

# Collider Signatures of Dark Matter

## Lecture 1

- **Dark Matter Paradigm**
- **Missing Energy Signatures**
  - **Tevatron**
  - **LHC**

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# Dark Matter at Colliders

**There is a remarkable optimism about “observing” Dark Matter at colliders.**

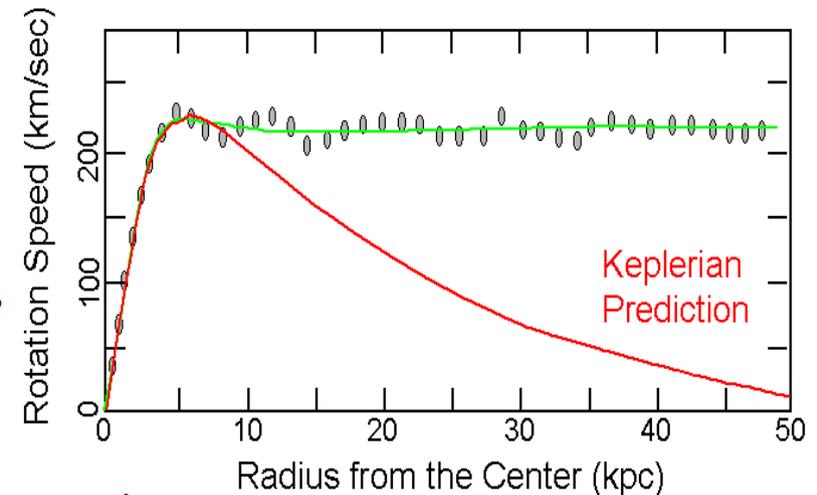
All evidence for Dark Matter is purely gravitational.

→ *amazing that particle accelerator experiments can tell you anything about this.*

The key is Jonathan Feng's “WIMP Miracle”

→ *(assume dark matter is particulate), take TeV or EWK-scale masses, take coupling constants of order 1, you get the right annihilation cross-section.*

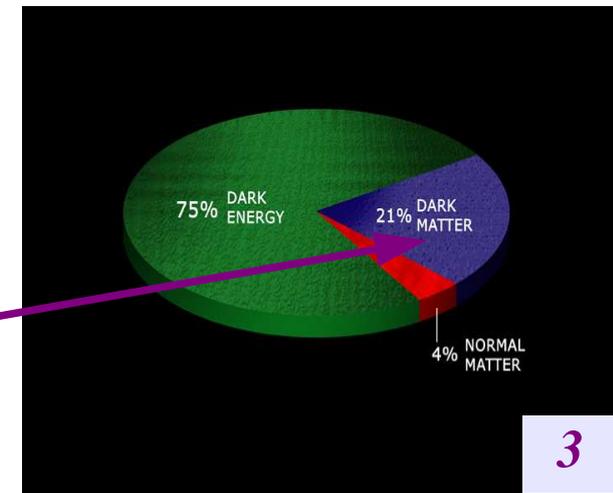
Observed vs. Predicted Keplerian



# DM (particle) paradigm

- **dark matter particles are weakly-interacting**
  - for sure no electric charge and no color,
  - and we *hope* that they will oblige us with weak interactions
- **they are massive**
  - happy coincidence argument: 50 – 5000 GeV
  - they could be much lighter or heavier, if we forget particle physics
- **there is only one type of dark matter**
  - and it can be produced directly or in “simple” cascades
- **there exists an efficient annihilation channel**
  - needed to obtain the observed relic density
  - implies the existence of *another* particle

*simple composition?*



# Bridging Colliders to the Universe

- If the particle physics prejudices are correct, new particles are likely to be observed at the LHC - and maybe at the Tevatron.
- There may be evidence of massive, weakly-interacting, neutral particles.
- This would support a particle-physics explanation for dark matter.

## Can we go from there to validating this paradigm?

- ★ obviously, identify the WIMP and measure its properties
- ★ essential to identify the particle(s) responsible for annihilation
- ★ cannot prove long-term stability, so corroboration with direct-detection experiments is essential.
- ★ don't know local dark matter density, so indirect-detection needed to tie direct-detection + collider information to astrophysics data

**Colliders provide the means to measure particle properties, and one of these particles may turn out to be the dark matter particle.**

# What are Colliders?

## Tevatron

- collide protons and anti-protons at c.m. energy of 2 TeV
- currently operating at Fermilab (Illinois)
- well-established and successful: (top quark,  $B_s$  oscillations, ...)

## LHC

- collide protons on protons at c.m. energy of 14 TeV
- currently under construction & commissioning
- expected by most to find New Physics beyond the S.M.
- should produce WIMPs if they exist

## ILC

- collide electrons and positrons at c.m. energy of 0.5 – 1 TeV
- a well-supported proposal for the future
- not yet funded, nor any site chosen
- intended to make precise measurements of new particles which will allow us to infer the correct new theory beyond the S.M.
- if successful, first principle calculations of relic density possible.

# High-Energy Colliders: testing the paradigm

## Can the LHC rule out the standard paradigm?

- there should be a missing energy signal from particle  $X$ !
- more interesting: can we find the particle  $Y$  participating in annihilation?
- can we show that the mass difference  $M_Y - M_X$  is appropriate?
- to what extent can we test the properties of  $X$  and  $Y$ ?

## Can the LHC fail to observe dark matter particles?

- ★ yes, if it were very light or very heavy
- ★ moreover, we could fail to find particle  $Y$

## What can the ILC do?

- One would like to confirm relic density calculations based on particle physics.
- impossible to pin down the precise properties of WIMPs at hadron colliders
- an appropriate high-energy  $e^+e^-$  machine would provide the right data.

# Supersymmetry

The Standard Model (SM) of particle physics is theoretically incomplete – there are many questions it cannot answer, and many aspects which are *ad hoc*.

We believe there is a better theory which rectifies at least some of the deficiencies of the SM, and which will also predict phenomena beyond the SM (BSM).

Probably the best candidate for the correct theory BSM is Supersymmetry (SUSY), though other very different theories are interesting and deserve attention. Today, however, SUSY!

There are many motivations for the theory of Supersymmetry, and there are reasons why it is so popular among speculations.

# Motivation 1: Extend the Poincaré Group

We would like to unify all the forces of Nature, including gravity.

Spin-1 (gauge) bosons and spin-2 bosons (gravity) cannot be placed in the same representation, in general.

The only exception is: **SUPERSYMMETRY.**

If  $Q$  is a generator of SUSY algebra, then by definition

$$Q |fermion\rangle = |boson\rangle \quad \text{and} \quad Q |boson\rangle = |fermion\rangle$$

This allows the sequence

$$spin\ 2 \rightarrow spin\ 3/2 \rightarrow spin\ 1 \rightarrow spin\ 1/2 \rightarrow spin\ 0$$

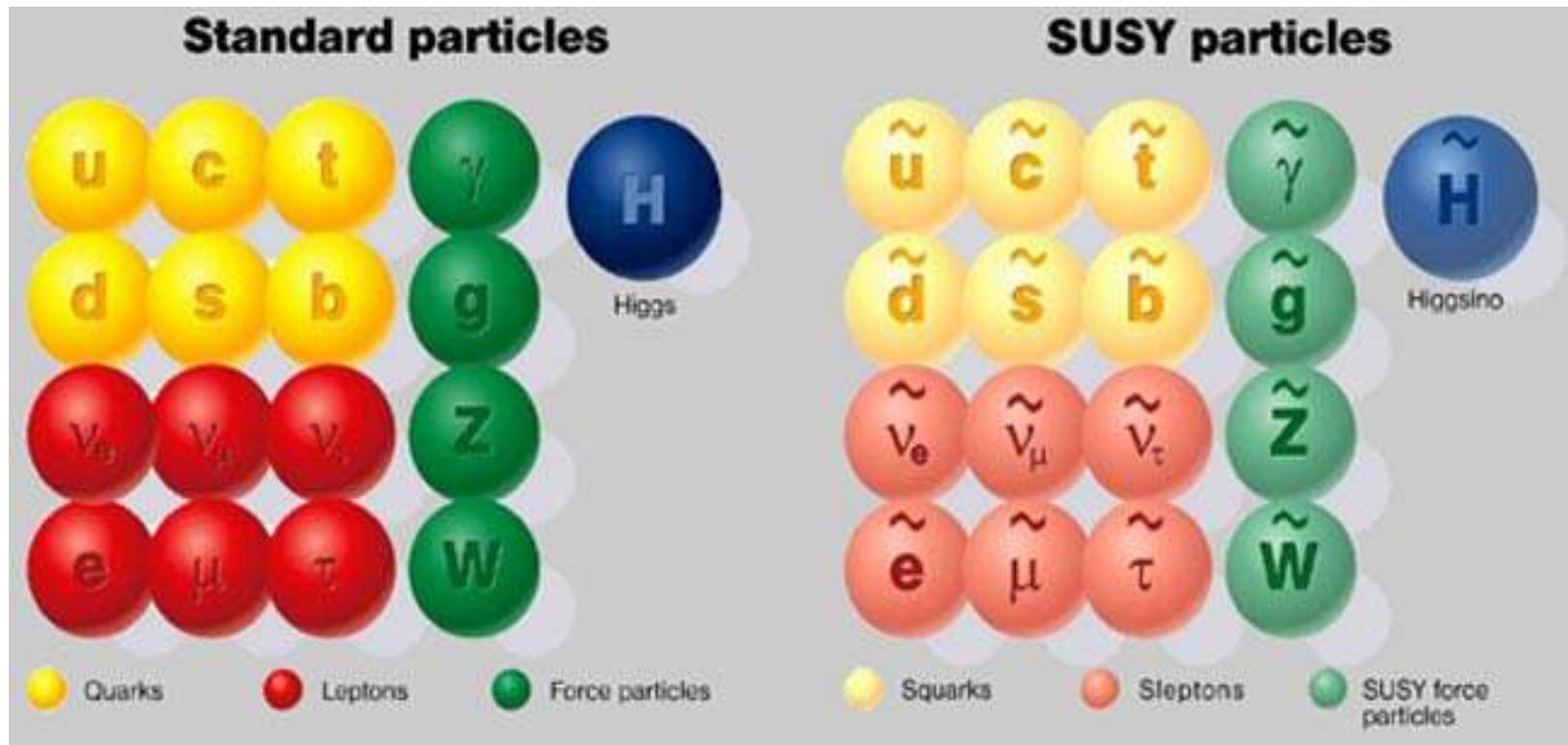
which shows that unification with gravity implies boson/fermion symmetry.

Taking infinitesimal transformations based on  $Q_\alpha$ , and demanding that they be local, requires a theory like General Relativity.

This makes Supersymmetry mathematically unique, and valuable.

Finally, one should note that String Theories require Supersymmetry.

# The particle mirror



For every SM fermion (the matter particles), there is a SUSY boson (spin-0).

For every SM boson (the force carriers), there is a SUSY fermion (spin-1/2).

*Note, also, that particles mix to form mass states, when not forbidden by some symmetry (conservation rule).*

## Motivation 2: Dark Matter Candidate

The lightest supersymmetric particle (LSP), typically is neutral and interacts only weakly with matter. Of course it has mass, too...

If this LSP is stable (which has to be postulated) then there will be relic particles left over from the big bang.

It turns out that the density and mass of the LSP today easily matches that of dark matter!

There are a number of scenarios which have been carefully explored and calculated, which lead to a variety of related observations in colliders – should SUSY be the correct theory BSM!

# Motivation 3: Unification of Forces

Unifying the known four forces has always been a goal – a paradigm – of particle physics. (These are the famous “GUTs”)

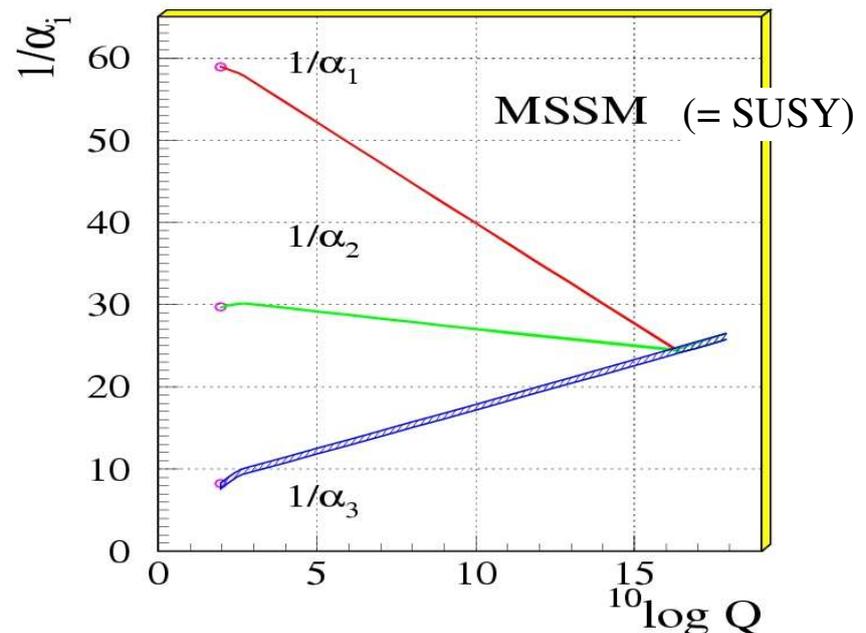
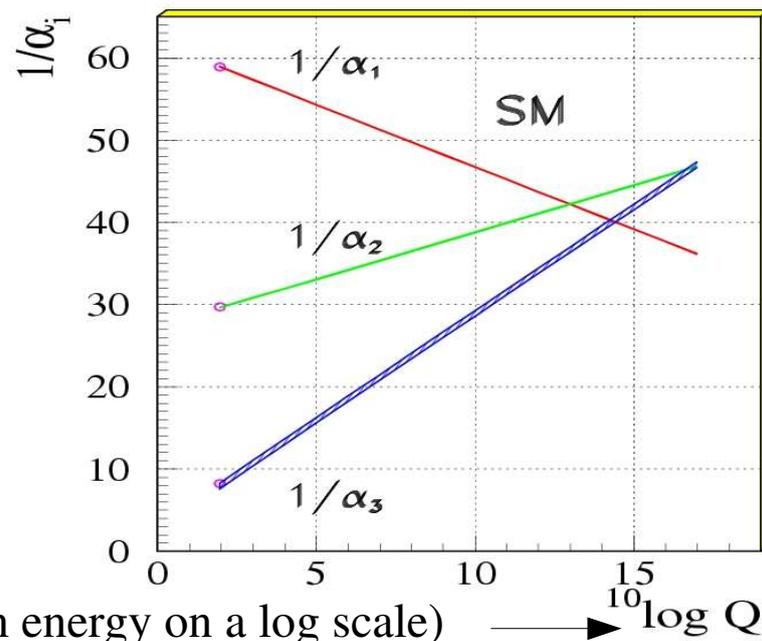
“Unifying” means that there is a mass scale (or interaction energy) at which the electromagnetic, weak, and strong interactions have the same strength.

(Gravity is left out of the picture most of the time.)

The way the forces change with interaction energy is well known from precision measurements. One can extrapolate to high energies.

In the SM, the three forces do not unify at a common point.

In SUSY, they do!



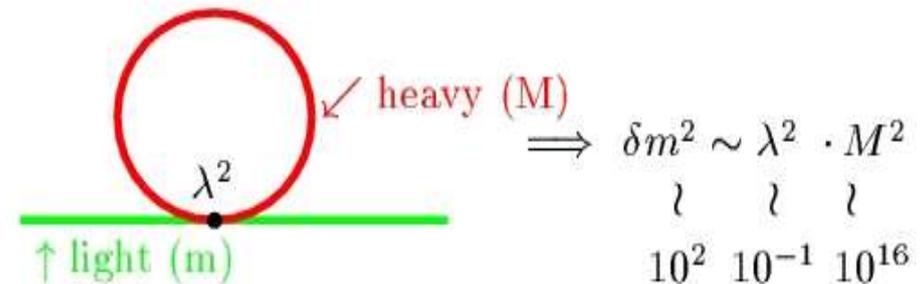
(interaction energy on a log scale)  $\longrightarrow 10^{\log Q}$

# Motivation 4: Taming Higgs UV Divergence (also known as the “Hierarchy Problem”)

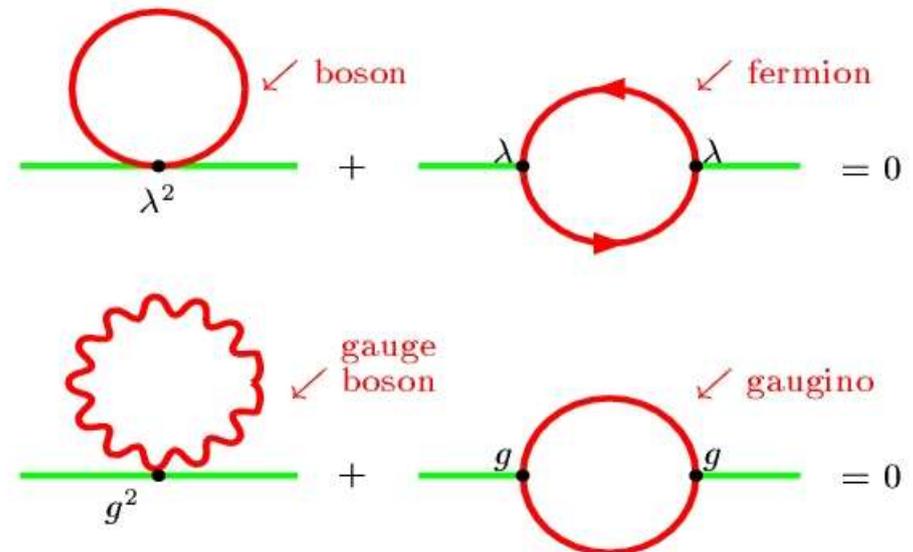
The Higgs mechanism provides an explanation for the masses of the gauge bosons (via “Electroweak Symmetry Breaking” - EWSB), and hence is a fundamental feature – and success – of the SM.

hep-ph/0012288

Unfortunately, if you calculate radiative corrections to the Higgs mass, you obtain divergent contributions which are many orders of magnitude larger (e.g.,  $10^{17}$  GeV) than the mass needed to provide EWSB (around  $10^2$  GeV), and in the SM there is no good way to cure this.



It turns out that SUSY naturally solves this problem, since the boson contributions have opposite sign to the fermion contributions. Due to the symmetry between bosons and fermions, the sum of all contributions is strictly limited!



# Why Colliders?

The symmetry between SM particles and their SUSY partners clearly is not maintained (otherwise we would have a light selectron, *etc. etc.*)

It is fair to assume that sparticles must be heavy.

**So, in order to observe and study them, we need high energy collisions.**

Hadron colliders provide the highest C.M. energies anywhere on earth. The **TEVATRON** collides proton and anti-proton beams of energy nearly  $1 \text{ TeV} = 1000 \text{ GeV}$  (about 1000 x proton mass).

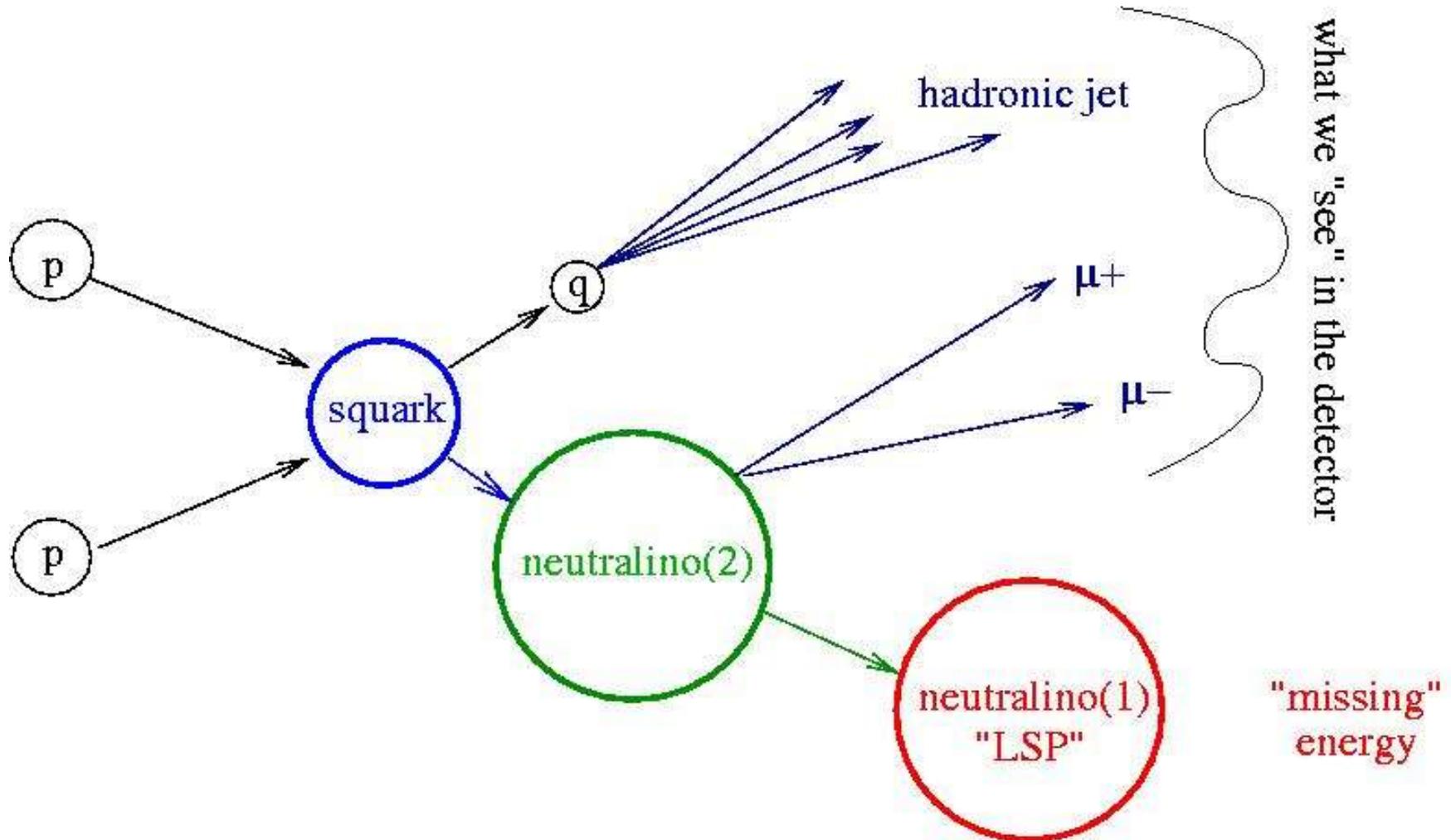
The LHC will be seven times more energetic – and even better able to produce heavy particles.

Keep in mind that only the quarks and gluons inside the proton actually collide, so only a small fraction of the TeV energy is available for any given interaction, or “event.”

—► even a 0.5 GeV  $e^+e^-$  collider can “compete”

# Experimenter's Toolkit

All sparticles except the LSP will decay.



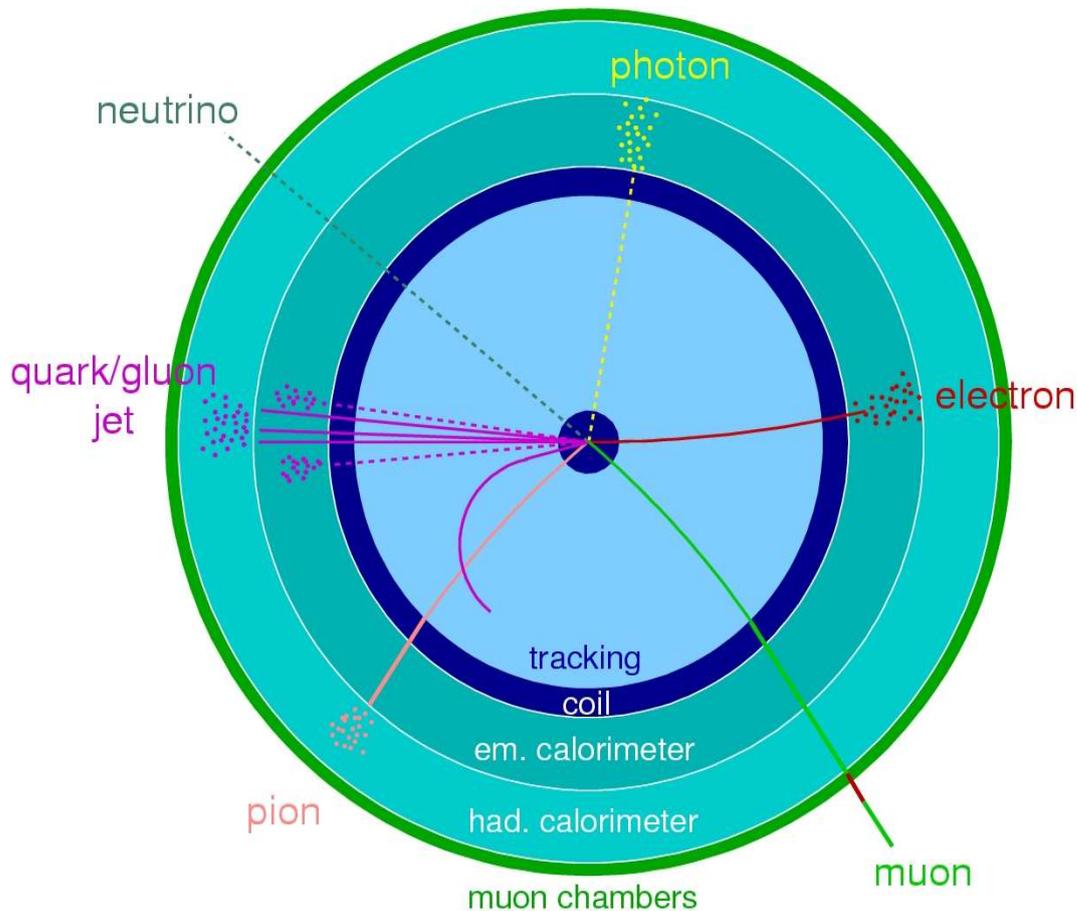
By and large, the decay products will be SM particles, which we need to detect, measure and correlate in order to reconstruct the sparticle that decayed.

The (quasi-)stable SM particles are the relevant ones:  $e$ ,  $\gamma$ ,  $\mu$  and hadrons.

# Collider Detectors

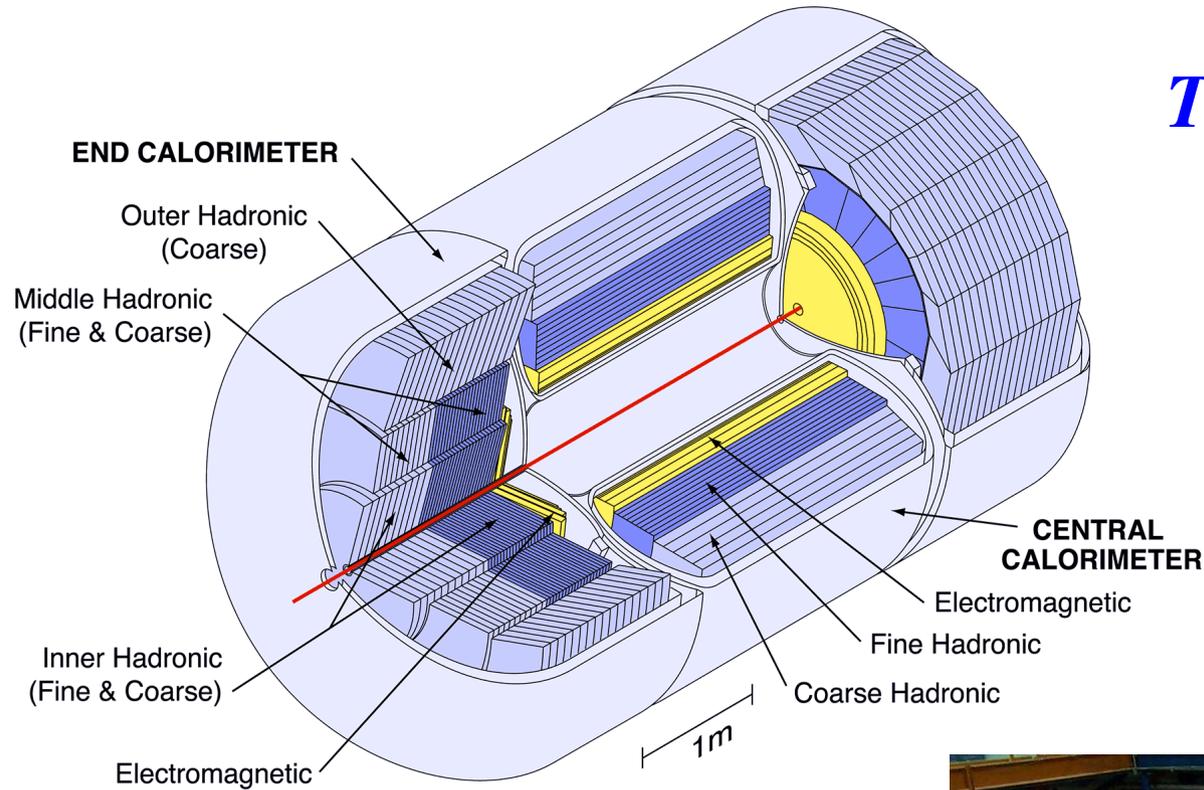
Collider detectors are like a set of nested Russian dolls, each of which tells us something useful.

With all that information, we decide what kind of particles were are detecting, and whether they might come from the decay of one or more SUSY particles.



- charged particles leave tracks
- curvature (B-field) tells us  $p_T$
- e &  $\gamma$  shower in the EM-CAL
- hadrons shower in the H-CAL
- $\mu$  don't shower and reach  $\mu$ -det
- $\nu$  (and LSP's) are undetected

## The $D\bar{0}$ Detector



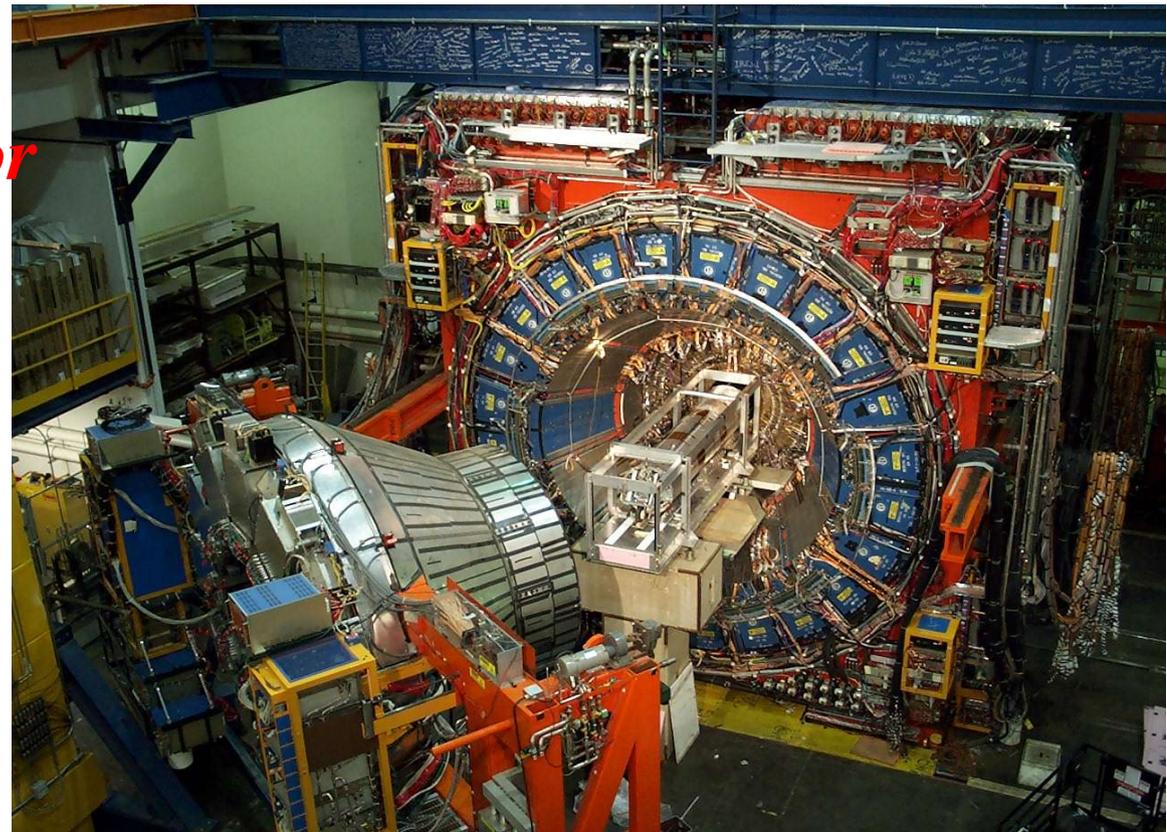
A general-purpose detector with particularly good calorimetry.

Several upgrades for Run II, including new tracker, magnetic field, and Si vertex detector.

## The CDF Detector

Strongest point is the tracking.

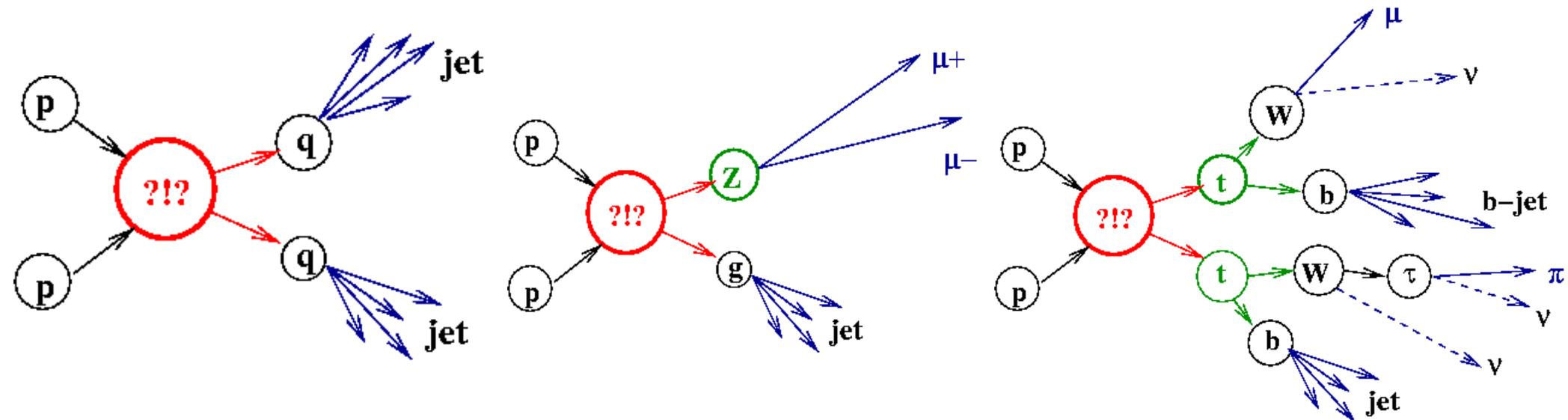
Run II upgrades included advanced Si-based triggering, improved vertex reconstruction & tracking, and improvements to “endcap” calorimetry and muon systems.



# The SM is in the way!

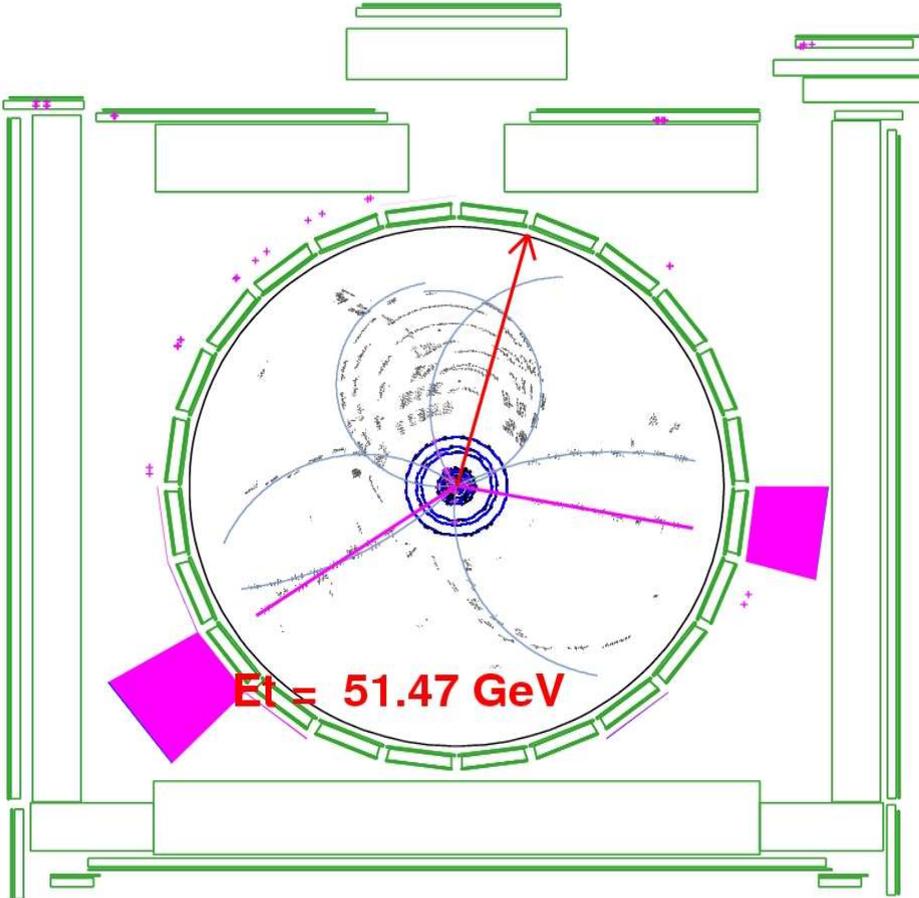
Unfortunately (!?!), there are many SM processes which also produce  $e$ ,  $\gamma$ ,  $\mu$ , and jets, and they obscure any SUSY process that might be present!

- the biggest source of events is q-q or q-g scattering, which leads to jets of hadrons with quite high energies sometimes.
- more interesting are the W and Z events which yield energetic (and isolated) electrons and muons, and sometimes neutrinos
- the top quark (discovered with the TEVATRON in 1995) has a non-trivial decay pattern to b-quark jets, leptons and neutrinos
- boson pairs (such as WW, WZ & ZZ) are produced at very low levels, but are “interesting” because they mimic some of the most distinctive signals for SUSY particles.



Examples of real events:

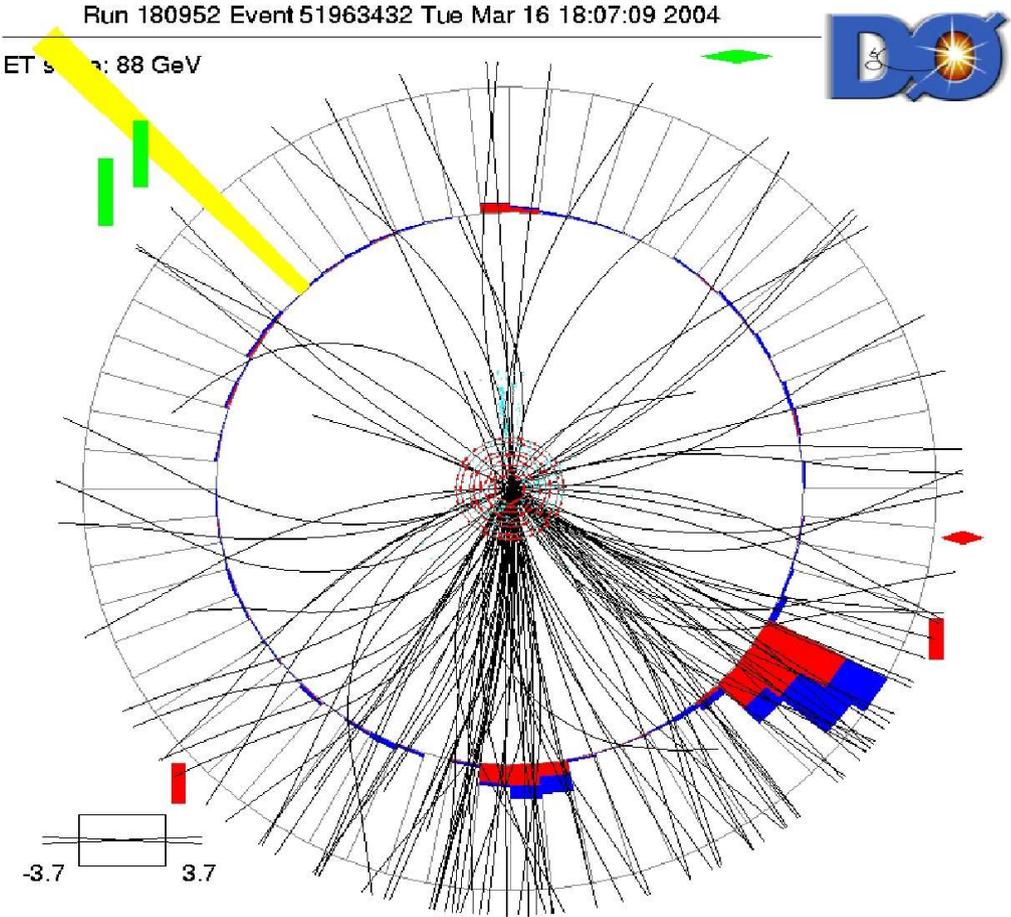
*CDF*



*two electrons and  
“missing” energy*

(from search for di-boson production)

*D0*



*two hadronic jets  
and “missing” energy*

(from search for SUSY)

# Example: Jets and Missing Energy

Since the TEVATRON collides protons and anti-protons, which are made of quarks, anti-quarks and gluons, it makes a lot of sense to look for squarks and gluinos (the SUSY partners of quarks and gluons).

The task is to separate events with squarks and gluinos from ordinary SM events (which we call “QCD events” since they are characterized by strong-interaction processes).

The typical TEVATRON event consists of 2 or 3 energetic jets.

What would be different about an event with squarks or gluinos?

→ *missing transverse energy (MET)*  $\cancel{E}_T$

# What is MET?

The calorimeters are segmented, so we know what energy is recorded where.

Since the incoming quark/gluon energy is not known event-by-event, we focus on kinematic quantities transverse to the beam direction.

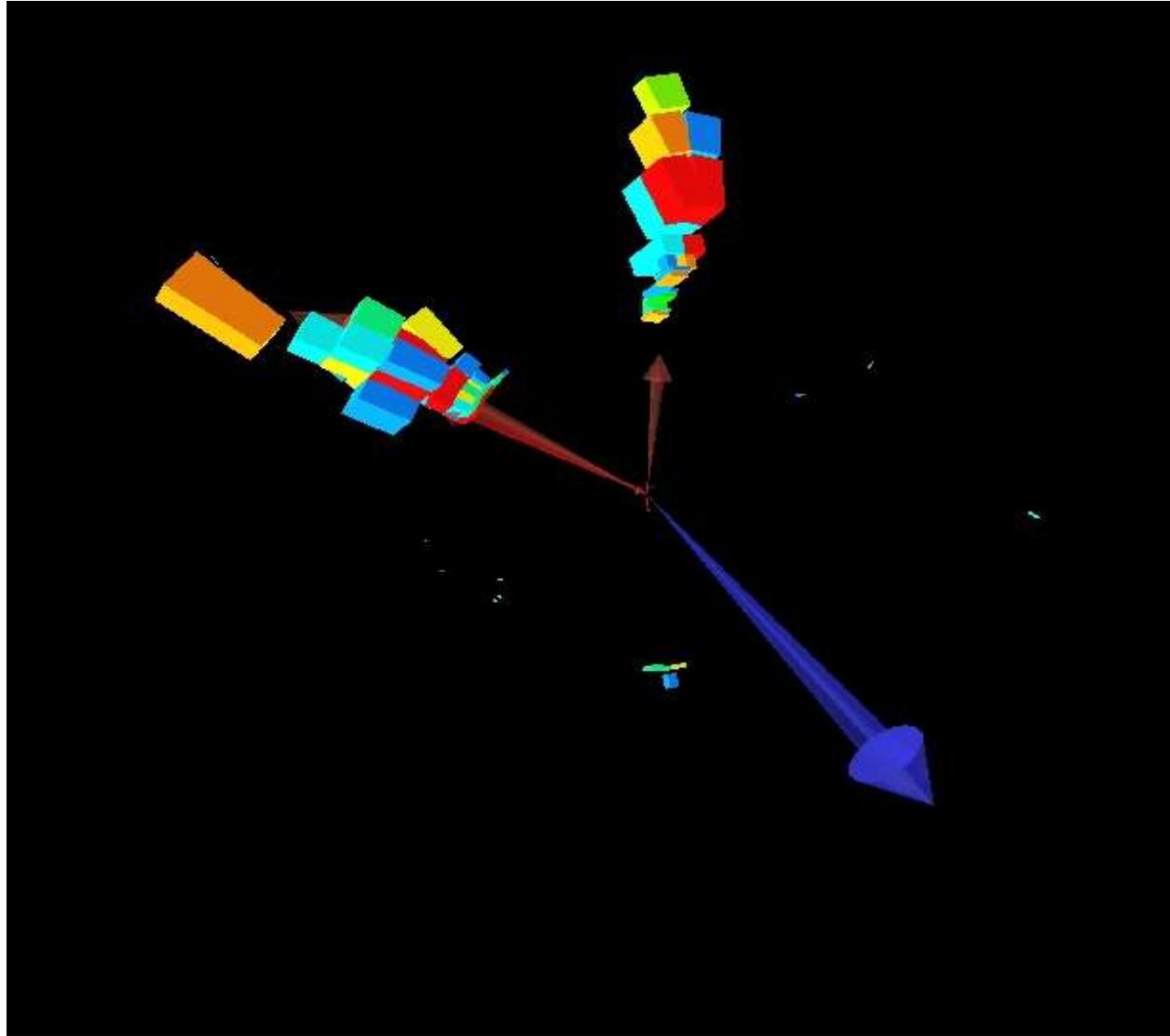
The vector sum of all transverse momenta must be zero!

If something invisible is produced (such as the LSP or a  $\nu$ ), then the sum of all transverse momenta will not be zero: it will be the opposite of the transverse momentum of the undetected particle(s).

This “missing transverse energy” (MET) is absent for most SM processes, but is the hallmark of most SUSY particles.

*exploit this distinction!*

## Example of a real event with large MET, from D0



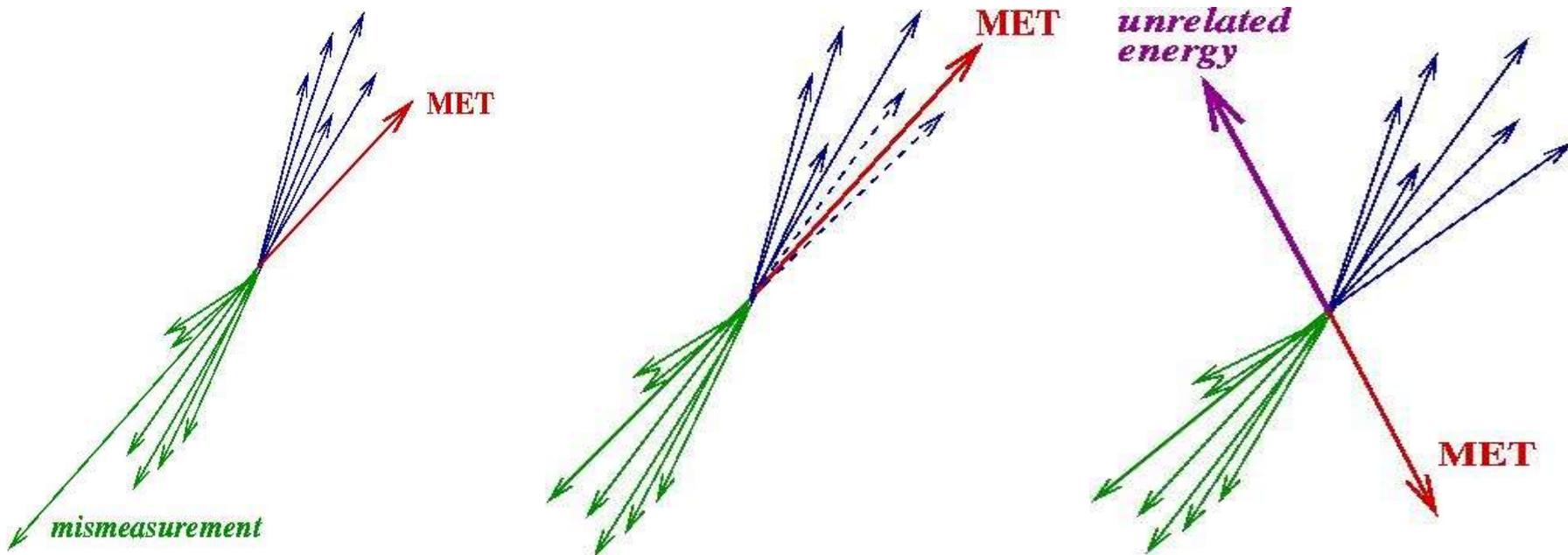
The colored boxes indicate energy deposits in the calorimeter.

The blue arrow shows the direction & magnitude of MET.

It is not so easy to “measure” the missing energy, due to difficult limitations in our instruments.

## What are the sources of MET?

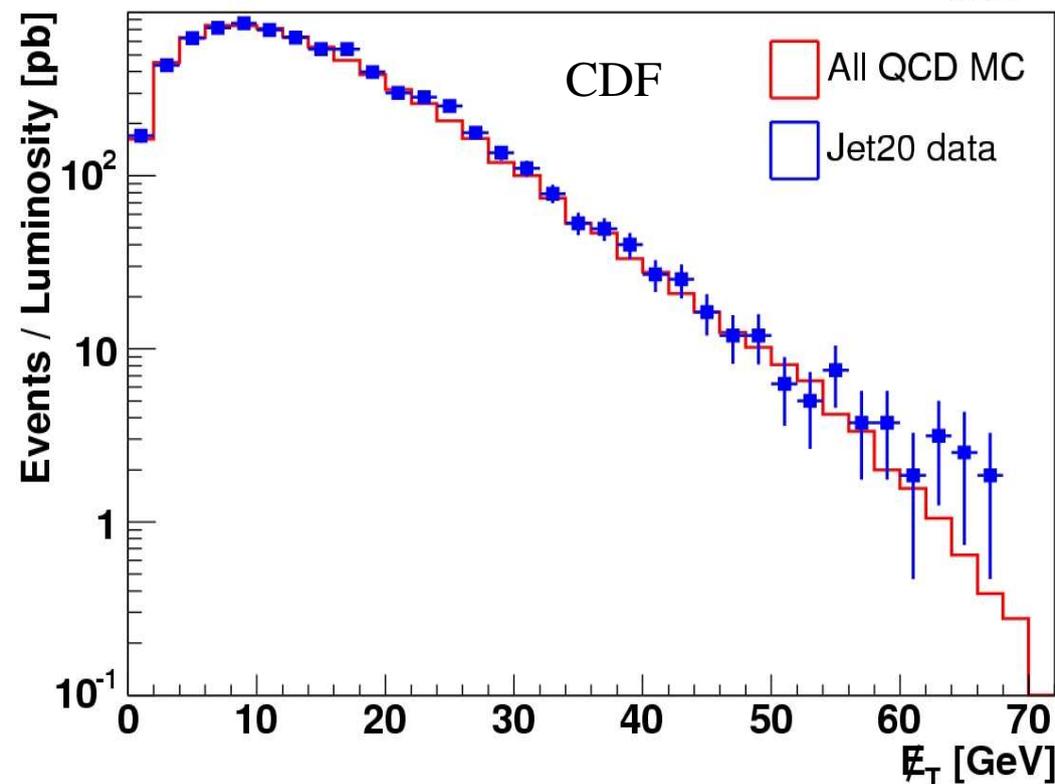
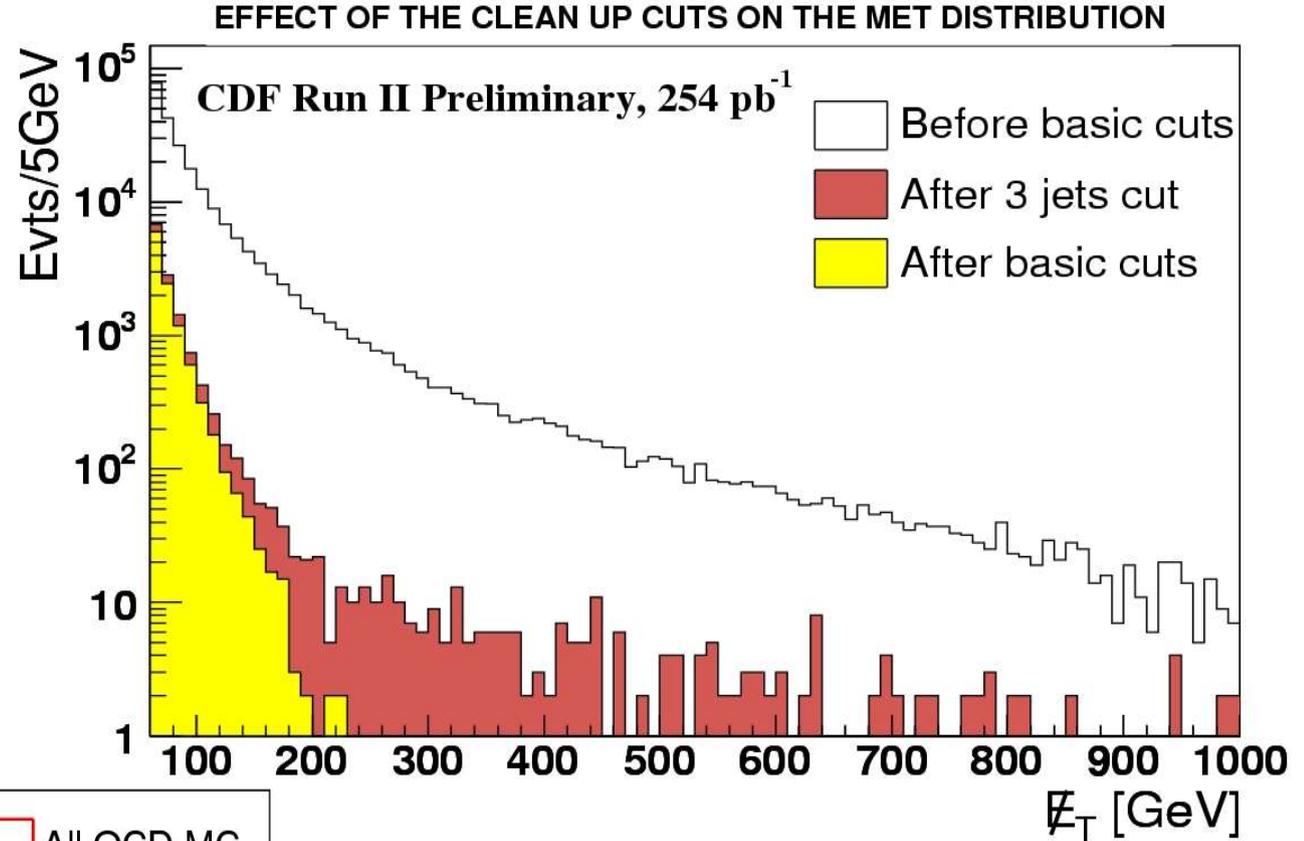
- calorimeter resolution on the jet energies
- losses of energy in uninstrumented regions (“cracks”)
- additional energy unrelated to the primary interaction
- neutrinos and also long-lived neutral kaons plus neutrons
- real LSP's, we hope....



# MET “clean-up”

After a lot of work, we learn how to remove “junk” from our data sample.

- *cosmic rays,*
- *beam halo,*
- *beam-gas events,*
- *calorimeter noise,*
- *etc.*



It is now possible to model the QCD backgrounds from simulation.

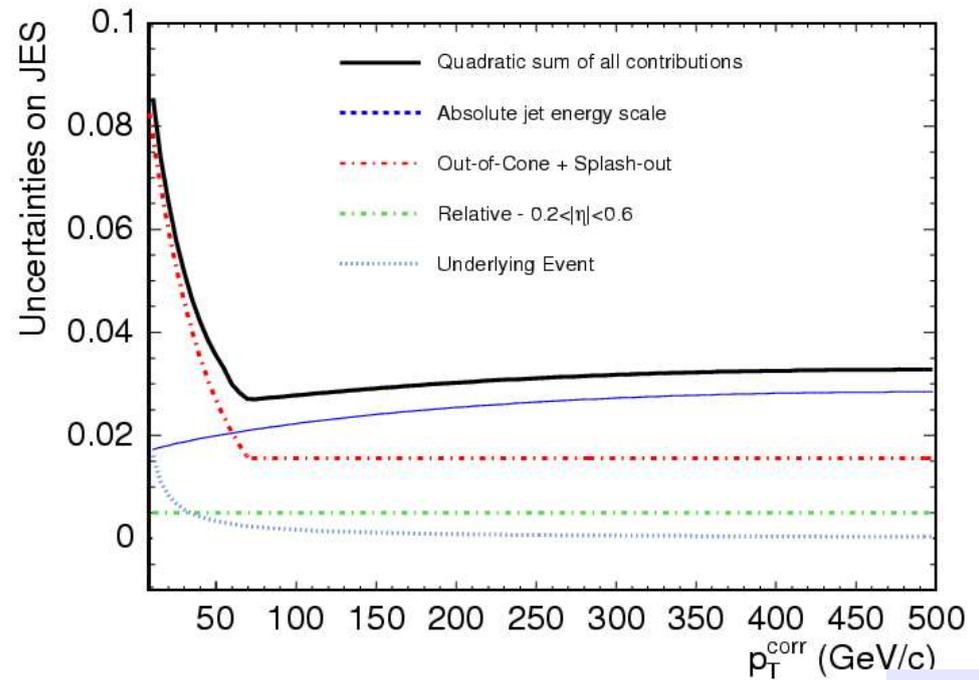
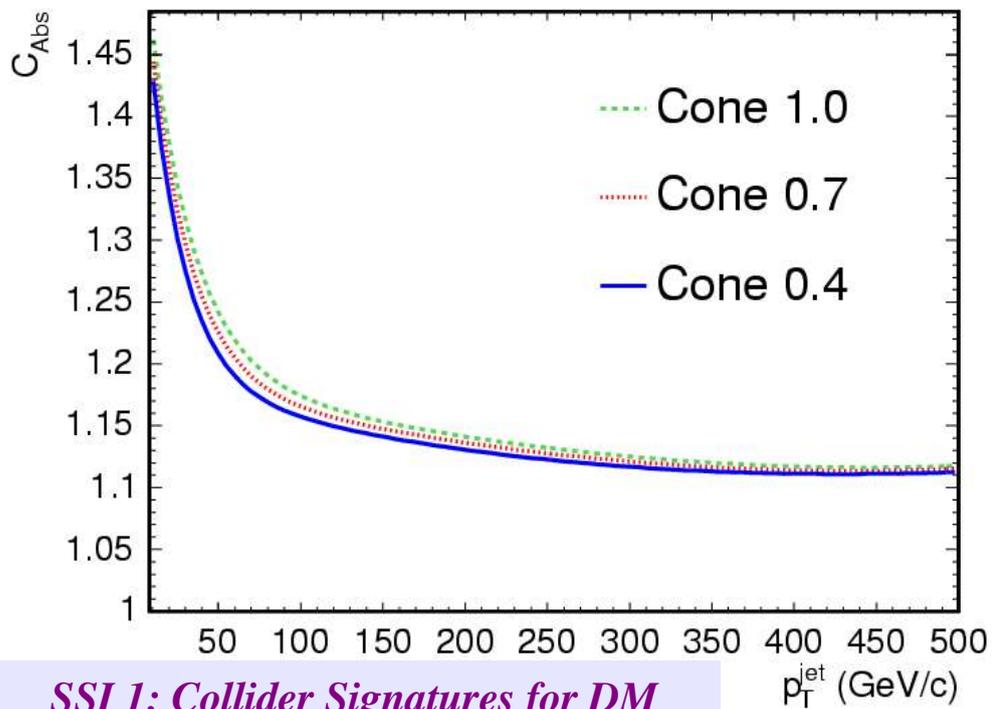
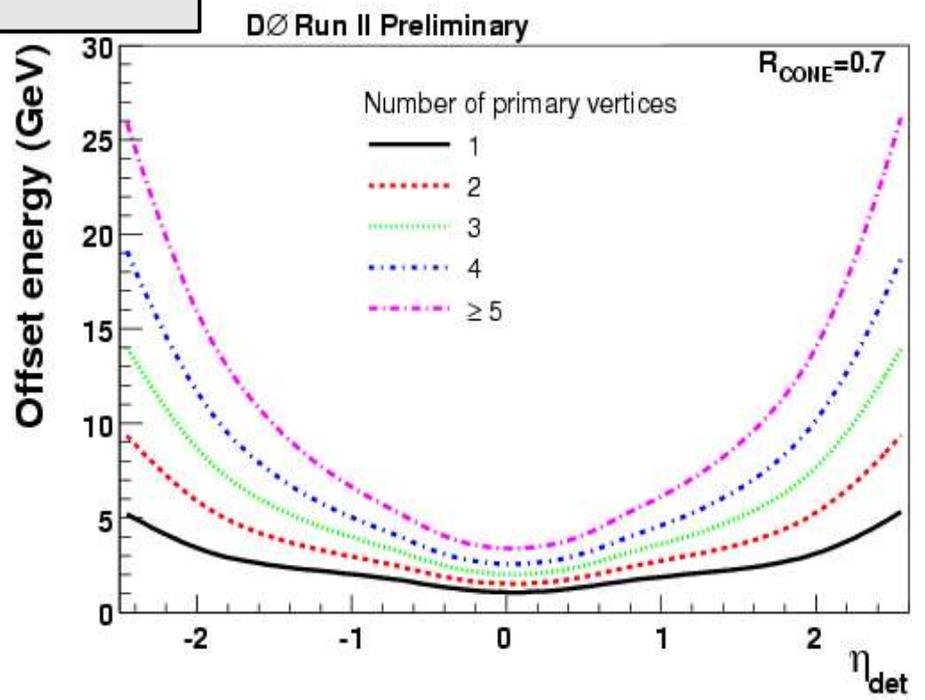
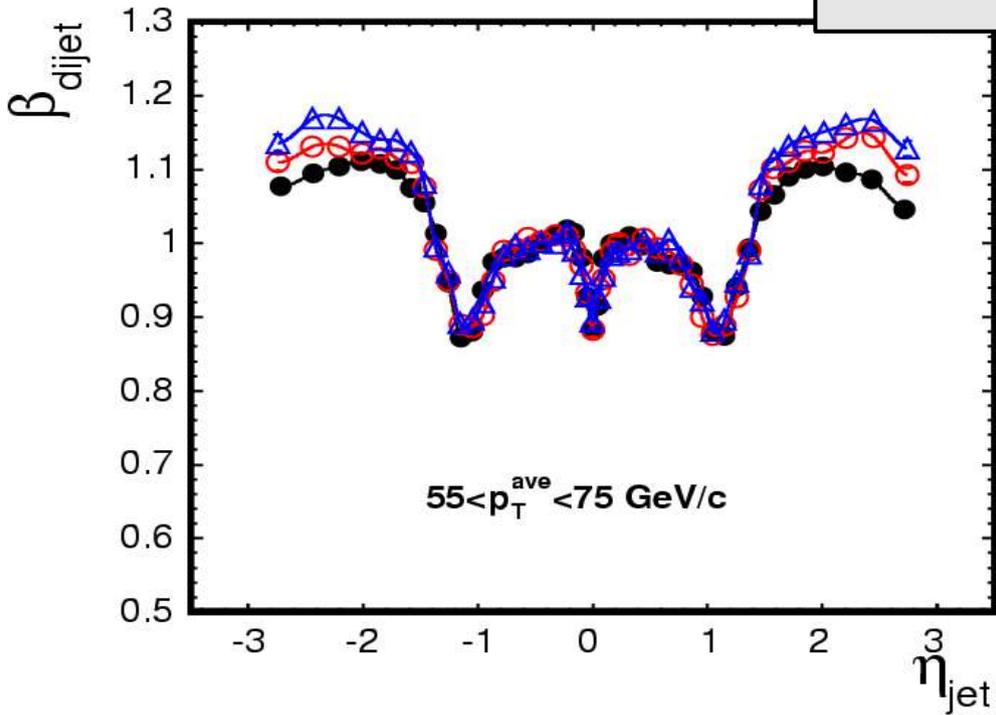
This is important as the QCD background is the most severe for this kind of search.

# After removing “junk” events, one must **CORRECT** the measurements...

## Jet Corrections:

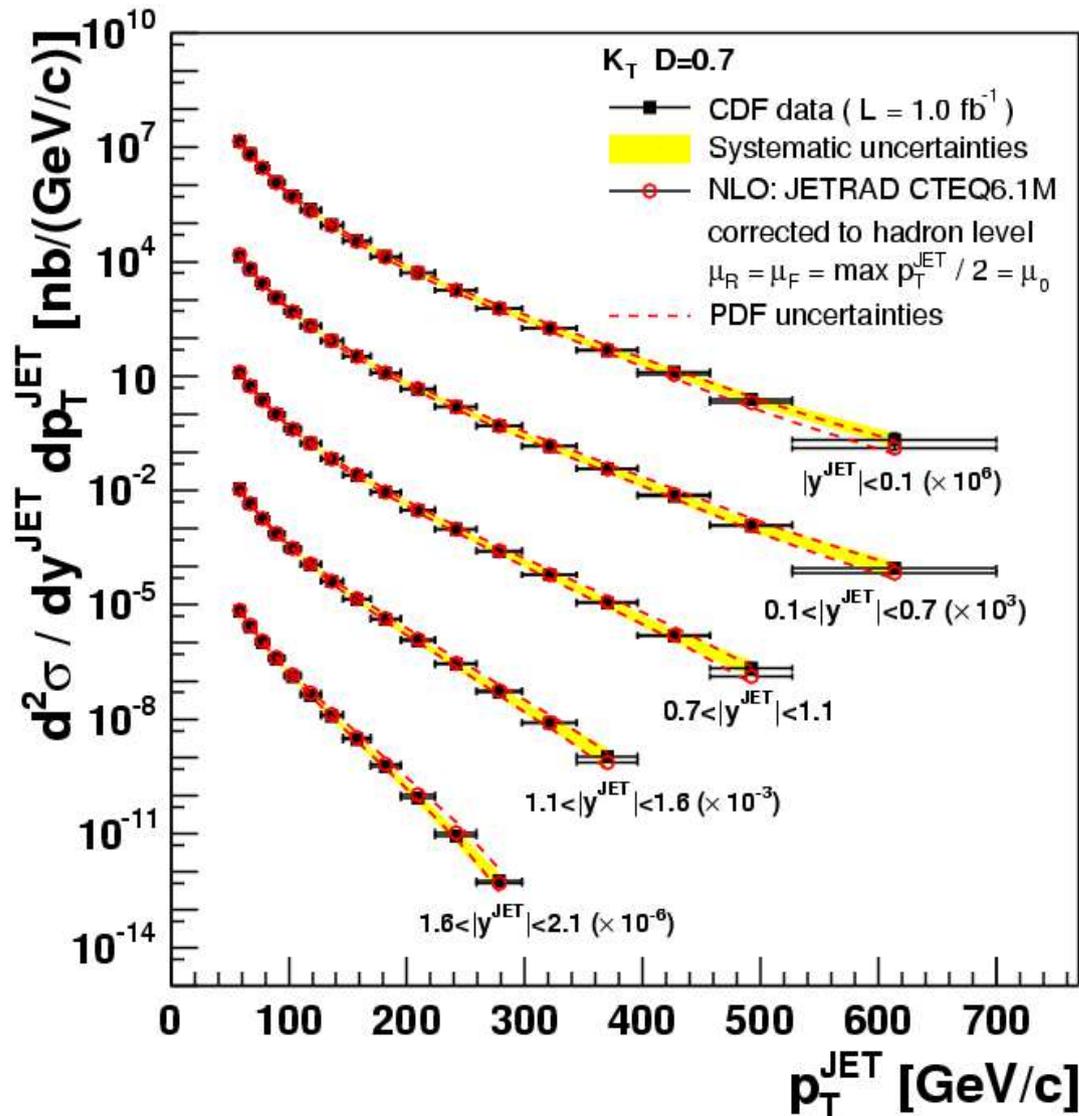
- a jet is not a quark or gluon!
- relating a jet energy to fundamental kinematic quantities is difficult
- instrumental effects
  - ◆ multiple parton interactions
  - ◆ contributions from other simultaneous collisions
  - ◆ readout threshold and zero suppression
  - ◆ “cracks” and other features of the real detector
  - ◆ overall energy scale (When is a GeV a GeV?) & linearity
- physics effects
  - ◆ real particles that deviate from the basic jet (“out-of-cone”)
  - ◆ muons and neutrinos from b-quark and c-quark decays
  - ◆ relating real particles to fundamental quarks & gluons

# Jet Corrections:



This is long and tedious work, but after years of effort, glorious results:

## One example: new measurement of inclusive jet cross-sections ( $1 \text{ fb}^{-1}$ )



*Excellent agreement  
over 7 orders of magnitude!*

- ◆  $k_T$  algorithm
  - ◆ infrared & collinear safe
- ◆ 5 bins in jet rapidity (out to 2.1)
- ◆ “tune A” for underlying event
- ◆ jet-energy scale uncertainty dominates
  - ◆ 5% at low- $p_T$ , 50% at high- $p_T$
- ◆ pQCD NLO calculations: JETRAD
- ◆ non-perturbative theory important
  - ◆ underlying event
  - ◆ fragmentation
- ◆ PDF uncertainties larger than measurement uncertainties

## After you have your best measurement of **Jets** and **MET**, what then?

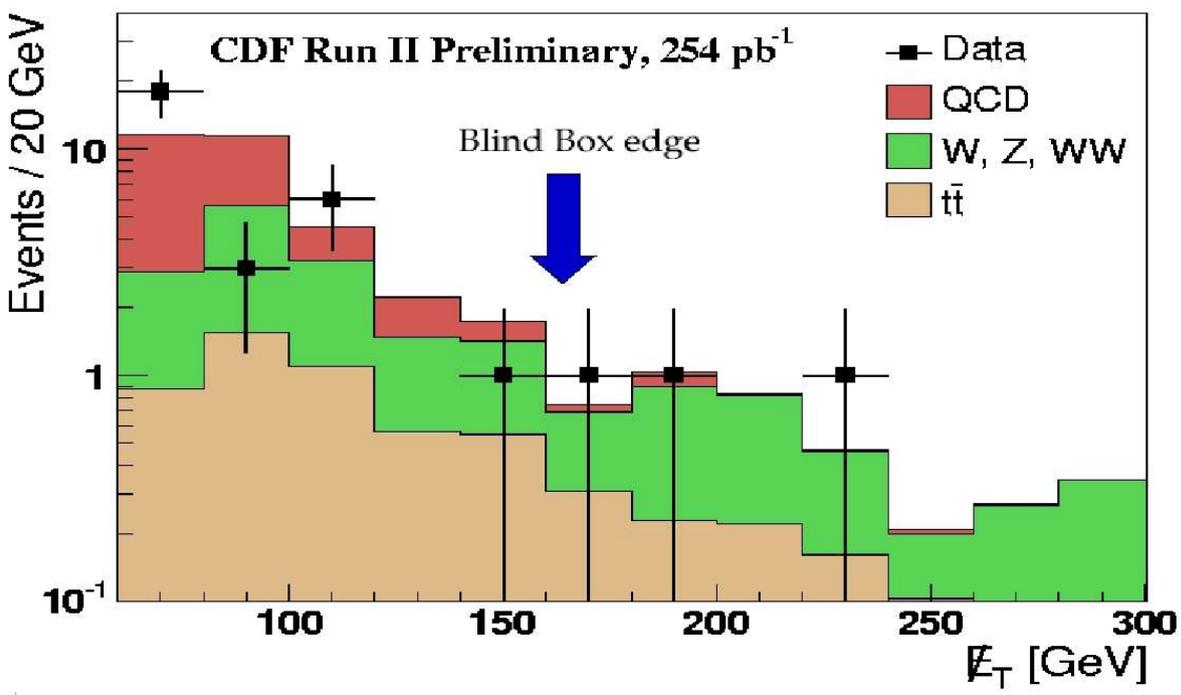
We need to think about the kinematic features of the SUSY events, and see how they might differ from ordinary QCD events.

- if  $M(\text{squarks}) < M(\text{gluinos})$  then
  - ★ • squarks decay to quarks and LSP's  $\longrightarrow 2 \text{ jets} + \text{MET}$
  - gluinos decay to squarks and gluons
- if  $M(\text{squarks}) > M(\text{gluinos})$  then
  - ★ • gluinos decay to a pair of quarks and an LSP  $\longrightarrow 4 \text{ jets} + \text{MET}$
  - squarks decay to a quark and a gluino

Note that we expect  $M(\text{squarks}), M(\text{gluinos})$  to be  $> 300 \text{ GeV}$  or so (mainly because they have not been found for masses less than that).

The **JETS** that come from the SUSY decays will always be **energetic**, in distinction to ordinary jets which tend to have less energy.

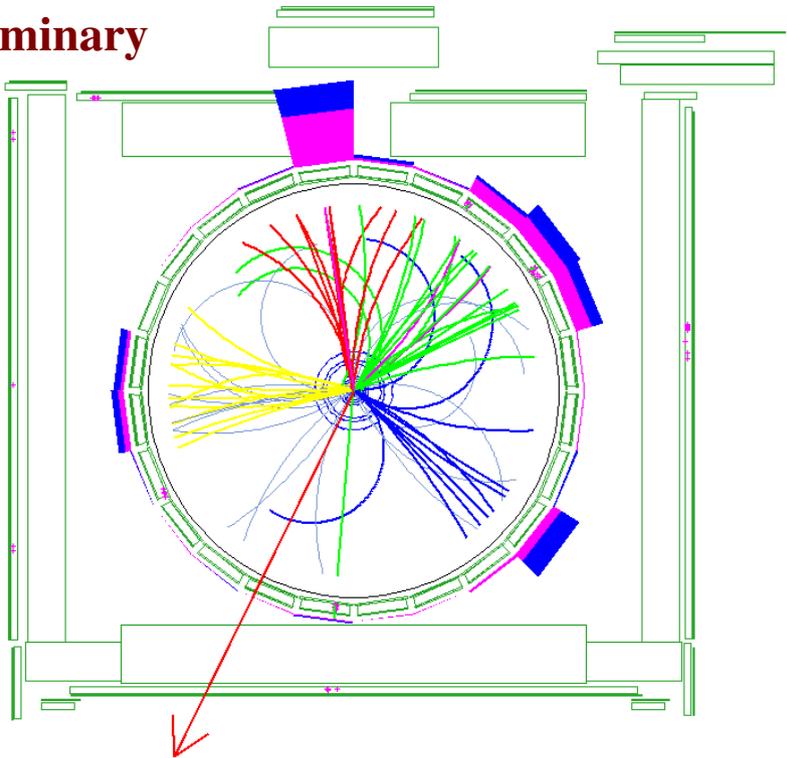
$\longrightarrow$  Require high energies for the jets, and require the sum of jet energies ( $H_T$ ) to be high.



After lots of hard work, one can examine the last few events in the MET distribution.

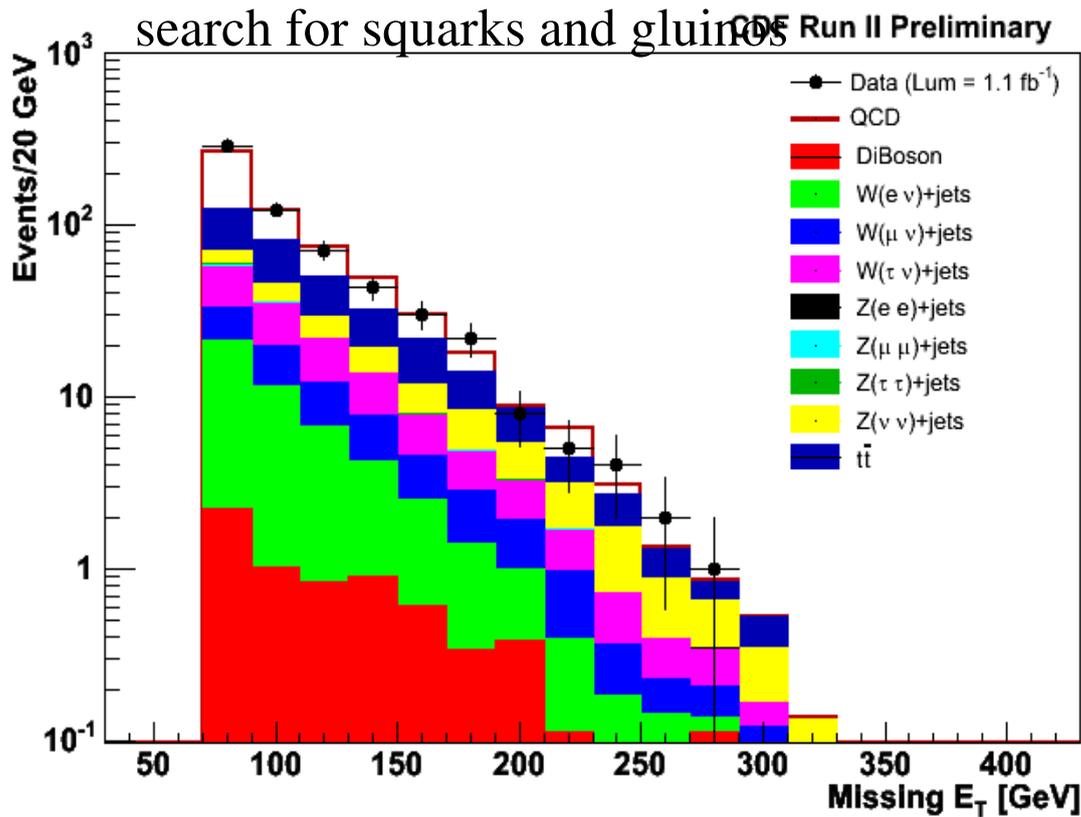
We see no evidence for any excess of events above those expected from SM processes...

CDF preliminary

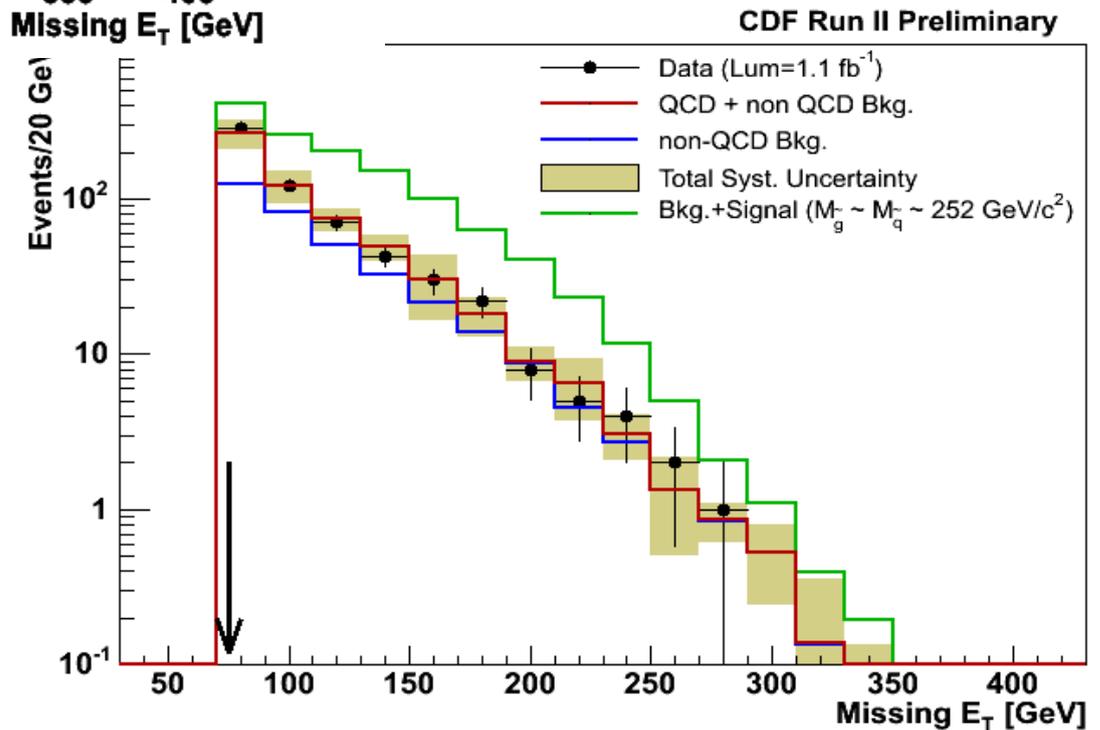


Here is the event with the highest MET.

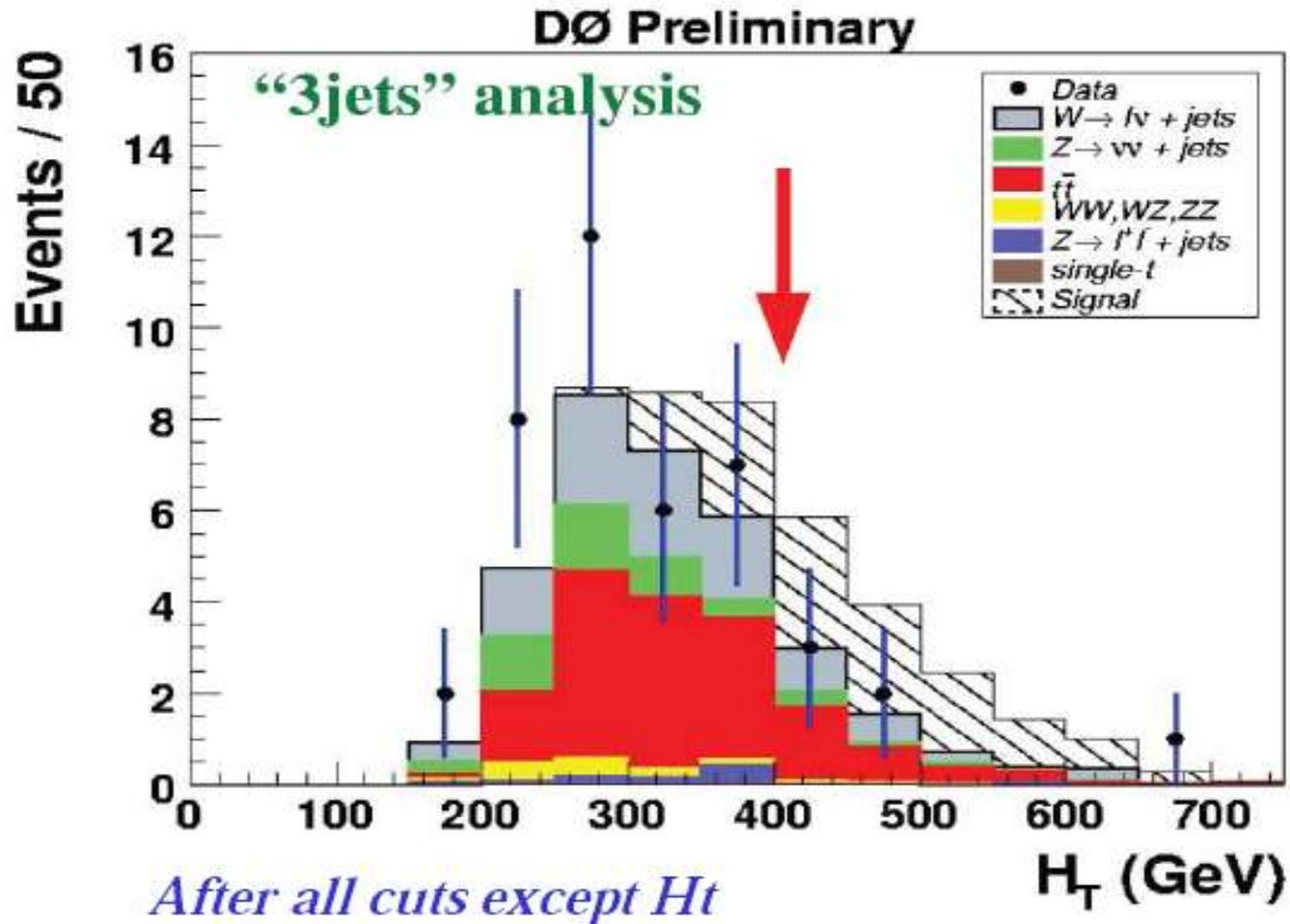
One clearly sees four energetic jets, and a large MET (red arrow).



MET distribution  
for  $1.1 \text{ fb}^{-1}$

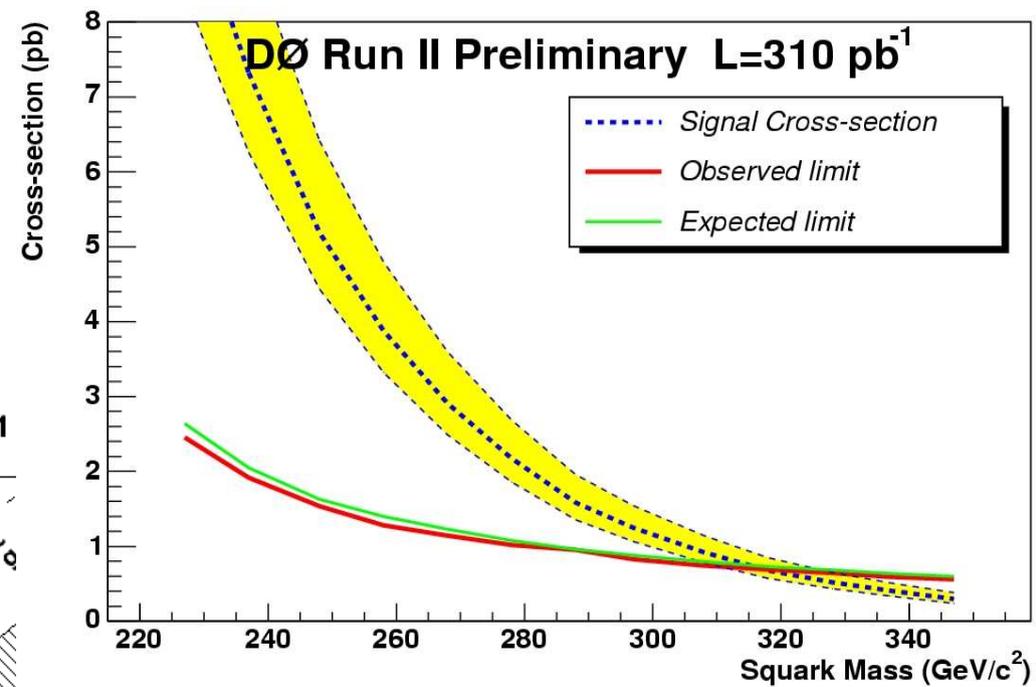
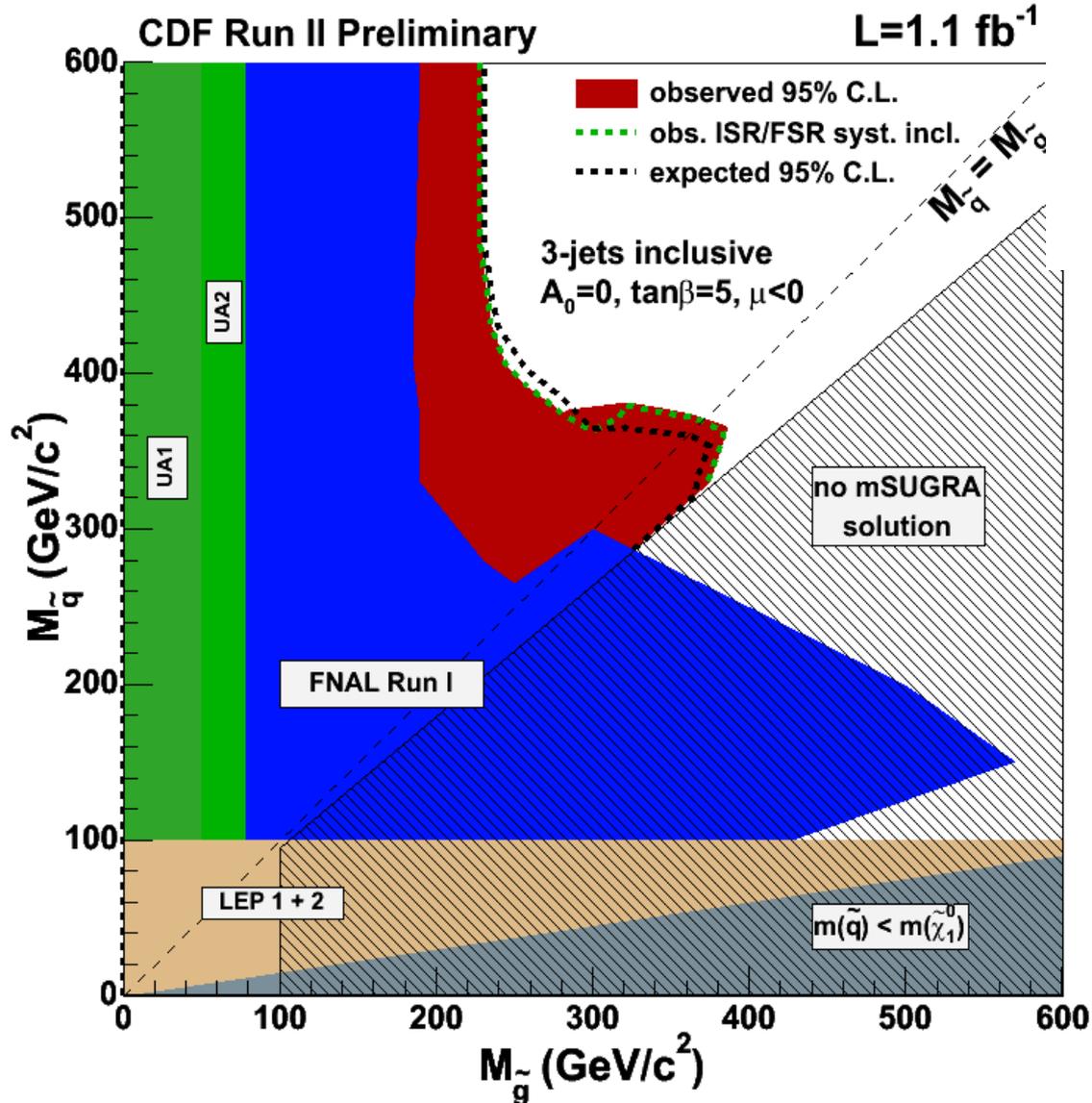


# another example of a MET-related distribution



$$H_T = MET + \sum E_T^{jet}$$

No evidence for squarks or gluinos.

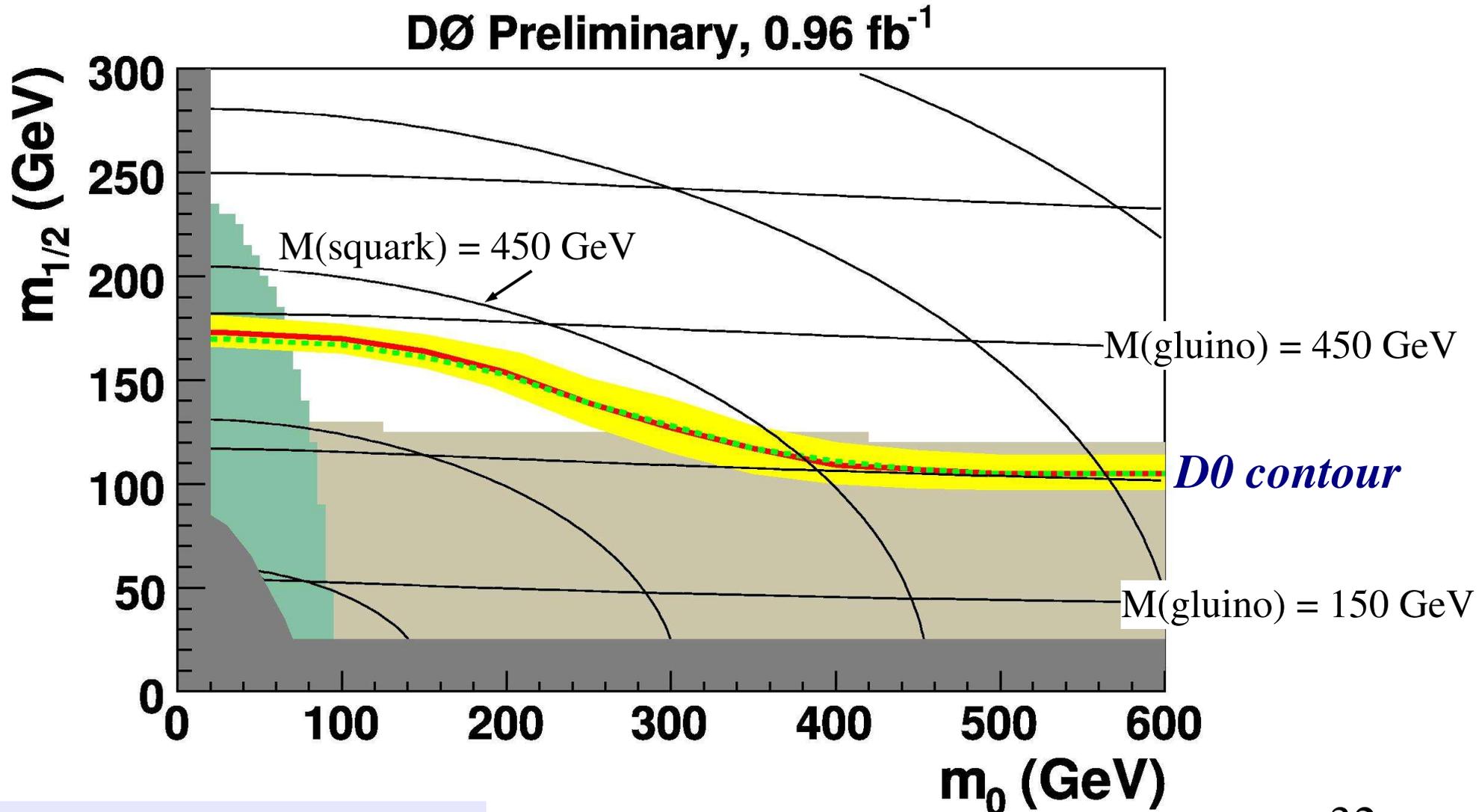


In view of the negative results of these searches, one can only say that squarks and gluinos do not exist, provided they would have been produced at a rate which would have been visible...

In practice this is translated into excluded ranges for the squark and gluino masses.

No evidence for squarks or gluinos.

*D0 translated their null result into an exclusion contour in the theoretical parameter plane ( $m_0, m_{1/2}$ ).*



# After the TEVATRON: The LHC

We still hope the TEVATRON will find the first evidence for SUSY.

However, it does not have the capability to study all SUSY particles in detail.

The **Large Hadron Collider (LHC)** will begin data *soon* ,  
at CERN in Geneva, Switzerland.

- collide protons and protons at **14 TeV** (Tevatron is 2 TeV)
- two experiments called **ATLAS** and **CMS**
- nominally “must” discover SUSY if it exists at “low” energy

As before, the *Experimenter's Toolkit* consists of leptons, jets, MET and photons, plus a bag of kinematic magic tricks.

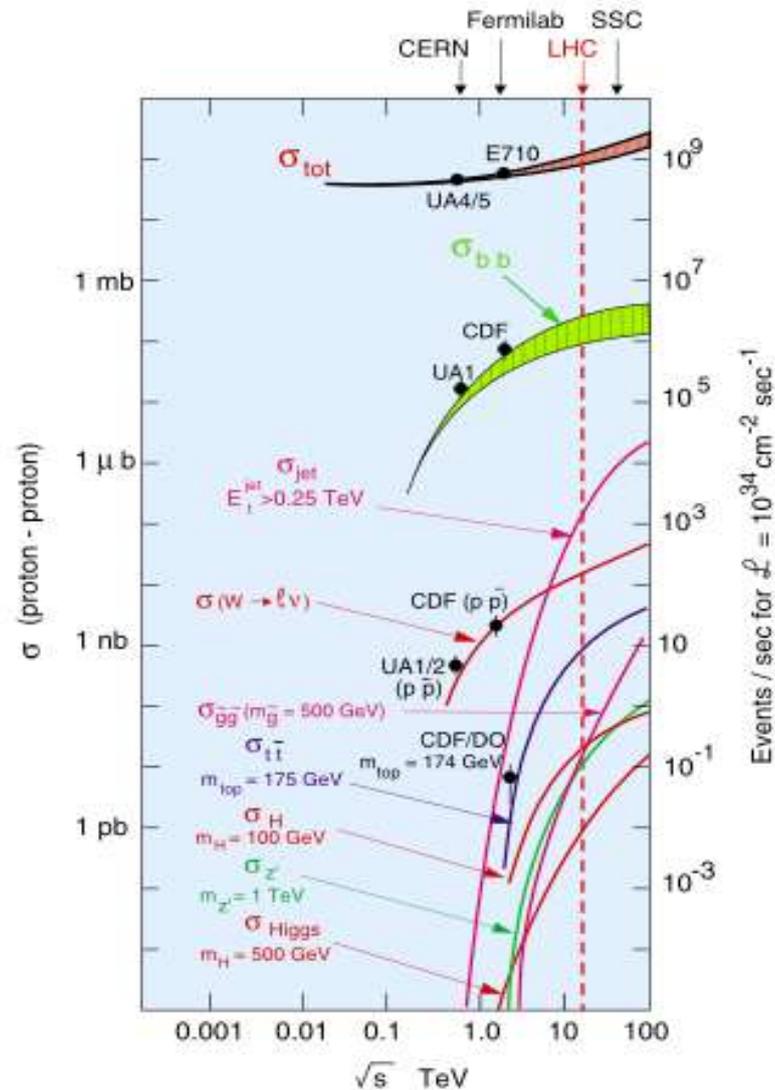
# What is the LHC ?

Let's compare to the TEVATRON  $p \bar{p}$  collider:

	<i>TEVATRON</i>	<i>LHC</i>
beams	p-pbar	p-p
circumference	6 km	27 km
energy	2 TeV	14 TeV
luminosity	$10^{32}$	$10^{34} \text{ cm}^{-2}\text{s}^{-1}$
	$8 \text{ fb}^{-1}$	$300 \text{ fb}^{-1}$
bunch spacing	392 ns	25 ns
collisions/xing	6	20
collab'n size	600 each	2000 each
running mo/yr	12	6

*LHC*

# What is the LHC ?



*approximate event rates for  $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$   
(which would give  $20 \text{ fb}^{-1}$  in one year)*

	<i>events / s</i>	<i>events/year</i>
$W \rightarrow e \nu$	40	$4 \times 10^8$
$Z \rightarrow ee$	4	$4 \times 10^7$
$t \bar{t}$	1.6	$1.6 \times 10^7$
QCD jets ( $E_T > 200 \text{ GeV}$ )	$10^2$	$10^9$
$b \bar{b}$	$10^6$	$10^{13}$
gluino pairs (1 TeV)	0.002	$10^4$
Higgs (120 GeV)	0.08	$8 \times 10^5$

# Official LHC Run Plan

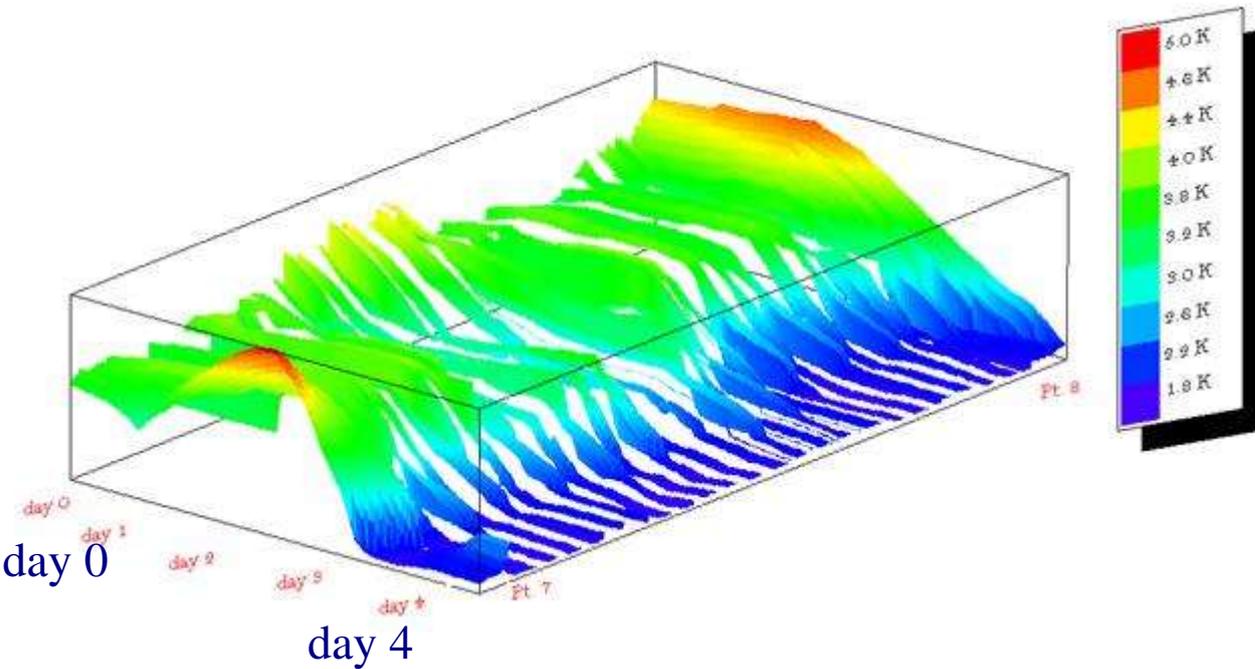
2007

- cool-down of LHC magnets proceeding nicely so far
- planned engineering run at 980 GeV is now *unlikely*
- failed quadrupole magnet – in-situ repair seems possible
- CMS and ATLAS will close up in November for CR's

2008

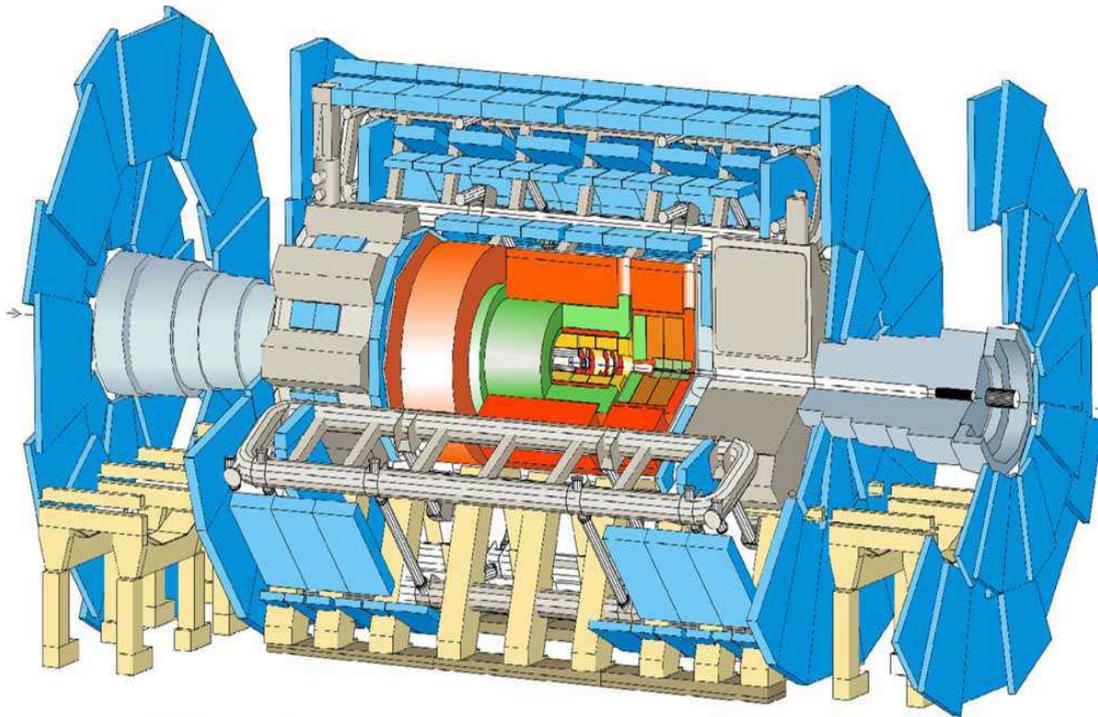
- **14 TeV** run planned for mid-2008
- aiming for a delivered luminosity of about **1 fb<sup>-1</sup>**
- CMS and ATLAS both will be ready for collision data
- first calibrations & alignment to be done with 100 pb<sup>-1</sup>

# Cooling Sector 7-8



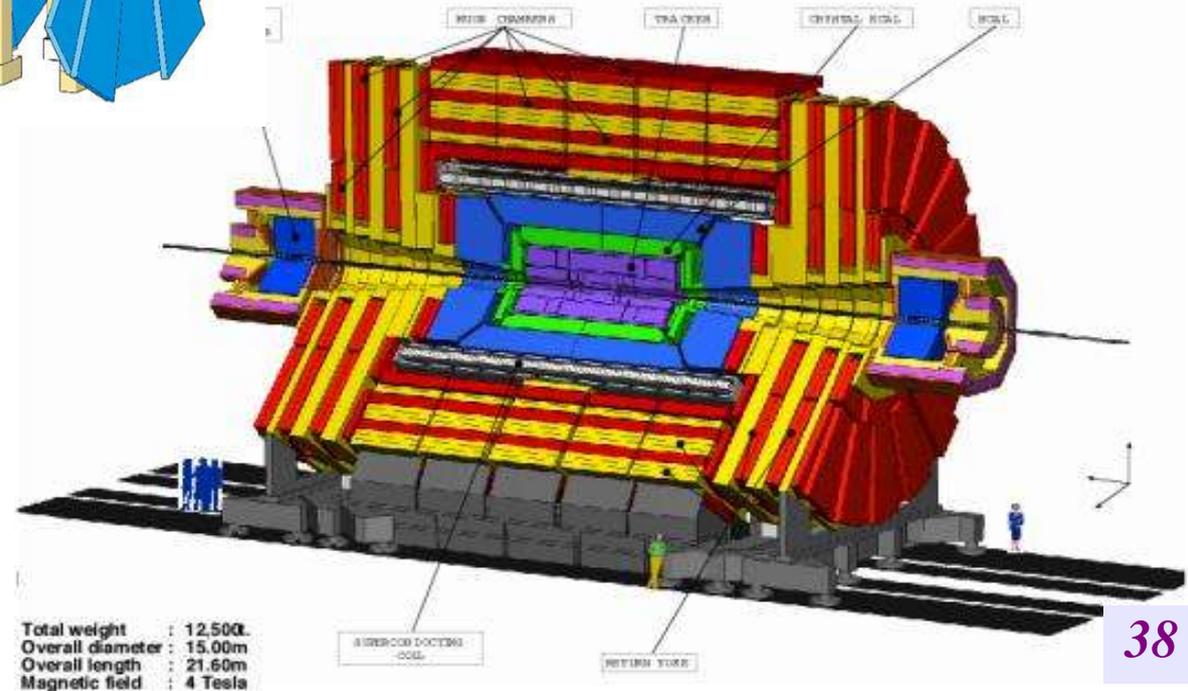
- ★ slightly below 2° K
- ★ 1/8 of the complete LHC ring
- ★ 3.3 km long – world's largest superconducting installation
- ★ 200 dipoles arranged in 30 cooling cells

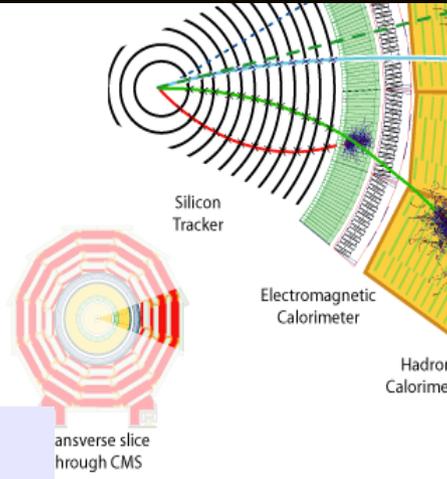
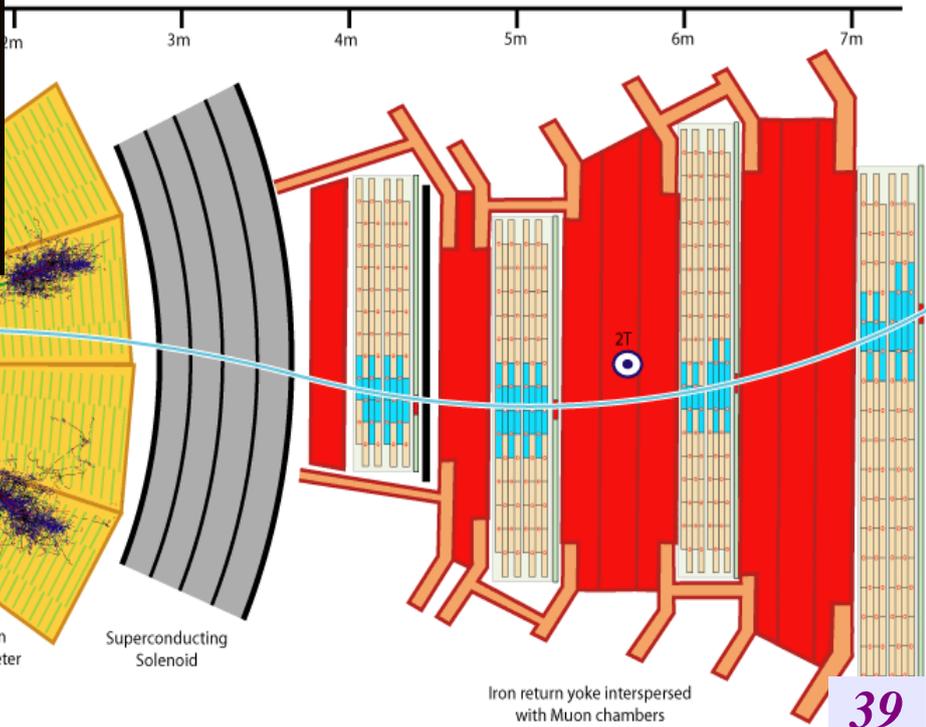
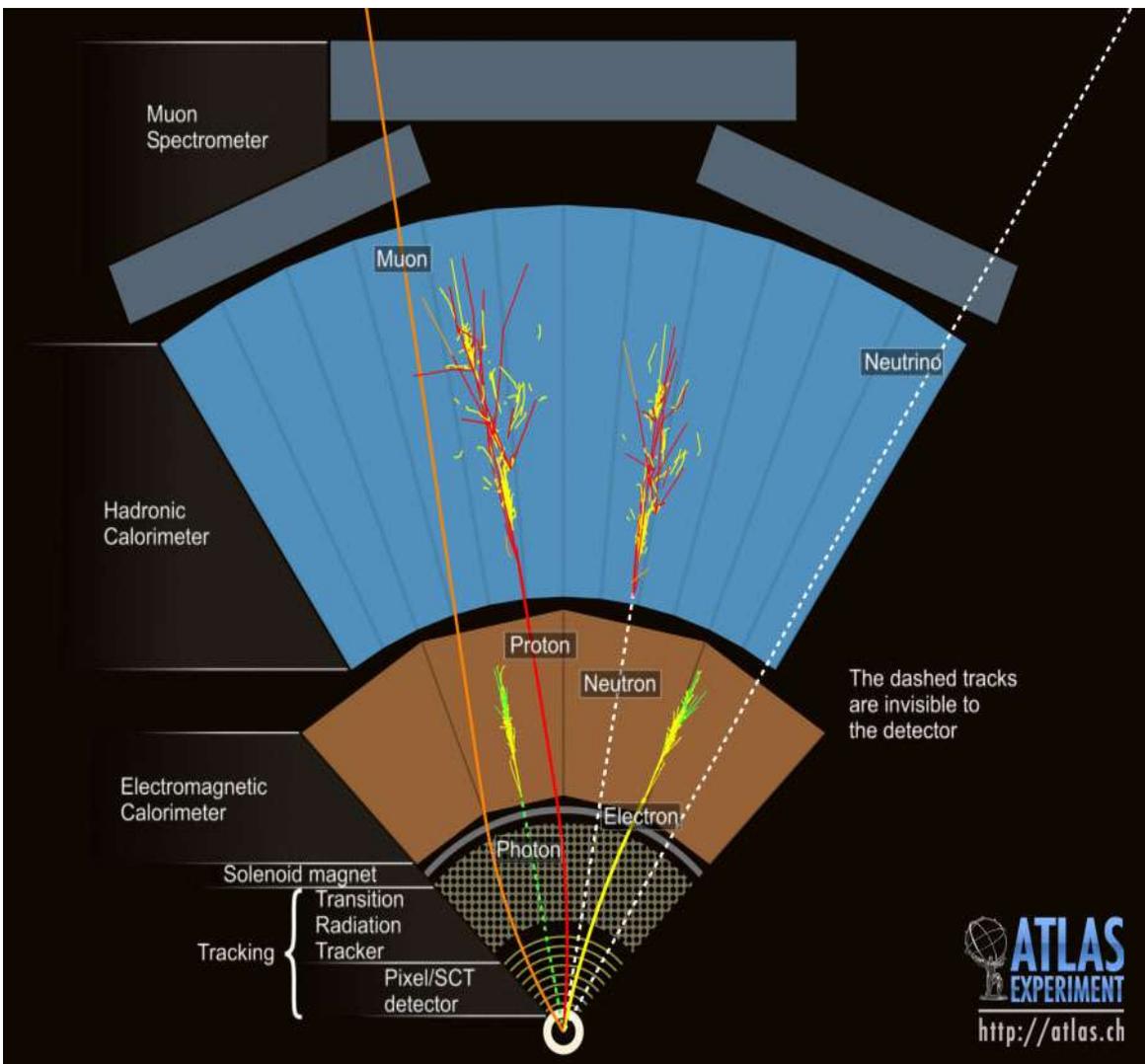
# LHC Detectors: the state of the art



ATLAS

CMS  
Compact Solenoidal Detector for LHC





*SSI 1 : Collider Signatures for DM*

D. Barney, CERN, February 2004

# Jets + MET at the LHC

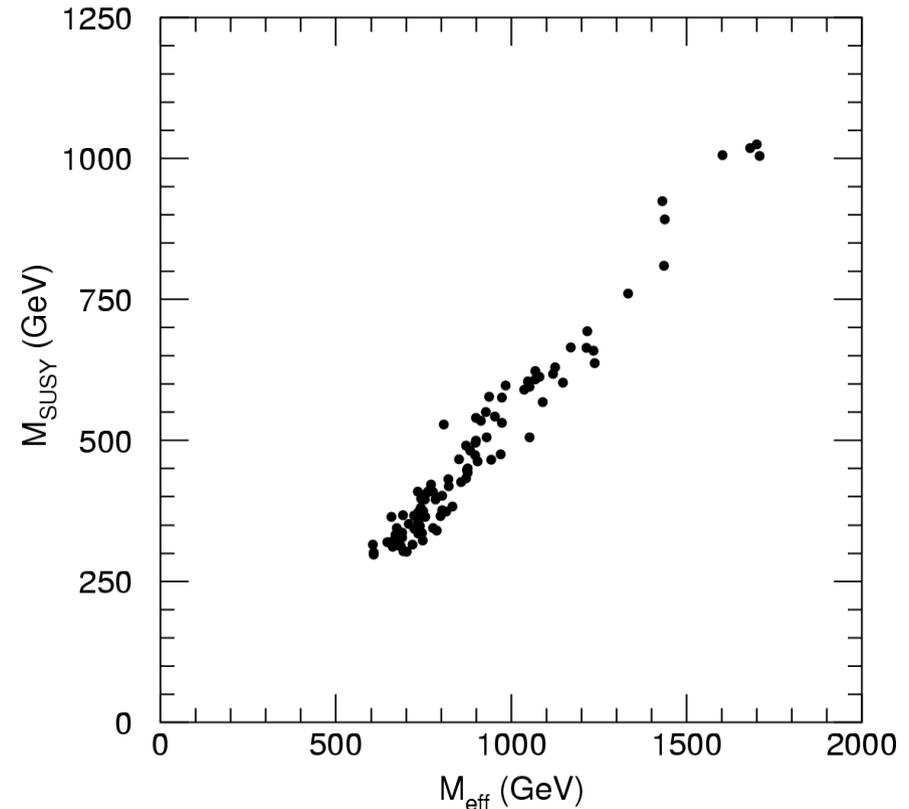
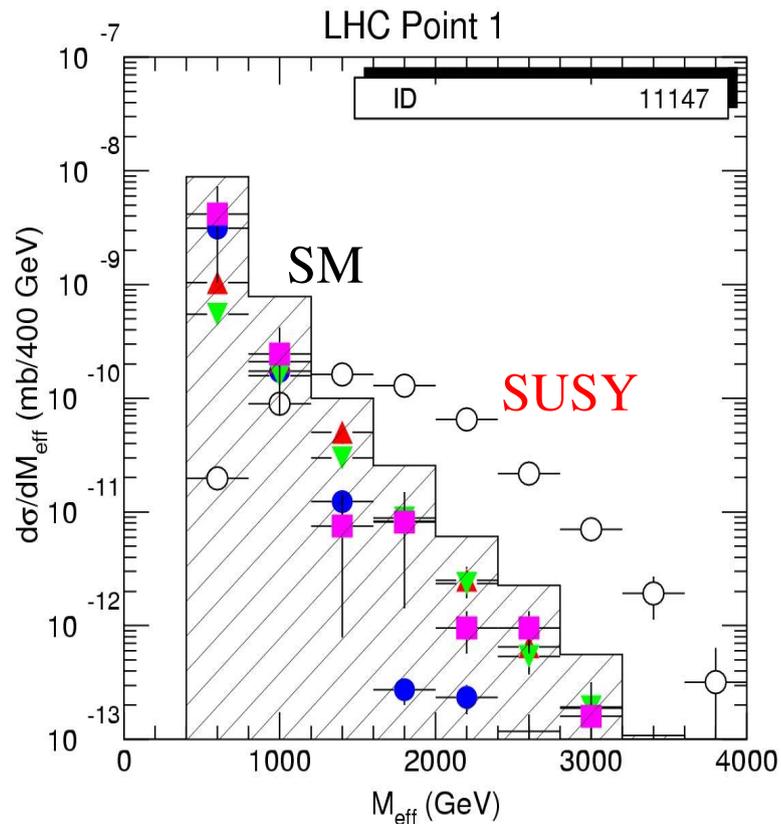
Since the LHC has so much energy, one expects it will produce **all** squarks and gluinos.

In our usual scenario, the decays of SUSY particles eventually yield two LSP's which results in large MET, and a number of energetic jets.

The production of squarks and gluons should be so copious that the simplest possible measure of “lots of energetic jets + MET” will already reveal SUSY beyond the SM.

$$M_{eff} = E_{T1} + E_{T2} + E_{T3} + E_{T4} + MET \quad \text{correlates with SUSY mass scale!}$$

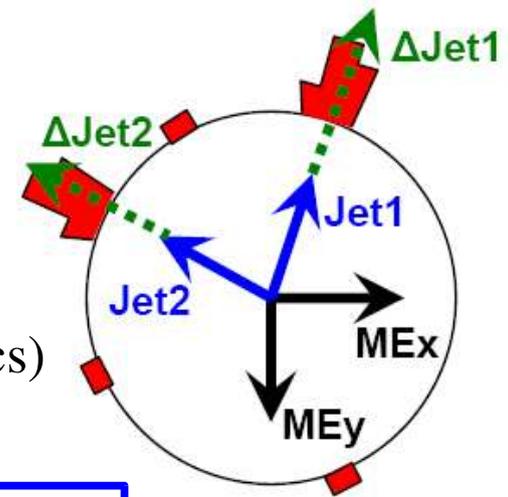
hep-ph/9610544



# Establish a Missing Energy Signal

How do we establish a **genuine** missing energy signal?

- ♦ missing energy is an apparent azimuthal imbalance in calorimeter energy.
- ♦ many sources of fake missing energy
  - muons
  - energy lost in uninstrumented regions
  - severe measurement errors (calorimetry, tracking)
  - energy from unrelated processes (other interactions, cosmics)
- ♦ neutrinos...

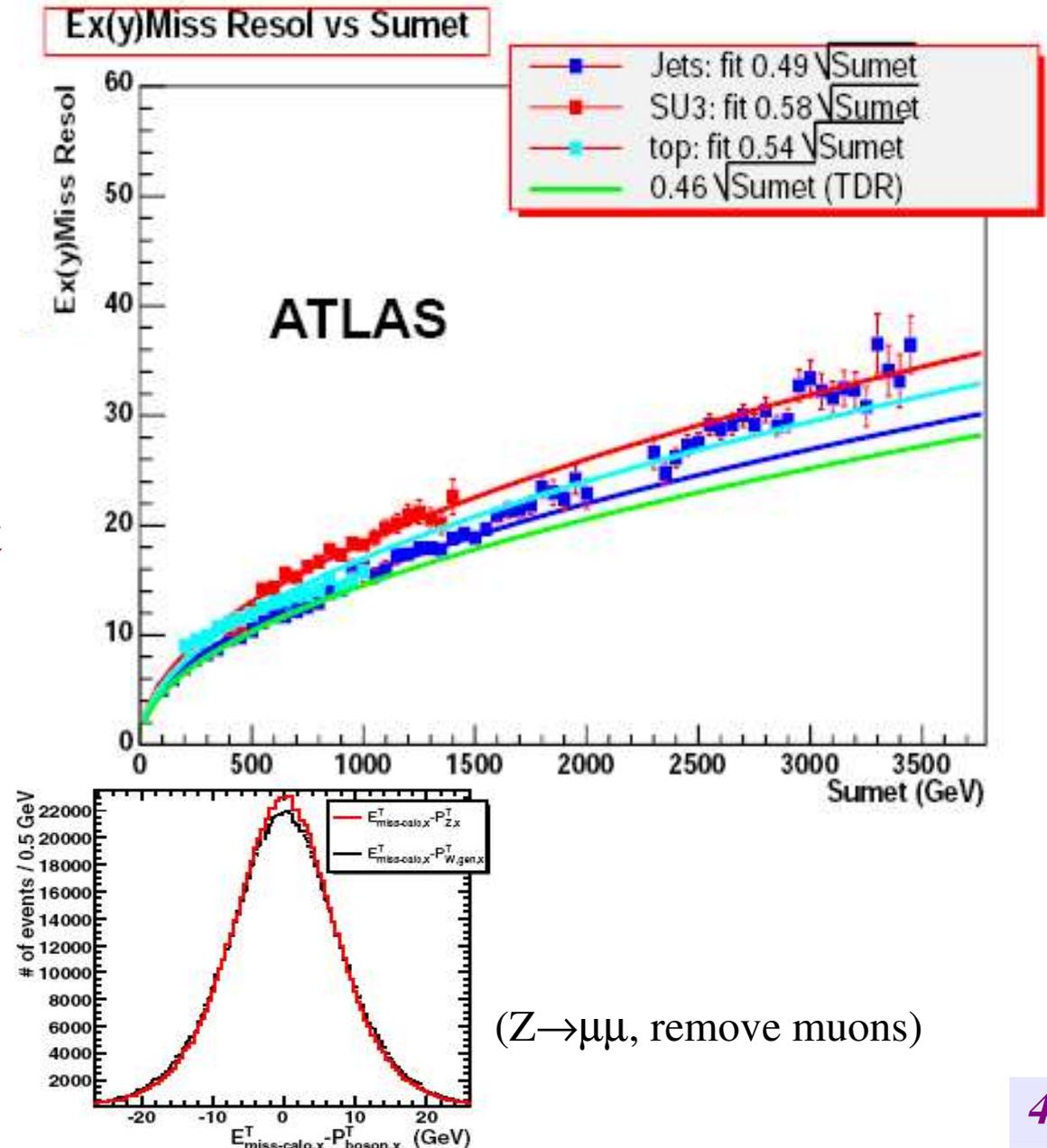


- ♦ resolution on MET determines the shape
  - ▶ how long are the tails ??
- ♦ must calibrate the rates of all sources of fake MET

# MET resolution is understood on basis of “SUMET”

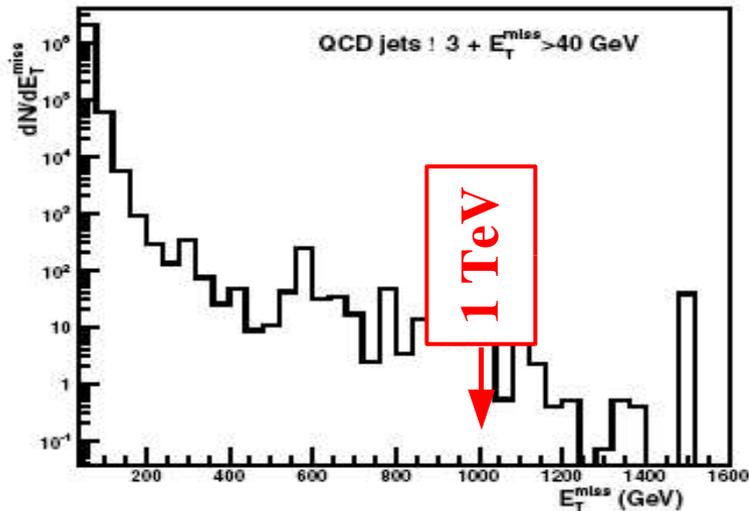
SUMET = straight sum of calorimeter energies

- ◆ noise & stochastic terms important at low SUMET
- ◆ constant term in calor'y resolution at high SUMET
- ◆ resolution depends on event type due to differing particle content
- ◆ validate resolution using source of neutrinos: W's, Z's and top

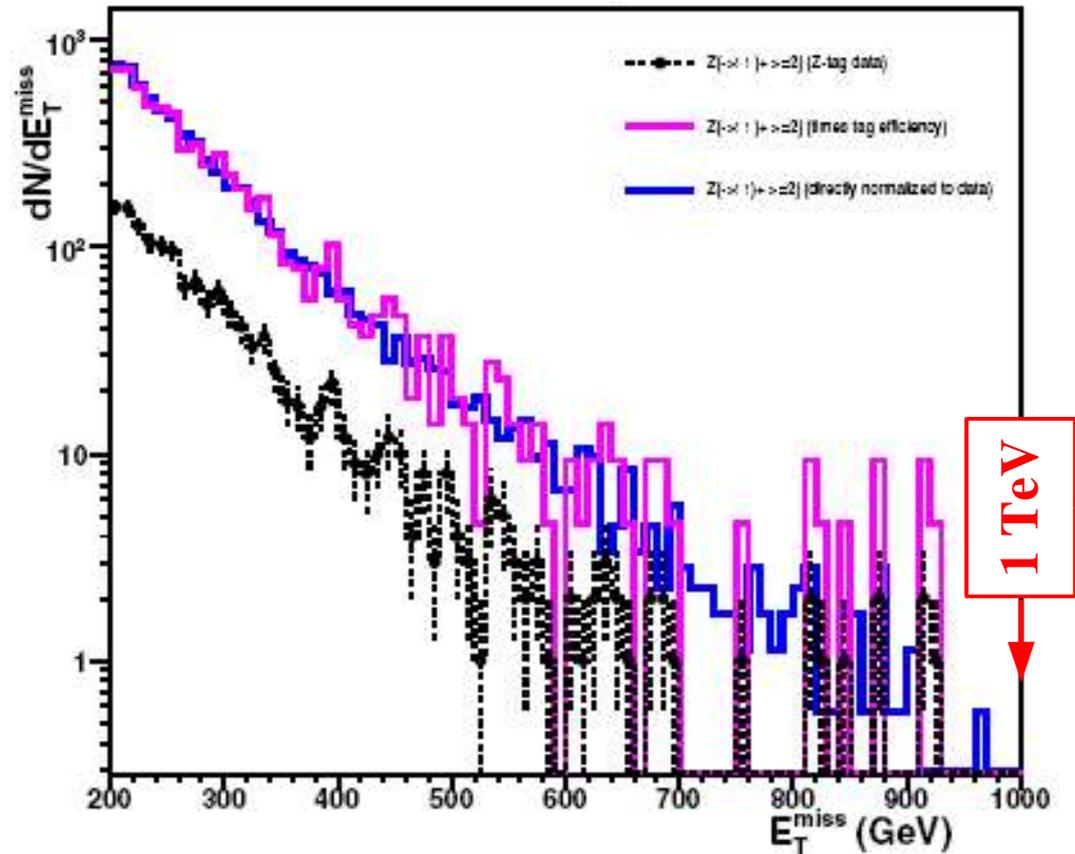


# Backgrounds normalized by appropriate reference processes.

- ◆ important backgrounds:
  - ◆ top quark production
  - ◆ di-bosons  $WW, WZ, ZZ$
  - ◆  $Z \rightarrow \nu\nu + \text{jets}$
  - ◆ multi-jet QCD
- ◆ normalize to similar processes
  - ◆ example:  $Z \rightarrow \mu\mu + \text{jets}$
  - ◆ similarly for  $t\bar{t}$



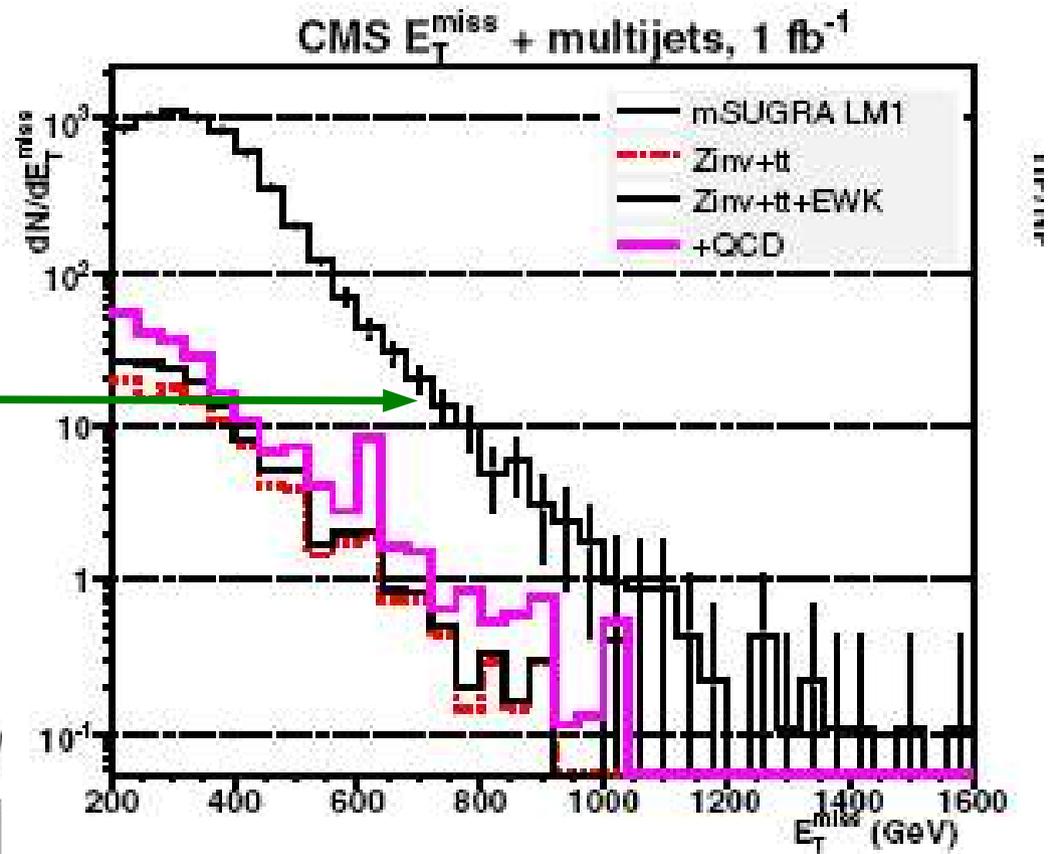
Z-candle normalization,  $E_T^{\text{miss}} > 200$  GeV CMS



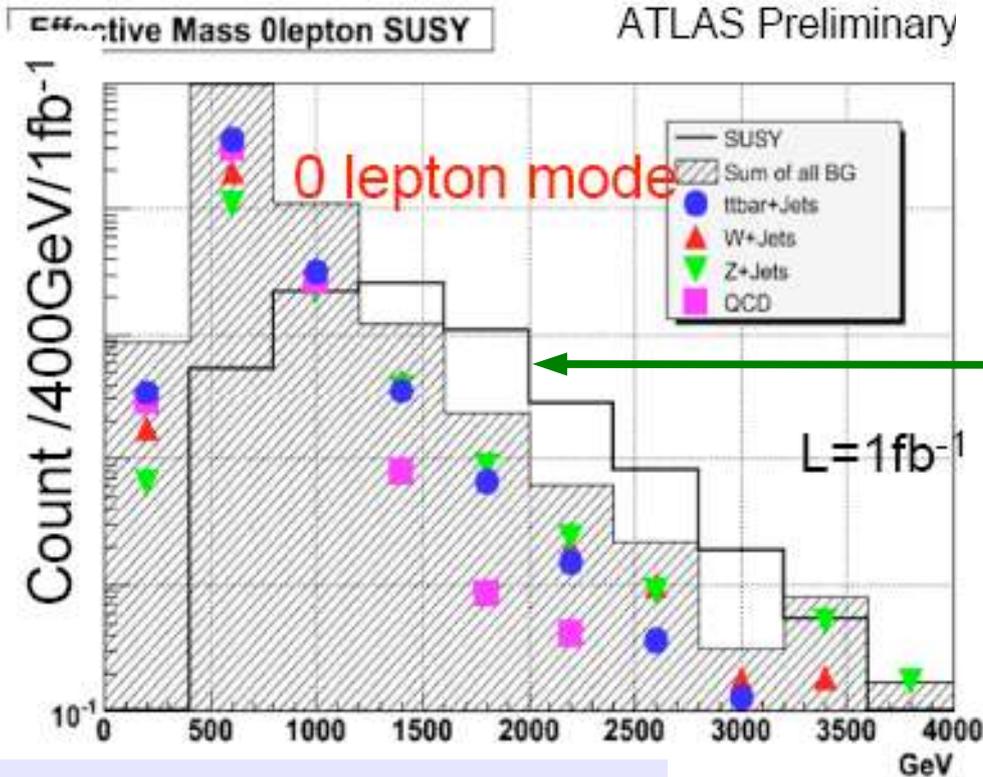
- ◆ shape of multi-jet background (**scary!**) obtained from reference samples
- ◆ (release certain topological cuts)

# MET signals for $1 \text{ fb}^{-1}$ (1<sup>st</sup> year?)

low mass point ( $M_{\text{gluino}} = 600 \text{ GeV}$ )



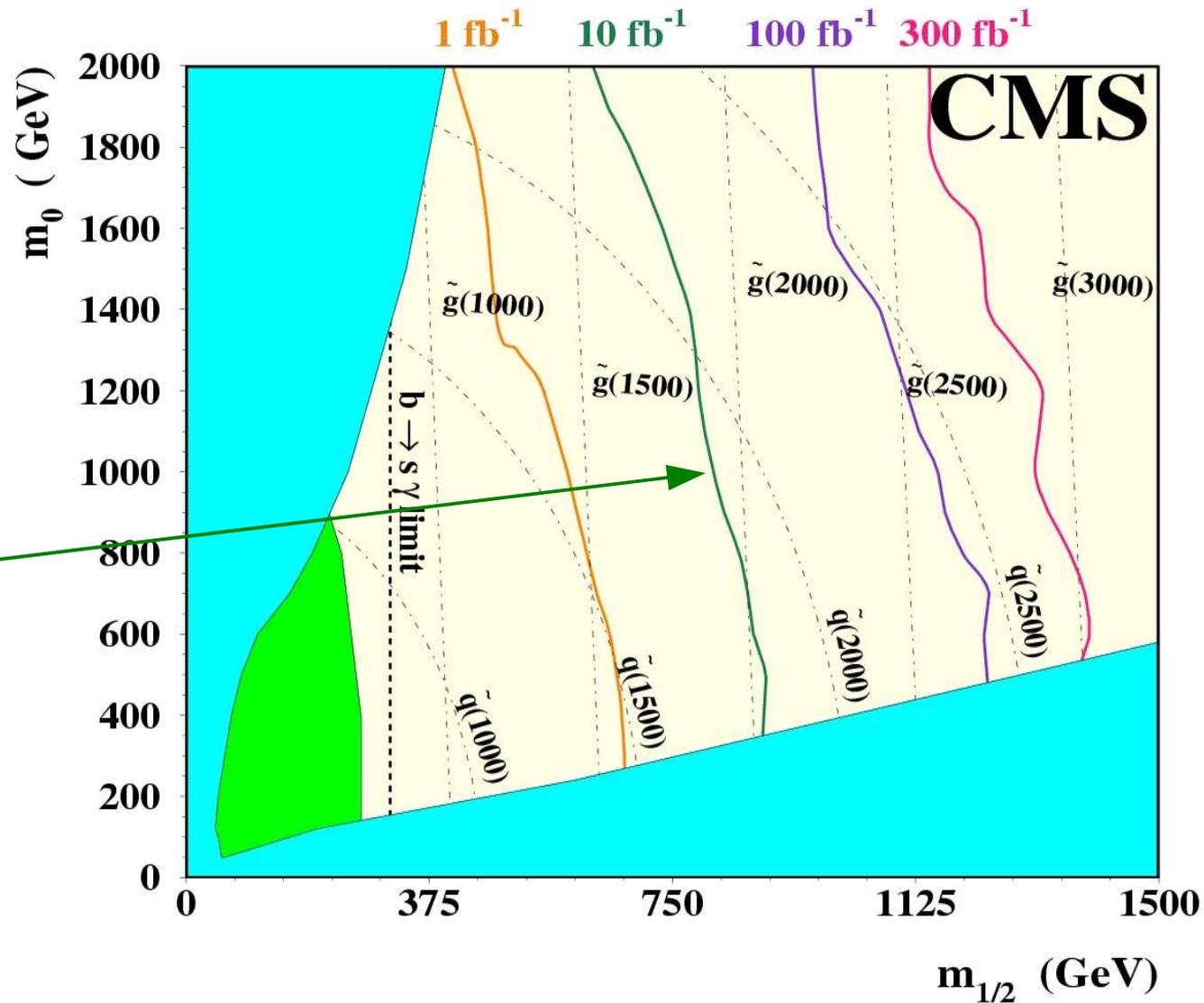
high mass point ( $M_{\text{gluino}} = 1 \text{ TeV}$ )



$m_0$  and  $M_{1/2}$  are fundamental SUSY parameters (in the CMSSM version). They control the masses of squarks and gluinos, and other particles.

This plot shows the reach of CMS as more and more data are collected.

Once the LHC is up and running, it will log a luminosity  $10 \text{ fb}^{-1}$  in one year.



(ATLAS has a very similar capability.)

# High-Energy Colliders: testing the paradigm

- A missing-energy signal is required if the WIMP-miracle paradigm is true.
- So far, no sign for dark matter particles at the Tevatron.
- We plan to follow the same approach at the LHC, and we expect to see a signal...

**Suppose we observe a signal in the Jets+MET channel -  
how do we confirm that we are producing DM particles?**

**→ We need to confirm the underlying theory in detail.**