Dark Forces at Accelerators

Steven Robertson
Institute of Particle Physics
& McGill University

On behalf of the *BABAR* Collaboration

FPCP 2019
Victoria B.C. Canada
May 7, 2019

INSTITUTE OF PARTICLE PHYSICS

McGill

Outline

Experimental overview of (selected) dark sector results

- Minimal dark photon searches
  - Visible decays
  - Invisible decays
  - Prompt & displaced vertex
- Muonic dark force Z_d
- Dark Higgs
- Higgs portal Z_d
- Future prospects

See talk by
C. Hearty
Thurs. Parallel 2

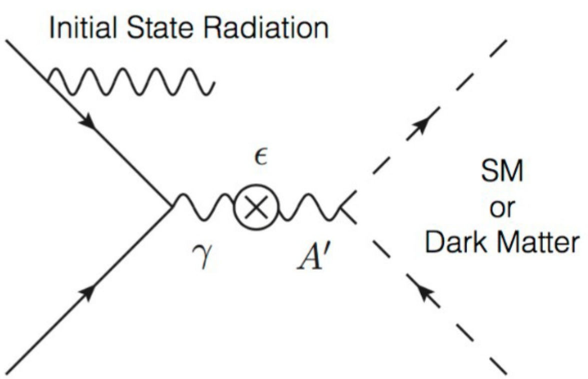
Dark photon

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

Simplest dark sector scenario: add a new U(1) gauge symmetry, with associated charge carried by dark-sector fermions

- Spin-1 gauge boson “dark photon” A' (or γ_d, or Z_d in non-minimal models) can mix with SM photon, providing a “portal” to the dark sector.

Kinetic mixing: $\frac{1}{2}\epsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$



ϵ is the strength of the kinetic mixing

- could be as large as 10^{-2} for $m_{A'}$ in the GeV range,

Lifetime $\tau_{A'} \sim 1/(\epsilon^2 m_{A'})$

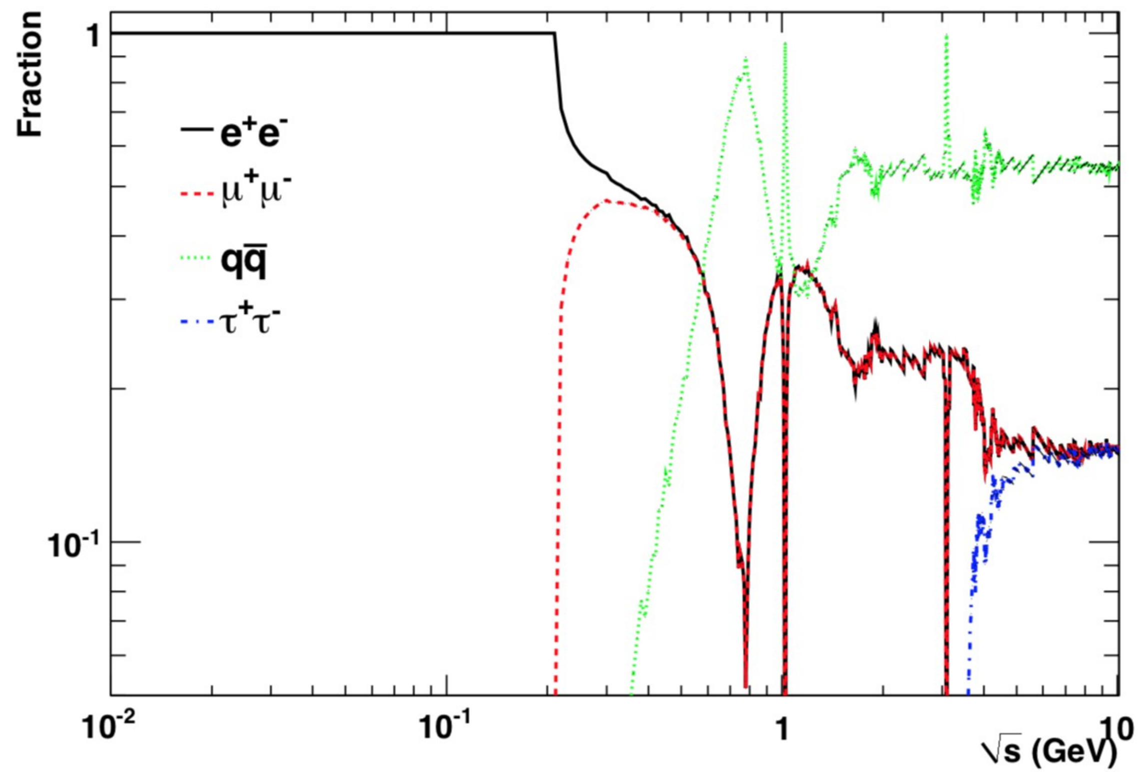
- visible decays can either be “prompt” (relative to experimental resolution) or “displaced” (relative to production vertex)

... however, dark sector could be much more extensive, with one or more Abelian or non-Abelian interactions, fermions and Higgs bosons

Dark photon

Permitted decays depend on the relative masses of dark fermions and mediator, and of SM fermions

- Models are highly predictive:



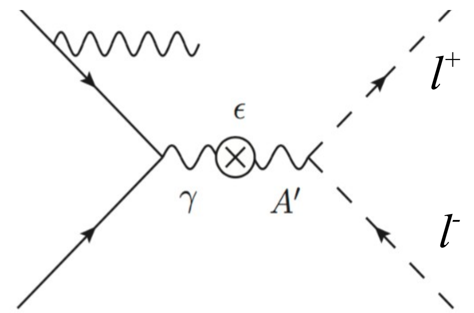
Experimentally, the important feature is a reconstructable narrow A' resonance in a clearly defined topology, i.e a "bump hunt"

- E.g. search for decay of $e^+e^- \to \gamma A'$ via $A' \to \chi\bar{\chi}$ or into SM particles
  - "visible" $A' \to l^+l^-$, decaying promptly or with a displaced vertex
  - "Invisible" A' decays, with A' mass determined from missing energy constraints

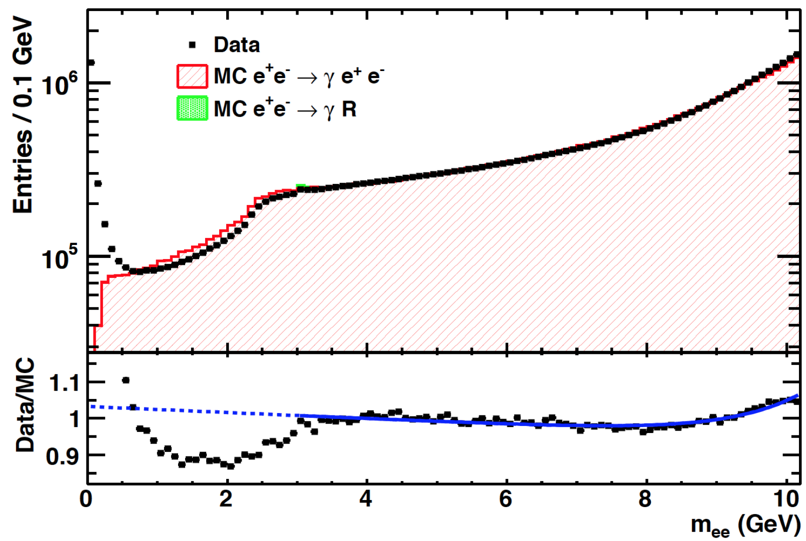
Visible dark photon decays

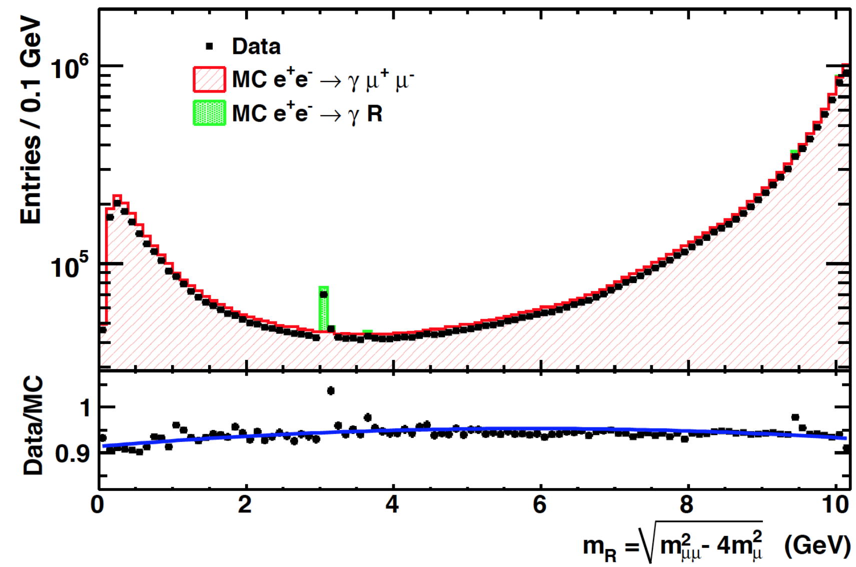
Phys. Rev. Lett. 113, 201801 (2014)
arXiv:1406.2980 [hep-ex]

BABAR search for $e^+e^- \to \gamma A'$ with $A' \to l^+l^-$ ($l = e, \mu$) using 516 fb^{-1} of data



- "Continuum" production, hence can use all available CM energy data
- Dark photon width well below detector resolution hence use simulation templates to model signal



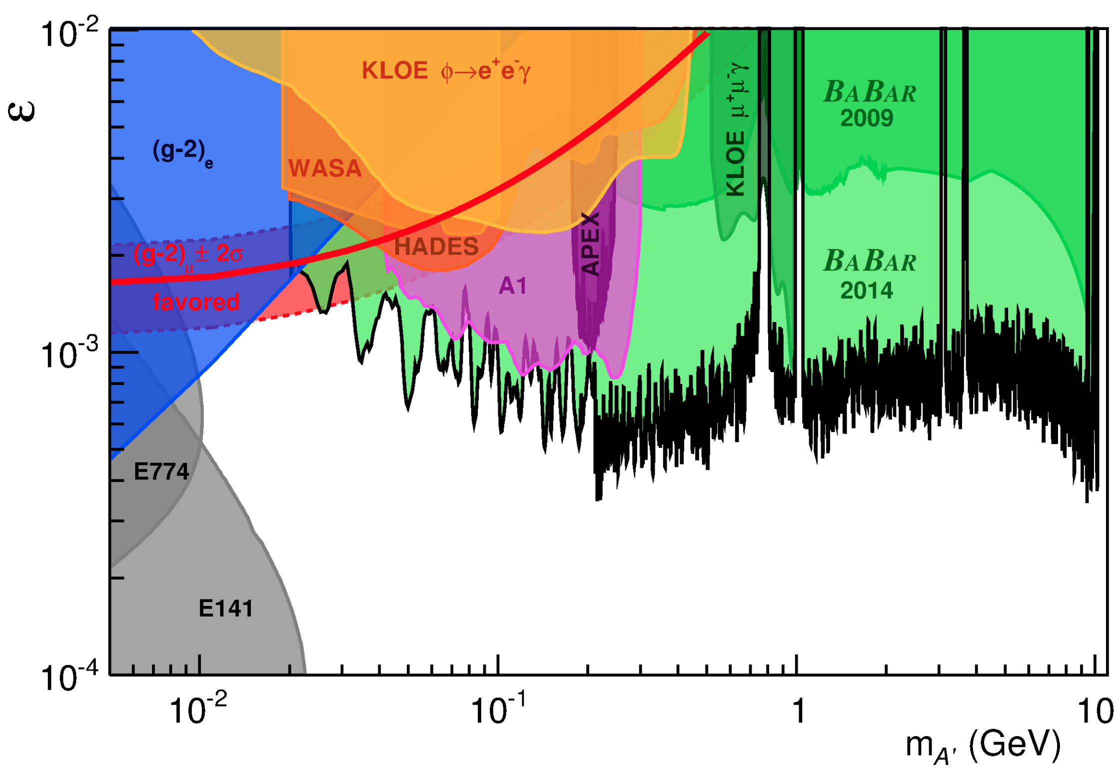


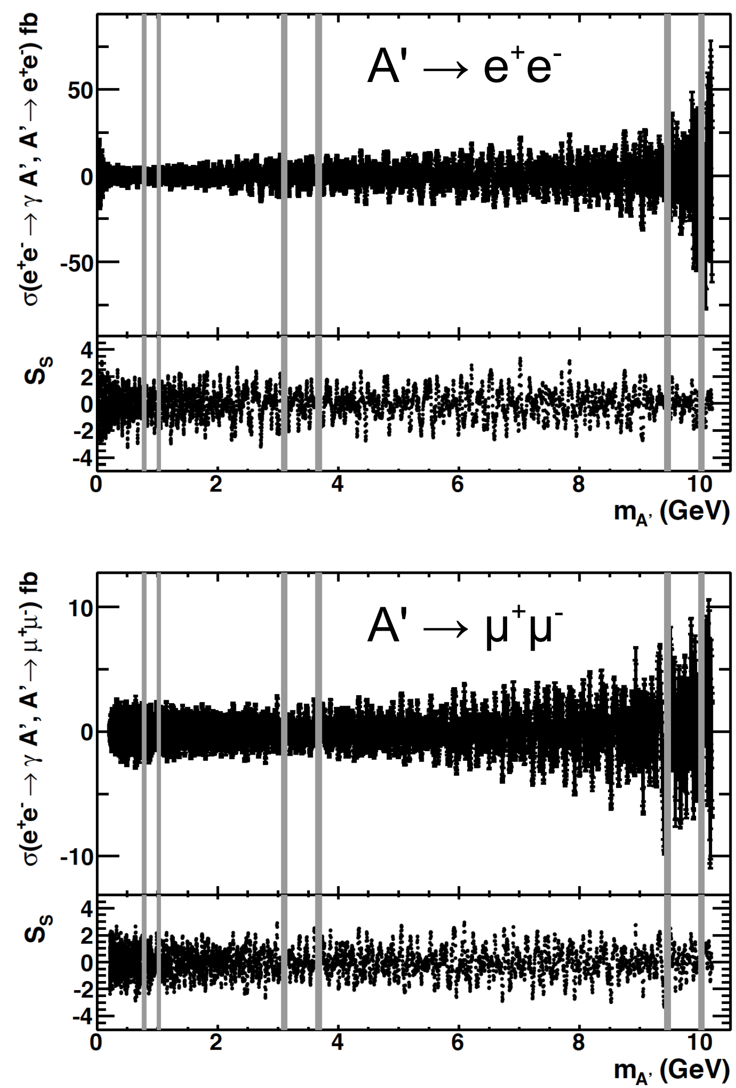
- Require photon energy >200 MeV
- Resonant backgrounds from J/ψ, $\psi(2S)$ etc but otherwise smoothly varying background, i.e. low reliance on simulation

Visible dark photon decays

Phys. Rev. Lett. 113, 201801 (2014)
arXiv:1406.2980 [hep-ex]

- Scan di-lepton invariant mass in the range $0.02\ \text{GeV} < m_{A'} < 10.2\ \text{GeV}$
- Obtain 90% C.L. upper limit on mixing strength ε as a function of A' mass at level of $O(10^{-3})$



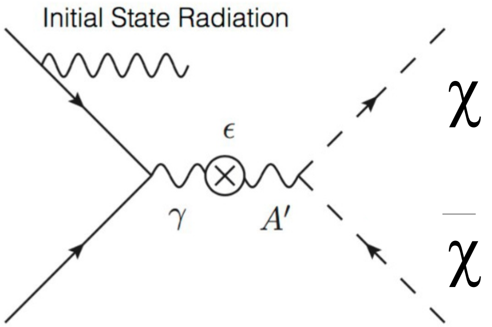


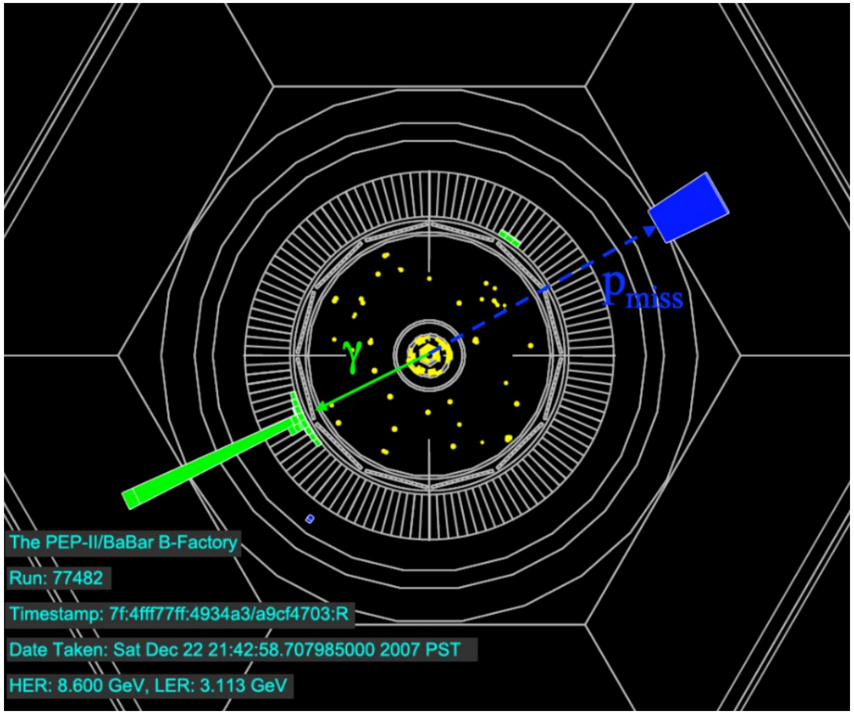
Invisible dark photon decays

Phys.Rev.Lett. 119, 131804 (2017)
arXiv:1702.03327 [hep-ex]

B Factories provide an excellent environment for missing energy searches

- Precisely known e^+e^- initial state
- Hermetic detector and good missing energy reconstruction





Search for invisible decay of $A' \rightarrow \chi\bar{\chi}$ via $e^+e^- \rightarrow \gamma A'$

- Final state contains only a single isolated photon in the detector
- A' mass determined from photon energy and CM energy:

$$E^*_\gamma = E^*_{beam} - \frac{m^2_{A'}}{4E^*_{beam}}$$

Invisible dark photon decays

NOT what B factories were designed to do...

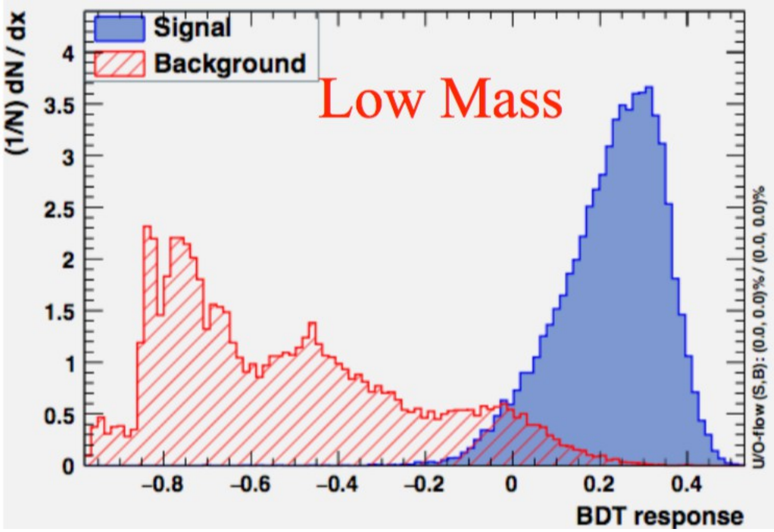
Phys.Rev.Lett. 119, 131804 (2017)
arXiv:1702.03327 [hep-ex]

- “Open trigger” intended to target higher-multiplicity BB hadronic decay events
- Single photon trigger only implemented during final running period (53 fb^{-1})
  - L1 (hardware) : 1 or more clusters with E_{lab} > 0.8 GeV
  - L3 (software): Two trigger lines: E_γ^* > 2 GeV or
    E_γ^* > 1 GeV and track veto

Backgrounds from $e^+e^- \rightarrow \gamma\gamma$ and $e^+e^- \rightarrow e^+e^-\gamma$ events with undetected particles

- Offline selection aims to suppress events containing additional detector activity

BDT:
- Signal cluster shape parameters
- Additional calorimeter energy
- Properties of the second most energetic cluster: E^*, θ^*, $\Delta\Phi^*$
- Properties of muon system cluster (E^*, θ^*, $\Delta\Phi^*$) closest to the missing momentum direction

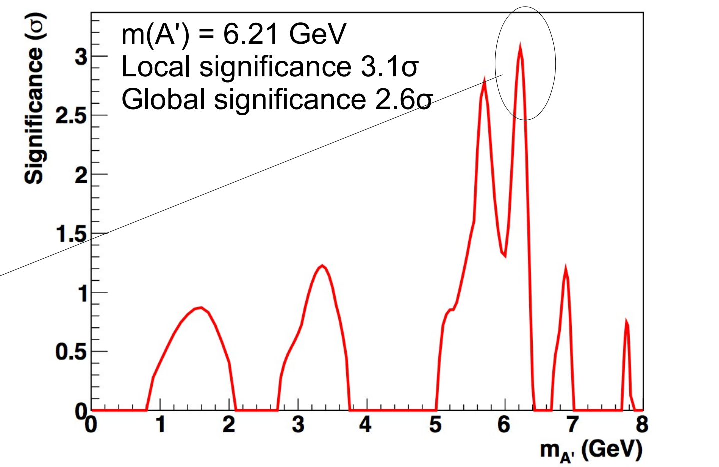


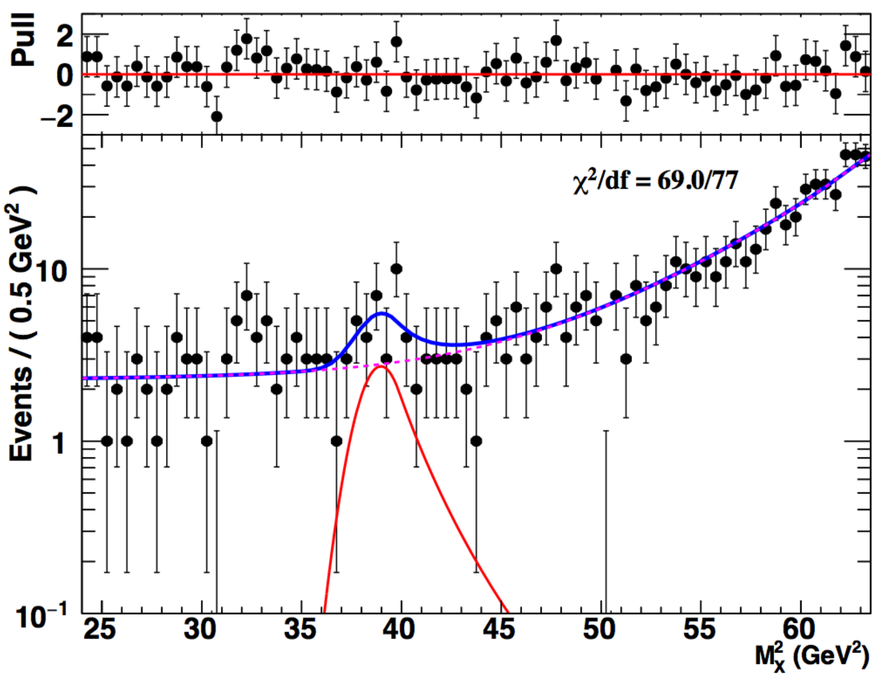
Invisible dark photon decays

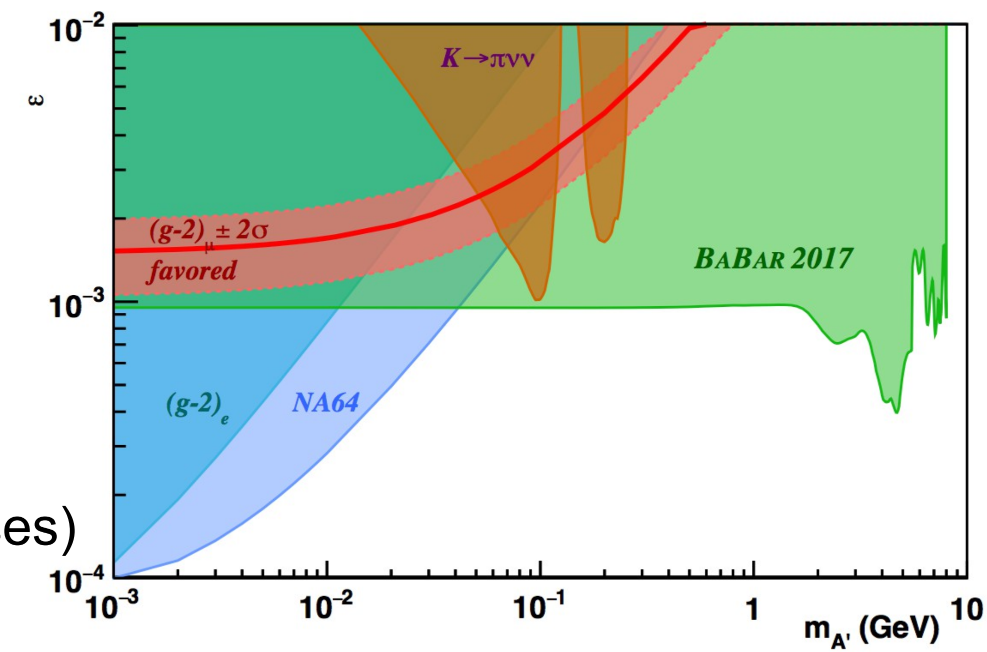
Phys.Rev.Lett. 119, 131804 (2017)
arXiv:1702.03327 [hep-ex]

Signal yield extracted from fits to the photon recoil mass

- Mass resolution driven by calorimeter resolution
- Background ultimately limited by detector hermeticity







No evidence of signal (116 mass hypotheses)

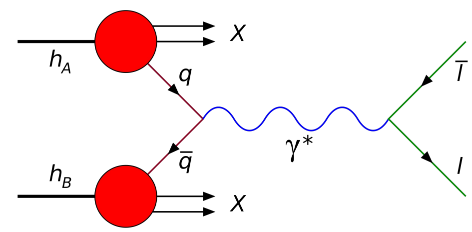
- Set limits on ε as a function of A' mass

Dark photon @ LHCb

Vector portal production of visible dark photon

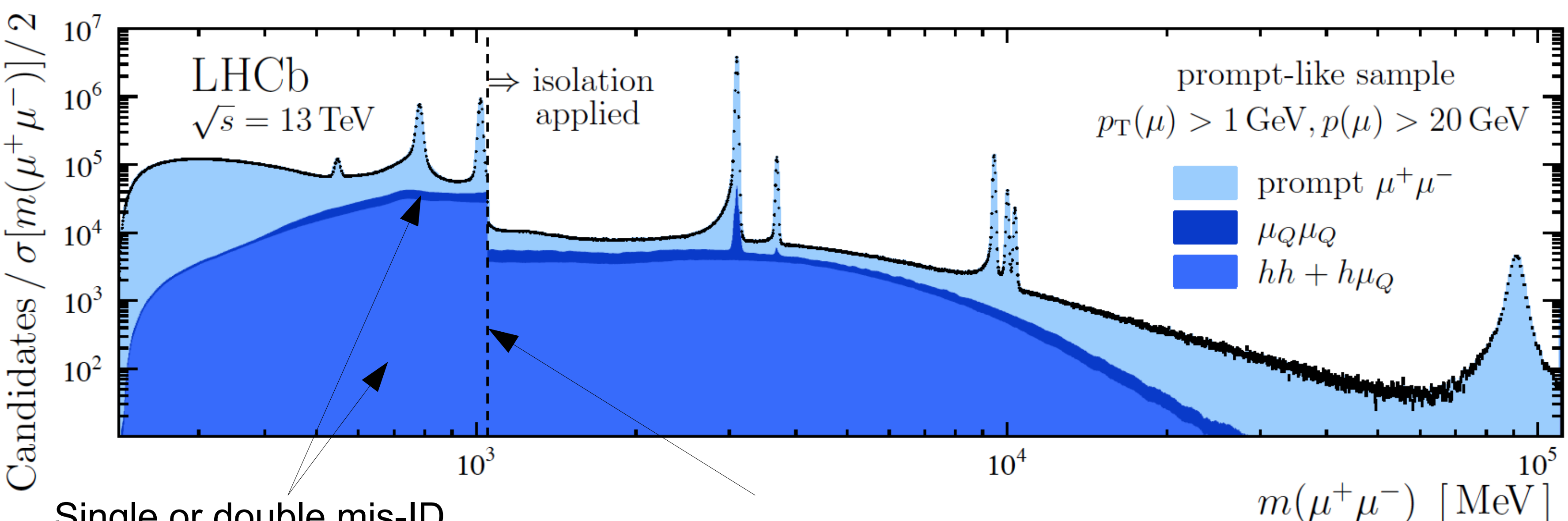
Phys. Rev. Lett. 120, 061801
arXiv:1710.02867 [hep-ex]
(13 TeV pp 1.6 fb^{-1})

- Same production and decay kinematics for $A' \rightarrow \mu^+\mu^-$ as $\gamma^* \rightarrow \mu^+\mu^-$



If $\tau(A')$ is small $A' \rightarrow \mu^+\mu^-$ are "prompt" and kinematically indistinguishable from $\gamma^* \rightarrow \mu^+\mu^-$

- "Bump hunt" in $\mu^+\mu^-$ spectrum:



Single or double mis-ID or muons from B hadron decays

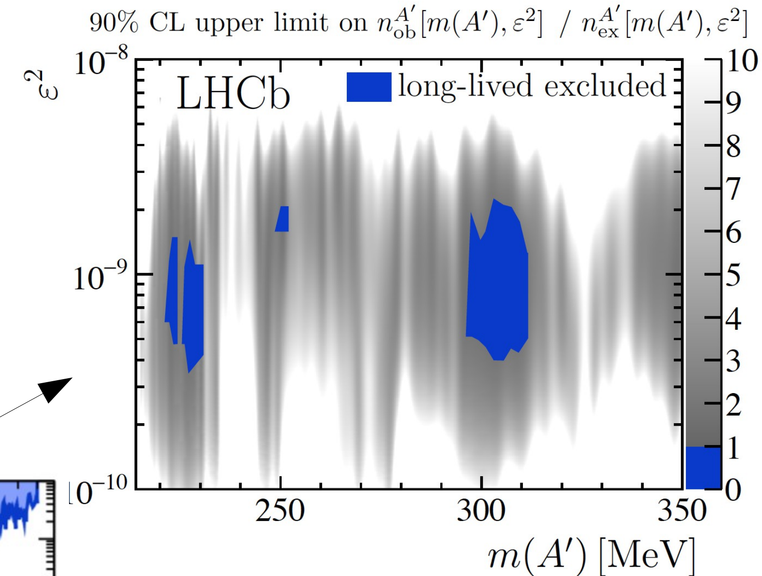
Isolation applied above Φ to reduce jet backgrounds (Drell-Yan $\gamma^* \rightarrow \mu^+\mu^-$ dominates)

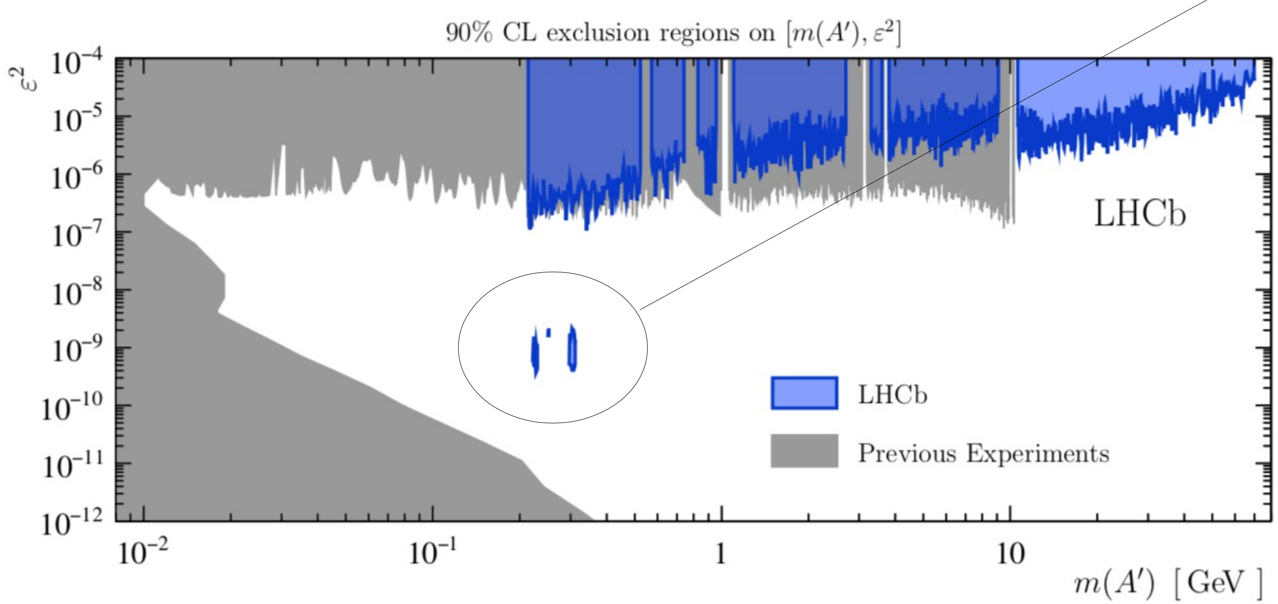
Dark photon @ LHCb

Phys. Rev. Lett. 120, 061801
arXiv:1710.02867 [hep-ex]
(13 TeV pp 1.6 fb[-1])

Alternatively, large $\tau_{A'} \sim 1/(\varepsilon^2 m_{A'})$ can lead to observable displaced vertex:

- Require individual muons to be inconsistent with originating from primary vertex, and use detailed vertex detector (VELO) map to veto material conversions
- Use BDT to suppress background from B hadrons (based on presence of additional tracks)





Long-lived A' search restricted to $214 < m_{A'} < 350$ MeV

- Relatively small regions of parameter space ruled out by displaced vertex search, but sensitivity expected to improve substantially with addition of data

Muonic dark force

Phys. Rev. D94 011102 (2016)
arXiv:1606.03501 [hep-ex]

Non-minimal dark sector models can permit additional interactions between dark boson and SM particles

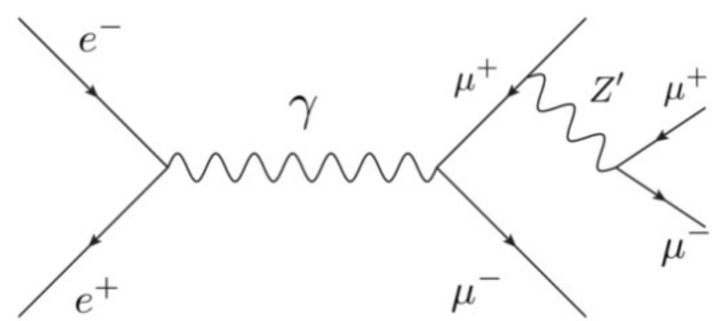
- Dark boson Z' which couples only to second and third generation leptons (SM fields are directly charged under dark force)

Motivated by various anomalies observed in the muon sector

- g-2 discrepancy
- could also account for dark matter as sterile neutrinos by increasing their cosmological abundance via new interactions with SM neutrinos.

"Z'-strahlung" production of a dark sector Z' in $e^+e^- \rightarrow \mu^+\mu^-$

$$e^+e^- \rightarrow \mu^+\mu^- Z' \,,\; Z' \rightarrow \mu^+\mu^-$$



However, no model assumptions in analysis; results are more generally applicable

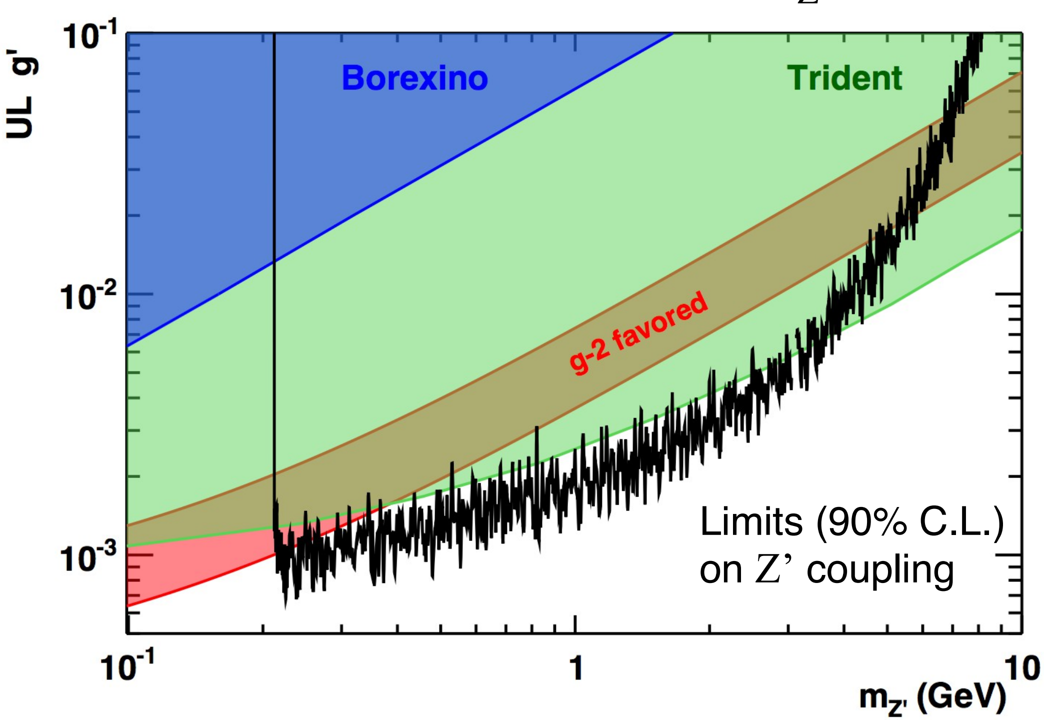
Muonic dark force

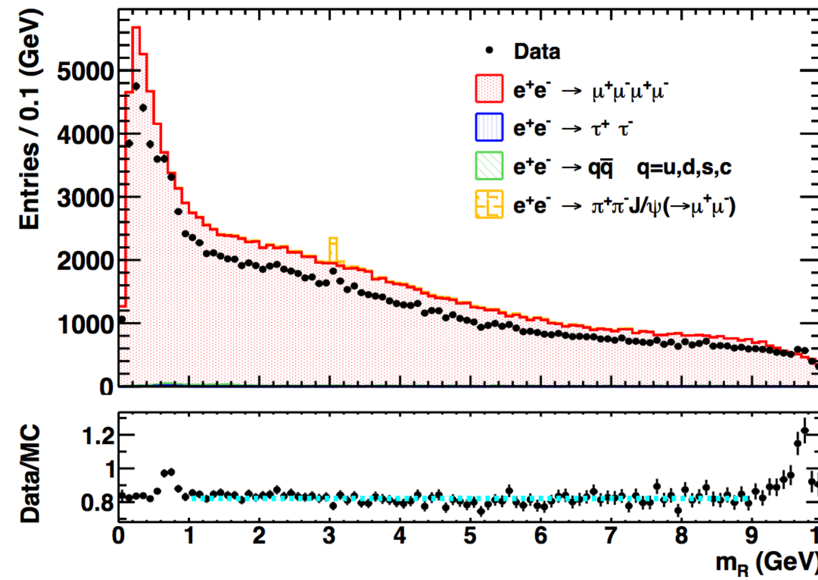
Phys. Rev. D94 011102 (2016)
arXiv:1606.03501 [hep-ex]

Search for a di-muon mass peak in
$e^+e^- \to \mu^+\mu^-\mu^+\mu^-$

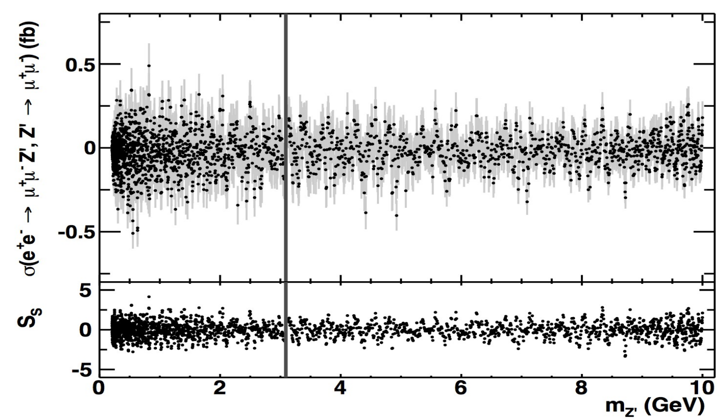
- QED combinatorial backgrounds, as well as peaking backgrounds from $e^+e^- \to \pi^+\pi^- J/\psi$ and ρ, but very little reliance on MC

- No signal observed; cross section limits obtained at 90% C.L. at level of ~0.2 fb below $m_{Z'}$ of 10 GeV





Di-muon reduced mass: $m_R = (m_{\mu\mu}^2 - 4m_\mu^2)^{1/2}$



First direct experimental limits on Z' coupling; excludes most of region favoured by g-2 results

Dark Higgs

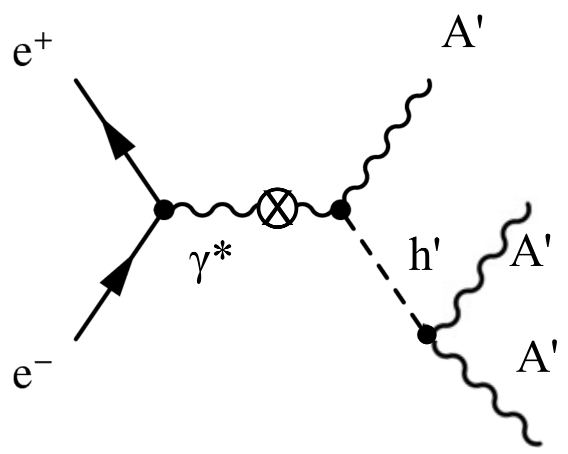
Phys. Rev. Lett. 114, 211801 (2015)
arXiv:1502.00084 [hep-ex]

Dark U(1) spontaneously broken by Higgs mechanism, resulting in one or more dark Higgs bosons h'

- Three possible scenarios:
  - $m_{h'} < m_{A'}$ leads to long-lived h' (decays to SM fermions)
  - $m_{A'} < m_{h'} < 2m_{A'}$; $h' \rightarrow A'A'^*$, with $A'^* \rightarrow l^+l^-$
  - $m_{h'} > 2m_{A'}$; $h' \rightarrow A'A'$

Belle analysis considers the third case

- Production via "Higgs-strahlung" in $e^+e^- \rightarrow A'h'$ with $h' \rightarrow A'A'$
- A' decaying to SM or invisible particles



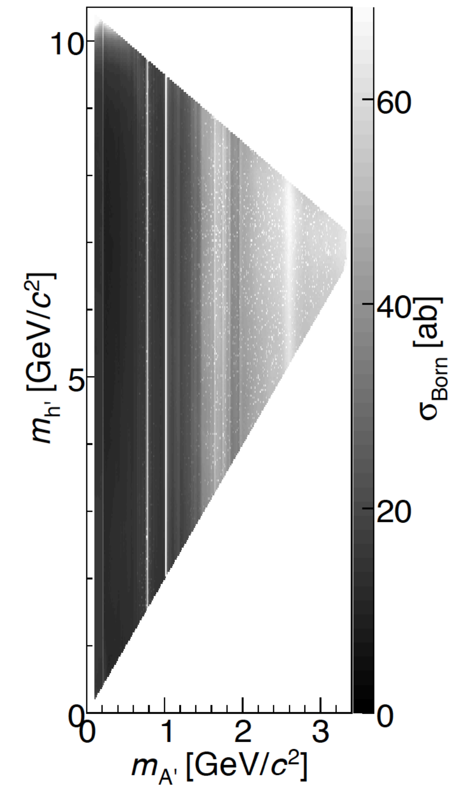
Previous *BABAR* study
Phys. Rev. Lett. 108, 211801 (2012)
arXiv:1202.1313 [hep-ex]

Dark Higgs

Phys. Rev. Lett. 114, 211801 (2015)
arXiv:1502.00084 [hep-ex]

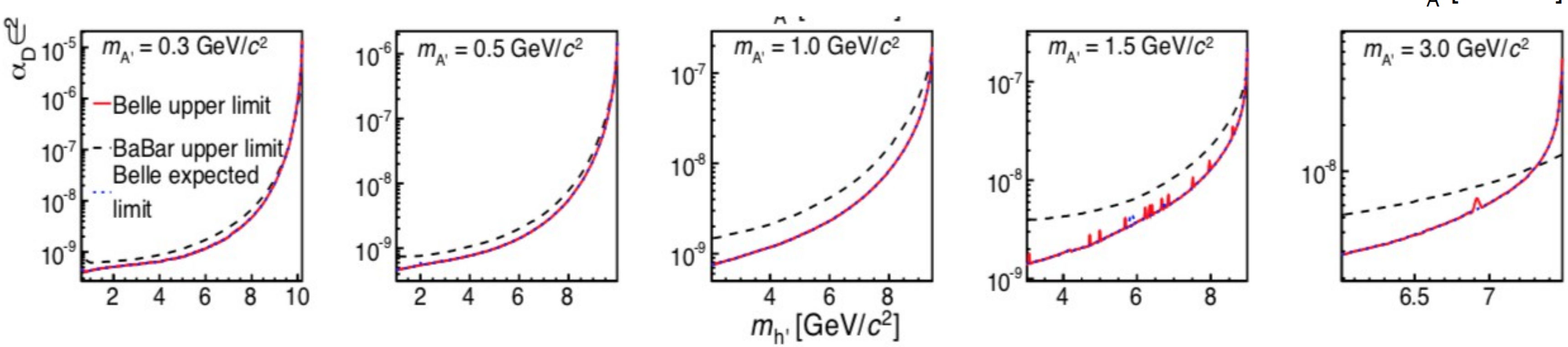
Experimentally, higher multiplicity final states and additional mass constraints results in very low QED backgrounds

- Vertex constraints enforce "prompt" production
- Require multiple pairs of oppositely charged particles
- Use event kinematics to determine missing mass in "invisible X" channels



Search for 13 final states including missing energy channels:

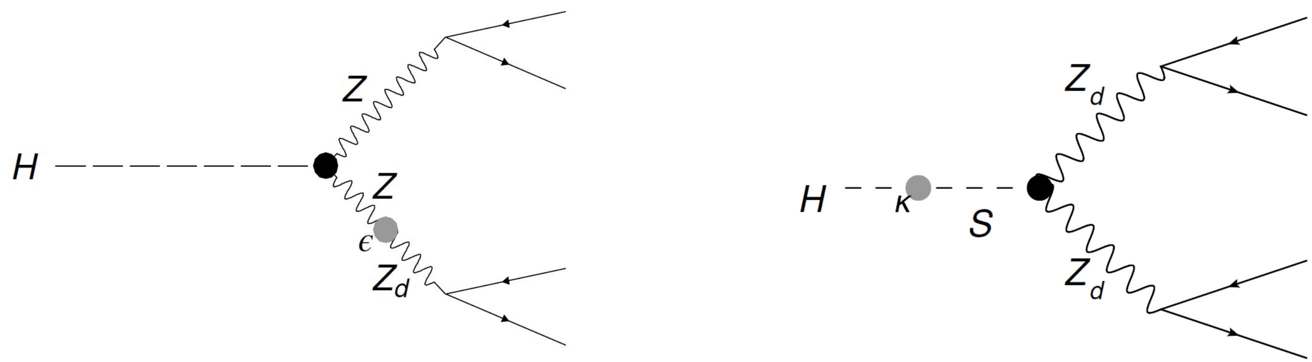
Final-state	Events	Final-state	Events
$3(e^-e^+)$	1	$2(\mu^+\mu^-)(e^+e^-)$	1
$3(\mu^+\mu^-)$	2	$2(\mu^+\mu^-)(\pi^+\pi^-)$	1
$3(\pi^+\pi^-)$	147	$2(\pi^+\pi^-)(e^+e^-)$	5
$2(e^+e^-)(\mu^+\mu^-)$	7	$2(\pi^+\pi^-)(\mu^+\mu^-)$	6
$2(e^+e^-)(\pi^+\pi^-)$	2	$(e^+e^-)(\mu^+\mu^-)(\pi^+\pi^-)$	7
$2(e^+e^-)X$	572	$(e^+e^-)(\mu^+\mu^-)X$	30
$2(\mu^+\mu^-)X$	20		



Higgs portal Z_d

JHEP 06 (2018) 166
arXiv:1802.03388 [hep-ex]

Dark gauge boson Z_d produced in decays of SM Higgs:



Vector portal:
SM Z mixing with Zd

Higgs portal:
SM H mixing with dark sector scalar S
(mixing parameter κ)

4 lepton signature, each with two opposite-sign lepton pairs:

- Require m_{12} = mZ; search for di-lepton resonance in m_{34}

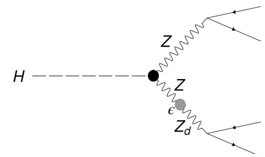
or

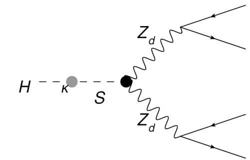
- Require consistent di-lepton mass in both pairs, m_{12} and m_{34}

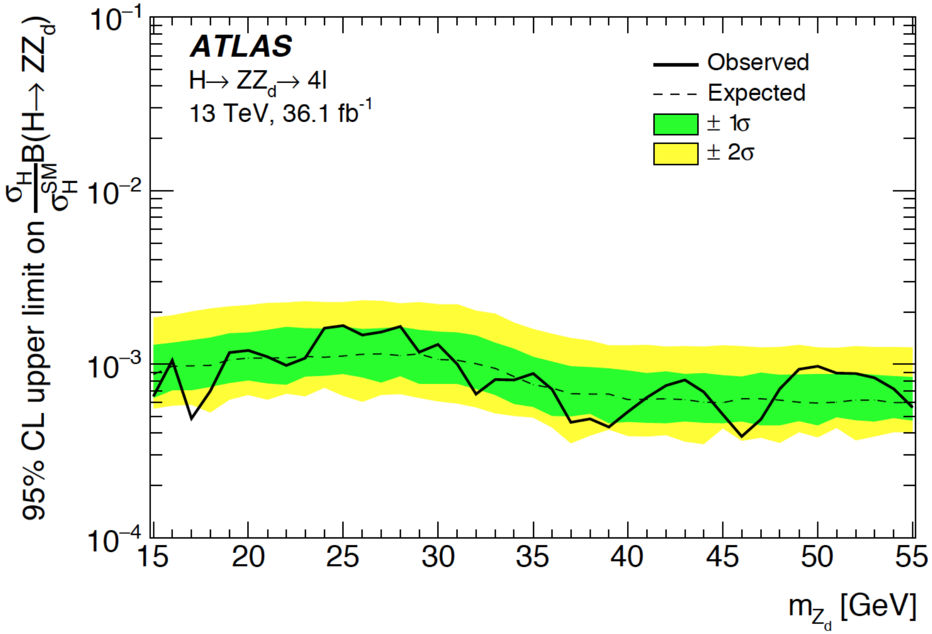
More generally, these are model-independent searches for H → ZX and H → XX, with X → l^+l^- interpreted in a dark sector context

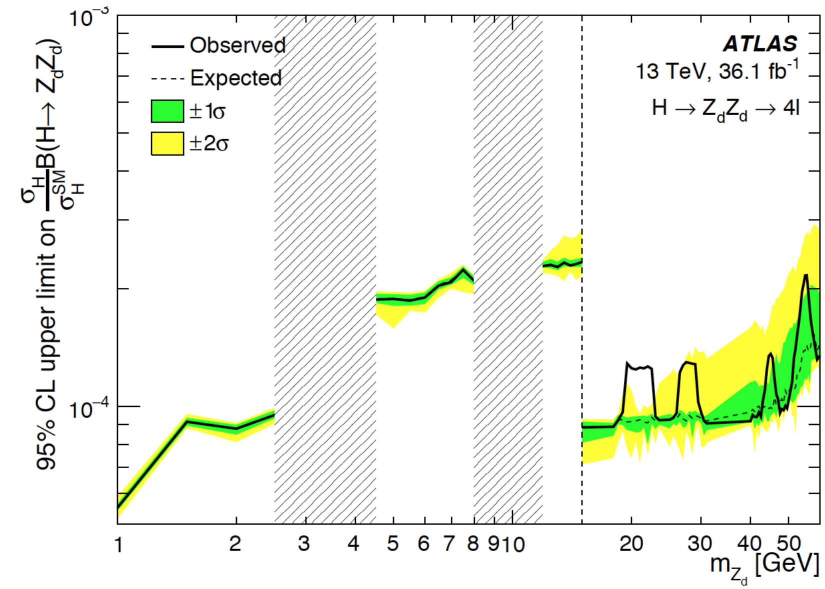
Higgs portal

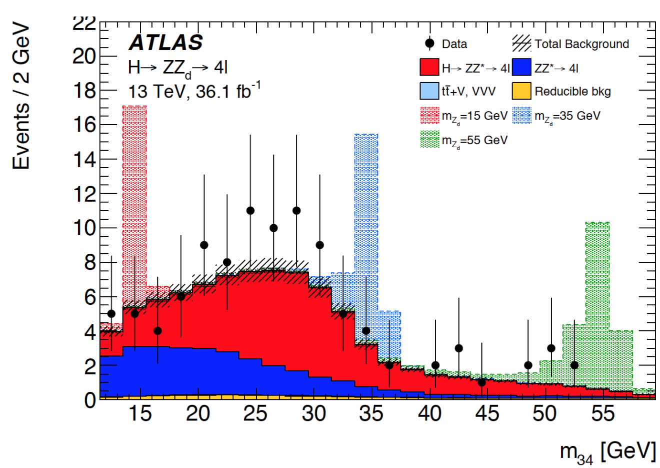
JHEP 06 (2018) 166
arXiv:1802.03388 [hep-ex]







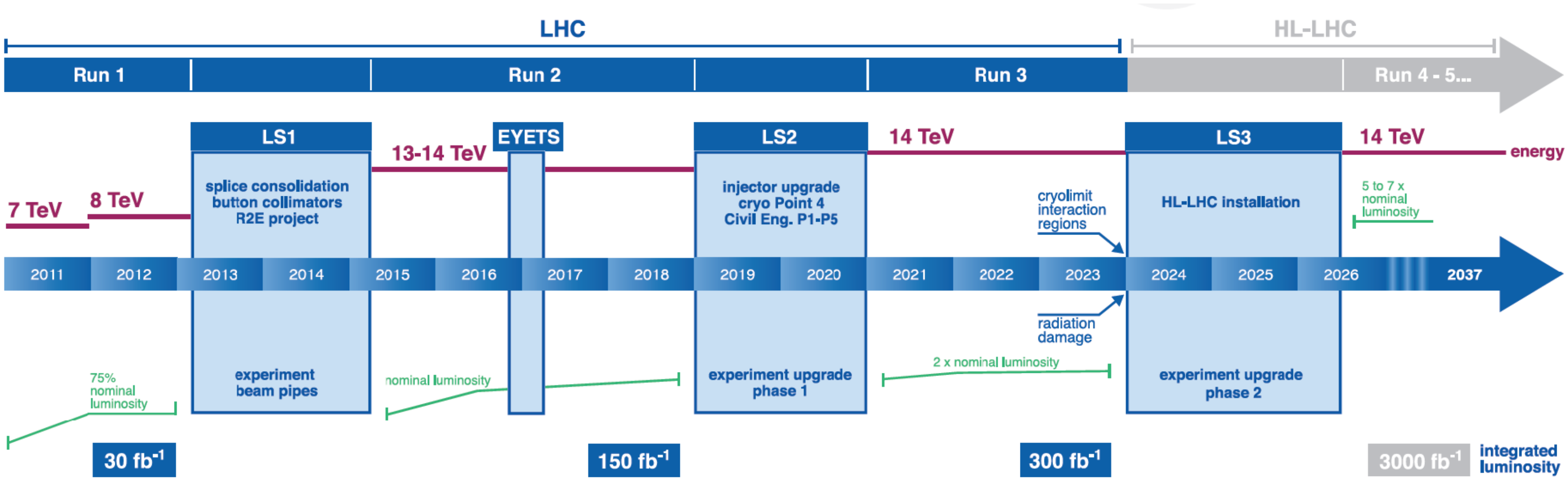




Results expressed as branching fractions relative to SM Higgs production

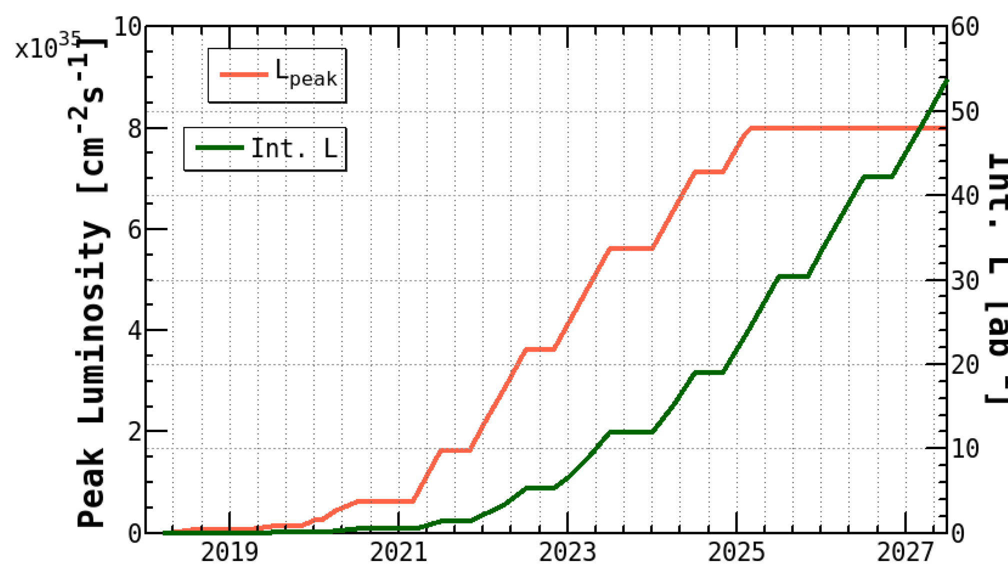
- Higgs portal probes to ~1 GeV Z_d range

Future



Substantial new data with upgraded detectors to become available in the coming decade

- LHC Run3 ~300fb^{-1}
- Belle II ~50ab^{-1}



Belle II

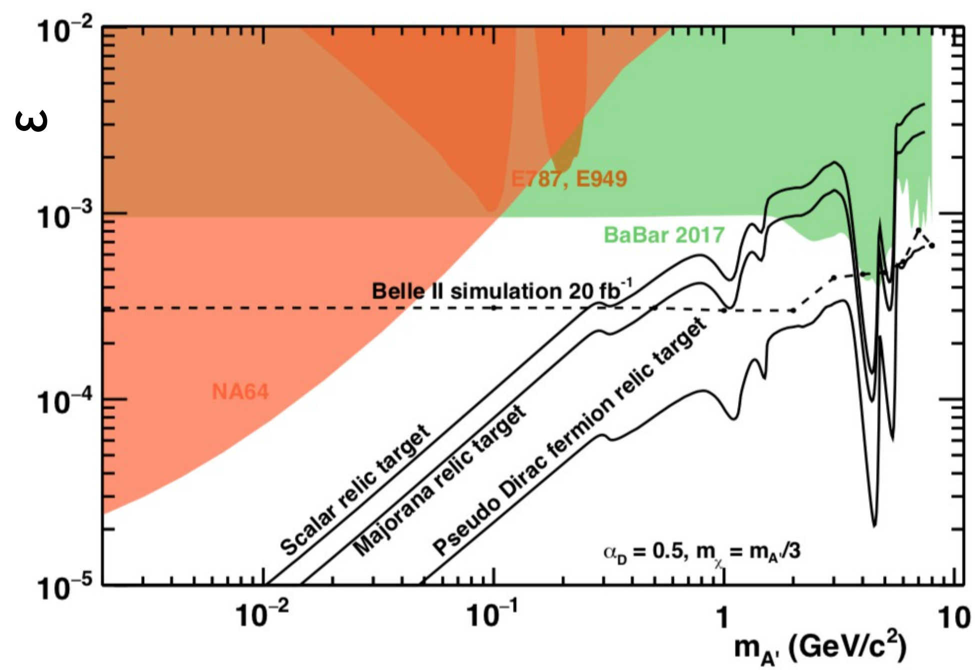
arXiv: 1808.10567 [hep-ex]

Belle II will operate in a similar experimental environment to previous generation of B factories, but at considerably higher luminosity

- Active experimental effort to study dark sector (see talk by C. Hearty)
  - Development of hardware and software triggers for low multiplicity channels (e.g. single photon)
  - Detector performance studies (e.g. Calorimeter hermeticity)

Invisible dark photon anticipated to be competitive with relatively little data

- *BABAR* result based on ~50 fb^{-1}
- Improved calorimeter hermeticity

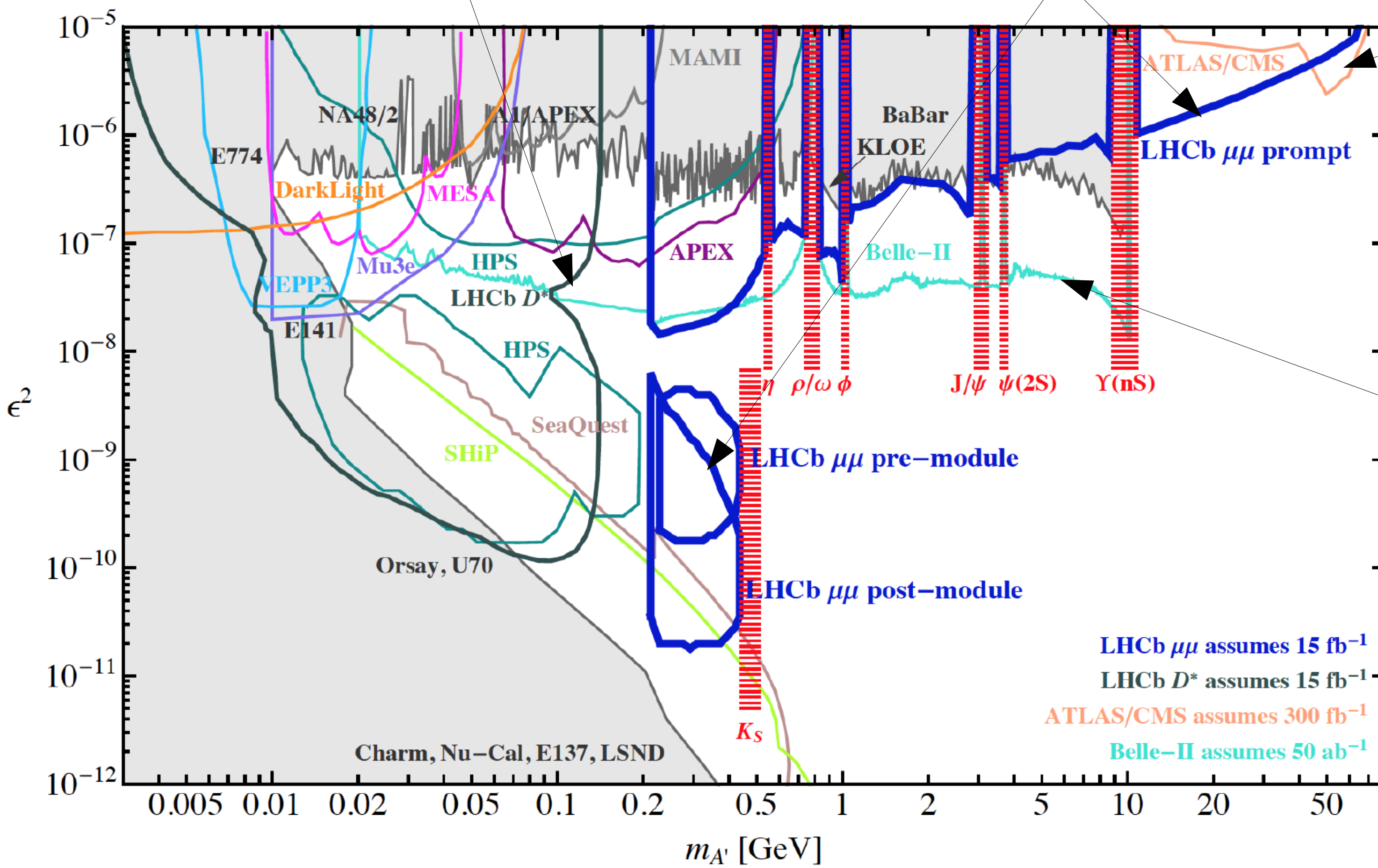


Visible dark photon prospects

Phys. Rev. Lett. 116, 251803
arXiv:1603.08926 [hep-ex]

$D^{*0} \rightarrow D^0 e^+ e^-$
(prompt and displaced)

$A' \rightarrow \mu^+ \mu^-$



Similar methodology can be used by CMS and ATLAS (bump hunt in di-muon spectrum)

Belle II projection

Light meson Dalitz decays

$\pi^0,\ \eta \rightarrow e^+ e^- \gamma$

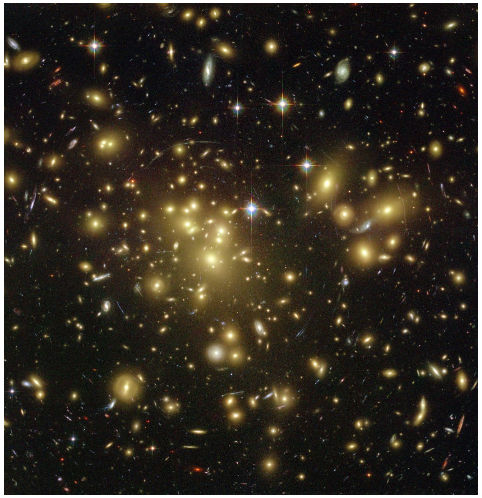
Conclusions

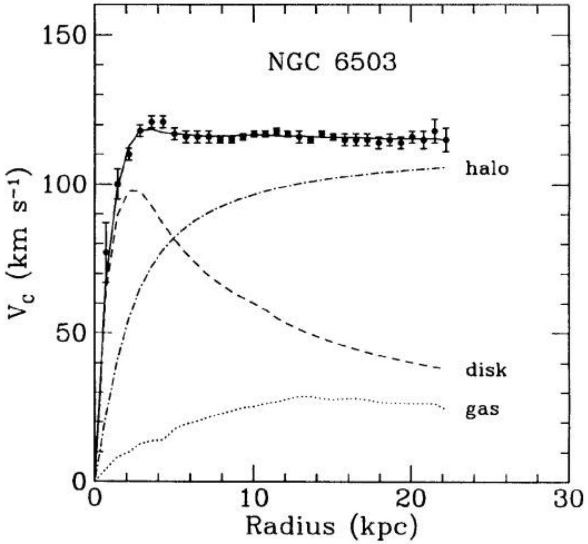
Experimental searches are providing a unique window on the existence of a possible light dark sector

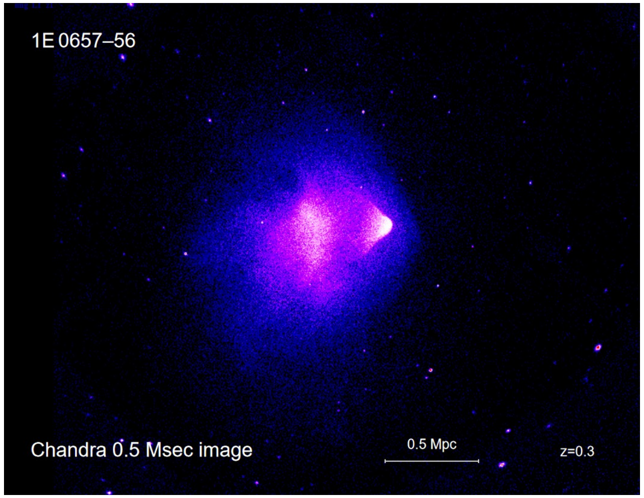
- Searches typically "bump hunts" in distinctive decay topologies, with relatively little model dependence or reliance on simulation
  - Either dedicated searches or "re-casting" of related Z' searches
- Future experiments and search techniques (e.g. LHC data scouting) promise interesting sensitivity to low mass and long-lived mediators
  - Belle II (see talk by C. Hearty) and LHC run 3

Backup slides

Dark matter

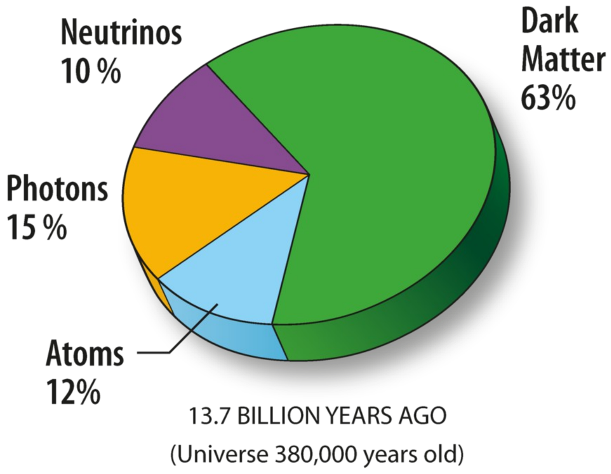






Although astronomical evidence for non-luminous dark matter is overwhelming, all measurements to date are gravitational in nature

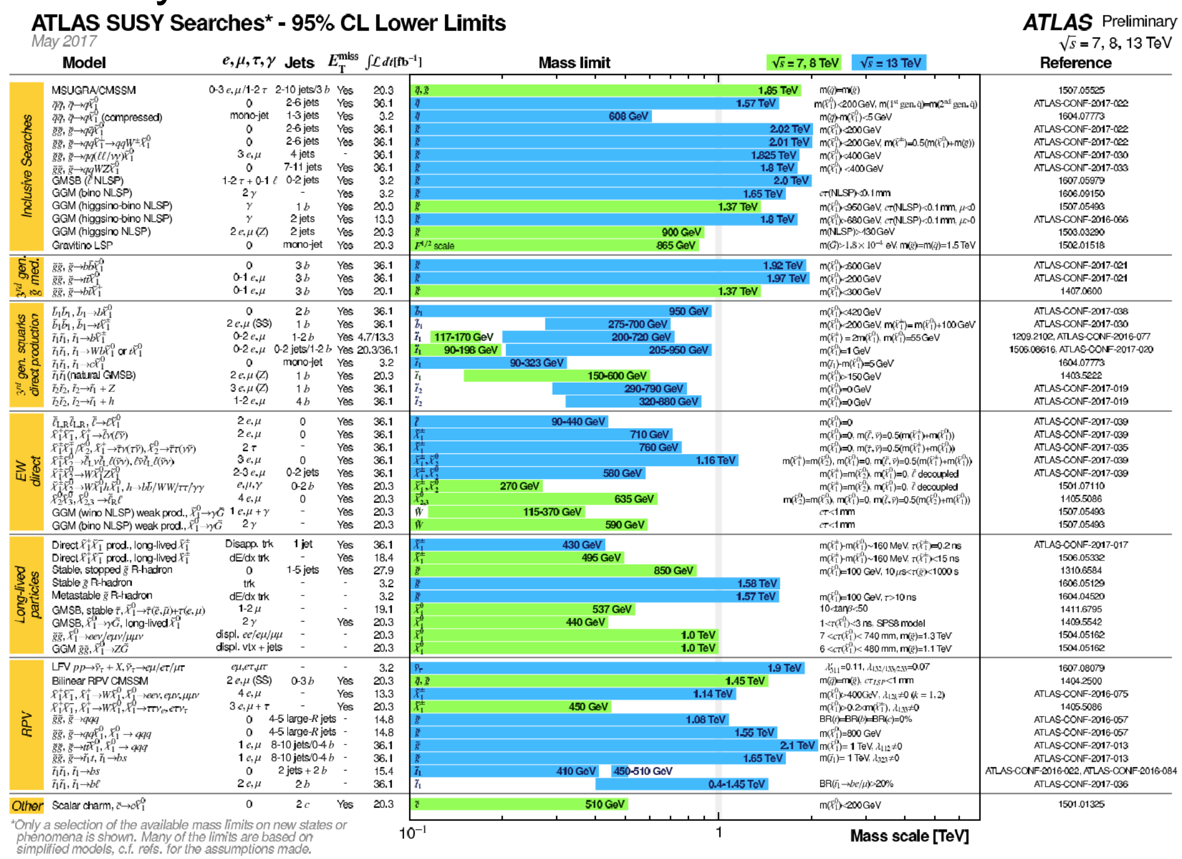
- Clearly DM does not interact via strong or EM forces
- Not known if DM interacts via weak force or the (SM) Higgs field



WIMP-candidate searches

"WIMP miracle" suggestive of possibility that dark matter may relate to TeV-scale new physics

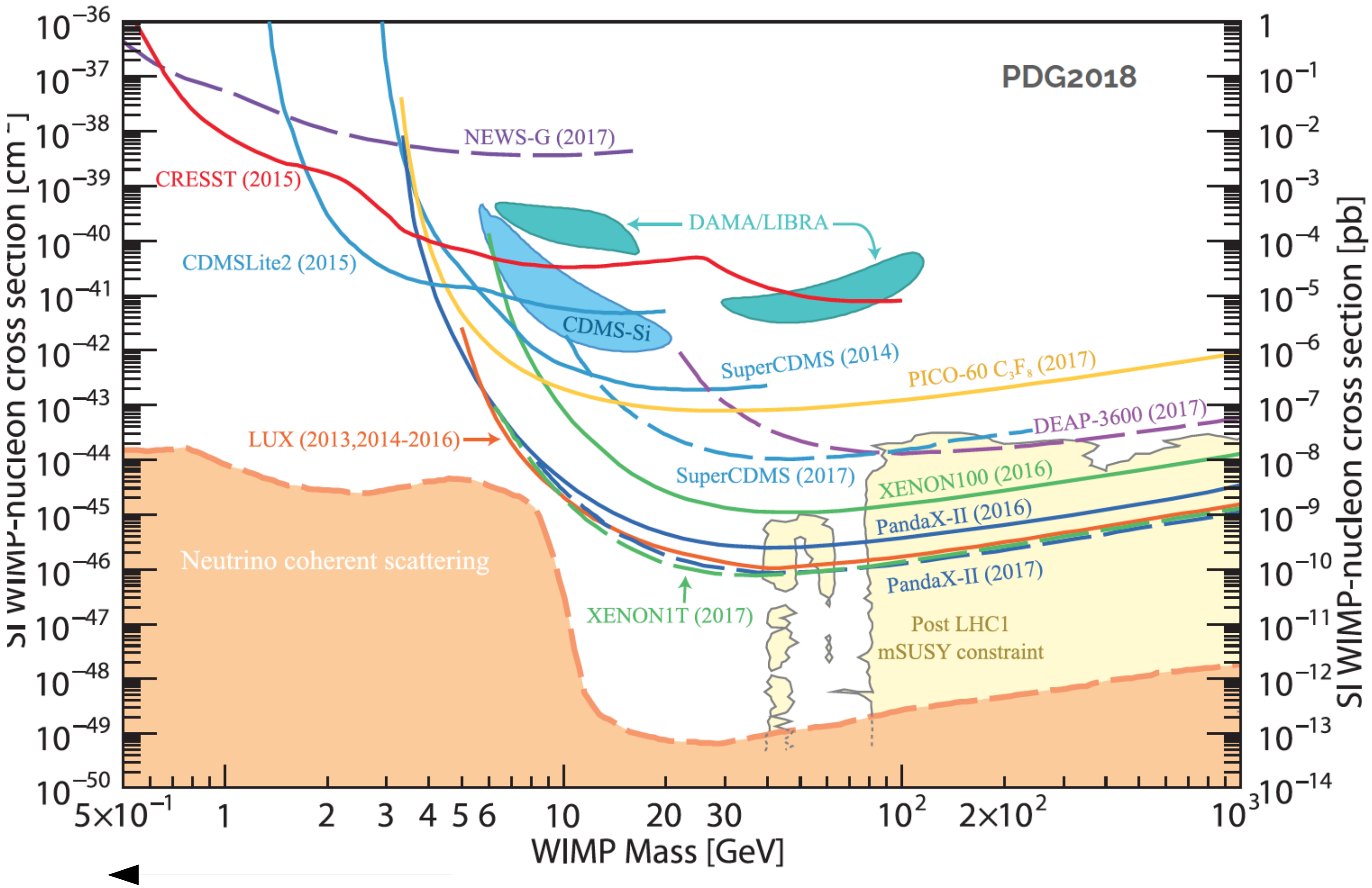
- Dark matter candidate with weak-scale masses and couplings would yield correct relic density



...but no convincing evidence of TeV-scale new physics which would provide stable dark matter candidates

WIMP "direct" searches

Similarly, no indication so far of WIMP dark matter in dark matter direct search experiments



If DM is too light, it may need its own mediator

$\sigma_{ann} \propto m_{DM}^2/m_{med}^4$

Dark sectors

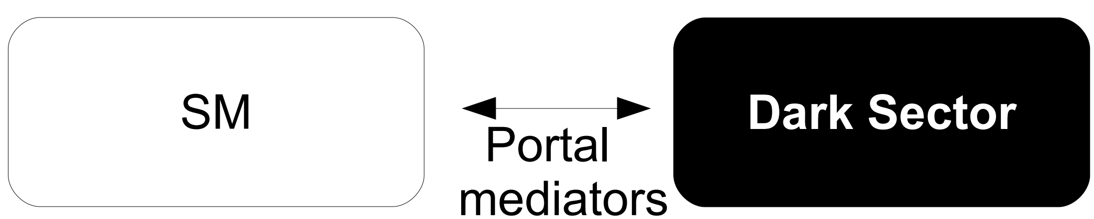
Maybe dark matter is not specifically related to solution to problems of the SM and is, in effect, a distinct "sector"

- Dark sector fermions which carry charges for non-SM gauge interactions, possibly acquiring mass via dark sector Higgs etc.
- EFT provides a number of "portals" to access this dark sector

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H \left(AS + \lambda S^2\right) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

Vector portal   Higgs portal   Neutrino portal



Dark sector can be probed via mixing of the portal mediators with SM bosons