Exploring dark sectors with low-energy experiments

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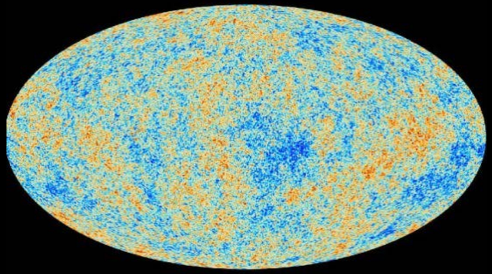
Caltech

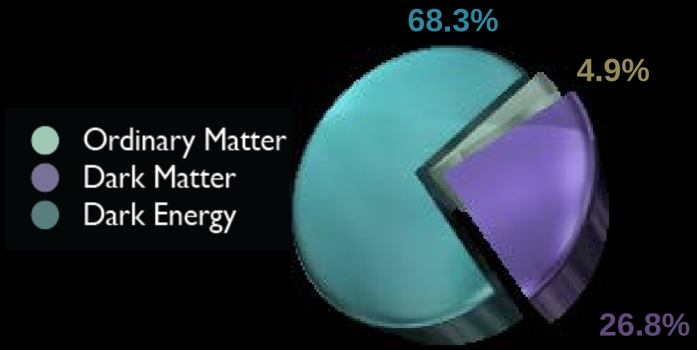
SMU physics seminar
SMU – May 2014

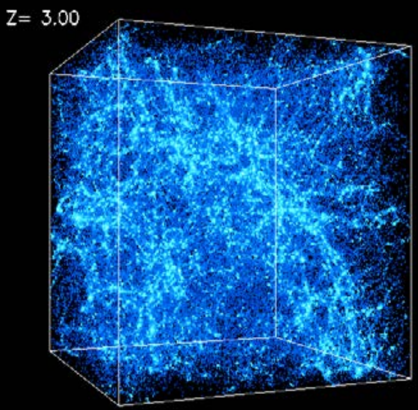
Dark matter

Lensing

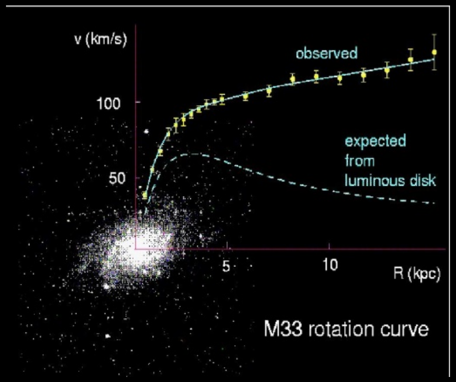
CMB



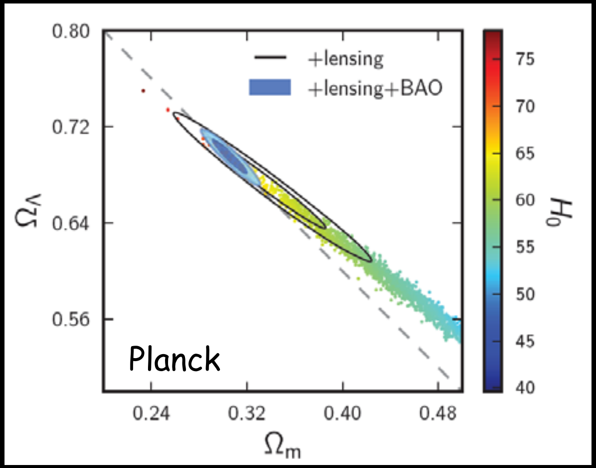




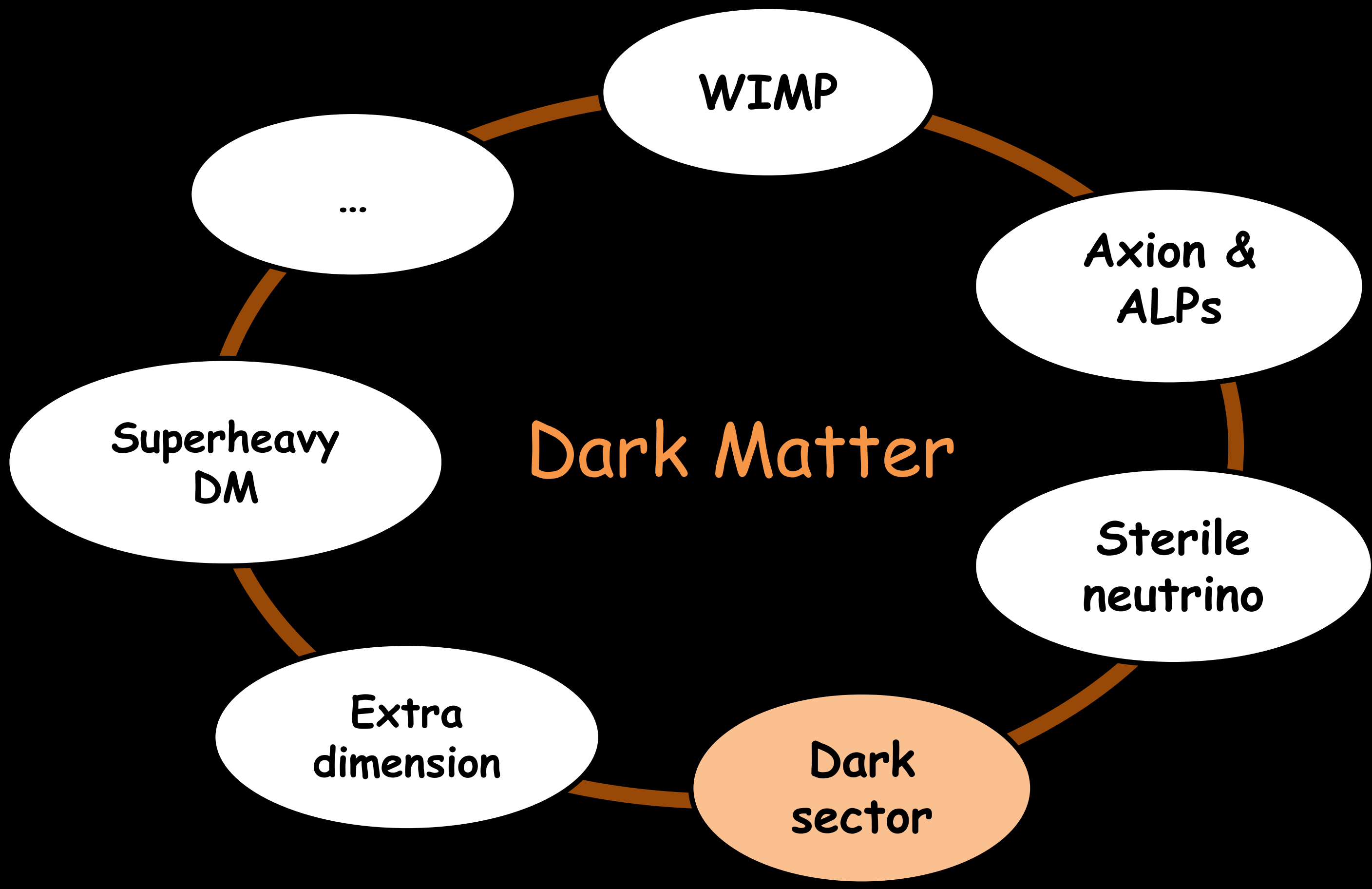
Structure



Rotation curve



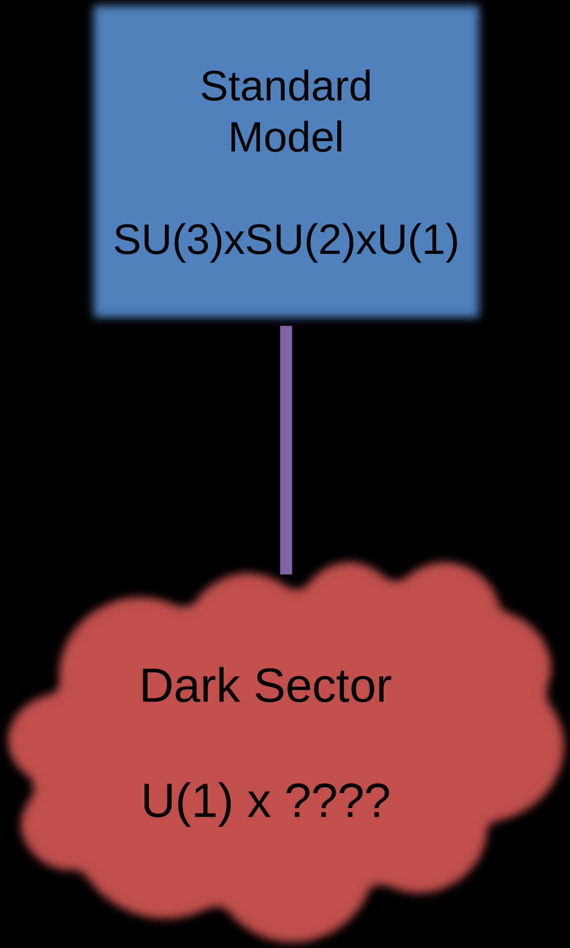
We know dark matter exists, but its nature remains unknown !



Recent results from the LHC and direct detection experiments "challenge" the traditional WIMP paradigm and motivate the exploration of new ideas.

A new possibility – dark sectors

- Recent anomalies observed by satellite and terrestrial experiments have motivated dark matter models introducing a new sector with a 'dark' force.
- Dark sector = new particles that do not couple directly to the SM content, but…
- There are "portals" between the dark sector and the SM.
- Implications for astrophysics, cosmology and particle physics.
- In particular, low-energy colliders and fixed target experiments offer an ideal environment to probe these new ideas.



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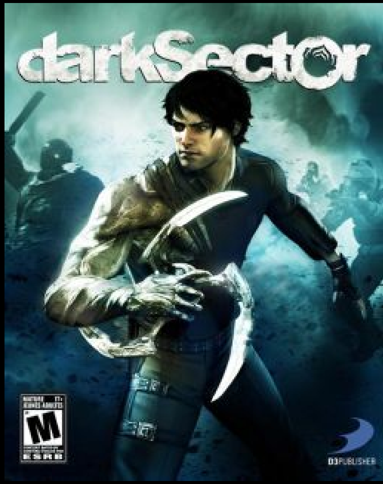
Notation confusion

dark sector
=
hidden sector
=
secluded sector

Tip:
Do not try to google "dark sector" anymore, use hidden sector instead!

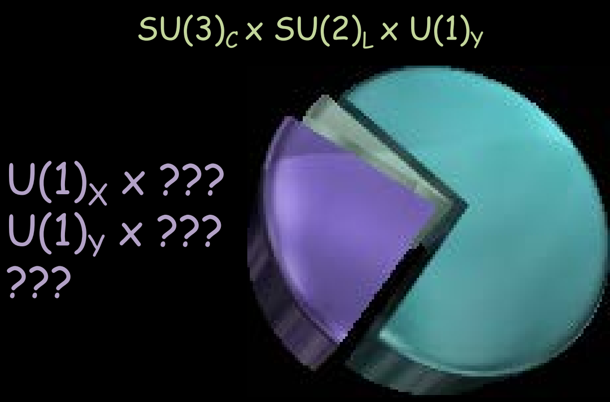


There might be dark sectors

- New sectors that don't couple directly to the Standard Model.
- Theoretically motivated: string theory and many BSM scenarios include dark sectors with extra U(1).
- Holdum's question ('86) : are there additional U(1)? (PLB 166 (1986) 196)
- Dark photons (A') are the corresponding U(1) gauge bosons, mediating this dark force.

Dark matter could be part of a dark sector

- Dark matter and other new particles may reside in dark sectors.
- Could have a very rich structure.

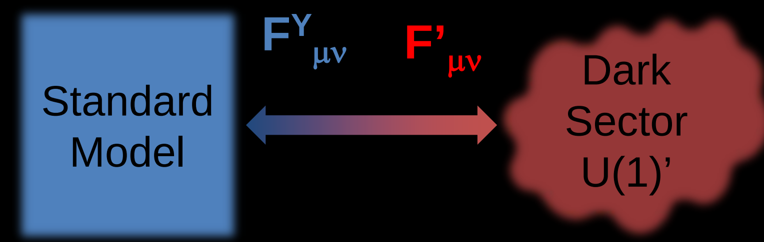


How could we detect them?

- Interaction between dark sector and SM occurs through high-dimension operator, often referred to as "portals". At low-energy, the "vector portal" is dominant.

Dark sector and vector portal

- Dark sector with a new U(1)'
- Interaction dark sector - SM via kinetic mixing between the hypercharge and U(1)' fields with a mixing strength ε_Y



$$\Delta\mathcal{L} = \frac{\varepsilon_Y}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

Holdom, Galison, Manohar

Dark sector and vector portal

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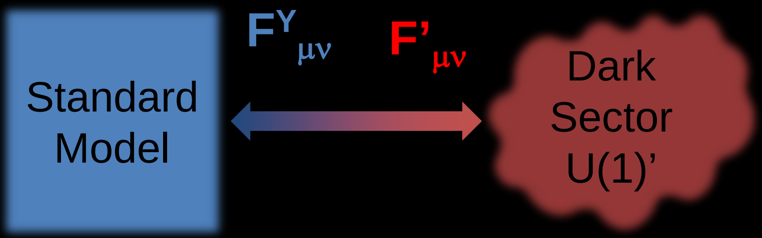
- Interaction dark sector - SM via kinetic mixing between the hypercharge and U(1)' fields with a mixing strength ε_Y
- After EWSB, there is a coupling ε between the dark photon and the photon (also the Z, less important at low energies).
- In other words, there is a dark photon – SM fermion coupling $\alpha' = \varepsilon^2\alpha$.

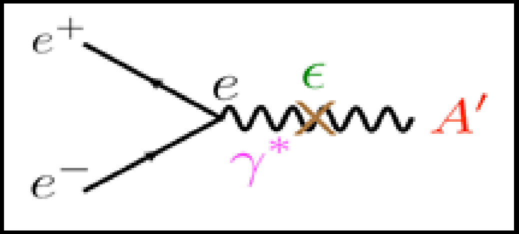


$$\Delta\mathcal{L} = \frac{\varepsilon_Y}{2} F^{Y,\mu\upsilon} F'_{\mu\upsilon}$$

$\downarrow$ EWSB

$$\Delta\mathcal{L} = \frac{\varepsilon}{2} F^{EM,\mu\upsilon} F'_{\mu\upsilon} \quad (+Z)$$

$$\varepsilon = \varepsilon_Y \cos\theta_w$$



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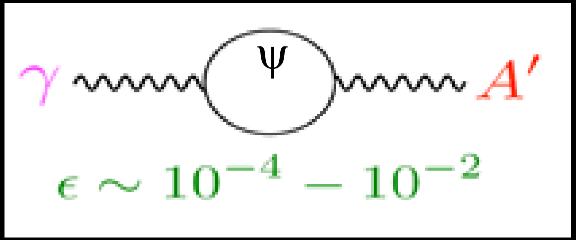
- In other words, there is a dark photon – SM fermion coupling $\alpha' = \varepsilon^2 \alpha$.
- Mixing can be generated by perturbative effect, strength typically $\varepsilon \sim 10^{-5} - 10^{-2}$, but could be smaller.
- Theoretical prejudice for a mass scale
  $m_{A'} \sim \sqrt{\varepsilon}\, m_{EW} \sim$ MeV – GeV,

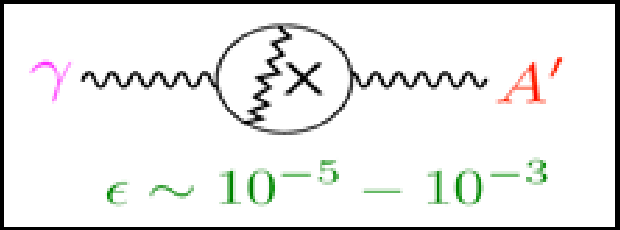
Any evidence for such a scenario?

Mixing can be generated by perturbative effect, e.g.

heavy particle ψ with both dark and EM charges.



GUT (2 loops)

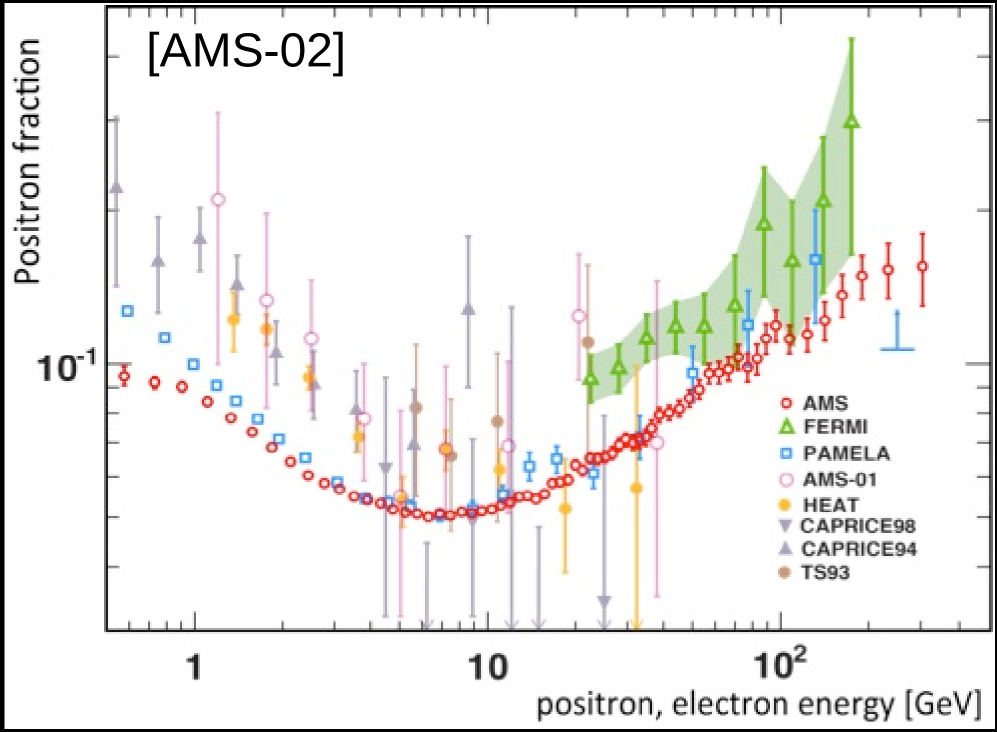


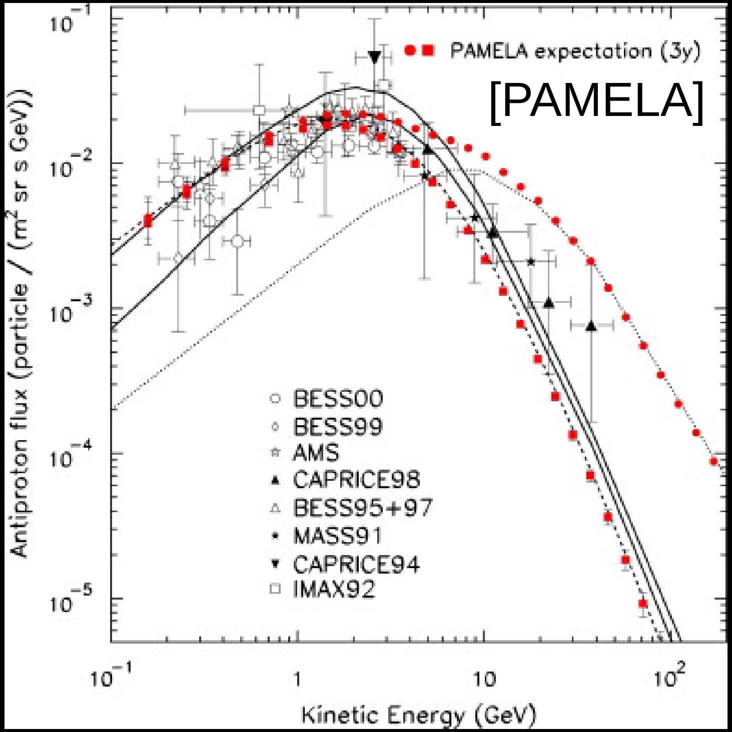
($\rightarrow 10^{-7}$ if both U(1)'s are in unified groups)

e.g. Arkani-Hamed & Weiner;
Cheung, Ruderman, Wang, Yavin;
Morrissey, Poland, Zurek;
Essig, Schuster, Toro;

Astrophysical hints

Excess of electrons/positrons in the cosmic rays, first seen by Pamela, confirmed by Fermi & AMS-02.

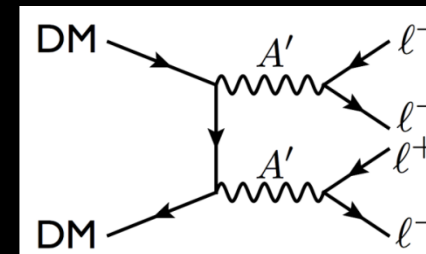




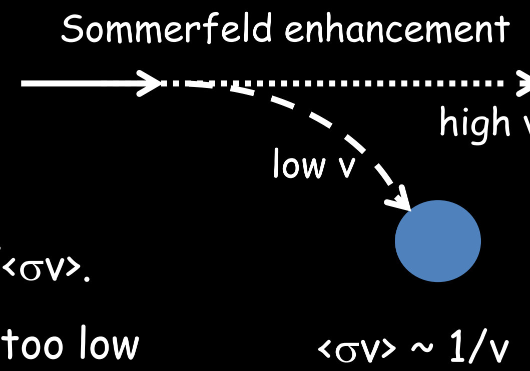
No comparable enhancement of antiprotons!

A light dark sector model

Wimp-like TeV-scale dark matter particles annihilate into light dark photons (10 MeV – few GeV range), which subsequently decay to electrons/positrons (Arkani-Hamed et al., Pospelov & Ritz):



- Large branching fraction to leptons
- Protons kinematically suppressed
- Hard energy spectrum
- Correct relic abundance with Sommerfeld enhancement

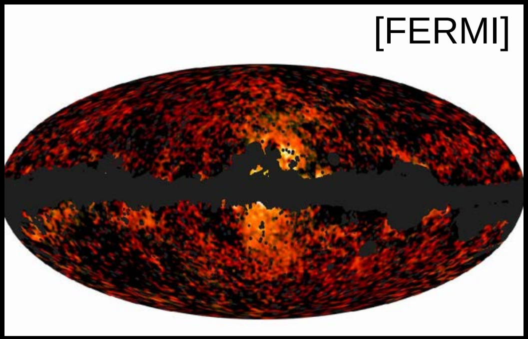


  - Relic abundance depends on annihilation rate $\Omega_{DM} \sim 1/\langle\sigma v\rangle$.
  - Annihilation rate derived from cosmic flux gives Ω_{DM} too low by a factor 100-1000 ("boost" factors invoked to solve this problem for many models).
  - Cross-section is enhanced at low velocities for light A′, boosting Ω_{DM} to observed values.

Such a model could also explain several other anomalies

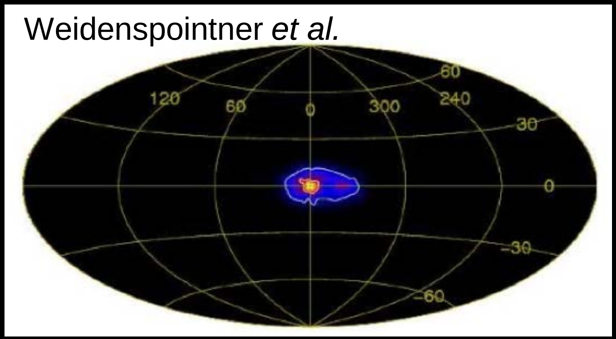
Recent anomalies

WMAP / Fermi haze



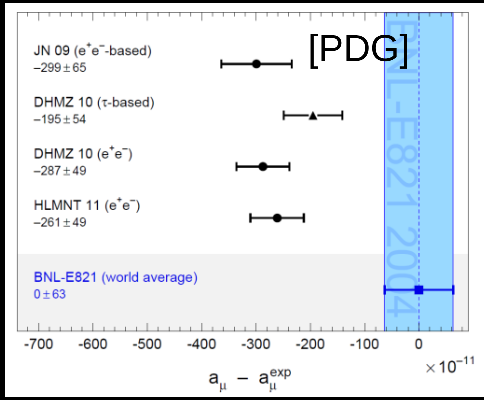
[Finkbeiner Dobler et al.,]

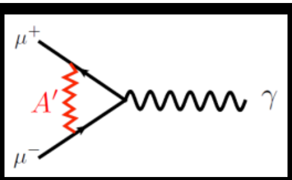
Integral 511 keV line



[Finkbeiner & Weiner]

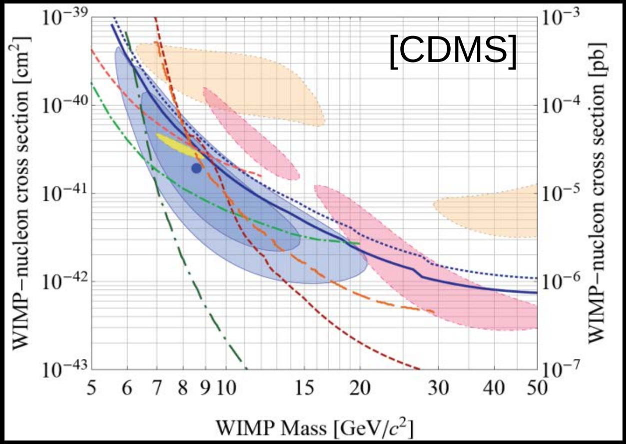
Anomalous muon g-2



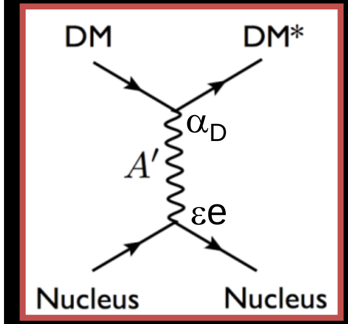


[Pospelov]

Direct detection anomalies



CDMS, arXiv:1304.4279



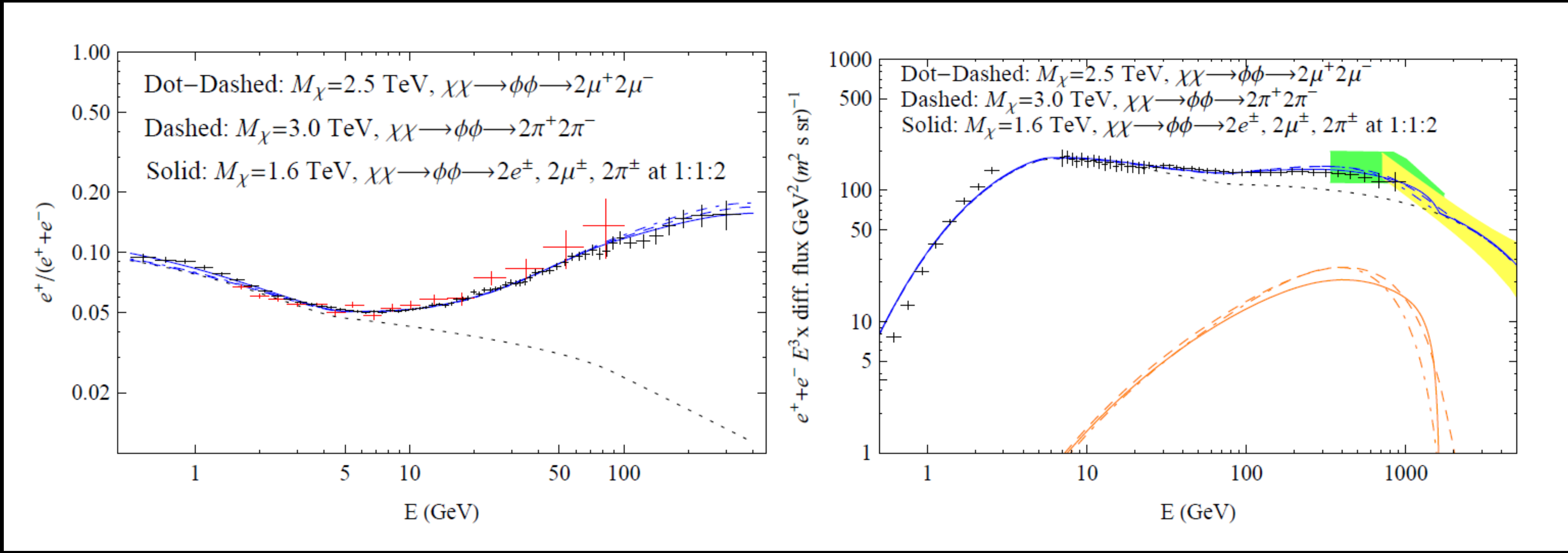
[Slatyer, Schuster&Toro,...]

And several others....

Would require another seminar to discuss them all...

Latest astrophysical fits

Cholis & Hooper , arXiv:1304.1840

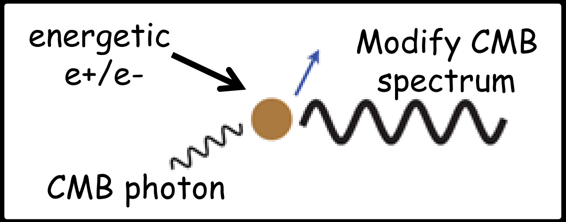


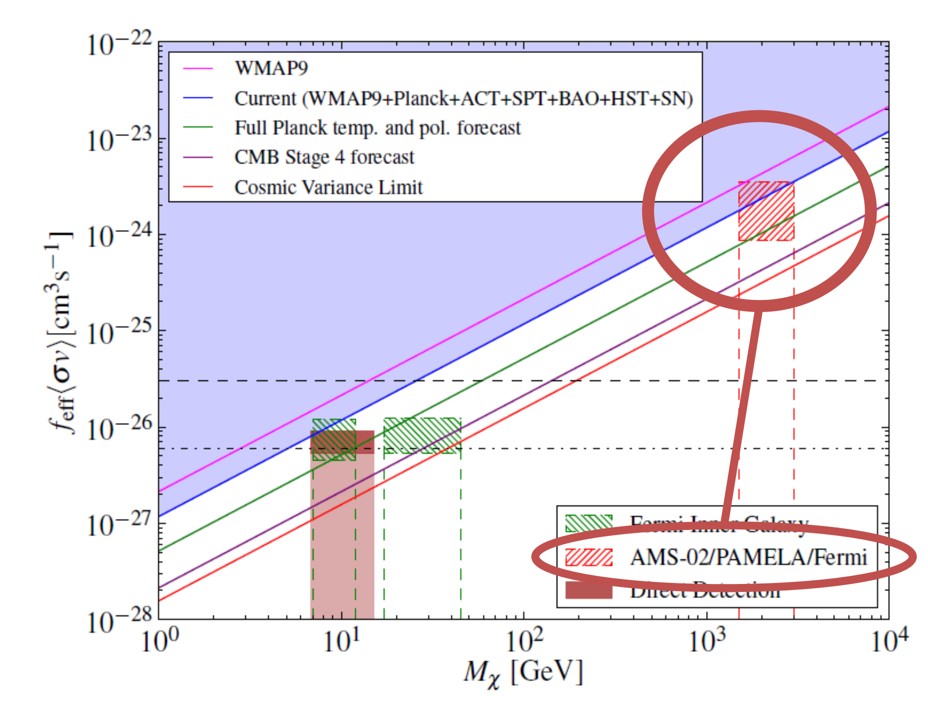
Fits to the cosmic ray spectra prefer few TeV dark matter particles and A' mass above the muon decay threshold, but there are still many uncertainties!

Cosmological constraints – clouds on the horizon ?

If DM annihilation into light dark photons is the source of e-/e+ excess, other astrophysical phenomena should be observable (e.g. diffuse gamma ray emission, CMB).

In particular, primordial DM annihilation injects energy in the CMB → distorts spectrum





Madhavacheril, Sehgal and Slatyer, arXiv:1310.3815

CMB spectrum

- Powerful constraints, start probing dark photon models
- Planck polarization data and additional AMS-02 data may provide an answer
- Model uncertainties are not negligible and could weaken constraints!

This is actively debated !!!

At this point…

New theory of dark matter based on dark sector(s)

- Light new mediator (dark photon A') with a MeV – GeV mass
- Mixing between dark sector – SM with $\varepsilon \sim 10^{-5} - 10^{-2}$ (could be smaller)
- Could have a rich structure

Anomalies from astrophysical data, direct detection and precision measurements

- Could be explained by dark sector
- Could have another origin, be statistical fluctuations or instrumental effects
- Dark matter could be composite with a dark sector sub-component
- …

But it made us realize the amazing possibilities at the GeV-scale, and the possibilities to probe them in laboratory at low energy!

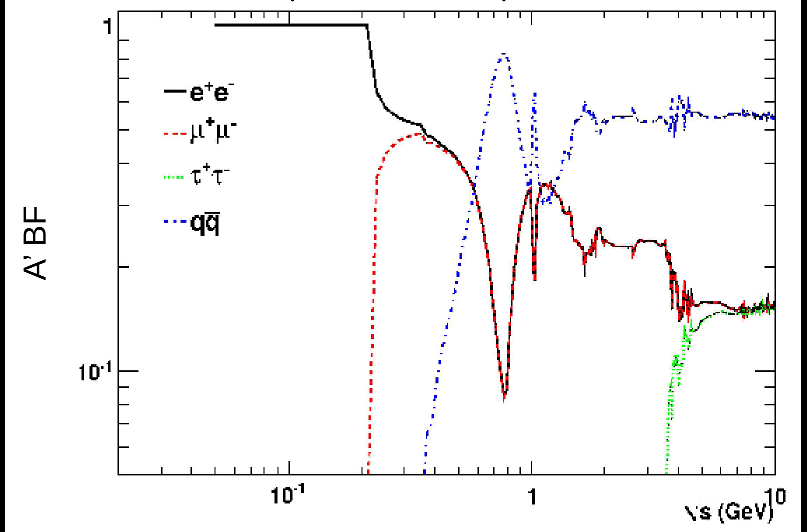
Probing dark sectors

at low-energy (and high-energy) colliders

Particle physics experiments

- Can produce dark photons. In fact, photons in any process can be replaced by dark photons (with an extra factor of ε).
- Decays back to lepton/quark pairs → search for resonances

Dark photon decay channels



Lepton contribution dominates at low masses, and is still ~30% at high masses!
(binning too large to show narrow resonances)

Particle physics experiments

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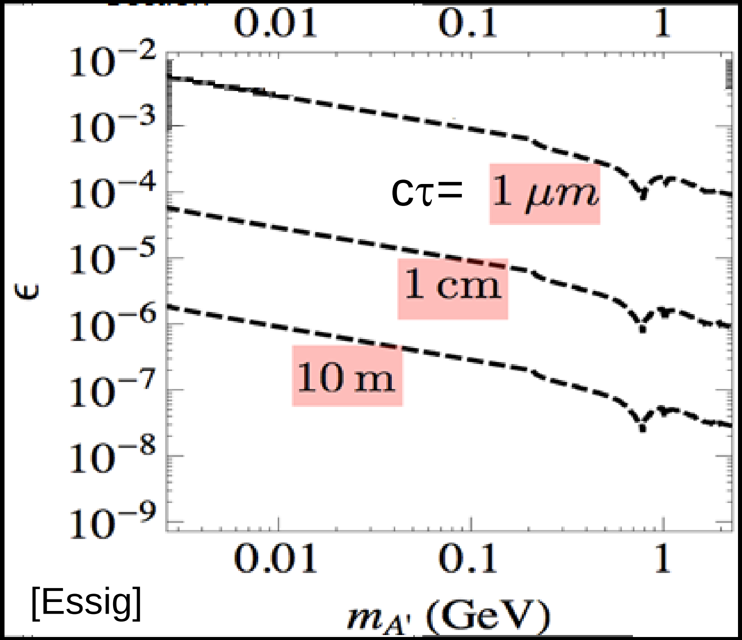
- Dark photon width is small (~ mε) and could be short or long-lived → prompt or displaced decay vertex



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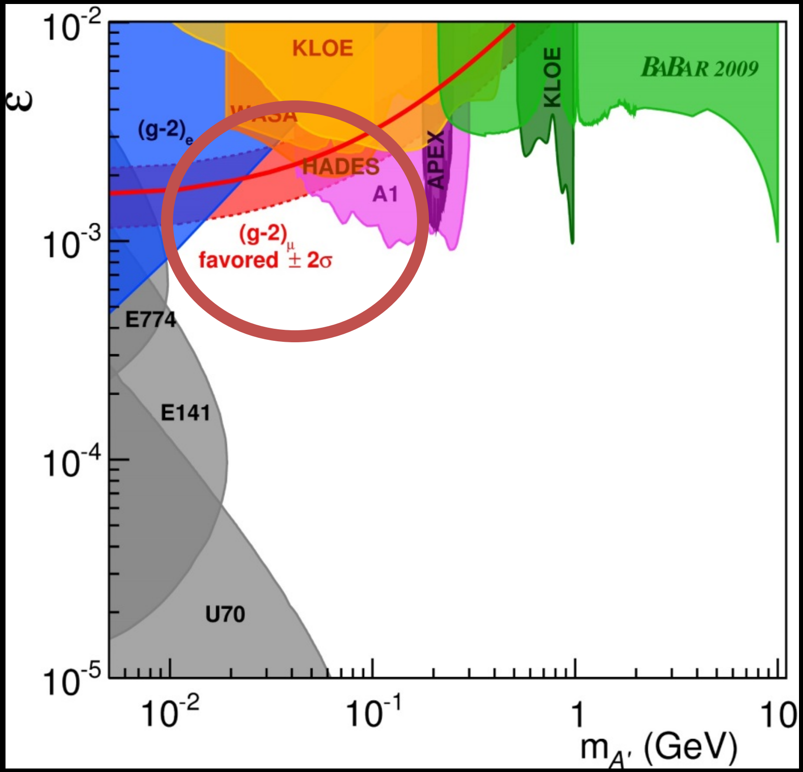
- Decays back to lepton/quark pairs → search for resonances
- Dark photon width is small (~ $m\varepsilon$) and could be short or long-lived → prompt or displaced decay vertex
- Current bounds on the mixing parameter ε are shown as a function of the dark photon mass.
- Constraints from electron/muon g-2, beam dump and fixed target experiments and e^+e^- colliders (some constraints reinterpreted from limits of other measurements by theorists, e.g. BABAR)

Constraints on ε vs. $m_{A'}$

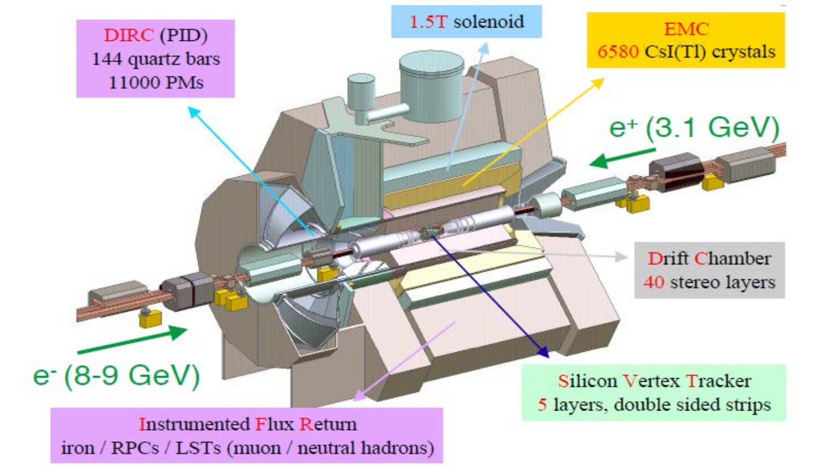


Pospelov;
Bjorken, Essig, Schuster, Toro
Andreas, Niebuhr, Ringwald
Batell, Pospelov, Ritz;
Essig, Harnik, Kaplan, Toro
Blumlein, Brunner;
Dent, Ferrer, Krauss
Essig Schuster, Toro, Wojtsekhowski
KLOE, APEX, MAMI/A1 Collab.
Davoudiasl, Lee, Marciano;
Endo, Hamaguchi, Mishima

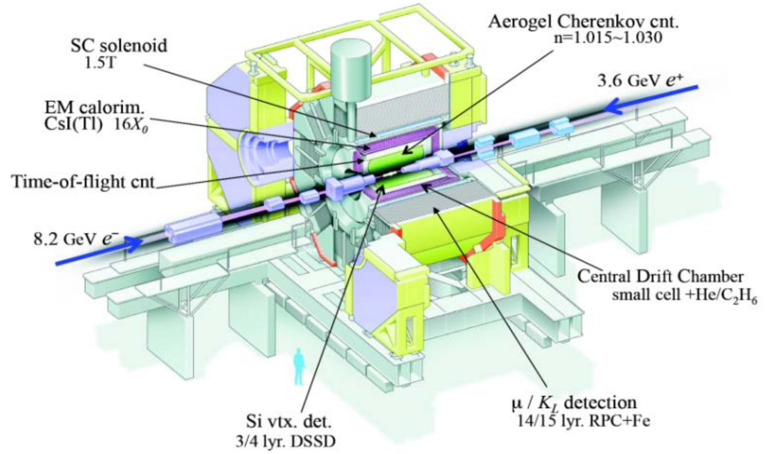
Low-energy high-luminosity e^+e^- colliders offer a low-background environment to search for MeV/GeV-scale hidden sector (in particular high masses) and probe their structure

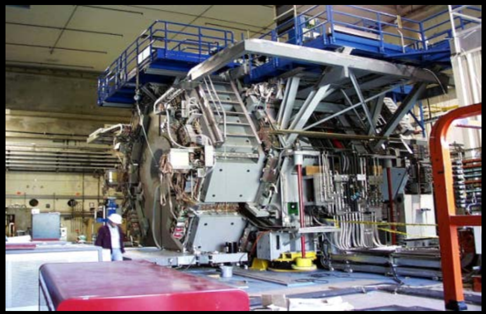
***BABAR* / Belle collected around 500/1000 fb^{-1} of data around the Υ(4S) resonance**

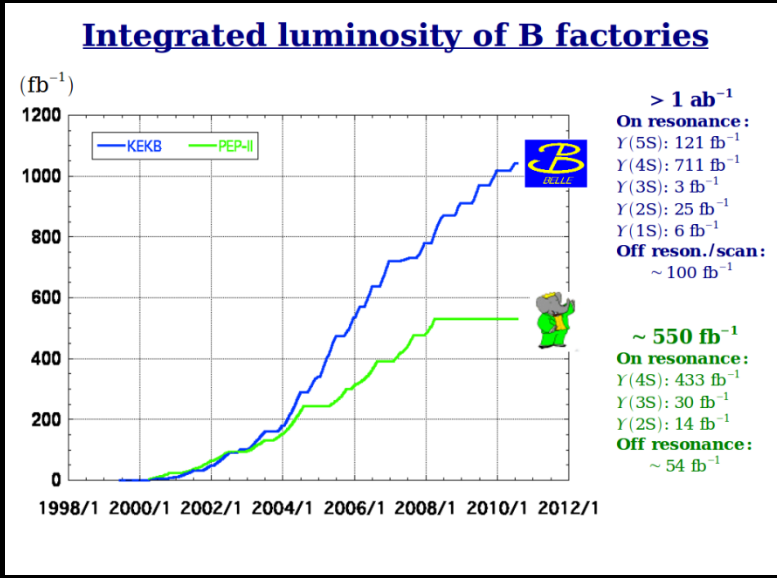
BABAR detector



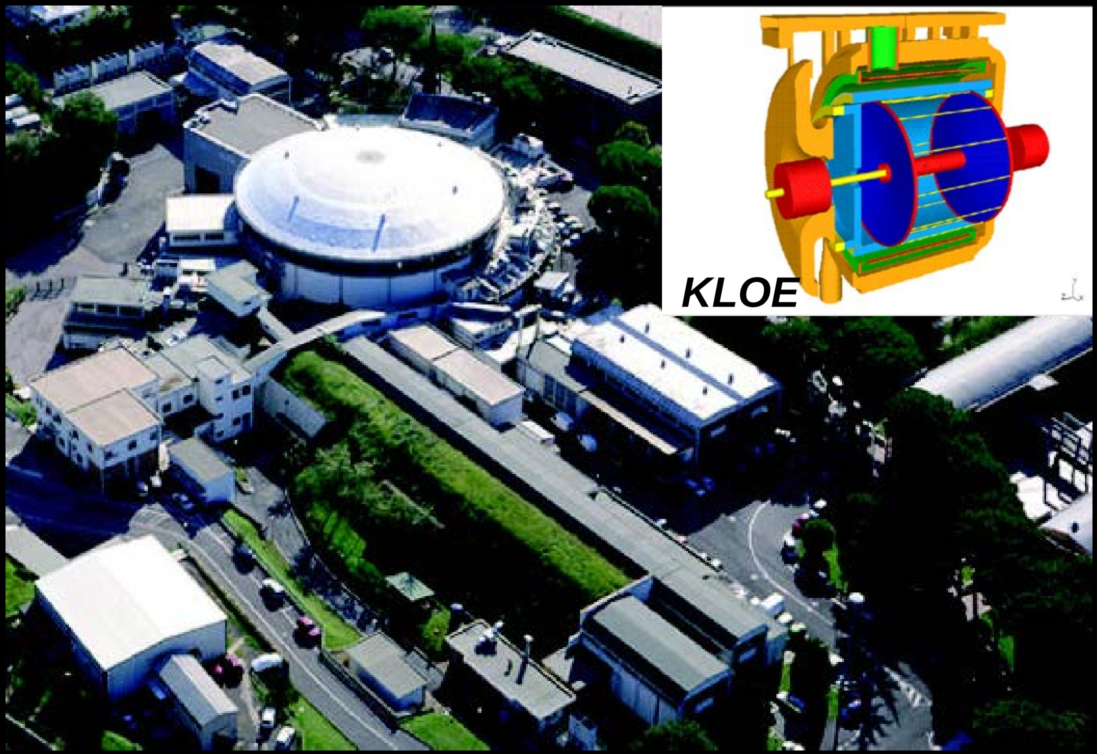
Belle detector

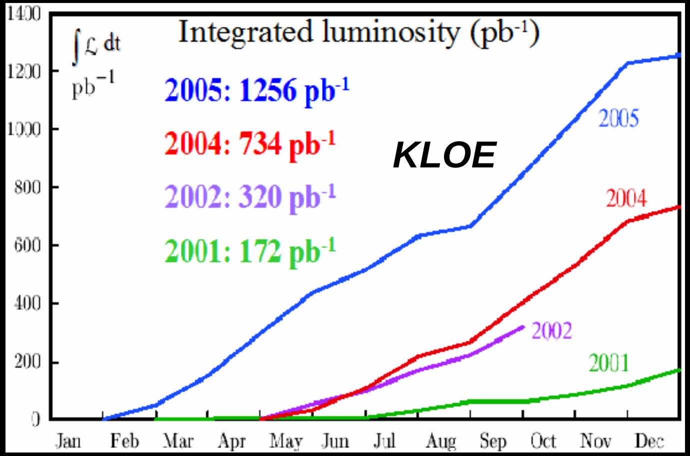






KLOE collected around 2.5 fb^{-1} of data around the ϕ resonance





Cross-section for dark photon production σ~1/s, partially compensating the lower luminosity (still an advantage for B-factories)

Possible dark sector searches at e^+e^- colliders

Search for dark photon

$e^+e^- \to \gamma A'$, $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$
$e^+e^- \to \gamma A'$, $A' \to$ invisible

Search for dark photon in meson decays

$\pi^0 \to \gamma\, l^+l^-$, $\eta \to \gamma\, l^+l^-$, $\phi \to \eta\, l^+l^-$,...

Search for dark Higgs boson

$e^+e^- \to h' A'$, $h' \to A' A'$
$e^+e^- \to h' A'$, $h' \to$ invisible

Search for dark boson(s)

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

Search for dark hadrons

$e^+e^- \to \pi_D + X$, $\pi_D \to e^+e^-, \mu^+\mu^-$

Search for dark scalar (s) and dark pseudoscalar (a)

$B \to K^{(*)}s \to K^{(*)}\, l^+l^-$
$B \to K^{(*)}a \to K^{(*)}\, l^+l^-$
$B \to ss \to 2(l^+l^-)$
$B \to K\, 2(l^+l^-)$
$B \to 4(l^+l^-)$

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$B \rightarrow K^{(*)}a \rightarrow K^{(*)}\, l^+l^-$
$B \rightarrow ss \rightarrow 2(l^+l^-)$
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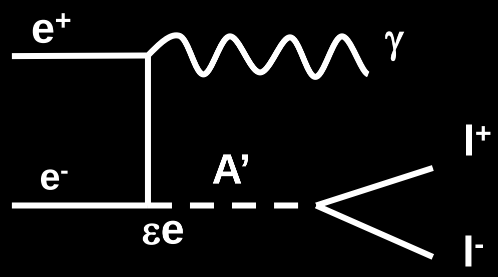
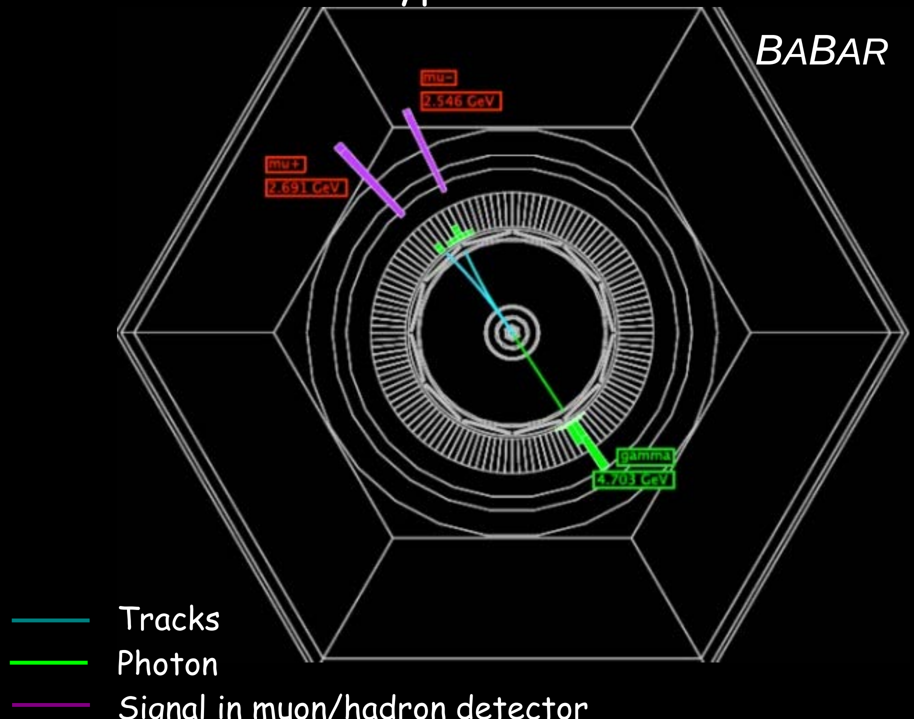
$B \rightarrow 4(l^+l^-)$

A dark photon can be produced in

$e^+e^- \rightarrow \gamma A', A' \rightarrow e^+e^-, \mu^+\mu^-$



Typical event



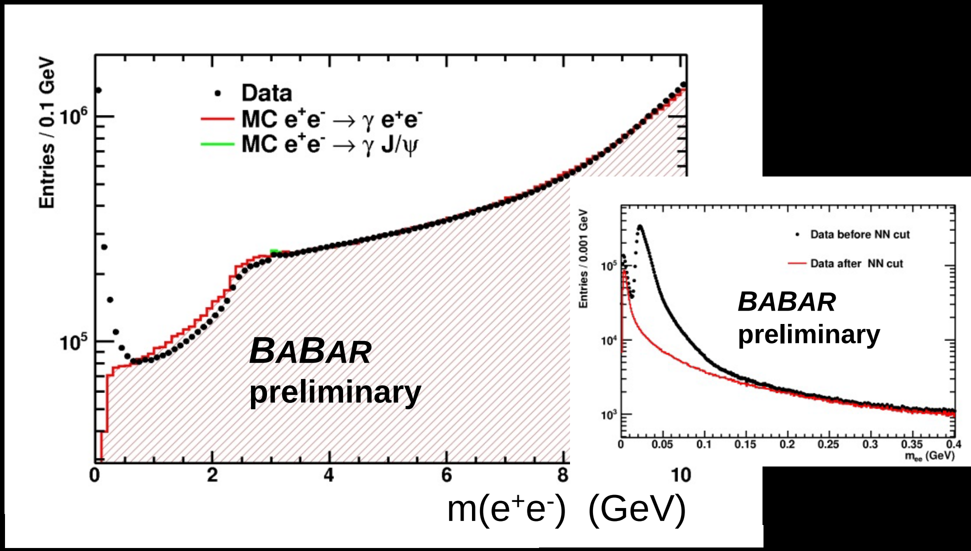
Event selection

- 2 tracks + 1 photon
- Constrained fit to the beam energy and beam spot
- Particle identification (e/mu)
- Kinematic cuts to improve purity
- Quality cuts on tracks and photons

Direct dark photon production

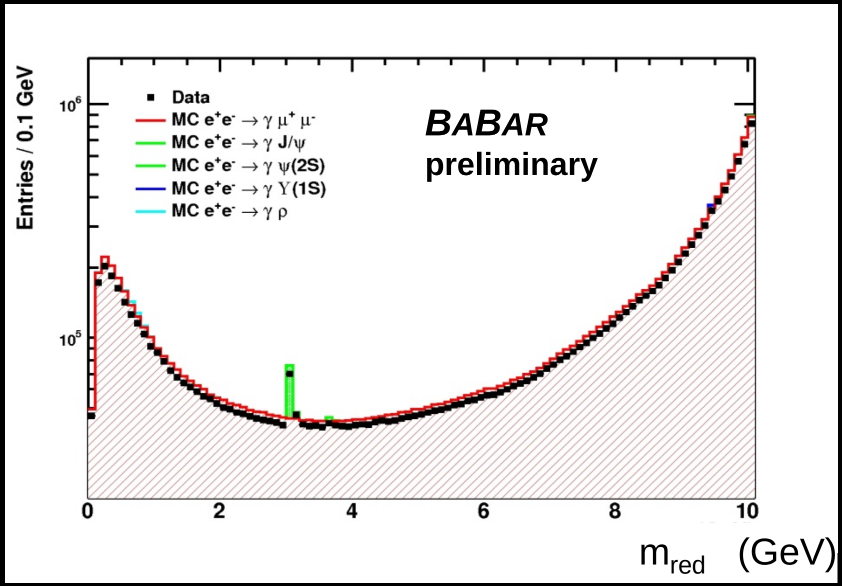
Di-electron mass spectrum

- Globally well reproduced by BHWIDE above 1 GeV, cut-off in the MC (co-linear tracks) affects low mass region. Madgraph reproduces well the low mass region.
- Background from photon conversions suppressed by neural network



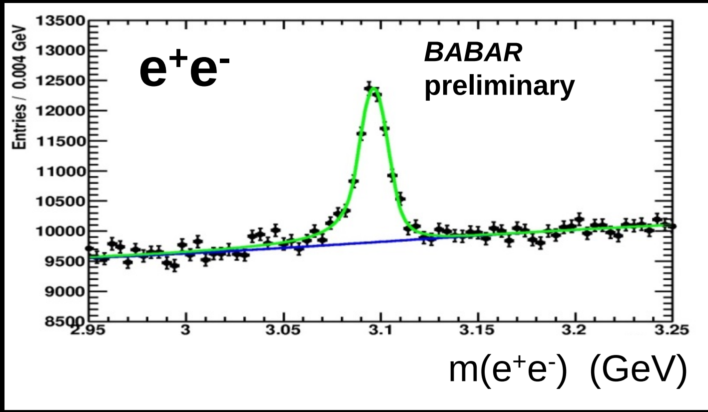
Di-muon mass spectrum

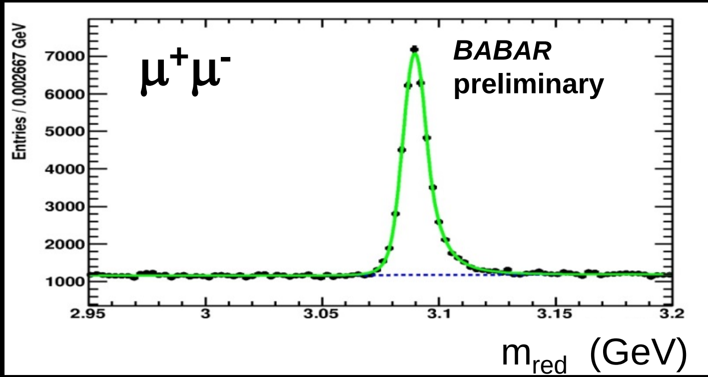
- Plot the reduced mass (smoother near threshold): $m_{red} = (m_{\mu\mu}^2 - 4\, m_\mu^2)^{1/2}$
- Globally well reproduced by KK2F, correct for differences in efficiencies

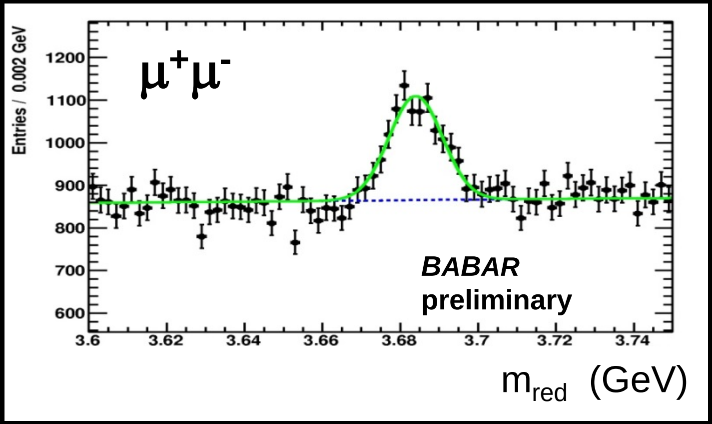


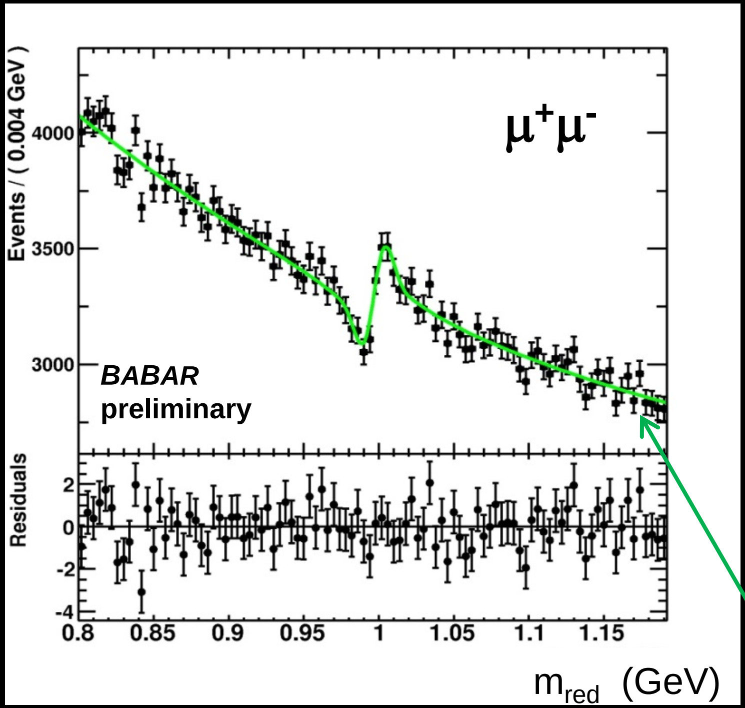
Good data-MC agreement at the J/ψ, $\Psi(2S)$, $\Upsilon(1S)$ resonances

Resonance / interference with continuum









$$f(x) = (a + bx + cx^2 + dx^3)\left|1 - Q\frac{m\Gamma}{s - m^2 - im\Gamma}\right|^2$$

Exclude resonant region

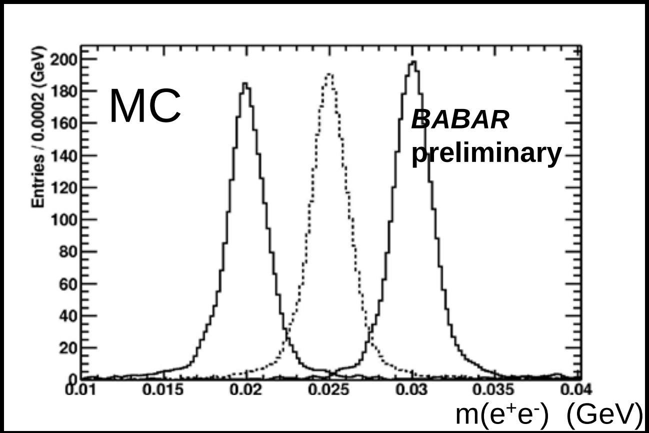
± 30 MeV around ω/ϕ

± 50 MeV around J/ψ, $\Psi(2S)$, $\Upsilon(1S,2S)$

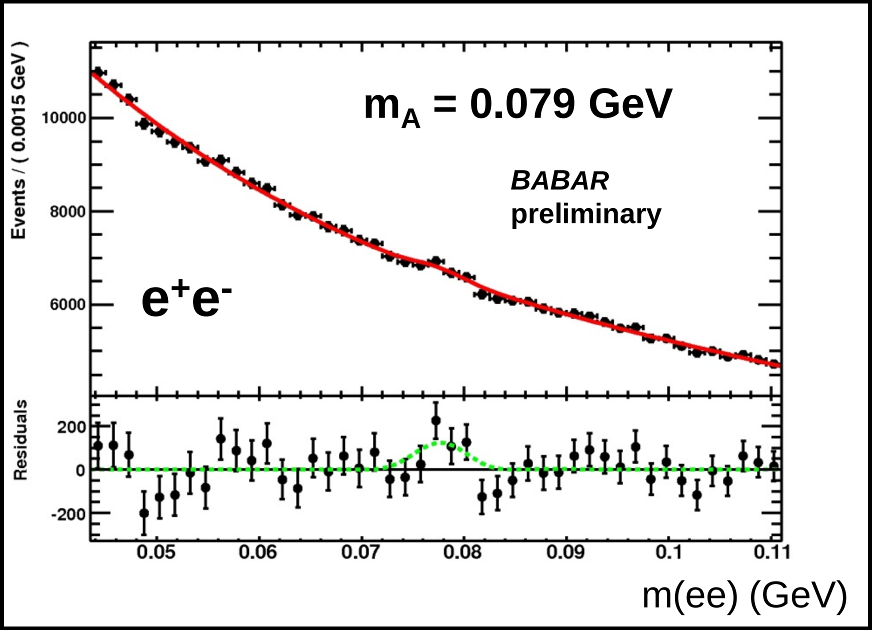
Direct dark photon production

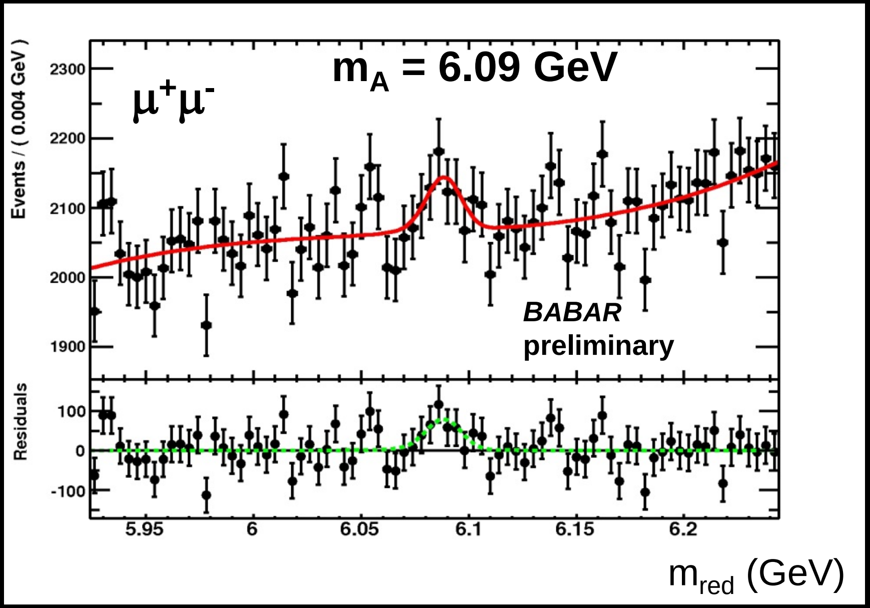
Extract signal by a series of maximum likelihood fits to the data over sliding mass intervals centered around the A' mass.

Signal modeled using mass histograms from MC, interpolated between known points (cdf interpolation).



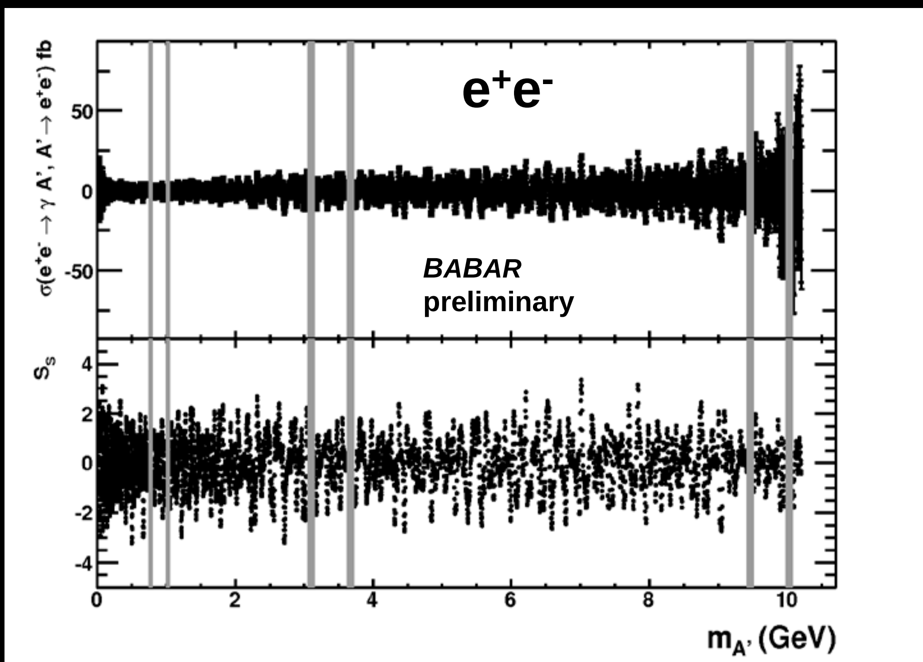
Example of fits to the data

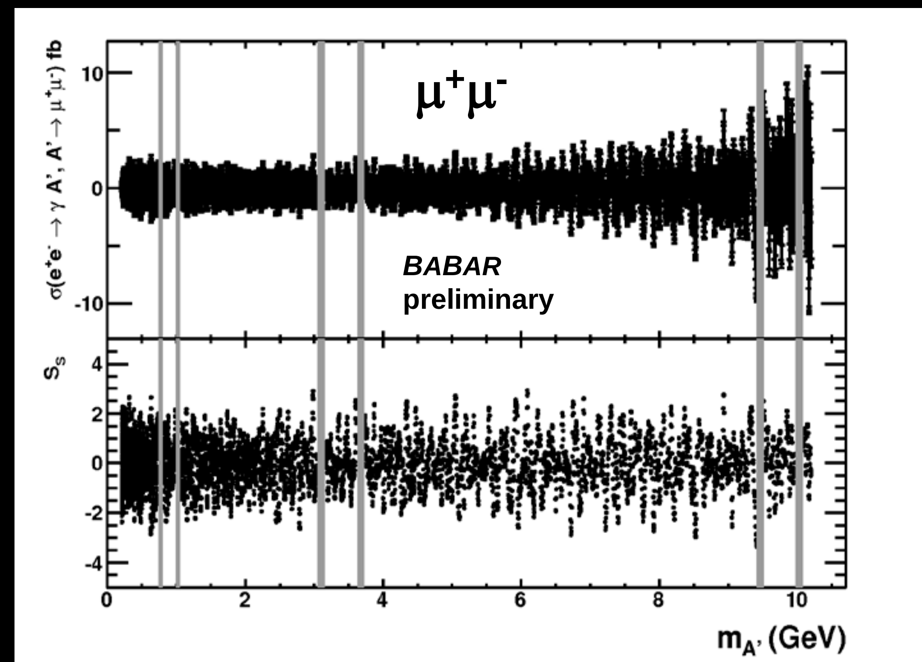




Results – cross sections

Results on $\sigma(e^+e^- \to \gamma A', A' \to l^+l^-)$ for combined $\Upsilon(2S,3S,4S)$ datasets

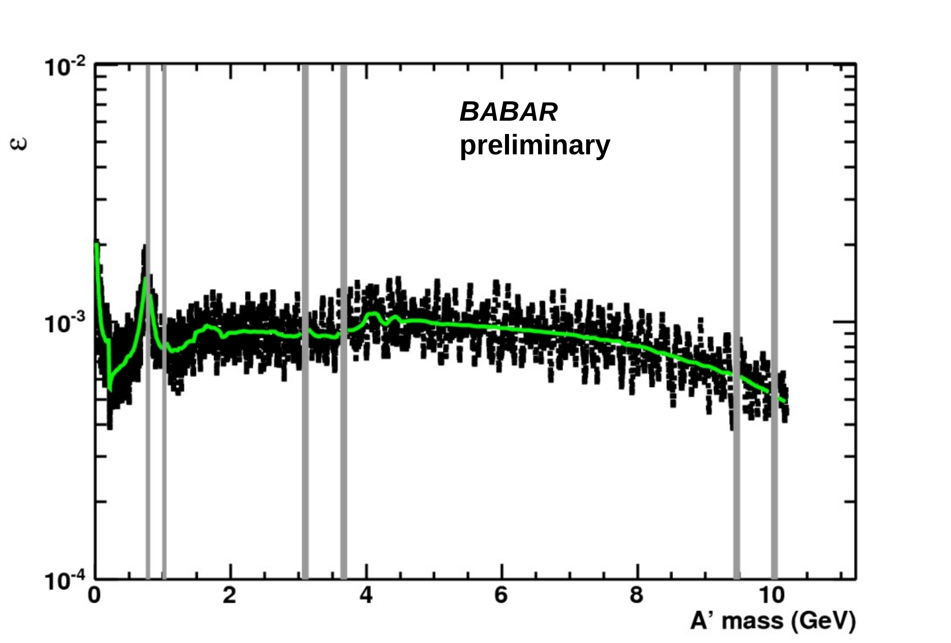


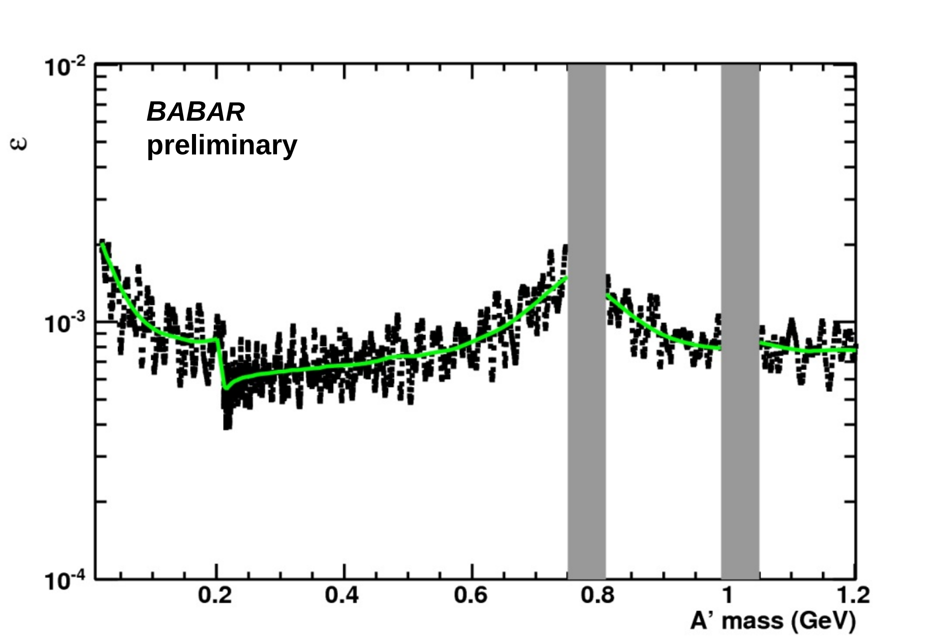


Largest significances:

3.4σ for electrons @ 7.02 GeV → 0.6σ with trial factors
2.9σ for muons @ 6.09 GeV → 0.1σ with trial factors

95% CL upper limits on the mixing parameter ε

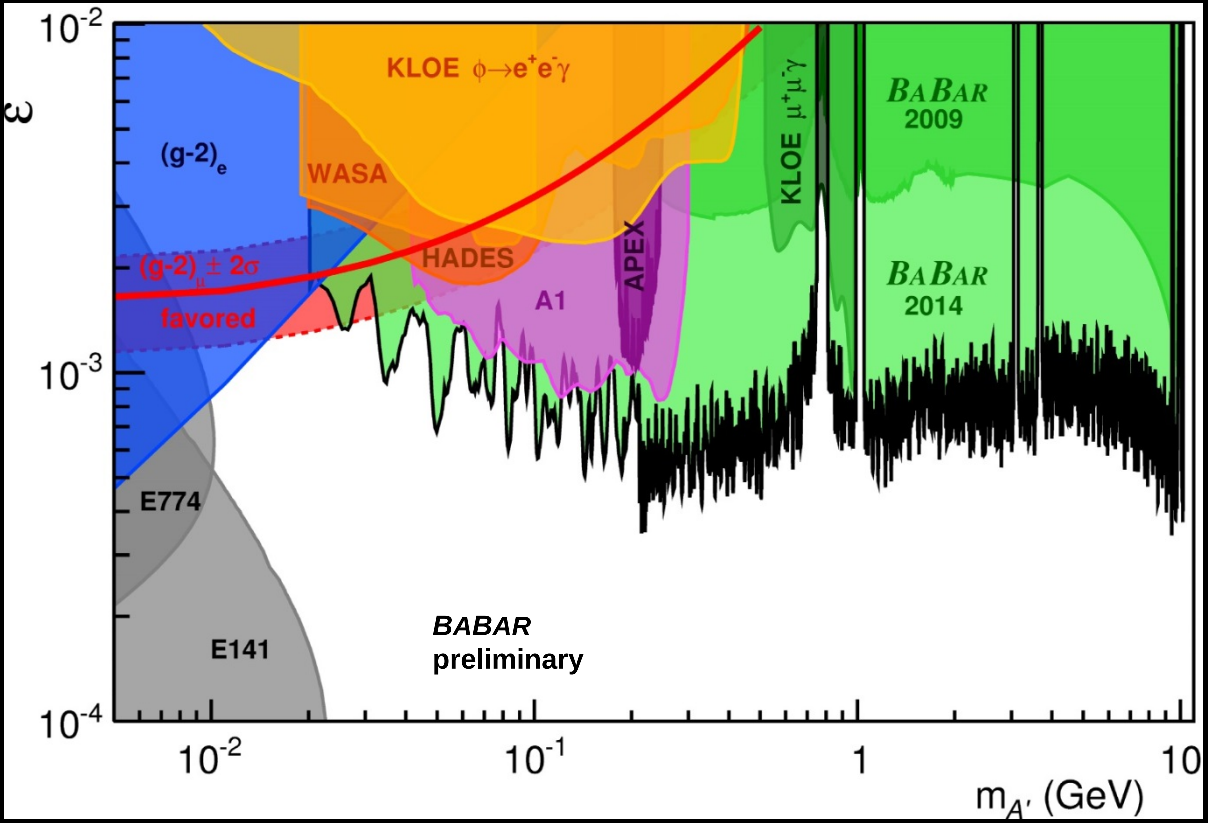


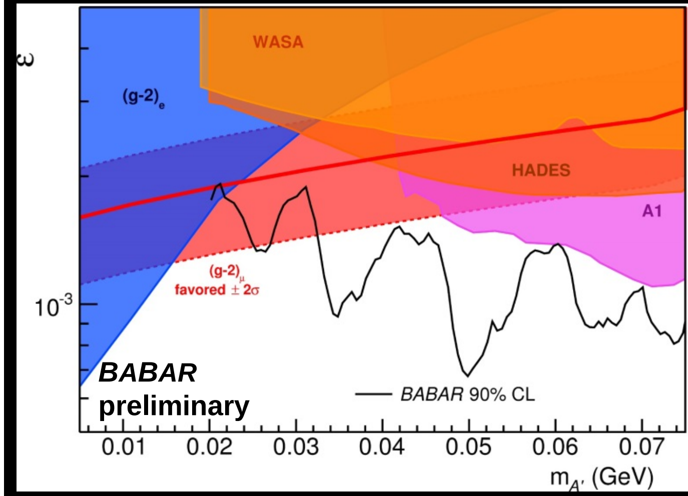


— Moving average to guide the eye

Limits at the level of $O(10^{-4} - 10^{-3})$

Results – dark sector mixing

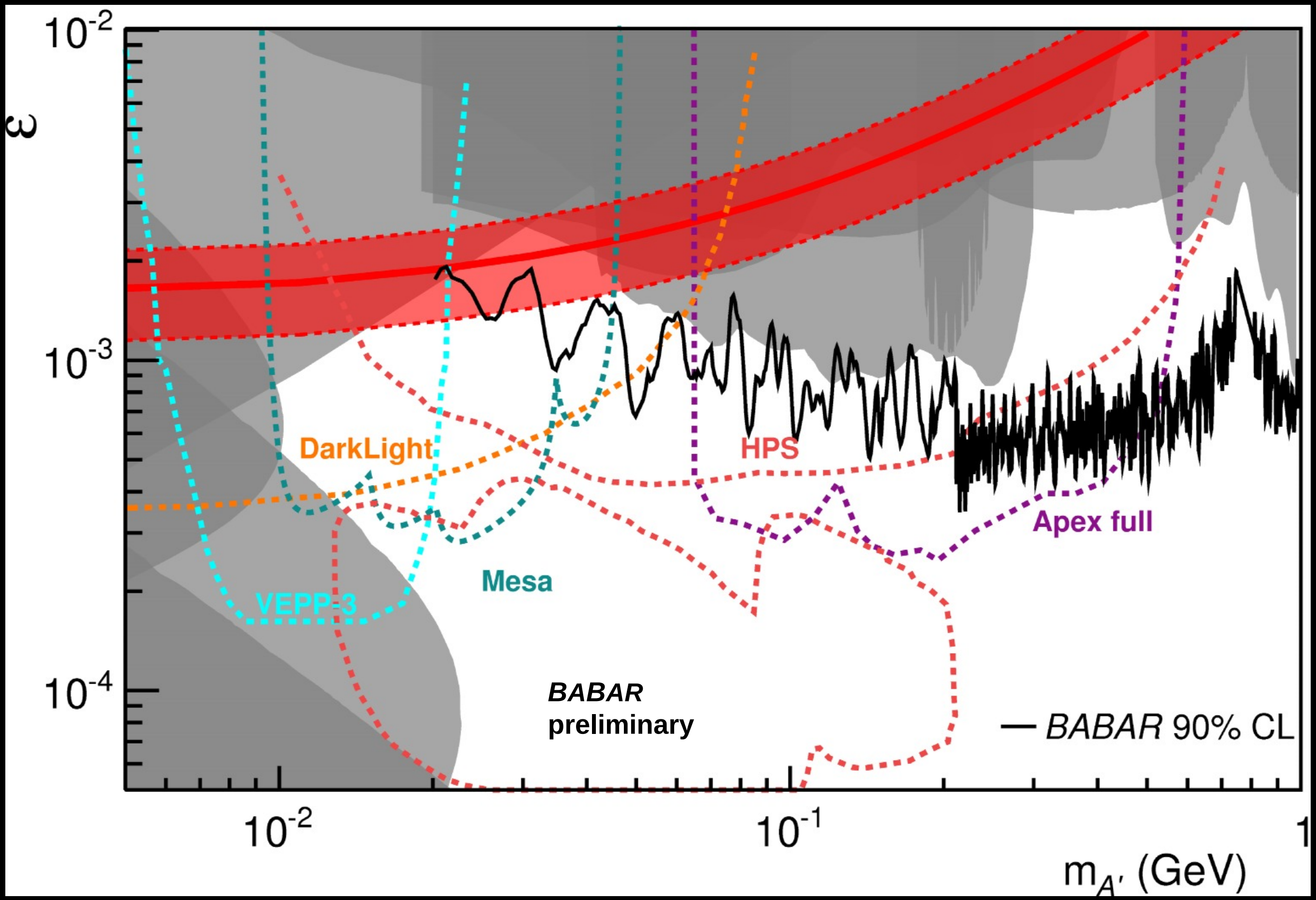




- Exclude a substantial fraction of the remaining region favored by the "g-2" measurement and improve the existing constraints over a wide range of masses.

- The $e^+e^- \rightarrow \gamma A'$, $A' \rightarrow \pi^+\pi^-$ final state can further probe the region near the ρ meson.

Comparison with expected sensitivity of future experiments



- Dedicated experiments will be more sensitive in the low mass region, but *BABAR* set the stringent limits above ~500 MeV arxiv:0808.0017

Invisible dark sector

- Several scenarios where dark photons decay to invisible final states, e.g lighter dark sector particles (sub-GeV),…

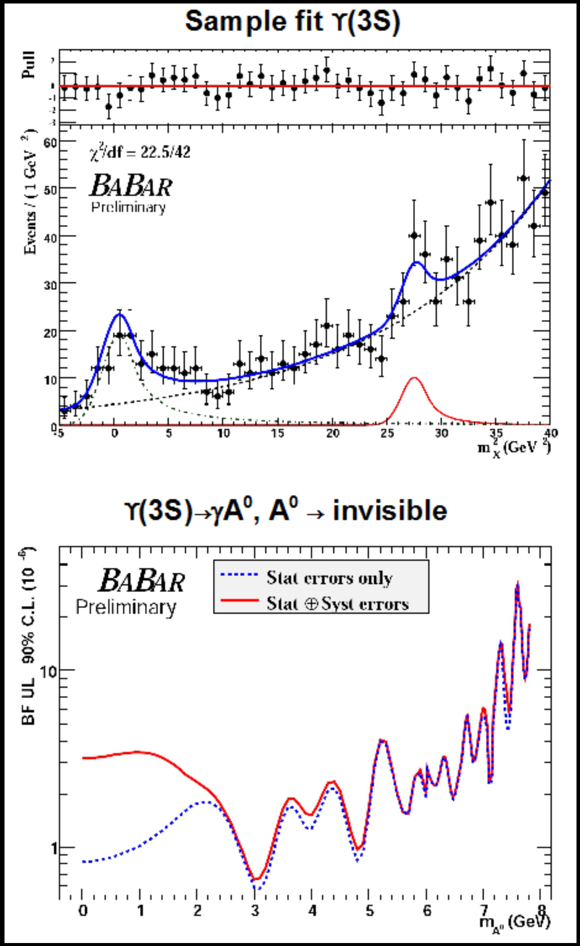
- At e^+e^- colliders, we can search for

$$e^+e^- \rightarrow \gamma A' \ , \ A' \rightarrow \text{invisible}$$

by tagging the recoil photon in "single photon" events.

- Currently only a measurement of $\Upsilon(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible at *BABAR* with A^0 a light CP-odd Higgs

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible, new analysis in progress + extension to A'



Invisible dark photon decays

Invisible dark sector

- Several scenarios where dark photons decay to invisible final states, e.g lighter dark sector particles (sub-GeV),…

- At e^+e^- colliders, we can search for

  $$e^+e^- \rightarrow \gamma A' \;,\;\; A' \rightarrow \text{invisible}$$

  by tagging the recoil photon in "single photon" events.

- Currently only a measurement of

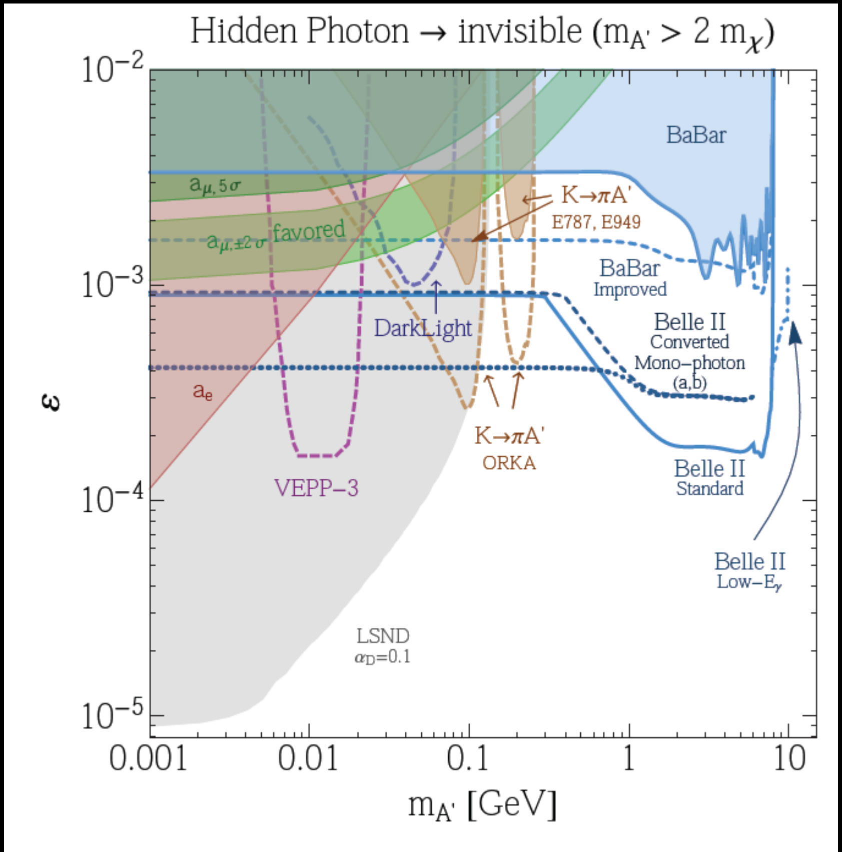
  $$\Upsilon(2S,3S) \rightarrow \gamma A^0,\; A^0 \rightarrow \text{invisible}$$

  at *BABAR* with A^0 a light CP-odd Higgs

- Analysis extended to full dataset and the dark photon case, expect limits on ε at the level of 10^{-3}.

- Also constraints from (g-2)e, (g-2)μ, $K \rightarrow \pi\nu\nu$ decays

Essig *et al.*, arXiv:1309.5084



Major improvement possible with future experiments (e.g. Belle II)

Dark Higgs boson

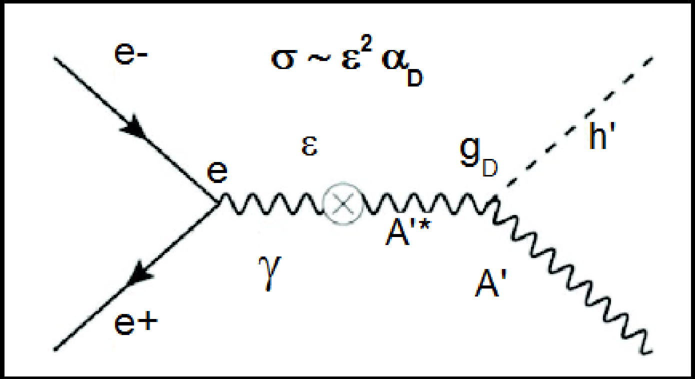
- Dark photon mass is generated via the Higgs mechanism, adding a dark Higgs boson (h')
- A minimal scenario has a single dark photon and a single dark Higgs boson.
- Theoretical prejudice for dark Higgs mass at the MeV-GeV scale.
- The Higgsstrahlung process

$$e^+e^- \rightarrow A'^* \rightarrow h'\ A'$$

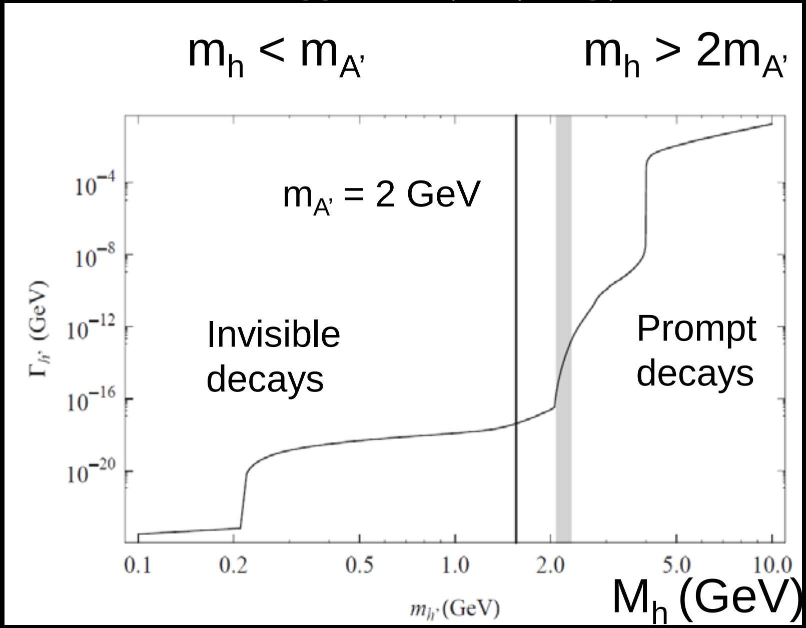
is very interesting, as it is only suppressed by ε^2 and should have low background

- Also sensitive to the dark sector coupling constant $\alpha_D = g_D^2 / 4\pi$

Search for prompt h' decays at BABAR:
$e^+e^- \rightarrow A'^* \rightarrow h'\ A',\ h' \rightarrow A'\ A'$

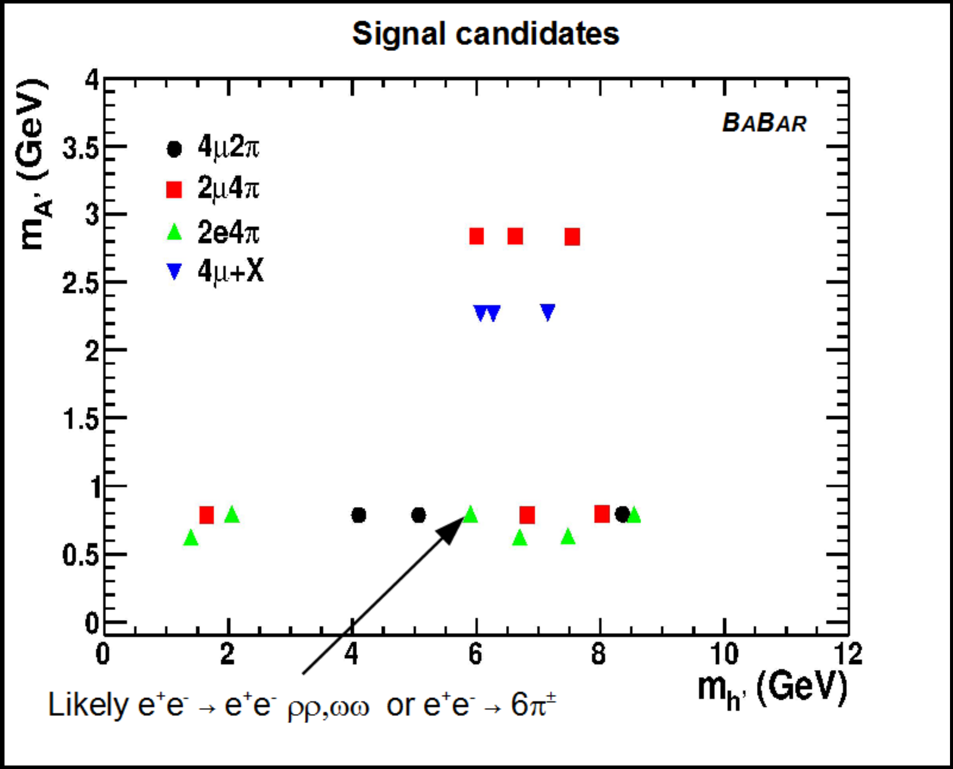


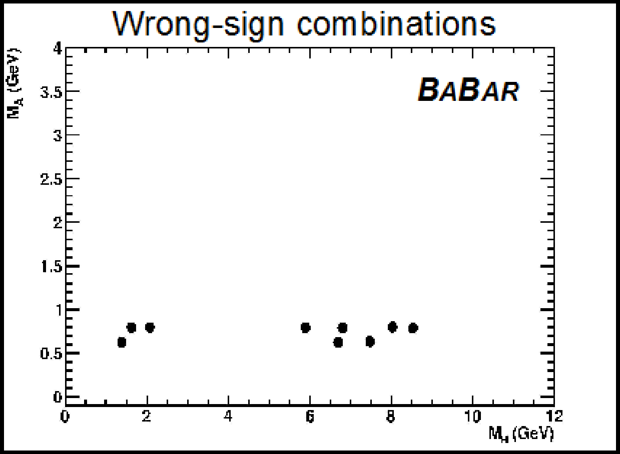
Dark Higgs decay topology



PRL 108 (2012) 211801

- Six candidates are selected from the full *BABAR* dataset (~500 fb^{-1})
- Three entries for each event, corresponding to the three possible assignments of the h' → A'A' decay
- Estimate background from
  - wrong-sign combinations, e.g. $e^+e^- \rightarrow (e^+e^+)\,(e^-e^-)\,(\mu^+\mu^-)$
  - sidebands from final sample
  - rate for 6 leptons ~ 100x rate for $4\pi+2l$ above 1.5 GeV

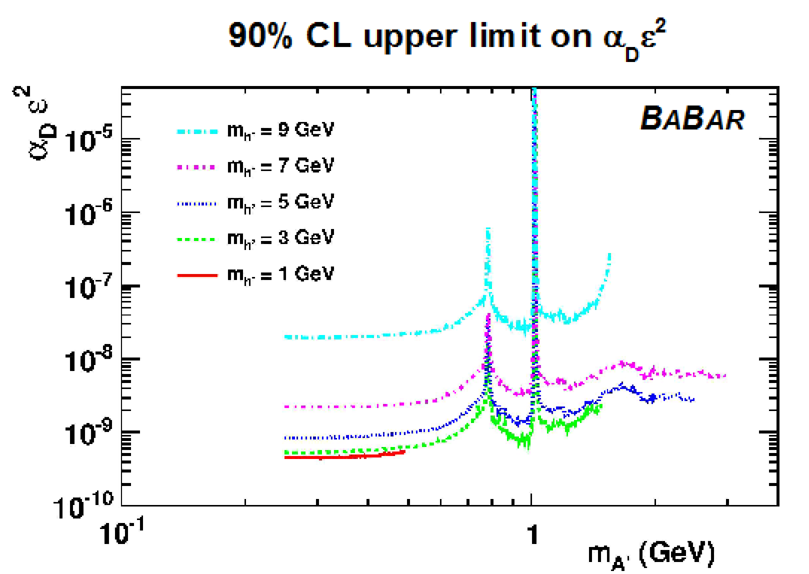


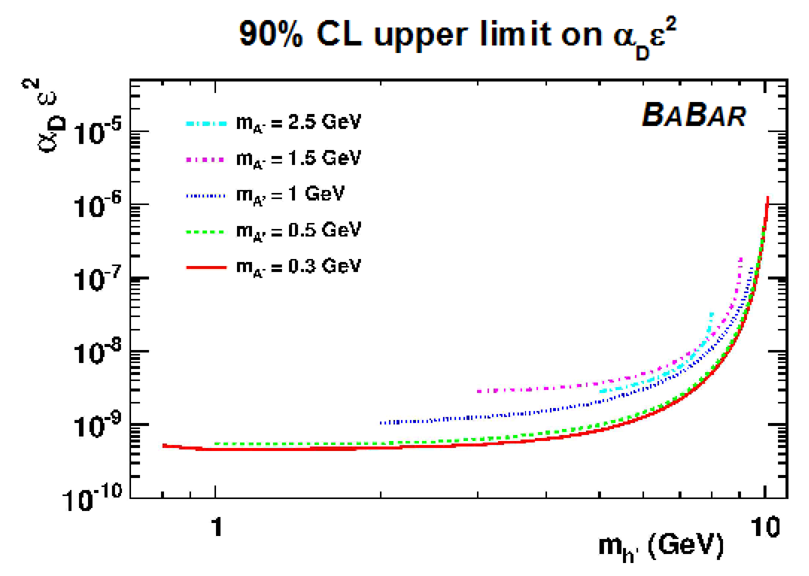


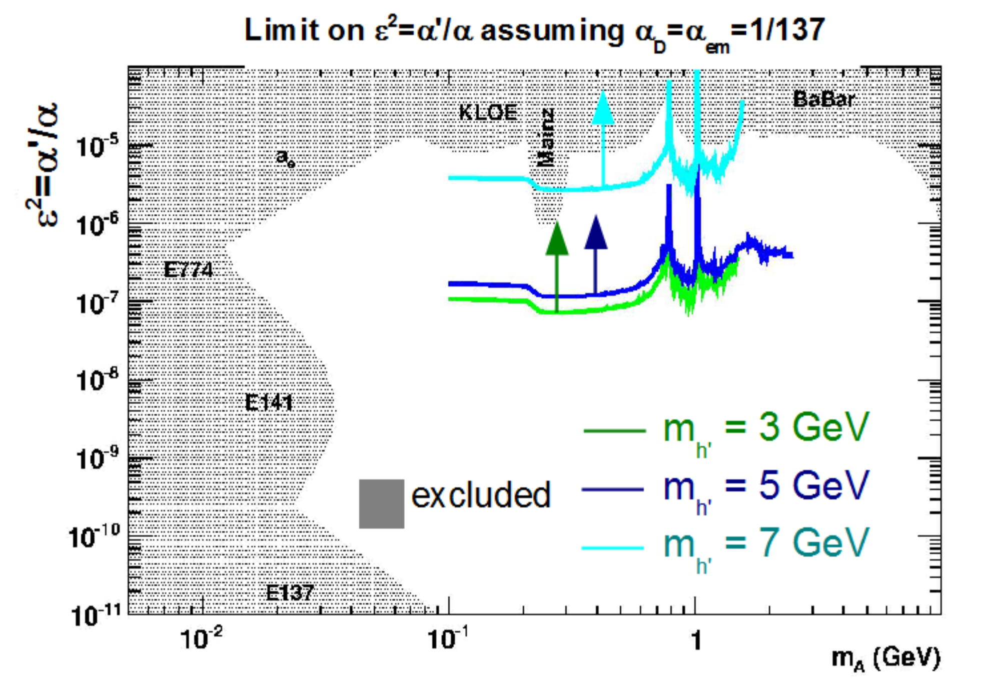
No events with 6 leptons, consistent with the pure background hypothesis

Dark Higgs boson

PRL 108 (2012) 211801





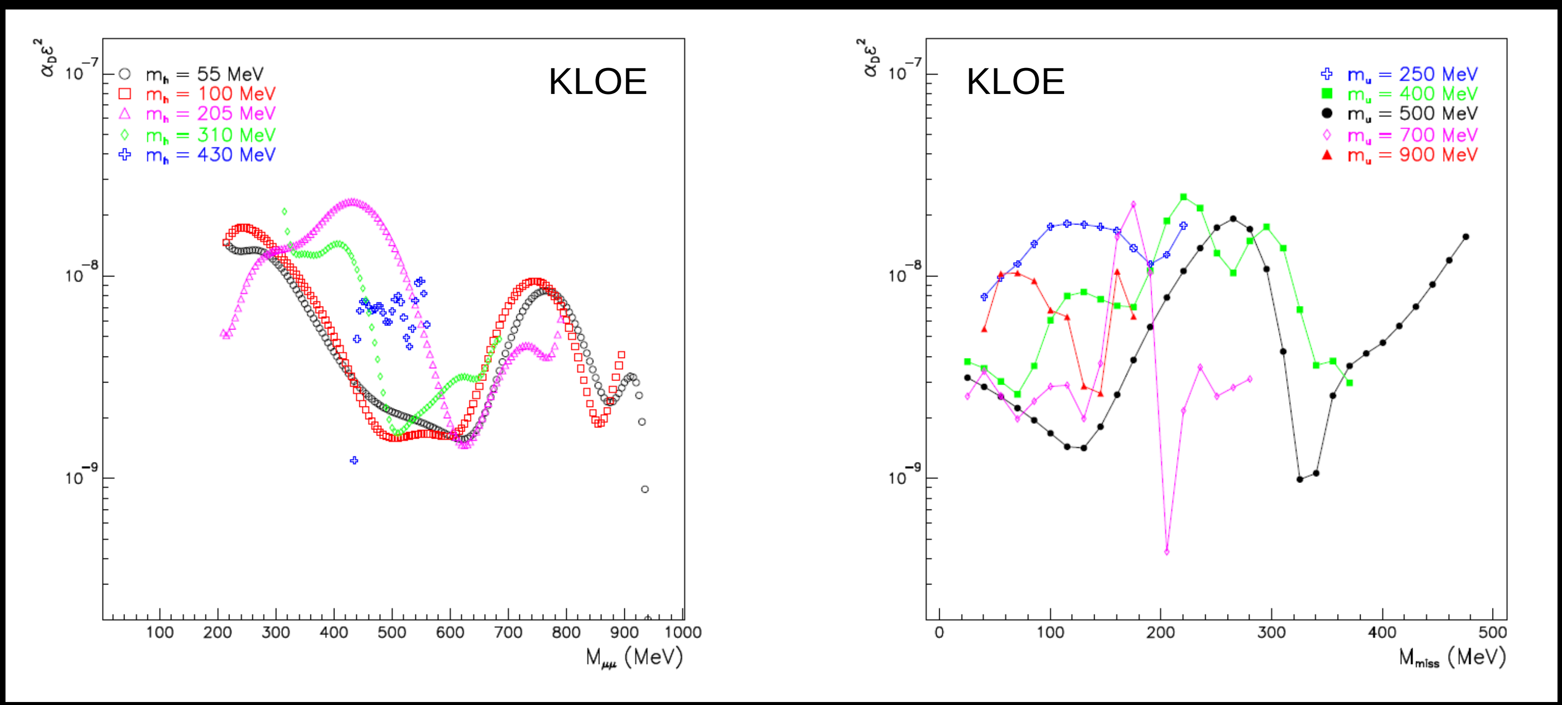


Substantial improvement over existing limits for $m_{h'}$ < 5 - 7 GeV
(if a light dark Higgs boson exists, of course)

Frascati Phys.Ser. 56 (2012) 150-161

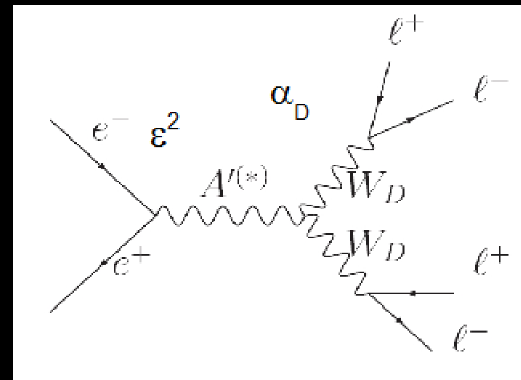
Invisible dark Higgs decay at KLOE

- Kinematic range $m_{h'} < m_{A'}$
- Signal: 2 leptons + missing energy
- Limits on $\alpha_D\varepsilon^2 \sim 10^{-9} - 10^{-8}$ for $2m_\mu < m_{A'} < 1000$ MeV and $m_{h'} < m_A$

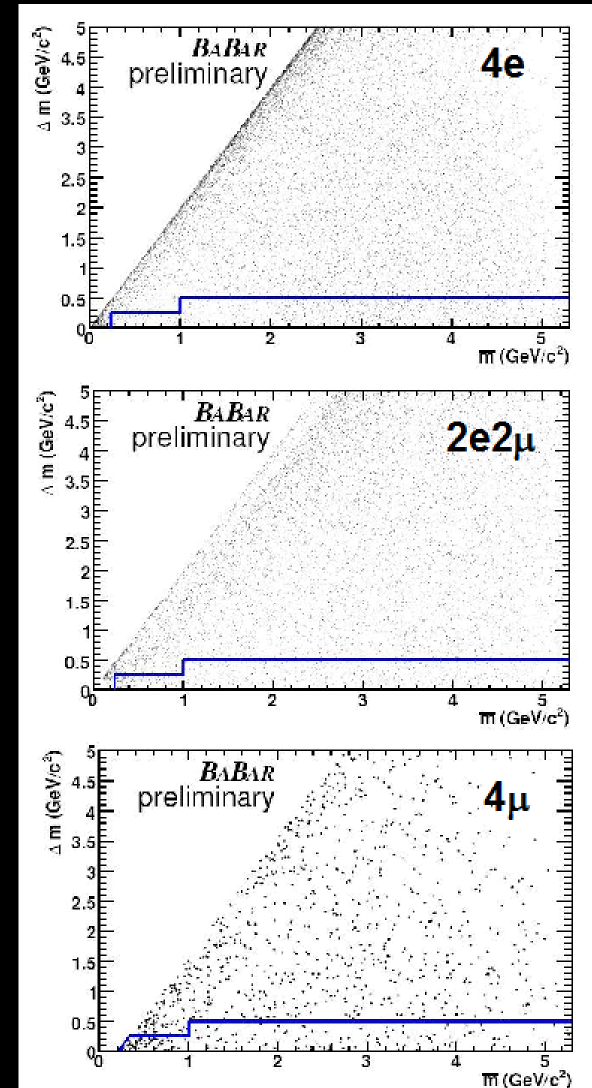


arXiv:0908.2821

$e^+e^- \to A'^* \to W_D\, W_D'$,
$W_D^{(\prime)} \to e^+e^-, \mu^+\mu^-$



$\alpha_D = g_D^2 / 4\pi$
g_D dark sector gauge coupling

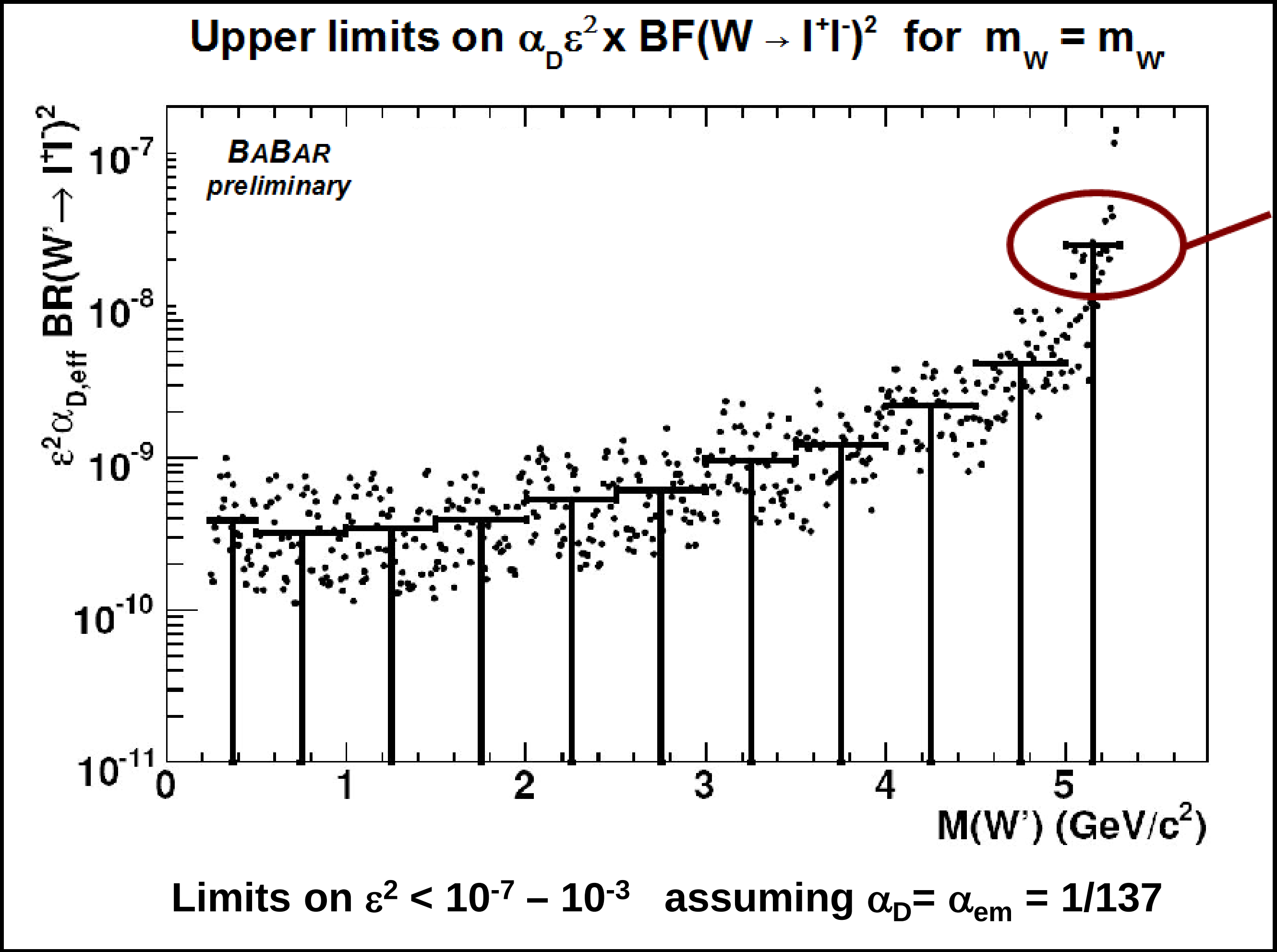


$\overline{m} = (m_{min}+m_{max})/2$
$\Delta m = (m_{max}-m_{min})/2$

- The simplest extension to a non-Abelian case is SU(2)xU(1), which has 4 bosons: A', W_D, W_D' and W_D''
- Can produce a pair of dark bosons though an off-shell A'.
- Search for two dileptonic resonances with similar mass

Non-Abelian dark sector

arXiv:0908.2821

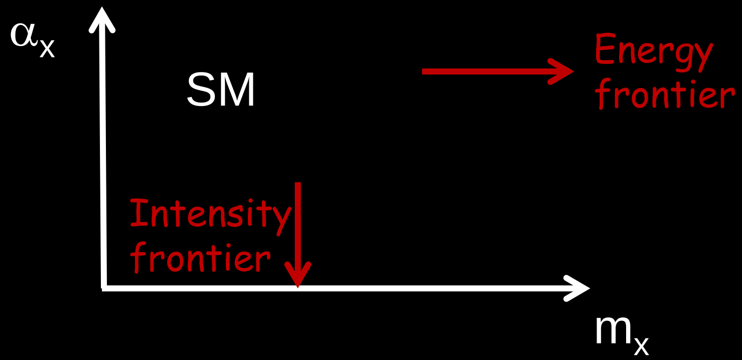


Average limit over many bins

Expect similar limits for $m_W - m_{W'} >> 0$

Dark sector searches at LHC

Direct production of dark photon suppressed at high energy



$$\text{Amplitude} \sim \frac{\alpha_X}{q^2+m_X^2}$$

Difficult to probe $\alpha_X < 10^{-6}$ and $m_x \sim$ GeV at LHC
(hard ISR emission also suppressed)

Instead, new particles (e.g SUSY) could decay into dark sector particles with a large BF.

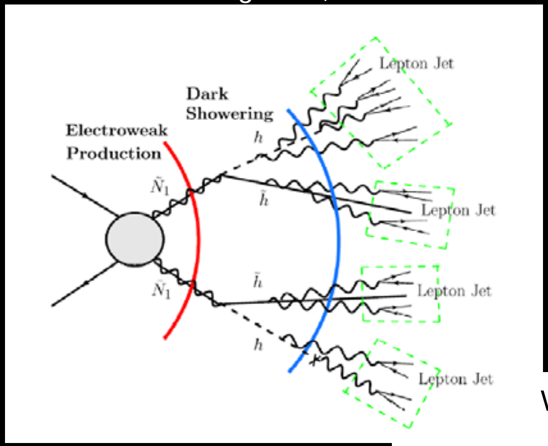
In case of SUSY, bottom of cascade no longer stable, decays into dark photons → lepton jets.

Main characteristics:

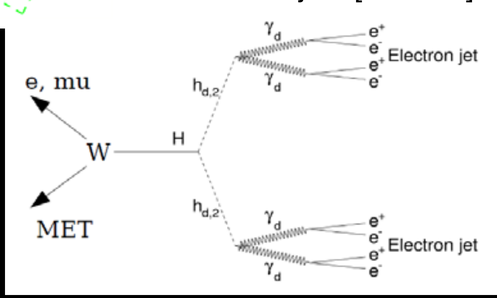
- Many leptons final state (e.g. lepton jets)
- Boosted dark sector particles → displaced vertices

But New Physics needed in some models !!!

Cheung et al., arXiv:0909.0290



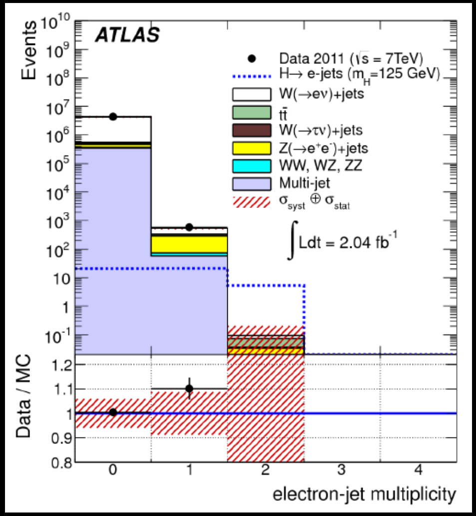
W+H → e- jet [A. Haas]



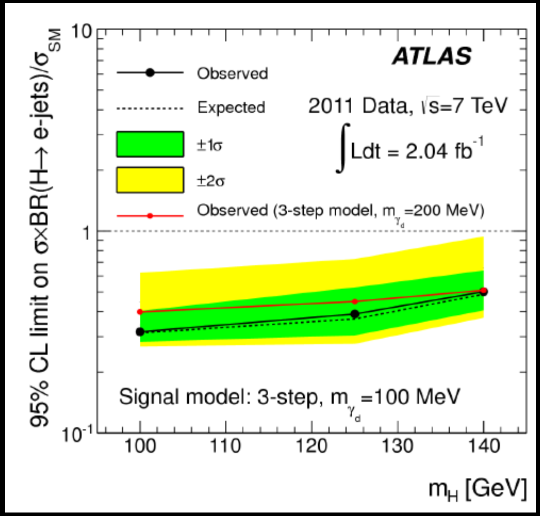
Dark sector searches at LHC

Search for
W+H → electron-jets + X

No excess of events with two electron jets observed

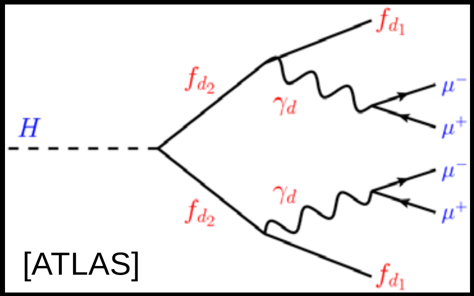


ATLAS Collab., New J.Phys. 15 (2013) 043009

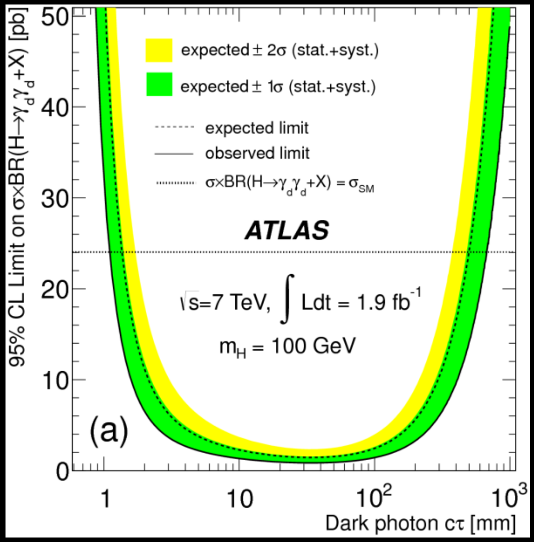


Search for
H → A' A' + X

No signal observed



Atlas Collab., PLB 721 (2013) 32

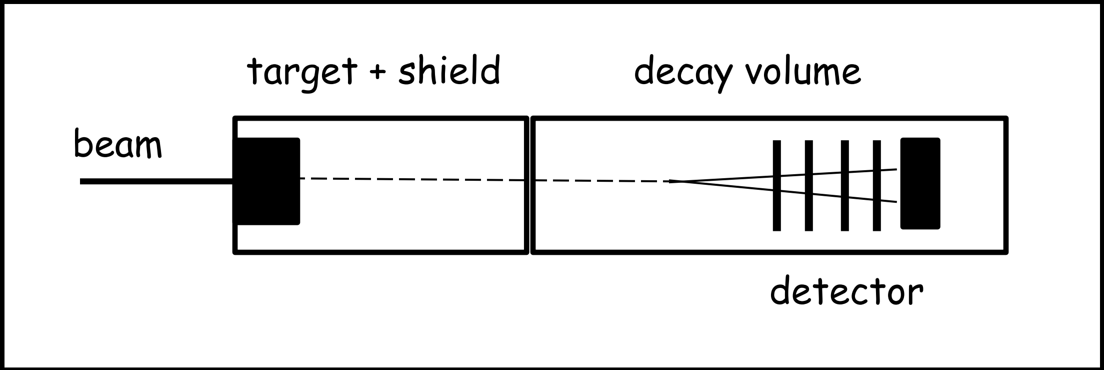


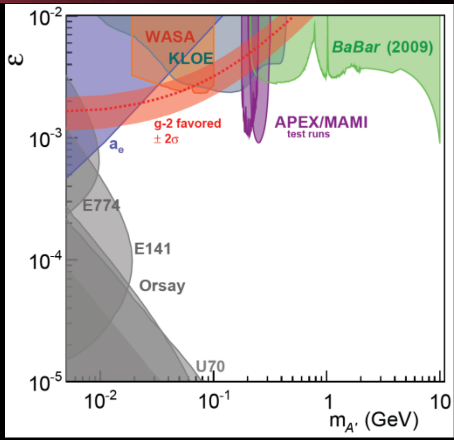
+ searches for SUSY lepton jets, H→muon jets
and possible searches for direct production, rare Z decays,..

Interesting program pursued at LHC

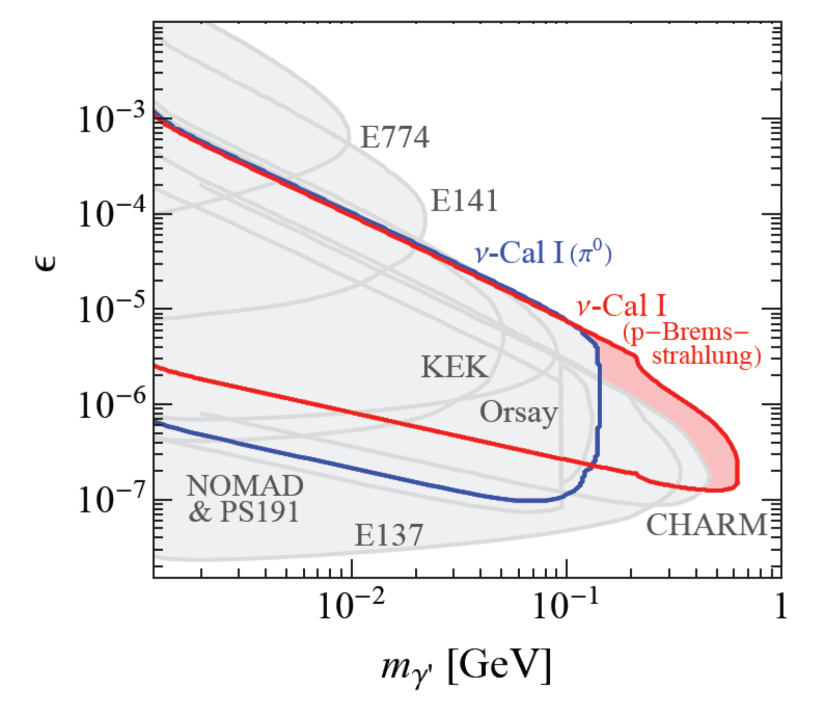
Other constraints and future initiatives

Beam dump experiments





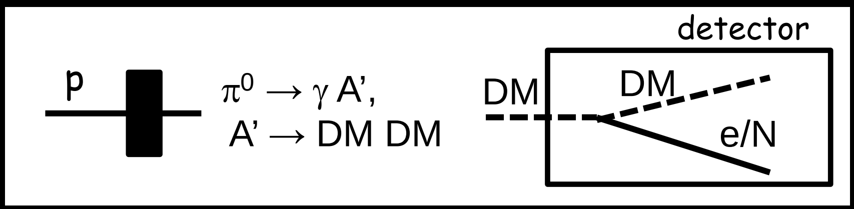
Blumlein & Brunner, arXiv: 1311.3870



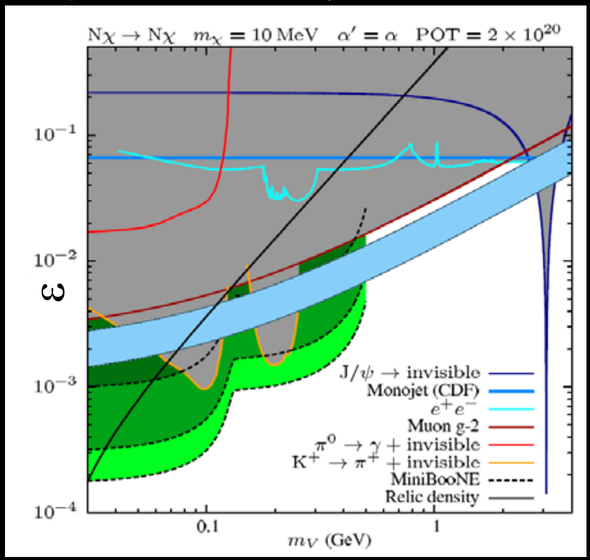
- Beam produces hadronic and/or EM shower
- Secondary particles emit A'
- Dark photons can decay near the detector, and be reconstructed as narrow resonances
- Original experiments looking for ν, axions, light Higgs,… have been reinterpreted as constraints on dark photon production
- Sensitive to low mixing values at large masses, complementary to other approaches

Proton-beam

- Invisible DM produced in pion decay
- Neutrino factory ideal for probing this scenario (MicroBoone, Nova, LBNE,...)



E.g MiniBoone expected reach

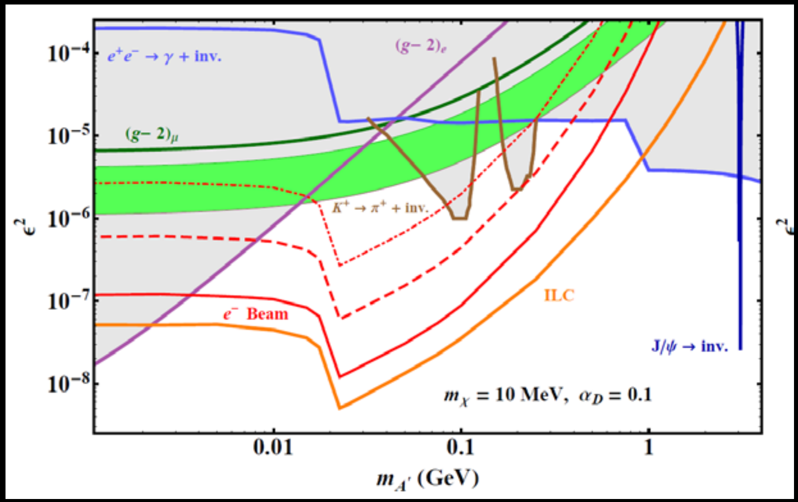


Aguilar-Arevalo *et al.*, arXiv:1211.2258

Electron-beam

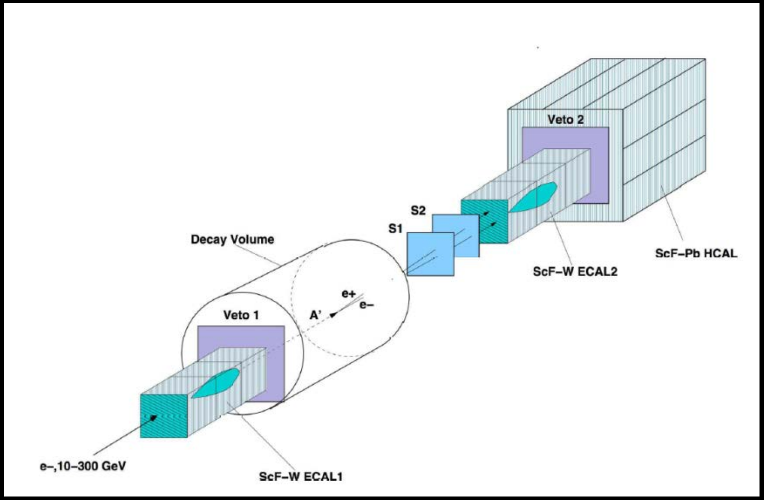
- Low background
- Small mass detector
- Favorable kinematics

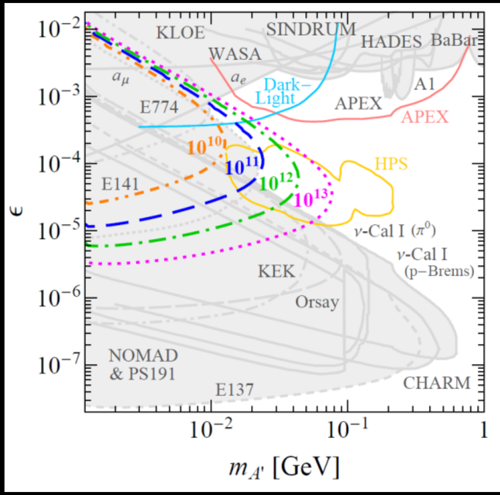
Izaguirre *et al.*, arXiv:1307.6554

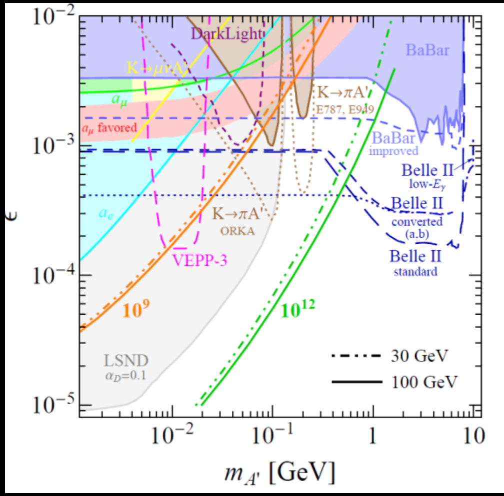


Proposal at CERN using the SPS e- beam

- Dark photon produced by electron in ECAL 1, incoming electron absorbed.
- Decay products measured in ECAL 2
- Veto additional activity in VETO 1/2
- Possibility to measure visible and invisible A' decays
- Coverage complementary to existing proposals







Fixed target experiments

Fixed target experiments

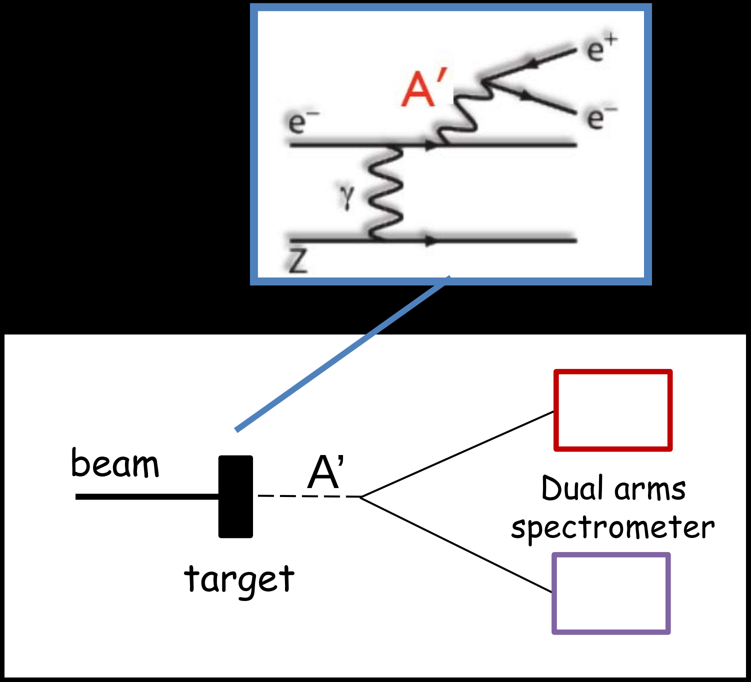
- Electron beam on fixed target radiates A'
- Decay product detected by dual arm spectrometer

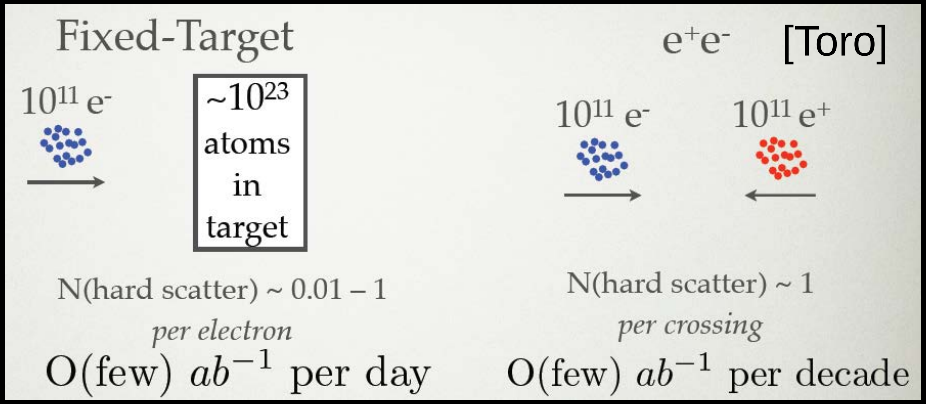
Fixed target have huge luminosity

- Much denser target
- Cross-section $\propto Z^2$ and $1/m^2$

But small signal and large background

- Small bump on top of background
- Displaced vertices boosts sensitivity





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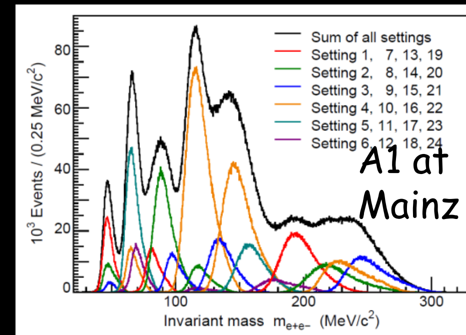
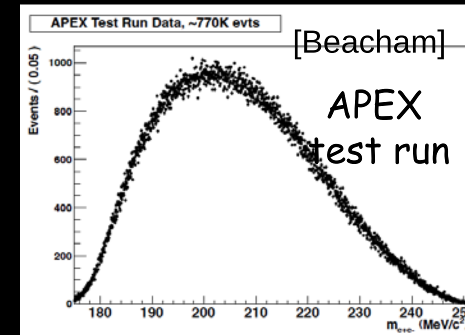
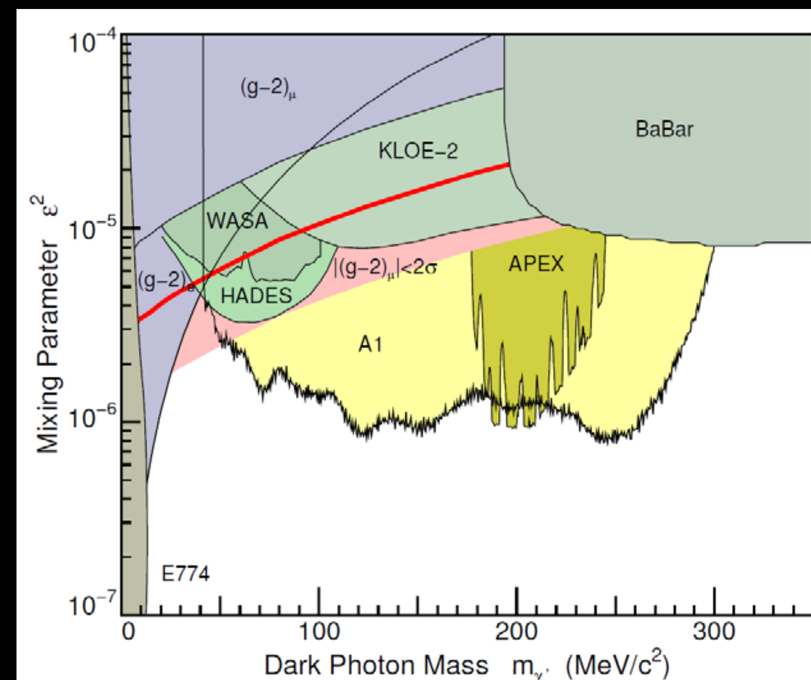
Recent results

- A1 at Mainz: 850 MeV e^- beam
- APEX at Jlab: 6 GeV e^- beam





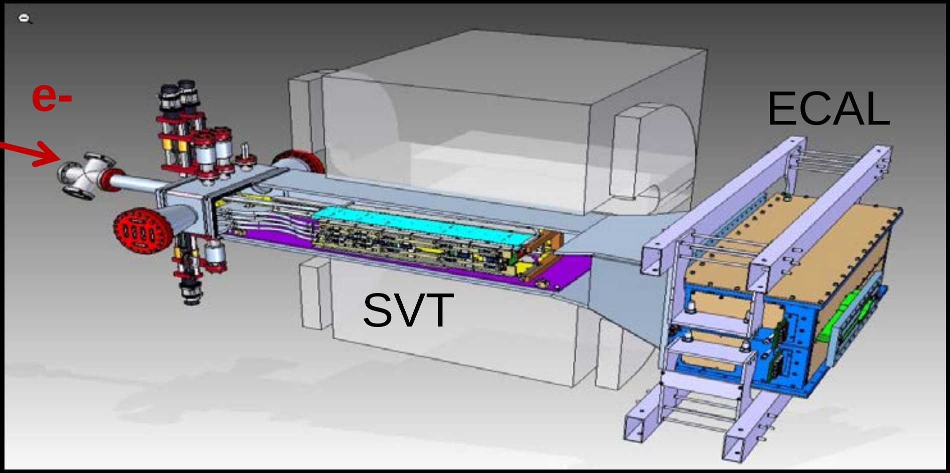


Expect to improve sensitivity in near future

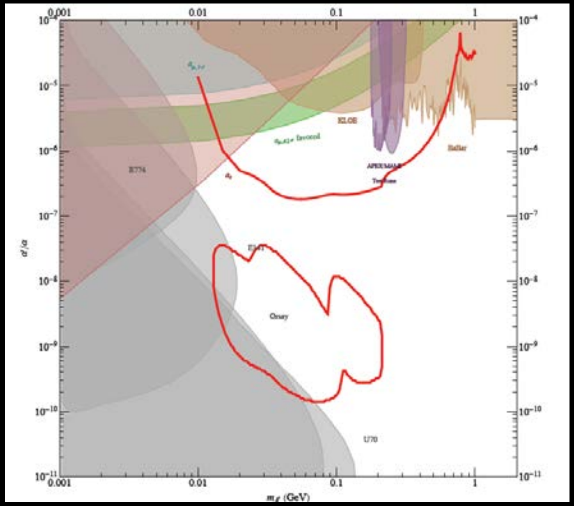
HPS proposal*

Heavy Photon Search experiment at JLab

- Large forward-acceptance spectrometer
- Silicon vertex tracker to measure e^+e^- mass and vertex position
- $PbWO_4$ crystal calorimeter to identify e^+e^- and trigger
- High rate trigger and DAQ
- Search for prompt and displaced A' decays
- Test run in 2012 to validate the concept
- Should be running in 2014-2015



HPS expected reach (HPS proposal)



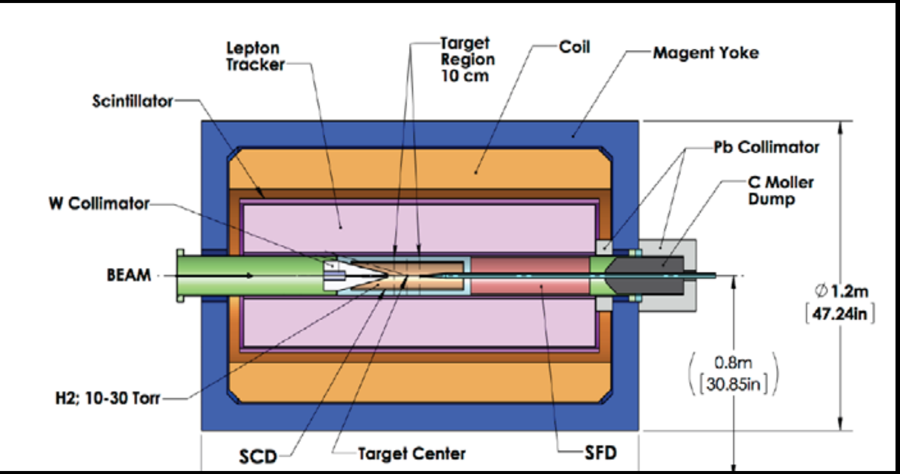
1 week 1.1 GeV
+3 weeks 2.2 GeV
+3 weeks 6.6 GeV

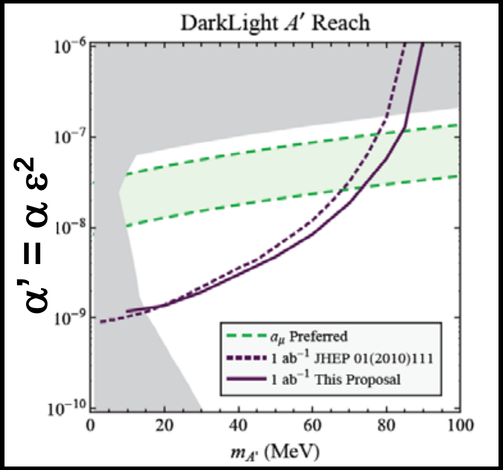
*https://confluence.slac.stanford.edu/display/hpsg/HPS+Proposals

DarkLight proposal

DarkLight* at Jlab

- Compact 4π detector
- Electron beam (100 MeV) on gaseous hydrogen target
- Measure the full reaction
  $e^- p \rightarrow e^- p A' \rightarrow e^- p \ e^+ e^-$
- Measure visible and invisible A' decays for $m_{A'} < 90$ MeV
- Test run at Jlab FEL to demonstrate concept
- Expect to run in 2016 (?)

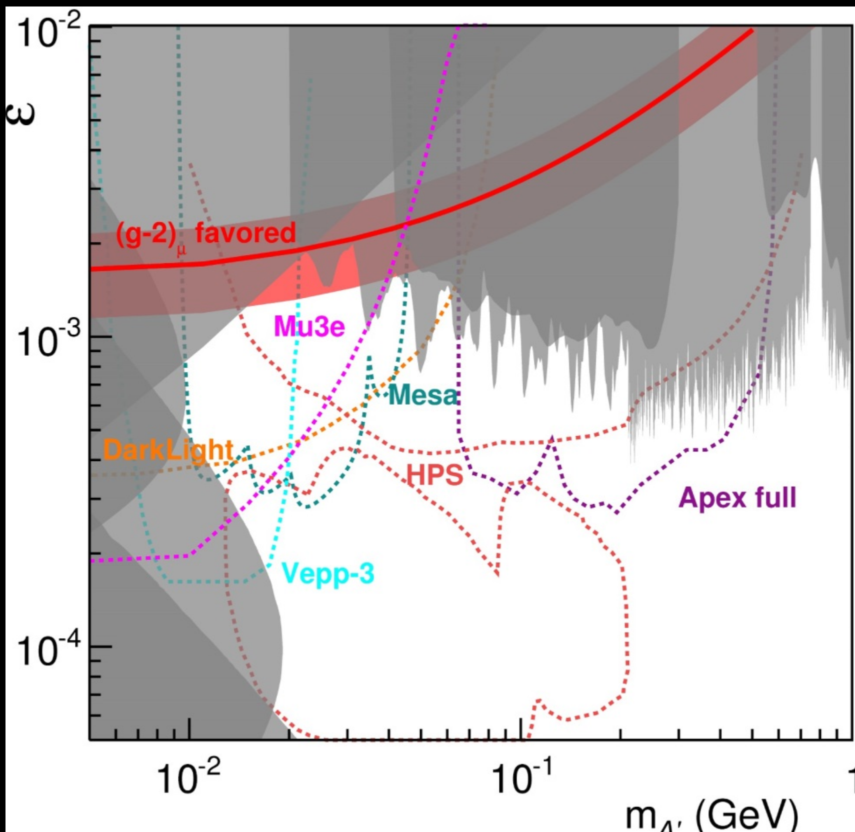




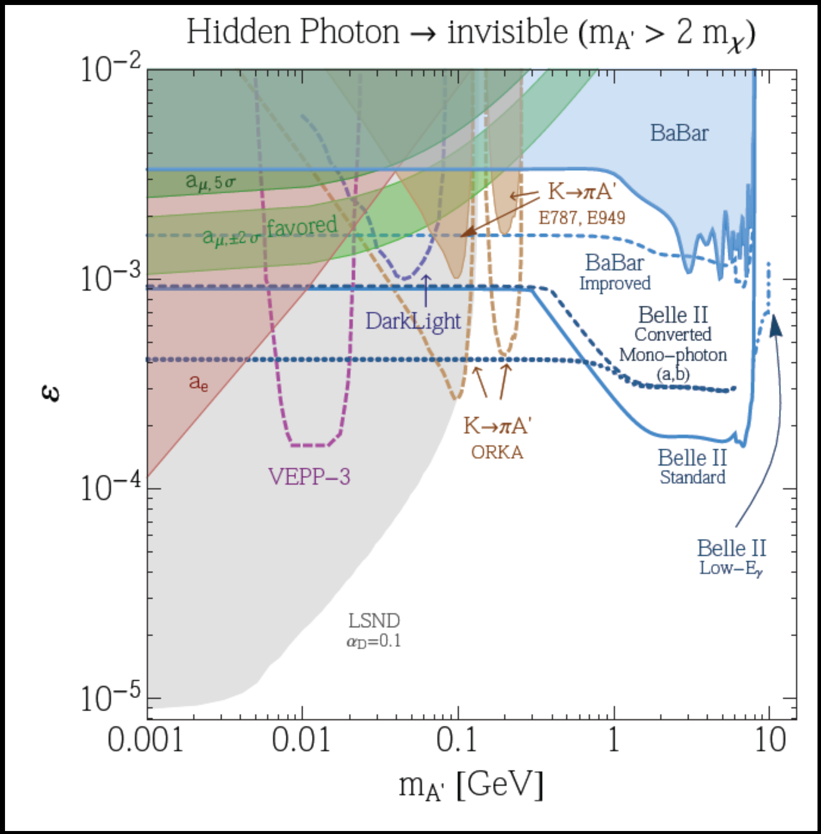
*DarkLight = Detecting A Resonance Kinematically with eLectrons Incident on a Gaseous Hydrogen Target
http://dmtpc.mit.edu/DarkLight/DarkLightProposal_PAC39.pdf

Future prospects

A' → visible



A' → invisible



Essig *et al.*, arXiv:1309.5084

Start probing parameter space, but still a large fraction of uncovered territory!

Dark fun

Summary

- Dark forces open a new window on physics far beyond the SM.
- In particular, a light dark sector as a dark matter candidate is well motivated by theory, astrophysics and particle physics measurements.
- A fraction of the allowed parameter space has already been probed by current experiments: *g*-2, fixed target, beam dump, e^+e^- colliders,…
- But there is still a lot of uncharted territory!
- Small-scale, inexpensive experiments at existing facilities will further explore this parameter space, hopefully resulting in a game-changing discovery.
- In other words, a possibility of huge payoff with small investment !