(Super)heavy Z'-Portal Dark Matter Scenario and Complementarity between Direct Dark Matter Detection Experiments and Z' Boson Searches at the LHC

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Introduction and Motivation:-

- Proposing Z' mediated dark matter production from incompletely thermalized plasma
- Finding mass bounds of dark matter and Z' from the complementarity between the dark matter search and Z' boson search at LHC

$U(1)_X$ extended Dark Matter Model:-

- $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$ scenario considered for incompletely thermalized DM generation.
- 3 BSM ν_R, 1 BSM Higgs, 1 Dirac fermion dark matter considered in this model.

Particle	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
q_L^i	3	2	$\frac{1}{6}$	$\frac{1}{6}x_H + \frac{1}{3}$
u_R^i	3	1	$\frac{2}{3}$	$\frac{2}{3}x_H + \frac{1}{3}$
d_R^i	3	1	$\frac{-1}{3}$	$-\frac{1}{3}x_H + \frac{1}{3}$
l_L^i	1	2	$\frac{-1}{2}$	$-\frac{1}{2}x_H - 1$
e_R^i	1	1	-1	$-x_H - 1$
ν_R^i	1	1	-1	-1
Φ_2	1	2	$\frac{1}{2}$	$\frac{1}{2}x_H$
Φ_1	1	2	$\frac{1}{2}$	$\frac{1}{2}x_H$
ζ	1	2	$-\frac{1}{2}$	g_ζ

For $U(1)_X$-breakir

BSM-Fermion

ζ pair production in thermal bath:-

- BSM Z' mediated ζ production cross section comes out to be $\sigma v|_{nR} = \frac{g_\zeta^2 g_{Z'}^2}{\pi} \sum_f N_c^f (Q_{A_f}^2 + Q_{V_f}^2) \frac{m_\zeta^2}{(4m_\zeta^2 - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2}$

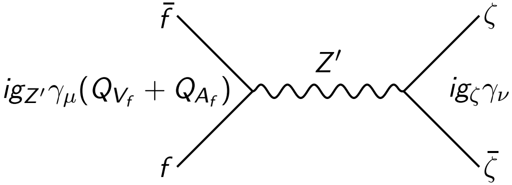


Figure: Freeze-In Dark matter production from SM fermion annihilation

Model Constraint from Early Universe:-

- Early universe p, n abundance constraints DM relic density with $\Omega_{DM}h^2 = 0.12$
- DM Yield satisfies Boltzmann equation $\frac{dY}{dx} = -\frac{<\sigma v>}{x^2}\frac{s(m_\zeta)}{H_\zeta}(Y^2 - Y_{EQ}^2)$
- We are considering ζ has never been in thermal equilibrium with plasma SM particle
- Considering $x_{RH} = m_\zeta / T_{R_H} > 1$ and negligible initial abundance of ζ, $Y(x_{R_H}) = 0$,and the yield solution leads to

$$Y_0 = \int_0^{x_{R_H}} \frac{s(m_\zeta)}{x^2 H(m_\zeta)} < \sigma v > Y_{EQ}^2 dT \tag{1}$$

-where,

$s(m_\zeta) = \frac{2\pi^2}{45} g_* m_\zeta^3$

$Y_{EQ} = \frac{g_{DM}}{2\pi^2}\frac{x^2 m_\zeta^3}{s(m_\zeta)} K_2(x)$

$n_{EQ} = \frac{s(m_\zeta) Y_{EQ}}{x^3}$

$H(m_\zeta) = \sqrt{\pi^2 g_* 90} \frac{m_{zeta}^2}{M_p}$

Model Constraint from Early Universe:-

$$< \sigma v > \\ = \frac{g_\zeta^2 g_{Z'}^2}{\pi}(9x_H^2 + 14x_H + 16)\frac{m_\zeta^2}{(4m_\zeta^2 - m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2}\times \\ \frac{g_{DM}^2}{64\pi^4}\frac{m_\zeta}{x}\frac{1}{n_{EQ}^2}\int_{4m_\zeta^2}^{\infty} dss\sqrt{s - 4m_\zeta^2}K_1(\frac{x\sqrt{s}}{m_\zeta}) \tag{2}$$

- Non relativistic nature of dark matter density brings forth exponential suppression and thus keeps up with dark matter abundance constraint using $\Omega_\zeta h^2 = \frac{m_\zeta}{\rho_c/h_0}Y_0$,

Direct Detection Experiments to search Dark Matter :-

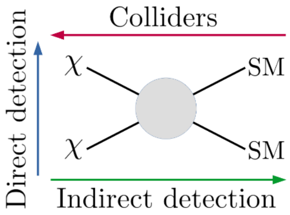


Figure: Schematic diagram of different dark matter searches

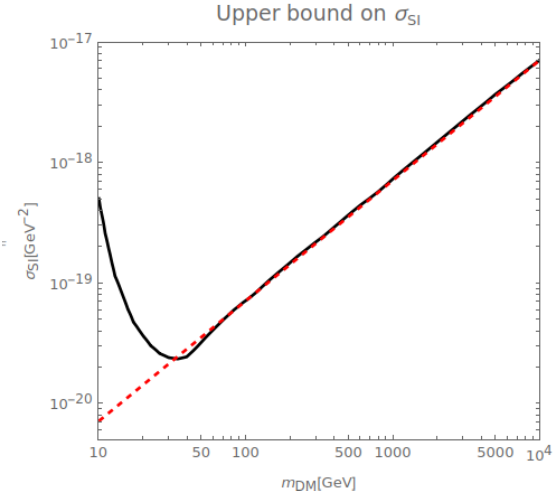
- Involves DM elastic scattering with lab target(can be Nucleon or electrons), by which target can get excited and (or) can attain recoil energy.
- De-excited state of target directly or indirectly emits different known form of SM particles, and can be detected by the detectors.
- Detection relies on the energy transferred, this method works the best, when DM mass is closer to that of the target.

Direct Detection Constraints from LZ Experiment:-

- Spin-Independent cross section from LZ data gives

$$\sigma_{SI-fitted}[Gev^{-2}] = 10^{-20} \times (1.162 + 0.0738\frac{m_\zeta}{1GeV}) \qquad (3)$$

- DM of masses greater than 50 GeV has been considered.



DM-Nucleon Spin Independent Cross -section :-

- Spin-Independent cross section of DM-Nucleon elastic scattering mediated by Z' boson is calculated to be

$$\sigma_{SI} = \frac{\mu^2_{\zeta N}}{\pi}\frac{g^2_{\zeta}g^2_{Z'}}{m^4_{Z'}}[x_H(0.5 + \frac{Z}{A}) + 2]^2 \quad (4)$$

- For Xenon target $Z = 54$, $A = 131$, $m_N = .983 \times 10^{-3}$ GeV
- LZ' results lead to

$$m_{\zeta} = \frac{1}{.285}[\frac{g^2_{\zeta}g^2_{Z'}}{m^4_{Z'}}\frac{3.89[x_H(0.5 + \frac{Z}{A}) + 2]^2}{10^{-20} \times 0.983^{-2}} - 4.53] \quad (5)$$

Constraint on $g_{Z'}$ and $m_{Z'}$ from LHC Run2 data:-

- From ATLAS and LHC data , correlation between $g_{Z'}$ and $M_{Z'}$ can be drawn, getting rid of one parameter of the model.

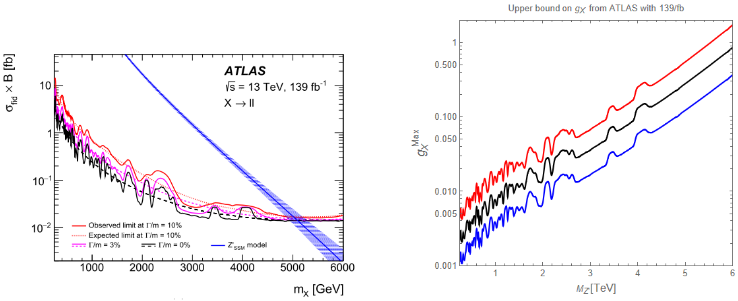


Figure: Z' decay cross section vs. $m_{Z'}$(at left), Upper bound on $g_{Z'}$ vs. $m_{Z'}$ (at right), Red, Black and Blue curve represents $x_H = -1$, $x_H = 0$, $x_H = 1$ respectively

Constraint on DM mass:-

- With fixed x_H, m_ζ can be parametrized by $M_{Z'}$ only

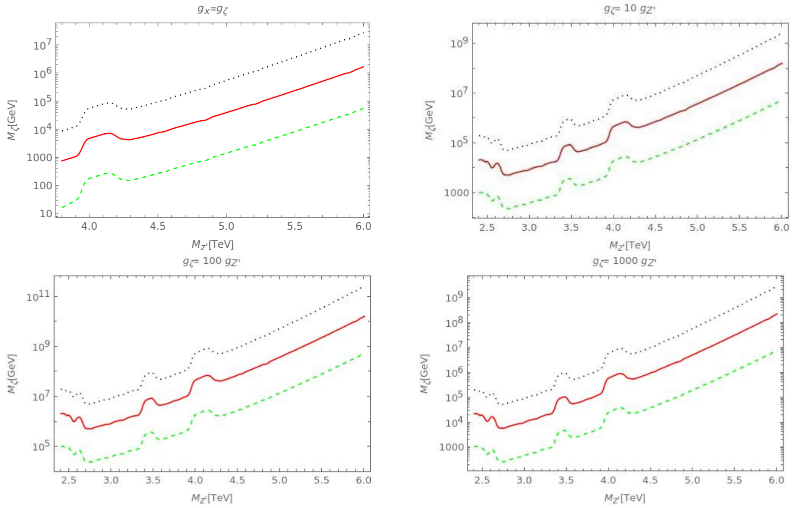


Figure: Dark matter mass m_ζ as function of Z' mass $m_{Z'}$. Green,red and black dashed curves represents $x_H = 1$, $x_H = 0$, $x_H = -1$ respectively

Constraint on DM mass:-

- As we are considering $m_\zeta > m_{Z'}$, for $g_{Z'} = g_\zeta$, $x_H = 1$ excludes the Z' mass range below 4.5TeV, though for $x_H = -1$, $m_{Z'} > 3.5 TeV$ is allowed.
- For higher g_ζ values; lower end x_H accommodate larger mass parameter range for Z'.
- For fixed x_H value, the allowed dark matter mass range shifts toward higher end of mass, considering $\sigma_{SI} \propto g_\zeta^2$.

Spin Independent Cross Section bound from $M_{Z'}$:-

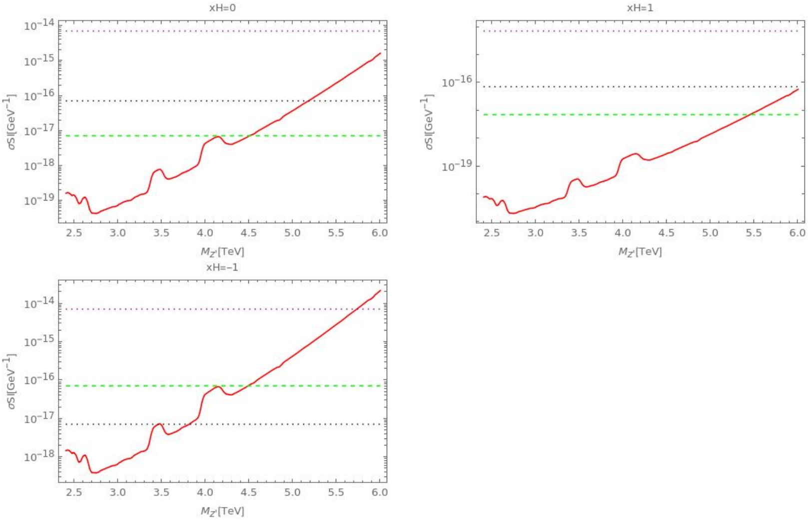


Figure: Spin-Independent cross section σ_{SI} as function of Z' mass $m_{Z'}$, green, black, purple dashed curves represents LZ data fitted cross-section $\sigma_{LZ_f itted}$ for $m_\zeta = 10$TeV, $m_\zeta = 100$TeV, $m_\zeta = 1000$TeV respectively

Spin Independent Cross Section bound from $M_{Z'}$:-

- Spin-independent cross-section derived can be expressed with one free parameter $m_{Z'}$ only by fixing $g_\zeta = g_{Z'}$.
- As the LZ data gives the upper bound for the cross-section, areas above the the point horizontal dotted $\sigma_{LZ\,fitted}$ line cutting σ_{SI}, are excluded. For $x_H = 0$, and $m_\zeta = 10$TeV, the upper bound of $m_{Z'}$ would be around 4TeV, so for $m_\zeta = 100$TeV would be 5TeV.
- For fixed m_ζ, we get higher bound of allowed $m_{Z'}$ as x_H goes from -1 to 1.

Finding Reheating Temperature:-

- $m_\zeta >$ Reheating temperature T_{RH}, keeps ζ throughout off equilibrium in plasma.
- Dark matter abundance constraint condition $\Omega_\zeta h^2 = 0.12$ meets only if $x_{R_H} = 10$

Summary:-

- We have considered incompletely thermalized WIMP dark matter production from SM particles using inhomogeneous temperature distribution in thermal plasma.
- Using the LHC and LZ' data, the lower bound of dark matter mass found is 10TeV, while the same for $m_{Z'}$ is around 2.5TeV.
- The relic density constraint can be addressed using reheating temperature $T_{R_H} = m_\zeta/10$.