Beyond Standard Model (BSM) MeV – GeV searches

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Thanks to contributions from experiments representatives

- **Codex-b** (LLPs from LHCb at 25m)- Michele Papucci
- **FASER** (LLPs from ATLAS at 450m)- Jonathan Feng
- **KLEVER** (K^0_L -> π^0 ν ν) - Cristina Lazzeronii
- **LDMX/e-LINAC** (electron beam dump) - Philip Schuster
- **MATHUSLA** (LLPs from ATLAS/CMS at 150m)- David Curtin
- **MilliQan** (millicharged particles at 33m from CMS) - Albert de Roeck
- **NA62-dump** ($K^+ \rightarrow \pi^+ \nu \nu$, $K^+ \rightarrow \mu^+ \nu_h$, $K^+ \rightarrow e^+ \nu_h$, $\pi^0 \rightarrow$ ν1ν2, $\pi^0 \rightarrow \gamma A'$, 400 GeV proton beam dump: ee, μμ, ππ, KK states for NHL, ALPs, A',S) - Tommaso Spadaro
- **NA64++** (dark particles in missing energy events in electron, muon , proton interactions)- Sergei Gninenko
- **SHiP** (proton beam dump with decay and target emulsion detectors) - Kostas Petridis
- **TauFV** (τ-> μ μ μ at BDF) - Guy Wilkinson
- **RedTop** ($\eta \rightarrow \gamma A' \rightarrow \gamma l^+ l^-$, $\eta \rightarrow \pi^0 S$; $S \rightarrow \mu^+\mu^-$ or e^+e^-) - Isabel Pedraza
- **LongLivedParticles@LHC** -(LLPs in LHC detectors) James Beacham

Possible scenarios in different mass range

- Low (sub eV) mass range: very weak couplings: axions and Axion Like ParticleS (ALPS) – see talk Giuseppe Ruoso
- Medium mass range (MeV-GeV): very weak couplings, light thermal Dark Matter, light mediators, Neutrino Minimal Standard Model (nuMSM)
- High Mass range (GeV-TeV): SUSY at LHC/FCC, direct DM detection, rare decays, flavor universality violation

BSM – Simplified models

- Dark Photons with or without dark decays
- Dark Scalars – Dark Higgs
- Axions and ALPS with photon coupling or fermion coupling or gluon coupling
- Heavy Neutral Leptons (HNL), Sterile Neutrino
- Details on Benchmark Cases BC1-BC11 – see talk of Clare Burrage and spare slides.

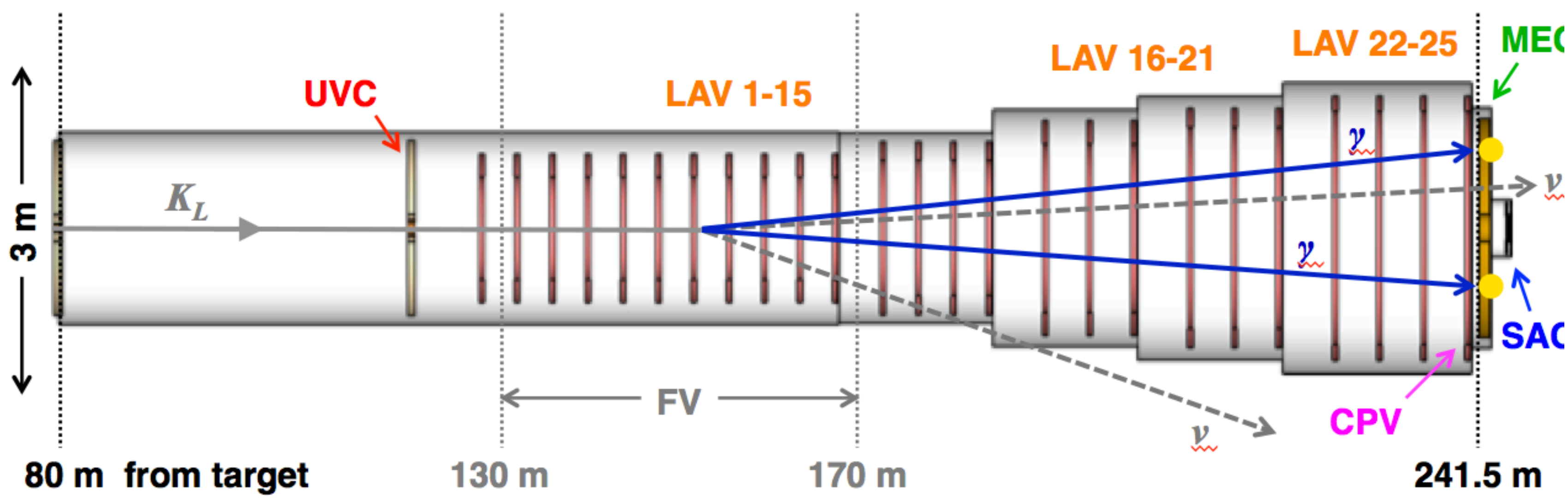
Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Sterile Neutrino, N	$y_N L H N$

How PBC projects address open questions

- Light Dark Matter and Mediators, Neutrino Minimal Model, search at fixed targets (MeV-GeV) (NA-62++dump, NA64++, SHIP , LDMX, REDTOP) and LHC interaction (FASER, MATUSLA, CODEX-B, MilliQan, LLP@ATLAS/CMS)
- New Physics at flavor sector (TeV and higher scales):
- KLEVER ($K^0_L \to \pi^0 \nu \nu$)
- TauFV $\tau \to \mu \mu \mu$ - see talk of Guy Wilkinson

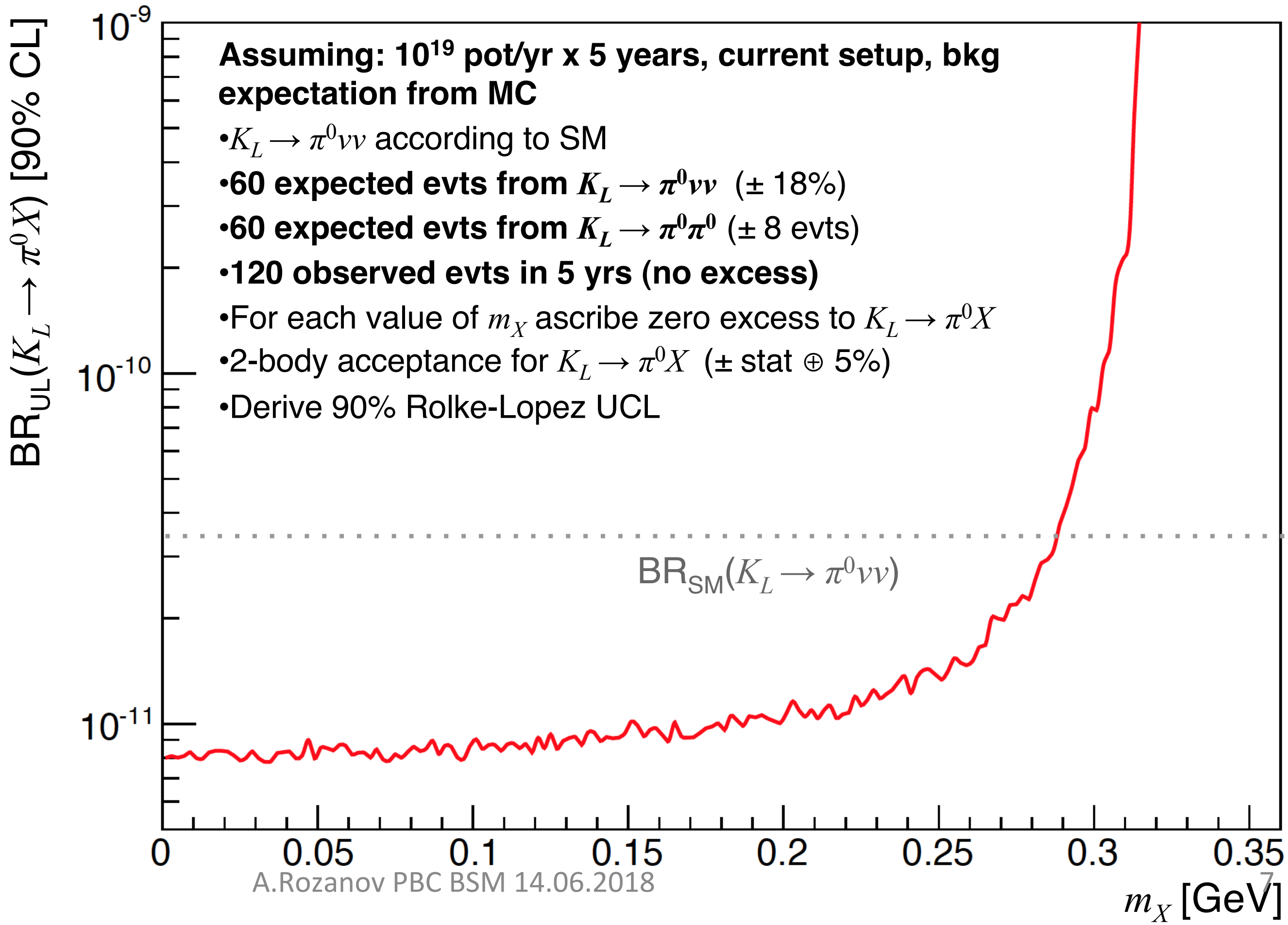
KLEVER:New physics up to TeV scales in loops

- $K^+ \rightarrow \pi^+ \nu \nu$ BR(SM)=$(8.4\pm1.0)\times10^{-11}$
  BR(exp)=$(17.1^{+11.5}_{-10.5})\times10^{-11}$
- $K^0_L \rightarrow \pi^0 \nu \nu$ BR(SM)=$(3.4\pm0.6)\times10^{-11}$
  BR(exp) < 2600×10^{-11} at 90% CL
- KLEVER proposal: in 5 years observe 60 SM events



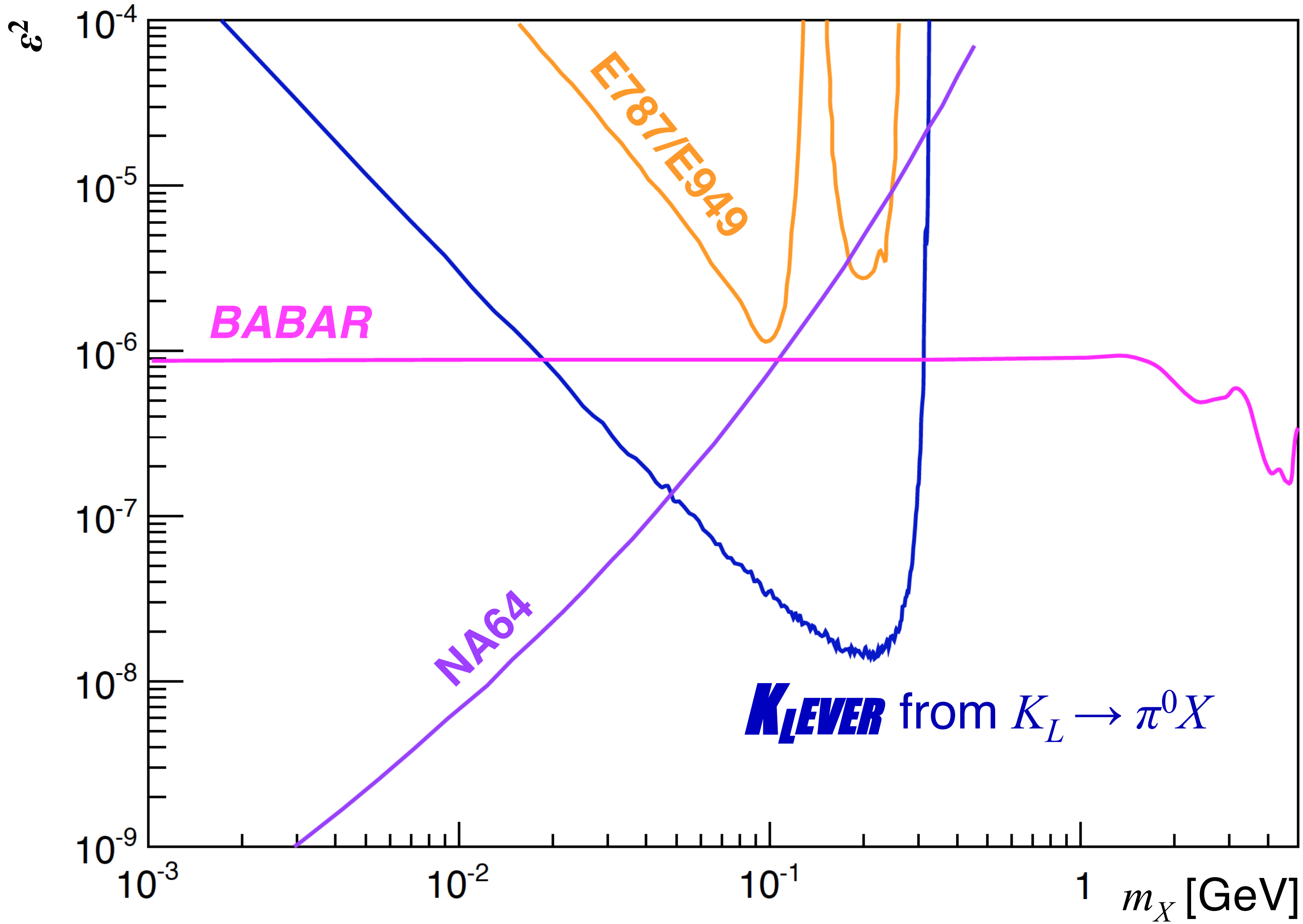
KLEVER: Limits $K_L \rightarrow \pi^0 X$ from $K_L \rightarrow \pi^0 \nu\nu$

- Full beam simulation in progress , reduce $\Lambda \rightarrow n\pi^0$ background by moving vertex region by 25 m downstream, compensate by new 8 mrad beamline, experimental optimization, 25 large angle vetos, LKr->preshower+e.m.calorimeter, Shashlyk prototype in Protvino

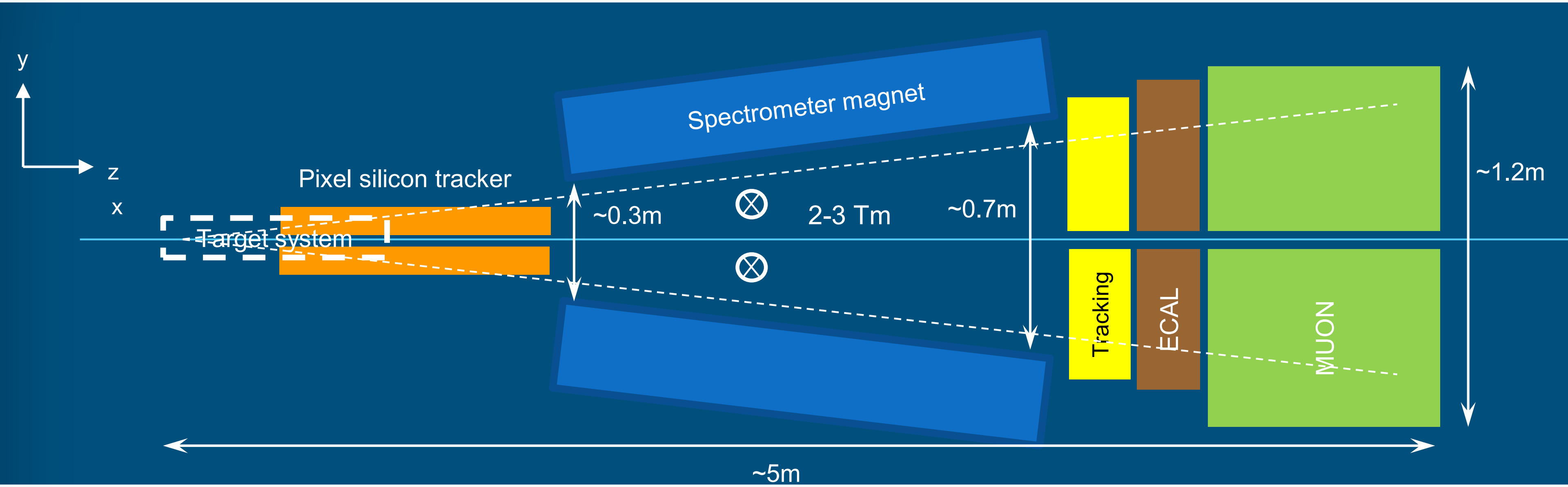


KLEVER: Limits dark photon from $K_L \to \pi^0 \nu\nu$

- Interpret as Davoudiasl, Lee, Marciano 2014 (E787/E949)
- Dark Photon decays to Dark Matter (BC2)

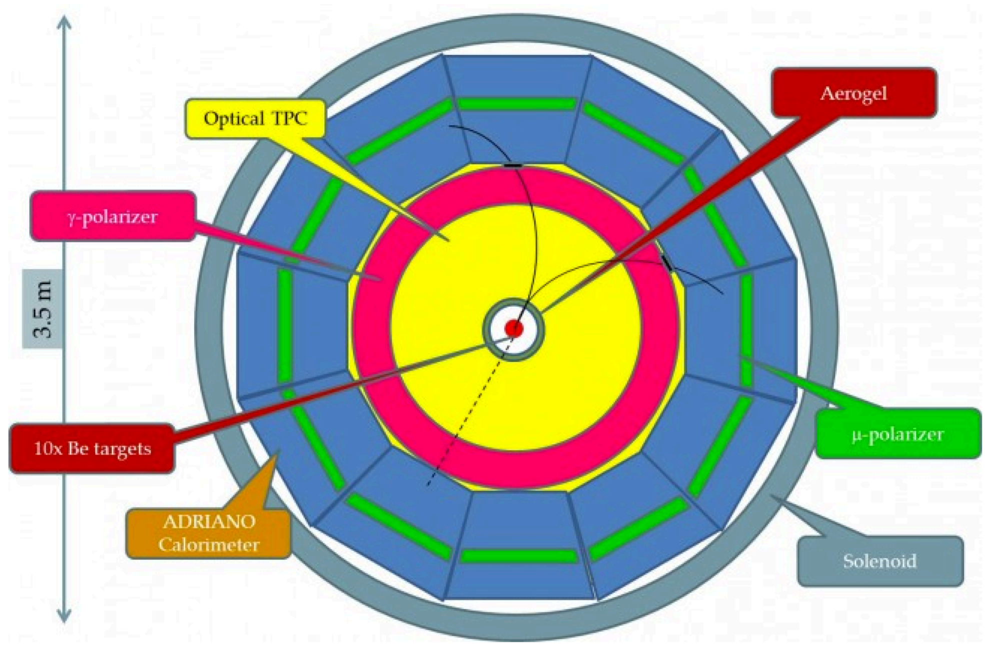


TauFV



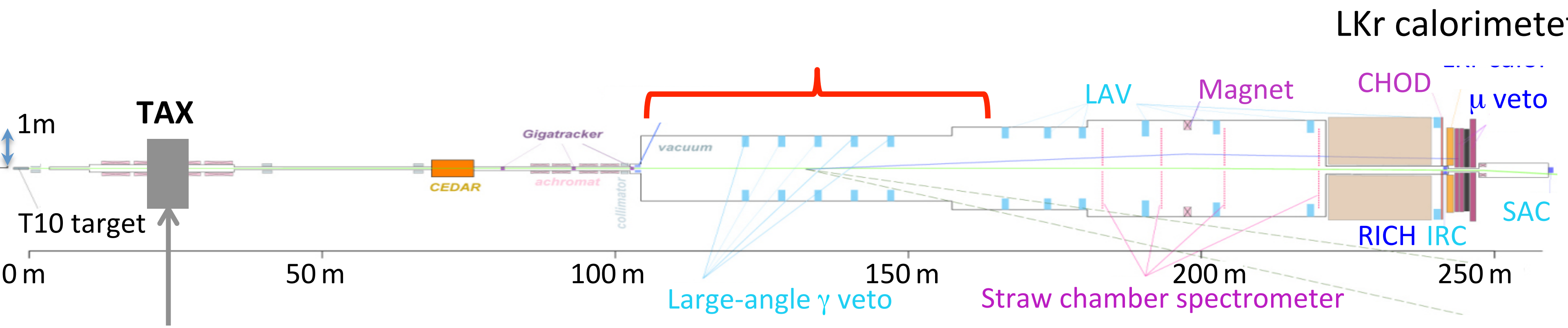
- $\tau \rightarrow \mu\ \mu\ \mu$ Lepton Flavor Violation (LFV) for example by new Z' (few TeV)
- In BDF line in front of SHIP, probably wire targets, use ~ 5% of the protons
- see talk Guy Wilkinson

REDTOP



- Rare Eta Decays with a TPC for Optical Photons
- 1.8-3.5 GeV proton beam at PS, request 10^{18} POT
- Use narrow width of η and η' for Dark Particle search
- $\eta, \eta' \to \gamma A' \to \gamma l^+ l^-$, $\eta \to \pi^0 S$; $S \to \mu^+ \mu^-$ or $e^+ e^-$
- see talk of Isabel Pedraza

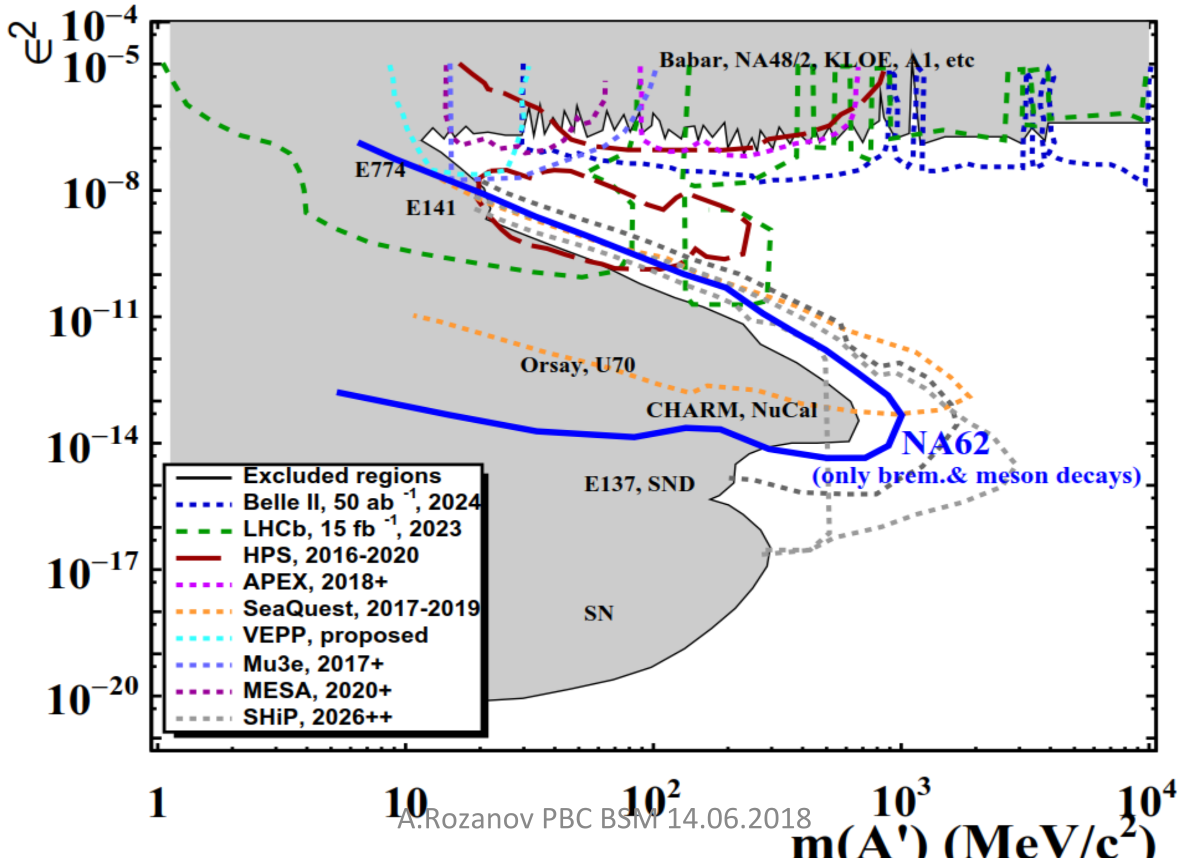
NA62++



- Originally: $K^+ \rightarrow \pi^+ \nu \nu$ decays
- After LS2: beam dump hidden sector search
- 400 GeV protons, 10^{18} pot/year
- 11 λ Cu target (TAX)
- 60 m long decay volume in vacuum
- 8m active muon shielding (Lau Gatignon)

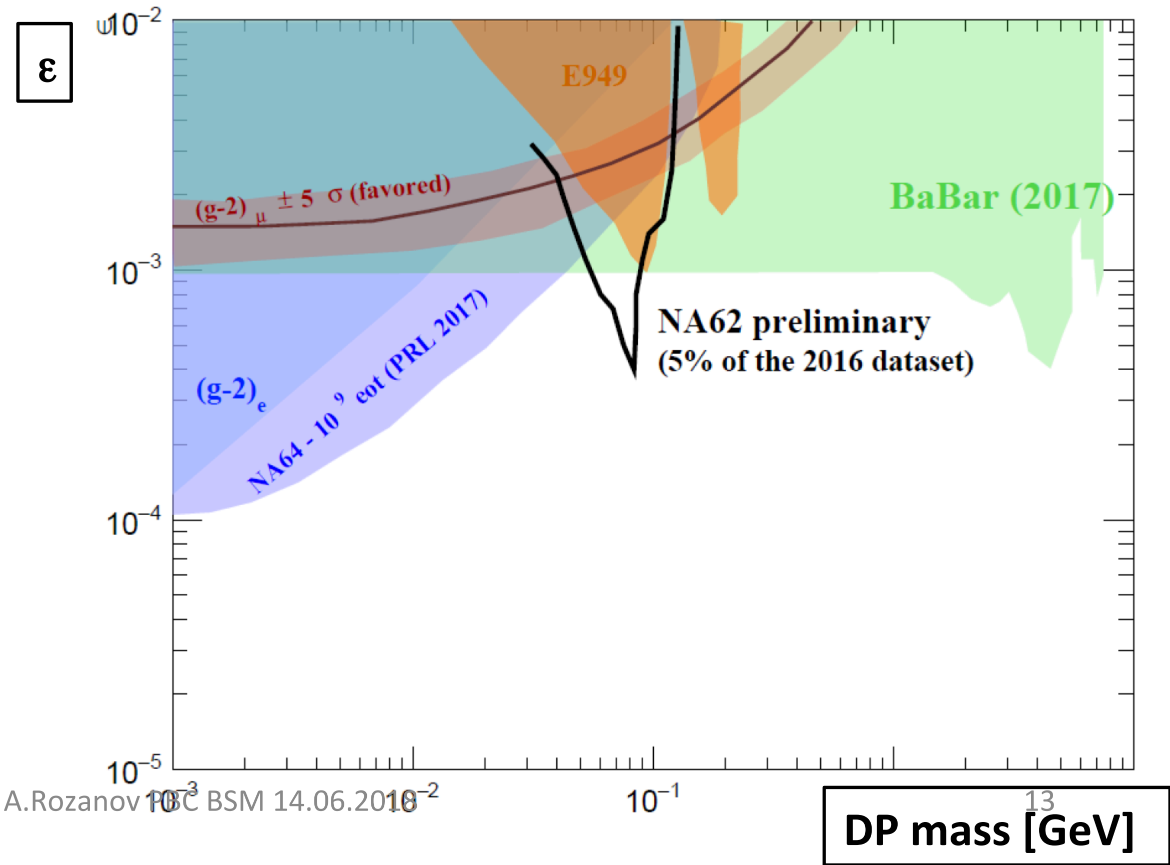
NA62++: visible dark photon (BC1)

- Decay $A' \rightarrow \gamma\gamma$
- 1×10^{18} pot
- Zero background assumed verified for data @ 4×10^{15} POT, toy MC, verified on full sim, with acceptance, trigger and efficiency included



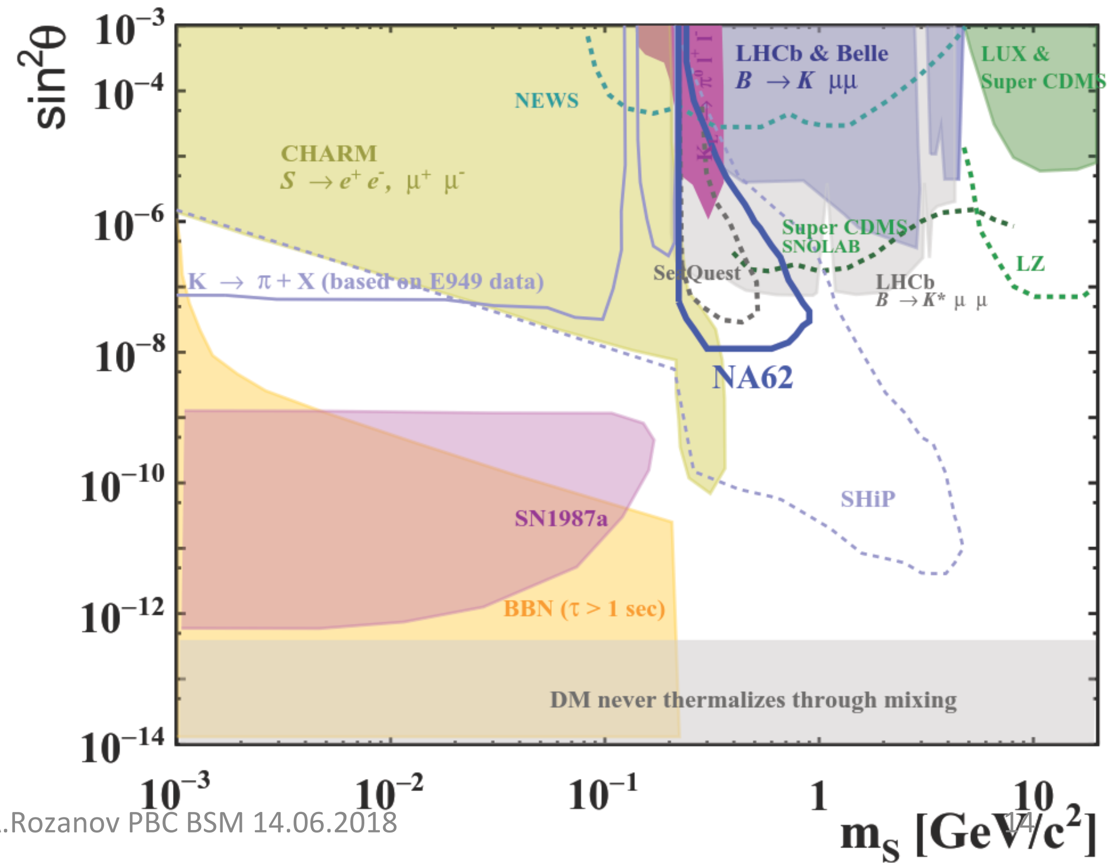
NA62++: invisible dark photon (BC2)

- Production: $\pi^0 \rightarrow A'\gamma$, Decay: $A' \rightarrow \chi\chi$
- BC2.1 $\alpha_{Dark} >> \varepsilon\alpha$ $M_{A'} > 2M_\chi$
- 5% of 2016 statistics [~2 10^8 tagged π^0's]
- Final sensitivity for 1 x 10^{18} pot needed



NA62++: Higgs mixed scalar λ=0 (BC4)

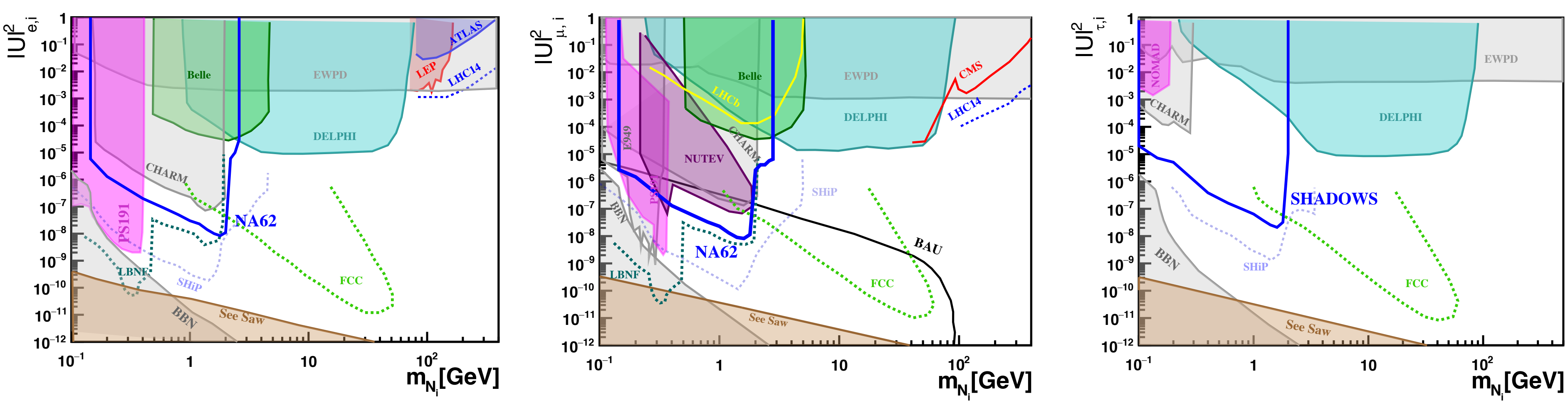
- no pair production
- toy MC, with acceptance, 1 x 10^{18} pot
- zero background assumed verified data @ few 10^{15} POT



NA62++: NHL (BC6, BC7, BC8)

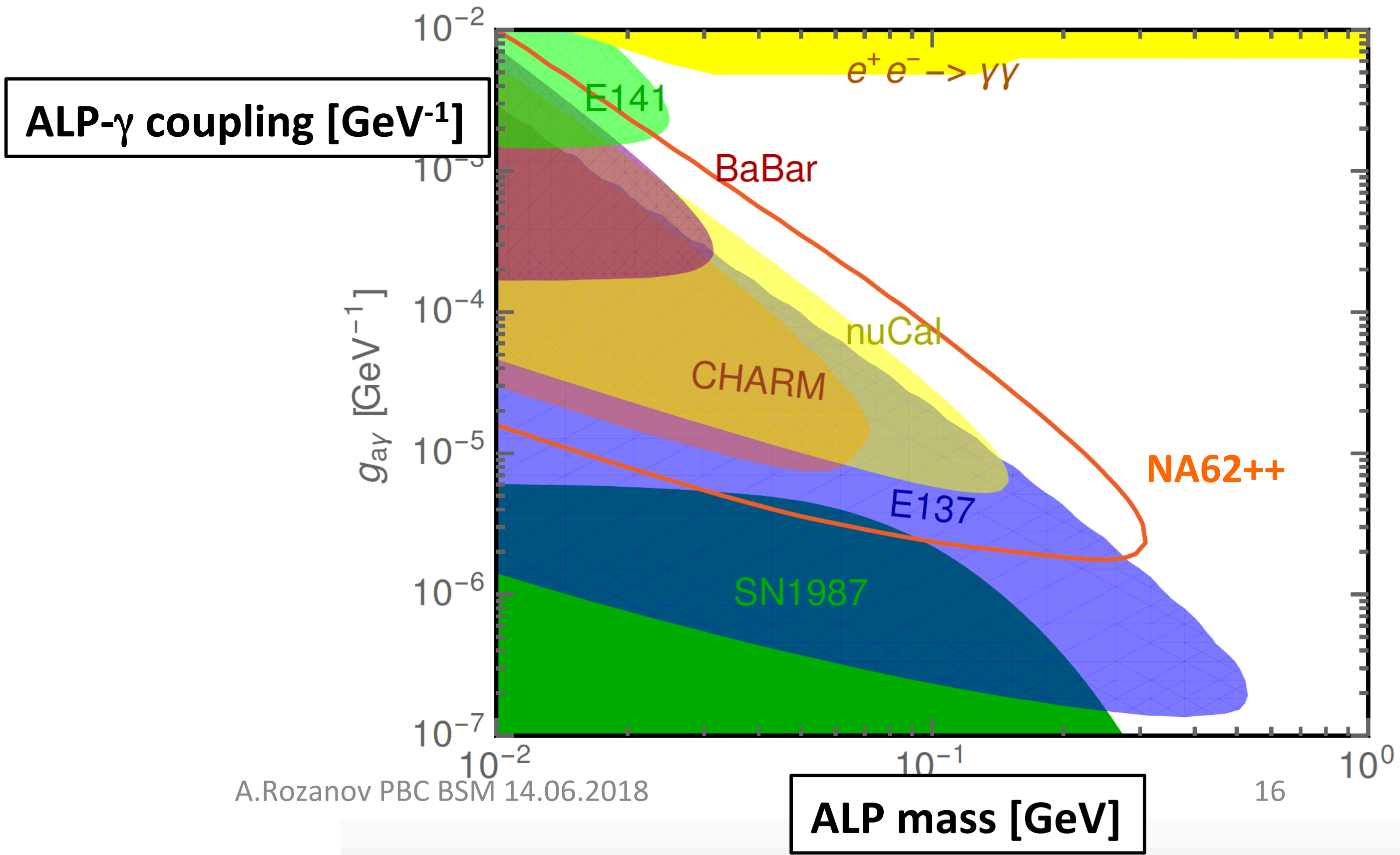
- Decay NHL: two body
- Statistics 1 x 10^{18} pot
- Zero background assumed, toy MC checked with NA62MC foe 2 body decays, acceptance included

$U^2e : U^2\mu : U^2\tau = 52: 1 : 1,$ $U^2e : U^2\mu : U^2\tau = 1: 16 : 3.8$ $U^2e : U^2\mu : U^2\tau = 0.061: 1 : 4.3$



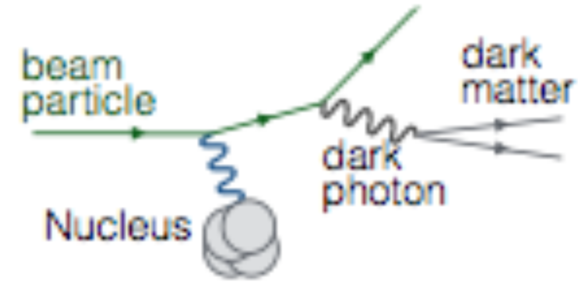
NA62++:Single ALP state a with photon dominance (BC9)

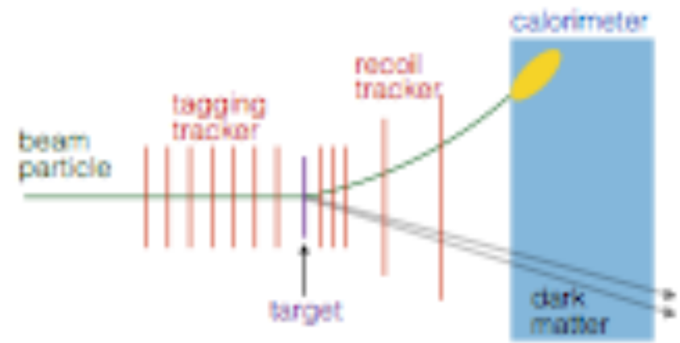
- Decay ALP: two photons
- Statistics 1 x 10^{18} pot
- Zero background assumed, Data study, few 10^{15} POT
- toy MC, acceptance included

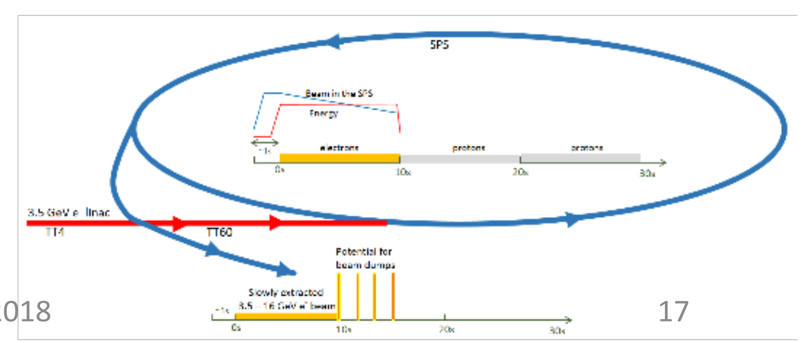


LDMX at DASEL-SLAC/JLAB or SPS

- electron beam dump
- DASEL-SLAC/JLAB 8 GeV ~$10^{16\text{-}18}$ electrons in target
- SPS option 16 GeV ~$10^{16\text{-}18}$ electrons on target with 3 GeV linac based on CLIC technologies
- Program: Axions, milli-charges, dark photons, visible and invisible channels

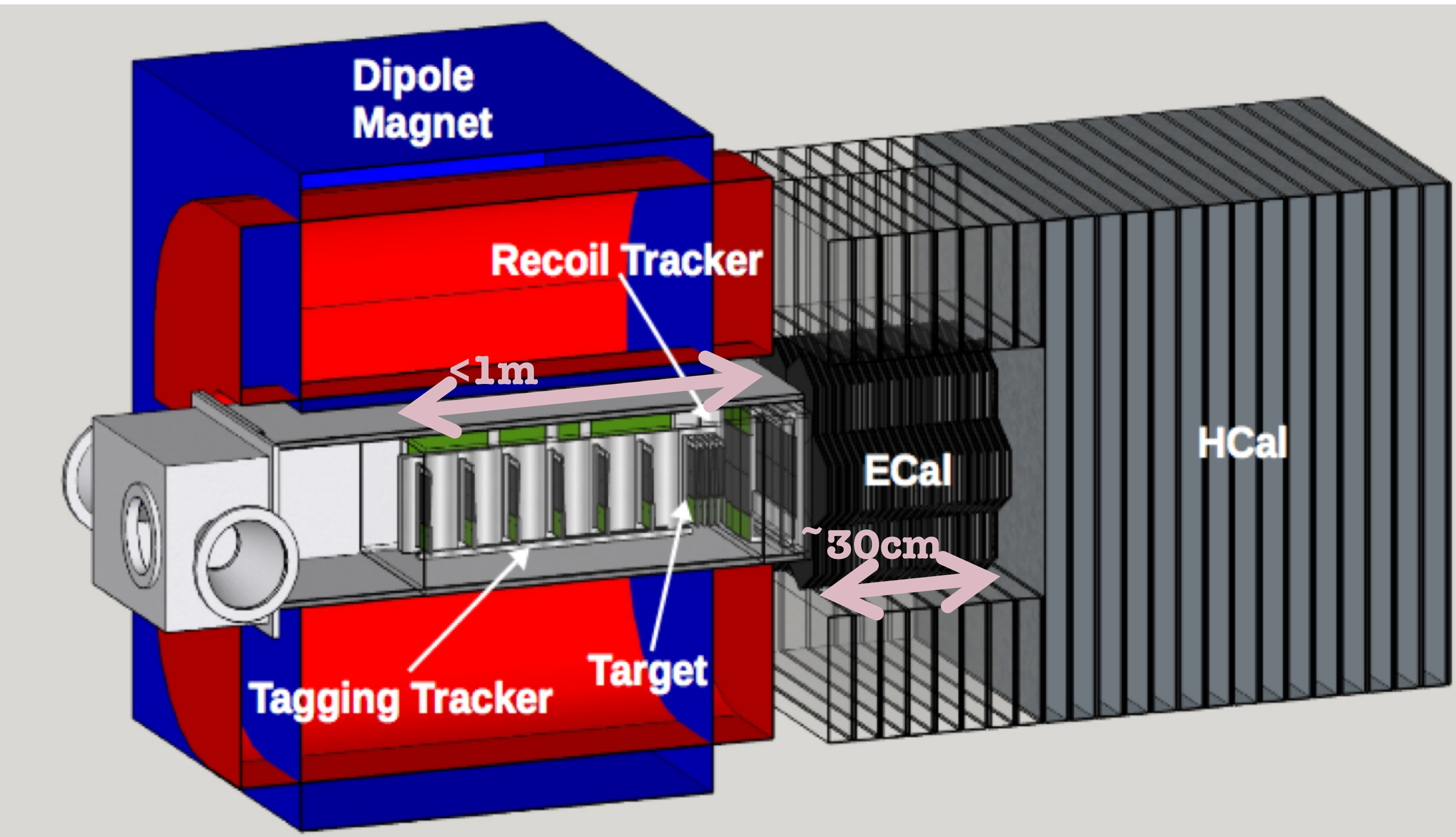






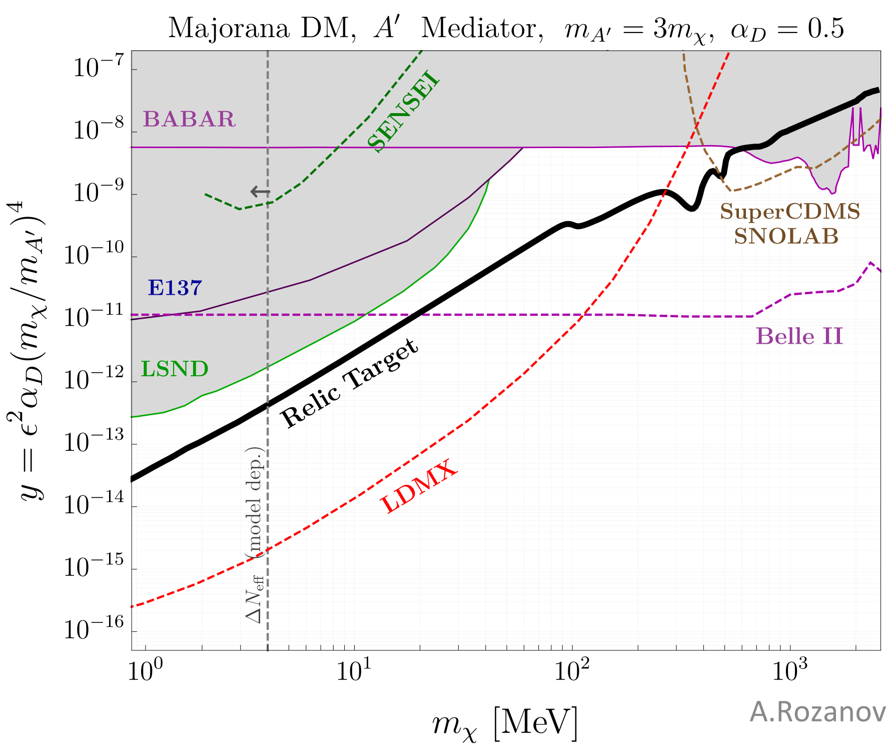
LDMX at SLAC or SPS

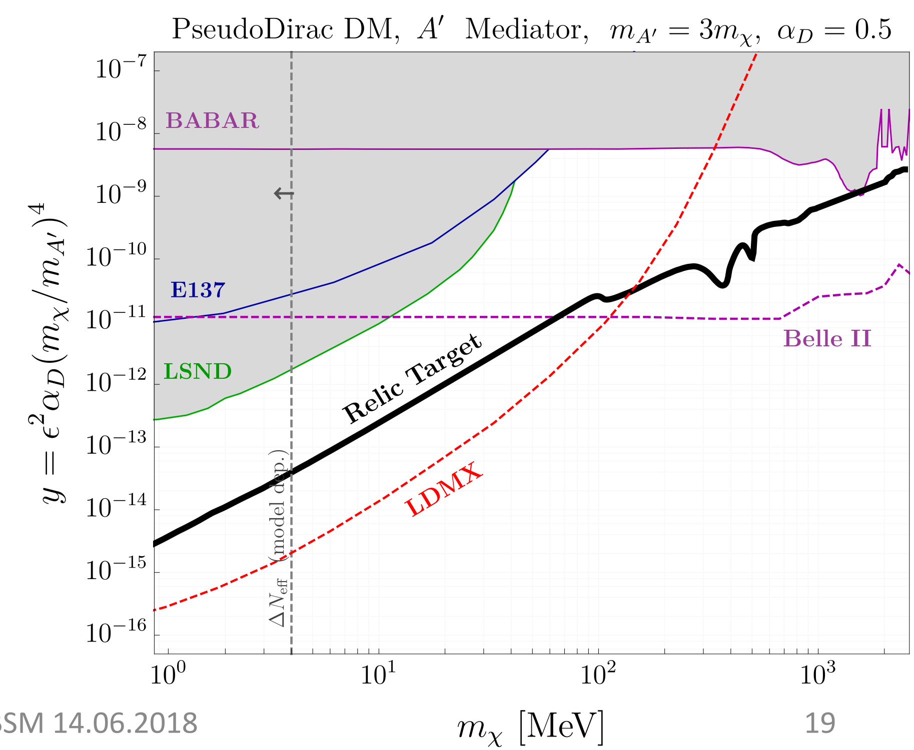
- Low number of electrons per bunch (1-5)
- Dipole magnet, recoil tracker, Ecal, tagging tracker
- Back Hcal, Side HCAL



LDMX: Dark Matter

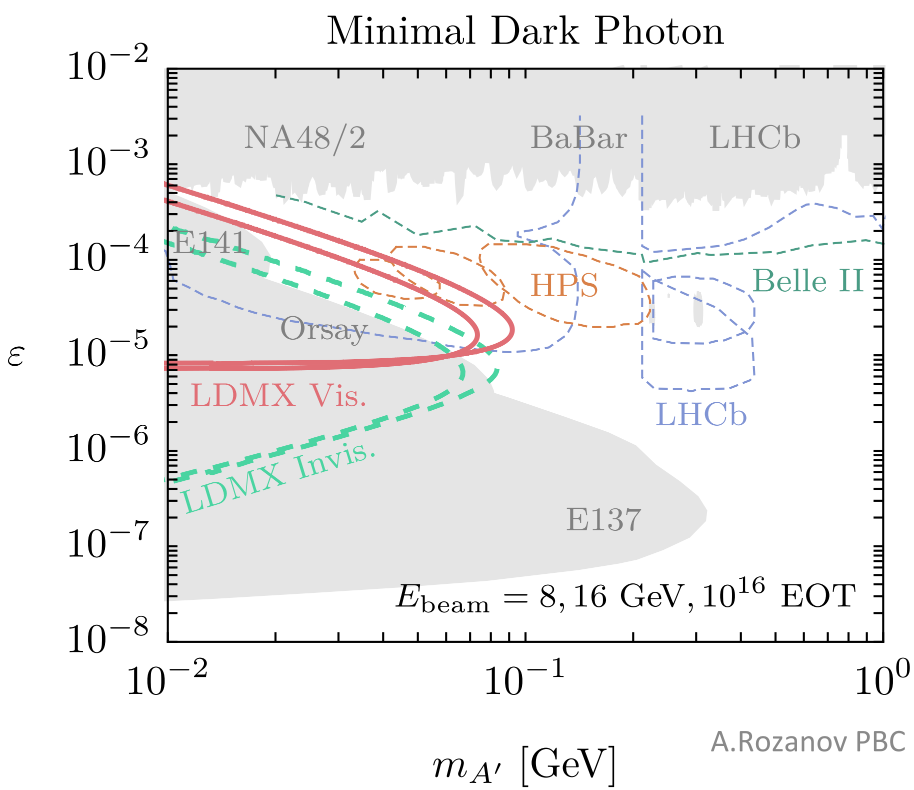
- Original toy MC simulations: reach Thermal Relic DM Targets
- Now confirmed with full GEANT simulation. Close to zero background.
- Majorana and PseudoDirac Dark matter from A' decays (BC2), α_D=0.5 and $m_{A'}/m_\chi$=3, 8 GeV electrons 10^{16} eot
- Scalar Dark Matter has more easy Thermal Relic DM Target

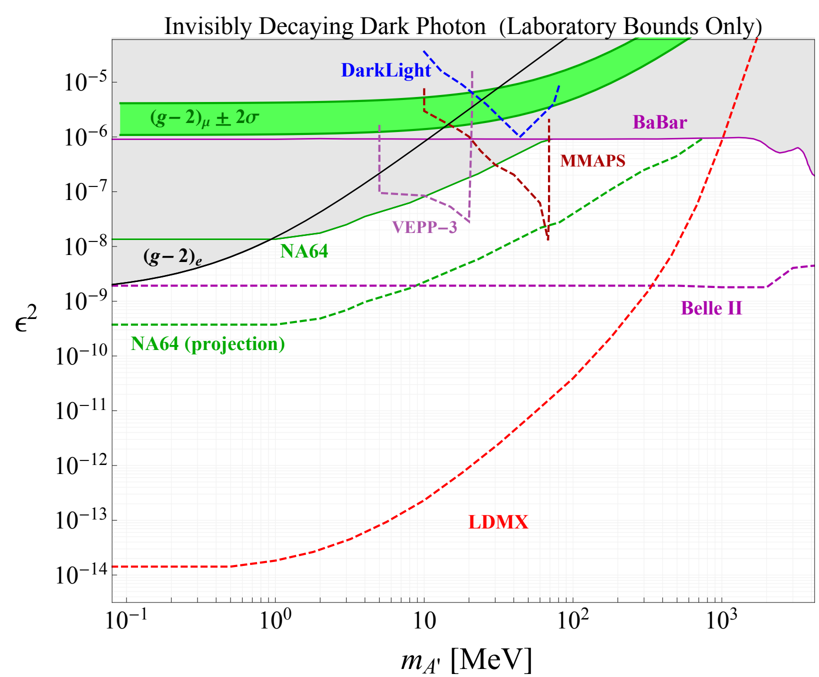




LDMX: Dark Photon

- Visible A' decays to SM particles (BC1), (decay inside calorimeter red, outside green), 8-16 GeV electrons 10^{16} eot
- Invisible A' dark photons (BC2), 8 GeV electrons 10^{16} eot

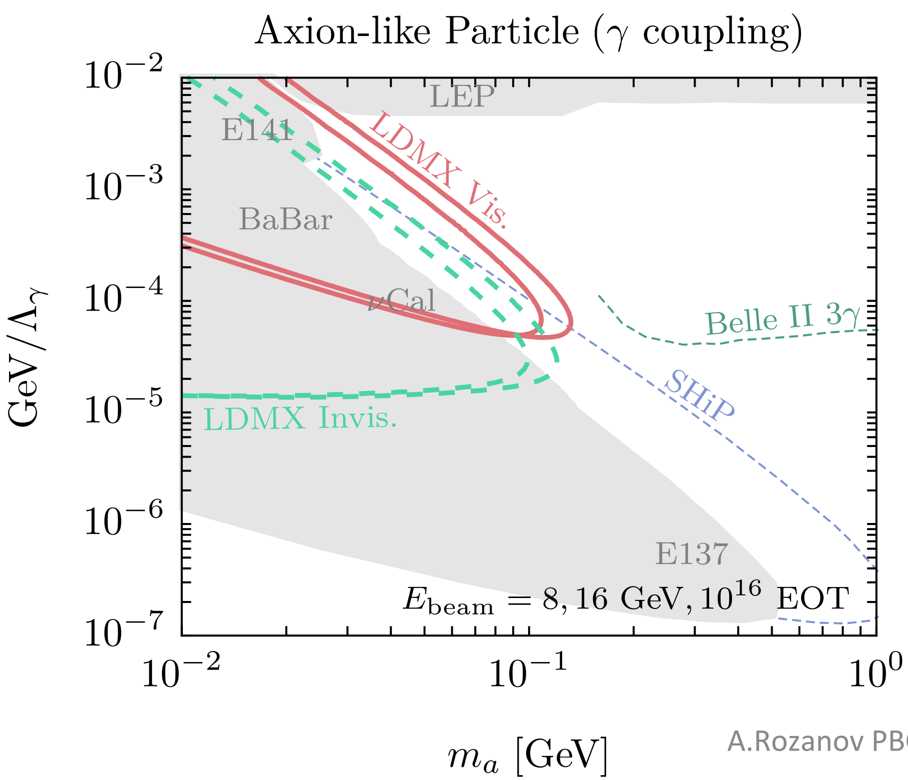


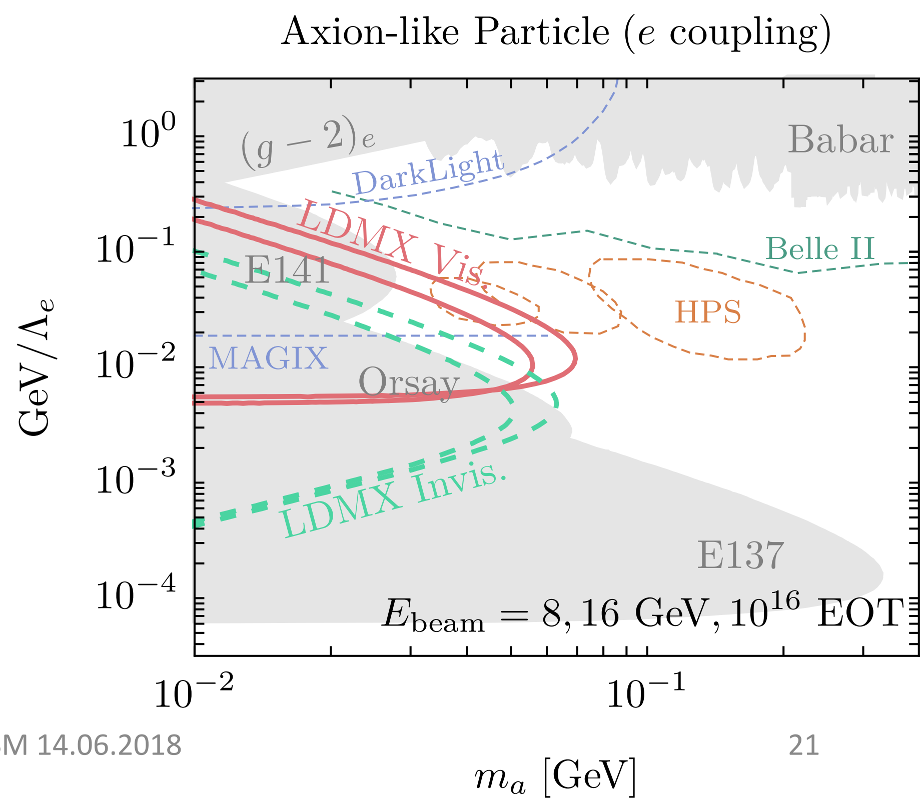


LDMX: ALPs photon or electron coupled

- ALPs photon coupled (BC9), decay inside calorimeter red, outside green
- 8-16 GeV electrons, 10^{16} eot

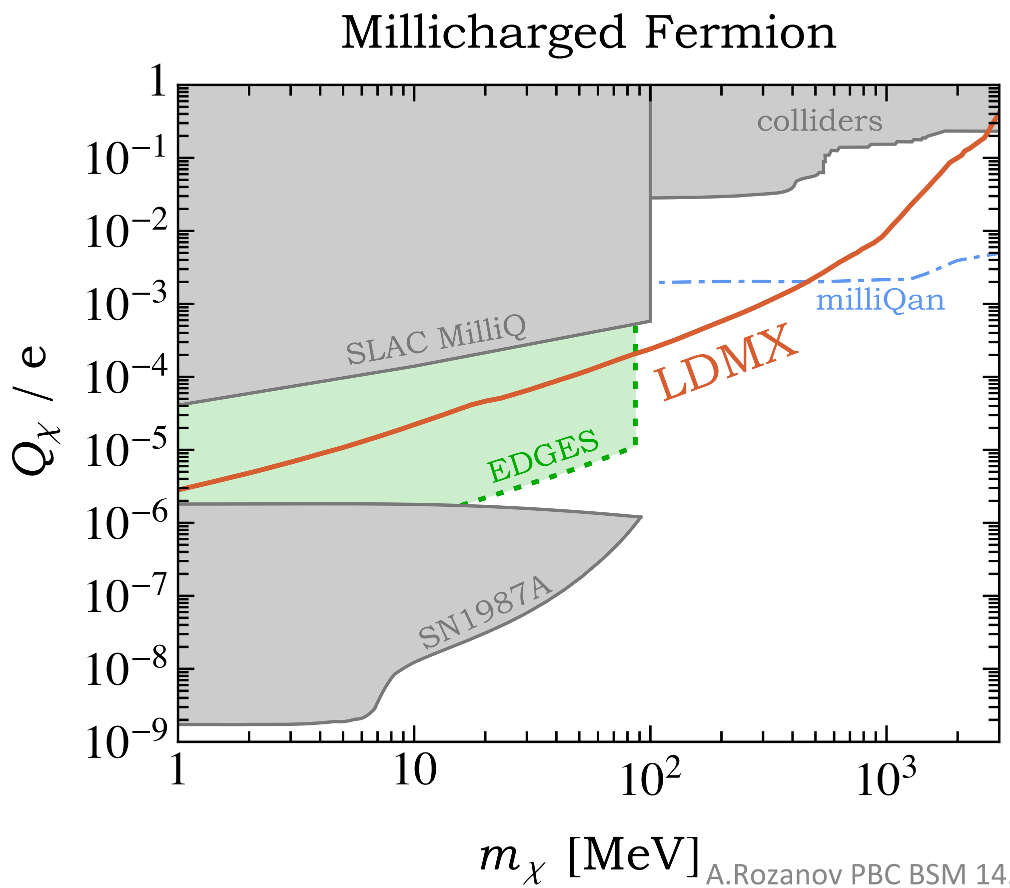
- ALPs electron coupled (BC10) , decay inside calorimeter red, outside green





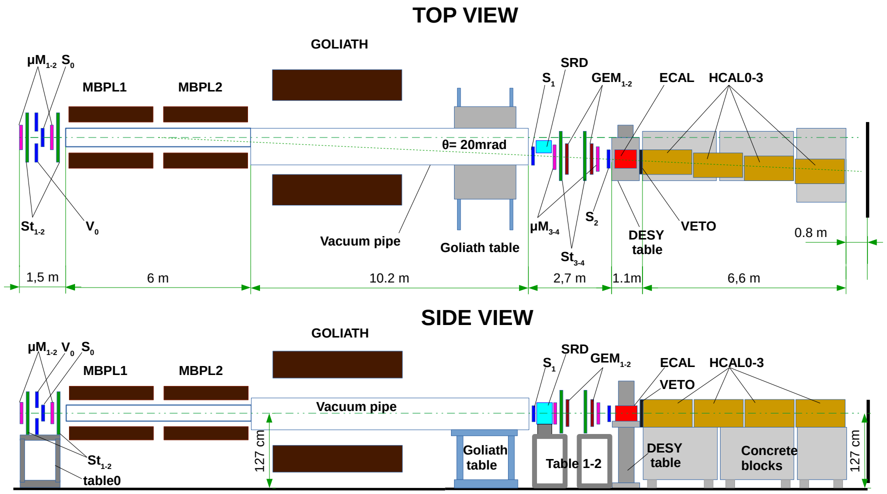
LDMX: Millicharged fermions (BC3)

- Millicharged χ escape detection
- 0.3 rad. length tungsten target
- 16 GeV electrons, 10^{16} eot



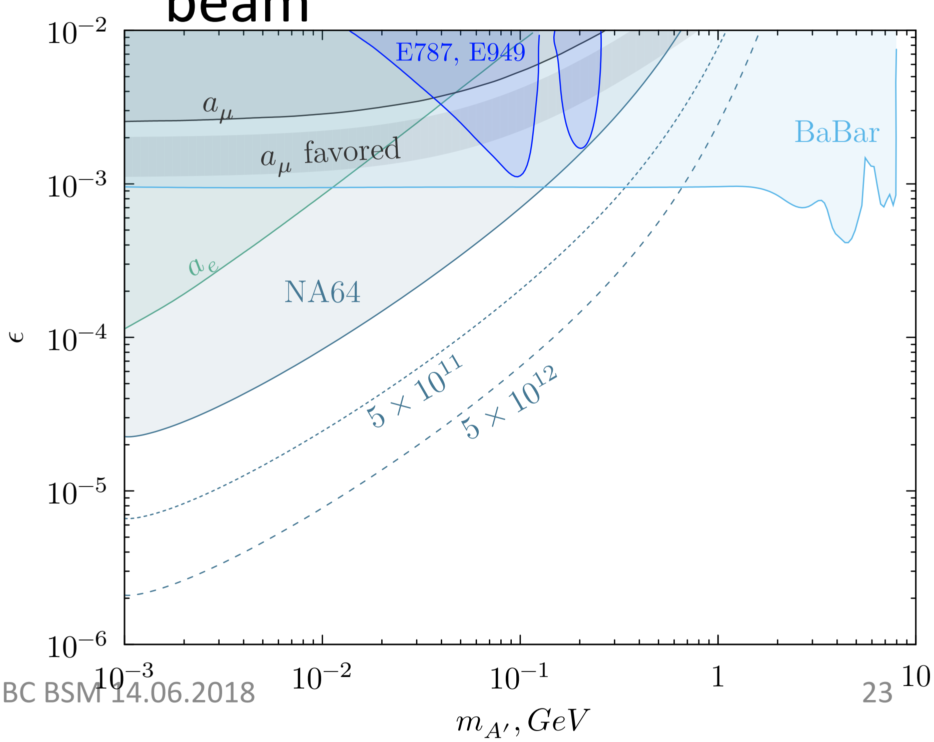
LDMX probe the region of the EDGE 21 cm hydrogen emission spectra anomaly at big z-shifts

NA64++: invisible dark photons (BC2)

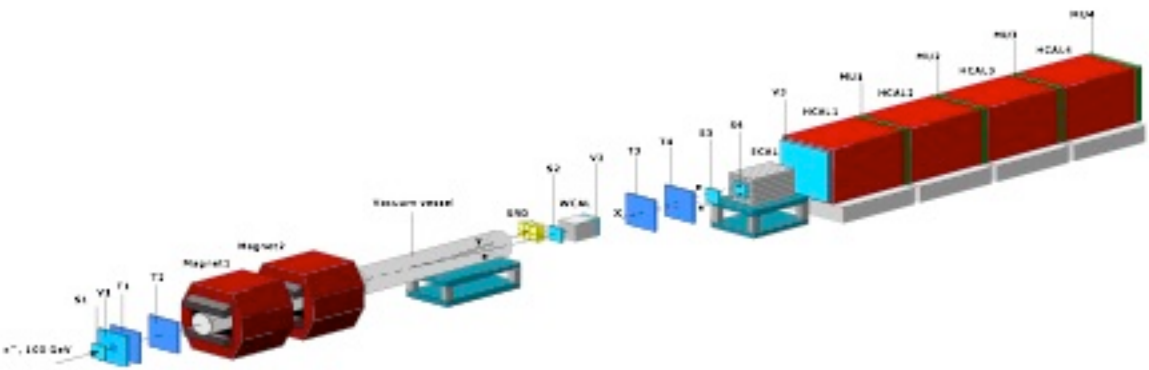


- Missing energy method
- Actually in 100 GeV electron beam
- Muon beam dump with missing momentum in M2
- Feasibility studies for hadron beam

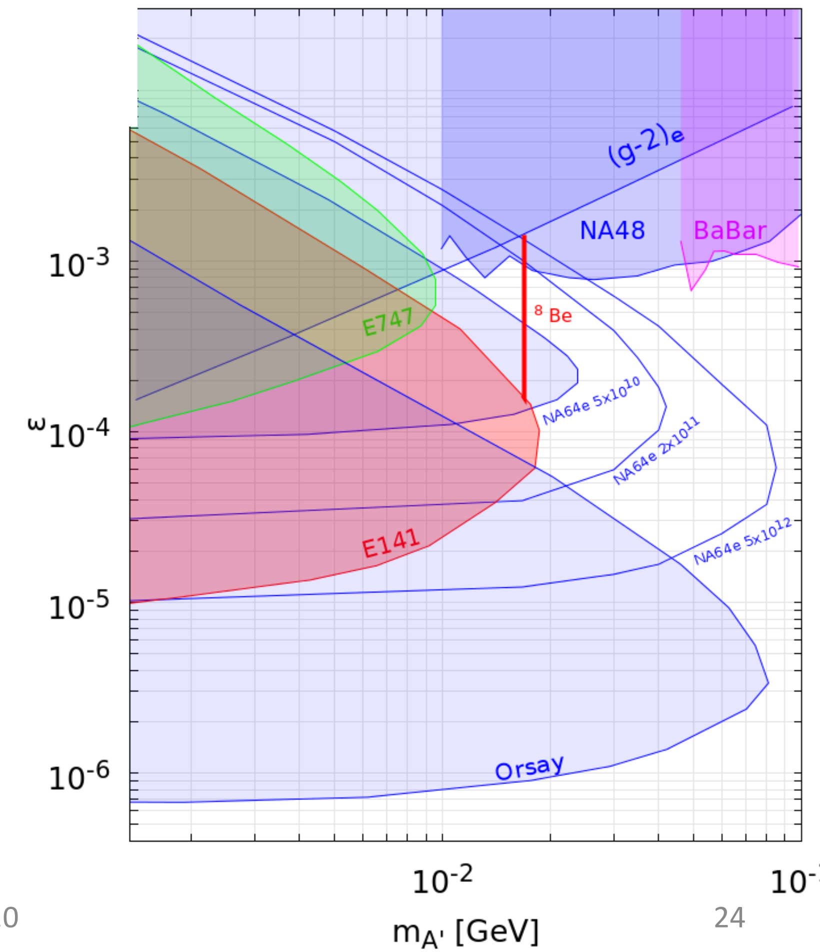
- Now electron beam with ~5x10^{10} eot in H4. Proposal to increase up to 5 x10^{12} eot after LS2
- Invisible Dark photons: $e^-Z \rightarrow e^-ZA'$; $A' \rightarrow \chi\chi$



NA64++: visible dark photons (BC1)

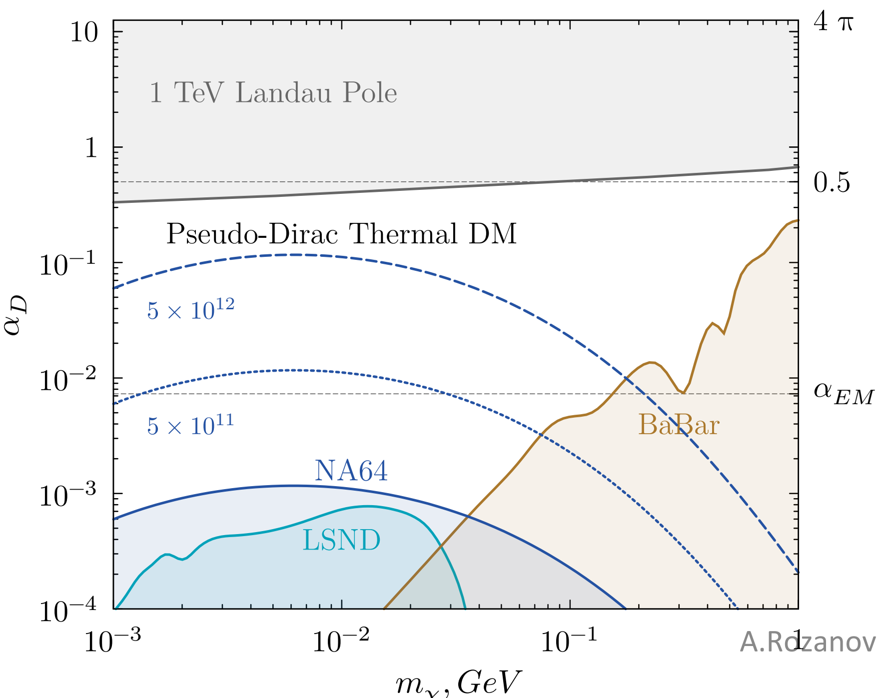


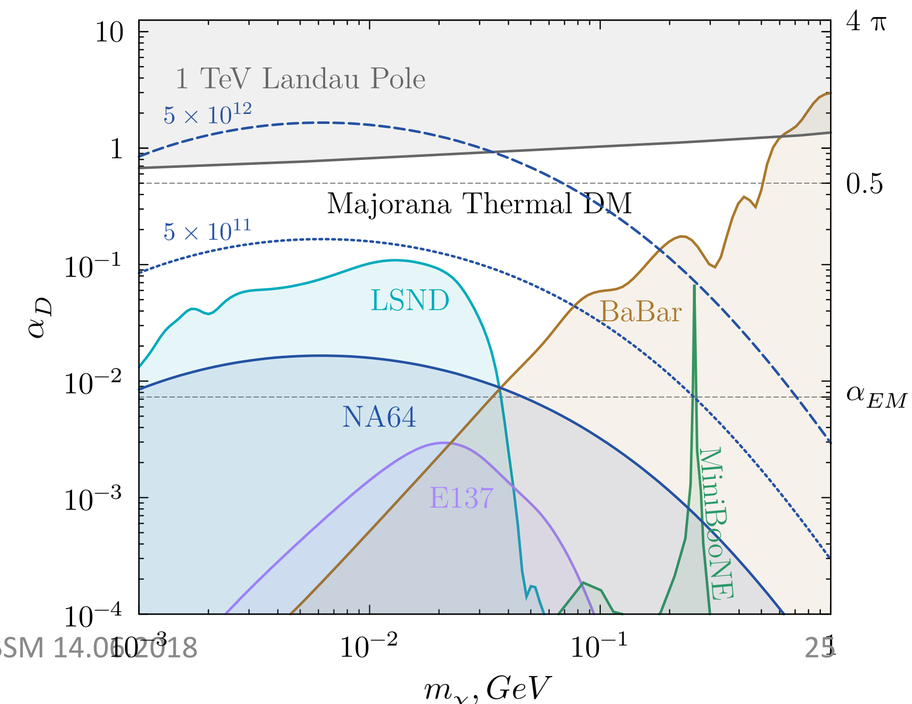
- Visible Dark photons(BC1): $e^-Z \rightarrow e^-ZA'$; $A' \rightarrow e^+e^-$
- A' is longlived and measured in another calorimeter
- To probe the 16.7 MeV boson observed in $^8Be^*$ decay (6.8 σ) the increase of intensity up to 5×10^{11} eot is needed.
- Proposal for 5×10^{12} eot



NA64++: sub-GeV dark matter (BC2)

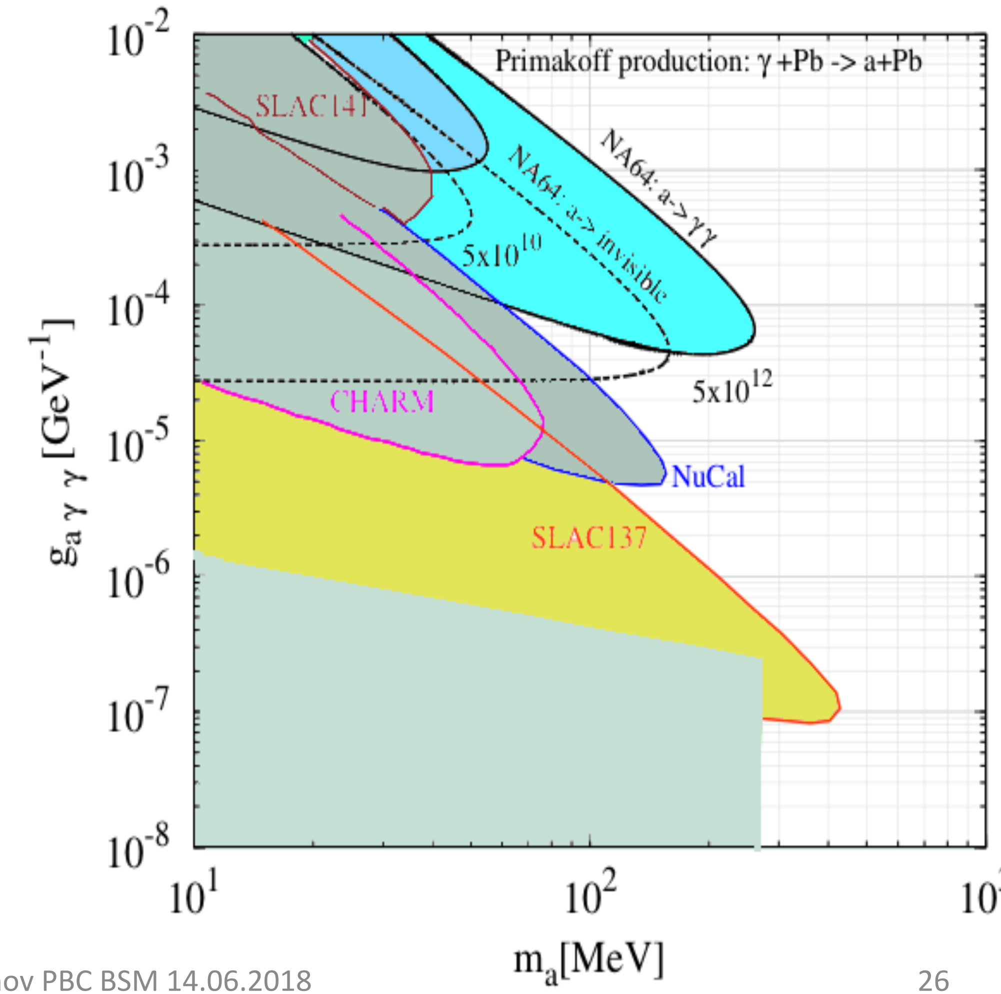
- Dark Matter from A' decays interact with electrons in the electromagnetic calorimeter . If low coupling α_D~f, DM escapes, create missing energy.
- Actually in 100 GeV electron beam with ~5×10^{10} eot in H4. Proposal to increase up to 5 $\times 10^{12}$ eot after LS2, observed relic DM density assumed
- Dark Matter scattering on electrons (f=0.25(Dirac) and f=3(Majorana)): $e^- Z \rightarrow e^- Z A'$; $A' \rightarrow \chi\chi$; ; $\chi e^- \rightarrow \chi e^-$



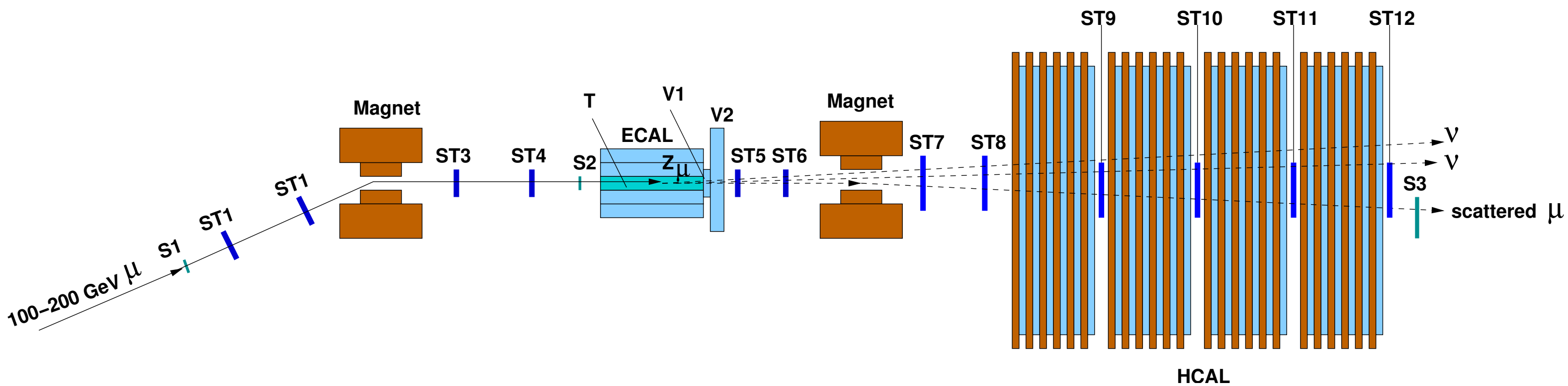


NA64++: ALP with gamma coupling (BC11)

- ALPs, Primakoff production:
  $\gamma Z \rightarrow a\, Z$ and $a \rightarrow \gamma\gamma$
  or invisible
- If a is longlived it is measured in another calorimeter
- Proposal for 5×10^{12} eot

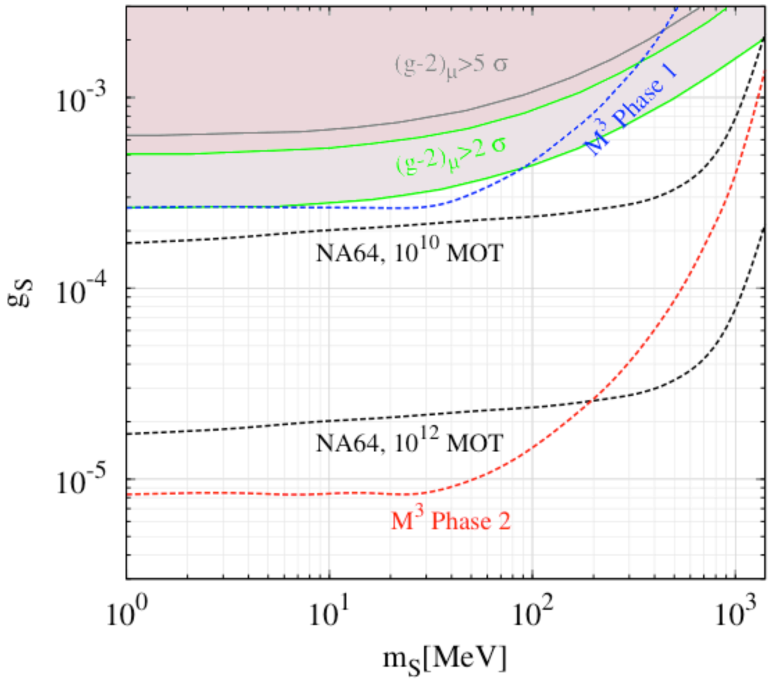


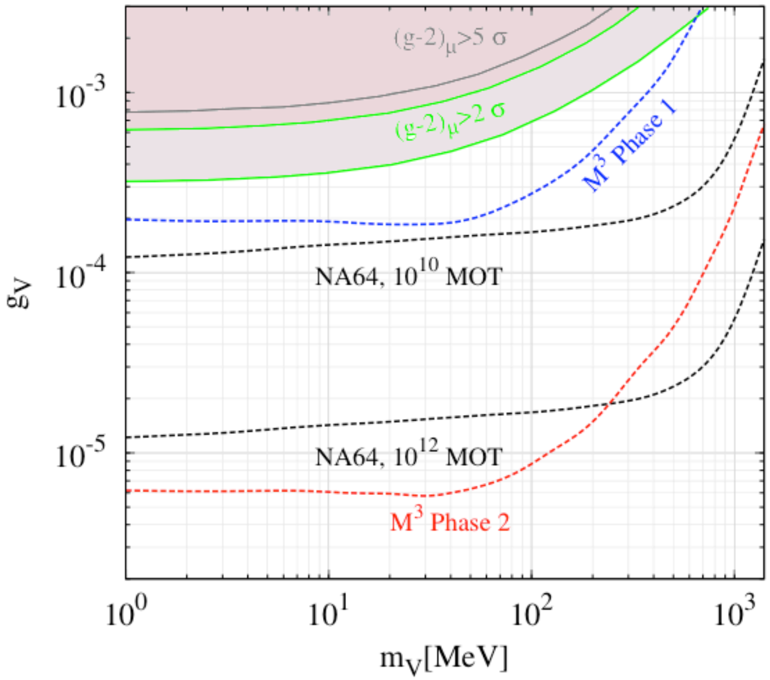
NA64++: muon program



- Search for dark muon photon Z_μ: $\mu+Z \rightarrow \mu+Z+Z_\mu$ $Z_\mu \rightarrow \nu\nu$
- Missing muon energy method, 100-150 GeV muon beam with high purity momentum selection, hermetic HCAL, Si tracker, Goal for 5×10^{12} mot
- Z_μ motivated by $(g\text{-}2)_\mu$ and evading universal dark photon limits
- Muonic photon proposed by Lev Okun in 1993, searched in CHARM-II
- Pseudo-scalar mediator dominantly coupled to muon, invisible decays
- U(1)L_μ-L_τ vector Z_μ dominantly coupled to muon, invisible decays
- Z_μ model gauging L_μ-L_τ lepton number can explain the LFU violations in R_K and R_{K*}
- sub-GeV dark matter coupled to Z_μ mediator

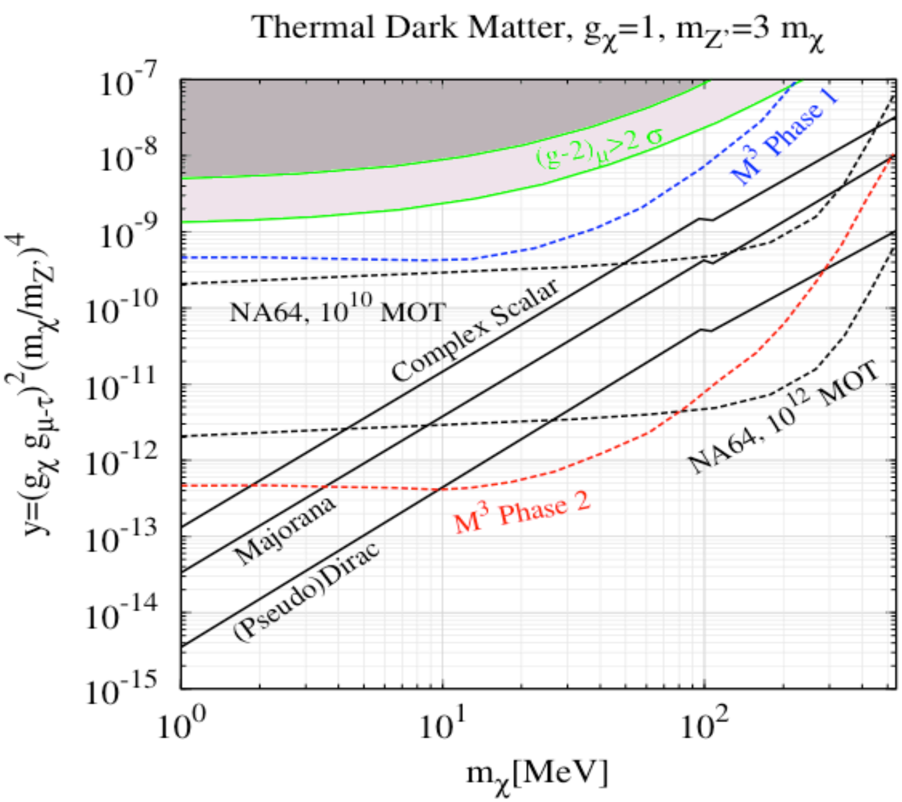
NA64++:muonic photon

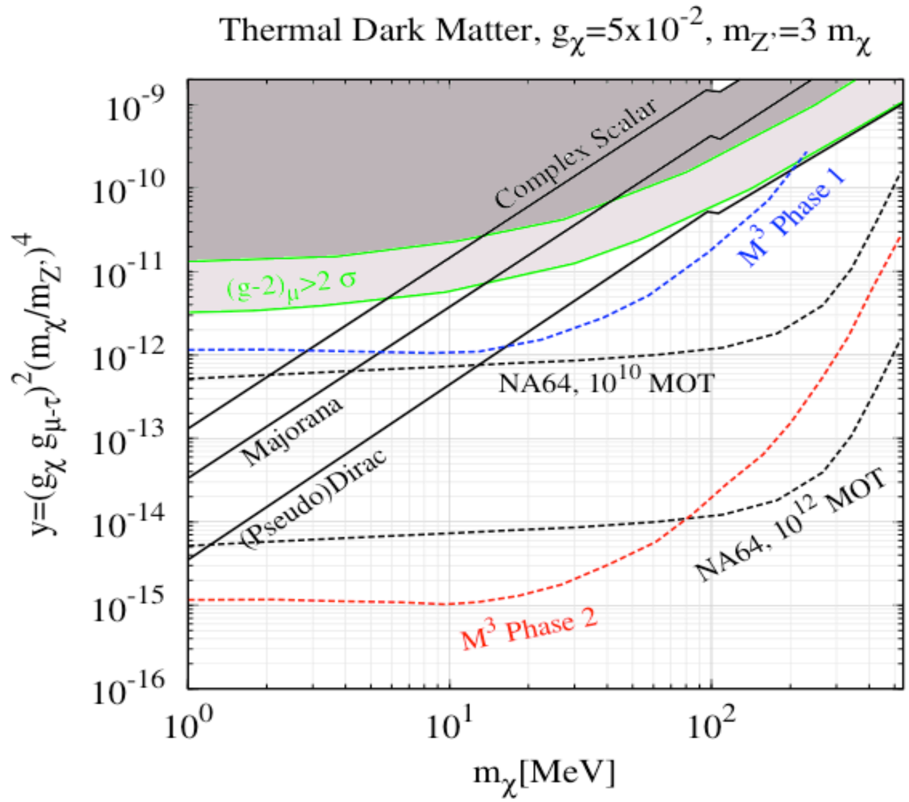




- Restrict mass and coupling of muon-philic scalar S or vector V boson, probe $(g\text{-}2)_\mu$ sensitive region

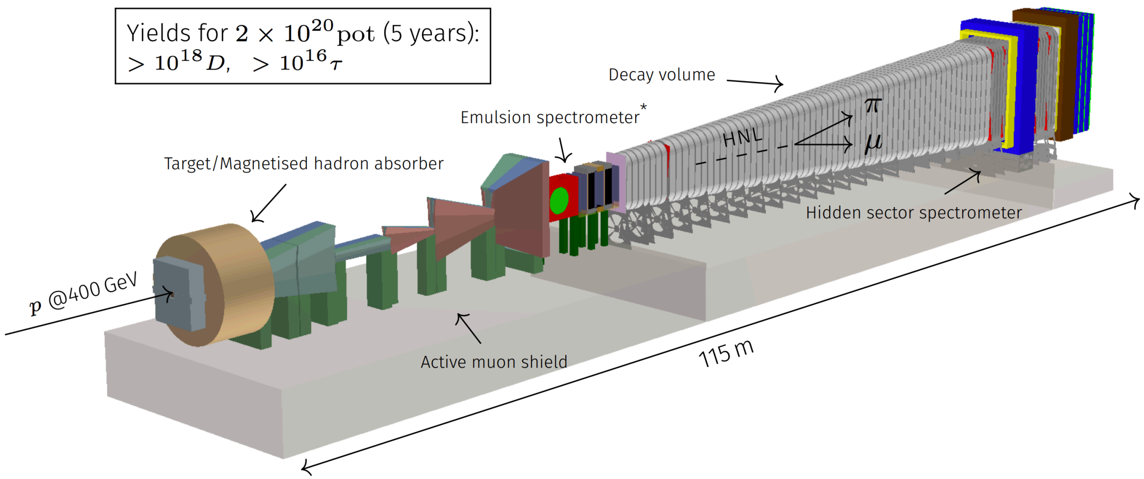
NA64++: DM with muonic photon

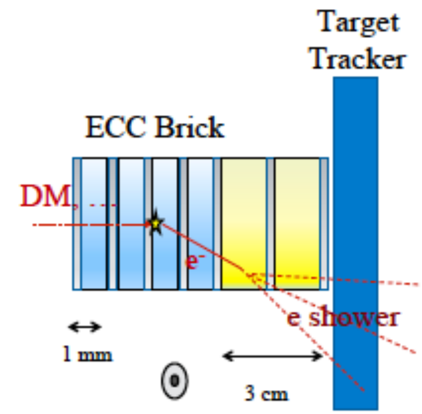




- Thermal DM charged under U(1)L_μ-L_τ
- Enchanced DM coupling (left), suppressed DM coupling (right)

SHIP – 400 GeV p beam dump



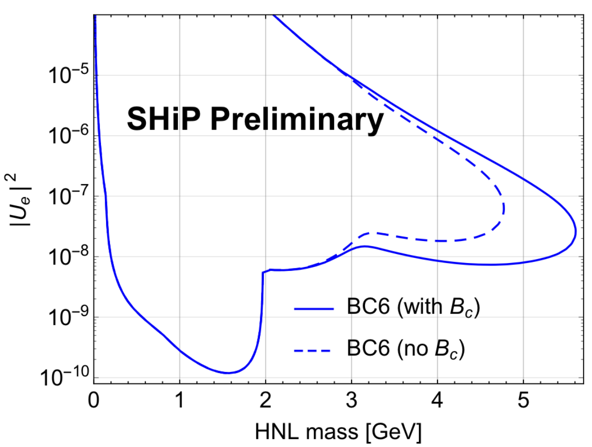


- In fact two experiments: big decay detector (NHL, A', S, ALP) and emulsion interaction detector in front (DM and τ physics)
- Re-optimization of muon shielding and detector
- Cascade processes are now included in NHL and scalar production
- Dark photons are now from meson decays and photon brems. But still no contribution from QCD production.
- Strong prototype program: muon spectra from SHIP replica target, inclusive charm beam dump cross section with emulsions
- Dark photon coupled to Light Dark Matter results will come later
- Discovery oriented experiment: strong signatures, "zero" background

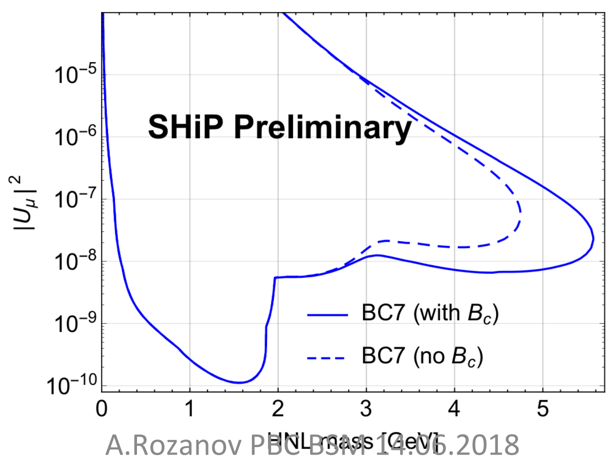
SHIP Heavy Neutral Leptons (BC6,7,8)

- 5 years, 2 x 10^{20} pot, spectacular final states: μπ, μK, eπ, eK, eeυ, μμυ,μe …
- B_c contribution is shown separately: rate as at LHC (too high), p_T as for B^+
- Full simulation with full reconstruction. Simulation statistics: 5 years of SHIP
- "Zero" background < ~0.1 events, even one or two signal events may be the discovery
- Precise quantitative estimation of the background is coming. For background details see talk of Konstantinos Petridis

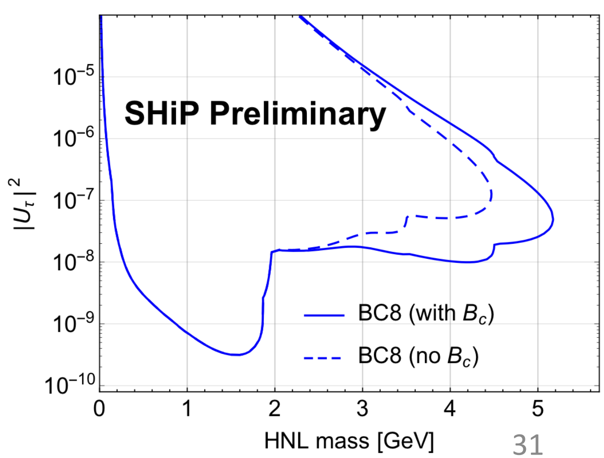
Mixing to electron neutrinos



Mixing to muon neutrinos

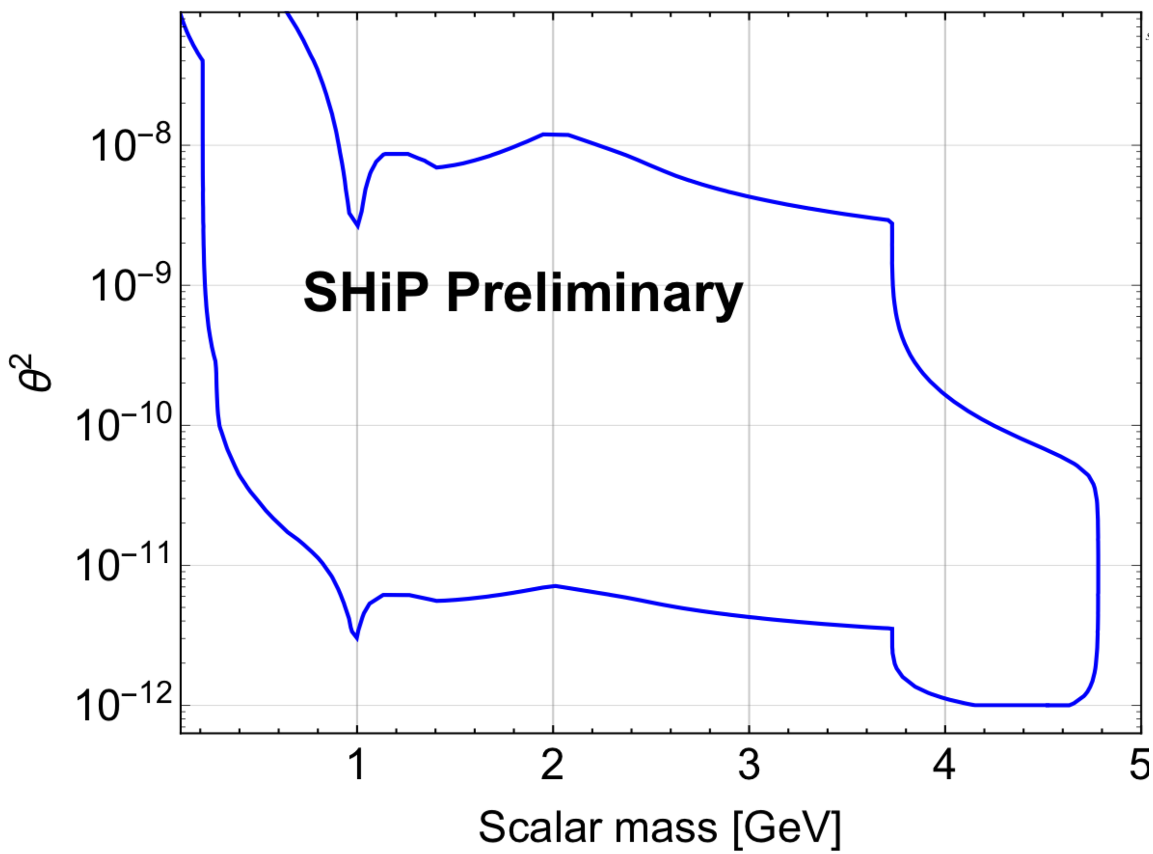


Mixing to tau neutrinos



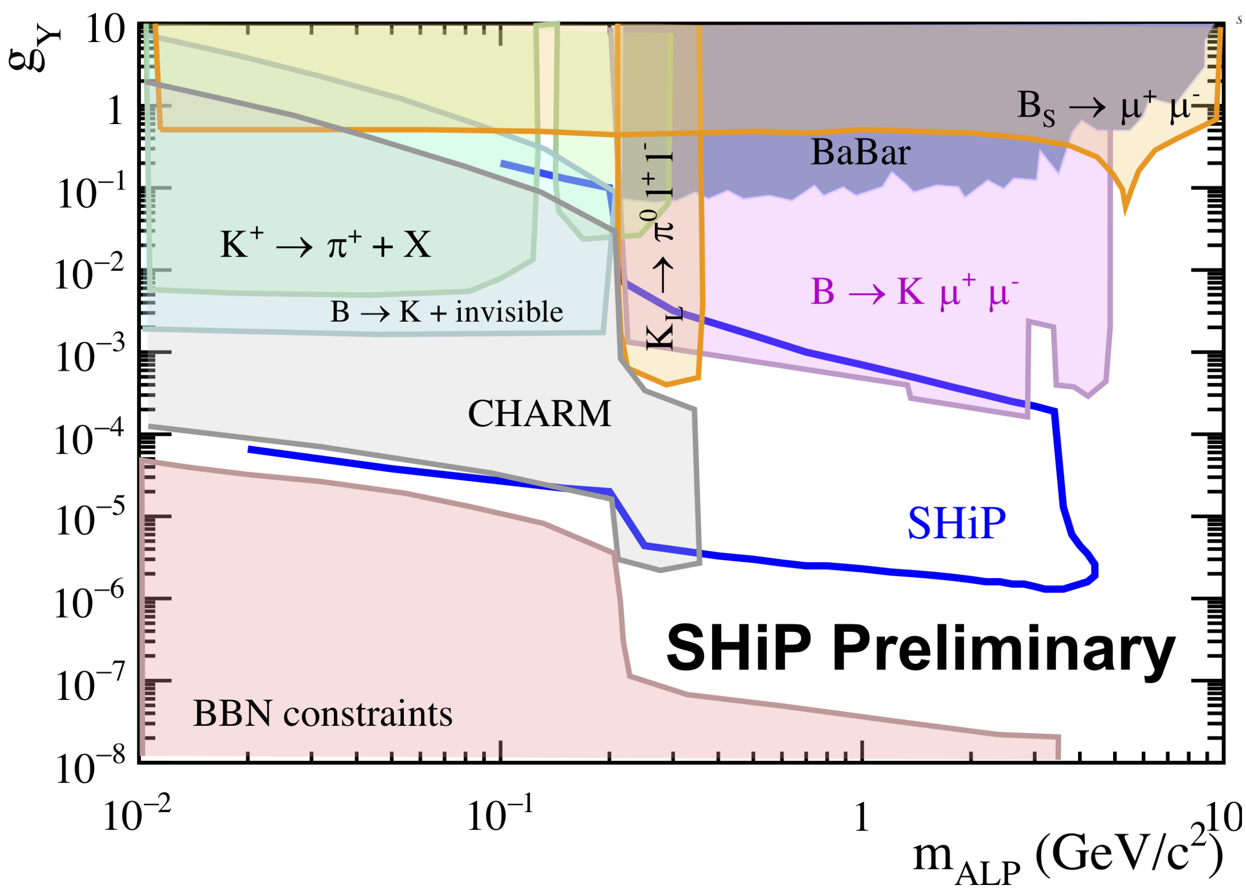
SHIP: Higgs mixed Scalar $\lambda=0$

- BC4, Production in B^+ and B^0 decays
- $m_S < 2\, m_\pi$ $S \rightarrow l\, l$
- $2\, m_\pi < m_S < 1.4$ GeV $S \rightarrow \pi\, \pi$, $S \rightarrow K\, K$
- $m_S > 1.4$ GeV pQCD



SHIP: ALPs with fermion coupling (BC10)

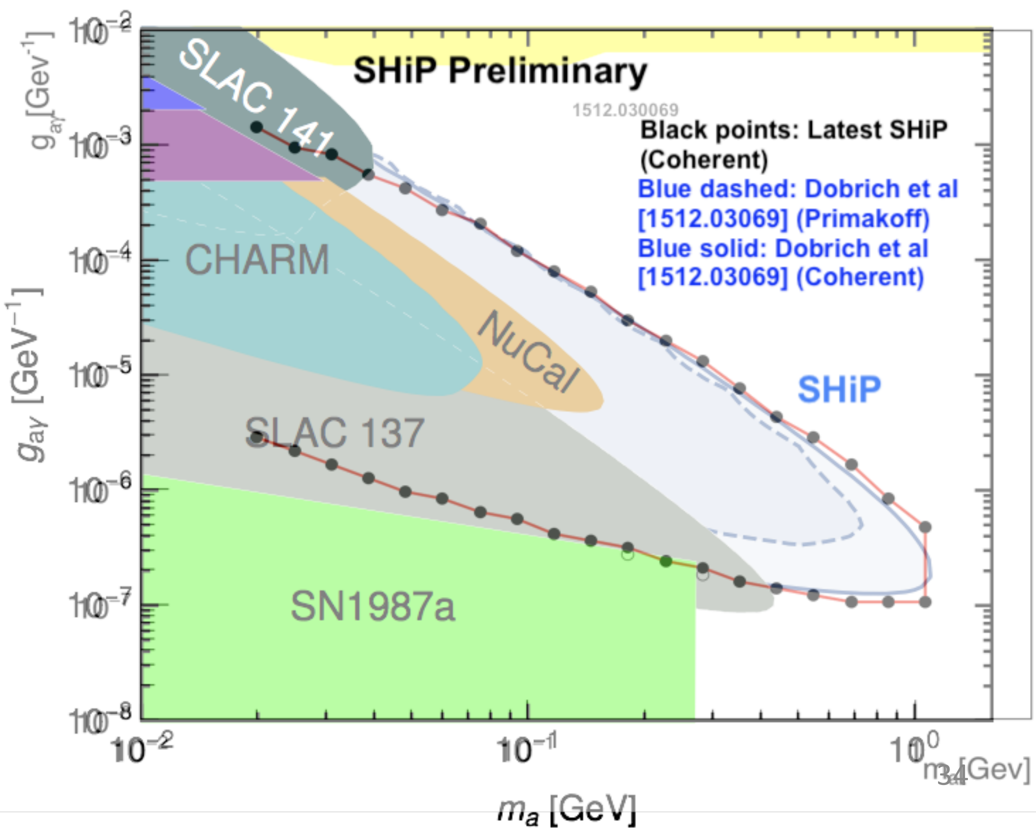
- Toy simulation
- Production B → K a
- Decay a → μμ, a → ee



SHIP: ALPs with photon coupling (BC9)

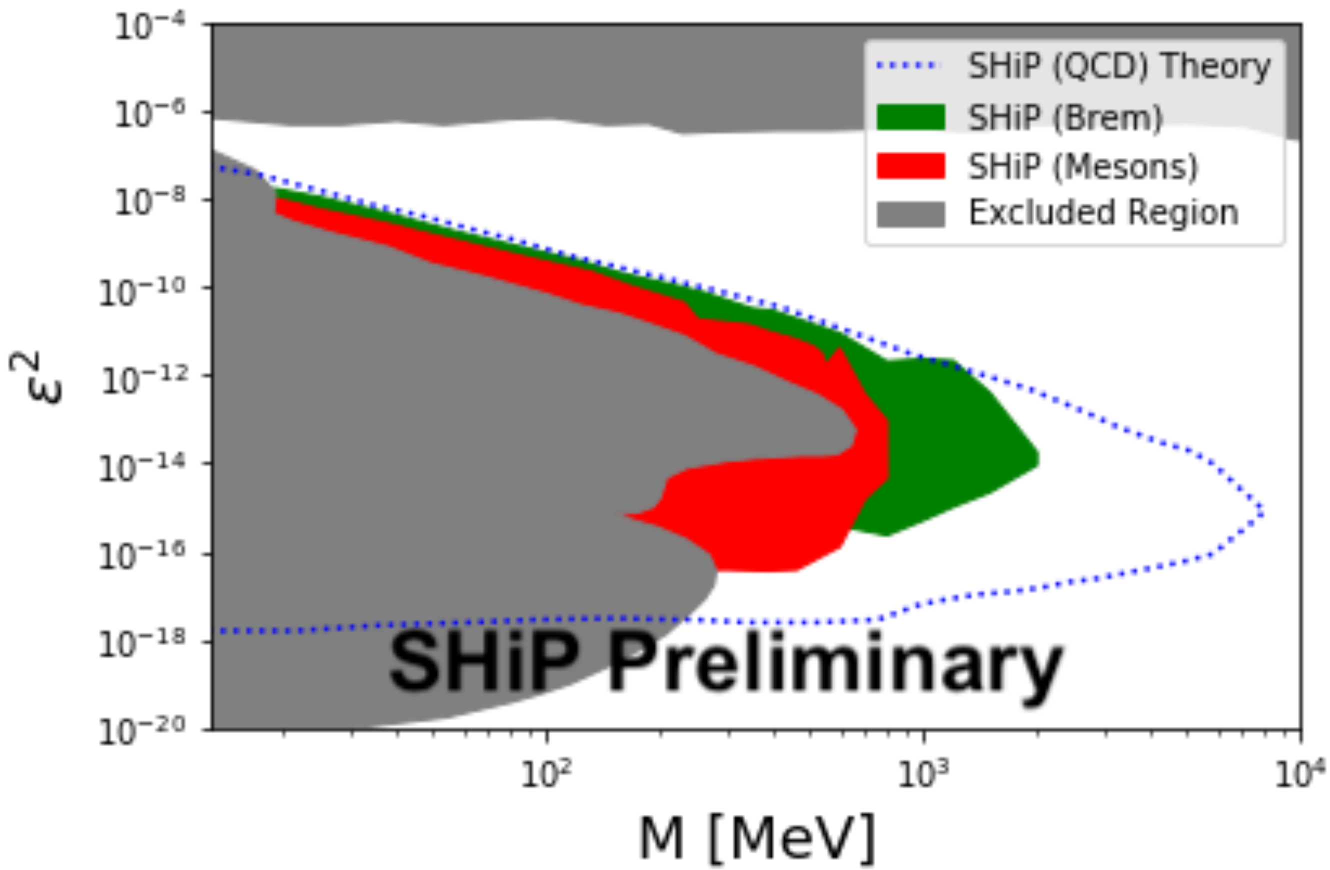
- Primakoff Production pp → p a p, coherent pZ → p a Z to be added later
- Decay a → γγ Not only discovery, but prove scalar nature !

  - Using toy MC with SHIP acceptance
  - Both photons in ECAL
  - $E_\gamma > 3$ GeV
  - Photons hits in ECAL surface > 10 cm



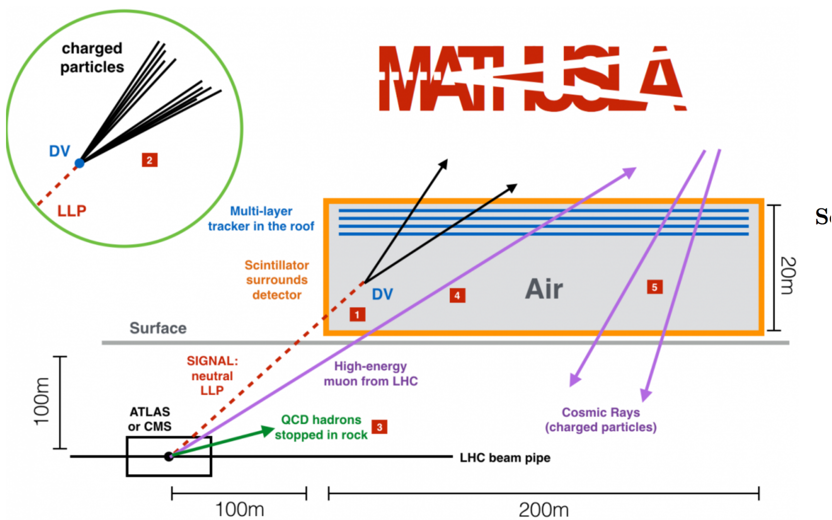
SHIP: Dark Photon (BC1)

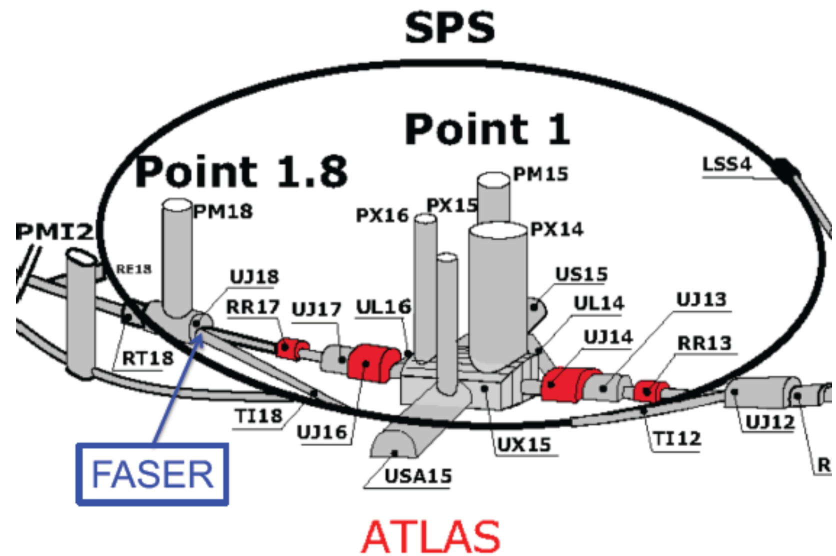
- Source of Dark Photons A’: meson decays and brems from protons. QCD source not yet included in simulation (plot TP result).
- Only A’ $\rightarrow \mu\mu$ now, electrons and hadrons will be included later



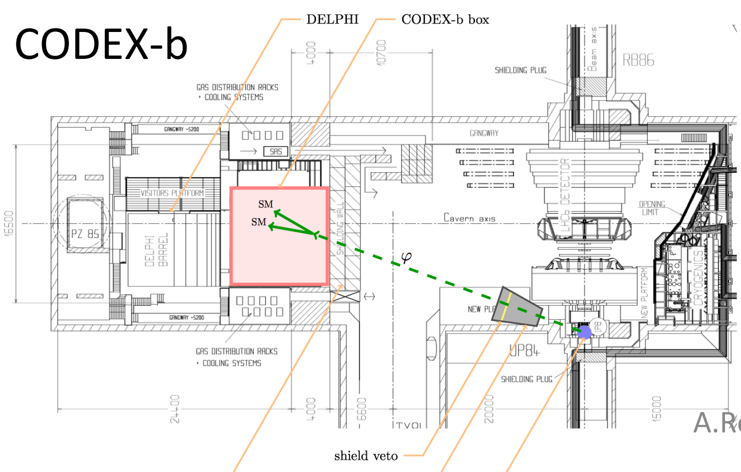
Surrounding LHC collisions for LLPs

- Long Lived Particles @ LHC (inside LHC detectors) – see talk of James Beacham
- MATUSLA (150m from ATLAS/CMS) - see talk of David Curtin
- FASER (480 m from ATLAS) in 1 mrad – see talk of Jonathan Lee Feng
- Codex-B (25 m from LHCb) - see talk of Michele Papucci
- MilliQan (33m from CMS) – see talk of Andrew Haas

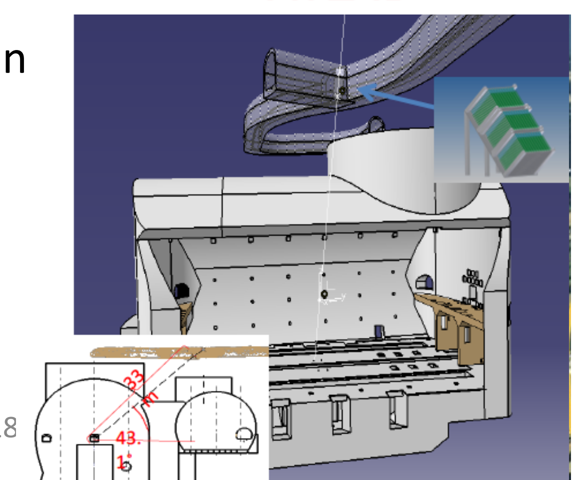




CODEX-b



MilliQan



Conclusions

- Significant progress and many new ideas in BSM group
- Benchmark Case model studies are now very useful for horizontal communication between projects and experiments
- Present projects covers significant phase space of Mev-GeV masses in the Dark Sector benchmark models − see the talk of Gaia Lanfranchi and spare slides
- Still a lot of work for the documents to be presented to European Strategy Upgrade (ESU)

Spares

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Benchmark Models - Vector Portal

- Benchmark Cases (BC) proposed by Maxim Pospelov
- BC1 – Minimal Dark Photon model. Dark photon A’ decays to SM particles
- BC2 - Light Dark Matter coupled to Dark Photon. Dark coupling α_D such that A’ $\rightarrow \chi\,\chi^*$ states. Dark States χ scatters with coupling ε on electrons and nuclei. Possible choice α_D=0.1 and $m_{A'}/m_\chi$=3
- BC3 - Millicharged particles $m_{A'} \rightarrow 0$ and χ have small effective electric charge

Benchmark Models - Scalar Portal

- BC4 − Higgs mixed scalar $\lambda=0$. All production and decays defined by parameter $\theta = \mu\, v/(m_h^2 - m_S^2)$, EW vacuum expectation v=246 GeV
- BC5 − Higgs mixed scalar with large pair-production channel. Production dominated by $h \to SS$, $B \to K\, S$, $B^0 \to SS$. Reasonable choice of λ such that $Br(h \to SS) = 10^{-3}$

Benchmark Models − Neutrino Portal

- BC6 − single Majorana Neutral Heavy Lepton (NHL) N with predominant mixing to electron neutrinos.
- BC7 − single Majorana Neutral Heavy Lepton (NHL) N with predominant mixing to muon neutrinos.
- BC8 − single Majorana Neutral Heavy Lepton (NHL) N with predominant mixing to tau neutrino

Benchmark Models − Axion Portal

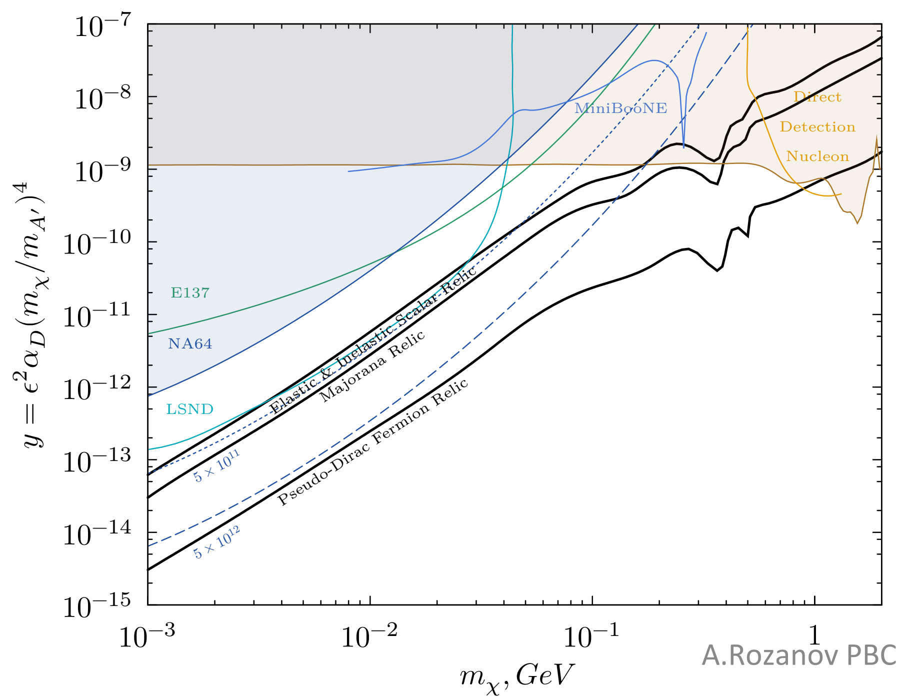
- QCD axions are an important idea to explain the absence of CP violation in strong interactions. Restricted to sub-ev mass range. So generalization to Axion Like Particles (ALP).
- BC9 − Single ALP state a with photon dominance
- BC10 − Single ALP state a with fermion dominance For simplicity f_q=f_l. Require UV cut off Λ_{UV}= f_q
- BC11 − Single ALP state a with gluon dominance. However coupling to gluons lead to non-perturbative contributions to m_a

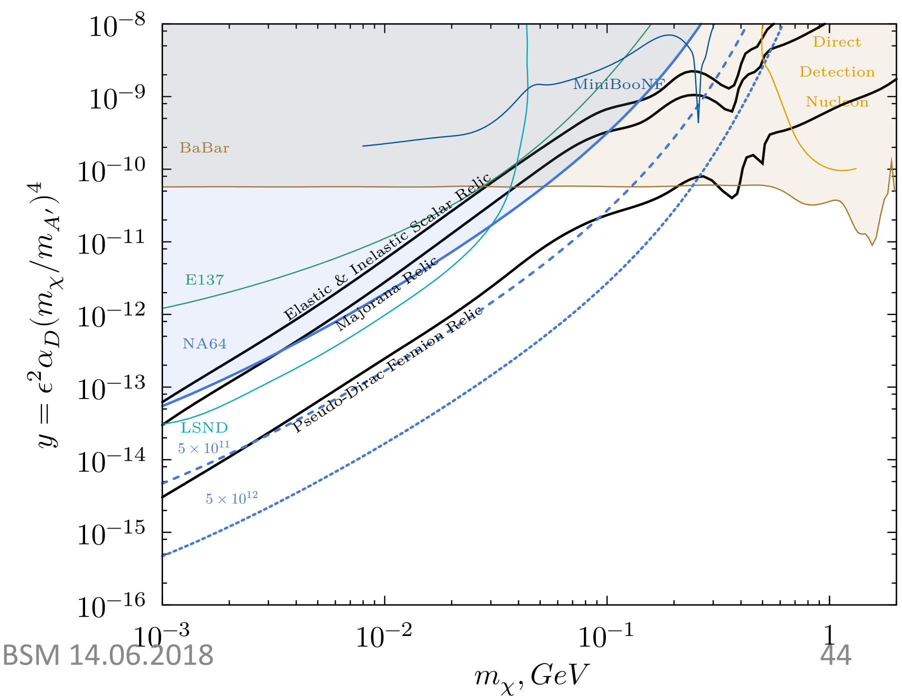
Beyond Standard Model (BSM) experimental facts and arguments

- Dark Matter: fast rotation of stars and galaxies
- Absence of antimatter in the Universe
- Nature of neutrino masses and oscillations
- Dark energy or cosmological constant
- CP violation and Electric Dipole Moments (EDM)
- Strong CP problem (CP is not broken in strong interactions)
- Higgs mass radiative corrections and fine tuning

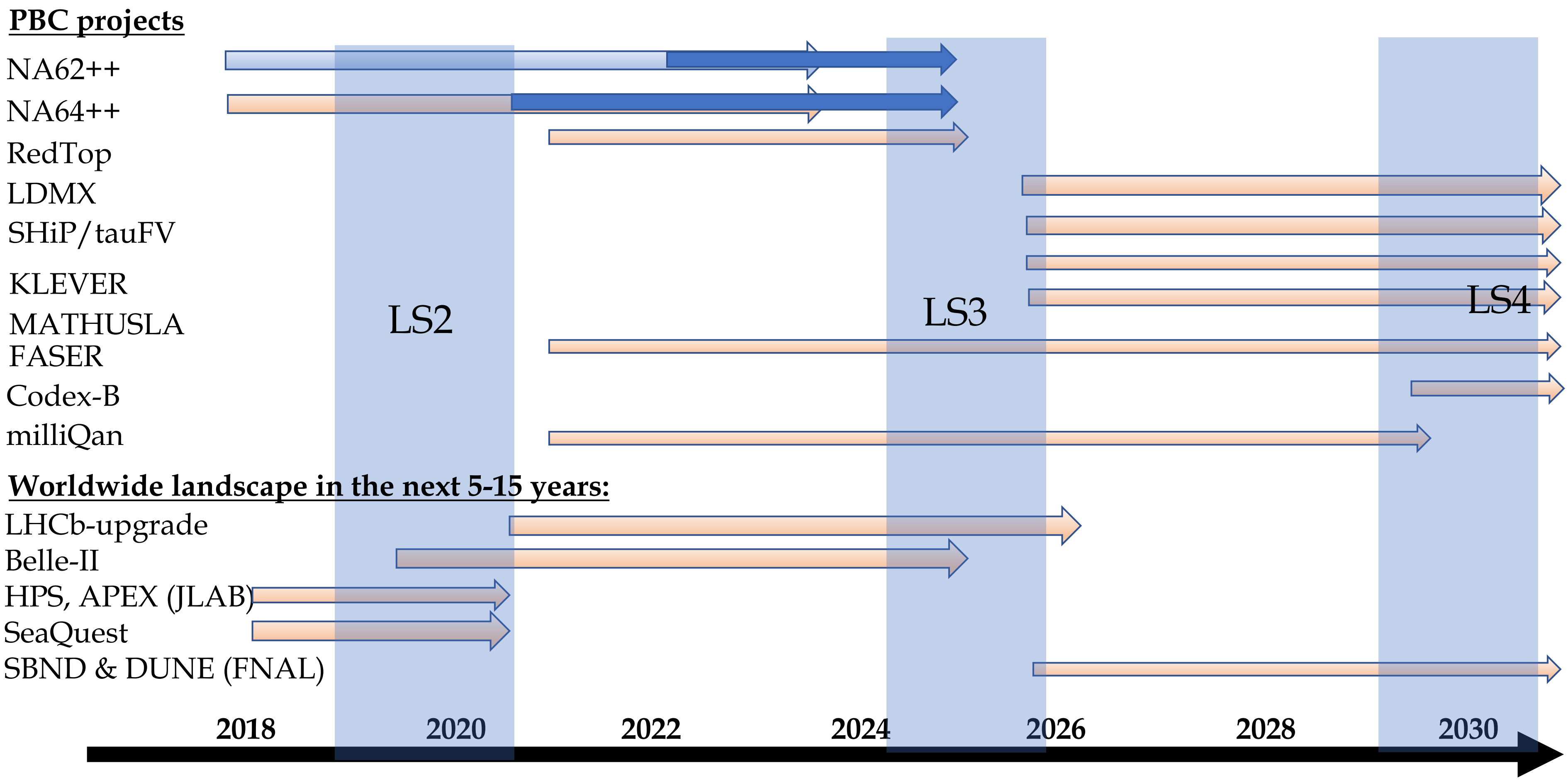
NA64: sub-GeV dark matter (BC2)

- Dark Matter from A' decays interact with electrons in the electromagnetic calorimeter . If low coupling α_D, DM escapes, create missing energy
- Dark Matter scattering on electrons: $e^- Z \rightarrow e^- Z A'$; $A' \rightarrow \chi\chi$; ; $\chi e^- \rightarrow \chi e^-$
- α_D=0.1 (left) or α_D=0.005 (right) and $m_{A'}/m_\chi$=3

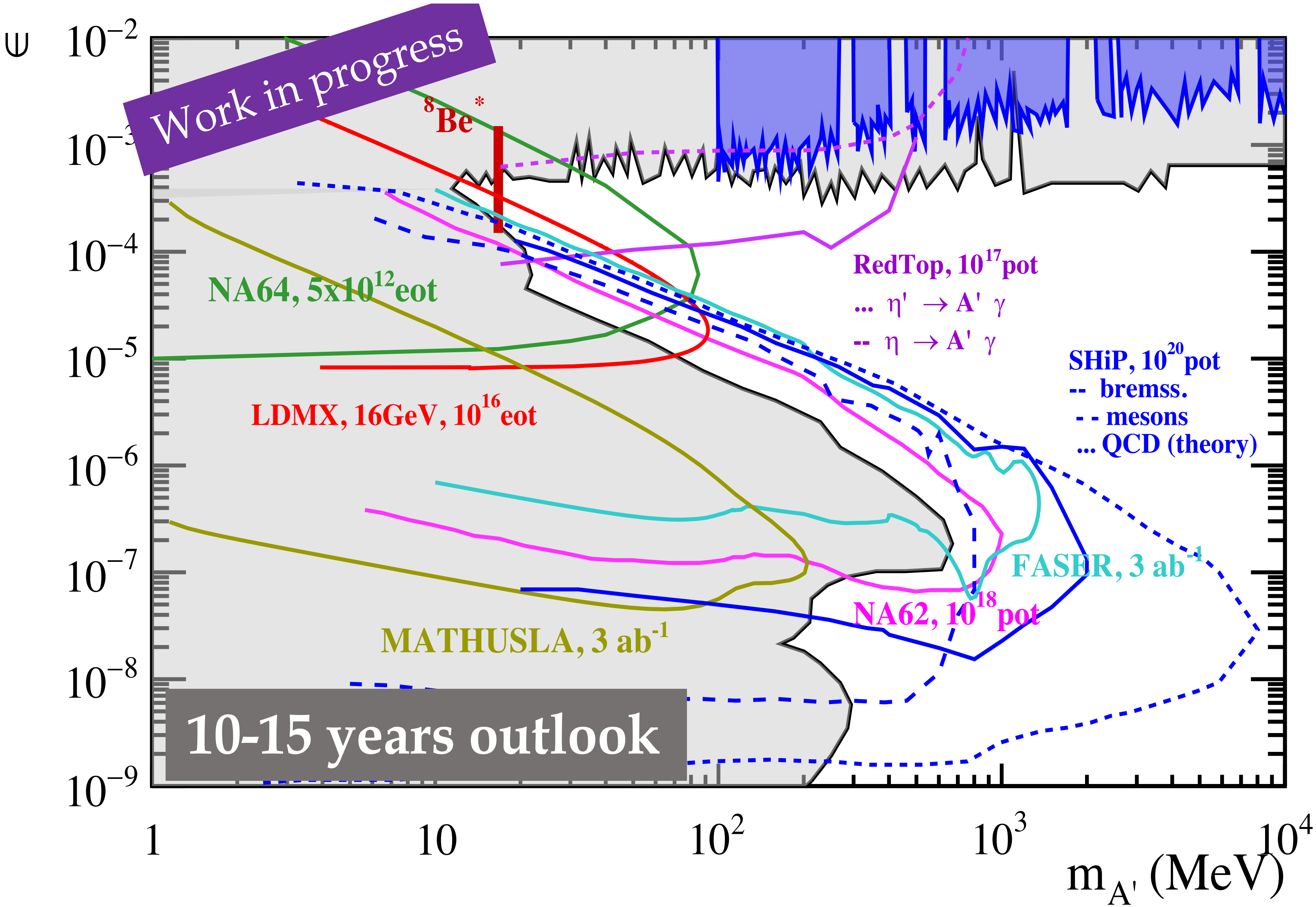




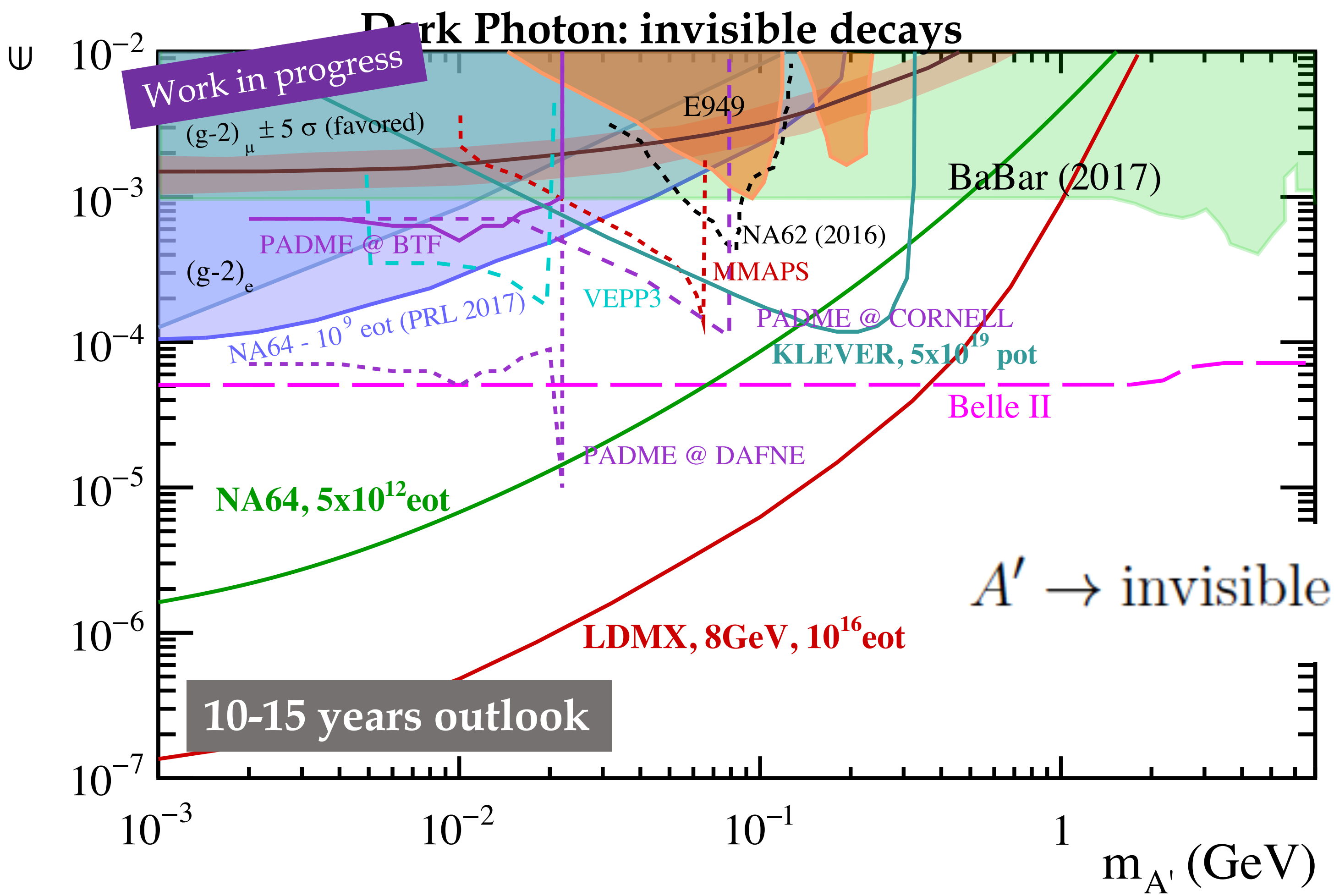
Timescale of the PBC BSM projects accelerator-based



Dark Photon to SM particles (BC1)

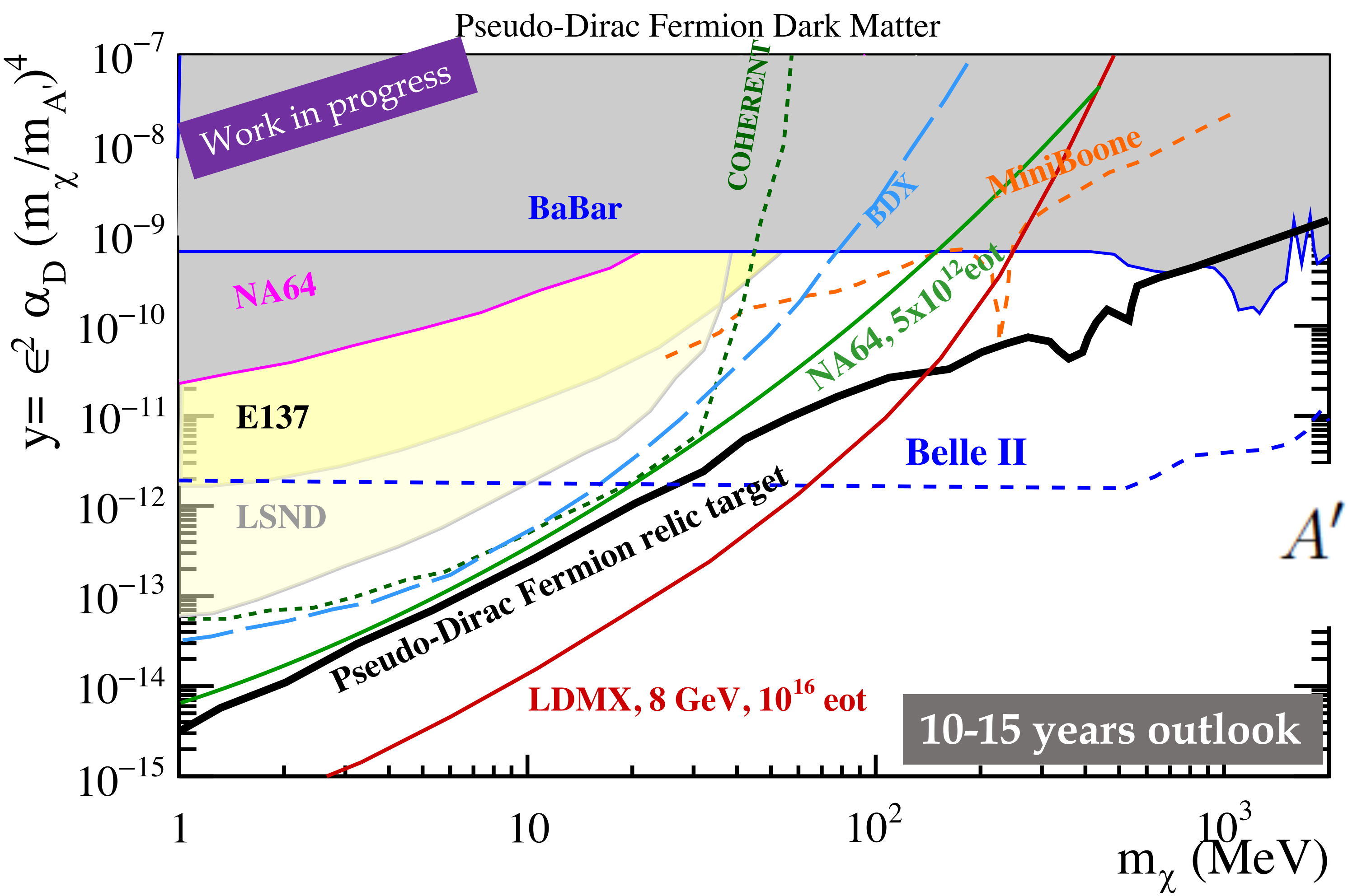


Dark Photon to Invisible (BC2)



$A' \to$ invisible final states

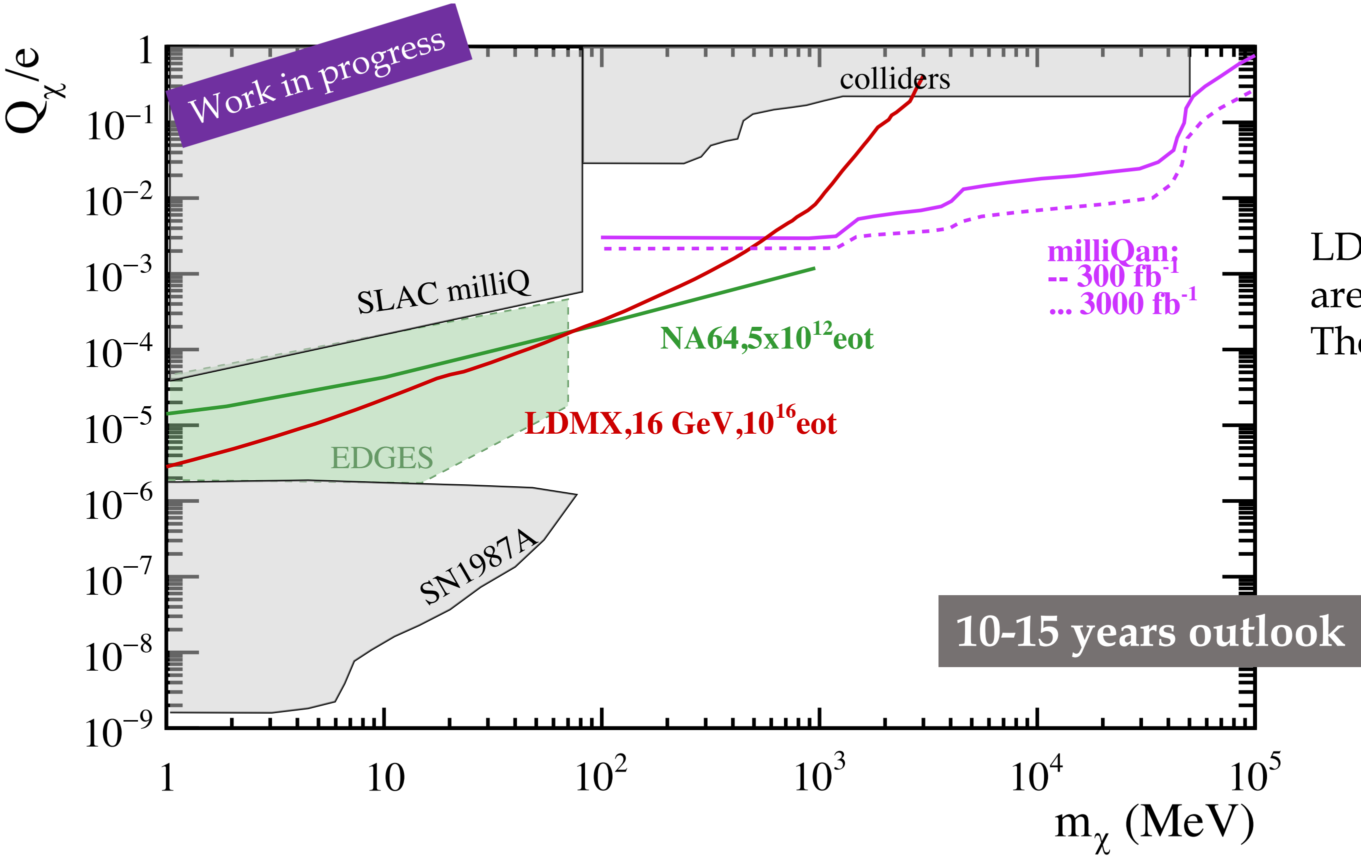
Dark Photon to Dark Matter (BC2)



$m(A') = 3\, m(\chi)$
$\alpha(D) = 0.1$

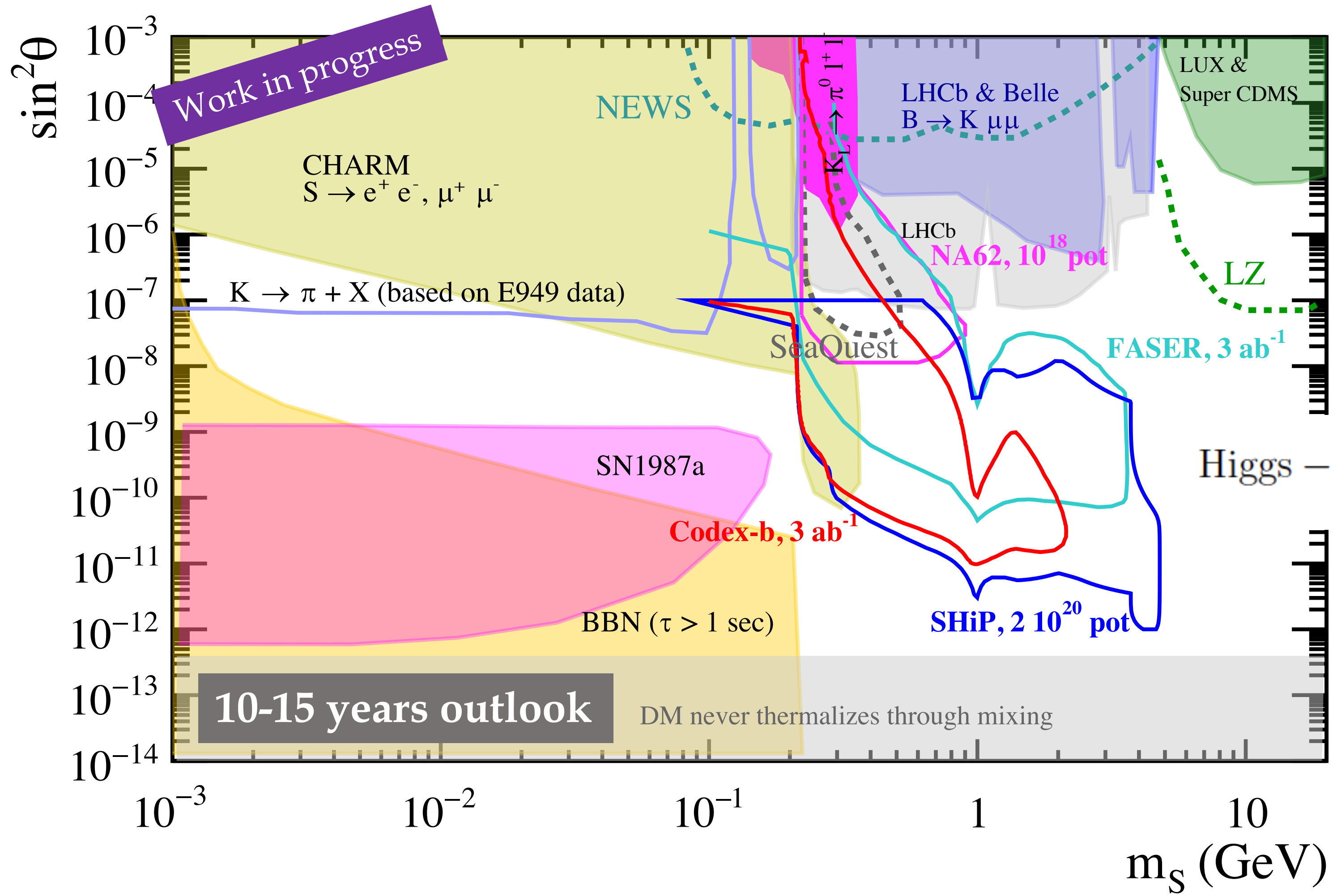
$A' \to \chi\chi$

Milli-charged particles (BC3)



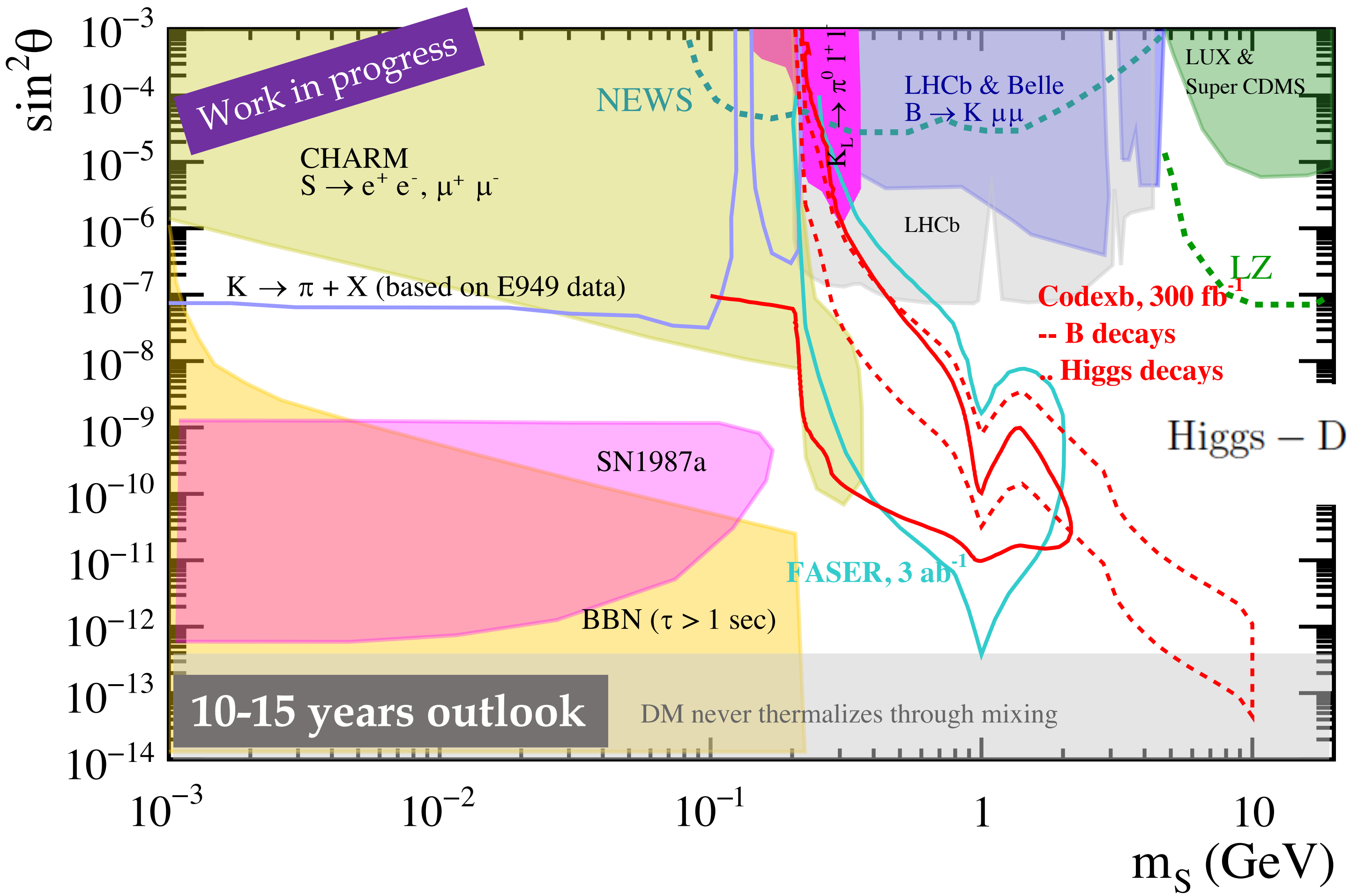
LDMX and NA64 collaborations are cross-checking their curves. They could change in the future.

Dark Higgs (BC4)



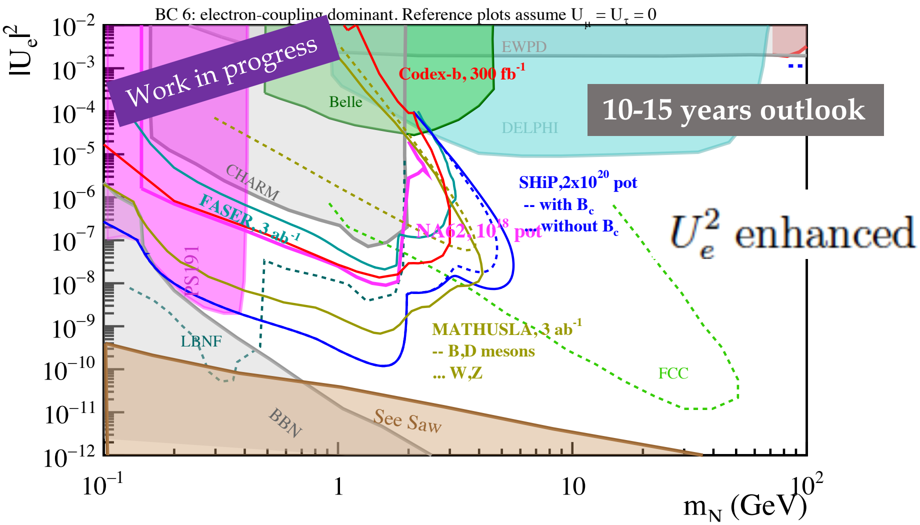
$$\text{Dark Higgs, } S \quad (\mu S + \cancel{\lambda S^2}) H^\dagger H$$

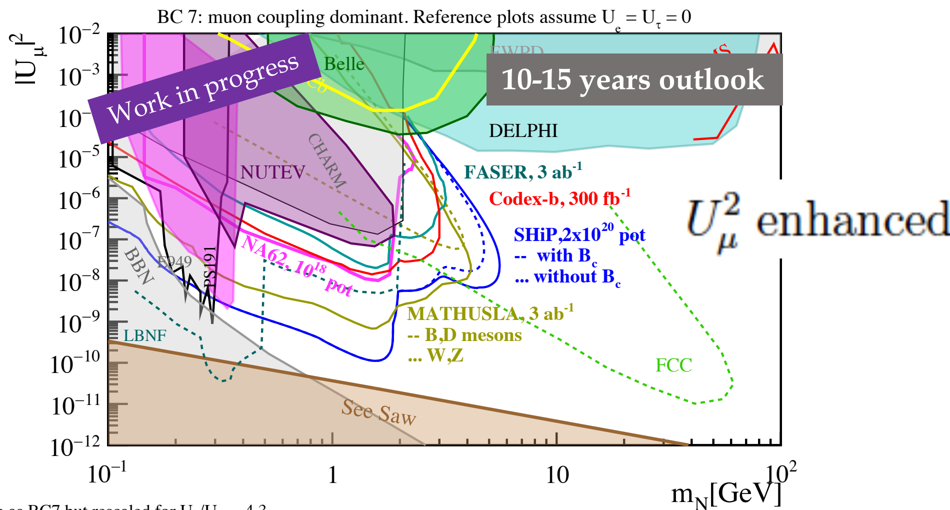
Light Dark Scalar mixing with Higgs (BC5)

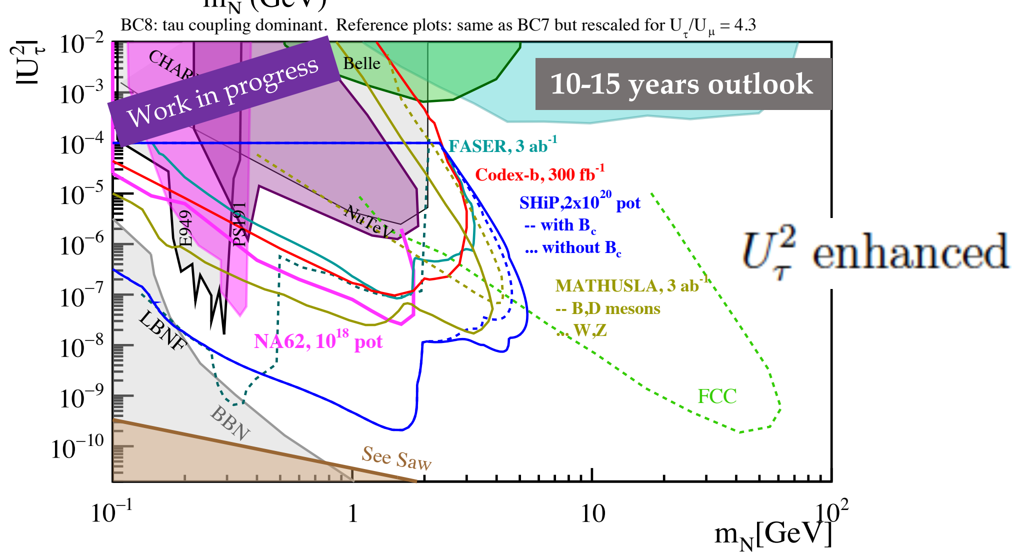


$$\text{Dark Higgs, } S \quad (\mu S + \lambda S^2) H^\dagger H$$

Right Hand Neutrinos (BC6,7,8)

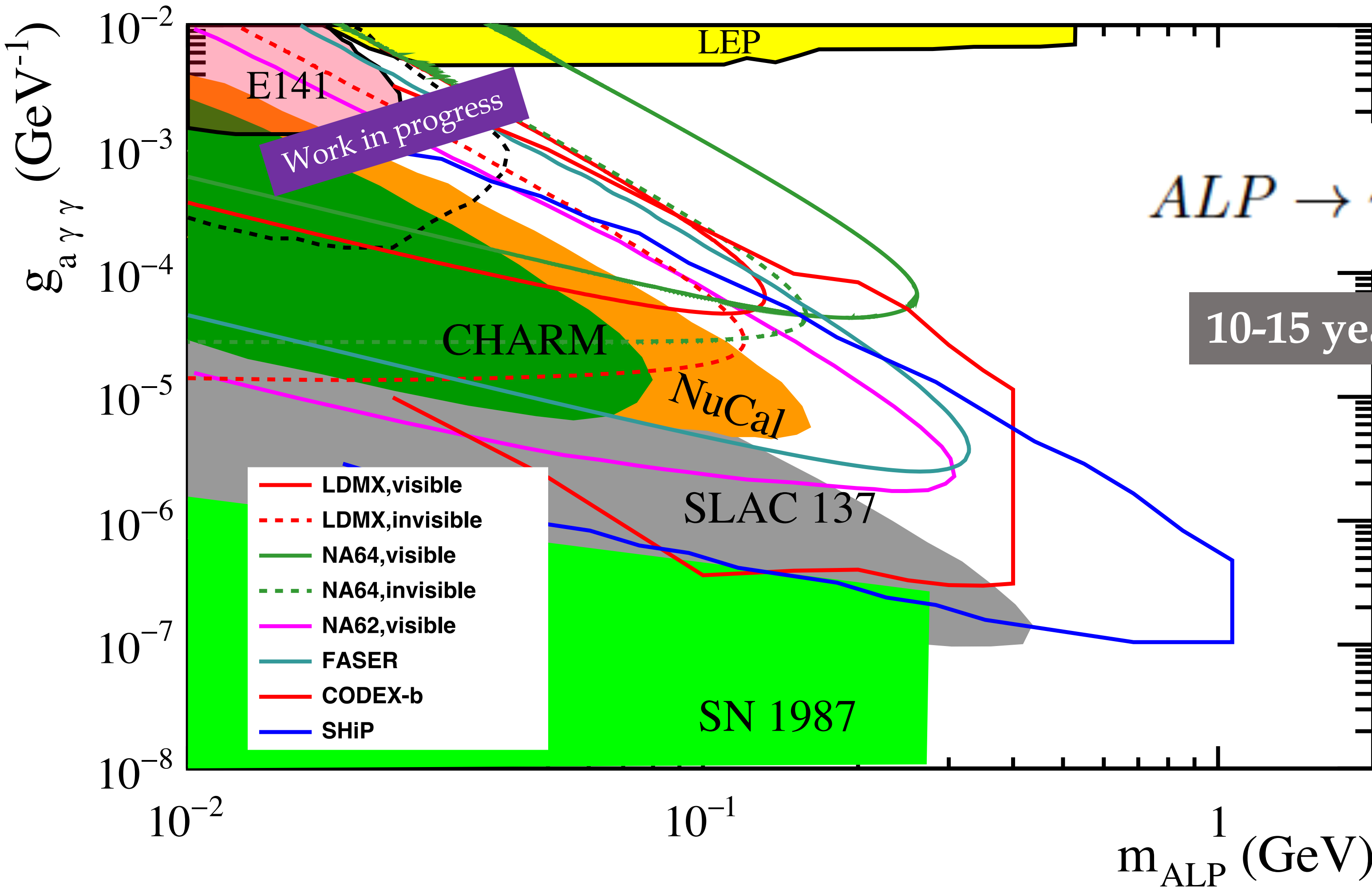






64

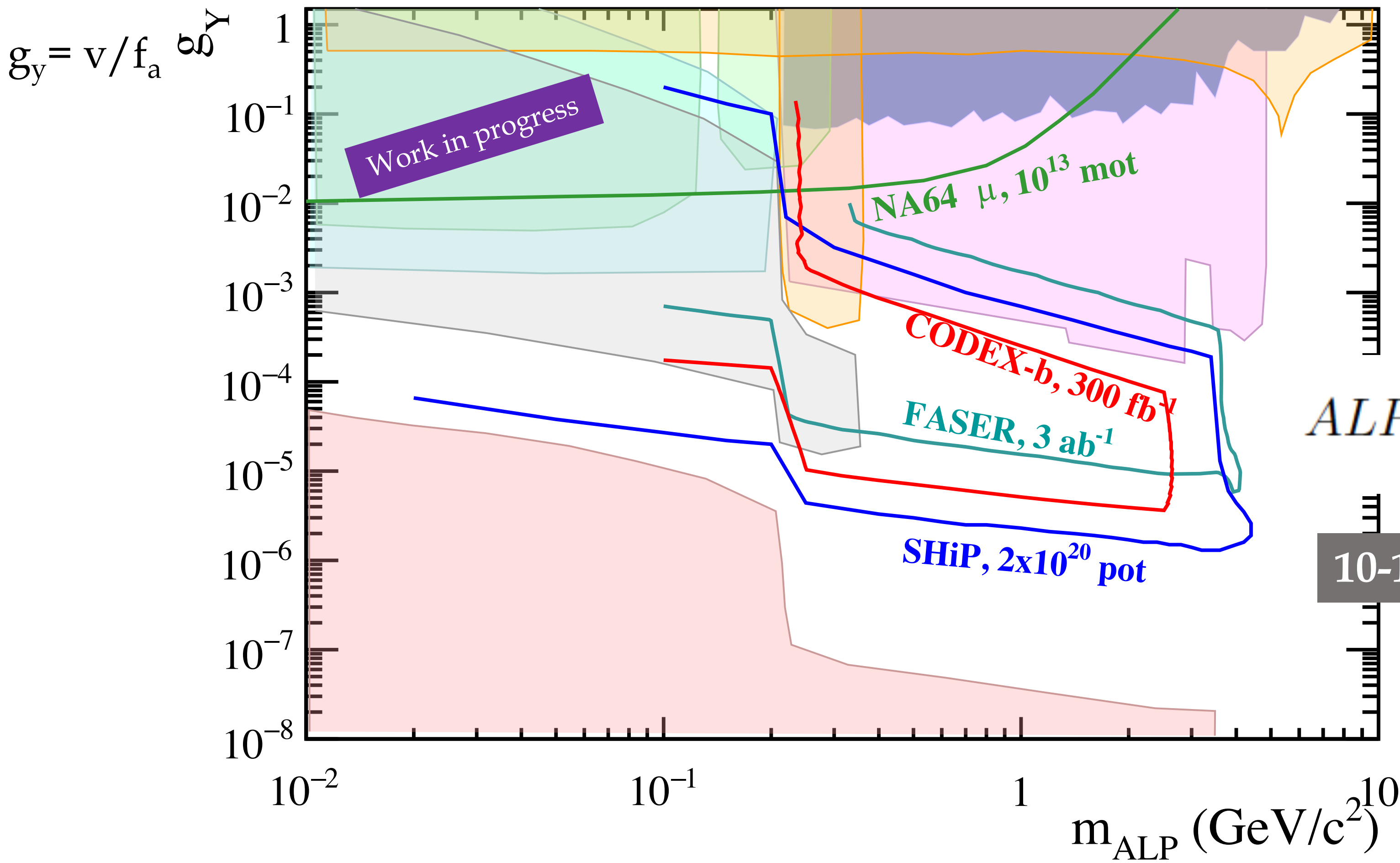
ALPs with photon coupling (BC9)



$ALP \to \gamma\gamma$, invisible

10-15 years outlook

ALPs with fermion coupling (BC10)



$ALP \rightarrow f^+ f^-$

10-15 years outlook

ALPs with gluon coupling (BC11)