Where does an extra force fit?

How could additional forces have escaped detection?

• very high mass force carrier
• small coupling to SM particles
Where does an extra force fit?

How could additional forces have escaped detection?

• very high mass force carrier
• small coupling to SM particles
  • $0_{(direct)}$ coupling to SM!
Portals to a hidden sector

Standard Model
SU(3) × SU(2) × U(1)

“portal”

Dark Sector

vector

$$\frac{1}{2} \epsilon F_{\mu \nu} F'^{\mu \nu}$$
dark photon

dark scalar

Higgs

$$\epsilon_h |h|^2 |\phi|^2$$

sterile neutrino

neutrino

$$\epsilon_\nu (hL) \psi$$

axion

$$\frac{1}{f_a} a F_{\mu \nu} \tilde{F}^{\mu \nu}$$

ALPSs
an old idea: if there is an additional $U(1)$ symmetry in nature, there will be mixing between the photon and the new gauge boson

$$L_{U(1)'} = -\frac{1}{4} V_{\mu\nu}^2 - \left(\frac{\epsilon}{2} V_{\mu\nu} F_{\mu\nu}^\mu\nu\right) + |D_\mu \phi|^2 - V(\phi)$$

• extremely general conclusion...even arises from broken symmetries
• gives coupling of normal charged matter to the new “dark photon” $q=\epsilon e$
30 decades of heavy photons

...there is a lot of physics here!

Jaeckel and Ringwald, hep-ph/1002.0329
Terminology break

- The literature is infested with different terms for (basically) the same things...
  - dark sector=hidden sector=secluded sector
  - dark photon=hidden photon=heavy photon=$A'=U$-boson
  - $\varepsilon^2=\kappa^2=\alpha'/\alpha$

I will try to stick to dark sector, $A'$, and $\varepsilon$!
What coupling?

• Coupling is generated from non-perturbative loops
  • One-loop if the heavy particle is charged under both U(1)s
    \[ \epsilon \sim \frac{e g D}{16\pi^2} \]
    ...depends on coupling in dark sector
  • Two-loop if one of the U(1)s is embedded into a higher symmetry...

\[ \frac{1}{2} e F^Y_{\mu\nu} F'_{\mu\nu} \]
Ok, what about the mass?

- Could be massless \( \Rightarrow \) millicharges!
- Non-perturbative \( \Rightarrow \) chaos!
- Same origin as weak scale \( \Rightarrow O(M_Z) \)

Depending on model, mass scales like:

\[
\frac{M(A')}{M(W)} \sim \varepsilon^{1-\varepsilon^{1/2}}
\]

leading to

\[
M(A') \sim \text{MeV-GeV}
\]

N. Weiner, JLAB PAC37 Talk

\[ \alpha' = \alpha \varepsilon \]
A hint from above?

- Excess in $e^+/e^-$ ratio
- But not in $\bar{p}/p$ ratio

- FERMI sees it too!

Unknown source of high energy positrons...

Is this astrophysics or particle physics?
• new “dark force” with gauge boson ~ GeV while the dark matter particle (charged under the new force) ~ TeV
• decays to lepton pairs (e^+e^−, μ^+μ^−) but p̅p̅ decays are kinematically forbidden
Some existing constraints

\[ g_{\mu}^{-2} - 2 \]

\[ g_{e}^{-2} - 2 \]

\[ e^+ e^- \rightarrow \mu^+ \mu^- \gamma \]

\[ \text{E774, E137, E141} \]

<table>
<thead>
<tr>
<th>Shield (m)</th>
<th>E_{beam} (GeV)</th>
<th>Lumi (e^-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E137</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>E141</td>
<td>0.12</td>
<td>9</td>
</tr>
<tr>
<td>E774</td>
<td>0.3</td>
<td>27.5</td>
</tr>
</tbody>
</table>
Dark photons and the g-2 anomaly

If the g-2 anomaly is due to a heavy photon

If the g-2 anomaly is due to a heavy photon.
A' decay products

...up to ~500 MeV, decay to leptons dominates
\[ \gamma \epsilon \tau \propto \left( \frac{10^{-4}}{\epsilon} \right)^2 \left( \frac{100 \text{ MeV}}{m_{A'}} \right)^2 \]

lower \( \epsilon \), lower mass
\( \rightarrow \) longer lifetime

Much of parameter space will have displaced vertex
Collider vs. Fixed Target

Wherever there is a photon there is a dark photon...

Collider

\[ \sigma \sim \frac{\alpha^2 e^2}{E^2} \sim O(10 \ fb) \]

\[ O \ ab^{-1} \ per \ decade \]

month

Fixed Target

\[ \sigma \sim \frac{\alpha^3 Z^2 e^2}{m^2} \sim O(10 \ pb) \]

\[ O \ ab^{-1} \ per \ day \]

...much higher backgrounds
Backgrounds at fixed target

Two main backgrounds

Bethe-Heitler

Radiative

Production rates of A' and radiative are related:

\[
\frac{d\sigma(e^-Z \rightarrow e^-Z(A' \rightarrow e^+e^-))}{d\sigma(e^-Z \rightarrow e^-Z(\gamma^* \rightarrow e^+e^-))} = \left( \frac{3\pi e^2}{2N_{eff}\alpha} \right) \left( \frac{m_{A'}}{\delta m} \right)
\]

Cross-section for BH >> Radiative, but kinematics much different...
Even after energy cut, BH background ~5x radiative
...a little more subtle...

**Problem:** cover the low coupling ($<10^{-4}$), intermediate mass (20-200 MeV) region

- low rate $\Rightarrow$ intense beam
- high background $\Rightarrow$ high resolution
- *still* high background $\Rightarrow$ measure displaced vertex

**Solution:** HPS

![Graph showing $\epsilon$ vs $m_A$]
• high rate, high acceptance, high mass & vertex resolution detector intended to run in Hall B

- Silicon strip tracker inside an evacuated dipole for excellent vtx & mom resolution. Use Si sensors donated from Fermilab & APV25 readout chips
- Borrow & reconfigure the CLAS inner calorimeter for high rate triggering
The HPS approach

- good mass resolution, dominated by MS in the detector
- use small beam-spot (~10µm) to constrain A’ to point back to IP
  - beat down vertex tails of prompt decays to ~ 0 expected background
  - tails dominated by fake tracks...rate dependent
- Estimate coverage $10^{-4} < \varepsilon < 10^{-5}$ for $200 > mA' > 20$ MeV
  - running 3 months each at $E_{\text{beam}} = 2.2$ and 6.6 GeV

$\Delta m/m \sim 1\%$

$\vec{p}_{e^+} + \vec{p}_{e^-}$
HPS Expected Reach

Blue:
200nA @ 2.2GeV
target: 0.125%

Red:
450nA @ 6.6GeV
target: 0.25%

3 months of beam at each energy

...
Many experiments in the works to look for Dark Forces:

- **Mainz** and **APEX (JLab)** ~ forward spectrometers
- **HPS (JLab)** ~ compact Si-based vertex-tracker
- **DarkLight (JLab FEL)** ~ high acceptance, H$_2$ gas target
- **HIPS (DESY)** ~ beam dump (not shown)
Other direct dark force searches

- Searches at $e^+e^-$ colliders: BaBar & Belle(II), KLOE, BES
  - Lower luminosity + lower backgrounds
  - Higher mass reach (up to $\sim$10GeV)
  - “exotic” dark force states: dark higgs, dark mesons

- Searches at hadrons colliders: ATLAS/CMS & CDF/D0
  - possible unique production path $\Rightarrow$ cascades from SUSY particles
  - “lepton-jets” signatures along with typical di-lepton mass peak
  - potentially covers vast area of coupling-mass space, but with model assumptions

$\Rightarrow$ many public results already with more on the way...very active area of study!
What now? My conclusions

• The search for new gauge bosons has a long history over a huge range of mass scales

• Something like a dark photon is very well theoretically motivated and if we live in a GU universe it probably exists
  • What coupling? What mass? Who knows? I have my favorite region!

• Dark matter naturally fits in this dark sector
  • by the way, this doesn’t override SUSY...dark sector models and SUSY get along fine!

• It’s very cool to think that there might be very complicated, very different physics going on all around us which we can’t examine but through this weak, tenuous connection
What now next?

• Ok, say we are seeing DM annihilating (maybe via dark photons) in the PAMELA & FERMI data...what else should we see
  • \( f(e^+/e^-) \) should cut off at \( \sim \) DM mass
  • high energy photons from inverse Compton scattering & final state radiation \( \Rightarrow \) constraints from Fermi are discouraging
  • imprints on the CMB \( \Rightarrow \) PLANK will be crucial...2013?
• Possibly large impact on direct DM experiments
  • iDM \( \Rightarrow \) lower recoil energy
  • DAMA/CoGeNT/CRESST anomalies?
  • Xenon100, CDMS are putting big dent in iDM parameter space

“DM could have shown it’s face in many places, and didn’t...but has wiggle-room left.” - Rouven Essig

Apart from these anomalies, the upcoming direct heavy-photon searches will block out a very interesting part of parameter space...maybe the dark sector will show it’s head before dark matter