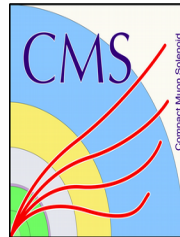


# *Hunting Higgs & Supersymmetry with the CMS detector*

**Dr. Pedrame Bargassa**  
**CMS collaboration, LIP - Lisbon**

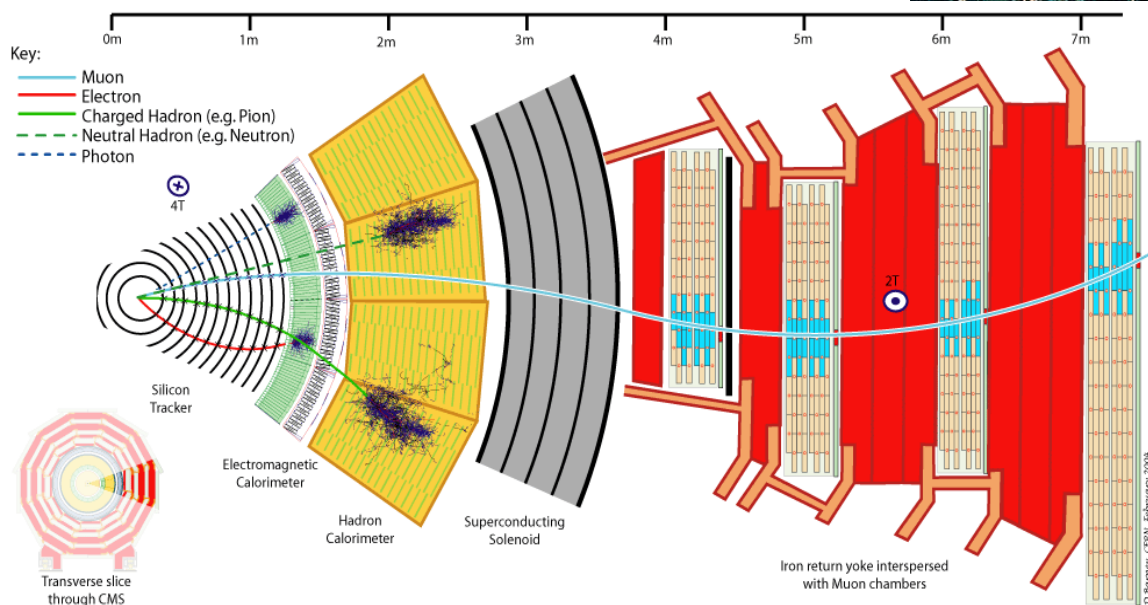
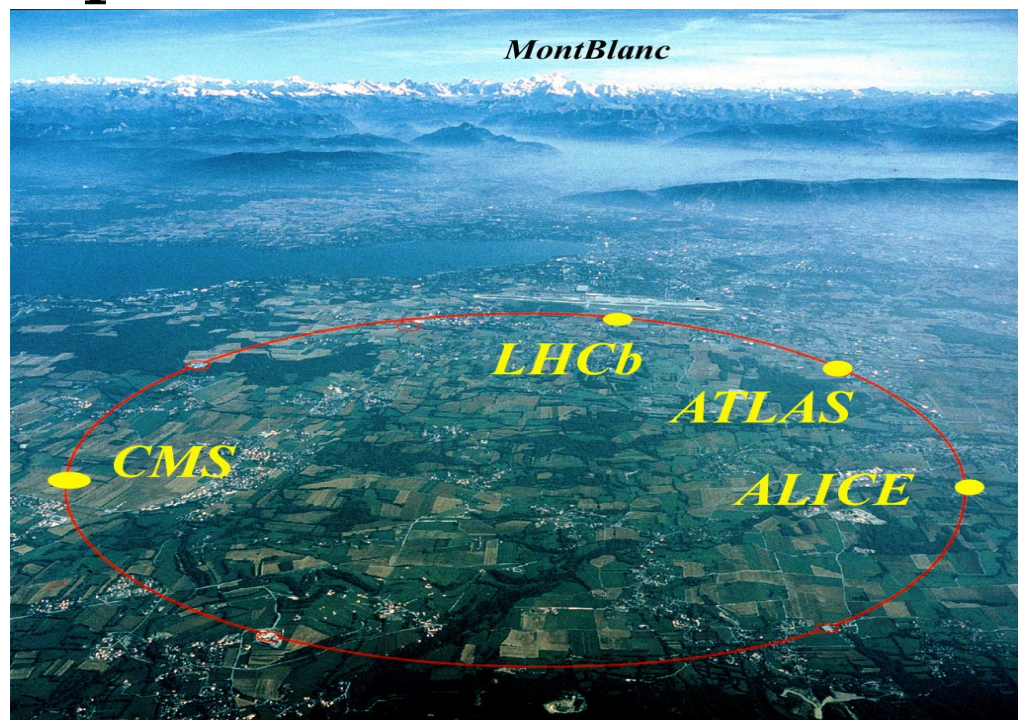


- ***Introduction to HEP searches***
- ***Susy search:***
  - ***Susy hunt: Stop***
- ***Higgs search:***
  - ***Double-Higgs***
  - ***$H \rightarrow 2 \tau$***
- ***Why are these interesting***
- ***How do-we hunt them:  
Multi-Variate Analysis tools***



# How do-we search for new particles

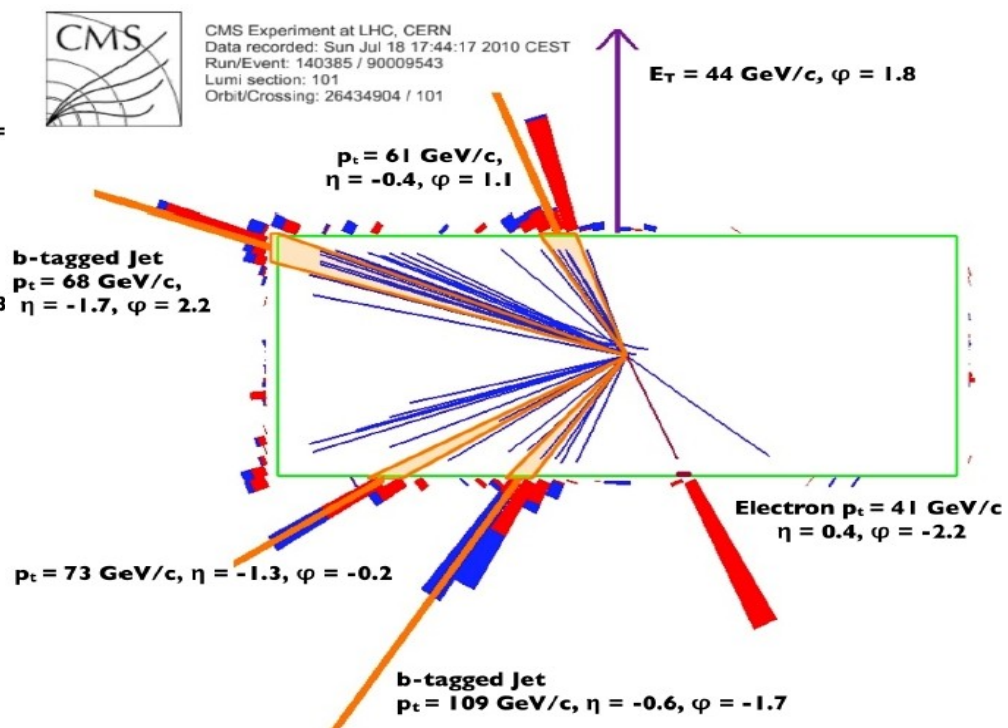
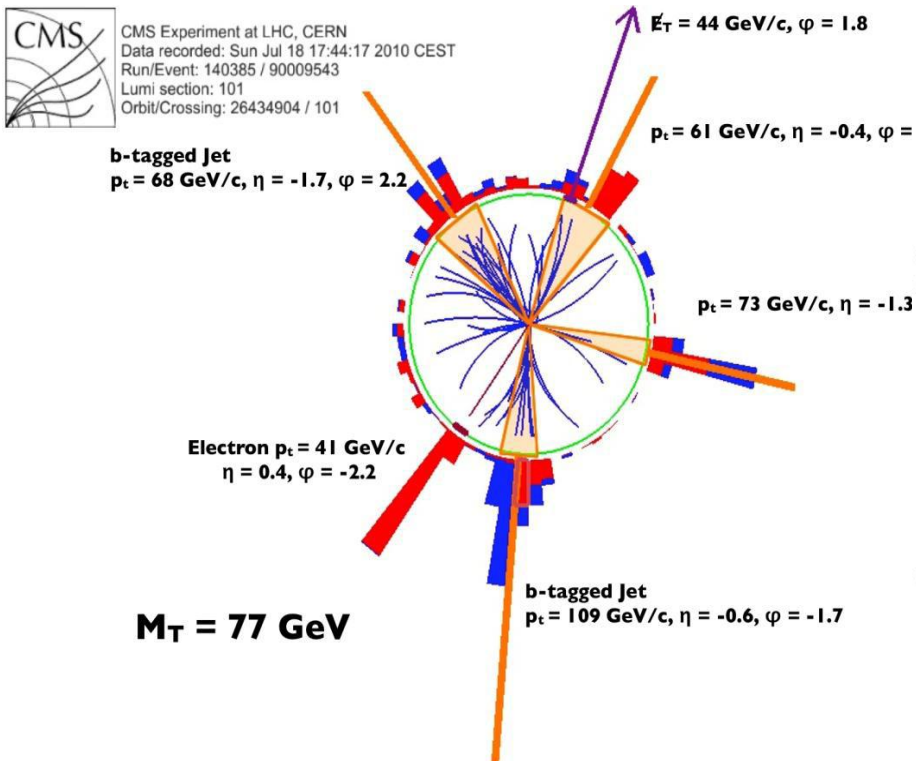
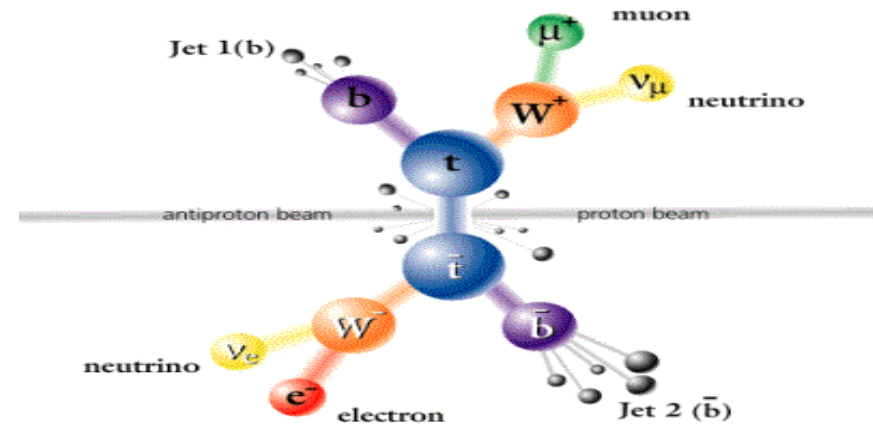
- **Collide** protons:  
Produce higher mass particles which would not exist @ our energies
- i.e. if new ones would exist @ our energies/“temperatures”, we would now since long time ;-)



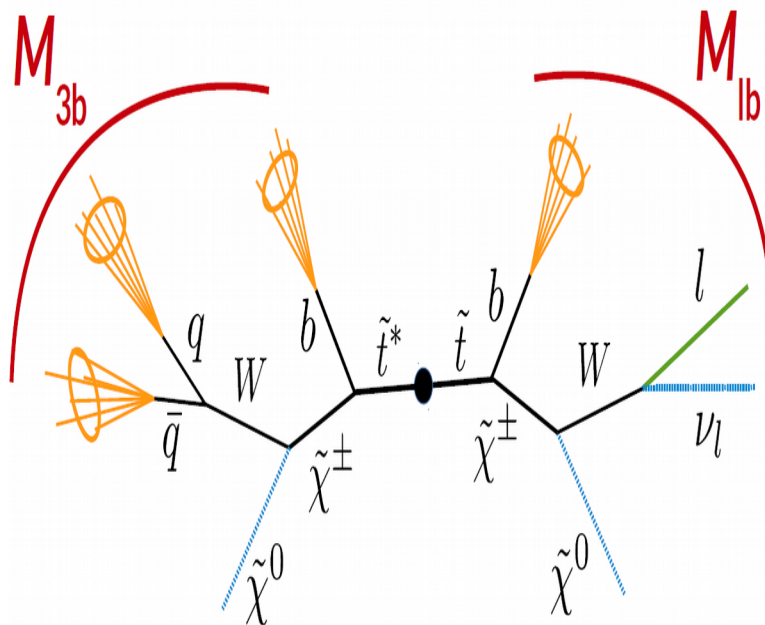
- $\sim 11000$  rev/s
- Every 25 ns
- “Focus” of the beams:  
 $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- $\sqrt{s} = 13 \text{ TeV}$

# How do-we search for new particles

- **Reconstruct** produced particles:
  - 1<sup>st</sup> the daughter particles, having interacted in detector
  - 2<sup>nd</sup>: From them, the mother particles
- **Reconstruct** kinematics



# How do-we search for new particles

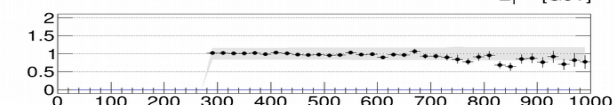
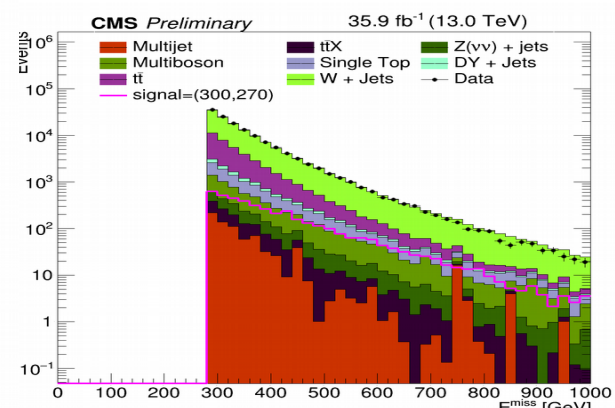
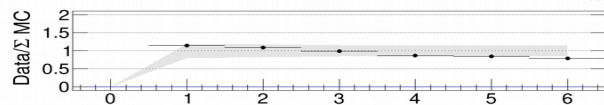
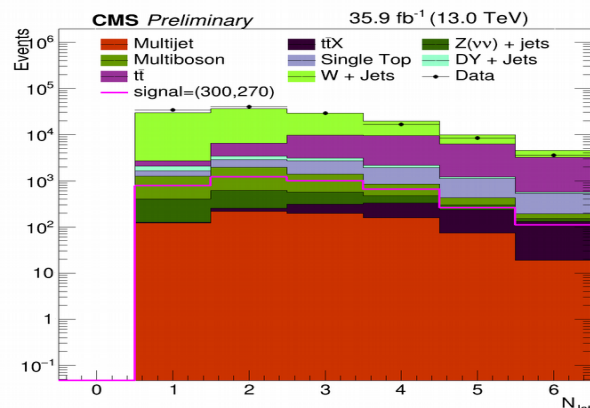
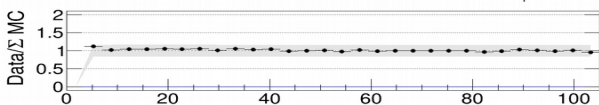
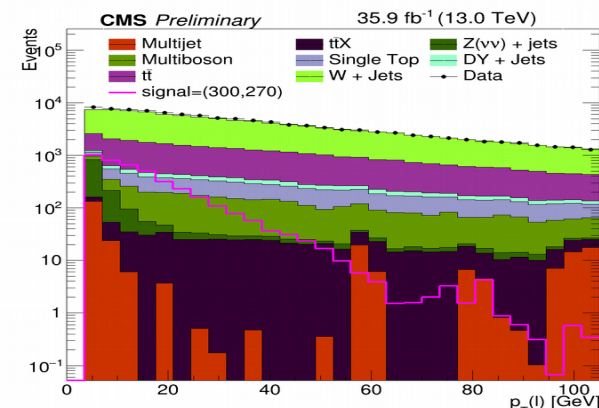


➤ **Sign** wanted events

➤ Here, we are looking for events with **4 jets**, **1 lepton** & **missing energy**

➤ **Careful !** SM does imitate this **signature** while not being Susy...

➤ Each measurable quantity in this event might be a precious source of information, i.e. disentangle between Signal & Background



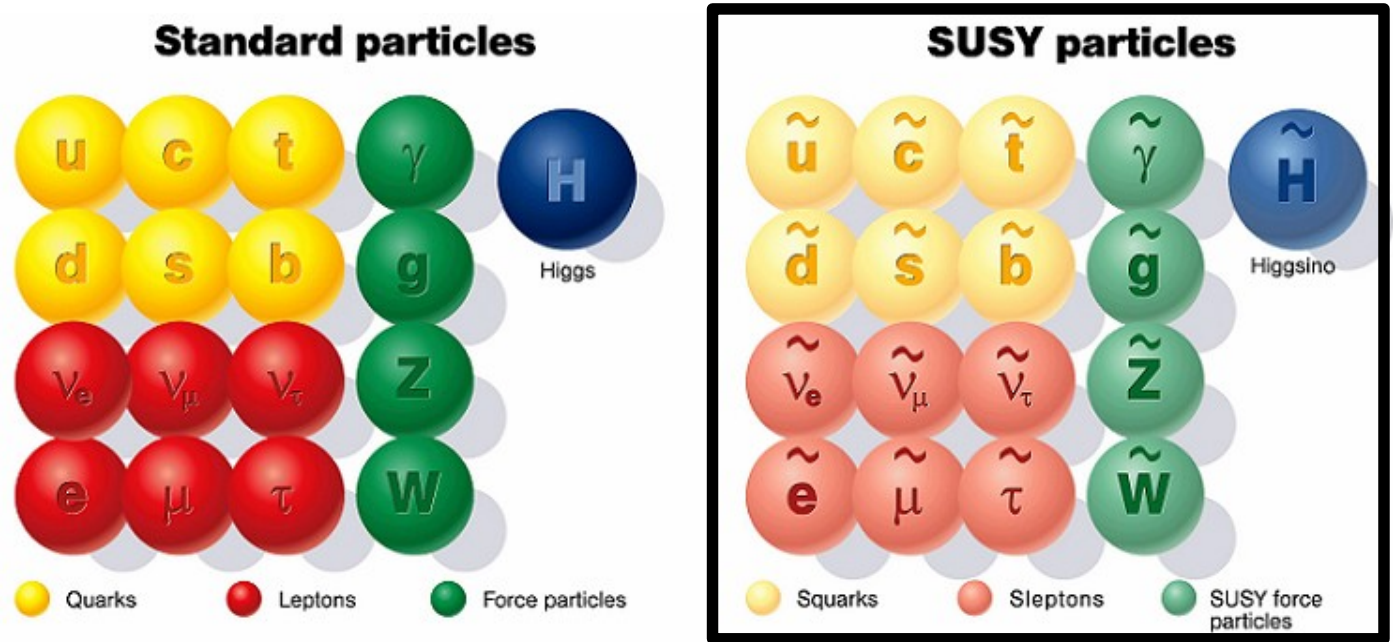


# ***SUperSYmmetry***



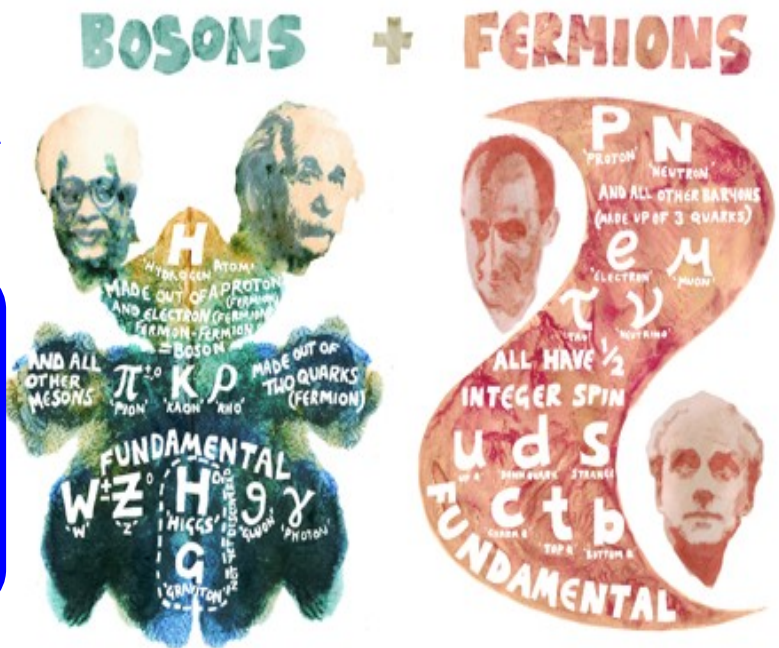
P. Bargassa, C. da Cruz e Silva, D. de Bastos

# SUPerSYmmetry: What it is



Matter fields could also exist in bosonic form  
Force carriers also exist in fermionic form

**SUSY:**  
Simple spin symmetrization  
between what we know of matter  
& force carrier fields/particles

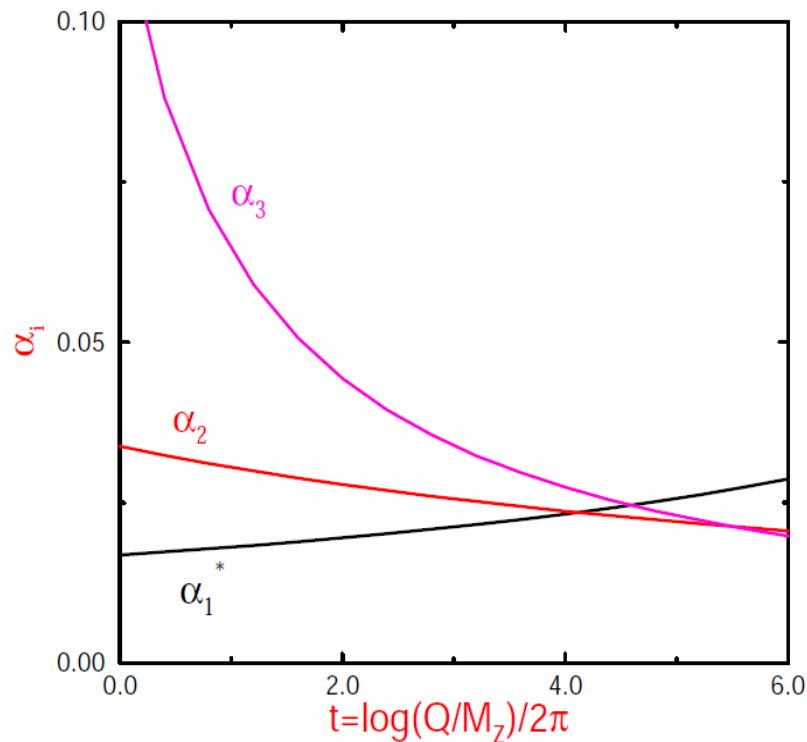




Present  
Billion Years  
3°K

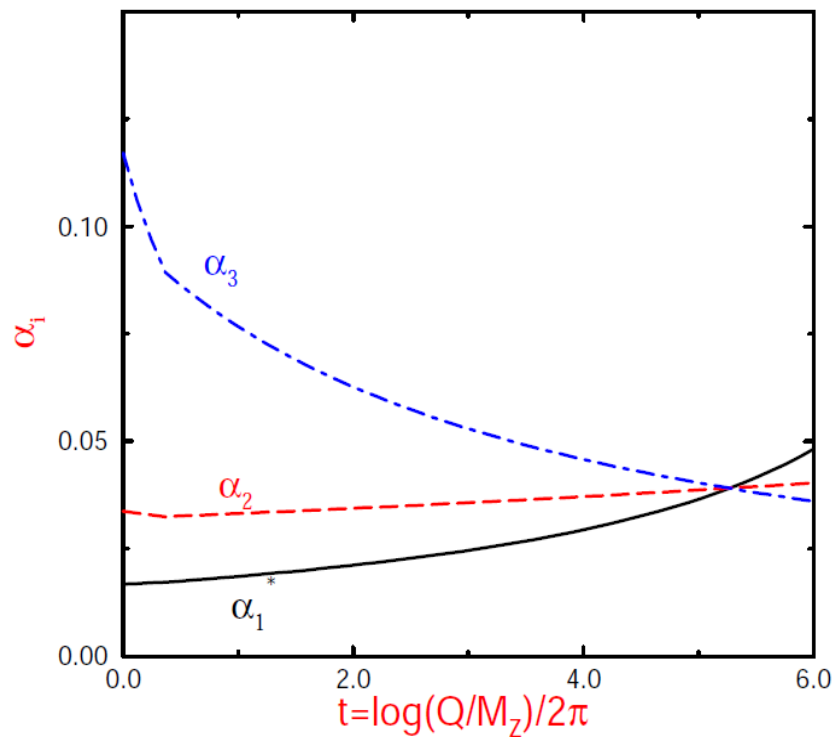
# SUSY

Coupling Constant Evolution  
Standard Model



Unifies the different interactions... quite elegantly

Coupling Constant Evolution  
SUSY Model



History of the Universe

1 Billion Years  
Matter-Radiation  
becomes Transparent  
Formation of Quarks  
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# SUSY

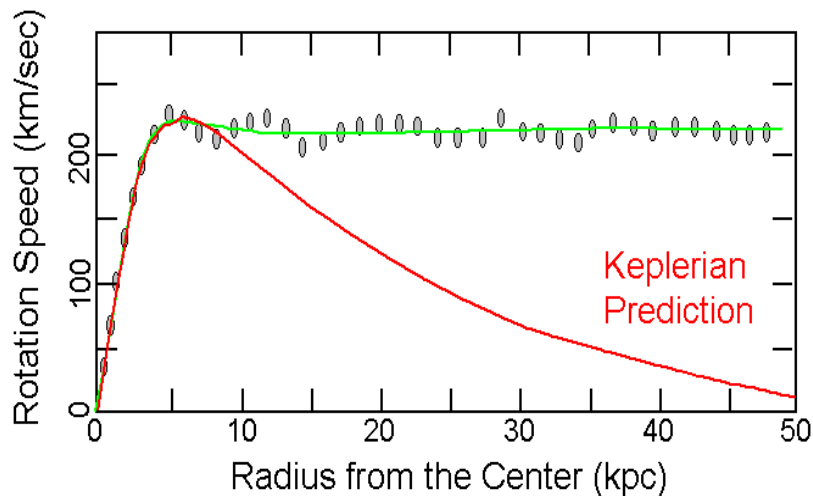
## Has natural candidate(s) for the Cold Dark Matter

Sneutrino: Susy partner of the neutrino  $\nu$

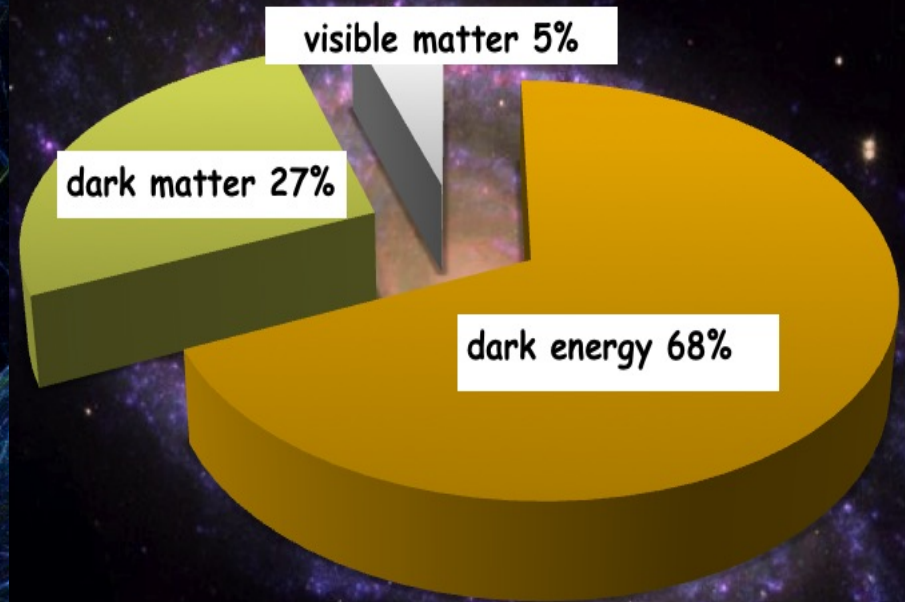
Neutralino: Mixture of partners of neutral SM bosons

...

Observed vs. Predicted Keplerian

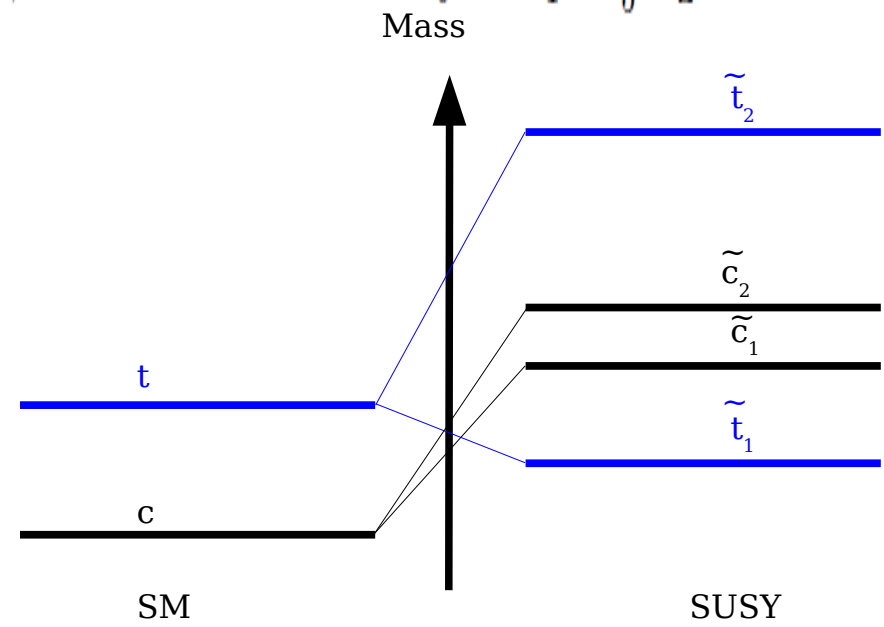


Universe content



# SUSY search: One of our best bets

$$M_{\tilde{t}}^2 = \begin{pmatrix} \tilde{M}_Q^2 + M_T^2 + M_Z^2(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)\cos 2\beta & M_T(A_T + \mu \cot \beta) \\ M_T(A_T + \mu \cot \beta) & \tilde{M}_U^2 + M_T^2 + \frac{2}{3}M_Z^2\sin^2\theta_W\cos 2\beta \end{pmatrix}$$



## Mass difference of squarks:

Proportional to  $M_Q = M_t$  :

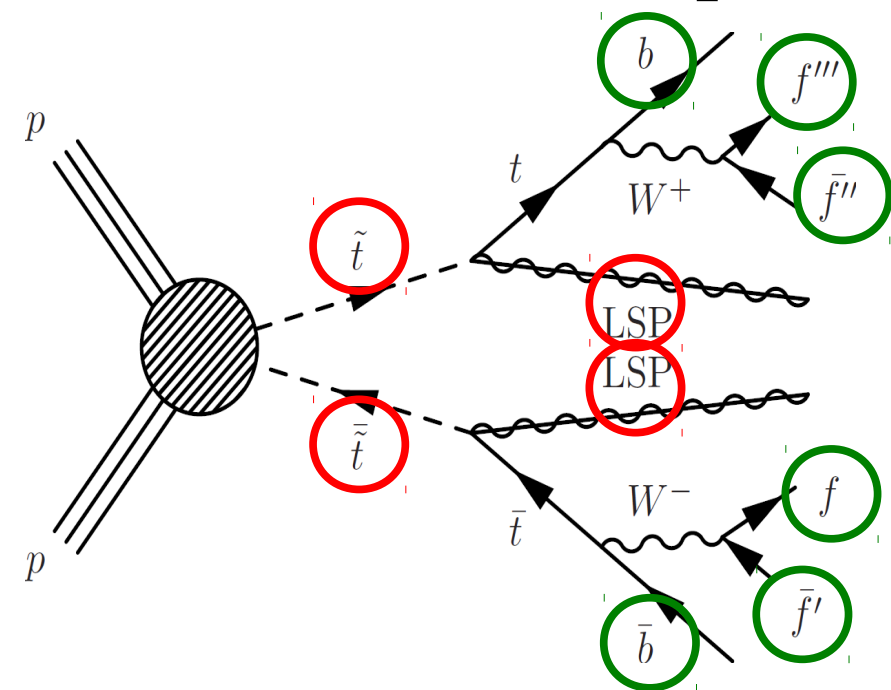
Strong mixing in the stops  $\tilde{t}_{1,2}$  sector

$\tilde{t}_1$  might be the lightest squark





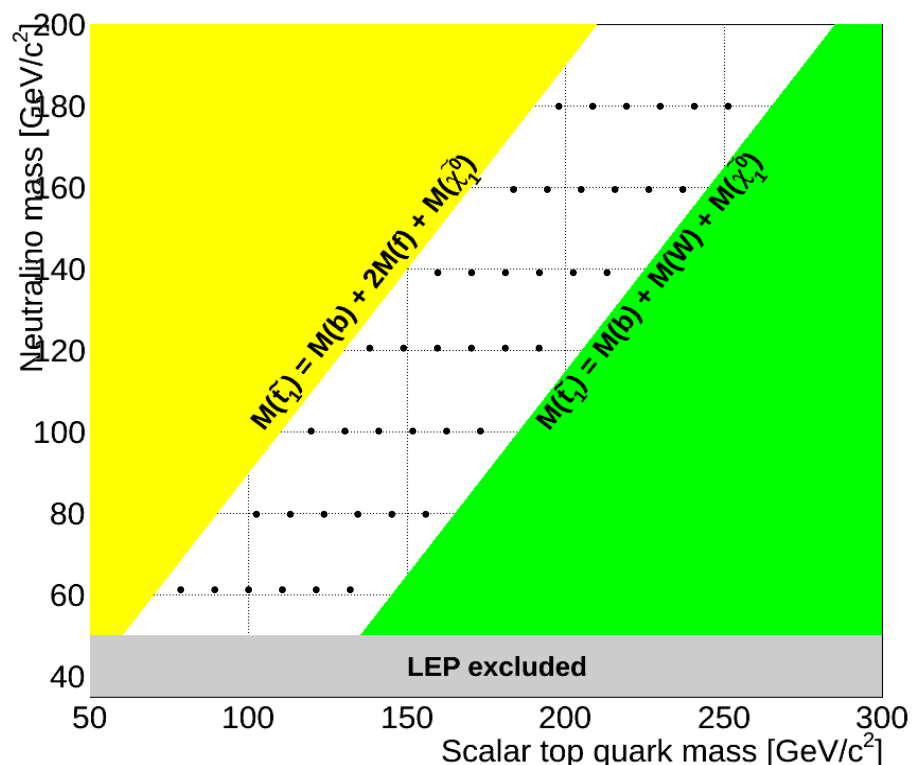
# SUSY search: Example of a challenge



- **SM particles:** We
  - Know them
  - Measure them in the detector
- **SUSY particles:** We don't know them ! i.e. we don't know their mass  
 → **Affects all the kinematics of the reconstructed events...**

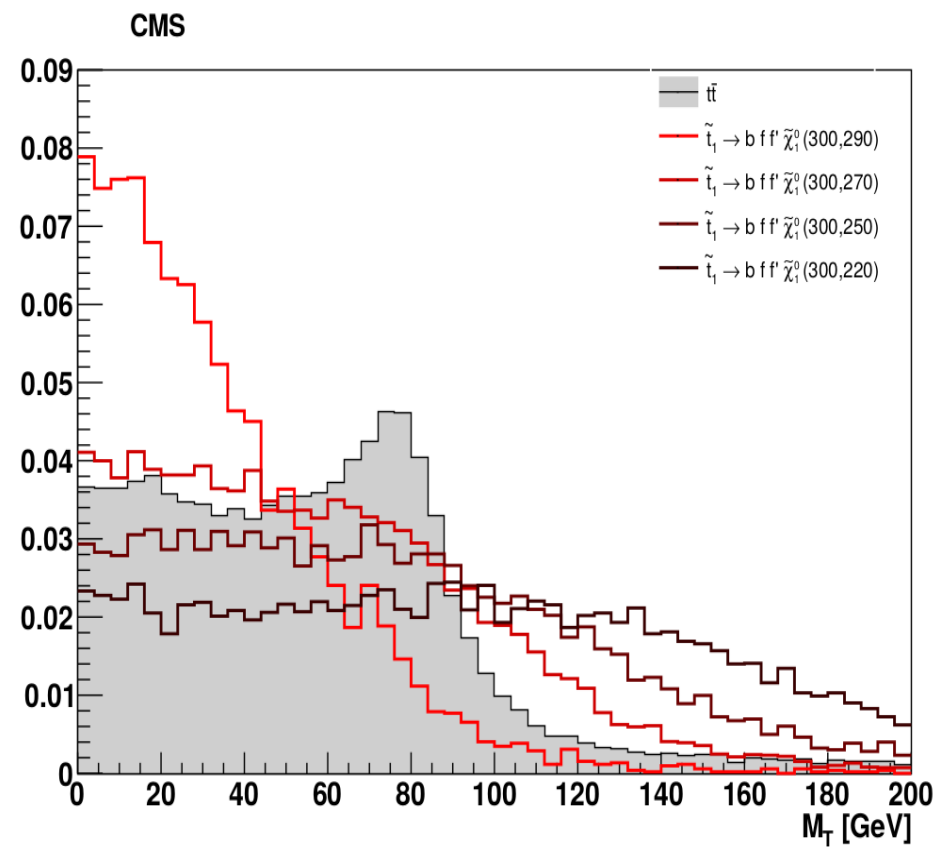
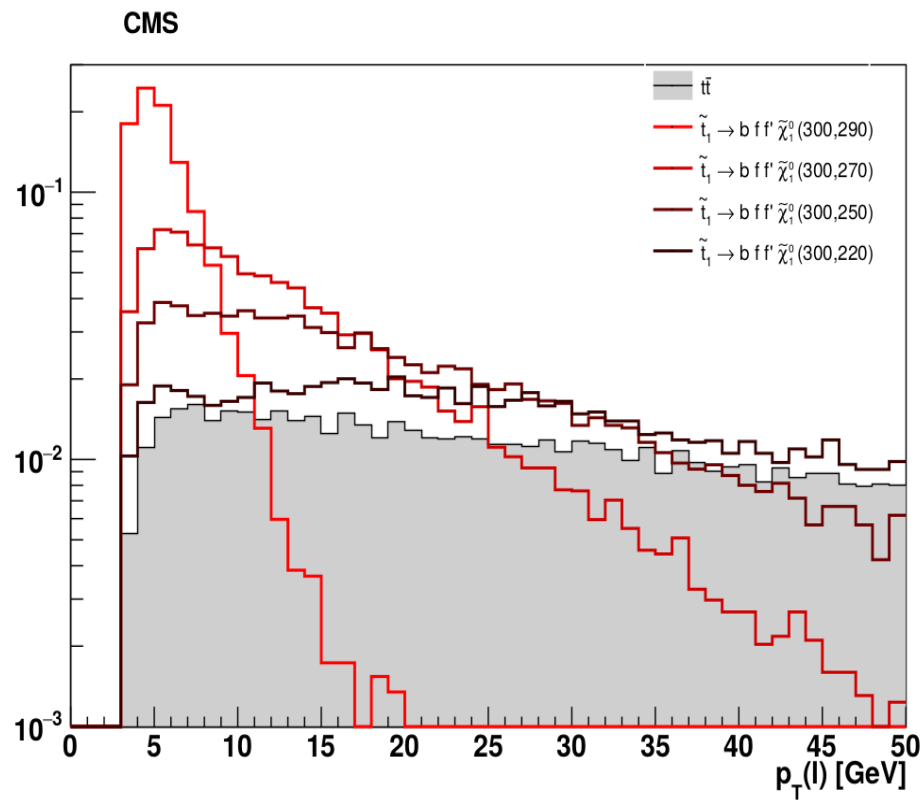
- We have to consider all mass possibilities for the 2 unknowns of this search:

**Scan through the mass plane & search for all kinematic signatures of the same signal**



# How do-we search for it

- Characterize **signal** versus background events in any possible measurable



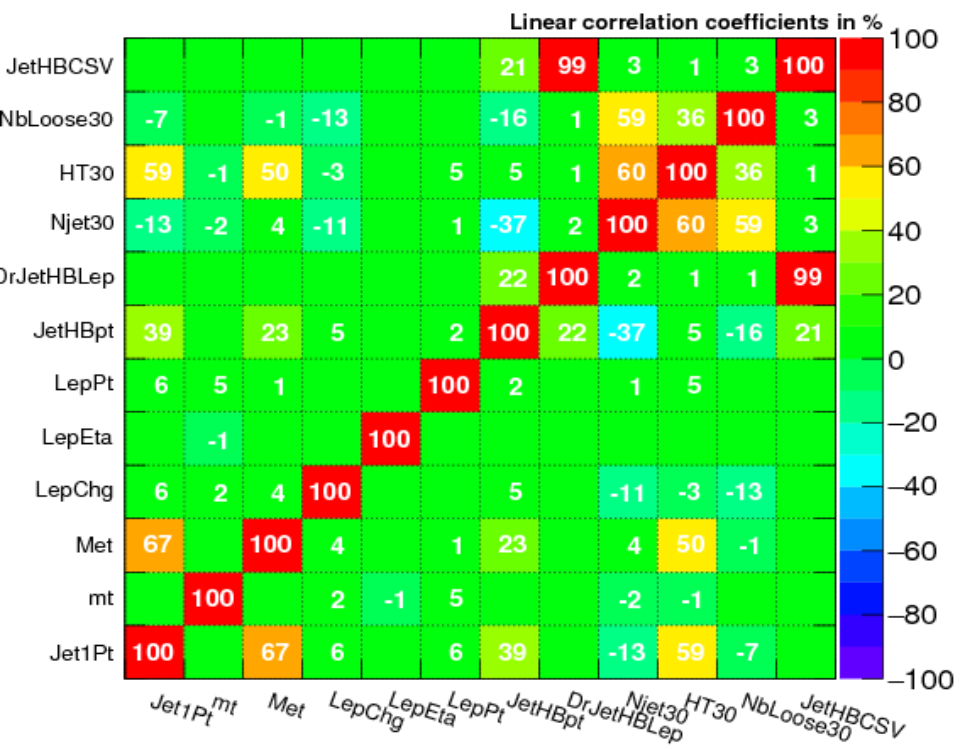
Some 21 other discriminating variables...



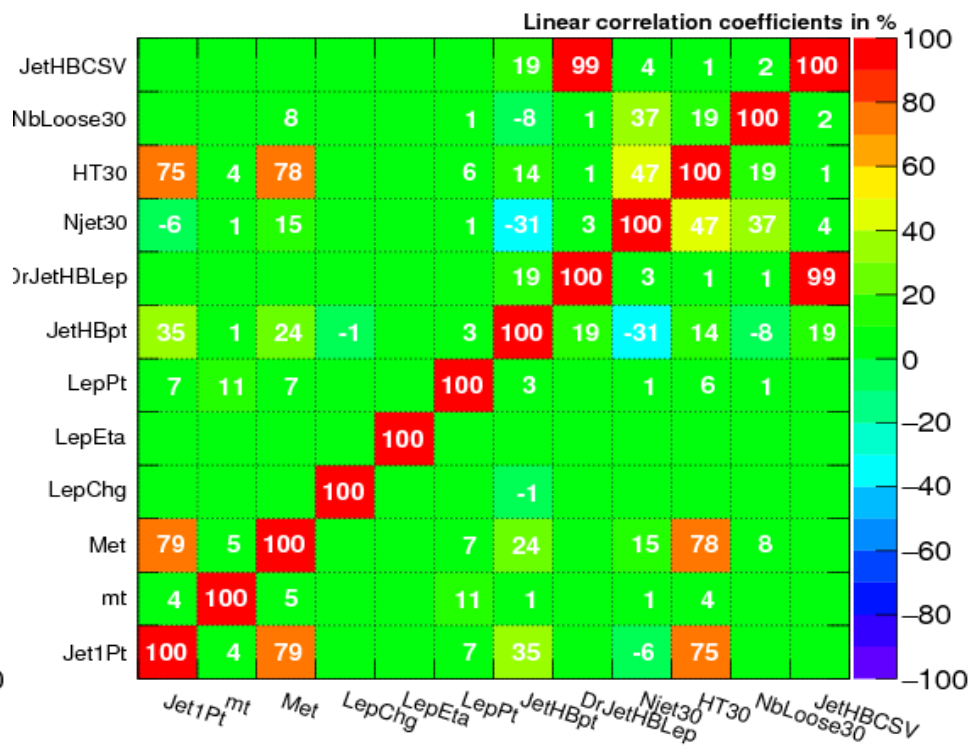
# How do we search for it: Multi-Variate Analysis tool

- **Be smart** in separating **Signal** from **Background**: Feed our best knowledge to a **Multi-Variate Analysis** tool, which combines the separation capacity of all variables:
  - Not only in 1 dimensional space...
  - ...but also in 2 dimensional : **Makes use of the differences of correlation between S & B**

Correlation Matrix (background)



Correlation Matrix (signal)

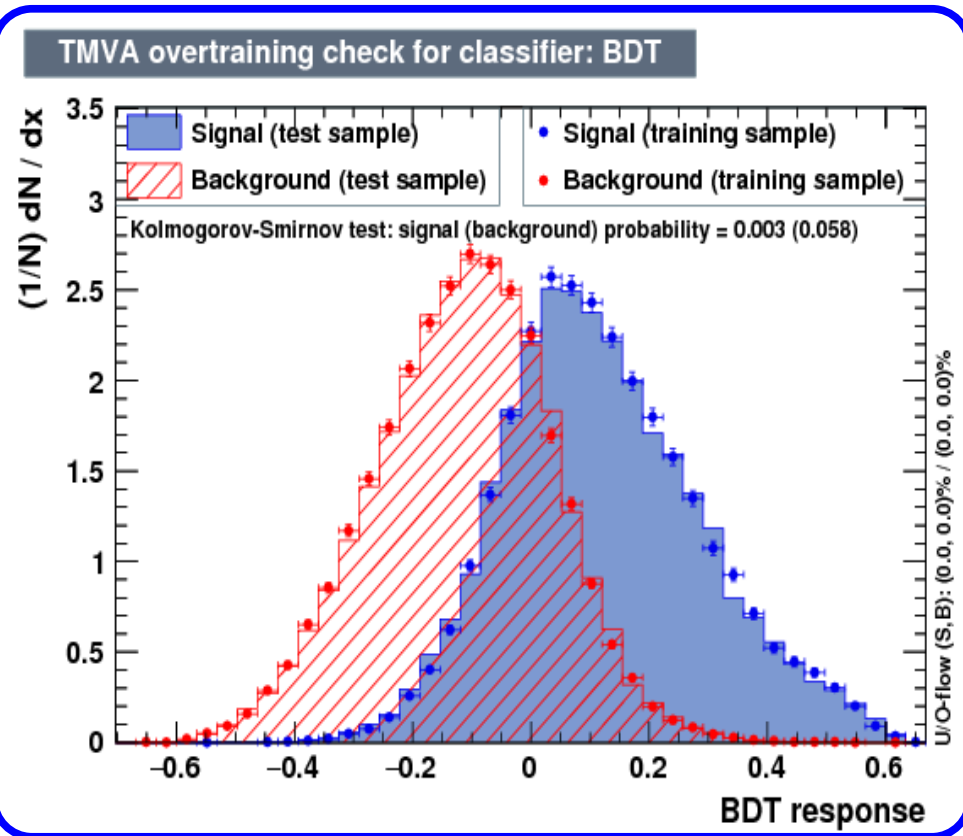
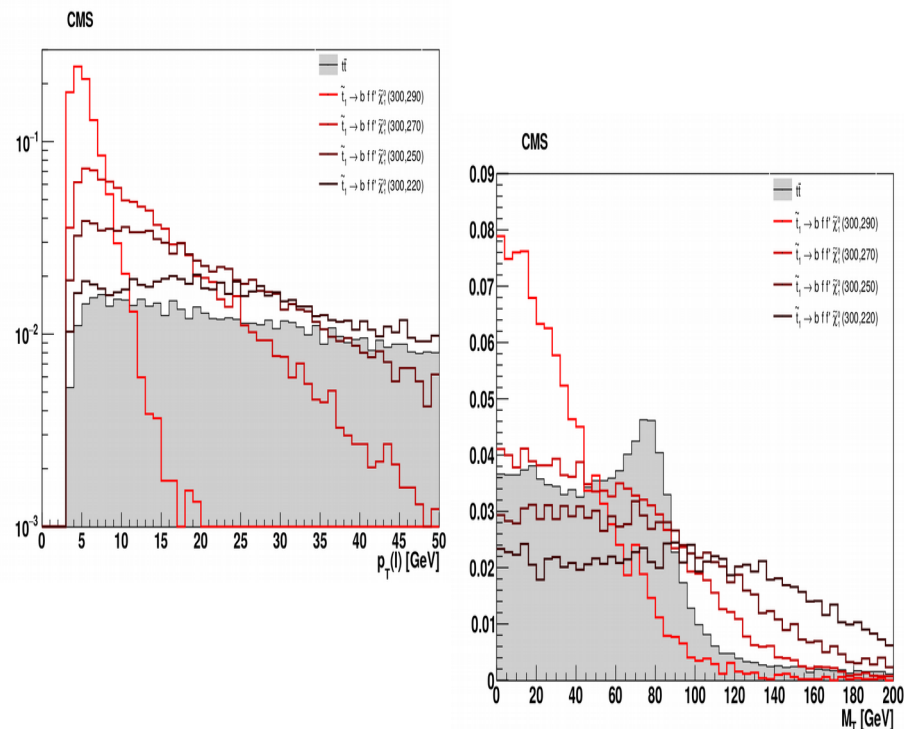


# How do we search for it: MVA tool

- **Be smart** in separating **signal** from **background**: Feed your best knowledge of these to a Multi-Variate Analysis tool, which combines the separation capacity of all single variables
  - Now compare the separation capacity between :-)

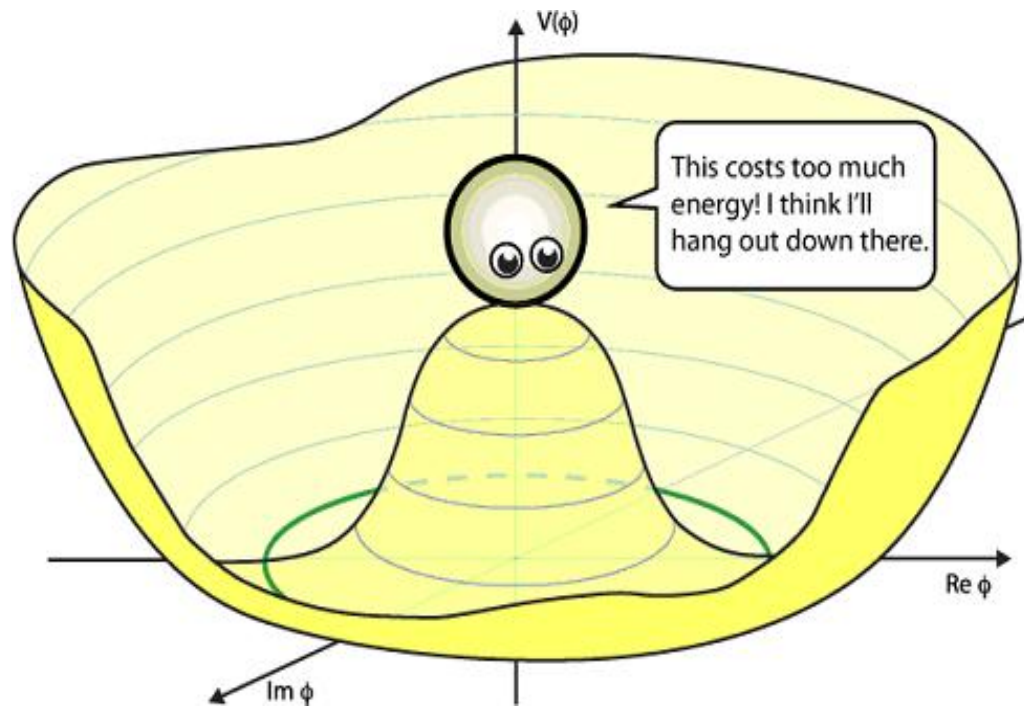
Here...

...and here: **All the discriminating power of the MVA tool in 1 variable !**



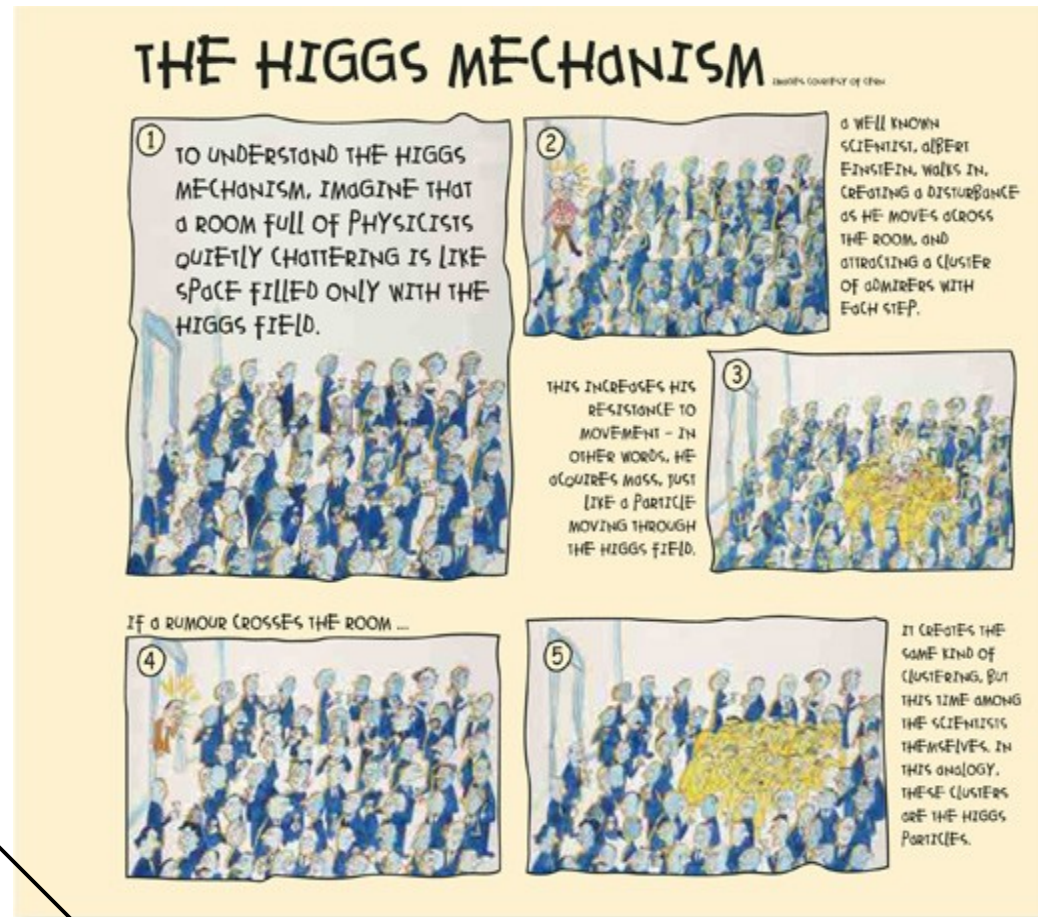
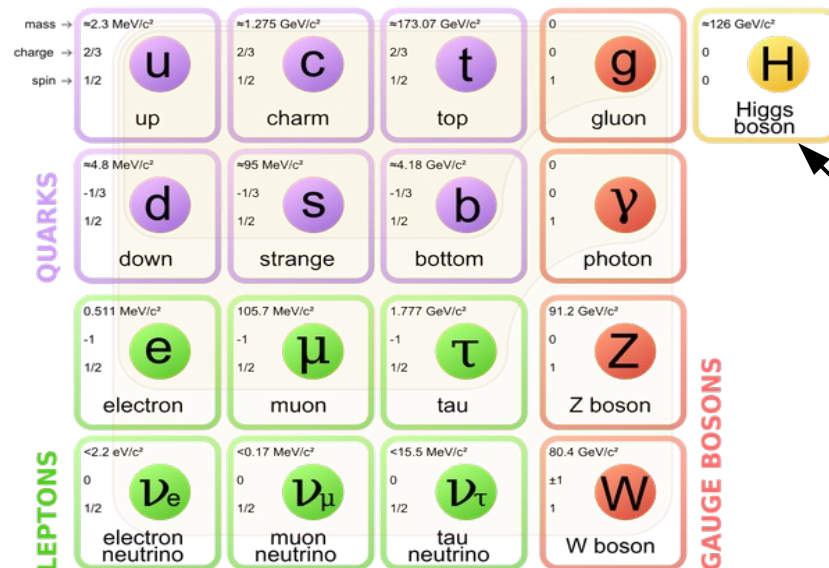


# *Higgs*



# *Why is Higgs interesting to study ?*

- **It is the last particle discovered:**  
The one we know the least
- **It is not *any* particle:** Higgs mechanism is responsible of giving mass to all matter & interaction fields in universe

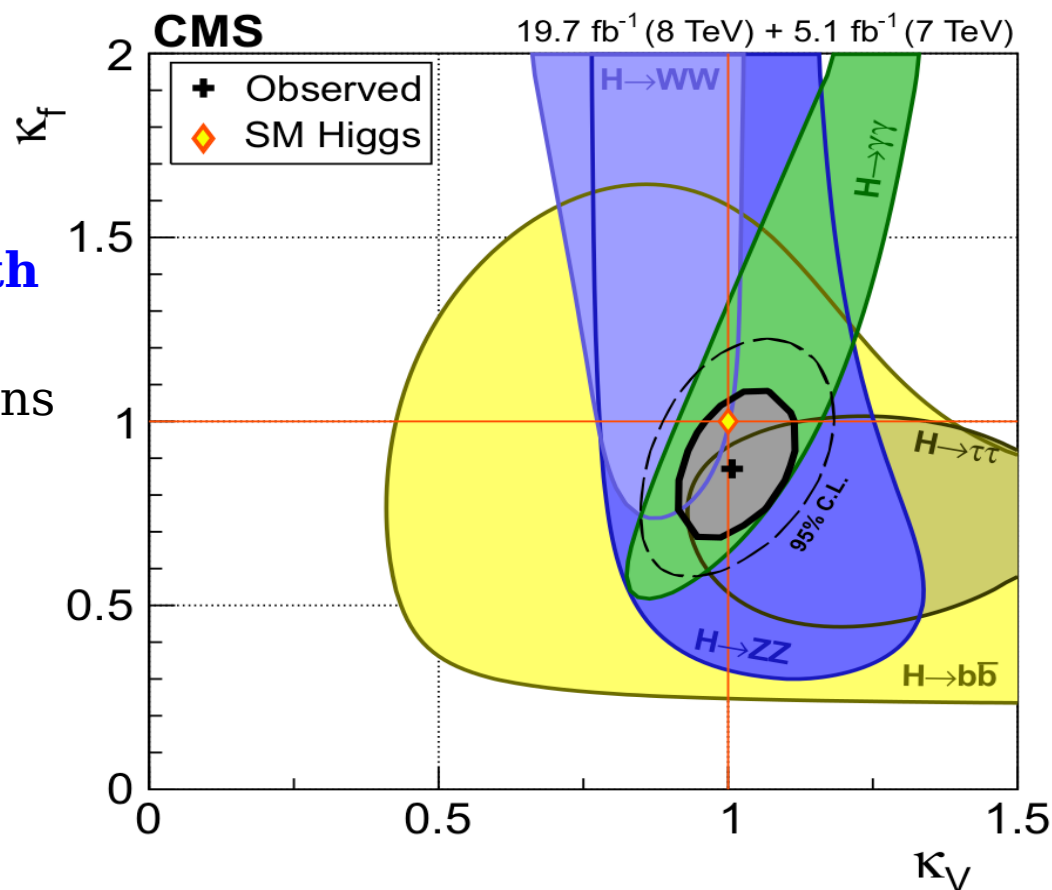


- **Does the Higgs boson only belong to SM ?**
- Are-there other, “bigger brothers” of the Higgs boson ??? i.e. other ones beyond the SM ?

# Higgs properties: Couplings

- Measure the “strength” with which Higgs couples to different fermions & bosons of the SM
- Is this coupling SM-compliant ? It can “look like” a SM Higgs, but in reality be part of a bigger theory, where there are several Higgs bosons
- Higgs belonging to something than SM would show in “details” of couplings

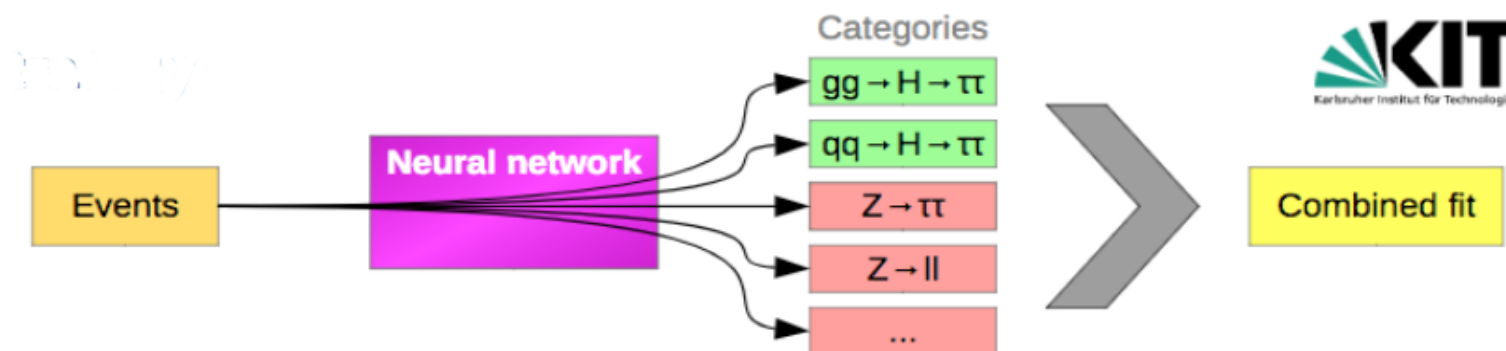
- **Measure the couplings with precision**
- Couplings to different fermions & bosons have different precisions
- One of the most promising decays of Higgs:  $H \rightarrow 2 \tau$





$$H \rightarrow 2 \tau$$

- For each channel ( $e\tau$ ,  $\mu\tau$ ,  $\tau\tau$ ), train a multiclass NN using Keras



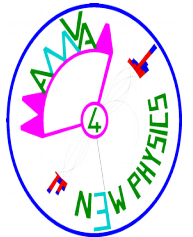
- For each event, the trained NN gives, for each class, a probability that the event belongs to the class
- Build “exclusive probability”
  - Give each event the value corresponding to the highest probability across all classes
  - Place each event in a category corresponding to the class with highest probability
- Perform combined fit to all categories for the three channels to extract the cross section

P. Bargassa, C. da Cruz e Silva

# Di-Higgs production at the LHC

M. Gallinaro, G. Strong, J. Varela

[giles.strong@outlook.com](mailto:giles.strong@outlook.com)  
[twitter.com/Giles\\_C\\_Strong](https://twitter.com/Giles_C_Strong)  
[amva4newphysics.wordpress.com](http://amva4newphysics.wordpress.com)



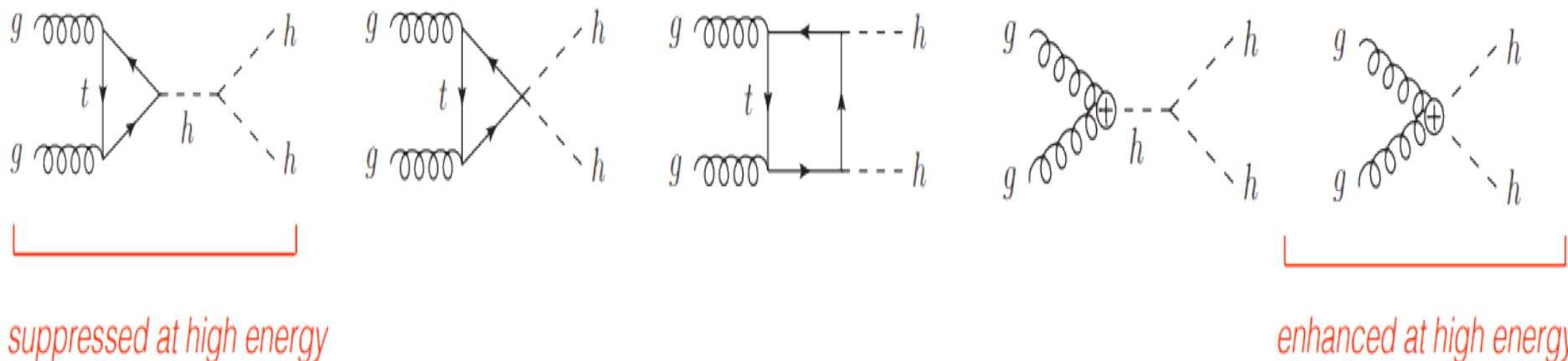
# ***Why search for di-Higgs***

- Di-Higgs production = creation of two Higgs bosons
- There are many parameters in the SM which have not yet been precisely measured
- A subset of these are the strengths to which the Higgs boson *couples* to itself and other particles
- It can also help find New Physics: an undiscovered particle might decay to Higgs bosons



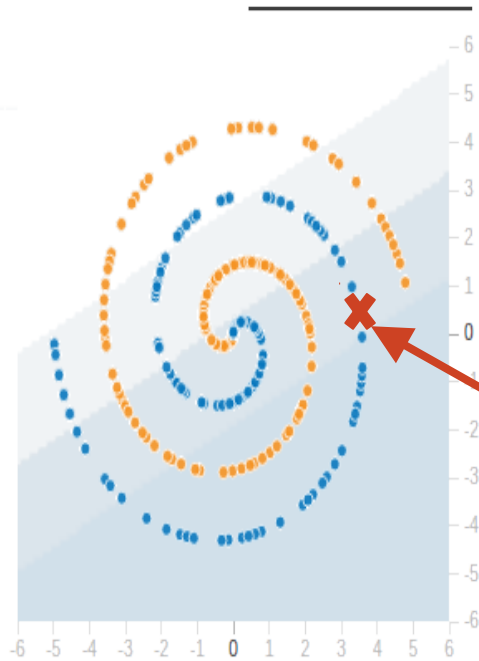
# ***How search for di-Higgs***

- Di-Higgs can be produced in many ways, and these production mechanisms vary according to the energy level\*:



- Di-Higgs can decay to different final-states = many search channels & a variety of strategies
- The low rate of production requires efficient use of the data available
- LIP is currently involved in developing Machine Learning tools for this search

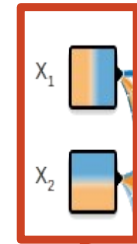
# Another illustration of MVA/ML



Is a point  
here blue  
or  
orange?

## FEATURES

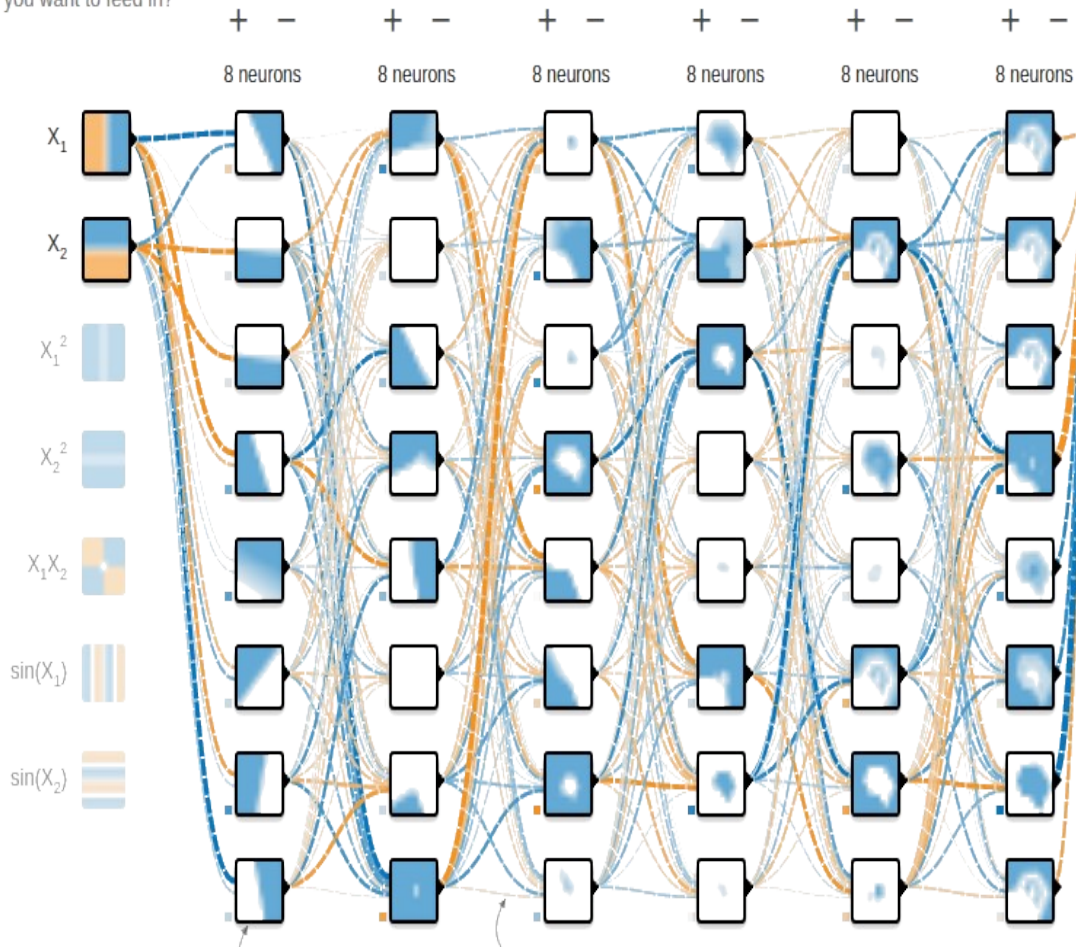
Which properties do  
you want to feed in?



Input-level  
information:  
(X,Y) coordinates  
Color

## FEATURES

Which properties do you want to feed in?

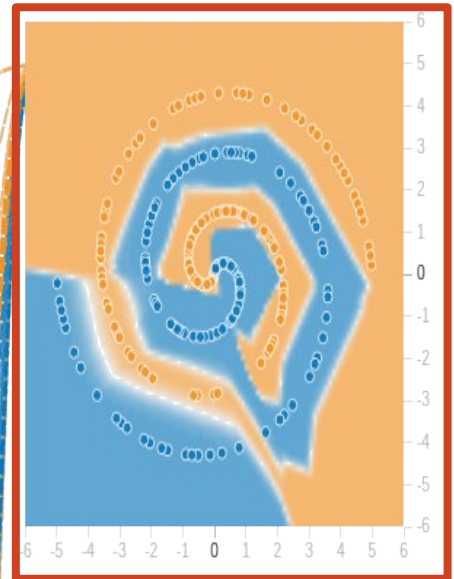
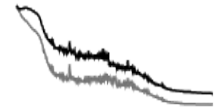


+ - 6 HIDDEN LAYERS

## OUTPUT

Test loss 0.056

Training loss 0.001



Colors shows data, neuron and weight values.



☐ Show test data

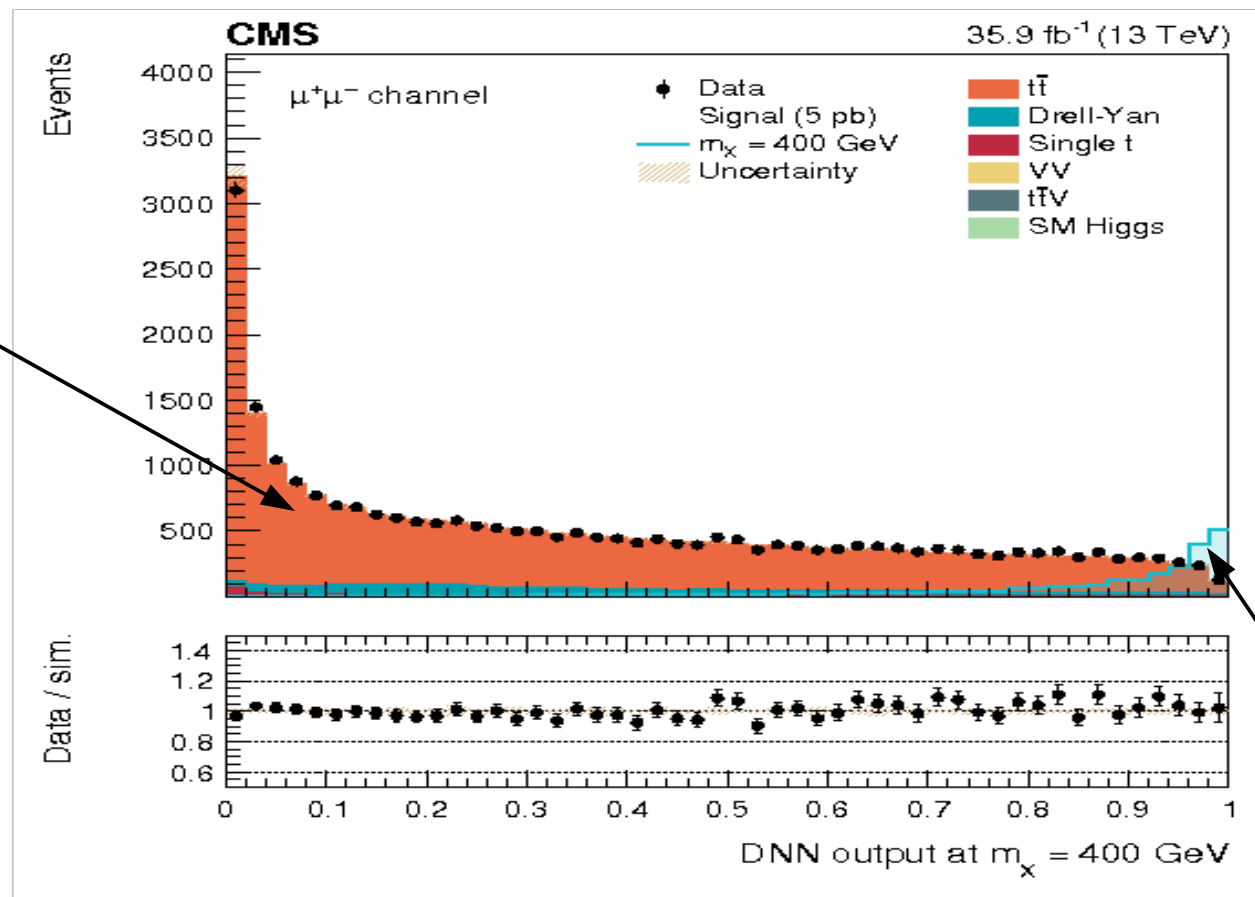
☐ Discretize output

Train on example data



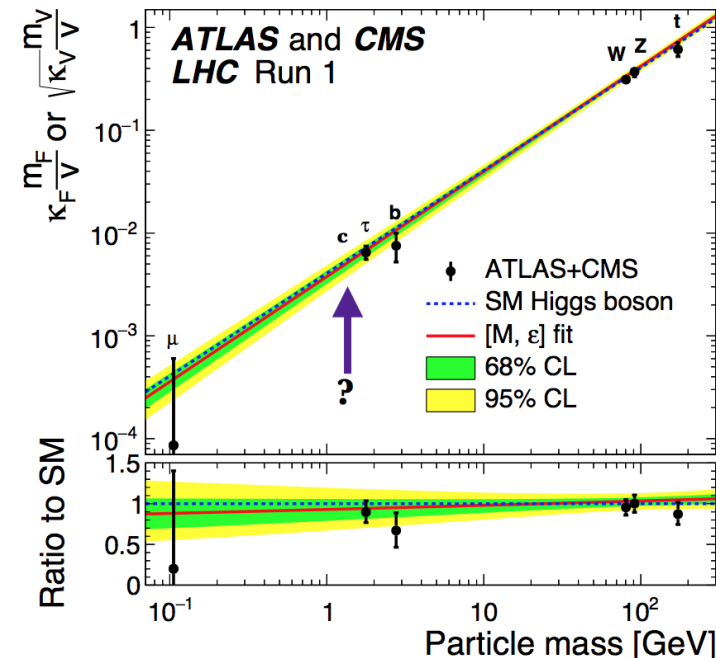
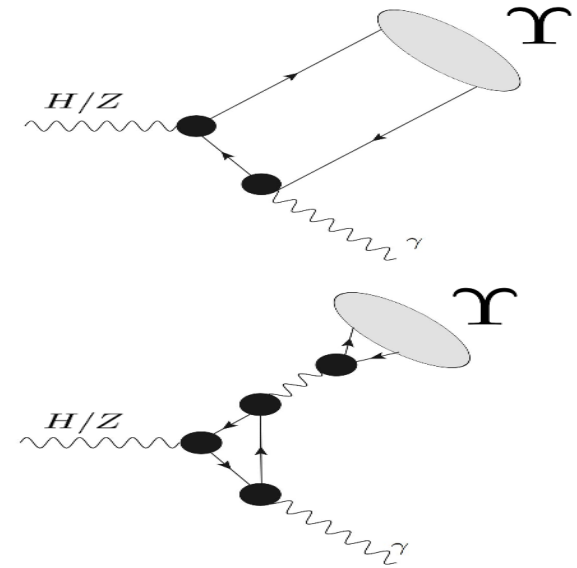
# Preliminary result for di-Higgs

- Search for rare processes by predicting what process occurs in a particle collision
- E.g. Di-Higgs production - [1708.04188](#)



# Higgs (& Z) rare decays

- rare processes in the SM (BR:  $10^{-7}$ - $10^{-9}$ )
  - sensitive to NP
- allows to measure quark-Higgs couplings
  - alternative to  $H \rightarrow qq$  (challenging due to QCD)
- Z provides experimental benchmark for the H decay
  - larger production cross section, nearby mass
- valuable tool for probing nature of quarkonium production
  - a topic LIP's exploration is @ forefront



# How do-we work: Tools / Methods / Environment

- **Code:** You will be using & contributing to code being used by  $O(10^3)$  physicists:
  - Highly prized in HEP, but also in industry, financing
- **Statistical analysis**
  - Essential in HEP, highly prized in financing
- **Data analysis:** Your capacity to understand data & find 1 interesting event out of  $O(10^4, 10^6)$ 
  - @ this level, you should be good for a job in HEP, in industry or banks
- **Working in team:**
  - Large collaboration: ~2500 people
    - Physics groups / sub-groups: 10 / 200 people
  - LIP: Students helped by senior researchers & post-doctoral fellows
- **“Can I bring something as student ?”**
  - Yes: 2 summer students of 2<sup>nd</sup>-3<sup>rd</sup> year helped us improve the selection power of our MVA tool !
- Dedicated courses to help our students in (all) these aspects:
- [http://www.idpasc.lip.pt/LIP/events/2018\\_lhc\\_physics/](http://www.idpasc.lip.pt/LIP/events/2018_lhc_physics/)
- **Contact me: [bargassa@cern.ch](mailto:bargassa@cern.ch)**



***Backup***

# Particles... Interactions... wait a minute...

## ELEMENTARY PARTICLES

Quarks

$u$   
up

$d$   
down

$\nu_e$   
electron neutrino

$e$   
electron

$c$   
charm

$s$   
strange

$\nu_\mu$   
muon neutrino

$\mu$   
muon

$t$   
top

$b$   
bottom

$\nu_\tau$   
tau neutrino

$\tau$   
tau

Force Carriers

$\gamma$   
photon

$g$   
gluon

$Z$   
Z boson

$W$   
W boson

I

II

III

Three Generations of Matter

Fermilab 95-759

BOSONS			force carriers spin = 0, 1, 2, ...		
Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge	Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0	$g$ gluon	0	0
$W^-$	80.39	-1	Higgs Boson spin = 0		
$W^+$	80.39	+1	Name	Mass GeV/c <sup>2</sup>	Electric charge
$Z^0$ Z boson	91.188	0	$H$ Higgs	126	0

## FERMIONS

matter constituents  
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ electron neutrino	<1×10 <sup>-8</sup>	0	$u$ up	0.003	2/3
$e$ electron	0.000511	-1	$d$ down	0.006	-1/3
$\nu_\mu$ muon neutrino	<0.0002	0	$c$ charm	1.3	2/3
$\mu$ muon	0.106	-1	$s$ strange	0.1	-1/3
$\nu_\tau$ tau neutrino	<0.02	0	$t$ top	175	2/3
$\tau$ tau	1.7771	-1	$b$ bottom	4.3	-1/3

Why would matter exist only in fermionic, and force carriers exist only in bosonic form in the universe ?

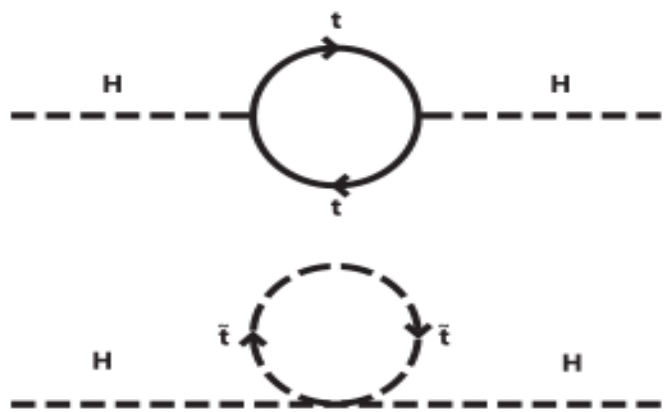
Is this a “happens to be” ? Or there is a hidden symmetry behind this ?

Let's symmetrize things between matter & interaction fields...

# SUSY

- **Higgs field introduces huge divergences in the mass of all known SM particles**
- But: Are we mass-unstable ? Fortunately not ;-)
  - There has to be another theory which stabilizes masses

$$+ \frac{g_F^2}{4\pi^2} \left( \Lambda^2 + m_F^2 \right)$$



$$- \frac{g_S^2}{4\pi^2} \left( \Lambda^2 + m_S^2 \right)$$

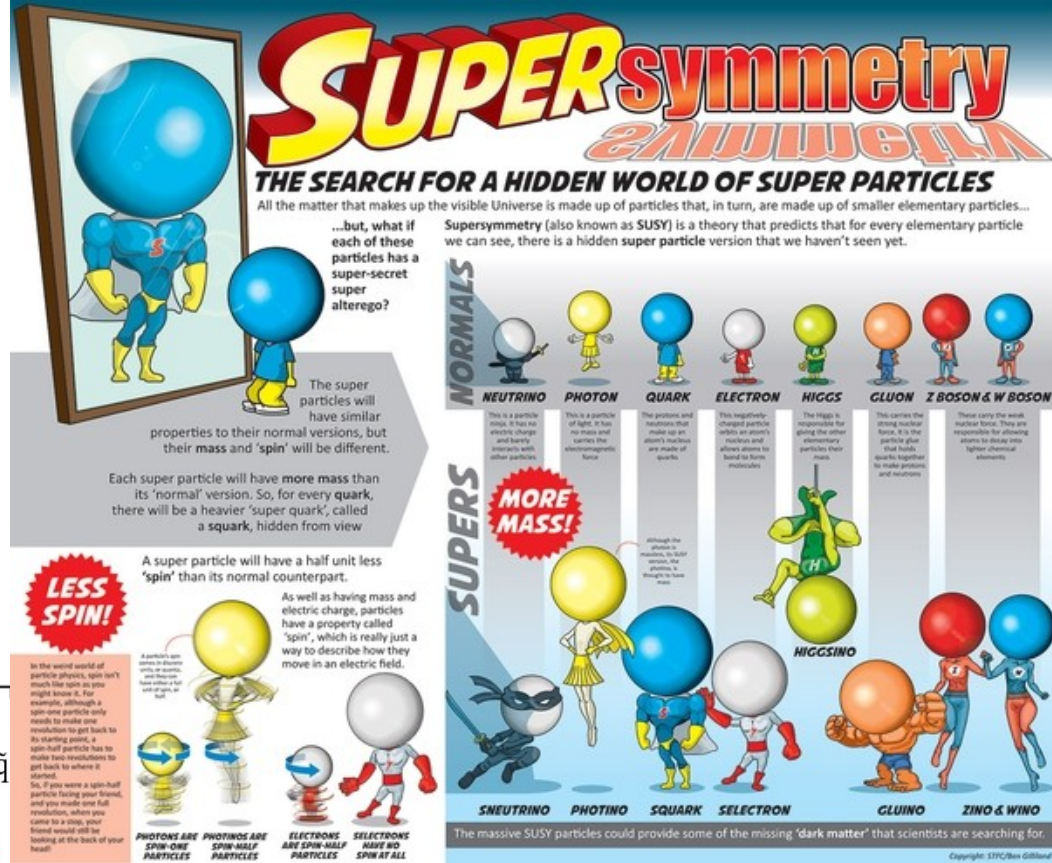
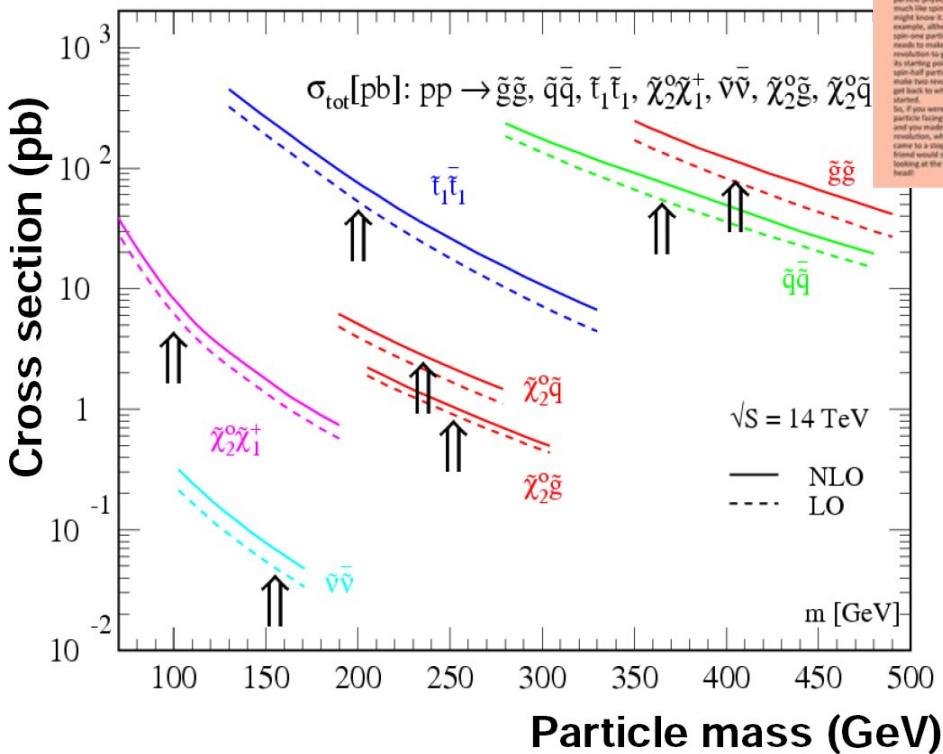
- **SUSY cures the divergences of the SM by definition: Associates a scalar partner (-) to each SM fermion (+)**



# sParticles are special:

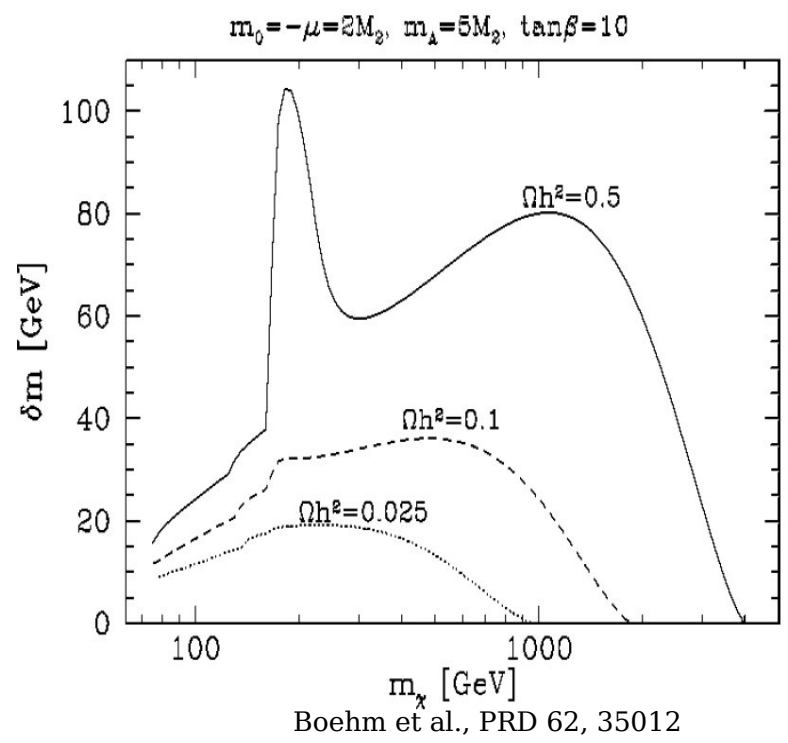
If SUSY exists, it's a broken symmetry:

- Physical sParticles are mixtures of Susy particles
- They exist @ higher masses



Among all sParticles:  
Which one is our best bet ?

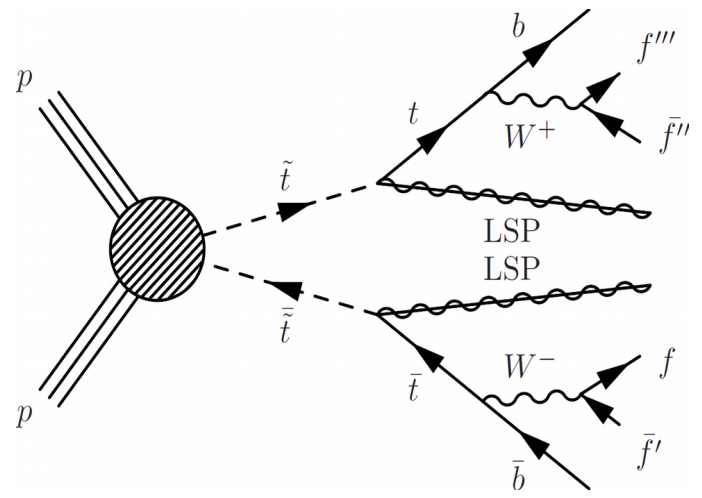
# SUSY search: One of our best bets



**IF :  $\delta m = M(\tilde{P}) - M(\tilde{\chi}_1^0)$  small,**  
 co-annihilations dominates  $\rightarrow \Omega_{\text{CDM}} h^2 \approx 0.1$

**Data on Cold Dark Matter:**  
 $\Omega_{\text{CDM}} h^2 = 0.11 \pm 0.01$  @ 95% CL (WMAP)

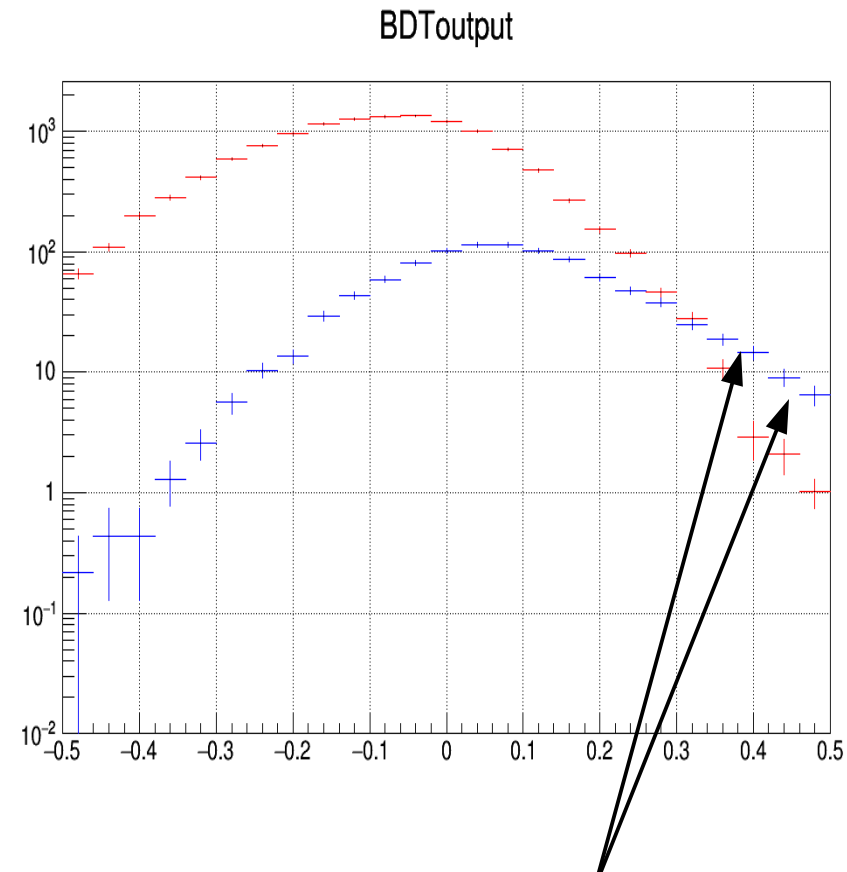
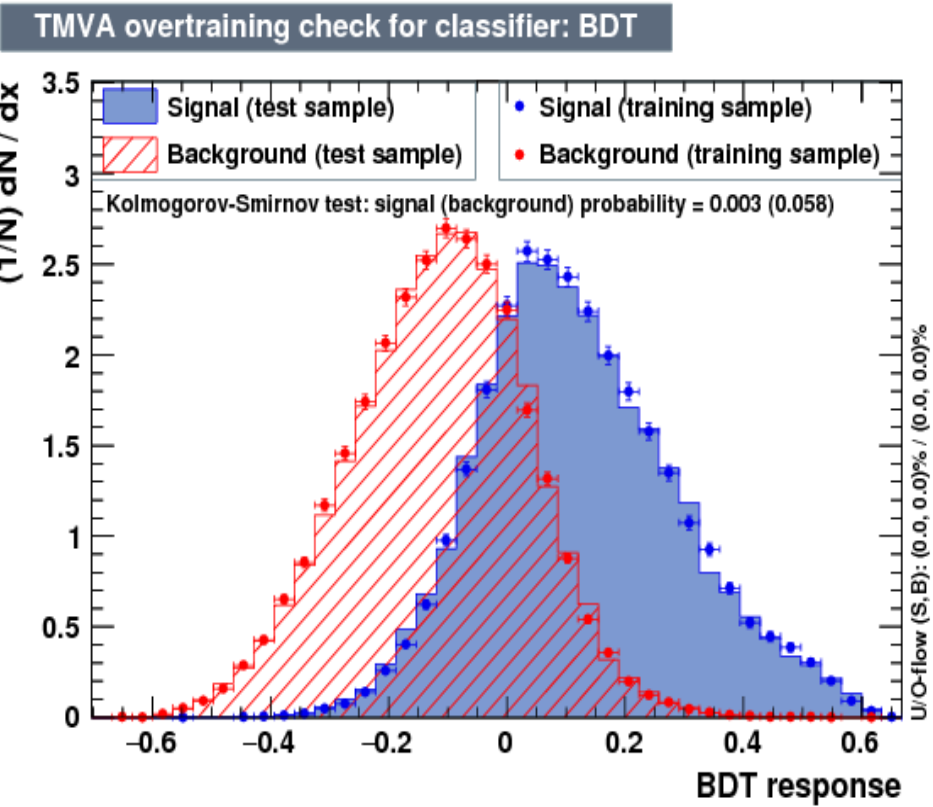
Gives preference to  
 $\Delta m = M(\tilde{t}_1) - M(\tilde{\chi}_1^0) \leq 50 \text{ GeV}/c^2$   
 Gives preference to 4-body decays



# How do we search for it: MVA tool

- We have to be realistic: Account for:
  - Abundance of production of SM background & our possible signal
  - Reconstruction efficiencies
  - Detector effects...

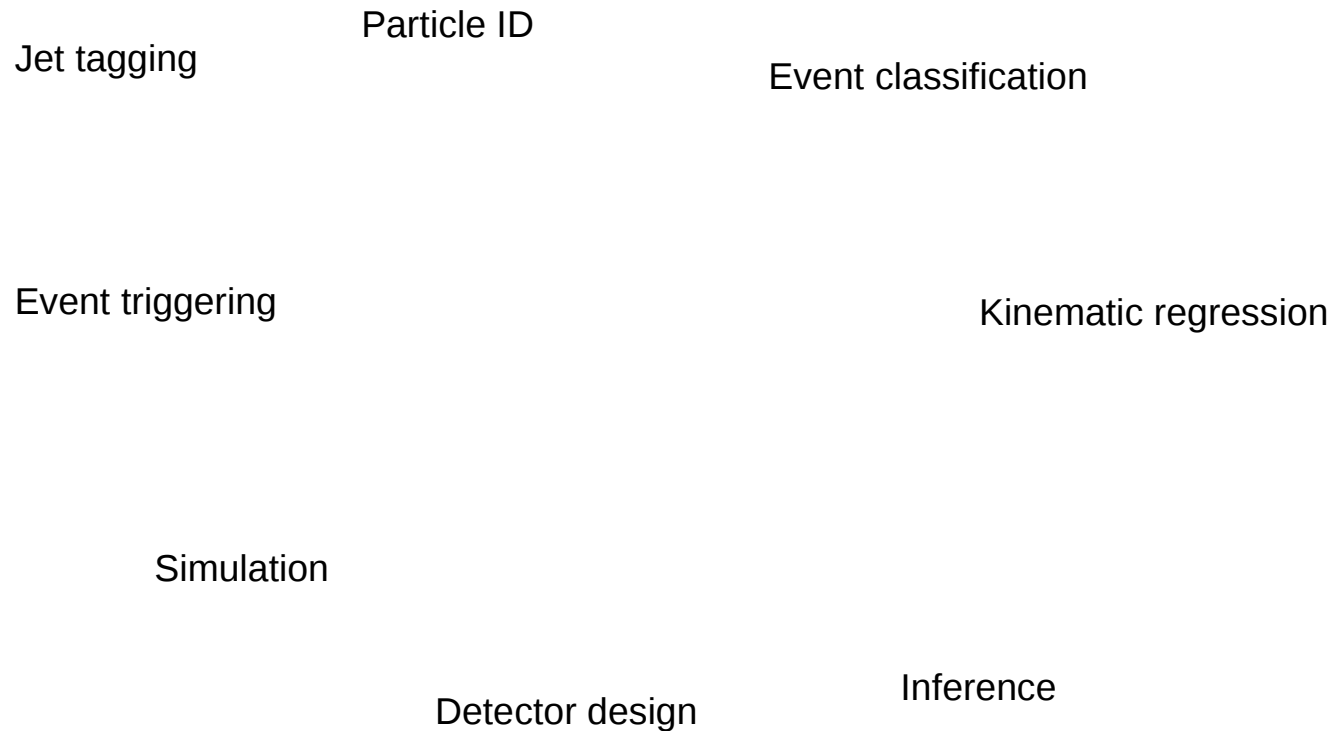
Here is the real picture ;-)



If something shows up here, in Data: Discovery !



# Many possible applications



# Further reading

- Play in browser: [Tensorflow playground](#), [gradient boosting playground](#)
- Seminars and lectures: [MLHEP-17](#), [Karpathy](#), [Hastie](#), [HEP repository](#)
- My resources: [NN summary posts](#), [example classifier](#)