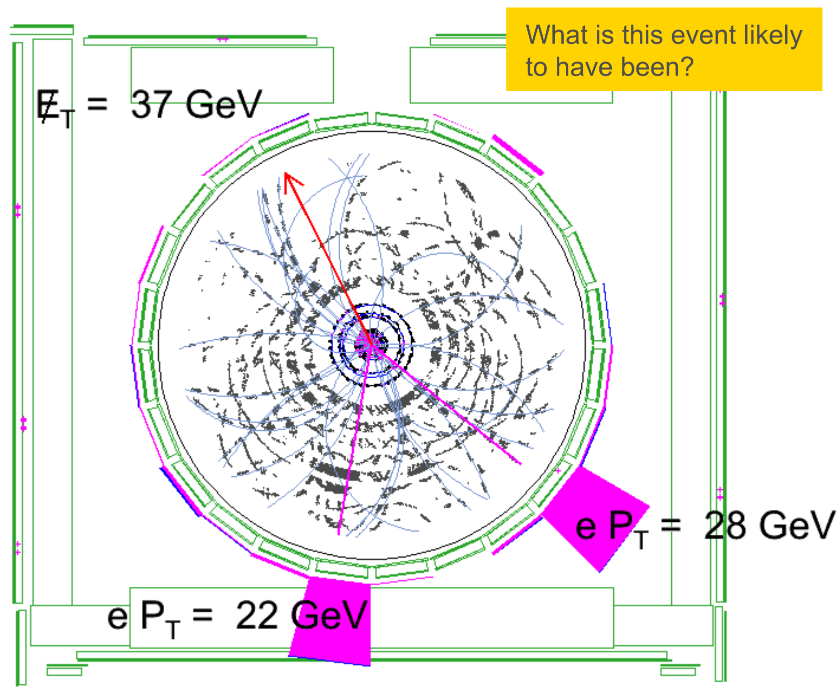
# Hard Scattering in Hadron-Hadron Collisions: Physics and Anatomy

## 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



# Measurement Techniques

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

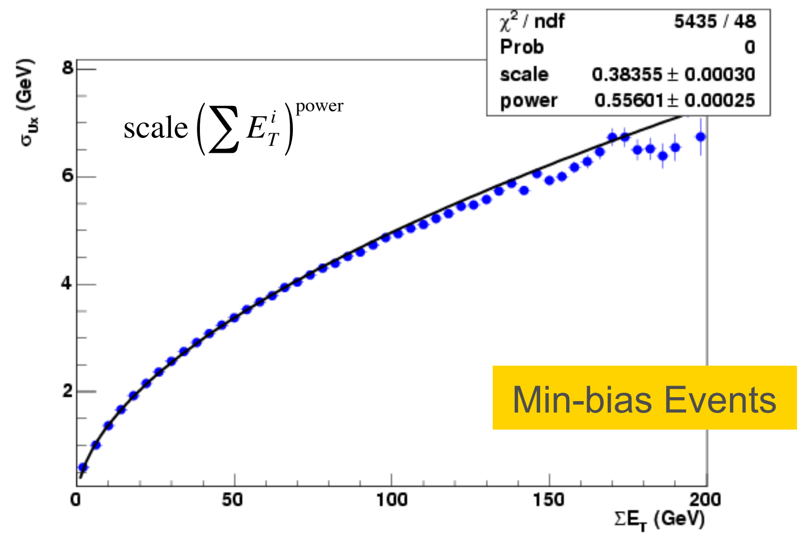
$$\vec{\not\!E}_T = -\sum_{\substack{i\ cal\\ towers}} \left( E_T^i \vec{x} + E_T^i \vec{y} \right) \quad \text{and} \quad \not\!E_T \equiv |\vec{\not\!E}_T|$$

  - **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**

$$\sigma(\not\!E_T) \approx k\sqrt{\sum E_T^i}$$

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



# Further Improvement at LHC

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

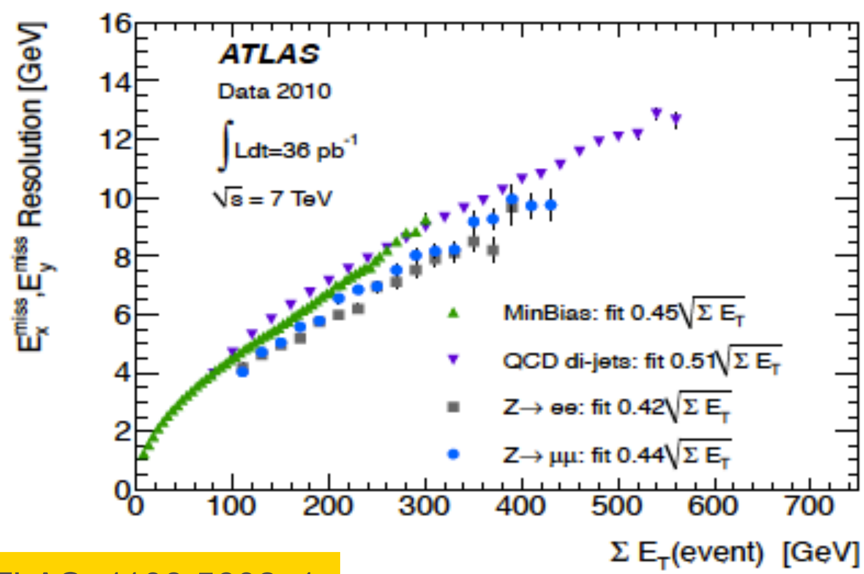
$$E_{x(y)}^{\text{miss,calo}} = E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,softjets}} + (E_{x(y)}^{\text{miss,calo},\mu}) + E_{x(y)}^{\text{miss,CellOut}}$$

  - **Identify e, γ, τ μ, jet candidates**
    - Correct each for appropriate calorimeter response
  - **Jets 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**

$$\sigma(\not{E}_T) \approx k\sqrt{\sum E_T^i}$$

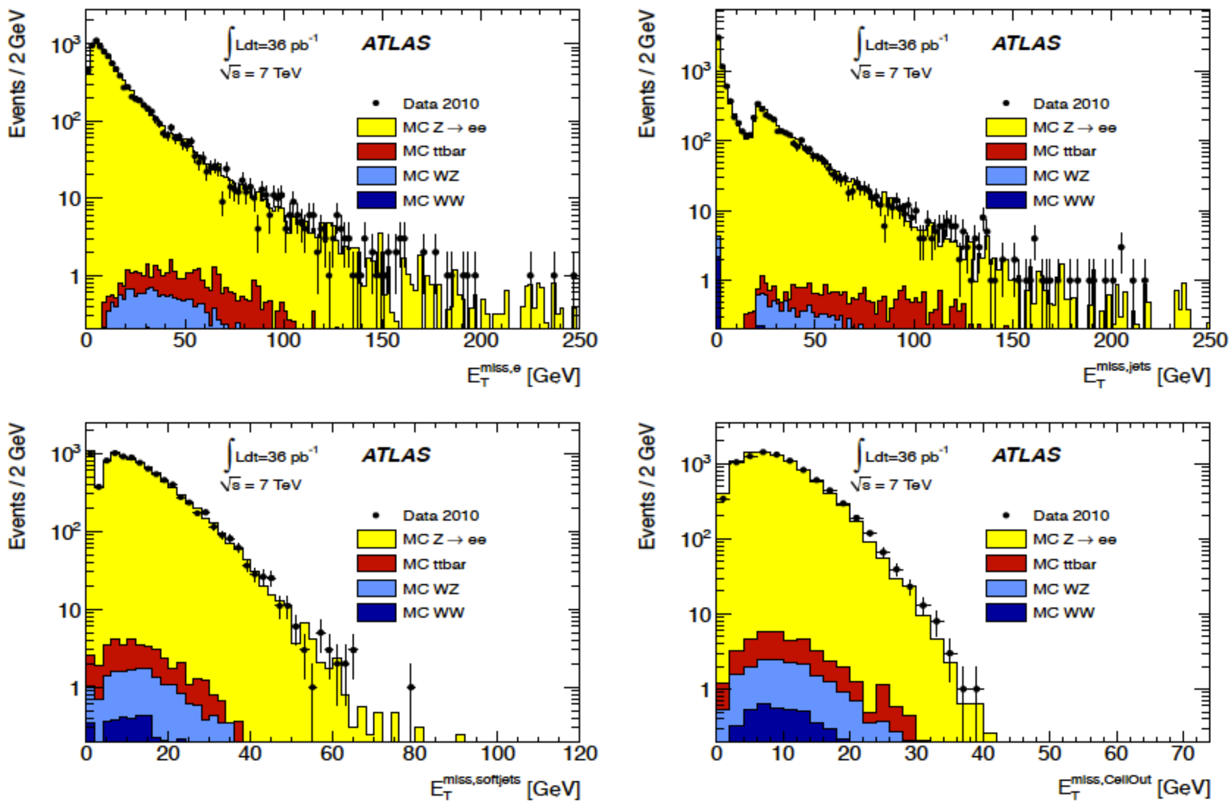
  - ***k* is now around 0.4-0.5**




ATLAS, 1108.5602v1

# What Dominates MET at LHC?

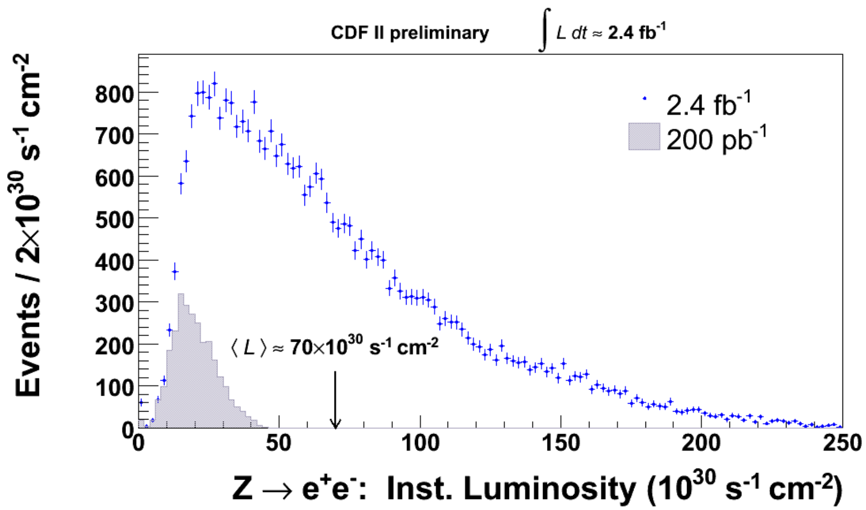
- Can study the sources of MET from the various terms

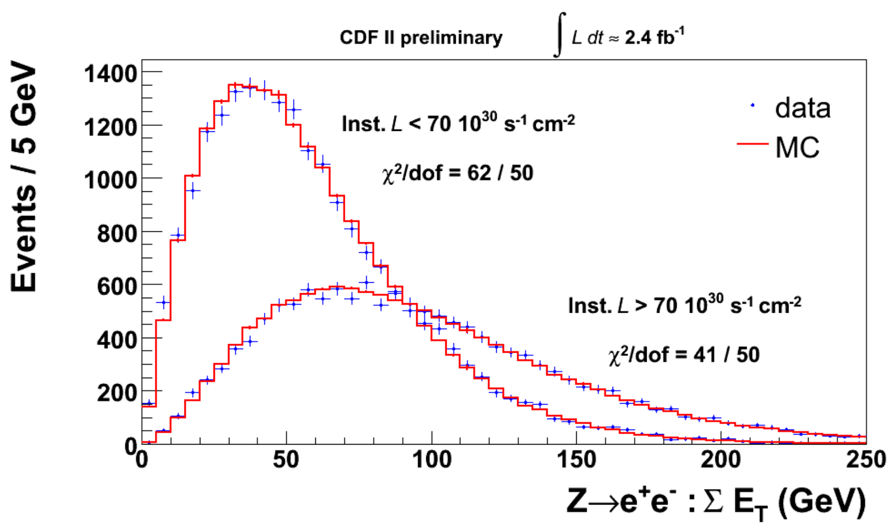



- Although this is channel specific, one sees that "jets" still play the single dominant role

# Sensitivity to Luminosity

- **Because 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->e+e- for W mass measurement**

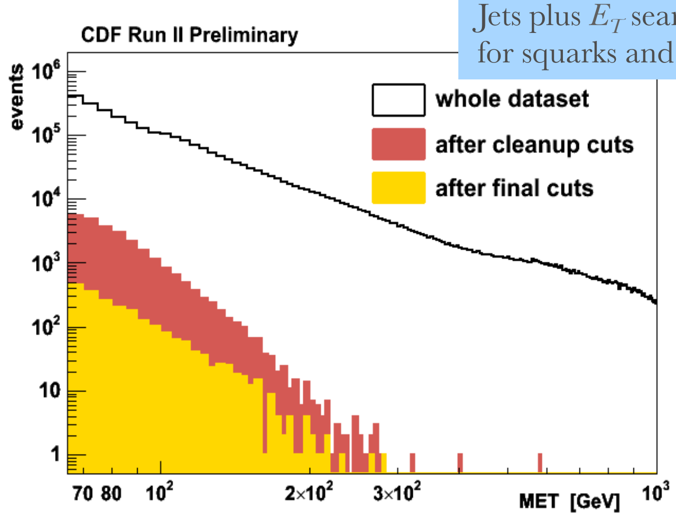


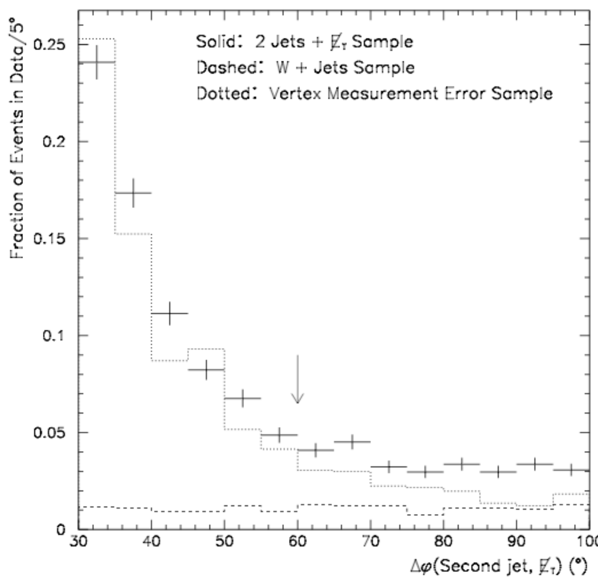



# Fake MET Signatures

- **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



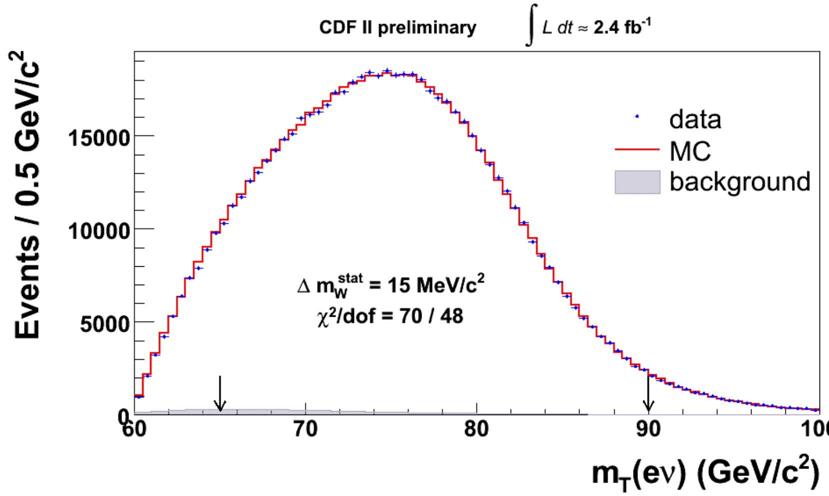

- **In CDF and D0, biggest source of MET comes from "poorly measured" jets**
  - **Two sources**
    - Statistical fluctuations in energy
    - Cracks and/or dead regions
  - **Reduce these by rejecting events with MET correlated with large energy deposition (such as a jet)**
  - **Attempting to correct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

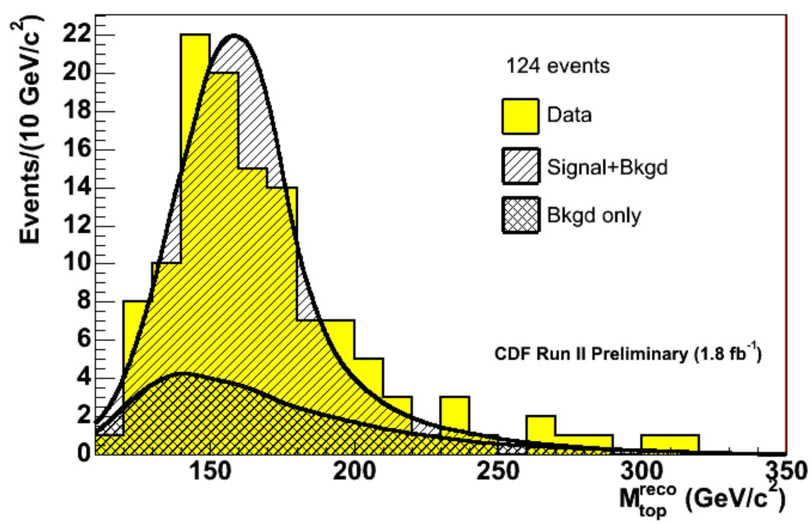
# Use of MET in Analyses

- **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"**

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

  - **Virtue is that it is approximately Lorentz-invariant**
  - **Retains significant amount of information in measurements such as $M_W$**
- **Use in top dilepton events shows that one can deal with multiple ν final states**

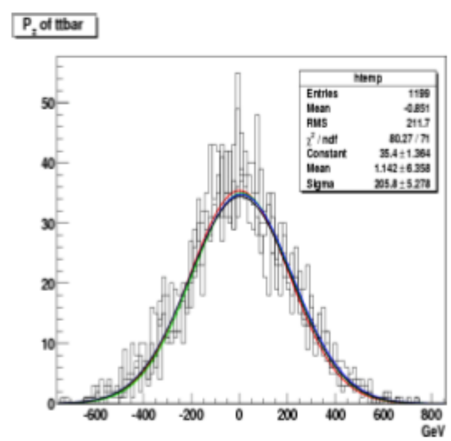


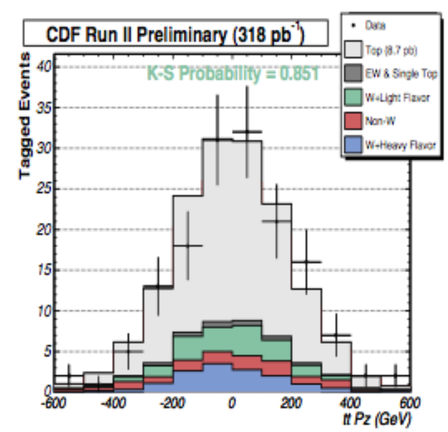



# Can One Recover $P_z$?

- **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



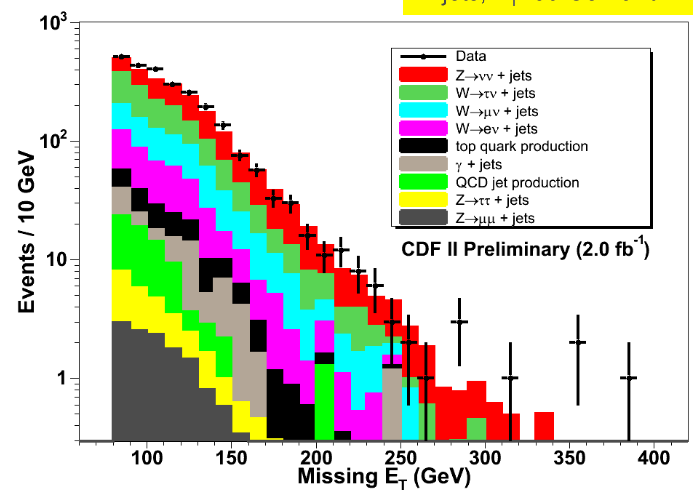



# Background Considerations

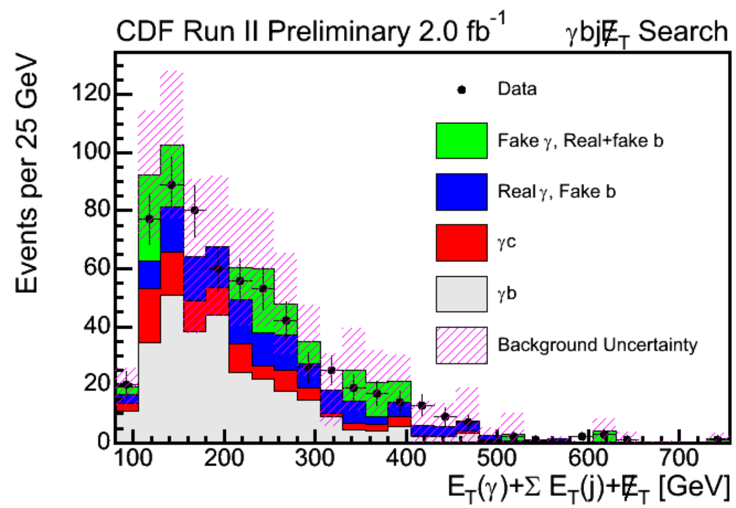
- At very large MET (aside from instrumental effects), most serious backgrounds are "irreducible"
  - Physics signatures that produce real MET, e.g.

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

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



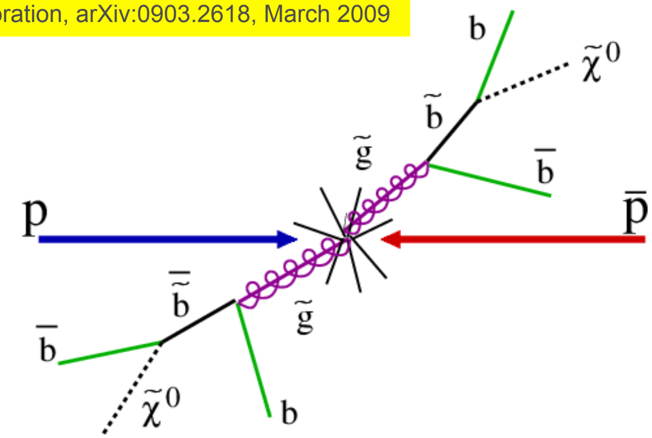

- Several strategies to estimate and control these
  - For invisible Z decays, use $Z \rightarrow l^+l^-$ as control sample
  - Many examples of this technique from CDF & D0



# 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 | $10 \pm 7$ | $19 \pm 14$ | $29 \pm 22$ |
| Diboson production | $0.4 \pm 0.1$ | $2 \pm 0.6$ | $4 \pm 1$ |
| Top pair production | $18 \pm 6$ | $107 \pm 34$ | $140 \pm 45$ |
| Single top production | $1 \pm 0.2$ | $4 \pm 1$ | $6 \pm 1$ |
| HF QCD Multijets | $864 \pm 432$ | $23 \pm 11$ | $273 \pm 136$ |
| Light-flavour contamination | $238 \pm 48$ | $8 \pm 2$ | $57 \pm 11$ |
| Total expected | $1132 \pm 435$ | $164 \pm 38$ | $510 \pm 145$ |
| 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