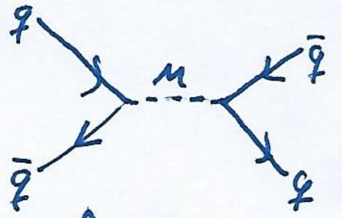
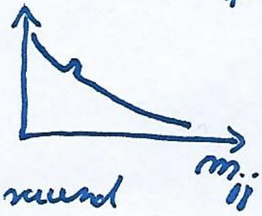
Lecture 2: Dark Matter Searches at the ATLAS experiment

2 main categories:

1.) Resonance searches: - Mediator decays to SM particles

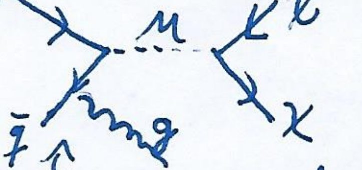


- "bump-hunt" in invariant mass spectrum

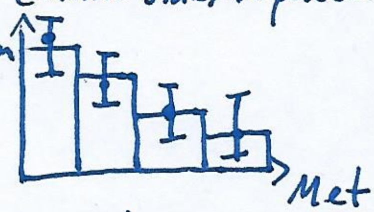


- challenges: • description of QCD background
  • searches at low m_{jj} (trigger)

2.) Missing transverse energy searches: e.g. Mono-jet



- typical hierachy:
  Mono-jet > Mono-photon > Mono-Z additional radiation (initial state) requiered
- challenges: • background estimation
  • description of tail



Mono-X searches are especially sensitive to pseudoscalar mediators compared to direct detection experiments → $\boxed{\text{construct DM model with PS mediator:}}$

I. Effective Field Theory approach (mediator integrated out):

$$\mathcal{L}_{DM-EFT,P} = \sum_f \frac{\overbrace{c^f}^{\text{Wilson coefficient}}}{\underbrace{\Lambda^2}_{\text{energy scale of new physics } (\Lambda \sim m_p}} \bar{f}\gamma_5 f \bar{\chi}\gamma_5\chi$$; fully described by $\{m_\chi, \frac{c^f}{\Lambda^2}\}$

- valid for momentum transfer $q^2 \ll \Lambda^2$; justified for DM-nucleon scattering in DD experiments where non-relativistic velocity of DM halo

$\boxed{\text{@LHC: } q^2 \gg \Lambda^2 \text{ for many DM theories} \rightarrow \text{mediator can be produced resonantly!}}$

II. Simplified Models (representation of large set of possible extensions of UV complete model)

$$\mathcal{L}_{DM-simp,P} = -ig_\chi a\bar{\chi}\gamma_5\chi - i\overset{\text{SM singlet}}{a}\sum_{\underset{\text{flavor}}{j}} (g_u Y_j^u \bar{u}_j\gamma_5 u_j + g_d Y_j^d \bar{d}_j\gamma_5 d_j + g_l Y_j^l \bar{l}_j\gamma_5 l)$$

with renormalizable potential:

$$V_{DM-simp,P} = \frac{1}{2} m_a^2 a^2 + b_a a^3 + \lambda_a a^4 + b_H a H^\dagger H + \lambda_H a^2 H^\dagger H$$

will influence Higgs physics

$\Rightarrow b_H \ll m_a$; $\lambda_H \ll 1$

by $\mathbb{Z}_2$ symmetry

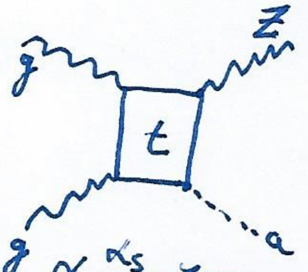
accidentally small for $m_a < 100\,\mathrm{GeV}$ to avoid $h \to a,a$ constraints

fully described by $\{m_\chi, m_a, g_\chi, g_{u,d,\ell}\}$

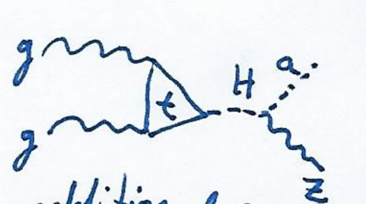
for $m_a \to \infty$ $\mathcal{L}_{DM-simp,P} \longrightarrow \mathcal{L}_{DM-EFT,P}$ as tree-level matching $\frac{c_f}{\Lambda^2} = \frac{g_\chi g_f y_f}{m_a^2}$

both $\mathcal{L}_{DM-EFT,P}$ & $\mathcal{L}_{DM-simp,P}$ violate gauge invariance (left- & right handed fermions follow same representation)

leads to unitarity violating amplitudes for



$\propto \frac{\alpha_s}{4\pi} y_t g_t \log^2\left(\frac{s}{m_t^2}\right)$



additional scalar H unitarises amplitude

$\boxed{\hookrightarrow \text{need to embed } a \text{ in EW multiplet!}}$

These additional degrees of freedom will change phenomenology if accessable.

II.b.) Renormalizable Simplified Models (e.g. 2HDM+a)

$$\mathcal{L}_{2HDM+a} = -i y_\chi P \bar{\chi} \gamma_5 \chi - \sum_{i=1,2} \left(\bar{Q} Y_u^i \tilde{H}_i u_R + \bar{Q} Y_d^i H_i d_R + \bar{L} Y_e^i H_i \ell_R + h.c. \right)$$

To assure absence of Flavor Changing Neutral Currents impose $\mathbb{Z}_2$ symmetry $H_1 \to H_1$; $H_2 \to -H_2$

Each fermion only couples to one Higgs doublet $Y_u^1 = Y_d^2 = Y_e^2 = 0$ (type II)

Under $\mathbb{Z}_2$ $P \to P$; $\chi \to -\chi$ $\Rightarrow \bar{L} \tilde{H}_1 \chi_R + h.c.$ forbidden

Scalar potential constructed s.t. parameters are real $\to$ CP eigenstates = mass eigenstates

$$V = V_{2HDM} + V_{2HDM,P} + V_P$$

breaks $\mathbb{Z}_2$ softly

$$V_{2HDM} = \mu_1 H_1^\dagger H_1 + \mu_2 H_2^\dagger H_2 + \mu_3 (H_1^\dagger H_2 + h.c.) + \lambda_1 (H_1^\dagger H_1)^2 + \lambda_2 (H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \left[\lambda_5 (H_1^\dagger H_2)^2 + h.c.\right]$$

$$V_{2HDM,P} = P(i b_P H_1^\dagger H_2 + h.c.) + P^2 (\lambda_{P_1} H_1^\dagger H_1 + \lambda_{P_2} H_2^\dagger H_2)$$

breaks $\mathbb{Z}_2$ softly

$$V_P = \frac{1}{2} m_P P^2 + \lambda_{P_4} P^4$$

physical parameters

$$\begin{Bmatrix} \mu_{1\ldots3}, \lambda_{1\ldots5} \\ m_\chi, b_P, m_P \\ y_\chi, \lambda_{P_1}, \lambda_{P_2} \end{Bmatrix} \longleftrightarrow \begin{Bmatrix} m_a, m_H, m_A, m_{H^\pm}, m_h \\ m_\chi, v, \tan\beta = \frac{v_2}{v_1}, \cos(\beta-\alpha) \\ \sin\theta, y_\chi, \lambda_3, \lambda_{P_1}, \lambda_{P_2} \end{Bmatrix}$$

for $m_A \gg m_a$ + narrow width approximation: $\frac{\sigma(pp \to j + E_T^{miss})_{II.b}}{\sigma(pp \to j + E_T^{miss})_{II}} \approx \left(\frac{y_\chi \sin\theta}{g_\chi g_q \tan\beta}\right)^2$

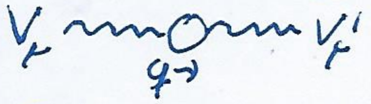
Constraints on 2HDM+a physical parameters:

- Electroweak precision observables:

Oblique parameters representation of radiative correction variables $\Delta r(m_W)$; $\Delta \kappa(\sin^2\theta)$,

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

1 loop self-energy corrections to $\gamma, W^\pm, Z$:



$i[\Pi_{VV'}(q^2) g^{\mu\nu} - \Delta_{VV'}(q^2) q^\mu q^\nu]$ 2-point correlation functions

vanishes in light quark limit

$\Rightarrow m_V'^2 = m_V^2 + \Pi_{VV'}(q^2 = m_V^2)$

γ is massless $\rightarrow \Pi_{\gamma\gamma}(0) = \Pi_{\gamma Z}(0) = 0$

define S, T, U:

$$\frac{\alpha S}{4 s_W^2 c_W^2} = \frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2} - \frac{c_W^2 s_W^2}{c_W s_W} \frac{\Pi_{\gamma Z}(m_Z^2)}{m_Z^2} - \frac{\Pi_{\gamma\gamma}(m_Z^2)}{m_Z^2}$$

$$\alpha T = \frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2} = \Delta\rho$$

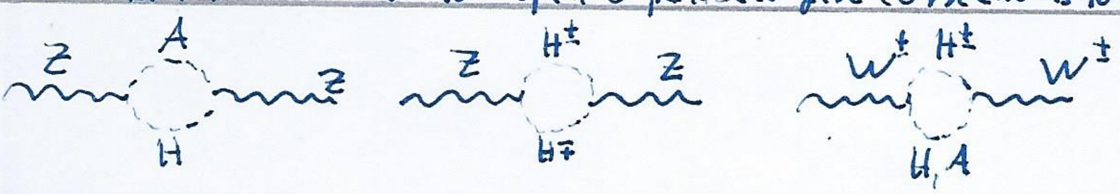
$$\frac{\alpha U}{4 s_W^2} = \frac{\Pi_{WW}(m_W^2) - \Pi_{WW}(0)}{m_W^2} - c_W^2 \frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2} - 2 c_W s_W \frac{\Pi_{\gamma Z}(m_Z^2)}{m_Z^2} - s_W \frac{\Pi_{\gamma\gamma}(m_Z^2)}{m_Z^2}$$

T is sensitive to difference of NP contributions to neutral & charged current processes at low energies

S, T, U constructed s.t. vanish in SM

Global EW fit: $S = -0.01 \pm 0.10$
$T = 0.03 \pm 0.12$
$U = 0.02 \pm 0.11$

For 2HDM the additional spin 0 particles give corrections to the gaugboson masses via:



$\Rightarrow$ T requiers $m_H \approx m_{H^\pm}$ or $m_A \simeq m_{H^\pm}$ to restore custodial symmetry

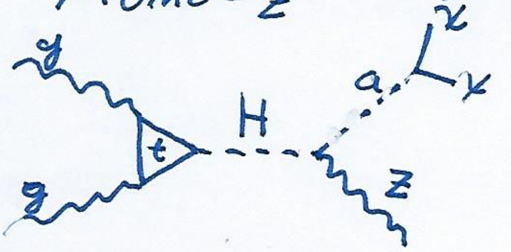
for 2HDM+a if m_a & $\sin\theta$ should be free $\rightarrow$ $\boxed{m_A \simeq m_H \simeq m_{H^\pm}}$

- Higgs signal strengh fit pushes $\cos(\beta - \alpha) \simeq 0$ alignment limit
- Flavor observables s.a. $B_s \rightarrow \mu^+\mu^-$; $b \rightarrow s\gamma$ set constraints on $\tan\beta$ & $m_{H^\pm}$
- Requiring V_{2HDM+a} to be bounded from below fixes λ_3

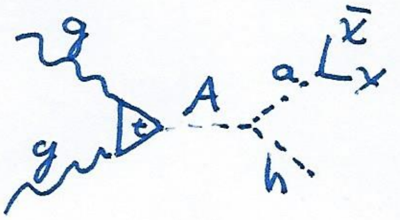
2HDM+a Model has a rich phenomenology for its allowed parameter space:

1.) Resonant E_T^{miss} signatures:

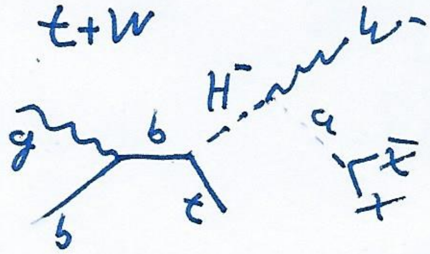
Mono-Z



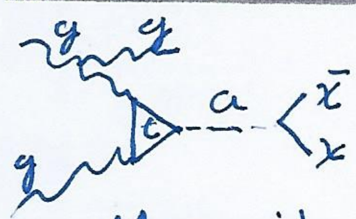
Mono-h



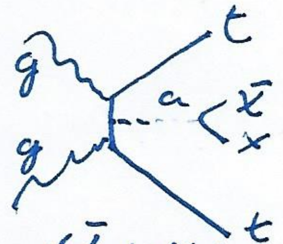
t+W



2.) Non-resonant E_T^{miss} signatures

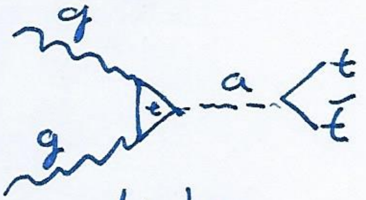


Mono-jet



$t\bar{t}$ + Met

3.) Non E_T^{miss} signatures for $m_a \gtrsim 2 m_t$



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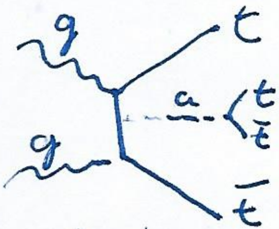

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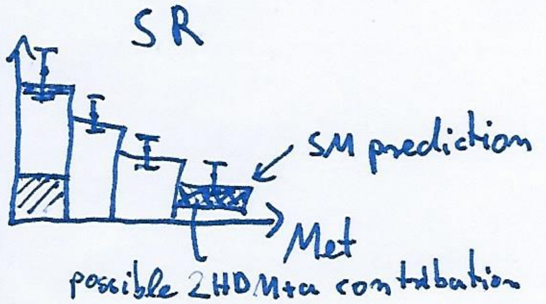
$\Rightarrow$ 2HDM+a has become a widely studied benchmark Model at the LHC!

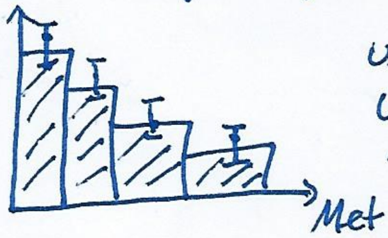
Also in Mono-jet analysis can try to constraint 2HDM+a:

Main selections cuts: - Met > 200 GeV
- at least 1 jet with $p_T > 120$ GeV
- no leptons

SR



Control Region e.g. Zee



use to constrain the uncertainties & normalization of prediction in SR

$\Rightarrow$ can set limits on DM models such as 2HDM+a by deriving CL_s limits with combined fit

Next Lecture: Use Z CRs to determine Γ_Z (inv)

$\hookrightarrow$ 2 major challenges: - Multijet background
- unfolding