Searches with Missing E_T at the LHC

Meenakshi Narain
Brown University
April 1st, 2009

EFTI Missing Energy Signals
at LHC Workshop
UC Davis

Acknowledgements, and References

- Work presented here is derived/taken from
  - ATLAS, CMS TDRs, analysis & conference notes and presentations
- Thanks!

- ATLAS Physics TDR: CERN/LHCC 1999-14/15
- CSC book: Expected Performance of the ATLAS Experiment Detector, Trigger and Physics CERN-OPEN-2008-020, Geneva, 2008

- CMS PTDR II CERN/LHCC 2006-021
- Data driven estimation of invisible Z background in the SUSY MET plus jets search CMS PAS SUS-08-002
- SUSY searches with di-jet events CMS PAS SUS-08-005
- CMS search plans and sensitivity to new physics using dijets CMS PAS SBM-07-001

- http://arxiv.org/abs/0805.2398 Hubisz et al

Models with Missing Energy Signatures

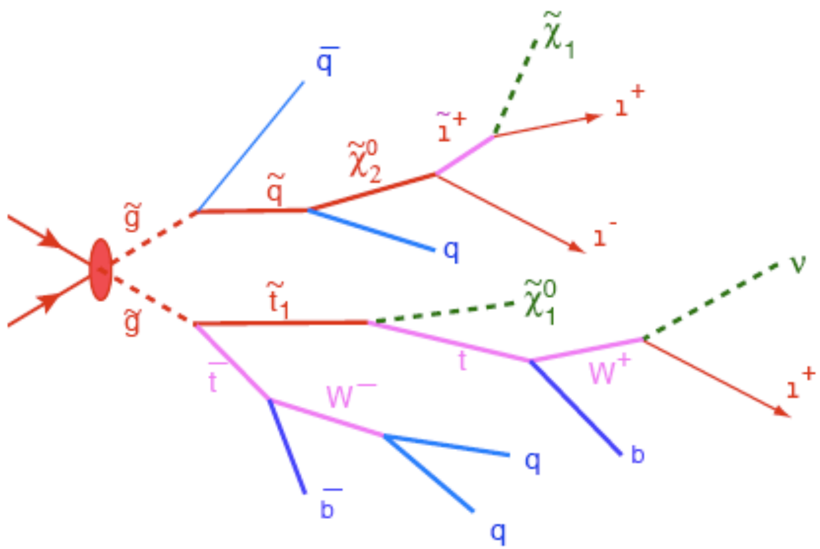
- Many New Physics Models provide signatures with Missing Energy in the final state
  - R-parity conserving Supersymmetry
    - minimal super gravity mSugra (neutralino)
    - Gauge mediated SUSY (gravitino)
  - Universal Extra Dimensions
  - Warped Extra Dimensions
  - Little Higgs Models
  - Technicolor Models
  - plus more…. (and probably more can be made available…)
- Production of WIMP’s in cascade decays of heavy new particles
  - WIMP’s escape the detector and remain undetected
  - Leads to a missing energy signature

Sources

- E_{Tmiss} from neutrinos: from the direct decay of new heavy particles to neutrinos, or decays of new heavy particles to top, W's, Z's, or γ's.
  - look for anomalies in the energetic tails of data sets with reconstructed top, W's or Z's.
- E_{Tmiss} originates from a single weakly interacting exotic particle in the final state.
  - graviton production in models with large extra dimensions leading to monojets+large E_{tmiss} in case of strong production.
- E_{Tmiss} originates from many weakly interacting exotic particles in the final state.
  - Hidden valley models (light pions of the hidden sector)

Missing ET signatures:
An Example from SUSY

- E_{Tmiss} originates from two weakly interacting exotic particles in the final state
  - SUSY with R-parity conserved
  - e.g. gluino pair-production
- lots of missing energy, many jets, and possibly leptons in the final state



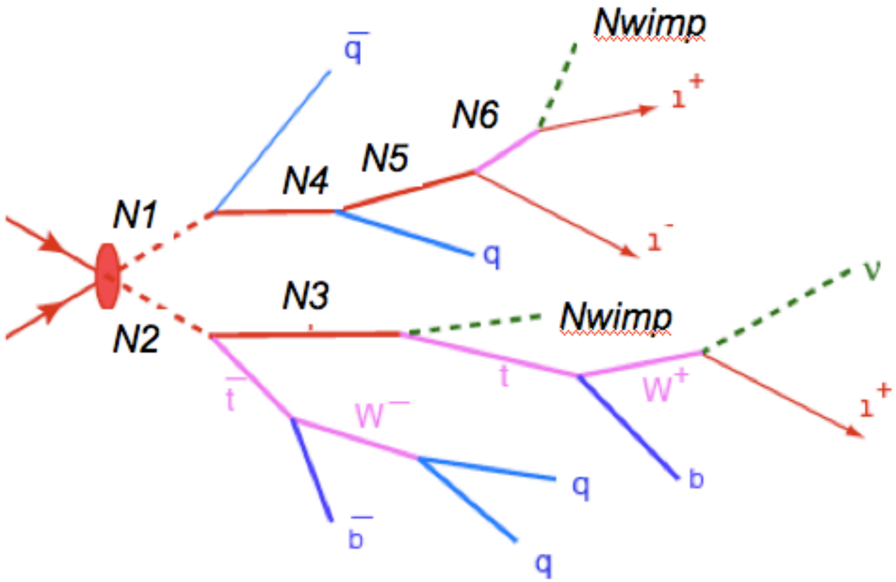
Missing Energy:
- from LSP

Multi-Jet:
- from cascade decay (gaugino)

Multi-Leptons:
- from decay of charginos and neutralinos

Missing E_T signatures: ...in more general scenario

- pair production of new heavy particles



Missing Energy:
- Nwimp - end of the cascade

Multi-Jet:
- from decay of the Ns (possibly via heavy SM particles like top, W/Z)

Multi-Leptons:
- from decay of the N's

Model examples are Extra dimensions, Little Higgs, Technicolour, etc

Searches using Missing Energy

- Most of the signatures which have missing energy in the final state have been studied in the context of SUSY searches.
- However, the procedures for determination of SM backgrounds for these searches are applicable to other similar searches as well.

- Before claiming SUSY/other discovery need to understand SM at LHC with high precision
- If excess beyond SM is observed, then still much work needed to determine underlying model (SUSY or others)

- Typical analysis based on final state lepton and jet multiplicity
  - More leptons →less signal but better S/B

Signatures:

- Analyses designed by number of leptons and or jets in the final state. In the table ✓ means covered by CMS/ATLAS

	1 jet	2 jet	3 jets	4 jets
0 lepton		✓	✓	✓
1 lepton		✓	✓	✓
2 lepton SS / OS		✓	✓	✓
3 leptons	✓			
taus		✓	✓	✓
b's		✓	✓	✓

- Dominant backgrounds are
  - W+jets, top pair production, Z →$\nu\nu$+jets, Z→ll+jets, QCD multijet

Definition of some Observables

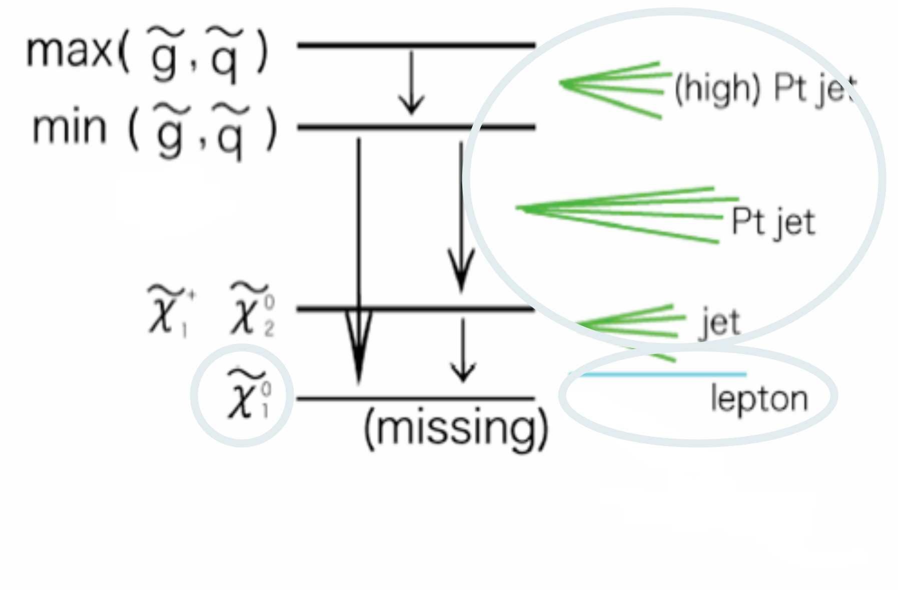
- ATLAS:
  - $$M_{eff} = \sum_{i=1}^{N} p_T^{jet,i} + \sum_{i=1}^{N} p_T^{lep,i} + \not{E}_T$$

    4 highest p_T jets in $|\eta| < 2.5$
  - $$S_T = \frac{2\lambda_2}{(\lambda_1 + \lambda_2)}$$ with $\lambda_1\ \lambda_2$ eigenvalues of $S_{ij} = \sum_k p_{ki} p^{kj}$

    all jets with $p_T > 20$ GeV and leptons in $|\eta| < 2.5$
  - $$m_{T2}^2 \equiv \min_{\not{q}_T^{(1)} + \not{q}_T^{(2)} = \not{E}_T} \left[\max \left\{ m_T^2(\mathbf{p}_T^\alpha, \not{q}_T^{(1)}; m_\alpha, m_\chi),\ m_T^2(\mathbf{p}_T^\beta, \not{q}_T^{(2)}; m_\beta, m_\chi) \right\} \right]$$
    - C. Lester, D. Summers, Phys. Lett. B463 (1999) 99
    - A. Barr, C. Lester, P. Stephens, J. Phys. G. 29 (2003) 2343
- CMS:
  - $$H_T \equiv E_{T(2)} + E_{T(3)} + E_{T(4)} + E_T^{miss}$$
    - Where 2, 3, 4 index selected jets sorted by p_T

One Lepton + jets + Missing Energy

One lepton mode SUSY:



Dominant backgrounds:

sample	*x-sec (pb)*
top pair	833
W+jets	10 -10000
QCD	10000 -1000000000
Z+jets	10 -1000
SUSY	5 -300

SUSY event selection:

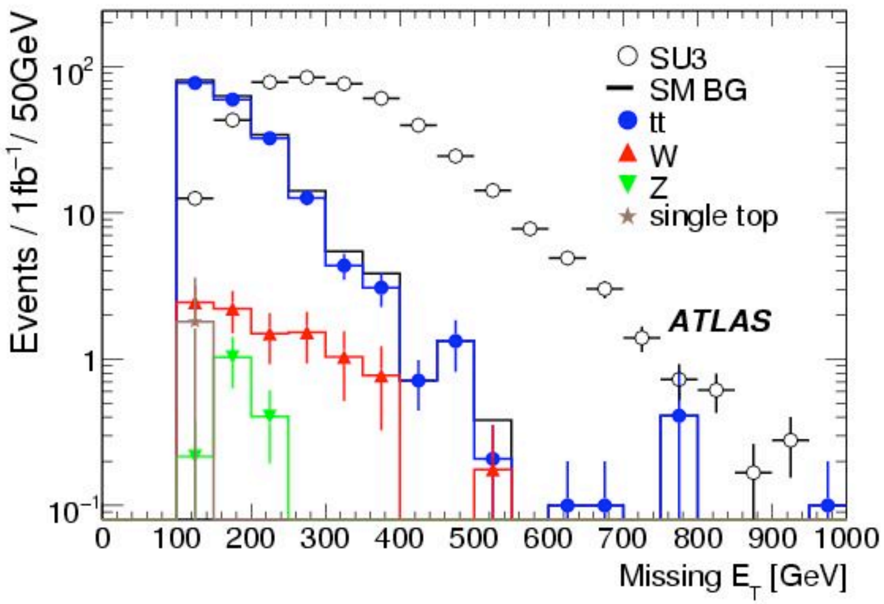
$$1\,jet\,p_T > 100\,GeV$$

$$4\,jets\,p_T > 50\,GeV$$

$$lepton\ p_T > 20\,GeV$$

$$2nd\ lepton\,veto$$

$$\not{E}_T > 100\,GeV$$



Background Estimation

- Problem:
  - no clean SM measurement possible if SUSY exists
  - SM shape at high missing ET unknown & MC possibly unreliable

➔ data-driven estimation

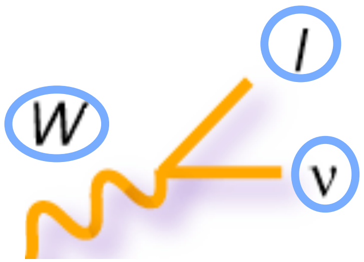
- Control region:
  - dominated by SM + small contamination SUSY
- Signal region:
  - dominated by SUSY + small SM background

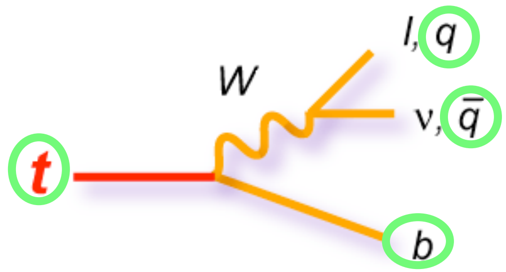
Background Estimation

- Problem:
  - no clean SM measurement possible if SUSY exists
  - SM shape at high missing ET unknown & MC possibly unreliable

➔ data-driven estimation

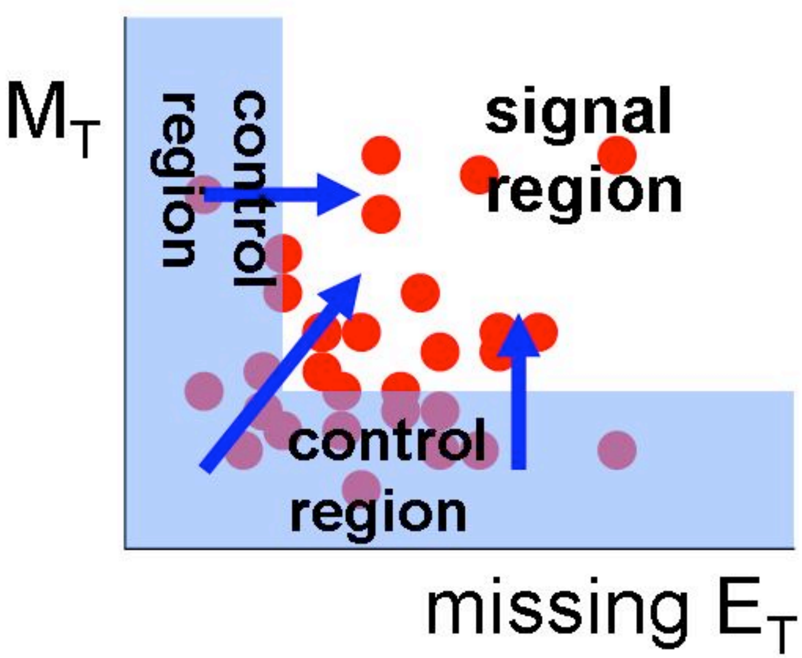
- Observables helpful in removing Wjets, ttbar background
  - M_T = transverse mass mass missing E_T+lepton
  - (needed to distinguish W+jets background)
  - M_{top} = invariant mass of 3 jet system with highest sum p_T
  - (needed to distinguish ttbar background)





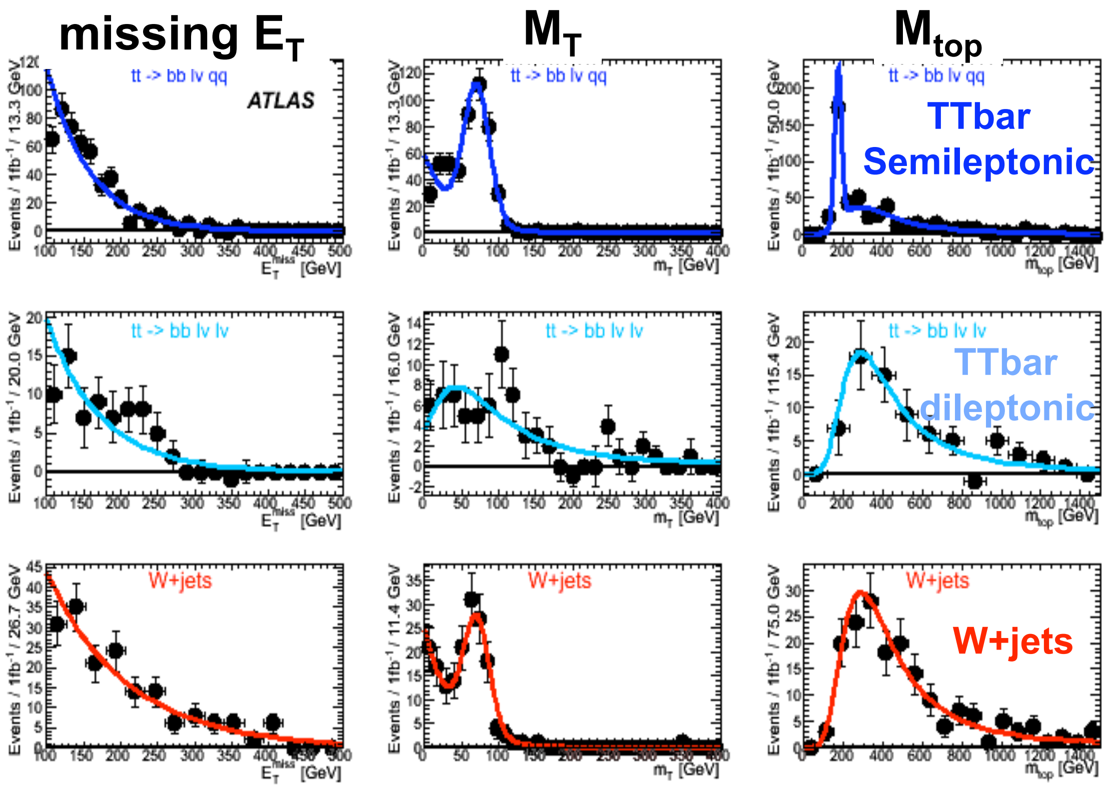
Method 1: W+jets, ttbar backgrounds

- Analyse data in an L-shaped region at both:
  - low missing E_T in full MT-range
  - low M_T in full missing ET-range
  - (both regions practically SUSY-free from kinematic considerations)
- Perform a 2D extrapolation into the SUSY signal region (high missing E_T, M_T)
- Explicitly account for SUSY contamination in control region



Method 1: W+jets, ttbar backgrounds

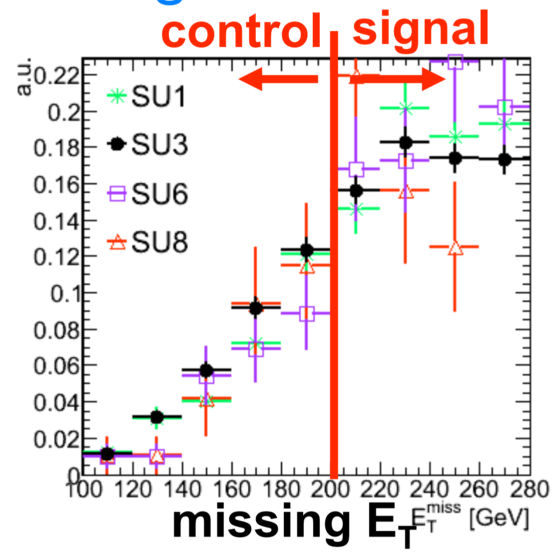
- Combined fit method:
  - Construct a 3D model for each background
  - Build combined model by simple addition
  - Separate three distinct components of background by fitting combined model to data

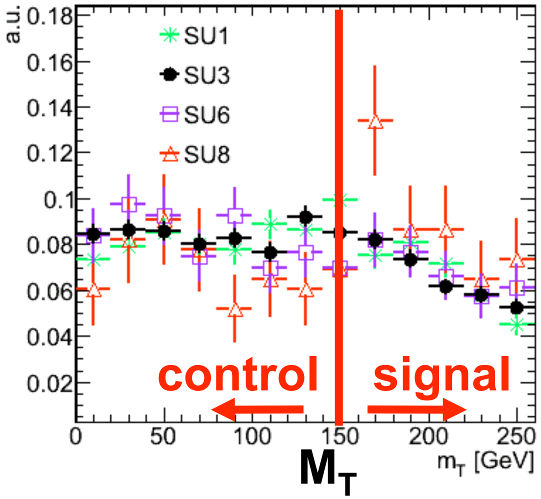


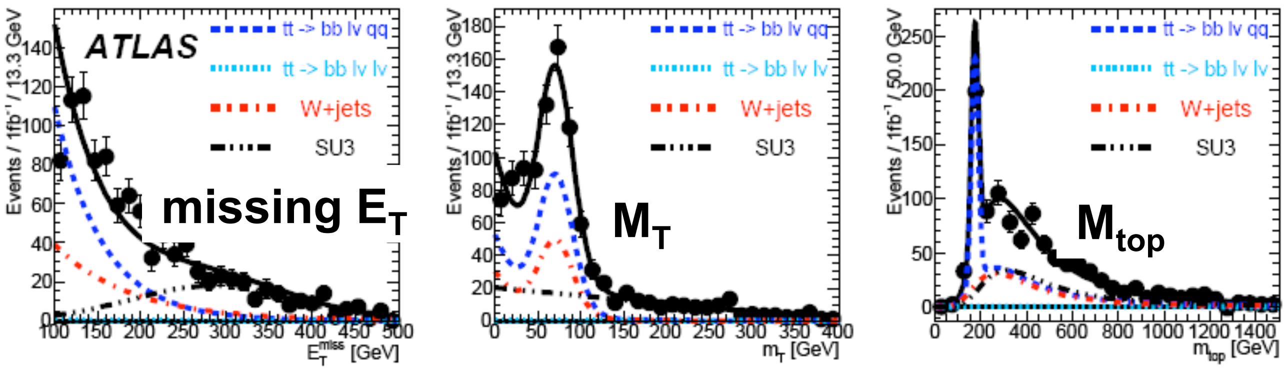
- Empirical models taking physics features into account:
  - 1) Top mass peak
  - 2) Jacobian W-peak in M_T
  - 3) Dileptonic ttbar different from semileptonic

Method 1: accounting for SUSY in bkg

- Different SUSY models look surprisingly similar in control region
- SUSY contamination in control region determined by adding a generic Ansatz shape to the combined fit







- Almost no dependence on simulation as shape parameters are floated as well as yields of backgrounds

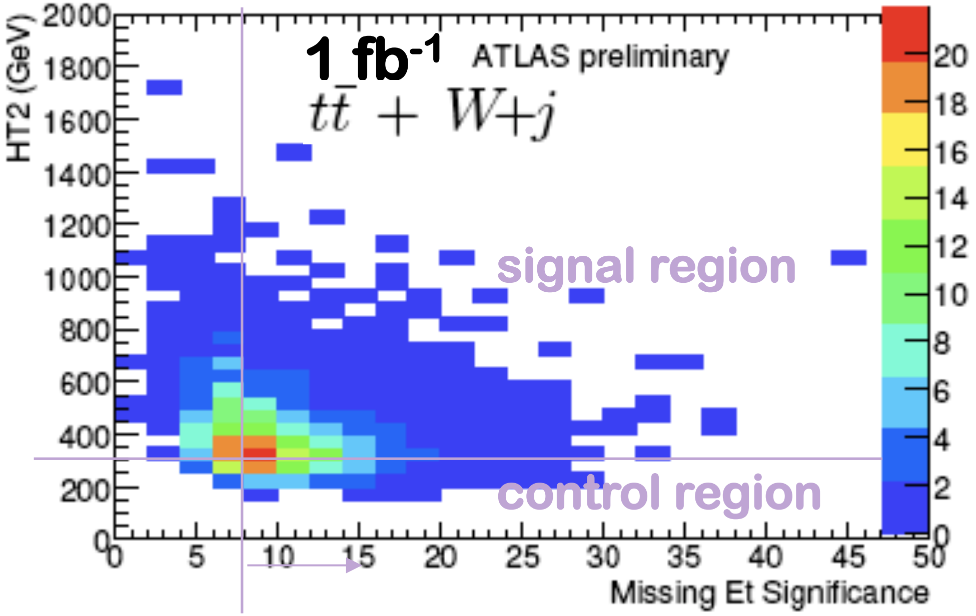
	Extrapolated Yield in SIG	True Yield in SIG
N_{tt1l} =	-1.1 ± 3.9	0
N_{tt2l} =	4.7 ± 7.9	5
N_{wjets} =	-1.2 ± 2.7	2
N_{su3} =	95.6 ± 4.0	91

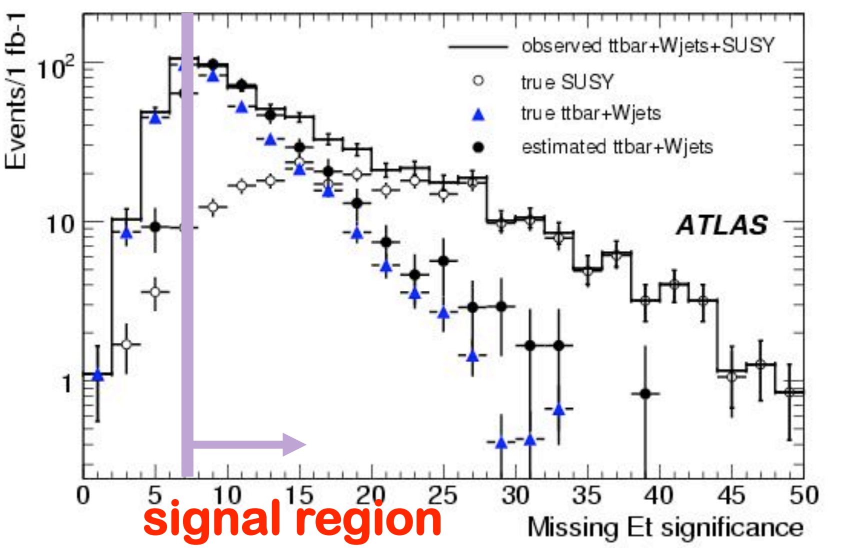
Method 2: HT2 method

- Use HT2 (leading jet excluded) and missing ET significance as nearly independent variables

$$E_T^{miss}\,\text{significance} = E_T^{miss} / [0.49 \cdot \sqrt{\sum E_T}] \qquad \text{HT2} = \sum_{i=2}^{4} p_T^{jet\,i} + p_T^{lepton}$$

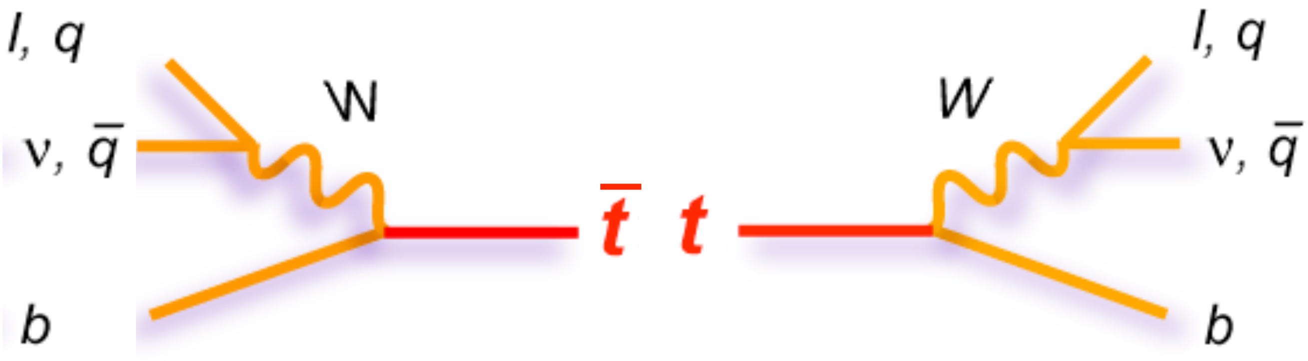
  - Define signal region as HT2 >300 GeV (control region HT2 < 300 GeV)
  - Shape of missing ET significance is taken from control region
- This distribution is normalized to the number of events in signal region
- Subtract background estimation from measured distribution of missing ET significance





Removing Dileptonic top background

- With an additional cut on M_T>100 GeV dileptonic ttbar left as the main background component
  - How dileptonic ttbar passes veto on 2nd lepton:
    - 1 lepton is tau (51%)
    - 1 lepton misidentified (20%)
    - 1 lepton inside a jet (17%)
    - 1 lepton out of acceptance (9%)
    - both leptons are tau (3%)

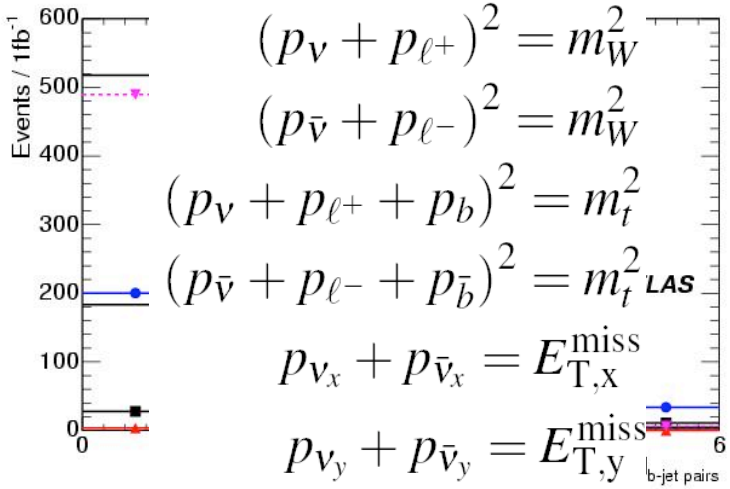


Dileptonic top background: Kinematic reconstruction method

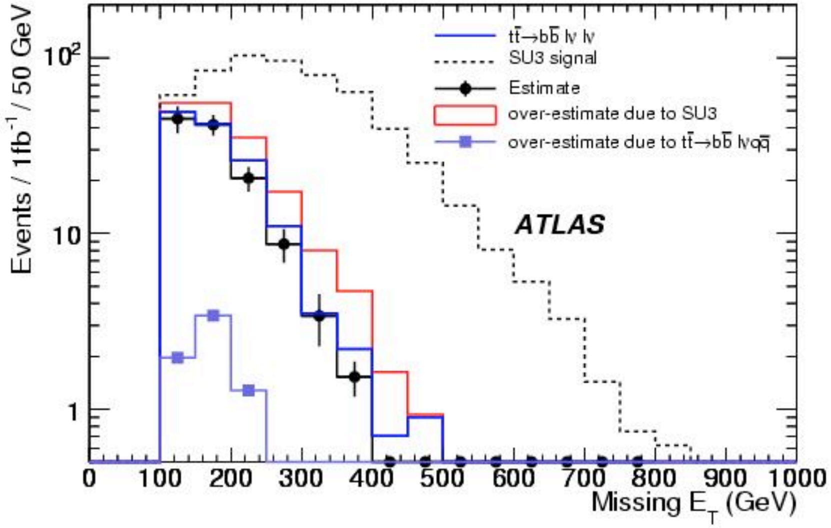
- Define dileptonic top control sample:
  - 2 opposite charge leptons
  - N jets ≥ 3 (p_T >50 GeV)

- Solve system of equations for every combination of jets:
  - If system has a real solution the jet-pair is considered a b-jet pair
  - Selecting N b-jetpair ≥ 1 enhances dileptonic ttbar in background

- Take background events and resimulate:
  - resimulate decay of one lepton as a tau
  - replace 1 lepton by jet (misidentified lepton)
  - estimate background from resimulated events



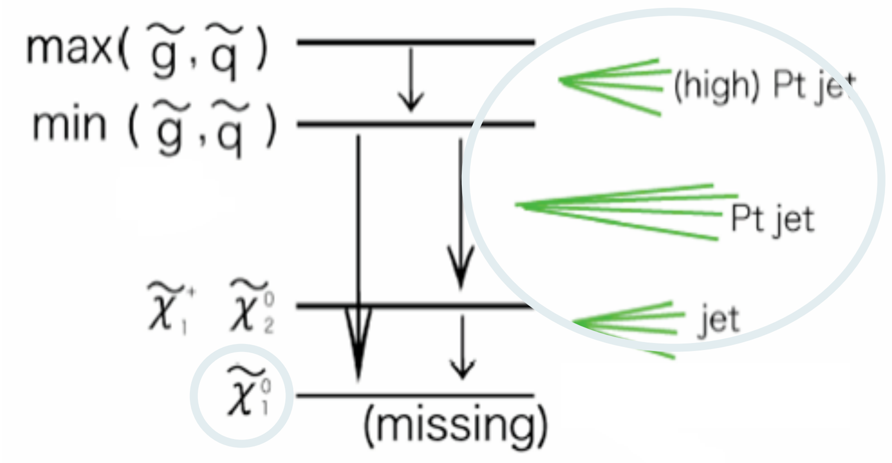
$$(p_\nu + p_{\ell^+})^2 = m_W^2$$
$$(p_{\bar\nu} + p_{\ell^-})^2 = m_W^2$$
$$(p_\nu + p_{\ell^+} + p_b)^2 = m_t^2$$
$$(p_{\bar\nu} + p_{\ell^-} + p_{\bar b})^2 = m_t^2$$
$$p_{\nu_x} + p_{\bar\nu_x} = E_{T,x}^{miss}$$
$$p_{\nu_y} + p_{\bar\nu_y} = E_{T,y}^{miss}$$



Jets + Missing Energy

(no lepton)

Four Jets + Missing Energy



SUSY event selection:

$$1\,jet\,p_T > 100\,GeV$$

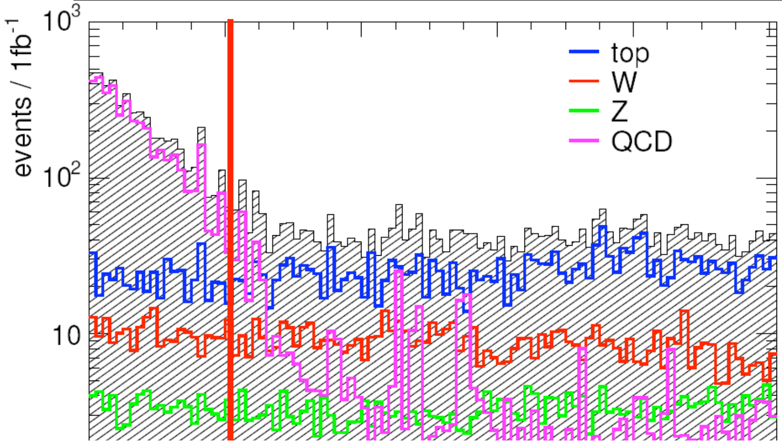
$$4\,jets\,p_T > 50\,GeV$$

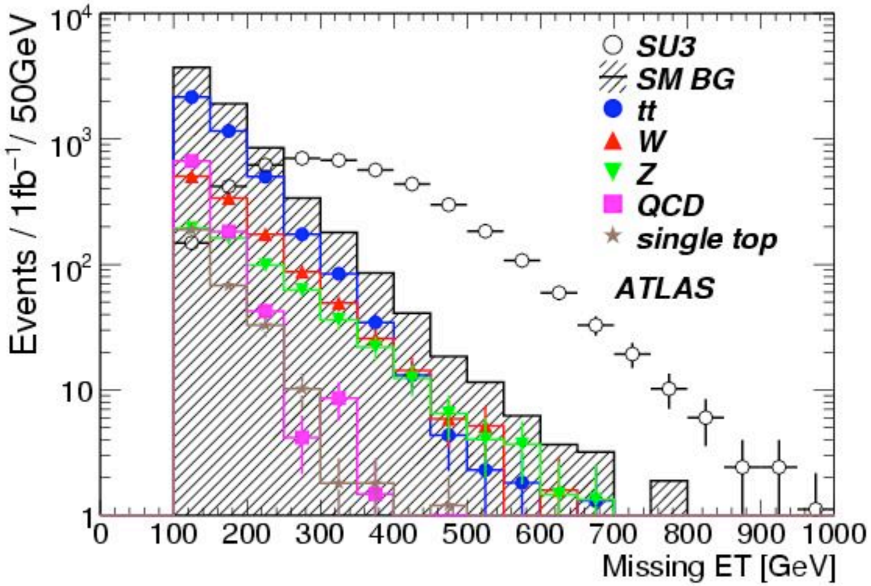
$$\not{E}_T > 100\,GeV$$

$$lepton\,veto$$

$$\Delta\phi(\not{E}_T - jet_i) > 0.2 \quad (i = 1,2,3)$$

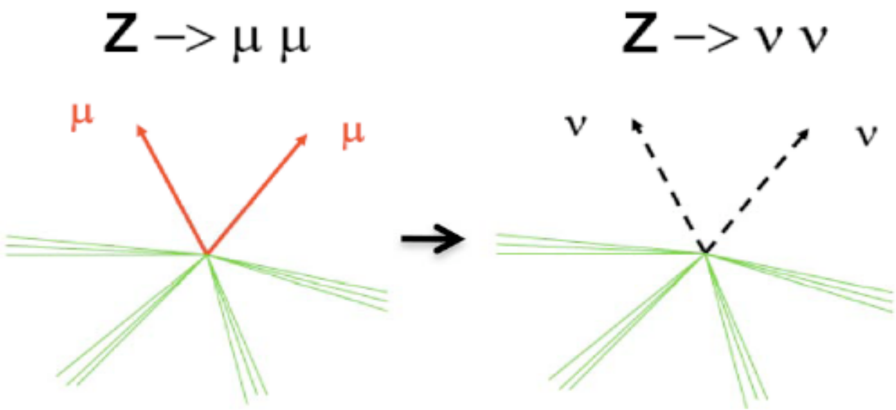
Dominant backgrounds:



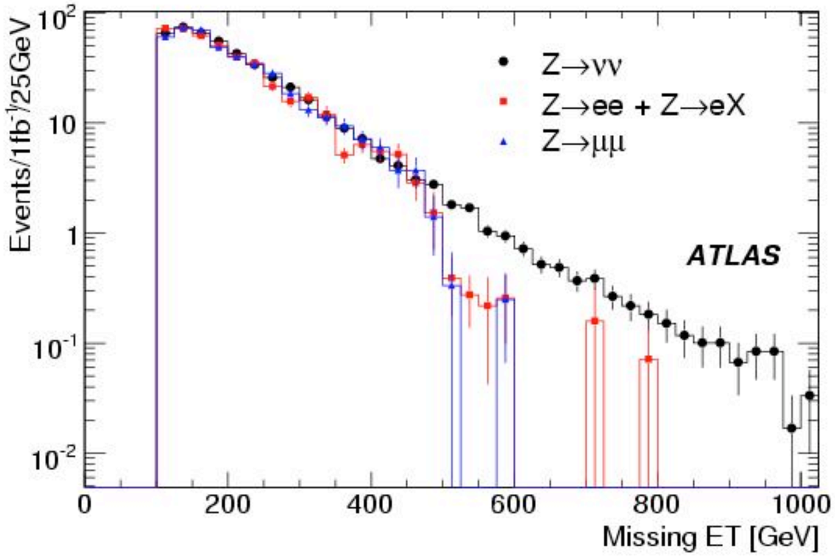


Z+jets background using replace method

- $Z \rightarrow \nu\nu$ and associated jets is one of the main backgrounds
- Use $Z \rightarrow ll$+jets as control sample with standard selection and:
  - replace missing E_T by pT (ll)
  - 81 < M (ll) <101 GeV
  - missing E_T<30 GeV



- Corrections:
  - Kinematic: additional cuts used
  - Fiducial: good lepton detection only for $|\eta| < 2.5$
  - Lepton identification efficiency using tag-and-probe method



Three jets + Missing Energy

- Potentially high QCD backgrounds
- L1: $E_T^{miss,L1} > 46\,\mathrm{GeV}$, $E_T > 88\,\mathrm{GeV}$, HLT: $E_T^{miss} > 200\,\mathrm{GeV}$
- Cuts:
  - 3 jets:

$$E_{T,j(1)} > 180\,\mathrm{GeV} \quad |\eta_d^{1j}| < 1.7$$
$$E_{T,j(2)} > 110\,\mathrm{GeV} \quad |\eta| < 3$$
$$E_T > 30\,\mathrm{GeV} \quad |\eta| < 3$$

$E_T^{miss} > 200\,\mathrm{GeV}$

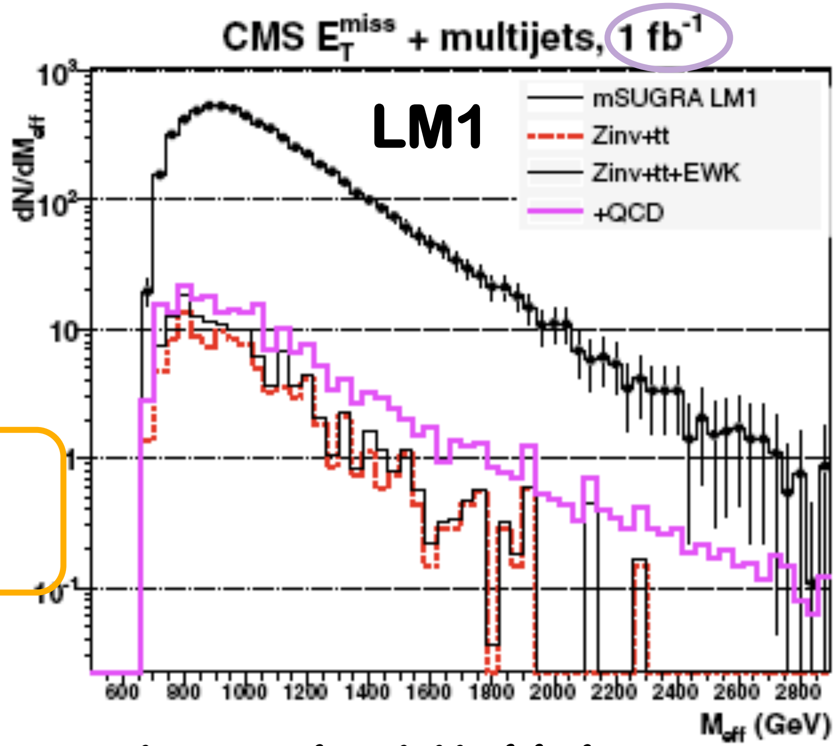
$\delta\phi_{min}(E_T^{miss} - jet) \geqslant 0.3$ rad

$\delta\phi(E_T^{miss} - j(2)) > 20°$

  - No isol. tracks with pT > 15 GeV

$f_{em(j(1))},\ f_{em(j(2))} < 0.9$

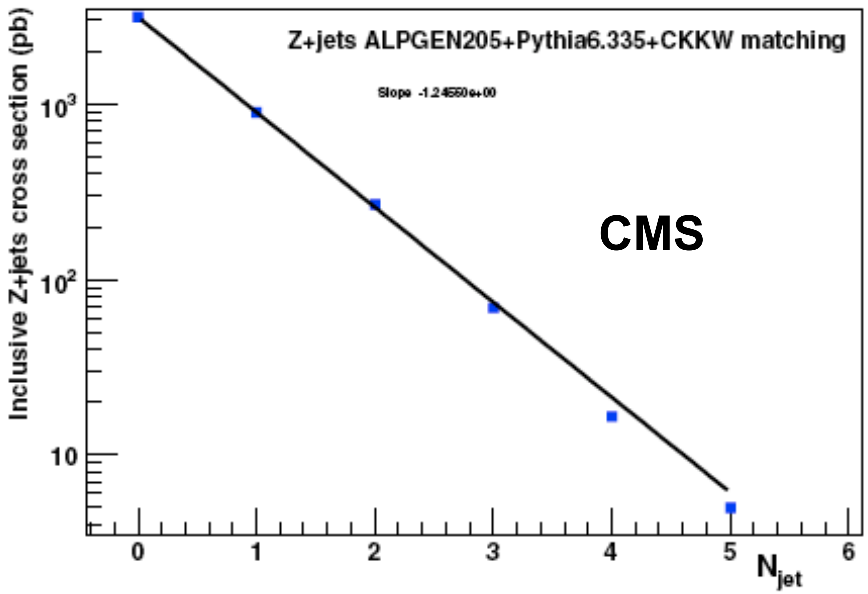
$H_T > 500\,\mathrm{GeV}$



Implicit lepton veto against tt, V+j

Background Estimation

- Use the dataset $Z(\to \mu\mu)+\ 2\ \text{jets}$ for normalisation:
  - Estimate the $Z(\to \nu\bar{\nu})+\geqslant 3\ \text{jets}$ contribution from data:
  - Normalize using:
    - $R = \frac{dN_{events}}{dN_{jets}} = \frac{\mathcal{L}d\sigma}{dN_{jets}}$
    - Ratio of $Z(\to \mu\mu)$ to $Z(\to \nu\bar{\nu})$
    - Require Z boson $P_T > 200\,\text{GeV}$ in all samples
  - Similarly, estimate $W(\to \tau\nu)+\geqslant 2\ \text{jets}$:
  - Use:
    - $\rho \equiv \frac{\sigma(pp \to W(\to \mu\nu)+jets)}{\sigma(pp \to Z(\to \mu^+\mu^-)+jets)}$
- Needed data sample:
  - $\sim 1.5\ \text{fb}^{-1}$
- Estimate systematics due to raw E_T^{miss} from data



di-jets + Missing Energy (M_{T2} method)

- Using variable m_{T2} (large p_T , $\not{E}_T$ and $\delta\phi$):

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

- Trigger: $E_T^{\rm jet} > 70\,{\rm GeV}$ and $\not{E}_T > 70\,{\rm GeV}$
- Cuts:

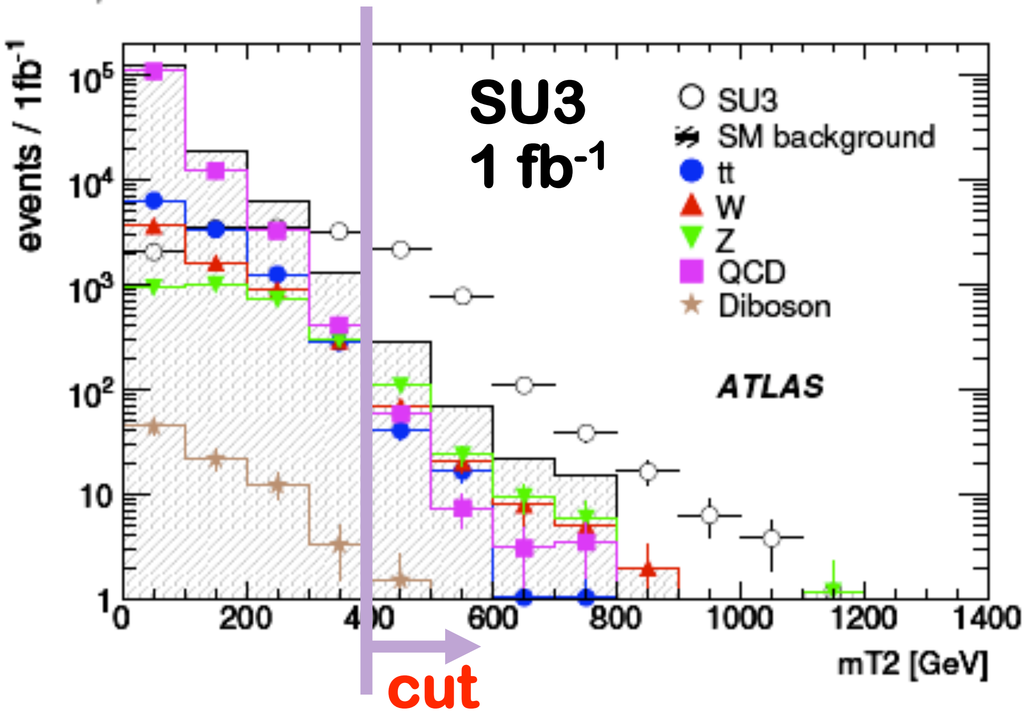
  2 jets in |η| < 2.5 :

    - j_1: $P_T^{jet1} > 150$ GeV
    - j_2: $P_T^{jet2} > 100$ GeV

  $\not{E}_T > 100$ GeV

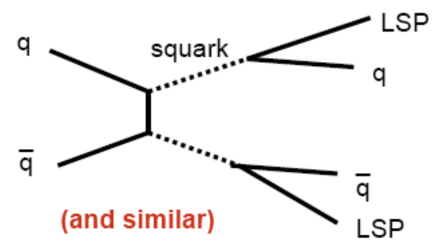
  $m_{T2} > 400$ GeV

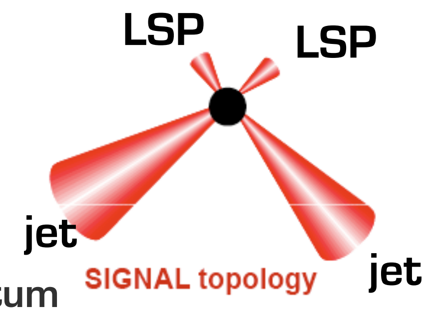
  - No isolated leptons



di-jets + Missing Energy (α method)

- CMS study: PAS-SUS-08/005
  - Based on: L. Randall, D.Tucker-Smith (Phys.Rev.Lett.101:221803,2008)
- Idea:
  - Squarks pair produced and directly decaying to quarks and neutralinos
- Event topology
  - Only two jets + missing energy
- Background:
  - QCD dijet events
    - No real missing momentum
  - Z→νν events
    - Irreducible background due to real missing ET
  - W→lν
    - Leads to missing Et when lepton not reconstructed or out of acceptance

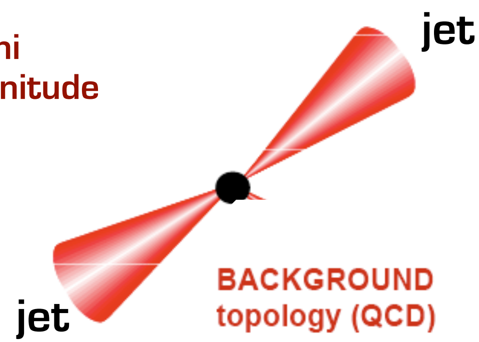




Transverse momentum conservation

Jets back-to-back in phi

E_T of jets equal in magnitude



Discriminating Variables

- Exploit kinematics of the event
  - Define variable α (Randall – Tucker-Smith):

$$\alpha = \frac{E_{T\ j2}}{M_{j1\,j2}} = \frac{E_{T\ j2}}{\sqrt{2E_1E_2(1-\cos\theta)}}$$

    - Can be at most 0.5 for QCD, $\alpha < 0.5$
    - $\alpha > 0.5$ implies missing momentum
  - And transverse α_T:

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

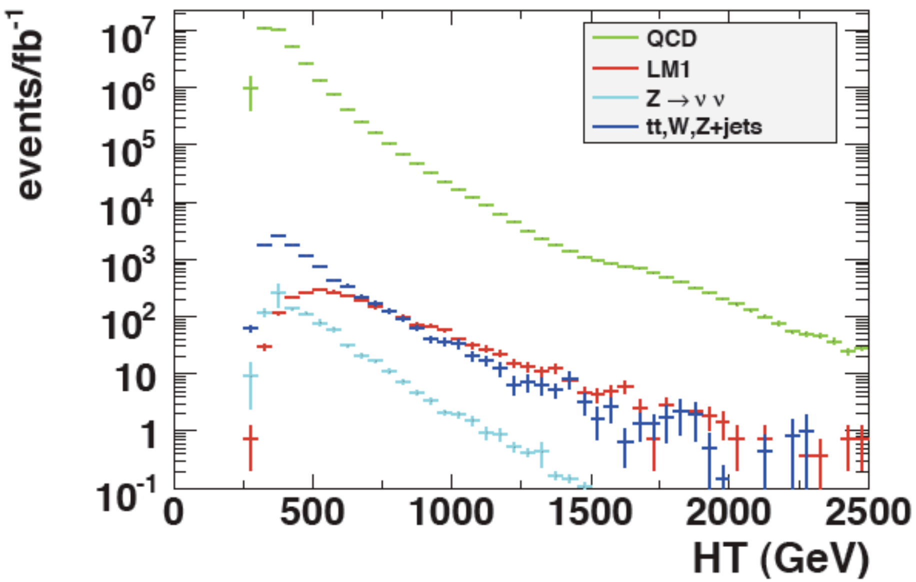
    - Exploits that for QCD jets need to be back-to-back and of equal magnitude
    - For QCD dijets $\alpha = 0.5$

Analysis does not rely on calorimetric MET, MHT inferred from 2 jets

⇒ well suited for early data

Event Selection

- **Main variables of interest**
  - $\Delta\varphi$ between the jets
  - α (α_T) from 2 leading jets
  - Scalar sum of Jet p_T's:
    - $HT = p_T^{Jet1} + p_T^{Jet2}$
  - Jet based missing E_T
    - $MHT = -(\vec{p}_T^{Jet1} + \vec{p}_T^{Jet2})$
  - but also p_T of a possible 3rd jet



- Trigger
  - di-jet trigger
    - two jets with pt > 150 GeV
- Preselection:
  - Jet Selection
    - 2 jets with pt > 50 GeV, Fem< 0.9
    - 3rd jet veto: pt < 50 GeV
    - $\Delta\varphi$(MHT,jet1,2,3) > 0.3 rad
    - $|\eta j1| < 2.5$
  - Lepton veto's:
    - no e, μ with pt >10 GeV
- Full Selection
  - HT > 500 GeV
  - α (αT) > 0.55
  - ($\Delta\phi < 2\pi/3$)

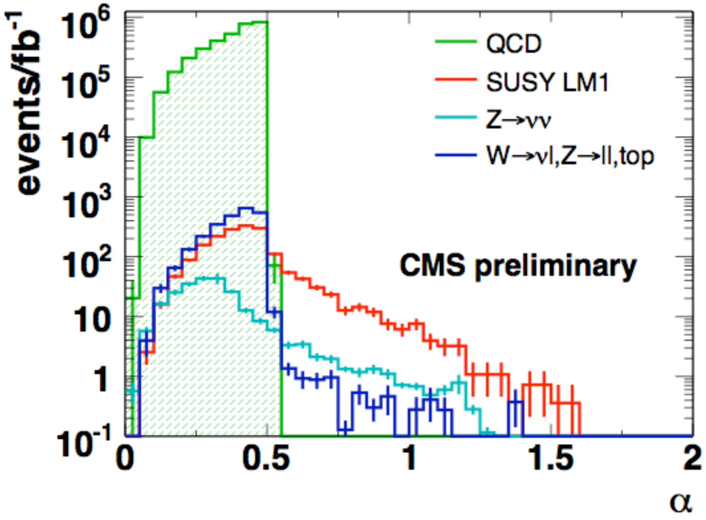
Discriminating Variables

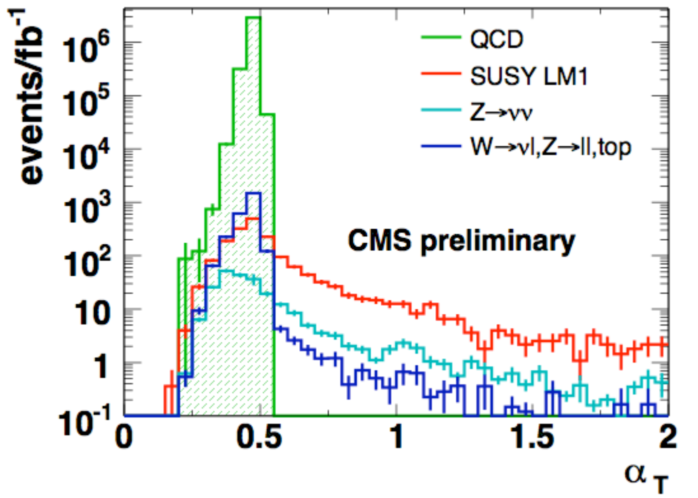
- Cuts applied: Preselection & HT > 500 GeV
- .

- Z→νν is main background
- W and other Z decays small

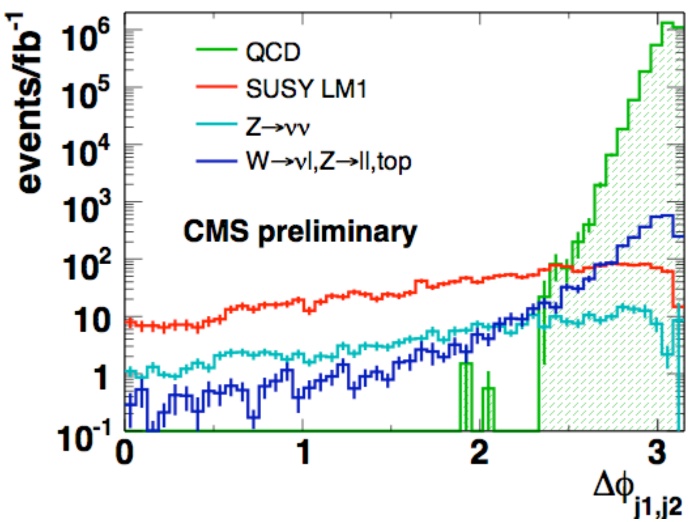
1 fb^{-1}

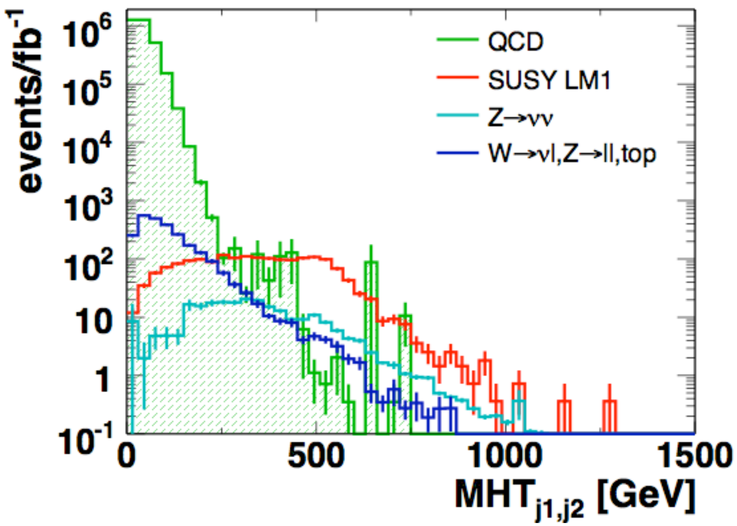
Sharp drop of QCD background for α (α_T) > 0.5





QCD peaking at Δϕ = π

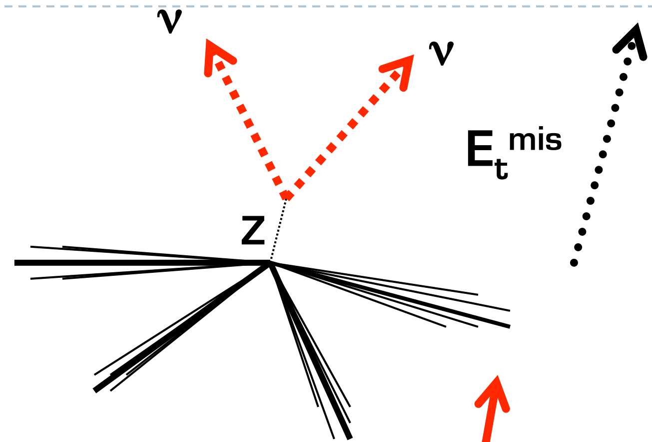




Background Estimation

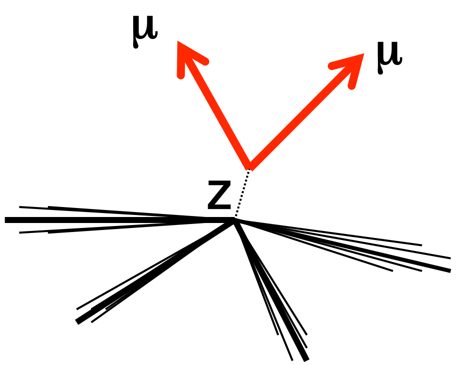
An illustrative example: **$Z \to \nu\nu$+jets**

Irreducible background for Jets+E_t^{mis} search

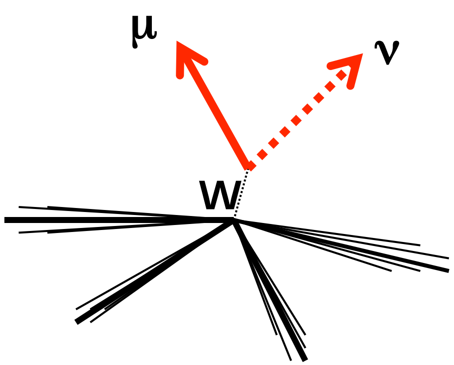


Data driven strategy:

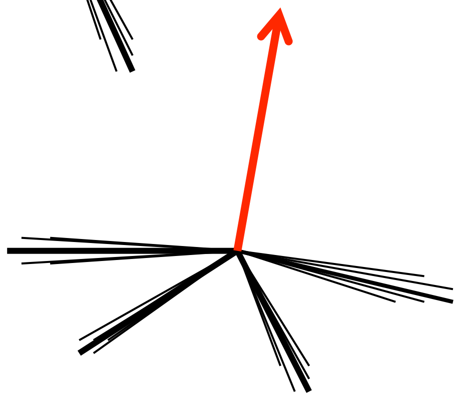
- define control samples and understand their strength and weaknesses:



$Z \to ll$+jets



$W \to l\nu$+jets



γ+jets

Strength:
- very clean, easy to select

Weakness:
- low statistic: factor 6 suppressed wrt. to $Z \to \nu\nu$

Strength:
- larger statistic

Weakness:
- not so clean, SM and signal contamination

Strength:
- large stat, clean for high E_γ

Weakness:
- not clean for E_γ<100 GeV,
- possible theo. issues for normalization (u. investigation)

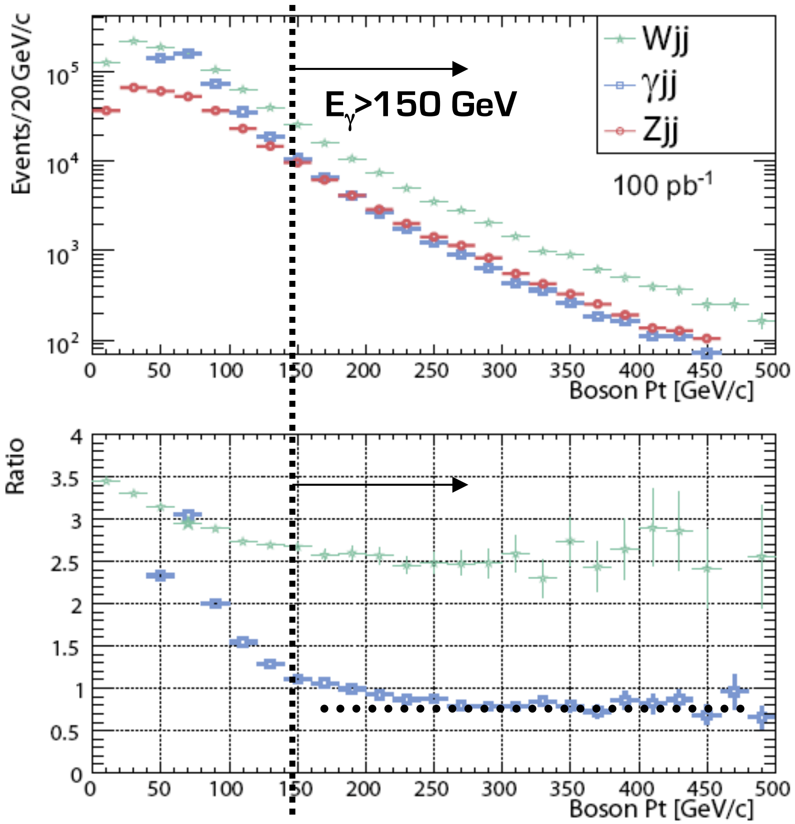
γ+jets: Estimate Z to invisible

γ+jets selection & properties:

- E_γ>150 GeV

→ clean sample: S/B>20

→ ratio σ(Z+jet)/σ(γ+jet) constant

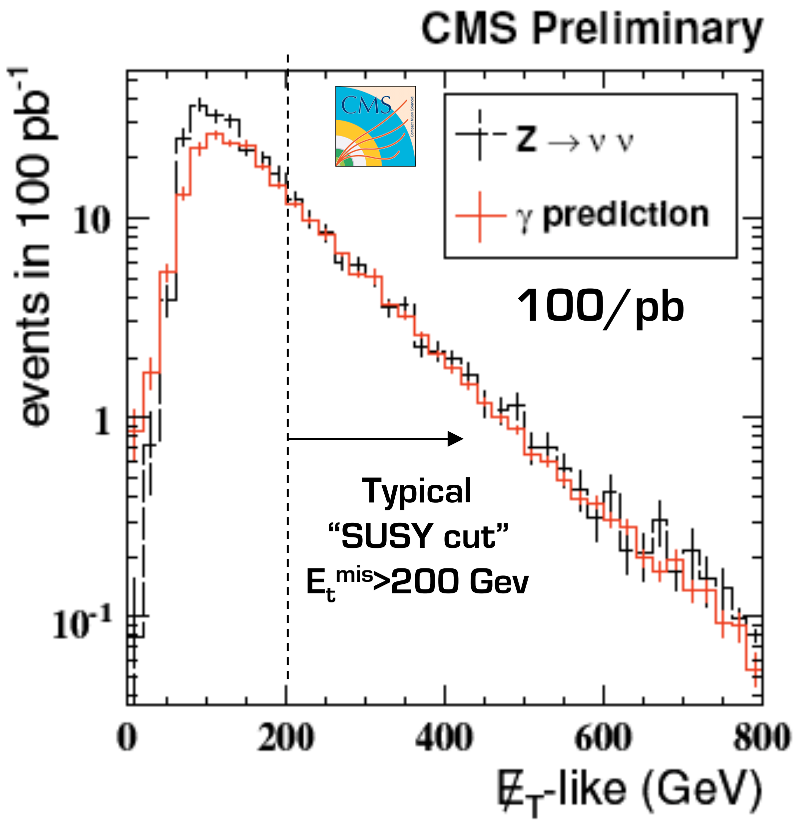


γ+jets: Strategy:

- remove γ from the event:

  → γ becomes E_T^{mis}

- take σ(Z+jet)/σ(γ+jet) for E_γ>200 GeV from MC or measure in data



Conclusions

- Discussed some examples of analyses for events with Missing E_T.
- Data-driven backgrounds determinations have been developed
  - Exploit uncorrelated observables to predict backgrounds in signal region from control samples (HT2, Missing Energy Significance, M_T)
  - Subtraction of all backgrounds using matrix method
  - Modeling of $Z \rightarrow \nu\nu$ from $Z \rightarrow ll$ and from γ + jets
- Di-jet analysis exploiting particular event topology
  - Shown results do not rely on calorimetric MET
    - Useful for early running.
- Extension to a calorimetric MET independent multi-jet analyses under study
- Eagerly awaiting first collisions and discoveries in fall of this year.