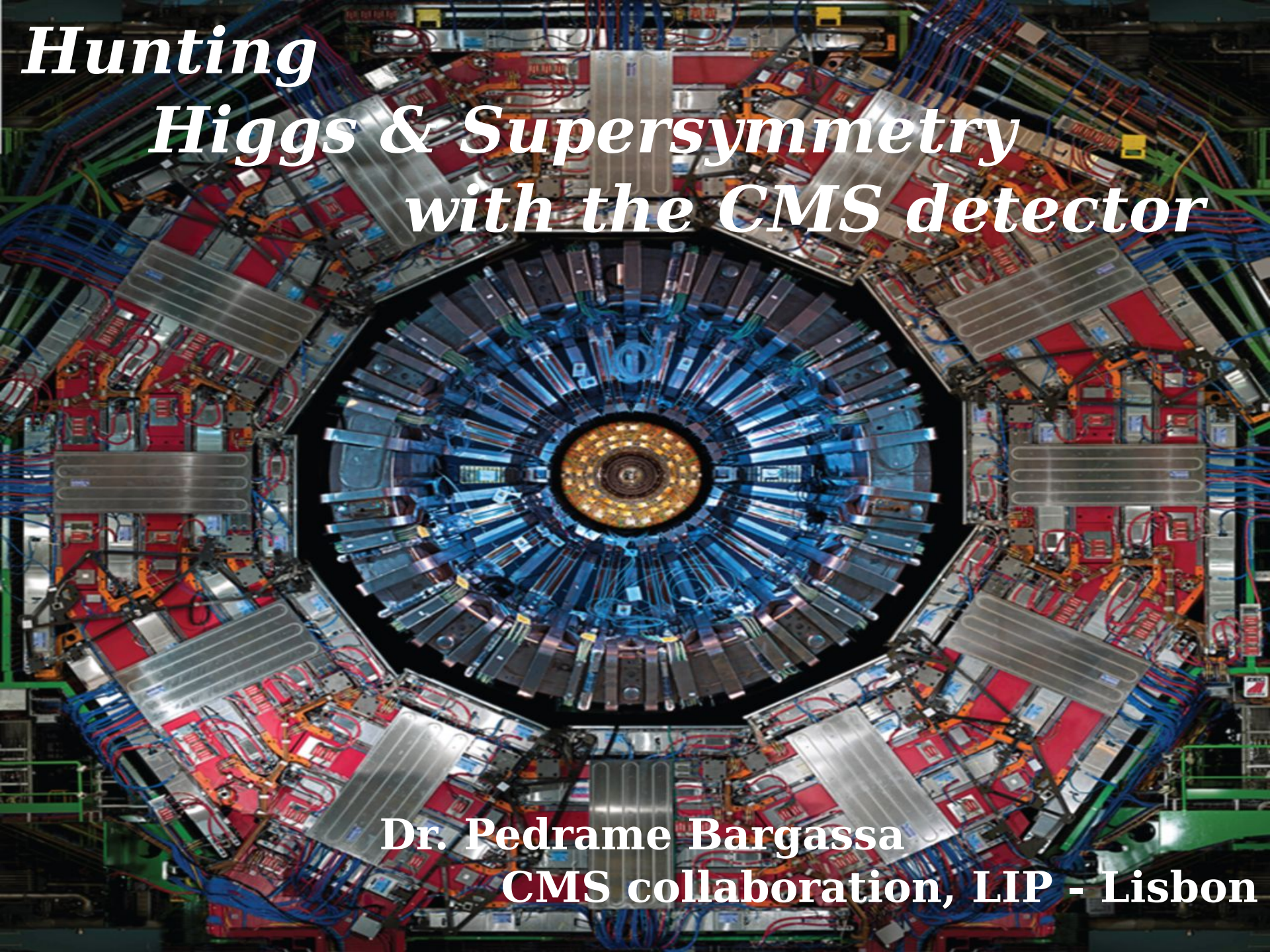
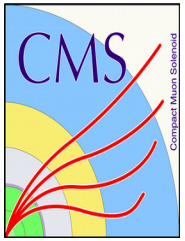


Hunting Higgs & Supersymmetry with the CMS detector

Dr. Pedrame Bargassa
CMS collaboration, LIP - Lisbon

- ***Introduction to HEP searches***
- ***Susy search:***
  - ***Susy hunt: Stop***
- ***Higgs search:***
  - ***Double-Higgs***
  - ***$H \rightarrow 2\ \tau$***

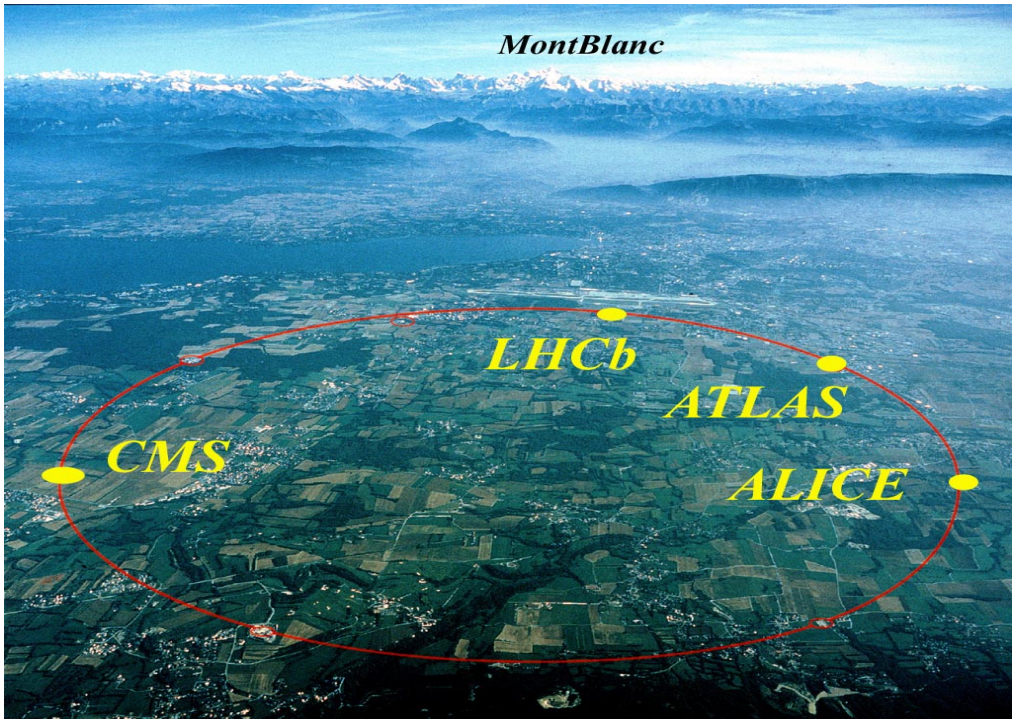
- ***Why are these interesting***
- ***How do-we hunt them: Multi-Variate Analysis tools***

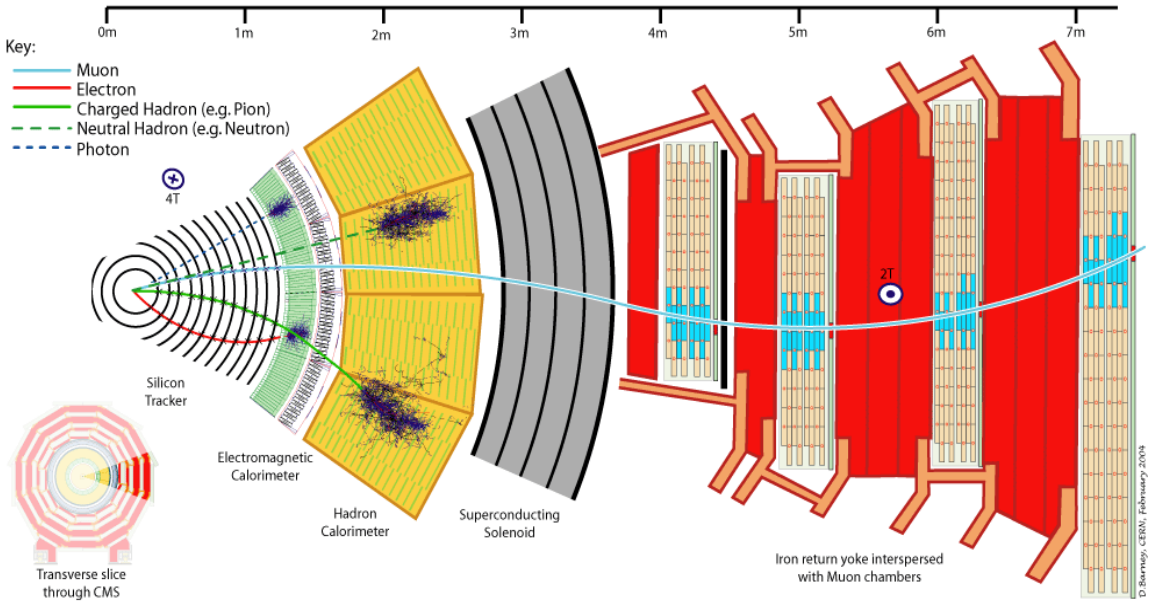


How do-we search for new particles

- **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 ;-)

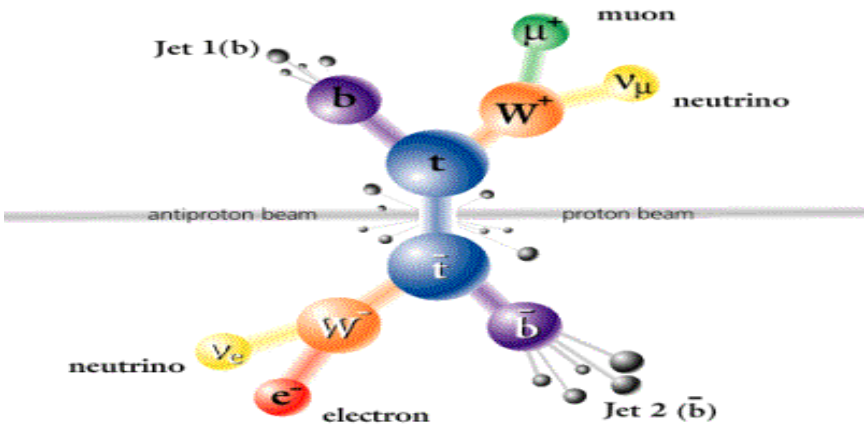




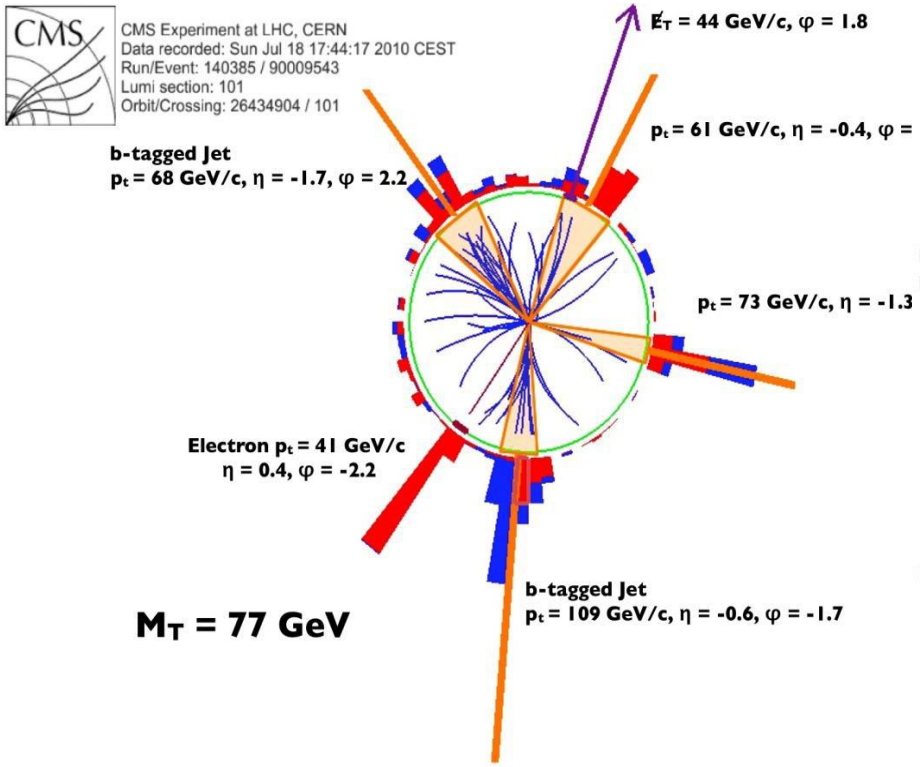
- ~11000 rev/s
- Every 25 ns
- “Focus” of the beams: 10^{34} $cm^{-2}s^{-1}$
- $\sqrt{s}$ = 13 TeV

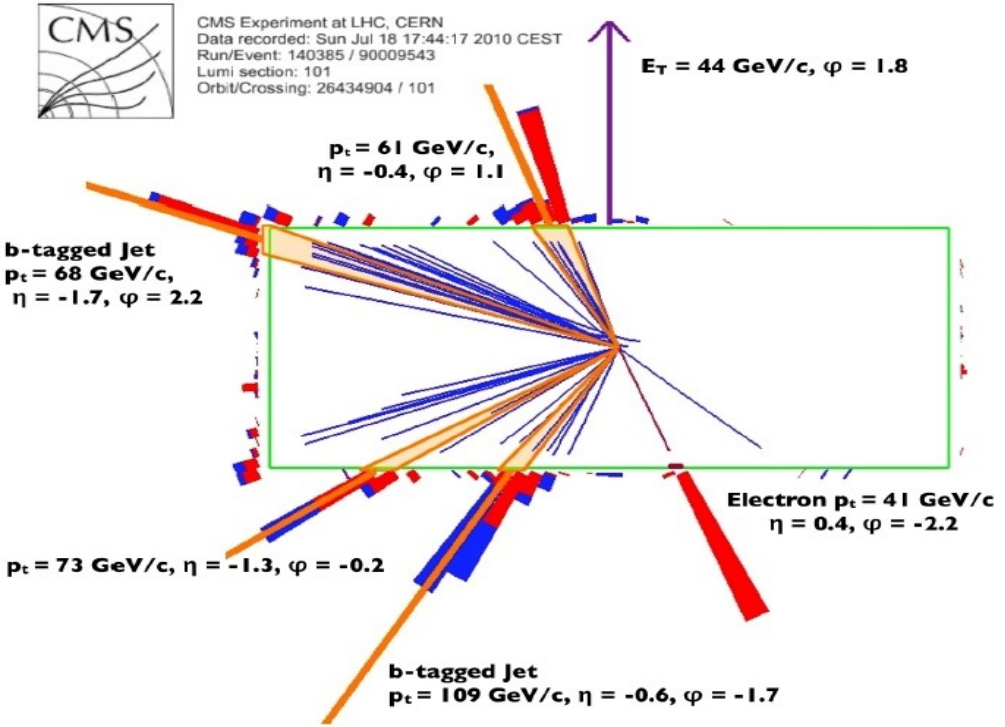
How do-we search for new particles

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

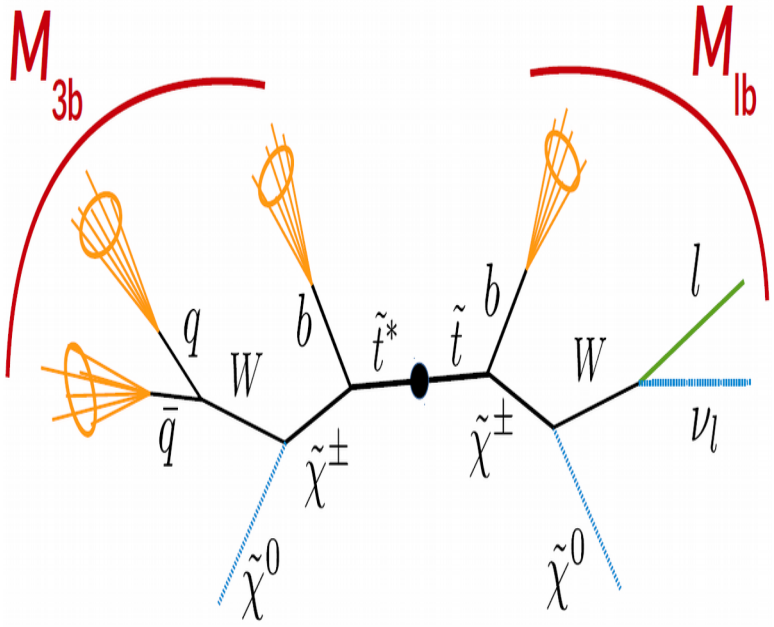


- **Reconstruct** kinematics



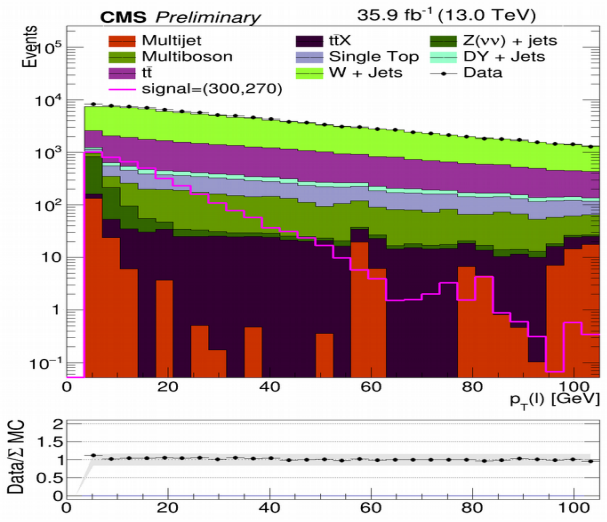


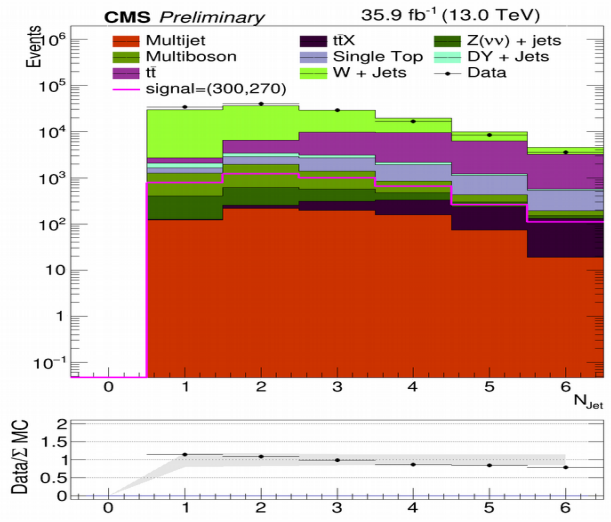
How do-we search for new particles

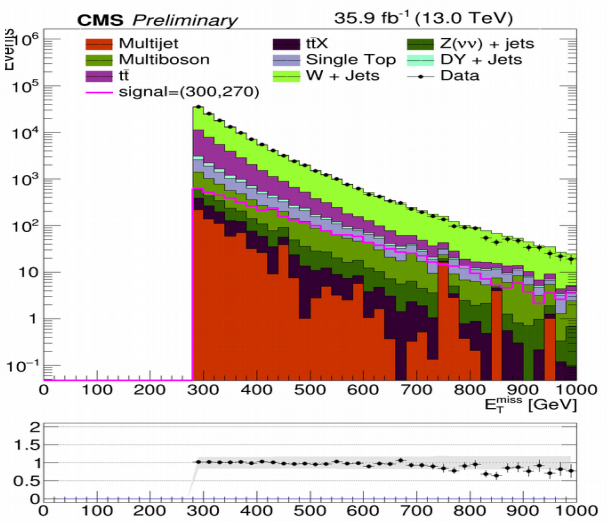


- **Sign** wanted events
- Here, we are looking for events with **4 jets**, **1 lepton** & **missing energy**
- **Careful !** SM does imitate this **signature** while not being Susy...

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



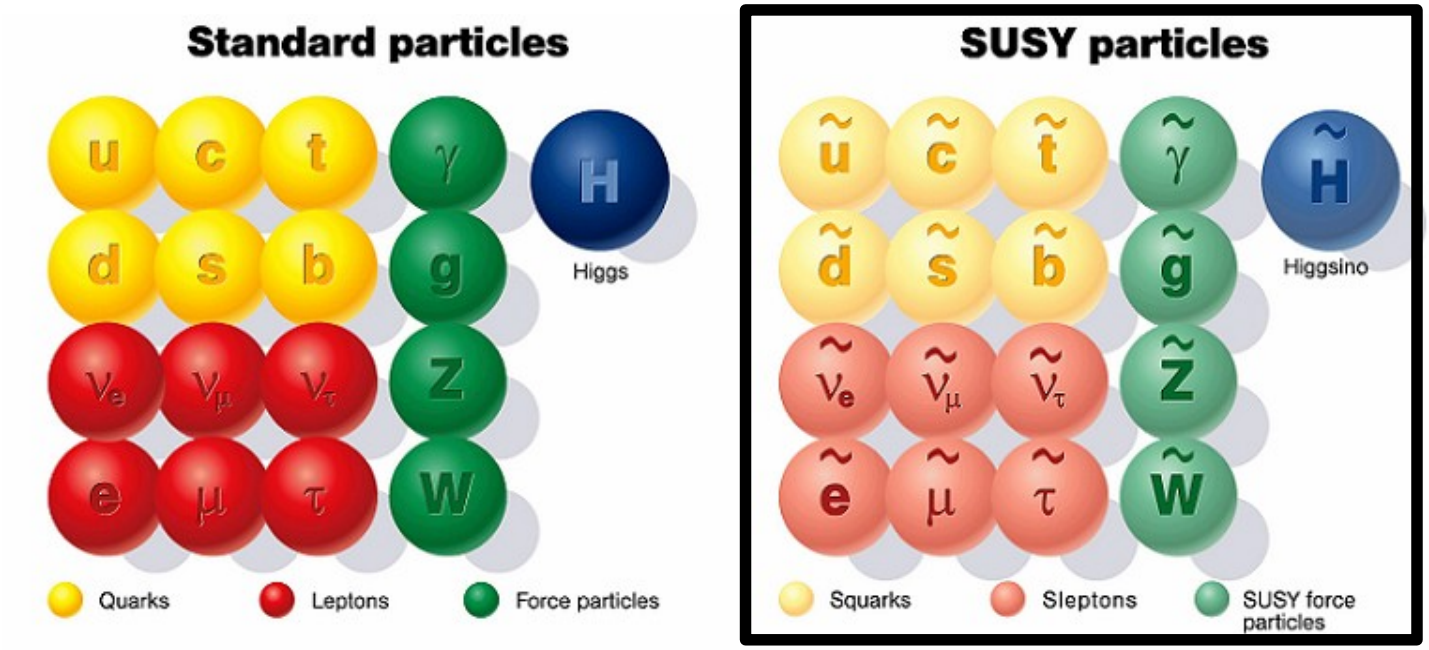




SUperSYmmetry

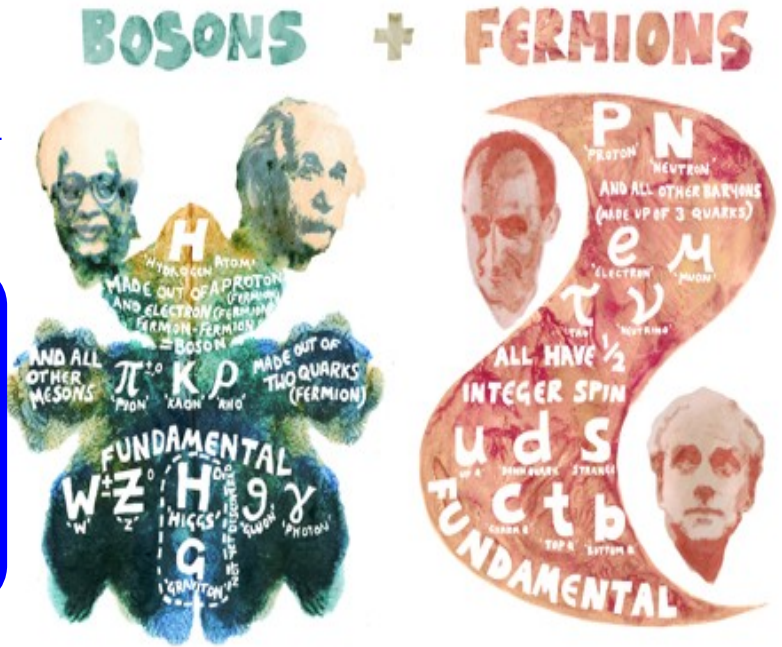
P. Bargassa, C. da Cruz e Silva, D. de Bastos

SUperSYmmetry: What it is

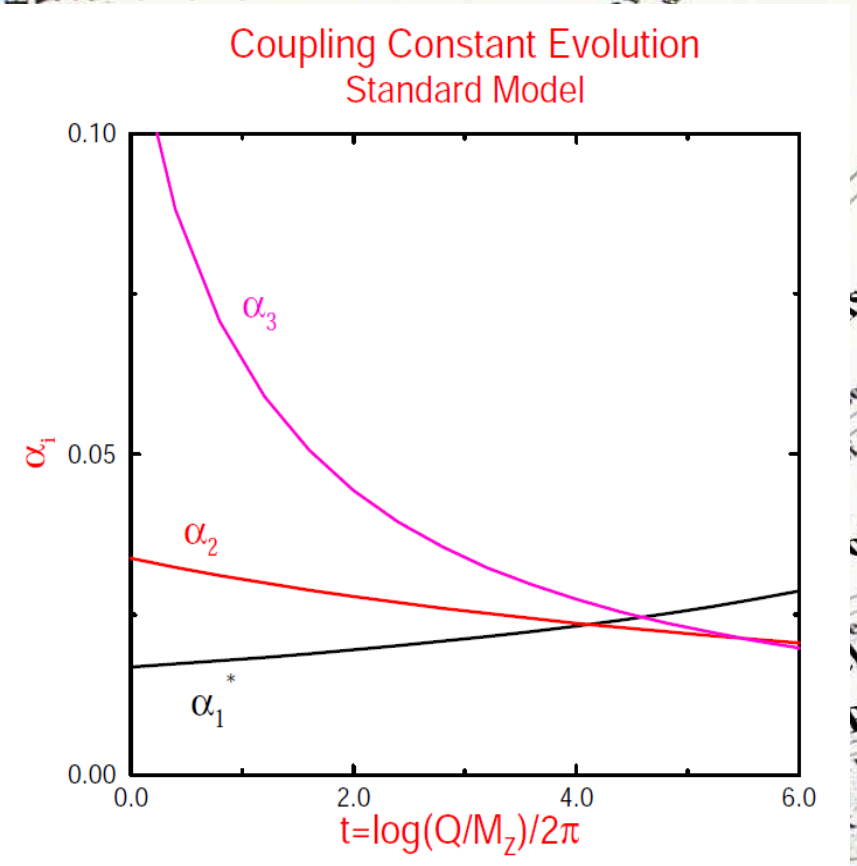


Matter fields could also exist in bosonic form
Force carriers also exist in fermionic form

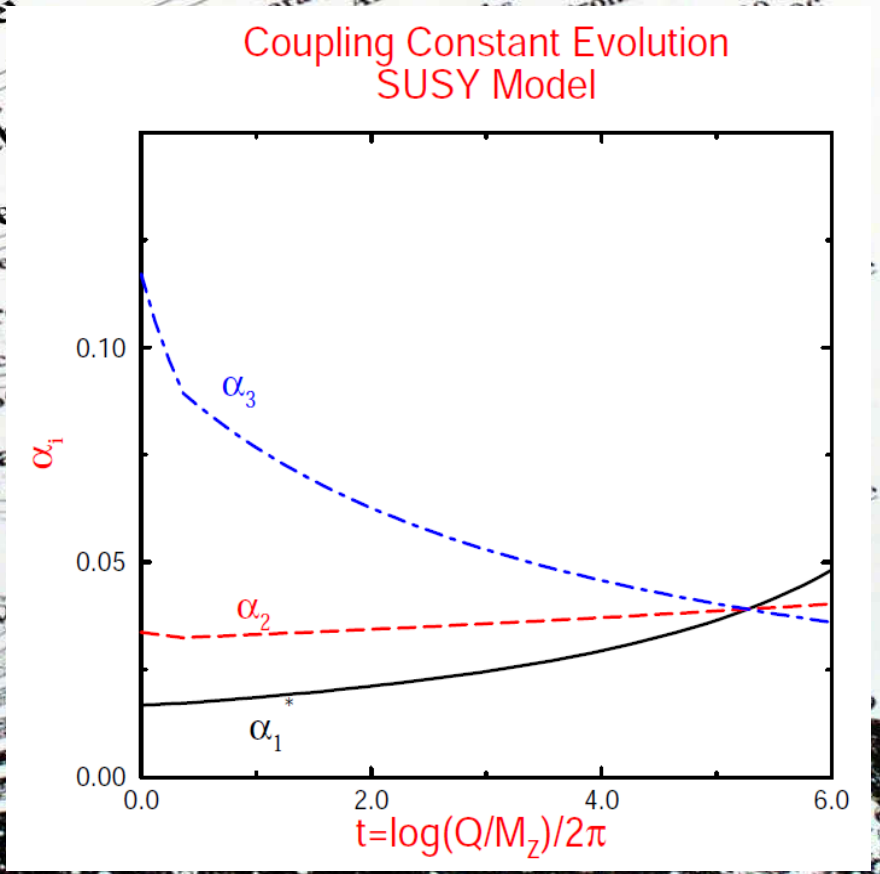
SUSY:
Simple spin symmetrization between what we know of matter & force carrier fields/particles



SUSY

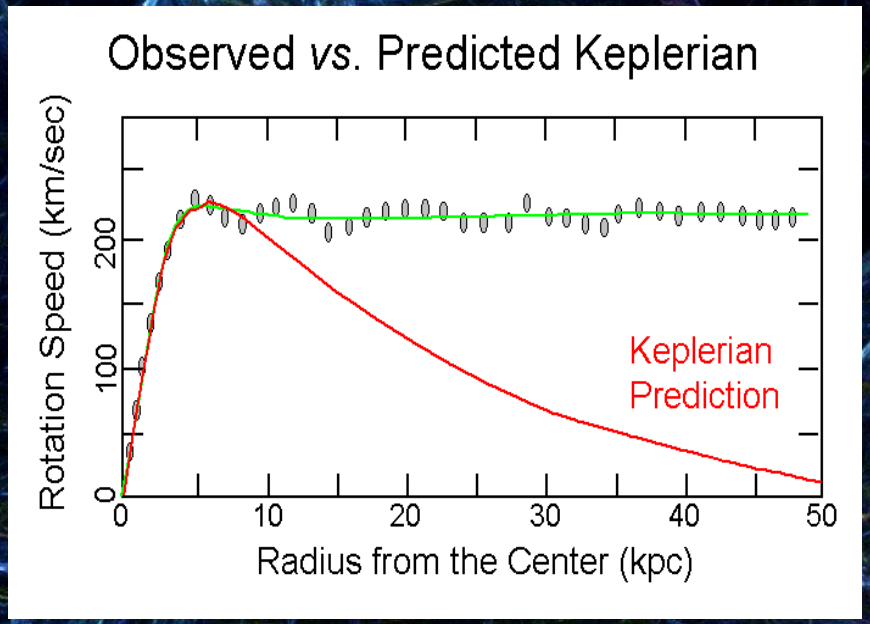


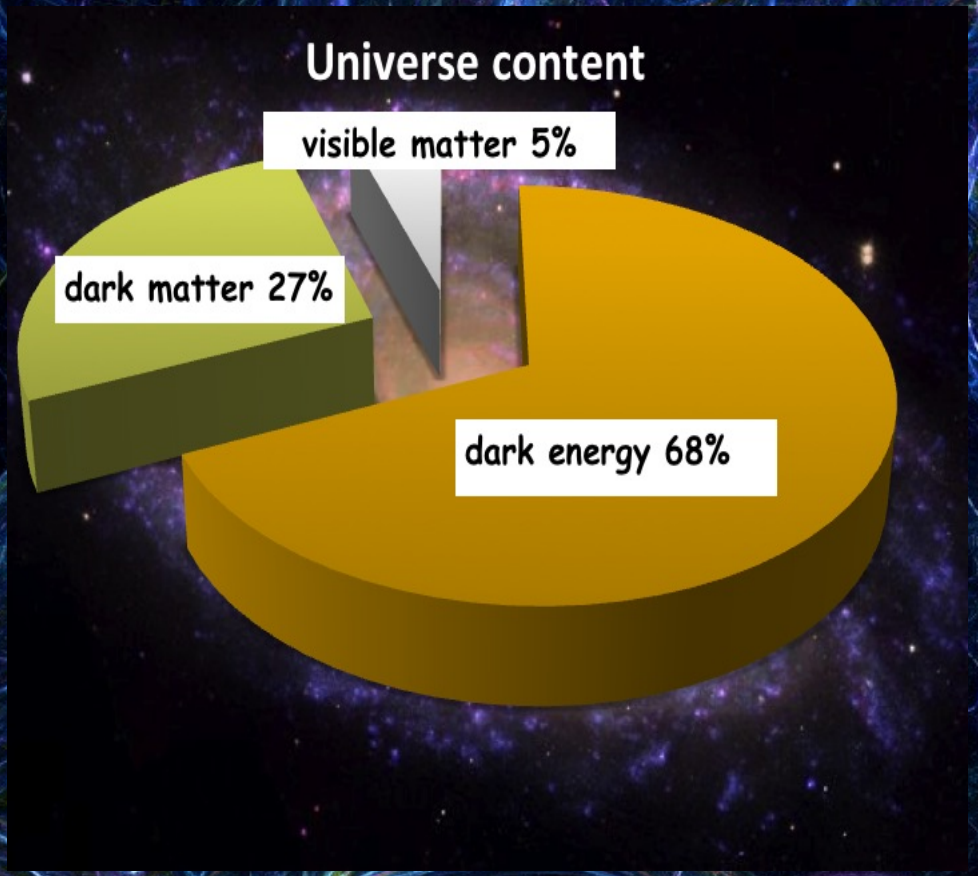
Unifies the different interactions... quite elegantly



SUSY

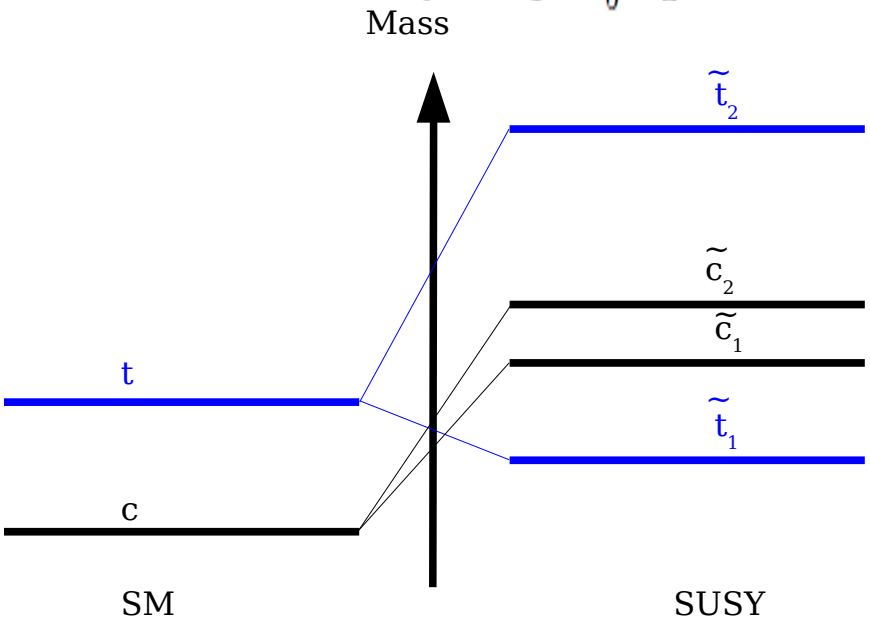
- **Has natural candidate(s) for the Cold Dark Matter**
  - Sneutrino: Susy partner of the neutrino ν
  - Neutralino: Mixture of partners of neutral SM bosons
  - …





SUSY search: One of our best bets

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



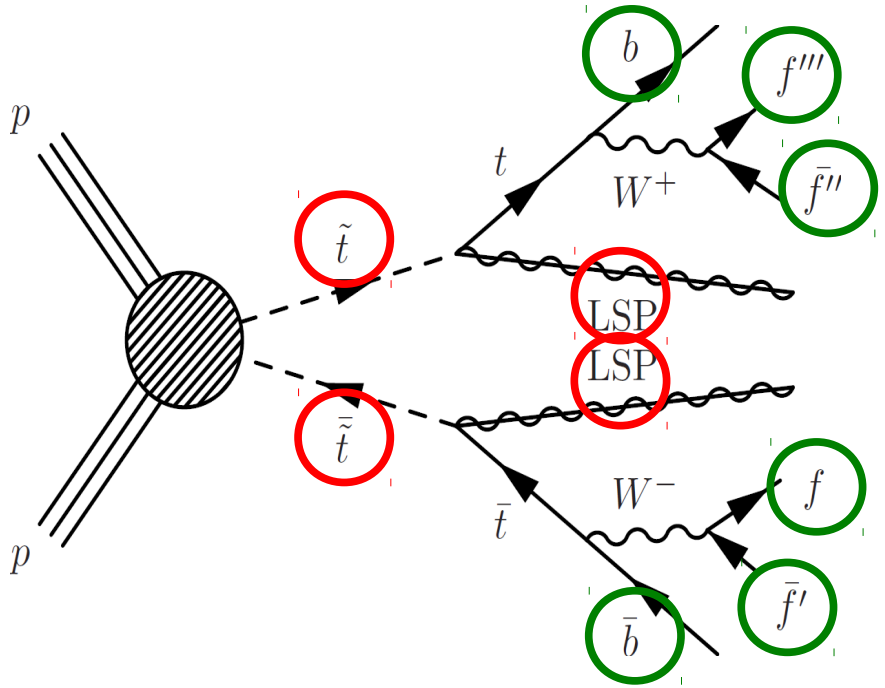
Mass difference of squarks:

Proportional to $M_Q = M_t$:

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

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

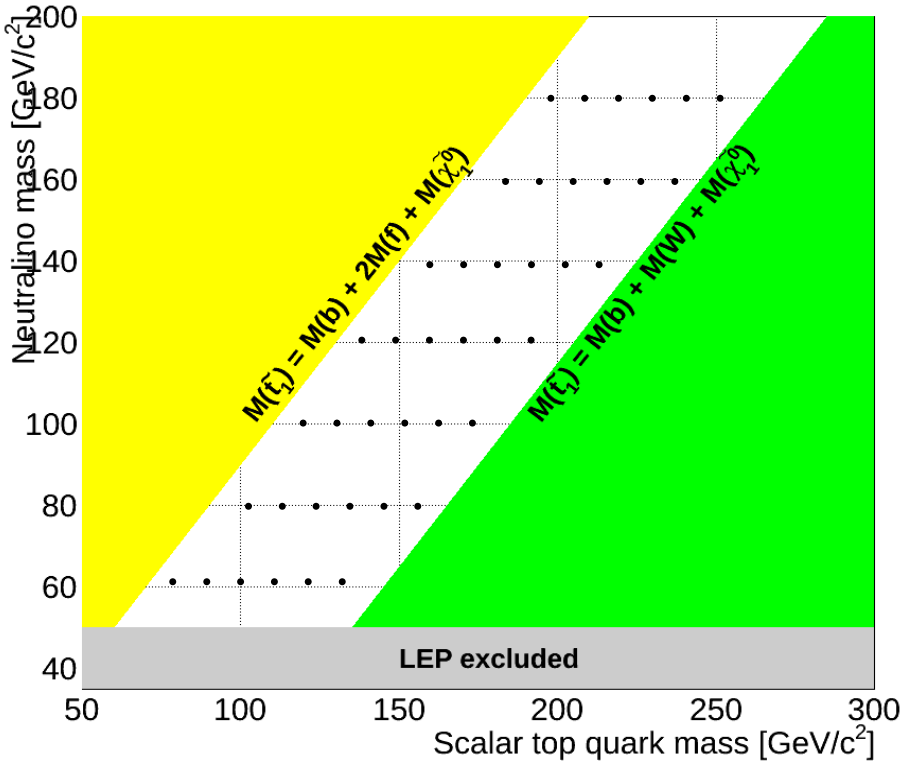
SUSY search: Example of a challenge



- **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...**

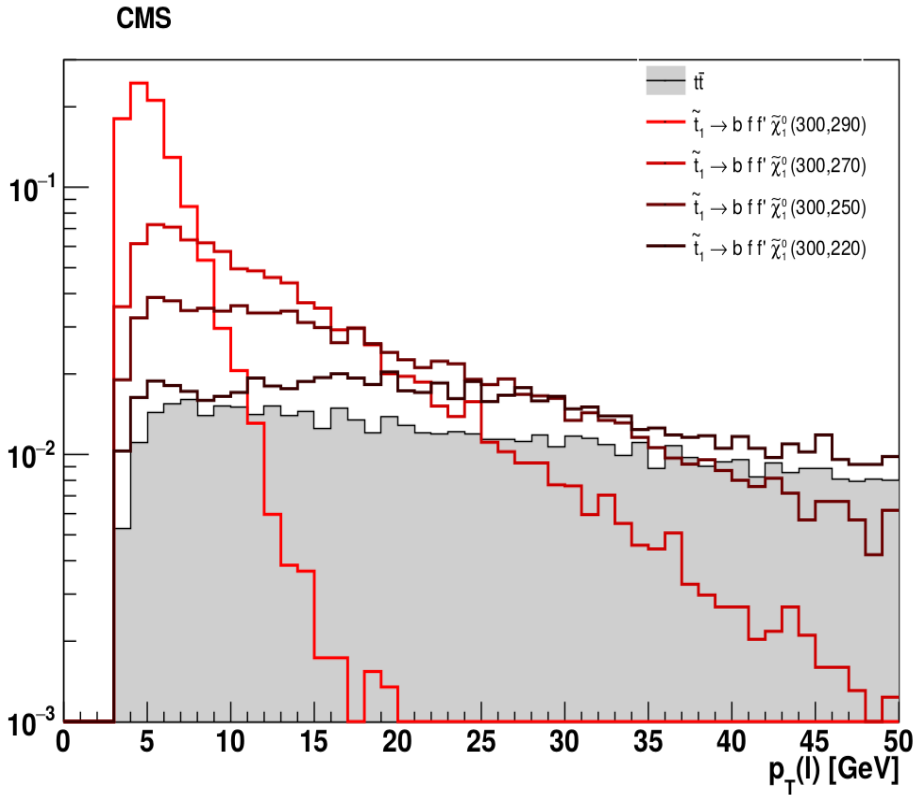
- We have to consider all mass possibilities for the 2 unknowns of this search:

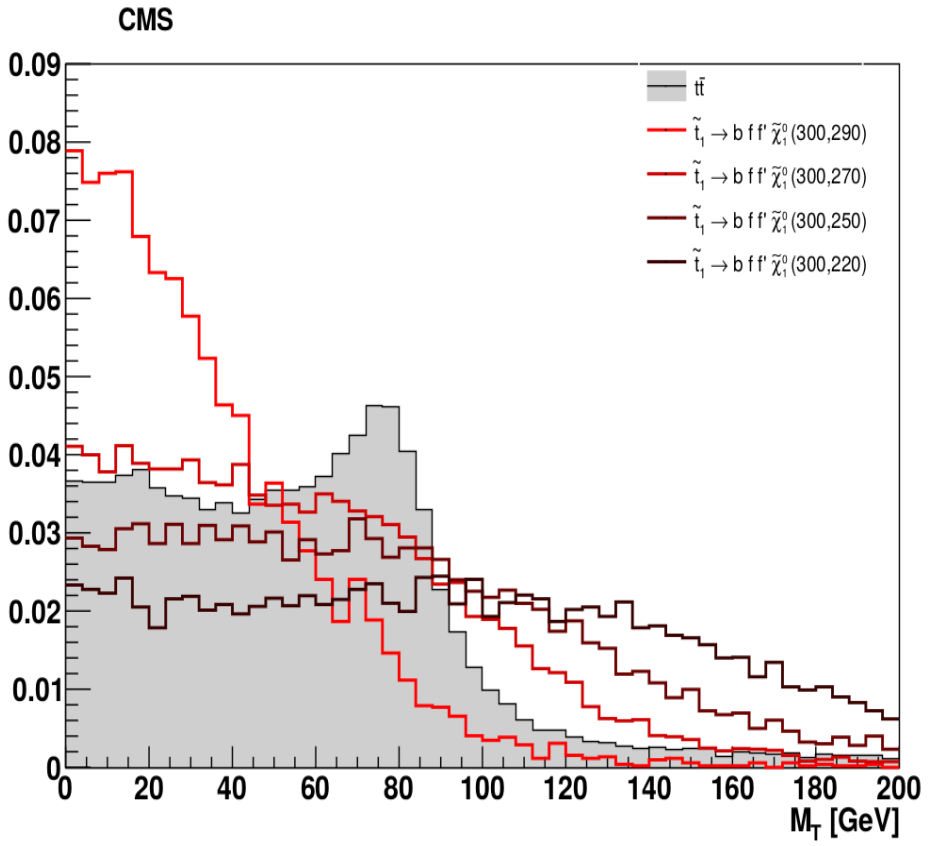
  Scan through the mass plane & search for all kinematic signatures of the same signal



How do-we search for it

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

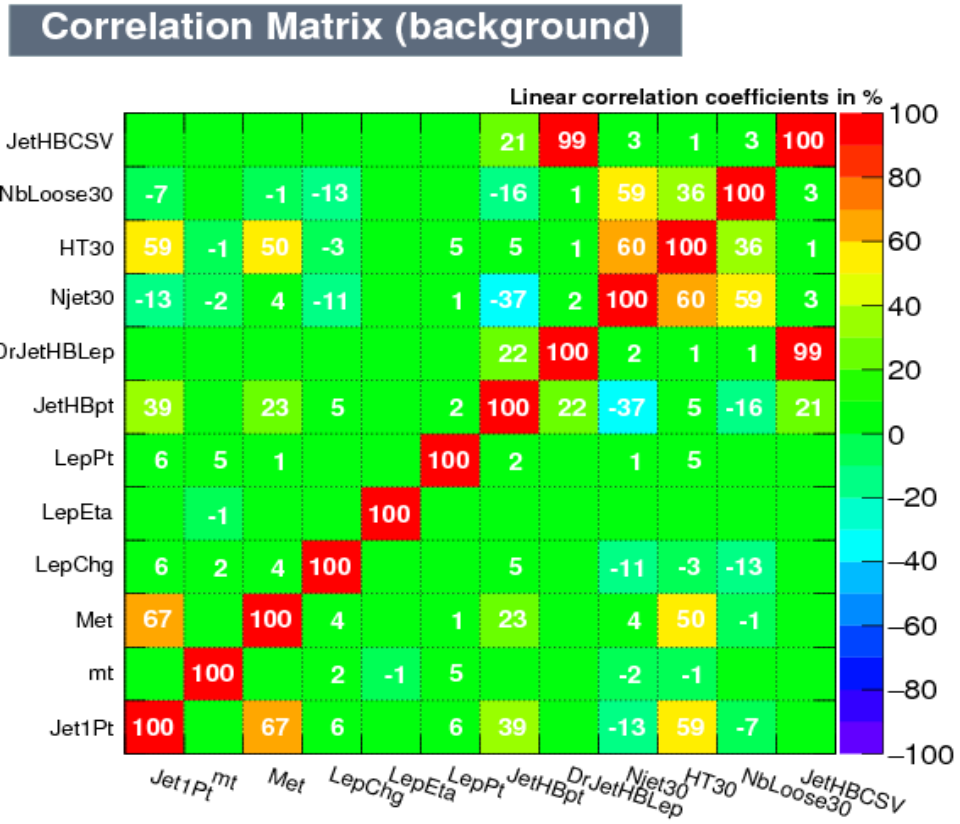


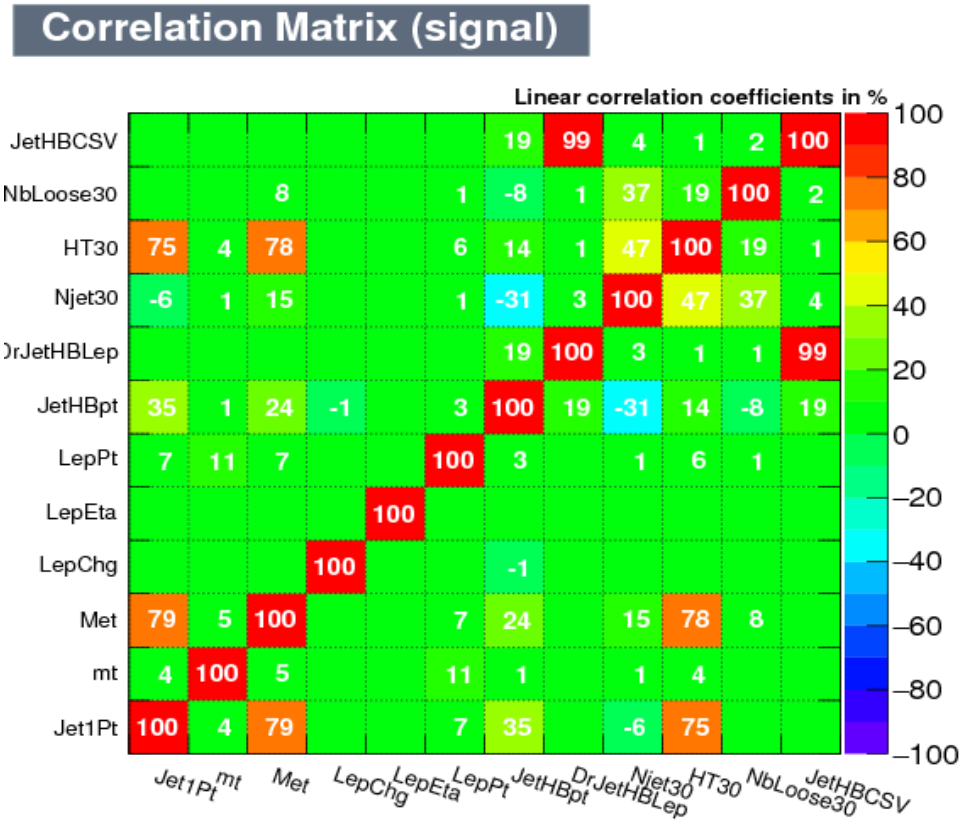


Some 21 other discriminating variables…

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 btween S & B**

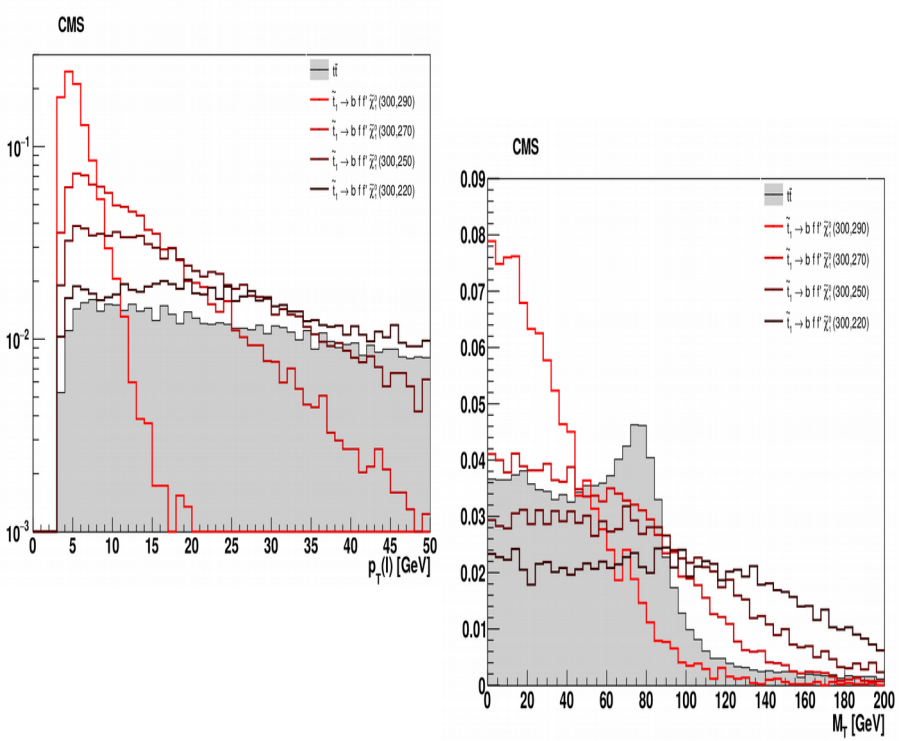




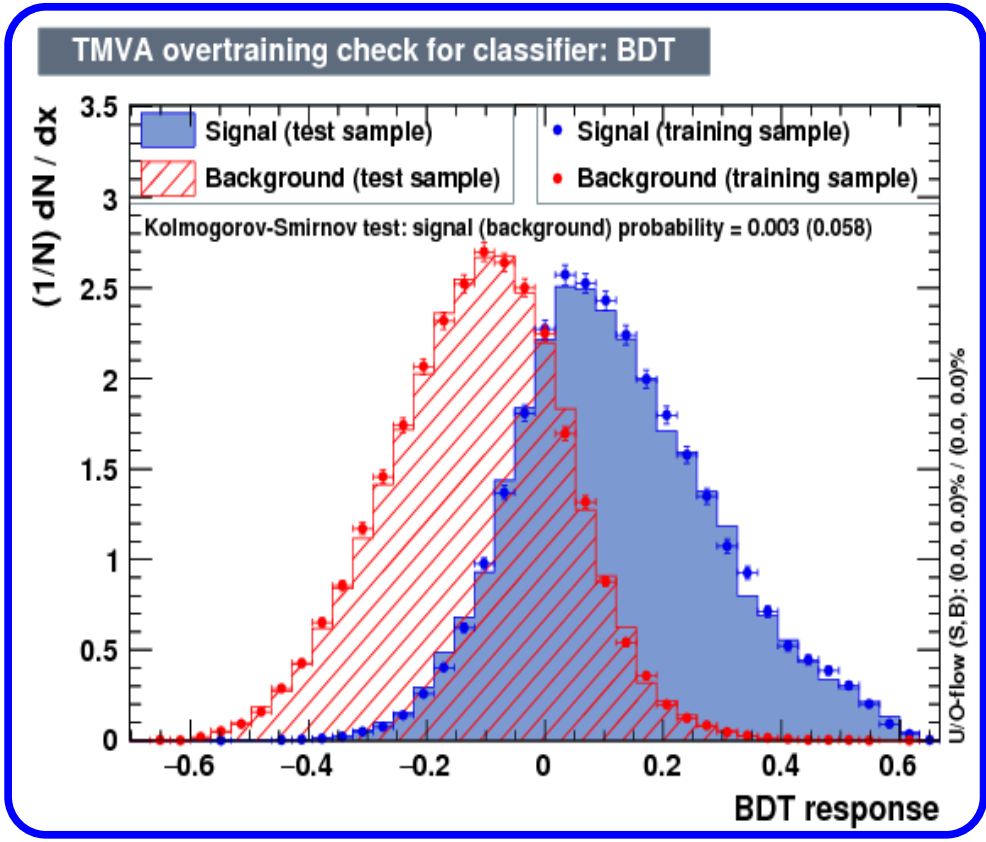
How do we search for it: MVA tool

- **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 :-)

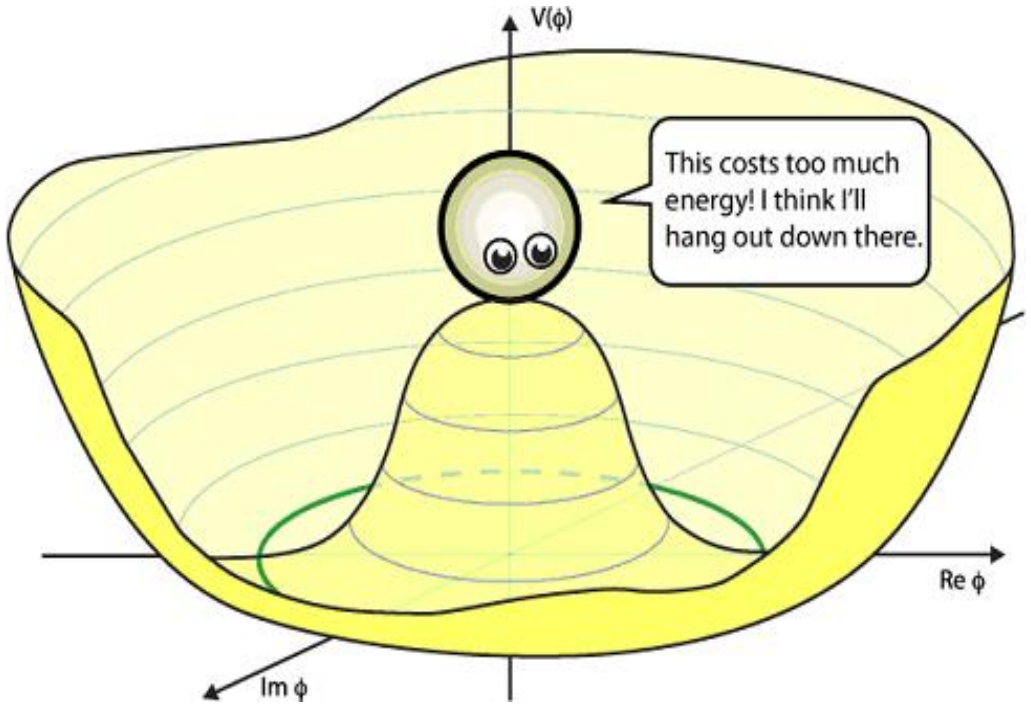
Here...



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



Higgs

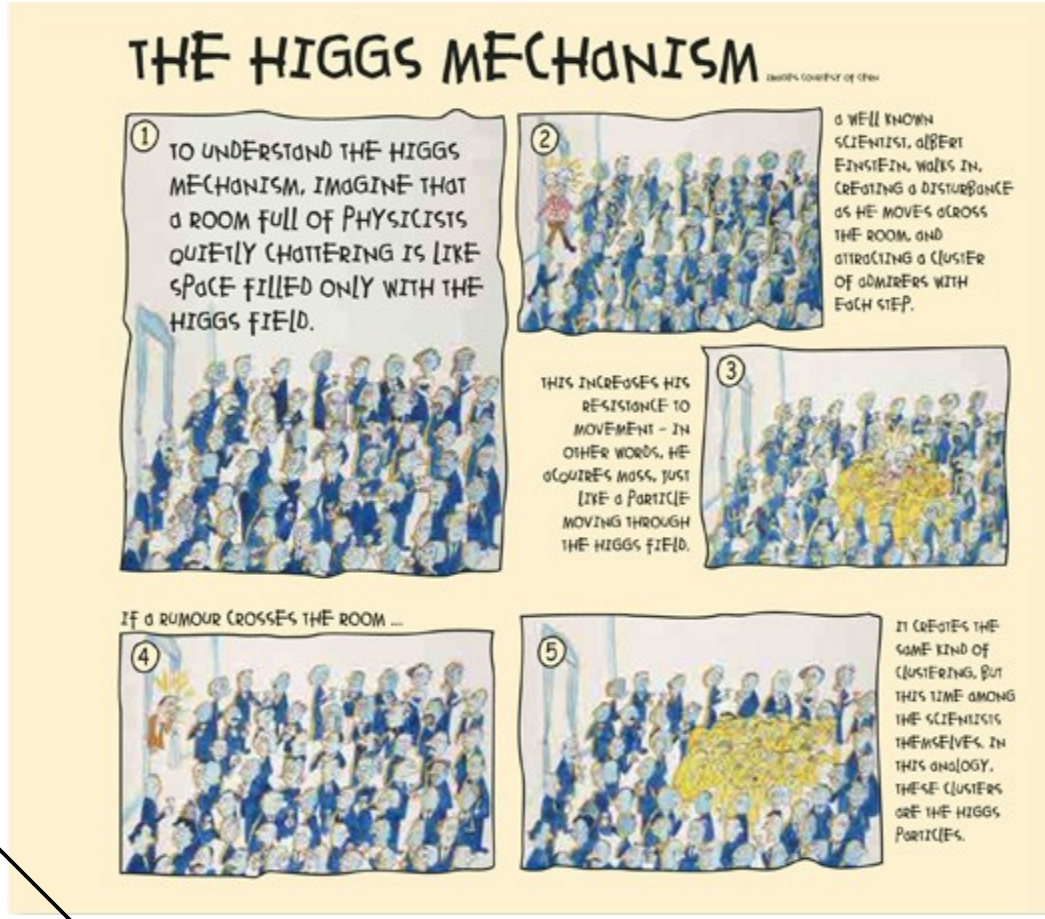

V(ϕ)
This costs too much energy! I think I'll hang out down there.
Re ϕ
Im ϕ

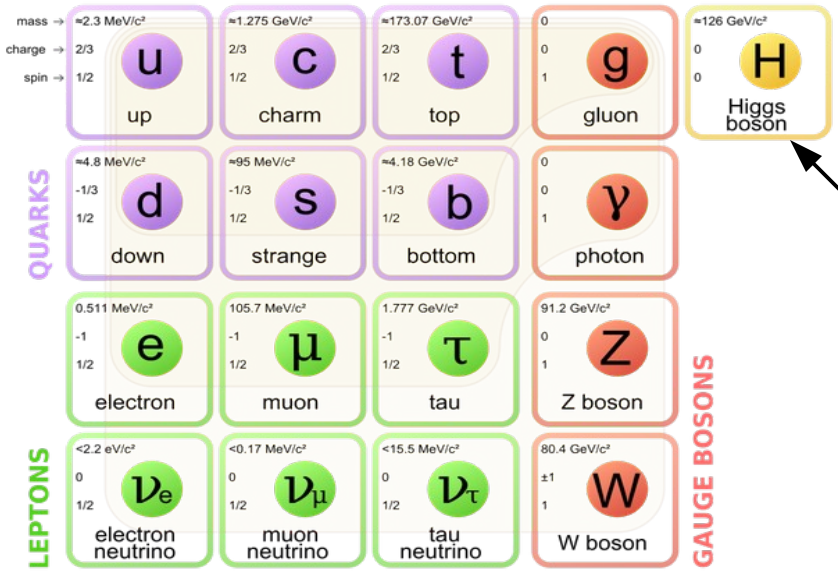
Why is Higgs interesting to study ?

- **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



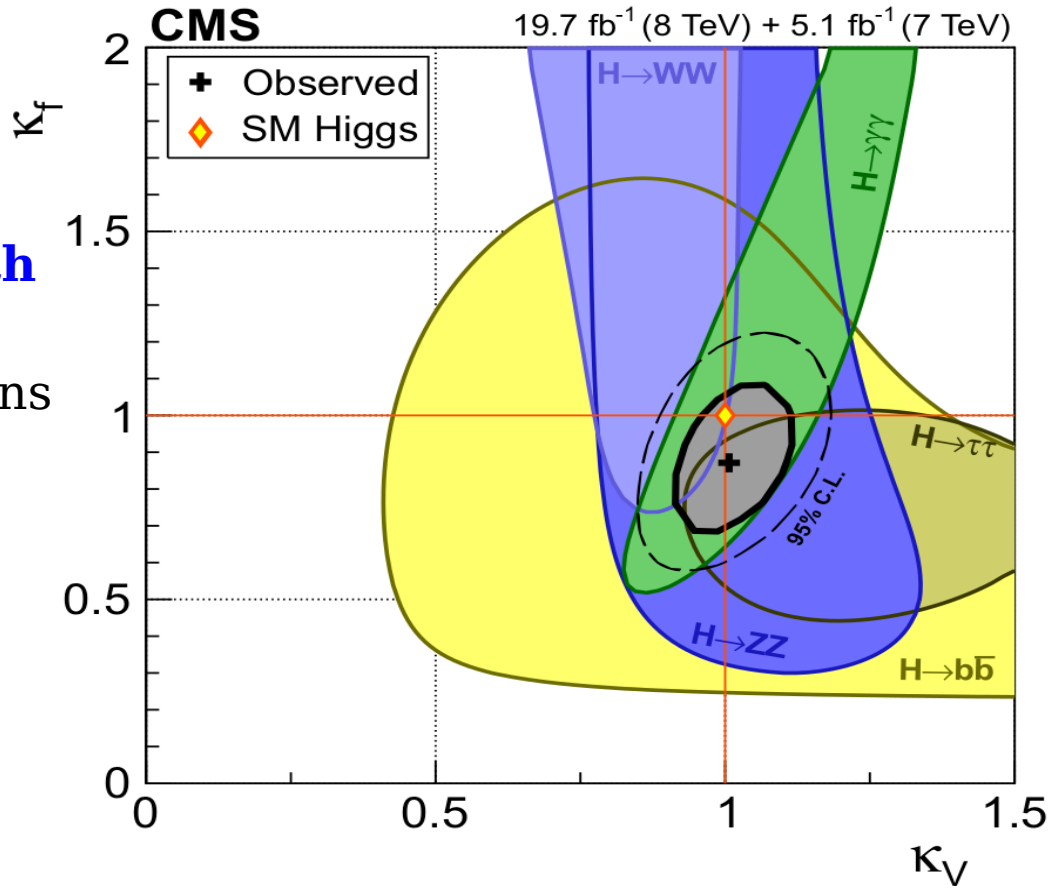


- **Does the Higgs boson only belong to SM ?**
- Are-there other, “bigger brothers” of the Higgs boson ??? i.e. other ones beyond the SM ?

Higgs properties: Couplings

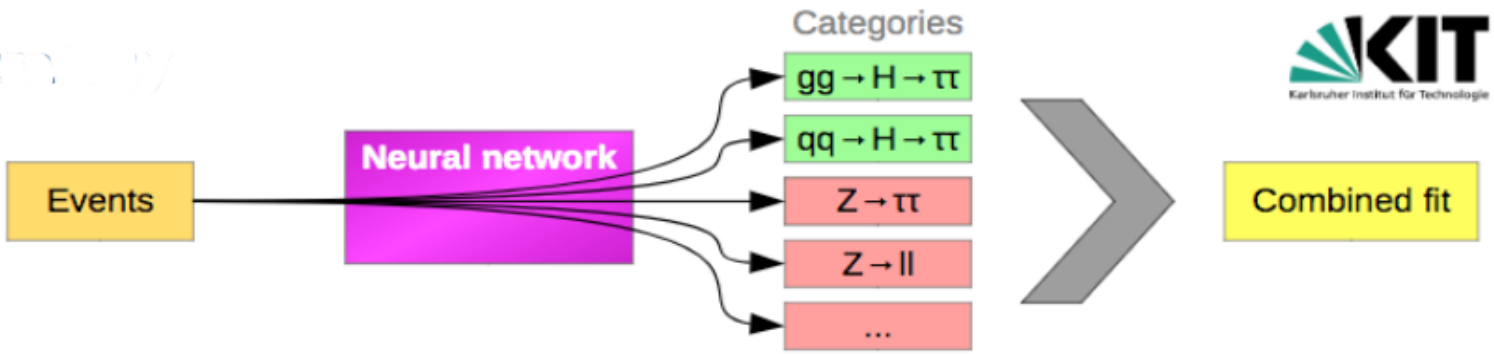
- Measure the **"strength" with which Higgs couples to different fermions & bosons of the SM**
- Is this coupling SM-compliant ? It can "look like" a SM Higgs, but in reality be part of a bigger theory, where there are several Higgs bosons
- Higgs belonging to something than SM would show in "details"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

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



$H \rightarrow 2\,\tau$

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



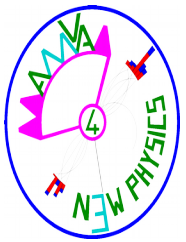
- For each event, the trained NN gives, for each class, a probability that the event belongs to the class
- Build "exclusive probability"
  - Give each event the value corresponding to the highest probability across all classes
  - Place each event in a category corresponding to the class with highest 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
twitter.com/Giles_C_Strong
amva4newphysics.wordpress.com

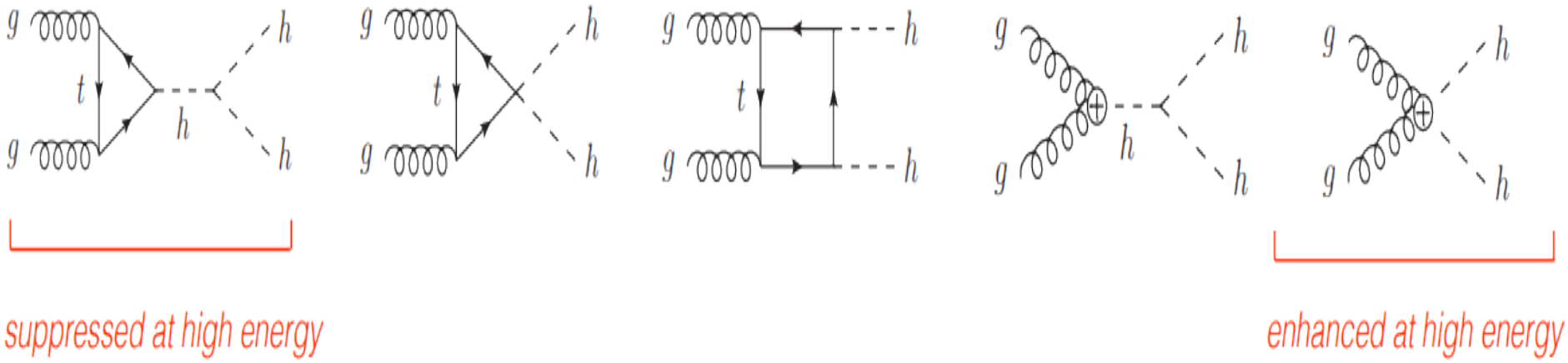


Why search for di-Higgs

- 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

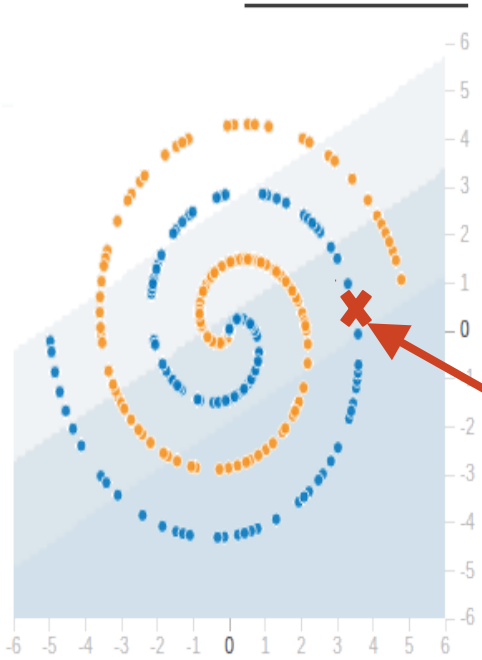
- Di-Higgs can be produced in many ways, and these production mechanisms vary according to the energy level*:



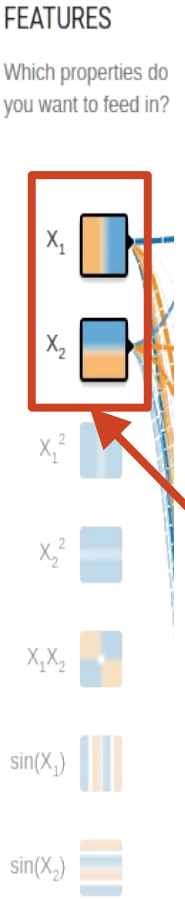
- Di-Higgs can decay to different final-states = many search channels & a variety of strategies
- The low rate of production requires efficient use of the data available
- LIP is currently involved in developing Machine Learning tools for this search

* Diagrams by Roberto Contino, INFN-Pisa

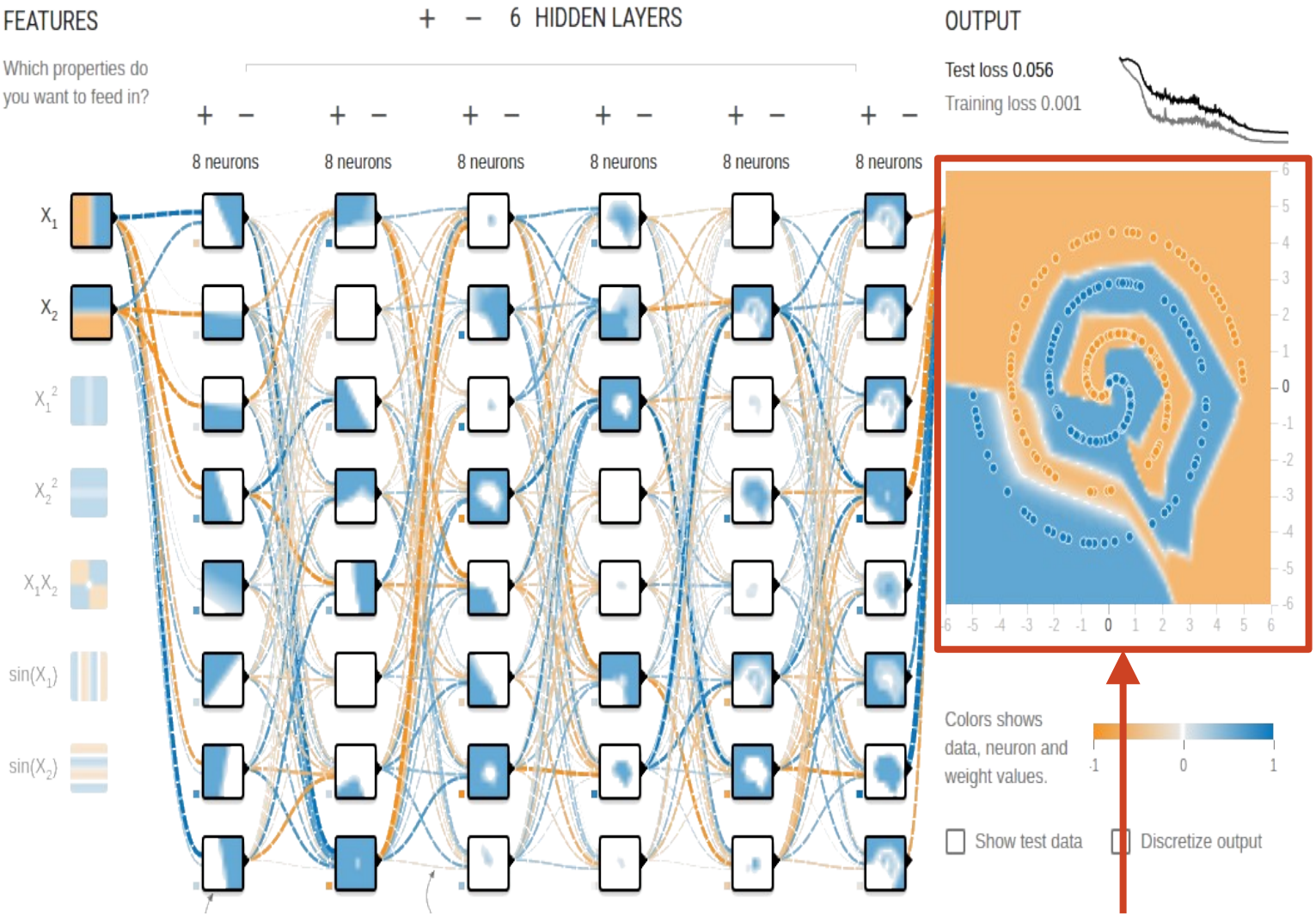
Another illustration of MVA/ML



Is a point here blue or orange?



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

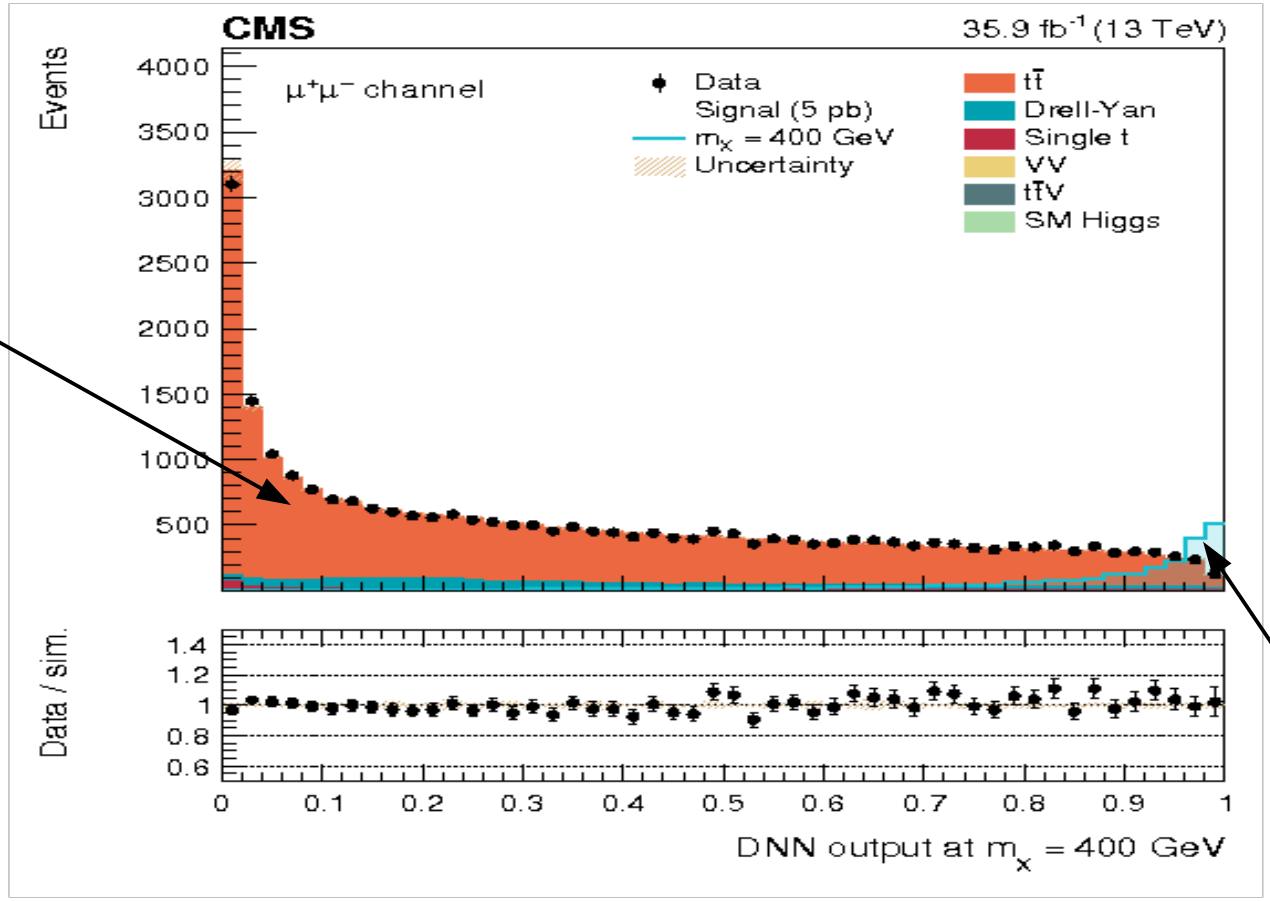


Train on example data

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]

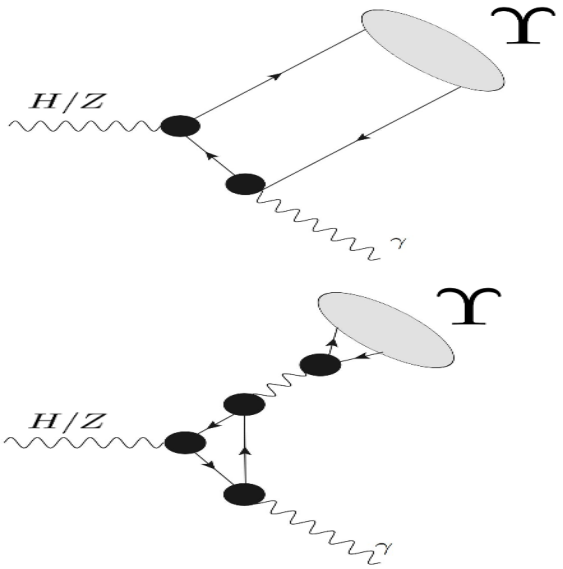
SM background

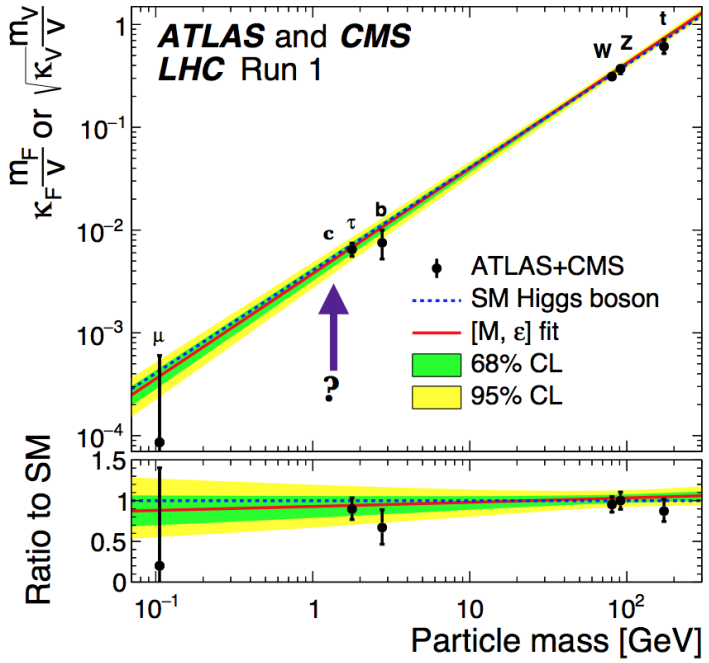


Signal

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→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





N. Leonardo, E. Melo

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

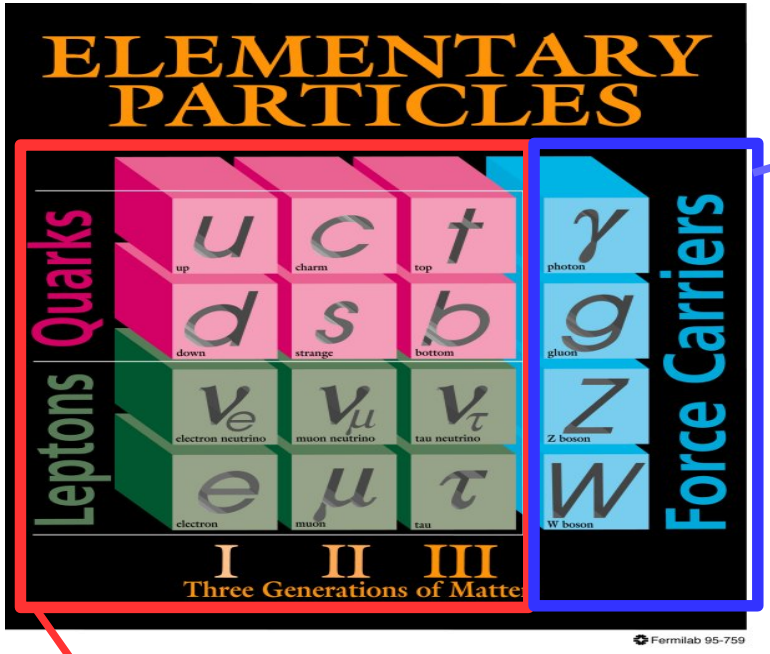
- **Data analysis**: Your capacity to understand data & find 1 interesting event out of O(10^4,10^6)

  @ 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 2nd-3rd 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/
- **Contact me: bargassa@cern.ch**

Backup

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



BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	−1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

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

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	<1×10^{-8}	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

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

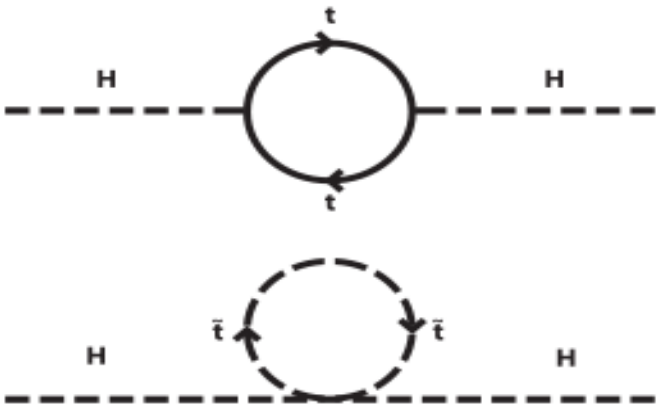
Is this a “happens to be” ? Or there is a hidden symmetry behind this ?

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-instable ? Fortunately not ;-)
  - There has to be another theory which stabilizes masses

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



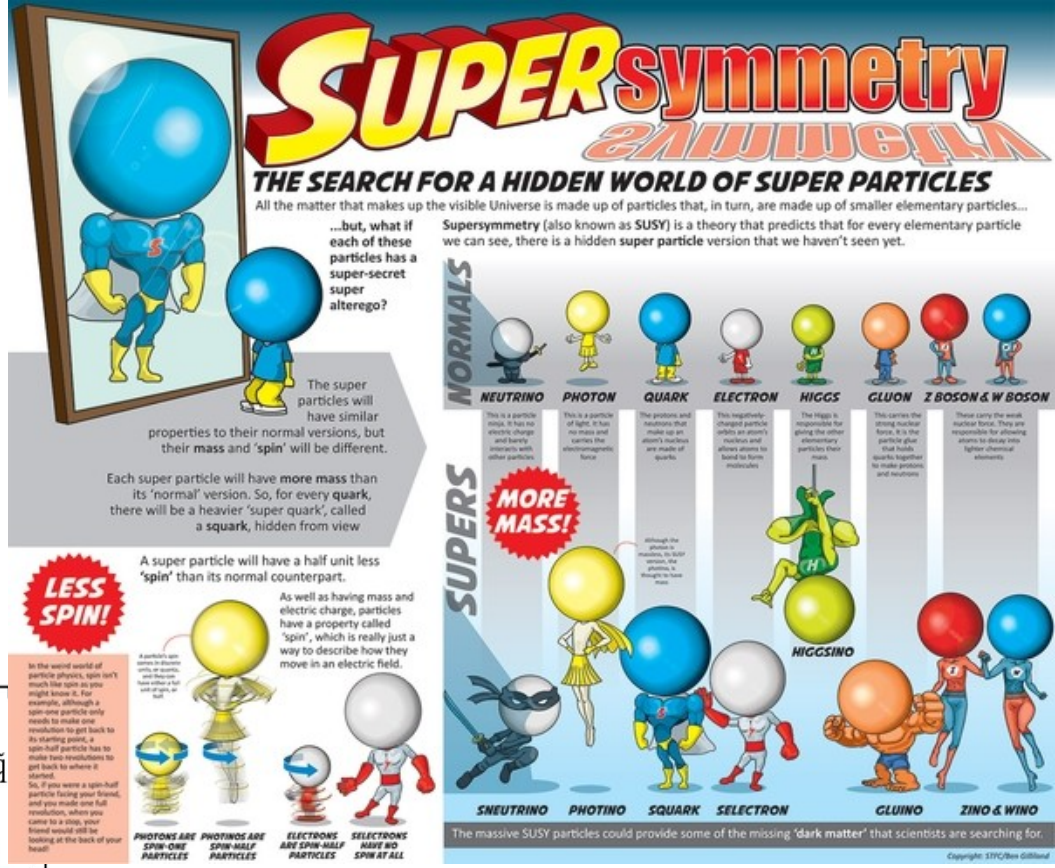
$$- \frac{g_S^2}{4\pi^2}\left(\Lambda^2 + m_S^2\right)$$

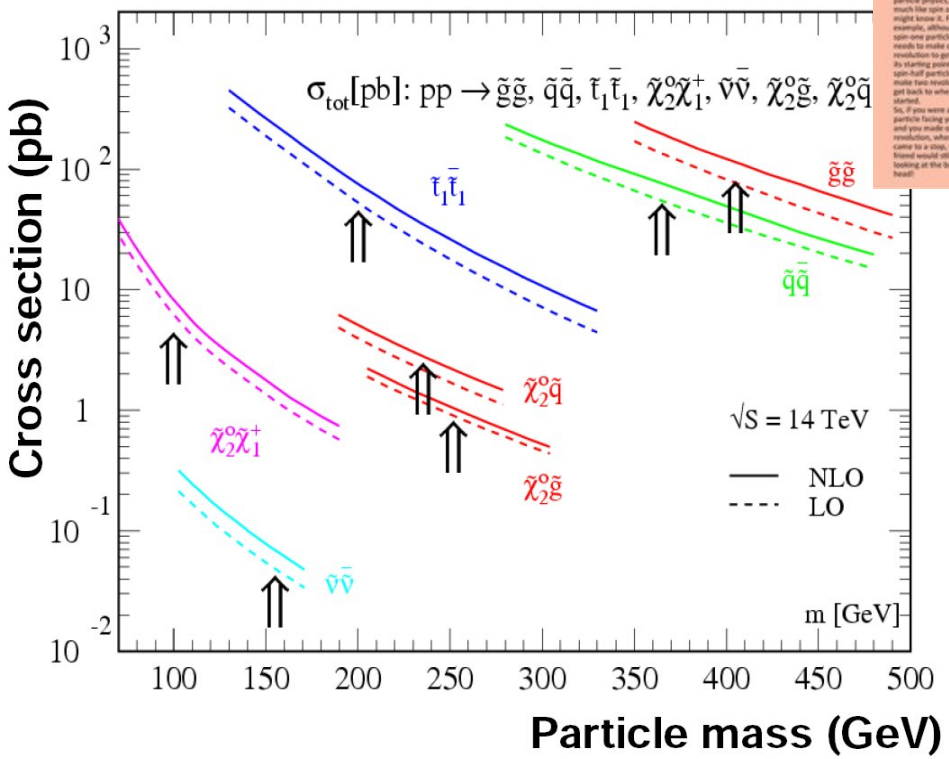
- **SUSY cures the divergences of the SM <u>by definition</u>: Associates a scalar partner (-) to each SM fermion (+)**

sParticles are special:

If SUSY exists, it's a broken symmetry:

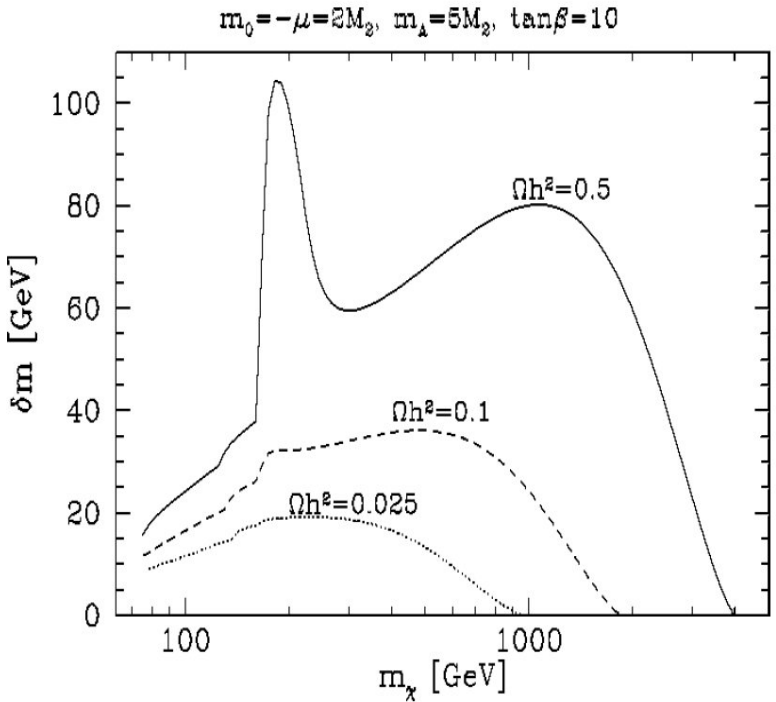
- Physical sParticles are mixtures of Susy particles
- They exist @ higher masses





Among all sParticles:
Which one is our best bet ?

SUSY search: One of our best bets



Boehm et al., PRD 62, 35012

IF : $\delta m = M(\tilde{P}) - M(\tilde{\chi}^0_1)$ small,

co-annihilations dominates → $\Omega_{CDM} h^2 \approx 0.1$

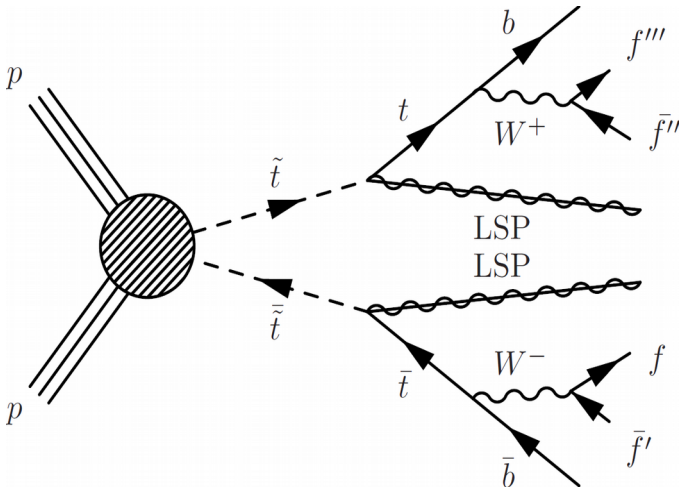
Data on Cold Dark Matter:

$\Omega_{CDM} h^2 = 0.11 \pm 0.01$ @ 95% CL (WMAP)

Gives preference to

$\Delta m = M(\tilde{t}_1) - M(\tilde{\chi}^0_1) \leq 50$ GeV/c^2

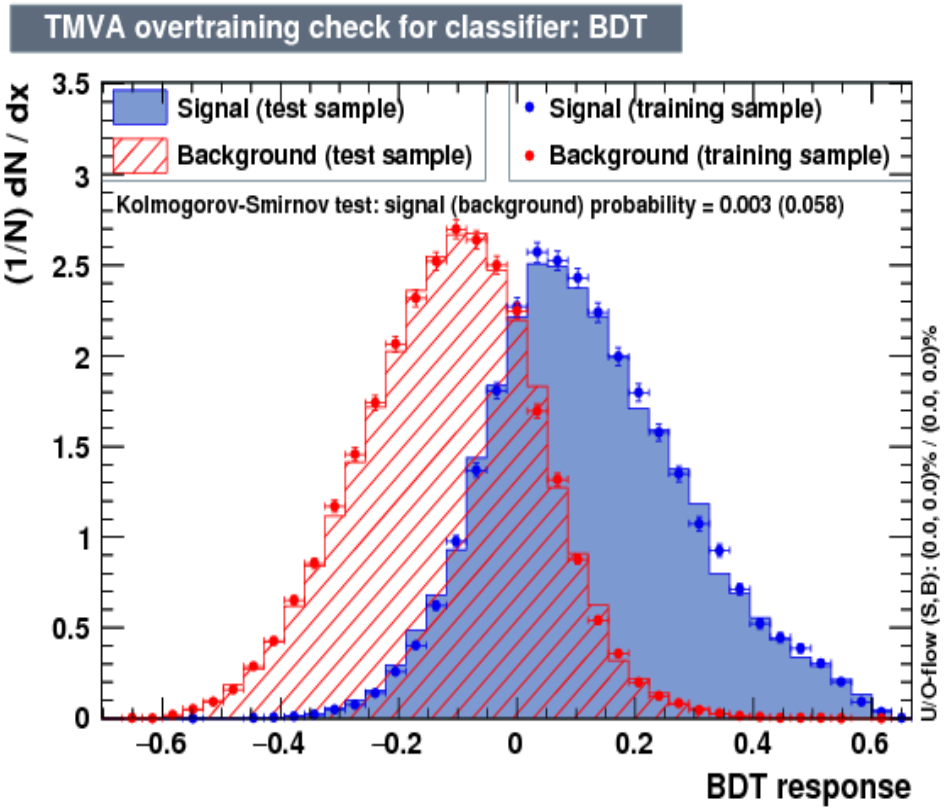
Gives preference to 4-body decays

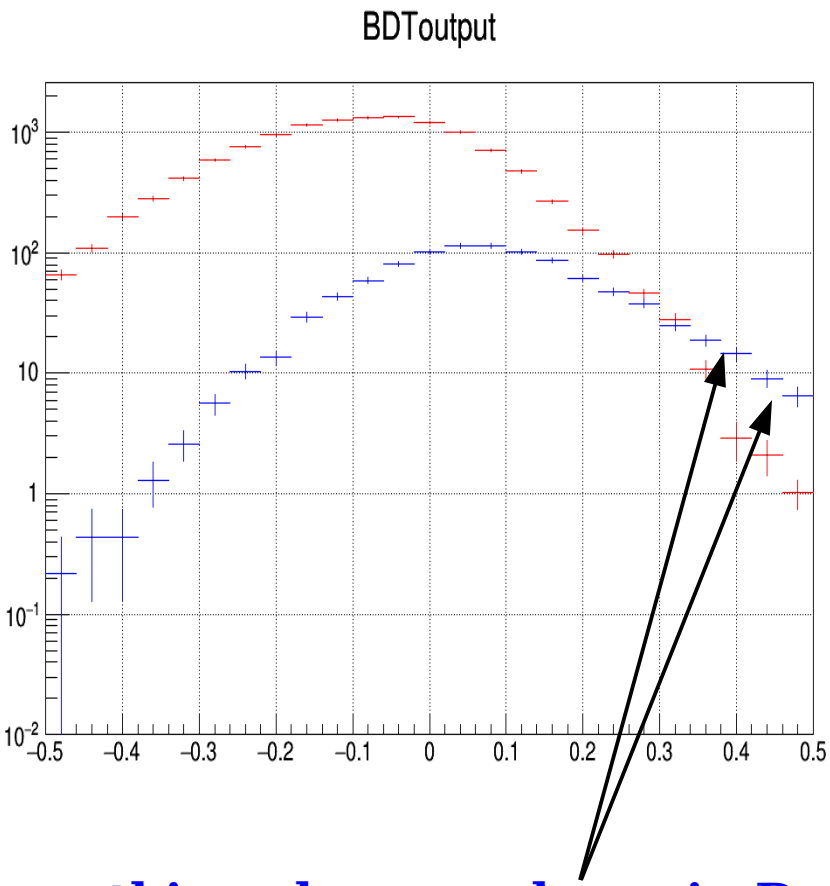


How do we search for it: MVA tool

- 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

Jet tagging

Particle ID

Event classification

Event triggering

Kinematic regression

Simulation

Detector design

Inference

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