Probing Dark Sectors With Invisible Vector Meson Decays

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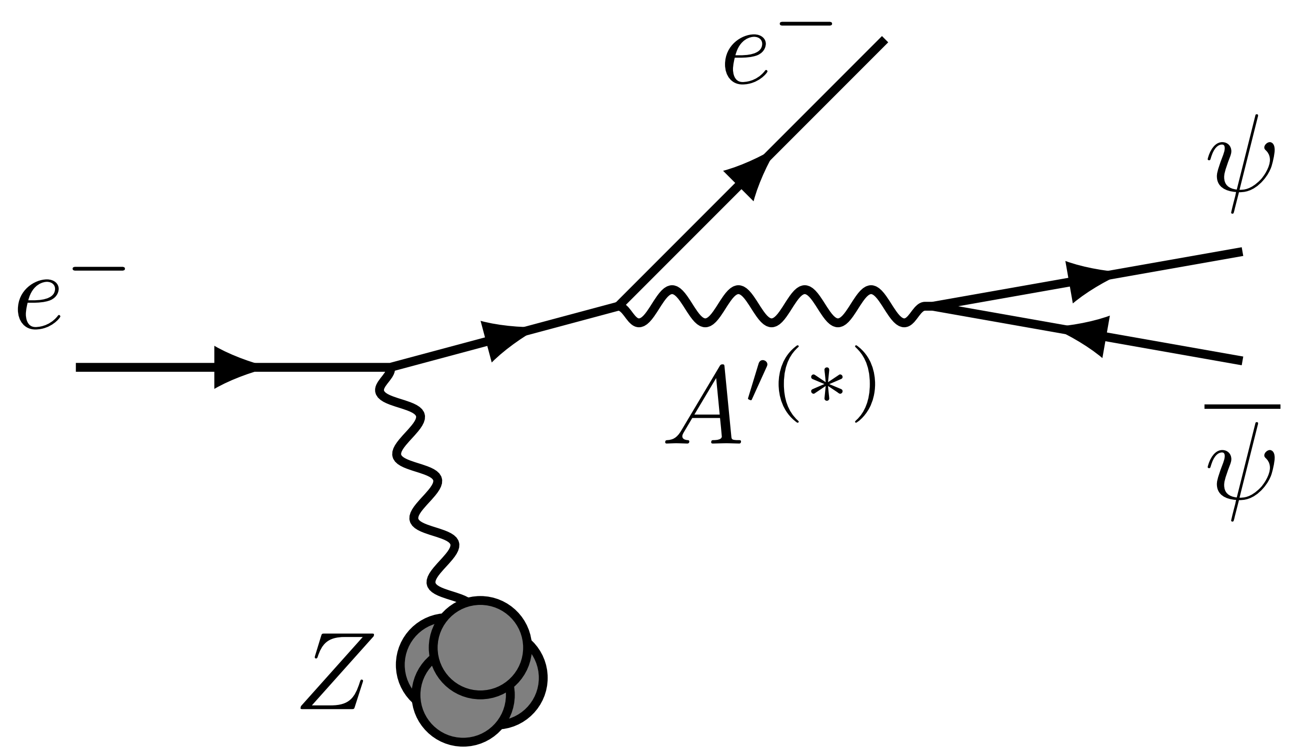
arXiv: 2111.xxxxx

with Philip Schuster and Natalia Toro

ILCX Workshop — October 27, 2021

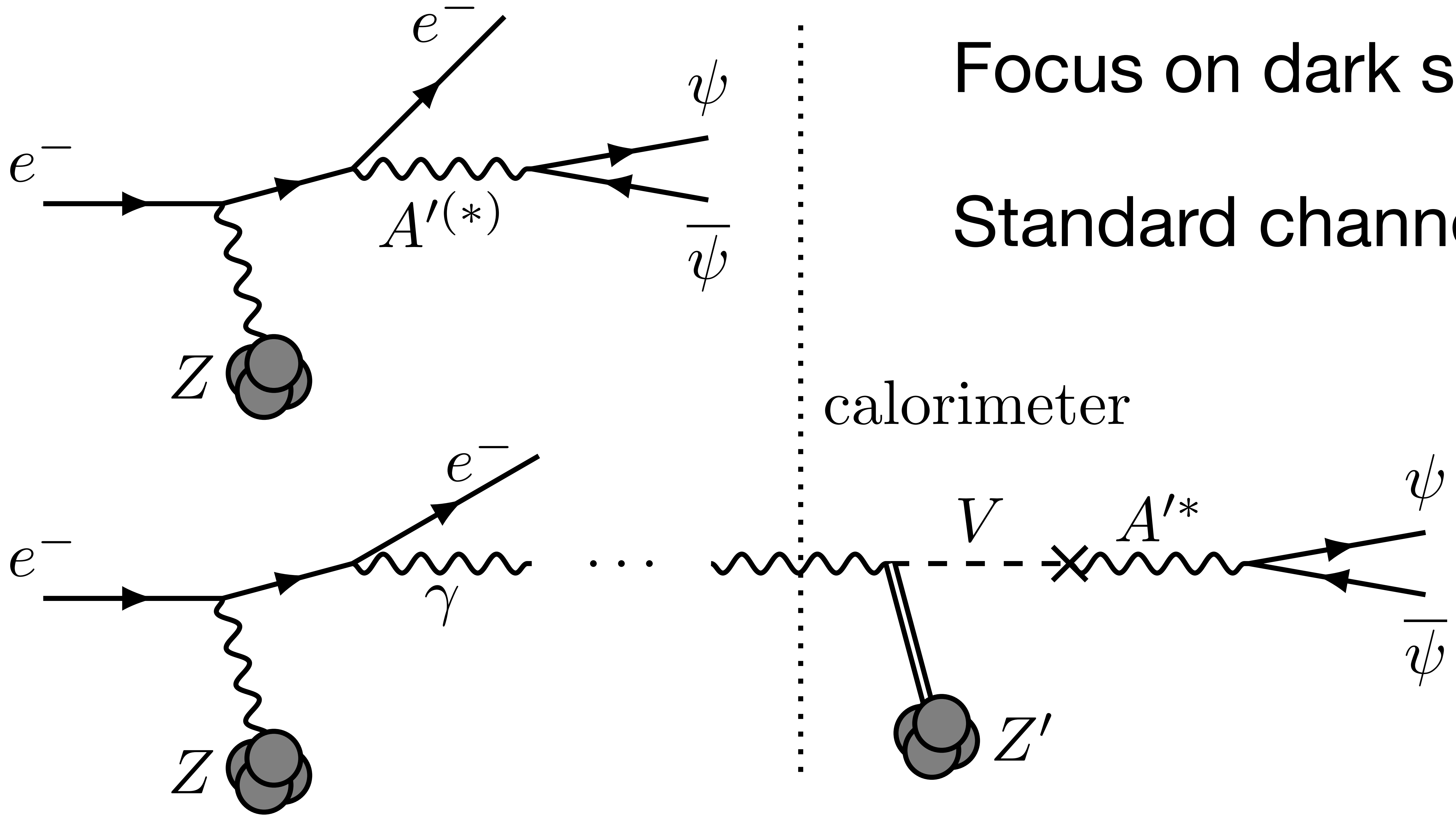
Producing Dark Matter at LDMX



Focus on dark sector with dark photon mediator

Standard channel: A'-Bremsstrahlung in target

Producing Dark Matter at LDMX



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This talk: ordinary Bremsstrahlung in target followed by photoproduction and decay of light vector mesons,

$$V = \rho, \omega, \phi$$

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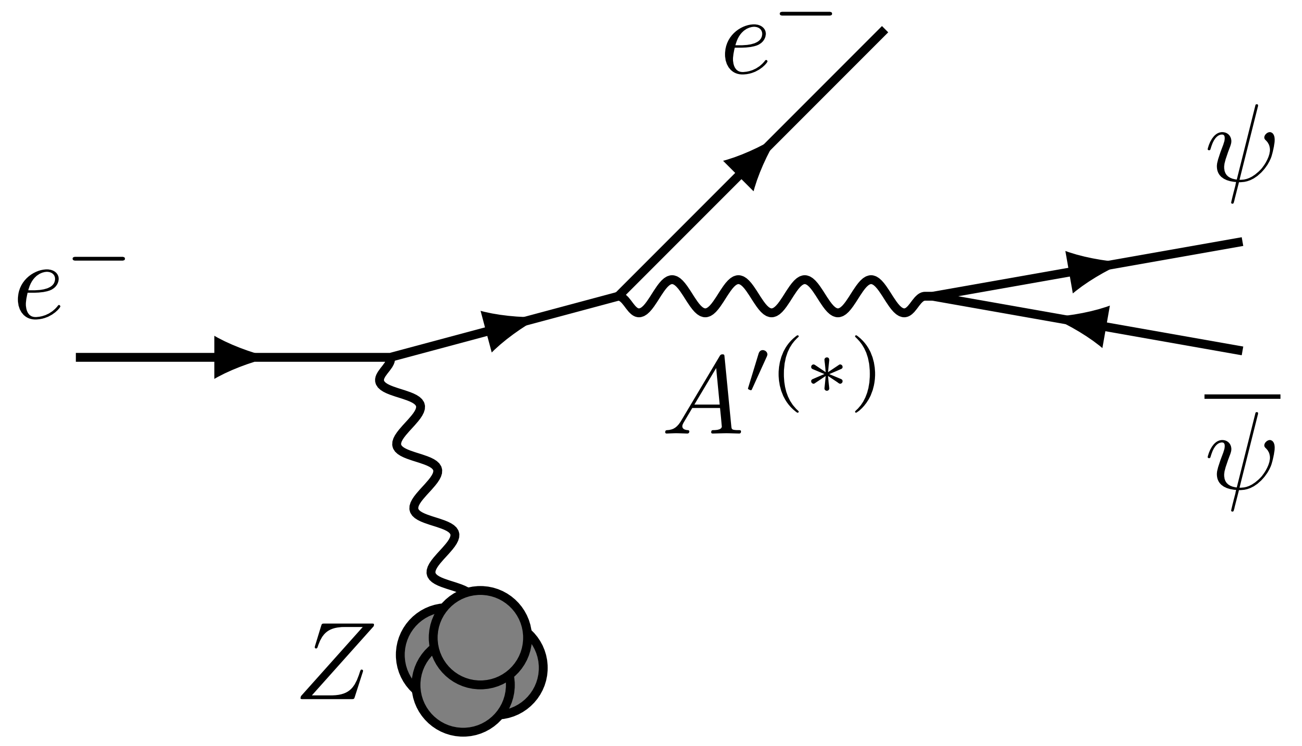

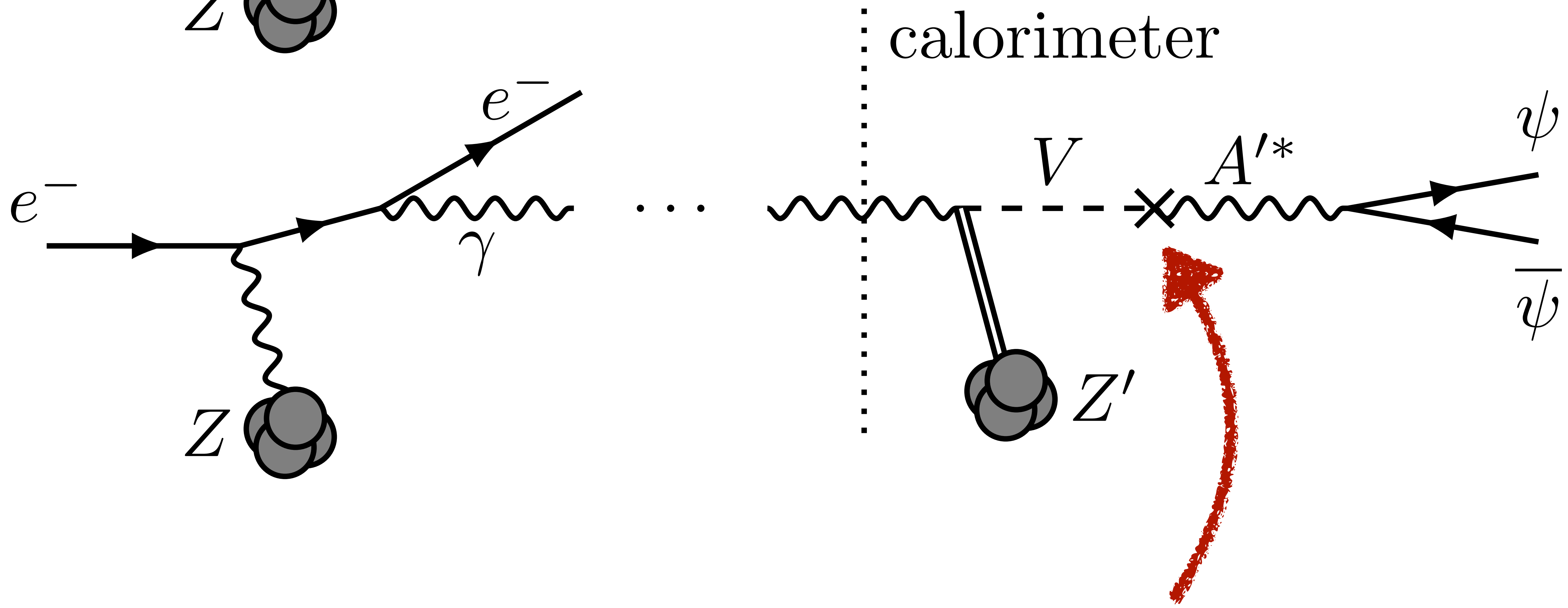

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This talk: ordinary Bremsstrahlung in target followed by photoproduction and decay of light vector mesons,

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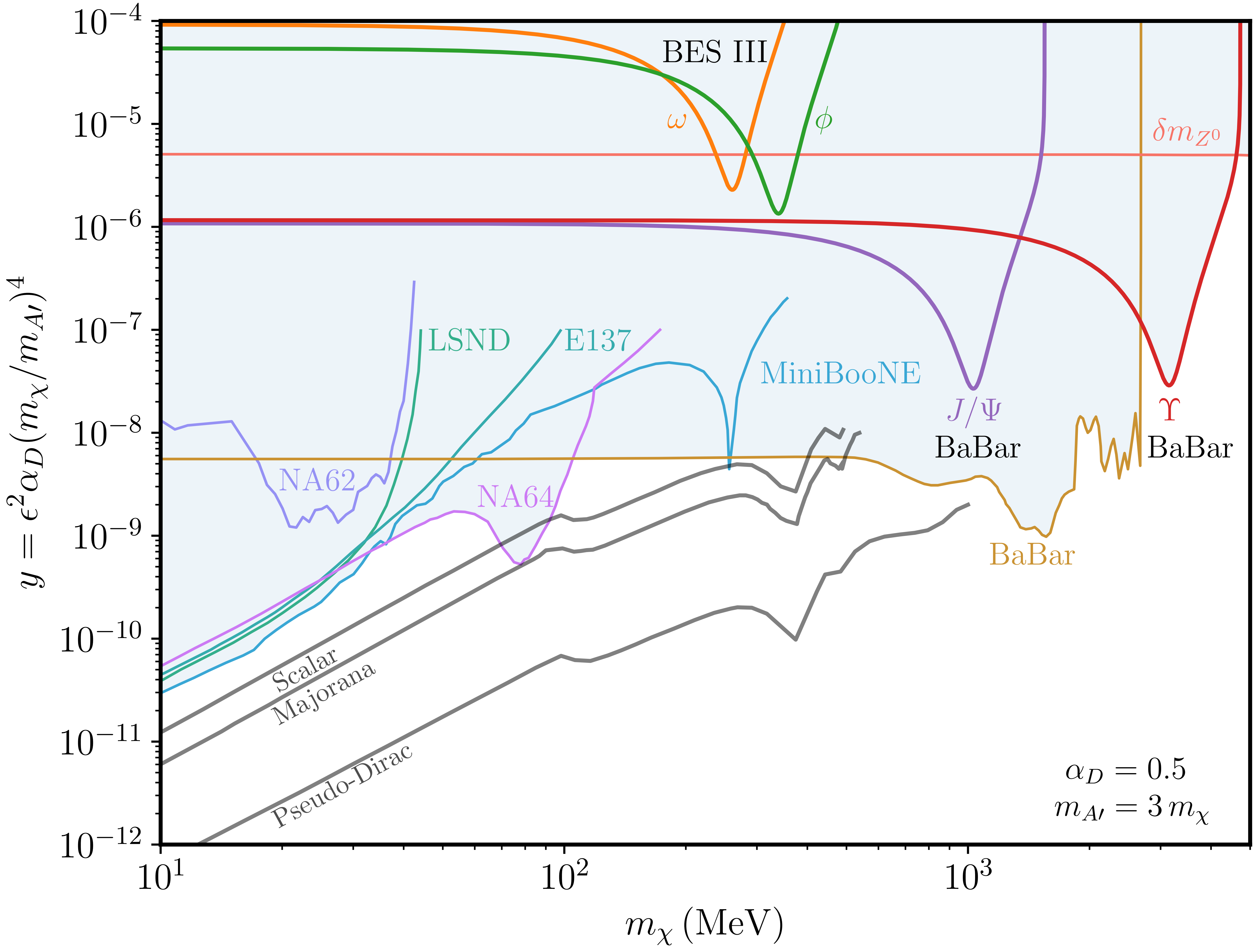
Key points: **probes hadronic couplings**, substantially improves reach for $m_{A'} \gtrsim 0.1\ \mathrm{GeV}$

Why Meson Decays?



Currently, invisible vector meson decays get less attention, as constraints are weak

$$\mathrm{Br}(\omega \to \mathrm{inv}) \lesssim 7 \times 10^{-5}$$
$$\mathrm{Br}(\phi \to \mathrm{inv}) \lesssim 2 \times 10^{-4}$$

at BES III

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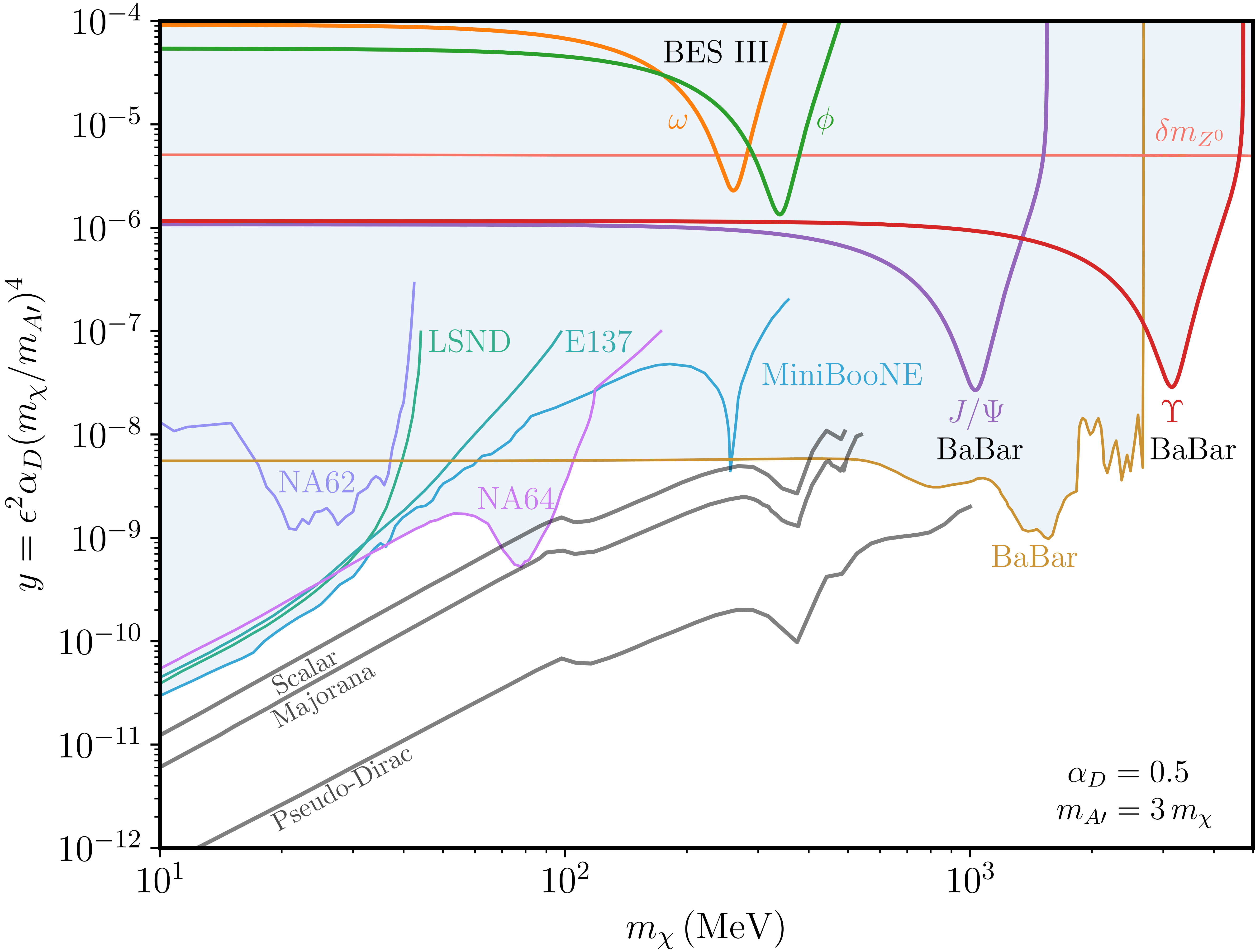

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at BES III

These imply bounds because mesons can decay to DM by mixing with virtual A',

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

(pseudo-Dirac DM, $m_\chi \ll m_V$, form factor f_V)

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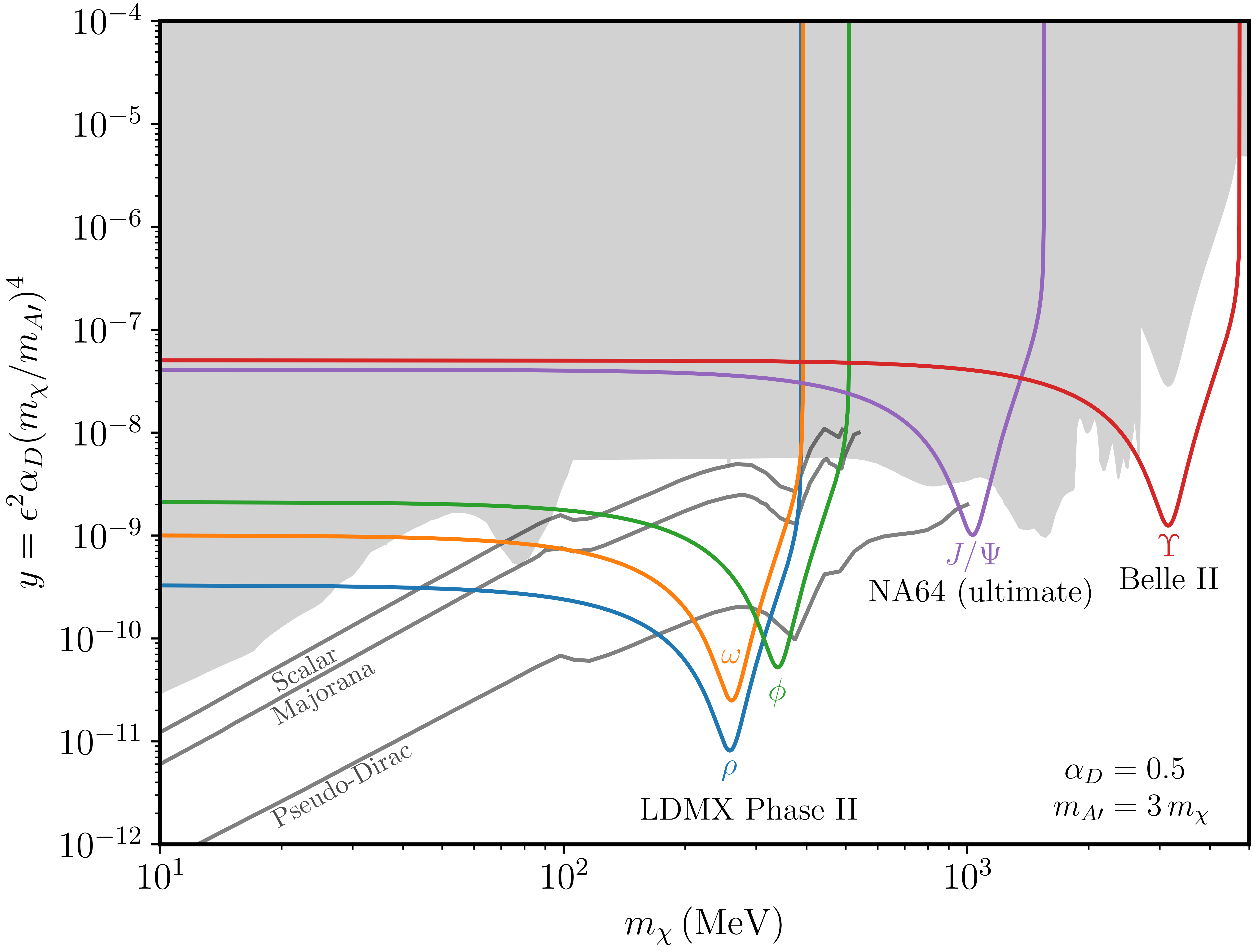

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at BES III

However, LDMX could improve bounds by up to 5 orders of magnitude, probing thermal targets!

To show this, start with rough estimate…

Rough Production Estimate

$$N_V = N_e\, f_{\mathrm{brem}}\, p_{\mathrm{pn}}\, p_V$$

$$\text{electrons} \times \frac{\text{hard photons}}{\text{electron}} \times \frac{\text{photonuclear reactions}}{\text{photon}} \times \frac{\text{exclusive meson productions}}{\text{photonuclear reactions}}$$

Rough Production Estimate

$$N_V = N_e \, f_{\text{brem}} \, p_{\text{pn}} \, p_V$$

LDMX Phase II:
$N_e = 10^{16}$

Thin target:
$f_{\text{brem}} \simeq 0.03$

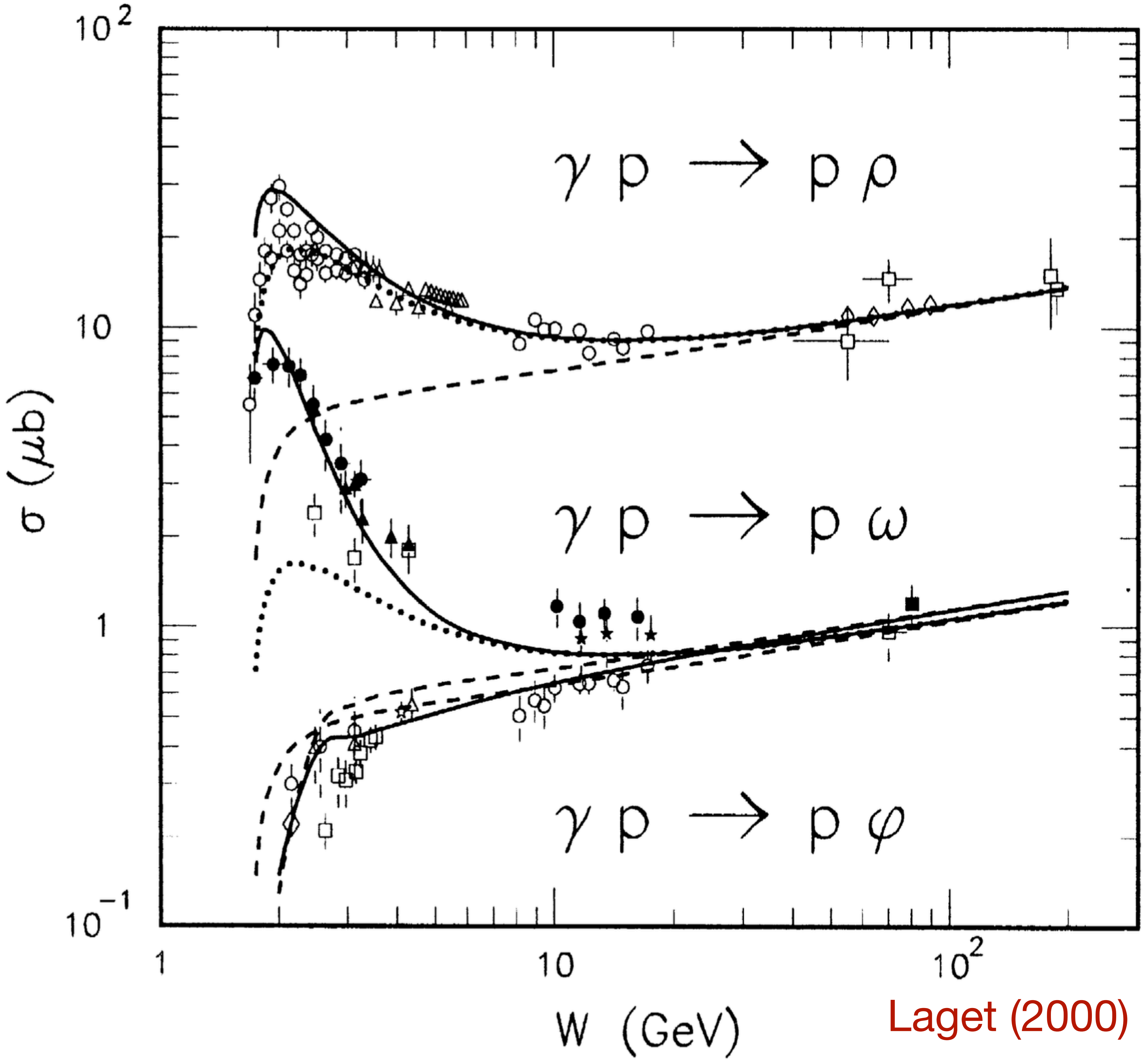
Implies $\sim 10^{11}$ photonuclear reactions

For Tungsten:

$$p_{\text{pn}} = \frac{\sigma_{\text{pn}}}{\sigma_{\gamma N \to e^+ e^- N}} \simeq \frac{A \times 120\,\mu\text{b}}{35\ \text{b}} \sim 10^{-3}$$

Rough Production Estimate

$$N_V = \underbrace{N_e\, f_{\text{brem}}\, p_{\text{pn}}}_{\sim 10^{11}}\, p_V$$



Laget (2000)

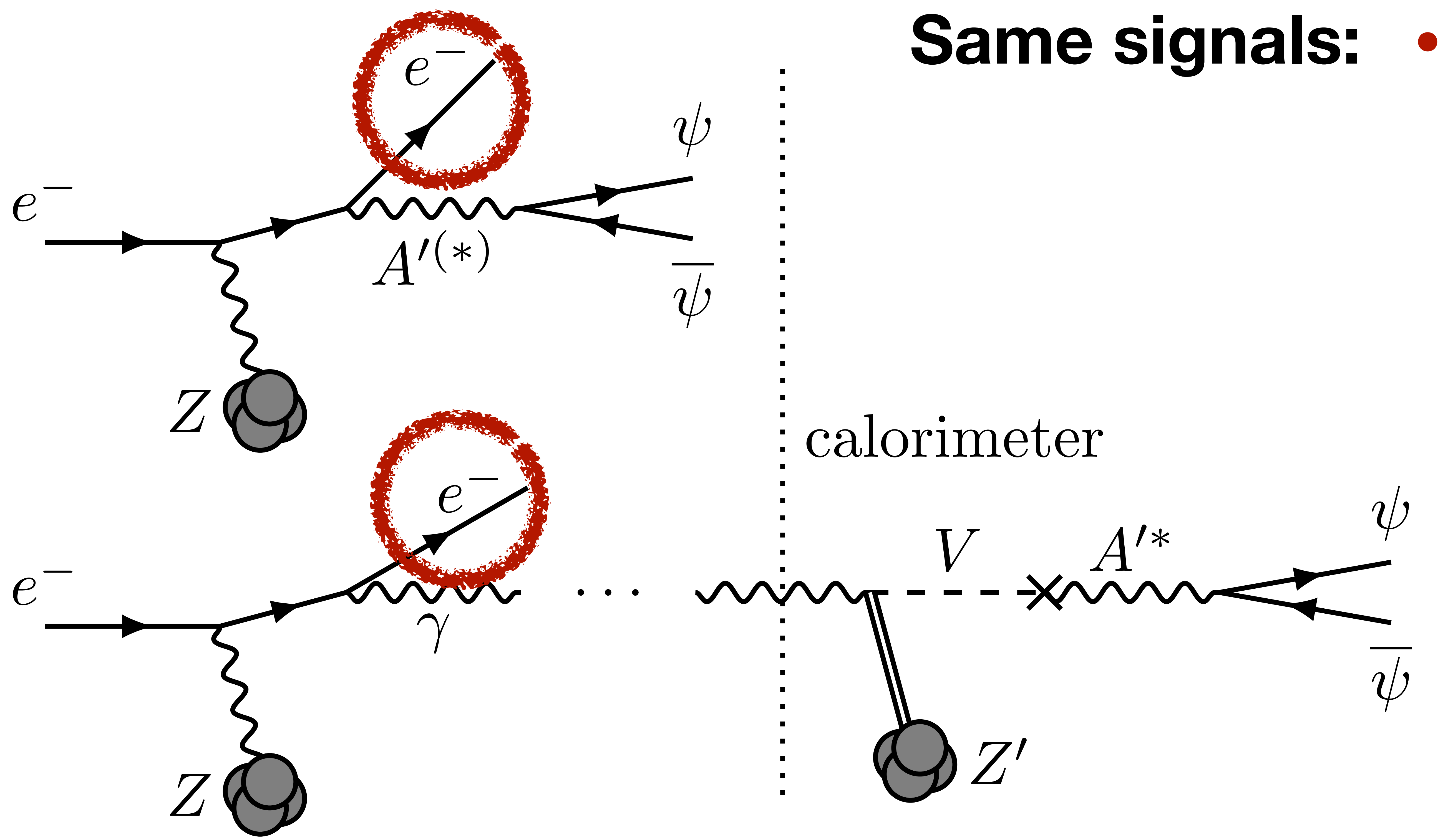
To roughly estimate p_V, consider cross sections for single nucleons (governed by Pomeron exchange)

$$p_V \sim \frac{\sigma_{\gamma p \to Vp}}{100\ \mu\text{b}} \sim \begin{cases} 10^{-1} & \rho \\ 10^{-2} & \omega, \phi \end{cases}$$

Implies meson yields

$$N_V \sim \begin{cases} 10^{10} & \rho \\ 10^{9} & \omega, \phi \end{cases}$$

Experimental Detection

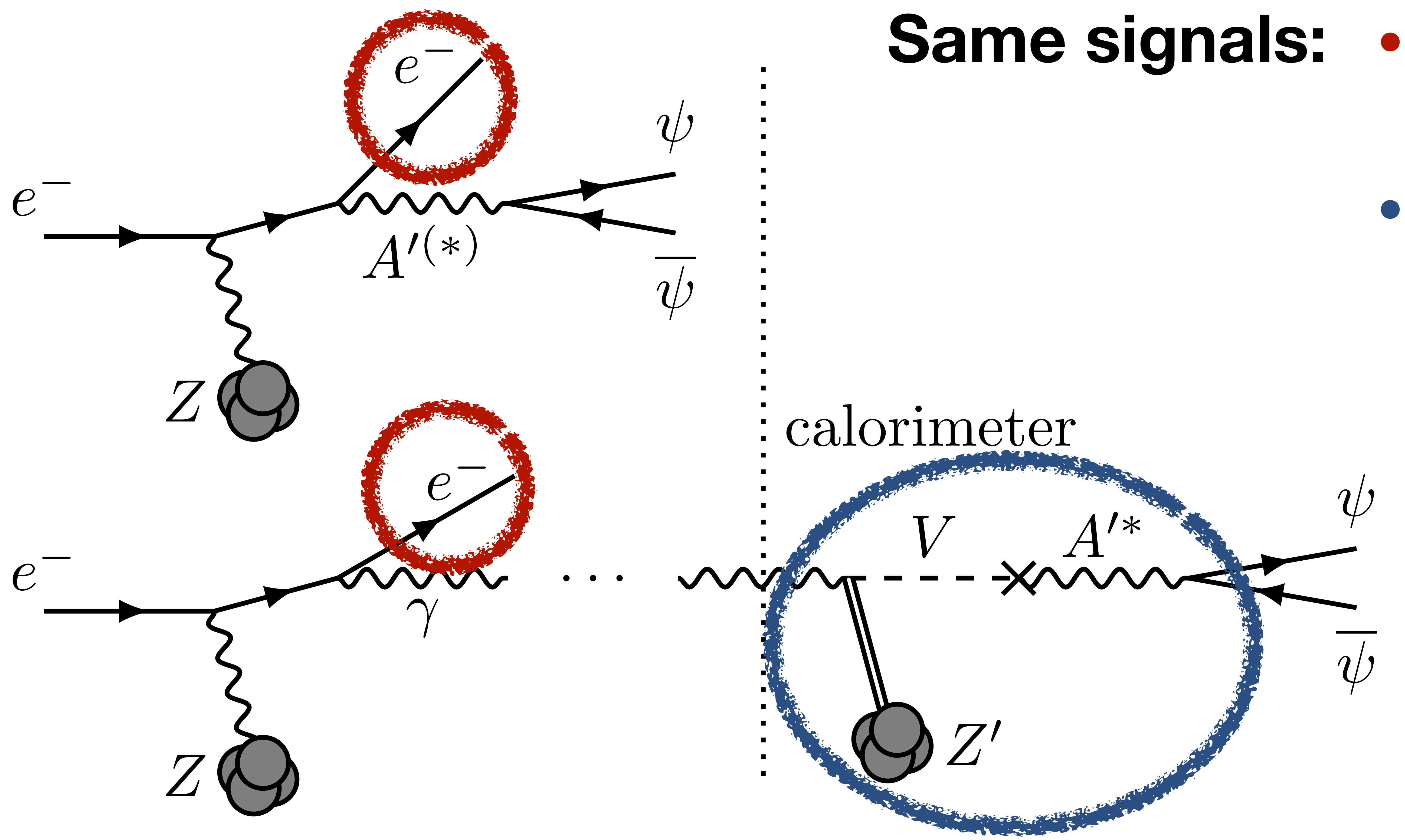


Same signals:

- Missing electron energy

(but electron energy and p_T distributions are the same as for background)

Experimental Detection



Same signals:

- Missing electron energy
- Nothing seen in calorimeters
  - V exclusively produced before photon initiates shower
  - Negligible nuclear recoil
  - V decays to DM before interacting

Refining Meson Production

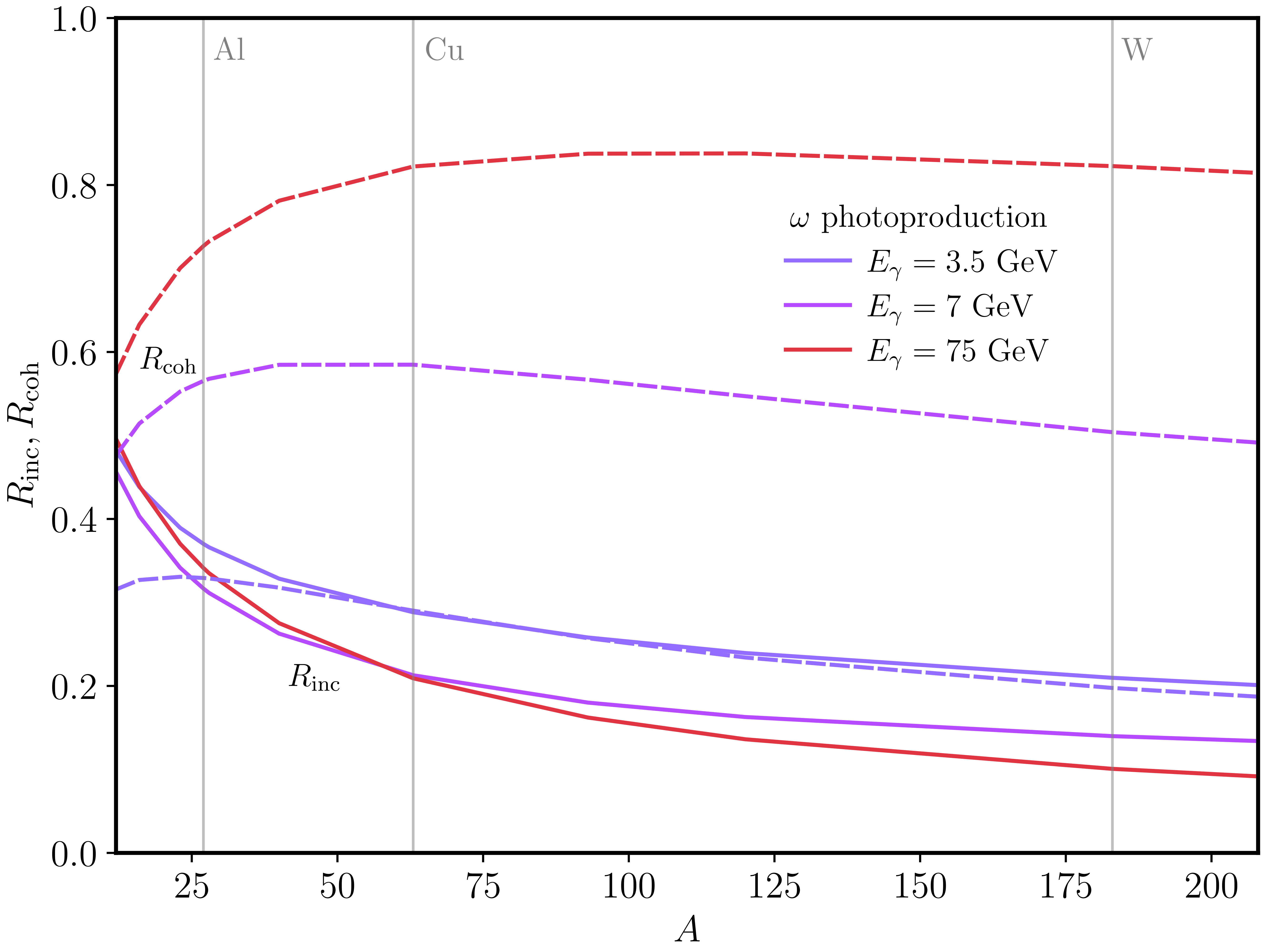
Naively, incoherently sum over nucleons: $d\sigma_i/dt = A\, d\sigma_0/dt$

There is also a coherent process leaving nucleus in the ground state, $d\sigma_c/dt \propto A^2$

Coherent process is invisible to semiclassical Monte Carlo, but **dominates** for heavy nuclei at high energies!

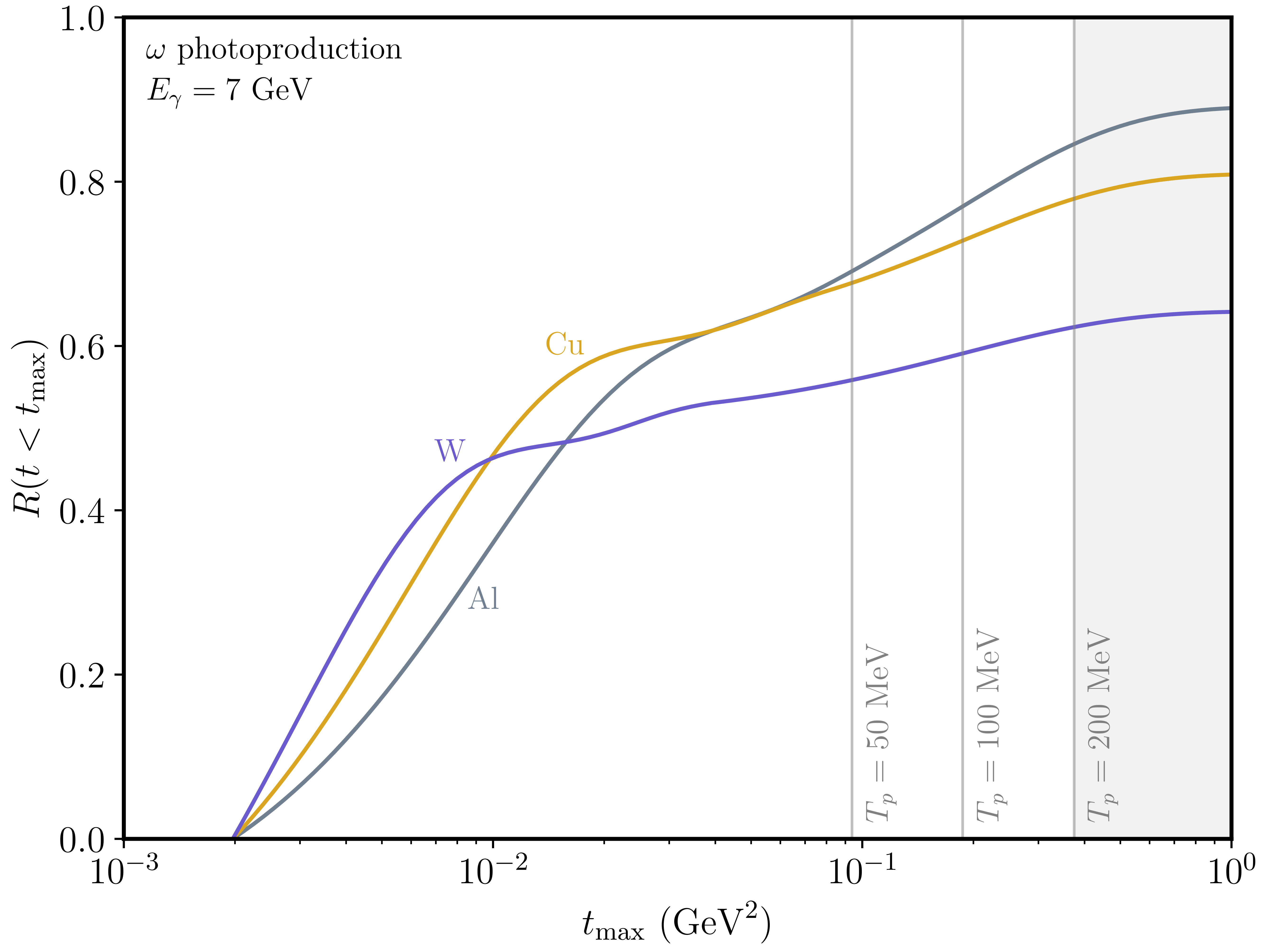
Suppressed by final state interactions and nuclear shadowing

Total Cross Sections



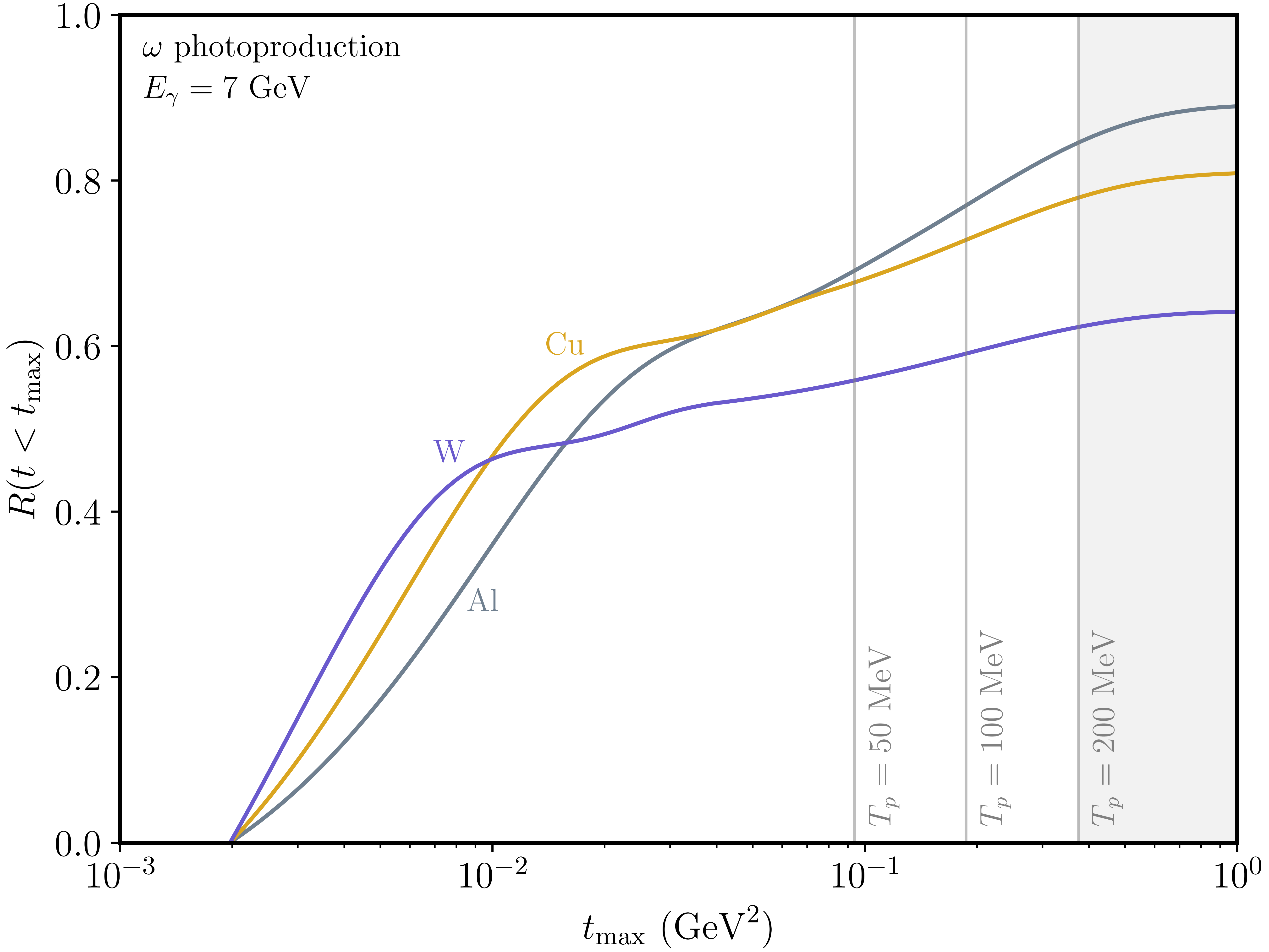
- Define ratio $R = \sigma/A\sigma_0$ of total cross section to naively multiplying per-nucleon cross section by A
- For heavy nuclei at high energies, incoherent R is as small as 0.1, but compensated by coherent process
- Since $\sigma_{\gamma N \to e^+e^- N} \propto Z^2$, calorimeter with lighter nuclei would produce more mesons (but also more photonuclear background)

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

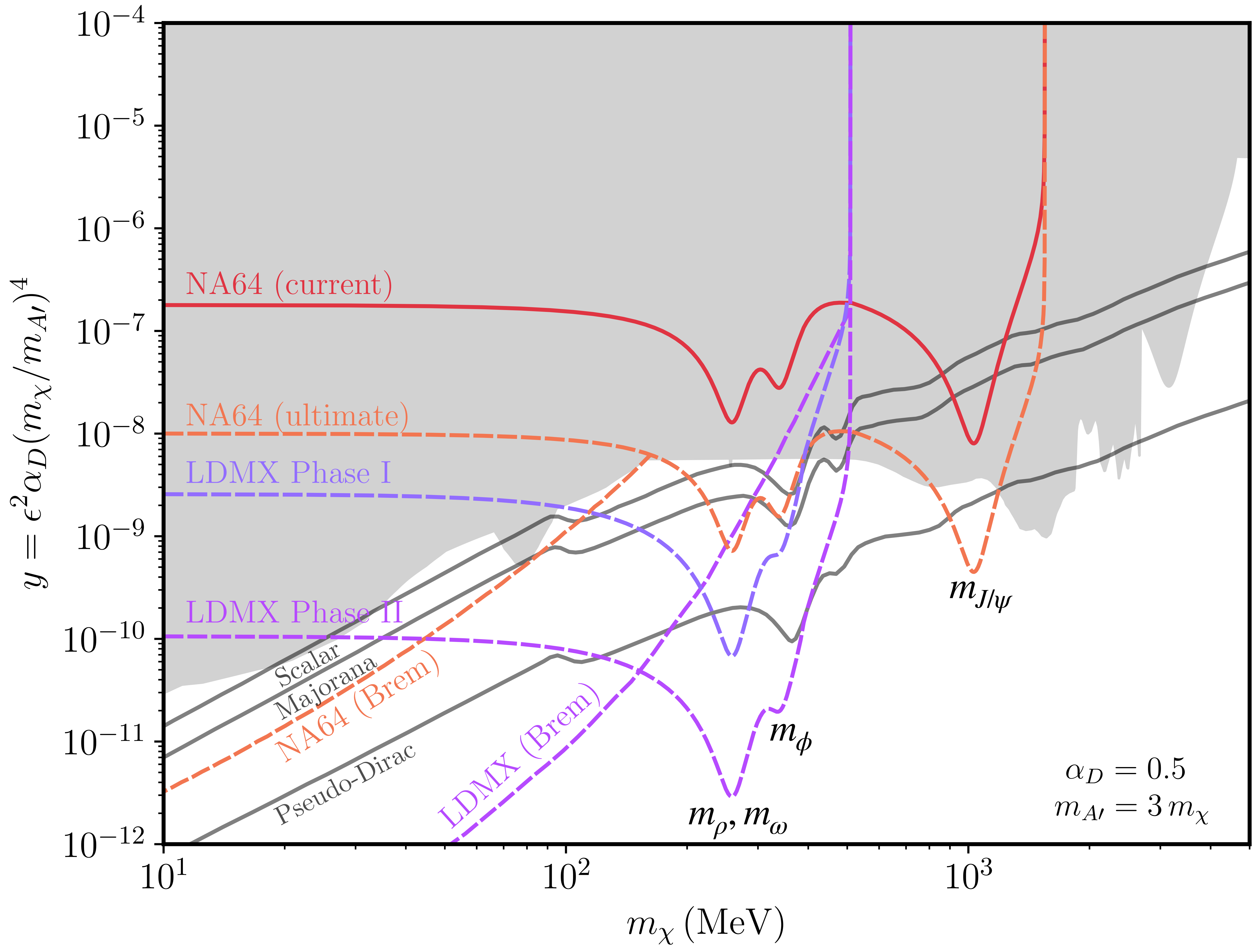


- Falls off exponentially in t, scale $\sim 0.2\ \mathrm{GeV}^2$ set by Pomeron
- Nucleon recoils with kinetic energy $T_p \simeq |t|/2m_p$, we impose $T_p \leq 200\ \mathrm{MeV}$
- Less well-measured, but can be predicted at 50% level from coherent process measurements

Dark Photon Reach

Meson decay channel probes **complementary** parameter space

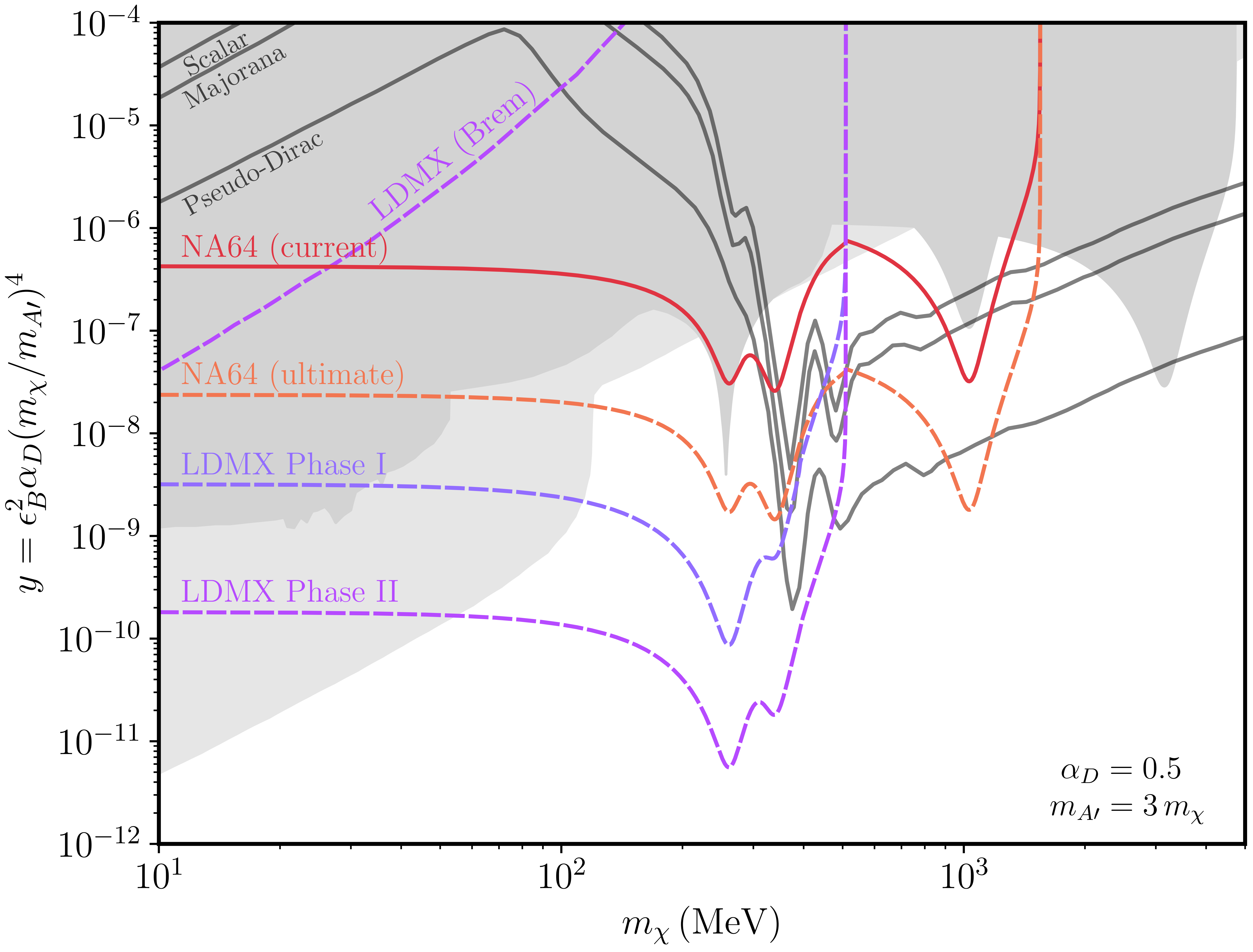
- Independent of $m_{A'}$ for $m_{A'} \ll m_V$
- Resonantly enhanced for $m_{A'} \approx m_V$
- Significant until $2m_\chi \gtrsim m_V$
- Extends reach to thermal target upward by factor of 2 in mass



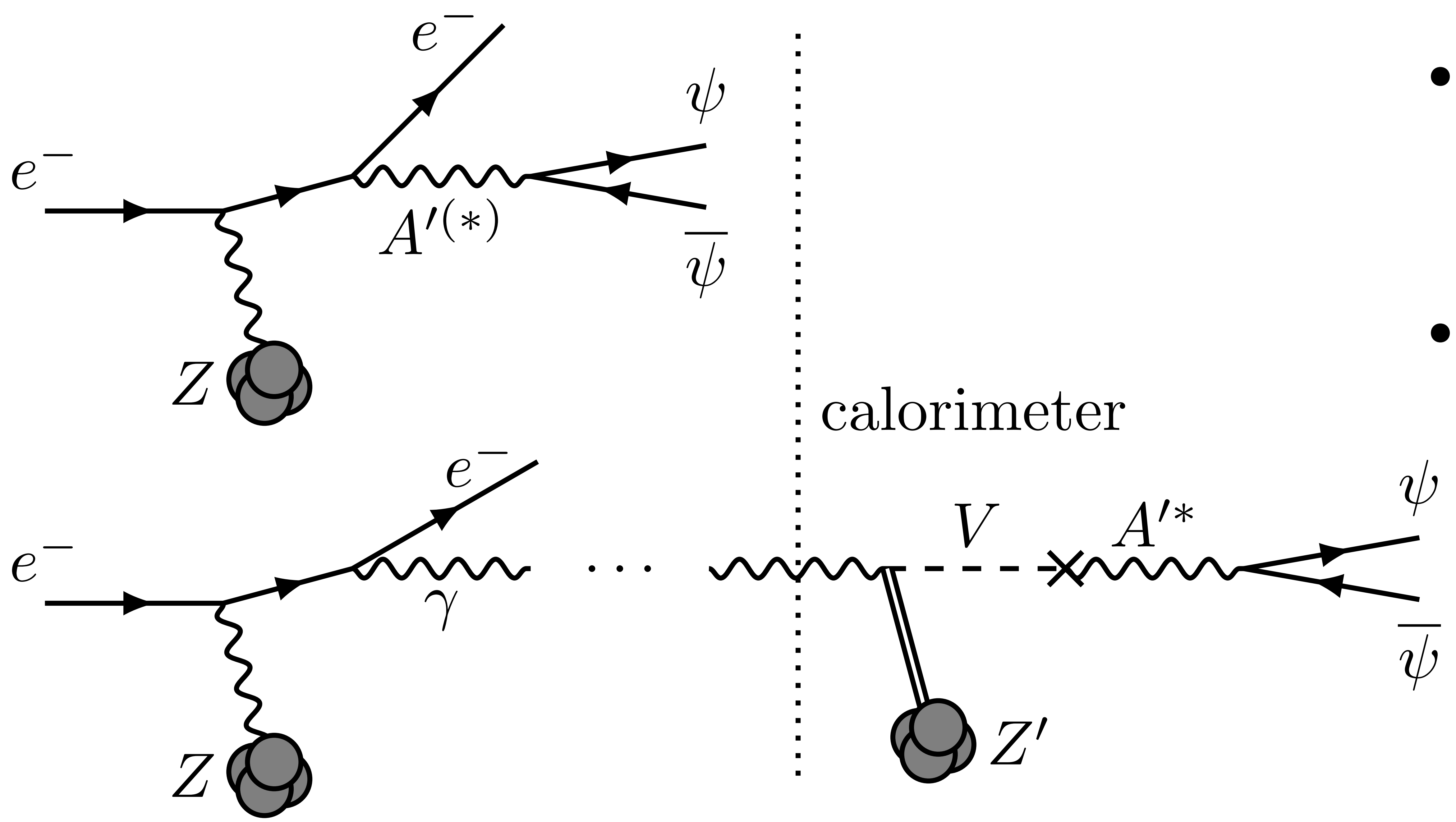
$U(1)_B$ Gauge Boson Reach

Meson decay channel depends only on **quark** couplings

- Dramatically improves reach to mediators that don't couple to electrons, like $U(1)_B$ gauge bosons
- Doesn't rely on loop-suppressed coupling to electrons, and doesn't need a proton beam

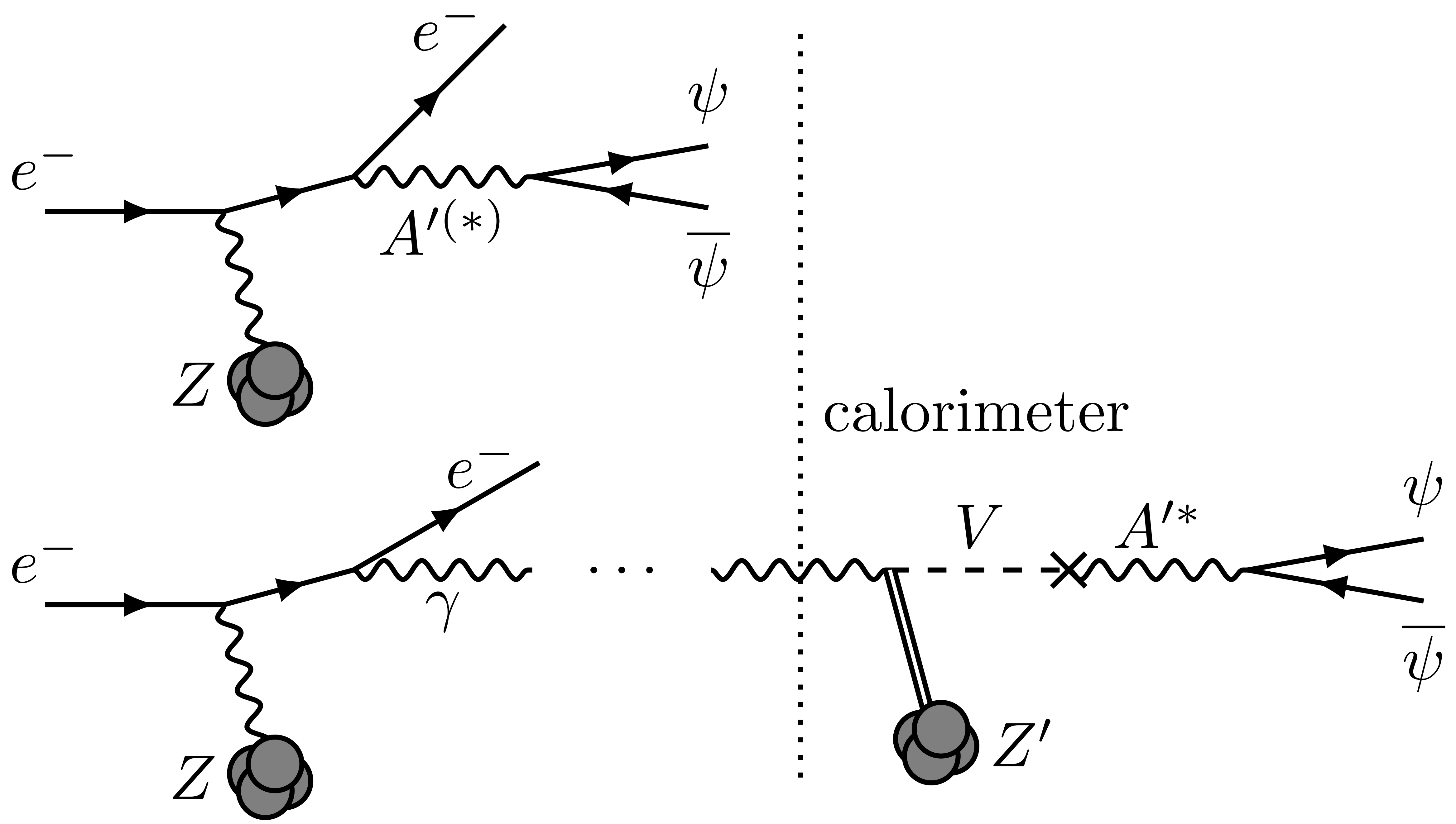


Experimental Challenges



- Unlike A'-Bremsstrahlung signature, electron recoil not peaked at high p_T
- If signal seen, cannot identify which meson is invisibly decaying
- Important to consider **in situ** measurements to confirm meson production modeling
    - Meson photoproduction on complex nuclei is not thoroughly measured
    - Yield depends on calorimeter material
    - Confirm detector non-response to recoiling nucleon in incoherent reactions

Future Opportunities



- Meson yield can be enhanced with thicker target, or putting ~ 1 radiation length of lower Z material at front of calorimeter
- Considering production of heavier resonances of ρ, ω, ϕ may extend reach higher in mass

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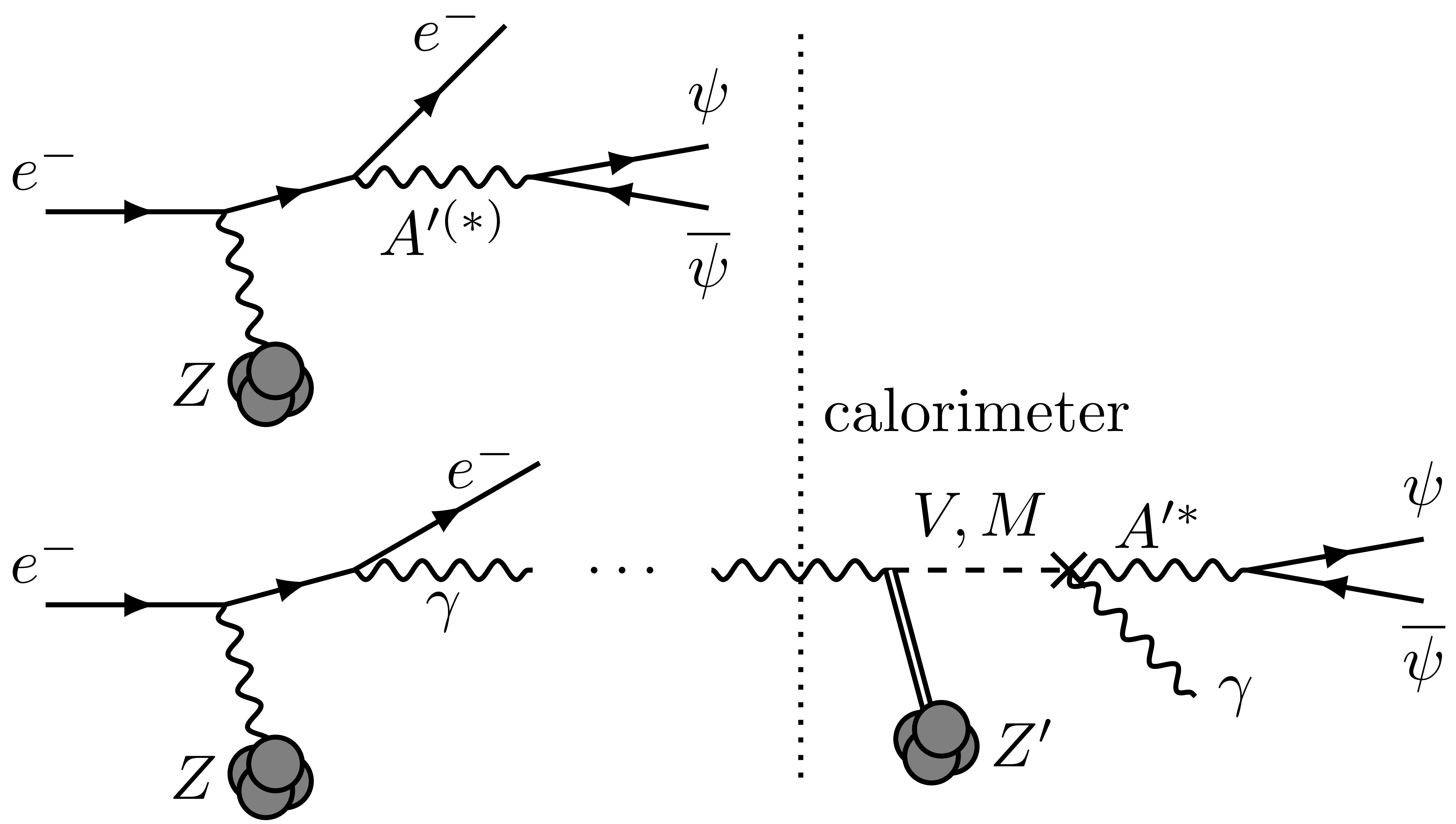


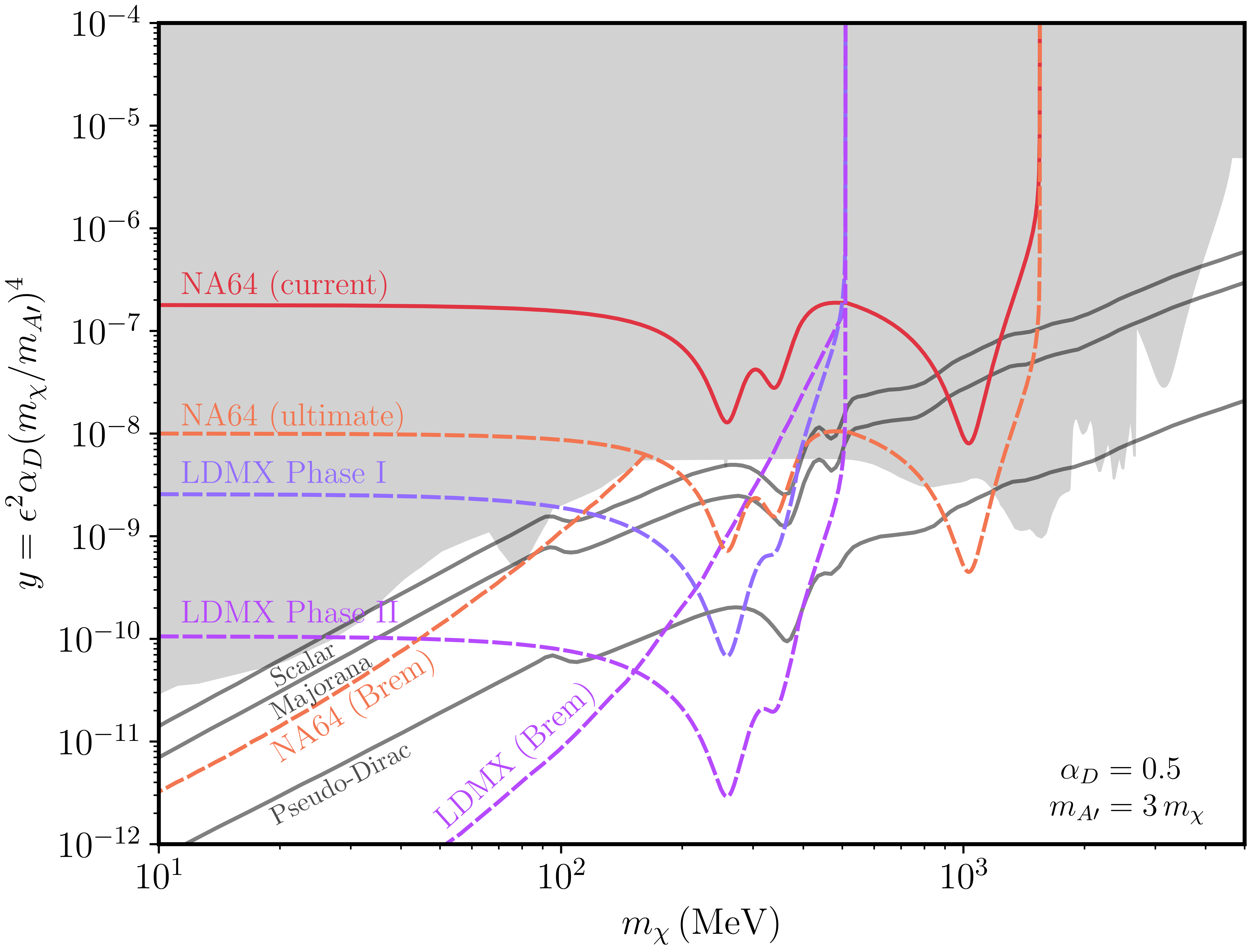
- Meson yield can be enhanced with thicker target, or putting ~ 1 radiation length of lower Z material at front of calorimeter
- Considering production of heavier resonances of ρ, ω, ϕ may extend reach higher in mass
- Other meson decays, such as invisible pseudoscalar meson decay or radiative decays, can probe other mediators

Conclusion

Meson decay channel:

- Works “out of the box”, does not require new triggers
- Improves reach at high mass
- Gives direct sensitivity to quark couplings

Photonuclear modeling may be useful for calculating hard meson yields at electron beam dump experiments



Backup Slides

Probing Other Mediators

	$V \to \chi\bar{\chi}$	$V \to \gamma\chi\bar{\chi}$	$M \to \chi\bar{\chi}$	$M \to \gamma\chi\bar{\chi}$
$\bar{q}q$		✓		
$\bar{q}\gamma^5 q$		✓	✓	
$\bar{q}\gamma^\mu q$	✓			✓
$\bar{q}\gamma^\mu\gamma^5 q$		✓	✓	

Invisible pseudoscalar meson decay probes pseudoscalar and axial vector mediators

Radiative decays look like DM signal in the rare cases where the photon is very soft, can probe all types of mediators

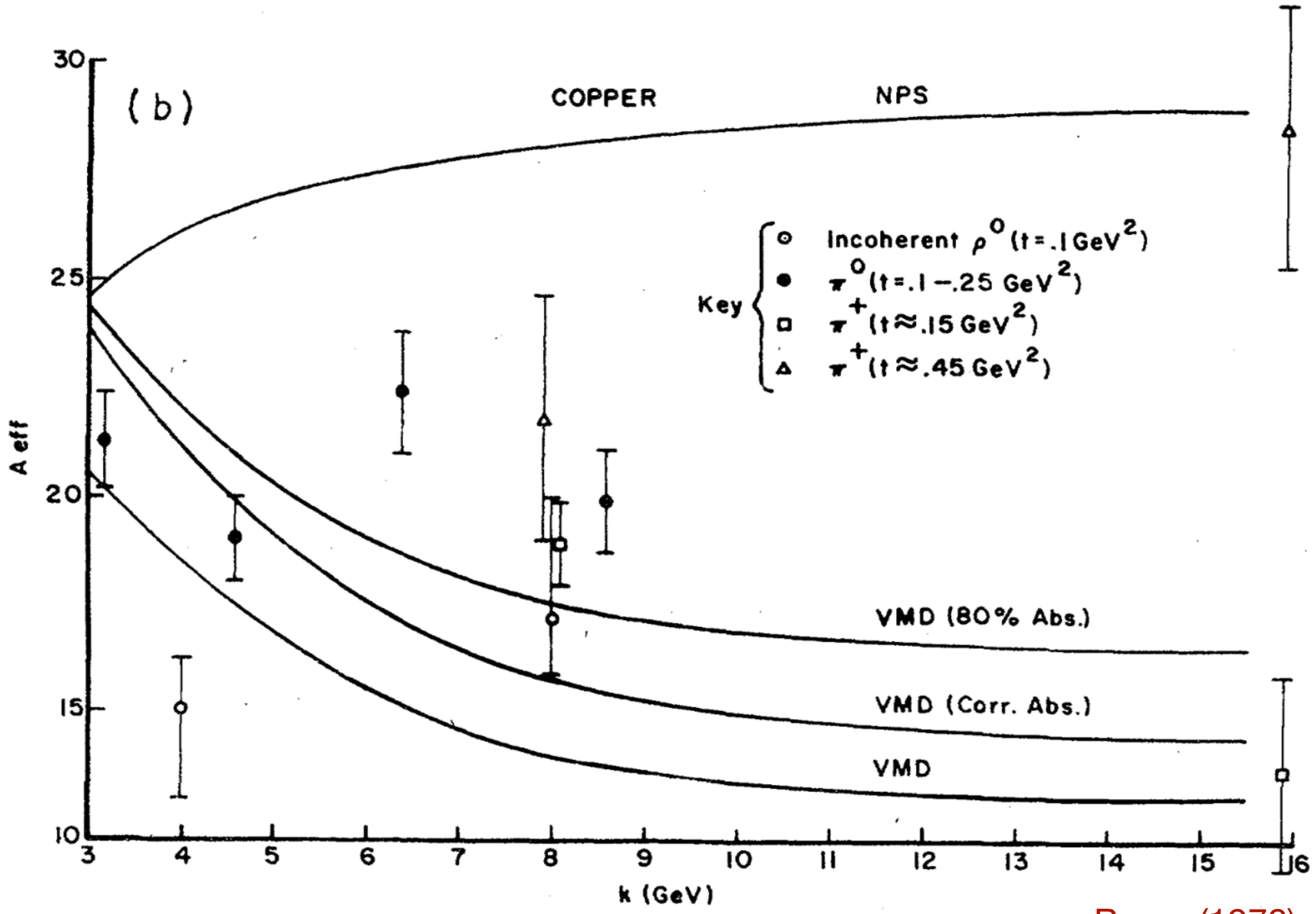
Full Glauber Optical Model

$$\frac{d\sigma_c}{dt} = \frac{d\sigma_0}{dt}\bigg|_{t=0} \left| \int d^2b \, dz \, e^{i(\mathbf{q}_T \cdot \mathbf{b} + q_\parallel z)} n(b,z) \exp\left(-\frac{\sigma_V}{2}(1 - i\alpha_V) \int_z^\infty dz' \, n(b,z') \right) \right|^2$$

$$\frac{d\sigma_i}{dt} = \frac{d\sigma_0}{dt} \int d^2b \, dz \, n(b,z) \exp\left(-\sigma_V \int_z^\infty dz' \, n(b,z') \right)$$

$$\times \left| 1 - \int_{-\infty}^z dz'' \, n(b,z'') \frac{\sigma_V}{2}(1 - i\alpha_V) e^{iq_\parallel(z''-z)} \exp\left(-\frac{\sigma_V}{2}(1 - i\alpha_V) \int_{z''}^z dz''' \, n(b,z''') \right) \right|^2$$

Comparison to Data



Bauer (1978)