Light Hidden Sector Search

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AstroCeNT
NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES
NCBJ
National Science Centre Poland
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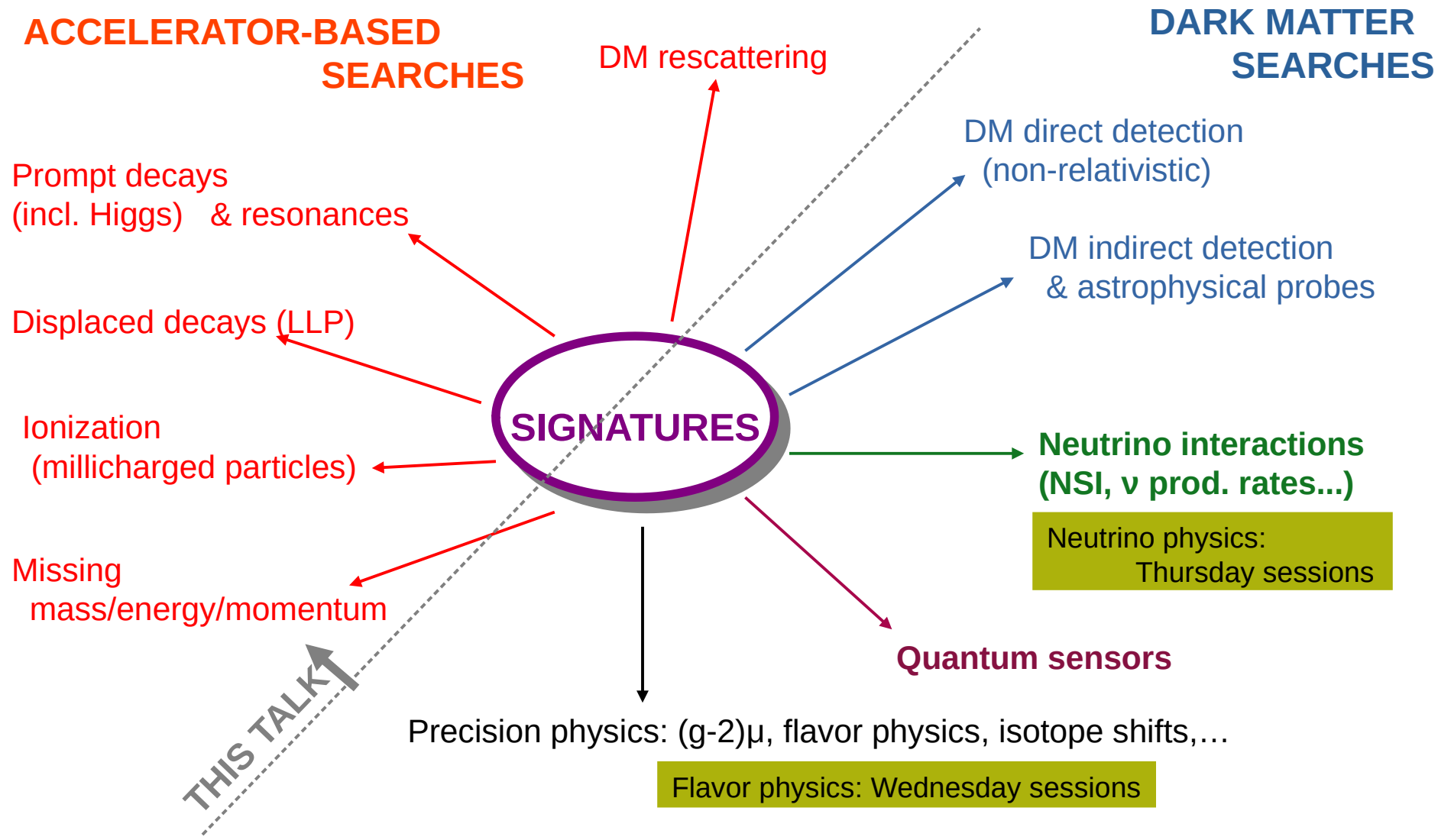
Dark Wave

MULTIPLE SIGNATURES



Snowmass 2021: hep-ex/2206.04220

EXPERIMENTAL LANDSCAPE (ACCELERATOR)

Experiment	Facility	Beam Config	Beam Energy	Det Signature	Timeline
US-based					
HPS	CEBAF @ JLab	electron FT	1-6 GeV	LLP	running
COHERENT	SNS @ ORNL	proton FT	1 GeV	rescattering	running
CCM	LANSE @ LANL	proton FT	0.8 GeV	rescattering	running
SpinQuest/DarkQuest	MI @ FNAL	proton FT	120 GeV	LLP	construction, proposed upgrade
LDMX	LESA @ SLAC	electron FT	4-8 GeV	Missing X	R&D funding, 2024
BDX	CEBAF @ JLab	electron BD	11 GeV	rescattering, Millicharged	proposed
JPOS	CEBAF @ JLab	positron FT	11 GeV	Missing X	proposed
PIP-II BD	PIP-II @ FNAL	proton FT	1 GeV	rescattering, LLP	proposed (2029)
SBN-BD	Booster @ FNAL	proton BD	8 GeV	rescattering	proposed (2029)
REDTOP	TBD	proton FT	1-5 GeV	Missing X, LLP, Prompt	proposed
M^3	MI @ FNAL	muon FT	15 GeV muons	Missing X	proposed
FNAL-μ	muon campus @ FNAL	muon FT	3 GeV	LLP	proposed
International					
Belle-II	SuperKEKB @ KEK	e+e- collider	150 MeV	Missing X, LLP, Prompt	running
CODEX-β	LHC @ CERN	pp collider	6.5-7 TeV	LLP	construction (2023)
CODEX-b	LHC @ CERN	pp collider	6.5-7 TeV	LLP	proposed (2026)
LHCb	LHC @ CERN	pp collider	6.5-7 TeV	LLP, Prompt	running, future upgrade planned
NA62	SPS-H4 @ CERN	proton BD	400 GeV	LLP	dedicated running planned
FASERnu	LHC @ CERN	pp collider	6.5-7 TeV	rescattering	running
milliQAN	LHC @ CERN	pp collider	6.5-7 TeV	Millicharged	running
DarkMESA	MESA @ Mainz	Electron FT	150 MeV	rescattering, LLP	construction (2023)
NA64-e	SPS-H4 @ CERN	electron FT	100-150 GeV	Missing X, Prompt	running
NA64-mu	SPS-M2 @ CERN	muon FT	160-160 GeV	Missing X	commissioning
NA64/POKER	SPS-H4 @ CERN	positron FT	100 GeV	Missing X	planned (2024)
PIONEER	πE5 @ PSI	proton FT	10-20 MeV pions	Prompt	planned (2028)
FASER2	FPF @ CERN	pp collider	6.5-7 TeV	LLP	proposed (2029)
FORMOSA	FPF @ CERN	pp collider	6.5-7 TeV	Millicharged	proposed (2029)
FASERnu2	FPF @ CERN	pp collider	6.5-7 TeV	rescattering	proposed (2029)
FLArE	FPF @ CERN	pp collider	6.5-7 TeV	rescattering	proposed (2029)
SND@LHC	LHC @ CERN	pp collider	6.5-7 TeV	rescattering	running
Advanced SND@LHC	FPF	pp collider	6.5-7 TeV	rescattering	proposed (2029)

PROTOTYPE SCENARIO – DARK PHOTON

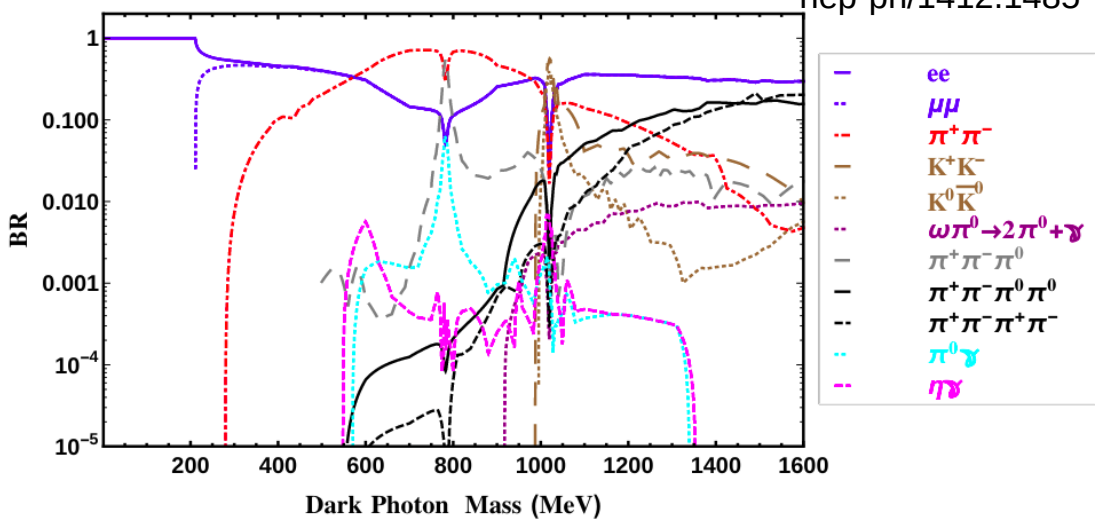
- New light (~sub-GeV) vector secluded from the SM, coupled via kinetic mixing
  (can be induced by heavy new fields at the loop level charged under both U(1) and $U(1)_D$)
- Suppressed couplings to SM fermions

- Dark photons can decay into SM fermions

- Lifetime depends on ε
  Decays can be PROMPT
  and DISPLACED

- Various final states are possible
  Below 500 MeV mass di-lepton
  final states e^+e^- & $\mu^+\mu^-$

hep-ph/1412.1485



LHCb

PROMPT DECAYS + RESONANCES & DISPLACED DECAYS

- Inclusive A' production + decay into di-muon pairs A' → $\mu^+\mu^-$
- Search for A' resonance excess over expected SM $\mu^+\mu^-$ backgrounds
- Both **PROMPT** and **DISPLACED** decays are studied

(Run 2 results: hep-ex/1710.02867 & 1910.06926)

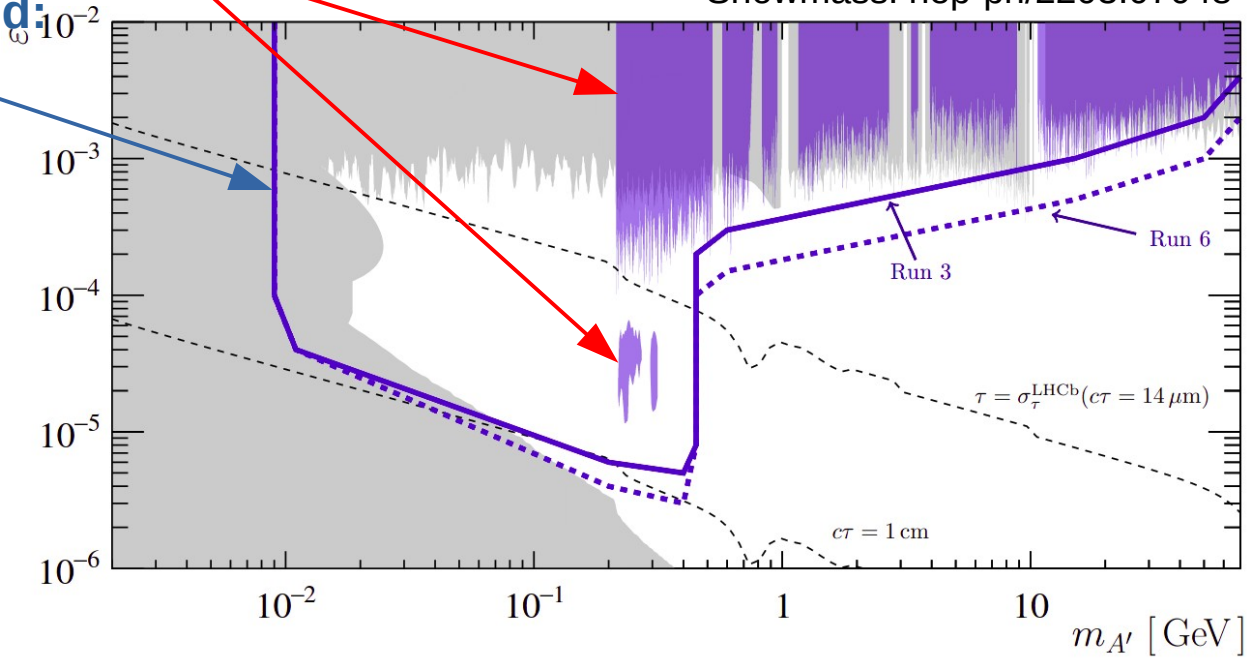
- **Substantial improvements possible in Run 3 and beyond:**

– electron identification in the high-level trigger allows to study A' → e^+e^-

– further improvement of the first level trigger (Allen)

physics.ins-det/1912.09161

Snowmass: hep-ph/2203.07048



PROMPT DECAYS + RESONANCES

OTHER BOUNDS

NA48/2, NA62 (past: hep-ex/1504.00607, future Run 3)

Large sample of tagged π^0 from kaon decays

Search for dark photon via

$$\pi^0 \to \gamma A', \; A' \to e^+e^-$$

BaBar (hep-ex/1406.2980)

Search for narrow resonances in $e^+e^- \to \gamma(e/\mu)^+(e/\mu)^-$

Dark photon: $e^+e^- \to \gamma A', A' \to e^+e^-, \mu^+\mu^-$

Expected bounds (selected):

- Belle-II

SuperKEKB e^+e^- collider

Data taking from 2019, upgrade (2022-23)

Expected 2-3 ab-1 in 2026

Full dataset 50ab^{-1} (100 x BaBar)

- Heavy Photon Search (HPS)

Few GeV electron fixed target

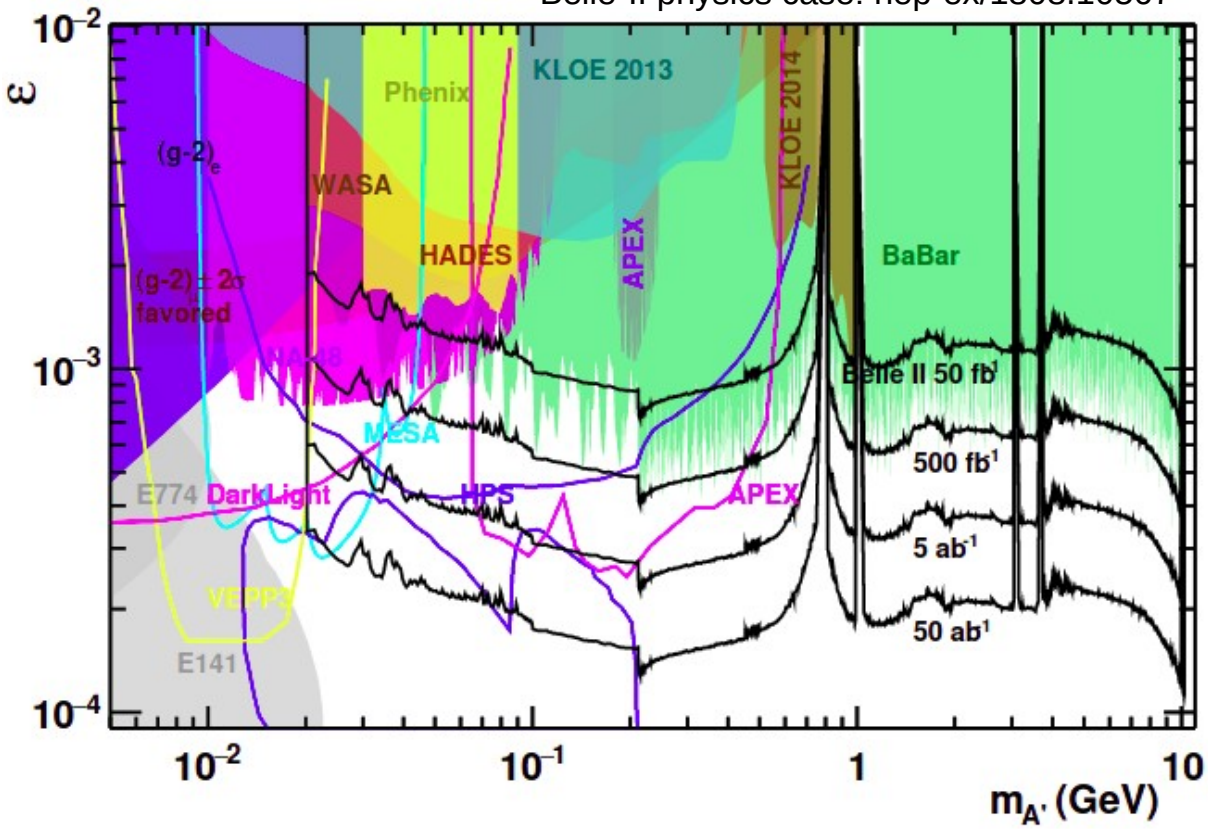
Thin target (<1% X_0)

Dark bremsstrahlung $e^- N \to e^- A' N$

followed by $A' \to e^+e^-$

Data taken in 2019 & 2021 + more to come

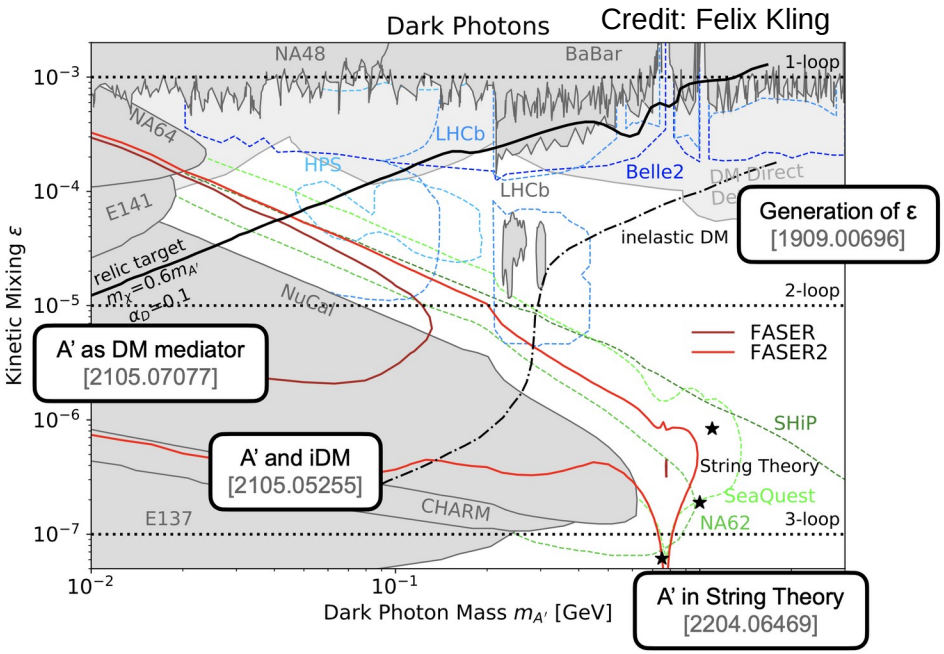
Belle-II physics case: hep-ex/1808.10567



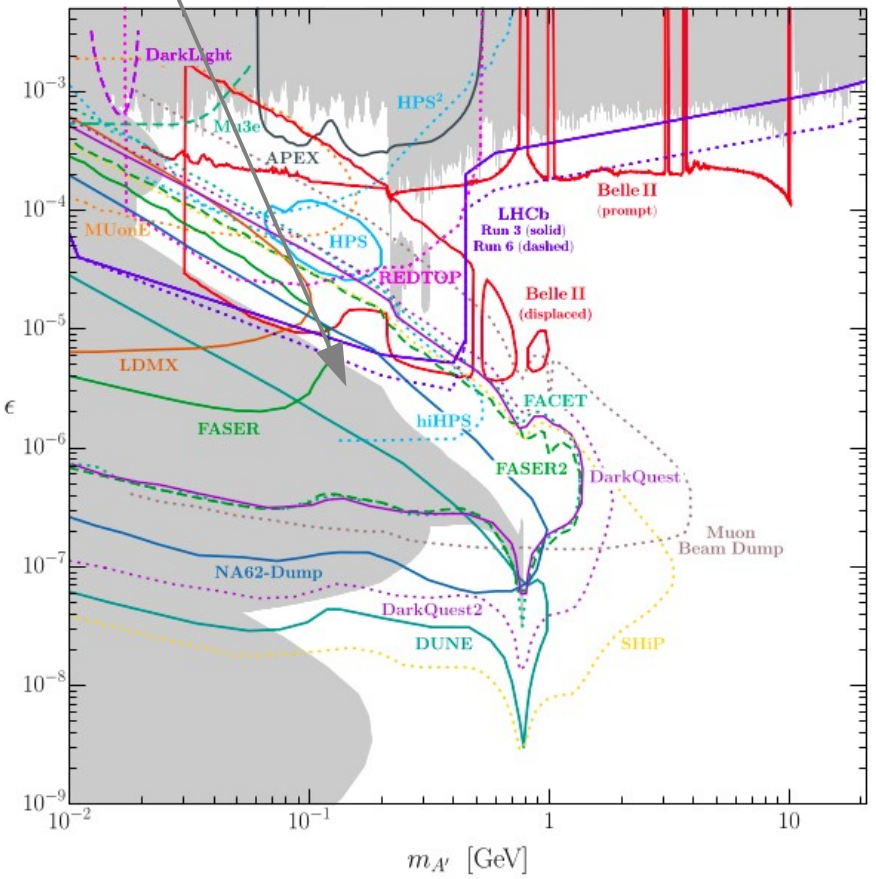
(HIGHLY) DISPLACED DECAYS

RACE FOR LOWER COUPLINGS

- Many past bounds (CHARM, E141, LSND, NuCal, Orsay, …)
- Multiple future experimental proposals (beam-dumps, collider, neutrino...)
- Interesting theory targets



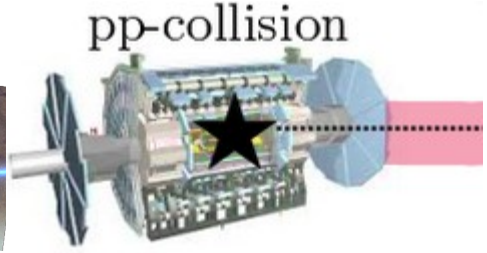
hep-ph/2207.06898



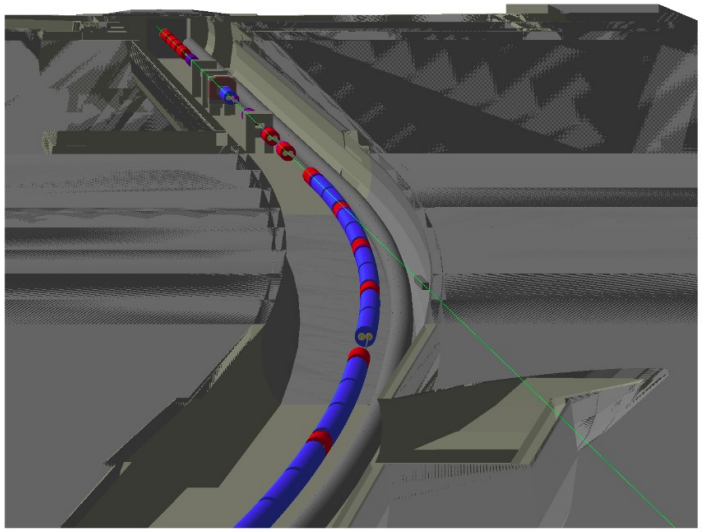
physics.ins-det/1812.09139
hep-ph/1811.12522
physics.ins-det/1811.10243
hep-ph/1708.09389

FASER

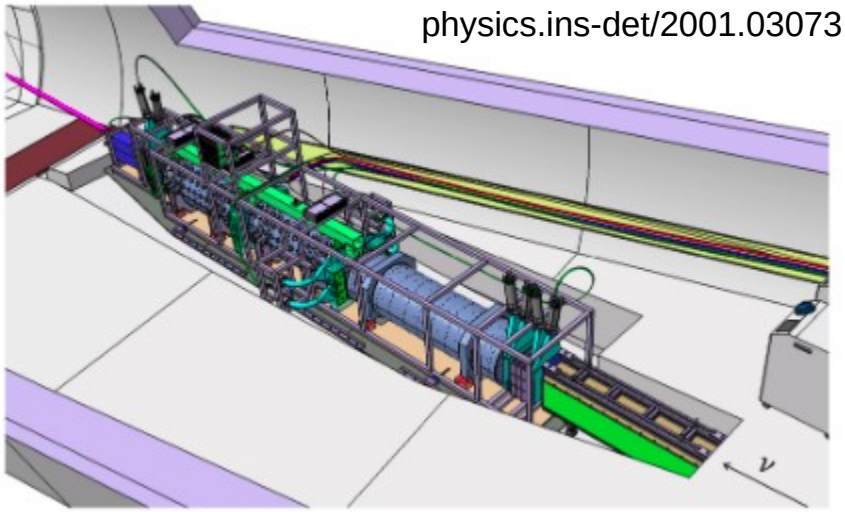
- Far-forward region of the LHC (~480m away from the ATLAS IP)



- Exploits large forward p-p scat. cross section
- High-intensity of pions π^0 etc.
  e.g. rare A' production ($\pi^0 \rightarrow A'\gamma$)
- Detection: $A' \rightarrow e^+e^-$



physics.ins-det/2001.03073



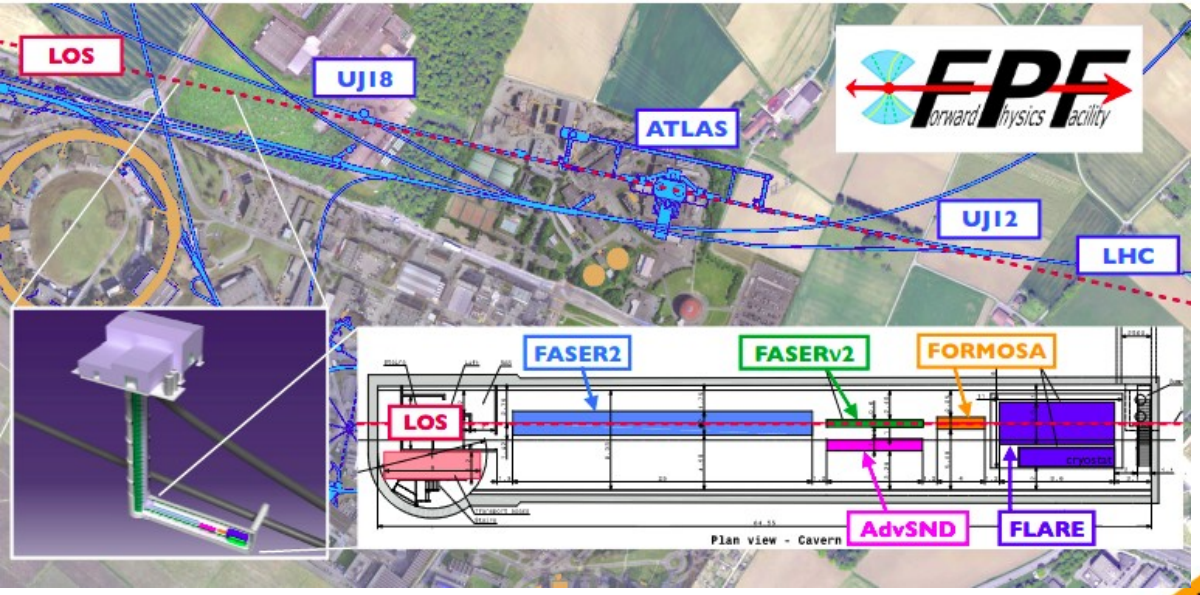
Data taking started with LHC Run 3

Preliminary study from Run 2 → first neutrino candidate events at the LHC

hep-ex/2105.06197

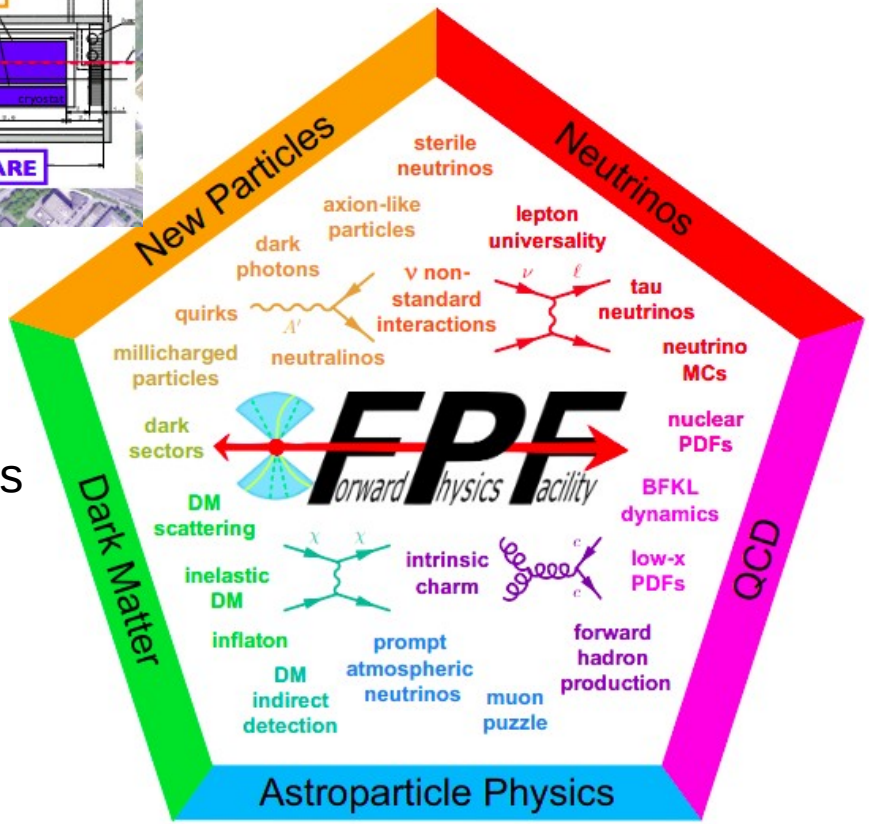
Snowmass: hep-ex/2203.05090
hep-ph/2109.10905

FORWARD PHYSICS FACILITY



- Proposed for the HL-LHC era
- New underground facility to host several experiments

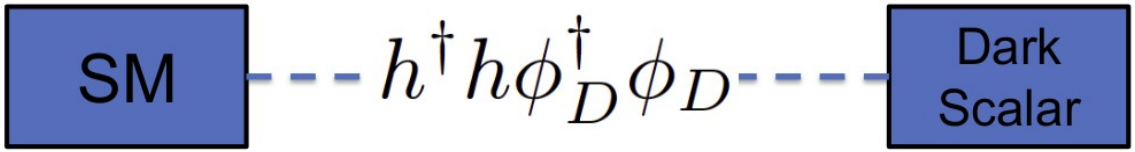
- Rich physics program for both SM and BSM
- FASER 2: search for dark photons and other light unstable species
- Light dark matter
- Neutrino physics & QCD
- Connections to astrophysics



(HIGHLY) DISPLACED DECAYS

LIGHT DARK SCALARS

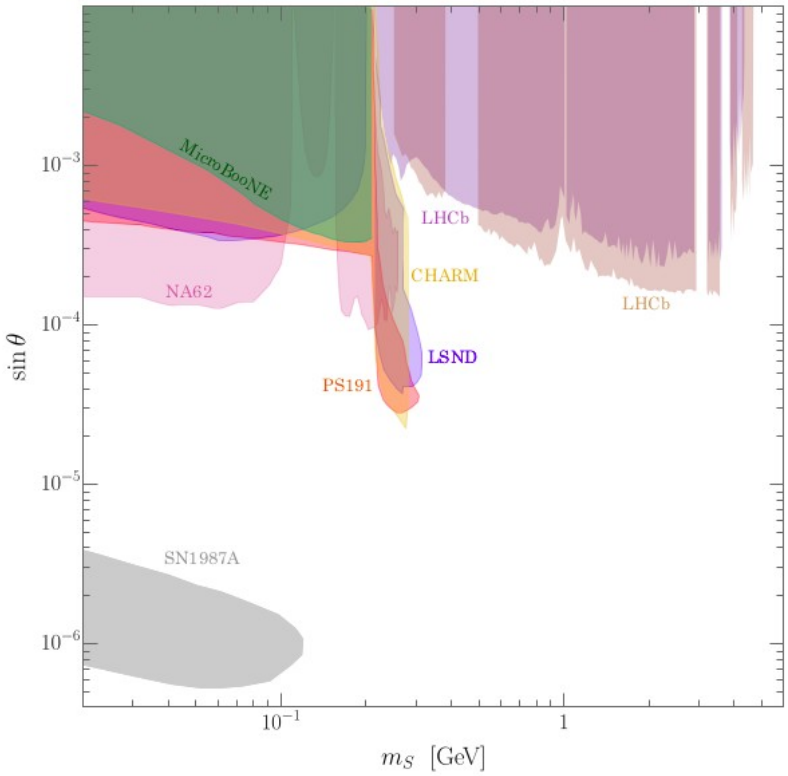
- Coupling to SM fermions
due to the mixing with the SM Higgs
- Mixing angle θ
- **Recent progress:**

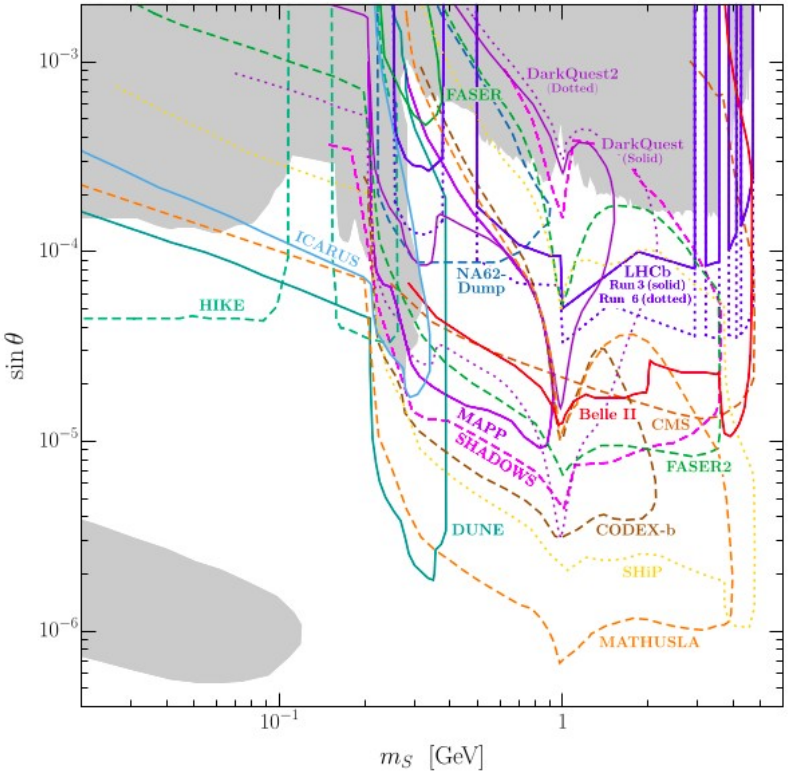


recast of past boounds from LSND (hep-ph/2004.14515, added bremsstrahlung) and PS191 (hep-ph/2105.11102)
MicroBooNE search for $K^+ \to \pi^+ S \to e^+e^-$ (hep-ex/2106.00568)

- Numerous future proposals

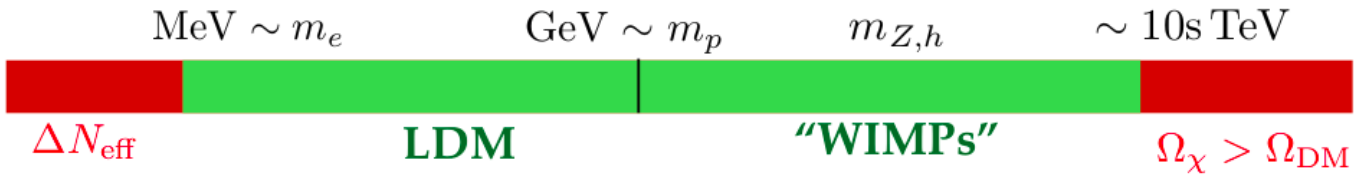
hep-ph/2207.06898





LIGHT DARK MATTER VIA DARK PHOTON

- Dark photon can also mediate interactions between the SM and a ``thermal'' DM relic χ
- Suppressed SM couplings of A' yield correct DM relic density for ~MeV-GeV χ **LDM**



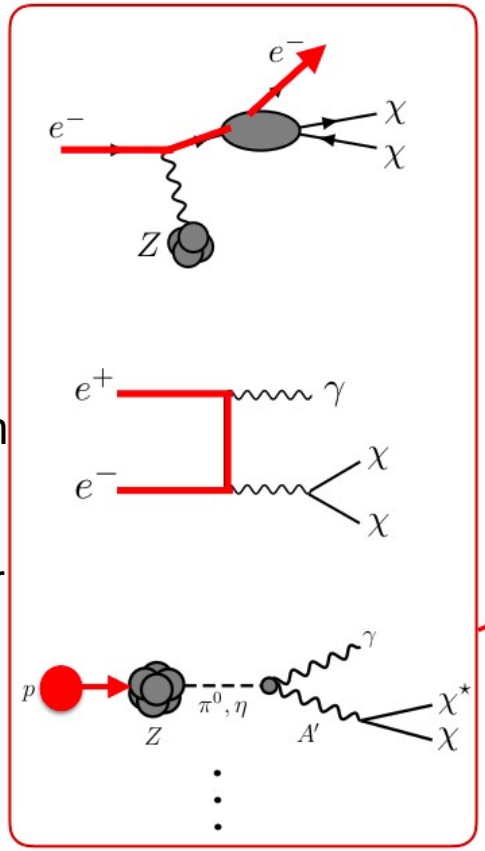
- If kinematically available A' can dominantly decay into two DM particles

  A' → χ χ

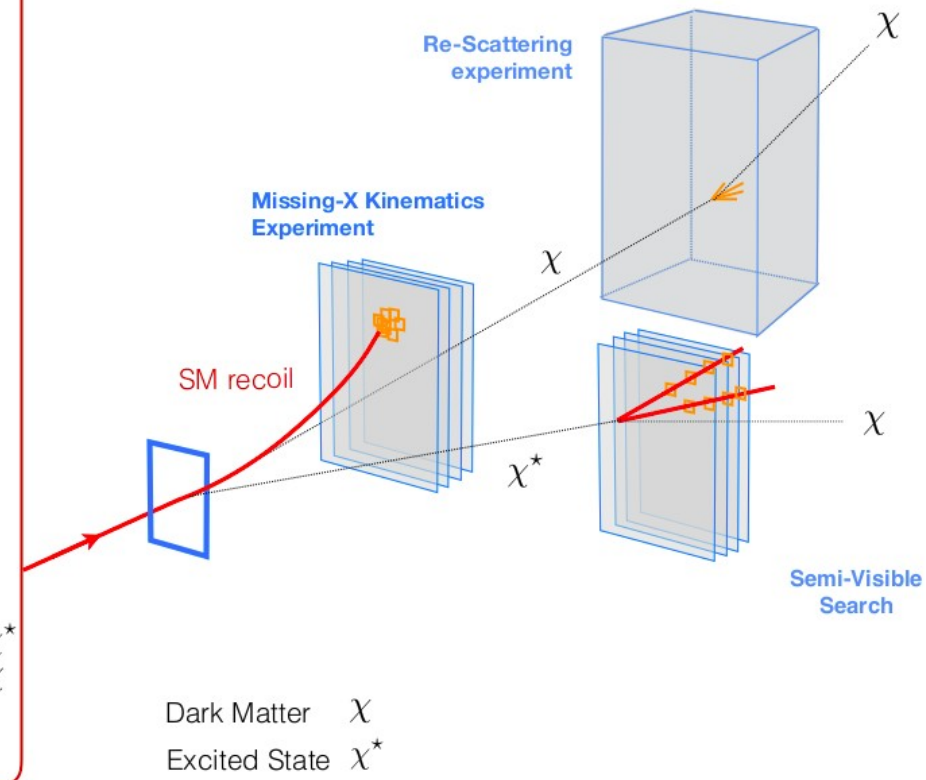
- This can be detected:

- as missing mass/energy/momentum

- via DM re-scatterings in a distant detector



Snowmass: hep-ph/2207.00597



MISSING X

BaBar, NA64

BaBar (hep-ex/1702.03327)

Single photon signature in $e^+e^- \rightarrow \gamma A'$, $A' \rightarrow \chi\chi$ (inv.)

Missing mass: initial 4-momenta known,
final-state photon momentum reconstructed

to be improved by Belle-II

NA64 (1906.00176)

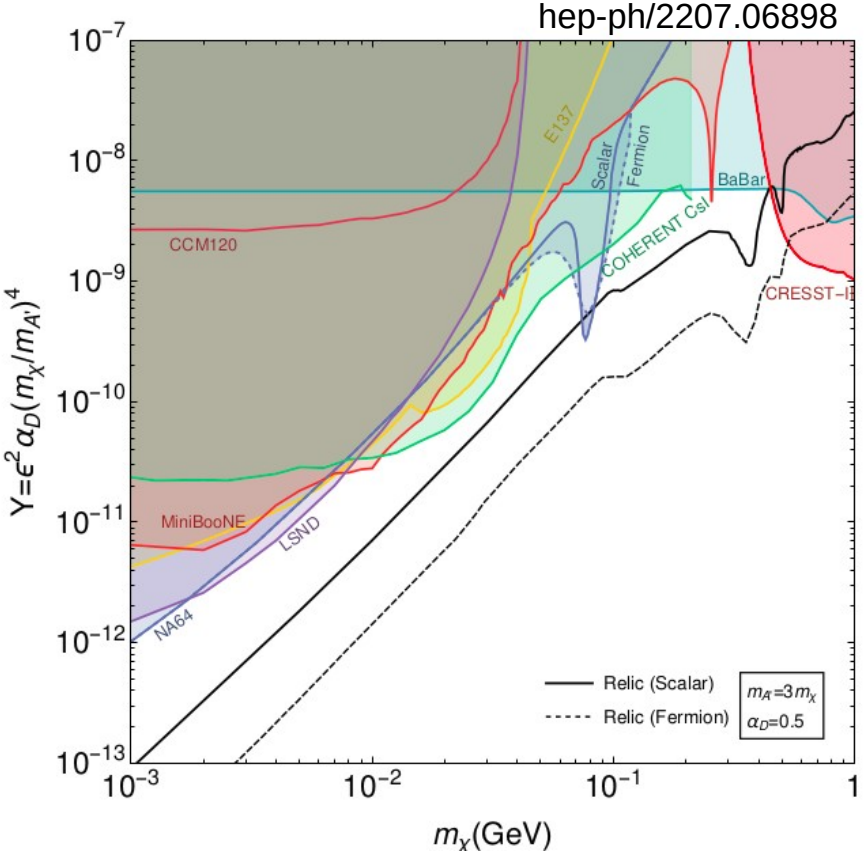
Electron beam-dump (SPS, primary p beam)

Dark photon bremsstrahlung $e^- Z \rightarrow e^- A' Z$
& $A' \rightarrow \chi\chi$

Missing energy:
final-state Z momentum unknown…
but it carries away a very small fraction of E
so it has negligible impact on E budget

First runs: 2016-18,
Current run 2021-22

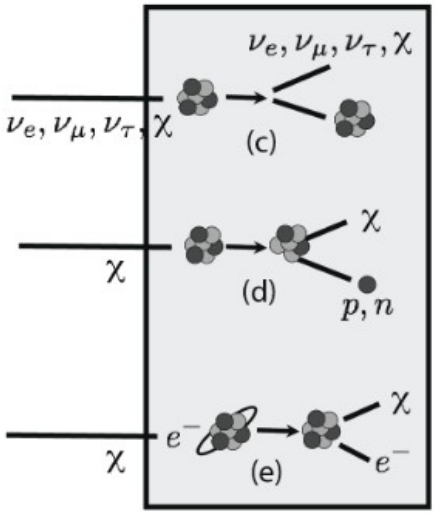
hep-ph/2207.06898



RE-SCATTERING

DM RE-SCATTERING

- Idea: sufficiently intense flux of LDM particles can lead to secondary scatterings in distant detectors



- Various scattering signatures:

– coherent scatterings

– DM-electron scatterings

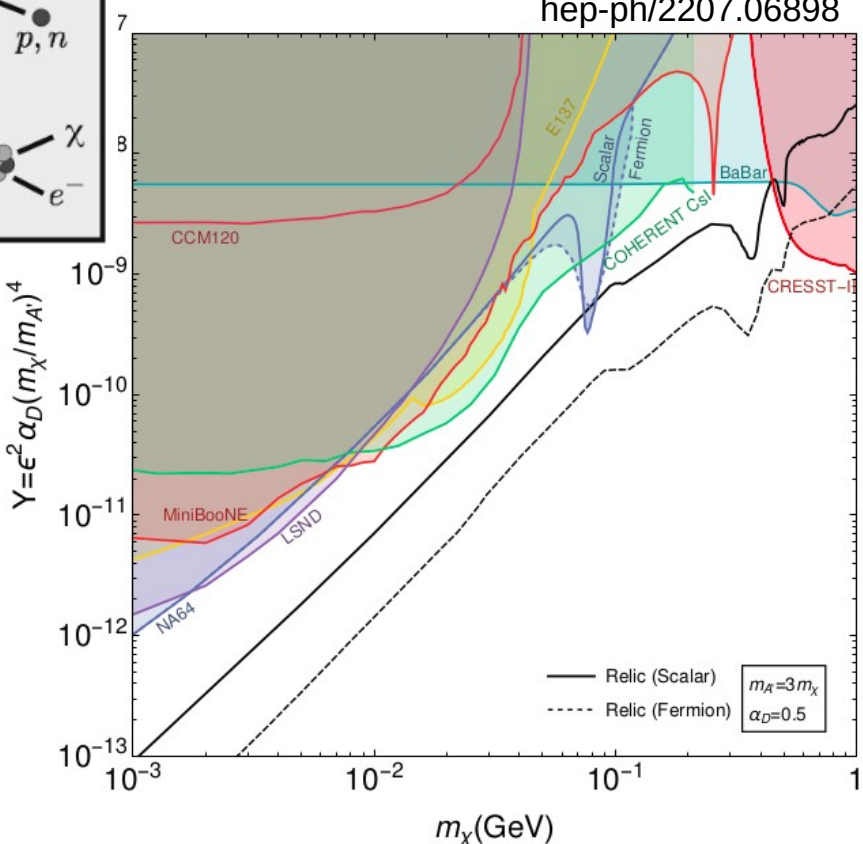
– DM-nucleon scatterings (quasi-)elastic

– Deep Inelastic Scattering (DIS)

Important to reject ν-induced backgrounds

CCM120 (hep-ex/2105.14020)
COHERENT CsI (hep-ex/1911.06422)
LSND (hep-ph/1107.4580, recast)
MiniBooNE (hep-ex/1807.06137)

hep-ph/2207.06898



OTHER PROSPECTS (selected)

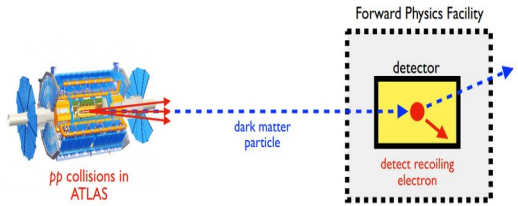
MISSING X

– **Missing momentum**
additional final-state e^- transverse momentum meas.
helps significantly reducing backgrounds
e.g. LDMX, M^3 hep-ph/1411.1404

– **Positron missing energy**
Positron beam annihilations on electrons in the target
$e^+e^- \rightarrow A' \rightarrow$ inv.; peak in missing E → DM mass
e.g. POKER ($NA64_{e+}$) hep-ex/1807.05884

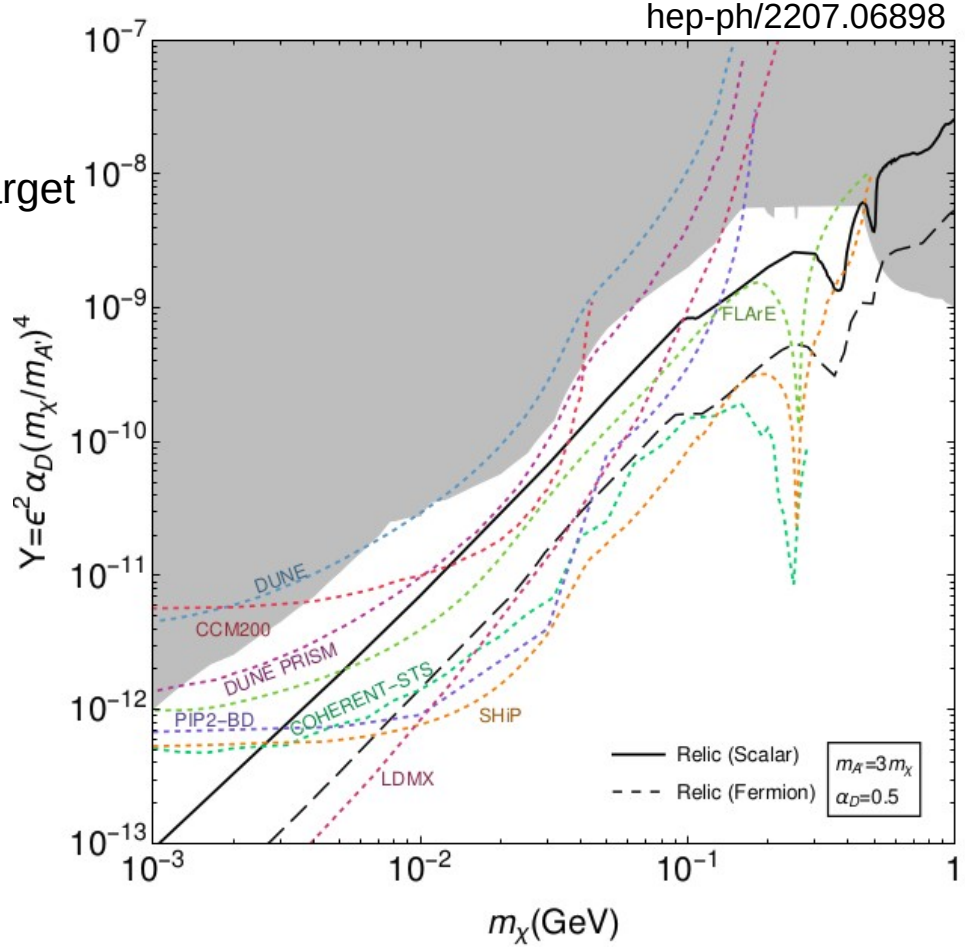
RE-SCATTERING

- **F**orward **L**iquid **Ar**gon **E**xperiment (**FLArE**)
in the Forward Physics Facility (LHC)



hep-ph/2101.10338
hep-ph/2107.00666
hep-ex/2203.05090

hep-ph/2207.06898



IONIZATION

MILLICHARGED PARTICLES

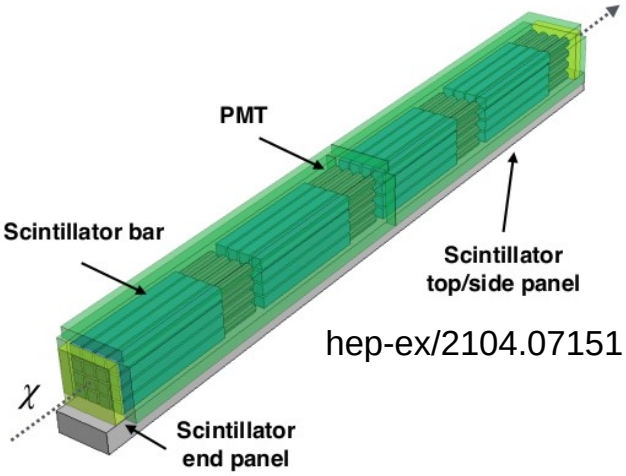
- Test of charge quantization, new particles with Q<0.1 e

GUT and string theory motivations
Also induced by massless dark photons

- **milliQan** detector

Sensitive to small energy depositions dE/dx
Plastic scintillator for detection
Segmented into 4 longitudinal ``layers''

- signature (E_{dep}~eV) 4 time-coincident hits



hep-ex/2104.07151

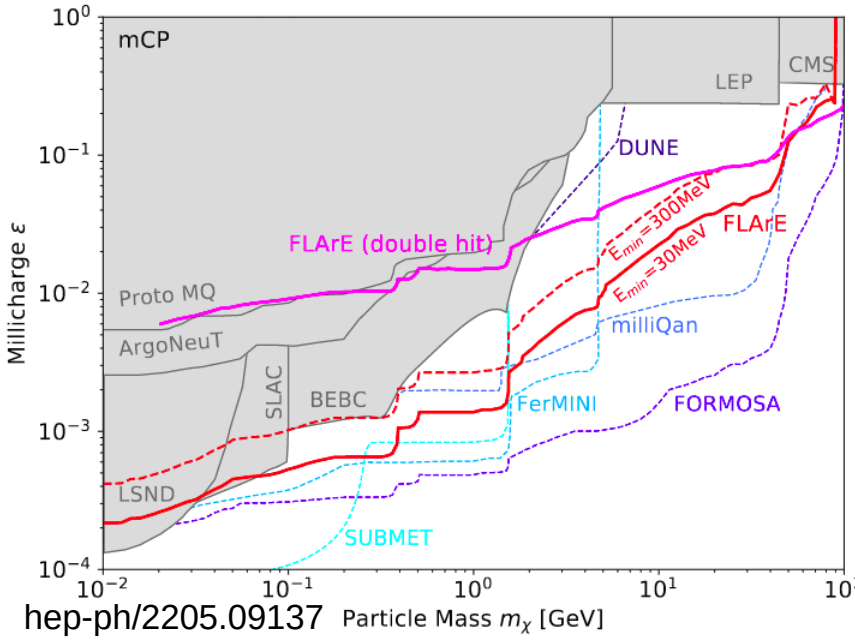
Data taking started with LHC Run 3

- Future similar proposals:

- milliQan-like in proton beam-dump
FerMINI (FermiLAB), SUBMET (J-PARC)
(hep-ph/1812.03998, hep-ex/2102.11493)

- Forward Physics Facility at the LHC
FORMOSA (hep-ph/2010.07941)

FLArE (LArTPC, re-scattering signature a-la-DM)



hep-ph/2205.09137

CONCLUSIONS

- Light Hidden Sectors – exciting target for the ongoing & future proposed searches

- Motivations: dark matter, top-down (GUT, string theory,…), anomalies, ...

- Multiple signatures are possible & past bounds can be recast

See also: Physics Beyond Colliders, LHC@LLP working group, ...

- Accelerator-based search for MeV-GeV new particles:

- search for decays (prompt & displaced)

- search for missing mass/energy/momentum

- search for re-scattering or ionization

- Selected facilities:

- CERN: SPS (NA62, NA64,…), LHC (FASER, LHCb, milliQan,...)
- FermiLAB, e.g. neutrino beams and experiments, KEK (Belle-II), ...and many other

THANK YOU!

Snowmass 2021: hep-ph/2207.06898

EXP. LANDSCAPE (2) (NEUTRINO BEAMS)

- Current and future neutrino experiments are also great lab to study light new physics
- High statistics, large volumes and detector capabilities
- Specific BSM runs might also be used (e.g. MiniBooNE beam-dump mode hep-ex/1807.06137)

Experiment			μ BooNE	SBN (ICARUS/SBND)	NOVA	DUNE	Hyper-K	JSNS2	CCM
L_{base} (km)/ L_{T2ND} (km)			0.47	0.6/ 0.11	810/0.9	1300/ 0.574	295/ 0.28/~1	0.024/ 0.048	0.023/ NA
ν Beam	Ep (GeV)		8	8	120	80 – 120	30	3	0.8
	Intensity (MW)		0.03	0.03	0.75	1.2 - 2.4	1.3	1	0.1
	$<E_\nu>$ (GeV)		0.6	0.6	2	3	0.6	0.04	0.03
Detector Parameters	ND	Tech	LArTPC	LArTPC	Liquid Scint.	LArTPC	Scint./H2O Cerenkov	Gd-Liquid Scint.	LArScint
		V_A(t)	96	112	300	147	4/100	17	5
	FD	Tech	NA	LArTPC	Liquid Scint.	LArTPC	H2O Cerenkov	Gd-Liquid Scint. Cerenkov	NA
		V_A(t)	NA	470	14k	40k	188k	35	NA

(2015-20)