XLIV Congresso Paulo Leal Ferreira de Física

Probing the Top-Higgs sector with clustering techniques

Ricardo D'Elia Matheus

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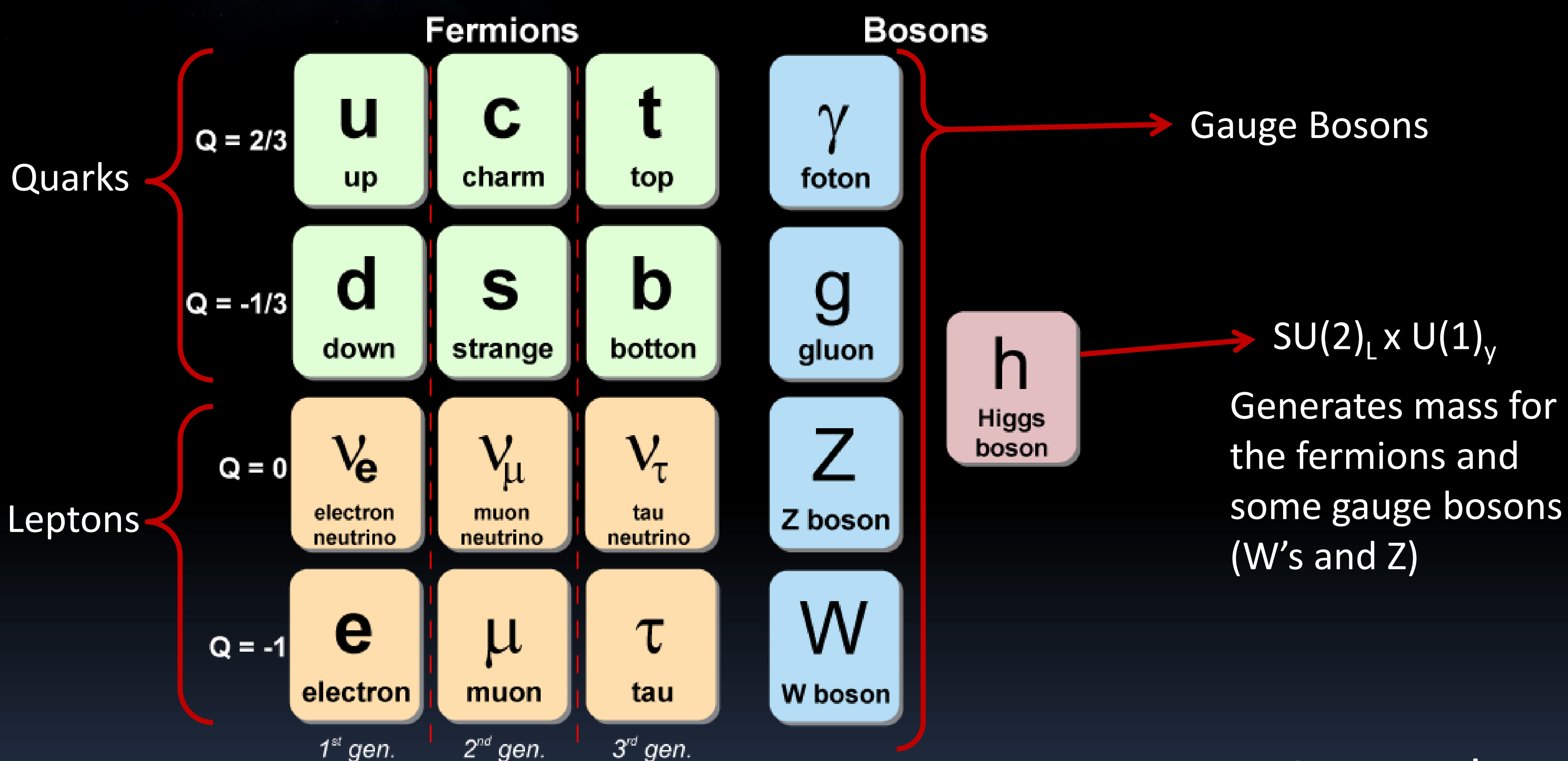
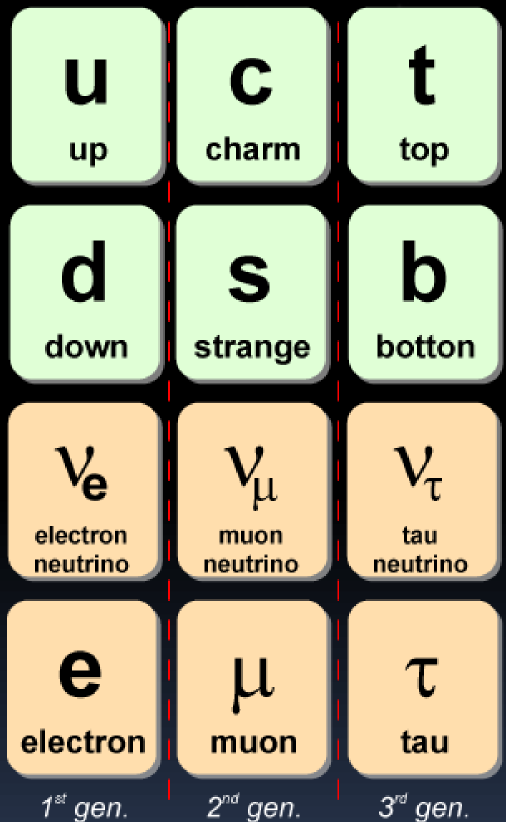
The Standard Model of Particle Physics (SM)



Are we done?

The Standard Model (SM)
its problems and shortcomings

The physics flavor/family structure (shortcoming)



$$\mathcal{L}_Y = y_\psi \left(\bar{\psi}_L \phi \psi_R\right) + h.c.$$

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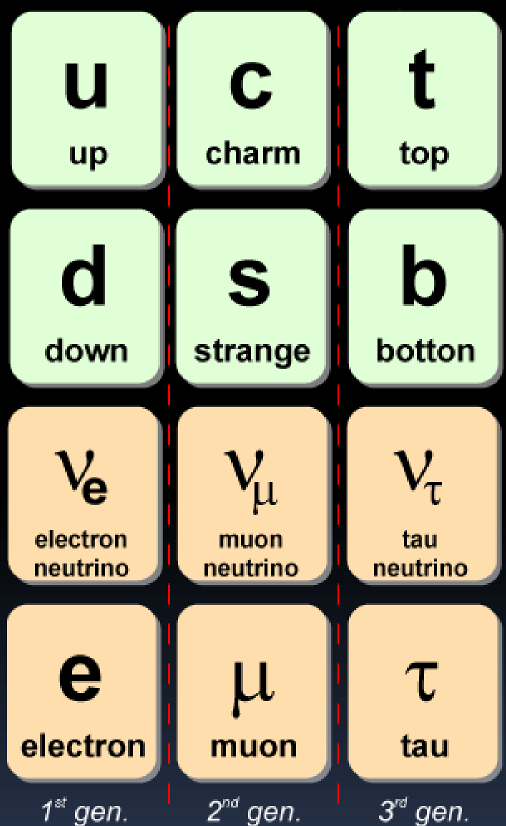

$$\mathcal{L}_Y = y_\psi \left(\bar{\psi}_L \phi \psi_R \right) + h.c.$$

Electroweak Symmetry Breaking $\phi = \begin{pmatrix} 0 \\ \mathrm{h} + \mathrm{v} \end{pmatrix}$

$$\mathcal{L}_Y = \frac{v}{\sqrt{2}} y_\psi \bar{\psi}_L \psi_R + h.c.$$

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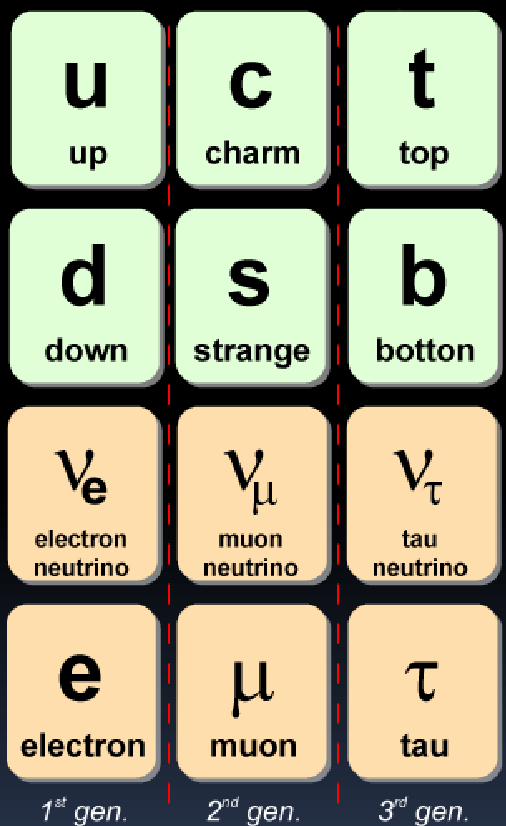

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$$m_\psi = y_\psi \frac{v}{\sqrt{2}}$$

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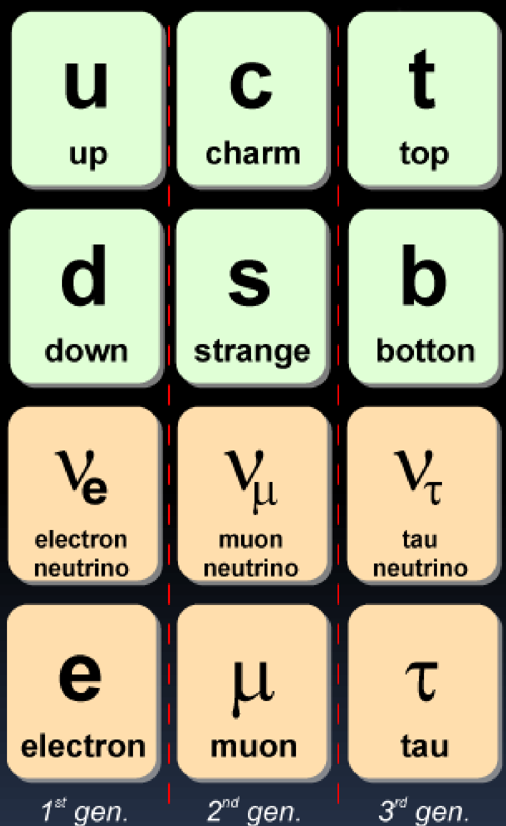

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$$\mathcal{L}_Y = \frac{v}{\sqrt{2}} y_\psi \bar{\psi}_L \psi_R + h.c.$$

$$m_\psi = y_\psi \frac{v}{\sqrt{2}}$$

$$v \approx 246\ \mathrm{GeV}$$

These "Yukawa" couplings are chosen to fit all the fermion masses (plus mixings in the CKM and CP violation)

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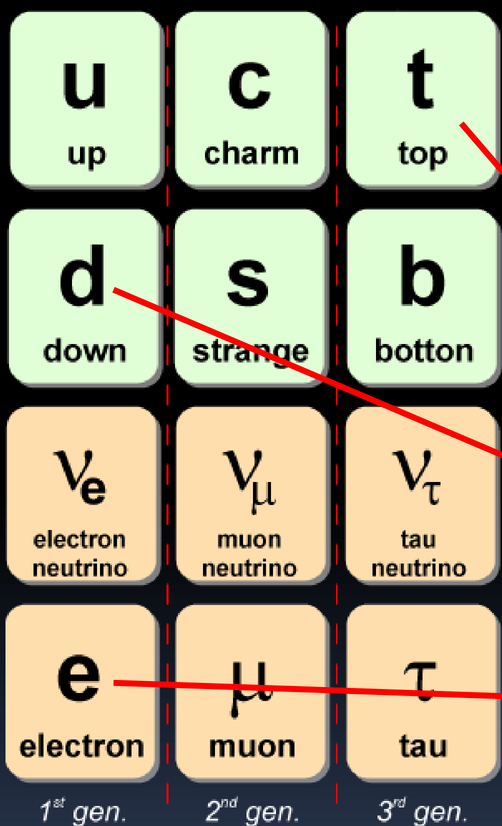

$$m_\psi = y_\psi \frac{v}{\sqrt{2}}$$

$$m_t = 171 GeV \qquad Y_t \sim 1$$

$$m_d = 5 MeV \qquad Y_d \sim 10^{-5}$$

$$m_e = 0.5 MeV \qquad Y_e \sim 10^{-6}$$

Fermion mass hierarchy (which is technically natural)

The Standard Model (SM)
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The physics flavor/family structure (shortcoming)

m_e	Electron mass	511 keV
m_μ	Muon mass	105.7 MeV
m_t	Tau mass	1.78 GeV
m_u	Up quark mass	1.9 MeV
m_d	Down quark mass	4.4 MeV
m_s	Strange quark mass	87 MeV
m_c	Charm quark mass	1.32 GeV
m_b	Bottom quark mass	4.24 GeV
m_t	Top quark mass	173.5 GeV
θ_{12}	CKM 12-mixing angle	$13.1°$
θ_{23}	CKM 23-mixing angle	$2.4°$
θ_{13}	CKM 13-mixing angle	$0.2°$
δ	CKM CP violation Phase	0.995
g'	U(1) gauge coupling	0.357
g	SU(2) gauge coupling	0.652
g_s	SU(3) gauge coupling	1.221
θ_{QCD}	QCD vacuum angle	~ 0
v	Higgs vacuum expectation value	246 GeV
m_H	Higgs mass	125.09 ± 0.24 GeV

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All of these are equivalent to fixing Yukawa couplings, in total we have 13 parameters (12 modules and 1 complex phase)

This is the majority of the 19 parameters of the standard model!

The Standard Model (SM)
its problems and shortcomings

Hierarchy of Scales (Problem?)

$$\mathcal{L} = (D_\mu H)^\dagger (D^\mu H) - V\left(H^\dagger H\right)$$

$$V\left(H^\dagger H\right) = \kappa\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2$$

At “tree level” this will produce scalar resonances with mass:

$$m_h^2 = -\kappa = 2\lambda v^2$$

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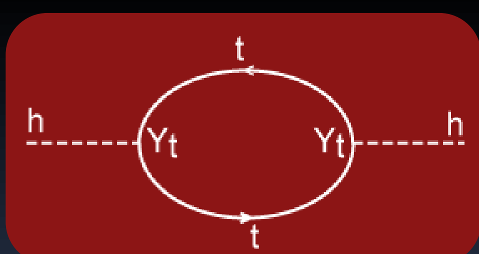
But once I take quantum corrections into consideration, I get extra terms, e.g.:

$$m_h^2 = -\kappa = 2\lambda v^2$$

+



$$\delta m_h^2 \propto \frac{\Lambda^2}{16\pi^2}$$

$$m_h \sim \sqrt{-\kappa + \frac{\Lambda^2}{16\pi^2}}$$

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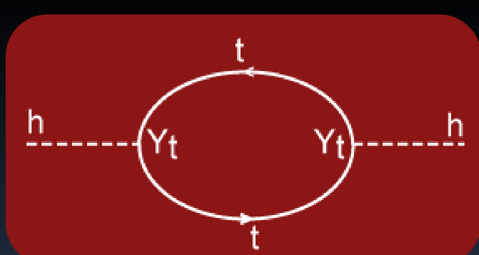

$$\delta m_h^2 \propto \frac{\Lambda^2}{16\pi^2}$$

$$m_h \sim \sqrt{-\kappa + \frac{\Lambda^2}{16\pi^2}}$$

Λ is the theory's cut-off, that means the energy where this model is no longer valid. **This is determined by the UV completion!**

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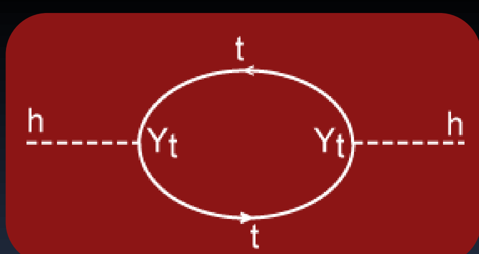
$$V\left(H^\dagger H\right) = \kappa\left(H^\dagger H\right) + \lambda\left(H^\dagger H\right)^2$$

This is a parameter of the low energy theory, **ideally independent of energies away from the regime you are measuring**

But once I take quantum corrections into consideration, I get extra terms, e.g.:

$$m_h^2 = -\kappa = 2\lambda v^2$$

\+



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$$m_h \sim \sqrt{-\kappa + \frac{\Lambda^2}{16\pi^2}}$$

$$\Lambda \sim 10^{18}\ \text{GeV} \quad (M_p)$$

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$$m_h \sim \sqrt{-\kappa + 10^{34}}\ \mathrm{GeV}$$

$$m_h^{exp} \approx 125\ \mathrm{GeV}$$

Fine tuning of $1/10^{30}$

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Fine tuning of $1/10^{30}$

$\Lambda' = \frac{\Lambda^2}{16\pi^2}$

(warning! Numbers below are made up as an example)

Λ' = 6497582134685281997542418963879543

=

κ = 6497582134685281997542418963863918

Attention: I don't need to know any of these parameters but they need to cancel to get ~125^2 GeV^2

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Λ' = 64975821346852819975424189638**79543**

=

κ = 64975821346852819975424189638**63918**

Attention: I don't need to know any of these parameters but they need to cancel to get ~125^2 GeV^2

Q&A

Q: Is this impossible? A: No

Q: Is this unlikely? A: The question makes no sense (to me).

Q: Is it interesting?

Q: Is it worth investigating?

The Standard Model (SM)
its problems and shortcomings

Hierarchy of Scales (Problem?!?!?!?!?)

Q&A

Q: Is it hard to solve? Theoretician A: Not much

$$m_h \sim \sqrt{-\kappa + \frac{\Lambda^2}{16\pi^2}}$$

$$\Lambda \sim 10^3 \text{ GeV}$$

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$$\Lambda \sim 10^3 \text{ GeV}$$

$$m_h \sim \sqrt{-\kappa + 10^4} \text{ GeV}$$

Now k is of order (100 GeV)^2 and the cancelation is between two numbers of the same order, **set by the same physics (because now we are close to the cut-off).**

New physics at O(1000 GeV)!

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New physics at O(1000 GeV)!

Q: All good then? Experimentalist A: Well… no new physics has been found (yet)…

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The Standard Model (SM)
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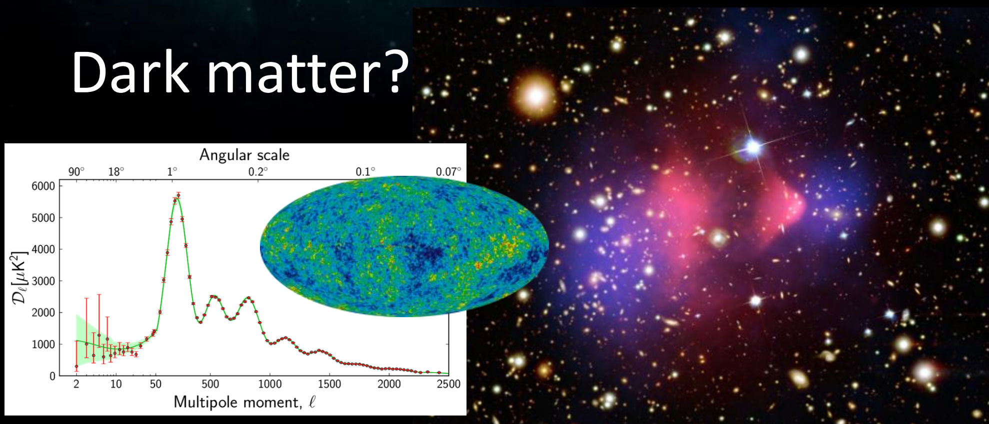
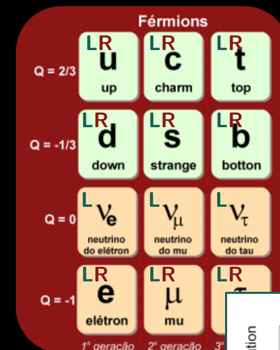
Dark matter?

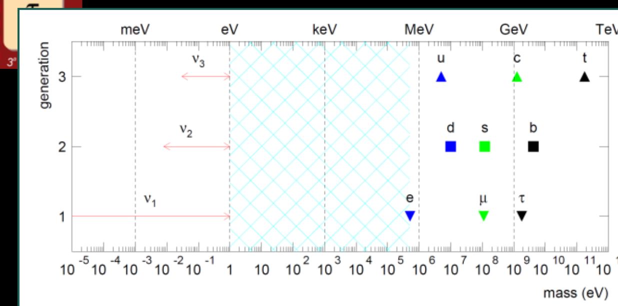




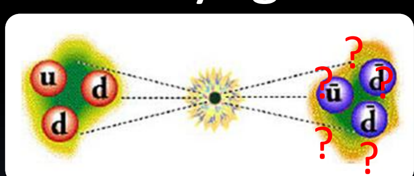
Neutrino Masses?

(are they Dirac → New DoF

are they Majorana → New scale)



Baryogenesis?



- ☐ B-number violation? SM: Good!
- ☐ Out thermal equilibrium? SM: Bad (no first order transition)
- ☐ CP violation? SM: Bad (not enough CP)

Strong CP? Axions?

$$\mathcal{L}_{SCP} \backsim \theta F_{\mu\nu} \tilde{F}^{\mu\nu}$$

not in the SM

Experimentally θ is constrained to be smaller than 10^{-9}, but quantum effects should generate a θ of O(1)

Another fine tuning issue!

New physics is needed to solve most of these problems!

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Beyond SM (BSM)

The solution to most of these shortcomings involve new models:

- UV Complete, detailed models ← Theoreticians used to love these

    (e.g.: SUSY)

- Simplified models ← Most experimental constraints apply here

- Effective models (inspired by some UV completion)

    (e.g.: Composite Higgs Model)

    ← We will talk about the Minimal Composite Higgs Model (MCHM soon)

- Model Independent EFT ← All the rage nowadays (theoreticians and Increasingly experimentalists too)

A common problem

Model parameter space is multidimensional

$$\mathcal{L} = \mathcal{L}_{\rm elem} + \mathcal{L}^{\bf 14}_{\rm comp} + \mathcal{L}^{\bf 14}_{\rm mix} + \mathcal{L}^{\bf 14}_{\rm int}$$

e.g.: MCHM_{14}

$$\mathcal{L}^{\bf 14}_{\rm int} = -i c_4 \overline{\Psi}_4 \not{d} \Psi_1 - i c_9 \overline{\Psi}^{ij}_{\bf 9} \not{d}^i \Psi^j_{\bf 4} - i \frac{c_{T9}}{4\pi f} \overline{\Psi}^{ij}_{\bf 9} d^i_\mu d^{j\,\mu} \tilde{T} + \text{h.c.}$$

$$\begin{aligned}\mathcal{L}^{\bf 14}_{\rm mix} &= f \,\text{Tr}\left[U^\intercal \overline{Q}^{\bf 14}_L U \left(y_{L9}\Psi_{\bf 9} + y_{L4}\Psi_{\bf 4} + y_{L1}\Psi_{\bf 1}\right)\right] + \text{h.c.} \\ &+ f \,\text{Tr}\left[U^\intercal \overline{T}^{\bf 14}_R U \left(y_{R9}\Psi_{\bf 9} + y_{R4}\Psi_{\bf 4} + y_{R1}\Psi_{\bf 1}\right)\right] + \text{h.c.}\end{aligned}$$

A common problem

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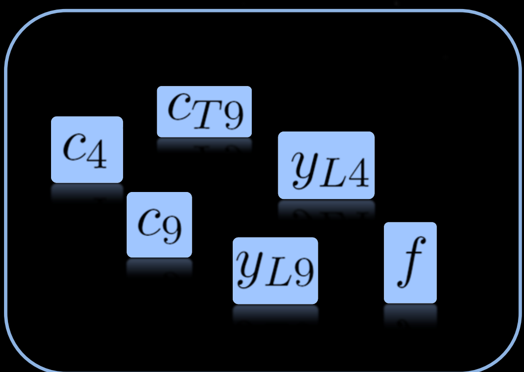

Model parameters

A common problem

Model parameter space is multidimensional…

c_4 c_{T9} y_{L4} c_9 y_{L9} f

Model parameters

Mass Eigenstates

- Masses
- Widths
- Branching Ratios

Physical parameters

… and not trivially connected to observables

A common problem

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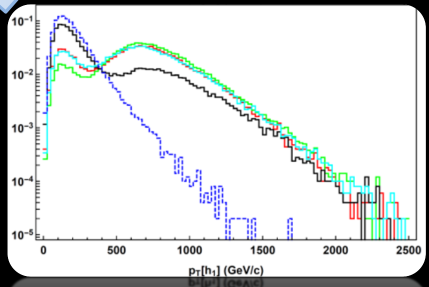

Observables

… and not trivially connected to observables

Common Solutions

Full Model

Parameter Space

$c_4 \in \Re$

$y_{L1} = y_{L4}$

$y_{R1} = y_{R4} = y_{R9}$

Reduce the dimensionality

Convenient Pheno:

- Not many light states
- Narrow
- Long Lived

Restricts region

It is the sound approach!

... but we were not lucky

Common Solutions

Full Model

Parameter Space

$c_4 \in \mathfrak{R}$

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Reduce the dimensionality

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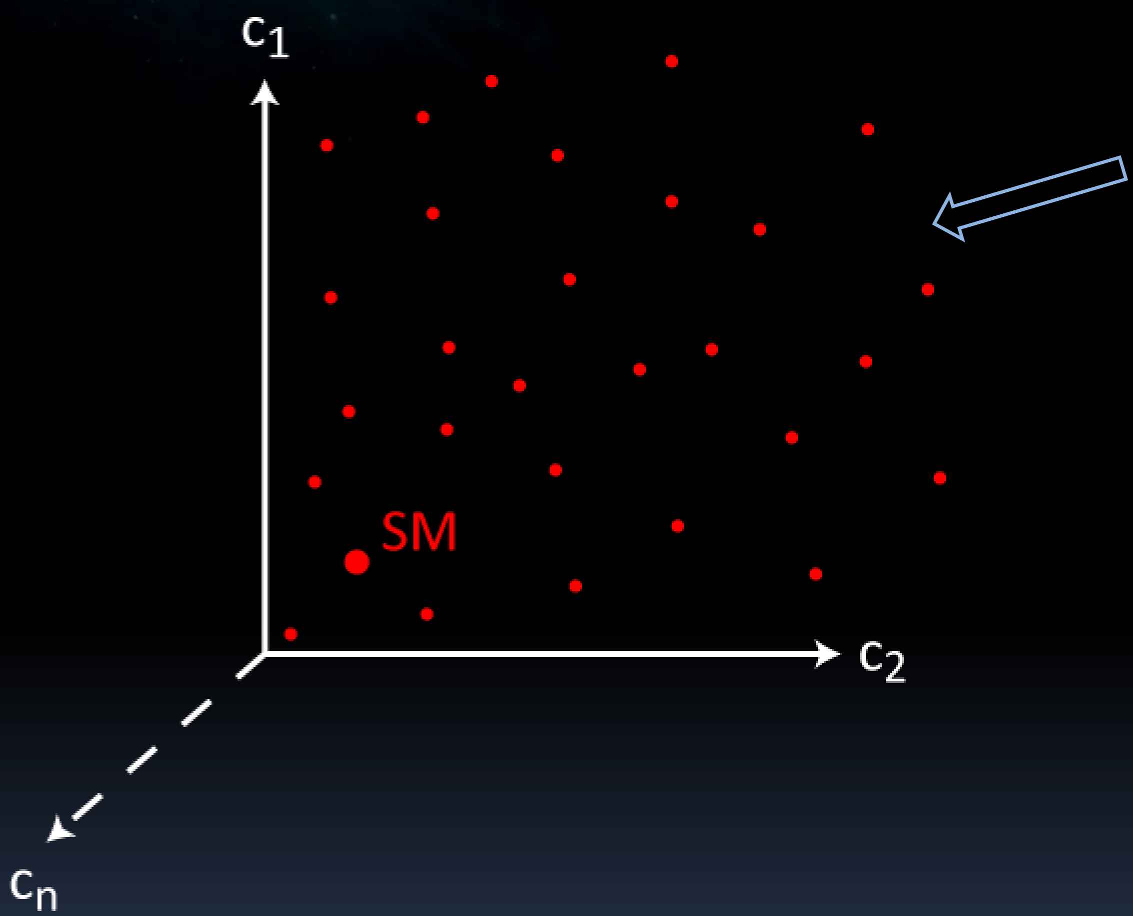
Restricts region

Brave through the multidimensional darkness

Global fits using smart computing

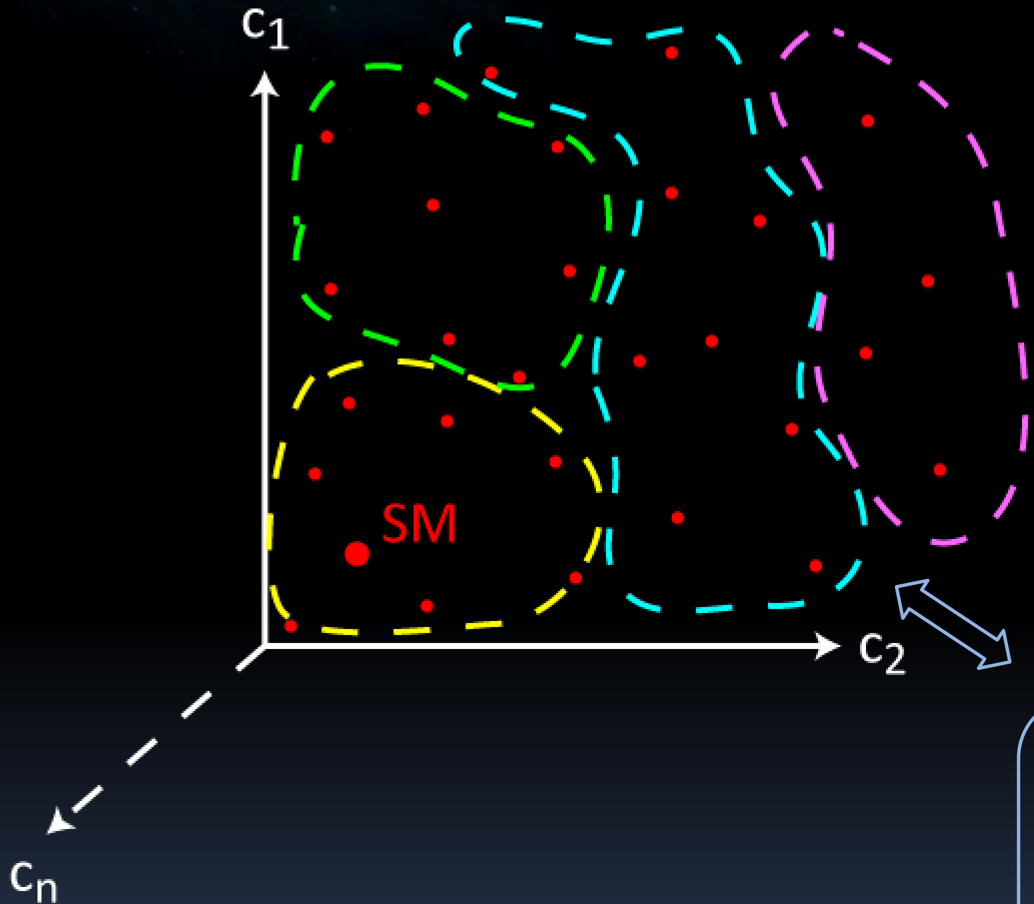
- SMEFT is going this way, with good theoretician-experimentalist cooperation
- BSM models face a bigger sociological challenge

Clustering



We want to group these points into clusters that have similar phenomenology

Clustering



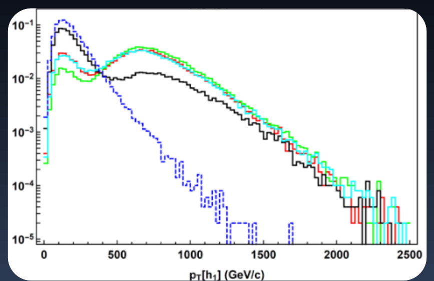
What criteria to use?

Physical parameters

Mass Eigenstates

- Masses
- Widths
- Branching Ratios

Observables



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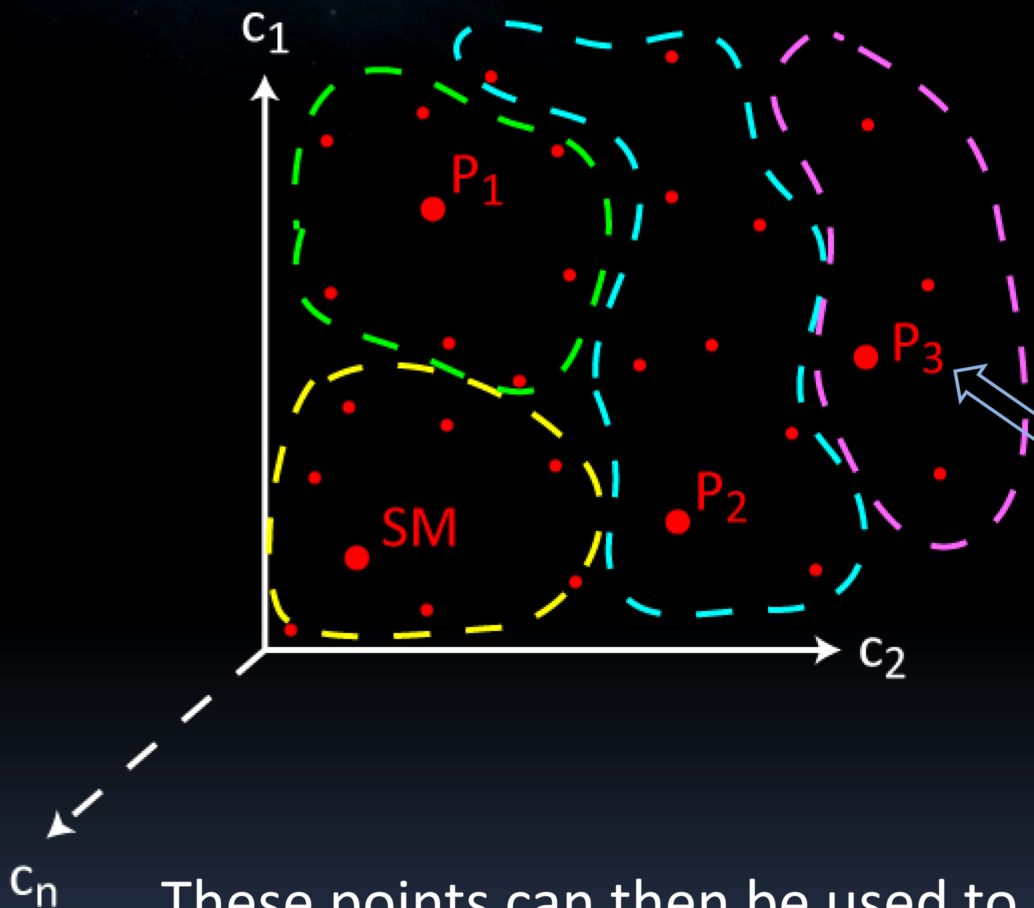
Clustering



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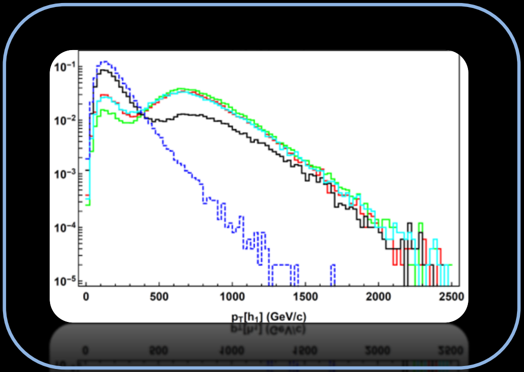


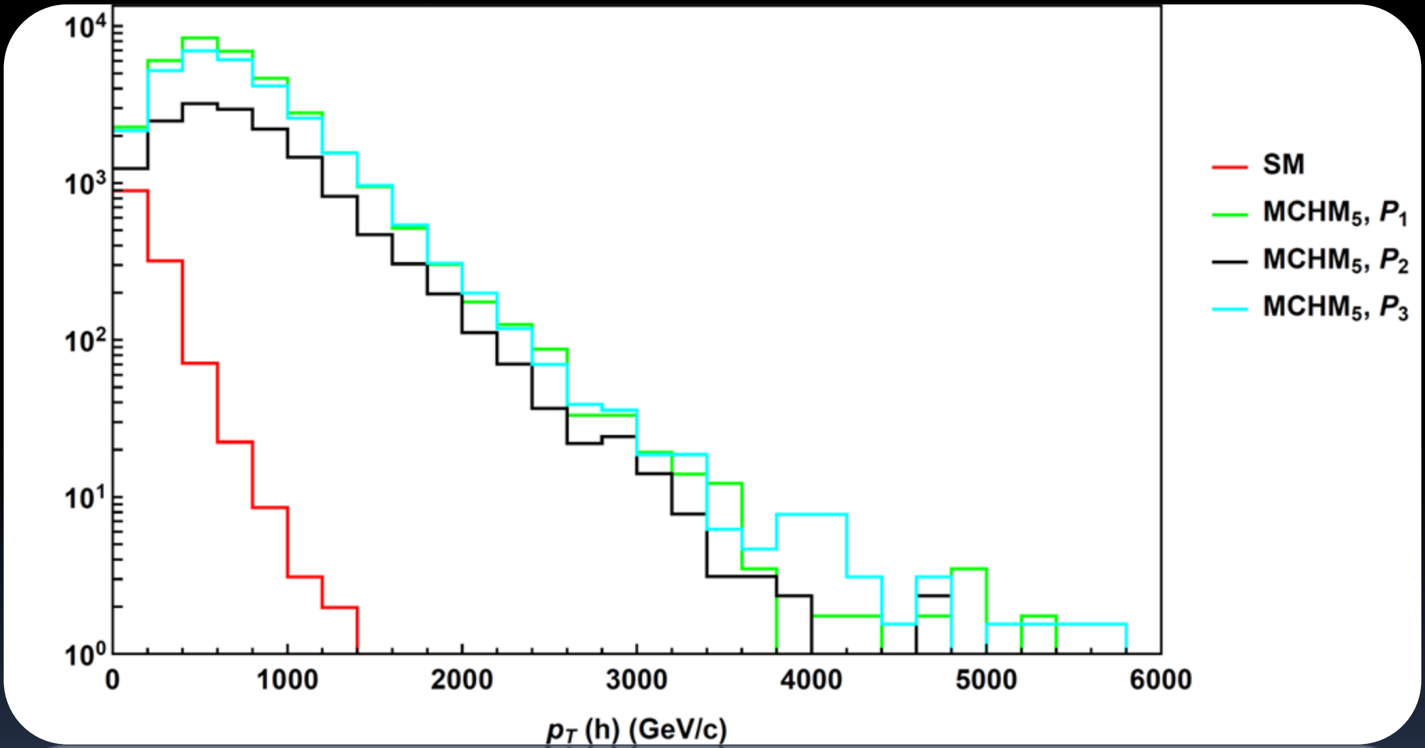
We can also get a representative benchmark point for each cluster

These points can then be used to design search strategies or figure out constraints that apply across the cluster

Clustering Algorithm

As proposed in: A. Carvalho, M. Dall'Osso, T. Dorigo, F. Goertz, C. A. Gottardo and M. Tosi, JHEP 04 (2016) 126, arXiv: 1507.02245

We will do a bin by bin comparison of distributions obtained at different points in parameter space



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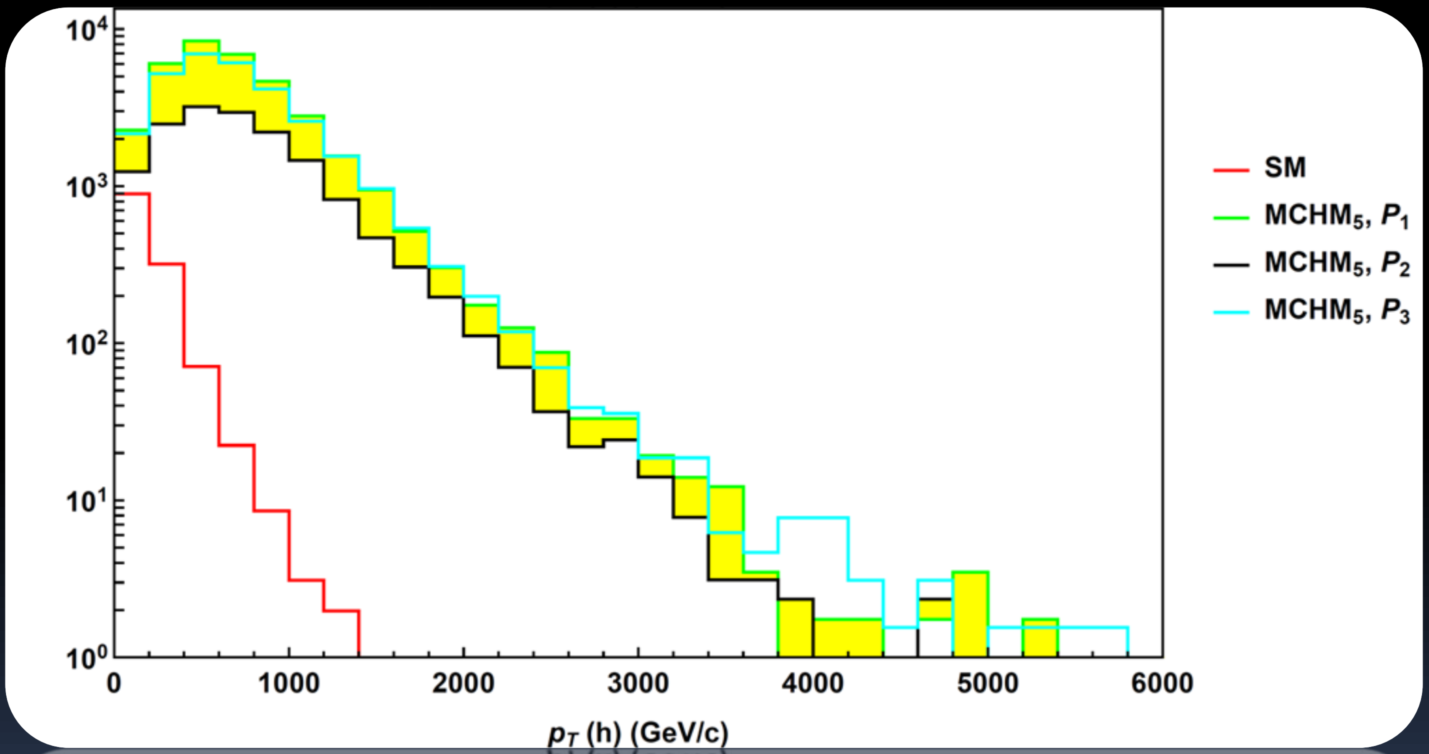

P_1 vs. P_2

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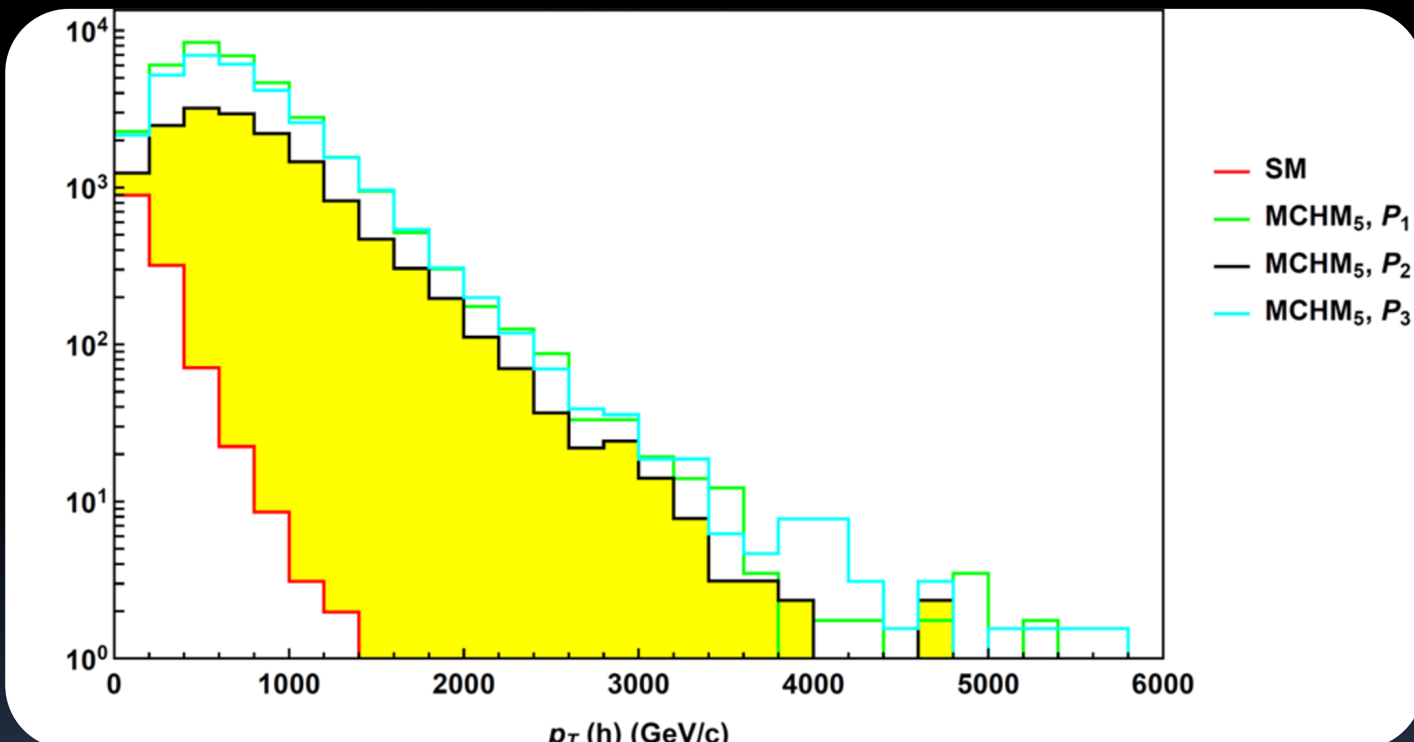
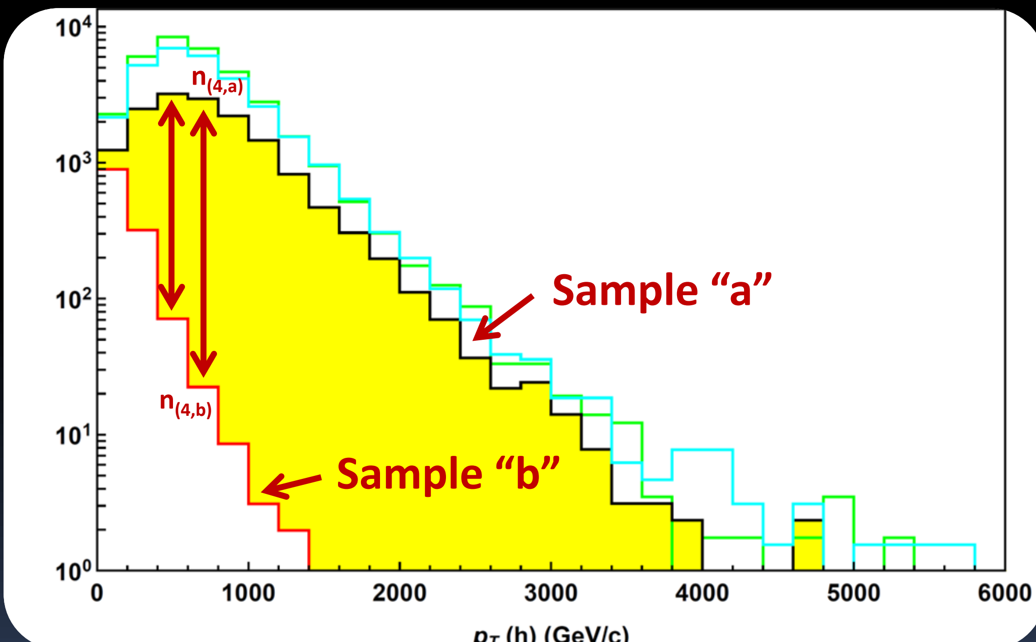


SM vs. P_2

Clustering Algorithm

As proposed in: A. Carvalho, M. Dall'Osso, T. Dorigo, F. Goertz, C. A. Gottardo and M. Tosi, JHEP 04 (2016) 126, arXiv: 1507.02245

$$TS_{ab} = -2\sum_{i=1}^{N_{bins}}\left[log(n_{(i,a)}!) + log(n_{(i,b)}!) - 2log\left(\frac{n_{(i,a)}+n_{(i,b)}}{2}!\right)\right]$$



If $S_a = S_b \rightarrow TS_{ab} = 0$

$TS_{ab} < 0 \leftrightarrow S_a \neq S_b$
(increasingly so)

$TS_{ab} > TS_{cd}$ means
S_a and S_b are more alike
than S_c and S_d

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Clustering Algorithm

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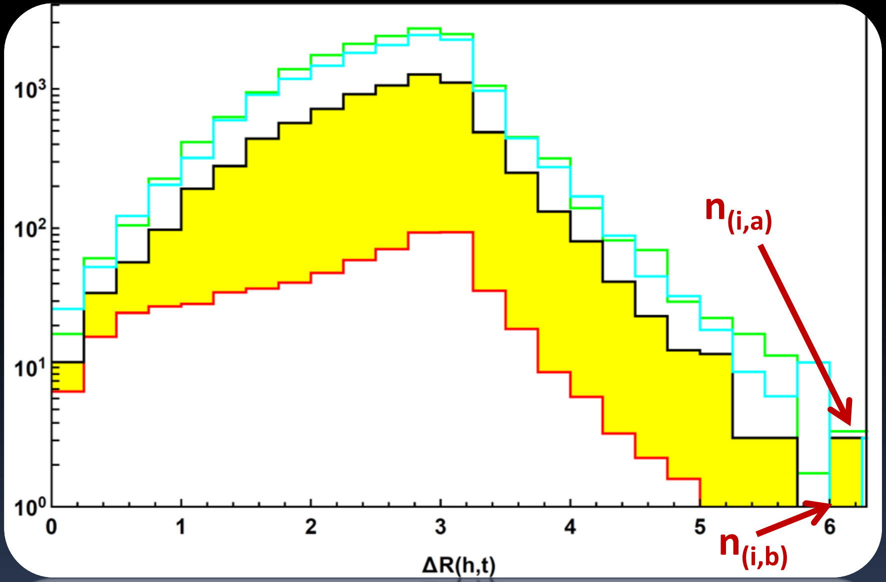
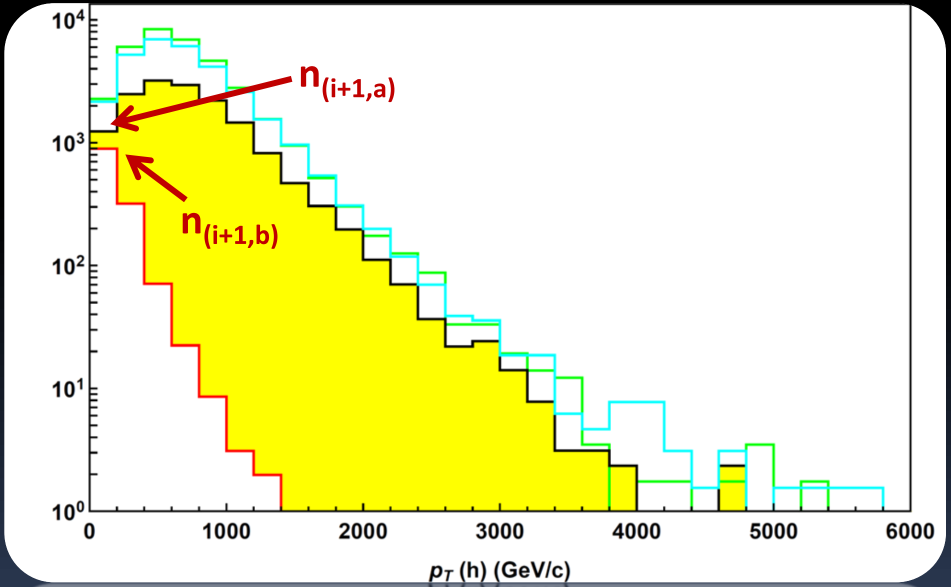
We can also sum over more than one kinematical distribution





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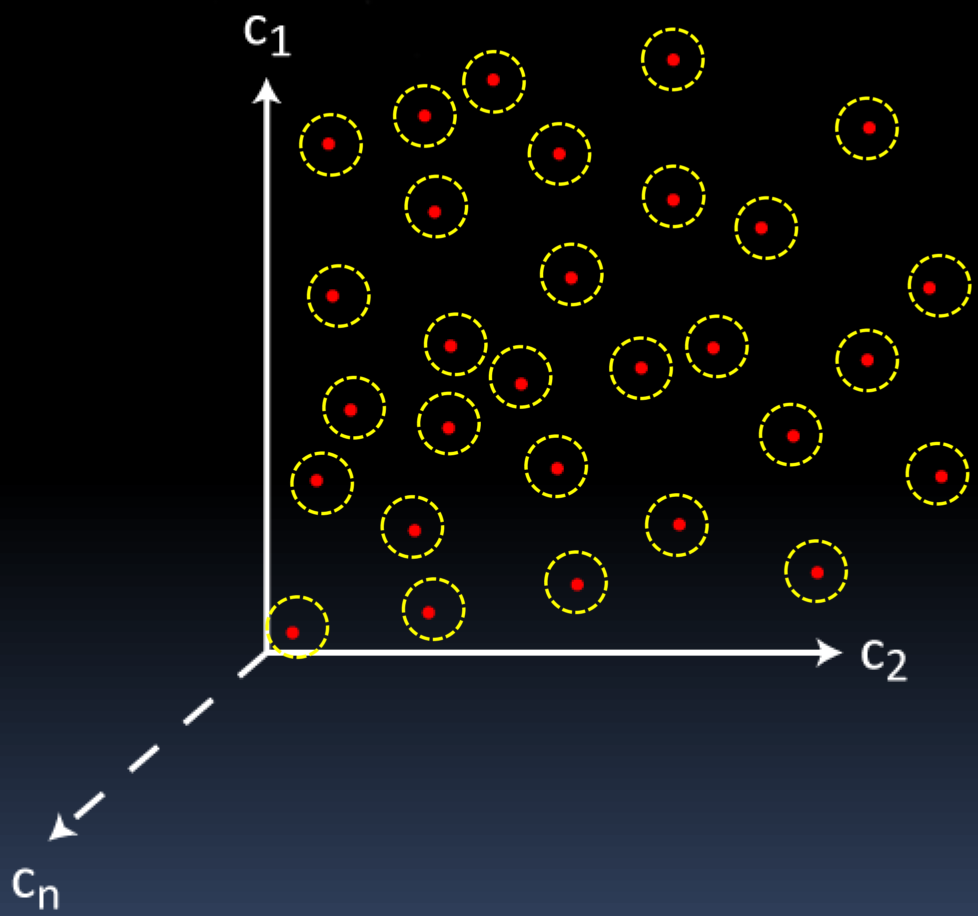
Let the clustering begin!



Step 0

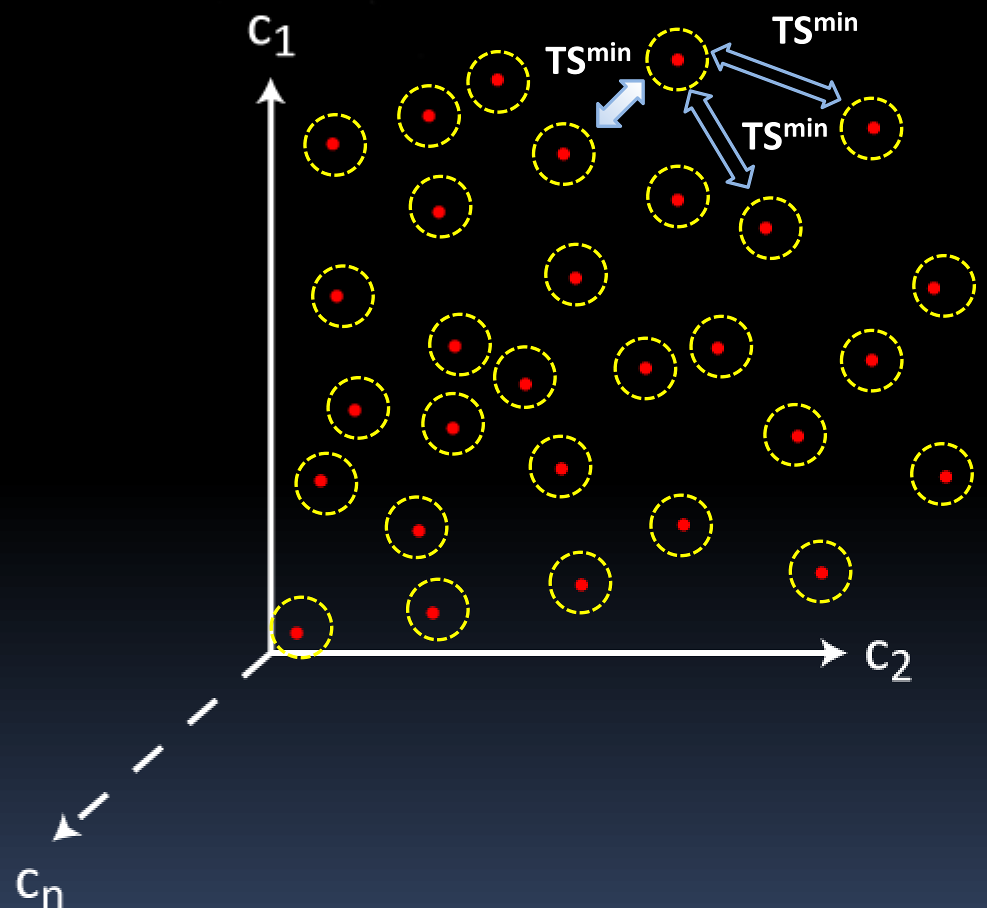
Simulate events for all points and get the kinematical distributions (build samples)

Each point will be its own cluster

Clustering Algorithm

As proposed in: A. Carvalho, M. Dall'Osso, T. Dorigo, F. Goertz, C. A. Gottardo and M. Tosi, JHEP 04 (2016) 126, arXiv: 1507.02245

Let the clustering begin!



Step 1

Compare all pairs of clusters

$$TS^{min} = min_{ab}(\{TS_{ab}\})$$

a and *b* run over all points in their cluster

Clustering Algorithm

As proposed in: A. Carvalho, M. Dall'Osso, T. Dorigo, F. Goertz, C. A. Gottardo and M. Tosi, JHEP 04 (2016) 126, arXiv: 1507.02245

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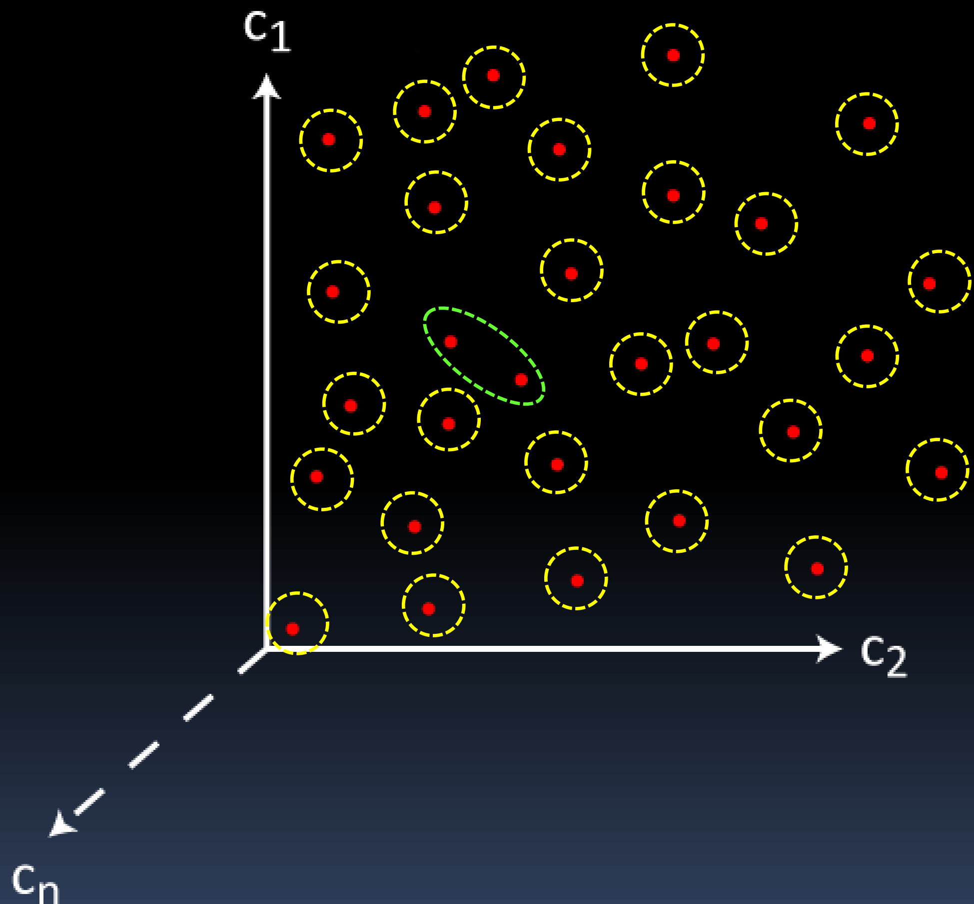


Step 1

Compare all pairs of clusters

$$TS^{min} = min_{ab}(\{TS_{ab}\})$$

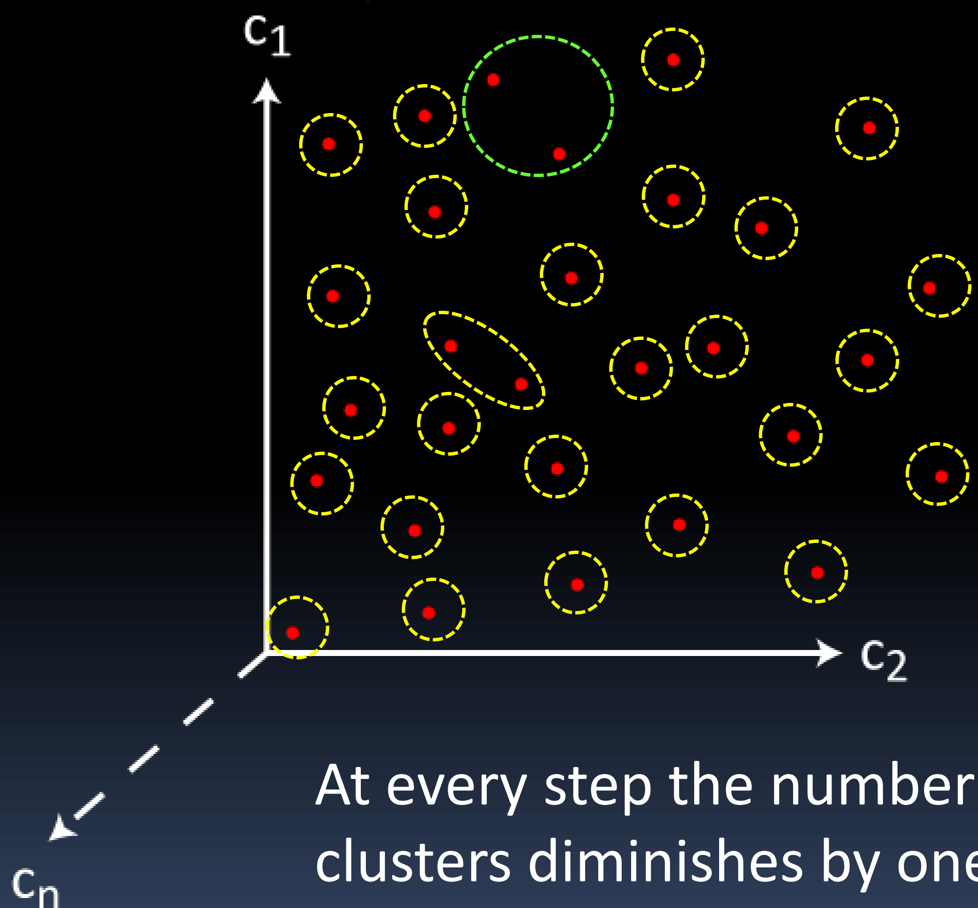
a and *b* run over all points in their cluster

Merge the pair with the highest TS^{min}

Clustering Algorithm

As proposed in: A. Carvalho, M. Dall'Osso, T. Dorigo, F. Goertz, C. A. Gottardo and M. Tosi, JHEP 04 (2016) 126, arXiv: 1507.02245

Let the clustering begin!



Step 3

Compare all pairs of clusters

$$TS^{min} = min_{ab}(\{TS_{ab}\})$$

a and *b* run over all points in their cluster

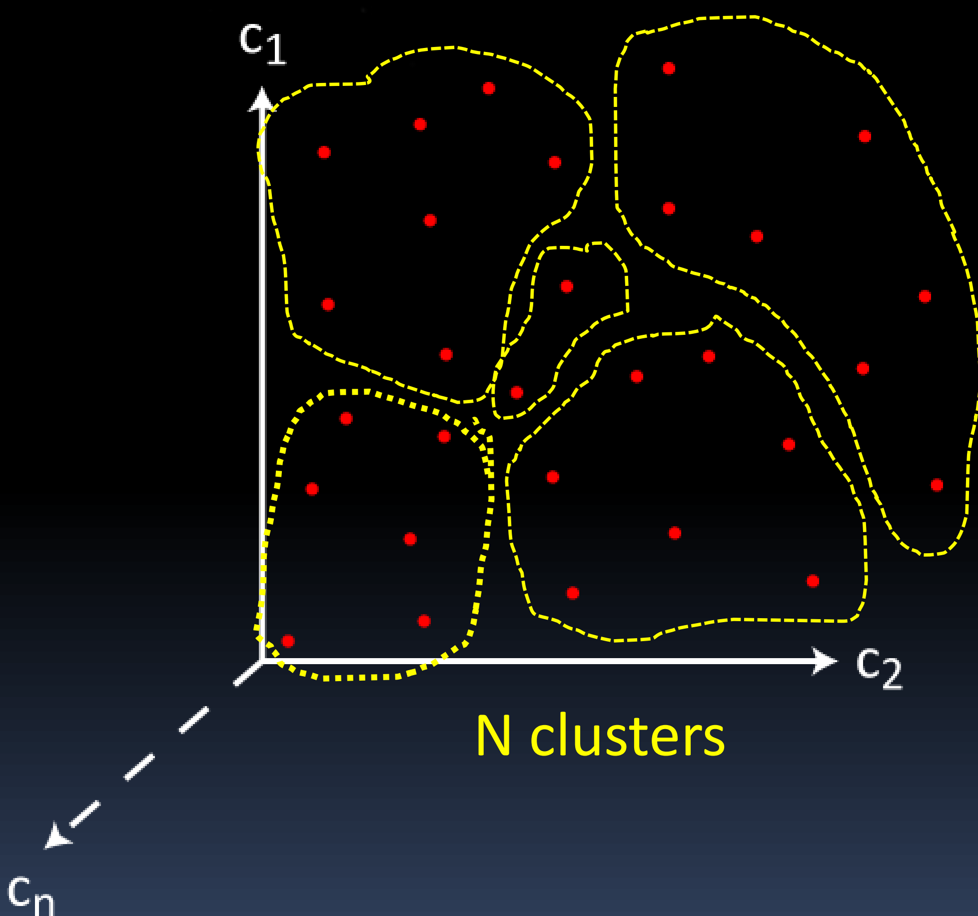
Merge the pair with the highest TS^{min}

At every step the number of clusters diminishes by one

Clustering Algorithm

As proposed in: A. Carvalho, M. Dall'Osso, T. Dorigo, F. Goertz, C. A. Gottardo and M. Tosi, JHEP 04 (2016) 126, arXiv: 1507.02245

Let the clustering begin!



Step n (final)

Criteria: avoid the extremes

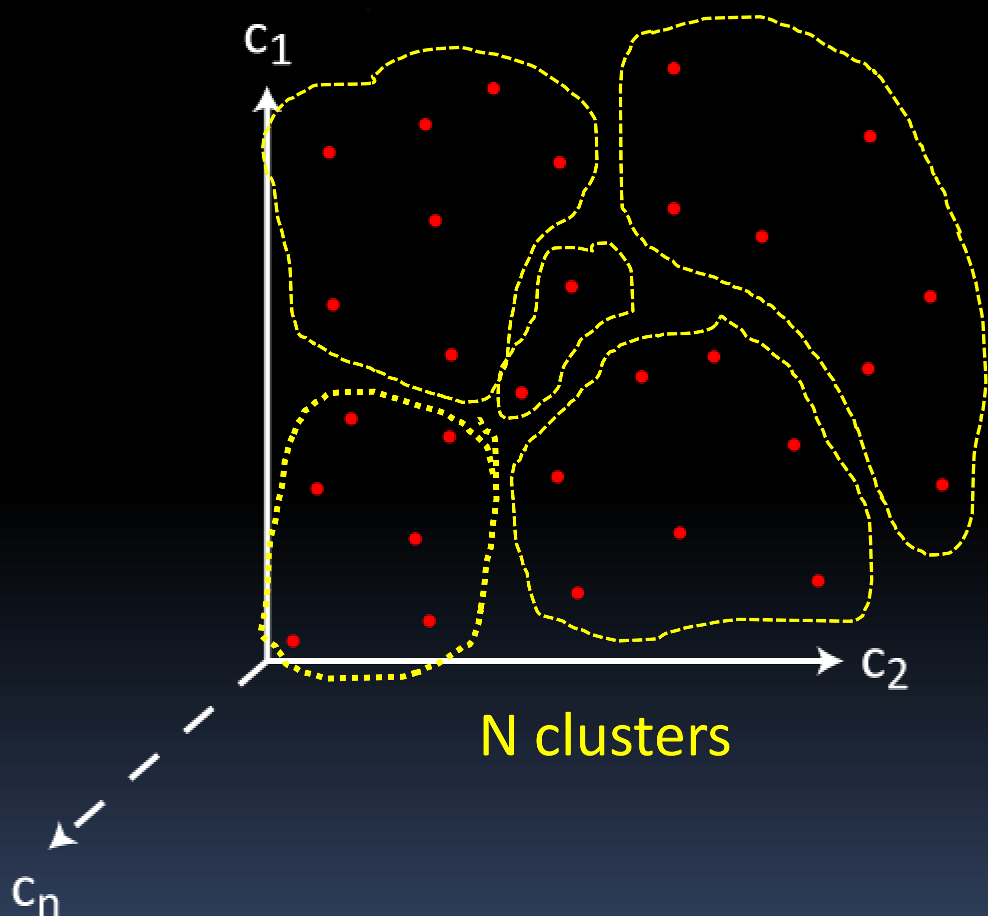
N too big → highly homogeneous clusters, unwieldy number

N too small → highly heterogeneous clusters

Clustering Algorithm

As proposed in: A. Carvalho, M. Dall'Osso, T. Dorigo, F. Goertz, C. A. Gottardo and M. Tosi, JHEP 04 (2016) 126, arXiv: 1507.02245

Let the clustering begin!



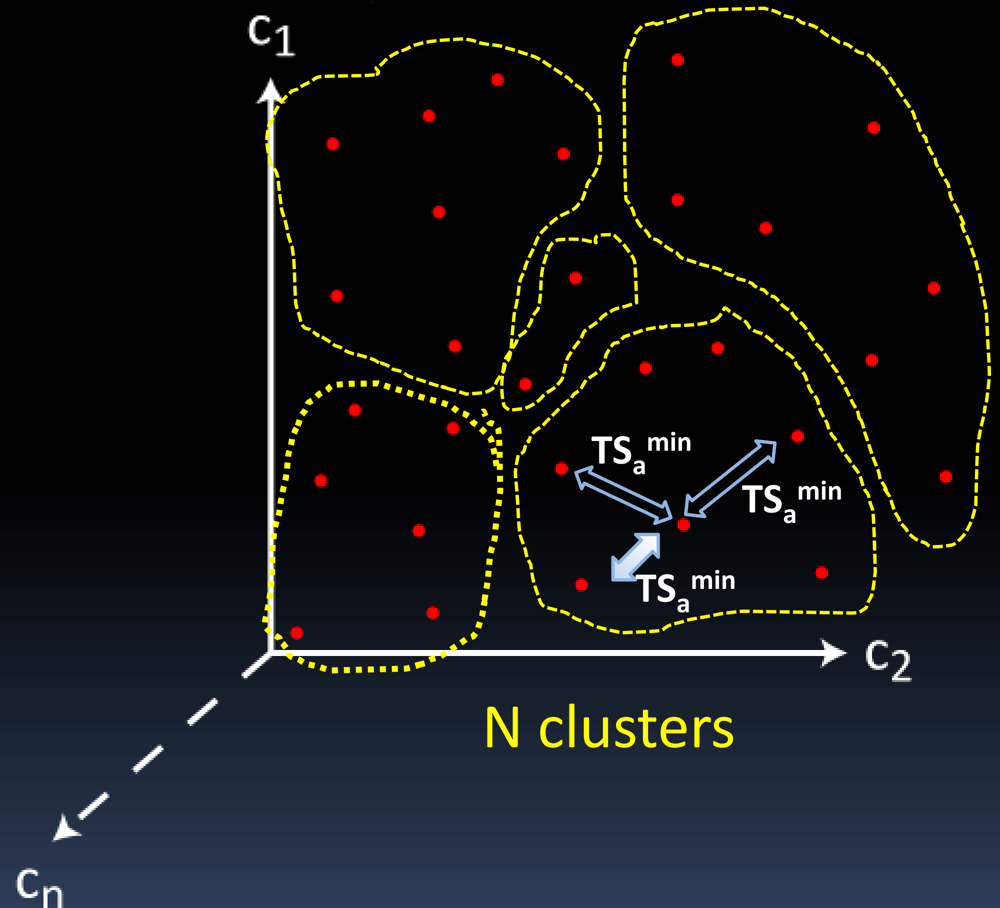
Step n (final)

Criteria: in practice it is a bit subjective, we look for a step were decreasing N will merge two big unlike clusters

Clustering Algorithm

As proposed in: A. Carvalho, M. Dall'Osso, T. Dorigo, F. Goertz, C. A. Gottardo and M. Tosi, JHEP 04 (2016) 126, arXiv: 1507.02245

Benchmarks Points



For each of the clusters we can chose a point *a* maximizing:

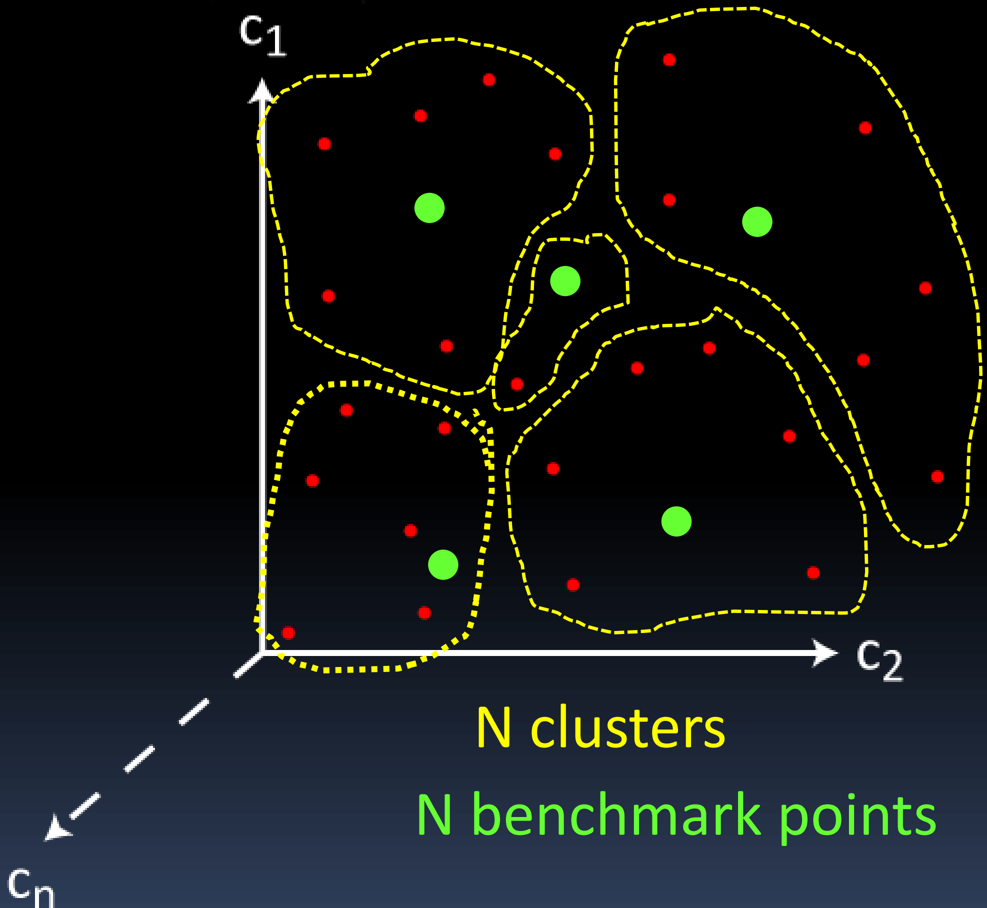
$$TS_a^{min} = min_b(\{TS_{ab}\})$$

where *b* runs over all other points in that cluster

Clustering Algorithm

As proposed in: A. Carvalho, M. Dall'Osso, T. Dorigo, F. Goertz, C. A. Gottardo and M. Tosi, JHEP 04 (2016) 126, arXiv: 1507.02245

Benchmarks Points



N clusters

N benchmark points

For each of the clusters we can chose a point *a* maximizing:

$$TS_a^{min} = min_b(\{TS_{ab}\})$$

where *b* runs over all other points in that cluster

Those are the benchmark points

R.D.Matheus

Application to the Minimal Composite Higgs Model (MCHM)

C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

h
Higgs
boson

pNGB of SO(5) → SO(4)

New fermionic DoFs introduced in some representation of the SO(5)

$MCHM_5$: 5 of SO(5) → 4+1 of SO(4)

$\Psi_4 \leftrightarrow X_{5/3}\quad X_{2/3}\quad T\quad B$

$\Psi_1 \leftrightarrow \tilde{T}$

Application to the Minimal Composite Higgs Model (MCHM)

C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

Mix with SM (3rd gen.): Partial Compositeness

$MCHM_5$: 5 of SO(5) → 4+1 of SO(4)

$\Psi_4 \leftrightarrow X_{5/3} \; X_{2/3} \; T \; B$

$X_{5/3}, X_{2/3}$: 2 of $SU(2)_L$, Y = 7/6

T, B: 2 of $SU(2)_L$, Y = 1/6

Same as q_L !

$\Psi_1 \leftrightarrow \tilde{T}$

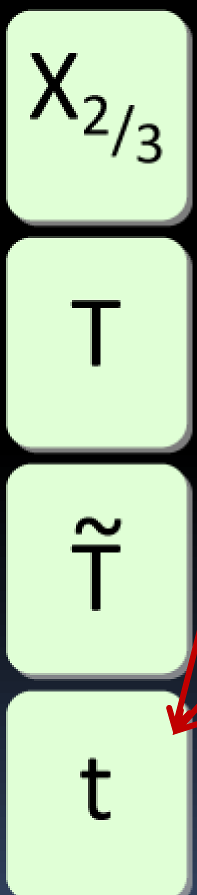
1 of $SU(2)_L$, Y = 2/3

Same as t_R !

Application to the Minimal Composite Higgs Model (MCHM)

C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

Charge 2/3 sector



$$\mathcal{L}^{\mathbf{5}}_{\rm comp} = \overline{\Psi}_{\mathbf{4}} i(\not{D} - i\not{e})\Psi_{\mathbf{4}} - M_4 \overline{\Psi}_{\mathbf{4}}\Psi_{\mathbf{4}} + \overline{\Psi}_{\mathbf{1}} i\not{D}\Psi_{\mathbf{1}} - M_1 \overline{\Psi}_{\mathbf{1}}\Psi_{\mathbf{1}}$$

$$\begin{aligned} \mathcal{L}^{\mathbf{5}}_{\rm mix} &= f\,\overline{Q}^{\mathbf{5}}_L U \left[y_{L4}\Psi_{\mathbf{4}} + y_{L1}\Psi_{\mathbf{1}}\right] + \text{h.c.} \\ &+ f\,\overline{T}^{\mathbf{5}}_R U \left[y_{R4}\Psi_{\mathbf{4}} + y_{R1}\Psi_{\mathbf{1}}\right] + \text{h.c.} \end{aligned}$$

$$\mathcal{M}^{\mathbf{5}}_{2/3} = \begin{bmatrix} 0 & \frac{1}{2}y_{L4}f(1+\sqrt{1-\xi}) & \frac{1}{2}y_{L4}f(1-\sqrt{1-\xi}) & \frac{1}{\sqrt{2}}y_{L1}f\sqrt{\xi} \\ -\frac{1}{\sqrt{2}}y_{R4}f\sqrt{\xi} & -M_4 & 0 & 0 \\ \frac{1}{\sqrt{2}}y_{R4}f\sqrt{\xi} & 0 & -M_4 & 0 \\ y_{R1}f\sqrt{1-\xi} & 0 & 0 & -M_1 \end{bmatrix}$$

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Charge 2/3 sector

$X_{2/3}$, T, $\tilde{T}$, t → $T^{(3)}$, $T^{(2)}$, $T^{(1)}$, t (top)

$$\mathcal{L}^{\mathbf{5}}_{\rm comp} = \overline{\Psi}_{\mathbf{4}} i(\not{D} - i\not{e})\Psi_{\mathbf{4}} - M_4 \overline{\Psi}_{\mathbf{4}}\Psi_{\mathbf{4}} + \overline{\Psi}_{\mathbf{1}} i\not{D}\Psi_{\mathbf{1}} - M_1 \overline{\Psi}_{\mathbf{1}}\Psi_{\mathbf{1}}$$

$$\begin{aligned}\mathcal{L}^{\mathbf{5}}_{\rm mix} &= f\, \overline{Q}^{\mathbf{5}}_L U \left[y_{L4}\Psi_{\mathbf{4}} + y_{L1}\Psi_{\mathbf{1}}\right] + \text{h.c.} \\ &+ f\, \overline{T}^{\mathbf{5}}_R U \left[y_{R4}\Psi_{\mathbf{4}} + y_{R1}\Psi_{\mathbf{1}}\right] + \text{h.c.}\end{aligned}$$

$$\mathcal{M}^{\mathbf{5}}_{2/3} = \begin{bmatrix} 0 & \frac{1}{2} y_{L4} f(1+\sqrt{1-\xi}) & \frac{1}{2} y_{L4} f(1-\sqrt{1-\xi}) & \frac{1}{\sqrt{2}} y_{L1} f\sqrt{\xi} \\ -\frac{1}{\sqrt{2}} y_{R4} f\sqrt{\xi} & -M_4 & 0 & 0 \\ \frac{1}{\sqrt{2}} y_{R4} f\sqrt{\xi} & 0 & -M_4 & 0 \\ y_{R1} f\sqrt{1-\xi} & 0 & 0 & -M_1 \end{bmatrix}$$

Application to the Minimal Composite Higgs Model (MCHM)

C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

$MCHM_5$: $T^{(1)}$ $T^{(2)}$ $T^{(3)}$ B $X_{5/3}$

$$f,\ |M_1|,\ |M_4|,\ \mathrm{sign}(M_1),\ y_L \text{ and } y_R$$

Fixed by the mass of the top

$MCHM_{14}$: 14 of SO(5) → 9+4+1 of SO(4)

7 top partners

$$\mathcal{M}^{\mathbf{14}}_{2/3} = \begin{bmatrix} 0 & \frac{1}{2}y_{L4}fa_+ & -\frac{1}{2}y_{L4}fa_- & -\frac{\sqrt{5}}{4}y_{L1}fs_{2h} & -\frac{1}{2}y_{L9}fb_- & -\frac{1}{2}y_{L9}fs_{2h} & \frac{1}{4}y_{L9}fb_+ \\ \frac{\sqrt{5}}{4}y_{R4}fs_{2h} & -M_4 & 0 & 0 & 0 & 0 & 0 \\ -\frac{\sqrt{5}}{4}y_{R4}fs_{2h} & 0 & -M_4 & 0 & 0 & 0 & 0 \\ y_{R1}f\left(1-\frac{5}{4}s_h^2\right) & 0 & 0 & -M_1 & 0 & 0 & 0 \\ \frac{\sqrt{5}}{4}y_{R9}fs_h^2 & 0 & 0 & 0 & -M_9 & 0 & 0 \\ -\frac{\sqrt{5}}{4}y_{R9}fs_h^2 & 0 & 0 & 0 & 0 & -M_9 & 0 \\ \frac{\sqrt{5}}{4}y_{R9}fs_h^2 & 0 & 0 & 0 & 0 & 0 & -M_9 \end{bmatrix}$$

$$f,\ |M_1|,\ |M_4|,\ |M_9|,\ \mathrm{sign}(M_1),\ \mathrm{sign}(M_4),\ y_L \text{ and } y_R$$

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$MCHM_5$: $T^{(1)}$ $T^{(2)}$ $T^{(3)}$ B $X_{5/3}$

$$f,\ |M_1|,\ |M_4|,\ \text{sign}(M_1),\ y_L \text{ and } y_R$$

Fixed by the mass of the top

“Low” scale (HL-LHC):

$$|M_1| \in [0.8, 3.0] \text{ TeV}, \qquad M_4 \in [1.2, 3.0] \text{ TeV}$$
$$f \in [0.8, 2.0] \text{ TeV}, \qquad y_L \in [0.5, 3.0].$$

Region I: $M_1, M_4 > 0$

Region II: $M_1 < 0,\ M_4 > 0$

“High” scale (FCC and other “future” colliders):

$$|M_1| \in [2, 30] \text{ TeV}, \qquad M_4 \in [2, 30] \text{ TeV},$$
$$f \in [0.8, 8.0] \text{ TeV}, \qquad y_L \in [0.5, 3.0],$$

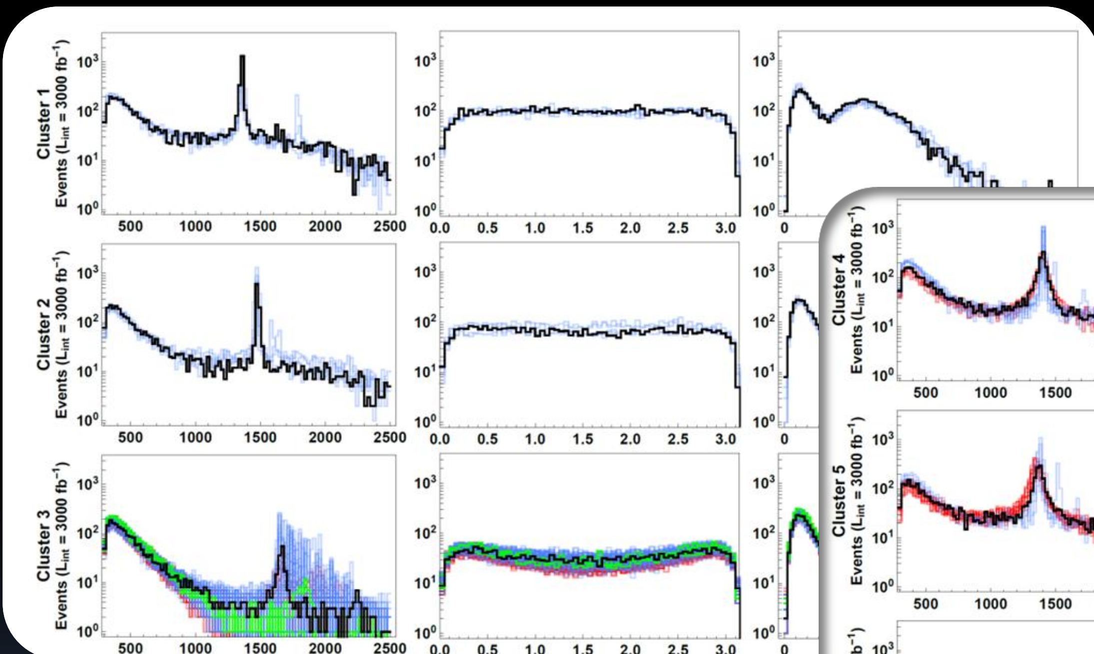
Clustering for the $MCHM_5$ (low scale)

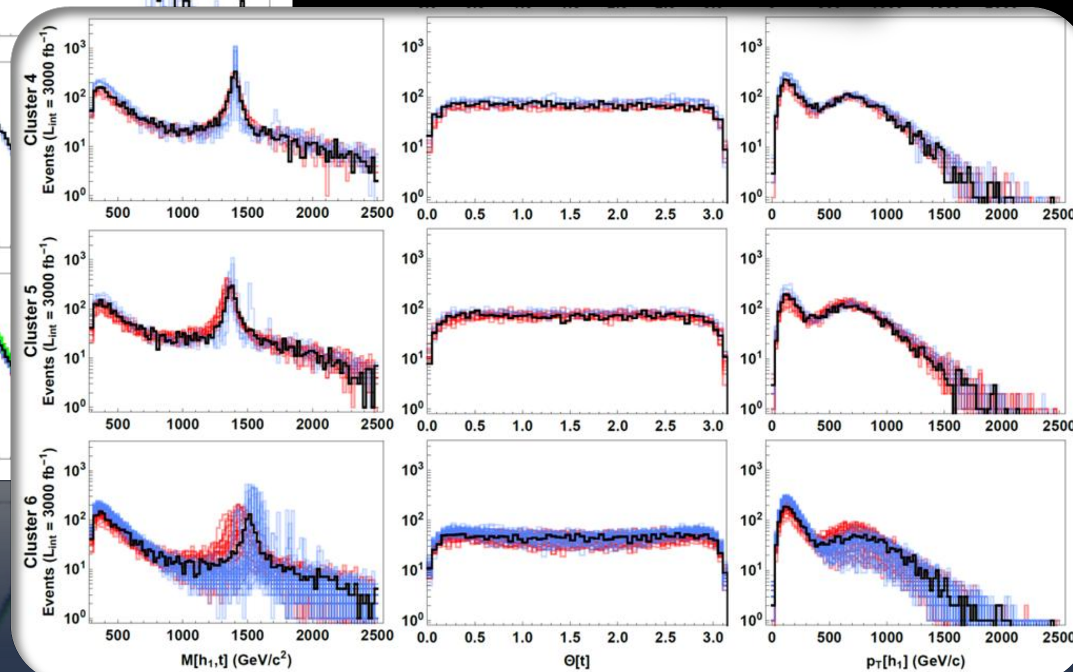
C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

Ideal clustering found for: N = 11; variables: *M[t,h]* & *θ[t]*

Region I: $M_1, M_4 > 0$

Region II: $M_1 < 0, M_4 > 0$





348 parameter space points

pp → t $\bar{t}$ h h

(simulated at MG5 @LO)

R.D.Matheus

Clustering for the $MCHM_5$ (low scale)

C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

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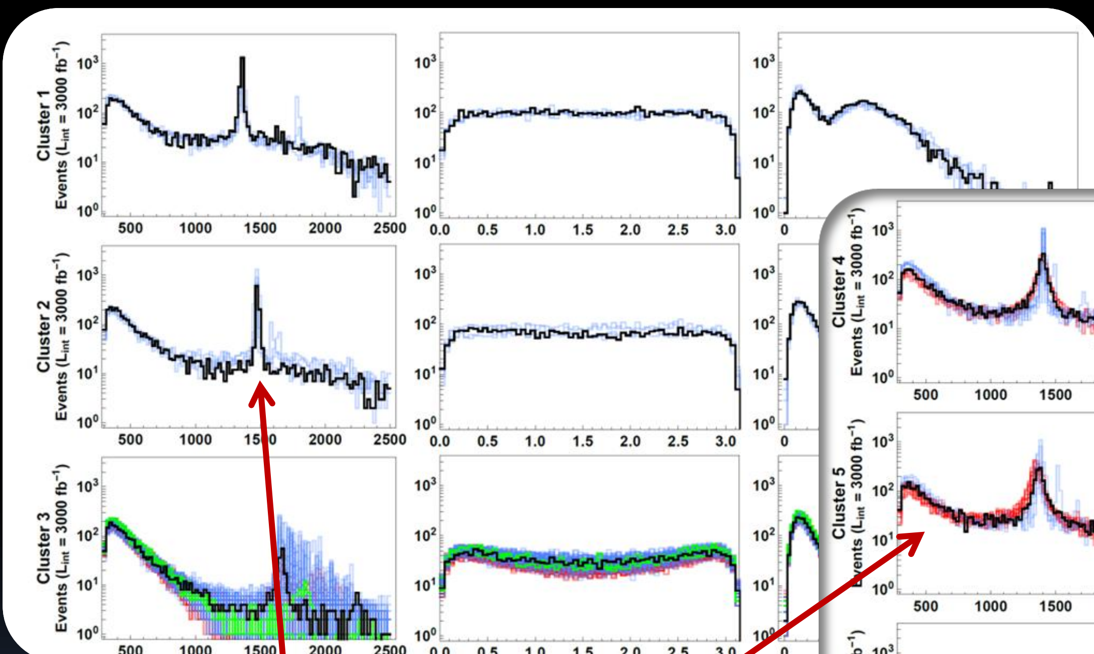

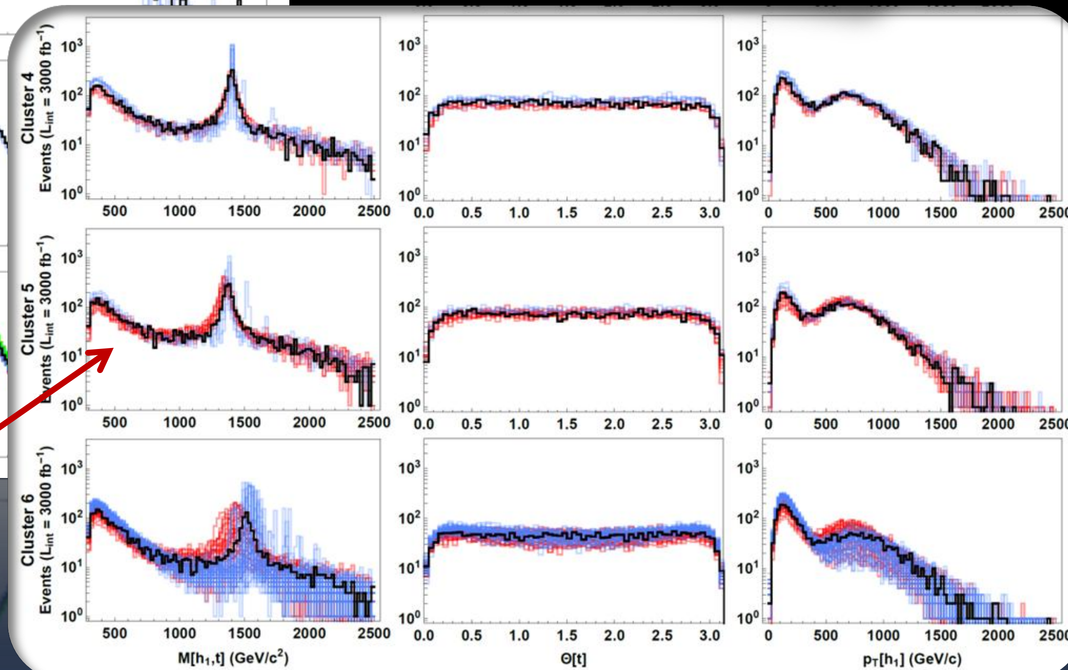

Roughly separates regions I and II

Clustering for the $MCHM_5$ (low scale)

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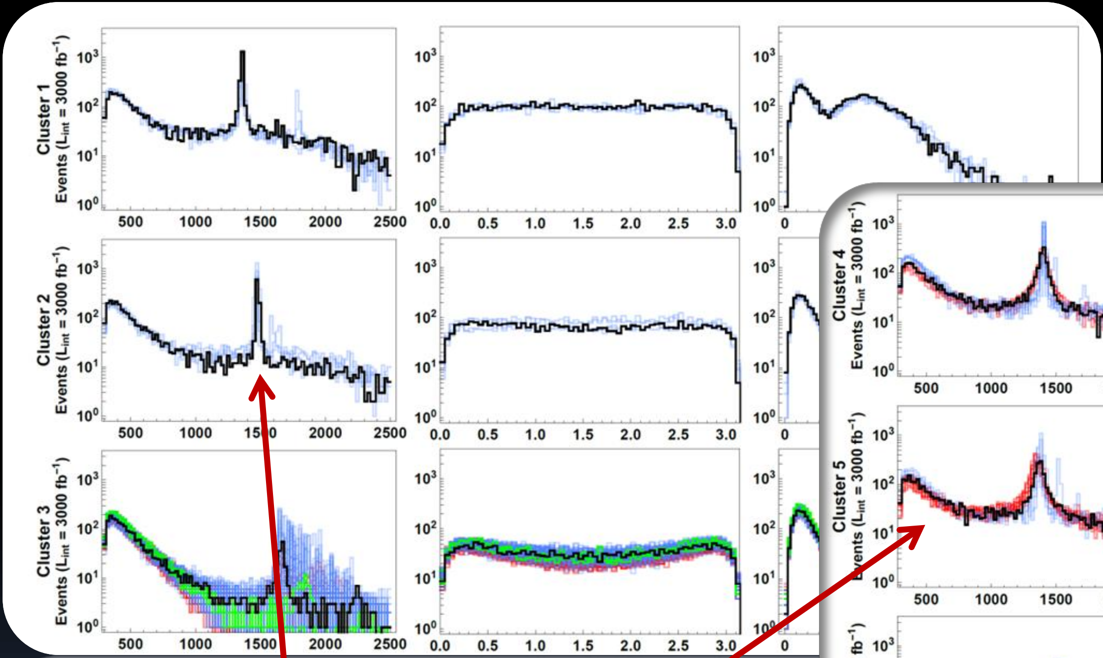
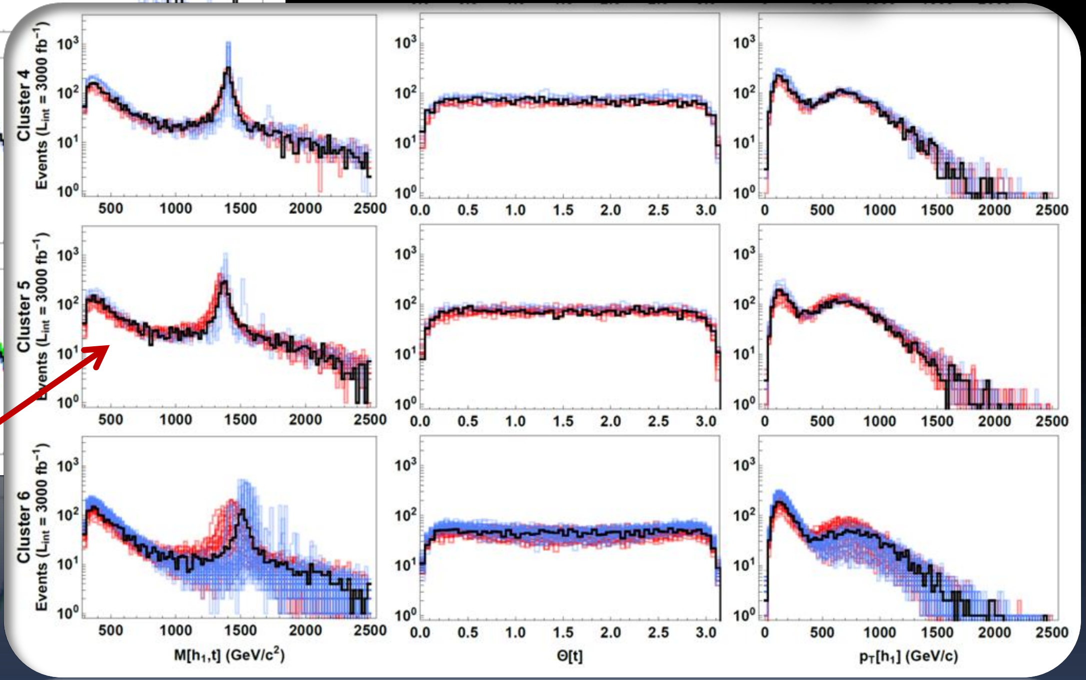




Region I resonances are wider!

R.D.Matheus

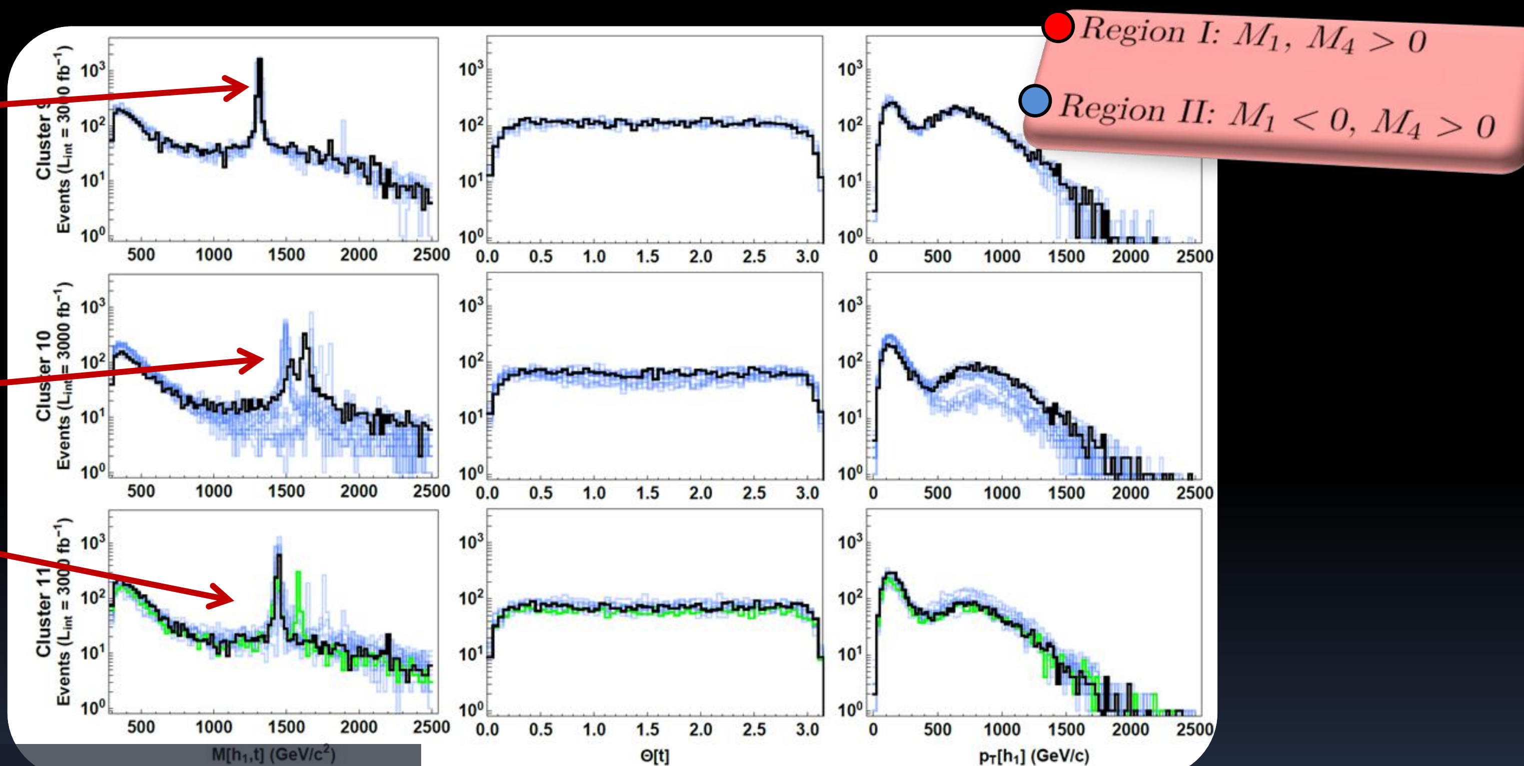
Clustering for the $MCHM_5$ (low scale)

C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

Ideal clustering found for: N = 11; variables: *M[t,h]* & *θ[t]*

Usual simplifying assumption

Multiple peaks



Many points have overlapping top partners!

Clustering for the $MCHM_5$ (low scale)

C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

Benchmark points

Region I: $M_1, M_4 > 0$

Region II: $M_1 < 0, M_4 > 0$

		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
parameters	M_1(GeV)	-1323	-1809	-1483	2965	2882	2999	3000	-1400	-1618	-2384	-2892
	M_4(GeV)	1357	1479	2235	1370	1339	1479	1295	1339	1309	1519	1437
	f(GeV)	1199	1593	1071	1393	1220	1168	1484	1265	1229	1110	1646
	y_L	0.91	2.25	1.38	2.35	1.83	2.33	1.98	1.34	1.22	0.51	1.03
	y_R	0.88	0.58	0.72	3.38	3.57	3.28	3.25	0.66	0.74	2.30	0.85
$\mu(t\bar{t}h)$ (All Energies)		0.90	0.94	0.86	0.83	0.78	0.79	0.84	0.91	0.90	0.81	0.94
$\mu(t\bar{t}hh)$ (14 TeV)		2.14	1.47	0.80	1.51	1.53	1.02	2.00	2.25	2.41	1.39	1.58
$\mu(t\bar{t}hh)$ (100 TeV)		14.58	8.84	3.28	10.28	11.18	7.04	13.42	15.20	16.11	13.68	10.57
NR-$t\bar{t}hh/t\bar{t}hh$ (14 TeV)		0.37	0.59	0.88	0.45	0.40	0.61	0.35	0.36	0.33	0.46	0.55
NR-$t\bar{t}hh/t\bar{t}hh$ (100 TeV)		0.05	0.10	0.22	0.07	0.05	0.09	0.05	0.05	0.05	0.05	0.08
$M_{T^{(1)}}$ (TeV)		1.36	1.48	1.66	1.40	1.38	1.51	1.32	1.34	1.31	1.54	1.44
$M_{T^{(2)}}$ (TeV)		1.63	2.02	2.24	3.55	2.61	3.10	3.22	1.61	1.80	1.63	2.20
$M_{T^{(3)}}$ (TeV)		1.79	3.88	2.68	5.55	5.21	4.85	5.67	2.17	2.02	3.47	3.21
$M_{B^{(1)}}$ (TeV)		1.74	3.87	2.68	3.55	2.60	3.10	3.22	2.16	1.99	1.62	2.22
$M_{X_{5/3}}$ (TeV)		1.36	1.48	2.24	1.37	1.34	1.48	1.29	1.34	1.31	1.52	1.44
$\Gamma_{T^{(1)}}$ (GeV)		8.83	5.49	26.22	51.92	60.01	71.68	44.33	6.44	7.49	43.78	10.63
BR($T^{(1)} \rightarrow$th)		0.49	0.45	0.31	0.44	0.43	0.42	0.44	0.47	0.47	0.34	0.45
BR($T^{(1)} \rightarrow W^+b$)		0.018	0	0.47	0.004	0.004	0.003	0.006	0.024	0.016	0.005	0.010
BR($T^{(1)} \rightarrow$tZ)		0.39	0.41	0.22	0.42	0.43	0.42	0.43	0.40	0.41	0.50	0.41
BR($T^{(1)} \rightarrow W^+W^-t$)		0.11	0.13	0	0.13	0.13	0.16	0.12	0.10	0.10	0.14	0.12

Clustering for the $MCHM_5$ (low scale)

C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

Benchmark points

Region I: $M_1, M_4 > 0$
Region II: $M_1 < 0$, $M_4 > 0$

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
parameters: M_1(GeV)	-1323	-1809	-1483	2965	2882	2999	3000	-1400	-1618	-2384	-2892
M_4(GeV)	1357	1479	2235	1370	1339	1479	1295	1339	1309	1519	1437
f(GeV)	1199	1593	1071	1393	1220	1168	1484	1265	1229	1110	1646
y_L	0.91	2.25	1.38	2.35	1.83	2.33	1.98	1.34	1.22	0.51	1.03
y_R	0.88	0.58	0.72	3.38	3.57	3.28	3.25	0.66	0.74	2.30	0.85
$\mu(t\bar{t}h)$ (All Energies)	0.90	0.94	0.86	0.83	0.78	0.79	0.84	0.91	0.90	0.81	0.94
$\mu(t\bar{t}hh)$ (14 TeV)	2.14	1.47	0.80	1.51	[illegible]	[illegible]	[illegible]	[illegible]	2.41	1.39	1.58
$\mu(t\bar{t}hh)$ (100 TeV)	14.58	8.84	3.28	10.28	11.18	7.04	13.42	15.20	16.11	13.68	10.57
NR-$t\bar{t}hh/t\bar{t}hh$ (14 TeV)	0.37	0.59	0.88	0.45	0.40	0.61	0.35	0.36	0.33	0.46	0.55
NR-$t\bar{t}hh/t\bar{t}hh$ (100 TeV)	0.05	0.10	0.22	0.07	0.05	0.09	0.05	0.05	0.05	0.05	0.08
$M_{T^{(1)}}$ (TeV)	1.36	1.48	1.66	1.40	1.38	1.51	1.32	1.34	1.31	1.54	1.44
$M_{T^{(2)}}$ (TeV)	1.63	2.02	2.24	3.55	2.61	3.10	3.22	1.61	1.80	1.63	2.20
$M_{T^{(3)}}$ (TeV)	1.79	3.88	2.68	5.55	5.21	4.85	5.67	2.17	2.02	3.47	3.21
$M_{B^{(1)}}$ (TeV)	1.74	3.87	2.68	3.55	[illegible]	3.10	3.22	2.16	1.99	1.62	2.22
$M_{X_{5/3}}$ (TeV)	1.36	1.48	2.24	1.37	1.34	1.48	1.29	1.34	1.31	1.52	1.44
$\Gamma_{T^{(1)}}$ (GeV)	8.83	5.49	26.22	51.92	60.01	71.68	44.33	6.44	7.49	43.78	10.63
BR($T^{(1)} \to th$)	0.49	0.45	0.31	0.44	0.43	0.42	0.44	0.47	0.47	0.34	0.45
BR($T^{(1)} \to W^+b$)	0.018	0	0.47	0.004	0.004	0.003	0.006	0.024	0.016	0.005	0.010
BR($T^{(1)} \to tZ$)	0.39	0.41	0.22	0.42	0.43	0.42	0.43	0.40	0.41	0.50	0.41
BR($T^{(1)} \to W^+W^-t$)	0.11	0.13	0	0.13	0.13	0.16	0.12	0.10	0.10	0.14	0.12

Stronger mixing

Wider top partner

Clustering for the $MCHM_5$ (low scale)

C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

Benchmark points

Region I: $M_1, M_4 > 0$

Region II: $M_1 < 0$, $M_4 > 0$

		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
parameters	M_1(GeV)	-1323	-1809	-1483	2965	2882	2999	3000	-1400	-1618	-2384	-2892
	M_4(GeV)	1357	1479	2235	1370	1339	1479	1295	1339	1309	1519	1437
	f(GeV)	1199	1593	1071	1393	1220	1168	1484	1265	1229	1110	1646
	y_L	0.91	2.25	1.38	2.35	1.83	2.33	1.98	1.34	1.22	0.51	1.03
	y_R	0.88	0.58	0.72	3.38	3.57	3.28	3.25	0.66	0.74	2.30	0.85
$\mu(t\bar{t}h)$ (All Energies)		0.90	0.94	0.86	0.83	0.78	0.79	0.84	0.91	0.90	0.81	0.94
$\mu(t\bar{t}hh)$ (14 TeV)		2.14	1.47	0.80	1.51	1.53	1.02	2.00	2.25	2.41	1.39	1.58
$\mu(t\bar{t}hh)$ (100 TeV)		14.58	8.84	3.28	10.28	11.18	7.04	13.42	15.20	16.11	13.68	10.57
NR-$t\bar{t}hh$/$t\bar{t}hh$ (14 TeV)		0.37	0.59	0.88	0.45	0.40	0.61	0.35	0.36	0.33	0.46	0.55
NR-$t\bar{t}hh$/$t\bar{t}hh$ (100 TeV)		[illegible]	0.10	0.22	0.07	0.05	0.09	0.05	0.05	0.05	0.05	0.08
$M_{T^{(1)}}$ (TeV)		1.36	1.48	1.66	1.40	1.38	1.51	1.32	1.34	1.31	1.54	1.44
$M_{T^{(2)}}$ (TeV)		1.63	2.02	2.24	3.55	2.61	3.10	3.22	1.61	1.80	1.63	2.20
$M_{T^{(3)}}$ (TeV)		1.79	3.88	2.68	5.55	5.21	4.85	5.67	2.17	2.02	3.47	3.21
$M_{B^{(1)}}$ (TeV)		1.74	3.87	2.68	3.55	2.60	3.10	3.22	2.16	1.99	1.62	2.22
$M_{X_{5/3}}$ (TeV)		1.36	1.48	2.24	1.37	1.34	1.48	1.29	1.34	1.31	1.52	1.44
$\Gamma_{T^{(1)}}$ (GeV)		8.83	5.49	26.22	51.92	60.01	71.68	44.33	6.44	7.49	43.78	10.63
BR($T^{(1)} \to th$)		0.49	0.45	0.31	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
BR($T^{(1)} \to W^+ b$)		0.018	0	0.47	0.004	0.004	0.003	0.006	0.024	0.016	0.005	0.010
BR($T^{(1)} \to tZ$)		0.39	0.41	0.22	0.42	0.43	0.42	0.43	0.40	0.41	0.50	0.41
BR($T^{(1)} \to W^+ W^- t$)		0.11	0.13	0	0.13	0.13	0.16	0.12	0.10	0.10	0.14	0.12

3-body decays

Only C3 satisfies the usual assumption

Clustering for the $MCHM_5$ (low scale)

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Benchmark points

Region I: $M_1, M_4 > 0$
Region II: $M_1 < 0,\ M_4 > 0$

		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}
parameters	M_1(GeV)	-1323	-1809	-1483	2965	2882	2999	3000	-1400	-1618	-2384	-2892
	M_4(GeV)	1357	1479	2235	1370	1339	1479	1295	1339	1309	1519	1437
	f(GeV)	1199	1593	1071	1393	1220	1168	1484	1265	1229	1110	1646
	y_L	0.91	2.25	1.38	2.35	1.83	2.33	1.98	1.34	1.22	0.51	1.03
	y_R	0.88	0.58	0.72	3.38	3.57	3.28	3.25	0.66	0.74	2.30	0.85
$\mu(t\bar{t}h)$ (All Energies)		0.90	0.94	0.86	0.83	0.78	0.79	0.84	0.91	0.90	0.81	0.94
$\mu(t\bar{t}hh)$ (14 TeV)		2.14	1.47	0.80	1.51	1.53	1.02	2.00	2.25	2.41	1.39	1.58
$\mu(t\bar{t}hh)$ (100 TeV)		14.58	8.84	3.28	10.28	11.18	7.04	13.42	15.20	16.11	13.68	10.57
NR-$t\bar{t}hh/t\bar{t}hh$ (14 TeV)		0.37	0.59	0.88	0.45	0.40	0.61	0.35	0.36	0.33	0.46	0.55
NR-$t\bar{t}hh/t\bar{t}hh$ (100 TeV)		[illegible]	0.10	0.22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$M_{T^{(1)}}$ (TeV)		1.36	1.48	1.66	1.40	1.38	1.51	1.32	1.34	1.31	1.54	1.44
$M_{T^{(2)}}$ (TeV)		1.63	2.02	2.24	3.55	2.61	3.10	3.22	1.61	1.80	1.63	2.20
$M_{T^{(3)}}$ (TeV)		1.79	3.88	2.68	5.55	5.21	4.85	5.67	2.17	2.02	3.47	3.21
$M_{B^{(1)}}$ (TeV)		1.74	3.87	2.68	3.55	2.60	3.10	3.22	2.16	1.99	1.62	2.22
$M_{X_{5/3}}$ (TeV)		1.36	1.48	2.24	1.37	1.34	1.48	1.29	1.34	1.31	1.52	1.44
$\Gamma_{T^{(1)}}$ (GeV)		8.83	5.49	26.22	51.92	60.01	71.68	44.33	6.44	7.49	43.78	10.63
BR($T^{(1)} \to th$)		0.49	0.45	0.31	0.44	0.43	0.42	0.44	0.47	0.47	0.34	0.45
BR($T^{(1)} \to W^+b$)		0.018	0	0.47	0.004	0.004	0.003	0.006	0.024	0.016	0.005	0.010
BR($T^{(1)} \to tZ$)		0.39	0.41	0.22	0.42	0.43	0.42	0.43	0.40	0.41	0.50	0.41
BR($T^{(1)} \to W^+W^-t$)		0.11	0.13	0	0.13	0.13	0.16	0.12	0.10	0.10	0.14	0.12

3-body decays

The b channel is also mostly suppressed

Clustering for the $MCHM_5$ (high scale)

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Benchmark points

Region I: $M_1, M_4 > 0$
Region II: $M_1 < 0, M_4 > 0$

		E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}
parameters	M_1(TeV)	22.7	19.2	11.1	23.0	26.5	3.6	19.3	10.5	-10.7	-27.5
	M_4(TeV)	2.4	2.1	3.2	3.2	4.0	22.5	5.1	5.1	25.6	11.3
	f(GeV)	1913	3273	7144	1190	1300	1711	1288	2812	2432	1412
	y_L	2.45	0.87	2.85	2.43	0.99	2.00	2.35	1.84	2.57	1.73
	y_R	1.10	1.24	2.01	1.54	3.53	1.31	2.35	3.13	1.11	2.96
$\mu(t\bar{t}h)$ (All Energies)		0.95	0.97	0.99	0.88	0.83	0.94	0.88	0.97	0.96	0.90
$\mu(t\bar{t}hh)$ (100 TeV)		1.26	1.91	1.03	0.82	0.81	0.86	0.75	0.91	0.92	0.78
NR-$t\bar{t}hh/t\bar{t}hh$ (100 TeV)		0.71	0.48	0.95	0.90	0.82	1.00	1.00	1.02	1.01	1.01
$M_{T^{(1)}}$ (TeV)		2.45	2.12	3.21	3.23	4.07	4.28	5.08	5.15	11.0	11.3
$M_{T^{(2)}}$ (TeV)		5.27	3.55	18.1	4.32	4.28	22.5	5.90	7.31	25.6	11.6
$M_{T^{(3)}}$ (TeV)		22.8	19.7	20.6	23.1	26.9	22.8	19.5	13.7	26.4	27.8
$M_{B^{(1)}}$ (TeV)		5.28	3.55	20.6	4.33	4.24	22.8	5.90	7.30	26.4	11.6
$M_{X_{5/3}}$ (TeV)		2.44	2.11	3.20	3.22	4.04	22.5	5.06	5.14	25.6	11.3
$\Gamma_{T^{(1)}}$ (TeV)		0.04	0.04	0.08	0.14	0.96	0.28	0.76	0.84	1.22	8.97
$\Gamma_{T^{(1)}}/M_{T^{(1)}}$		1.6%	1.9%	2.5%	4.3%	24%	6.5%	15%	16%	11%	79%
BR($T^{(1)} \to th$)		0.35	0.38	0.29	0.29	0.15	0.26	0.18	0.17	0.25	0.05
BR($T^{(1)} \to W^+b$)		0.003	0.004	0	0.001	0	0.50	0	0	0.50	0
BR($T^{(1)} \to tZ$)		0.34	0.37	0.28	0.28	0.33	0.25	0.18	0.18	0.25	0.06
BR($T^{(1)} \to W^+W^-t$)		0.30	0.25	0.43	0.43	0.52	0	0.64	0.65	0	0.89

Clustering for the $MCHM_5$ (high scale)

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Benchmark points

● Region I: $M_1, M_4 > 0$
● Region II: $M_1 < 0, M_4 > 0$

3-body decays

	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}
parameters: M_1(TeV)	22.7	19.2	11.1	23.0	26.5	3.6	19.3	10.5	-10.7	-27.5
M_4(TeV)	2.4	2.1	3.2	3.2	4.0	22.5	5.1	5.1	25.6	11.3
f(GeV)	1913	3273	7144	1190	1300	1711	1288	2812	2432	1412
[illegible]	2.45	0.87	2.85	2.43	0.99	2.00	2.35	1.84	2.57	1.73
y_R	1.10	1.24	2.01	1.54	3.53	1.31	2.35	3.13	1.11	2.96
$\mu(t\bar{t}h)$ (All Energies)	0.95	0.97	0.99	0.88	0.83	0.94	0.88	0.97	0.96	0.90
$\mu(t\bar{t}hh)$ (100 TeV)	1.26	1.91	1.03	0.82	0.81	0.86	0.75	0.91	0.92	0.78
NR-$t\bar{t}hh/t\bar{t}hh$ (100 TeV)	0.71	0.48	0.95	0.90	0.82	1.00	1.00	1.02	1.01	1.01
$M_{T^{(1)}}$ (TeV)	2.45	2.12	3.21	3.23	4.07	4.28	5.08	5.15	11.0	11.3
$M_{T^{(2)}}$ (TeV)	5.27	3.55	18.1	4.32	4.28	22.5	5.90	7.31	25.6	11.6
$M_{T^{(3)}}$ (TeV)	22.8	19.7	20.6	23.1	26.9	22.8	19.5	13.7	26.4	27.8
$M_{B^{(1)}}$ (TeV)	5.28	3.55	20.6	4.33	4.24	22.8	5.90	7.30	26.4	11.6
$M_{X_{5/3}}$ (TeV)	2.44	2.11	3.20	3.22	4.04	22.5	5.06	5.14	25.6	11.3
$\Gamma_{T^{(1)}}$ (TeV)	0.04	0.04	0.08	0.14	0.96	0.28	0.76	0.84	1.22	8.97
$\Gamma_{T^{(1)}}/M_{T^{(1)}}$	1.6%	1.9%	2.5%	4.3%	24%	6.5%	15%	16%	11%	79%
BR($T^{(1)} \to th$)	0.35	0.38	0.29	0.29	0.15	0.26	0.18	0.17	0.25	0.05
BR($T^{(1)} \to W^+b$)	0.003	0.004	0	0.001	0	0.50	0	0	0.50	0
BR($T^{(1)} \to tZ$)	0.34	0.37	0.28	0.28	0.33	0.25	0.18	0.18	0.25	0.06
BR($T^{(1)} \to W^+W^-t$)	0.30	0.25	0.43	0.43	0.52	0	0.64	0.65	0	0.89

Clustering for the $MCHM_5$ (high scale)

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Benchmark points

Region I: $M_1, M_4 > 0$

Region II: $M_1 < 0, M_4 > 0$

3-body decays

	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}
parameters: M_1(TeV)	22.7	19.2	11.1	23.0	26.5	3.6	19.3	10.5	-10.7	-27.5
M_4(TeV)	2.4	2.1	3.2	3.2	4.0	22.5	5.1	5.1	25.6	11.3
f(GeV)	1913	3273	7144	1190	1300	1711	1288	2812	2432	1412
[illegible]	2.45	0.87	2.85	2.43	0.99	2.00	2.35	1.84	2.57	1.73
y_R	1.10	1.24	2.01	1.54	3.53	1.31	2.35	3.13	1.11	2.96
$\mu(t\bar{t}h)$ (All Energies)	0.95	0.97	0.99	0.88	0.83	0.94	0.88	0.97	0.96	0.90
$\mu(t\bar{t}hh)$ (100 TeV)	1.26	1.91	1.03	0.82	0.81	0.86	0.75	0.91	0.92	0.78
NR-$t\bar{t}hh/t\bar{t}hh$ (100 TeV)	0.71	0.48	0.95	0.90	0.82	1.00	1.00	1.02	1.01	1.01
$M_{T^{(1)}}$ (TeV)	2.45	2.12	3.21	3.23	4.07	4.28	5.08	5.15	11.0	11.3
$M_{T^{(2)}}$ (TeV)	5.27	3.55	18.1	4.32	4.28	22.5	5.90	7.31	25.6	11.6
$M_{T^{(3)}}$ (TeV)	22.8	19.7	20.6	23.1	26.9	22.8	19.5	13.7	26.4	27.8
$M_{B^{(1)}}$ (TeV)	5.28	3.55	20.6	4.33	4.24	22.8	5.90	7.30	26.4	11.6
$M_{X_{5/3}}$ (TeV)	2.44	2.11	3.20	3.22	4.04	22.5	5.06	5.14	25.6	11.3
$\Gamma_{T^{(1)}}$ (TeV)	0.04	0.04	0.08	0.14	0.96	0.28	0.76	0.84	1.22	8.97
$\Gamma_{T^{(1)}}/M_{T^{(1)}}$	1.6%	1.9%	2.5%	4.3%	24%	6.5%	15%	16%	11%	79%
BR($T^{(1)} \to th$)	0.35	0.38	0.29	0.29	0.15	0.26	0.18	0.17	0.25	0.05
BR($T^{(1)} \to W^+b$)	0.003	0.004	0	0.001	0	0.50	0	0	0.50	0
BR($T^{(1)} \to tZ$)	0.34	0.37	0.28	0.28	0.33	0.25	0.18	0.18	0.25	0.06
BR($T^{(1)} \to W^+W^-t$)	0.30	0.25	0.43	0.43	0.52	0	0.64	0.65	0	0.89

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3-body decays

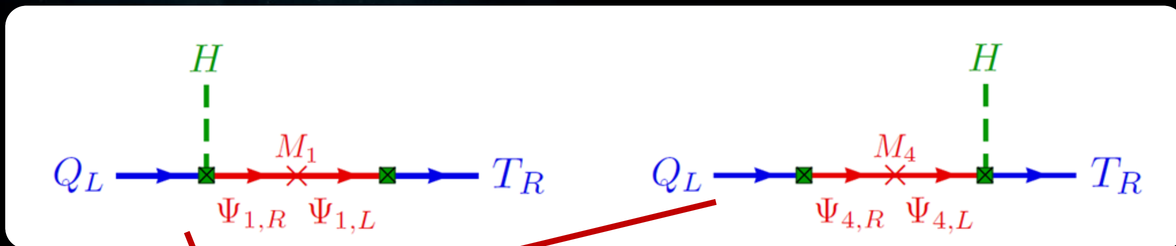
	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}
parameters: M_1(TeV)	22.7	19.2	11.1	23.0	26.5	3.6	19.3	10.5	-10.7	-27.5
M_4(TeV)	2.4	2.1	3.2	3.2	4.0	22.5	5.1	5.1	25.6	11.3
f(GeV)	1913	3273	7144	1190	1300	1711	1288	2812	2432	1412
[illegible]	2.45	0.87	2.85	2.43	0.99	2.00	2.35	1.84	2.57	1.73
y_R	1.10	1.24	2.01	1.54	3.53	1.31	2.35	3.13	1.11	2.96
$\mu(t\bar{t}h)$ (All Energies)	0.95	0.97	0.99	0.88	0.83	0.94	0.88	0.97	0.96	0.90
$\mu(t\bar{t}hh)$ (100 TeV)	1.26	1.91	1.03	0.82	0.81	0.86	0.75	0.91	0.92	0.78
NR-$t\bar{t}hh/t\bar{t}hh$ (100 TeV)	0.71	0.48	0.95	0.90	0.82	1.00	1.00	1.02	1.01	1.01
$M_{T^{(1)}}$ (TeV)	2.45	2.12	3.21	3.23	4.07	4.28	5.08	5.15	11.0	11.3
$M_{T^{(2)}}$ (TeV)	5.27	3.55	18.1	4.32	4.28	22.5	5.90	7.31	25.6	11.6
$M_{T^{(3)}}$ (TeV)	22.8	19.7	20.6	23.1	26.9	22.8	19.5	13.7	26.4	27.8
$M_{B^{(1)}}$ (TeV)	5.28	3.55	20.6	4.33	4.24	22.8	5.90	7.30	26.4	11.6
$M_{X_{5/3}}$ (TeV)	2.44	2.11	3.20	3.22	4.04	22.5	5.06	5.14	25.6	11.3
$\Gamma_{T^{(1)}}$ (TeV)	0.04	0.04	0.08	0.14	0.96	0.28	0.76	0.84	1.22	8.97
$\Gamma_{T^{(1)}}/M_{T^{(1)}}$	1.6%	1.9%	2.5%	4.3%	24%	6.5%	15%	16%	11%	79%
BR($T^{(1)} \to th$)	0.35	0.38	0.29	0.29	0.15	0.26	0.18	0.17	0.25	0.05
BR($T^{(1)} \to W^+b$)	0.003	0.004	0	0.001	0	0.50	0	0	0.50	0
BR($T^{(1)} \to tZ$)	0.34	0.37	0.28	0.28	0.33	0.25	0.18	0.18	0.25	0.06
BR($T^{(1)} \to W^+W^-t$)	0.30	0.25	0.43	0.43	0.52	0	0.64	0.65	0	0.89

Conclusions

- We have to look far from the street lamp now
- "Smart" algorithms can help to understand complete models
- Regarding top parners:
  - Three body decays are important
  - A simplified hierarchical spectrum is only realized in small regions of the MCHM

Extras

Wider resonances in Region I



Must interfere negatively as mass must vanish in the SO(5) restoration limit *($M_1 - M_4$)*

$$m_t \sim y_L y_R |M_4 - M_1|$$

In region I, both parameters are positive, and this can be small

To compensate, and obtain the correct m_t, the couplings must be larger, leading to wider resonances

Higgs Sector

$$U = \begin{pmatrix} \mathbb{1}_{3\times 3} & \vec{0} & \vec{0} \\ \vec{0}^T & \cos\frac{h_0+h}{f} & \sin\frac{h_0+h}{f} \\ \vec{0}^T & -\sin\frac{h_0+h}{f} & \cos\frac{h_0+h}{f}, \end{pmatrix}$$

$$f \sin\frac{h_0}{f} \equiv v = 246\ \text{GeV}$$

$$\xi = \frac{v^2}{f^2} = \sin^2\frac{h_0}{f}$$

MCHM$_5$

$$\mathcal{L} = \mathcal{L}_{\text{elem}} + \mathcal{L}^{\mathbf{5}}_{\text{comp}} + \mathcal{L}^{\mathbf{5}}_{\text{mix}} + \mathcal{L}^{\mathbf{5}}_{\text{int}}$$

$$\mathcal{L}_{\text{elem}} = \overline{q}_L i \not{D} q_L + \overline{t}_R i \not{D} t_R$$

$$\Psi_1 \sim \tilde{T}$$

$$\Psi_4 \sim (X_{5/3}, X_{2/3}, T, B)$$

$$\mathcal{L}^{\mathbf{5}}_{\text{comp}} = \overline{\Psi}_{\mathbf{4}} i(\not{D} - i\not{e})\Psi_{\mathbf{4}} - M_4 \overline{\Psi}_{\mathbf{4}}\Psi_{\mathbf{4}} + \overline{\Psi}_{\mathbf{1}} i\not{D}\Psi_{\mathbf{1}} - M_1 \overline{\Psi}_{\mathbf{1}}\Psi_{\mathbf{1}}$$

$$\begin{aligned}\mathcal{L}^{\mathbf{5}}_{\text{mix}} &= f\, \overline{Q}^{\mathbf{5}}_L U \left[y_{L4}\Psi_{\mathbf{4}} + y_{L1}\Psi_{\mathbf{1}}\right] + \text{h.c.} \\ &+ f\, \overline{T}^{\mathbf{5}}_R U \left[y_{R4}\Psi_{\mathbf{4}} + y_{R1}\Psi_{\mathbf{1}}\right] + \text{h.c}\end{aligned}$$

$$\mathcal{L}^{\mathbf{5}}_{\text{int}} = -i\, c_L\, \overline{\Psi}_{\mathbf{4}} P_L \not{d}\, \Psi_{\mathbf{1}} - i\, c_R\, \overline{\Psi}_{\mathbf{4}} P_R \not{d}\, \Psi_{\mathbf{1}} + \text{h.c.}$$

MCHM_{14}

$$\mathcal{L} = \mathcal{L}_{\text{elem}} + \mathcal{L}^{\mathbf{14}}_{\text{comp}} + \mathcal{L}^{\mathbf{14}}_{\text{mix}} + \mathcal{L}^{\mathbf{14}}_{\text{int}}$$

$$\Psi_{\mathbf{9}} \sim (U_{8/3}, U_{5/3}, U_{2/3}, V_{5/3}, V_{2/3}, V_{-1/3}, F_{2/3}, F_{-1/3}, F_{-4/3})$$

$$\mathcal{L}^{\mathbf{14}}_{\text{comp}} = \mathcal{L}^{\mathbf{5}}_{\text{comp}} + \mathrm{Tr}\left[\overline{\Psi}_{\mathbf{9}}\left(i\not{D}\Psi_{\mathbf{9}} - i\left[\not{e}, \Psi_{\mathbf{9}}\right]\right)\right] - M_9 \mathrm{Tr}\left[\overline{\Psi}_{\mathbf{9}}\Psi_{\mathbf{9}}\right]$$

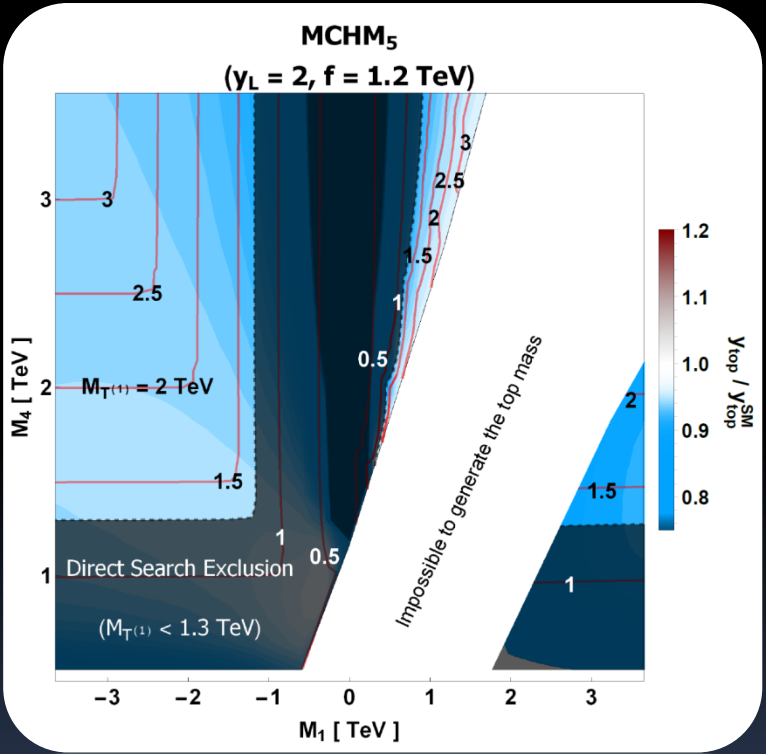
$$\begin{aligned} \mathcal{L}^{\mathbf{14}}_{\text{mix}} = & \ f\,\mathrm{Tr}\left[U^{\intercal}\overline{Q}^{\mathbf{14}}_{L}U\left(y_{L9}\Psi_{\mathbf{9}} + y_{L4}\Psi_{\mathbf{4}} + y_{L1}\Psi_{\mathbf{1}}\right)\right] + \text{h.c.} \\ & + f\,\mathrm{Tr}\left[U^{\intercal}\overline{T}^{\mathbf{14}}_{R}U\left(y_{R9}\Psi_{\mathbf{9}} + y_{R4}\Psi_{\mathbf{4}} + y_{R1}\Psi_{\mathbf{1}}\right)\right] + \text{h.c.} \end{aligned}$$

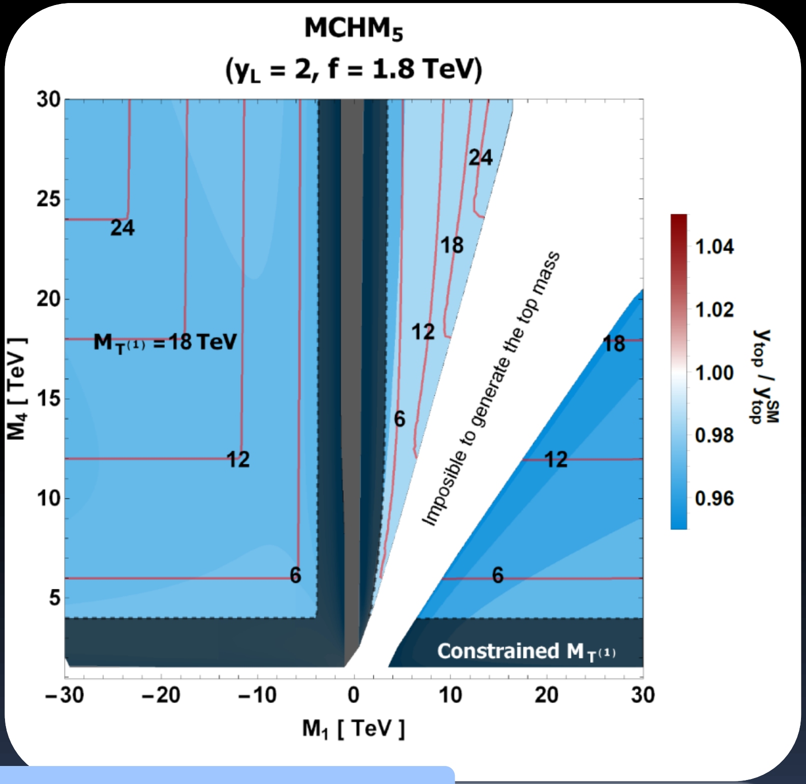
$$\mathcal{L}^{\mathbf{14}}_{\text{int}} = -i\,c_4\,\overline{\Psi}_4\,\not{d}\,\Psi_1 - i\,c_9\,\overline{\Psi}^{ij}_{\mathbf{9}}\,\not{d}^{i}\,\Psi^{j}_{\mathbf{4}} - i\,\frac{c_{T9}}{4\pi f}\,\overline{\Psi}^{ij}_{\mathbf{9}}\,d^{i}_{\mu}d^{j\,\mu}\,\tilde{T} + \text{h.c.}$$

R.D.Matheus

Constraints $MCHM_5$

Overlayed regions indicate constraints: the dark one is given by direct exclusion of top partners in the left plot and by expected constraints in the HL-LHC in the right one ($M_{T(1)} < 4$ TeV). In the white region, the top mass cannot be reached without violating perturbativity.



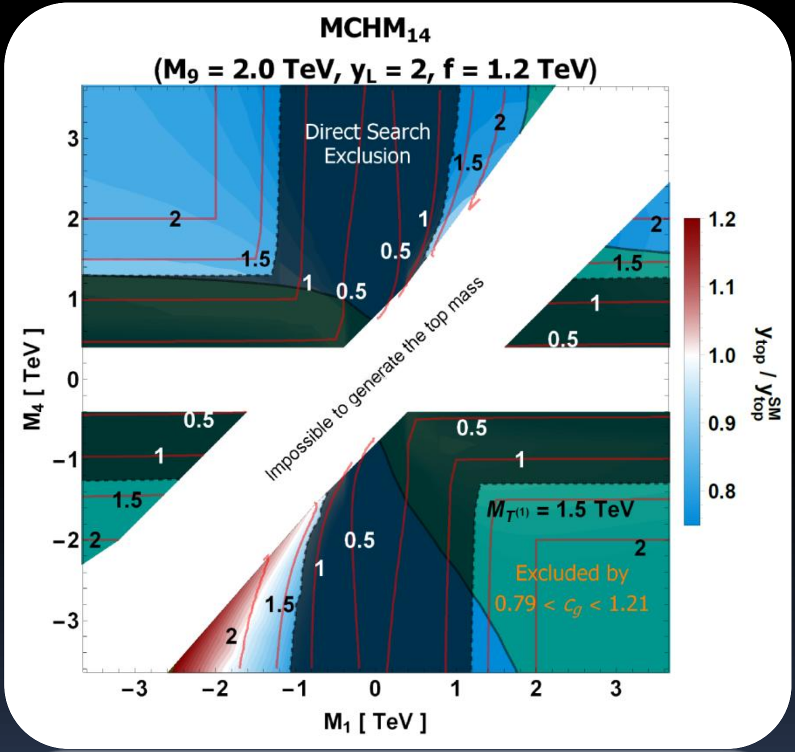


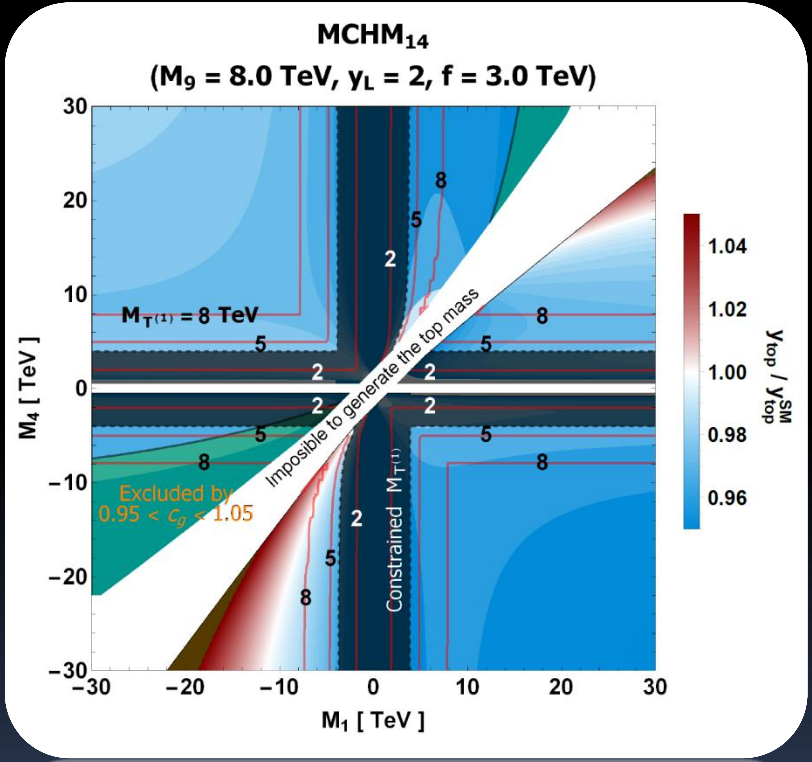
$$0.69 \le c_g \le 1.33$$

$$0.33 \le \mu(t\bar{t}h) \le 2.07$$

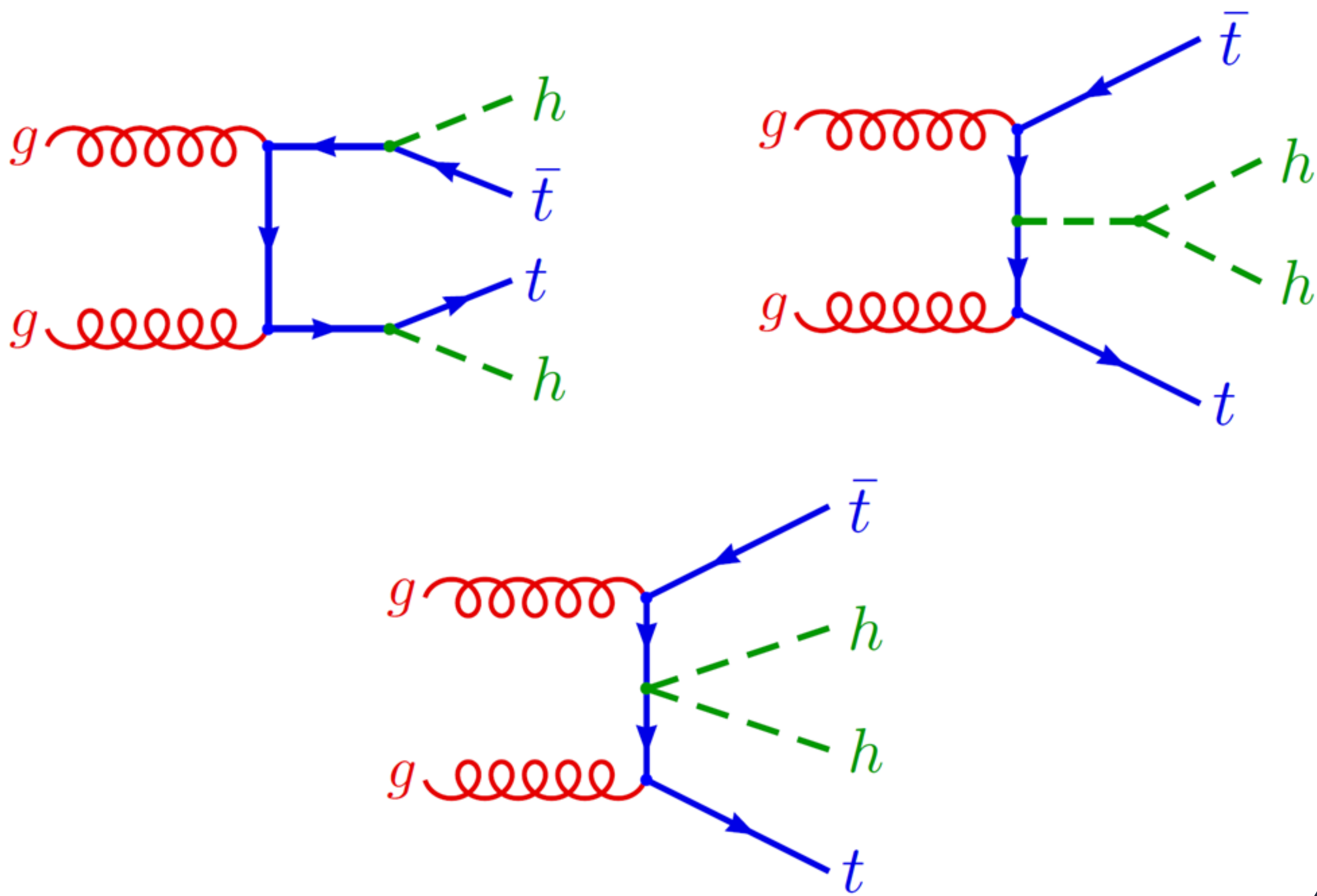
Constraints $MCHM_{14}$

Overlayed regions indicate constraints: the dark one is given by direct exclusion of top partners in the left plot and by expected constraints in the HL-LHC in the right one ($M_{T(1)} < 4$ TeV). In the white region, the top mass cannot be reached without violating perturbativity. The green region is constrained by c_g measurements in the left and by the c_g expected constraints in the right.

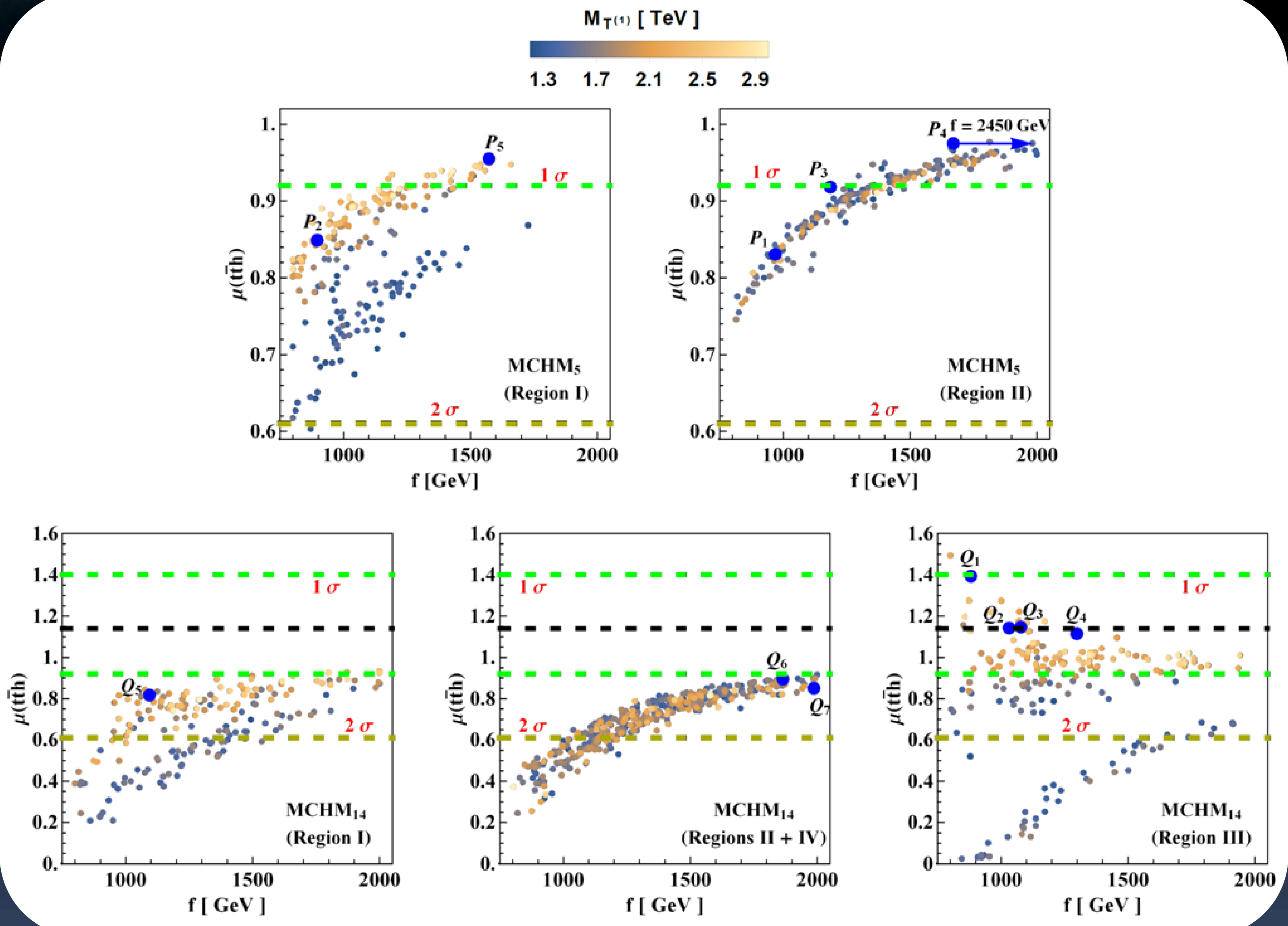




tthh process



tth



$M_{T^{(1)}}$ [TeV]
1.3
1.7
2.1
2.5
2.9
MCHM5 (Region I)
MCHM5 (Region II)
P_4 f = 2450 GeV
MCHM14 (Region I)
MCHM14 (Regions II + IV)
MCHM14 (Region III)
$\mu(t\bar{t}h)$
f [GeV]
1 σ
2 σ

NR-tthh

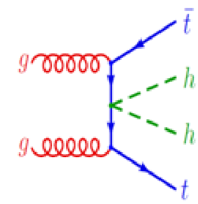
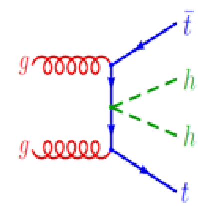
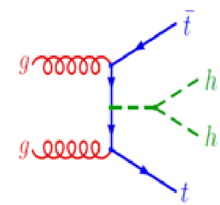
		P_1	P_2	P_3	P_4	P_5	Disregarded diagrams
$\sigma_{\not{h}\not{h}}/\sigma^{t\bar{t}hh}_{\rm NR}$ $\sigma_{\not{h}\not{h}}/\sigma^{t\bar{t}hh}_{\rm NR}$	(14 TeV) (100 TeV)	1.05 1.05	1.04 1.03	1.03 1.03	1.01 1.01	1.01 1.01	
$\sigma_{\rm Yuk}/\sigma^{t\bar{t}hh}_{\rm NR}$ $\sigma_{\rm Yuk}/\sigma^{t\bar{t}hh}_{\rm NR}$	(14 TeV) (100 TeV)	0.86 0.87	0.85 0.87	0.84 0.87	0.82 0.85	0.82 0.85	 
$\sigma^{t\bar{t}hh}_{\rm NR}/\sigma^{t\bar{t}hh}_{\rm SM}$ $\sigma^{t\bar{t}hh}_{\rm NR}/\sigma^{t\bar{t}hh}_{\rm SM}$ $(y_t/y_t^{\rm SM})^4$	(14 TeV) (100 TeV) 	0.65 0.65 0.69	0.69 0.69 0.72	0.82 0.82 0.85	0.94 0.93 0.95	0.90 0.89 0.91	

Table 3. Study of NR-$t\bar{t}hh$ for the MCHM$_5$ points in table 1. The cross sections $\sigma_{\not{h}\not{h}}$ and $\sigma_{\rm Yuk}$ are obtained by disregarding the classes of diagrams on the last column and $\sigma_{\rm NR}$ is the total NR-$t\bar{t}hh$. The LO SM $t\bar{t}hh$ production is indicated by $\sigma^{\rm SM}$ and $\sigma^{\rm SM}_{\rm Yuk}$ means we disregarded the SM trilinear Higgs coupling. The top Yukawa couplings are indicated by y_t and y_t^{SM} in the MCHM and SM respectively.

EFT

$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2} m_h^2 h^2 - \kappa_\lambda \lambda_{\rm SM} v h^3 - \frac{m_t}{v}\left(v + \kappa_t h + \frac{c_2}{v} hh\right)(\bar{t}_L t_R + \text{h.c.})$$
$$+ \frac{1}{4}\frac{\alpha_s}{3\pi v}\left(c_g h - \frac{c_{2g}}{2v} hh\right) G^{\mu\nu} G_{\mu\nu}$$

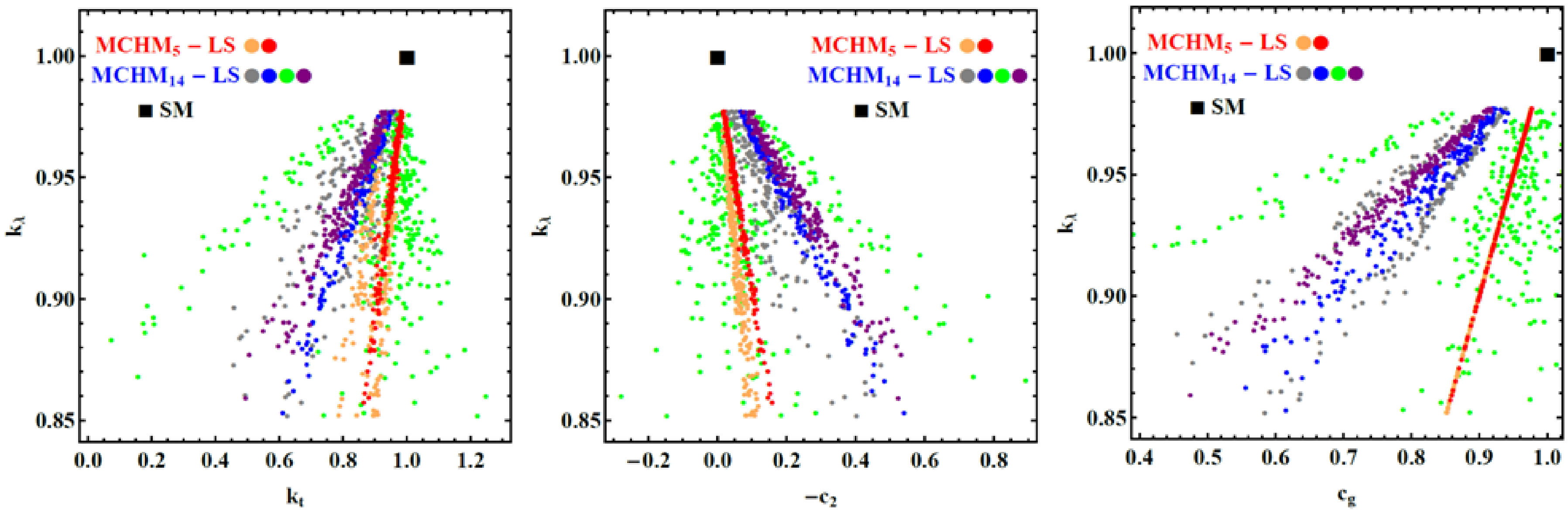


Figure 20. Values of some selected EFT parameters in the low scale scan of the MCHM_5 and the MCHM_{14} parameter spaces. The colors indicate the different Regions in each model (I and II for the MCHM_5 and I, II, III and IV for the MCHM_{14}, in that order). The SM is represented by the black square.