SCTM 模型 Tripletino 暗物质研究

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报 告 提 纲

1. 模型与动机

标准模型希格斯势中存在 Custodial 对称性，

$$SU(2)_L \times SU(2)_R$$

希格斯势发生自发对称性破缺(SSB)，

$$SU(2)_L \times SU(2)_R \xrightarrow{\text{SSB}} SU(2)_V$$

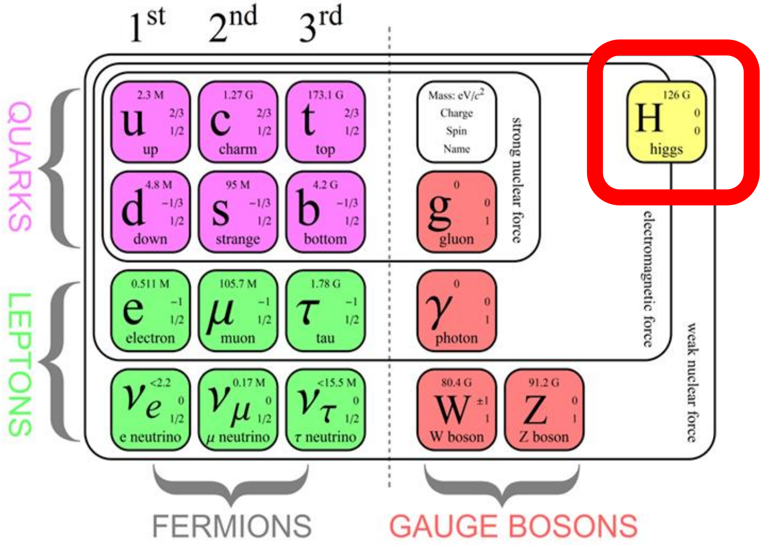
ρ参数在树图阶为1.

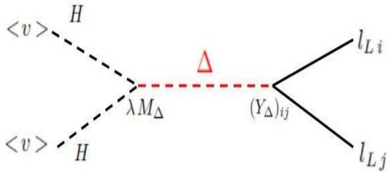
$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$

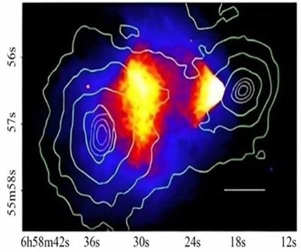
PDG 2025:

$$\Delta\rho \equiv \rho - 1 = (3.1 \pm 1.9) \times 10^{-4}$$

Supersymmetric Custodial Triplet Model (SCTM):
自然满足 $\Delta\rho$ 实验结果。







1. 模型与动机

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SCTM

标量场	$H_d = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$	$H_u = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$	$\Sigma_- = \begin{pmatrix} \frac{\chi^-}{\sqrt{2}} & \chi^0 \\ \chi^{--} & -\frac{\chi^-}{\sqrt{2}} \end{pmatrix}$	$\Sigma_0 = \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix}$	$\Sigma_+ = \begin{pmatrix} \frac{\psi^+}{\sqrt{2}} & \psi^{++} \\ \psi^0 & -\frac{\psi^+}{\sqrt{2}} \end{pmatrix}$
$SU(2)_L$	2	2	3	3	3
Y	$-\frac{1}{2}$	$\frac{1}{2}$	-1	0	1
$Q = T_3 + Y$	$0,-1$	$1,0$	$0,-1,-2$	$1,0,-1$	$2,1,0$

SCTM模型的超势：

$$W_{\mathrm{SCTM}} = W_{\mathrm{MSSM}/\mu} + W_0$$

$$W_{\mathrm{MSSM}/\mu} = y_d D^c Q \cdot H_1 + y_e E^c L \cdot H_1 - y_u U^c Q \cdot H_2$$

$$W_0 = \lambda \bar{H} \cdot \Delta \bar{H} + \frac{\lambda_3}{3} \mathrm{Tr}(\bar{\Delta}\bar{\Delta}\bar{\Delta}) + \frac{\mu}{2} \bar{H} \cdot \bar{H} + \frac{\mu_\Delta}{2} \mathrm{Tr}(\bar{\Delta}\bar{\Delta})$$

SCTM模型的软破缺项：

$$-\mathcal{L}^{soft}_{\mathrm{SCTM}} = -\mathcal{L}^{soft}_{\mathrm{MSSM}} - \mathcal{L}^{soft}_0$$

$$-\mathcal{L}^{soft}_{\mathrm{MSSM}} = m_H^2 |\bar{H}|^2 + \frac{1}{2} B_\mu \bar{H} \cdot \bar{H} + m_L^2 \tilde{L}^\dagger \tilde{L} + m_E^2 \tilde{E}^* \tilde{E} + m_Q^2 \tilde{Q}^\dagger \tilde{Q} + m_U^2 \tilde{U}^* \tilde{U} + m_D^2 \tilde{D}^* \tilde{D}$$
$$+ \left[-H_u \tilde{Q}_I \tilde{A}_u \tilde{U} + H_d \tilde{Q}_I \tilde{A}_d \tilde{D}_J + H_d \tilde{L}_I \tilde{A}_e \tilde{E}_J + \frac{M_3}{2} \tilde{g}\tilde{g} + \frac{M_2}{2} \tilde{W}^a \tilde{W}^a + \frac{M_1}{2} \tilde{B}\tilde{B} + h.c. \right]$$

$$-\mathcal{L}^{soft}_0 = m_\Delta^2 \mathrm{tr}|\bar{\Delta}|^2 + \left\{ \frac{1}{2} B_\Delta \mathrm{tr}\bar{\Delta}^2 + A_\lambda \bar{H} \cdot \bar{\Delta} \bar{H} + \frac{1}{3} A_\Delta \mathrm{tr}\bar{\Delta}^3 + \mathrm{h.c.} \right\}$$

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$$\mathcal{L}_{\text{neutralino mass}} = -\frac{1}{2}(\psi_N)^T M_N \psi_N + \text{c.c.}$$

Neutralino 基矢 $\psi_N = \left(\tilde{B}, \tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{\phi}^0, \tilde{\chi}^0, \tilde{\psi}^0\right)$

质量矩阵

$$\mathcal{M}_N = \begin{pmatrix} M_1 & 0 & -\frac{g' \cos_\beta v_H}{\sqrt{2}} & \frac{g' \sin_\beta v_H}{\sqrt{2}} & 0 & -\sqrt{2}g' v_\Delta & \sqrt{2}g' v_\Delta \\ 0 & M_2 & \frac{g \cos_\beta v_H}{\sqrt{2}} & -\frac{g \sin_\beta v_H}{\sqrt{2}} & 0 & \sqrt{2}g v_\Delta & -\sqrt{2}g v_\Delta \\ -\frac{g' \cos_\beta v_H}{\sqrt{2}} & \frac{g \cos_\beta v_H}{\sqrt{2}} & 2\lambda v_\Delta & \lambda v_\Delta - \mu & \lambda \sin_\beta v_H & 0 & 2\lambda \cos_\beta v_H \\ \frac{g' \sin_\beta v_H}{\sqrt{2}} & -\frac{g \sin_\beta v_H}{\sqrt{2}} & \lambda v_\Delta - \mu & 2\lambda v_\Delta & \lambda \cos_\beta v_H & 2\lambda \sin_\beta v_H & 0 \\ 0 & 0 & \lambda \sin_\beta v_H & \lambda \cos_\beta v_H & \mu_\Delta & -\lambda_3 v_\Delta & -\lambda_3 v_\Delta \\ -\sqrt{2}g' v_\Delta & \sqrt{2}g v_\Delta & 0 & 2\lambda \sin_\beta v_H & -\lambda_3 v_\Delta & 0 & -\lambda_3 v_\Delta + \mu_\Delta \\ \sqrt{2}g' v_\Delta & -\sqrt{2}g v_\Delta & 2\lambda \cos_\beta v_H & 0 & -\lambda_3 v_\Delta & -\lambda_3 v_\Delta + \mu_\Delta & 0 \end{pmatrix}$$

希格斯粒子按 $SU(2)_V$ 群分类

$$H_d = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix},\ H_u = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix},\ \Sigma_- = \begin{pmatrix} \frac{\chi^-}{\sqrt{2}} & \chi^0 \\ \chi^{--} & -\frac{\chi^-}{\sqrt{2}} \end{pmatrix},\ \Sigma_0 = \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix},\ \Sigma_+ = \begin{pmatrix} \frac{\psi^+}{\sqrt{2}} & \psi^{++} \\ \psi^0 & -\frac{\psi^+}{\sqrt{2}} \end{pmatrix},\ \bar{H} = \begin{pmatrix} H_d \\ H_u \end{pmatrix},\ \bar{\Delta} = \begin{pmatrix} -\frac{\Sigma_0}{\sqrt{2}} & \Sigma_- \\ -\Sigma_+ & \frac{\Sigma_0}{\sqrt{2}} \end{pmatrix}$$

$$(2,\bar{2})\Big|_{SU(2)_V} = 1 \oplus 3,\ (3,\bar{3})\Big|_{SU(2)_V} = 1 \oplus 3 \oplus 5$$

$$h_1^0 = \frac{1}{\sqrt{2}}(H_1^0 + H_2^0), \quad h_3^+ = H_2^+, \quad h_3^0 = \frac{1}{\sqrt{2}}(H_1^0 - H_2^0), \quad h_3^- = H_1^-.$$

$$\delta_1^0 = \frac{\phi^0 + \chi^0 + \psi^0}{\sqrt{3}},\ \delta_3^+ = \frac{\psi^+ - \phi^+}{\sqrt{2}},\ \delta_3^0 = \frac{\chi^0 - \psi^0}{\sqrt{2}},\ \delta_3^- = \frac{\phi^- - \chi^-}{\sqrt{2}},$$

$$\delta_5^{++} = \psi^{++},\ \delta_5^+ = \frac{\phi^+ + \psi^+}{\sqrt{2}}, \delta_5^0 = \frac{-2\phi^0 + \psi^0 + \chi^0}{\sqrt{6}},\ \delta_5^- = \frac{\phi^- + \chi^-}{\sqrt{2}},\ \delta_5^{--} = \chi^{--}.$$

2. Tripletino暗物质的唯象学分析

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Neutralino 在 $SU(2)_V$ 群下基矢

custodial singlet tripletino　custodial triplet tripletino

$$\Psi_N = \left(\tilde{h}_1, \boxed{\tilde{\delta}_1}, \tilde{\gamma}, \tilde{z}, \tilde{h}_3^0, \boxed{\tilde{\delta}_3^0}, \boxed{\tilde{\delta}_5^0}\right) \qquad \tilde{\chi}_i^0 = N_{ij}\Psi_{Nj}$$

custodial fiveplet tripletino

$$g_Z = \sqrt{g^2 + g'^2}$$

$$\mathcal{M}_N = \begin{pmatrix} 3\lambda v_\Delta - \mu & \sqrt{6}\lambda v_H & 0 & 0 & 0 & 0 & 0 \\ \sqrt{6}\lambda v_H & -2\lambda_3 v_\Delta + \mu_\Delta & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{g^2 M_1 + g'^2 M_2}{g_Z^2} & \frac{gg'(M_2 - M_1)}{g_Z^2} & 0 & 0 & 0 \\ 0 & 0 & \frac{gg'(M_2 - M_1)}{g_Z^2} & \frac{g'^2 M_1 + g^2 M_2}{g_Z^2} & g_Z v_H & 2g_Z v_\Delta & 0 \\ 0 & 0 & 0 & g_Z v_H & \lambda v_\Delta + \mu & -2\lambda v_H & 0 \\ 0 & 0 & 0 & 2g_Z v_\Delta & -2\lambda v_H & \lambda_3 v_\Delta - \mu_\Delta & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda_3 v_\Delta + \mu_\Delta \end{pmatrix}$$

扫描参数：

$$\mu,\ \mu_\Delta,\ \lambda,\ \lambda_3,\ v_\Delta,\ M_1,\ M_2,\ M_3,\ A_{t,b,\tau},\ M_{\tilde{Q}_3, \tilde{U}_3, \tilde{L}_3},\ m_\Delta,\ B_\Delta$$

实验限制：

$$m_{\tilde{g}} \gtrsim 2.4\ \text{TeV},\ m_{\tilde{t}_1, \tilde{b}_1} \gtrsim 1.25\ \text{TeV},\ m_{\tilde{\tau}} \gtrsim 0.48\ \text{TeV},\ m_{\tilde{\chi}^\pm} > 103.5\ \text{GeV},\ 122\ \text{GeV} < M_h < 128\ \text{GeV}$$

2. Tripletino暗物质的唯象学分析

SCTM模型的扫描结果：

λ	λ_3	μ / TeV	v_Δ/ GeV	μ_Δ/ TeV	M_1/ TeV	M_3/ TeV
[0.3,0.35]	< 0.75	[0.54,0.9]	[9,11]	[0.29,0.32]	[0.3,0.4]	> 2.2

约束条件：$v^2=2v_H^2+8v_\Delta^2\simeq(174\,\mathrm{GeV})^2,\ M_1<M_2<M_3$

典型数值结果：

$$\begin{array}{cc} & \begin{array}{ccccccc} \tilde{h}_1, & \tilde{\delta}_1, & \tilde{\gamma}, & \tilde{z}, & \tilde{h}_3^0, & \tilde{\delta}_3^0, & \tilde{\delta}_5^0 \end{array} \\ \mathcal{M}_N = & \begin{pmatrix} -590.4 & \boxed{95.1} & 0 & 0 & 0 & 0 & 0 \\ 95.1 & \boxed{\mathbf{300.0}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 428.7 & 146.1 & 0 & 0 & 0 \\ 0 & 0 & 146.1 & 621.3 & 89.6 & 14.8 & 0 \\ 0 & 0 & 0 & 89.6 & 603.2 & \boxed{-77.7} & 0 \\ 0 & 0 & 0 & 14.8 & -77.7 & \boxed{\mathbf{-305.0}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \boxed{\mathbf{315.0}} \end{pmatrix} \end{array}$$

$\tilde{\delta}_3^0, \tilde{\delta}_3^\pm$　　$\tilde{\delta}_5^0, \tilde{\delta}_5^\pm, \tilde{\delta}_5^{\pm\pm}$

I. Tripletino 暗物质满足暗物质残留密度上限：

$$\Omega_{\mathrm{DM}}h^2 \ll 0.12$$

♦残留密度主要由共湮灭决定。当宇宙膨胀冷却到退耦温度 T_f 时，暗物质开始"冻结"。对于质量为$m\approx 300$ GeV 的弱相互作用大质量粒子，退耦温度通常发生在：

$$T_f \approx \frac{m}{20} \sim 15\ \mathrm{GeV}$$

根据玻尔兹曼分布，较重的暗物质与最轻的暗物质的数量密度比：

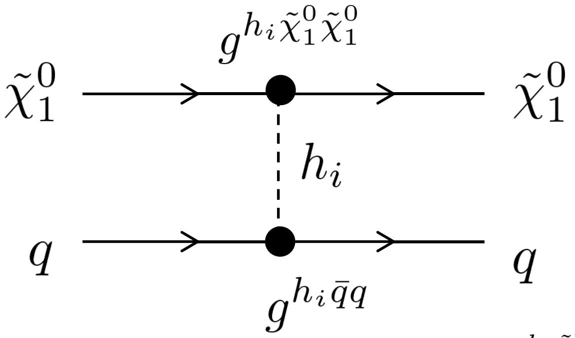
$$\frac{n_i}{n_1} \approx \exp\left(-\frac{\Delta m_i}{T_f}\right) \approx \exp\left(-\frac{5}{15}\right) \approx 71\%$$

♦共振湮灭：

$$\sigma \propto \frac{1}{s-m_{h_i}^2+im_{h_i}\Gamma_{h_i}}, \qquad s\approx 4m_{\tilde{\chi}_1^0}^2$$

2. Tripletino暗物质的唯象学分析

II. Tripletino暗物质的自旋无关散射结果



低能有效相互作用拉格朗日量：$\mathcal{L}_{\text{eff}} = \sum_i \frac{g^{h_i\tilde{\chi}_1^0\tilde{\chi}_1^0} g^{h_i\bar{q}q}}{m_{h_i}^2} \left(\bar{\tilde{\chi}}_1^0\tilde{\chi}_1^0\right)(\bar{q}q)$

自旋无关散射截面： $\sigma^{SI} \propto \left(g^{h_i\tilde{\chi}_1^0\tilde{\chi}_1^0} \times g^{h_i\bar{q}q}\right)^2$

h_i与夸克q的耦合： h_i是以二重态为主

h_i与暗物质$\widetilde{\chi}_1^0$的耦合：

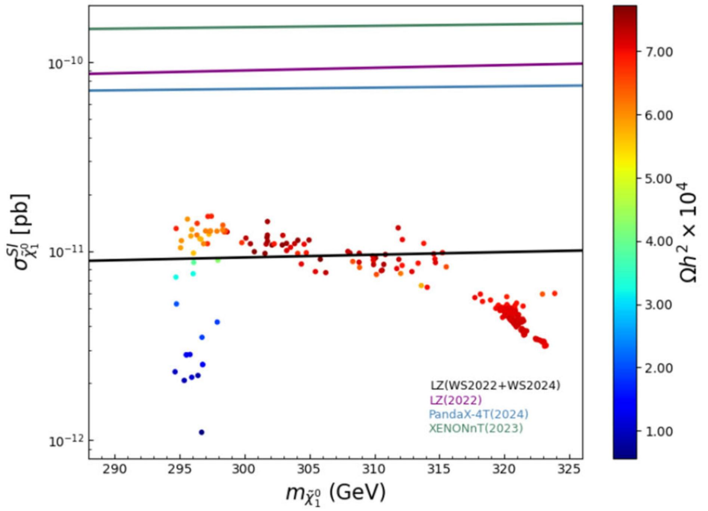
$$W_0 \supset \boxed{\lambda\bar{H}\cdot\Delta\bar{H}} + \boxed{\frac{\lambda_3}{3}\mathrm{Tr}(\bar{\Delta}^3)}$$

- 二重态为主Higgs中混入标量三重态

  贡献大小：$\lambda_3\frac{v_\Delta}{v_H} \approx 0.5 \times 0.08 \approx 0.04$

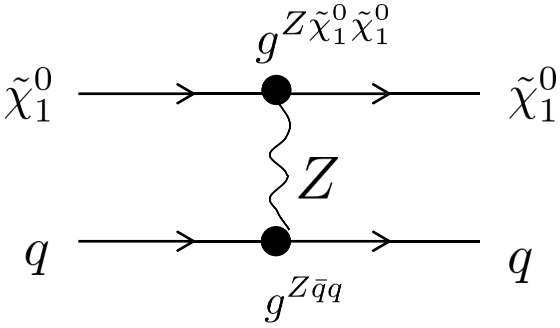
- Tripletino为主暗物质中混入Higgsino

  贡献大小：$\lambda N_{1,H} \approx 0.32 \times 0.1 \approx 0.032$



2. Tripletino暗物质的唯象学分析

III. Tripletino暗物质的自旋相关散射结果



$$g^{(B)}_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0} \propto g'\langle\tilde{\delta}_1^0|Y|\tilde{\delta}_1^0\rangle$$

$\tilde{\delta}_1^0$ 的超荷结构： $\delta_1^0 = \left(\phi^0 + \chi^0 + \psi^0\right)/\sqrt{3}$

由于Custodial 对称性，Tripletino 暗物质与 Z 玻色子之间的相互作用受到极大压低，使得该模型能够很容易满足暗物质自旋相关散射结果。

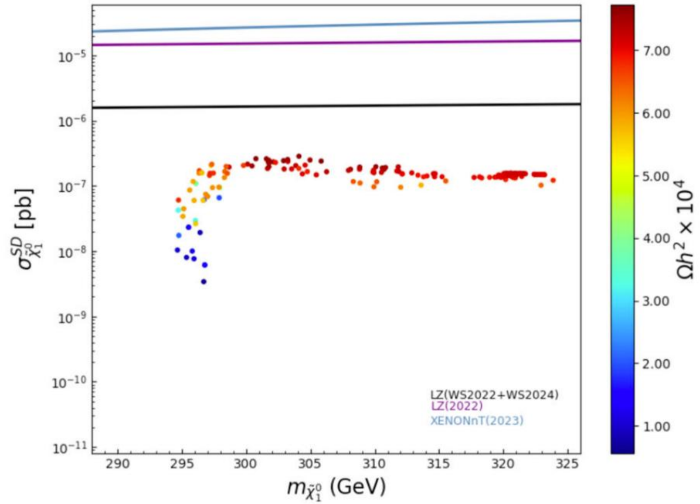
低能有效相互作用拉格朗日量： $\mathcal{L}_{eff} = \dfrac{g^{Z\tilde{\chi}_1^0\tilde{\chi}_1^0}g^{Z\bar{q}q}}{m_Z^2}\left(\bar{\tilde{\chi}}_1^0\gamma^\mu\gamma^5\tilde{\chi}_1^0\right)\left(\bar{q}\gamma_\mu\gamma^5 q\right)$

自旋相关散射截面： $\sigma^{SD} \propto \left(g^{Z\tilde{\chi}_1^0\tilde{\chi}_1^0} \times g^{Z\bar{q}q}\right)^2$

Z与暗物质$\tilde{\chi}_1^0$的耦合： $g_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0} = g^{(W^3)}_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0} + g^{(B)}_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0}$

$\tilde{\chi}_1^0 \sim \tilde{\delta}_1^0$，在 $SU(2)_V$ 群下：

$$g^{(W^3)}_{Z\tilde{\chi}_1^0\tilde{\chi}_1^0} \propto \langle\tilde{\delta}_1^0|W_\mu^3|\tilde{\delta}_1^0\rangle \propto \langle\mathbf{1}|\mathbf{3}|\mathbf{1}\rangle = 0$$



3. 总结与展望

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1

SCTM模型：

- Custodial 对称性保证 $\rho = 1$
- Higgs 部分包含二重态和三重态
- 提供 Tripletino 暗物质候选

2

Tripletino暗物质：

- 共湮灭机制保证满足暗物质残留密度上限
- 自旋无关散射：Doublet-Triplet 混合与 Higgsino-Tripletino 混合共同压低散射截面
- 自旋相关散射：受 Custodial 对称性保护而极小

3

展望：

- 基于 EasyScan_HEP 的完整参数空间扫描
- 解析表达式

感谢大家的关注，敬请批评指正。