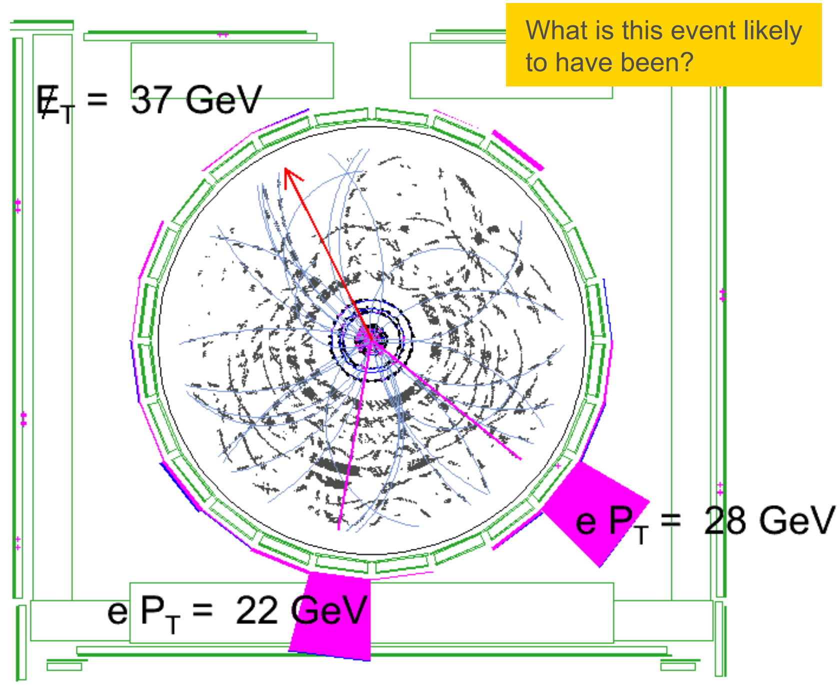
Hard Scattering in Hadron-Hadron Collisions: Physics and Anatomy

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**

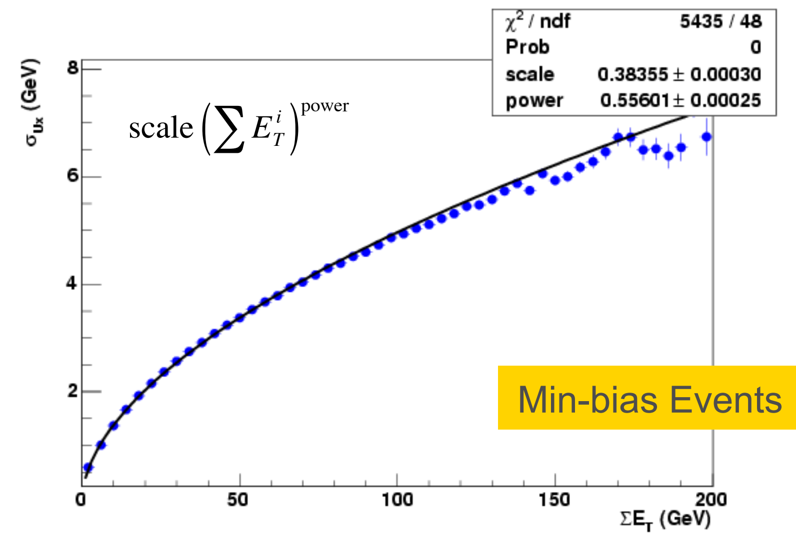
$$\vec{\not{E}}_T = -\sum_{\substack{i\ cal\\ towers}} \left(E_T^i \vec{x} + E_T^i \vec{y} \right) \quad \text{and} \quad \not{E}_T \equiv |\vec{\not{E}}_T|$$

  - **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**

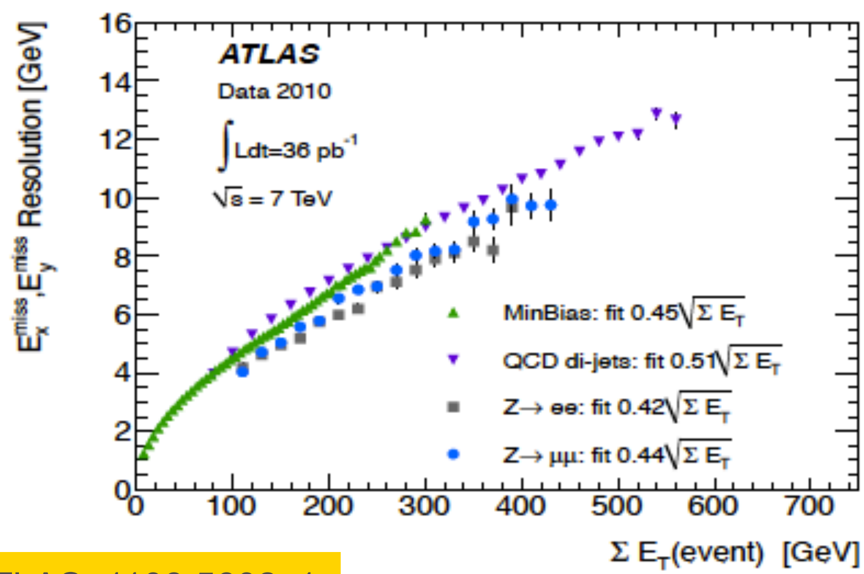
$$E_{x(y)}^{\text{miss,calo}} = E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,softjets}} + (E_{x(y)}^{\text{miss,calo},\mu}) + E_{x(y)}^{\text{miss,CellOut}}$$

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

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

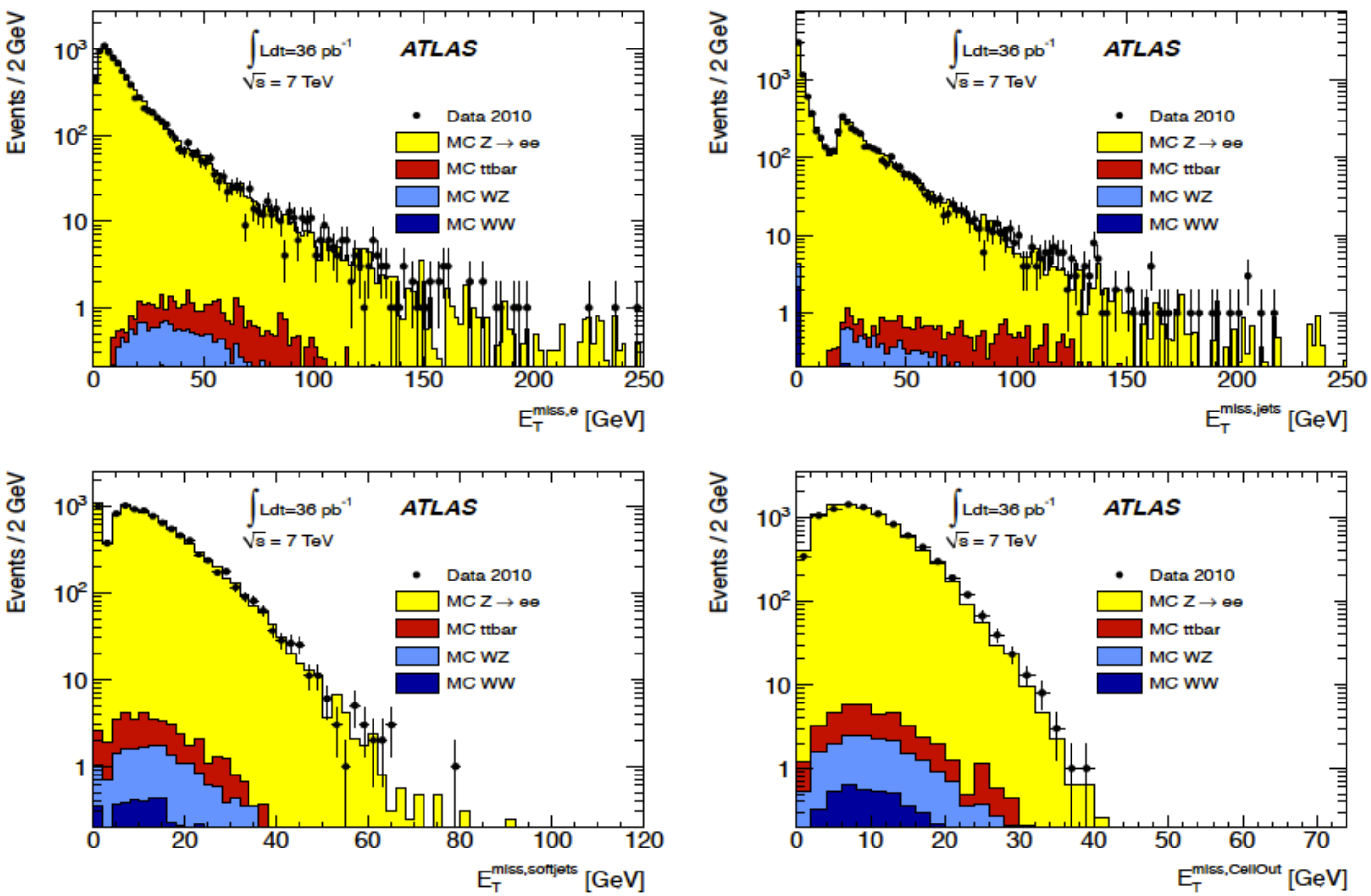
  - ***k* is now around 0.4-0.5**



ATLAS, 1108.5602v1

What Dominates MET at LHC?

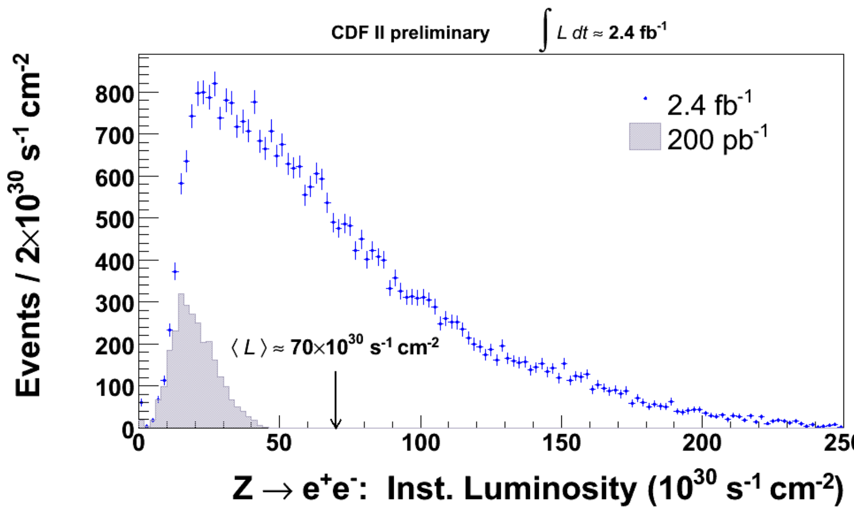
- **Can study the sources of MET from the various terms**

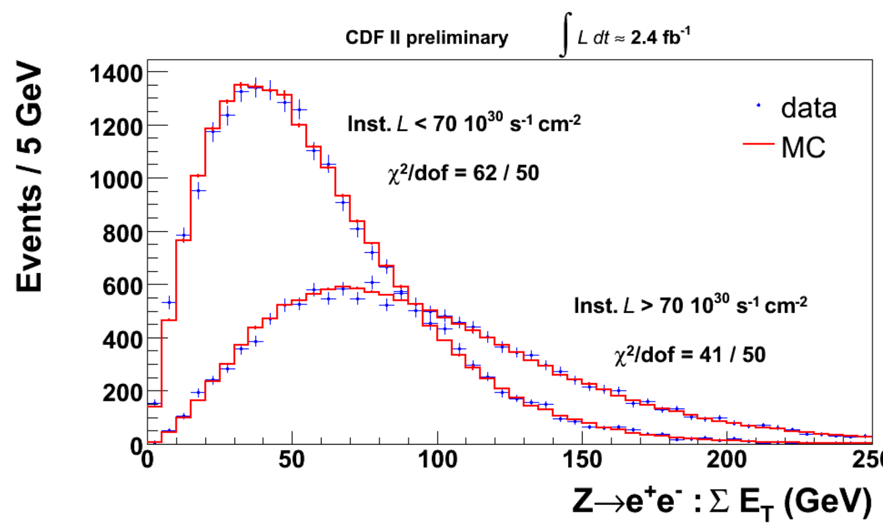


- **Although this is channel specific, one sees that "jets" still play the single dominant role**

Sensitivity to Luminosity

- **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 $Z \rightarrow e^+e^-$ for W mass measurement

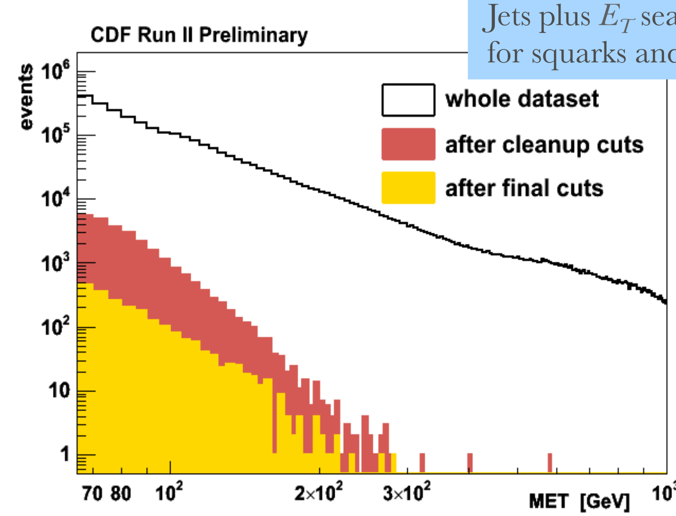


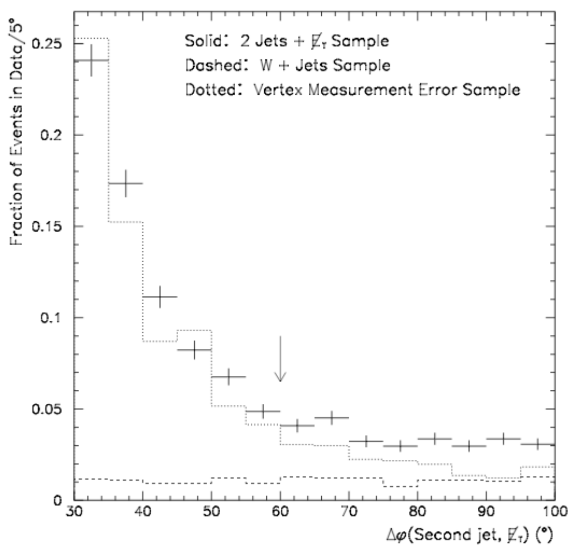


Fake MET Signatures

- **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





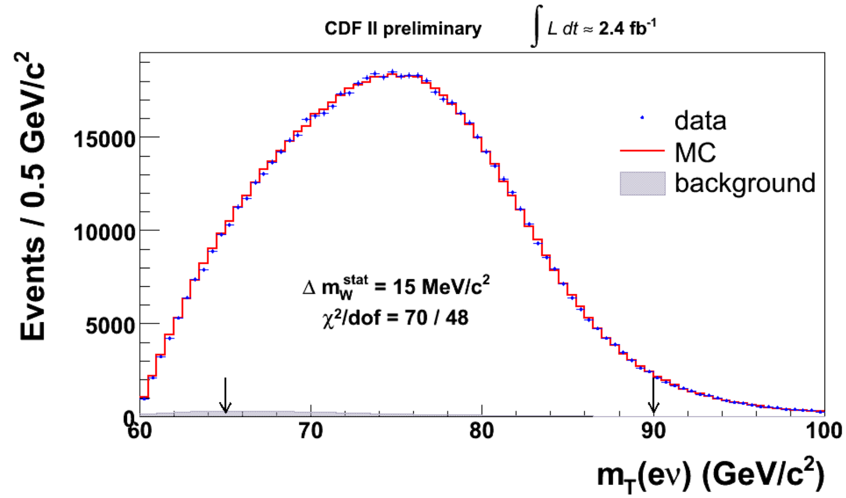
- **In CDF and D0, biggest source of MET comes from "poorly measured" jets**
  - **Two sources**
    - Statistical fluctuations in energy
    - Cracks and/or dead regions
  - **Reduce these by rejecting events with MET correlated with large energy deposition (such as a jet)**
  - **Attempting to correct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

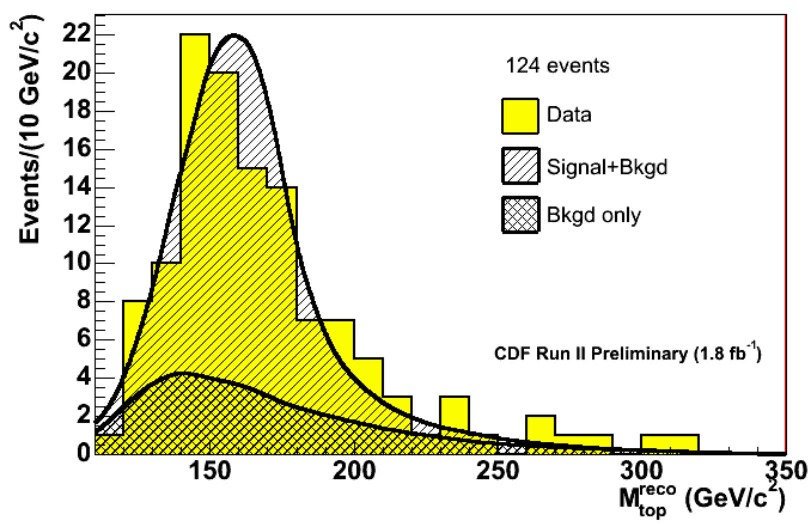
Use of MET in Analyses

- **MET is primarily a measure of ν P_T**
  - **What you DON'T get is the P_z of the neutrino**
    - Don't know x_1 or x_2 of 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 information in measurements such as M_W**
- **Use in top dilepton events shows that one can deal with multiple ν final states**

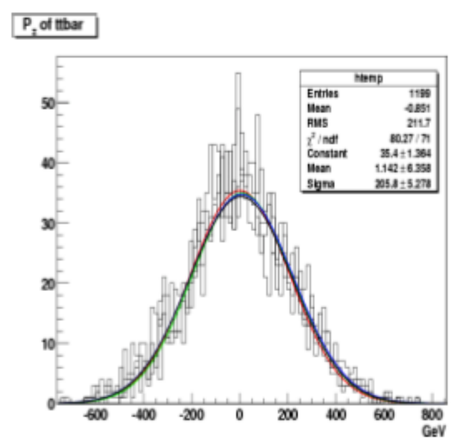


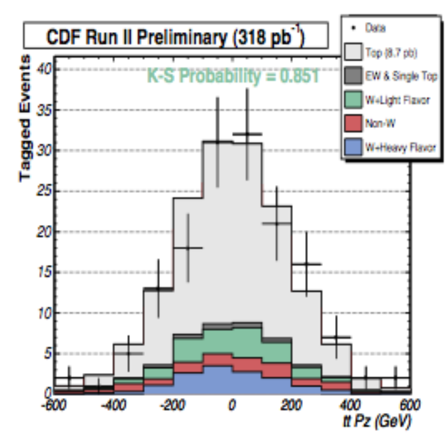


Can One Recover P_z?

- **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" 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





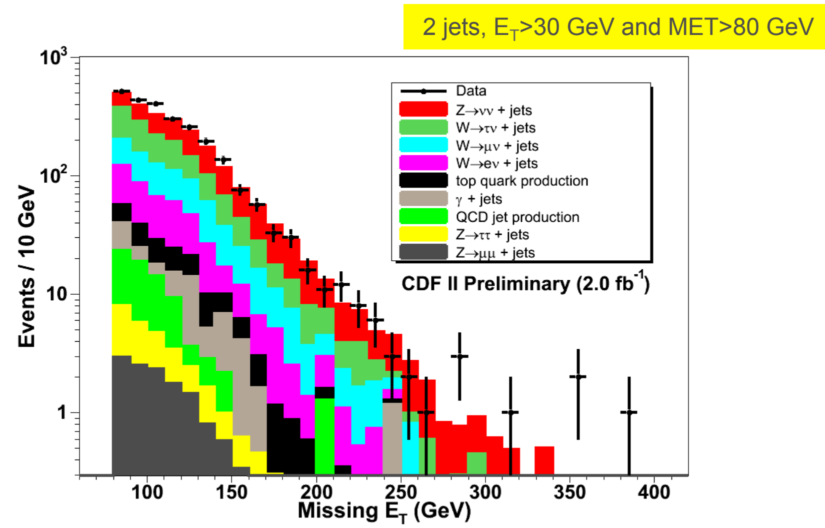
Background Considerations

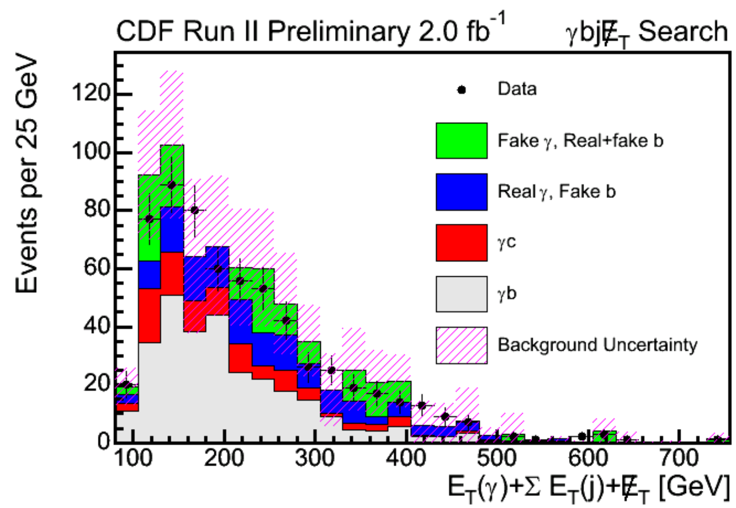
- **At very large MET (aside from instrumental effects), most serious backgrounds are "irreducible"**
  - **Physics signatures that produce real MET, e.g.**

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

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

- **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**

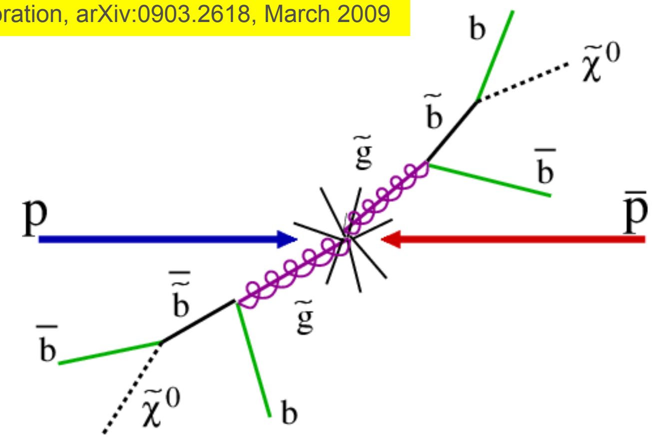




Example: MET in Gluino Search

- **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

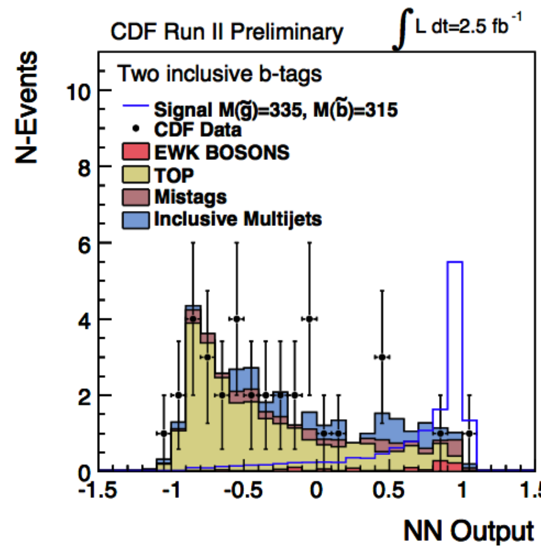


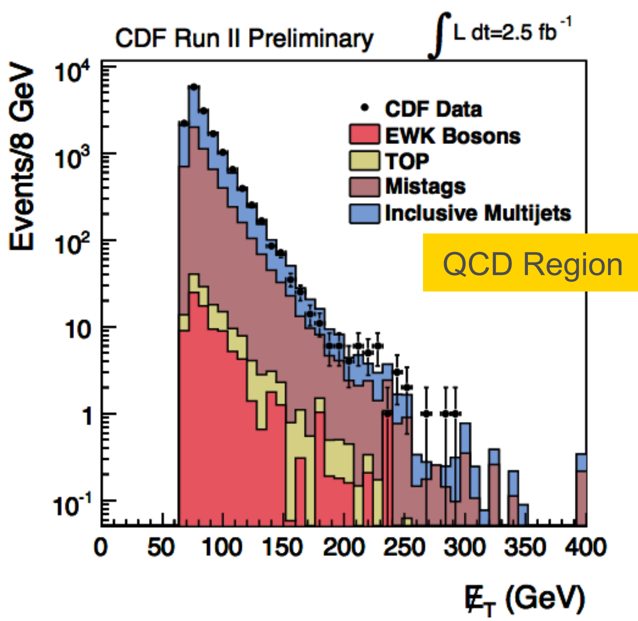
CDF Run II Preliminary 2.5 fb^{-1}

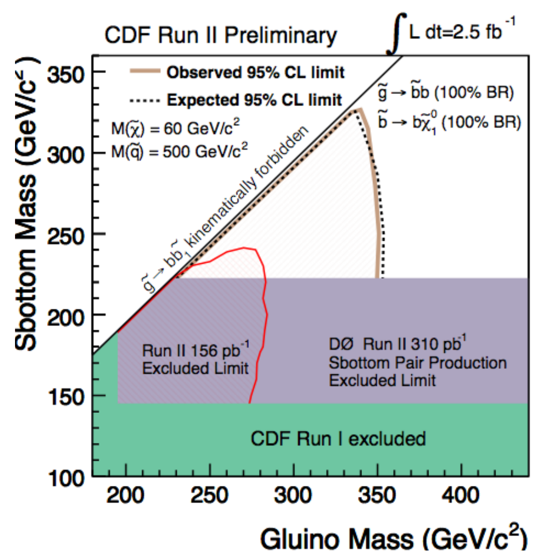
Two Inclusive Tags	QCD Region	Lepton Region	Preoptimization Region
W/Z + jets production	10 ± 7	19 ± 14	29 ± 22
Diboson production	0.4 ± 0.1	2 ± 0.6	4 ± 1
Top pair production	18 ± 6	107 ± 34	140 ± 45
Single top production	1 ± 0.2	4 ± 1	6 ± 1
HF QCD Multijets	864 ± 432	23 ± 11	273 ± 136
Light-flavour 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







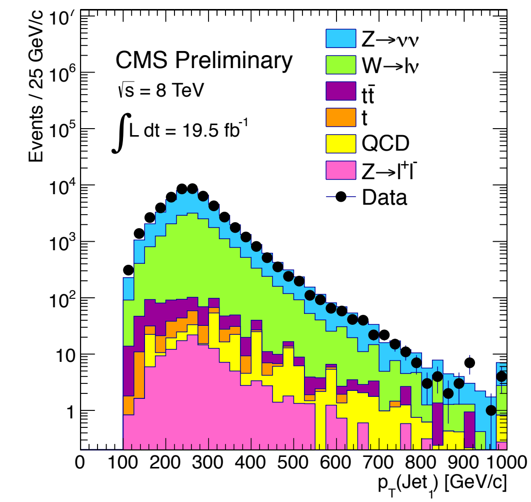
CMS Monojet Search

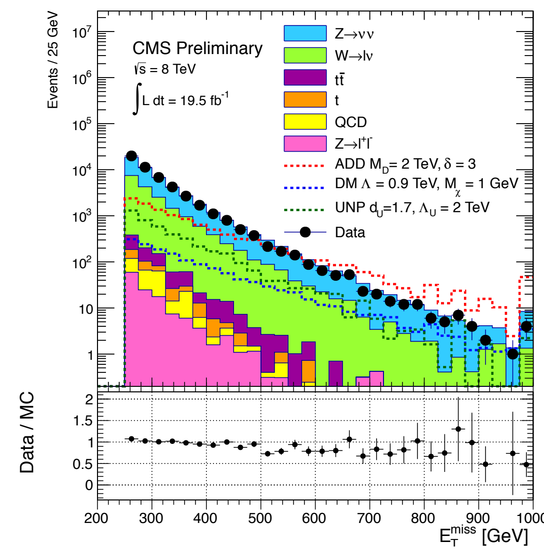
CMS has looked at monojets in 19.5 fb^{-1}

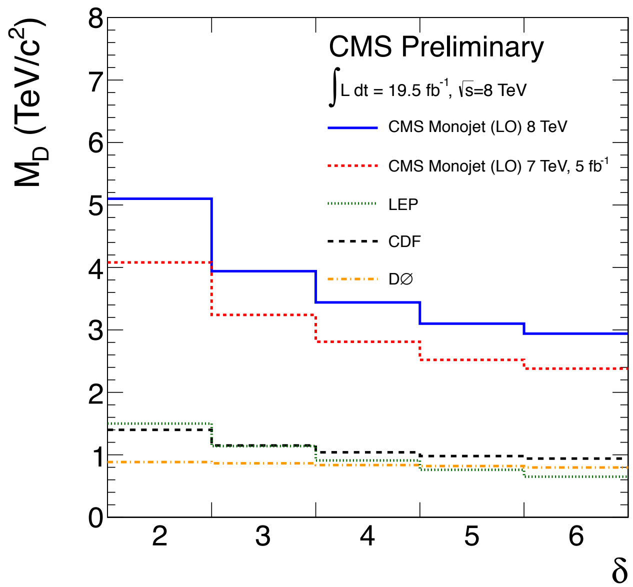
- Looks in 7 regions with E_T^{miss} >250 GeV to E_T^{miss}>550 GeV in 50 GeV steps
- Looks at events with only one recoil jet

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