Frontiers in New Physics
Searches with Hadrons

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HADRON 17
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And the cosmic baryon symmetry

\[ \eta = \frac{n_{\text{baryon}}}{n_{\text{photon}}} = (5.96 \pm 0.28) \times 10^{-10} \]

so large?
The Puzzle of the Missing Antimatter

The observed cosmic $^2$H abundance in context of big-bang nucleosynthesis yields a baryon asymmetry:

$$\eta = n_{\text{baryon}}/n_{\text{photon}} = (5.96 \pm 0.28) \times 10^{-10} \quad [\text{Steigman, 2012}]$$

The particle physics of the early universe can explain this asymmetry if $B$, $C$, and $CP$ violation exists in a non-equilibrium environment. [Sakharov, 1967]

But estimates of the baryon excess in the Standard Model have always been much too small, [Farrar and Shaposhnikov, 1993; Gavela et al., 1994; Huet and Sather, 1995.]

$$\eta < 10^{-26}$$

But with a 125 GeV Higgs there is no EWPT [Aoki et al., 1999]

So that the SM mechanism fails altogether
Perspective

Our dark-dominated universe and its baryon asymmetry speaks to possible hidden (or visible?!)
particles, interactions, symmetries and more that we may yet discover.

Such new physics could arise at either
i) high energies with $\mathcal{O}(1)$ couplings to SM particles

Here low energy & collider studies are complementary – or –

ii) low energies with very weak couplings to SM particles

Largely unexplored! Low energy studies have unique discovery potential!
Flavor Physics Snapshot

with a focus on quarks & symmetries

Heavy Quarks

- Quark Mixing & CPV: CKM?

Light Quarks

- non-CKM CPV?
  (EDMs (d), D)
- non-V-A currents?
  (a, A, B, ...)
- n Electric Charge?
  - B-L violation?
  - “Dark” Forces?

- Lepton Flavor Universality? (B to τν, ...)
- Non-V-A currents? (B to K* ll, ...)
- New CPV? (charm, ...)
- “Dark” Forces? (D* to D A', ...)

[Lepton Flavor Violation & τ decays... Higgs Physics... ν’s]
On Complementarity

Can the limits from such searches be related in a model independent way?

Suppose new physics enters at energies beyond a scale $\Lambda$

Then for $E < \Lambda$ we can extend the SM as per

$$\mathcal{L}_{\text{SM}} \implies \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^{D-4}} O_i^D,$$

where the new operators have mass dimension $D > 4$

Symmetry guides their construction: impose $SU(2) \times U(1)$

If $\Lambda \gg \Lambda_{\text{EW}}$, then heavy & light hadrons can share an EFT framework, even if the flavor structure is different

Otherwise not.
Today

New physics searches with light hadrons

• Permanent electric dipole moment searches, quantities that break P and T
  – and how these are distinct from –

• Dalitz plot analyses for C and CP violation

• Rare decays & their interplay in searches for hidden forces, to go beyond “dark photons”

[emphasis on accelerator tests]
Permanent Electric Dipole Moments

A fundamental EDM points along the particle’s spin, breaking both T and P

$$\mathcal{H} = -d\vec{E} \cdot \frac{\vec{S}}{S} - \mu\vec{B} \cdot \frac{\vec{S}}{S}$$

Applied electric fields can be enormously enhanced in atoms and molecules [Purcell and Ramsey, 1950]

Searches in different systems:
paramagnetic & diamagnetic & the neutron

ACME (ThO) [Baron et al., 2014]
YbF [Hudson et al., 2011]
Tl [Regan et al., 2002]

Hg [Graner et al., 2016] ★
Xe [Rosenberry & Chupp, 2001]
Ra [Bishof et al., 2016]

n [Pendlebury et al., 2015]

with many more under development!

[For reviews, see Pospelov and Ritz, 2005; Engel, Ramsey-Musolf, and van Kolck 2013]
Heavy Atom & Molecular EDMs

Naturally involve multiple energy scales

 atomic/molecular level
  nuclear level
    nucleon level
      quark level
          particle level CP models

[Ginges and Flambaum, 2004]

Energy

[Diagram showing various energy scales and processes related to EDMs, including atomic/molecular, nuclear, nucleon, and quark levels, with arrows indicating energy transitions and labels such as eeNN, eeqq, d, MQM, S, d_n, d_q, Higgs, Supersymmetric, Left-right, Strong CP.]
Operator Analysis of EDMs

The flavor-diagonal effective Lagrangian at ~1 GeV

can appear in the IR even if an axion acts [Chien et al., arXiv:1510.00725, JHEP 2016]

\[ \mathcal{L}_{\text{dim } 4} \supset \bar{\theta} \alpha_s G \tilde{G} \]

\[ \mathcal{L}^{\text{dim } 6} \supset \sum_{q=u,d,s} \left( d_q \bar{q} F \sigma_5 q + \tilde{d}_q \bar{q} G \sigma_5 q \right) + \sum_{l=e,\mu} d_l \bar{l} F \sigma_5 l \]

\[ \mathcal{L}_{\text{dim } 6} \supset w g_s^3 G G \tilde{G} + \sum_{f,f',\Gamma} C'_{ff'} (\bar{f} \Gamma f')_{LL} (\bar{f} \Gamma f')_{RR} \]

\[ \mathcal{L}^{\text{dim } 8} \supset \sum_{q,\Gamma} C_{qq} \bar{q} \Gamma q q \Gamma i \gamma_5 q + C_{qe} \bar{q} \Gamma q e \Gamma i \gamma_5 e + \cdots \]

[Ritz, CIPANP, 2015]

Many sources: note effective hierarchy imposed by \( SU(2) \times U(1) \) gauge invariance (chirality change!)

Limits on new CPV sources taken “one at a time”
Operator Analysis of EDMs
Operator mixing & renormalization effects now included

A single TeV scale CPV source may give rise to multiple GeV scale sources

First systematic studies for EDMs since HADRON 15!
[Chien et al., arXiv:1510.00725, JHEP 2016; Cirigliano, Dekens, de Vries, Merenghetti, 2016 & 2016

- Start with no higher than dimension six at the TeV scale [Buchmuller & Wyler, 1986; Grzadkowski et al.,2010]

- Cf. collider, EDM, flavor CPV constraints

- EDM constraints on new CPV sources can weaken but are still strong!

What room is there for other CPV searches?
Pros and cons of Dalitz plots

Pros

● More observables (B & A CP at each Dalitz plot point)
● Using isobar formalism, can express total amplitude as coherent sum of quasi-two-body contributions

- n.b. each c & F contain the weak and strong physics, respectively
- n.b. each c is itself a sum of contributions from tree, penguin, etc.

● Interference provides additional sensitivity to CP violation

Cons

● Need to understand hadronic (F) factors – lineshapes, angular terms, barrier factors, ...
● Isobar formalism only an approximation
● Model dependence

\[
A\left(m_{12}^2, m_{23}^2\right) = \sum c F\left(m_{12}^2, m_{23}^2\right)
\]

Tim Gershon

Introduction to Dalitz Plot Analysis

Dalitz Studies of CP Violation
Apropos to both heavy and light flavor decays

\[D \rightarrow K_s \pi^+ \pi^-\]

Consider population asymmetry about the mirror line in neutral 0- decay

If the initial and final states are C definite, then mirror symmetry is also a CP test

[SG & Tandean, 2004]

[Image Credit: Tom Latham [Tim Gershon]]
Dalitz Studies of CP Violation

For $|\Delta F|=1$ decays

- In untagged $B \rightarrow \pi^+ \pi^- \pi^0$ decay CPV appears in the SM
- All such dimension six operators can be rewritten as C definite combinations, the asymmetry is C and CP odd

To realize C violation in dimension six $|\Delta F|=1$ operators are necessary


For $|\Delta F|=0$ decays [Enter $\eta$ decays!]

C violation first appears in dimension eight (in SM EFT), in distinction to the dimension six operators for EDMs

Note old “C odd” papers [TD Lee & L Wolfenstein, 1965; Lee, 1965; Nauenberg, 1965]
[ Bernstein, Feinberg, & Lee, 1965; Barshay, 1965]
Hunting Hidden Forces

“Early” positron excesses in the gamma-ray sky from dark matter annihilation

Circa 2008

new gauge boson is a “portal” to a hidden sector

Could explain size of excesses if new GeV-scale gauge bosons exist

[Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2009; also Fox & Poppitz, 2009,...Pospelov 2009 (μ g-2)]

Conventional explanations were ultimately found, but the possibility was opened nonetheless....
Dark Photons

Hunting new forces in fixed target experiments

The interactions that generate DM annihilation could also be discovered at accelerators:

The new gauge boson could stem from a dark electromagnetism, and the photon and dark photon could mix

[E.g., Bjorken, Essig, Schuester, Toro, 2009]

But different gauge symmetries (& portals) are possible!
New Gauge Bosons

We may only be able to probe part of a rich dark sector

E.g., let $A'$ be the gauge field of a $U(1)'$ group

But Coulomb-like DM-DM forces do not appear to exist, so that the $A'$ must have mass

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\varepsilon}{2} F_{\mu\nu}^Y F'_{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'_{\mu\nu} + M_{A'}^2 A'_{\mu} A'_{\mu} + \ldots$$

With $A_\mu \rightarrow A_\mu - \varepsilon A'_{\mu}$ the $A'$ couples to SM fermions with strength $Q_e \varepsilon$

[Holdom, 1986]
Dark Photon Decays to Visibles (Only)

Exclude a “dark” explanation of the muon g-2 anomaly

[Passpelev, 2009]

But this may only speak to our assumptions…
Anomaly in IPC in Be-8 Transitions

A.J. Krasznahorkay et al., 1504.01527 [nucl-ex]; note also 1504.00489 (Gulyas et al., NIM A808 (2016), 21)

• Resonant selection of $^8\text{Be}^*$ state via $p$ beam energy
• Select transition to $^8\text{Be}$ g.s. via detected $e^+e^-$ energy
• Measure $e^+e^-$ invariant mass & opening angle

N.B. Earlier axion searches & more...
[Treiman & Wilczek, 1978; Donnelly et al., 1978; Savage et al., 1986 & 1988....]
But it cannot be a dark photon…

There are many constraints in the Be-8 signal region

- To get the right signal strength: $\varepsilon \approx 0.011$
- To decay within 1 cm: $|\varepsilon| \geq 1.3 \times 10^{-5}$
- N.B. no signal in the 17.64 MeV $^8$Be to g.s. transition; suppressed by phase space if it were 17 MeV in mass

[Feng, Fornal, Galon, SG, Smolinsky, Tait, Tanedo, 2016]
But it cannot be a dark photon…

The solution is to introduce separate fermion couplings

- The dominant constraints are null results from searches for $\pi^0 \to A' \gamma \to e^+ e^- \gamma$

- Eliminated if $Q_u X_u - Q_d X_d \approx 0$ or $2X_u + X_d \approx 0$ or $X_p \approx 0$

- A protophobic gauge boson with couplings to neutrons, but suppressed couplings to protons, can explain the $^8\text{Be}$ signal without violating other constraints

N.B. The couplings to neutrinos must also be small!
Coupling Constraints...

Lepton Sector

At $M_X=16.7$ MeV...

$\Delta g-2_e: |\epsilon_e| < 1.4 \times 10^{-3}$

KLOE 2 (if $\epsilon_d=\epsilon_s$):

$$\phi \rightarrow \eta(X \rightarrow e^+e^-)$$

$$|\epsilon_e| < 2 \times 10^{-3}$$

E141: $|\epsilon_e| > 2 \times 10^{-4}$

TEXONOO (\nu-e):

$$\sqrt{|\epsilon_e\epsilon_\nu|} < 3 \times 10^{-4} \text{ (dest.)}$$

$$\sqrt{|\epsilon_e\epsilon_\nu|} < 7 \times 10^{-5} \text{ (const.)}$$
What’s the model?
There’s no unique choice, but here’s one:

[Feng, Fornal, Galon, SG, Smolinsky, Tait, Tanedo, 2016]

- Gauge the $U(1)_{B-L}$ global symmetry of the SM
- This is anomaly-free with the addition of 3 sterile neutrinos
- Generically the $B$-$L$ boson mixes with the photon:
  \[
  \varepsilon_u : \frac{2}{3} \varepsilon + \frac{1}{3} \varepsilon_{B-L} \\
  \varepsilon_d : -\frac{1}{3} \varepsilon + \frac{1}{3} \varepsilon_{B-L} \\
  \varepsilon_{\nu} : -\varepsilon_{B-L} \\
  \varepsilon_e : -\varepsilon - \varepsilon_{B-L} ,
  \]
- For $\varepsilon + \varepsilon_{B-L} \approx 0$, we get both $\varepsilon_u \approx \varepsilon/3$ and $\varepsilon_d \approx -2\varepsilon/3$ (protophobia) and $\varepsilon_e \ll \varepsilon_{u,d}$!
- The neutrino $X$-charge is too large. This problem is mitigated if $X$ is heavier, then $\varepsilon_{B-L}$ can be smaller. It can be remedied in different ways – e.g., by mixing with $X$-charged sterile neutrinos.

More model possibilities are being developed….
Future Experiments
Can confirm or exclude our particle interpretation

- Also TREK, SHiP, SeaQuest… but should repeat $^8$Be expt!

N.B. $(g-2)_e$ constraint
Future $\eta$ decay studies also key
Summary

We have reviewed new physics searches with hadrons, focusing particularly on searches for new sources of CP violation and new probes of light hidden sectors.

Opportunities for such studies with $\eta$ (and $\eta'$) decays beckon....
Detecting BSM Physics with REDTOP ($\eta/\bar{\eta}$ factory)

The experiment will yield $2.5 \times 10^{13} \, \eta$ mesons/yr and $2 \times 10^{11} \, \eta'$ mesons/yr

C, T, CP-violation
- CP Violation via Dalitz plot mirror asymmetry: $\eta \rightarrow \pi^+ \pi^- \pi^0$
- CP Violation (Type I - $P$ and $T$ odd, $C$ even): $\eta \rightarrow 4\pi^0 \rightarrow 8\gamma$
- CP Violation (Type II - $C$ and $T$ odd, $P$ even): $\eta \rightarrow \pi^+ \pi^- \ell^+ \ell^-$ and $\eta \rightarrow 3\gamma$
- Test of CP invariance via $\mu$ longitudinal polarization: $\eta \rightarrow \mu^+ \mu^-$
- Test of CP invariance via $\gamma^*$ polarization studies: $\eta \rightarrow \pi^+ \pi^- e^+ e^-$ and $\eta \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$
- Test of CP invariance in angular correlation studies: $\eta \rightarrow \mu^+ \mu^- e^+ e^-$
- Test of $T$ invariance via $\mu$ transverse polarization: $\eta \rightarrow \pi^+ \mu^- \mu^-$ and $\eta \rightarrow \gamma \mu^+ \mu^-$
- CPT violation: $\mu$ polarization in $\eta \rightarrow \pi^+ \mu^+ \nu$ vs $\eta \rightarrow \pi^- \mu^- \nu$ and $\gamma$
- Polarization in $\eta \rightarrow \gamma \gamma$

Other discrete symmetry violations
- Lepton Flavor Violation: $\eta \rightarrow \mu^+ e^- + c.c.$
- Double lepton Flavor Violation: $\eta \rightarrow \mu^+ \mu^- e^+ e^- + c.c.$

Non-$\eta/\eta'$ based BSM Physics
- Dark photon and ALP searches in Drell-Yan processes: $q\bar{q} \rightarrow A'/a \rightarrow l^+l^-$
- ALP's searches in Primakoff processes: $pZ \rightarrow pZ \, a \rightarrow l^+l^-$ (F. Kahlhoefer)
- Charged pion and kaon decays: $\pi^+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ \nu e^+ e^-$ and $K^+ \rightarrow \mu^+ \nu A' \rightarrow \mu^+ \nu e^+ e^-$
- Neutral pion decay: $\pi^0 \rightarrow \gamma A' \rightarrow \gamma e^+ e^-$

New particles and forces searches
- Scalar meson searches (charged channel): $\eta \rightarrow \pi^0 H$ with $H \rightarrow e^+ e^-$ and $H \rightarrow \mu^+ \mu^-$
- Dark photon searches: $\eta \rightarrow \gamma A'$ with $A' \rightarrow e^+ e^-$
- Protophobic fifth force searches: $\eta \rightarrow \gamma X_{17}$ with $X_{17} \rightarrow e^+ e^-$
- New leptophobic baryonic force searches: $\eta \rightarrow \gamma B$ with $B \rightarrow e^+ e^-$ or $B \rightarrow \gamma \pi^0$
- Indirect searches for dark photons new gauge bosons and leptoquark: $\eta \rightarrow \mu^+ \mu^-$ and $\eta \rightarrow e^+ e^-$
- Search for true muonium: $\eta \rightarrow \gamma \mu^+ \mu^-$

Other Precision Physics measurements
- Proton radius anomaly: $\eta \rightarrow \gamma \mu^+ \mu^-$ vs $\eta \rightarrow \gamma e^+ e^-$
- All unseen leptonic decay mode of $\eta / \eta'$ (SM predicts $10^{-6}$ - $10^{-9}$)

High precision studies on low energy physics
- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- Electromagnetic transition form-factors (important input for $g-2$)

[Slide Credit: Corrado Gatto]
- Use delivery ring and extract beam at AP50
- Decelerate the 8 GeV beam to desired energy

- Existing $\eta/\eta'$ world sample not sufficient for decays violating conservation laws or searching for new particles
- Currently the collaboration is forming and working at a proposal (20 institutions, 61 members)
- Total cost: < 40 M$ (depending on re-use of existing infra-structure)
- 2018: proposal to Fermilab’s PAC
- 2021: Detector construction + engineering run
- >2022: Start physics run
Backup Slides
New Low or High Energy Physics?

How can these possibilities be distinguished?

[Le Dall, Pospelov, and Ritz, 2015]

Consider the ν mass: it can come from...

- a dimension-five operator (Weinberg)
  N.B. not “UV complete” — new high E BSM is required!

  \[ |B - L| \] violating!

- introducing a right-handed neutrino and using the Higgs mechanism

This in itself is UV complete.

But which mechanism operates?

Or do both?

But only the one with B-L violation allows 0 ν ββ decay
Today

We consider an anomaly of $6.8\sigma$ significance in $^8\text{Be}$ transitions, namely:

A.J. Krasznahorkay et al., 1504.01527 [nucl-ex]; note also 1504.00489 (Gulyas et al., NIM A808 (2016), 21)
Operator Analysis of EDMs

The effective Lagrangian in hadron and nuclear degrees of freedom

There has been much activity, with more ongoing

- First “dim 6” lattice QCD matrix elements for the neutron EDM [Bhattacharya et al., 2015]

- Much effort to develop low-energy EFTs for nuclei with consistent chiral power counting [... de Vries et al., 2011, 2012; Dekens et al., 2014]

Outcome is to interpret nucleon and few-body nuclei EDMs in terms of a set of LECs, potentially determinable via storage ring expts

Still more complicated systems contain enhancements that might enable an EDM discovery
EDMs: Broader Impacts

Low or high energy physics?

The discovery of the electron EDM at anticipated sensitivity would reveal weak scale new physics

[Le Dall, Pospelov, and Ritz, 2015]

The limits anticipated in next generation EDM experiments give decisive tests of EWB in popular models

[Cirigliano et al., 2010; Chao and Ramsey-Musolf, 2014]
Hidden Sector Portals

Only a Few “Sizeable” Portals Exist

\[ \mathcal{L}_{\text{dim} \leq 4} = \kappa B^{\mu\nu} V_{\mu\nu} - H^\dagger H (A_S + \lambda S^2) - Y_N L H N \]

[Batell, Pospelov, and Ritz, 2009; Le Dall, Pospelov, Ritz, 2015]

- Vector Portal
- Higgs Portal
- Neutrino Portal

All deserve systematic study; N.B. low E Higgs portal constrained by rare B, K decays

Here we focus on vector portals

Enter the dark photon \( A' \) and its field strength tensor \( V^{\mu\nu} \)

\[ \mathcal{L}_{A'} = \frac{1}{2} \kappa B^{\mu\nu} V_{\mu\nu} - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'^\mu A'_\mu \]

Note “kinetic mixing” of visible & hidden sectors