Dark sectors in collisions

Maxim Pospelov

University of Victoria, Victoria / Perimeter Institute, Waterloo

CERN theory Division

University of Victoria | British Columbia Canada

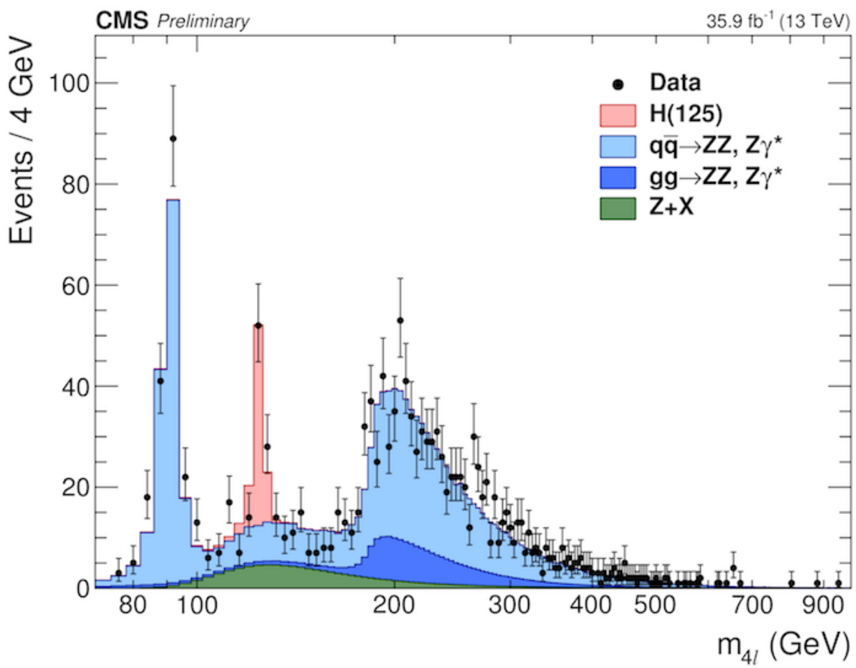
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

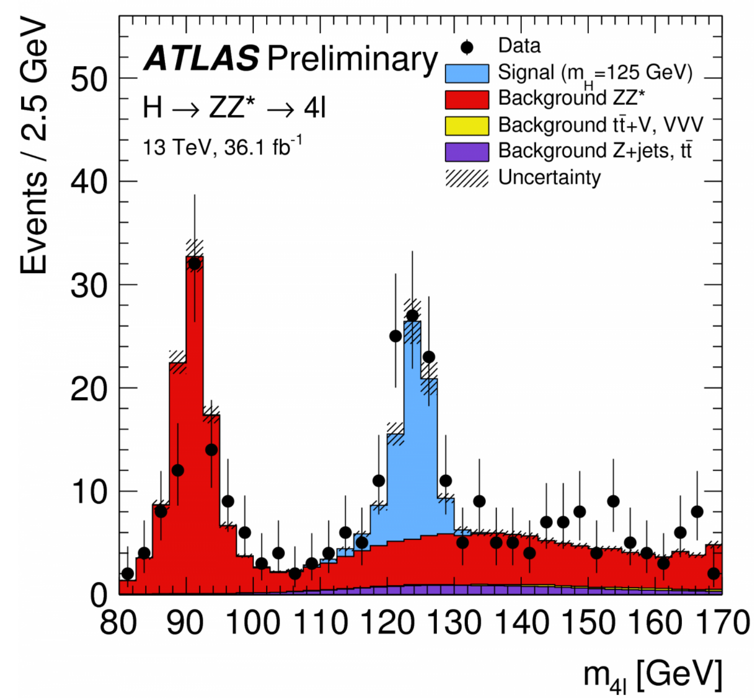
Outline of the talk

1. *Status of particle physics after the Higgs discovery.*
2. A case for dark sectors – connection to astrophysics
3. Systematic approach to dark sectors – vector, neutrino, Higgs, ALP portals.
4. *Probes of vector, scalar, neutrino portal models in collisions.*
5. Conclusions.

Higgs boson discovery

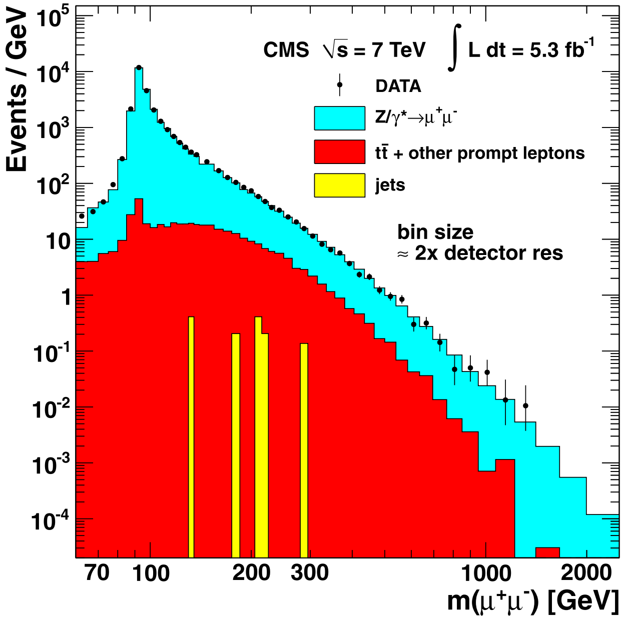
New particle and new type of fundamental force:

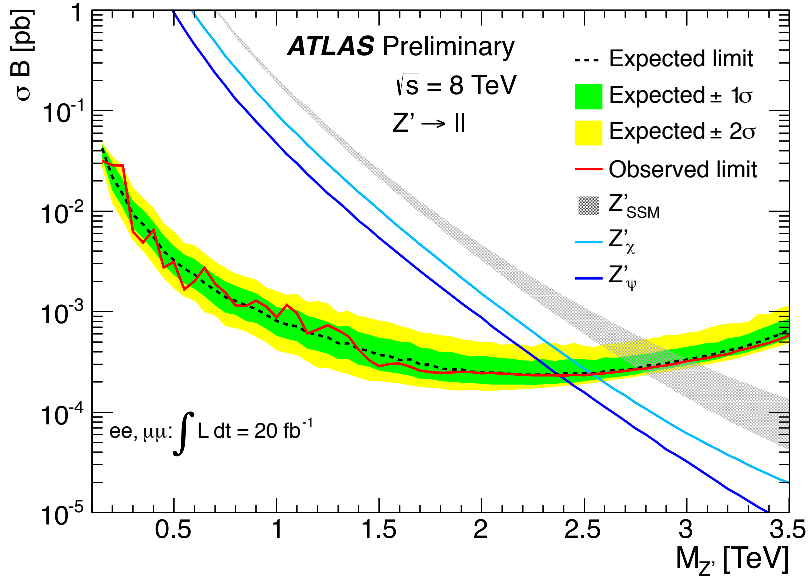


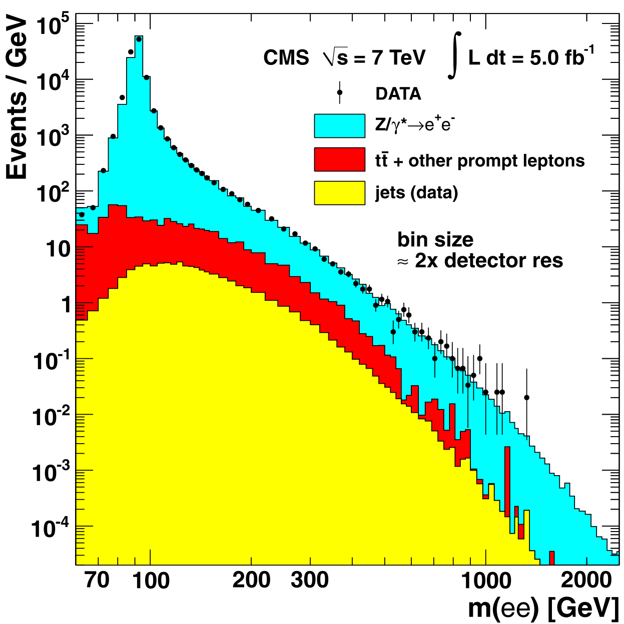


1. A new 0^+ resonance is observed at the LHC. ~50 years after prediction
2. Its properties are fully consistent with the properties of the Standard Model Higgs boson. Mass = 125 GeV (to 0.25%).
3. The discovery is remarkable because the prediction of the Higgs boson was based on theoretical consistency (and minimality!)

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





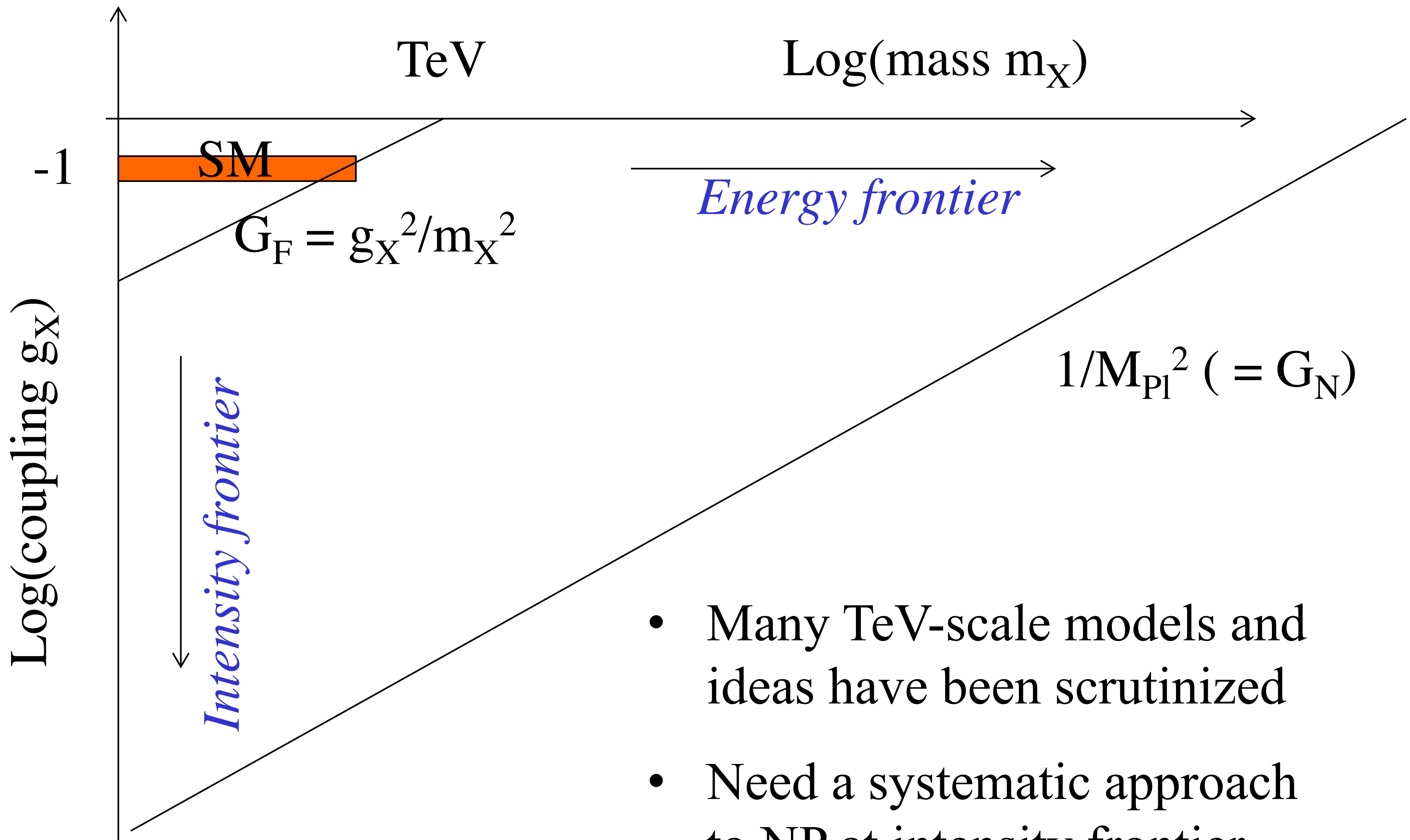


No hints for any kind of new physics. Strong constraints on SUSY, extra dimensions, technicolor resonances, etc.

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

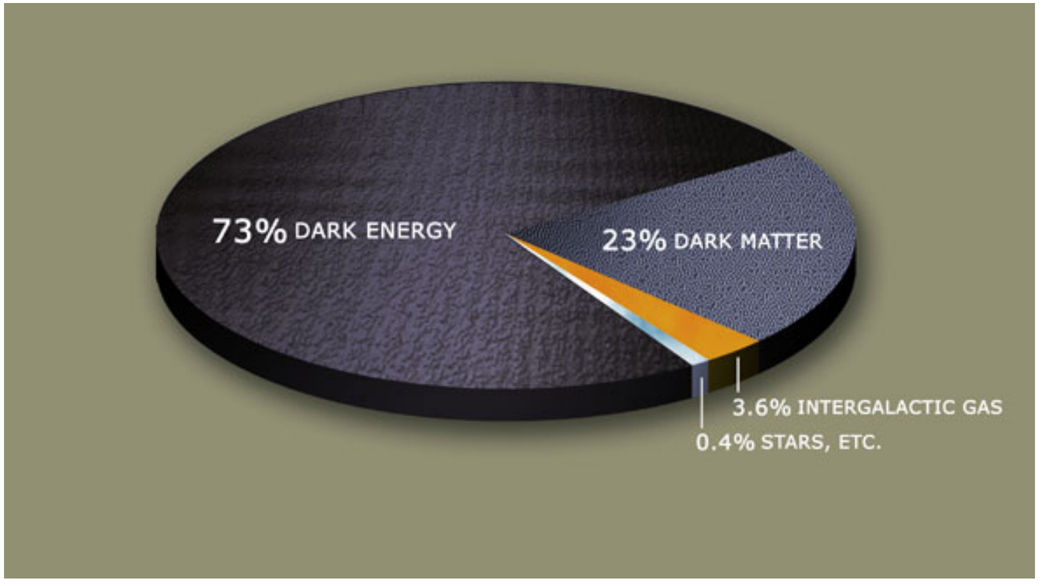
Are our basic assumptions wrong? Where else to look? What to do?

Energy and Intensity frontiers



- Many TeV-scale models and ideas have been scrutinized
- Need a systematic approach to NP at intensity frontier

Cosmological surprises

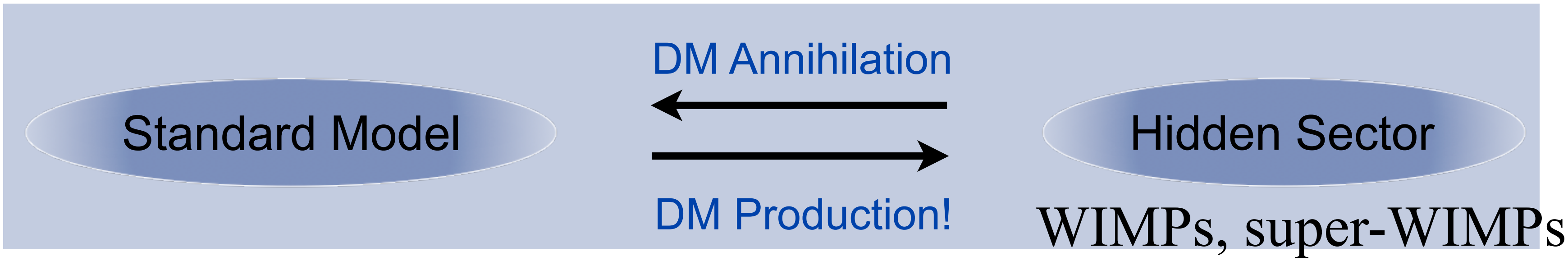


Existence of dark matter and dark energy calls into question whether there are other dark components:

Dark Forces?

Dark radiation?

Dark sectors = WIMP dark matter + mediators



Mediators (SM Z, h etc or dark force)

Heavy WIMP/heavy mediators: - "mainstream" literature

Light WIMPs/light mediators: applied to 511 keV anomaly

Heavy WIMPs/light mediators: applied to Pamela/AMS positron rise

Light WIMPs/heavy mediators: does not work. (Except for super-WIMPs; or non-standard thermal history)

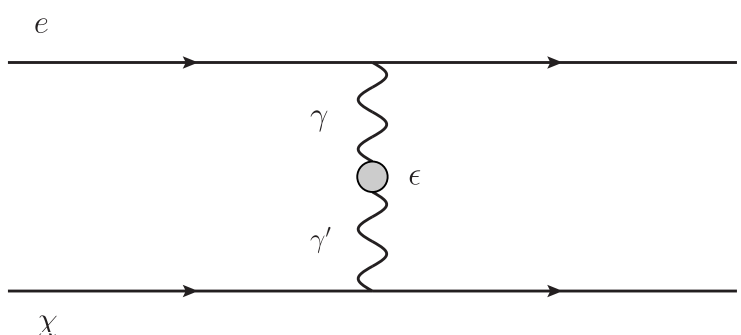
Light mediators allow to speculatively tie several anomalies to the possible effects of WIMP dark matter.

A simple model of dark sector

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

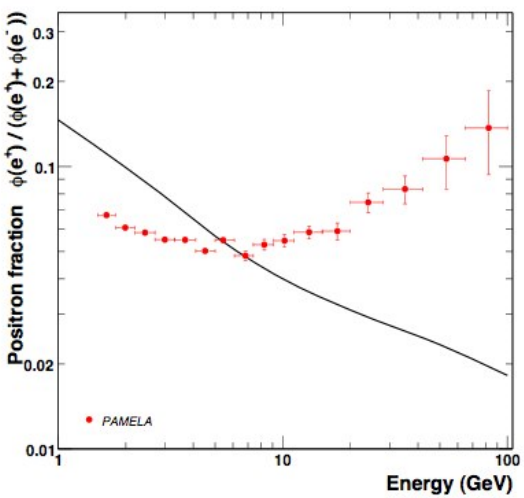
$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F^2_{\mu\nu} + \bar{\psi}[\gamma_\mu (i\partial_\mu - eA_\mu) - m_\psi]\psi$$

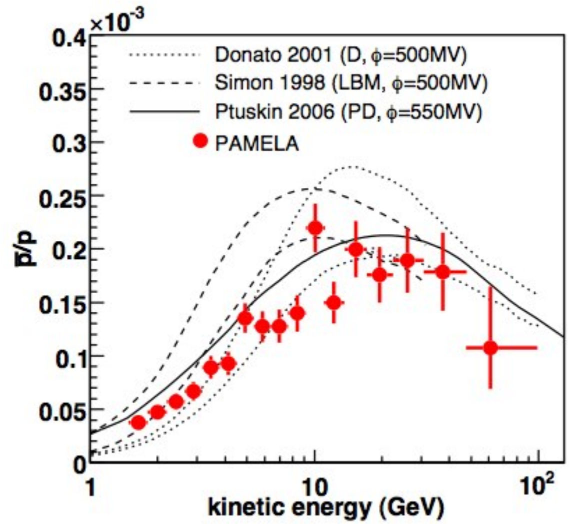
$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu (i\partial_\mu - g' A'_\mu) - m_\chi]\chi,$$

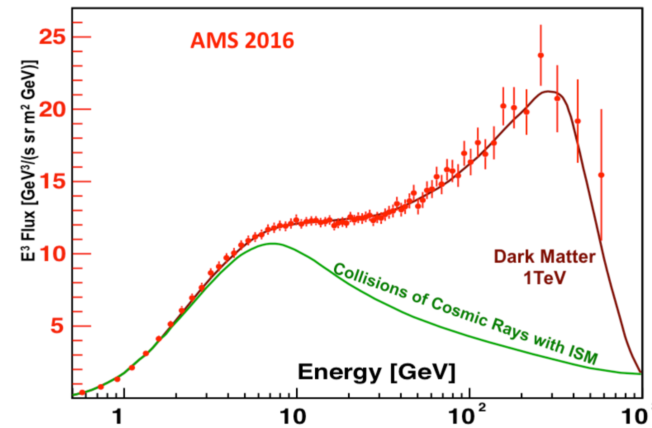


- "Effective" charge of the "dark sector" particle χ is Q = e × ε (if momentum scale $q > m_V$). At $q < m_V$ one can say that particle χ has a non-vanishing *EM charge radius,* $r^2_\chi \simeq 6\epsilon m_V^{-2}$.
- Dark photon can "communicate" interaction between SM and dark matter. Very light χ can be possible.
- *Enables models of light Dark Matter, including MeV-to-GeV scale WIMP*

10 yrs of ``PAMELA positron fraction”







No huge surprises with antiprotons, but there is seemingly a need for a new source of positrons!

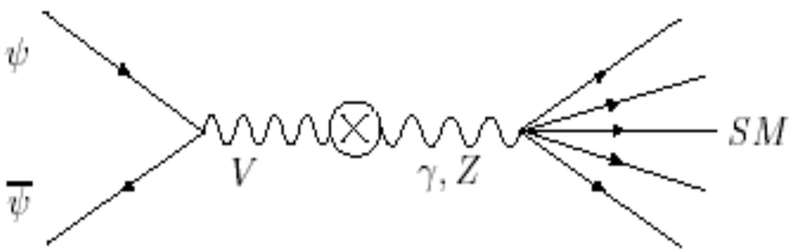
This is a “boost” factor of 100-1000 “needed” for the WIMP interpretation of PAMELA signal. E.g. SUSY neutralinos would not work, because $<\sigma v>$ is too small. Enhancing it “by hand” does not work because WIMP abundance goes down. Dark forces allow bridging this gap due to the late time enhancement by Coulomb (Sommerfeld).

Finkbeiner et al, MP and Ritz, 2008

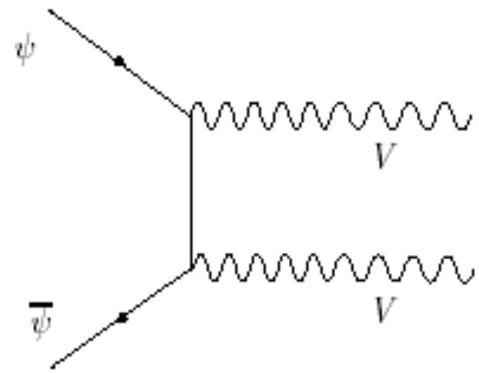
Dark sectors provide model-building flexibility

ψ – weak scale Dark Matter; V –mediator particle.

$m_{mediator} > m_{WIMP}$



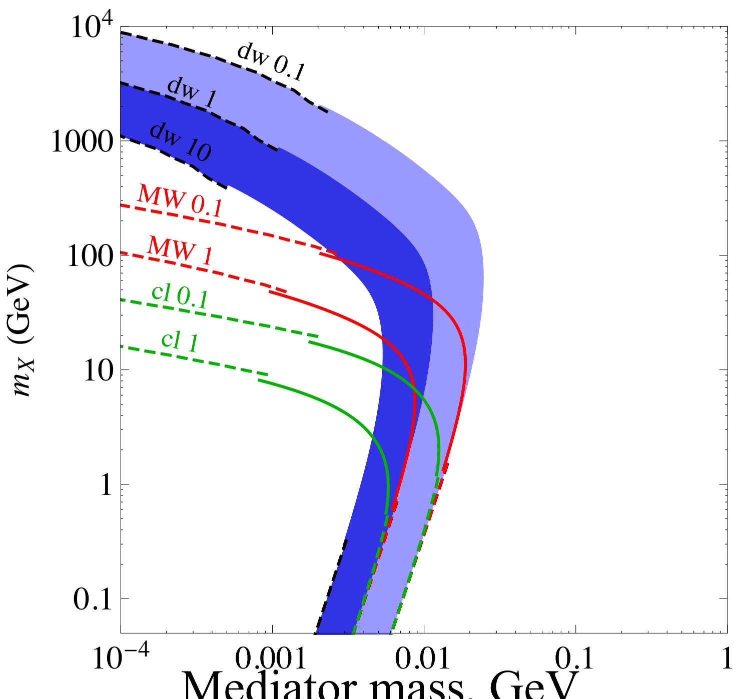
$m_{mediator} < m_{WIMP}$



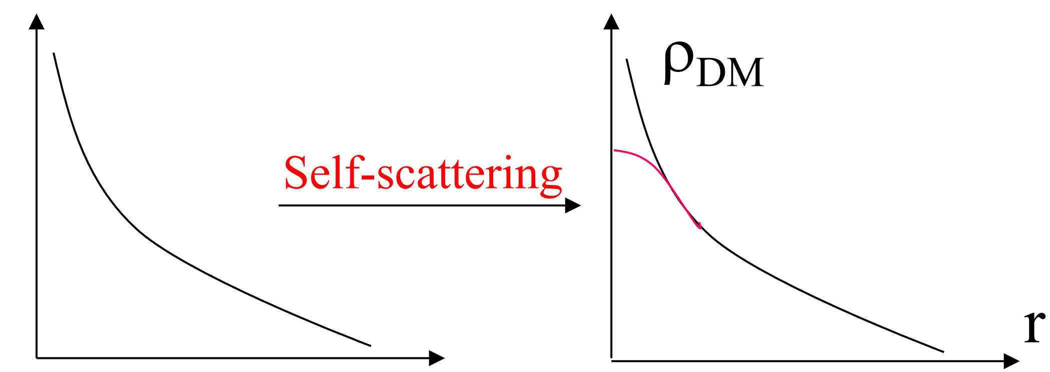
Second regime of annihilation into on-shell mediators (called *secluded*) does not have any restrictions on the size of mixing angle ε. It turns out *this helps* to tie PAMELA positron rise and WIMP idea together. Baryons are kinetically excluded, while the cross section for annihilation are enhanced at low velocity, by $\pi\alpha_D/v \sim 100\text{-}1000$ if $m_{mediator} \ll m_{DM}$. (Astrophysics explanation, i.e. new source, is also plausible.) *Need direct particle physics searches to make progress.*

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 $\alpha_d = 0.1$



Sub-100 MeV mediator is needed

Possible motivations for light DM: 511 keV line

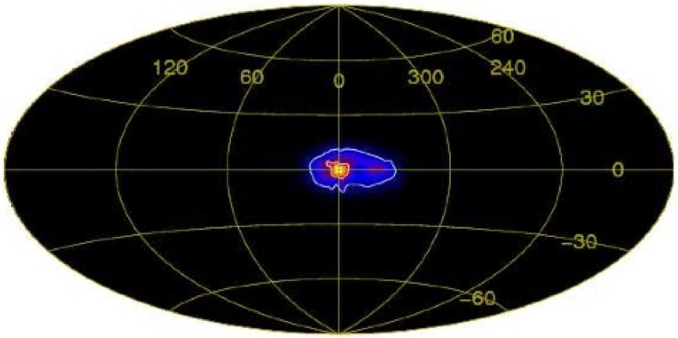


FIG. 4 511 keV line map derived from 5 years of INTEGRAL/SPI data (from Weidenspointner *et al.*, 2008a).

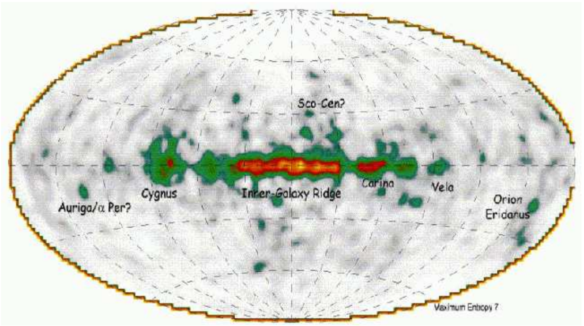


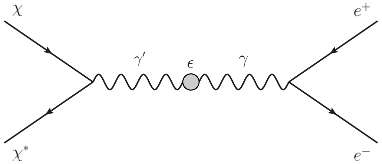
FIG. 7 Map of Galactic ^{26}Al γ-ray emission after 9-year observations with COMPTEL/CGRO (from Plüschke *et al.*, 2001).

There is a lot more positrons coming from the Galactic Center and the bulge that expected. The emission seems to be diffuse.

1. "Normal" astro explanations are possible. (e.g. positrons are created by episodic violent events near central BH?)

2. Positrons being produced by DM? Could it be ~ few MeV in mass?

If DM annihilation occurs via a force carrier with light mass, DM can be as light as ~ MeV (and not ruled out by the CMB if it is a scalar).



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

Boehm, Fayet

An attempt to systematize: 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

……….

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

Importantly, the scale for new physics is not tied up to EW scale !

"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 $2m_{DM} < m_{mediator}$.

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

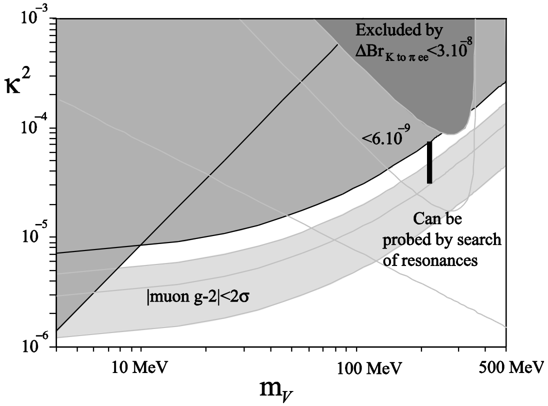
- Fermionic dark matter talking to the SM via a "dark scalar" that mixes with the Higgs. With $m_{DM} > m_{mediator}$.

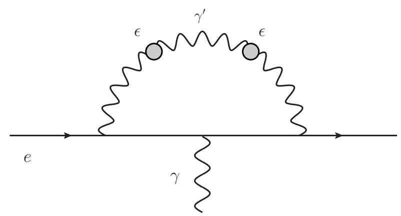
$$\mathcal{L} = \overline{\chi}(i\partial_\mu \gamma_\mu - m_\chi)\chi + \lambda \overline{\chi}\chi S + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - AS(H^\dagger H)$$

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

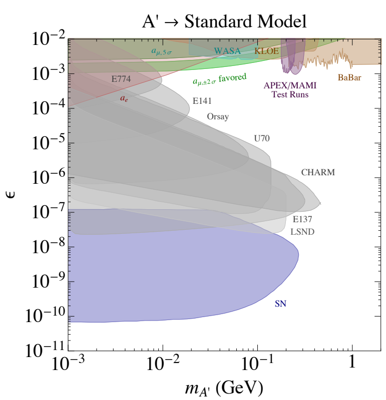
Take away point: these models have both stable (DM) and unstable (mediator) light weakly coupled particles.

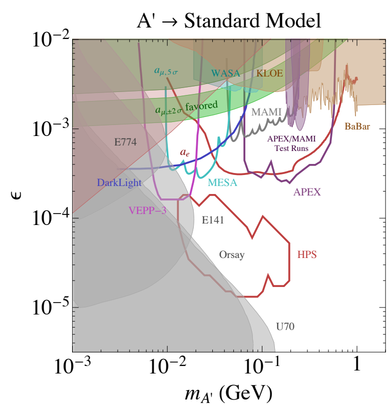
Search for dark photons



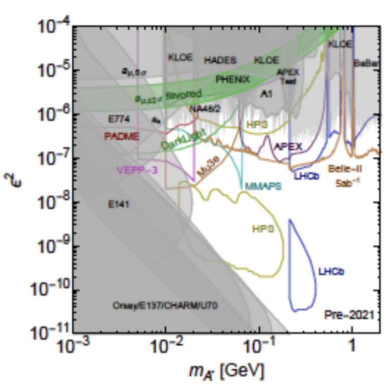


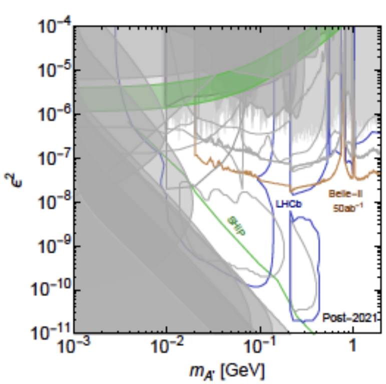
Dark photon with kinetic mixing ~ 10^{-3} is the simplest model that can account for anomalous $\Delta a_\mu \sim 3\ 10^{-9}$, MP, 2008





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



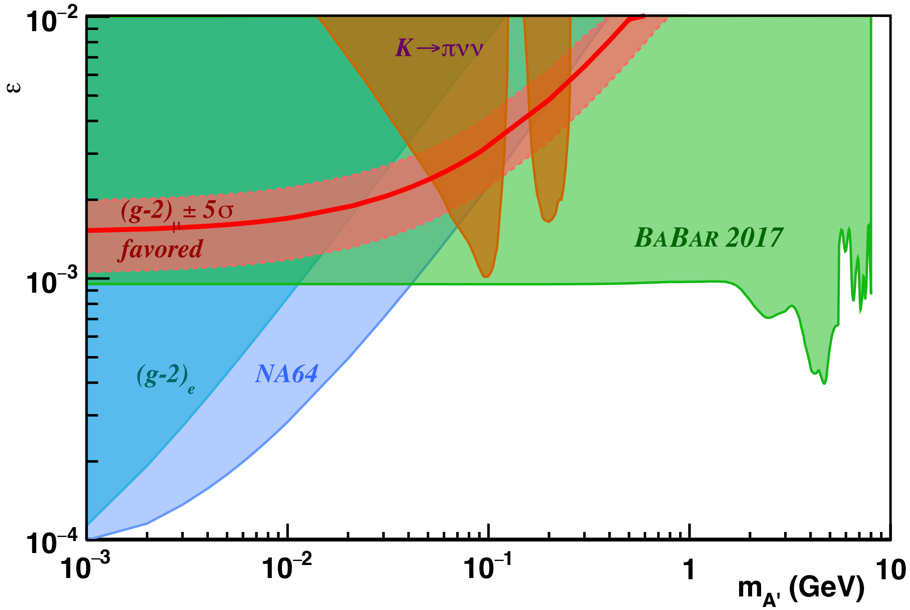


By 2018, there is a large community in place (”Cosmic Vision” summary, 100s of authors, 2017), where the search for dark photon is one of the priorities. (My hypothesis from 2008 is ruled out.)

Collider searches include KLOE, BaBar, BES-III, and most recently LHCb.

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 $e^+e^- \rightarrow \gamma + A' \rightarrow \gamma + \chi\chi$

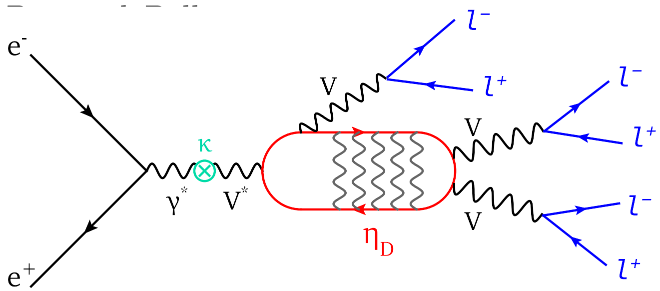


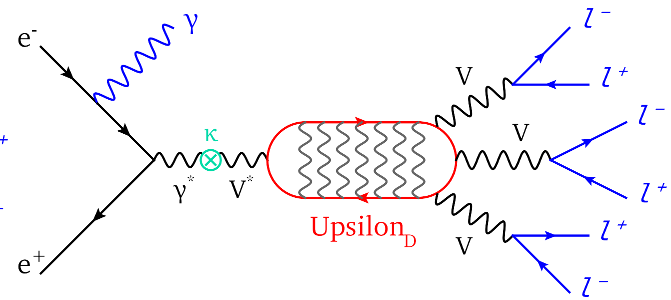
- Complementary results from NA64, BaBar and Kaon decays
- Covers all of the dark photon parameter space, decaying invisibly, consistent with alleviating the muon g-2 discrepancy
- *Belle-II will be able to significantly improve sensitivity*

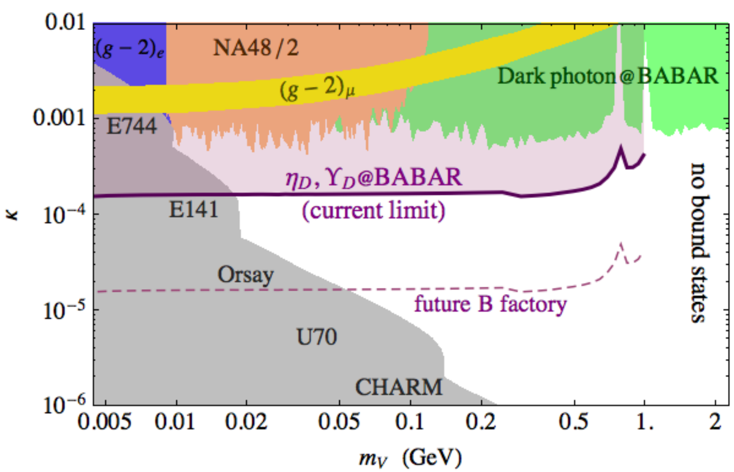
Example: dark matter bound states at B-factories

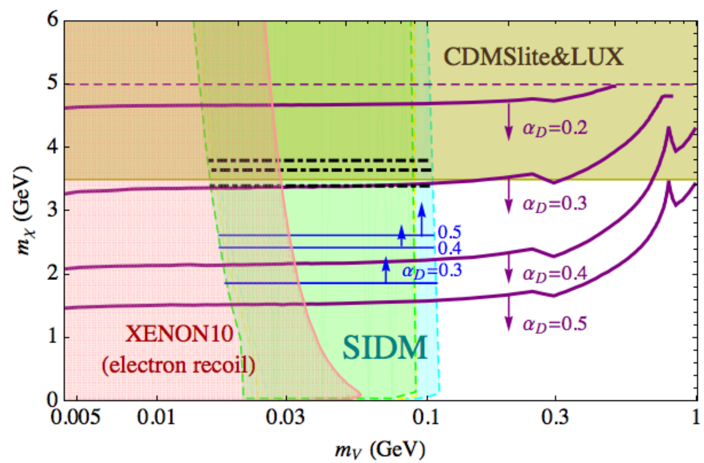
- If $\alpha_d > 0.2$, the sub-5 GeV Dark matter *can increase the sensitivity to dark force* via production of "dark Upsilon" that decays producing multiple charged particles

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







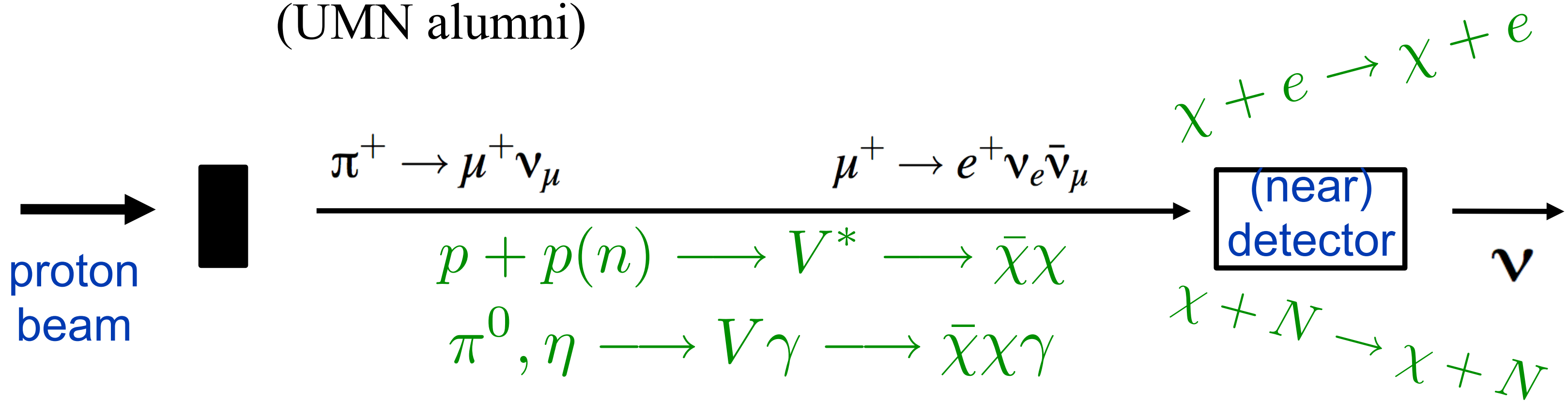


3 pairs of charged particles appear "for free" once Upsilon_dark is produced. This is limited by previous searches of "dark Higgsstrahlung" by BaBar and Belle. An, Echenard, MP, Zhang, PRL, 2016

Fixed target probes - Neutrino Beams

Proposed in Batell, MP, Ritz, 2009. Strongest constraints on MeV DM

(UMN alumni)

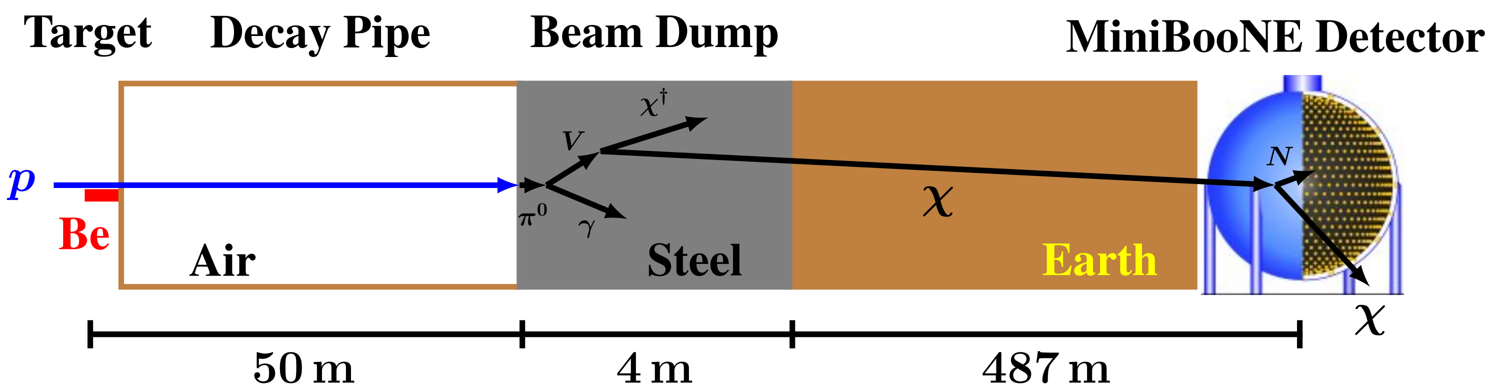


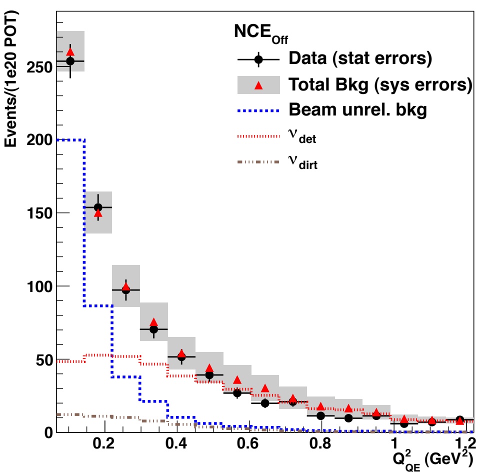
We can use the neutrino (near) detector as a dark matter detector, looking for recoil, but now from a relativistic beam. E.g.

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

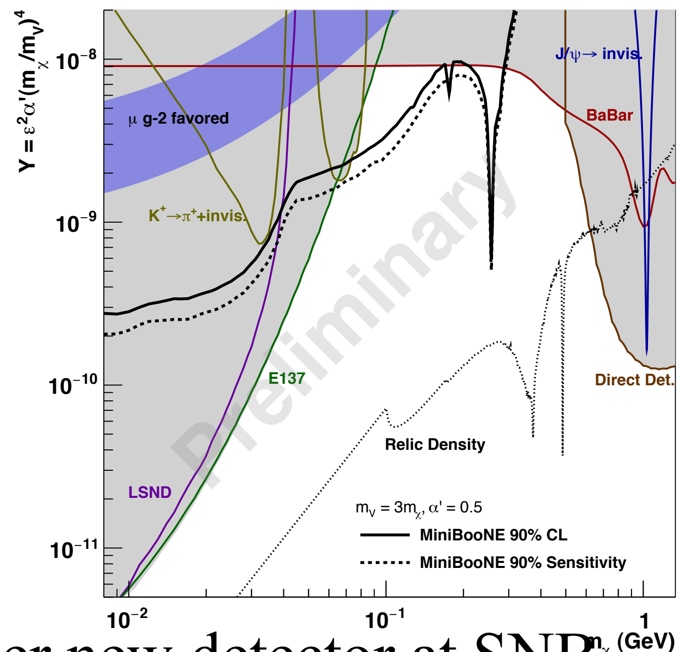
MiniBooNE search for light DM

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.
Also, there are parallel efforts with electron beams: BDX.

Simplest models of Higgs mediation

Silveira, Zee (1985); McDonald (1993); Burgess, MP, ter Veldhuis(2000)

DM through the Higgs portal – *minimal model of DM*

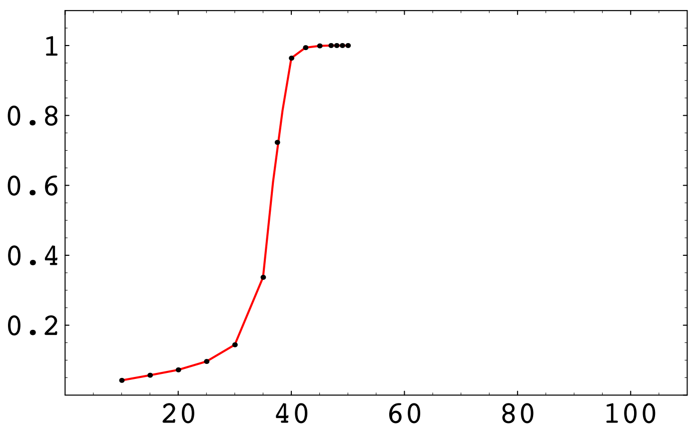
$$-\mathcal{L}_S = \frac{\lambda_S}{4}S^4 + \frac{m_0^2}{2}S^2 + \lambda S^2 H^\dagger H$$

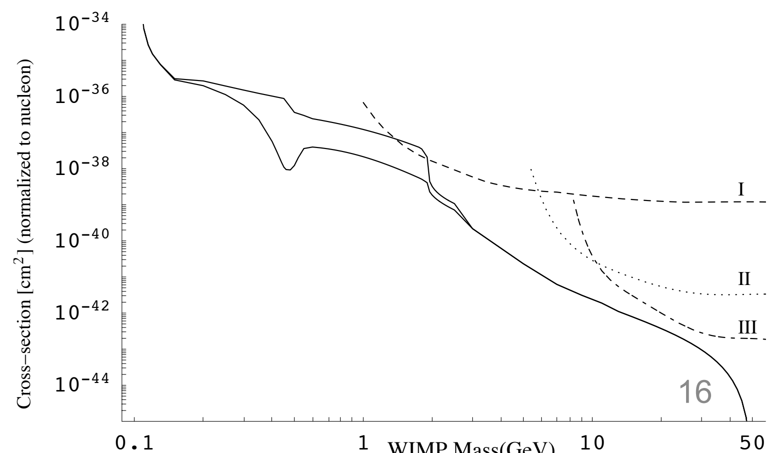
$$= \frac{\lambda_S}{4}S^4 + \frac{1}{2}(m_0^2 + \lambda v_{EW}^2)S^2 + \lambda v_{EW} S^2 h + \frac{\lambda}{2}S^2 h^2.$$

125 GeV Higgs is "very fragile" because its with is ~ y_b^2 – very small

R = $\Gamma_{\text{SM modes}}/(\Gamma_{\text{SM modes}}+\Gamma_{\text{DM modes}})$. Light DM can kill Higgs boson easily

(missing Higgs Γ: van der Bij et al., 1990s, Eboli, Zeppenfeld,2000)





Updates on the minimal Higgs-portal DM model:

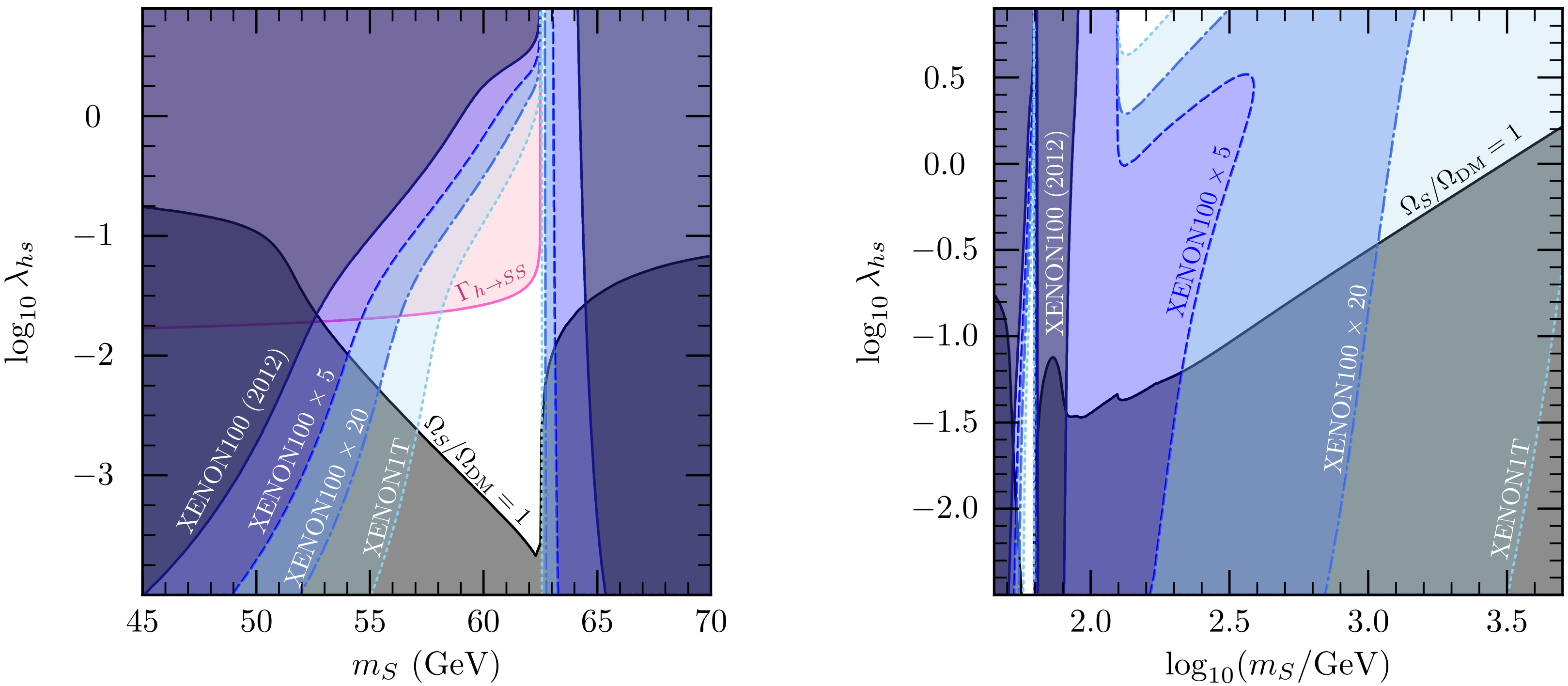


Figure from Cline, Scott, Kainulainen, Weniger, 2013.

Direct detection is competitive with the Higgs constraints.
Only > TeV masses survive.

Search for small mass mediators

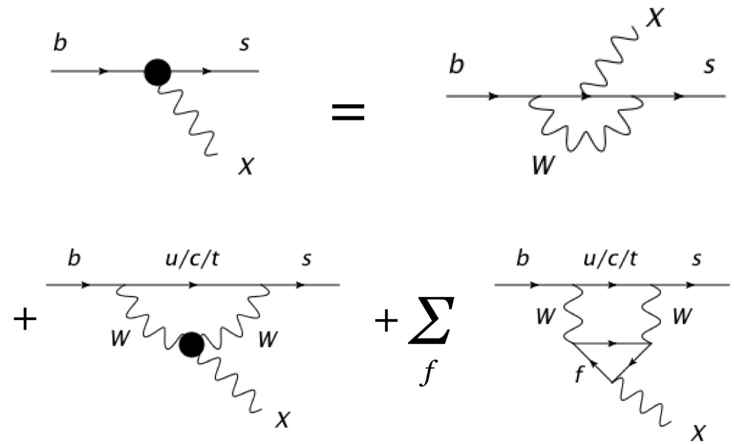
$$\mathcal{L} = \overline{\chi}(i\partial_\mu\gamma_\mu - m_\chi)\chi + \lambda\overline{\chi}\chi S + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - AS(H^\dagger H)$$

$$\to \ldots.\frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 + S\theta(y_f\overline{f}f + \ldots) \qquad \theta = \frac{Av}{m_h^2}$$

- If $m_{mediator} < m_{DM}$ the best strategy is to look for the mediator itself directly.
- Dark photon portal search (and any conserved vector current portal) does not induce large FCNC
- Other portals (axial vectors, dark Higgses and scalars in general, ALPs, baryonic vector) are severely constrained by flavor physics.

Scalar currents are very different from conserved vector currents

Conserved vector currents are uniquely positioned to avoid very strong flavor constraints.

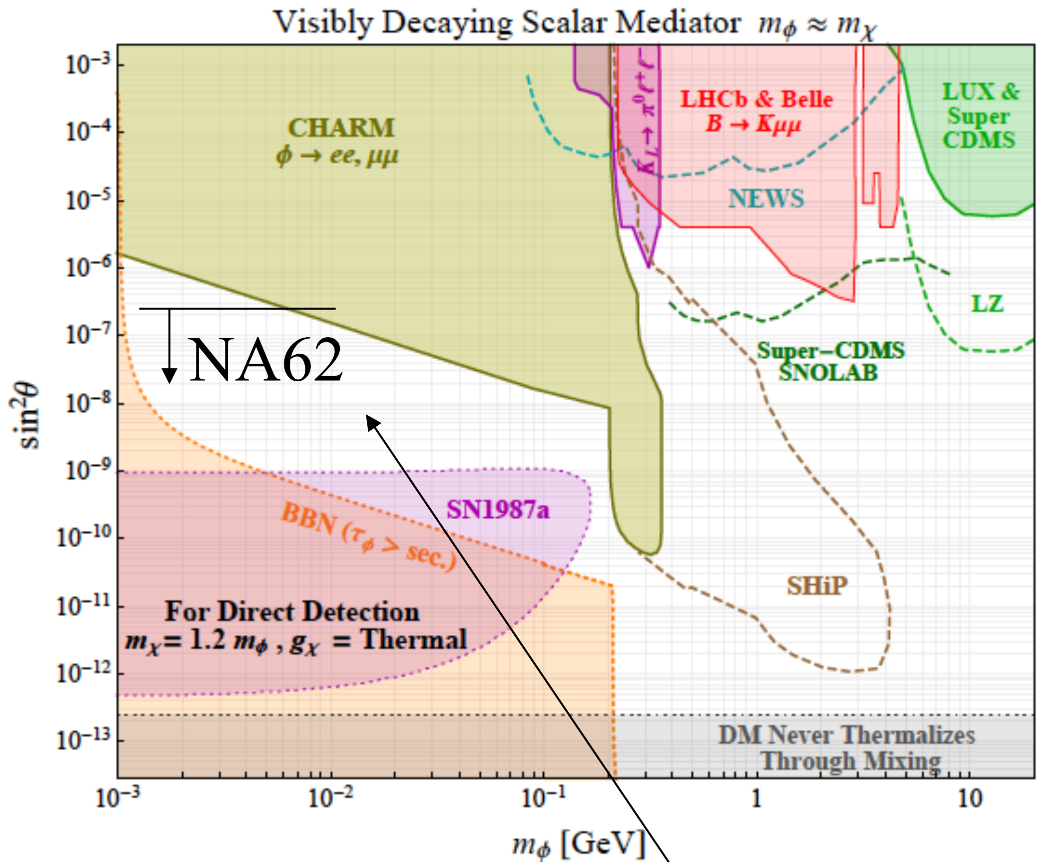


$$\simeq \left[C V_{tb} V_{tc}^* \frac{m_t^2}{m_W^2} \right] X_\mu \bar{s} \gamma^\mu \mathcal{P}_L b + \frac{1}{m_W^2} \dots$$

For a conserved vector current, $G_F\, q^2$ For scalar current, $G_F\, m_t^2$

There is extremely strong sensitivity to new scalars, pseudoscalars axial-vectors in rare K and B decays.

Constraints on Higgs-like mediators



From Krnjaic 2015 (certain curves need to be revised)

Question: Is there a further sensitivity to S from K→π S followed by S decay in the near detector at SNB (LAr1ND)?

An attempt for a comprehensive overview has been made in 2016 and 2017, and in the on-going Physics Beyond Colliders exercise at CERN

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

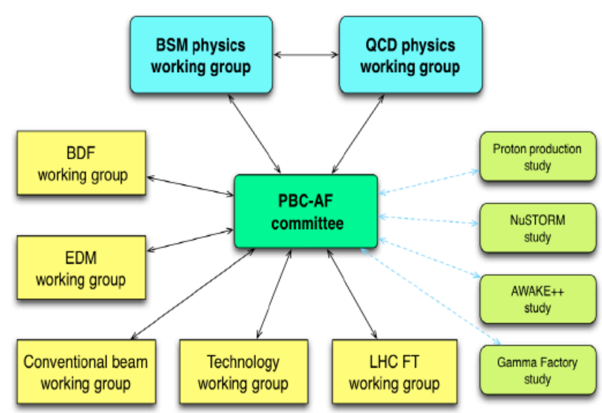
arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

… very long list of authors

Dark Sectors 2016 Workshop: Community Report

Jim Alexander (VDP Convener),[1] Marco Battaglieri (DMA Convener),[2] Bertrand Echenard (RDS Convener),[3] Rouven Essig (Organizer),[4,*] Matthew Graham (Organizer),[5,†] Eder Izaguirre (DMA Convener),[6] John Jaros (Organizer),[5,‡] Gordan

CERN PBC exercise led by Lamont, Jaeckel, Valee



Models vs Experiments

Benchmark Cases (MP and PBC, 2018)

1. *Dark photon*
2. *Dark photon + light dark matter*
3. *Millicharged particles*
4. *Singlet scalar mixed with Higgs*
5. *Quartic-dominated singlet scalar*
6. *HNL, e-flavour dominance*
7. *HNL, μ-flavour dominance*
8. *HNL, τ-flavour dominance*
9. *ALPs, coupling to photons*
10. *ALPs, coupling to fermion*
11. *ALPs, coupling to gluons*

Experimental proposals, mostly CERN

- *SHiP*
- *NA62+*
- *FASER*
- *MATHUSLA*
- *Codex-B*
- *MilliQan*
- *NA64*
- *KLEVER*
- *REDTOP*
- *IAXO*
- *ALPs-II*
- ……..

I hope that in the end, a clear strategy for building up CERN intensity frontier program will emerge, with new sensitivity to sub-EW scales

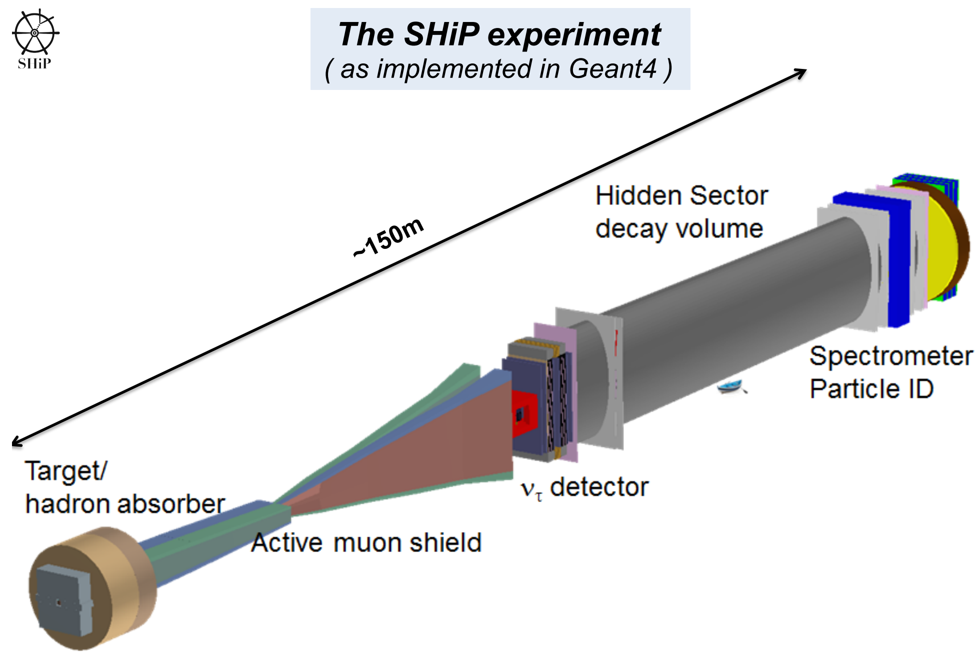
Conclusions

- *Dark sectors = dark matter + mediators is a simple yet flexible framework* [and it was used to tie some of the astro anomalies to dark matter physics – without a definitive prove so far]
- Searches of dark sectors are done at the LHC, but not only – the mass scale of particles involved can be much smaller than weak scale, and couplings weaker.
- Combination of collider and fixed target searches seem to rule out dark photon as the simplest explanation of the muon g-2 discrepancy
- Scalar portal models provide *the simplest* WIMP dark matter that in recent years have been severely limited by Higgs physics and direct detection searches. Higgs-portal mediator is still viable.
- Systematic evaluation of new experimental proposals relative to simplest portal model is underway.

Future [monster-size] direction

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

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



SHiP may become the most important project at CERN after LHC