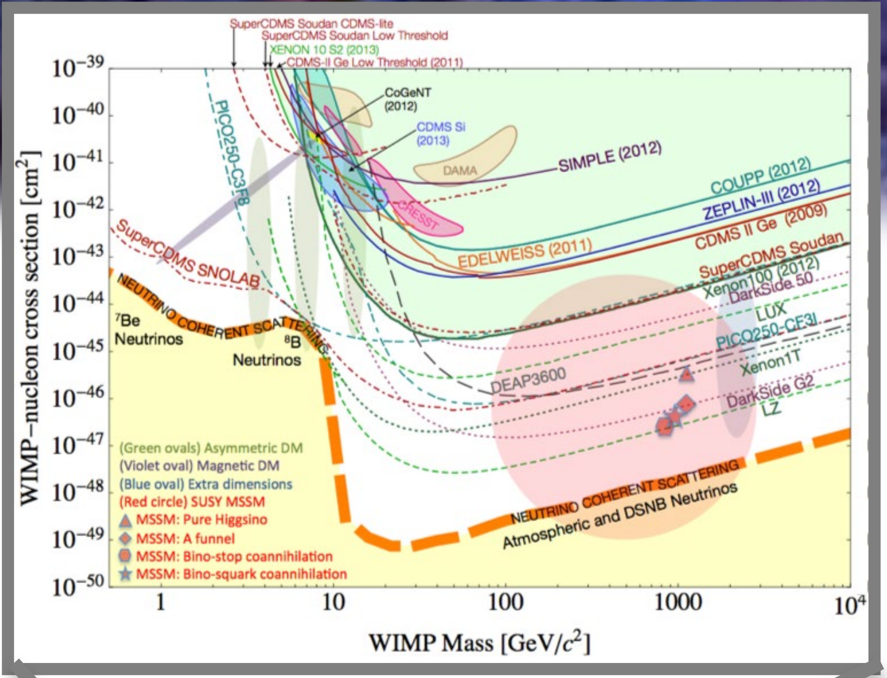
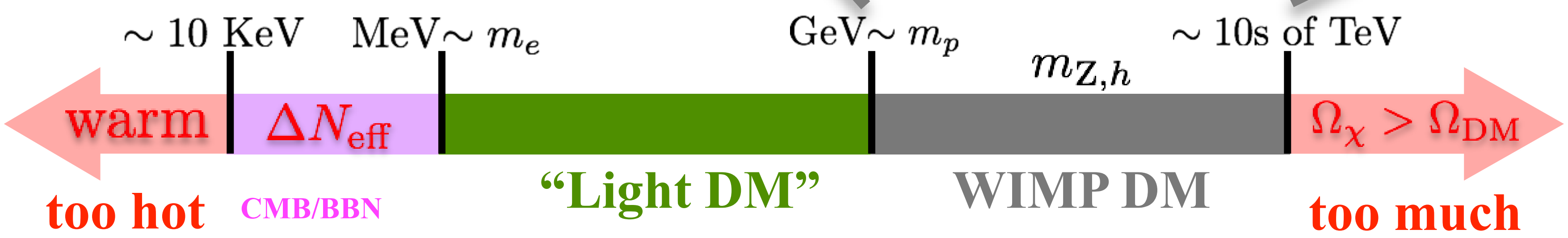
Dark Sectors at Fixed-Target and Collider-Adjacent Experiments

Dark Sector Search Motivations

- "Thermal Relic" Weakly Interacting Massive Particles: seemingly the simplest scenario
- But haven't shown up in mass range where we most expected them!





- Thermal Relic DM actually works fine at least down to $2m_e$
- But "light DM" requires new, comparably low-mass mediators to achieve required annihilation cross-section for thermal relics

Dark Sector Search Motivations

The Standard Model is only ~5% of the universe.
It includes 3 forces.

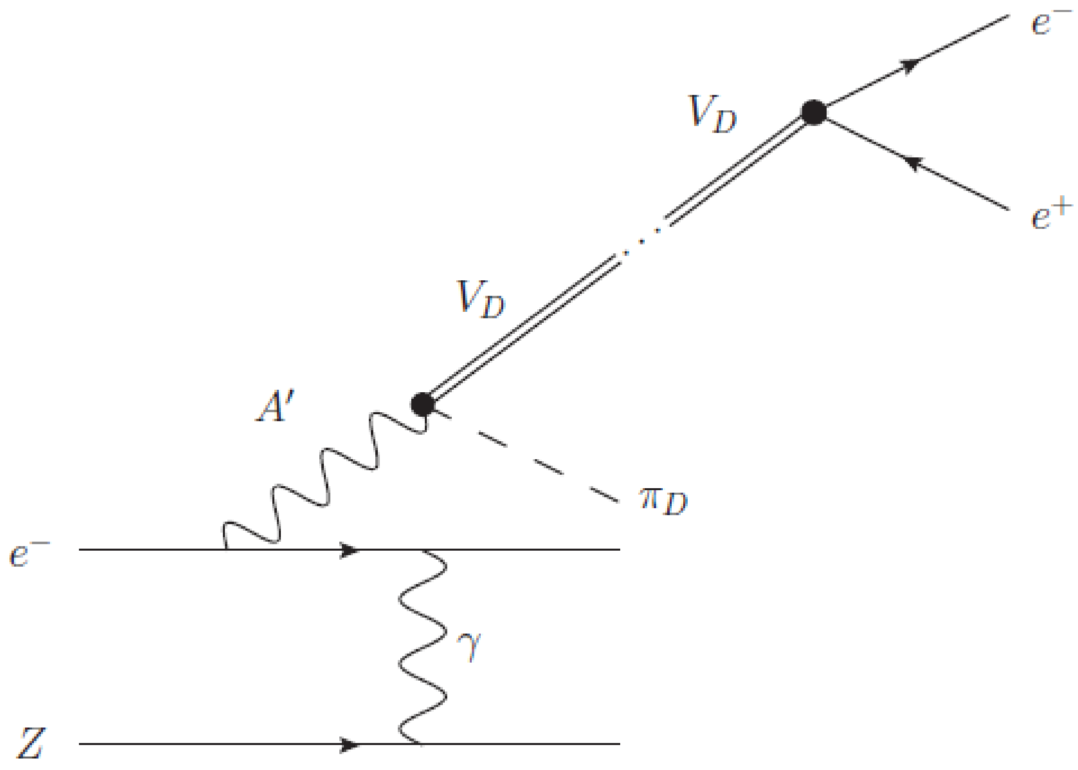
Why should the ~25% that is Dark Matter be any simpler?
Dark Forces?

How would DM interact with the SM?
Mediator particles?

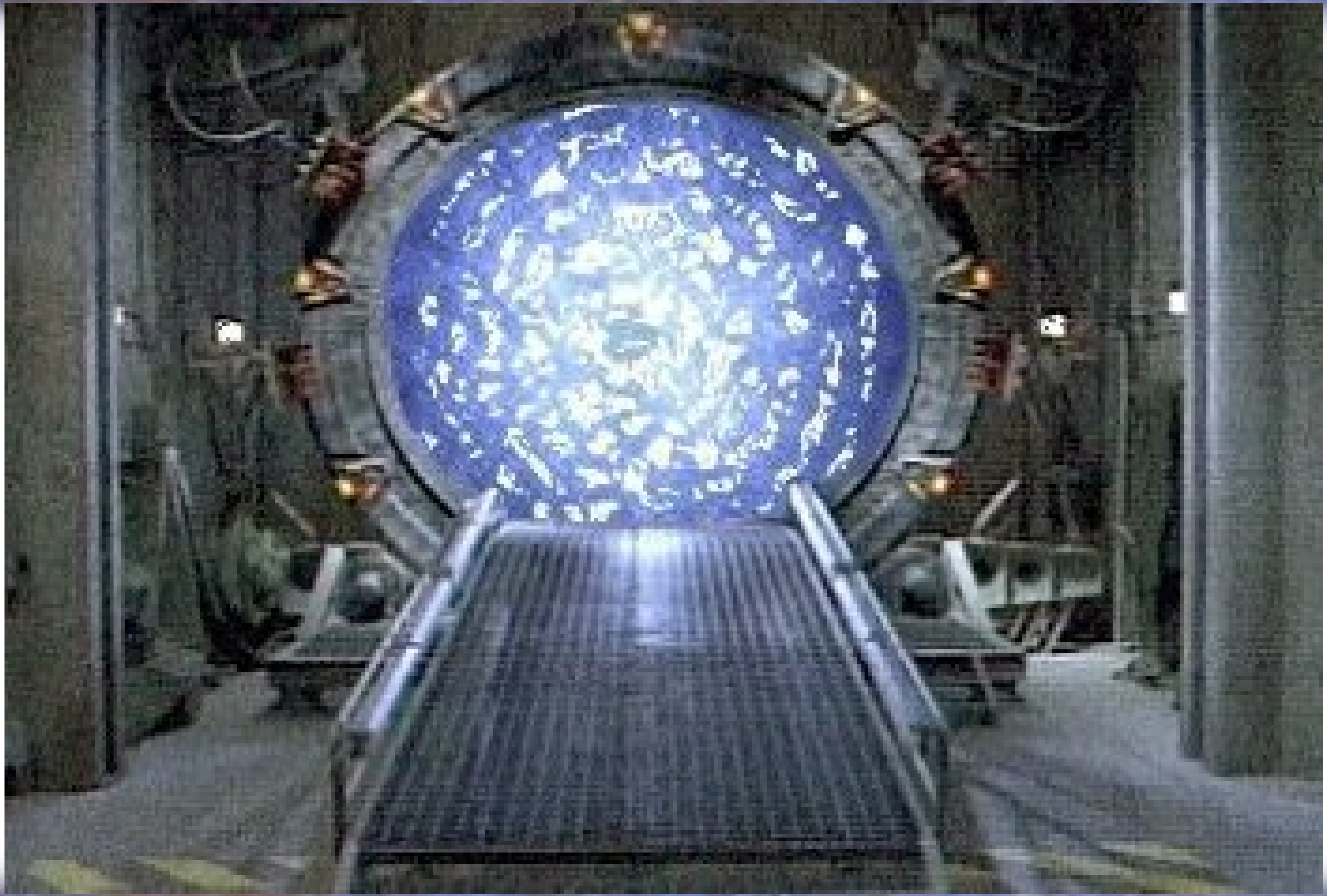
Dark Sector Search Motivations

- Hidden Valley: sector of dark particles, interacting amongst themselves, weakly coupled to SM through loops of TeV-scale particles or marginal operators
  - Lowest particle in Valley forced to decay to SM due to mass gap or symmetry
  - "Portal" couples both to SM and Valley operators
- "Bottom-up" astrophysics models with *A'*:
  - Inelastic DM
  - Exciting DM
  - Secluded DM
  - Self-Interacting Massive Particles

In some models with Long Lived Particles (LLPs): the only way to see the DM is LLP → DM + SM decay



Careful of the Portal



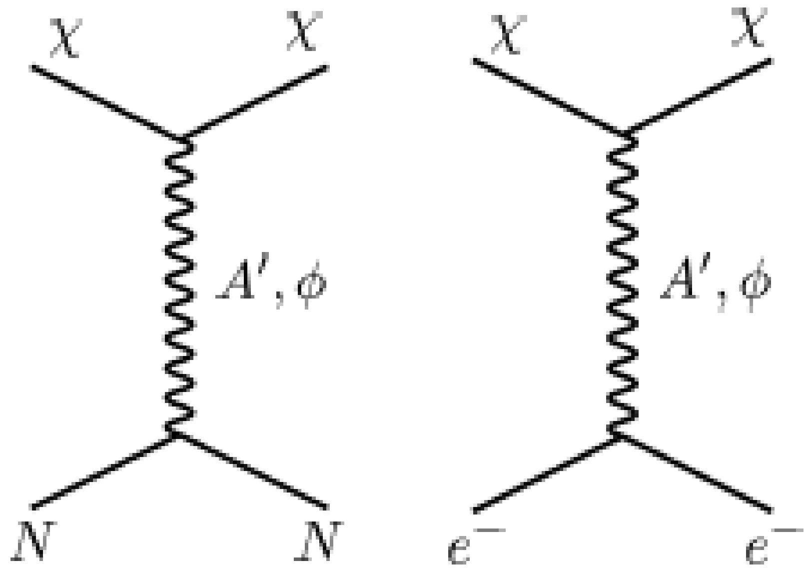
Careful of the Portal

In other words…
Treat the mediator differently at high energies than at low energies!

How to look for the mediator itself?

In scattering processes, can we "integrate out" the mediator?

- "Heavy" vs "light" mediator, "on-shell" vs "off-shell", "high" vs "low" momentum transfer

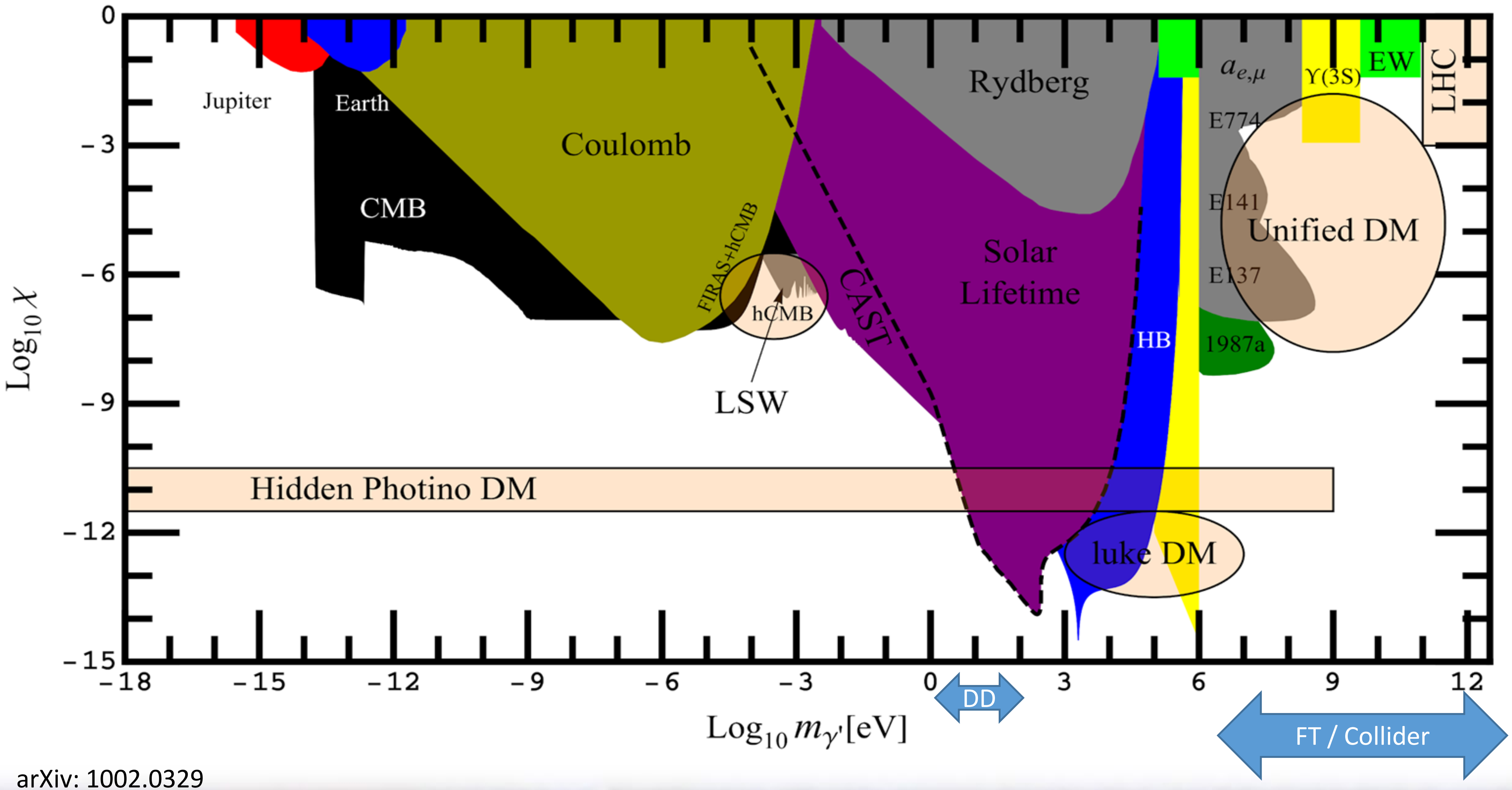


At high energies, parameterize limits in terms of y:

$$\sigma v \propto \epsilon^2 \alpha_D \frac{m_\chi^2}{m_{A'}^4} \equiv \frac{y}{m_\chi^2}$$

$$y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

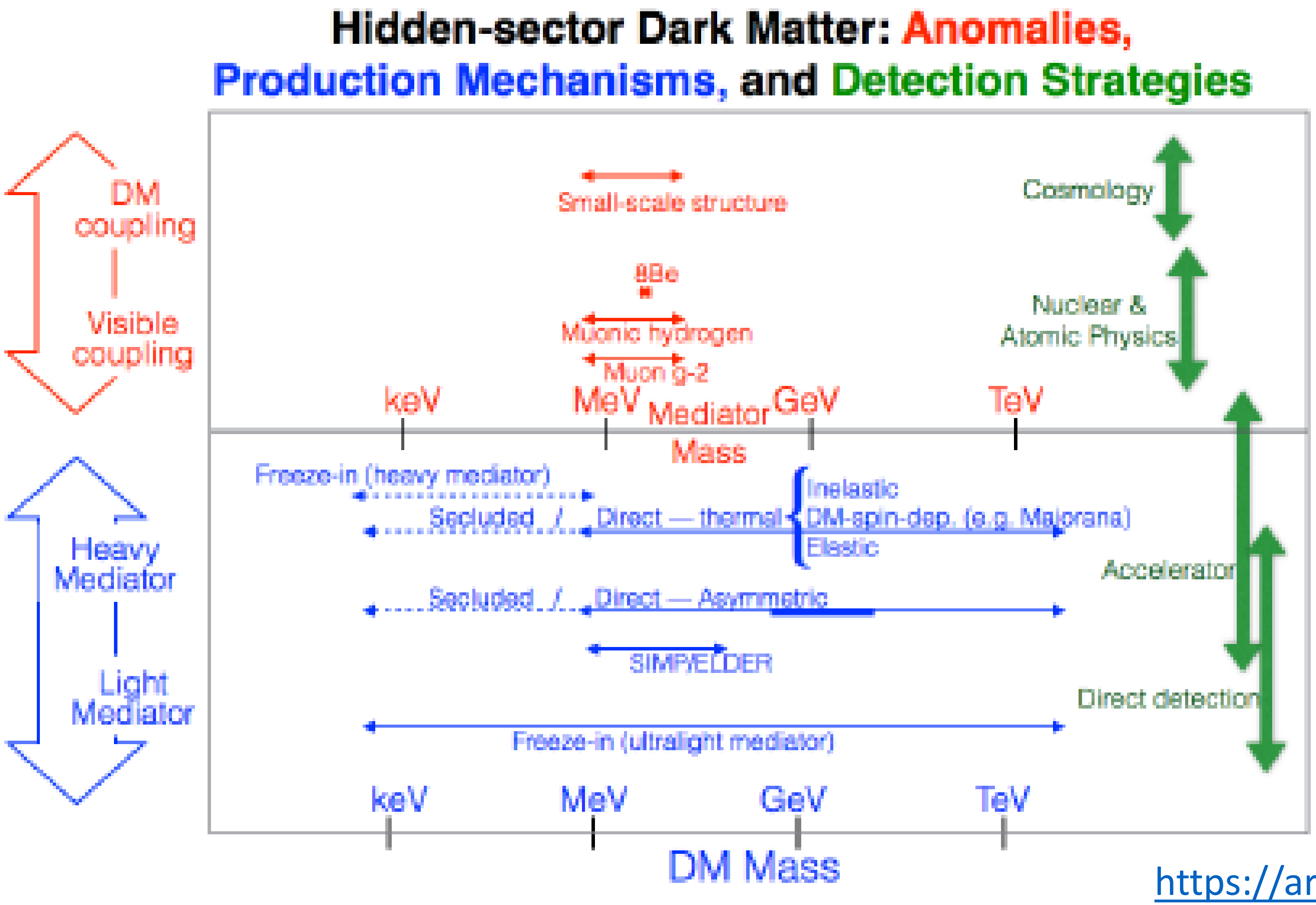
Example: Dark Photon Search Landscape



arXiv: 1002.0329

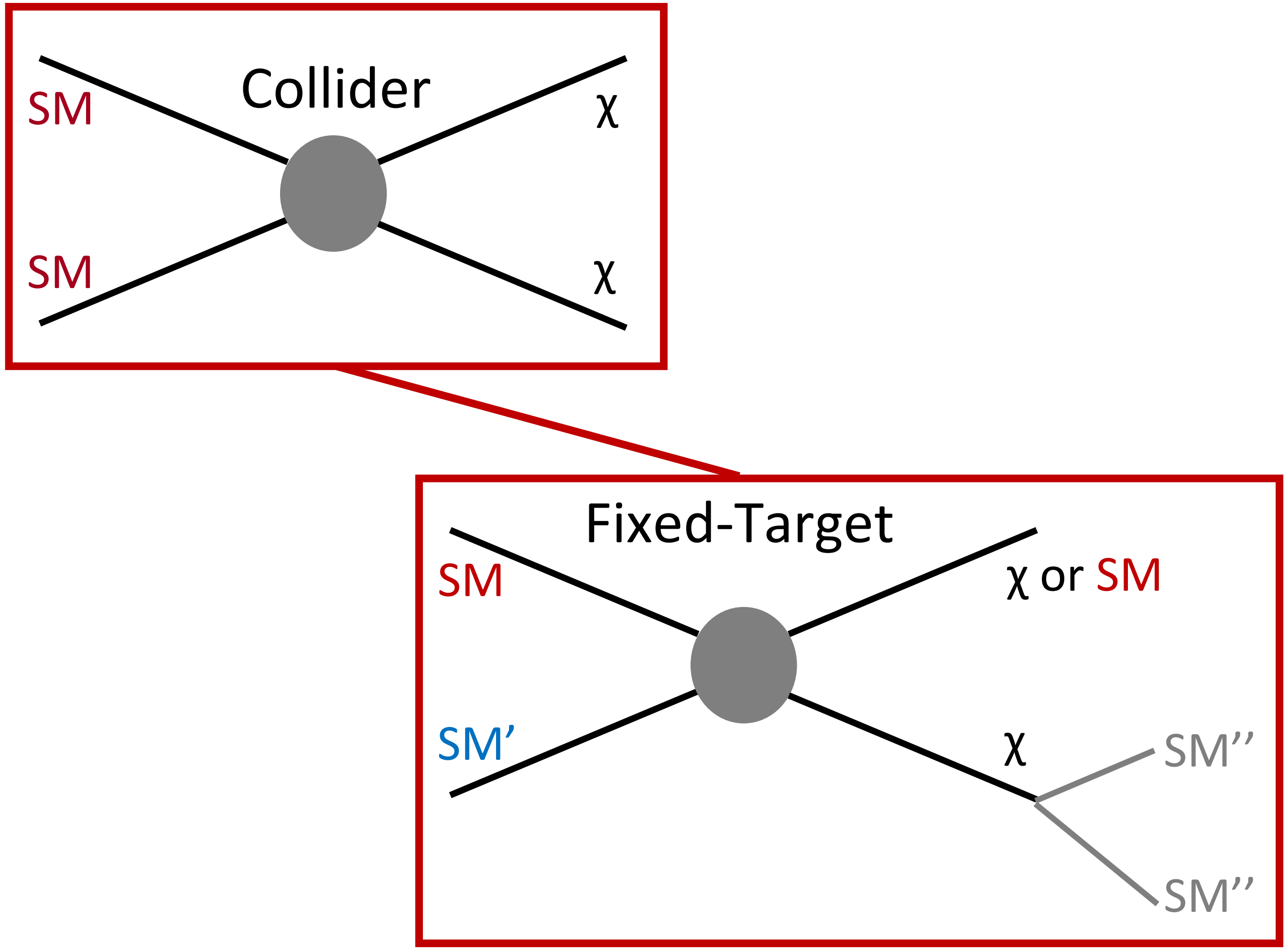
Fixed-Target Searches for Dark Sectors

"Cosmic Visions" for Hidden Sectors



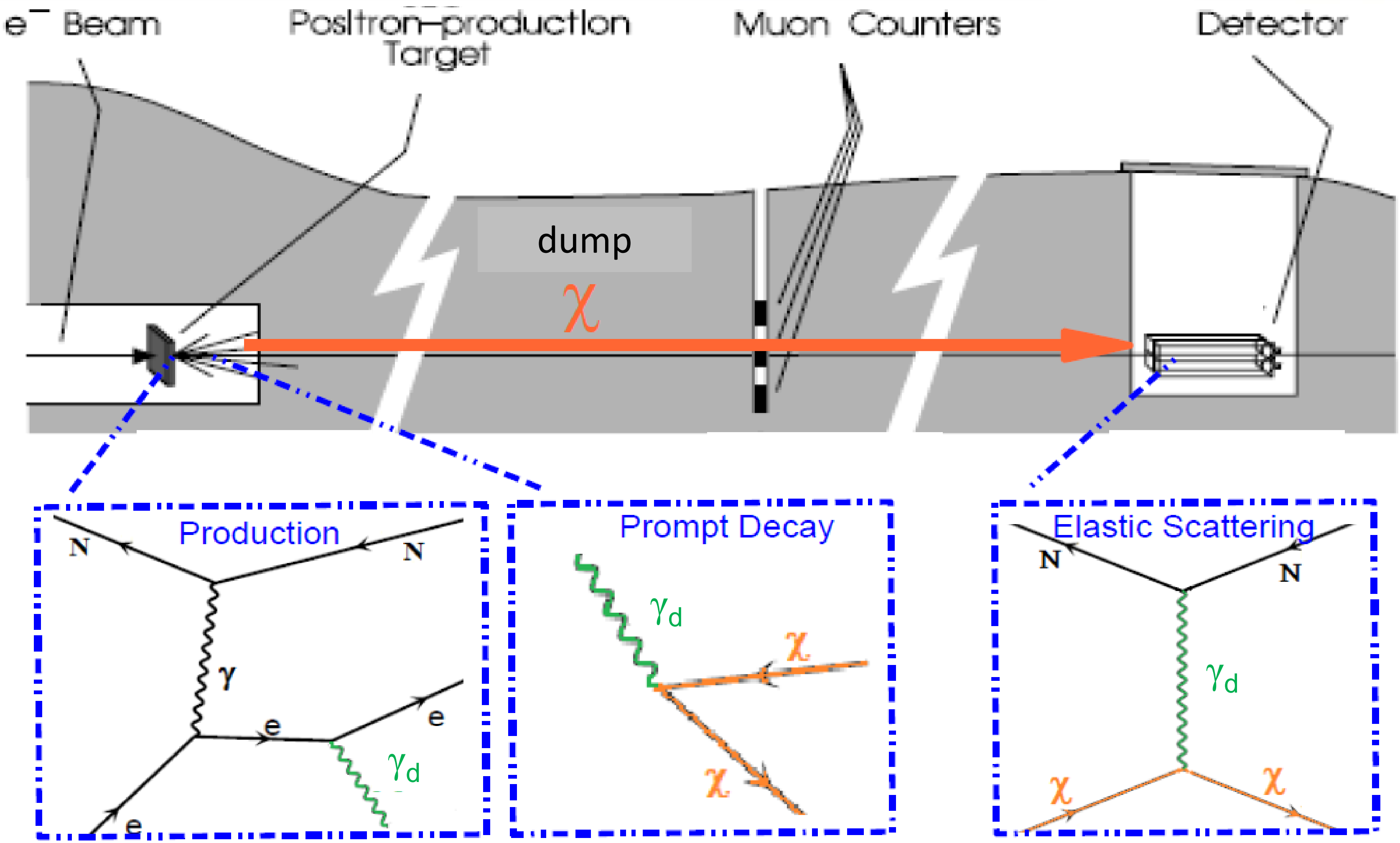
https://arxiv.org/abs/1707.04591

Fixed-Target Search Strategies



Dumps Aren't Just for Garbage…

Simplest beam dump



Phys. Rev. Lett. **111**, 221803 (2013)

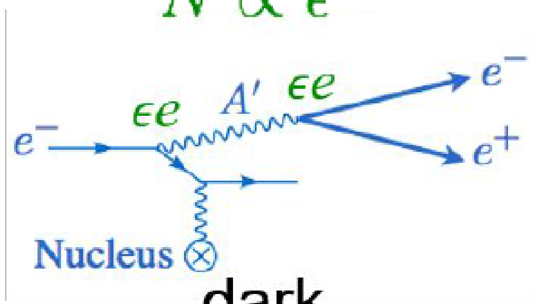
… They Can Get Complicated

More complex setups: target final-state dilepton signatures

(assuming dark photon is lowest-mass dark state)

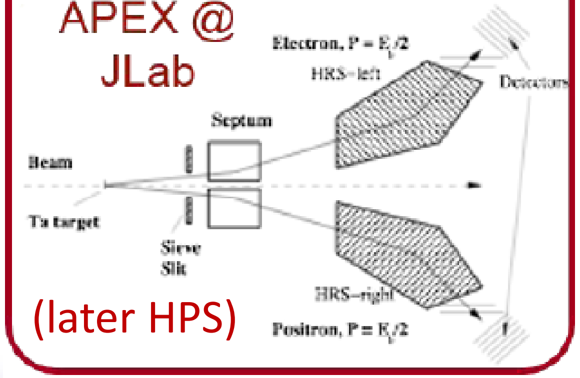
e^- fixed target

$N \propto \epsilon^2$



dark bremsstrahlung

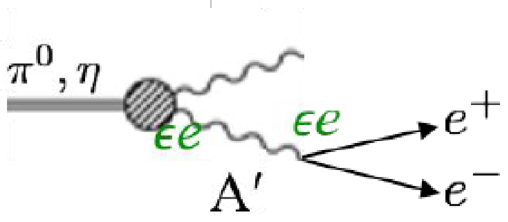
APEX @ JLab



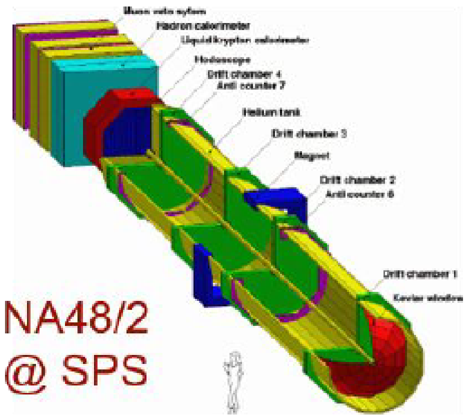
(later HPS)

p fixed target

$N \propto \epsilon^2$



meson decays



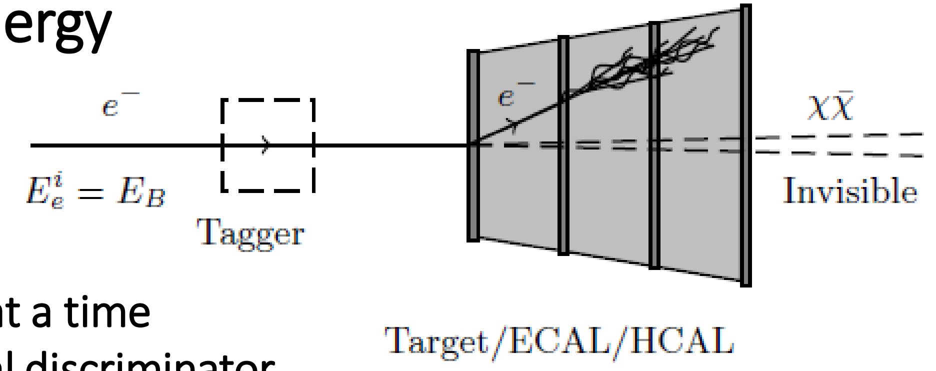
NA48/2 @ SPS

Uncloaking Invisibility

Even more sophisticated: also look for signatures of invisible decay products of dark photon

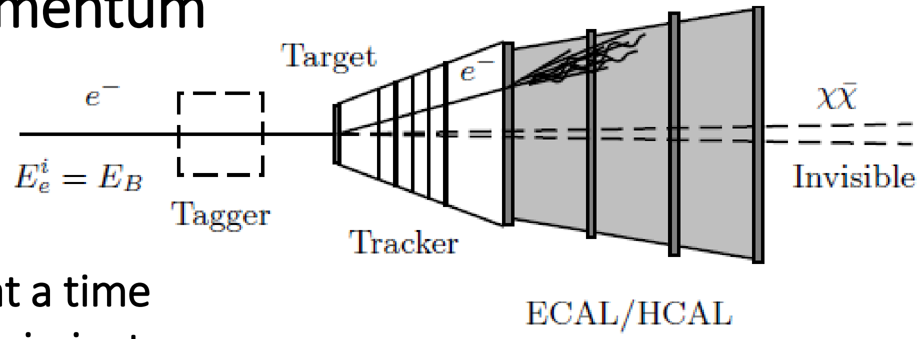
(assuming other dark sector particles are lower-mass than dark photon)

Missing Energy



One electron at a time
Only one signal discriminator
Insensitive to nature of interactions
Challenging backgrounds

Missing Momentum



One electron at a time
Two signal discriminators
Sensitive to *A′* mass
"Zero-background"

Fixed Target Dark Sector Search Experiments

- Re-interpreted electron beam-dump results
  - E141
  - E774
  - E137

- Proton
  - **NA48/2 & NA64**
  - TREK
  - SHIP
  - SBN
  - SeaQuest

- Electron (specialized)
  - APEX
  - **Heavy Photon Search (HPS)**
  - **Light Dark Matter Search (LDMX)**
  - BDX
  - MAGIX
  - DarkLight

- Positron
  - **PADME**
  - VEPP3
  - MMAPS

US Cosmic Visions: New Ideas in Dark Matter 2017 Community Report, arXiv:1707.04591

NA 48/2, NA62

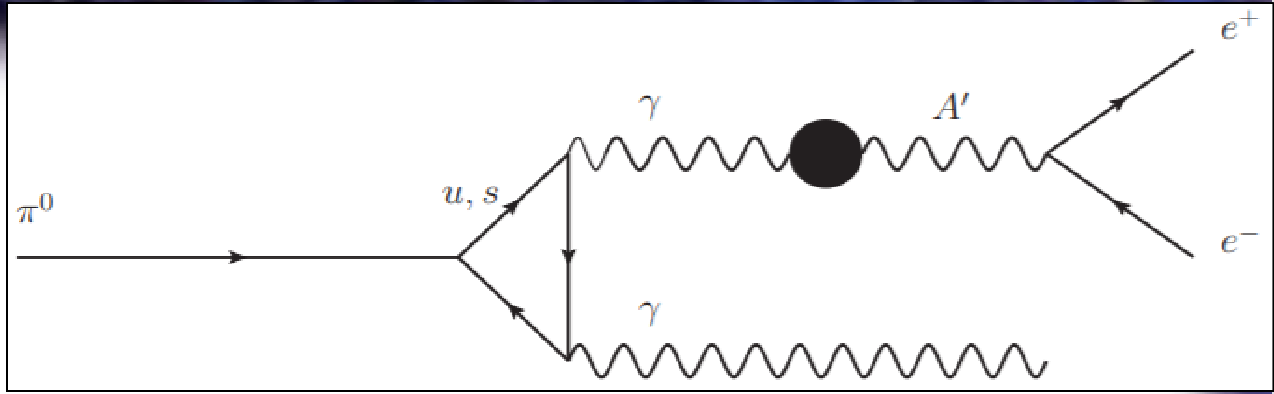
- Proton beam from SPS at CERN
- Protons on fixed target produce kaons
- Kaon decays (in-flight) produce pions

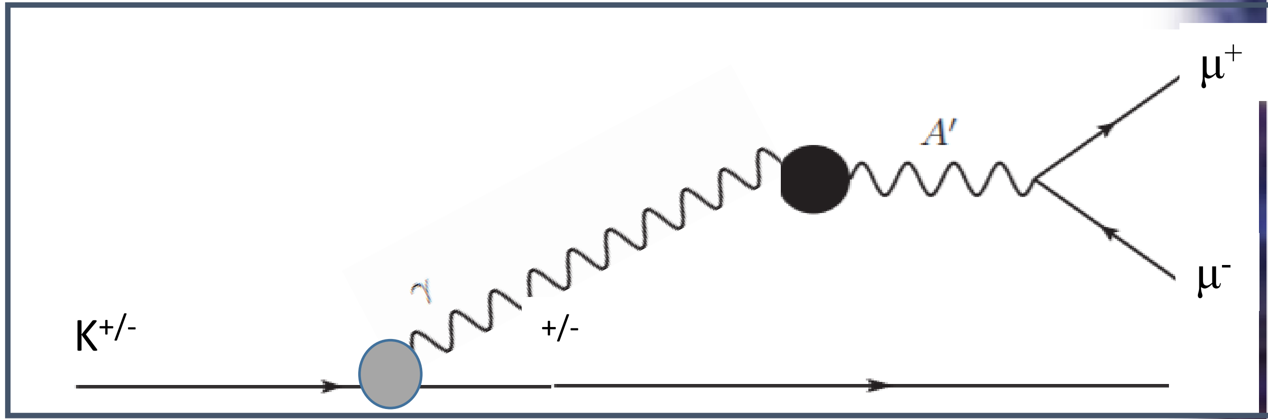
NA48/2 :

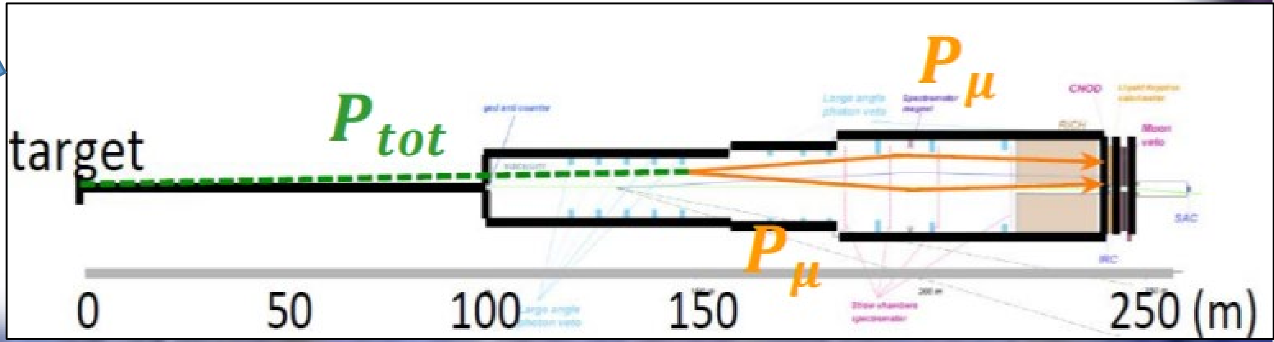
- Resonance: $\pi^0 \rightarrow \gamma\,(A' \rightarrow e^+ e^-)$
- Resonance: $K^{+/-} \rightarrow \pi^{+/-}\,(A' \rightarrow \mu^+ \mu^-)$

NA62 :

- Resonance: $\pi^0 \rightarrow \gamma\,(A' \rightarrow e^+ e^-)$
- Beam-dump: long-lived $A' \rightarrow \mu^+ \mu^-$

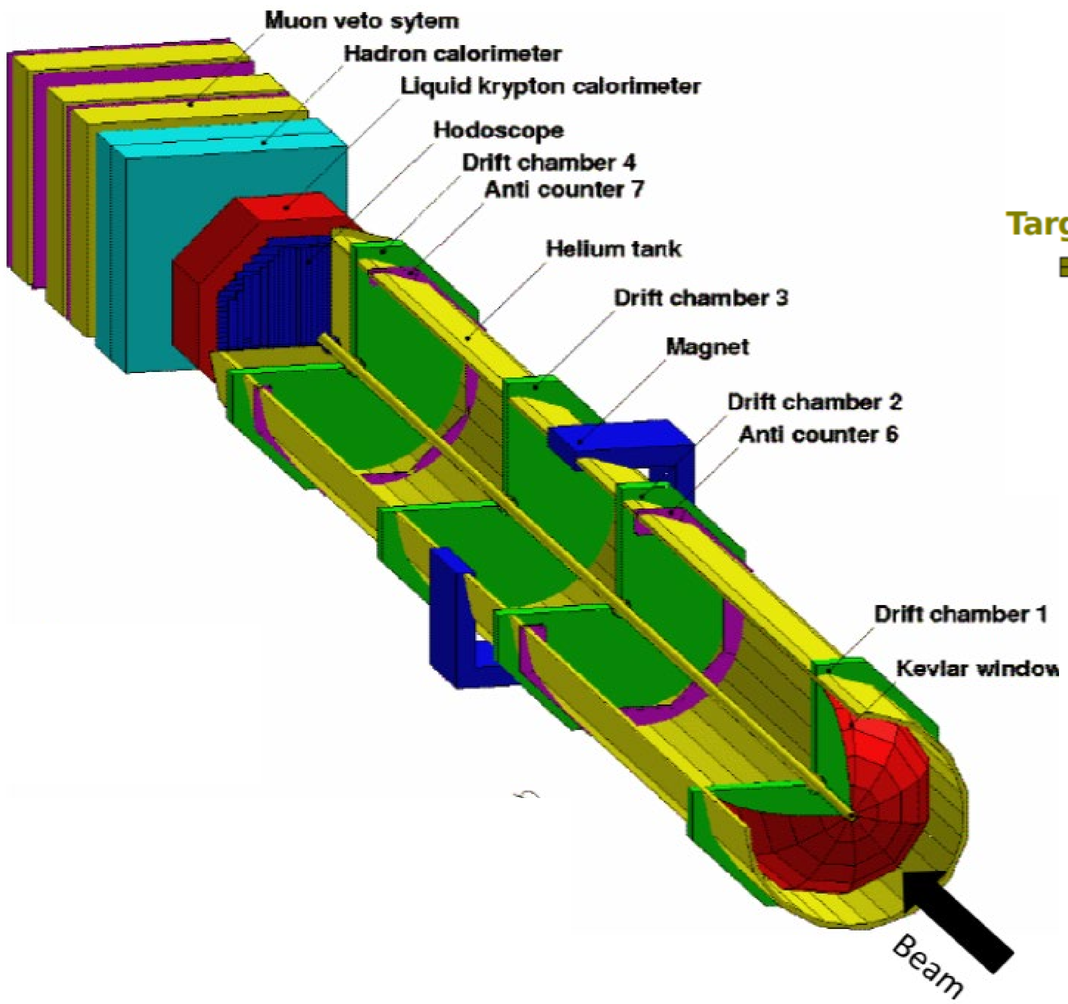




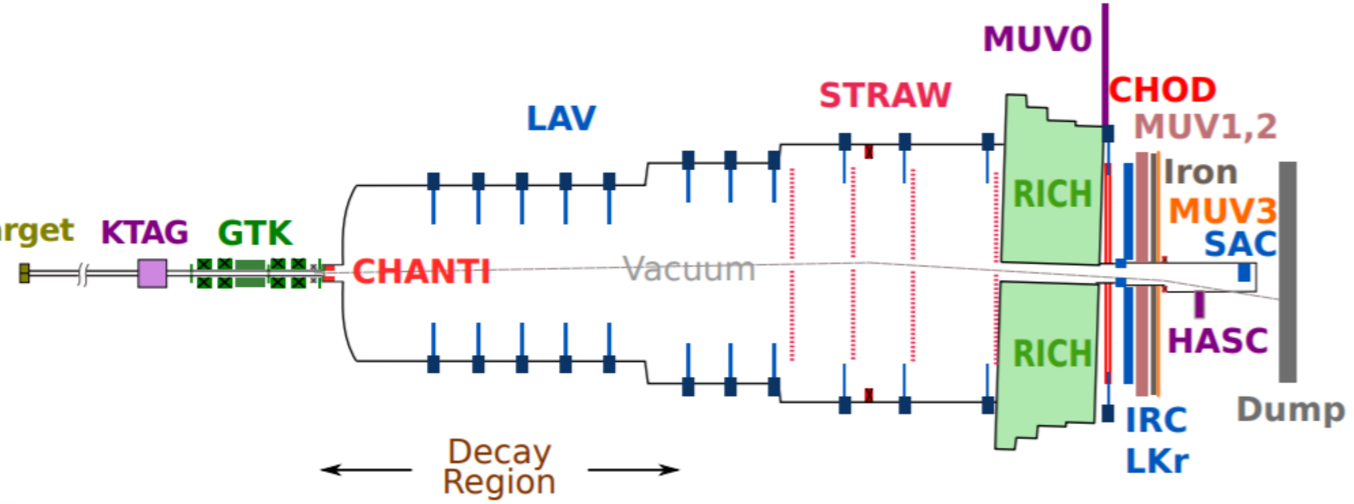


NA 48/2

NA62

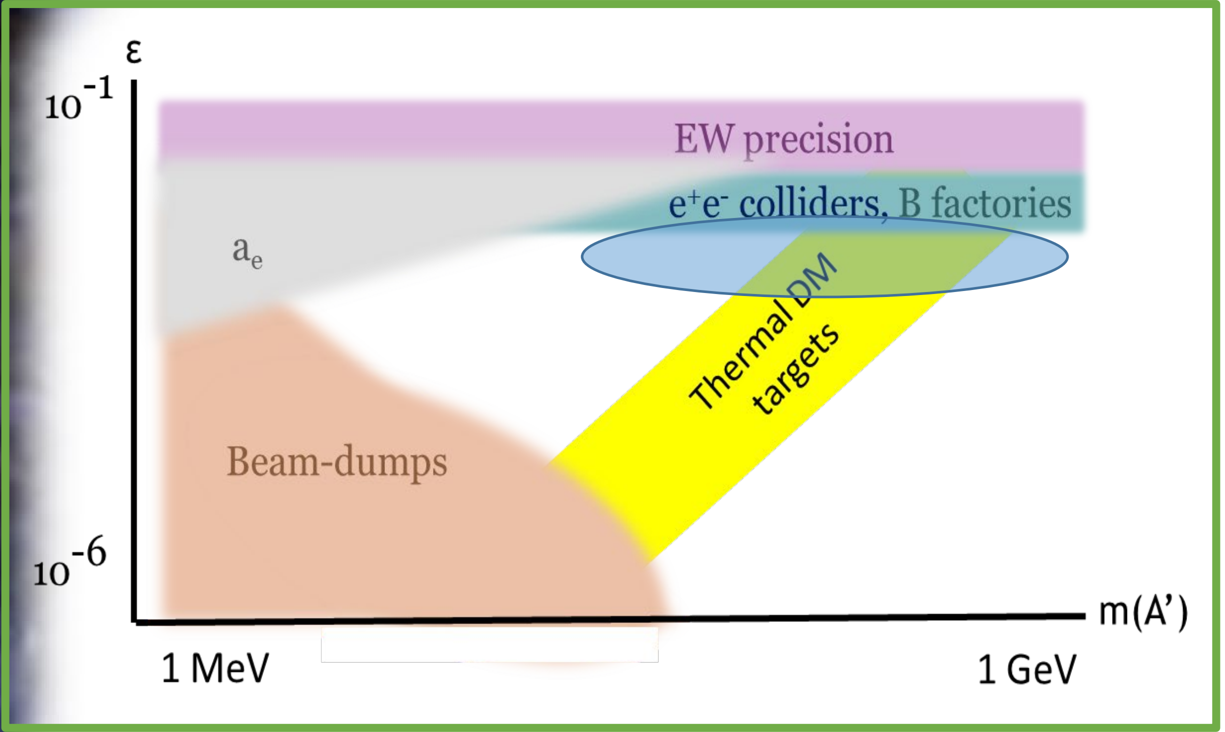


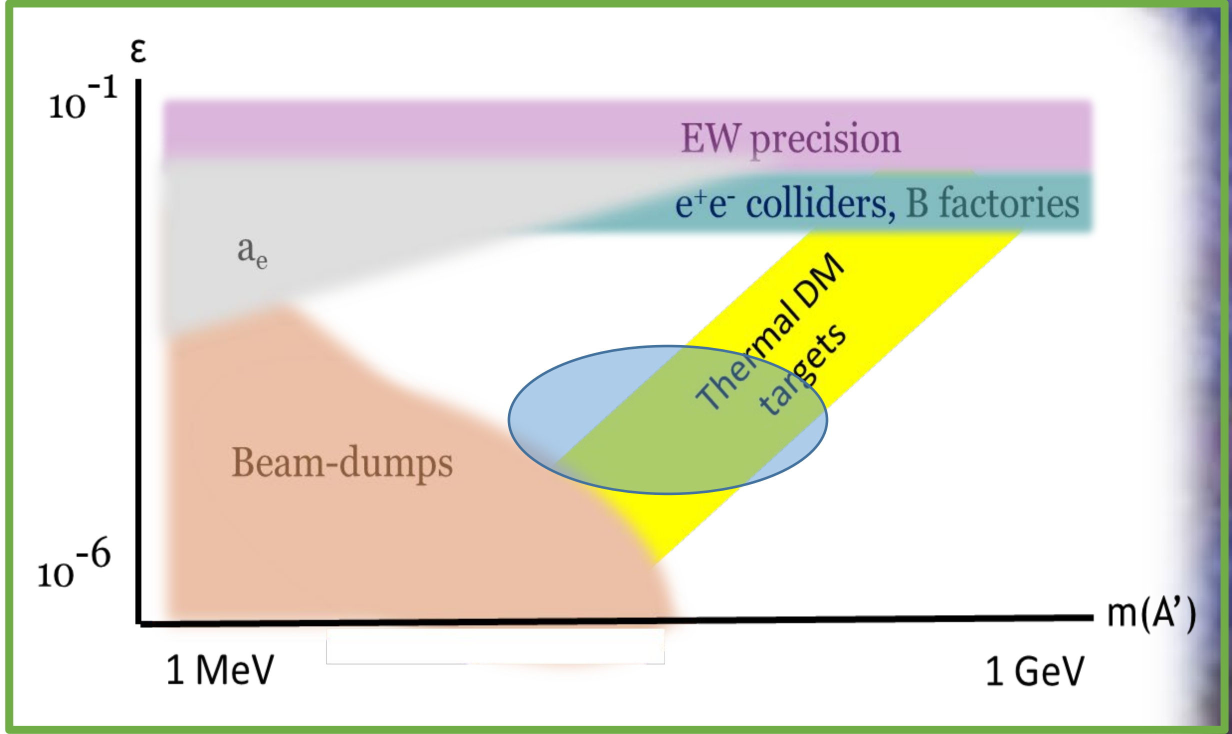
Muon veto sytem
Hadron calorimeter
Liquid krypton calorimeter
Hodoscope
Drift chamber 4
Anti counter 7
Helium tank
Drift chamber 3
Magnet
Drift chamber 2
Anti counter 6
Drift chamber 1
Kevlar window
Beam



MUV0
CHOD
STRAW
MUV1,2
LAV
Iron
RICH
MUV3
SAC
Target
KTAG
GTK
CHANTI
Vacuum
RICH
HASC
Dump
IRC
LKr
Decay Region

Heavy Photon Search





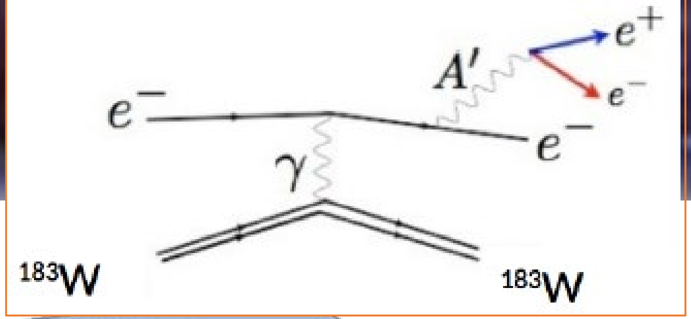
Resonance Search

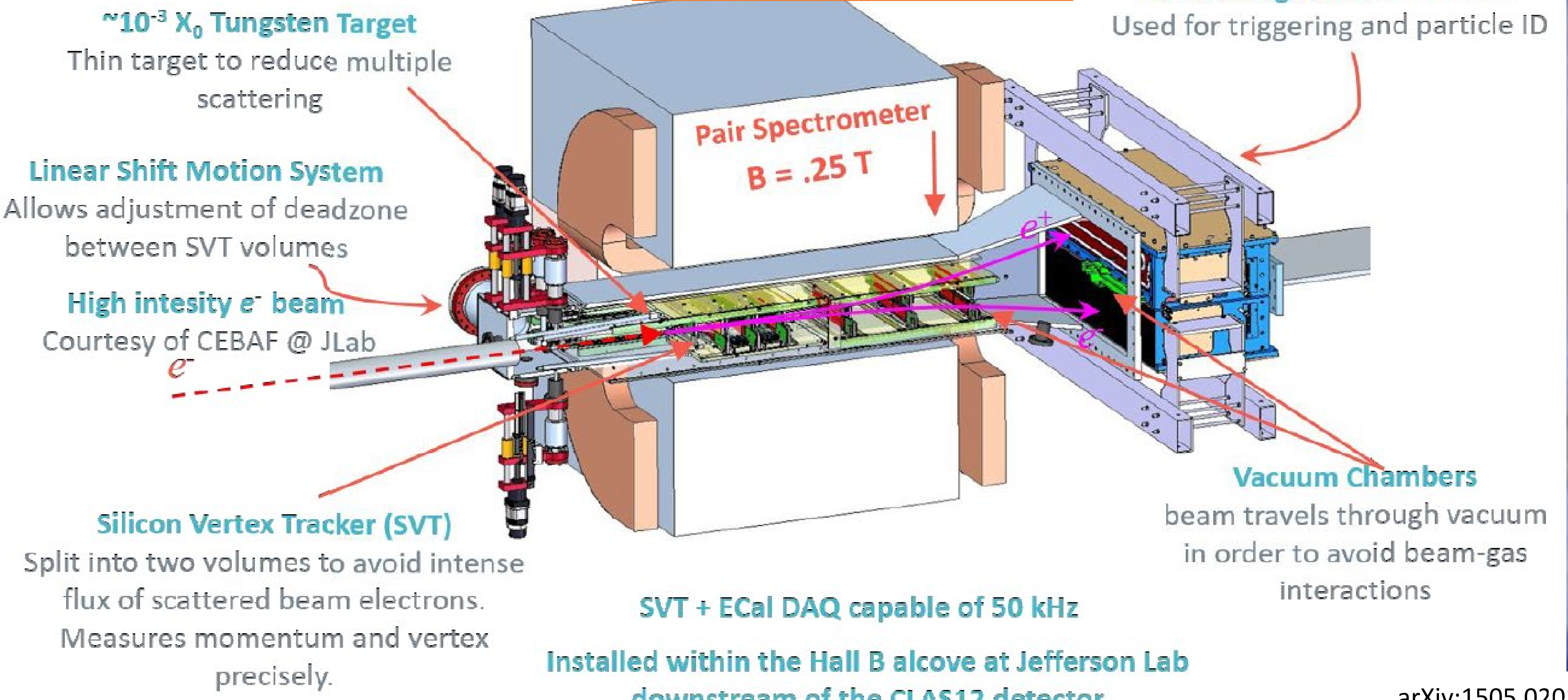
- Prompt *A'*
- Excess in $m(e^+e^-)$ above large QED bg

Displaced Vertex Search

- Longer-lived *A'*
- Lower background, smaller signal

Heavy Photon Search





SVT + ECal DAQ capable of 50 kHz

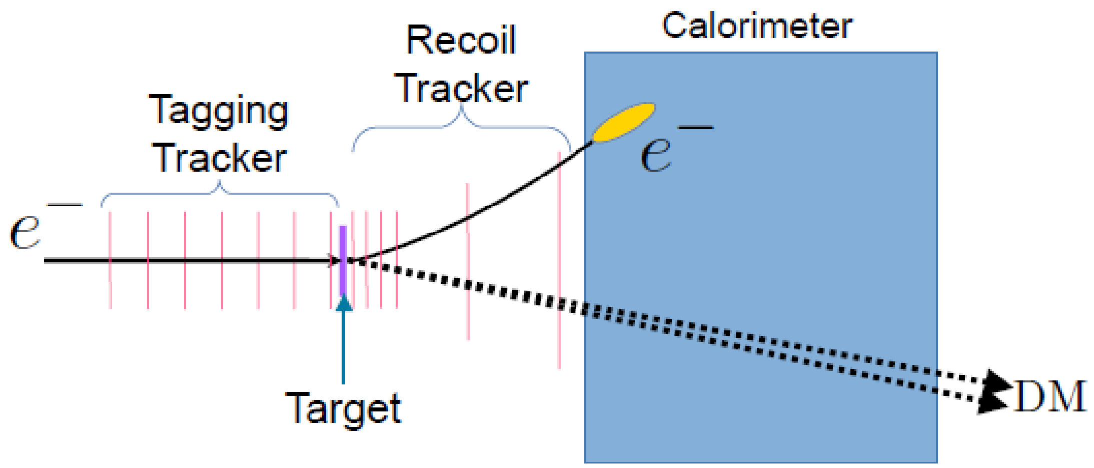
Installed within the Hall B alcove at Jefferson Lab downstream of the CLAS12 detector

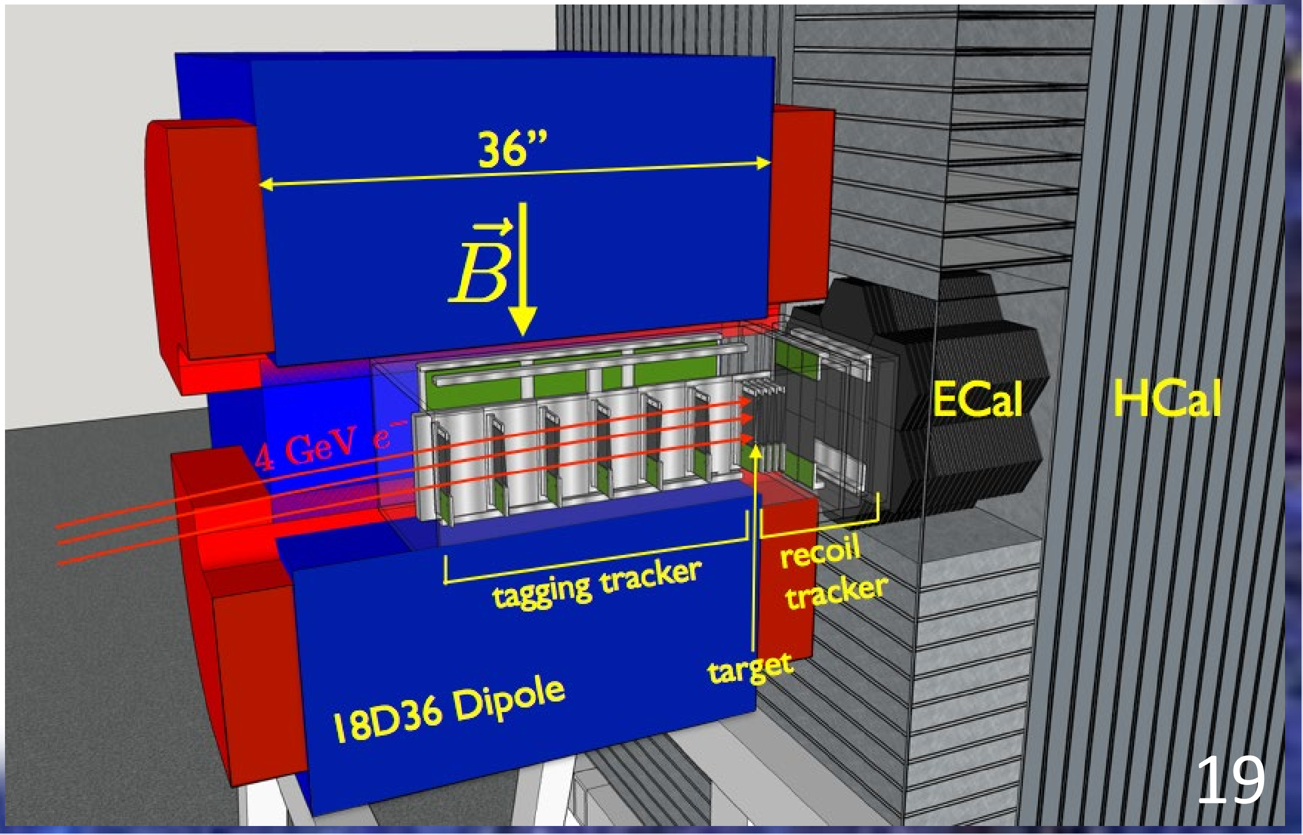
arXiv:1505.02025

Light Dark Matter Experiment

So far, have only looked for the visible A' decay products. What about the invisibles?

Light Dark Matter Experiment (LDMX): "zero-background" missing momentum experiment, under construction at SLAC

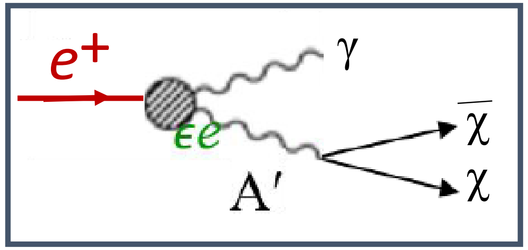


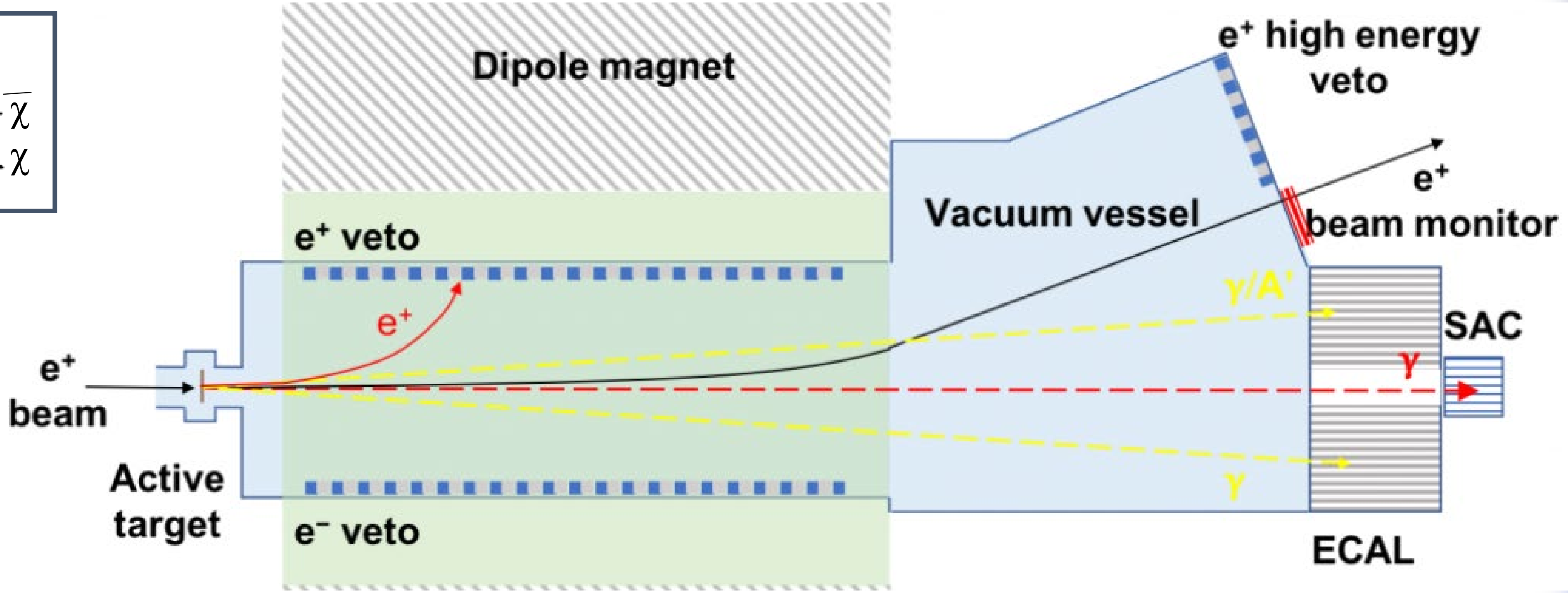


arXiv:1808.05219

Positron Annihilation into Dark Matter Experiment

PADME @ Laboratori Nazionali di Frascati of INFN: positron-on-target collisions at DAΦNE Beam Test Facility



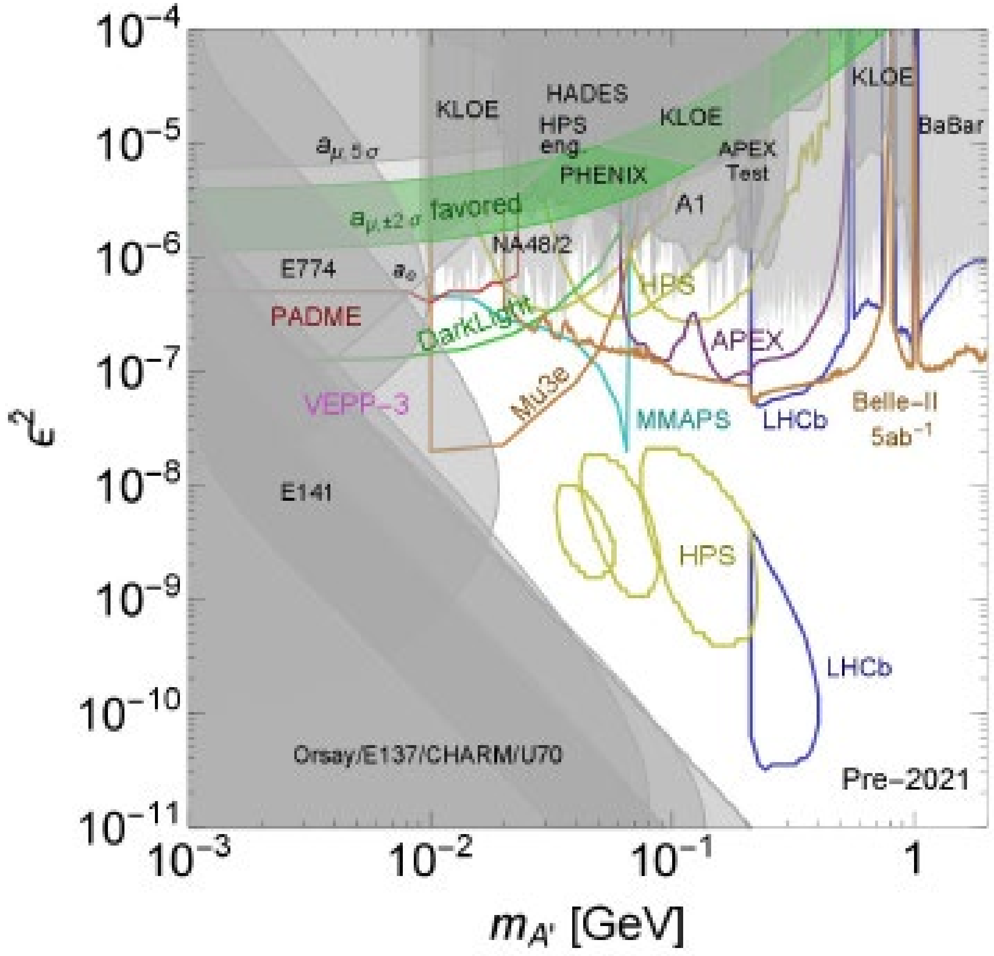


- Search for peak in missing energy distribution of incoming e^+ vs outgoing γ
- Detector fully installed Sept 2018

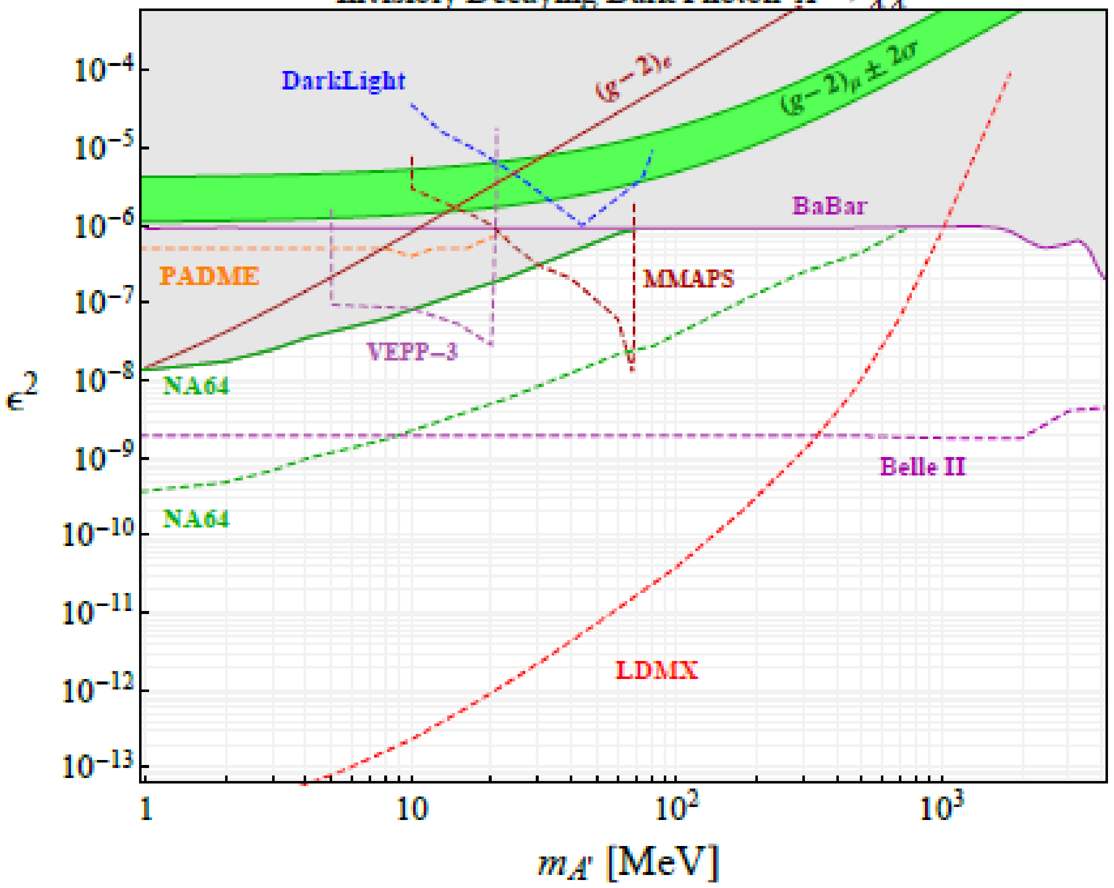
Fabio Bossi, Dark Interactions, BLN, 2018

Fixed-Target Limits on Dark Photons

Visibly Decaying Dark Photon

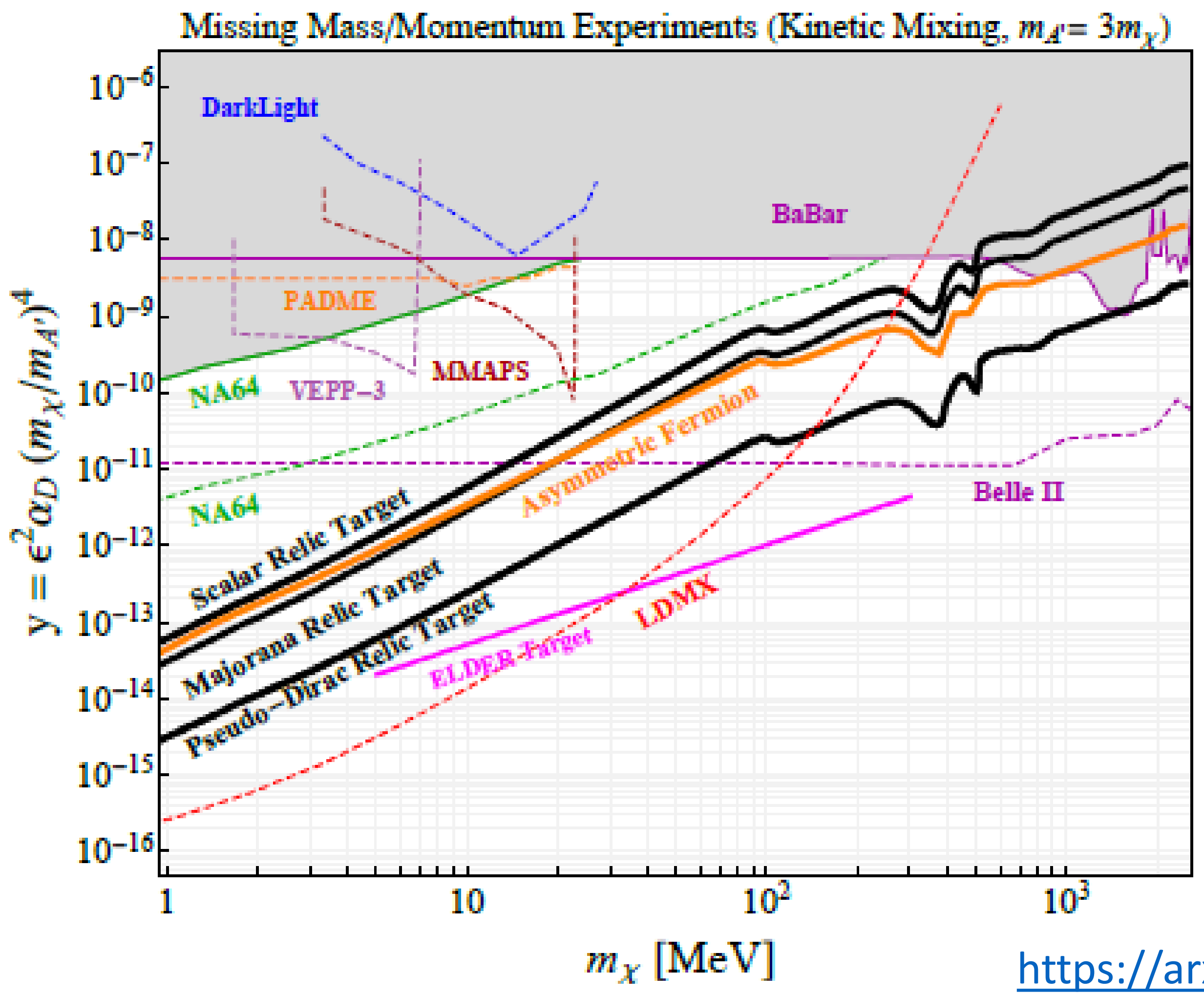


Invisibly Decaying Dark Photon $A' \to \bar{\chi}\chi$



https://arxiv.org/abs/1707.04591

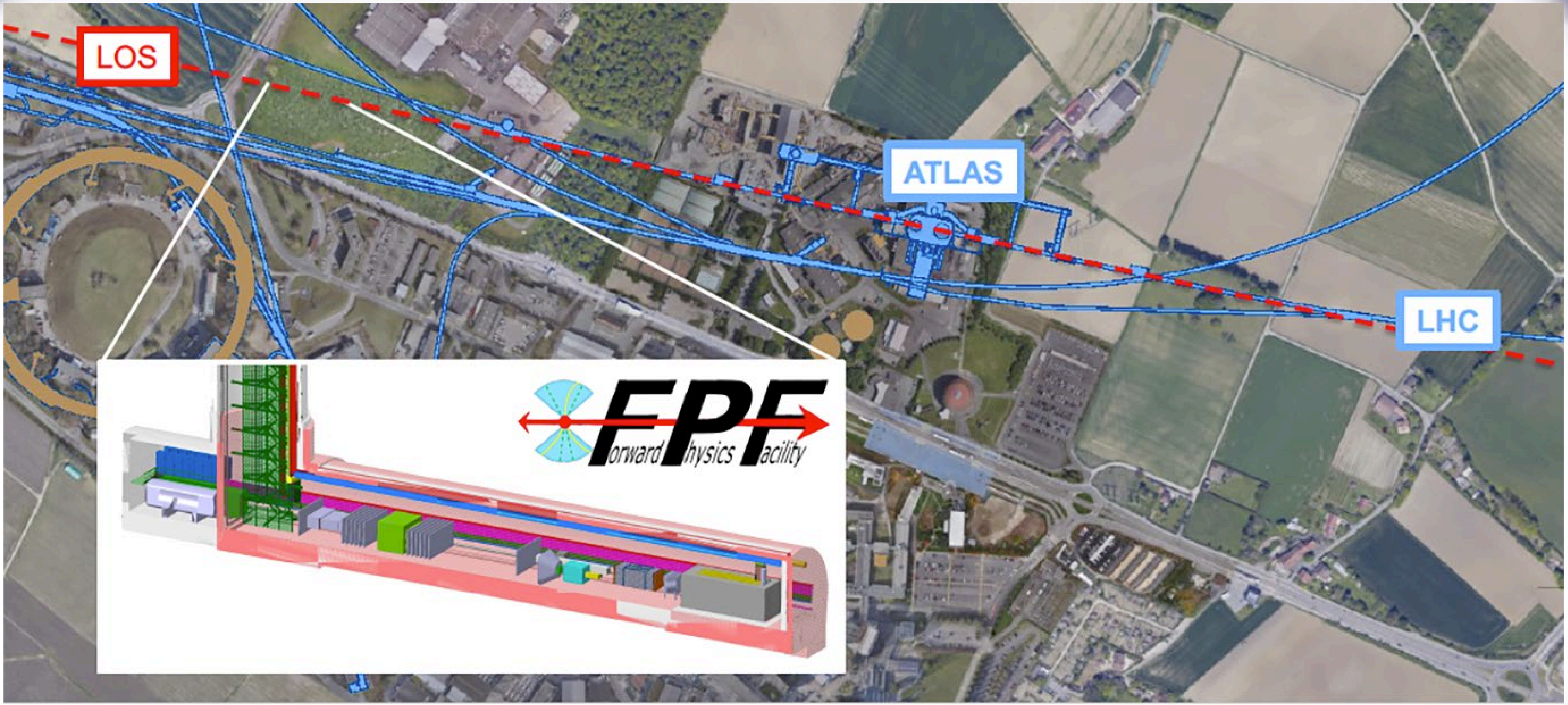
Fixed-Target Limits on Dark Sectors



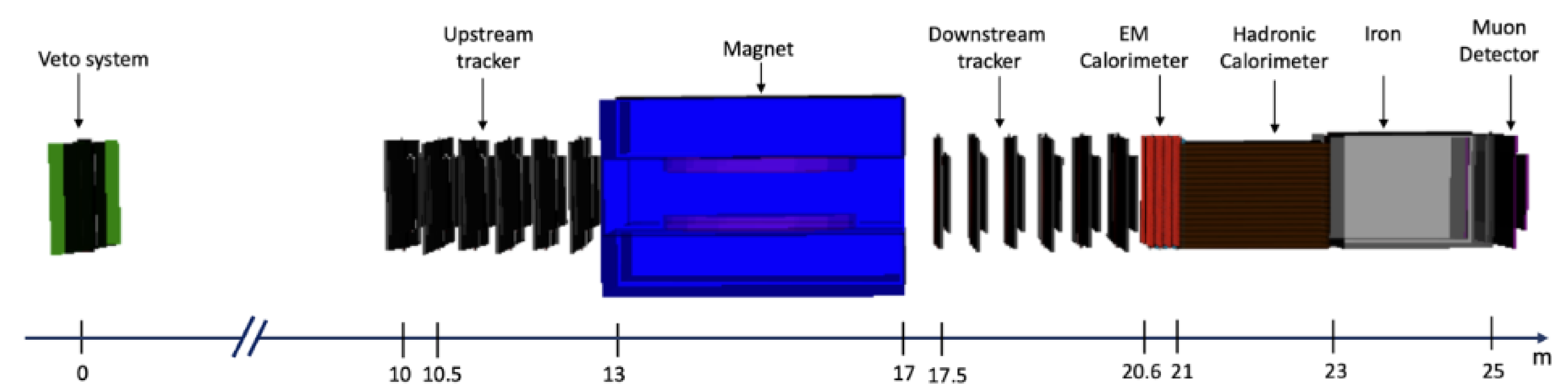
https://arxiv.org/abs/1707.04591

Proposed LHC-adjacent Long-Lived Particle Detectors

Example: Forward Physics Facility



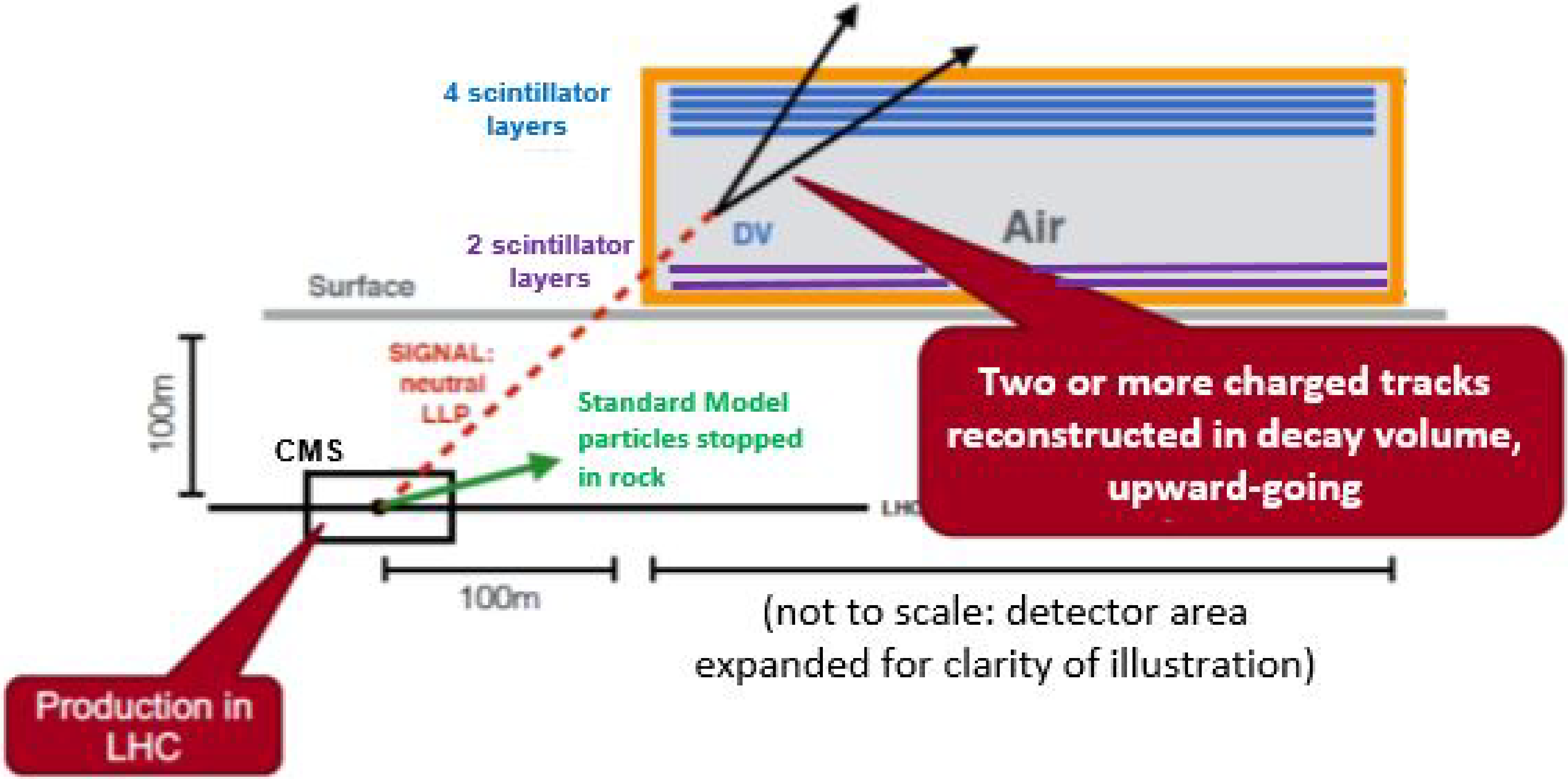
Example: FASER2 at Forward Physics Facility



BSM signal searches would include dark Higgses, heavy neutral leptons, axion-like particles, …

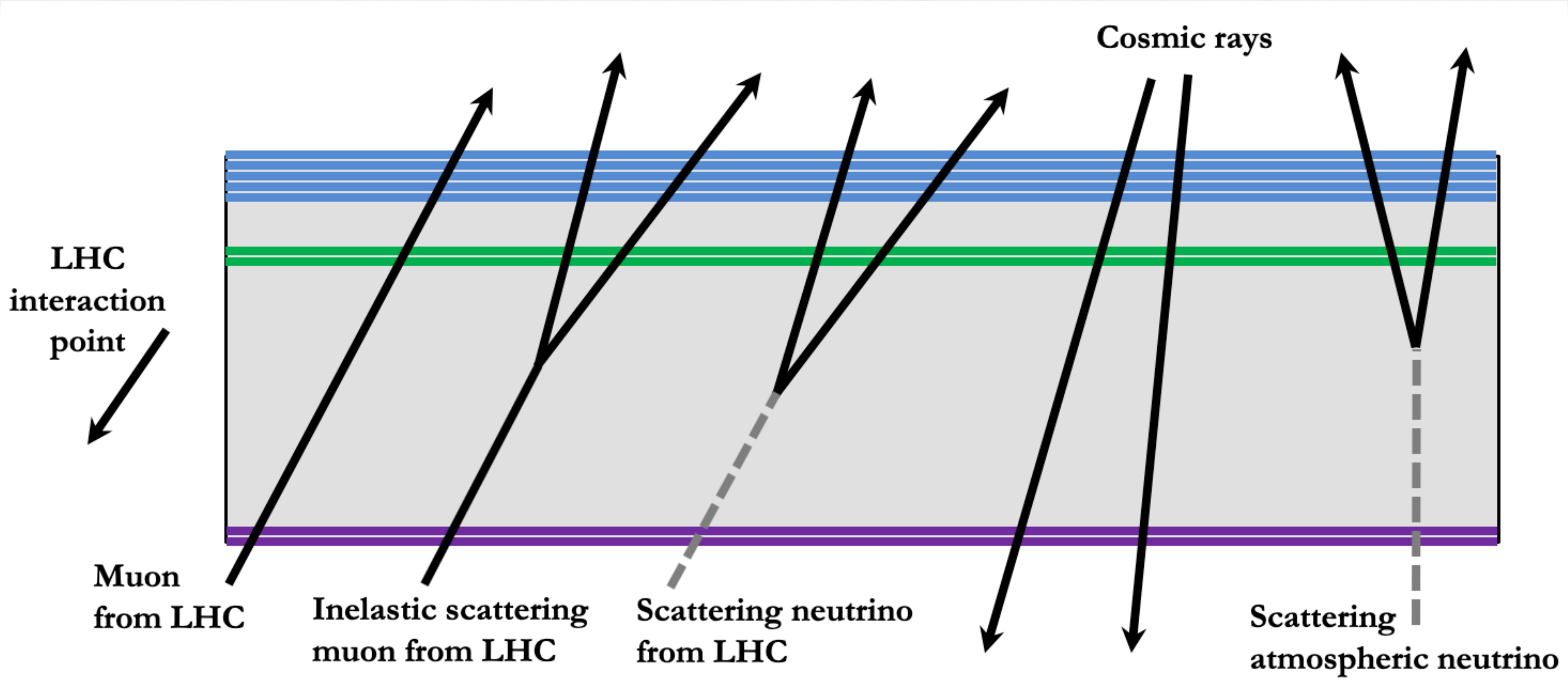
Example: MATHUSLA

MAssive **T**iming **H**odoscope for **U**ltra-**S**table Neutra**L** P**A**rticles



(not to scale: detector area expanded for clarity of illustration)

Example: MATHUSLA



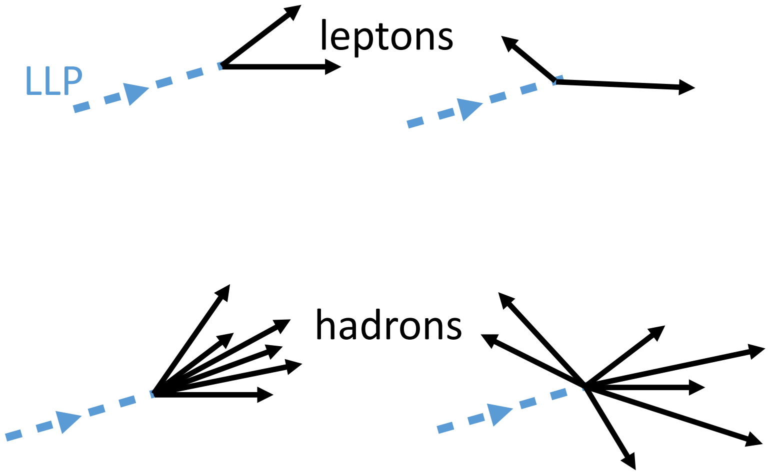
LLP displaced vertex (DV) signal has to satisfy many stringent geometrical and timing requirements ("4D vertexing" with cm/ns precision)

These requirements, plus a few extra geometry & timing cuts, provide "near-zero background" (< 1 event per year) for neutral LLP decays!

Example: MATHUSLA

MATHUSLA can't measure particle momentum or energy, but:

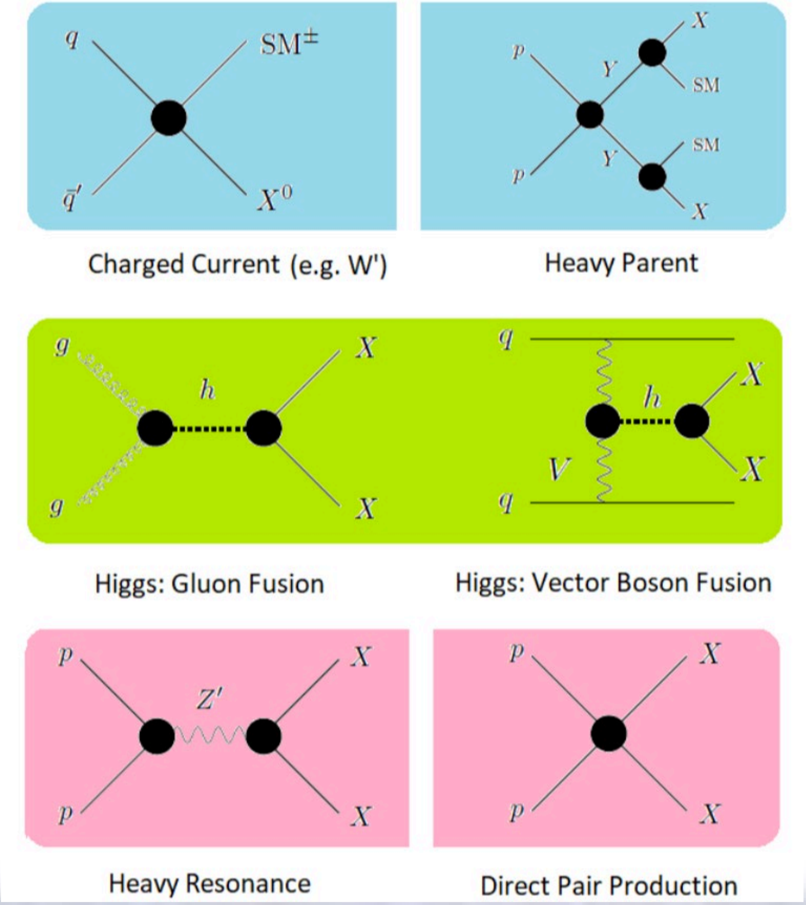
track geometry → measure of LLP boost event-by-event



arXiv:1705.06327

Incorporate MATHUSLA into CMS L1 Trigger

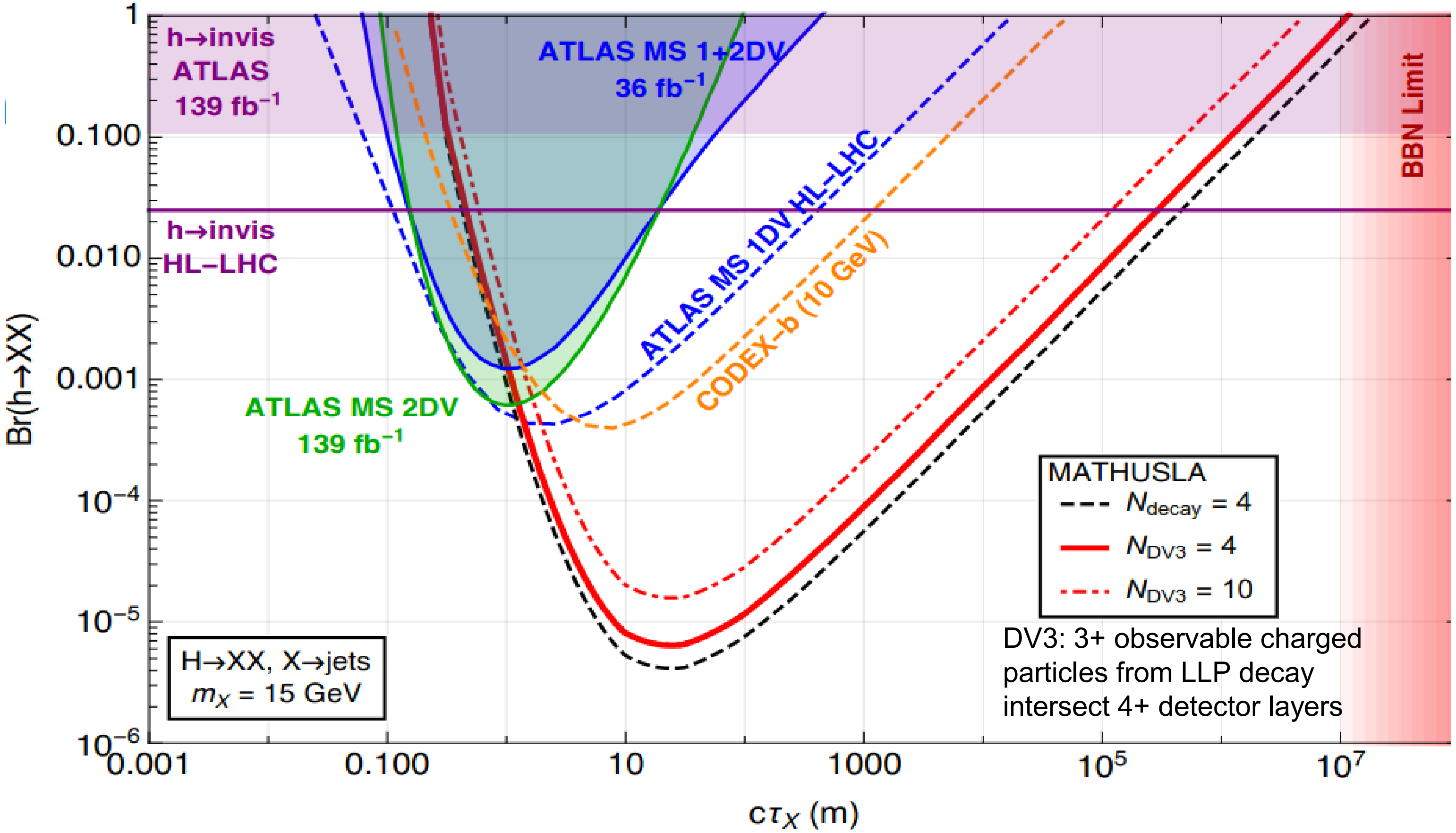
Correlate event info off-line → determine LLP production mode



Example: MATHUSLA

LLPs at weak- to TeV-scale: up to 1000x better sensitivity than LHC main detectors

e.g. hadronically-decaying LLPs in exotic Higgs decay



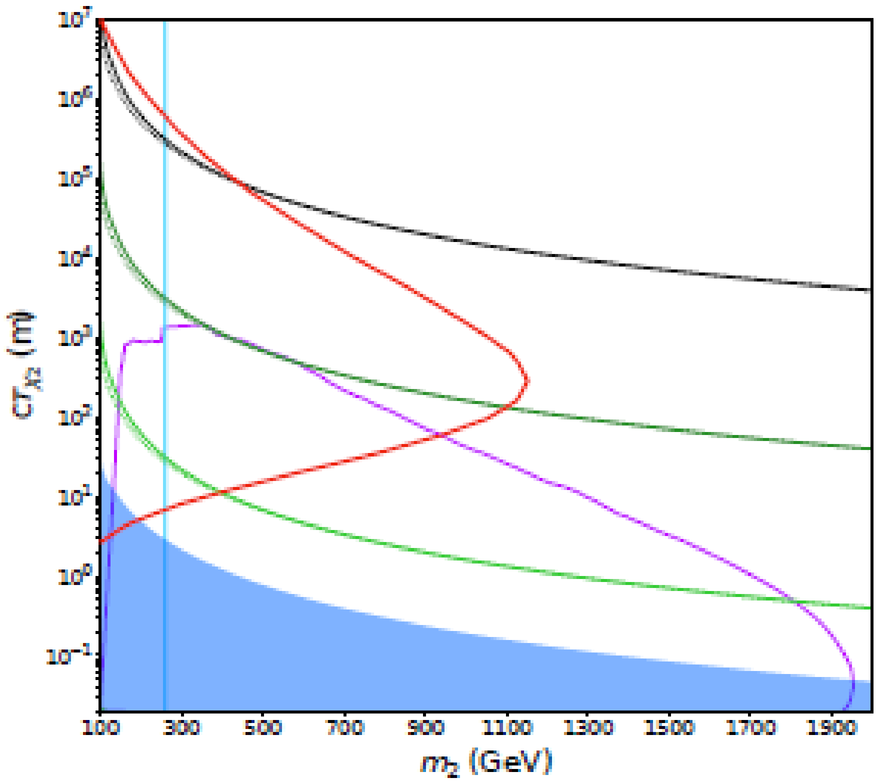
Any LLP production process with σ > fb can give signal in MATHUSLA

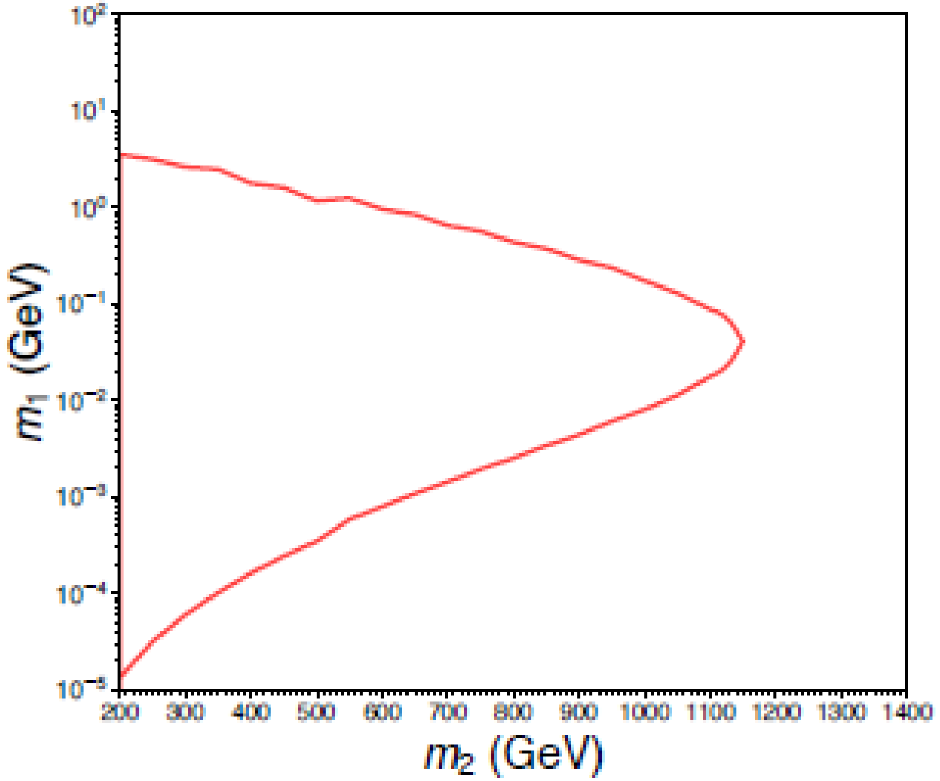
arXiv:2001.04750

Example: MATHUSLA

Scenarios where LLP → DM + SM decay is the only way to see the DM

- **e.g. Freeze-In Dark Matter: BSM mass eigenstates χ_1 (DM) and χ_2 (LLP), where χ_2 was in thermal equilibrium with primordial plasma**

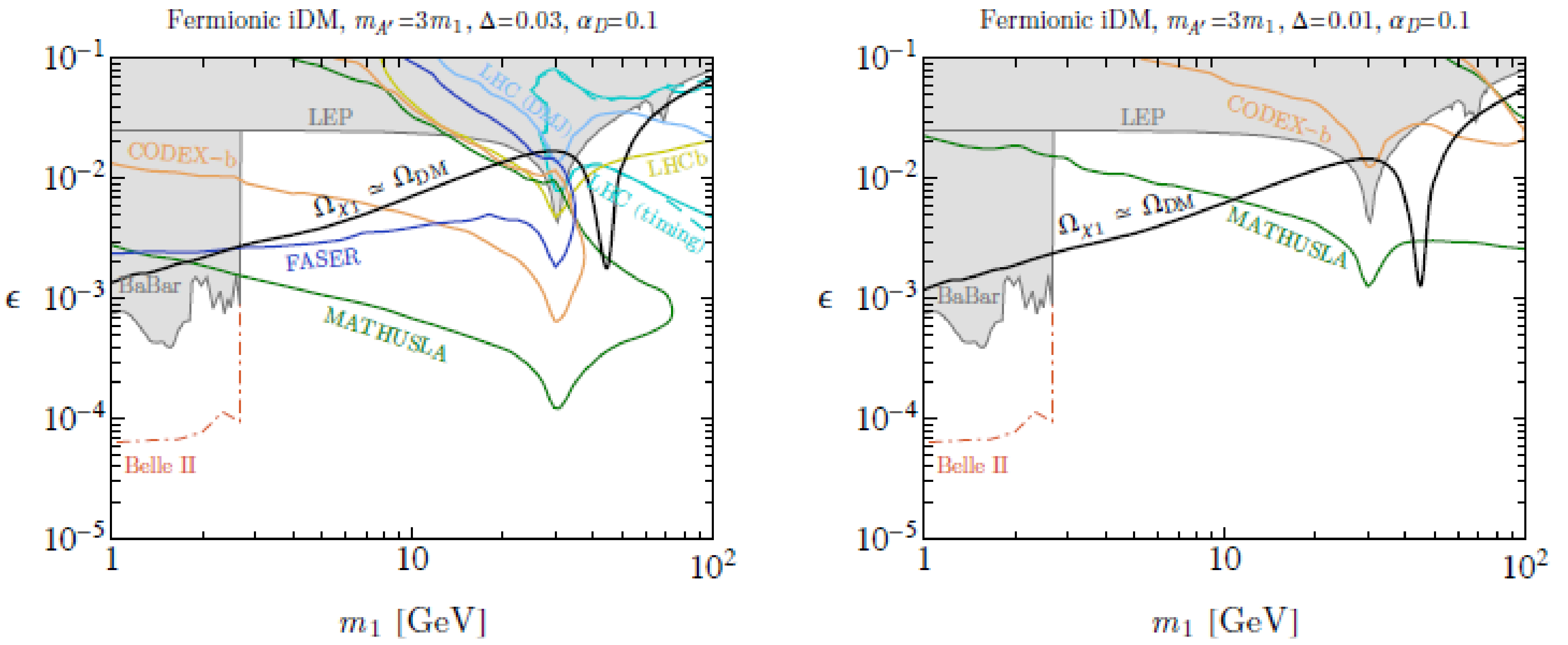




Example: MATHUSLA

Scenarios where LLP → DM + SM decay is the only way to see the DM

e.g. Inelastic Dark Matter: BSM mass eigenstates χ_1 (DM) and χ_2 (LLP) with mass splitting Δ , dark photon A' with mixing ϵ with SM photon



Black curve: thermal o-annihilations $\chi_2\chi_1 \rightarrow A' \rightarrow f\bar{f}$ yield observed DM relic density

Example: MATHUSLA

Scenarios where DM model requires existence of LLP, but LLP signature does not involve the DM particle directly

e.g. Co-Annihilating DM: BSM χ and χ_2 with mass splitting δ,

$\chi\,\chi_2 \rightarrow \phi\phi$ where scalar ϕ has mixing angle θ with SM Higgs