Visible decays; dark photons++

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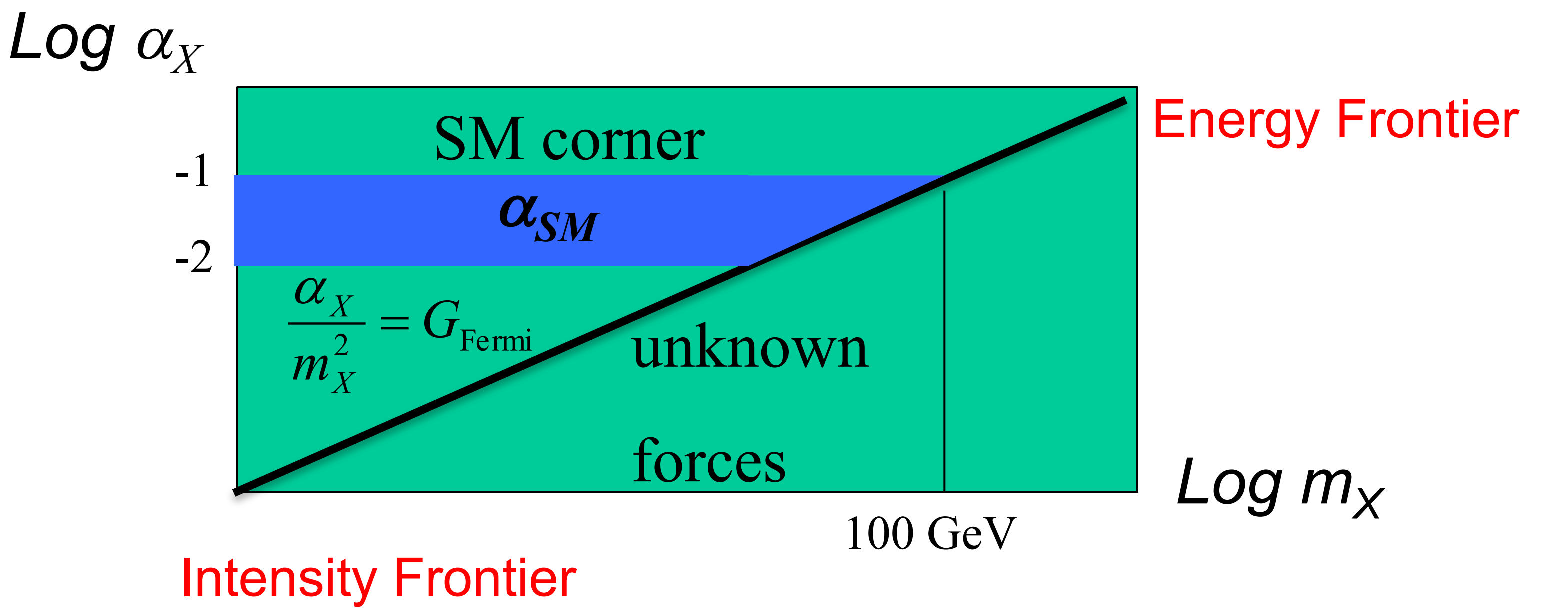
Outline of the talk

1. Introduction.
2. Dark photons. Variations on dark photons.
3. Constraints on dark photons ++
4. g-2 and dark scalars
5. Conclusions.

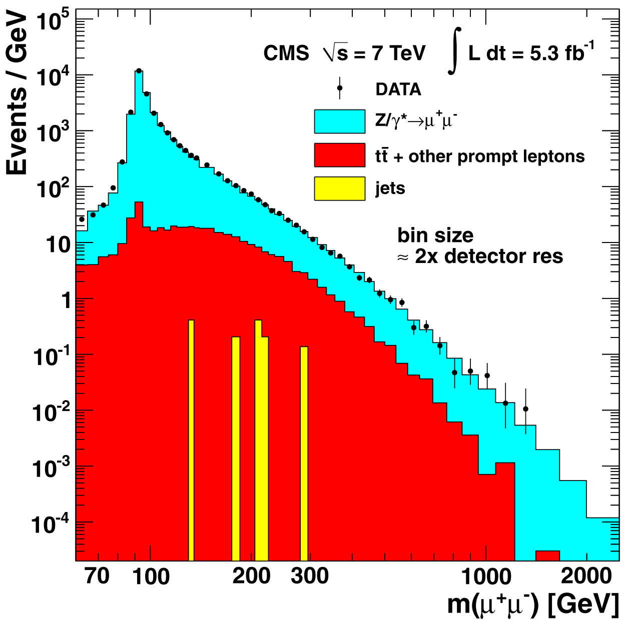
Intensity and Energy Frontiers

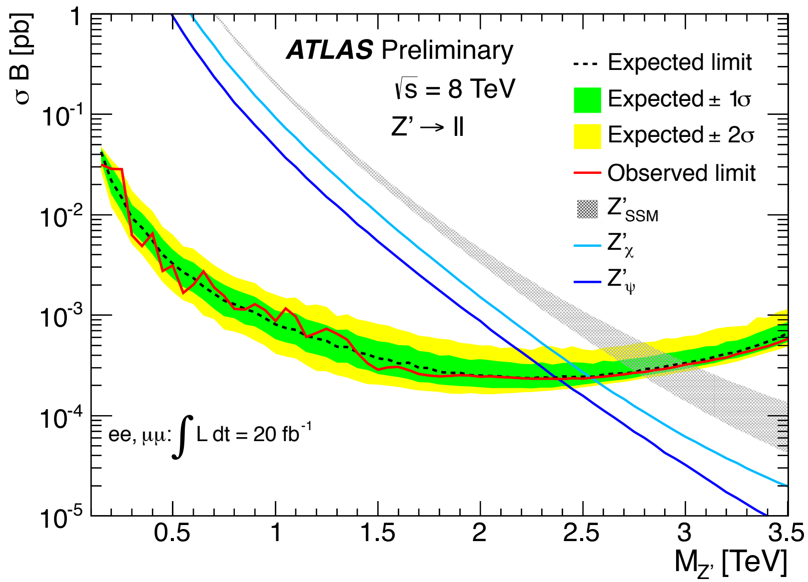


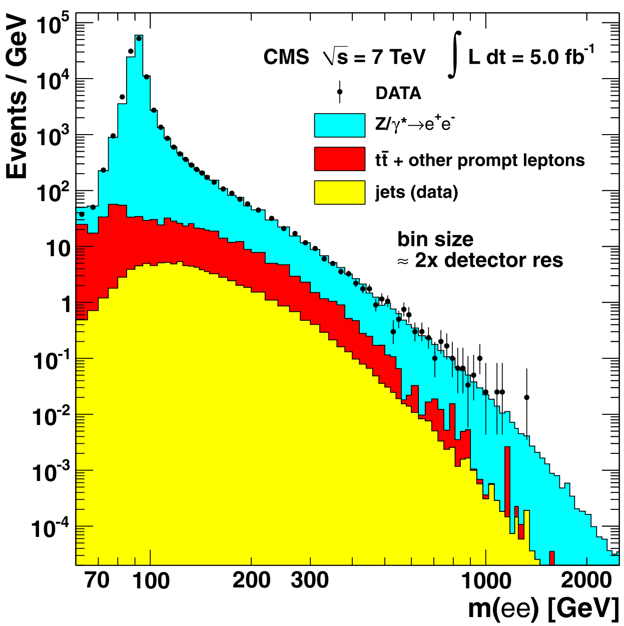
$$V(r) = \frac{\alpha_X}{r}\exp(-r/\lambda_X) = \frac{\alpha_X}{r}\exp(-rm_X) \longrightarrow \text{Amplitude} \approx \frac{\alpha_X}{q^2 + m_X^2}$$

LHC can realistically pick up New Physics with $\alpha_X \sim \alpha_{SM}$, and $m_X \sim$ 1TeV, but may have little success with $\alpha_X \sim 10^{-6}$, and $m_X \sim$ GeV.

No New Physics at high energy thus far (?!)







No hints for any kind of new physics. Strong constraints on SUSY, extra dimensions, technicolor resonances.

Constraints on new *Z'* bosons push the mediator mass into multi-TeV territory.

Neutral "portals" to the SM

Let us *classify* possible connections between Dark sector and SM

$H^+H\,(\lambda\, S^2 + A\, S)$ Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu} V_{\mu\nu}$ "Kinetic mixing" with additional U(1)' group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

$LH\,N$ neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

$J_\mu^A\ \partial_\mu a\,/f$ axionic portal

……….

$$\mathcal{L}_{\rm mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}^{(k)}_{\rm med}\mathcal{O}^{(l)}_{\rm SM}}{\Lambda^n},$$

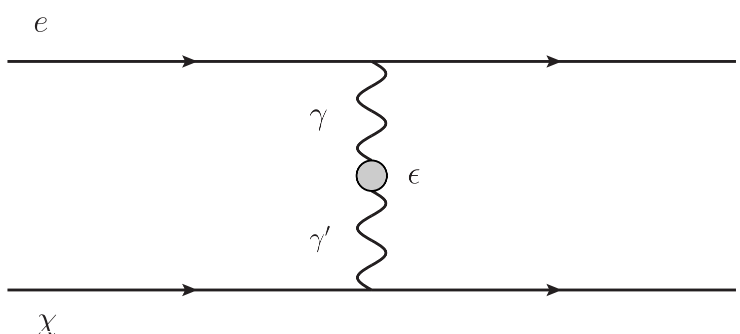
"Simplified model" for dark sector

(Okun', Holdom,…)

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m^2_{A'} (A'_\mu)^2.$$

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F^2_{\mu\nu} + \bar{\psi}[\gamma_\mu (i\partial_\mu - eA_\mu) - m_\psi]\psi$$

$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu (i\partial_\mu - g' A'_\mu) - m_\chi]\chi,$$

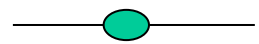


A – photon, *A'* – "dark photon", ψ - an electron, χ - a DM state, *g'* – a "dark" charge

- "Effective" charge of the "dark sector" particle χ is Q = e × ε (if momentum scale q > m_V). At q < m_V one can say that particle χ has a non-vanishing EM charge radius, $r^2_\chi \simeq 6\epsilon m_V^{-2}$.
- Dark photon can "communicate" interaction between SM and dark matter. *It represents a simple example of BSM physics*.

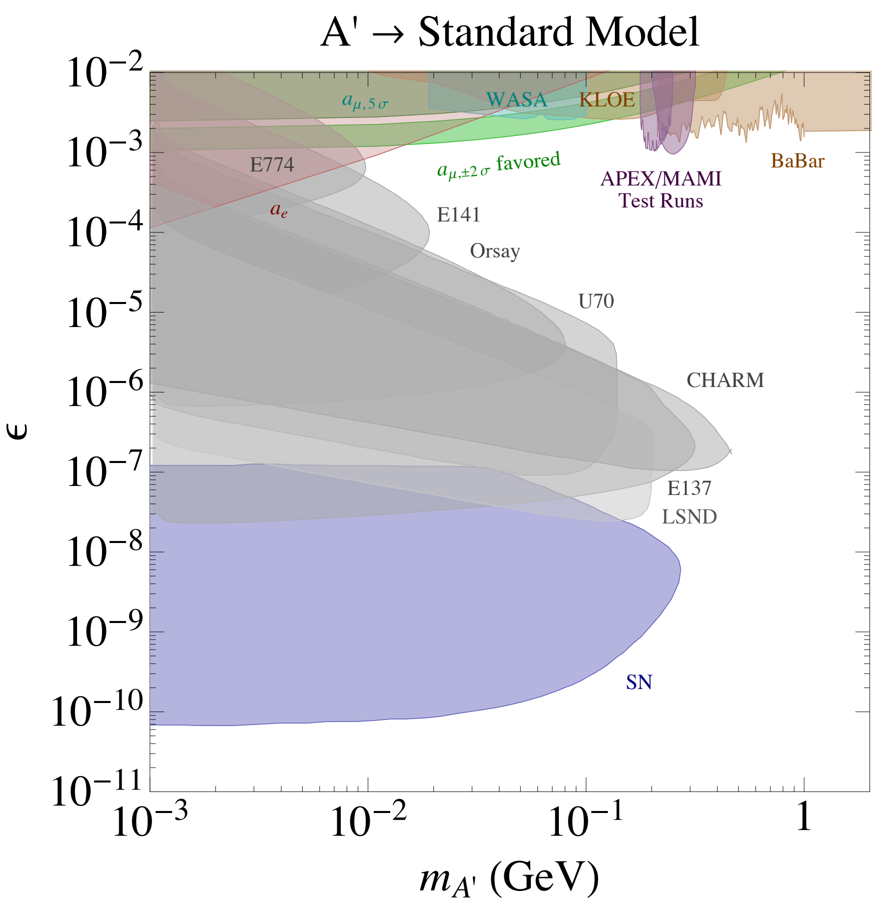
Dark photons ++

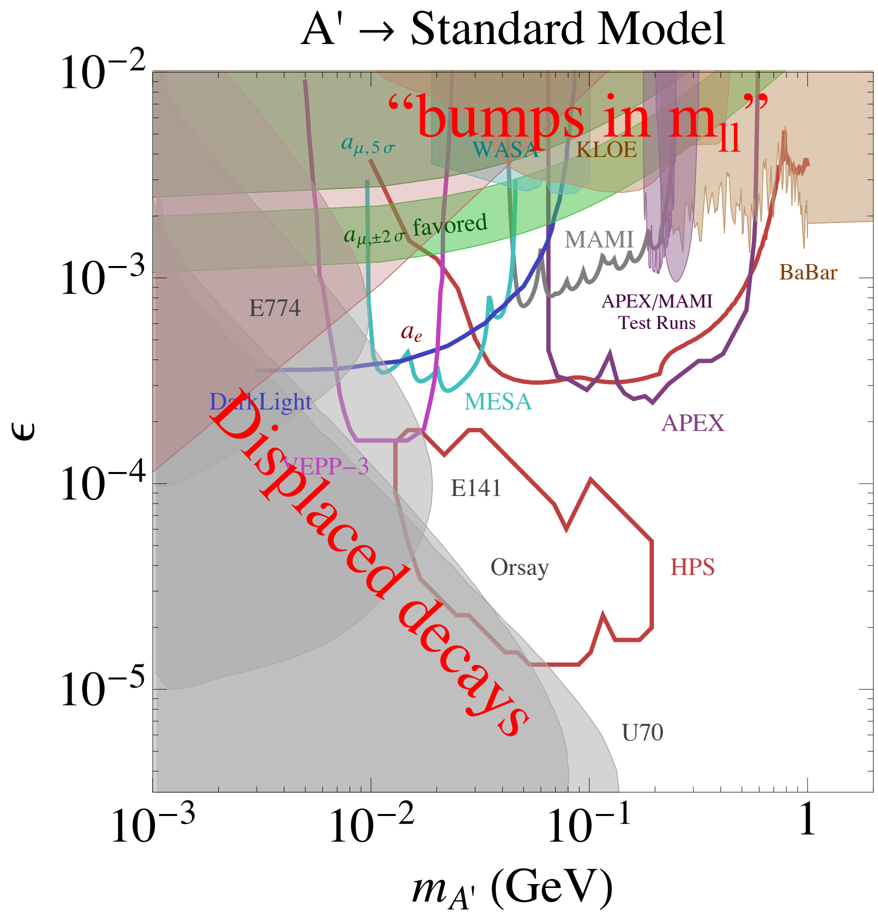
Let's classify them into 3 cartegories

1. *Dark photon: technically natural, UV complete, couple to a conserved current.* $\varepsilon =$ 
2. *B-L, L_μ-L_τ, and other anomaly free combinations: all of the above, but coupling constant g_X is small – somewhat unusual. Strong constraints from neutrino physics.*
3. *Models coupled to the tree-level conserved current broken by anomalies. E.g. gauged baryon number, or lepton number. Presumes cancellation of anomalies at high-energy. Nice low energy behaviour, weak constraints on gauged baryon number?*
4. *Models coupled to a non-conserved current. (e.g. vector particle coupled to an axial-vector current)*

- Phenomenology-driven demand often force speculators to consider 3 and 4. (proton charge radius, ^{8}Be decay anomaly)

Search for dark photons, Snowmass study, 2013





Dark photon models with mass under 1 GeV, and mixing angles ~ 10^{-3} represent a "window of opportunity" for the high-intensity experiments, not least because of the tantalizing positive ~ $(\alpha/\pi)\varepsilon^2$ correction to the muon g - 2.

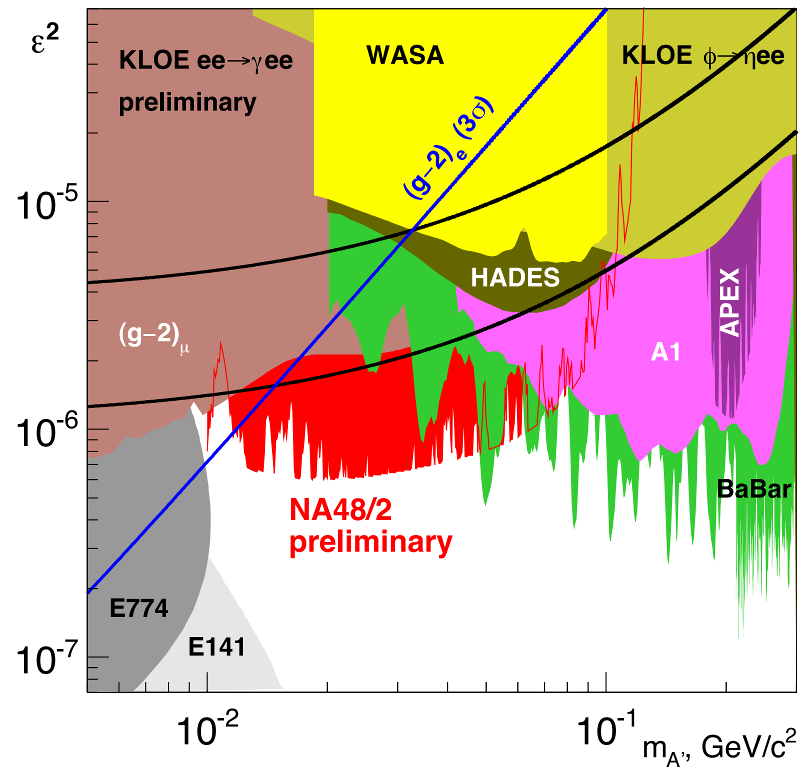
Zooming in: A1, Babar, NA48

Signature: "bump" at invariant mass of e^+e^- pairs = $m_{A'}$

Babar: $e^+e^- \to \gamma V \to \gamma l^+l^-$

A1(+ APEX): $Z e^- \to Z e^- V \to Z e^- e^+e^-$

NA48: $\pi^0 \to \gamma V \to \gamma e^+e^-$



Latest results by NA48 exclude the remainder of parameter space relevant for g-2 discrepancy.

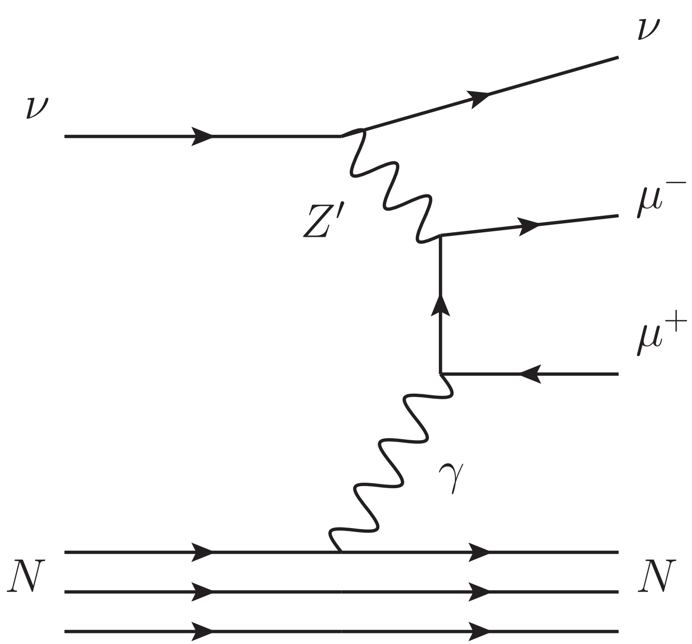
Only more contrived options for muon g-2 explanation remain, e.g. $L_\mu - L_\tau$, or ~~dark photons *decaying to light dark matter.*~~

Constraints on Z' of $L_\mu - L_\tau$

Experimental results

$$\sigma_{\mathrm{CHARM-II}}/\sigma_{\mathrm{SM}} = 1.58 \pm 0.57 \ ,$$
$$\sigma_{\mathrm{CCFR}}/\sigma_{\mathrm{SM}} = 0.82 \pm 0.28 \ ,$$
$$\sigma_{\mathrm{NuTeV}}/\sigma_{\mathrm{SM}} = 0.67 \pm 0.27 \ .$$

Hypothetical Z' (any Z' coupled to L_μ) contributes constructively to cross section.



In the heavy Z' limit the effect simply renormalizes SM answer:

$$\frac{\sigma}{\sigma_{\mathrm{SM}}} \simeq \frac{1 + \left(1 + 4s_W^2 + \overbrace{2v^2/v_\phi^2}^{\approx 4}\right)^2}{1 + \left(1 + 4s_W^2\right)^2}$$

~8-fold enhancement of cross section

Muon pair-production by neutrinos

VOLUME 66, NUMBER 24 PHYSICAL REVIEW LETTERS 17 JUNE 1991

Neutrino Tridents and *W*-*Z* Interference

S. R. Mishra,[a] S. A. Rabinowitz, C. Arroyo, K. T. Bachmann,[b] R. E. Blair,[c] C. Foudas,[d] B. J. King,

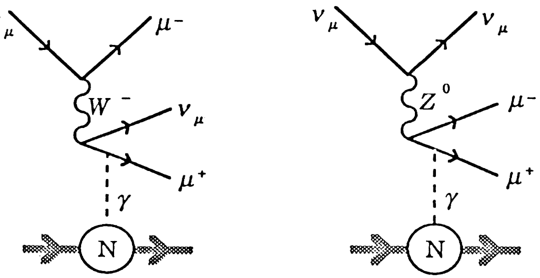


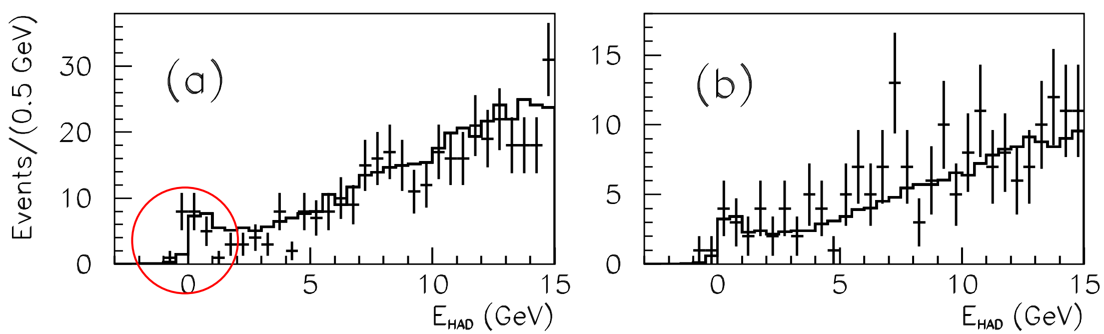
FIG. 1. Feynman diagram showing the neutrino trident production in ν_μ-A scattering via the W and the Z channels.

$$\sigma_{\nu N}(\mathrm{CC}) = (0.680 \pm 0.015) E_\nu \times 10^{-38}\ \mathrm{cm}^2/\mathrm{GeV}\,,$$

$$\sigma(\nu\ \mathrm{trident}) = (4.7 \pm 1.6) E_\nu \times 10^{-42}\ \frac{\mathrm{cm}^2}{\mathrm{Fe\ nucleus}}$$

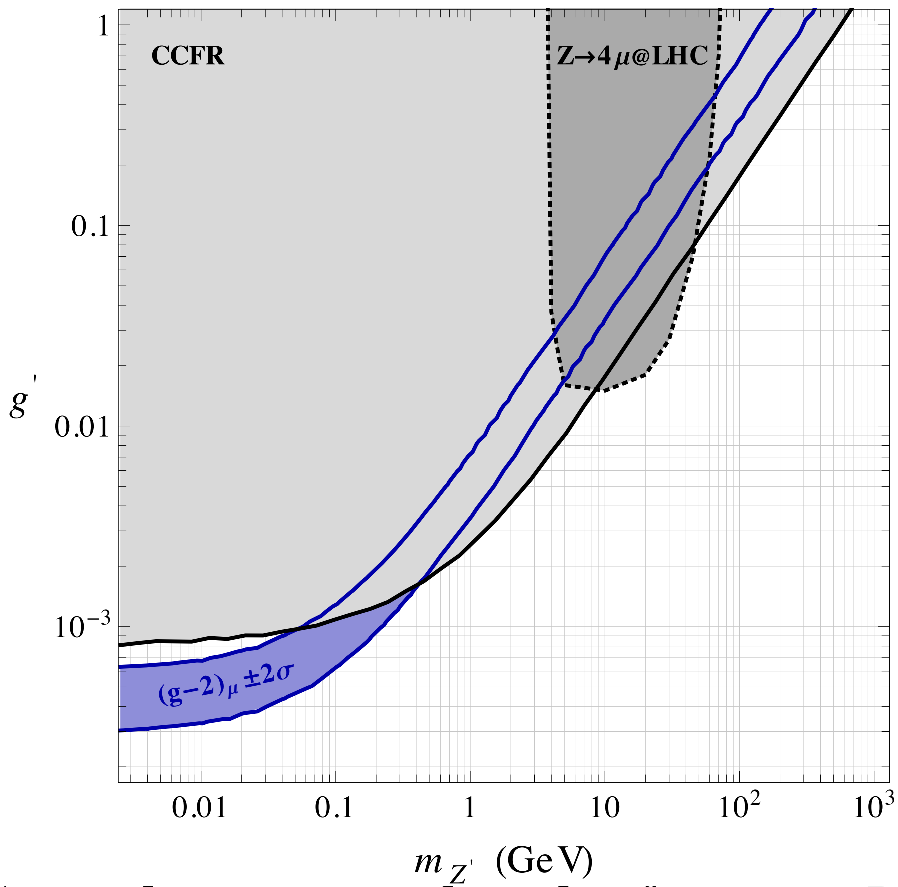
$$\text{at } \langle E_\nu \rangle = 160\ \mathrm{GeV}\,.$$

- NuTeV results:



Trident production was seeing with O(20) events, and is fully consistent with the SM destructive W-Z interference.

Full result on $M_{Z'}$ - g' parameter space



Muon pair production process excludes solutions to muon g-2 discrepancy via gauged muon number in the whole range of

$M_{Z'} > 400$ MeV

In the "contact" regime of heavy Z'>5 GeV, the best resolution to g-2 overpredicts muon trident cross section by a factor of ~ 8.

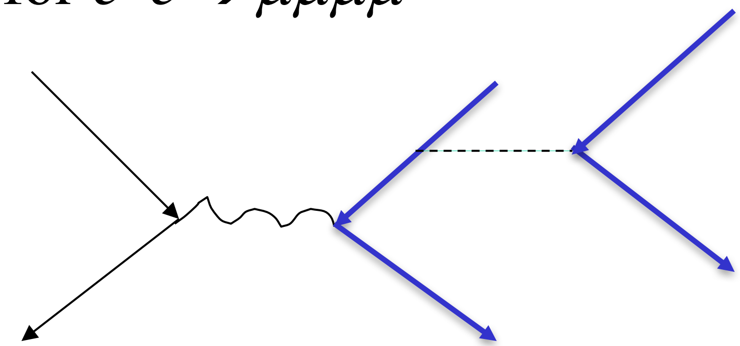
Can it be improved in the future at DUNE (O(50) events /yr) ???

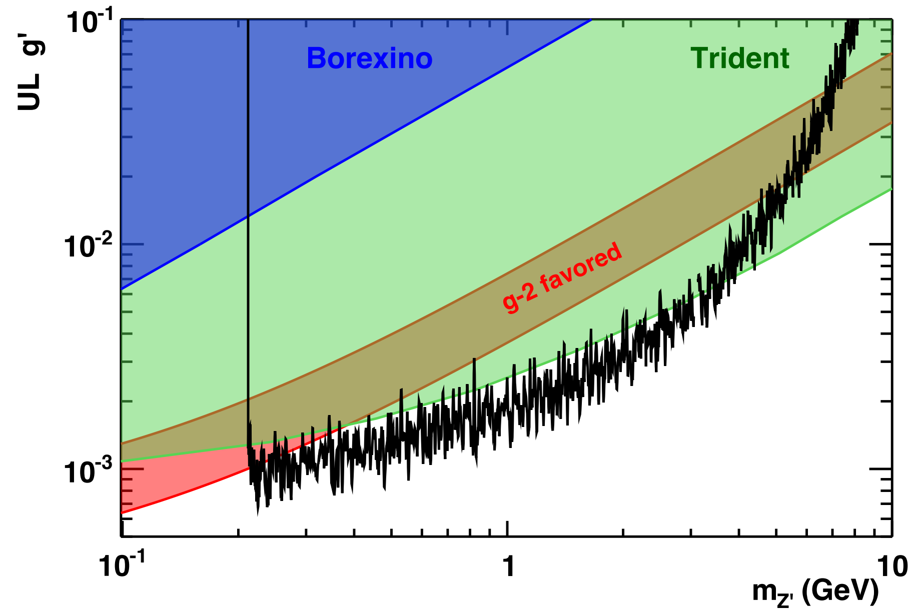
Altmannshofer, Gori, MP, Yavin, 2014

(There are also variations of the simplest model Altmannshofer et al., C.Y. Chen et al, that can correct g-2 in a wider range of masses)

Recent constraint from BaBar on L_μ-L_τ

Babar + B. Shuve have looked for $e^+e^- \rightarrow \mu\mu\mu\mu$

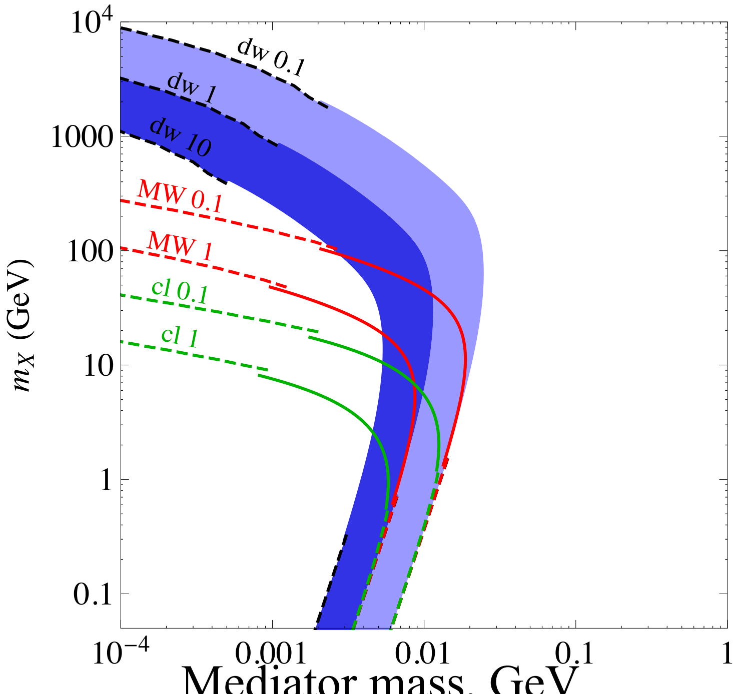




- Absence of peaks in invariant mass improves constraints in 210 MeV – 4 GeV window.
- Below 2muon threshold, L_μ-L_τ model is the most difficult: Z'$\rightarrow$neutrinos. NA64 with muons, or LDMX?

DM with a hint on self-interaction?

- Comparison of observations and simulations seem to point to problems with dwarf galaxy substructures (also known as "too-big-to-fail" problem).
- It may or may not be a real problem (it is an astrophycist-dependent problem).
- Self-scattering due to a dark force, at 1 cm^2/g level, seems to help, as it flattens out central spikes of DM (which is a reported problem).



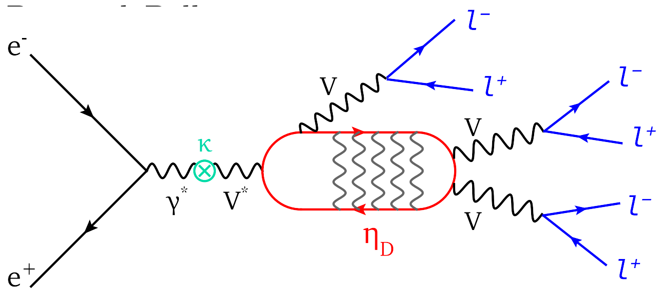
Example of parameter space that creates a core and solves the problem (from Tulin, Yu, Zurek) for $\alpha_d = 0.1$

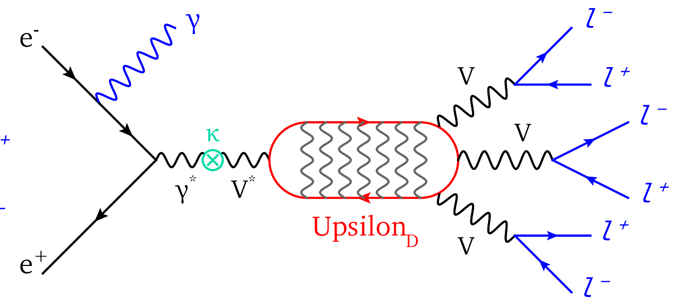
Some of the parameter space is within reach of B-factories.

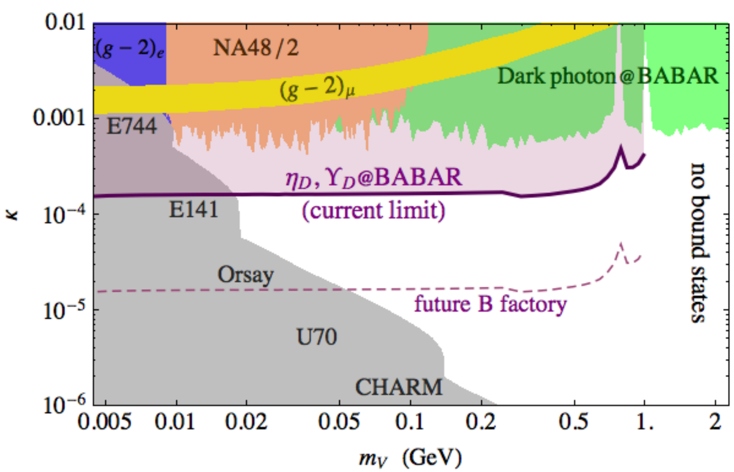
Dark matter bound states at B-factories

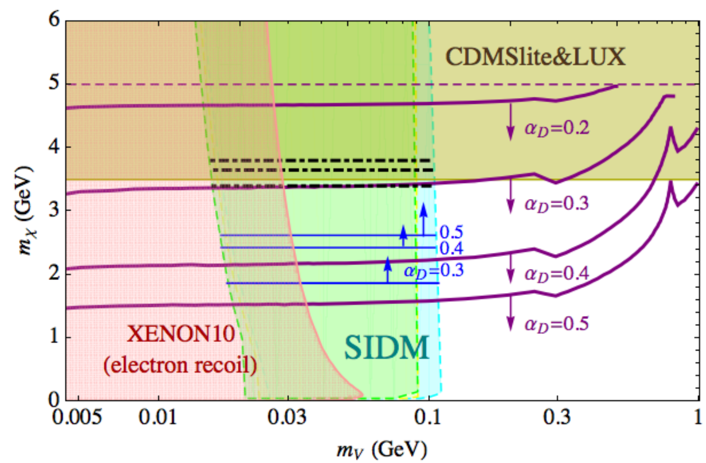
- If $\alpha_d > 0.2$, the sub-5 GeV Dark matter *can increase the sensitivity to dark force* via production of "dark Upsilon" that decays producing multiple charged particles

$\Upsilon_D \rightarrow 3V \rightarrow 3(l^+l^-)\ (l = e, \mu, \pi)$









3 pairs of charged particles appear "for free" once Upsilon_dark is produced. This is limited by previous searches of "dark Higgsstrahlung" by BaBar and Belle. An, Echenard, MP, Zhang, PRL, 2016

Vector mediators coupled to non-conserved currents

- Naïve model for the charge radius anomaly

$$\mathcal{L}_{\rm int} = -V_\nu \left[\kappa J^{\rm em}_\nu - \bar\psi_\mu (g_V\gamma_\nu + g_A\gamma_\nu\gamma_5)\psi_\mu\right]$$
$$= -V_\nu \left[e\kappa\bar\psi_p\gamma_\nu\psi_p - e\kappa\bar\psi_e\gamma_\nu\psi_e\right.$$
$$\left.-\bar\psi_\mu((e\kappa+g_V)\gamma_\nu + g_A\gamma_\nu\gamma_5)\psi_\mu + ...\right],$$

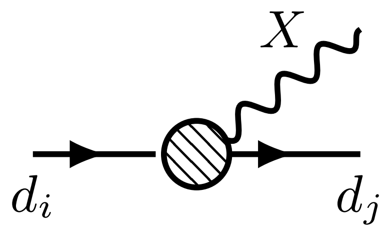
- New vector coupling to muons and no coupling to neutrinos will lead to breaking of SU(2)×U(1) and lead to a troublesome (Energy/m_V) behavior of amplitudes. For example, in the decay of W-bosons (which is normally *not* a precision measurement!) we have a huge enhancement of the three-body rate.

$$\Gamma\left(W \to \mu\nu V\right) = \frac{g_V^2}{512\sqrt{2}\pi^3}\frac{G_F m_W^5}{m_V^2}$$
$$= 1.74~\mathrm{GeV}\left(\frac{g_V}{10^{-2}}\right)^2\left(\frac{10~\mathrm{MeV}}{m_V}\right)^2$$

- At even higher energies one will end up with strong coupling behavior, non-unitarity etc.

Non-conserved currents will be sensitive to high-mass scales through loops

- Another well know example are enhancement of non-conserved currents inside loops leading to FCNC. The key – access to momenta ~ m_W and m_t.



- For a fully conserved current, like couplings of dark photon,

Amplitude ~ $G_F\, m^2_{meson}$

For a non-conserved current,

Amplitude ~ $G_F\, m^2_{top}$

Application to an axial-vector coupling leads to

$$\frac{g_{\mathrm{axial}}}{10^{-6}} \times \left(\frac{17\ \mathrm{MeV}}{m_X}\right) < 0.1 - 1$$

Gauge symmetry broken by anomalies

- Consider $L = g_X X_\mu \, \Sigma (\bar{q} \, \gamma_\mu \, q)$ which is the coupling of a vector particle "X" to a baryon current. If we stay at the tree level, then the current is exactly conserved, and nothing would be wrong with such a $\mathrm{U(1)}_{\mathrm{baryon}}$.

- However [and famously], this symmetry is broken by the triangle chiral anomaly (Adler++):

$$\partial^\mu J_\mu^{\mathrm{baryon}} = \frac{\mathcal{A}}{16\pi^2} \left(g^2 W^a_{\mu\nu} (\tilde{W}^a)^{\mu\nu} - g'^2 B_{\mu\nu} \tilde{B}^{\mu\nu} \right)$$

- The vector X cannot stay massless, and a strong interaction will develop at scales $\lesssim \frac{4\pi m_X}{g_X} / \left(\frac{3g^2}{16\pi^2} \right)$ (Preskill) unless such theory is UV completed, and anomaly is cancelled in full theory

Cancellation of anomalies for a baryonic U(1)

Anomaly of the baryon current can be cancelled by a new sector that is *heavier* than the SM. There are two main ways of doing it (and possibilities in between)

Option 1

Anomaly is cancelled by a non-chiral sector charged under SM gauge group. “Vector-like fermions”

m_{anomalon} stays finite as SM vev → 0

Chiral under $U(1)_X$, get their masses due to v_X. This is a preferred option so far.

Option 2

Anomaly is cancelled by new fermions that are SM-like. Their mass is due to SM vev.

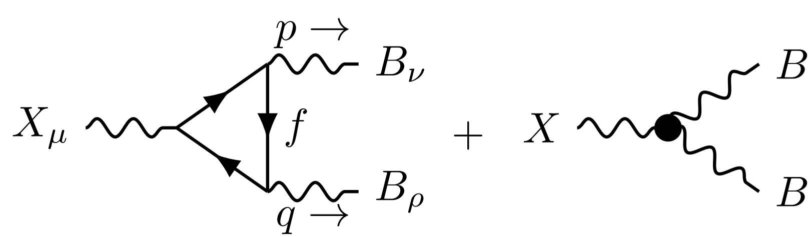
Big implications to EW precision, huge modifications to Higgs physics. Are these models still alive?

Wess-Zumino term and low-energy EFT

Combining the anomalous contributions and WZ term, we get full longitudinal X amplitude for such theory. Its form is independent on exact composition of the sector that cancels anomaly – only on the fact that anomaly-cancelling sector preserves SM gauge invariance.

$$-(p+q)_\mu \mathcal{M}^{\mu\nu\rho} = \frac{\mathcal{A}_{BBX}}{4\pi^2} g_X g'^2 \epsilon^{\nu\rho\lambda\sigma} p_\lambda q_\sigma \,,$$
$$p_\nu \mathcal{M}^{\mu\nu\rho} = q_\rho \mathcal{M}^{\mu\nu\rho} = 0 \qquad (5)$$

$$\mathcal{M}^{\mu\nu\rho} \equiv \sum_f$$



One can confirm this by repeating the calculation with UV complete theory, where the result ($M^{\mu\nu\rho}$) emerges from the dependence of triangular diagrams on masses of anomaly-cancelling fermions.

Non-decoupling of the longitudinal mode

- In equivalent language, one can use a Stuckelberg substitution, $X_\mu \rightarrow \partial_\mu\varphi \times (g_X/m_X)$.

Previously obtained results are equivalent to the pseudoscalar coupled to SM gauge bosons in the following way:

$$
\begin{aligned}
&\frac{\mathcal{A}}{16\pi^2}\frac{g_X\varphi}{m_X}(g^2 W^a\tilde{W}^a - g'^2 B\tilde{B}) = \\
&\frac{\mathcal{A}}{16\pi^2}\frac{g_X\varphi}{m_X}\Big(g^2(W^+\tilde{W}^- + W^-\tilde{W}^+) \\
&\quad +gg'(\cot\theta_w - \tan\theta_w)Z\tilde{Z} + 2gg'Z\tilde{F}) \\
&\quad -ieg^2\tilde{F}^{\mu\nu}(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) + \ldots\Big)
\end{aligned}
$$

There is no coupling to γγ, but there are couplings to WW and Zγ, which will result in serious phenomenological consequences

Z → γ X decay

- At one loop, Z boson will decay to γ X final state, and the emission of longitudinal scalar is m_Z^2/m_X^2 enhanced. (A=3/2 for the baryonic X).

$$\Gamma_{Z\to\gamma X} \simeq \frac{\mathcal{A}^2}{384\pi^5} g_X^2 g^2 g'^2 \frac{m_Z^3}{m_X^2}$$

This corresponds to

$$\frac{\Gamma_{Z\to\gamma X}}{\Gamma_Z} \simeq 10^{-7}\mathcal{A}^2 \left(\frac{\mathrm{TeV}}{m_X/g_X}\right)^2$$

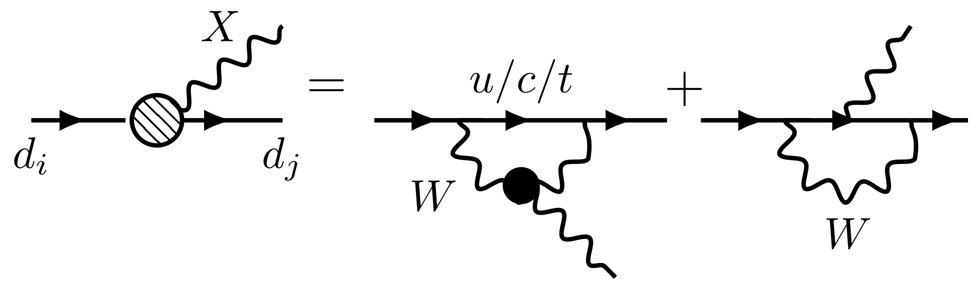
- One can use previous LEP measurements for Z→ gamma + invisible, as well as Tevatron Z→ gamma + pi0.

- LHC will have huge sensitivity through studies of $l^- l^+ \gamma$ final states.

FCNC amplitudes at two loop

- Anomalous [two-loop] contributions to FCNC amplitudes are important

$$\mathcal{L} \supset g_{X d_i d_j} X_\mu \bar{d}_j \gamma^\mu \mathcal{P}_L d_i + \text{h.c.} + \ldots$$



$$g_{X d_i d_j} = -\frac{3 g^4 \mathcal{A}}{(16\pi^2)^2} g_X \sum_{\alpha \in \{u,c,t\}} V_{\alpha i} V^*_{\alpha j} F\left(\frac{m_\alpha^2}{m_W^2}\right)$$

$$\simeq -\frac{3 g^4 \mathcal{A}}{(16\pi^2)^2} g_X V_{ti} V^*_{tj} F\left(\frac{m_t^2}{m_W^2}\right) + \ldots ,$$

where

$$F(x) \equiv \frac{x(1 + x(\log x - 1))}{(1-x)^2} \simeq x \quad (\text{for } x \ll 1)$$

- As anticipated, m^2_{top} enhancement is there.

Comparison of one- and two-loop effects

- I remind that 1-loop level the current is conserved, and so only derivative type operators, (b-s current)$_\mu \partial_\mu X_{\mu\nu}$ etc, are induced (in the context of dark photon and 1-loop baryonic vector they were calculated in MP 2008, Batell et al 2014). There is no enhancement (only a suppression) of longitudinal X amplitude at one loop.

- For the B→KX decay, for example,

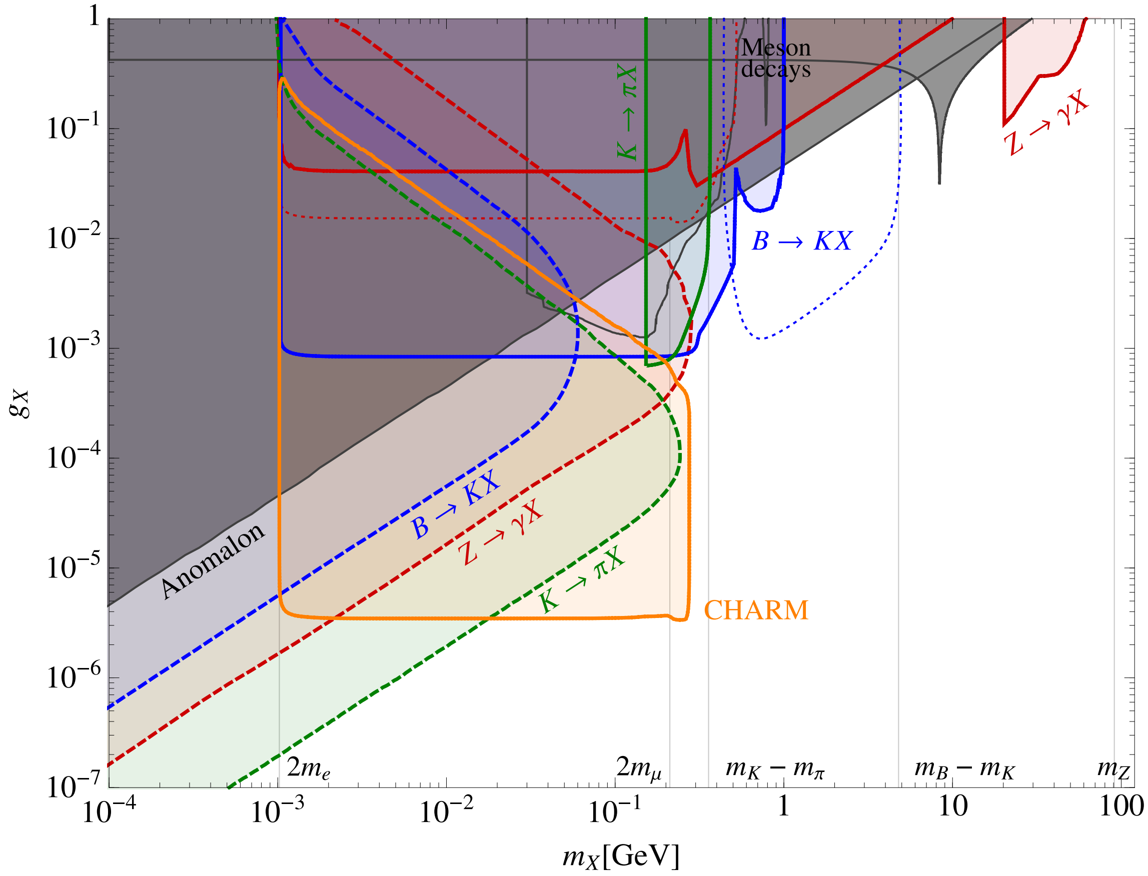
$$\mathcal{M}^{2-\mathrm{loop}}/\mathcal{M}^{1-\mathrm{loop}} \propto g^2/(16\pi^2) \times (m_t/m_X)^2$$

This is >> 1. Neglecting one loop altogether, we calculate B and K decays to πX, KX, K^*X etc final states.

Exact signatures depend on what m_X is. Low mass X decays through radiatively induced kinetic mixing. It also decays to $\pi^0\gamma$ and 3π final states.

Resulting constraints on gauged baryon number

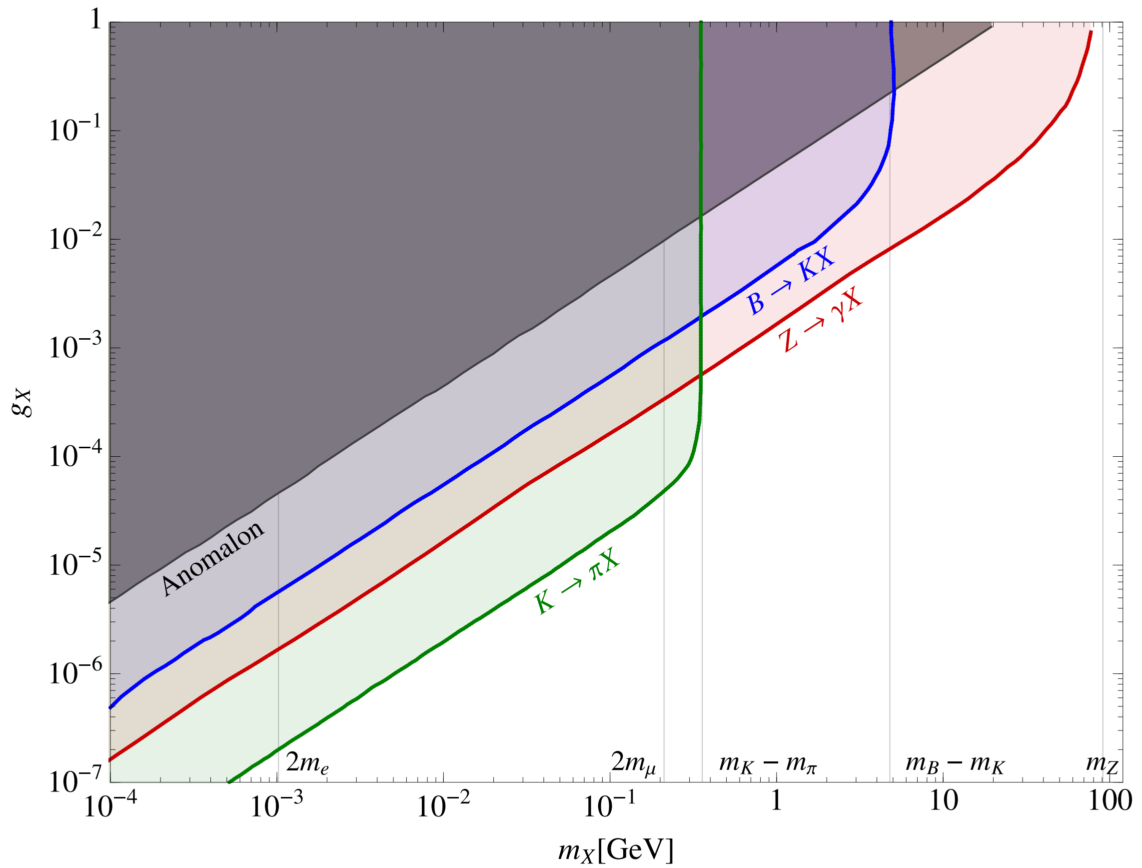
- No additional X→ invisible channels.



- Constraints can be improved via additional studies at LHC, B-factories, and new experiments like SHiP.

Resulting constraints on gauged baryon number

- With additional X→ invisible channels.

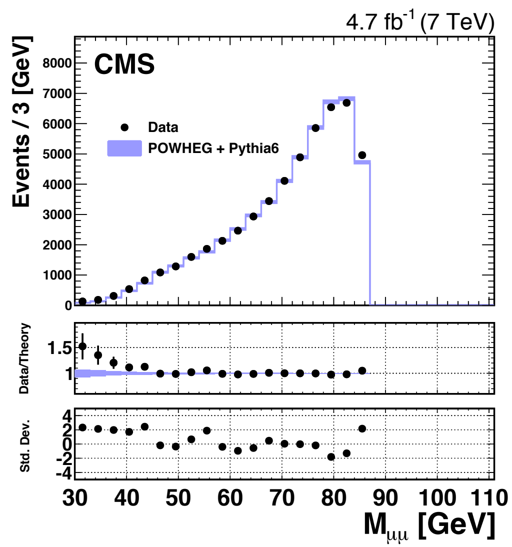


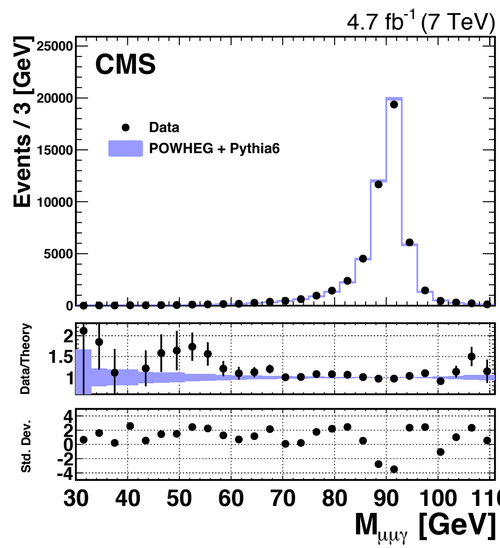
- The baryonic force in this case is limited to be below weak interaction strength, $(g_X^2/m_X^2) < G_F$.

Future searches, LHC

- To be provocative, I'd say that the LHC may quickly become "intensity frontier machine", as energy will remain the same, while dataset will be increased by at least ×10, and may be almost 100.
- Billions of weak gauge bosons will be observed. Time to do the rare decays of the Z.
- 7 TeV CMS analysis of

Z → mu mu gamma





- Channels such as lepton pairs + gamma, jets + gamma, exclusive hadronic states (e.g. 3π + gamma) will have impact on Z→ γ X final state constraints.

Sensitivity to a light Higgs-mixed scalar

Example: new particle admixed with a Higgs.

$$\mathcal{L}_{\text{Higgs portal}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - ASH^\dagger H$$

After (Higgs Field = vev + fluctuation h), the actual Higgs boson mixes with S.

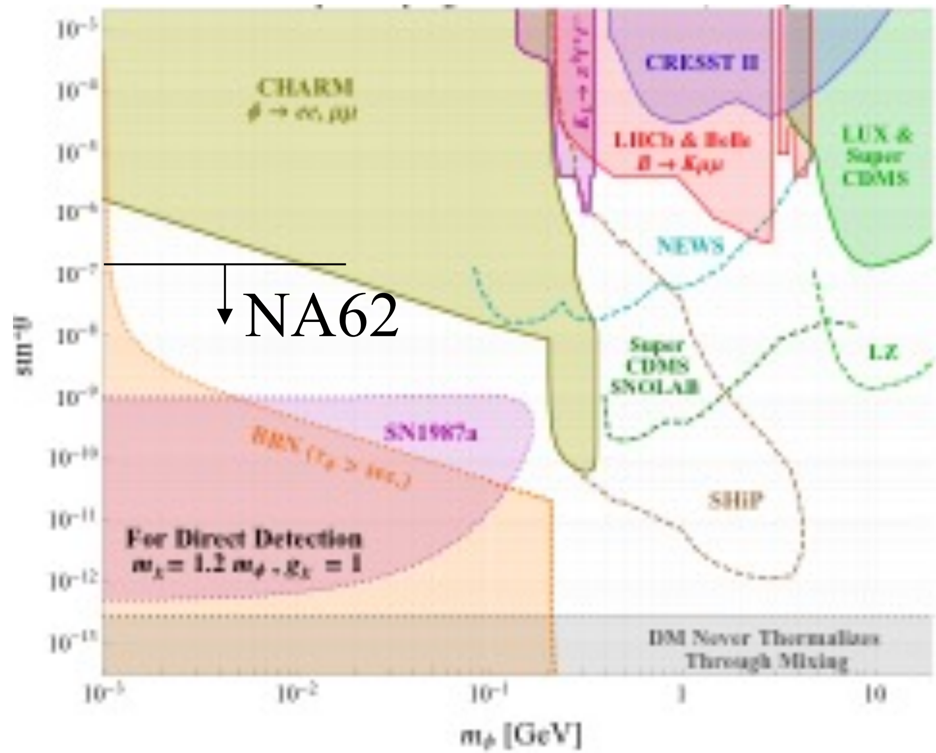
Mixing angle: $$\theta = \frac{Av}{m_h^2}$$

The model is technically natural as long as A not much larger than m_S

Low energy: new particle with Higgs couplings multiplied by θ

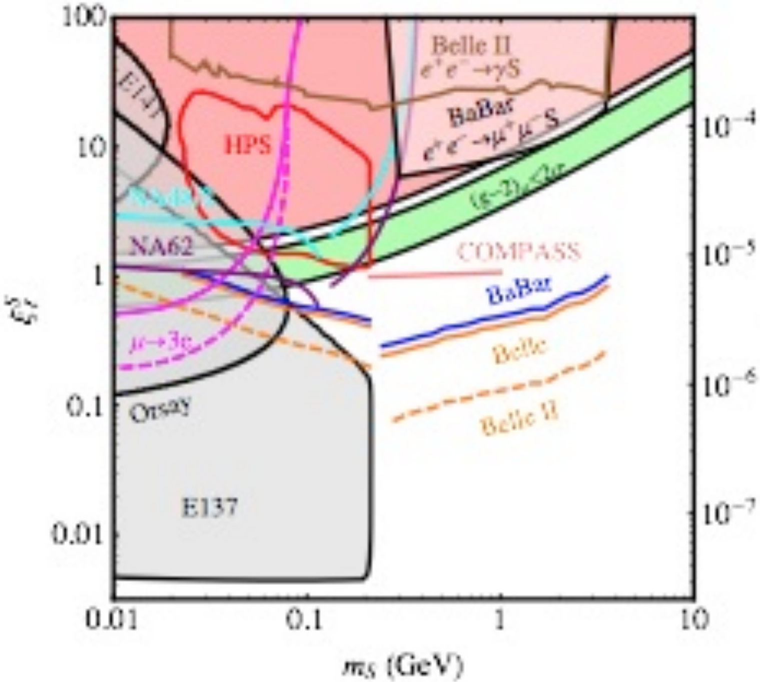
New effects in Kaon and B-decays. Constraint: (mixing angle)^2 < 2×10^{-7}, in the technically natural range of mixings. Above the di-muon threshold the best constraints come from bump hunt, B→ $K^{(*)}\mu\mu$ performed by the LHCb.

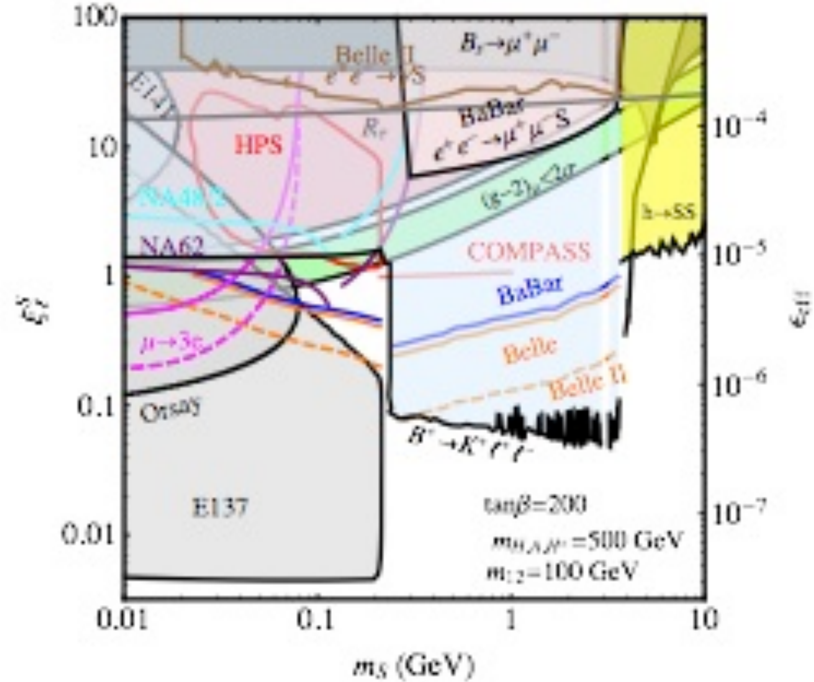
Constraints on a light Higgs-mixed scalar



Compilation of constraints from G. Krnjaic 2015.

- NA62 and SHiP will improve sensitivity





$$\kappa_{\rm eff} \equiv m_e \xi_{\ell\ell}/ev$$

Scalar that interacts mostly with leptons. One can still "fix" the g-2 discrepancy with such scalar.

Batell, Lange, McKeen, Pospelov, Ritz, *2016*.

B-factory signal from the associated $\tau^+\tau^- + Scalar \rightarrow \tau^+\tau^-\ \mu^+\mu^-$ production will test the model below $m_S \sim 3.5$GeV. Kaon decay studies are also warranted ($K \rightarrow \mu\nu\ \ l^+l^-$ including low m_{ee})

Conclusions

- Light New Physics (not-so-large masses, tiny couplings) is a generic possibility. Some models (dark photon, scalar coupled Higgs portal) are quite natural, and *helpful* in explaining a number of puzzles in particle physics and astrophysics.

- Many searches have resulted in tight constraints on new vector particles, in particular ruling out dark photons as a "fix" for the g-2 discrepancy.

- Strong constraints on vectors that couple to anomalous currents follow from the Z decay and FCNC with K and B mesons, due to (weak scale / $m_X)^2$ enhancement.

- Dark scalars mixed through SM Higgs are best constrained by B and K decay studies. "Leptonic" scalar better be studied using τ.