Search for Supersymmetry in Hadronic Final States with the CMS Detector at the LHC

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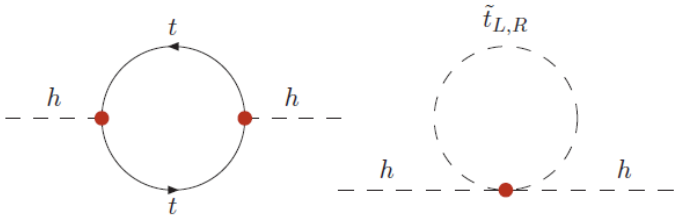
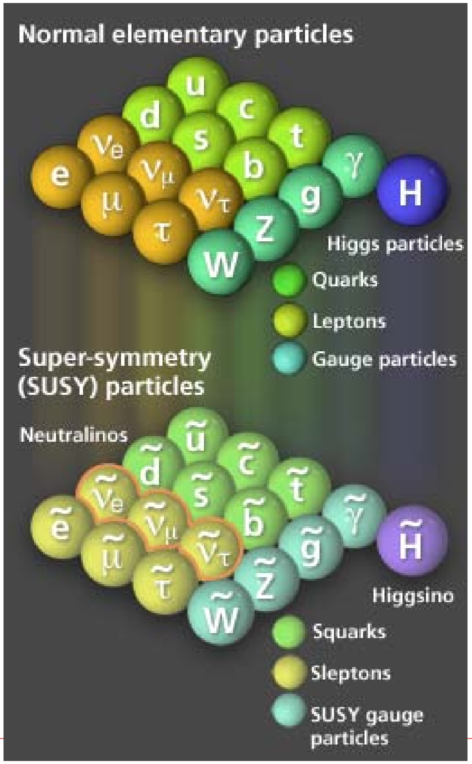
Supersymmetry (SUSY)

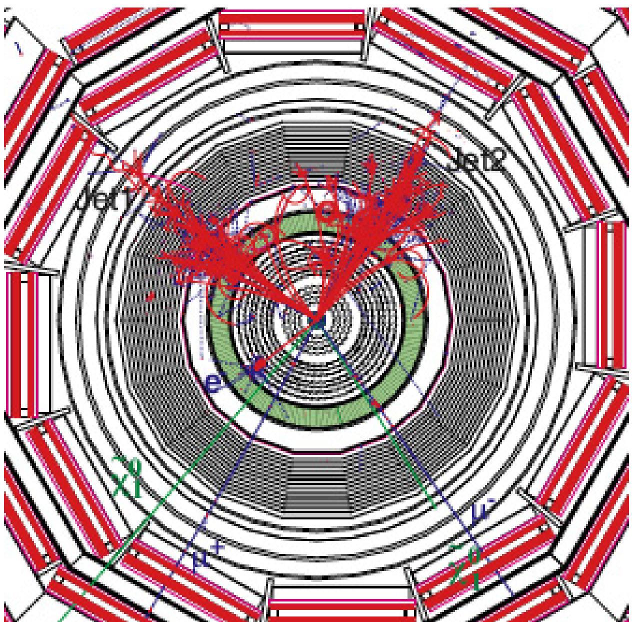
- SUSY is a fundamental global symmetry between fermions and bosons.
  - Each fermion has a boson super partner, and vice versa
  - Higgs mass stabilizes against loop correction (fine tuning problem)
  - Modifies running of SM gauge couplings just enough to give "Grand Unification" at single scale
  - SUSY is broken (sparticles have not been seen)
- MSSM: Simple SUSY model consistent w/ SM
  - R-parity conservation
    - $R=(-1)^{2S+3B+L}$
    - Sparticles produced in pairs, decay to an odd number of Lightest Supersymmetry Particle (LSP)
    - LSP is a dark matter candidate
  - SUSY breaking
    - mSUGRA, GMSB, …

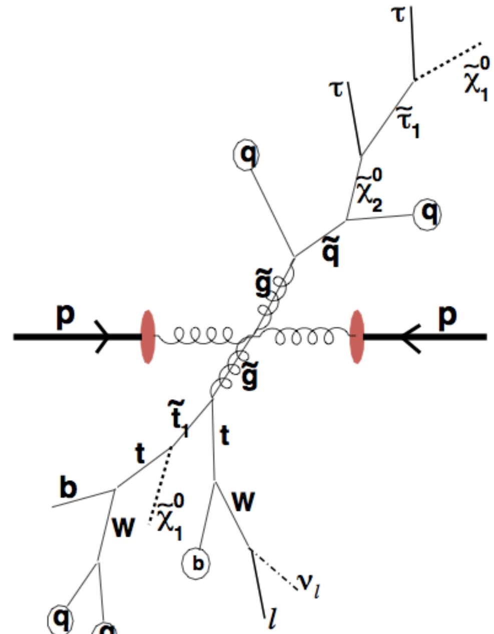


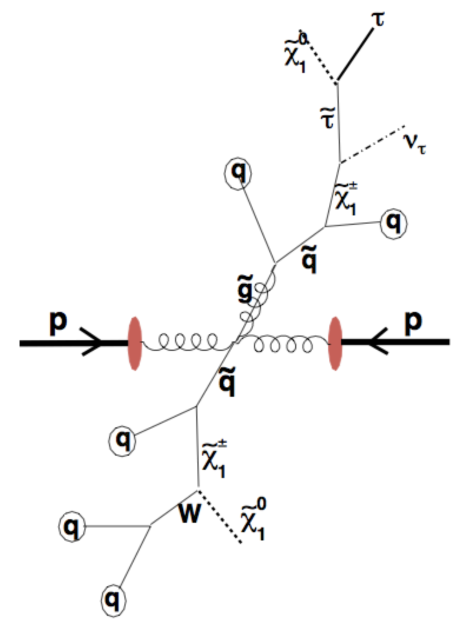


Experimental Signature

- Signature: MultiJets + MET
- Squarks & Gluinos cascade decays: produce a number of quarks and gluons, leptons and possibly weakly interacting stable neutral particles (WIMP).







In the detector,
WIMPs / Lightest SUSY particles appears as the momentum imbalance in the transverse plane (Missing ET!)

SUSY Searches at CMS using 2010 Data

- Fully hadronic searches
  - SUS-10-005: Inclusive search in jets + MET (>=3 jets)
  - arXiv:1101.1628: Search in jets+MET with α_T
  - SUS-10-009: Inclusive search with ``Razor variables''
  - SUS-10-011: Search in b-tagged jets + MET with α_T
- Searches with leptons
  - SUS-10-006: Search with single lepton + jets + MET
  - arXiv1104.3168: SUS-10-004: Search with same sign dileptons + jets + MET
  - arXiv1103:1348, SUS-10-007: Search with opposite sign dileptons
  - SUS-10-008: Search with multileptons
- Searches with photons
  - arXiv:1103.0953, SUS-10-002: Search in Jets+MET+diphotons
  - SUS-11-002: Search with lepton + photon + MET

Analysis written in blue are highlighted. Full results are available on:

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

Hadronic Search in Jets + MET

Event Selection:

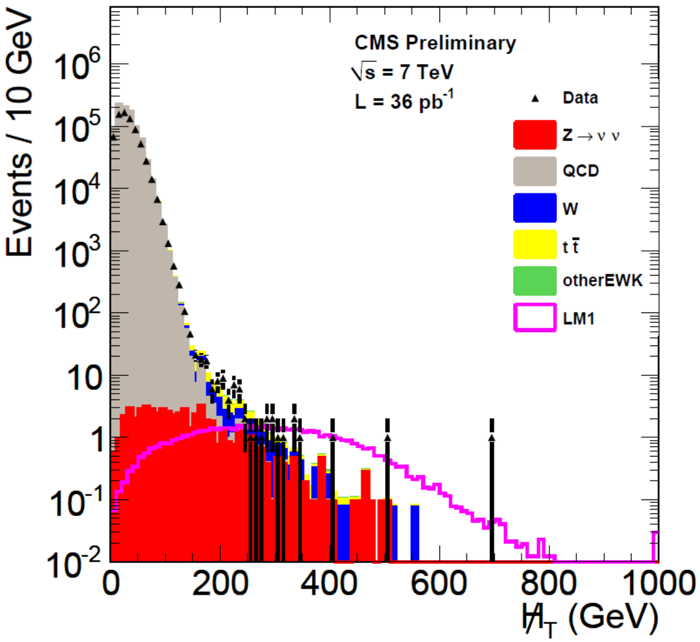
- $\geq$3 jets
  - $|\eta|<2.5$, $P_T>50$ GeV
- Veto isolated e/mu
  - Suppress W, Z & Top BGs
- $\Delta\varphi$(MHT,j1,2,3) > 0.5,0.5,0.3 (rad)
  - Suppress QCD background
- Baseline:
  - HT>300 GeV, MHT>150 GeV
- Search Selection:
  - HT>300 GeV, MHT>250 GeV
  - HT>500 GeV, MHT>150 GeV

Main Backgrounds:

- QCD
- Top & W+jets
- $Z(\rightarrow\nu\nu)$+jets

Determined by data-driven techniques

CMS-PAS-SUS-10-005



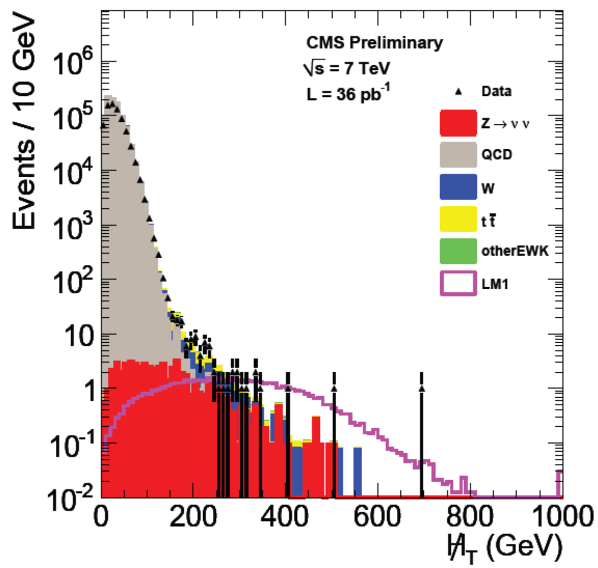
MC-based backgrounds for illustration.

LM1*: m_0=60GeV, $m_{1/2}$=250 GeV, A_0=0, tanß=10, sign(μ)>0
m_gluino=611, m_squark=599,m_LPS=96 GeV

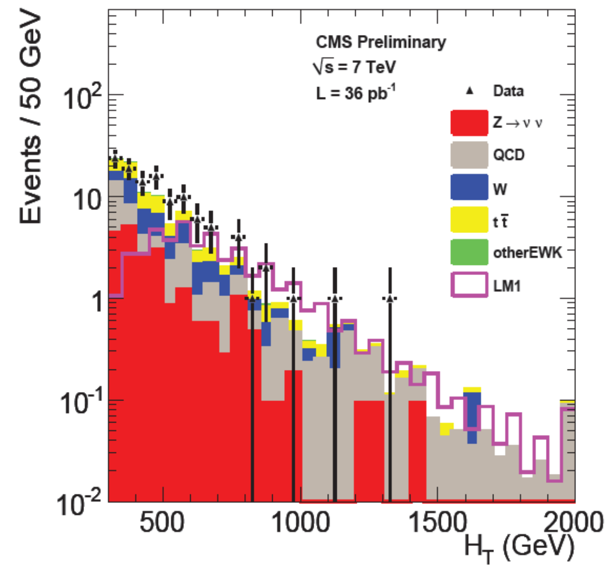
Data vs Standard Model MCs

An out-of-box comparison of Data vs MC for search variables HT and MHT

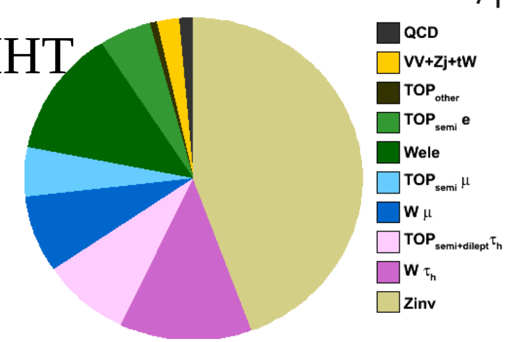
Baseline selection w/o MHT cut



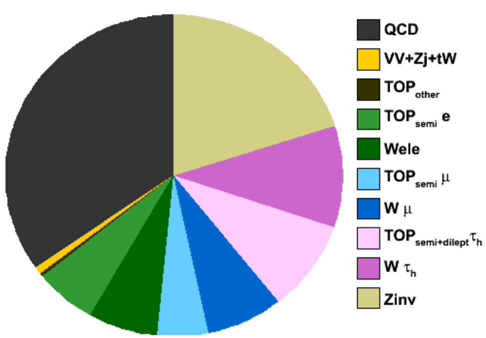
Baseline selection



High MHT

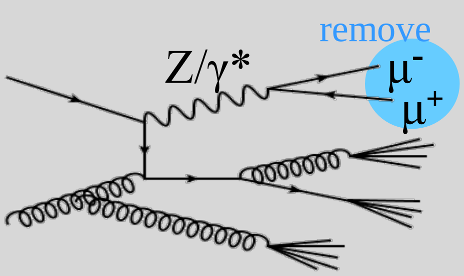


High HT

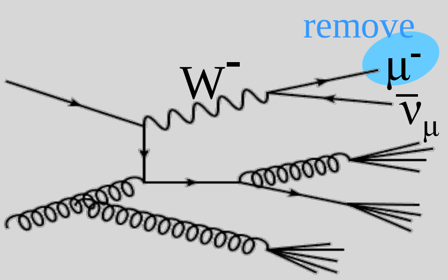


Invisible Z background

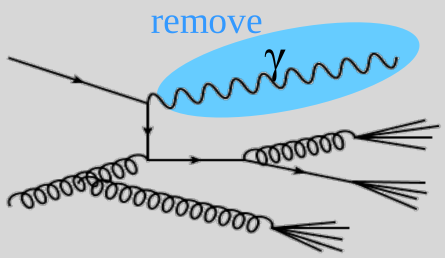
- Z(→νν) + multijets: Irreducible background in this search
- Three different methods using boson+jets were employed to obtain the data-driven estimates of this background (substitute boson with MHT)



– Lower statistics than γ and W
Suffer from Br(Z→μμ) / Br(Z→νν)=1/6



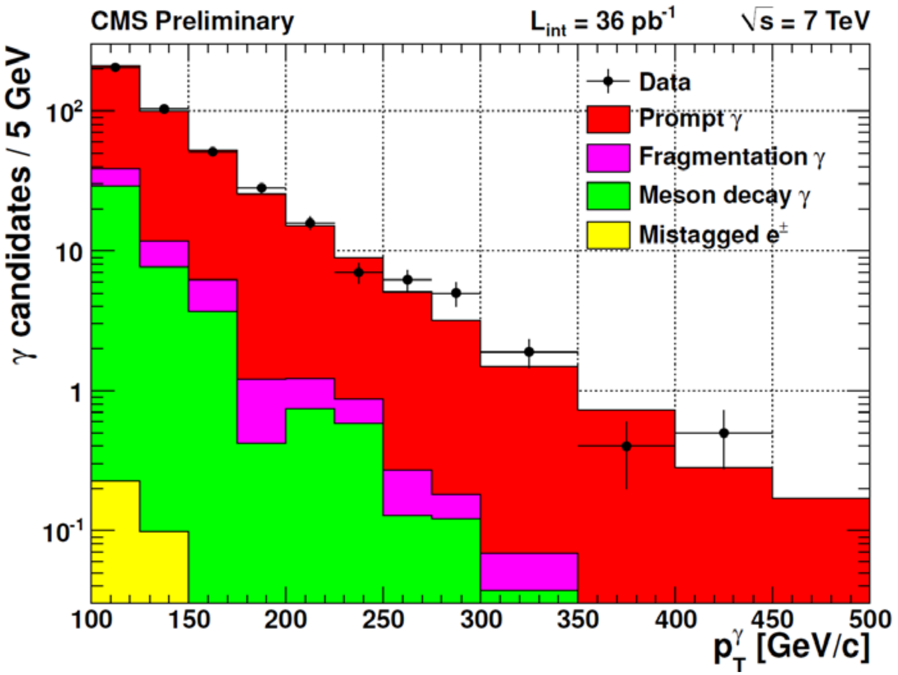
– Similar event topology
– Higher stat than Z→νν
(W+jets rate is about x 2.5 of Z+jets)

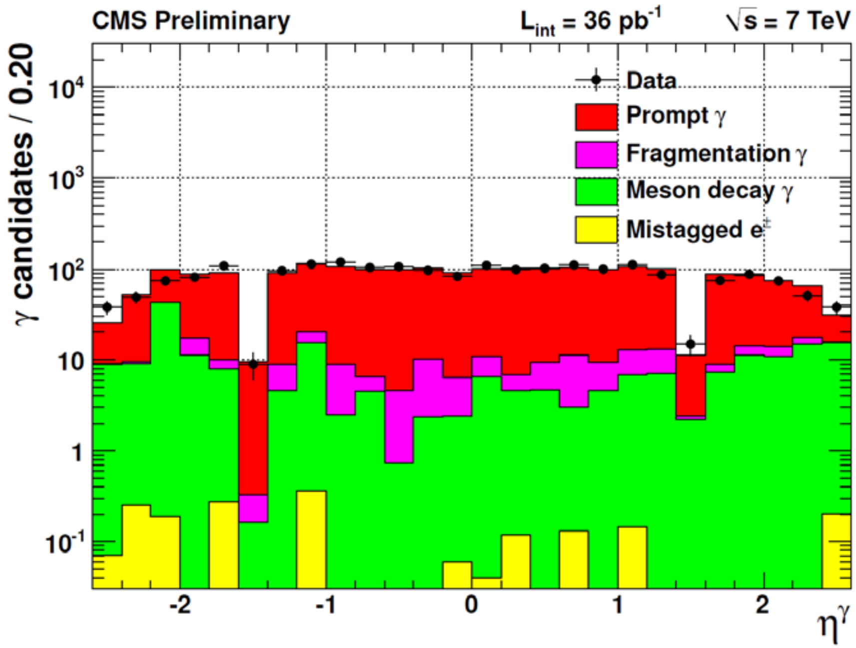


– Similar to Z+jets at large Pt (MHT)
– High stat (no branching ratio)

Cross check of different channels is important as they have different sensitivities to potential new physics signal

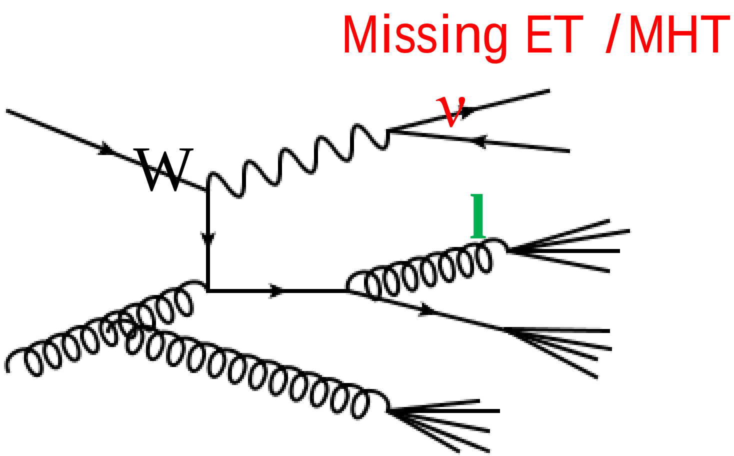
Z Invisible From Photons





	# events in γ+jets data sample	# $Z \rightarrow \nu\bar{\nu}$ events predicted	# $Z \rightarrow \nu\bar{\nu}$ events from simulation
Baseline selection	72	$26.3 \pm 3.2(\text{stat.}) \pm 3.6(\text{syst.})$	21.2 ± 1.4
High-$\not{H}_T$ selection	16	$7.1 \pm 1.8(\text{stat.}) \pm 1.3(\text{syst.})$	6.3 ± 0.8
High-H_T selection	22	$8.4 \pm 1.8(\text{stat.}) \pm 1.4(\text{syst.})$	5.8 ± 0.7

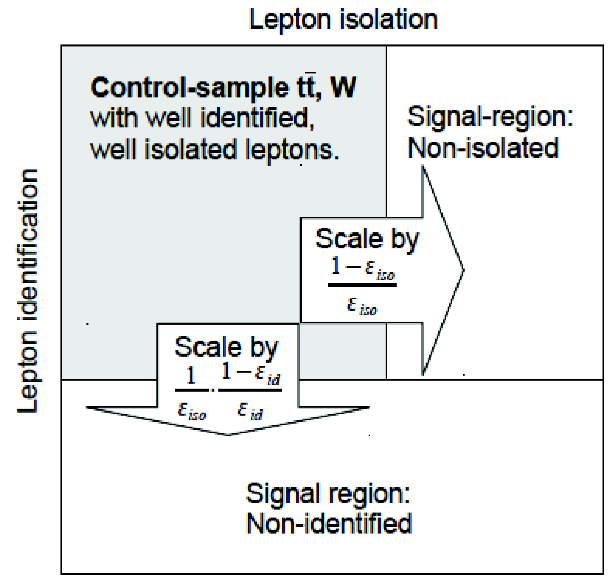
W and Top Background



Veto leptons (e,μ) to suppress BGs, still occasionally fail to find and veto leptons. Hadronically-decaying taus also constitute BG

W/Top + (Lost Leptons) + ν + Jets

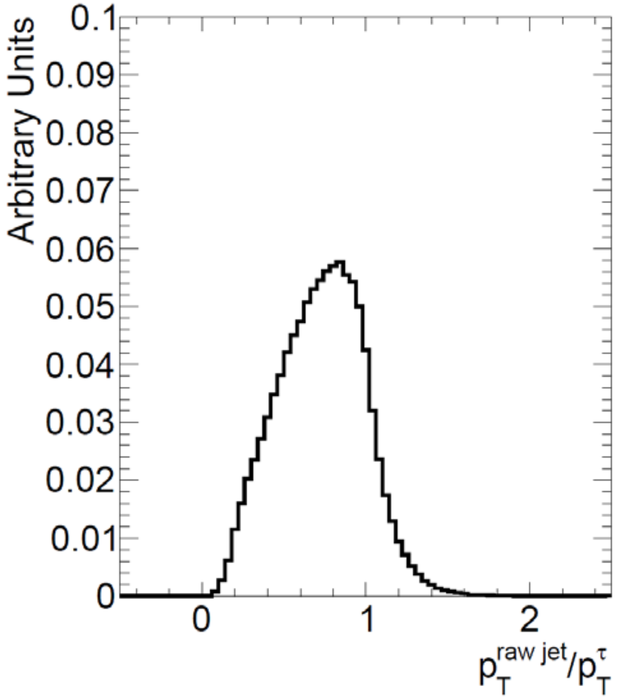
- Leptons failing the lepton veto contribute to background
- There can be 3 reasons to lose leptons
  - the lepton is not reconstructed
  - not isolated
  - out of acceptance
- Start with a control sample of events with exactly one muon
- Measure the identification and isolation (in)efficiencies from data
- Scale the control sample according to the measured (in)efficiencies from data



Method	Baseline selection	(stat.)	(syst.)	High-$\not{H}_T$ selection			High-H_T selection		
Estimate from data	33.0	±5.5	$^{+6.0}_{-5.7}$	4.8	±1.8	$^{+0.8}_{-0.6}$	10.9	±3.0	$^{+1.7}_{-1.7}$
Estimate (PYTHIA)	22.9	±1.3	$^{+2.7}_{-2.6}$	3.2	±0.4	$^{+0.5}_{-0.5}$	7.2	±0.7	$^{+1.1}_{-1.1}$
MC Truth (PYTHIA)	23.6	±1.0		3.6	±0.3		7.8	±0.5	
Estimate (MADGRAPH)	20.4	±1.5	$^{+2.6}_{-2.5}$	2.4	±0.3	$^{+0.3}_{-0.3}$	4.8	±0.4	$^{+0.6}_{-0.5}$
MC Truth (MADGRAPH)	21.4	±0.7		3.0	±0.3		5.9	±0.4	

Top / W + hadronic tau + ν + Jets

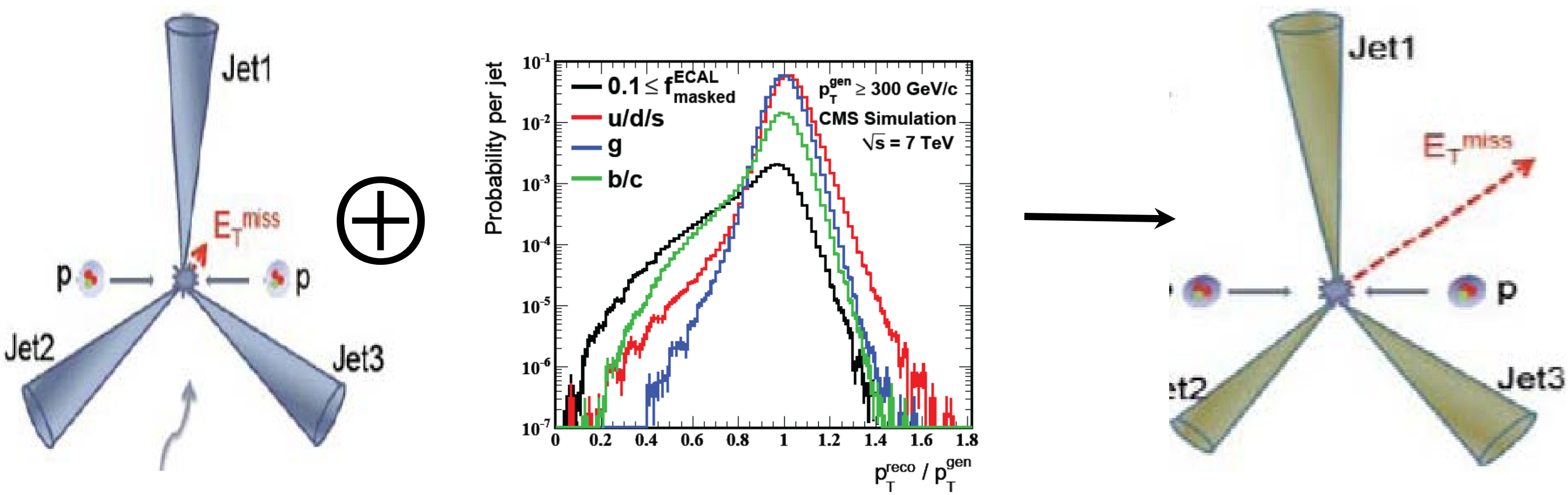
- Start with a muon+jets sample
- Replace the muon by tau response template derived from MC
- Recalculate HT and MHT including this expected energy from Tau
- Correct for
  - muon acceptance
  - Trigger efficiency, Reco efficiency
  - BR(W →Tau)/BR(W →mu) * BR(Tau->Hadrons)



	Predicted $W/t\bar{t} \to \tau_{hadr}$
Baseline selection	22.3 ±4.0 (stat.) ±2.2 (syst.)
High-$\not{H}_T$ selection	6.7 ±2.1 (stat.) ±0.5 (syst.)
High-H_T selection	8.5 ±2.5 (stat.) ±0.7 (syst.)

QCD Rebalance + Smear

- Jet Response functions can be used to smear a sample of perfectly balanced events and get back the QCD sample as measured in Data.



- Requirement : Full jet response (including tails) measured from data to rebalance and resmear the multijet events.
- Resolution is measured using Gamma+Jets events (low pT) and DiJet events (high pT)

QCD: Rebalance + Smear

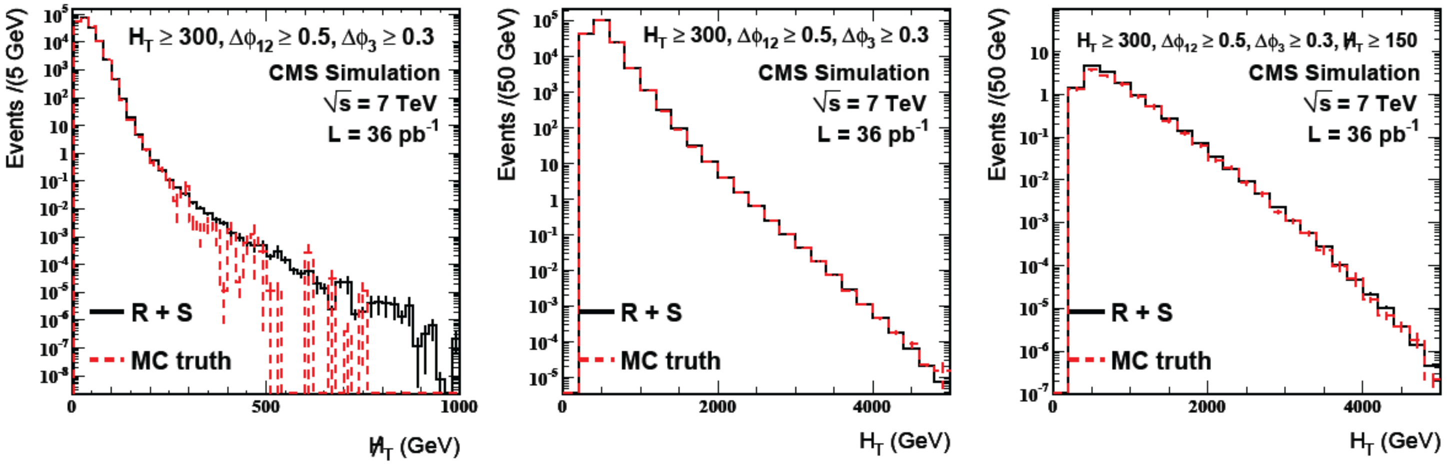
- Step 1 : Rebalance the data events (jets with Pt>10 GeV) using jet Pt resolutions by maximizing likelihood, L_{Jets} subject to constraint MHT=0

  ===> create the pseudo-particle-level QCD events

$$L_{jets}(p_{T,1}^{true}, \ldots, p_{T,n}^{true}) = \prod_{i=1}^{n} r(p_{T,i}^{reco} | p_{T,i}^{true})$$

- Step 2 : Smear rebalanced jets with Pt>10 GeV with resolution functions

  R+S predicts full event kinematics (jet Pt and angular distributions)



- Contamination by SM & Signal processes with real MHT is negligible as such events are made “QCD like” by rebalancing

Results

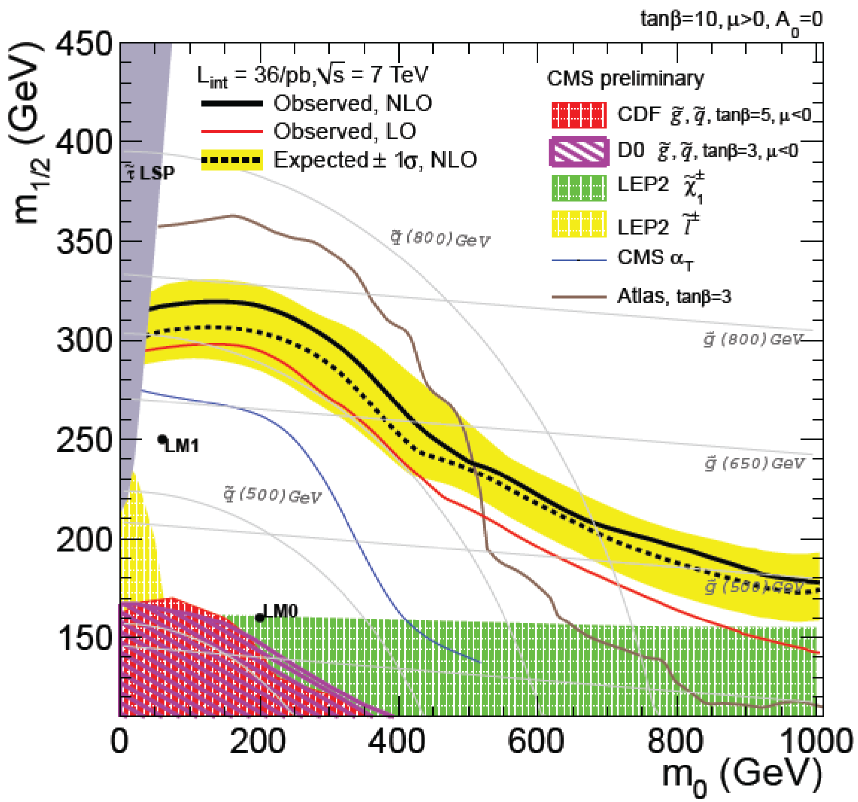
Method	Baseline selection		High-$\not{H}_T$ selection		High-H_T selection	
$Z \rightarrow \nu\bar{\nu}$ from γ+jets	26.3	± 4.8	7.1	± 2.2	8.4	± 2.3
$t\bar{t}/W \rightarrow e, \mu$+X lost-lepton method	33.0	± 8.1	4.8	± 1.9	10.9	± 3.4
$t\bar{t}/W \rightarrow \tau_{hadr}$+X method	22.3	± 4.6	6.7	± 2.1	8.5	± 2.5
QCD Rebalance+Smear method	29.7	± 15.2	0.16	± 0.10	16.0	± 7.9
QCD factorization method	25.2	± 13.4	0.4	± 0.3	17.3	± 9.4
Total data-driven background	111.3	± 18.5	18.8	± 3.5	43.8	± 9.2
Observed in 36 pb^{-1} of data	111		15		40	
95% C.L. limit on signal events	40.4		9.6		19.6	

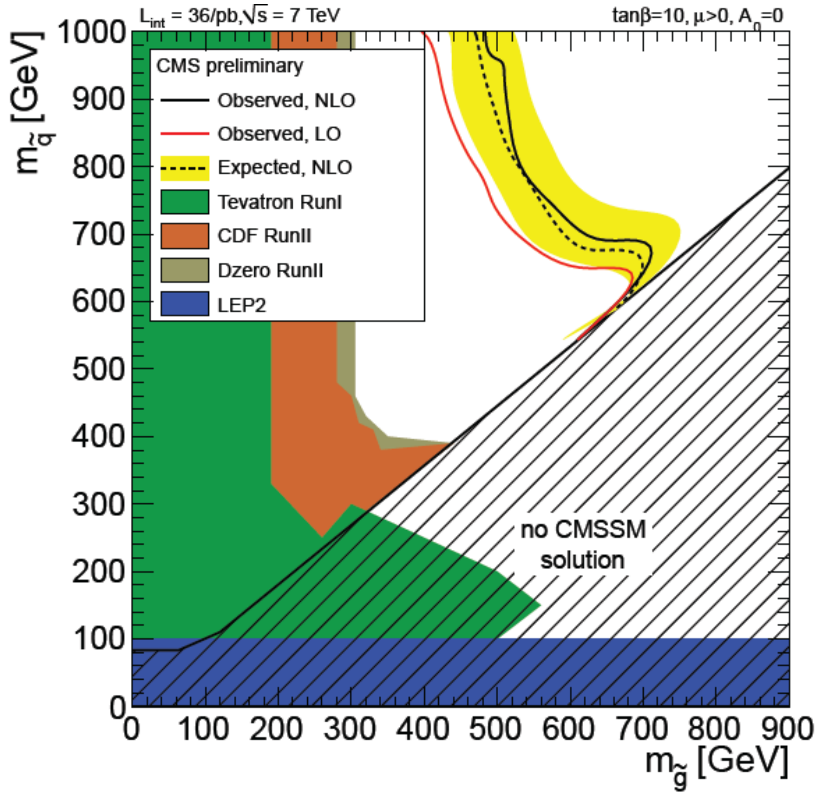
No excess of data events over expected Standard Model prediction observed ☹ Setting limits.

Hadronic Search in Jets + MHT

	Expected	Observed
MHT>250 GeV	18.8 ± 3.5	15

	Expected	Observed
HT>500 GeV	43.8 ± 9.2	40





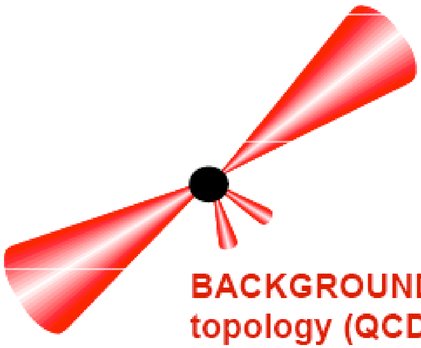
- Results expressed in terms of 95% CL in CMSSM
- Extend limit from Tevatron searches

CMS-PAS-SUS-10-005

SUSY search using kinematic variable α_T

α(Randal-Tucker-Smith) arXiv:0806.1049

$$\alpha = E_T^{j2} / M_{inv}^{j1,j2} \qquad \alpha = \frac{E_T^{j2}}{\sqrt{2E^{j1}E^{j2}(1-\cos\Theta)}}$$

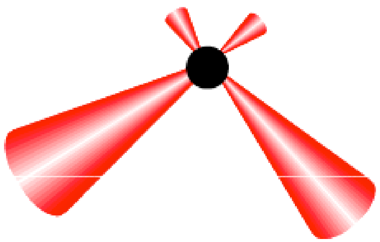


Transverse α_T

$$\alpha_T = E_T^{j2} / M_{inv\,T}^{j1,j2} \qquad \alpha_T = \frac{E_T^{j2}}{\sqrt{2E_T^{j1}E_T^{j2}(1-\cos\Delta\phi)}}$$

QCD : back to back jets i.e. $\cos\Delta\varphi < 1$ ➔ $\alpha(\alpha_T) \leq 0.5$.

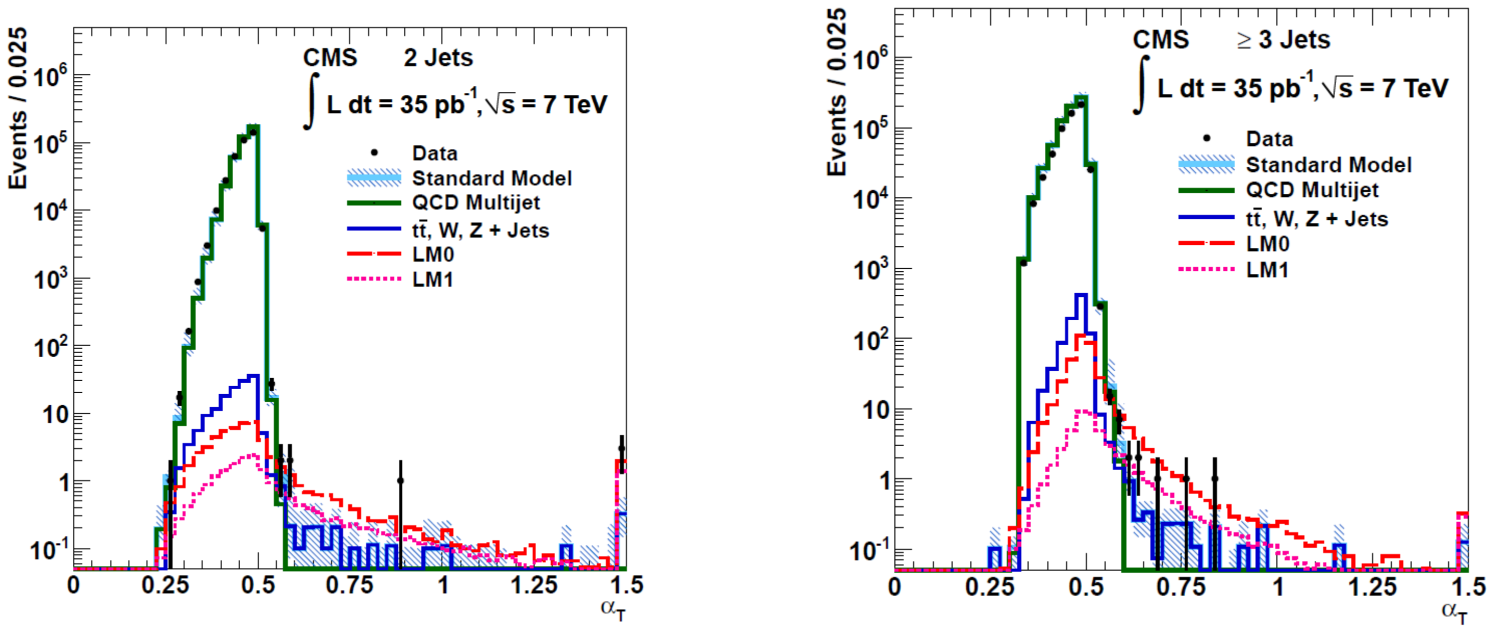
SUSY: α (α_T) can be > 0.5.



Generalized to multijet events by reconstructing psuedo jets J1 and J2 from primary jets from clustering algorithm

$$\text{N-Jet system: } \alpha_T = \frac{1}{2}\frac{H_T - \Delta H_T}{M_T}, \quad \Delta H_T = E_T(PJ_1) - E_T(PJ_2)$$

α_T Search

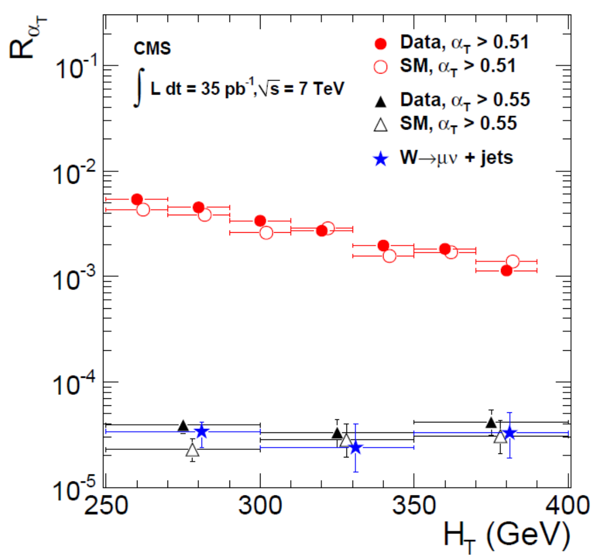


•Event Selection:

- At least twoAK5 calorimeter jets p_T>50 GeV and |η|<3.0
- Two leading jets with p_T> 100 GeV, leading jet |η| <2.5
- Veto on isolated leptons and photons
- H_T > 350 GeV   13 events

Data-driven Background Estimate

Inclusive background estimate



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

- θ =0.51 QCD dominated, ratio falls with HT
- θ =0.55 EW dominated, ratio flat with HT

➔ α_T >0.55 almost free of QCD

Assume

$$R_R = \frac{R_{\alpha_T}(H_T > 350)}{R_{\alpha_T}(H_T > 300)} = \frac{R_{\alpha_T}(H_T > 300)}{R_{\alpha_T}(H_T > 250)}$$

$N(H_T 350)$ = $9.4^{+4.8}_{-4.0}$ (stat) ± 1.0 (syst)

Impendent EWK background estimations

$N(W + \text{jets}, t\bar{t}) = 6.1^{2.8}_{-1.9}(\text{stat}) \pm 1.8(\text{syst})$ from $W(\mu\nu)$ + jets

$N(Z(\nu\nu) + \text{jets}) = 4.4^{+2.3}_{-1.6}(\text{stat}) \pm 1.8(\text{syst})$ from γ + jets (see later)

Total: $10.5^{+3.6}_{-2.5}$ in agreement with inclusive prediction $9.4^{+4.8}_{-4.0}(\text{stat}) \pm 1.0(\text{syst})$

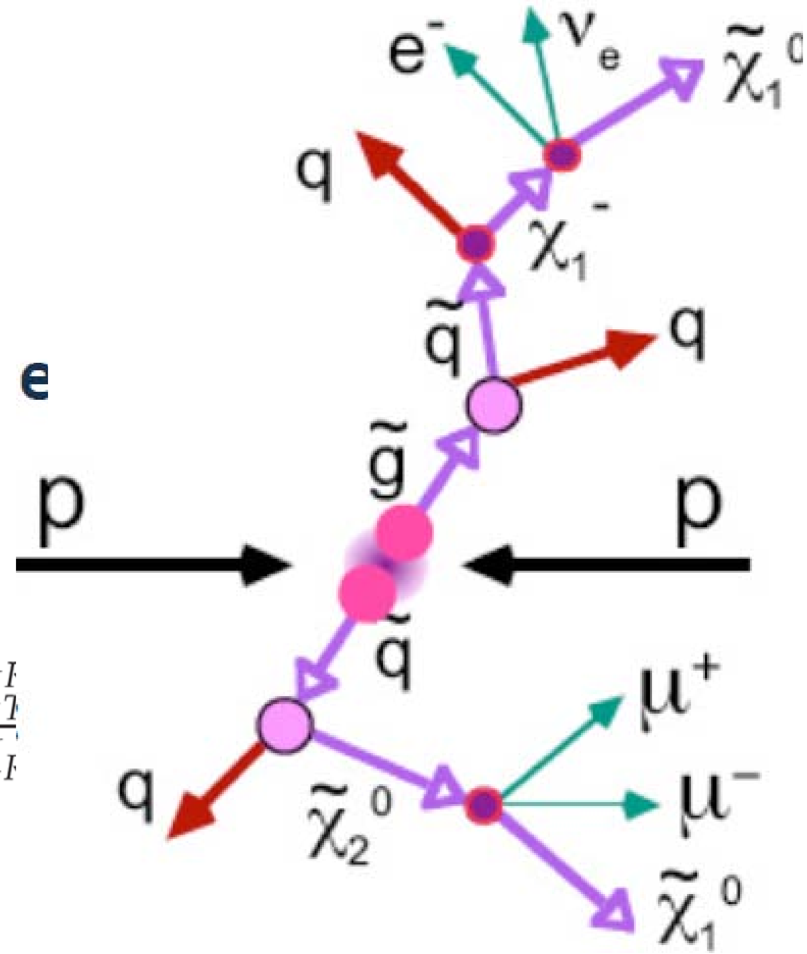
Further x-checks: $W(\mu\nu)$ from γ and $Z(\nu\nu)$ from $W(\mu\nu)$ all within agreement

RAZOR

- Assume heavy particle pair produce and decay in LSP+X
- Define two variables related to the mass scale

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

- M_R is estimator of M_Δ , peaks at mass scale.
- $M^R{}_T$ transverse mass with endpoint at M_Δ
- Use dimensionless ratio $R \equiv \frac{M_T^R}{M_R}$
- Reduce event into two mega jets by clustering the visible decay products
- In terms of mega jets, event resembles $\mathrm{pp} \rightarrow \tilde{\mathrm{q}}\tilde{\mathrm{q}} \rightarrow \mathrm{j}_1\,\mathrm{j}_2\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$



R and M_R distributions for different events

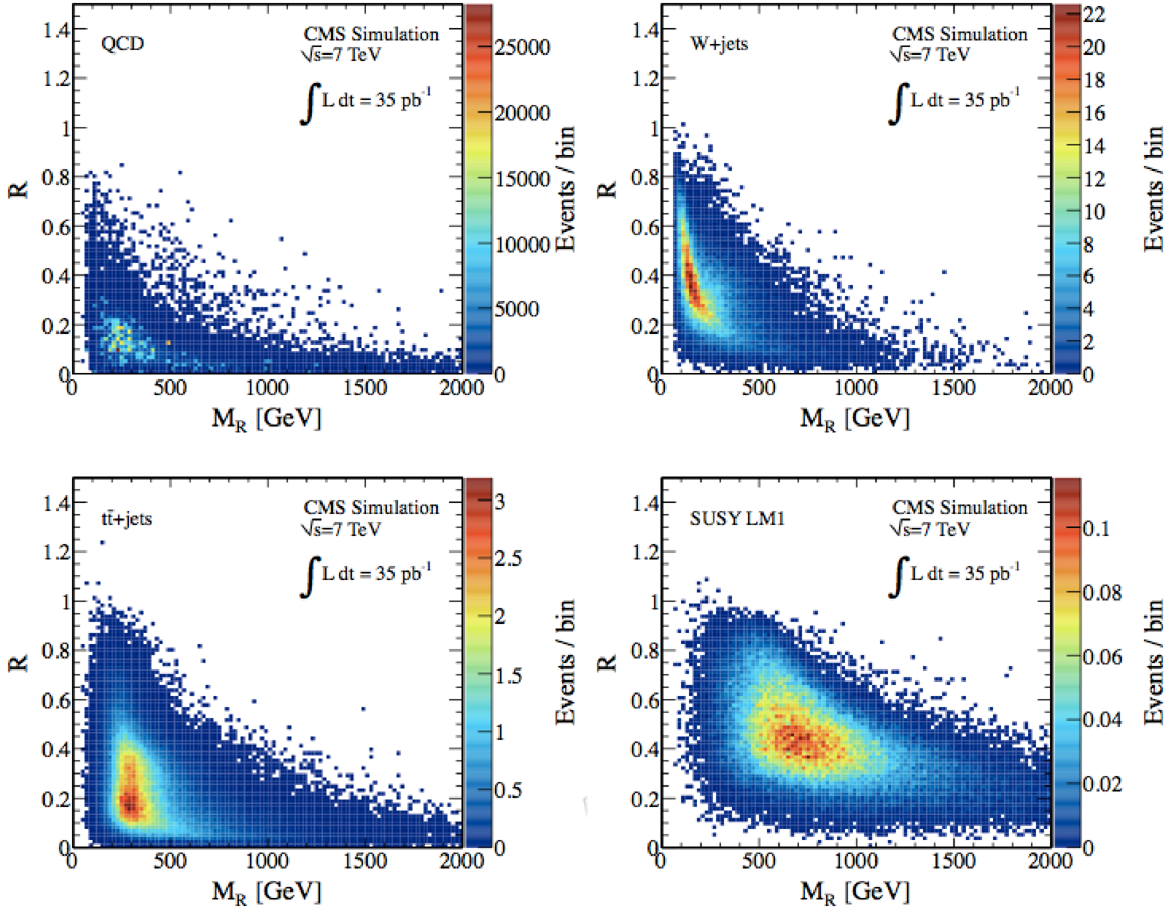


Figure 1: The razor plane: M_R versus R yields for 10 pb^{-1} Monte Carlo simulated samples: QCD multijets (top left), W+jets (top right), t+X (bottom left) and a CMS SUSY benchmark model (LM1 [8]) with $M_\Delta = 597$ GeV.

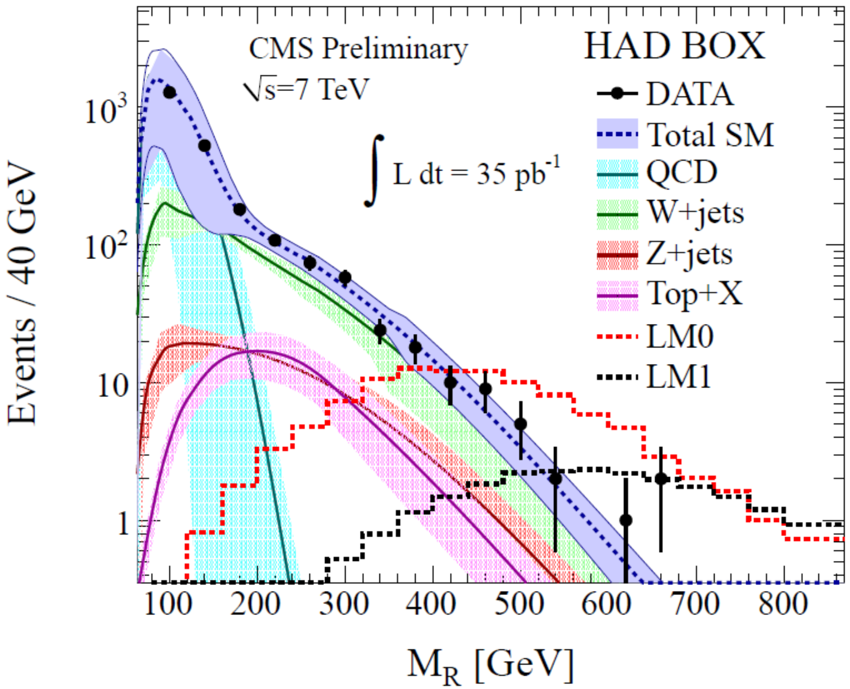
Hadronic RAZOR Search

Basic Selection:

- At least two jets PtJet>30 GeV, |η|< 3.0
- Classify events as hadron, muon and electron boxes.
- Decompose event in two hemispheres.
- Cluster particles in each hemisphere into a mega-jet
- Require $\Delta\varphi$ (mega-jets) < 2.8

Background:

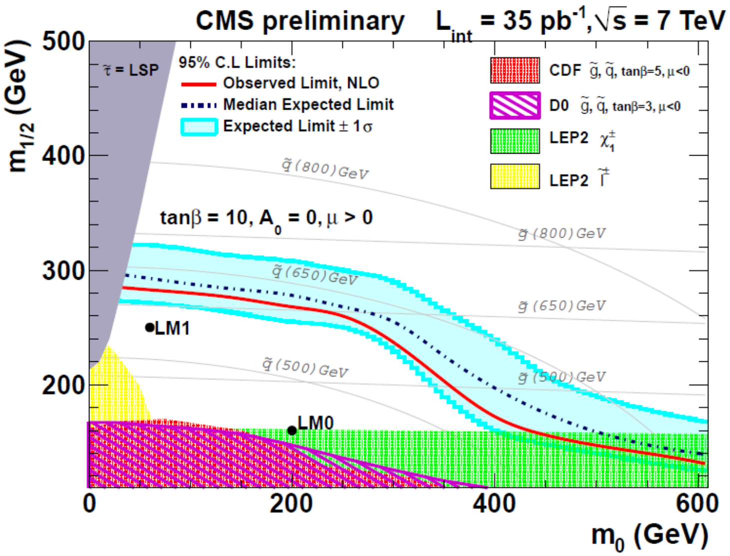
- Shapes from lepton boxes
- QCD shape from low threshold dijet data
- $Z(\nu\nu)$ Shapes from 2^{nd} component of W
- $Z(ll)$ Efficiencies from data
- Fit in $80 < M_R < 400$ GeV region
- Normalization from lepton boxes
- Extrapolate to high M_R region

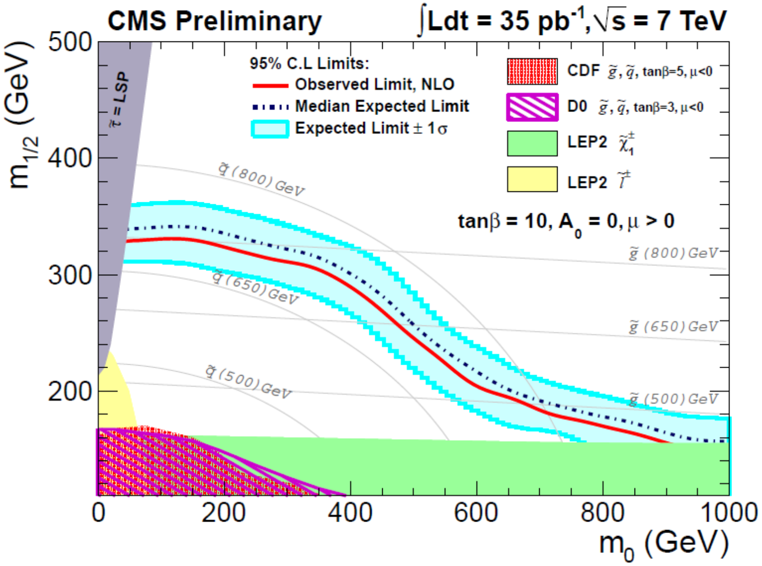


$R > 0.5$ and $M_R > 500$ GeV

M_R cut	Predicted	Observed
$M_R > 500$ GeV	5.5 ± 1.4	7

α_T and RAZOR results





- Kinematic variable α_T
  - Optimized for fast discovery

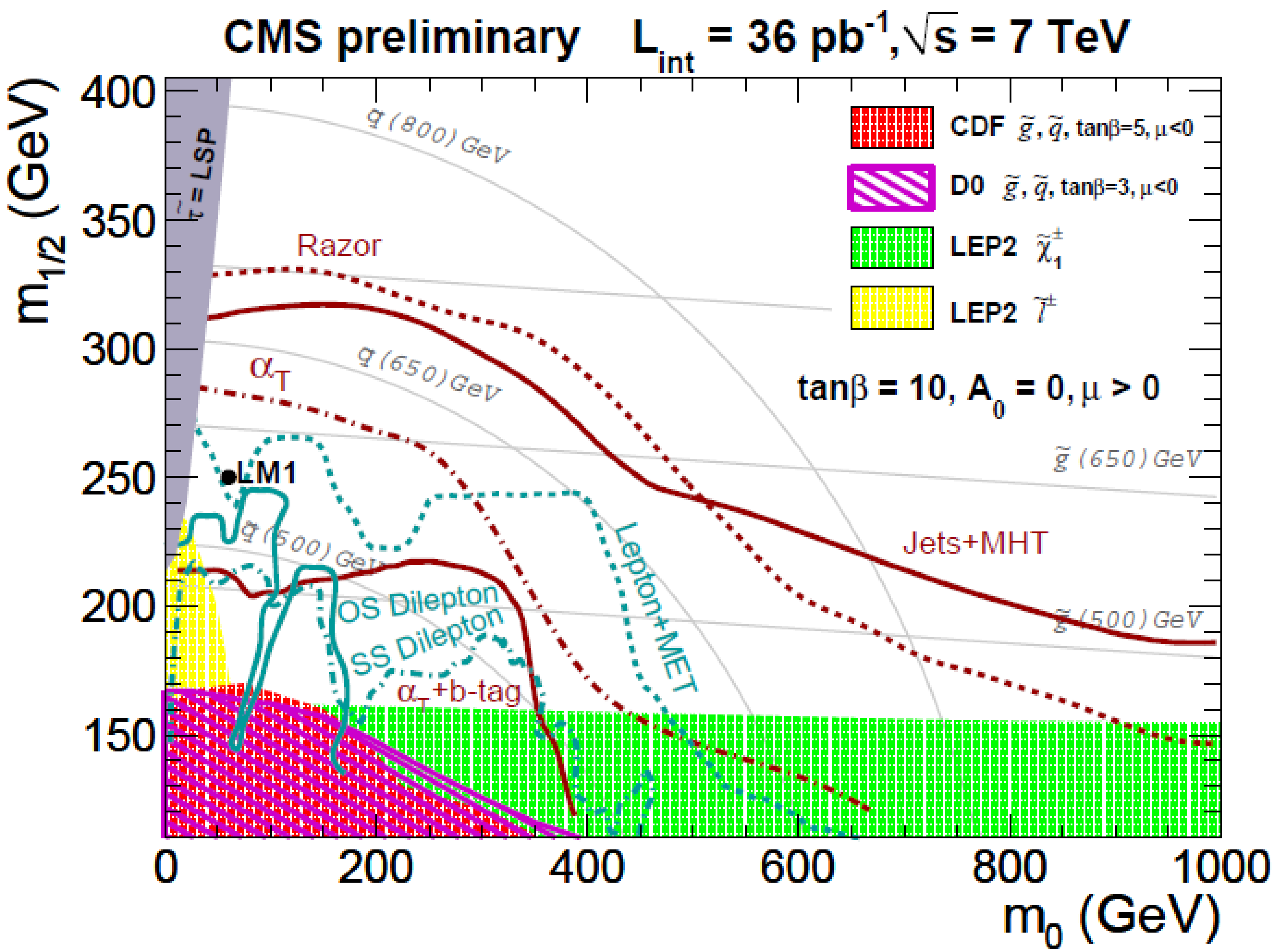
$$\alpha_T = \frac{E_{T,j2}}{M_{T,j12}} = \frac{\sqrt{E_{T,j2}/E_{T,j1}}}{\sqrt{2(1-\cos\Delta\phi)}}$$

- ``Razor'' variables: M_R & R
  - Designed to characterize pair-production of heavy particles
  - Combine all particles into two hemispheres, boost back to rest frame

These kinematics-based searches are complementary in approach to the jets + MHT search which is based on understanding the detector in detail.

arXiv:1101.1628, CMS-PAS-SUS-10-003 & 11-001 CMS-PAS-SUS-10-009

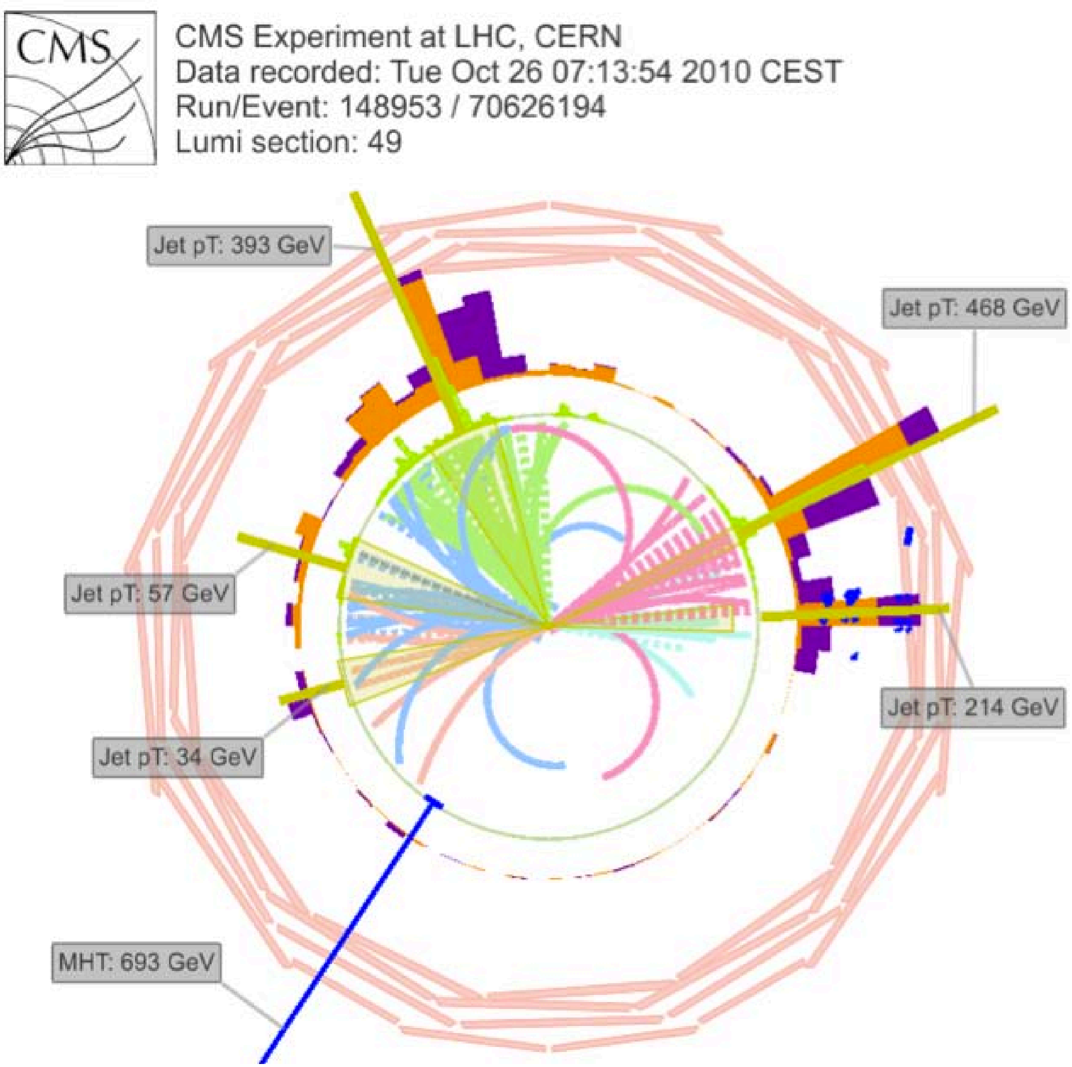
Comparison of different techniques



Summary

- CMS has performed hadromic SUSY search using three different methods using 2010 data.
- SM backgrounds are directly measured from the data using minimal information from the Monte Carlo event generators.
- No excess of events over the SM expectation is observed.
- These data are used to further constraint the susy parameter space.
- Ready and looking forward to discovering new physics in 2011.

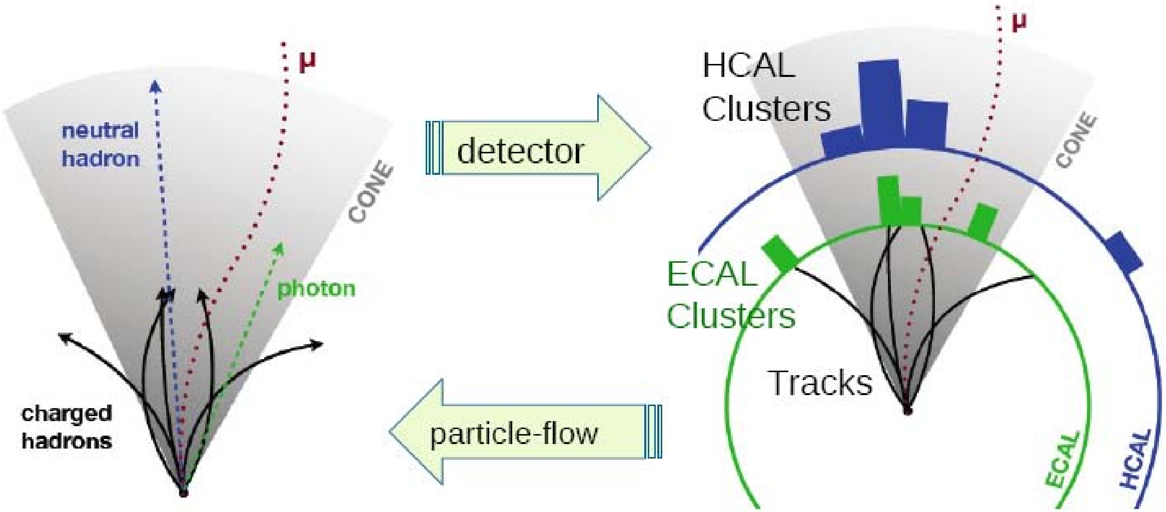
An interesting event



- MHT = 693 GeV
- HT = 1132 GeV
- M_{eff} = MHT+HT = 1.83 TeV
- No b-tagged jet
- No isolated lepton
- Incompatible with W or top mass
- Invisible Z???

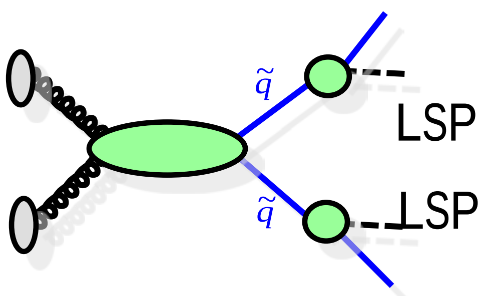
Particle Flow (PF) Algorithm

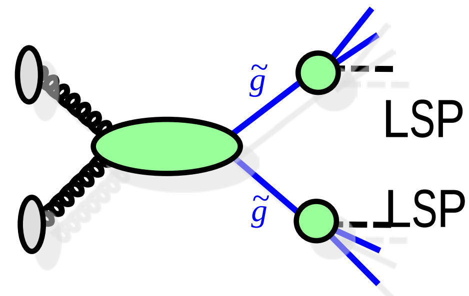
- In this search, all physics objects (jets, leptons, HT, MHT etc) are reconstructed with the particle flow algorithm
- Basic idea:
  - Reconstruct and identify all different types of particles
  - Apply corresponding calibrations
  - The list of “particles” is given to the jet clustering and missing ET (MET) reconstruction algorithm

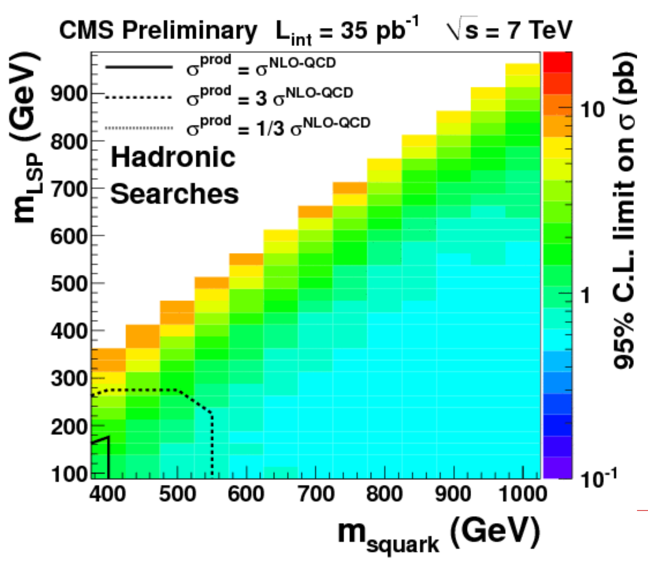


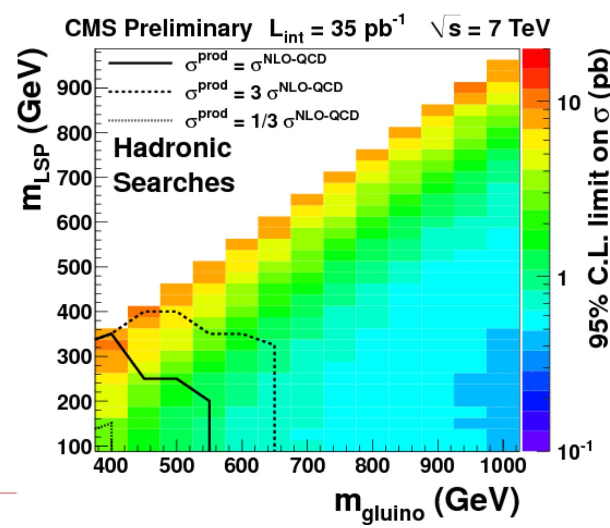
Simplified Model

- Focus on topology instead of underlying physics model
- Any model with same topology (parent particle mass, decay chain, daughters mass) can be "easily" compared with experimental results.





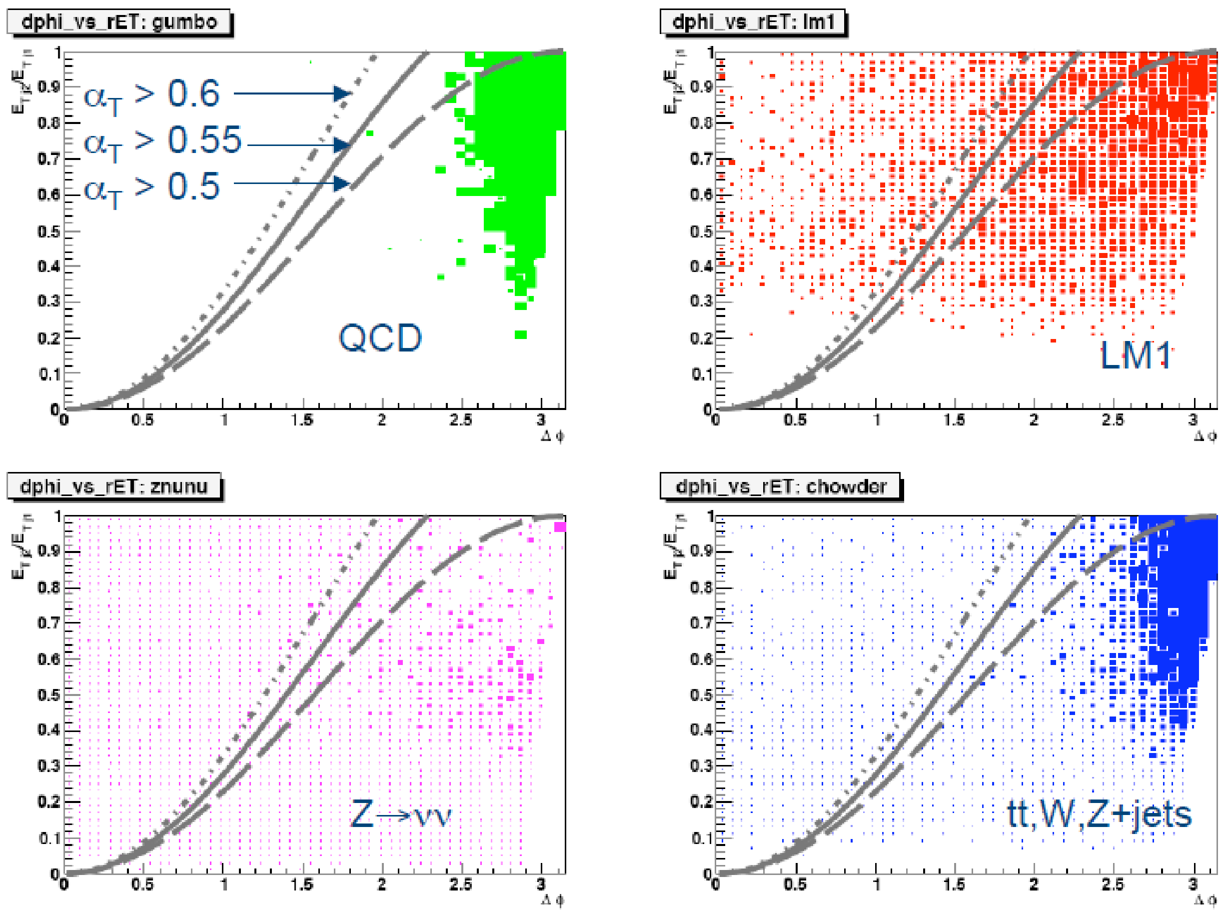




Combined results for:

- α_T
- jets + MHT
- Razor

Relation of α_T to E_{Tj2}/E_{Tj1} and $\Delta\varphi$



Data-Driven Background Estimates

Invisible Z ($\rightarrow \nu\,\nu$) + Jets

- Remove the identified boson (photon/W/Z) to mimic neutrino
- Photon+Jets : high event yield (use photon/Z correction from theory)
- Z $\rightarrow$l l + Jets (straightforward prediction but limited by statistics)

Top / W + Jets

- Top/W ($\rightarrow$ lost lepton + ν) + Jets :
  - Lepton is not identified or is outside detector acceptance. Estimated from W$\rightarrow\mu\nu$ sample.
- Top/W ($\rightarrow$ hadronic τ + ν)+ Jets :
  - Estimated by replacing μ in W$\rightarrow$ $\mu\nu$ events with τ using a τ response template

QCD MultiJets (jet mis-measurements resulting in imbalance)

- R+S : rebalance event and smear 'rebalanced' sample with jet resolutions
- Factorization : extrapolate two-variable correlation to signal region