SEARCHING FOR DARK PHOTONS AT THE FPF

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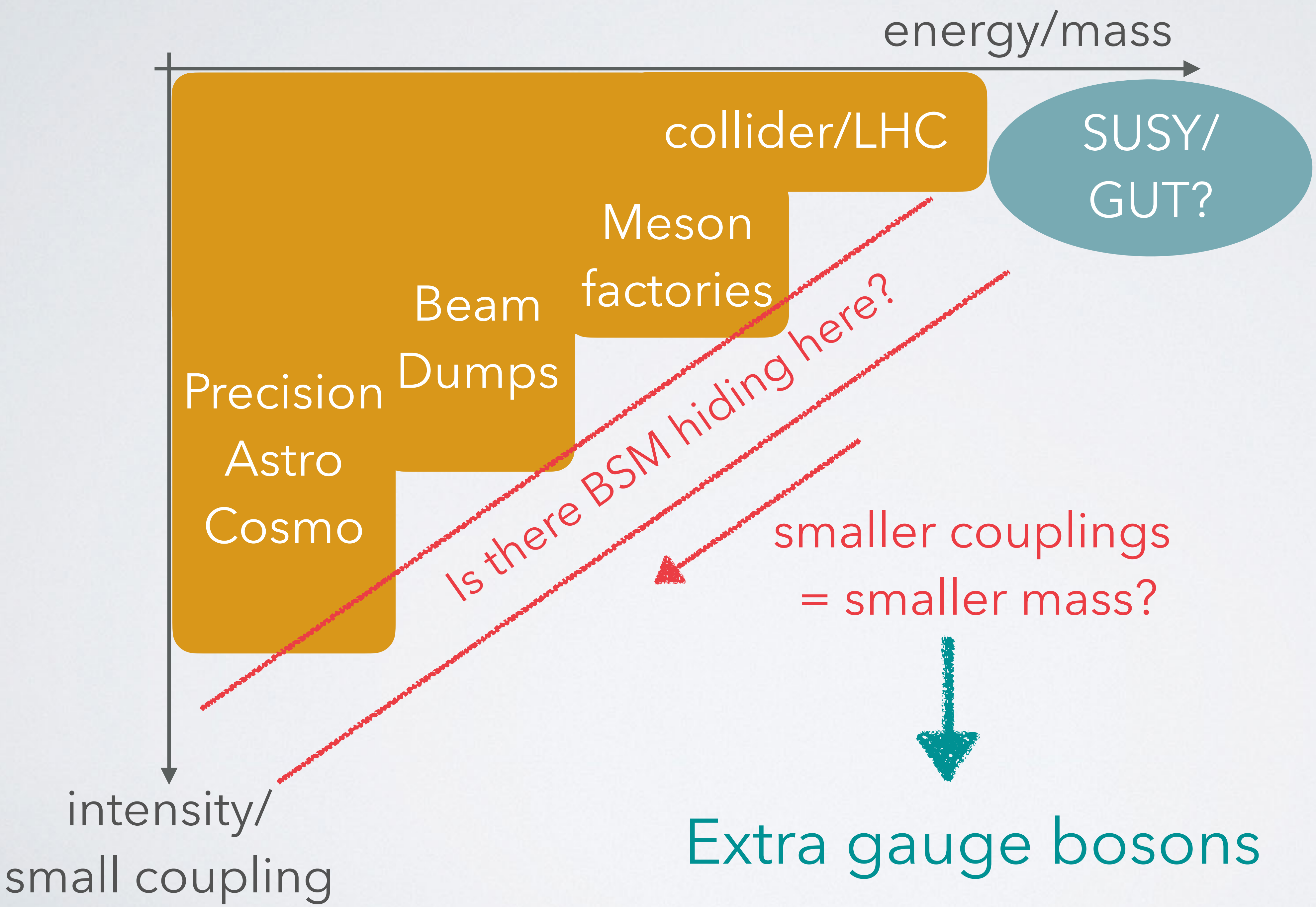
WHERE TO LOOK FOR BSM

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



DARK PHOTONS

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

[Holdom; PLB 166, 196]

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

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

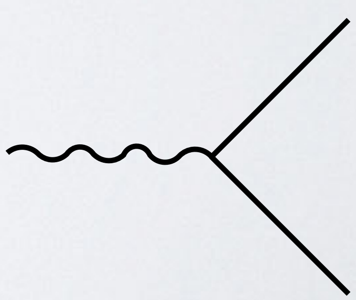
$$\Rightarrow \quad \boxed{M_{A'} = g_x \, f}$$

smaller couplings

$\Rightarrow$ smaller mass!

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

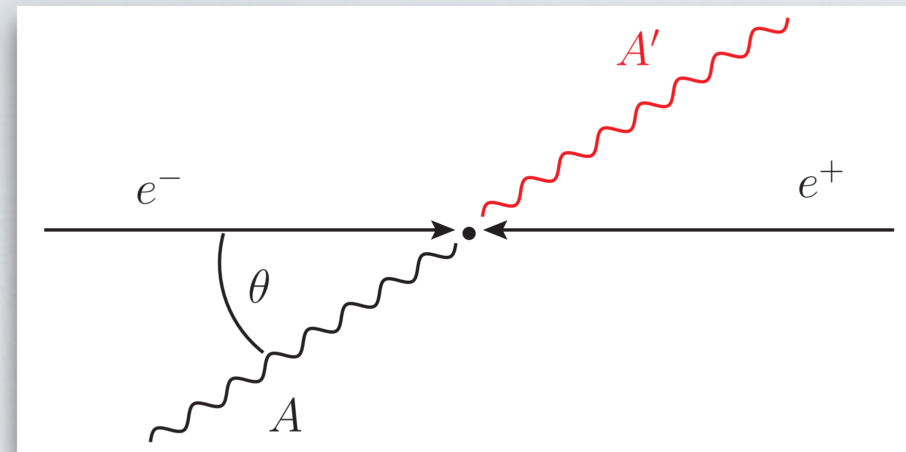
$$A^\mu \to A^\mu - \epsilon A'^\mu \quad \longrightarrow \quad e A_\mu J^\mu_{\rm EM} - \epsilon \, e A'_\mu J^\mu_{\rm EM}$$



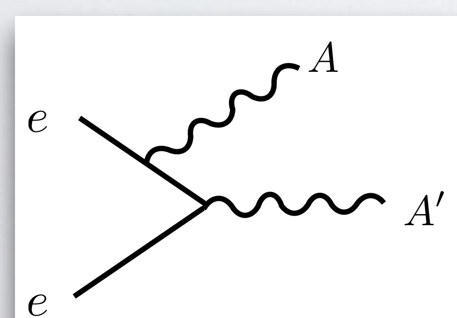
Hidden Photon couples to EM current suppressed by ϵ !

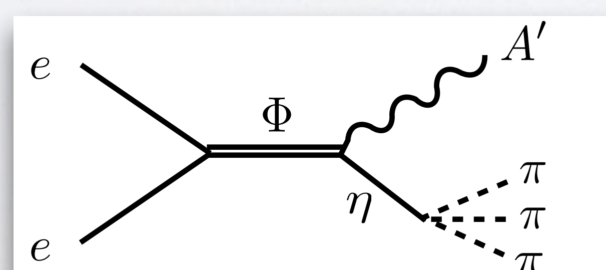
DARK PHOTON SEARCHES

Colliders:



- Production:

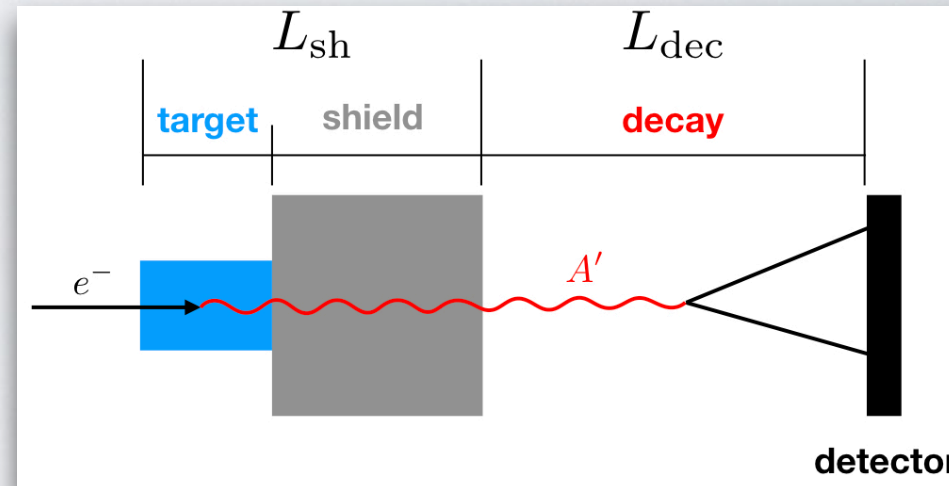




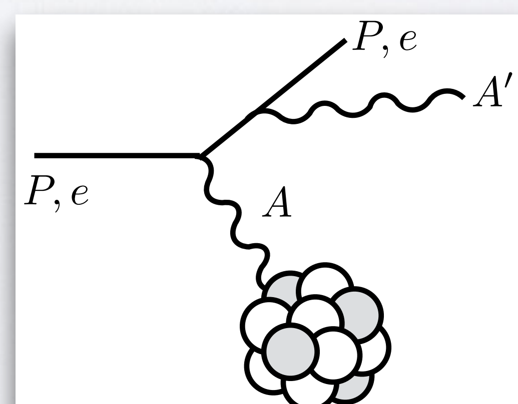
$$\mathscr{L}^{\rm coll} \approx \mathcal{O}(10^{-1})\ \mathrm{ab}^{-1}\mathrm{yr}^{-1}$$

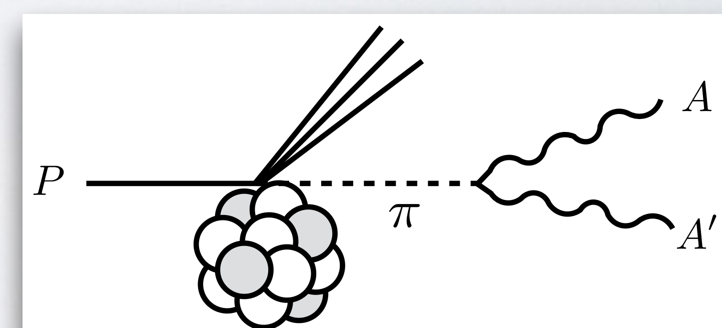
$$\sigma^{\rm coll}_{A'} \propto \frac{\alpha^2\, \epsilon^2}{E^2_{\rm CM}}$$

Beam dumps/forward experiments:



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



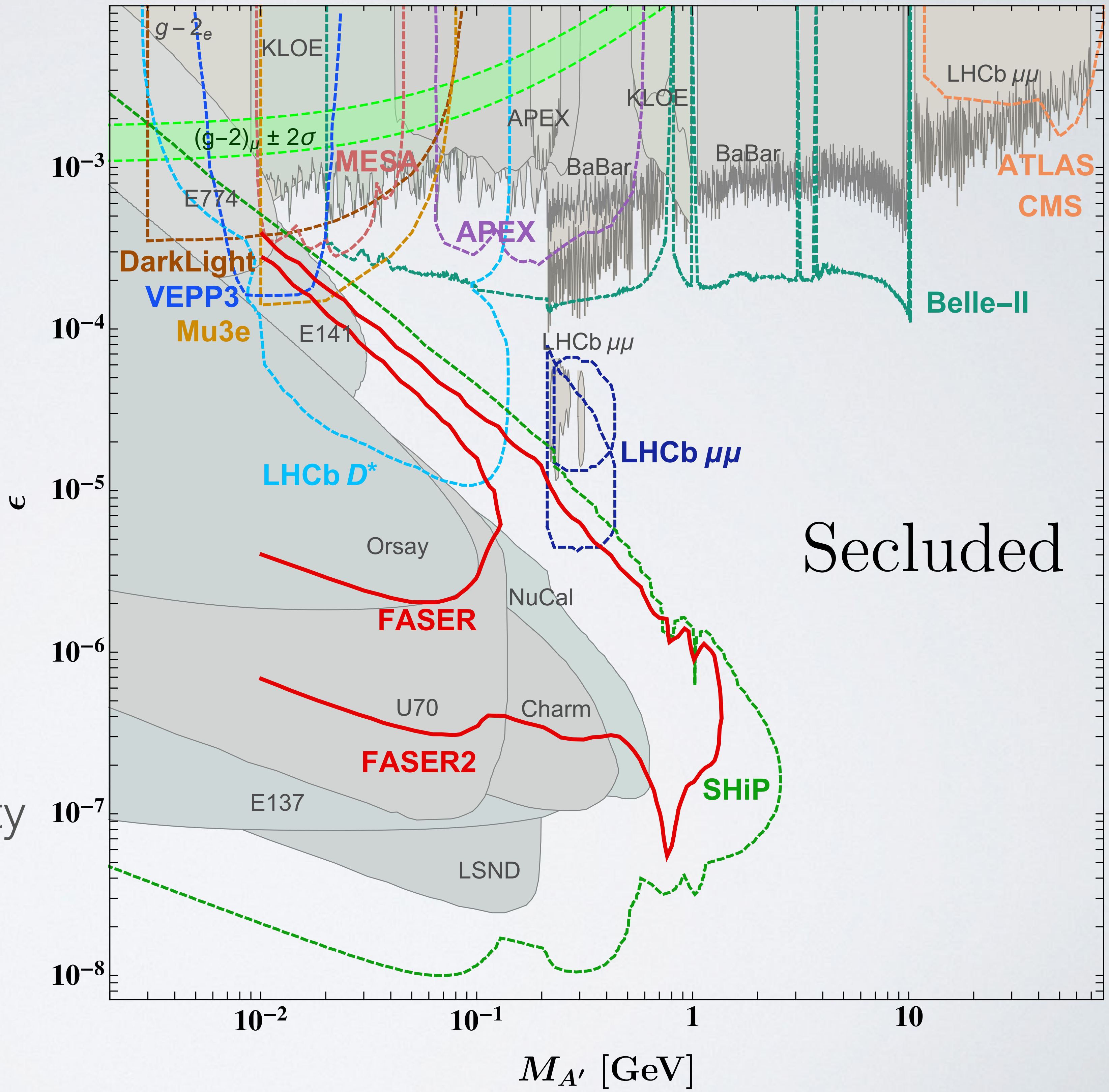


$$\mathscr{L}^{\rm bd} \approx \mathcal{O}(1)\ \mathrm{ab}^{-1}\mathrm{d}^{-1}$$

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

SECLUDED $U(1)_X$

- Minimal secluded $U(1)_X$ model for $J_\mu^X = 0$ (only kinetic mixing)
- A' produced in EM processes like bremsstrahlung, radiative return and meson decays
- FASER(2) will be able to search for A′ in visible decays and push sensitivity significantly



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

ANOMALY FREE GAUGE EXTENSIONS

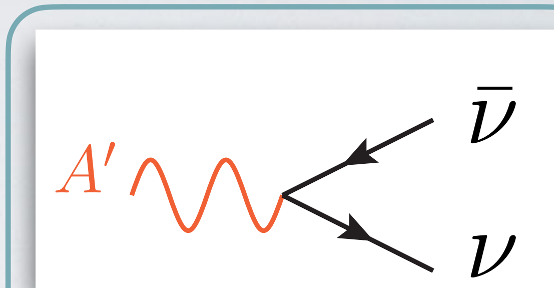
$$J_X^\mu \neq 0$$

GAUGING SM SYMMETRIES

- In general, there are two possibilities for anomaly free $U(1)_X$:

$$(i) \quad X = B - x_e\, L_e - x_\mu\, L_\mu - (3 - x_e - x_\mu)\, L_\tau\,,$$

$$(ii) \quad X = y_e\, L_e + y_\mu\, L_\mu - (y_e + y_\mu)\, L_\tau\,,$$



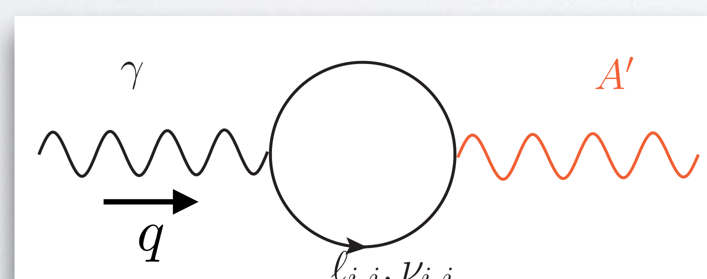
$$g_X\, Q_\nu\, \bar{\nu}\gamma^\mu \nu\, A'_\mu$$

- Consider three popular anomaly-free models:

$B - L$	$L_i - L_j$	$B - 3L_i$
Universal quark & lepton charges	charging *i*th & *j*th generation leptons	Universal quark & family-specific lepton charges

Generic feature:
Neutrino interactions

- Loop-induced mixing is unavoidable!
  However, it is finite and calculable for $L_i - L_j$:

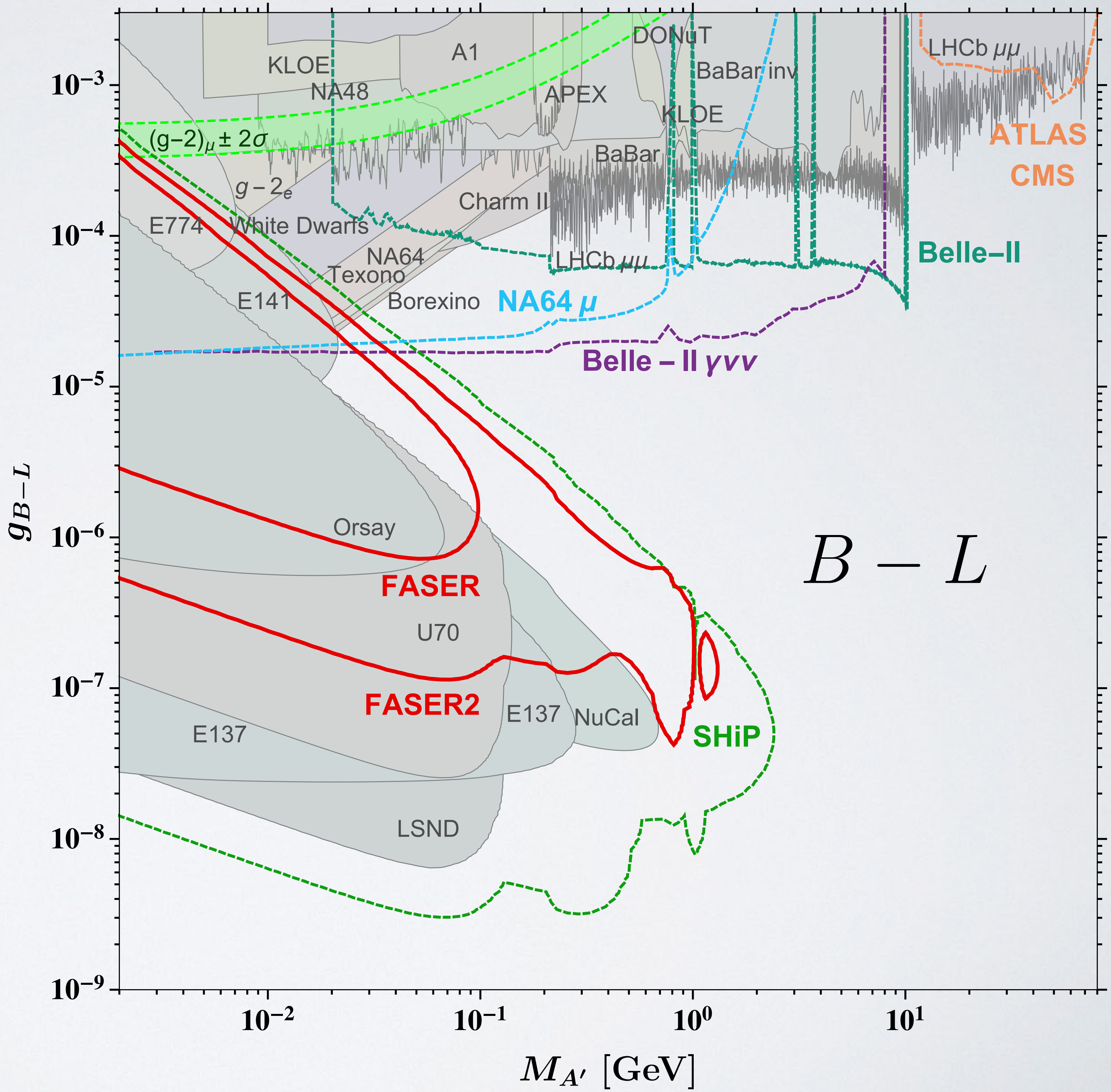


$$\Rightarrow \quad \frac{\epsilon_{ij}(q^2)}{2}\, F^{\mu\nu} F'_{\mu\nu}$$

$$\epsilon_{ij}(q^2) = \frac{e\, g_{ij}}{2\pi^2} \int_0^1 dx\, x(1-x) \left[\log\left(\frac{m_i^2 - x(1-x)q^2}{m_j^2 - x(1-x)q^2} \right) \right]$$

$B - L$

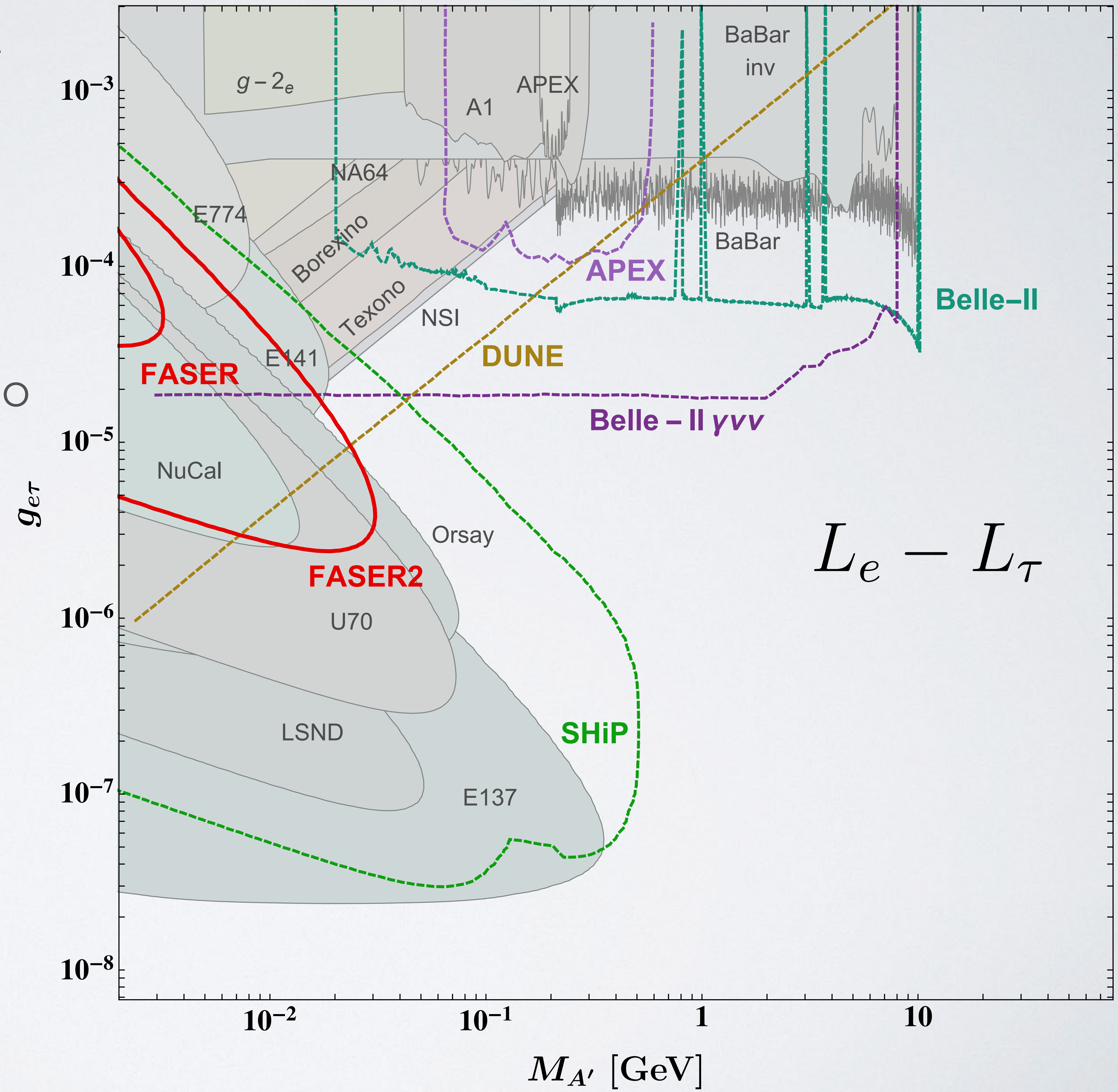
- Collider & beam dump limits very similar to *secluded* case
- Strong limits arise from neutrino scattering and invisible searches (Texono, Borexino, NA64)
- LHC can abundantly produce $B - L$ boson, FASER(2) has large sensitivity due to visible hadronic and leptonic decays



adapt.[Bauer, PF, Jaeckel; 1803.05466]

$L_e - L_\tau$

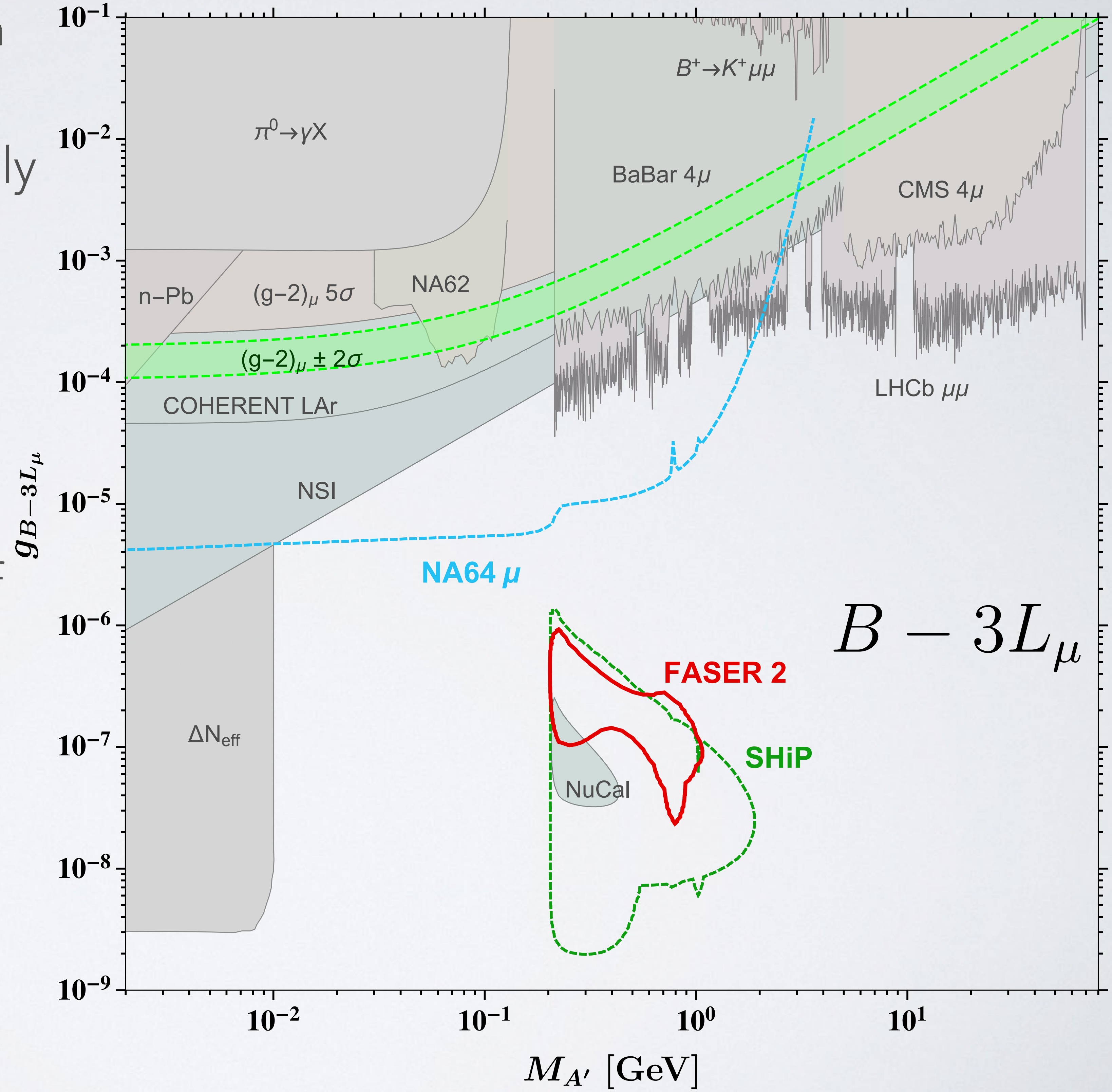
- LHC production of $L_i - L_j$ bosons proceeds only via loop-suppressed kinetic mixing!
- Strong limits from neutrino scattering, invisible searches and electron scattering
- FASER2 only sensitive to very small region of parameter space due to suppressed production



adapt.[Bauer, PF, Jaeckel; 1803.05466]

$B - 3L_\mu$

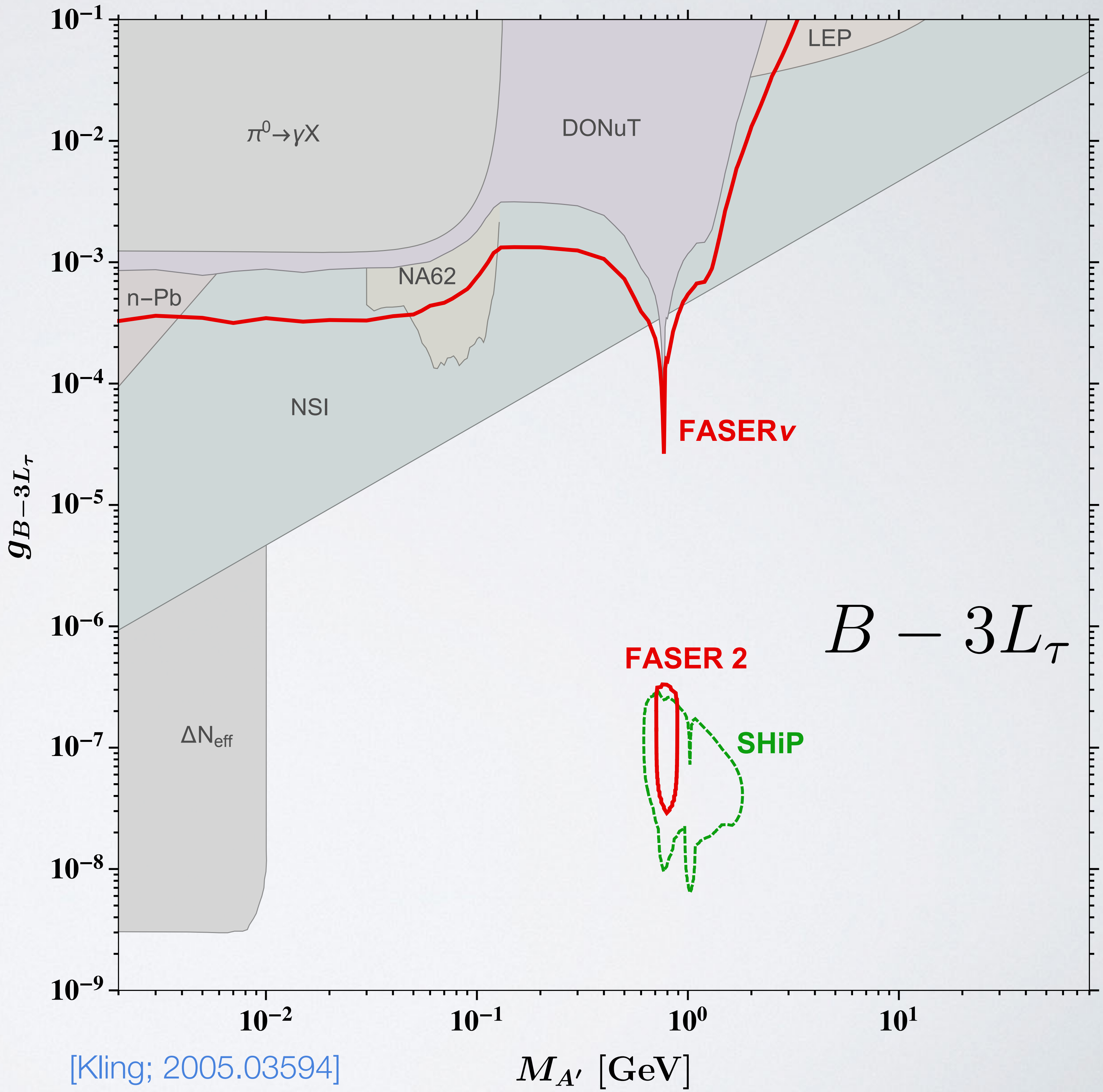
- Production and detection of gauge boson in electronic processes highly suppressed!
- FASER2 sensitive to displaced muonic decays
- ($B - 3L_e$ similar to case of $B - L$, -> see Backup)



[Bauer, PF, Mosny; 2011.12973]

$B - 3L_\tau$

- Production and detection of gauge boson in electronic and muonic processes highly suppressed!
- FASER2 sensitive to displaced hadronic decays at ω resonance
- FASERν sensitive to extra tau neutrino scattering from A′ decay



[Kling; 2005.03594]
[Bauer, PF, Mosny; 2011.12973]

OPPORTUNITIES AT FPF

- The **FPF** will be an excellent facility to undertake a broad dark photon search program in displaced forward decays

- FASER can look for a plethora of anomaly-free $U(1)_X$ bosons in model-independent **searches of charged dilepton and hadron decays**

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

- If you favourite dark photon search is still missing please do get in touch!

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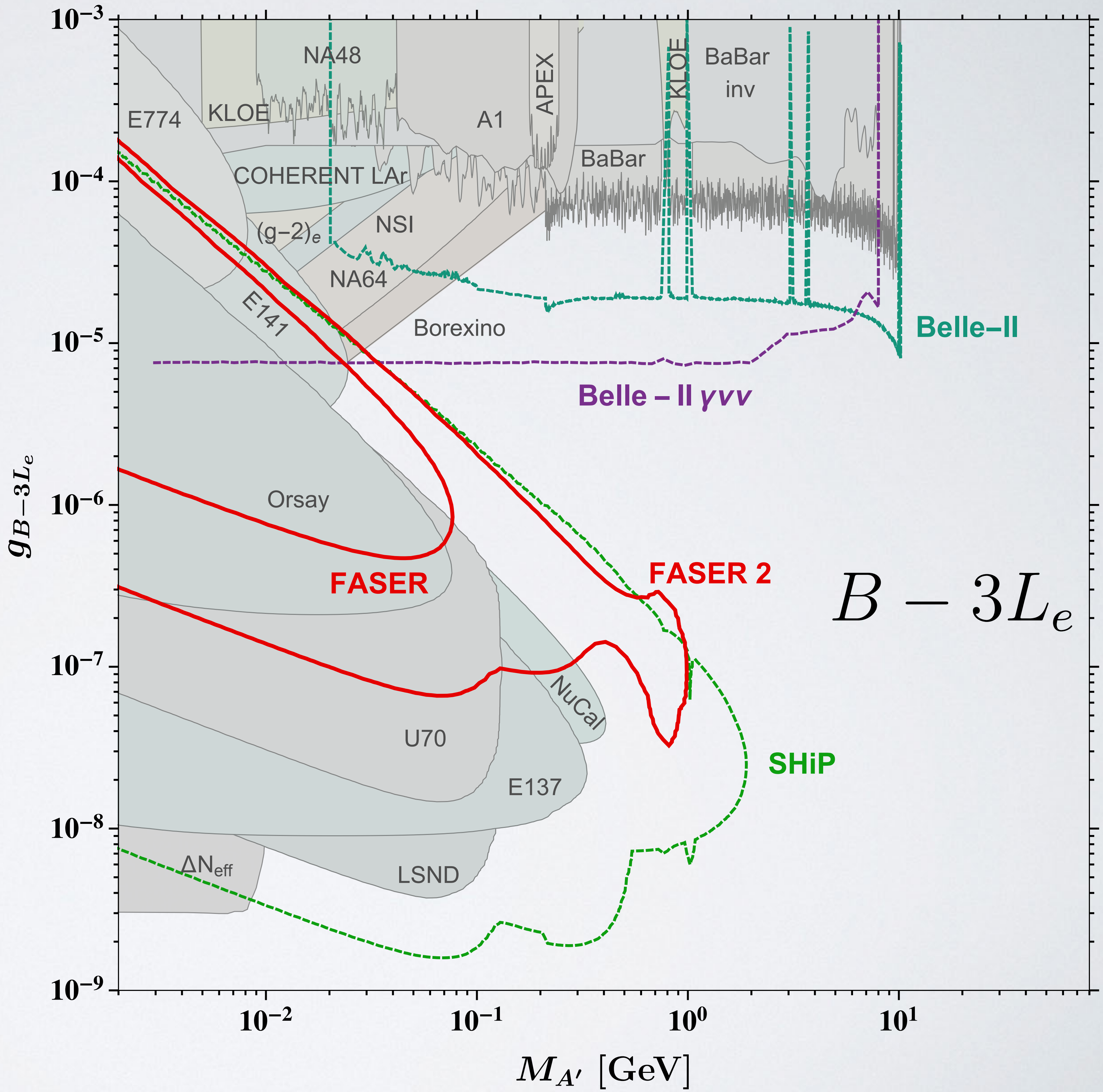
THANK YOU!

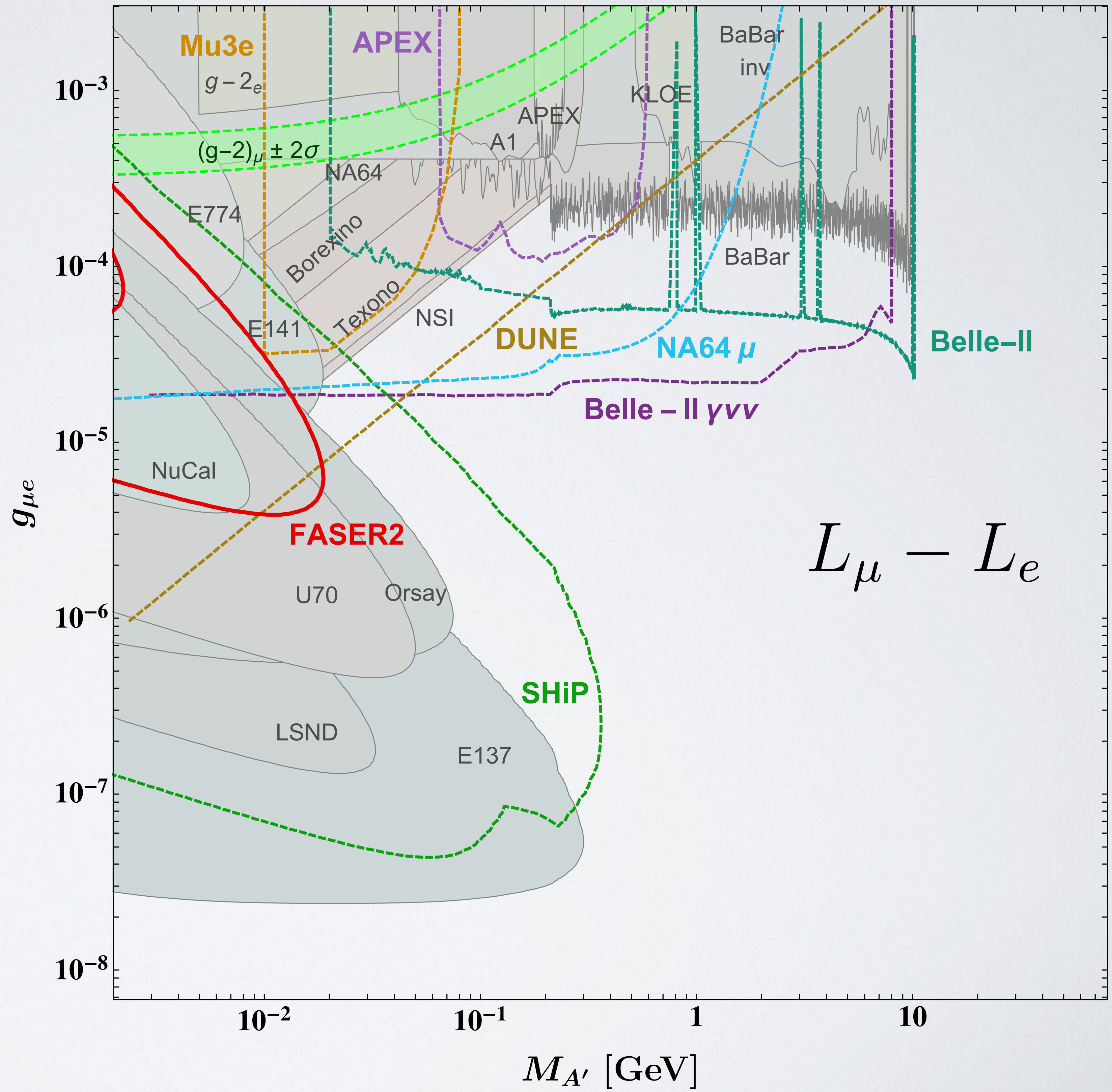
BACKUP

$B - 3L_e$



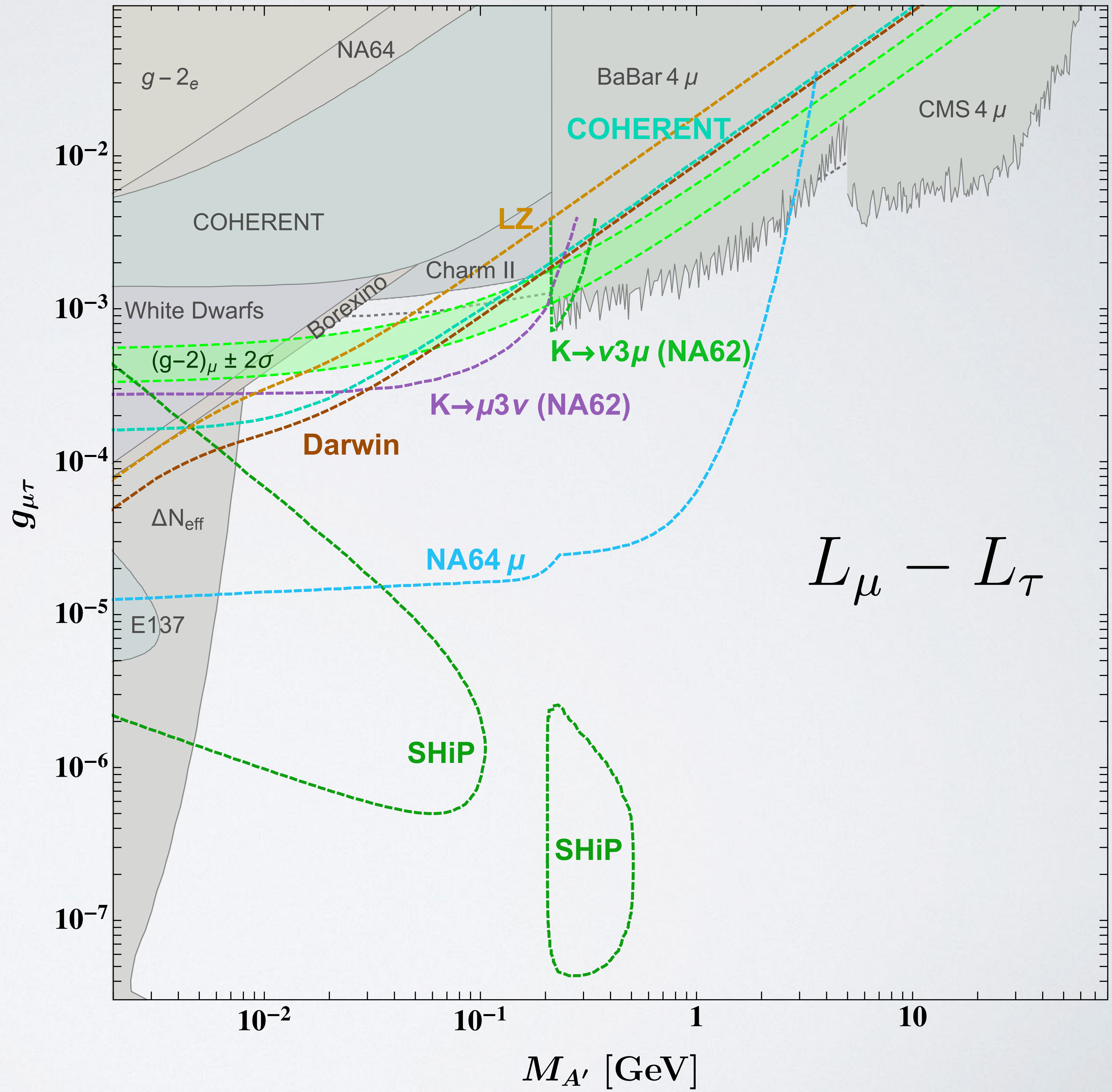
[Bauer, PF, Mosny; 2011.12973]

$L_\mu - L_e$



adapt.[Bauer, PF, Jaeckel; 1803.05466]

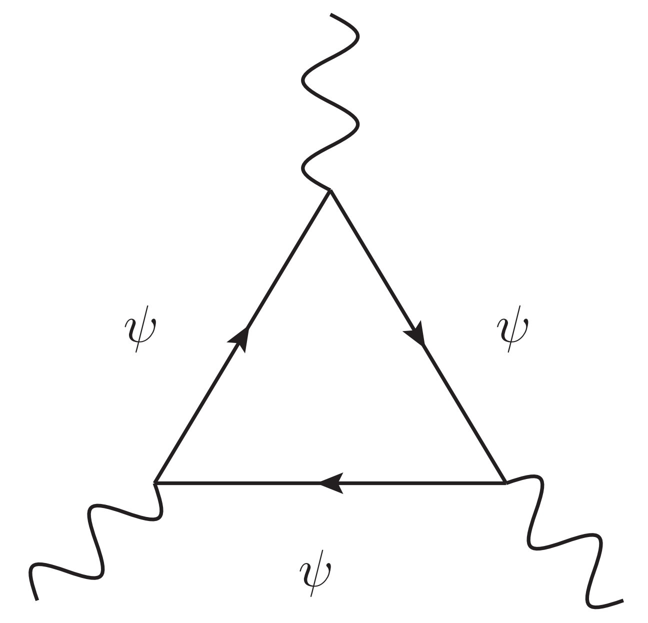
$L_\mu - L_\tau$



adapt.[Bauer, PF, Jaeckel; 1803.05466, Amaral, Cerdeño, PF, Reid; 2006.11225]

ANOMALY FREE $U(1)_X$ MODELS

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



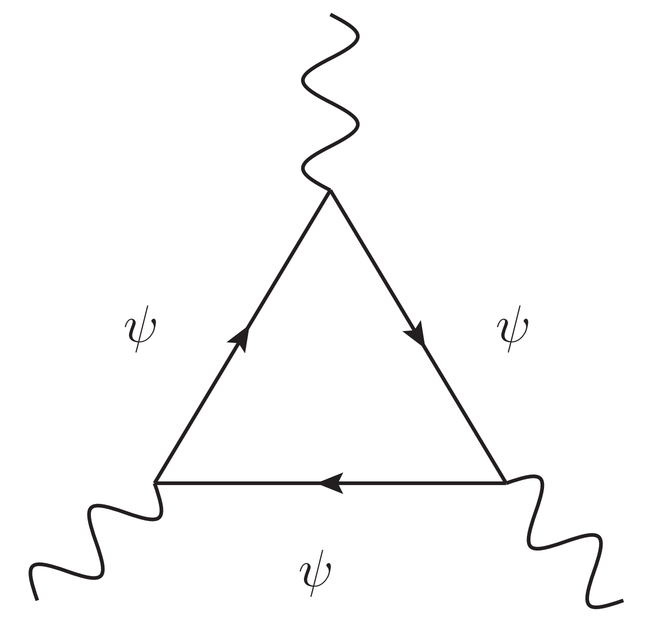
$$J^\mu_X = \sum_\psi \bar{\psi}\, Q_\psi\, \gamma^\mu \psi \qquad \text{with} \quad \psi = Q, L, u, d, \ell, \nu$$

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

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

ANOMALY FREE $U(1)_X$ MODELS

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



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

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

- Additional constraints from **Yukawa terms:**

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

[Bauer, PF, Mosny; 2011.12973]

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
$SU(2)^2 U(1)_X$	$2X_L + 6X_Q$	$2X_L + 6X_Q$
$\text{grav}^2 U(1)_X$	$2X_L + 6X_Q - X_\ell - X_\nu - 3(X_u + X_d)$	$X_L - X_\nu$