



# HIDDEN PHOTONS IN LIGHT OF g-2

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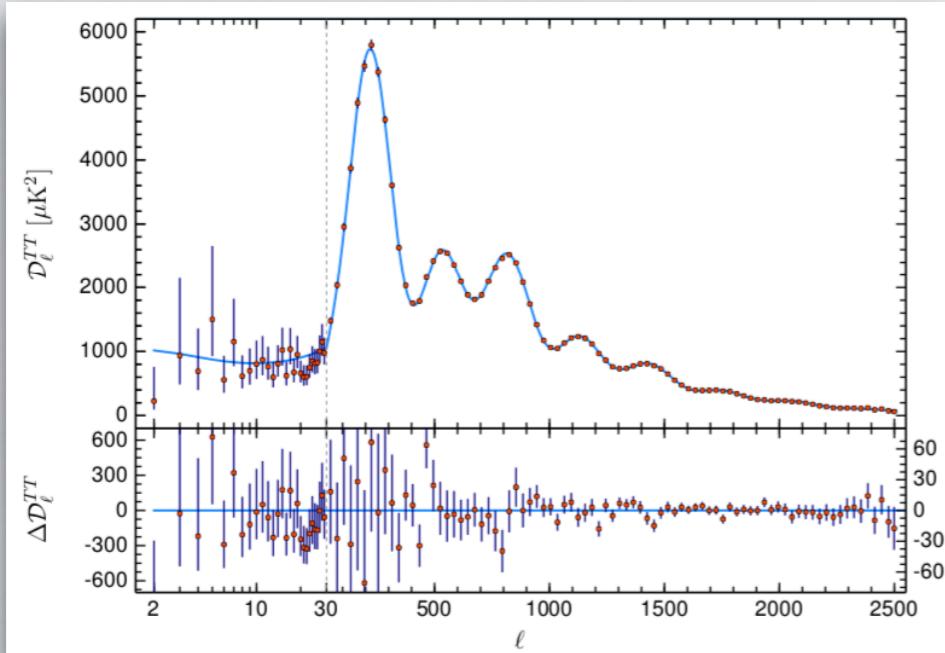
Patrick Foldenauer

Work in collaboration with  
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CP3 Seminar/virtual – **May 4<sup>th</sup>, 2021**

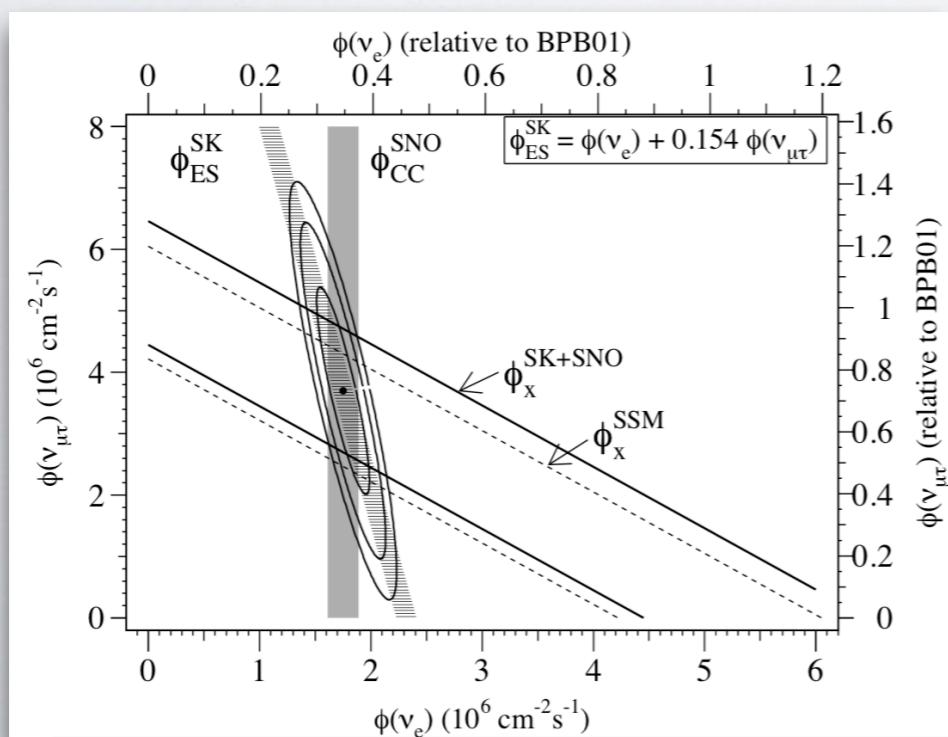
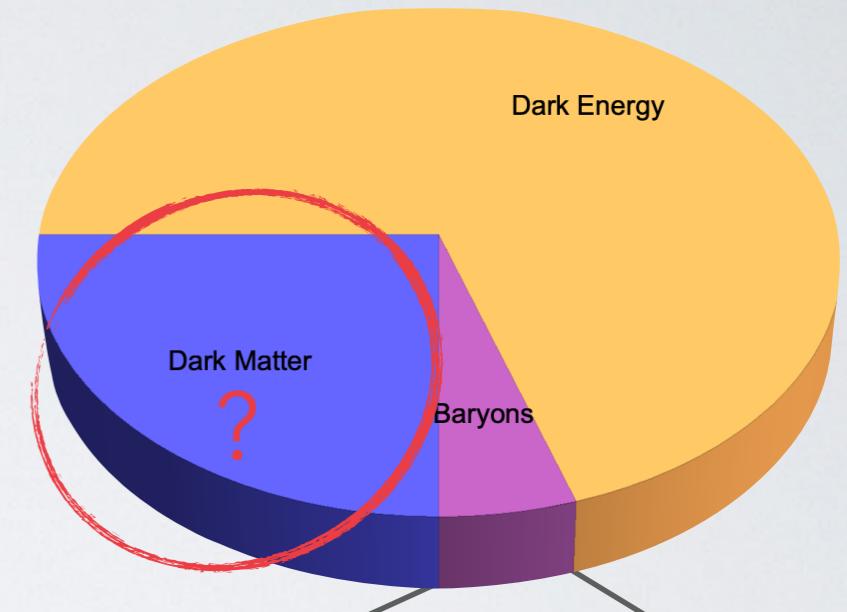
# WHY GO BEYOND THE SM?

Two obvious reasons:



[Planck Collaboration; 1807.06209]

CMB informs us  
about energy  
budget



Oscillations  
require  
massive  
neutrinos

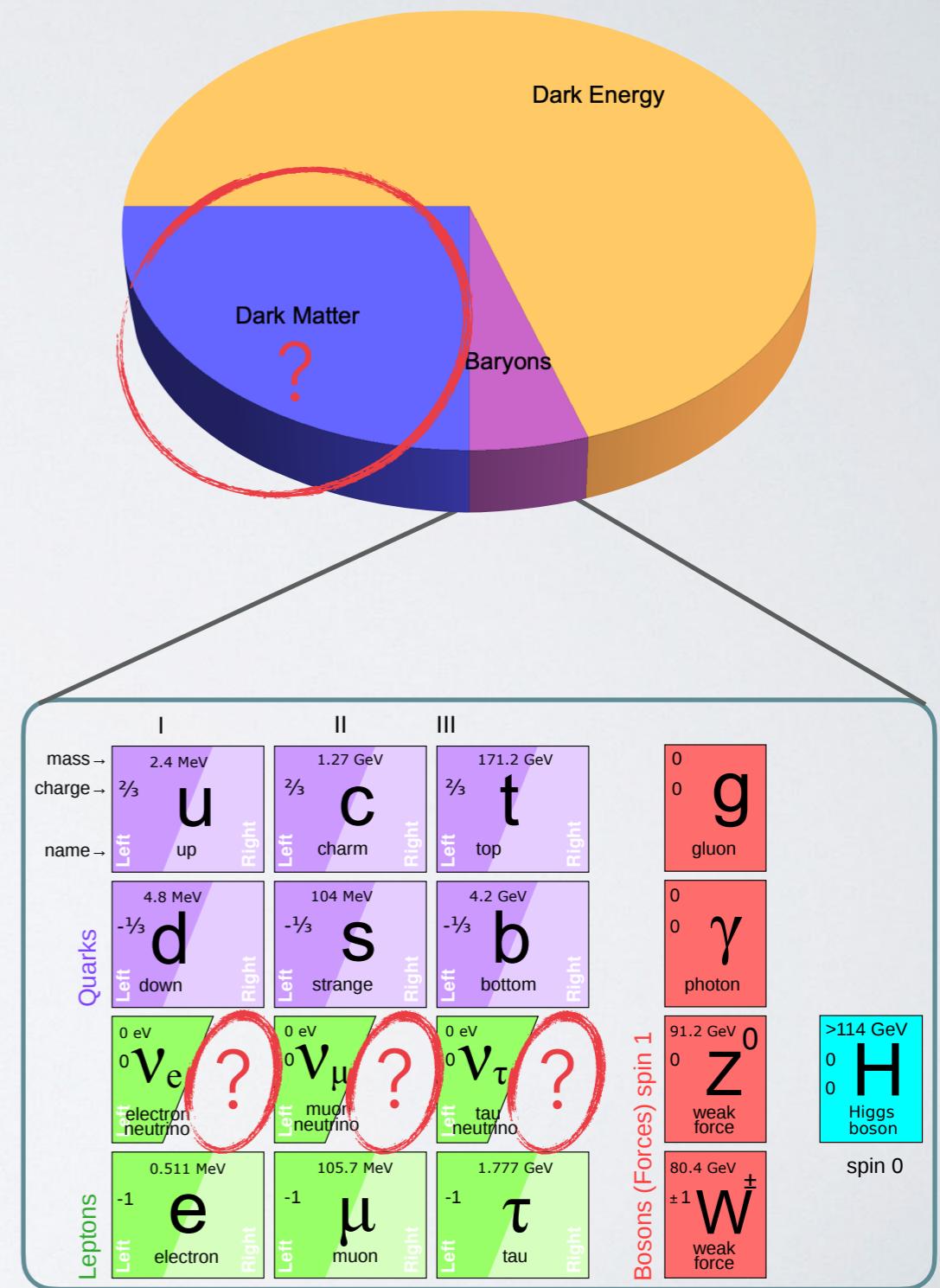
Quarks		Leptons		Bosons (Forces) spin 1	
mass →		mass →		mass →	
charge →	$\frac{2}{3}$	charge →	$\frac{2}{3}$	charge →	$\frac{0}{0}$
name →	<b>u</b> up	name →	<b>c</b> charm	name →	<b>g</b> gluon
Left		Left		Left	
Right		Right		Right	
4.8 MeV		104 MeV		91.2 GeV	
$-\frac{1}{3}$		$-\frac{1}{3}$		$0$	
<b>d</b> down		<b>s</b> strange		<b>Z</b> weak force	
Left		Left		Left	
Right		Right		Right	
4.2 GeV		4.2 GeV		80.4 GeV	
$-\frac{1}{3}$		$-\frac{1}{3}$		$\pm 1$	
<b>b</b> bottom		<b>τ</b> tau		<b>W</b> weak force	
Left		Left		Left	
Right		Right		Right	
0 eV		0 eV		0 eV	
0		0		0	
<b>ν<sub>e</sub></b> electron neutrino		<b>ν<sub>μ</sub></b> muon neutrino		<b>ν<sub>τ</sub></b> tau neutrino	
Left		Left		Left	
Right		Right		Right	
0.511 MeV		105.7 MeV		1.777 GeV	
-1		-1		-1	
<b>e</b> electron		<b>μ</b> muon		<b>τ</b> tau	
Left		Left		Left	
Right		Right		Right	

[Gninenko et al., 1301.5516]

# WHY GO BEYOND THE SM?

Possible hints for New Physics:

- **$(g - 2)_\mu$  anomaly**
- **Flavour anomalies**  $R_{K^{(*)}}$  and  $R_{D^{(*)}}$   
(BaBar, Belle, LHCb)
- **$H_0$  tension**
- Cosmic ray **positron excess**  
(PAMELA, FermiLAT, AMS-02)
- **XENON1T** excess



[Gninenko et al., 1301.5516]

# BRIEF EXCURSION: G-2

- Elementary particles with spin  $s$  have a magnetic dipole moment

$$\vec{\mu} = g \frac{e}{2m} \vec{S}$$

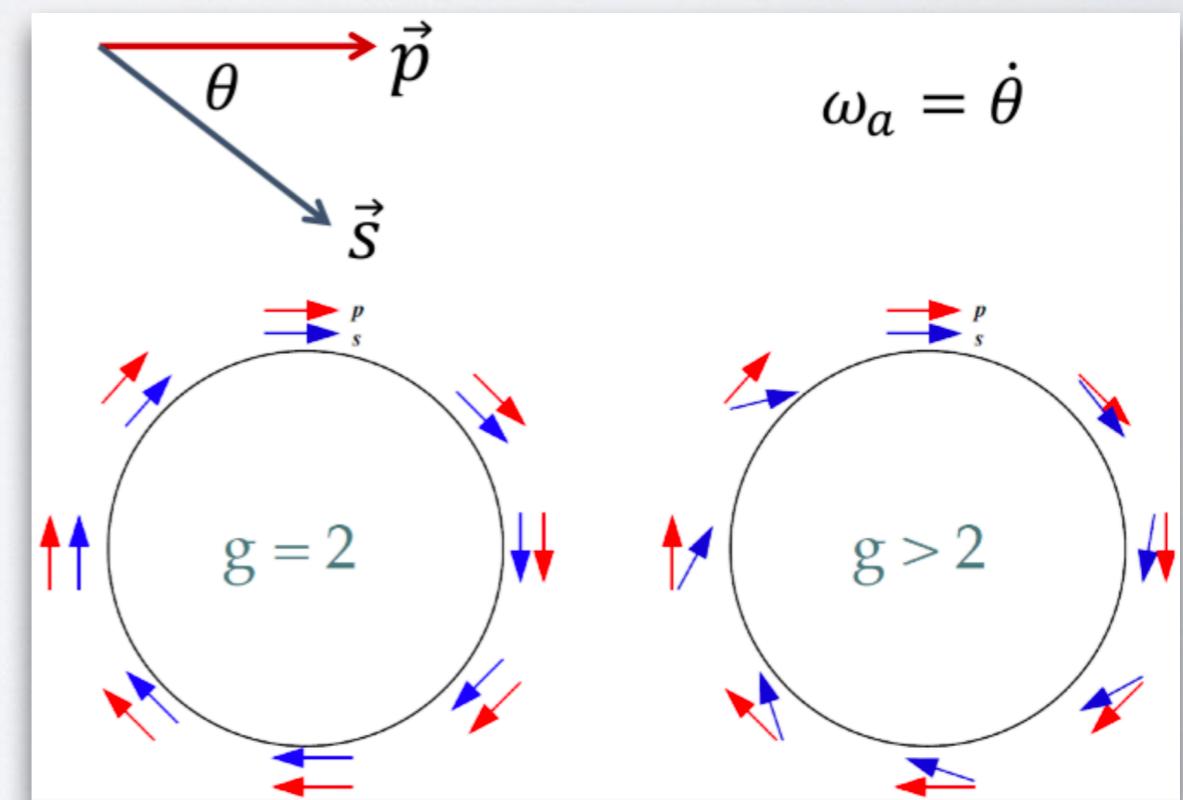
- In a magnetic field the spin and the momentum of the muon precesses around the field with frequencies

$$\omega_c = \frac{eB}{m}$$

$$\omega_s = g \frac{eB}{2m}$$

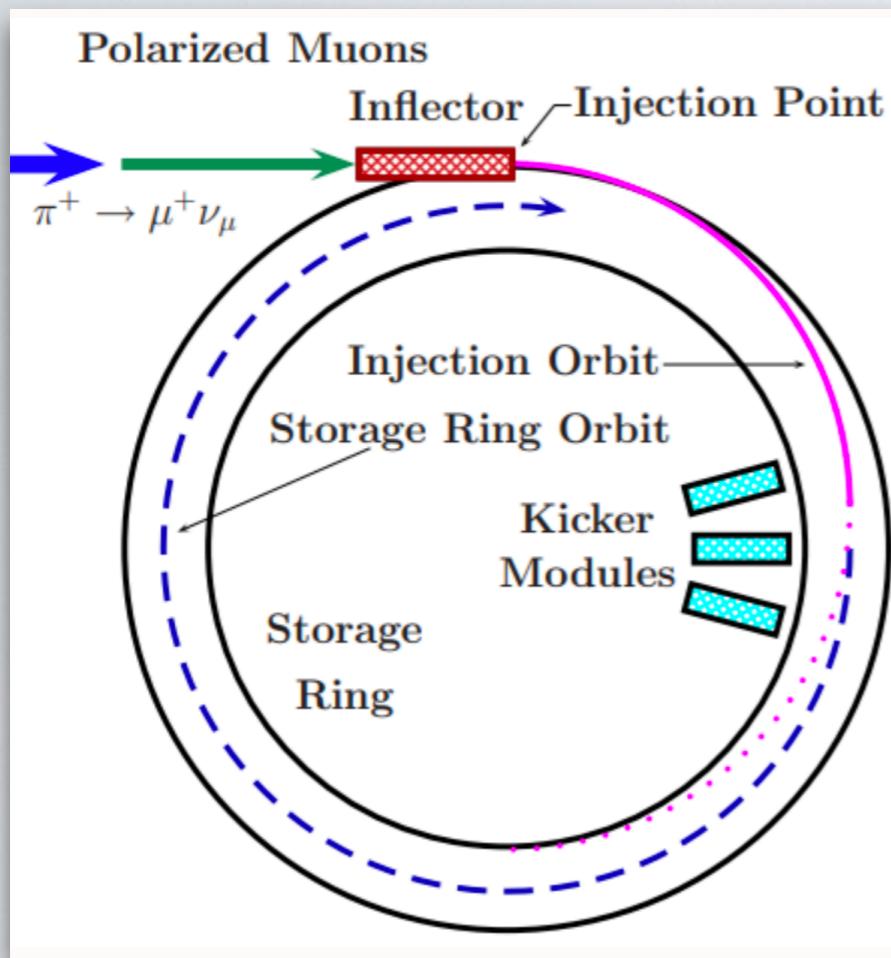
- The frequency difference is connected to the anomalous magnetic moment  $a_\mu$

$$\omega_a = \left( \frac{g_\mu - 2}{2} \right) \frac{eB}{m} = a_\mu \frac{eB}{m}$$

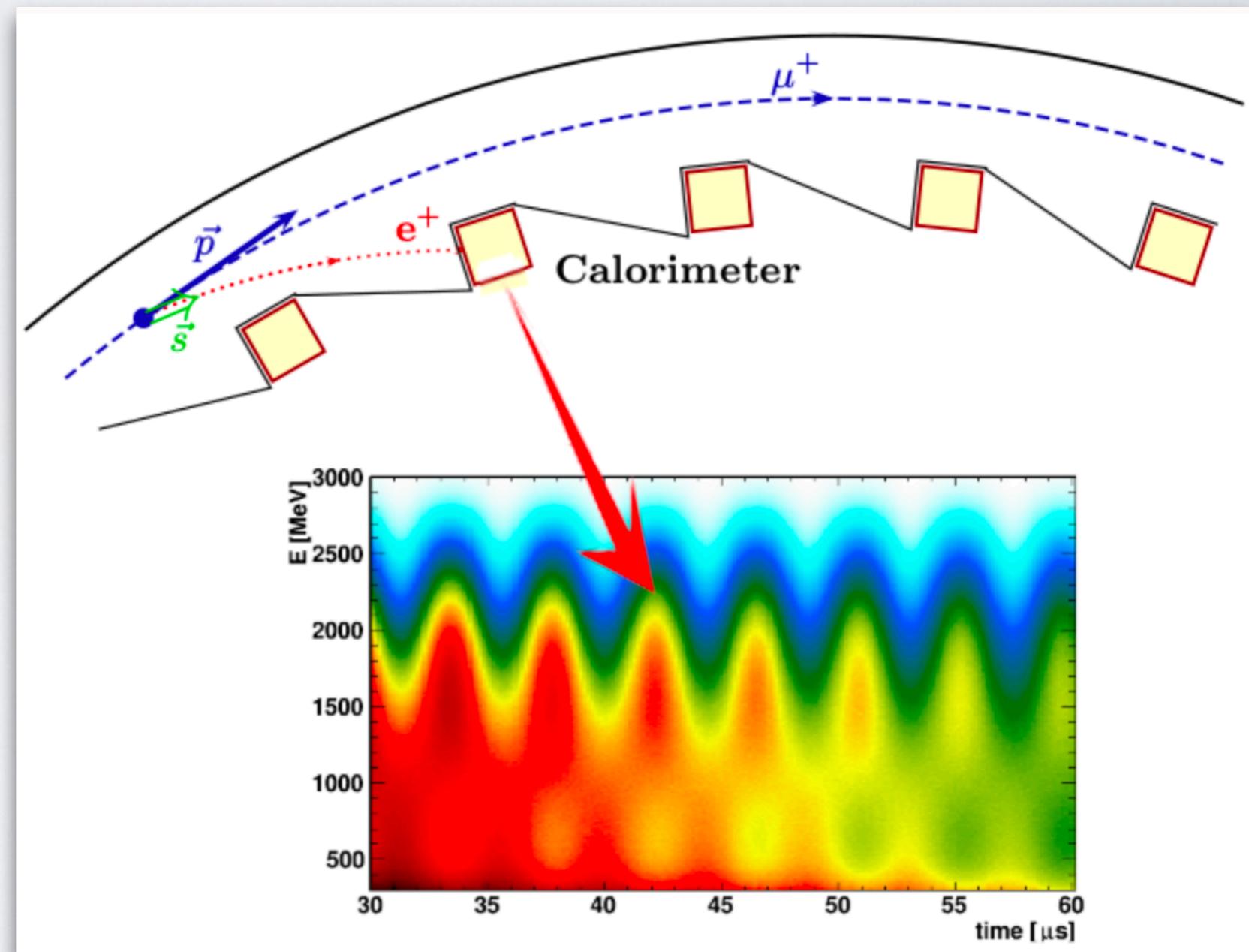


[taken from Atanu Nath, *Muon g-2 and Physics BSM*, 2018]

# THE E989 EXPERIMENT

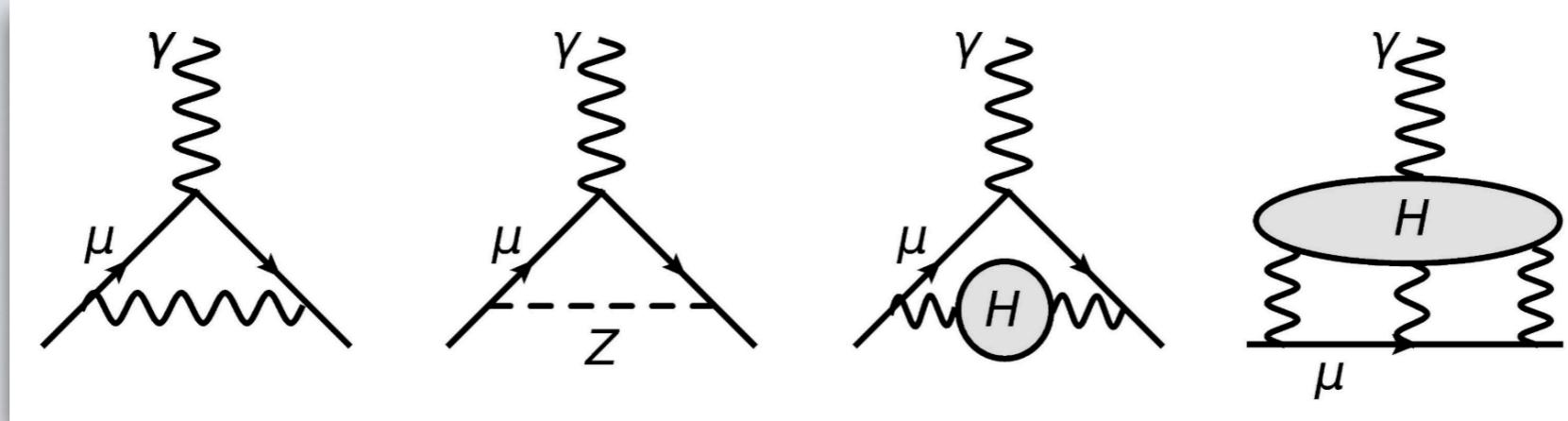


- High energy positrons decay preferentially along muon spin directions and get deflected inward into calorimeter system



[taken from Atanu Nath, *Muon g-2 and Physics BSM*, 2018]

# THE E989 EXPERIMENT



- The theoretical prediction for (g-2) within the SM has been recently determined to

$$a_\mu^{\text{SM}} = 116\ 591\ 810(43) \times 10^{-11}$$

[Aoyama et al; *Phys.Rept.* 887 (2020) 1-166]

- The recent Fermilab E989 result

$$a_\mu^{\text{FNAL}} = 116\ 592\ 040(54) \times 10^{-11}$$

[MUON g-2; *PRL* 126 (2021) 14, 141801]

when combined with the previous BNL results leads to the  $4.2\ \sigma$  tension of

$$\Delta a_\mu = 251(59) \times 10^{-11}$$

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- **XENON1T** excess



➡ Are these manifestations of a Dark Sector?

# NEW PHYSICS FROM BOTTOM UP

- Suppose there is a dark sector
- Strategy:
  - Replace (combinations of) SM fields that are **total singlets** under SM gauge group by new DS fields.
  - Replace **dimensionful SM couplings** (i.e.  $[g] > 0$ ) by DS fields.
- In SM there are 3 possible places where DS fields could hide:

$$V(H) = -\mu^2 H^\dagger H + \frac{1}{4} \lambda (H^\dagger H)^2$$

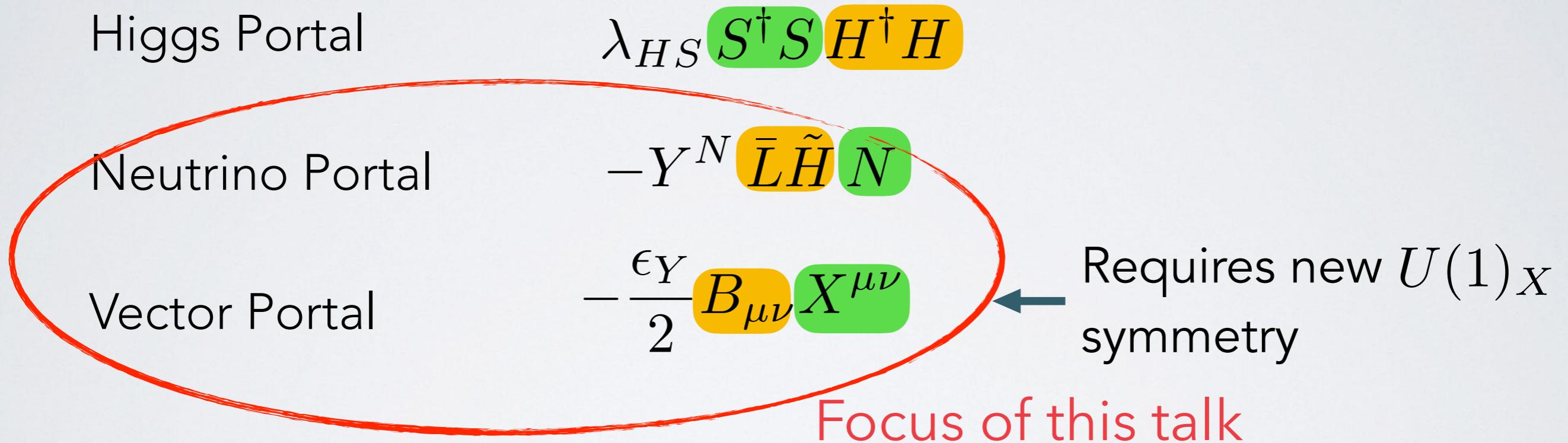
$$\begin{aligned}\mathcal{L}_{\text{Yuk}} = & -Y^D \bar{Q} H d_R - Y^U \bar{Q} \tilde{H} u_R \\ & - Y^\ell \bar{L} H \ell_R - Y^\nu \bar{L} \tilde{H} \cancel{\nu R} + h.c.\end{aligned}$$

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} \text{Tr}[W_{\mu\nu} W^{\mu\nu}] - \frac{1}{4} \text{Tr}[G_{\mu\nu} G^{\mu\nu}]$$



# PORALS TO NEW PHYSICS

- Can build three renormalisable dim-4 portal interactions from the SM singlets  $H^\dagger H$ ,  $\bar{L}\tilde{H}$  and  $B_{\mu\nu}$  by combining them with  
Dark Sector singlets

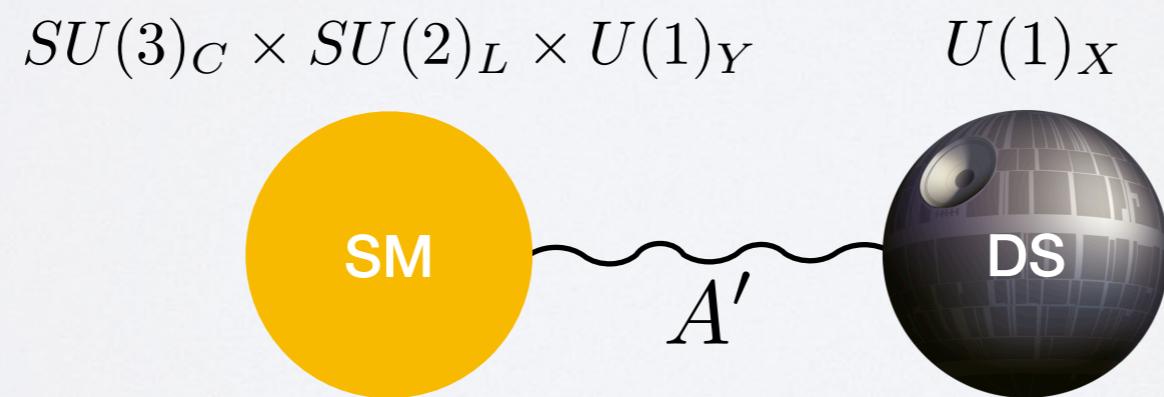


- Plus non-renormalisable dim-5 portal interaction:

$$\frac{G_{agg}}{4} a \text{Tr}[G_{\mu\nu} \tilde{G}^{\mu\nu}]$$

# A NEW DARK SYMMETRY

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# SECLUDED HIDDEN PHOTONS

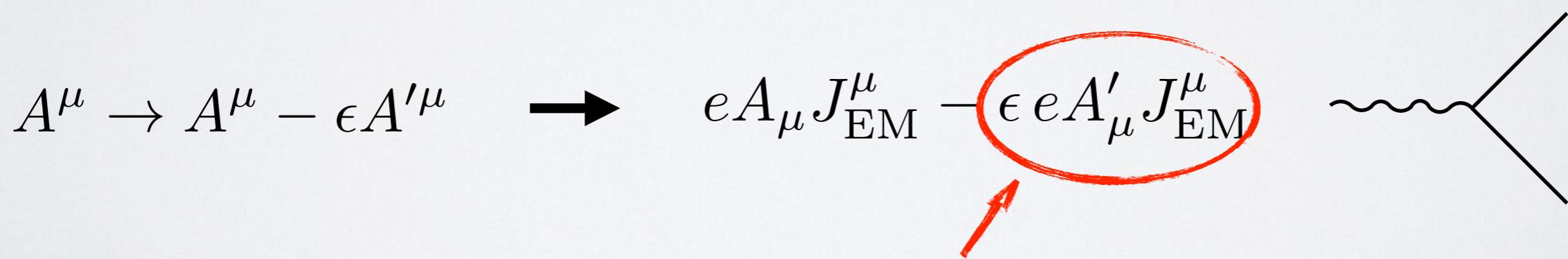
$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\epsilon}{2} B_{\mu\nu} X^{\mu\nu} - \frac{M_X^2}{2} X_\mu X^\mu - g_x J_\mu^X X^\mu$$

[Holdom; PLB 166, 196]

- Minimal choice is pure secluded U(1) symmetry with

$$J_X^\mu = 0$$

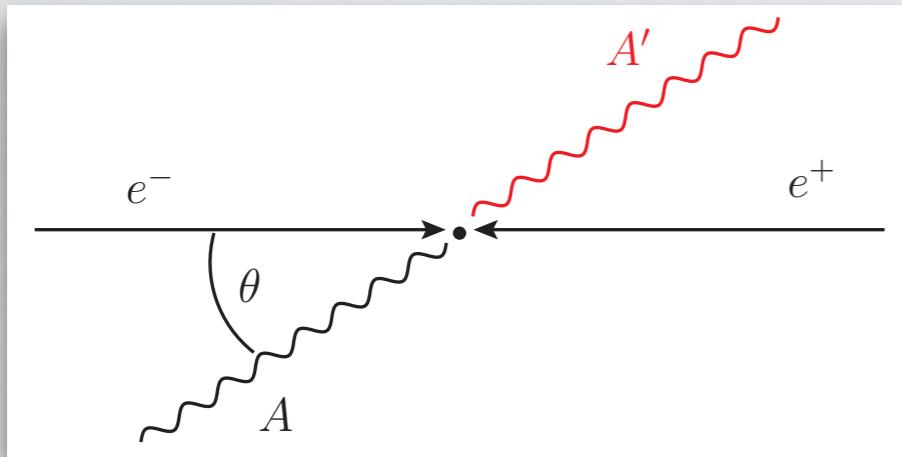
- For light mediators  $M_{A'} \ll M_W \sim \mathcal{O}(v)$  the kinetic mixing term in the mass basis can be diagonalised by the field redefinition:



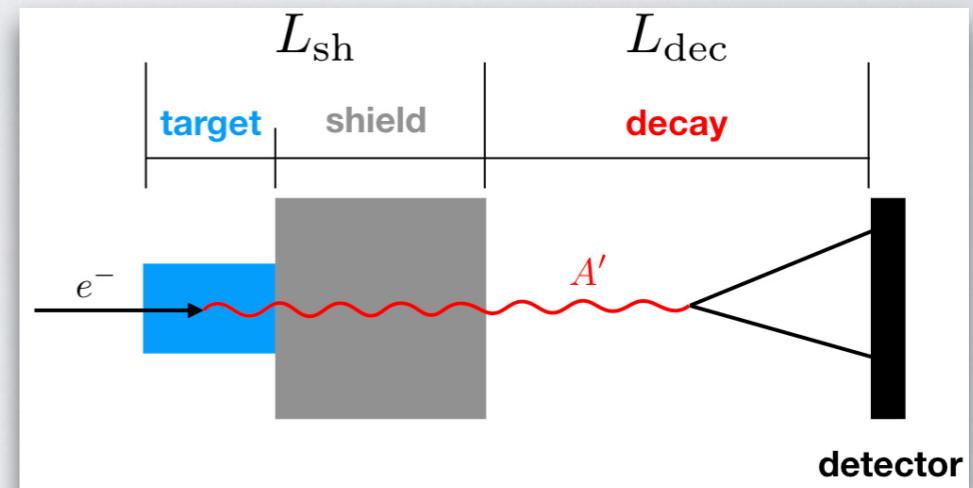
Hidden Photon couples to EM current suppressed by  $\epsilon$ !

# HIDDEN PHOTON SEARCHES

Colliders:

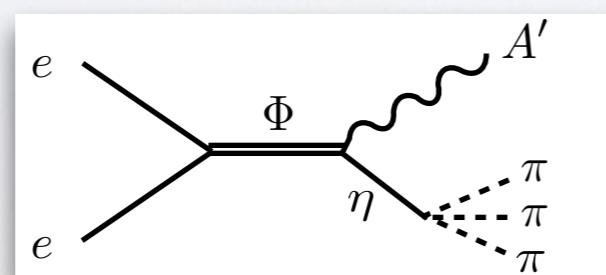
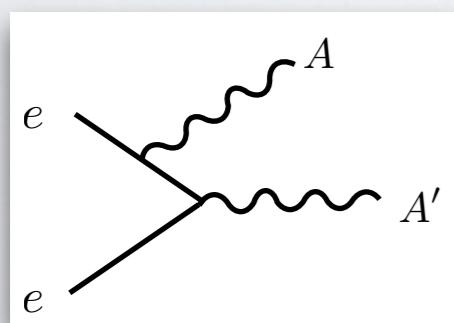


Beam dumps:



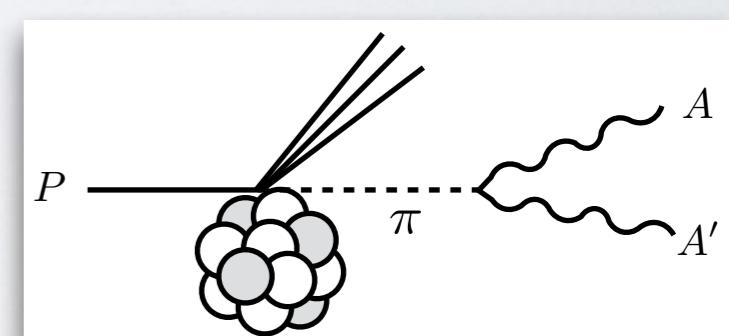
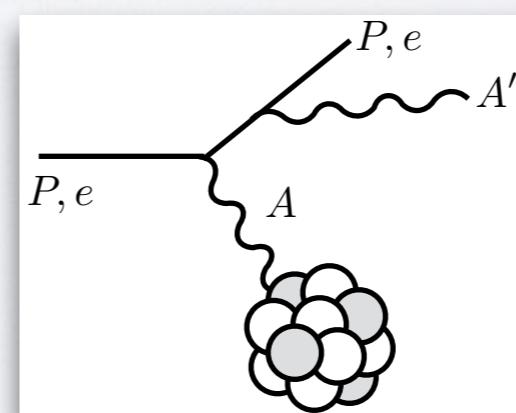
$$P_{\text{dec}} = e^{-\frac{L_{\text{sh}}}{\ell_{A'}}} \left( 1 - e^{-\frac{L_{\text{dec}}}{\ell_{A'}}} \right)$$

- Production:



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

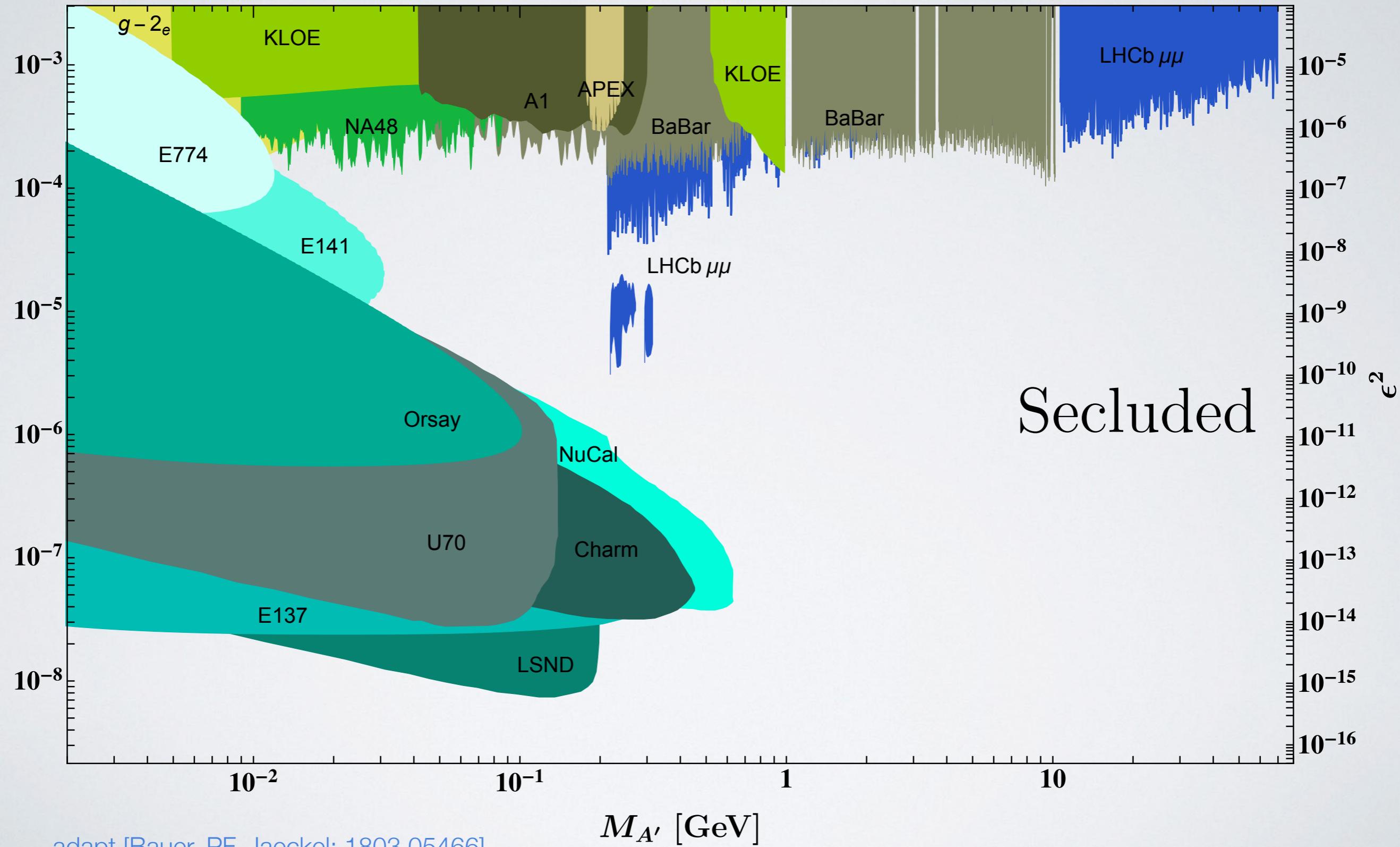
$$\sigma_{A'}^{\text{coll}} \propto \frac{\alpha^2 \epsilon^2}{E_{\text{CM}}^2}$$



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

$$\sigma_{A'}^{\text{bd}} \propto \frac{\alpha^3 Z^2 \epsilon^2}{M_{A'}^2}$$

# SECLUDED $U(1)_X$

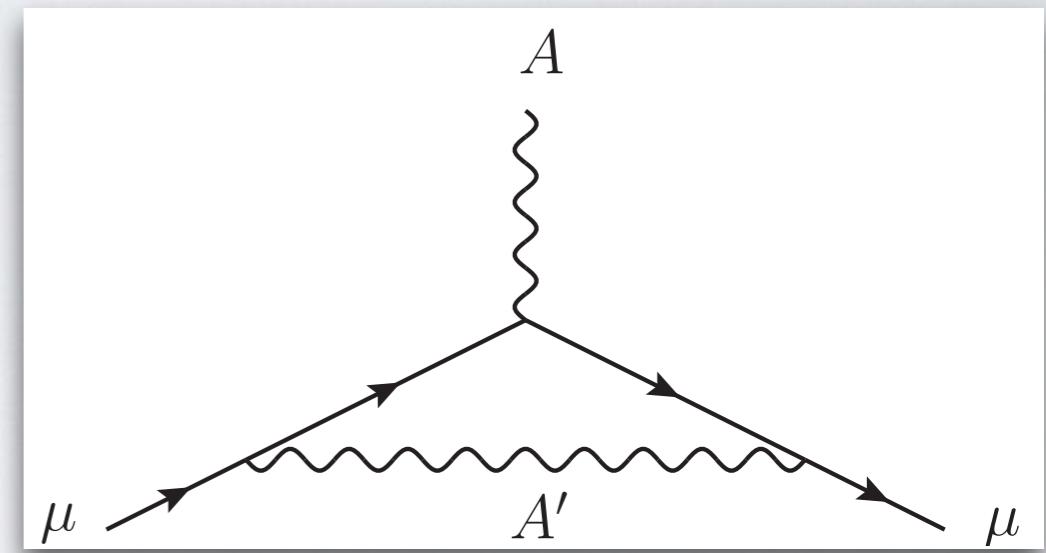


# HOW A' CONTRIBUTES TO G-2

- U(1) bosons vectorially coupled to muons contribute to g-2 at one-loop level

$$\Delta a_\mu = \frac{g_\mu^2}{4\pi^2} \int_0^1 du \frac{u^2(1-u)}{u^2 + \frac{(1-u)}{x_\mu^2}}$$

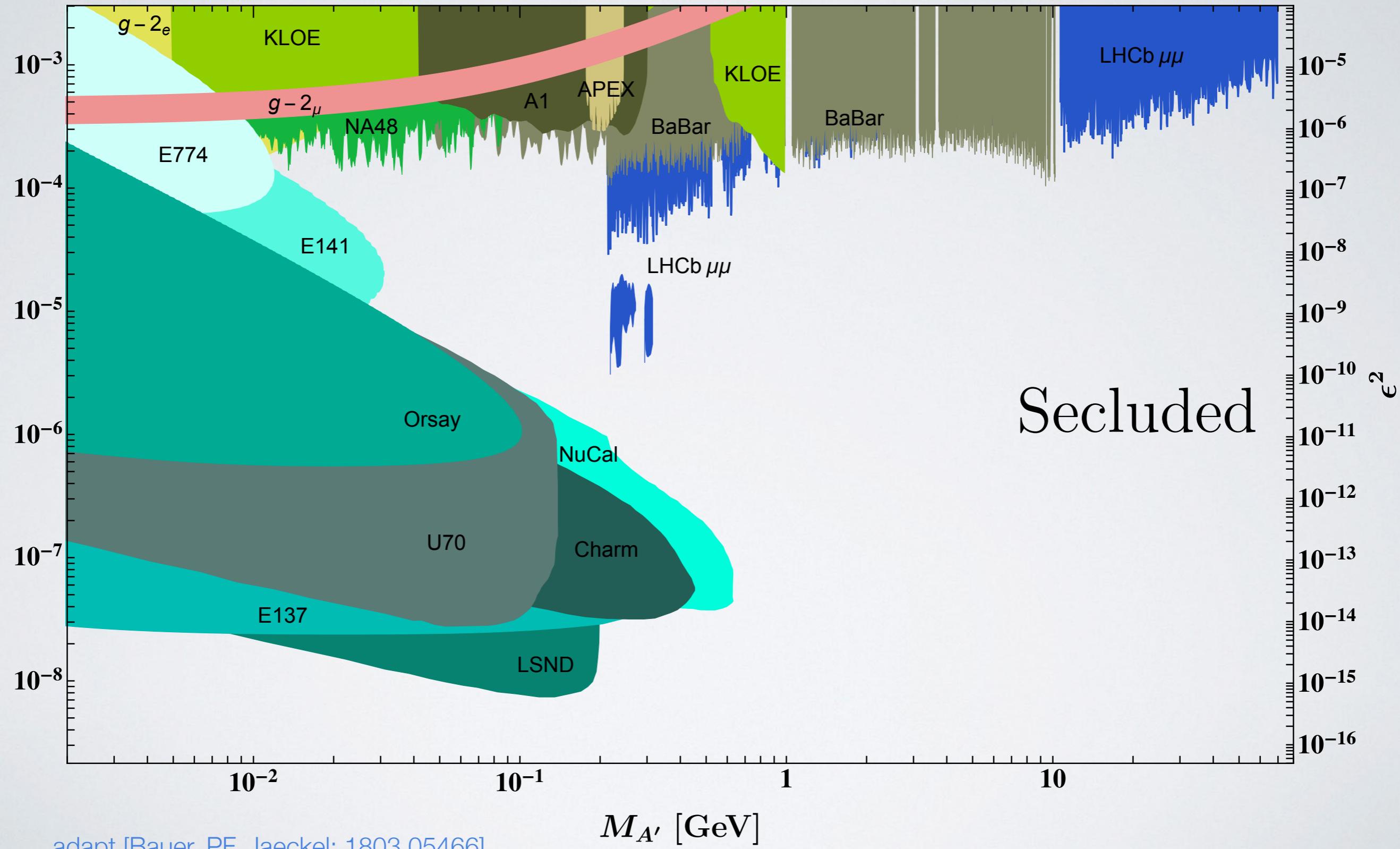
where  $x_\mu = m_\mu/M_{A'}$



- The muon coupling depends on the U(1) extension. In general

$$g_\mu = \begin{cases} \epsilon_x e & \text{for kinetic mixing} \\ g_x Q_\mu & \text{for muon - philic gauge boson} \end{cases}$$

# SECLUDED $U(1)_X$



# ANOMALY FREE GAUGE EXTENSIONS

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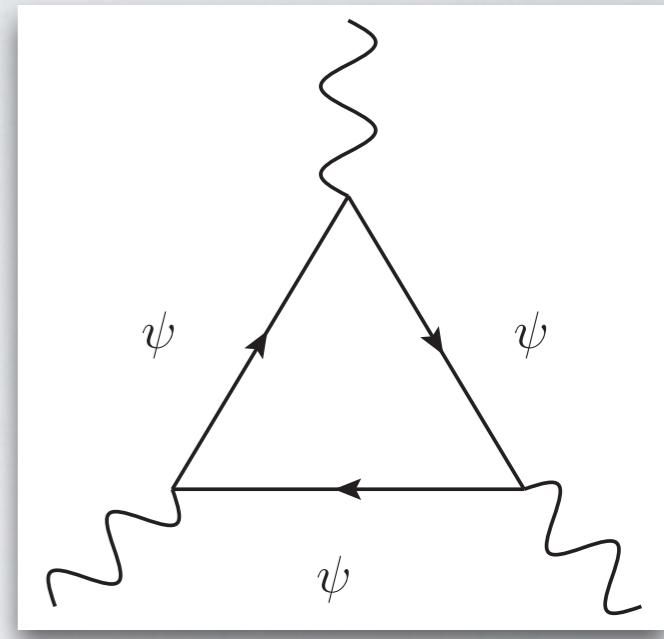
$$J_X^\mu \neq 0$$

# ANOMALY FREE MODELS

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

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

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




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

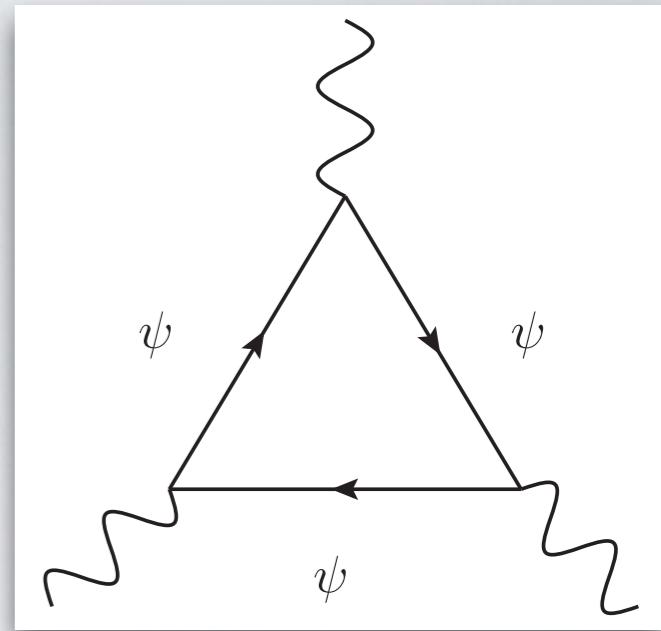
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$$J_X^\mu = \sum_\psi \bar{\psi} Q_\psi \gamma^\mu \psi \quad \text{with } \psi = Q, L, u, d, \ell, \nu$$

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



- Additional constraints from **Yukawa terms**:

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

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.  $Q_Q = Q_u = Q_d$  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

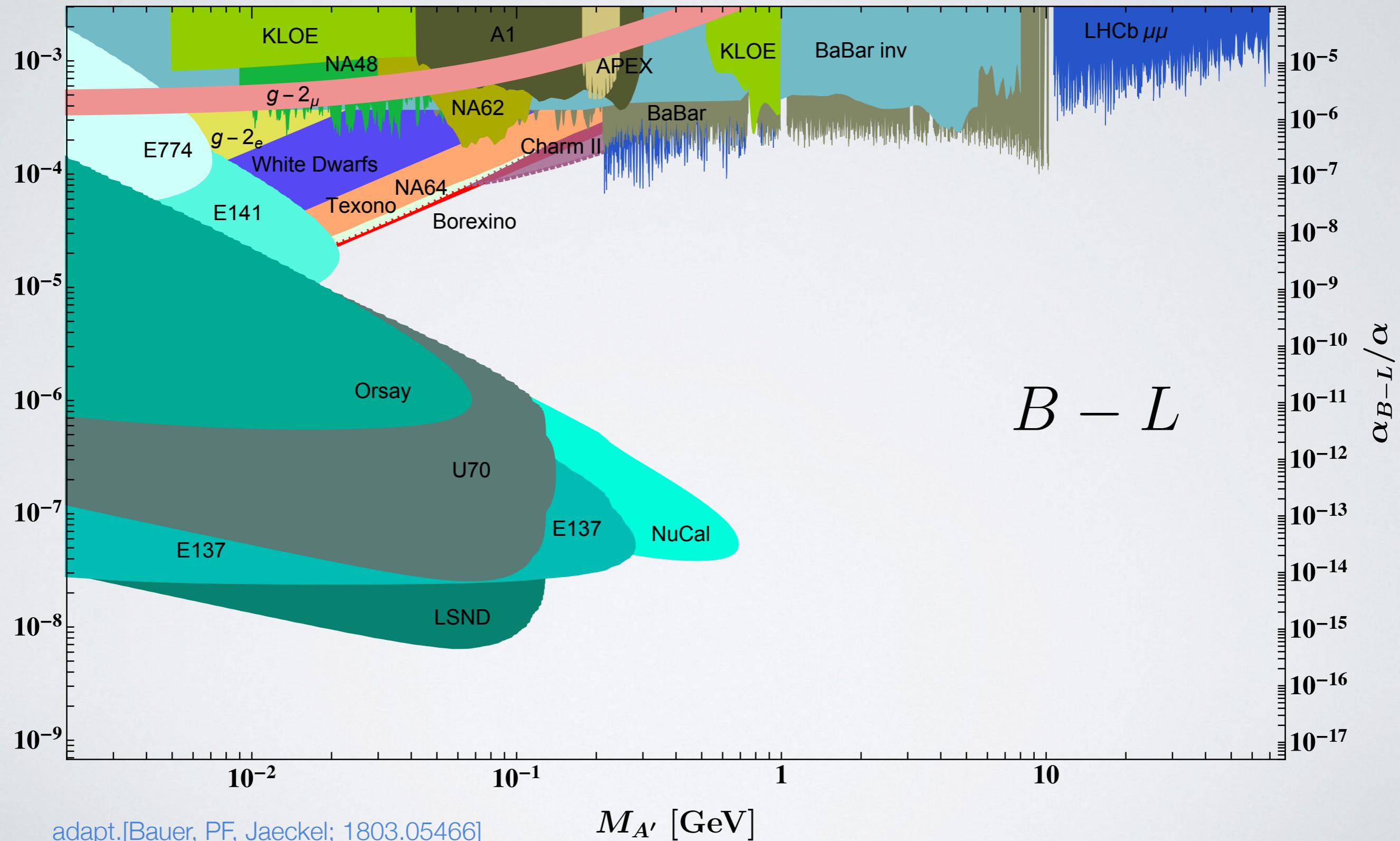
$$V_{\text{CKM}} = U_u U_d^\dagger$$

$$V_{\text{PMNS}} = U_\ell U_\nu^\dagger$$

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

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

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



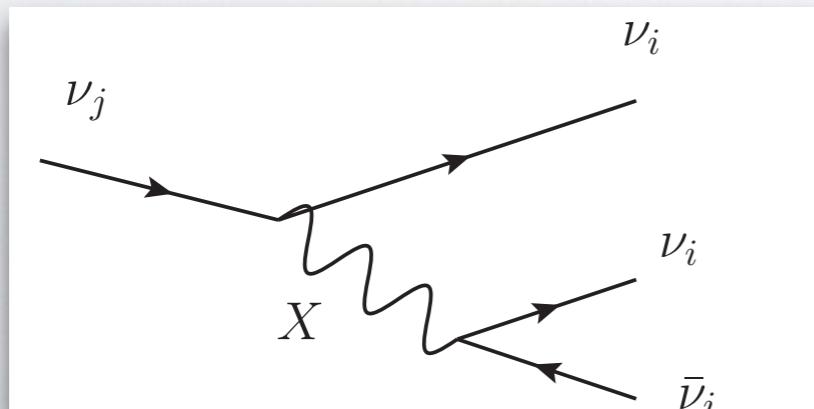
# MAJORANA NEUTRINOS

- All other anomaly free groups **must have Majorana neutrinos!**
- e.g.  $U(1)_{L_i - L_j}$  ,  $U(1)_{B - 3L_i}$  , ...
- Majorana mass terms induce **neutrino flavour changing couplings** of neutrino mass eigenstates

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

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

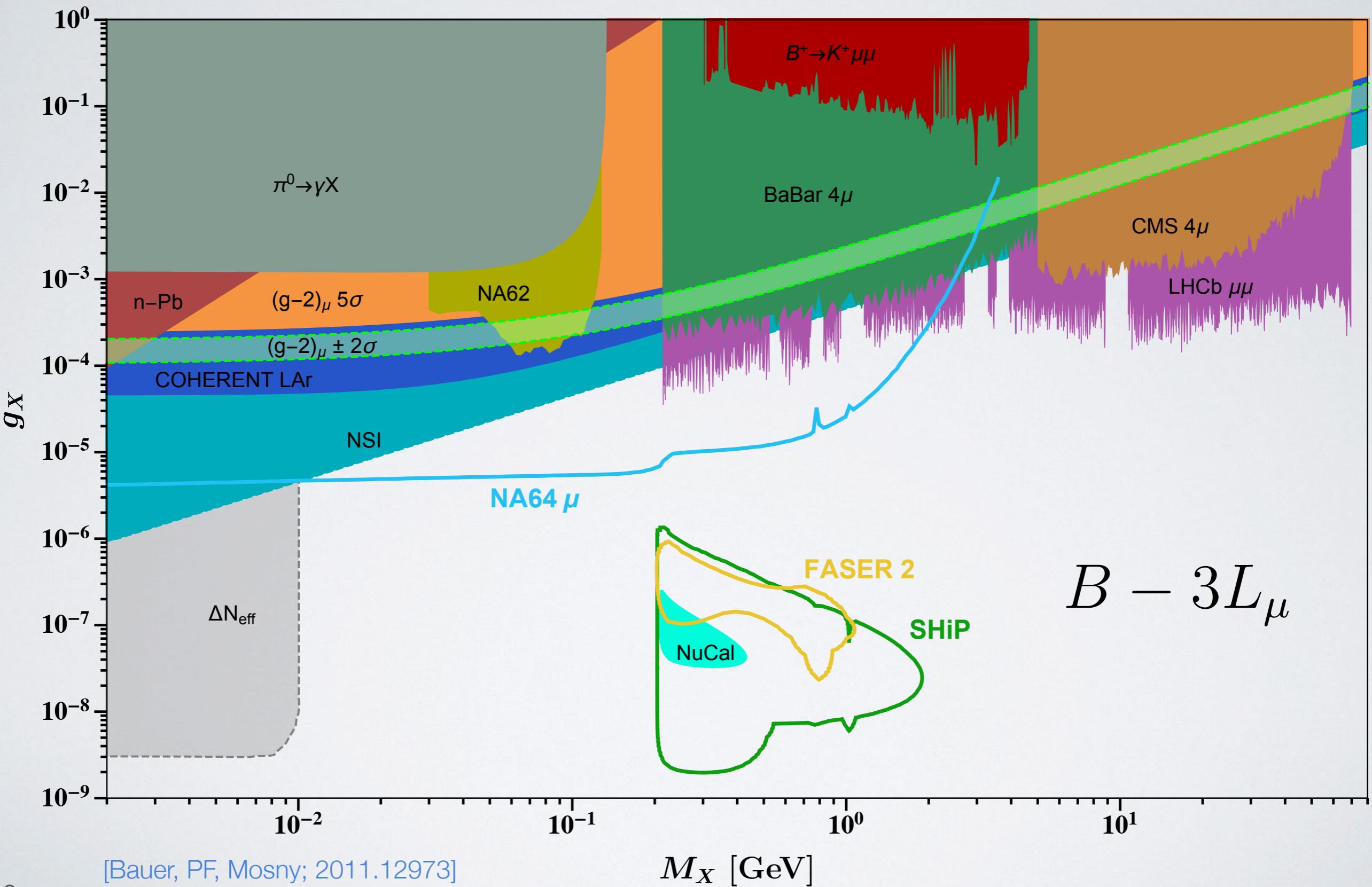
- This could in principle induce neutrino decays. Potentially interesting for astrophysical neutrinos



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

[Bauer, PF, Mosny; 2011.12973]

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



# GAUGING LEPTON SYMMETRIES

$$L_\mu - L_e$$

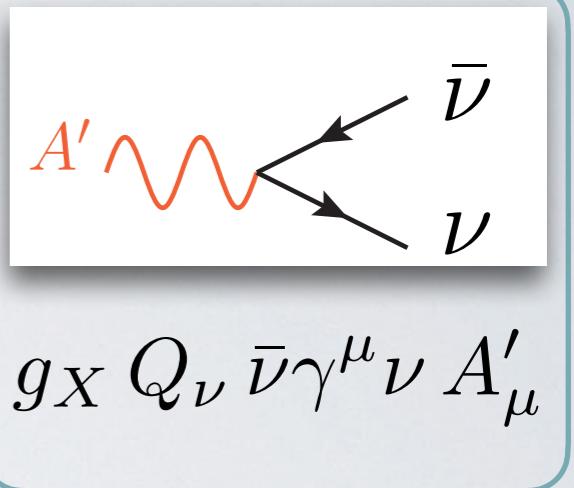
charging 1st &  
2nd generation  
leptons

$$L_e - L_\tau$$

charging 1st &  
3rd generation  
leptons

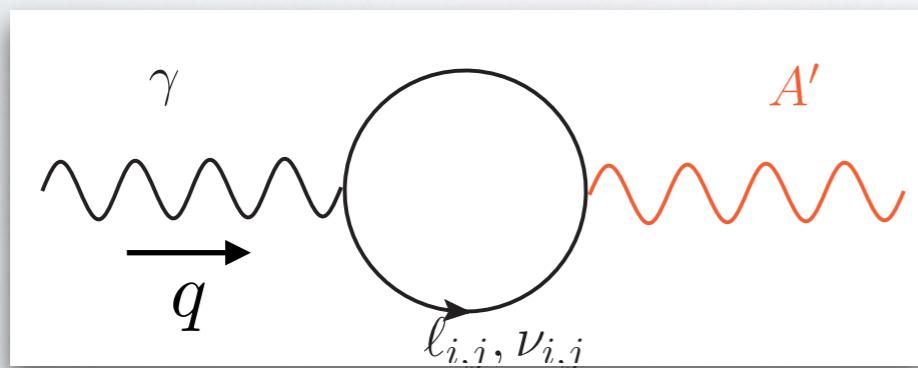
$$L_\mu - L_\tau$$

charging 2nd &  
3rd generation  
leptons



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

[del Aguila, Masip, Perez-Victoria; *Nucl.Phys.B* 456 (1995) 531-549]



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

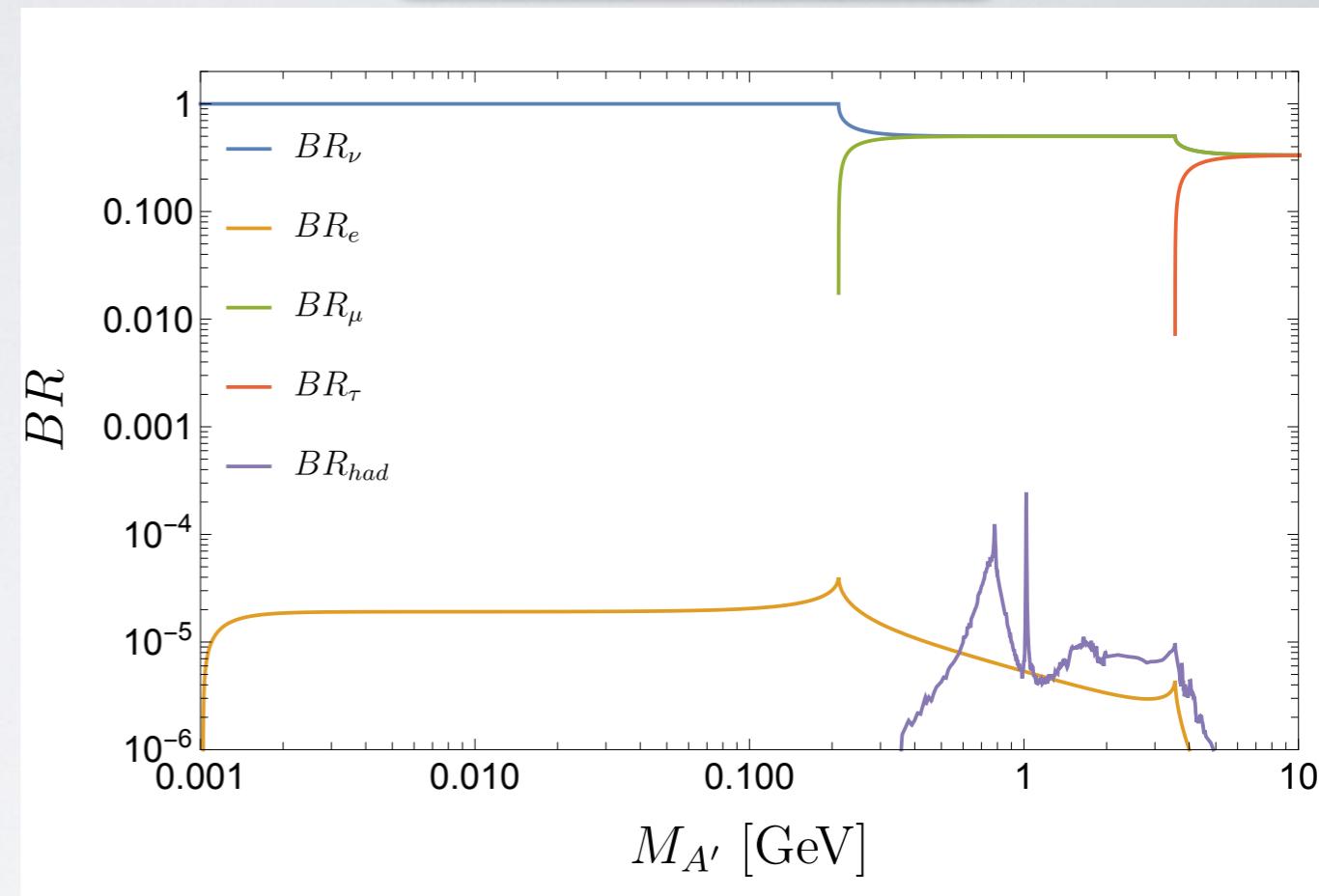
$$\epsilon_{ij}(q^2) = \frac{e g_{ij}}{2\pi^2} \int_0^1 dx x(1-x) \left[ \log \left( \frac{m_i^2 - x(1-x)q^2}{m_j^2 - x(1-x)q^2} \right) \right]$$

# SPECIAL CASE OF $U(1)_{L_\mu - L_\tau}$

Why is this interesting?

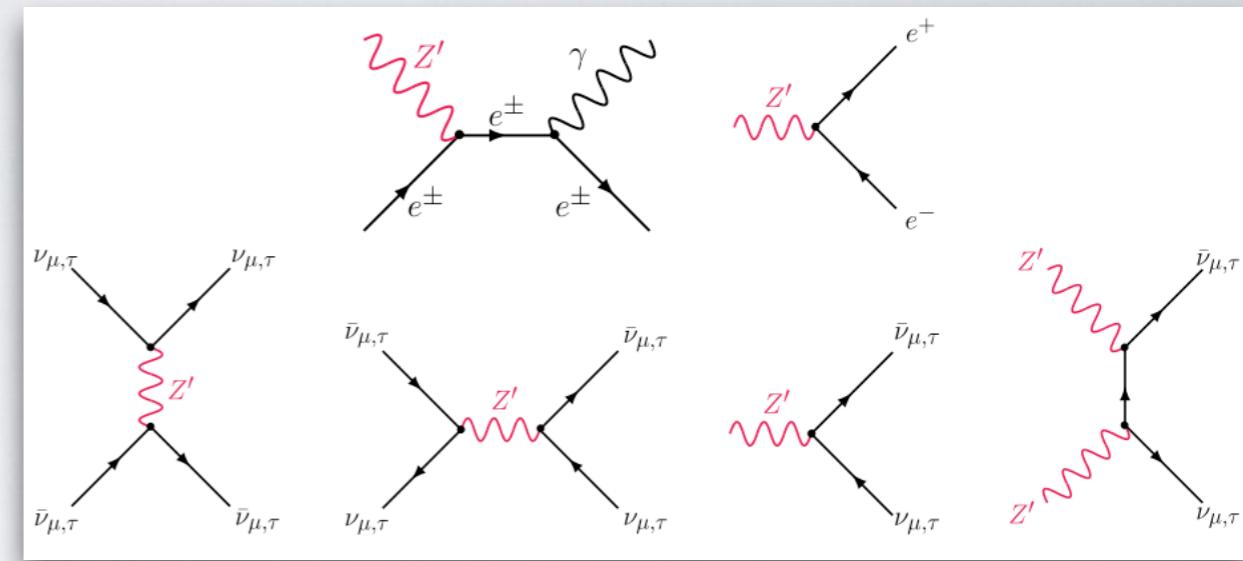
- **No gauge interactions with ordinary matter ( $q, e$ )!**
- Below dimuon threshold **only decays to neutrinos** (almost)
- Only remaining minimal  $U(1)$  extension with viable  $(g - 2)_\mu$  **solution**
- **Finite kinetic mixing:**

$$\epsilon_{\mu\tau} \approx \frac{e g_{\mu\tau}}{6\pi^2} \log \left( \frac{m_\mu}{m_\tau} \right) \approx -\frac{g_{\mu\tau}}{70}$$

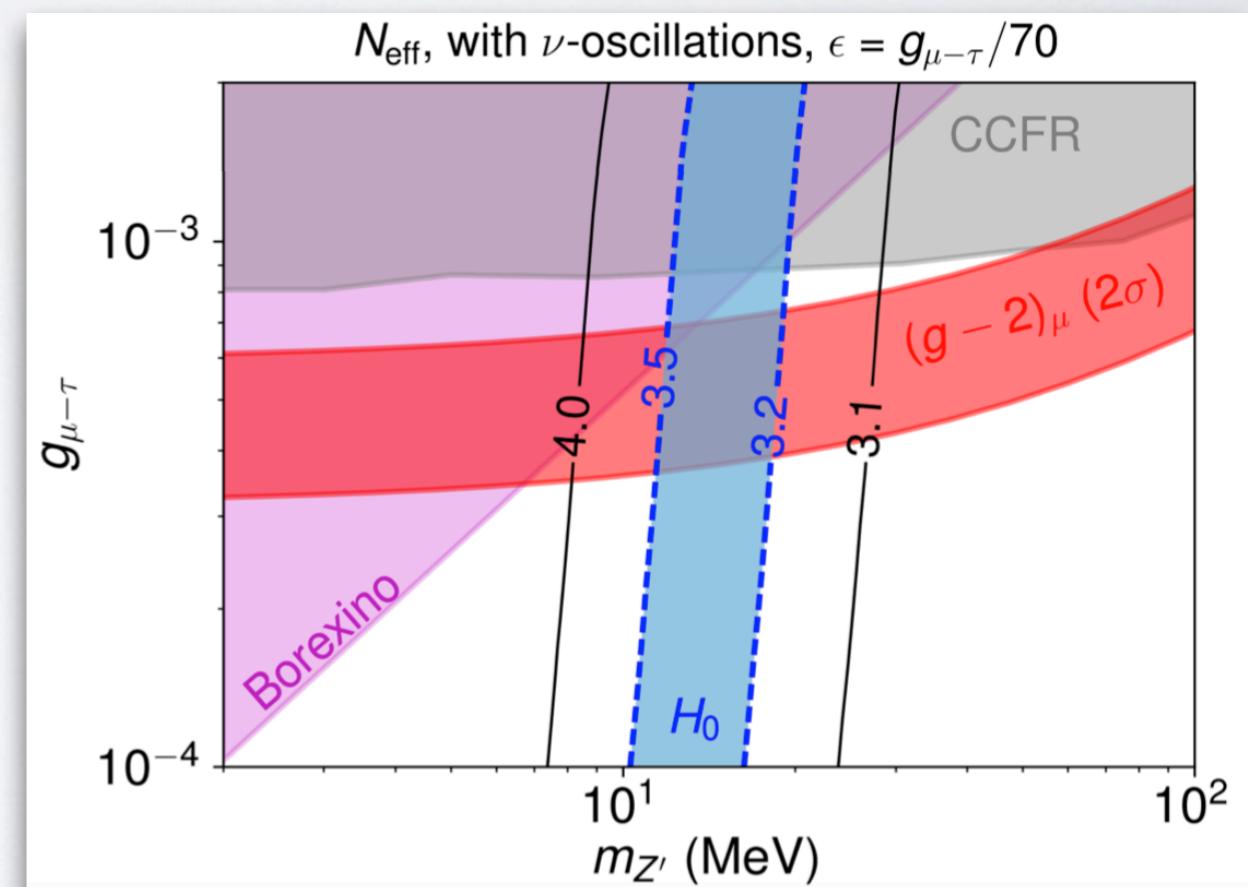
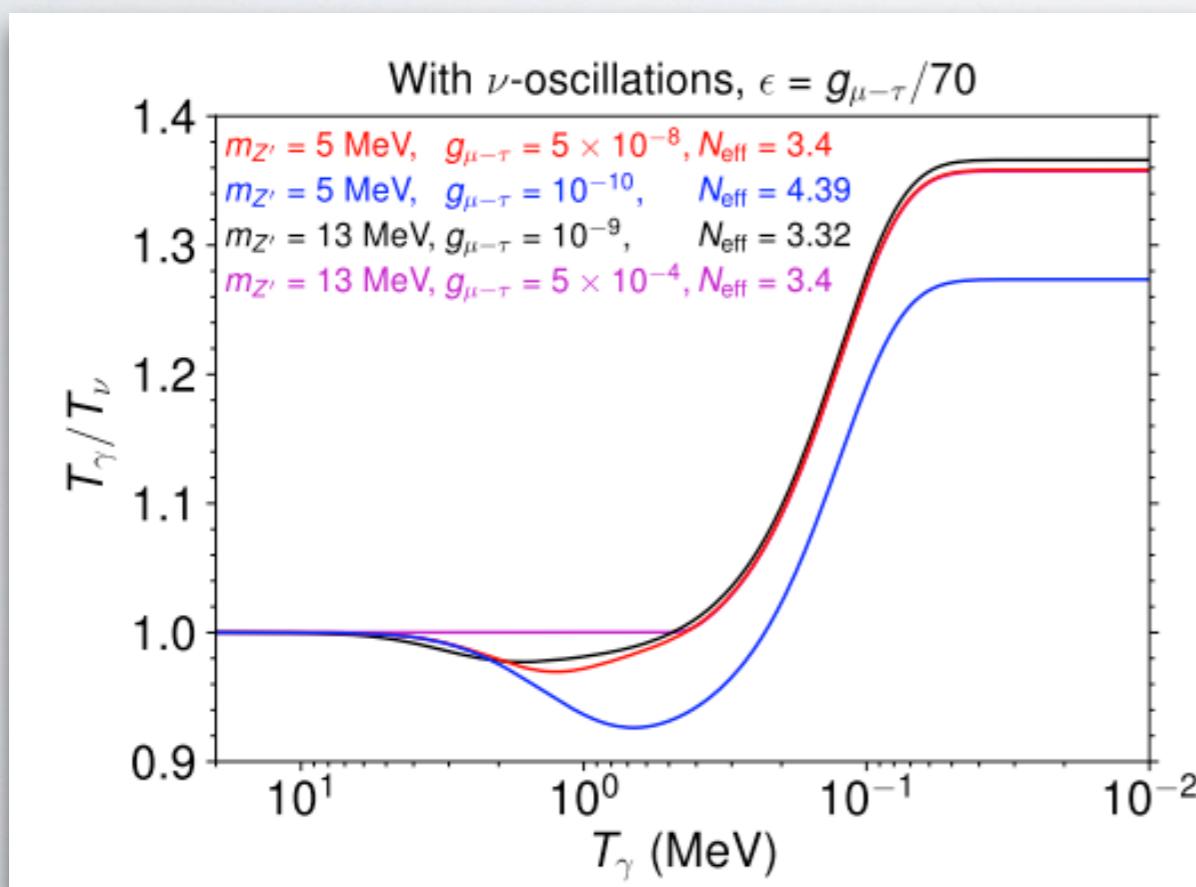


# NEUTRINOS AND HUBBLE

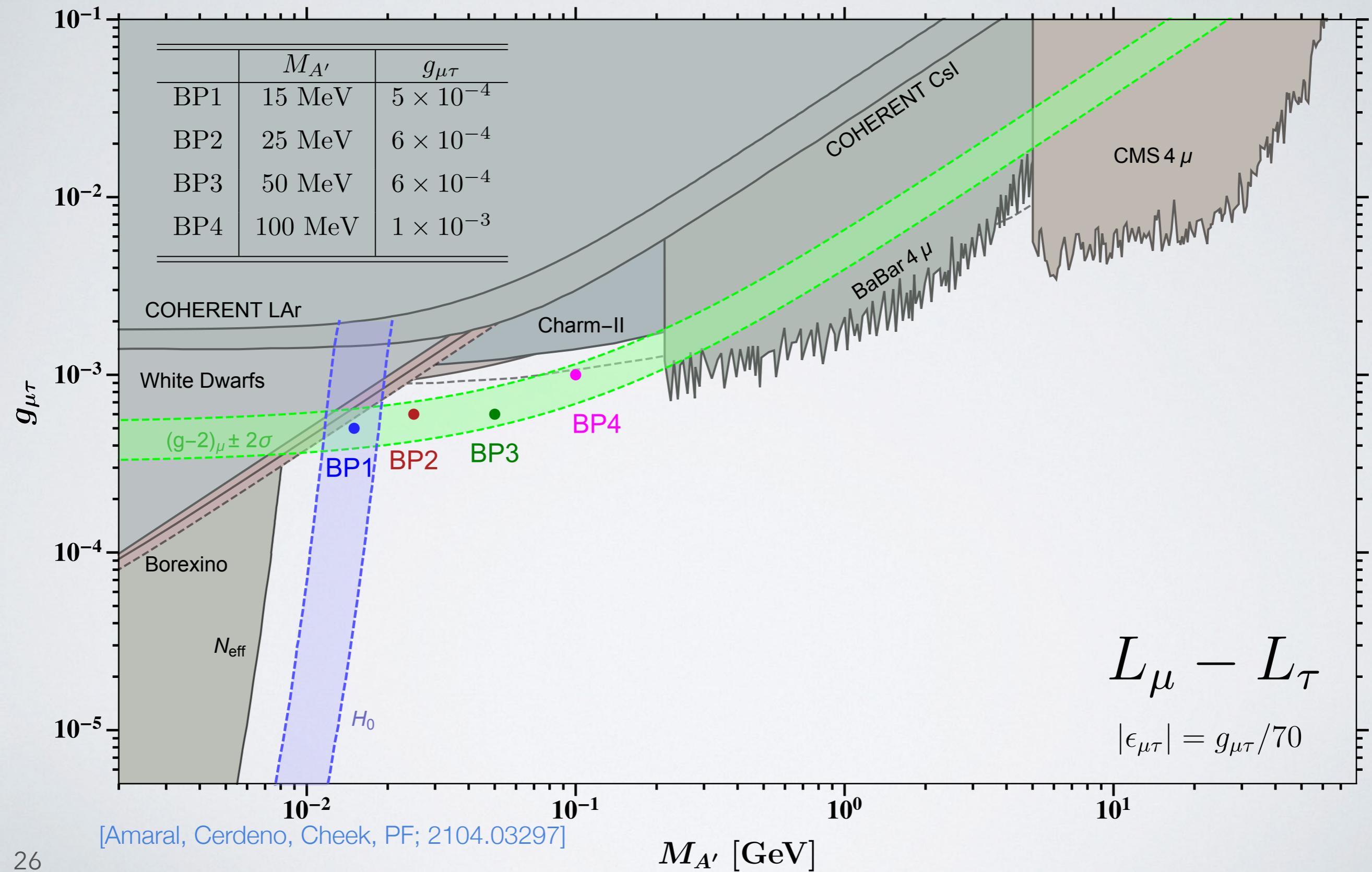
- Decay of  $A'$  heats neutrino gas and delays the decoupling  
 $\Rightarrow$  increase of  $N_{\text{eff}}$  at early times



- Leads to larger  $H_0$



# $U(1)_{L_\mu - L_\tau}$ — CURRENT



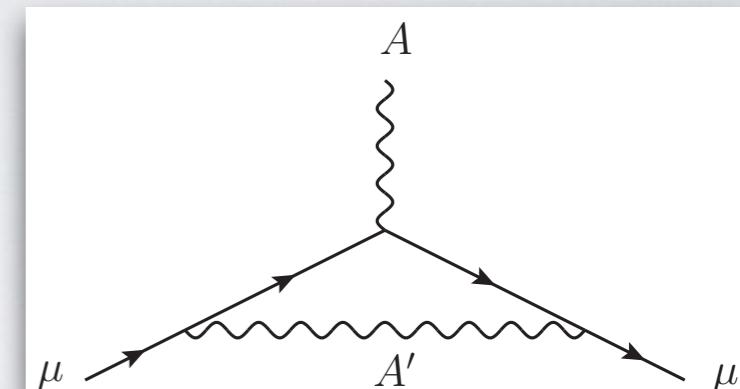
# COMPLEMENTARY SEARCHES FOR $U(1)_{L_\mu - L_\tau}$ BOSON

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# STRATEGY TO TEST $U(1)_{L_\mu - L_\tau}$ SOLUTION

- Suppose  $(g - 2)_\mu$  is due to a new  $U(1)_{L_\mu - L_\tau}$  boson.  
How can we independently test this?

- $(g - 2)_\mu$  only sensitive to muon coupling



- Have to **establish** also **neutrino couplings**:

→ Invisible decays at NA64. Potential degeneracy with DM!



→ CE $\nu$ NS at spallation sources. Only 2nd generation!

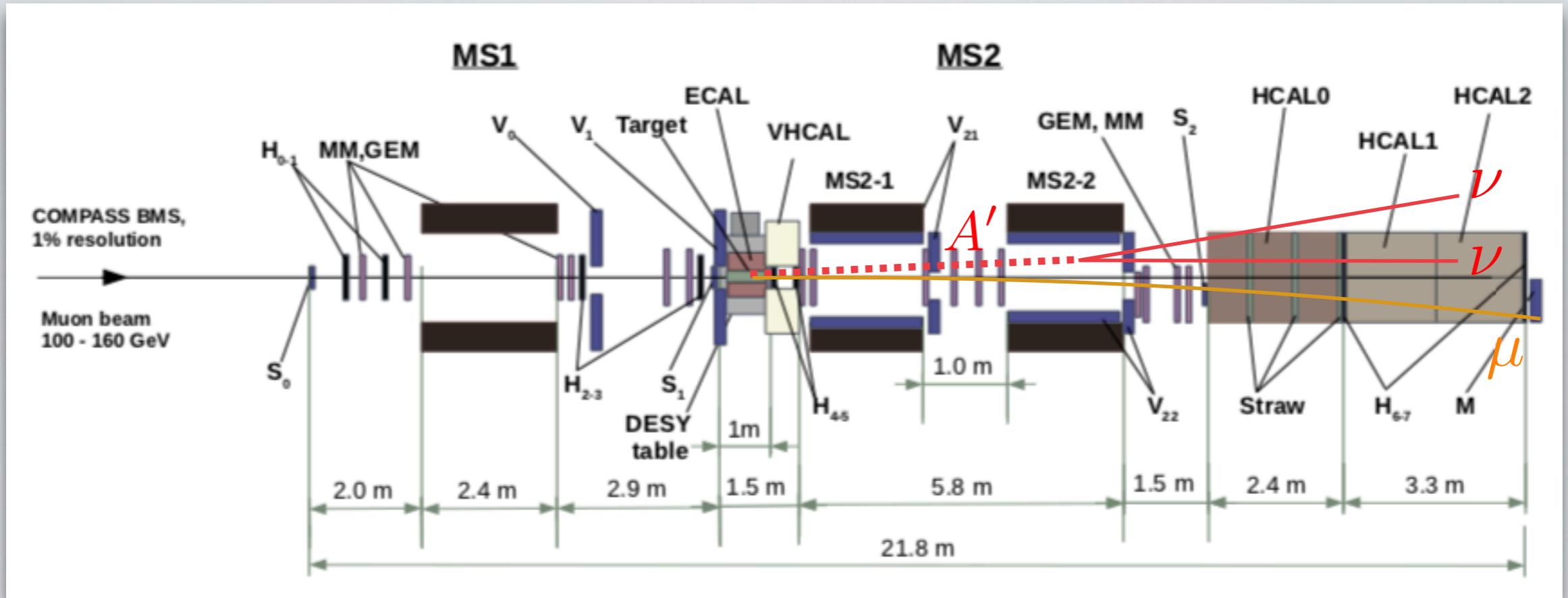


→ Solar neutrino scattering. Also 3rd generation neutrino flux!



- **Combination** can **lift degeneracy with a  $U(1)_{L_\mu}$  mediator!**

# NA64 $\mu$



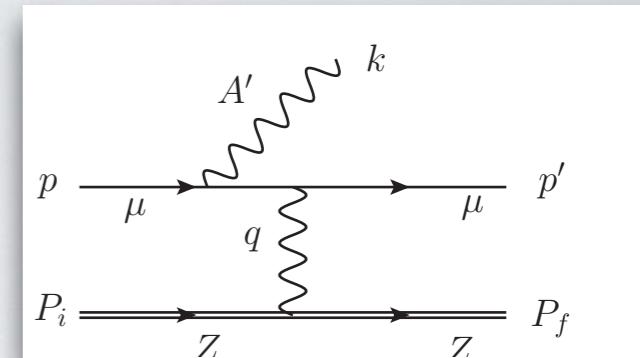
[NA64 proposal; CERN-SPSC-2019-002]

- Fixed target experiment with 160 GeV muon beam.  
→ Muonic HPs are abundantly produced in Bremsstrahlung, decay invisibly
- Expected to take data with  $\sim 10^{11}$  muons on target (MOT) in 2021
- Target momentum resolution of 1~2.5 GeV, gives good handle on spectra

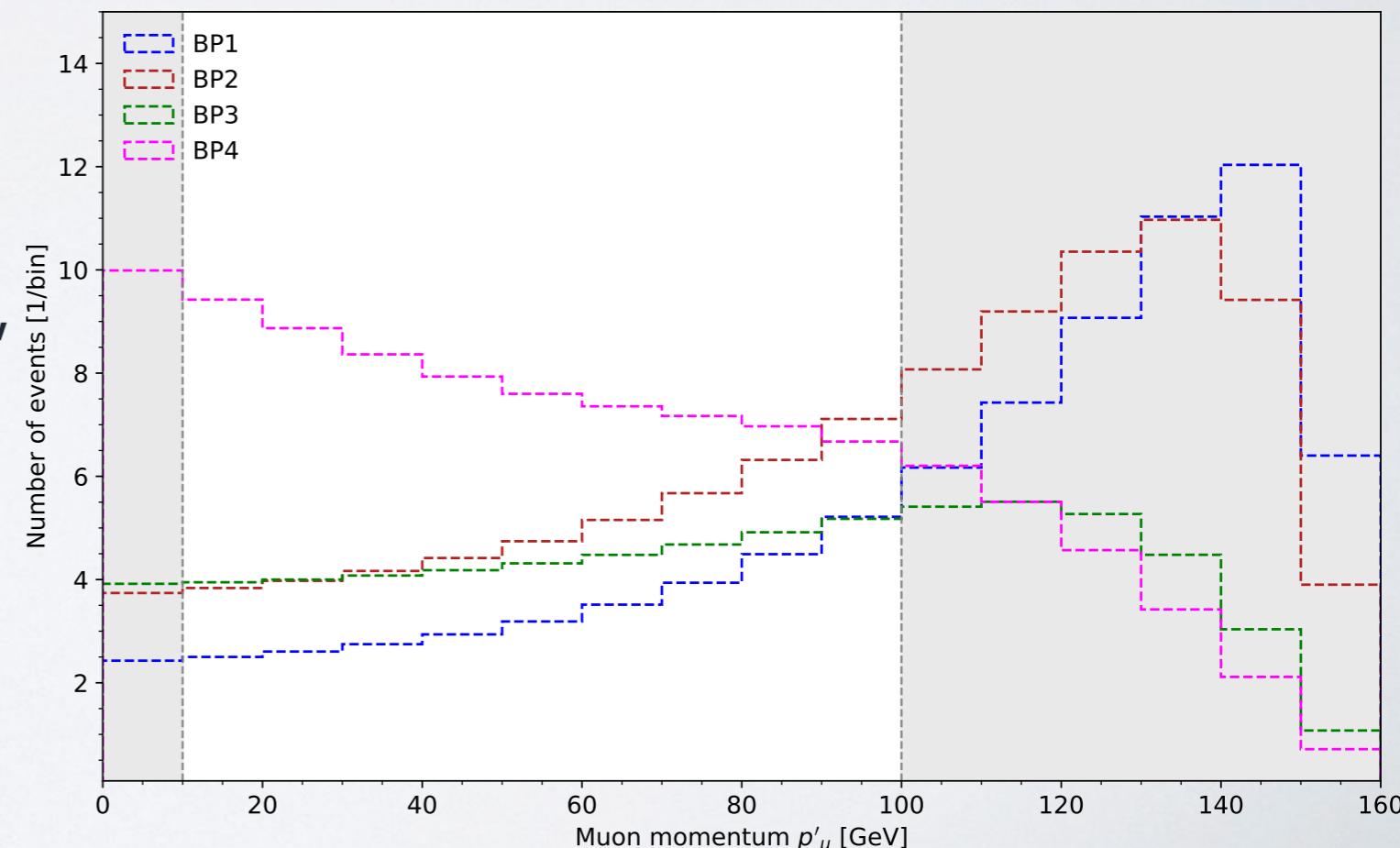
# NA64 $\mu$

- We can compute theoretical spectra for our benchmark points from bremsstrahlung:

$$N_{A',\text{inv}} = \text{MOT} \frac{\rho N_A}{A} L_T \int_{x_{\min}}^{x_{\max}} dx \frac{d\sigma_{2 \rightarrow 3}}{dx} \left( \text{BR}_{\text{inv}} + \text{BR}_{\text{vis}} e^{-\frac{L_{\text{det}}}{\ell_{A'}(x)}} \right)$$

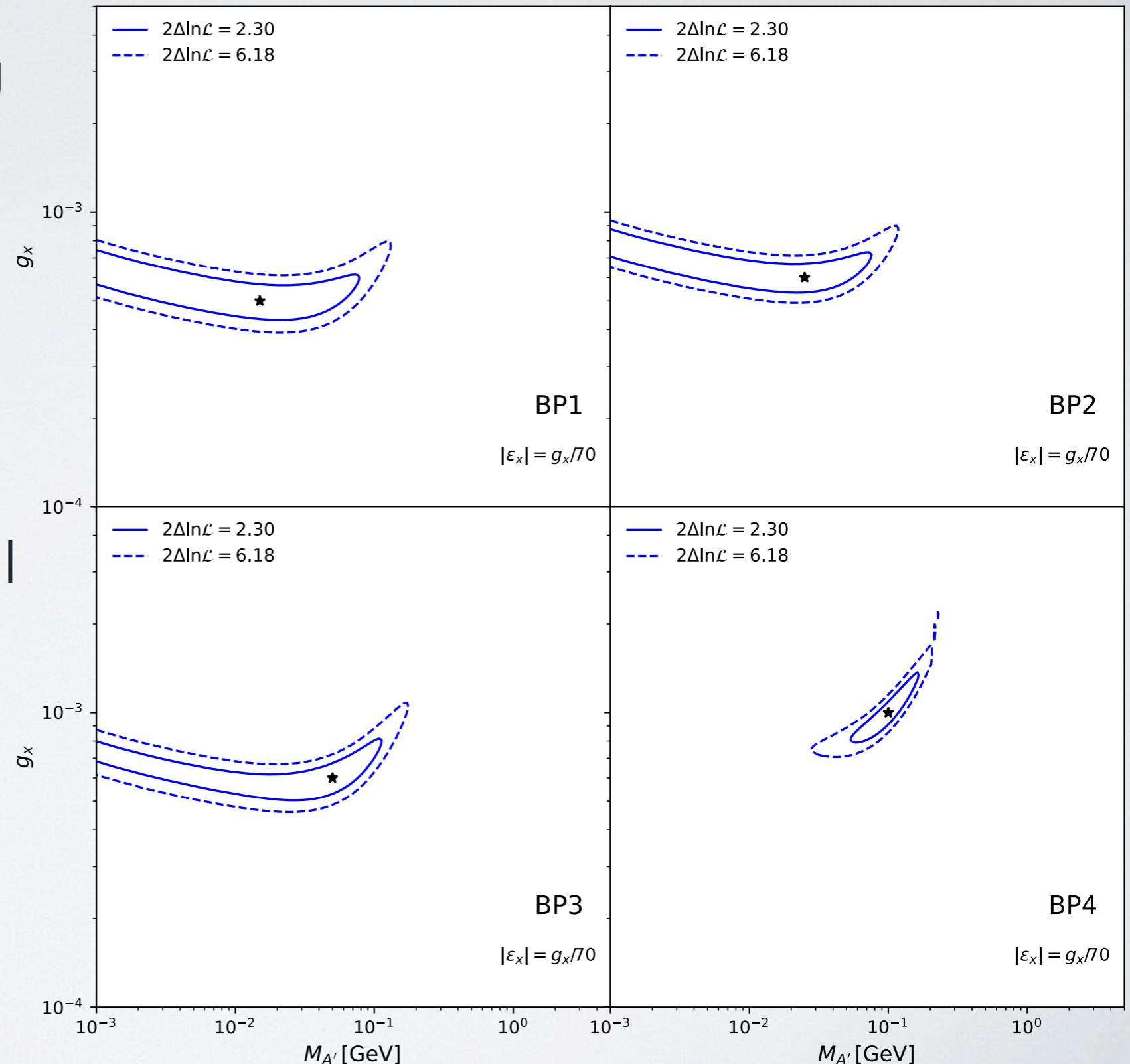


- NA64 defines a signal window for muon between  $10 \text{ GeV} < E < 100 \text{ GeV}$
- In particular, for low mass  $A'$  ( $\lesssim 50 \text{ MeV}$ ) characteristic spectral shapes outside signal window



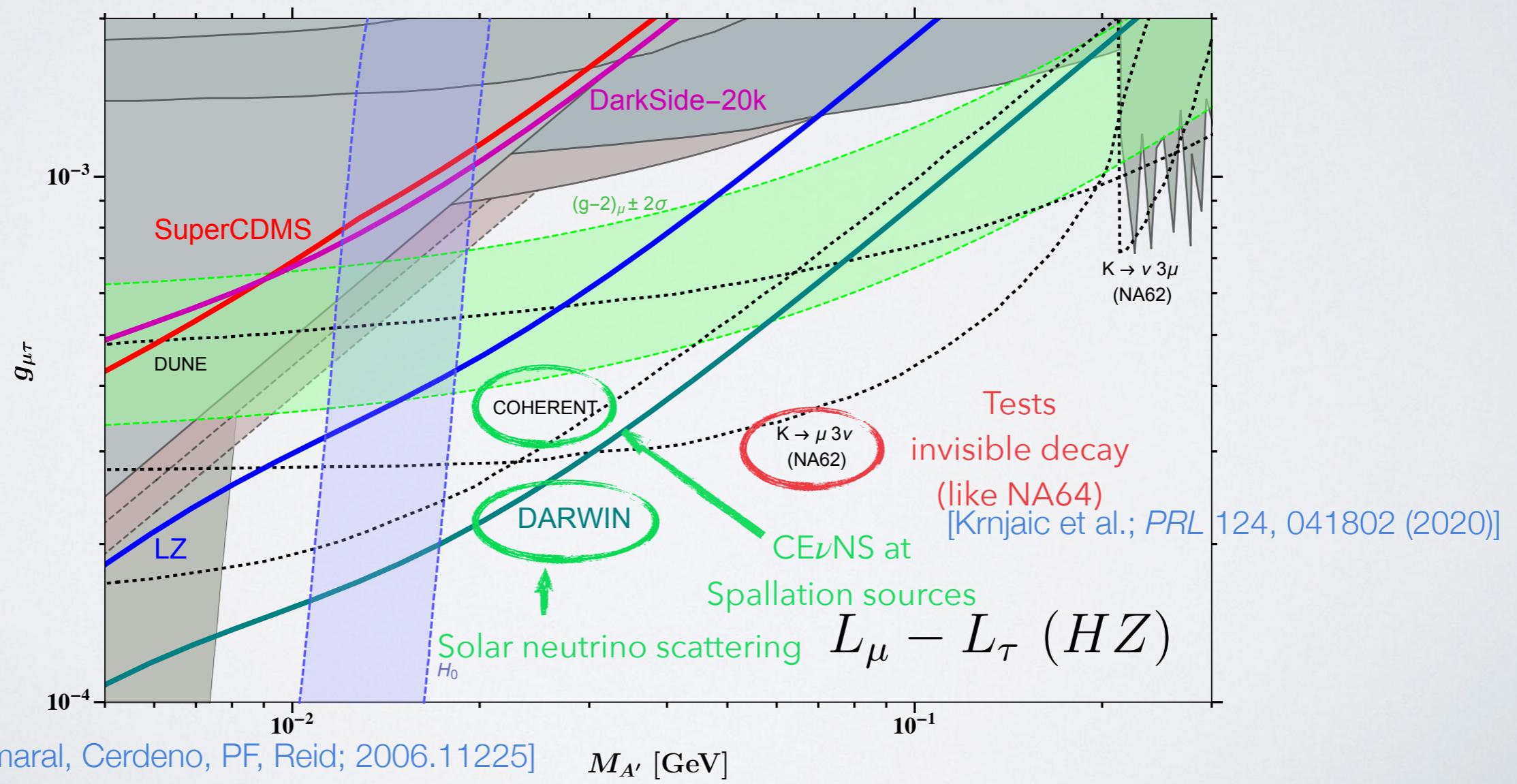
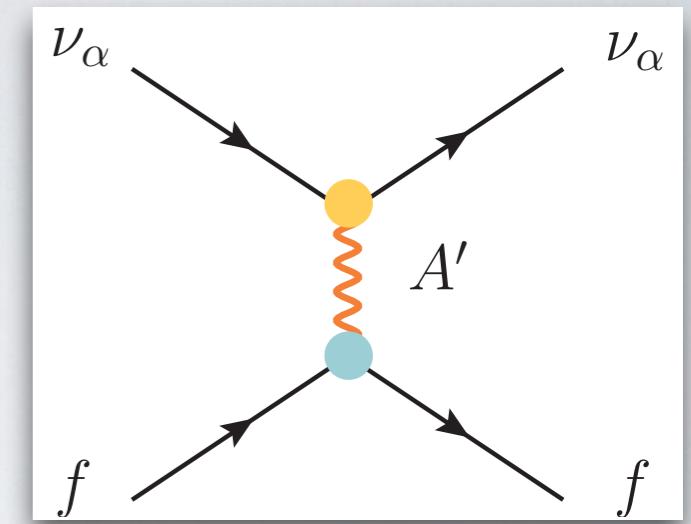
# NA64 $\mu$

- NA64 $\mu$  has good sensitivity to coupling
- Upper bound on low mass A'
- BP4 can be well resolved, since spectral peak in signal window
- No discrimination from simple muonophilic mediator and/or DM decays



# NEUTRINO INTERACTIONS

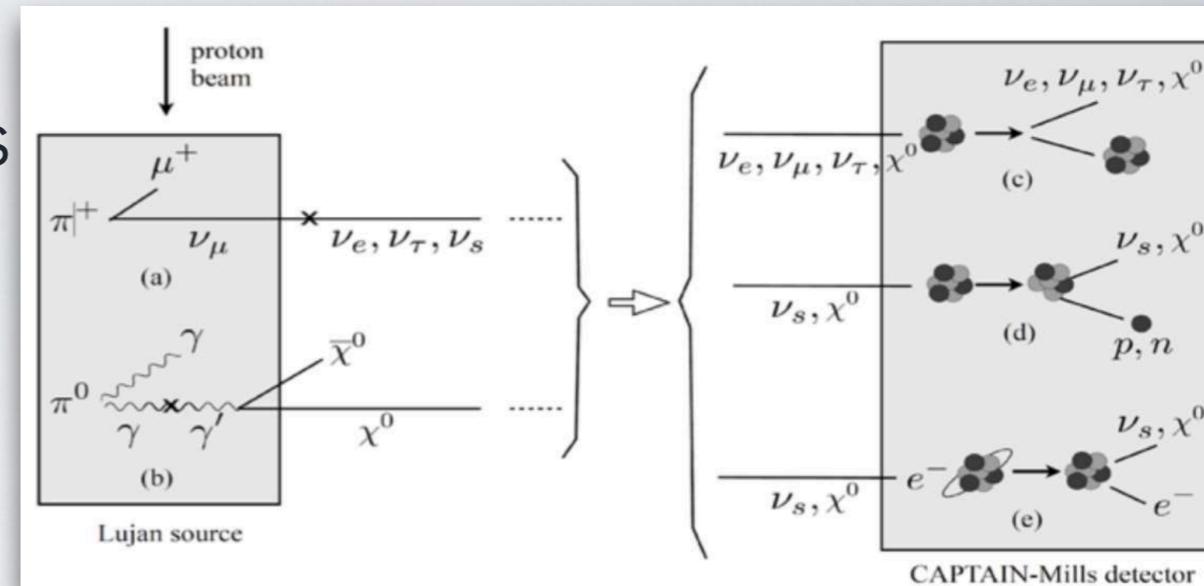
- Can we utilise gauge-neutrino interactions directly to test interesting parameter space?
- IDEA:  $A'$  contributes to **neutrino-electron and -nucleus scattering** via kinetic mixing.



# CE $\nu$ NS AT SPALLATION SOURCES

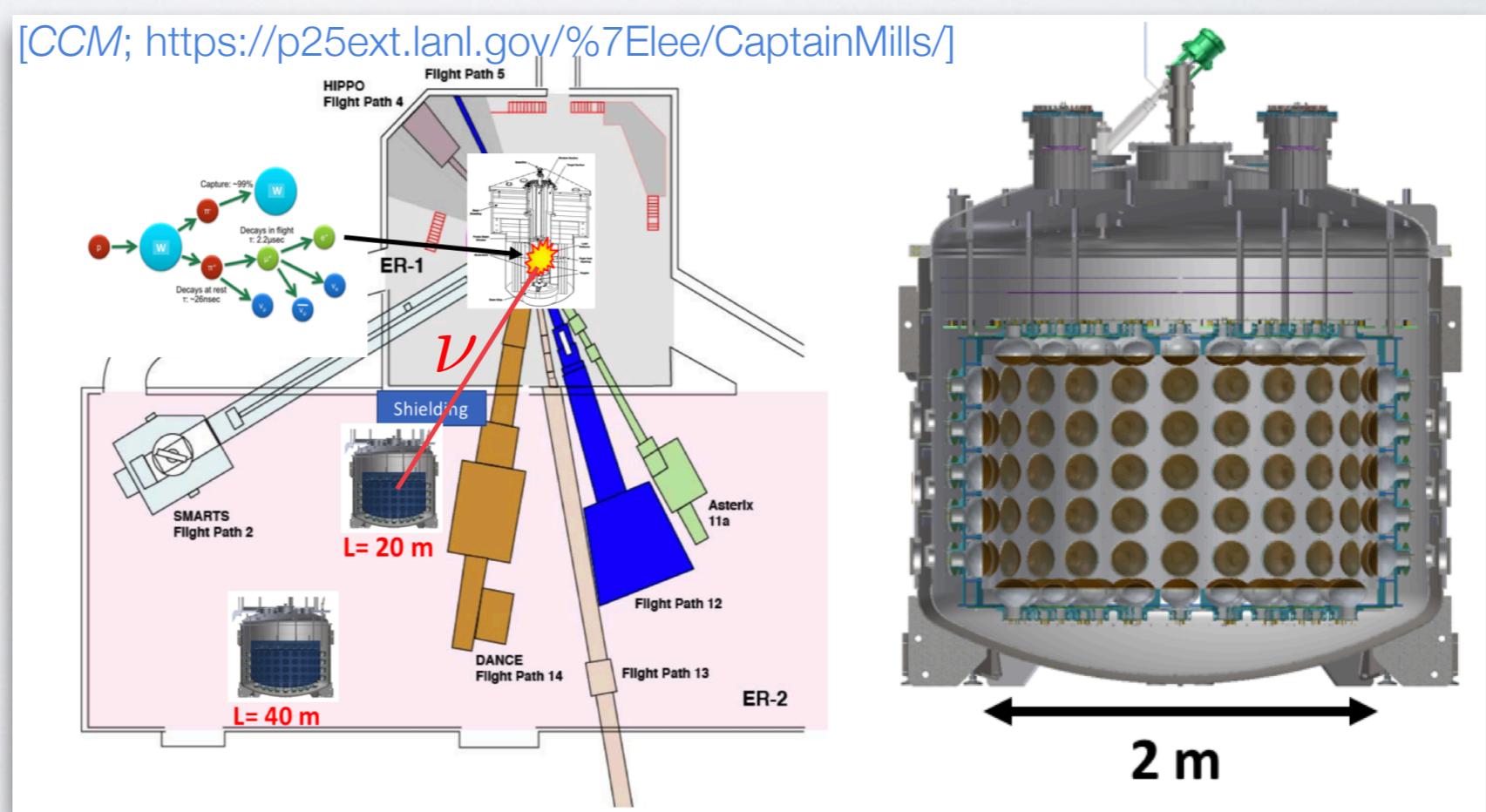
- At spallation sources stopped pions decay into muons and neutrinos

$$\pi^+ \rightarrow \nu_\mu \mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$



- Future neutrino detectors as e.g. CCM are sensitive to neutrino NSI in coherent elastic neutrino-nucleus scattering (CE $\nu$ NS)

- Example CCM:  
7 tons LAr  
 $E_{th}=10\sim 30$  keV  
220 PMT  
 $L=20/40$  m



# CE $\nu$ NS AT SPALLATION SOURCES

Experiment	Mass [ton]	$E_{th}$ [keV <sub>nr</sub> ]	NPOT [ $10^{23}/\text{yr}$ ]	r	L [m]	$\sigma_{\text{sys}}$
CENNS610	0.61	$\sim 20$	1.5	0.08	28.4	8.5%
ESS10	0.01	0.1	2.8	0.3	20	5%
CCM	7	10	0.177	0.0425	20	5%
ESS	1	20	2.8	0.3	20	5%

- Since  $\nu$  flux contains  $\mu$ -component, both  $U(1)_{L_\mu - L_\tau}$  and  $U(1)_{L_\mu}$  bosons can lead to extra CE $\nu$ NS:

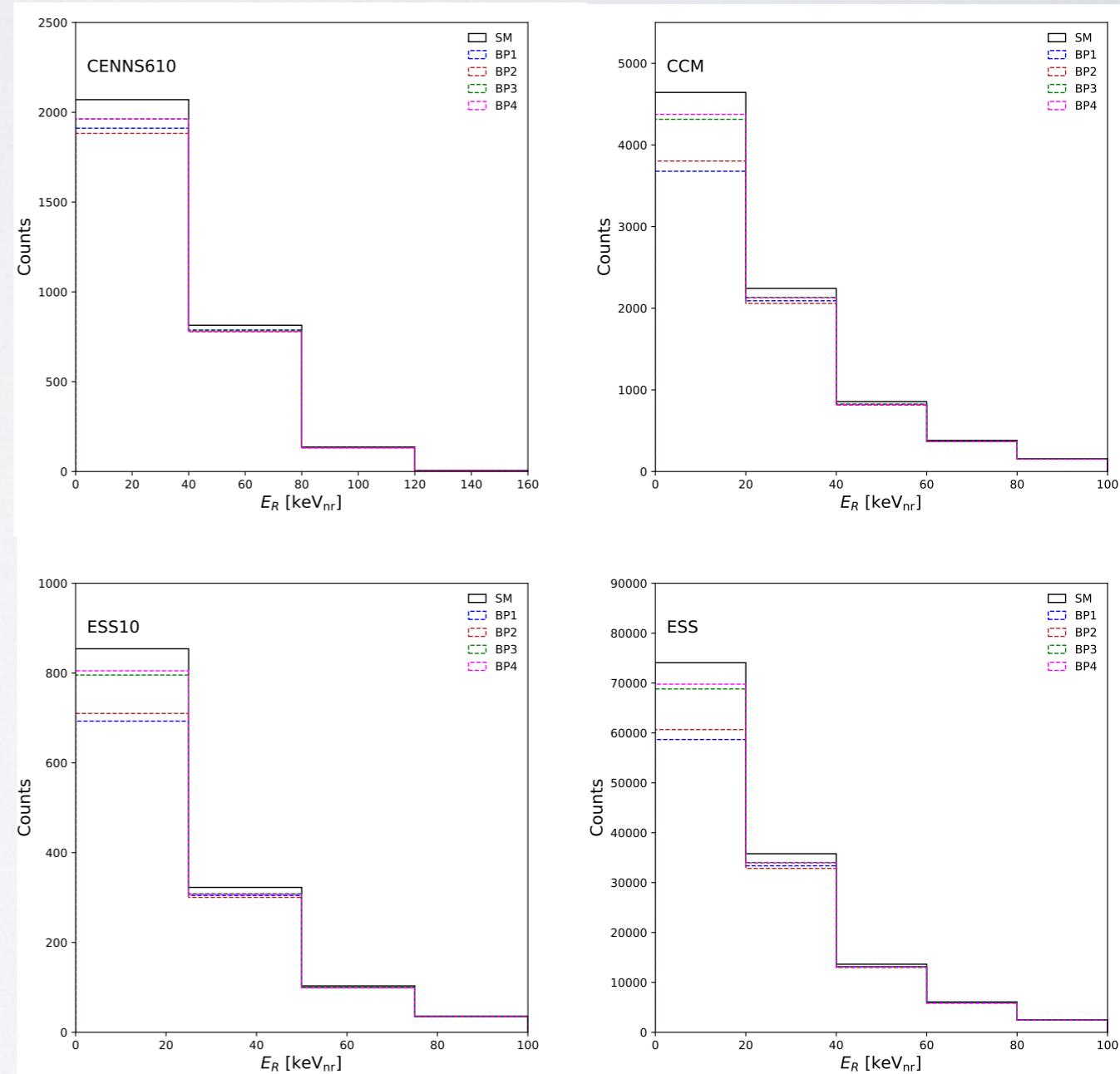
$$\frac{d\sigma_{\nu_\alpha N}}{dE_R} = \frac{G_F^2 M_N}{\pi} \left(1 - \frac{M_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

$$\times \left\{ \frac{Q_{\nu N}^2}{4} + 1 \text{ for } \nu_\mu \right. \quad \text{(SM)}$$

$$\epsilon_x < 0 \rightarrow g_x \epsilon_x e Z Q_{\nu_\alpha}^x Q_{\nu N} \quad \text{(int)}$$

deficit!

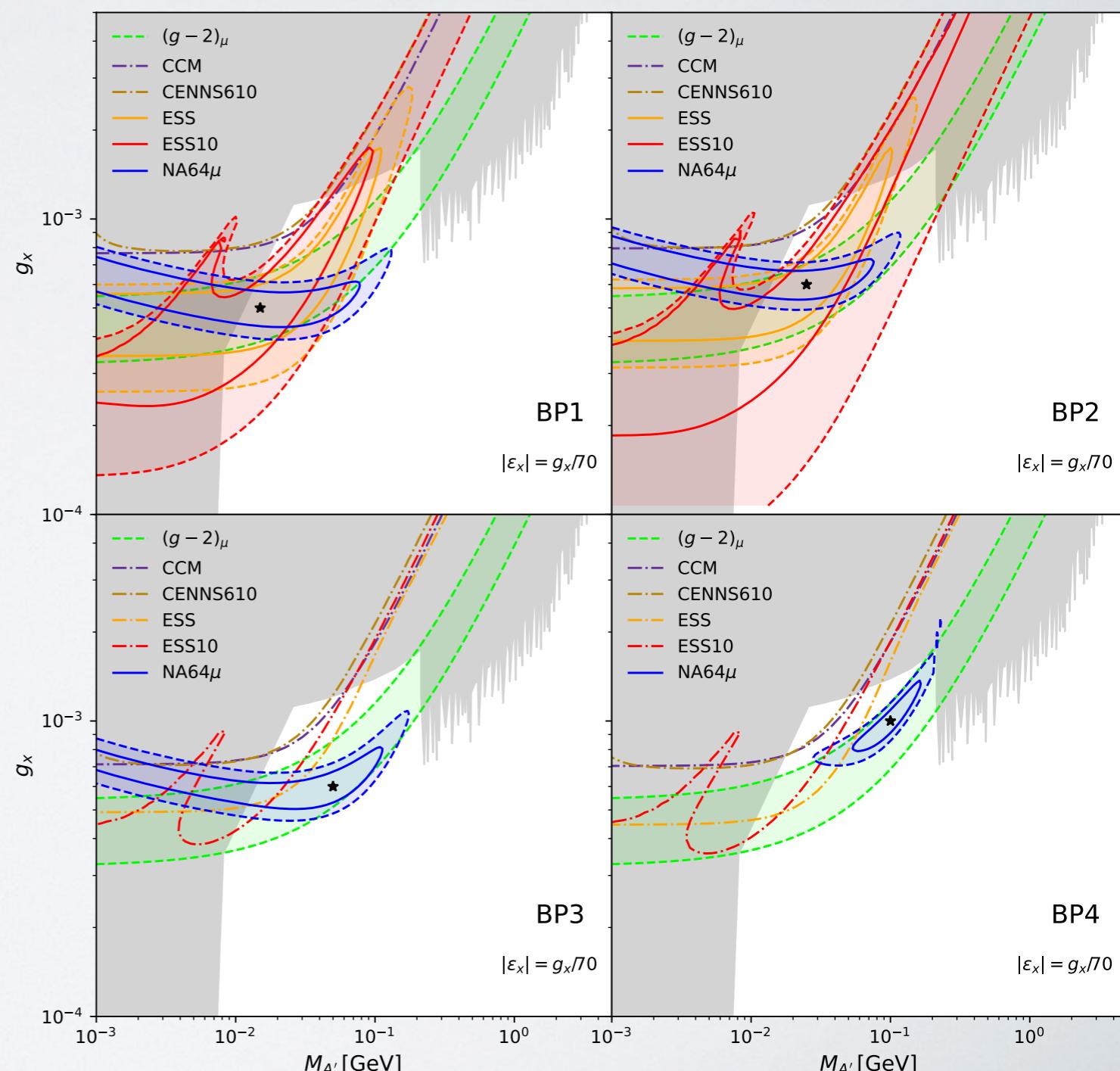
$$+ \frac{g_x \epsilon_x e Z Q_{\nu_\alpha}^x Q_{\nu N}}{\sqrt{2} G_F (2M_N E_R + M_{A'}^2)} + \left. \frac{g_x^2 \epsilon_x^2 e^2 Z^2 Q_{\nu_\alpha}^{x^2}}{2 G_F^2 (2M_N E_R + M_{A'}^2)^2} \right\} \quad \text{(BSM)}$$



# CE $\nu$ NS AT SPALLATION SOURCES

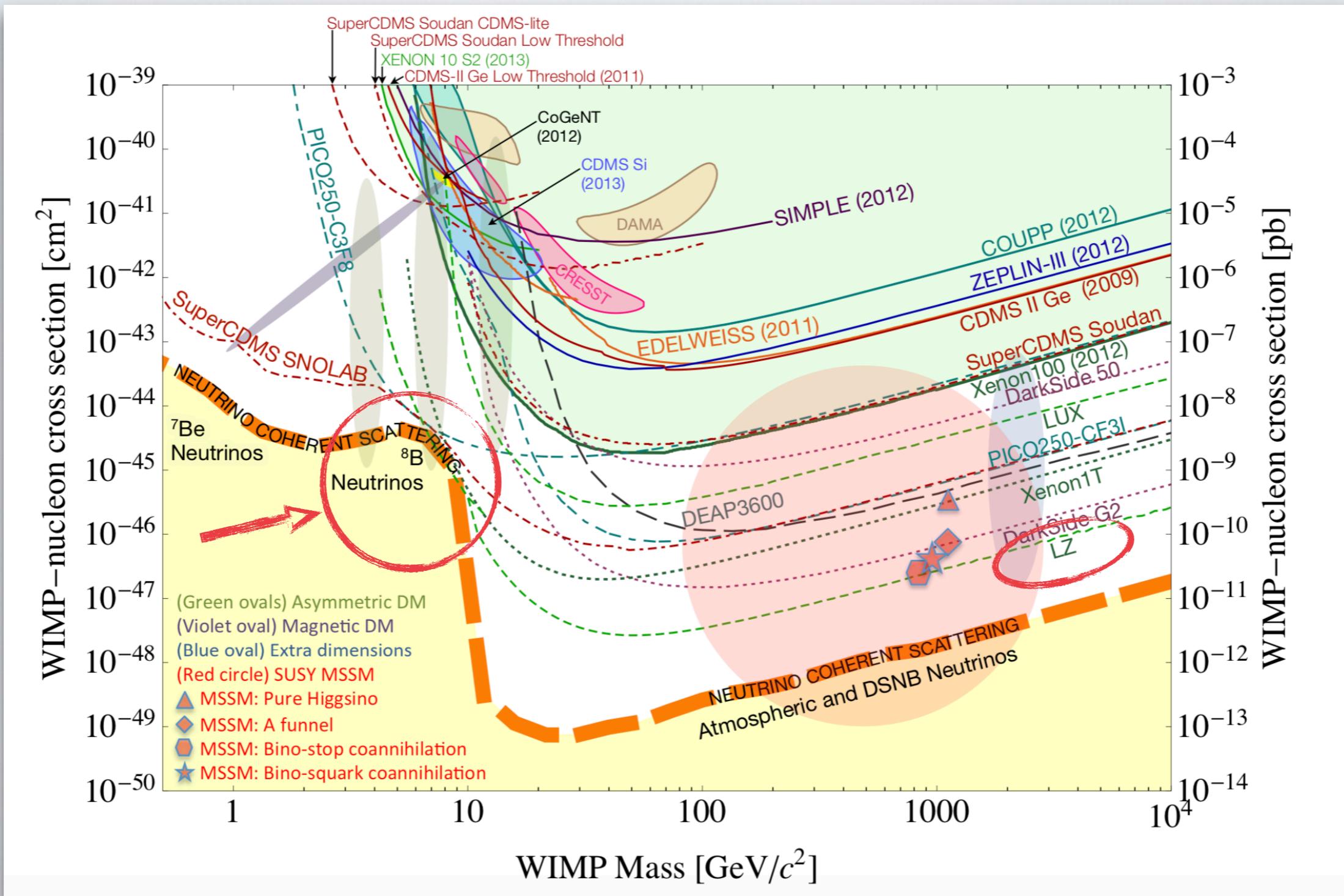
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- CCM and CENNS (LAr) can only place upper bounds
- ESS detectors (CsI[Na]) can reconstruct BP1&2
- Combined with NA64 limit range of parameters
- Still degeneracy between  $U(1)_{L_\mu-L_\tau}$  and  $U(1)_{L_\mu}$



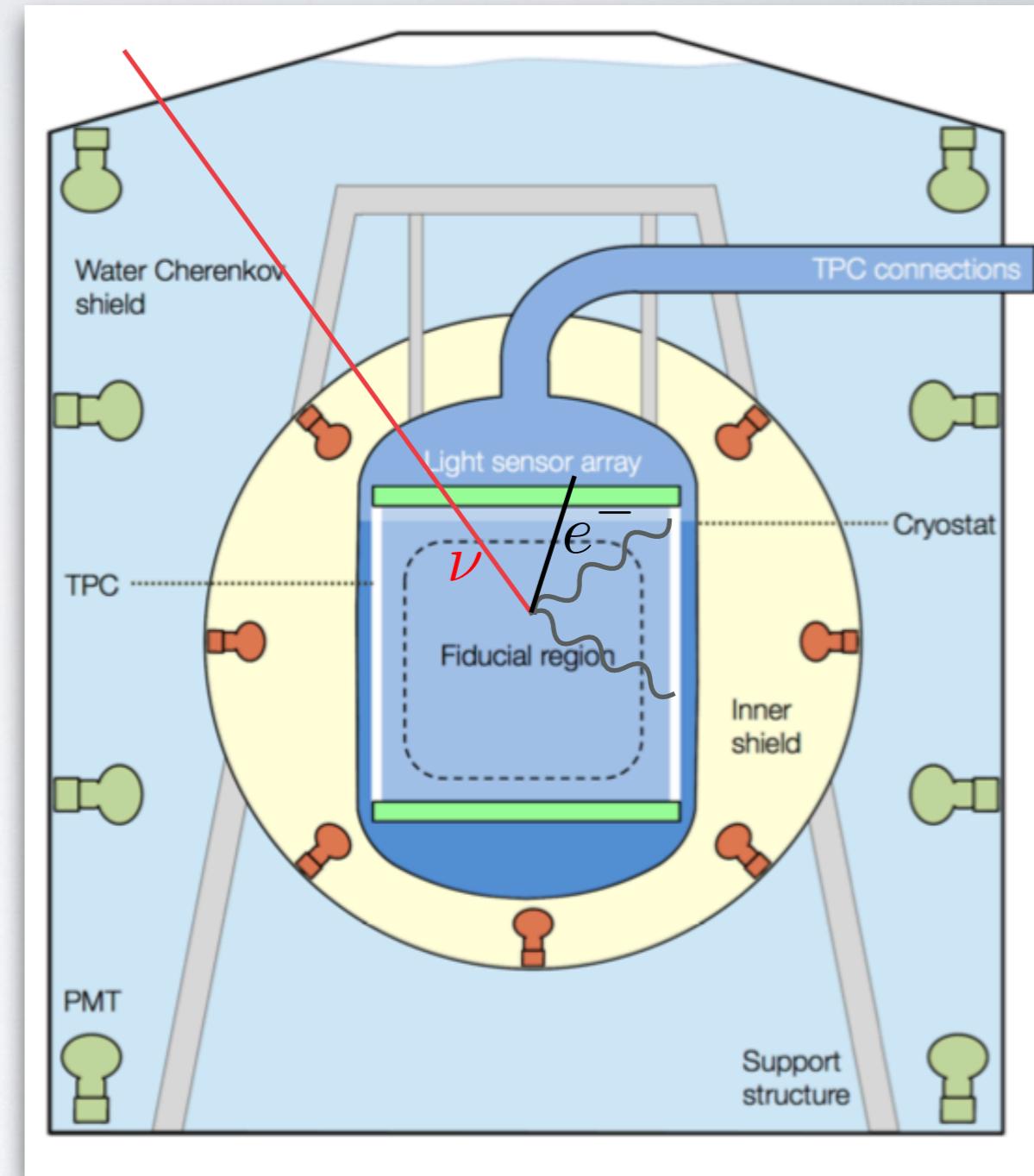
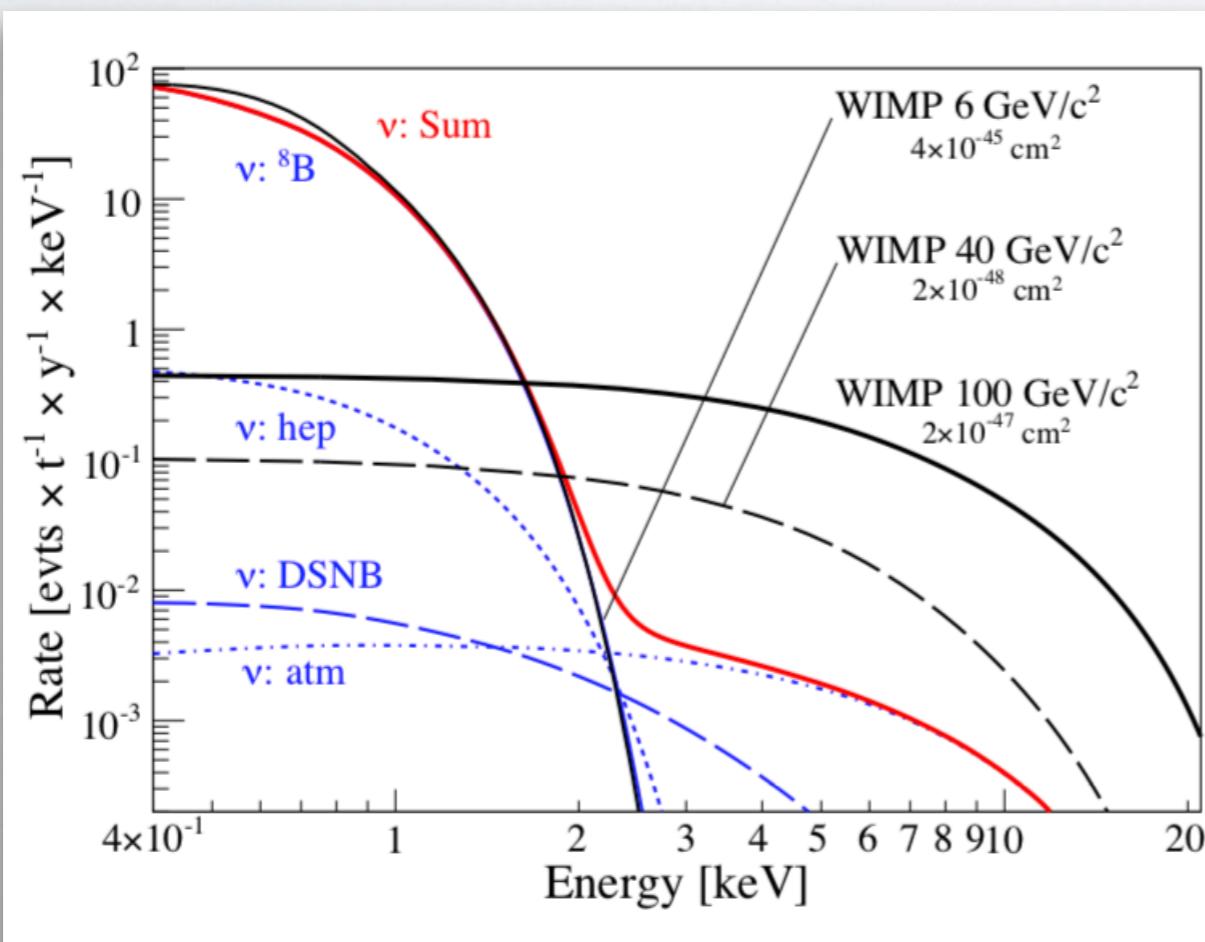
# NEUTRINO FLOOR

- Direct detection experiments will become sensitive to solar neutrino scattering (in particular coherent scattering)



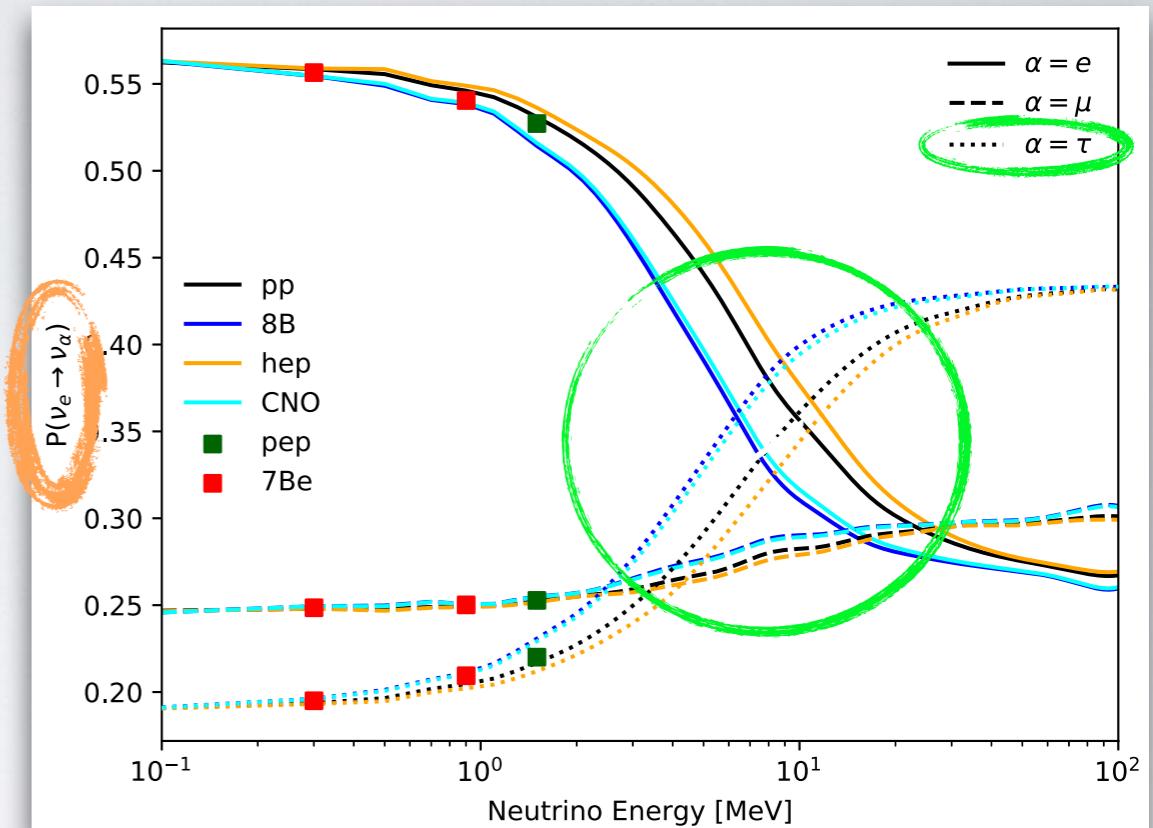
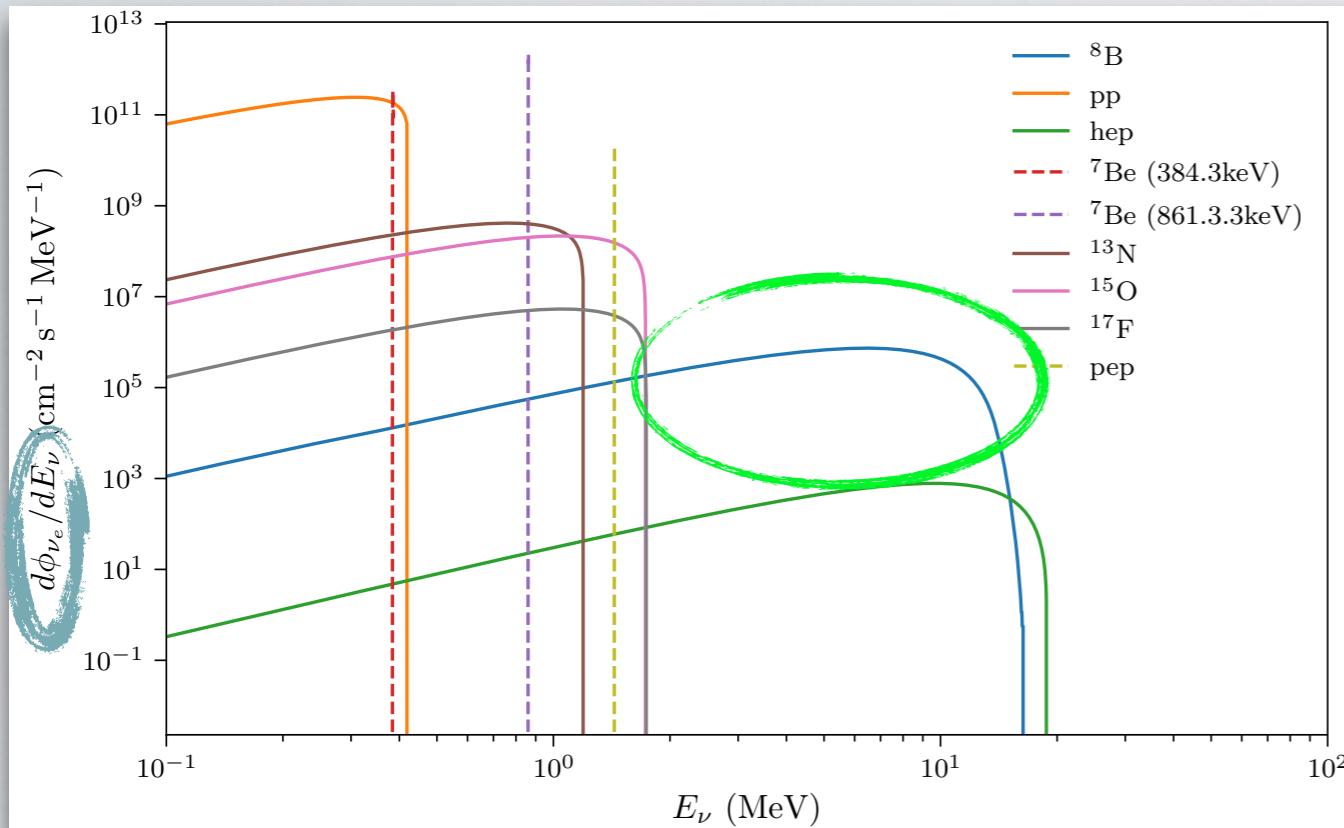
# DARWIN

- DARWIN is a future LXe time-projection chamber operated with 40 t of LXe for 5-7 years. First run is planned for ~2023
- Outer Water Cherenkov muon veto and inner neutron veto
- Nominal 5 keV threshold for DM search  
**here CEVNS is BG!**
- LUX has achieved 1.1 keV with NR/ER discrimination



[DARWIN collaboration; JCAP 1611 (2016) no.11, 017]

# SOLAR NEUTRINO SCATTERING



[Amaral, Cerdeno, PF, Reid; 2006.11225]

- Solar neutrinos produced in various processes, but initially always in electron flavour.
- In-medium oscillation within solar matter dominates flavour composition reaching earth. **More  $\nu_\tau$  than  $\nu_\mu$  at  $\sim 10$  MeV ( $^8\text{B}$ )!**
- Total counts in scattering experiment given by

$$N = \varepsilon n_T \int_{E_{\text{th}}}^{E_{\text{max}}} \sum_{\nu_\alpha} \int_{E_\nu^{\text{min}}} \frac{d\phi_{\nu_e}}{dE_\nu} P(\nu_e \rightarrow \nu_\alpha) \frac{d\sigma_{\nu_\alpha T}}{dE_R} dE_\nu dE_R$$

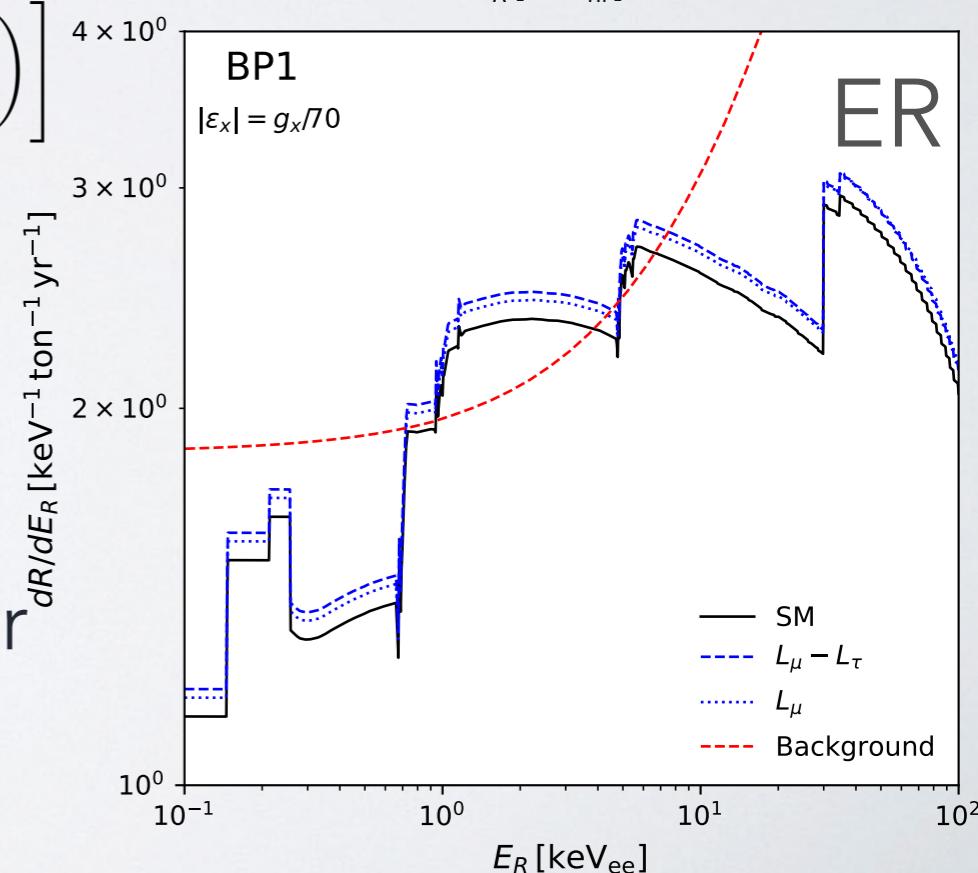
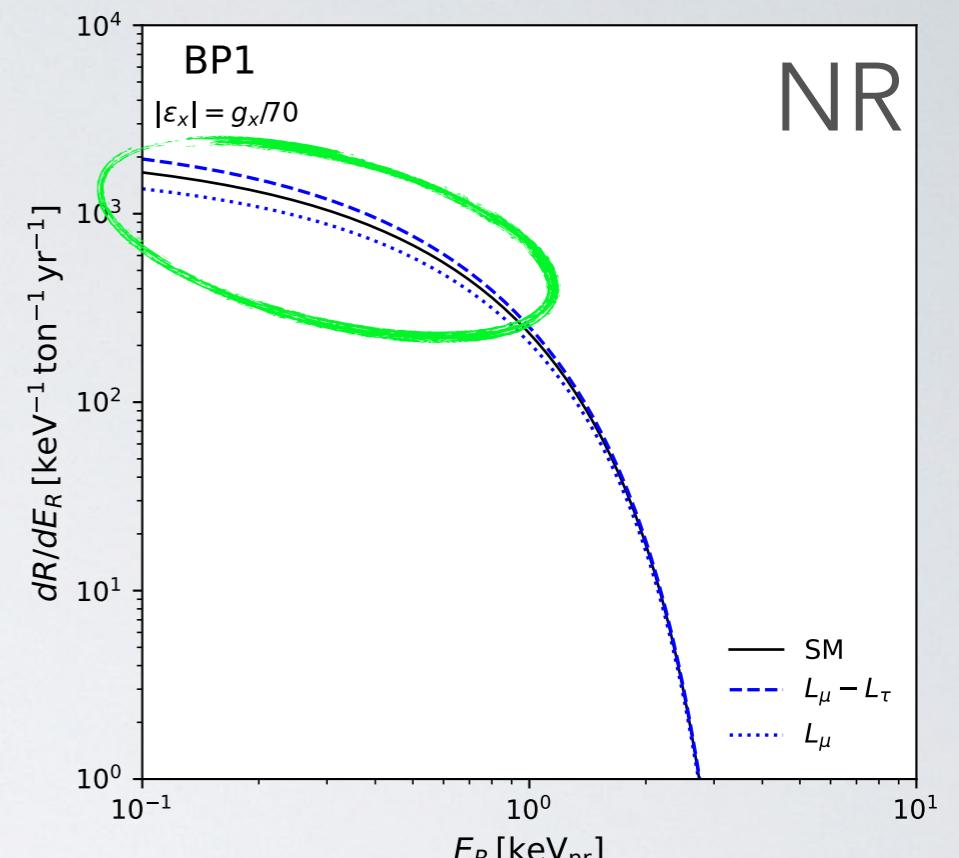
# DIRECT DETECTION

- Future low-threshold DD experiments will be sensitive to NR and ER of solar neutrino scattering
- Coherent neutrino-nucleus scattering:

$$\frac{d\sigma_{\nu_\alpha e}}{dE_R} = \frac{2 G_F^2 m_e}{\pi} \left\{ \left[ g_L^e {}^2 + g_R^e {}^2 \left( 1 - \frac{E_R}{E_\nu} \right)^2 - g_L^e g_R^e \frac{m_e E_R}{E_\nu^2} \right] + \frac{g_x \epsilon_x e Q_{\nu_\alpha}^x}{\sqrt{2} G_F (2 E_R m_e + M_{A'}^2)} \left[ (g_L^e + g_R^e) \left( 1 - \frac{m_e E_R}{2 E_\nu^2} \right) - g_R^e \frac{E_R}{E_\nu} \left( 2 - \frac{E_R}{E_\nu} \right) \right] + \frac{g_x^2 \epsilon_x^2 e^2 Q_{\nu_\alpha}^{x^2}}{4 G_F^2 (2 E_R m_e + M_{A'}^2)^2} \left[ 1 - \frac{E_R}{E_\nu} \left( 1 - \frac{E_R - m_e}{2 E_\nu} \right) \right] \right\}$$

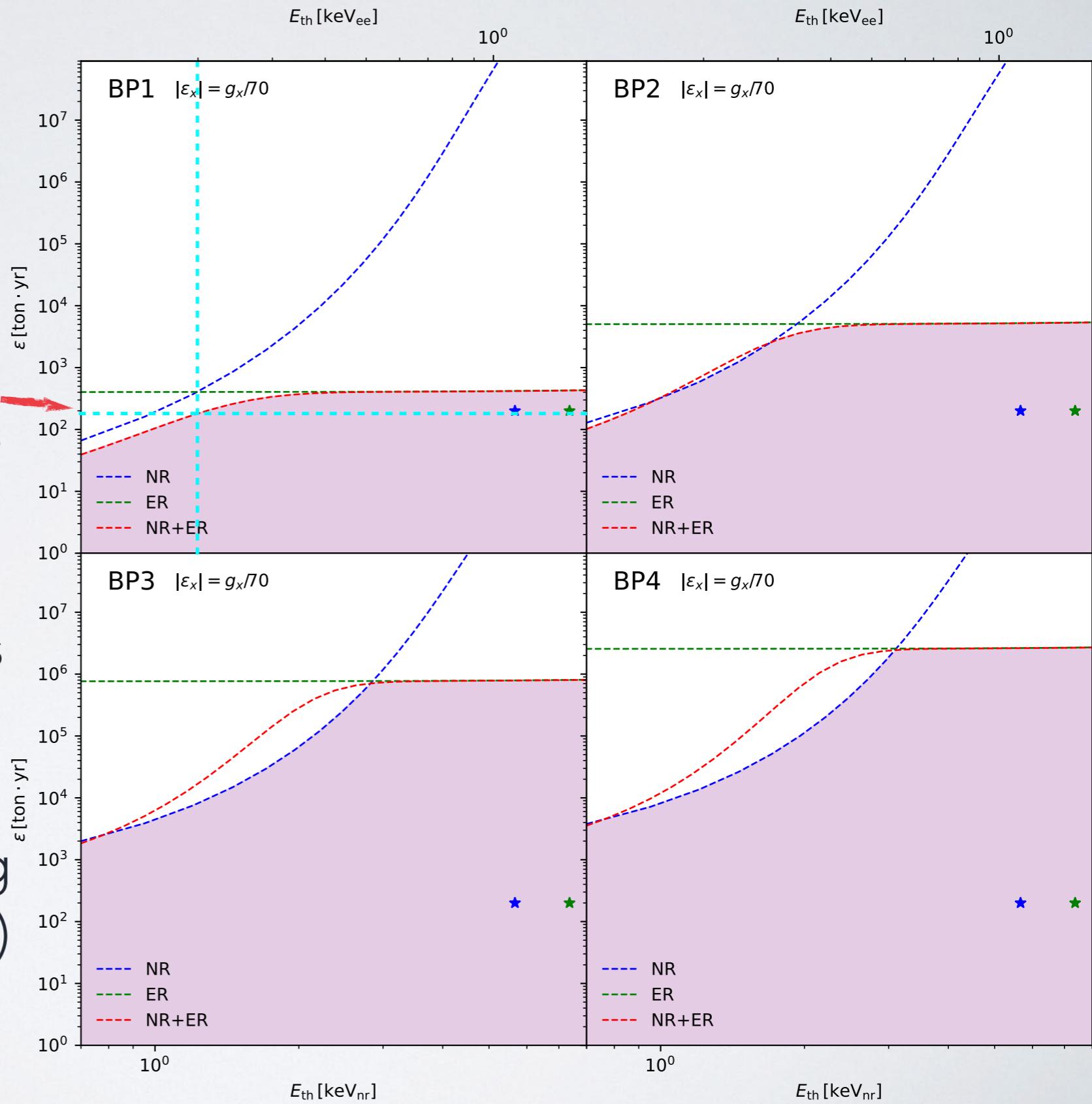
with  $g_L^e = \sin^2 \theta_W - 1/2$  and  $g_R^e = \sin^2 \theta_W$

- Due to small suppression scale  $m_e$ , the BSM term wins for ER. Excess of events for both  $U(1)_{L_\mu - L_\tau}$  and  $U(1)_{L_\mu}$ !



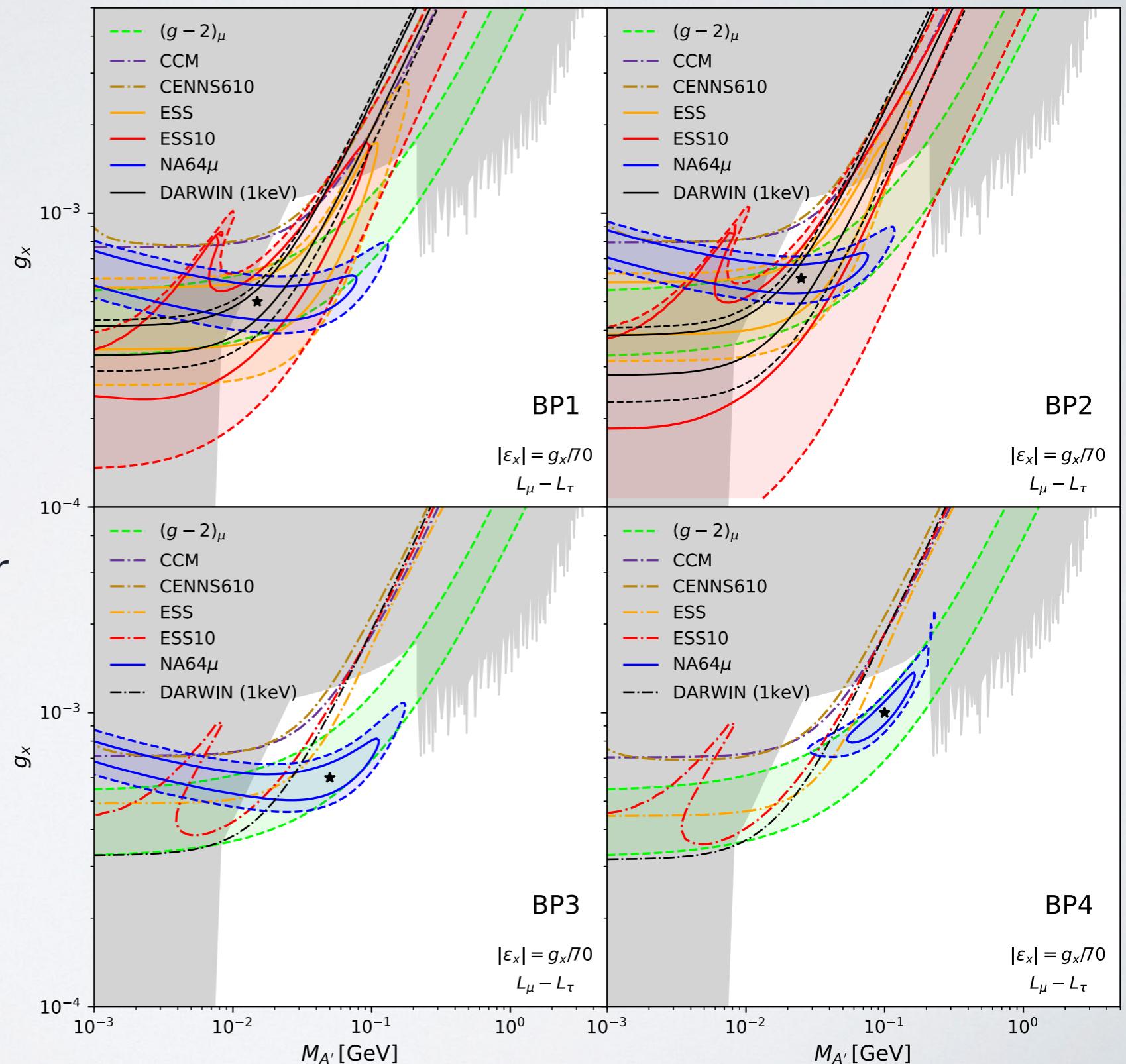
# DARWIN SENSITIVITY

- Derived  $5\sigma$  discovery lines for NR, ER, NR+ER analyses
- Lowering the threshold to 1 keV in a NR+ER analysis would make discovery of low-mass A' feasible
- Alternatively doubling the exposure (for BP1)



# DARWIN SENSITIVITY

- DARWIN 1keV significantly narrows down the reconstructed parameter region for BP1 and BP2
- Still competitive upper limits for higher mass  $A'$  ( $M > 50$  MeV)
- Breaks degeneracy with  $U(1)_{L_\mu}$  (deficit expected) !



# SUMMARY

- General minimal **phenomenologically viable  $U(1)$**  models require **Majorana neutrinos (except  $B-L$ )** leading to neutrino flavour changing interactions
- Only minimal  $U(1)_{L_\mu - L_\tau}$  left as an explanation of  $(g - 2)_\mu$
- **NA64** will be the **first** (muon beam) experiment to test a  $U(1)_{L_\mu - L_\tau}$  solution. But only sensitive to muon coupling
- **CE $\nu$ NS experiments** can narrow down parameter space and test kinetic mixing via  $\nu_\mu$  interactions
- **DARWIN** could observe a  $5\sigma$  **excess** with 1 keV threshold in solar neutrinos. Can **establish**  $U(1)_{L_\mu - L_\tau}$  via  $\nu_\tau$  interactions



THANK YOU!

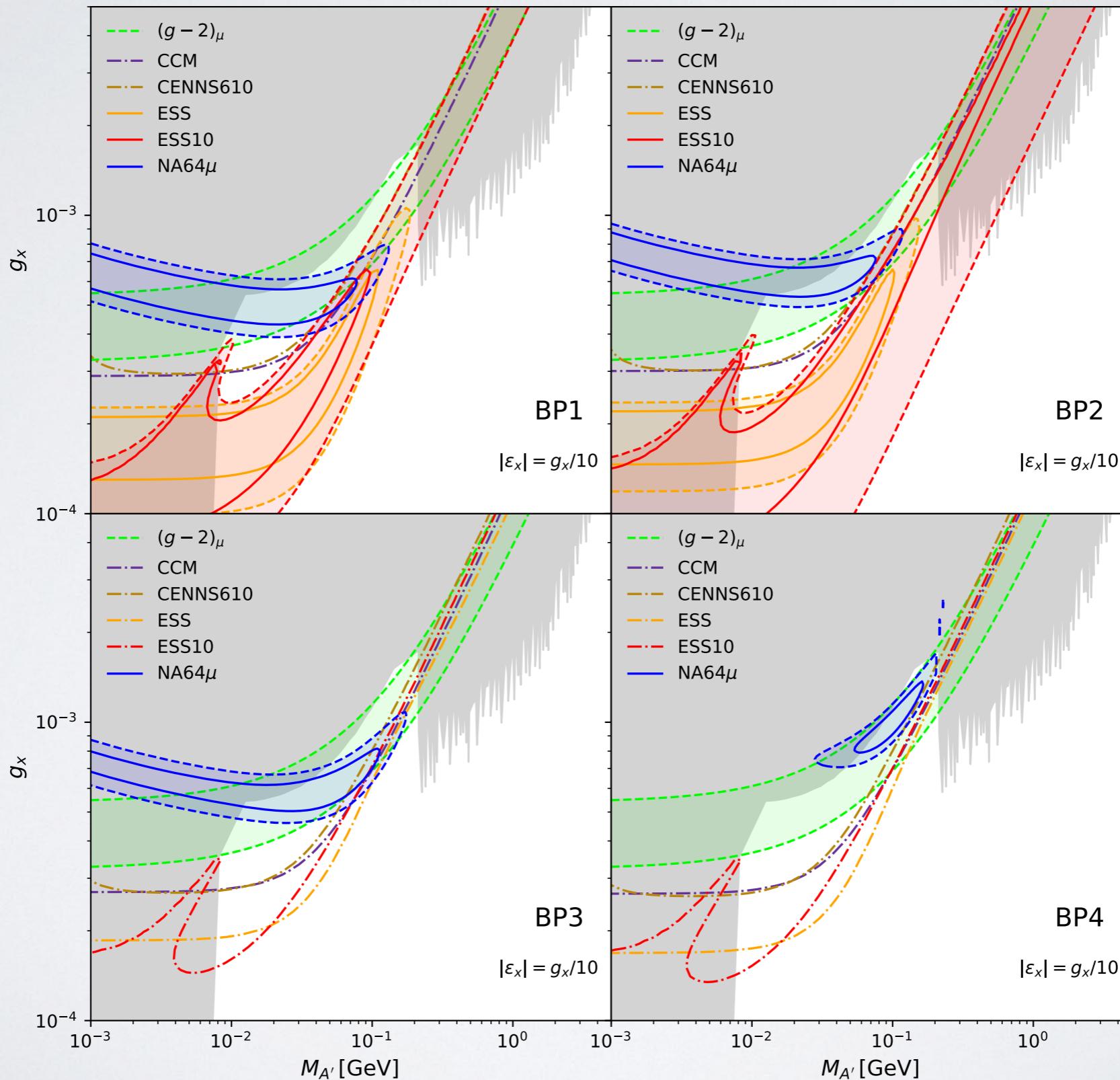


# BACKUP

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# RECONSTRUCTION FOR $U(1)_{L_\mu}$

- Reconstruction of NA64 and spallation sources point to different regions



# NA64

- The decay length of the  $A'$  is so short that it will decay inside the target once it is above the dimuon threshold

