Triplet Charged Higgs at the LHC

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SM+Real Triplet

- SM with a Y=0 real SU(2) triplet

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad T = \begin{bmatrix} \frac{T^0}{\sqrt{2}} & T^+ \\ T^- & -\frac{T^0}{\sqrt{2}} \end{bmatrix}$$

$$V(\Phi, T) = m_\Phi^2 \Phi^\dagger \Phi + m_T^2 Tr(T^\dagger T) + \lambda_1 |\Phi^\dagger \Phi|^2$$
$$+ \lambda_2 (Tr|T^\dagger T|)^2 + \lambda_3 \Phi^\dagger \Phi Tr(T^\dagger T) + A(\Phi^\dagger T \Phi)$$

- EWSB condition: $\phi^0 = v_1 + \phi_r^0 + iG^0 \text{ and } \mathrm{T^0 = v_T + T_r^0}$

Doublet

Triplets

- Particle spectrum: $h_1(h_{125}), h_2(\sim T^0), H^\pm(\sim T^\pm)$
- $A(\Phi^\dagger T \Phi)$ term causes the mixing between doublet and triplet
- Triplets do not couple to fermions: as no SU(2) gauge invariant vertex is possible.

Inert Triplet

- If the triplet field is odd under Z_2 then potential takes a form

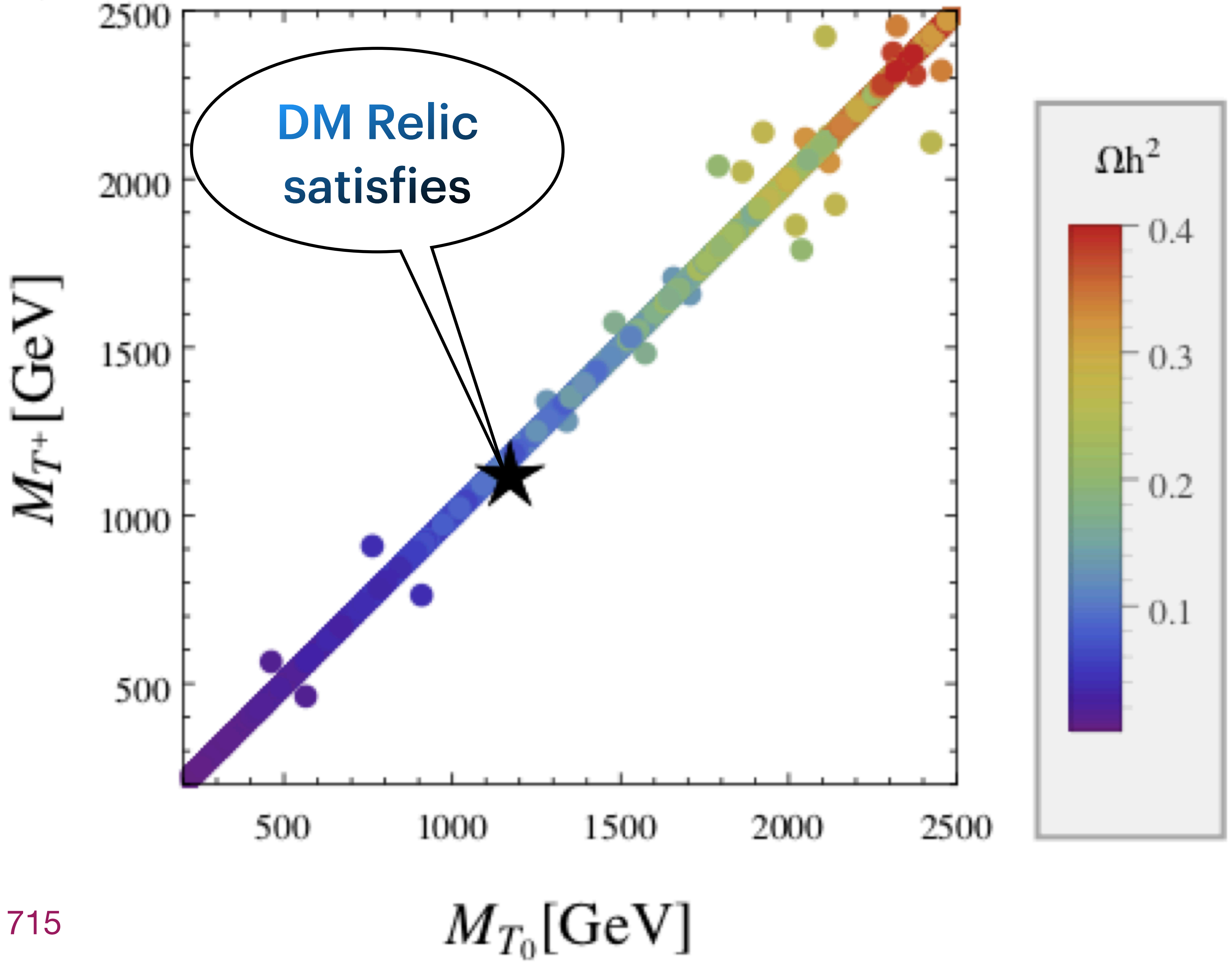
$$V(\Phi, T) = m_\Phi^2 \Phi^\dagger \Phi + m_T^2 Tr(T^\dagger T) + \lambda_1 |\Phi^\dagger \Phi|^2 + \lambda_2 (Tr|T^\dagger T|)^2 + \lambda_3 \Phi^\dagger \Phi Tr(T^\dagger T)$$

- Triplet does not get vev and neutral component T^0 can become lightest inert particle (ITP) and a candidate dark matter.
- In this case triplet and doublet does not mix at all.
- Both $T^0, T^\pm$ are pure triplets and do not couple to fermions directly
- T^0 does not couple to Z boson also
- There is no tree-level mass splitting between
- At one-loop the mass splitting is $\Delta m(T^\pm, T^0) = m_{T^\pm} - m_{T^0} = 166\,\mathrm{MeV}$

Constraints from DM relic

- The dominating annihilation channel for T^0 is $\mathrm{T^0T^0} \rightarrow \mathrm{W^{\pm}W^{\mp}}$
- The sub-dominant co-annihilation is $T^0T^{\pm} \rightarrow ZW^{\mp}$
- The DM relic satisfies at $\Omega_{\mathrm{DM}}\mathrm{h}^2 = 0.1199 \pm 0.0027$,
- This gives strict lower bound of 1176 GeV

on the DM mass



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Charged Higgs Phenomenology

- The charged Higgs cannot directly decay to τ, ν or t, τ
- However, having SU(2) charged it couples to $W^{\pm}$ boson
- Due to less mass gap, it has three body decays: $T^{\pm} \to (W^{\pm})^{*} T^{0} \to \ell + \not{p}_T,\ 2j + \not{p}_T$
- This leads to displaced rest mass decay length of the order of meter
- The searches in LHC and other collider may depend on the details below

Masses in GeV	Decay Modes	BR in %	Decay Width in GeV	Decay Length in m
$M_{T_0} = 1178.60$	$T^{\pm} \to T_0 \bar{d} u$	72.72	7.58×10^{-17}	2.64
$M_T^{\pm} = 1178.76$	$T^{\pm} \to T_0 \nu \ell^{\pm}$	24.30		

- The relevant production modes can be $pp \to T^{\pm} T^{\mp},\ T^{\pm} T^{0}$

Displaced mono-lepton plus missing energy

- Due to TeV scale mass and purely electroweak processes, the cross-sections are small
- One can only expect healthy numbers at 100 TeV collider
- A demand of $n_\ell \geq 1 + 1\,\mathrm{mm} \leq \mathrm{d} \leq 10\,\mathrm{m}$

with a displaced charged lepton can probe such scenario with early data at the LHC/FCC at 100 TeV

- The addition of scalar also enhances the vacuum stability
- Bounds can come from perturbativity More @HiggsIV by Shilpa Jangid

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Complex Y=0 Triplet

we consider a complex triplet with $Y=0$ hypercharge, namely

$$T = \frac{1}{\sqrt{2}} \begin{pmatrix} t_0 & \sqrt{2}\, t_1^+ \\ \sqrt{2}\, t_2^- & -t_0 \end{pmatrix}. \qquad (t_1^+)^* \neq t_2^- \text{ and } t_0 \text{ is also complex.}$$

- The scalar potential is given by $V = V_1 + V_2,$

$$\begin{aligned} V_1 &= \mu^2 \Phi^\dagger \Phi + \frac{\lambda_H}{2} \Phi^\dagger \Phi \Phi^\dagger \Phi + m_T^2\, \mathtt{tr}[T^\dagger T] + \frac{\lambda_T}{2} \mathtt{tr}[T^\dagger T] \mathtt{tr}[T^\dagger T] + \frac{\lambda_{T'}}{2} \mathtt{tr}[T^\dagger T\, T^\dagger T] \\ &+ \frac{\lambda_{HT}}{2} \Phi^\dagger \Phi\, \mathtt{tr}[T^\dagger T] + \kappa_{HT} \left(\mathtt{tr}[\Phi^\dagger T \Phi] + \mathtt{h.c.} \right), \end{aligned}$$

Z_3 Symmetric

$$\begin{aligned} V_2 &= \left(m_T'^2\, \mathtt{tr}[T\, T] + \frac{\lambda_T^{(2)}}{2} \mathtt{tr}[T\, T\, T\, T] + \frac{\lambda_T^{(3)}}{2} \mathtt{tr}[T^\dagger T\, T\, T] \right. \\ &\left. + \frac{\lambda_{HT}^{(2)}}{2} \Phi^\dagger \Phi\, \mathtt{tr}[T\, T] \right) + \mathtt{h.c.}. \end{aligned}$$

- The EWSB conditions: $\Phi_0 = \frac{1}{\sqrt{2}} (v + \phi_0 + i\, \sigma_0)\,, \qquad t_0 = \frac{1}{\sqrt{2}} \left(v_T + \phi_0^t + i\, \sigma_0^t \right).$

$$\rho^{\text{ex}} = 1.00038 \pm 0.00020, \quad \Longrightarrow \quad v_T \lesssim 5 \text{ GeV}\ .$$

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Complex Y=0 Triplet: Pseudoscalar

- Unlike real Y=0 triplet, it has a pseudosclar
- The Physical pseudo scalar is pure triplet $a_P = \sigma_0^t.$
- The mass of the pseudo scalar is

$$m_{a_P}^2 = \kappa_{HT}\frac{v^2}{2v_T} - 4m_T'^2 - \lambda_{HT}^{(2)}v^2 - (4\lambda_T^{(2)} + \lambda_T^{(3)})v_T^2,$$

- Being Y=0, it does not couple to fermions and Z boson
- Being speudoscalar it does not couple to $W^\pm W^\mp,\, ZZ$
- Corresponding loop-level couplings are also zero
- Thus without any additional discrete symmetry a_P is promoted as the dark matter candidate

Complex Y=0 Triplet: CP-even neutral Higgs boson

- For CP-even scalar both doublet and triplet fields mix

$$
\begin{aligned}
h_D &= \frac{1}{N_{h_D}}\Big((8\,v^2\kappa_{HT}^3+\ldots)\,\phi_0+16\,\kappa_{HT}^3 v\,v_T\,\phi_0^t\Big),\\
h_T &= \frac{1}{N_{h_T}}\Big((-2\kappa_{HT}v_T+(\lambda_{HT}+2\lambda_{HT}^{(2)}-4\lambda_H)v_T^2)\,\phi_0+\kappa_{HT}\,v\,\phi_0^t\Big)\,.
\end{aligned}
$$

- With masses

$$
\begin{aligned}
m_{h_D}^2 &= \lambda_H v^2-2\kappa_{HT}\,v_T+2\left(\lambda_{HT}+2\lambda_{HT}^{(2)}-2\lambda_H\right)v_T^2,\\
m_{h_T}^2 &= \frac{\kappa_{HT}}{2v_T}\left(v^2+4v_T^2\right)+\left(4\lambda_H-2\lambda_{HT}-4\lambda_{HT}^{(2)}+\lambda_T+\frac{\lambda_{T'}2}{+}2(\lambda_T^{(2)}+\lambda_T^{(3)})\right)v_T^2
\end{aligned}
$$

- The model parameters get constraints from the recent Higgs boson mass and branching measurements at ATLAS and CMS experiments at the LHC

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Complex Y=0 Triplet: Charged Higgs boson

- The charged Higgs spectrum is more complex with $h_0^\pm$ as charged Goldstone

$$
\begin{aligned}
h_T^+ &= \frac{2v_T}{\sqrt{v^2+4v_T^2}}\phi^+ + \frac{2v}{\sqrt{2}\sqrt{v^2+4v_T^2}}(t_2^-)^* + \frac{2v}{\sqrt{2}\sqrt{v^2+4v_T^2}}t_1^+, \\
h_P^+ &= -\frac{1}{\sqrt{2}}(t_2^-)^* + \frac{1}{\sqrt{2}}t_1^+, \\
h_0^+ &= -\frac{v}{\sqrt{v^2+4v_T^2}}\phi^+ + \frac{\sqrt{2}v_T}{\sqrt{v^2+4v_T^2}}(t_2^-)^* + \frac{\sqrt{2}v_T}{\sqrt{v^2+4v_T^2}}t_1^+.
\end{aligned}
$$

- $h_T^\pm$ Is the orthogonal to Glodstone is a mixed but mostly triplet charged Higgs
- $h_P^\pm$ stays as pure triplet charged Higgs and does not couple to fermions
- The mass spectrum looks like

$$
\begin{aligned}
m^2_{h_T^\pm} &= \kappa_{HT}\left(\frac{v^2}{2\,v_T}+2\,v_T\right), \\
m^2_{h_P^\pm} &= \kappa_{HT}\frac{v^2}{2\,v_T} - 4m_T'^2 - \lambda_{HT}^{(2)}v^2 - (2\lambda_T^{(2)} + \lambda_T^{(3)} + \frac{\lambda_{T'}}{2})v_T^2
\end{aligned}
$$

- With a tree-level splitting with the pseudo scalar

$$
m^2_{h_P^\pm} - m^2_{a_P} = \left(2\lambda_T^{(2)} + \frac{\lambda_{T'}}{2}\right)v_T^2
$$

Decays of the Charged Higgs bosons

- Odd number of pure state in a vertex i.e. a_P or $h^\pm_P$, vanishes

$$g_{a_P\, h^+_{i=P,\,T} W^-} = -\frac{g_L}{2}\left(\mathcal{R}^P_{21}\mathcal{R}^C_{i1} - \sqrt{2}\mathcal{R}^P_{22}(\mathcal{R}^C_{i2} - \mathcal{R}^C_{i3})\right),$$

$$g_{Z\, h^+_{i=P,\,T} W^-} = -\frac{i}{2} g_L \left(g_Y v \sin\theta_W \mathcal{R}^C_{i1} + \sqrt{2} g_L v_T \cos\theta_W (\mathcal{R}^C_{i2} - \mathcal{R}^C_{i3})\right).$$

- $g_{a_P\, h^+_T W^-}$, $g_{Z\, h^+_P W^-}$ vanish but $g_{Z\, h^+_T W^-}$ remains non-zero.
- Appearance of pure states twice makes the vertices non-zero e.g. $a_P h^+_P W^-$
- The pure triplet nature acts effectively as an odd number in a discrete symmetry

Z_3 Symmetric limit

- In the Z_3 symmetric limit $T \to e^{\frac{2\pi i}{3}} T$ and others remain invariant
- The V_2 part of the potential goes to zero leaving

$$m_{a_P}^2 = \kappa_{HT} \frac{v^2}{2\, v_T}, \quad m_{h_P^\pm}^2 = \kappa_{HT} \frac{v^2}{2\, v_T} + \frac{\lambda_{T'}}{2} v_T^2, \quad m_{h_T^\pm}^2 = \kappa_{HT} \left(\frac{v^2}{2\, v_T} + 2\, v_T \right)$$

- In the limit of $\lambda_{T'} \to 0$, the pure pseudo scalar and pure charged Higgs are degenerate at the tree-level
- An one-loop splitting of 166 MeV between $h_P^\pm, a_P$ comes as the real triplet case
- However, mass splitting between $h_T^\pm, a_P$ can be larger proportional to $2\kappa_{HT} v_T$
- $h_P^\pm$ gives rise to displaced charged lepton
- $h_T^\pm$ Have prompt decays

Custodial Limit

- In the Custodial limit $v_T \to 0$ and we get $\rho \equiv 1$
- The mass spectrum and fields take the following form

$$
\begin{aligned}
m_{h_D}^2 &= \lambda_H v^2, \quad h_D = \phi_0, \\
m_{h_T}^2 &= m_T^2 + 2m_T'^2 + \frac{1}{2}(\frac{\lambda_{HT}}{2} + \lambda_{HT}^{(2)})v^2, \quad h_T = \phi_0^t, \\
m_{a_P}^2 &= m_T^2 - 2m_T'^2 + \frac{1}{2}(\frac{\lambda_{HT}}{2} - \lambda_{HT}^{(2)})v^2, \quad a_P = \sigma_0^t, \\
m_{h_{T/P}^+}^2 &= m_T^2 \pm 2m_T'^2 + \frac{1}{2}(\frac{\lambda_{HT}}{2} \pm \lambda_{HT}^{(2)})v^2, \quad h_{T/P}^+ = \frac{1}{\sqrt{2}}(t_1^+ \pm (t_2^-)^*).
\end{aligned}
$$

- Both the charged Higgs bosons are pure triplet and none decays to ZW
- In the Z_3 limit $h_T^\pm, h_P^\pm$ become degenerate with a_P, h_T at the tree-level

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Dark Matter Phenomenology

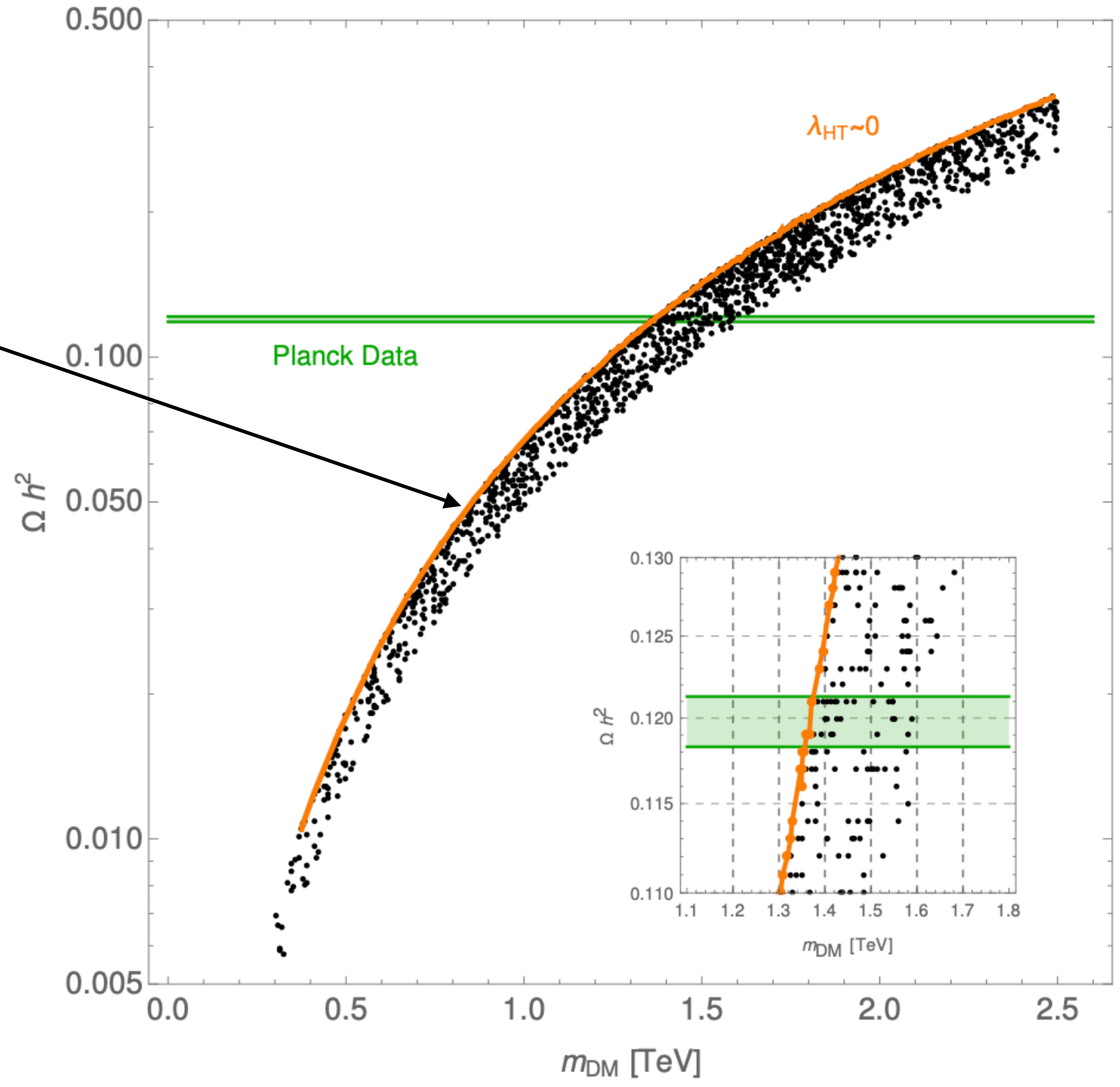
- From Higgs data we get a lower bound of $h^{\pm}_{T/P} \gtrsim 600\,\mathrm{GeV}$
- Similar to the real triplets dominant annihilation modes is $a_P a_P \to W^{\pm} W^{\mp}$
- The co-annihilation mode is $a_P h^{\pm}_P \to Z W^{\mp}$
- However, $\sigma(a_P h^{\pm}_T \to Z W^{\mp}) = 0$ due to purity non-conservation
- This implies

$$m_{DM}^{min} \equiv m_{a_P}^{min} \sim 1.35\,\mathrm{TeV},$$

corresponds to the $\lambda_{HT} \sim 0$ case.

- Whereas

$$m_{DM}^{max} \equiv m_{a_P}^{max} \sim 1.60\,\mathrm{TeV}$$



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LHC Phenomenology

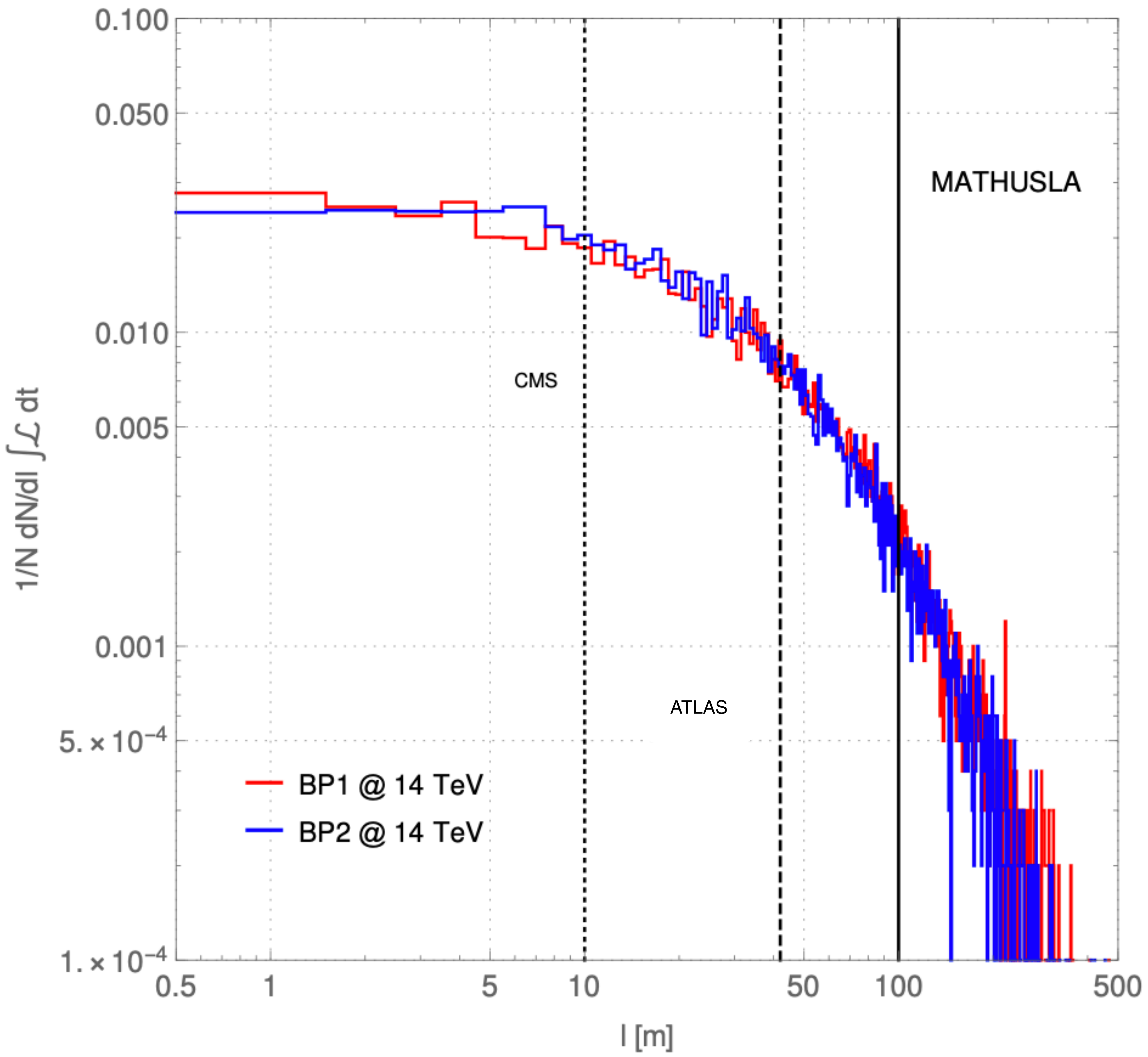
- The existence of two triplet charged Higgs bosons but phenomenologically different $h_T^{\pm}, h_P^{\pm}$
- $h_T^{\pm}$ has prompt decay with dominant modes $Br(h_T^+ \to W^+ Z) \sim Br(h_T^+ \to W^+ h_D) \sim 0.48.$
- $h_T^{\pm}$ decays to tb is restricted to ~ 4%
- $h_P^{\pm}$ Has displaced decay of width $\sim 10^{-16}\,\mathrm{GeV}$

$h_P^{\pm} \to a_P (W^{\pm})^*$, where the $W^{\pm}$ remains off-shell.

- Along with LHC muon collider can also probe

the triplet charged Higgs bosons with

$$\frac{\sigma_\mu^{14\,\mathrm{TeV}}(X)}{\sigma_p^{14\,\mathrm{TeV}}(X)} = 10^4 - 10^2. \qquad \sigma_\mu^{14\,\mathrm{TeV}}(X) \gtrsim 10^2\, \sigma_p^{100\,\mathrm{TeV}}(X)$$



More @BSMV by A. Costantini on 26/05: (New) Physics at multi-TeV muon Collider

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Conclusions

- The real Y=0, triplet gives rise to one charged Higgs with displaced decay
- The complex Y=0, triplet gives rise to one displaced and one prompt decays of Charged Higgs bosons
- For the real case to have a dark matter we need a Z_2 symmetry
- In case of complex Y=0 triplet, purity of triplet behaves like a discrete symmetry
- Displaced Mono/di-lepton plus missing energy can probe the real Y=0 triplet
- Existence of both displaced and prompt lepton plus missing energy can probe Y=0 complex triplet
- Muon collider and be promising along with the LHC


THANK
YOU!