Low Energy New Physics

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(William and Mary / Jefferson Lab)

Workshop on Hadron Physics in China and Opportunities in US
Huangshan, Anhui, China
July 2013
Low Energy New Physics
(with an example of “Dark Force”)

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Prelude
We live in a Dark World

[Diagram showing 74% Dark Energy, 22% Dark Matter, and 4% Atoms]
We live in a Dark World

Galaxy rotation curve

Gravitational lensing

Cosmic Microwave Background

Accelerating Universe (Supernovae)
We live in a Dark World

still mystery

511 keV gamma-ray

Positron excess
We live in a Dark World

“Dark Force”
(Force among Dark Matters)

511 keV gamma-ray
Positron excess
Dark Force  (Force among Dark Matters)

$Z'$
(Dark Force carrier)

- New gauge boson of $O(1)$ GeV scale  \(\text{(cf. Proton: 1 GeV)}\)
- Extremely weak couplings to the SM particles

Dark Trilogy (of Dark World)

1. Dark Energy  (Accelerating expansion, CMB, ...)

2. Dark Matter  (Galaxy rotation curves, Gravitational lensing, ...)

3. Dark Force  (511 keV gamma-ray, Positron excess, ...)

Focus of this talk
Particularly interesting: One of the New physics scenarios that can be tested with Low-energy experimental facilities (Nuclear/Hadronic physics labs).

Dark force carrier $Z'$ scale (GeV) \( \approx \frac{1}{1000} \times \) Most new physics scale (TeV)

“various Low-E Labs”

“LHC”
Hunting for New fundamental force

Fundamental forces (interactions) known to us:
(1) Gravity [I. Newton, ... in 17C]
(2) Electromagnetic force [J. Maxwell, ... in 19C]
(3) Weak nuclear force [E. Fermi, ... in 20C]
(4) Strong nuclear force [M. Gell-Mann, ... in 20C]

Each and every fundamental force made huge impact in understanding physical world.

Discovery of another fundamental force will do the same.
Outline

- Dark Force Models
- Dark Force Searches (Dark Photon)
- Additional Dark Force Searches (Dark Z)
- High-energy experiments
Dark Force Models
Standard Model + Dark Force

Gauge symmetry = $\text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y \times \text{U}(1)_{\text{dark}}$

It may interact with DM, but SM particles have zero charges

Z' can couple to SM particles through kinetic mixing of U(1)$_Y$ & U(1)$_{\text{dark}}$. [Holdom (1986)]

$$L_{\text{kin}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{2} \frac{\varepsilon}{\cos \theta_W} B_{\mu\nu} Z'^{\mu\nu} - \frac{1}{4} Z_{\mu\nu} Z'^{\mu\nu}$$

$B_{\mu} = \cos \theta_W A_{\mu} - \sin \theta_W Z_{\mu}$
Types of Dark Force

\[ Z' \]: couplings to the SM particles are suppressed by small mixing.

(model-dependent)

[Arkani-Hamed, et al (2008); and many others]

Popular Model: **Dark Photon**

coupling = \( \varepsilon \times (\text{Photon coupling}) \)

[Davoudiasl, Lee, Marciano (2012)]

New Model: **Dark Z**

coupling = \( \varepsilon \times (\text{Photon coupling}) + \varepsilon_Z \times (Z \text{ coupling}) \)

inherits properties of Z boson like parity violation.

(different couplings for left/right-handed particles)
Model-dependence comes from **how the Z’ gets the mass** (i.e. Higgs sector).
- Dark Photon: (ex) additional Higgs singlet gives mass to Z’
- Dark Z: (ex) additional Higgs doublet gives mass to Z’

(Ex) Dark Photon case:
Z-Z’ kinetic mixing is cancelled by **Z-Z’ mass mixing** (which is “induced by kinetic mixing”) at Leading order.

\[
\mathcal{L}_{\text{int}} \sim -eJ_{em}^{\mu}A_\mu - \left( g/\cos \theta_W \right) J_{NC}^{\mu}Z_\mu
\]

(Kinetic mixing diagonalization)
\[
\rightarrow -eJ_{em}^{\mu}[A_\mu + \varepsilon Z'_\mu] - \left( g/\cos \theta_W \right) J_{NC}^{\mu}[Z_\mu + O(\varepsilon)Z'_\mu]
\]

(Z-Z’ mass matrix diagonalization)
depends on Higgs sector

for Higgs singlet

\[
J_{\mu}^{NC} = \left( \frac{1}{2} T_{3f} - Q_f \sin^2 \theta_W \right) \bar{f} \gamma_\mu f - \left( \frac{1}{2} T_{3f} \right) \bar{f} \gamma_\mu \gamma_5 f
\]

Dark Force couplings depend on Higgs sector.
Effects of New Model (Dark Z)

Parameter space is extended from 2D to 3D.

\[ L_{\text{int}} = -\varepsilon e J_{em}^\mu Z'_\mu \]

\[ L_{\text{int}} = -\left[ \varepsilon e J_{em}^\mu + \varepsilon_Z \left( g / \cos \theta_W \right) J_{NC}^\mu \right] Z'_\mu \]

Dark Photon = a special case of Dark Z (\( \varepsilon_Z = 0 \) limit).

Some experiments irrelevant to Dark Photon searches become relevant to Dark Z searches (Low-E parity test, ... : will be discussed later).

\[ L_{\text{int}}(\text{SM}) = -e J_{em}^\mu A_\mu - \left( g / \cos \theta_W \right) J_{NC}^\mu Z_\mu \]
Dark Force Searches: relevant to Dark Photon
Dark Photon Searches

1. Anomalous magnetic moment (g-2) for e, μ.
2. Beam-dump experiments (E137, E141 at SLAC; E774 at Fermilab)
3. Meson decays: \( \Upsilon(bb) \rightarrow \gamma Z' \) (BaBar); \( \phi(ss) \rightarrow \eta Z' \) (KLOE); \( \pi(dd) \rightarrow \gamma Z' \) (COSY)
4. Fixed target experiments: New experiments designed for direct Dark Photon search (APEX, HPS, DarkLight, MAMI, VEPP3)

Green band: explains 3.6σ deviation in \( g_\mu - 2 \) (possibly early hint of Dark Force) [Fayet (2007); Pospelov (2008)]

\[
\varepsilon^2 = \alpha'/\alpha
\]

\[
(magnetic \ moment) = -\frac{g\mu_BS}{\hbar}
\]
1. Anomalous magnetic moment (g-2) for e, μ.
2. Beam-dump experiments (E137, E141 at SLAC; E774 at Fermilab)
3. Meson decays: \( \Upsilon(bb) \rightarrow \gamma Z' \) (BaBar); \( \phi(ss) \rightarrow \eta Z' \) (KLOE); \( \pi(dd) \rightarrow \gamma Z' \) (COSY)
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Current and Future coverage (parts). [Plots from R. McKeown’s talk (2011) + subsequent updates]
Dark Force searches at Jefferson Lab
Nuclear/Hadronic Physics Lab

Free Electron Laser
FEL: DarkLight

Continuous Electron Beam

Hall A: APEX
Hall B: HPS

Dark Photon
Bremsstrahlung

3 Direct bump searches

"Dark Photon" searches
(3 fixed target experiments)
New Fixed target (Tantalium $Z=73$) experiment designed for direct Dark Photon production/detection.

($Z' \rightarrow e^+e^-$ narrow resonance search using HRS)

[APEX Collaboration]

[APEX test-run result (2011)]
Additional Dark Force Searches
: relevant to Dark Z
Dark Z effects on Neutral Current phenomenology

Dark Z effect comes as **modification** of eff Lagrangian of Neutral Current scattering.

\[
\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} J_{NC}^\mu (\sin^2 \theta_W) J_{NC}^\mu (\sin^2 \theta_W) \\
G_F \rightarrow \left( 1 + \delta^2 \frac{1}{1 + Q^2/m_{Z'}^2} \right) G_F \\
\sin^2 \theta_W \rightarrow \left( 1 - \varepsilon \delta \frac{m_Z}{m'_{Z'}} \cos \theta_W \frac{1}{\sin \theta_W \left( 1 + Q^2/m_{Z'}^2 \right)} \right) \sin^2 \theta_W
\]

- Sensitive only to Low-\(Q^2\) (momentum transfer). (Effect negligible for \(Q^2 \gg m_Z^2\))
- For typical parameter values, \(\Delta \sin^2 \theta_W\) (Weinberg angle shift) is more sensitive.

“Low-\(Q^2\) Parity-Violating experiments (measuring Weinberg angle)” seem to be a right place to look: (i) Atomic parity violation, (ii) Polarized electron scattering.

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Scattering mediated by Dark Force (Light \(Z'\)) can be observed “only” in Low-Energy experiments.

[Davoudiasl, Lee, Marciano (2012)]
Past Low-$Q^2$ Parity-Violating Experiments

(i) Atomic Parity Violation [Weak nuclear charge $Q_W(Z,N) \approx -N+Z(1-4\sin^2\theta_W)$]:

- $Q_W^{(133)\text{Cs}} = -72.58(43)$ in Cesium Experiment [C. Wieman et al (1985-1988)]
- $Q_W^{(133)\text{Cs}} = -73.23(2)$ in SM [reflecting new result by Flambaum et al (2012)]

in reasonable agreement (1.5σ).

(ii) Polarized Electron Scattering [Left-Right asymmetry $A_{LR} = \sigma_L - \sigma_R / \sigma_L + \sigma_R$]:

- $\sin^2\theta_W(m_Z)=0.2329(13)$ in Moller scattering; $<Q>\approx 160$ MeV [SLAC E158 (2005)]
- $\sin^2\theta_W(m_Z)=0.23125(16)$ directly measured at Z-pole [LEP, SLC average]

in good agreement.

$$\Delta \sin^2 \theta_W \simeq -0.42 \varepsilon \delta \frac{m_Z}{m_{Z'}} f(Q^2/m_Z'^2)$$
Dark Force searches at Jefferson Lab
Nuclear/Hadronic Physics Lab

Free Electron Laser
FEL: DarkLight

Continuous Electron Beam

Low-Q² polarized electron scatterings

Hall A: APEX
Hall B: HPS
Hall A: Moller
Hall C: Qweak

“Dark Z” searches
(2 more experiments relevant to Dark Force searches)

3 Direct bump searches
+ 2 Parity violation searches
Parameter space is extended by another axis for a new parameter (for Z-Z' mixing). The new axis is explored by various current/future Low-energy parity violating experiments.
High-energy experiments for Dark Force
SM-like Higgs boson (mass \( \sim 125 \text{ GeV} \)) was discovered at the LHC experiments (2012). Next step: Precision study (detailed decay modes, ...)

Peter Higgs (UK)
Higgs decay can produce a Dark Force carrier
(Connection of Higgs and Dark Force)

- LHC can search for Dark Force, too (ex: Higgs decay).
  (It needs \(L \approx \text{few} \times 100 \text{ fb}^{-1}\) for 5\(\sigma\) discovery, for typical parameters.)
- Complementary to Low-E experiments (JLab, B factory, ...) in \(Z'\) mass coverage.
  (LHC loses sensitivity for \(m_{Z'} \lesssim \text{several GeV}\).)

[Davoudiasl, Lee, Lewis, Marciano (2013)]
Extended Range
Extended range of parameters (of Dark Photon)

Not every parameter space related to astrophysical anomalies, but there are vast parameter space unexplored, waiting for us:

(i) Heavier mass or (ii) Smaller coupling
Summary
- Originally introduced to explain various astrophysical data.
- Mass $\approx O(1)$ GeV.
- Coupling $\approx$ Extremely weak (model-dependent) to the SM particles.
- Searchable at Low-energy Labs. (Fixed target, Low-$Q^2$ parity test, ...)
- May affect LHC experiments, too. (Rare Higgs decays, ...)
**High-E experiments**: Rely on Higher energy facility to find direct evidence of New heavy particles (LHC, etc).

**Low-E experiments**: Rely on Higher precision to find indirect evidence of New heavy particles (JLab, B-factories, etc).
Low-energy experiments provide unique windows to discover some New physics.

Emerging Alternative View

High-E experiments: Rely on Higher energy facility to find direct evidence of New heavy particles (LHC, etc).

Traditionally considered as most important Discovery Frontier

Low-E experiments: Rely on Higher precision to find indirect evidence of New heavy particles (JLab, B-factories, etc).

Emerging as an “equally important Discovery Frontier” with New Low-E scale particles (Dark force carriers) motivated from Dark sector. (Ex) Some Z’ bumps and parity violations can be seen only at Low-E experiments.

Low-energy experiments provide unique windows to discover some New physics.

- Thank you -