Searching in 2-D Mass Space for Final States with 2 Invisible Particles

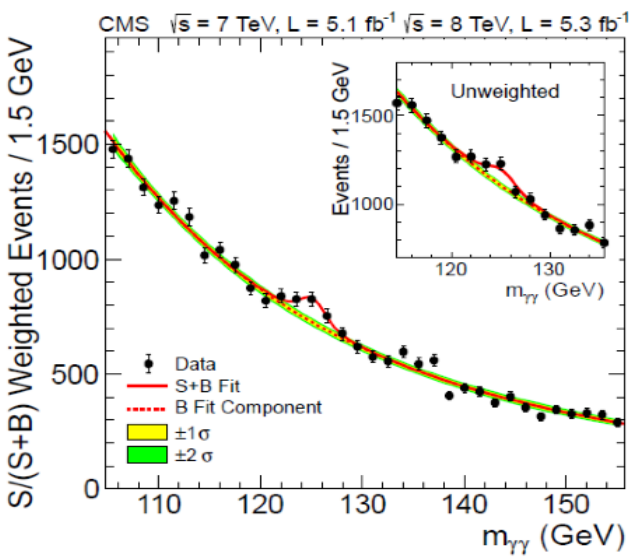
Dark Matter Identification: Connecting Theory and Signature Space

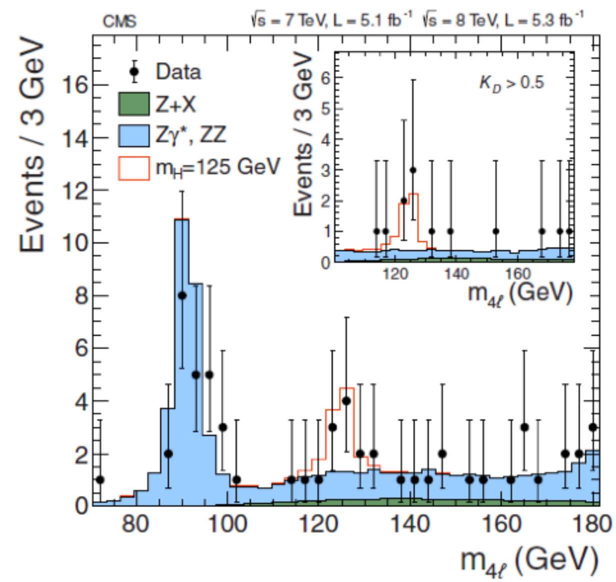
Giorgos Anagnostou

Mainz 5 April 2019

How to search for dark matter @ the LHC?

Higgs discovery "easy": mass peaks at predicted region:





Many models with dark matter particles (e.g susy) have at least 2 invisible (undetectable) particles

use missing energy – like observables.

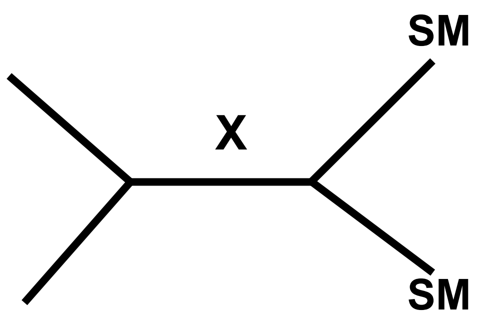
How to search for dark matter @ the LHC?

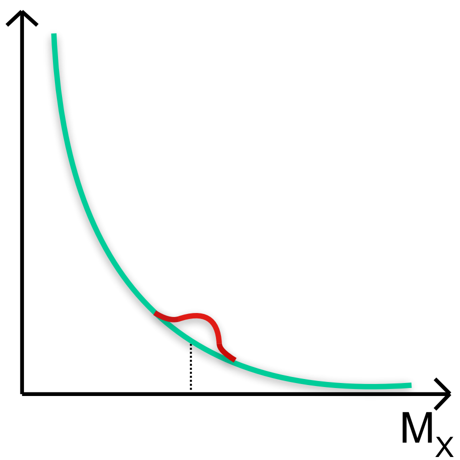
Discovery with missing energy difficult to be established (tail of a rapidly falling distribution).

Even if established what can we say about the model?

Is there an optimum parameter space? 1-Dimension

Let's assume a model with 1 New Particle X decaying to visible particles
The experimental observables would be M_X, Γ_X, σ_X





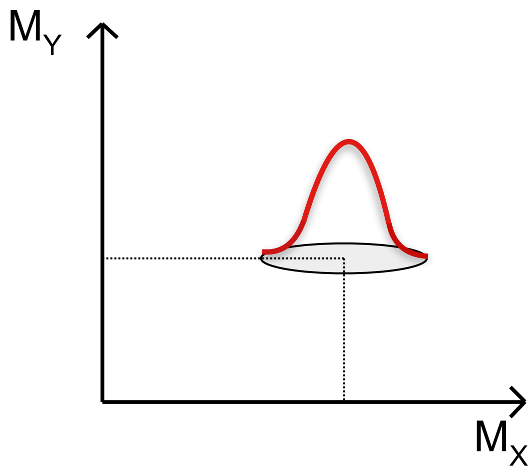
What about Signal to Background ratio? Particle X is concentrated around M_X

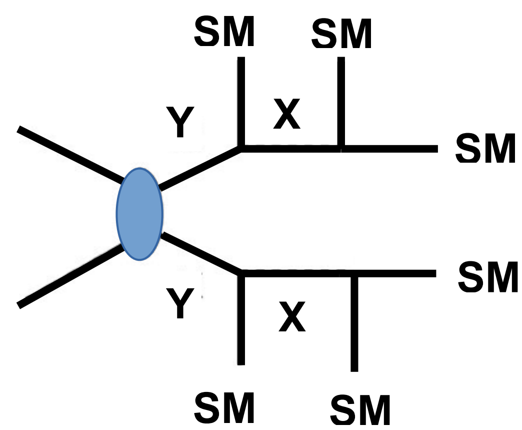
As SM has no such particle, the background has no reason to prefer M_X region.
It is actually a decreasing function $f(M_X) \to 0$ for higher M_X.

S/B is maximized around M_X. The M_X is the optimum single observable to search X

2-Dimensional Mass Space

Model with 2 New Particles X, Y.
The experimental observables would be M_X,Γ_X,σ_X M_Y,Γ_Y ,$\sigma_{Y.}$
Signal is concentrated in 2-Dimensional mass space around ($M_{X,}M_Y$) point.





As SM has no X,Y resonances, the background has no reason to prefer the same region.

S/B is maximized around ($M_{X,}M_Y$) point.

Why Mass Space?

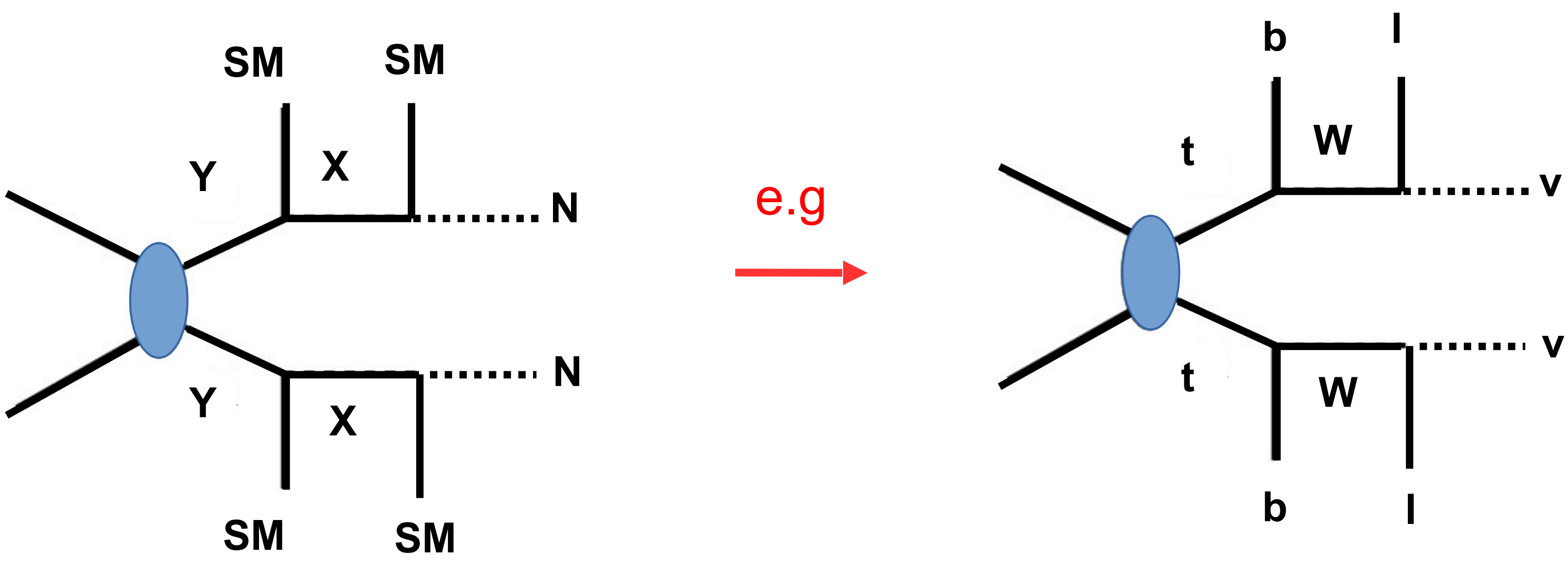
Most important characteristic of elementary particles → mass, spin. So why not search in mass space (if possible) with

Dimensions = number of unknown particles

is mass reconstruction possible in final states with 2 invisible particles?

What about invisible particles?

What if we have in the end of each decay chain an invisible particle (N)?
What can we do?



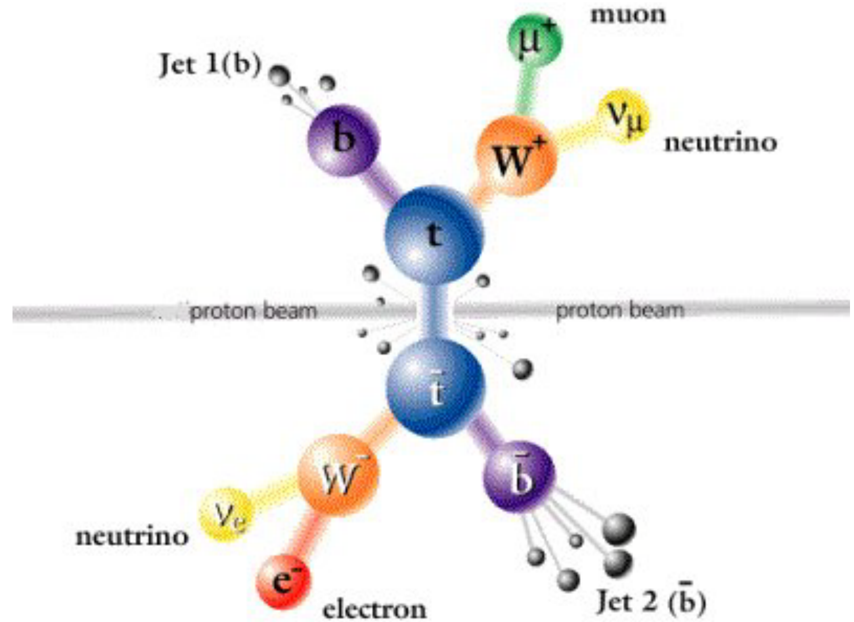
Question(s)

Could we find the mass of the top quark and W boson in LHC from top-pairs decaying leptonically in the hypothetical case in which both m_t and m_W were unknown?

Could we establish a discovery by observing the mass peaks above background for both particles without assumptions about the underlying theory, except the decay topology?

Why top-pairs?

"Rediscovery" of both top and W would be a "proof of principle" for the method.



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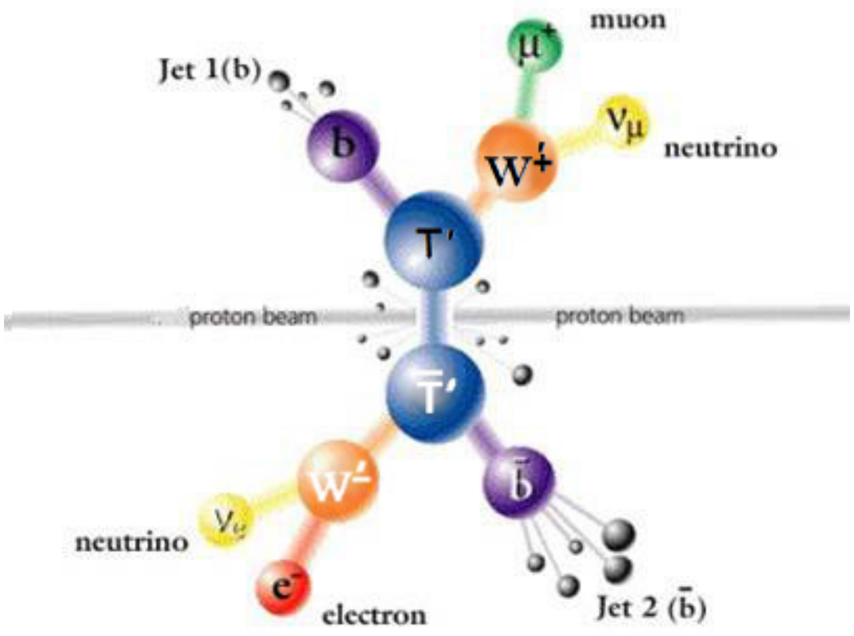


T' search, W' search:

pp → T'T' → Wb Wb

pp → T'T' → W'b W'b

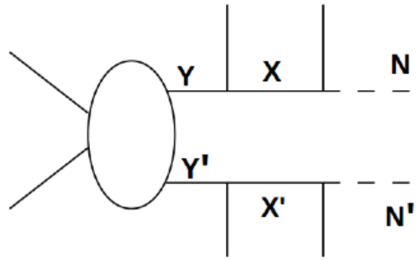
Z' search:

pp →Z'→ tt,

pp →Z'→ T'T'

We can search for anything decaying like dilepton top-pairs

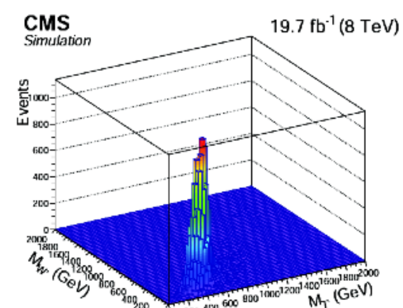
2-D mass reconstruction for final state with 2 invisible particles - What is it?



Topology

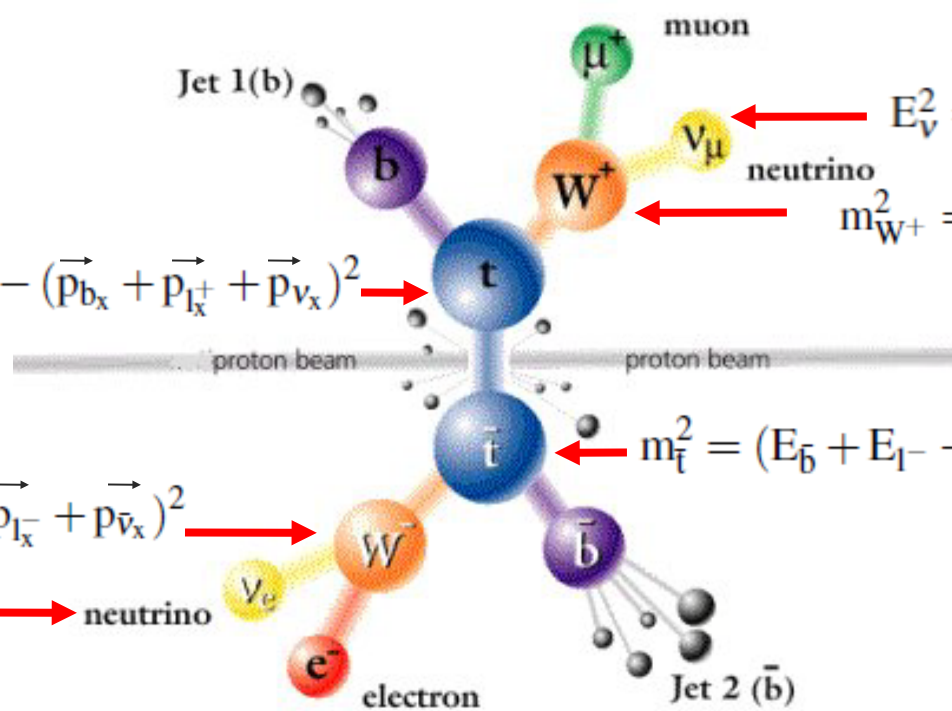
MET+
Visible particles
momenta

2 unknown masses
M_X & M_Y per event



- Needs the solvable topology
- 2 invisible particles

Analytical Solution of dilepton top pairs



① $$m_t^2 = (E_b + E_{l^+} + E_\nu)^2 - (\vec{p}_{b_x} + \vec{p}_{l_x^+} + \vec{p}_{\nu_x})^2$$

② $$E_\nu^2 = p_{\nu_x}^2 + p_{\nu_y}^2 + p_{\nu_z}^2$$

③ $$m_{W^+}^2 = (E_{l^+} + E_\nu)^2 - (\vec{p}_{l_x^+} + \vec{p}_{\nu_x})^2$$

④ $$m_{\bar{t}}^2 = (E_{\bar{b}} + E_{l^-} + E_{\bar{\nu}})^2 - (\vec{p}_{\bar{b}_x} + \vec{p}_{l_x^-} + \vec{p}_{\bar{\nu}_x})^2$$

⑤ $$m_{W^-}^2 = (E_{l^-} + E_{\bar{\nu}})^2 - (\vec{p}_{l_x^-} + \vec{p}_{\bar{\nu}_x})^2$$

⑥ $$E_{\bar{\nu}}^2 = p_{\bar{\nu}_x}^2 + p_{\bar{\nu}_y}^2 + p_{\bar{\nu}_z}^2$$

+ missing energy

⑦ $$M_{ET_y} = p_{\nu_y} + p_{\bar{\nu}_y}$$

⑧ $$M_{ET_x} = p_{\nu_x} + p_{\bar{\nu}_x}$$

Analytical Solution of dilepton top pairs

An analytical solution for the equations of the top-pair system is described in L. Sonnenschein, "Analytical solution of tt dilepton equations", [Phys. Rev. D 73, 054015 2006)]

$\text{MET}_{x,y}$
2 jets momenta
2leptons momenta
M_{top}, M_W

$$m_{W^+}^2 = (E_{l^+}+E_{\nu})^2 - (p_{l^+_x}+p_{\nu_x})^2 - (p_{l^+_y}+p_{\nu_y})^2 - (p_{l^+_z}+p_{\nu_z})^2$$

$$m_{W^-}^2 = (E_{l^-}+E_{\bar{\nu}})^2 - (p_{l^-_x}+p_{\bar{\nu}_x})^2 - (p_{l^-_y}+p_{\bar{\nu}_y})^2 - (p_{l^-_z}+p_{\bar{\nu}_z})^2$$

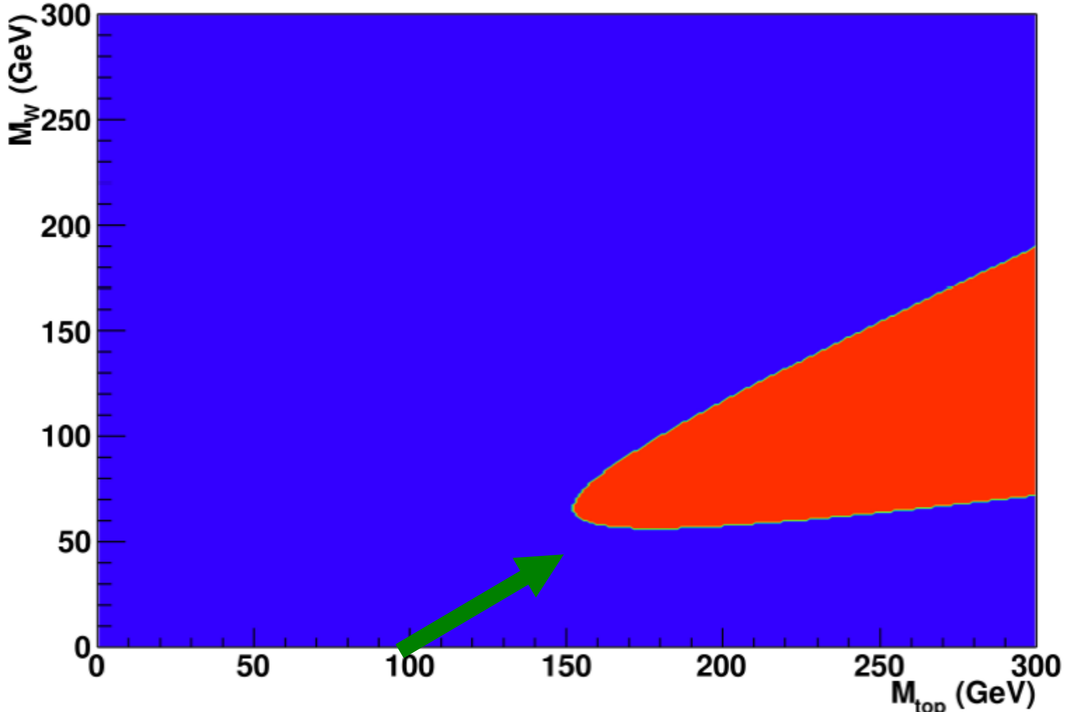
system of 8 equations

0,2 or 4 solutions/ combination
x 2 combinations/event

Each solution gives the momentum vectors of the 2 neutrinos

Solvability of a single event in mass plane

Masses of the particles are unknown → only option is to test every point of the m_t, m_W plane for possible solutions.

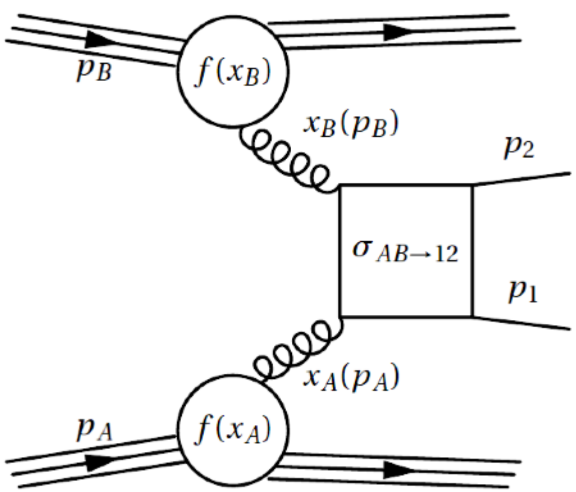


solvability is bound only from below for m_t & m_W.

Solvability = existance of a specific solution in a specific mass point

Upper bound ?

Due to the finite collision energy there is also an upper limit on the allowed masses produced.



Full reconstruction of event kinematics → energy E and P_Z of the tt system.

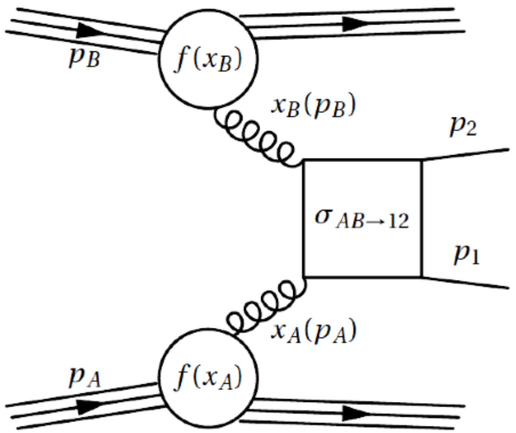
⇩

Calculation of fraction of beam energy of the two partons ($x_{A,B} = (E \pm p_z)/2$).

⇩

Each parton with fraction $x_{A/B}$ has a probability $f(x_{A/B})$ to originate from a p-p collision.

Upper bound (II)



So $f(x_A)f(x_B)$ is weight per solution and incoming parton combination

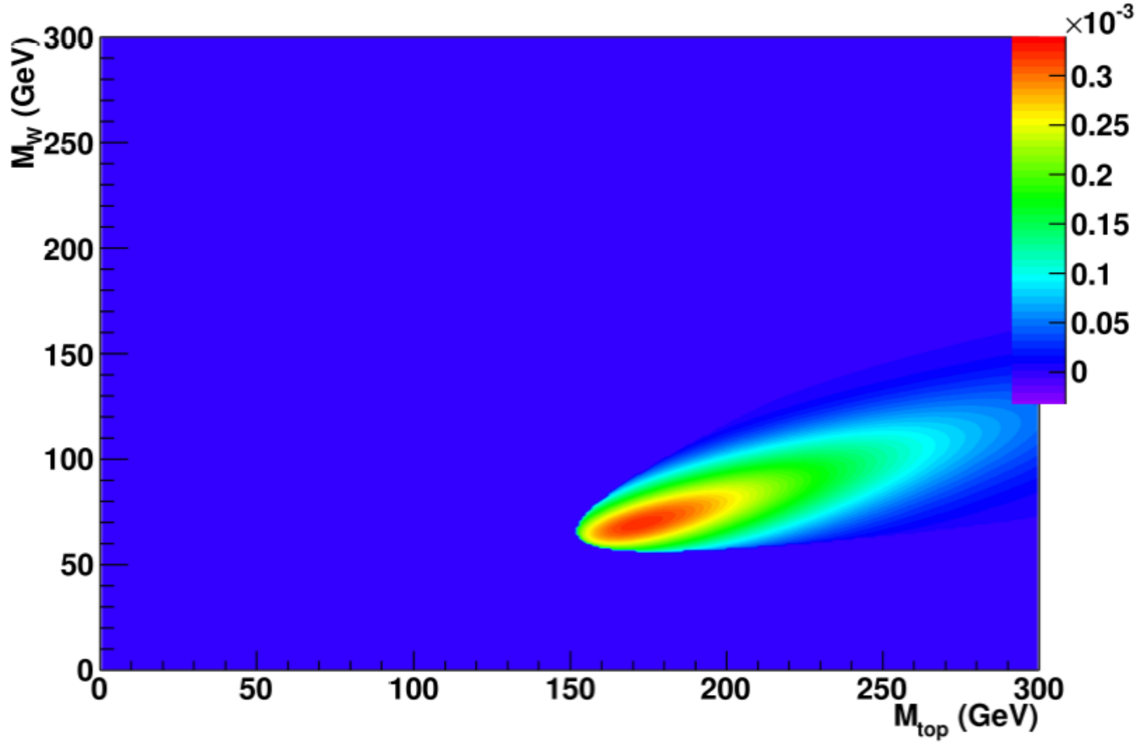
sum over all possible incoming partons $u\bar{u}$, $\bar{u}u$, $d\bar{d}$, $\bar{d}d$, gg

PDF weight = $\sum f(x_A)f(x_B)$ is final event weight per solution, per mass point

$S(m_t,m_W) \times PDF(m_t,m_W)$, $PDF=\sum f(x_A)f(x_B)$

Solvability S=0/1 of a solution for test masses m_t, m_W can be multiplied with its PDF weight to provide upper bound.

Solvability times PDF weight

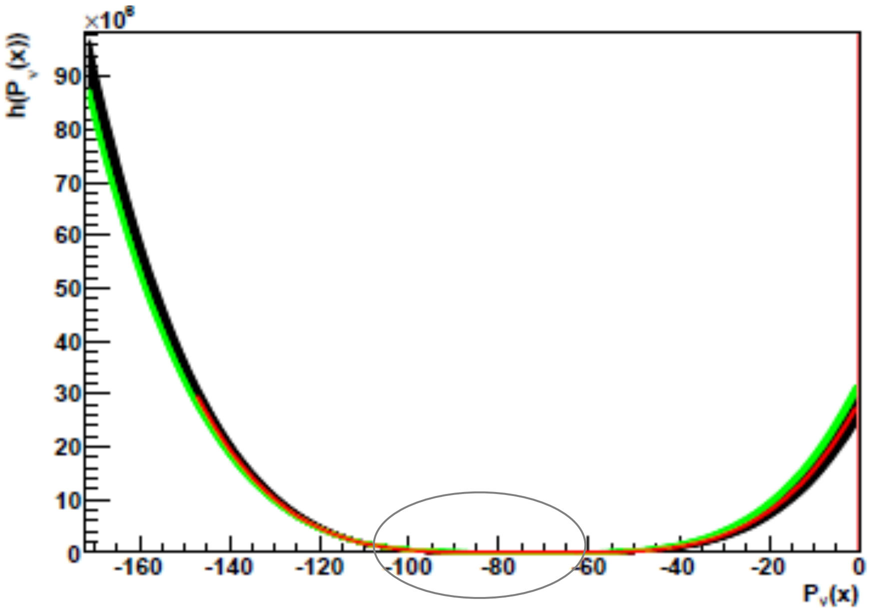


$$\boxed{S(m_t, m_W) \times PDF(m_t, m_W), \quad PDF = \sum f(x_A) f(x_B)}$$

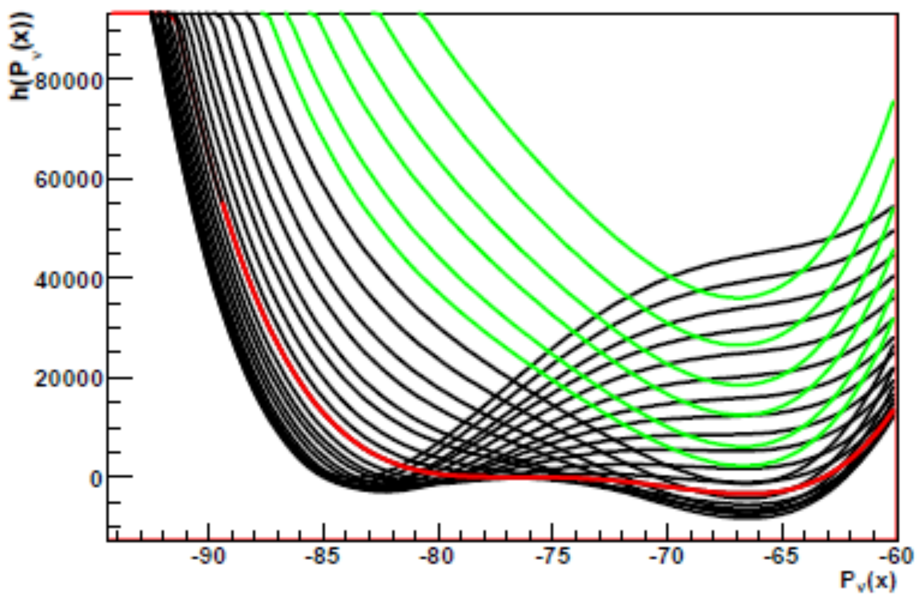
single event in mass space!

Detector effects – Loss of a solution

Polynomial for 1 GeV changes in Jet Px



Zoom in solution area

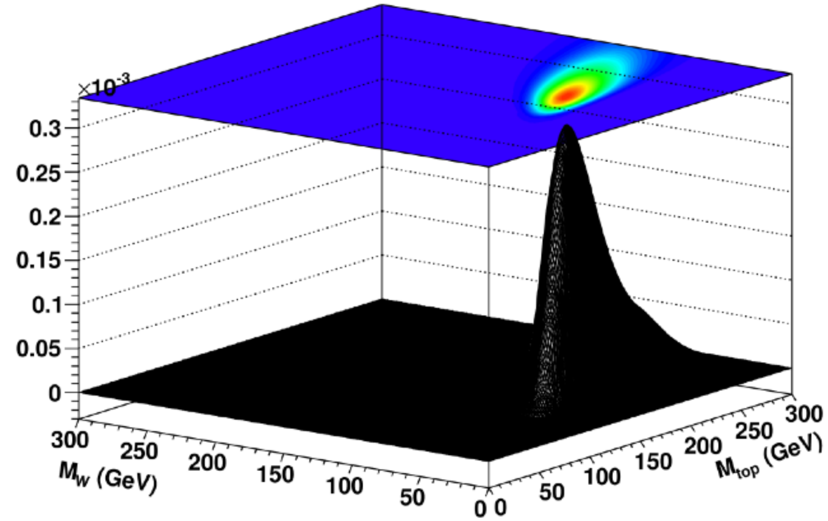


Detector effects can change a solvable event to not-solvable.

Solvability can be recovered by smearing the leptons and jets according to detector resolution.

Solvability x PDF weight (II)

PDF weight= $\sum_{a,b} F_a(x_1, Q) F_b(x_2, Q),$



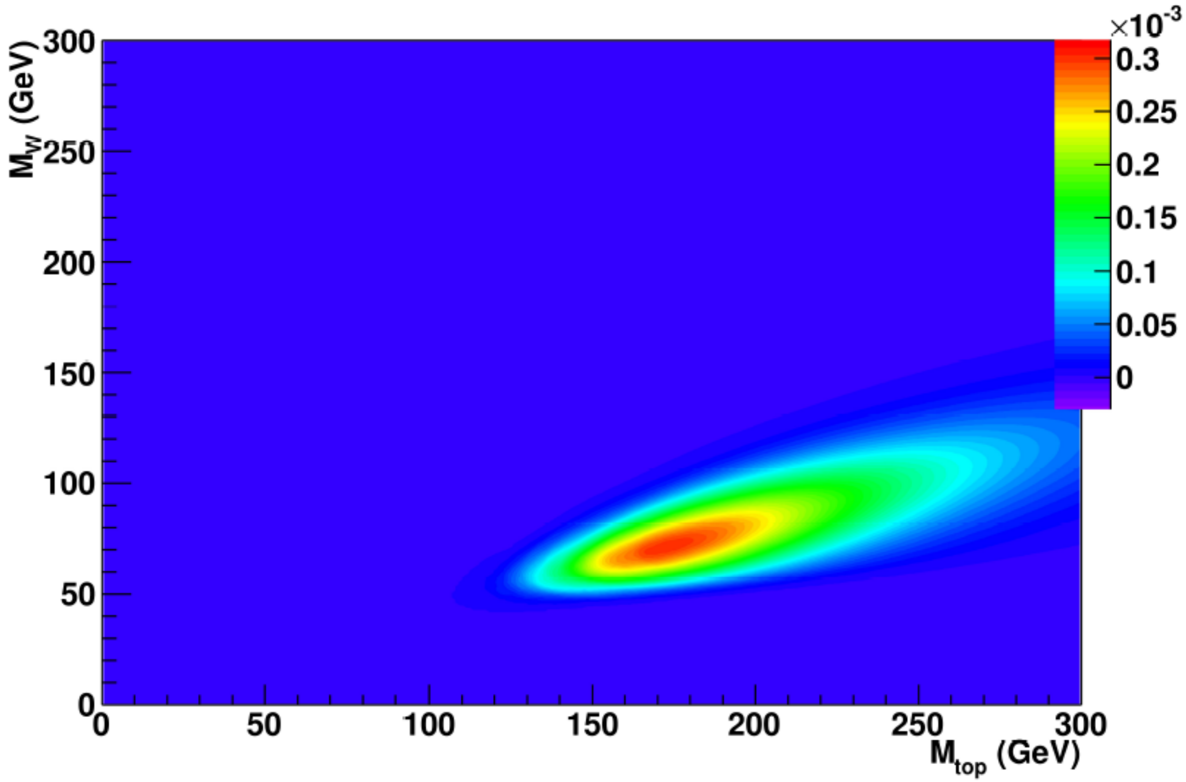
The value obtained is averaged over all N test events and normalized to unit volume.

$$P(M_1, M_2) = \frac{1}{N} \sum_{i=1}^{N} \sum_{a,b} F_a^{(i)}(x_1, Q) \cdot F_b^{(i)}(x_2, Q) \cdot S^{(i)}(M_1, M_2)$$

Such a distribution can be constructed for all possible solutions. Among all solutions, the one with the highest PDF weight is chosen.

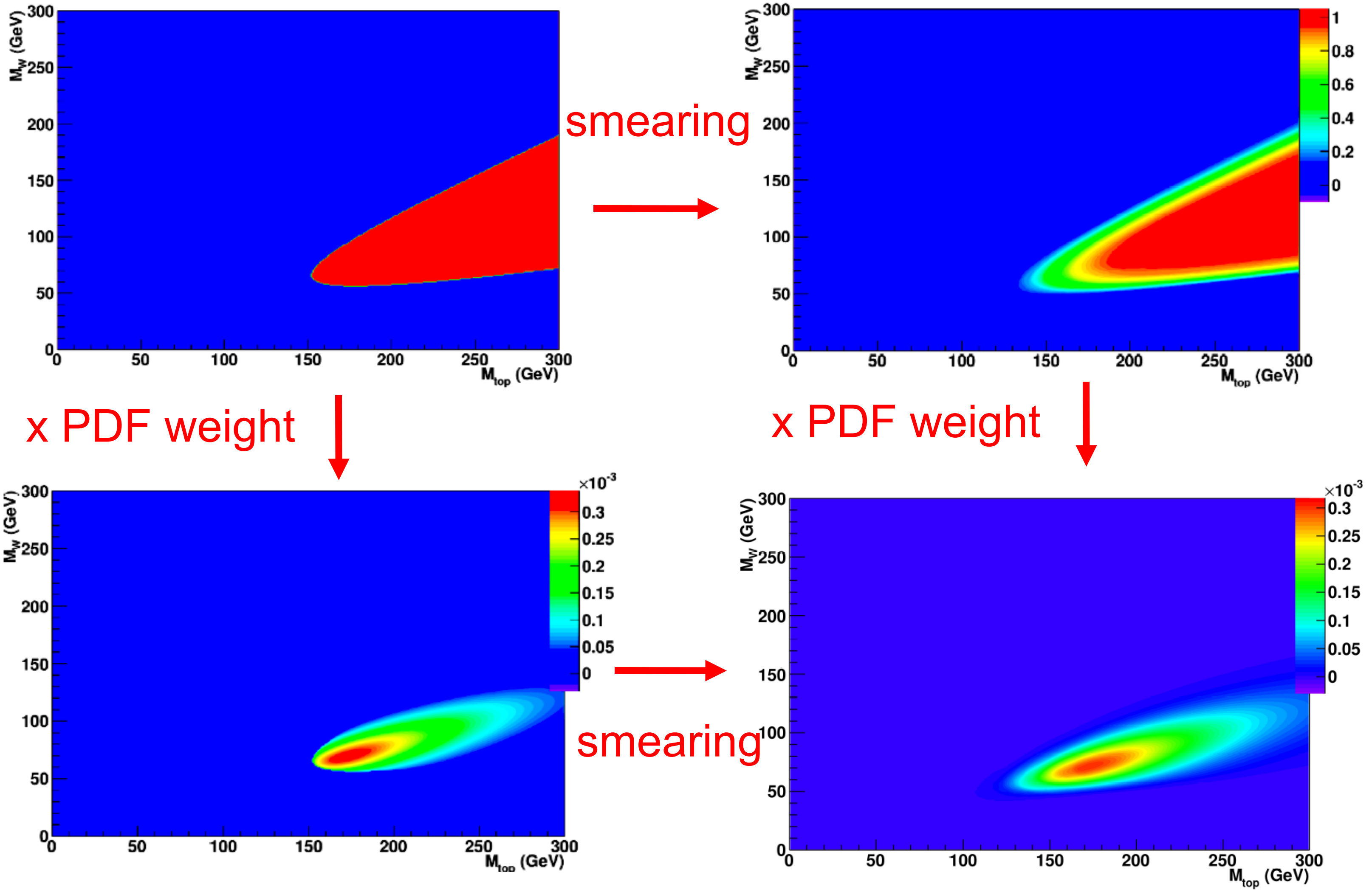
Final distribution per event

The final m_t and m_W estimation is the point where the distribution of the prefered solution is maximized.

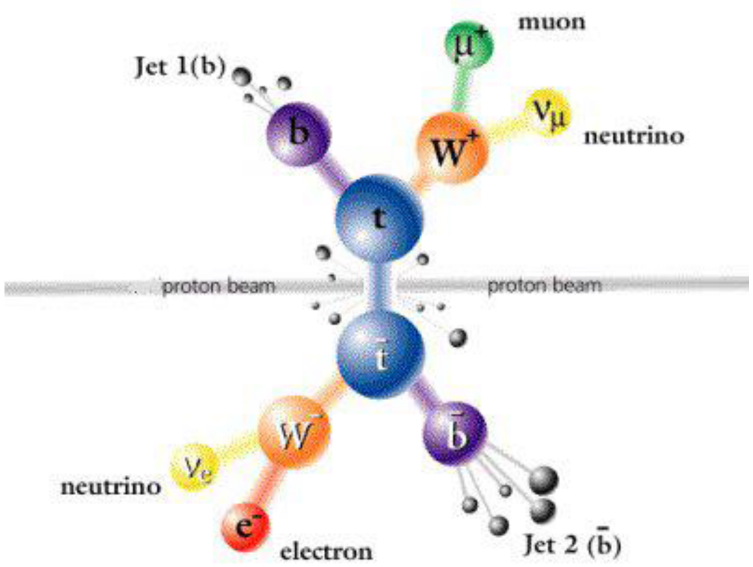


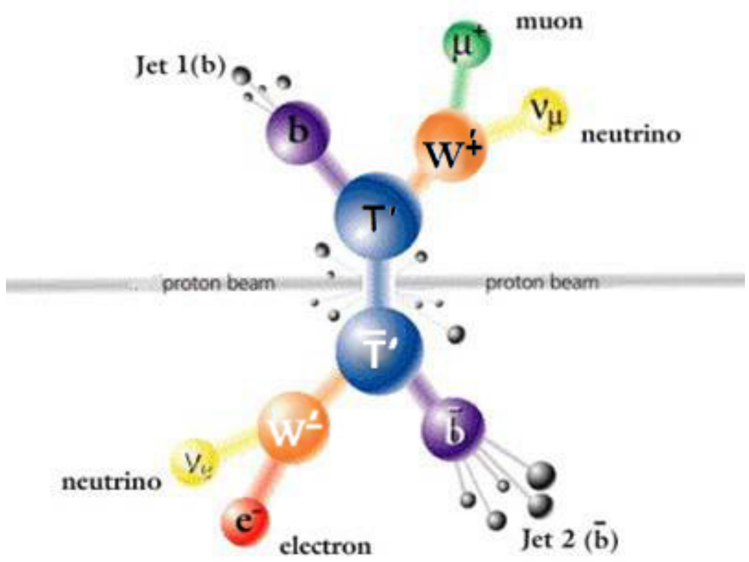
The above procedure gives a single mass point per event!

Finally for a single event



2-D mass search for anything decaying like dilepton top-pairs





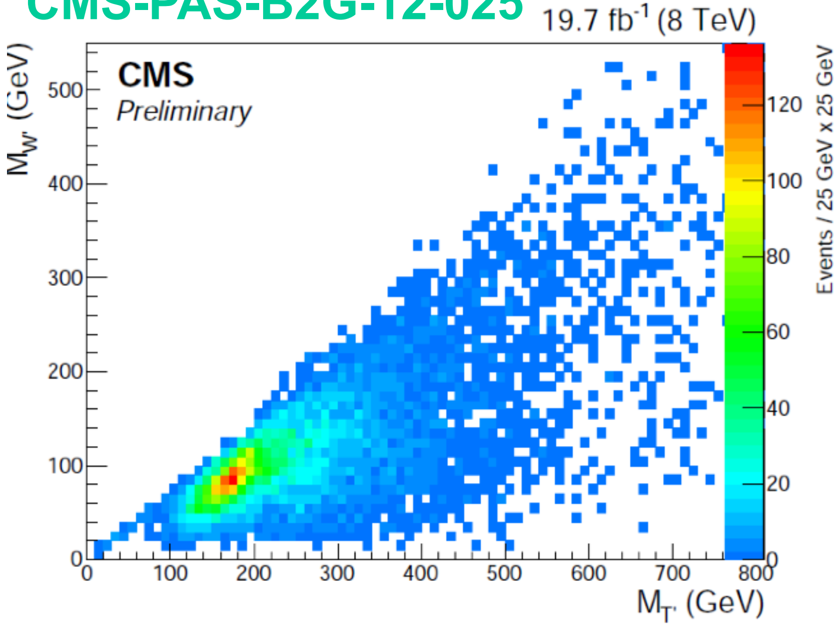
generic topology with 2 unknown particles

Searching simultaneously for both a heavy top partner T' and a new gauge boson W'.

Many BSM models predict both for cancelations in M_{Higgs} – e.g Little Higgs – susy, extra dimensions etc

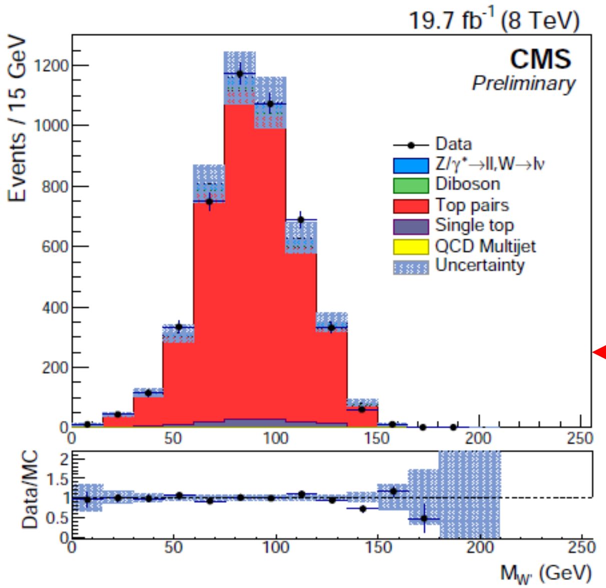
2-D mass reconstruction – data (only!)

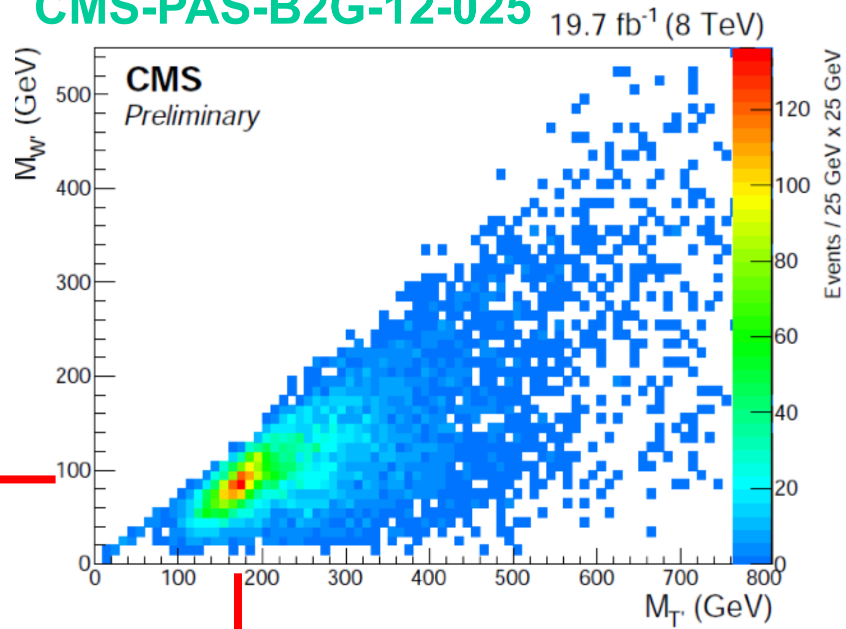
CMS-PAS-B2G-12-025

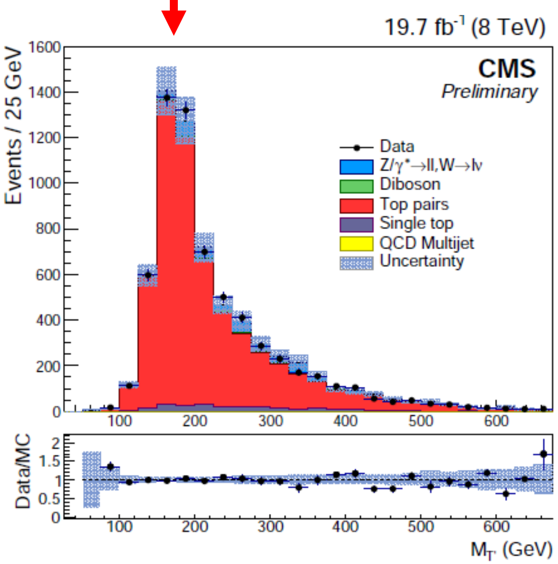


2-D mass reconstruction – data (only!)

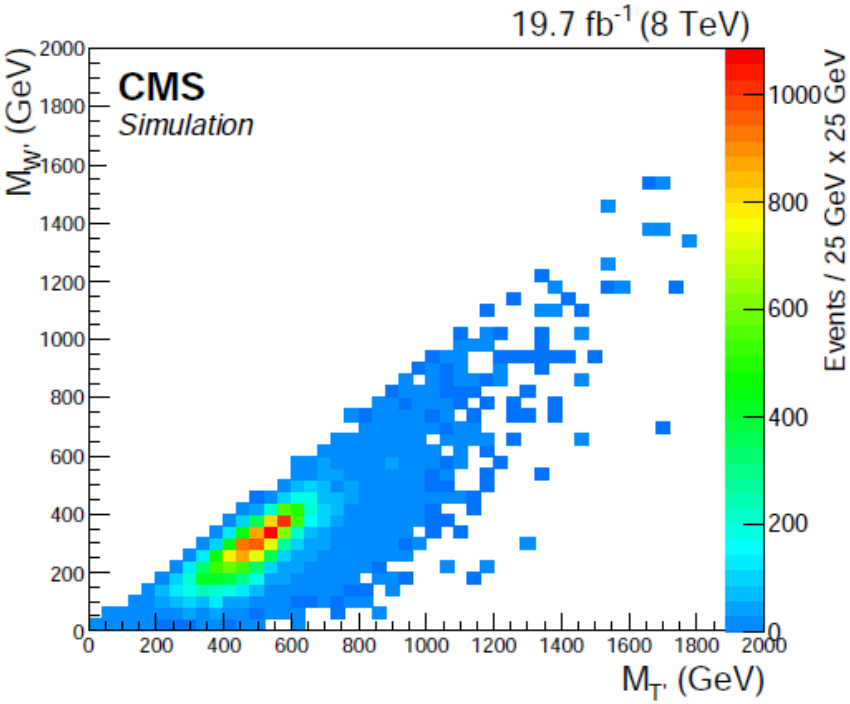
CMS-PAS-B2G-12-025



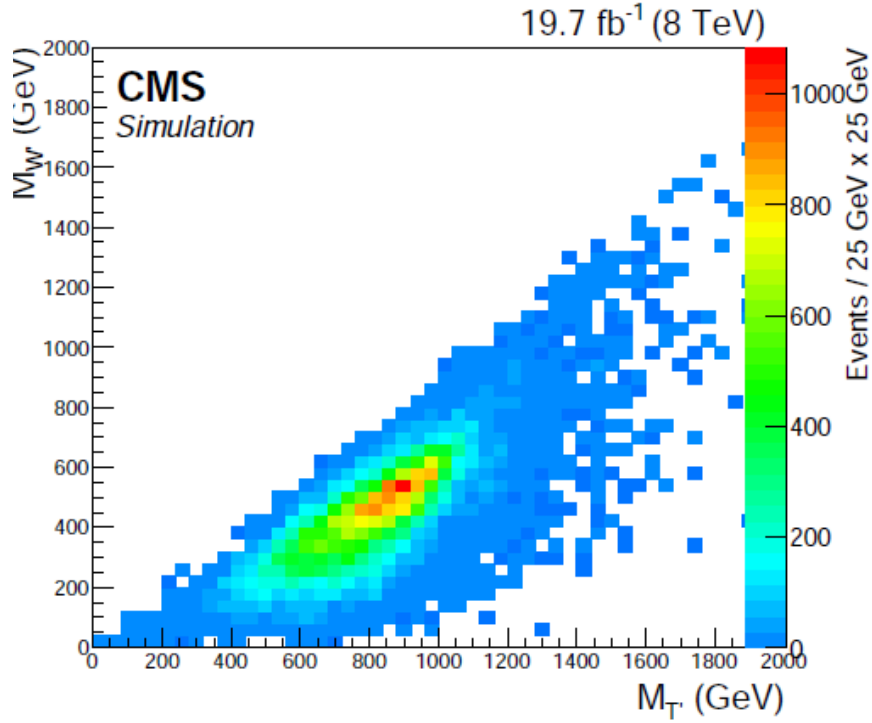




How a possible signal would looking 2-D mass space



MT'=800 GeV, MW'=400 GeV

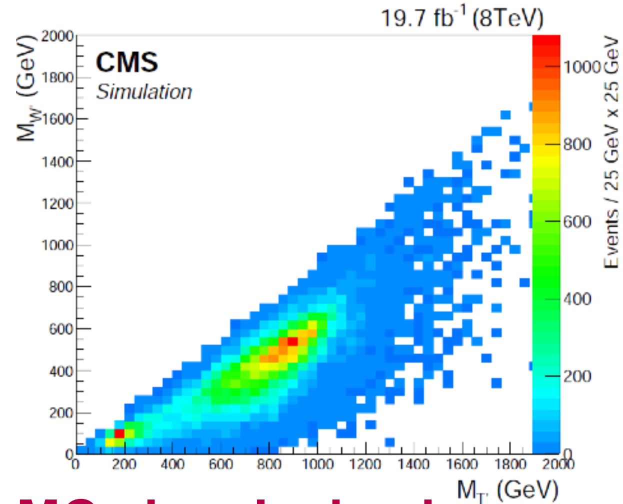


MT'=1000 GeV, MW'=600 GeV

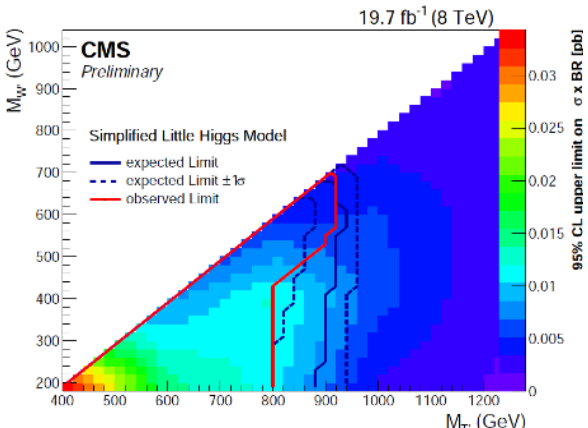
Search in 2-dimensional mass space

PDFs have been used in the past for top mass measurements in Tevatron and LHC (see backup slides)

New: Search in the 2-dimensional mass space of the 2 unknown particles in final states with 2 invisible particles, no matrix elements.

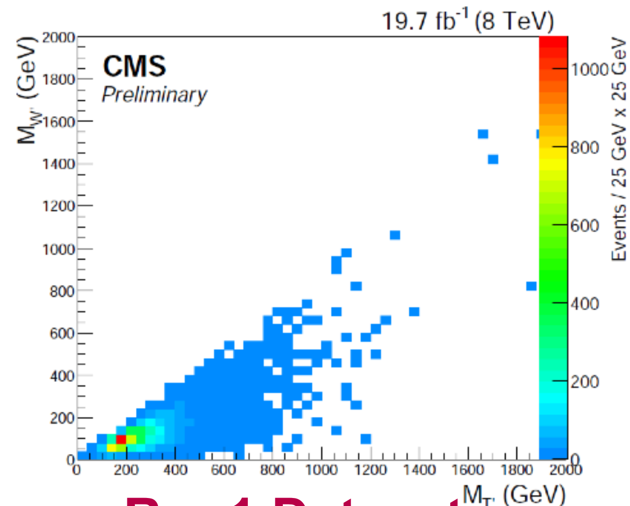


MC signal + background



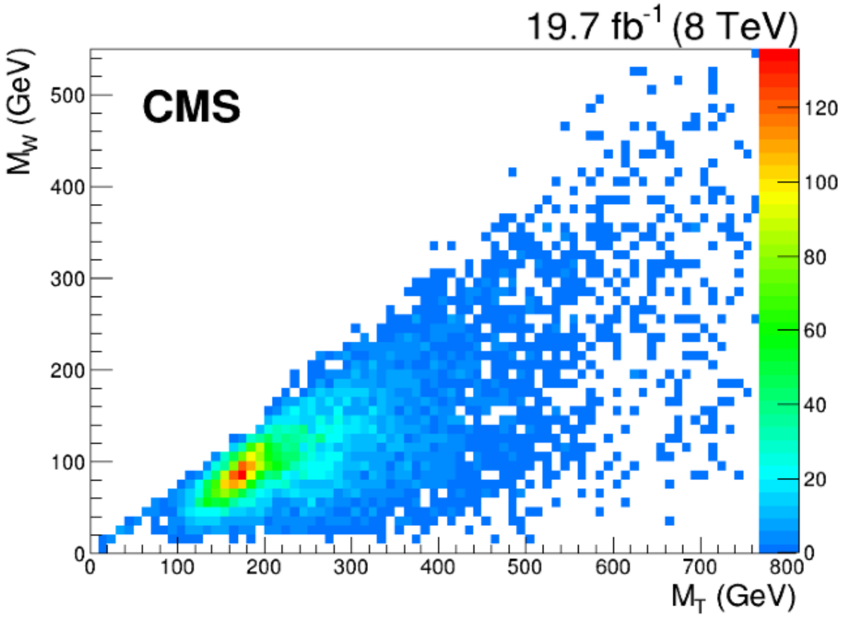
Limits:

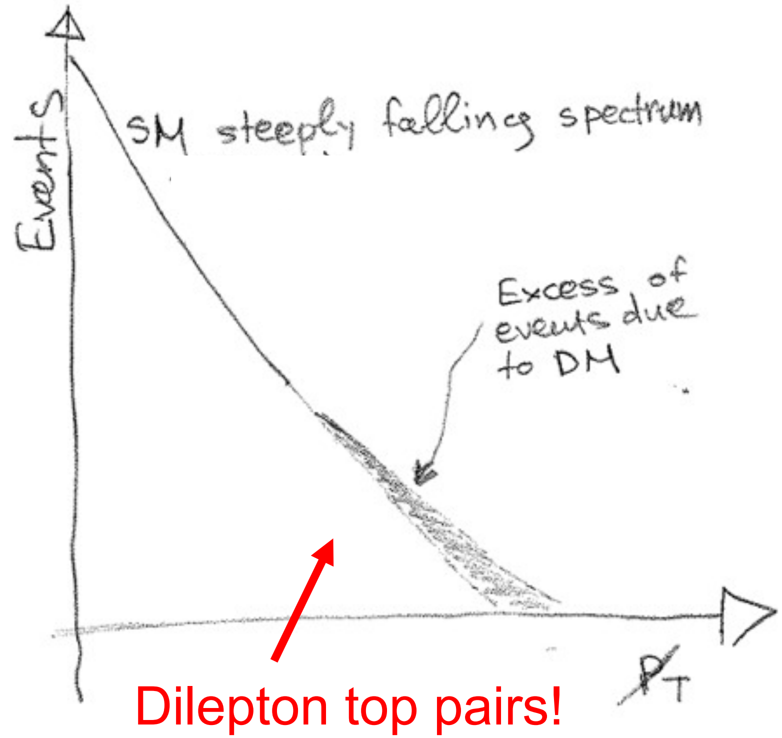
800 – 920 GeV for MT' depending on MW'



Run1 Dataset

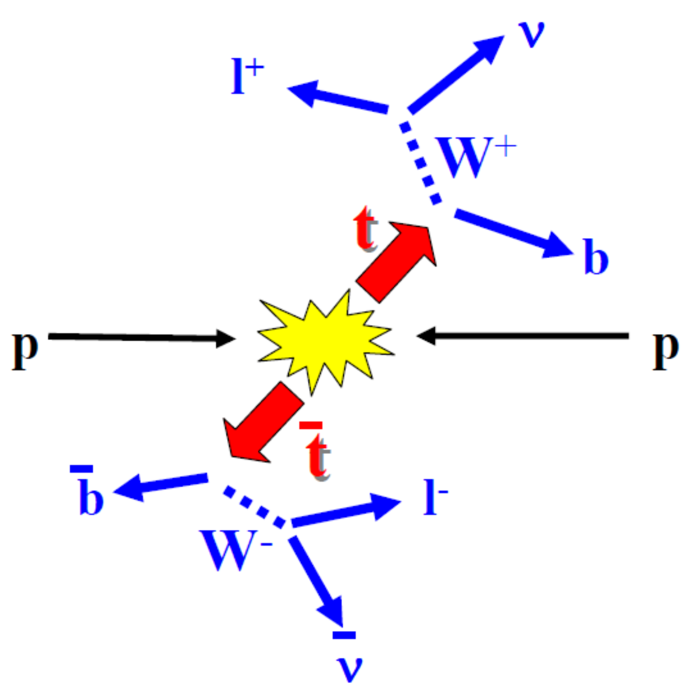
Top pair identification with 2-D mass reconstruction

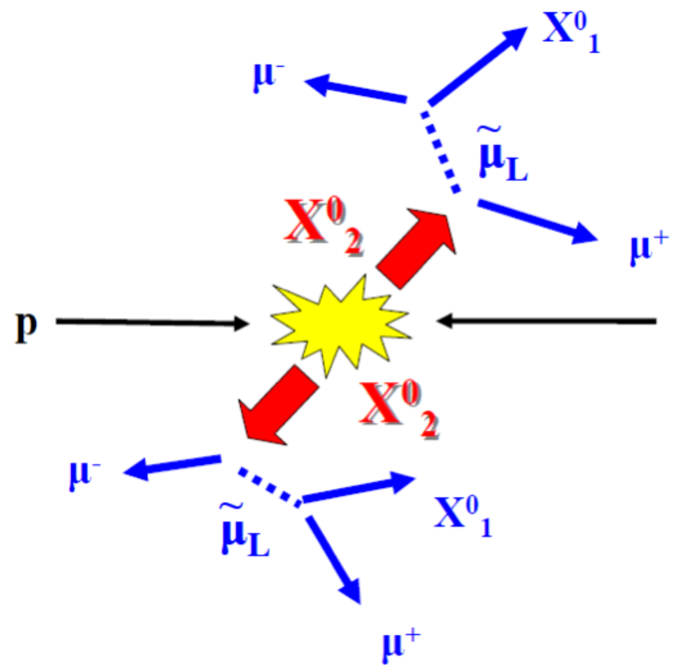




If we can reconstruct the 2 masses MW, MT per event in the dilepton case then we have a powerful tool to discriminate the dilepton top pairs

Search for susy in 4 leptons +MET final state

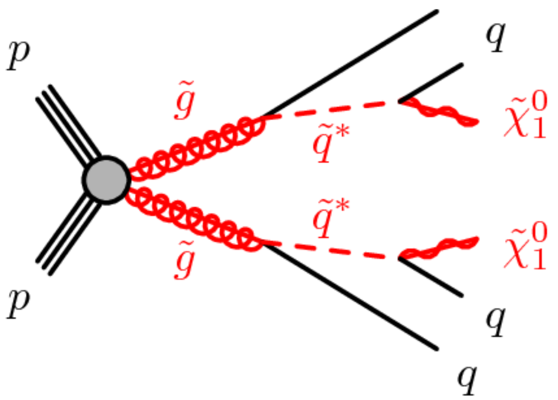




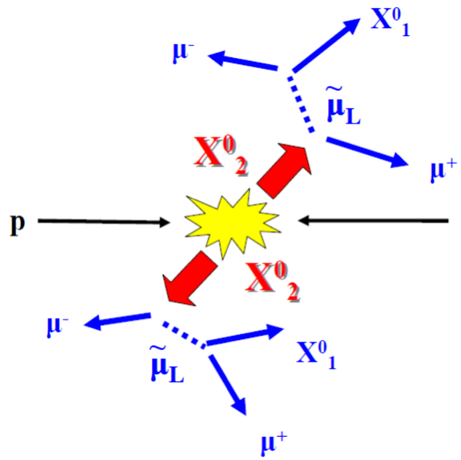
- Topology of dilepton top pairs is similar with susy cascades
 2-dimensional mass reconstruction can be performed in this topology.

- Searching for peaks in 2-dimensional mass plane instead of the tail of a distribution.

More signatures for LHC?



4 jets + missing energy



4 leptons + missing energy

The invisible particle mass means that we have 3 unknown masses.

Still we can reconstruct bumps in 2-D mass plane assuming zero mass for the lightest.

In terms of discovery, still a bump hunt with all the advantages.

For the model we can have 2 of the 3 masses - a good starting point for knowing what the new physics is!

Conclusions

It is feasible to reconstruct particle masses in several solvable topologies with two invisible particles.

2-Dimensional mass search is already performed using Run1 dataset.

Other applications are identification of top pairs for rejection e.g in susy searches and any final state with large MET.

Search for susy in 2D using the 4leptons+MET, 4 jets+MET final state will be interesting.

Back-up slides

More details..

1. G. Anagnostou, “Model Independent Search in 2-Dimensional Mass Space”, in 2nd International Conference on New Frontiers in Physics, EPJ Web of Conferences, Volume 71, 2014, https://doi.org/10.1051/epjconf/20147100006

2. CMS Collaboration, "Search in two-dimensional mass space for pp→T'T→W'b W'b in the dilepton final state in proton-proton collisions at √s= 8 TeV" , CMS-PAS-B2G-12-025, http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G-12-025/B2G-12-025_PAS.pdf

3. G.Anagnostou, "Beyond 2 Generations", EPJ Web of Conferences 126 04001 (2016) , CMS-CR-2015-293, https://doi.org/10.1051/epjconf/201612604001

4. S.Beranek,“Model independent search for new particles in two-dimensional mass space using events with missing energy, two jets and two leptons with the CMS detector”,CERN-THESIS-2017-115 ; RWTH-2017-06454, https://cds.cern.ch/record/2280171

Even more details..

K.Kondo, Dynamical Likelihood Method for Reconstruction of Events with Missing Momentum I, Method and Toy Models, Journal of the Physical Society of Japan, Vol 57, No 12, Dec 1988.

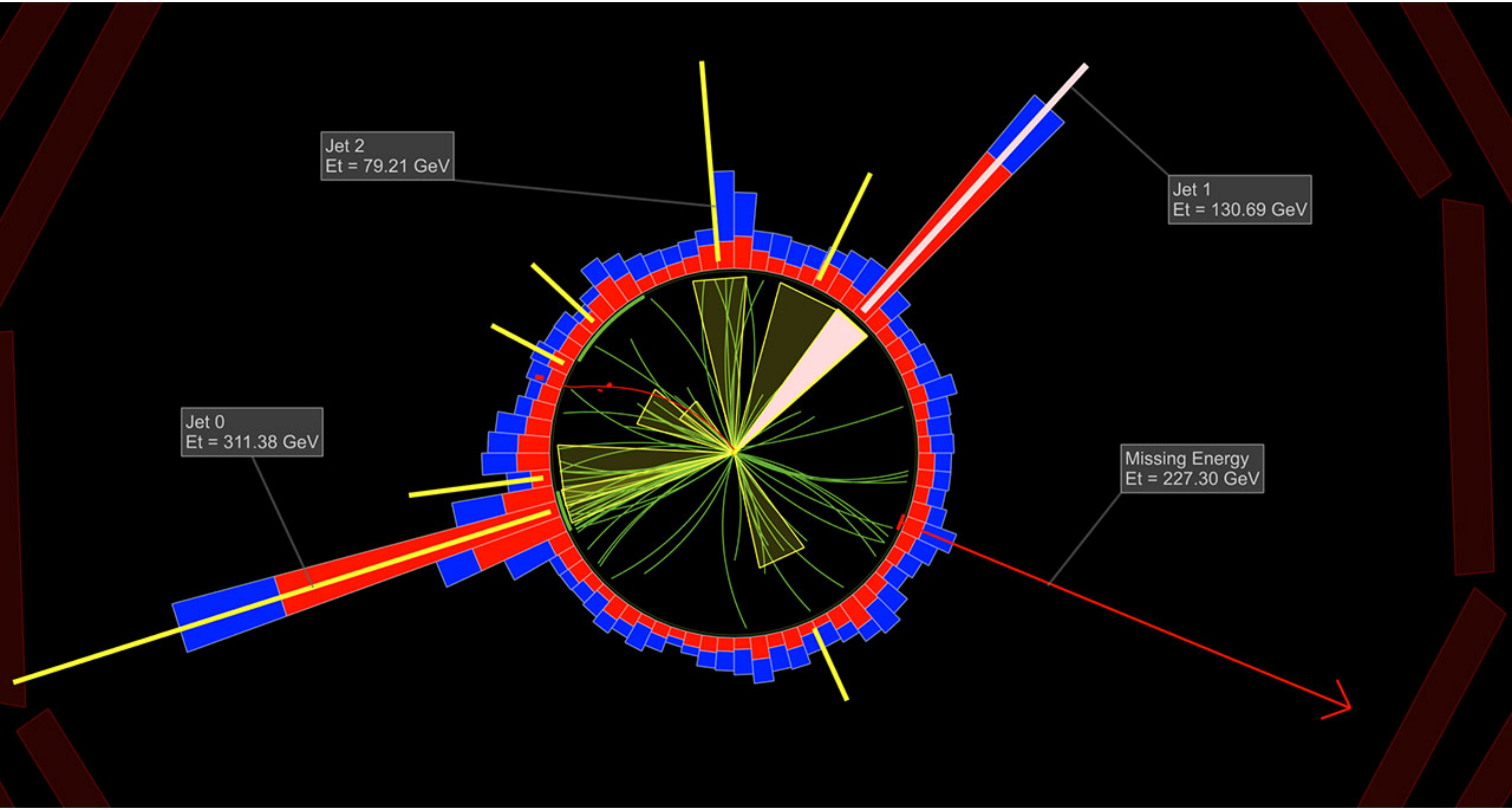
K.Kondo, Dynamical Likelihood Method for Reconstruction of Events with Missing Momentum I, Mass Spectra for 2->2 Processes, Journal of the Physical Society of Japan, Vol 60, No 3, Mars 1991.

R. H. Dalitz and G. R. Goldstein, The decay and polarization properties of the top quark, Phys. Rev. D45 (1992) 1531. doi:10.1103/PhysRevD.45.153.

D0 Collaboration, Measurement of the top quark mass in final states with two leptons Phys. Rev. D80, 092006 (2009).

L. Sonnenschein, Analytical solution of tt dilepton equations, Phys. Rev. D 73, 054015, 2006.

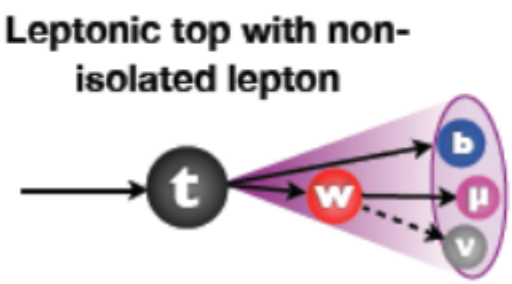
Typical missing energy signatures @ the LHC

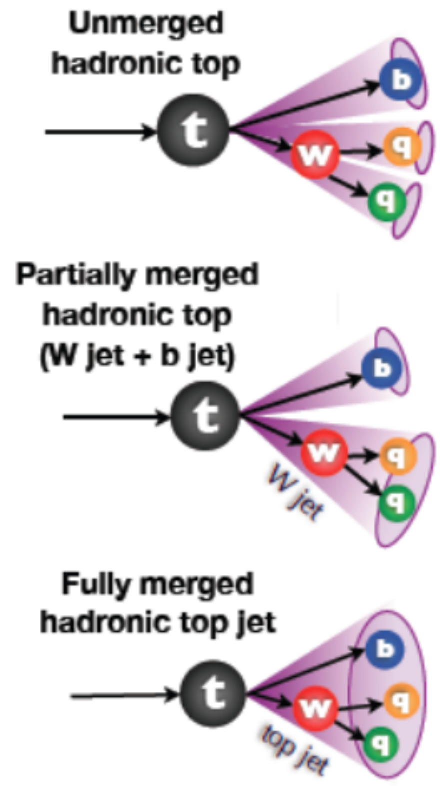


Top pairs-dilepton case

Sophisticated top tagging algorithms for the fully hadronic and semi-leptonic cases – for the hadronic top decays.

Dilepton decay has different objects to identify – instead of 3 (sub)jets we need to identify a lepton and a jet.





For large boosts relatively easier to separate a lepton and a jet rather than 3 jets which merge.