Discussion

What light particles can couple to SM?

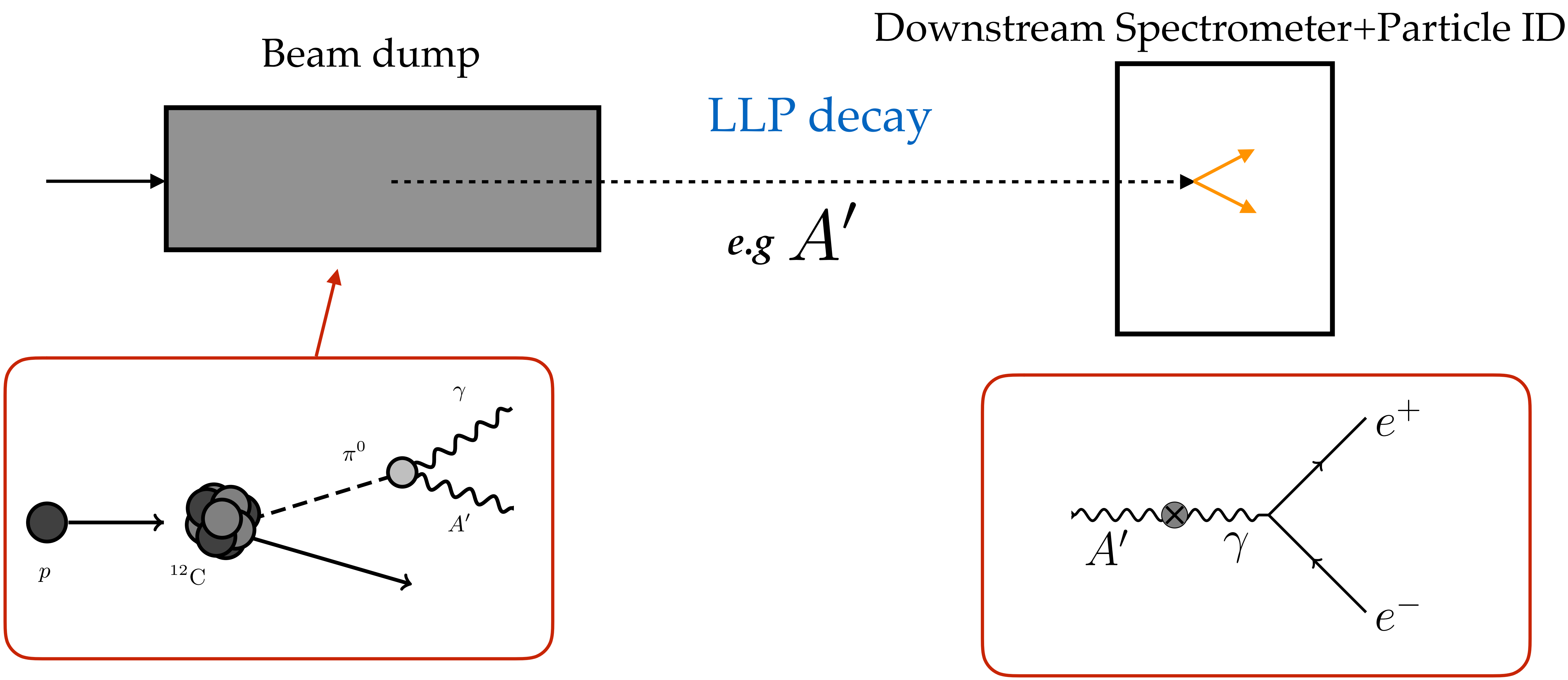
New particles <~GeV must couple to SM neutral operators

$\phi H^\dagger H$	**Scalar ϕ mix w/ Higgs** (similar for pseudo)	$\phi \frac{m_f}{v} \bar{f} f$
$F'_{\mu\nu} F^{\mu\nu}$	**Vector A′ mix w/ photon**	$A'_\mu J^\mu_{\rm EM}$
$V_\mu J^\mu_{\rm SM}$	**Vector V anomaly free U(1)** $B-L\ ,\ L_i - L_j\ ,\ B - 3L_i$	$V_\mu J^\mu_{\rm SM}$
$\epsilon N H L$	**New lepton mix w/ neutrinos**	$N \nu_L$

Complete List of lowest dimensionality super renormalizable couplings

New Particle Decays to SM: LLP @ Beam Dumps

Procedure to probe for Dark Photon, Scalar, Vector and Neutrino portals

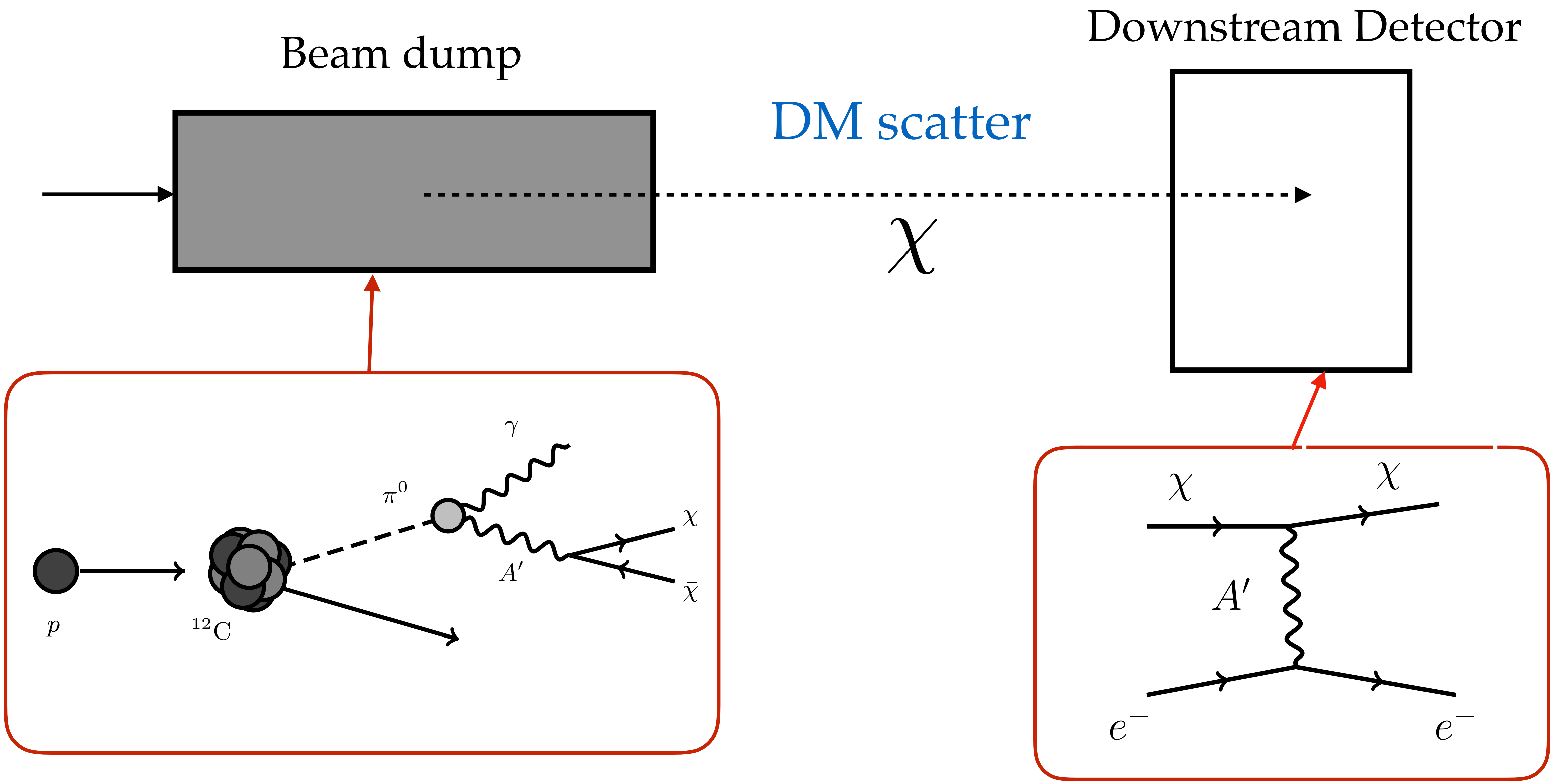


$\propto g_{\mathrm{SM}}^2$ $\propto g_{\mathrm{SM}}^2$

The energy deposited in detector is the signal

Rate $\propto g_{\mathrm{SM}}^4$

New Particle Decays to DM: Scatter @ Beam Dumps



A′ decays promptly to DM

$$\propto g_{\mathrm{SM}}^2$$

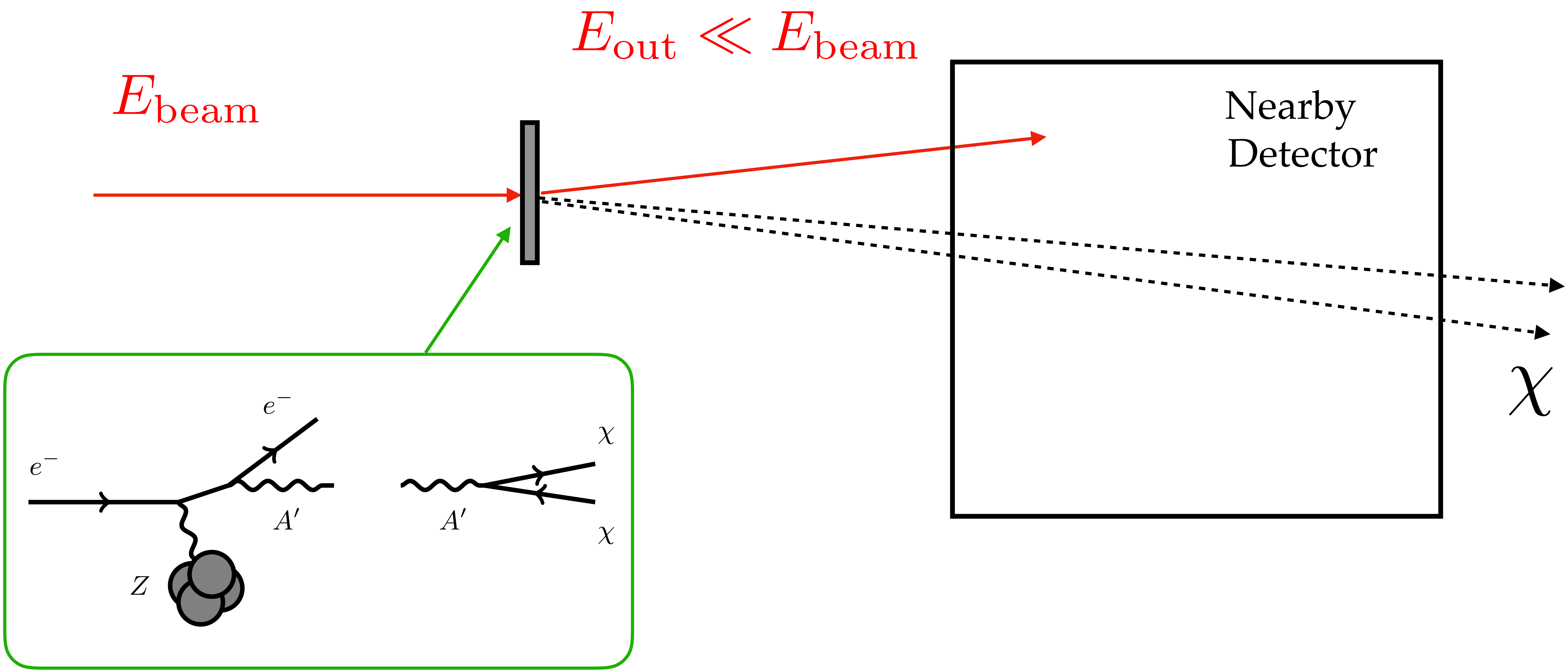
DM scatters inside detector

$$\propto g_{\mathrm{SM}}^2$$

The energy deposited in detector is the signal

$$\text{Rate} \ \propto g_{\mathrm{SM}}^4$$

Mediator Decays to DM : Missing Energy / Momentum



The beam is the signal, don't observe DM

$$\text{Rate} \propto g_{\text{SM}}^2$$

Relevant Experiments

Signal: Energy in detector

SHiP: proton Beam Dump Facility
NA62(++): proton beam (dump mode)
REDTOP: proton beam

Signal: Energy of the beam

LDMX: electron beam / muon beam
NA64(++): electron/muon beam

Keep an eye out for Flavour Physics, particularly pertinent given current Flavour anomalies. SPS ideal playground

TauFV: proton Beam Dump Facility
KLEVER: proton beam
NA62(++): proton beam

International Complementarity

Belle II
LHCb(+UpgradeII)
FASER, Codex-b, MATHUSLA
DUNE/LBNF
SBN
BDX
T2K
JSNS**2
MiniBoone
SeaQuest/(DarkQuest?)

Scope of Fixed Target BSM Program: Visible Decays

Broad search for new forces (pseudo) scalar, vector

Scenarios related to νMSM

Low Scale Leptogenesis HNL search

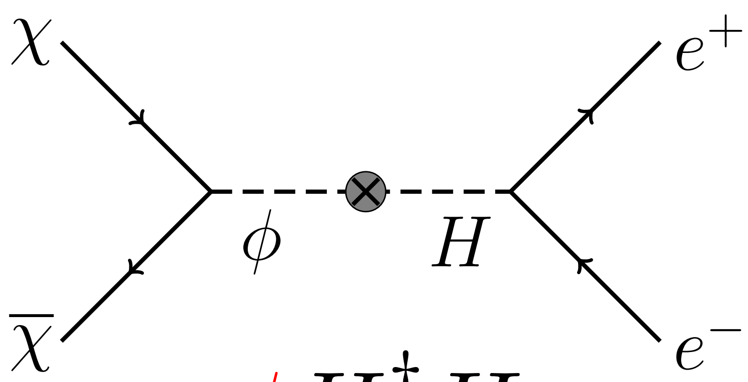
Origin of neutrino masses

νMSM also contains non thermal DM candidate (indirect detection)

Light physics related to hierarchy problem (relaxion)

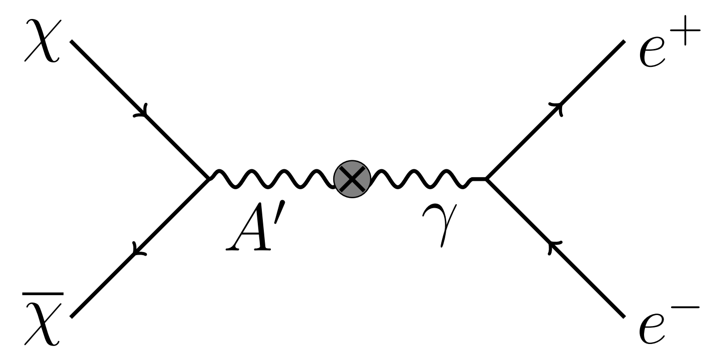
Scope of Fixed Target BSM Program: Invisible Decays

Covers nearly all predictive direct-annihilation models < GeV



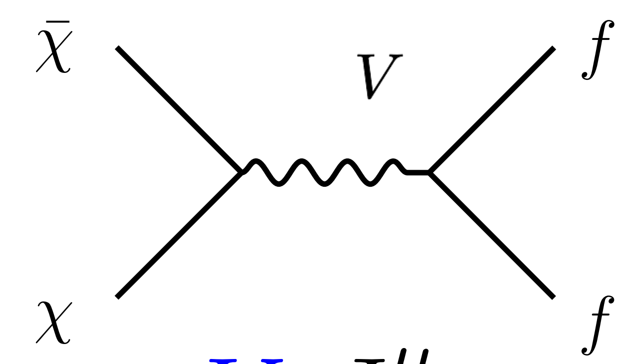
$\phi H^\dagger H$

Scalar
Ruled out



$F'_{\mu\nu} F^{\mu\nu}$

Dark photon



$V_\mu J^\mu_{\rm SM}$

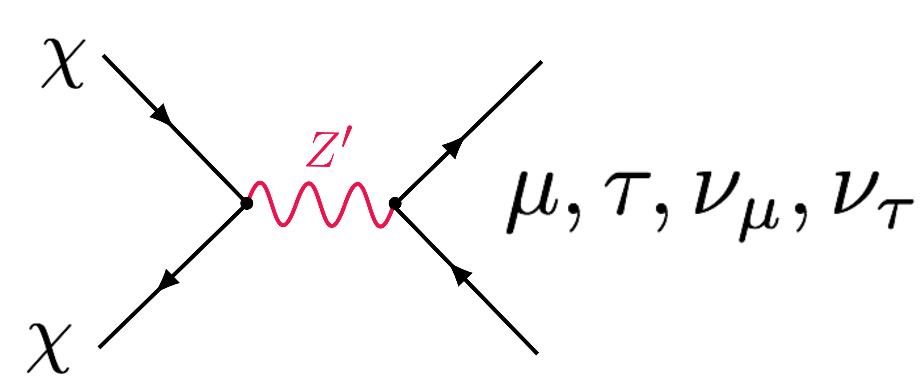
Anomaly free U(1)
B-L, *B-3Le* … etc.

Thermal coverage: LDMX, SHiP, MiniBooNE…

Also with muon/tau flavor couplings (need muon beam LDMX/NA64)

Only one anomaly free U(1) group

$$L_\mu - L_\tau$$



What is the connection to Future Collider programme at CERN?

What is the optimal use of facilities in light of the international effort of broadening our strategies?

(why CERN vs SLAC vs FNAL vs…)

How are these approaches complementary to Direct or Indirect Detection, Collider (including B-factories) searches etc?

Case Study 1

We first see a signal at existing/near future experiments

(eg. FASER, NA62, SENSEI…)

What do SHiP, LDMX, NA64++… uniquely bring to the table?

Case Study 2

We first see signal at SHiP or LDMX

How can one experiment confirm/uncover model behind signature of another?

How can other techniques help?

How can experiments best confirm that a potential signal is not an instrumental effect or unaccounted background?

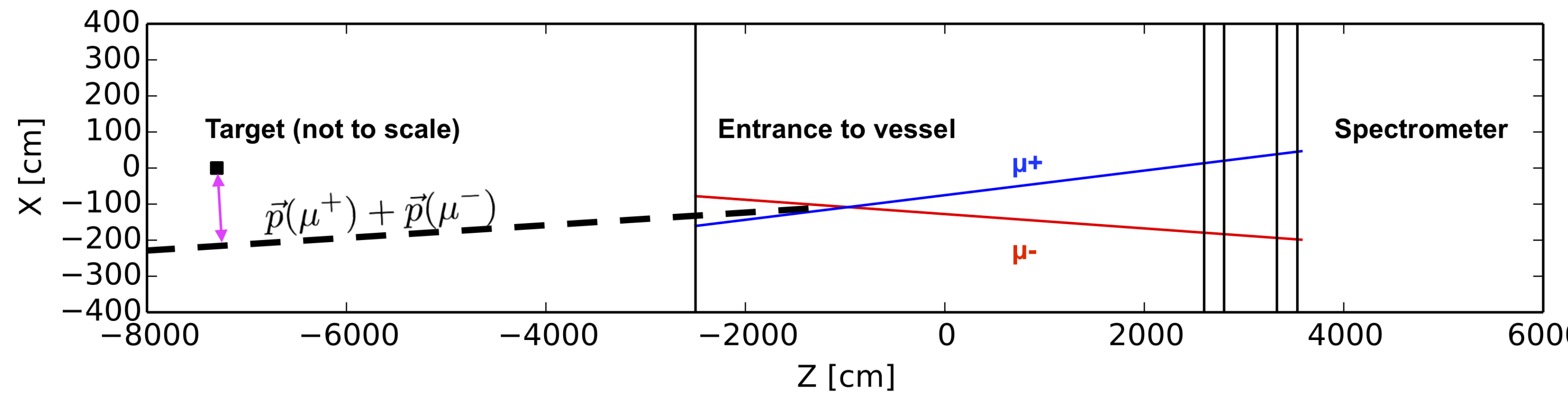
Backup

Experimental aspects

- Looking for very rare signatures requiring background suppression of multiple orders of magnitudes
- Need to be able to validate understanding of residual backgrounds or instrumental effects
- Can achieve this through the use of redundant systems to define control regions in data.

Example from SHiP

1. Combination of momentum and vertex information to reject candidates not originating from collision point

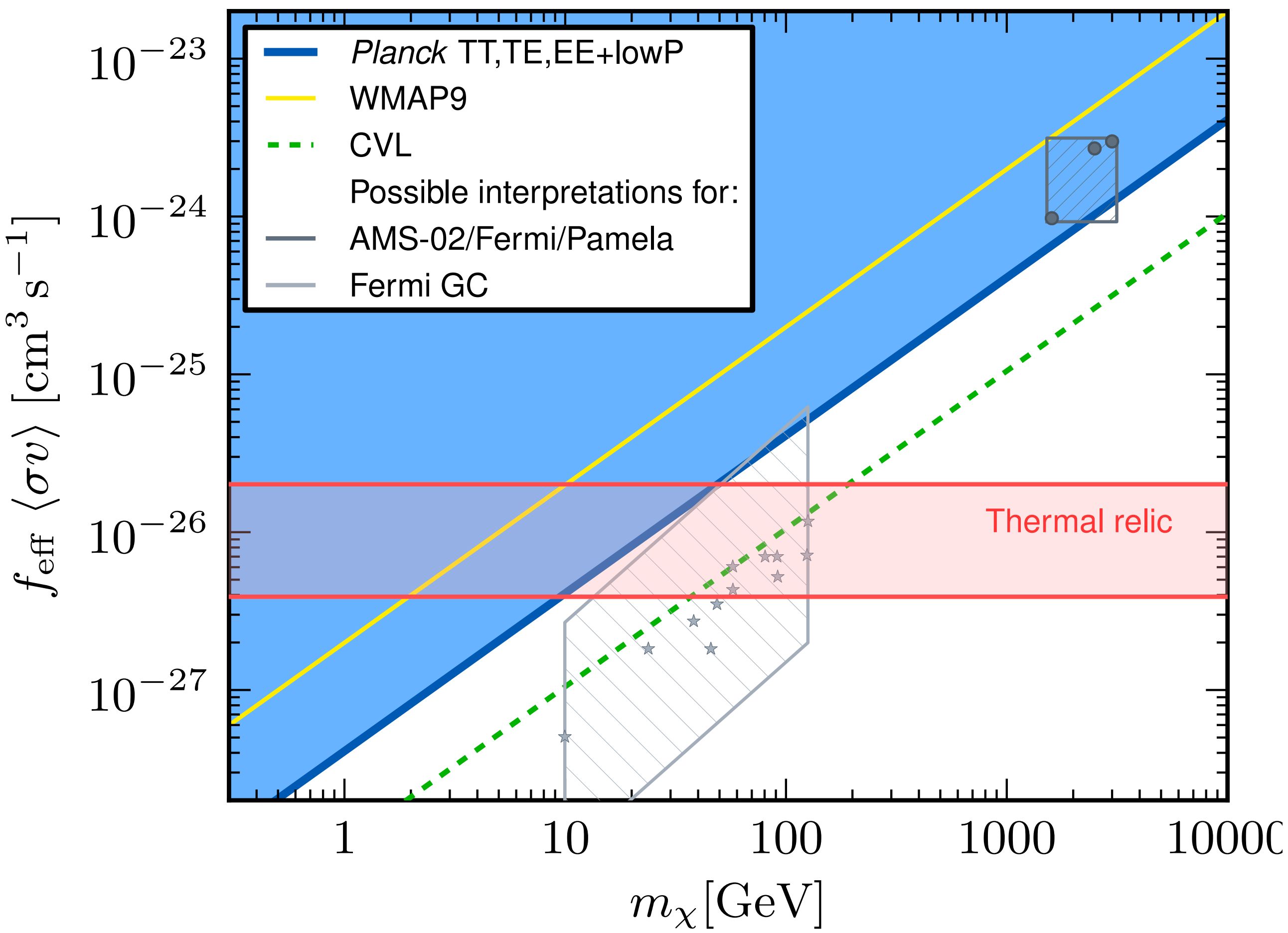


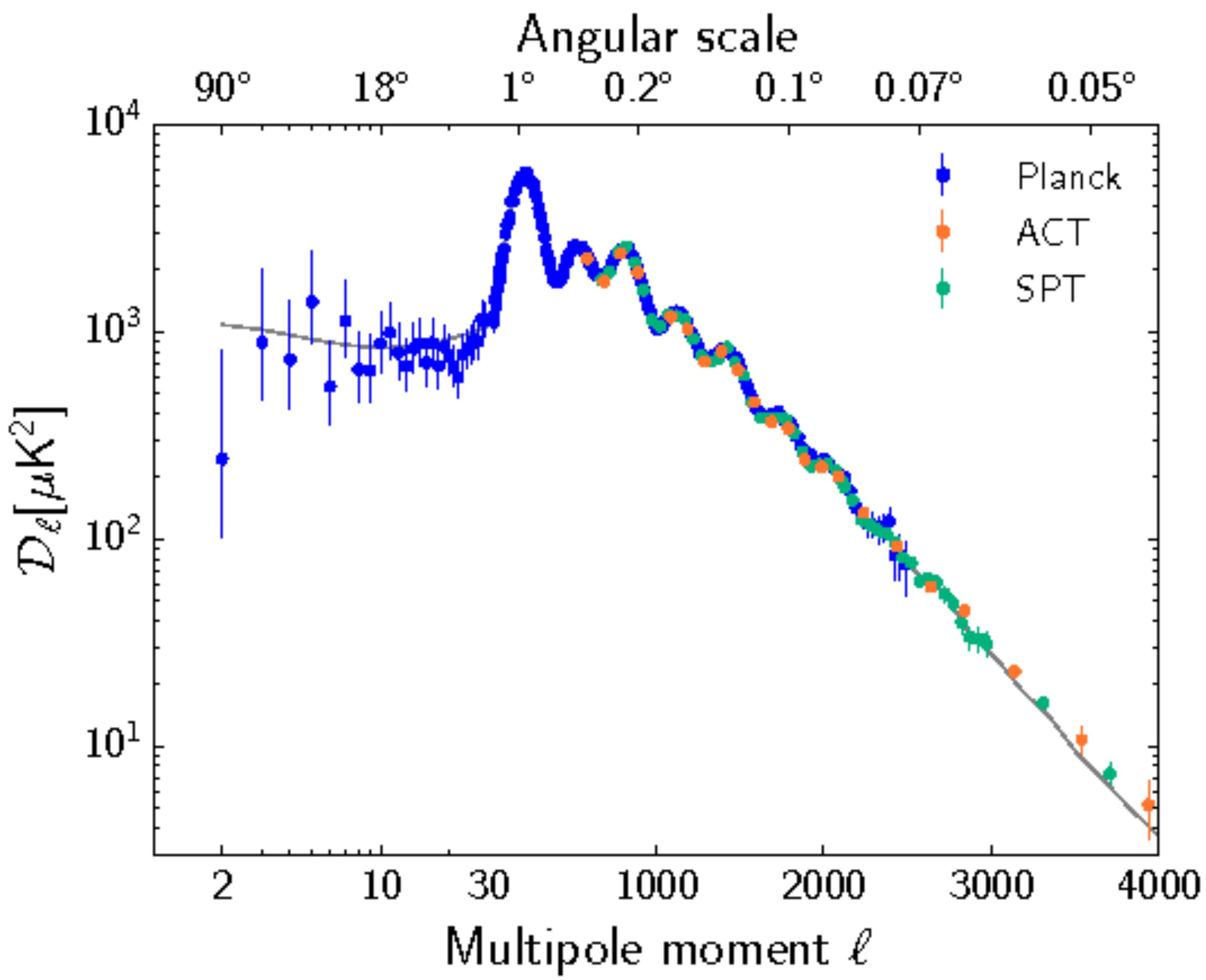
2. Combine with veto subsystems
   - ▷ Surrounding the decay vessel
   - ▷ At the entrance of the decay vessel
   - ▷ Backgrounds leave multiple hits in veto systems → very effective vetos
3. Add timing information between candidate tracks (σ=100 ps)

Complementarity

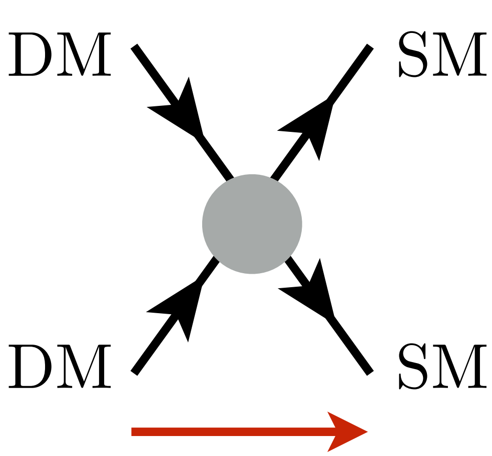
- Comprehensive coverage of Hidden Sector models
  - Without a smoking gun, need to probe multitude of potential sectors with maximum coverage
- Wide range of couplings and mass
  - Multiple experiments to maximise coverage
- Variety of approaches
  - Different techniques to search for same physics
- SHiP and LDMX approaches satisfy these
  - Important to consider interplay with Direct DM searches, LHC, B-factories…

Classify DM by Annihilation During CMB Era





Planck Collaboration 1502.01589



Rare out-of-equilibrium annihilation ionizes H (z=1100)

CMB photons pass through more plasma (modifies peaks)

Rules out s-wave relic cross section for DM < 10 GeV

Classify DM by Annihilation During CMB Era

$$\mathcal{L} \supset g_D A'_\mu J^\mu_\chi$$

$$J^\mu_\chi = \begin{cases} \overline{\chi}\gamma^\mu\chi & \text{Asym. Dirac} \\ \overline{\chi}_1\gamma^\mu\chi_2 & \text{Pseudo}-\text{Dirac} \\ \frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi & \text{Majorana} \\ i\chi^*\partial_\mu\chi & \text{Scalar} \end{cases}$$

Asym. Dirac → $\overline{\chi}$ all annihilate away pre-CMB
no more **annihilation** partners

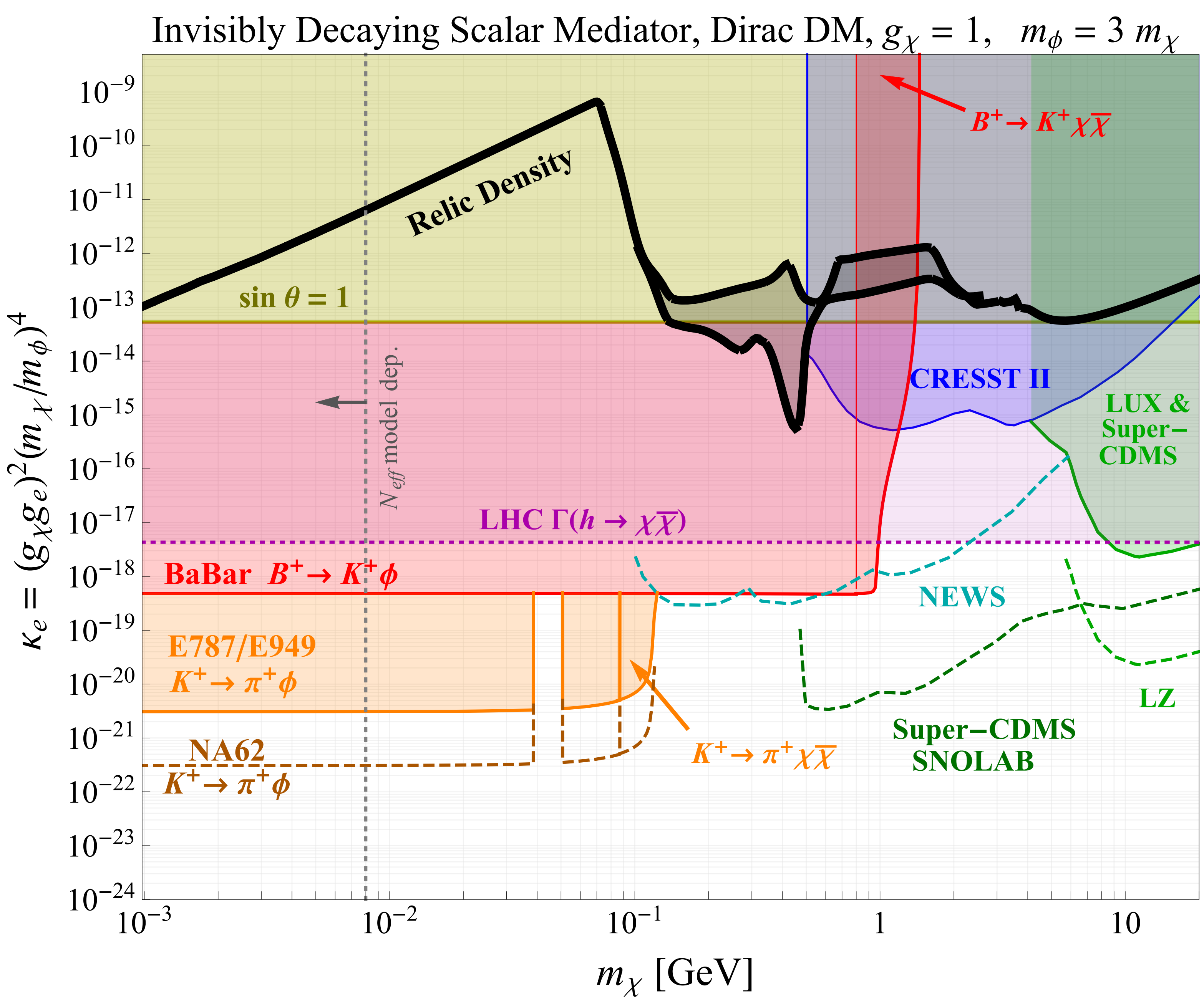
Pseudo-Dirac → Heavier χ_2 decays pre-CMB
no more **coannihilation** partners

Majorana, Scalar → $\sigma v \propto v^2$ velocity redshifts
tiny annihilation rate at CMB

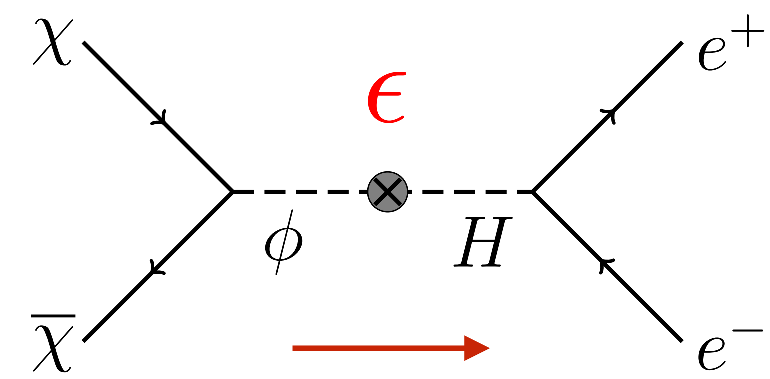
Safe models require either:

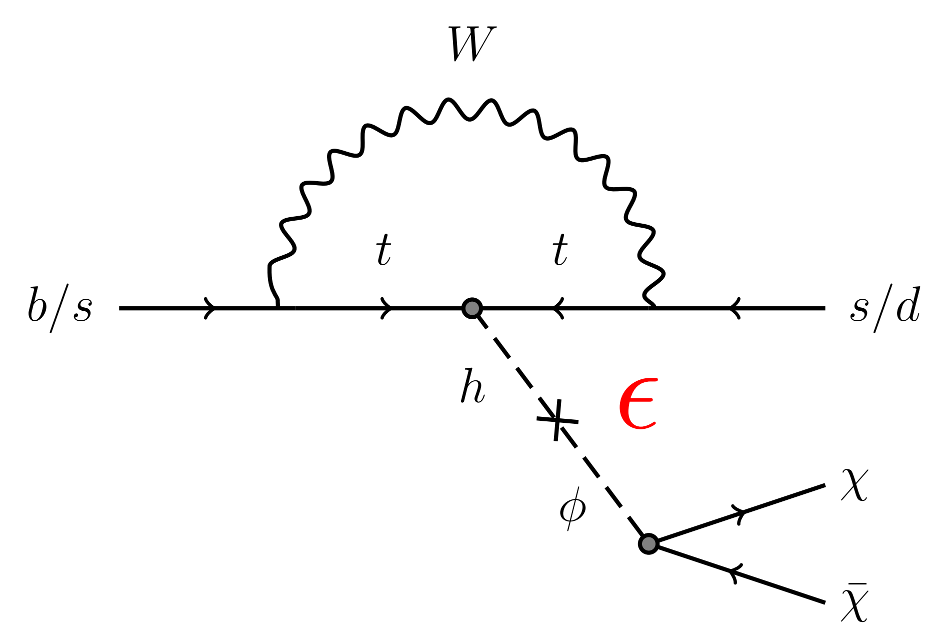
P-wave annihilation	**Different DM population @ CMB**
Scalar or Majorana	Asymmetric Dirac or Pseudo-Dirac

Higgs Portal Direct-Annihilation Ruled Out!



$\epsilon\, \phi H^\dagger H$



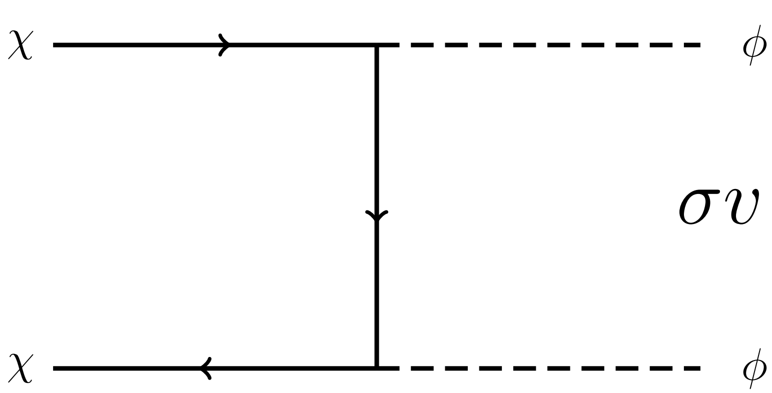


Conclusion independent of DM candidate

Similar situation for pseudo-scalar mediator

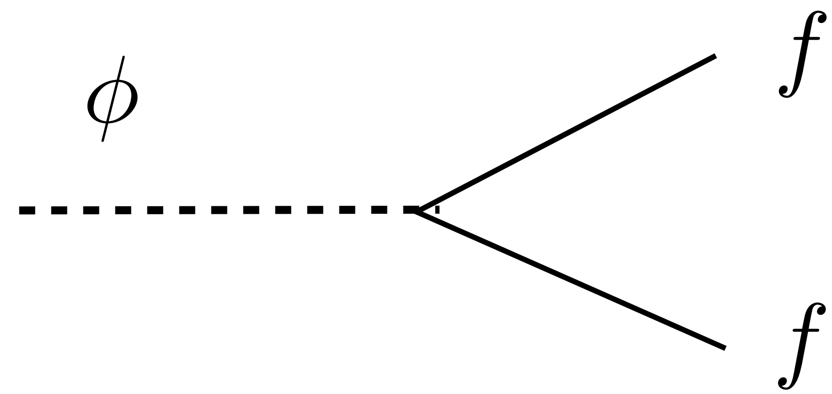
GK arXiv:1512.04119

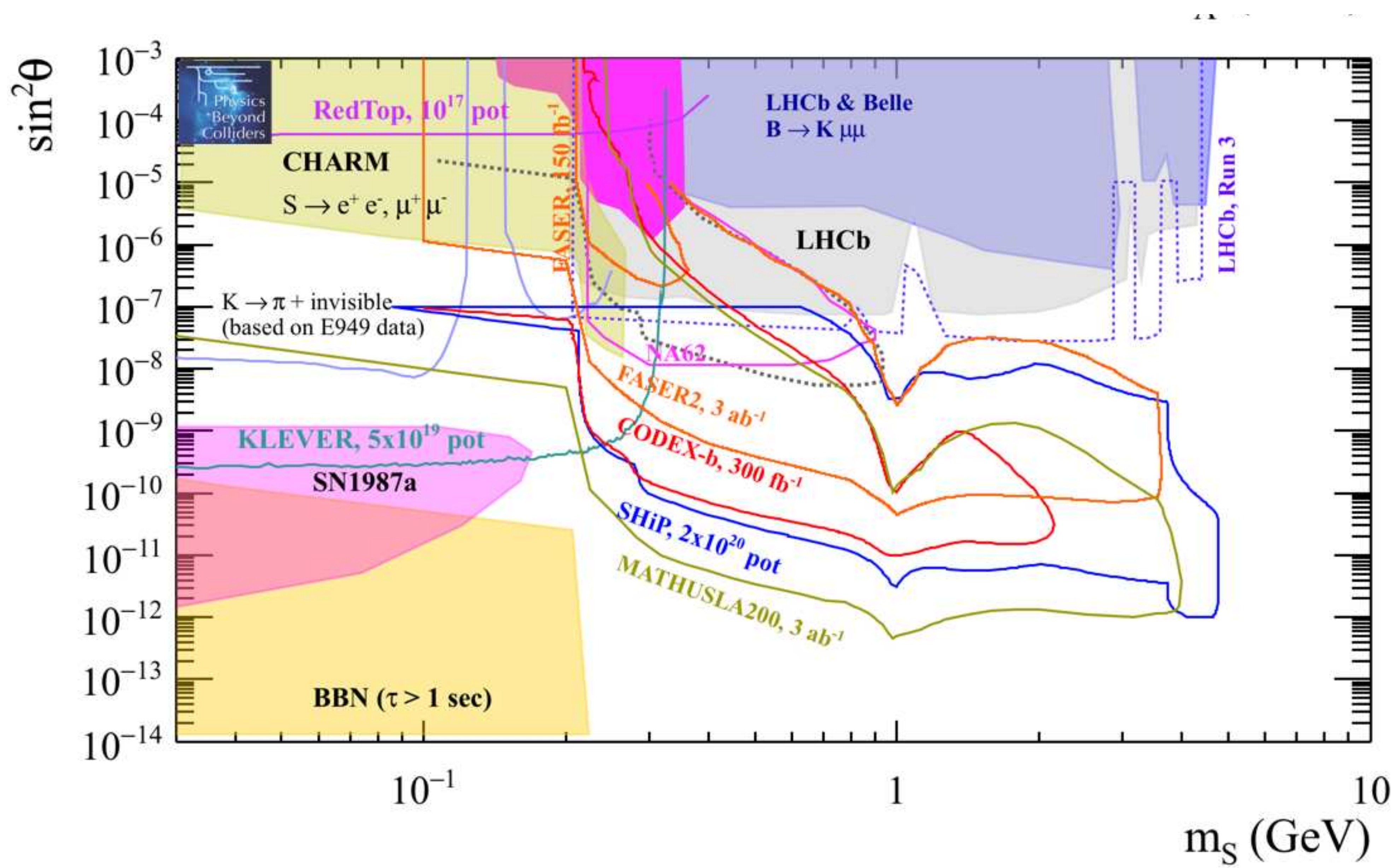
Higgs Portal Secluded-Annihilation OK



$$(m_\phi < m_\chi)$$

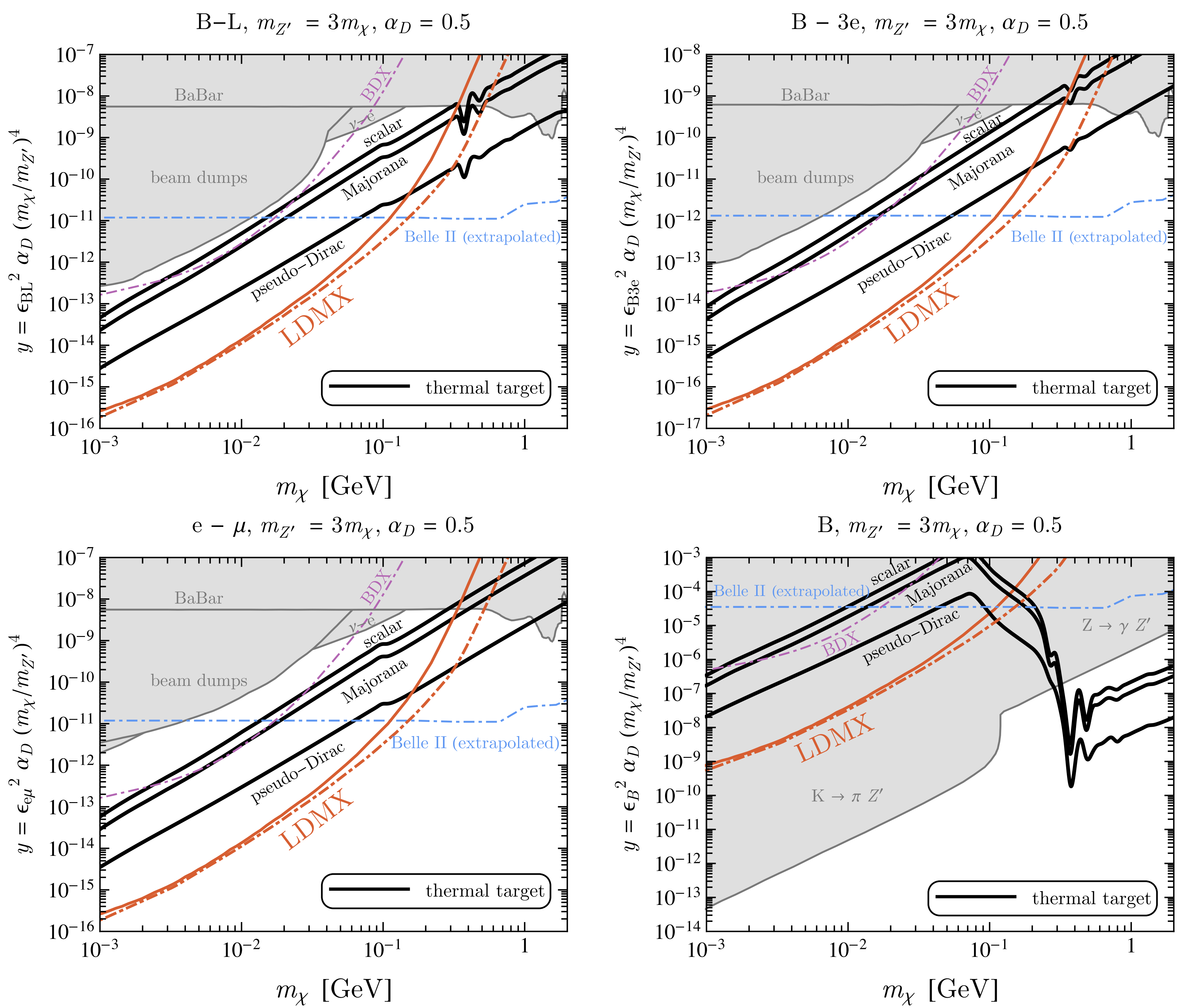
$$\sigma v \propto g_\chi^4$$





E. Gaverini's talk

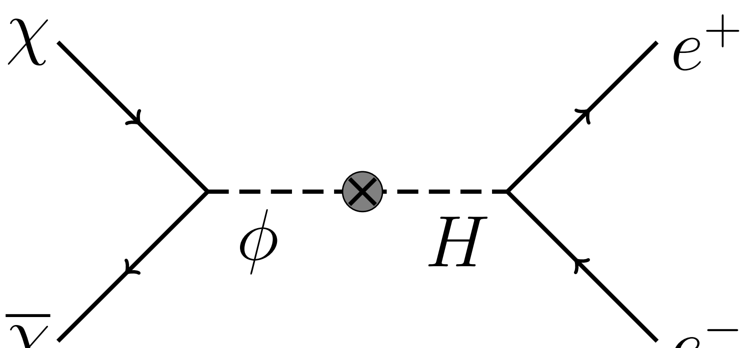
Comprehensive Coverage: Other Viable Mediators



Test of other direct-annihilation models

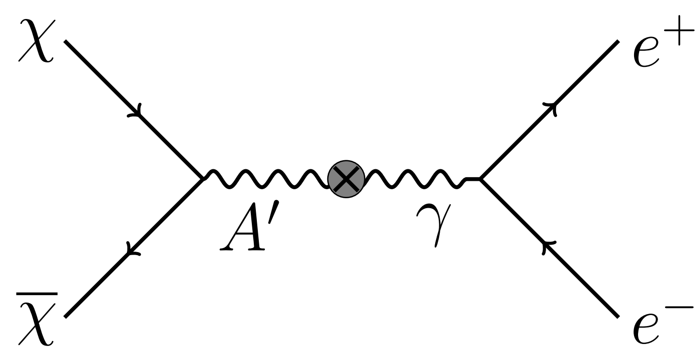
Berlin, Blinov GK, Schuster, Toro arXiv: 1807.01730

Predictive Direct Annihilation Targets



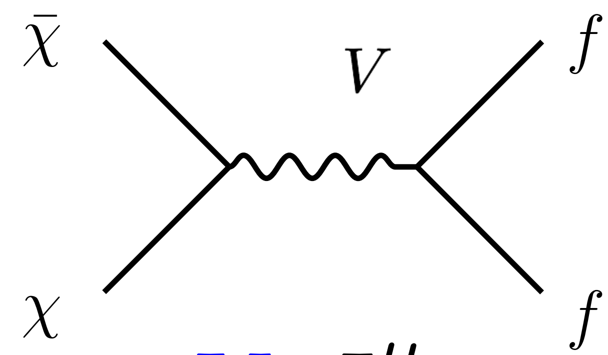
$\phi H^\dagger H$

Scalar
Ruled out



$F'_{\mu\nu} F^{\mu\nu}$

Dark photon



$V_\mu J^\mu_{\rm SM}$

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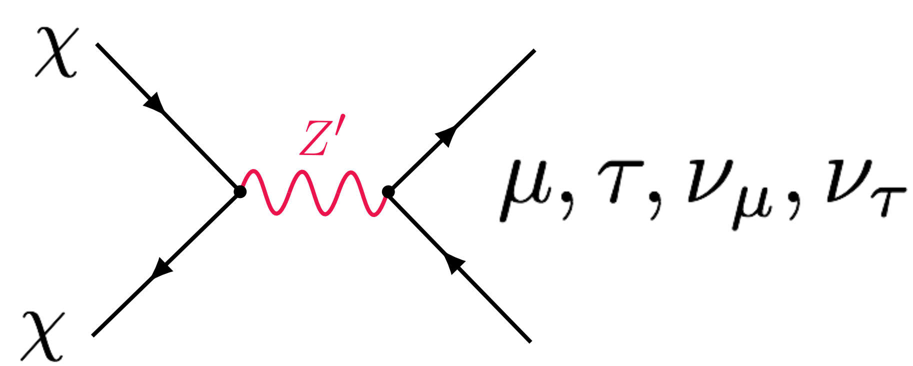
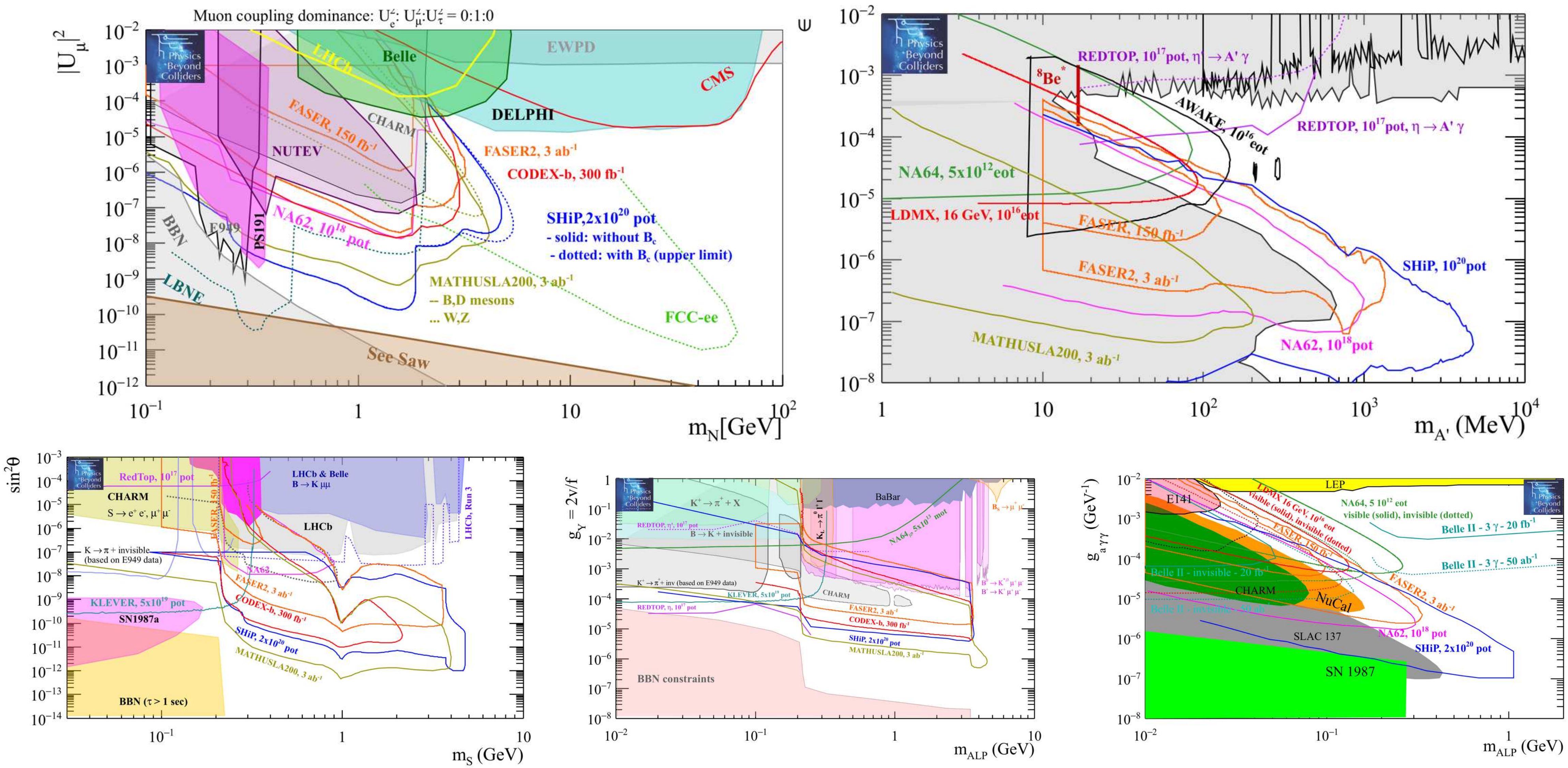
Thermal coverage: LDMX, BDX, MiniBooNE, SENSEI, Super-CDMS, Belle II

Also with muon/tau flavor couplings (need muon beam LDMX/NA64)

Only one anomaly free U(1) group
$L_\mu - L_\tau$



Physics performance: visible decays

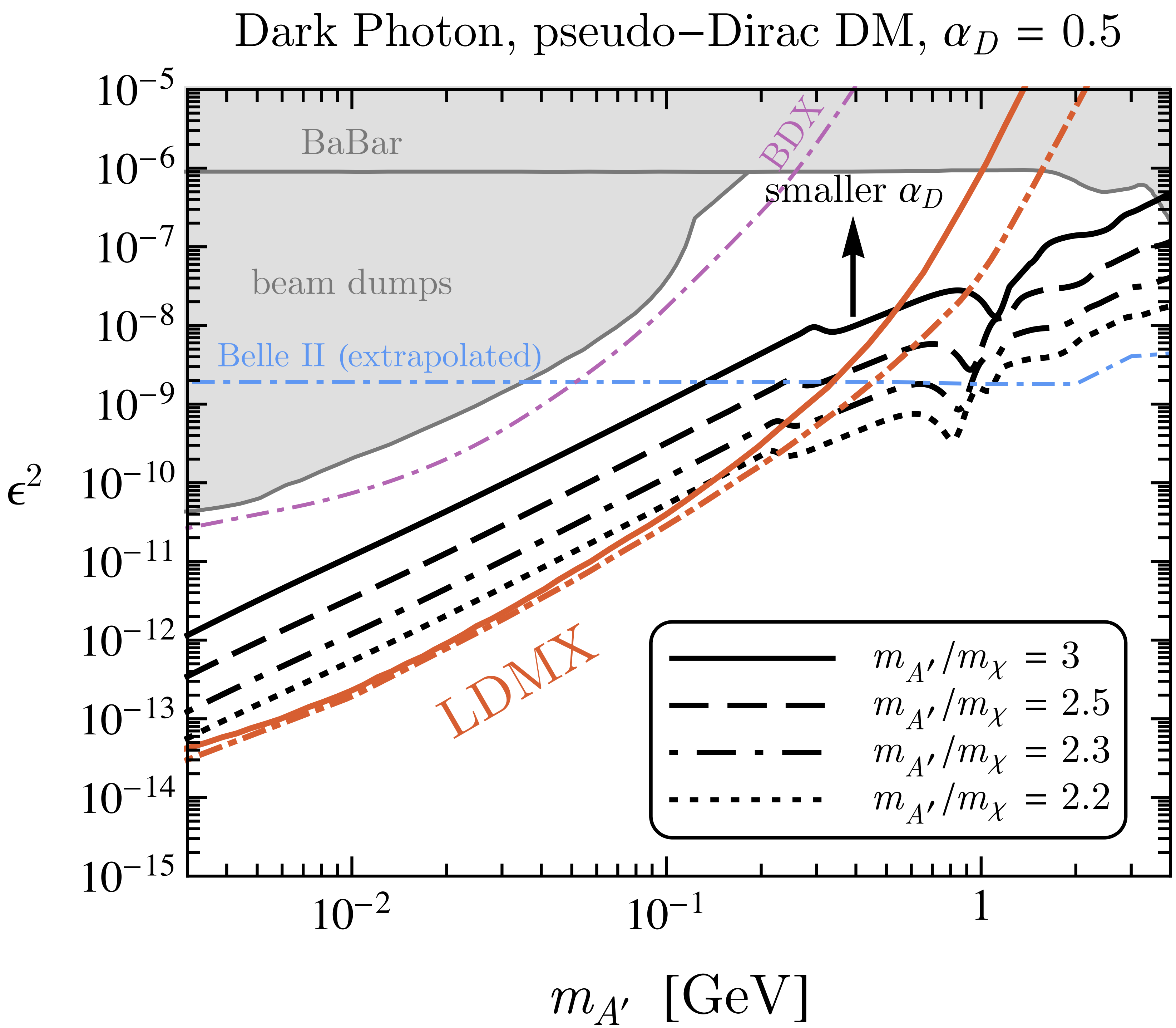


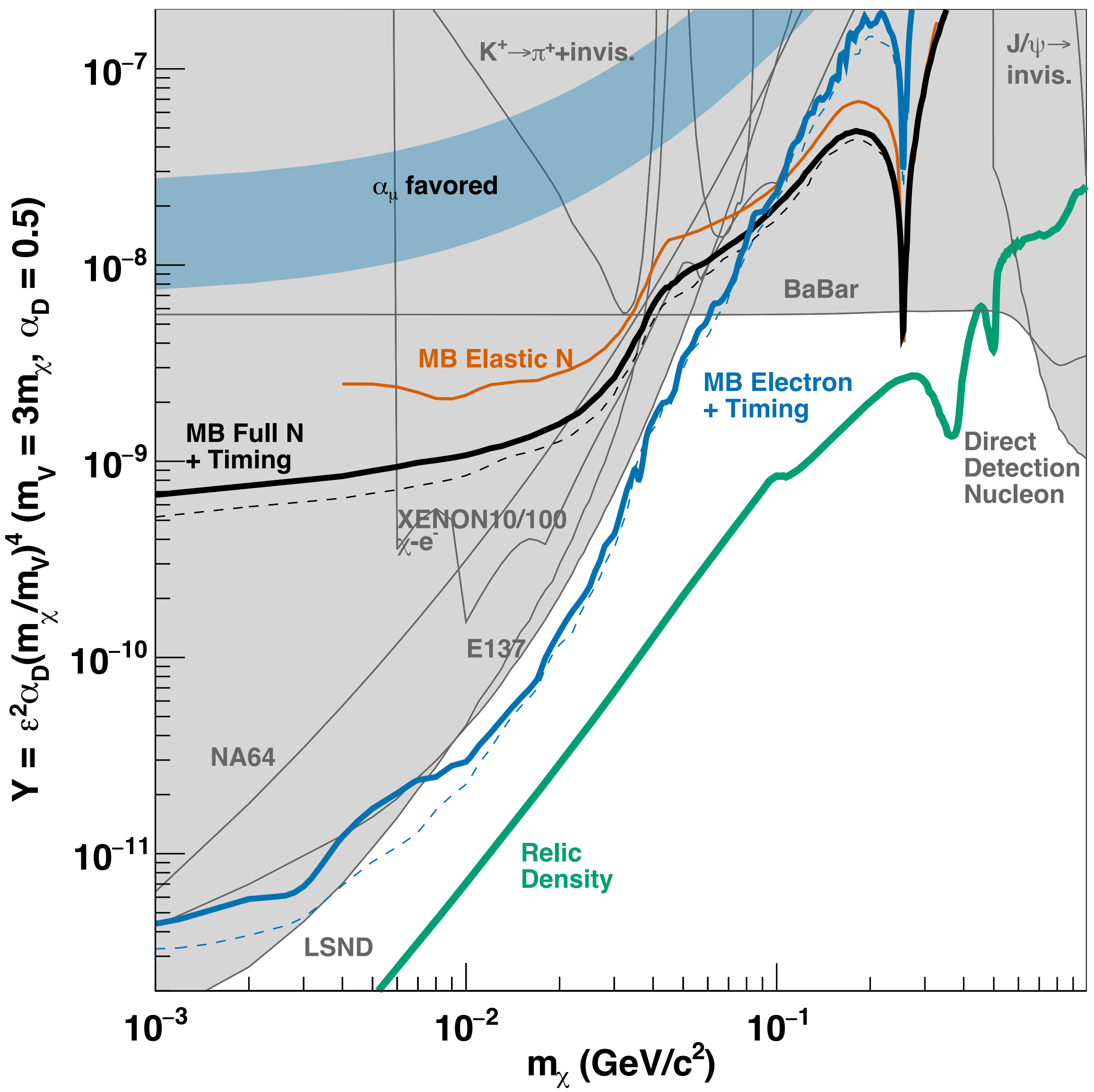
[1504.04956, 1504.04855, 1811.00930, 1901.09966]

- from top left: HNL (heavy meson decays), dark photon (decays + bremsstrahlung + QCD), scalar (K and B decays), ALPs coupled to fermions, ALPs coupled to photons
- event selection: high signal efficiency + redundant BG suppression

E. Gaverini's talk

Thermal Targets Down Around Near Resonance





$Y = \varepsilon^2\alpha_D(m_\chi/m_V)^4$ ($m_V = 3m_\chi$, $\alpha_D = 0.5$)
m_χ (GeV/c^2)
$K^+\to\pi^++$invis.
$J/\psi\to$ invis.
α_μ favored
BaBar
MB Elastic N
MB Electron + Timing
MB Full N + Timing
Direct Detection Nucleon
XENON10/100 χ-e$^-$
E137
NA64
Relic Density
LSND

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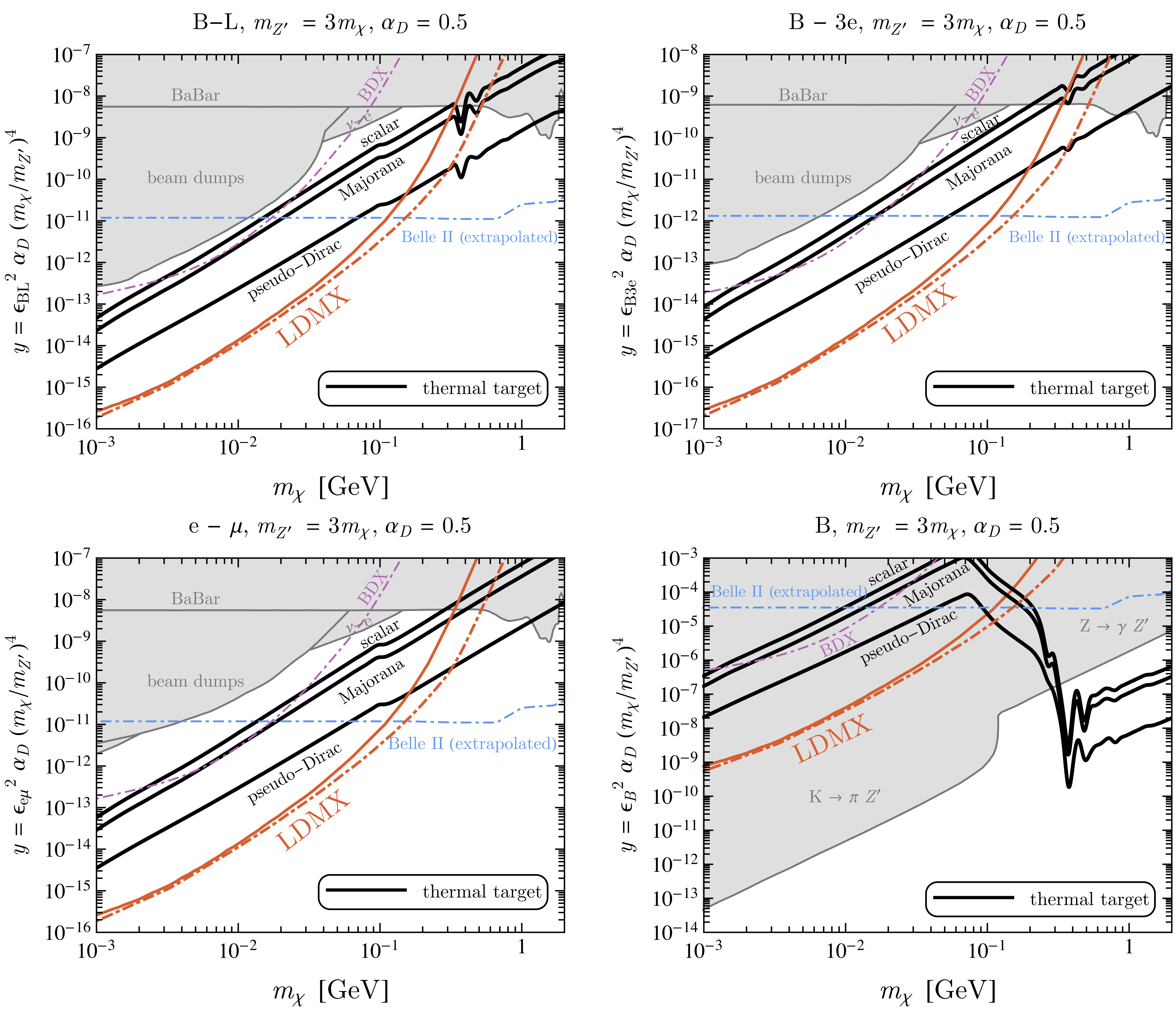

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