Hard Scattering in Hadron-Hadron Collisions: Physics and Anatomy

Section 6: Neutrinos and Missing Transverse Energy

1. Philosophy of MET techniques

2. Instrumental strengths and compromises

3. Measurement techniques

4. Background considerations

5. Example: MET in SUSY events

Basic MET Philosophy

- **UA1 pioneered "missing energy" technique to detect non-interacting particles**
  - **Build "hermetic" calorimeter**
    - > Most hadrons interact in calorimeter
    - > EM objects also measured in calorimeter
  - **Can identify and measure μ leptons separately**
  - **Correct for cracks, non-linear energy response**

- **Worked surprisingly well**
  - **Discovery of W boson**

- **Become essential to most measurements**
  - **Require it when expect a non-interacting particle in final state**
  - **Require little MET if one expects all particles to be observable**

What is this event likely to have been?

$\not{E}_T = 37$ GeV

e $P_T = 28$ GeV

e $P_T = 22$ GeV
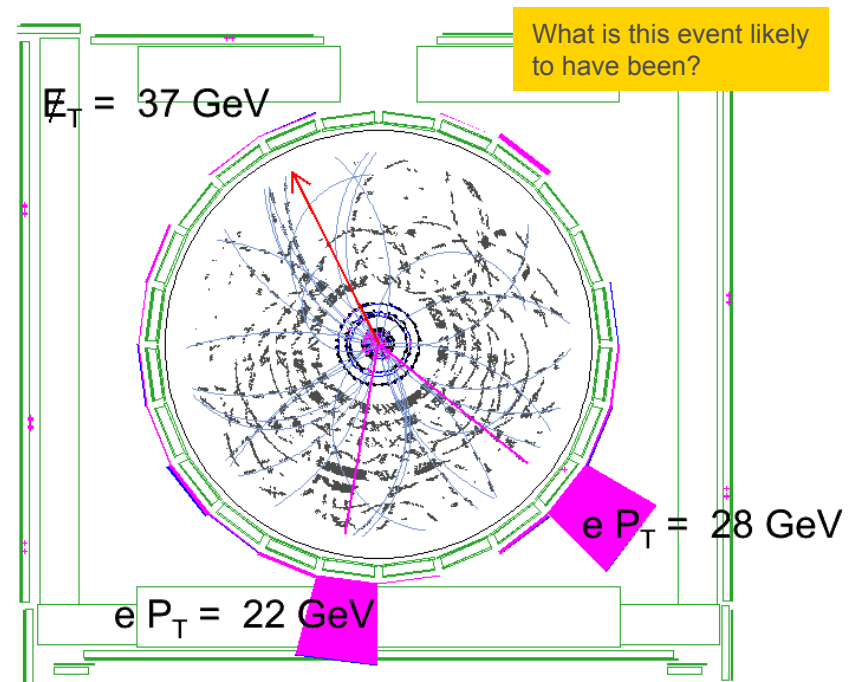
Measurement Techniques

- **Usual strategy is to take "raw" energy in each cell i**
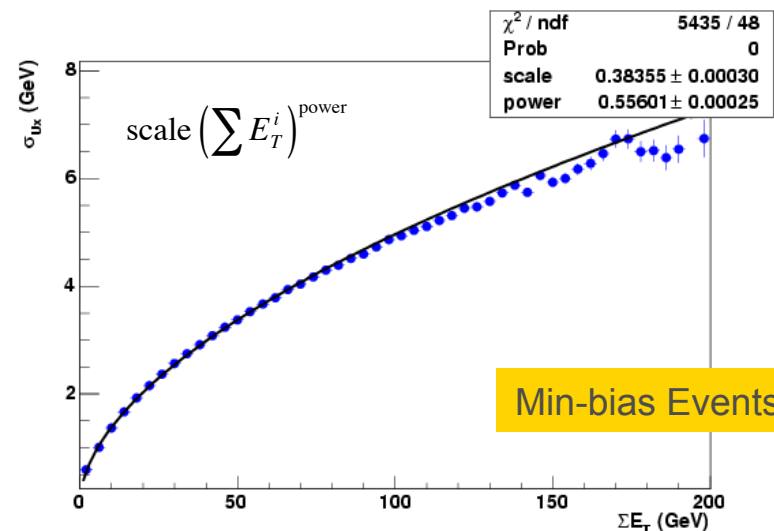 - **Compute vector MET**

$$\vec{E}_T = -\sum_{\substack{i\ cal \\ towers}} \left(E_T^i \vec{x} + E_T^i \vec{y} \right) \quad \text{and} \quad E_T \equiv |\vec{E}_T|$$

  - **Identify μ, jet candidates**
    - > For muons, identify energy deposition in calorimeter
      - – Substract EM+Had deposition
      - – Add -ve of μ momentum to MET
    - > For jets, identify jet objects
      - – Subtract ET of towers making up jet
      - – Add back in "corrected" jet energies
  - **Remaining "unclustered" energy**
    - > Correct on average for energy response
  - **Corrected MET thus depends on definition of other objects**

- **Resolution depends on "average" calorimeter resolution**

$$\sigma(E_T) \approx k \sqrt{\sum E_T^i}$$

  - **But also varies with final state**
    - > Need to measure it
    - > Example from W mass measurement
      - – Fit gives k~0.4 and 0.5 power

$$\text{scale} \left(\sum E_T^i \right)^{power}$$

χ^2 / ndf	5435 / 48
Prob	0
scale	0.38355 ± 0.00030
power	0.55601 ± 0.00025

Min-bias Events

Further Improvement at LHC

■ **ATLAS uses the following calculation for each component**

$$E_{x(y)}^{\mathrm{miss,calo}} = E_{x(y)}^{\mathrm{miss},e} + E_{x(y)}^{\mathrm{miss},\gamma} + E_{x(y)}^{\mathrm{miss},\tau} + E_{x(y)}^{\mathrm{miss,jets}}$$
$$+ E_{x(y)}^{\mathrm{miss,softjets}} + (E_{x(y)}^{\mathrm{miss,calo},\mu}) + E_{x(y)}^{\mathrm{miss,CellOut}}$$

– **Identify e, γ, τ, μ & jet candidates**
  > Correct each for appropriate calorimeter response

– **Jet term restricted to jets with p_T>20 GeV/c**

– **Soft jets with 7 > p_T > 20 GeV/c corrected with a different response**

– **Include all calorimeter cells not part of one of these objects in "CellOut" term**

– **Each gets its own adjustment to energy response**

■ **Has been investigated in detail in various event samples**

  ■ **Resolutions still behaves**

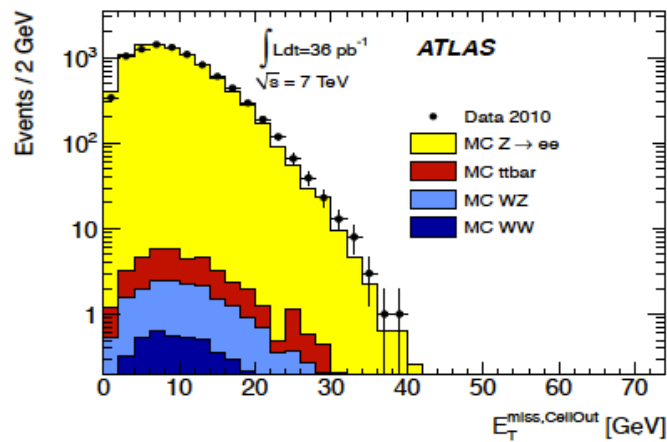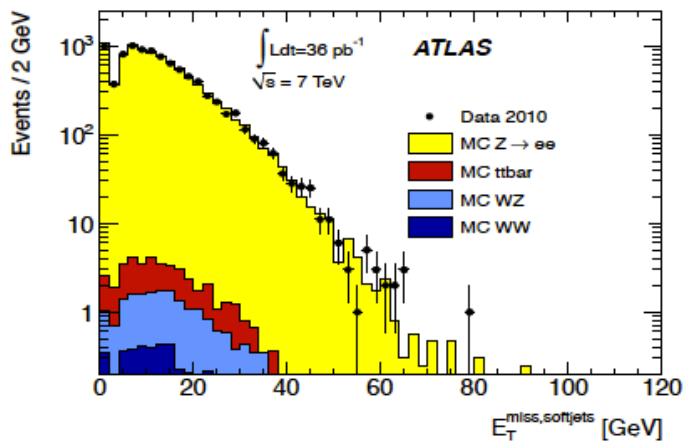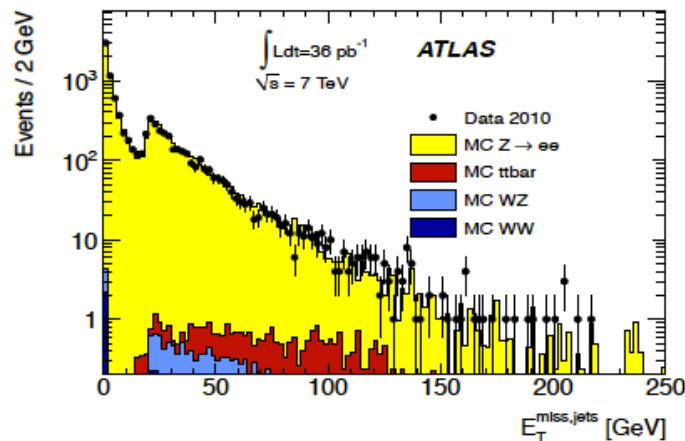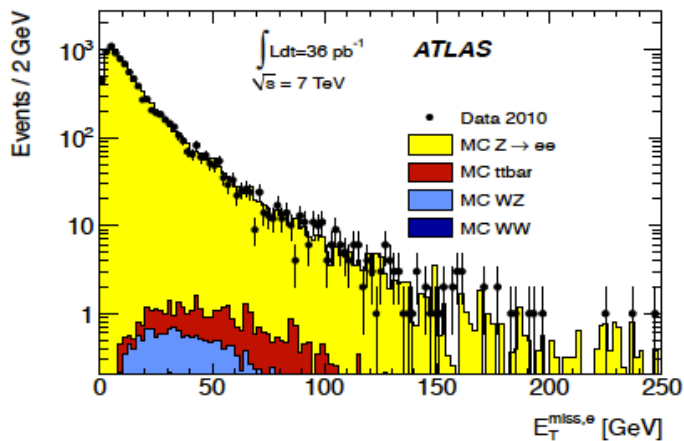 $$\sigma(E_T) \approx k\sqrt{\sum E_T^i}$$

  – **k is now around 0.4-0.5**
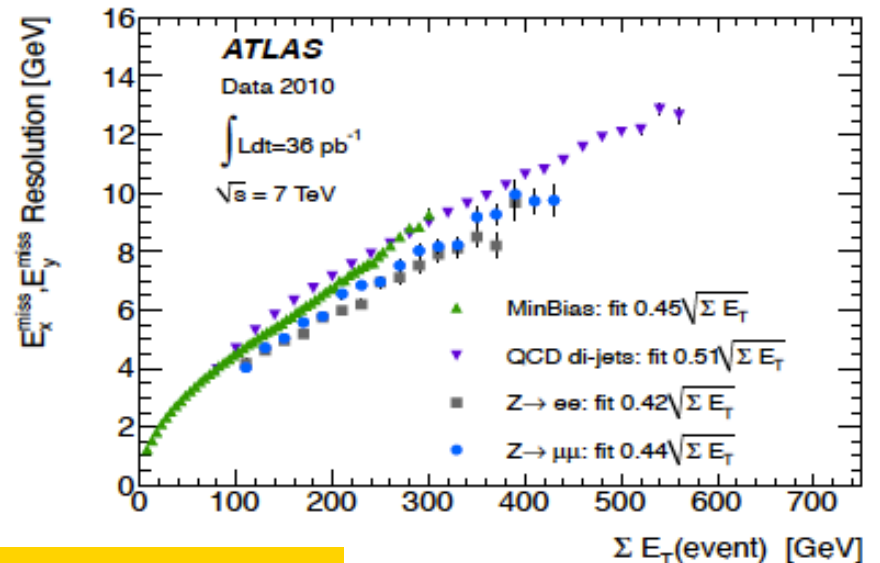
What Dominates MET at LHC?

■ **Can study the sources of MET from the various terms**


■ **Although this is channel specific, one sees that "jets" still play the single dominant role**

# Sensitivity to Luminosity

- **Measurement averages over entire calorimeter**
  - **Sensitive to # of multiple interactions**
    - > instantaneous luminosity

- **Take this into account**
  - **Typically by including luminosity profile in simulated events**
  - **Constrain simulation using real data**
   - > Example here is $Z \to e^+e^-$ for W mass measurement
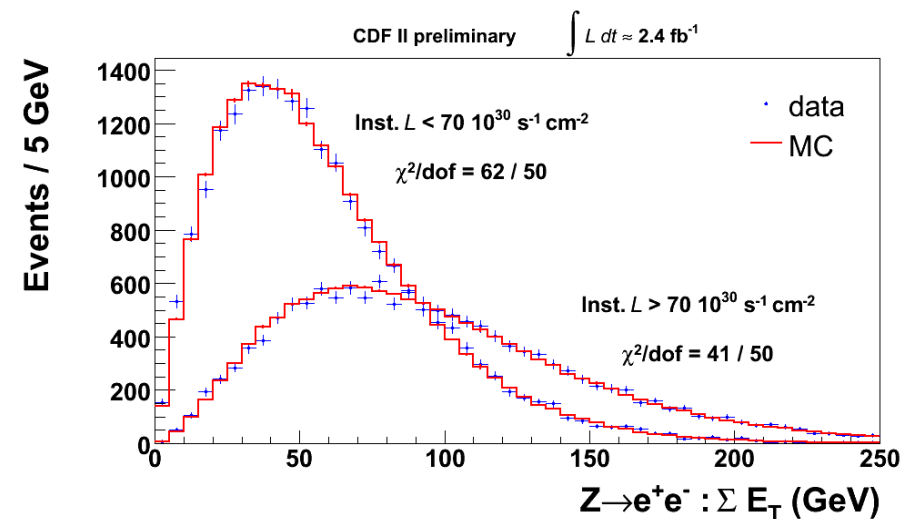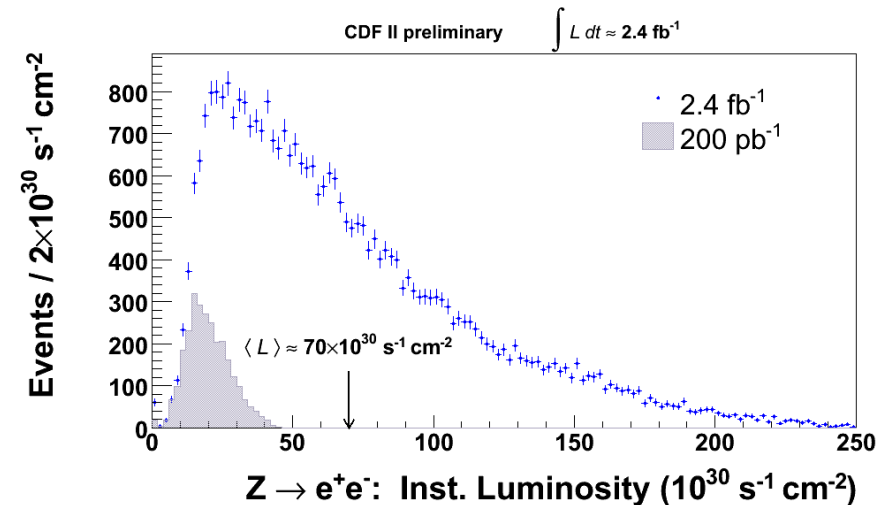
Fake MET Signatures

- **Instrumental effects are largest single source of MET**
  - **Calorimeter misbehaviour**
    - Hot/warm cells
  - **Cracks in calorimeter**
    - Especially when you believe there is a jet nearby

- **Other backgrounds come from a host of sources (depending on the analysis):**
  - **Cosmic rays, beam halo, beam "splash"**
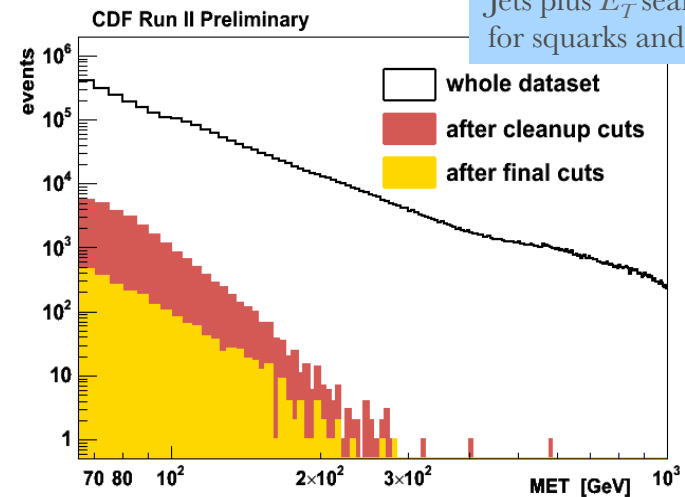
Jets plus E_T search for squarks and gluinos

CDF Run II Preliminary

- whole dataset
- after cleanup cuts
- after final cuts
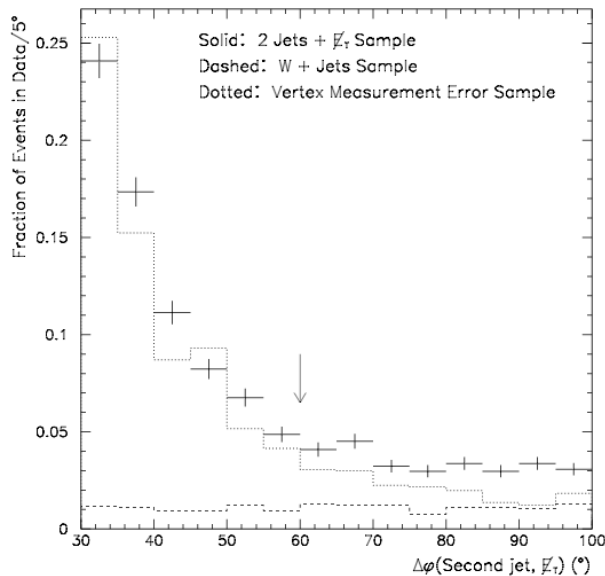
- **In CDF and D0, biggest source of MET comes from "poorly measured" jets**
  - **Two sources**
    - Statistical fluctuations in energy
    - Cracks and/or dead regions
  - **Reduce these by rejecting events with MET correlated with large energy deposition (such as a jet)**
  - **Attempting to correct MET for these has not worked particularly well**

Use of MET in Analyses

■ **MET is primarily used as a measure of ν P_T**

- **What you DON'T get is the P_z of the neutrino**
  - > You don't know x_1 or x_2 of the initial state partons
  - > And life is complicated if there are ≥ 2 ν's expected

■ **Lack of P_z motivated introduction of "transverse mass"**

$$M_T \equiv \sqrt{2 P_T^l \not{E}_T (1 - \cos \Delta \phi)}$$

- **Virtue is that it is approximately Lorentz-invariant**
- **Retains significant information in measurements such as M_W**

■ **Use in top dilepton events shows that one can deal with multiple ν final states**

CDF II preliminary $\int L\, dt \approx 2.4$ fb^{-1}

$\Delta m_W^{stat} = 15$ MeV/c^2
$\chi^2/dof = 70 / 48$

data
MC
background

$m_T(e\nu)$ (GeV/c^2)

124 events

Data
Signal+Bkgd
Bkgd only

CDF Run II Preliminary (1.8 fb^{-1})

M_{top}^{reco} (GeV/c^2)
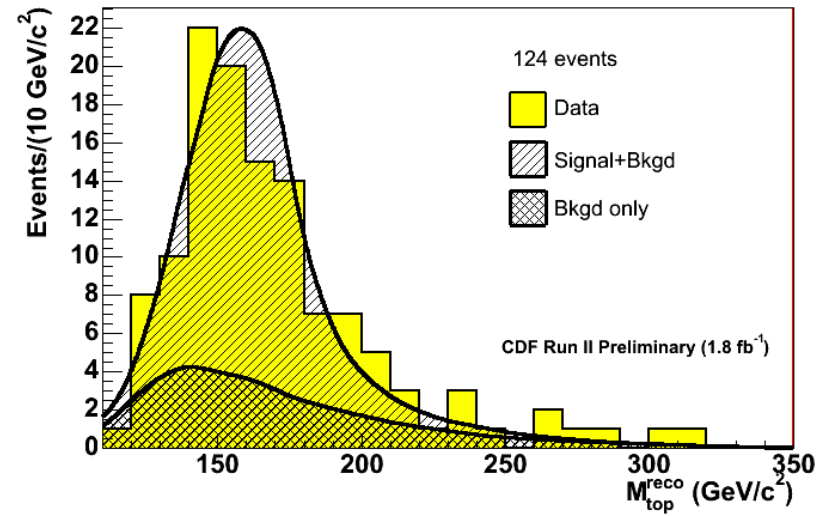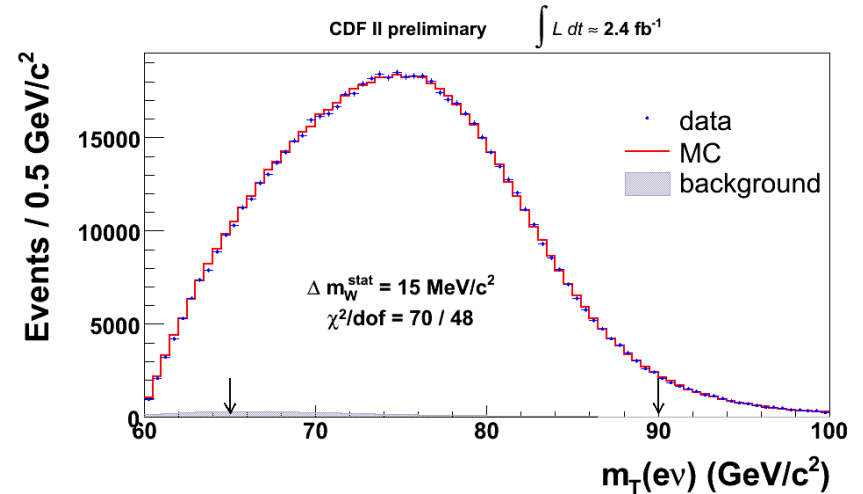
Can One Recover P_z?

- **Traditional way of recovering P_z is to employ kinematic constraints**
  - **In top quark mass measurement, require l+MET come from W**
    - > Constrain to W mass gives quadratic equation in P_z
    - > Solve and choose one solution
      - – **One algorithm is to choose the most probable one (ie., smallest P_z)**

- **Variants of this used in some Top & SUSY analyses**
  - **It doesn't "buy" you a lot because of the integration over the initial state partons**

- **One example comes from M_{top} analysis in dilepton events**
  - **Use all kinematic constraints**
    - > 23 equations and 24 variables
  - **Solve for P_z of ttbar system**
    - > Independent of M_{top}
  - **For each event, can define a posteriori probability vs M_{top}**
  - **Product probability used to estimate M_{top}**
    - > Bottom line is that it doesn't create more information
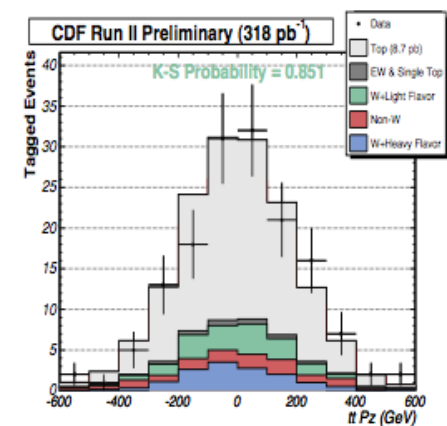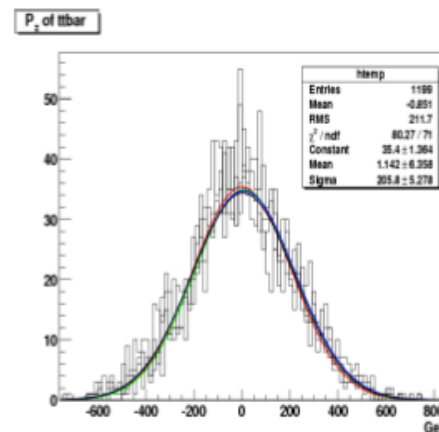
Background Considerations

- **At very large MET (aside from instrumental effects), most serious backgrounds are "irreducible"**
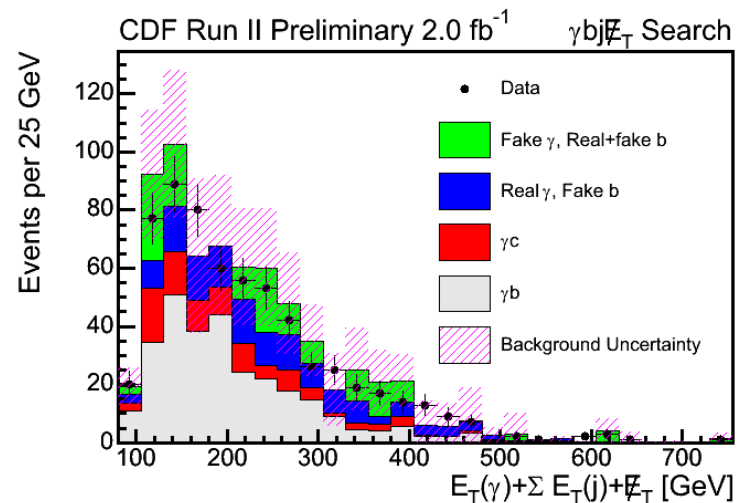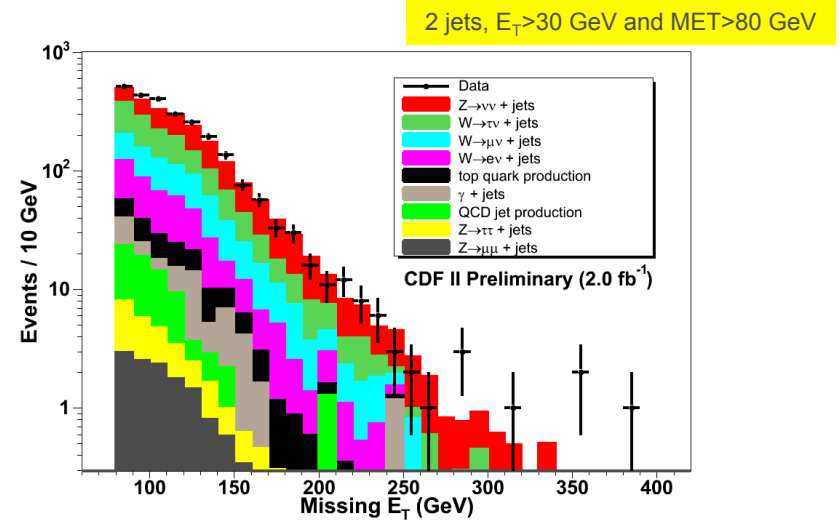 - **Physics signatures that produce real MET, e.g.**

$$Z + X \rightarrow (\nu\bar{\nu}) + X$$

$$W + X \rightarrow (\tau\bar{\nu}) + X$$

- **Several strategies to estimate and control these**
  - **For invisible Z decays, use $Z \rightarrow l^+ l^-$ as control sample**
  - **Many examples of this technique from CDF & D0**
  - **ATLAS and CMS have also employed this**

2 jets, E_T>30 GeV and MET>80 GeV

CDF II Preliminary (2.0 fb^{-1})

Legend: Data; $Z\rightarrow\nu\nu$ + jets; $W\rightarrow\tau\nu$ + jets; $W\rightarrow\mu\nu$ + jets; $W\rightarrow e\nu$ + jets; top quark production; γ + jets; QCD jet production; $Z\rightarrow\tau\tau$ + jets; $Z\rightarrow\mu\mu$ + jets

Missing E_T (GeV)

CDF Run II Preliminary 2.0 fb^{-1} $\gamma b \not{E}_T$ Search

Legend: Data; Fake γ, Real+fake b; Real γ, Fake b; γc; γb; Background Uncertainty

$E_T(\gamma)+\Sigma\ E_T(j)+\not{E}_T$ [GeV]

Example: MET in Gluino Search

- **Search for gluino production**
  - **Assume sbottom+b decay**
  - **Look for >=2 b-tagged jets + MET**

- **Selection**
  - **MET**
    - L1/L2/L3 trigger > 25/35/45 GeV
      - **Offline MET>70 GeV**
  - **Jet cuts**
    - >=2 jets E_T>25 GeV and |η|<2.4
    - Leading jet E_T>35 GeV
    - At least two b-tags

- **Define three control regions**
  - **QCD, Lepton, Pre-optimization**
    - Defined so that should be dominated by SM sources
      - **QCD: 2nd jet "aligned" with MET -- |Δφ|<0.4**
      - **Lepton: require isolated lepton with P_T>10 GeV**
      - **Pro-optimization: no alignment of jets with MET and no lepton**
  - **Check that event rates made sense**
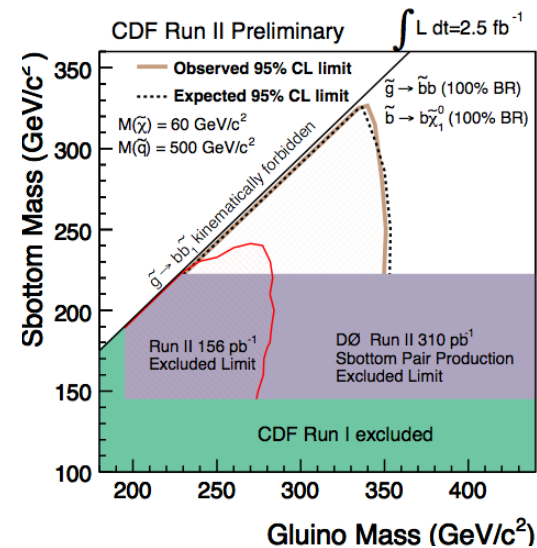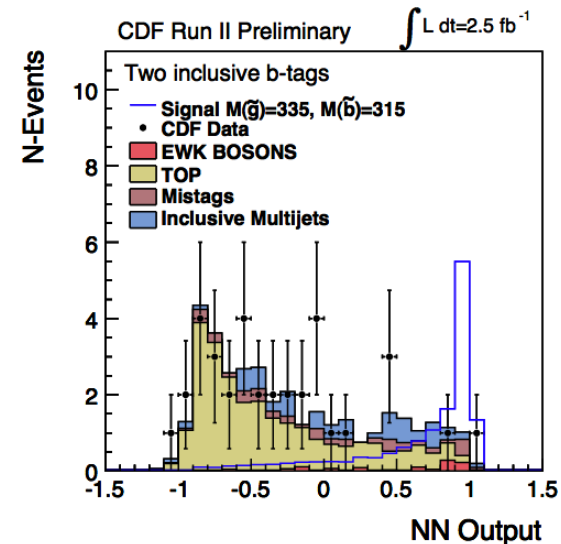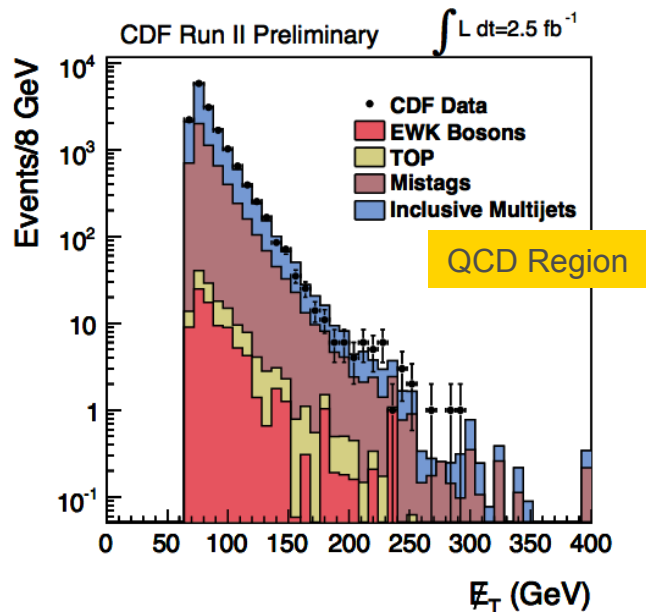
CDF Collaboration, arXiv:0903.2618, March 2009
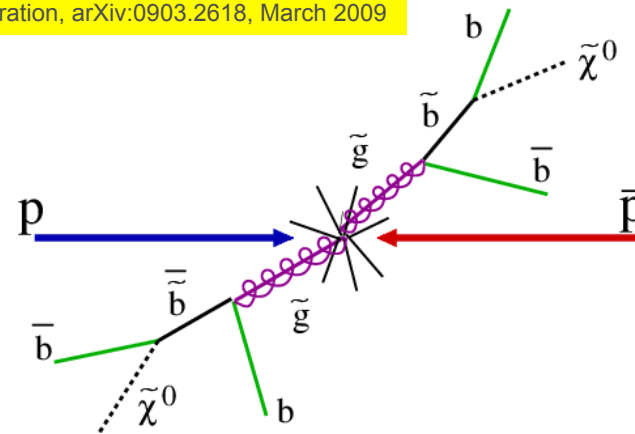
CDF Run II Preliminary 2.5 fb^{-1}

Two Inclusive Tags	QCD Region	Lepton Region	Preoptimization Region
W/Z + jets production	10 ± 7	19 ± 14	29 ± 22
Diboson production	0.4 ± 0.1	2 ± 0.6	4 ± 1
Top pair production	18 ± 6	107 ± 34	140 ± 45
Single top production	1 ± 0.2	4 ± 1	6 ± 1
HF QCD Multijets	864 ± 432	23 ± 11	273 ± 136
Light-flavour contamination	238 ± 48	8 ± 2	57 ± 11
Total expected	1132 ± 435	164 ± 38	510 ± 145
Observed	1104	156	455

SUSY Search Results

- **Employ a NN to further discriminate signal from background**
  - **Trained on pre-optimization region (for background) and MC (for signal)**
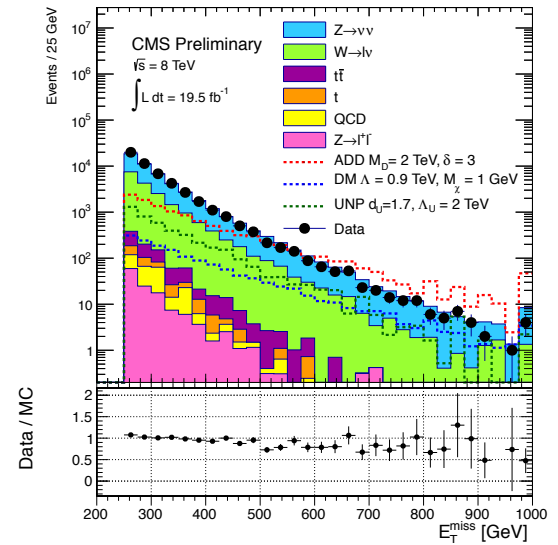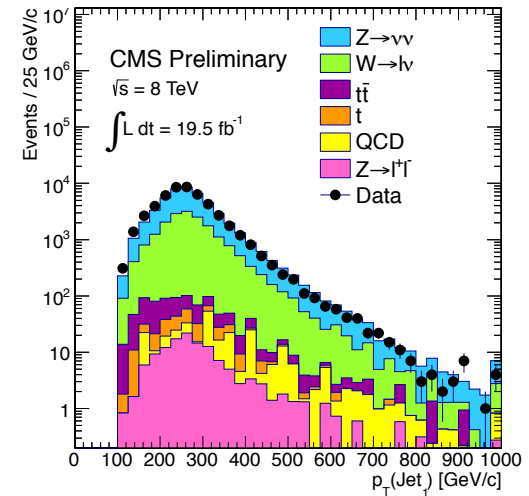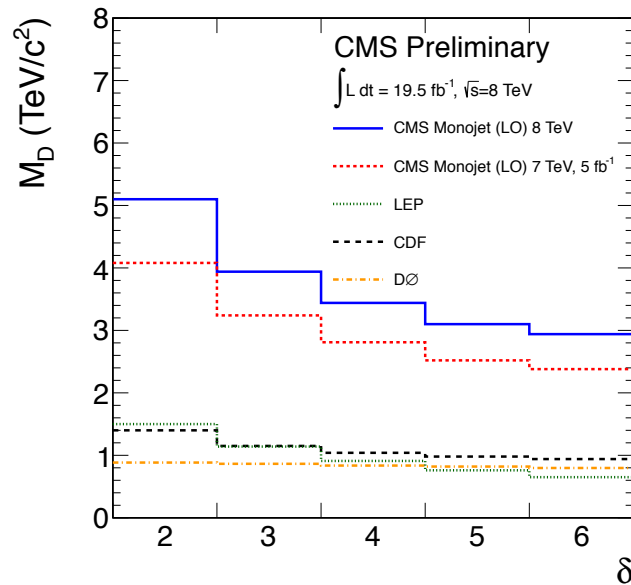   - > No evidence of signal
    - > Set limit using NN output

CDF Run II Preliminary $\int L\, dt = 2.5\ fb^{-1}$

Two inclusive b-tags

Signal $M(\tilde{g})$=335, $M(\tilde{b})$=315
CDF Data
EWK BOSONS
TOP
Mistags
Inclusive Multijets

N-Events vs NN Output

CDF Run II Preliminary $\int L\, dt = 2.5\ fb^{-1}$

- CDF Data
- EWK Bosons
- TOP
- Mistags
- Inclusive Multijets

QCD Region

Events/8 GeV vs E_T (GeV)

CDF Run II Preliminary $\int L\, dt = 2.5\ fb^{-1}$

Observed 95% CL limit
Expected 95% CL limit
$\tilde{g} \rightarrow \tilde{b}\bar{b}$ (100% BR)
$\tilde{b} \rightarrow b\tilde{\chi}_1^0$ (100% BR)
$M(\tilde{\chi}) = 60\ GeV/c^2$
$M(\tilde{q}) = 500\ GeV/c^2$

$\tilde{g} \rightarrow \tilde{b}\bar{b}$, kinematically forbidden

Run II 156 pb^{-1} Excluded Limit
DØ Run II 310 pb^{-1} Sbottom Pair Production Excluded Limit
CDF Run I excluded

Sbottom Mass (GeV/c^2) vs Gluino Mass (GeV/c^2)

CMS Monojet Search

CMS has looked at monojets in 19.5 fb^{-1}

- Looks in 7 regions with $E_T^{miss} > 250$ GeV to $E_T^{miss} > 550$ GeV in 50 GeV steps

- Looks at events with only one recoil jet

Compares with expected SM backgrounds

- Set 95% CL limits on possible DM yield as a function of M_D and δ (number of extra dimensions)

CMS EXO-12-048