New Directions in
Particle Physics

Clustering techniques as a way to explore the parameter space of BSM models’

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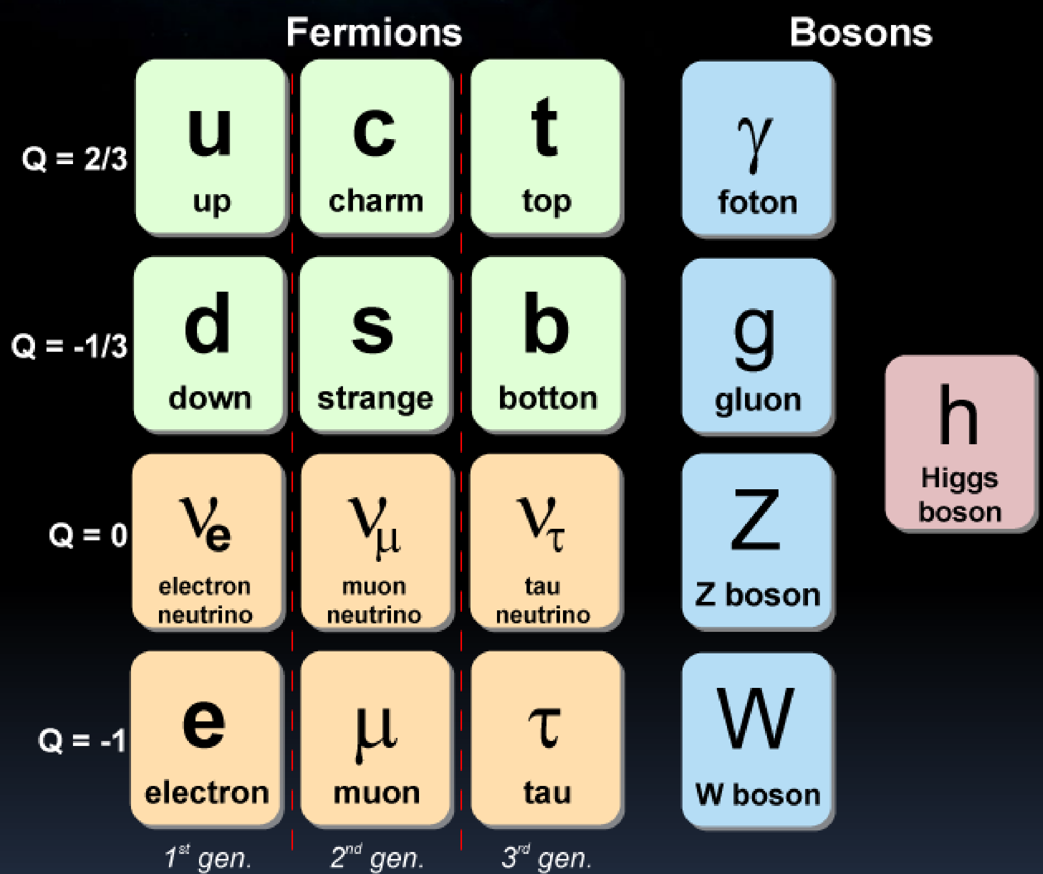
Obligatory "problems of the SM slide"



Dark matter?

Flavor Structure?
(most parameters of the SM)

Hierarchy of Scales?

Neutrino Masses?
(are they Dirac → New DoF
are they Majorana → New scale)

Baryogenesis?

Strong CP? Axions?

Gravitons?

Particle physics is only "over" if you are satisfied with: "I don't know"

Beyond SM

The solution to most of these shortcomings involve new models:

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

  (e.g.: SUSY)

- Simplified models

- Effective models (inspired by some UV completion)

  (e.g.: Composite Higgs Model)

- Model Independent EFT

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  (e.g.: Composite Higgs Model)

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

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  (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

A common problem

Model parameter space is multidimensional

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

e.g.: MCHM_{14}

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

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

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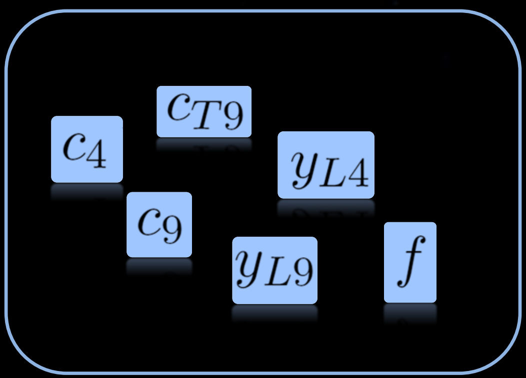


Model parameters

A common problem

Model parameter space is multidimensional…

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

Model parameters

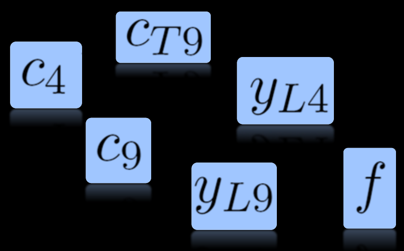
- Masses
- Widths
- Branching Ratios
- Couplings

Physical parameters

… and not trivially connected to observables

A common problem

Model parameter space is multidimensional…



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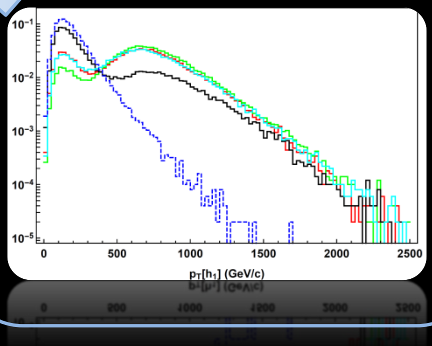

Observables

… and not trivially connected to observables

Common Solutions

Full Model

Parameter Space

Common Solutions

Full Model

Parameter Space

$c_4 \in \Re$

$y_{L1} = y_{L4}$

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

Reduce the dimensionality

Common Solutions

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Convenient Pheno:

- Not many light states
- Narrow
- Long Lived

Restricts region

Common Solutions

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It is the sound approach!

... but we were not lucky

R.D.Matheus

Common Solutions

Full Model

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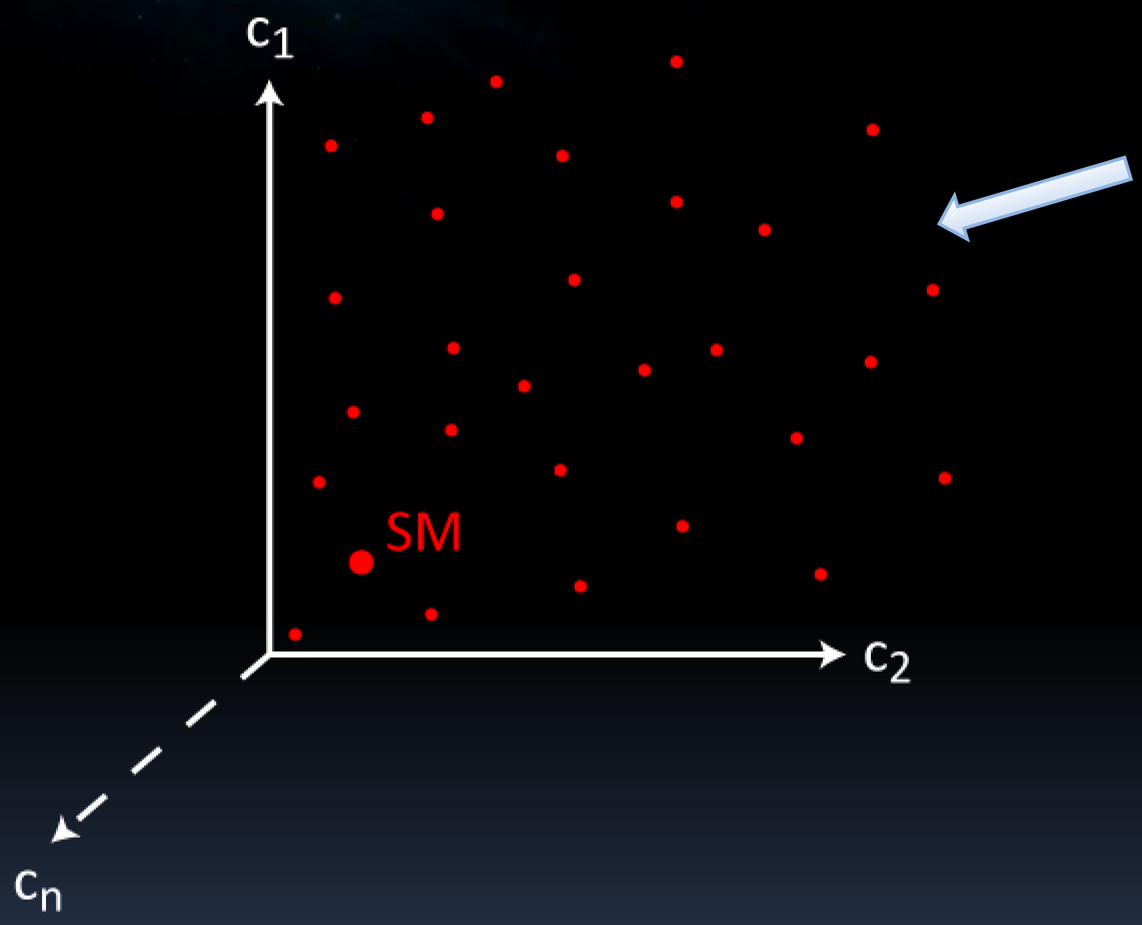
Restricts region

Brave through the multidimensional darkness

Global fits using smart computing

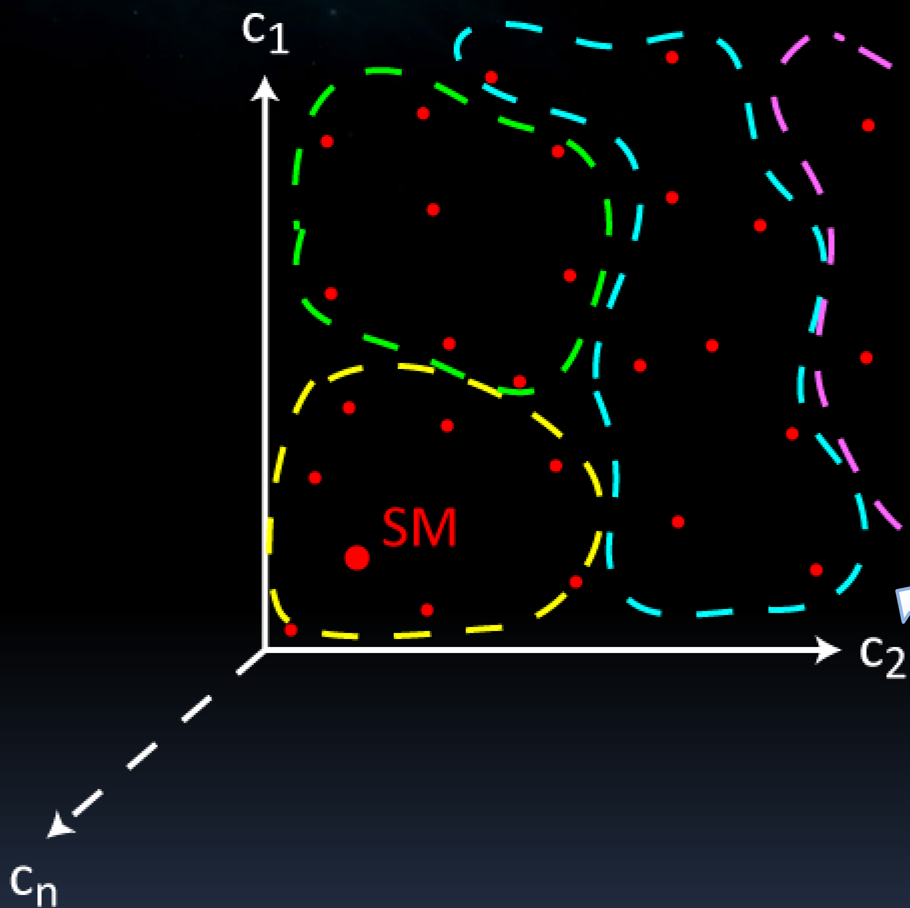
- SMEFT is going this way, with good theoretician-experimentalist cooperation
- BSM models face a bigger sociological challenge

Clustering



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

Clustering

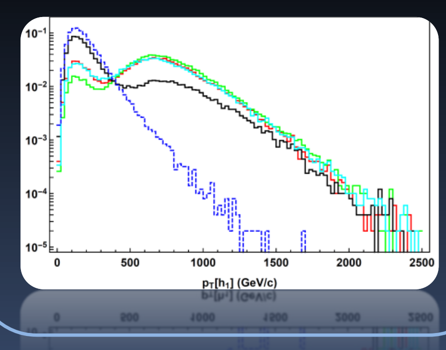


What criteria to use?

Physical parameters

- Masses
- Widths
- Branching Ratios
- Couplings

Observables ✓



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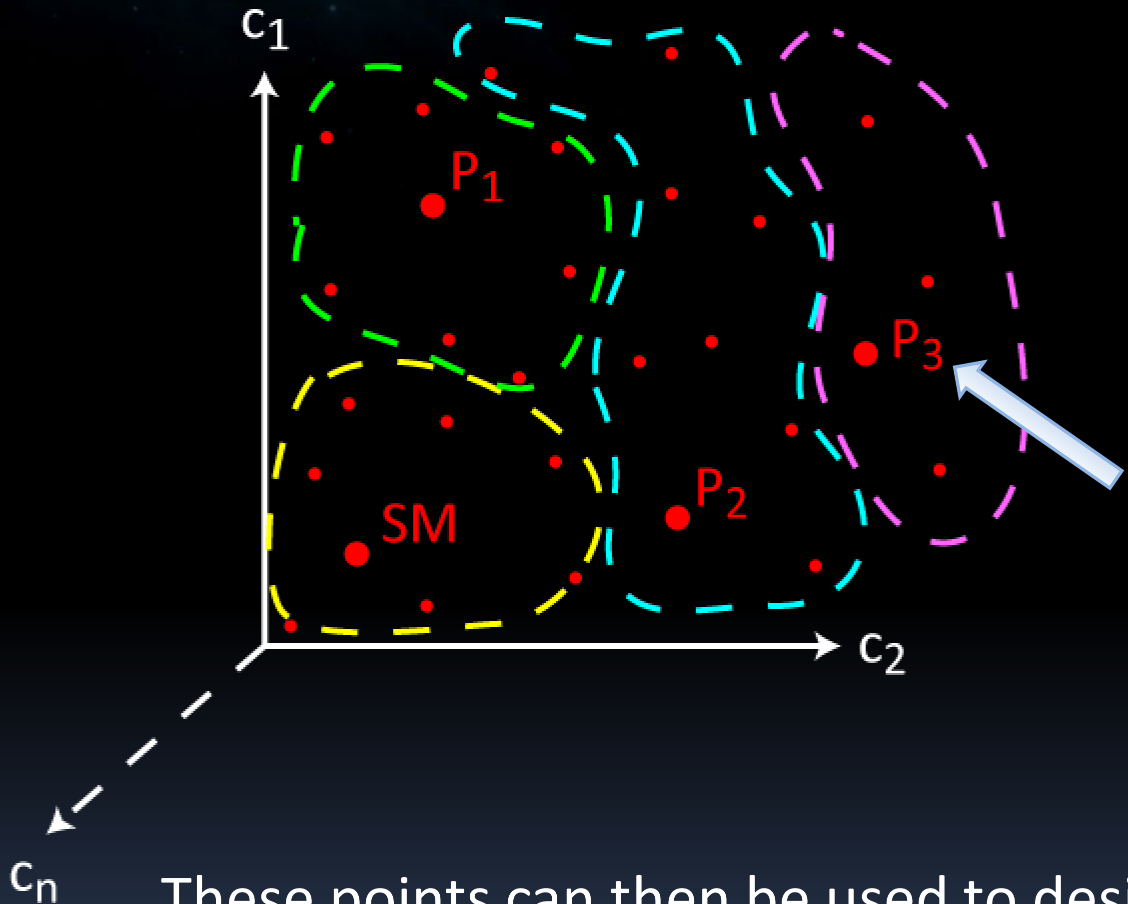
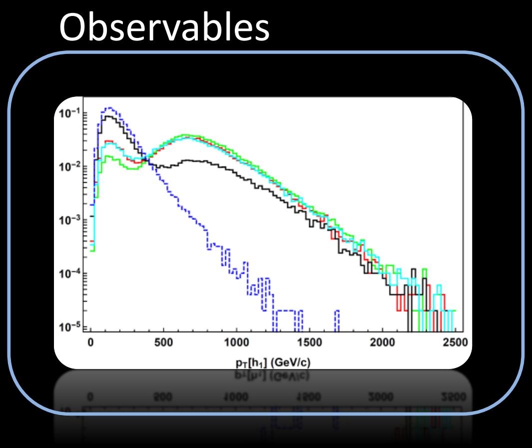




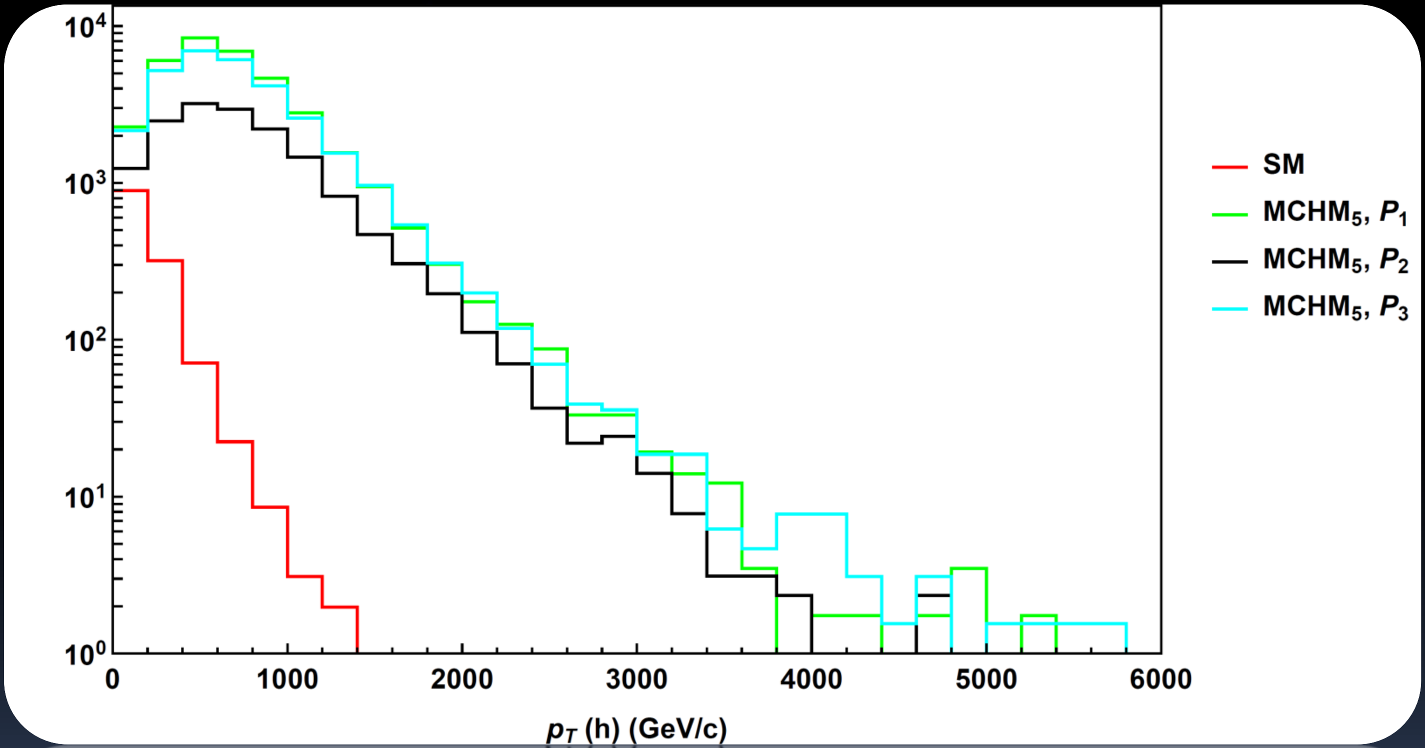
We can also get a representative benchmark point for each cluster

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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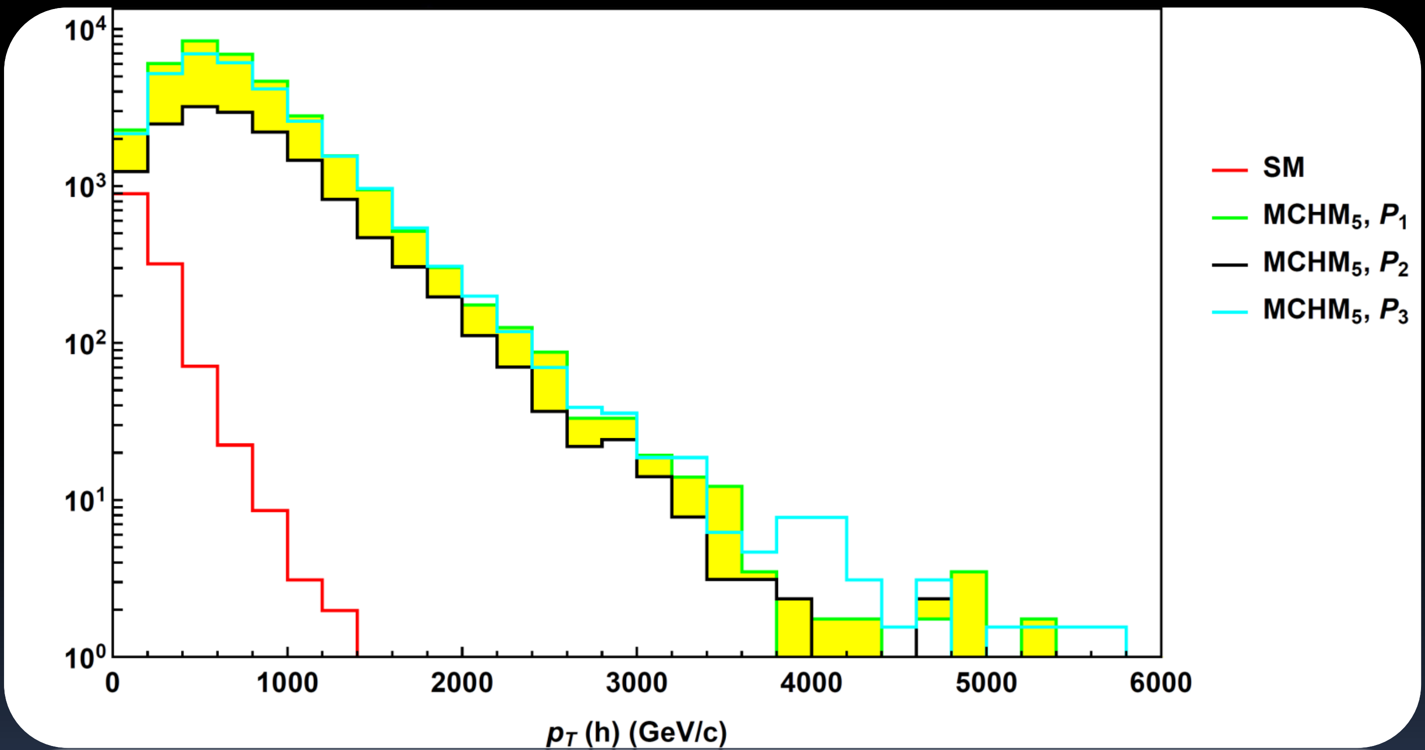

P_1 vs. P_2

R.D.Matheus

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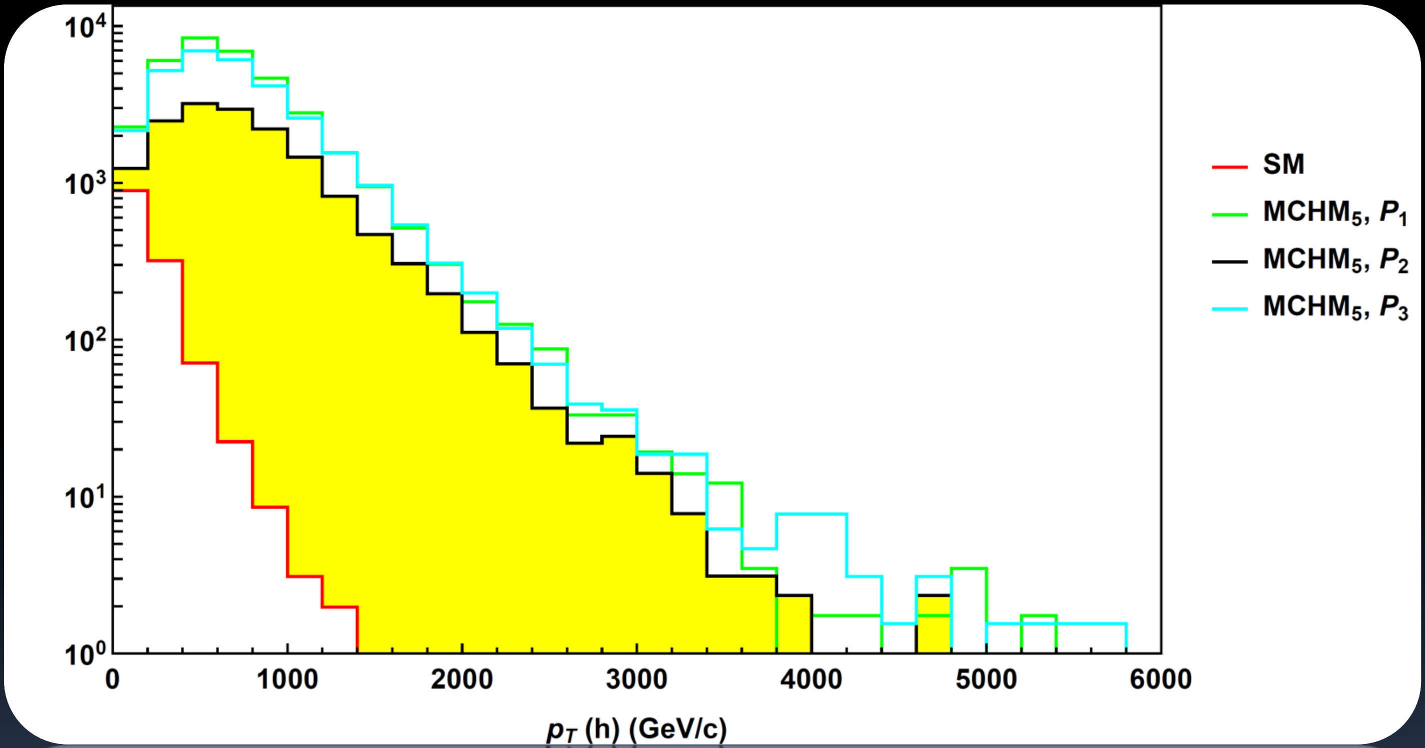

SM vs. P_2

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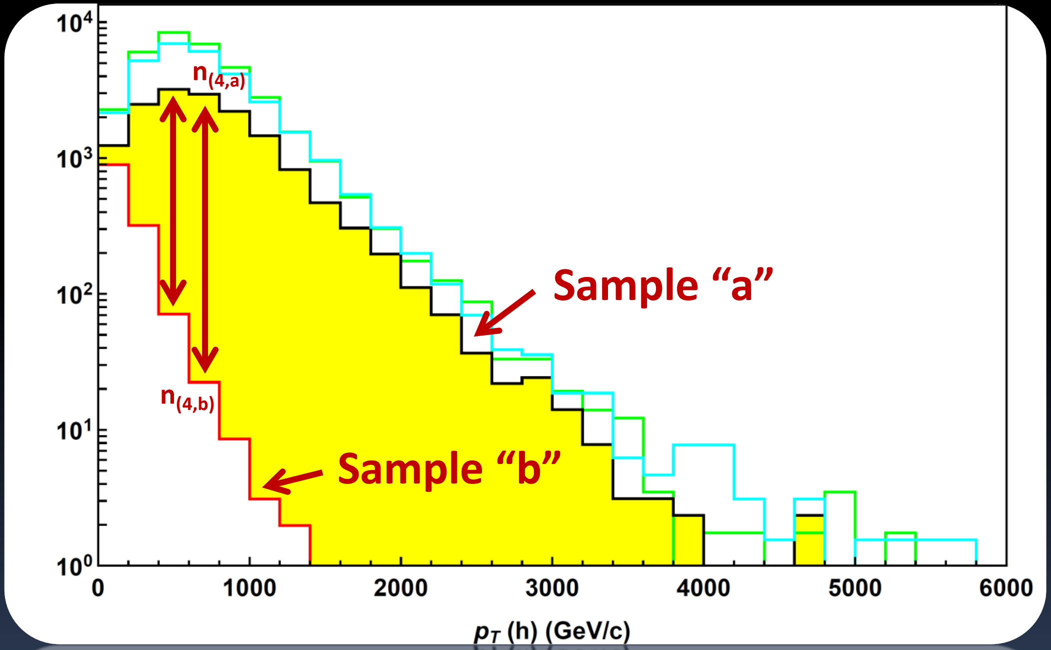
Log-likelihood:

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



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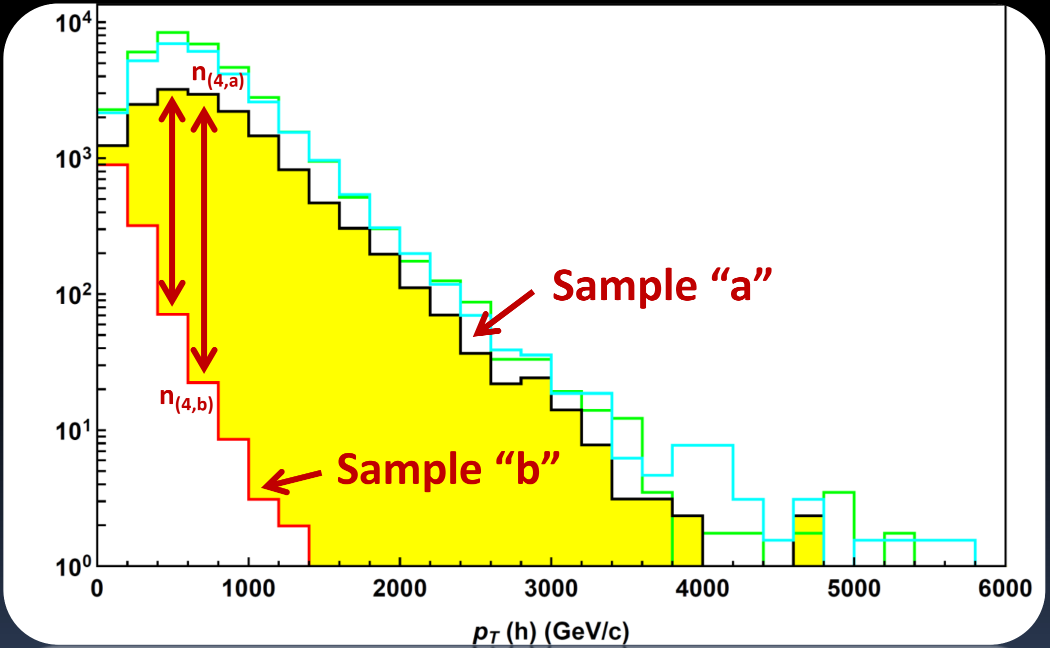

If $S_a = S_b \rightarrow TS_{ab} = 0$

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

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

R.D.Matheus

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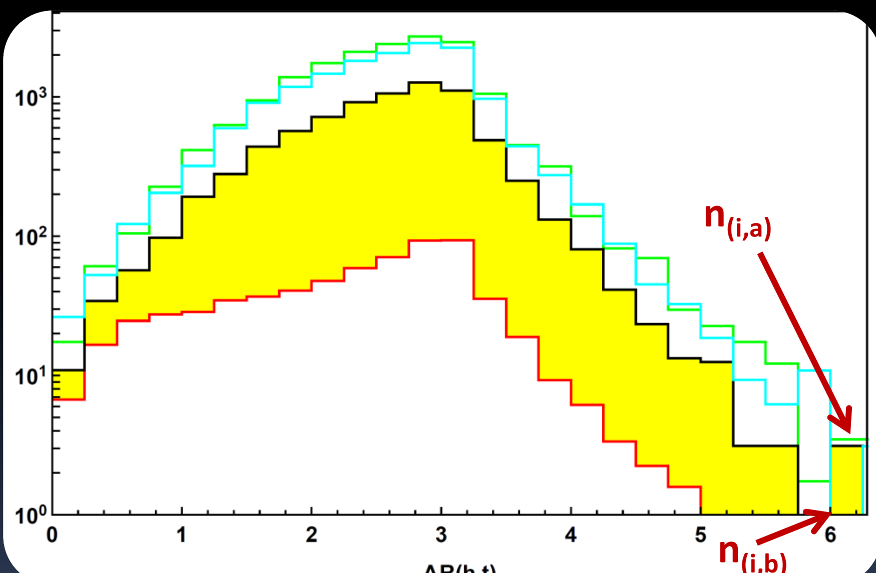
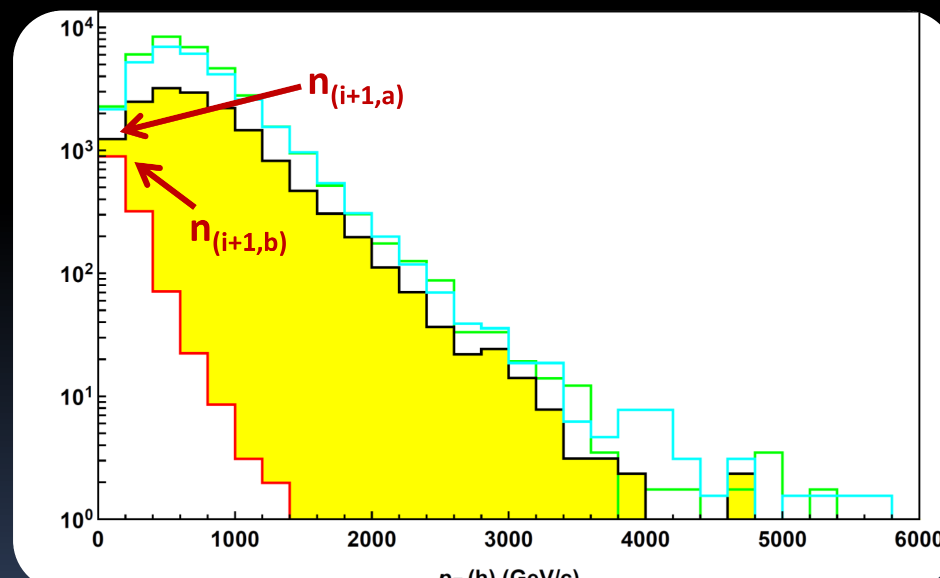
We can also sum over more than one kinematical distribution





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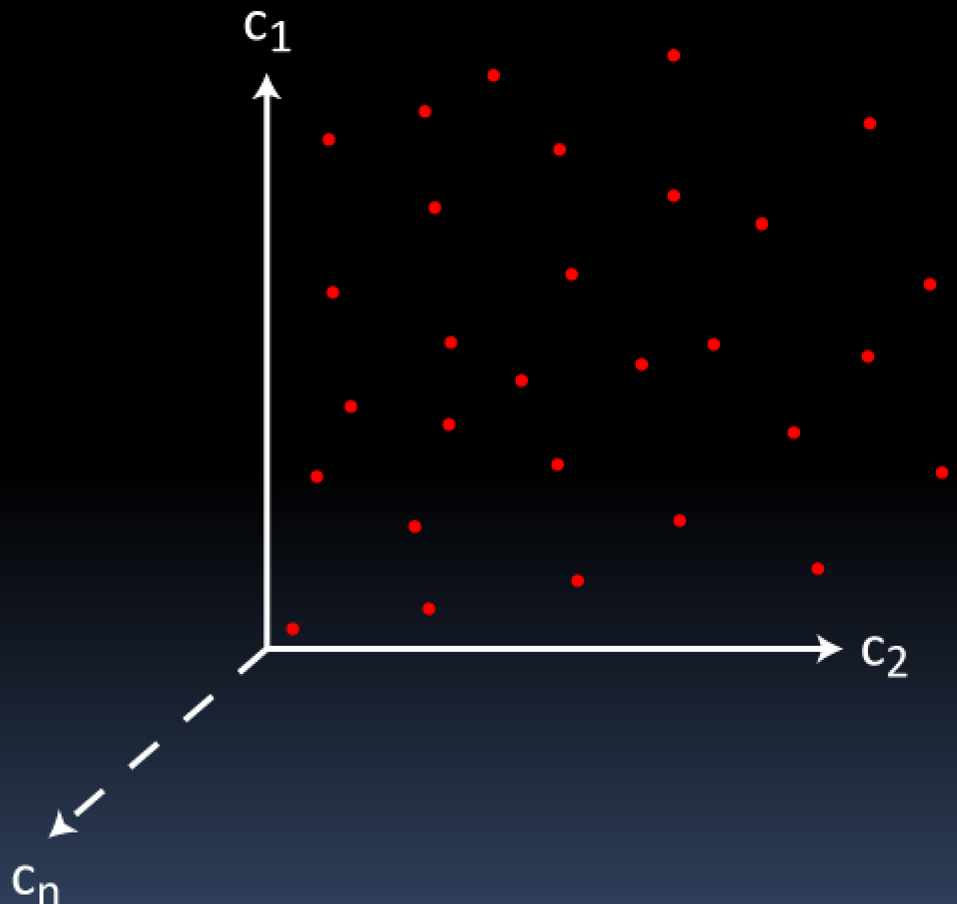
Let the clustering begin!



Step 0

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

Clustering Algorithm

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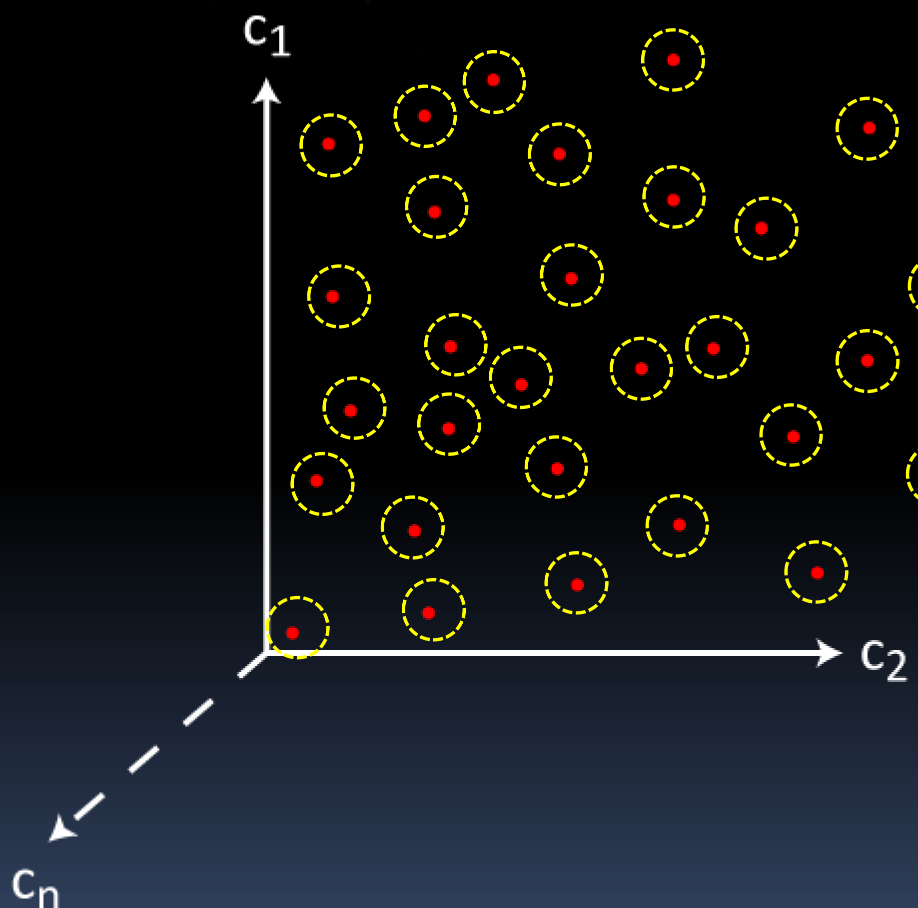

Step 0

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

Each point will be its own cluster

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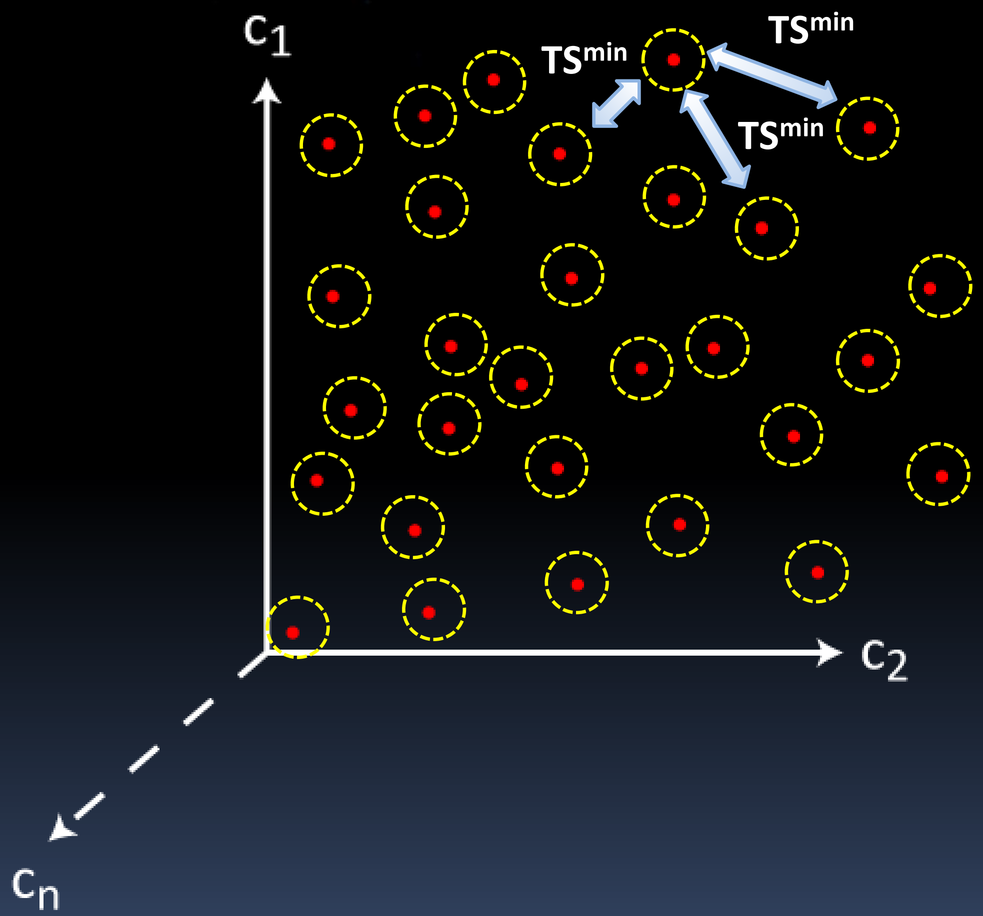

Step 1

Compare all pairs of clusters

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

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

Clustering Algorithm

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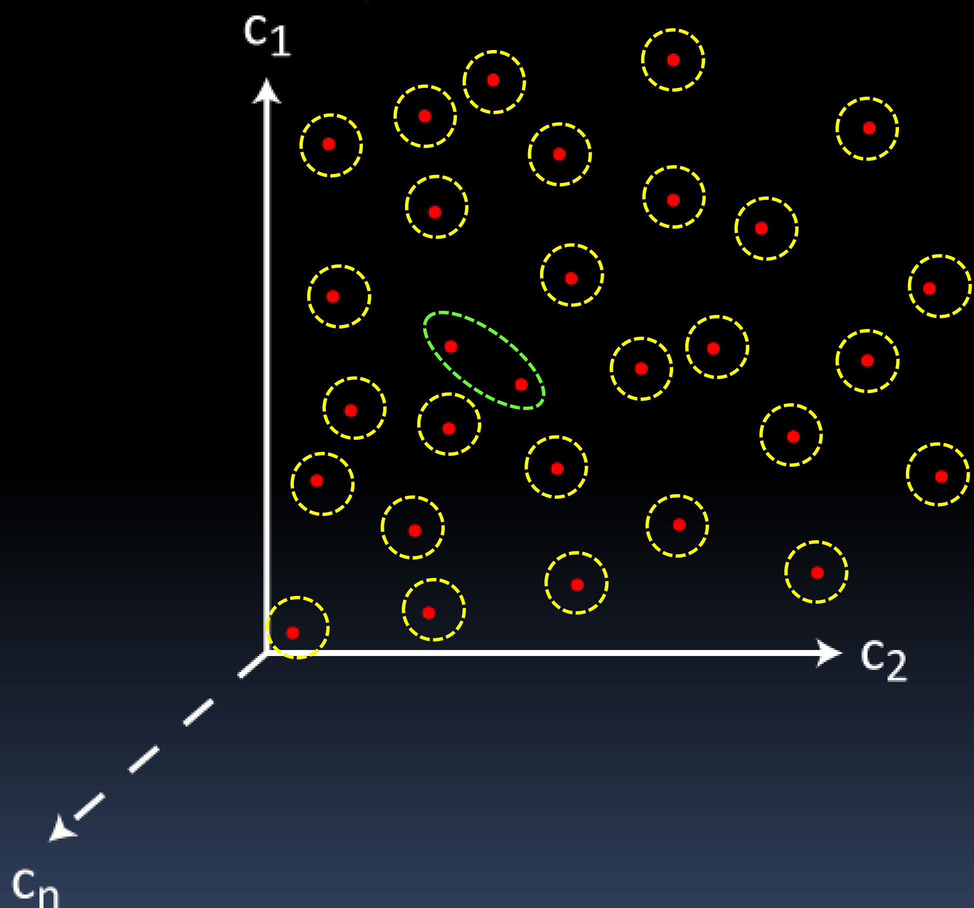

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Merge the pair with the highest TS^{min}

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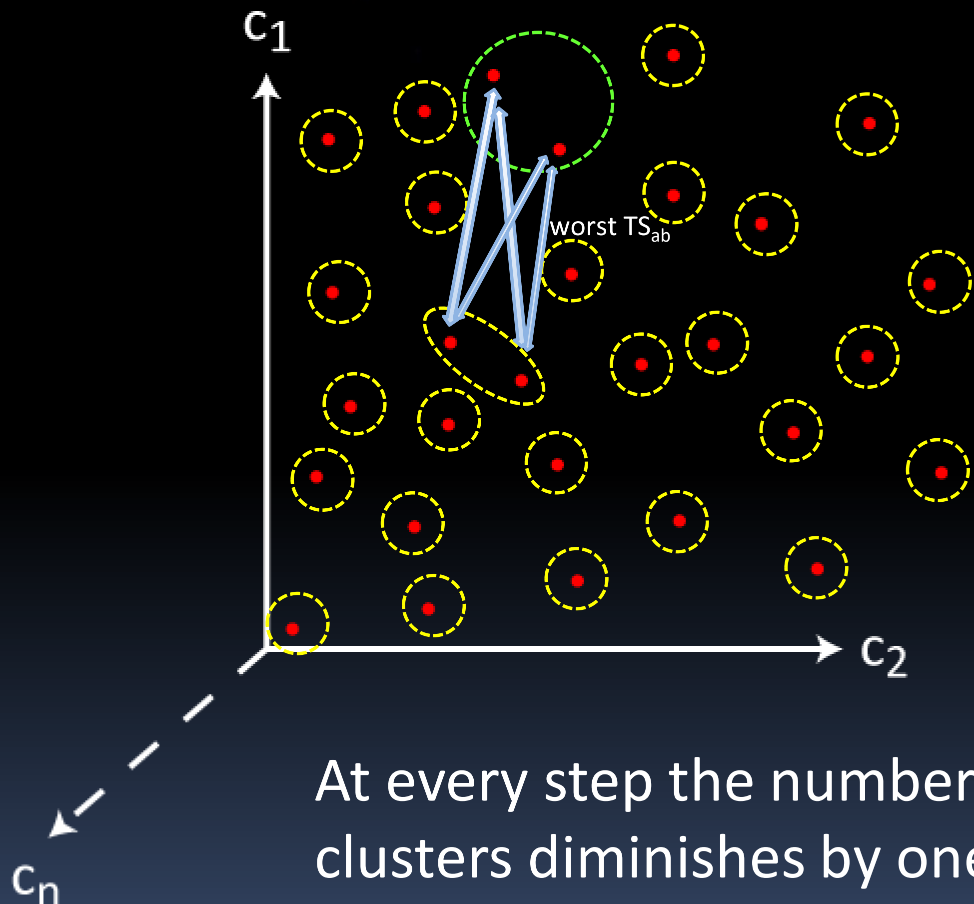

Step 3

Compare all pairs of clusters

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

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Merge the pair with the highest TS^{min}

At every step the number of clusters diminishes by one

Clustering Algorithm

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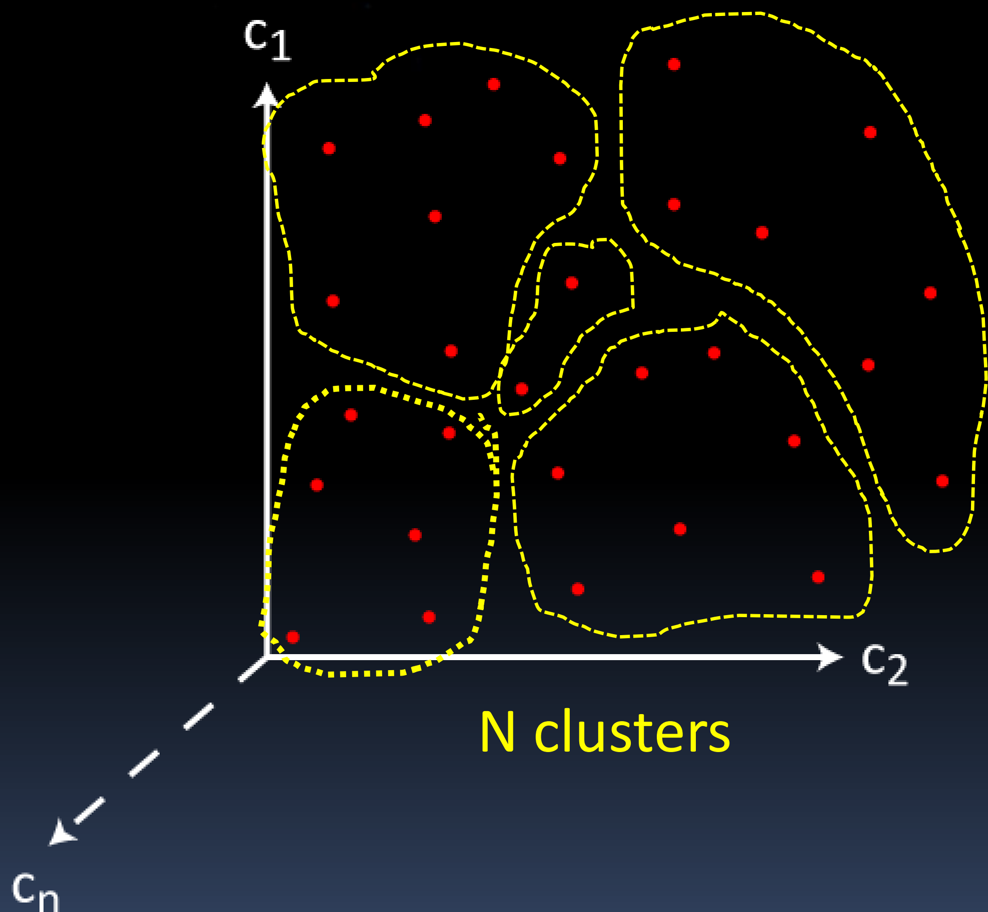

Step n (final)

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

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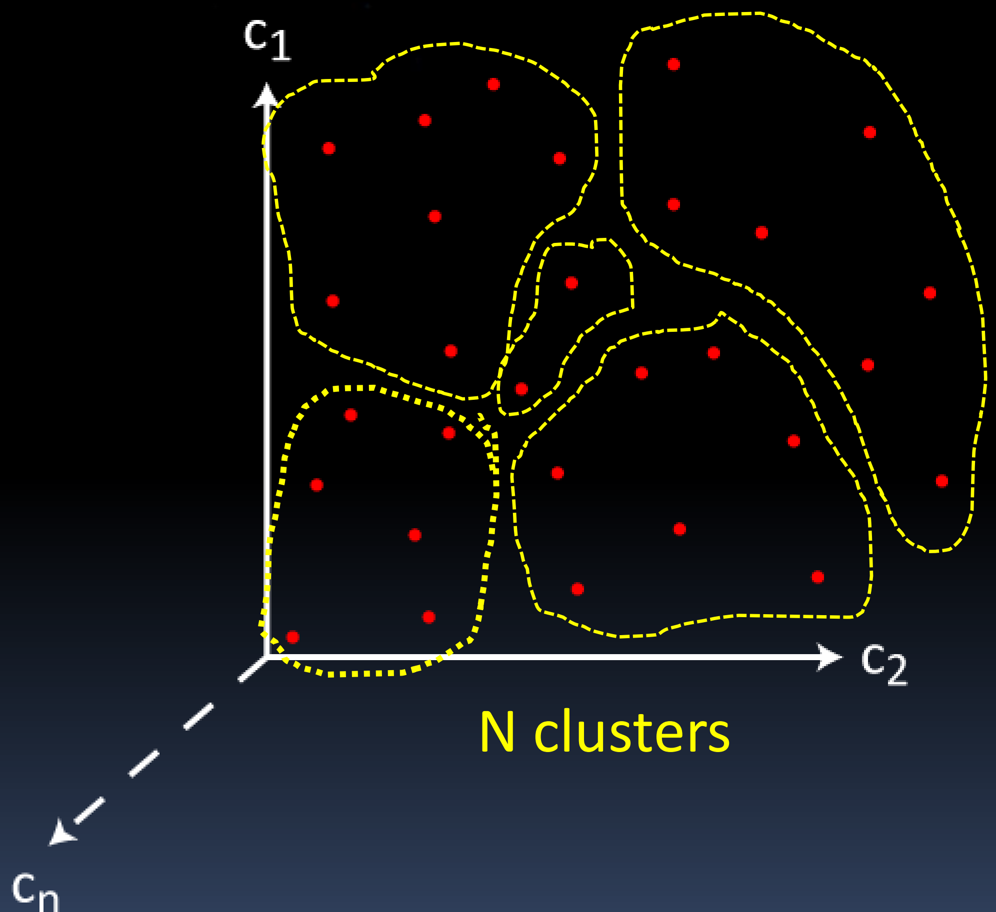


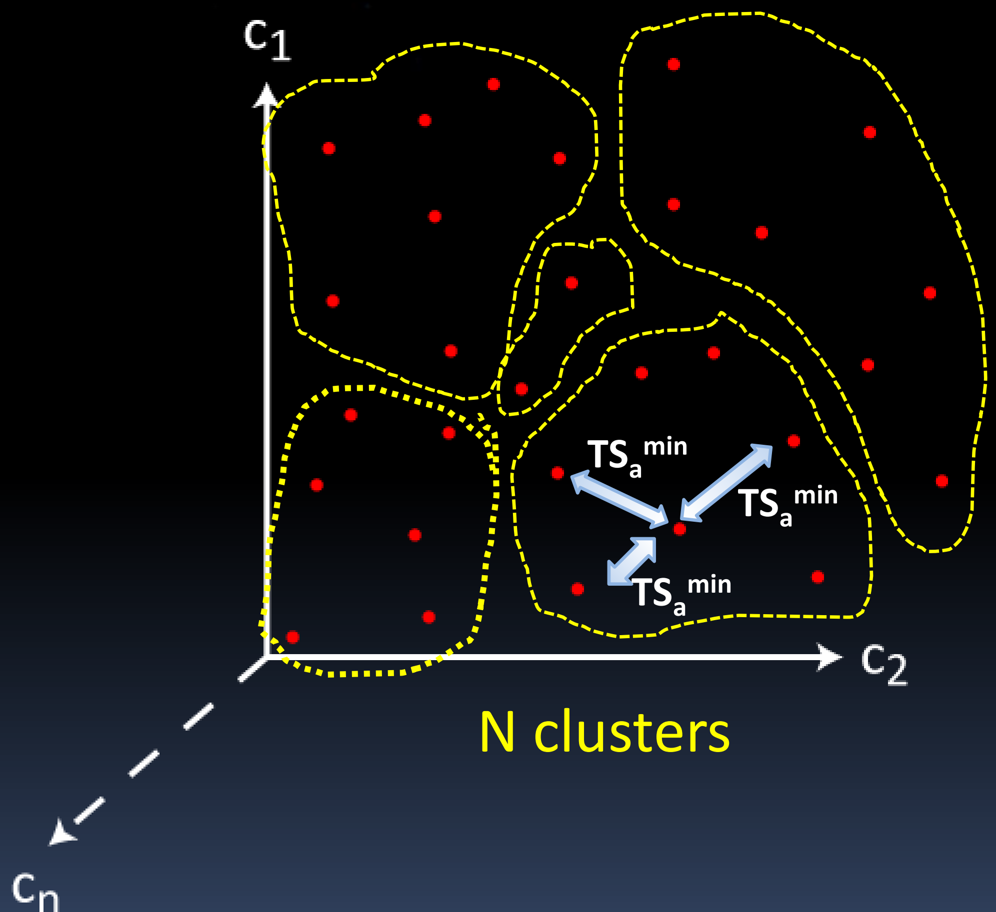
Step n (final)

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:

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

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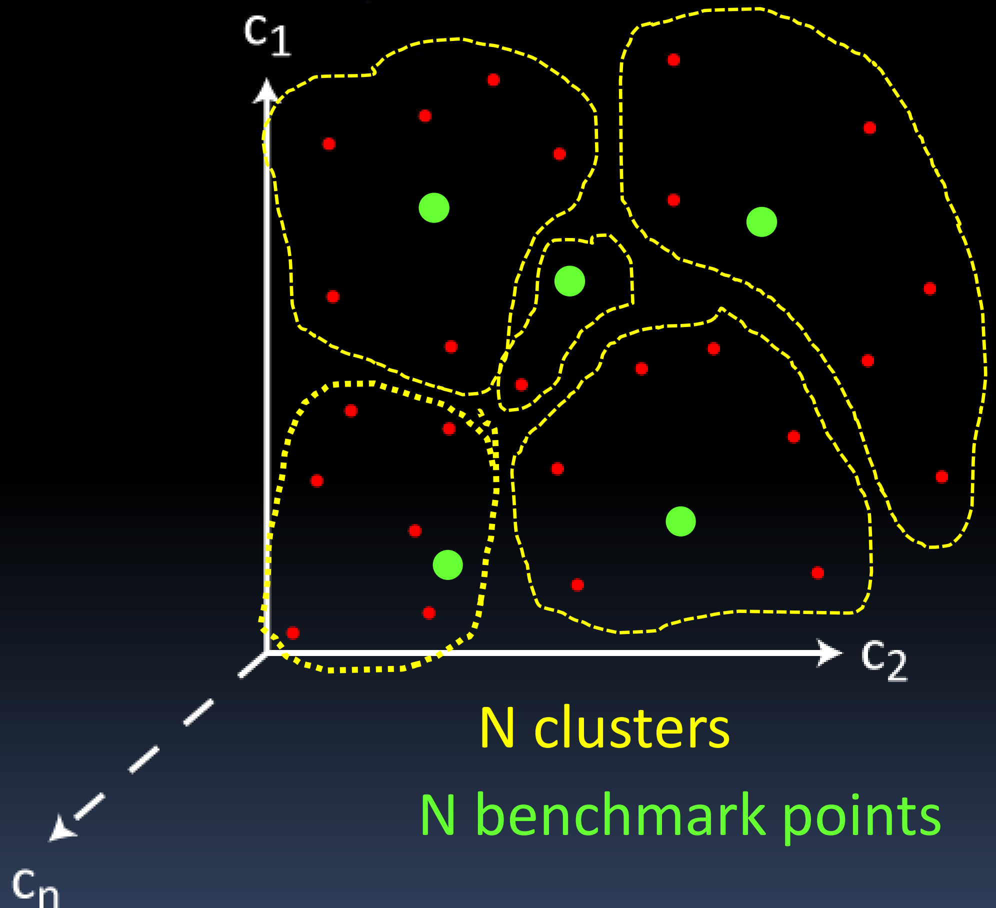

N clusters

N benchmark points

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

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

Those are the benchmark points

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)

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)

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

$\Psi_1 \leftrightarrow \tilde{T}$

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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 !

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Charge 2/3 sector

- $X_{2/3}$
- T
- $\tilde{T}$
- t

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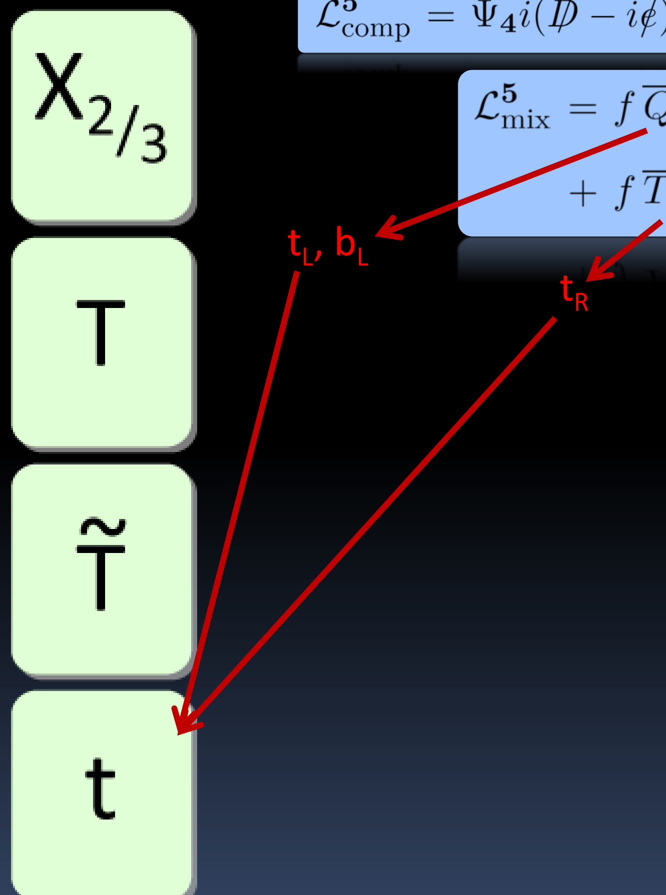
$$\mathcal{L}^{\mathbf{5}}_{\text{mix}} = f\,\overline{Q}^{\mathbf{5}}_L U\left[y_{L4}\Psi_{\mathbf{4}} + y_{L1}\Psi_{\mathbf{1}}\right] + \text{h.c.} + f\,\overline{T}^{\mathbf{5}}_R U\left[y_{R4}\Psi_{\mathbf{4}} + y_{R1}\Psi_{\mathbf{1}}\right] + \text{h.c.}$$



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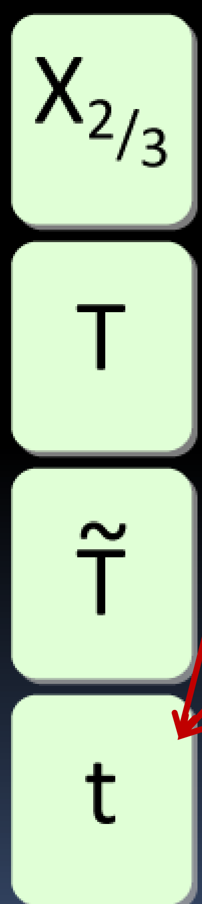

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$$\mathcal{M}^{\mathbf{5}}_{2/3} = \begin{bmatrix} 0 & \frac{1}{2}y_{L4}f(1+\sqrt{1-\xi}) & \frac{1}{2}y_{L4}f(1-\sqrt{1-\xi}) & \frac{1}{\sqrt{2}}y_{L1}f\sqrt{\xi} \\ -\frac{1}{\sqrt{2}}y_{R4}f\sqrt{\xi} & -M_4 & 0 & 0 \\ \frac{1}{\sqrt{2}}y_{R4}f\sqrt{\xi}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

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$X_{2/3}$, T, $\tilde{T}$, t

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

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

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

$T^{(3)}$, $T^{(2)}$, $T^{(1)}$, **t** top

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

7 top partners

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

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

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

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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: $M_1,\ M_4 > 0$

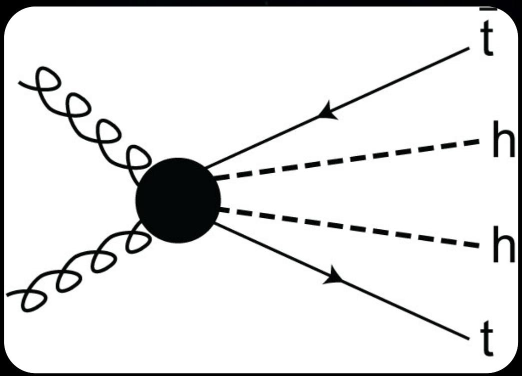
Region II: $M_1 < 0,\ M_4 > 0$

"High" scale (FCC and other "future" colliders):

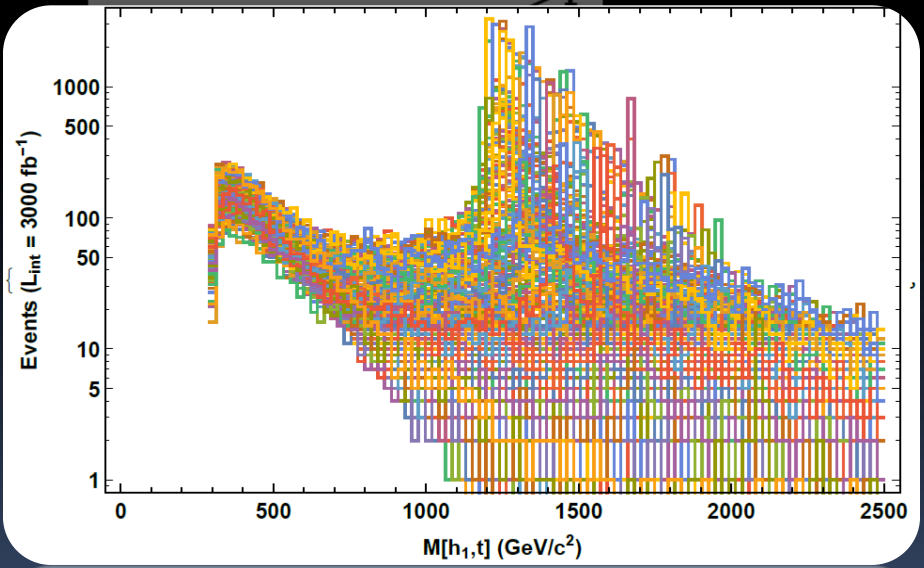
$$|M_1| \in [2, 30] \text{ TeV}, \qquad M_4 \in [2, 30] \text{ TeV},$$
$$f \in [0.8, 8.0] \text{ TeV}, \qquad y_L \in [0.5, 3.0],$$

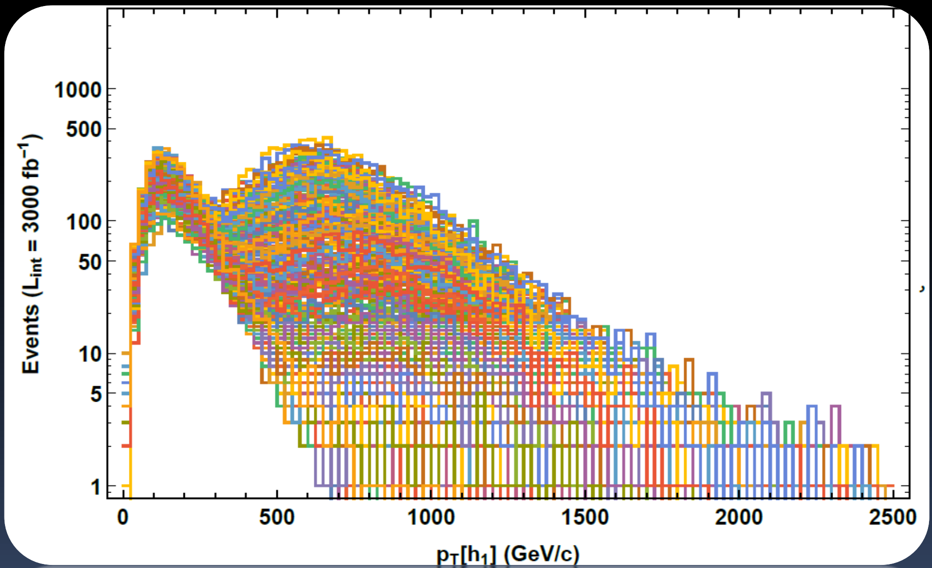
Application to the Minimal Composite Higgs Model (MCHM)

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



LOW SCALE
348 parameter space points
pp → t $\bar{t}$ h h
(simulated at MG5 @LO)

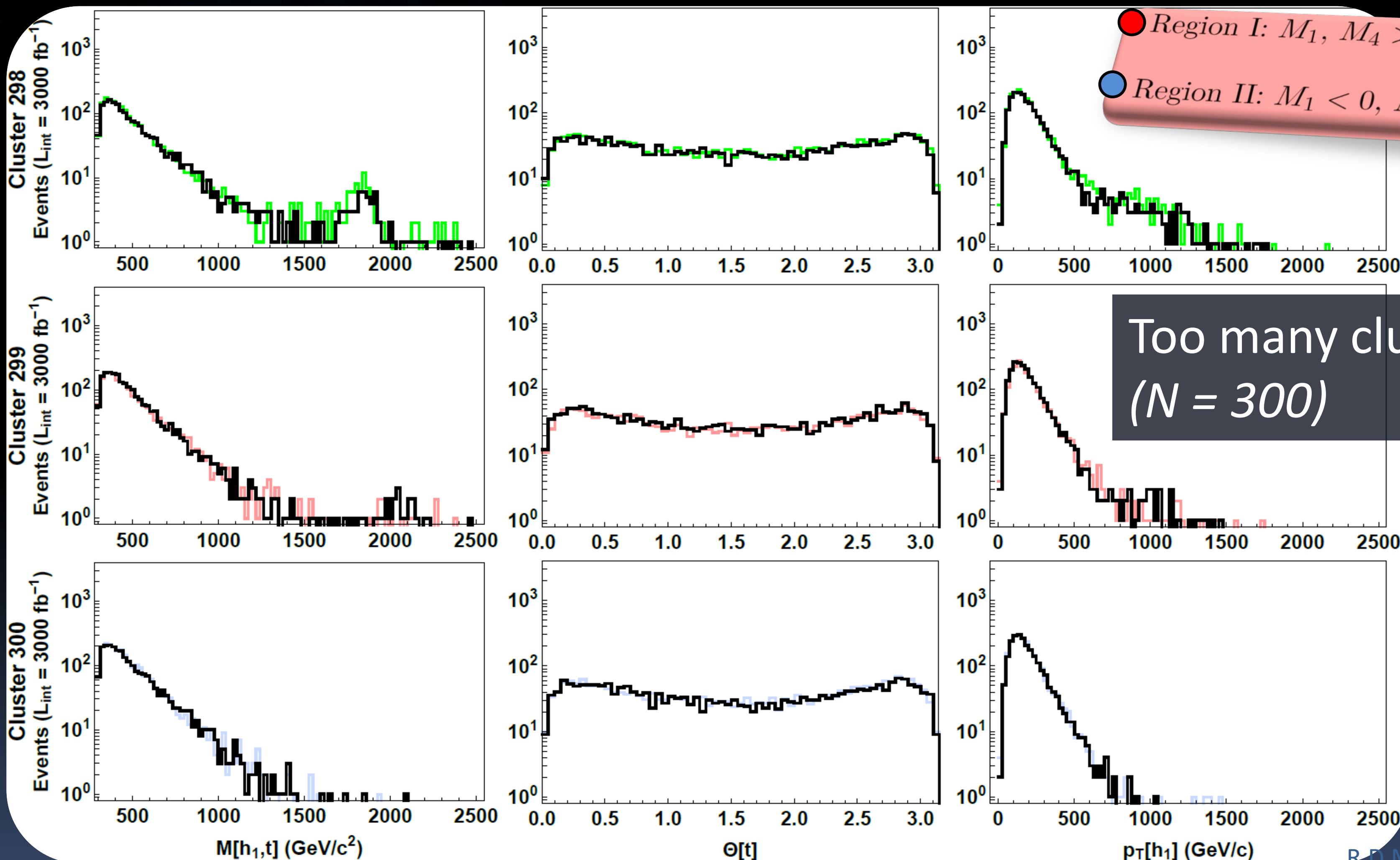




R.D.Matheus

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)



Too many clusters!
(N = 300)

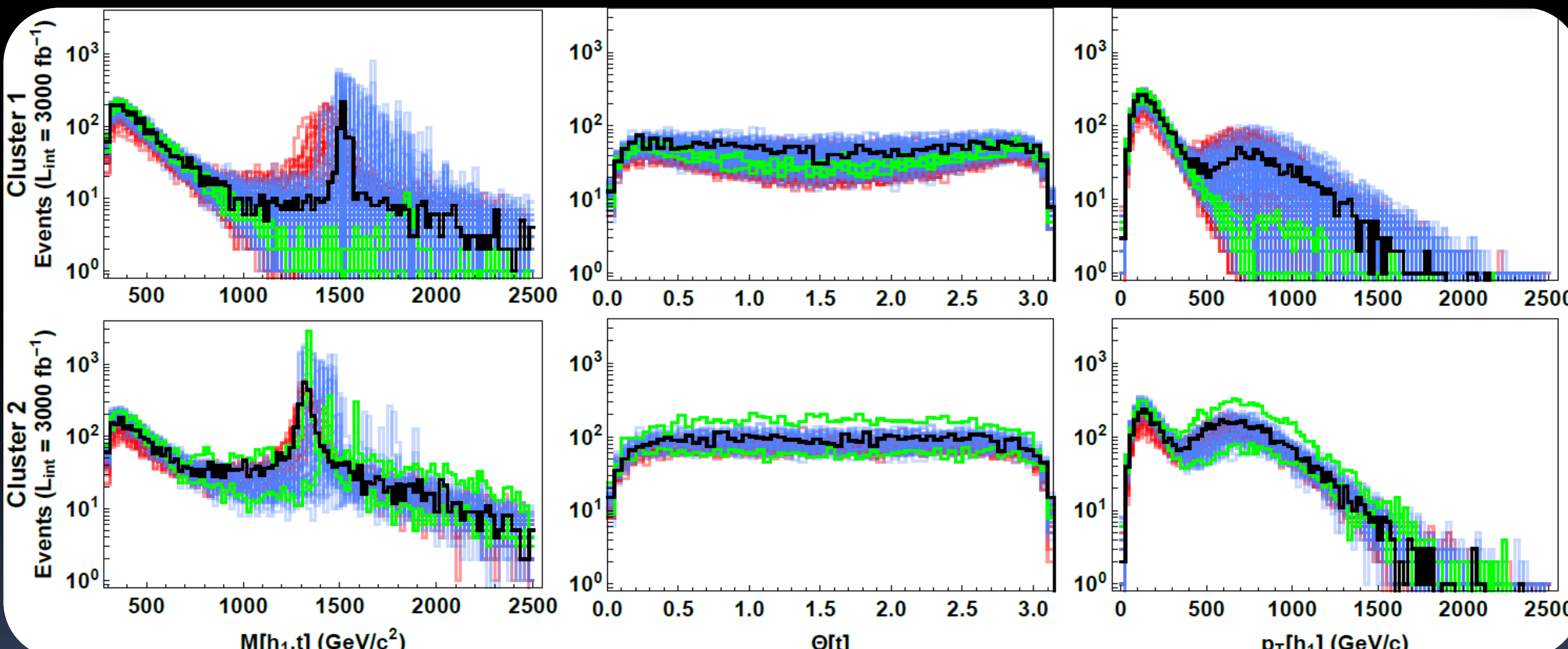
R.D.Matheus

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)

Too few clusters!
(N = 2)

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



Clustering for the $MCHM_5$ (low scale)

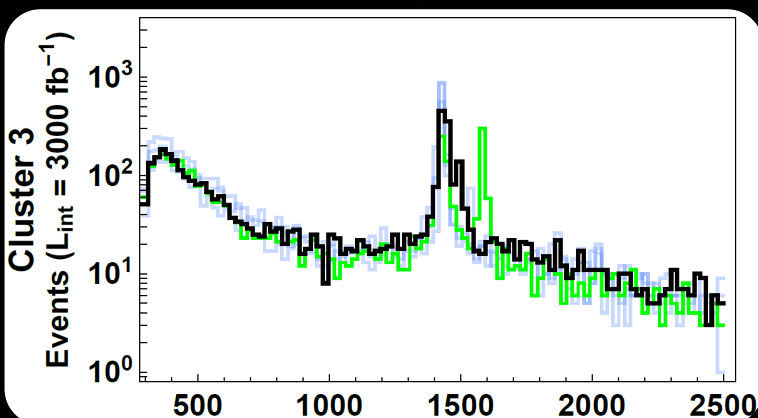
C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

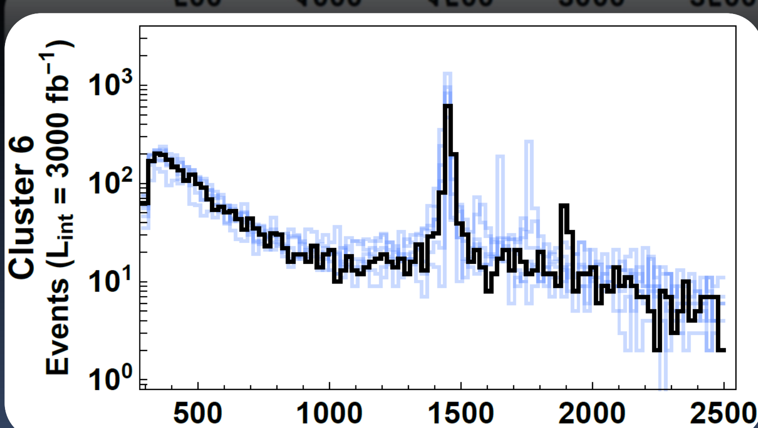
Looking for a sweet spot:

Region I: $M_1, M_4 > 0$

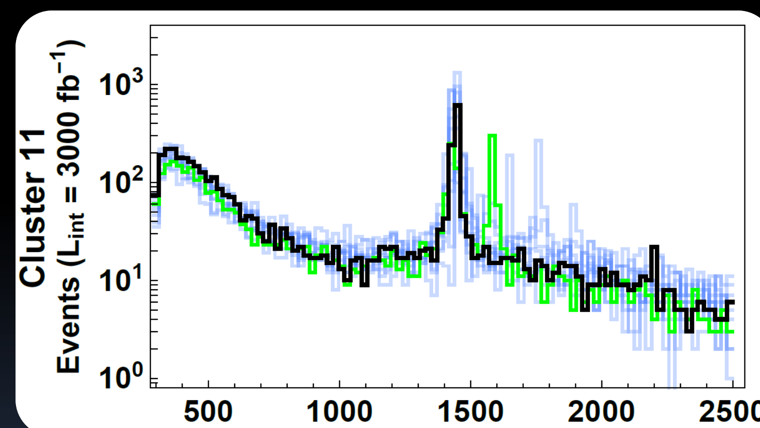
Region II: $M_1 < 0, M_4 > 0$

N = 12





N = 11



R.D.Matheus

Clustering for the $MCHM_5$ (low scale)

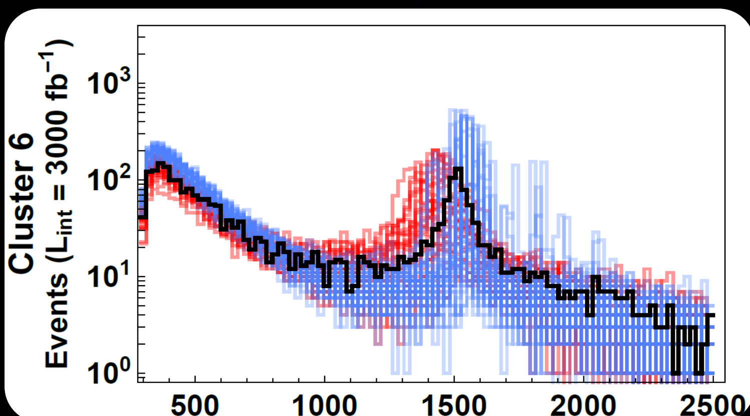
C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

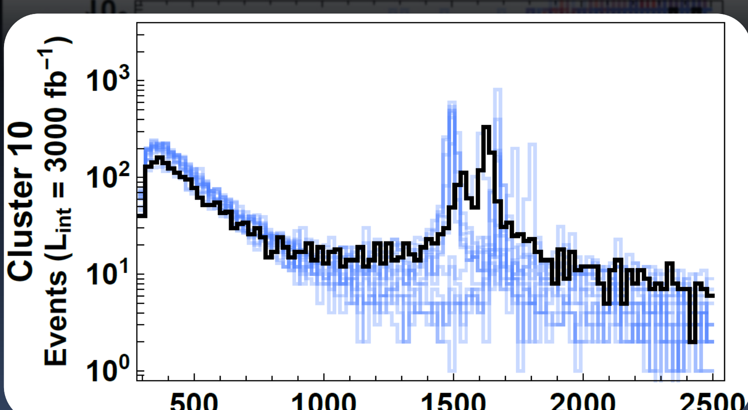
Looking for a sweet spot:

Region I: $M_1, M_4 > 0$

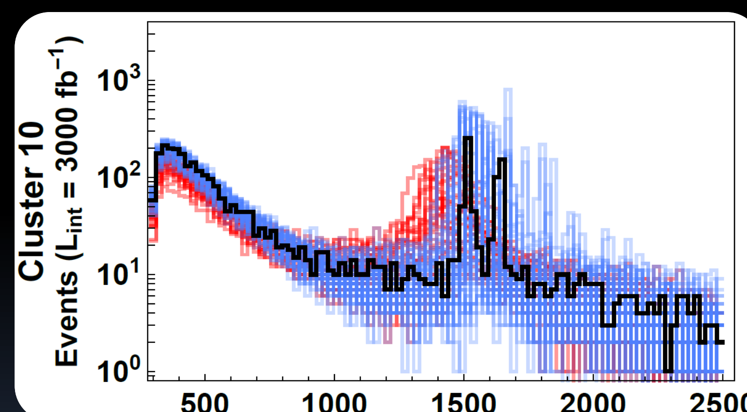
Region II: $M_1 < 0, M_4 > 0$

N = 11





N = 10



Lumping big clusters together is not good, and it gets worse at N = 9

Clustering for the $MCHM_5$ (low scale)

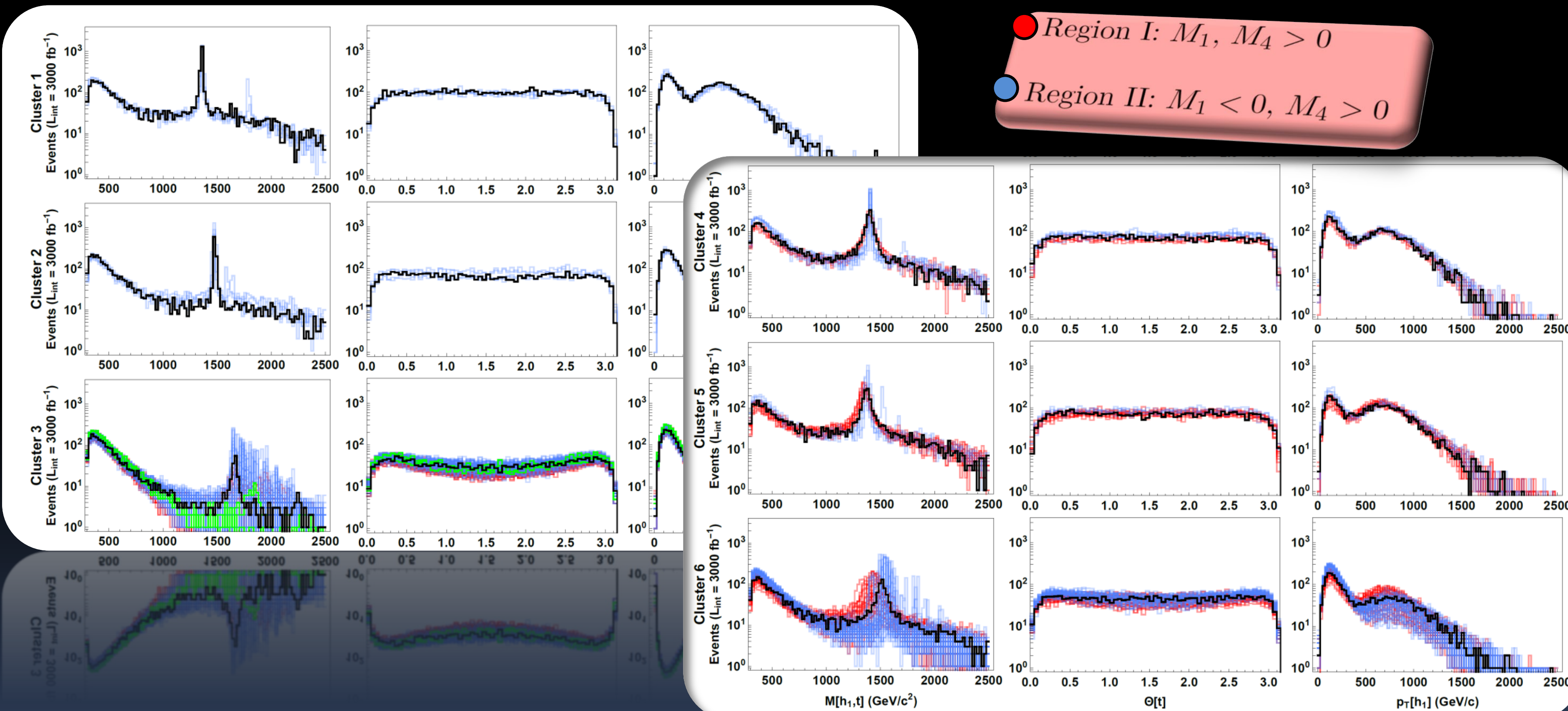
C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

Ideal clustering found for: N = 11; variables: $M[t,h]$ & $\theta[t]$

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)

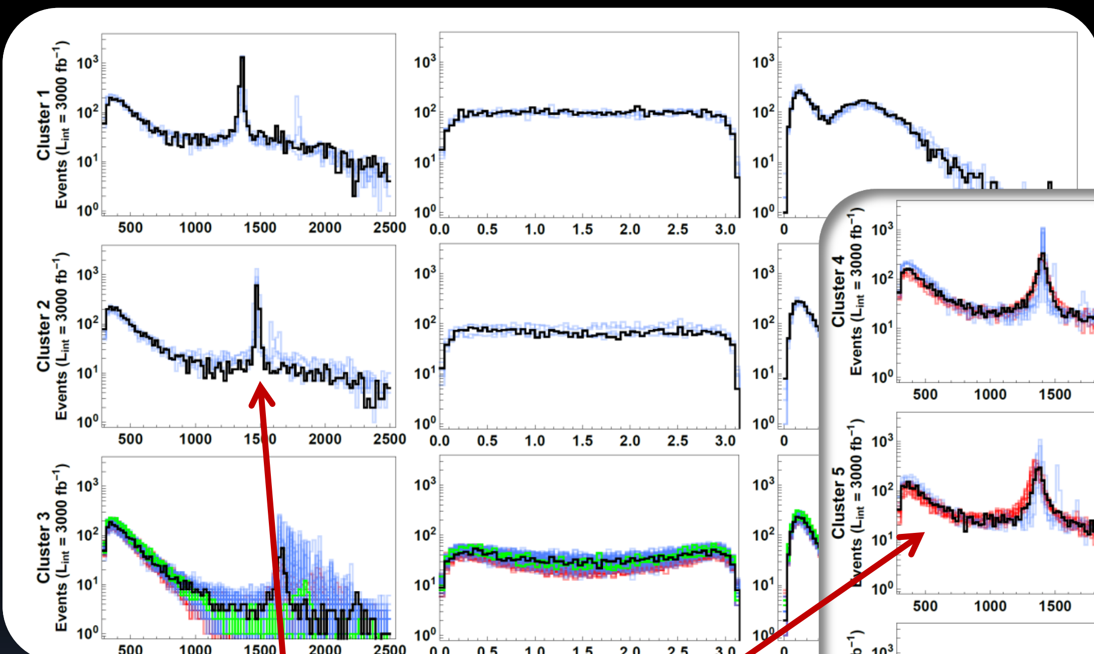
Ideal clustering found for: N = 11; variables: *M[t,h]* & $\theta[t]$



Clustering for the $MCHM_5$ (low scale)

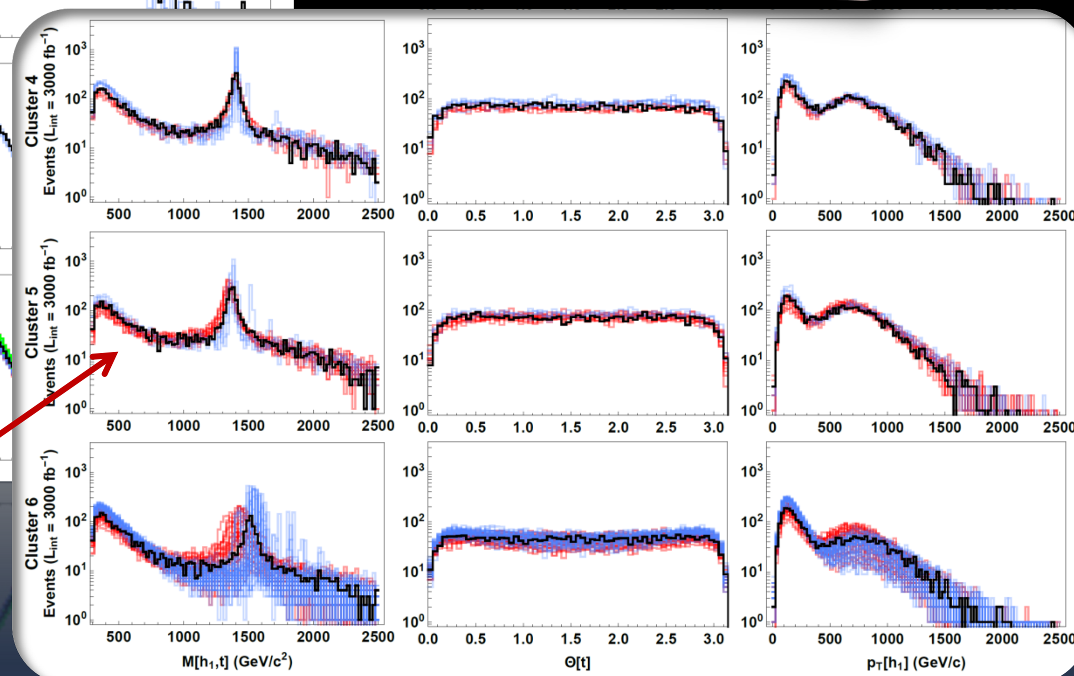
C. Bautista, L. de Lima, R. D. Matheus, E. Pontón, L. A. F. do Prado, A Savoy-Navarro. JHEP 2021, 49 (2021)

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



Region I: $M_1, M_4 > 0$

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

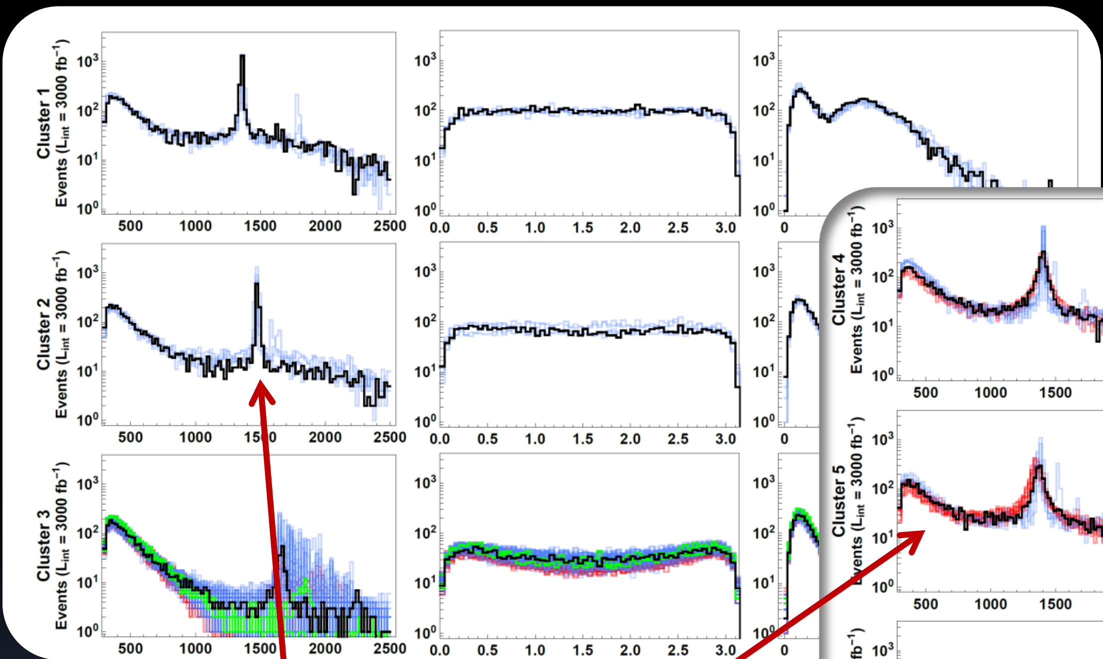


Roughly separates regions I and II

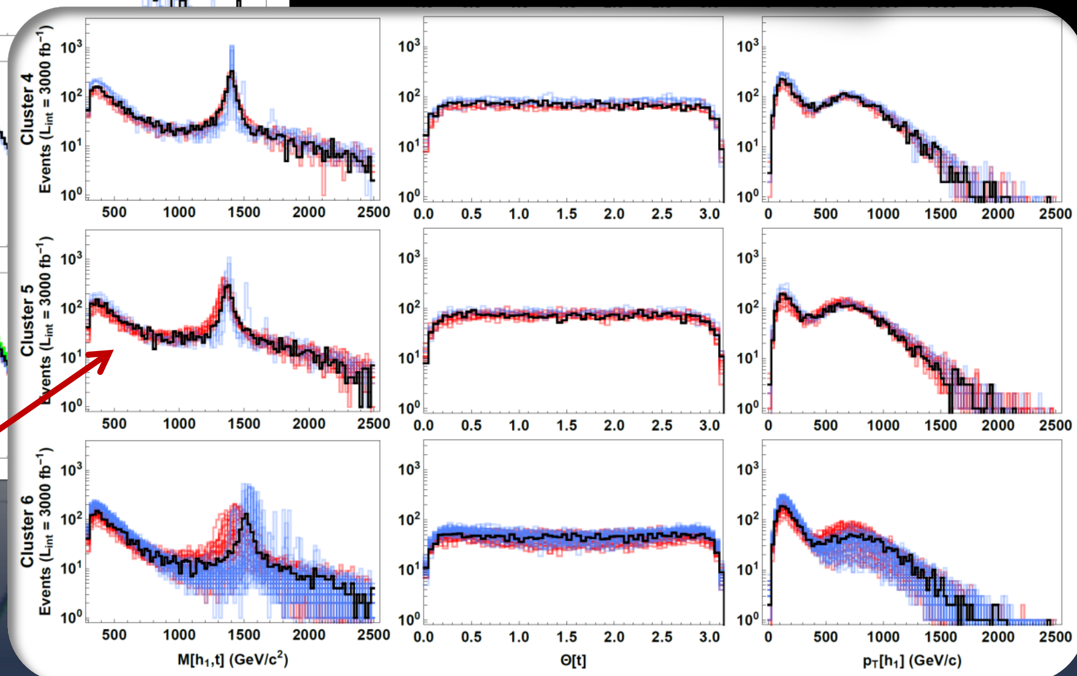
Clustering for the $MCHM_5$ (low scale)

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]* & $\theta[t]$



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



Region I resonances are wider!

R.D.Matheus

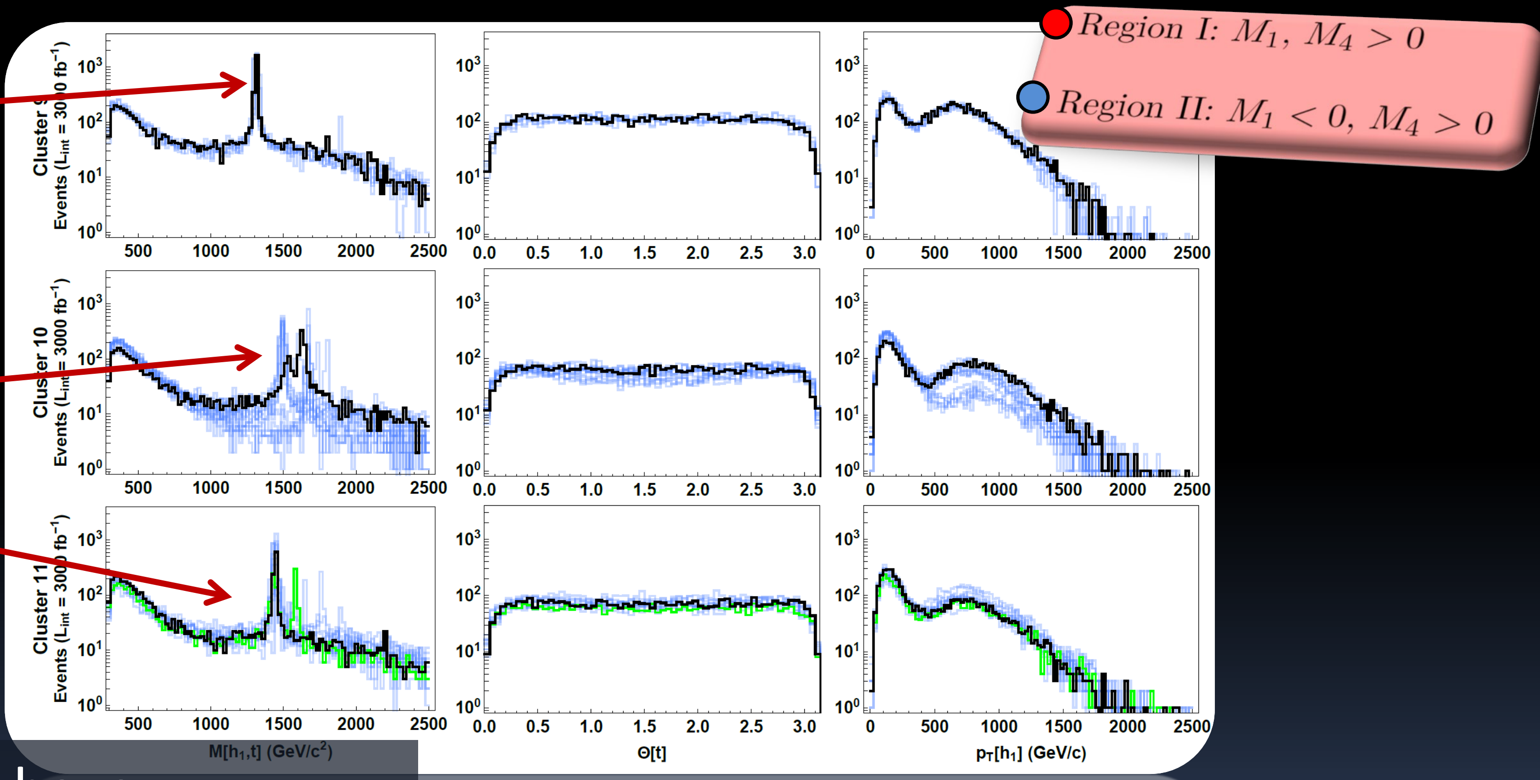
Clustering for the MCHM$_5$ (low scale)

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($T^{(1)} \to th$)		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

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
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$M_{B^{(1)}}$ (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
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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)

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Benchmark points

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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}
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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
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$M_{B^{(1)}}$ (TeV)		1.74	3.87	2.68	3.55	2.60	3.10	3.22	2.16	1.99	1.62	2.22
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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)

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
parameters	M_1(GeV)	-1323	-1809	-1483	2965	2882	2999
	M_4(GeV)	1357	1479	2235	1370	1339	1479
	f(GeV)	1199	1593	1071	1393	1220	1168
	y_L	0.91	2.25	1.38	2.35	1.83	2.33
	y_R	0.88	0.58	0.72	3.38	3.57	3.28
$\mu(t\bar{t}h)$ (All Energies)		0.90	0.94	0.86	0.83	0.78	0.79
$\mu(t\bar{t}hh)$ (14 TeV)		2.14	1.47	0.80	1.51	1.53	1.02
$\mu(t\bar{t}hh)$ (100 TeV)		14.58	8.84	3.28	10.28	11.18	7.04
NR-$t\bar{t}hh/t\bar{t}hh$ (14 TeV)		0.37	0.59	0.88	0.45	0.40	0.61
NR-$t\bar{t}hh$/[illegible]		[illegible]	0.10	0.22	[illegible]	[illegible]	[illegible]
$M_{T^{(1)}}$ (TeV)		1.36	1.48	1.66	1.40	1.38	1.51
$M_{T^{(2)}}$ (TeV)		1.63	2.02	2.24	3.55	2.61	3.10
$M_{T^{(3)}}$ (TeV)		1.79	3.88	2.68	5.55	5.21	4.85
$M_{B^{(1)}}$ (TeV)		1.74	3.87	2.68	3.55	2.60	3.10
$M_{X_{5/3}}$ (TeV)		1.36	1.48	2.24	1.37	1.34	1.48
$\Gamma_{T^{(1)}}$ (GeV)		8.83	5.49	26.22	51.92	60.01	71.68
BR($T^{(1)} \to th$)		0.49	0.45	0.31	0.44	0.43	0.42
BR($T^{(1)} \to W^+b$)		0.018	0	0.47	0.004	0.004	0.003
BR($T^{(1)} \to tZ$)		0.39	0.41	0.22	0.42	0.43	0.42
BR($T^{(1)} \to W^+W^-t$)		0.11	0.13	0	0.13	0.13	0.16

		C_7	C_8	C_9	C_{10}	C_{11}
parameters	M_1(GeV)	3000	-1400	-1618	-2384	-2892
	M_4(GeV)	1295	1339	1309	1519	1437
	f(GeV)	1484	1265	1229	1110	1646
	y_L	1.98	1.34	1.22	0.51	1.03
	y_R	3.25	0.66	0.74	2.30	0.85
$\mu(t\bar{t}h)$ (All Energies)		0.84	0.91	0.90	0.81	0.94
$\mu(t\bar{t}hh)$ (14 TeV)		2.00	2.25	2.41	1.39	1.58
$\mu(t\bar{t}hh)$ (100 TeV)		13.42	15.20	16.11	13.68	10.57
NR-$t\bar{t}hh/t\bar{t}hh$ (14 TeV)		0.35	0.36	0.33	0.46	0.55
NR-$t\bar{t}hh$/[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	0.08
$M_{T^{(1)}}$ (TeV)		1.32	1.34	1.31	1.54	1.44
$M_{T^{(2)}}$ (TeV)		3.22	1.61	1.80	1.63	2.20
$M_{T^{(3)}}$ (TeV)		5.67	2.17	2.02	3.47	3.21
$M_{B^{(1)}}$ (TeV)		3.22	2.16	1.99	1.62	2.22
$M_{X_{5/3}}$ (TeV)		1.29	1.34	1.31	1.52	1.44
$\Gamma_{T^{(1)}}$ (GeV)		44.33	6.44	7.49	43.78	10.63
BR($T^{(1)} \to th$)		0.44	0.47	0.47	0.34	0.45
BR($T^{(1)} \to W^+b$)		0.006	0.024	0.016	0.005	0.010
BR($T^{(1)} \to tZ$)		0.43	0.40	0.41	0.50	0.41
BR($T^{(1)} \to W^+W^-t$)		0.12	0.10	0.10	0.14	0.12

3-body decays

The b channel is also mostly suppressed

R.D.Matheus

Clustering for the $MCHM_5$ (high 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: $M_1 < 0, M_4 > 0$

		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)

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: $M_1 < 0,\ M_4 > 0$

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
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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
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	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

	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}
$M_{T^{(1)}}$ (TeV)	2.45	2.12	3.21	3.23	4.07	4.28	5.08	5.15	11.0	11.3
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$M_{T^{(3)}}$ (TeV)	22.8	19.7	20.6	23.1	26.9	22.8	19.5	13.7	26.4	27.8
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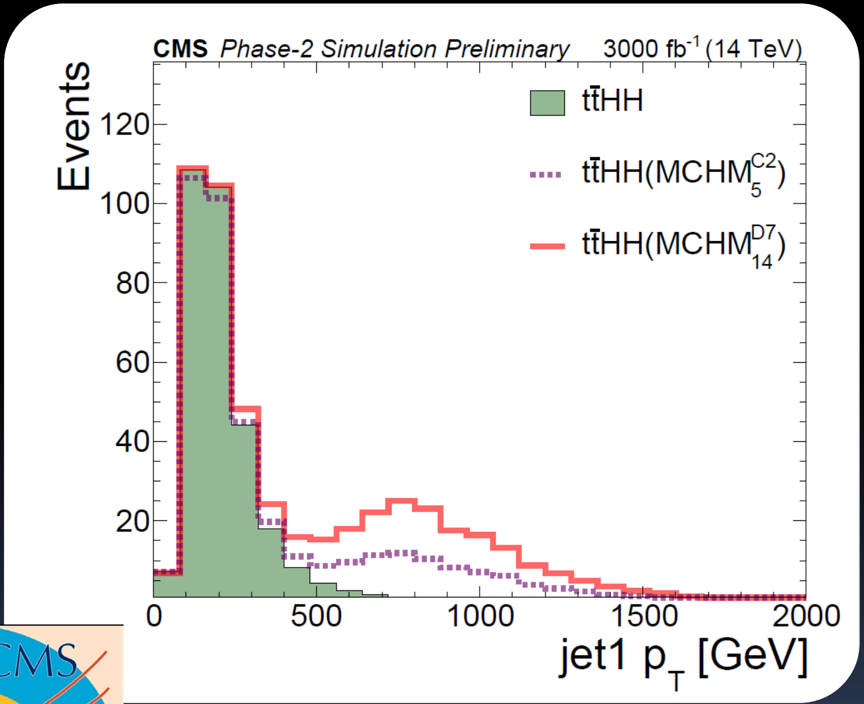
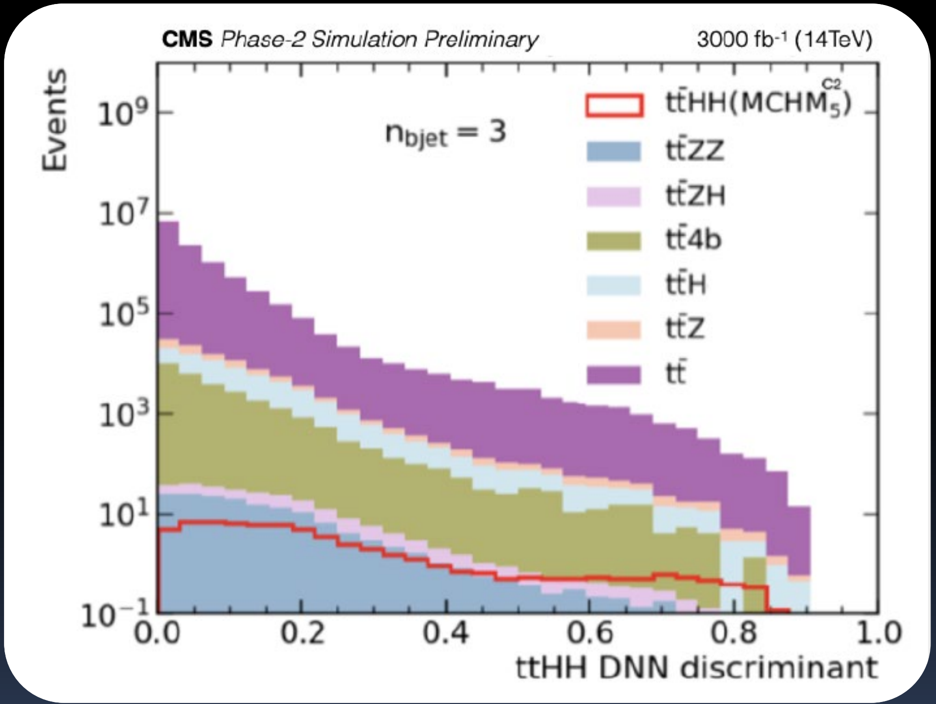
BR($T^{(1)} \to W^+b$)	0.003	0.004	0	0.001	0	0.50	0	0	0.50	0
BR($T^{(1)} \to tZ$)	0.34	0.37	0.28	0.28	0.33	0.25	0.18	0.18	0.25	0.06
BR($T^{(1)} \to W^+W^-t$)	0.30	0.25	0.43	0.43	0.52	0	0.64	0.65	0	0.89

Interface with Experiments

CMS Collaboration, Snowmass White Paper Contribution, CMS-PAS-FTR-22-001 (2022)
CMS Collaboration, Search for the nonresonant tbar t HH production […] at the HL-LHC, CMS-PAS-FTR-21-010 (2022)

Benchmark points C2 ($MCHM_5$) and D7 ($MCHM_{14}$) where implemented in ongoing experimental search for $\bar{t}tHH$

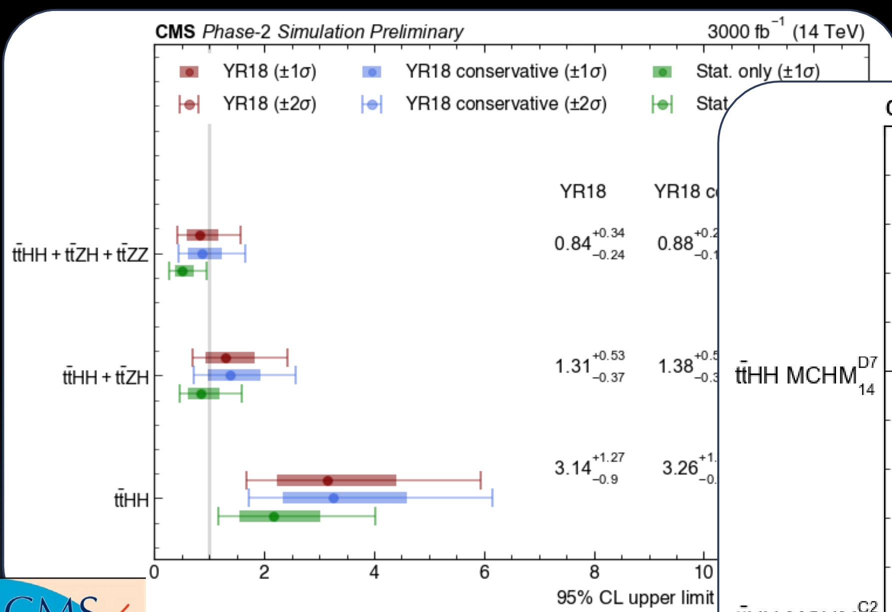


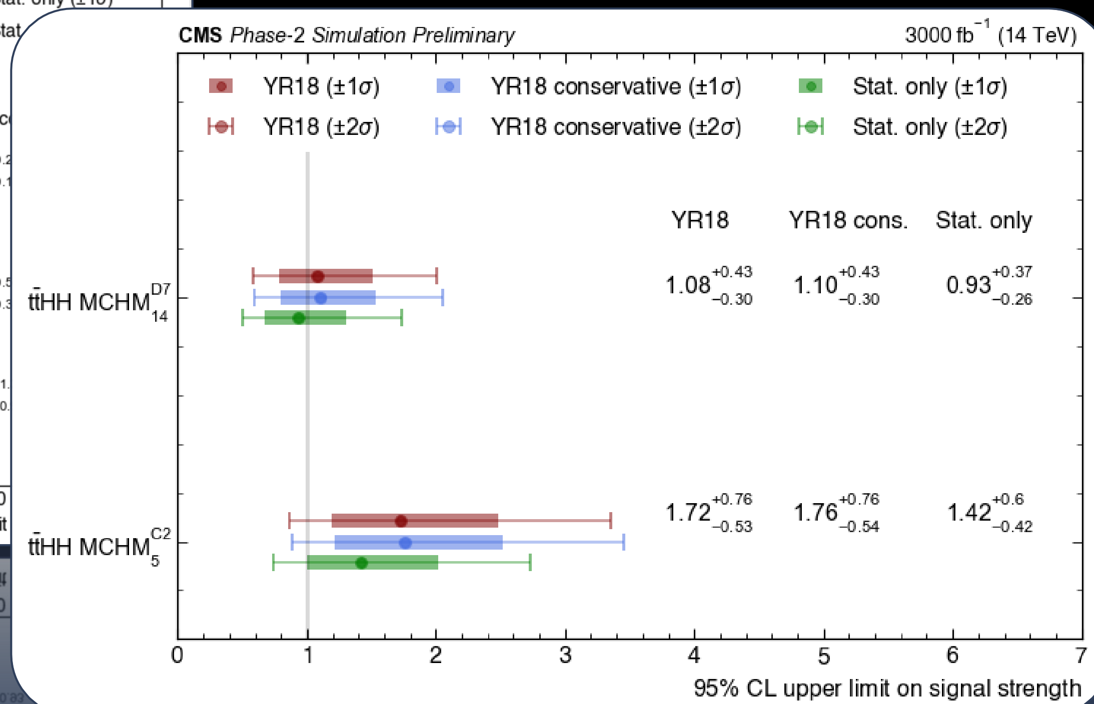


Interface with Experiments

CMS Collaboration, Snowmass White Paper Contribution, CMS-PAS-FTR-22-001 (2022)
CMS Collaboration, Search for the nonresonant tbar t HH production […] at the HL-LHC, CMS-PAS-FTR-21-010 (2022)

Benchmark points C2 ($MCHM_5$) and D7 ($MCHM_{14}$) where implemented in ongoing experimental search for $\bar{t}tHH$





Conclusions

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

Extras

Log-likelihood ratio

Probability of observing $n_{i,1}$, $n_{i,2}$, given: $\hat{\mu}_i = (n_{i,1} + n_{i,2})/2$ (maximum likelihood estimate for the expected contents in bin i)

$$Pois(n_{i,1}|\hat{\mu}_i) \times Pois(n_{i,2}|\hat{\mu}_i) = \underbrace{Pois(n_{i,1} + n_{i,2})}_{\text{Ancillary statistic}} \times Binomial(n_{i,1}/(n_{i,1} + n_{i,2})).$$

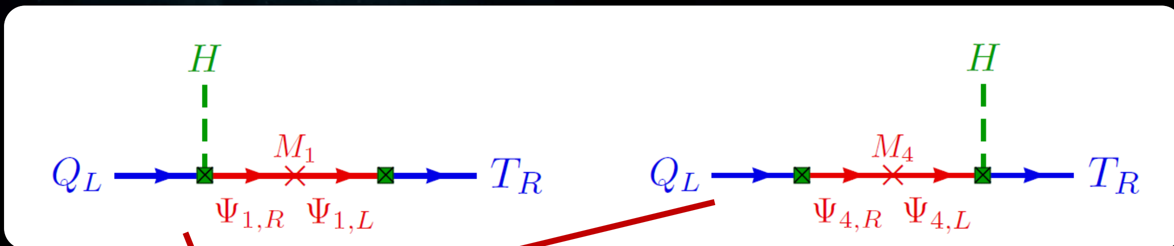
$$L = Binomial(n_{i,1}/(n_{i,1} + n_{i,2})) = \frac{(n_{i,1} + n_{i,2})!}{n_{i,1}!n_{i,2}!} \left(\frac{1}{2}\right)^{n_{i,1}} \left(\frac{1}{2}\right)^{n_{i,2}}$$

Saturated hypothesis: $L_S = Binomial(n_{i,1} = n_{i,2} = \hat{\mu}_i) = \frac{(2\hat{\mu}_i)!}{(\hat{\mu}_i!)^2} \left(\frac{1}{2}\right)^{2\hat{\mu}_i}$

$$TS = 2\ log\left(\frac{L}{L_S}\right) = -2 \sum_{i=1}^{N_{bins}} \left[log(n_{i,1}!) + log(n_{i,2}!) - 2log\left(\frac{n_{i,1} + n_{i,2}}{2}!\right)\right]$$

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

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$_5$

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

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

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

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

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

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

$$+ f\, \overline{T}^{\mathbf{5}}_R U \left[y_{R4} \Psi_{\mathbf{4}} + y_{R1} \Psi_{\mathbf{1}} \right] + \text{h.c}$$

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

MCHM_{14}

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

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

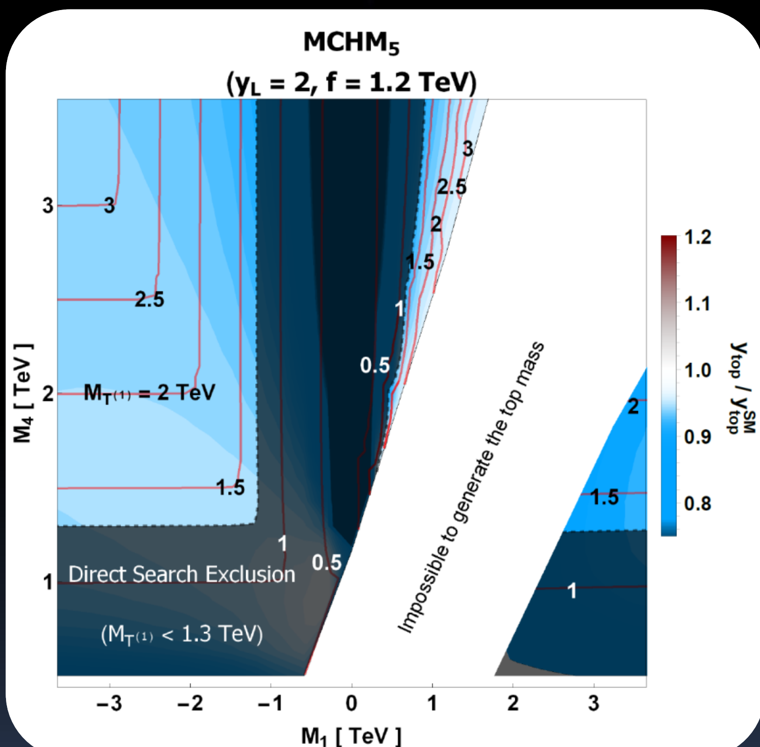
$$\mathcal{L}^{\mathbf{14}}_{\text{comp}} = \mathcal{L}^{\mathbf{5}}_{\text{comp}} + \text{Tr}\left[\overline{\Psi}_{\mathbf{9}}\left(i\not{D}\Psi_{\mathbf{9}} - i\left[\not{e}, \Psi_{\mathbf{9}}\right]\right)\right] - M_9 \text{Tr}\left[\overline{\Psi}_{\mathbf{9}}\Psi_{\mathbf{9}}\right]$$

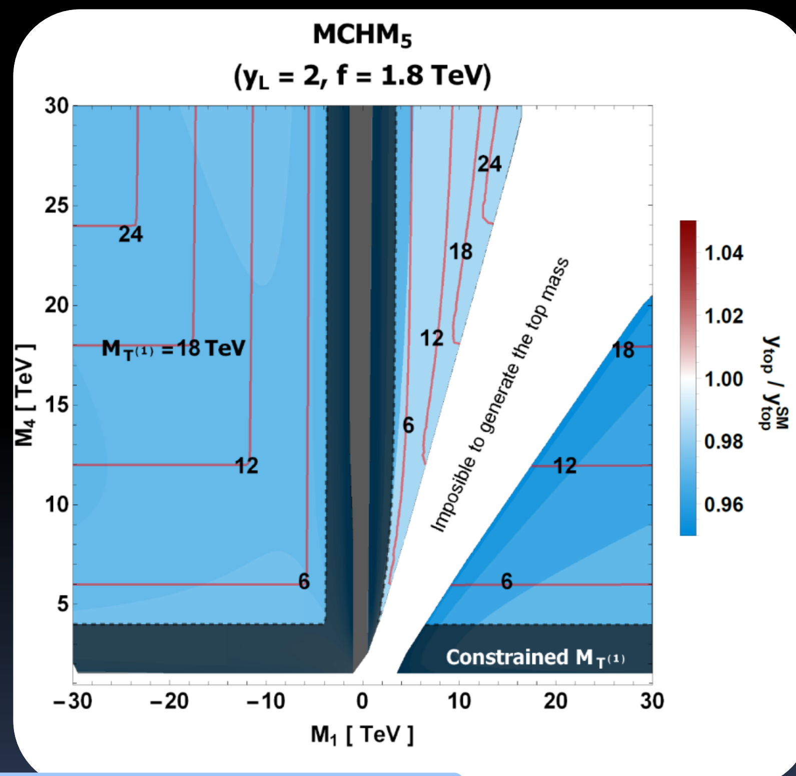
$$\begin{aligned}\mathcal{L}^{\mathbf{14}}_{\text{mix}} &= f\, \text{Tr}\left[U^{\intercal}\overline{Q}^{\mathbf{14}}_{L} U\left(y_{L9}\Psi_{\mathbf{9}} + y_{L4}\Psi_{\mathbf{4}} + y_{L1}\Psi_{\mathbf{1}}\right)\right] + \text{h.c.} \\ &+ f\, \text{Tr}\left[U^{\intercal}\overline{T}^{\mathbf{14}}_{R}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

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

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.





$$0.69 \leq c_g \leq 1.33$$

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

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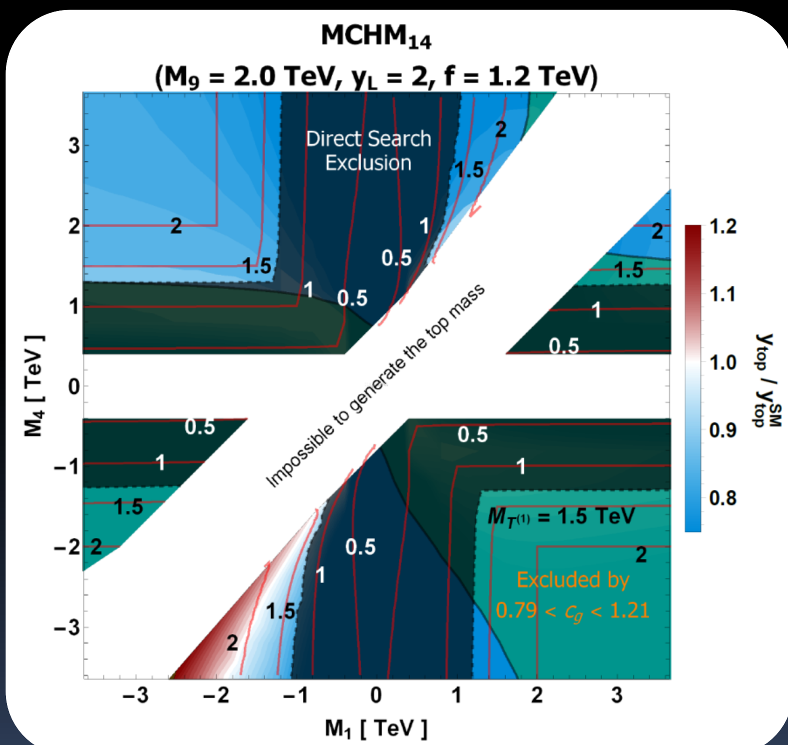
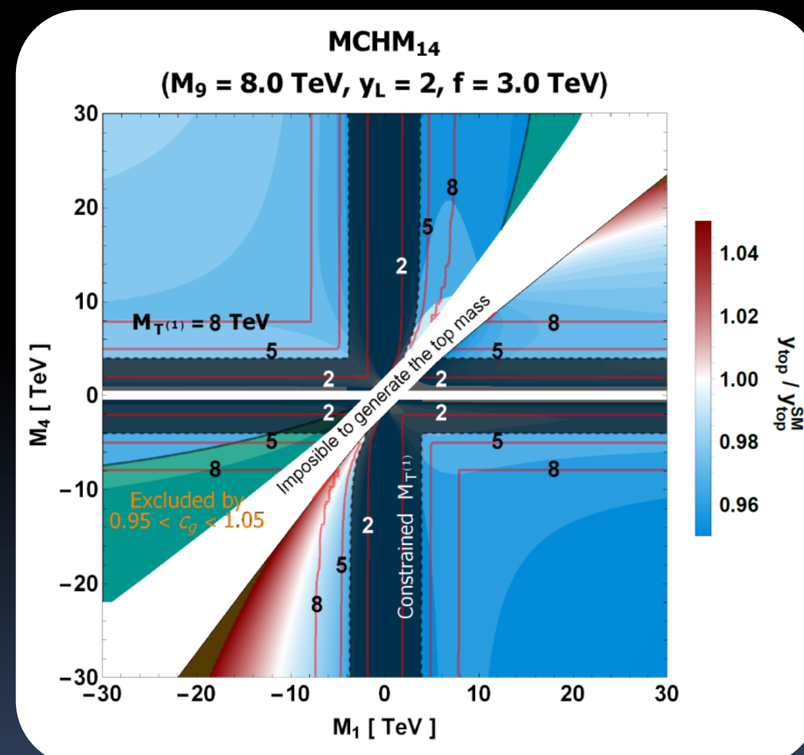
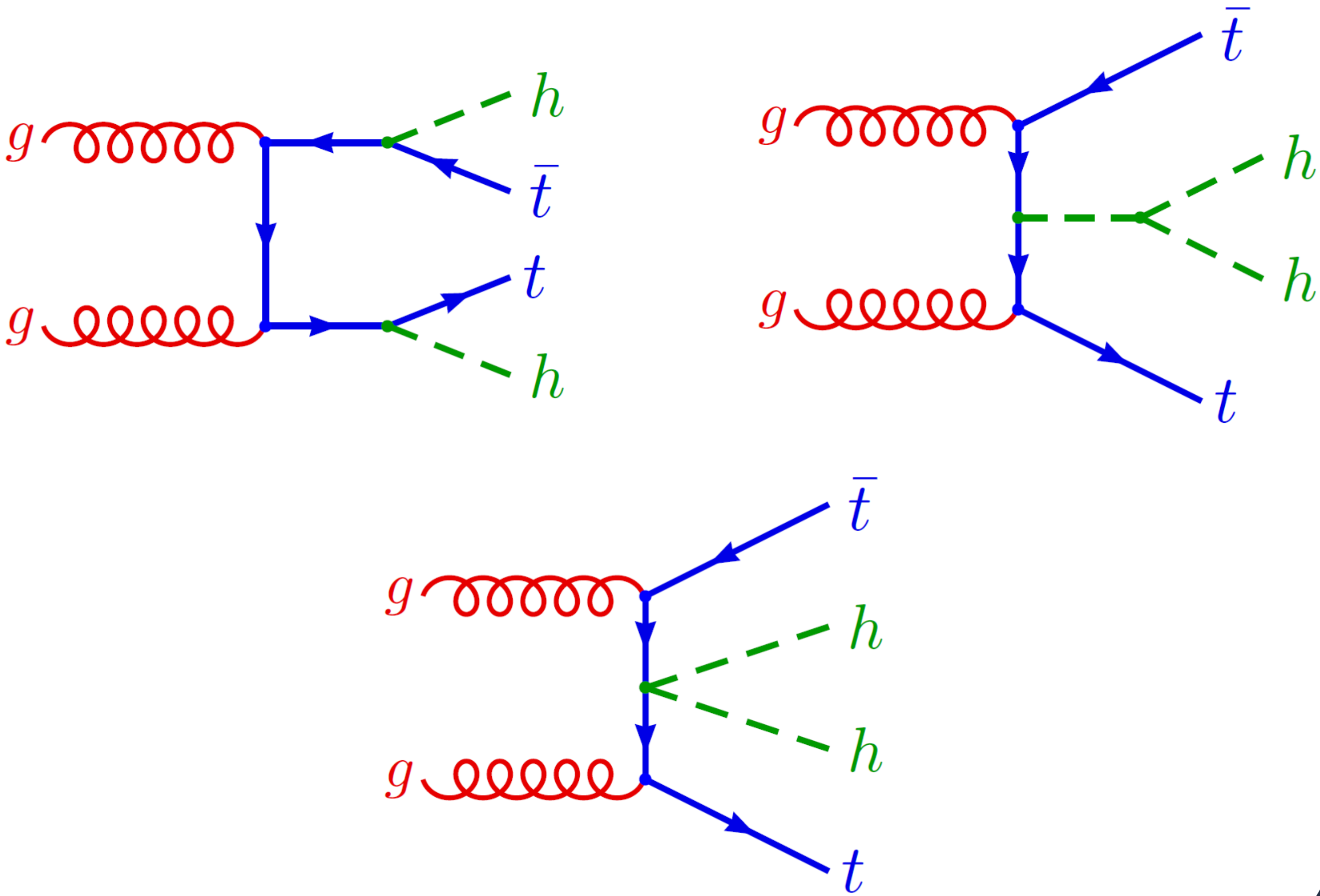
Constraints $MCHM_{14}$

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 (ggH coupling) measurements in the left and by the c_g expected constraints in the right.





tthh process



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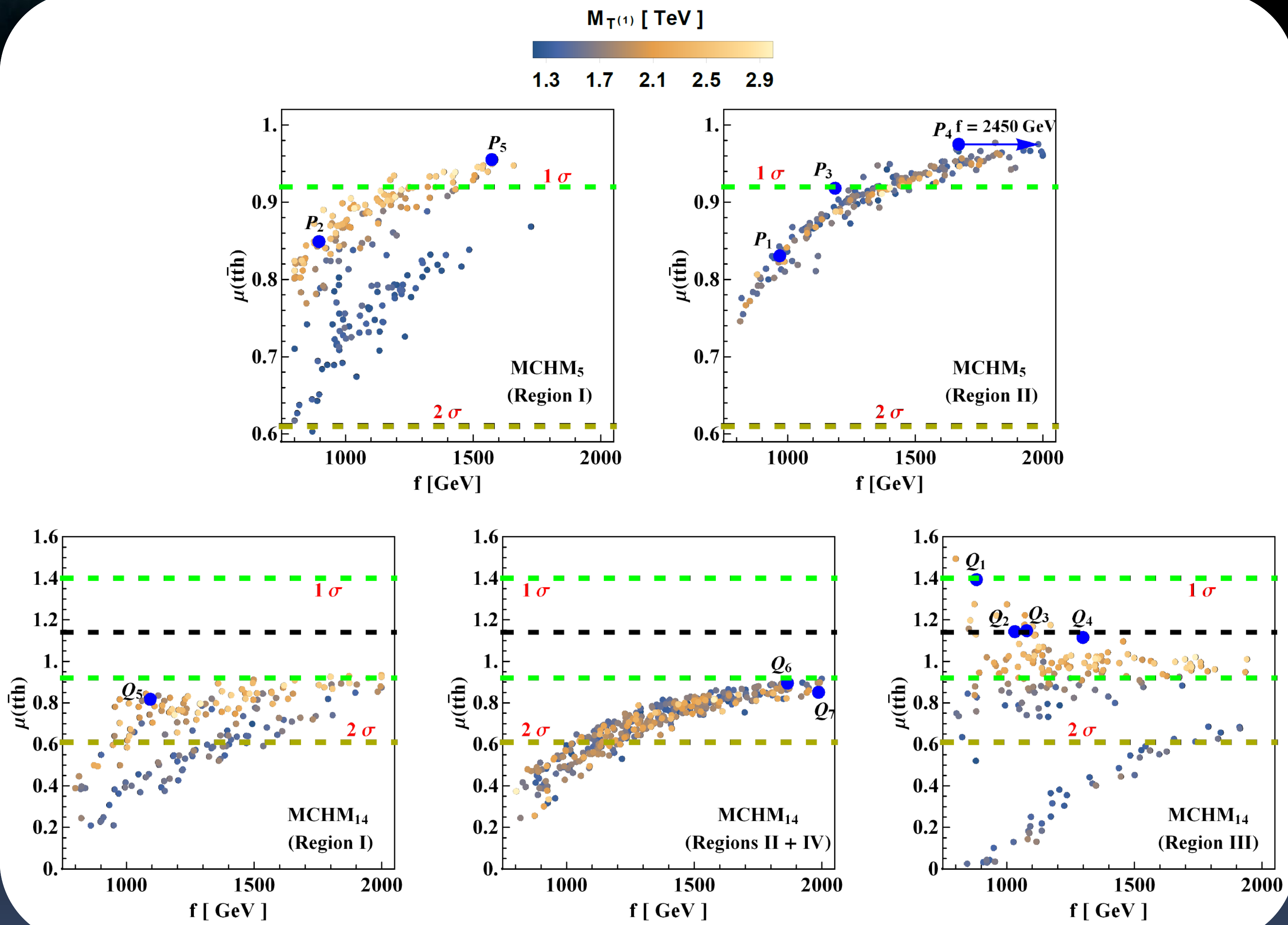
tth



M T(1) [TeV]
1.3 1.7 2.1 2.5 2.9
μ(tt̄h)
f [GeV]
P5
P2
1 σ
2 σ
MCHM5
(Region I)
P4 f = 2450 GeV
P3
P1
MCHM5
(Region II)
Q5
MCHM14
(Region I)
Q6
Q7
MCHM14
(Regions II + IV)
Q1
Q2
Q3
Q4
MCHM14
(Region III)
f [GeV]

NR-tthh

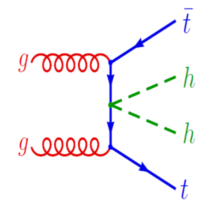
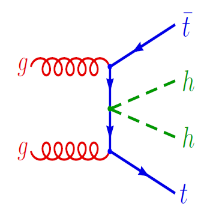
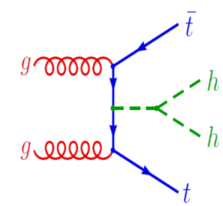
		P_1	P_2	P_3	P_4	P_5	Disregarded diagrams
$\sigma_{\not{hh}}/\sigma^{t\bar{t}hh}_{\rm NR}$ $\sigma_{\not{hh}}/\sigma^{t\bar{t}hh}_{\rm NR}$	(14 TeV) (100 TeV)	1.05 1.05	1.04 1.03	1.03 1.03	1.01 1.01	1.01 1.01	
$\sigma_{\rm Yuk}/\sigma^{t\bar{t}hh}_{\rm NR}$ $\sigma_{\rm Yuk}/\sigma^{t\bar{t}hh}_{\rm NR}$	(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 $\rm MCHM_5$ points in table 1. The cross sections $\sigma_{\not{hh}}$ 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.

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EFT

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

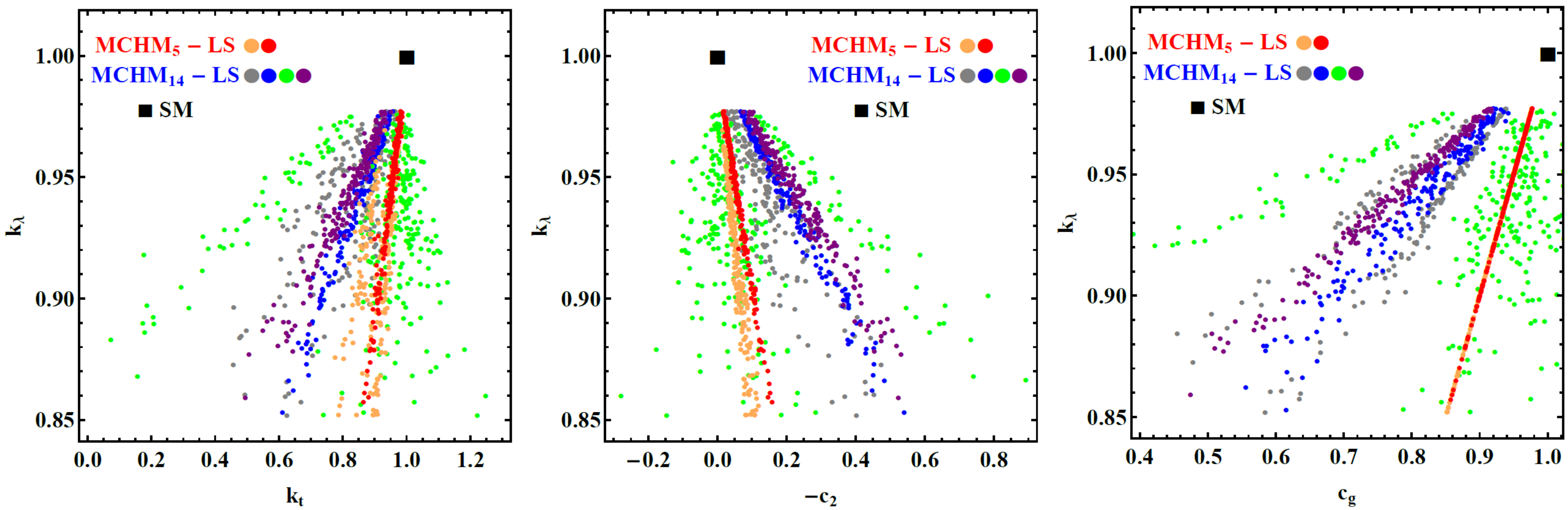

Figure 20. Values of some selected EFT parameters in the low scale scan of the $MCHM_5$ and the $MCHM_{14}$ parameter spaces. The colors indicate the different Regions in each model (I and II for the $MCHM_5$ and I, II, III and IV for the $MCHM_{14}$, in that order). The SM is represented by the black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