ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

HEPHY Institut für Hochenergiephysik

Search for dark sector physics at proton-beam experiments

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(HEPHY, Vienna)

Next Frontiers in the Search for Dark Matter

Sep 23, 2019 - Sep 27, 2019

The Galileo Galilei Institute For Theoretical Physics

Outlines

- **Part I: What is the dark sector physics?**
- **Part II: Experimental signatures of dark sector physics in proton-beam experiments**
- **Part III: Summary**

I. Dark sector physics

Motivations for a dark sector:

<u>Primary goal:</u> to find **dark matter** particles, or a portal to them;

New physics → ***Heavier mass***

keV — MeV — GeV — TeV

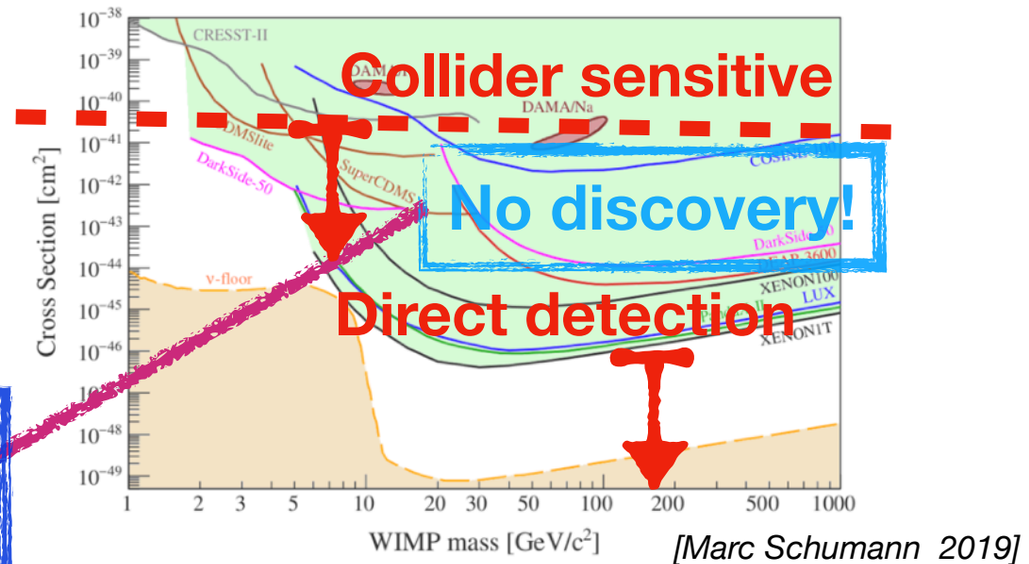
10^{-4}

10^{-8}

Coupling to SM

Conventional detections may not work

Dark matter may never thermalize with SM bath, different phenomenology.



[Marc Schumann 2019]

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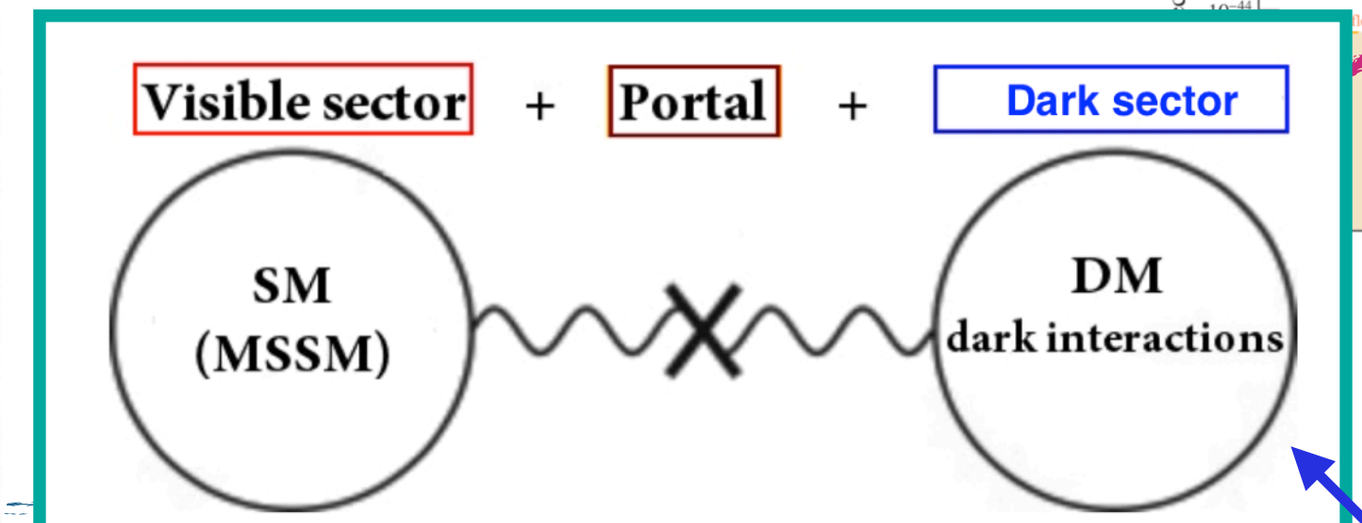

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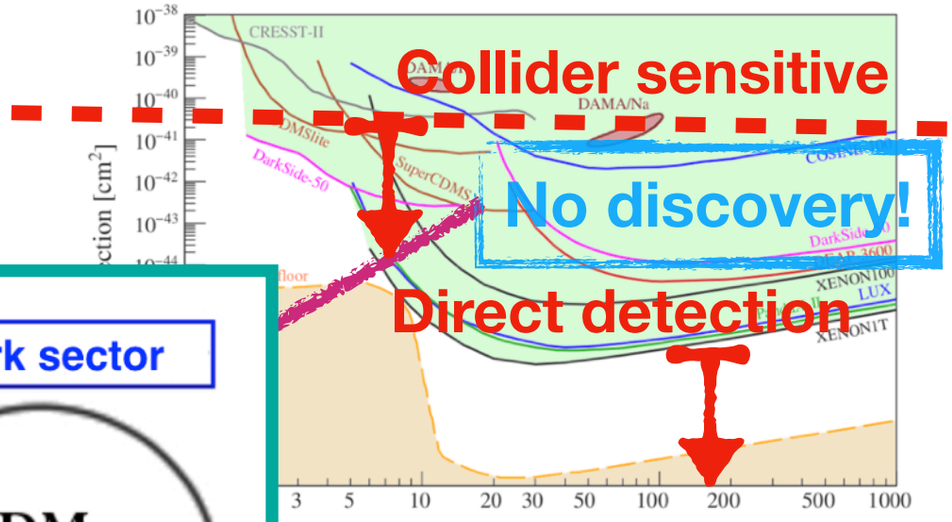


[Marc Schumann 2019]

New light sector, coupled very weakly to SM, with its own interaction structures.

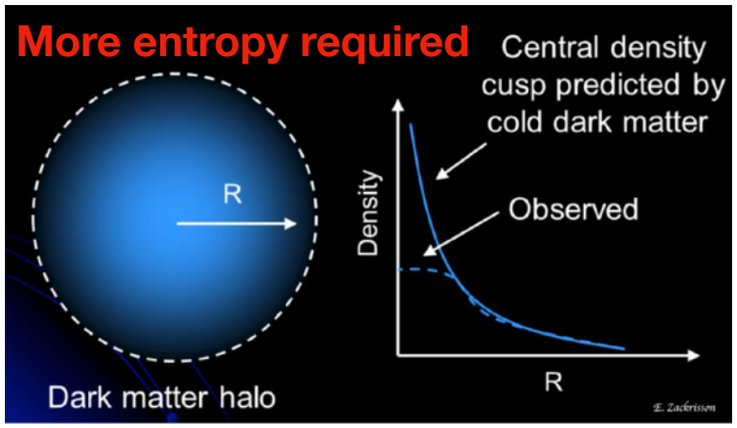
More motivations:

E.g. light dark physics helps to solve **long-standing puzzles:**

Self-interacting dark matter

[Spergel & Steinhardt, 1999]

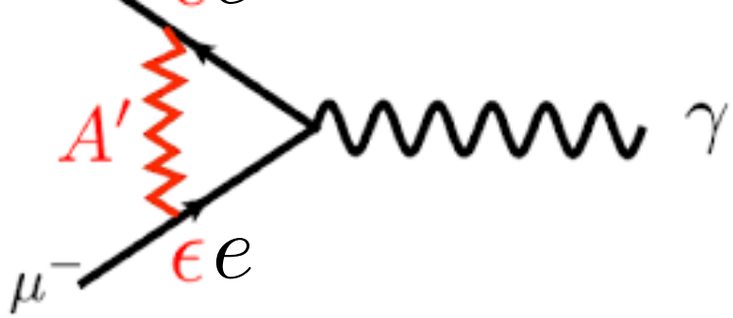
- *Core-cusp problem in halo center;*



- *Heavier halos missing (too-big-to fail);*
- *Unexpected diversity in halo profiles,…*

Massive A' for measured muonic g-2

$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{th} = (274 \pm 73) \times 10^{-11}$$

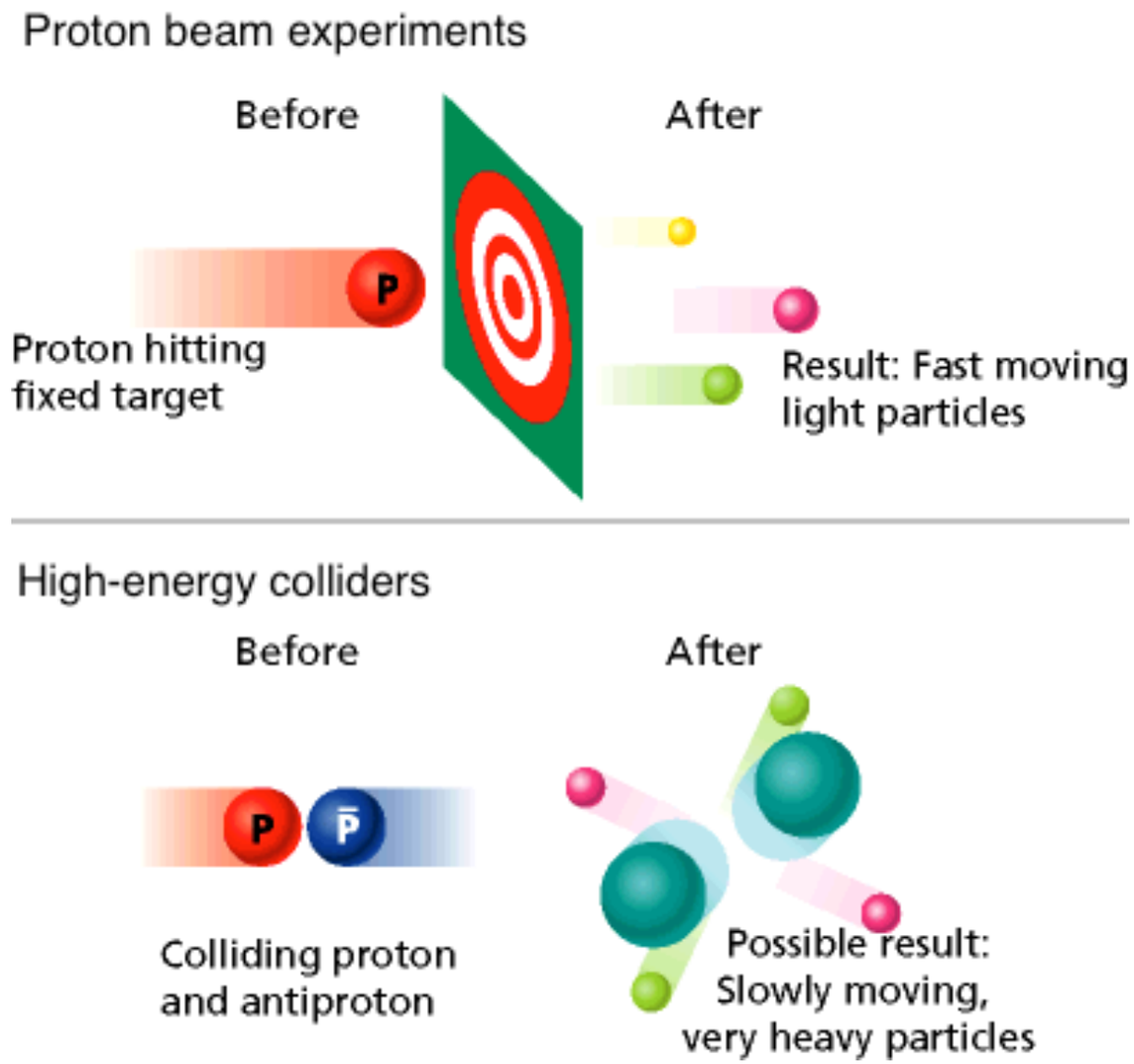


MeV-GeV massive dark photon with

$$\epsilon \sim 10^{-3} - 10^{-2}$$

Also, cosmic ray excesses, strong CP, theoretical hidden valleys, …

Proton-beam experiments probe dark sector



Pic from Jason St-Hilaire

Proton-beam experiments probe dark sector

Pros:

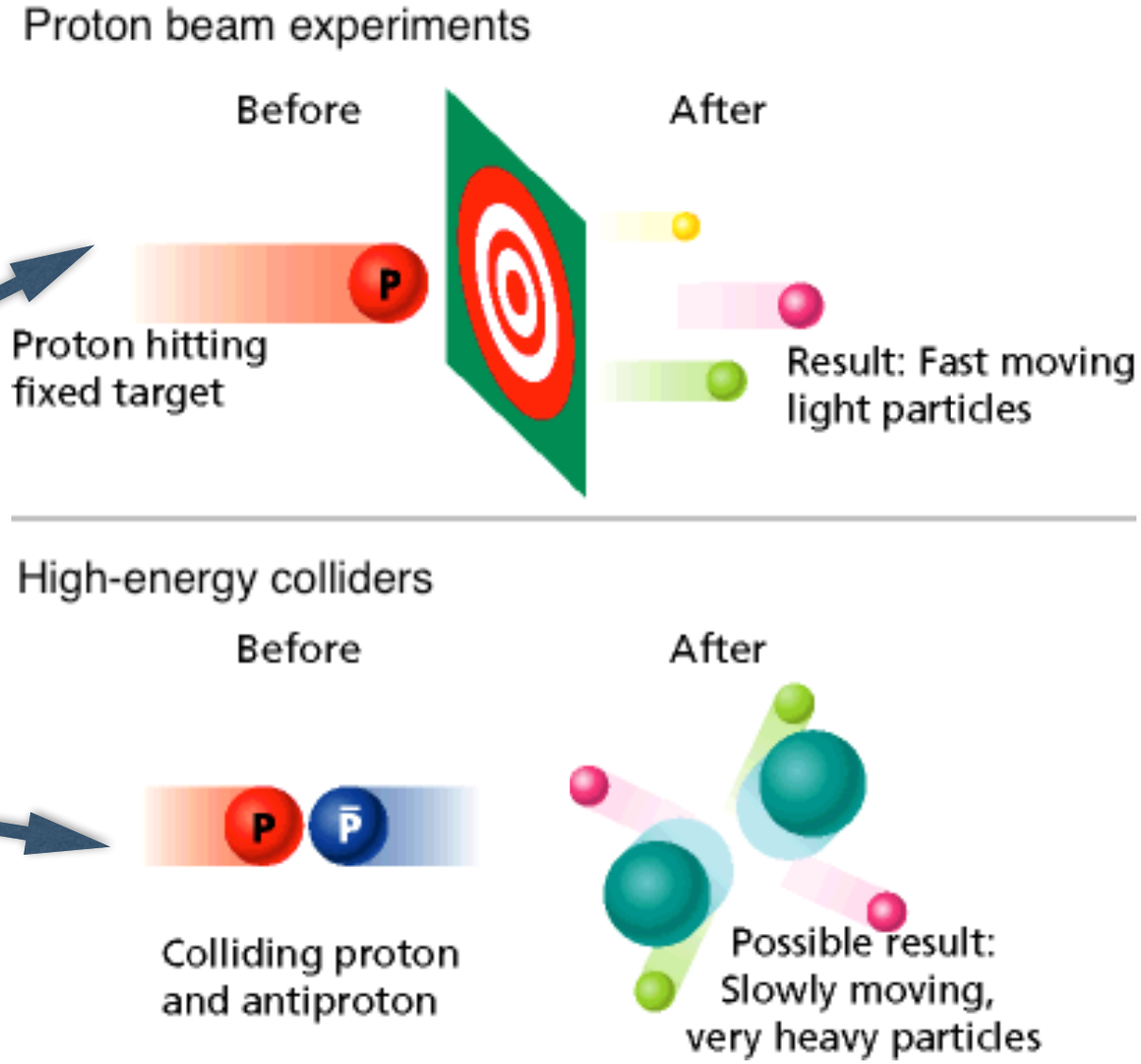
- **Very high intensity** *[Batell,Pospelov & Ritz 0906.5614, …]*

Luminosity from proton on target (POT)

$$10^{20}\,\mathrm{POT} \times \frac{\mathrm{kg/cm^2}}{\mathrm{GeV}} \sim 10^{23}\mathrm{barn}^{-1}$$

Luminosity at colliders

$$1\mathrm{ab}^{-1} = 10^{18}\mathrm{barn}^{-1}$$



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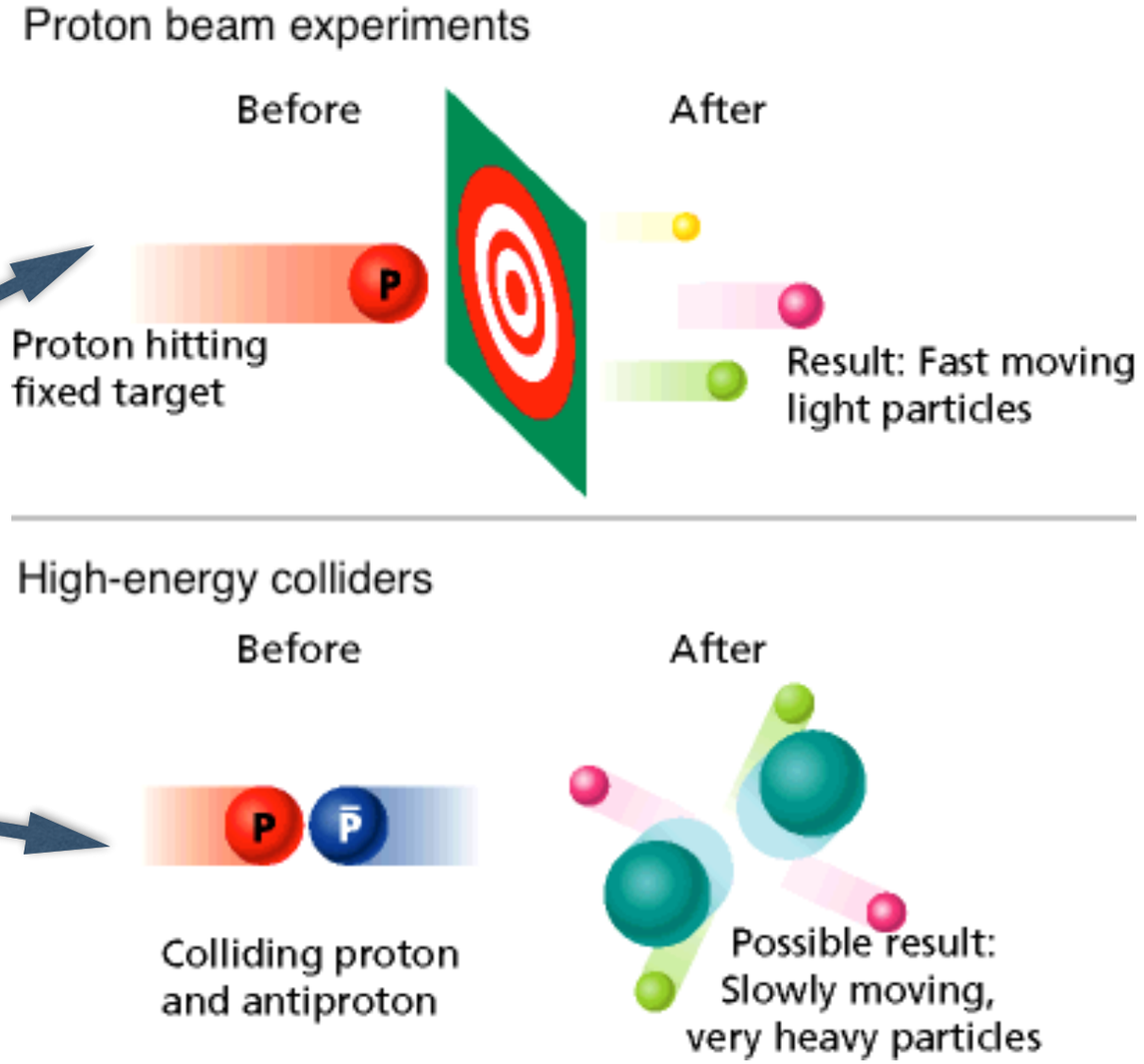


Pic from Jason St-Hilaire

- **Some existing/well-understood experiments** (bkgs, efficiencies, …);

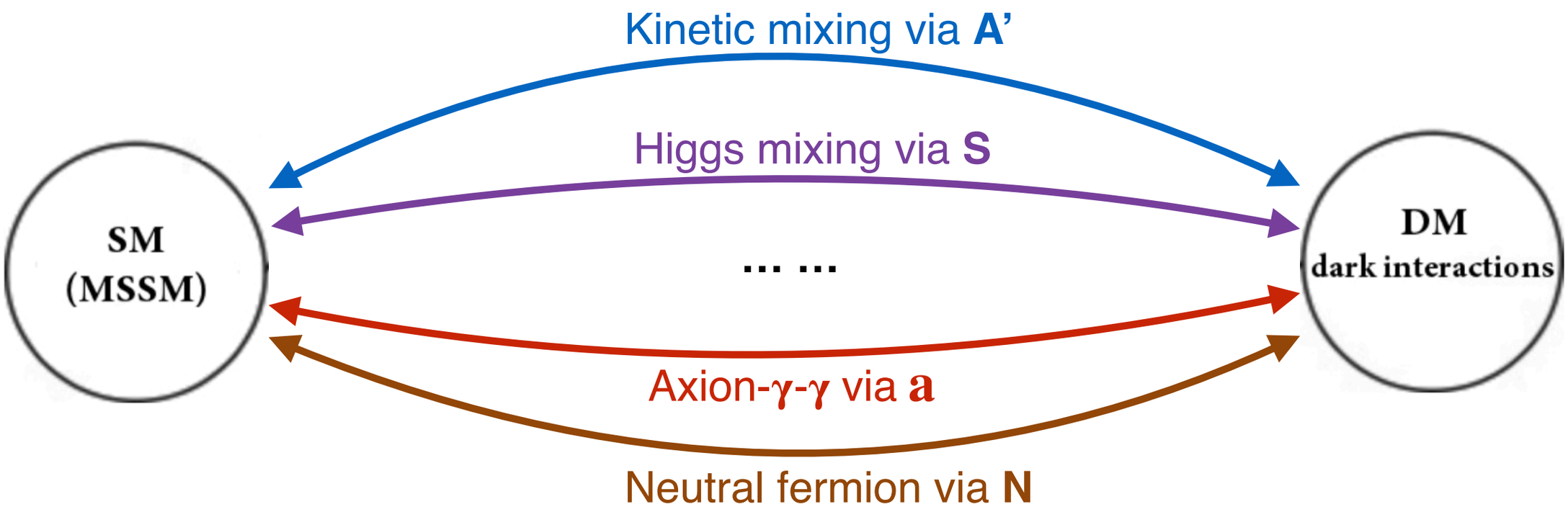
Cons:

- **Difficult to reduce neutrino backgrounds;**
- **Difficult for missing energy searches;**

II. Experimental signatures of dark sector (DS) particles

Signatures of dark sector physics

Minimally-coupled Portal



[Apologies for not being able to mentioning more models and references..]

Signatures of dark sector physics

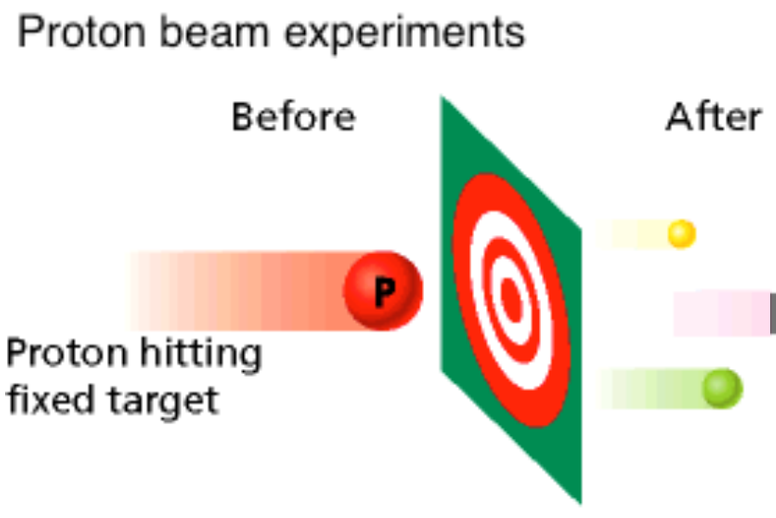
Minimally-coupled Portal

Kinetic mixing via **A'** $\Longrightarrow$ **Minimal** DM interaction

[Holdom 1986, Dienes, Kolda, March-Russell 1996, …]

Neutral fermion via **N** $\Longrightarrow$ neutrino **Minimal** SM

[Asaka & Shaposhnikov 2005]



(On/off-shell) **portal** appears, then **decays**

Shield

Signatures

If to DS: **(in)elastic scattering**

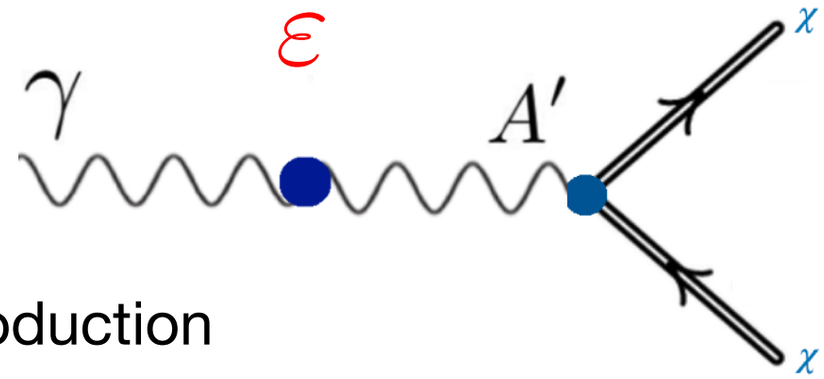
If to SM: **displaced vertices**

II.A (In)elastic scattering excess

(CHARM, SHiP, MilliQan, … , as well as neutrino experiments such as LSND, MiniBooNE, T2K, COHERENT, DUNE, SBND, ….)

Kinetic mixing via A'-portal

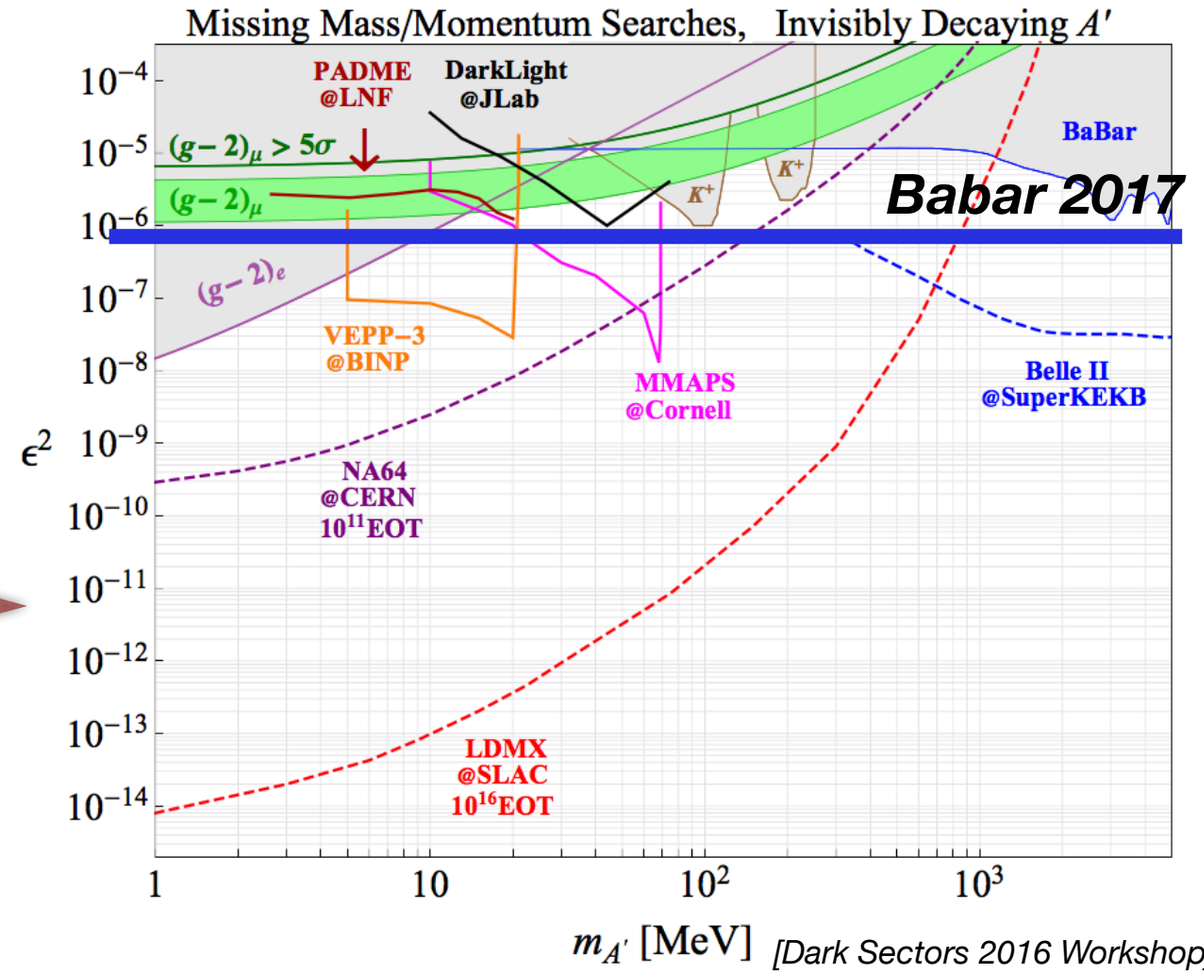
$$-\frac{\epsilon}{4}F_{\mu\nu}F'^{\mu\nu} + igA'_{\mu}(\bar{\chi}\gamma^{\mu}\chi)$$



It greatly enriches dark matter physics, such as various production mechanisms [XC, T.Hambye, M.Tytgat 2011, XC, Y. Mambrini, J.Quevillon, B.Zaldivar 2013, C.Dvorkin,T.Lin, K.Schutz 2019, T.Hambye, M.Tytgat, J.Vandecasteele, L.Vanderheyden 2019, J. Evans, C.Gaidau, J. Shelton 2019,….], ...

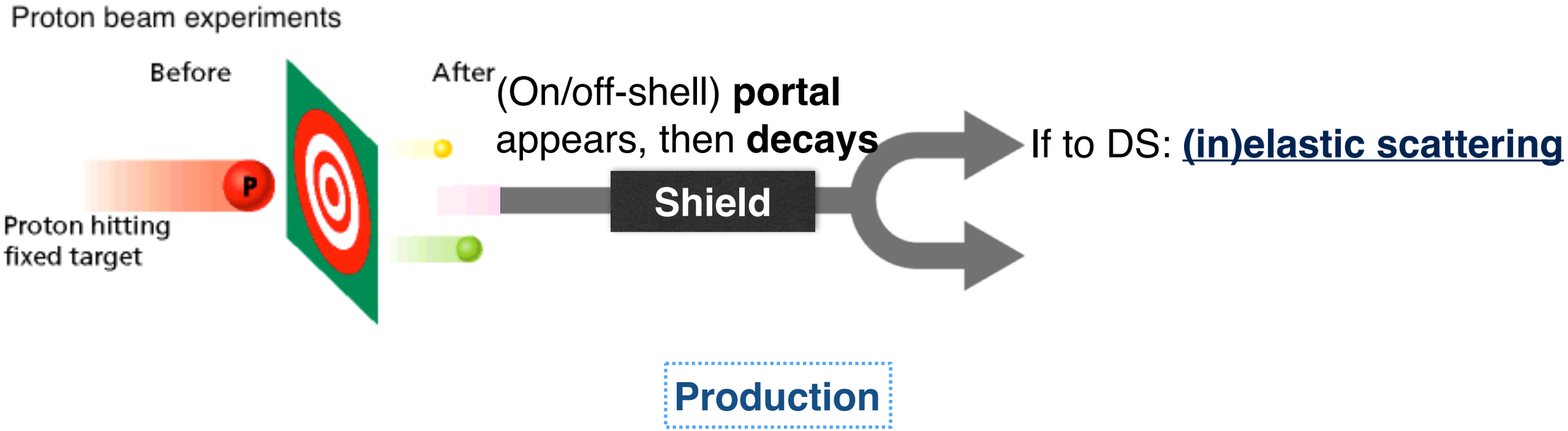
If A' dominantly couples to light dark pairs or $m_{A'} < 2m_e$, it decays **invisibly**:

Electron-beam experiments search for missing energy/ momentum:

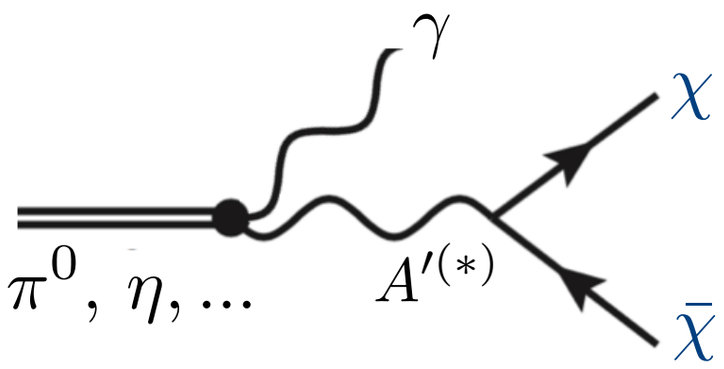


[Dark Sectors 2016 Workshop]

A'-portal for proton-beam experiments



- Parton collisions via **pp→DS pair (DY)**;
- Proton Bremsstrahlung via **pp→pp'+DS pair**;
- Secondary production via **meson decay**
  (possible double-counting e.g. conversion of vector meson to dark photon);
- Secondary collisions by produced electron/photon/pion/etc. *(interesting for quark-phobic states).*



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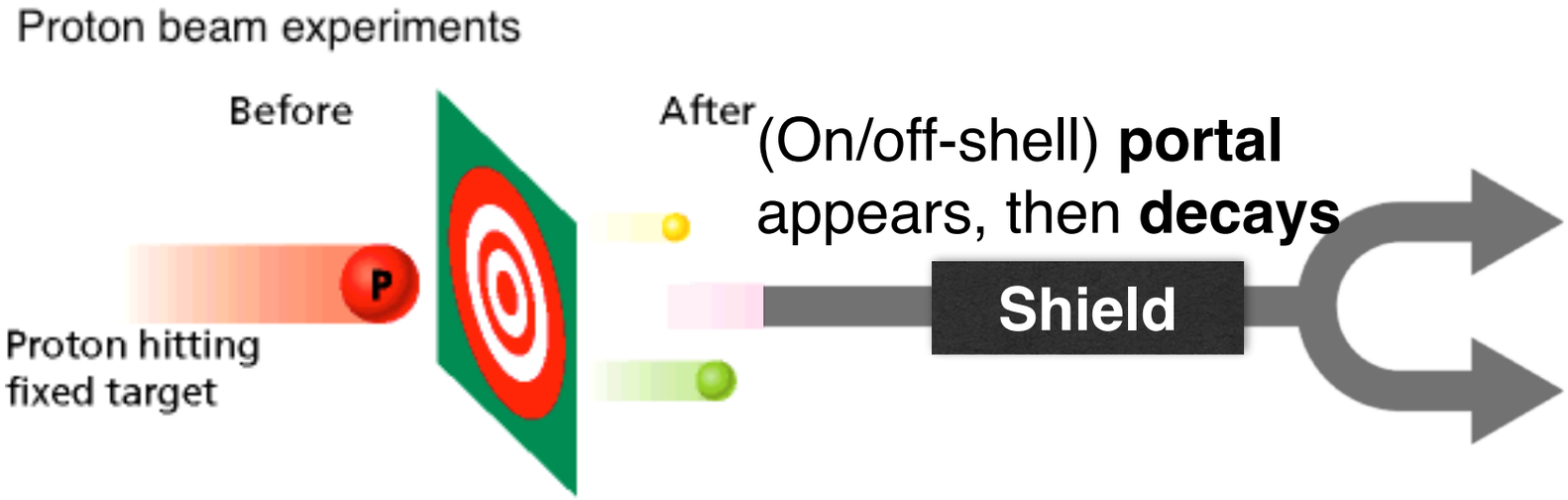

Production

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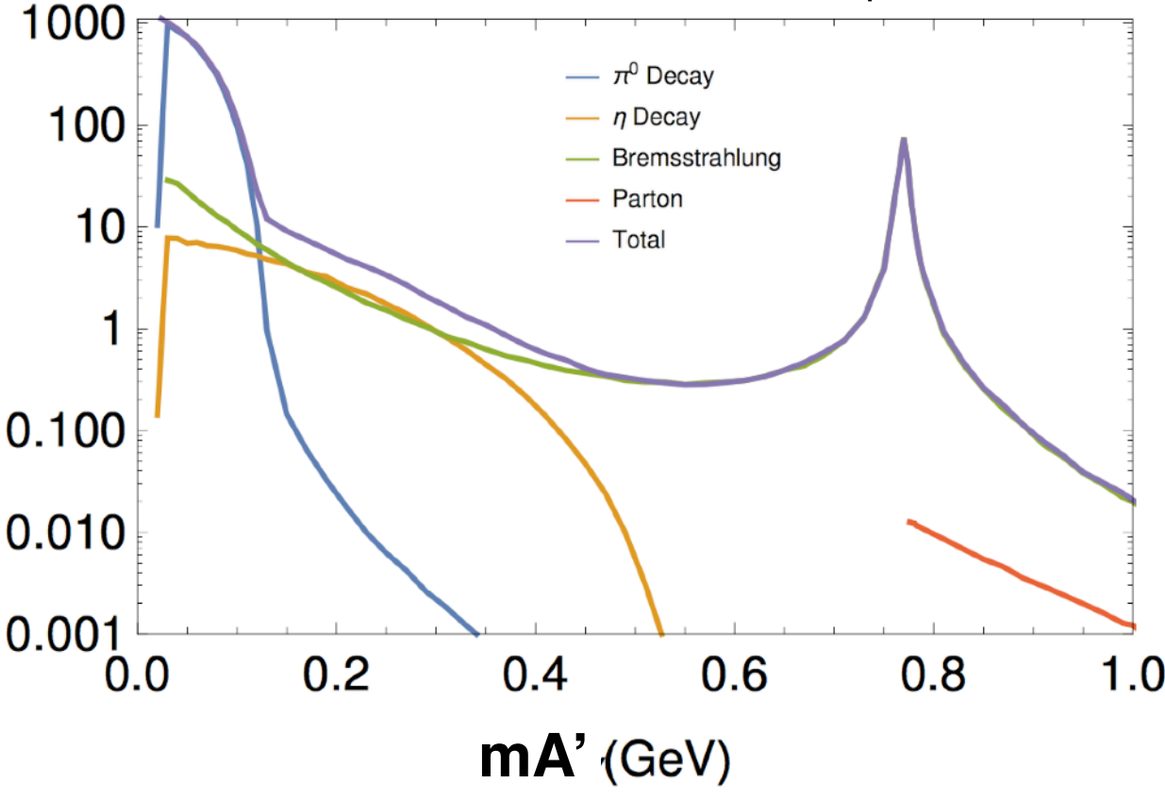
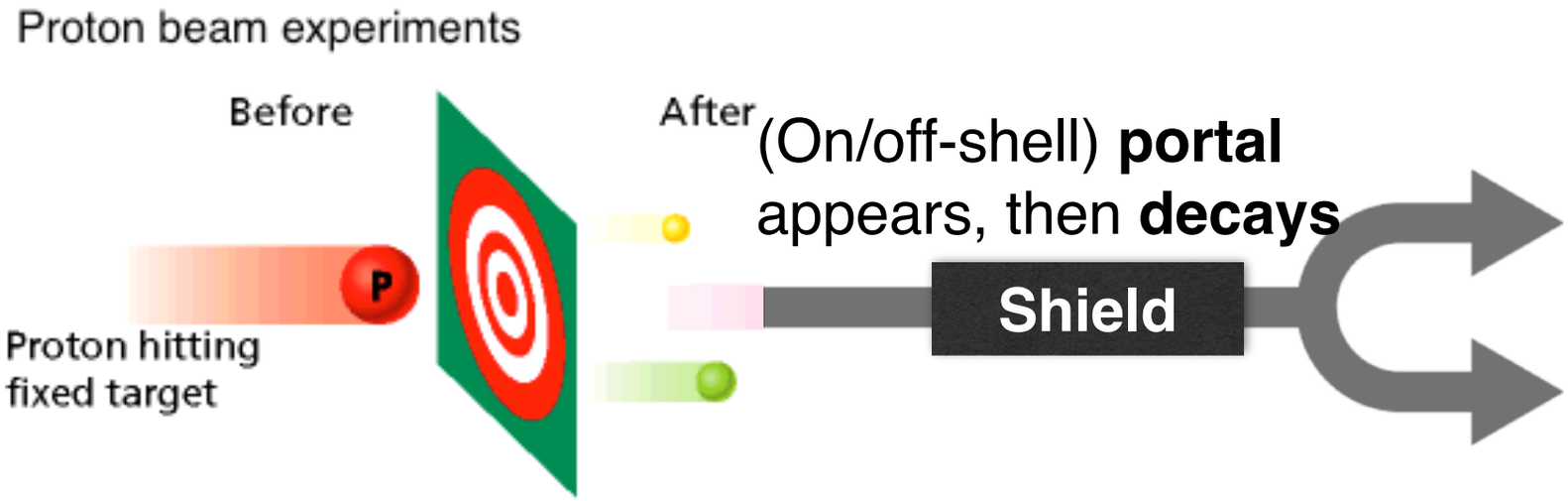
MiniBooNE / 8 GeV proton



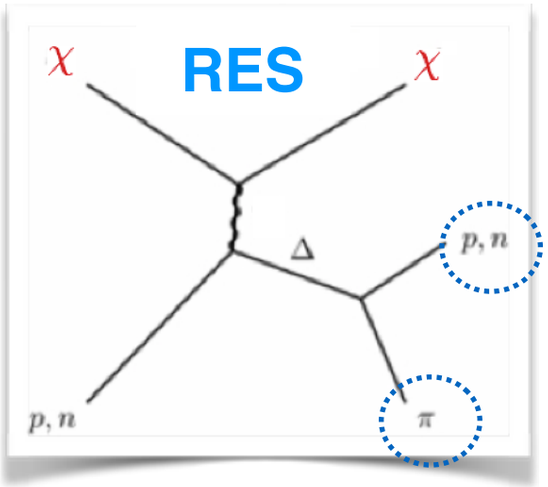
A illustration from [deNiverville, Chen, Pospelov &Ritz 1609.01770]

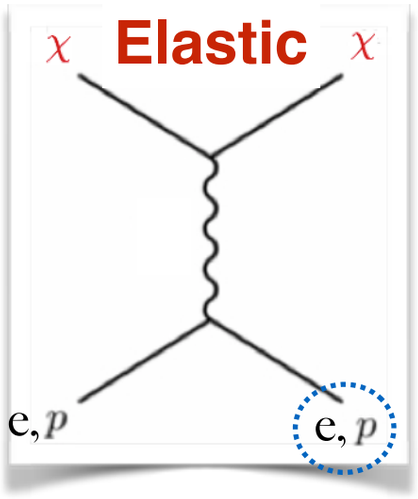
A'-portal for proton-beam experiments

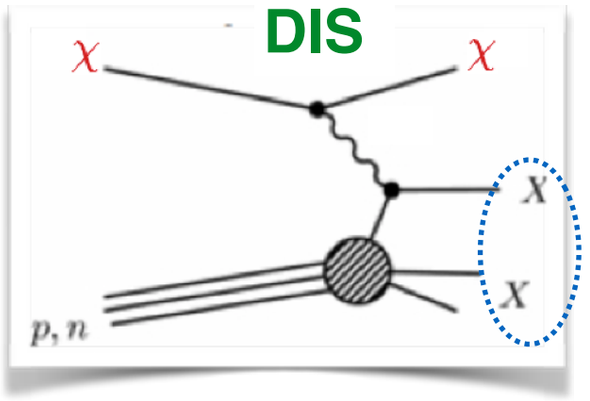


Detection

- **Electron/nucleon recoils** (Elastic);
- Single-pion scattering (RES);
- Deep inelastic scattering (DIS)
- Coherent scattering effects, …







Backgrounds (mostly neutrino induced):

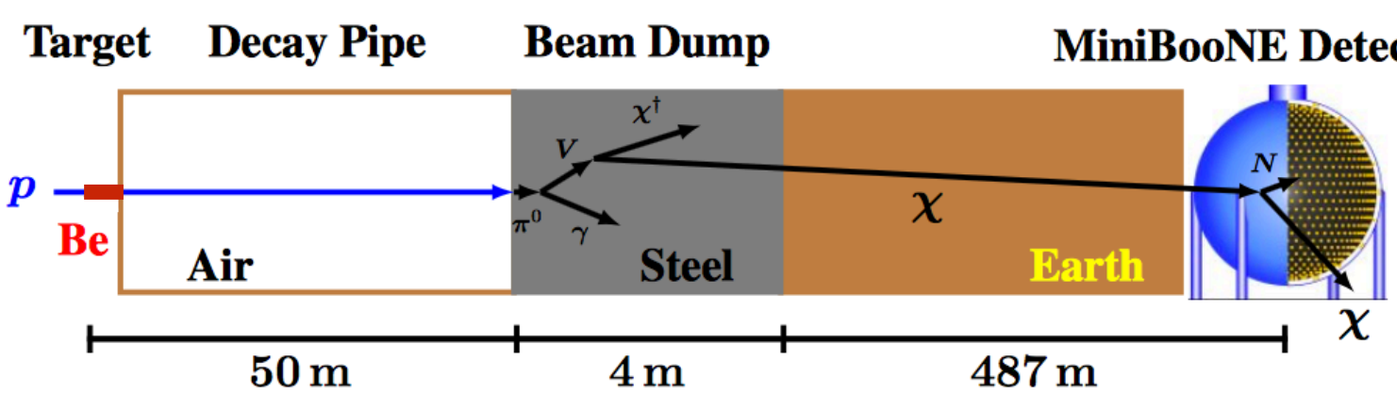
Take MiniBooNE **on-target mode**:

visible energy $75 \leq E^e_{\rm vis}\,({\rm MeV}) \leq 850$
reconstructed angle $\cos\theta_e \geq 0.99$

Predicted single-e bkgs

8 GeV beam with $1.3 \times 10^{21}\,{\rm POT}$ → ~ 100 events [MiniBooNE 1211.2258]

Much fewer than nucleon recoils, but still a lot.



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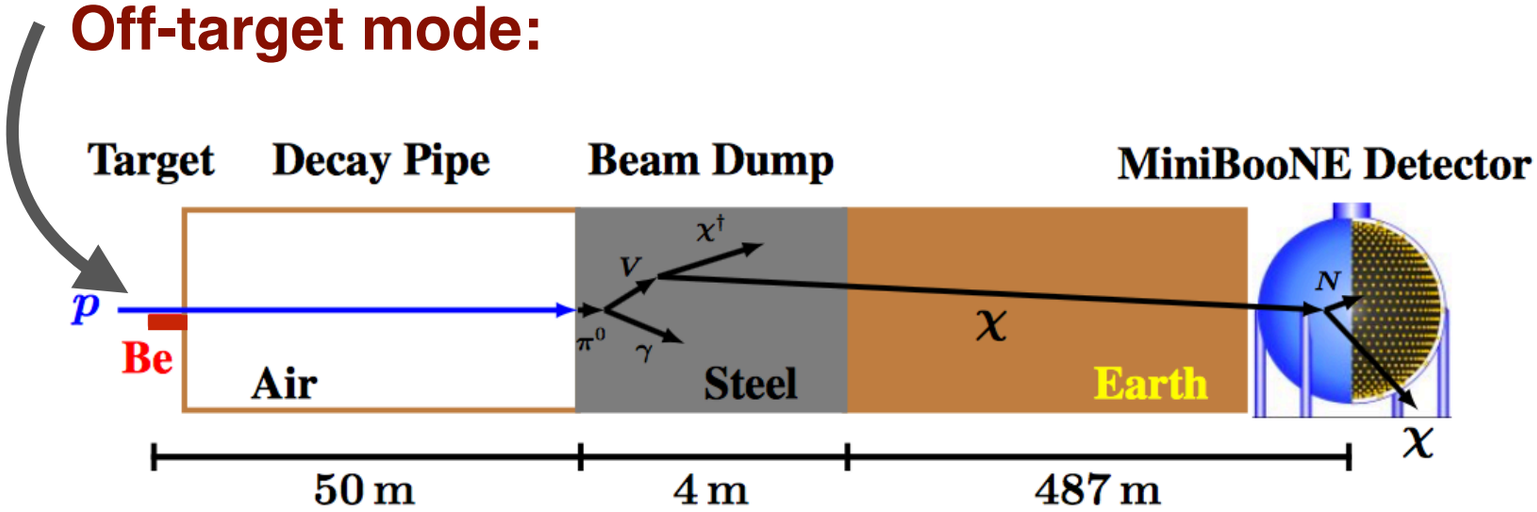

$\mathcal{L}_\nu \to \mathcal{L}_\nu/30$

Suppress neutrinos produced from charged mesons

[MiniBooNE-DM Collaboration 1211.2258, 1702.02688, 1807.06137];

$1.8 \times 10^{20}\,{\rm POT}$ **produced no single-e events (after cut)!**

1461 NC Elastic N / 148 NC π^0 events.

Backgrounds (mostly neutrino induced):

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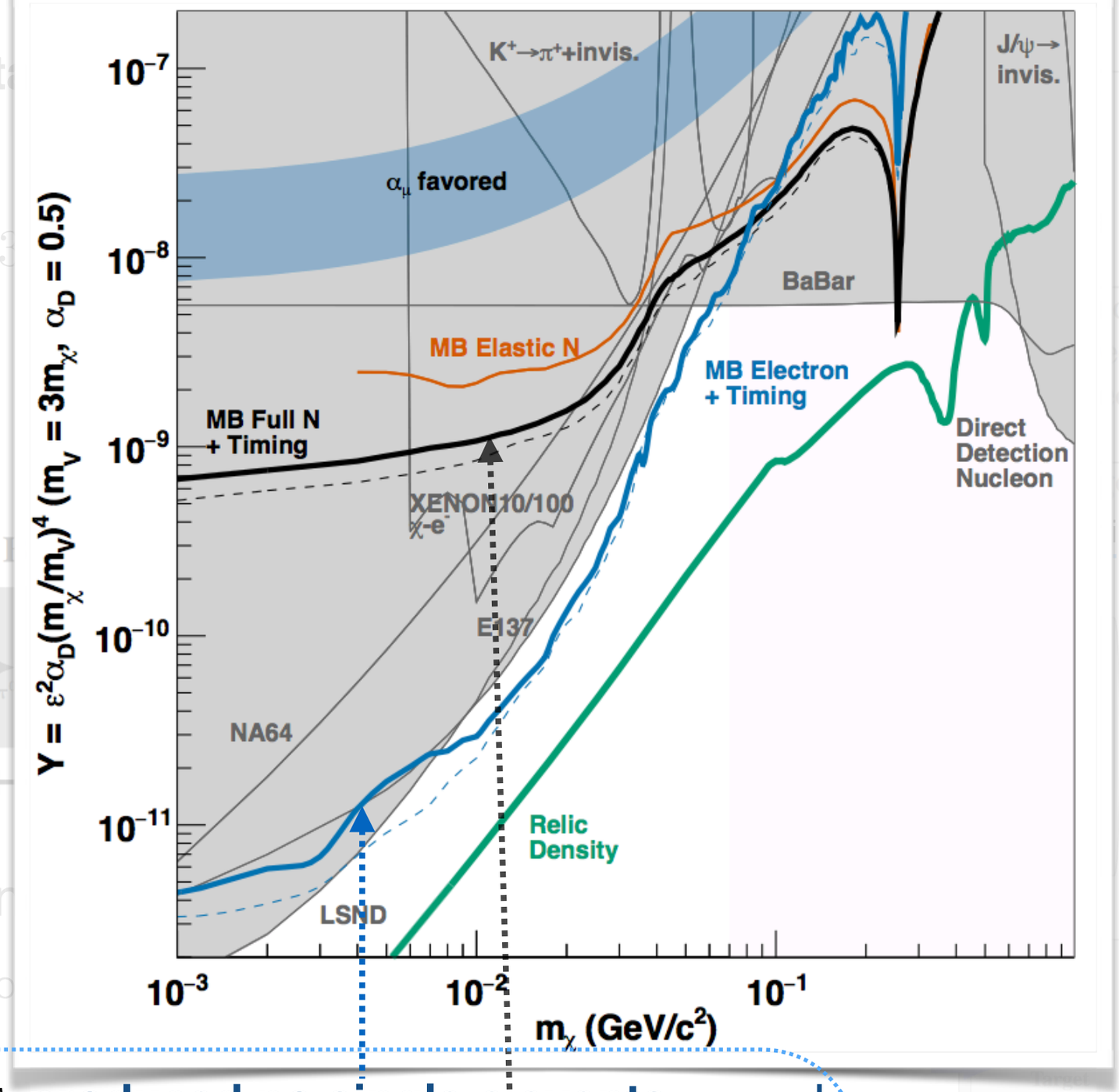

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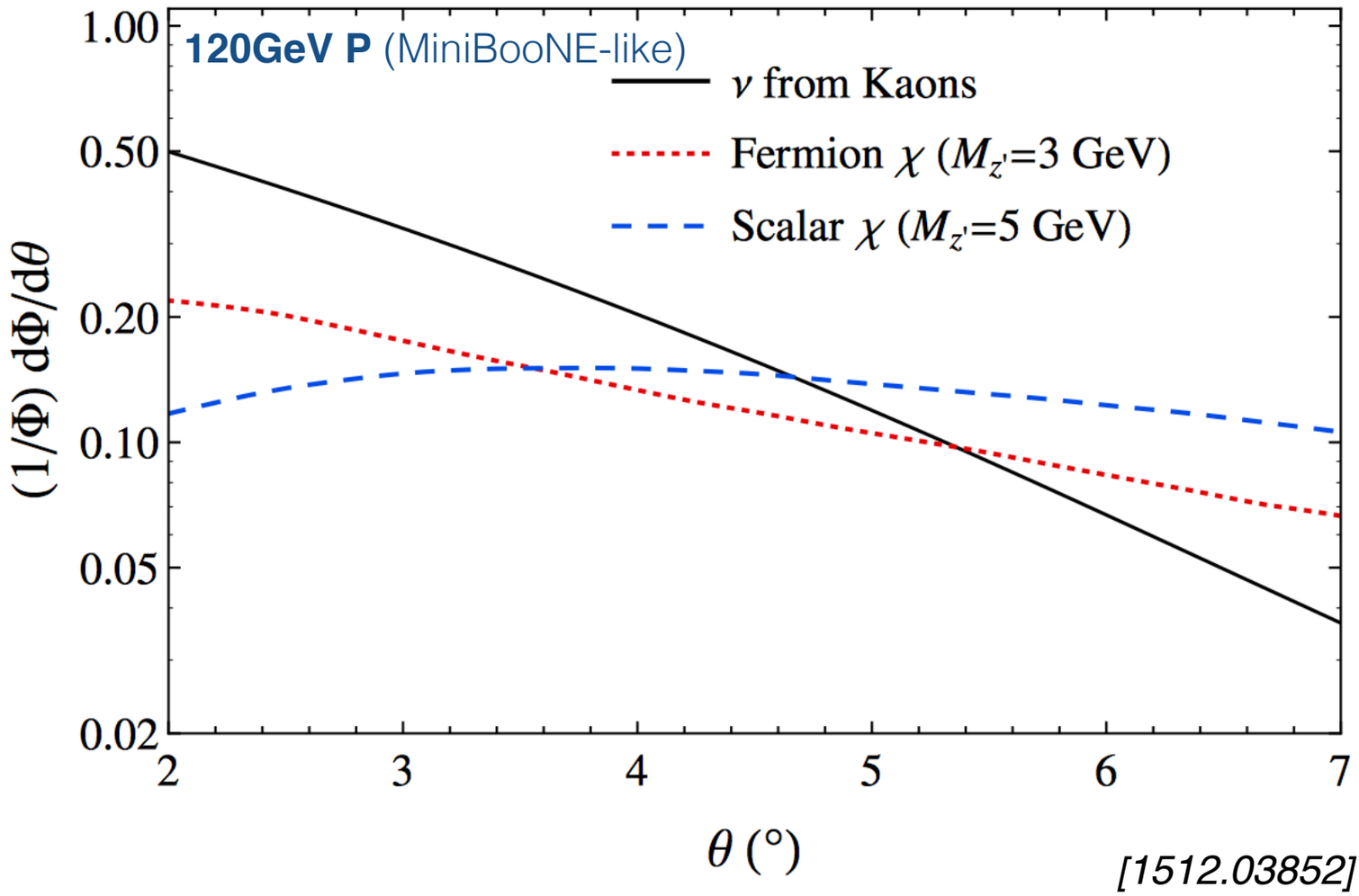
[MiniBooNE-DM Collaboration 1807.06137]

More on background cut:

To reduce neutrino backgrounds:

- **Off-axis detector**: dark particles usually have a much wider beam;
  - Especially for **heavy dark particles**, different from neutrinos (charged mesons focused by magnets & two-body decay); *[Coloma, Dobrescu, Frugiuele & Harnik **1512.03852**, Frugiuele 1701.05464, deNiverville & Frugiuele 1807.06501, Gouvêa, Fox, Harnik, Kelly & Zhang 1809.06388,…]*

$$m_{A'} \gg 2m_\chi$$



[1512.03852]

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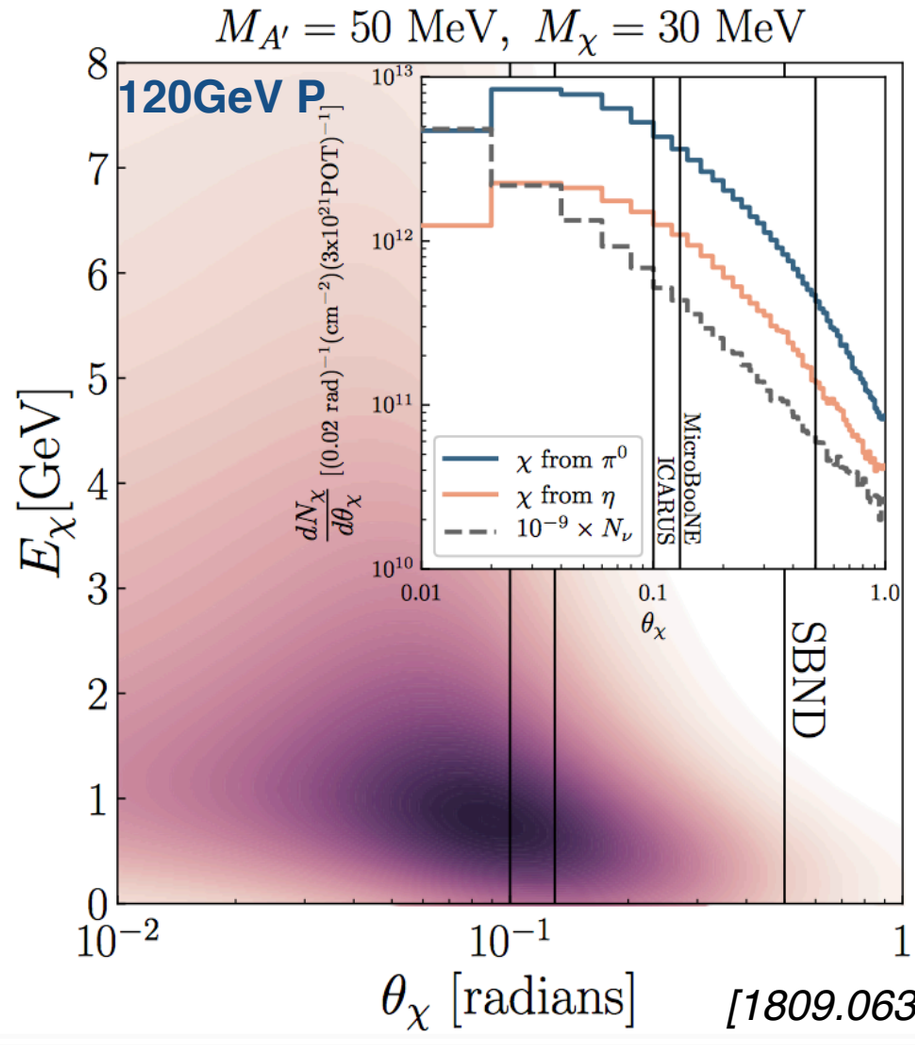
$$m_{A'} \leq 2m_{\chi}$$



[1809.06388]

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- **Timing cut**: massive dark particles take longer to reach the far detector;
  - E.g. Super-K gives ns - μs delay *[deNiverville, Chen, Pospelov & Ritz 1609.01770], …*;

- **Kinetic cut** on the SM particle scattered by massive dark particle;
  - E.g. MiniBooNE-DM, DIS, ….

More on background cut:

Interestingly, if A' is massless, one can always define the **2 d.o.f.** coupled to QED current as **the SM photon**, so A' does not couple to SM charged particles:

→ Produce **milli-charged dark particles** directly in **proton beam!**

[Haas, Hill, Izaguirre & Yavin 1410.6816, Magill, Plestid, Pospelov & Tsai 1806.03310, Kelly & Tsai 1812.03998, KeHarnik, Liu & Palamara 1902.03246, Romer, Kelly & Machado 1903.10505…]

To distinguish **soft dark collisions** from backgrounds:

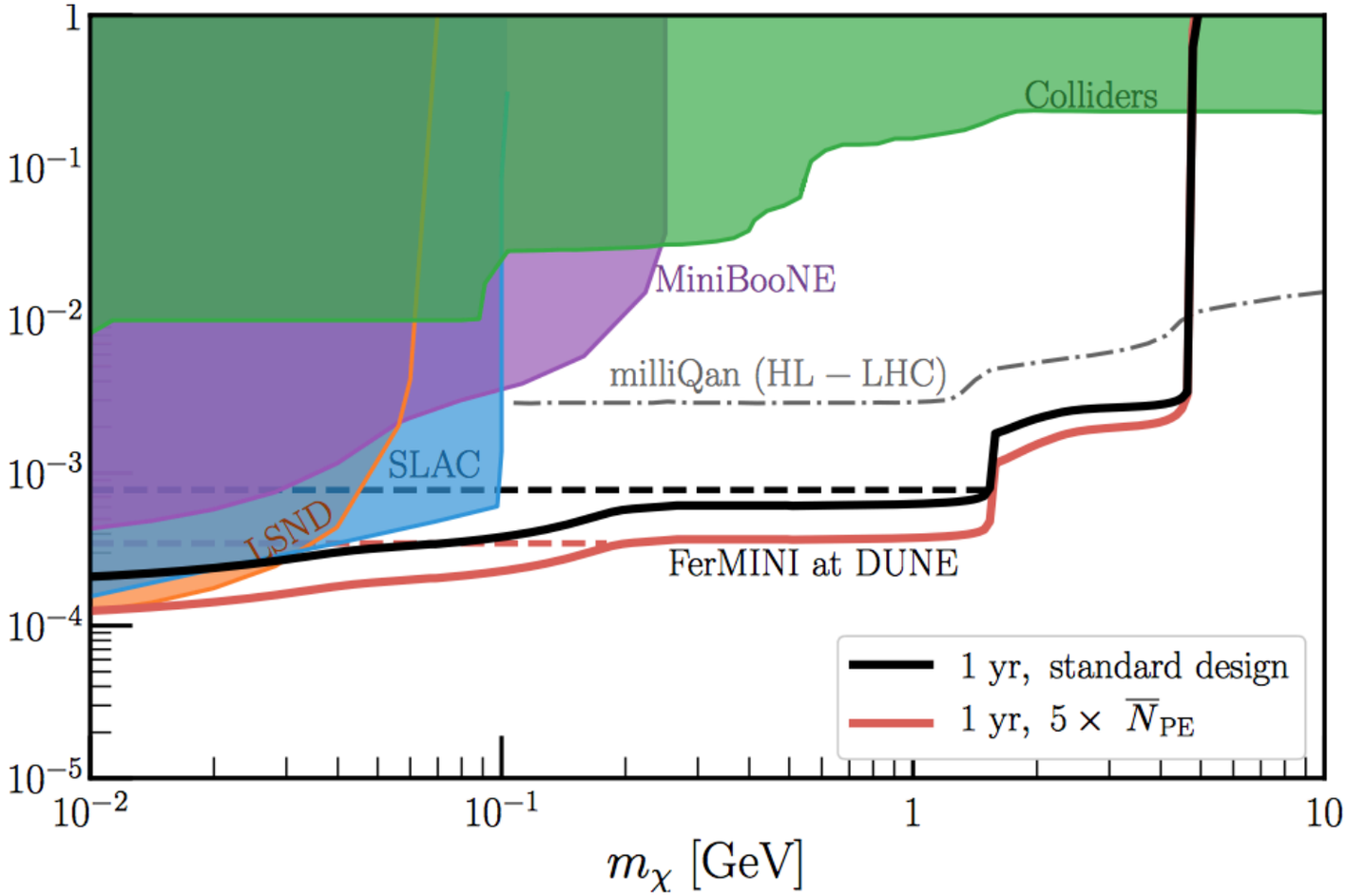
Triple coincidence with only low recoils in three scintillation detectors;

e.g. MilliQan [Ball, Brooke et al. 1607.04669], FerMINI array [Kelly & Tsai 1812.03998], …;

More on background cut:

Interes **.f.** coupled to

QED cu arged particles:



in **proton beam!**

belov & Tsai
nara 1902.03246,

To distir

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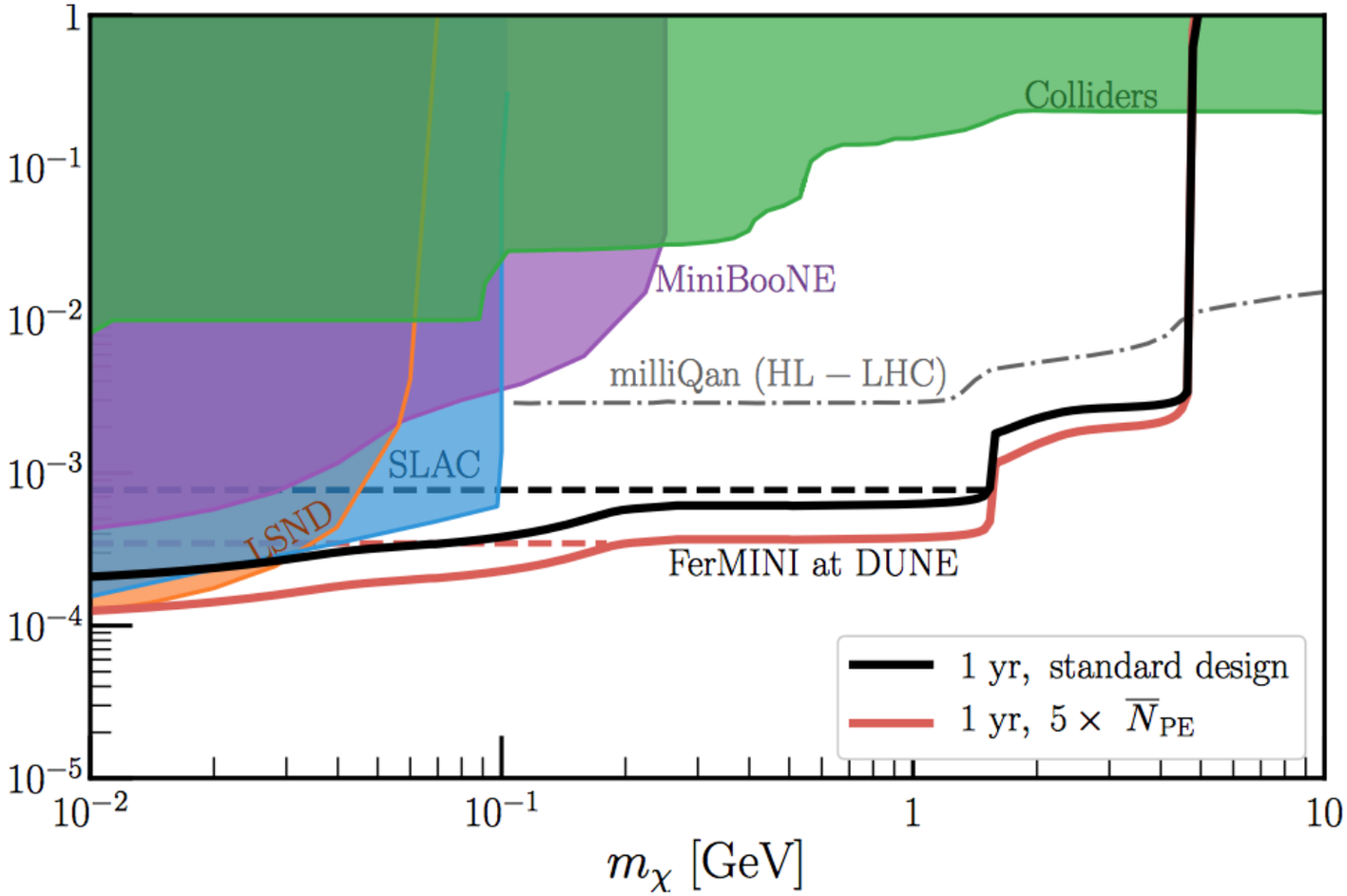

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In contrast, if portal particle decays visibly to SM particles:

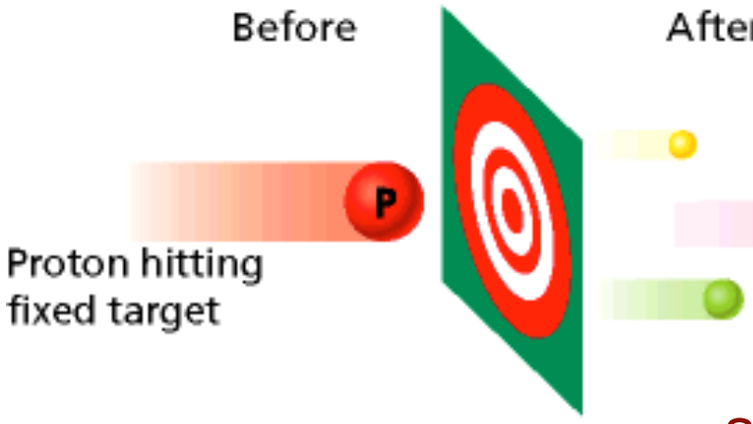
→ **Displaced vertices (with little backgrounds)!**

II.B Displaced vertices

(CMS/ATLAS/LHCb, SHiP, MATHUSLA, FASER, CODEX-b, SeaQuest, NA62, ….)

A'-portal for proton-beam experiments

Proton beam experiments



On-shell **portal** appears, then **decays**

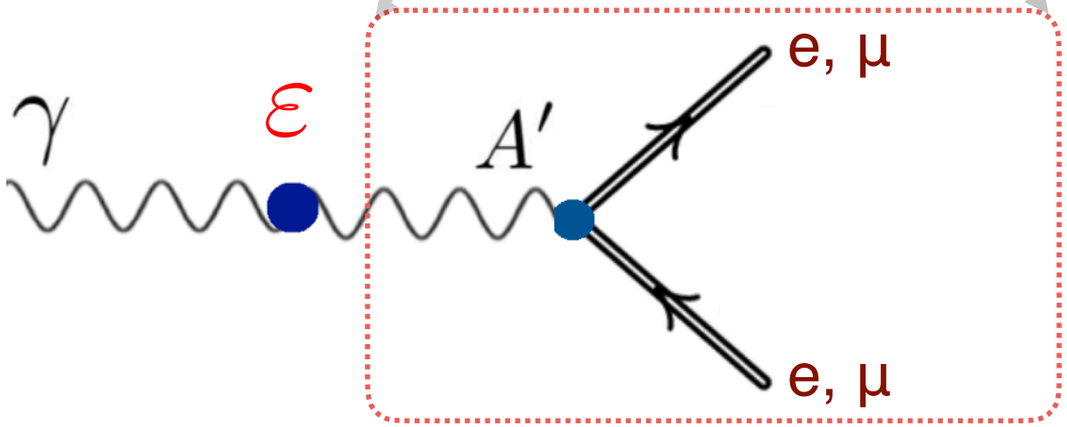
ten to hundreds meters away from the primary vertex

If to SM: **displaced vertices**

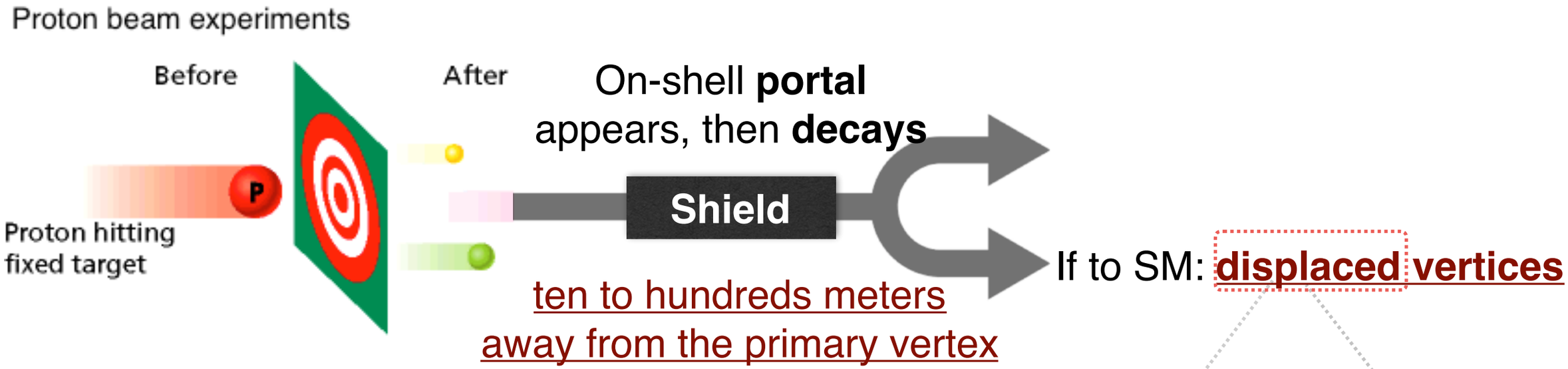
Decay-at-flight

$$L_d \sim \left(\frac{10^{-6}}{\epsilon}\right)^2 \left(\frac{0.1\,\mathrm{GeV}}{m_{A'}}\right)^2 \left(\frac{E_{A'}}{\mathrm{TeV}}\right) \text{ meter}$$

Emerging in a long detector



A'-portal for proton-beam experiments



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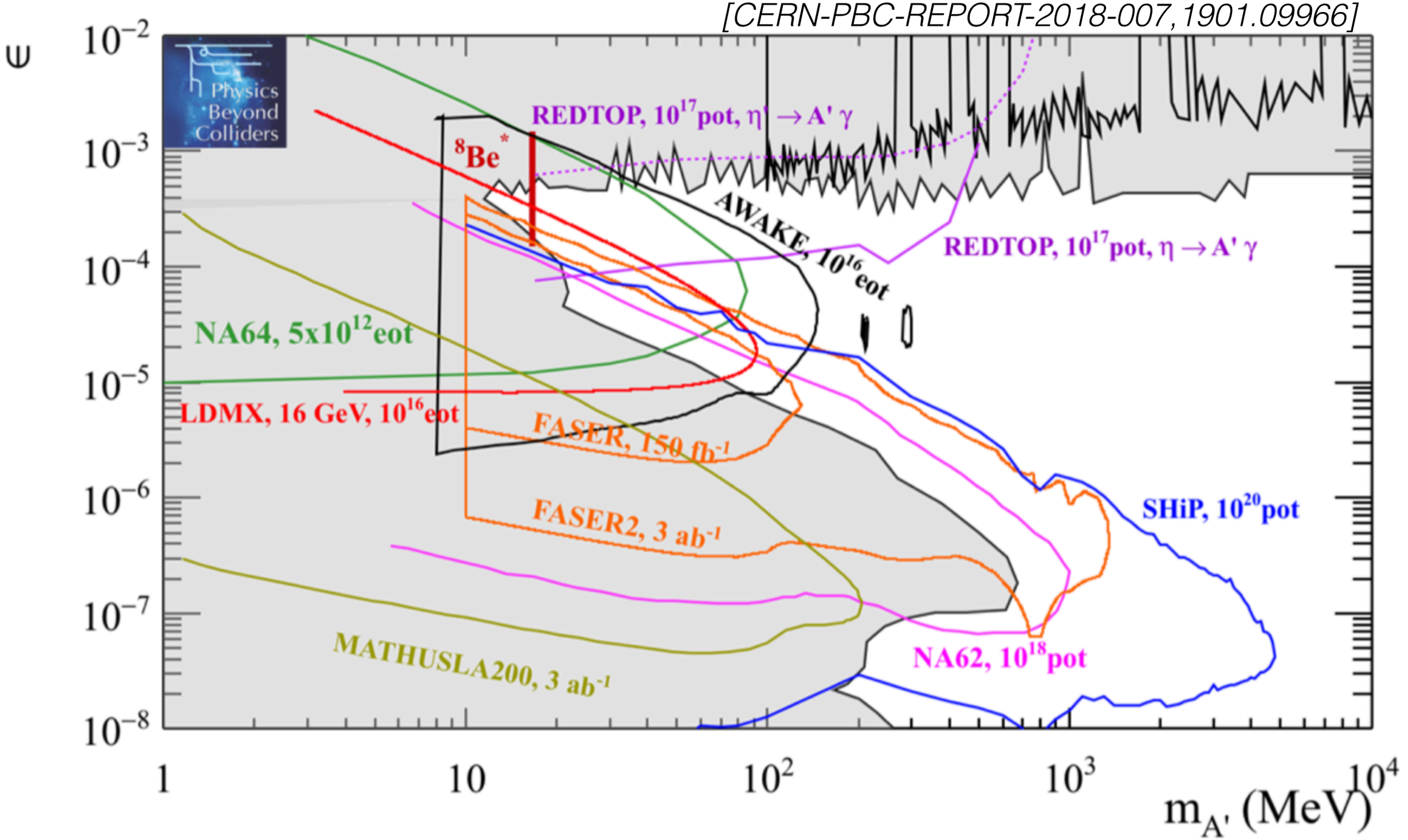
Backgrounds:

- **Inelastic scatterings** induced by beam-related (or cosmic) **muons/neutrinos**;
- Their **coincident** combinations.

Nearly no backgrounds after reconstruction veto.

A'-portal for proton-beam experiments

[CERN-PBC-REPORT-2018-007, 1901.09966]



Nearly no backgrounds after reconstruction veto.

Neutrino-portal for proton-beam experiments

Neutrino Minimal Standard Model

[Asaka & Shaposhnikov 2005]

Three right-handed neutrinos with majorana masses: **seesaw**

N_1 of keV scale

Tiny mixing with SM neutrino

Dark matter

$N_{2,3}$ of GeV scale

CP-violating oscillation

"out-of-equilibrium"

[Akhmedov, Rubakov & Smirnov, 1998]

Baryonic asymmetry

$t_N \sim 10^{-5} - 0.1\,\mathrm{sec}$

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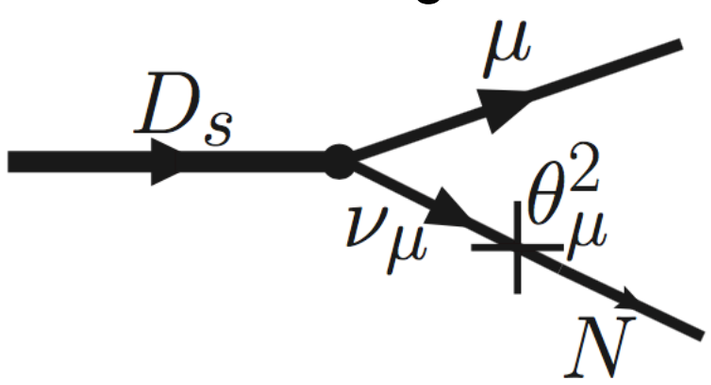
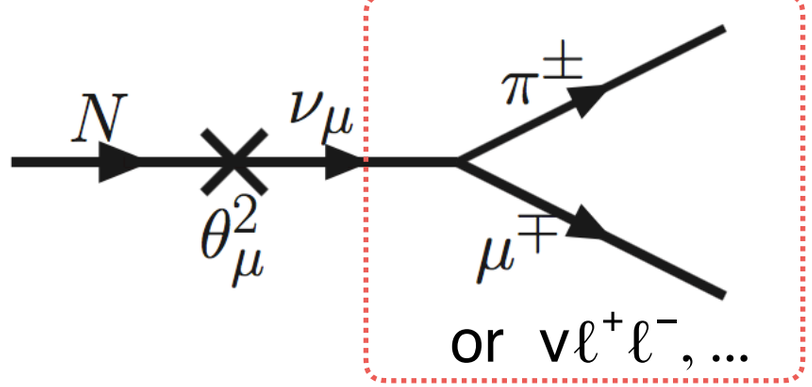
In a long detector

E.g. take muon neutrino mixing:





[Alimena, Beacham et al. 1903.04497]

Neutrino-portal for proton-beam experiments

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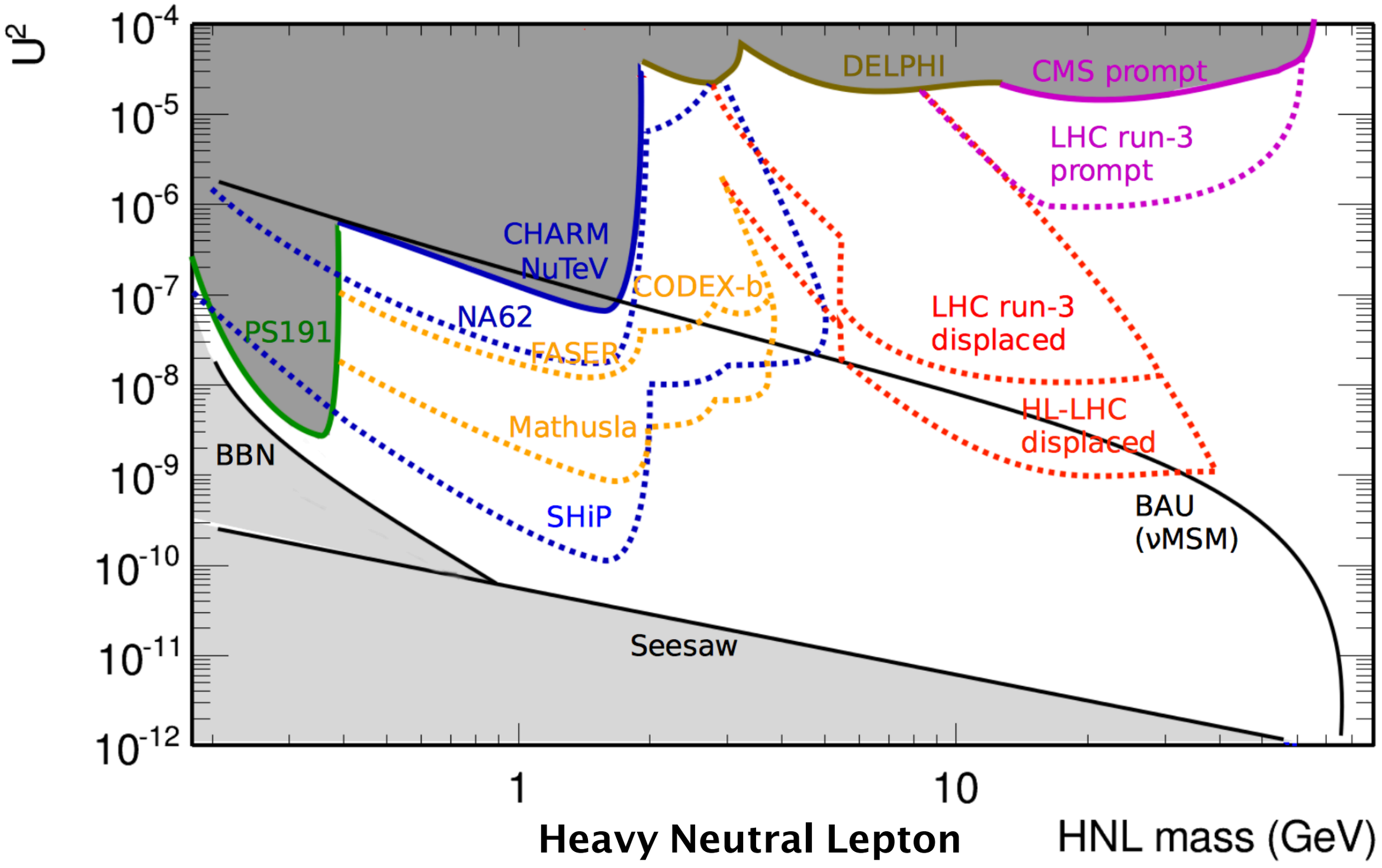

[Alimena, Beacham et al. 1903.04497]

More exotic signatures

- **Complicated displaced vertex;**
  - A composite decay [An, Echenard, Pospelov & Zhang, 1510.05020, …];
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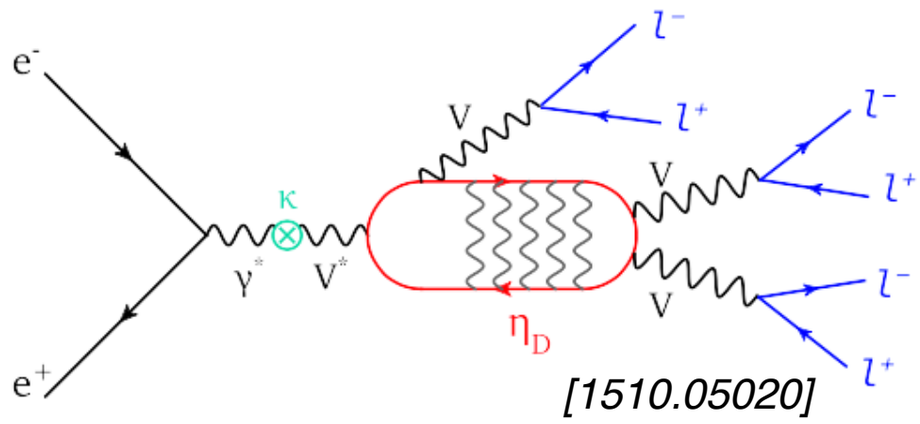

[1510.05020]

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  - Using large LAr time-projection chambers: good reconstruction of 3D particle tracks;
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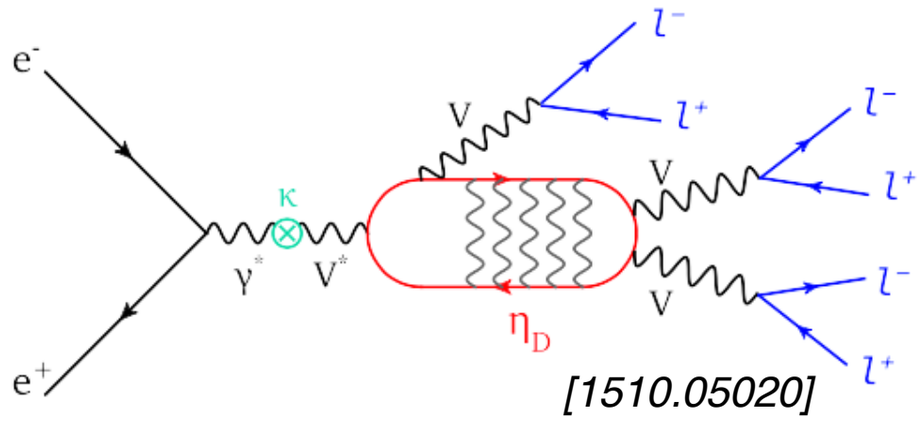
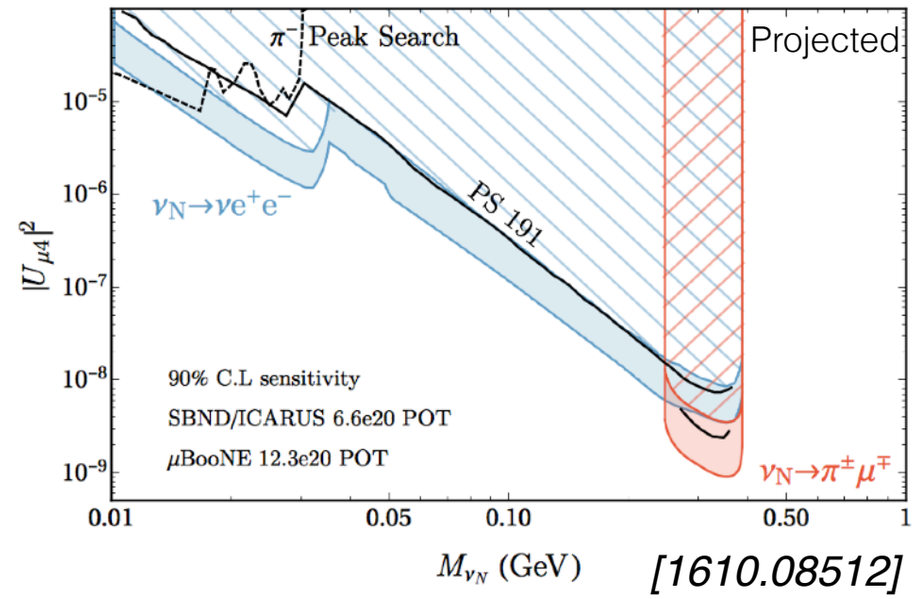


[1510.05020]



[1610.08512]

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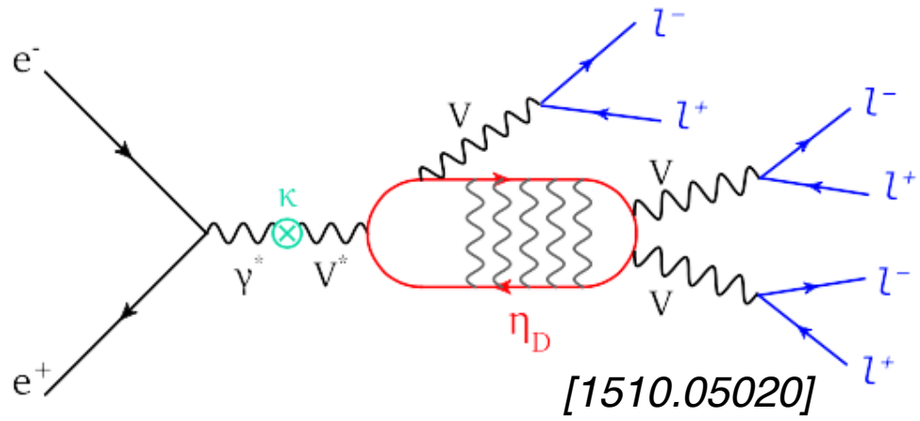
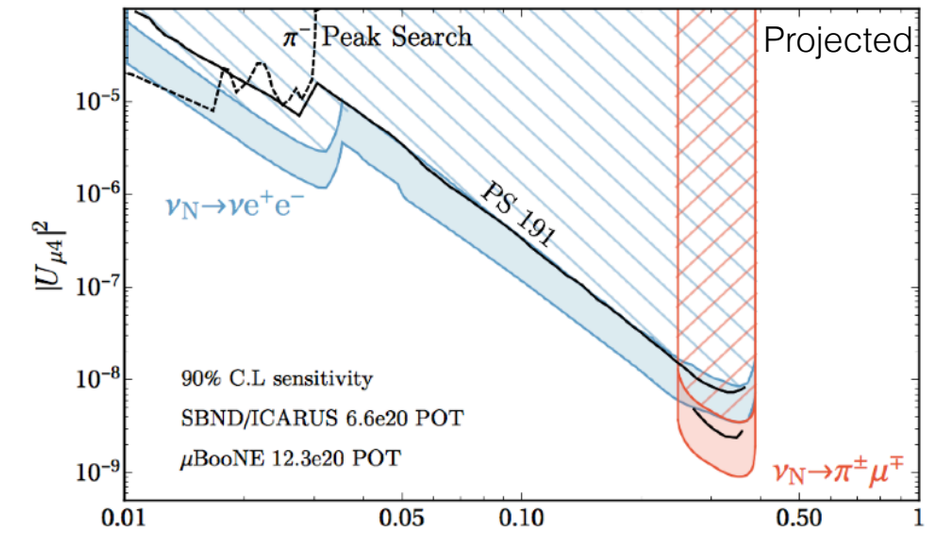
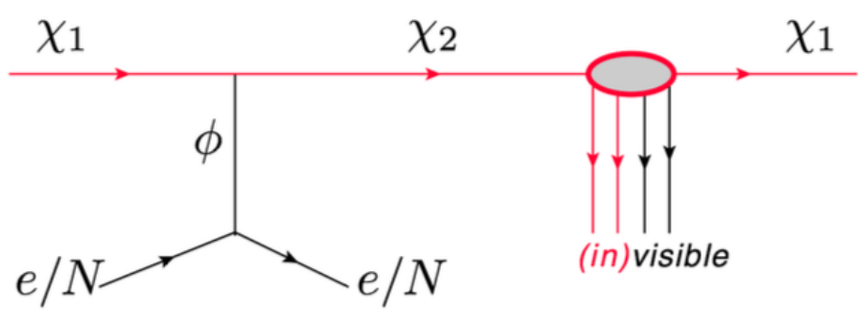
- **Combining scattering and displaced vertex:**
  - Up-scattering *[Kim, Park & Shin 1612.06867, ….]*,
  - Dark trident [*Gouvêa, Fox, Harnik, Kelly & Zhang 1809.06388, …*].



[1510.05020]



[1610.08512]



[1612.06867]

III. Summary

Summary

- A **dark sector** may contain dark matter and its interaction structures.

- Proton-beam experiments suitable for feebly-coupled **light dark particles**, complementary to high-energy colliders:

  - (in)elastic scatterings: naively coupling of $10^{-2} - 10^{-5}$;
  - displaced vertices: naively coupling of $10^{-4} - 10^{-7}$.

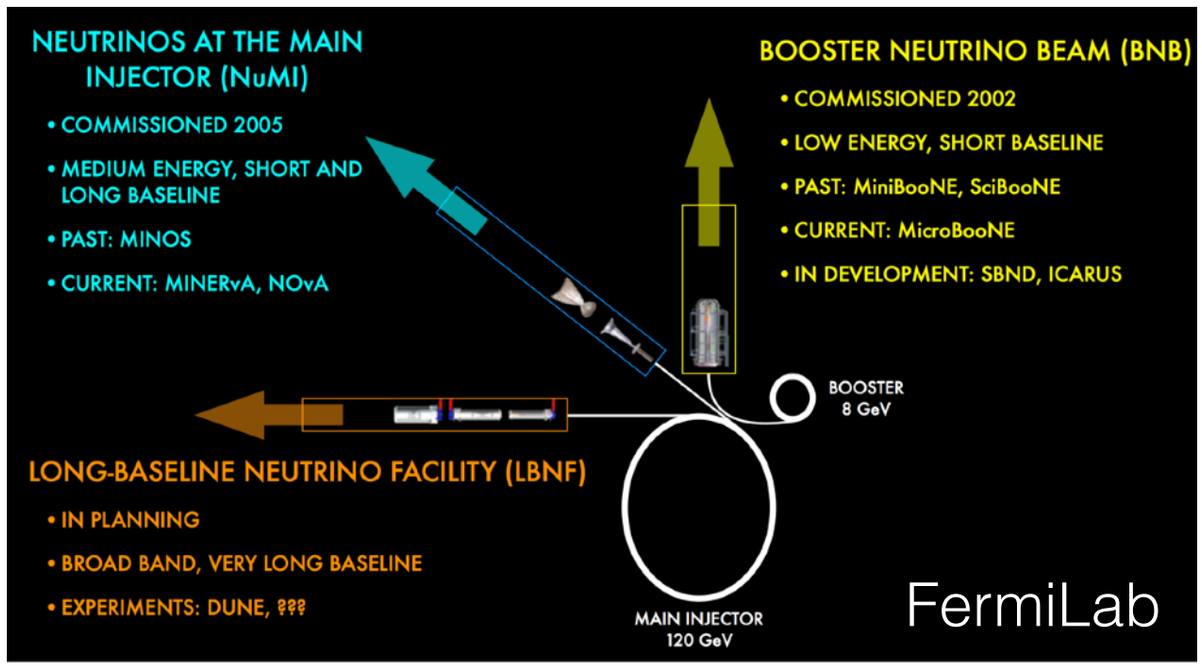
- What **new search strategies** can be?

  - To further reduce neutrino backgrounds;
  - To search for quark-phobic / neutrino-philic dark particles, …

Grazie!

Proton beam experiments (scatter v.s. displaced)

1. **CERN** (400GeV SPS: **CHARM, NA62, SHiP,** …);
2. LHC (13TeV: MilliQan, MoEDAL, MATHUSLA, FASER, …);
3. **FermiLab** (120GeV NuMI: **SeaQuest, Minos, DUNE,** …);
4. **FermiLab** (p=8GeV Booster: **MiniBooNE, SBND,** …);
5. **J-PARC** (30GeV: **T2K, JSNS², Super-K**…);
6. **Las Alamos** (p=0.8GeV: **LSND**);
7. **COHERENT, CODEX-b**, etc.



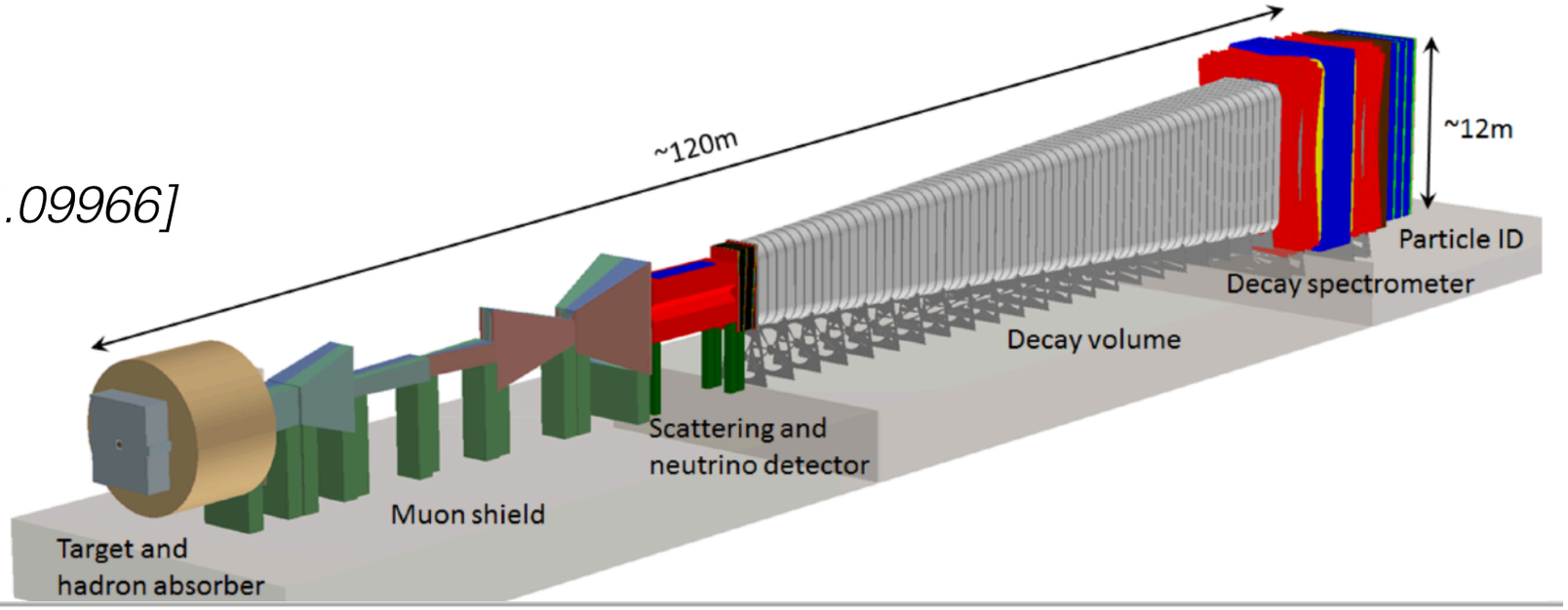
Details of experiments

	N $[\times 10^{20}]$		$A_{\rm geo}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
Exp.	π^0	η	1 MeV	100 MeV	$E_e^{\rm min}$	$E_e^{\rm max}$	Bkg
LSND	130	—	20	—	18	52	300
mBooNE	17	0.56	1.2	0.68	130	530	2K
mBooNE*	1.3	0.04	1.2	0.68	18	—	0^*
μBooNE	9.2	0.31	0.09	0.05	0.8	40	16
SBND	4.6	0.15	4.6	2.6	0.8	40	240
DUNE	830	16	3.3	5.1	2	40	$19K$
SHiP	4.7	0.11	130	220	**2000**	**20000**	**300**

[1806.03310]

Details of experiments

[CERN-PBC-REPORT-2018-007, 1901.09966]

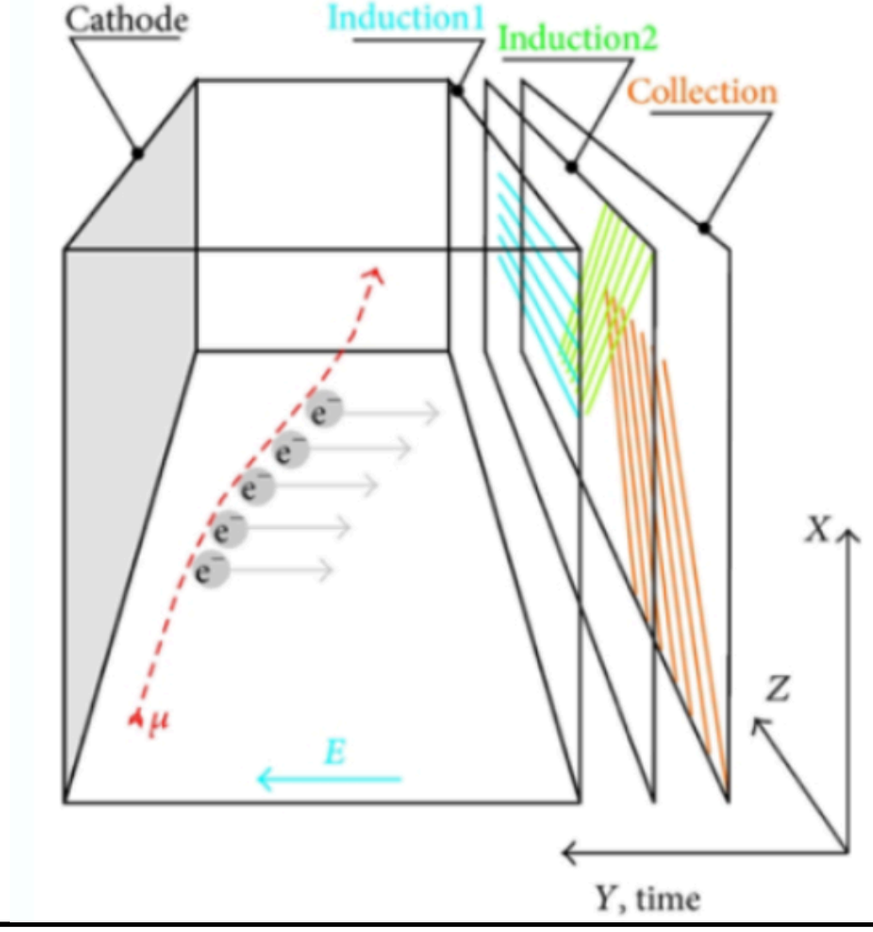


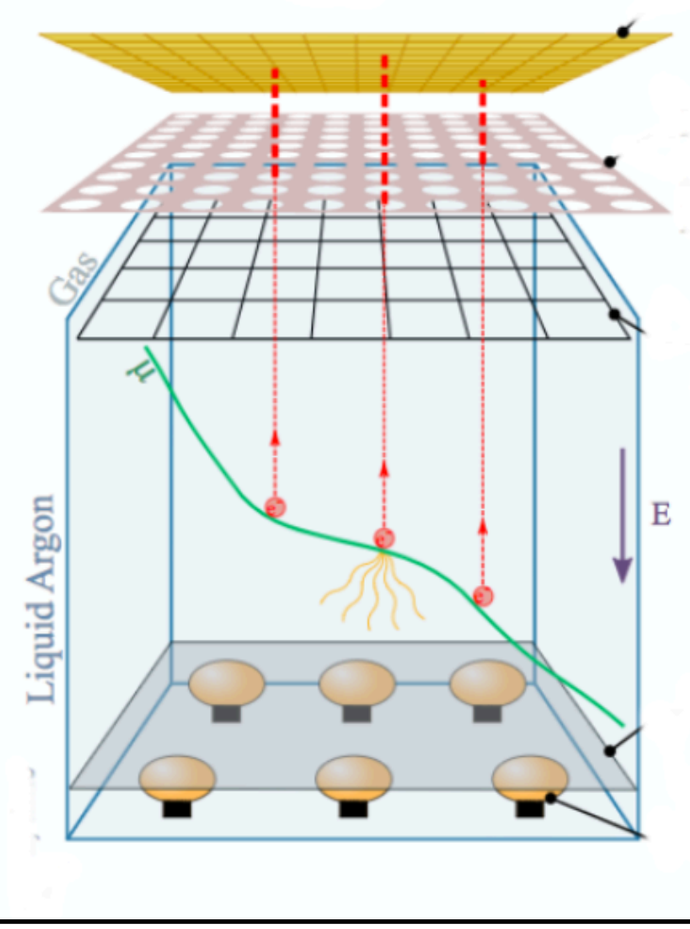
MeV-GeV mass range:

SHiP	ALPs, Dark Photons, Dark Scalars LDM, HNLs, lepto-phobic DM, ..	BDF, SPS	400 GeV p	$2 \cdot 10^{20}$/5 years
NA62^{++}	ALPs, Dark Photons, Dark Scalars, HNLs	K12, SPS	400 GeV p	up to $3 \cdot 10^{18}$/year
NA64^{++}	ALPs, Dark Photons, Dark Scalars, LDM	H4, SPS	100 GeV e^-	$5 \cdot 10^{12}$ eot/year
	$+ L_\mu - L_\tau$	M2, SPS	160 GeV μ	$10^{12} - 10^{13}$ mot/year
	+ CP, CPT, leptophobic DM	H2-H8, T9	~ 40 GeV π, K, p	$5 \cdot 10^{12}$/year
LDMX	Dark Photon, LDM, ALPs,...	eSPS	8 (SLAC) -16 (eSPS) GeV e^-	$10^{16} - 10^{18}$ eot/year
AWAKE/NA64	Dark Photon	AWAKE beam	30-50 GeV e^-	10^{16} eot/year
RedTop	Dark Photon, Dark scalar, ALPs	CERN PS	1.8 or 3.5 GeV	10^{17} pot
MATHUSLA200	weak-scale LLPs, Dark Scalar, Dark Photon, ALPs, HNLs	ATLAS or CMS IP	14 TeV p	3000 fb^{-1}
FASER	Dark Photon, Dark Scalar, ALPs, HNLs, $B - L$ gauge bosons	ATLAS IP	14 TeV p	3000 fb^{-1}
MilliQan	milli charge	CMS IP	14 TeV p	300-3000 fb^{-1}
CODEX-b	Dark Scalar, HNLs, ALPs, LDM, Higgs decays	LHCb IP	14 TeV p	300 fb^{-1}

LArTPC (in DUNE, ICARUS, MicroBooNE, SBND):

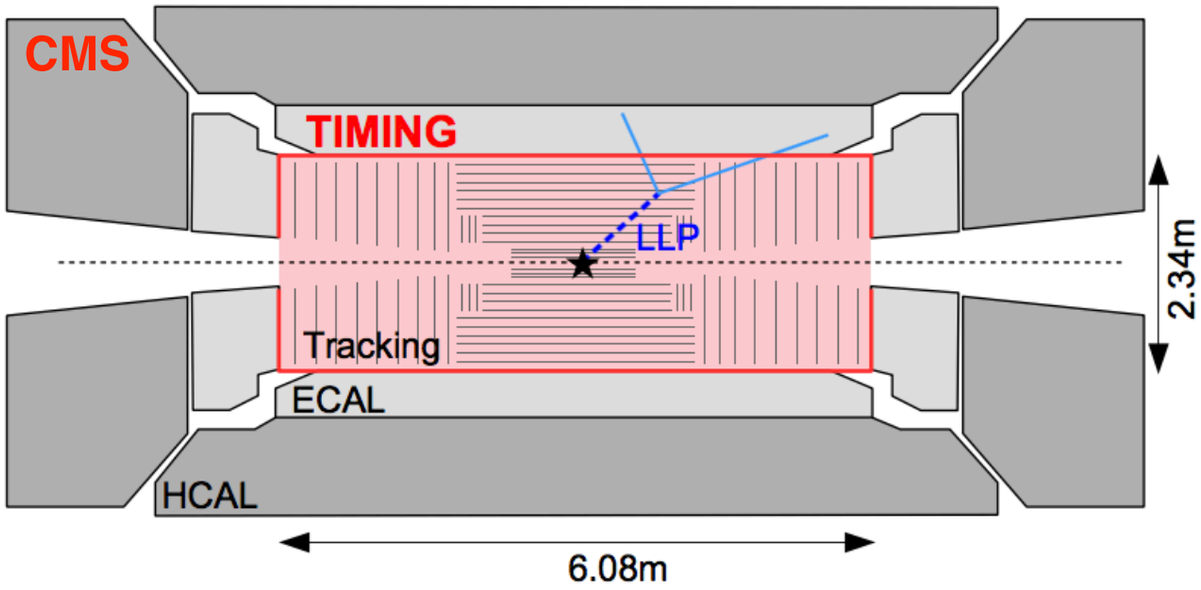
1. Electric/magnetic fields together with a sensitive volume of gas or liquid to perform a three-dimensional reconstruction of a particle trajectory in nuclear emulsion *by* ***ionization***.
2. *detecting recoil of proton above tens of MeV, leading to* ***separation between sub-GeV neutrinos and antineutrinos****, since the former is more likely to kick out a proton from Argon.*
3. *Solve MiniBooNE misidentified photon.*

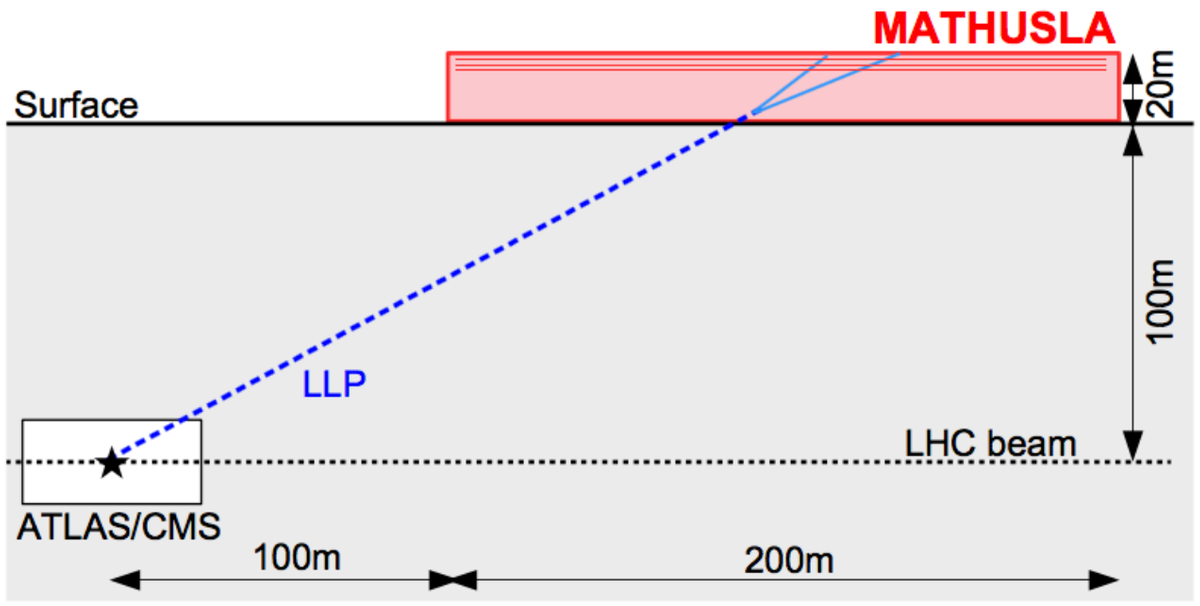


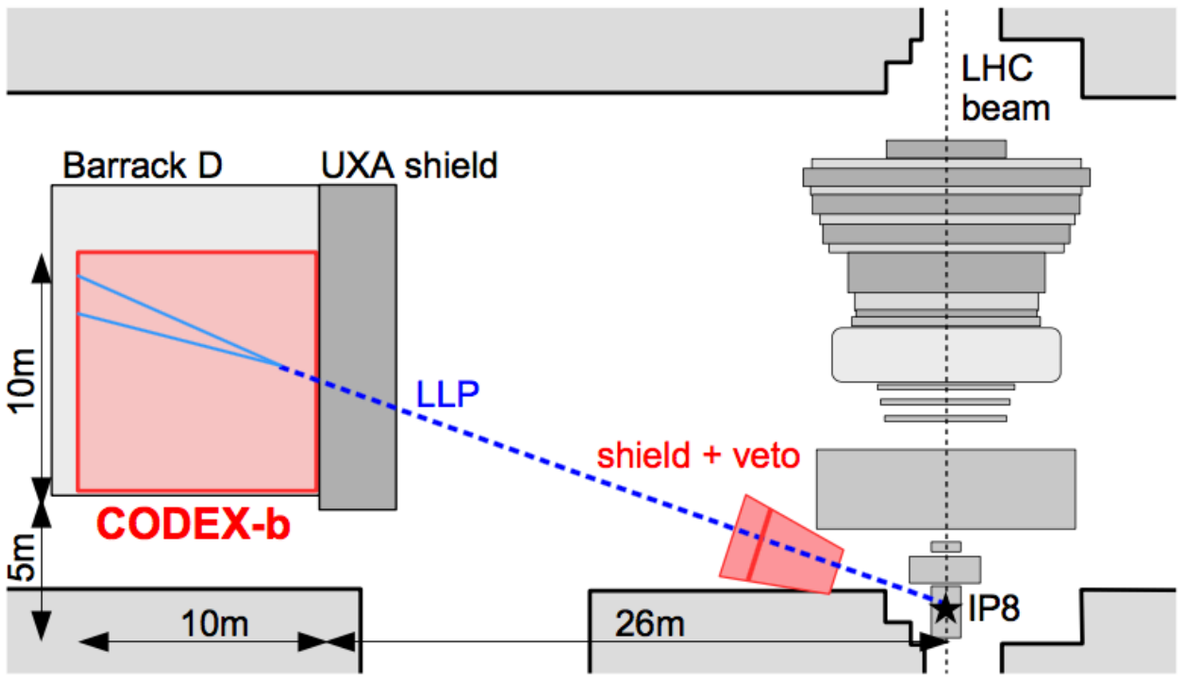


DUNE
1902.04780

Displaced vertices







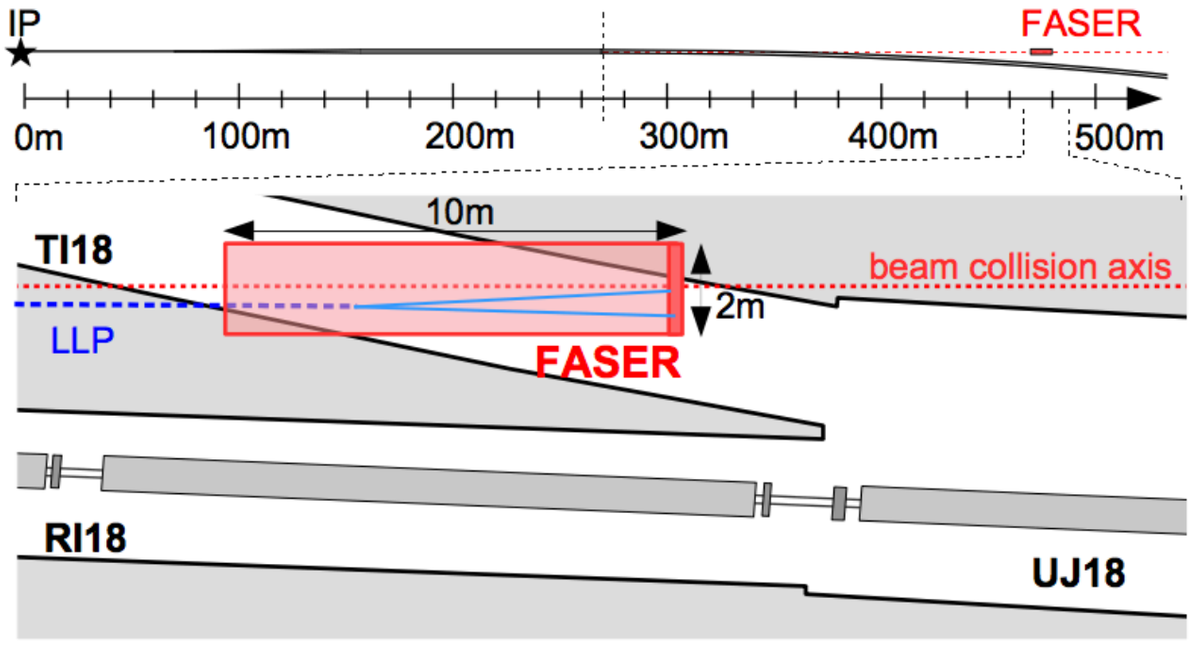
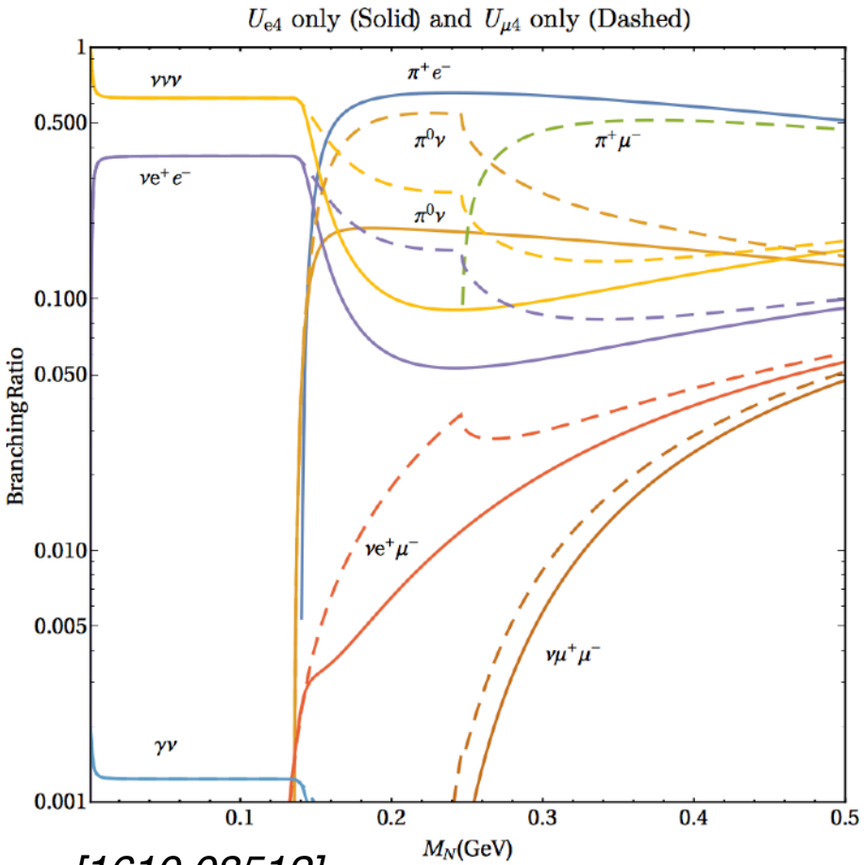


FIG. 2. Schematic drawings of a timing layer at CMS (top-left), MATHUSLA (top-right), CODEX-b (bottom-left), and FASER (bottom-right), along with their locations with respect to the LHC ring. The red shaded region indicates the decay volume for each experiment.

[Berlin & Kling1810.01879]

Displaced vertices



[1610.08512]

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