Importance of Dark Sector Searches

Nina Arkani-Hamed
1960's View

NP = New Heavy Particles
More Broadly

\[ NP = \text{New Phenomena} \rightarrow \text{New Principles} \]
* CRUCIAL

* HARD

* EXPENSIVE

---

100 TeV Collider

10 TeV

LHC

TeV

2030's

2010's

1950's

Time

---

SUSY?
Natural, Un-natural?

Effective QFT

PARTICLE
EXPLOSION
* Searches for WIMP Dark Matter complement colliders

[e.g. 1 TeV "Higgsino" directly inaccessible @ LHC; copiously produced @ 100 TeV collider]
* Scores of experiments indirectly probe collider accessible higher scales:
  * EDM's [10 TeV scale]
  * QCD flavor [100 TeV scale]
Axions

* Not just solution of strong CP....
* More importantly: First confirmation of DYNAMICAL COUPLING “CONSTANTS”

* Crucial feature of Unification [+] reason for ubiquity of axions in string theory
* There are Exciting, New ideas for probing fA ~ M0

* Super-radiance of Rotating BH’s

* Time-varying EDM’s + NMR

MORE LIKE THIS NEEDED!
* Short-range gravity experiments can also probe light "moduli."

Direct indication of Dynamical Coupling "Constants"
(Light) Dark Sectors:

Robust, New Frontier in Fundamental Physics
DARK SECTOR EXPLOSION?

\[ \text{En. TeV} \rightarrow \text{time 2010's} \rightarrow \text{SUSY, Naturalness?} \]

\[ \text{GeV} \rightarrow \text{1950's PARTICLE EXPLOSION} \]

SUSY, Naturalness!

NO GUARANTEES

BUT, if it's there: FUTURE OF HEP

* NOT HARD  * NOT EXPENSIVE
(Light)
Dark Sector

SM (+ SUSY)

Gauge Kinetic Mixing
\[ Z = Z_{us} + Z_{dark} + Z_{mix} \]

\[ Z_{mix} = \sum_{ij} K_{ij} \theta_{us} \theta_{ij} \]

Leading couplings are dimensionless, [otherwise really tiny]
Most obvious candidates with UCD Dark:

\[ \mathcal{E} \quad E_{\text{Dark}} E_{\mu \nu} \quad \nabla \quad \text{After EWSB} \]

\[ \mathcal{E} \quad E_{\text{Dark}} E_{\mu \nu} \quad \nabla \quad \text{EM} \quad \uparrow \quad \text{Still dimless, dominates @ low E.} \]

Other candidate:

\[ \mathcal{E} \quad h h \quad \gamma_{\text{dark}} \quad \gamma_{\text{dark}} \quad \nabla \quad \text{After EWSB} \]

\[ \mathcal{E} \quad e^\ast e^\ast \quad \frac{e^\ast e^\ast}{M_W^2} \quad \nabla \quad \text{Suppressed @ low E} \]
\( \mathcal{E} \int F_{\mu \nu}^D F_{\mu \nu} \)

Unification \( \Rightarrow \) \( \mathcal{E} \ll 1 \)!
Above GUT scale, can't have mixing

But mixing generated radiatively after GUT is broken!
\[ \mathcal{E} \sim \frac{g_{\text{Dark}} g_Y}{16\pi^2} \left( \frac{g^2}{16\pi^2} \log \frac{M_{\text{cut}}}{M_X} \right) \sim 10^{-5} \rightarrow 10^3 \text{ naturally} \]
Could even have dark GUT:

$$\epsilon = \frac{g_{\text{dark}}}{16\pi^2} \frac{1}{16\pi^2} \left( \frac{\frac{1}{16\pi^2} \log \frac{M_6}{M_X}}{\frac{1}{16\pi^2} \log \frac{M_6}{M_X}} \right)$$

- as small as $10^{-7}$ perhaps
\[-\frac{1}{4} \left( F_{\mu\nu}^{\text{Dark}} \right)^2 - \frac{1}{4} \left( F_{\mu\nu}^{\text{EM}} \right)^2 + \epsilon J_{\mu}^{\text{DM}} F_{\mu\nu}^{\text{EM}} \]

\[+ \quad m_{\text{Dark}}^2 \left( A_{\mu}^{\text{Dark}} \right)^2 + j_{\mu}^{\text{EM}} A_{\mu}^{\text{EM}} \]

\[A_{\mu}^{\text{EM}} \rightarrow A_{\mu}^{\text{EM}} + \epsilon A_{\mu}^{\text{Dark}} \quad \text{eliminates mixing} \]

\[\Rightarrow \quad j_{\mu}^{\text{EM}} \left[ A_{\mu}^{\text{EM}} + \epsilon A_{\mu}^{\text{Dark}} \right] \]
Amazing that $\mathcal{E} \sim 10^{-3}$, $m_{\text{Dark}} \sim \text{GeV}$ is not ruled out!
The Territory
(A' Electron/Muon Decays)

A' → Standard Model

Unexplored
THE TERRITORY
(A’ invisible “dark matter” Decays)

(lzaguirre, Knjaic, PS, Toro)
Radiative Origin of Dark Scale

\[ E \mathcal{F}_{\mu
u} \mathcal{F}^{\mu\nu} \]

\[ g^2 \gamma \rightarrow \gamma^* \gamma \]

\[ E \mathcal{F}_{\mu
u} \mathcal{F}^{\mu\nu} \]

\[ g^2 \gamma \rightarrow \gamma^* \gamma \]

\[ E, g, g_{\text{Dark}} \]

\[ higgs \rightarrow higgs \]

\[ \gamma_{\text{dark}}, \gamma_{\text{dark}} \]
a minimal contribution to dark scalar masses

$\mu^2 \sim \epsilon m_W^2 ; \quad \epsilon \sim \alpha^2$ most naturally,

$\mu \sim \alpha m_W \sim \text{GeV}$. 
NOT

SU/SY

SM

Dark

Essentially anything else: e.g.

SU/SY

SM

Dark

[Familiar from Gauge Mediated SU(5)]
*Note: all that is needed is for \( G_{\text{Dark}} = G_{\text{Non-Ab.}} \times U(1) \text{'s} \)

\[ \text{Could be present \ up \ kin. mix with \ } U(1) \text{Y} \]

After \( G_{\text{Dark}} \) is broken, abelian + non-abelian pieces get all mixed up \[ \Rightarrow A_{\text{Dark}} \text{ } e^g \text{ electric charge} \]
Robustness

* Mixing can come from any scale
* Dark sector can be simple or complicated — so long as it has UCD's.

Look For Same Signatures
Dark Forces + Dark Matter

(Light) Dark

SM + SUSY

True LSP is here!

Usual LSP is unstable!

$\ell \gtrsim 10^{-4}$: Dark Sector + Us thermalized at Dark scale $\Rightarrow$ tiny time LSP abundance
$\sim \text{TeV}$ New vector-like states w/ common origin of mass [e.g. PQ breaking]

- Dark photons can decay back to SM
- They can decay to $\sim \text{GeV}$ DM in Dark Sector
* Early motivation for studying dark forces came from certain models for DM.

* Those models aren’t especially relevant to discussion now—they merely shone a light on this important new experimental frontier.
I F such a sector exists we find it, not merely "very cool".

It could revolutionize fundamental physics by allowing us to study the core principles we care about @ low- E!
e.g. probe SUSY + SY/SY in the Dark Sector! Also suppose we find Dark Unification at same $M_{GUT}$!
Naturalness

* There may be some degree of EWSB tuning, for anthropic reasons

* No such anthropic reason in Dark Sector!

* Better be perfectly natural—window into physics free of "environmental pressure"
Finding Dark Sectors would be analogous to Galileo’s discovery of a new “solar system” in the moons of Jupiter.
Possibility of huge payoff on small investment. It's the American way!