SUSY: new search channels and new search techniques

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Disclaimer

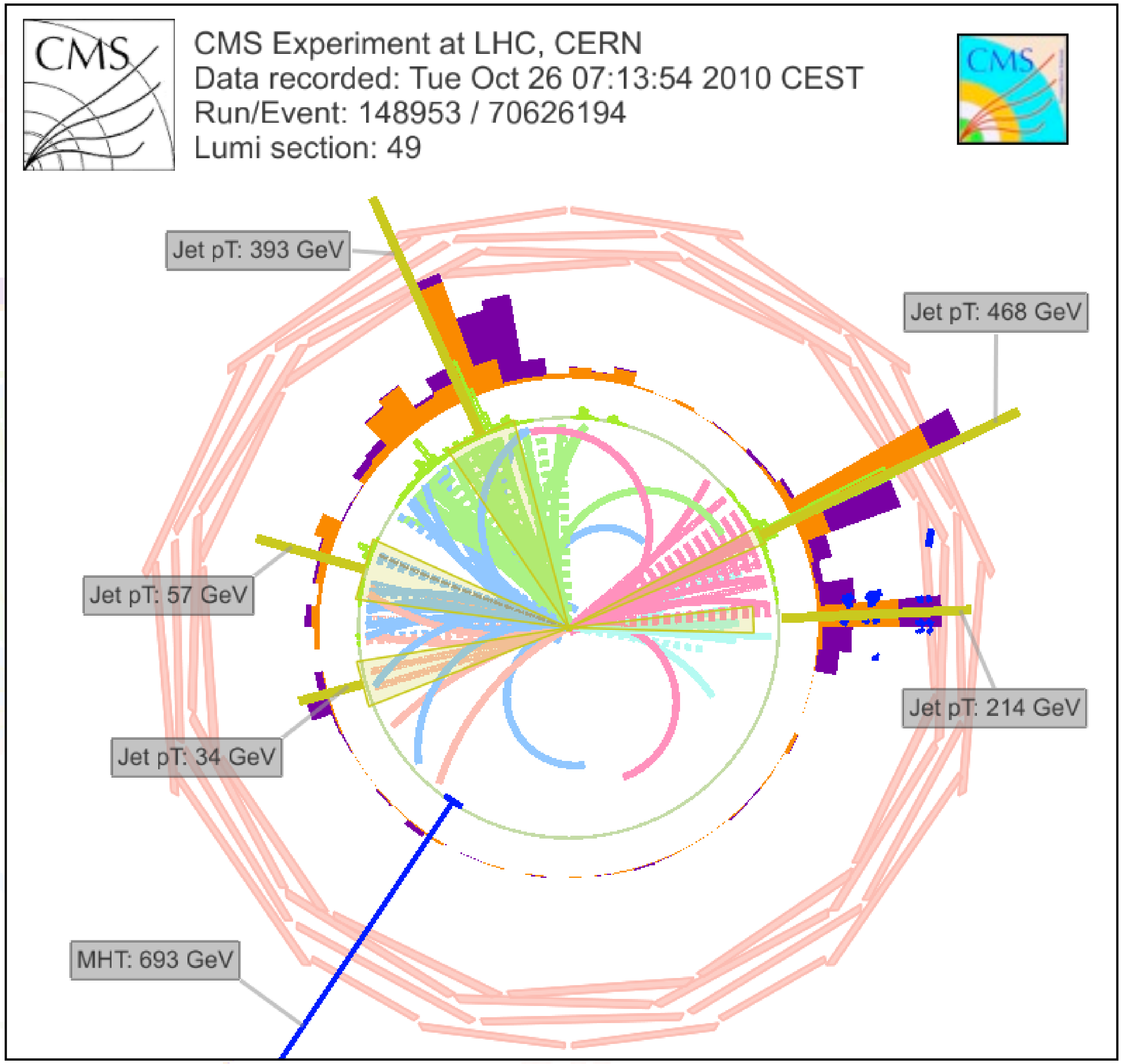
- I was asked to talk about new searches, so I will not cover classic approaches
- I will focus on hadronic searches, which I know better
- I will not show results. There are specific talks for that
- The talk is CMS-centric, because I am biased and because results based on “new” approaches mainly come from CMS

Outline

- The lesson from Tevatron: the “classic” approach
- αT: rejecting QCD
- M_{T2}: characterizing signal as two-missing-particles signature
- The Razor: merging the two in a consistent framework
- A few considerations thunking at 2012

A "classic" SUSY search

The typical signature: a lot of energy seen in the detector, recoiling against a lot of MET



Several variables to quantify this behavior:

$$HT = \Sigma_{jet} |p_T^{jet}|$$

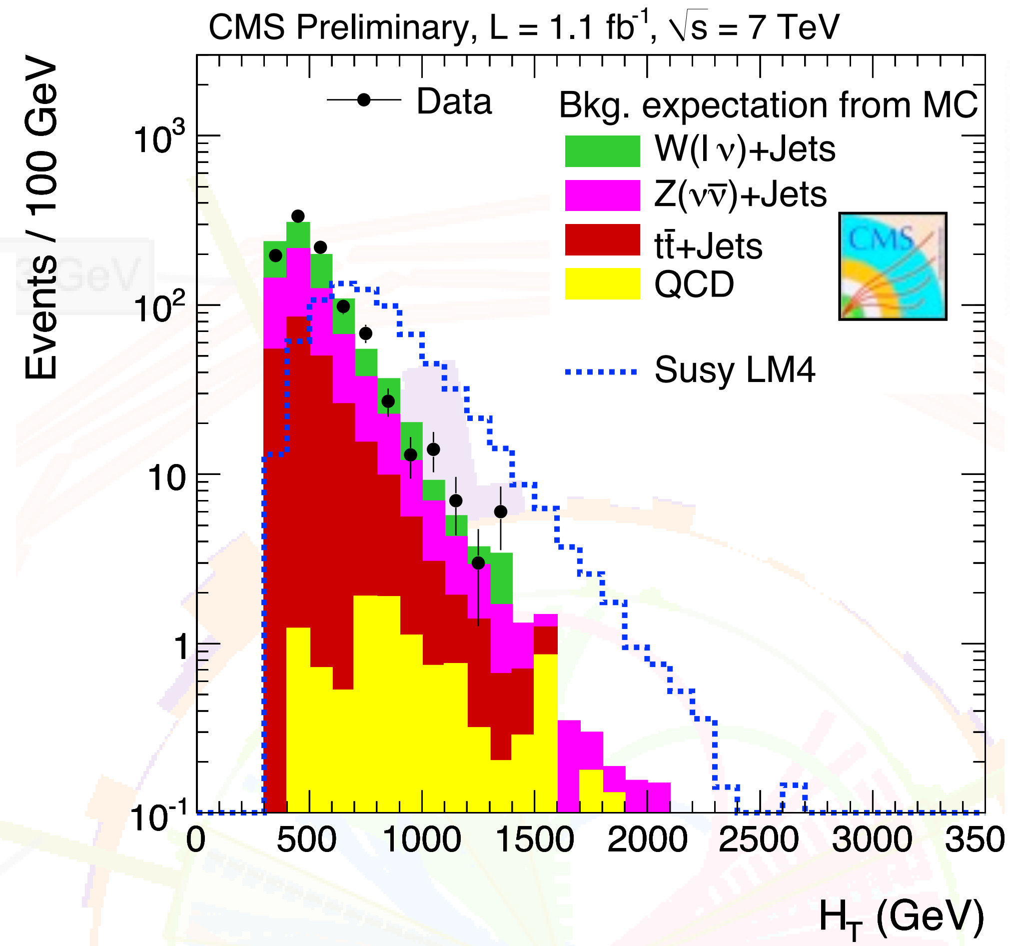
$$|MHT| = |\Sigma_{jet} p_T^{jet}|$$

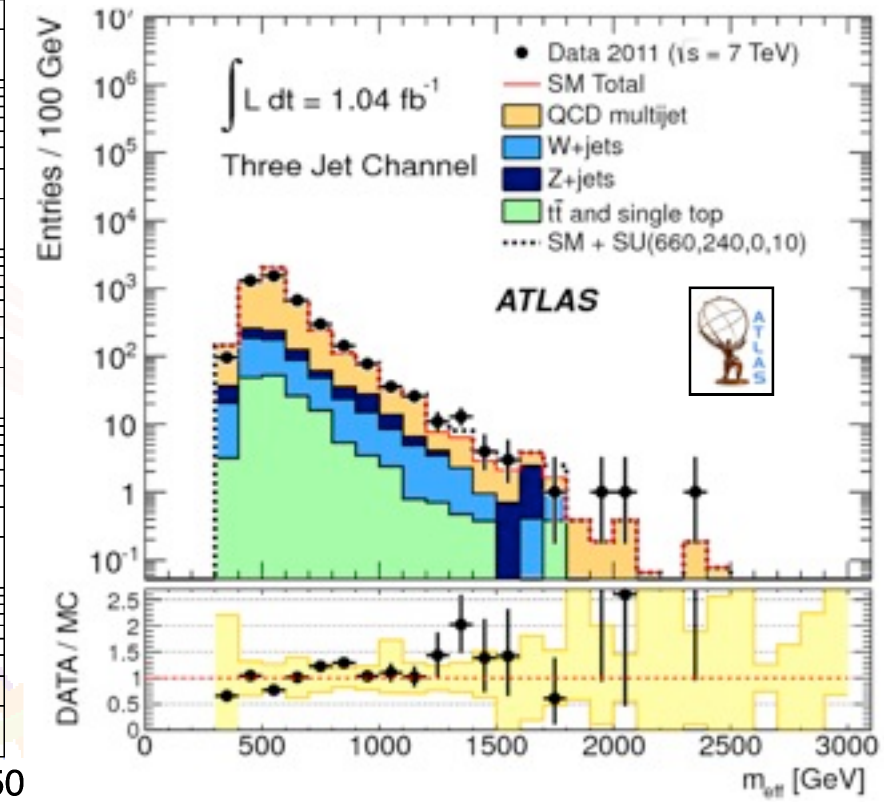
$$|MET| = |\Sigma_{cell} E_T^{cell}|$$

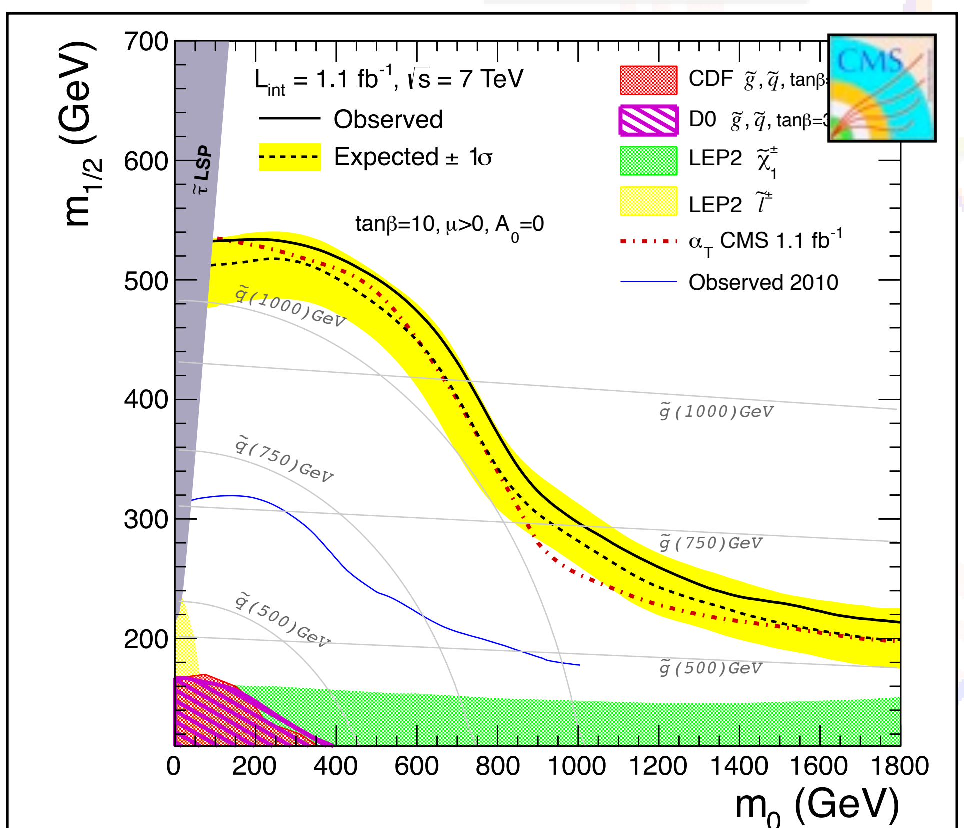
$$m_{eff} = HT + |MET|$$

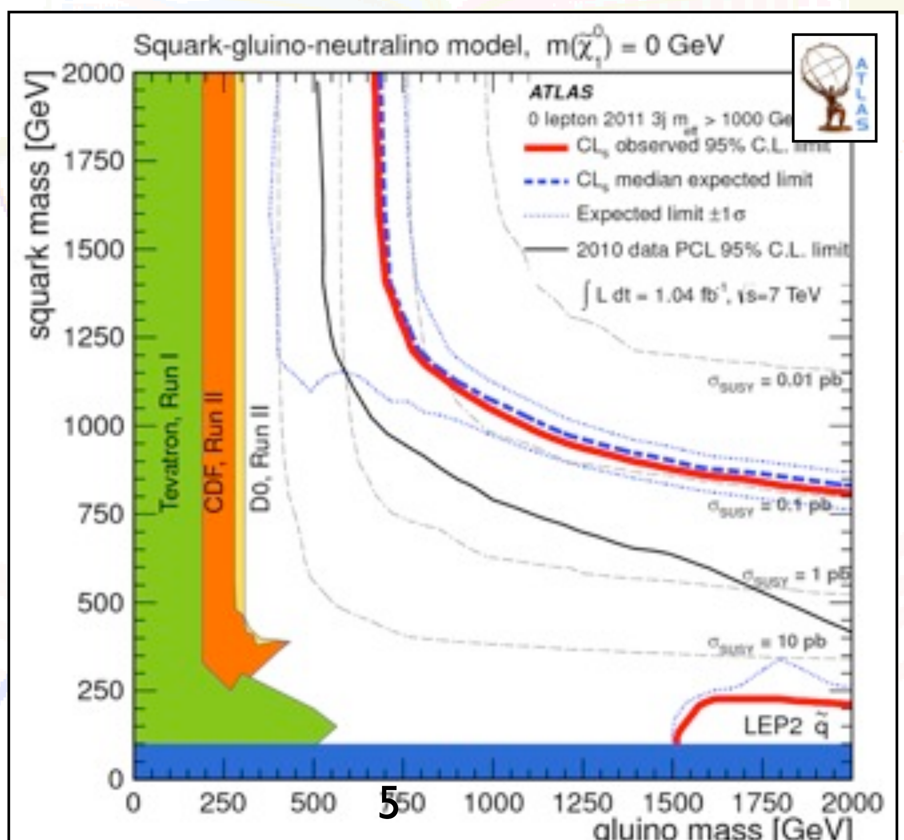
A “classic” SUSY search

A counting experiment is performed on the tail of the distribution



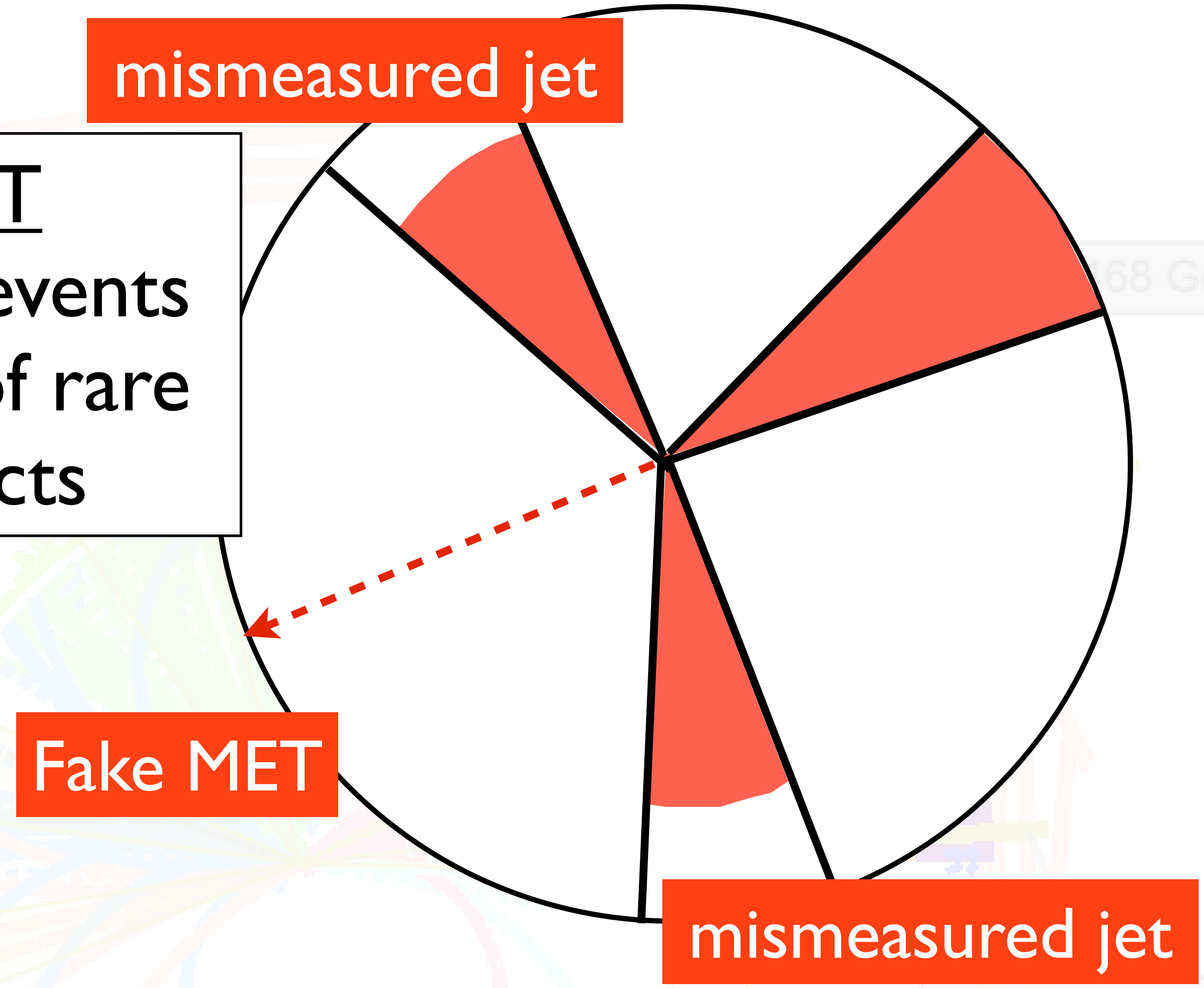




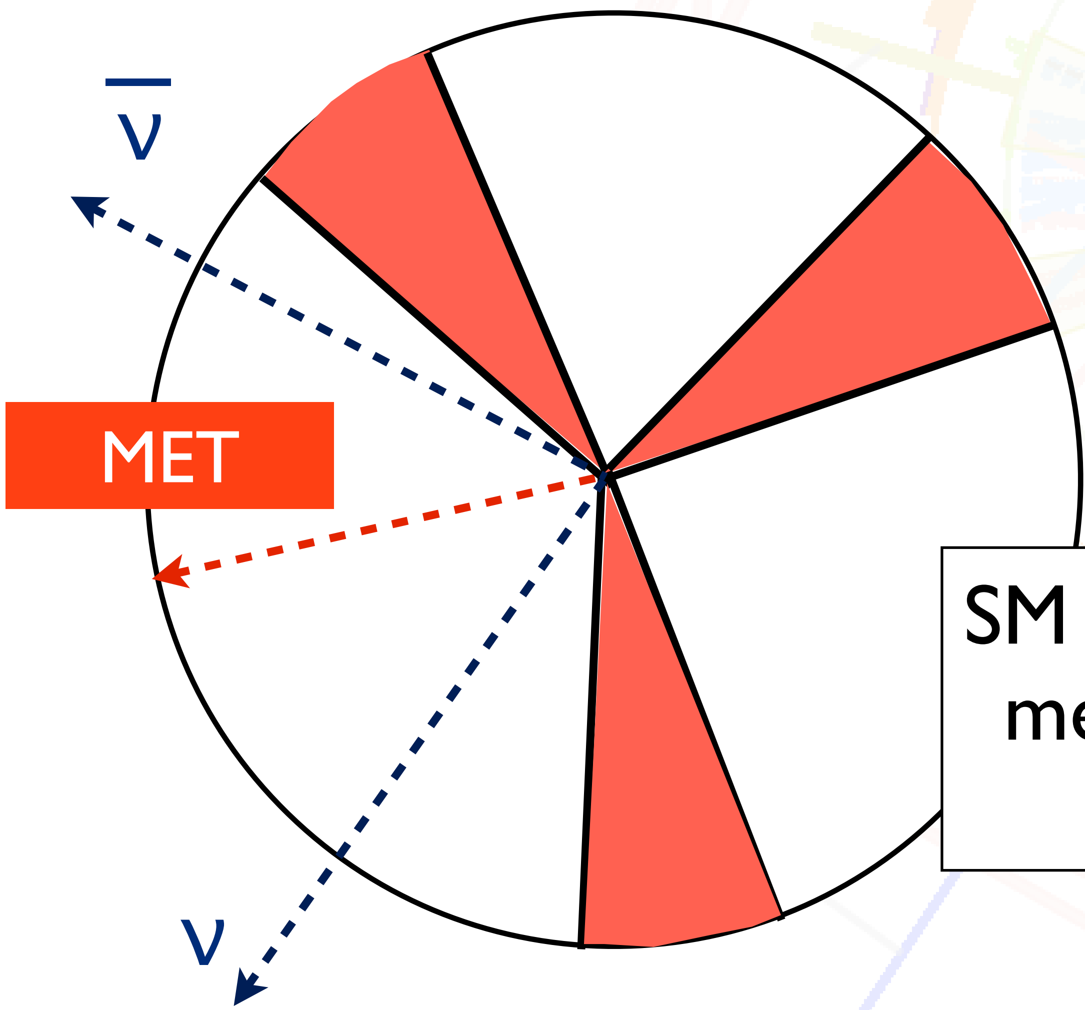


An exclusion limit is set on some NP parameter space

Backgrounds To Fight



<u>QCD with fake MET</u>
related to pathological events
require understanding of rare
detector-related effects



SM processes with real MET, e.g. $Z(\nu\nu)$+jets
measurable from control samples defined
on data

The New Ways

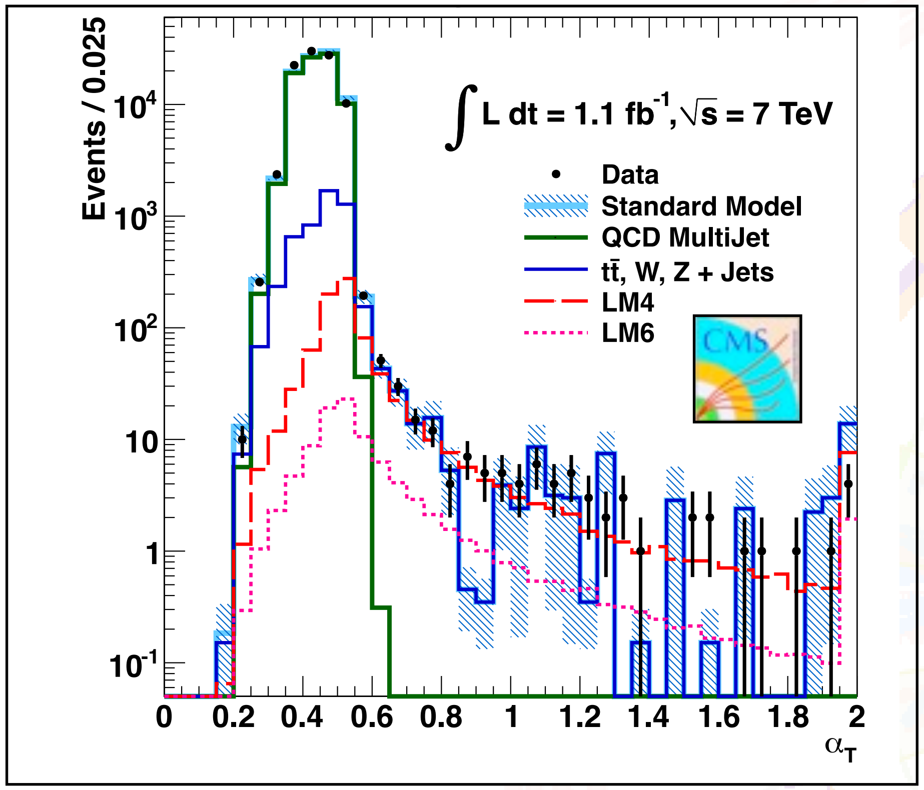
- The "classic" approach is still pursued by CMS and ATLAS, adapted to the new detectors
- New approaches proposed to reduce the QCD to negligible level and deal with the residual SM background through data-driven control samples
- Different layers of extra assumptions give different signal vs. background separation
  - αT: unbalanced events
  - M_{T2}: MET coming from two particles
  - RAZOR variables: pair production of heavy objects producing two missing particles

α_T: Rejecting QCD

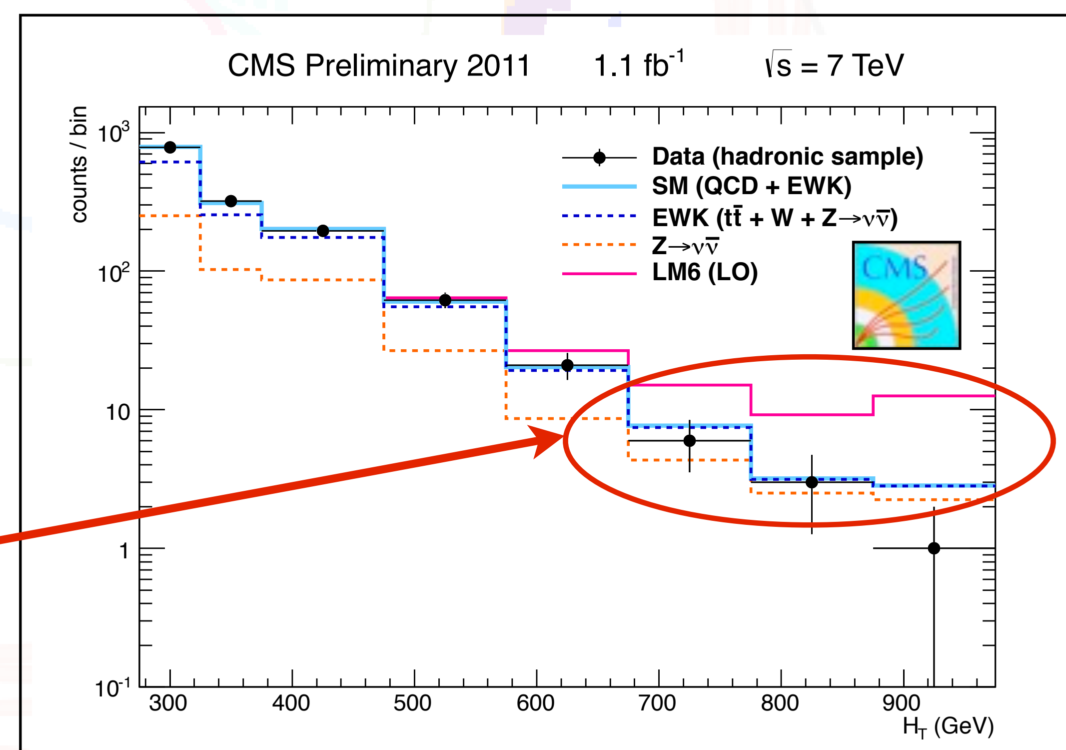
$$\alpha \equiv \frac{p_{T2}}{m_{jj}}.$$

$$\alpha_{\rm T} = \frac{E_{\rm T}^{\rm jet_2}}{M_{\rm T}} = \frac{E_{\rm T}^{\rm jet_2}}{\sqrt{\left(\sum_{i=1}^{2} E_{\rm T}^{{\rm jet}_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{{\rm jet}_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{{\rm jet}_i}\right)^2}}$$

Randall & Tucker-Smith



- αT = 0.5 for perfectly balanced dijet events
- αT<0.5 for dijet + mismeasurements
- EW main bkg after αT cut
- QCD events could leak to αT>0.5 because of detector effects (rare)
- large fraction of signal events removed (efficiency vs purity)



- After αT cut the signal looks similar to bkg in αT
- another variable needs to be used to characterize the signal
- Back to the "classic" paradigm": HT used by CMS

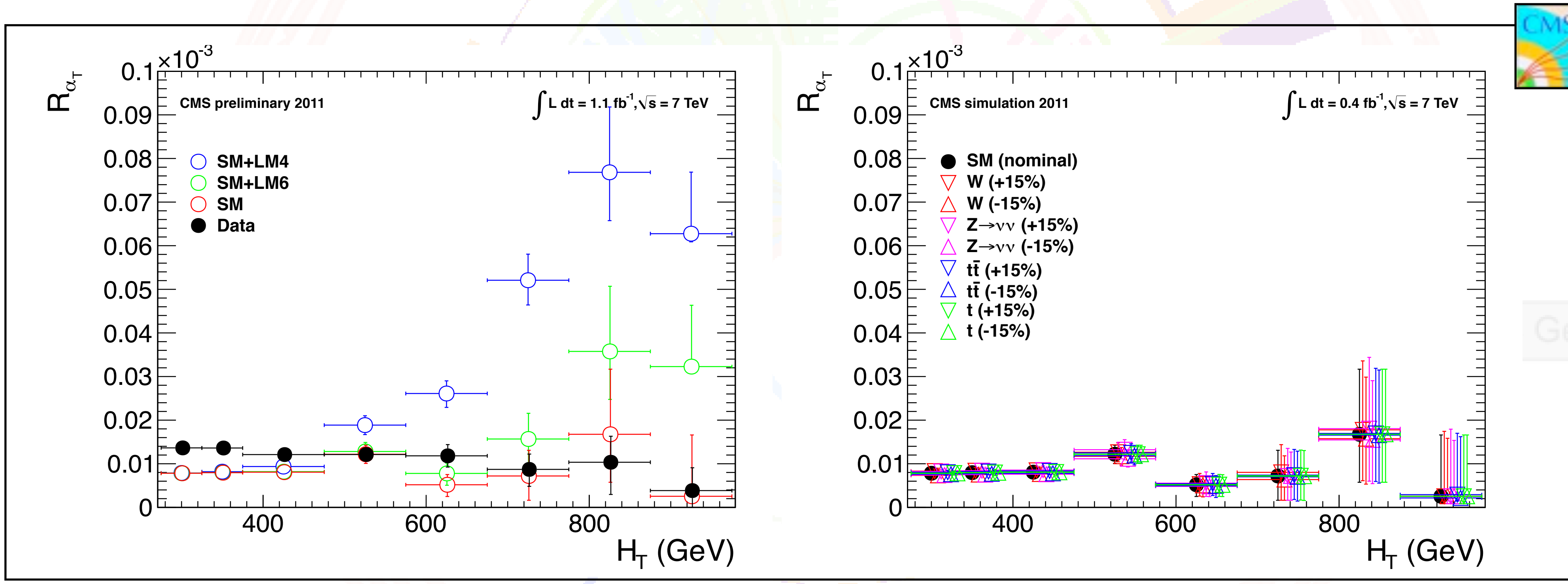
α_T: BKG Estimate

- EW bkg is estimated using the $R_{\alpha T}$ (*) ratio

$$R_{\alpha_T} = N^{\alpha_T > \theta} / N^{\alpha_T < \theta}$$

- This is computed scaling the p_T of the jets with the HT threshold, to event topology

- The ratio is found to be compatible with the flat hypothesis within the available data and SM MC statistics

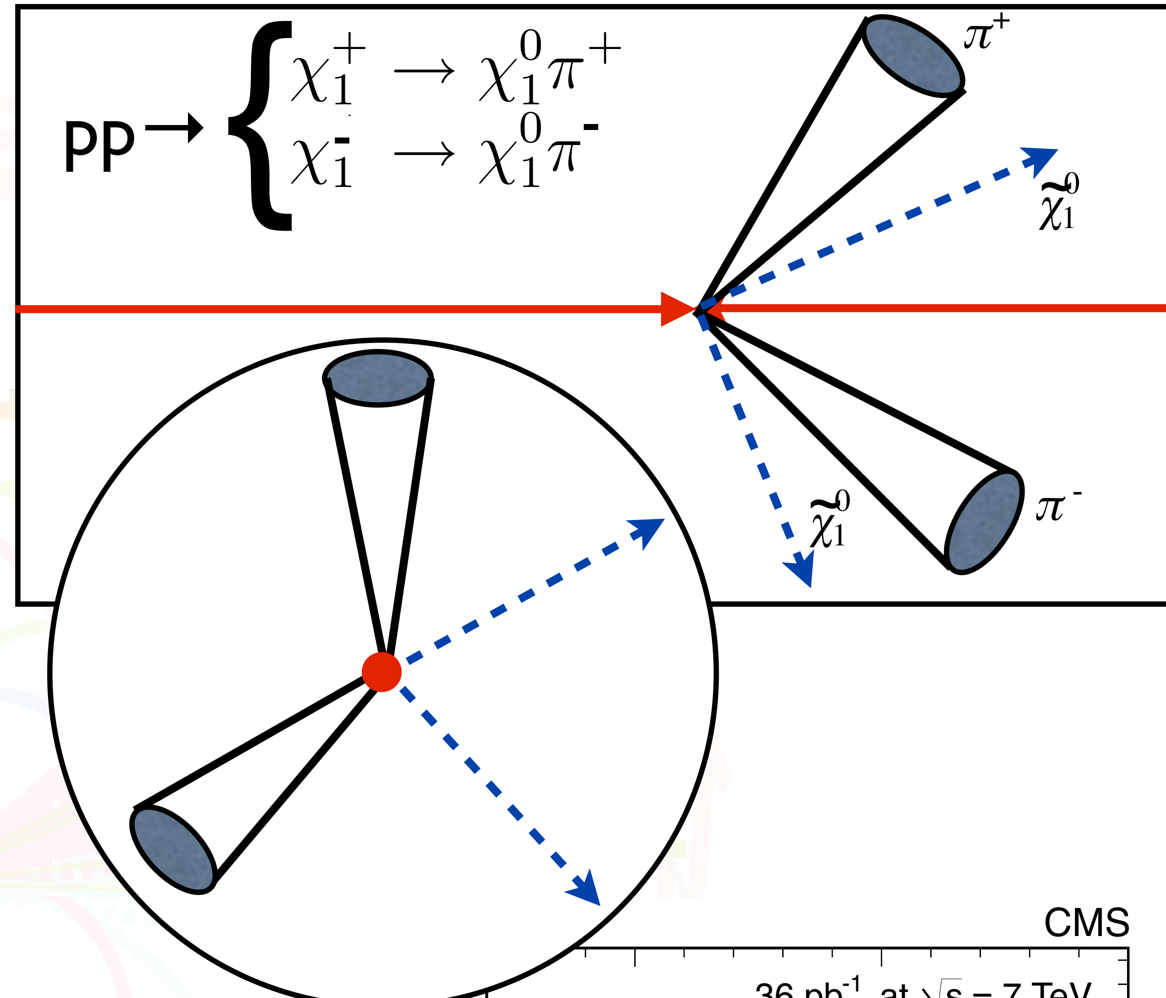


- This is used to predict the bkg expected in each bin of HT. Then a fit to the HT shape is used

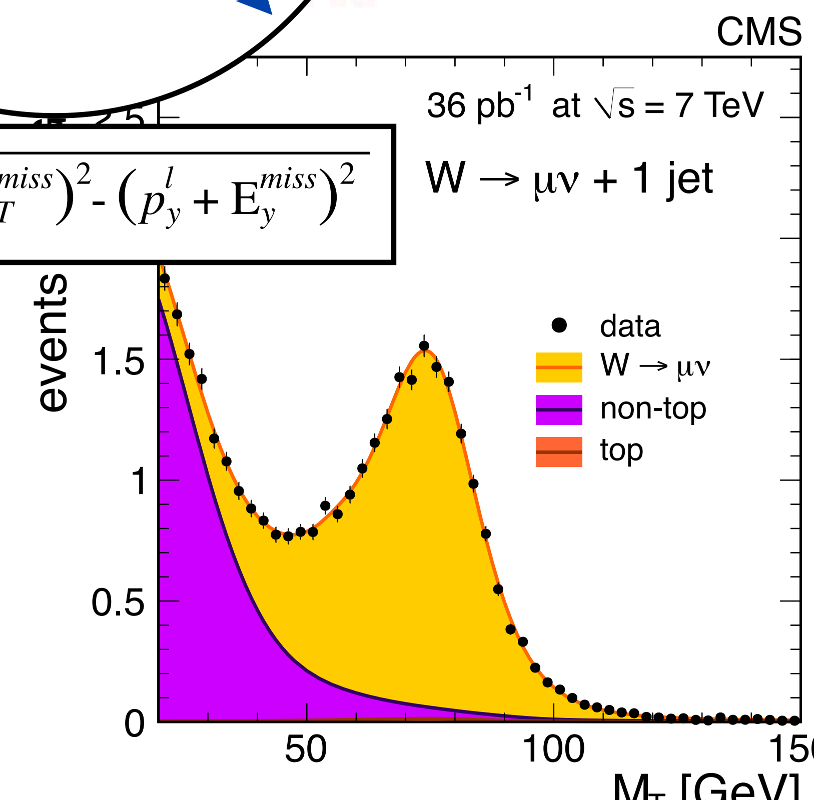
(*) Number of EW events with $\alpha T > \theta$ / number of QCD events with $\alpha T < \theta$

M_{T2}: two missing particles

- We are looking for events with two undetected neutral particles leaving the detector
- We measure the sum of their pT as MET
- This is similar to the detection of the W, for which the edge of the mT distribution is used
- The presence of two missing particles make the picture more complicated. But the physics intuition holds



$$M_T = \sqrt{E_T^l E_T^{miss} - (p_x^l + E_T^{miss})^2 - (p_y^l + E_y^{miss})^2}$$



M_{T2}: two missing particles

- If we could see all the particles, we could compute

$$m^2_{\chi_1^+} = m^2_\pi + m^2_{\chi_1^0} + 2\left[E_T^\pi E_T^{\chi_1^0}\cosh(\Delta\eta) - \mathbf{p}_T^\pi \cdot \mathbf{p}_T^{\chi_1^0}\right]$$

- If we could measure $p_T(X^0)$, but not $p_z(X^0)$, the best we could do would be

$$m_T^2(\mathbf{p}_T^\pi, \mathbf{p}_T^{\chi_1^0}; m_{\chi_1^0}) \equiv m^2_{\pi^+} + m^2_{\chi_1^0} + 2(E_T^\pi E_T^{\chi_1^0} - \mathbf{p}_T^\pi \cdot \mathbf{p}_T^{\chi_1^0})$$

- Since cosh>1, $m_T \leq m$, the equality holding for both $pz(X^0)=0$. This means that $\max(m_T)$ has an "edge" at m

- For each event we have two values of m_T (two copies of the same decay). Both are such that $m_T<m$. This means that $\max(m_T(1), m_T(2))<m$

- We only know $p_T(X^0{}_1)+ p_T(X^0{}_2)=E_T^{miss}$. A wrong assignment of the missing momenta brakes the $m_T<m$ condition. But the condition would hold for the correct assignment. This means that $\min(m_T)<m_T(\text{true})<m$.

- This defined m_{T2} as

$$m^2_{T2}(\chi) \equiv \min_{\not{q}_T^{(1)}+\not{q}_T^{(2)}=\not{p}_T}\left[\max\left\{m_T^2(\mathbf{p}_T^{\pi^{(1)}}, \not{q}_T^{(1)}; \chi),\ m_T^2(\mathbf{p}_T^{\pi^{(2)}}, \not{q}_T^{(2)}; \chi)\right\}\right]$$

M_{T2}: two missing particles

- The variable we have is a function of the mass of the LSP

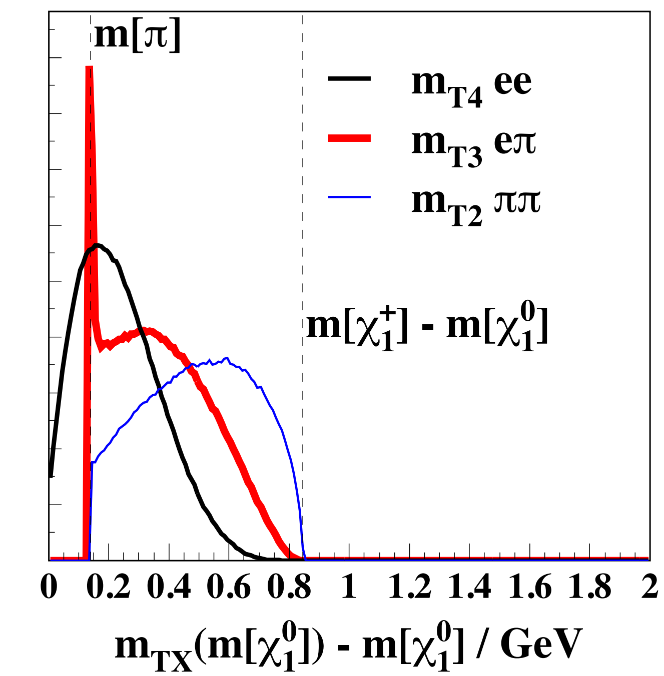


Figure 3: *Simulations of* $m_{TX}(m_{\chi_1^0}) - m_{\chi_1^0}$ *for* $X = 2, 3, 4$ *using a simple phase-space Monte-Carlo generator program for a pair of decays* $\tilde{q} \to \chi_1^+ q$ *followed by* $\chi_1^+ \to \chi_1^0\, \pi$ *or* $\chi_1^+ \to \chi_1^0\, e\, \nu_e$*. As the number of invisible particles increases, the proportion of events near the upper limit decreases. Within the figure, subscripts are indicated by square brackets.*

- <u>SUSY characterization:</u>

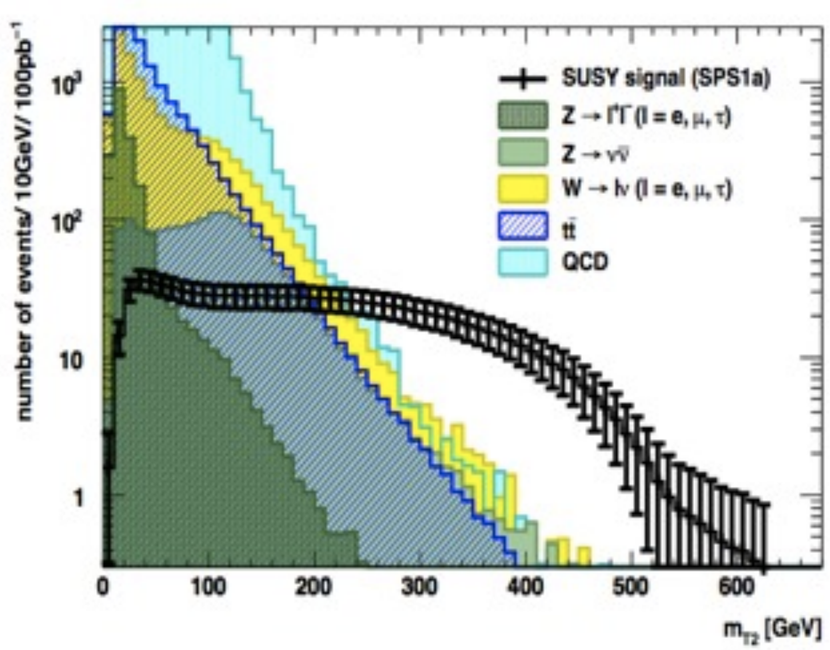
  - Scan the LSP mass and look for the edge developing in your sample of SUSY events (if you have one...)

- <u>SUSY search:</u>

  - Assume a mass value (eg mLSP=0)
  - Assume that the visible system in has 0 mass
  - An analytical expression for M_{T2} is found

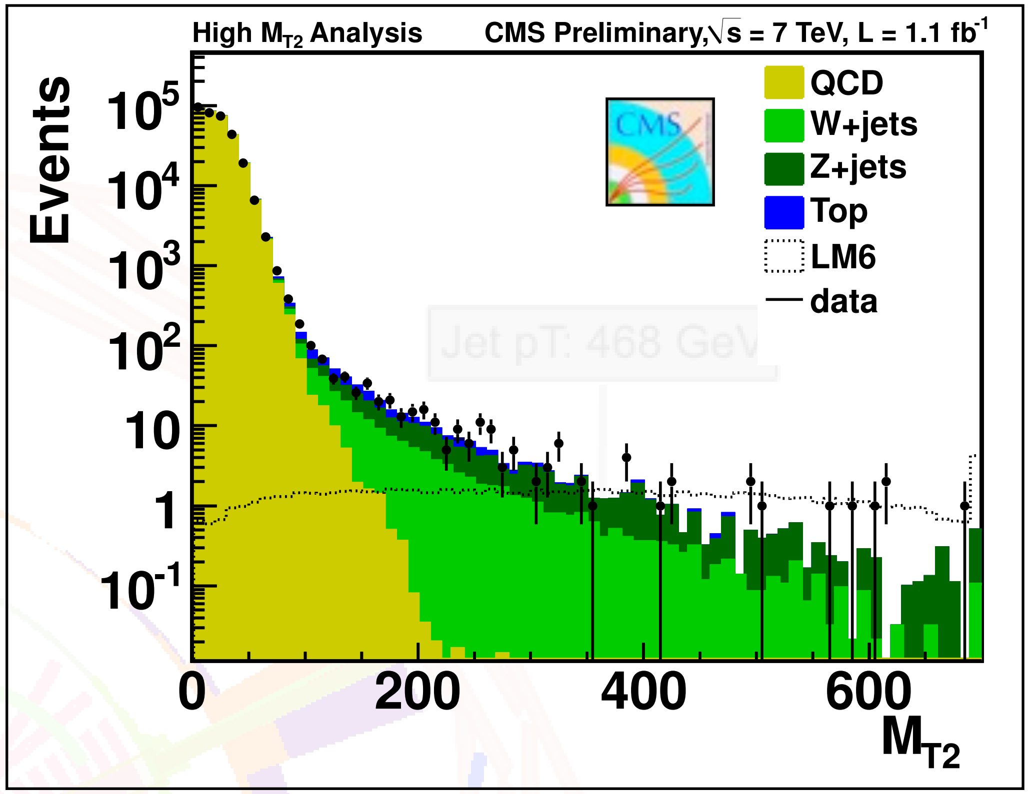
$$(M_{T2})^2 = 2A_T = 2p_T^{vis(1)} p_T^{vis(2)} (1 + cos\phi_{12})$$

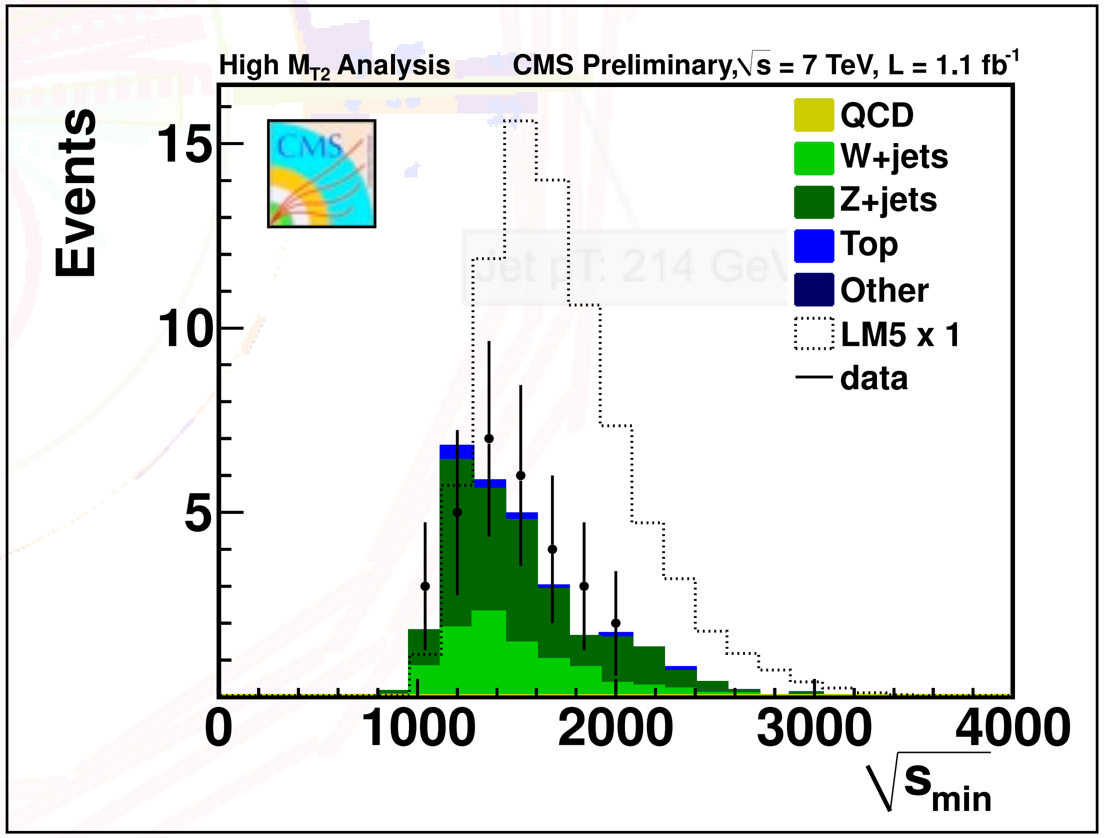
  - The edge is lost but we have an α_T-like variable to kill the QCD



M_{T2}: two missing particles

- M_{T2} is found to be useful for searches, since it allows to reduce QCD to negligible level
- Signal is searched on the tail of M_{T2} in a counting experiment
- Other variables could be used to characterize the signal, in case of a discovery. CMS would use $\sqrt{s}_{min}$ for that



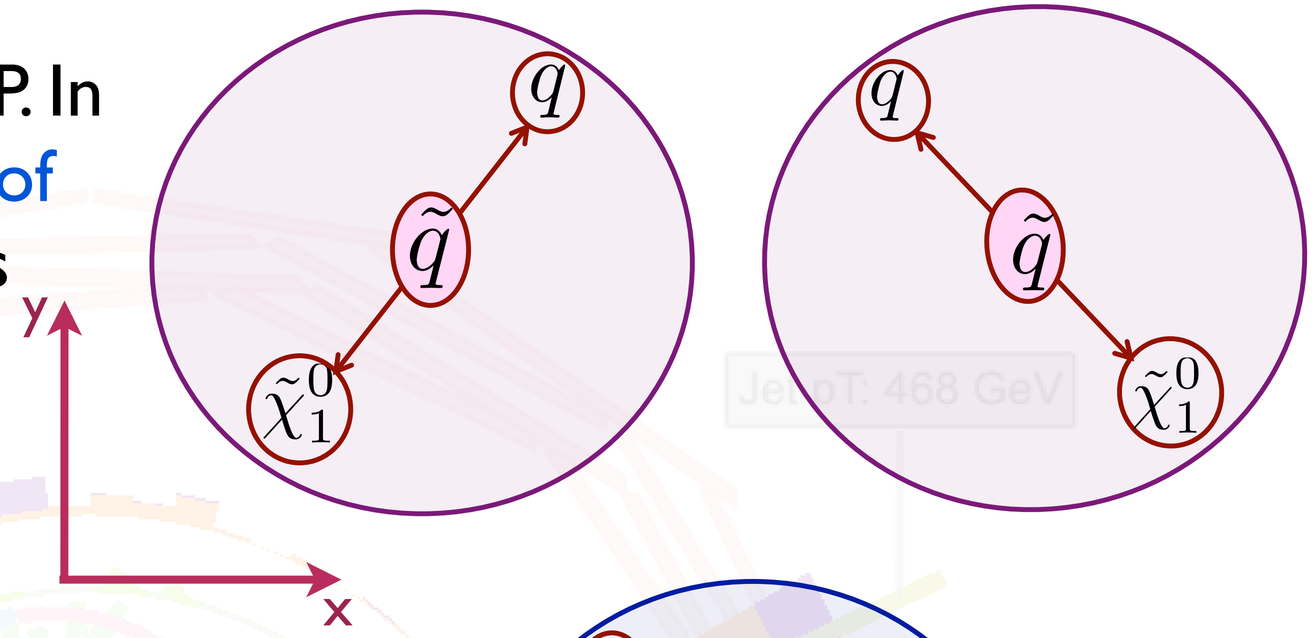


$$\sqrt{s}_{min}(M_{miss,min}) = \sqrt{M_{vis}^2 + P_{T,vis}^2} + \sqrt{M_{miss,min}^2 + \not{E}_T{}^2}$$

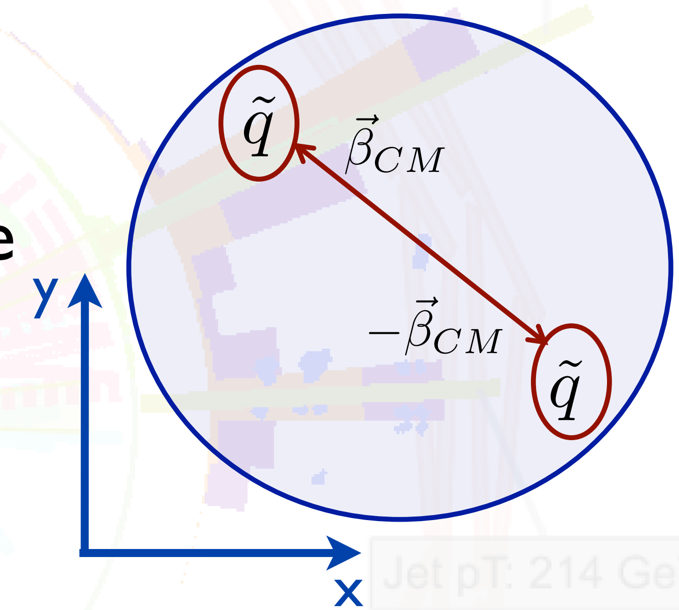
The Razor Frame

- Two squarks decaying to quark and LSP. In their rest frames, they are two copies of the same monochromatic decay. In this frame p(q) measures M_Δ

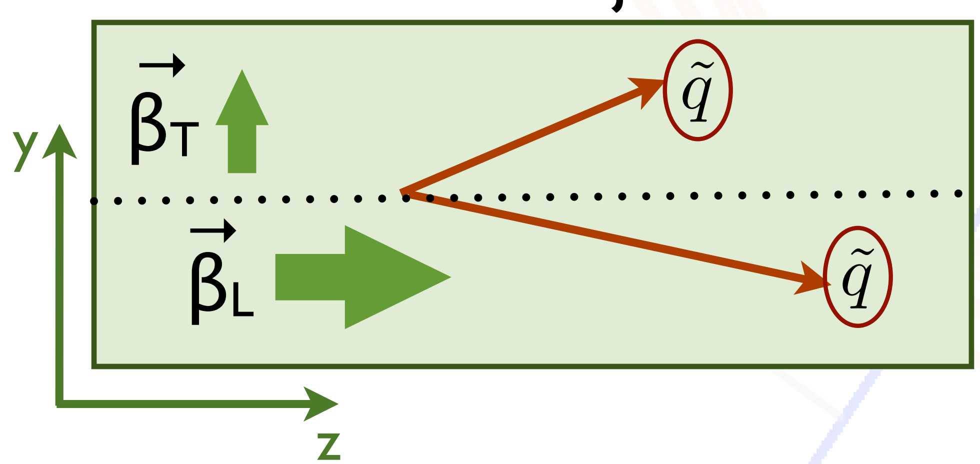
$$M_\Delta \equiv \frac{M_{\tilde{q}}^2 - M_{\tilde{\chi}}^2}{M_{\tilde{q}}} = 2M_{\tilde{\chi}}\gamma_\Delta\beta_\Delta$$



- In the rest frame of the two incoming partons, the two squarks recoil one against each other.



- In the lab frame, the two squarks are boosted longitudinally. The LSPs escape detection and the quarks are detected as two jets

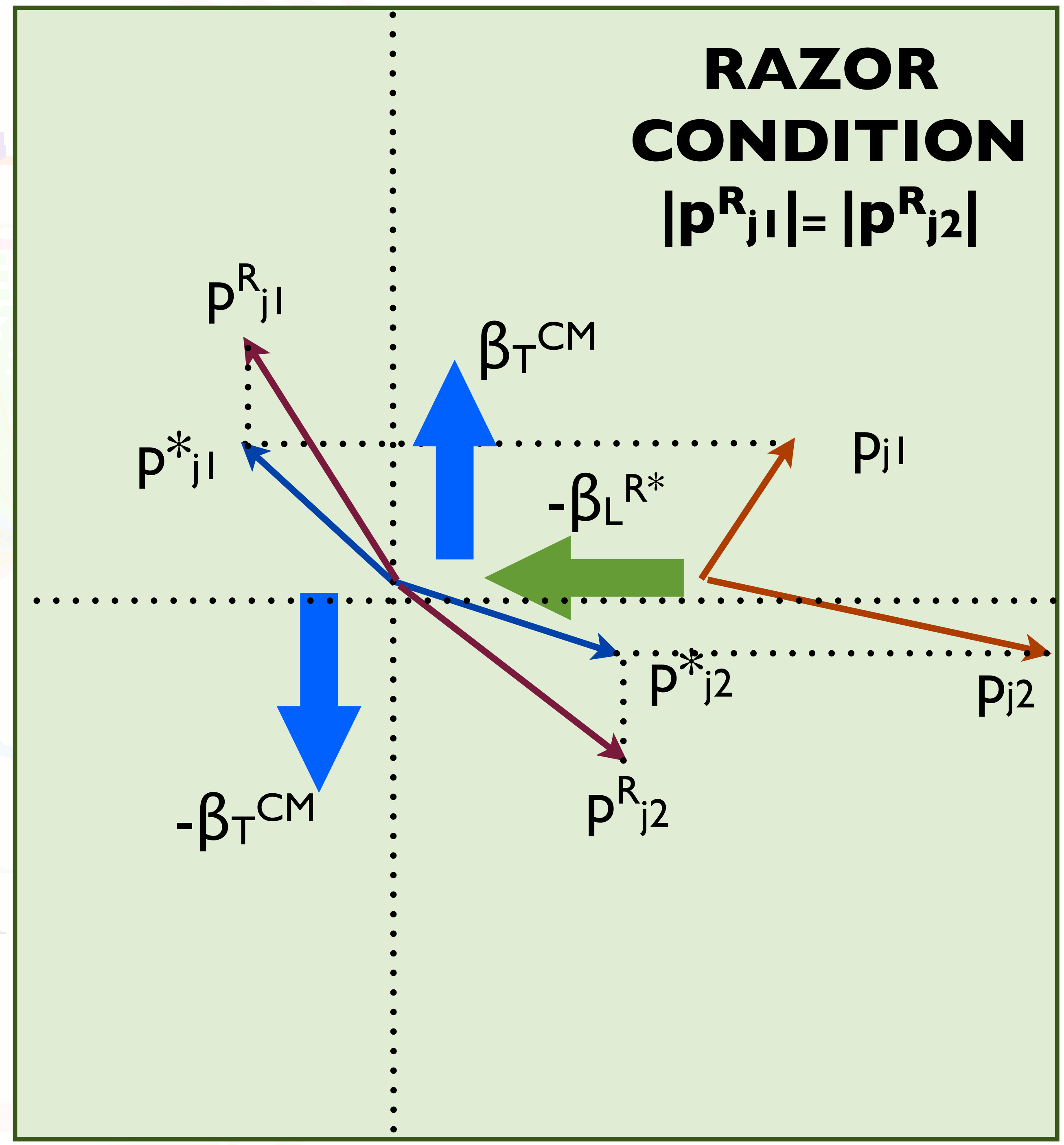


If we could see the LSPs, we could boost back by β_L, β_T, and β_{CM}
In this frame, we would then get
$|p_{j1}| = |p_{j2}|$
Too many missing degrees of freedom to do just this

The Razor Frame

- In reality, the best we can do is to compensate the missing degrees of freedom with assumptions on the boost direction

  - The parton boost is forced to be longitudinal
  - The squark boost in the CM frame is assumed to be transverse



- We can then determine the two by requiring that the two jets have the same momentum after the transformation

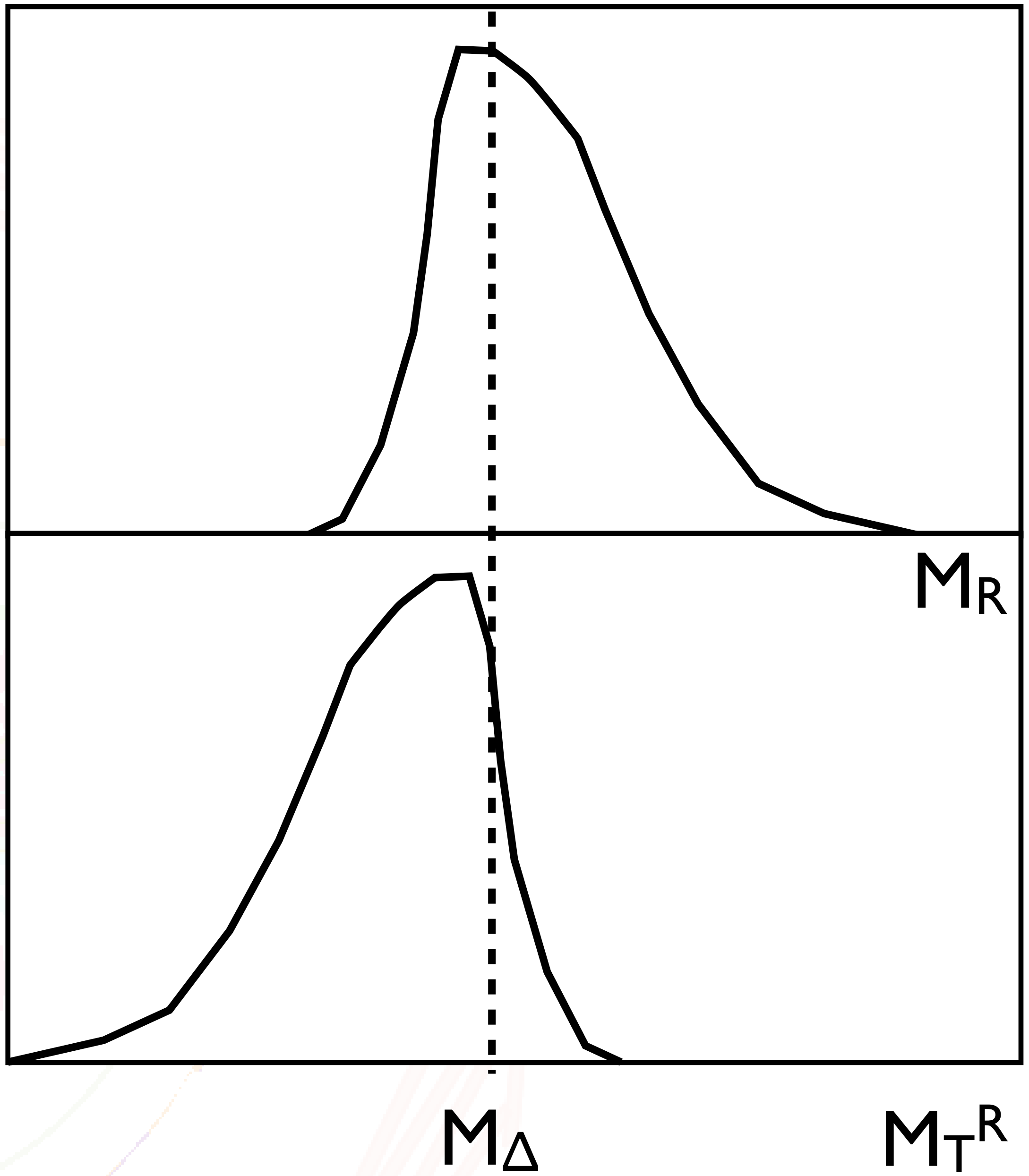
- The transformed momentum defines the M_R variable

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

The Razor Variable

- M_R is boost invariant, even if defined from 3D momenta
- No information on the MET is used
- The peak of the M_R distribution provides an estimate of M_Δ
- M_Δ could be also estimated as the "edge" of M_T^R

$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$



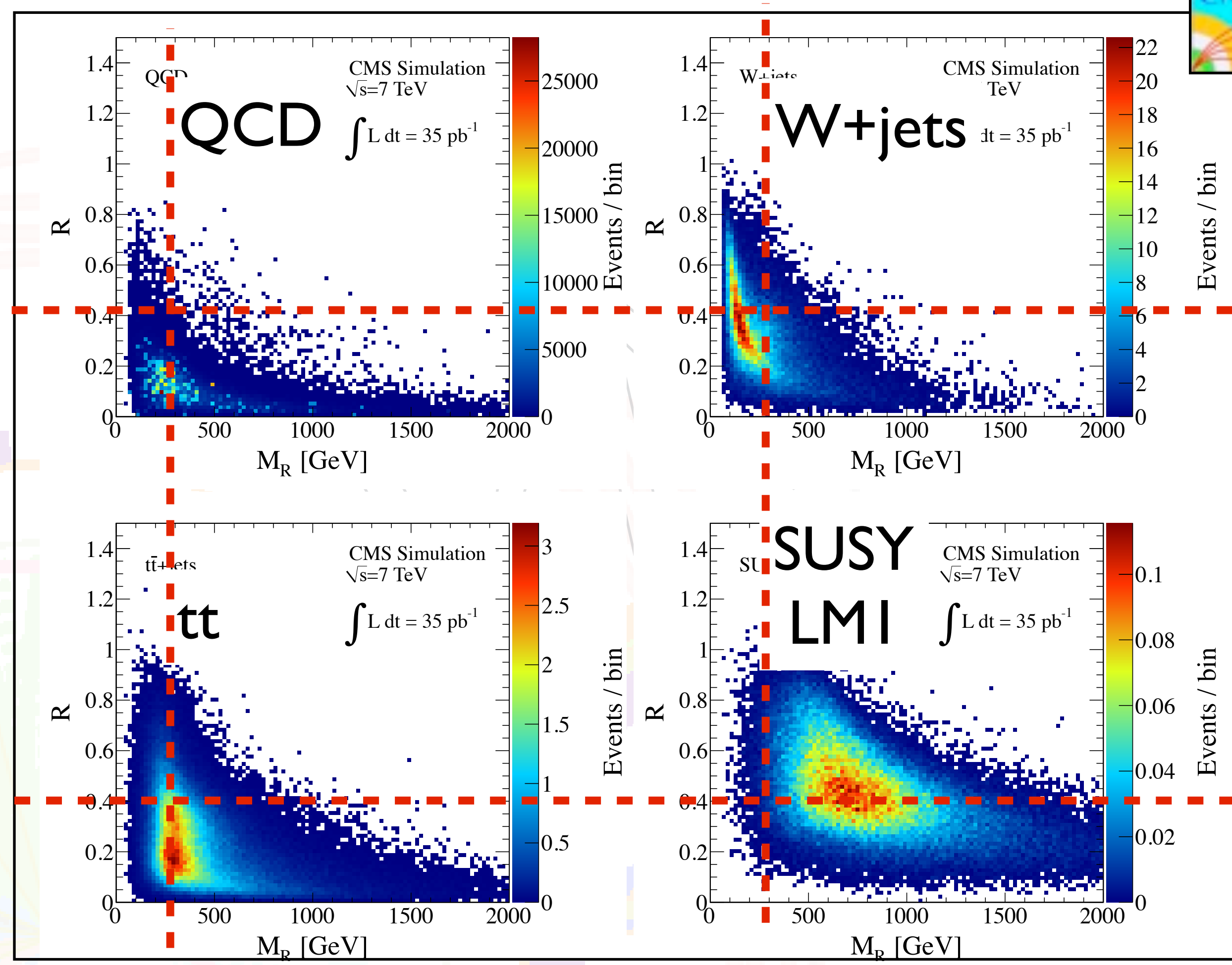
- M_T^R is defined using transverse quantities and it is MET-related
- The Razor (aka R) is defined as the ratio of the two variables

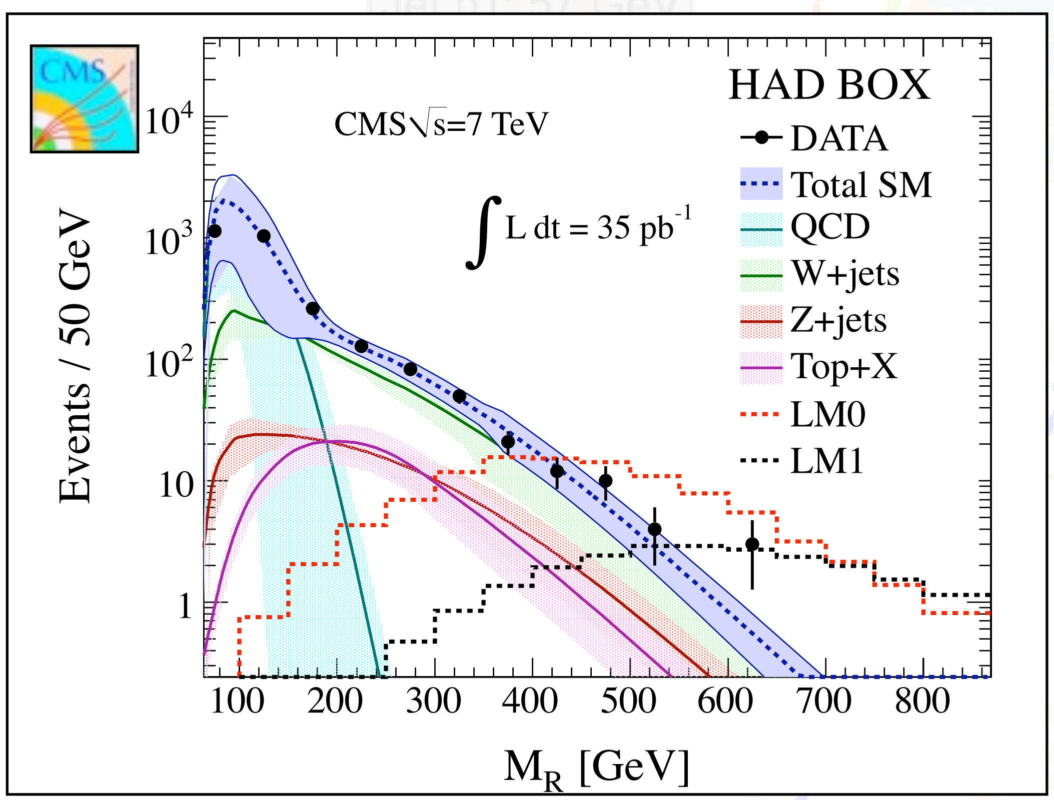
$$R \equiv \frac{M_T^R}{M_R}$$

The Razor Analysis

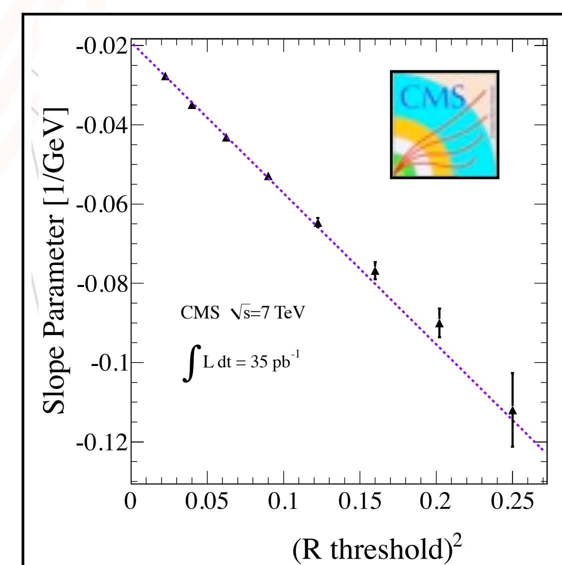
- The backgrounds are characterized by a turn-on (they have their own M_Δ), after which they decay ~ exponentially

- The two variables exhibit a clear correlation, regardless of the process under consideration



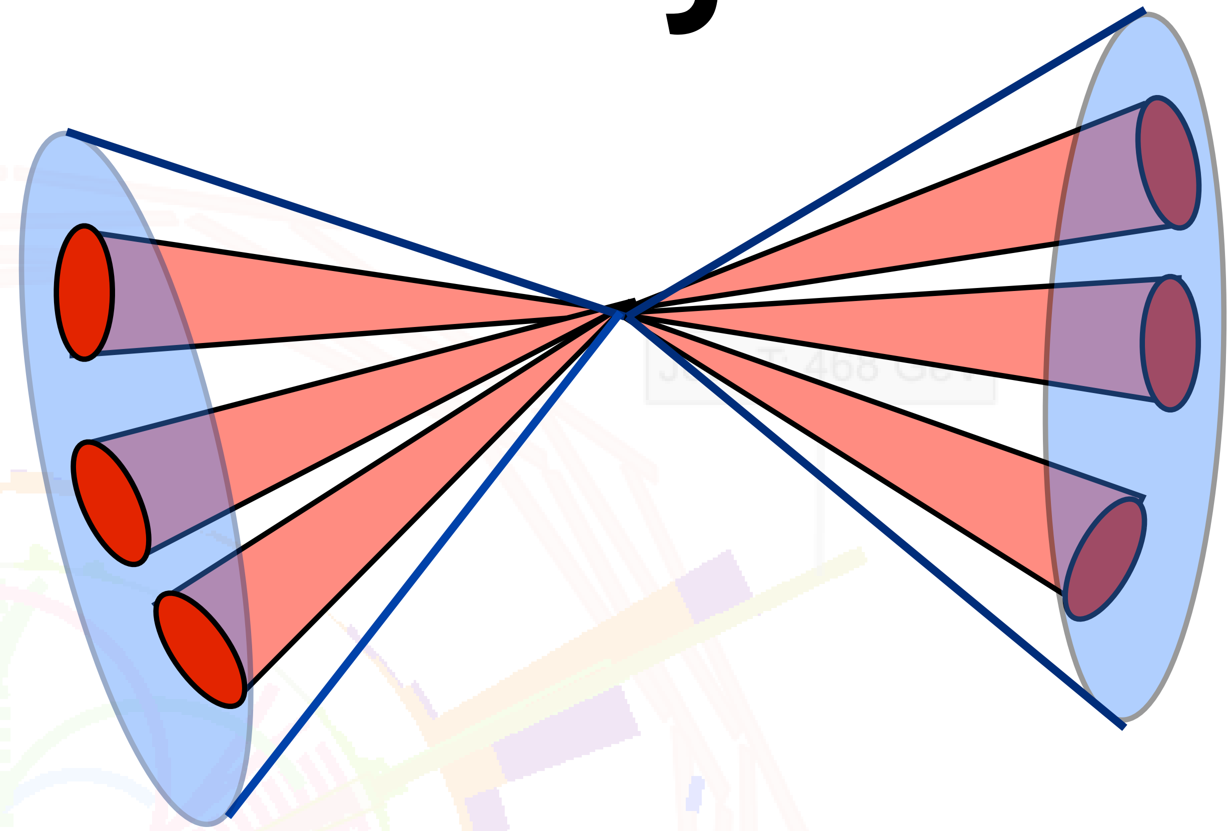


- As a consequence of the correlation, the shape of mR (exponential) depends on the cut applied on R



From DiJet To MultiJets

- The "new" variables rely on the dijet +MET final state as a paradigm
- All the analyses have been extended to the case of multijet final states clustering jets in two hemispheres (aka mega-jets)



Several approaches used

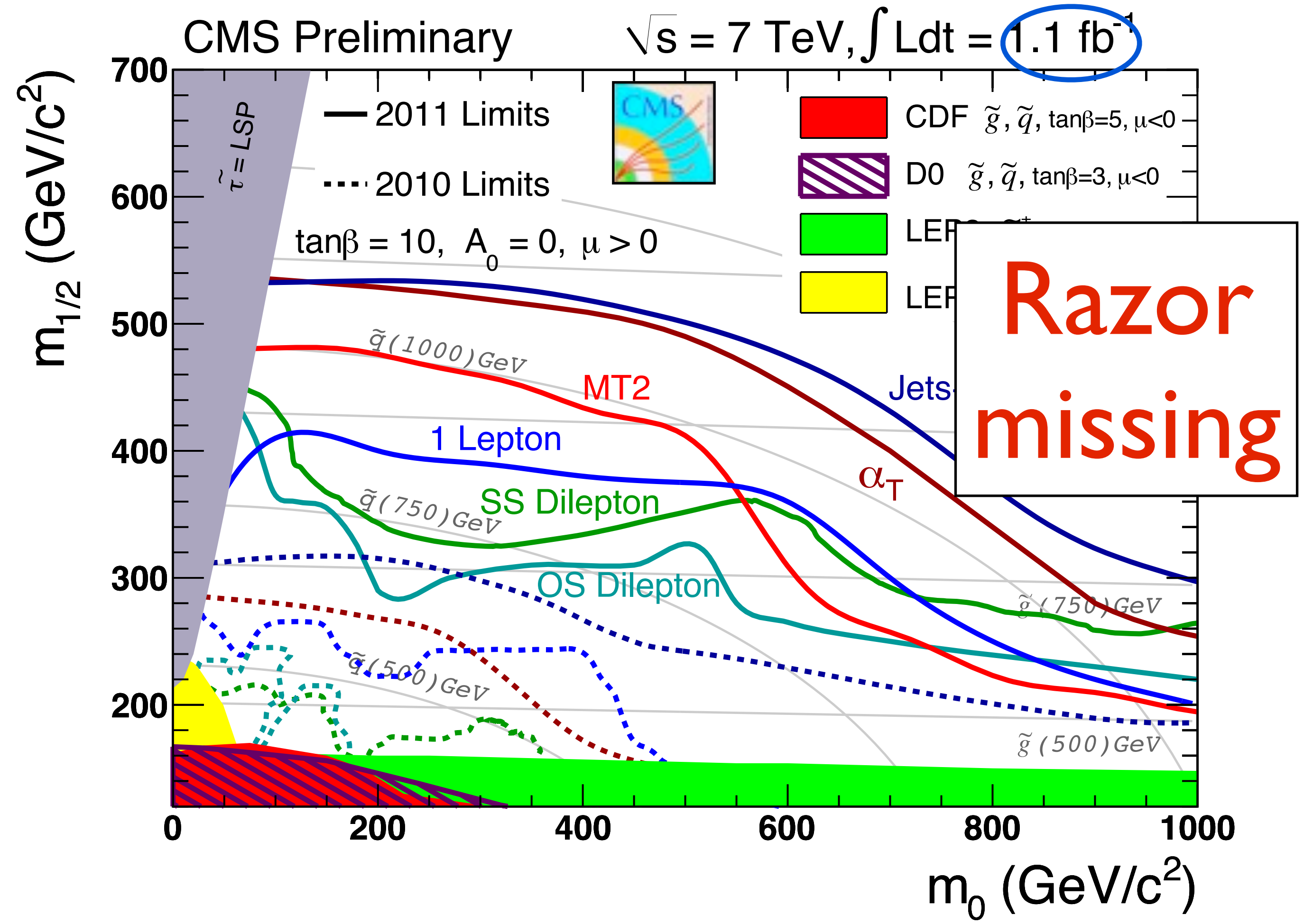
- minimizing the HT difference between the mega-jets (aT CMS)
- minimizing the invariant masses of the two jets (Razor CMS)
- minimizing the Lund distance (MT2 CMS)
- ...

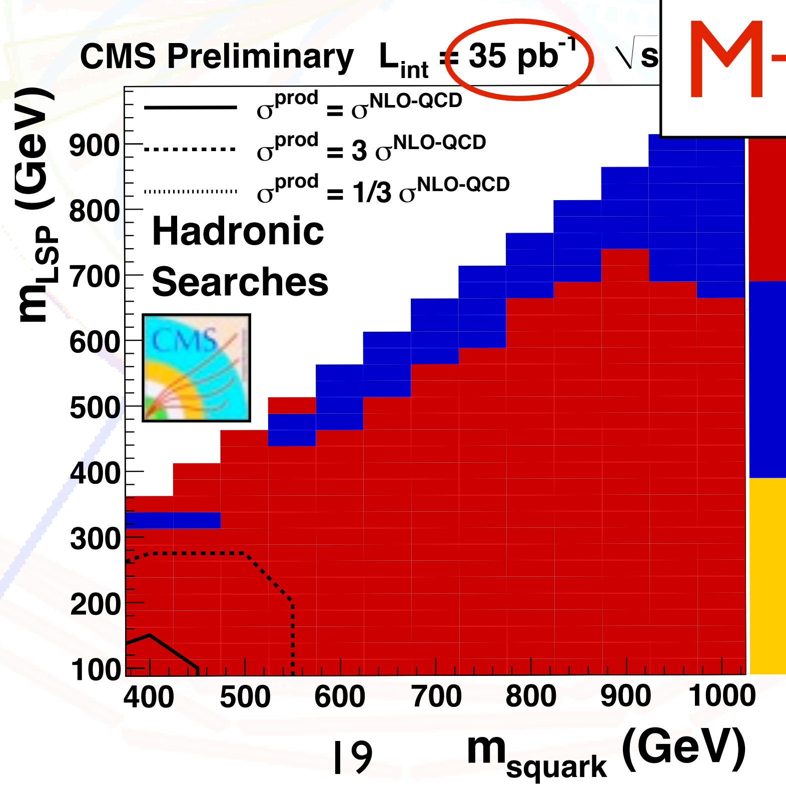
$$(E_i - p_i cos\theta_{ik})\frac{E_i}{(E_i+E_k)^2} \leq (E_j - p_j cos\theta_{jk})\frac{E_j}{(E_j+E_k)^2}$$

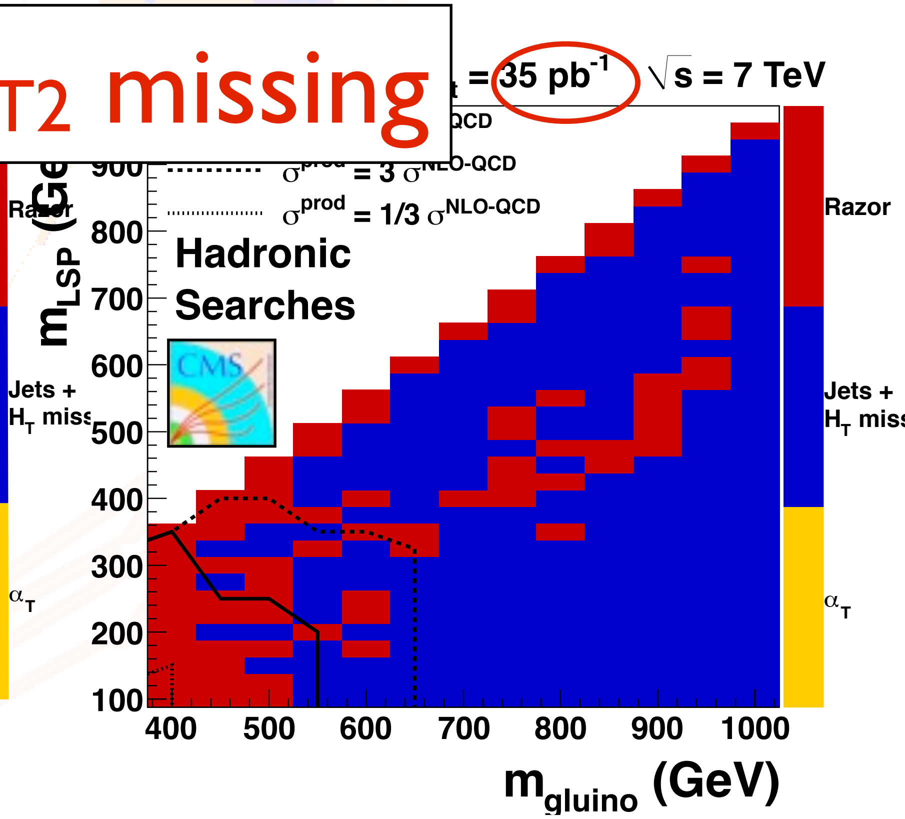
- Is the ultimate hemisphere definition out there (I am not aware of studies on this)?
- Could this improve the signal sensitivity in a significant way?

How Do These Approaches Compare?

- A fair comparison is difficult, because not all the results are provided with the same luminosity
- A new variable/approach is not the end of the story. The actual analysis is more than the variable it uses
- The best limit is not the best sensitivity. The best limit is not the best analysis (particularly if the cuts are so tight that nothing is left and nothing is expected to be left)
- The best I found are these three CMS plot

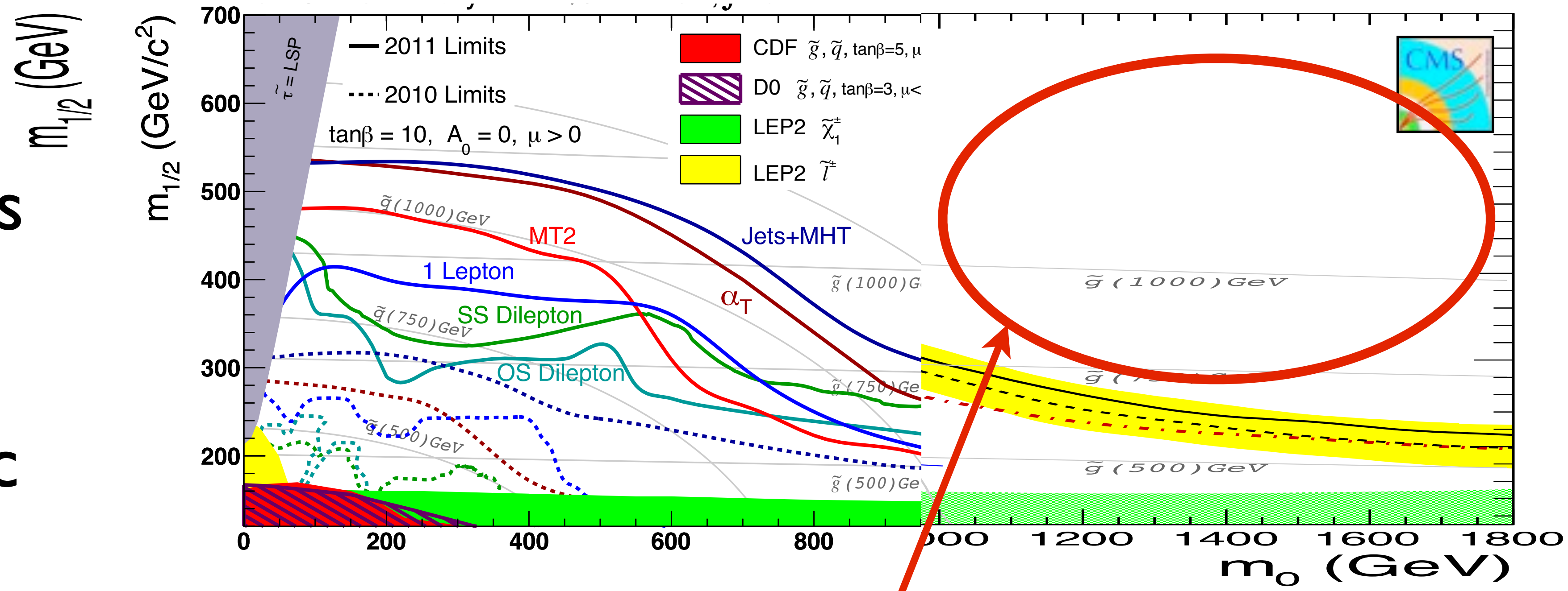






What's Next

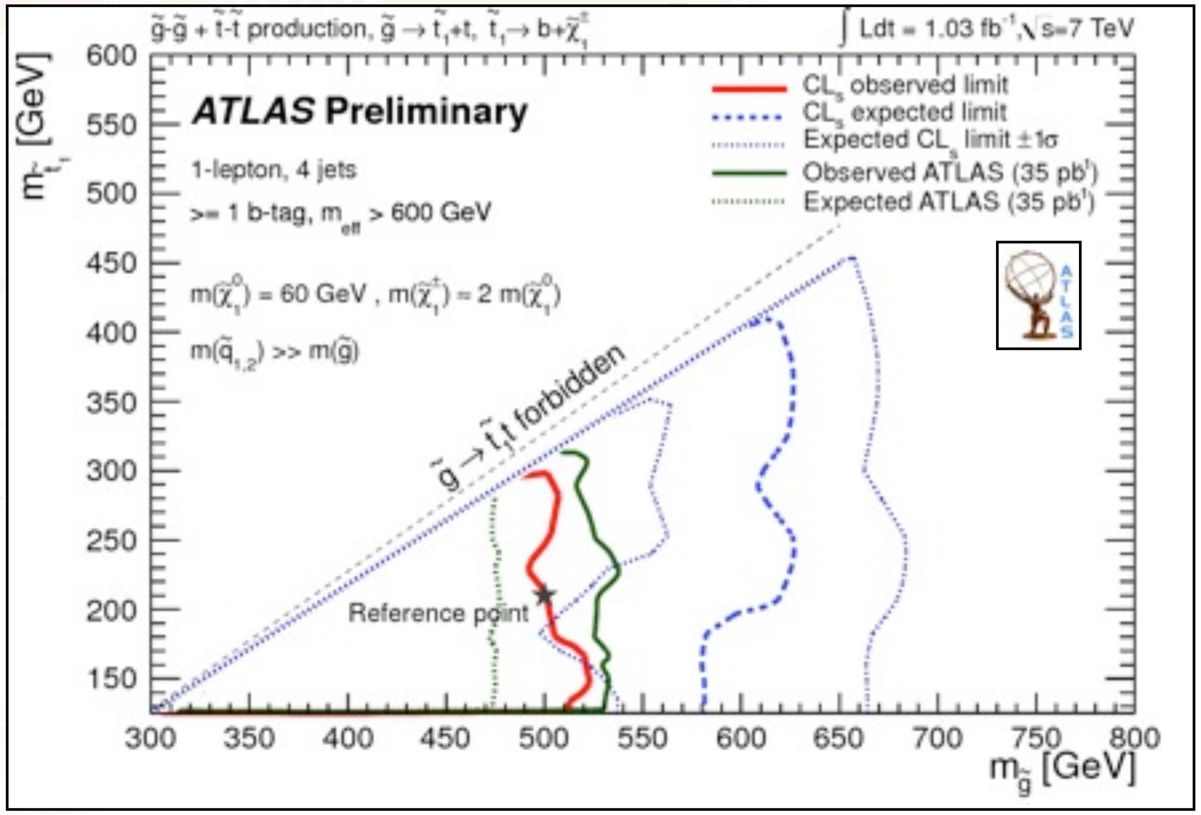
- The current physics program will be repeated as it is, with higher statistic



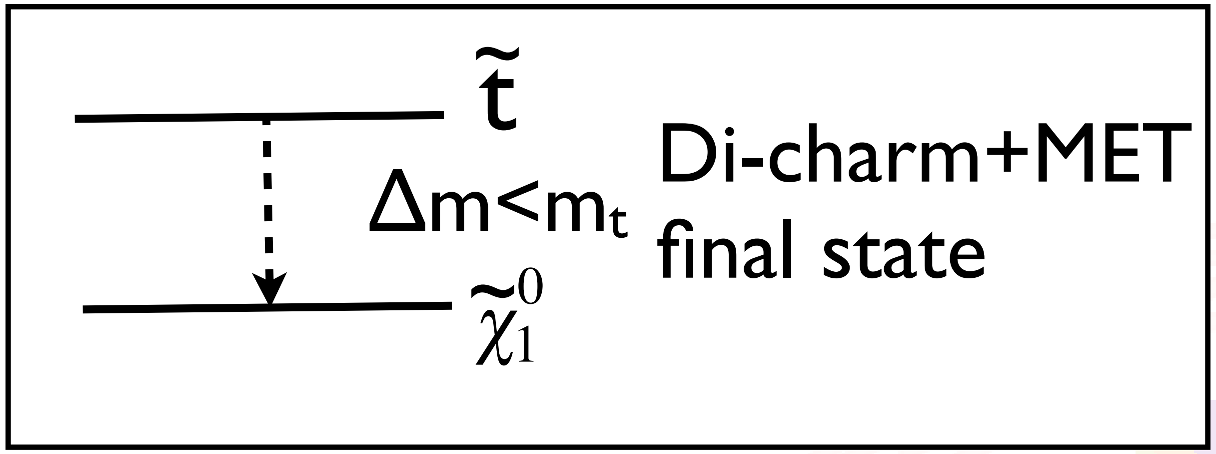
- In case of a negative result, the focus will move from the hadronic to the leptonic analyses, as a probe of SUSY EW production

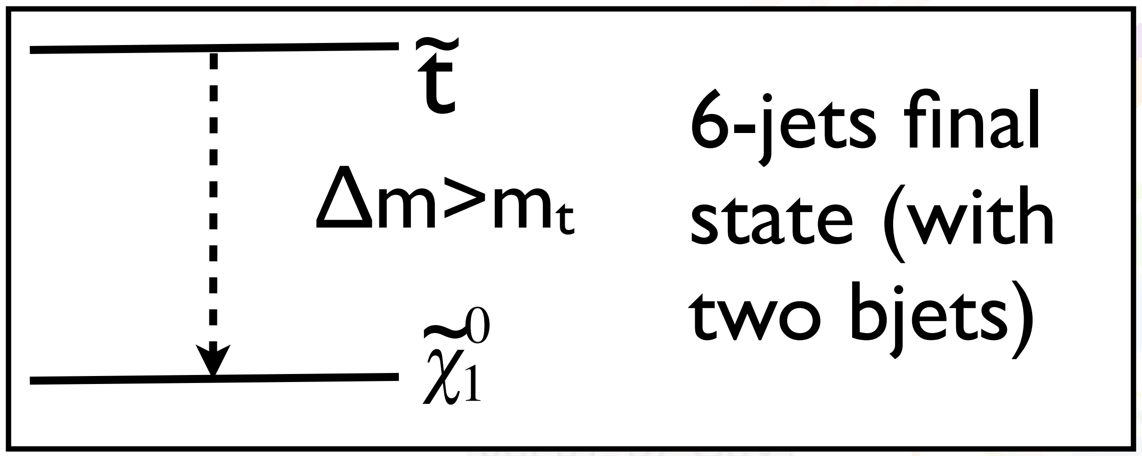
- The expertise gained in hadronic analyses could be used for SUSY searches in specific scenarios, e.g. the light-stop scenario

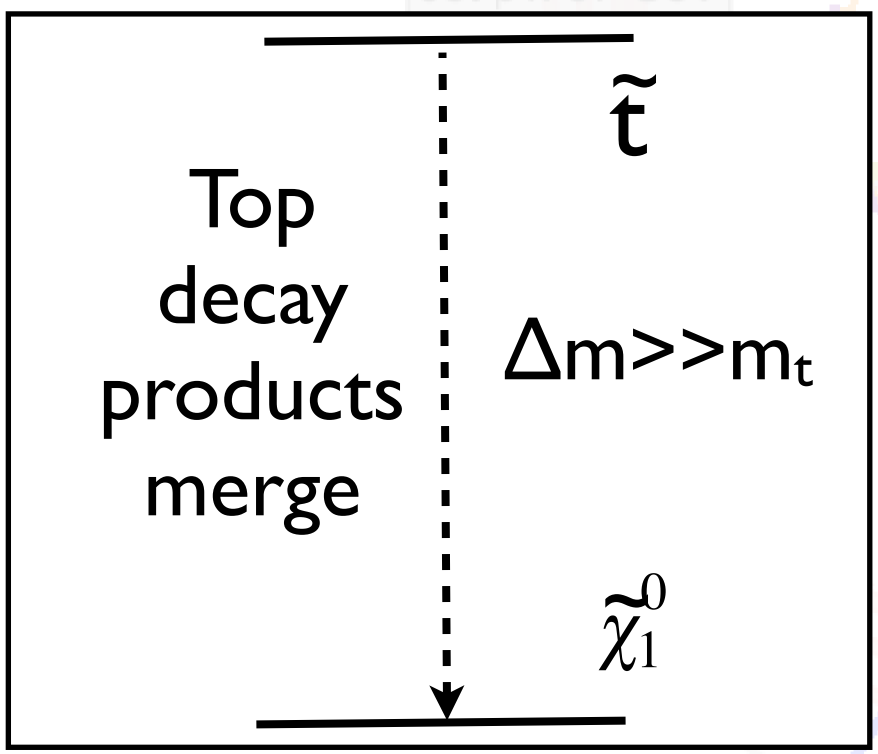
- Analyses will have to be modified

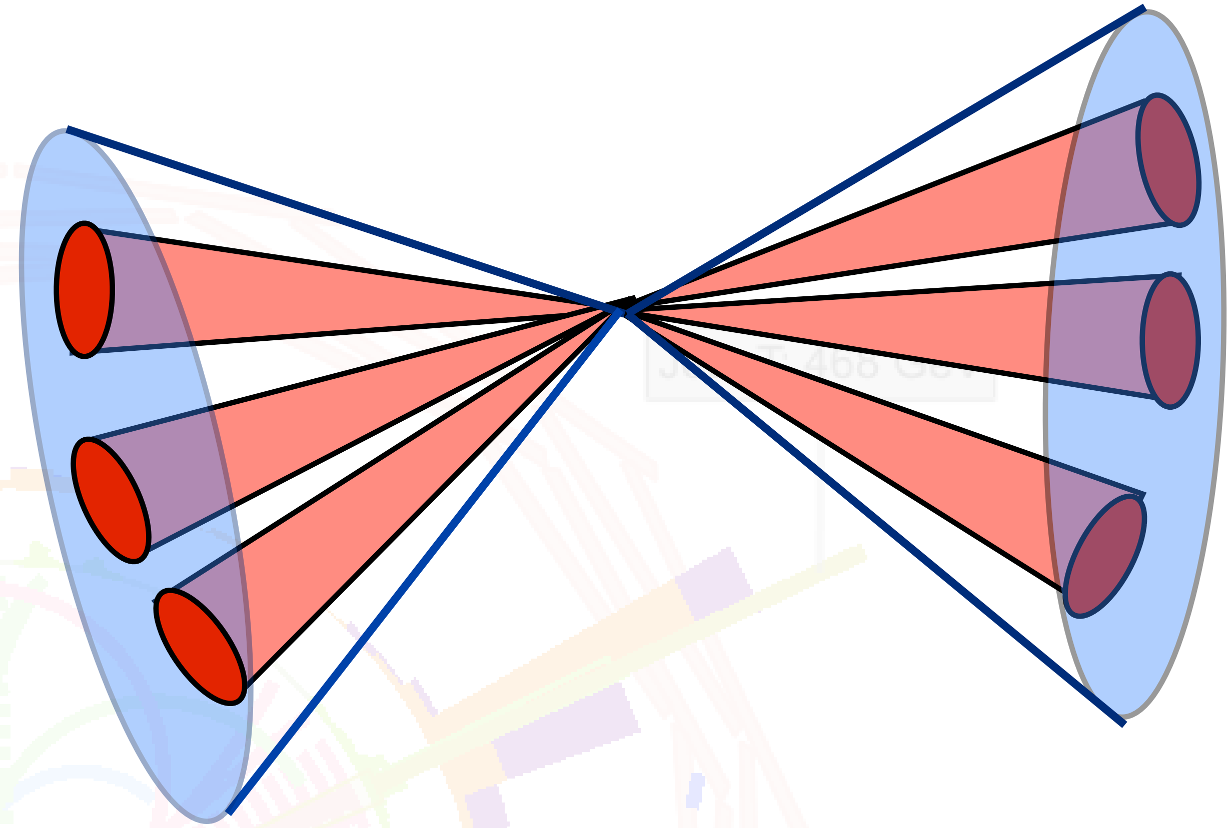


Stop production vs Megajets









- The “inclusive” hemisphere definition is inappropriate
- One could inject already at this level specific features of the considered topology
    - force three jets per side, one b-jet per side
    - consider two-heavy jets + jet substructure

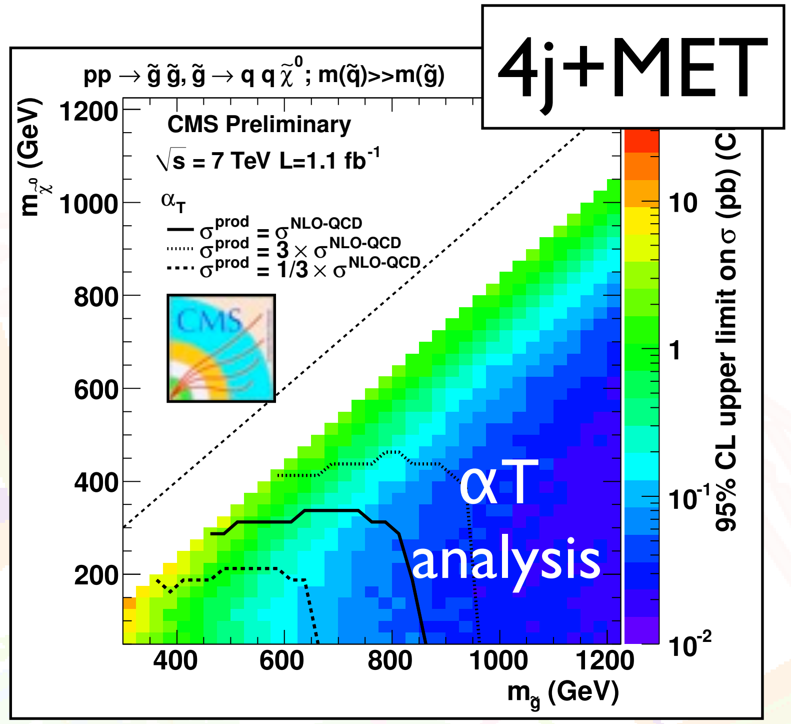
Stop production vs MET

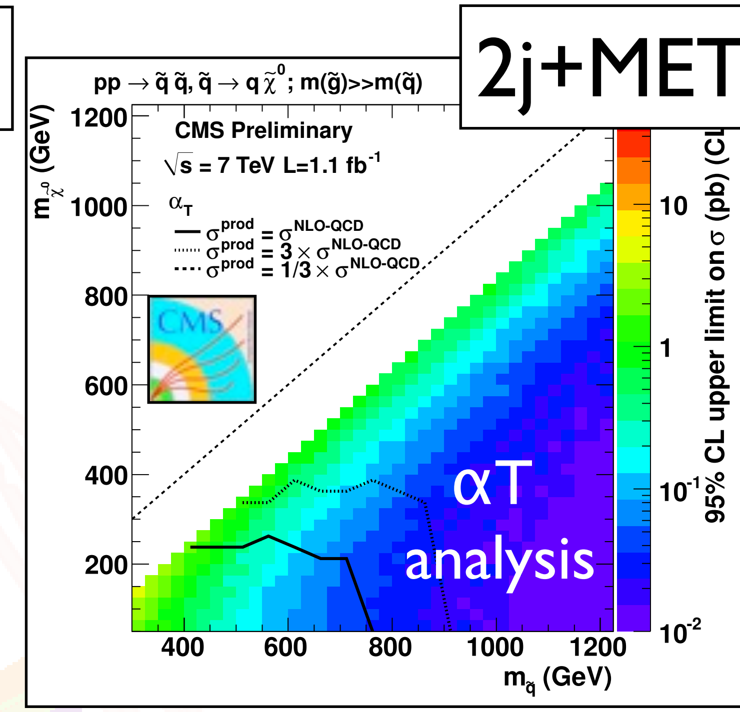
- With increasing jet multiplicity, the analyses based on MET are less sensitive to a signal

- If objects are light the situation gets worse (not enough phase space)

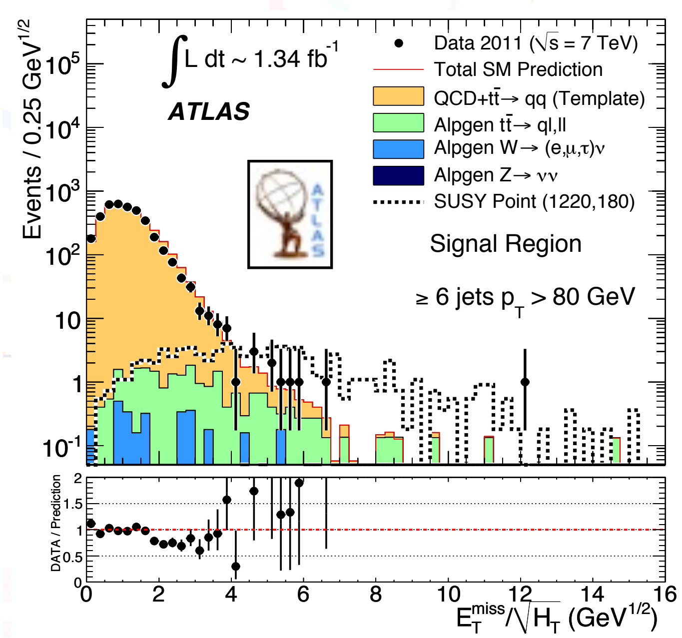
- Analyses have to be modified

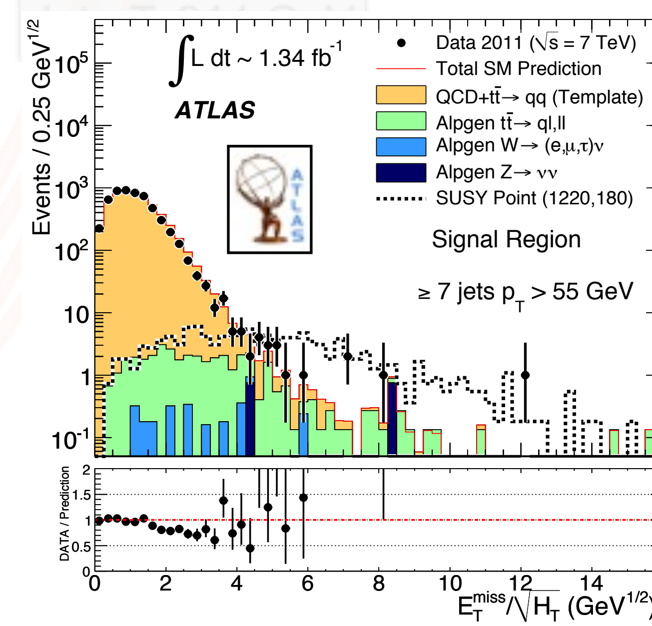
  - reduce the role of MET-based variables (aT, MET, R,MT2)
  - base the analysis on the visible part (HT, MR, $\sqrt{s}_{min}$)
  - reduce the bkg to manageable level by other requirements (e.g. jet multiplicity and/or b-tagging)
  - if done at the trigger level, one can go looser on the kinematic requirements





Signal region	7j55	8j55	6j80	7j80
Jet p_T	> 55 GeV		> 80 GeV	
Jet $\|\eta\|$	< 2.8			
ΔR_{jj}	> 0.6 for any pair of jets			
Number of jets	≥ 7	≥ 8	≥ 6	≥ 7
$E_T^{miss}/\sqrt{H_T}$	> 3.5 GeV$^{1/2}$			





Conclusion

- Lesson from Tevatron taken: CMS and ATLAS fully committed to "classic" Jet+MET searches
- In parallel, new directions have been explored, exploiting specific features of the signal under considerations
- First results showed the power of the new methods. More results are coming
- Increasing luminosity and no excess seen moves to interest to specific scenarios (eg light stop).
- Classic analyses migrated already. The new approaches should too

Basic/Incomplete Bibliography

- ATLAS SUSY results

  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

- CMS SUSY results

  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

- Other papers
  - Original paper on α http://arxiv.org/pdf/0806.1049
  - Modified α_T paper by CMS http://cdsweb.cern.ch/record/1149915/files/SUS-08-005-pas.pdf
  - MT2 http://arXiv.org/pdf/hep-ph/0304226 http://arxiv.org/pdf/0810.5576v2
  - $\sqrt{s}_{min}$ http://www.arxiv.org/pdf/1006.0653
  - Razor http://arxiv.org/pdf/1006.2727