Dark Sectors 2016

Theory and Visible Dark Photons Primer

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Welcome!
Looking Back

In 2009, SLAC held a “Dark Forces” workshop. At that time…

- Astrophysics data spurred renewed theoretical interest

- Re-analysis of data from multi-purpose detectors opened window to the dark sector

- First-generation experiments were starting to take shape.
Now is a great time!

Broad, international activity searching for dark sectors!

Many of the first-generation dedicated experiments are still ongoing. Their reach can be anticipated reliably, and it’s clear what limits they run into.

It’s a perfect time to ask: Where do we go next? That’s the focus of this workshop.

Next 3 talks: assessing the state of the field today, to set stage for these discussions.
Where to now?

- What new ideas will propel us past the obstacles found in designing the first-generation experiments?

- What important possibilities are we overlooking, that we should be searching for?

- What opportunities do we have with upcoming facilities and/or new technologies that didn’t exist 7 years ago?

- What do we want this field to look like in 5-10 years? What is within reach? What should we focus on?
Outline

• Why Dark Sectors?

• Organizing Questions

• Visibly Decaying Dark Photon Searches
  – Properties
  – Search Strategies
  – Outstanding Challenges
Why Dark Sectors?

- Nature seems well described by SU(3)xSU(2)xU(1) gauge theory
  - We need to check this assumption!

- Precedent in Standard Model for rare/subtle effects to be important (Radioactivity, Rutherford scattering, neutrinos, parity violation…)

- We *already* know we are missing something…
There is a dark sector!

- What is it?
- Where did it come from?
Theory Prejudice

Least addition of new particles?

Motivates SM weak multiplet or axion

[SM itself is far from minimal in this sense]
Theory Prejudice

Least addition of new particles?

Motivates SM weak multiplet or axion

Parallel structure to Standard Model ⇒

Motivates weak coupling searches at modest energy

[SM itself is far from minimal in this sense]
Looking for Dark Sectors

Whatever is in the dark sector, only three sizeable interactions allowed by Standard Model symmetries:

- **Vector Portal**
  \[ \frac{1}{2} \epsilon_Y F^Y_{\mu \nu} F'^{\mu \nu} \]

- **Higgs Portal**
  \[ \epsilon_h |h|^2 |\phi|^2 \]  
  exotic rare Higgs decays

- **Neutrino Portal**
  \[ \epsilon_\nu (h L) \psi \]  
  not-so-sterile neutrinos
New gauge interactions

Gauge Portal \( g \sum_i q_i \bar{\psi}_i \sigma^\mu \psi_i V_\mu \)

A new vector can also couple to **anomaly-free global symmetries** of the Standard Model (or, with appropriate new matter, to anomalous symmetries)

e.g. B-L, L_μ-L_τ, ...
Looking for Dark Sectors

Whatever is in the dark sector, only three sizeable interactions allowed by Standard Model symmetries:

**Vector Portal**

\[ \frac{1}{2} \epsilon_Y F_{\mu\nu}^Y F_{\mu\nu}' \]

focus for this talk – big opportunity for low-energy experiments

**Higgs Portal**

\[ \epsilon_h |h|^2 |\phi|^2 \]

exotic rare Higgs decays

**Neutrino Portal**

\[ \epsilon_\nu (hL) \psi \]

not-so-sterile neutrinos

**Gauge Portal**

\[ g \sum_i q_i \bar{\psi}_i \bar{\sigma}^\mu \psi_i V_\mu \]

sometimes “bycatch” in vector portal searches, but some interesting cases require dedicated searches!
Sources and Sizes of Kinetic Mixing \( \frac{1}{2} \epsilon_Y F^Y_{\mu\nu} F'_{\mu\nu} \)

- If absent from fundamental theory, can still be generated by perturbative (or non-perturbative) quantum effects

  - Simplest case: one heavy particle \( \psi \) with both EM charge & dark charge

  \[
  \gamma \ \psi \ \epsilon \ \gamma \ \psi \ \epsilon \ \gamma \ \psi \ \epsilon \ \gamma \\
  \text{generates} \quad \epsilon \sim \frac{e g_D}{16\pi^2} \log \frac{m_\psi}{M_*} \sim 10^{-2} - 10^{-4}
  \]
Sources and Sizes of Kinetic Mixing \( \frac{1}{2} \epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu} \)

- If absent from fundamental theory, can still be generated by **perturbative** (or non-perturbative) quantum effects

  - In Grand Unified Theory, symmetry forbids tree-level & 1-loop mechanisms. **GUT-breaking** enters at 2 loops

\[ \gamma \xrightarrow{\psi} e \xrightarrow{g_D} A' \]

generating \( \epsilon \sim 10^{-3} - 10^{-5} \)

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

Regardless of where it comes from, kinetic mixing can always be re-interpreted as (mainly) giving matter of electric charge $qe$ an $A'$ coupling $\propto q\varepsilon e$

Dark-sector matter can have an independent coupling $g_D$ to $A'$
Hints of Dark Forces?

- High-energy cosmic ray anomalies
- Direct detection anomalies
- Muon g-2
- Muonic hydrogen Lamb shift
- $^8$Be decay resonance
- Astrophysical hints of dark matter self-interaction?
- 511 keV line
- keV γ-ray excess
- Galactic center excess
Taxonomy of Dark Sectors

A few simple questions about the new physics…

1. What is the mediator?
   - Kinetically mixed dark photon?
   - Scalar? Flavor gauge boson?
   - SM dipole interaction?

2. Is it lighter or heavier than…
   - any dark matter in dark sector? (invisible decays)
   - relevant SM particles? $2m_e$ (visible decays)
   - new unstable particles? (“rich” multi-body decays)
Taxonomy of Dark Sectors

If dark matter is relevant…

3. How is it produced?
   - Thermally (through annihilation to SM)?
   - Asymmetric?
   - Other?

   *May imply constraints/relations among dark-sector couplings*

4. Fermion or scalar?

5. Elastic (mass-diagonal) or inelastic (mass-off-diagonal) interactions?

   *Affect signals in various experiments and the comparisons among them*
Taxonomy of Dark Sectors

Kinetically mixed dark photon decays to SM

Not produced on-shell
* can still mediate dark sector production

Visible decays –
width $\Gamma \sim \alpha m_{A'} \epsilon^2$

Long-lived $A' \rightarrow 3\gamma$

Dark sector **millicharges**
Taxonomy of Dark Sectors

Kinetically mixed dark photon decays to SM

Not produced on-shell
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Visible decays – width $\Gamma \sim \alpha m_{A'} e^2$

Long-lived $A' \rightarrow 3\gamma$

Dark sector millicharges

Visible & missing mass searches

Cosmological & stellar bounds, solar production, light thru walls
Taxonomy of Dark Sectors

Kinetically mixed dark photon coupled to DM

Not produced on-shell
* can still mediate DM production

Decays mainly to DM anti-DM pair,
width $\Gamma \sim \alpha_D m_{A'}$
+ subleasing visible decay
Rightarrow invisible signal

Visible decays –
width $\Gamma \sim \alpha m_{A'} \epsilon^2$

$m_{A'} = 2 m_{DM}$

Long-lived
$A' \rightarrow 3\gamma$
Taxonomy of Dark Sectors

DM Signals at colliders

- Contact operator DM production
- Resonant DM production
- Near-threshold DM production (off-shell light mediator)

$m_{A'} = 2 m_{DM}$

Dark photon mass

$2m_e$

0

Dark matter mass
Sub-MeV Dark Photons

[Figure from 2013 Intensity Frontier report – Javier Redondo]
Sub-MeV Dark Photons

Cavity searches

Light thru walls

Solar+scatter

Future

FIG. 2: Constraints on dark photons, including results from XENON10 [10] and CoGeNT [11, 12], CAST [13], and other experiments. The conservative limits are shown (see Ref. [17] for details). The dashed, dot-dashed and dotted curves show constraints from the CAST experiment [18] by considering the non-zero finite limit on the detecting rate to be below 1 keV. A dark photon of 1 keV energy can at most be extracted from the total photoabsorption cross section signals by the XENON10 [10] and CoGeNT [11, 12] collaborations yield far more stringent limits.

The XENON10 collaboration has published a study [10] showing that the dark photon flux from the Sun drops almost exponentially with energy, whereas the observed spectrum in CoGeNT [11, 12] is quite significant, considering that the signal scales as \( m_A \times T_A \). This will happen because the sterile state is also dominantly absorbed by the wall, and the state evolves to \( |A_i^+\rangle \) after traveling a further distance \( L \approx 10^{15} \) cm. We also collate main constraints in Table I.

The unprecedented sensitivity for dark photons, including very tight stellar energy loss constraints, was supported by the Sun.

Conclusions

The results provided here will allow the determination of dark photons, including very tight stellar energy loss constraints, to be performed with a high level of confidence.
Taxonomy of Dark Sectors

Kinetically mixed dark photon coupled to DM

Not produced on-shell
* can still mediate DM production

Dark photon mass

Decays mainly to DM anti-DM pair,
width $\Gamma \sim \alpha_D m_{A'}$
+ subleasing visible decay

$2 m_e$

$m_{A'} = 2 m_{DM}$

Visible decays – width $\Gamma \sim \alpha m_{A'} \epsilon^2$

Long-lived $A' \rightarrow 3\gamma$

Dark matter mass
Decay Modes & Lifetimes

Far from Z-pole, same breakdown as $e^+e^-$ annihilation modes
Visible Dark Photons

• Decay Modes and Lifetime

• Search Strategies

• Outstanding Challenges
## Dark Photon Searches

<table>
<thead>
<tr>
<th>Production Modes</th>
<th>Detection Signatures</th>
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<td>• Electron-positron annihilation</td>
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Dark Photon Searches

Production Modes

- Electron-positron annihilation
  ~constant yield up to threshold
- Meson Decays
- Drell-Yan (collider or fixed target)
  Yield falls steeply with mass
- Bremsstrahlung
Production: $e^- \text{ bremsstrahlung}$

Distinctive kinematics: for $m_e \ll m_{A'} \ll E_{\text{beam}}$, $A'$ carries most of beam energy & very forward-peaked

$$e^- \rightarrow A' \sim \left(\frac{m_A}{E}\right)^{3/2} \text{ (narrow)}$$

$$e^- \text{(wide)} \sim \left(\frac{m_A}{E}\right)^{1/2}$$

$$l^+ \sim \frac{m_A}{E}$$

$$E_{A'} \approx E_{\text{beam}} - m_{A'}$$

$$E_{e^-} \approx m_{A'}$$
Dark Photon Search: Current Constraints

Red/green: e,μ anomalous dipole moments

All other colors: Pair resonance searches

Gray: Beam Dump
New Dark Photon Searches: Visible Vertex Searches

Look for $A'$ decay displaced from target by reconstructing final-state tracks

Enables substantial background reduction $\Rightarrow$ sensitivity to lower $\epsilon$ (assuming no other decays that broaden $A'$ resonance)
New Dark Photon Searches: Fixed Target Missing Mass Searches

New technique, being pursued by several proposed experiments:

"Easier" missing mass: $e^+$ beam on atomic $e^-$: measure $\gamma$ [e.g. MMAPS, VEPP-3]

"Harder" missing mass: $e^-$ beam on H, reconstruct $e^-$ & [e.g. DarkLight, in conjunction with visible resonance or veto to reject background]
Ongoing Efforts

Broad worldwide effort to search for dark forces!
(this is the list of ongoing searches for visible dark photons)

- DarkLight
- APEX
- HPS
- CMS & ATLAS lepton jets & exotic Higgs decays
- LHCb
- Belle II
- MMAPS

- VEPP-3
- MESA
- Future MAMI-A1
- SHiP
- SeaQuest
- KLOE-II
- NA64
- ???
The NA48/2 detector

Principal subdetectors:

- Magnetic spectrometer (4 DCHs views/DCH: redundancy; $G_{\text{p/p}} = 0.48\% \oplus 0.009\% [\text{GeV}/c]$ (in 2007))
- Scintillator hodoscope (HOD) (fast trigger, time measurement (150ps))
- Liquid Krypton EM calorimeter ($L\text{Kr}$) (high granularity, quasi-homogeneous; $V_{E/E} = 3.2\% / E^{1/2} \oplus 9\% / E \oplus 0.42\% [\text{GeV}]; V_x = V_y = 4.2\text{mm} / E^{1/2} \oplus 0.6\text{mm}$ (1.5mm@10GeV))

Narrow momentum band $K$ beams:

$P_K = 60 (74) \text{ GeV}/c, G_P K / P_K \sim 1 \%$ (rms).

Maximum $K$ decay rate $\sim 100 \text{ kHz}$;

NA48/2: six months in 2003–2004

NA62 - $R K$: four months in 2007

What Next?

• Opportunities
  – Are these lists missing something? Can we combine them in new and exciting ways?

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• Challenges
  – What do present experiments teach us about obstacles we’ll have to confront to go further?
  – What milestones do we really want to hit?
The Limit to Bump Hunts?

This is what a signal looked like in APEX test run

Detection requires excellent statistics & mass resolution and exquisite bkg model

theory & exp uncertainties → most analyses parametrize bg

Not unique challenge (cf h→γ γ), but future dark photon searches push it even further.

What’s the ultimate limit?

%‐level $\sigma_m$

~$10^6$ events

Test mass:

$m_{A'} = 224.5$ MeV
Closing “Mont’s” Vertexing Gap

Closing from above (bump hunt) runs into systematics

Closing from below requires great vertex resolution in high luminosity environment

1/5 B meson lifetime
1/50 the energy
orders of magnitude lower S/B
Extending to Higher Masses

How to reach lower $\epsilon$ at $O$(GeV) masses?

• Yield…
  – Fixed-target yields falling precipitously (form factors, pdfs, …)
  – Still mostly “low-pT” for LHC
  – Is Belle II best we can do?

• Hadronic channels start to dominate branching ratios

![Drell-Yan (120 GeV p on target)]

$\epsilon = 0.01$

plot by Stefania Gori
Conclusion

• Exploring Dark Sectors is an important and growing element of physics beyond the Standard Model
  – Requires searching for several complementary signatures (more in subsequent primer talks)
  – A wealth of exciting ongoing experiments (more in WG's)
  – Important hurdles to surpass for the next generation of experiments (more in WG's)

• Workshop aims to stimulate thinking about the next steps. Thanks for coming!