Exploring the Hidden Sector @ Low Energies

J. Jaeckel**

S. Abel†, M.Goodsellxx, S. Gardiner†, H. Gies0
V. Khoze†, A. Lobanovγ, J. Redondoγ, A. Ringwald*, C. Wallace†

**ITP Heidelberg, †IPPP Durham, *DESY,
γMPIfR Bonn, *MPI Munich, xxCern, 0ITP Jena
Where we want to go...
The Standard Model + Beyond the SM (directly accessible to colliders)
We need...

Physics beyond the Standard Model
The Standard Model

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>Charge</td>
</tr>
<tr>
<td>+2/3</td>
<td>-1/3</td>
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<tr>
<td>Up</td>
<td>Down</td>
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<td>u</td>
<td>d</td>
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<tr>
<td>Charm</td>
<td>Strange</td>
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<tr>
<td>c</td>
<td>s</td>
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<td>Top</td>
<td>Bottom</td>
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<tr>
<td>t</td>
<td>b</td>
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<tr>
<td>Tau</td>
<td>e</td>
</tr>
<tr>
<td>1. Family</td>
<td>2. Family</td>
</tr>
<tr>
<td>3. Family</td>
<td>e-Neutrino</td>
</tr>
<tr>
<td>2012!!!!</td>
<td>ν_e</td>
</tr>
<tr>
<td>Gravitation</td>
<td>Weak forces</td>
</tr>
<tr>
<td>graviton</td>
<td>W- und Z-bosons</td>
</tr>
<tr>
<td>Electromagnetism</td>
<td>photons (γ)</td>
</tr>
<tr>
<td>Strong forces</td>
<td></td>
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<tr>
<td>gluons</td>
<td></td>
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</table>

+ h = Higgs
Inventory of the Universe

- Dark Energy: 68%
- Dark Matter: 27%
- Ordinary Matter: 5%
- Neutrinos: 0.1 - 0.5%
Where does it hide?
Exploring is (at least) 2 dimensional
Exploring is (at least) 2 dimensional

Energy, Mass

known knowns

LHC

LHCb B-phys
guessed unknowns

V, Fixed target

DM

unknown unknowns

Precision, Intensity, Small coupling

“dark” = weakly coupled
A „visible“ Hint for new Physics

The strong CP Problem
A dirty little secret...

\[ S = \int d^4 x \left[ -\frac{1}{4} G^{\mu \nu} G_{\mu \nu} - \frac{\theta}{4} G^{\mu \nu} \tilde{G}_{\mu \nu} + i \bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \right] \]

\[ \sim \theta \vec{E} \cdot \vec{B} \]

- The $\theta$-term violates time reversal (T=CP)!
- Connected to strong interactions!

Electric dipole moment of the neutron!
Measure neutron electric dipole moment

- $\theta$ would cause neutron EDM $\longrightarrow$ Experiment

\[ \hbar \omega = 2 |\vec{d} \cdot \vec{E}| \]

\[ \vec{E} \]

Measure transition frequency.
No neutron electric dipole moment...

\[ |d| < 3 \times 10^{-26} \text{ e cm} \]

\[ = 3 \times 10^{-13} \text{ e fm} \]
No neutron electric dipole moment...

\[ |\vec{d}| < 3 \times 10^{-26} \text{ e cm} \]

\[ = 3 \times 10^{-13} \text{ e fm} \]

\[ \frac{\theta}{16\pi^2} \text{ e fm} \]

Very unnatural!
Hints for new Physics

Model Building

Bottom-up (pheno)

- Fix problem "here and now"

Top-down (theory)

- Go back to drawing board "Start from scratch"
The axion solution to the strong CP problem

- Make $\theta$ dynamical $\Rightarrow$ it can change its value
The axion solution to the strong CP problem

- Make $\theta$ dynamical $\Rightarrow$ it can change its value

Initially

Classical potential

With QCD quantum corrections
The axion solution to the strong CP problem

- Make $\theta$ dynamical $\Rightarrow$ it can change its value

- QCD likes to be CP conserving (if we allow it)
The axion solution to the strong CP problem

- Make $\theta$ dynamical $\Rightarrow$ it can change its value

- Can still move

$\Rightarrow$ new particle = axion
Axions

- Classical flatness from symmetry
- Quantum corrections are small
- New light particle: The Axion (it’s a Weakly Interacting Sub-eV Particle)

Dark matter candidate
Good motivation for axion/WISP experiments
Hints for new Physics

Model Building

Bottom-up (pheno)

Experiments

Top-down (theory)
Exploring fundamental high energy physics...

- The direct approach: MORE POWER
  
  LHC, Tevatron + ILC, CLIC

- Detects most things within energy range
- E.g. may find SUSY particles, WIMPs etc.
But...

- May miss very weakly interacting matter (Axions, Hidden Photons, WIMPs, WISPs...)
- Current maximal energy few TeV
But...

• May miss very weakly interacting matter (Axions, Hidden Photons, WIMPs, WISPs...)
• Current maximal energy few TeV

• Man its DANGEROUS... 😊
But...

- May miss very weakly interacting matter: Hidden photons, Axions, WIMPs, WISPs...
- Current maximal energy few TeV

- Or much much more horrifying:

**NO SIGNAL ABOVE BACKGROUND!**
Recycling... Complementary approaches
Light shining through walls

“Light shining through a wall”

Laser → X → Detector
Light shining through walls

“Light shining through a wall”

Laser

\[ 10^{20} / \text{s} \]

\[ \gamma \quad \rightarrow \quad X \quad \rightarrow \quad \gamma \]

Detector

\[ 1 / \text{s} \]

- Test \[ P_{\gamma \rightarrow X \rightarrow \gamma} \lesssim 10^{-20} \]
- Enormous precision!
- Study extremely weak couplings!
Photons coming through the wall!

- It could be Axion(-like particle)s!

- Coupling to two photons:

\[ \frac{1}{M} a \tilde{F} F \sim \frac{1}{M} a \vec{E} \cdot \vec{B} \]

\[ P_{\gamma \rightarrow a \rightarrow \gamma} \sim N_{\text{pass}} \left( \frac{B L}{M} \right)^4 \]
Light Shining Through Walls

- A lot of activity
  - ALPS
  - BMV
  - GammeV
  - LIPPS
  - OSQAR
Small coupling, small mass

Axion band

mass/energy

Weaker interaction

$\pi^0$
Helioscopes

CAST@CERN
SUMICO@Tokyo
SHIPS@Hamburg

“Light shining through a wall”

Sun → \gamma \rightarrow \text{Ion} \rightarrow \text{Detector} \rightarrow \gamma^*
Sensitivity
WISPS=Weakly interacting sub-eV particles

- Axions

- Massive hidden photons (without B-field) = analog $\nu$-oscillations

- Hidden photon + minicharged particle (MCP)
Hidden Photons

LSW already competitive + testing interesting area
Hints for new Physics

Model Building
Coincidences?

- Neutrino masses:

\[ m_{\nu} \sim \text{meV} \]

- Scale of dark energy:

\[ \rho_{\Lambda} \sim (\text{meV})^4 \]

- Energy density of the Universe:

\[ \rho_{\text{today}} \sim (\text{meV})^4 \]
Hidden Photons

LSW already competitive + testing interesting area

Dark energy scale
High Scale

Small Coupling
Example: Axion coupling

- Effective higher dimensional coupling

\[ L_{Int} = -\frac{1}{4} g a F_{\mu\nu} \tilde{F}_{\mu\nu} = -g a E \cdot B \]

- Small coupling for large axion scale:

\[ g \sim \frac{\alpha}{2\pi f_a} \]
Huge Scale $>>$ LHC Energy!

- ca $10^4 - 10^5$ GeV
- ca $10^7 - 10^8$ GeV
- ca $10^{12} - 10^{13}$ GeV
High Scale

↓

Small Mass
Example: Axion See-Saw

- The axion mass is small, too!

$$m_a \sim \frac{m_\pi f_\pi}{f_a}$$
Example: Axion See-Saw

- The axion mass is small, too!

\[ m_a \sim \frac{m_\pi f_\pi}{f_a} \]

Pseudo-Goldstone Boson!
Example: Axion See-Saw

- The axion mass is small, too!

\[ m_a \sim \frac{m_\pi f_\pi}{f_a} \]

\[ \sim 0.6 \text{ meV} \left( \frac{10^{10} \text{ GeV}}{f_a} \right) \]

Sub-eV mass

Large scale
Large Scale but light!

ca $10^4 - 10^5$ GeV

ca $10^7 - 10^8$ GeV

ca $10^{12} - 10^{13}$ GeV

$\pi^0$
Hints for new Physics

Model Building

Bottom-up (pheno)

Go back to drawing board `Start from scratch`

Top-down (theory)
WISPs from String Theory
String theory

- Attempt to unify SM with gravity
- New concept: strings instead of point particles
Axion(-like particles)
String theory: Moduli and Axions

• String theory needs Extra Dimensions
  
  Must compactify

• Shape and size deformations correspond to fields:
  
  Moduli (WISPs) and Axions
  
  Connected to the fundamental scale, here string scale

WISP candidates
Axion (like particles): Where are we?
Axion (like particles): Where are we?
Axion (like particles): Where are we?

Intermediate strings
Funny Higgs arguments
Hidden Photons
String theory likes extra gauge groups

Many extra $U(1)$s!

Candidates for WISPs
Hidden by distance

\[ \chi \sim \frac{g_s}{8\pi Volumex} \]

\[ g_{hid} \sim 1 \]
Hidden Photons, all over the place
Hints for new Physics

Model Building

Bottom-up (pheno)

Top-down (theory)

New, cool Experiments
Tests new area

Exciting things go on NOW!!!
Dark Matter(s)
Properties of Dark Matter

- Dark matter is dark, i.e. it doesn't radiate!
  (and also doesn't absorb)

→ very, very weak interactions with light and with ordinary matter

→ Exactly the properties of axions
The axion has no clue where to start

Early times
High $T > T_{QCD}$

Can sit anywhere

$V(\theta)$
The axion has no clue where to start

Early times
High $T > T_{QCD}$

$t \gtrsim 10 \mu s$
Low $T < T_{QCD}$

Can start moving...
Axion Dark Matter

\[ \ddot{a} + 3H \dot{a} + m_a^2 a = 0 \]

\[ H = \frac{\dot{R}(t)}{R(t)} \]

- \( H \gg m_a \) \( \Rightarrow \) overdamped oscillator

- \( H \ll m_a \) \( \Rightarrow \) damped oscillator

\[ \rho_a(t) = \frac{\rho_{ini}}{R^3(t)} \]

\( \Rightarrow \) Dark Matter
Axion(-like particle) Dark Matter

\[
\begin{align*}
\text{Log}_{10} g \text{ [GeV}^{-1}] & \\
\text{Log}_{10} m_\phi \text{ [eV]} & \\
\end{align*}
\]
Hidden Photon Dark Matter works similar
Use a plentiful source of axions

- Photon Regeneration

Photon

(amplified in resonator)

axion

(dark matter)
Signal: Total energy of axion

\[ h \nu = m_a c^2 \left[ 1 + O(\beta^2 \sim 10^{-6}) \right] \]
An extremely sensitive probe!!!
Electricity from Dark Matter ;-).

- Photon Regeneration

Photon (amplified in resonator)

axion (dark matter)

10^{-23} W!
Also for hidden photons!!!
@ DESY + Bonn: WISPDpery
Broadband Search Strategy
Dark Matter Antenna (HP and axion...)

- Antenna converts HP→photon
- Radiation concentrated in center
- Detector

Probes here; very sensitive!!
Works also for axion-like particles
A Dream for Astrology ehhm Astronomy

- Emission from moving dark matter
  \[ V_{DM} = 0 \]
  \[ V_{DM} \neq 0 = \downarrow \]

- A picture of the DM-velocity distribution

Screen
@ DESY + Bonn
Beyond Photon Couplings
Light bosons can couple to fermions

- Goldstone bosons naturally couple to fermions (charged under the symmetry)

- E.g. Family symmetry changing e into $\mu$

\[(\partial_\mu \phi) \bar{\mu} \gamma^\mu e + h.c.\]

Interestingly these couplings are not very constrained from astrophysics!
(not enough energy to make $\mu$ s)
Plenty of room for dark matter
Conclusions
Conclusions

- Good Physics Case for Axions and WISPs
- explore `The Low Energy Frontier`
- Low energy experiments test energy scales much higher than accelerators
- Complementary!
- May provide information on hidden sectors and thereby into the underlying fundamental theory
- Dark Matter may be WISPy 😊
Hidden sector