Searching anomaly-free Gauge Bosons at Forward Physics Experiments

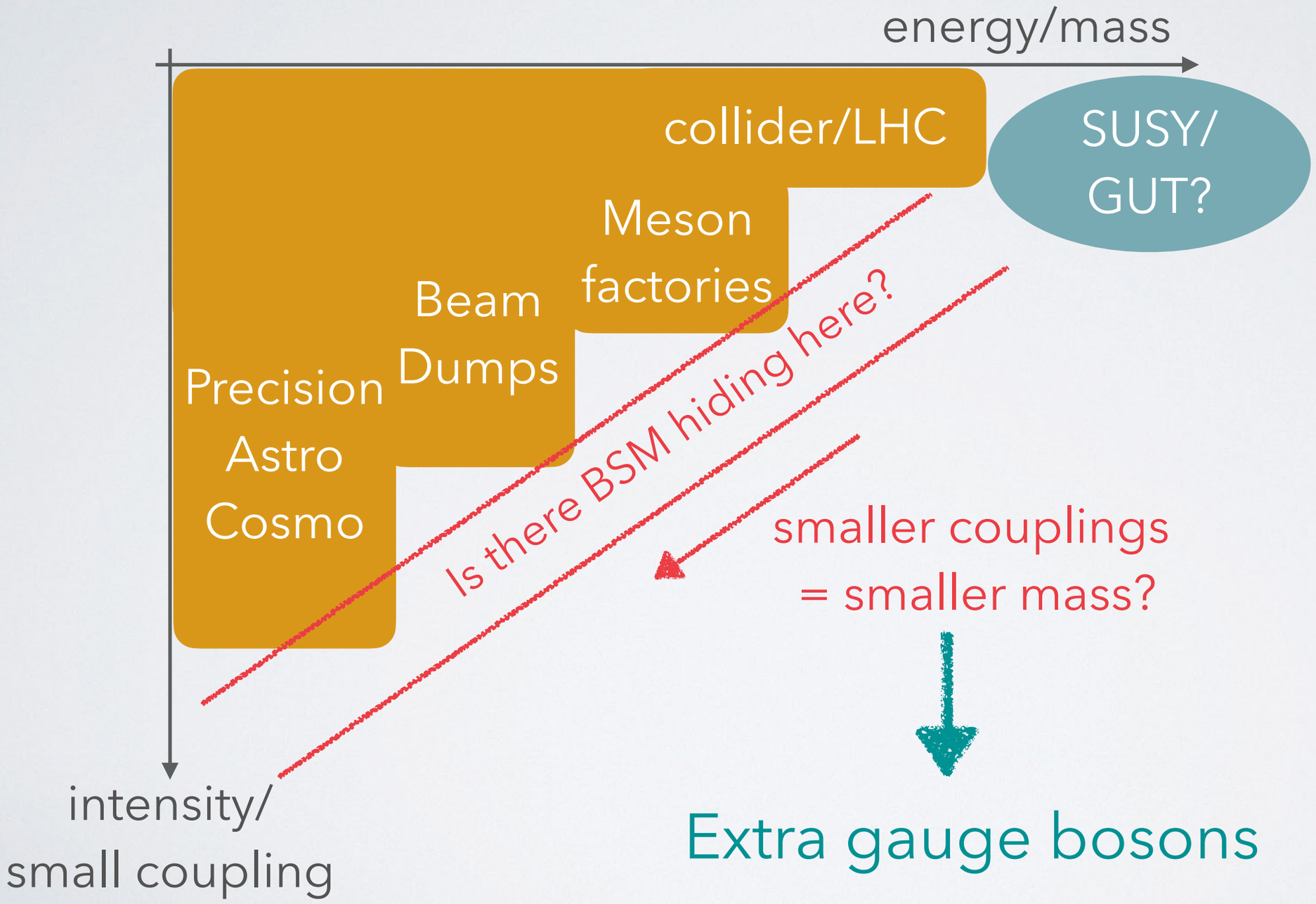
Patrick Foldenauer

IPPP Durham

2nd Forward Physics Facility Meeting –– May 28, 2021

WHERE TO LOOK FOR BSM

- Many UV theories predict heavy new states with sizeable couplings (e.g. SUSY, GUTs, String Models, …)



SECLUDED HIDDEN PHOTONS

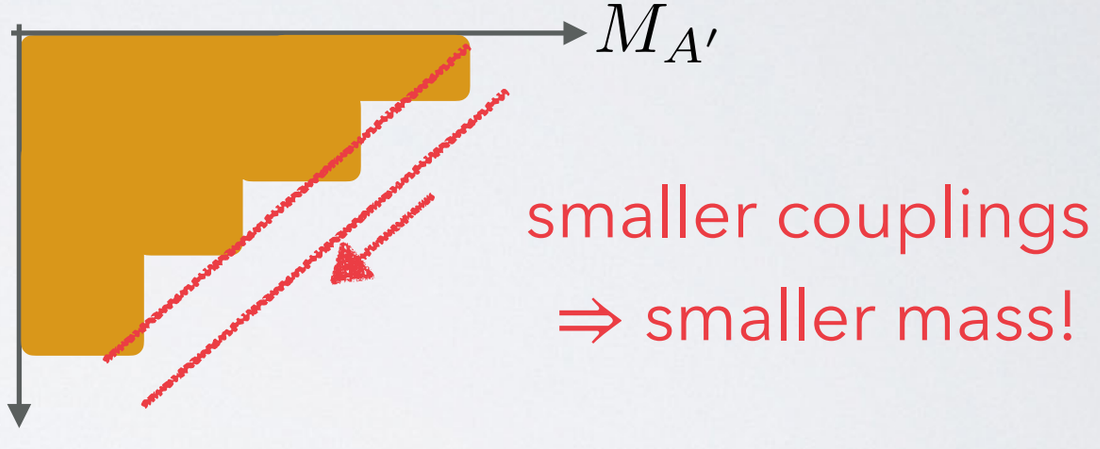
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\epsilon}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_X^2}{2} X_\mu \, X^\mu - g_x \, J_\mu^X X^\mu$$

[Holdom; PLB 166, 196]

- If $U(1)_X$ is broken by VEV f of scalar, mass is related to coupling:

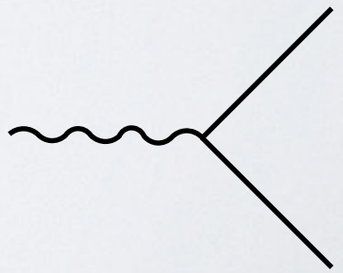
$$\mathcal{L} = (D_\mu S)^\dagger D^\mu S \supset g_x^2 f^2 A'_\mu A'^\mu$$

$$\Rightarrow \quad \boxed{M_{A'} = g_x \, f}$$



- For light mediators $M_{A'} \ll M_Z$ kinetic terms can be diagonalised by simple field redefinition:

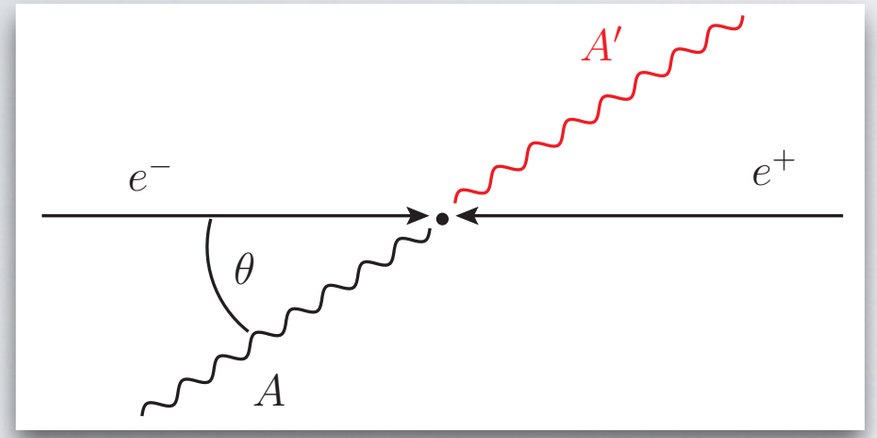
$$A^\mu \to A^\mu - \epsilon A'^\mu \quad \longrightarrow \quad e A_\mu J^\mu_{\mathrm{EM}} - \epsilon \, e A'_\mu J^\mu_{\mathrm{EM}}$$



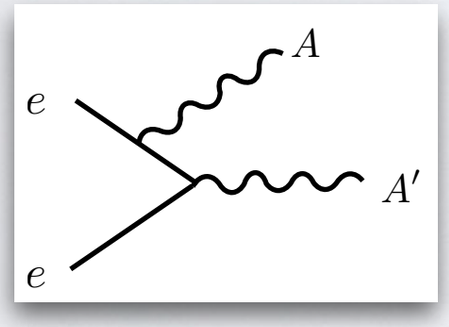
Hidden Photon couples to EM current suppressed by ϵ !

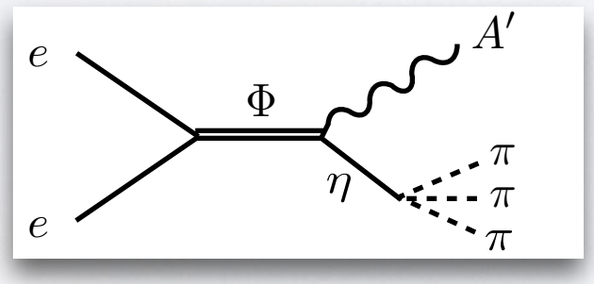
HIDDEN PHOTON SEARCHES

Colliders:



- Production:

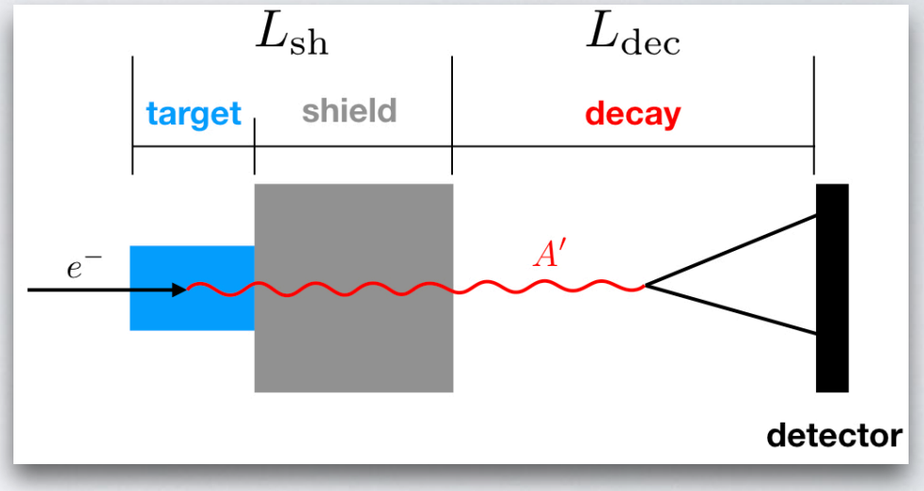




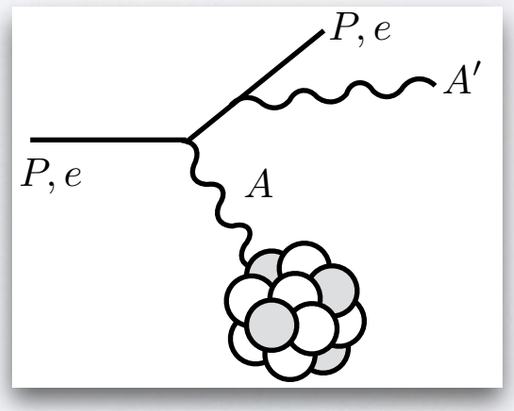
$$\mathscr{L}^{\rm coll} \approx \mathcal{O}(10^{-1})\ {\rm ab}^{-1}{\rm yr}^{-1}$$

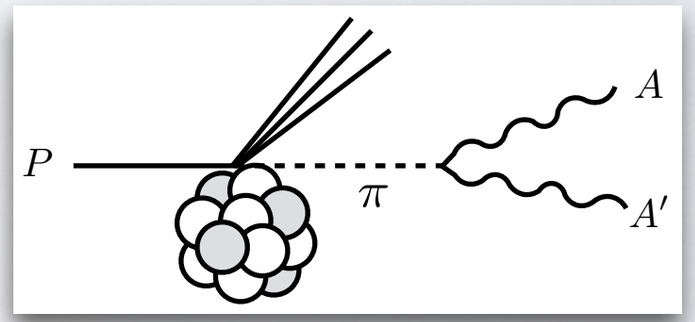
$$\sigma^{\rm coll}_{A'} \propto \frac{\alpha^2\,\epsilon^2}{E^2_{\rm CM}}$$

Beam dumps/forward experiments:



$$P_{\rm dec} = e^{-\frac{L_{\rm sh}}{\ell_{A'}}}\left(1 - e^{-\frac{L_{\rm dec}}{\ell_{A'}}}\right)$$

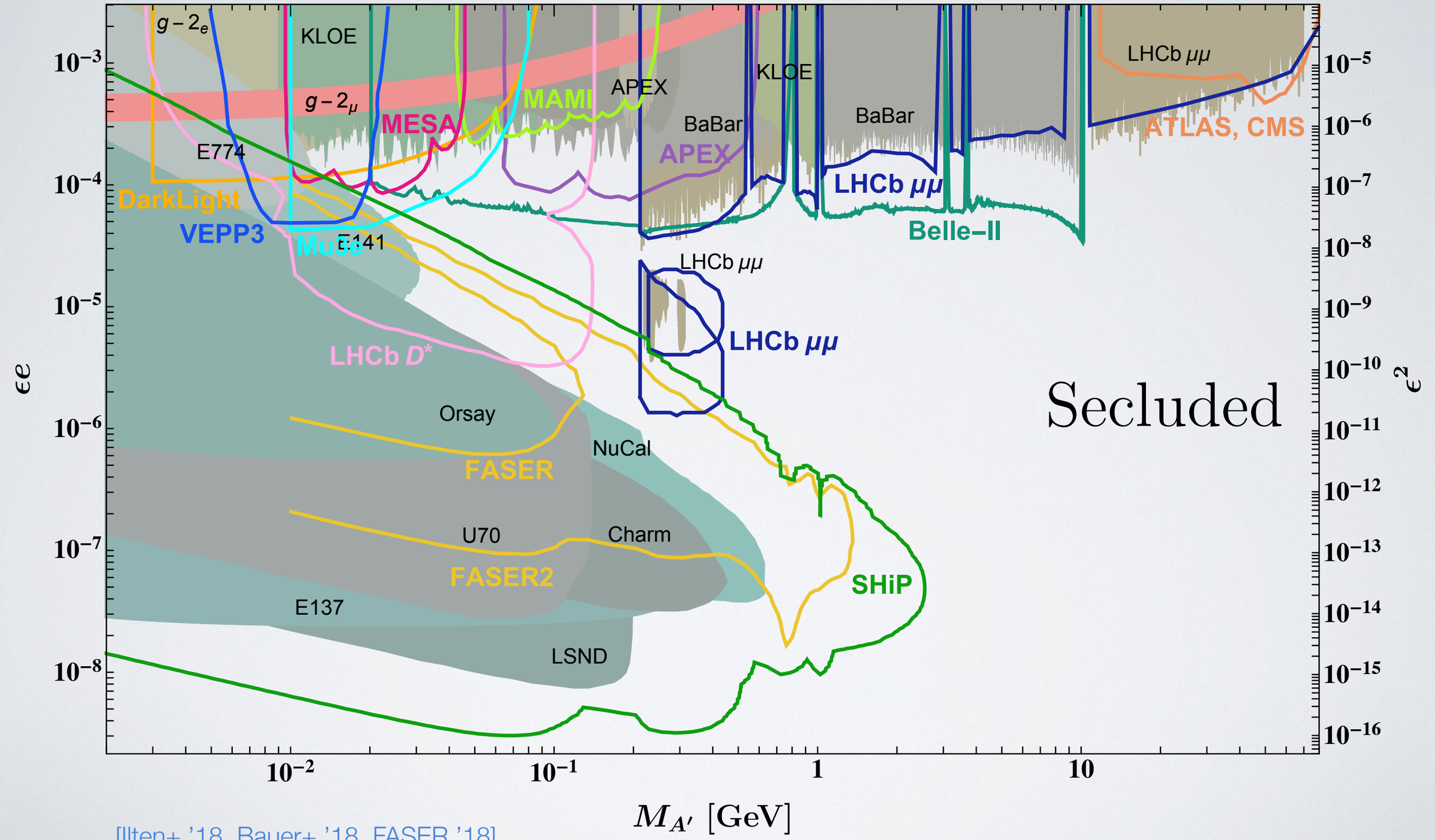




$$\mathscr{L}^{\rm bd} \approx \mathcal{O}(1)\ {\rm ab}^{-1}{\rm d}^{-1}$$

$$\sigma^{\rm bd}_{A'} \propto \frac{\alpha^3\,Z^2\,\epsilon^2}{M^2_{A'}}$$

SECLUDED $U(1)_X$



[Ilten+ '18, Bauer+ '18, FASER '18]

ANOMALY FREE GAUGE EXTENSIONS

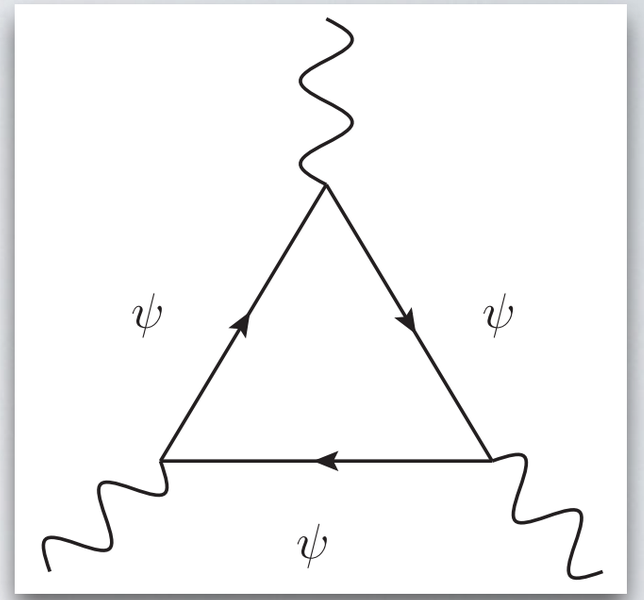
$$J^{\mu}_{X} \neq 0$$

ANOMALY FREE MODELS

- Constraints on possible charge assignments of SM fields plus 3 RH neutrinos from **anomaly cancellation:**

$$J^\mu_X = \sum_\psi \bar{\psi}\, Q_\psi\, \gamma^\mu \psi \qquad \text{with} \quad \psi = Q, L, u, d, \ell, \nu$$

Define sum of family charges $\quad X^n_\psi = \sum_i^3 (Q_{\psi_i})^n$



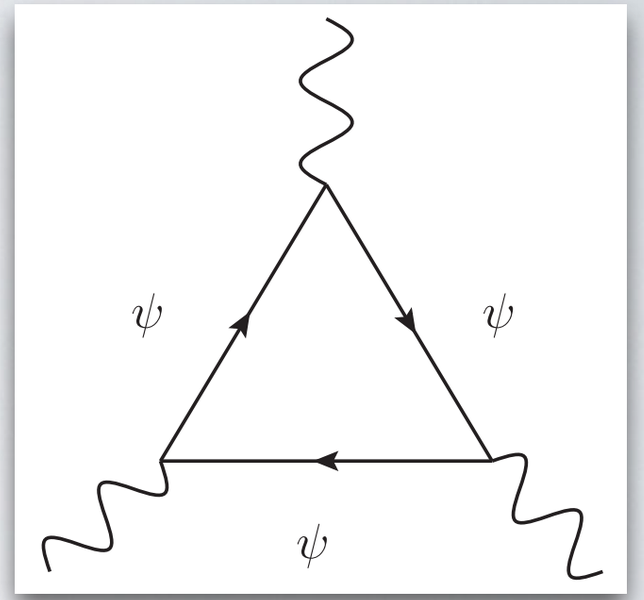
Anomaly	Charge combinations
$U(1)_X^3$	$2X_L^3 + 6X_Q^3 - X_\ell^3 - X_\nu^3 - 3(X_u^3 + X_d^3)$
$U(1)_X^2 U(1)_Y$	$2Y_L X_L^2 + 6Y_Q X_Q^2 - Y_\ell X_\ell^2 - Y_\nu X_\nu^2 - 3(Y_u X_u^2 + Y_d X_d^2)$
$U(1)_X U(1)_Y^2$	$2Y_L^2 X_L + 6Y_Q^2 X_Q - Y_\ell^2 X_\ell - Y_\nu^2 X_\nu - 3(Y_u^2 X_u + Y_d^2 X_d)$
$SU(3)^2 U(1)_X$	$2X_Q - X_u - X_d$
$SU(2)^2 U(1)_X$	$2X_L + 6X_Q$
$\text{grav}^2 U(1)_X$	$2X_L + 6X_Q - X_\ell - X_\nu - 3(X_u + X_d)$

ANOMALY FREE MODELS

- Constraints on possible charge assignments of SM fields plus 3 RH neutrinos from **anomaly cancellation:**

$$J^\mu_X = \sum_\psi \bar{\psi}\, Q_\psi\, \gamma^\mu \psi \qquad \text{with} \quad \psi = Q, L, u, d, \ell, \nu$$

Define sum of family charges $\quad X^n_\psi = \sum_i^3 (Q_{\psi_i})^n$



- Additional constraints from **Yukawa terms:**

$$\mathcal{L}_Y = \frac{v}{\sqrt{2}} \sum_\psi \bar{\psi} y_\psi \psi$$

Anomaly	Charge combinations	with Yukawa constraints
$U(1)_X^3$	$2X_L^3 + 6X_Q^3 - X_\ell^3 - X_\nu^3 - 3(X_u^3 + X_d^3)$	$X_L^3 - X_\nu^3$
$U(1)_X^2 U(1)_Y$	$2Y_L X_L^2 + 6Y_Q X_Q^2 - Y_\ell X_\ell^2 - Y_\nu X_\nu^2 - 3(Y_u X_u^2 + Y_d X_d^2)$	0
$U(1)_X U(1)_Y^2$	$2Y_L^2 X_L + 6Y_Q^2 X_Q - Y_\ell^2 X_\ell - Y_\nu^2 X_\nu - 3(Y_u^2 X_u + Y_d^2 X_d)$	$-\frac{1}{2}(X_L + 3X_Q)$
$SU(3)^2 U(1)_X$	$2X_Q - X_u - X_d$	0
$SU(2)^2 U(1)_X$	$2X_L + 6X_Q$	$2X_L + 6X_Q$
$\text{grav}^2 U(1)_X$	$2X_L + 6X_Q - X_\ell - X_\nu - 3(X_u + X_d)$	$X_L - X_\nu$

DIRAC NEUTRINOS

- Structural invariance of Yukawa terms allows for **three different classes** of **family charges**

$$Q_\psi = (a,a,a) \quad (a,a,b) \quad (a,b,c)$$

and hence w.l.o.g. $Q_Q = Q_u = Qd$ and $Q_L = Q_\ell = Q_\nu$

- After diagonalising the mass terms $\bar{\psi}_L\, U_\psi\, M_\psi\, W_\psi^\dagger\, \psi_R$ final set of **constraints** from

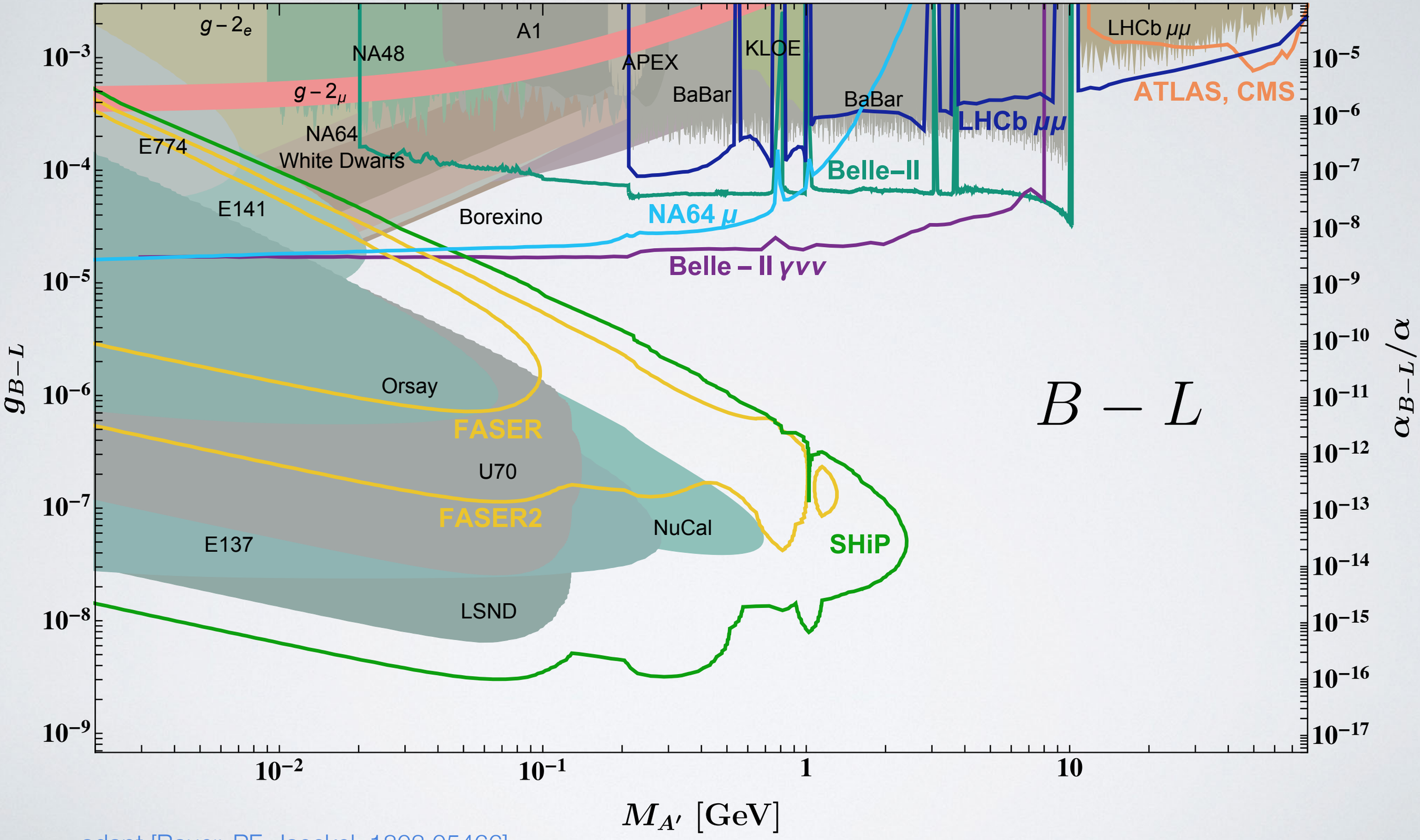
$$V_{\rm CKM} = U_u U_d^\dagger \qquad V_{\rm PMNS} = U_\ell U_\nu^\dagger$$

- In **absence** of **Majorana masses** (Dirac neutrinos) only a^3 lepton charges can reproduce viable PMNS matrix! Thus:

$$X_{\rm leptons} + 3X_{\rm quarks} = 0 \quad \Longrightarrow \quad U(1)_{B-L}$$

[Bauer, PF, Mosny; 2011.12973]

$U(1)_{B-L}$



adapt.[Bauer, PF, Jaeckel; 1803.05466]

MAJORANA NEUTRINOS

- All other anomaly free groups **must have Majorana neutrinos!**

e.g. $U(1)_{B-3L_i}$, $U(1)_{L_i-L_j}$, $\cdots$

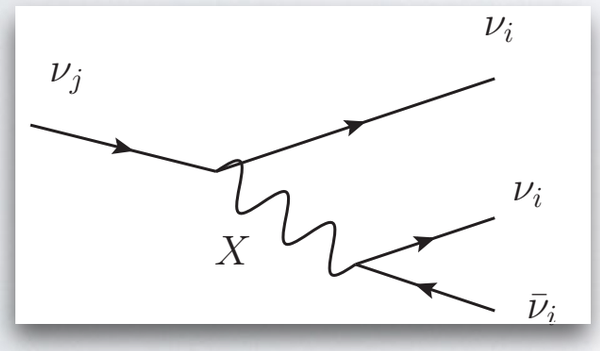
- Majorana mass terms induce **neutrino flavour changing couplings** of neutrino mass eigenstates

$$[Q_\ell, U_\nu^M] = [Q_\nu, U_\nu^M] \neq 0$$

$$\bar{\nu}_\alpha \, Q_{\alpha\alpha} \gamma^\mu \, \nu_\alpha \; X_\mu \quad \rightarrow \quad \bar{\nu}_i \; \underbrace{U_{i\alpha}^\dagger Q_{\alpha\alpha} U_{\alpha j}}_{Q_{ij}} \; \gamma^\mu \, \nu_j \; X_\mu$$

[Bauer, PF, Mosny; 2011.12973]

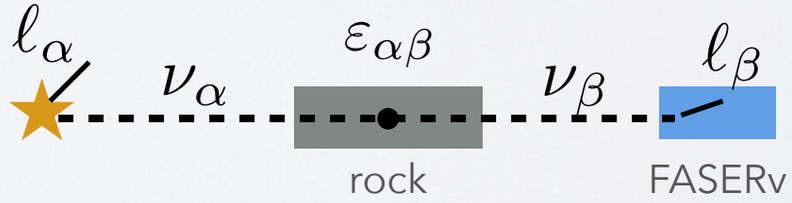
- This induces neutrino decays. Potentially interesting for astrophysical neutrinos

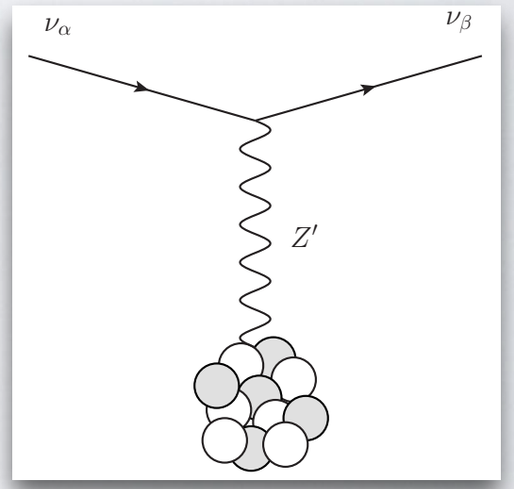


but

$$\Gamma \propto \frac{g^2 m_\nu^5}{M_X^4}$$

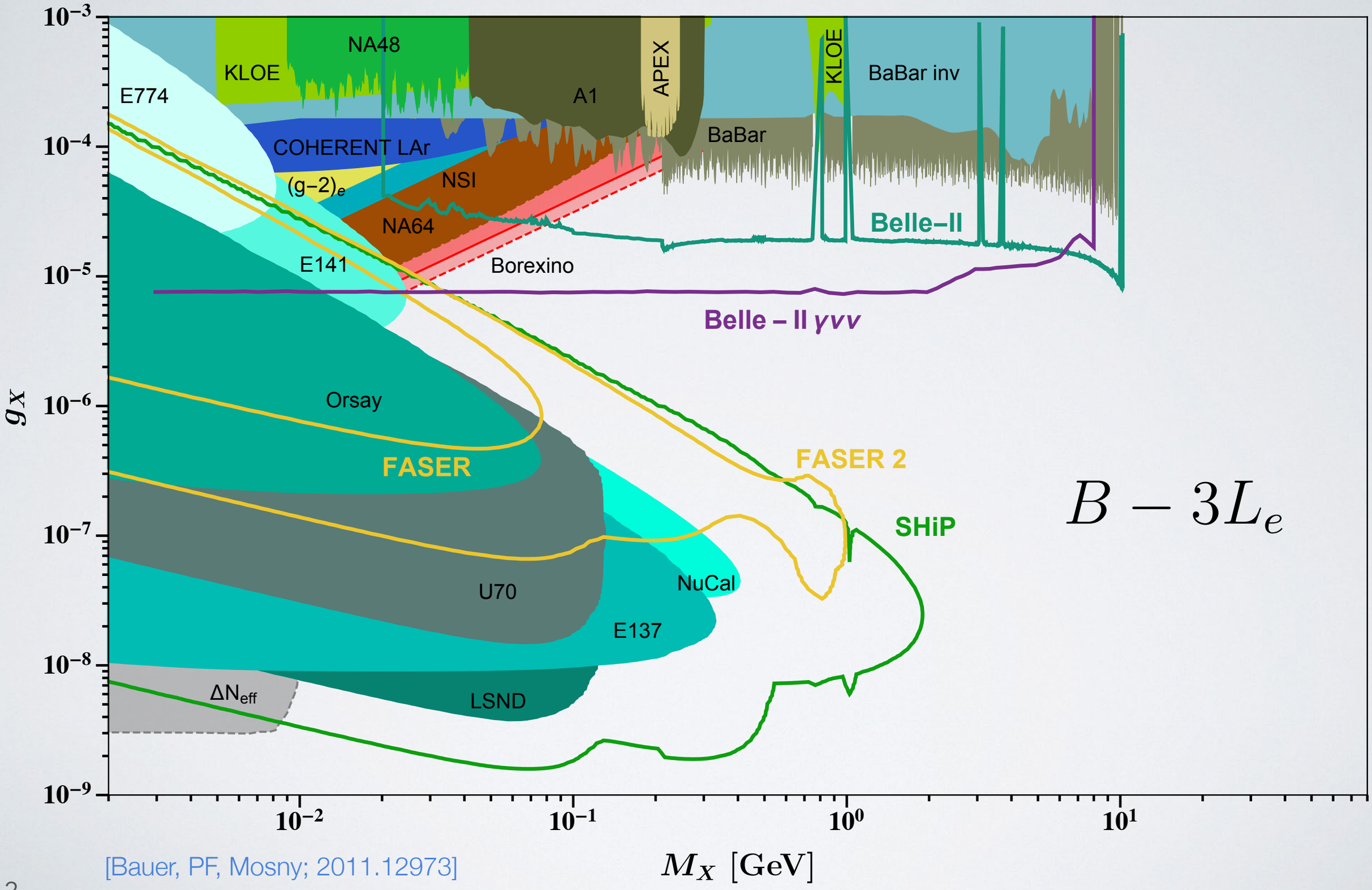
Can this be tested at neutrino experiments at FPF via matter effects?





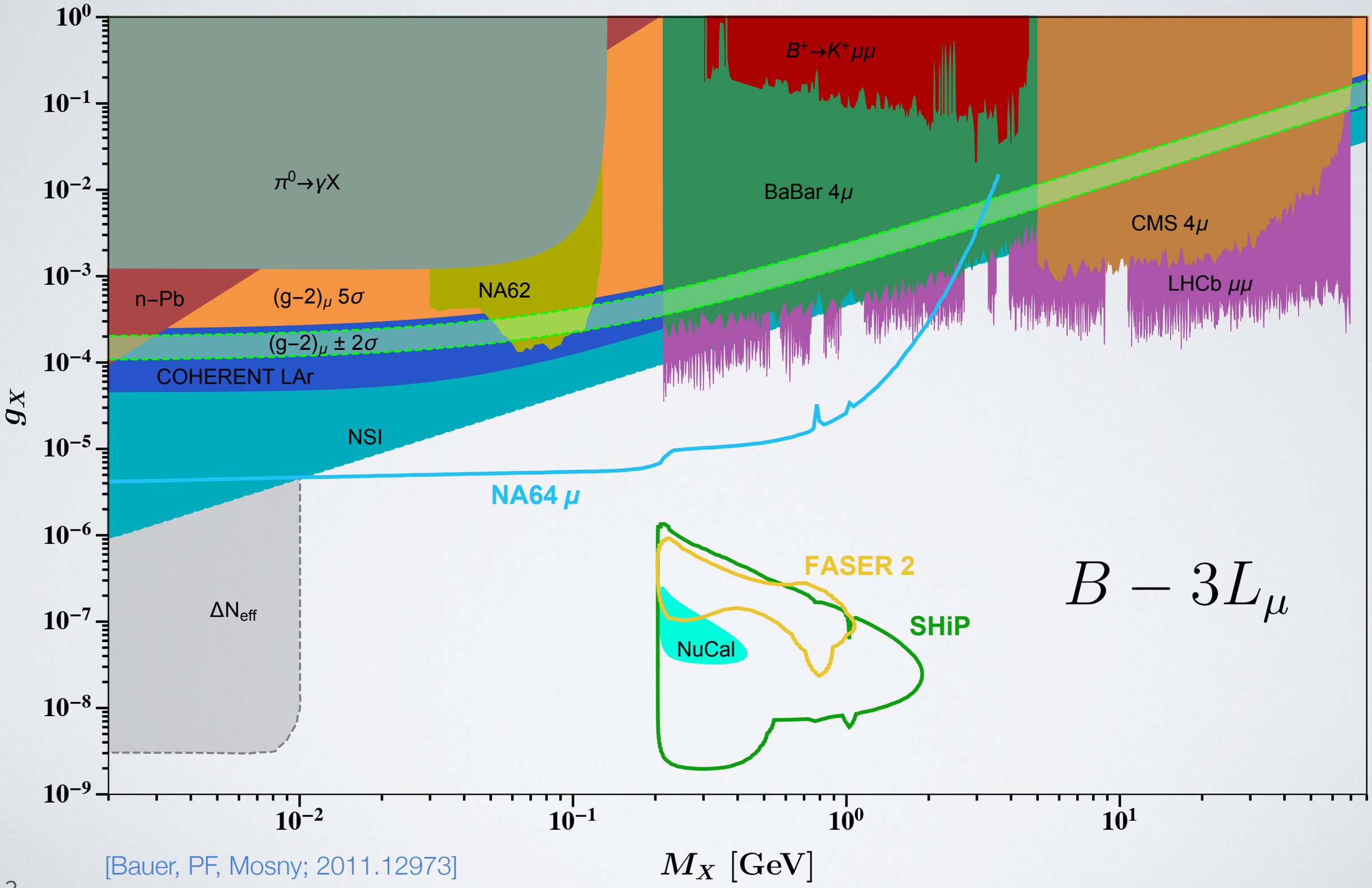
- Can still look for these bosons via charged leptons and hadrons

$U(1)_{B-3L_e}$



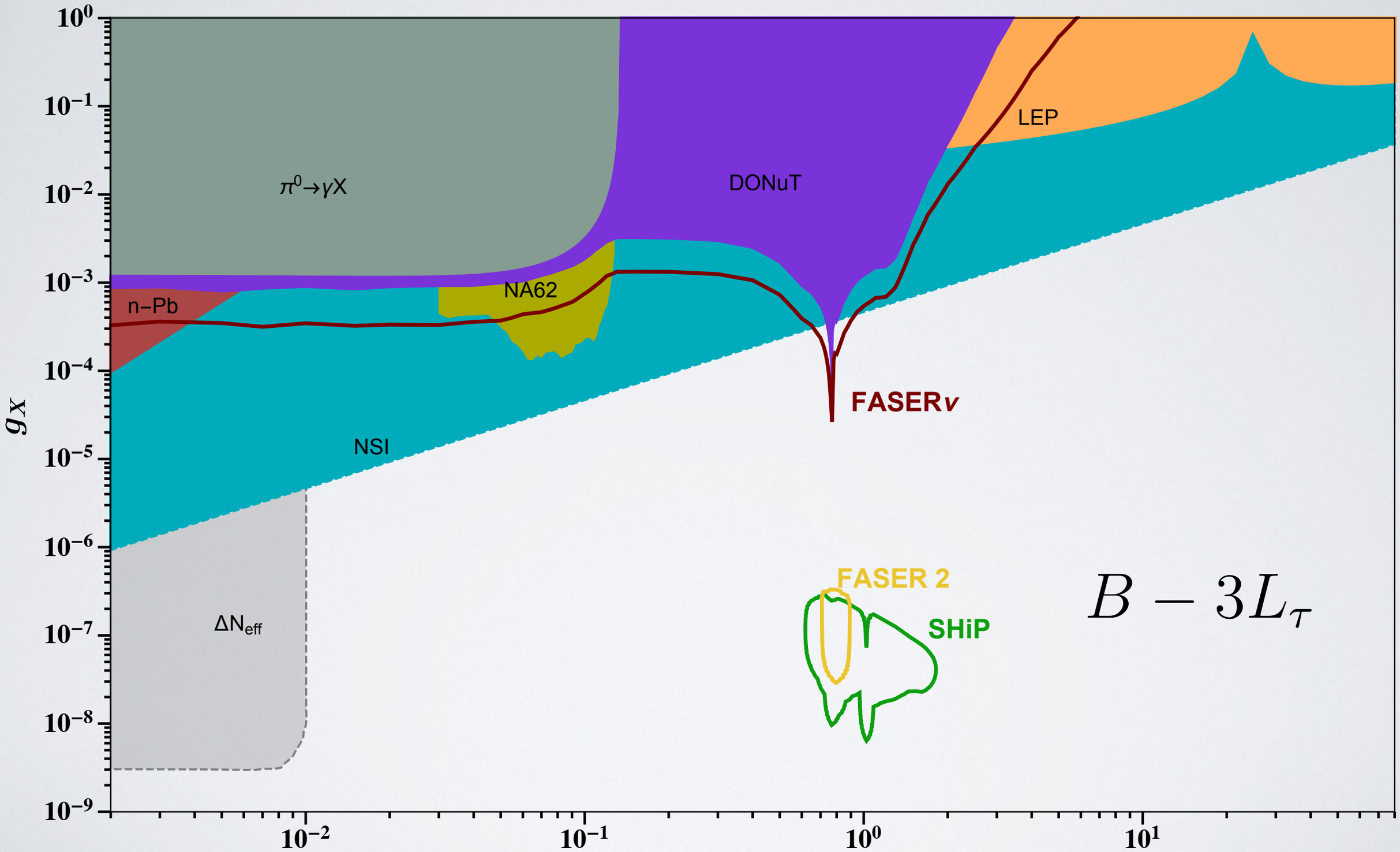
[Bauer, PF, Mosny; 2011.12973]

$U(1)_{B-3L_\mu}$



[Bauer, PF, Mosny; 2011.12973]

$U(1)_{B-3L_\tau}$



[Kling; 2005.03594]

[Bauer, PF, Mosny; 2011.12973]

OPPORTUNITIES AT FPF

- Neutrinos are unique way to distinguish **minimal** from **non-minimal realisations**

- FASER can look for $U(1)_{B-3L_i}$ bosons in model-independent **searches of charged dilepton decays**

- FASERv can probe ν_τ **scattering** of extra neutrino production. Similar analysis for electron and muon flavoured interactions?

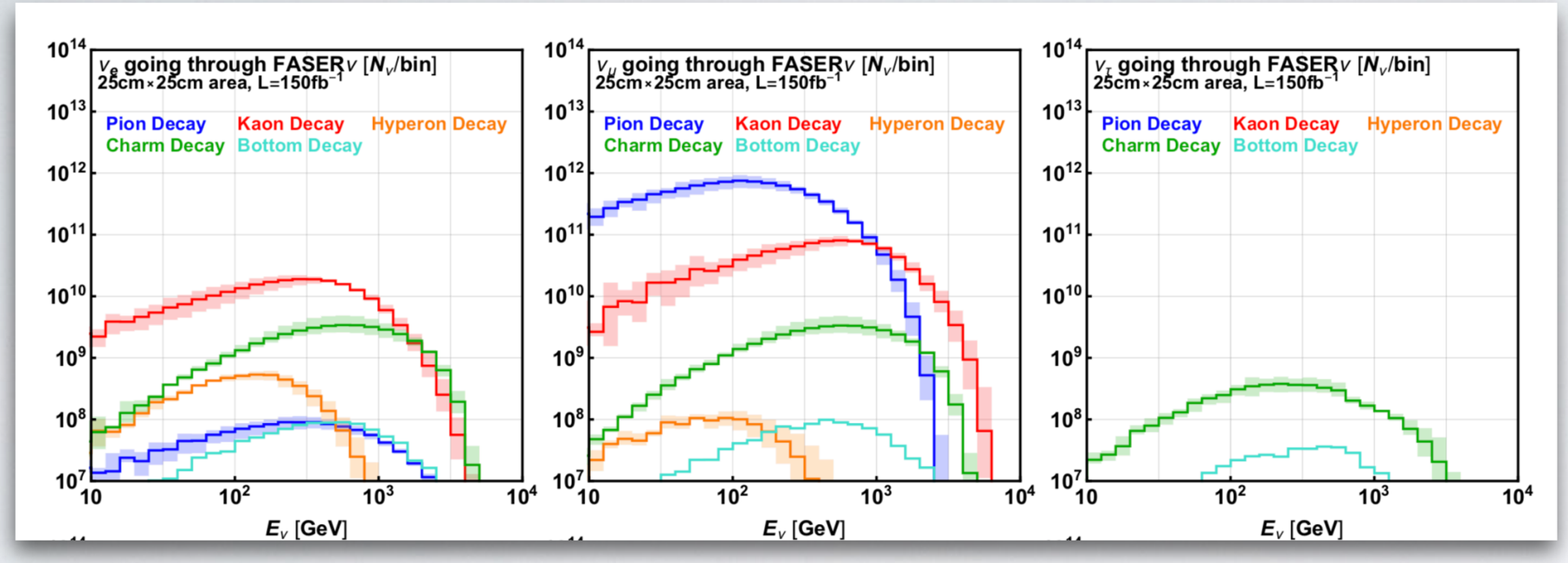
- Can neutrino FNCNs be probed via **in-medium interactions** with new gauge boson leading to **different flavour composition** reaching FPF experiments?

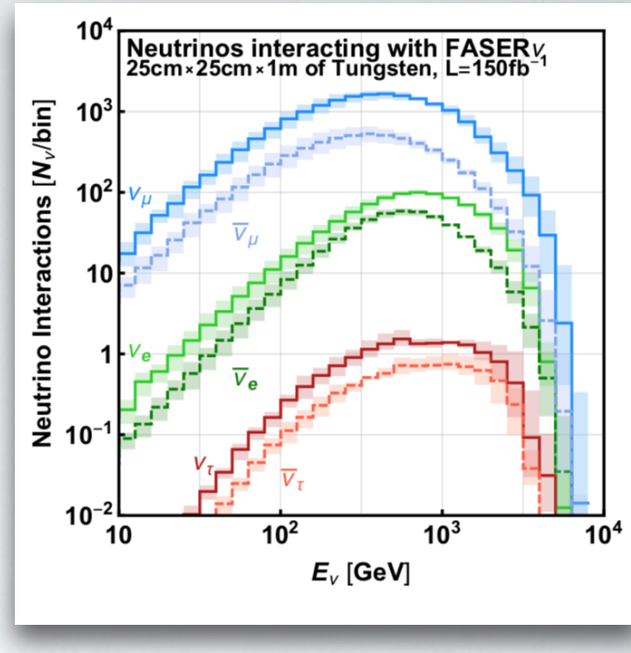
THANK YOU!

BACKUP

NEUTRINO FCNCS @ FASERν2 ?

- FASERv sees largely different fluxes of ν_e, ν_μ and ν_τ

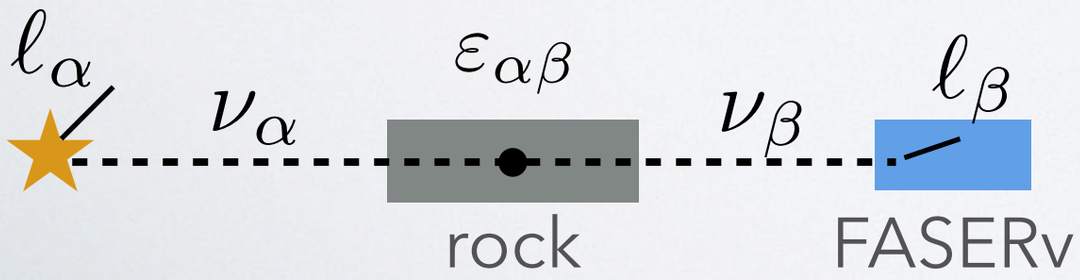


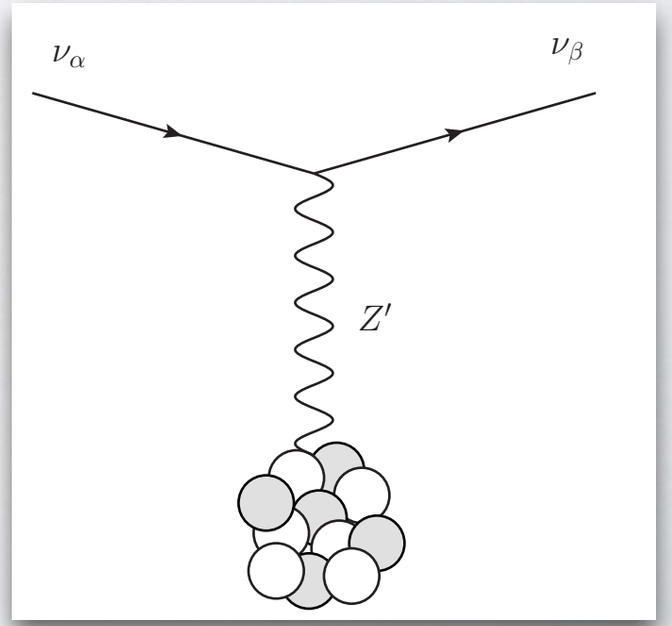


[FASER Collaboration; 1908.02310]

- Unique opportunity to search for neutrino FCNCs as we can tag initial and final state flavour!

- This would signal **non-minimal realisation!**

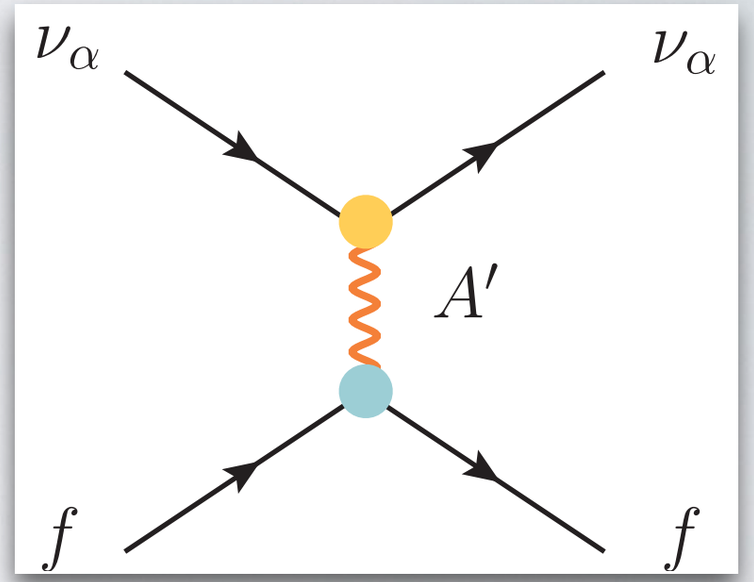




NEUTRINO INTERACTIONS

- QUESTION: Can we test this interesting parameter space with neutrino interactions?

- IDEA: A' contributes to neutrino-electron and -nucleus scattering via mixing.



- Can be effectively treated as NSI interaction:

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}\,G_F \sum_{\substack{f=u,d,e \\ \alpha=e,\mu,\tau}} \varepsilon^{fP}_{\alpha\alpha}\ \left[\bar{\nu}_\alpha \gamma_\rho P_L \nu_\alpha\right]\ \left[\bar{f}\gamma^\rho P f\right]$$

with

$$\varepsilon^{fP}_{\alpha\alpha}(E_R) = -\frac{g_{\mu\tau}\, Q'_{\nu_\alpha}\; e\,\epsilon_{\mu\tau}\, Q^{\rm EM}_f}{2\sqrt{2}\,G_F\,(2m_f E_R + M^2_{A'})}$$