Light New Physics
(selective review)

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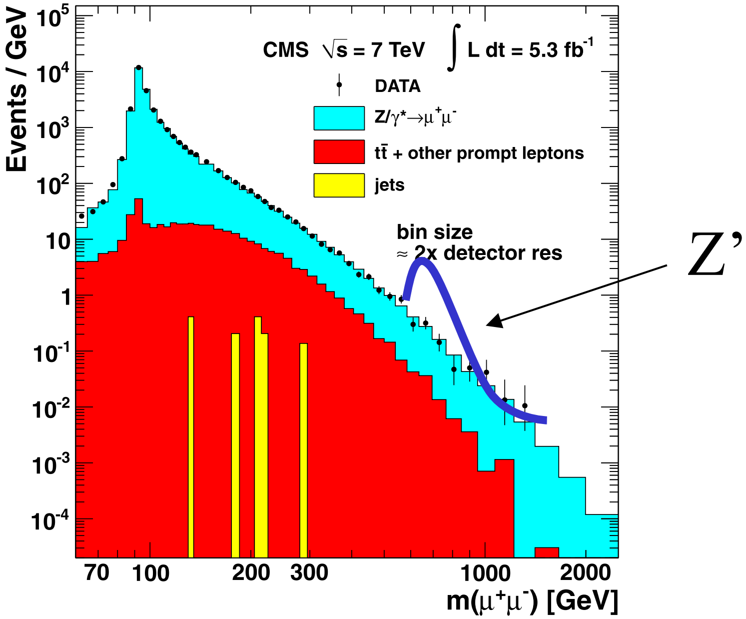
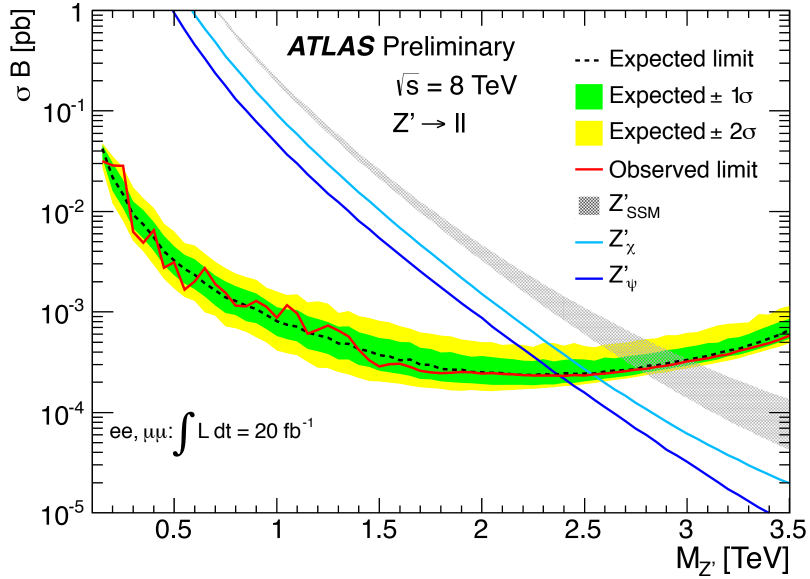
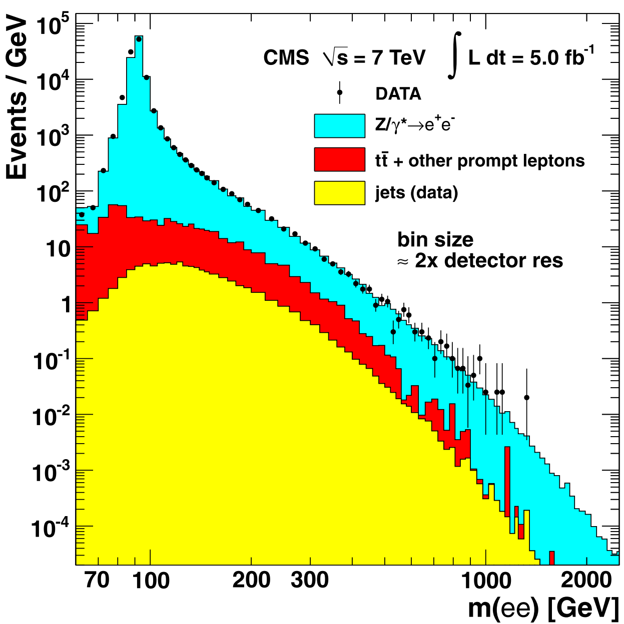
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Higgs, but no New Physics at high energy thus far (?!)







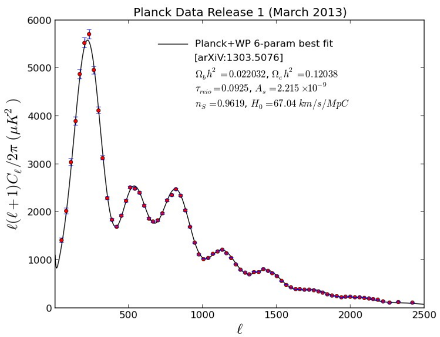
No hints for any kind of new physics. Strong constraints on SUSY, extra dimensions, technicolor resonances, etc.

Constraints on new *Z'* bosons push new gauge groups into multi-TeV territory.

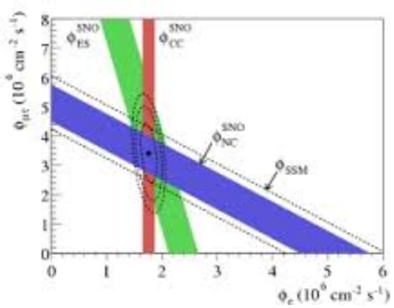
(*This meeting, "sequential" Z' is limited to **4 TeV or heavier** at the LHC*)

Clues for new physics

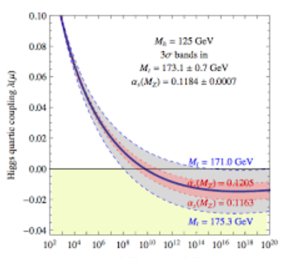
1. *Precision cosmology:* 6 parameter model (Λ-CDM) correctly describes statistics of 10^6 CMB patches. Existence of dark matter and dark energy. Strong evidence for inflation.



2. *Neutrino masses and mixing:* Give us a clue [perhaps] that there are new matter fields beyond SM. Some of them are not charged under SM.



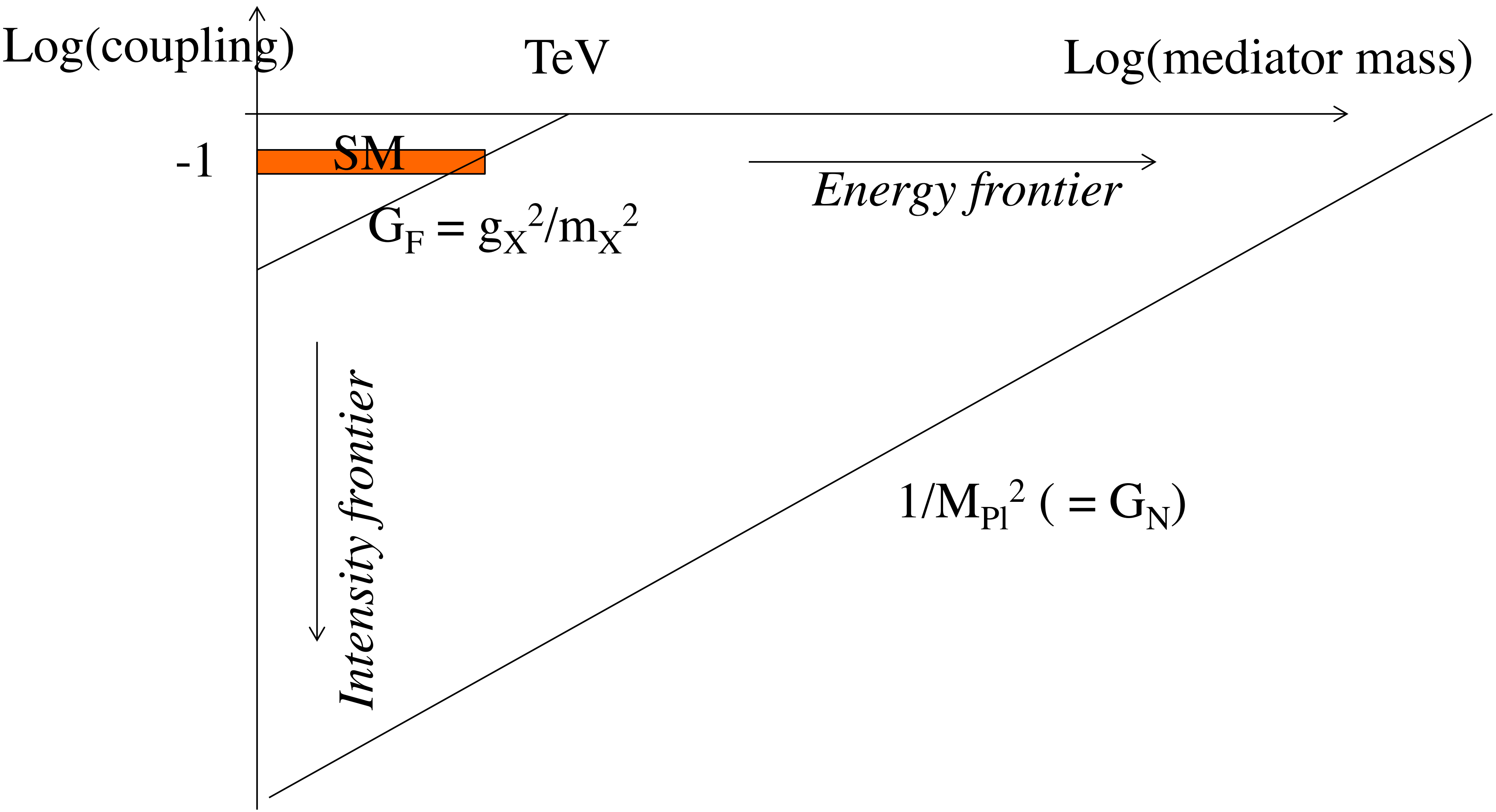
3. *Theoretical puzzles:* Strong CP problem, vacuum stability, hints on unification, smallness of m_h relative to highest scales (GUT, M_{Planck})



4. *"Anomalous results":* muon g-2, "proton radius puzzle", "B-physics anomalies", small scale CDM problems…

Coupling vs mass scale

In 2012-2013 LHC experiments discovered a new particle (Higgs boson) and a new force (Yukawa force). What do we know about forces in nature ?



Do not assume new physics is heavy – put it back in the effective Lagrangian

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

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

……….

Owing to small couplings, such particles are called "dark sector"

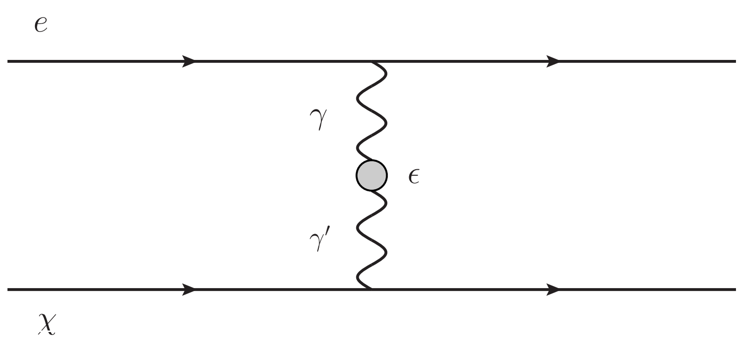
"Simplified model" for dark sector

(Okun', Holdom,…)

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

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

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



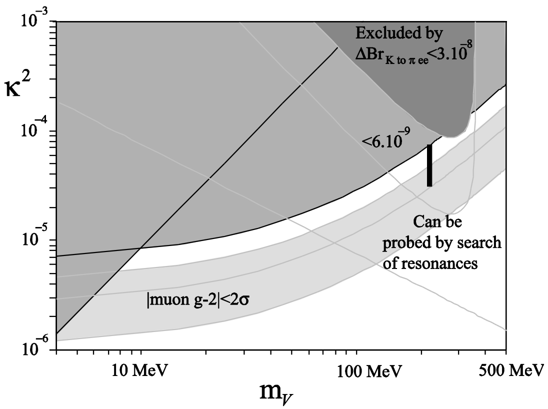
A – photon, *A'* – "dark photon", ψ - an electron, χ - a DM state, *g'* – a "dark" charge

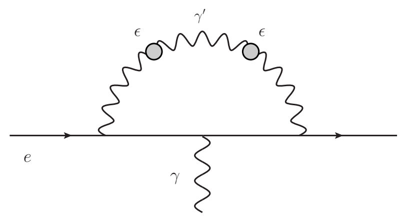
- "Effective" charge of the "dark sector" particle χ is Q = e × ε (if momentum scale q > m_V). At q < m_V one can say that particle χ has a non-vanishing EM charge radius, $r_\chi^2 \simeq 6\epsilon m_V^{-2}$.
- Dark photon can "communicate" interaction between SM and dark matter. *It represents a simple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

Some speculative motivations for new states/new forces below GeV

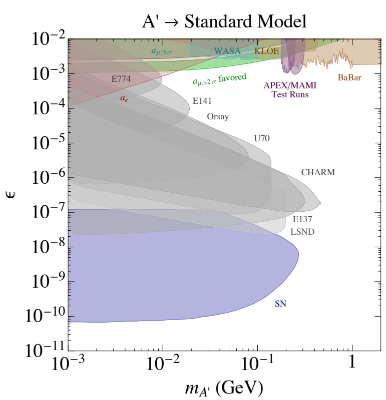
1. A 1.5 decade old discrepancy of the muon g-2.
2. Discrepancy of the muonic hydrogen Lamb shift.
3. Decade old intriguing results in astrophysics. 511 keV line, PAMELA (+Fermi, AMS2) positron rise.
4. Too-big-to-fail etc problems of CDM + solution via a DM self-interaction (re-scattering) via a light mediator.
5. Other motivations (most recently, a claim of new particles in the decay of the 18.15 MeV state in ^{8}Be).
6. Lowest bin R_{K*} anomaly?

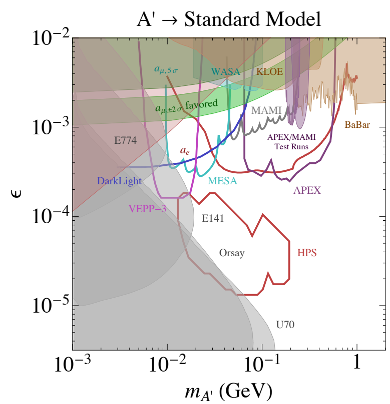
Muon g-2 and search for dark photons



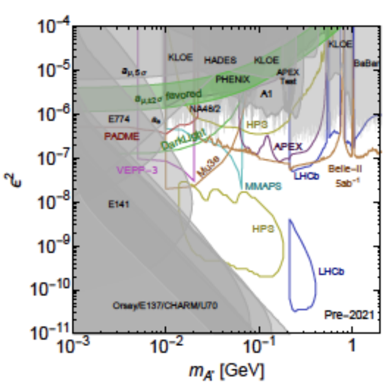


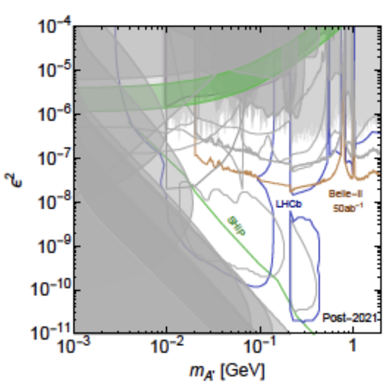
Dark photon with kinetic mixing ~ 10^{-3} is the simplest model that can account for anomalous Δa_μ~3 10^{-9}, MP, 2008





Search for dark photons (A'→ e^+e^-) has become an important part of the intensity frontier program, Snowmass exercise, Minneapolis, 2013





By 2018, there is a large community in place ("Cosmic Vision" summary, 100s of authors, 2017), where the search for dark photon is one of the priorities.

Dark sectors may contain different types of dark matter

At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

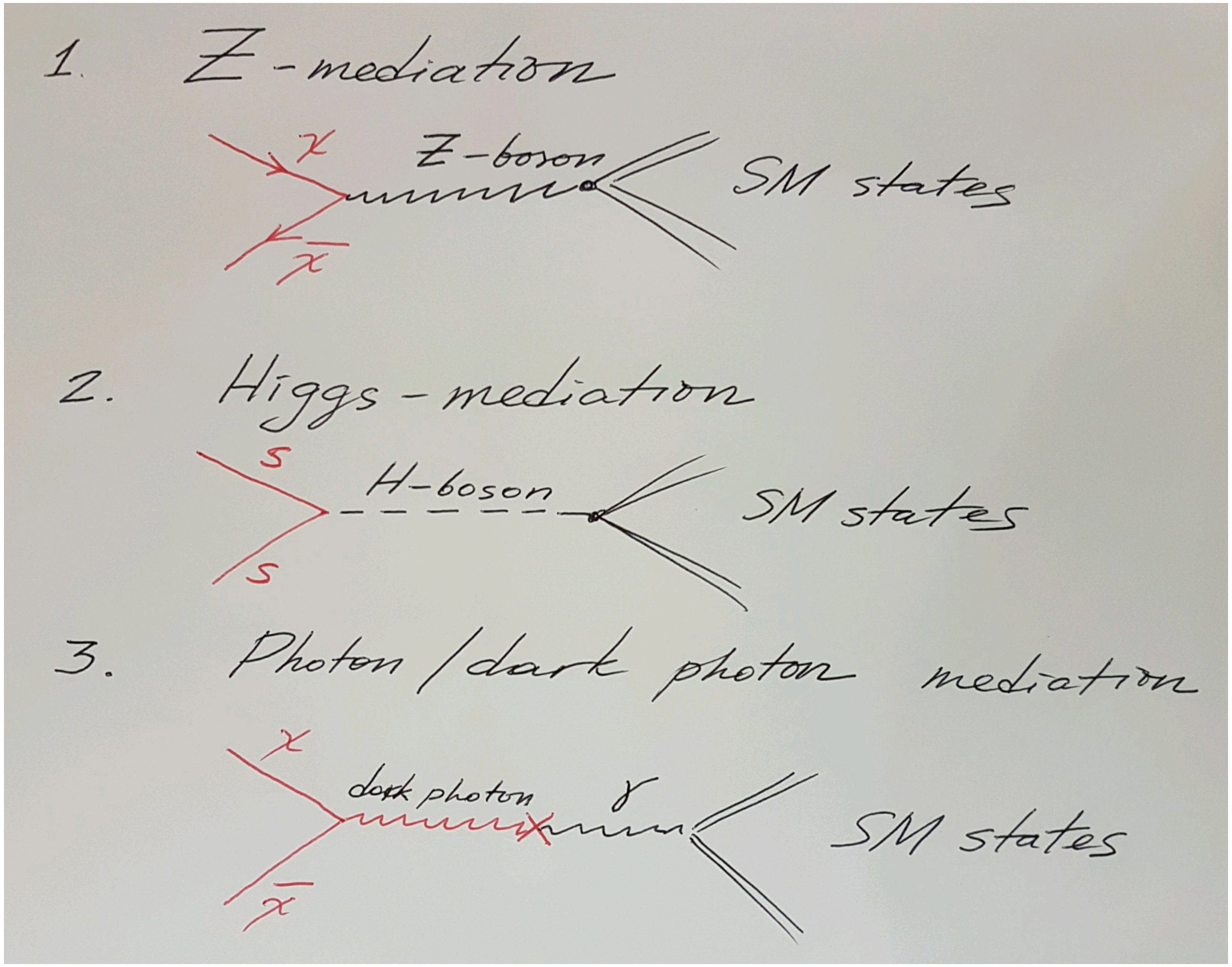
Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_\gamma = 1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM --> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**. Asymmetric DM is also in this category.

Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other "feeble" creatures – call them **superweakly interacting MPs**]

Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_\gamma \sim 10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

Mass ? Case 1 and 2, m_{DM} > keV, *Case 3 – there is no bottom (down to 10^{-21} eV)*

Examples of DM-SM mediation



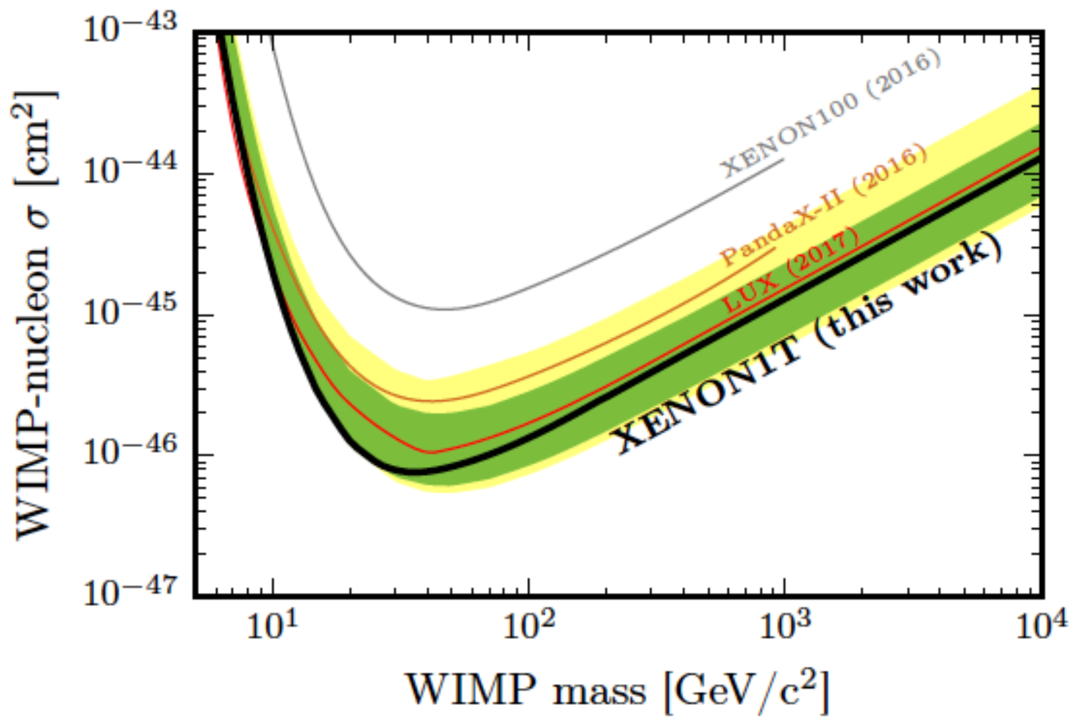
Very economical extensions of the SM.

DM particles themselves + may be extra mediator force. Can be very predictive.

If dark matter annihilation is mediated by weak scale particles, the mass of dark matter is confined to ~ 10 –to-10000 GeV (Lee, Weinberg)

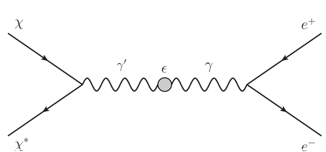
Search for WIMP-nucleus scattering
(latest LUX, XENON 1T and PANDA-X results)

What about MeV mass range ?



- *Possibility of light mediators opens up parameter space below M_{WIMP} < GeV, below a lower end of the so-called Lee-Weinberg window.*

$$\sigma(v/c) \propto \begin{cases} G_F^2 m_\chi^2 & \text{for} \quad m_\chi \ll m_W, \\ 1/m_\chi^2 & \text{for} \quad m_\chi \gg m_W. \end{cases} \quad \Longrightarrow \quad \text{few GeV} < m_\chi < \text{few TeV}$$



$$\sigma_{\text{annih}}(v/c) \simeq \frac{8\pi\alpha\alpha_D\epsilon^2(m_\chi^2 + 2m_e^2)v^2}{3(m_{A'}^2 - 4m_\chi^2)^2}\sqrt{1 - m_e^2/m_\chi^2}.$$

"Simplified models" for light DM

some examples

- Scalar dark matter talking to the SM via a "dark photon" (variants: L_{mu}-L_{tau} etc gauge bosons). With $2m_{DM} < m_{mediator}$.

$$\mathcal{L} = |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4} V_{\mu\nu}^2 + \frac{1}{2} m_V^2 V_\mu^2 - \frac{\epsilon}{2} V_{\mu\nu} F_{\mu\nu}$$

- Fermionic dark matter talking to the SM via a "dark scalar" that mixes with the Higgs. With $m_{DM} > m_{mediator}$.

$$\mathcal{L} = \overline{\chi}(i\partial_\mu \gamma_\mu - m_\chi)\chi + \lambda \overline{\chi}\chi S + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - AS(H^\dagger H)$$

After EW symmetry breaking *S* ("dark Higgs") mixes with physical *h*, and can be light and weakly coupled provided that coupling A is small.

Take away point: these models have both stable (DM) and unstable (mediator) light weakly coupled particles.

How to look for light WIMP DM and light *mediator* particles ?

1. Produce light dark matter/mediator in a beam dump experiment, and detect its subsequent scattering/decay in a large [neutrino] detector

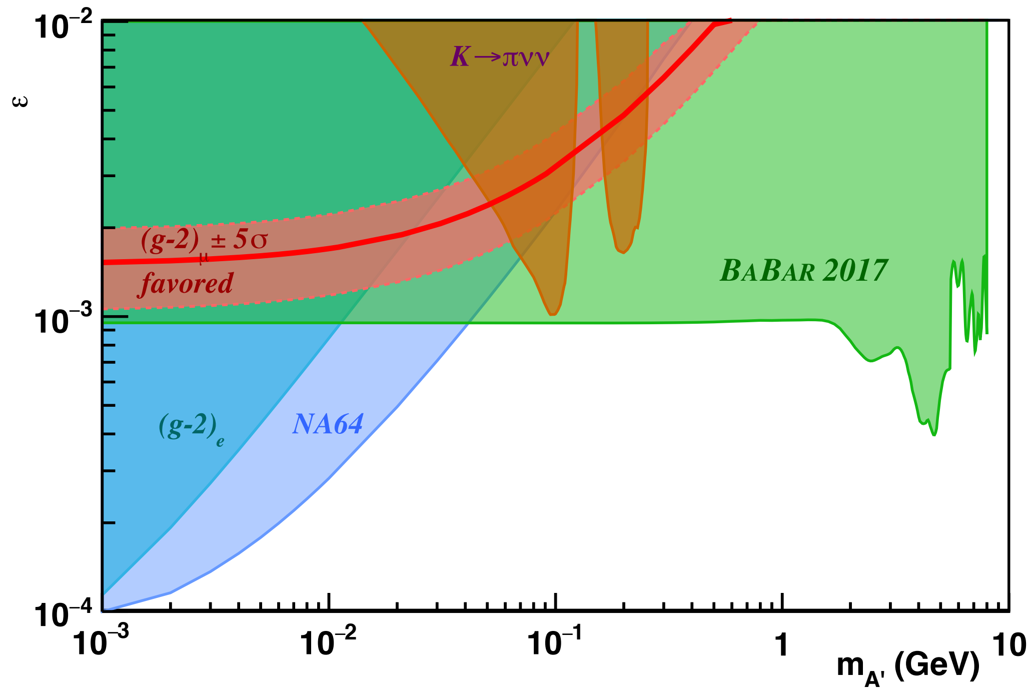
2. Detect missing energy associated with DM produced in collisions of ordinary particles

3. Detect scattering of light ambient DM on electrons, and keep lowering the thresholds in energy deposition.

All three strategies are being actively worked on, and pursued by several ongoing and planned experiments.

Constraints on invisibly decaying “dark photons”

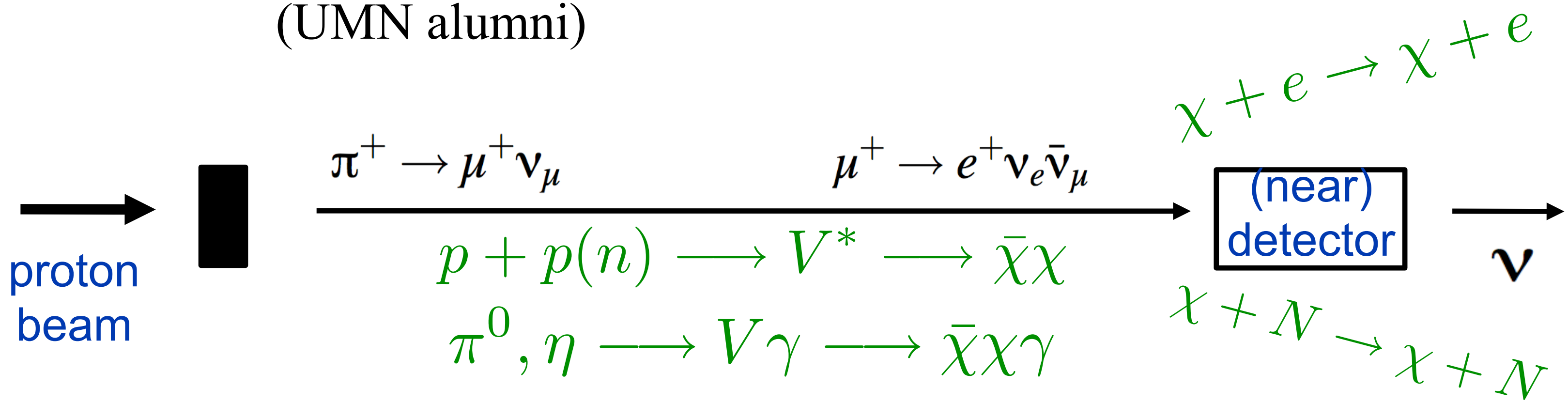
If dark photon decays invisibly, for example to a pair of DM particles, the search for dark photon is the search for “anomalous energy loss”, such $e^+e^- \rightarrow \gamma + A' \rightarrow \gamma + \chi\chi$



- Complementary results from NA64, BaBar and Kaon decays
- Covers all of the dark photon parameter space, decaying invisibly, consistent with alleviating the muon g-2 discrepancy

Fixed target probes - Neutrino Beams

Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM
(UMN alumni)

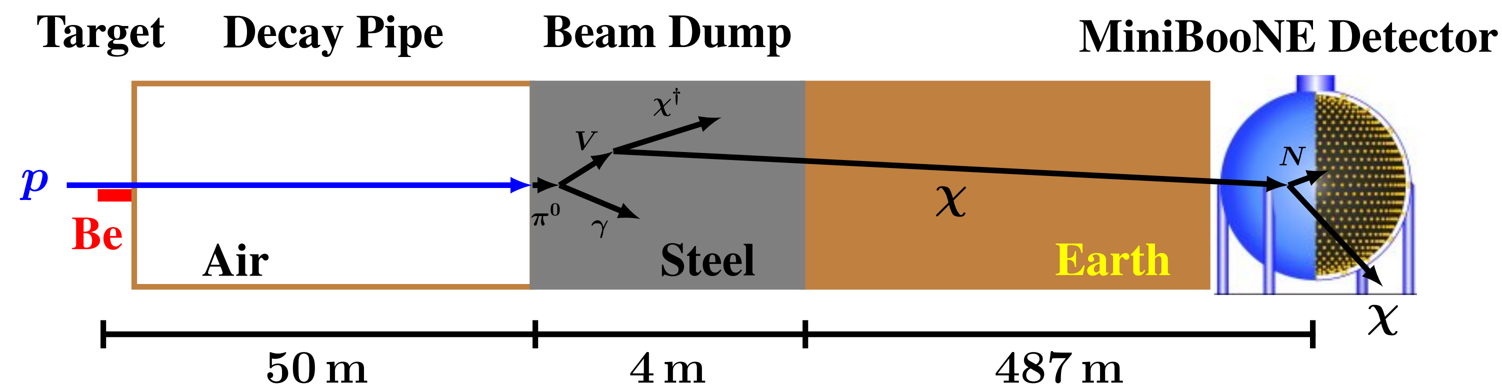


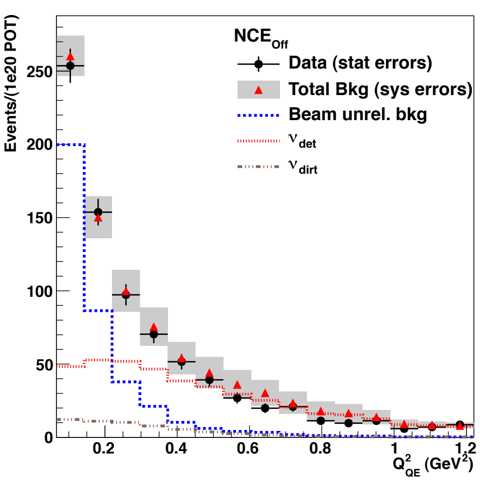
We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

T2K	MINOS	MiniBooNE
30 GeV protons (➠ ~5x10^{21} POT)	120 GeV protons 10^{21} POT	8.9 GeV protons 10^{21} POT
280m to on- and off-axis detectors	1km to (~27ton) segmented detector	540m to (~650ton) mineral oil detector

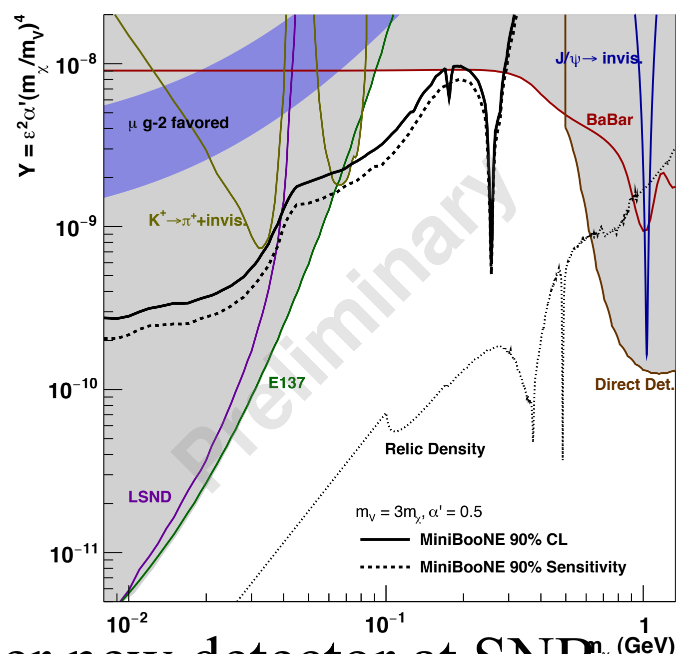
MiniBooNE search for light DM

arXiv:1702.02688, PRL 2017



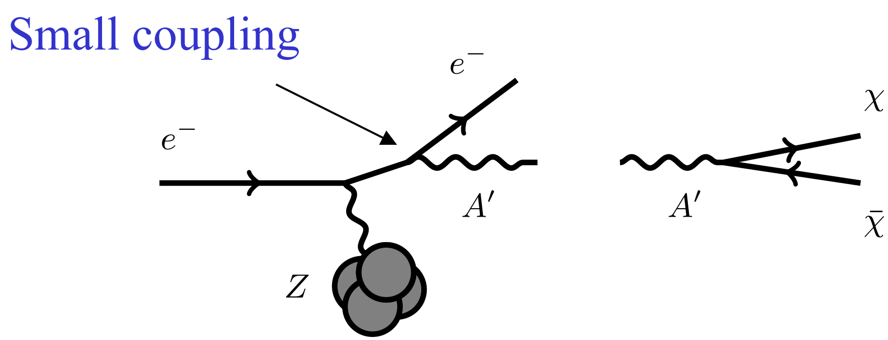


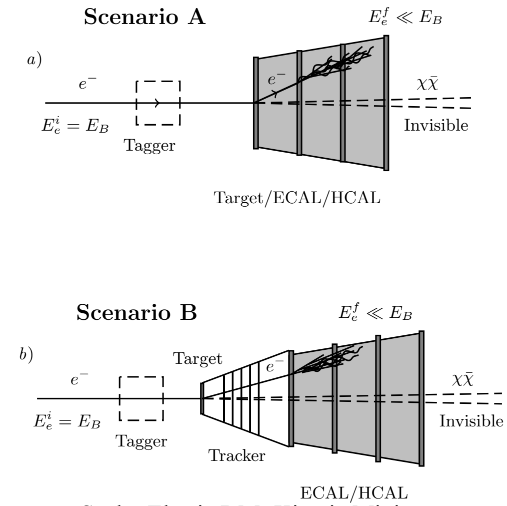
	#events	uncertainty
BUB	697	
ν_{det} bkg	775	
ν_{dirt} bkg	107	
Total Bkg	1579	14.3% (pred. sys.)
Data	1465	2.6% (stat.)

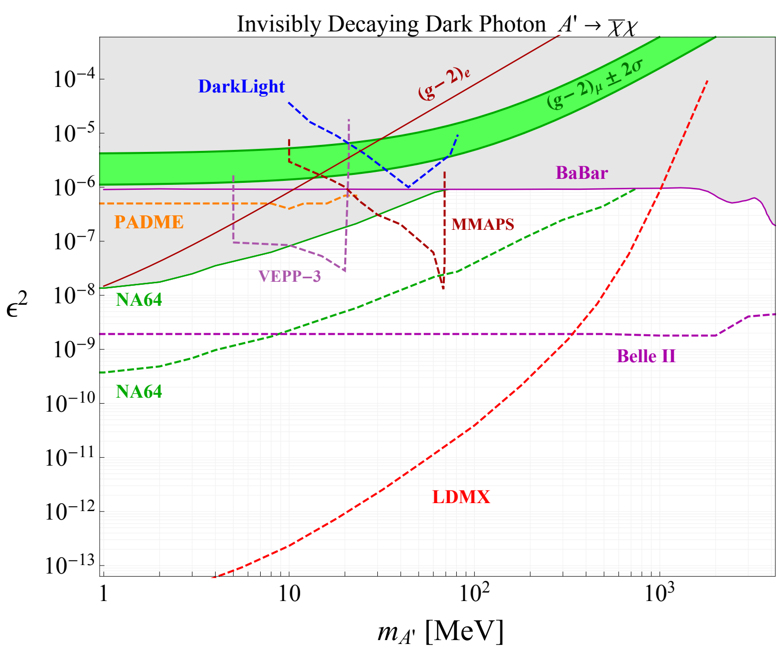


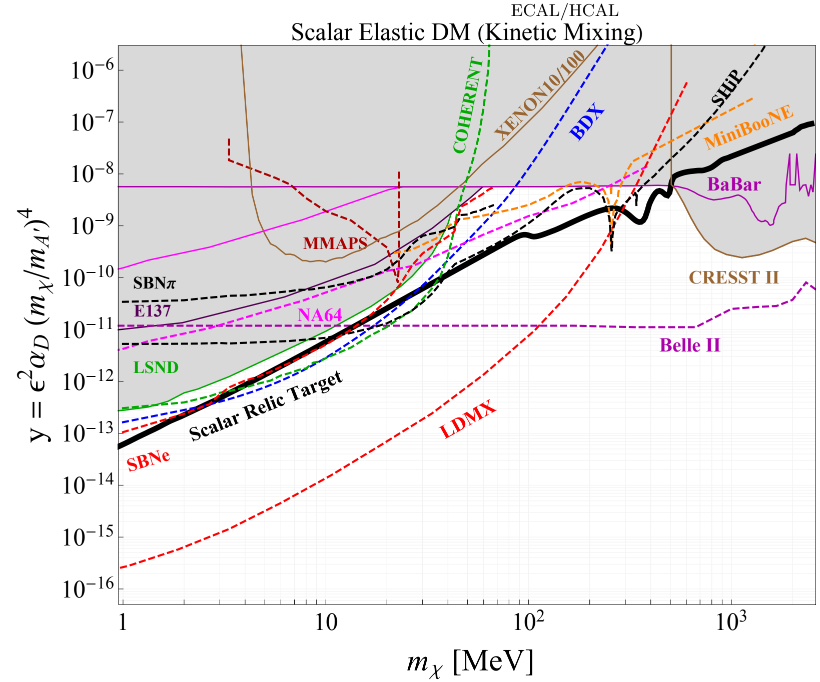
Subject to future improvement with much closer new detector at SNB

New project in the US: LDMX







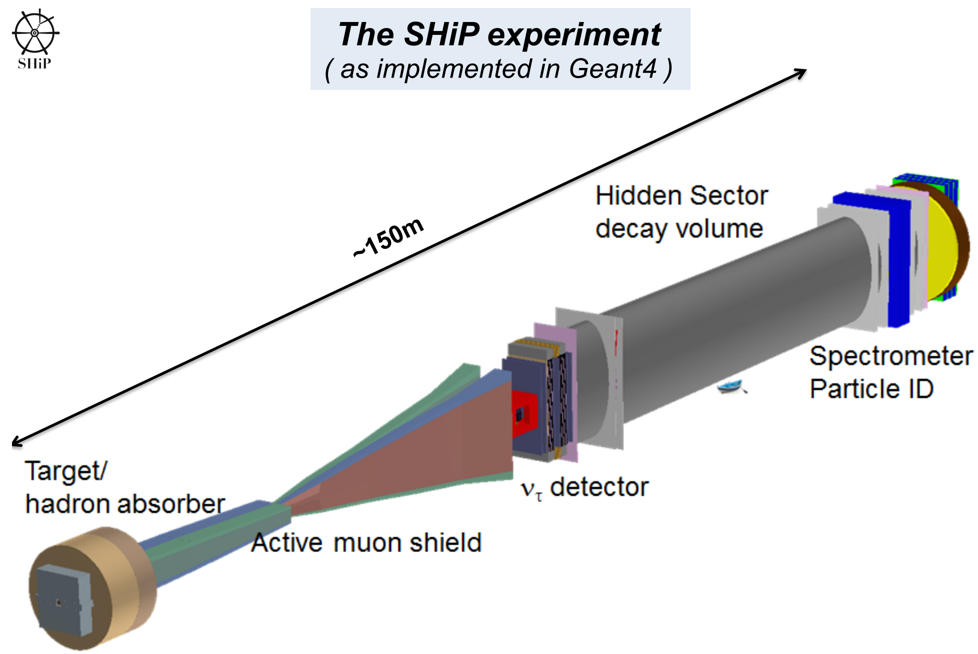


From Izaguirre et al 2014, Battaglieri et al 2017

Future [monster-size] direction

To improve on sensitivity to light dark matter in beam dump/fixed target experiments.

SHIP proposal at CERN: over 10^{21} of 400 GeV protons on target

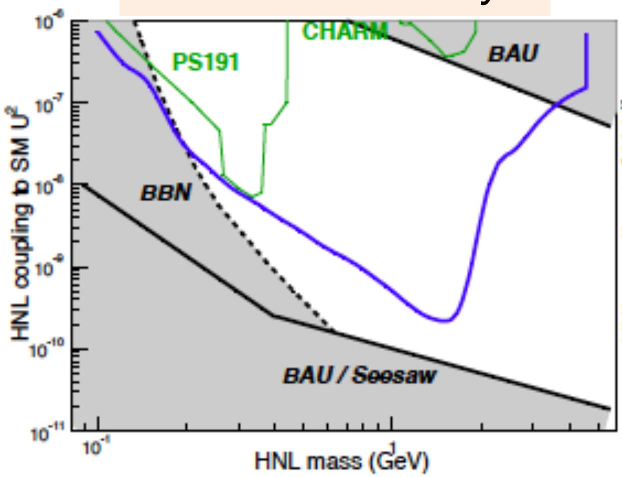


SHiP may become the most important project at CERN after LHC

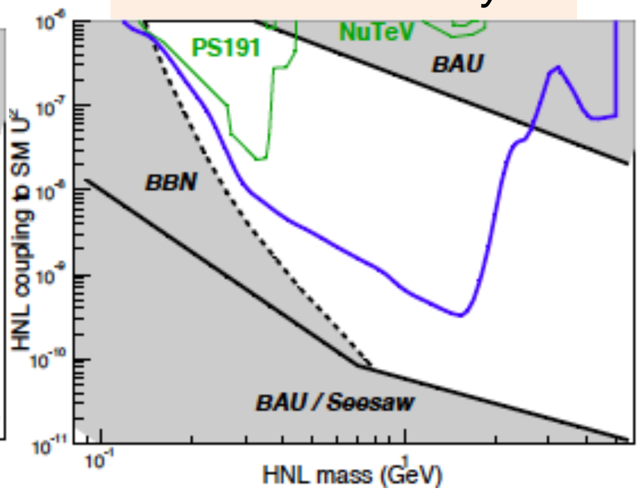
Search for Heavy Neutral Leptons

- Production channel is through charm pp → c cbar → N_R. (N_R are often called Heavy Neutral Leptons, or HNL)
- Detection is through their occasional decay via small mixing angle *U*, with charged states in the final state, e.g. $\pi^+\mu^-$, $\pi^-\mu^+$, etc.
- Decays are slow, so that the sensitivity is proportional to (Mixing angle)^4. *Massive improvements over old ressults possible. Low-scale leptogenesis (ARS) can be probed.*

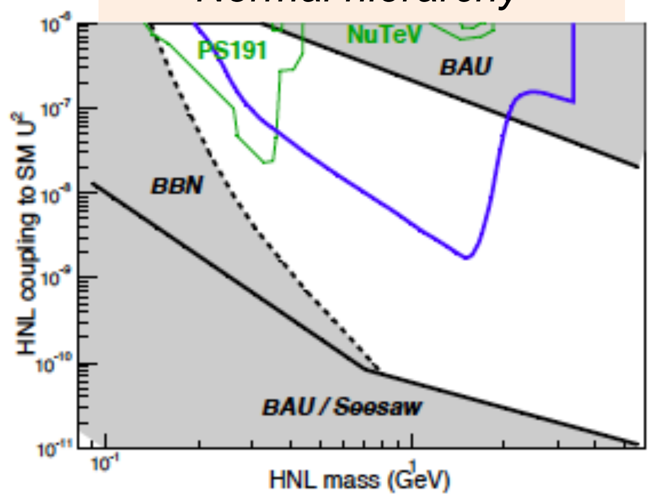
U^2_e: U^2_μ: U^2_τ~52:1:1
Inverted hierarchy



U^2_e: U^2_μ: U^2_τ~1:16:3.8
Normal hierarchy

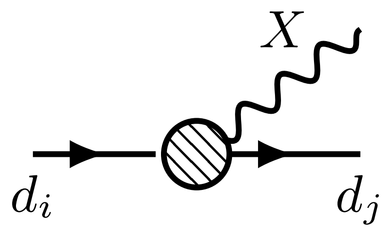


U^2_e: U^2_μ: U^2_τ~0.061:1:4.3
Normal hierarchy



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

- It is well known that there is an enhancement of non-conserved currents inside loops leading to FCNC. The key – access to momenta ~ m_W and m_t.



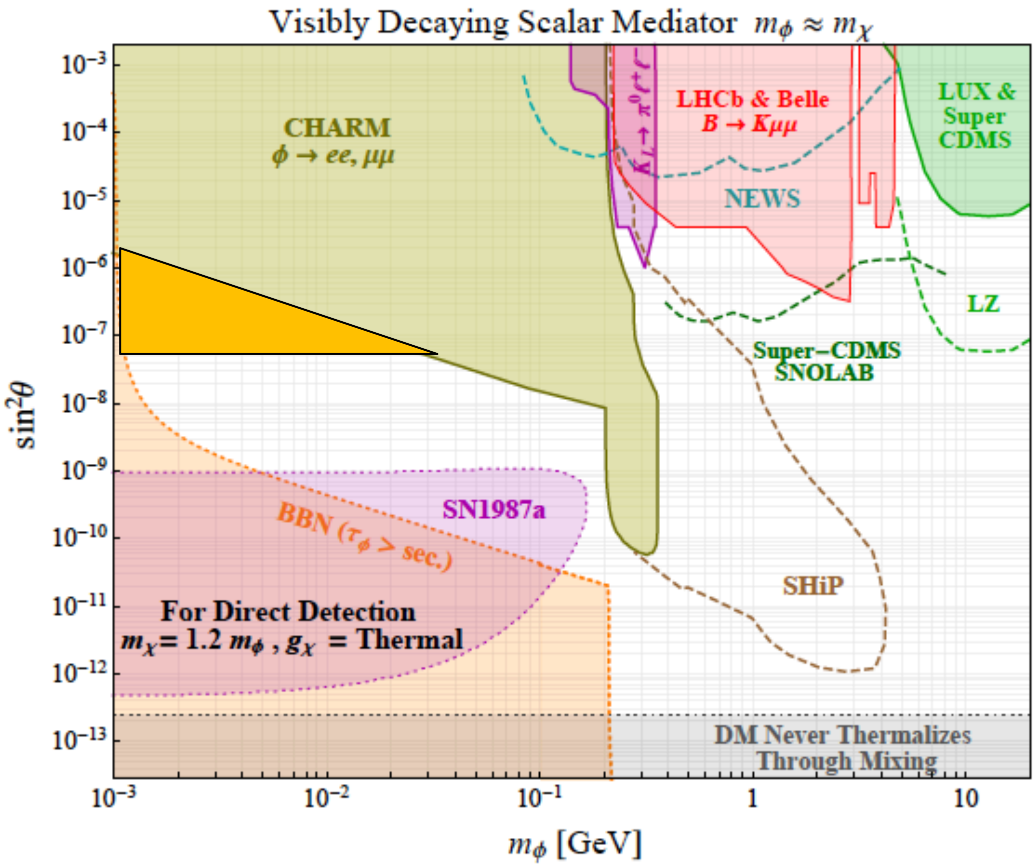
- For a fully conserved current, like couplings of dark photon,

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

For a non-conserved current,

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

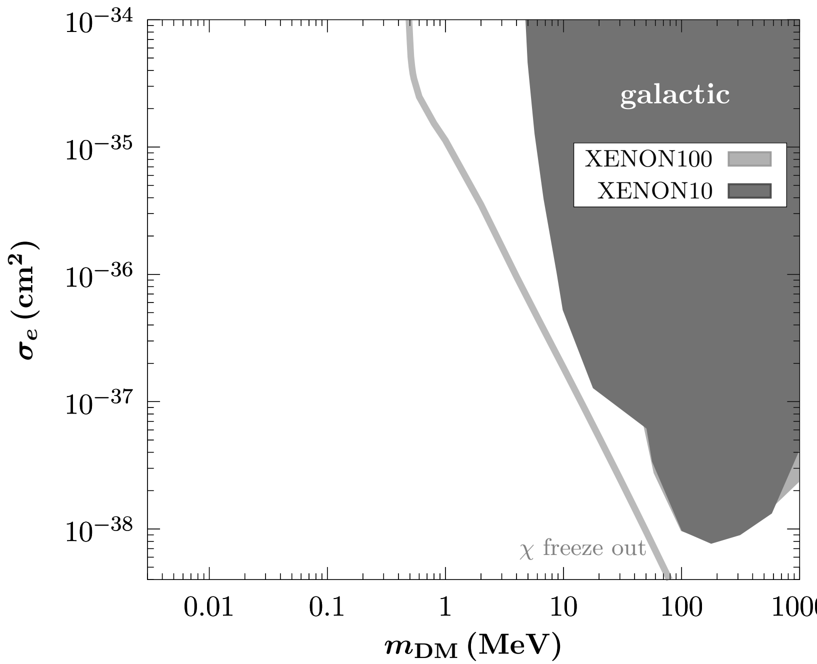
Constraints on Higgs-like mediators



Possible future improvements at NA62, SHiP, possibly SNB experiments, and new proposals such as MATHUSLA, CODEX-B, FASER etc.

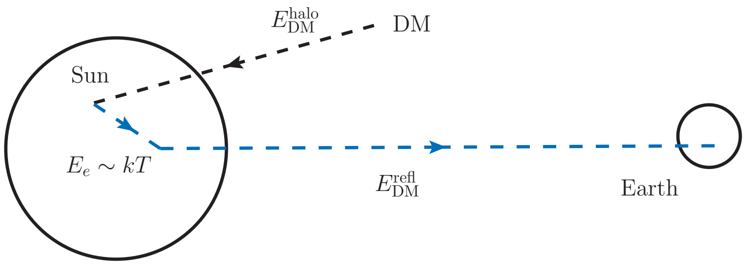
Direct detection, scattering of DM on electrons

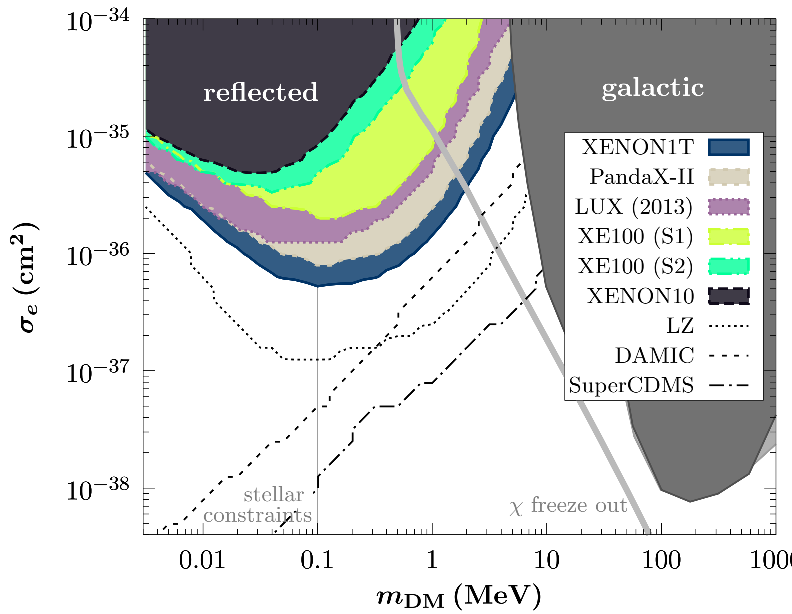
Main Science Goal	Experiment	Target	Readout	Estimated Timeline
Sub-GeV Dark Matter (Electron Interactions)	SENSEI	Si	charge	ready to start project (2 yr to deploy 100g)
	DAMIC-1K	Si	charge	ongoing R&D 2018 ready to start project (2 yr to deploy 1 kg)
	UA′(1) liquid Xe TPC	Xe	charge	ready to start project (2 yr to deploy 10kg)
	Scintillator w/ TES readout	GaAs(Si,B)	light	2 yr R&D 2020 in sCDMS cryostat
	NICE; NaI/CsI cooled crystals	NaI CsI	light	3 yr R&D 2020 ready to start project
	Ge Detector w/ Avalanche Ionization Amplification	Ge	charge	3 yr R&D 1 yr 10kg detector 1 yr 100kg detector
	PTOLEMY-G3, 2d graphene	graphene	charge directionality	1 yr fab prototype 1 yr data
	supercond. Al cube	Al	heat	10+ yr program



- For a given DM mass particle, in the MeV and sub-MeV range, the recoil energy of electrons is enhanced compared to nuclear recoil by M_{nucl}/m_e
- Sensitivity to energy depositions as low as 10's of eV – reality *now*.
- Near future – O(1eV) sensitivity
- Huge number of suggestions: *using superconductors, graphene, Weyl semimetals, DNA, to push threshold lower.* Belongs to distant future at this point.

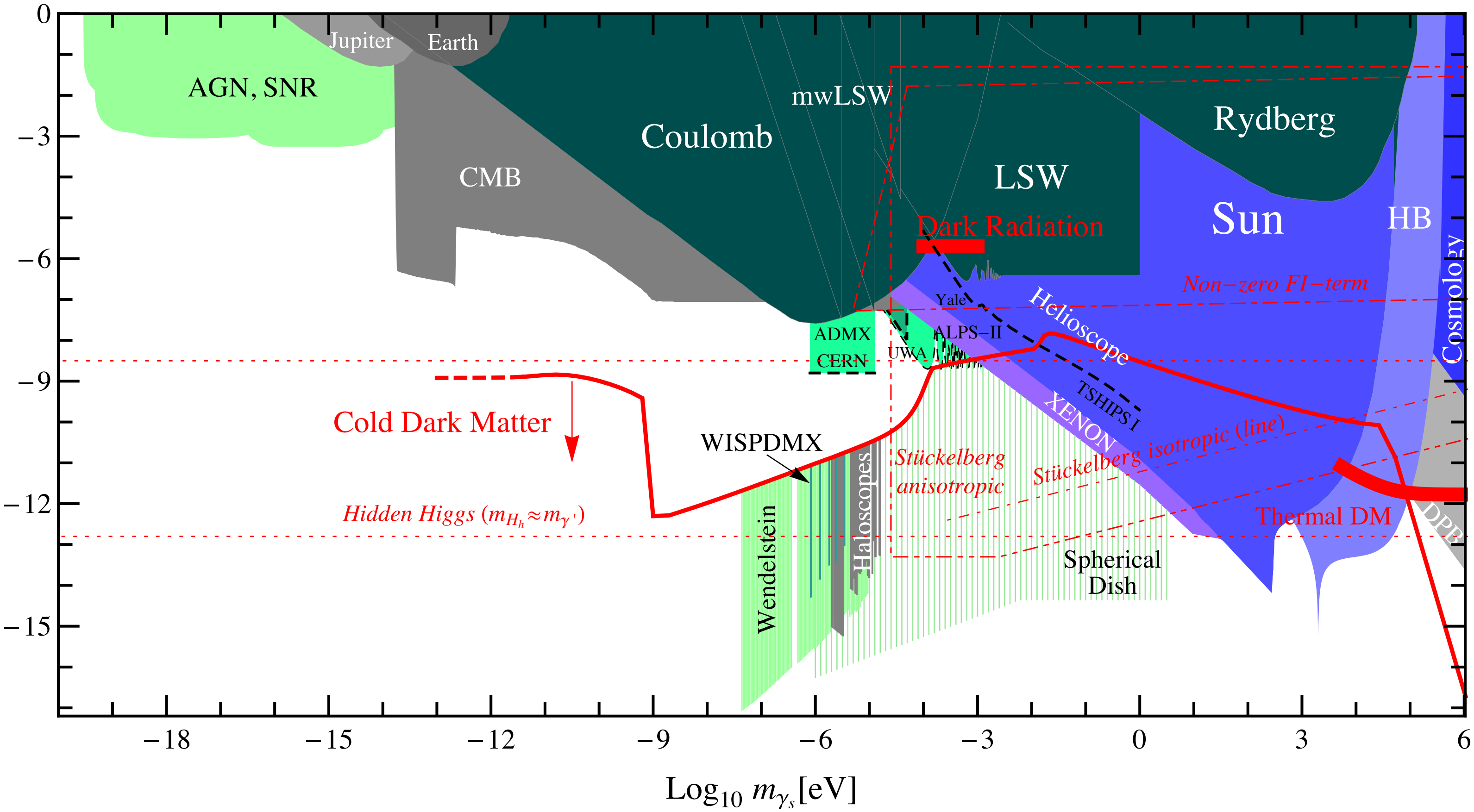
New sensitivity to σ_e at low masses through dark matter reflected from the Sun





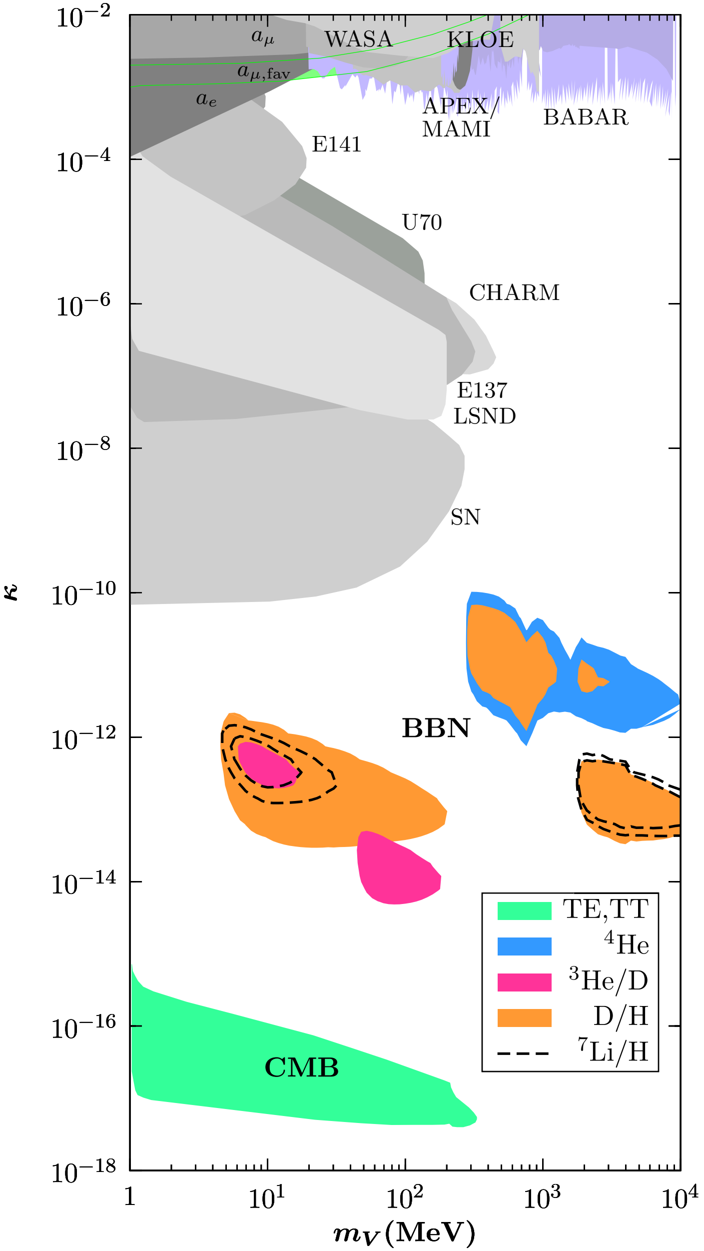
- Initial kinetic energy $m_{dm}(v_{dm})^2/2$ with v_{dm}~10^{-3}c (that has an endpoint at ~600 km/sec)can be changed by scattering with electrons, $v_{el} \sim (2\ T_{core}/m_e)^{1/2}$ ~ up to 0.1 c. In particular $E_{reflected}$ can become larger than $E_{ionization}$.
- New exclusion regions. Reflected DM is simulated.
- This provides a new benchmark for exotic proposals. Can you beat new constraints? (See An et al, 2017)

Constraints on dark photon in broader range



Going to smaller mass range opens up a possibility for stable dark photons as dark matter. (our group, An et al, 2013, has derived correct stellar energy loss constraints)

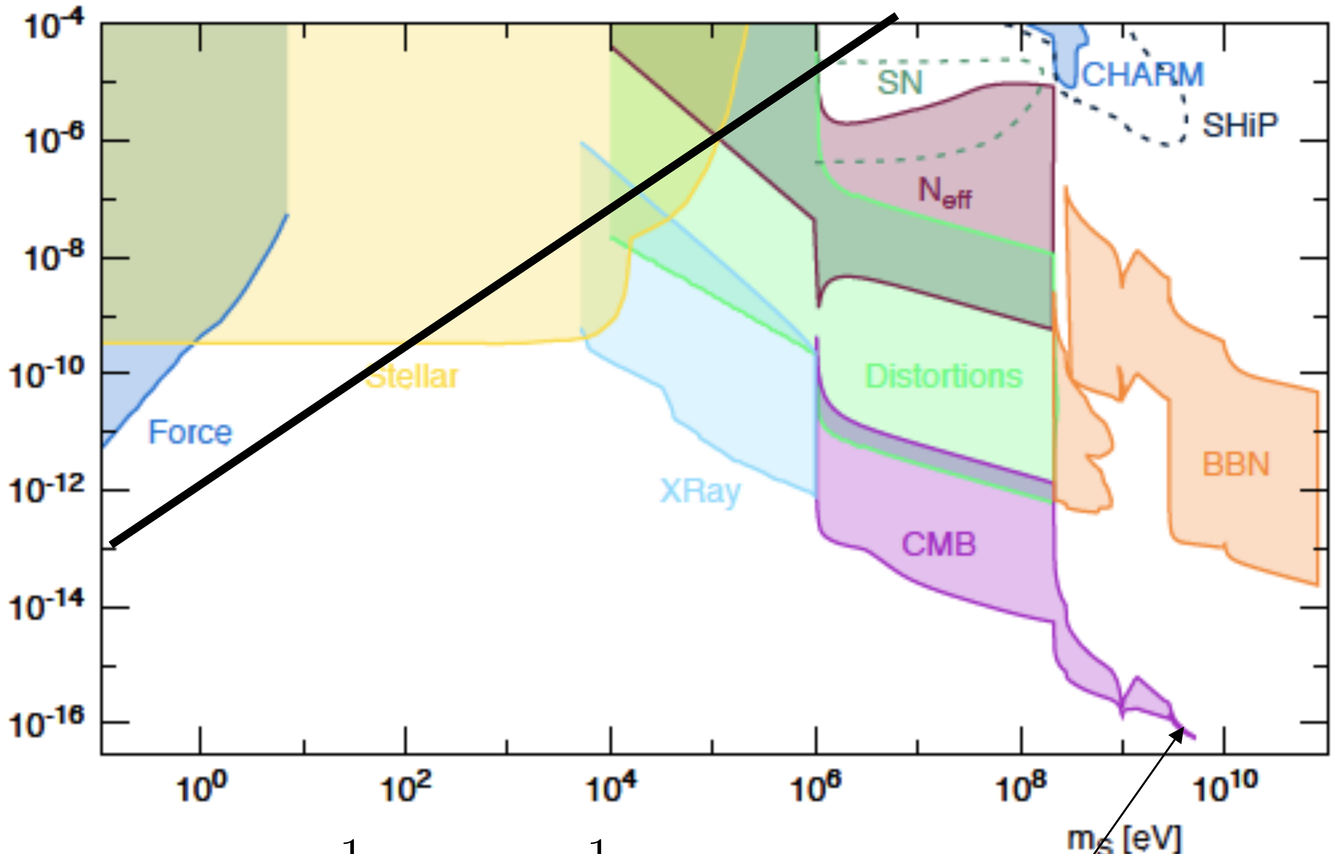
Constraints on dark photon in broader range



- *Going to smaller couplings*: new primordial nucleosynthesis and CMB constraints from late decays of dark photons, (our group, Fradette et al, 2014)
- When the mixing angle is 10^{-16}, the production cross sections are below 10^{-60} cm2
- However, once produced such particles will live for a long time, decaying during e.g. CMB epoch, falling under generic energy release constraints.

Cosmological constraints on dark Higgs

$$\theta = \frac{Av}{m_h^2}$$



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

Coupling of a new state S to electron here is ~ 10^{-22} , very similar to m_e/M_{Pl} (Sensitive to graviton-strength couplings)

Conclusions:

Studies of dark sector, not rigidly linked to the weak scale are motivated and is becoming ever widening effort.

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

Marco Battaglieri (SAC co-chair),[1] Alberto Belloni (Coordinator),[2] Aaron Chou (WG2 Convener),[3] Priscilla Cushman (Coordinator),[4] Bertrand Echenard (WG3 Convener),[5] Rouven Essig (WG1 Convener),[6] Juan Estrada (WG1 Convener),[3] Jonathan L. Feng

arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

… very long list of authors

Dark Sectors 2016 Workshop: Community Report

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- Similar effort underway at CERN: Physics Beyond Colliders exercise aimed [among other things] to understand CERN capabilities to probe light BSM physics.

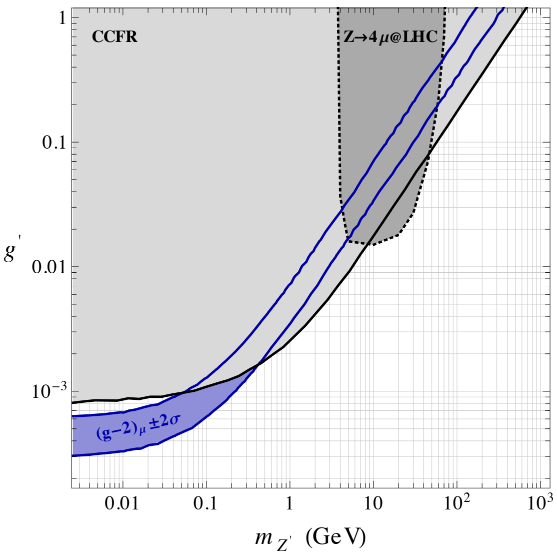
Additional tests of lepton universality

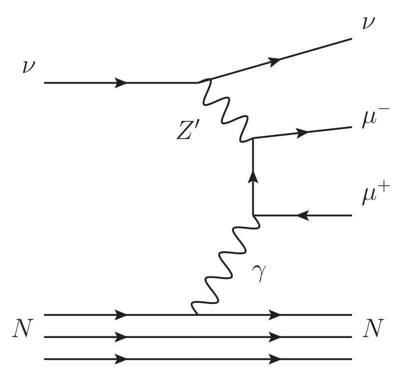
- In light of the anomalies (particularly e-mu non-universality) observed in the B-meson decays, it would be great to check lepton universality in situations where you expect it to be *not* broken (to have additional tests of electron reconstructions)
- Tests of phi universality in D-decays provide such an opportunity. (Phi is known to be universal to 5% accuracy, KLOE)

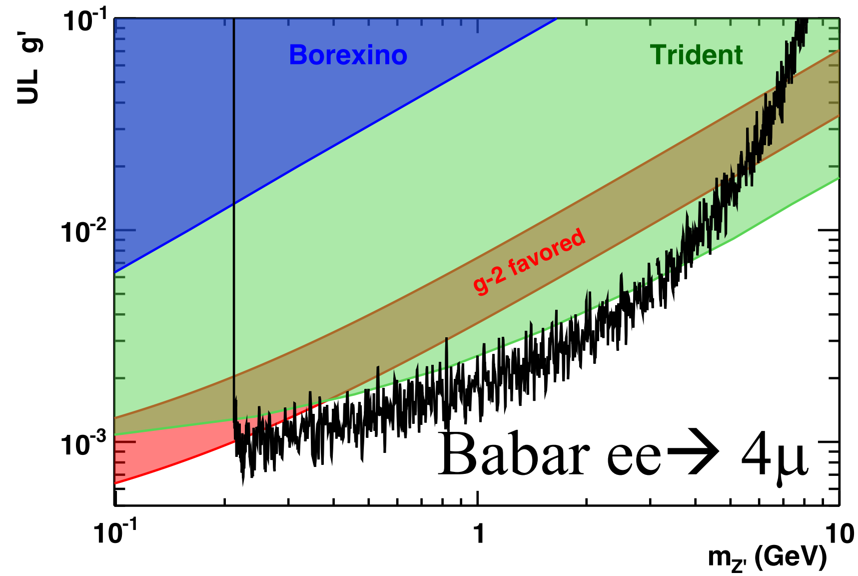
Decay mode	BR	Semileptonic BR, $\mu^+\mu^-$ or e^+e^-	N_{decays} at $5\,\text{fb}^{-1}$
$D^\pm \to \pi^\pm \phi$	$5.4 \cdot 10^{-3}$	$1.6 \cdot 10^{-6}$	$\mathcal{O}(10^4)$
$D^0 \to \pi^+\pi^-\phi$	$2.6 \cdot 10^{-3}$	$7.6 \cdot 10^{-7}$	$\mathcal{O}(10^4)$
$D_s^\pm \to \pi^\pm \phi$	$2.5 \cdot 10^{-2}$	$1.3 \cdot 10^{-5}$	$\mathcal{O}(10^4)$
$D_s^\pm \to K^\pm \phi$	$1.8 \cdot 10^{-4}$	$5.3 \cdot 10^{-8}$	$\mathcal{O}(10^2)$

- From Altmannshofer et al., 1711.07494, to appear in JHEP. *If the B-anomalies persist, it would be useful to perform such measurement*

Constraints on L_μ-L_τ $M_{Z'}$ - 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.

Altmannshofer, Gori, MP, Yavin, 2014

See the improved analysis by Magill and Plestid, 2016.

Limits on $(g')^2/(m_Z')^2$ are better than G_{Fermi}.