
# Getting to 1 $fb^{-1}$ at the LHC

*Thomas J. LeCompte*

High Energy Physics Division
Argonne National Laboratory

# *The Main Message*

- The most important thing we can do in the early year's running is to get ready for later, high luminosity running
  - I hope to present an overview of the path from $10^{31}$ to $10^{33}$+
- In any measurement, there are two components:
  - 1. Making the measurement correctly
  - 2. Convincing yourself that you've made the measurement correctly
  - Usually #2 is harder than #1

# Prediction #1

**Prediction #1:**
**Early LHC Luminosity Will be Lower Than We Think/Hope**

# *Why not $10^{34}$ on Day One?*

Luminosity Equation: $$L = \frac{fE}{\varepsilon_n}\frac{n_b N_p^2}{\beta^*}$$

- Quantities we cannot easily change:
  - *f*: revolution frequency of the LHC
    - *set by radius and c*
  - *E*: beam energy
    - *set by physics goals*
  - $\varepsilon_n$: beam emittance at injection
    - *set by getting the beam into the LHC*

- Quantities we can change
  - $n_b$: number of bunches
    - *Factor of 3 lower initially*
  - $\beta^*$ : strength of final focus
    - *Factor of ~2 possible*
  - $N_p$: protons per bunch
    - *Can be as small as we want*
    - *Initially, can be within a factor of ~2 of design*

This works out to $4 \times 10^{32}$ on Day One

# *LHC Stored Energy in Perspective*

USS New Jersey (BB-62)
16”/50 guns firing

- LHC stored energy at design ~700 MJ
  - Power if that energy is deposited in a single orbit: ~10 TW (world energy production is ~13 TW)
- Battleship gun kinetic energy ~300 MJ

# Prudence and Luminosity Profile

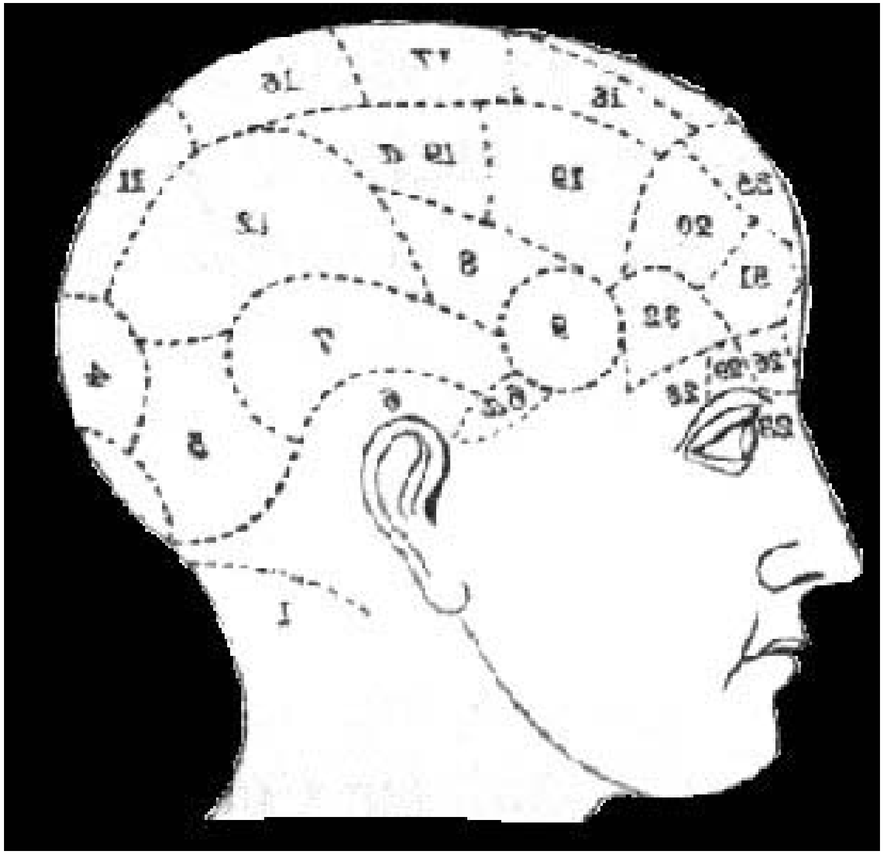
- There is a HUGE amount of stored energy in the LHC at design
- Safety/sanity requires that we operate with less stored energy until we have plenty of experience with beam aborts
  - This means less intense proton beams
  - This means substantially lower luminosity
    - *luminosity goes as the square of stored energy*
  - We will probably insist on many successful unintentional store terminations before putting more beam in the machine
- Expect that the luminosity will grow slowly
  - Perhaps $10^{31}$ in 2007
  - Perhaps growing by an order of magnitude a year.
    - *If we are not absolutely confident in our ability to tolerate an unintentional store termination, this will grow more slowly*

# *What is 1 $fb^{-1}$?*

- 1 $fb^{-1} = 10^{14}$ collisions
  - 2 nanograms of matter produced in collisions (about the same mass as a cell)
- 1 $fb^{-1} = 10^{7}$ seconds of running at $10^{32}$
  - More likely $5 \times 10^{6}$ seconds at $2 \times 10^{32}$
    - The LHC running schedule is not very aggressive
    - $2 \times 10^{32}$ is an accepted guess for pre-$10^{34}$ luminosity
- My best guess: this will happen some time in Year 3

- Note that the Tevatron has just hit the 1 $fb^{-1}$ milestone, 20 years after the first collisions
  - Probably 75% of the collisions it will ever produce will be in the last few years of operation

# Prediction #2



***Prediction #2:***
***The Staging of the ATLAS Detector will be Largely Unnoticed outside of ATLAS***

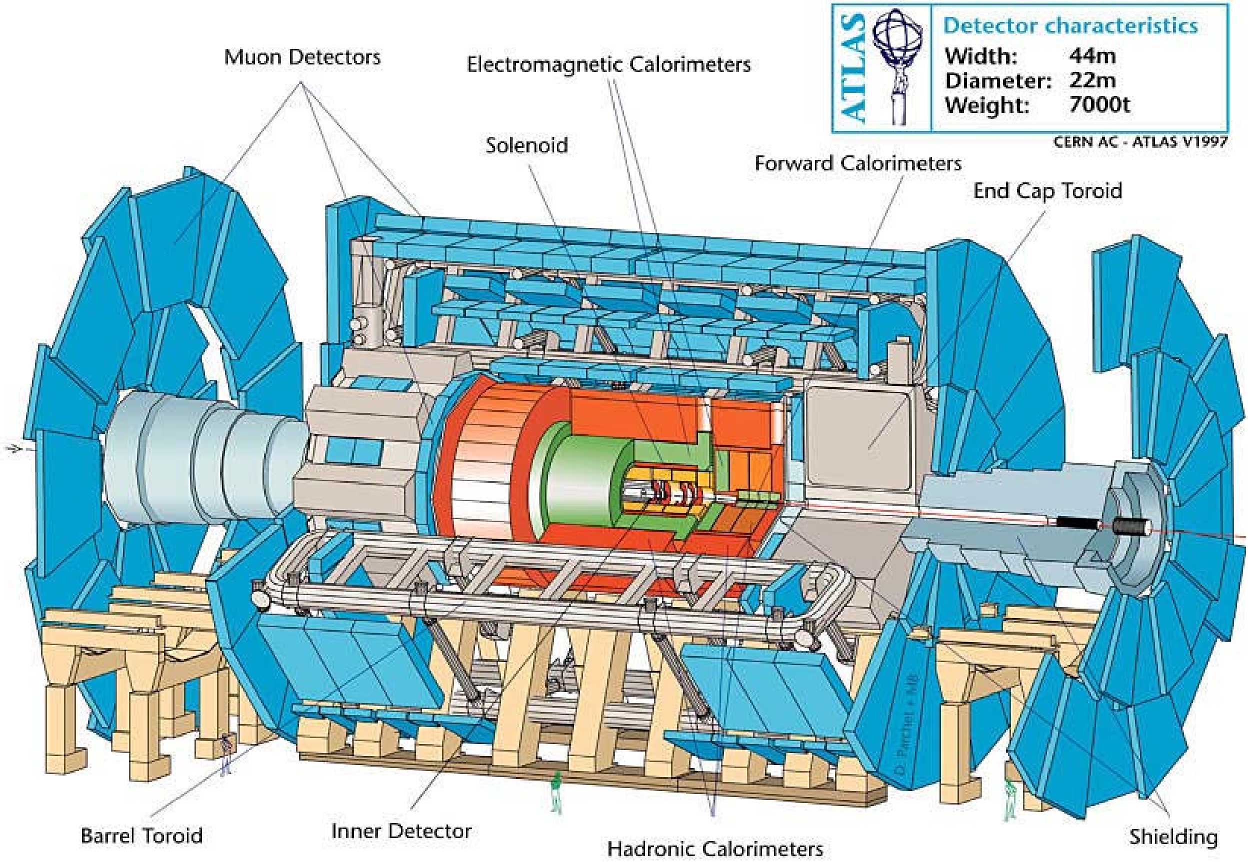
## Descoping and Staging

Early descoping: Bent Pyramid of Sneferu c. 2600 BCE

- Not all of ATLAS will be ready to be installed on time
  - See next slide
- “You have to go with the detector you have, not the detector you wish you had”

# What Will Be Staged? (My Best Guess)

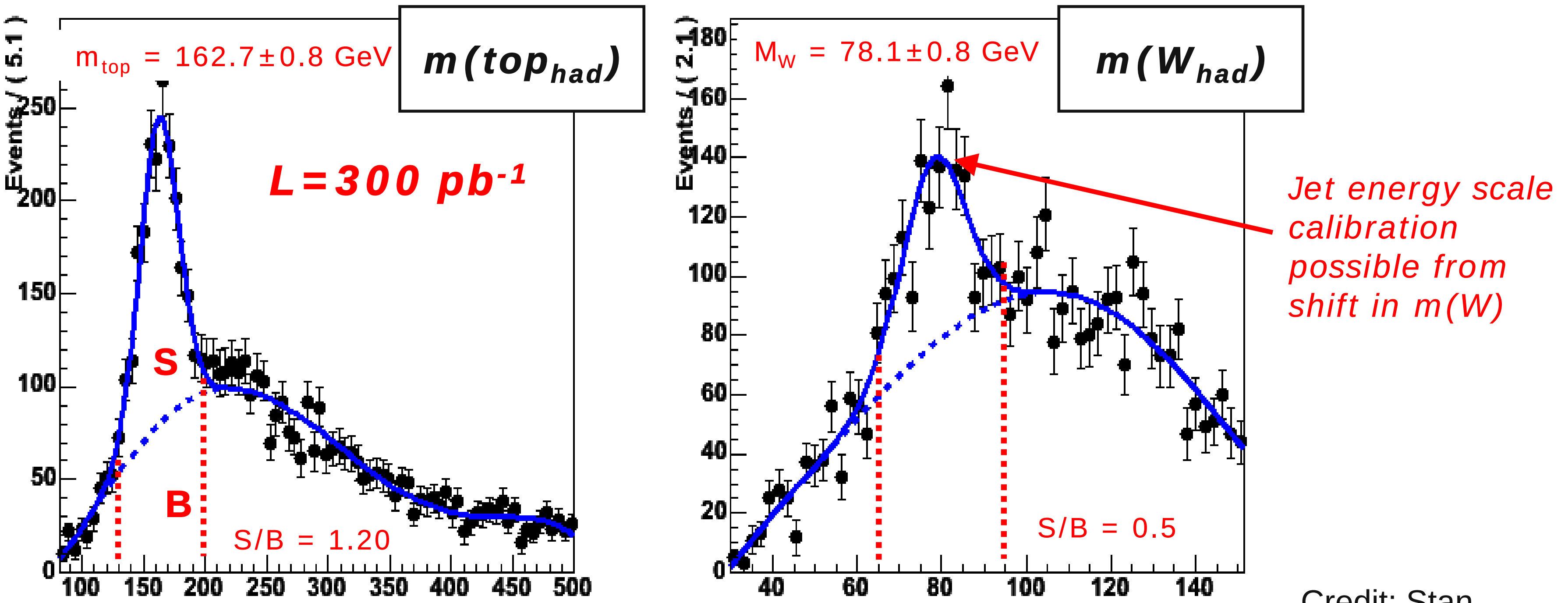
- Some of the central muon planes –
  - Degrades momentum resolution
- Some (more) of the forward muon system
  - Reduces muon acceptance
- Innermost silicon layer
  - Reduces B-tagging efficiency
- Trigger and DAQ
  - Lowers maximum luminosity




Staging details depend on who finishes first – the detector or the accelerator

# How much does poorer B-tagging hurt us?

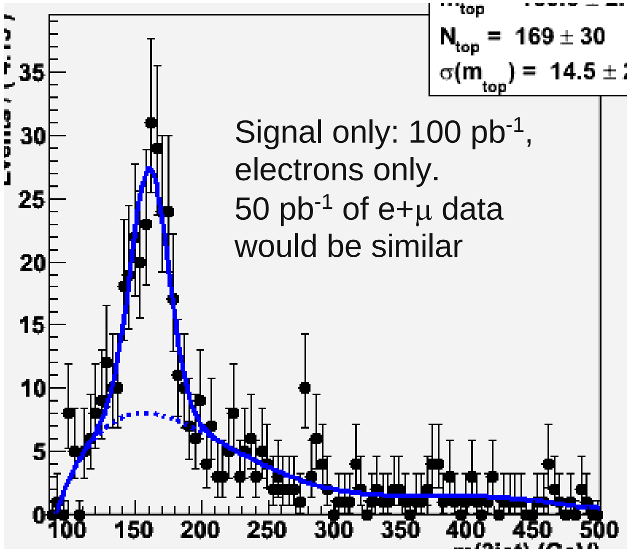
Top reconstruction at ATLAS without B tagging: just pick the three highest $E_T$ jets in a lepton+4 jets event, and plot.

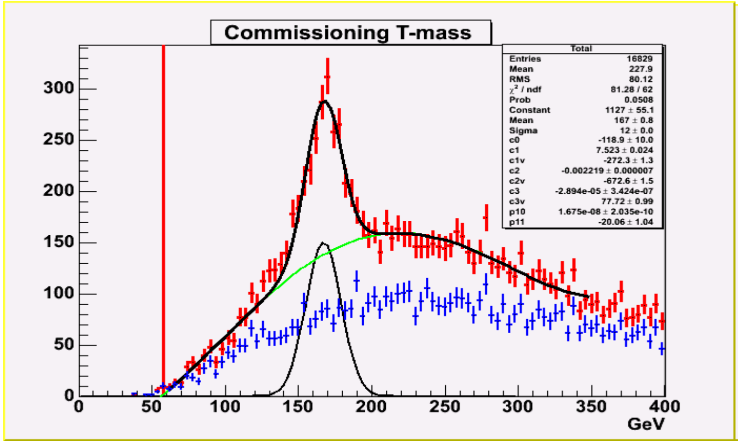


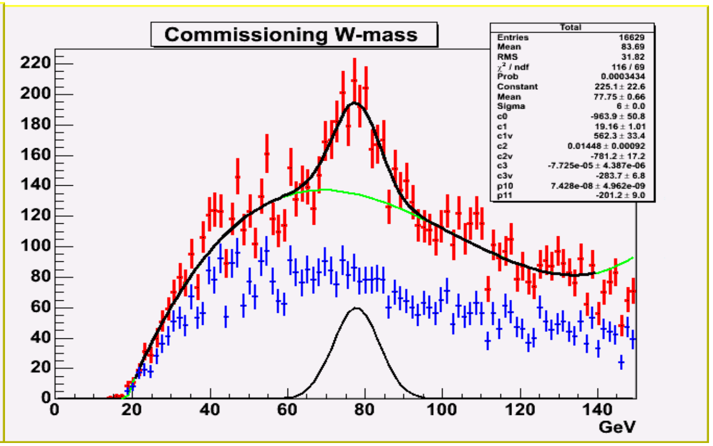

Credit: Stan Bentvelsen

# Early Top Details

- Why is B-tagging less important at the LHC?
  - Top cross-section is growing: σ(t)/σ(W) (and by extension, W+jets) is an order of magnitude larger (exact value is still uncertain)
  - The top and anti-top are more separated
    - *kinematic advantage to higher center of mass energy*
    - *Reduces combinatoric confusion (big problem at the TeVatron)*
- Even without the innermost silicon layer, some B-tagging will be possible (comparable to the TeVatron)
  - These predictions are on the pessimistic side



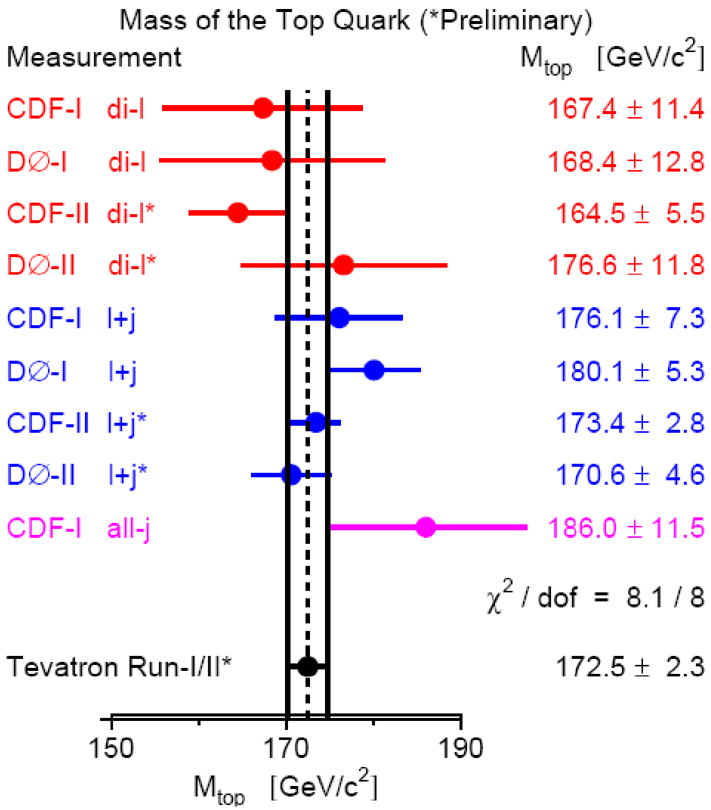




Includes background estimate

# *Top Mass at a Femtobarn*

- Today's TeVatron top mass uncertainty is 2.3 MeV (hep-ex/0603039)
  - 40% of the uncertainty is statistical, 60% is systematic
  - Based on up to 750 $pb^{-1}$ (CDF) and 390 $pb^{-1}$ (D0)
- (My own) scaling to 4 $fb^{-1}$ suggests an uncertainty near 1.8 MeV
  - Dominated by systematics (1.7 MeV)
- To improve on this, the LHC has to get the systematics under control at the 1% level
  - Typically, this takes years
  - Luminosity helps, but what this level of systematic understanding really needs is time
- This may be difficult to do and to *demonstrate* early on.
  - Can we "cherry pick" events? We will have ~10000 of them.



# *Rare Top Decays*

- After 1 $fb^{-1}$ , the LHC will have ~an order of magnitude more top quarks than than Tevatron
- Most rare decay signatures do not require the same level of systematic control as m(t). Consider $t \rightarrow c\gamma$
  - Signature 1: $\gamma$ + 4jets, $m(\gamma j_1) = m(t)$, $m(j_2 j_3) = m(W)$, $m(j_2 j_3 b_4) = m(t)$
  - Signature 2: W + $\gamma$ + 2jets: $m(\gamma j_1) = m(t)$, $m(Wb_2) = m(t)$
    - Technical Note: two values for $m(Wb_2)$: only one has to be near m(t)
  - Essentially, the measurement is "cut and count". Jet energy scale uncertainty is a few percent uncertainty on the background; cuts are tuned so that the expected background is ~½ an event
  - B-tagging helps somewhat: there is a tradeoff between kinematic and B-tagging cuts
- 1 $fb^{-1}$ would give limits like $10^{-3}$ – $10^{-4}$ for FCNC decays

Wish list: it would be very nice if we had a Monte Carlo that could give a boson + N hard jets, with the details of the jet kinematics being predicted well enough to predict the effect of mass cuts like these.

# *Are Rare Top Decays Even Interesting?*

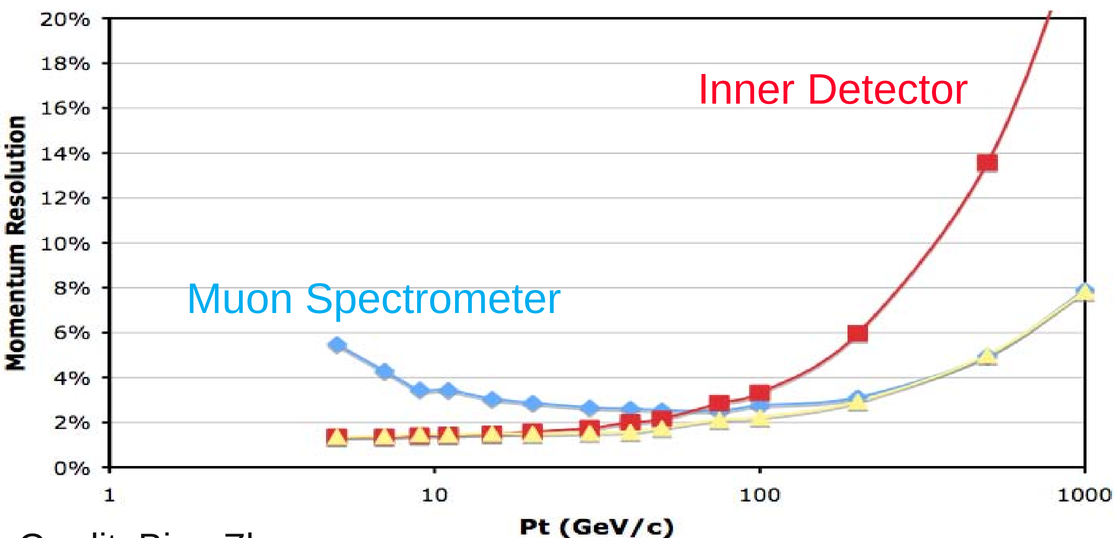
- Even Standard Model top FCNC decays have partial widths millions of times larger than the bottom counterparts
- The problem is that they compete with
  - 2 GeV of $t \rightarrow b$ decays, instead of
  - 400 $\mu$eV of $b \rightarrow c$ decays
- For a theory to be interesting to experimenters, we need partial widths in the MeV ballpark

Wish list: If you want experimenters to set limits on a process that you don’t expect to be there, it helps to have a model that predicts that something will appear.

This model doesn’t have to be any good.

# Muon Identification

- The ATLAS muon system is designed for a resolution of 10% for 1 TeV muons
  - This requires knowledge of the detector position to ~10's of microns over 10's of meters
    - *To remind you, the coefficient of thermal expansion is ~$10^{-5}$/K*
  - For early running, there won't be any 1 TeV muons
  - Even if the muon spectrometer has initially poorer resolution, the effect on most muons is minimal

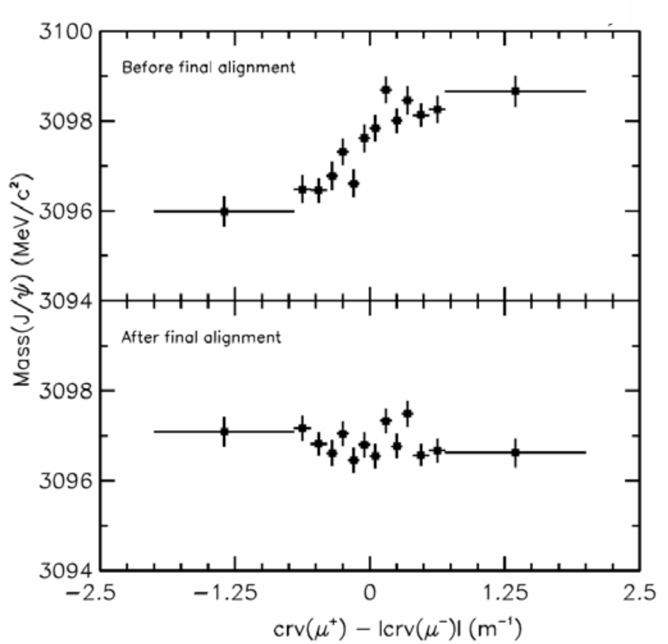



Worsening the outer muon spectrometer resolution has virtually no impact below ~100 GeV, and only minimal impact between 100 & 200 GeV.

Credit: Bing Zhou

# *More on Lepton Identification*

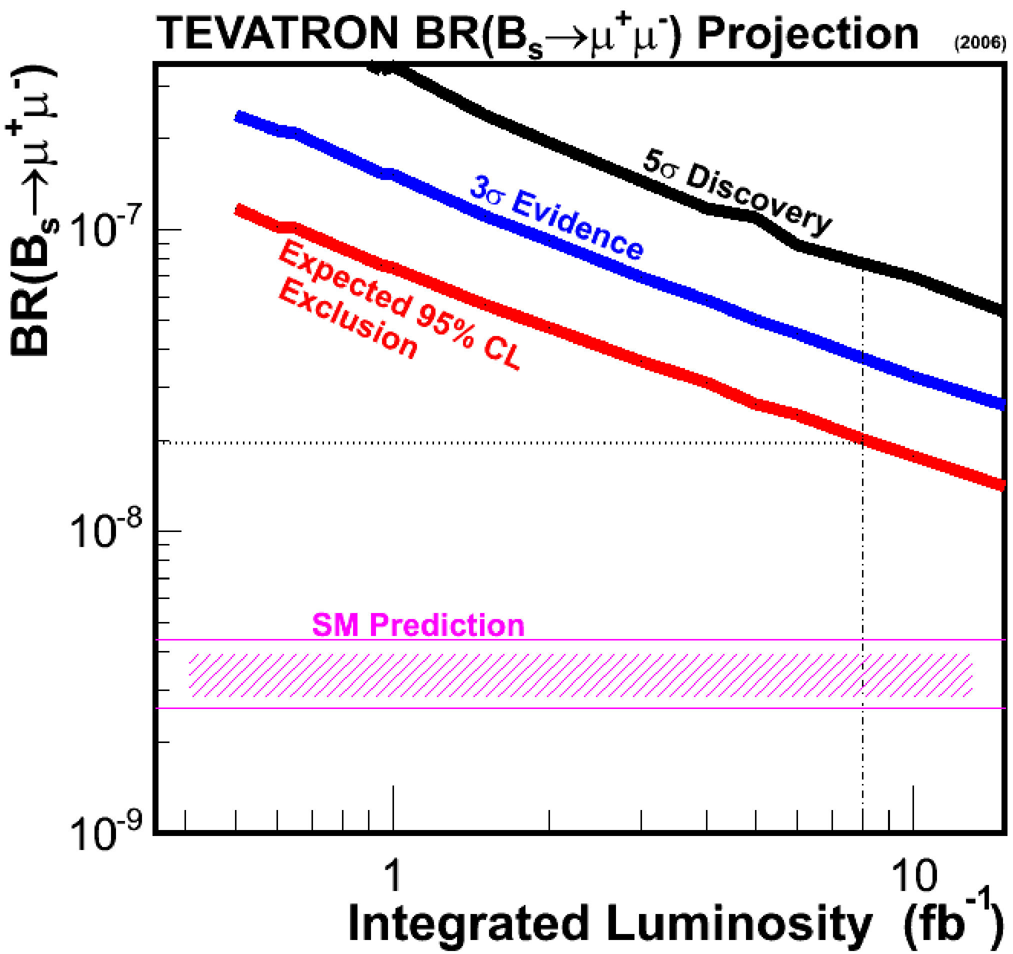
- We can use the Z decays to
  - Insure that the electromagnetic calorimeter energy scale is correct
  - Improve the alignment – and thus the resolution – of the muon spectrometer
- A 10 $pb^{-1}$ early run should give ~10,000 Z events in each channel
  - Later runs will improve our statistical uncertainty




An example from the Tevatron: tracking misalignments introduce a "false curvature". A particle of known mass (for them the J/ψ, for us the Z) can be used to identify and remove this problem.

Since trackers measure 1/p, not p, going to higher momentum is an interpolation, not an extrapolation.

# Tevatron B → $\mu\mu$ Searches




Br(Bs→$\mu\mu$)<8.0×$10^{-8}$ @ 90%CL
Br(Bs→$\mu\mu$)<1.0×$10^{-7}$ @ 95%CL

Br(Bd→$\mu\mu$)<2.3×$10^{-8}$ @ 90%CL
Br(Bd→$\mu\mu$)<3.0×$10^{-8}$ @ 95%CL

CDF and D0 limits have been leapfrogging each other since Run II began.

Generic comment about Tevatron discovery: With 1 fb$^{-1}$ on tape, if we were going to make a 5σ discovery, we would already be starting to see limits fail to improve.

# $B \rightarrow \mu\mu$ at the LHC

- Good news for the LHC
  - Cross-section goes up by ~6
  - Acceptance goes up by ~3
  - Thicker detectors beat down $B \rightarrow hh$ background
- Bad news for the LHC
  - Triggering forces the $p_T$ threshold up
  - Lose factor of ~5 (?)
- Maybe a reach of 6-8 x $10^{-8}$ is realistic in the 1st femtobarn

- At higher luminosities, the triggering problem becomes worse and worse
- A promising strategy is to trigger on 3 muons
  - Requiring the other B to decay via $b \rightarrow \mu X$ or $b \rightarrow c \rightarrow \mu X$
  - This reduces signal by 5-10
  - This should be devastating to our largest background, intertwined b pairs
- Ultimately, we want sensitivity beyond the SM prediction
  - We will reach this
  - Exactly when depends on background rates and triggerability.

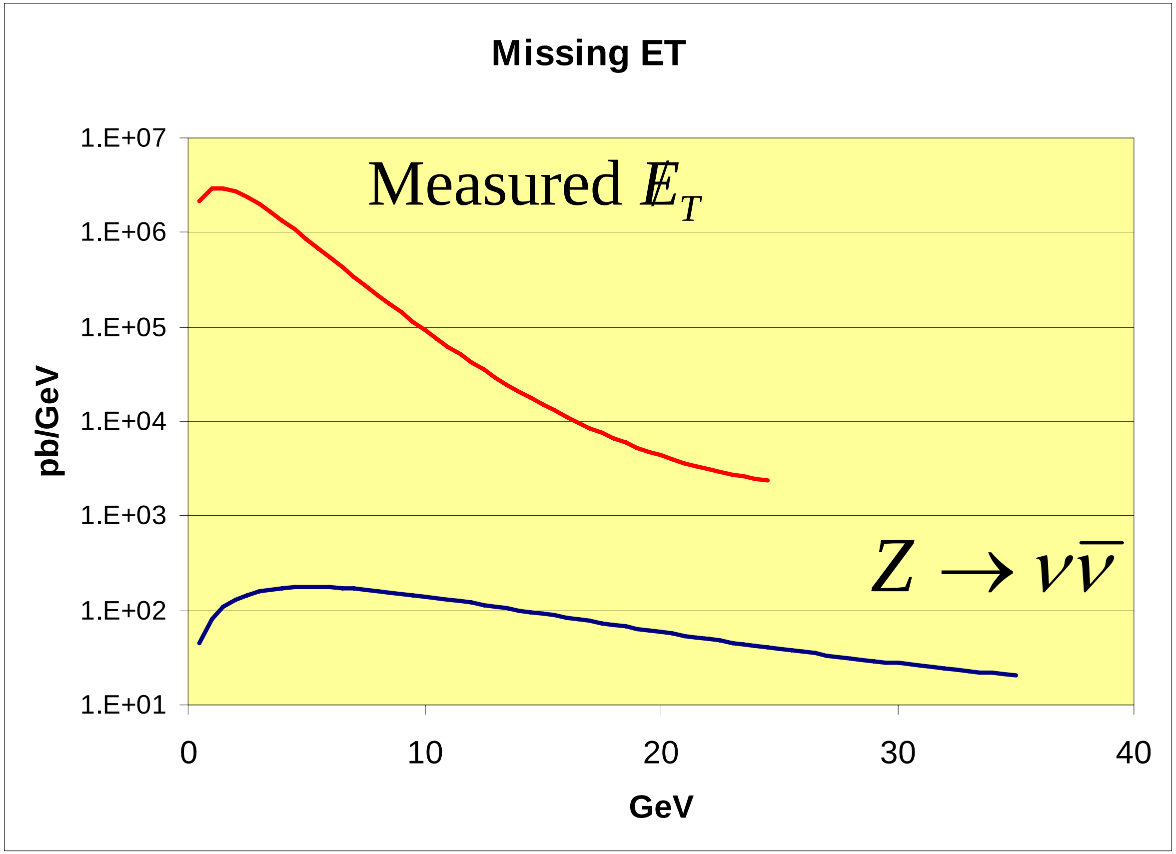
# Prediction #3


**Prediction #3:**
**Missing $E_T$ will be hard**

# *Why Are We Doing This Anyway?*

- Find the Higgs
  - This will take years, unless both the following are true:
    - *We are lucky*
    - *Nature is kind*
  - A single scalar Higgs and nothing else would be a disaster
    - *Progress is made by having disagreements between expectations and measurements*
    - *Verifying that there is a single scalar Higgs and nothing else will take more than a decade and maybe even an ILC*
- Search for SUSY
  - No SUSY would seriously irritate my colleague Carlos Wagner, which would have certain positive "quality of life" issues for me.
  - The party line is "Just look at the inclusive missing $E_T$ distribution; you can't miss it" and occasionally, "The background to SUSY is SUSY"
- Some other surprise

# Inclusive Missing $E_T$ is Hard




- This plot compares the measurement of inclusive missing $E_T$ with a known source (invisible width of the Z)
  - We're starting with a background ~2 orders of magnitude larger at reasonable $E_T$.
- This is all Monte Carlo, of course, and the usual disclaimers apply

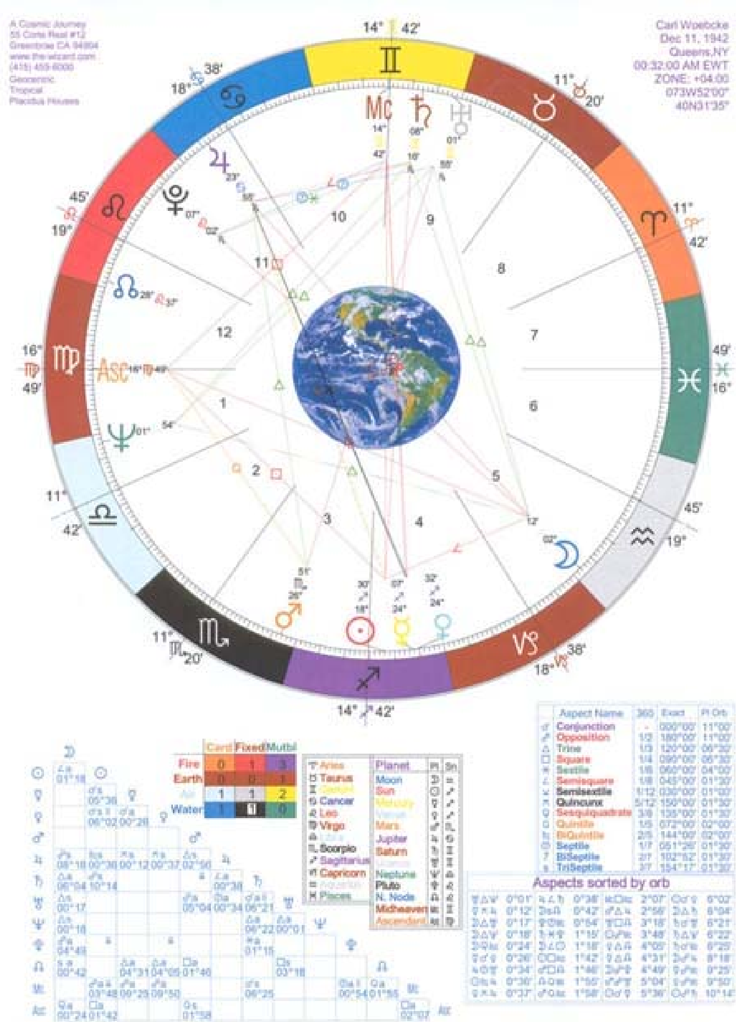
# *Where is All this Missing $E_T$ Coming From?*

- **It ain't SUSY.**
- ~98-99% is from mismeasured jets
  - Jet mismeasurement is rare, but there are a heckuva lot of them
  - About ½ of 1% of jets have significant energy loss to neutrinos
    - *From <u>light</u> flavor, not heavy flavor!*
  - Identification of this process is often – but not always - easy
- Much of the remainder is from missing ("crack seeking") leptons

Personal Conclusion: We can't do a credible Missing-$E_T$ based SUSY search until we understand jets.

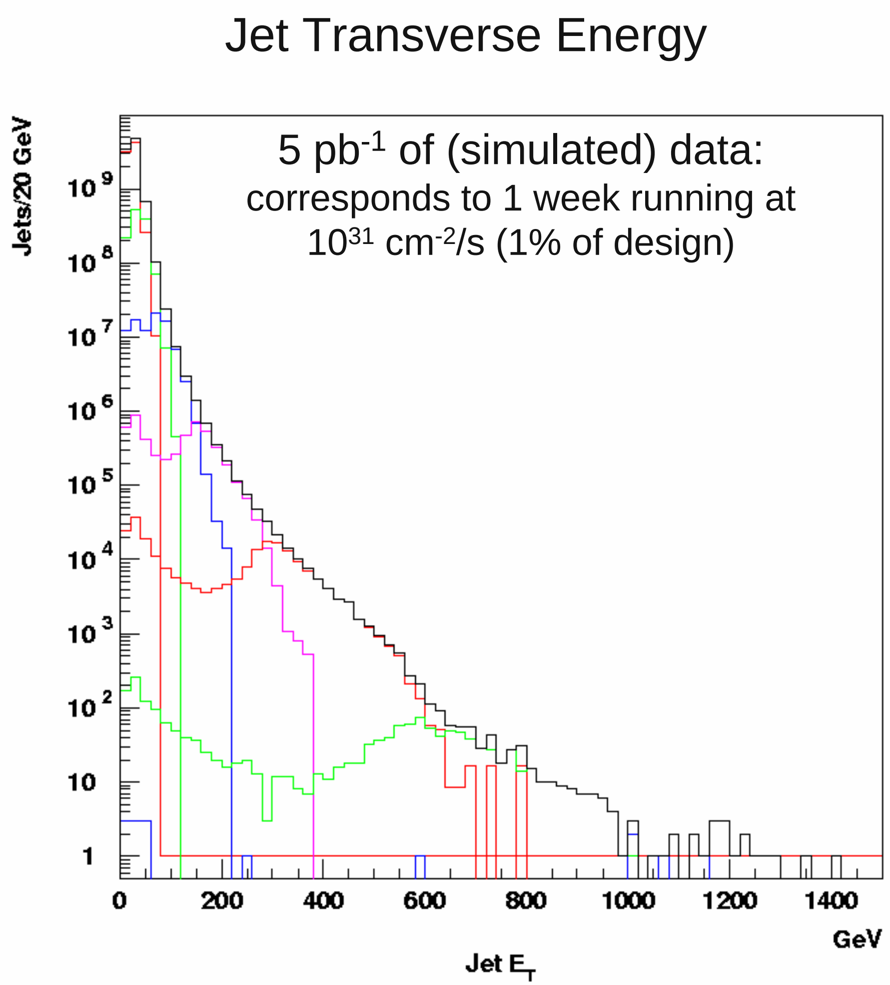
Question for the Audience: Would you believe a Missing-$E_T$ based SUSY search that didn't show a credible $Z \rightarrow \nu\nu$ signal?

# Prediction #4




## *Prediction #4:*
## *Jets Will Be Among Our Most Interesting Early Measurements*

# Early Jet Measurements



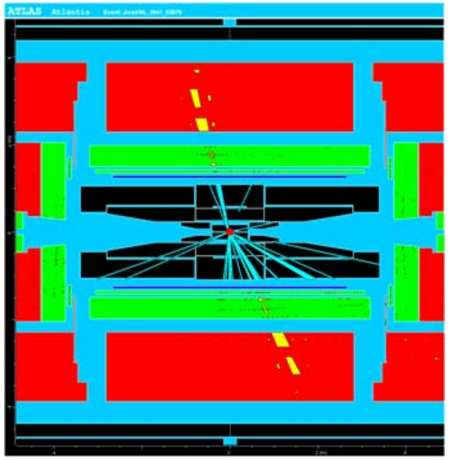

- Expected limit on contact interaction: Λ(qqqq) > ~6 TeV
  - Rule of thumb: 4x the $E_T$ of the most energetic jet you see
  - Present PDG limit is 2.4-2.7 TeV
  - Ultimate limit: ~20 TeV
  - The ATLAS measurement is at lower x than the Tevatron: PDF uncertainties are less problematic
- What about the addition of θ* distribution to improve the early limit sensitivity? Theoretical guidance would be appreciated here.
  - A nice feature is that this depends on the position of the jets instead of the energy.
    - *It's harder to mismeasure the position than the energy*

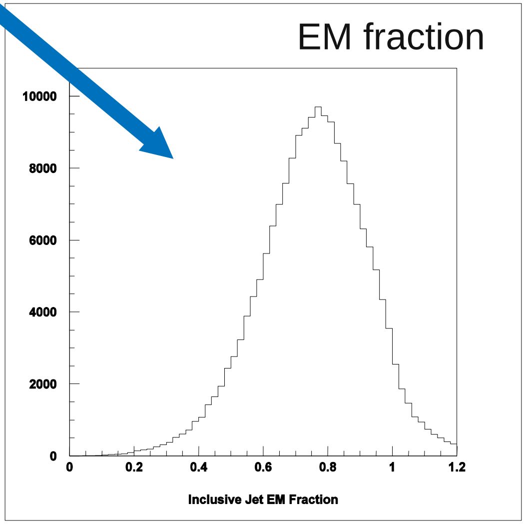
## *Outrunning the Bear*

- Present limits on 4-fermion contact interactions from the Tevatron are 2-4-2.7 TeV
- This may hit 3 TeV by LHC turn-on
  - Depends on how many people work on this
- If we shoot for 6 TeV at the LHC and only reach 5 TeV, we've already made substantial progress
- Note that there are ~a dozen jets that are above the Tevatron's kinematic limit: a day at the LHC will set a limit that the Tevatron can never reach.

# Getting the X-axis ($E_T$) Right

- Starting point:
  - The EM calorimeter is calibrated with the known Z mass using Z decays to electrons
  - Despite being hadrons, most (80%) of the jet energy at ATLAS ends up in the EM calorimeter, not the hadronic calorimeter.
  - The hadronic calorimeter is calibrated from test beam
  - This is probably good to 10% or better
- Improvements:
  - Look at balancing: a jet recoils against a Z, a photon, or another jet.  Their $p_T$'s should balance (within higher order effects like $k_T$)



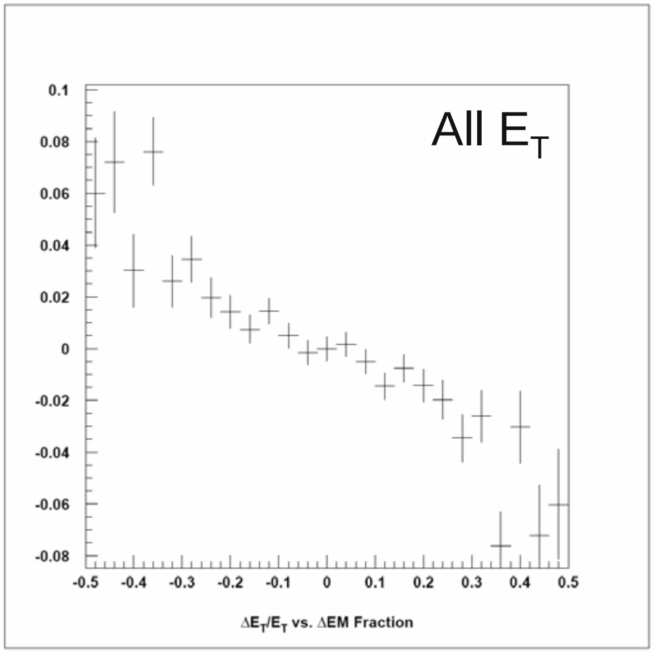


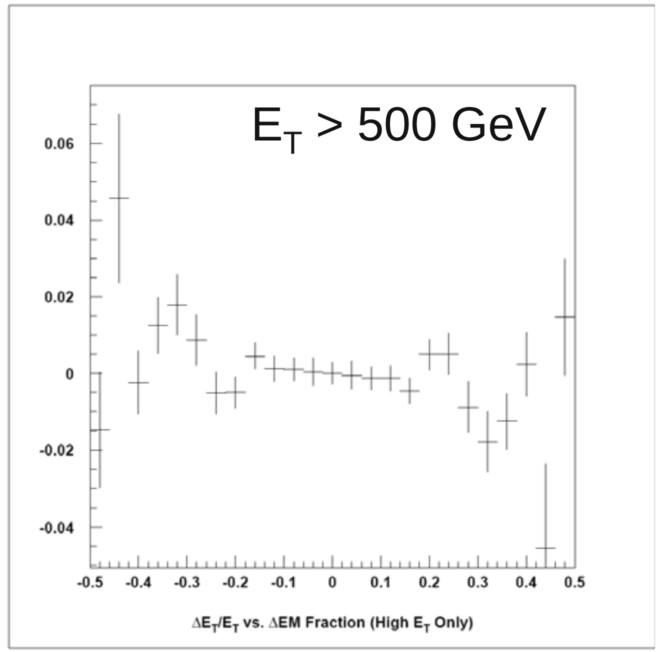
# Jet Energy Scale Job List

- See that the Z decay to electrons ends up in the right spot
  - Demonstrates that the EM calorimeter is calibrated
- Balance jets with high and low EM fractions
  - Demonstrates that the EM and hadronic calorimeters have the same calibration
- Balance one jet against two jets
  - Demonstrates that the calorimeter is linear
- Balance jets against Z's and photons
  - Verifies that the above processes work in an independent sample
  - Demonstrates that we have the same scale for quark and gluon jets
- Use top quark decays as a final check that we have the energy scale right
  - Is m(t) = 175 and m(W) = 80?  If not, fix it!

Note that most of the work isn't in getting the jet energy scale right.  It's in convincing ourselves that we got the jet energy scale right – and that we have assigned an appropriate and defensible systematic uncertainty to it.

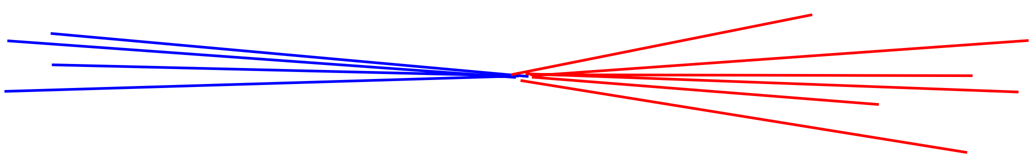
# Jet Balancing & EM Fraction




- Jet balance should not depend on the jets' EM fractions
- It does, at the few % level
- The effect is smaller for high $E_T$ jets, central jets, and jets that are very close to back-to-back

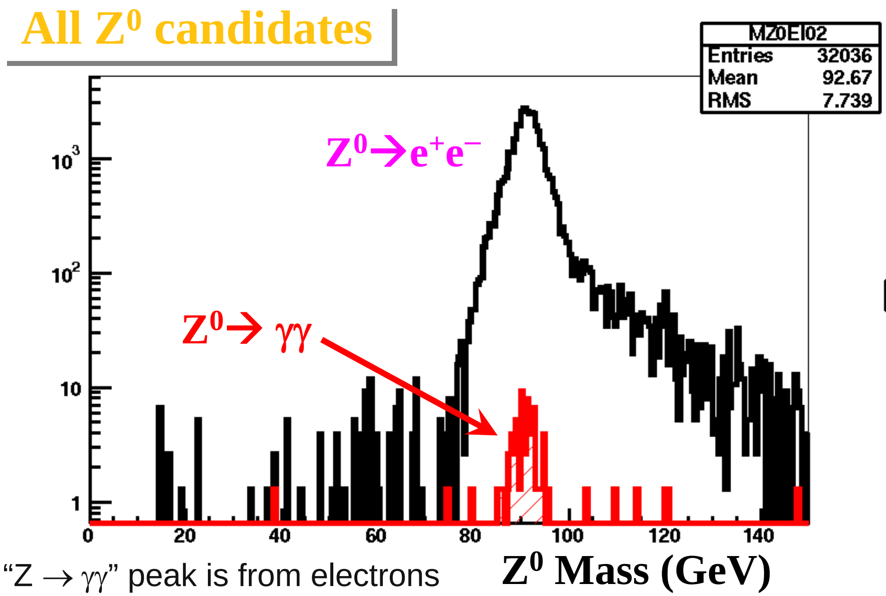
Look at events with exactly two back-to-back jets:



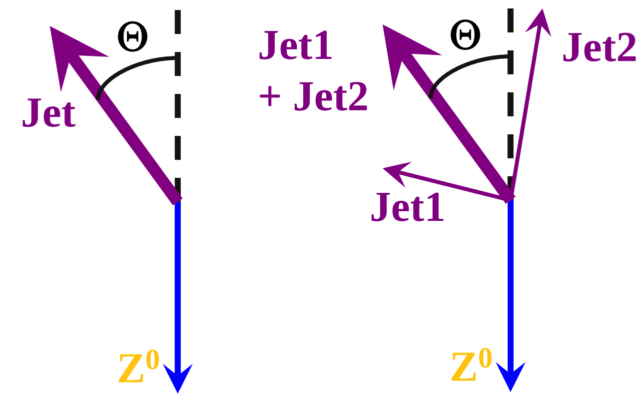
Two back-to-back jets should balance in $E_T$ irrespective of whether the energy is mostly electromagnetic or mostly hadronic.

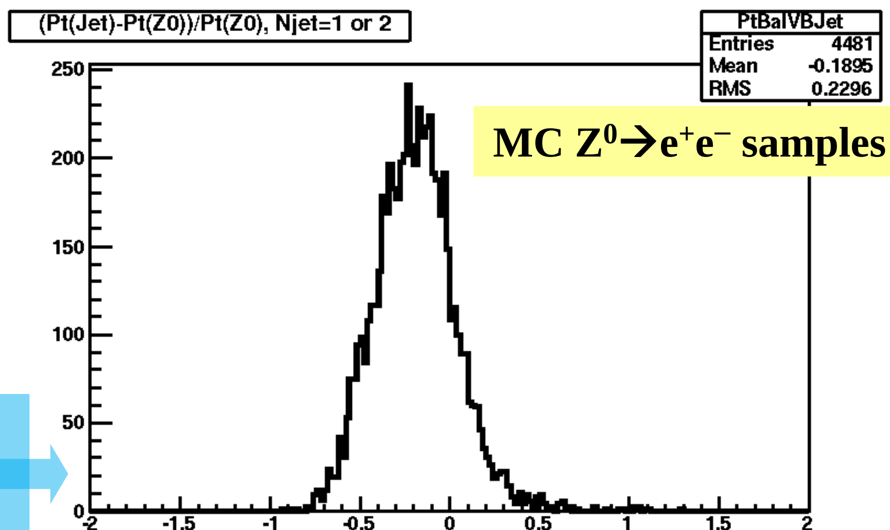
# *Z-Jet Balancing*

- Goal – set jet energy scale by balancing jets against a (well-measured) Z




The "$Z \rightarrow \gamma\gamma$" peak is from electrons where we miss the track.



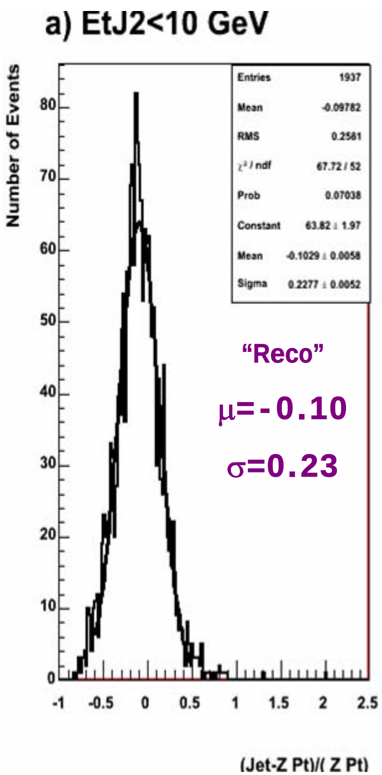




The jet energy is low with respect to the Z.

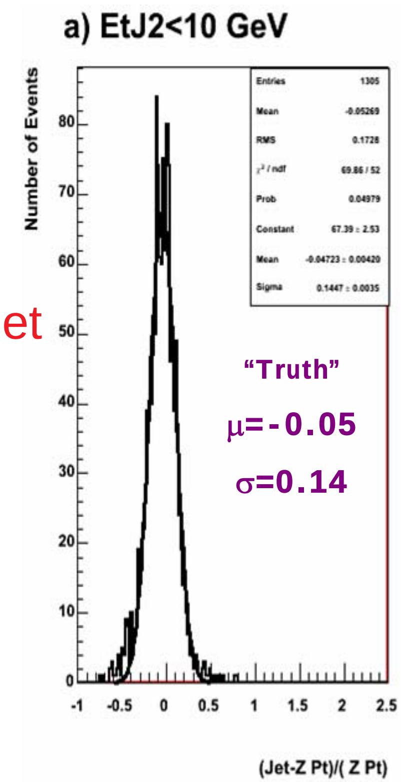
Wrong jet scale? Overcorrected leptons? Missing jets?

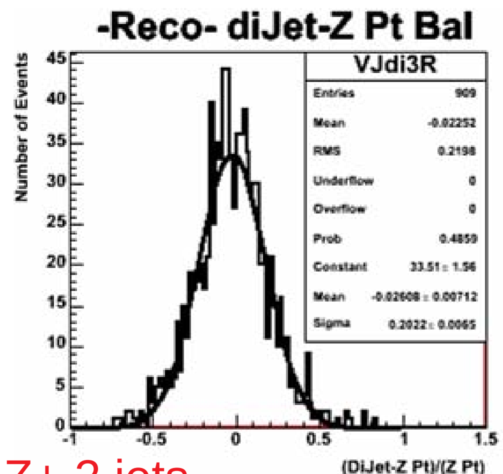
Credit: Heujin Lim

# *Two Jets Are Better Than One!*

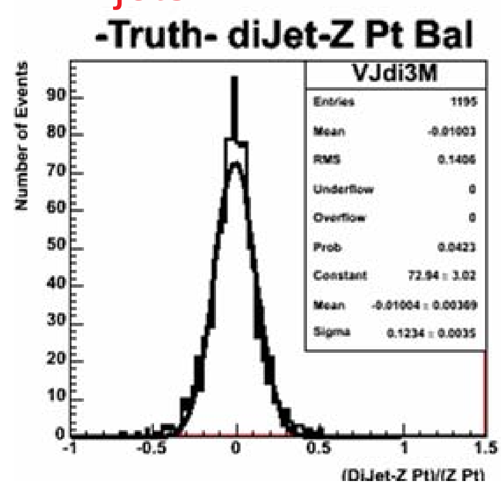



Z+ 1 jet




Z+ 2 jets




- Z+2 jets are better balanced than Z+1 jet events.
- Investigating why – perhaps related to low efficiency for finding soft jets?

Credit: Jimmy Proudfoot

# *A Short Shopping List for Theorists*

- At the TeVatron, there is often one dominant signal process and one dominant background process. This is not often the case at the LHC.
  - It appears that the root cause is the lack of antiquarks in the initial state. Getting them off gluons complicates things.
  - In the experimental world, this is known, but not yet felt in our guts
    - *Repetition will help here*
  - It would be good to have an idea of how uncertain predictions are because of this.
- Many LHC processes (signal or background) produce multiple hard jets
  - Does there exist a Monte Carlo that not only gets the number and spectrum right, but also the detailed kinematics? (e.g. dijet masses, angular separation, etc.)

# Conclusions and Prediction #5


- “It is difficult to predict, especially the future”
- I hope I convinced you that
  - We have a lot of work to do to get believable physics out of the LHC
  - We have a vision of the path we need to take to get there, and we’ve already started down the path (e.g. hunting down 5% effects in the jets)
  - Real life will be harder than our predictions
  - But real life will likely be more exciting than our predictions

# May All of Your Predictions Be Pleasant Ones