Searches for light new physics

Maxim Pospelov

U of Minnesota and FTPI

Pair production of dark particles in meson decays

M. Hostert, K. Kaneta, M. Pospelov, e-print 2005.07102

Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report

J. Beacham (Ohio State U., Columbus (main)), C. Burrage (U. Nottingham), D. Curtin (Toronto U.), A. De Roeck (CERN), J. Evans (Cincinnati U.), J.L. Feng (UC, Irvine), C. Gatto (INFN, Naples & NIU, DeKalb), S. Gninenko (Moscow, INR), A. Hartin (U. Coll. London), I. Irastorza (U. Zaragoza, LFNAE) *et al.* *Show all 33 authors*

Jan 20, 2019 - 150 pages

- CERN-PBC-REPORT-2018-007
- e-Print: arXiv:1901.09966 [hep-ex]

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Plan

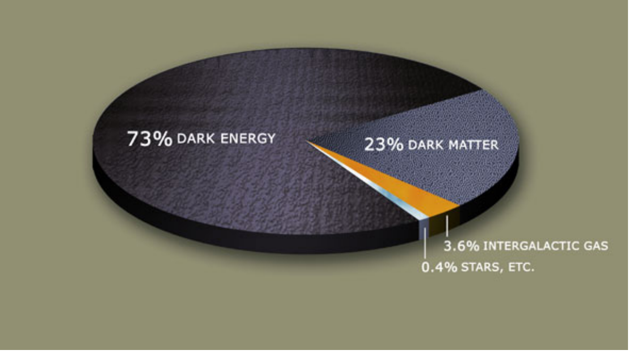
1. *Introduction.* Broad look at dark sectors.

2. Experimental "anomalies" and their interpretation with light particles.

3. Models that increase $K_L \rightarrow \pi^0 +$ missing energy decay.

4. Dark sector portals and CERN PBC benchmark models.

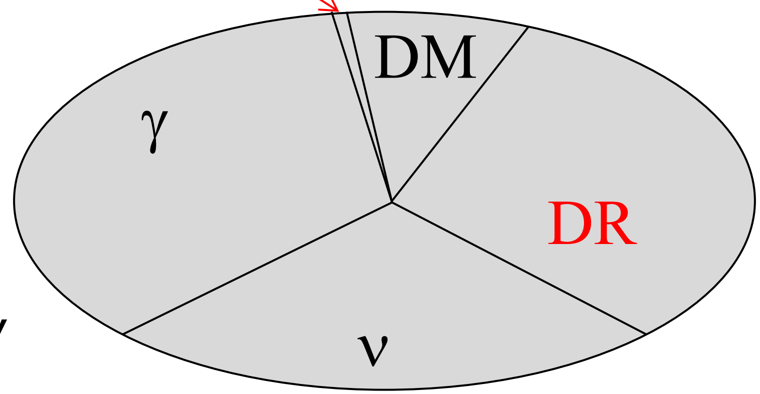
5. Conclusions



Is there a similar chart for *number densities*? Looks very different

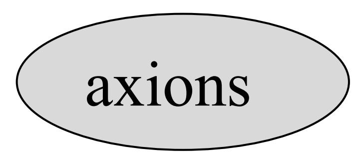
Atoms

In Energy chart they are 4%. In number density chart ~ 5×10^{-10} relative to γ



We have no idea about DM number densities. (WIMPs ~ 10^{-8} cm^{-3}; axions ~ 10^{9} cm^{-3}. Dark Radiation, Dark Forces – Who knows!).

Number density chart for axionic universe:



Lack of precise knowledge about nature of dark matter leaves a lot of room for existence of dark radiation, and dark forces – dark sector in general.

New IR degrees of freedom = light (e.g. sub-eV) beyond-Standard-Model states

Typical BSM model-independent approach is to include all possible BSM operators once very heavy new physics is integrated out

$L_{SM+BSM} = - m_H^2 \, (H^+{}_{SM} H_{SM})$ + all dim 4 terms $(A_{SM}, \psi_{SM}, H_{SM})$ +

(Wilson coeff. $/\Lambda^2$) $\times$ Dim 6 etc $(A_{SM}, \psi_{SM}, H_{SM})$ + …

But is this framework really all-inclusive – it is motivated by new heavy states often with sizeable couplings?

The alternative possibility for New Physics – weakly coupled light new physics - is equally viable

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(W.coeff. $/\Lambda^2$) $\times$ Dim 6 etc $(A_{SM}, \psi_{SM}, H_{SM}) + \ldots$

all lowest dimension portals $(A_{SM}, \psi_{SM}, H, A_{DS}, \psi_{DS}, H_{DS}) \times$ portal couplings

+ dark sector interactions $(A_{DS}, \psi_{DS}, H_{DS})$

SM = Standard Model

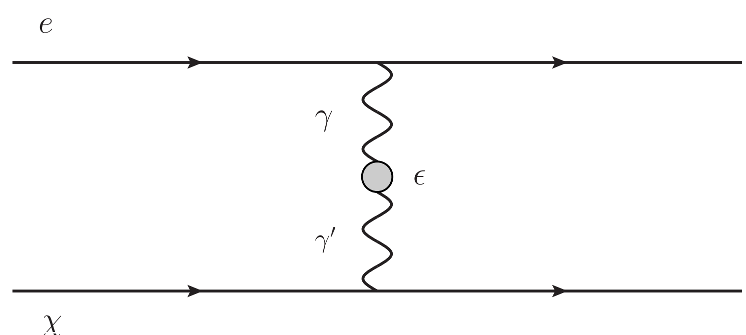
DS – Dark Sector

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*, $r_\chi^2 \simeq 6\epsilon m_V^{-2}$.
- Dark photon can "communicate" interaction between SM and dark matter. Very light χ can be possible.

Classes of portal interactions

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

……….

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

Excellent framework for light DM

some WIMP examples

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

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

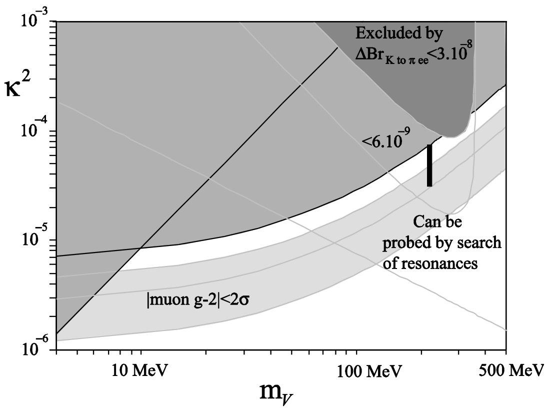
- Fermionic dark matter talking to the SM via a "dark scalar" that mixes with the Higgs. With $m_{DM} > m_{mediator}$.

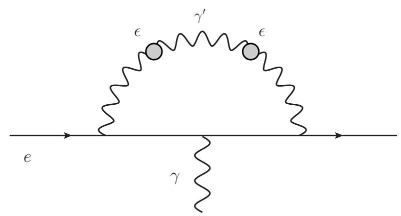
$$\mathcal{L} = \overline{\chi}(i\partial_\mu \gamma_\mu - m_\chi)\chi + \lambda \overline{\chi}\chi S + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - AS(H^\dagger H)$$

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

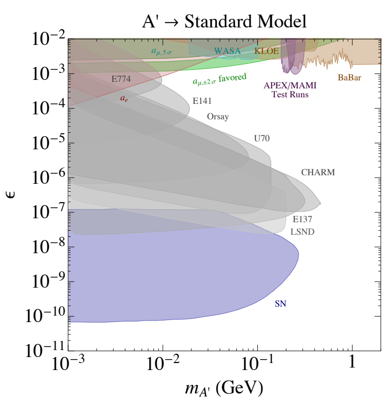
Take away point: *with lots of investment in searching for DM with masses > GeV, models with sub-GeV DM can be a blind spot.*

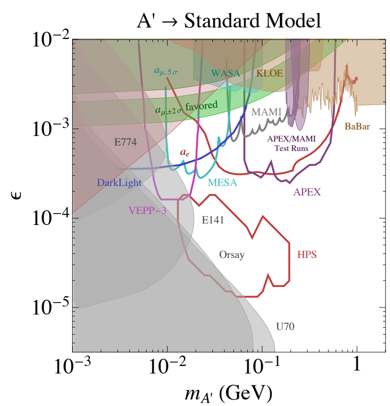
g-2 motivation for dark photons



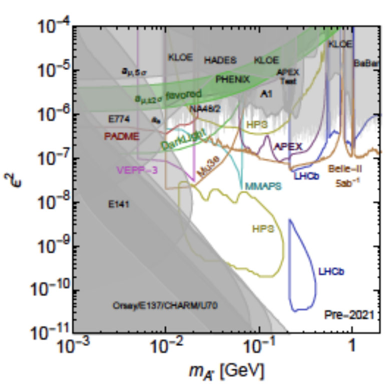


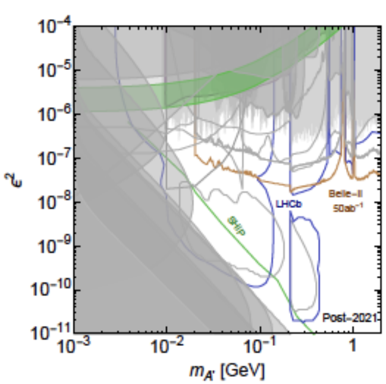
Dark photon with kinetic mixing $\sim 10^{-3}$ is the simplest model that can account for anomalous $\Delta a_\mu \sim 3\ 10^{-9}$, MP, 2008





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

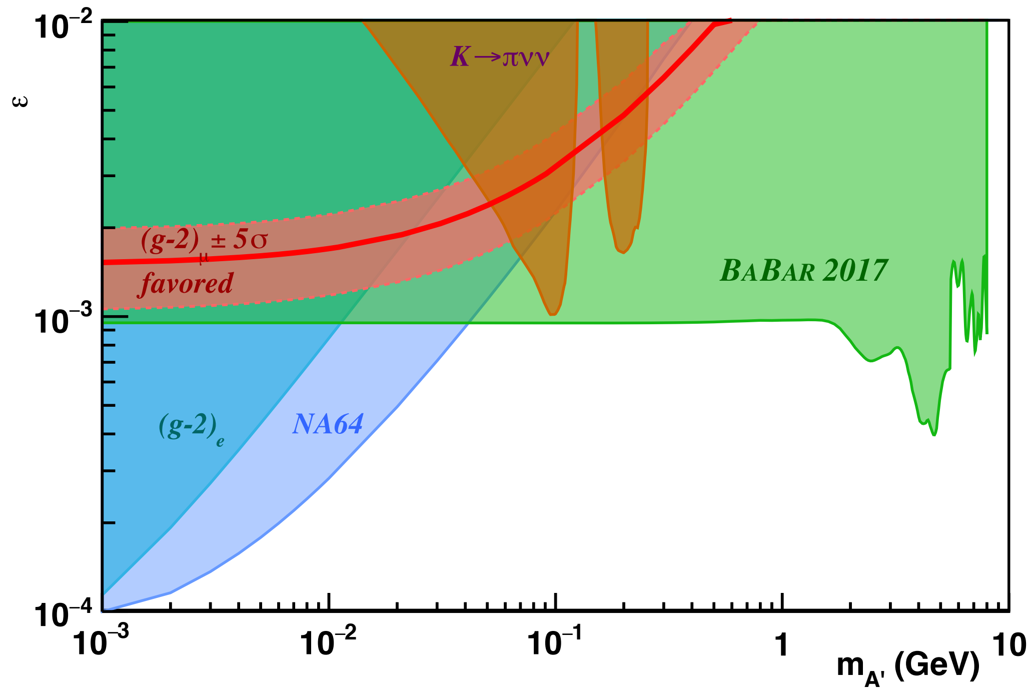




By 2018, there is a large community in place ("Cosmic Vision" summary, 100s of authors, 2017), where the search for dark photon is one of the priorities.

Constraints on invisibly decaying “dark photons”

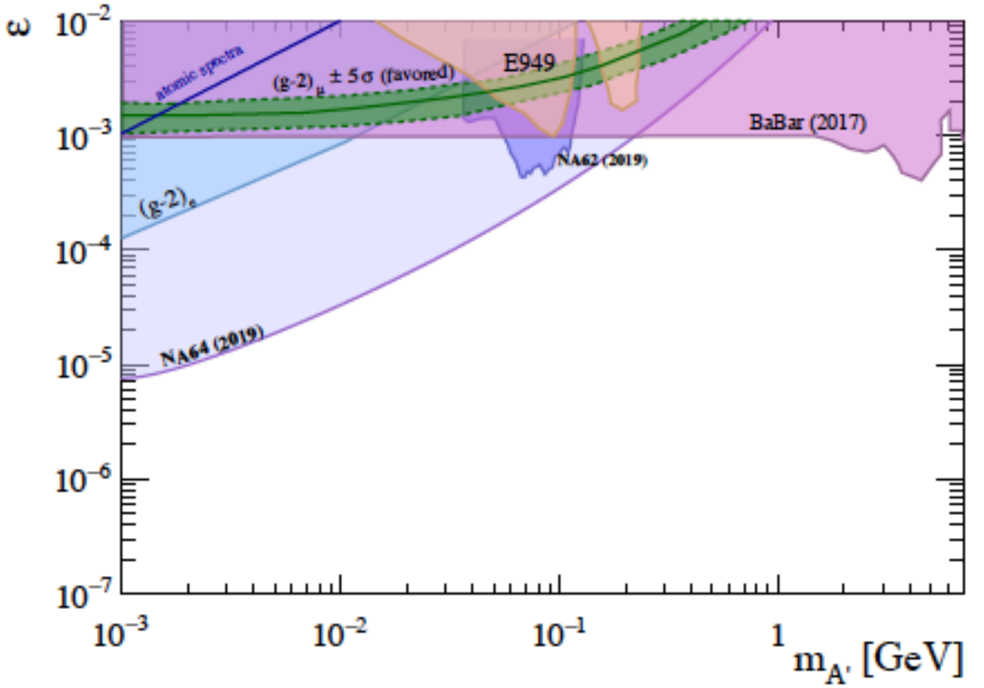
If dark photon decays invisibly, for example to a pair of DM particles, the search for dark photon is the search for “anomalous energy loss”, such $e^+e^- \rightarrow \gamma + A' \rightarrow \gamma + \chi\chi$



- 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

Updated plot

New results from NA62 and NA64



Plot is from recent review M. Fabbrichesi, E. Gabrielli, G. Lanfranchi, 2005.01515

NA64, in particular, probes the part of parameter space motivated by the freeze-out dark matter.

Are there any more models that can correct g-2?

This year [hopefully] the Fermilab-based experiment is going to present results that more than double the existing dataset.

Independently of that one can question whether other models can provide viable upward correction to g-2.

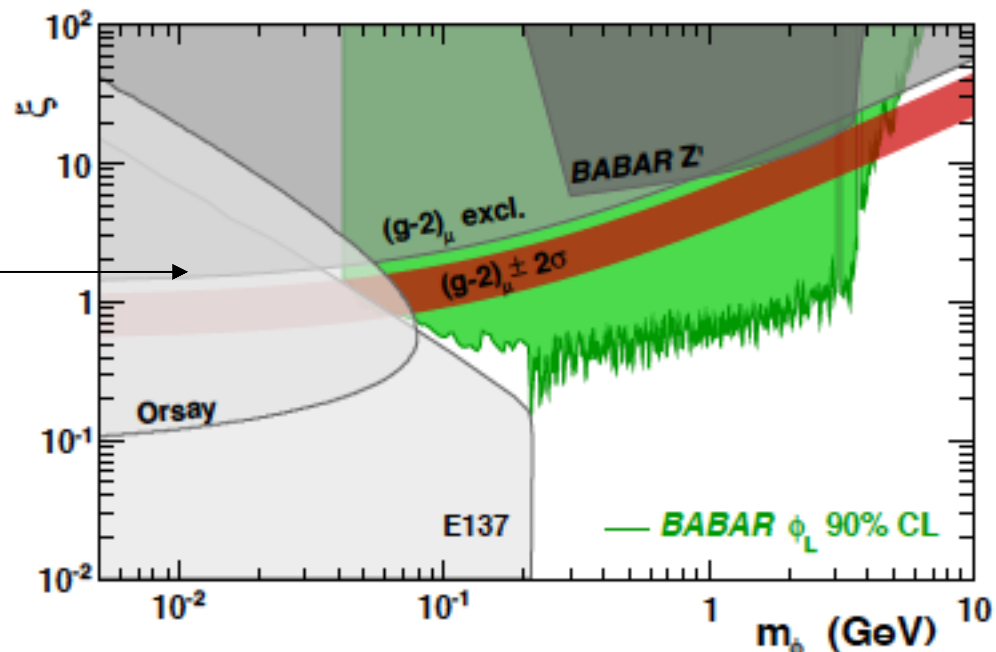
- Models based on muon-tau lepton number, with gauge coupling at $g \sim 10^{-3}$ level and mass above ~ 10 MeV (BBN) and below ~ 210 MeV (4-muon signal at B-factories, + trident neutrino + high-energy excludes higher masses). These models can be probed with NA64 style experiment with incoming muons (Gninenko, Krasnikov et al.)
- Models based on scalars coupled to leptons with "new Yukawa" at the level of SM Yukawa, but with light scalars. They are hard to build (see e.g. Batell et al., 2016, Chen et al, 2015)

Recent constraints from BaBar

In a minimal flavour violation framework, the coupling to leptons is proportional to their masses. Therefore the bremsstrahlung of scalars in $e^+ + e^- \rightarrow$ tau$^+$ + tau$^-$ + Scalar, with its subsequent decay to electrons or muons, is the promising channel (Batell et al, 2017)

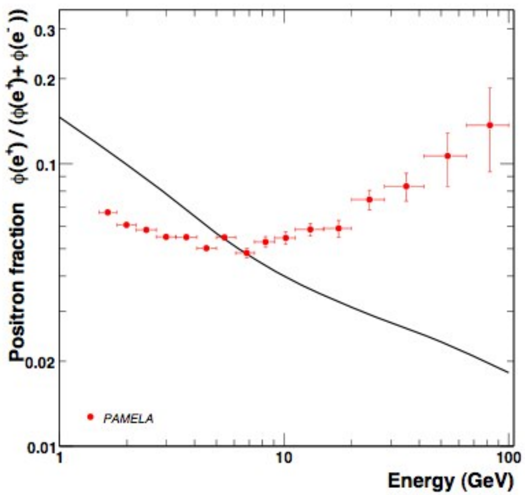
In an impressive new analysis led by B. Echenard and B. Shuve, Babar published a constraint from a corresponding search:

Beam dump regions are slightly too optimistic, based on old "recast", and will be updated soon.

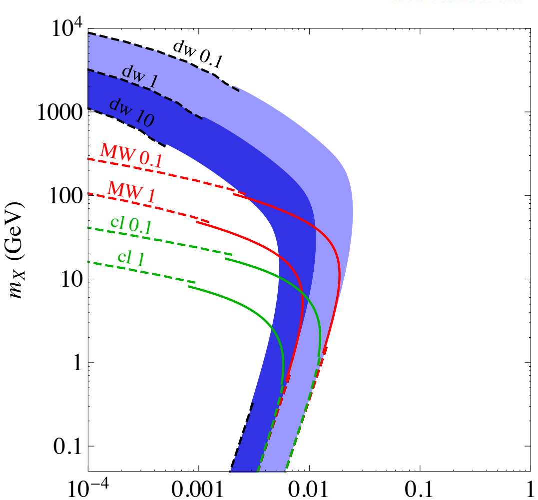


New Physics paradigm that include light particles have enormous flexibility in ”explaining” anomalies

- For example, cosmic positron fraction (“Pamela anomaly”)



Light new mediator particles V can A. dynamically enhance the annihilation cross section at low velocity, B. kinematically limit the annihilation products to electrons and positrons.



- Self-interaction of dark matter can be an attractive possibility to address over-concentration of cold dark matter in the central parts of galactic haloes. Self-scattering cross section of 10^{-24} cm^2/GeV implies that either DM or mediator is light, or both. (Plot from Tulin et al.)

Light particles allow by-passing "no-go" theorems

- Something very topical: KOTO vs NA62, or is it possible to see a large signal in neutral kaons in a generic new physics model?
- (*s*-*d* current)×(neutrino[dark] current) implies the limit on
  $K_L \to \pi^0 \nu\nu$ from $K^+ \to \pi^+ \nu\nu$ (Grossman-Nir bound).
- GN evasion with light particles (G. Hou, Kaon 2016, Kitahara et al. 1909.11111)
- Example model (MP): $L = (\Lambda_{sd})^{-1} (s\, i\gamma_5\, d)\, SP + (\Lambda_{dd})^{-1} (d\, i\gamma_5\, d)\, SP$

S - new light scalar, P - new light pseudoscalar, $m_S > m_P + m_\pi$.

- $K_L \to PS \to PP\pi^0$ occurs as sequential 2-body decays, with decay $K^+ \to SP\,\pi^+$, being phase space suppressed [forbidden], and parity forbidden.
- Naive estimate [eyeing "KOTO signal"]: $\Lambda_{sd} \sim 10^{12}$GeV. $\Lambda_{dd} \sim 10^{7}$GeV.

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- [Some numbers are off, but the idea is viable. Let's discuss it in detail]

Theorists are “un-phased” by the lack of published experimental paper by KOTO

Many interesting ideas are expressed of how light particles can induce Koto-like signal and be consistent with everything else:

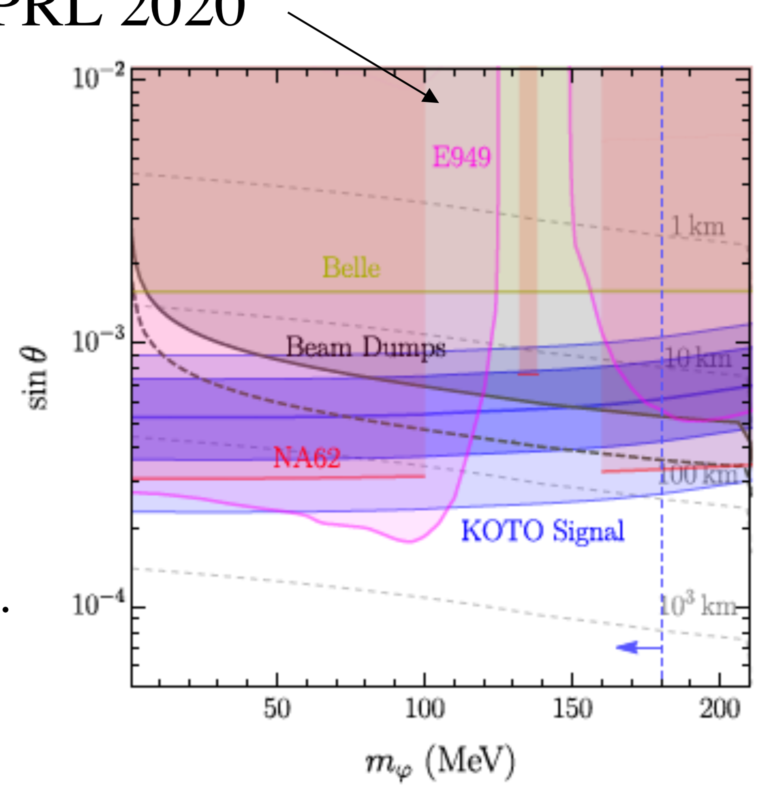
Kitahara, Okui, Perez, Soreq, Tobioka, PRL 2020

Egana-Ugrinovic, Homiller, Meade, PRL 2020

Ziegler, Zupan, Zwicky, May 2020

Gori, Perez, Tobioka, May 2020

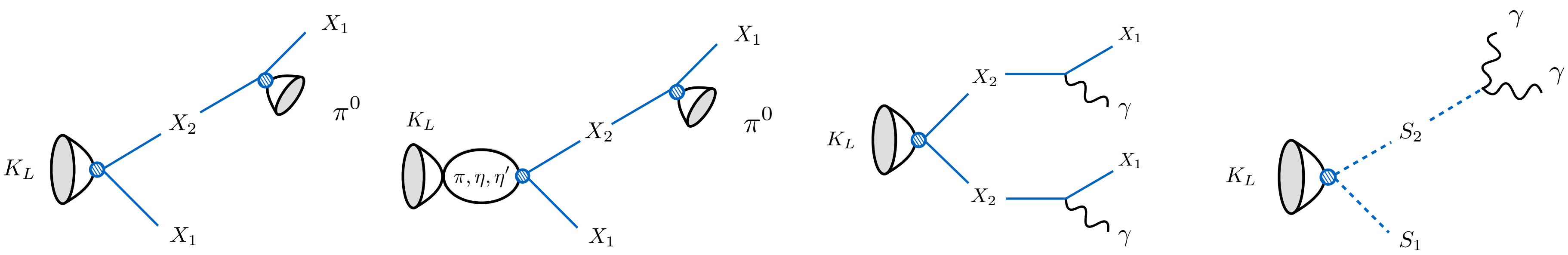
…..



The region that “survives” is close to pion mass, as the constraint from charged pion decay loosen up due to 2 pion background.

K_L decays to pairs of dark states

At a pheno level many such scenarios are plausible:



A) π^0 PRODUCTION B) DIPOLE PORTAL C) π^0 IMPOSTOR

We base our considerations on MFV type models:

$$O^V_{sd} = g^V_{sd}(\overline{s_L}\gamma_\mu d_L) \times J^\mu_X; \qquad O^S_{sd} = g^S_{sd} m_s(\overline{s_R} d_L) \times J_X,$$

$$g^V_{sd}(\overline{s_L}\gamma_\mu d_L) \subset a\overline{Q_L} Y_U Y_U^\dagger \gamma_\mu Q_L; \qquad g^S_{sd} m_s(\overline{s_R} d_L) \subset b\overline{D_R} M_D^\dagger Y_U Y_U^\dagger Q_L$$

$$J^\mu_X = X_1 \partial^\mu X_2 - (\partial^\mu X_1) X_2, ..., \qquad J_X = X_1^2,\, X_2^2,\, X_1 X_2, ...,$$

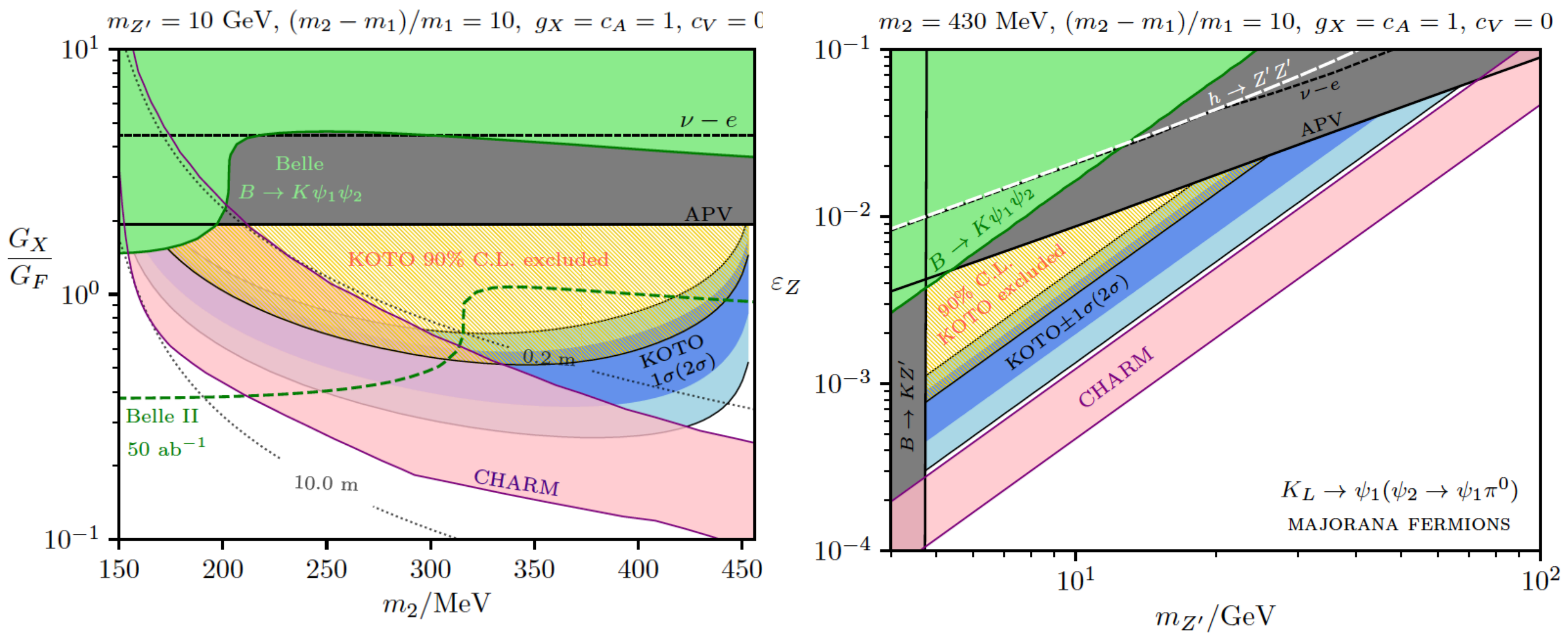
Lightest particle can be “promoted” into dark matter.

Viable models exist based both on Z' and Higgs portal interactions

In defense against obvious criticism of more conservative colleagues: why spending time on "signal" that is not even published, while it is not even clear whether experiment (KOTO) works properly. *We [theorists] are often driven by trying to understand what is possible and what is not. Are no-go theorems solid, or have exceptions etc? In many cases (e.g. proton charge radius discrepancy) any BSM-type model is so contrived that even 7σ discrepancy would not convince you it is new physics.*

Same parameter can regulate K_L and X_2 decays

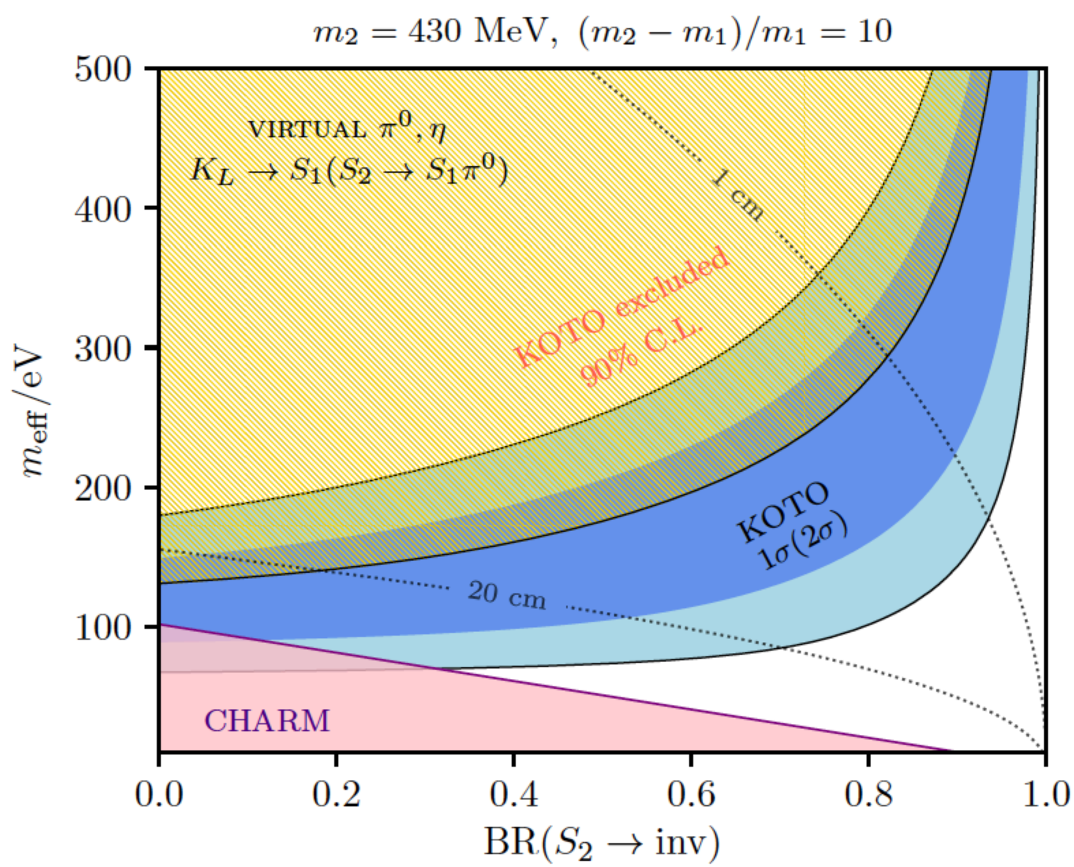
Models based on Z' exchange and the mass mixing of Z-Z':



Model based on extra Higgs exchange for the down-type quarks

$$\mathcal{L} = \frac{v\lambda^{\Phi}}{\sqrt{2}m_A^2}(y_d^{\Phi}\overline{d}i\gamma_5 d + y_s^{\Phi}\overline{s}i\gamma_5 s)S_1 S_2.$$

$$\mathcal{L} = m_{eff}S_1S_2\left(\pi^0 + \eta \times \frac{2}{\sqrt{3}} \times \frac{y_s^{\rm SM}}{y_d^{\rm SM}}\right) \simeq m_{eff}S_1S_2\left(\pi^0 + 22. \times \eta\right)$$



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

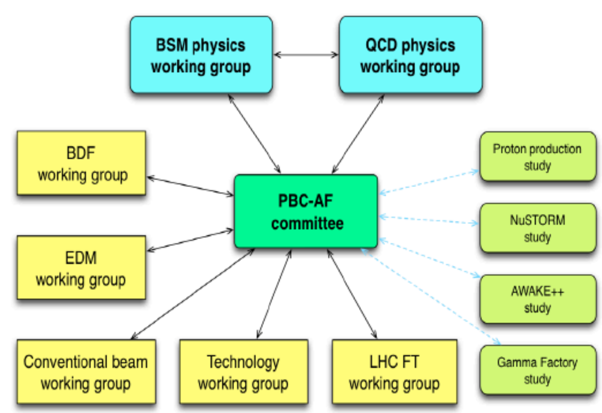
… very long list of authors

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

Jaeckel, Lamont, Vallee



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

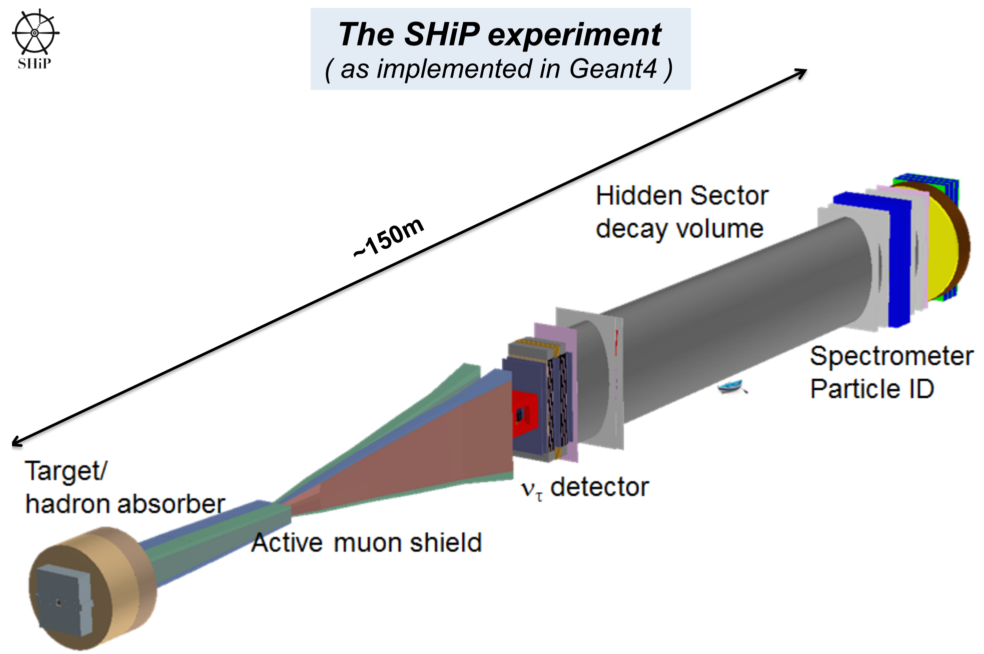
- *SHiP* — *Beam Dump*
- *NA62+* — *Flavour, possible BD*
- *FASER* — *LHC add-on*
- *MATHUSLA* — *large LHC add-on*
- *Codex-B* — *LHC add-on*
- *MilliQan* — *LHC add-on*
- *NA64* — *missing momentum*
- *KLEVER* — *flavour*
- *REDTOP* — *fixed target*
- *IAXO* — *axion exp*
- *ALPs-II* — *axion exp*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

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

Future [monster-size] direction

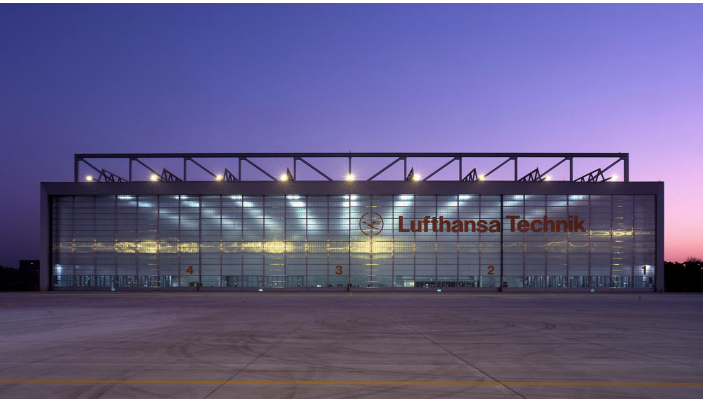
To improve on sensitivity to light dark matter in beam dump/fixed target experiments.

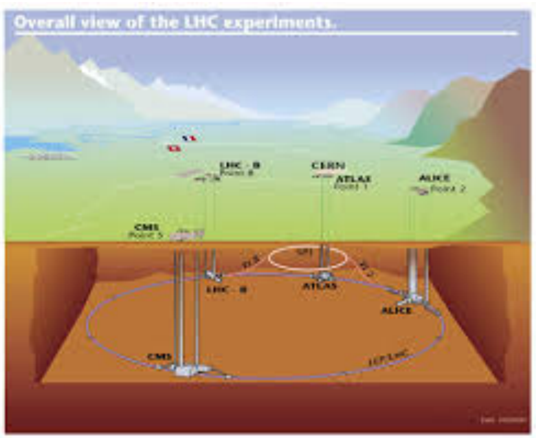
SHIP proposal at CERN: 10^{21} of 400 GeV protons on target



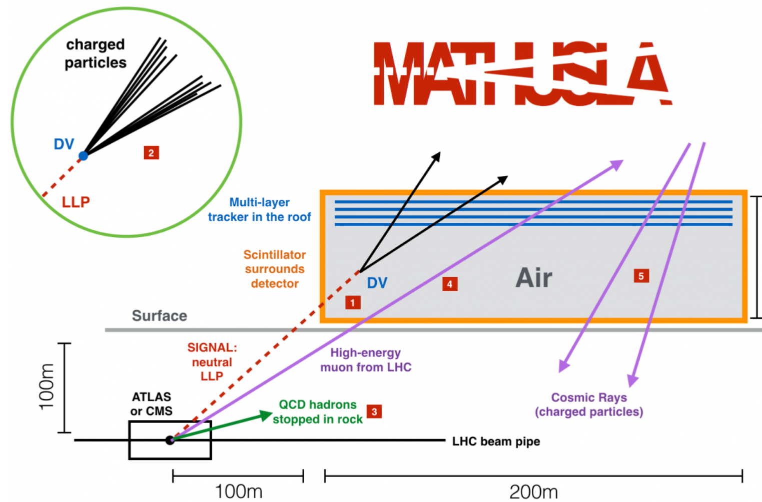
SHiP may become the most important project at CERN after LHC

MATHUSLA proposal





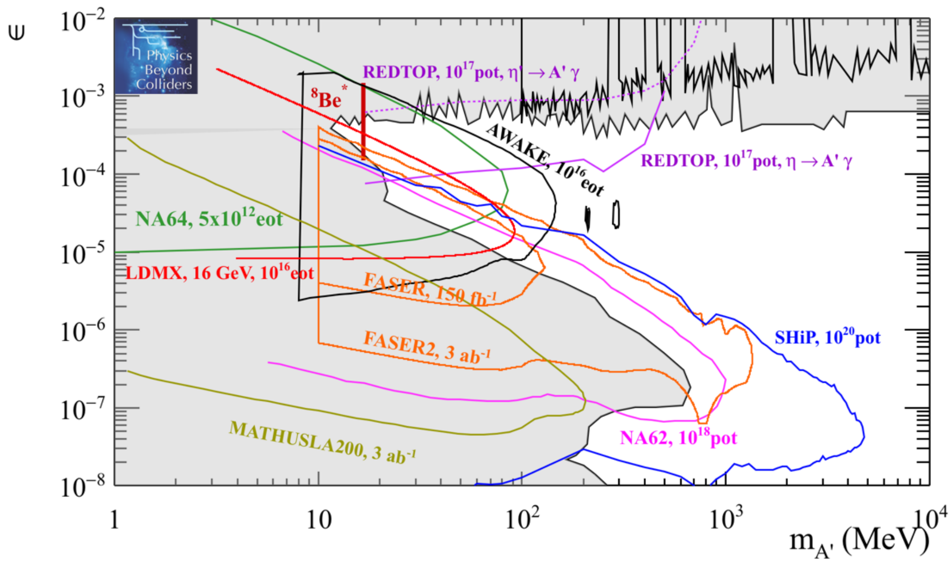
Industrial size O(200 m) hollow detector to be put on the surface, near the forward region of a particle detector at the LHC, e.g. CMS.

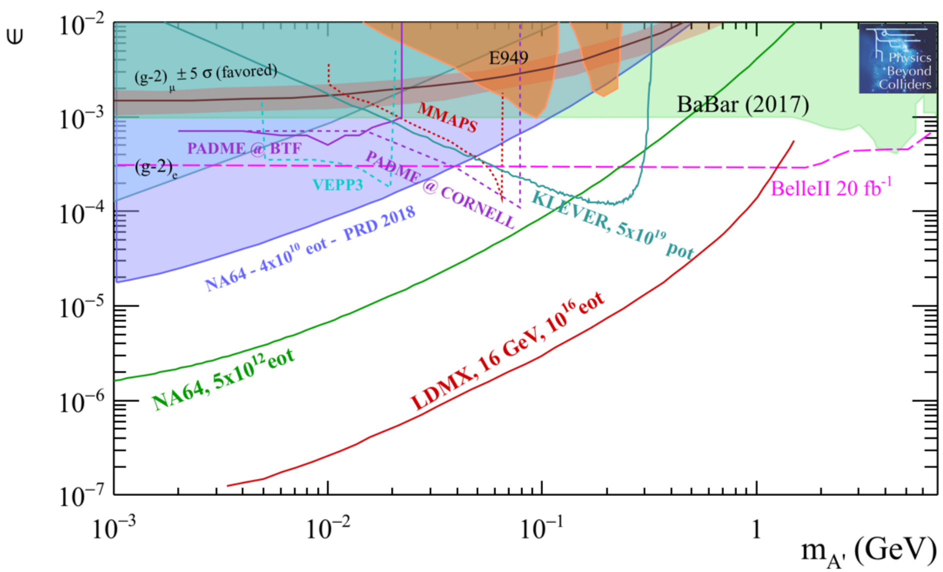


Time correlation between events at the LHC and decay vertex inside a large detector can drastically cut the number of background cosmic events

Highlights from recent PBC publication

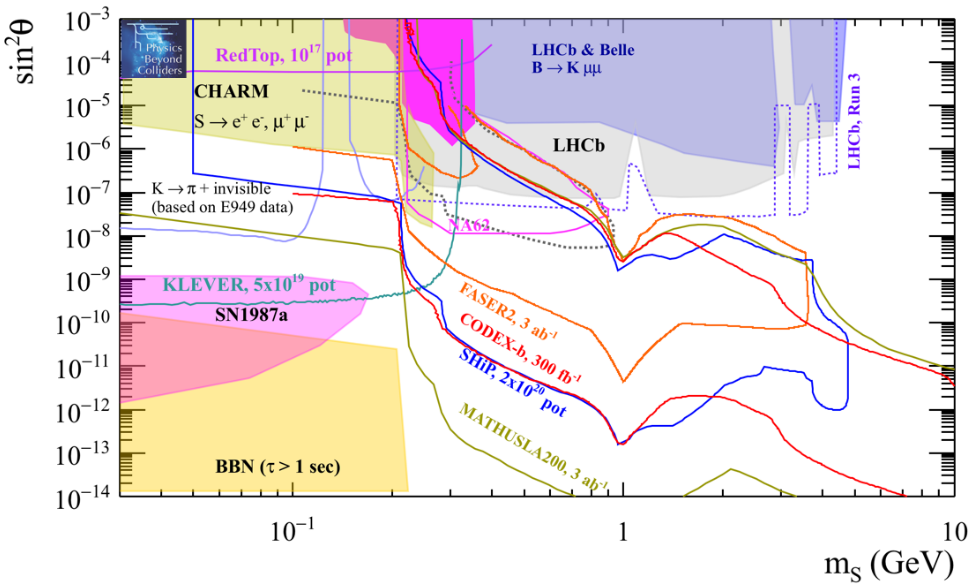
G. Lanfranchi et al, BSM group





Benchmark cases 1 and 2, models with visible [top] and invisible [bottom] decays of dark photons

Highlights from recent PBC publication



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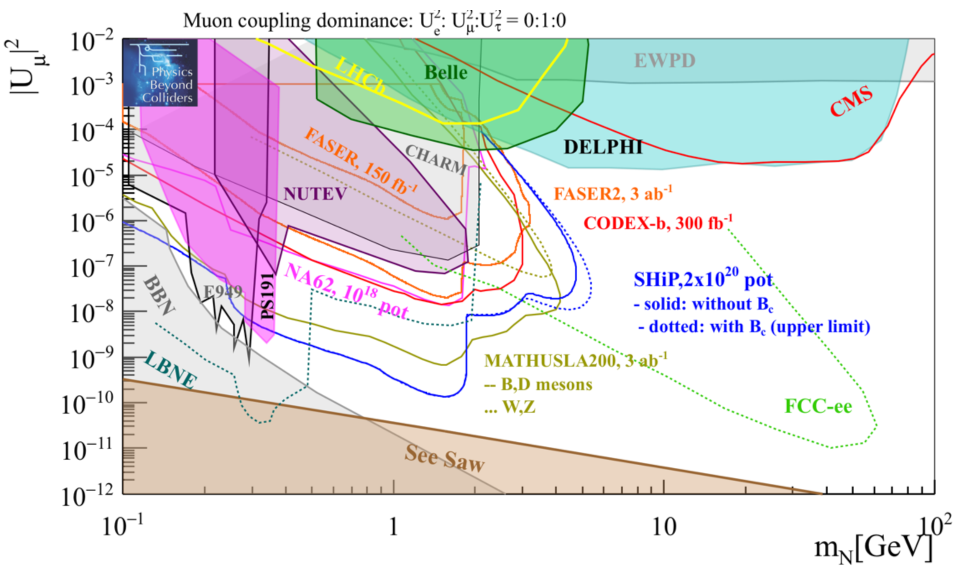
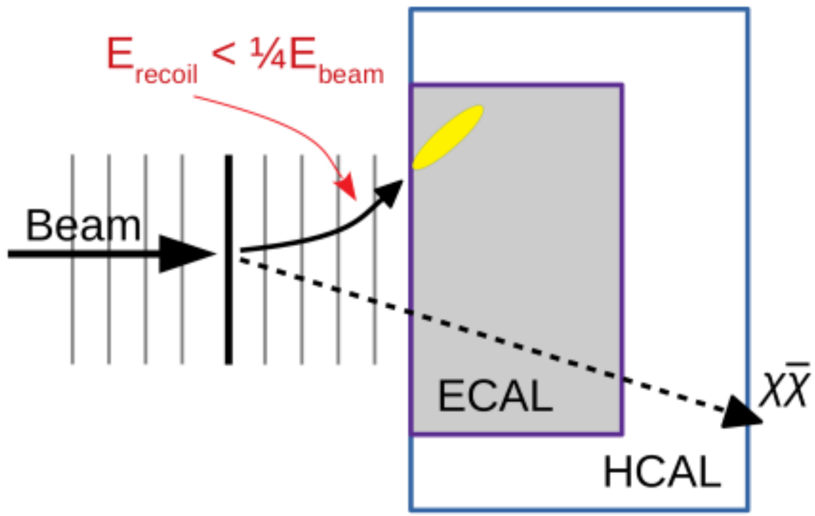


Benchmark cases 4 and 6, models with Higgs-mixed scalar [top] and muonic HNL [bottom]

Example of future hadronic physics challenges

Take NA64 and LDMX experiments

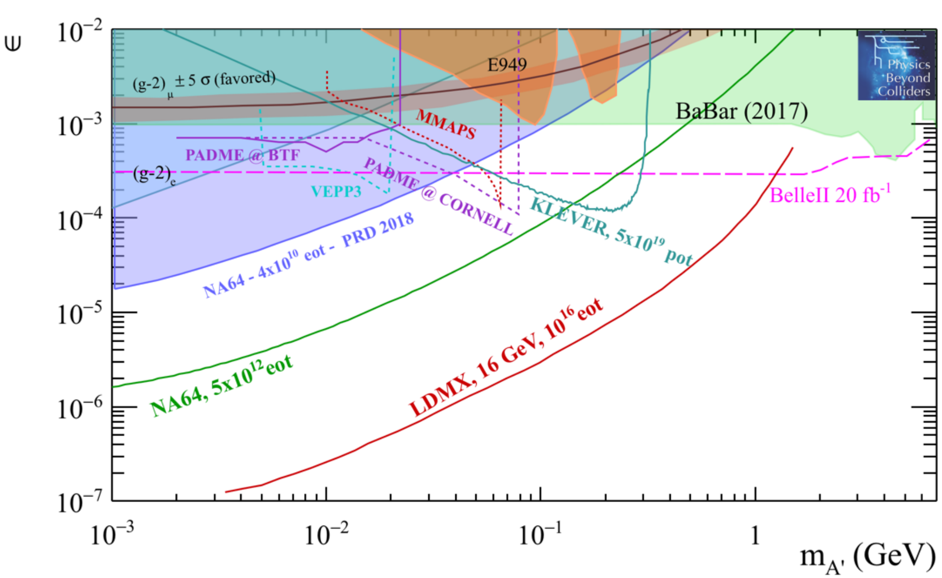


Eventual aim: to reach 10^{-14} level from the electron bremsstrahlung cross section.

It is clear that the goal is highly sensitive to rare nuclear processes:

Nucleus + e → e(lower energy) + lots of not so energetic nuclear debris

New level of understanding of rare photo-nuclear processes is required.



Conclusions

1. IR frontier is a modification of SM by light and weakly coupled BSM fields. ALPs or dark photons with small mass are an example.

2. New set of models [not necessarily too complex] was developed that gives enhanced $K_L \rightarrow$ dark state decays, with subsequent decay of one state into another with the production of neutral pion. No counterpart in charged Kaon decays.

3. PBC exercise has come up with an attempt of systematic approach to light New Physics in the sub-10-GeV regime. CERN will decide which experiments eventually to pursue [in additional to multi-decade LHC project].