Probing Invisible Vector Meson Decays with NA64 and LDMX

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based on: Schuster, Toro, and Zhou, Phys. Rev. D 105, 035036 (2022)
arXiv: 2112.02104

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Freeze Out Production

Freeze out is simple and predictive: if dark matter begins in thermal equilibrium and annihilates with itself, the right amount is left over if

$$\langle \sigma v \rangle \sim \frac{1}{M_{\mathrm{pl}} T_{\mathrm{eq}}} \sim \left(\frac{1}{10\,\mathrm{TeV}} \right)^2$$

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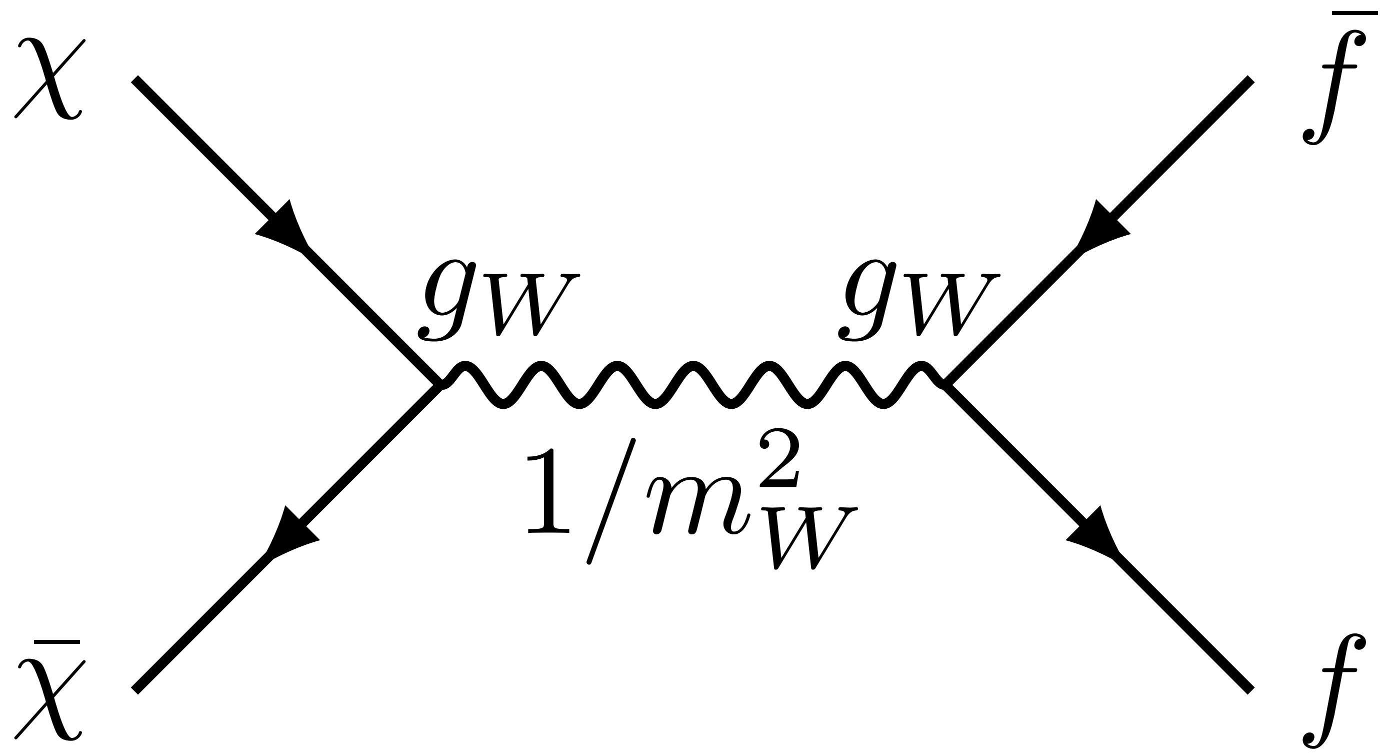
This is automatically realized by weak-scale masses and couplings

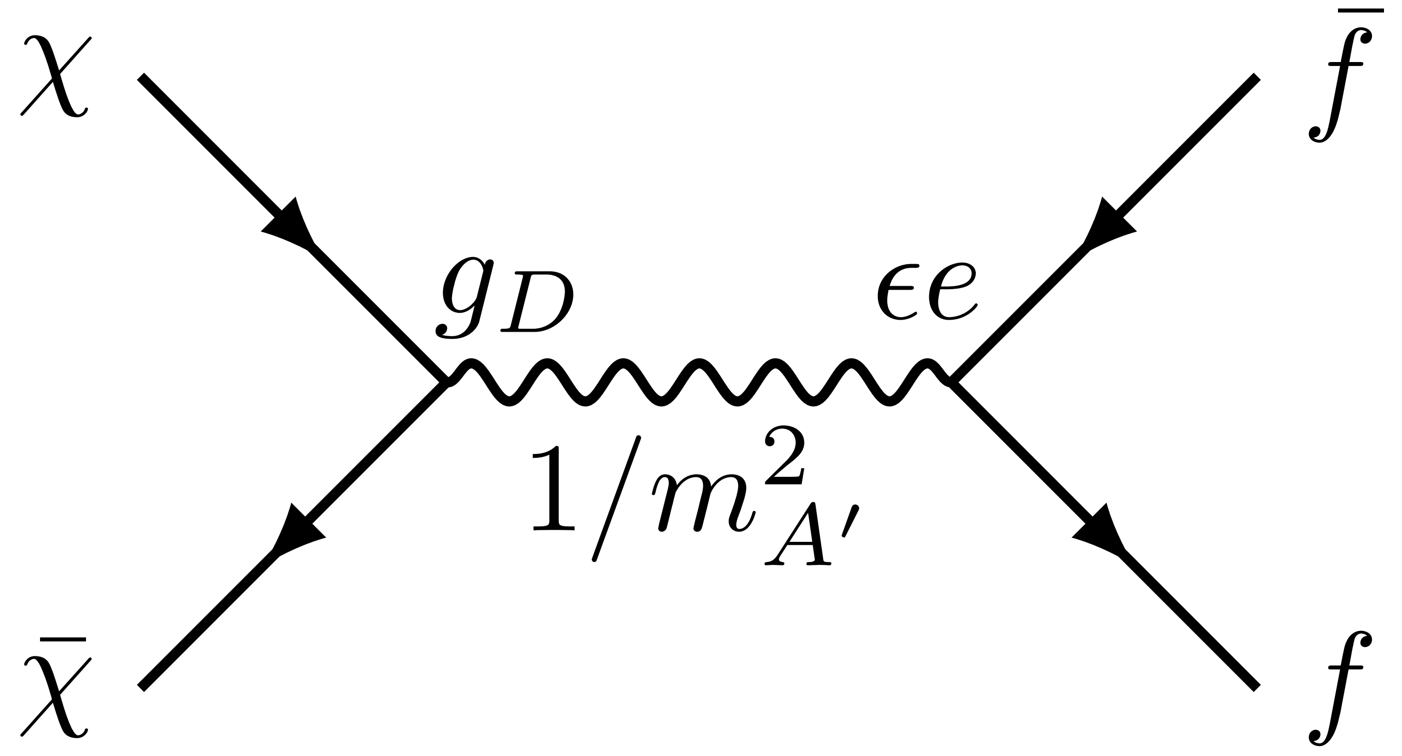


$$\langle \sigma v \rangle \sim \frac{g_W^4 m_\chi^2}{m_W^4} \quad \text{(for } m_\chi \sim m_W\text{)}$$

Motivates searches for dark matter particles at the GeV to TeV scale

Dark Sectors

But DM could also annihilate through a new mediator:



Focus on vector mediators such as the dark photon A' (simplest models compatible with flavor constraints)

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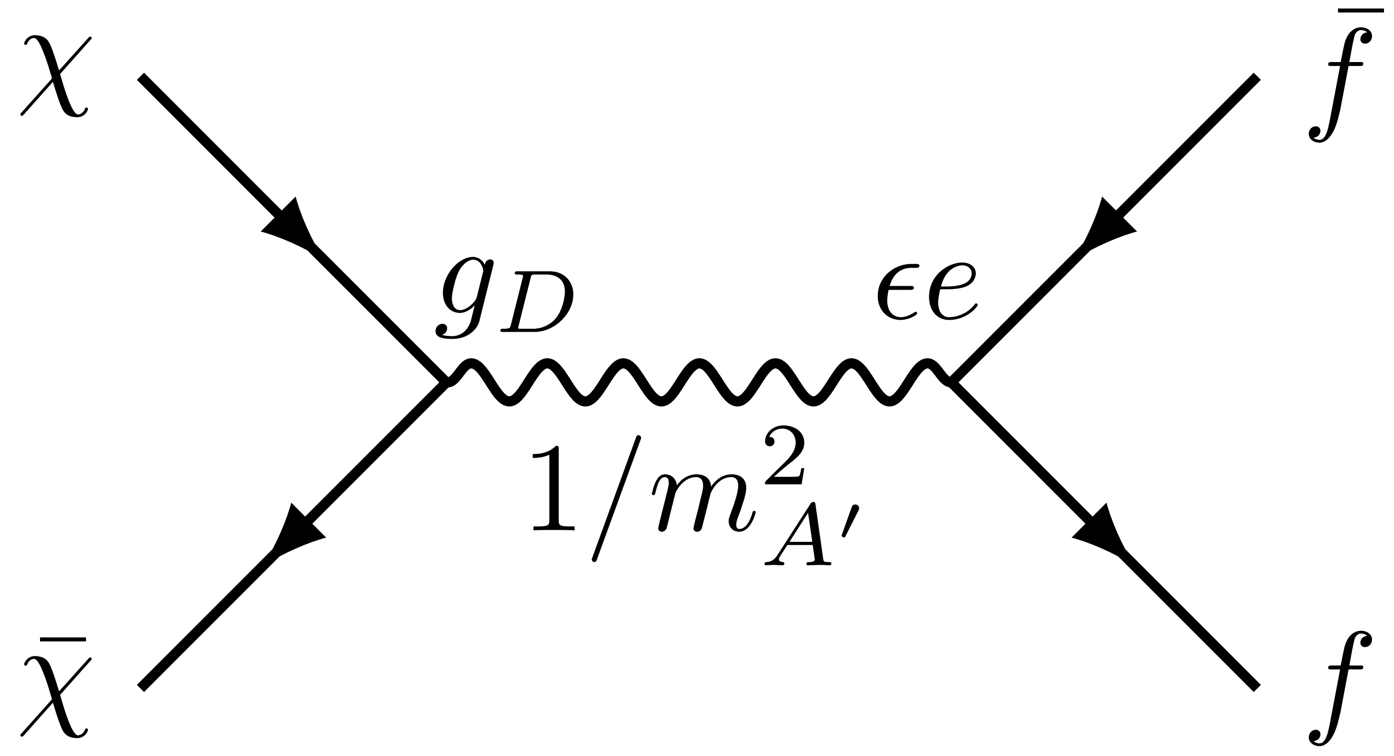
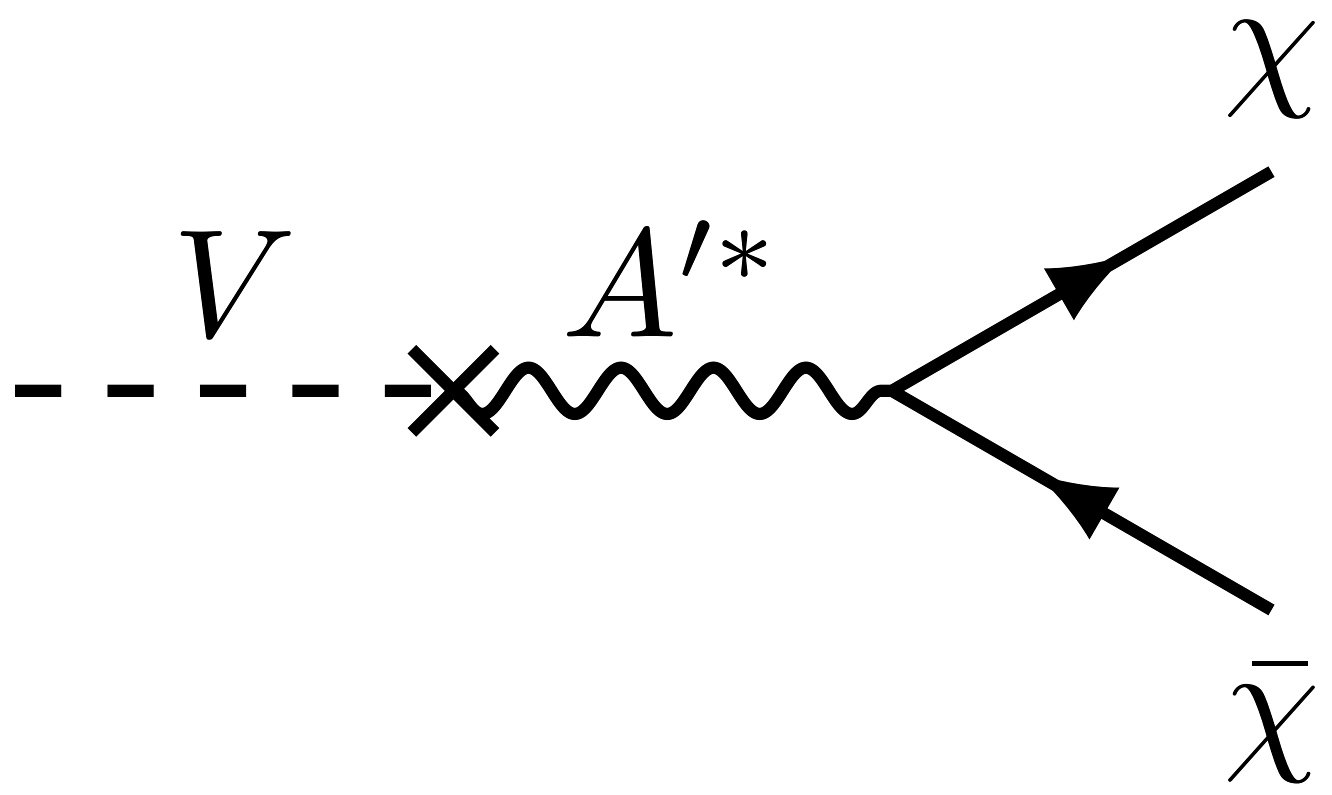


$$\langle \sigma v \rangle \sim \frac{\alpha_D (\epsilon e)^2 m_\chi^2}{m_{A'}^4}$$

Existing constraints imply $\epsilon \lesssim 10^{-3}$, so if $m_{A'} = (\text{few}) \times m_\chi$, freeze out motivates dark sector masses at the MeV to GeV scale

Invisible Meson Decay

Vector mesons generically mix with vector mediator A', leaving to decays to DM



$$\Gamma(V \to \chi\bar{\chi}) \sim \alpha_D \, (\epsilon e)^2 \frac{f_V^2 \, m_V^3}{(m_{A'}^2 - m_V^2)^2}$$

Invisible Meson Decay

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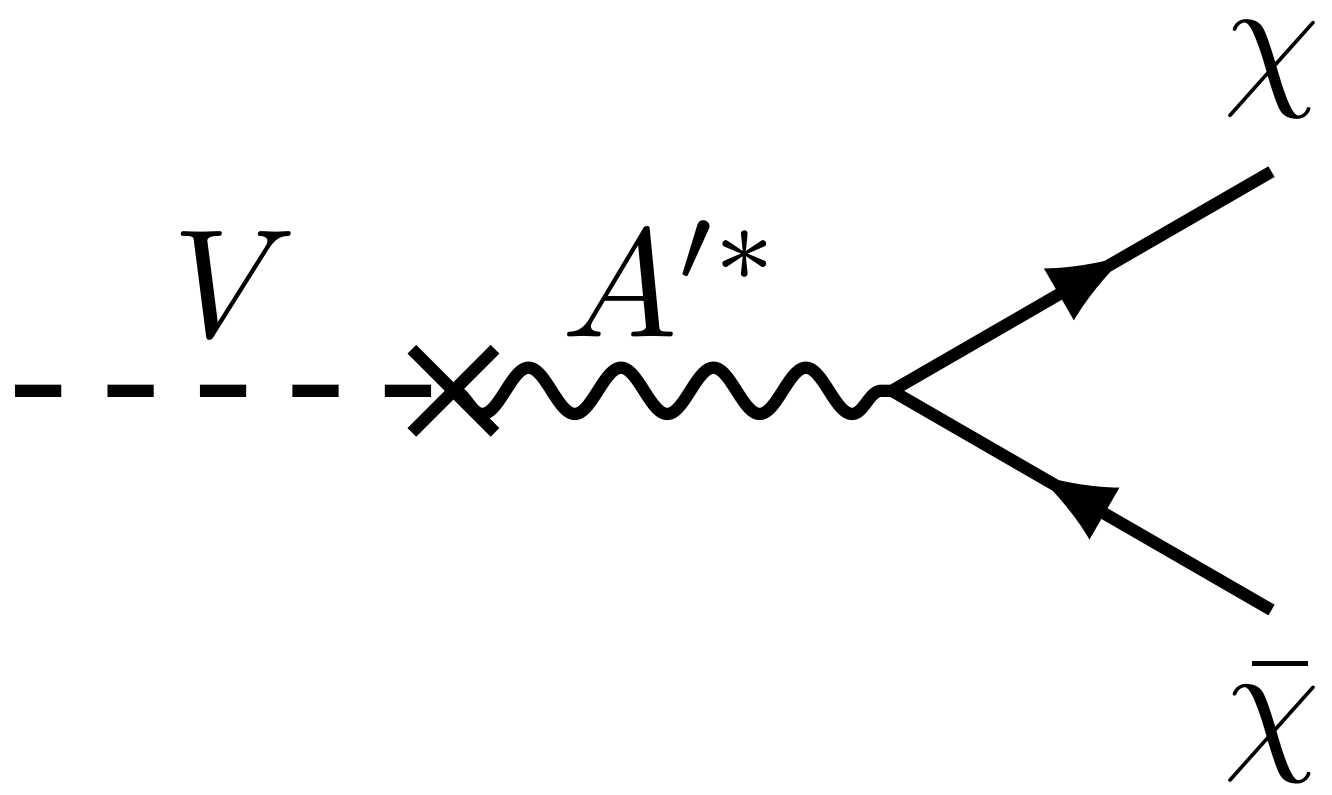

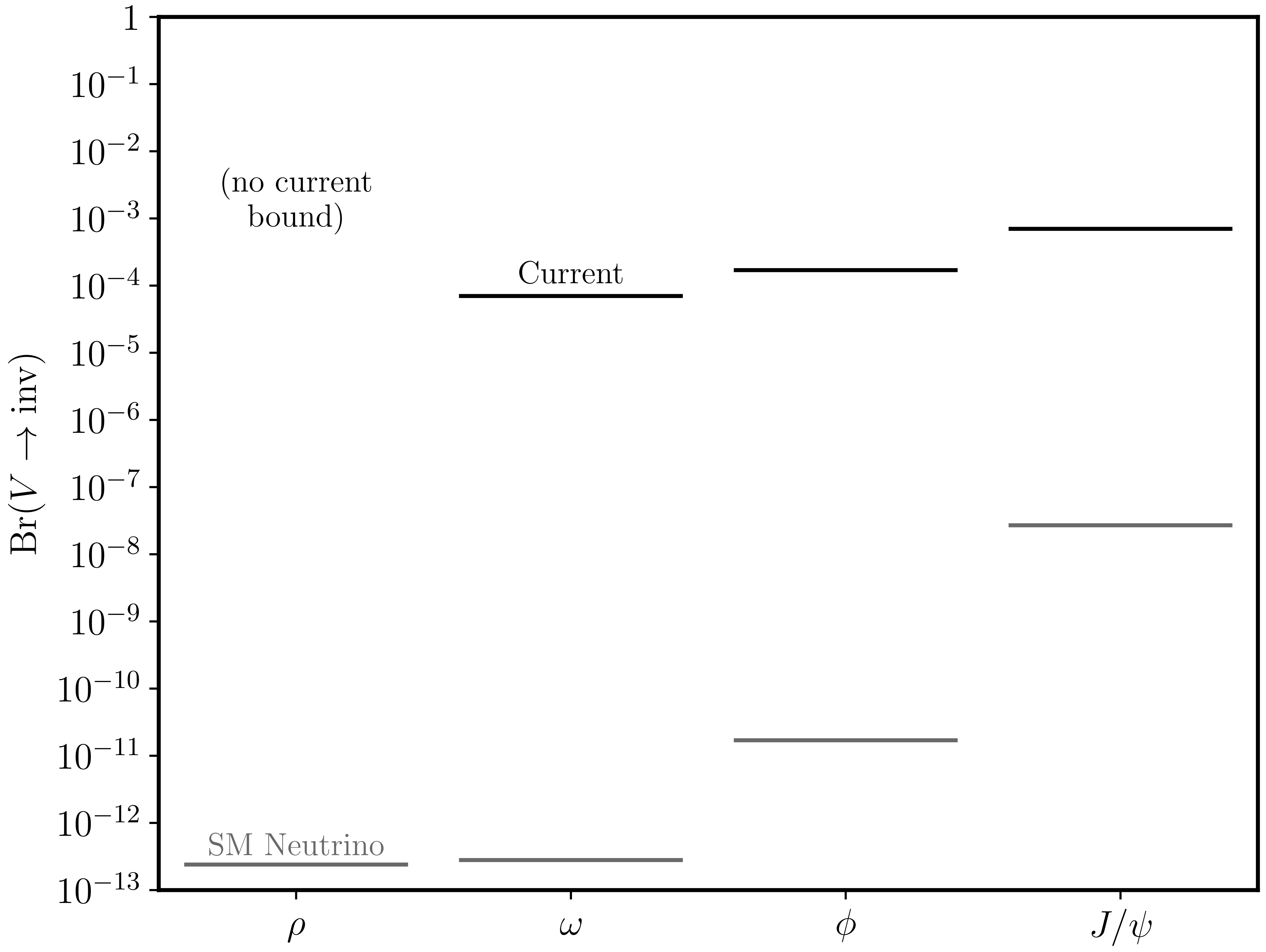

Existing collider bounds weak…

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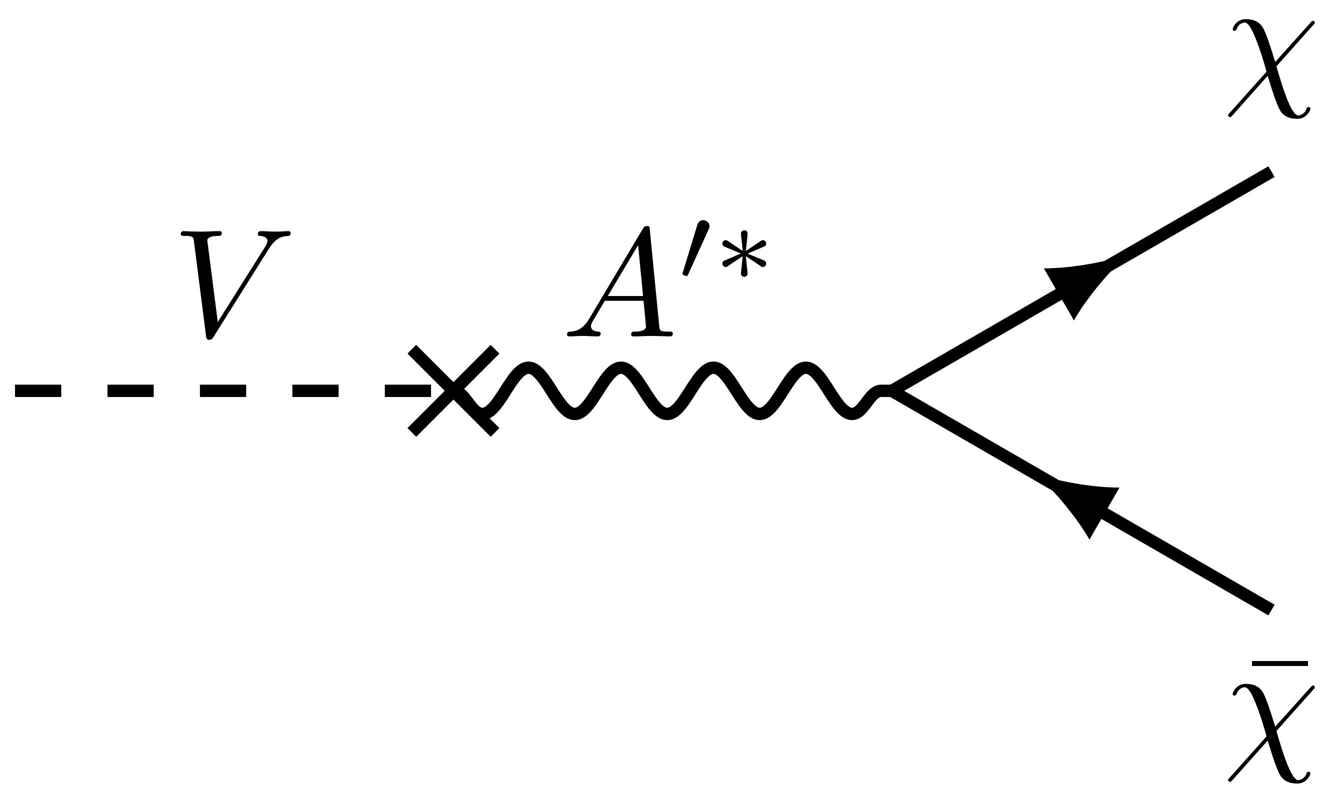
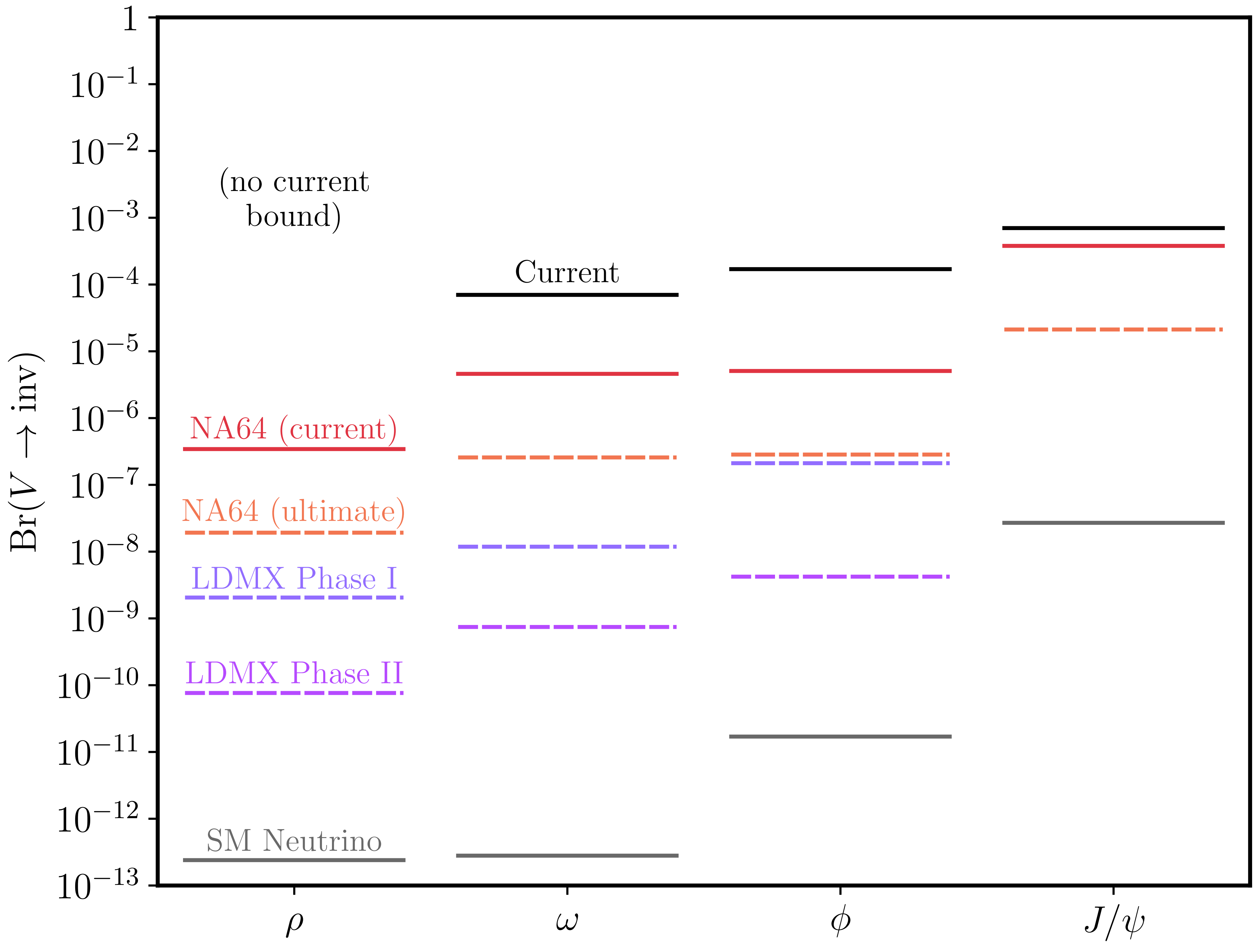




Existing collider bounds weak…

But missing energy/momentum experiments can improve by 10^5, leading to strong constraints on dark sectors!

Missing Energy/Momentum Experiments

Background free electron beam fixed target experiments
looking for energy loss by DM production

2108.04195

NA64: running at CERN, has set leading limits on dark photons

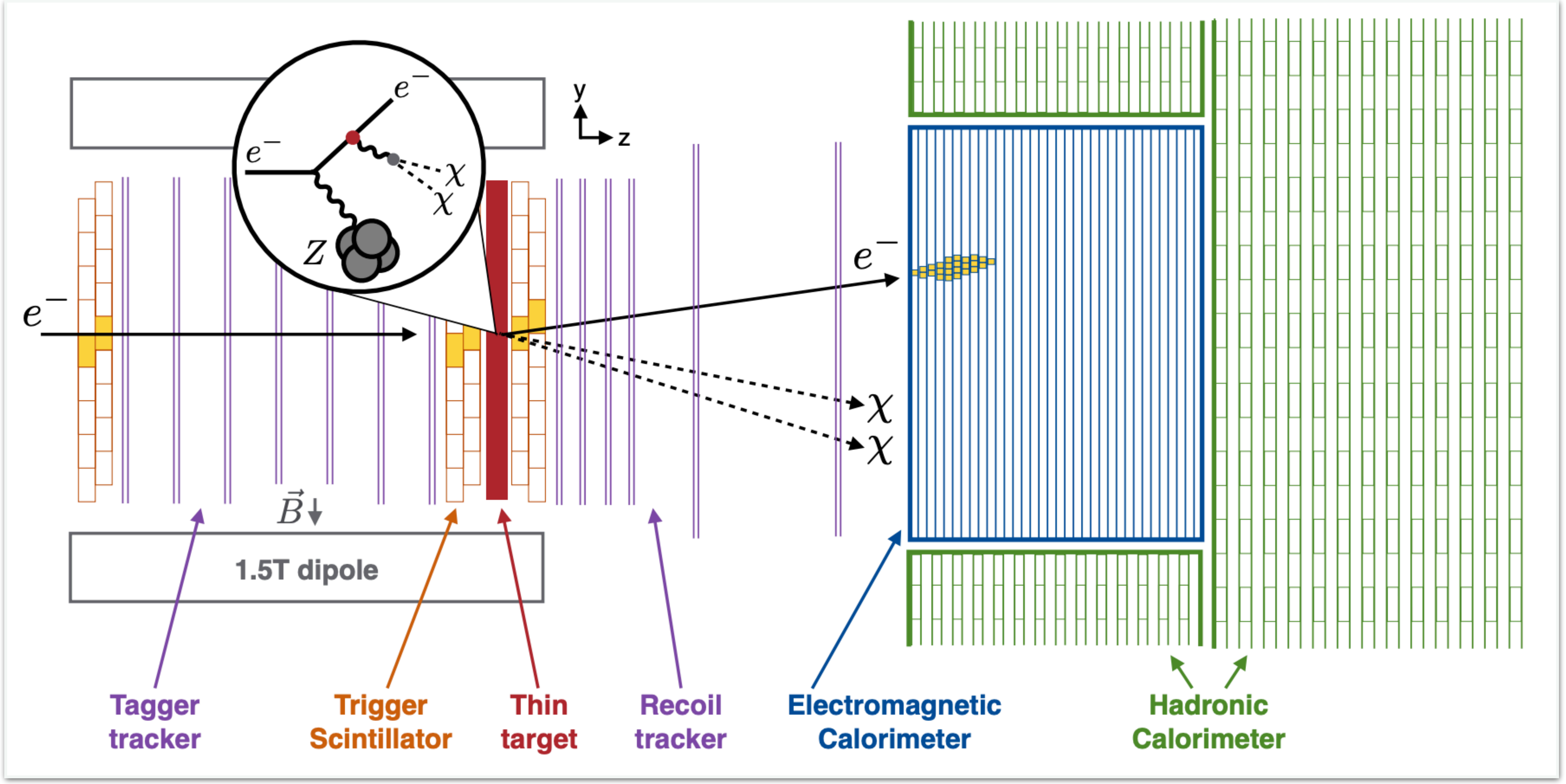
Future run will increase number of electrons by ~ 1 order of magnitude

Missing Energy/Momentum Experiments

Background free electron beam fixed target experiments
looking for energy loss by DM production

LDMX: proposed at SLAC in late 2020s, DMNI pre-project funding

Another $\sim 1-2$ orders of magnitude more electrons than NA64 "ultimate" run



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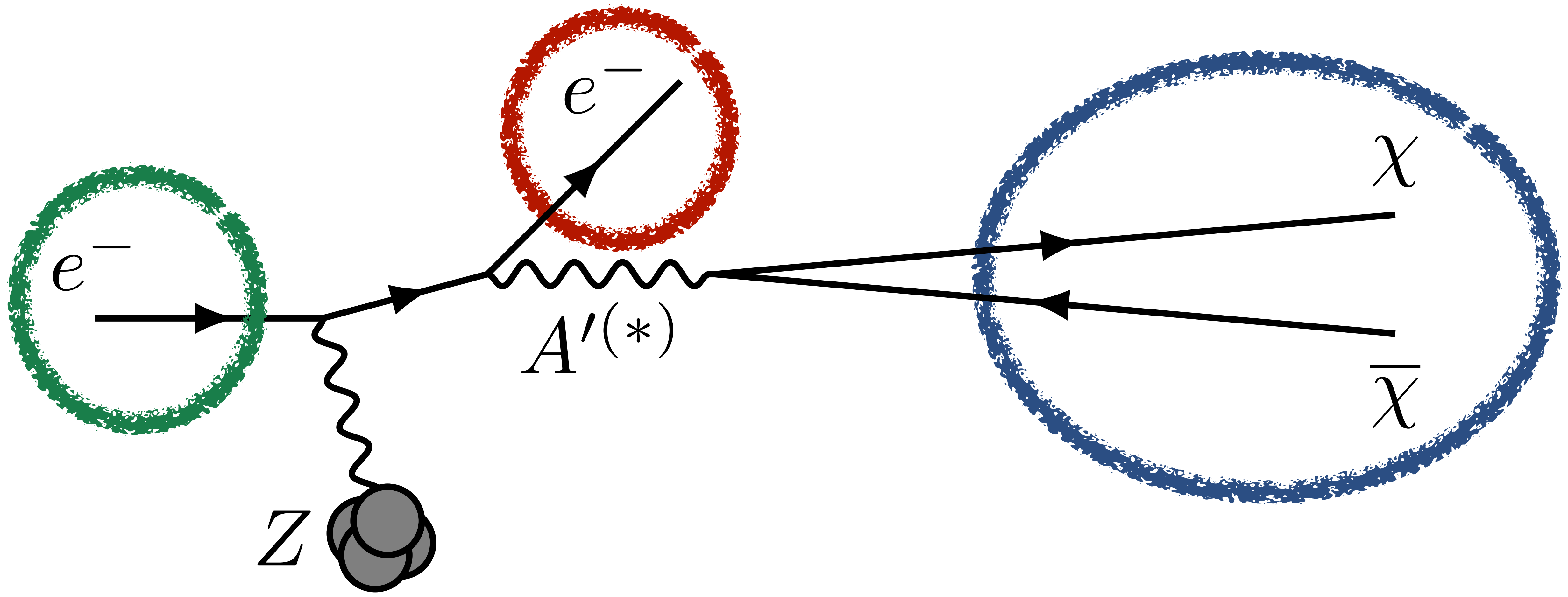
Dark Matter Production: A' Bremsstrahlung

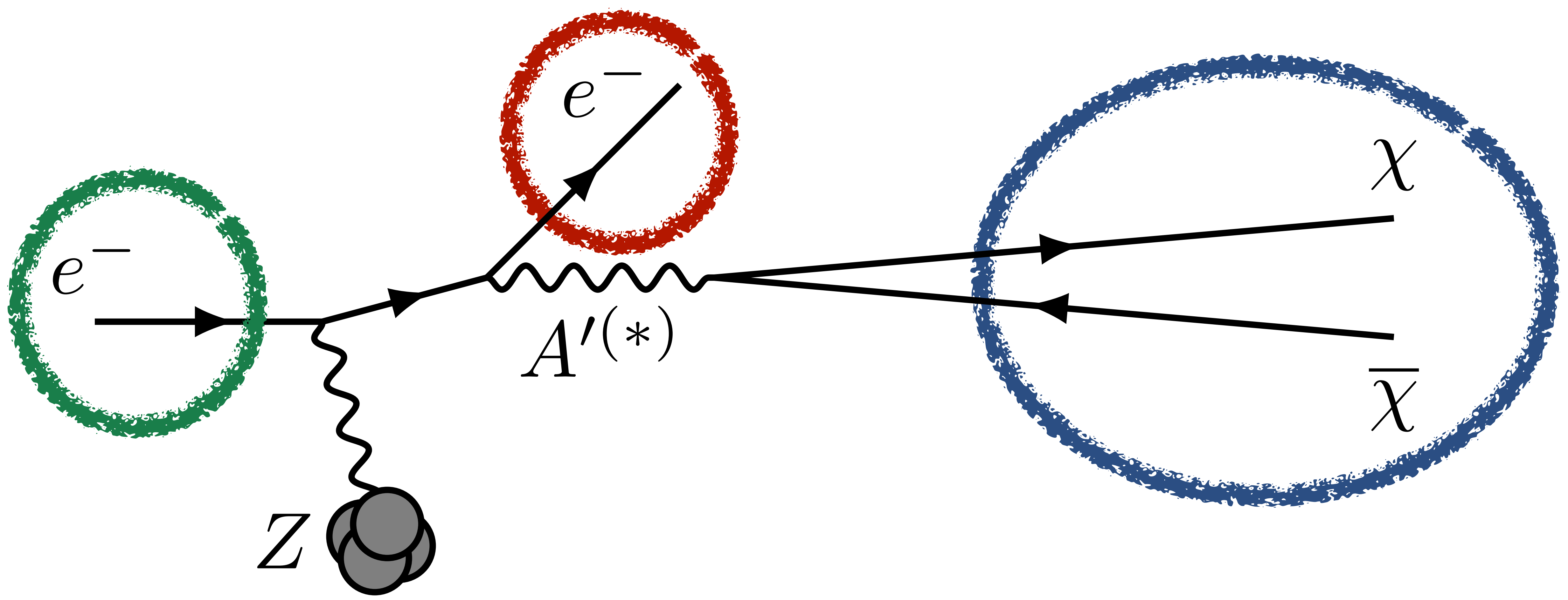


1. Track incoming electrons

2. Look for recoiling electrons with missing energy due to A' Bremsstrahlung

3. A' decays to DM, leaving no trace in calorimeters

Dark Matter Production: A' Bremsstrahlung



1. Track incoming electrons

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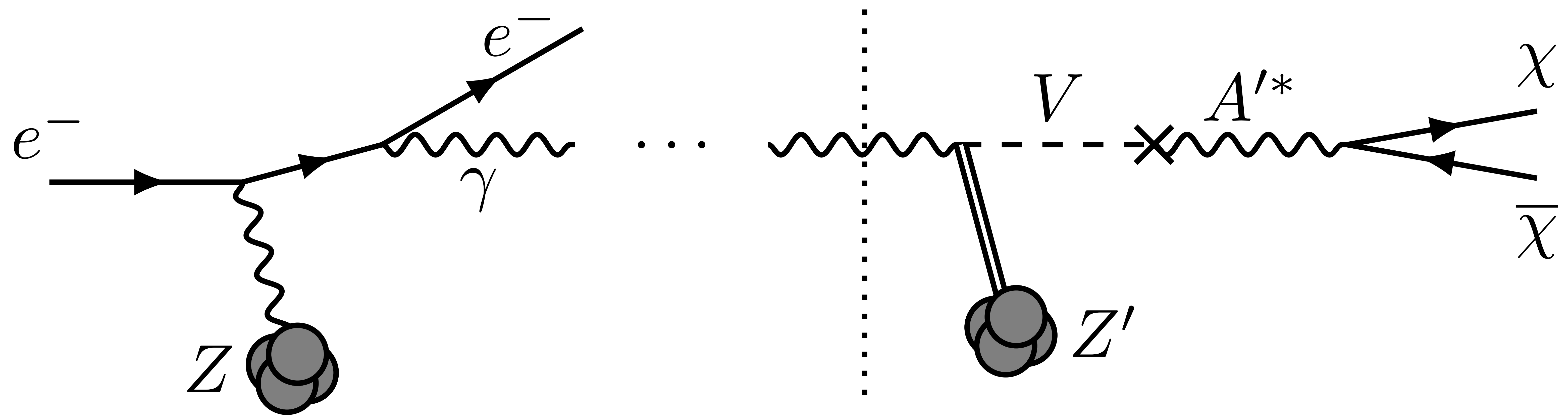
To realize target sensitivity: must detect and veto **all other** sources of electron energy loss

Dark Matter Production: Mesons

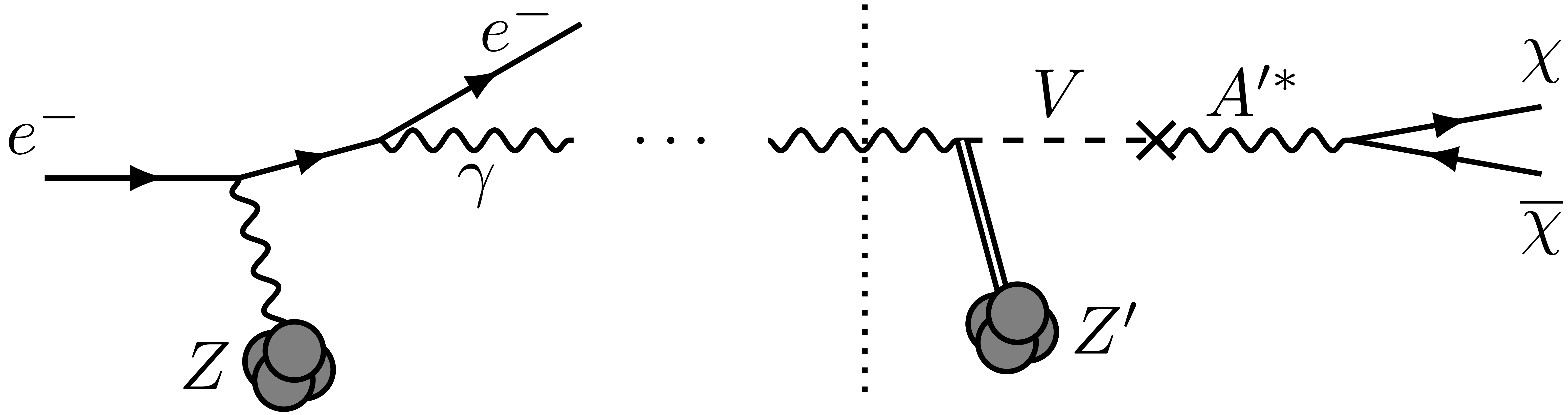


1. Track incoming electrons

2. Look for recoiling electrons with missing energy due to **ordinary** Bremsstrahlung

3. Photon converts to vector meson in calorimeter which decays to DM, leaving no trace in calorimeters

Dark Matter Production: Mesons



While A' Bremsstrahlung probes couplings to electrons, meson decay channel directly probes couplings to quarks

Estimating Meson Yield

$$N_V = N_\gamma p_V f_V$$

hard Bremsstrahlung photons

$$N_\gamma \sim \begin{cases} 10^8 & \text{NA64 (current)} \\ 10^9 & \text{NA64 (future)} \\ 10^{10} & \text{LDMX Phase I} \\ 10^{11} & \text{LDMX Phase II} \end{cases}$$

(depends on electron flux, target geometry)

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probability for exclusive V photoproduction per nucleon (governed by Pomeron exchange)

$$p_V \sim \begin{cases} 10^{-1} & \rho \\ 10^{-2} & \omega, \phi \end{cases}$$

leads to $\sim 10^9$ ω and ϕ mesons at LDMX!

Estimating Meson Yield

$$N_V = N_\gamma p_V f_V$$

order-one nuclear structure effects, dominant source of theoretical uncertainty (treated in detail in our paper)

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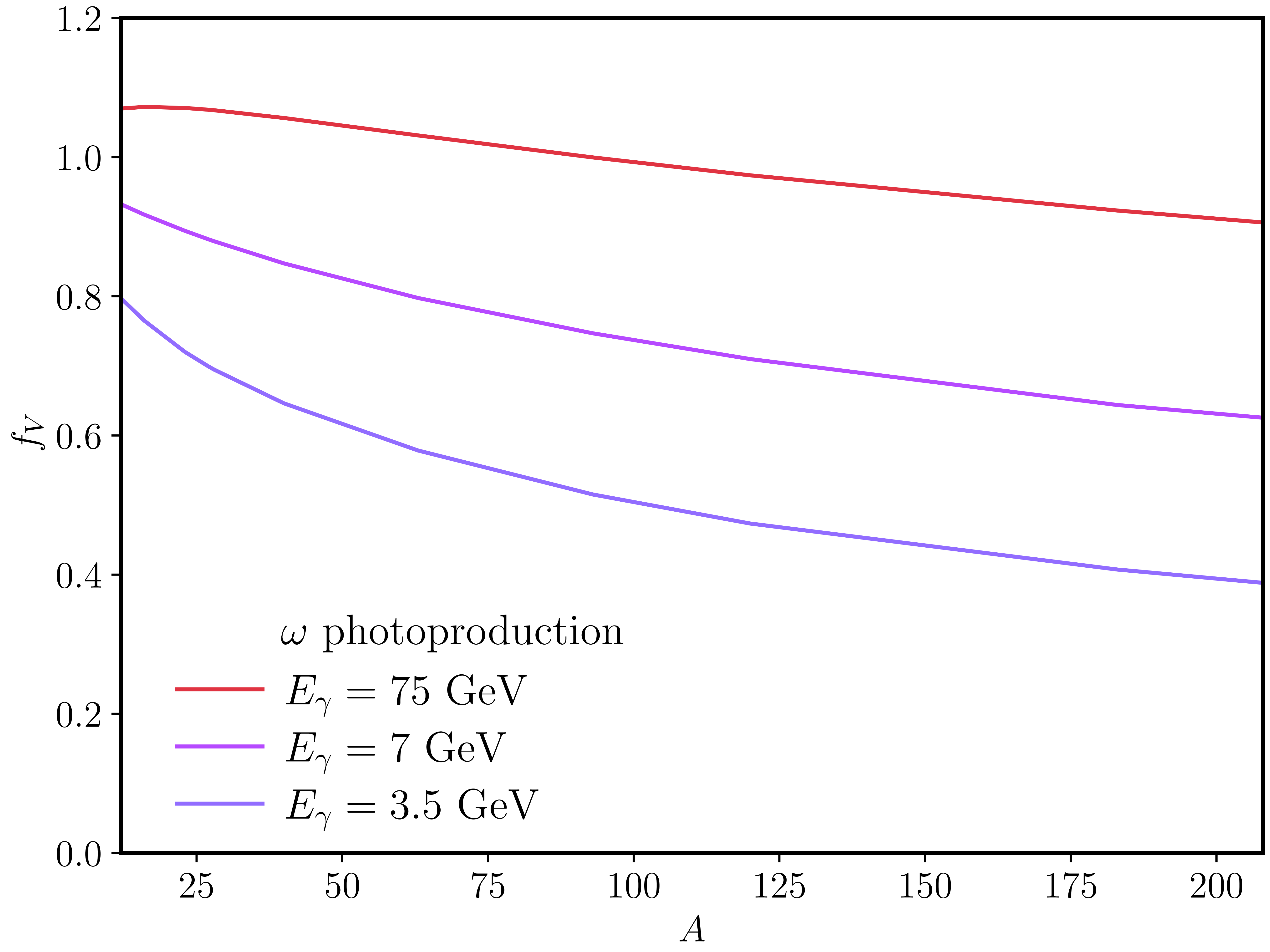
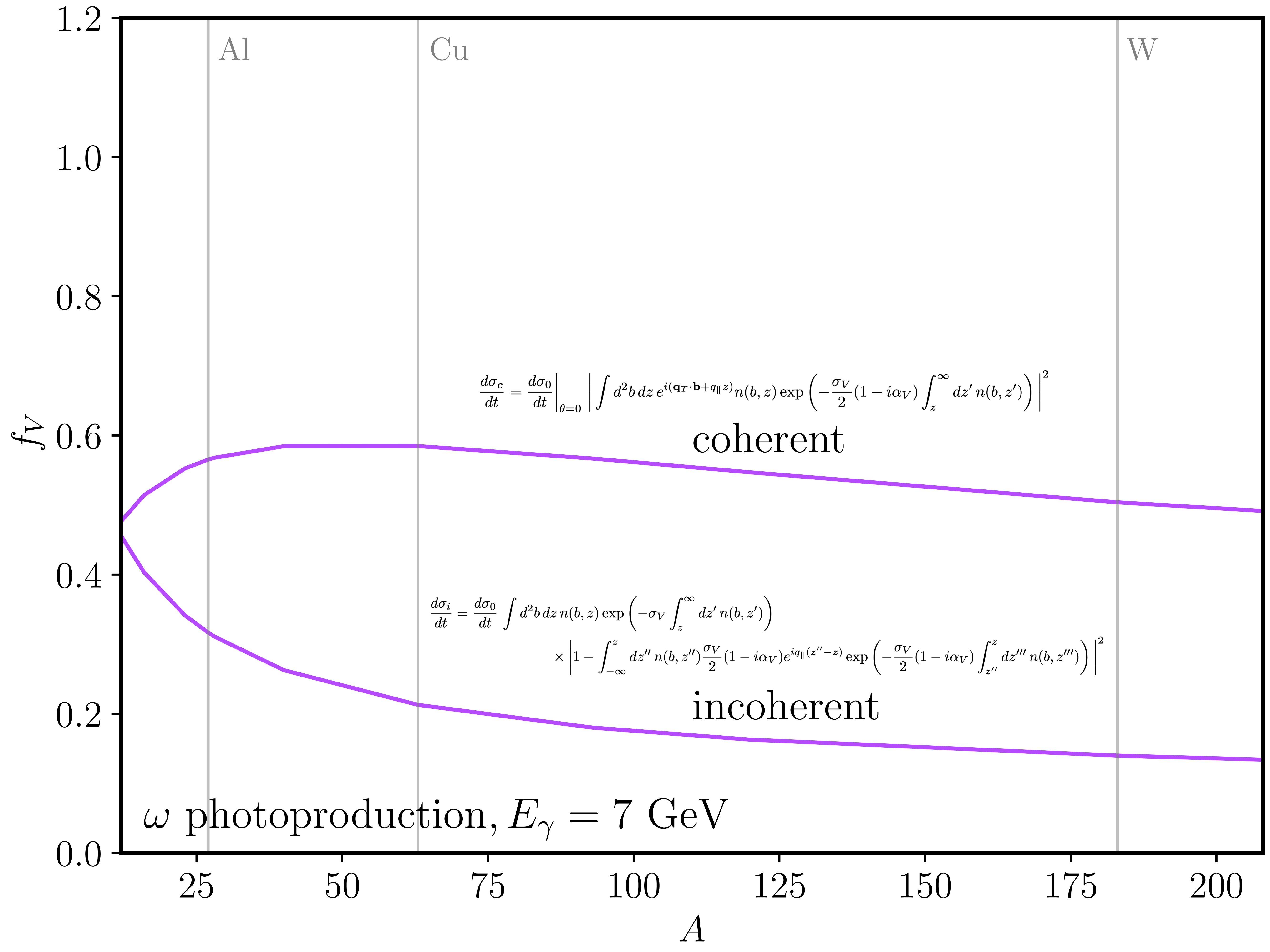
Nuclear Structure Effects



- Order-one effect for most mesons, more important at LDMX energies
- Not well-modeled in Geant!
- Our theoretical modeling based on partial experimental measurements, 25% uncertainty

Nuclear Structure Effects

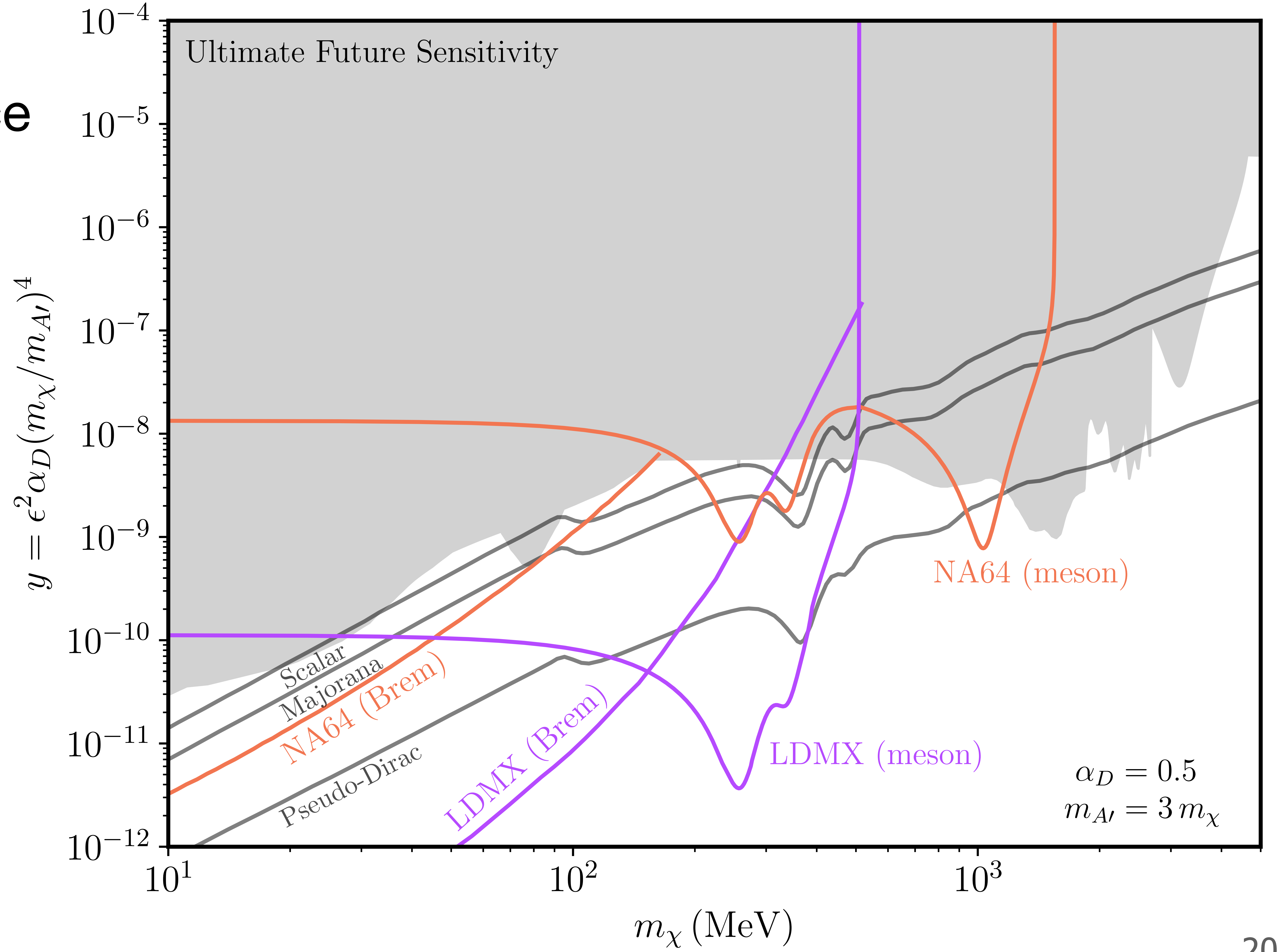


- Calculated using Glauber optical model, with absorption and nuclear shadowing
- Key subtlety: both coherent and incoherent processes contribute
- Coherent process dominates for heavy nuclei and produces softest nuclear recoils, but absent in semiclassical Monte Carlo!

Dark Photon Reach

Meson decay channel probes complementary parameter space to A'-Bremsstrahlung

- Extends reach to freeze-out target upward in mass
- Resonant at $m_{A'} \approx m_V$
- See LDMX Snowmass white paper for combined projections
  (2203.08192)

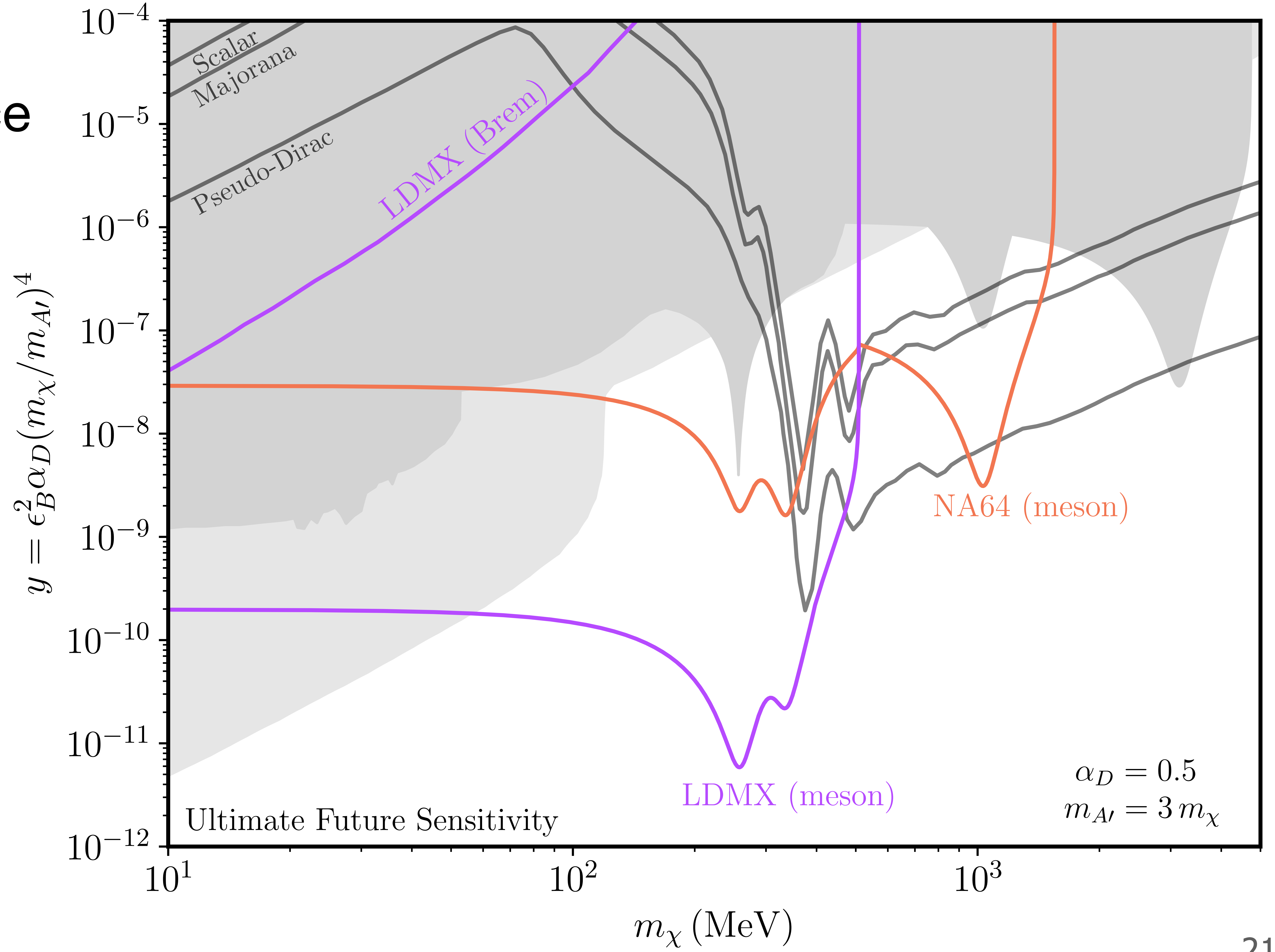


$U(1)_B$ Gauge Boson Reach

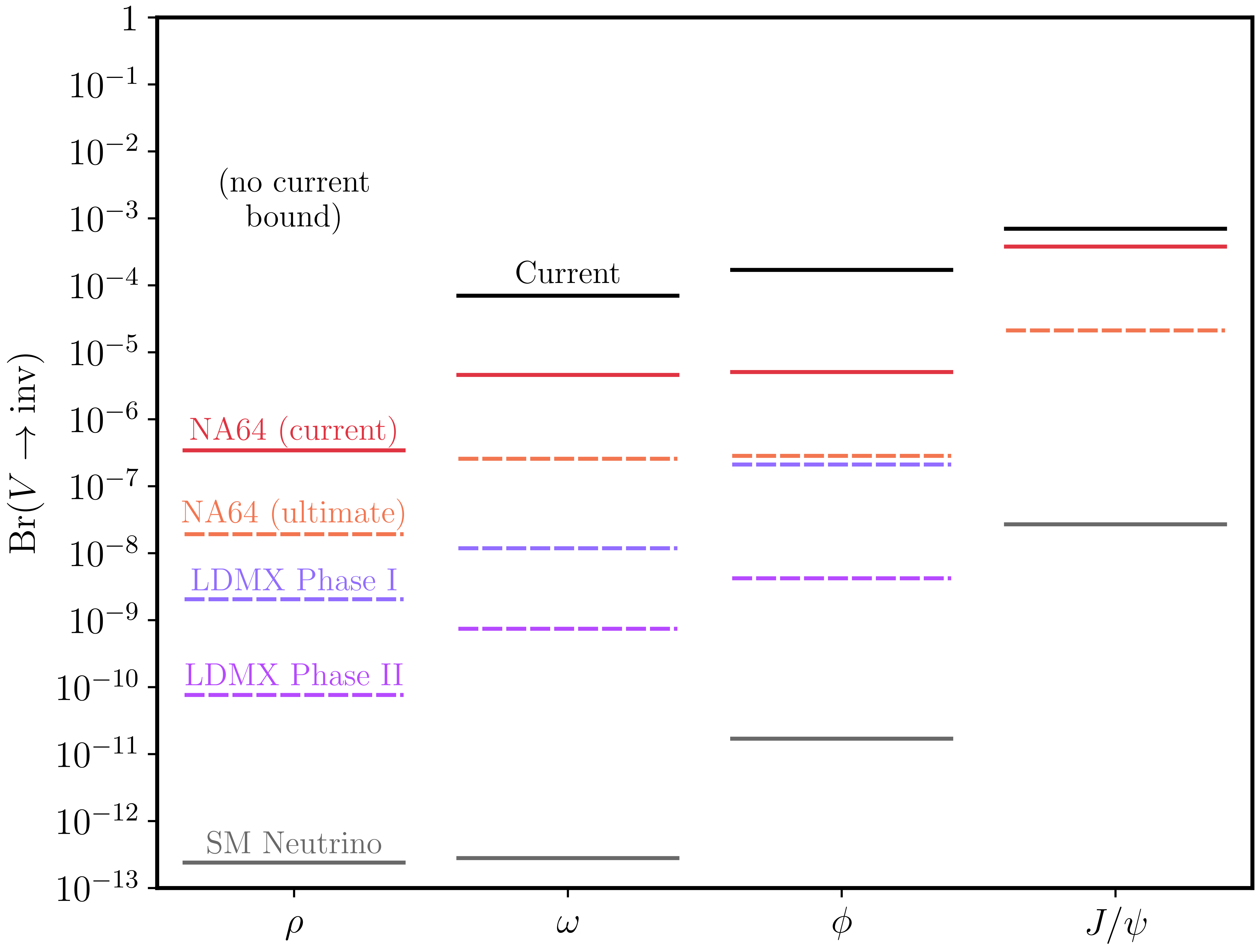
Meson decay channel probes complementary parameter space to A'-Bremsstrahlung

- Dramatically improves reach to mediators without direct coupling to electrons

- Simple examples: $U(1)_B$ gauge boson, or anomaly-free $U(1)_{B-3L_\mu}$ gauge boson



Outlook



Potential world-leading invisible meson decay bounds from existing NA64 data!

Outlook

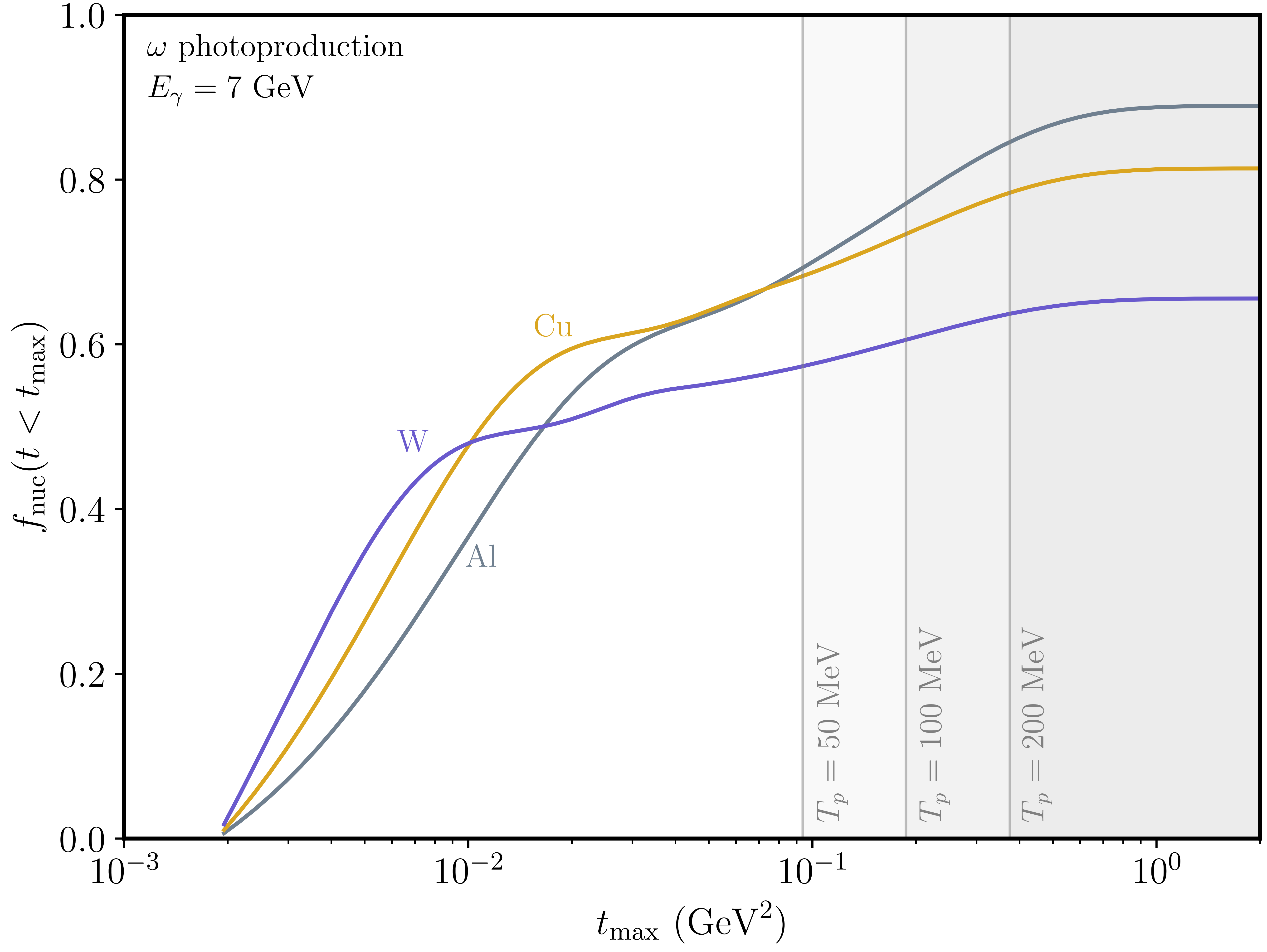
Improved meson photoproduction modeling could benefit many other experiments, such as electron beam dumps

Mediator coupling	$V \to \chi\bar{\chi}$	$V \to \gamma\chi\bar{\chi}$	$M \to \chi\bar{\chi}$	$M \to \gamma\chi\bar{\chi}$
Scalar $\bar{q}q$		✓		
Pseudoscalar $\bar{q}\gamma^5 q$		✓	✓	
Vector $\bar{q}\gamma^\mu q$	✓			✓
Axial vector $\bar{q}\gamma^\mu\gamma^5 q$		✓	✓	

Many other potentially interesting invisible (or partially invisible) decay signals, probing a wide range of mediators!

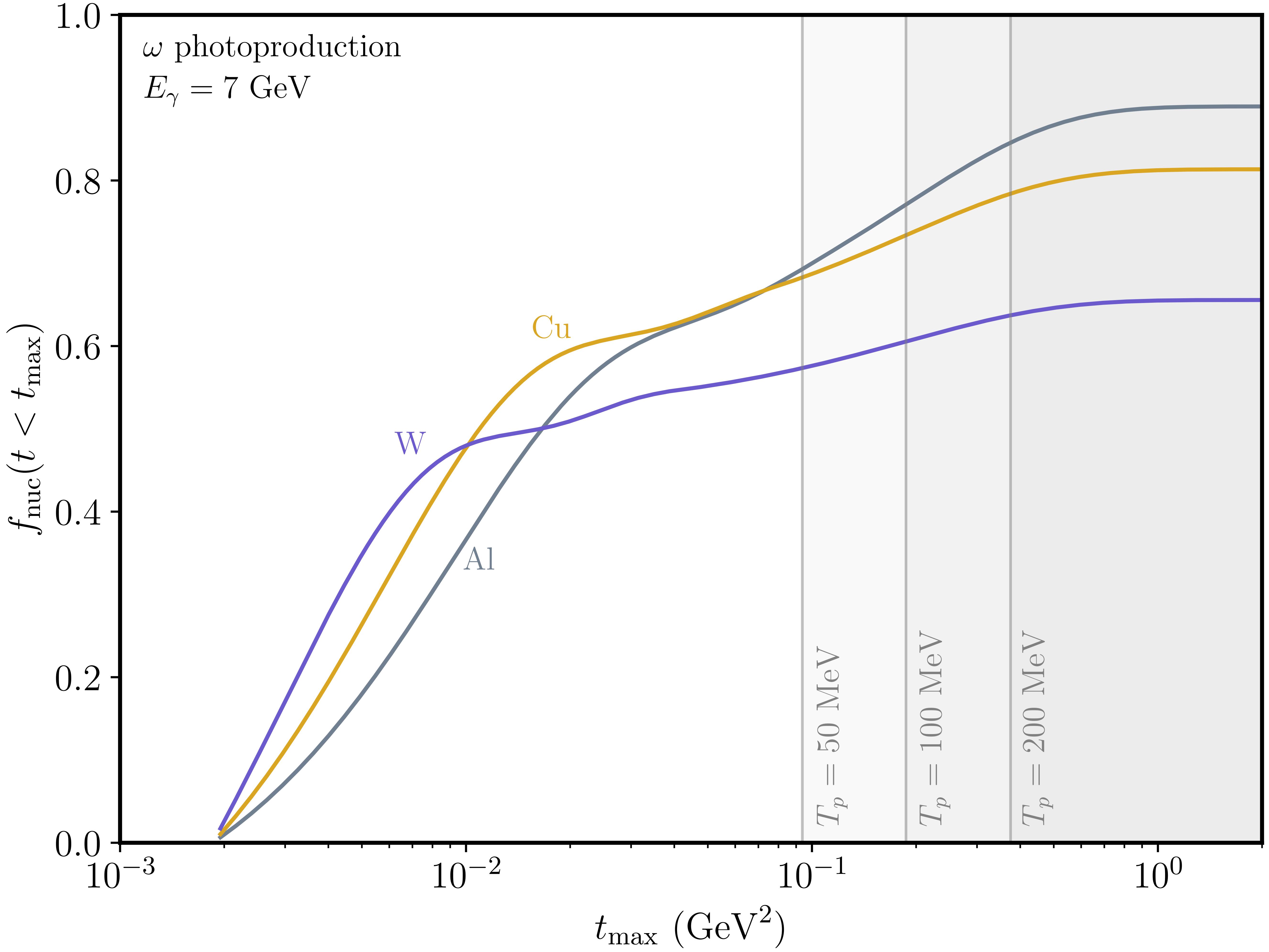
Backup Slides

Coherent Cross Sections



- Peaked at very low momentum transfer $|t| \simeq q^2 \leq (1/R_N)^2$
- Nucleus recoils as a whole, with tiny kinetic energy $T_N \simeq |t|/2m_N$
- Glauber formalism for computing coherent cross sections thoroughly tested in 1970s

Incoherent Cross Sections



- Falls off exponentially in t, scale $\sim 0.2\ \mathrm{GeV}^2$ set by Pomeron
- Nucleon recoils with kinetic energy $T_p \simeq |t|/2m_p$, we impose $T_p \leq 200\ \mathrm{MeV}$
- Less well-measured, but can be predicted at 50% level from coherent process measurements

LDMX Combined Projections