Dark Sector Phenomena

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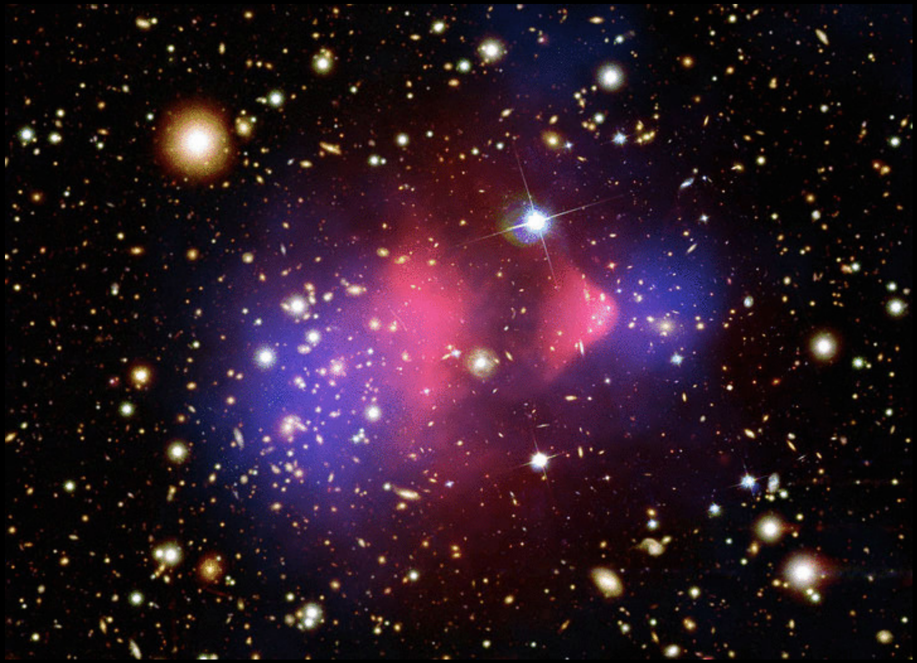


Belle II Summer School, Physics Department, BNL

August 1, 2019

BROOKHAVEN NATIONAL LABORATORY

$\hbar \approx 1.05 \times 10^{-34}$ J s ; $c \approx 3.0 \times 10^{8}$ m/s

In this talks (particle physics in general): $\hbar = c = 1$

Energy $\leftrightarrow$ Momentum $\leftrightarrow$ Mass measured in eV

Time $\leftrightarrow$ Length $\leftrightarrow$ 1/Mass

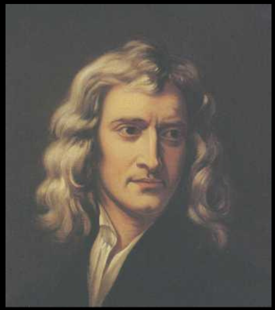
GeV (Giga eV) $= 10^{9}$ eV

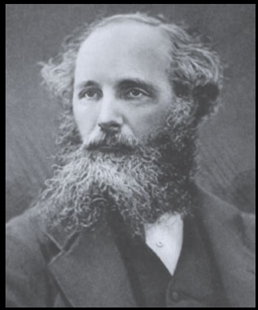
proton mass ≈ 1 GeV

TeV (Tera eV) $= 10^{12}$ eV

Everyday life: Gravity and Electromagnetism

For most everyday purposes Newtonian gravity and Maxwell's equations suffice





State of the Art for Gravity: General relativity (GR)

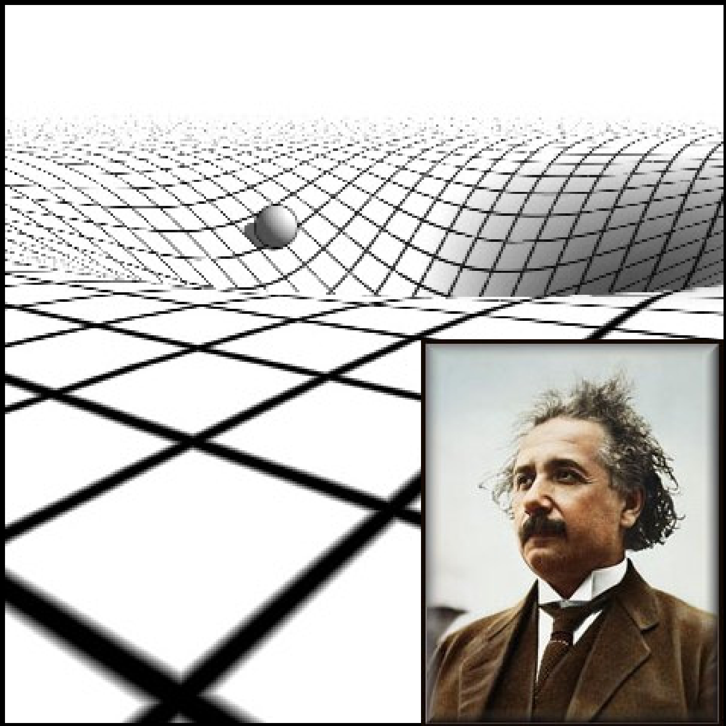
- Spacetime curved by matter/energy.

Sun

- Gravitational Force → Geodesic.

Earth's Orbit

- Basis of modern cosmology.



Einstein's equations:

Curvature $$\mathcal{G}_{\mu\nu} = 8\,\pi\,G_N\,\mathcal{T}_{\mu\nu}$$ Energy Distribution

G_N Newton's constant, $\mu, \nu = 0, 1, 2, 3$ (spacetime).

The Standard Model (SM):

Most precise description of microscopic physics

- **Gauge symmetry:** $SU(3)(\text{strong}) \times SU(2) \times U(1)(\text{electroweak})$

Vacuum: $SU(3) \times U(1)_{\text{EM}}$

- **Elementary fermions, spin-1/2**

Quarks $(+2/3, -1/3)$: Strong interactions

Leptons $(0, -1)$: No strong interactions

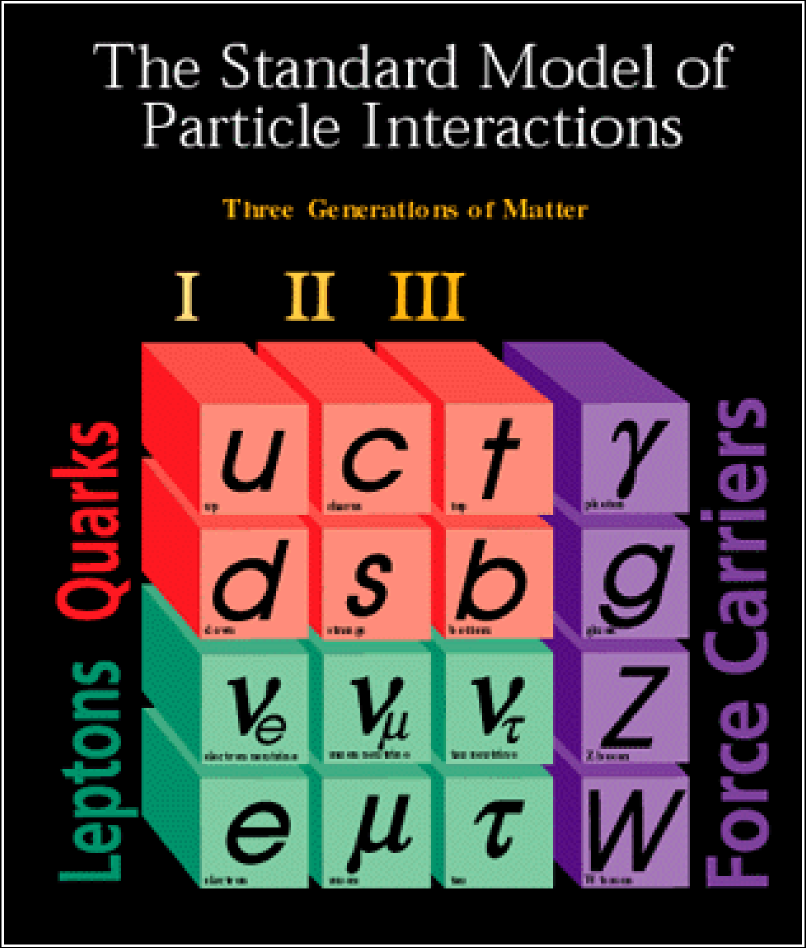
- **Gauge Fields, spin-1**

Force mediators, generalized photons

- **Higgs field, spin-0**

$SU(2) \times U(1) \to U(1)_{\text{EM}}$;
elementary particle masses (but $m_\nu = 0$)

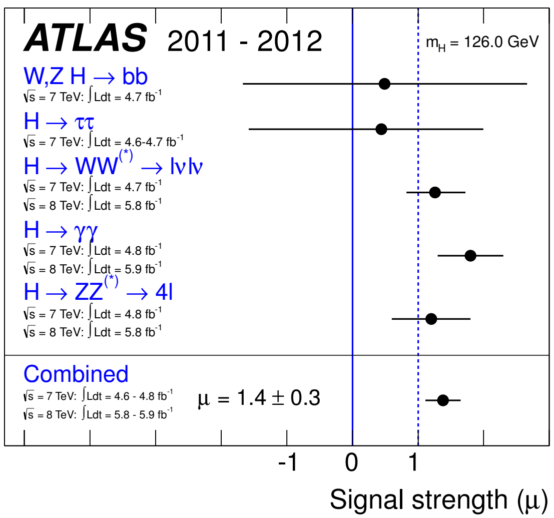
Q: Would the proton mass vanish if the Higgs field was turned off?

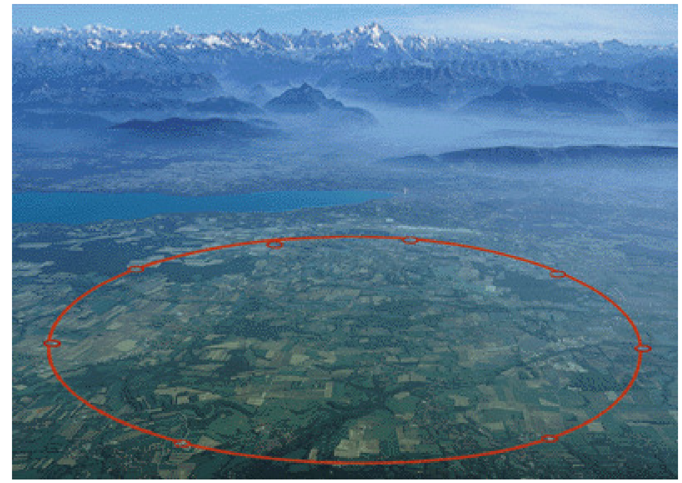


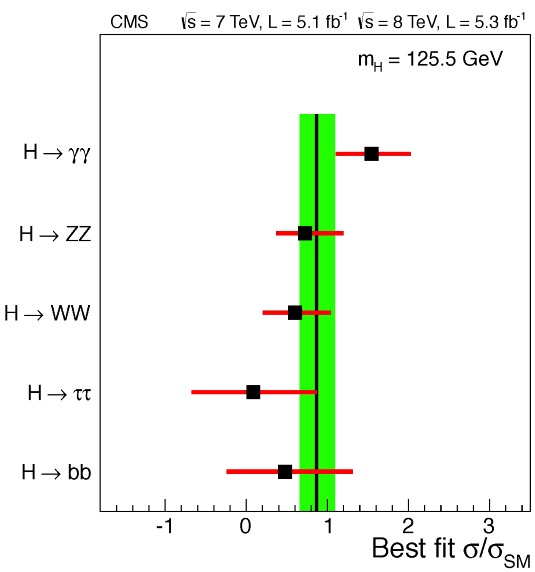
(Pre 2012)

July 4th, 2012, discovery announced at CERN:

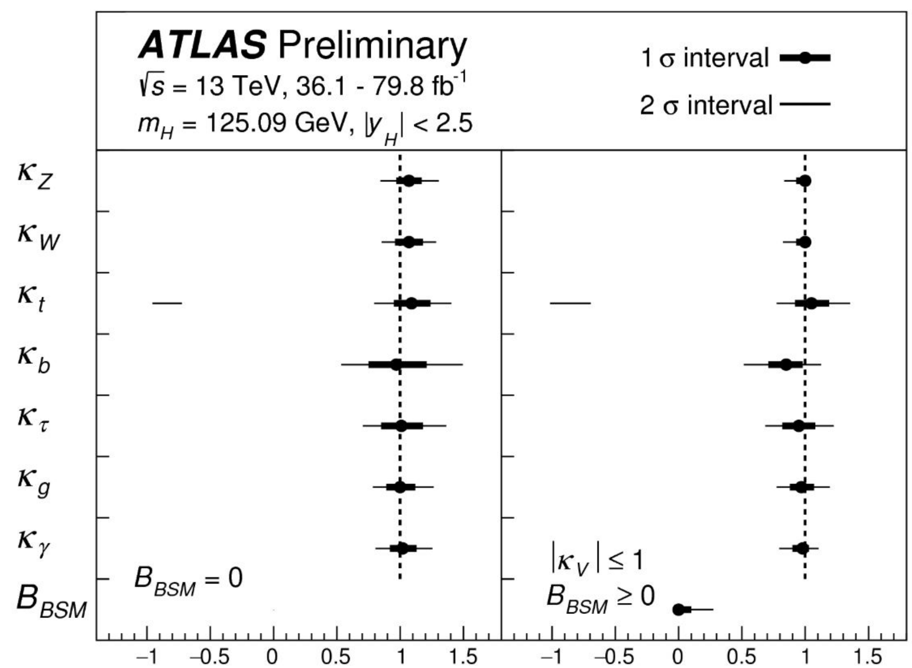
New scalar H discovered at ~ 125 GeV!







Early Run 1: ~ 10 fb^{-1}



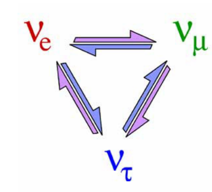
Run 2 data, ATLAS-CONF-2018-031

Standard Model:

A successful theoretical framework confirmed by numerous experiments, but an incomplete description of Nature

- **Strong Empirical Evidence**

- Neutrino flavor oscillations $\Rightarrow m_\nu \neq 0$



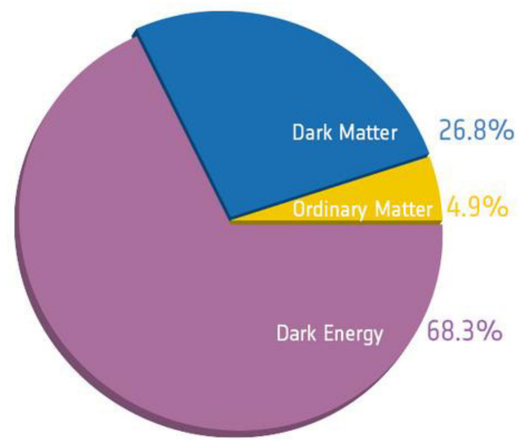
- In minimal SM $m_\nu = 0$

- Dark matter (DM)

- No candidate in SM

- $\sim 68\%$ *dark energy*; could be vacuum energy

Planck



. . .

$\sim 95\%$ of Cosmos: Unknown!

- **Theoretical Hints**

- Why is gravity so weak? That is, why $M_P/M_W \sim 10^{17}$?

- The "hierarchy problem"

. . .

Dark matter

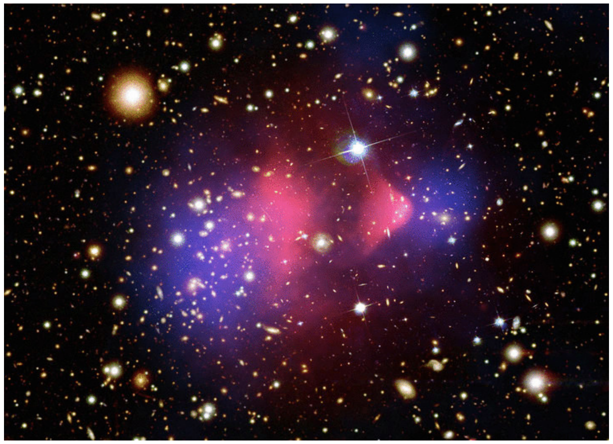
- $\sim 27\%$ of energy density

- Robust evidence from cosmology and astrophysics

  - CMB, BBN, rotation curves of galaxies, lensing, Bullet Cluster, . . .

- **Unknown origin**

  - Cosmologically stable
  - Feeble interactions with atoms, light
  - Self-interactions not strong ($\sigma \lesssim 1$ barn)
  - Not explained in SM



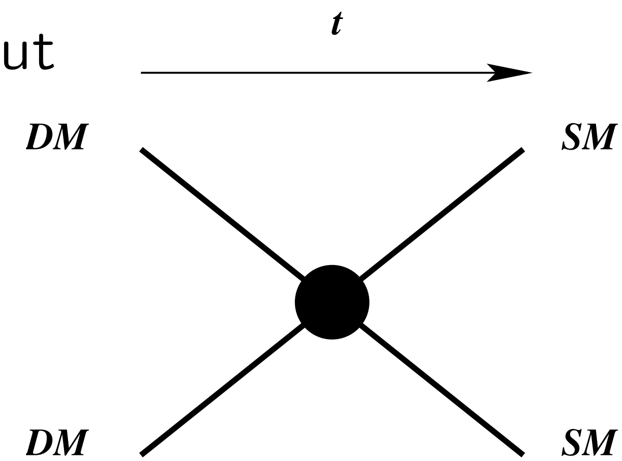
Strongly motivates new physics

- *So far, evidence limited to gravity effects*

- *Possible DM mass scale:* 10^{-22} *eV* $\lesssim M_{\mathrm{DM}} \lesssim 10^{68}$ *eV*

Weakly Interacting Massive Particles (WIMPs)

- Thermal relic density: annihilation, freeze-out



- $\rho_{\text{WIMP}} \propto 1/\sigma_{ann}$

- $\sigma_{ann} \sim g^4/M^2$

- $g \sim g_{\text{weak}}$, $M \sim$ TeV: roughly the right amount of DM

- Weak scale ($\sim$ TeV) theoretically motivated (close to M_H)

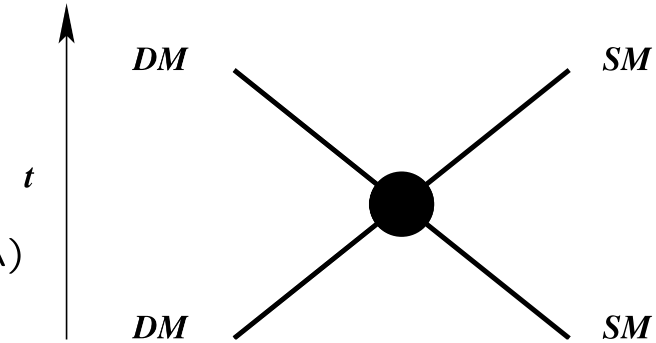
- Possible connection to EW physics, resolution of "hierarchy problem"

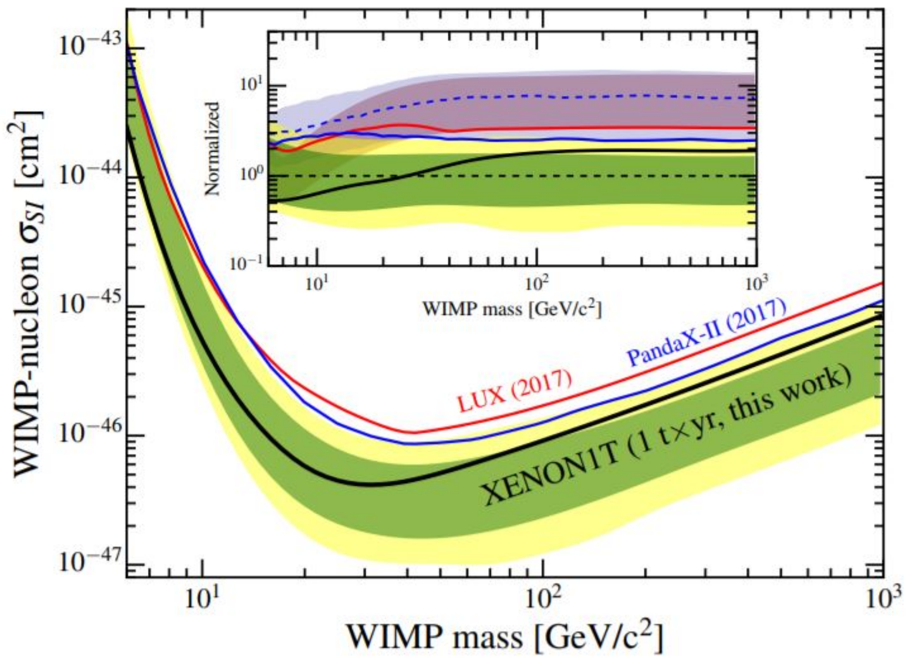
- WIMPs: focus of various searches over the years

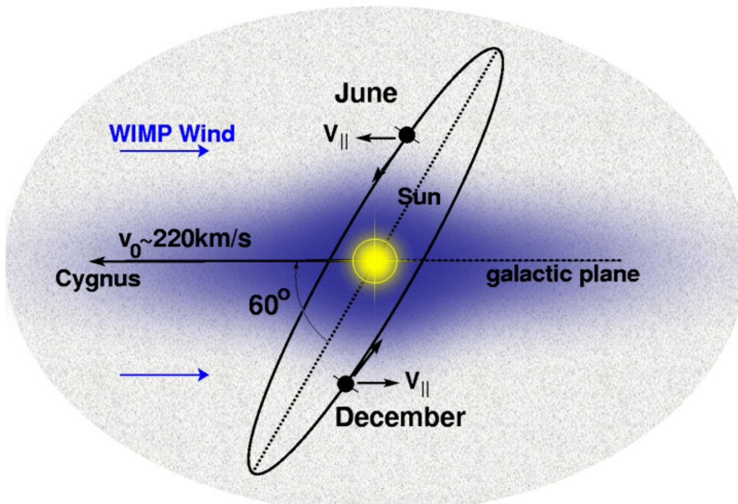
- However, so far no conclusive signals

Direct WIMP DM Searches

- Recoil off atomic nuclei (electrons)
  - Energy deposition (ionization, scintillation, . . .)
  - Motion of Sun within Galaxy: WIMP wind
  - Earth's motion: seasonal modulation (DAMA/LIBRA)







E. Aprile *et al.* [XENON Collaboration], Phys. Rev. Lett. **121**, no. 11, 111302 (2018)

- General feature: $m_{\rm DM} \lesssim$ **few GeV** poorly constrained (low recoil energy)

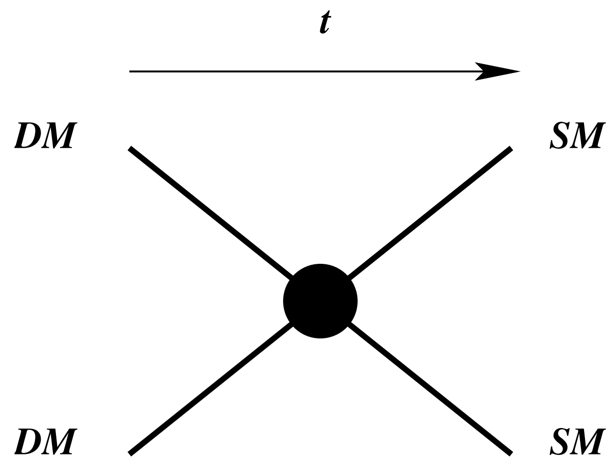
Q: Why does the constraint get weaker with larger WIMP mass?

Other avenues for WIMP search:

- Indirect searches: self-annihilation signals

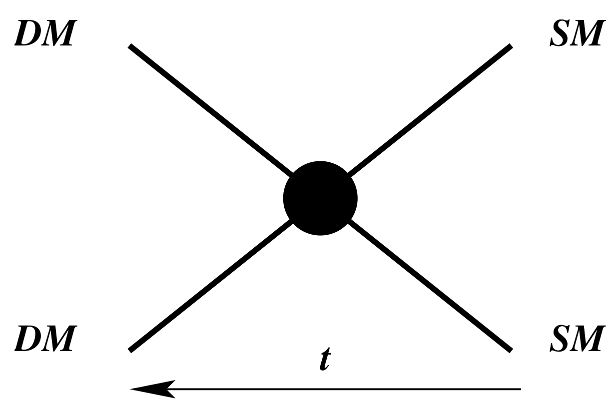
- Related to thermal relic density

- Complicated by astrophysical backgrounds



- Collider production: LHC

- Search for missing energy in events



Possible Dark Sectors

- No firm sign of new physics around TeV scale at LHC (or elsewhere)

- WIMP motivation was partly tied to the new physics close to M_H

- SM ($\sim$ 5%) has various particles and forces

- Perhaps DM ($\sim$ 27%) not an extension of SM and has its own sector, with multiple particles and forces

- Many possibilities, but one could start from a simple one:

- New $U(1)_d$ force: Dark analogue of $U(1)$ electromagnetism

- "Dark Photon" γ_d force carrier (sometimes denoted by $\mathbf{Z_d}$ or $\mathbf{A}'$ in this talk)

- DM: Dark sector particle χ charged under $U(1)_d$

- Dark gauge coupling g_d; in analogy with QED define: $\alpha_d \equiv g_d^2/(4\pi)$

- Certain astrophysical data might originate from DM annihilation

- Some models suggest that this could be mediated by $m_{\gamma_d} \lesssim 1$ GeV

For example, Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

- DM, if not tied to EW physics, may also be light $m_\chi \lesssim 1$ GeV

- In general, it would be interesting to consider light (GeV scale) DM

- New avenues for experiments at low energies

\- For example, flavor physics experiments like Babar, Belle, Belle II, ...

- GeV-scale dark particles: other possible hints of new physics

\- For example, the measured (BNL E821) muon anomalous magnetic moment $g_\mu - 2$ has a current ~ 3.5 standard deviation (σ) from SM prediction

Fayet 2007, Pospelov 2009

Dark Sector Interactions with the Visible World

• To find a signal of the dark sector, it needs to communicate with the visible world (SM sector)

• If these are two distinct sectors, the interactions are indirect

• Typically, such indirect couplings would be suppressed by large mass scales, *e.g.* coupling quarks to "dark quarks"

$$\frac{\overbrace{[\bar{Q}\gamma^{\mu}Q]}^{\text{visible}}\overbrace{[\bar{Q}_d\gamma_{\mu}Q_d]}^{\text{dark}}}{M^2}$$

Interactions in a "Lagrangian density" have mass dimension 4: $\int d^4x\mathcal{L} \to S$, $[S] = [\hbar] = 1$

Quark kinetic term $\bar{Q}\gamma^{\mu}\partial_{\mu}Q \in \mathcal{L} \to [Q] = 3/2$

At low energies $E \ll M$ interaction suppressed by $E^2/M^2 \ll 1$

• There are a few types of interactions – often called "portals" – that avoid the above situation

Portal Interactions

These interactions have mass dimension 4 and are not suppressed by large masses, can provide a connection to "dark" or "hidden" sectors

- Higgs Portal to another scalar sector: $\boxed{\xi H^\dagger H \Phi^\dagger \Phi}$

($[\partial_\mu H^\dagger \partial^\mu H] = 4 \Rightarrow [H] = 1$)

- Kinetic mixing of $U(1)_Y$ with another ("dark") $U(1)'$: $\boxed{\varepsilon\, F^Y_{\mu\nu} F'^{\mu\nu}}$

Holdom, 1986

($[F_{\mu\nu}] = 2$)

\- Leads to $\gamma - \gamma_d$ mixing. Note: $m^2 A_\mu A'^\mu$ not gauge-invariant

- Right-handed Neutrinos (spin-1/2 fermions, no charges): $\boxed{yHLN_R}$

(Possible explanation of neutrino masses)

\- Left-handed lepton doublet of $SU(2)$: $L_e = \begin{pmatrix} \nu_e \\ e \end{pmatrix}, \ldots$

Q: What is a right(left)-handed fermion?

Kinetic Mixing and the Dark Photon

- Let us focus on kinetic mixing with $U(1)' \to U(1)_d$: $\varepsilon F^Y_{\mu\nu} F^{d\mu\nu}$

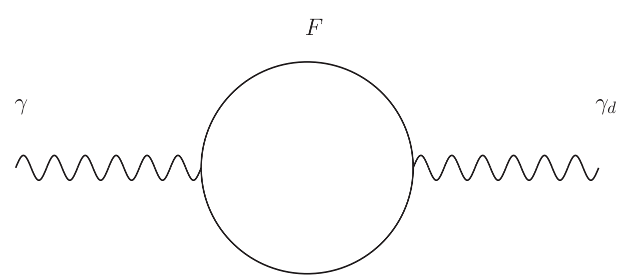
- Assume some mechanism, such as a dark Higgs, to give γ_d mass $m_{\gamma_d} \lesssim 1$ GeV

- One could show that the mixing can be removed and the result is $\sim e\varepsilon$ coupling of of γ_d to SM electric charge

- To avoid conflict with experimental data: $\varepsilon \lesssim 10^{-3}$ for $m_{\gamma_d} \lesssim 1$ GeV

- Since m_{γ_d} is not large, γ_d interactions suppressed by mixing parameter ε

- Small ε could be from quantum effects (loops): $\varepsilon \sim e\, g_d/(16\pi^2)$



• It is not energetically costly to produce γ_d (LHC: $\sqrt{s} \gtrsim 10^4\, m_{\gamma_d}$)

• Feeble interactions with SM imply rare processes, requiring large number of collision (luminosity), i.e. *intense* beams, other sources

- "Intensity Frontier" probes of γ_d (and other light hidden particles)

- In particular Belle II with a very large integrated-luminosity goal ($\sim$ 50 ab^{-1}) is a promising place to look for rare effects

• There are two main ways dark particles, such as the dark photon, could emerge in accelerator experiments:

(a) Direct production

(b) In decays of other states (Higgs, mesons,. . .)

• Both possibilities relevant at flavor experiments (Babar, NA48, Belle, Belle II, . . .)

• A longstanding $\sim 3.5\,\sigma$ discrepancy between the SM prediction and the measured value (BNL E821) of $a_\mu \equiv (g_\mu - 2)/2$:

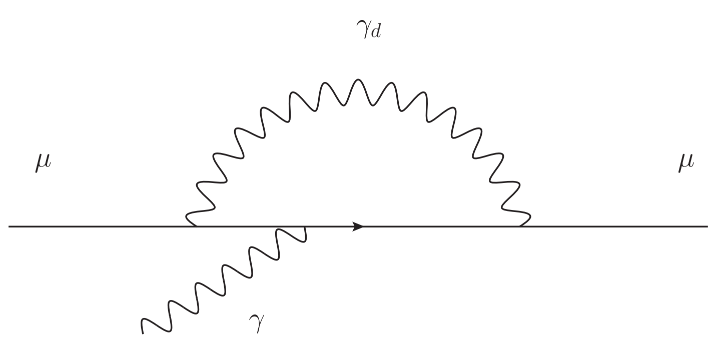
$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (268 \pm 76) \times 10^{-11}$$

Magnetic moment $\vec{M}_\mu = \frac{g_\mu e}{2m_\mu}\vec{S}$

- New measurement ongoing at Fermilab (E989); their first results might be released over the next few months

• A GeV-scale kinetically-mixed dark photon can provide a possible resolution, coupling to the charge of the muon with strength $\sim \varepsilon e$

Fayet 2007, Pospelov 2009

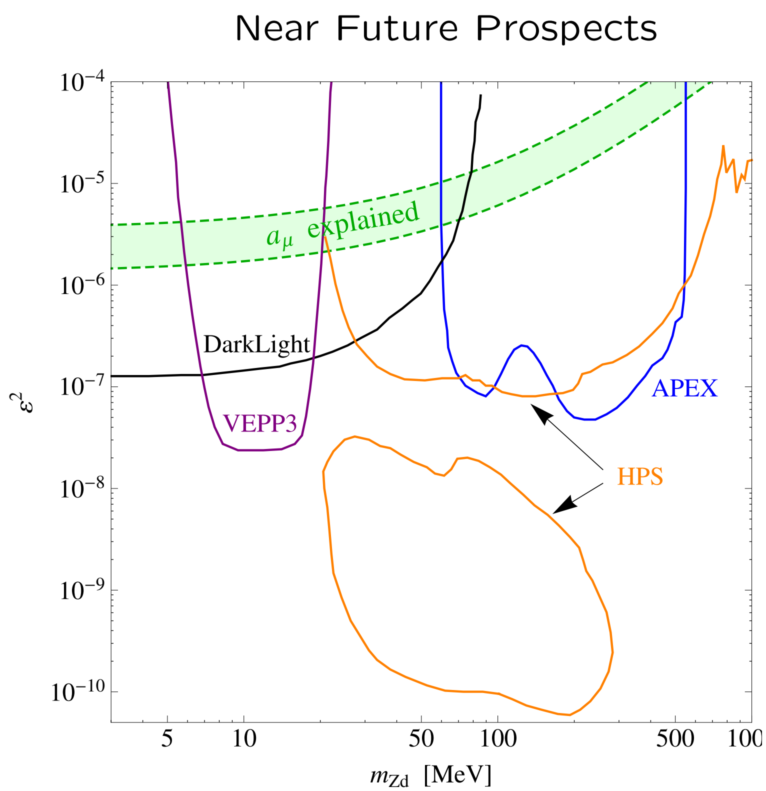


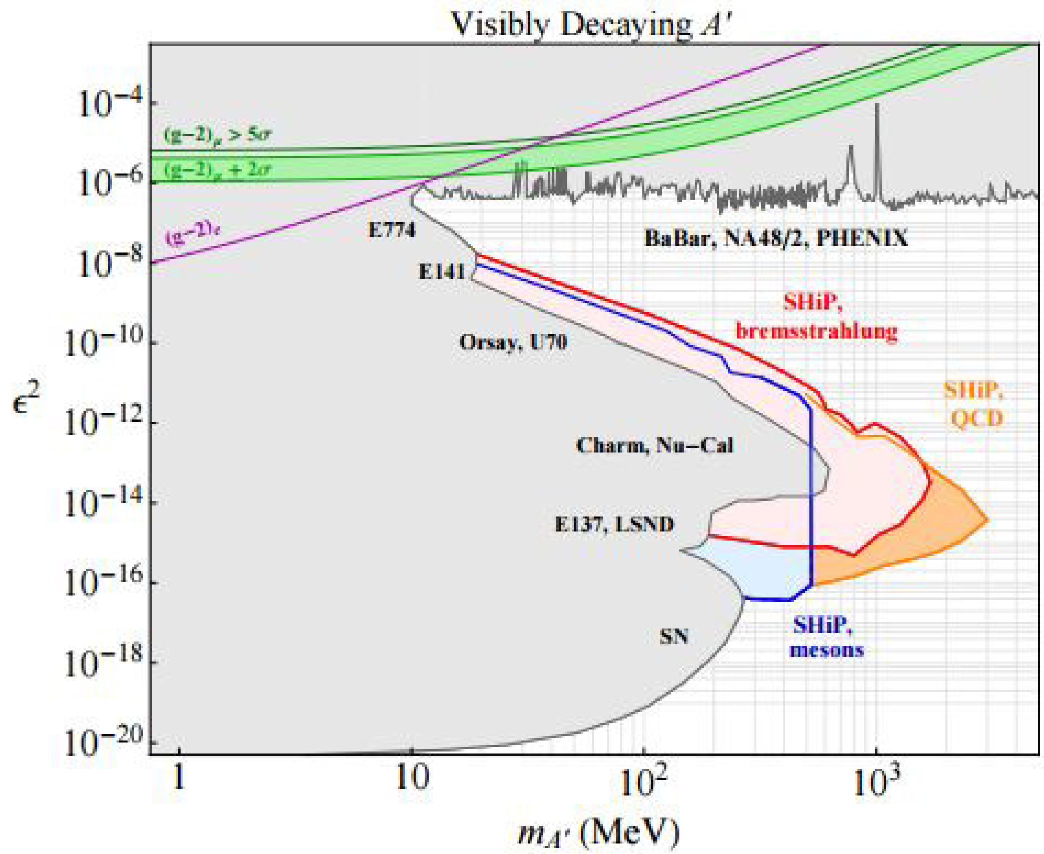
• Search for γ_d depends on its dominant decay branching fractions

- Active experimental program to search for dark photon

Pioneering work by Bjorken, Essig, Schuster, Toro, 2009

- An early experimental target: $g_\mu - 2$ parameter space (Here: $\gamma_d = A' = Z_d$)



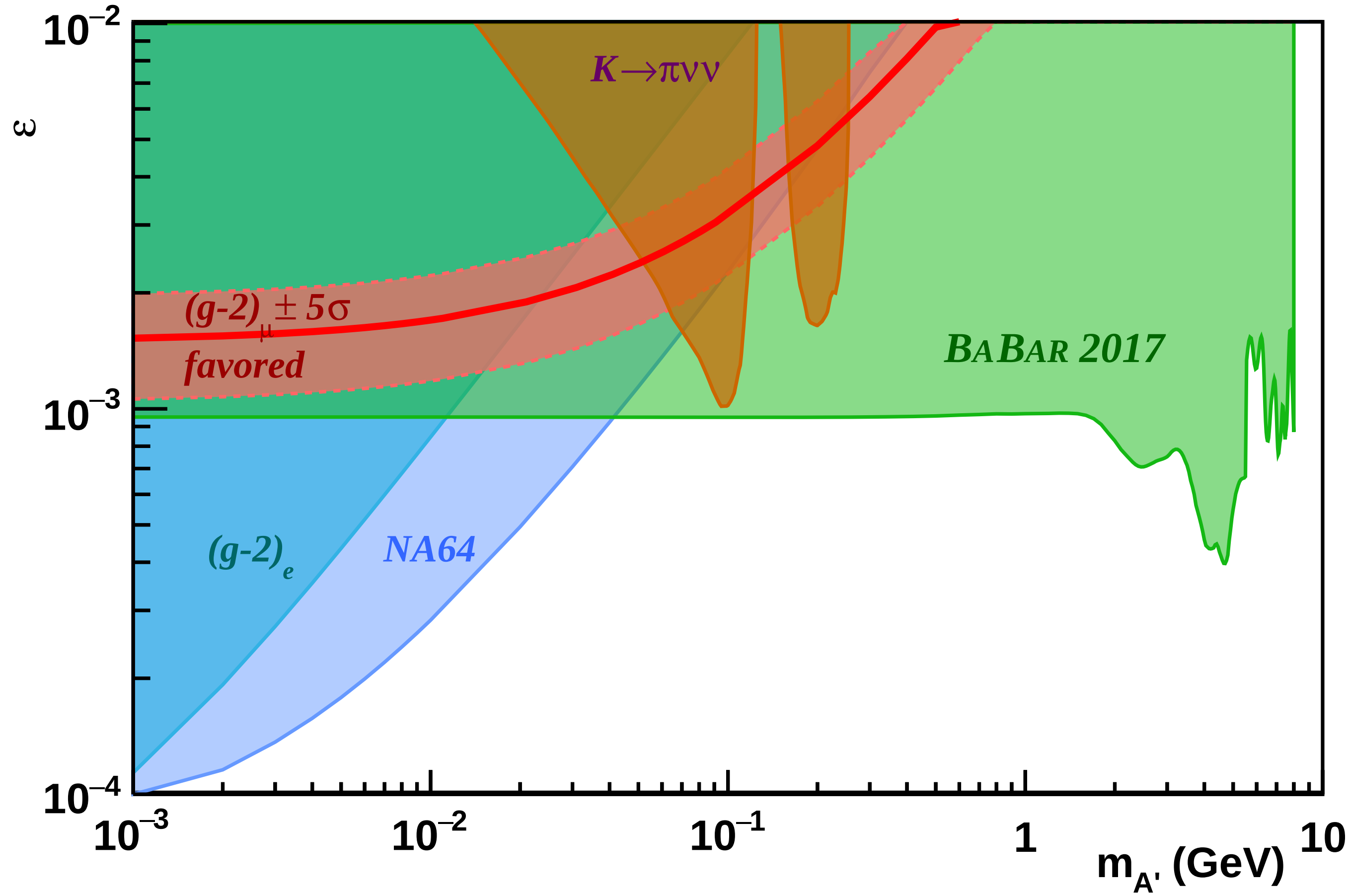


S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]

GeV-scale visibly decaying γ_d basically excluded as $g_\mu - 2$ explanation

“Invisible” Dark Photon

- $\exists$ dark X with $m_X < m_{Z_d}/2$ and $Q_d g_d \gg e\varepsilon \Rightarrow \text{Br}(Z_d \to X\bar{X}) \simeq 1$



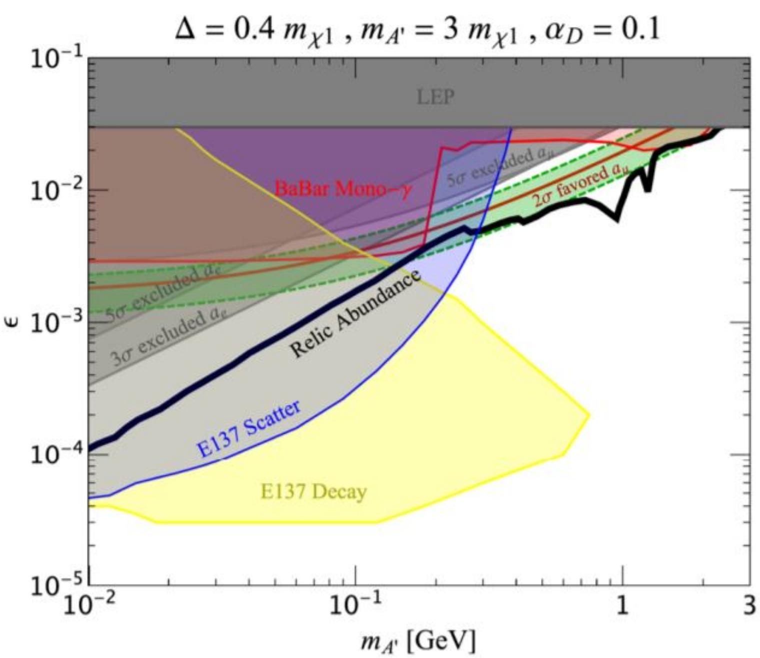
90% CL bound from Babar Collaboration, arXiv:1702.03327 [hep-ex]

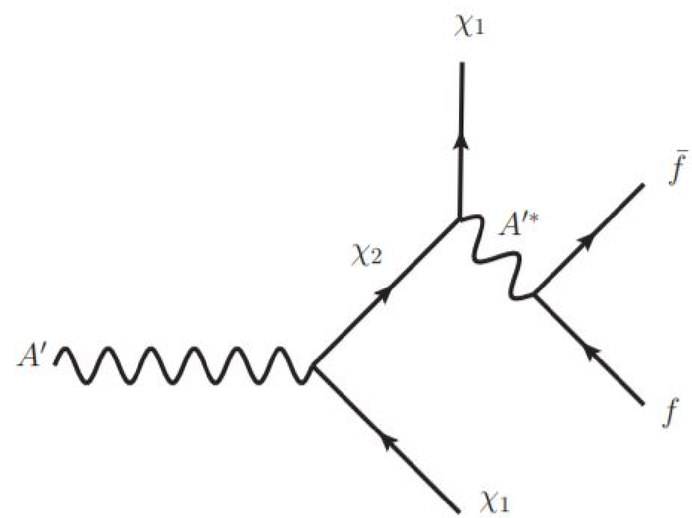
GeV-scale “invisible” dark photon $g_\mu - 2$ solution ruled out

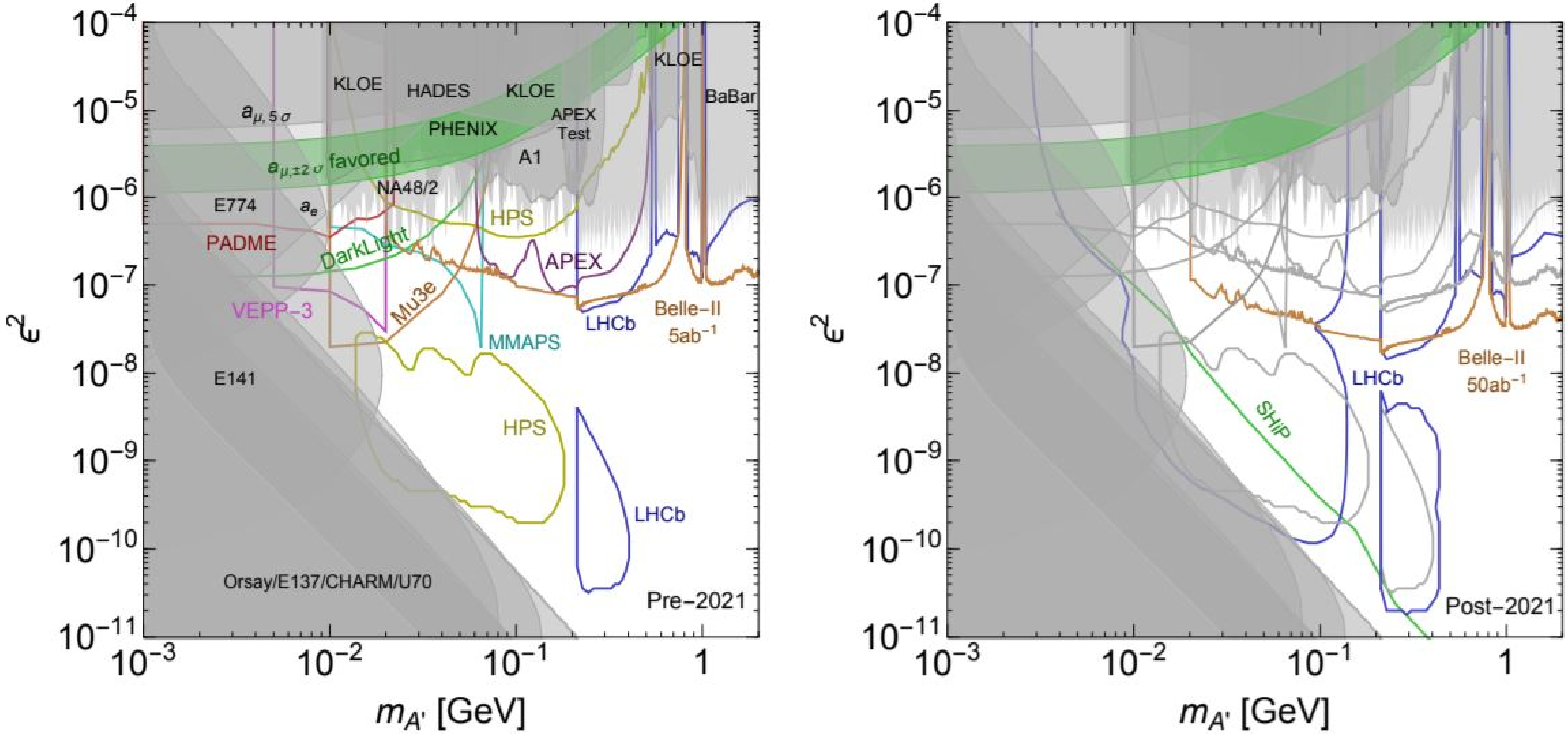
Potential Loophole

- Visible search: $e^+e^- \to \gamma\, \gamma_d \to \gamma + e^+e^- \ldots$
- Invisible search: $e^+e^- \to \gamma\, \gamma_d \to \gamma +$ invisible
- Possible evasion of γ_d constraints: semi-visible decays
- Requires γ_d dominantly decay into $\chi_1 \bar{\chi}_2$, with $\chi_2 \to \chi_1 +$ visible (*e.g.*, e^+e^-)

Figures from G. Mohlabeng, Phys.Rev. D99 (2019) no.11, 115001





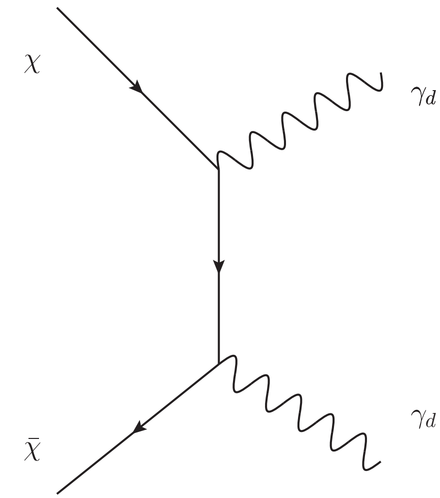


J. Alexander *et al.*, arXiv:1608.08632 [hep-ph]

Constraints and projections for visibly decaying dark photon: $\gamma_d \to \ell^+\ell^-$

Secluded versus Direct DM Annihilation

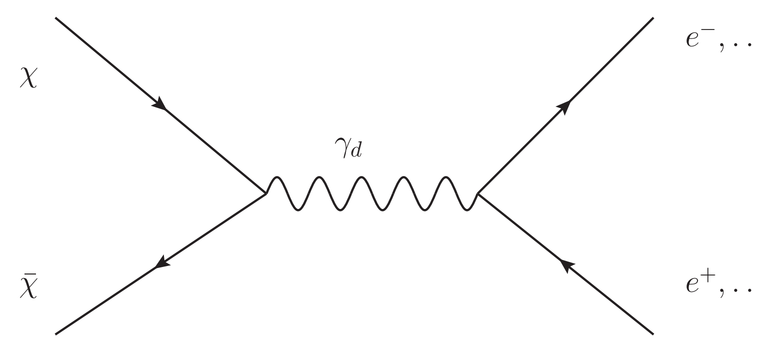
• Secluded: $m_\chi > m_{\gamma_d}$, DM can annihilate without substantial coupling to SM: $\chi\bar{\chi} \to \gamma_d \gamma_d$; later on $\gamma_d \to e^+e^-, \ldots$



- Cross section $\sigma \sim g_d^4/m_\chi^2$

- Kinetic mixing parameter ε could be very small

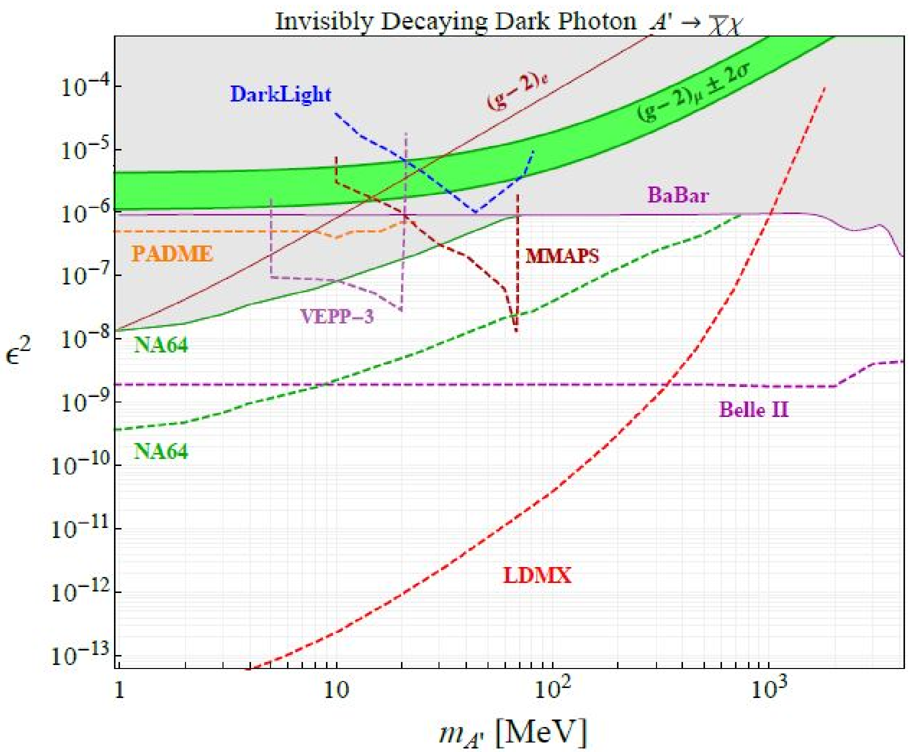
• Direct: DM lighter than γ_d, hence $\chi\bar{\chi} \to e^+e^-, \ldots$ dominant

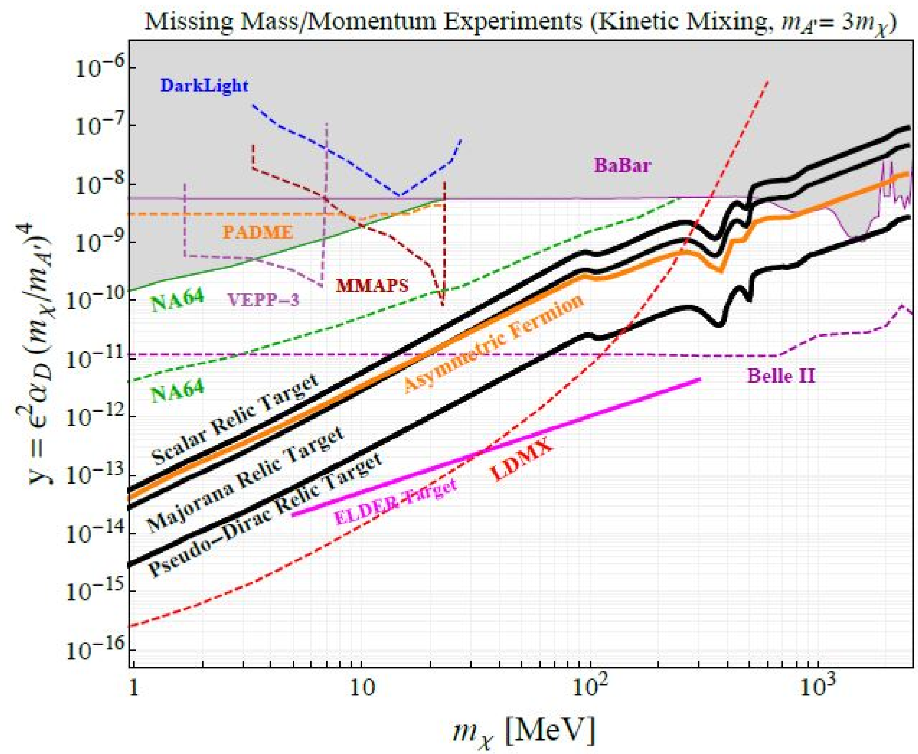


- Cross section $\sigma \sim g_d^2 \varepsilon^2 e^2 m_\chi^2 / m_{\gamma_d}^4$

$\Rightarrow \sigma \propto y/m_\chi^2$ with $y \equiv \varepsilon^2 \alpha_d (m_\chi/m_{\gamma_d})^4$

- Correct DM relic abundance (σ) determines y for each m_χ





$\alpha_d = 0.5$ and $m_{A'} = 3m_\chi$

M. Battaglieri *et al.*, arXiv:1707.04591 [hep-ph]

Constraints and projections for invisibly decaying dark photon

⋆ Note: Belle II can probe a wide range of parameter space for GeV scale DM

Dark Z

HD, Lee, Marciano, 2012

- γ_d may also have mass mixing with SM $Z \Rightarrow Z_d$

$$M_0^2 = m_Z^2 \begin{pmatrix} 1 & -\varepsilon_Z \\ -\varepsilon_Z & m_{Z_d}^2/m_Z^2 \end{pmatrix}$$

$\boxed{\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta}$ $Z - Z_d$ mixing parameter; $\delta \ll 1$ model-dependent

- Mass mixing can naturally occur in a 2-Higgs Doublet Model

- M_0 leads to Z-Z_d mixing angle ξ given by: $\tan 2\xi \simeq 2\frac{m_{Z_d}}{m_Z}\delta = 2\varepsilon_Z$

- Induced interactions with kinetic and mass mixing

$$\mathcal{L}_{\rm int} = \left(-e\varepsilon J_\mu^{em} - \frac{g}{2\cos\theta_W}\varepsilon_Z J_\mu^{NC}\right) Z_d^\mu$$

$J_\mu^{NC} = \sum_f (T_{3f} - 2Q_f \sin^2\theta_W)\bar{f}\gamma_\mu f - T_{3f}\bar{f}\gamma_\mu\gamma_5 f$; $T_{3f} = \pm 1/2$ and $\sin^2\theta_W \simeq 0.23$

- Neutral current coupling of Z_d like a Z, suppressed by ε_Z: "dark" Z

Notation: Z_d dark photon or dark Z, depending on the context

Dark Z Phenomenology

- "Dark" parity violation [independent of BR($Z_d \to$ visible)]

Polarized electron scattering, atomic parity violation, . . .

- Flavor physics ($m_{Z_d} < m_{\text{meson}}$)

- Longitudinal Z_d enhancement $\sim E/m_{Z_d}$

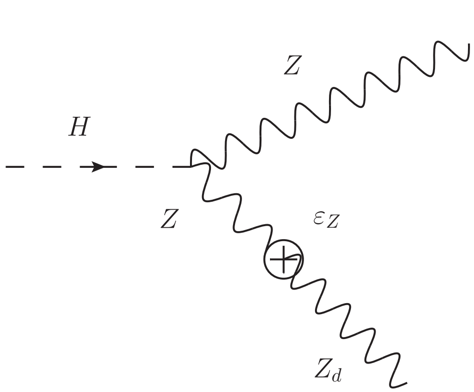
$\{\text{BR}(K^+ \to \pi^+ Z_d)_{\text{long}} \simeq 4 \times 10^{-4}\delta^2 \quad ; \quad \text{BR}(B \to K Z_d)_{\text{long}} \simeq 0.1\delta^2\} \to |\delta| \lesssim 10^{-3}$

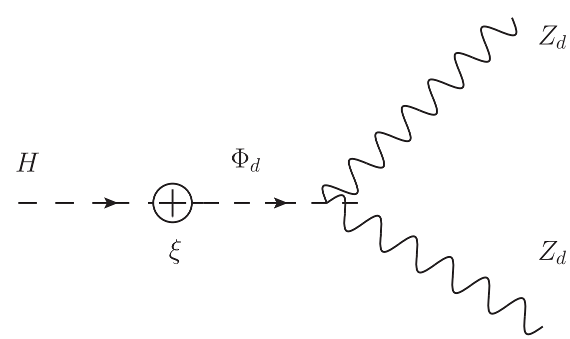
- Rare Higgs decays

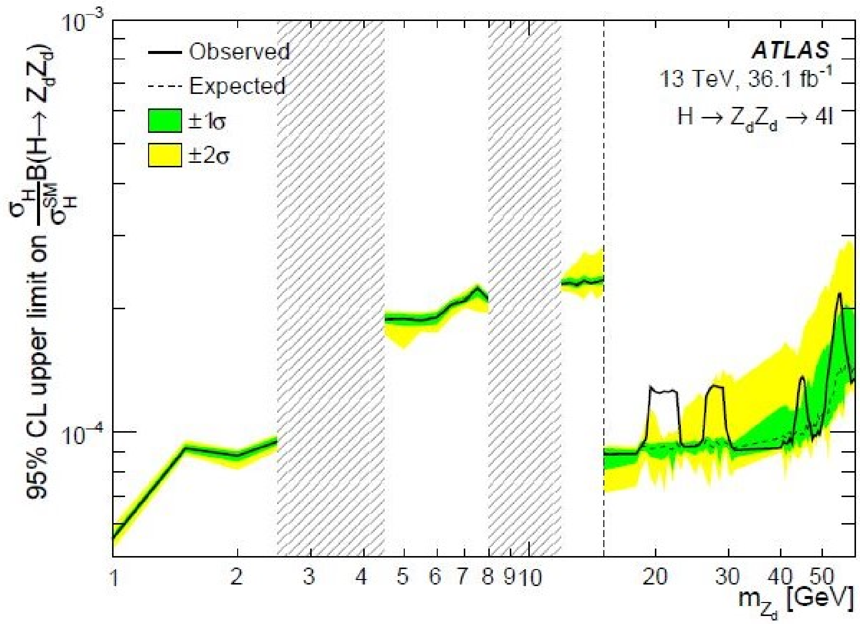
$Z - Z_d$ mixing: *e.g.* $H \to Z Z_d$ ($m_{Z_d} \ll m_Z$, on-shell Z_d)

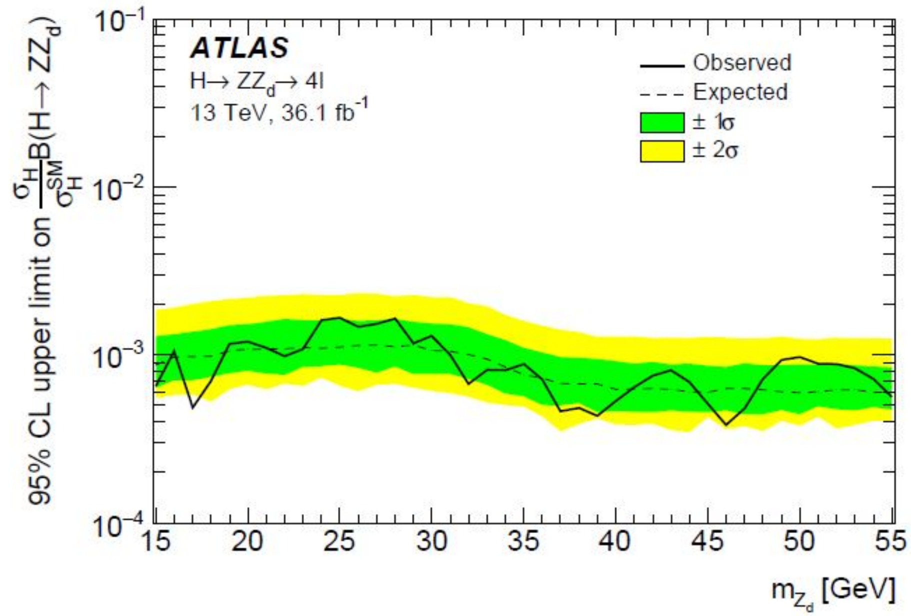
Higgs portal (Higgs-dark-Higgs mixing): $H \to Z_d Z_d$ ($m_{Z_d} \ll m_Z$, on-shell Z_d)

ATLAS Collaboration, 2015, 2018









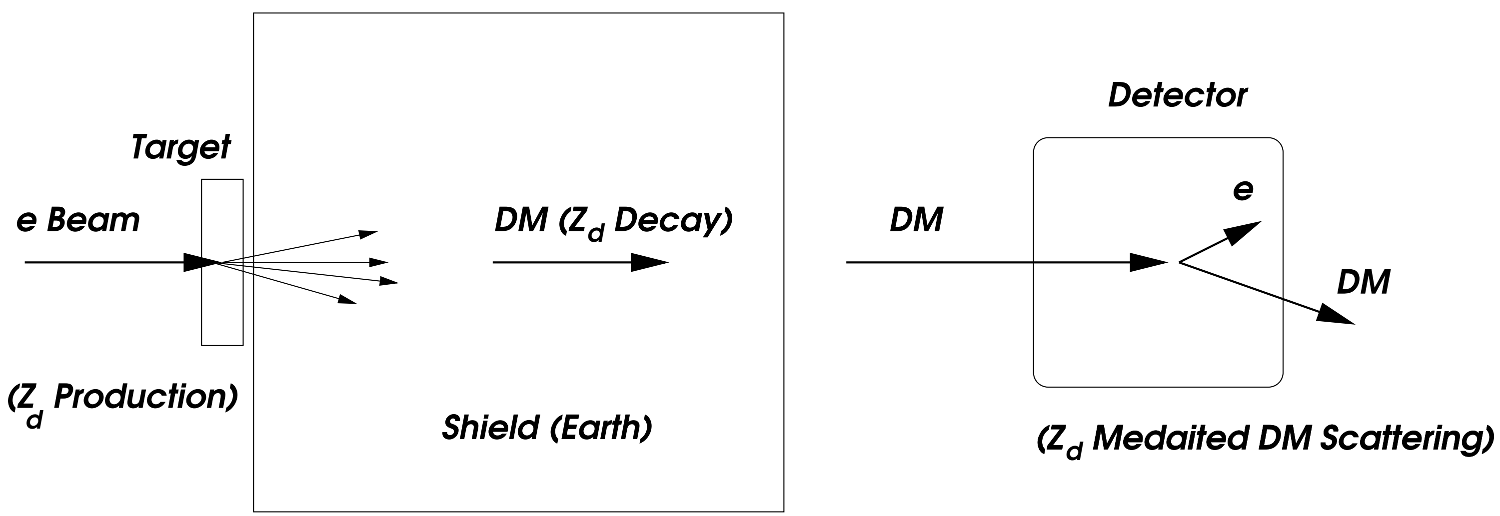
From M. Aaboud *et al.* [ATLAS Collaboration], JHEP **1806**, 166 (2018), [arXiv:1802.03388 [hep-ex]]

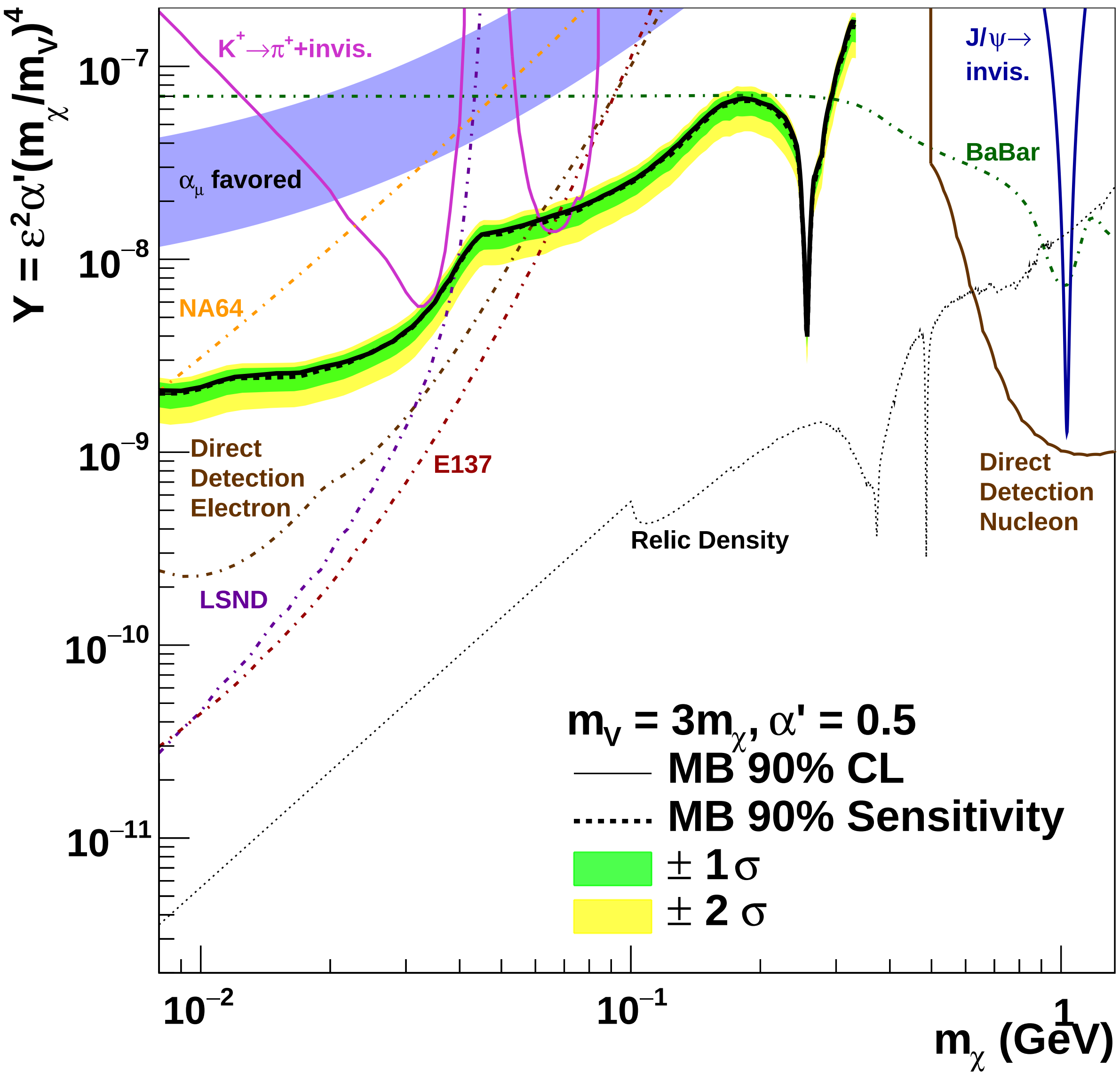
Invisible Z_d (γ_d) and Low Mass DM Production

- Possible production and detection of *DM beams* in experiments
- p or e on fixed target $\Rightarrow$ production of boosted Z_d (meson decays, bremsstrahlung,. . .)
- Z_d beam decays into DM which can be detected via Z_d exchange
- Event rate depends on $\alpha_d \equiv g_d^2/(4\pi)$ and ε^2

Batell, Pospelov, Ritz, 2009 (p beam); Izaguirre, Krnjaic, Schuster, Toro, 2013 (e beam dump)

- Interesting probe of GeV-scale DM (challenge for direct detection)





From arXiv:1702.02688 [hep-ex] (MiniBooNE Collaboration)

"Dark Matter Search in a Proton Beam Dump with MiniBooNE"

Solid line: quark/nucleon coupling; Dot-dashed: electron coupling; χ: scalar DM

Concluding Remarks

• SM: A consistent theoretical framework that precisely accounts for of a wide variety of microscopic phenomena

• SM+GR not a complete description of Nature

• In particular, a substance, DM, comprising $\sim 27\%$ of cosmic energy density not accounted for in the SM

• Lack of evidence for new physics near the Higgs mass scale ($\sim$ 100 GeV) may hint that DM not an extension of SM (weak scale WIMP)

• DM may have its own sector, like visible matter

• Wide range of possibilities, however GeV scale DM could be a good target for various experiments at the "intensity frontier"

• A simple but motivated possibility: DM coupled to a dark photon (kinetic and possibly also mass mixing connection to SM)

• Belle II has good prospects to probe this possibility

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Further material and details:

• *Dark Sectors 2016 Workshop: Community Report, arXiv:1608.08632*

• *US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report, arXiv:1707.04591*

Backup

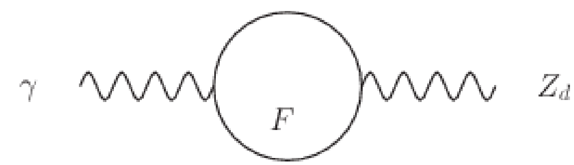
Dark Photon

- Kinetic mixing: Z_d of $U(1)_d$ and B of SM $U(1)_Y$ Holdom, 1986

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\mathbf{B}_{\mu\nu}\mathbf{B}^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_{\mathbf{W}}}\mathbf{B}_{\mu\nu}\mathbf{Z}_{\mathbf{d}}^{\mu\nu} - \frac{1}{4}\mathbf{Z}_{\mathbf{d}\mu\nu}\mathbf{Z}_{\mathbf{d}}^{\mu\nu}$$

$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$

  - $\varepsilon \ll 1$ may be loop induced: $\varepsilon \sim e g_d/(4\pi)^2 \lesssim 10^{-3}$



- Remove cross term, via B_μ field redefinition

$\Rightarrow Z_d$ couples to EM current: $\boxed{\mathcal{L}_{\text{int}} = -e\,\varepsilon\, J^\mu_{em} Z_{d\mu}}$ $J^\mu_{em} = \sum_f Q_f \bar{f}\gamma^\mu f + \cdots$

  - Like a photon, but ε-suppressed couplings: "dark" photon
  - Neutral current coupling suppressed by $m^2_{Z_d}/m^2_Z \ll 1$

- Add Z-Z_d mass mixing $\rightarrow Z_d$ as "dark" Z HD, Marciano, Lee, 2012
  - "Dark" parity violation, rare meson and Higgs decays, . . .

A Concrete Dark Z Model

- Mass mixing can naturally occur in a 2HDM

- Type I 2HDM: H_1 and H_2, where only H_1 has $Q_d \neq 0$
  - $U(1)_d$ as protective symmetry for FCNCs instead of the usual $\mathbb{Z}_2$
  - SM fermions only couple to H_2 (SM-like); $\langle H_i \rangle = v_i$
  - Generally, also a dark sector Higgs particle ϕ with $\langle \phi \rangle = v_d$

$$m_Z \simeq \frac{g}{2\cos\theta_W}\sqrt{v_1^2 + v_2^2} \quad \text{and} \quad m_{Z_d} \simeq g_d\, Q_d \sqrt{v_d^2 + v_1^2}$$

- With $\tan\beta = v_2/v_1$ and $\tan\beta_d = v_d/v_1$ we get

$$\varepsilon_Z \simeq (m_{Z_d}/m_Z)\cos\beta\cos\beta_d \Rightarrow \delta \simeq \cos\beta\cos\beta_d$$

- H_1 has $Q_Y Q_d \neq 0$ $\rightarrow$ generally also expect kinetic mixing