Searching for Dark Matter Signals COHERENT Way

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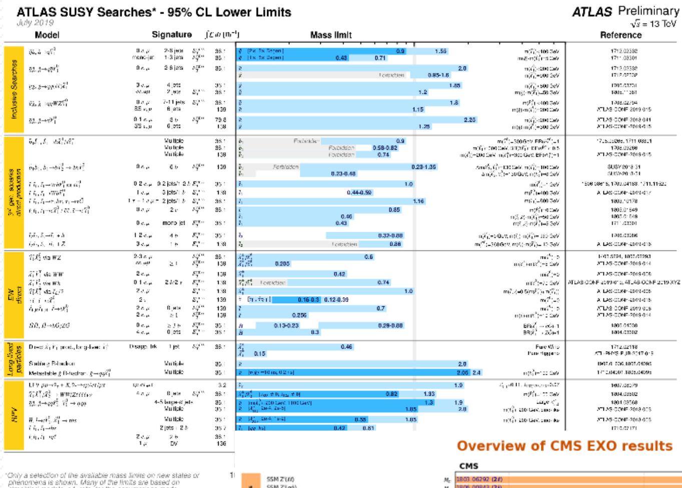
Magnificent CEνNS 2019

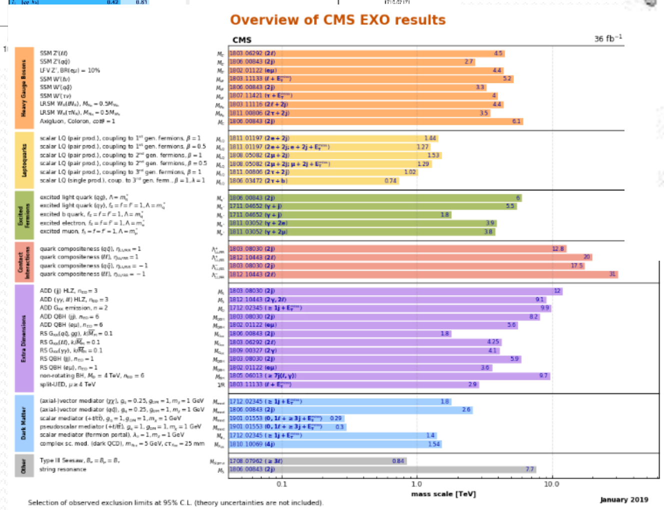
The PIT, Chapel Hill, NC, November 9st, 2019

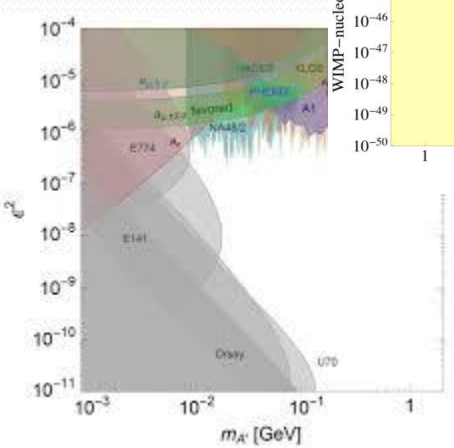
In collaboration with B. Dutta, S. Liao, J.-C. Park, S. Shin and L. Strigari [arXiv:1906.10745, PRL submitted]

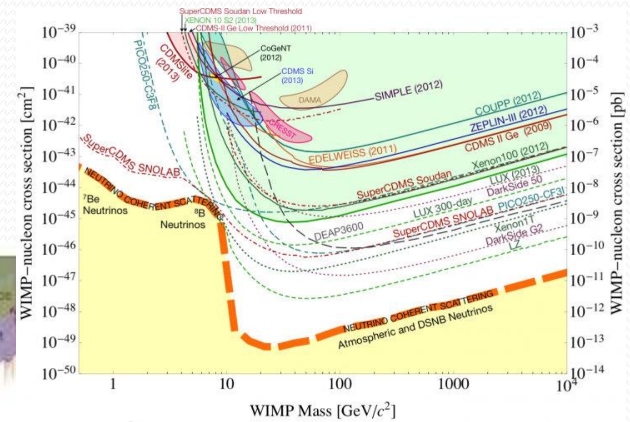
B. Dutta, S. Liao, J.-C. Park, S. Shin and L. Strigari, in progress

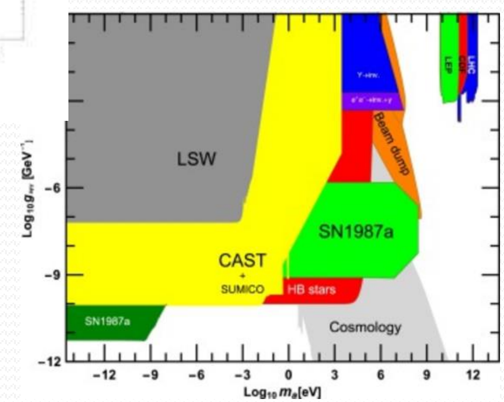
Hunt for New Physics: Current Status



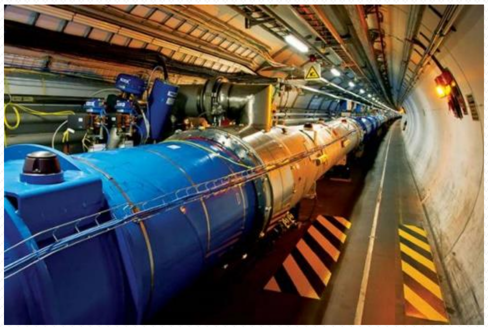




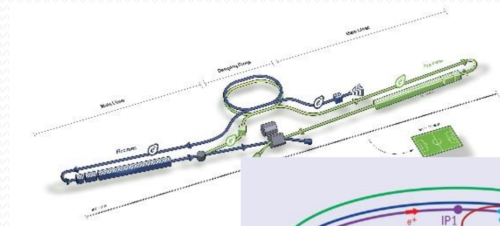


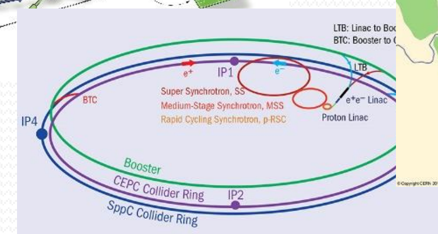


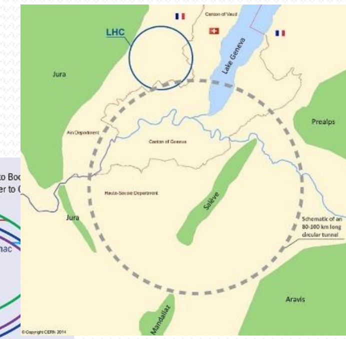
Hunt for New Physics: Future Directions



New physics searches at the LHC



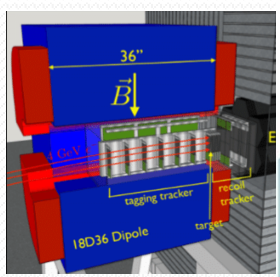


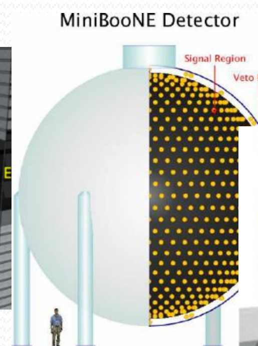


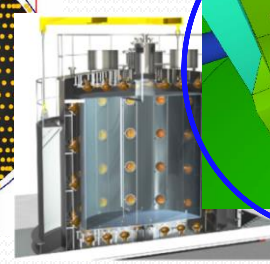
Higher-energy colliders, e.g., ILC, CEPC, CERN-FCC, etc

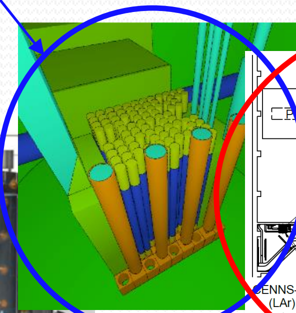
See S. Liao's talk for reactor exps.

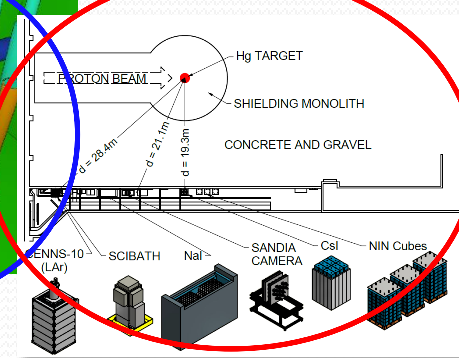
Today's focus









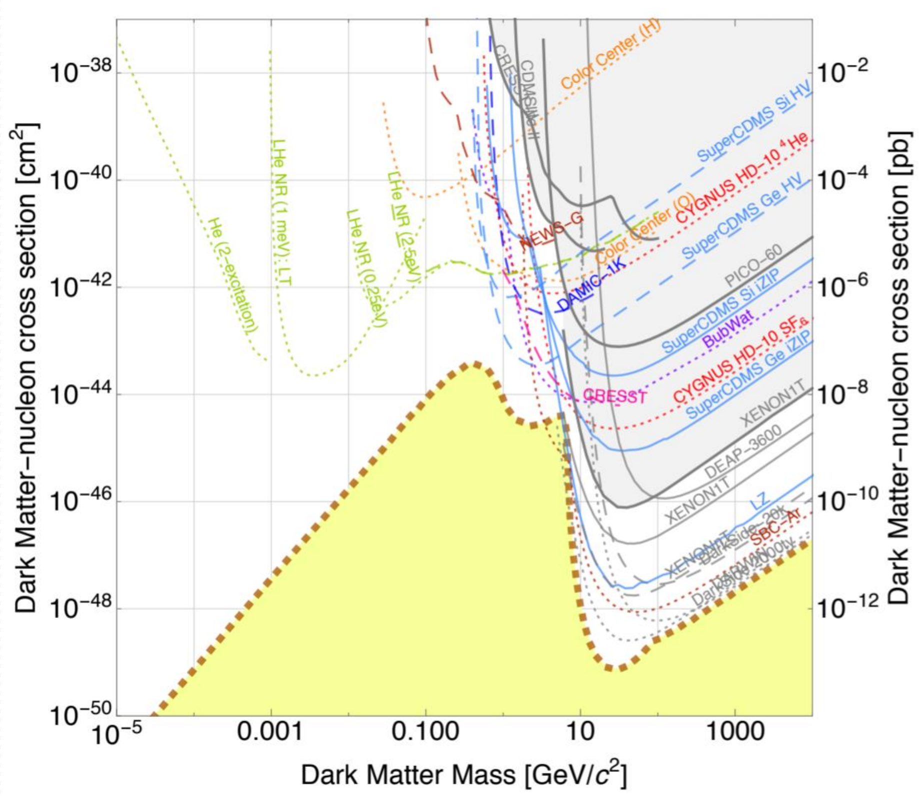


Various physics potentials in neutrino facilities, low-energy high-intensity experiments

Current Status of Dark Matter Searches

- **No observation** of DM signatures via non-gravitational interactions while many searches/interpretations designed/performed under nonrelativistic WIMP/WIMP-like scenarios

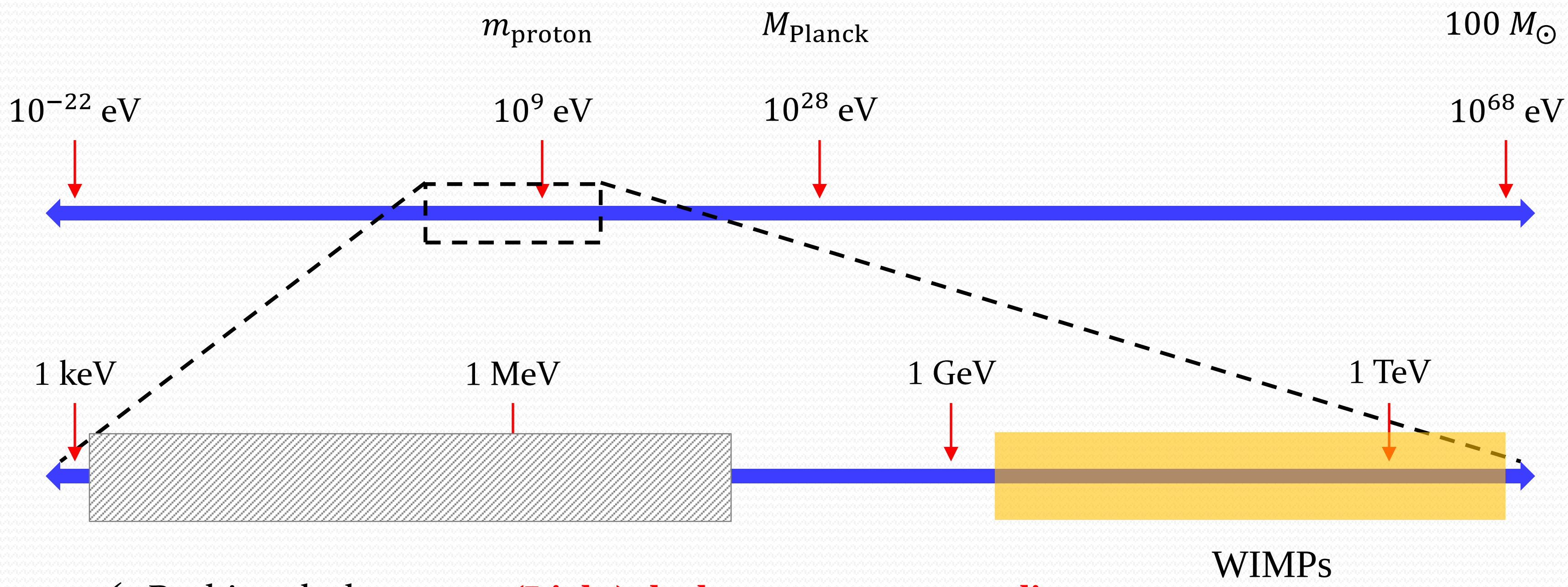
  ⇒ merely excluding more parameter space in dark matter models



[US Cosmic Visions, Battaglieri et al (2017)]

Time to pause, rethink and redesign our approach/search strategies, e.g., COHERENT Way!

The Dark Matter Landscape



- ✓ Probing dark sectors: **(Light) dark matter + new mediators**
- ✓ Less constrained by current searches

Light Dark-Sector Particle Models/Searches: Mediator

- ❑ Various light mediator scenarios have been proposed.
  - ✓ Dark matter scenarios based on hidden sectors: e.g., models of asymmetric dark matter, Sommerfeld enhancements motivated by SIMP, etc (see the review [Essig et al (2013)])
  - ✓ $g-2$ of electron: 2.4σ discrepancy [Davoudiasl, Marciano (2018)]
  - ✓ Neutrino sector physics: new neutrino interactions to satisfy the MiniBooNE excess [Bertuzzo, Jana, Machado, Funchal (2018)]
  - ✓ Solutions of Yukawa coupling hierarchy problem [Dutta, Ghosh, Kumar (2019)]
  - ✓ See also US cosmic vision [Battaglieri et al (2017)]

- ❑ Light mediator searches at existing/future experiments, e.g., NA64, Belle I/II, Babar, SHiP, FASER, MATHSULA, SeaQuest

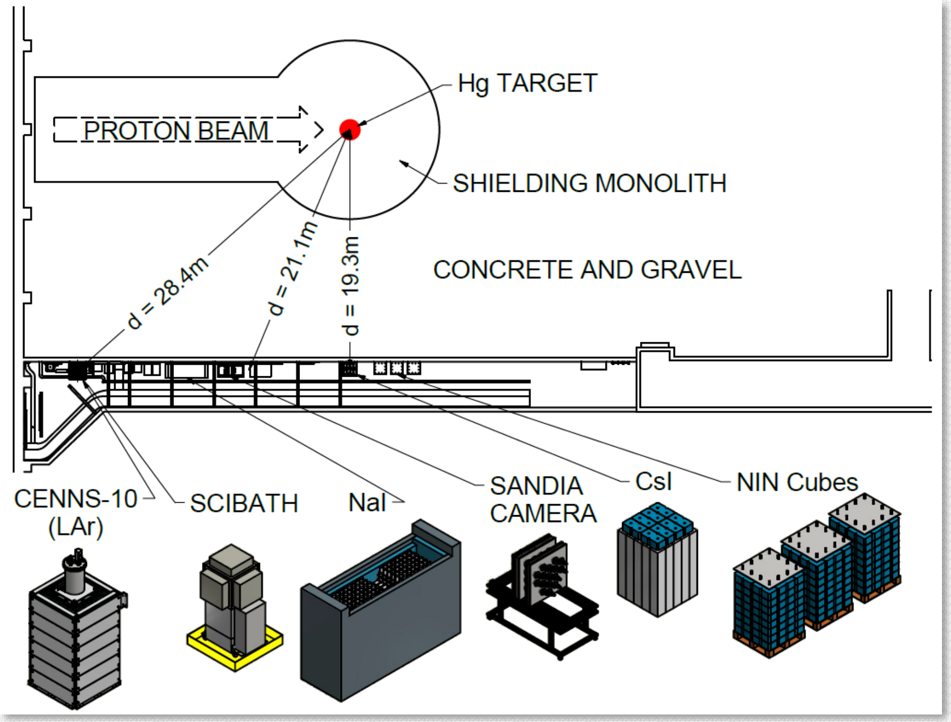
Light Dark-Sector Particle Models/Searches: Dark Matter

- Various light dark matter-involving pheno has been studied.
  - ✓ Boosted dark matter scenarios [Agashe, Cui, Necib, Thaler (2014); Berger, Cui, Zhao (2014); Kong, Mohlabeng, Park (2014); **DK**, Park, Shin (2016)]
  - ✓ Fast-moving DM via induced nucleon decays [Huang, Zhao (2013)]
  - ✓ MeV-range DM indirect detection at gamma-ray telescopes [Boddy, Kumar (2015)]
  - ✓ Energetic cosmic-ray-induced (semi-)relativistic dark matter scenarios [Yin (2018); Bringmann, Pospelov (2018); Ema, Sala, Sato (2018); Dent, Dutta, Newstead, Shoemaker (2019)]
  - ✓ Ultra high energy cosmic ray phenomena [Bhattacharya, Gandhi, Gupta (2014); Heutier, **DK**, Park, Shin (2019)]
- Cosmogenic light dark matter searches at existing/future experiments, e.g., SK/HK, COSINE-100, ProtoDUNE, DUNE
- Beam-produced light dark matter searches at existing/future experiments, e.g., BDX, MicroBooNE, SeaQuest, LDMX, T2HKK, DUNE, SHiP, and proposals [Bjorken, Essig, Schuster, Toro (2009); Batell, Pospelov, Ritz (2009); deNiverville, Pospelov, Ritz (2011); Izaguirre, Krnjaic, Schuster, Toro (2014); Berlin, Gori, Schuster, Toro (2018), and many more]

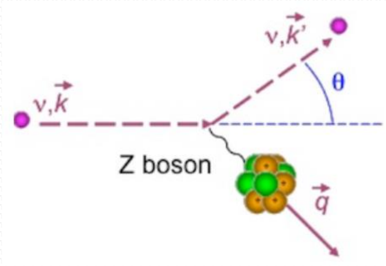
Goals

- How to **isolate (light) dark matter signal** events from the SM (neutrino) backgrounds with **timing spectra** at neutrino experiments, taking **COHERENT** as a benchmark experiment
- Application to the measurement data that COHERENT has released
- How to **interpret the result**

COHERENT Experiment: Primer



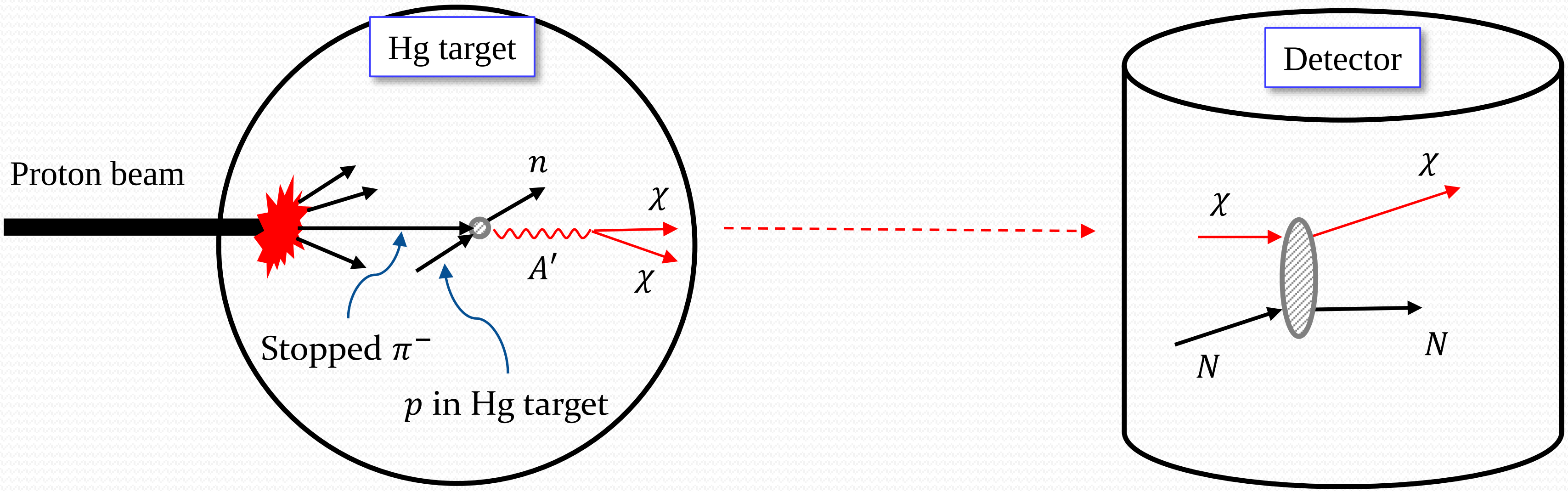
- ✓ Main mission (see M. Green's talk): first direct measurement of Coherent Elastic Neutrino-Nucleus Scattering (CEνNS).



  - Prompt ν's: $\pi \rightarrow \mu + \nu_\mu$
  - Delayed ν's: $\mu \rightarrow e + \nu_\mu + \nu_e$

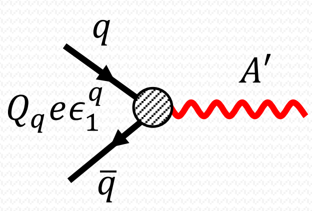
- ✓ ~1 GeV proton beam on Mercury target (pulse duration: 380 ns FWHM 60 Hz)
- ✓ 5×10^{20} protons-on-target (POT) delivered per day

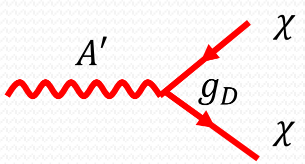
Dark Matter Scenarios in COHERENT

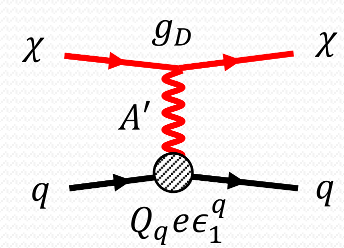


$\pi^- + p \to n + A'$ $\quad$ $A' \to \chi + \chi$ $\quad$ $\chi + N \to \chi + N$

[deNivervill, Pospelov, Ritz (2015)]



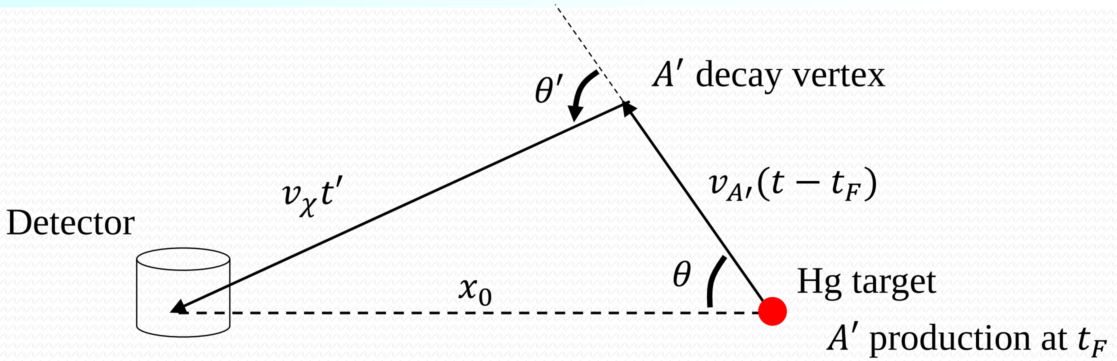




Cf.) Another (subdominant) process: charge exchange, $\pi^{-/+} + p/n \to \pi^0 + n/p$, $\pi^0 \to \gamma + A'$ [JSNS^2 TDR]

ν-induced background vs. dark photon decay into dark matter utilizing timing measurements!

Timing Spectrum of Dark-Matter Events



Dark matter flux at the detector: $f(T) = dN_\chi/dT$

$$f(T) = \int_{-1}^{1} d\cos\theta \int_0^{t_F^{\max}} dt_F \left|\frac{dT}{dt}\right|^{-1} \frac{d^2N_{A'}}{dtd\cos\theta} \cdot w(\cos\theta') \cdot \mathcal{F}(t_F)$$

$$T = t + v_\chi^{-1}\sqrt{x_0^2 + v_{A'}^2(t-t_F)^2 - 2x_0 v_{A'}(t-t_F)\cos\theta}$$

Model of π^- production timing ($\propto$ POT)

$$\frac{d^2N_{A'}}{dtd\cos\theta} = \frac{1}{2}\cdot\frac{1}{\tau_{A'}}e^{-\frac{t-t_F}{\tau_{A'}}}\Theta(t-t_F)$$ ← from the decay law

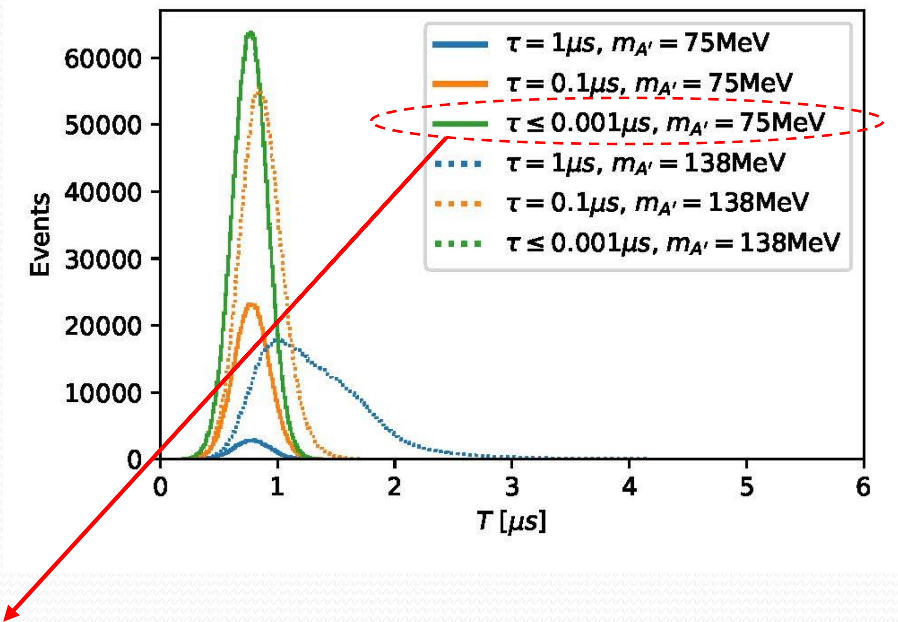
$$w(\cos\theta') = \frac{1}{2\pi(v_\chi t')^2}\left|\frac{d\cos\theta'}{d\cos\theta^*}\right|^{-1}\frac{dN_{A'\to\chi}}{d\cos\theta^*}$$ ← Probability that DM travels towards the detector

Cf.) Search strategy with timing information at the LHC [Liu, Liu, Wang (2018)]

Parameter Space: Dark Photon

- Various possibilities for dark photon A' (depending on ϵ_1^q and $m_{A'}$)

  - Short-lived (large ϵ_1^q)
    vs. Long-lived
  - Relativistic
    vs. Non-relativistic ($m_{A'}$~138 MeV)



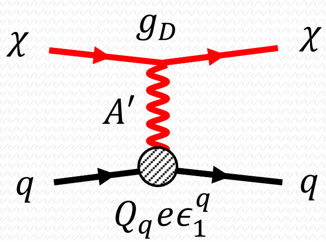
For τ<a few ns, we get maximum number of events

Dark matter events populate in prompt timing bins
(⇒ Data in delayed timing bins as a control sample)

Parameter Space: Dark Matter

- Dark matter scatters off nucleus:

$$\frac{d\sigma}{dE_r} = \frac{e^2\epsilon_q^2 g_D^2 Z^2 \cdot |F(2m_N E_r)|^2}{4\pi p_\chi^2 (2m_N E_r + M'^2)^2} \left\{ 2E_\chi^2 m_N \left(1 - \frac{E_r}{E_\chi} - \frac{m_N E_r}{2E_\chi^2}\right) + E_r^2 m_N \right\}$$



- ✓ In general, the scattering process could be mediated by a different particle (e.g., Baryon number gauged dark gauge boson [deNiverville, Pospelov, Ritz (2015)])

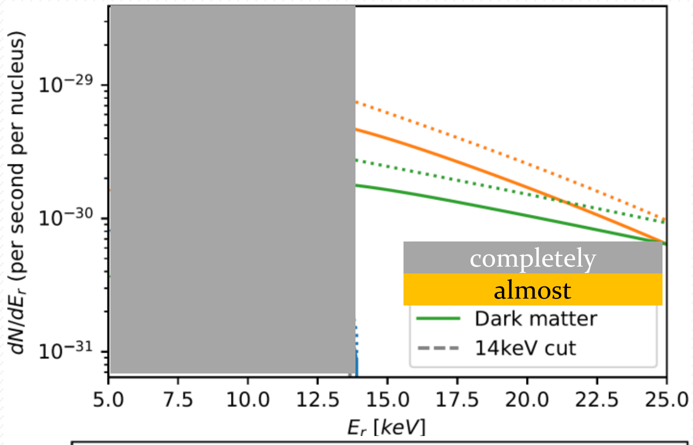
  $: A' \to V',\ m_{A'} \to M',\ Q_q e \epsilon_1^q \to Q_B e \epsilon_2^q,\ g_D = e\epsilon_1^D \to e\epsilon_2^D$

- Dark photon A' production to dark matter scattering can be described by **two variables**.

$$\epsilon \equiv \epsilon_1^q \epsilon_2^q \epsilon_2^D \sqrt{\mathrm{BR}_{A' \to \chi\chi}} \text{ and } M'$$

Proposed Search Strategy

❑ A combination of energy and timing cuts (i.e., cut-and-count exp., less assumptions on the ν sector)

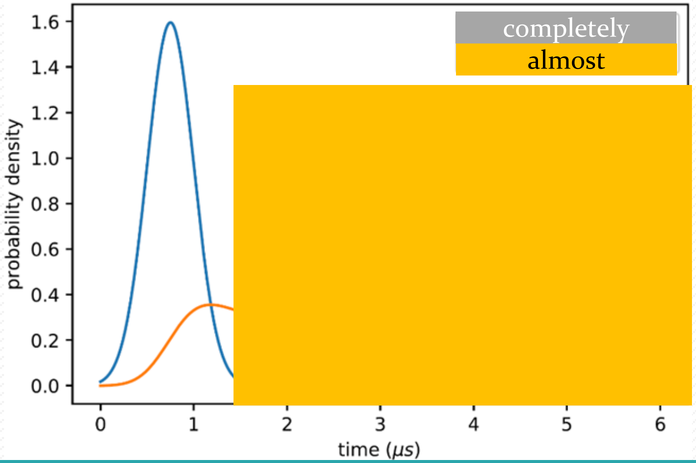


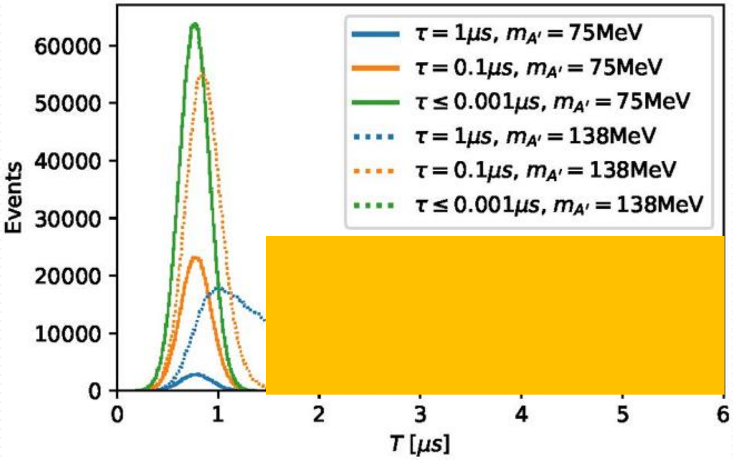
① $E_r > 14$ keV

- Prompt neutrino: completely removed
- Delayed neutrino (and DM signal): still remains

② $T < 1.5\ \mu s$

- Delayed neutrino: almost removed
- DM signal: still remains





Application to Existing CsI Data

- Data released by COHERENT: CsI 14.5 kg × 308 days = 4,466 kg·day [Akimov et al, 1804.09459]

- Analysis scheme (also following [Dutta, Liao, Sinha, Strigari (2019)] for background estimate)
  - Fix the size of neutron distribution to $R_n = 4.7$ fm
  - 14 keV $< E_r <$ 28 keV, $T < 1.5\ \mu$s

$$F_N^{\mathrm{Helm}}(q^2) = \frac{3 j_1(qR_0)}{qR_0} \exp\left(-\frac{q^2 s^2}{2}\right)$$
$$R_n^2 = R_0^2 + 5s^2$$

97 : total events
– 49 : classified as the steady-state (SS) background
– 19 : identified as delayed neutrino events (SM)
– 0 : identified as prompt neutrino events (SM)
– 3 : beam-related neutron (BRN) backgrounds

26 : "Excess"

Significance ($R_n = 4.7$ fm): **2.4 σ**

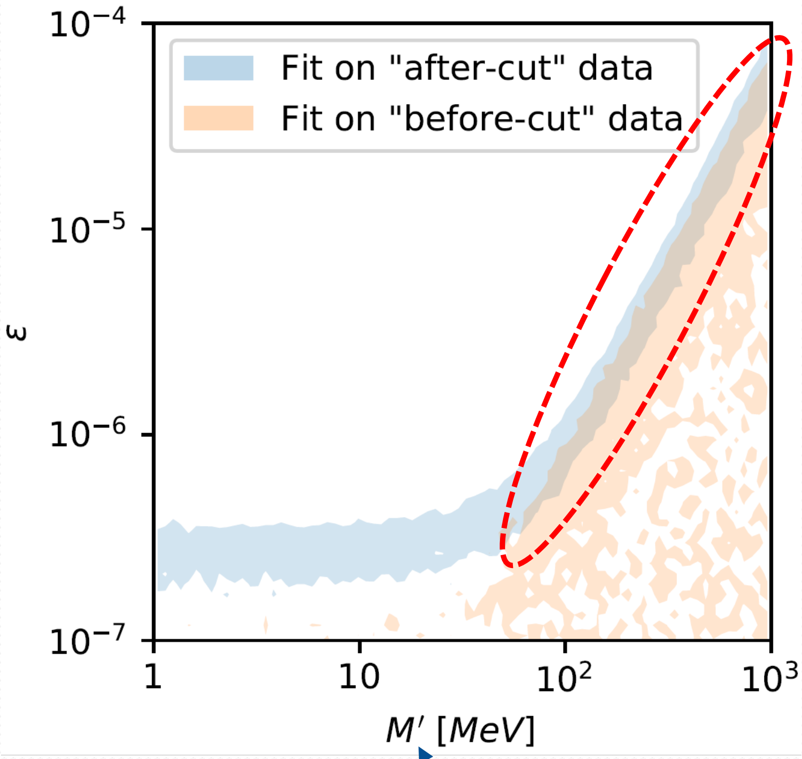
Significance ($R_n = 5.5$ fm): **3.0 σ**

$$\text{Significance} = \frac{\text{Excess}}{\sqrt{2\text{SS}+\text{BRN}+\text{SM}}}$$ [COHERENT, 1708.01294]

- Caveats: systematics on the SS background not considered, excess explained by other unidentified background (see also D. Pershey's talk for the latest DM search)

Mild Excess? – Dark Matter Interpretation

- Fit to the excess after the cuts needs to fit the full data set (before the cuts).



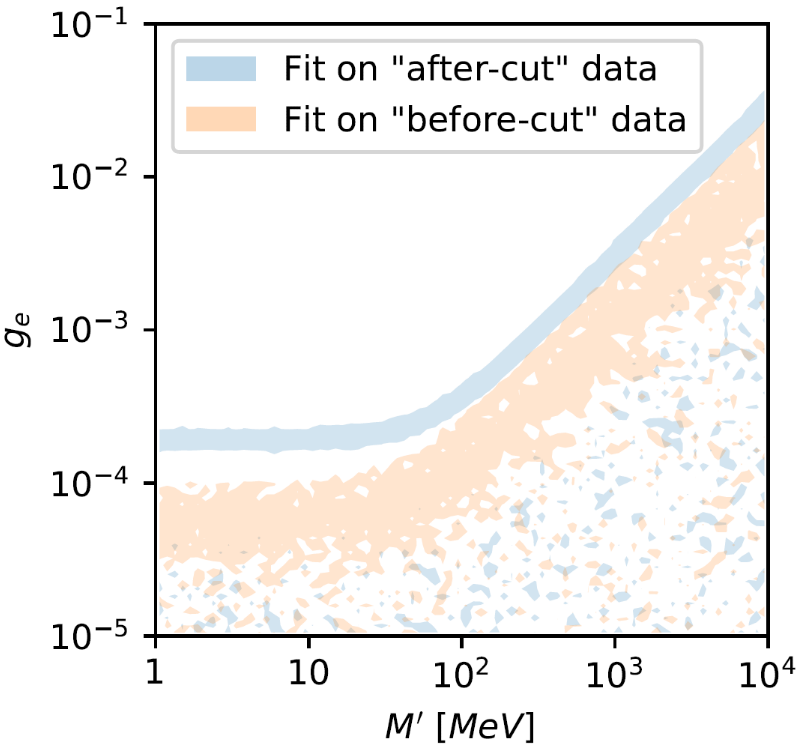
$$\epsilon = \epsilon_1^q \epsilon_2^q \epsilon_2^D \sqrt{\mathrm{BR}_{A'\to\chi\chi}}$$

The mass of the DM-nucleus interaction mediator

- Baseline model point for the figure in the left:
  $\tau = 1$ ns, $m_{A'} = 75$ MeV, $m_\chi = 5$ MeV
- Nevertheless, the figure holds for
  - ✓ $\tau \leq 4$ ns, $m_{A'} < 138$ MeV
  - ✓ $\tau \leq 30$ ns, $m_{A'} \cong 138$ MeV (non-relativistic dark photon case)
  - ✓ Any $m_\chi < m_{A'}/2$

Mild Excess? – Alternative Interpretation: NSI

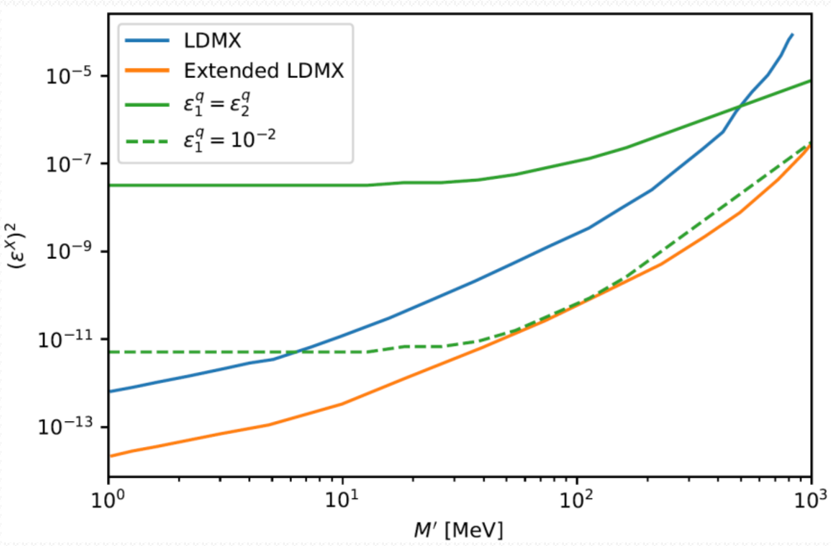
- Example alternative new physics possibility, Non-Standard Interaction



- Benchmark case: non-zero coupling g_e, the NSI in the ν_e neutral-current interaction (along with a new mediator).
  - $\Rightarrow$ No overlapping regions, especially the prompt timing bin (i.e., $T < 1.5\ \mu$s) doesn't show a good fit. NSI affects the overall normalization of neutrino flux!
- The situation becomes even worse with $g_\mu \neq 0$, since it affects not only the delayed but the prompt spectrum.

No Excess? – Constraining Parameter Space

❑ Assuming no excess is observed, we can constrain parameter space.

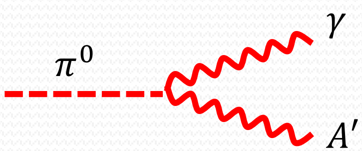


- $\alpha_D \equiv \frac{(e\epsilon_2^q)^2}{4\pi} = 0.5$
- M': the mass of the DM-nucleus interaction mediator
- Solid green line: single mediator scenario, i.e., $\epsilon^X = \epsilon_1^q = \epsilon_2^q$
- Dashed green line: multi-mediator scenario. One of them is fixed to 10^{-2} (e.g., Baryon number gauged dark gauge boson [deNiverville, Pospelov, Ritz (2015)])
- For LDMX, ϵ^e in [LDMX, 1808.05219] identified as ϵ^X.
- Sensitivity reach is already better than DUNE, compared to the result in [De Romeri, Kelly, Machado (2019)].

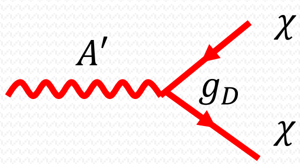
Upcoming Work

- We include the contribution from neutral pions and consider two more similar experiments, JSNS^2 (in J-PARC) and CCM (in Los Alamos).

$\pi^0 \rightarrow \gamma + A'$



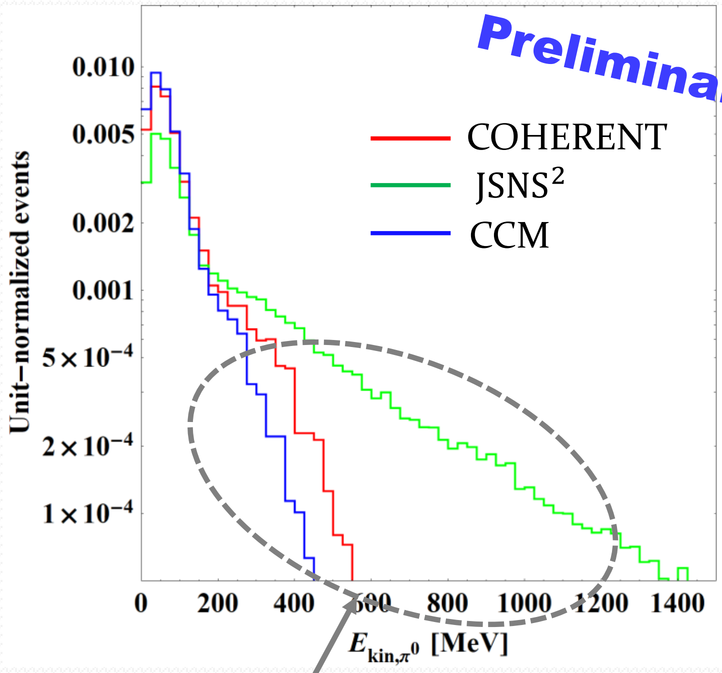
$A' \rightarrow \chi + \chi$

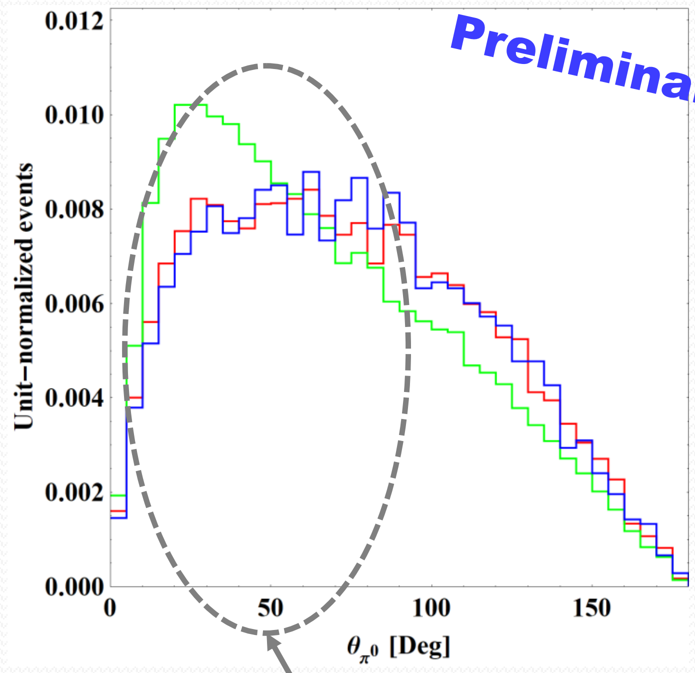


Experiment	$E_{\rm beam}$ [GeV]	POT [yr^{-1}]	Target	Detector (mass/distance/angle)
JSNS^2 [11]	3	3.8×10^{22}	Hg	Gd-LS (17 ton/24 m/70°)
CCM [12]	0.8	1.8×10^{22}	W	LAr (7 ton/20 m)

Upcoming Work

- ❑ π^0 are not produced at rest. ⇒ Detector-level (e.g. GEANT) simulation is needed.



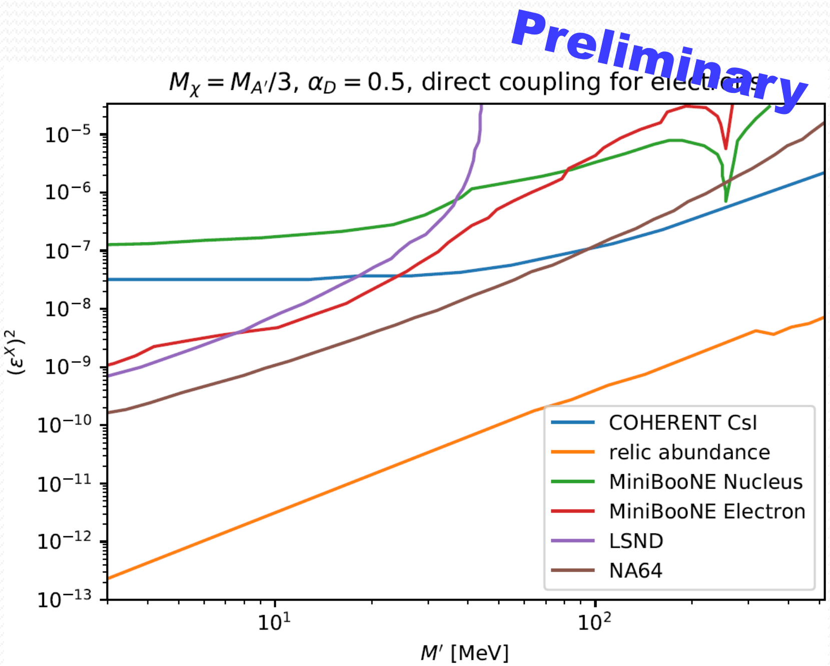


Dark matter can be more energetic.

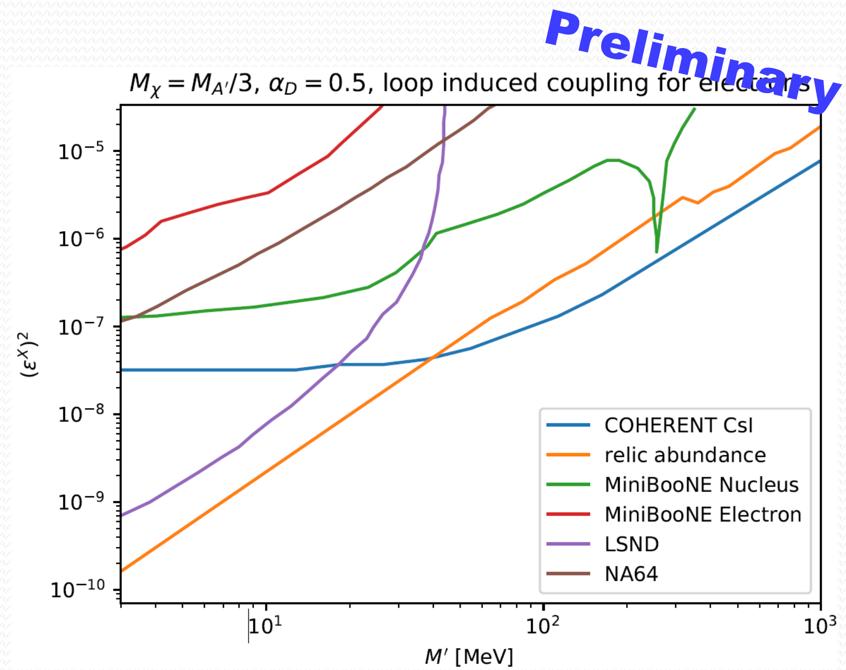
Dark matter flux is slightly forward-directed.

Improved Results

❑ Sensitivity reaches are improved.

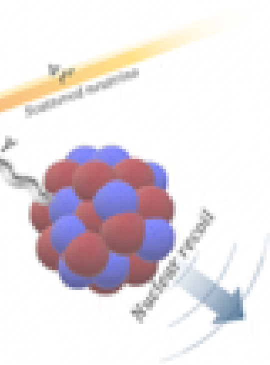


[Single mediator]



[loop-induced coupling to e]

Conclusions



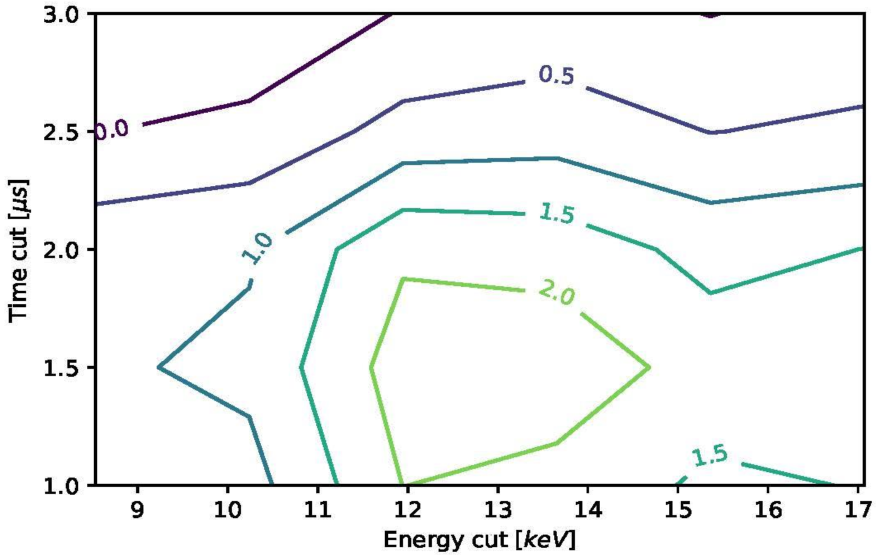
- Null signal observation at conventional dark matter detection experiments motivates us to look into mass scales other than that of WIMP.
- Models with light mediators and dark matter are interesting and receiving rising attention.
- Not only energy spectrum but also timing spectrum can be utilized in the search for light dark matter-induced signals: A combination of timing and energy cuts can eliminate SM neutrino backgrounds efficiently.
- The current CsI data shows a $2.4 - 3\sigma$ excess which can be explained by dark matter arising from dark photon decay.
- The experimental sensitivities for dark matter parameter space can be better than the existing bounds.
- More interesting results coming up. Stay tuned!

Thank you for your attention!

Bonus Slides

Cut Optimization

Significance Contours



- 14 keV $< E_r <$ 28 keV
- $T < 1.5\ \mu$s

Optimized set of cuts are independent of R_n

Preferred Parameter Values

- Single mediator scenario (i.e., the case where the dark photon A' mediates the scattering process of dark matter at the detector)

$$\epsilon = \epsilon_1^q \epsilon_2^q \epsilon_2^D \sqrt{\mathrm{BR}_{A'\to\chi\chi}} \to (\epsilon^q)^2 \epsilon_2^D \sqrt{\mathrm{BR}_{A'\to\chi\chi}} \to (\epsilon^q)^2/e$$

$\epsilon^q \equiv \epsilon_1^q = \epsilon_2^q$ $\qquad$ $\epsilon_2^D = 1/e$, BR $= 1$ for simplicity $(g_D \equiv e\epsilon_2^D)$

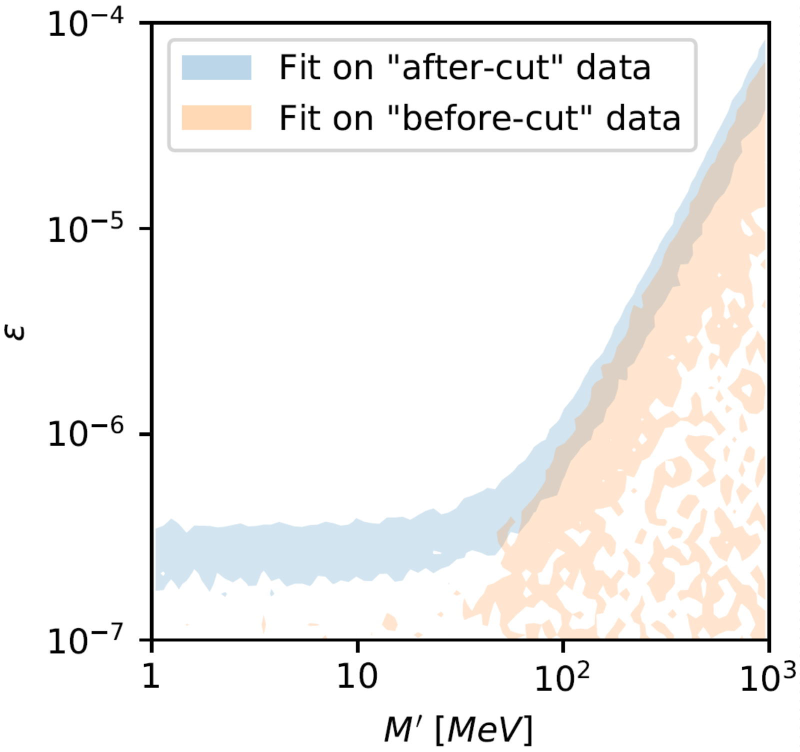
M'(MeV)	50	75	100	1000
ϵ^q	3.5×10^{-4}	4.4×10^{-4}	5.5×10^{-4}	4.6×10^{-3}

- Multi-mediator scenario (i.e., the case where another mediator mediates the scattering process of dark matter at the detector)

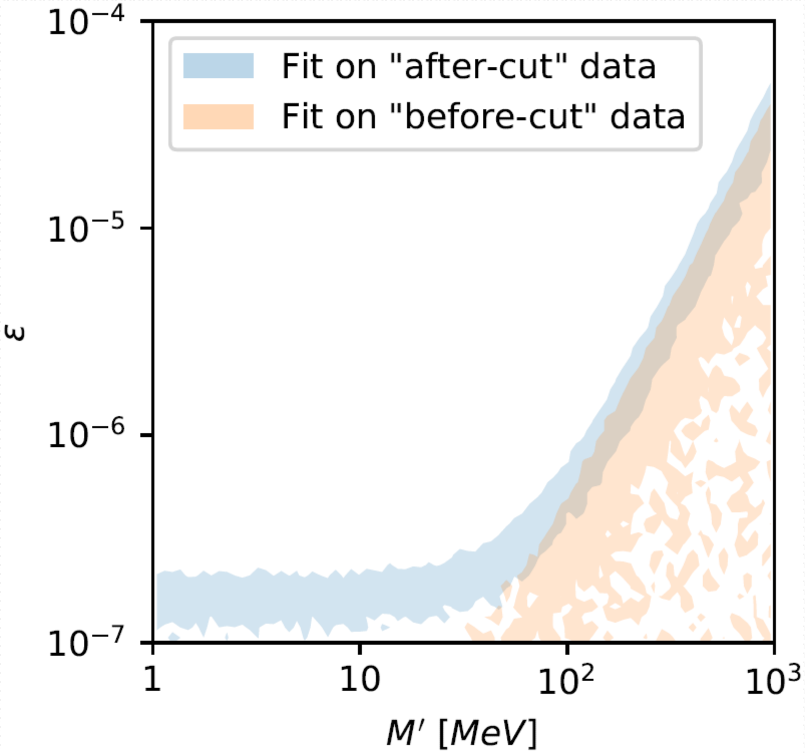
  $\Rightarrow$ ϵ^q above can be interpreted as $(\epsilon_1^q \epsilon_2^q \epsilon_2^D e)^{1/2}$

  $\Rightarrow$ ϵ_2^D is not the same as ϵ_1^D which controls τ of A', so longer-lived dark photon could be possible.

Excess – Dark Matter Interpretation



[Without π^0 contribution]



[With π^0 contribution]