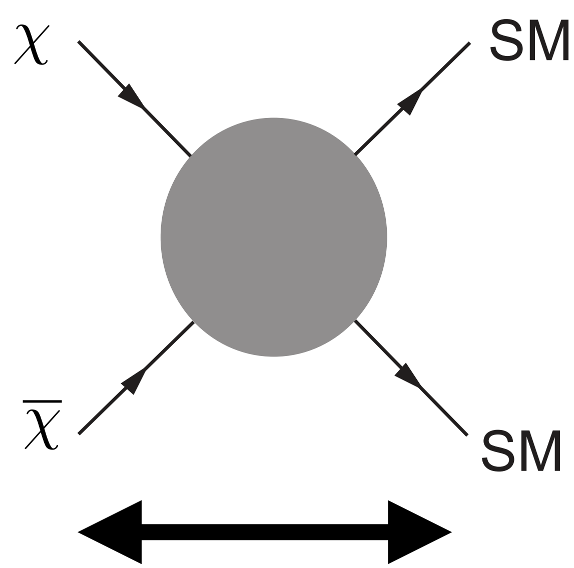
Probing the Dark Sector with Accelerator Experiments

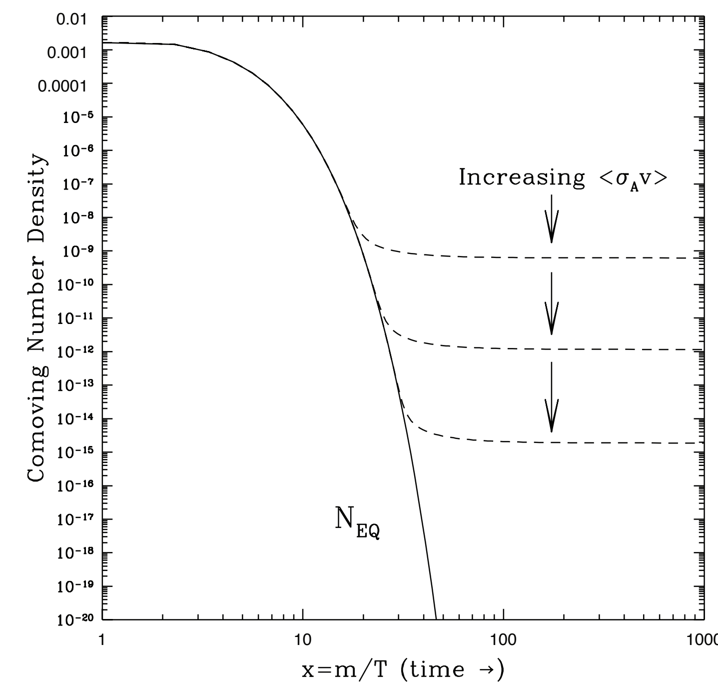
Brian Batell
University of Pittsburgh

TeVPA 2024
August 26-30, 2024

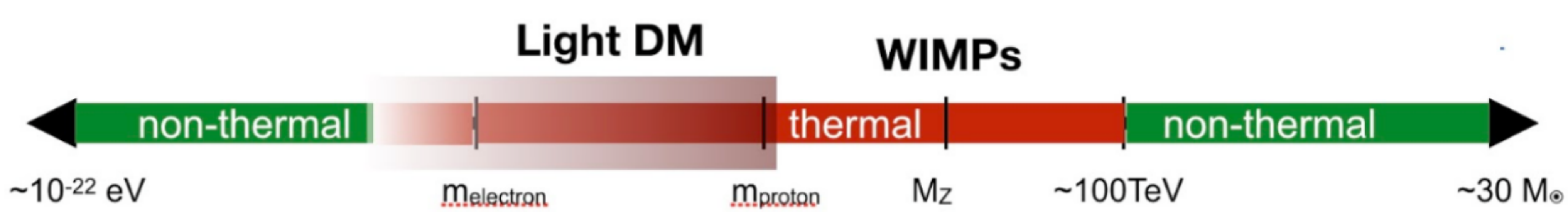
Motivation: dark matter as a thermal relic

- Basic idea: dark matter produced from reactions in the plasma during the Big Bang
- Requires non-gravitational dark matter interactions with the Standard Model





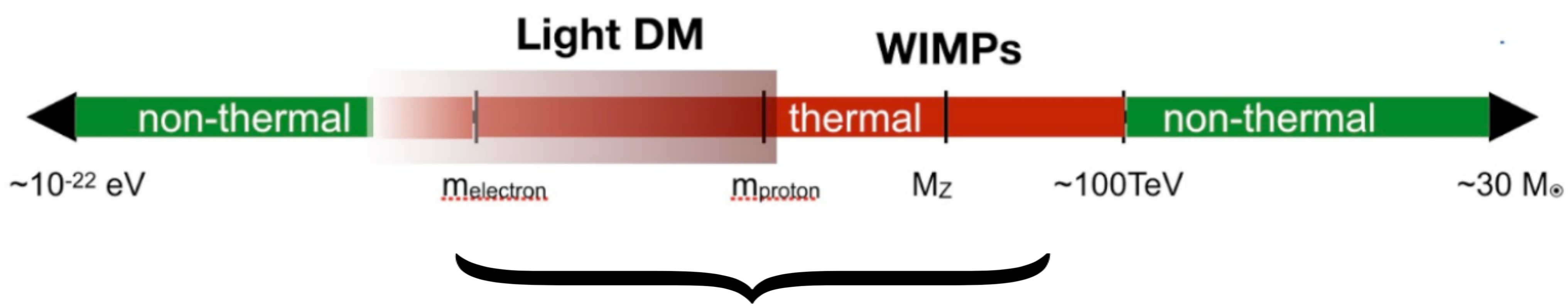
- Viable DM mass range between MeV - 10 TeV in simplest scenarios



See next talk by J. Ruderman for variations of thermally produced dark matter

Thermal dark matter at accelerator experiments

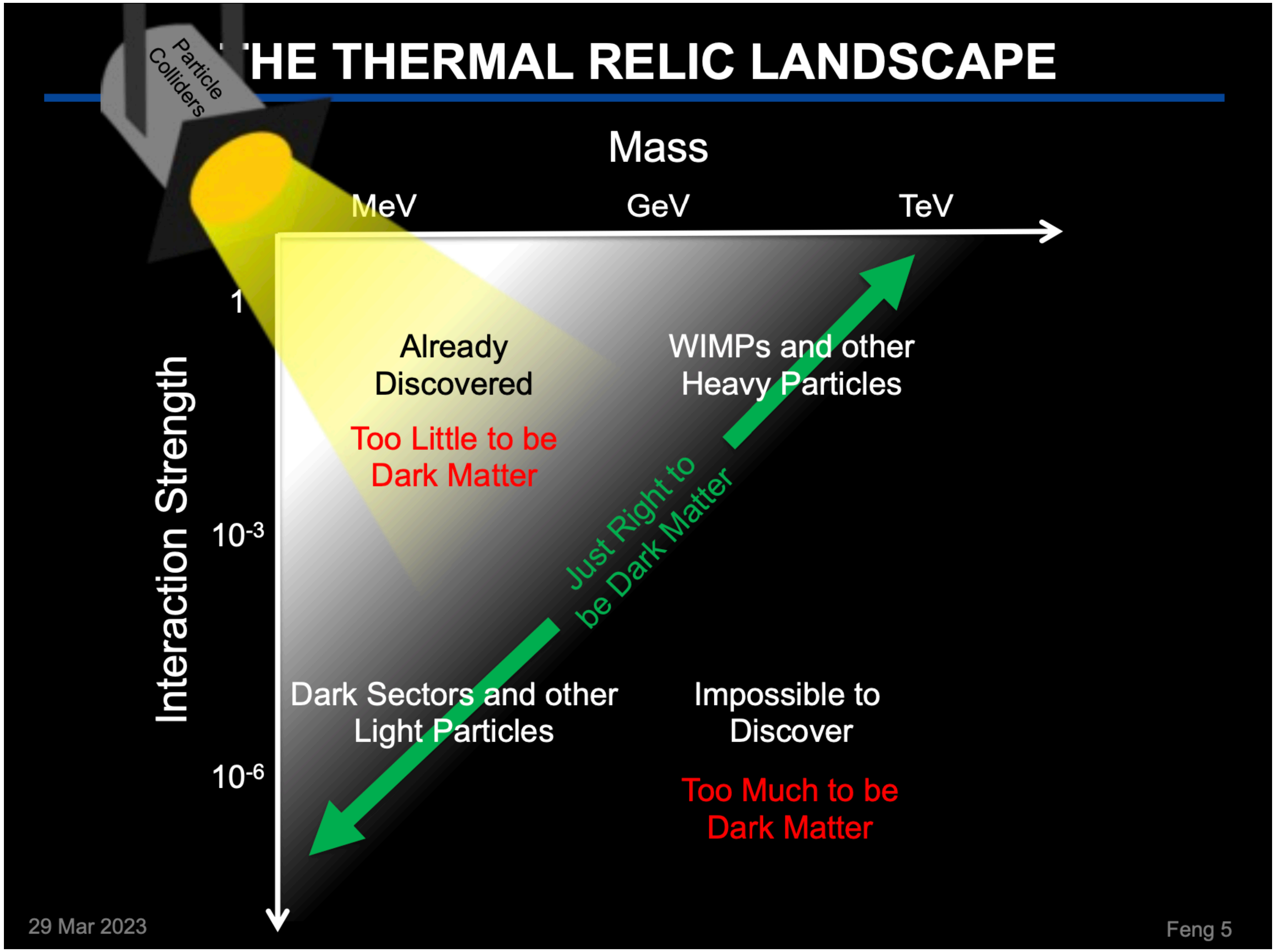
- Basic idea: collide Standard Model particles produce dark matter
- Same interaction governs DM annihilation and laboratory DM production



Thermal dark matter masses
are accessible at accelerators

- Upper bound: $m_{\rm DM} \sim$ TeV
  - Kinematic limit, maximum collider center-of-mass energy

- Lower bound: $m_{\rm DM} \sim$ MeV
  - Lighter DM typically strongly constrained by astrophysics and cosmology (stellar energy loss, modifications to nucleosynthesis, …)



[Figure from J. L. Feng]

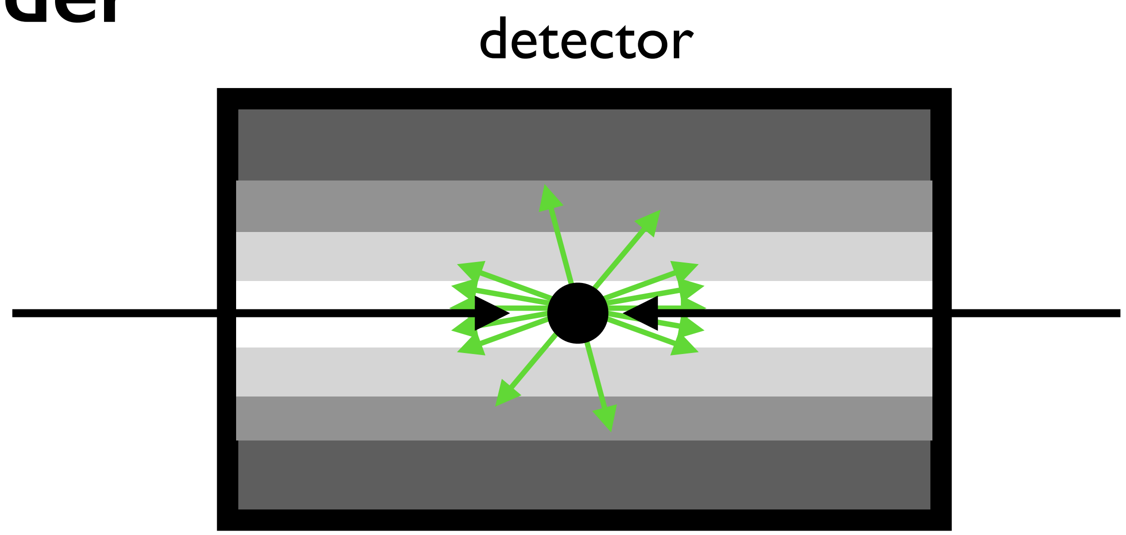
Non-gravitational coupling strengths required for thermal dark matter are accessible at accelerator experiments

Why accelerator experiments?

- Produce and study dark matter in a controlled laboratory setting
- Measure dark matter properties (mass, spin, couplings,…)
- Unlike direct and indirect detection, accelerator searches are not dependent on astrophysical assumptions
- Probe a variety of dark matter interaction channels
- Produce additional dark states associated with dark matter and probe the structure of the dark sector
- Dream scenario: reconstruct the dark matter thermal history!

Accelerator experiments: collider vs. fixed target

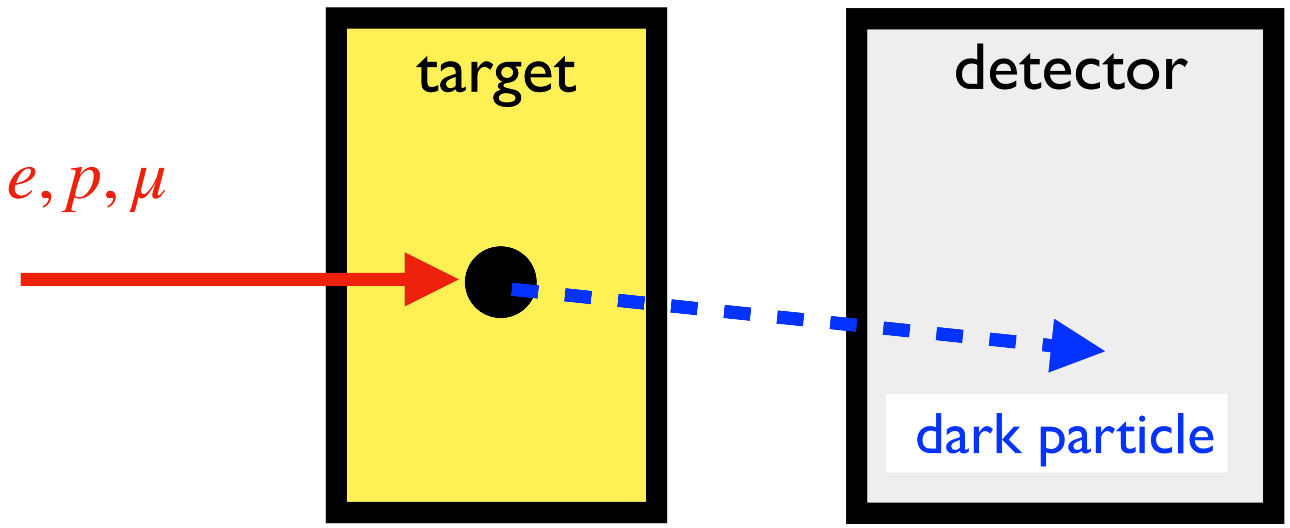
Collider



Advantages:
- higher center-of-mass energy
- hermetic detector, full event reconstruction

➡ ideal for WIMP searches

Fixed-target

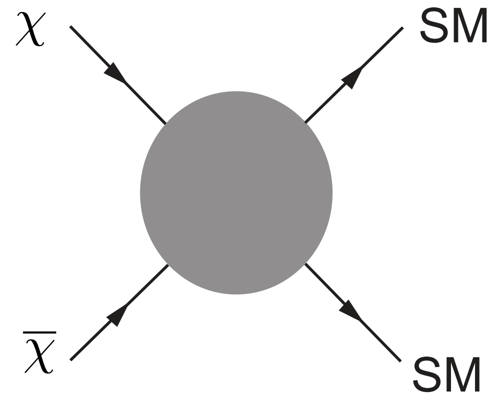


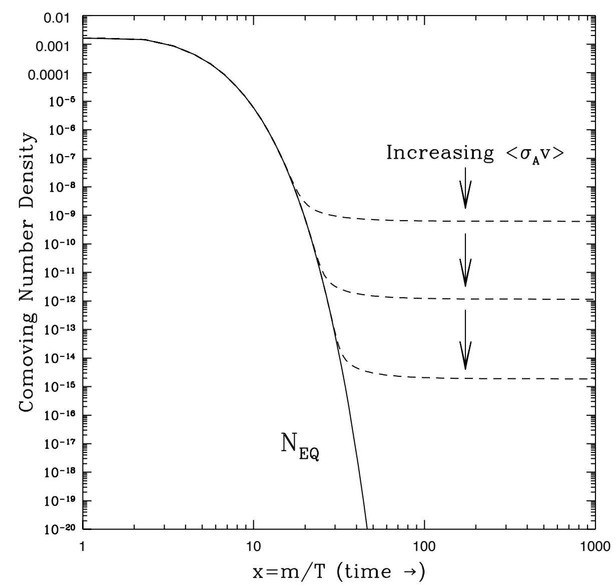
Advantages:
- high collision luminosity
- forward kinematics
- large production rates
- clean detector environment

➡ ideal for light sub-GeV dark matter searches

WIMPs

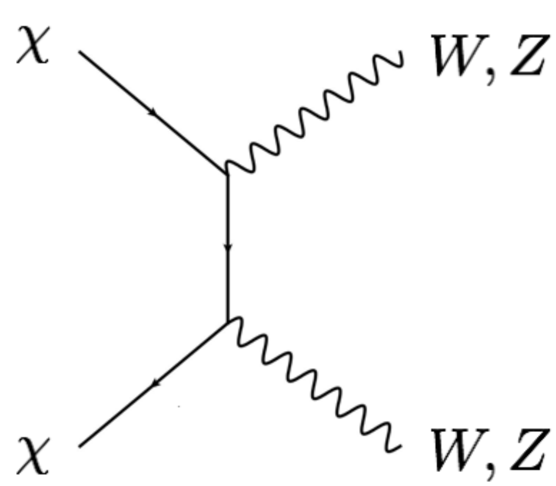
- "WIMP miracle" suggests dark matter mass scales in vicinity of weak scale



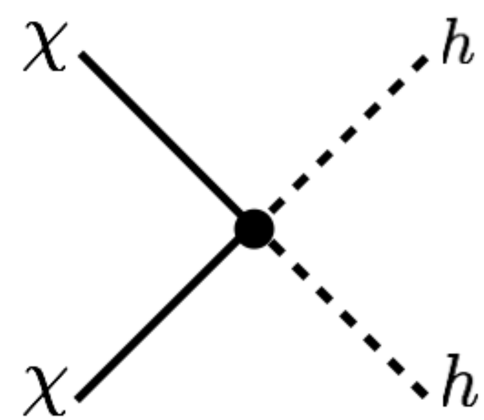


$$\langle \sigma v \rangle \sim \frac{\pi \alpha_W^2}{m_\chi^2} \sim 1\,\mathrm{pb} \times \left(\frac{\alpha_W}{(1/30)}\right)^2 \left(\frac{\mathrm{TeV}}{m_\chi}\right)^2$$

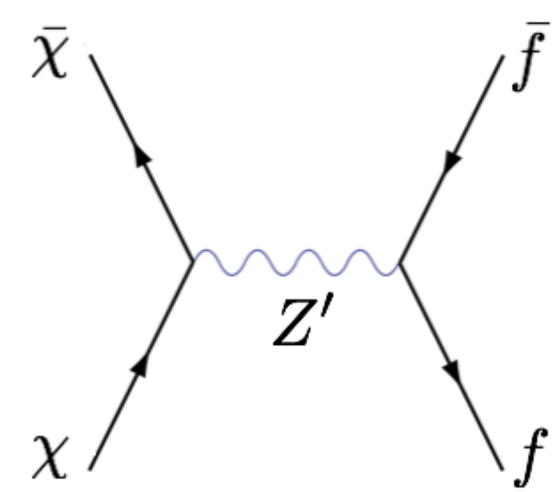
- Numerous model realizations



Electroweak DM



Higgs portal



BSM mediator
(Z', sfermion, etc.)

Electroweak dark matter

- Neutral component of $SU(2)_L \times U(1)_Y$ multiplet
  - Higgsino, Wino in MSSM
  - Minimal Dark Matter [Cirelli, Fornengo, Strumia]
- (co-) Annihilation to weak gauge bosons; observed relic abundance achieved for ~ 1 TeV Higgsino and ~ 3 TeV Wino
- Indirect probes (gamma rays) are placing relevant constraints on electroweak dark matter [Cohen, Lisanti, Pierce, Slatyer; Fan, Reece; +more recent studies]

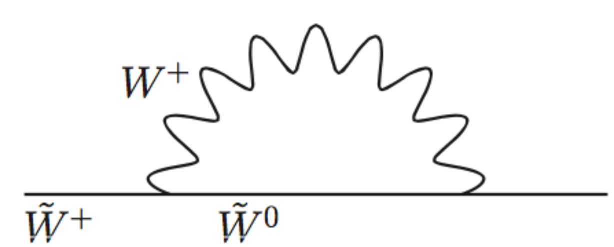
  See talks by T. Slatyer, M. Baumgart, W. L. Xu
- SI nuclear scattering suppressed (loop level + accidental cancellation)

$$\sigma_n \sim 10^{-47} - 10^{-49}\ \mathrm{cm}^2$$

[Hisano, Ishiwata, Nagata]
[Hill, Solon]

- Radiative mass splitting of electroweak multiplet:

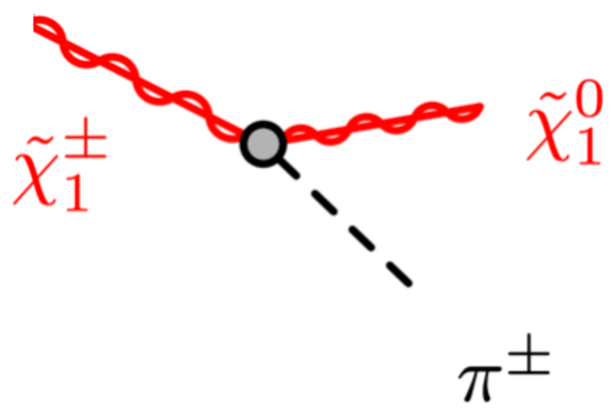
$$M_\pm - M_0 \approx \begin{cases} 300\,\mathrm{MeV} & \text{(Higgsino)} \\ 160\,\mathrm{MeV} & \text{(Wino)} \end{cases}$$

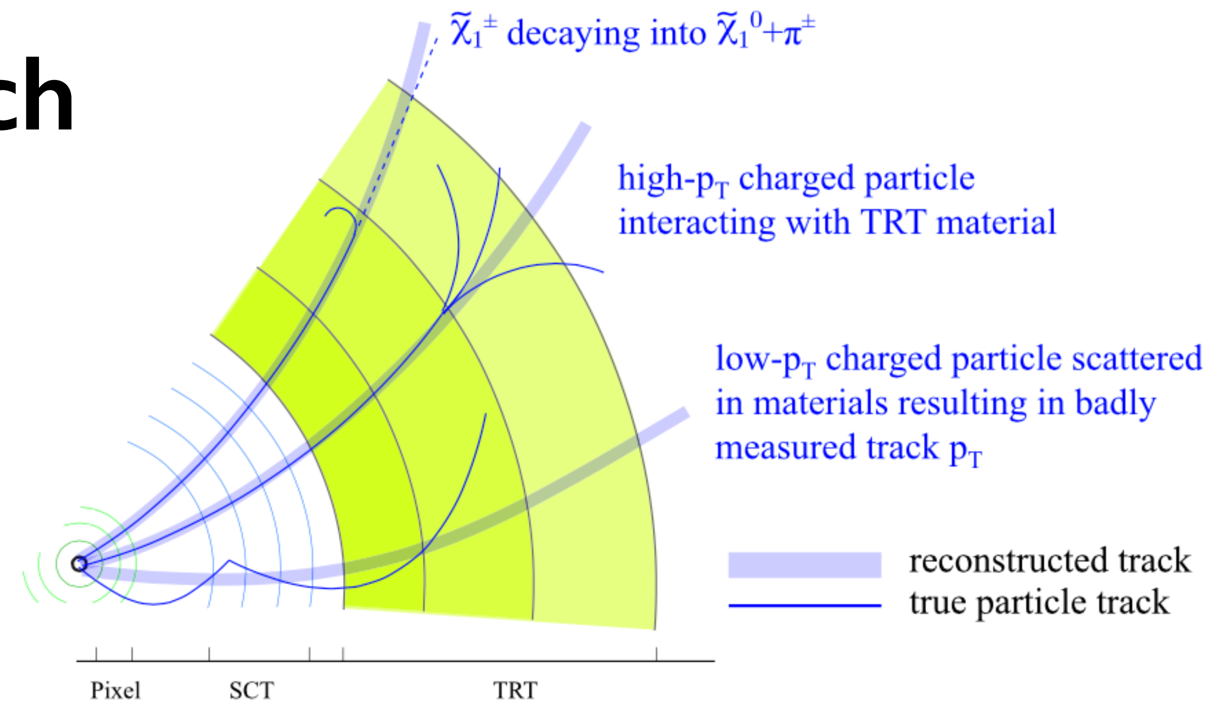


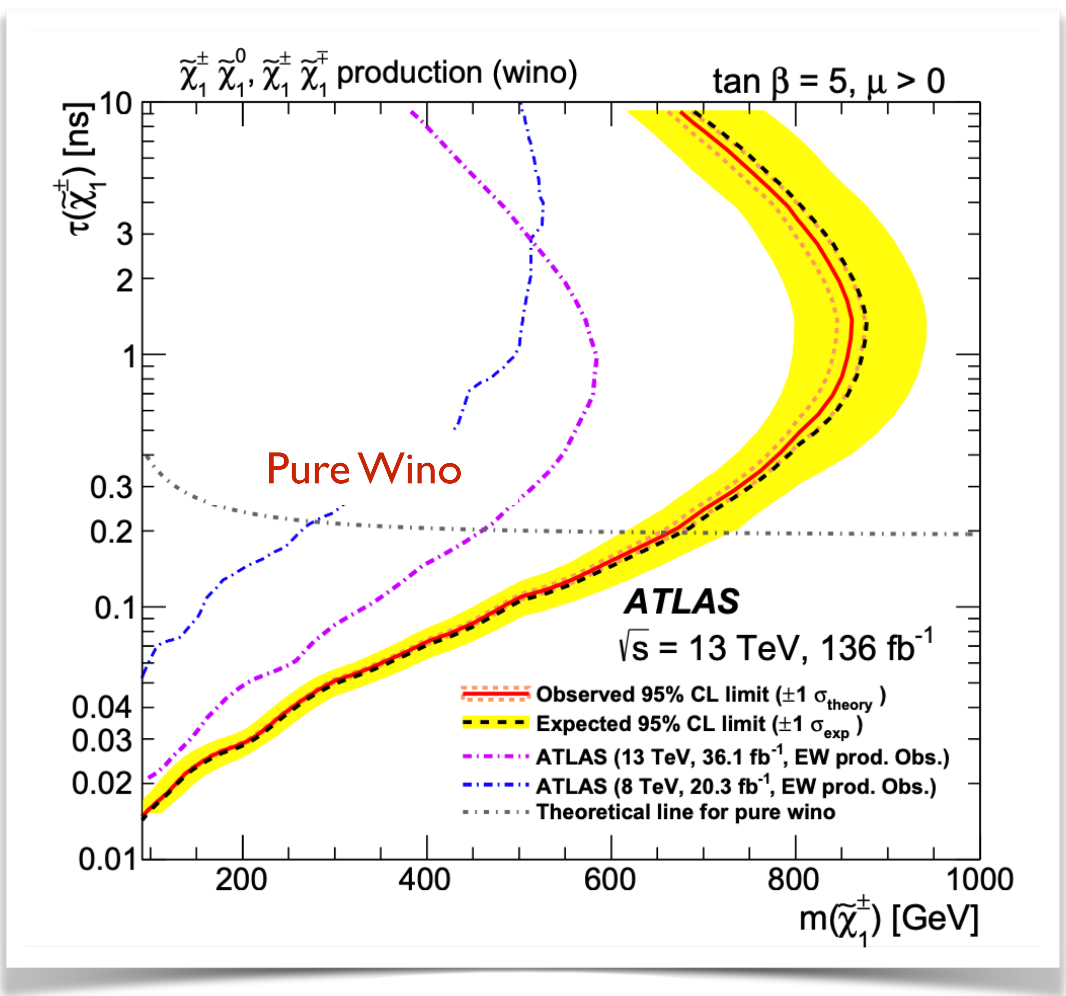
[Thomas, Wells; Ibe, Matsumoto, Sato]

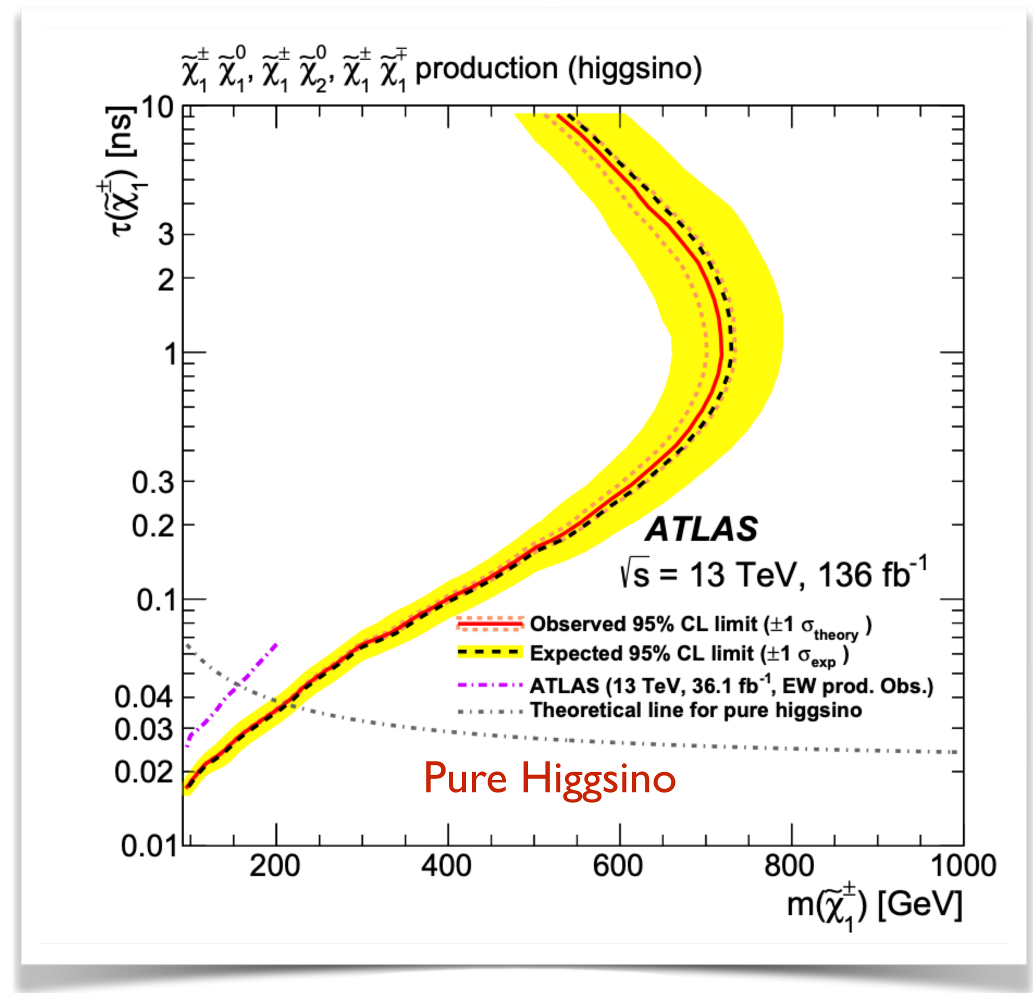
→ renders charginos long-lived, visible decay products soft

Disappearing track search



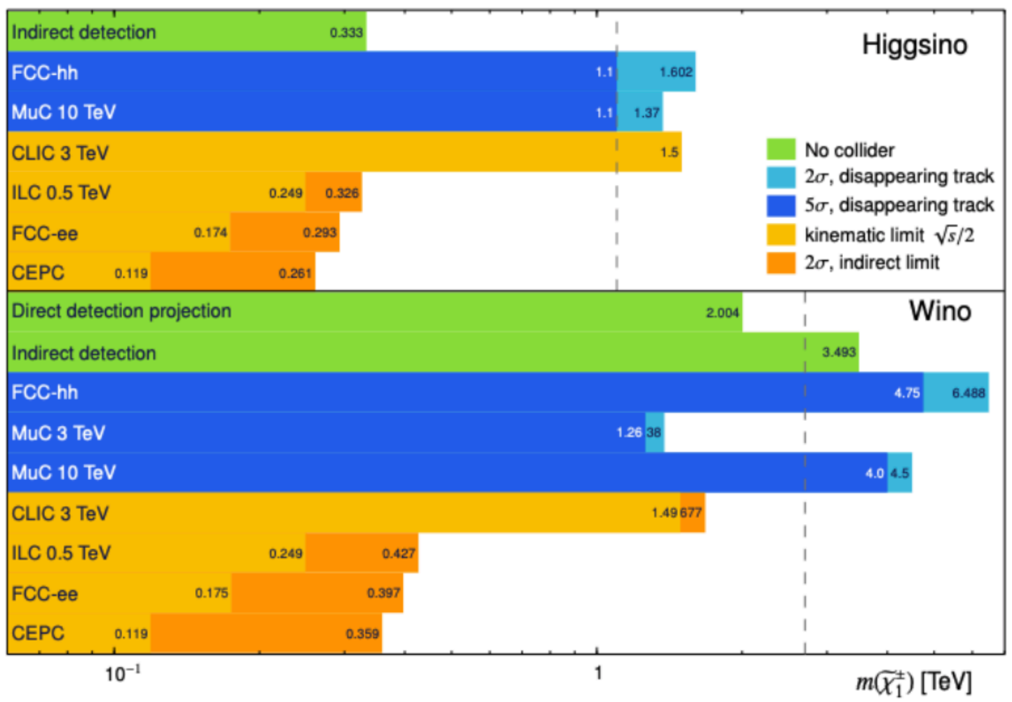




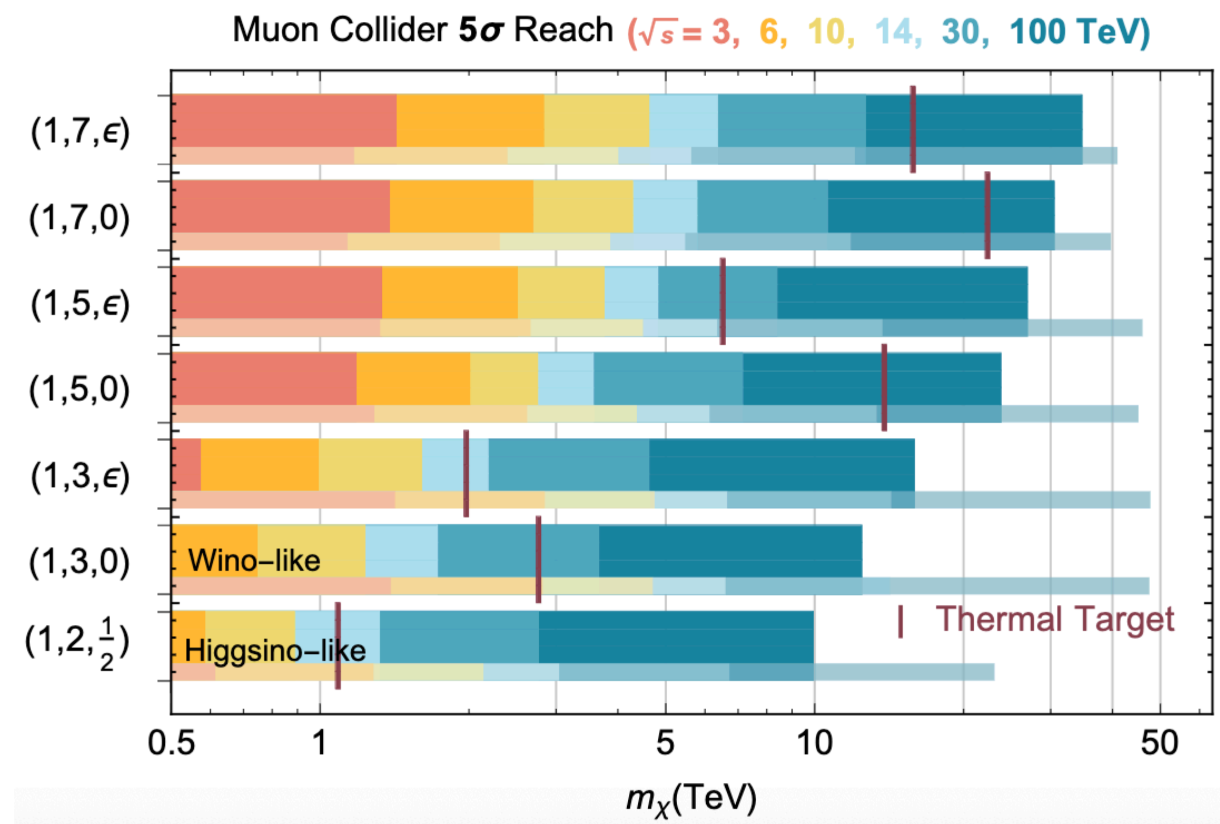


LHC has pushed beyond LEP limits, but thermal target out of reach

Electroweak DM at future colliders



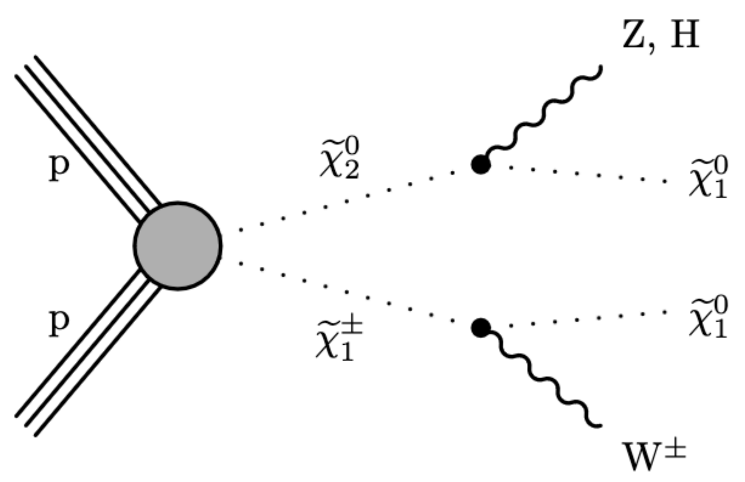
[Capdevilla, Meloni, Simoniello, Zurita]

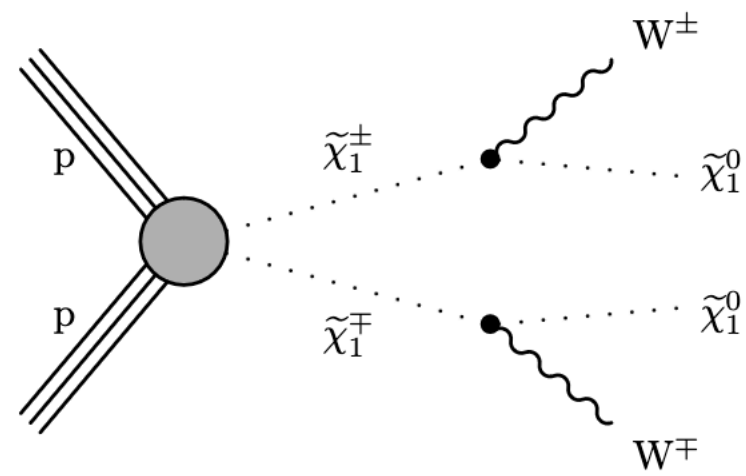


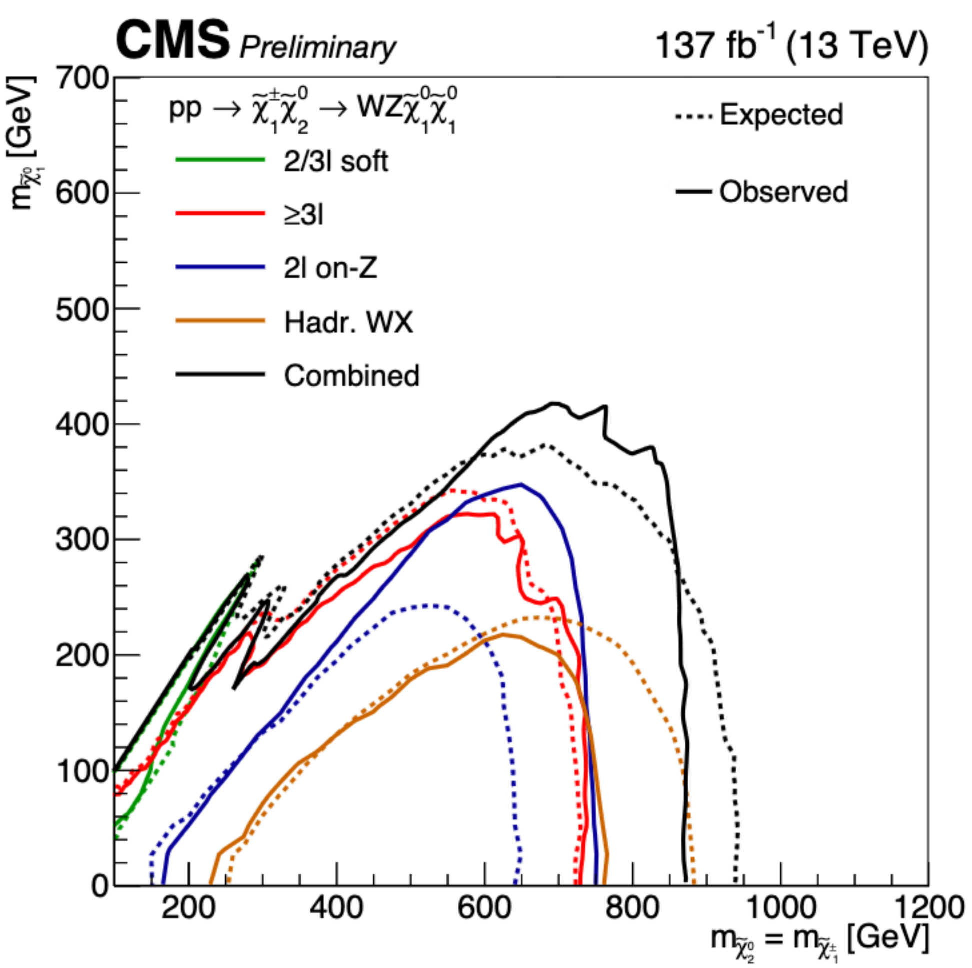
[Han, Liu, Wang, Wang]

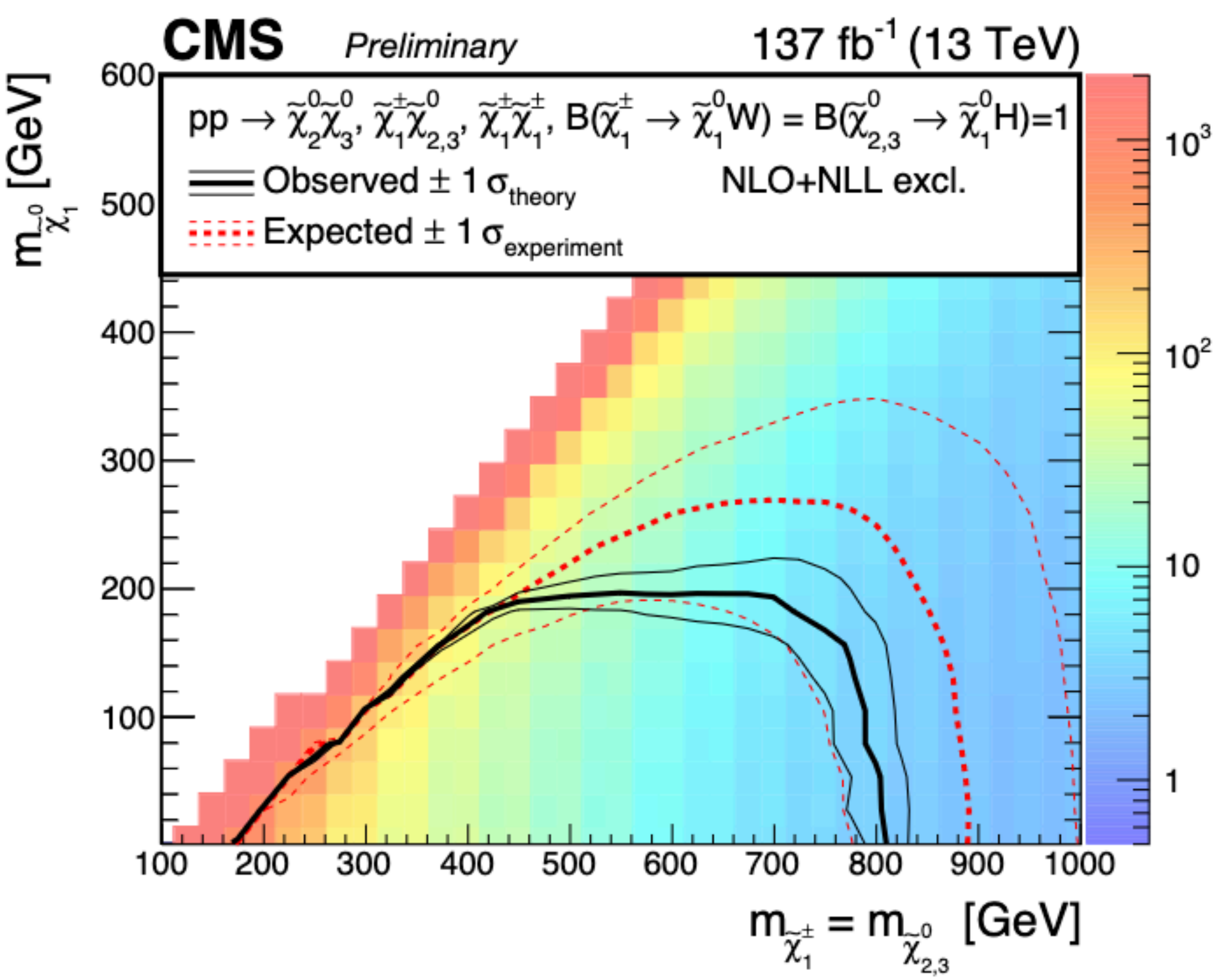
Both FCC-hh and a high-energy muon collider have the potential to test the Higgsino and Wino thermal targets

Electroweakino searches









Dark matter at the LHC

For overview, see
LHC Dark Matter Working Group Recommendations
CERN-LPCC-2017-01

EFT ➡ Simplified Models ➡ UV completions

- Bottom up approach (as opposed to SUSY DM)

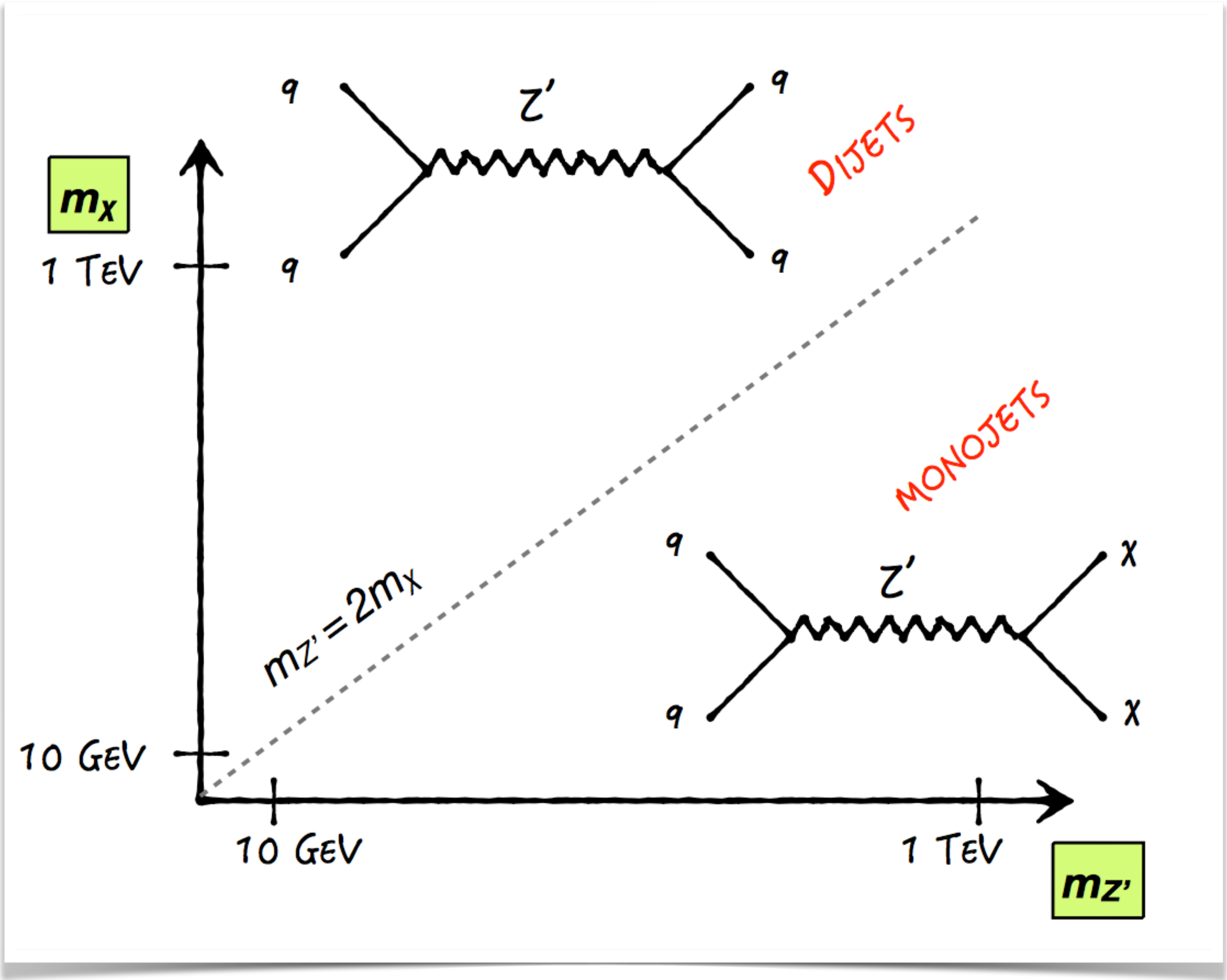
- EFT approach led to Mono-jet and a host of other Mono-X signatures

[Beltran, Hooper, Kolb, Krusberg, Tait;
Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu;
Bai, Fox, Harnik; + many other studies]

- Concerns regarding validity of EFT, unitarity violation, etc. prompted exploration of simplified models
  - Different kinematics, adjustments to search strategies, and new signals/searches for mediators

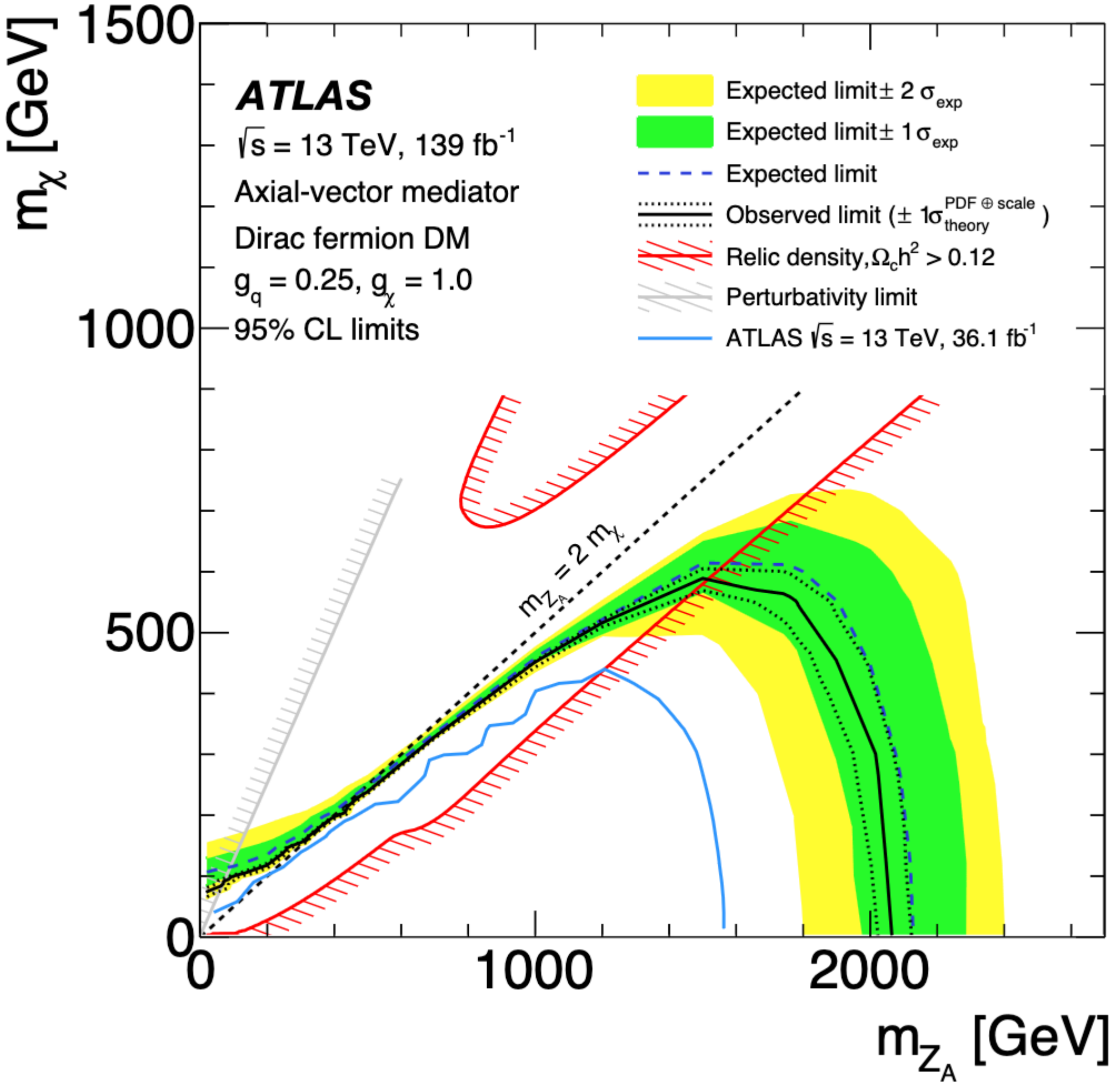
- Explorations of UV completions of simplified models - additional model-dependent phenomenology (but often different from SUSY DM)

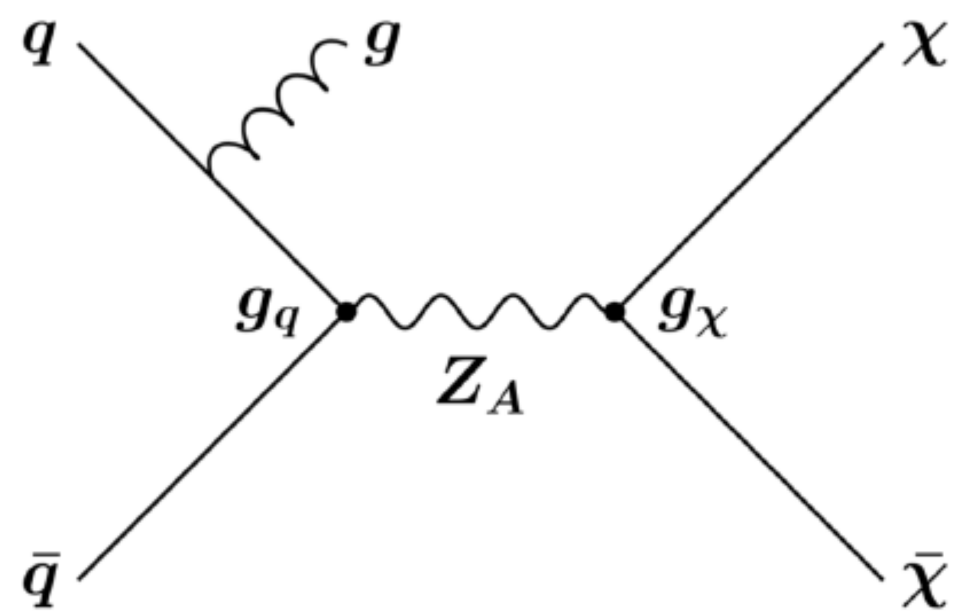
Monojet vs. Dijet



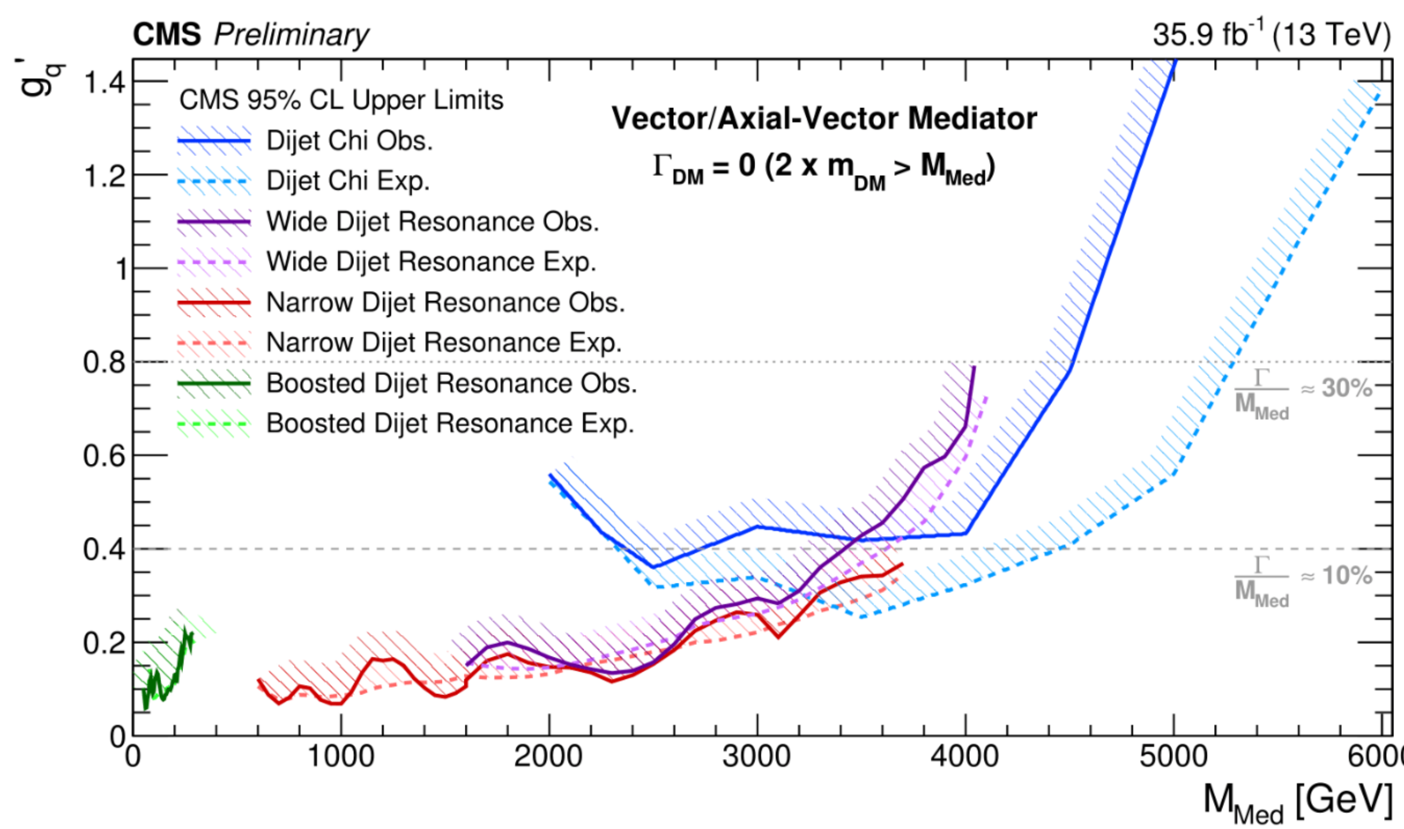
[Figure from N. Saoulidou]

Mono-jet





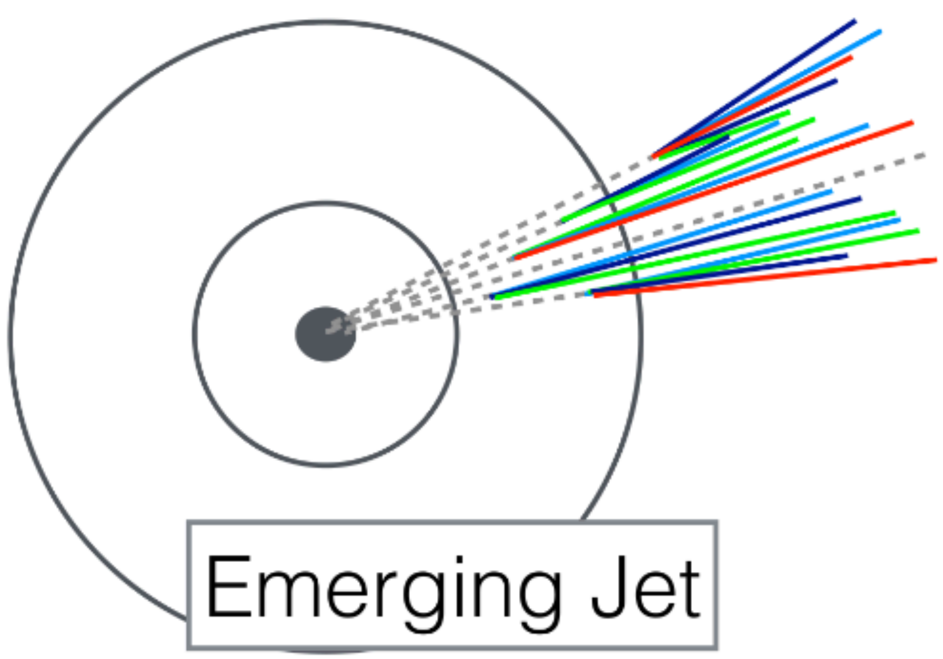
Di-jet

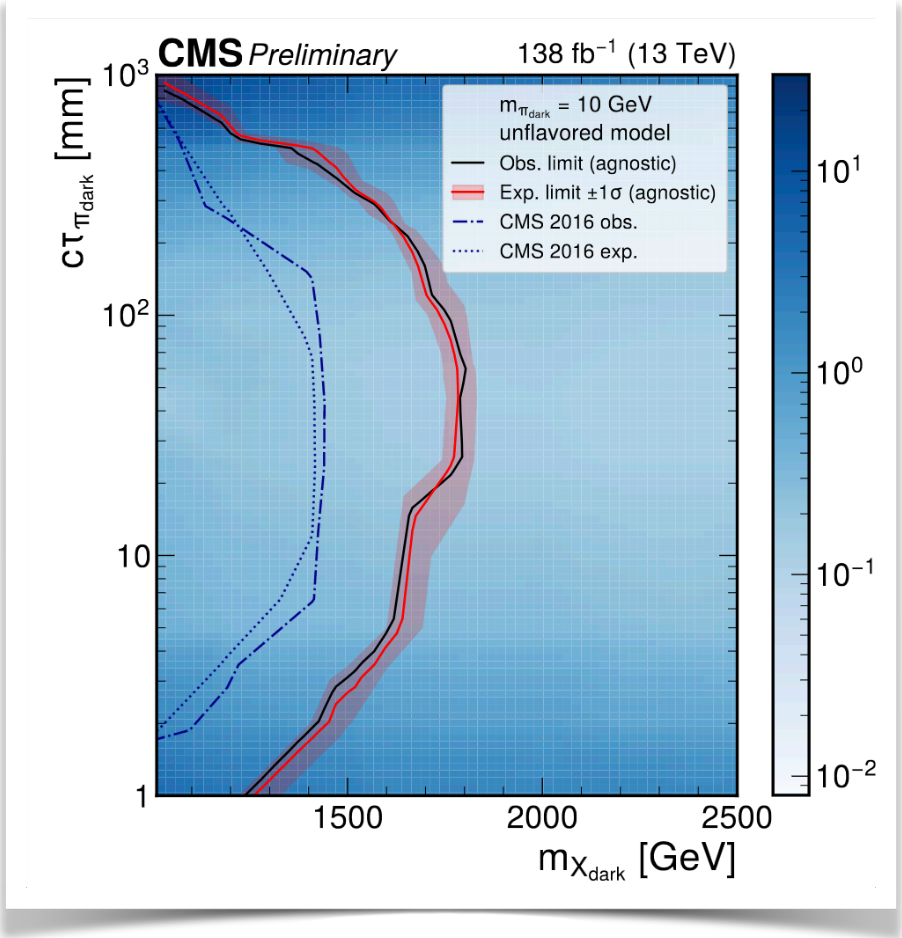


Dark Showers, Emerging Jets, Semi-visible Jets, …

[Schwaller, Stolarski, Weiler; Cohen, Lisanti, Lou; + others]

- Basic scenario: dark matter is part of a confining dark sector, which interacts with the Standard Model via a portal
- This can lead to novel signatures at the LHC, such as emerging or semi-visible jet, which require dedicated search strategies.





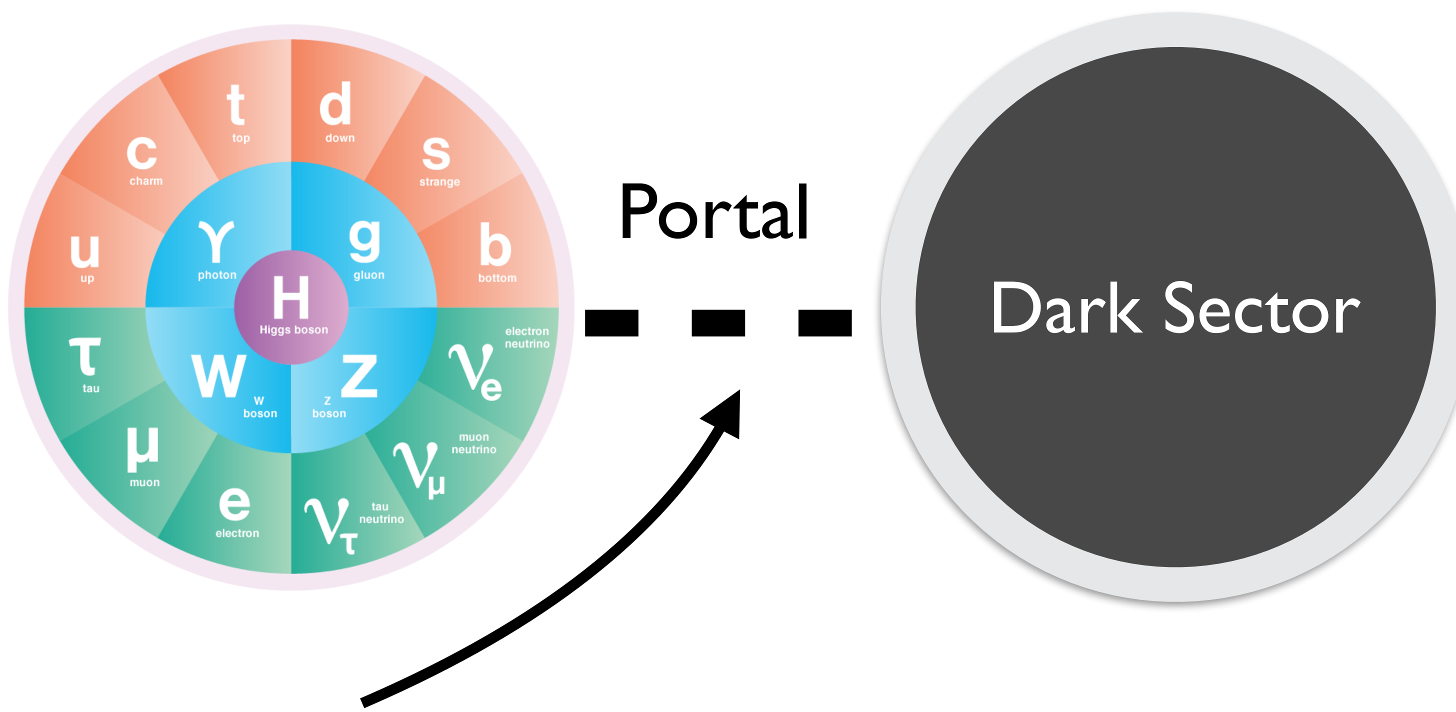
- This is an active field with opportunities for novel searches!

[For an overview, see the Dark Showers Snowmass report, arXiv:2203.09503]

Light dark matter and dark sectors

- Light (sub-GeV) dark sectors are an interesting framework for dark matter
- Relic abundance may be generated via thermal freezeout
- Extension of the WIMP below Lee-Weinberg bound — Requires new interactions beyond weak interaction

[Boehm, Fayet]
[Pospelov, Ritz, Voloshin]
[Feng, Kumar]



Non-gravitational interaction with ordinary matter

Dark matter, dark forces, other dark particles, …

Dark Sectors and Portals

- There are three minimal renormalizable portals that connect the visible and dark sectors

$\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$	Vector Portal
$(A\,S + \lambda\,S^2)\,H^\dagger H$	Higgs Portal
$yNLH$	Neutrino portal

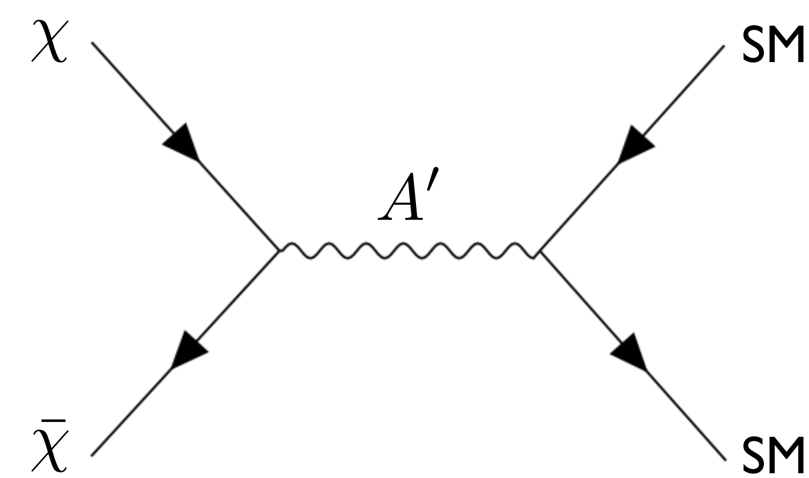
- There are other interesting options for the mediator:
  - Higher dimension portals, e.g. axion-like particle; anomaly free gauge bosons (e.g., $B - L, L_\mu - L_\tau$), etc.
  - In some cases, these mediators come with additional motivations (e.g., neutrino masses, heavy QCD axion, explanations of experimental anomalies, …)
- The dark sector itself can be minimal or have a rich structure (e.g., dark higgs, inelastic dark matter, dark confinement, …)

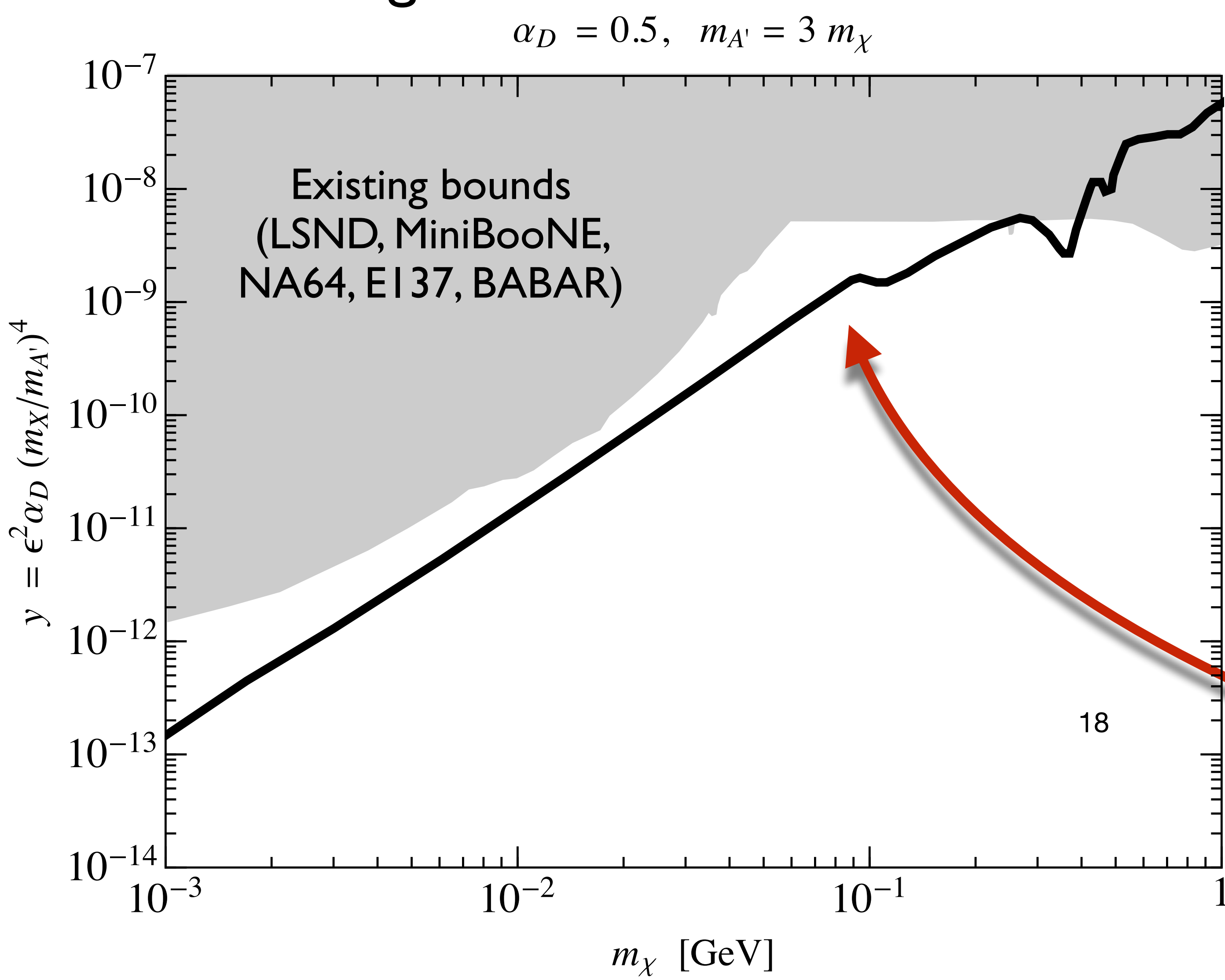
Benchmark model: Vector Portal Dark Matter

$$\mathcal{L} \supset |D_\mu \chi|^2 - m_\chi^2 |\chi|^2 - \frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2} m_{A'}^2 (A'_\mu)^2 - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \ldots$$

[Holdom]
[Pospelov, Ritz, Voloshin]

- Dark photon mediates interaction between DM and SM
- 4 new parameters: $m_\chi, m_{A'}, \alpha_D, \epsilon$
- Thermal target:





$$\langle \sigma v \rangle \sim \frac{\epsilon^2 \alpha_D \alpha m_\chi^2}{m_V^4} \sim \frac{y}{m_\chi^2}$$

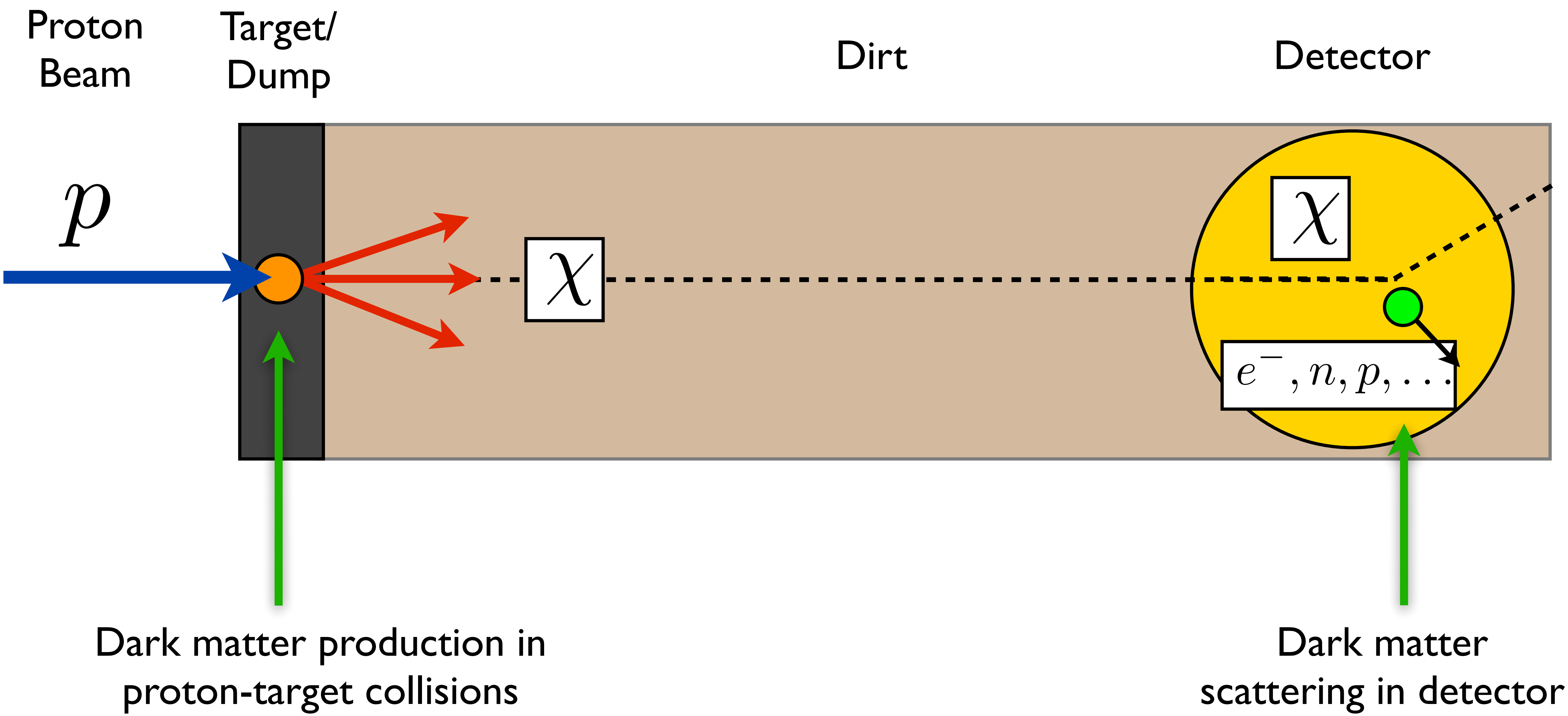
$$y \equiv \epsilon^2 \alpha_D (m_\chi / m_{A'})^4$$

Observed DM relic abundance predicted along this line

[Izaguirre, Krnjaic, Schuster, Toro]

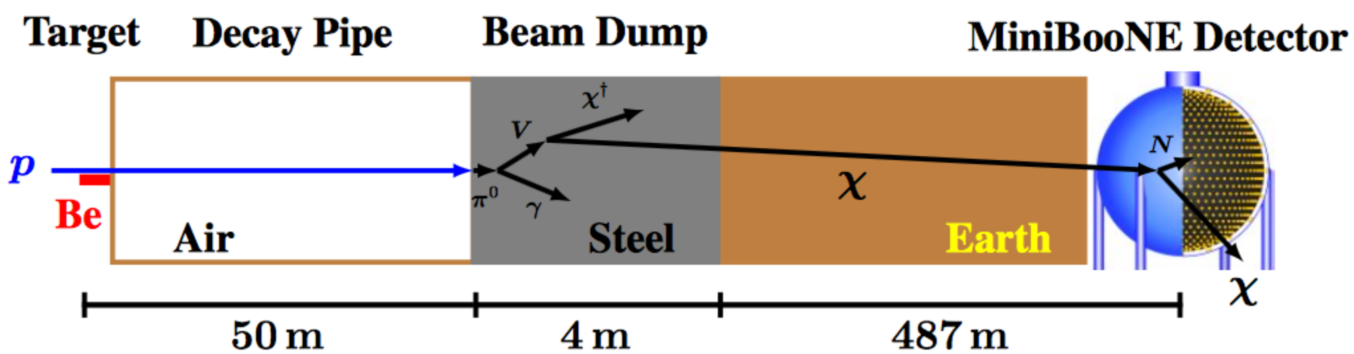
Beam Dump Search for Dark Matter

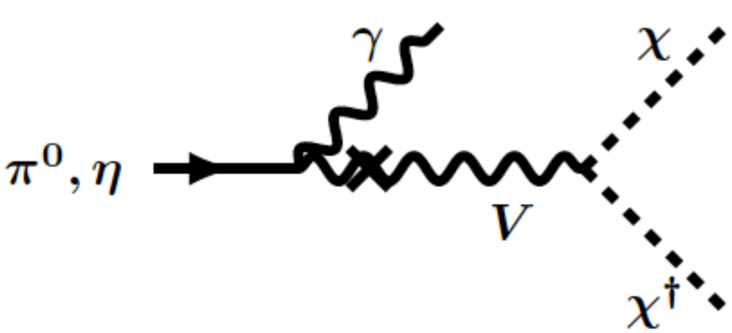
[BB, Pospelov, Ritz]



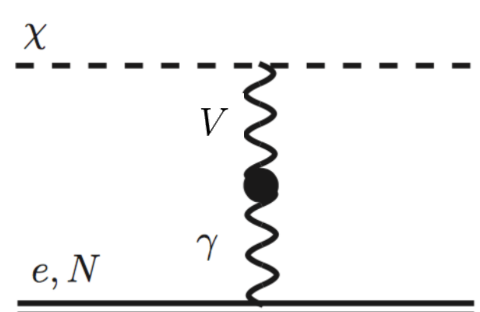
- Unique sensitivity for many models with light dark matter + light mediator
- Can be done with existing and near future accelerator neutrino experiments
  - MiniBooNE, NOvA, T2K, MicroBooNE, SBND, ICARUS, DUNE…

MiniBooNE-DM @ FNAL

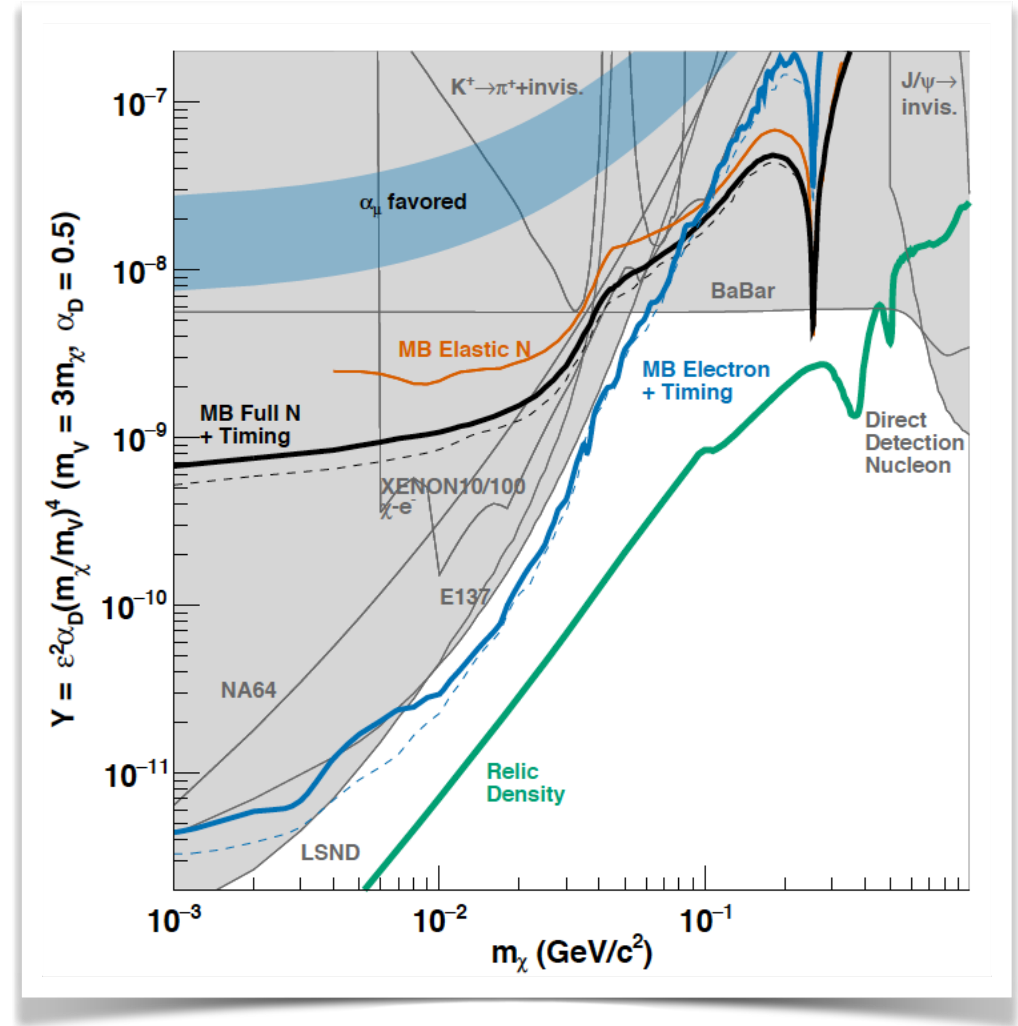




Production



Detection



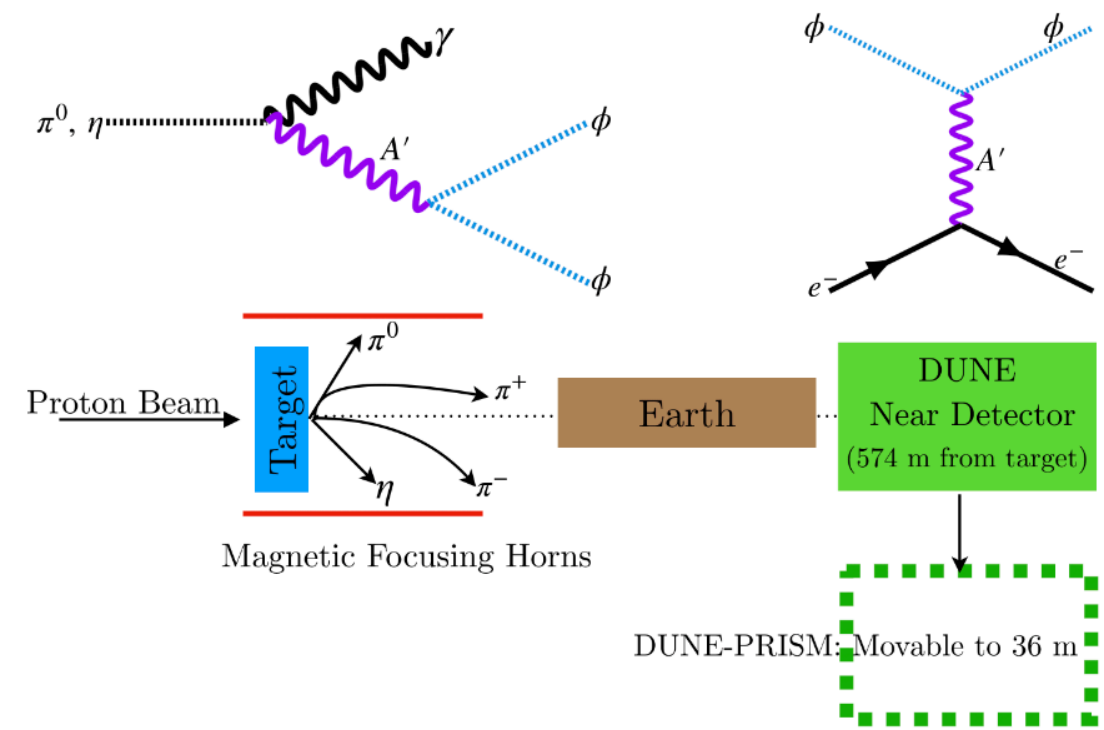
[MiniBooNE-DM
Phys. Rev. D (2018) 11, 112004]

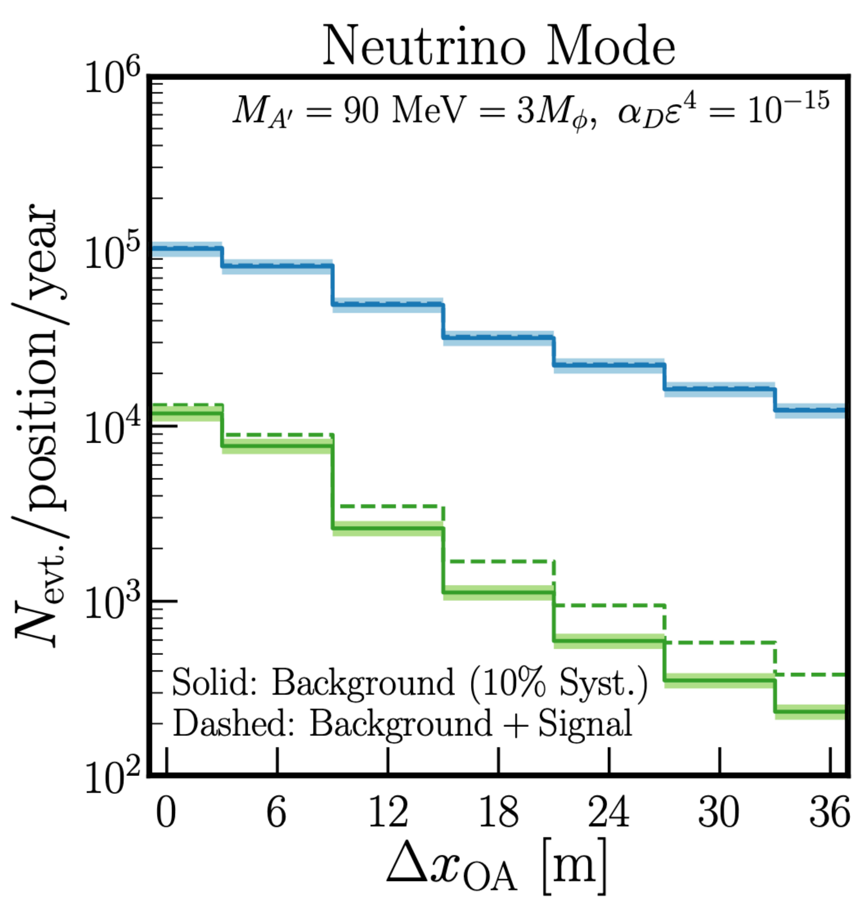
- 8 GeV protons on iron dump; 800 ton mineral oil detector
- Dedicated off target / beam dump run mode, collected 1.9E20 POT
- Leading limits on vector portal dark matter model for ~ 100 MeV mass range
- Demonstrates proton beam dump as an effective search method for light dark matter

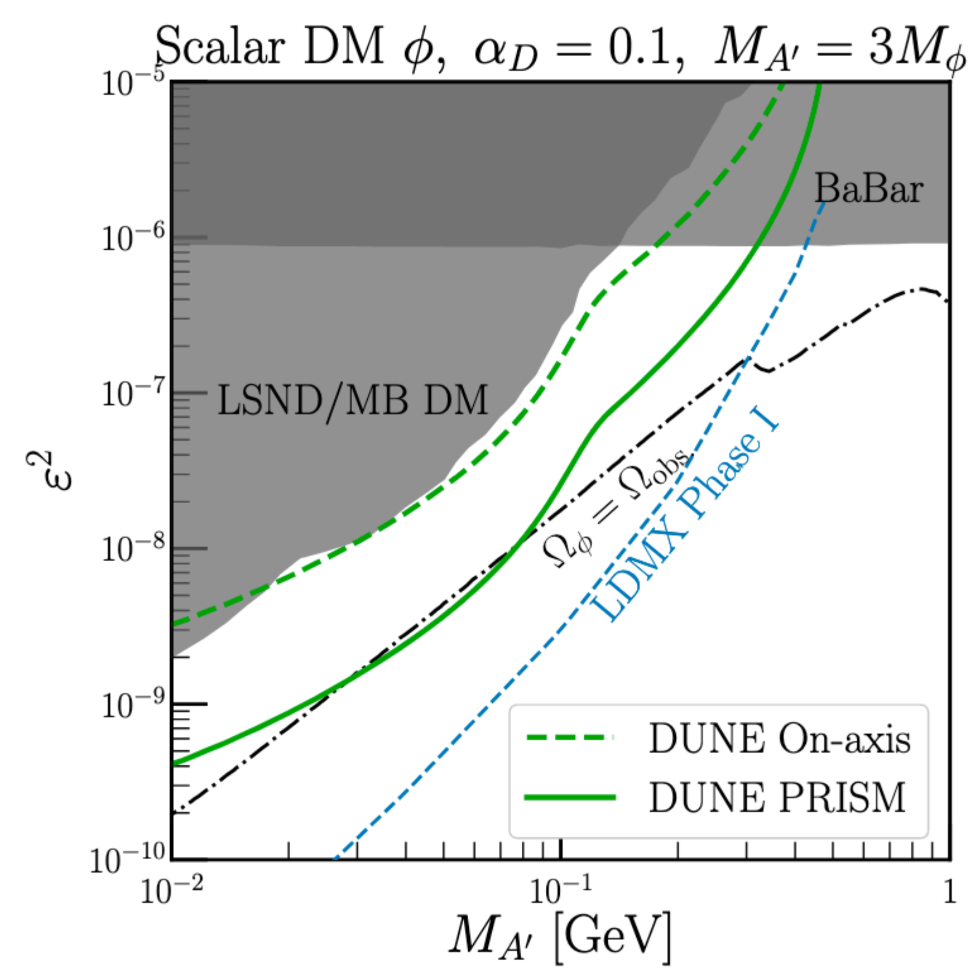
DUNE-PRISM @ FNAL

[De Romeri, Kelly, Machado]
[Breitbach, Buonocore, Frugiuele Kopp, Mittnacht]

- 120 GeV protons on graphite target
- DUNE-PRISM movable near detector allows sensitive search to light dark matter
- DM-to-neutrino flux increases as detector is moved off axis
    - Neutrinos produced through decay of charged mesons, which are focused by magnetic horn
    - DM produced through decay of unfocused neutral mesons







Opportunities with the FNAL Proton Improvement Project 2 (PIP-2)

- As part of FNAL PIP-2 upgrade, Booster will be replaced, Main Injector will be upgraded
- Excess protons at ~1 GeV, ~10 GeV, 120 GeV will be potentially available for a variety of physics applications, including dark sector studies.

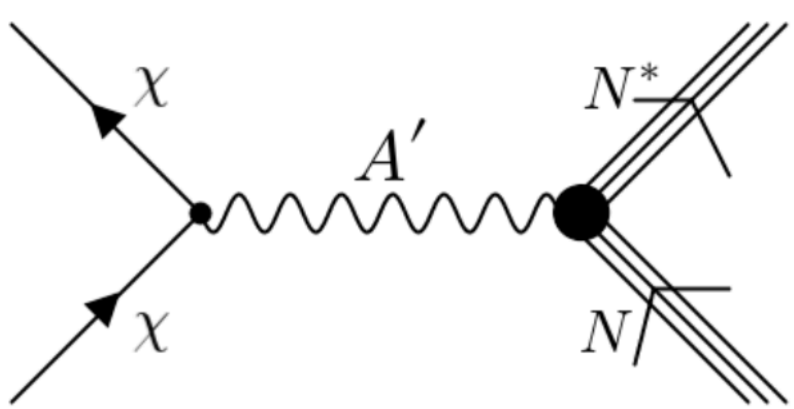
Fermilab Facility for Dark Sector Discovery (F2D2)

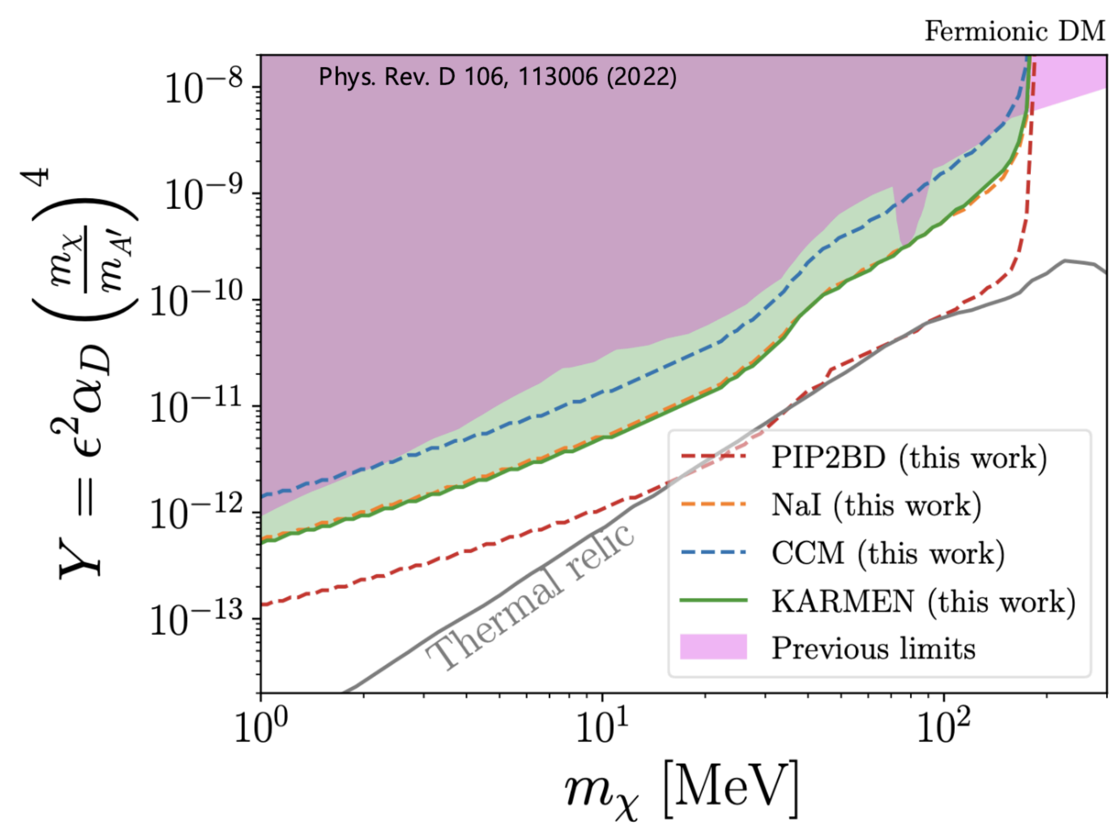
See talk by M. Toups

- 0.2-2 GeV proton beam dump facility for dark sector searches, 10^{22} - 10^{23} POT/year
- Physics opportunities: sub-GeV DM, ALPs, CEvNS studies, light sterile-ν …

Example: DM-nucleus inelastic scattering

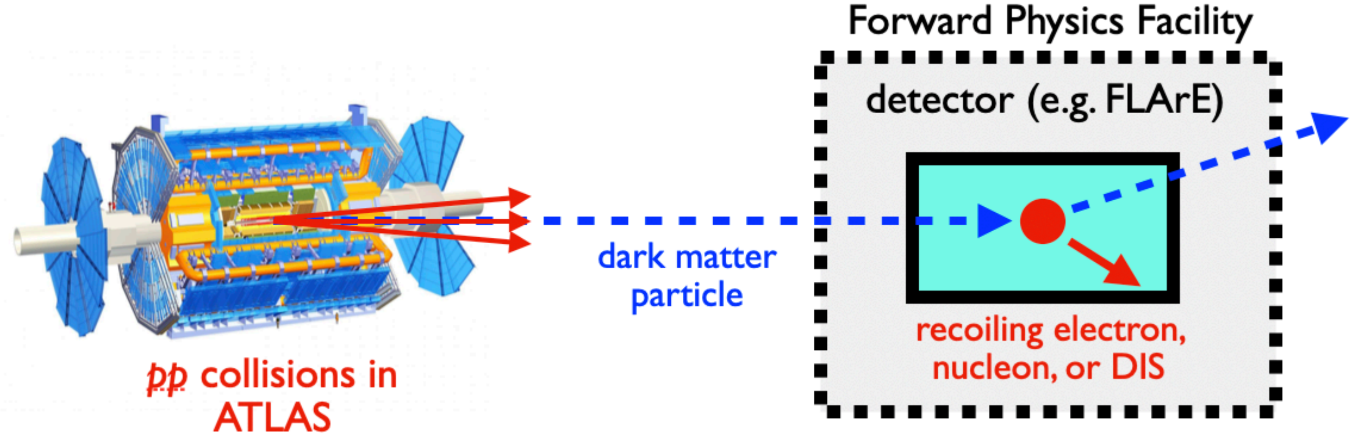
[Dutta, Huang, Newstead, Pandey]

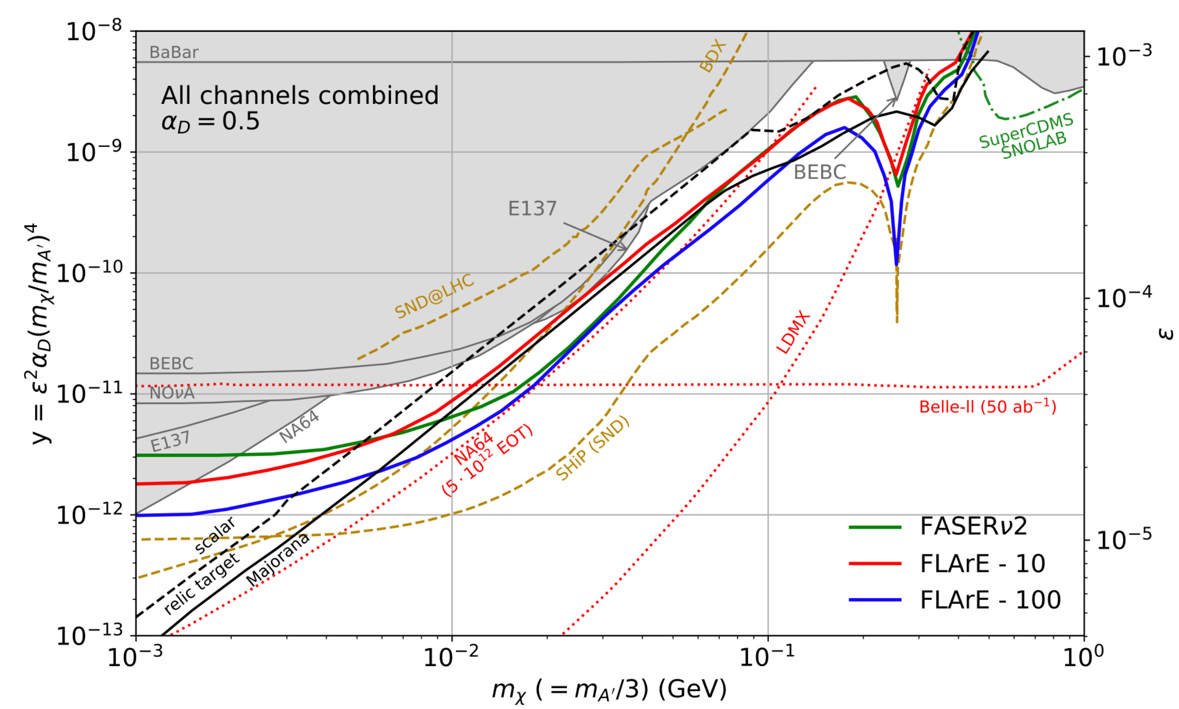




Forward LHC experiments (FASER, FASERν, FLArE, ...)

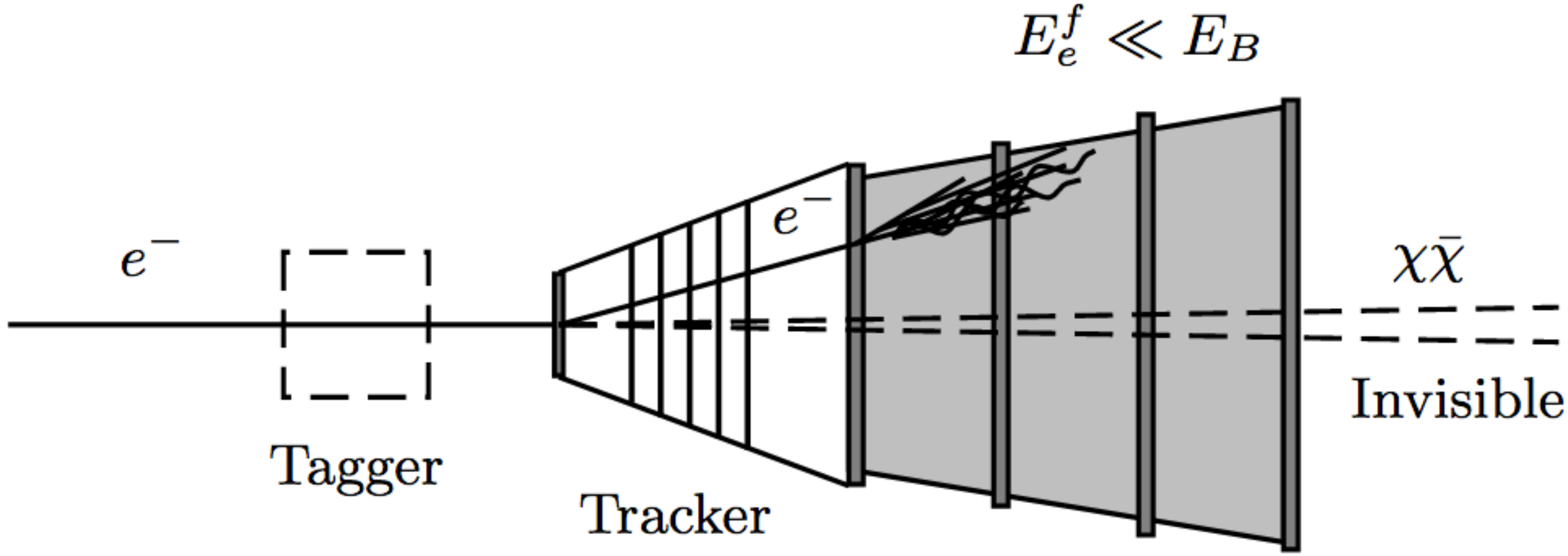
- Total LHC pp cross section is ~100 mb, and is directed in the forward region
  - Copious source of TeV energy neutrinos
  - First collider-produced neutrinos detected by FASERν [arXiv:2105.06197]
  - Exciting prospects at FASERν, SND@LHC (Run 3) and FASERν2, FLArE, FORMOSA (HL-LHC)
- Dark sectors can also be explored with forward LHC experiments
  - For full physics case, see Forward Physics Facility whitepaper [arXiv:2203.05090]
- Example: vector portal dark matter





[BB, Feng, Feig, Ismail, Kling, Abraham, Trojanowski]
[2101.10338, 2107.00666, 2111.10343]

Missing energy/momentum searches for dark matter

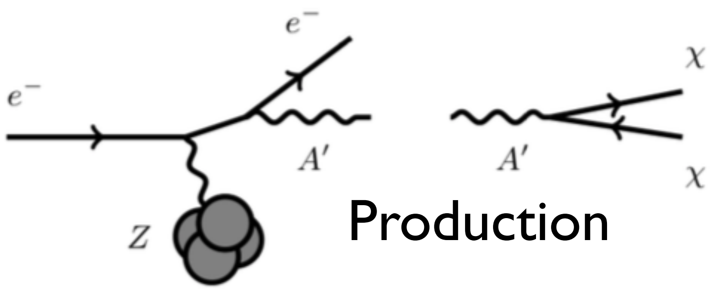


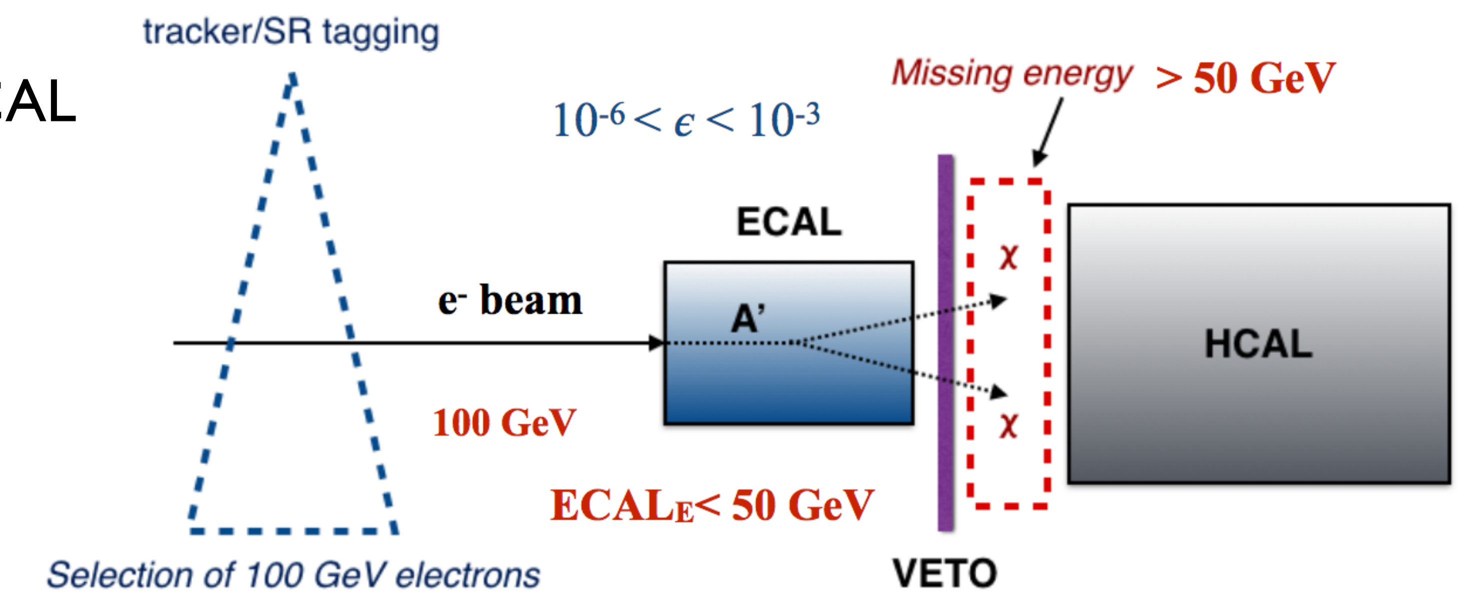
[Andreas. et al]

[Izaguirre, Krnjaic, Schuster, Toro]

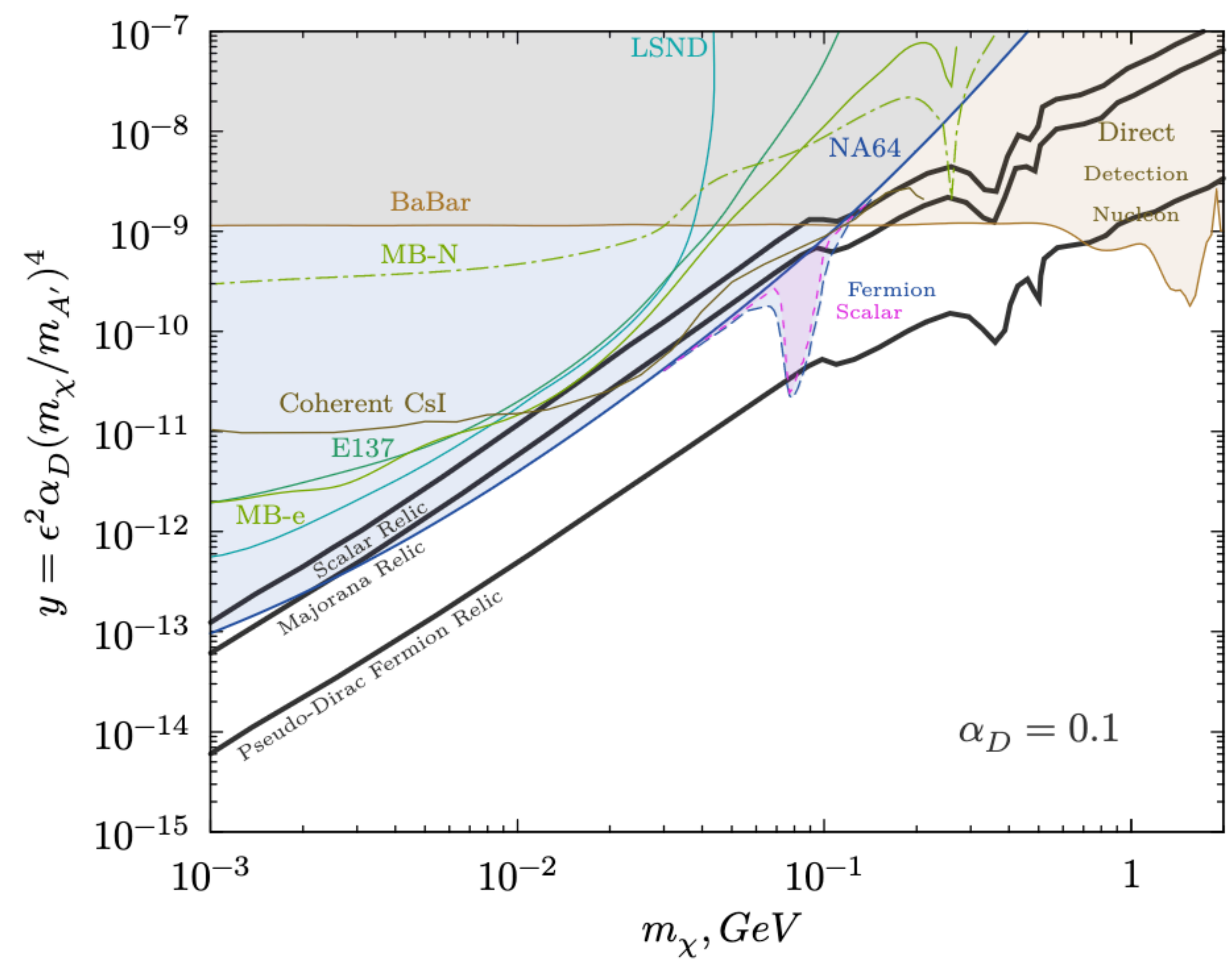
NA64@CERN

- 100 GeV electron beam incident on ECAL
- Dark matter produced in ECAL and carries most of the beam energy



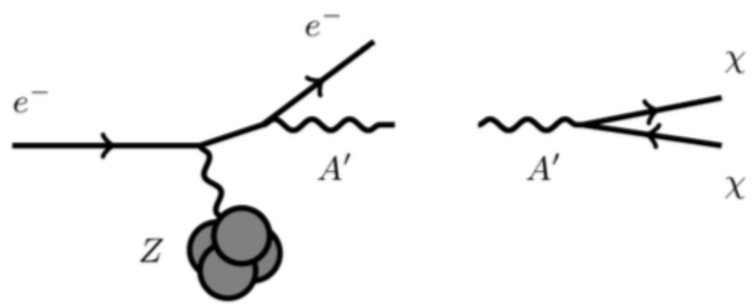


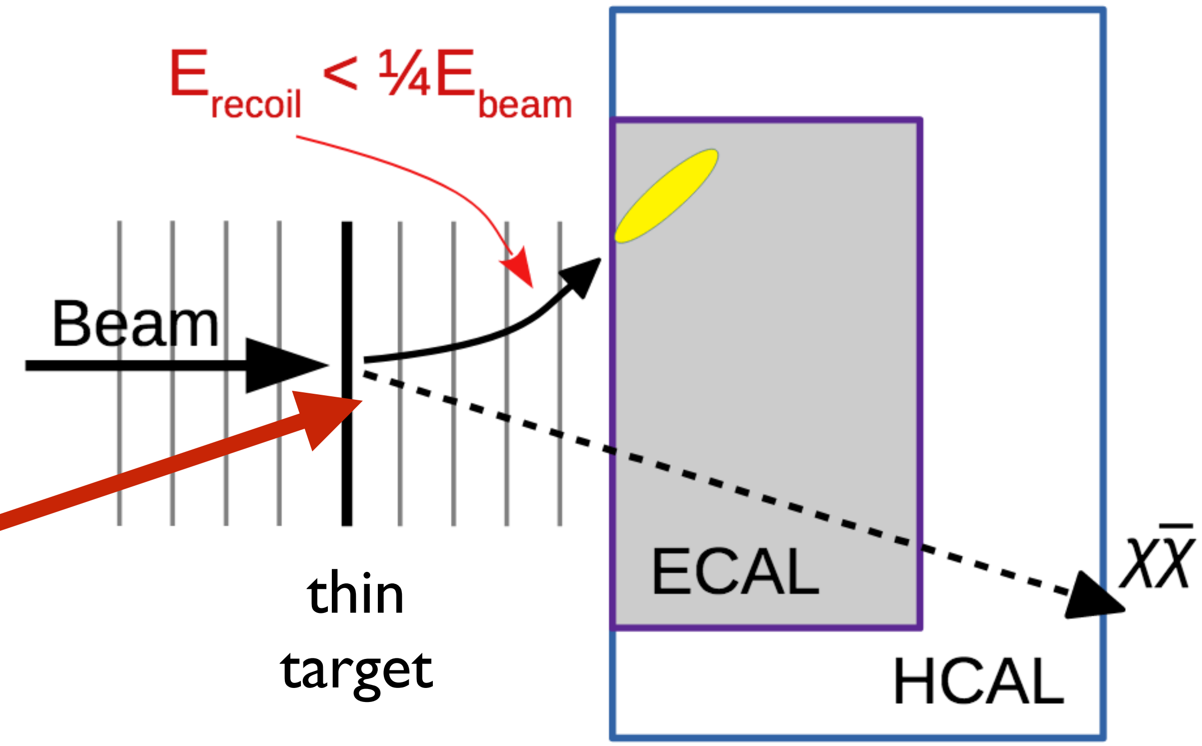
- Large missing energy signature (small energy deposition in ECAL, no energy deposition in HCAL)
- ~10^{12} EOT - best limits on vector portal dark matter below 300 MeV, starting to probe thermal relic targets



LDMX@SLAC

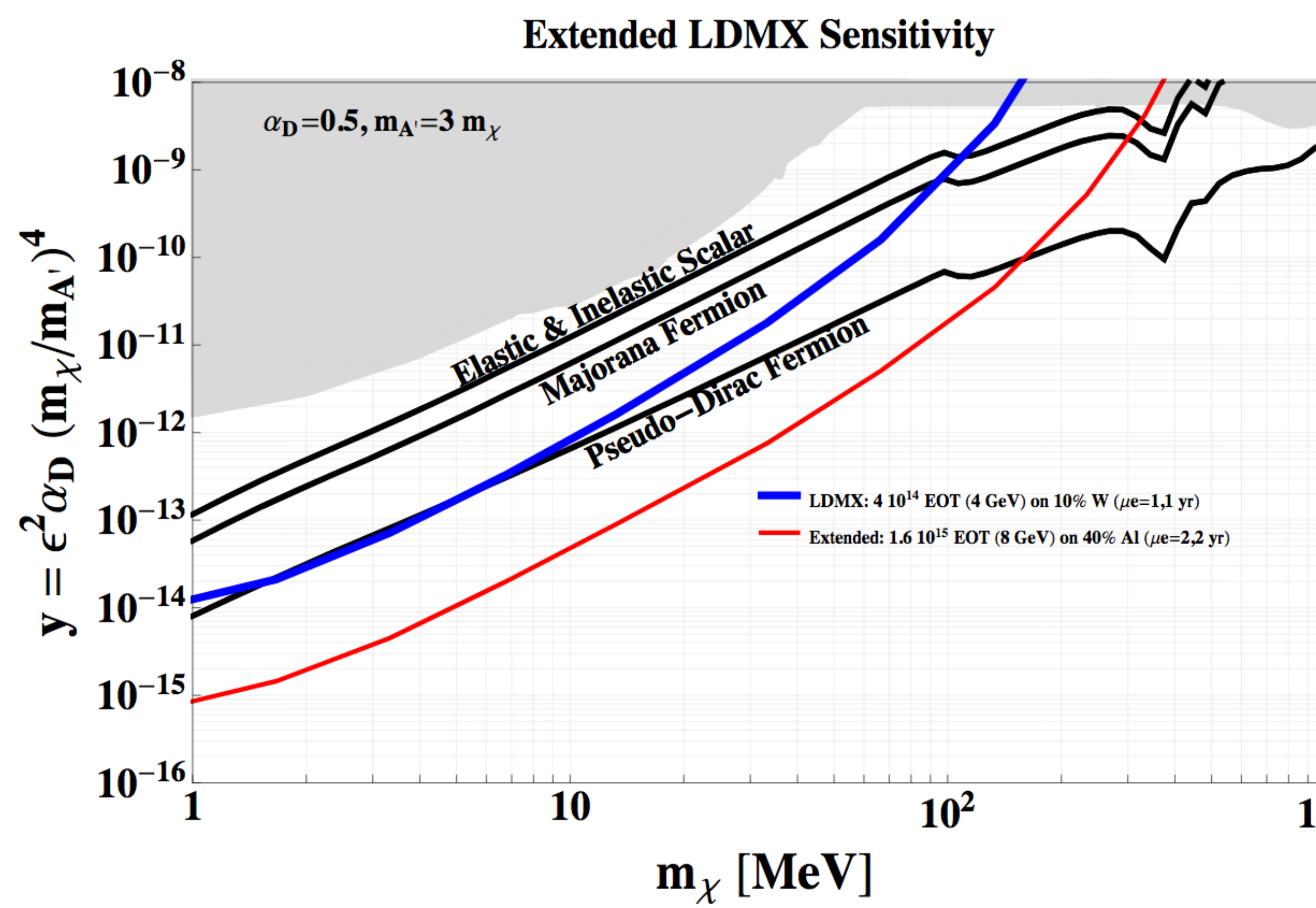
- Proposed electron beam experiment utilizing missing momentum technique





- More kinematic handles to reject backgrounds, discriminate final state electrons from photons

- Can cover most thermal targets, irrespective of DM particle nature

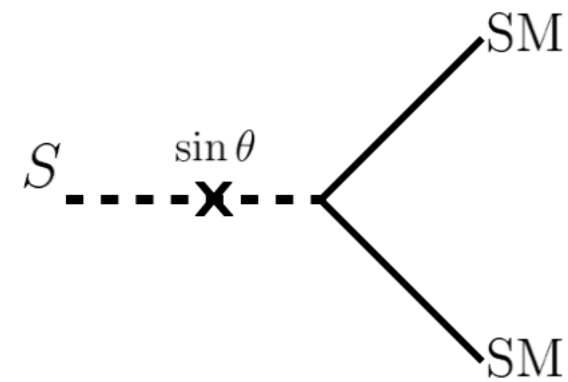


Initial design study, 1808.05219

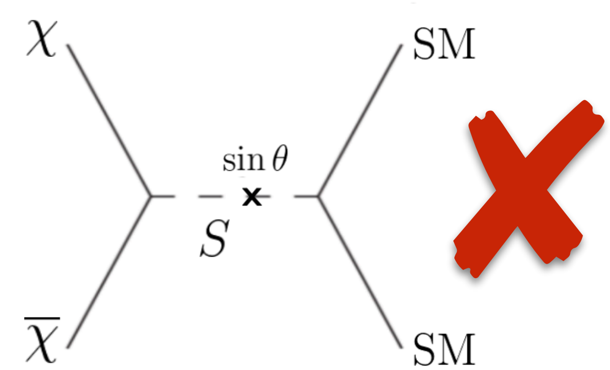
Visible Signatures of the Higgs Portal

- Dark scalar couples just like Higgs, but with couplings suppressed by mixing angle

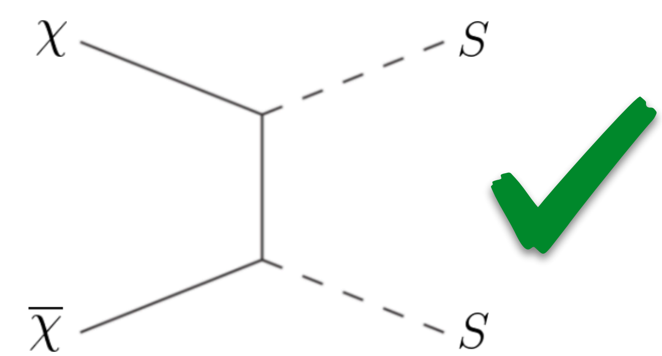
$$-\mathcal{L} \supset (AS + \lambda S^2)H^\dagger H \quad \Rightarrow \quad \sin\theta \, \frac{m_f}{v} \, S\,\bar{\psi}\psi + \ldots$$



- Past experiments strongly constrain dark matter annihilating to SM through the Higgs portal [Krnjaic]

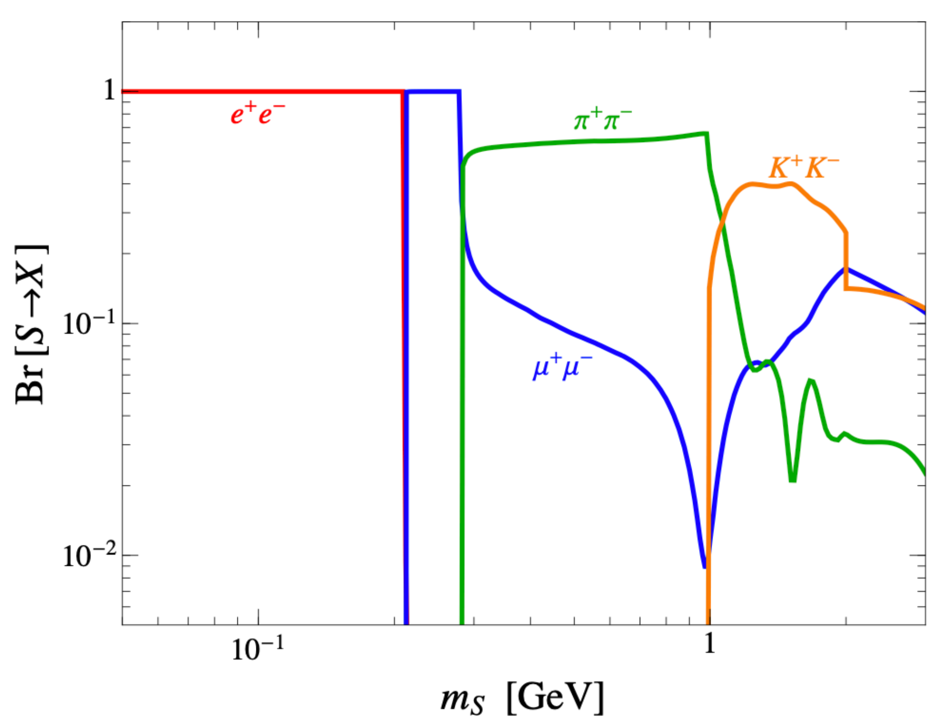


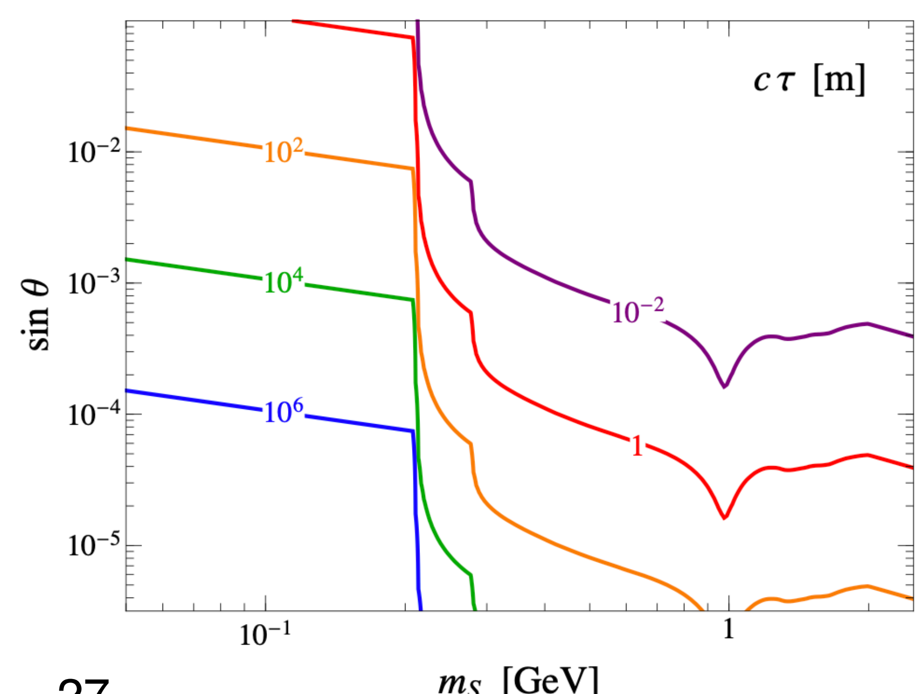
Direct annihilation



Secluded annihilation

- Expect dark matter is heavier than scalar and scalars decay to visible particles

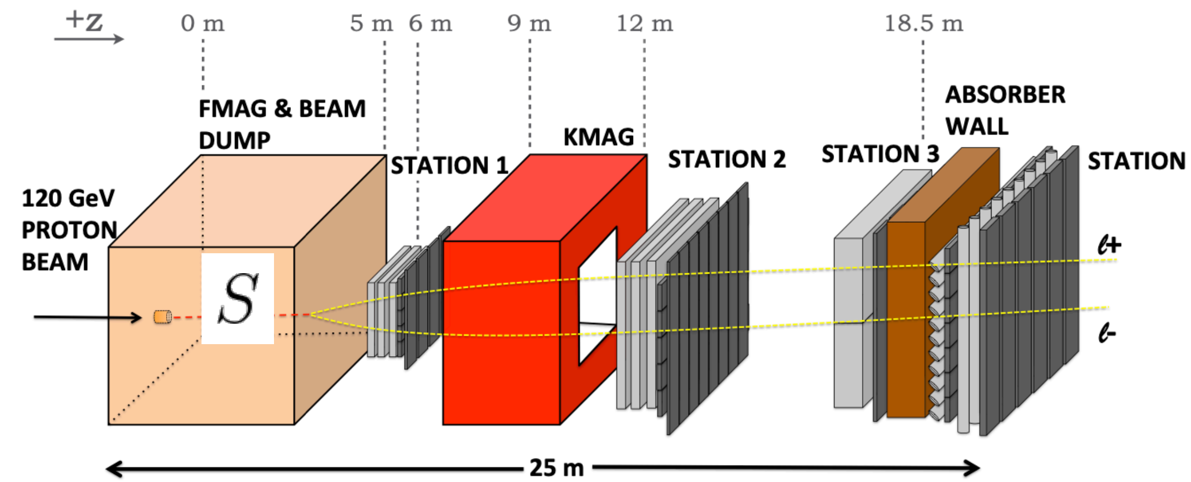




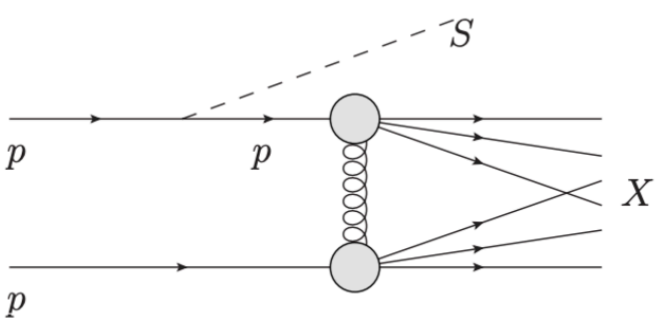
Scalar may be long-lived!

DarkQuest@FNAL

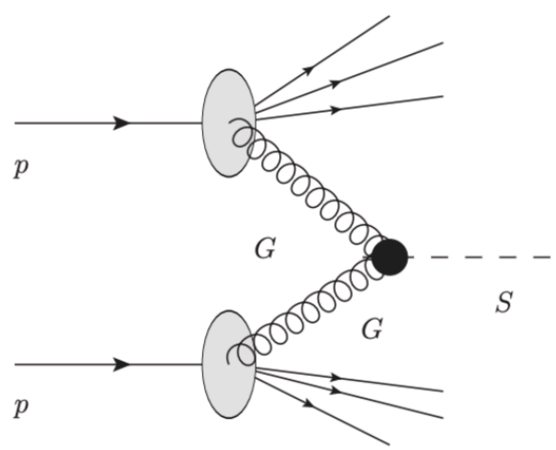
- 120 GeV protons from the Fermilab Main Injector impinge on ~ 5m iron beam dump
- Magnetic field (KMAG), 4 tracking stations, muon ID system, EM calorimeter
- High energies, short baseline allows to probe long-lived particles with moderate lifetimes
- Example: visibly decaying Higgs portal scalar



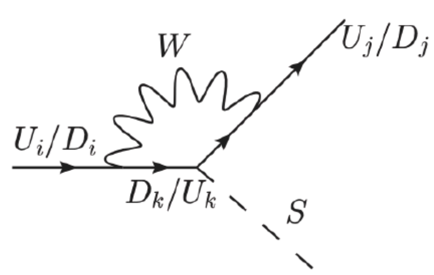
[Berlin, Gori, Schuster, Toro; Blinov, Kowalczyk, Wynne; Forbes, Herwig, Kahn, Krnjaic, Suarez, Tran, Whitbeck; + others]



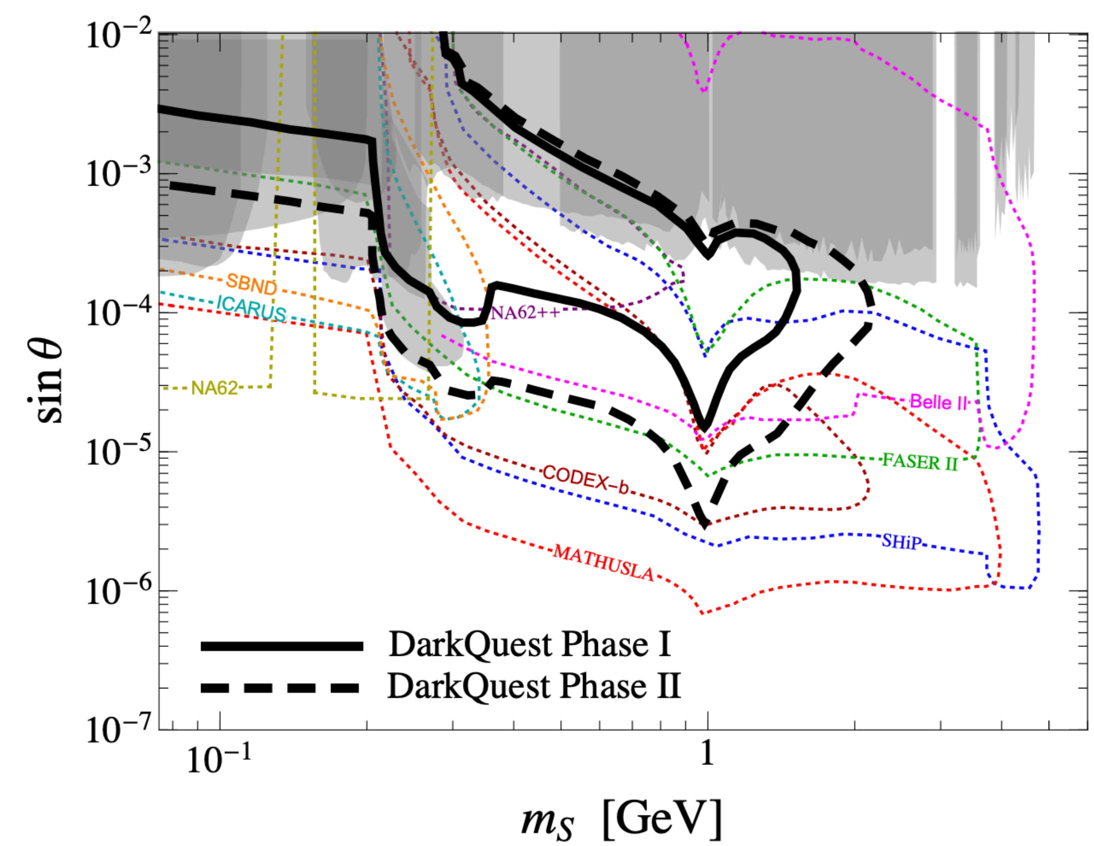
Proton Bremsstrahlung



Gluon fusion



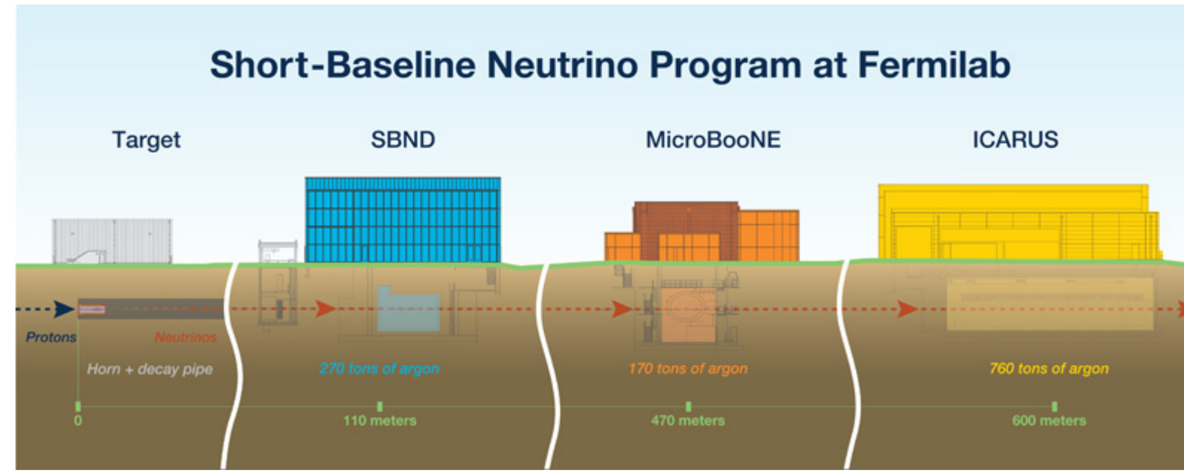
Meson decay

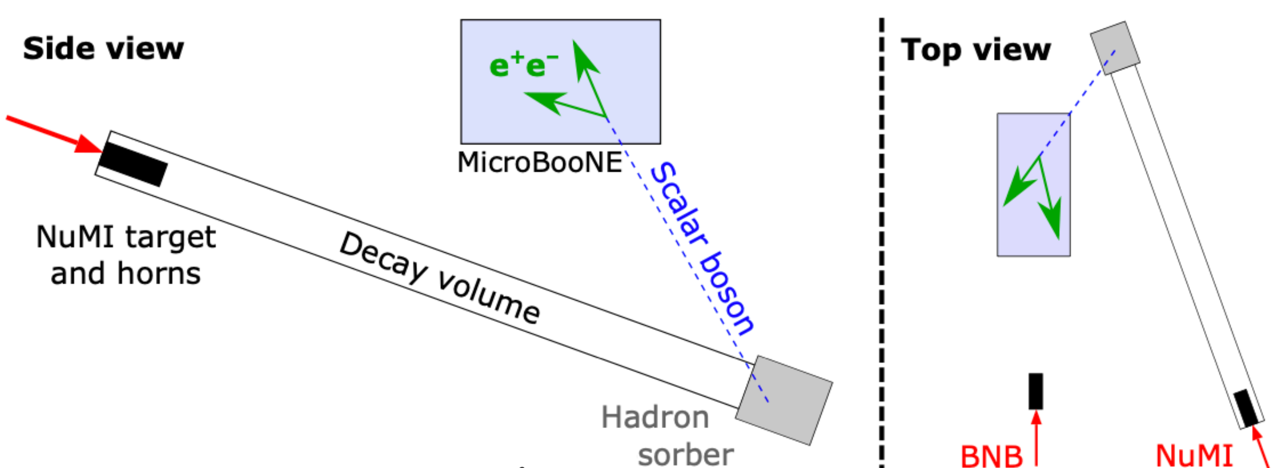


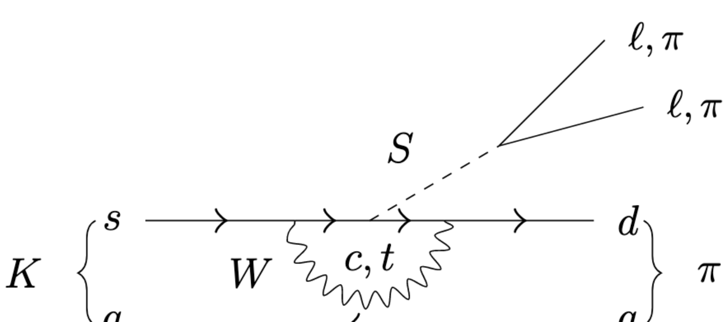
[BB, Evans, Gori, Rai]

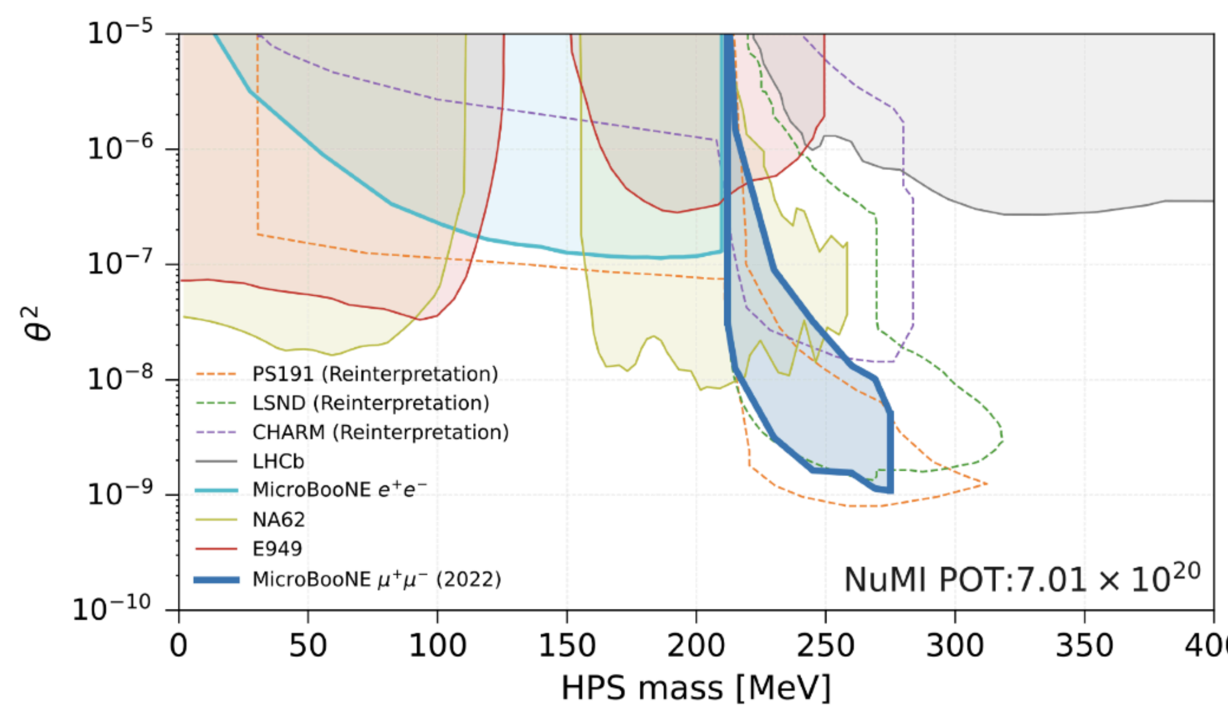
Short Baseline ν-Experiments @ FNAL

- MicroBooNE, SBND, ICARUS LArTPC detectors
- Situated along 8 GeV Booster beam line and slightly off axis from 120 GeV NuMi beam line
- Will collect ~ 10^{21} POT over next several years
- These experiments have sensitivity to a variety of dark sector models
- Example: MicroBooNE search for Higgs portal scalar





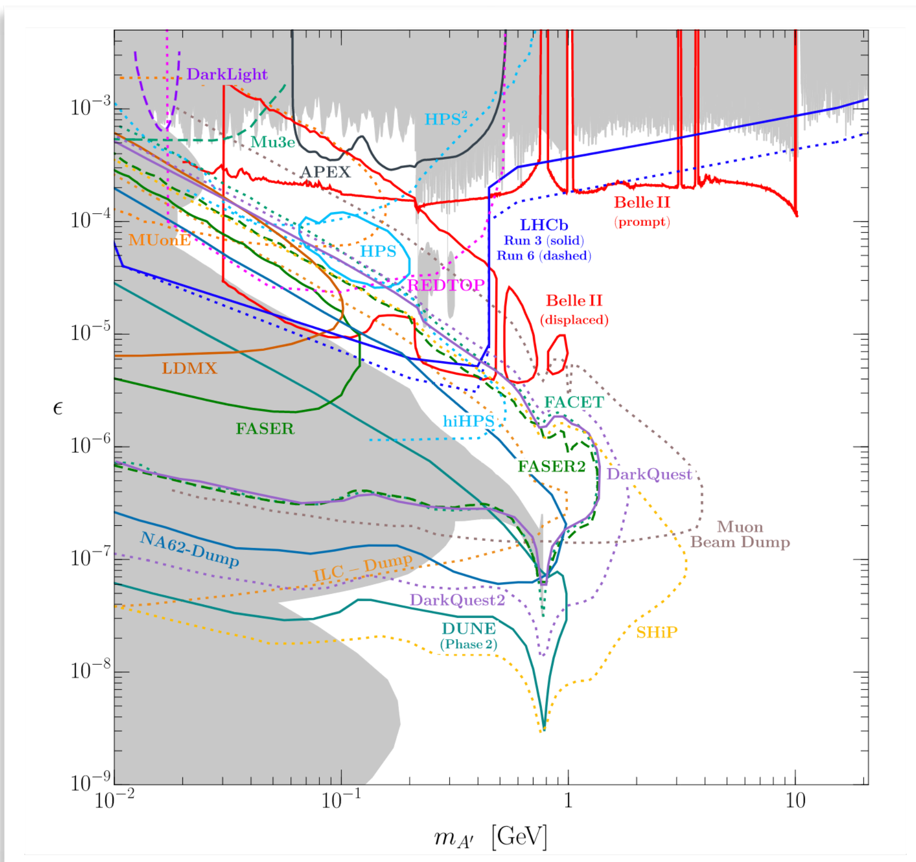




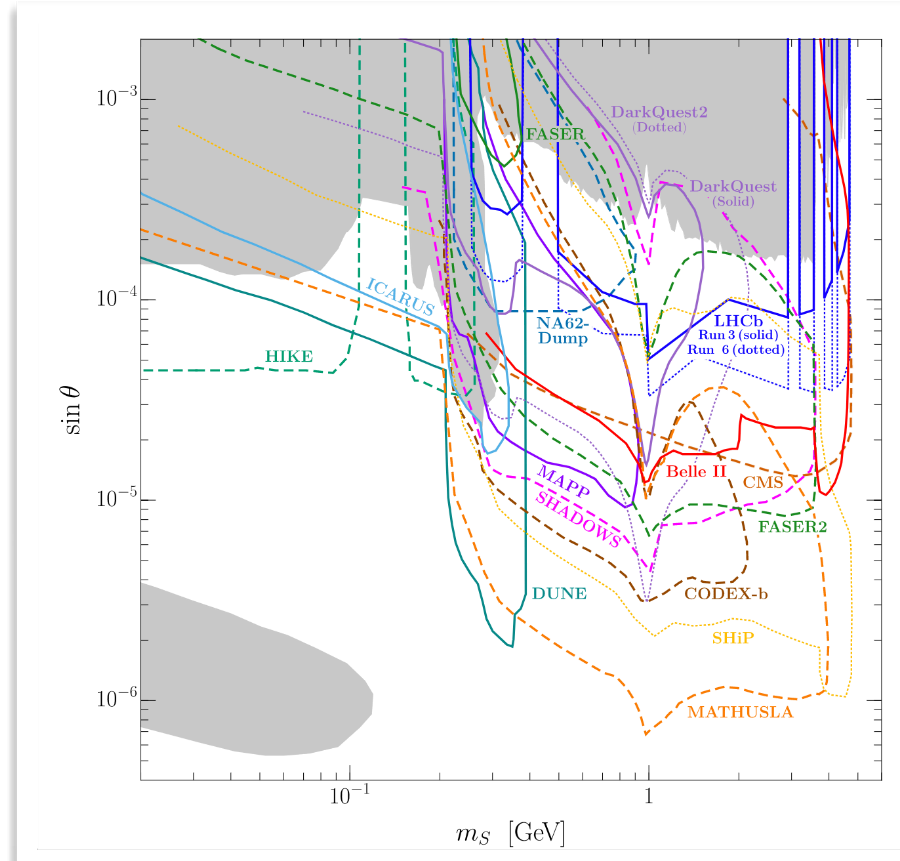
See talk by Lee Hagaman

[See also BB, Berger, Ismail, 1909.11670, for prospects at ICARUS and SBND]

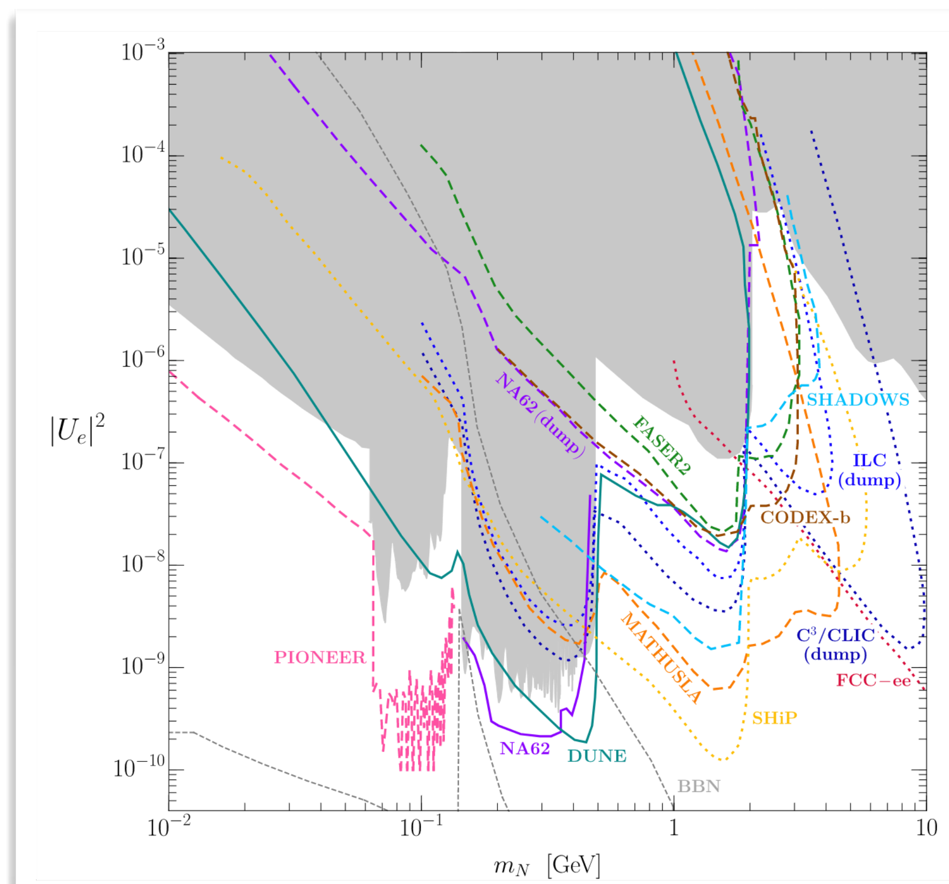
Visible Portal Benchmark Models



Vector Portal



Higgs Portal



Neutrino Portal

[Snowmass RF6 whitepaper, 2207.06905]

Other dark sector models

- I have mainly focused on the simplest vector and Higgs portal scenarios. There are many other interesting dark sector models.

  - Different particle nature/content/dynamics of the dark sector

    Spin, coupling structure, excited dark matter states, strongly interacting dark sector sector, spontaneous symmetry breaking, …

  - Different mediator couplings to the SM

    Leptophobic, Leptophilic, flavor specific, mediator spin…,

- This leads to interesting alternatives for the cosmological production of dark matter and distinct phenomenological signals

[See the Snowmass RF6 reports for a comprehensive survey of these possibilities, 2207.06905, 2207.08990, 2209.04671]

Summary and Outlook

- Dark matter is a profound mystery!
    - Many candidates, mass scale is largely unconstrained, rich variety of phenomena. Lots of work ahead!
- Accelerators provide an important tool to search for and study dark matter and dark sectors.
    - Complementary to direct detection, indirect detection, astrophysics, cosmology
    - Can test certain thermal dark matter production scenarios
    - Can provide information about dark sector structure
- Still room for exploration in model and signature space, which will provide motivation for new searches at colliders and fixed target experiments
- Many exciting experiments, searches, and results on the horizon!