Optimization of Boosted Dark Matter Searches

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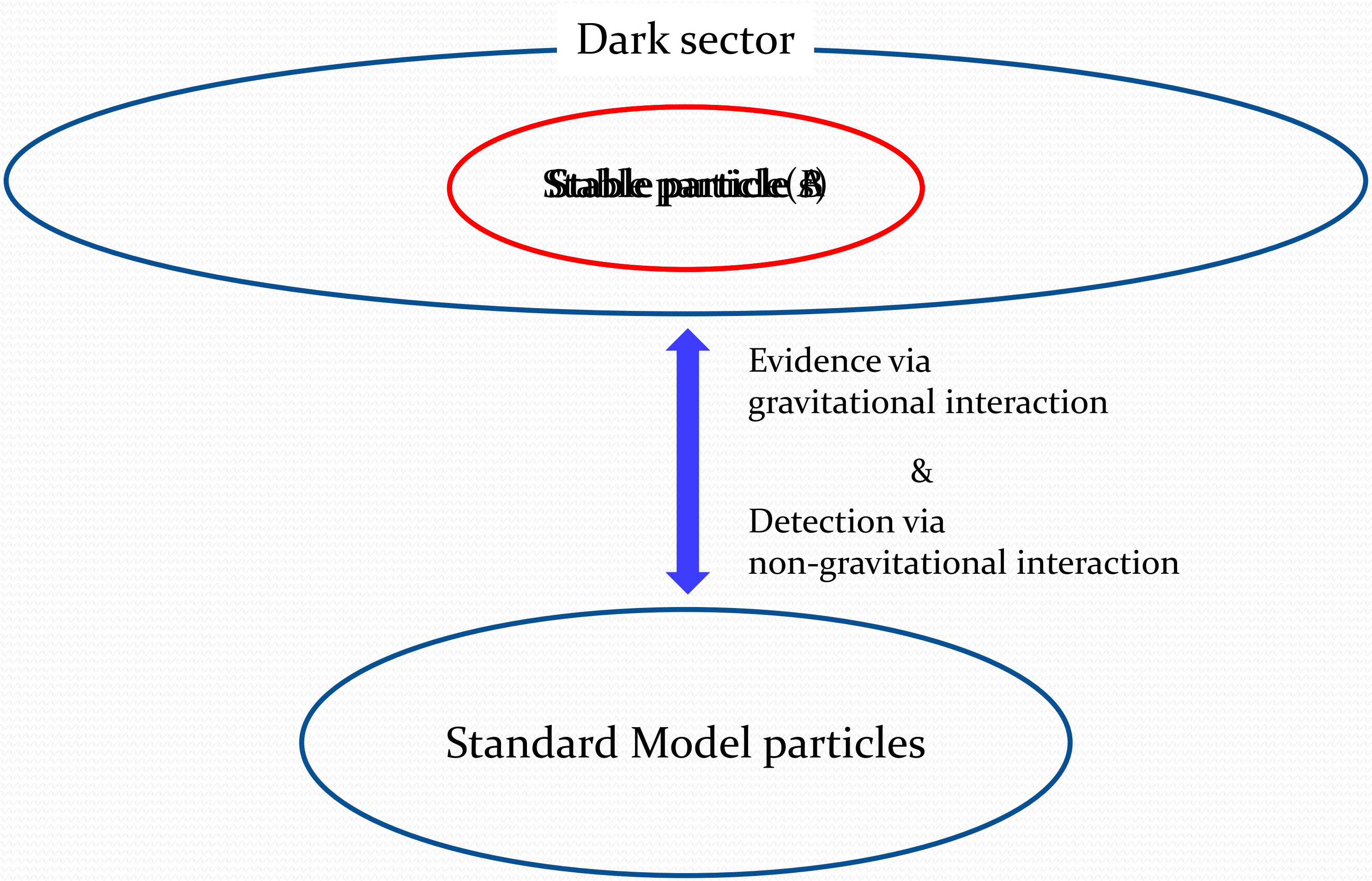
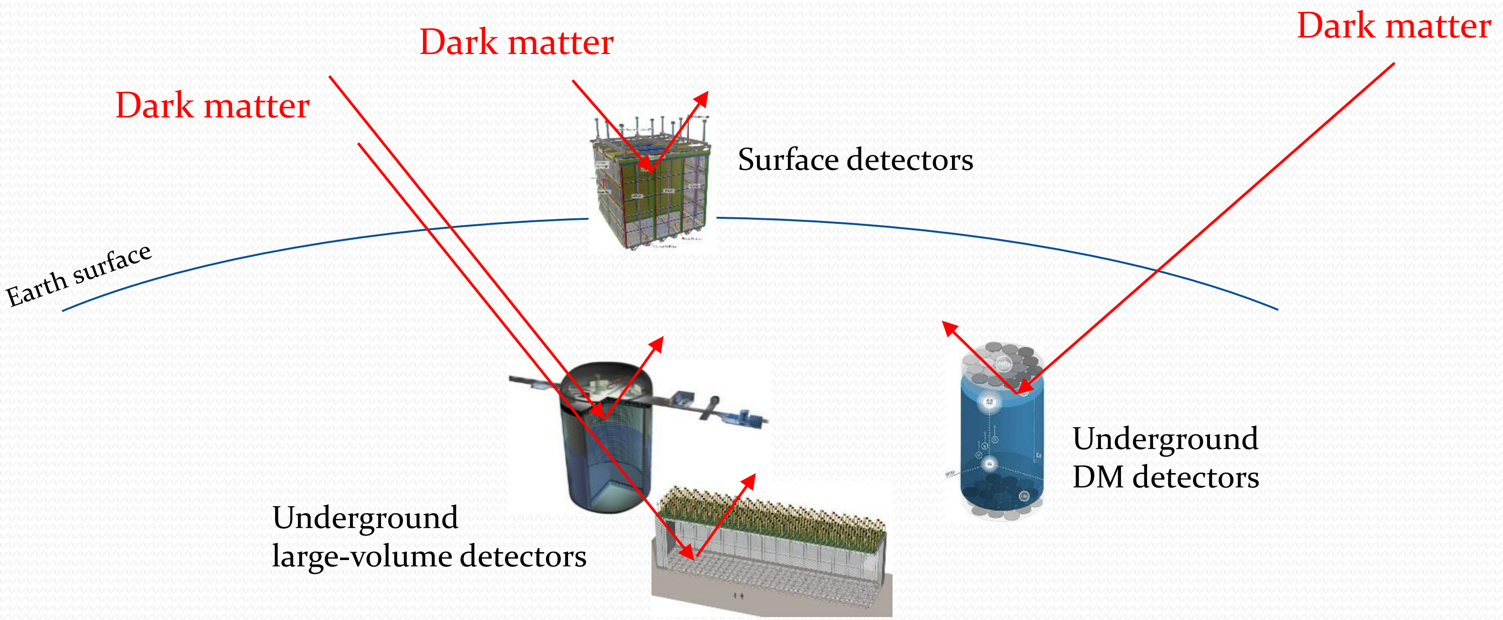
New Opportunities at the Next Generation Neutrino Experiments,

University of Texas at Arlington, April 12th, 2019

Two-Component Boosted Dark Matter Scenarios



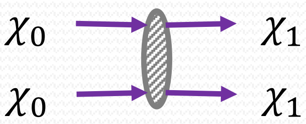
Detection of Boosted Dark Matter

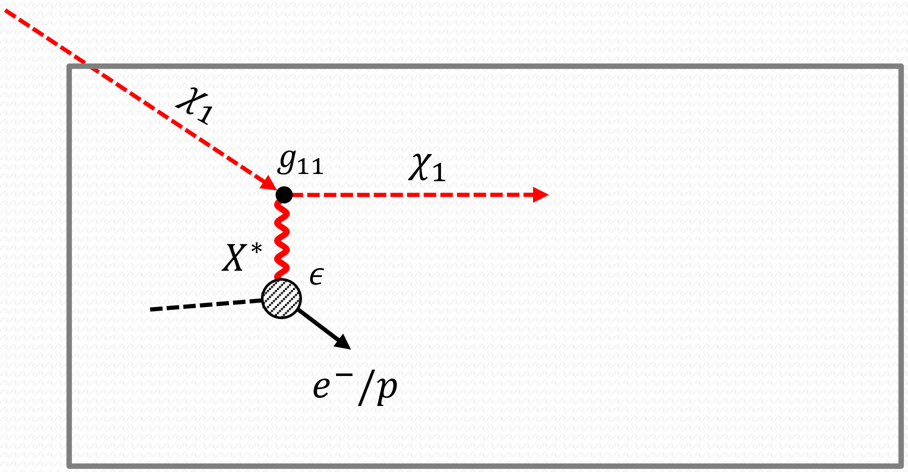


- Simply waiting for signals coming from the universe today
- (Often) doing nontrivial model building to create boosted dark matter (see Yanou Cui's talk for example mechanisms)
- (Typically) probing cosmological dark matter (nonrelativistic) through its boosted "partners"

Existing Searches

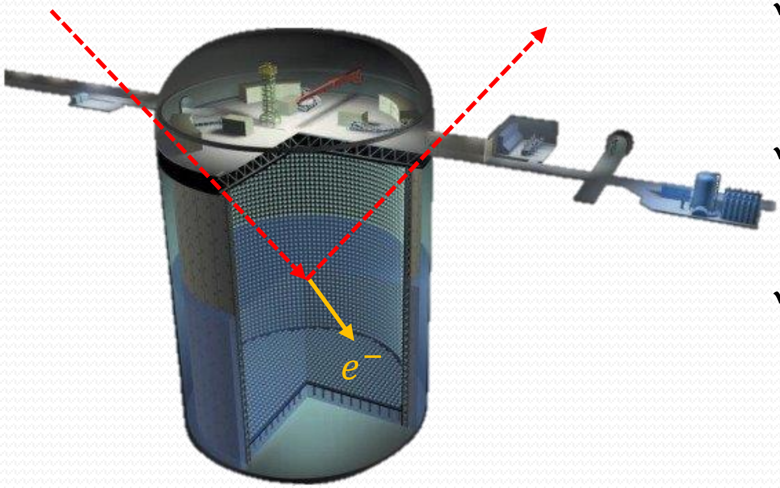
Expected BDM Signatures: Elastic Scattering





- Example model: dark gauge boson + fermionic dark matter
- (In principle,) electron and proton scattering channels are available.

BDM Search at SK Detector



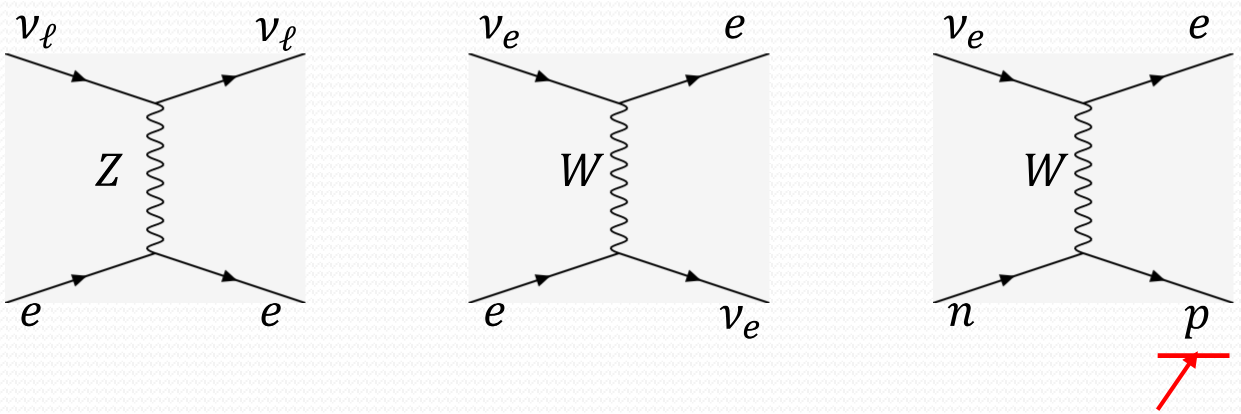
- ✓ 32 kt (22.5 kt fiducial) inner detector (ID) surrounded by 18 kt outer detector (OD).
- ✓ 11,129 inward-facing PMTs in ID and 1,885 outward-facing PMTs in OD.
- ✓ ID provides most of the information used in event reconstruction, while OD plays a role of an active veto region (e.g., cosmic muon tagging).

- ✓ Analyzing the 2,628.1 days (= 161.9 kt·yr) of SK-IV data containing scattered electron energies ranging from 100 MeV to 1 TeV.
- ✓ Search begins with the Fully-Contained Fiducial Volume (FCFV) dataset: no activities in OD, reconstructed vertex inside the fiducial volume of ID.
- ✓ Assumed that the boosted dark matter originates in the Galactic Center or the sun.

Event Selection and Major Background

- Selection criteria: i) 1-ring (if $E_{\text{vis}} < 100$ GeV): ring counting algorithm unreliable beyond 100 GeV, ii) Electron-like, iii) 0 decay electrons (to reject ν-nucleus interaction creating $\pi^{\pm} \to \mu^{\pm} \to e^{\pm}$), iv) 0 tagged neutrons (coming from atm. ν-induced DIS) - tagging algorithm available for SK-IV data only.

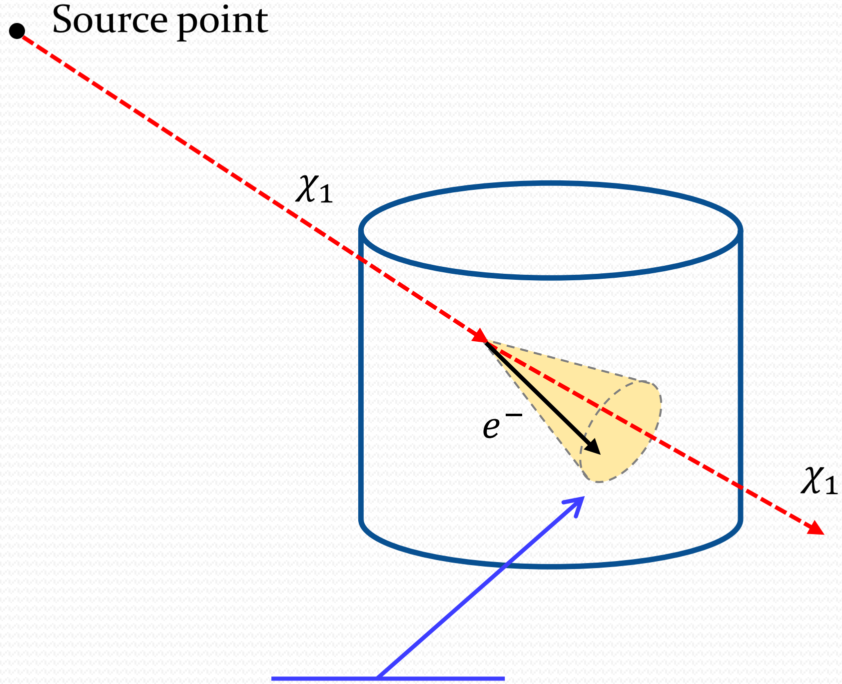
- Despite the selection cuts, many neutrino-induced events can survive, appearing as signal events (SK is a neutrino detector!). E.g.,



Not observed if too soft ($p_{\text{th},p} = 485$ MeV)

Angular Cut to Reduce Background

- Boosted DM is incoming ultra-relativistically!



- ✓ Final-state particles move very forward, and the scattering angle of the recoil electron is typically less than $\sim 6^\circ$ at $E_{\text{recoil}} = 100$ MeV (minor model dependence), i.e., directionality measured.
- ✓ Good angular resolution allows to isolate source regions (especially great for point-like sources such as the sun). SK: $\theta_{res} \lesssim 3^\circ$ for $E_{\text{recoil}} > 100$ MeV

Define "search cones" the half-opening angle of which ranges from 5° to 40° for the GC-originating and 5° for the Sun-originating.

Search Results

Entire sky

	100 MeV< E_{vis} < 1.33 GeV			1.33 GeV < E_{vis} < 20 GeV			E_{vis} > 20 GeV		
	Data	ν-MC	ϵ_{sig}(0.5 GeV)	Data	ν-MC	ϵ_{sig}(5 GeV)	Data	ν-MC	ϵ_{sig}(50 GeV)
FCFV	15206	14858.1	97.7%	4908	5109.7	93.8%	118	107.5	84.9%
& single ring	11367	10997.4	95.8%	2868	3161.8	93.3%	71	68.2	82.2%
& e-like	5655	5571.5	94.7%	1514	1644.2	93.0%	71	68.1	82.2%
& 0 decay-e	5049	5013.8	94.7%	1065	1207.2	93.0%	13	15.7	82.2%
& 0 neutrons	4042	3992.9	93.0%	658	772.6	91.3%	3	7.4	81.1%

TABLE I. Number of events over the entire sky passing each cut in 2628.1 days of SK4 data, simulated ν-MC background expectation, and signal efficiency at representative energy after each cut.

Search cone

Search Cone	100 MeV< E_{vis} < 1.33 GeV			1.33 GeV < E_{vis} < 20 GeV			E_{vis} > 20 GeV		
	Expected Bckg	Data	Sig Rate Limit (kT-y)$^{-1}$	Expected Bckg	Data	Sig Rate Limit (kT-y)$^{-1}$	Expected Bckg	Data	Sig Rate Limit (kT-y)$^{-1}$
GC 5°	8.4 ± 0.7	5	0.017	1.6 ± 0.3	1	0.018	0.016 ± 0.005	0	0.015
GC 10°	32.0 ± 1.9	24	0.023	6.3 ± 0.84	5	0.026	0.060 ± 0.018	0	0.015
GC 15°	72.5 ± 3.5	69	0.078	13.6 ± 1.6	11	0.032	0.14 ± 0.04	0	0.014
GC 20°	126.5 ± 5.4	125	0.123	23.3 ± 2.3	18	0.028	0.25 ± 0.07	0	0.014
GC 25°	196.8 ± 7.6	202	0.201	35.4 ± 3.3	31	0.049	0.37 ± 0.11	0	0.013
GC 30°	283.7 ± 10.1	285	0.214	49.3 ± 4.3	48	0.081	0.53 ± 0.16	0	0.012
GC 35°	384.8 ± 12.8	375	0.187	68.1 ± 5.4	67	0.101	0.70 ± 0.21	0	0.011
GC 40°	499.6 ± 15.9	494	0.249	90.2 ± 6.9	90	0.124	0.90 ± 0.27	0	0.011
Sun 5°	7.59 ± 0.18	5	0.017	1.25 ± 0.07	1	0.020	0.015 ± 0.004	0	0.015

TABLE II. Estimated backgrounds,numbers of events in data, and signal event rate limits for each cone and each energy sample. The event rate limits are at the 90% confidence level.

Interpretation

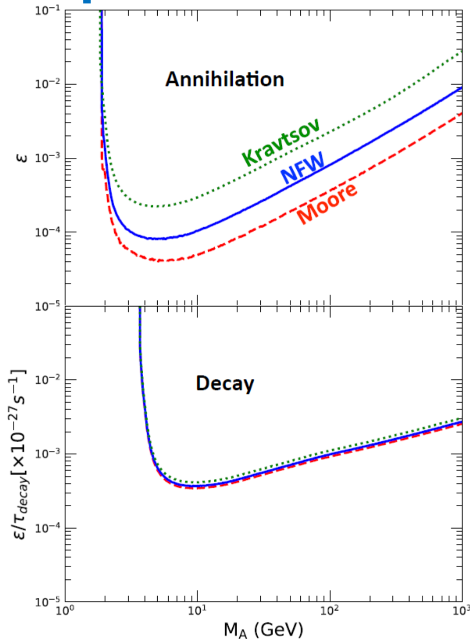


FIG. 3. 90% Confidence Interval upper limits for m_B=200 MeV, m'_γ=20 MeV, and g'=0.5, for boosted dark matter produced by annihilation (top) and decay (bottom).

- ❑ The observed data is consistent with neutrino-induced background prediction, i.e., no evidence for the boosted dark matter.

Motivation for Inelastic Boosted Dark Matter (iBDM)

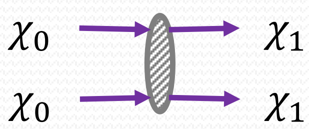
	Elastic scattering	Inelastic scattering
Non-relativistic	Conventional Dark Matter	Inelastic Dark Matter [Tucker-Smith, Weiner (2001)]
Relativistic	Boosted Dark Matter [Agashe, Cui, Necib, Thaler (2014)]	Inelastic Boosted Dark Matter [**DK**, Park, Shin (2016)]

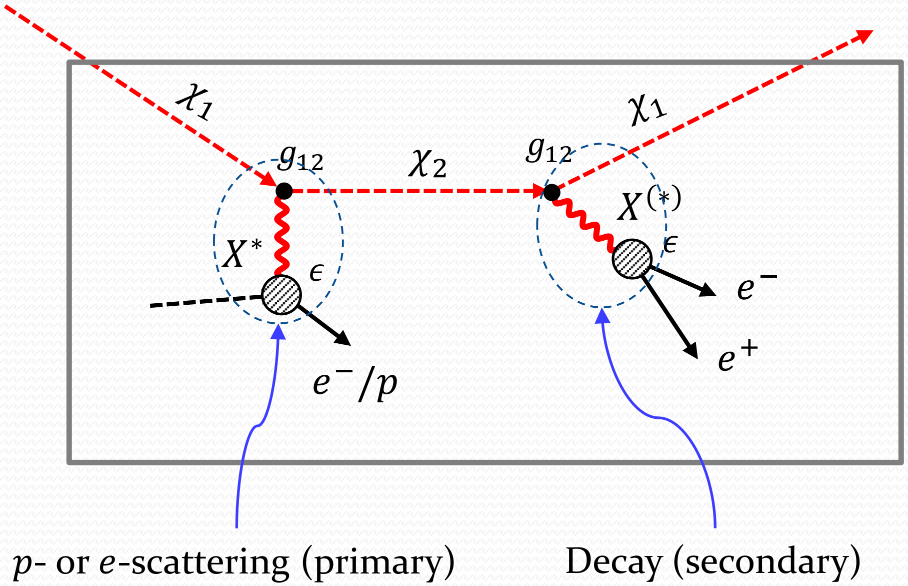
<u>Natural extension/combination</u>

Motivation for iBDM

- Signal events with more features
  - ✓ Boosted DM up-scattered to a dark-sector unstable heavier state which decays back into dark matter (potentially) along with visible particle(s). ⇒ Signal characterized by additional visible particle(s) on top of visible target recoil.
  - ✓ Signal suffers from less background contamination (nearly zero-background search can be possible). ⇒ Potentially better signal sensitivity. (cf. Improving signal sensitivity by an angular cut in searches for BDM coming from point-like sources, e.g, Sun [Berger, Cui, Zhao (2014); Kong, Mohlabeng, Park (2014); **DK**, Kong, Park, Shin (2018)], dwarf galaxy [Necib, Moon, Wongjirad, Conrad (2016)])

Expected BDM Signatures: Inelastic Scattering





- ❑ Distinctive signature arises if everything happens inside a detector fiducial volume.
- ❑ The secondary interaction point may be displaced due to either long-lived
  - ✓ χ_2 – when it decays via an off-shell X (i.e., $m_2 < m_1 + m_X$) – or
  - ✓ on-shell X – when kinetic mixing parameter is sufficiently small.
- ❑ If $\delta m = m_2 - m_1$ is large enough, other final states (e.g., $\mu^+\mu^-$, $\pi^+\pi^-$, etc) are available.

Challenge in iBDM Search at COSINE-100

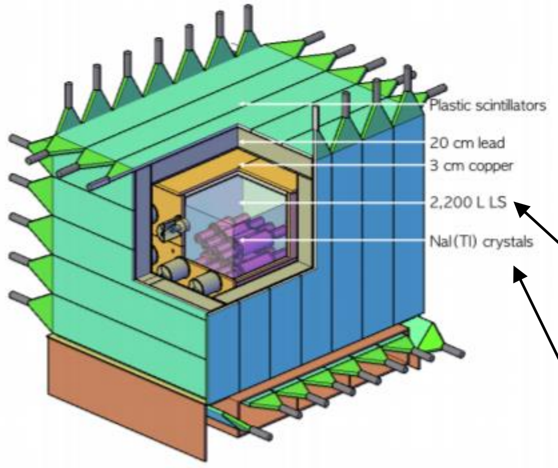


FIG. 2. Schematic of the COSINE-100 detector. The NaI(Tl) (106 kg) detectors are immersed in the 2,200 L LAB-LS that are surrounded by layers of shields.

- ✓ Shielding material including plastic scintillators to shield and reject other unwanted particles, e.g., cosmic muons
- ✓ 2,200 liters of linear alkylbenzene (LAB)-based liquid scintillator (LS)
- ✓ 106 kg of NaI(Tl) crystals

- ❑ Experimental challenge: **not enough target material inside the fiducial volume** to have signal sensitivity!

Fiducialization of Active Veto Detector

- Solution: fiducialize the 2,200 L of LS (as an active detection volume) to effectively create a ton-scale detector!

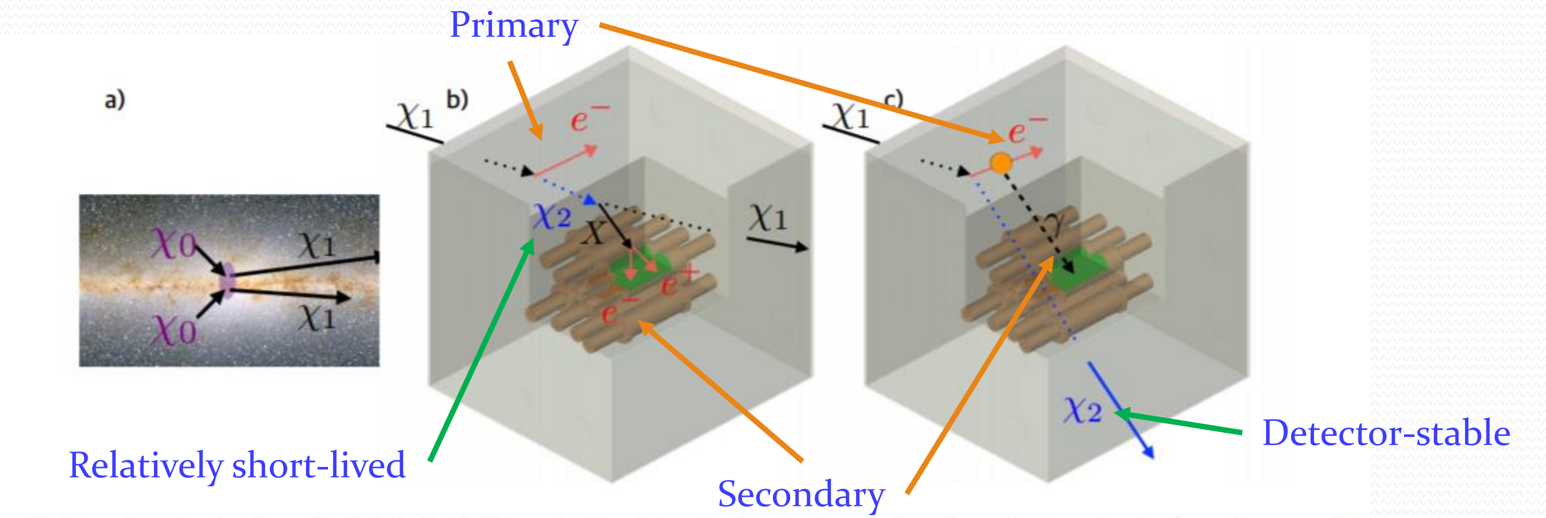


FIG. 1. (a) Production of relativistic BDM χ_1 in the Galactic Center by annihilation of a heavier dark matter χ_0. (b) Illustration of multiple-site hits from an inelastic interaction of BDM for the case of two interactions occurring in two different NaI(Tl) and LS detectors. (c) Illustration of Bremsstrahlung radiation-induced hits on two NaI(Tl) or LS detectors.

Cf.) Somewhat similar tricks: primary at passive volume and secondary at fiducial volume [Pospelov, Weiner, Yavin (2013)]

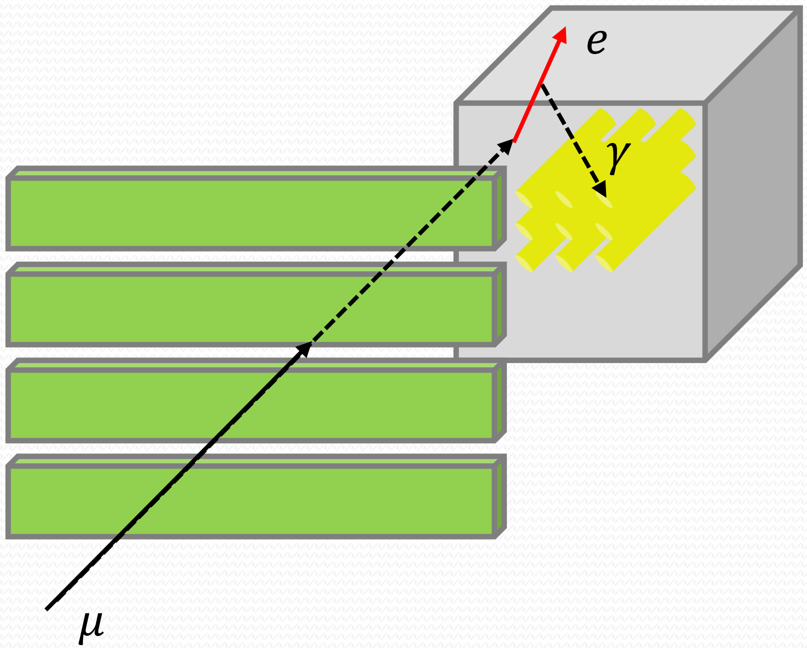
iBDM Search Strategy at COSINE-100

- Event selections based on the topology of iBDM events
  1) Energy of LS > 4 MeV
  2) No selected muons from the muon detector
  3) Total energy of the NaI(Tl) crystals > 4 MeV
  4) No α–induced events in the NaI(Tl) crystals (using a pulse shape discrimination method)

⇒ Observed 21 candidate events from the 59.5 days of the COSINE-100 data (Oct. 20th, 2016 to Dec. 19th, 2016)

Discovery of dark matter? 🙂 Well, background events! ☹

Background



- Major background: cosmic muons which sneak in through a tiny gap between muon taggers and stop in the LS or crystals

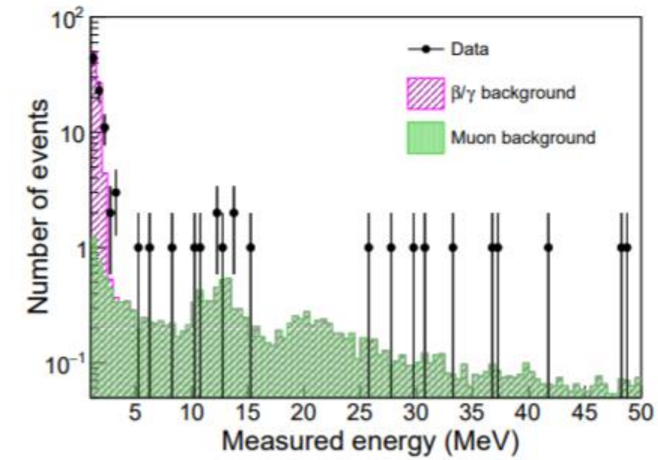


FIG. 3. Spectrum of the summed energy from all crystals (filled circle), after application of all selection criteria of the iBDM candidate events but with no requirement on the amount of energy observed in the crystals, is compared with the expected background (solid histogram). Contributions to the background from muon and β/γ events caused by radionuclide contaminations are indicated. In the region of interest (energy greater than 4 MeV), muons are the only contribution.

Muon untagging fraction = 2.14% $\Rightarrow$ Expected background 16.4 ± 2.1 which is consistent with 21.

Search Result

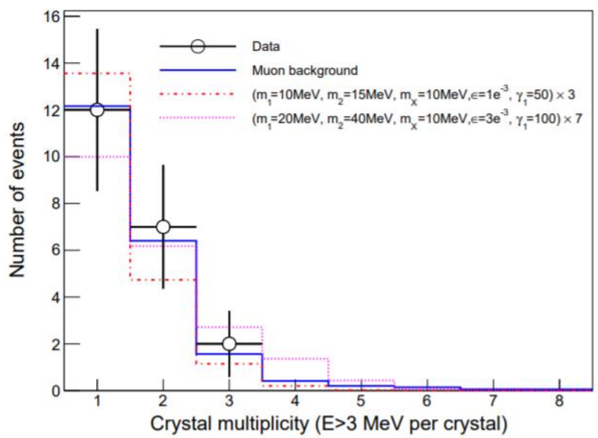
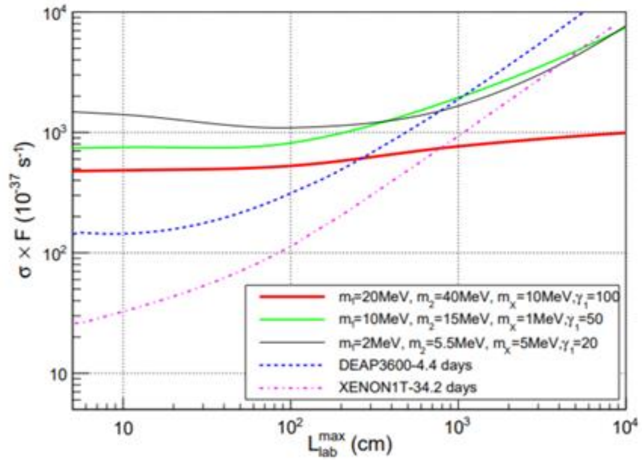


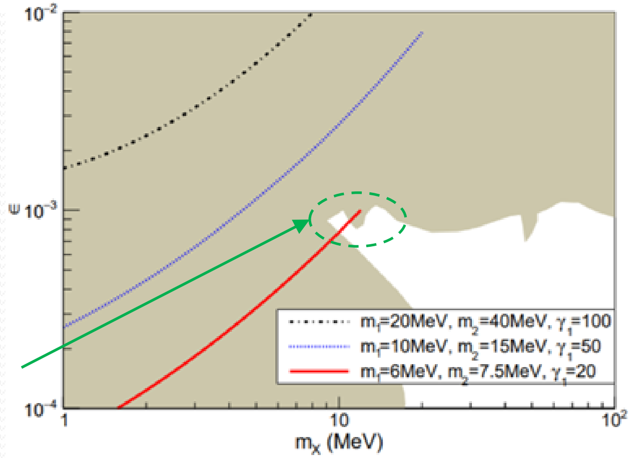
FIG. 4. Comparison of the event rate as a function of the crystal multiplicity in data with energy greater than 3 MeV per crystal (open circle) and the expected background from muons (solid line). The expected signal shapes for two different model parameters (dotted line and dashed line) are also shown. For easy comparison of the shapes, the dotted line and dashed line spectra are multiplied by a factor 7 and 3, respectively.



Interpretation based on the proposal in [Giudice, **DK**, Park, Shin (2017)].

- No signal observation, but consistent with muon background prediction.

Limits begin to explore parameter regions that have not been covered!



Optimizing Future BDM Searches

(Mostly based on the ongoing work with P. Machado, J.-C. Park, and S. Shin)

Many More Well-Motivated Experiments

DM Experiment	Target Material	Volume [t] Active	Volume [t] Fiducial	Depth [m]	E_{th} [keV]	Resolution Position [cm]	Resolution Angular [°]	Resolution Energy [%]	PID	Run Time	Refs.
DarkSide -50	LAr DP-TPC	46.4 kg	36.9 kg	3,800 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	$\lesssim 10$	–	2013-	[82]
DarkSide -20k	LAr DP-TPC	23	20	3,800 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	$\lesssim 10$	–	goal: 2021-	[53]
XENON1T	LXe DP-TPC	2.0	1.3	3,600 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	–	–	2016 -2018	[83, 84]
XENONnT	LXe DP-TPC	5.9	~ 4	3,600 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	–	–	goal: 2019-	[83]
DEAP -3600	SP LAr S1 only	3.26	2.2	2,000	$\mathcal{O}(10)$	< 10	–	$\sim 10-20$	–	2016-	[70–72]
DEAP -50T	SP LAr S1 only	150	50	2,000	$\mathcal{O}(10)$	15	–	–	–	–	[70]
LUX-ZEPLIN	LXe DP-TPC	7	5.6	4,300 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1-1$	–	2.5 MeV: 2	–	goal: 2020-	[85]
Neutrino Experiment	**Target Material**	**Volume [kt] Active**	**Volume [kt] Fiducial**	**Depth [m]**	**E_{th} [MeV]**	**Resolution Vertex [cm]**	**Resolution Angular [°]**	**Resolution Energy [%]**	**PID**	**Run Time**	**Refs.**
Borexino	organic LS	0.278	0.1	3,800 m.w.e.	~ 0.2	~9-17	–	$\frac{5}{\sqrt{E\,(\text{MeV})}}$	–	> 5.6 year	[86]
KamLAND	LS	1	0.2686	1,000	0.2 - 1	$\frac{12-13}{\sqrt{E\,(\text{MeV})}}$	–	$\frac{6.4-6.9}{\sqrt{E\,(\text{MeV})}}$	–	~ 10 year?	[87, 88]
JUNO	LS	–	20	700	< 1, goal: 0.1	$\frac{12}{\sqrt{E\,(\text{MeV})}}$	μ: $L > 5$ m: < 1, $L > 1$ m: < 10	$\frac{3}{\sqrt{E\,(\text{MeV})}}$	$\mu^\pm$ vs $\pi^\pm$, $e^\pm$ vs π^0: difficult	goal: 2020-	[89]
DUNE	LArTPC	Total: 17.5 ×4	(SP: 10 + DP: 10.6) ×2	1500	$e: 30$, p: 21-50	1-2	$e, \mu, \pi^\pm: 1$, $p, n: 5$	$e: 1 \oplus \frac{15}{\sqrt{E\,(\text{MeV})}}$ $p: 10\,(p < 0.4\,\text{GeV})$, $5 \oplus \frac{30}{\sqrt{E\,(\text{GeV})}}$ $(p > 0.4\,\text{GeV})$	good $e, \mu, \pi^\pm, p$ separation	10 kt: 2025-, 20 kt: 2026-	[6, 54–56]
SK	Water Cherenkov	Total: 50	22.5	1,000	$e: 5$, $p: 485$	5 MeV: 95, 10 MeV: 55, 20 MeV: 40	10 MeV: 25, 0.1 GeV: 3, 1.33 GeV: 1.2	10 MeV: 16, 1 GeV: 2.5	e, μ: good	$\gtrsim 15$ year	[90–92]
HK	Water Cherenkov	Total: 258 ×2	187 ×2	Japan: 650, Korea: 1,000	$e: < 5$, $p: 485$	5 MeV: 75, 10 MeV: 45, 15 MeV: 40, 0.5 GeV: 28	similar to SK	better than SK	e, μ: good, $\pi^0, \pi^\pm$: mild	goal: 2026-	[57–59]
	Target Material	**Effective Volume [Mt]**		**Depth [m]**	**E_{th} [GeV]**	**Resolution Vertex [m]**	**Resolution Angular [°]**	**Resolution Energy [%]**	**PID**	**Run Time**	**Refs.**
IceCube	Ice Cherenkov	100 GeV: ~ 30, 200 GeV: ~ 200		1,450 Ice	~ 100	vertical: 5, horizontal: 15	μ-track: ~ 1, shower: ~ 30	100 GeV: 28, 1 TeV: 16	only μ	2011- (2008)	[61, 93]
DeepCore	Ice Cherenkov	10 GeV: ~ 5, 100 GeV: ~ 30		2,100 Ice	~ 10	better	μ-track: ~ 1, shower: $\gtrsim 10$	–	only μ	2011- (2010)	[60, 61]
PINGU	Ice Cherenkov	1 GeV: ~ 1, 10 GeV: ~ 5		2,100 Ice	~ 1	much better	1 GeV: 25, 10 GeV: 10	1 GeV: 55, 10 GeV: 25	only μ	> 2023	[94]
Gen2	Ice Cherenkov	~ 10 Gt		1,360 Ice	~ 50 TeV	worse	μ-track: < 1 shower: ~ 15	–	only μ	–	[95]

- Many existing/upcoming experiments which are potentially capable of testing models conceiving boosted dark matter signals
- Additional physics opportunity on top of the main missions of experiments

[DK, Machado, Park, Shin, in progress]

Questions

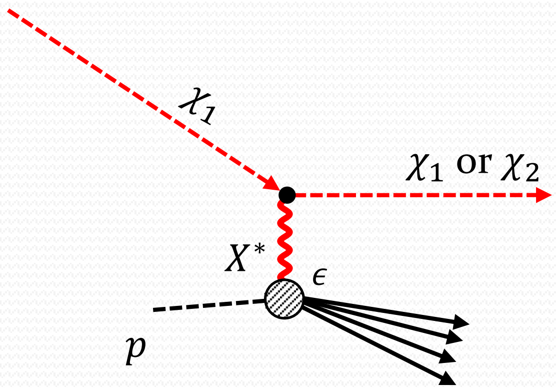
For a BDM model,

- Parameter space to which an experiment would be best sensitive?
- Better-motivated channels to investigate in terms of signal searches?

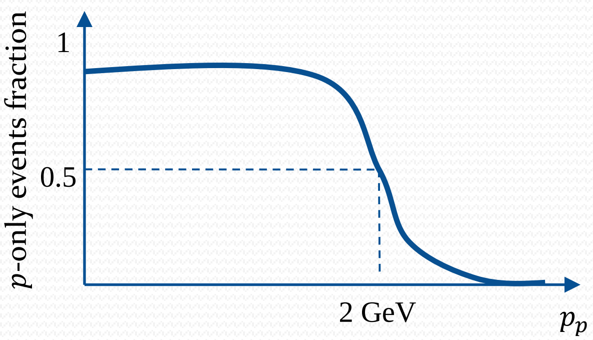
Topics in the Rest of the Talk

- Proton scattering vs. DIS in elastic/inelastic BDM searches
- Proton scattering vs. electron scattering in elastic/inelastic BDM searches
- Example data analysis (in DUNE and Hyper-K)

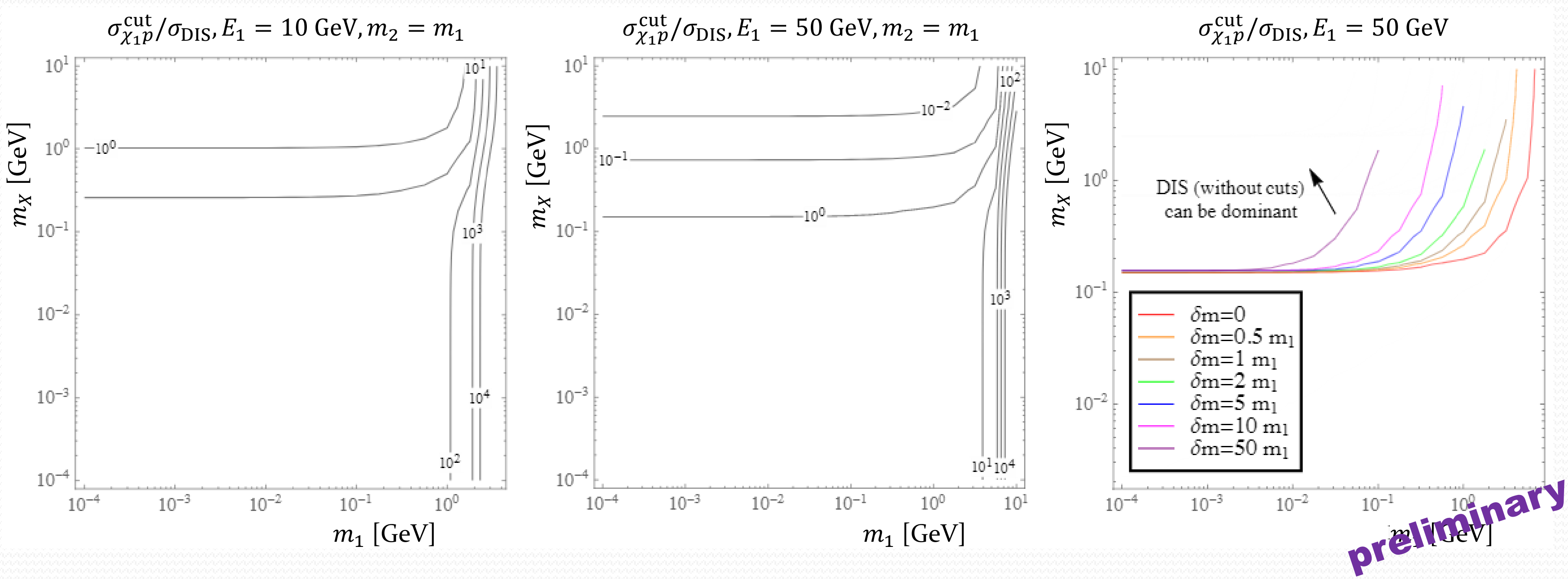
p-Scattering vs. DIS



- If a momentum transfer is too large, a proton may break apart.
- What is large? ⇒ A Super-K simulation study [Fechner et al, PRD (2009)] showed about 50 % events accompany (at least) a pion or a secondary particle for $p_p \approx 2$ GeV.
- We categorize any event with $p_p < 2$ GeV as the p-scattering (i.e., simplified step-function-like transition).

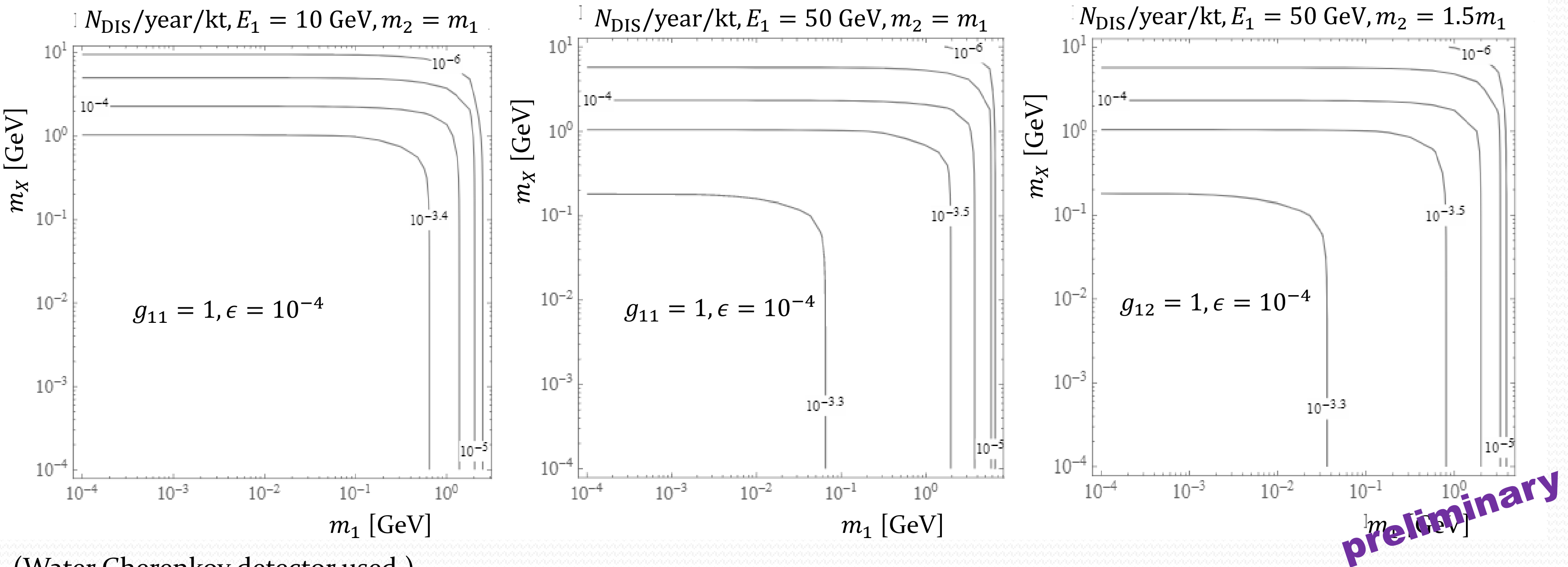


p-Scattering vs. DIS: Numerical Study



- We study $\sigma^{\rm cut}_{\chi_1 p}/\sigma_{\rm DIS}$ where 200 MeV $< p_p <$ 2 GeV is applied to $\sigma_{\chi_1 p}$ while no cuts are imposed to $\sigma_{\rm DIS}$.
- For sub-GeV or lighter mediator (here dark photon), p-scattering dominates over DIS.
- As the process becomes more "inelastic", p-scattering dominates over DIS for a given E_1.
- DIS-preferred region expands in increasing E_1.

p-Scattering vs. DIS: Numerical Study



(Water Cherenkov detector used.)

- ❑ Even in the region where DIS is sizable, the expected number of DIS events is small.
- ❑ (χ_1 with $E_1 > 50$ GeV may come with too small flux, depending on the underlying "boost" mechanism.)

(Semi-)analytic Understanding

- p-scattering:

$$\frac{d\sigma_{\chi_1 p}}{dp_p} \propto \frac{1}{\{2m_p(E_2 - E_1) - m_X^2\}^2} \simeq \frac{1}{({p_p}^2 + m_X^2)^2}$$

t-channel propagator — in the limit of $p_p \ll m_p$

- ✓ The differential cross section is peaking towards small recoil momentum.
- ✓ p-scattering cross section rises in decreasing $m_X (\ll m_p \approx 1$ GeV) as long as $p_p \lesssim m_X$.

- DIS:

$$\frac{d^2\sigma_{\rm DIS}}{dxdy} \propto \frac{1}{(Q^2 + m_X^2)^2} \approx \frac{1}{Q^4}$$

- ✓ The energy transfer Q is larger than ~2 GeV, and in turn, much larger than $m_X (\ll 1$ GeV) under consideration.
- ✓ DIS cross section does not vary much in decreasing $m_X (\ll m_p \approx 1$ GeV).

- Our numerical study suggests that $\sigma_{\chi_1 p}$ be larger than $\sigma_{\rm DIS}$ for $m_X \approx 0.1$ GeV and $E_1 < 100$ GeV.
- As far as a mediator is within sub-GeV or smaller, DIS-induced events, which often involve complicated final states, would be negligible (cf. neutrino-induced DIS via $\mathcal{O}(100$ GeV) W/Z gauge boson exchange).

p-Scattering vs. e-Scattering: a DUNE-like Detector

- Selection criteria

  i) $p_e > 30$ MeV, $200\,\text{MeV} < p_p < 2\,\text{GeV}$,

  ii) $\Delta\theta_{e-i} > 1°$, $\Delta\theta_{p-i} > 5°$ with i denoting the other visible final state particles, and

  iii) both primary and secondary vertices should appear in the detector fiducial volume.

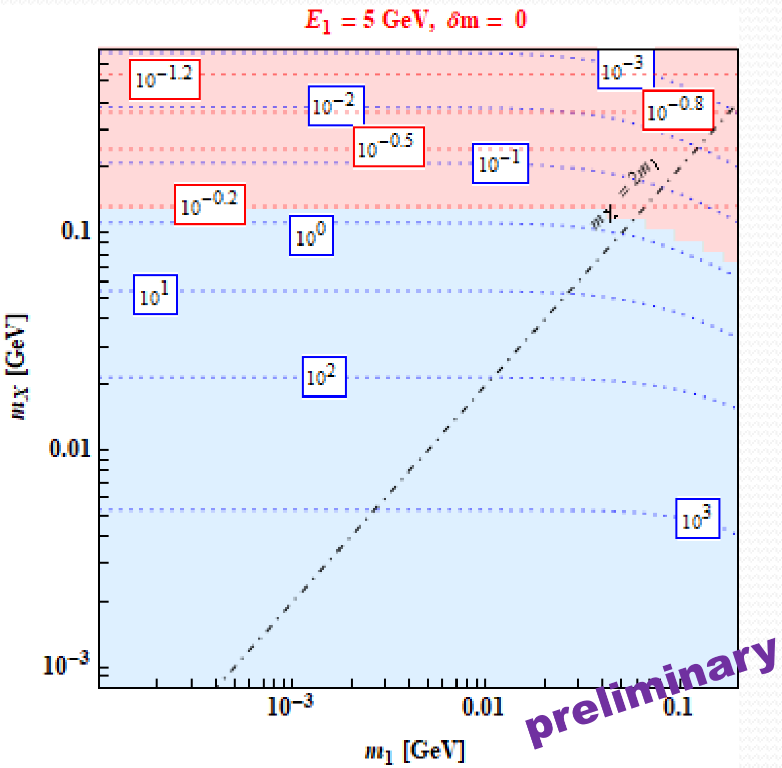
- For each of 5,600 scanning points over the parameter space of interest, we generate 5 million events using the TGenPhaseSpace module in the ROOT package and reweight them with matrix element values.

- The number of expected signal events are calculated by

$$N_{\text{sig}} = \sigma_{\chi_1 p(e)}\, \mathcal{F}_1\, A\, t_{\text{exp}}\, N_{p(e)}$$

with A calculated from considering all selection criteria and 40 kt·yr assumed.

p-Scattering vs. *e*-Scattering: a DUNE-like Detector

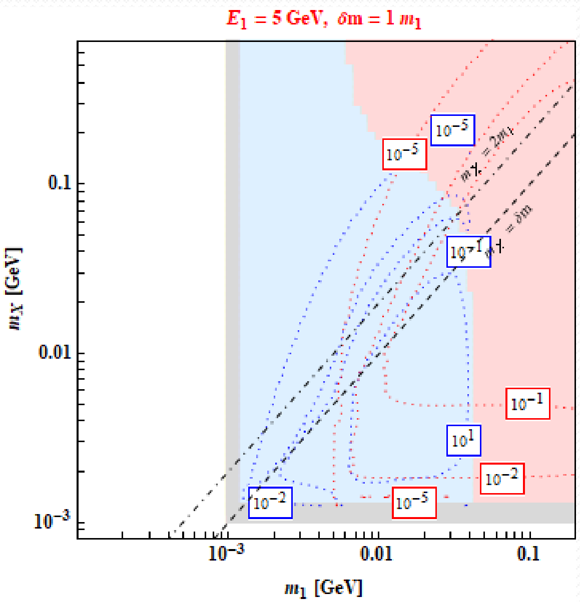


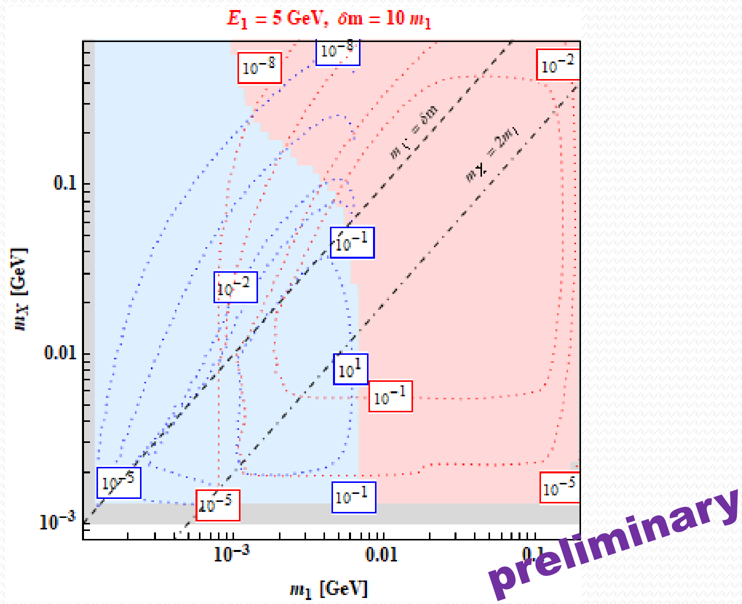
e-scattering preferred

p-scattering preferred

- *e*-scattering-preferred region is larger than expected: in the proton channel, more events populate in smaller proton recoil energy, and a harder angle cut on proton is applied → rejecting some fraction of events.
- Many signal events would be expected in the region with small m_X, but may suffer from large backgrounds such as neutrino-induced events (only target recoil).
  - ⇒ Directionality helps to suppress backgrounds.

p-Scattering vs. e-Scattering: a DUNE-like Detector





- White regions: kinematically not allowed to create an e^-e^+ pair.
- Gray regions: barely allowed to have inelastic BDM events, but fail to pass cuts.
- e-scattering is not allowed to up-scatter towards large m_1.
- e-scattering preferred region with large m_X, the e^-e^+ pair in the p-channel often fails to pass angle cut.

p-Scattering vs. e-Scattering: a HK-like Detector

- Selection criteria

  i) $p_e > 100$ MeV, 1.07 GeV $< p_p < 2$ GeV,

  ii) $\Delta\theta_{e-i} > 3^\circ$, $\Delta\theta_{p-i} > 3^\circ$ with i running over the other visible final state particles, and

  iii) both primary and secondary vertices should appear in the detector fiducial volume.

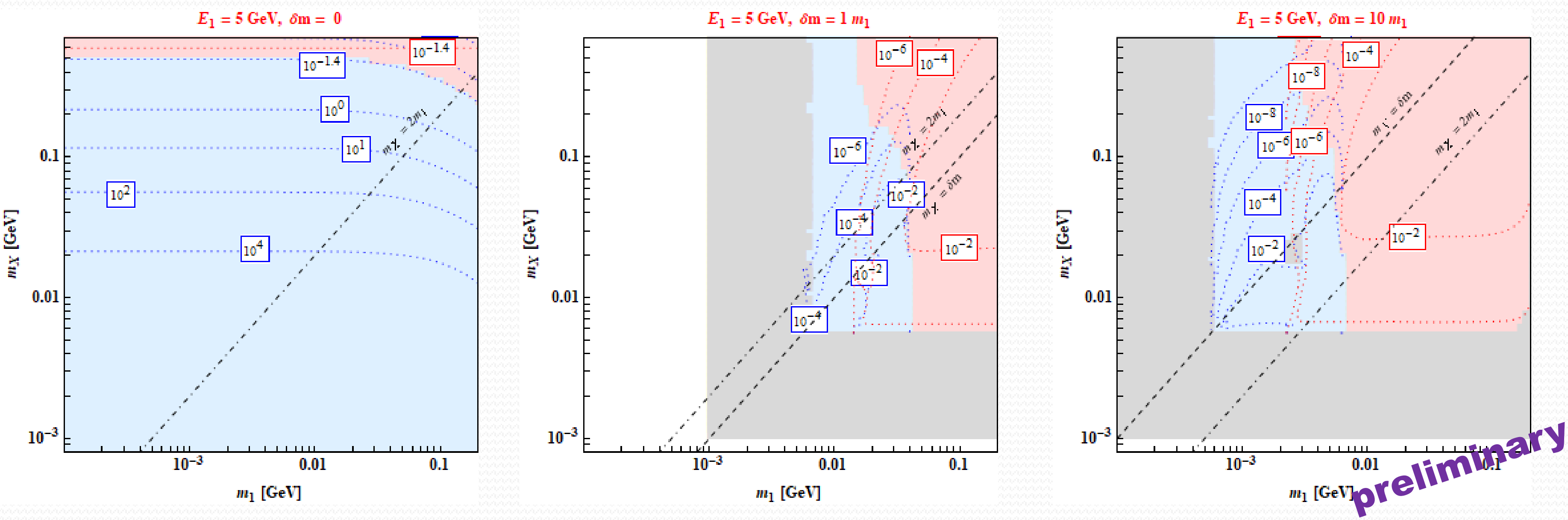
- For each of 5,600 scanning points over the parameter space of interest, we generate 5 million events using the TGenPhaseSpace module in the ROOT package and reweight them with matrix element values.

- The number of expected signal events are calculated by

$$N_{\rm sig} = \sigma_{\chi_1 p(e)}\,\mathcal{F}_1\,A\,t_{\rm exp}\,N_{p(e)}$$

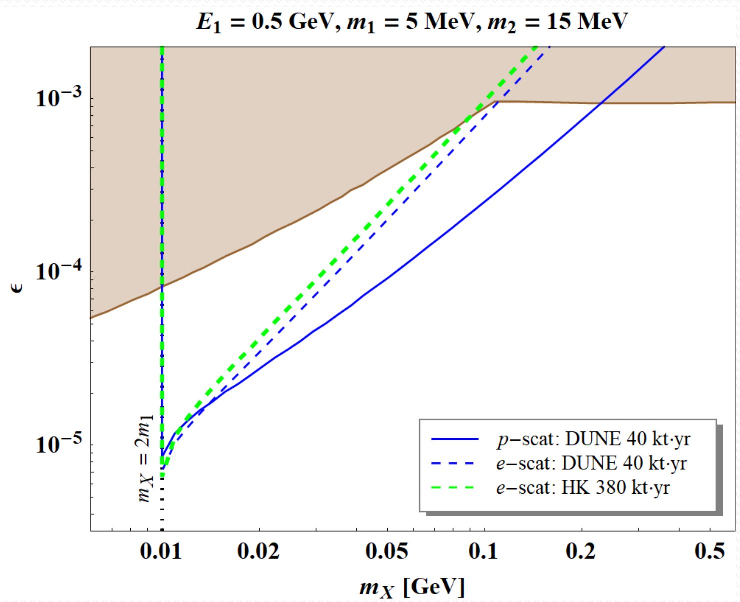
with A calculated from considering all selection criteria and 380 kt·yr assumed.

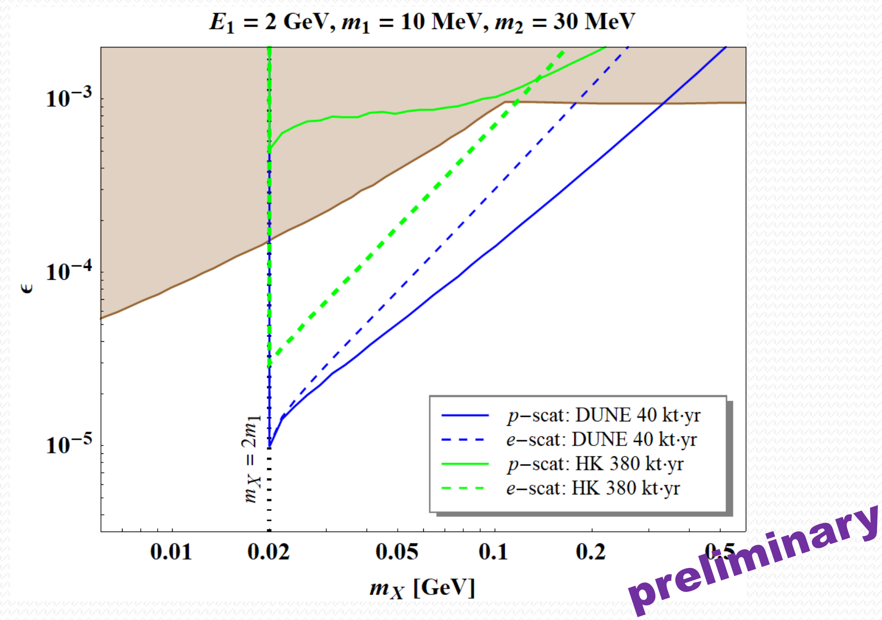
p-Scattering vs. e-Scattering: a HK-like Detector



- e-scattering preferred region is significantly extended because a proton needs enough kinetic energy to create Cherenkov radiation.
- Gray regions become much wider than corresponding results for DUNE due to the larger thresholds and angular resolution. ⇒ In order for HK to probe parameter space with small m_X and/or m_1, search strategies getting around these issues are motivated.

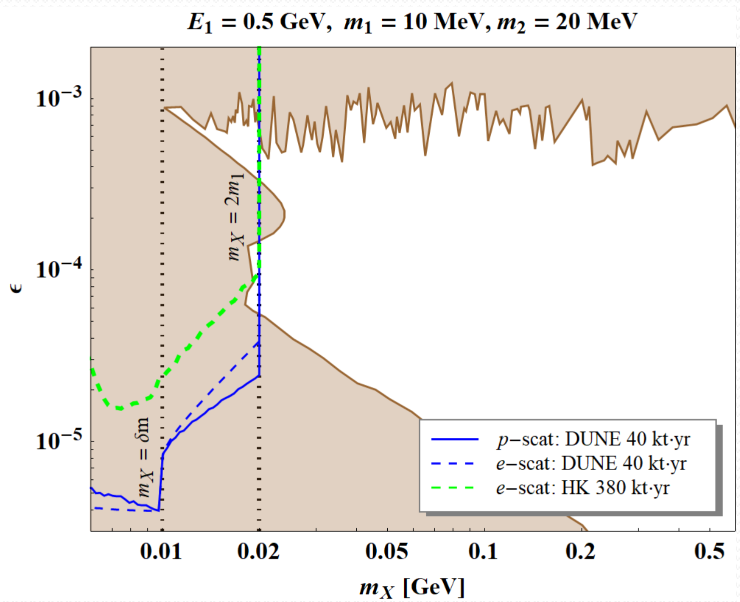
Exploring Dark Photon Parameter Space: HK vs. DUNE

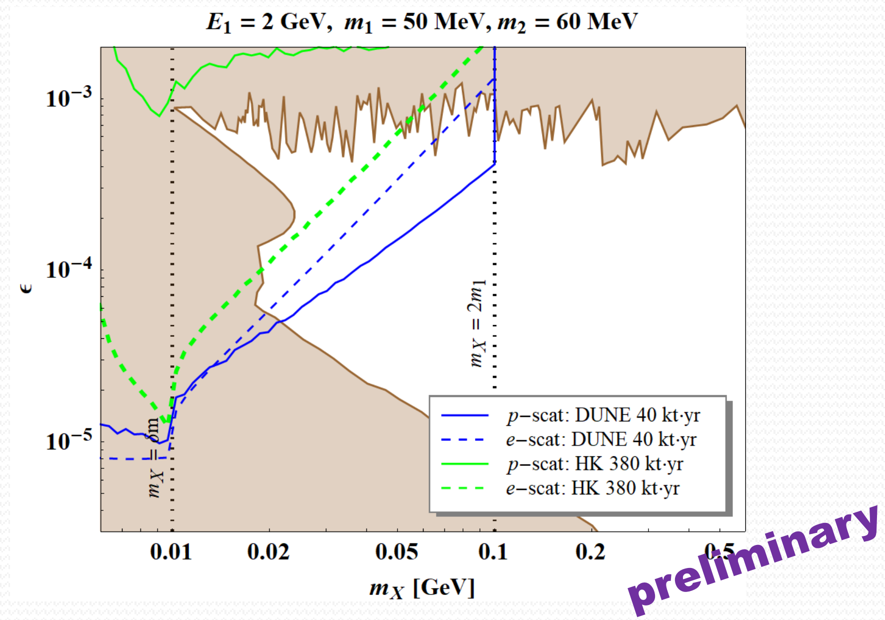




- ❑ The exclusion limits are for the case of $m_X > 2m_1$, but $\delta m = m_2 - m_1 < m_X$ so that χ_2 is guaranteed to decay visibly.
- ❑ p-scattering is advantageous than e-scattering in increasing m_X as expected.
- ❑ For larger E_1, the proton scattering channel in HK begins to cover some region of parameter space.
  - $\Rightarrow$ Better angular resolution, lower threshold energy would enable HK to cover more parameter space.

Exploring Dark Photon Parameter Space: HK vs. DUNE





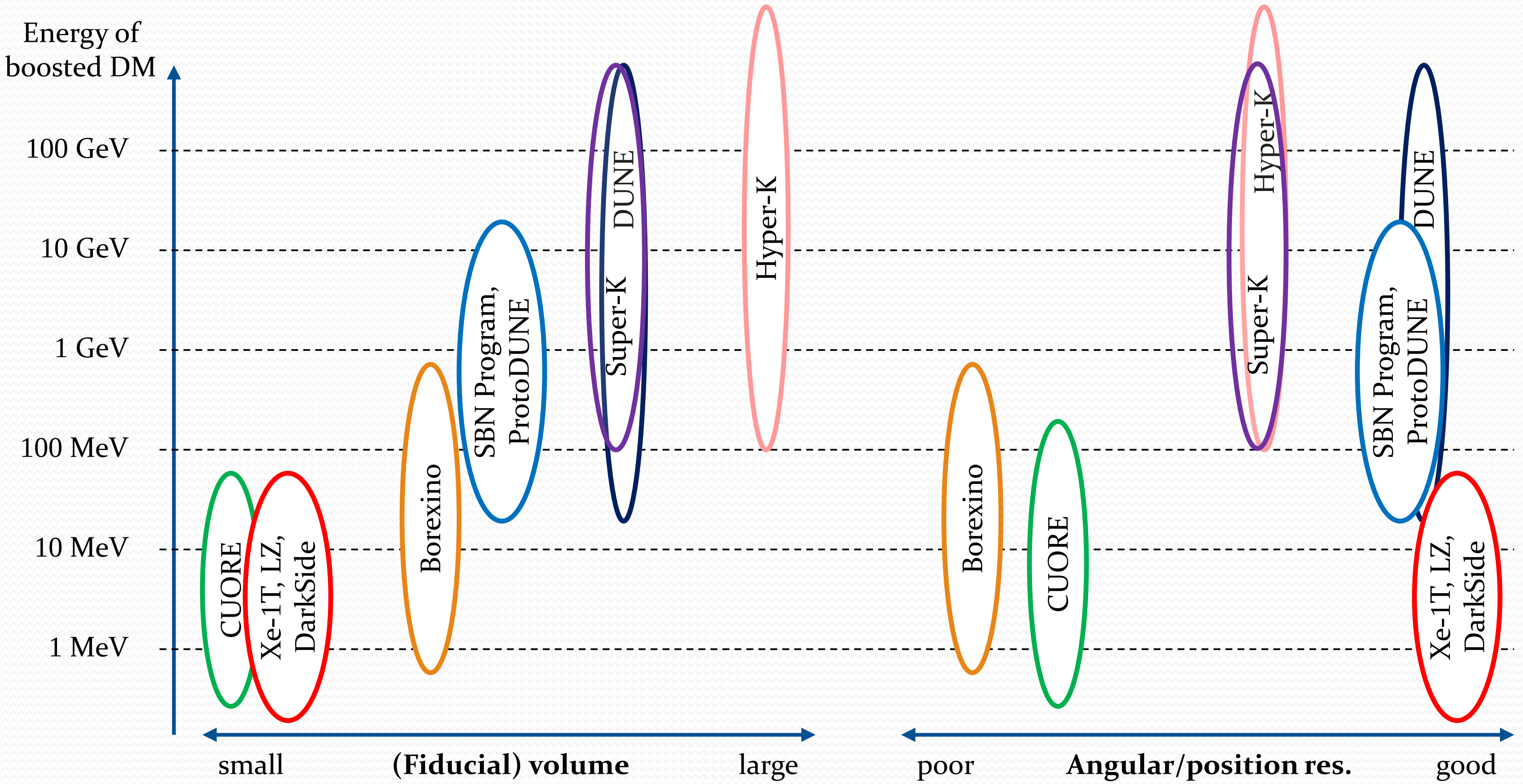
- The exclusion limits are for the case of $m_X < 2m_1$.
- p-scattering is advantageous than e-scattering in increasing m_X as expected.
- A transition happens at $\delta m = m_X$ where χ_2 decays to an e^-e^+ pair through on-shell $X \leftrightarrow$ off-shell X.
- For larger E_1, the proton scattering channel in HK begins to cover some region of parameter space.
  - $\Rightarrow$ Better angular resolution, lower threshold energy would enable HK to cover more parameter space.

Concluding Remarks

Search Proposals

- Example detectors and pheno. studies include
  - ✓ Super-K/Hyper-K [Huang, Zhao (2013); Agashe, Cui, Necib, Thaler (2014); Berger, Cui, Zhao (2014); Kong, Mohlabeng, Park (2014); Necib, Moon, Wongjirad, Conrad (2016); Alhazmi, Kong, Mohlabeng, Park (2016); **DK**, Park, Shin (2016); Aoki, Toma (2018); Ema, Sala, Sato (2018)]
  - ✓ DUNE [Necib, Moon, Wongjirad, Conrad (2016); Alhazmi, Kong, Mohlabeng, Park (2016); **DK**, Park, Shin (2016); Ema, Sala, Sato (2018); **DK**, Park, Shin (2019); Alhazmi, Dienes, **DK**, Kong, Park, Shin, Thomas, in progress]
  - ✓ IceCube/PINGU [Agashe, Cui, Necib, Thaler (2014); Bhattacharya, Gandhi, Gupta (2014); Kong, Mohlabeng, Park (2014); Kopp, Liu, Wang (2015); **DK**, Park, Park, Shin, in progress]
  - ✓ Dark Matter detectors (Xenon1T, LZ, etc) [Cherry, Frandsen, Shoemaker (2015); Giudice, **DK**, Park, Shin (2017); Bringmann, Pospelov (2018)]
  - ✓ Surface-based detectors (e.g., ProtoDUNE, SBN etc) [Chatterjee, De Roeck, **DK**, Moghaddam, Park, Shin, Whitehead, Yu (2018), **DK**, Kong, Park, Shin (2018)]

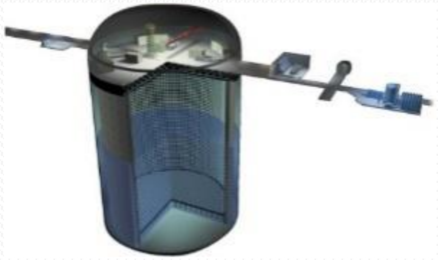
BDM Searches in Various Experiments

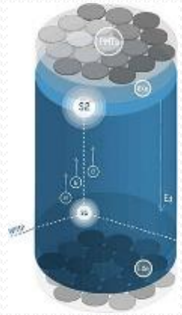


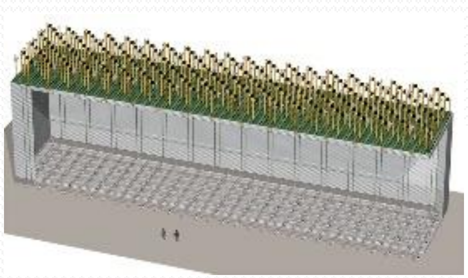
Detectors are **complementary** to one another rather than superior to the others!

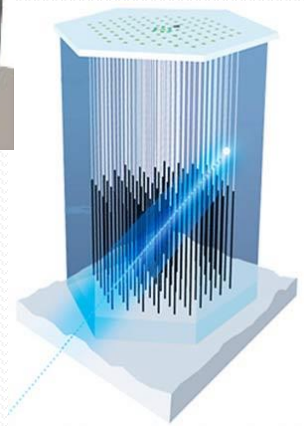
Conclusions

- ❑ Elastic/inelastic boosted dark matter searches are receiving rising attention not only theoretically but experimentally.
- ❑ Super-Kamiokande and COSINE-100 Collaborations performed the first searches for elastic BDM and inelastic BDM, respectively. No evidence is found yet, constraining BDM parameter space.
- ❑ There are **many** ongoing/projected **large-volume neutrino/dark matter experiments** in which BDM models can be tested.
- ❑ Search strategies and analysis designs **depend on models to explore**.
  - ✓ Elastic vs. inelastic BDM
  - ✓ Proton vs. electron scattering channels
  - ✓ High-performance detectors are better for signals with many features.





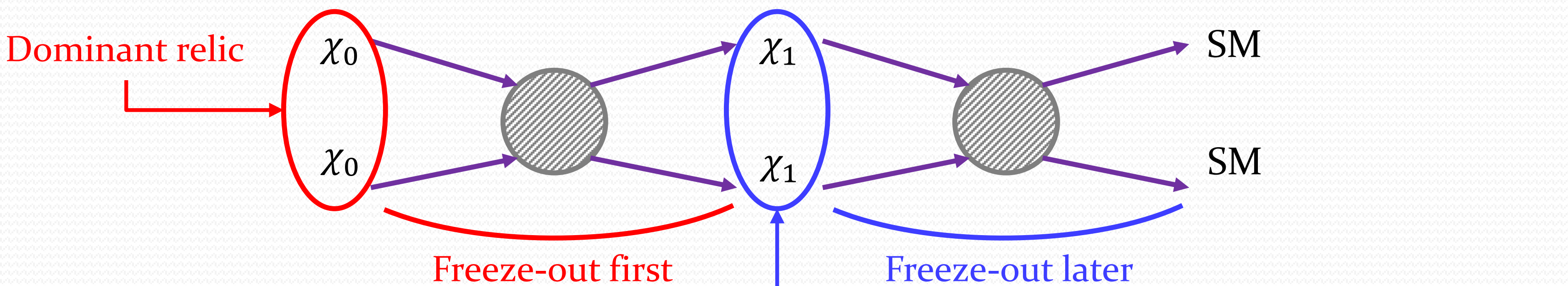


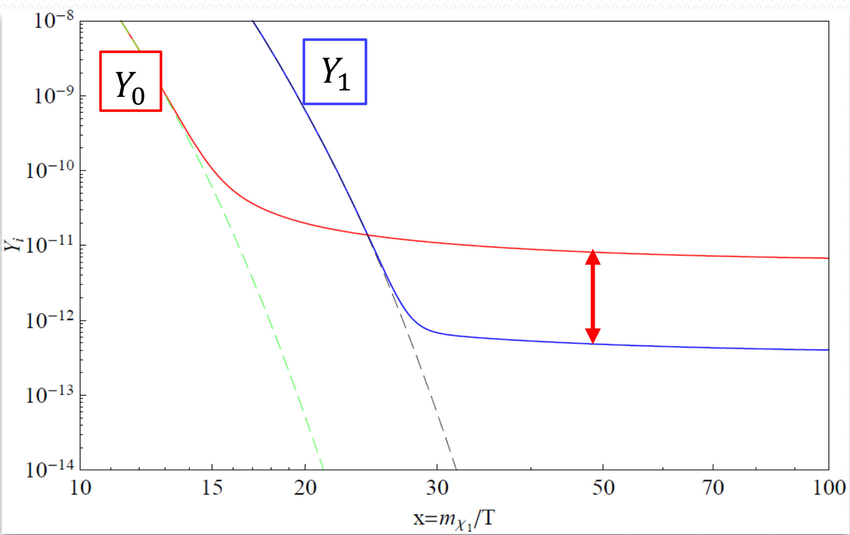


Backup

Two-component Boosted DM Scenario

- A possible relativistic source: BDM scenario (cosmic frontier), stability of the two DM species ensured by separate symmetries, e.g., $Z_2 \otimes Z_2'$, $U(1) \otimes U(1)'$, etc.

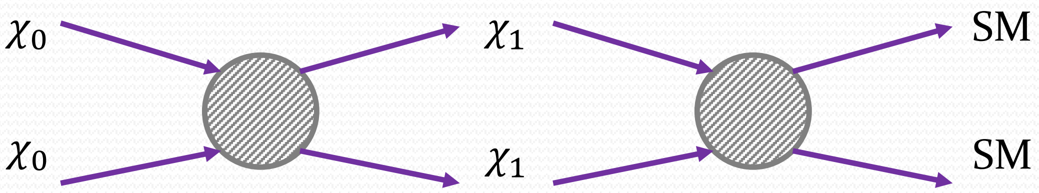




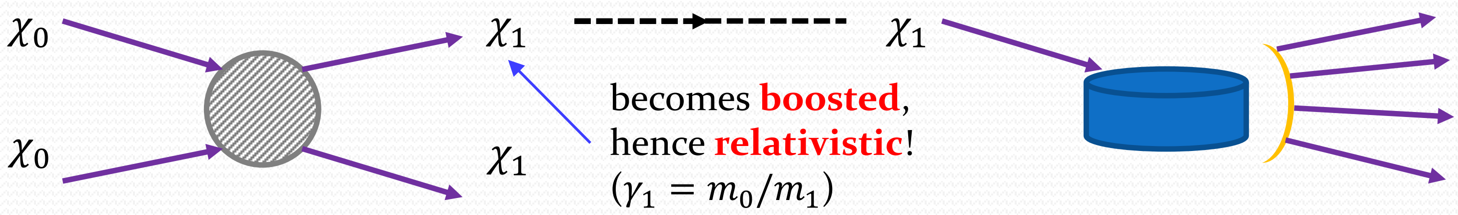
<u>"Assisted" freeze-out</u> mechanism

[Belanger, Park (2011)]

Motivation for BDM



- ✓ Heavier relic χ_0: hard to detect it due to tiny/negligible coupling to SM
- ✓ Lighter relic χ_1: hard to detect it due to small amount



(Galactic Center in the present universe) (Laboratory)

[Agashe, Cui, Necib, Thaler (2014)]

Other Mechanisms

- Boosted dark matter from decaying dark matter [Bhattacharya, Gandhi, Gupta (2014); Kopp, Liu, Wang (2015); **DK**, Park, Park, Shin, in progress]
- Semi-annihilation in e.g., Z_3 models [D'Eramo, Thaler (2010)]
- Fast-moving DM via induced nucleon decays [Huang, Zhao (2013)]
- Energetic cosmic-ray-induced (semi-)relativistic dark matter scenarios [Yin (2018); Bringmann, Pospelov (2018); Ema, Sala, Sato (2018)]

SK Signal Efficiency

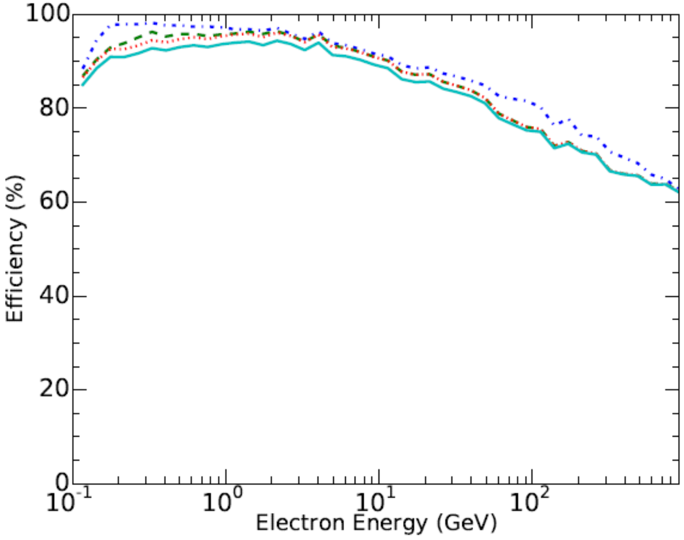
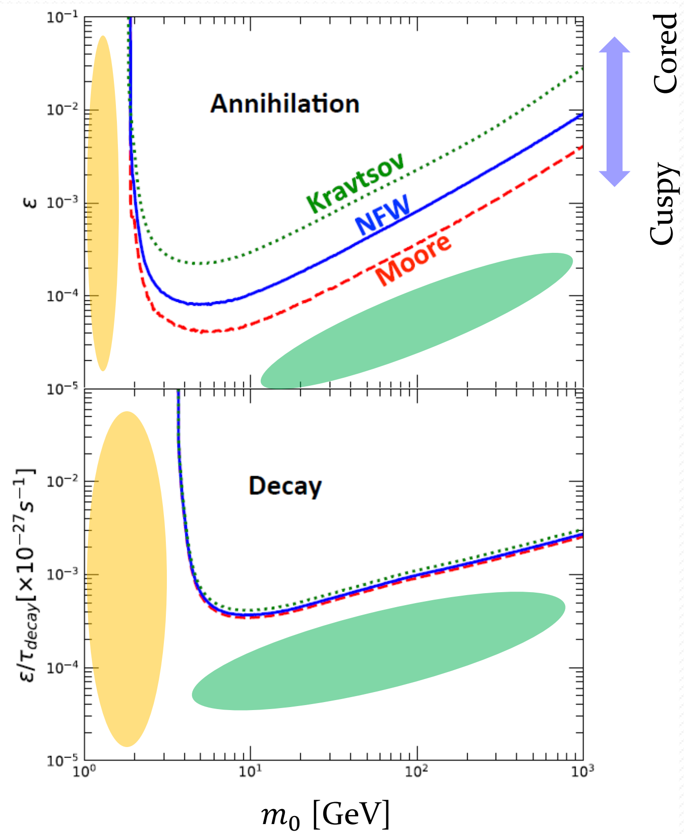


FIG. 1. Signal efficiency of the FCFV selection and analysis cuts as a function of energy. Beginning with the FCFV selection (dashed-dotted blue), the addition of the 1-ring (for E_{vis} <100GeV, dashed green), e-like (dotted red) and finally 0 decay electrons and 0 tagged neutrons cuts to arrive at the final efficiency (solid cyan) are shown. The efficiency of the 0 decay electrons cut is $> 99.99\%$, so that the drop from the dotted red line to solid cyan line is due solely to the neutron tagging cut.

Interpretation: Experimental Sensitivity in Dark Gauge Boson Models



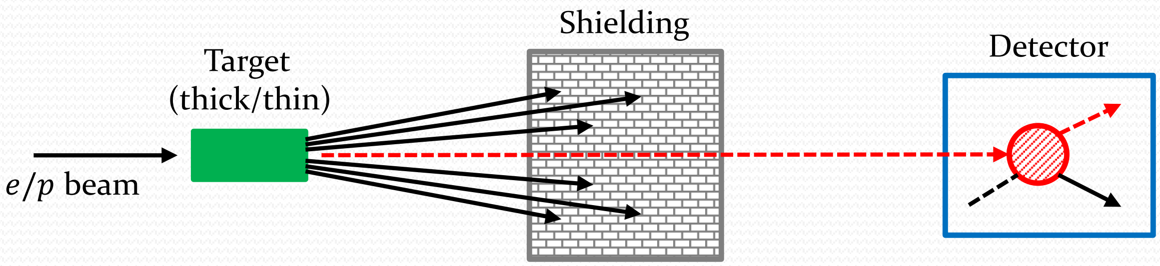
Mass of dominant halo DM

FIG. 3. 90% Confidence Interval upper limits for m_B=200 MeV, m'_γ=20 MeV, and g'=0.5, for boosted dark matter produced by annihilation (top) and decay (bottom).

- Recoil electron in most events is hard to exceed 100 MeV.
- Signal flux is varying by $\sim 1/m_0^2$ in the annihilation case and by $\sim 1/m_0$ in the decay case.
- Dark matter scenarios with cuspy halo profiles are more constrained in the annihilation case, while the decay case is less sensitive to profiles. $\Leftarrow$ The flux of the annihilation case is proportional to $n_{\rm DM}^2$.

Complementarity: Relativistic DM Searches in Fixed Target Exp.

- Signals coming from particle accelerators, additional model building not always necessary
- If dark sectors (containing dark matter) are more "weakly" connected to the SM sector, high intensity experiments such as fixed target experiments are also motivated.
    - ✓ BDX, NA64, MicroBooNE, SeaQuest, LDMX, T2HKK, DUNE, SHiP, and many more



- Similar/related searches are possible. ⇒ **Complementarity**!
- Quite a few phenomenological studies/proposals in the context of dark gauge boson decays, DM scattering via scalar/vector portal, etc. [LoSecco et al. (1980); Bjorken, Essig, Schuster, Toro (2009); Batell, Pospelov, Ritz (2009); deNiverville, Pospelov, Ritz (2011), and many more]

Relativistic DM Search at Cosmic vs. Intensity Frontiers

- Similarities
  - ✓ Relativistic DM searches (vs. non-relativistic DM searches in conventional DM direct detection experiments)
  - ✓ Experimental signatures, e.g., electron/proton recoil
- Differences
  - ✓ Physical interpretations: DM production and DM detection are governed by the same physics in fixed target experiments (e.g., minimal model), whereas boosted DM production mechanism is often independent of DM detection in BDM searches.
  - ✓ Indirect probe vs. direct probe for halo DM: Boosted DM in two-component BDM scenarios is not dominant halo dark matter, while DM in fixed target experiments may be cosmological dark matter.
  - ✓ Nevertheless, the observation of a subdominant component in BDM allows to obtain hints to the origin of boosted DM, e.g., cosmological DM mass, $\langle \sigma v \rangle_{\chi_0 \chi_0 \to \chi_1 \chi_1}$, DM halo profile etc.

Interpretations: Model-Independent Sensitivity

- **Non-trivial** to find appropriate parameterizations for providing **model-independent reaches** due to many parameters involved in the model
- Experimental sensitivity with e.g., 90% C.L.

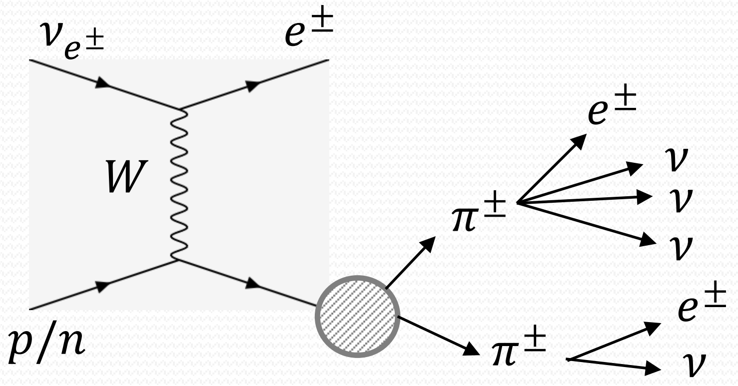
$$\Rightarrow N_{\text{sig}} = \sigma_\epsilon \mathcal{F} A t_{\text{exp}} N_e > N^{90}$$

- σ_ϵ: scattering cross section between χ_1 and (target) electron
- $\mathcal{F}$: flux of incoming boosted χ_1 (possibly BDM production mechanism-dependent)
- A: acceptance
- t_{exp}: exposure time
- N_e: total # of target electrons
- N^{90}: 90% C.L. for a given background assumption

Determined by distance between the primary (ER) and the secondary vertices, cuts, energy threshold, etc. Depending on analyses, some factors can be absorbed into σ_ϵ.

Expected Number of ν-Induced Background Events

- Atm.-ν may induce multi-track events (which could be backgrounds)
- The dominant source
  - ✓ **ν_e-induced C.C.** events

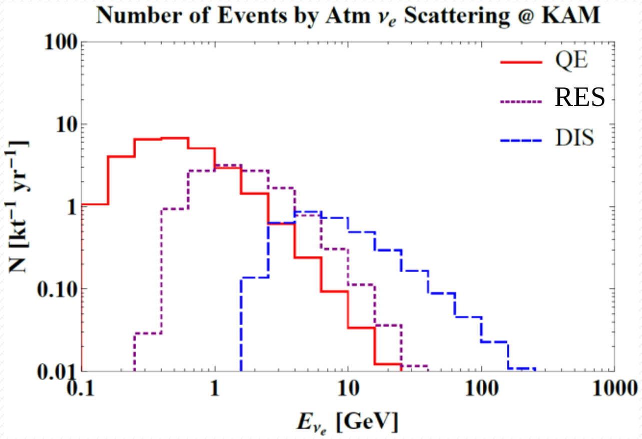


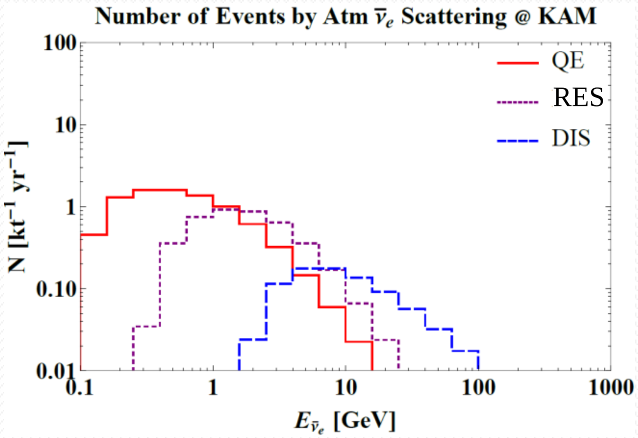
e.g. $\pi^\pm \to \mu^\pm \nu \to e^\pm \nu\nu\nu$, $\pi^\pm \to e^\pm \nu$

- Other subdominant sources
  - ✓ N.C. events: smaller cross section
  - ✓ ν_τ-induced: too small flux, hence negligible
  - ✓ ν_μ-induced C.C.: leaving an energetic (primary) muon (which can be tagged easily)

Expected Number of ν-Induced Background Events

- ν_e-flux [SK Collaboration, 1502.03916] ⊗ ν_e-cross section [Formaggio, Zeller, 1305.7513]





- Most DIS events result in messy final states, not mimicking signal events, while a majority of resonance events may create a few mesons in the final state [Formaggio, Zeller, 1305.7513].
  - ⇒ **12.2** events/kt/yr are potentially relevant.
  - ⇒ (quality) track-based particle identification, timing information etc at LArTPC detectors can suppress such events significantly. → **Zero BG is achievable**!

Recent, Related Effort in Particle Accelerator Experiments

- LHC
  - ✓ Monojet + displaced pions coming from the decay of the excited state [Bai, Tait (2011)]
  - ✓ Search for (semi-)long-lived excited dark-sector states [Berlin, Kling (2018)]
- Lepton colliders
  - ✓ Belle-II [Izaguirre, Kahn, Krnjaic, Moschella (2017)]
- Fixed target experiments
  - ✓ Relativistic dark matter-induced signature involving target recoil + electron-positron pair from the decay of the excited state [Izaguirre, Krnjaic, Schuster, Toro (2014)], LDMX, BDX, MiniBooNE [Izaguirre, Kahn, Krnjaic, Moschella (2017)], SeaQuest [Berlin, Gori, Schuster, Toro (2018)]

- Different platforms are sensitive to different parameter regions. ⇒ Complementarity!

Inelastic Scattering Event Topology

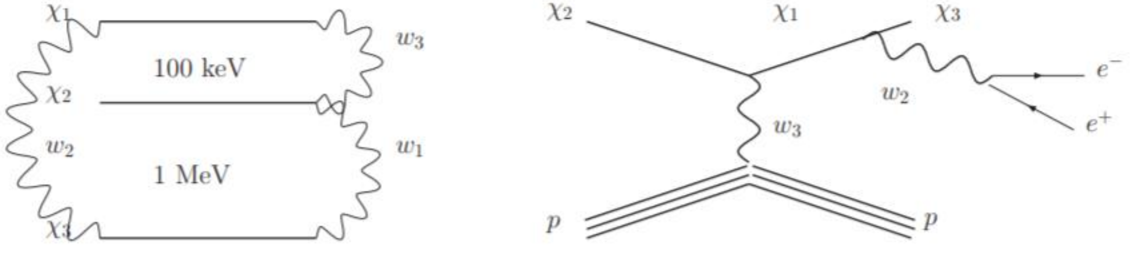


Figure 3: On the left pane we show the splittings induced in the $SU(2)$ triplet by radiative corrections, as well as all the relevant couplings. The mixing of the w_1 gauge boson to the SM hypercharge is further suppressed compared with the mixing of w_2 and w_3. This leads to the possibility of deexcitation processes that can be seen in direct detection experiments. The inelastic scattering off nuclei is depicted on the right.

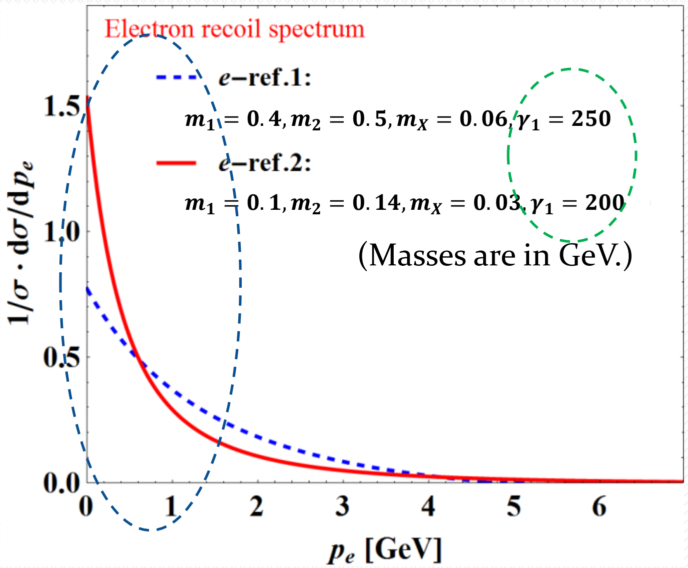
[Finkbeiner, Slatyer, Weiner, Yavin (2009)]

Generic Features: *e*-scattering - Cross Section

$$\frac{d\sigma}{dE_T} = \frac{m_T}{8\pi\lambda(s, m_T^2, m_1^2)} \frac{8(\epsilon e g_{12})^2 m_T}{\{2m_T(E_2 - E_1) - m_X^2\}^2} \left[m_T(E_1^2 + E_2^2) - \frac{(m_2 - m_1)^2}{2}(E_2 - E_1 + m_T) + m_T^2(E_2 - E_1) + m_1^2 E_2 - m_2^2 E_1 \right]$$

From PS, same for elastic scattering

From matrix element, expression for elastic scattering in the limit of $m_2 \to m_1$



- ❑ A **large boost factor** is preferred to access heavier dark sector states.
- ❑ Cross section is **peaking towards lower energy** electron recoil. (The generic trend is relevant to elastic scattering.)

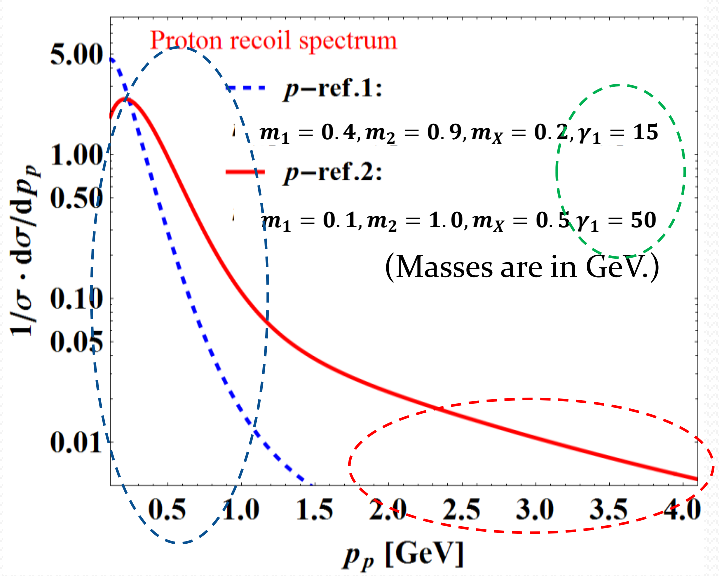
Generic Features: *p*-scattering - Cross Section

$$\frac{d\sigma}{dE_T} = \frac{m_T}{8\pi\lambda(s, m_T^2, m_1^2)}\overline{|\mathcal{M}|}^2$$

$$\overline{|\mathcal{M}|}^2 = \frac{8(\epsilon e g_{12})^2 m_T}{\{2m_T(E_2 - E_1) - m_X^2\}^2} \times \left[\mathcal{M}_0(F_1 + \kappa F_2)^2 + \mathcal{M}_1\left\{-(F_1+\kappa F_2)\kappa F_2 + \frac{(\kappa F_2)^2}{4m_T}(E_1 - E_2 + 2m_T)\right\}\right] . \quad (2)$$

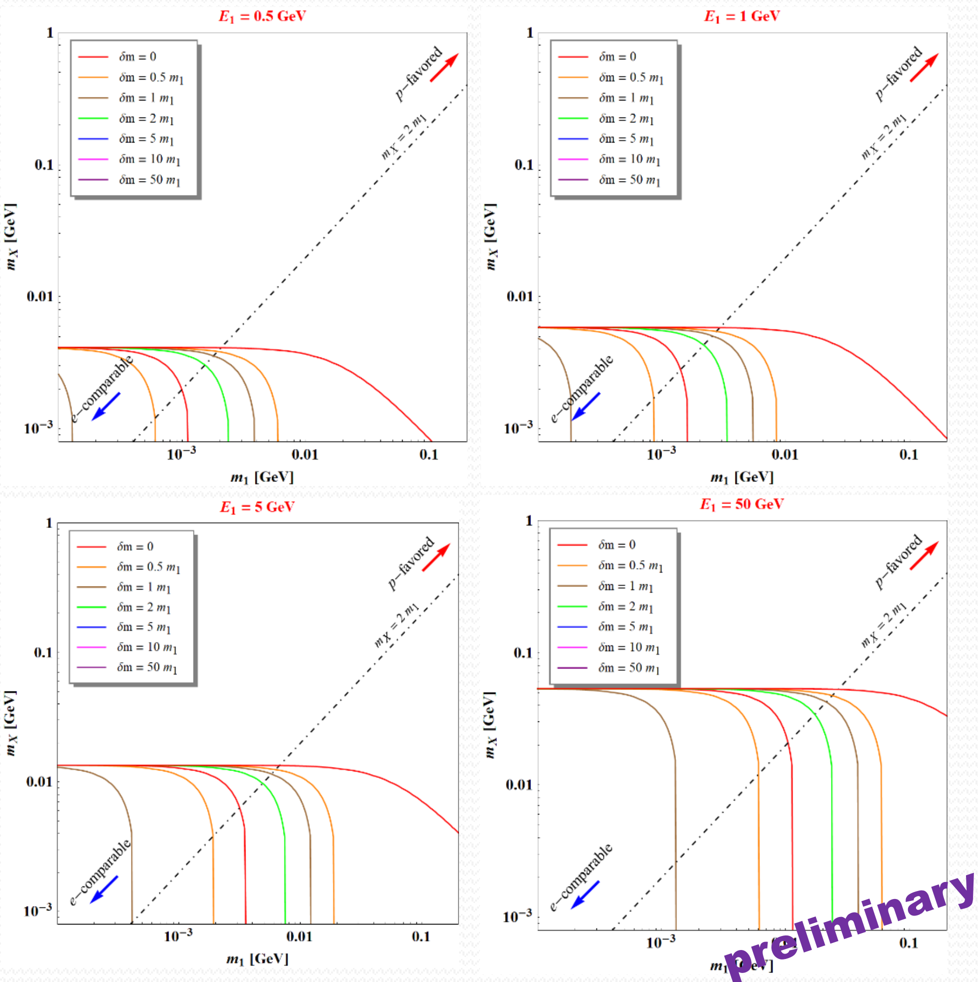
$$\mathcal{M}_0 = \left[m_T(E_1^2 + E_2^2) - \frac{(\delta m)^2}{2}(E_2 - E_1 + m_T) + m_T^2(E_2 - E_1) + m_1^2 E_2 - m_2^2 E_1\right] , \quad (3)$$

$$\mathcal{M}_1 = m_T\left[\left\{(E_1 + E_2) - \frac{m_2^2 - m_1^2}{2m_T}\right\}^2 + (E_1 - E_2 + 2m_T)\left\{(E_2 - E_1) - \frac{(\delta m)^2}{2m_T}\right\}\right] , \delta m \equiv m_2 - m_1 \quad (4)$$



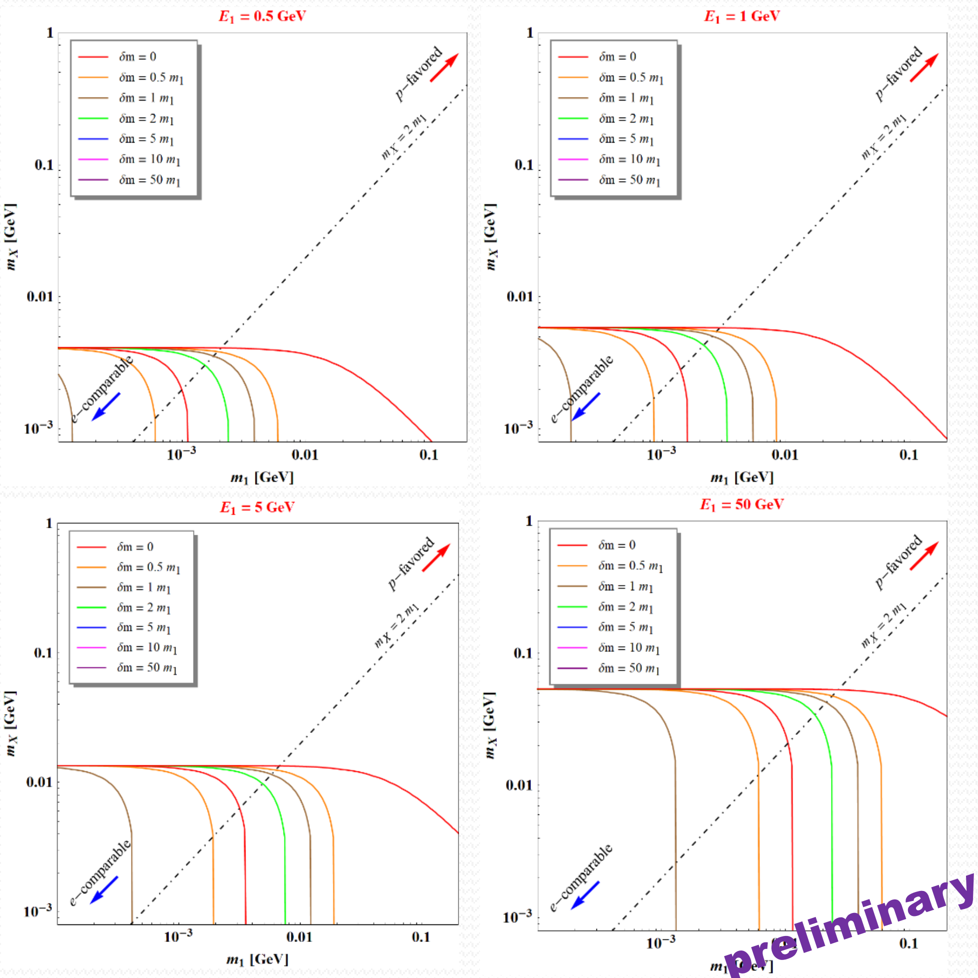
- A large boost factor is **not necessary** to access heavier dark sector states.
- Cross section is **peaking towards lower energy** proton recoil, while **high energy recoil regime** where DIS becomes relevant is negligible for small m_X (cf. for large m_X, the behavior becomes similar to that for neutrino scattering). ⇐ **large momentum transfer suppression** via the dark photon propagator.
- DIS-induced messy final states mostly come from backgrounds!

p-Scattering vs. e-Scattering: Theory Level



- A "perfect" detector (no resolution issue, no energy threshold, secondary decay appearing inside the detector) is assumed, only with $p_p < 2$ GeV taken into consideration.
- Boundaries are defined by $\sigma_{\chi_1 e} = 0.9\sigma_{\chi_1 p}$ as the p-scattering cross section is at least slightly greater than the e-scattering over the region of interest.

p-Scattering vs. e-Scattering: Moral



- If a BDM search hypothesizes a heavy dark photon (say, sub-GeV range), the proton channel may expedite discovery.
- If a model conceiving inelastic BDM (iBDM) signals allows for large mass gaps between χ_1 and χ_2, the proton channel is more advantageous.
- On the other hand, the electron channel becomes comparable/complementary in probing the parameter regions with smaller m_1 and m_X.
- As the boosted χ_1 comes with more energy, more parameter space where the electron channel is comparable opens up.