Supergravity/strings and physics of hidden sectors.

Supersymmetry and unification of fundamental interactions (SUSY2023)
University of Southampton, UK

July 17-21, 2023

PN

Northeastern University, Boston, Massachusetts, USA.

July17-21

Topics

- **Supergravity.**
- **Supergravity/strings and hidden sectors.**
- **Physics of hidden sectors**
- **Prospects of SUSY discovery at the LHC.**

First local supersymmetry

- ICHEP-17 (1974), London: First conf where SUSY was discussed. SUSY then was a global symmetry. However, successful theories of particle physics and gravity are gauge theories: Maxwell-Dirac, the standard model, and Einstein gravity. This was the motivating idea behind formulation of first gauge theory of supersymmetry called "Gauge Supersymmetry" [1],[2] and gauging of supersymmetry brings in gravity.
- Gauge supersymmetry is formulated in superspace with bose-fermi co-ordinates (x^μ, θ^α) with the background metric which preserves global supersymmetry.

$$g_{\mu\nu} = \eta_{\mu\nu}; \quad g_{\mu\alpha} = -i(\bar{\theta}\gamma^a)_\alpha \eta_{a\mu}, \qquad \eta^{\mu\nu} = \eta^{\nu\mu}$$
$$g_{\alpha\beta} = k\eta_{\alpha\beta} + (\bar{\theta}\gamma^a)_\alpha(\bar{\theta}\gamma_a)_\beta, \qquad \eta^{\alpha\beta} = -\eta^{\beta\alpha}.$$

- The tangent-space group of gauge supersymmetry is the inhomogeneous orthosymplectic group

$$IOSp(3, 1|4)$$

  This is the largest gauge group on the (4,4) dimensional supermanifold.
- Supergravity uses the supermultiplet $(2, \frac{3}{2})$ and is formulated in 4-space-time dimensions [3]

[1] P.N. and R. Arnowitt, Phys. Lett. 56B (1975) 177.

[2] B. Zumino, R. Arnowitt, P.N, Phys. Lett. (1975).

[3] D. Z. Freedman, P. van Nieuwenhuizen and S. Ferrara, Phys. Rev. Dl3 (1976) 3214; S. Deser and B. Zumino, Phys. Lett. 62B (1976) 335.

Superspace formulation of supergravity

- Since gauge supersymmetry has the largest gauge group $IOSP(3,1|4N)$ implies that the gauge group of Supergravity $IO(3,1) \times O(N)$ must be a sub-piece of gauge supersymmetry. This was demonstrated shortly after the FNF-paper [4].
  It is found that the $k \to 0$ reduces the Reimannian geometry of gauge supersymmetry to the non-Reimannian geometry of supergravity. This is achieved by expansion of the Lagrangian in powers of k which gives

$$\text{Gauge supersymmetry}(k \to 0) = \frac{1}{k^2} L_{-2} + \frac{1}{k} L_{-1} + (k^0) L_{\text{Supergravity}} + O(k^n, n \geq 1); \quad L_2 = L_{-1} = 0.$$

  A "gauge completion" technique was used in the reduction where local supersymmetry transformations are satisfied in superspace in each power of θ both in the metric and in the transformation laws.

- The "gauge completion technique" has been used in several subsequent works in the superspace formulations of $N = 1$ supergravity[5].

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[4] PN and R. Arnowitt, Phys. Lett. 65B (1976) 73.

[5] L. Brink, M. Gell-Mann, P. Ramond and J. H. Schwarz, Phys. Lett. 74B (1978) 336; Phys. Lett. 76B (1978) 417

J. Wess and B. Zumino, Phys. Lett. 79B (1978) 394

R. Grimm, J. Wess and B. Zumino, Nucl. Phys. B152 (1979) 255

E. Cremmer and S. Ferrara, Phys. Lett. 91B (1980) 61.

Supergravity theories in higher dimensions

- $\boldsymbol{D = 11}$ is the largest space-time dimension where supergravity theory with massless states of spin $\boldsymbol{J \leq 2}$ can exist [6].
- Thus $\boldsymbol{N = 8}$ supergravity in 4D can be gotten from $\boldsymbol{N = 1}$ $\boldsymbol{D = 11}$ supergravity by reducing it on a seven-dimensional torus $\boldsymbol{T^7}$ [7].
- For D=11 supergravity only on-shell formulations are known. An off-shell formulation of $\boldsymbol{D = 11}$ supergravity is an outstanding problem for over 40 years. For recent progress in this direction see [8].

[6] E. Cremmer, B. Julia, and J. Scherk, Phys. Lett. B 76, 409 (1978).

[7] E. Cremmer and B. Julia, Nucl. Phys. B 159, 141 (1979).

[8] K. Becker, D. Butter and A. Sengupta, JHEP **11**, 127 (2022) doi:10.1007/JHEP11(2022)127; K. Becker, D. Butter, W. D. Linch and A. Sengupta, JHEP **07**, 032 (2021) and the references therein.

Supergravity & strings

- Green-Schwarz [9] found that in the low energy limit of Type I strings the kinetic energy of 2-tensor B_{MN} of 10D supergravity multiplet has Yang-Mills and Lorentz group Chern-Simons terms.

$$\partial_{[P}B_{MN]} \to \partial_{[P}B_{MN]} + \omega^{(Y)}_{PMN} - \omega^{(L)}_{PMN}$$

Inclusion of the Chern-Simons terms fully requires that one extend the 10D Sugra Lagrangian to order $O(\kappa)^2$. This was accomplished subsequent to Green-Schwarz work [10].

- Dimensional reduction to 4D with a vacuum expectation value for the internal gauge field strength, $\langle F_{ij} \rangle \neq 0$, leads to

$$\partial_\mu B_{ij} + A_\mu F_{ij} + \cdots \ \sim \ \partial_\mu \sigma + m A_\mu \ ,$$

where the internal components B_{ij} give the pseudo-scalar σ and m arises from $< F_{ij} >$. Thus A_μ and σ have a Stueckelberg coupling of the form $A_\mu \partial^\mu \sigma$.

- This is the inspiration for building BSM models with the Stueckelberg mechanism[11] testable at colliders and in cosmology[12].

[9] M. B. Green and J. H. Schwarz, Phys. Lett. 149, 117(1983)

[10] A. Chamseddine, PN, PRD 34, 12, 3769 (1986);
L.J. Romans and N.P. Warner, Nucl. Phys. 8273, 320 (1986);
S. Gates and H. Nishino, PL 173B, 52 (1986);
E. Bergshoeff, A. Salam and E. Sezgin, Nucl. Phys. B **279**, 659-683 (1987).

[11] B. Kors and PN, Phys. Lett. B **586**, 366-372 (2004).

[12] D. Feldman, B. Kors and PN, Phys. Rev. D **75**, 023503 (2007).

Cosmologically consistent analysis of hidden and visible sectors

- As noted supergravity/strings contain hidden sectors and thus relevant to discuss their implications for observable physics.
- In most analyses in particle physics and cosmology a separate adiabatic expansion of hidden and visible sectors is assumed, i.e.,

$$\frac{dS_v}{dt} = 0, \ \frac{dS_h}{dt} = 0.$$

  This is inconsistent because of the interaction, though feeble, between the visible and the hidden sectors. In a cosmologically consistent analysis only the total entropy is conserved, i.e.,

$$\frac{d(S_v + S_h)}{dt} = 0.$$

- To implement a consistent thermal evolution of the visible and the hidden sectors, one needs an evolution equation for $\xi \equiv \frac{T_h}{T}$. Such an evolution was given recently[13].

$$\frac{d\xi}{dT} = \left[-\xi\frac{d\rho_h}{dT_h} + \frac{4H\zeta_h\rho_h - j_h}{4H\zeta\rho - 4H\zeta_h\rho_h + j_h}\frac{d\rho_v}{dT}\right](T\frac{d\rho_h}{dT_h})^{-1}.$$

  where temperature of the visible sector is used as the clock, and $\zeta = 1$ (radiation dominance), $\zeta = 3/4$ (matter dominance). j_h is the source for $d\rho_h/dt$.

[13] Aboubrahim, Feng, PN, Wang, Phys.Rev.D 103 (2021) 7, 075014. A. Aboubrahim and PN, JHEP **09**, 084 (2022).

Hidden sector models

- As a concrete example of a hidden sector, we consider a $U(1)'$ extension of SM with particle content

$$C_\mu : U(1)' \text{gauge boson}; D : \text{(Dirac fermion)}; \phi, s : \text{(spin 0 fields)}. \qquad (1)$$

- Communication with the visible sector occurs via kinetic [14] and Stueckelberg mass mixing [15] between the $U(1)'$ gauge field C_μ and the $U(1)_Y$ hypercharge gauge field B_μ of the SM

$$\begin{aligned} &(i) \text{ Kinetic mixing} : C^{\mu\nu} B_{\mu\nu}, \\ &(ii) \text{ Stueckelberg mass mixing} : (m_1 C_\mu + m_2 B_\mu + \partial_\mu \sigma)^2. \end{aligned} \qquad (2)$$

  Mass mixing generates a milli-charge on hidden sector matter if such matter is present.

- The supersymmetric extension of the Stueckelberg mechanism is given in Ref.[16]

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[14] B. Holdom, Phys. Lett. B **166**, 196-198 (1986)

[15] B. Kors and PN, Phys. Lett. B **586**, 366-372 (2004).

[16] B. Kors and P. Nath, JHEP **12**, 005 (2004).

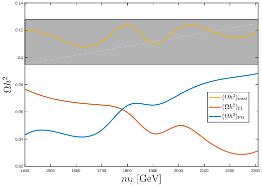
Phenomenology of Sugra & strings

- Sugra/strings $\supset$ visible sector + hidden sectors
- The above implies the true LSP($\mathrm{LSP}_{\boldsymbol{T}}$) could be either the LSP of the visible sector ($\mathrm{LSP}_{\boldsymbol{v}}$) or of the hidden sector ($\mathrm{LSP}_{\boldsymbol{h}}$).

$$\begin{aligned} \mathrm{LSP}_{\boldsymbol{T}} &\to \mathrm{LSP}_{\boldsymbol{v}}, \\ \text{or } &\to \mathrm{LSP}_{\boldsymbol{h}}. \end{aligned}$$

- There is no fundamental reason that $\mathrm{LSP}_{\boldsymbol{T}}$ should necessarily reside in the visible sector. But most searches for SUSY at colliders and cosmology are based on that.
- I will discuss several situations where the hidden sector is relevant and helps resolve phenomena not explained by the visible sector alone.
- I will broaden the discussion to include dark matter which may or may not be R parity odd, and could be bosonic or fermionic.

$\mathbf{LSP}_v = \tilde{t}_1$, $\mathbf{LSP}_T = \mathbf{LSP}_h(\xi^0)$. Stop decays to hidden neutralino $\tilde{t}_1 \to \xi^0 + t$[17].



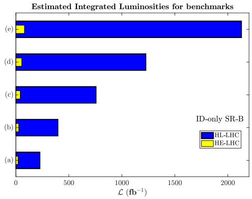
- In this case the dark matter density consists of a freeze-in part, where the relic density of $\boldsymbol{\xi_0}$ grows steadily from the out of equilibrium decays of the SM particles, and a part where freeze-out density of stops decays to the hidden sector neutralino $\boldsymbol{\xi}$.

$$(\Omega h^2) = (\Omega h^2)_{\mathrm{Freeze-in}} + \frac{m_{\tilde{\xi}_1^0}}{m_{\tilde{t}}} (\Omega h^2)^{\tilde{t}}_{\mathrm{Freeze-out}} .$$

[17] A. Aboubrahim, W. Z. Feng and PN, JHEP **02**, 118 (2020)
B. Kaufman, PN, B. D. Nelson and A. B. Spisak, Phys. Rev. D **92**, 095021 (2015).

Long lived stop can be detected at the LHC as $\boldsymbol{R}$-hadron

- For certain ranges of parameters the stop has a lifetime long enough to traverse the LHC detector without decay.
- Such a particle can be detected at the HL-LHC and HE-LHC as a $\boldsymbol{R}$-hadron which will look like a slow moving muon with a large transverse momentum $\boldsymbol{p_T}$ and so can be detected by the track it leaves in the inner tracker and in the muon spectrometer.



The integrated luminosity for discovery of a set of models which are discoverable at both HL-LHC and HE-LHC[18].

- A similar analysis can be done [19] when the stau $\tilde{\tau}_1$ is LSP$_v$ but $m_{\tilde{\tau}_1} > m_{\xi^0}$. Here the signature of charged long-lived stau is high-$\boldsymbol{p_T}$ track decaying into another charged track (resulting in a kinked track).

[18] A. Aboubrahim, W. Z. Feng and PN, JHEP **02**, 118 (2020).

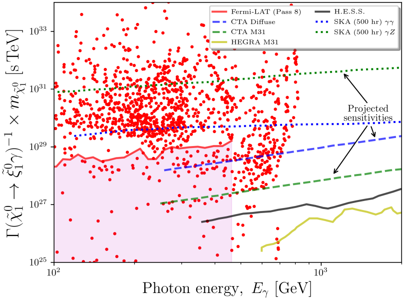
[19] A. Aboubrahim and PN, Phys. Rev. D **99**, no.5, 055037 (2019).

Decaying dark matter

$$\mathbf{LSP}_v = \tilde{\chi}^0,\ \mathbf{LSP}_T = \mathbf{LSP}_h(\xi^0)$$ [20].

$$\chi^0(\text{visible}) \to \xi^0(\text{hidden}) + \gamma.$$

- Decay lifetime greater than lifetime of the universe.
- χ^0 can still be dark matter and also be missing energy at the LHC.
- Decaying neutralino has gamma emission and the gamma spectrum is testable at improved Fermi-LAT, SKA, CTA [21]



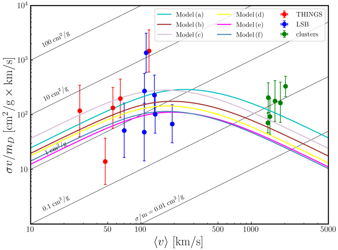
[20] A. Aboubrahim, T. Ibrahim, M. Klasen and PN, Eur. Phys. J. C **81**, no.8, 680 (2021).

[21] M. Ackermann et al., [Fermi-LAT], Astrophys. J. 799, 86 (2015); A. Weltman et al., Publ. Astron. Soc. Austral. 37, e002 (2020); H. Abdalla et al., CTA. JCAP 02, 048 (2021).(Marco Cirelli talk)

Self-interacting Hidden sector dark matter and galaxy data

Galaxy data indicates DM is collisional at short scales and collision-less at large scales [22].
WIMPS cannot explain it but self-interacting dark matter can[23]
($\boldsymbol{\sigma/m = 8 \times 10^{-(25-22)}}\text{cm}^{\mathbf{2}}/\text{GeV}$ or $\mathbf{0.45 - 450}\text{cm}^{\mathbf{2}}/\text{g}$).

Galaxy	$< v >$ in km/s	$< \sigma/m >$ in cm^2/g
Dwarf	10-100	1-50
Midsize	80-200	0.5-5
Clusters	>1000	0.1-1



The fit to the galaxy data indicates the existence of a dark force (the fifth force) arising from dark fermions exchanging hidden dark photons[24]. More data needed to confirm this.

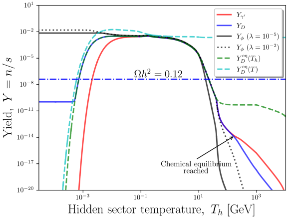
[22] Tulin, Yu, Phys. Rep.730, 1(2018).
[23] D. N. Spergel and P. J. Steinhardt, Phys. Rev. Lett. 84, 3760-3763 (2000).
[24] Aboubrahim, Feng, PN, Wang, Phys.Rev.D 103 (2021) 7, 075014.

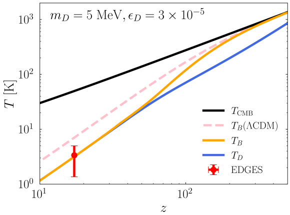
Edges anomaly

EDGES reported an absorption profile centered at the frequency $\boldsymbol{\nu = 78}$ MHz in the sky-averaged spectrum.The quantity of interest is the brightness temperature $\boldsymbol{T_{21}}$ of the 21-cm line defined by

$$\boldsymbol{T_{21}(z) = \frac{T_s - T_\gamma}{1+z}(1 - e^{-\tau}),}$$

$\boldsymbol{\tau}$ is the optical depth for the transition. The analysis of Bowman etal[25] finds that at $\boldsymbol{z \sim 17}$, $\boldsymbol{T_{21} = -500^{+200}_{-500}}$ mK at 99% C.L. $\boldsymbol{\Lambda}$CDM gives $\boldsymbol{T_{21} \simeq -250}$ mK, z=(6−40) [26]

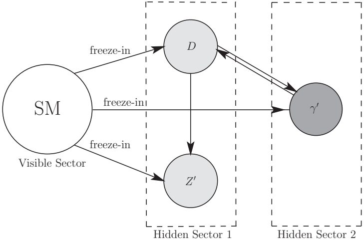


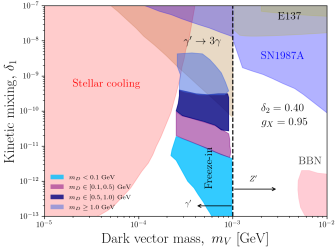


Left: 0.3% millicharged DM produced by Stueckelberg mechanism. Right: millicharge DM gives the desired $\boldsymbol{T_{21}}$ by cooling the baryons[27] by Rutherford scattering.

[25] J. D. Bowman eta., Nature **555**, no.7694, 67-70 (2018).
[26] A. Cohen, A. Fialkov and R. Barkana, Mon. Not. Roy. Astron. Soc. 478, no.2, 2193- 2217 (2018).
[27] A. Aboubrahim, PN and Z. Y. Wang, JHEP **12**, 148 (2021).

Dark photon as dark matter





- Needs at least two hidden sectors, with temperature (T_1, T_2) requiring two evolution functions η and ζ defined by $T = \eta T_1, T_2 = \zeta T_1$ [28]

$$\frac{d\eta}{dT_1} = -\frac{\eta}{T_1} + \left(\frac{4H\rho_v + j_1 + j_2}{4H\rho_1 - j_1}\right)\frac{d\rho_1/dT_1}{T_1 \frac{d\rho_v}{dT}},$$

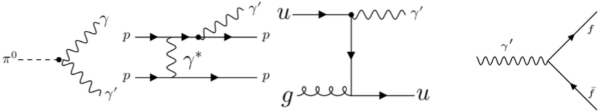
$$\frac{d\zeta}{dT_1} = -\frac{\zeta}{T_1} + \left(\frac{4H\rho_2 - j_2}{4H\rho_1 - j_1}\right)\frac{d\rho_1/dT_1}{T_1 \frac{d\rho_2}{dT_2}}$$

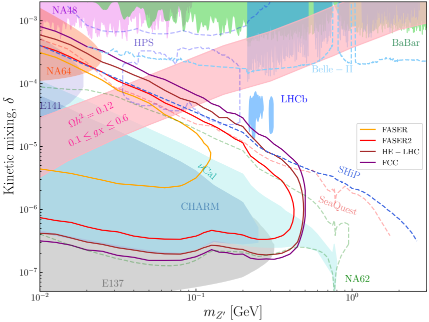
$$\tau^{-1}_{\gamma' \to 3\gamma} = \frac{17\alpha^3\alpha'}{2^7 3^6 5^3 \pi^3}\frac{m^9_{\gamma'}}{m^8_e}; \quad \tau_{\gamma' \to 3\gamma} \sim 5 \times 10^{15} \text{ yrs}, \quad \tau_{\gamma' \to \nu\bar{\nu}} \sim 10^{22} \text{ yrs}.$$

[28] A. Aboubrahim, W. Z. Feng, PN and Z. Y. Wang, JHEP **06**, 086 (2021).

Discovering the Stueckelberg dark photon at FASER: ForwArd Search ExpeRiment at the LHC.

For observation of weakly interacting light particles: dark photons, axion-like particles (ALPS), neutrinos.



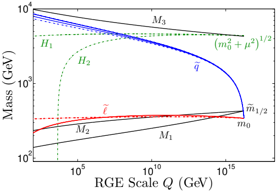


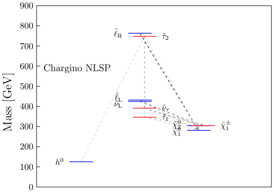
The predicted regions for the observation of a Stueckelberg dark photon consistent with all constraints are in the pink band.

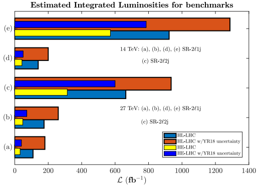
From: A. Aboubrahim, M. M. Altakach, M. Klasen, P.N. and Z. Y. Wang, JHEP **03**, 182

Prospects for the observation of sparticles at HL-LHC and HE-LHC

- The Fermilab g-2 experiment E989 [29] appears to give about $\sim 4\sigma$ deviation from the SM result. Could this arise from Sugra?
- A significant correction to $g-2$ was predicted early on [30] via the exchange of light charginos and light sleptons.
- In sugra models where radiative E-W symmetry breaking is driven by gluino ($\tilde{g}$Sugra) one has light chargino, neutralino, and sleptons and the light spectrum consistent with the current experimental constraints can explain (g-2) anomaly.
- The light sleptons and charginos should be accessible at the LHC [31] [32]







[29] B. Abi et al., Phys. Rev. Lett. 126, no.14, 141801 (2021) (Carlos Wagner talk)

[30] D. A. Kosower, L. M. Krauss and N. Sakai, Phys. Lett. B **133**, 305-310 (1983)
T. C. Yuan, R. L. Arnowitt, A. H. Chamseddine and PN, Z. Phys. C **26**, 407 (1984).

[31] A. Aboubrahim, M. Klasen and PN, Phys. Rev. D **104**, no.3, 035039 (2021).

[32] Other recent works: Baer, Carena, Ellis, Heinemeyer, King, Khalil, Olive, Shafi,$\cdots$

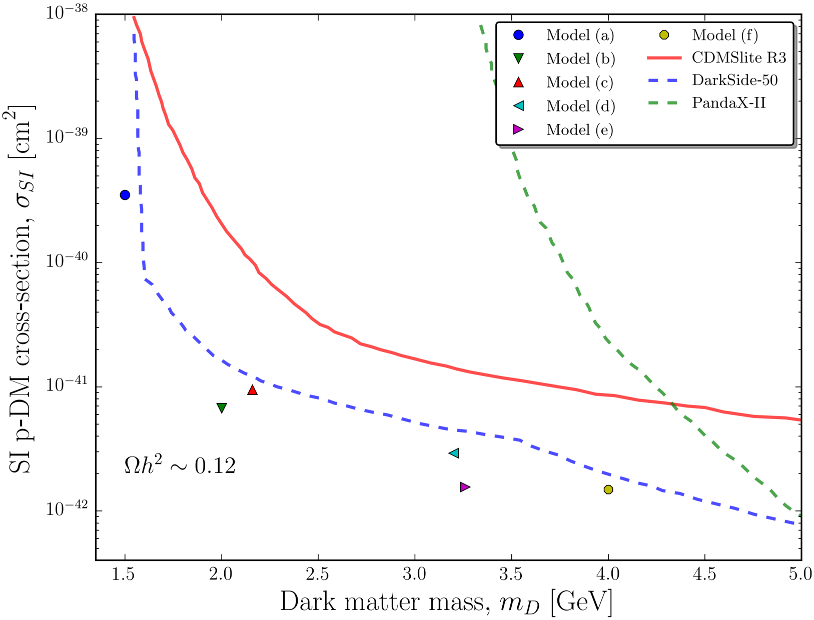
Conclusion

- SUSY $\to$ Sugra $\to$ strings

Provide a roadmap to quantum gravity/unification. No comparable alternative exists.

- Sugra/strings involve hidden sectors and hidden sectors have observable effects.
- A proper treatment of hidden sectors involves a synchronous thermal evolution of them with the visible sectors. A formalism for doing so now exists.
- **If** $\boldsymbol{g-2}$ anomaly is real and **if** SUSY is the explanation, then there is an excellent chance for one or more sparticles to show up at the LHC either at RUN3 or at RUN4.
- Finally let us keep in mind:
  - 1 part in $\mathbf{10^9}$ cancellation of up quark & charm quark loops lead to the discovery of the charm quark.
  - 1 part in $\mathbf{10^{28}}$ cancellation of quark & squark loops provides an overwhelming reason for the discovery the squarks (sparticles).

Extra slides



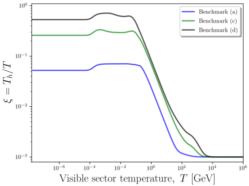
Model (a)
Model (b)
Model (c)
Model (d)
Model (e)
Model (f)
CDMSlite R3
DarkSide-50
PandaX-II
$\Omega h^2 \sim 0.12$
SI p-DM cross-section, σ_{SI} [cm^2]
Dark matter mass, m_D [GeV]
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

Hubble tension

SH0ES Collaboration[33] has confirmed a 5σ tension between high redshift ($z > 1000$) and low redshift ($z < 1$) measurements of Hubble parameter H_0 based on ΛCDM (H_0 units: km/s/Mpc)

$$H_0 = (67.4 \pm 0.5), \quad \text{(high } z\text{: BBN, CMB, BAO)},$$
$$H_0 = (73.04 \pm 1.04), \quad \text{(low } z\text{: Cepheids, SNIa)}.$$

- To help alleviate the tension we consider a hidden sector which contains a dark photon γ', a dark fermion D, a dark scalar s, and a dark pseudo-scalar ϕ with kinetic mixing with the visible sector.



The hidden sector is thermally out-of-equilibrium with the visible sector with $\xi < 1$ [34].

[33] A. G. Riess, *et al.* [arXiv:2112.04510 [astro-ph.CO]].

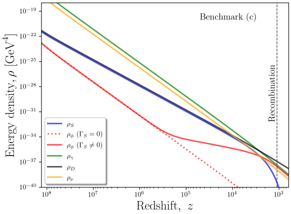
[34] A. Aboubrahim, M. Klasen and PN, JCAP **04**, no.04, 042 (2022).

Energy densities of particle species are computed from Boltzmann equations

$$\frac{d\rho_S}{dt} + 3H\rho_S = -\Gamma_S\,\rho_S,\ \ \frac{d\rho_\phi}{dt} + 4H\rho_\phi = \Gamma_S\,\rho_S,$$
$$\frac{d\rho_D}{dt} + 3H\rho_D = 0,\ \ \frac{d\rho_\gamma}{dt} + 4H\rho_\gamma = 0.$$

$$H(T) = \sqrt{\frac{8\pi}{3m_{\mathrm{Pl}}^2}(\rho_S + \rho_\phi + \rho_\gamma + \rho_D + 3\rho_\nu)}.$$

$$\Delta N_{\mathrm{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\phi(T_\phi)}{\rho_\gamma(T_\gamma)}.$$



Out-of-equilibrium decay of the massive scalar to the massless pseudo- scalar ($s \to \phi\phi$) close to recombination increases ΔN_{eff} that helps alleviate the Hubble tension.
$\Delta\mathcal{L} = y_s D\bar{D}s + \frac{1}{2}\lambda\phi s\phi^2 s^2$ [35].

CDF W mass anomaly

- Last year the CDF Collaboration[36] gave a measurement of W mass larger than the SM prediction
$$\Delta M_W = +76 \text{ MeV}.$$
- The measurement is violation of the custodial symmetry: $\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} \simeq 1$.
- If confirmed it would be a clear evidence of BSM physics. A possible explanation is via Stueckelberg-Higgs portal with[37]

$$\Delta\mathcal{L}_{\rm St} = (i\frac{g_c}{2} H^\dagger D^\mu H \bar{C}_\mu + h.c.) + \frac{g_c^2}{4} H^\dagger H \bar{C}_\mu^2, \quad \bar{C}_\mu \equiv C_\mu - \partial_\mu \sigma.$$

- Solution is simple: $SU(2)_L$ coupling is increased to fit the W-mass
$$\bar{g}_2 = g_2 (1 + \frac{\Delta M_W}{M_W}).$$
This increases the Z-boson mass, which is compensated by a negative correction from the Stueckelberg-Higgs portal.
$$\Delta M_Z^{\rm exp} + \Delta M_Z^{\rm St-Higgs} \simeq 0$$
$$\Delta M_Z^{\rm St-Higgs} \simeq -\frac{1}{2} M_Z \frac{M_W^2}{M_1^2 - M_Z^2} \left(\frac{g_c}{g_2}\right)^2.$$

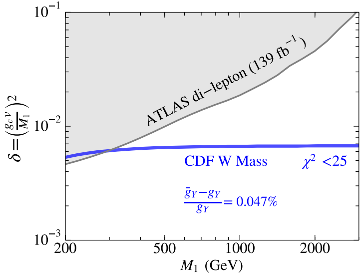
[36] T. Aaltonen *et al.* [CDF], Science **376**, no.6589, 170-176 (2022).

[37] M. Du, Z. Liu and PN Phys. Lett. B **834**, 137454 (2022).

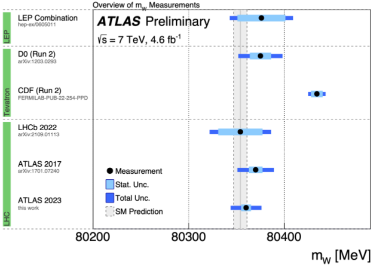
		LEP		SM-CDF		St	
	$O^{\text{exp}} \pm \delta O$	O^{th}	χ	O^{th}	χ	O^{th}	χ
Γ_Z [GeV]	2.4955±0.0023	2.4960	-0.20	2.5000	-1.96	2.4999	-1.92
σ_{had} [nb]	41.481±0.033	41.470	0.34	41.465	0.50	41.471	0.30
R_e	20.804±0.05	20.752	1.05	20.778	0.53	20.751	1.05
R_μ	20.784±0.034	20.752	0.95	20.778	0.18	20.751	0.96
R_τ	20.764±0.045	20.799	-0.77	20.825	-1.35	20.798	-0.76
R_b	0.21629±0.00066	0.21584	0.68	0.21578	0.77	0.21584	0.68
R_c	0.1721±0.003	0.1711	0.33	0.1712	0.30	0.1711	0.33
$A_{\text{FB}}^{(0,e)}$	0.0145±0.0025	0.0163	-0.71	0.0190	-1.81	0.0162	-0.70
$A_{\text{FB}}^{(0,\mu)}$	0.0169±0.0013	0.0163	0.48	0.0190	-1.64	0.0162	0.51
$A_{\text{FB}}^{(0,\tau)}$	0.0188±0.0017	0.0163	1.48	0.0190	-0.13	0.0162	1.50
$A_{\text{FB}}^{(0,b)}$	0.0996±0.0016	0.1033	-2.29	0.1118	-7.61	0.1032	-2.22
$A_{\text{FB}}^{(0,c)}$	0.0707±0.0035	0.0738	-0.89	0.0804	-2.78	0.0737	-0.86
$A_{\text{FB}}^{(0,s)}$	0.0976±0.0114	0.1034	-0.51	0.1119	-1.25	0.1033	-0.50
A_e	0.15138±0.00216	0.14733	1.88	0.15928	-3.66	0.14716	1.95
A_μ	0.142±0.015	0.147	-0.36	0.159	-1.15	0.147	-0.34
A_τ	0.136±0.015	0.147	-0.76	0.159	-1.55	0.147	-0.74
A_b	0.923±0.02	0.935	-0.58	0.936	-0.63	0.935	-0.58
A_c	0.67±0.027	0.67	0.07	0.67	-0.12	0.67	0.08
A_s	0.895±0.091	0.936	-0.45	0.937	-0.46	0.936	-0.45
χ^2			17.3		97.8		20.9

Table 1. Fits to 19 LEP Z pole observables [15] with three models: (1) LEP, (2) SM-CDF, and (3) St. The LEP fit is taken from [4]. The SM-CDF fit is the same as the LEP fit except that the weak mixing angle θ_W is modified as in Eq. (2.4) due to the new CDF M_W measurement [1]. The St Fit is described in the text; the parameters in the benchmark model here are: $M_1 = 725$ GeV, $g_c = 0.243$, $\bar{g}_Y = g_Y(1 + 0.047\%)$.

Test of the St-Higgs model at the LHC



(1).png



Left: The favored region (blue) in the parameter space spanned by $\boldsymbol{M_1}$ ($\boldsymbol{Z'}$ mass) and $\boldsymbol{\delta = (g_c v/M_1)^2}$ for the CDF $\boldsymbol{W}$ mass measurement.
Right: Recent measurement of ATLAS is consistent with the SM measurement (Taken from home.cern)