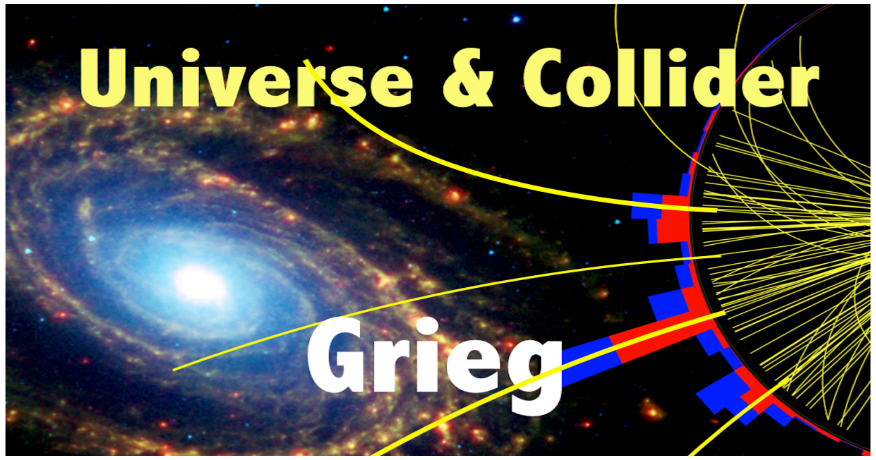
Dark photon lifetime: closer look at SM resonances

Ayuki Kamada (University of Warsaw)

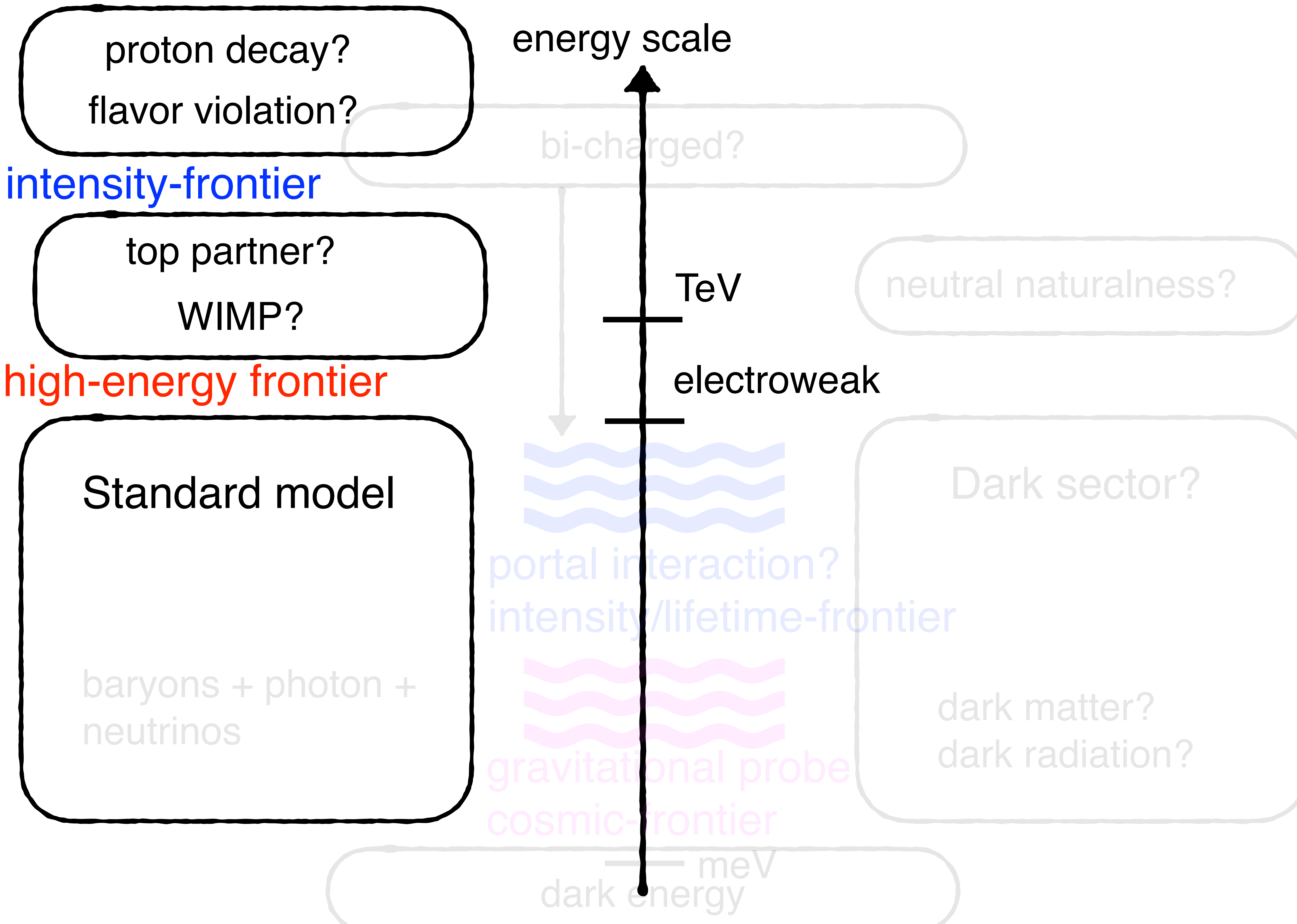


UNIVERSITY OF WARSAW

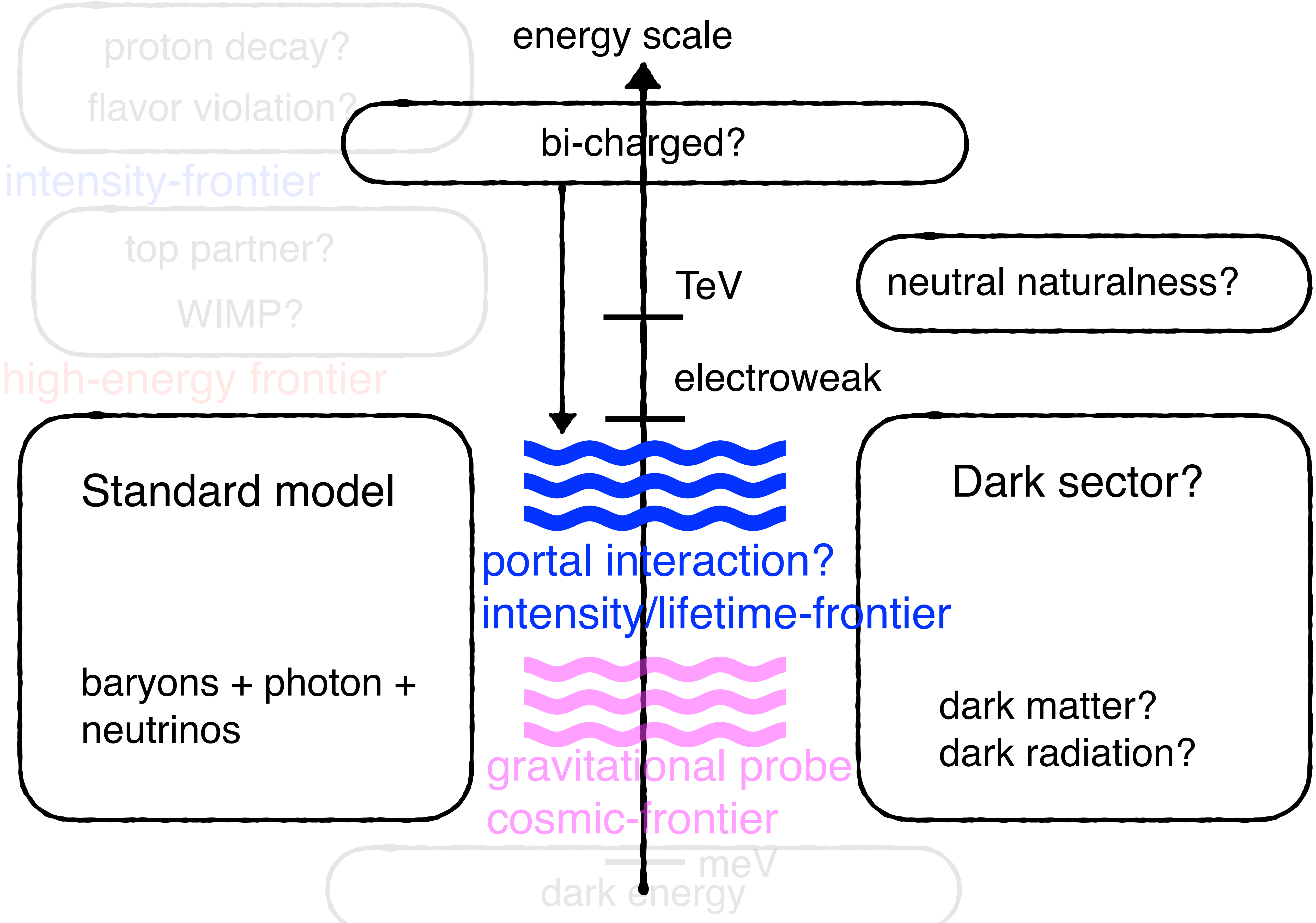
Based on
AK, Takumi Kuwahara, Shigeki Matsumoto, Yu Watanabe and Yuki Watanabe, arXiv:2404.06793

July 3, 2024 @ LLP2024

High-energy physics



High-energy? physics



Contents

Intensity frontier

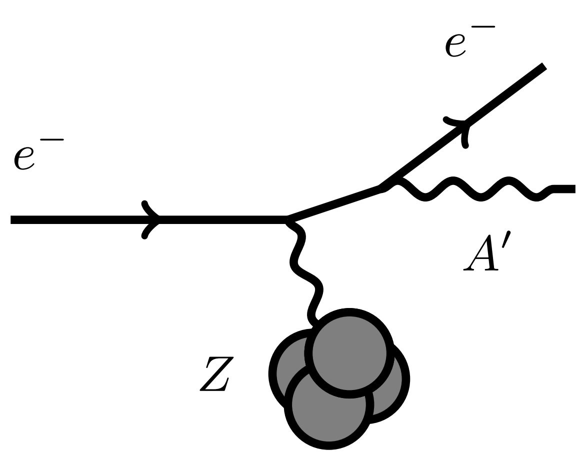
Dark photon portal $\mathscr{L} \supset \frac{\epsilon_Y}{2} Y^{\mu\nu} F'_{\mu\nu}$

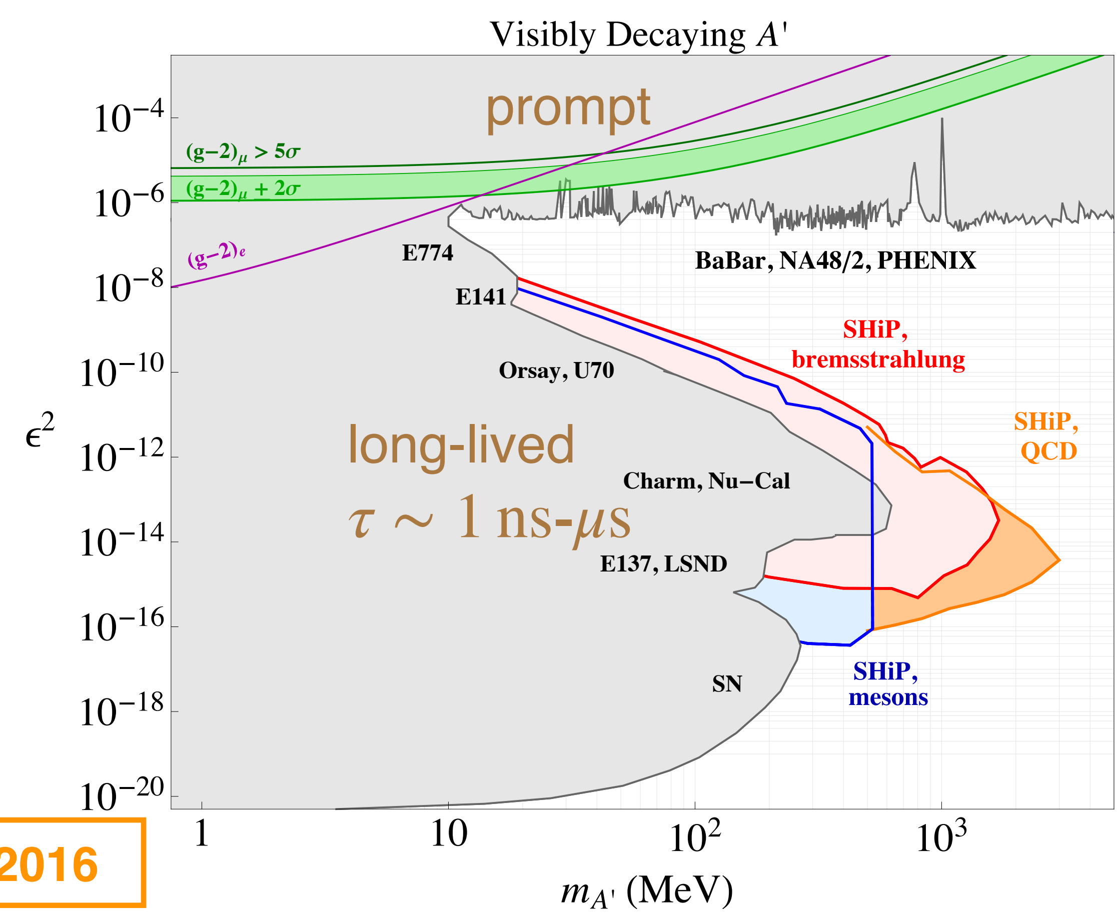
- kinetic mixing between the hyper-charge gauge boson and dark photon
- SM particles feebly couple to dark photon $\mathscr{L} \supset \epsilon e j^{\mu}_{\text{em}} A'_{\mu}$ $\quad \epsilon_Y \cos\theta_W = \epsilon$
- mass from dark Higgs (or Stueckelberg)

Beam-dump experiment e.g., CHARM, E137, SHiP…

Talk by Anne-Marie Magnan

target shield detector





$A' \to e^+ e^-$

SHiP collaboration, Rep. Prog. Phys., 2016

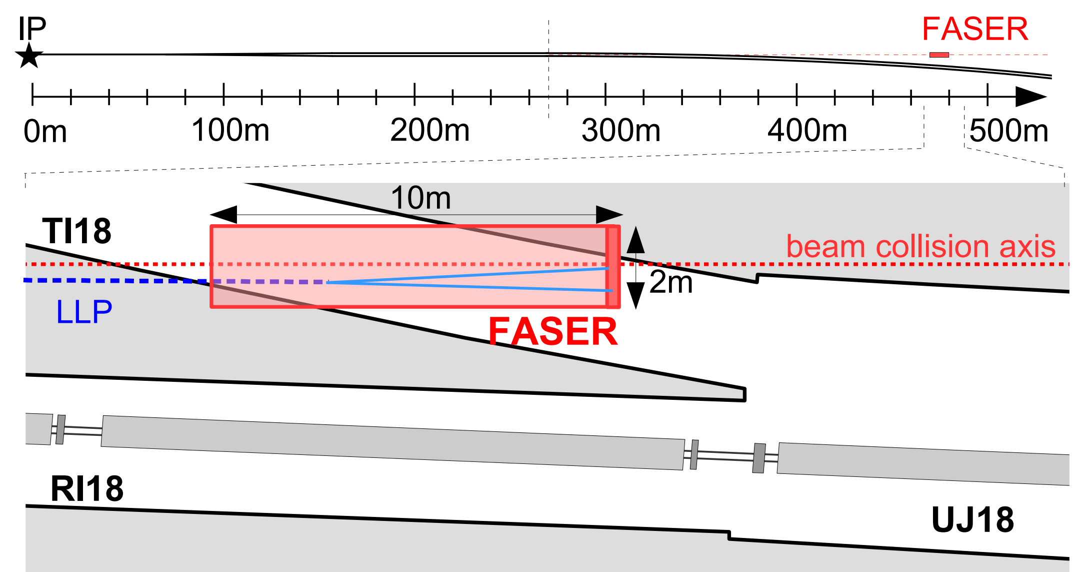
Lifetime frontier

LHC lifetime frontier

- HL-LHC (2027+) $\mathscr{L} = 3\,\mathrm{ab}^{-1}$
  - intensity frontier as well as high-energy frontier

Berlin and Kling, PRD, 2019

- FASER(2)
  - forward direction $\theta_{\rm det} = 2\times 10^{-3}$
  - more boosted and thus shorter lifetime particles come



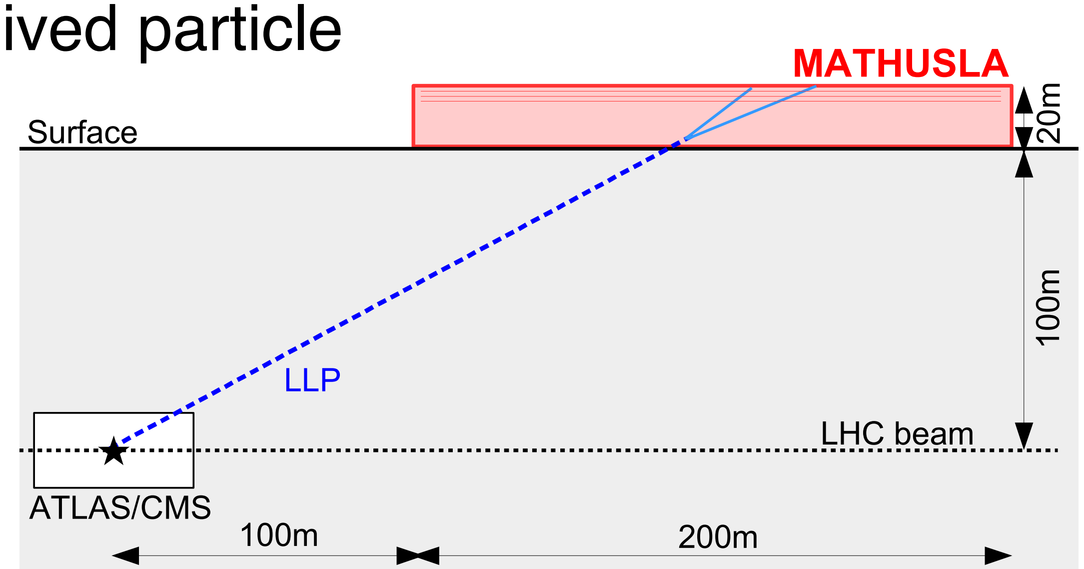
$p_{\rm geo} \sim p_T/\theta_{\rm det}$

Talks by Felix Kling, Yuxiao Wang and Motoya Nonaka

- typical transverse momentum is determined by the production process of long-lived particle

- MATHUSLA (CODEX-b)
  - off-axis $\theta_{\rm det} = 0.5$
  - less boosted and thus longer lifetime particles come

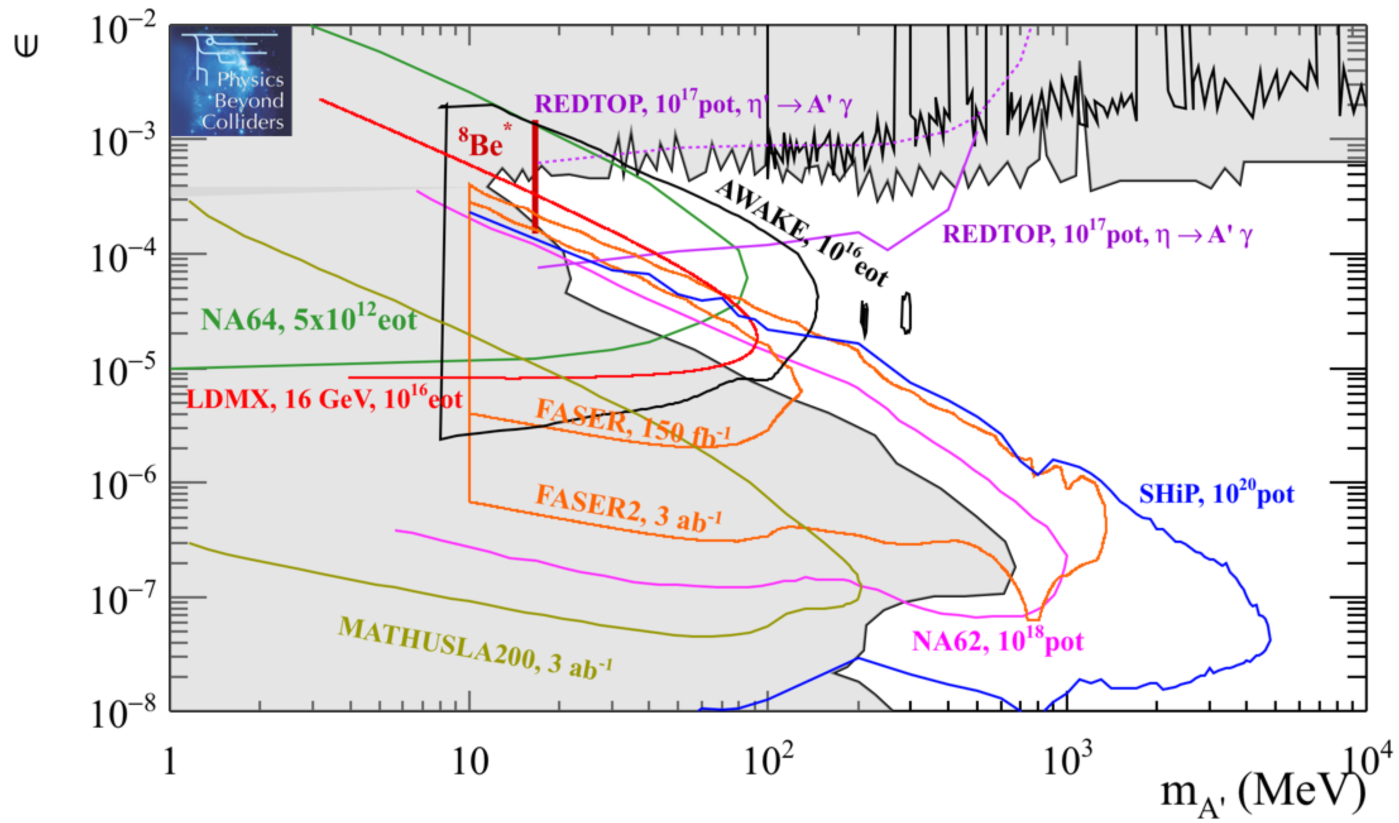
Talks by Jake Pfaller and Erez Etzion



Intensity/lifetime frontier

Dark photon portal

- minimal dark photon model



Physics Beyond Colliders collaboration, J. Phys. G, 2020

- upper bound determined by the lifetime (should be sufficiently long-lived)

- lower bound determined by the lifetime (should decay) and production

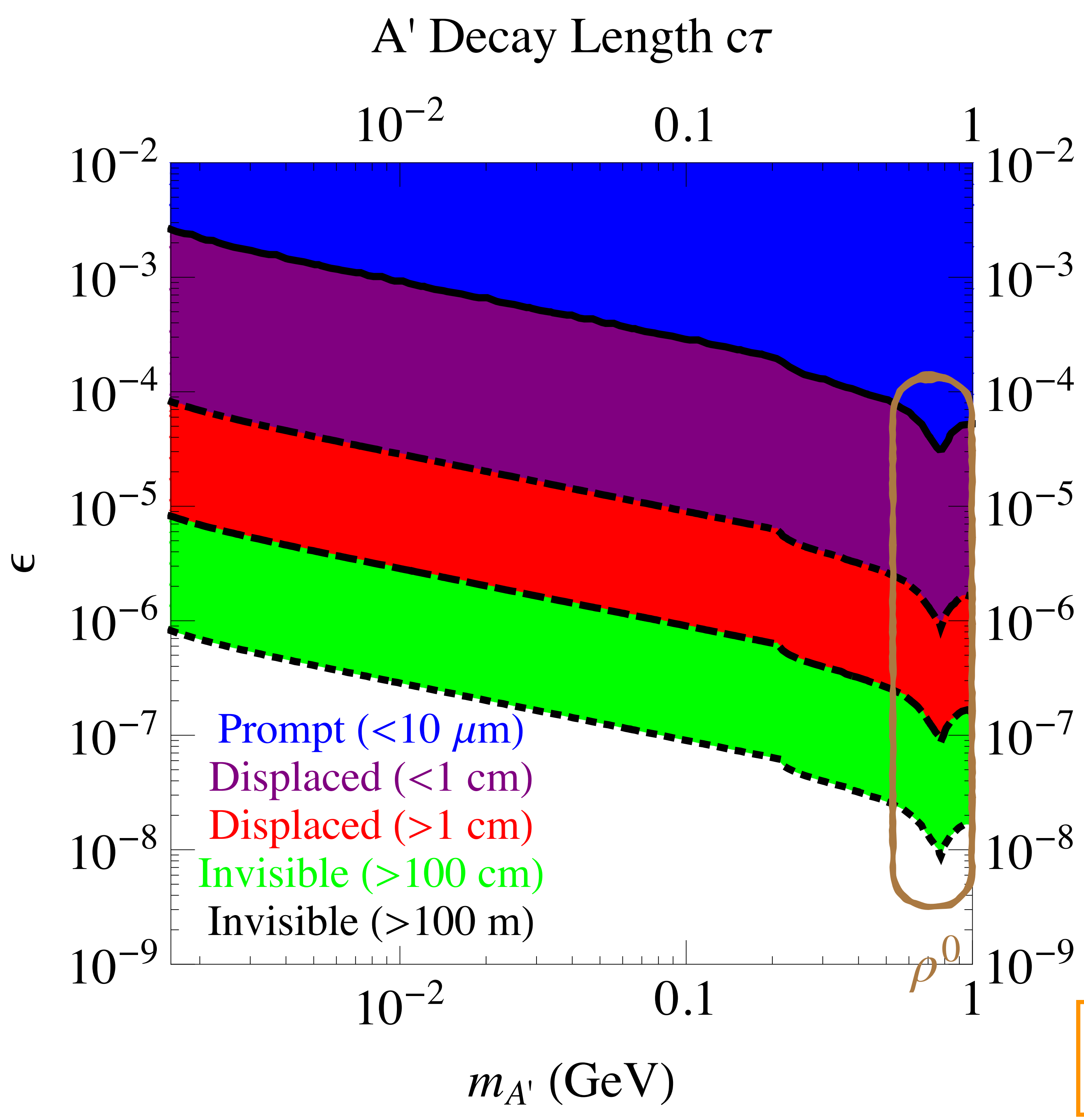
- in the minimal dark photon model, only one parameter (kinetic mixing) for a given dark photon mass

$$\Gamma(A' \to \bar{f}f) \simeq \frac{1}{3}\alpha\epsilon^2 Q_f^2 m_{A'}$$

Resonant decay through mixing

Short lifetime in a specific mass

- thorough mixing with SM resonances $A' \to V^* \to \bar{f}f$ or hardrons

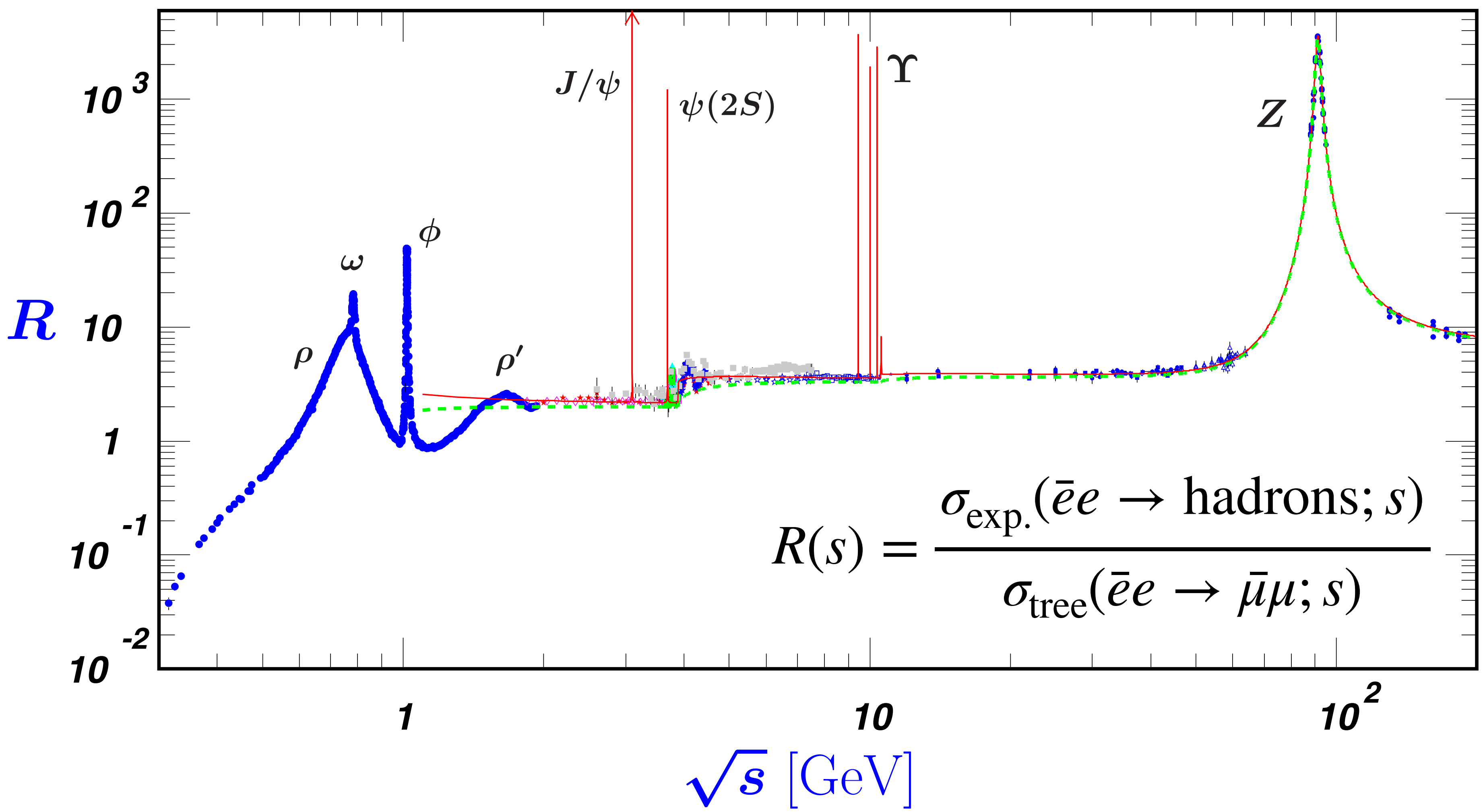


Essig, Harnik, Kaplan, and Toro, PRD, 2010

Conventional computation

All SM resonances are relevant

- with the same quantum number (neutral, spin 1)



PDG 2022

Multiplying R-ratio by decay width to muon pair

$$\Gamma(A' \to \text{hadrons}) = \Gamma(A' \to \bar{\mu}\mu) \times R(m_{A'}^2)$$

- misses non-hadronic resonances like true muonium (later)

Contents

Review of dark photon

- long-lived dark photon searches
- resonant decay though mixing with SM resonances

Closer look at mixing with SM resonances

- conventional computation of resonant decay
- caveat in large kinetic mixing

Closer look at conventional computation

Mass mixing basis

$$\mathscr{L} \supset \overline{m}_V^2 (V_\mu, A'_\mu) \begin{pmatrix} 1 & -\eta \\ -\eta & \delta^2 + \eta^2 \end{pmatrix} \begin{pmatrix} V^\mu \\ A'^\mu \end{pmatrix} \qquad \delta = \frac{\overline{m}_{A'}}{\overline{m}_V}$$

- ratio of mass parameter (input mass)

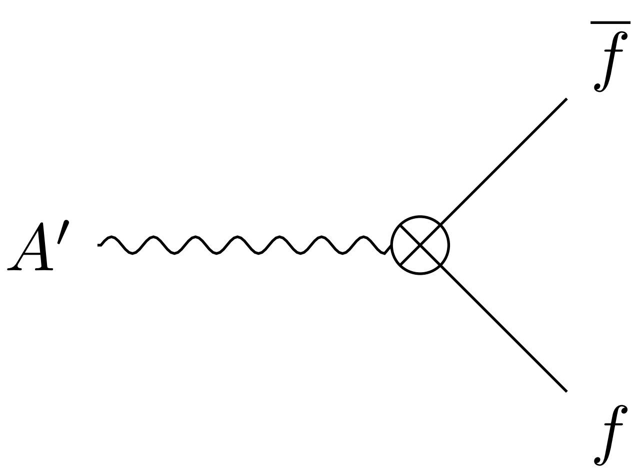
- effective mixing parameter $\propto \epsilon$

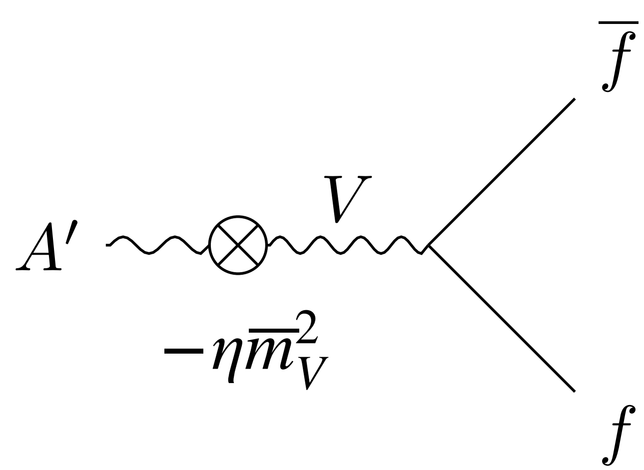
- one can obtain “classical” mass eigenstates by diagonalizing it

- δ=1 corresponds to mass degenerate limit
(though eigenvalues split by η)

“Mass insertion” method

- using off-diagonal part as a perturbation





“Mass insertion” method

Width of dark photon

$$\Gamma^{\rm MI}(A' \to \bar{f}f) = \frac{M_{A'}}{16\pi}\frac{4}{3}\left| \bar{g}_f^{A'} + \bar{g}_f^{V}\frac{-\eta \overline{m}_V^2}{M_{A'}^2 - \overline{m}_V^2 + i\overline{m}_V\overline{\Gamma}_V} \right|^2 \qquad M_{A'}^2 = \overline{m}_V^2(\delta^2+\eta^2)$$

$$\overline{\Gamma}_V = \frac{\overline{m}_V}{16\pi}\frac{4}{3}g_V^2$$ - decay width in the absence of dark photon

- in the mass degenerate limit, second term is resonantly large

$$\Gamma^{\rm MI}(A' \to \bar{f}f) \simeq \frac{M_{A'}}{16\pi}\frac{4}{3}\left(\bar{g}_f^{V}\frac{\eta}{\overline{\Gamma}_V/\overline{m}_V} \right)^2$$

- A’ width is larger than that of V for $\eta > \overline{\Gamma}_V/\overline{m}_V$

- the enhancement can be 10 orders of magnitude for narrow resonance like true muonium, J/ψ and Υ

- is perturbation valid?

“Classical” method

Width of dark photon

$$\mathscr{L} \supset \overline{m}_V^2 (V_\mu, A'_\mu) \begin{pmatrix} 1 & -\eta \\ -\eta & \delta^2 + \eta^2 \end{pmatrix} \begin{pmatrix} V^\mu \\ A'^\mu \end{pmatrix}$$

- diagonalizing mass and compute the width at tree level

- in the mass degenerate limit, one obtains nearly (but not exactly) identical particle with half width of original SM particles at the tree level

$$\Gamma(A' \to \bar{f}f) \simeq \Gamma(V \to \bar{f}f) \simeq \frac{m_{A'}}{16\pi}\frac{2}{3}g_V^2$$

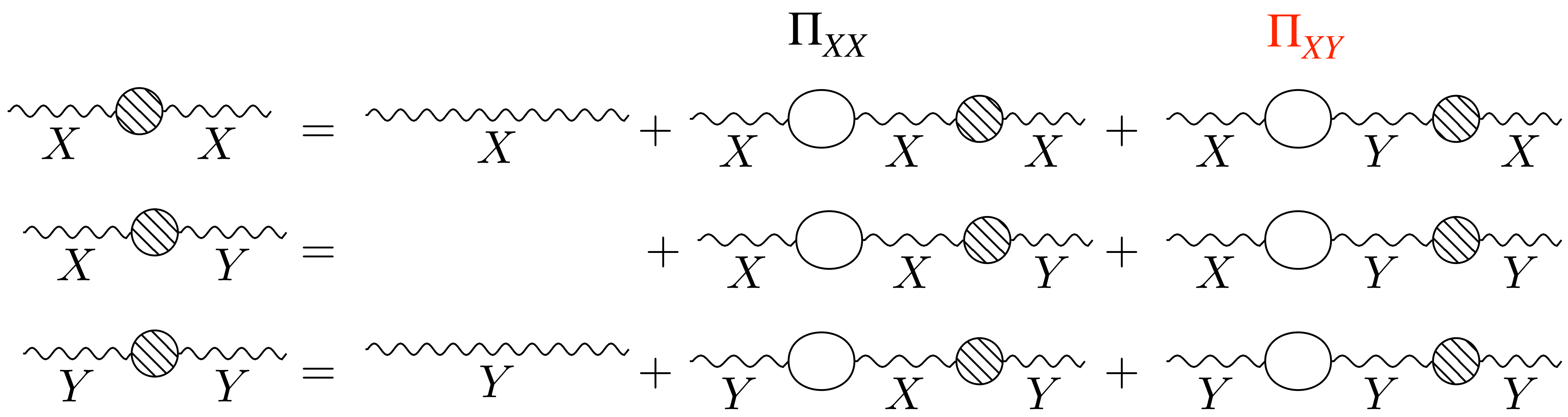
- this does not depend on mixing parameter and thus not valid at small mixing parameter

“Mass insertion” vs “Classical”

- (as demonstrated later) “mass insertion” is valid for small mixing parameter, while “classical” is valid for large

"Pole" method

Mixed propagator



$$D_{XX}(s) = \frac{1}{s - m_X^2 - \Pi_{XX}(s) - \frac{\Pi_{XY}(s)^2}{s - m_Y^2 - \Pi_{YY}(s)}}$$

- imaginary part of one-loop mixing does not have classical interpretation (i.e., quantum effect)

- find complex poles of mixed propagator (solution of Schwinger-Dyson)

- most robust (by definition of unstable "particles")

Trum muonium

Spin 1 bound states of muon-anti muon

Matsumoto, Watanabe and Watanabe, JHEP, 2023

AK, Kuwahara, Matsumoto, Watanabe and Watanabe, arXiv:2404.06793

- narrow resonance $\overline{m}_V \simeq 2m_\mu$

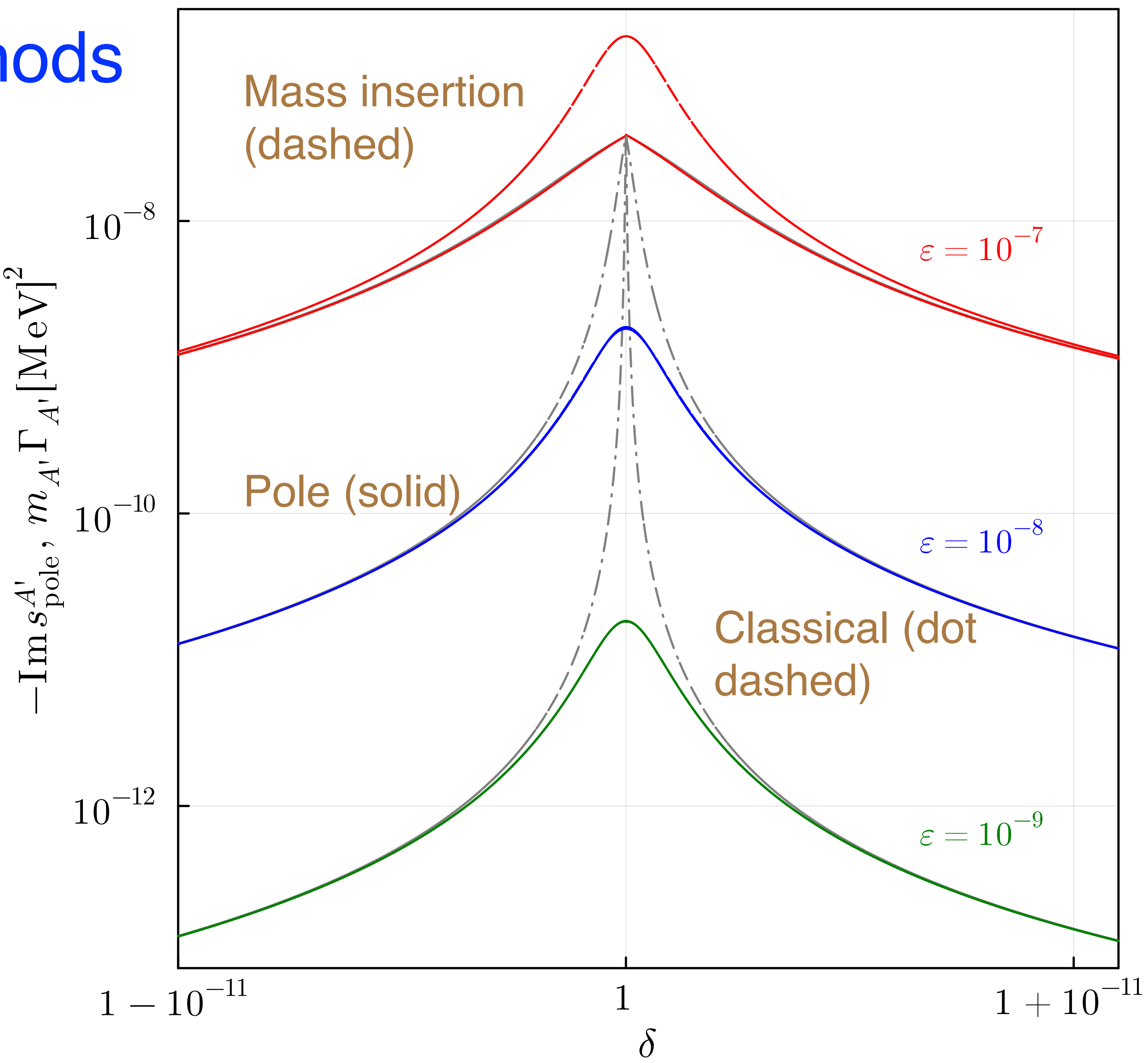
$\overline{\Gamma}_V \simeq 3.66 \times 10^{-10}\,\mathrm{MeV}$

Comparison of three methods

- all agree away from mass degenerate limit

- “mass insertion” is valid for $\epsilon < 3.2 \times 10^{-8}$ while “classical” is valid for $\epsilon > 3.2 \times 10^{-8}$

- critical value $\epsilon_{\rm cr}$ corresponds to $\eta = \overline{\Gamma}_V / \overline{m}_V$



Trum muonium

Anti-resonance of decay width

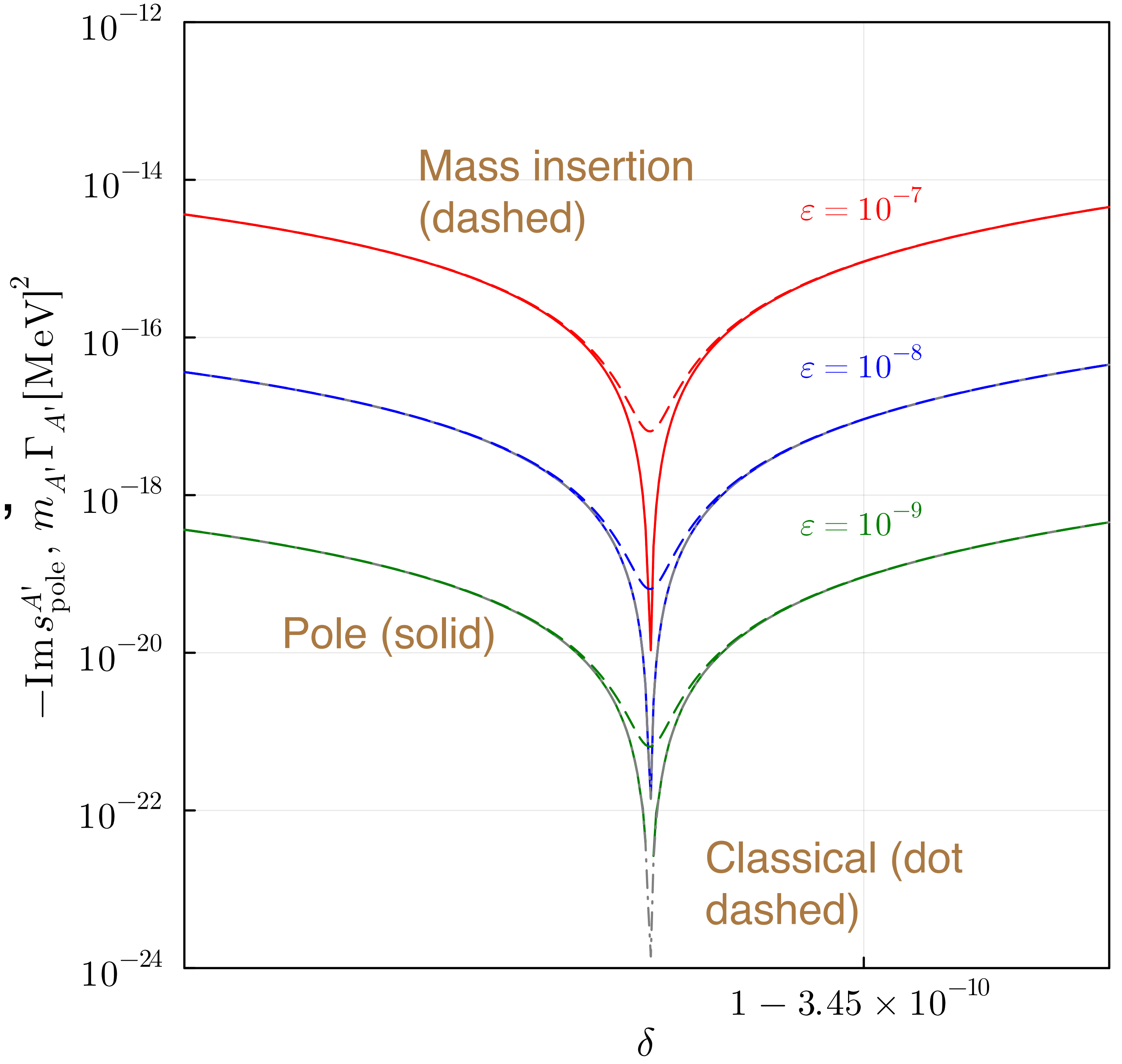
Matsumoto, Watanabe and Watanabe, JHEP, 2023

AK, Kuwahara, Matsumoto, Watanabe and Watanabe, arXiv:2404.06793

- slightly below resonance of decay width

- destructive interference of two contributions

$$\Gamma^{\rm MI}(A' \to \bar{f}f) = \frac{M_{A'}}{16\pi}\frac{4}{3}\left|\bar{g}_f^{A'} + \bar{g}_f^{V}\frac{-\eta\overline{m}_V^2}{M_{A'}^2 - \overline{m}_V^2 + i\overline{m}_V\overline{\Gamma}_V}\right|^2$$



- "classical" agrees with "Pole", but not "mass insertion"

Summary

AK, Kuwahara, Matsumoto, Watanabe and Watanabe, arXiv:2404.06793

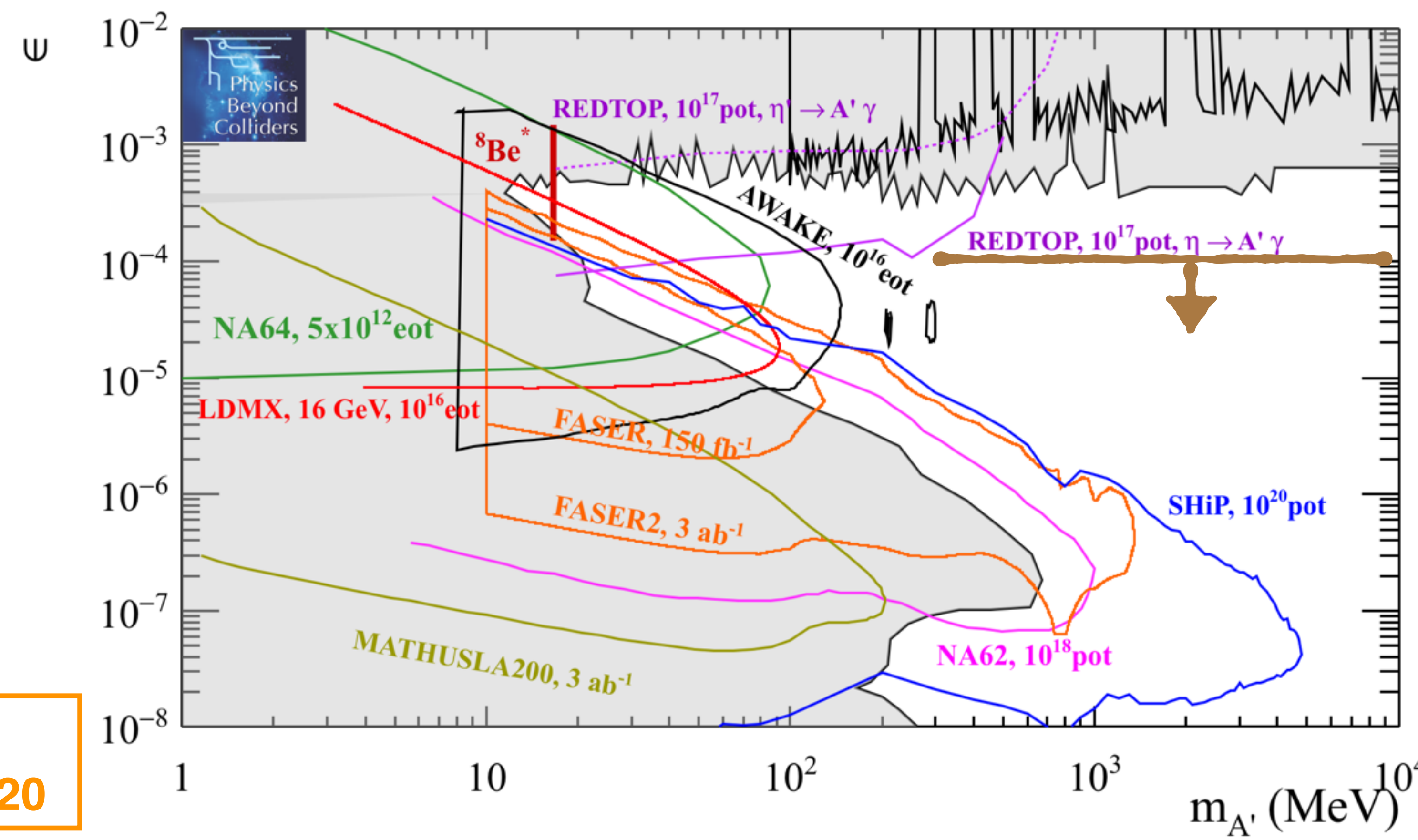
Critical mixing parameter

- corresponds to $\eta = \overline{\Gamma}_V / \overline{m}_V$
- checked for ρ and Z-boson as well as true monism
- conventional multiplication of R-ratio for hadrons is justified for $\epsilon < \epsilon_{\rm cr}$
- smaller for narrower resonance

Mesons	Mass (MeV)	Width (MeV)	Branching ratio to e^-e^+	Critical mixing $\epsilon_{\rm cr}$
$\rho\,(770)$	775.26	149.1	4.72×10^{-5}	9.53×10^{-1}
$\omega\,(782)$	782.66	8.68	7.38×10^{-5}	5.26×10^{-1}
$\phi\,(1020)$	1019.461	4.249	2.979×10^{-4}	1.81×10^{-1}
$J/\psi\,(1S)$	3090.9	9.26×10^{-2}	5.971×10^{-2}	1.10×10^{-3}
$\psi\,(2S)$	3686	2.94×10^{-1}	7.93×10^{-3}	4.95×10^{-3}
$\psi\,(3770)$	3773.7	27.2	9.6×10^{-6}	8.04×10^{-1}
$\psi\,(4040)$	4039	80	1.07×10^{-5}	9.05×10^{-1}
$\psi\,(4160)$	4191	70	6.9×10^{-6}	9.25×10^{-1}
$\Upsilon\,(1S)$	9460	5.4×10^{-2}	2.38×10^{-2}	7.64×10^{-4}
$\Upsilon\,(2S)$	10023	3.198×10^{-2}	1.91×10^{-2}	6.38×10^{-4}
$\Upsilon\,(3S)$	10355	2.032×10^{-2}	2.18×10^{-2}	4.68×10^{-4}
$\Upsilon\,(4S)$	10579.4	20.5	1.57×10^{-5}	4.81×10^{-1}
$\Upsilon\,(10860)$	10885.2	37	8.3×10^{-6}	7.67×10^{-1}
$\Upsilon\,(11020)$	11000	24	5.4×10^{-6}	7.04×10^{-1}

Non-hadronic resonance

- to be added by hand
- not only resonance but also anti-resonance



Physics Beyond Colliders collaboration, J. Phys. G, 2020

Thank you

GeV dark sector

Motivations

- weak top-down reason
  - closer to electroweak scale is more natural (Higgs portal)
  - with supersymmetry $v' = \sqrt{\frac{\epsilon g}{g'}} v$
- strong bottom-up reason
  - relic abundance of heavy (> 100 TeV) stable particles overclose the Universe (Unitarity bound)
  - light (sub-GeV) dark matter evades high-energy collider experiments
    - dominating background from $Z \to \nu\bar{\nu}$
    - higher-energy hadron collider is worse
  - light (sub-GeV) dark matter evades direct-detection experiments
    - not enough recoil energy

GeV dark sector

Motivations

- strong bottom-up reason
  - multiple dark matter candidates
    - most strongly coupled one does not need to be a dominant component
    - evade late-time annihilation constraints from CMB
      - this is not so trivial

XENON1T collaboration, PRL, 2019 & 2019

    - e.g., electron and proton from the dark-sector point of view

- dark sector phenomenology
  - in the following, dark matter = lightest stable particle in dark sector
    - lower bound of the coupling to SM from the relic abundance
    - need new experimental strategy (low background)

Geometric acceptance

Efficiency factor

$$N_{\text{signal}} \simeq N_{A'} \times \text{Br}(e^+e^-) \times \text{effic.}$$

$$\text{effic.} = \frac{1}{N_{\text{events}}} \int_{z_{\min}}^{z_{\max}} dz \sum_{\substack{\text{events} \\ \in\, \text{geom.}}} \frac{m}{p_z} \Gamma e^{-z(m/p_z)\Gamma} \qquad \frac{p_z}{m} = v_z \gamma$$

- Lorentz boost

- decay position

- events $\in$ geom. is generically z and p_z dependent

  - strong dependence in Sea Quest due to KMAG

  - if weak dependence

$$\text{effic.} \approx \mathscr{A} \frac{1}{N_{\text{events}}} \sum_{\text{events}} \left(e^{-z_{\min}(m/p_z)\Gamma} - e^{-z_{\max}(m/p_z)\Gamma} \right)$$

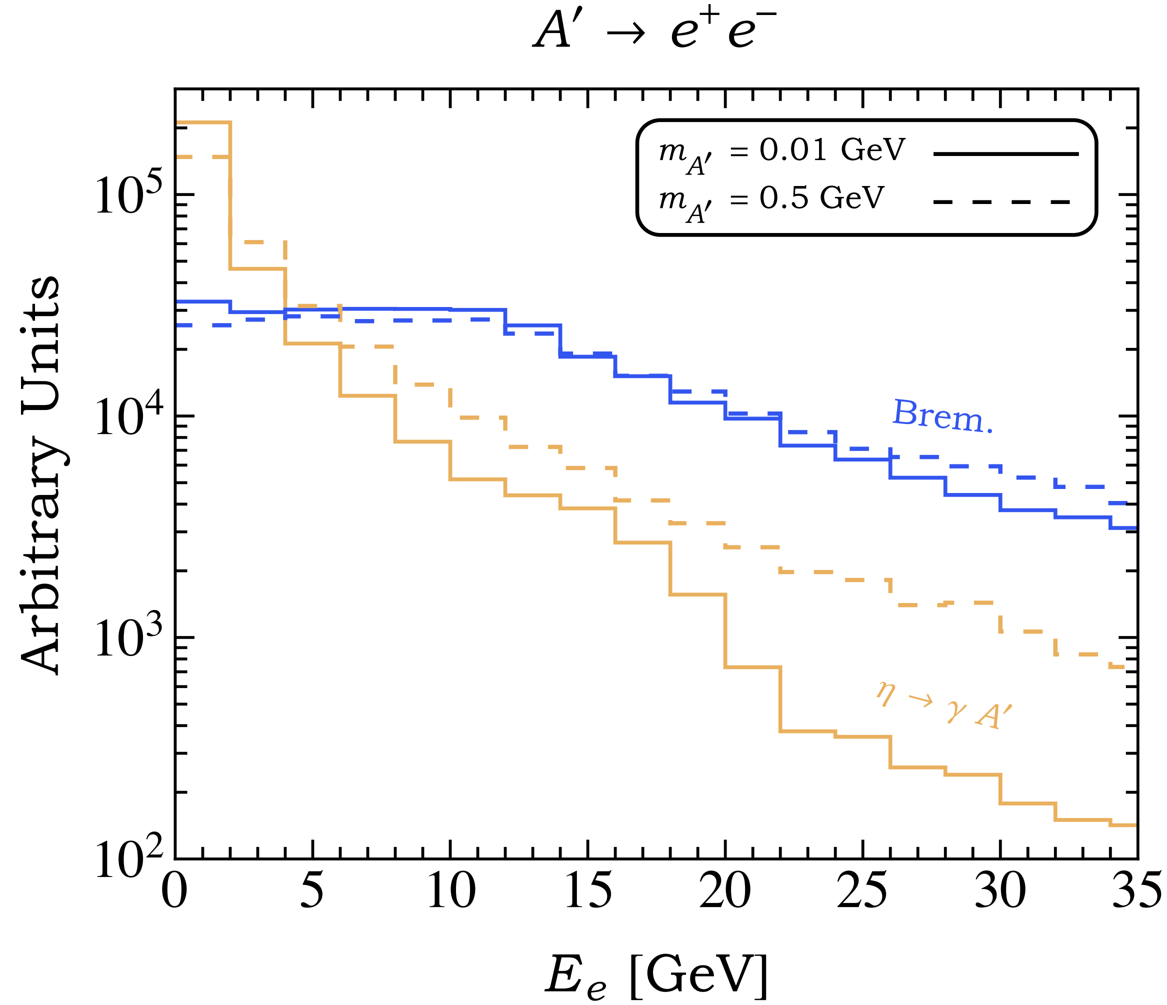
- geometrical acceptance

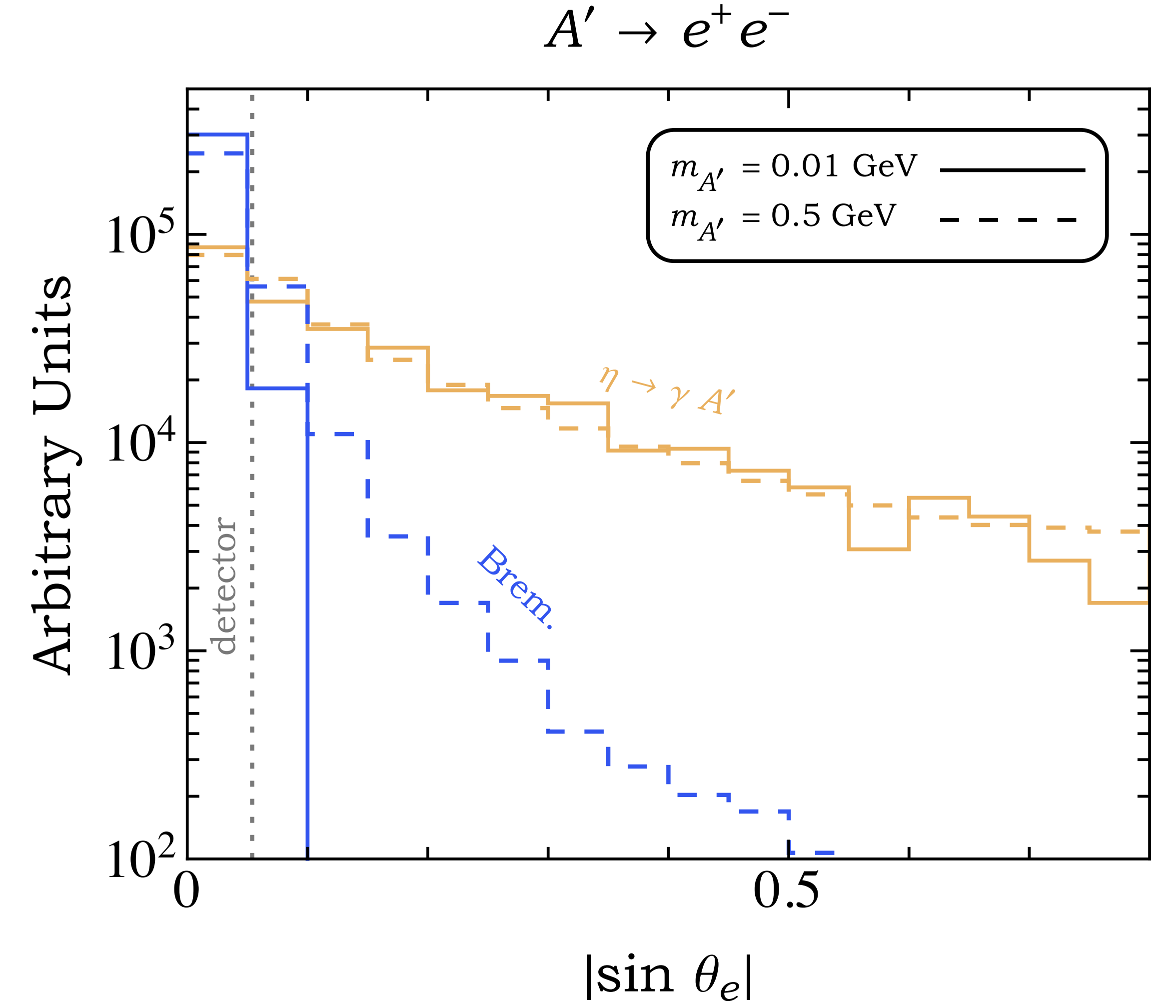
Geometric acceptance

Kinematics@SeaQuest

- minimal model

Berlin, Gori, Schuster, and Toro, PRD, 2018





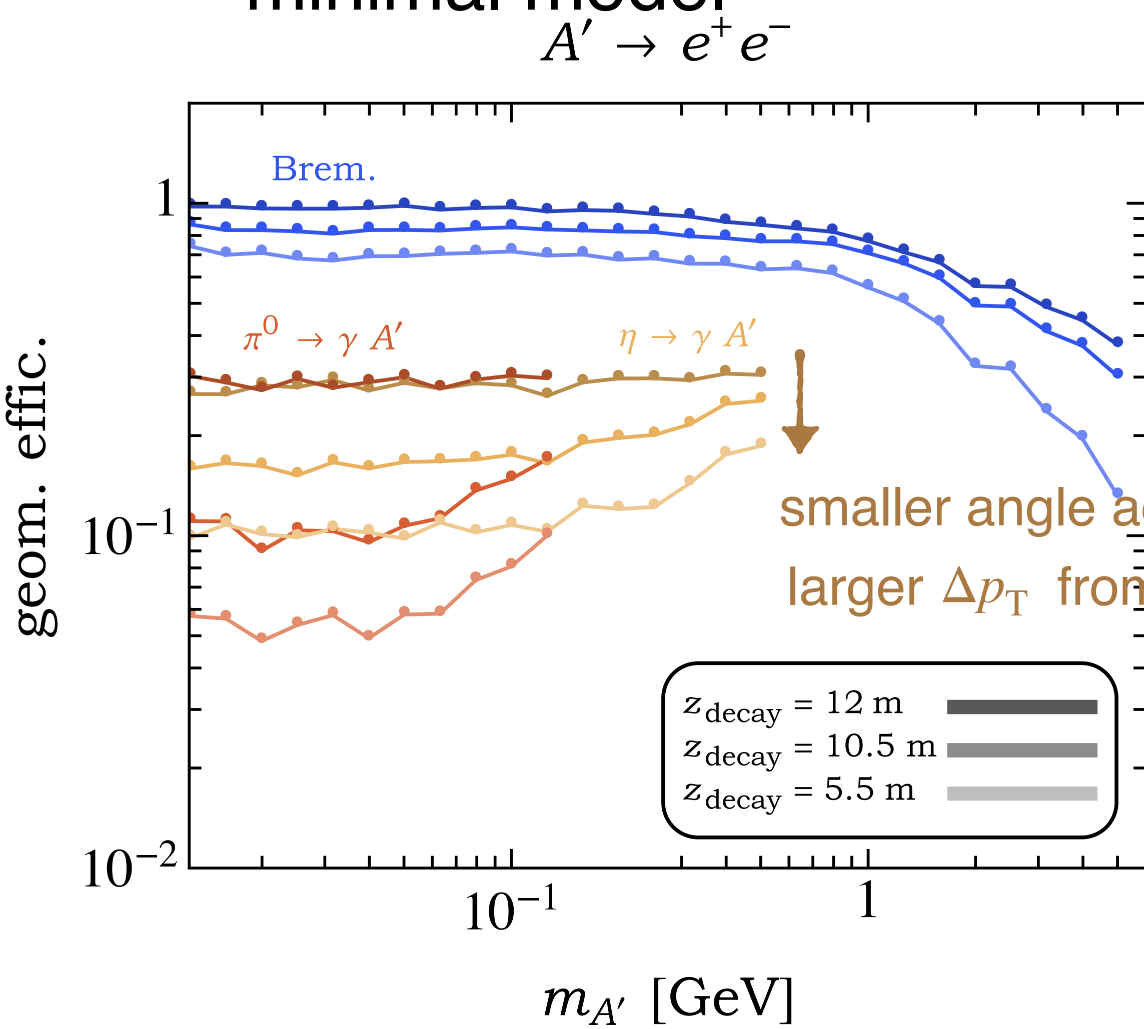
- A' from Bremsstrahlung is more energetic
    - γ takes away energy (smaller impact for heavier A')

- A' from Bremsstrahlung is more boosted
    - lower collimation for heavier

Geometric acceptance

Efficiency factor@SeaQuest

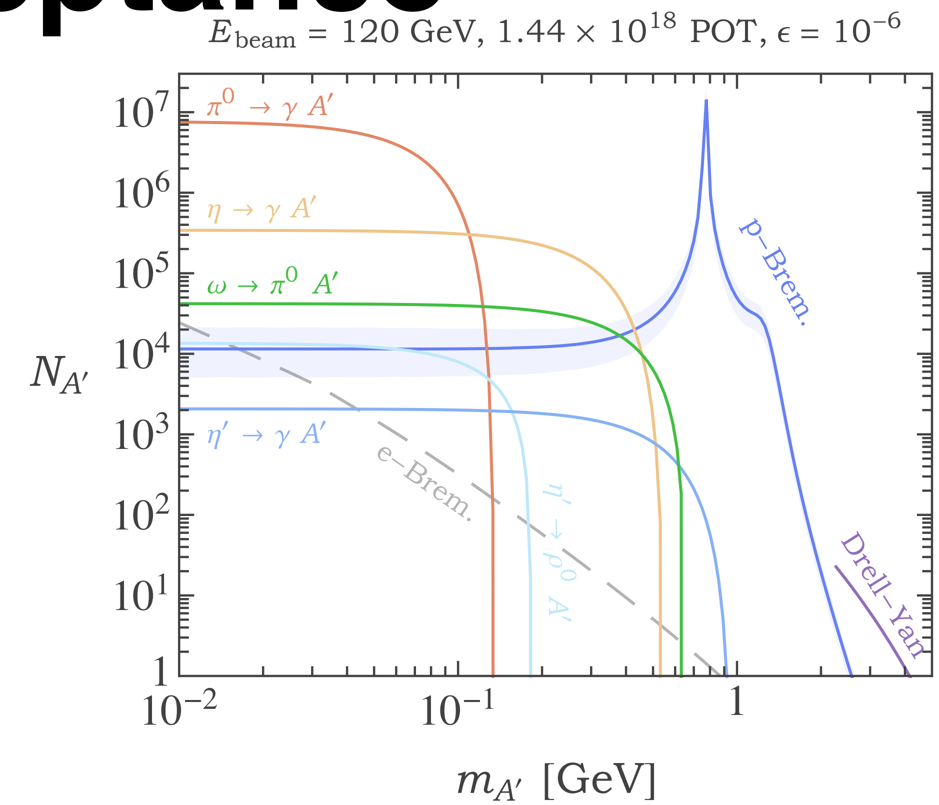
- minimal model

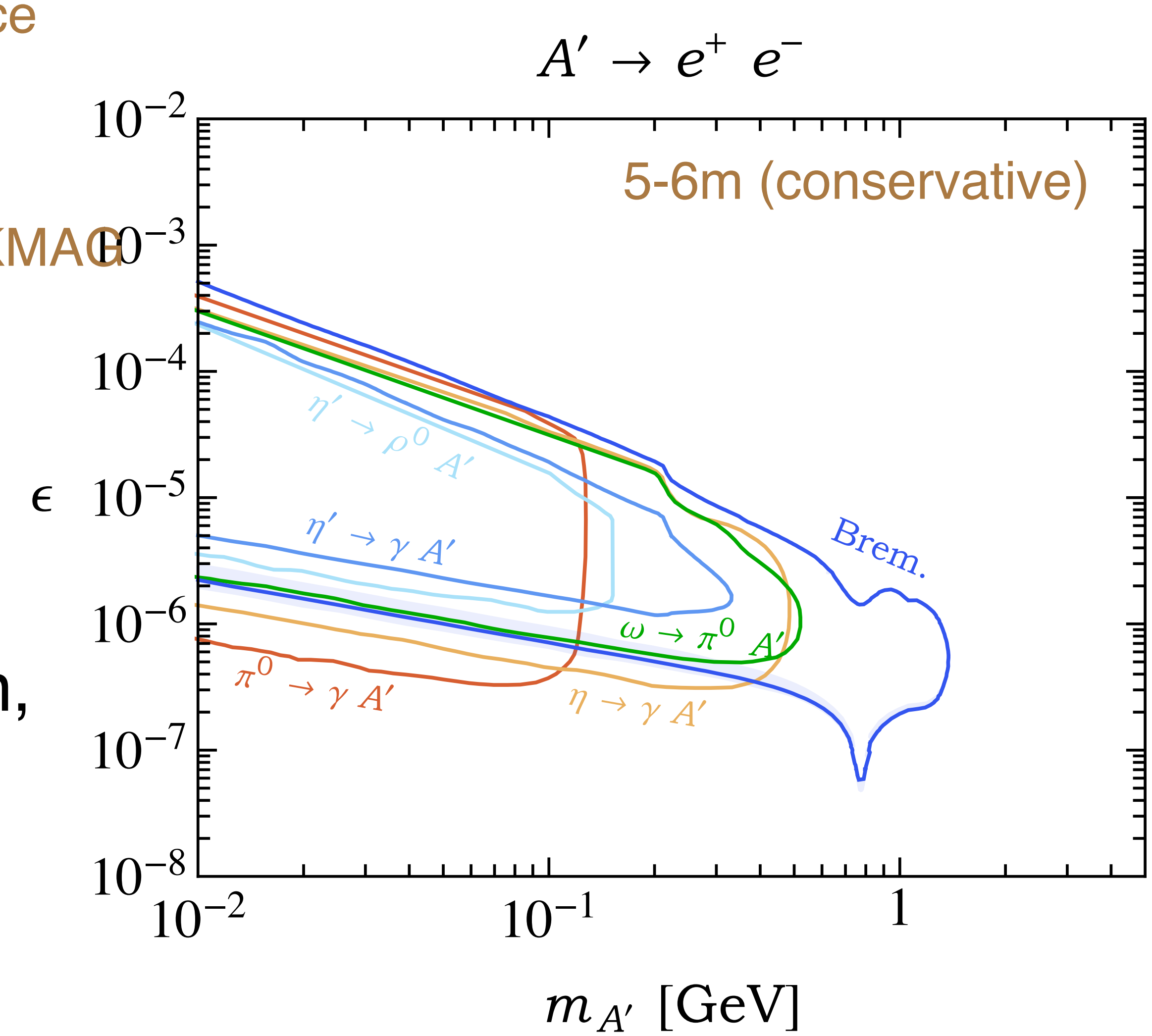


smaller angle acceptance

larger Δp_T from KMAG

after
inside KMAG
before





- meson decay is good in production, but bad in detection

Berlin, Gori, Schuster, and Toro, PRD, 2018

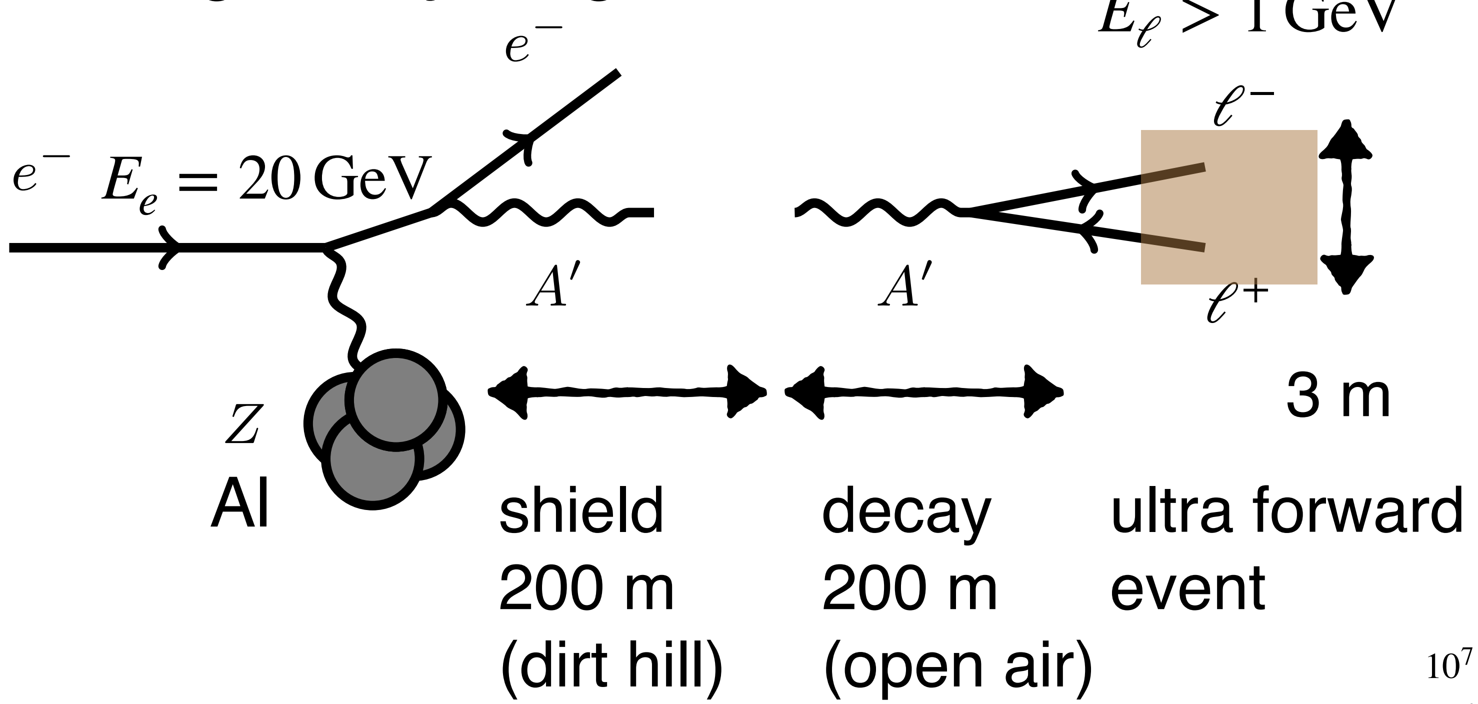
Electron beam dump

SLAC E137

- long decay length

# of events > 3

$E_\ell > 1\,\mathrm{GeV}$



- production
  - suppressed for $m_{A'} \gtrsim 2\,\mathrm{GeV}$