilibrium decays
- counterexample on the next slide:
  - baryon # need not be violated, if there is dark sector that carries away baryon #
  - SM CPV may suffice if there is dark sector
- many other options, e.g., baryogenesis can occur in the dark sector, baryon # then transferred to the visible sector

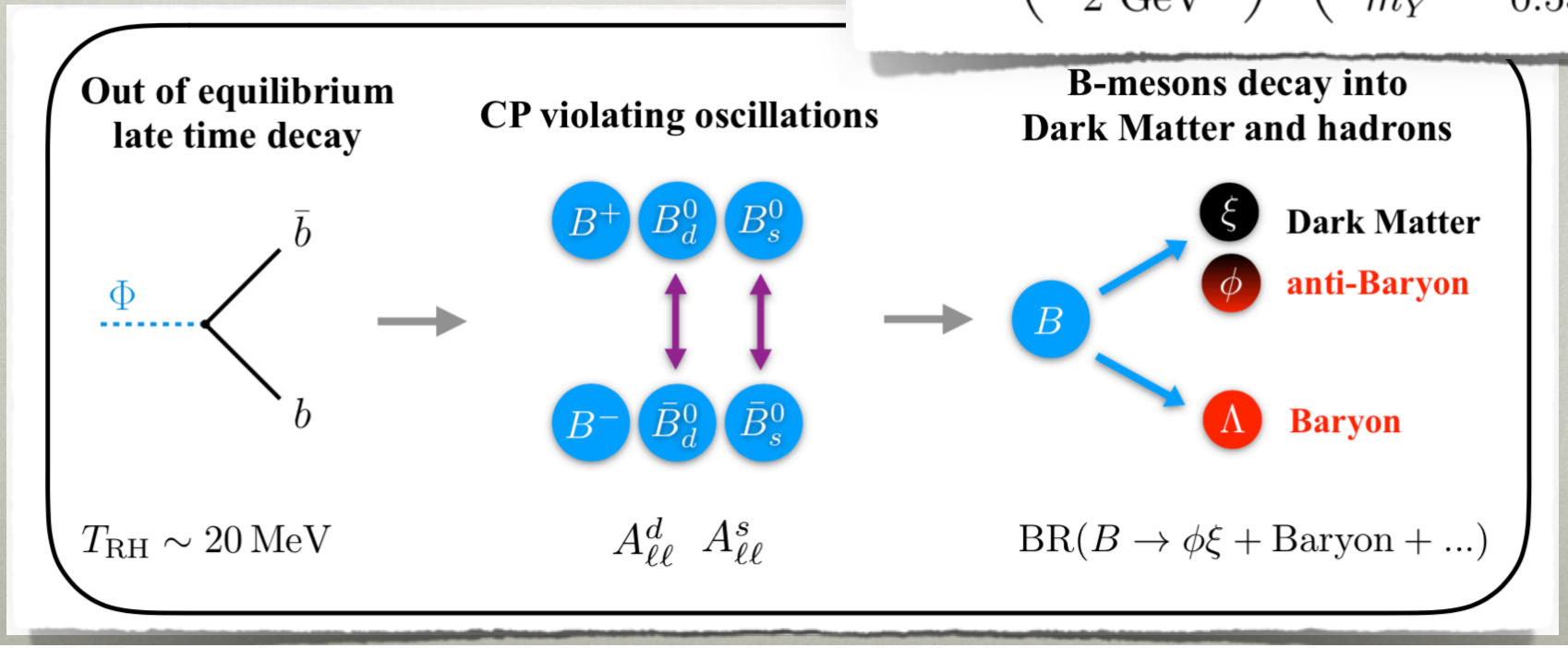
BARYOGENESIS FROM B MIXING

Elor, Escudero, Nelson, 1810.00880

- viable baryogenesis with only SM CPV
- dark particle ψ carries baryon number
  - search at Belle II, LHCb for $B \to$ baryon+MET
- needs a colored mediator, Y, search for it at ATLAS, CMS



$$\mathrm{Br}(B \to \xi\phi + \mathrm{Baryon}) \simeq 10^{-3} \left(\frac{m_B - m_\psi}{2\ \mathrm{GeV}}\right)^4 \left(\frac{1\ \mathrm{TeV}}{m_Y} \frac{\sqrt{y_{ub} y_{\psi s}}}{0.53}\right)^4 .$$



YOGENESIS FROM B MIXING

Initial State	Final state
B_d	$\psi + \Lambda\,(usd)$
B_s	$\psi + \Xi^0\,(uss)$
B^+	$\psi + \Sigma^+\,(uus)$
Λ_b	$\bar{\psi} + K^0$
B_d	$\psi + n\,(udd)$
B_s	$\psi + \Lambda\,(uds)$
B^+	$\psi + p\,(duu)$
Λ_b	$\bar{\psi} + \pi^0$
B_d	$\psi + \Xi_c^0\,(csd)$
B_s	$\psi + \Omega_c\,(css)$
B^+	$\psi + \Xi_c^+\,(csu)$
Λ_b	$\bar{\psi} + D^- + K^+$
B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$
B_s	$\psi + \Xi_c^0\,(cds)$
B^+	$\psi + \Lambda_c\,(dcu)$
Λ_b	$\bar{\psi} + \overline{D}^0$

El

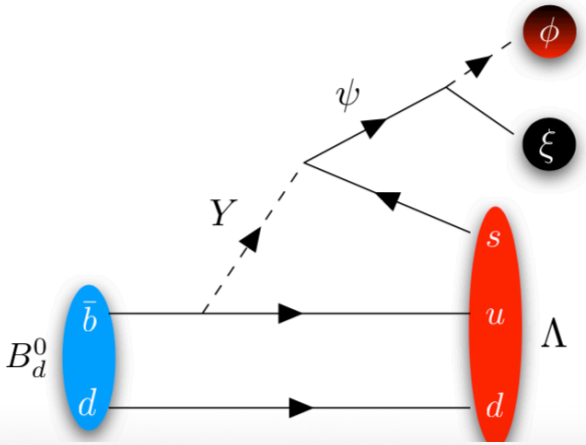
s with only SM CPV

ries baryon number

I, LHCb for $B \to$ baryon+MET

ediator, Y,

LAS, CMS



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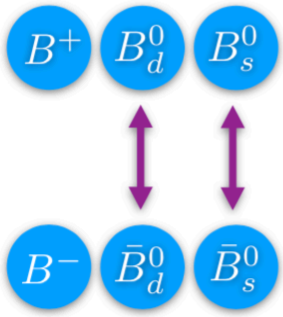
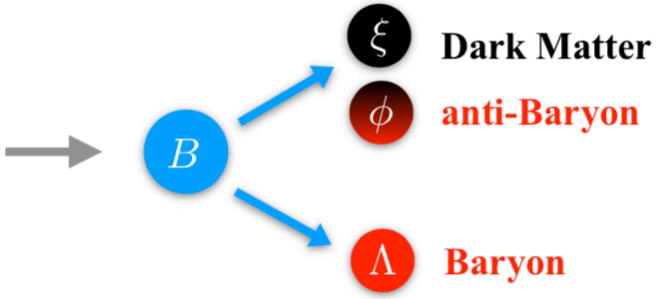
CP violating oscillations



$A_{\ell\ell}^d \quad A_{\ell\ell}^s$

B-mesons decay into Dark Matter and hadrons



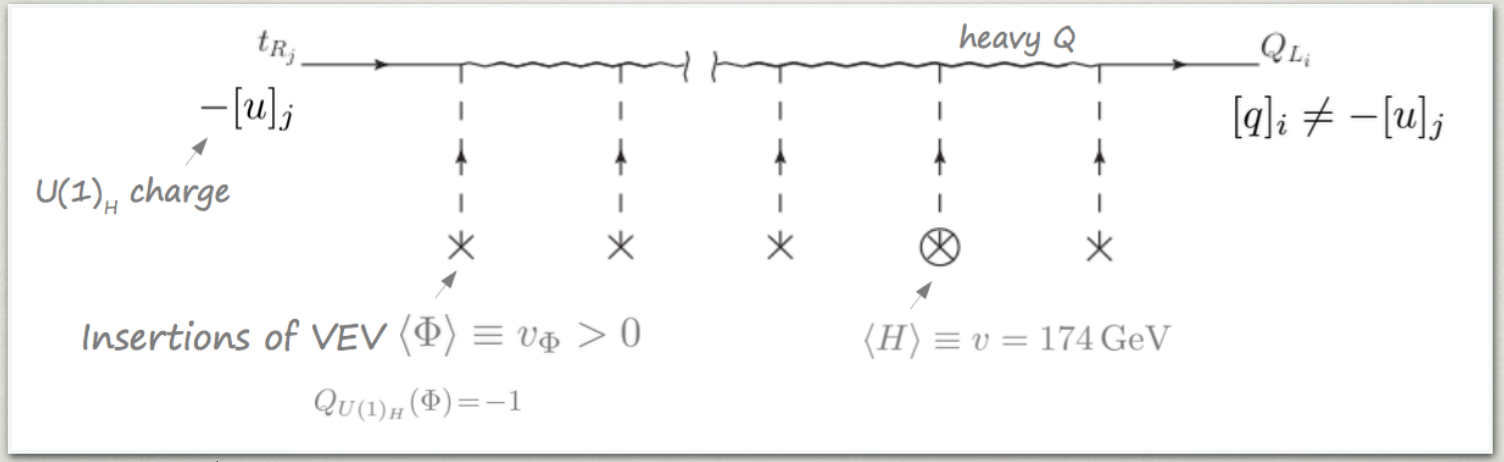
$\mathrm{BR}(B \to \phi\xi + \mathrm{Baryon} + \ldots)$

CONCLUSIONS/ RANKING

- rare flavor decays probe dark sector mediators to ~few GeV from on-shell process
- if FV sensitivity to much heavier mediators from off-shell
- ranking of facilities depends on your priors
  - versatility: LHCb Upgrade II +CODEXb, Belle III+Gazelle
  - ultimate reach for light portals : Mathusla, Ship
  - light invisible: NA62 (axiflavon), NA64(dark photon)
  - flavorful mediators: classic flavor probes, mu2e, K-$\bar{K}$ mixing, B-$\bar{B}$ mixing, etc.

BACKUP SLIDES

FLAVON



- FN mechanism involves
  - vector-like fermions (no QCD anomaly)
  - scalar flavon fields
- effective Yukawas governed by flavon insertions (so that invariant under flavor symm.)

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

  - hierarchy from powers of small parameter ε

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 $U(1)_H$ symmetry
  - SM LH and RH fermions have different $U(1)_H$ charges
  - hierarhical Higgs Yukawas after $U(1)_H$ broken via vev of scalar field, the flavon Φ

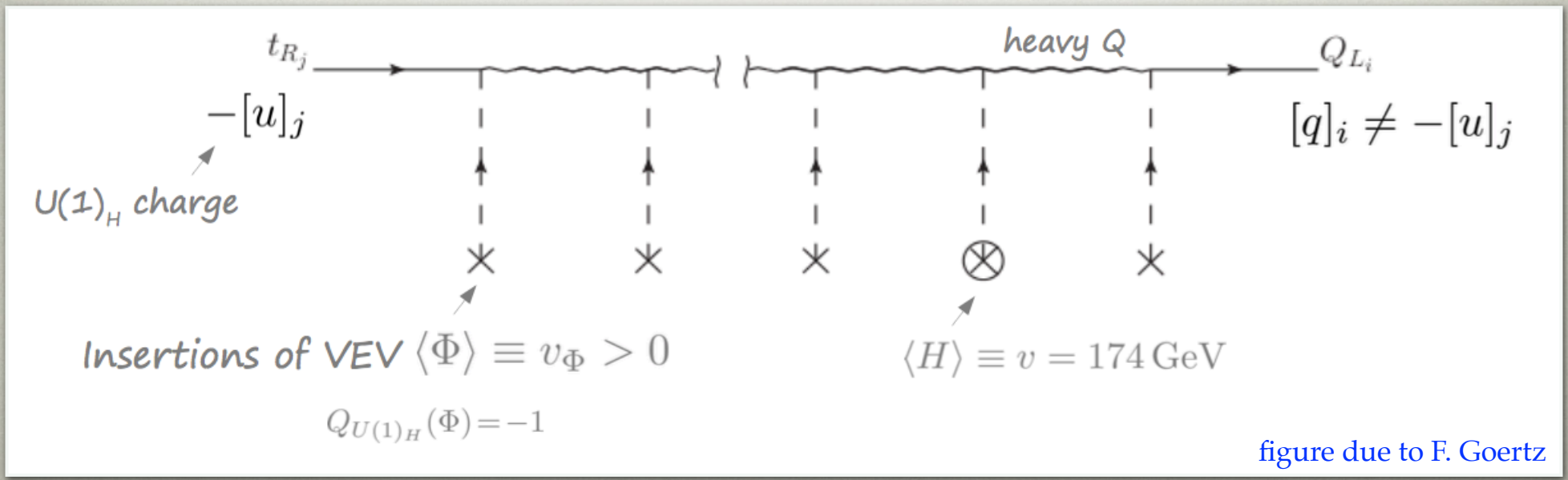
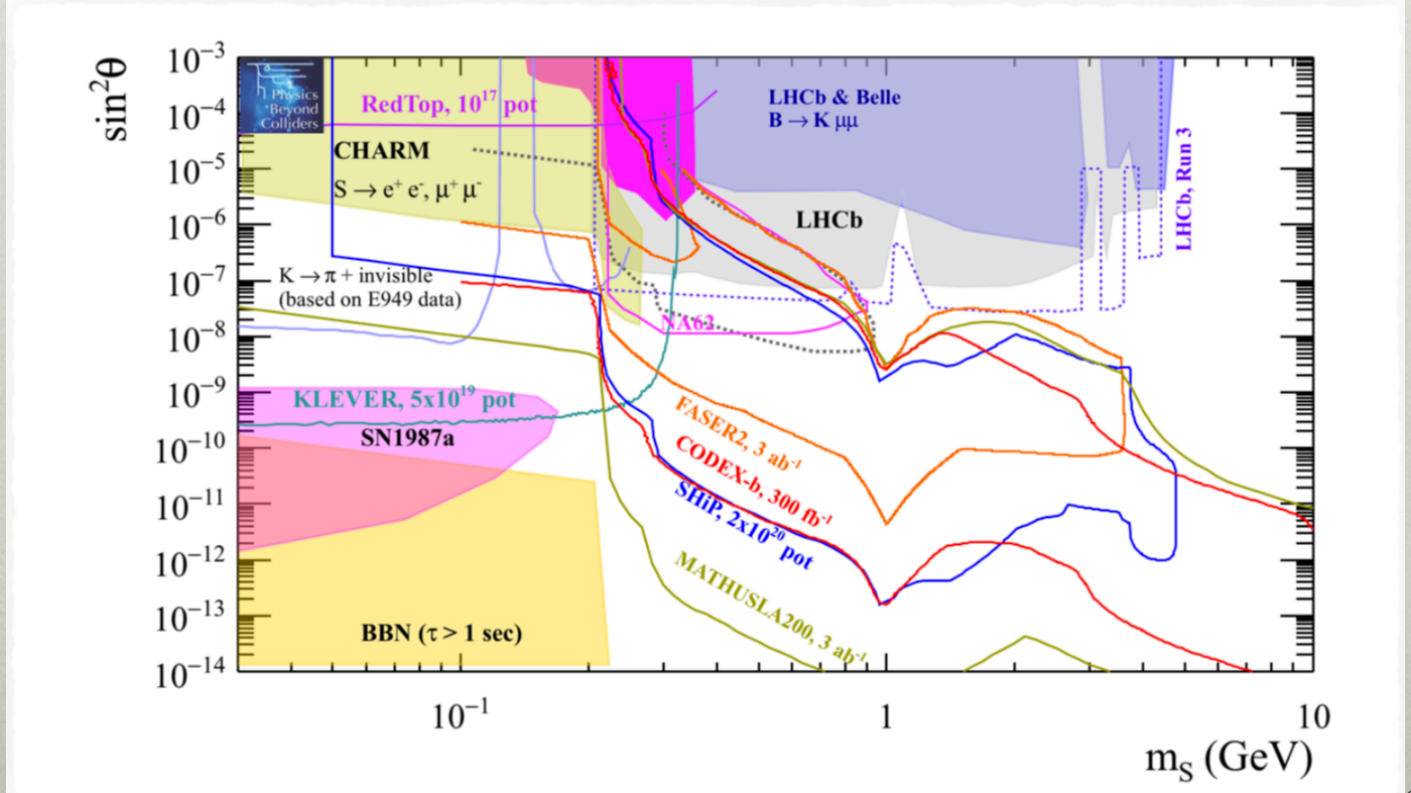


figure due to F. Goertz

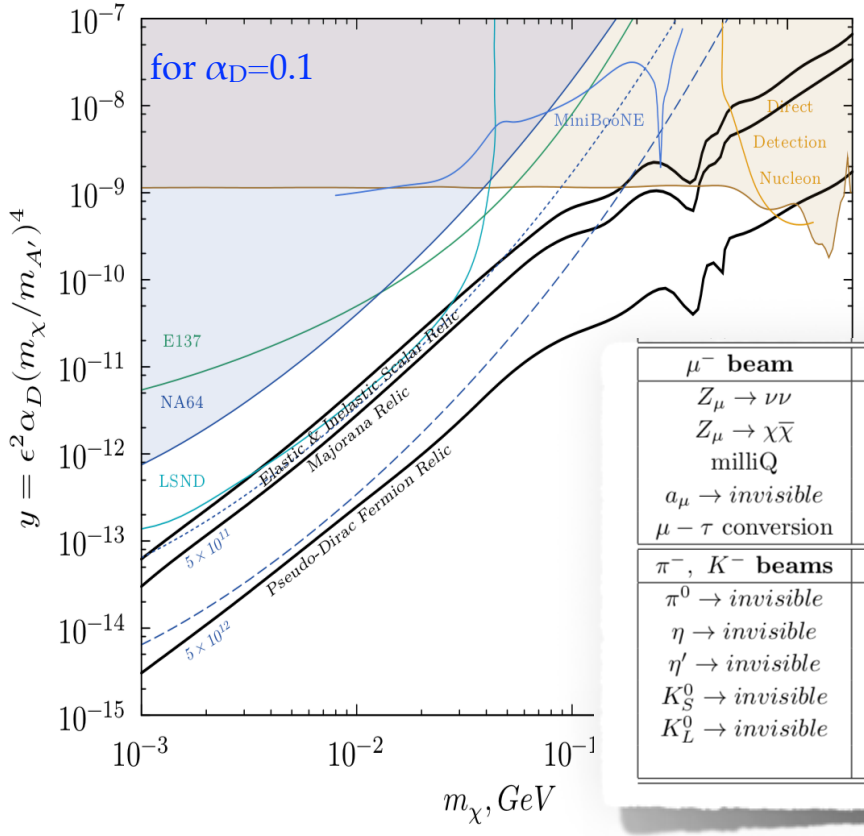
MIXING WITH THE HIGGS

- assuming also *hSS* coupling nonzero, giving $BR(h \to SS) = 10^{-2}$



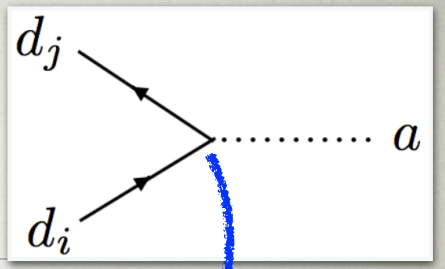
DARK PHOTON PORTAL TO DARK MATTER

- in NA64 a search for $e^- Z \to e^- Z A'; A' \to invisible.$



μ^- **beam**		Required number of MOT: $10^{11} - 5\times10^{13}$
$Z_\mu \to \nu\nu$	gauge Z_μ-boson of $L_\mu - L_\tau$, $< 2m_\mu$	(g-2)$_\mu$ anomaly; $g_\mu^V \lesssim 10^{-4}$, with $\lesssim 10^{11}$ MOT
$Z_\mu \to \chi\overline{\chi}$	$L_\mu - L_\tau$ charged Dark Matter (χ)	$y \lesssim 10^{-12}$ for $m_\chi \lesssim 300$ MeV with $\simeq 10^{12}$ MOT
milliQ	Dark Sector, charge quantisation	$10^{-4} < mQ < 0.1$ e, $10^{-3} < m_{mQ} < 2.5$ GeV
$a_\mu \to invisible$	non-universal ALP coupling	$g_Y \lesssim 10^{-2}$, $m_{a_\mu} \lesssim 1$ GeV
$\mu - \tau$ conversion	Lepton Flavour Violation	$\sigma(\mu-\tau)/\sigma(\mu \to all) \lesssim 10^{-11}$
π^-, K^- **beams**	Current limits, PDG'2018	Required number of POT(KOT):$5\times10^{12}(5\times10^{11})$
$\pi^0 \to invisible$	$Br(\pi^0 \to invisible) < 2.7\times10^{-7}$	$Br(\pi^0 \to invisible) \lesssim 10^{-9}$
$\eta \to invisible$	$Br(\eta \to invisible) < 1.0\times10^{-4}$	$Br(\eta \to invisible) \lesssim 10^{-8}$
$\eta' \to invisible$	$Br(\eta' \to invisible) < 5\times10^{-4}$	$Br(\eta \to invisible) \lesssim 10^{-7}$
$K_S^0 \to invisible$	no limits	$Br(K_S^0 \to invisible) \lesssim 10^{-9}$
$K_L^0 \to invisible$	no limits	$Br(K_L^0 \to invisible) \lesssim 10^{-7}$
		complementary to $K^- \to \pi\nu\nu$

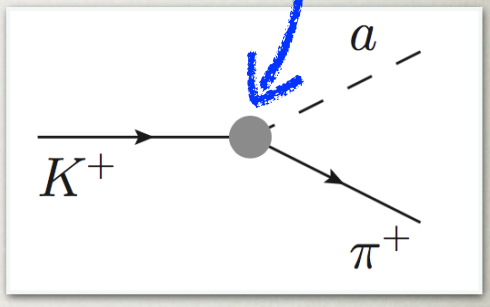
MINIMAL AXIFLAVON



- most stringent bounds from kaon sector

$$\mathrm{BR}(K^+ \to \pi^+ a) \simeq 1.2 \cdot 10^{-10} \left(\frac{m_a}{0.1\,\mathrm{meV}}\right)^2 \left(\frac{\kappa_{sd}}{N}\right)^2$$

O(1) factor



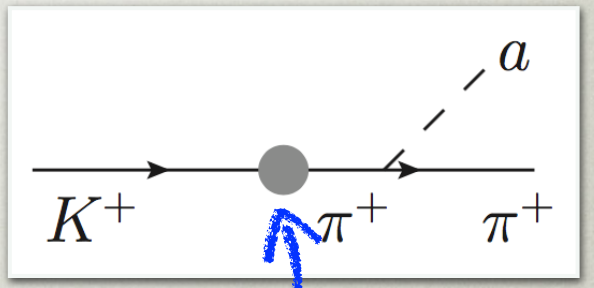
- 90% CL combined bound from E787 and E949

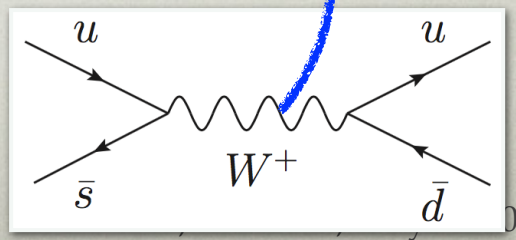
$$\mathrm{BR}(K^+ \to \pi^+ a) < 7.3 \cdot 10^{-11}$$

$$f_a \gtrsim \frac{\kappa_{sd}}{N} \times 7.5 \cdot 10^{10}\,\mathrm{GeV}$$

- note: the weak annihilation where FV from *W* exchange is always negligible

$$\frac{\Gamma(K^+ \to \pi + a)_{\mathrm{w.a.}}}{\Gamma(K^+ \to \pi + a)} \sim \left(\frac{f_K f_\pi}{m_W^2}\right)^2 \left(\frac{\lambda^d_{11,22}}{\lambda^d_{12,21}}\right)^2 \sim 10^{-12}$$

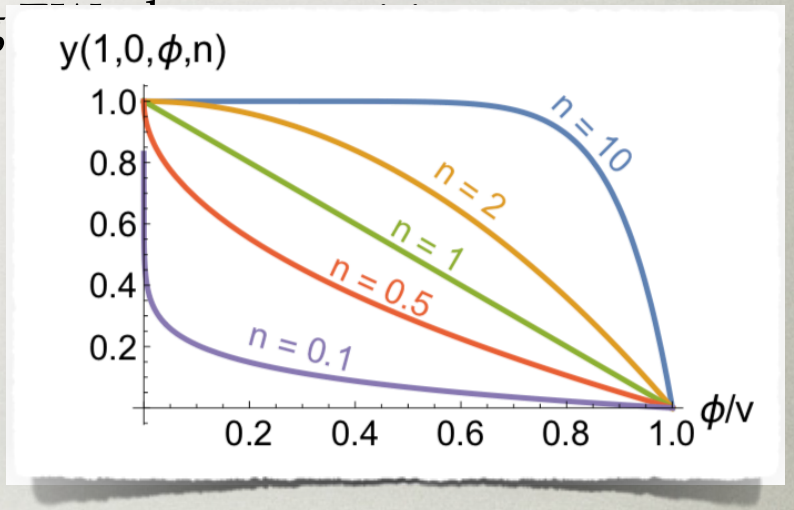




BARYOGENESIS AND VARYING YUKAWAS

review: Servant, 1807.11507

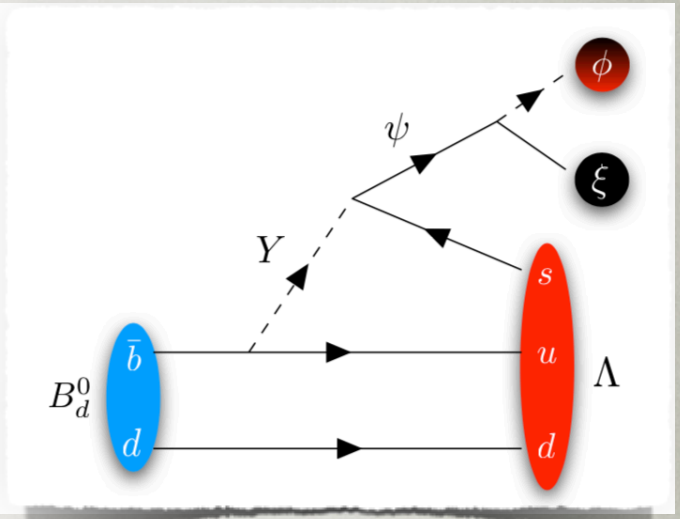
- in models of flavor Yukawas have dynamical origin
- viable EWBG if Yukawas change during
  - strong 1st order phase transition
  - large Yukawas at early times, thus enhanced sources of CPV
- models: two flavon FN, RS with Goldberger-Wise, composite Higgs
- searches at LHC: searches for flavons, radion/dilaton, other states part of complete models
- searches at Belle II: all the classic flavor observables - B mixing, etc,
  - sometimes model dep. modes, e.g. decay to axiflavon, a: $B\to Ka, D\to\pi a$, etc



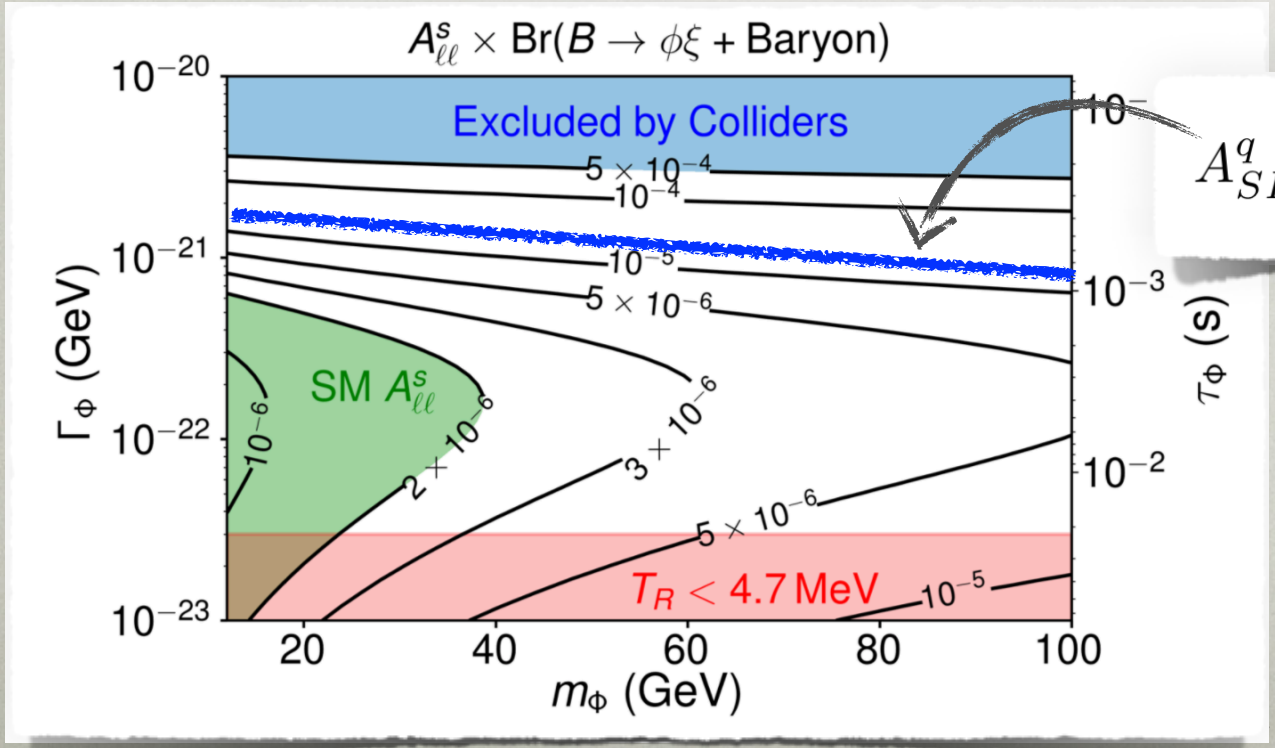
Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040

BARYOGENESIS FROM B MIXING

Elor, Escudero, Nelson, 1810.00880



- viable baryogenesis with only SM CPV
- dark particle ψ carries baryon number
  - search at Belle II, LHCb for $B \to$ baryon +MET
- needs a colored mediator, Y, search for it at ATLAS, CMS



$$A_{SL}^q = \mathrm{Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right)$$