Probing vector portal at the SPS

I. Timiryasov

INR
Institute for Nuclear Research
of the Russian Academy of Sciences

and
Moscow State University

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Outline

- Vector Portal
- Beam Dump experiments
- SHIP at the CERN SPS
- Dark photon production:
  - proton bremsstrahlung
  - electron bremsstrahlung
  - meson decays
- Dark photon decay channels
- Conclusions

Vector Portal

- The vector portal naturally arises in the framework of the Mirror World.
- Standard Model Lagrangian can be extended in a following way:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{m^2_{A'}}{2} A'_\mu A'^\mu, \tag{1}$$

  where $F'_{\mu\nu} = \partial_\mu A'_\mu - \partial_\nu A'_\mu$, A'_μ is extra $U'(1)$ boson.
- Massive (dark/para/...)photon can be produced in fixed target experiment.

Current limits

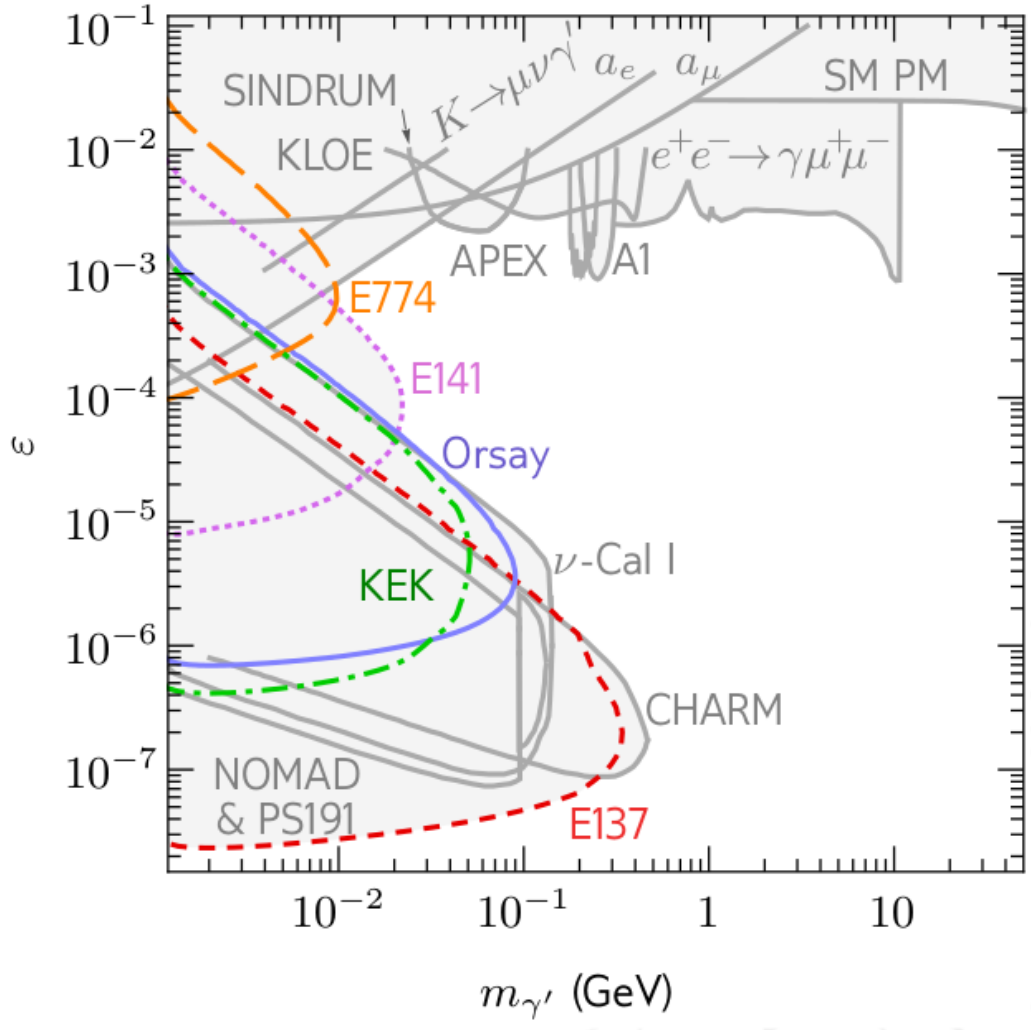
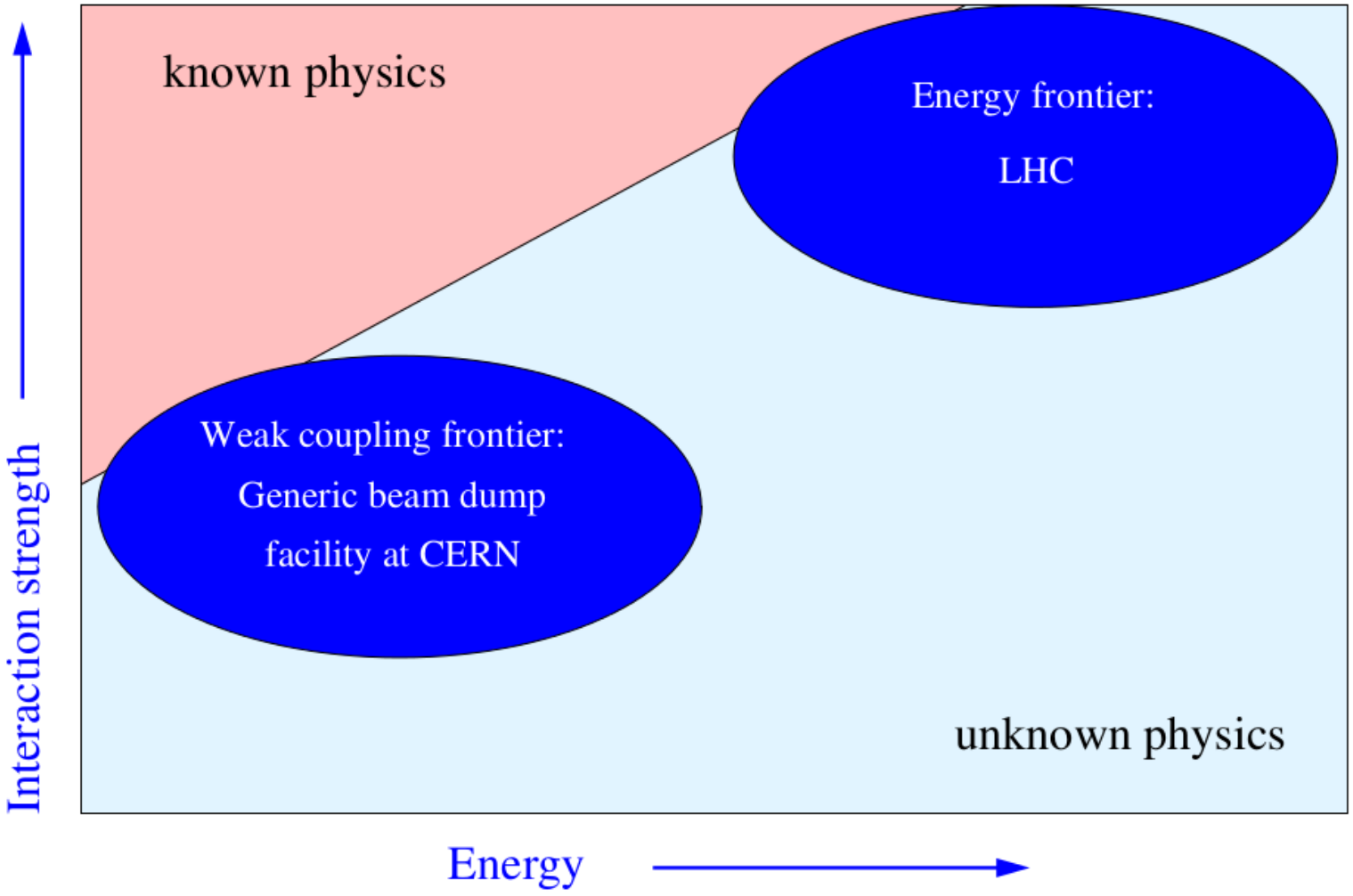
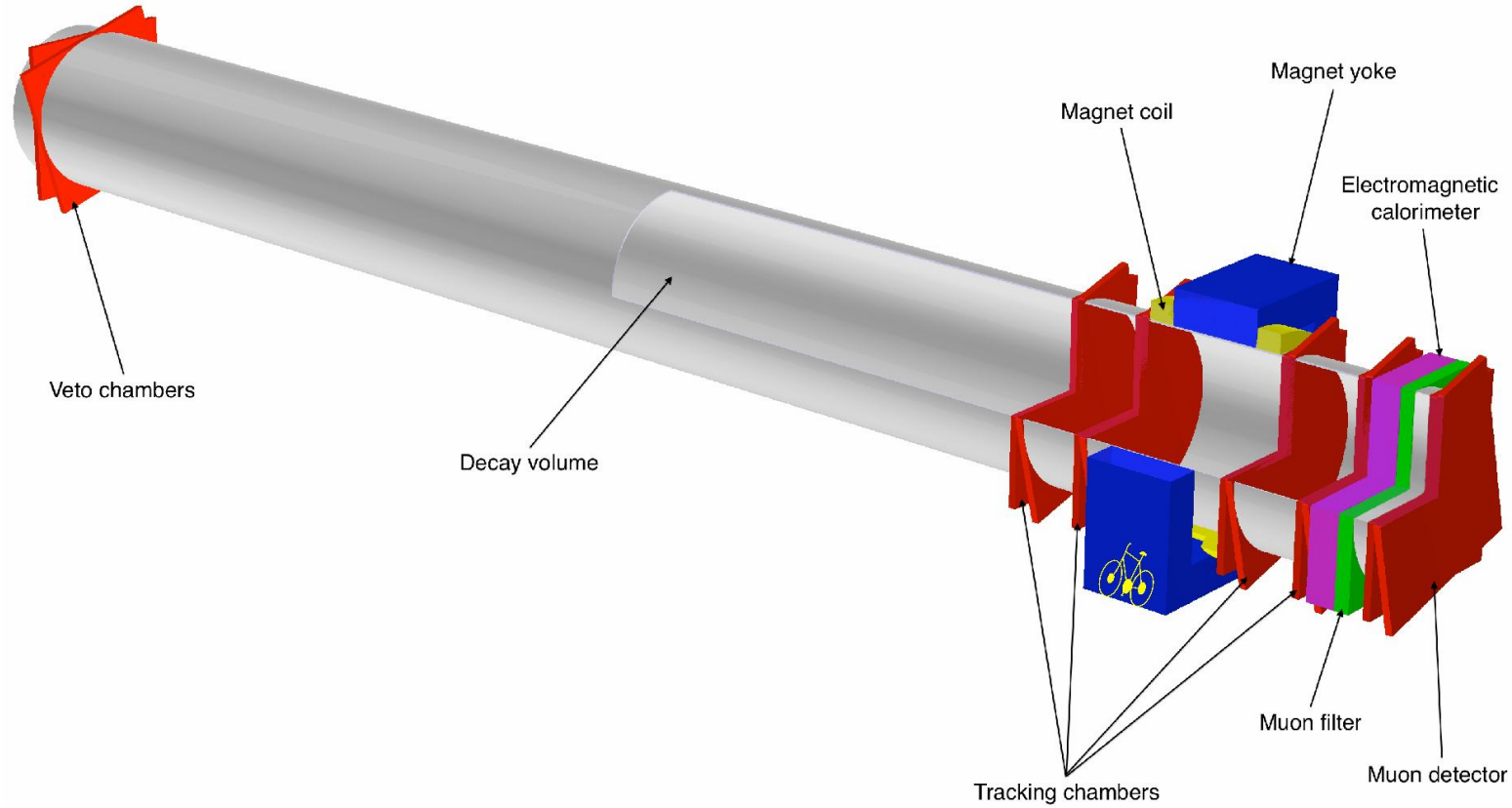


Figure by S. Andreas. " Light Weakly Interacting Particles: Constraints and Connection to Dark Matter"

Beam Dump

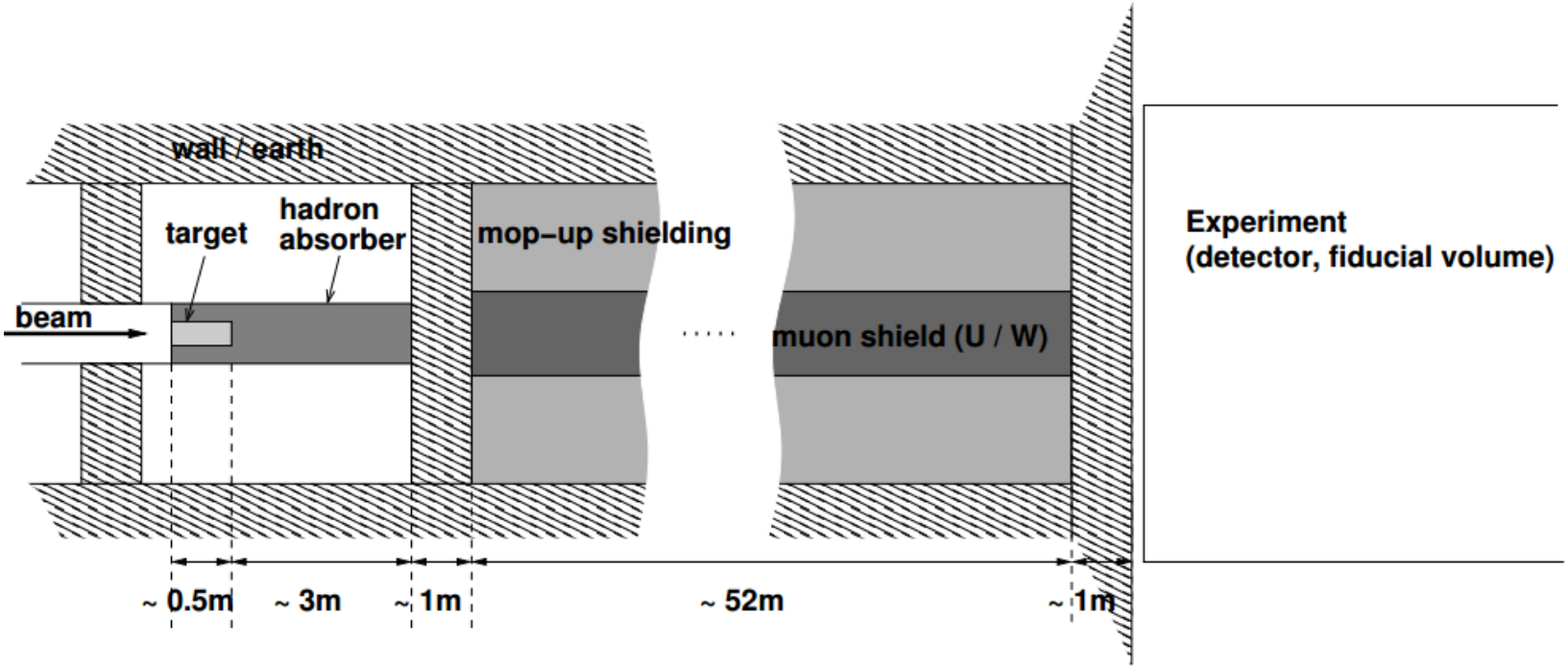

known physics
Energy frontier:
LHC
Weak coupling frontier:
Generic beam dump
facility at CERN
unknown physics
Interaction strength
Energy

SHIP @SPS



New fixed-target experiment designed to search for hidden particles

SHIP details



- $2 \cdot 10^{20}$ protons on target, $E_p \sim 400$ GeV.
- 52 m tungsten shield
- 50 m vacuum vessel

Paraphoton production in a beam dump

Considered channels:

- Proton bremsstrahlung
- Secondary electron bremsstrahlung
- Production in decays:

$$\pi^0 \to A'\gamma, \quad \eta \to A'\gamma, \quad \rho^\pm \to A'\pi^\pm, \ldots$$

Proton bremsstrahlung

- Differential A'-rate per proton interaction calculated in the Weizsäcker-Williams approximation reads[1]:

$$\frac{dN}{dzdp_\perp^2} = \frac{\sigma_{pA}(s')}{\sigma_{pA}(s)} w_{ba}(z, p_\perp^2), \tag{2}$$

  $\sigma_{pA}(s')$ is proton-Nucleus cross section after A' emission and z is fraction of the initial proton momentum P carried away by A' in the direction of incoming proton.

- Applicability conditions of WW approximation are:

$$E_p, E_{A'}, E_p - E_{A'} \gg m_p, m_{A'}, \sqrt{p_\perp^2} \tag{3}$$

[1] J. Bluemlein and J. Brunner, Phys. Lett. B **731** (2014) 320

Proton bremsstrahlung

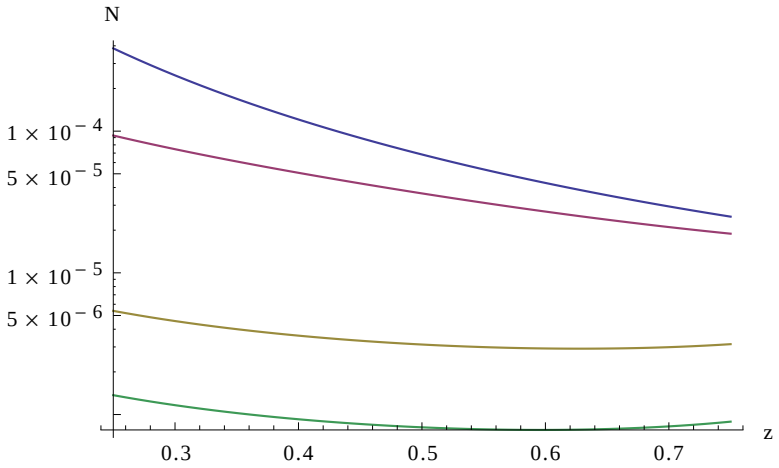


Figure: Flux of produced A' per beam proton as function of z.

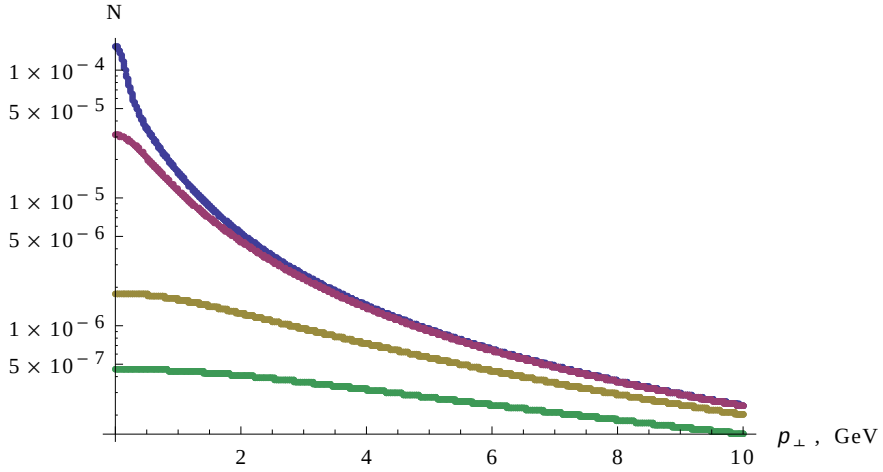


Figure: Flux of produced A' per beam proton as function of $p_\perp$.

Masses of A' are (up to down) 100 MeV, 1 GeV, 5 GeV, 10 GeV. Mixing parameter $\epsilon = 10^{-4}$.

Production by secondary electrons

A'-production cross section calculated[2] in the Weizsäcker-Williams approximation:

$$\frac{d\sigma}{dx d\cos\theta_{A'}} \approx \frac{8Z^2\alpha_{QED}^3\epsilon^2 E_0^2 x}{U^2}\frac{\chi}{Z^2}\left[(1-x+x^2/2)-\frac{x(1-x)m_{A'}^2 E_0^2 x\theta_{A'}^2}{U^2}\right],$$

where E_0 is energy of incoming electron, $E_{A'} = xE_0$, $\theta_{A'}$ is angle between A' and incoming electron in lab frame, Z is atomic number and

$$U = U(x,\theta_{A'}) = E_0 x\theta_{A'}^2 + m_{A'}^2\frac{1-x}{x} + m_e^2 x.$$

[2] J. D. Bjorken, R. Essig, P. Schuster and N. Toro, Phys. Rev. D **80** (2009) 075018

Production by secondary electrons

Effective flux of photons is given by

$$\chi \equiv \int_{t_{min}}^{t_{max}} dt \frac{t - t_{min}}{t^2} G_2(t), \tag{4}$$

where G_2 is a general electric form factor. As was shown in arXiv:1311.5104 the limits in (4) are crucial!

$$t_{min} = \left(\frac{U}{2E_0(1-x)} \right)^2, \quad t_{max} = m_{A'}^2$$

- $t_{min} = (m_{A'}/2E_0)^2$ could lead to $\approx 30\%$ overestimate of the cross section.

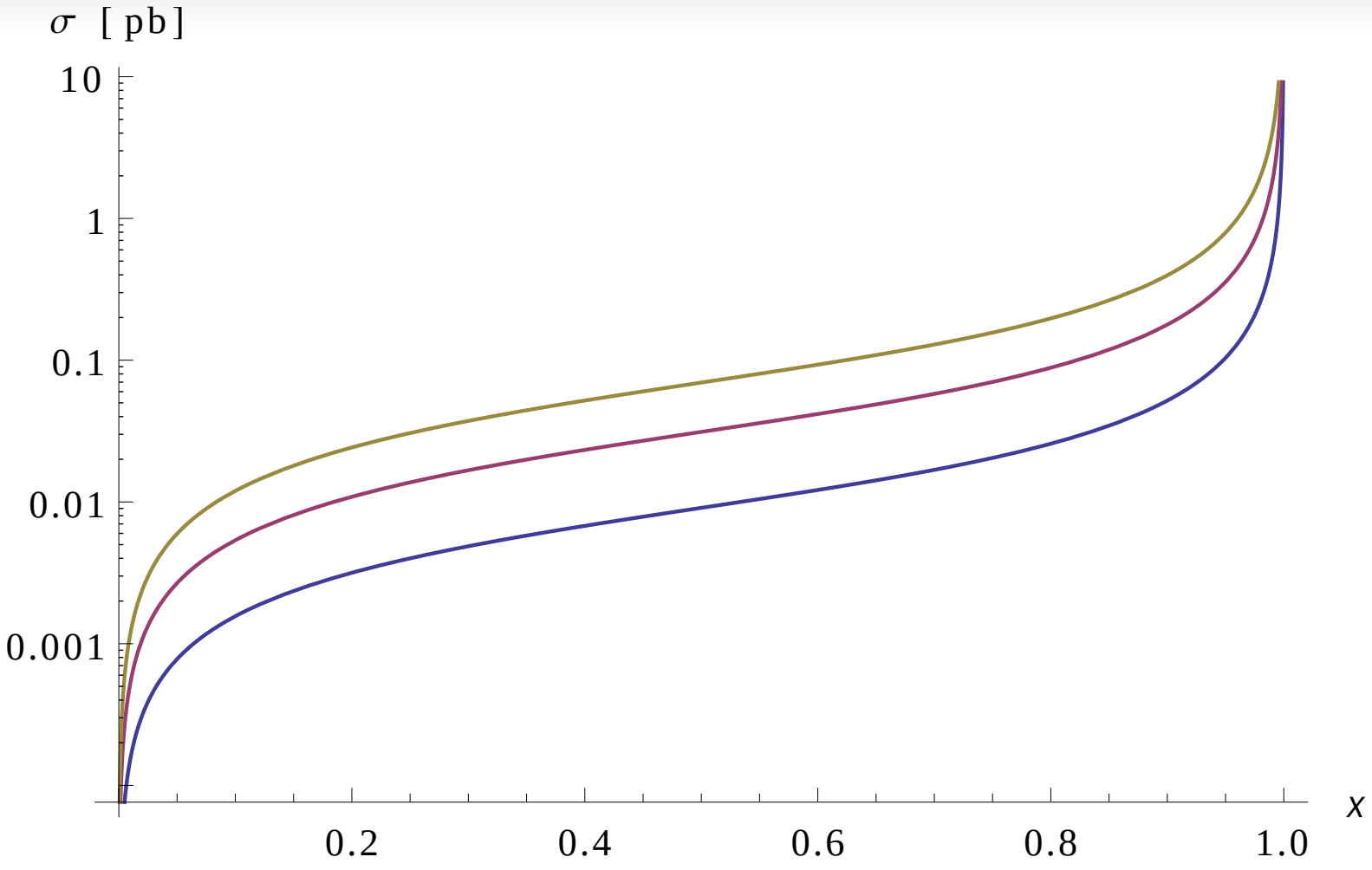
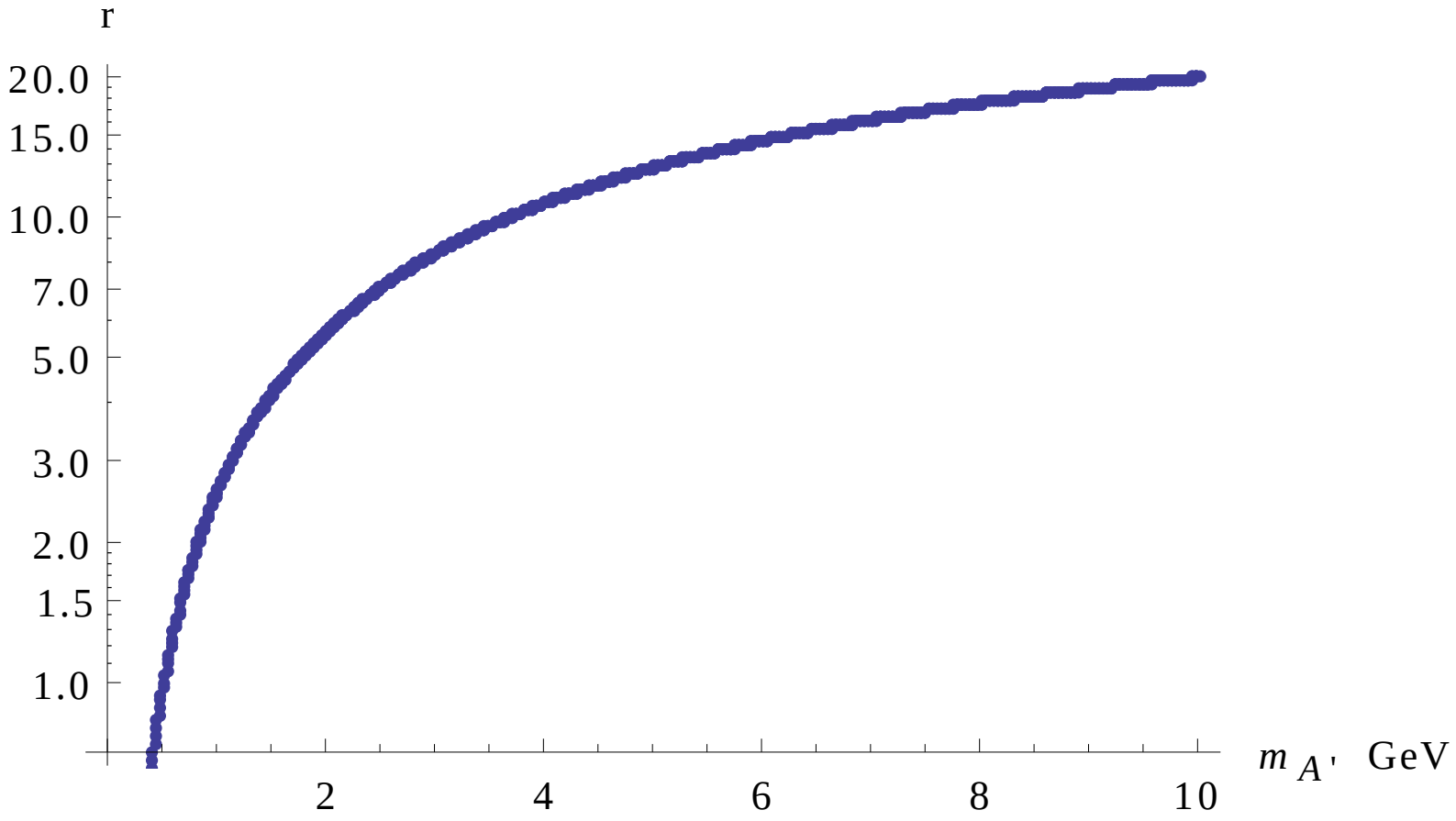


Figure: cross sections for $m_{A'} = 1$ GeV and initial electron energies (up to down) 40, 20 and 10 GeV. Mixing parameter $\epsilon = 10^{-4}$.

Proton vs Electron bremsstrahlung



$$r = \frac{N_{A'}(p + Z \to A' + X)}{N_{A'}(e + Z \to A' + X)} \tag{5}$$

A' lifetime doesn't exceed the length of detector.

Production in decay

Electromagnetic decay of π^0 meson:

$$Br(\pi^0 \to A'\gamma) \simeq 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_\pi^2}\right)^3 Br(\pi^0 \to \gamma\gamma)$$

Decay of vector meson V (e.g. $V = \rho^\pm, \rho^0, \omega$) into A' and pseudoscalar meson P ($P = \pi^\pm, \pi^0, \pi^0$, respectively):

$$Br(V \to PA') \simeq \epsilon^2 \frac{(m_V^2 - m_{A'}^2 - m_P^2)^2 \sqrt{(m_V^2 - m_{A'}^2 + m_P^2)^2 - 4m_V^2 m_P^2}}{(m_V^2 - m_{A'}^2)^3} Br(V \to P\gamma), \tag{6}$$

Decay channels and lifetime

- Partial decay width into a lepton pair:

$$\Gamma(A' \to l^+ l^-) = \frac{1}{3}\alpha_{QED} m_{A'} \epsilon^2 \sqrt{1 - \frac{4m_l^2}{m_{A'}^2}} \left(1 - \frac{2m_l^2}{m_{A'}^2}\right),$$

- Partial decay width into hadrons:

$$\Gamma(A' \to \text{hadrons}) = \frac{1}{3}\alpha_{QED} m_{A'} \epsilon^2 \cdot R(m_{A'}),$$

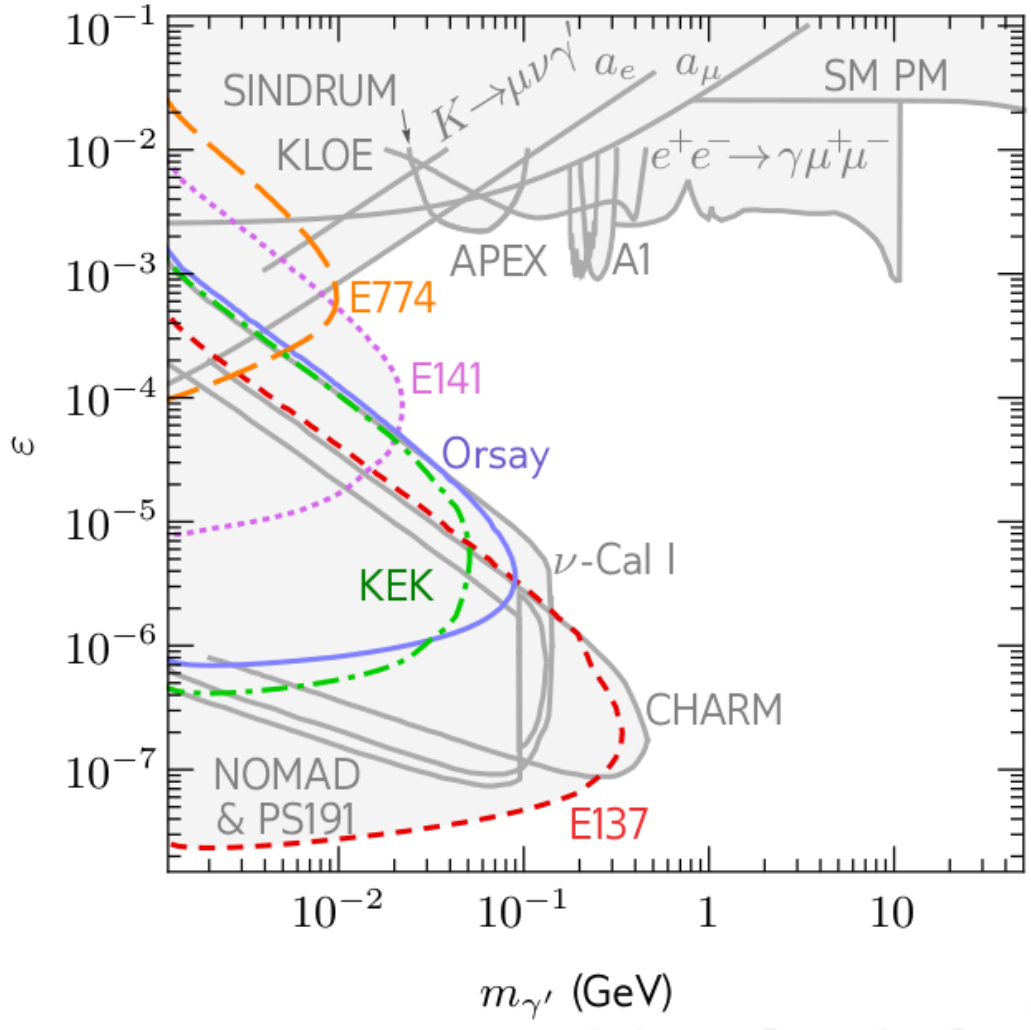
where

$$R(\sqrt{s}) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Lifetime:

$$c\tau = \frac{1}{\Gamma} \approx \frac{3}{(1 + R(m_{A'}))m_{A'}\alpha\epsilon^2} \simeq \frac{0.8\text{m}}{1 + R(m_{A'})} \left(\frac{10^{-6}}{\epsilon}\right)^2 \left(\frac{100\text{MeV}}{m_{A'}}\right).$$

Current limits



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Conclusions

- There are different production channels of dark photons at SHIP experiment.
- Planning experiment will be sensitive for Dark sector in a wide range of the parameters and will sufficiently increase current statistics.
- Large region of parameter space will be excluded.
- Accuracy of the WW-approximations in the case of proton bremsstrahlung remains to be an open question.