University of Victoria

Victoria Subatomic Physics and Accelerator Research Centre

VISPA

Search for low-mass New Physics states at BaBar

Bob Kowalewski
on behalf of the
BABAR Collaboration

NSERC CRSNG

INSTITUTE OF PARTICLE PHYSICS

INSTITUT DE PHYSIQUE DES PARTICULES

Is there New Physics at low mass?

University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

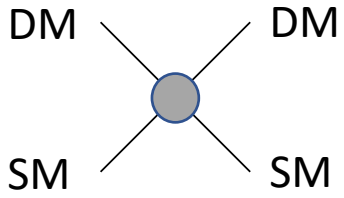
- There is convincing astrophysical evidence for Dark Matter – but its connection to particle physics is still unclear
- An interesting class of models suggests that DM might be light (a few GeV or less); these models are unconstrained by WIMP searches and can be explored in low-energy e^+e^- collisions and beam-dump experiments
- In these models, light DM couples to SM through a *portal* with a light mediator
  - Vector portal → dark photon A'
- Non-minimal DM models allow for different couplings to the $2^{\mathrm{nd}}/3^{\mathrm{rd}}$generation
  - Z' coupling to muons could contribute to $(g-2)_\mu$ anomaly, sterile neutrino abundance
- Tightly bound stable hexaquark (uuddss) could be DM candidate
  - Search for missing momentum recoiling against two strange antibaryons

DM searches at colliders

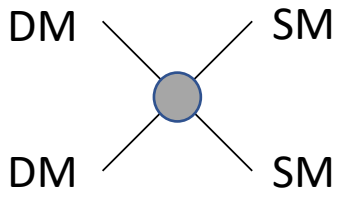
University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

- DM interactions with SM particles can be explored in several ways (*time* ⟶)

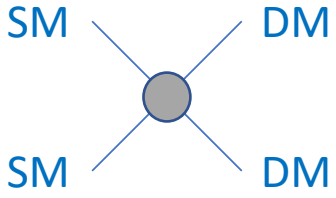
Direct detection



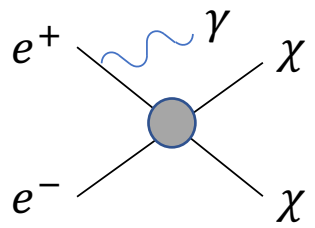
Indirect detection



Production (disappearance)



- Need to observe *something* – e.g. radiation off initial state or production of SM particles in final state
- At e^+e^- colliders Initial State Radiation (ISR) occurs in $\mathcal{O}(1\%)$ of collisions



- ISR results in a broad spectrum of CM energies, allowing searches for narrow mediators over a sizable mass range
- The ISR photon can be used to trigger the event by itself

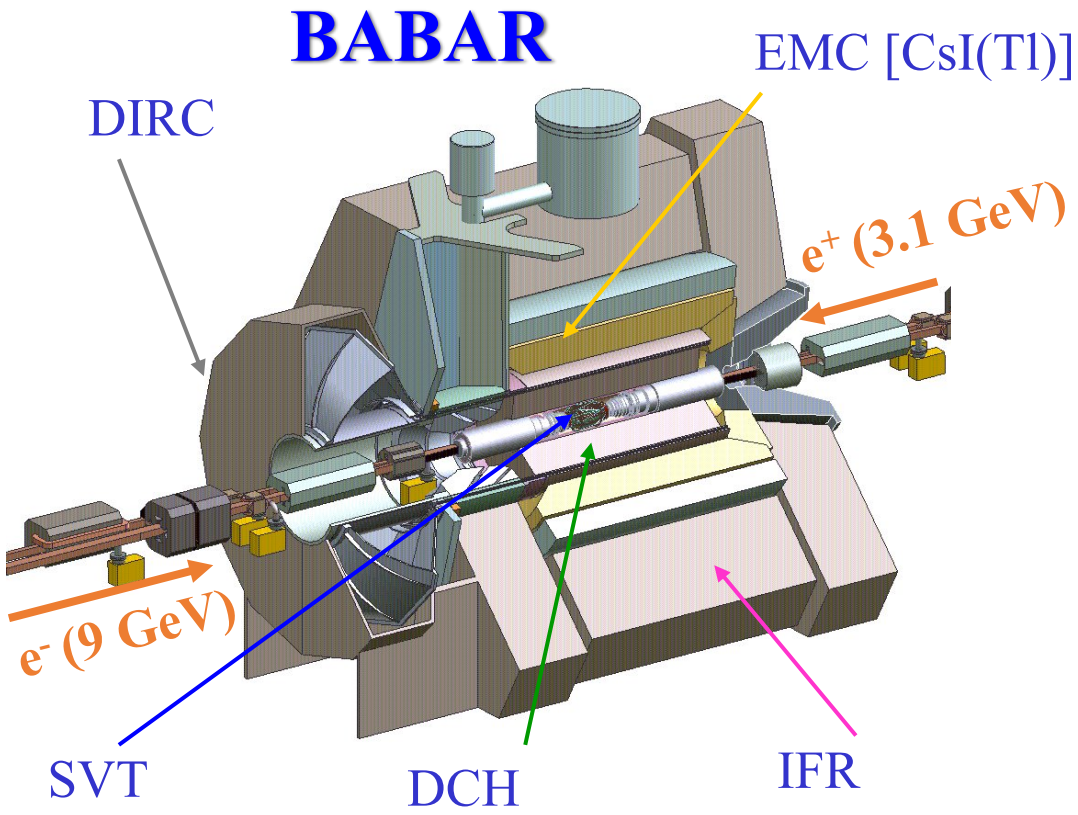
BaBar detector and dataset

University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

- Experiment collected $\int \mathcal{L}\, dt \approx 550\ \mathrm{fb}^{-1}$ between 1999 and 2008, mostly on $\Upsilon(4S)$ resonance at 10.58 GeV

- Asymmetric beam energies: CM is boosted. Good acceptance for final states with ISR off e^- beam

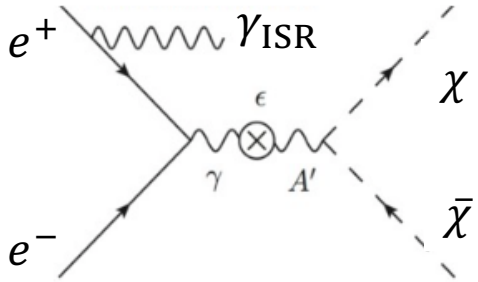
- Special run in 2007-08 with single photon trigger had $\int \mathcal{L}\, dt = 53\ \mathrm{fb}^{-1}$; essential for searches with invisible final states



Dark photons – vector portal

University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

- Postulate that DM particles are charged under a new U(1) gauge symmetry in the dark sector. The spin-1 "dark photon" A' will then mix with SM photon (*kinetic mixing [1]*) with a strength ε
- A' has narrow width if dark sector coupling $\alpha_D < 1$ (used in search strategy)
- If $m_\chi < \frac{1}{2} m_{A'}$, dominant decay of A' is to DM pair $\chi\bar{\chi}$; look for monochromatic γ
- Search for $e^+e^- \rightarrow \gamma_{\mathrm{ISR}} +$ missing energy;
  requires single photon trigger



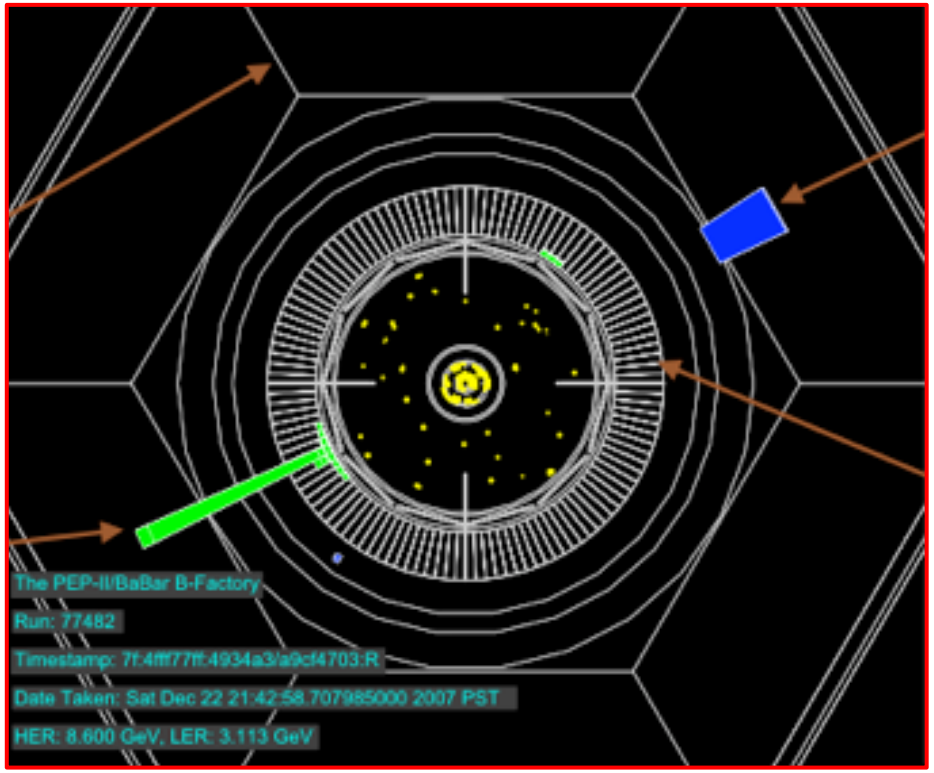
[1] P. Fayet, Phys. Lett. B 95, 285 (1980)
P. Fayet, Nucl. Phys. B 187, 184 (1981)
B. Holdom, Phys. Lett. B 166, 196 (1986)

Dark photon search in invisible final states [1]

University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

- BaBar data in 2007-08 (at $\Upsilon(2S), \Upsilon(3S), \Upsilon(4S)$) includes single photon triggers with $E_\gamma^* > 1$ (2) GeV for data samples of 36 (53) fb^{-1} (E_γ^* is energy in CM frame)
- Reject charged tracks, require $E_\gamma^* > 1.5$ (3.0) GeV for high (low-) mass selection
- Construct BDT based on EMC, IFR quantities
- Determine recoil mass M_X^2 from e^+e^- beam particles and γ_{ISR} momenta
- Backgrounds are due to detector *acceptance and inefficiency*
  - at small M_X^2 mostly from $e^+e^- \to \gamma\gamma$
  - at large M_X^2 radiative Bhabha ($e^+e^- \to e^+e^-\gamma$) are important

$e^+e^- \to \gamma\gamma$ backround

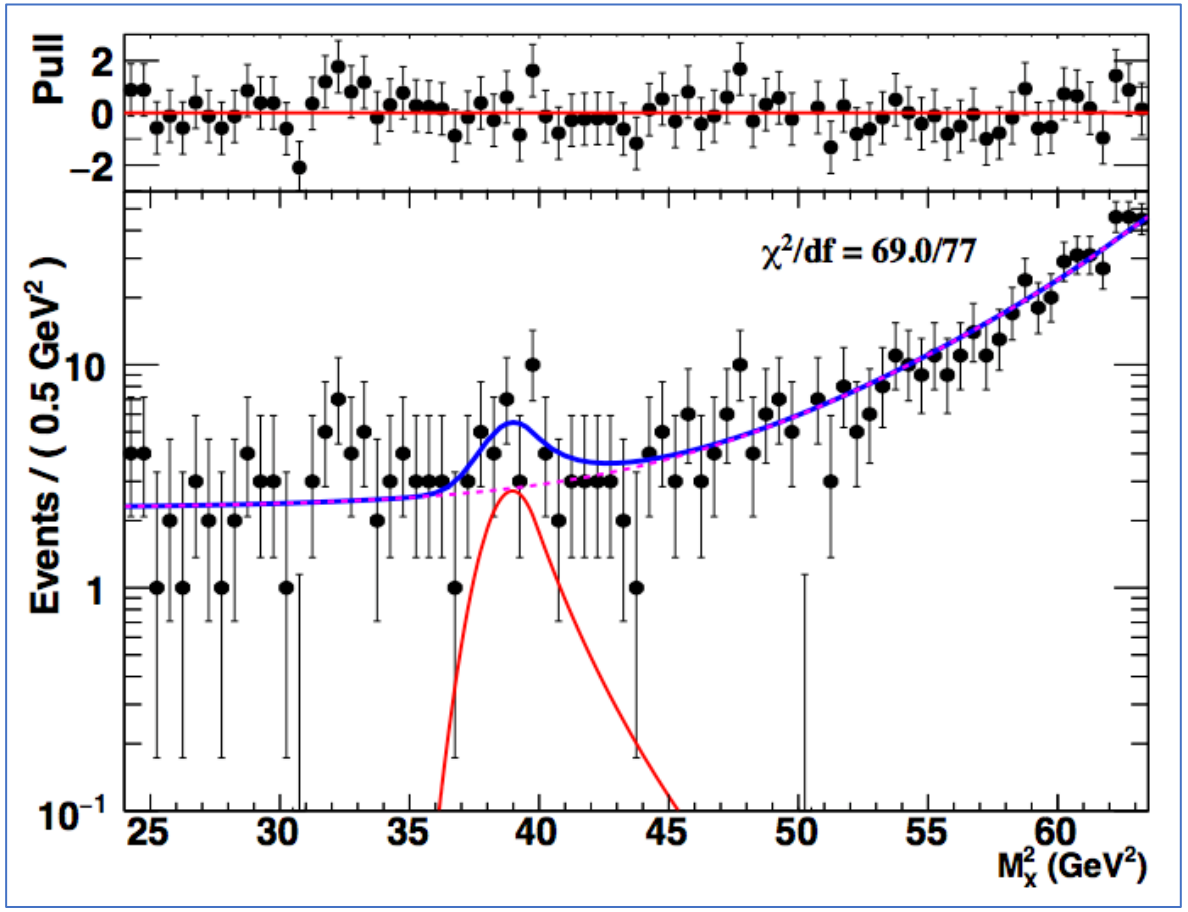


Dark photon search in invisible final states [2]

University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

- Distributions of M_X^2 (from $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$) fitted simultaneously to background and peaking signal
- Background PDF shape determined on large sample of events that fail BDT; background normalization floats in fit to signal distributions
- Signal parameterized by Crystal Ball function; test values of $m_{A'}$ scanned from 0 to 8 GeV in increments of $\approx \sigma_m/2$ (166 steps)

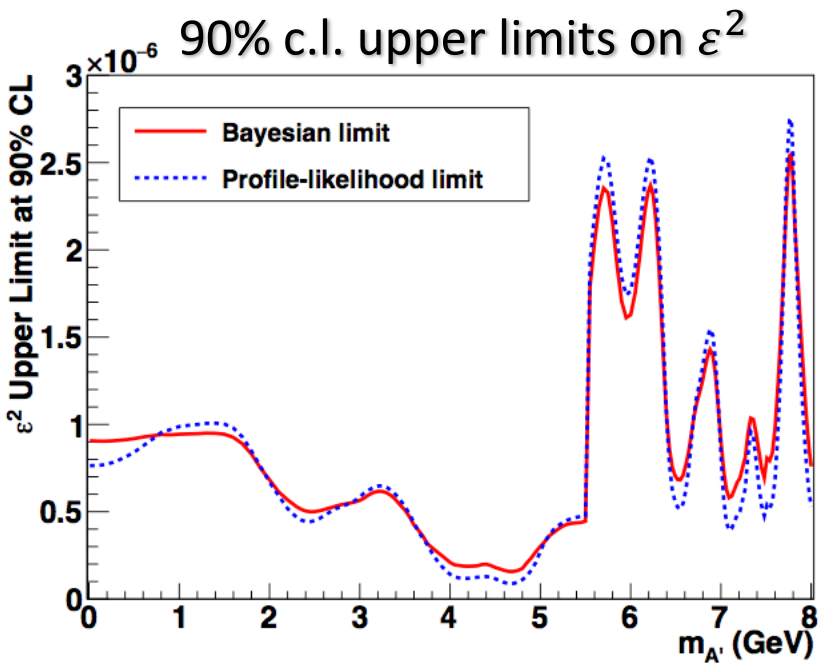
Largest signal fit for $m_{A'} = 6.21$ GeV;
local (global) significance is 3.1 (2.6) σ

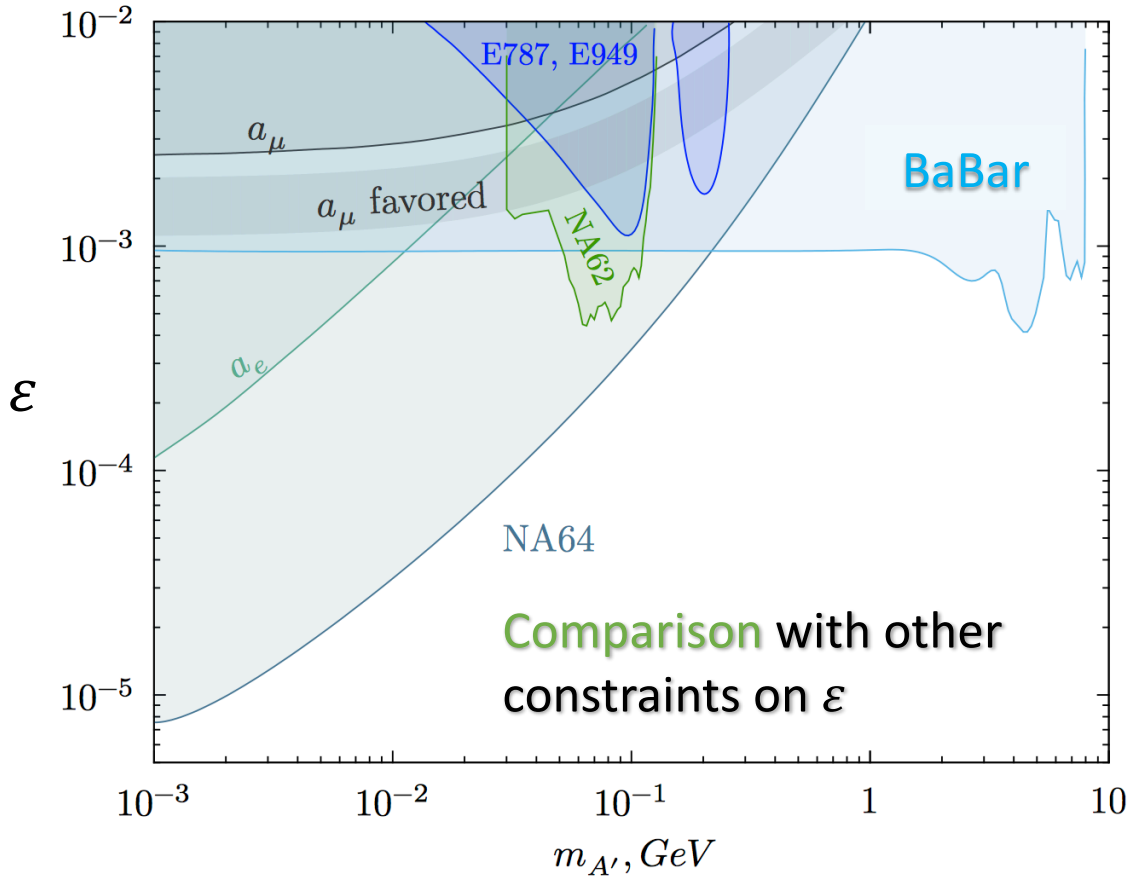


Dark photon search in invisible final states [3]

University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

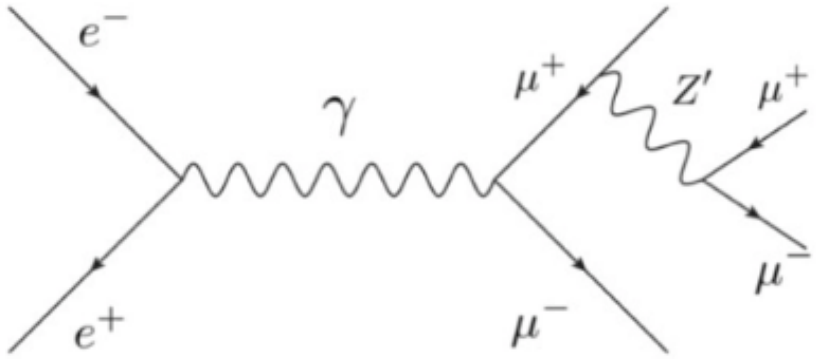
- Signal efficiency is $\sim 2 - 4\%$ and varies slowly with $m_{A'}$
- Systematic uncertainties from PDF shapes, efficiency determination
- Rules out dark photon coupling as explanation for $(g-2)_\mu$ anomaly





Muonic dark force

- Non-minimal model with dark Z' boson that couples only to 2^{nd}- and 3^{rd}-generation leptons [1]
- Could account for $(g-2)_\mu$ discrepancy [2]
- Could increase cosmological sterile neutrino abundance [3]
- Coupling to muons can be searched for in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$ in BaBar data
- Search is sensitive to *any* narrow $\mu^+\mu^-$ resonance



[1] He, Joshi, Lew, Volkas, Phys. Rev. D **43**, 22 (1991); Phys. Rev. D **44**, 2118 (1991)
[2] M. Pospelov, Phys. Rev. D **80**, 095002 (2009)
[3] Shuve and Yavin, Phys. Rev. D **89**, 113004 (2014)

Search for muonic dark force in [1]

University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

- Simple final state – require two pairs of opposite-charge tracks, at least two of which are identified as muons and veto events with $E_{\text{neutral}} > 0.2$ GeV
- Require $m(4\mu)$ to be within 0.5 GeV of CM energy and veto $\Upsilon(nS) \to \mu^+\mu^-$
- Tune analysis on 5% of data; use remaining $514\ \text{fb}^{-1}$ for search
- Consider dimuon reduced mass for all $\mu^+\mu^-$ combinations

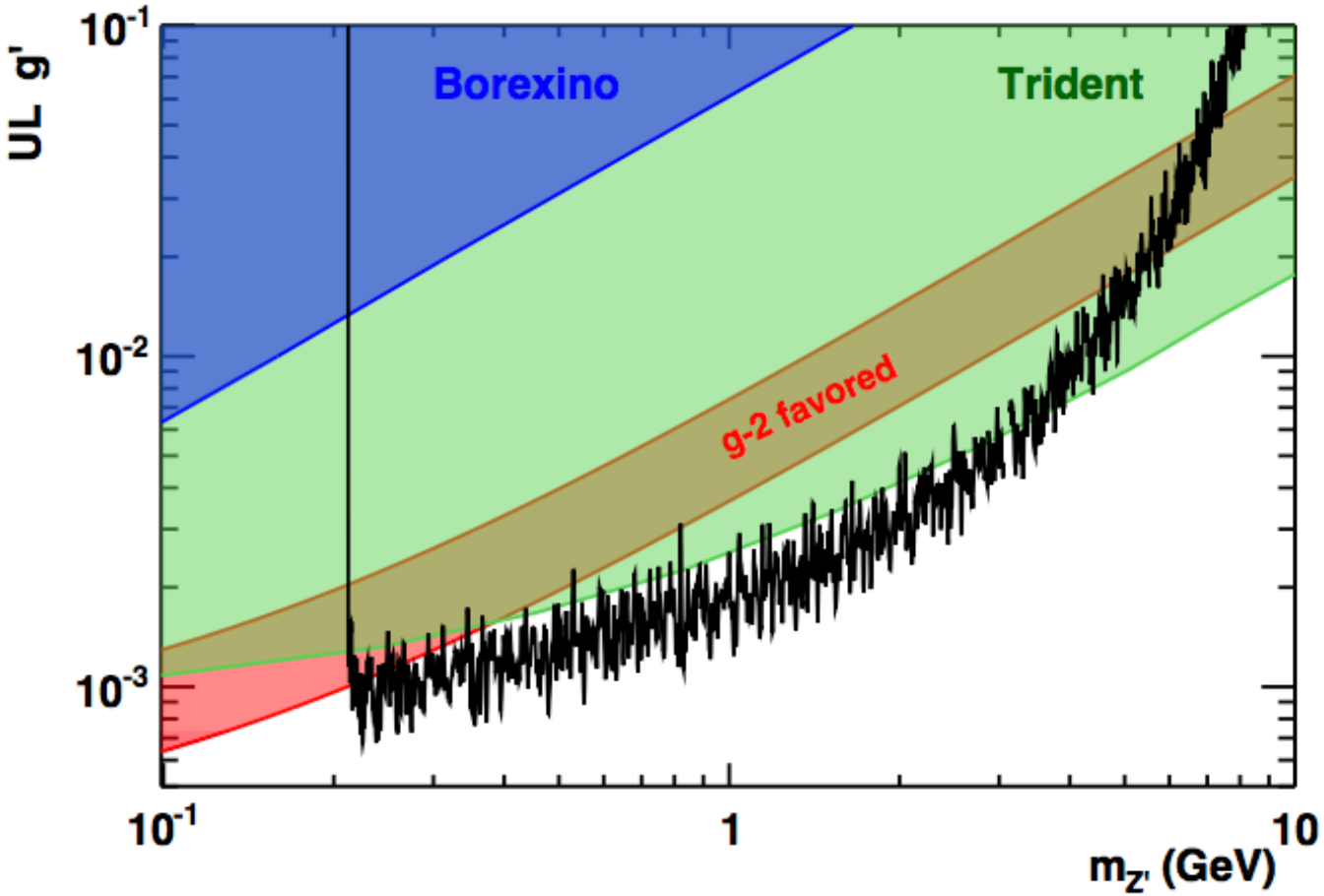
$$m_R \equiv \sqrt{m^2_{\mu^+\mu^-} - 4m^2_{\mu}}$$

- Main background from QED 4-muon production

Search for muonic dark force in [2]

University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

- Fit smooth background plus peak with width set by detector resolution (1-9 MeV) for $m_{Z'}$ values from $2m_\mu$ to 10 GeV
- No significant signal observed
- Efficiency 35-50%, rises with m_R.
- 90% CL Bayesian upper limits set on g' (assuming equal vector coupling of Z' to μ, τ and ν) using flat prior
- Search can be reinterpreted to constrain other new vectors and scalars that couple to muons



Search for stable six-quark state [1]

University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

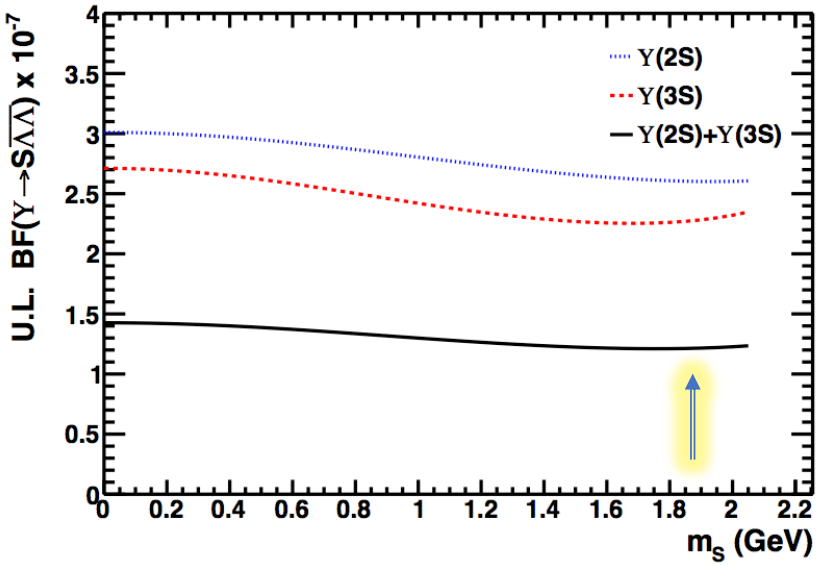
- Stable (uuddss) $J^P = 0^+$ bound state S might be very tightly bound
  → Lifetime exceeds age of universe if $m(S) < m_p + m_e + m_\Lambda = 2054$ MeV [1]
- Such a state might (or might not) have cosmological implications [2]
- Not ruled out by existing searches; LQCD favors larger S mass but is uncertain
- Flavor singlet – does not couple to pions; difficult to distinguish kinematically from a neutron in interactions hard enough to produce it
- Heuristic arguments suggest inclusive $\Upsilon(2S, 3S) \to SX$ BF at the level of 10^{-7}
- Dedicated search performed in $\Upsilon(2S, 3S) \to S\bar{\Lambda}\bar{\Lambda}$ final state ($14, 28$ fb^{-1})

[1] G. R. Farrar, arXiv:1708.08951
[2] Gross, Polosa, Strumia, Urbano, Xue, PRD **98**, 063005 (2018)
Kolb, Turner, arXiv:1809.06003
McDermott, Reddy, Sen, arXiv:1809.06765
G. R. Farrar, arXiv:1805.03723

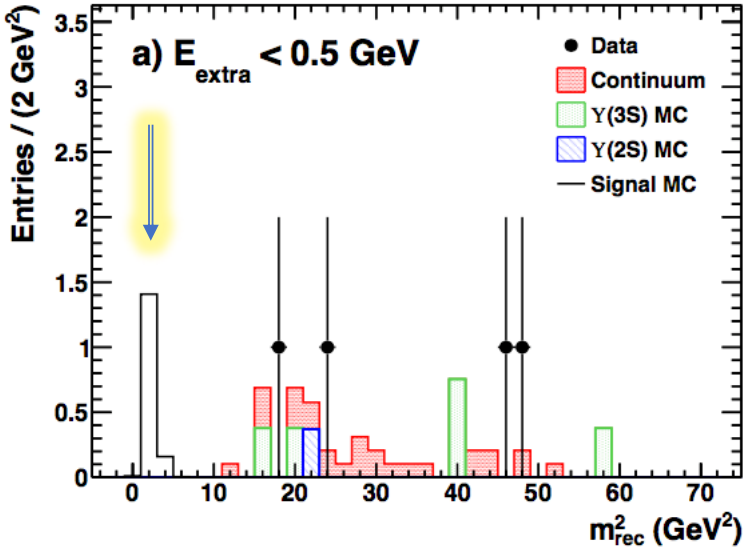
University of Victoria
Victoria Subatomic Physics and Accelerator

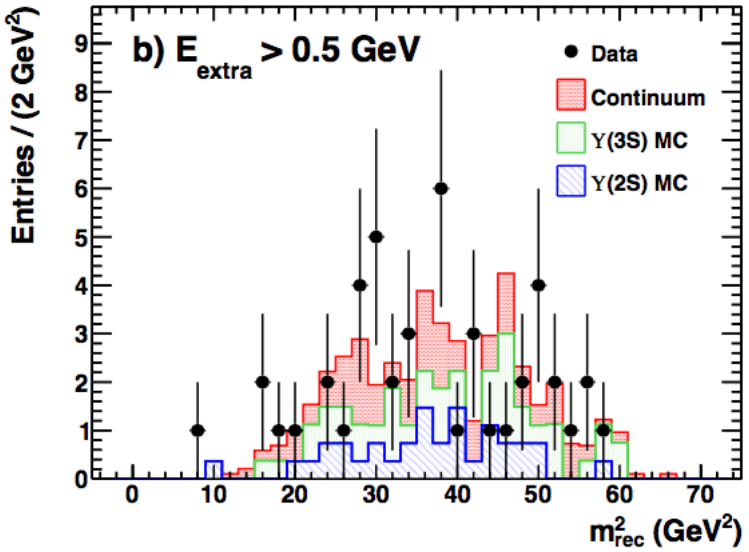
Search for stable six-quark state [2]

- Select two $\Lambda \to p\pi^-$ with identified protons and flight length $> 5\sigma$
- Veto on $E_{\rm extra}$ (excludes cone around S direction)
- Background from events with multiple strange baryons
- Fit determines recoil mass $m^2_{\rm rec}$; search for narrow peak from S
- Efficiency 7.2–8.2% depending on assumed S mass; 8% systematic
- 90% CL upper limit versus $m(S)$ ~1.3×10^{-7}



Stringent bounds on the existence of a stable, doubly strange six-quark state





Summary

University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

- BaBar data continues to provide competitive searches for new physics
- Dark photon portal investigated in invisible $A' \to \chi\bar{\chi}$ decays;
  → leading limits set for $0.05 < m_{A'} < 10$ GeV
- Search for muonic dark force (Z' that couples only to $2^{\mathrm{nd}}/\,3^{\mathrm{rd}}$ generation) over range $2m_\mu < 2m_{Z'} < 10$ GeV;
  → generic limits on coupling g' down to 10^{-3}
- First search for stable, doubly strange (uuddss) six-quark state S in $\Upsilon(2S, 3S)$ decays;
  → upper limit restricts possibilities for such a state

University of Victoria

Victoria Subatomic Physics and Accelerator Research Centre

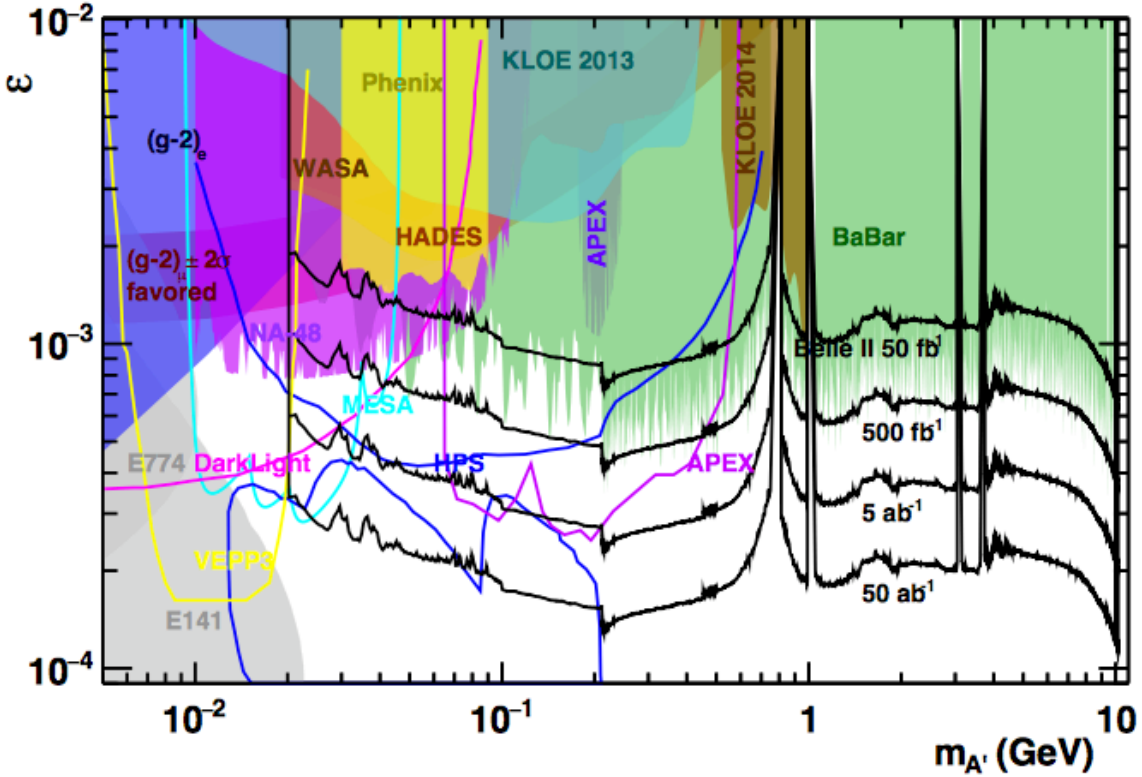
VISPA

Backup

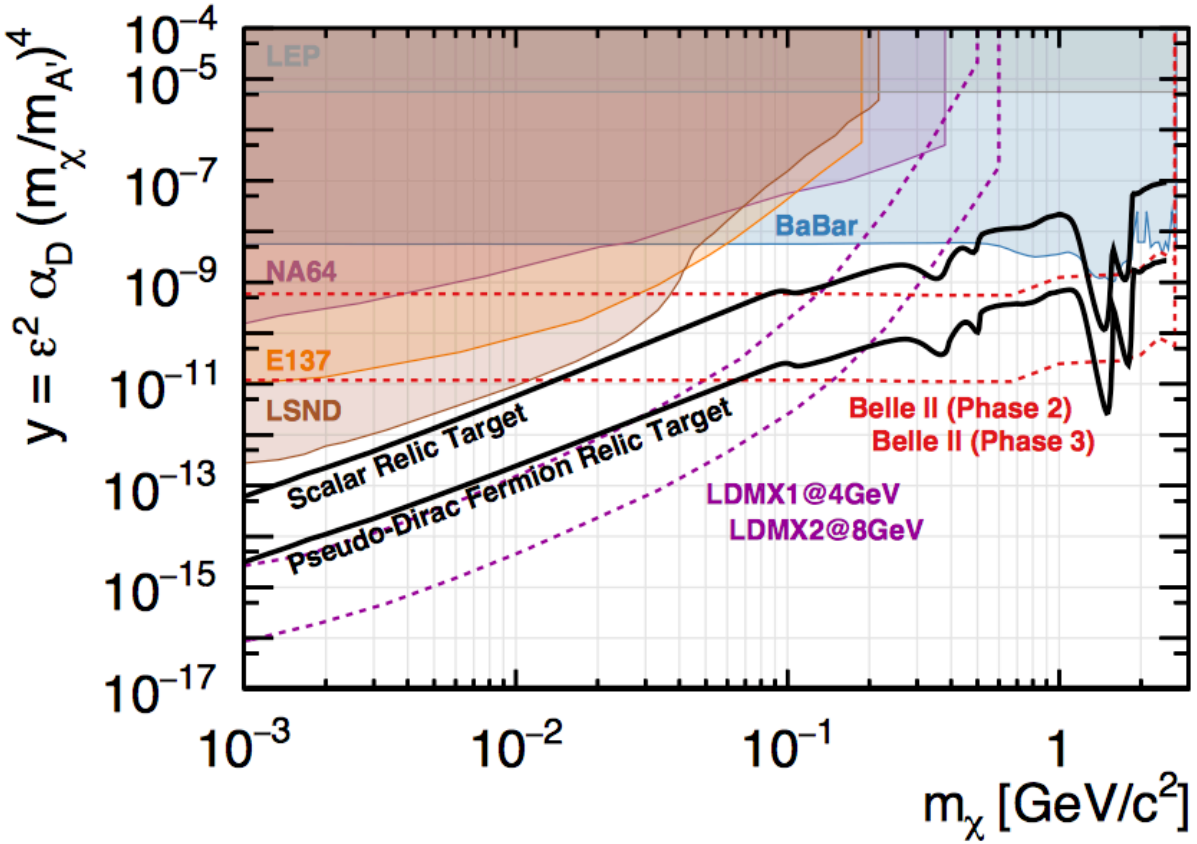
Future dark photon searches

- Future searches at Belle II and beam-dump experiments (from Belle-II physics book, arXiv:1808.10567)

Visible $A' \to \ell^+\ell^-$



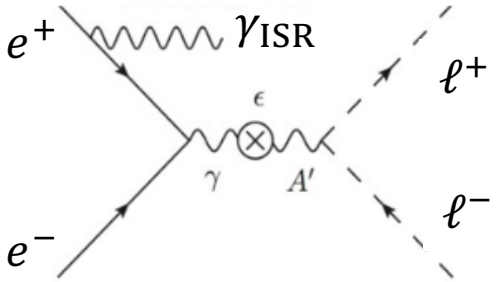
Invisible $A' \to \chi\bar{\chi}$

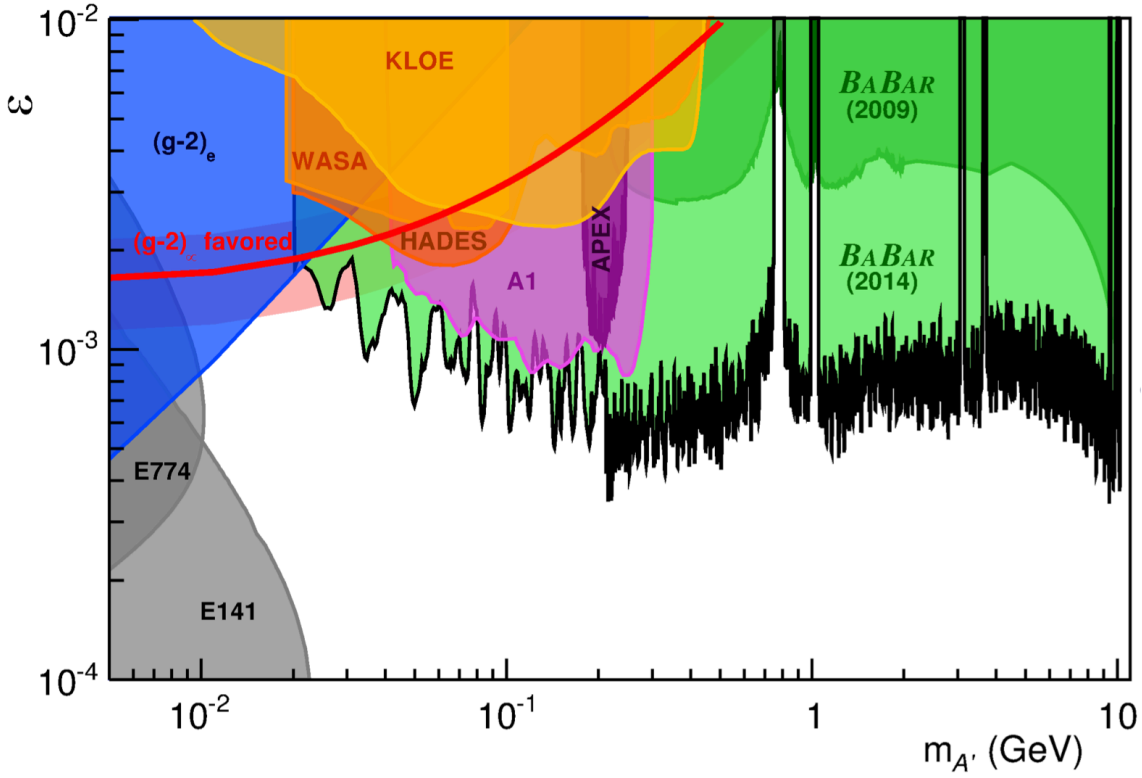


Dark photon search in visible final states

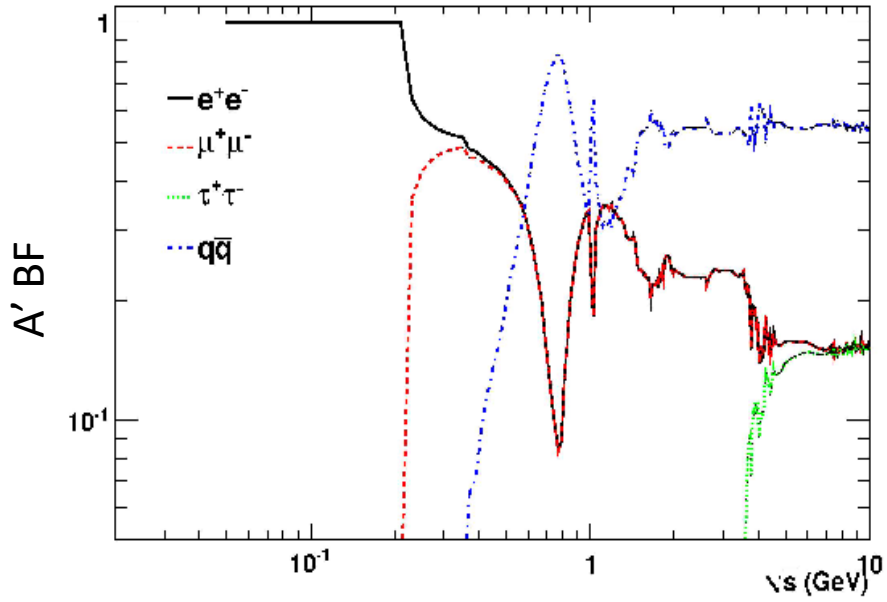
University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

- Look for narrow $A' \to \ell^+\ell^-$ resonances ($\ell = e, \mu$) in $e^+e^- \to \gamma_{\mathrm{ISR}} A'$
- Probes mass range of $20\ \mathrm{MeV} - 10\ \mathrm{GeV}$ with low background
- Bayesian upper limits set on $e^+e^- \to \gamma A'$ cross-section





BFs assume DM states have $m_\chi > m_{A'}/2$

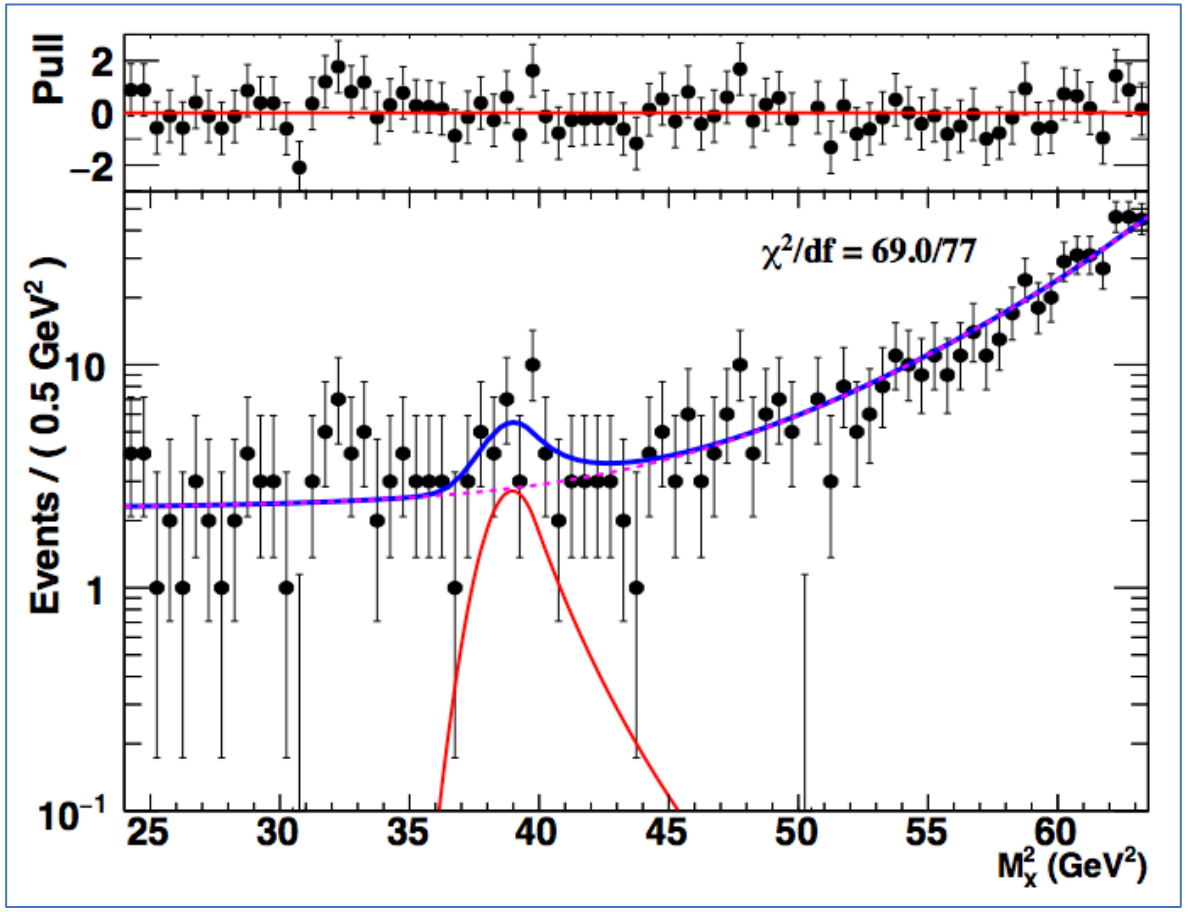


Dark photon search in invisible final states

University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

- Distributions of M_X^2 (from $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$) fitted simultaneously to background and peaking signal
- Background PDF shape determined on large sample of events that fail BDT; background normalization floats in fit to signal distributions
- Signal parameterized by Crystal Ball function; test values of $m_{A'}$ scanned from 0 to 8 GeV in increments of $\approx \sigma_m/2$ (166 steps)

Largest signal fit for $m_{A'} = 6.21$ GeV;
local (global) significance is 3.1 (2.6) σ

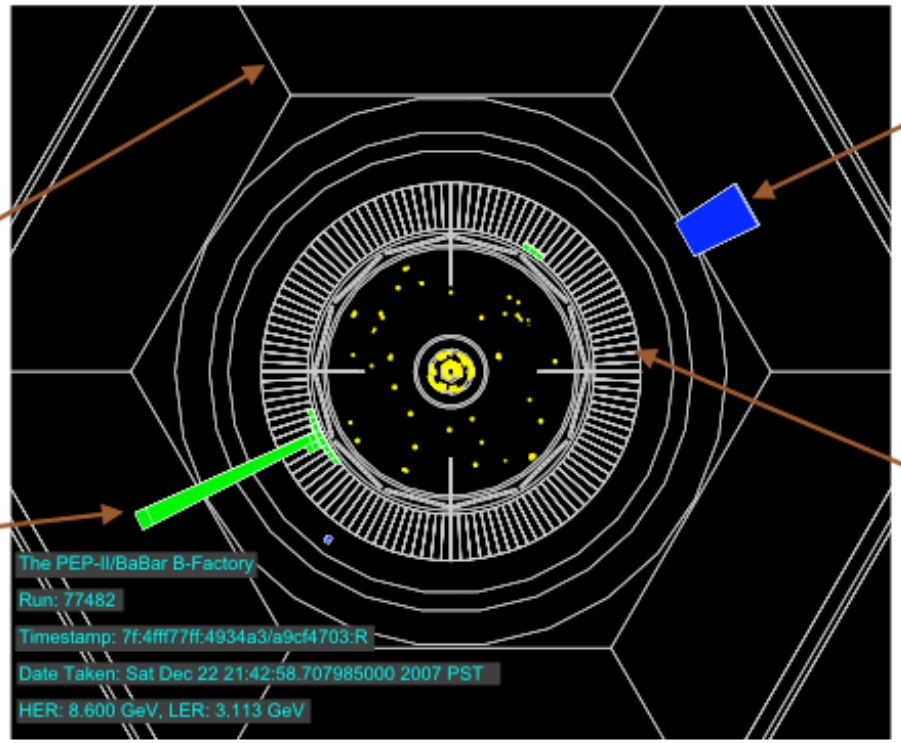


Dark photon search in invisible final states [2]

University of Victoria
Victoria Subatomic Physics and Accelerator Research Centre
VISPA

- Example background event

- $e^+e^- \rightarrow \gamma\gamma$ event



no efficiency in muon system near sector boundaries

beam-energy photon shower

photon shower detected in muon system. Inefficiency produces single photon events.

azimuthal gaps between crystals align with collision point