Beyond SM and PBC
physics beyond colliders

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Outline of the talk

1. *PBC and its role*
2. A case for dark sectors. Systematic approach to dark sectors – vector, neutrino, Higgs, ALP portals.
3. *Probes of light dark matter in the appearance and disappearence modes.*
4. Conclusions.

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

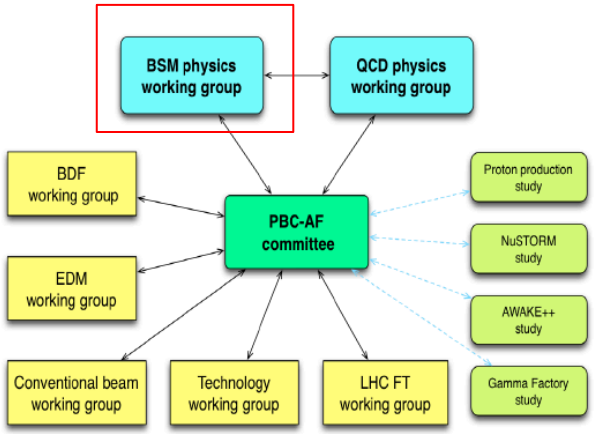
… very long list of authors

Dark Sectors 2016 Workshop: Community Report

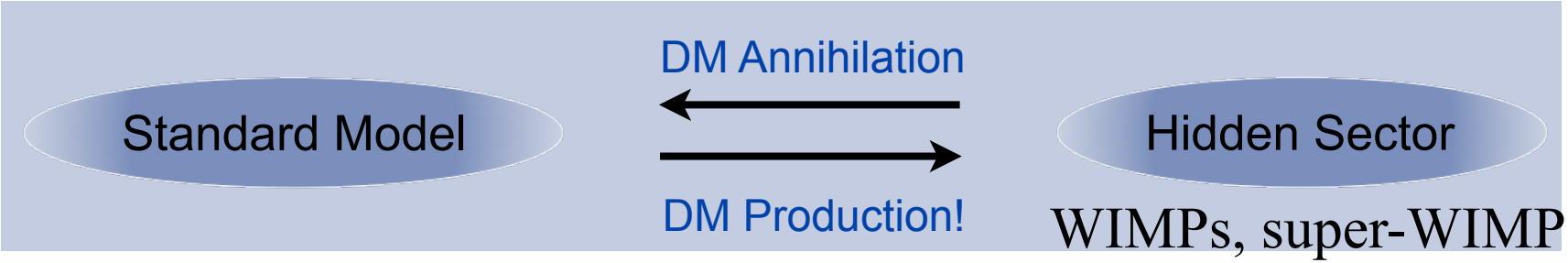
Jim Alexander (VDP Convener),[1] Marco Battaglieri (DMA Convener),[2] Bertrand Echenard (RDS Convener),[3] Rouven Essig (Organizer),[4,*] Matthew Graham (Organizer),[5,†] Eder Izaguirre (DMA Convener),[6] John Jaros (Organizer),[5,‡] Gordan

CERN PBC exercise led by Lamont, Jaeckel, Valee

BSM-PBC: G. Lanfranchi++



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)

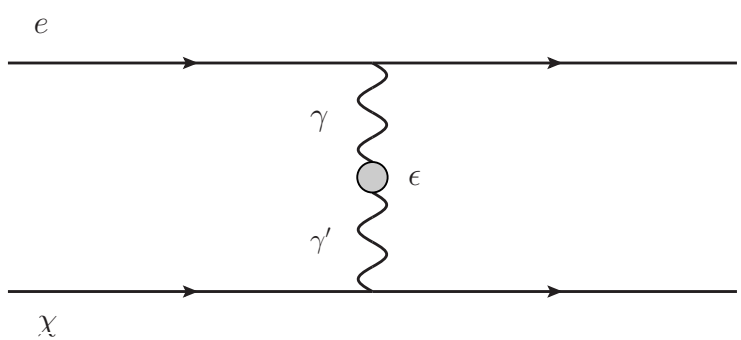
Light mediators allow to speculatively tie several anomalies to the possible effects of WIMP dark matter.

A simple model of dark sector

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

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

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

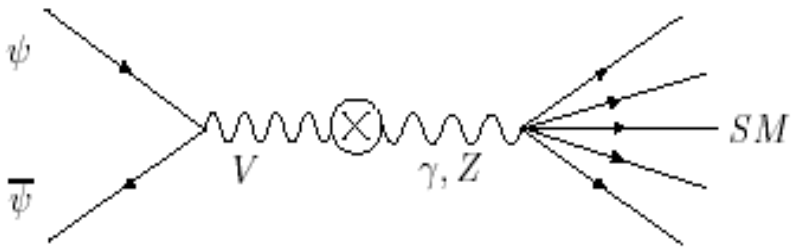


- "Effective" charge of the "dark sector" particle χ is Q = e × ε (if momentum scale q > m_V). At q < m_V one can say that particle χ has a non-vanishing *EM charge radius*, $r_\chi^2 \simeq 6\epsilon m_V^{-2}$.
- Dark photon can "communicate" interaction between SM and dark matter. Very light χ can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

Dark sectors provide model-building flexibility

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

$m_{mediator} > m_{WIMP}$



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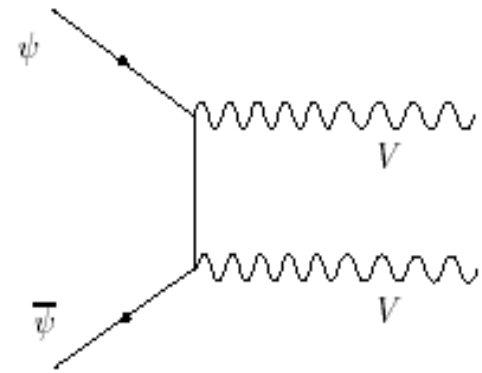

Second regime of annihilation into on-shell mediators (called *secluded*) does not have any restrictions on the size of mixing angle ε.

Allows also for freeze-in abundance, which is typically $\sim \varepsilon^2$.

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

…….

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

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.

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

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Vector

scalar

HNL

ALPs

Experimental proposals, mostly CERN

- *SHiP* — *Beam Dump*
- *NA62+* — *Flavour, possible BD*
- *FASER* — *LHC add-on*
- *MATHUSLA* — *large LHC add-on*
- *Codex-B* — *LHC add-on*
- *MilliQan* — *LHC add-on*
- *NA64* — *missing mom*
- *KLEVER* — *flavour*
- *REDTOP* — *fixed target*
- *IAXO* — *axion exp*
- *ALPs-II* — *axion exp*
- ……..

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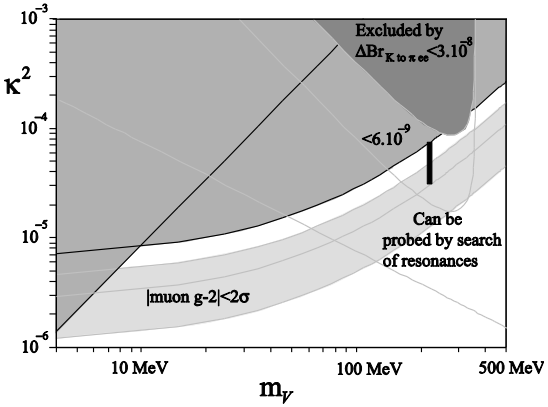
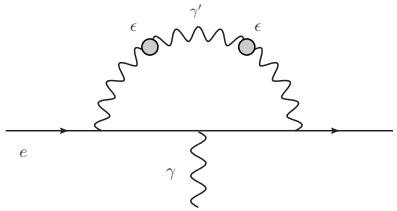
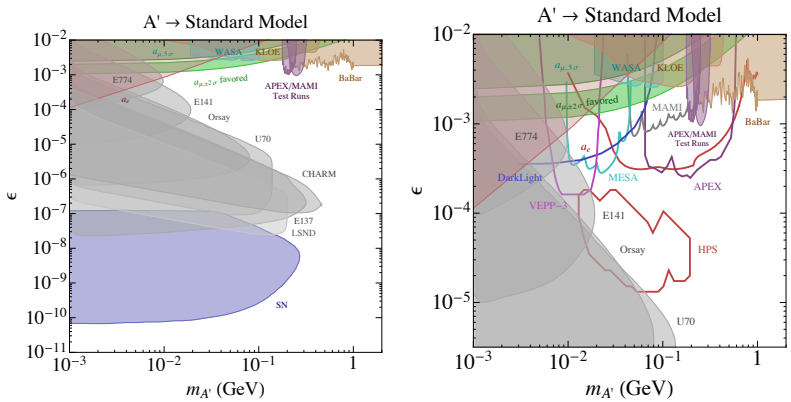
Search for dark photons



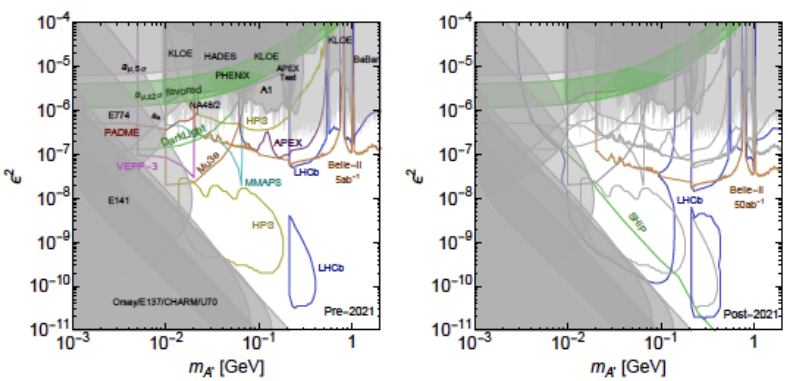


Dark photon with kinetic mixing ~ 10^{-3} is the simplest model that can account for anomalous $\Delta a_\mu \sim 3\ 10^{-9}$, MP, 2008



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

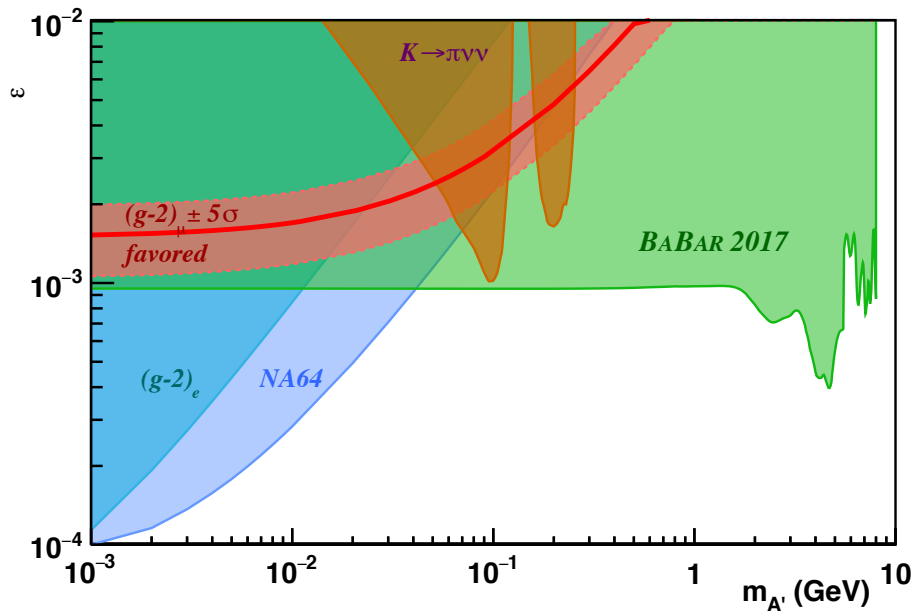
By 2018, there is a large community in place ("Cosmic Vision" summary, 100s of authors, 2017), where the search for dark photon is one of the priorities. (My hypothesis from 2008 is ruled out.)



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

Constraints on invisibly decaying "dark photons"

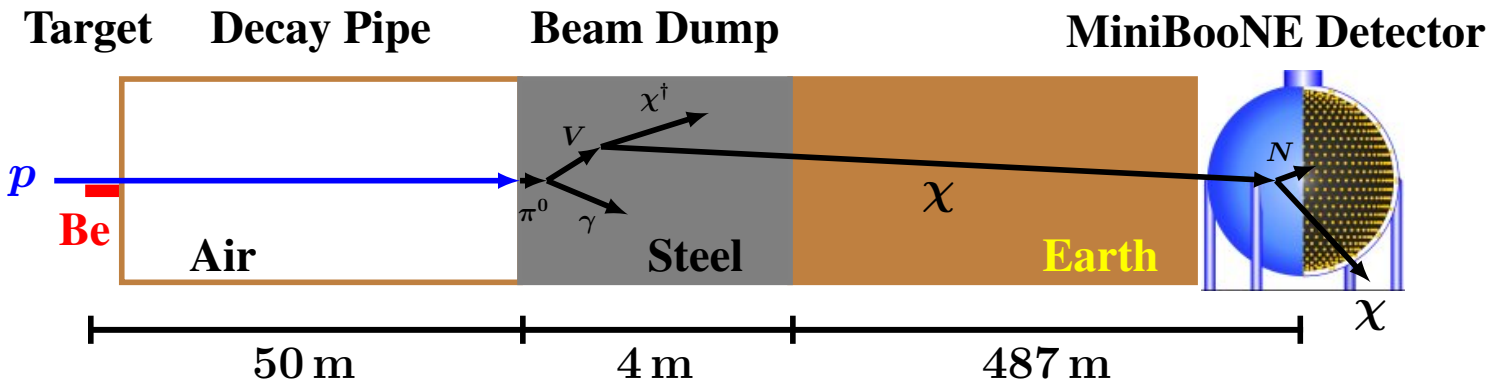
If dark photon decays invisibly, for example to a pair of DM particles, the search for dark photon is the search for "anomalous energy loss", such $e^+e^- \rightarrow \gamma + A' \rightarrow \gamma + \chi\chi$

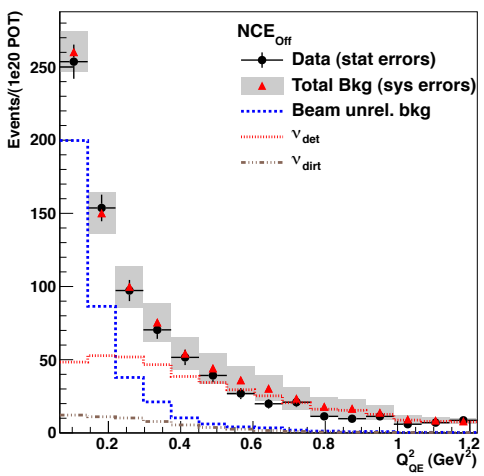


- Complementary results from NA64, BaBar and Kaon decays
- Covers all of the dark photon parameter space, decaying invisibly, consistent with alleviating the muon g-2 discrepancy
- *Belle-II will be able to significantly improve sensitivity*

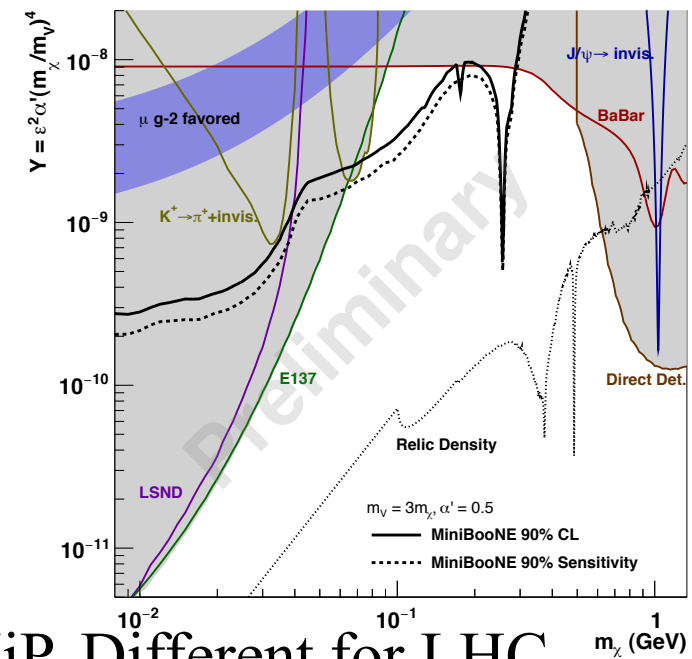
MiniBooNE search for light DM

arXiv:1702.02688, PRL 2017



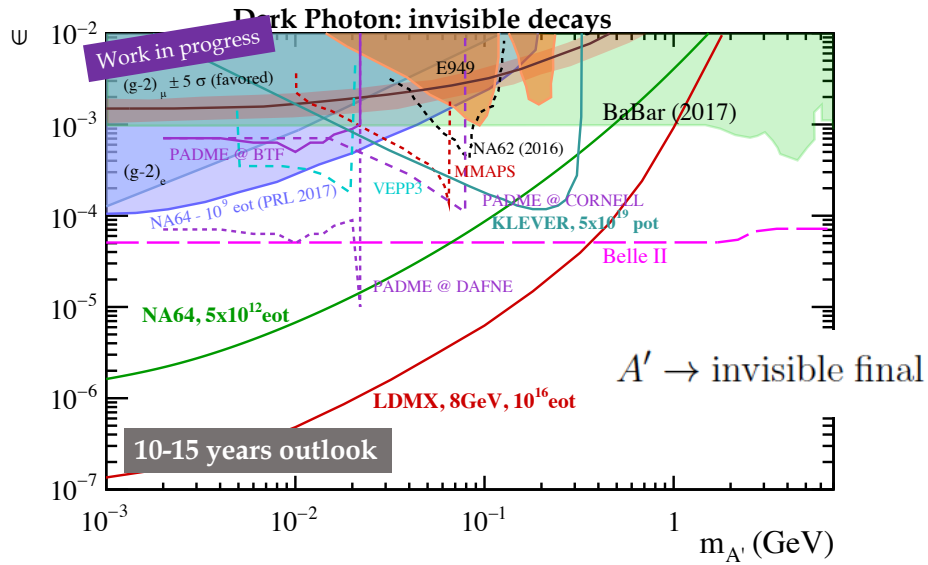


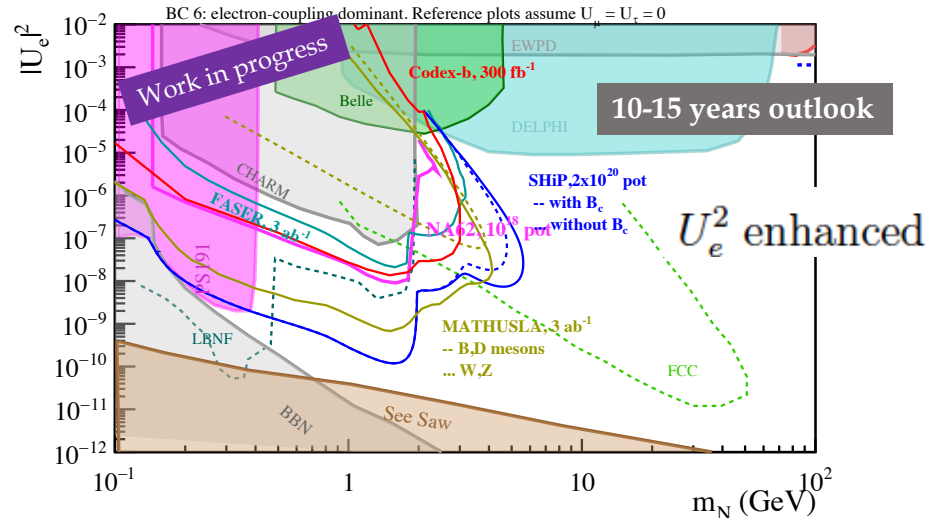
	#events	uncertainty
BUB	697	
ν_{det} bkg	775	
ν_{dirt} bkg	107	
Total Bkg	1579	14.3% (pred. sys.)
Data	1465	2.6% (stat.)

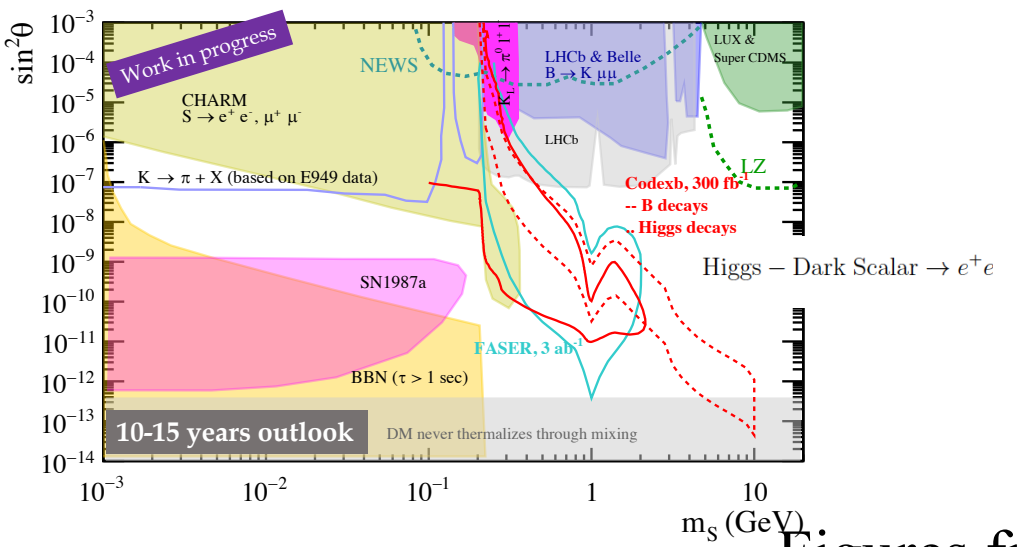


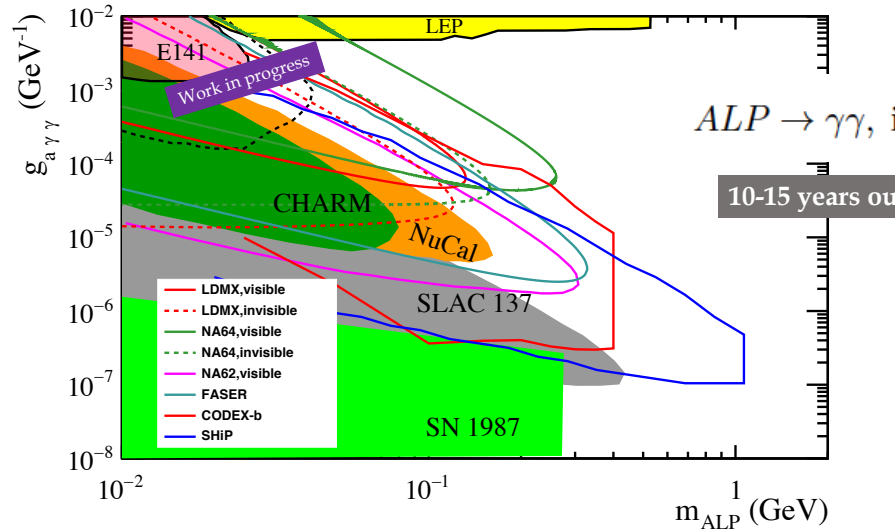
One can perform same style of searches at SHiP. Different for LHC where typically DM is missing energy.

Highlights from recent (June 2018) PBC meeting









Figures from G. Lanfranchi summary talk

Conclusions

- *11 benchmark cases that PBC has identified are extremely simple, and many naturally admit dark matter.*
- PBC will assess the reach of existing and proposed experiments to these models.
- *Including the LHC experimental reach on the same plot (within same models) would be a great plus.* Already now some results are available (heavy HNLs), GeV-scale dark photons from LHCb.
- Having a combined workshop sometime in the future would also be desirable.