# Precision Measurements, Small Crosssections, and Non-Standard Signatures: The Learning Curve at a Hadron Collider

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Lecture 1: Introduction to Collider Physics

Lecture 2: Tevatron Jets; W,Z,$\gamma$; Top, Bottom

Lecture 3:

1) Searching for the Higgs
2) Searching for Not-SM events
3) The Learning Curve at a Collider
4) Unsolved Problems

# Acknowledgements

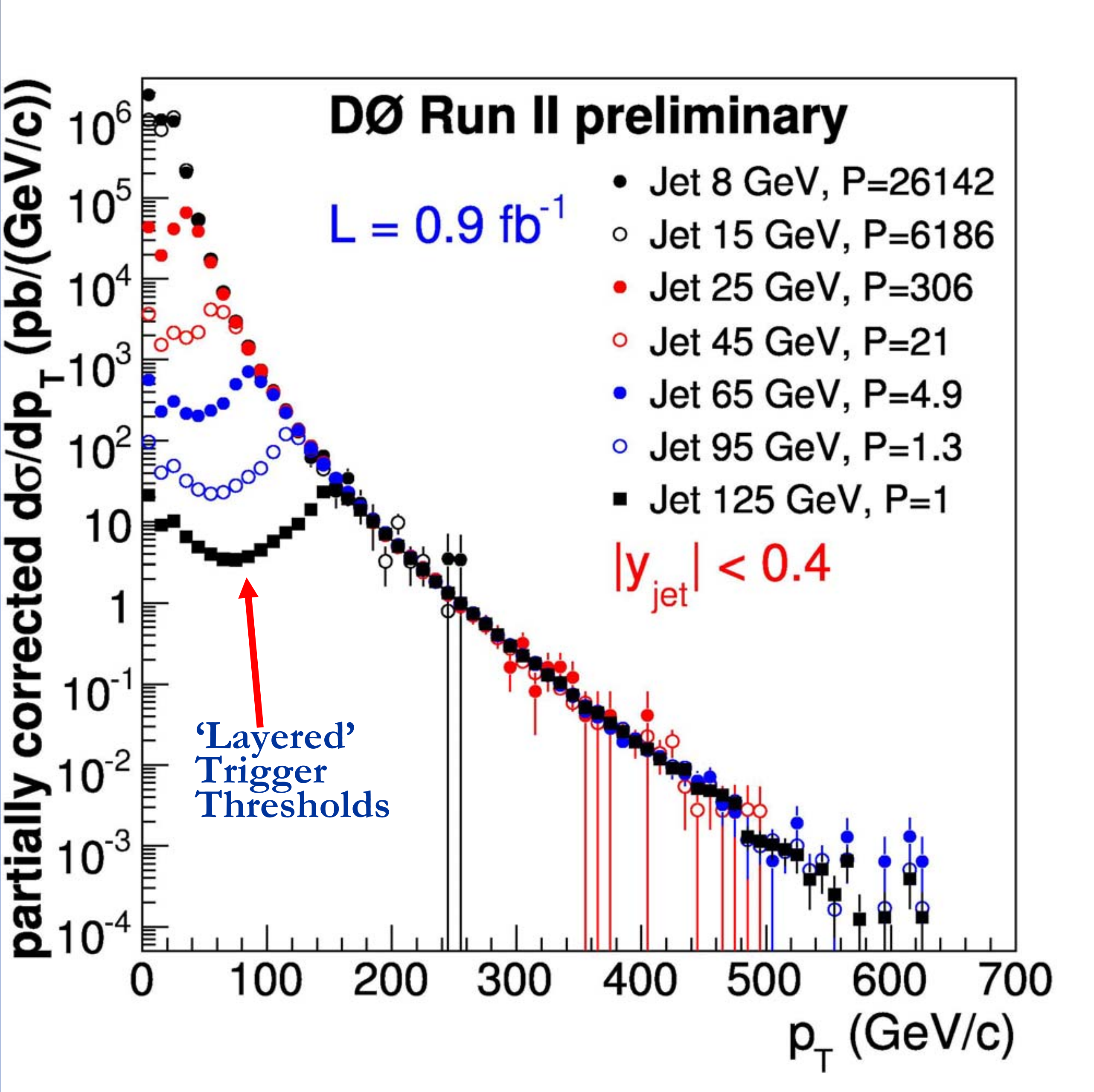
- Thanks to many CDF and D0 colleagues whose work I'll show… Also SM MC generator folks (these are the heros- we need more of them!)
- Apologies to D0- I tend to show much more CDF than D0 as I know it much better (happy for help on this).
- Opinions, errors, and some of the plots are my own, and do not represent any official anything.

Note-These lectures are frankly pedagogical- apologies to the experts in advance..

# QCD Results

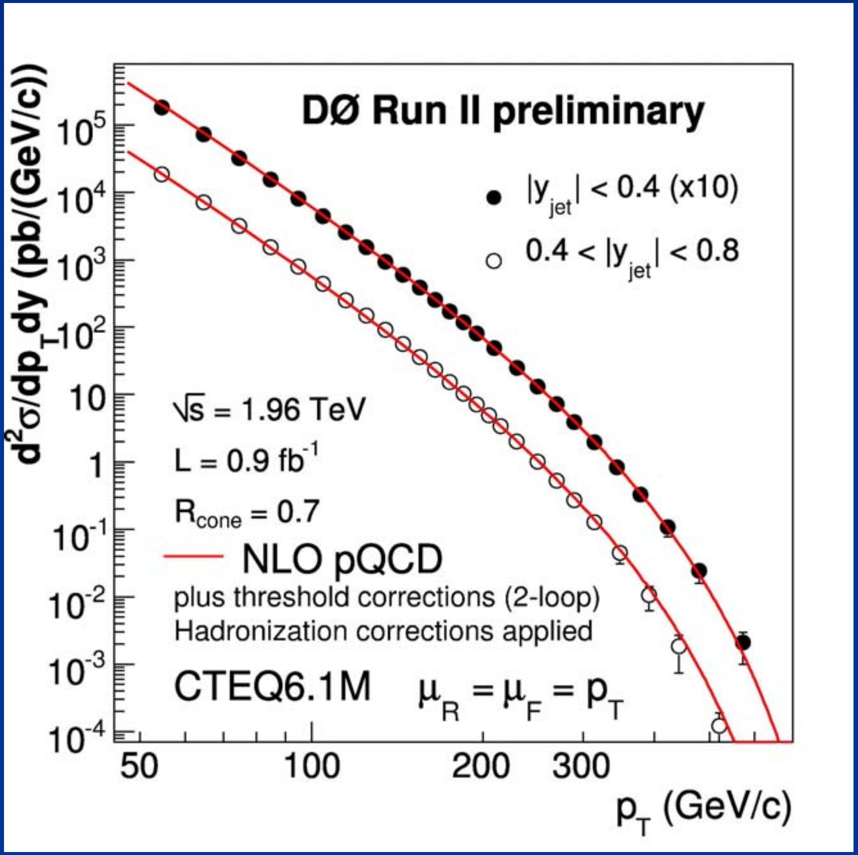
- At lower root-s reach farther in xT = pT/(root-s/2)
- Large xT corresponds to large x: sensitive to the valence quark distributions
- Shortest-distance (biggest momentum transfer) collisions observed – sensitive to new geometric crossections, thresholds (e.g. black holes?)
- W+jets, Z+jets, gamma+jets crucial backgrounds to new physics- we have to be able to predict the SM contribution to subtract off and get the new!
- Many critical details- underlying event, trigger biases, energy scales, fake rates for photons, taus, electrons, rapidity gaps,…- a wealth of important measurements to be made.

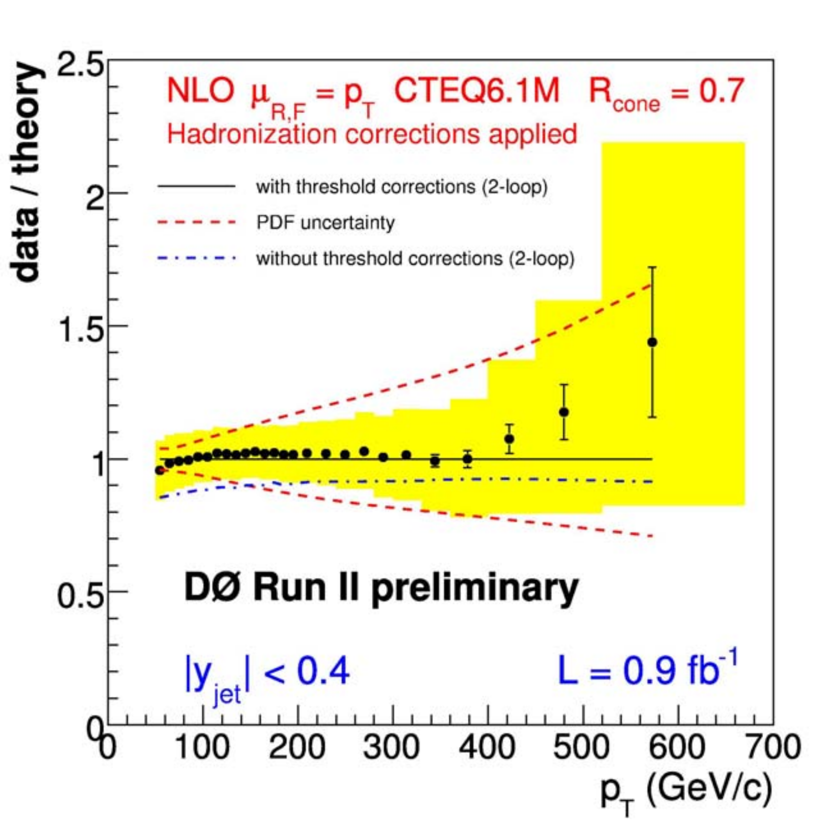
# High PT Jet Production and PDF's



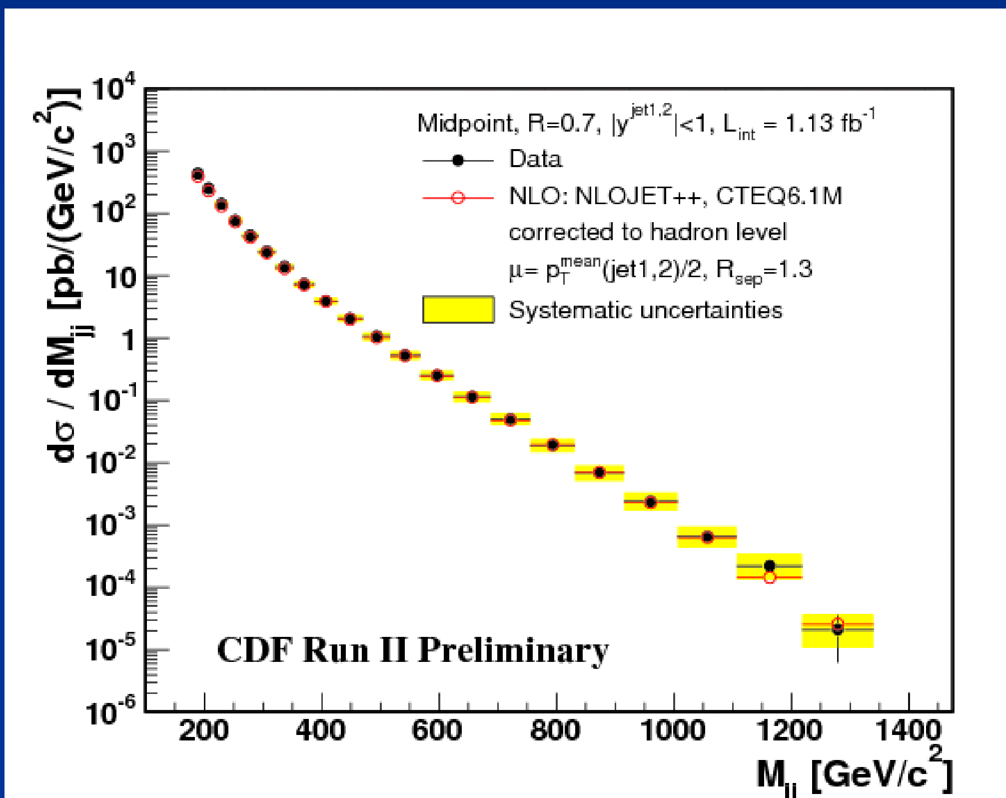

Jets are overwhelming – the dominant feature at a collider!

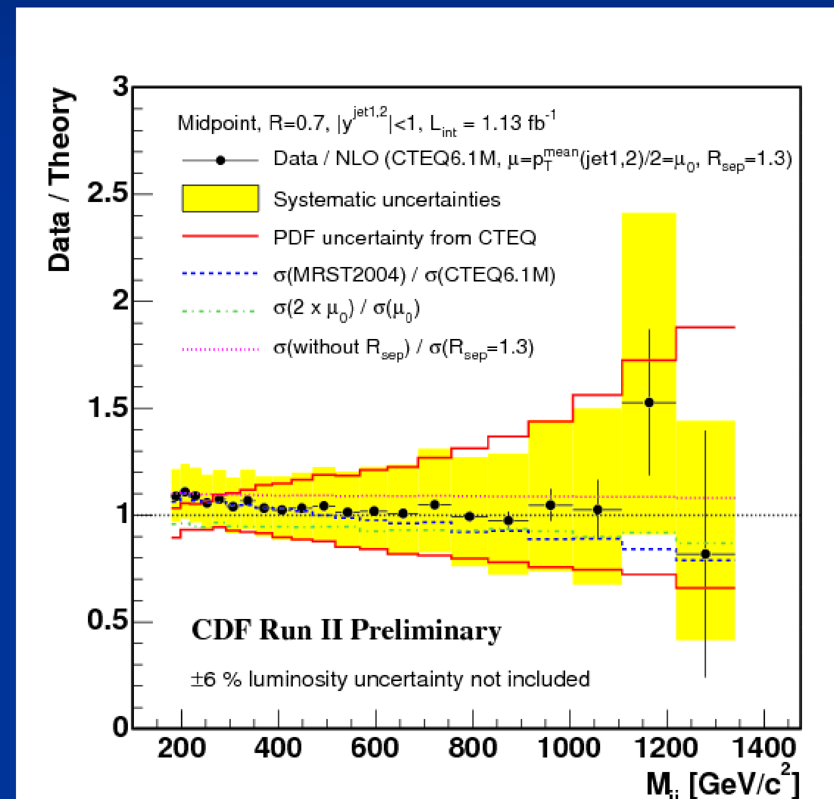
# High PT Jet Production and PDF's



# High PT Jet Production and PDF's

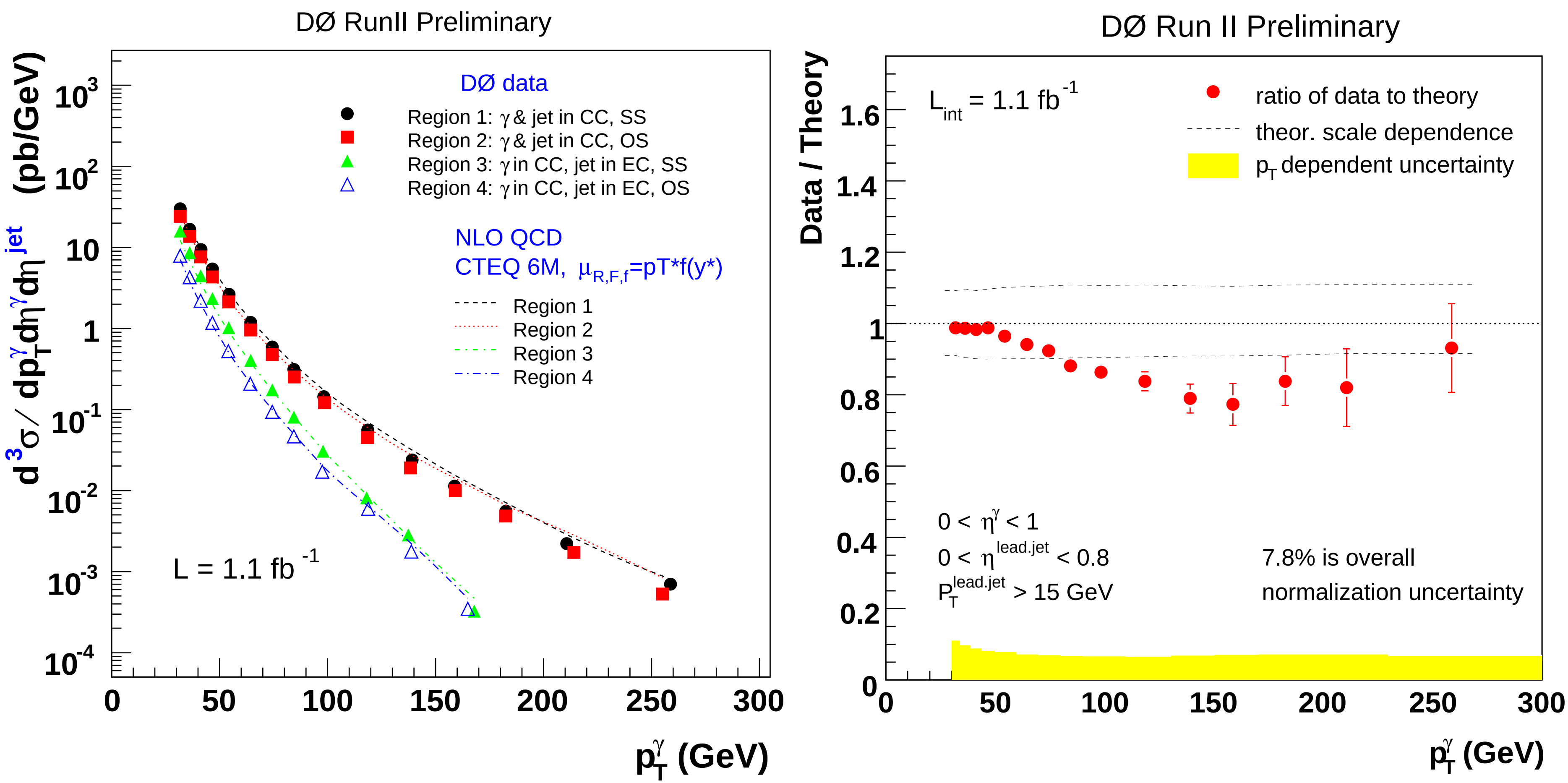



Really remarkable agreement with CTEQ PDF's in Mass(JJ)
Note # of decades, systematic uncertainty bands

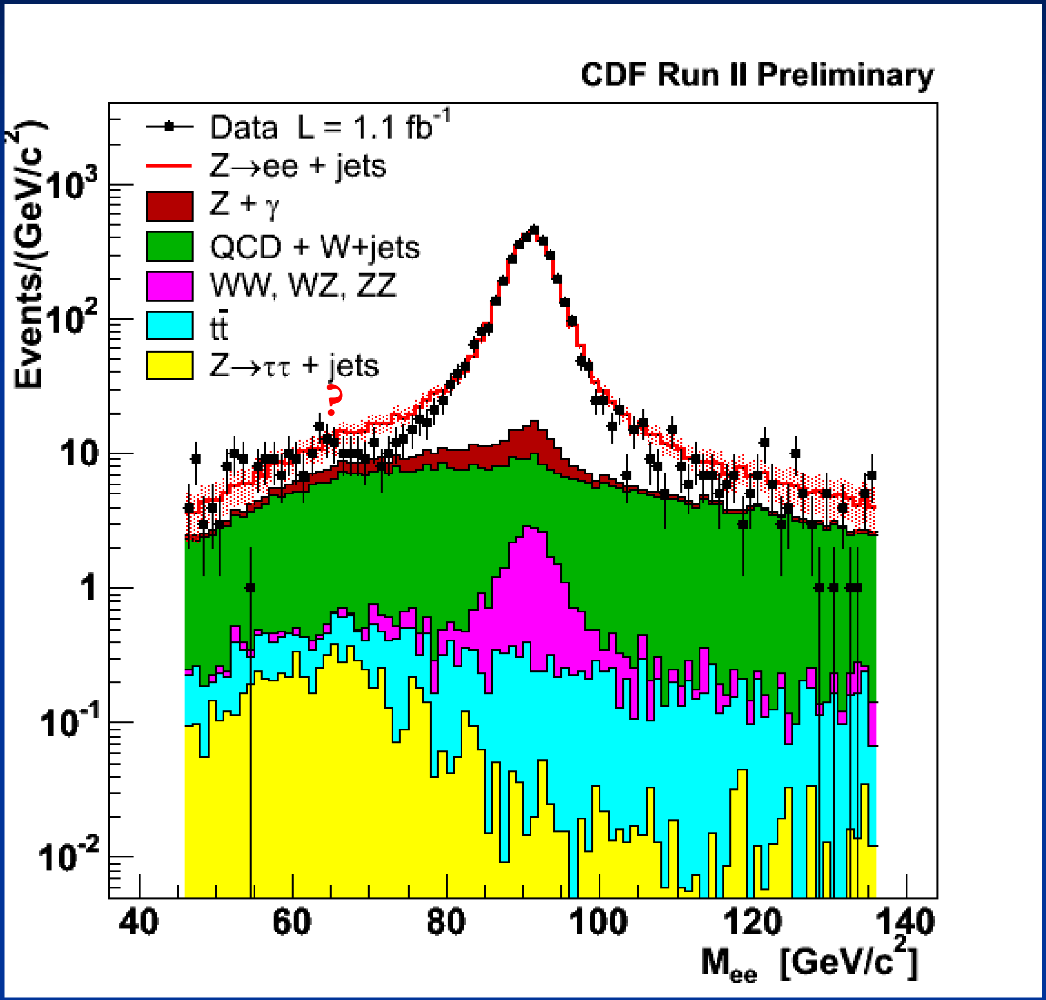
# Gamma+Jet Crossections

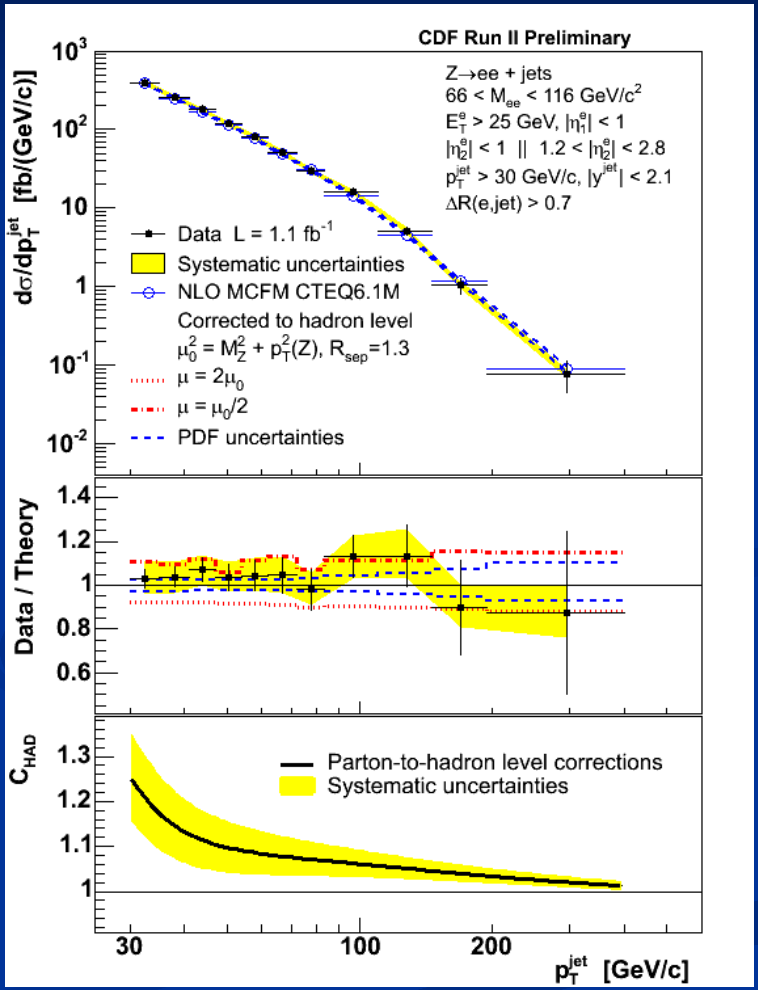
## 'Compton Scattering'- glue-q -> q-photon (would he (Arthur Holly) be surprised!)




Tests understanding of the gluon PDF

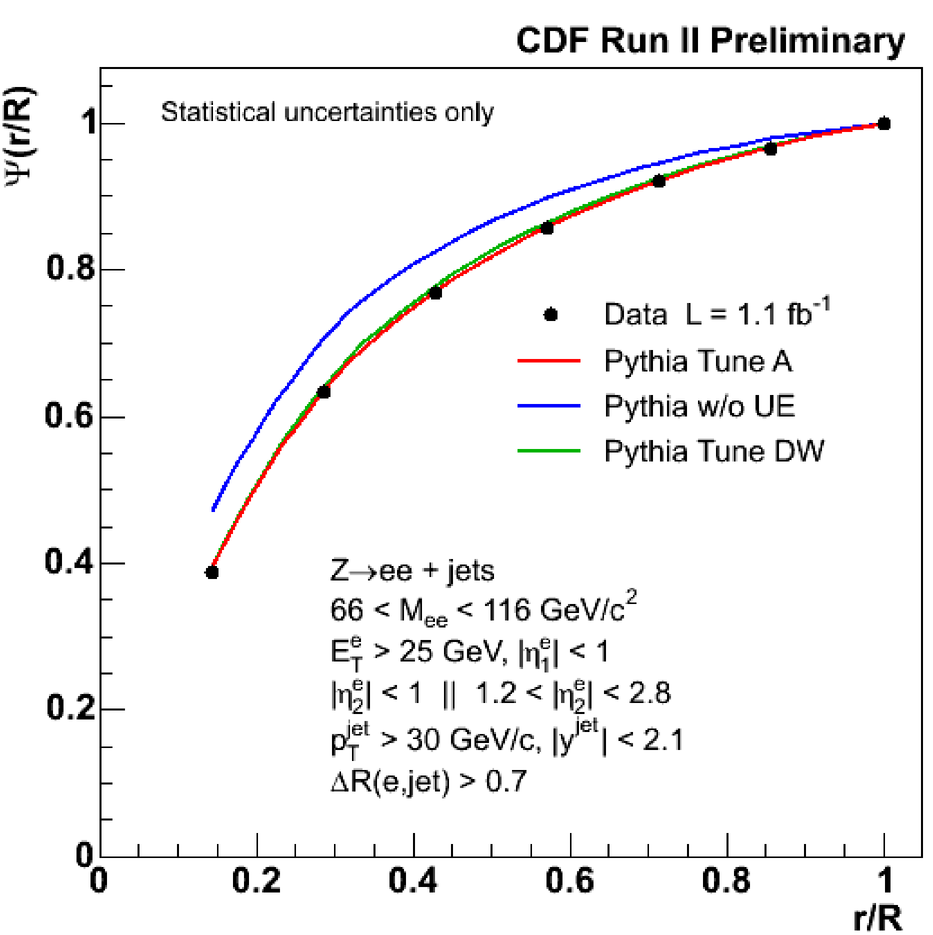
# Z+jet Production- THE Standard Candle

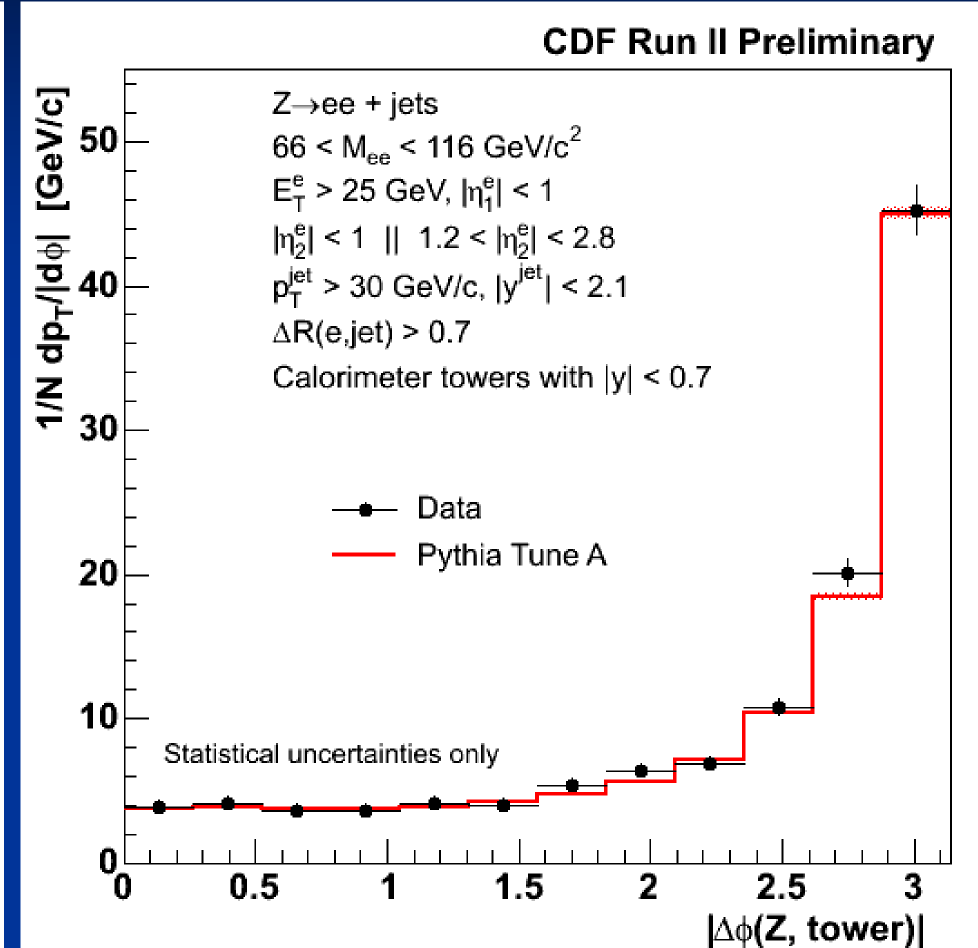



Really remarkable agreement with CTEQ PDF's - note # of decades, systematic uncertainty bands

# Z+jet Production and PDF’s




Jet Shape in eta-phi space (R)

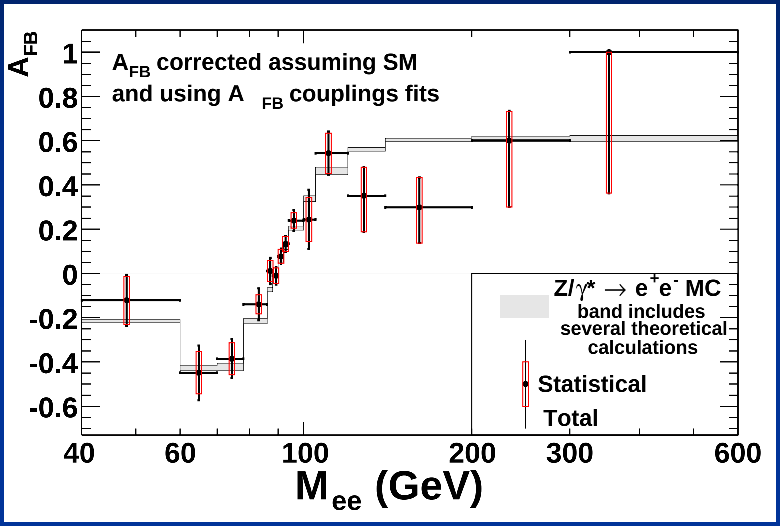
Energy flow in |Delta-y|=0.7

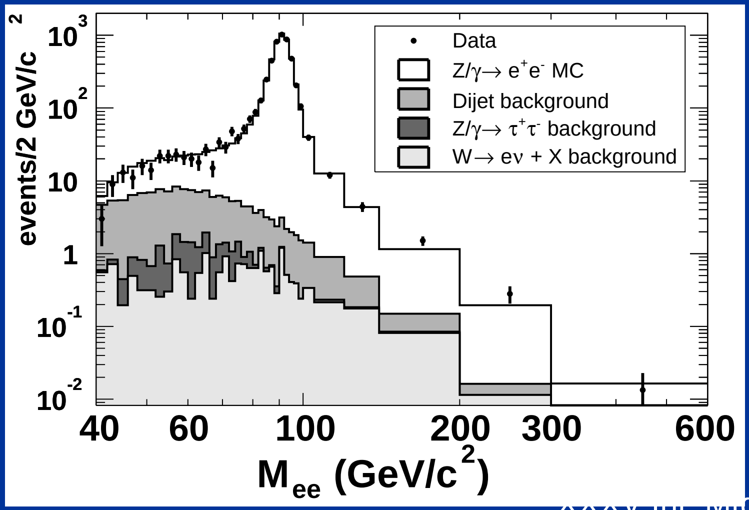
**Really remarkable agreement with CTEQ PDF’s - note # of decades, systematic uncertainty bands**

# EWK Results (not updated- apologies)

- At lower root-s the ratio of W/QCD-jet production is 10X larger at the Tevatron than the LHC, due to being at larger x, as $m^2 = (x_1 x_2) s$
- Unlike at LEP, the `beam energy' is a continuum- there is nothing external to set the scale of energies. The W and Z provide calibration for the energy (calorimeter) and momentum (tracking) scales.
- Many models of NP have a quantum number conserved by QCD, but not by EWK (e.g. flavor), so final states will involve W's, Z's,…
- Cascade decays (e.g. in SUSY ) often end up in W's, Z's, photons..- low transverse velocites => low boosts
- So scale of missing-Et, lepton pt thresholds is ~20 GeV (1/2 of 1/2 MW)- remarkably low..
- Precision measurements will require a good understanding of multiple parton interactions, multiple interactions, ISR, FSR, …long learning curve

# Z-γ Interference



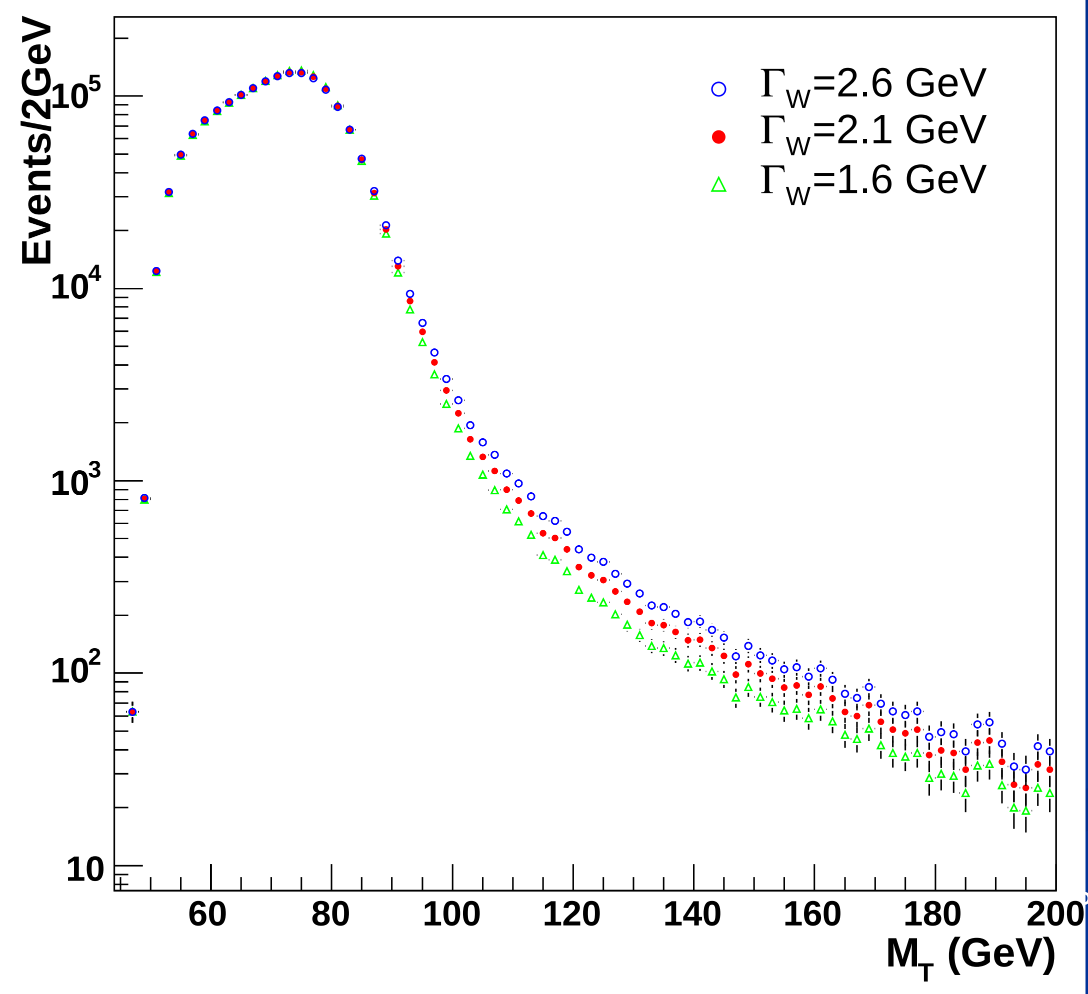

**Run 1 CDF two highest mass events were `backwards'- sensitive to higher-mass Z's through interference.**

**Lovely gamma-Z interference for QM class…**

# Above the Poles:

# The W Width Direct Measurement

**Idea (HF, Sacha Kopp, J. Rosner)- Breit-Wigner should fall slower than resolution (power law vs Gaussian, hopefully)…**

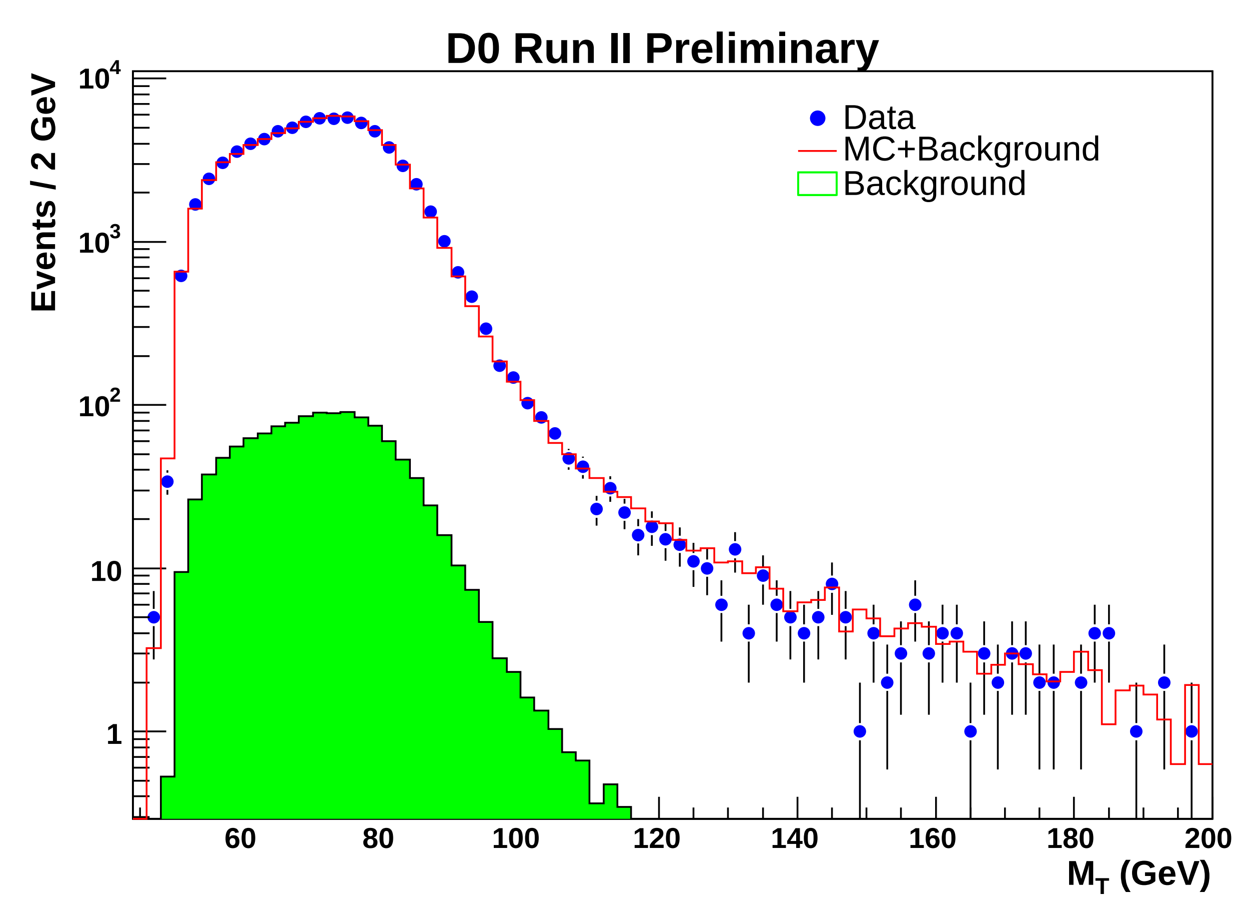



**Insensitive to radiative corrections- good place to look for new Jacobian peaks- see Rosner, Worah, and Takeuchi, PRD49,1363 (1994) (hep-ph/9309307)**

**From D0- MC**

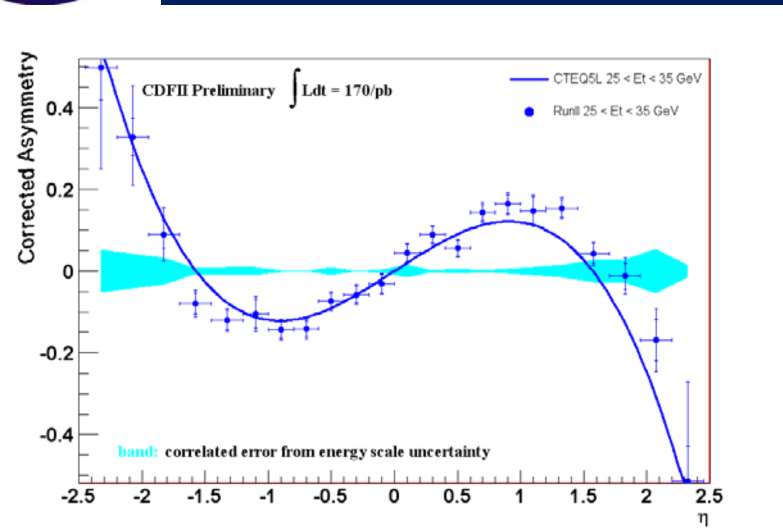
Physics:

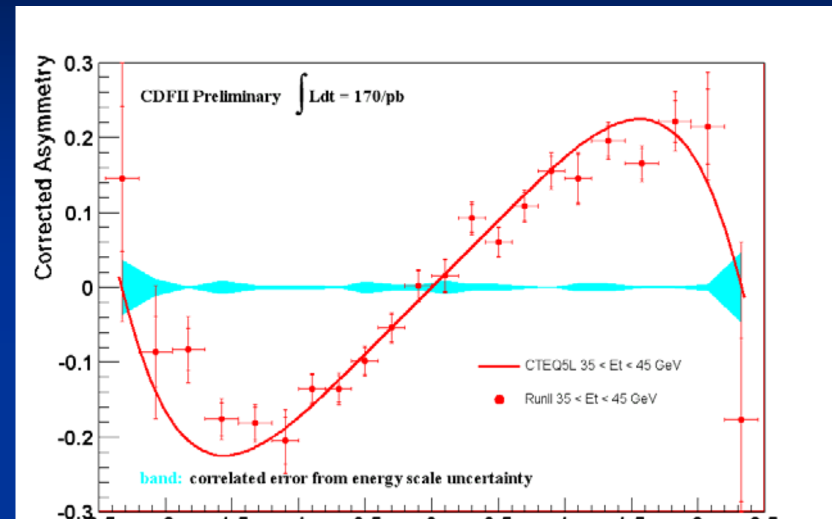
# Above the Poles: The W Width Direct Measurement




**Systematics are largely from the Z, hence statistics-limited: note Z/W is 1.25 at pt=100, 1.5 at pt=200 (Arnold and Reno, Nucl Phys B319, 37, 1989)**

# W Asymmetry


CDFII Preliminary
∫Ldt = 170/pb
CTEQ5L 25 < Et < 35 GeV
RunII 25 < Et < 35 GeV
band: correlated error from energy scale uncertainty
Corrected Asymmetry
η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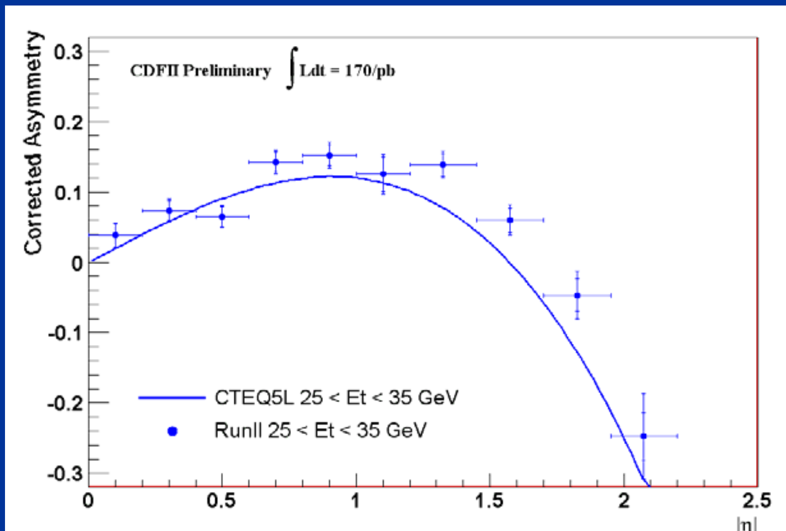
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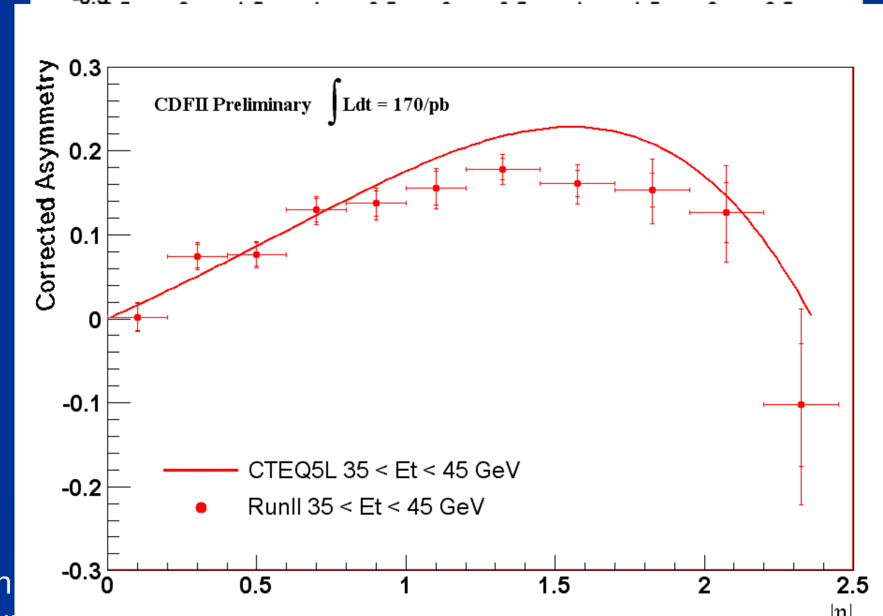
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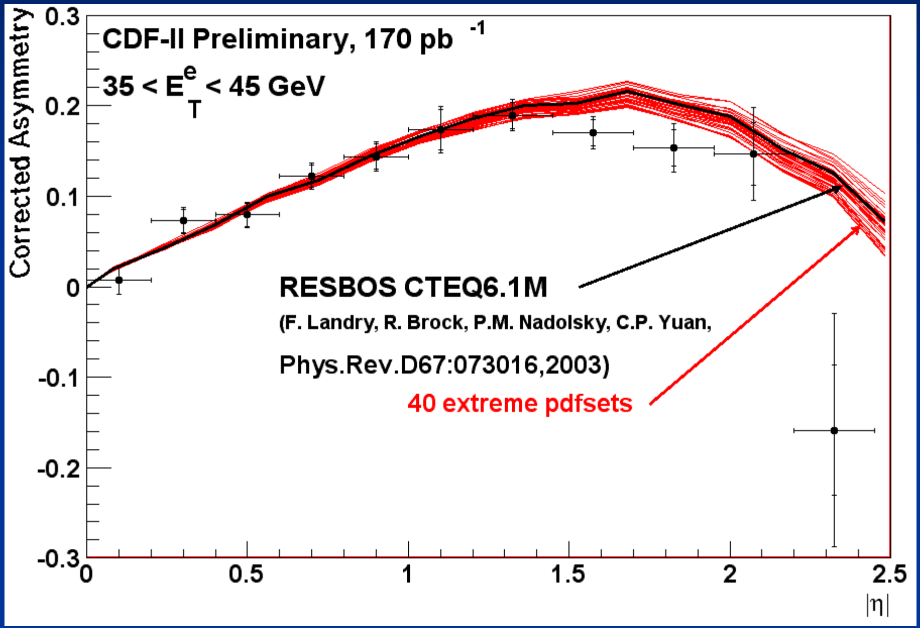
# W Asymmetry




CTEQ6 comparison with uncertainties

**Wish List Item: Answer to Q: is the ratio**

$$\frac{W^+ \rightarrow e^+}{Z^o/\gamma \rightarrow e^+}$$ vs $\eta$, $P_{T}$, (mass)

**sensitive to PDF's in a different way?**

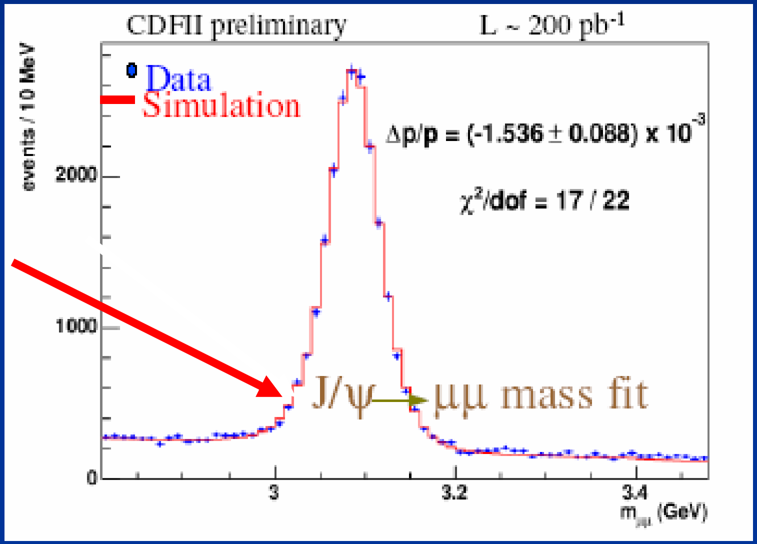
# New (Jan. 5, 07) CDF W Mass

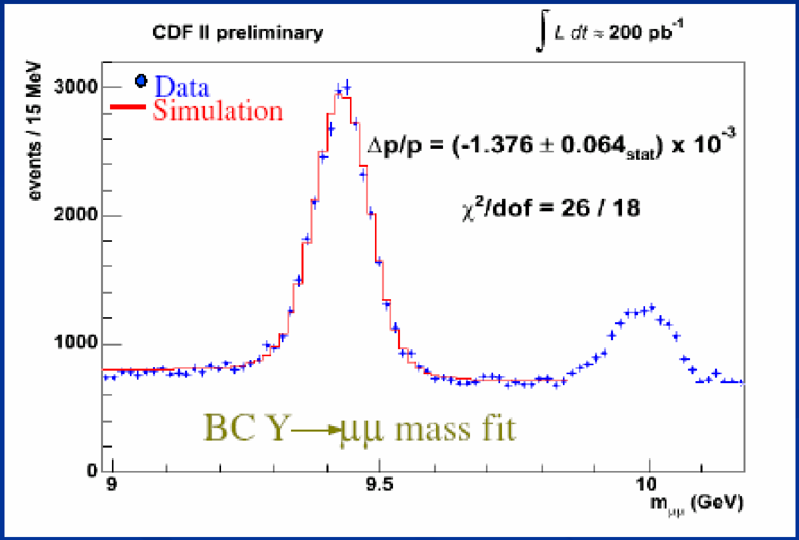
Data from Feb. 02-Sept 03

218 pb$^{-1}$ for e; 191 pb$^{-1}$ for $\mu$

A Systematics Intensive Measurement..
This is a precision spectrometer!

N.B.

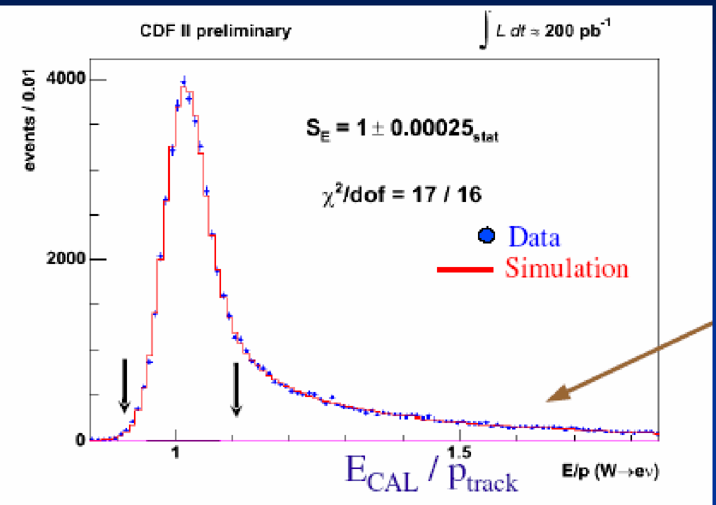


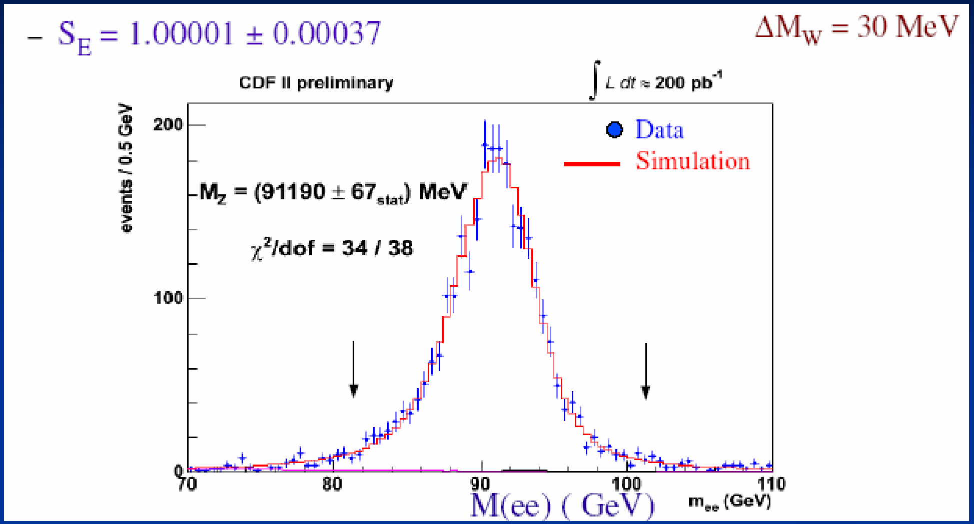




First, Calibrate the spectrometer momentum scale on the J/Psi and Upsilon- material traversed by muons really matters in electron Wmass measurement. (discussed in Lecture 1).

Note: This is a small fraction of data taken to date- this is to establish the calibrations and techniques (so far) for Run II.

# New (Jan. 5, 07) CDF W Mass




**Run Ib Problem Now Solved: 2 Calibrations of EM calorimeter: Zmass ≠ E(cal)/p(track)**

**Electron and Muon Transverse Mass Fits**

1. Electrons radiate in material near beam-pipe, but cal (E) gets both e and g; spectrometer sees only the momentum (not the g):
2. Use peak of E(cal)/p(spectrometer) to set EM calorimeter scale
3. Use tail of E/p to calibrate the amount of material
4. Check with mass of the Z. Run I didn't work well (Ia, Ib). Now understood (these were 2 of the dragons).

# New (Jan. 5, 07) CDF W Mass

See William Trischuk's talk for details, explanations

Transverse Mass Fit Uncertainties (MeV)

| | *electrons* | *muons* | *common* |
|---|---|---|---|
| W statistics | 48 | 54 | 0 |
| Lepton energy scale | 30 | 17 | 17 |
| Lepton resolution | 9 | 3 | -3 |
| Recoil energy scale | 9 | 9 | 9 |
| Recoil energy resolution | 7 | 7 | 7 |
| Selection bias | 3 | 1 | 0 |
| Lepton removal | 8 | 5 | 5 |
| Backgrounds | 8 | 9 | 0 |
| pT(W) model (g2,g3) | 3 | 3 | 3 |
| Parton dist. Functions | 11 | 11 | 11 |
| QED rad. Corrections | 11 | 12 | 11 |
| Total systematic | 39 | 27 | 26 |
| Total | 62 | 60 | |

Systematic uncertainties shown in green: statistics-limited by control data samples

| | *W mass* (MeV) |
|---|---|
| DELPHI | $80336 \pm 67$ |
| L3 | $80270 \pm 55$ |
| OPAL | $80416 \pm 53$ |
| ALEPH | $80440 \pm 51$ |
| CDF-I | $80433 \pm 79$ |
| D0-I | $80483 \pm 84$ |
| LEP Average | $80376 \pm 33$ |
| Tevatron-I Average | $80454 \pm 59$ |
| Previous World Average | $80392 \pm 29$ |
| CDF-II (preliminary) | $80413 \pm 48$ |
| New Tevatron Average | $80429 \pm 39$ |
| New World Average | $80398 \pm 25$ |

**Note: This is with only 0.2 $fb^{-1}$ and 1 experiment: have ~2 $fb^{-1}$...**

N.B. 48 Mev/80 GeV

CDF Wmass group believes each systematic in green scales like a statistical uncertainty =>

We will enter another round of learning at 600-1000 pb (typically a 3 year cycle or so)

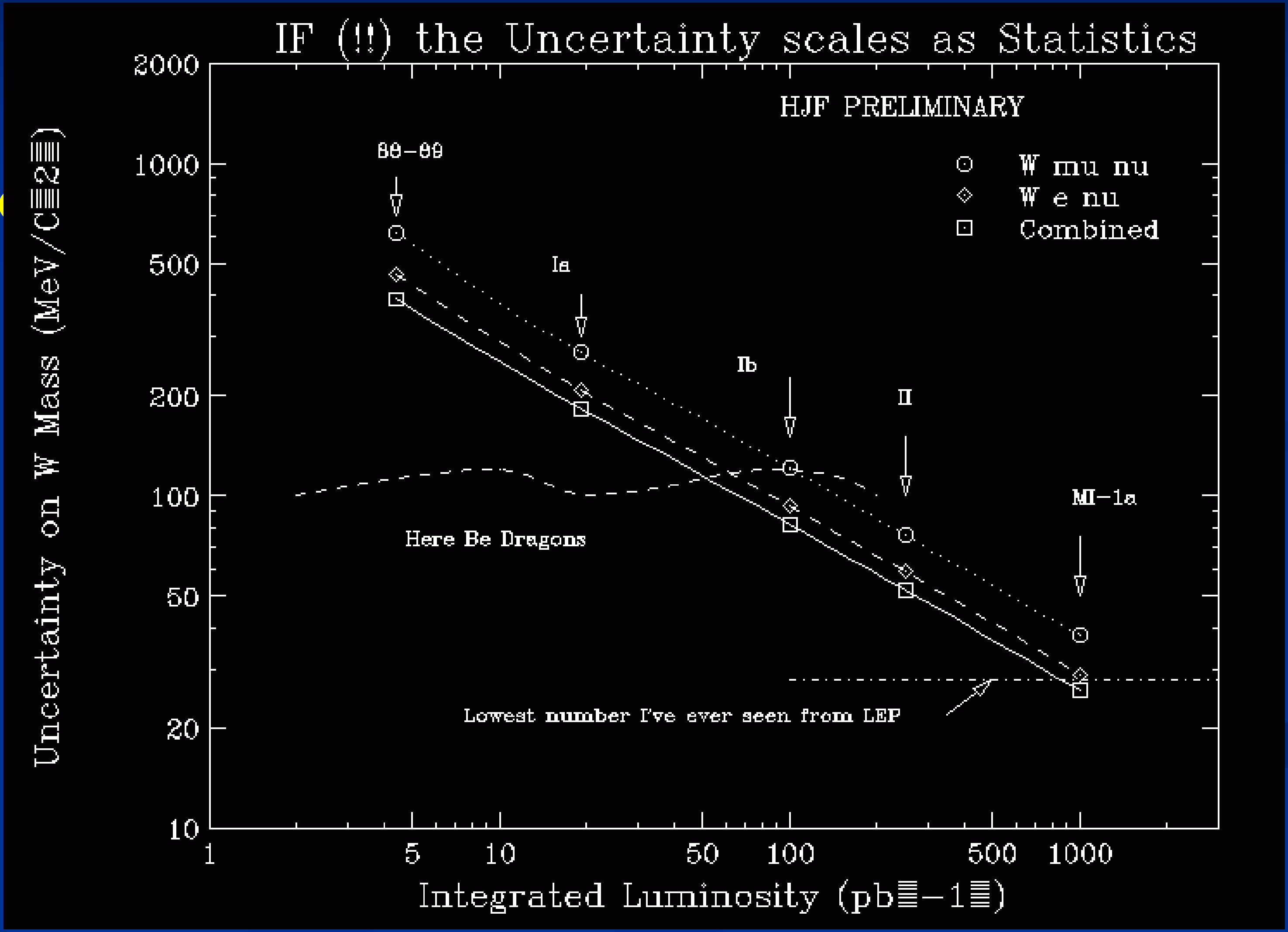
# Systematics scale with Statistics!

Take a systematics-dominated measurement: e.g. the W mass.

Dec 1994 (12 yrs ago)-

` Here Be Dragons' Slide: remarkable how precise one can do at the Tevatron (MW,Mtop, Bs mixing, …)- but has taken a long time- like any other precision measurements requires a learning process of techniques, details, detector upgrades….

The Le



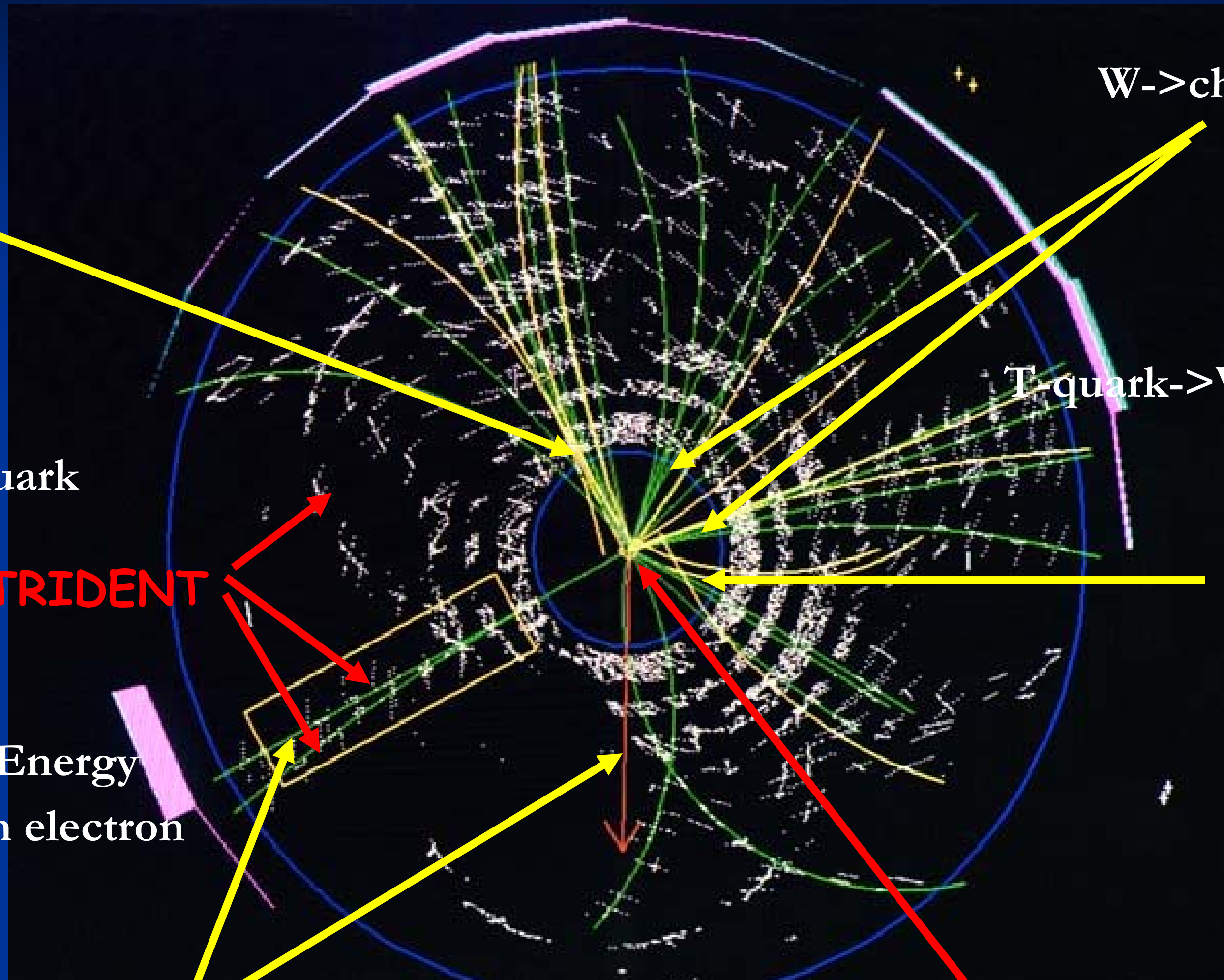

Theorists too(SM)

# Top Quark Results

- Top is uniquely heavy- only fermion heavier than the W or Z (in fact, mtop ~MW+MZ to high precision?!
- Top is unique- Yukawa =0.985+/-0.015.
- CDF and D0 are statistics-limited for top studies- cross-section ~ 8 pb, so in 1 fb-1 make only 8000, and BR's (e.g. lepton+jets=24/81) and acceptance x eff mean get only ~350 ttbar events with a b-tag per invfb.
- BUT, now for the first time we're getting a large enough sample to study the production and the decay using the data themselves for systematics-e.g. using the reconstructed W's in top decay to determine the jet energy scale. It's an exciting opportunity….

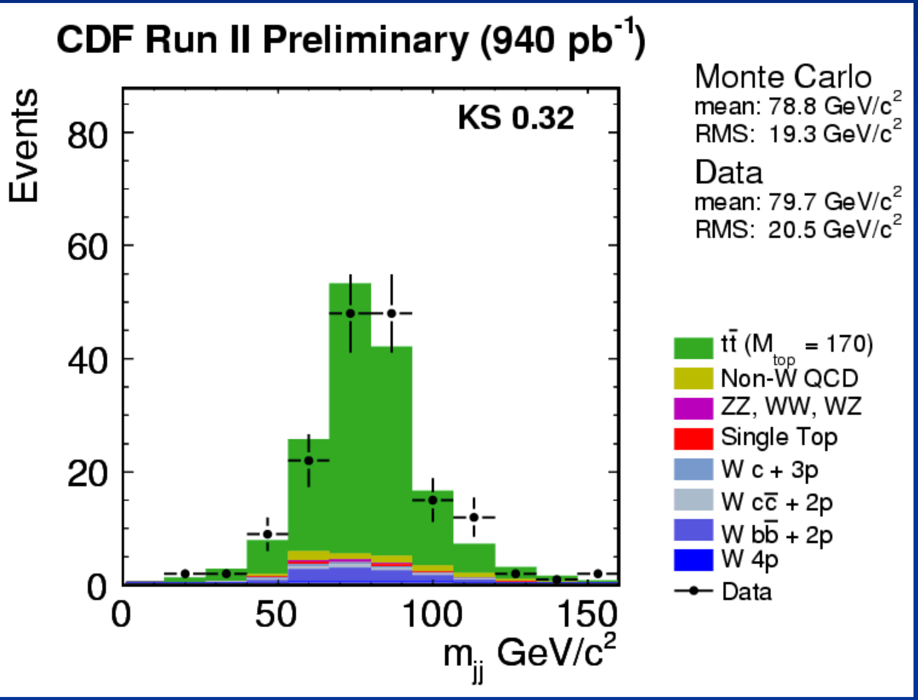
# TTbar-> WbWb->(eν)(jj)bbar

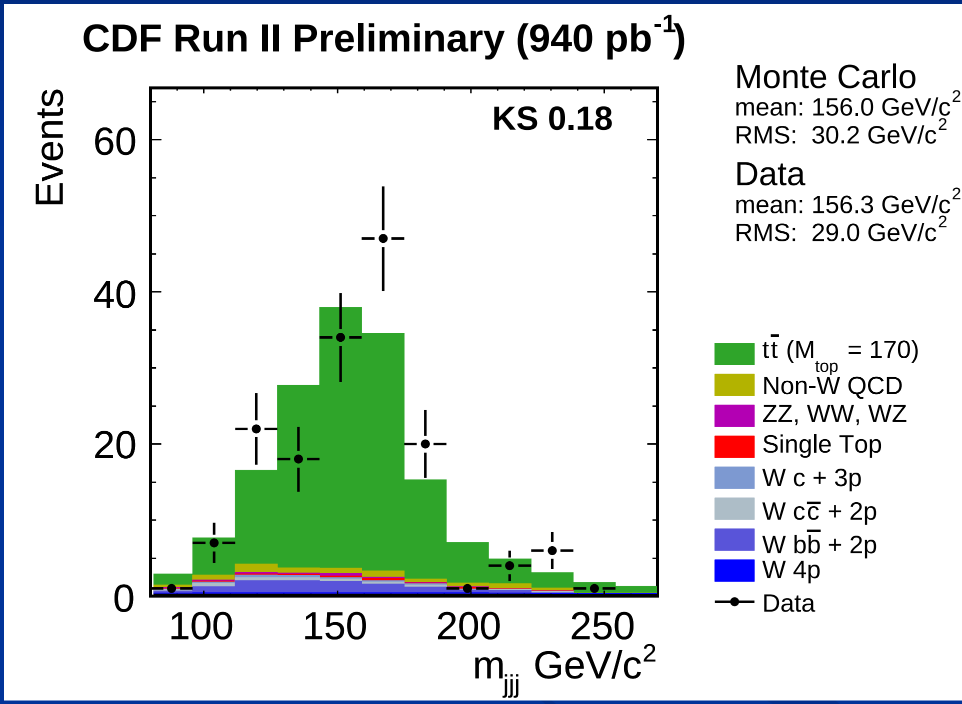
## T-Tbar -> $W^+bW^-$bbar




(Already saw this in Lecture 1)

# Precision Measuremnt of the Top Mass




M(2-jets)- should be $M_W$

M(3-jets)- should be $M_{top}$

**CDF e/μ-Met+4 Jets (1b) - 0.94 $fb^{-1}$, ~170 ttbar events**

# Precision Msremnt* of the Top Mass

*like Mrenna

**CDF Lepton+4jets:**

**Systematics:**

Jet Energy Scale (JES)

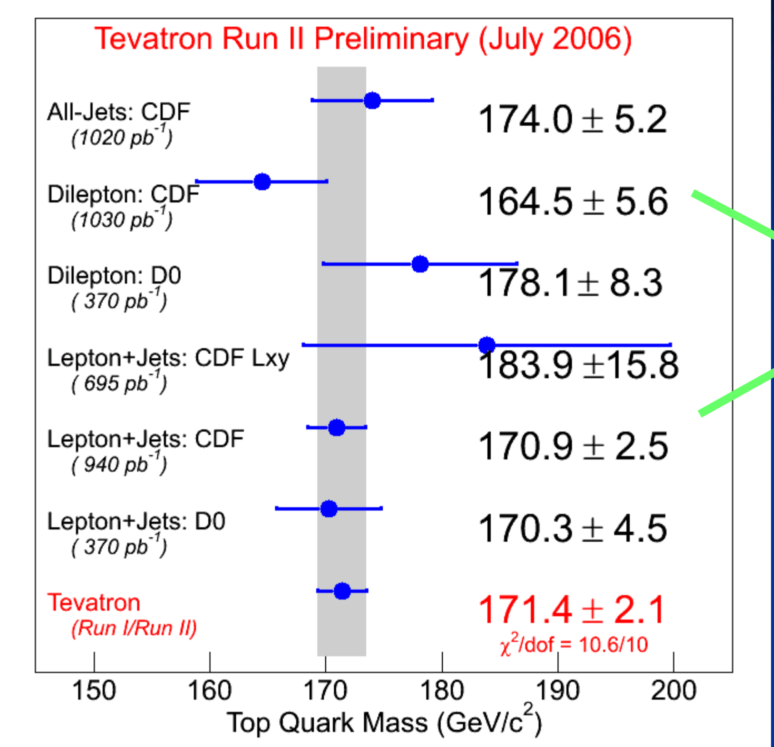
Now set by MW (jj)

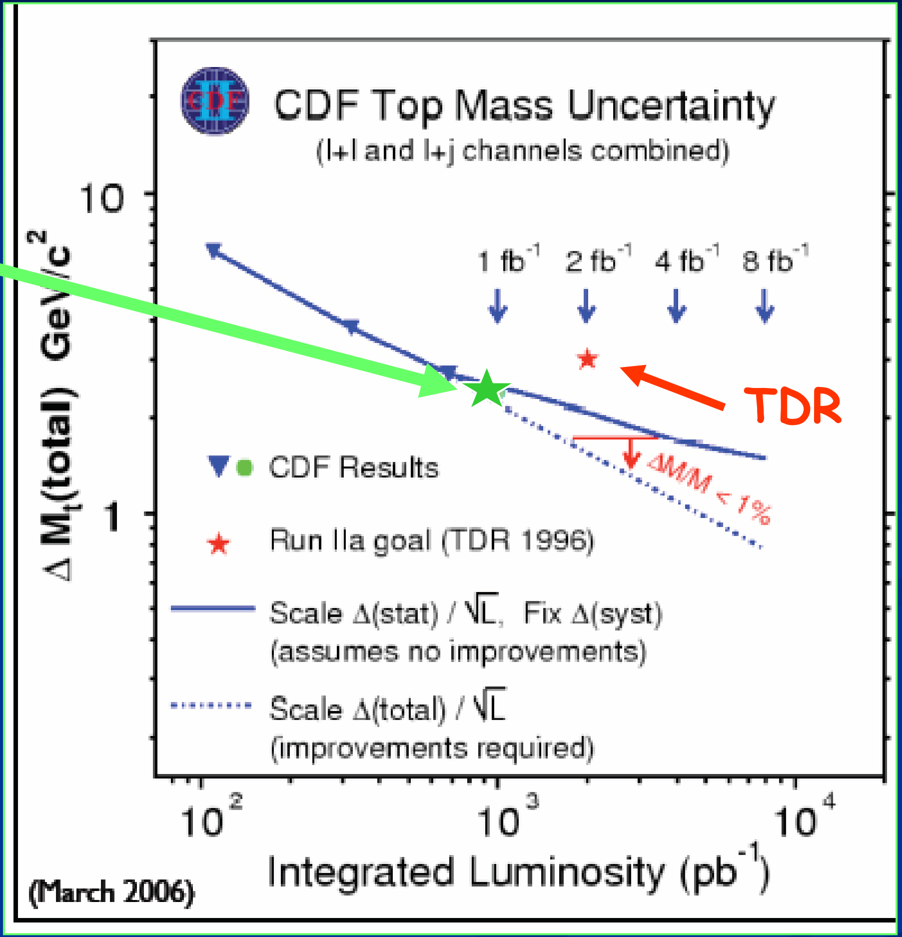
| Systematic uncertainties (GeV/$c^2$) | | |
|---|---|---|
| JES residual | 0.42 | 4 |
| Initial state radiation | 0.72 | 2 |
| Final state radiation | 0.76 | 1 |
| Generator | 0.19 | |
| Background composition and modeling | 0.21 | |
| Parton distribution functions | 0.12 | |
| b-JES | 0.60 | 3 |
| b-tagging | 0.31 | |
| Monte Carlo statistics | 0.04 | |
| Lepton $p_T$ | 0.22 | |
| Multiple Interactions | 0.05 | |
| Total | 1.36 | |

Note FSR, ISR, JES, and b/j JES dominate- all measurable with more data, at some level…

Again- systematics go down with statistics- no `wall' (yet).

# Precision Measurement of the Top Mass




**Aspen Conference Annual Values**
**(Doug Glenzinski Summary Talk)**

Jan-05: ΔMt = +/- 4.3 GeV
Jan-06: ΔMt = +/- 2.9 GeV
Jan-07: ΔMt = +/- 2.1 GeV

Note we are doing almost 1/root-L even now

Setting JES with MW puts us significantly ahead of the projection based on Run I in the Technical Design Report (TDR). Systematics are measurable with more data (at some level- but W and Z are bright standard candles.)

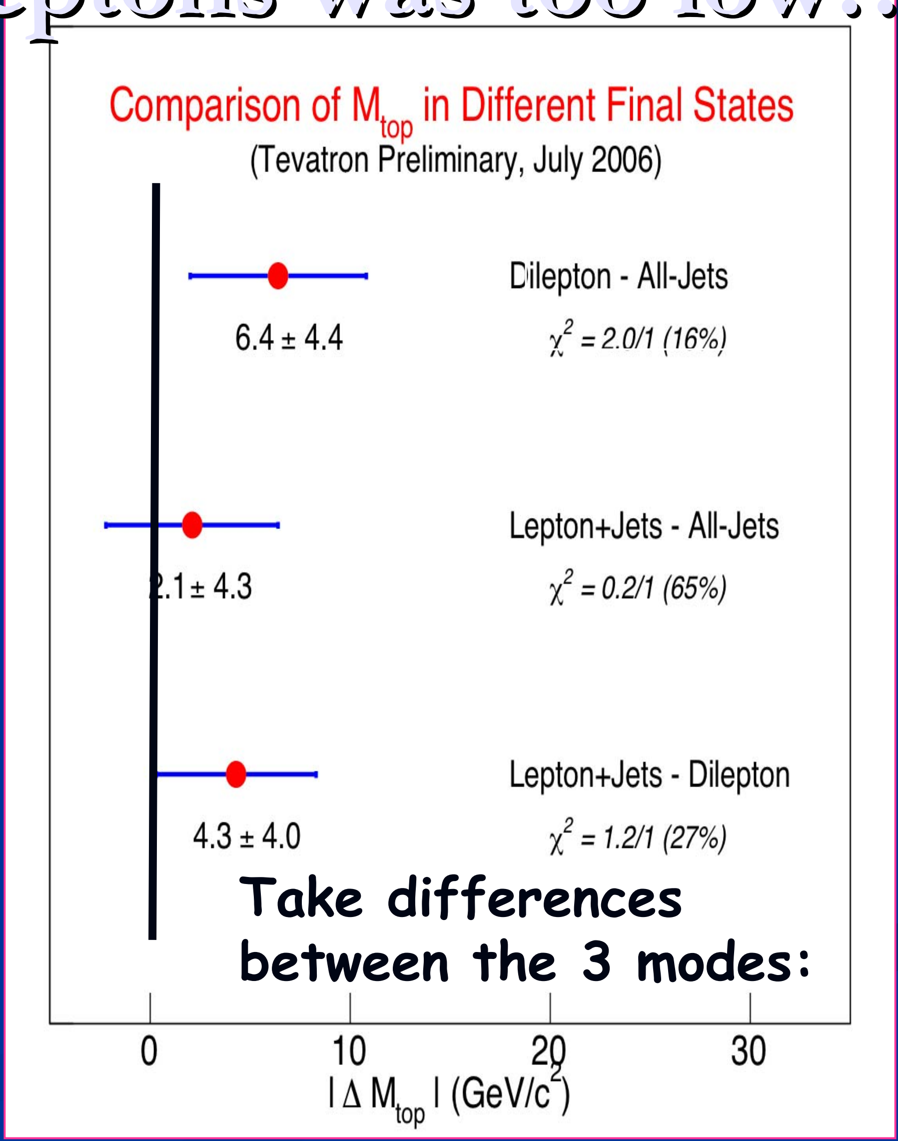
# Aside- One old feature may be going away-top mass in dileptons was too low…

$M_{top}$(All Jets) = 173.4 ± 4.3 GeV/$c^2$

$M_{top}$(Dilepton) = 167.0 ± 4.3 GeV/$c^2$

$M_{top}$(Lepton+Jets) = 171.3 ± 2.2 GeV/$c^2$

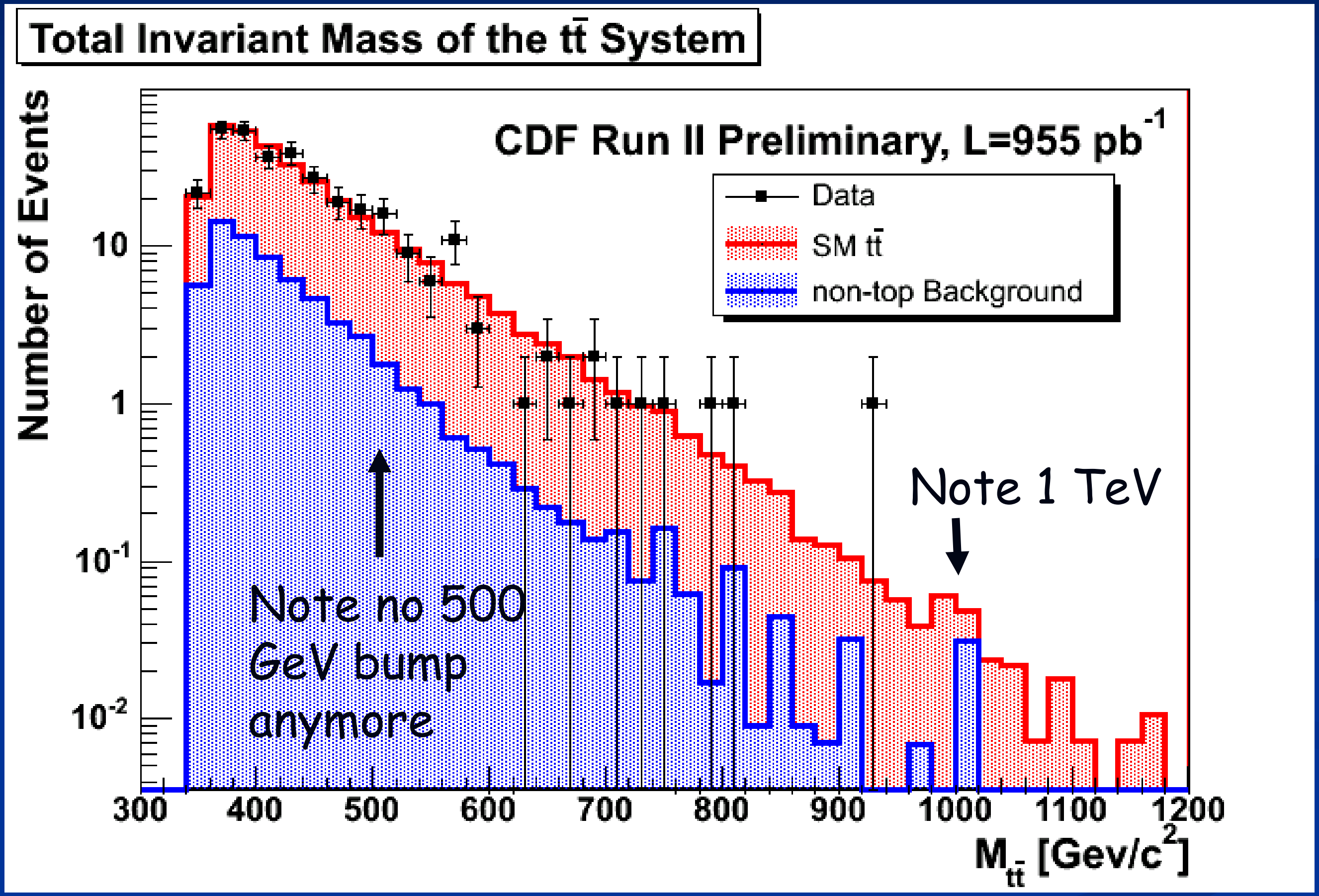
( Rainer Wallny, Aspen 07)




Take differences between the 3 modes:

Dilepton a little low, but statistically not significant- also D0 number not low now…

# New Physics in Top Production?

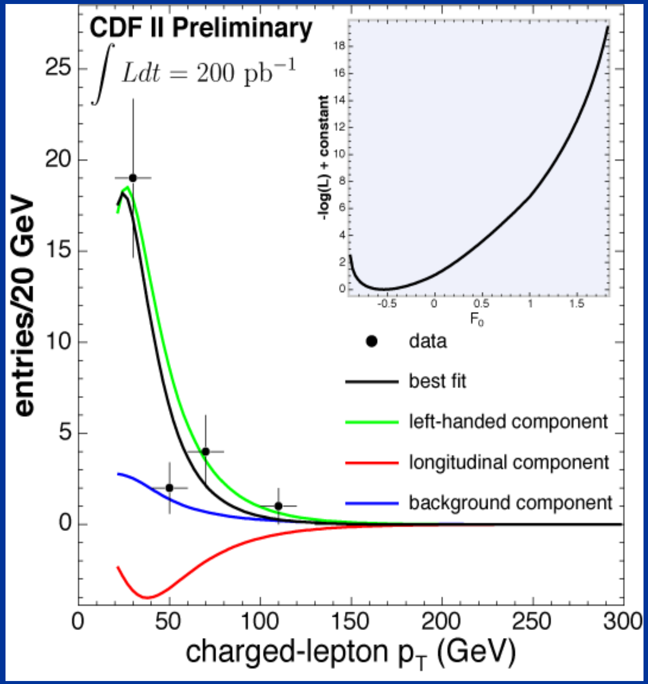



Fit ttbar system with known top mass(es) and compare $M_{tt}$, $pT_{tt}$, $eta_{tt}$, X, angular distributions, etc. with SM expectations. Global fit allows multi-dimensional comparisons. (Here is only $M_{tt}$, for reasons I don't understand- Dan?)

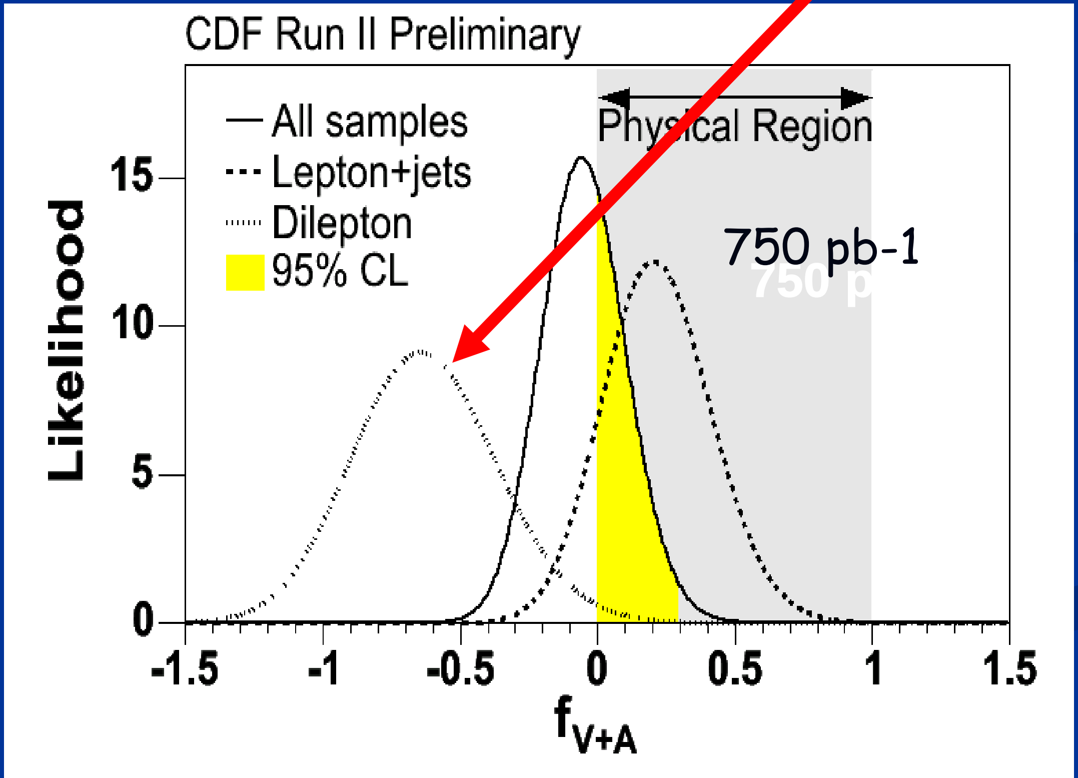
# New Physics in Top Decay?

1. Fit for V-A, V+A, longitudinal: So far no smoking guns
2. Charged Higgs (e,mu+tau+b)
3. Run I odd dilepton distributions

?

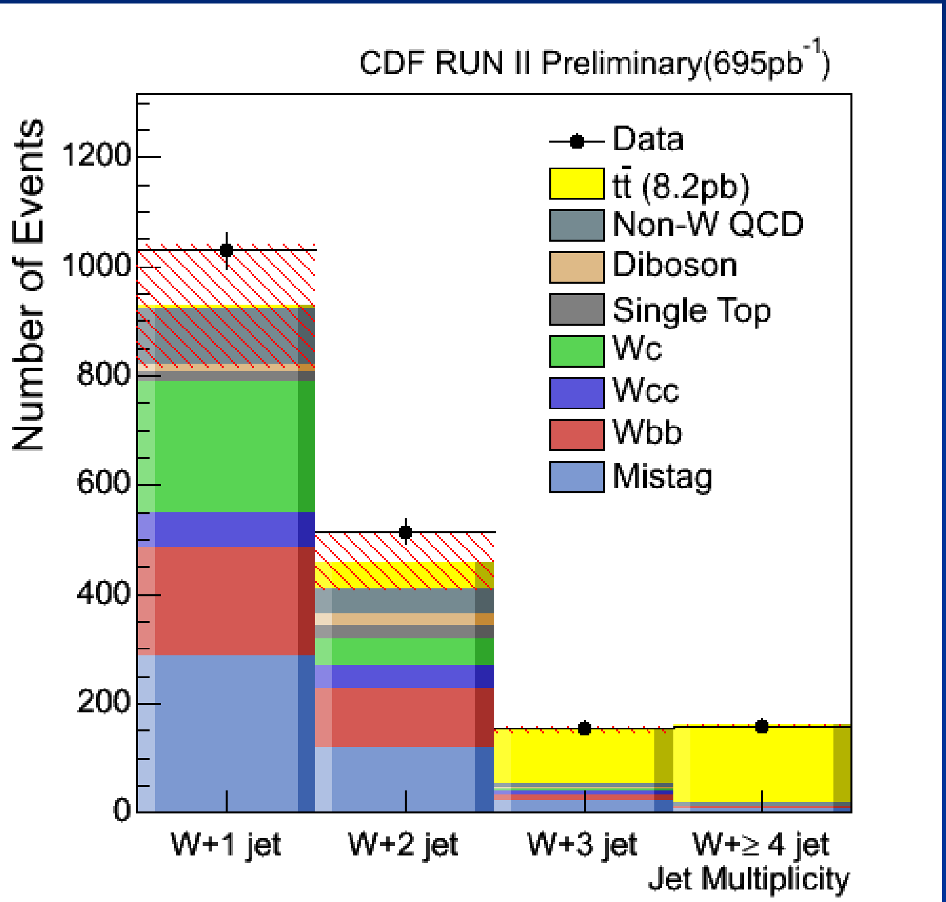


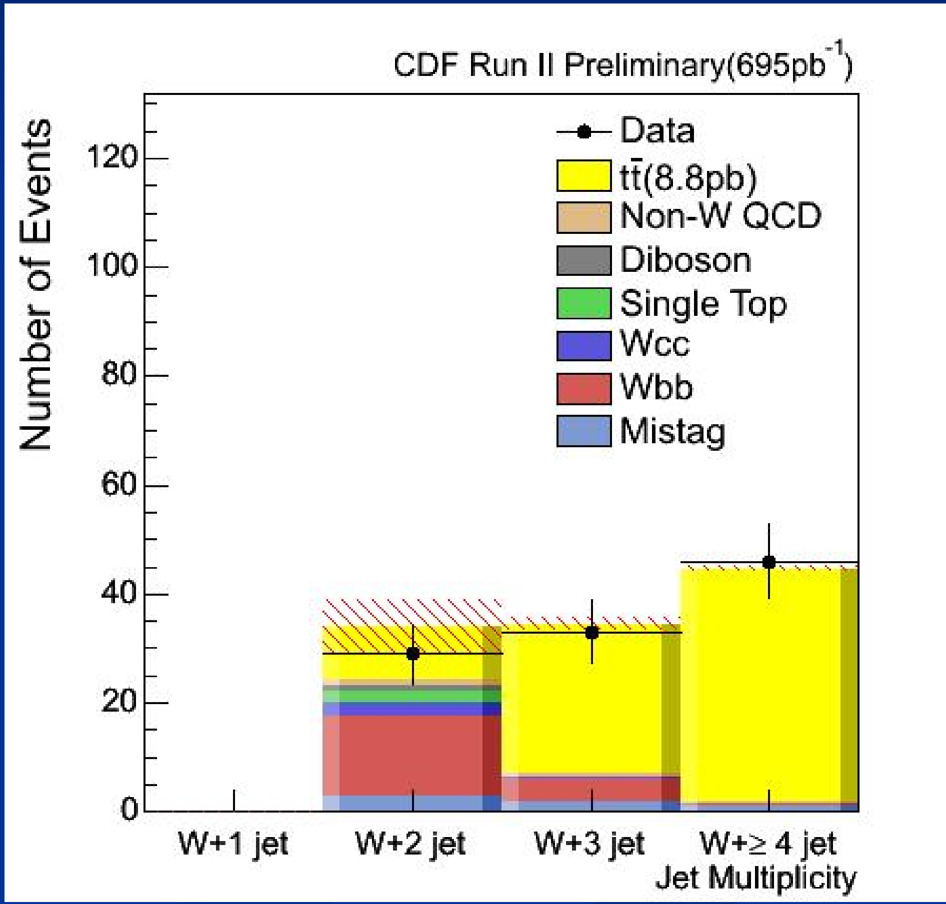

Dilepton only
200 $pb^{-1}$




V+A fits, e.g

# Huge effort in prediction number of jets in top events (`Njets')



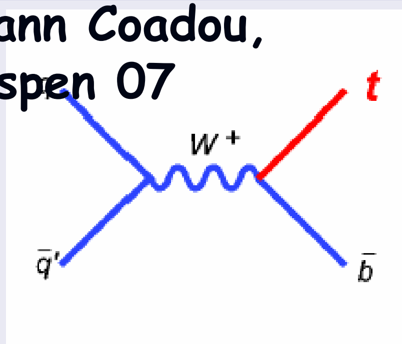

Single b-tag events

Double b-tag events

T

## $s$-channel (tb)

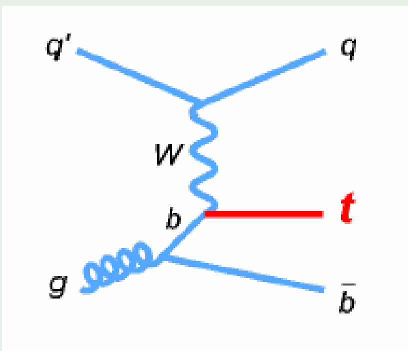
Yann Coadou, Aspen 07




- $\sigma_{NLO} = 0.88 \pm 0.11$ pb (*)
- previous limits (95% C.L.):

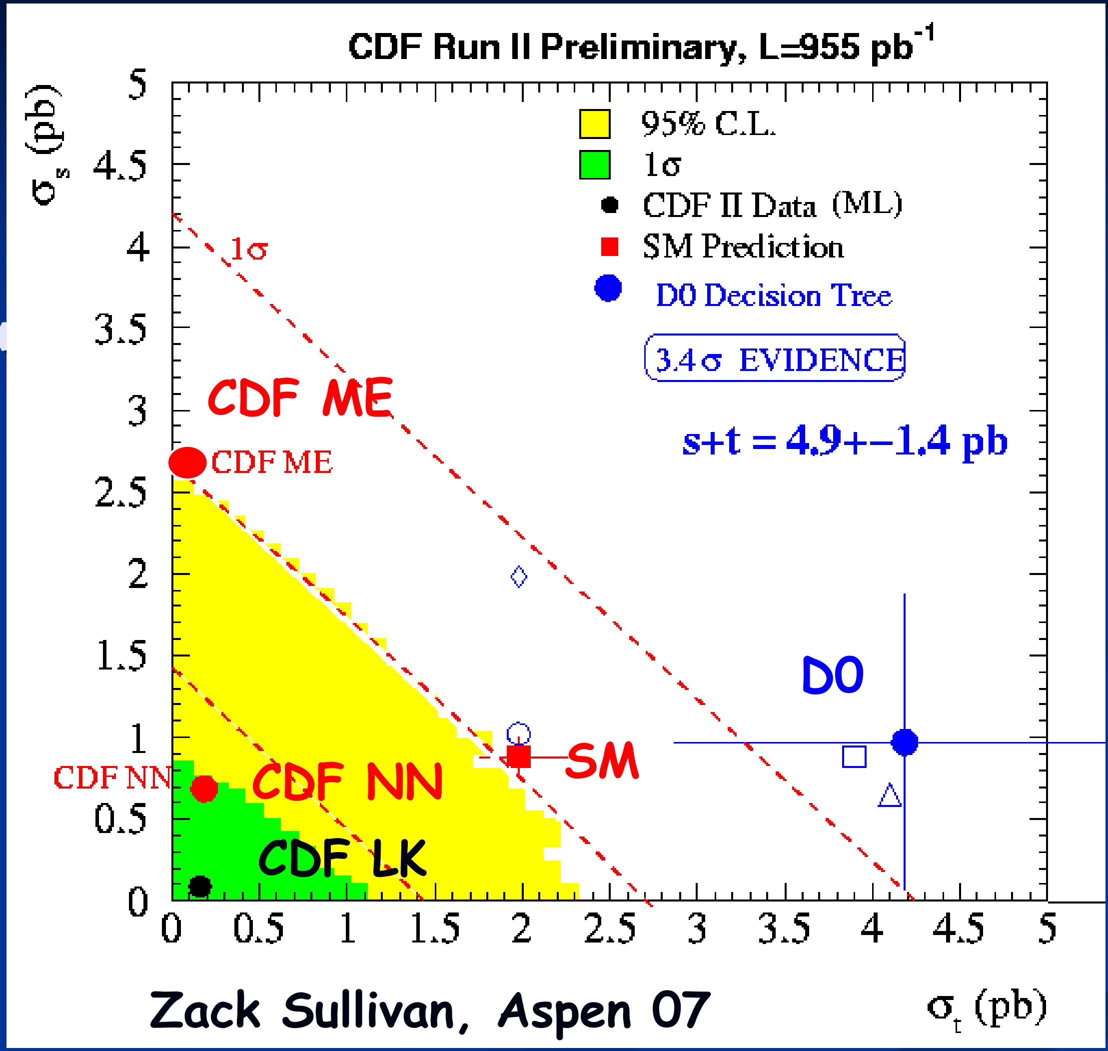
Run II DØ: $< 5.0$ pb (370 $pb^{-1}$)
Run II CDF: $< 3.1$ pb (700 $pb^{-1}$)

## $t$-channel (tqb)




- $\sigma_{NLO} = 1.98 \pm 0.25$ pb(*)
- previous limits (95% C.L.):

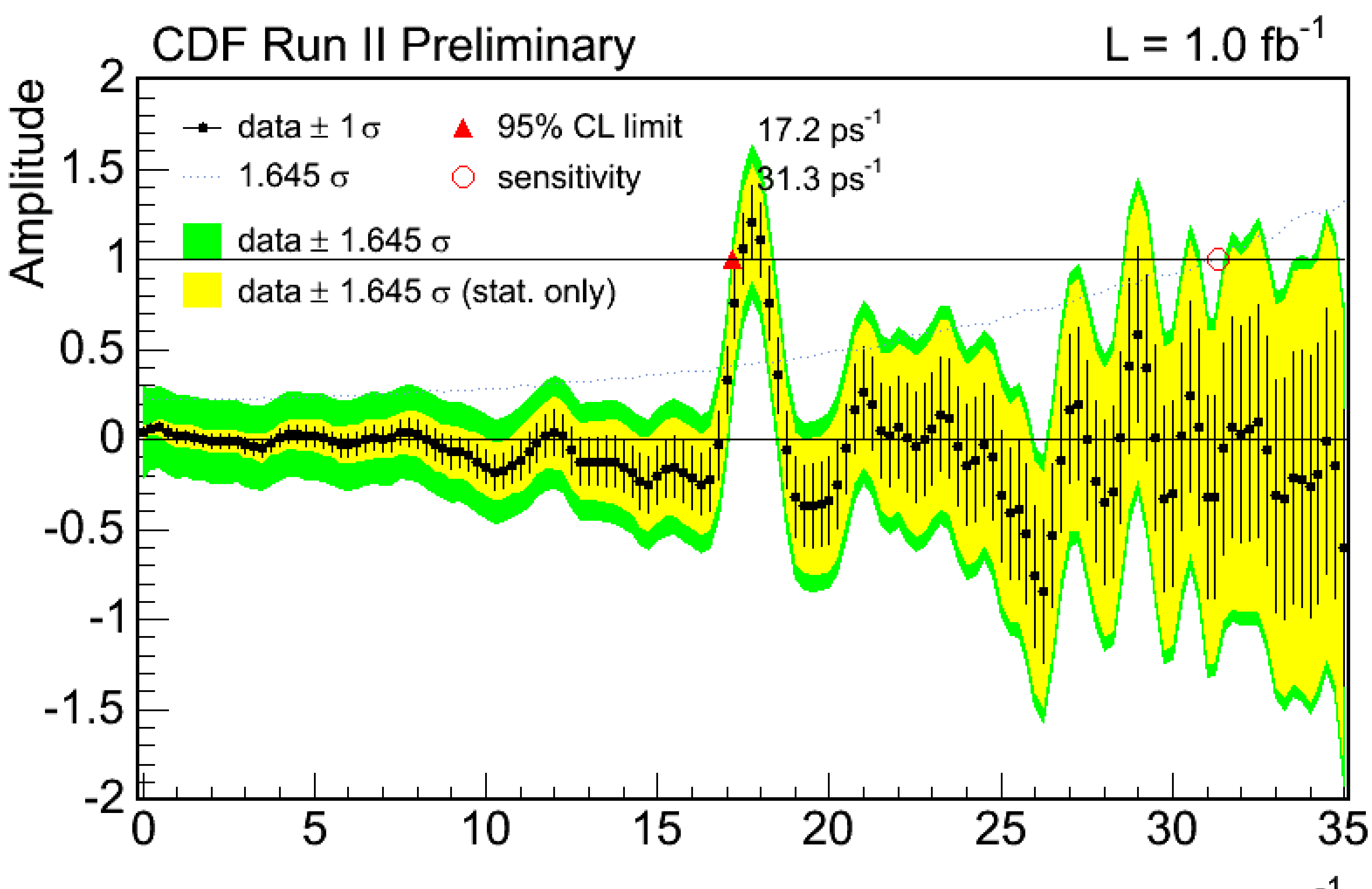
Run II DØ: $< 4.4$ pb (370 $pb^{-1}$)
Run II CDF: $< 3.2$ pb (700 $pb^{-1}$)




**Situation somewhat confused-**

**Expect 1 and 2 pb in s and t channels, respectively. Need more data, wits**

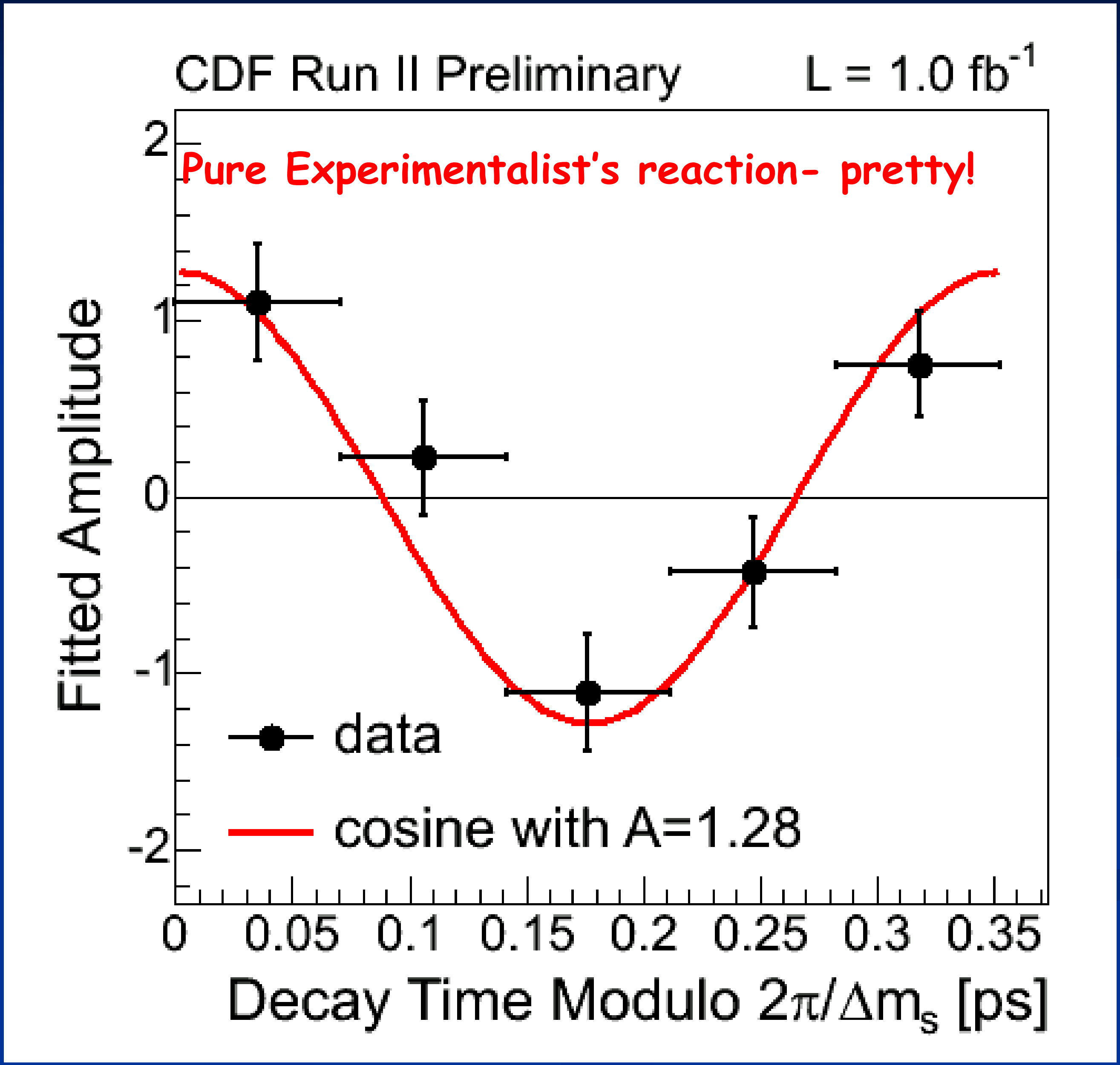
# High Precision B-physics; Mixing, $B_s \to \mu\mu$




**Note: 1 psec = 300 microns. SVT is critical.**

# High Precision B-physics; Mixing

Time-domain plot- not the discovery vehicle, but what I wanted to see…

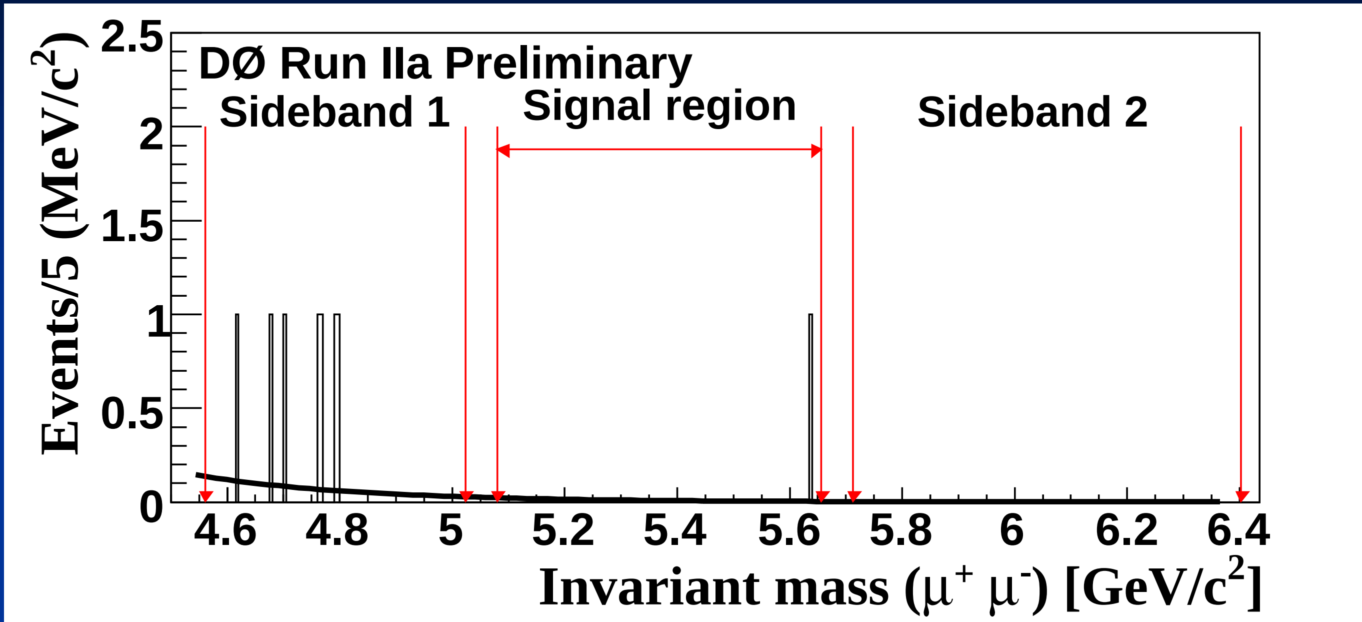


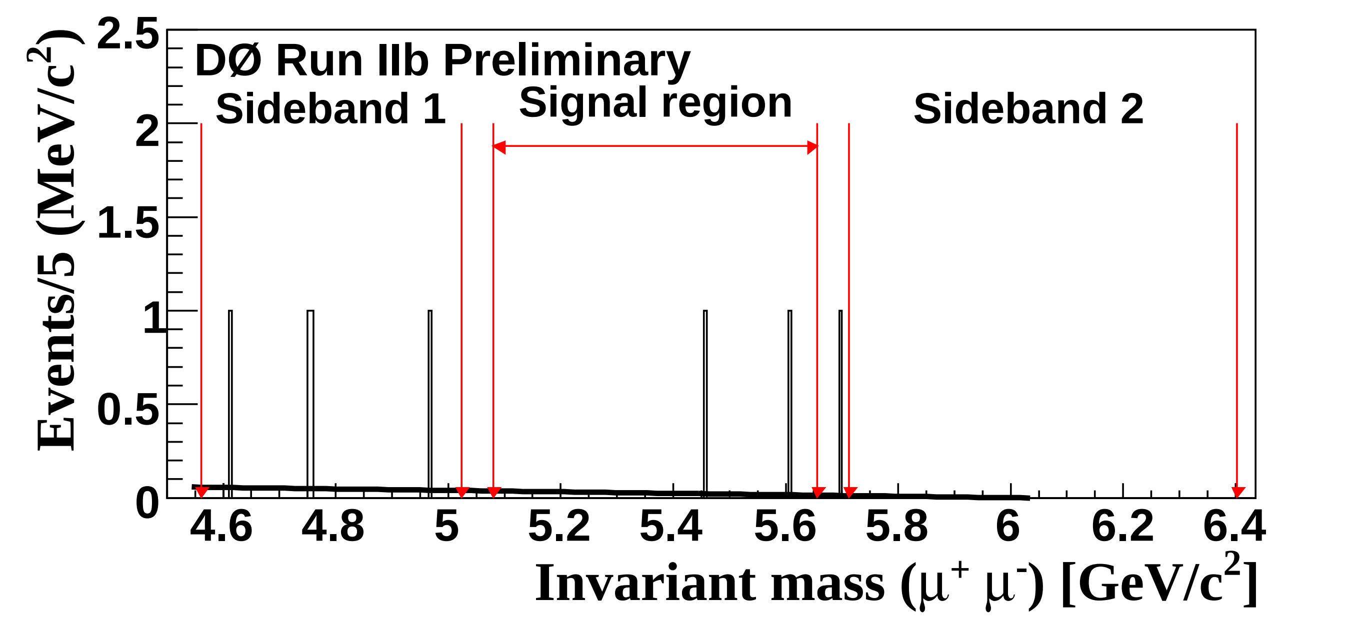
# D0 High Precision B-physics; $B_s \to \mu\mu$

Result: D0 has recently analyzed 2 fb-1- Run IIb didn't add much , but the combination gives world's best limit:

**BR( Bs → μμ ) < $9.3 \times 10^{-8}$ @95% CL**

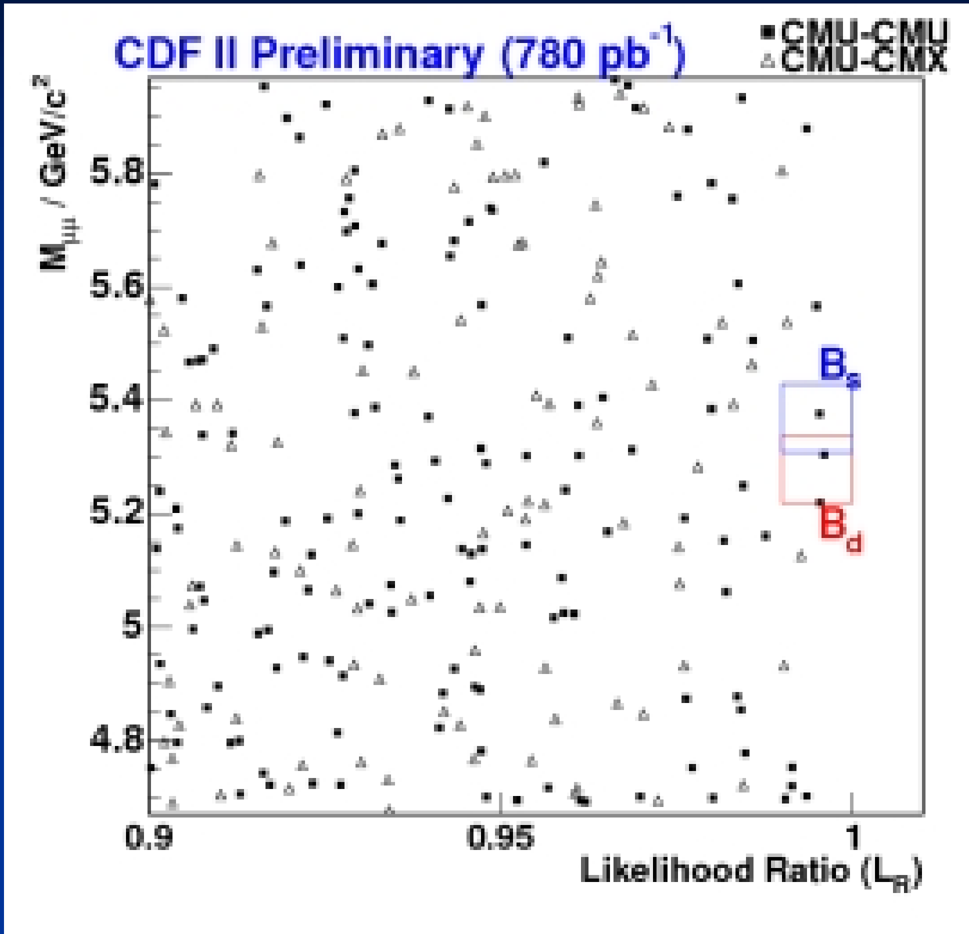
**BR( Bs → μμ ) < $7.5 \times 10^{-8}$ @90% CL**



# High Precision B-physics; $B_s \to \mu\mu$

Copious Source of B's;
Mass Resolution and Trigger




Result: D0 and CDF haveWorld's best limits: CDF::

BR( Bs → μμ ) < 1.0x10-7 @95% CL

BR( Bd → μμ ) < 3.0x10-8 @95% CL

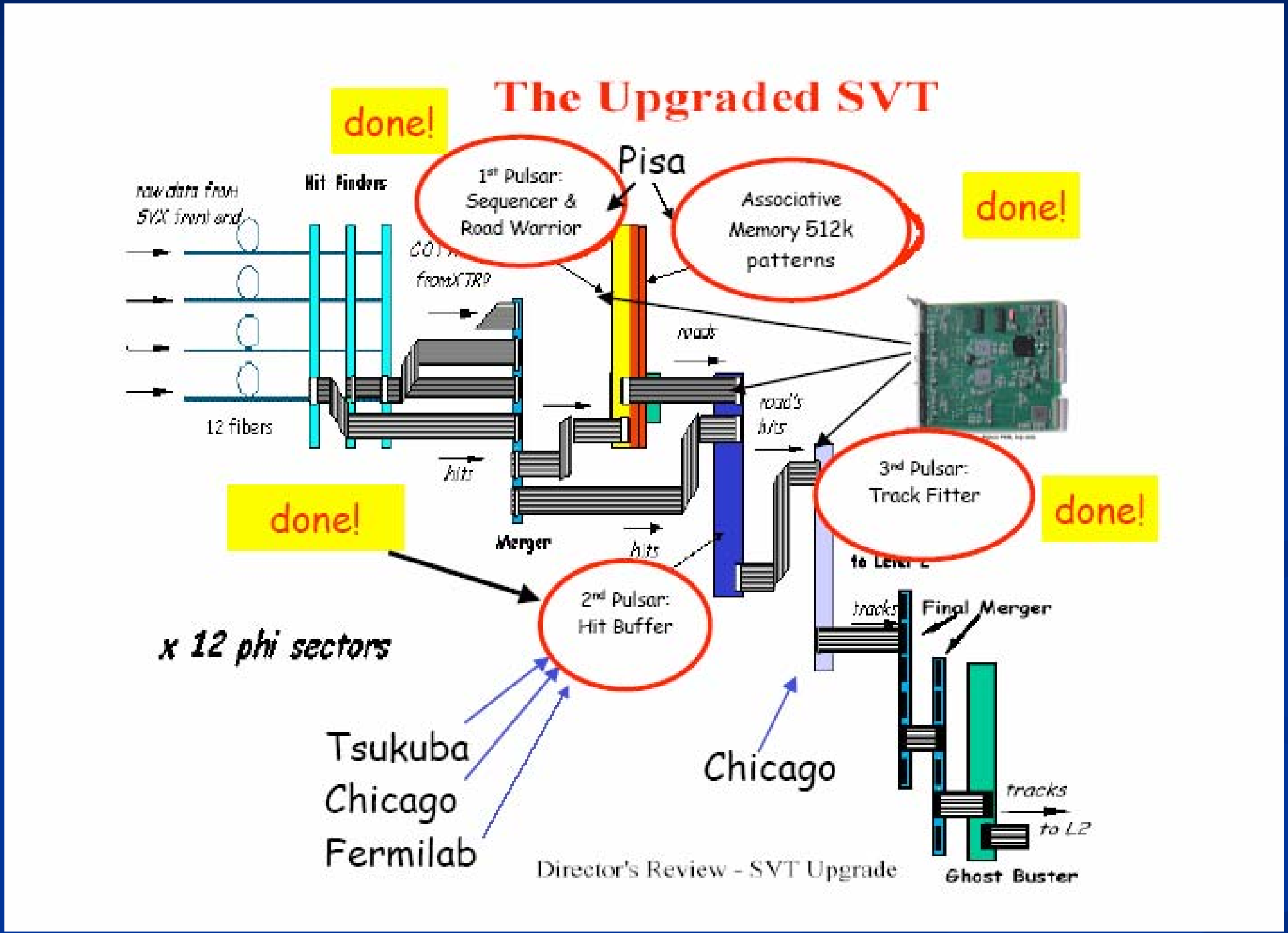
BR( Bs → μμ ) < 8.0x10-8 @90% CL

BR( Bd → μμ ) < 2.3x10-8 @90% CL

This is with 780 pb-1; have more, and have improved analysis sensitivity- new # very soon. Getting to have teeth (imagine 10X data+>Accept.).

One of a number of rare-decay mode searches; $B_s \to \mu\mu X$; also new states with B quarks, …. (whole industry).

# CDF can trigger on displaced tracks
## (Luciano Ristori and the SVT)




**Allows picking out low-mass b hadronic decays among 10 million events/sec**

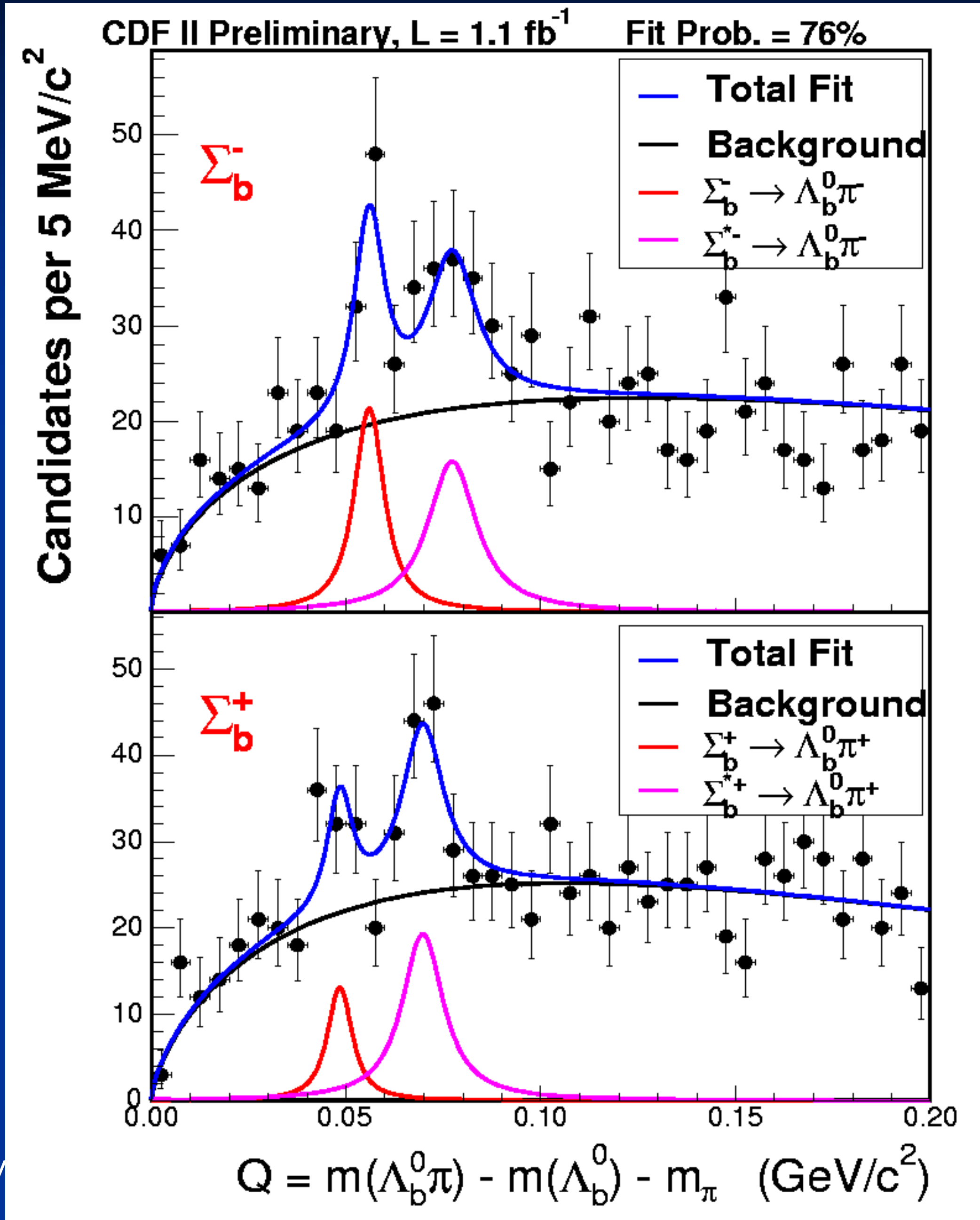
# CDF Observation of New Baryon States

4 New Baryons Discovered

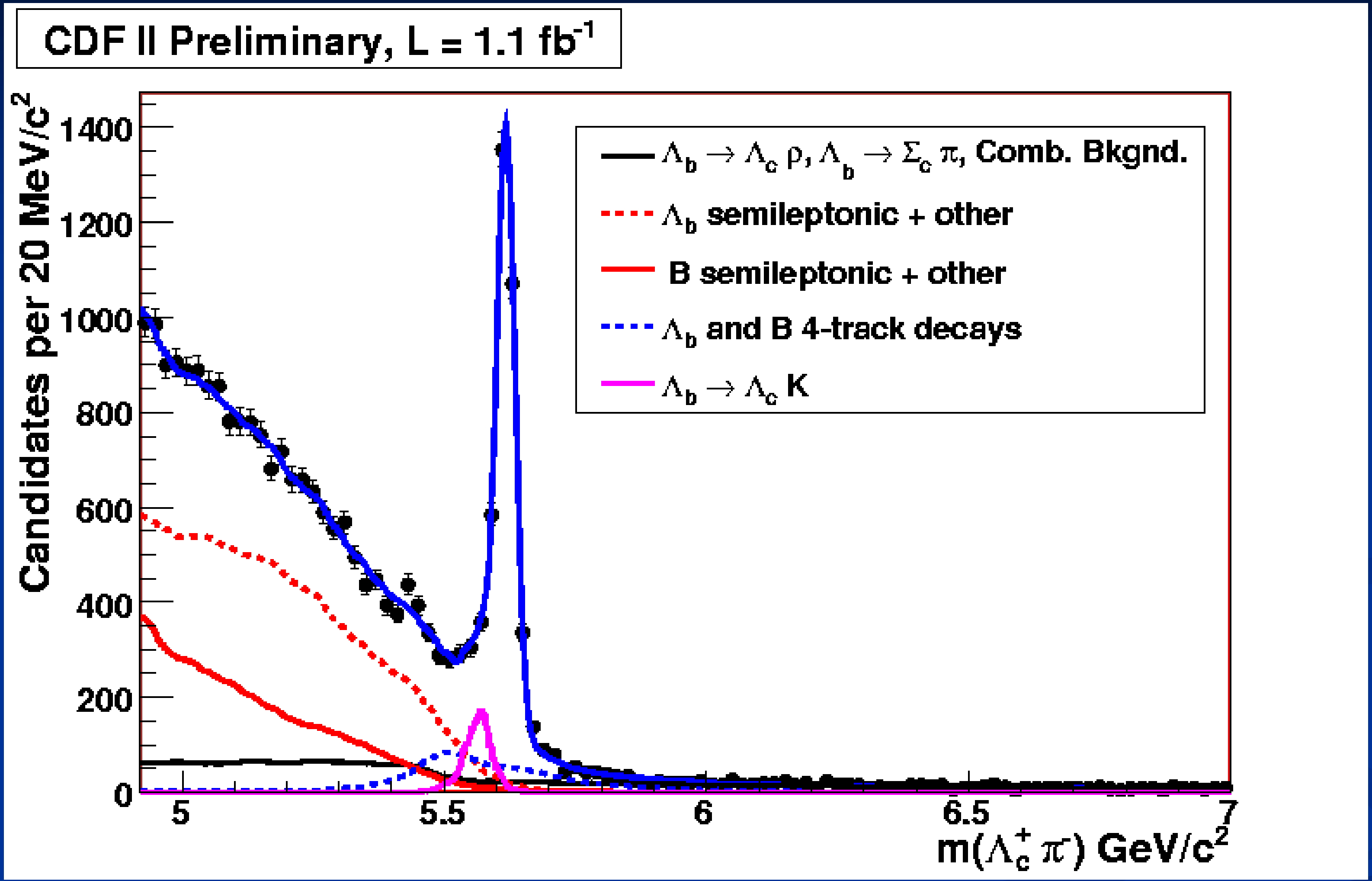
Σb(*)±→Λb0π±; Λb0→Λc+π- ; Λc+→pK-π+

*we measure:*

**m(Σb+) = 5808+2.0-2.3(stat.) ± 1.7(syst.) MeV/c2**
**m(Σb¯) = 5816+1.0-1.0(stat.) ± 1.7(syst.) MeV/c2**
**m(Σb*+) = 5829+1.6-1.8(stat.) ± 1.7(syst.) MeV/c2**
**m(Σb*¯) = 5837+2.1-1.9(stat.) ± 1.7(syst.) MeV/c2**



# CDF Observation of New Baryon States

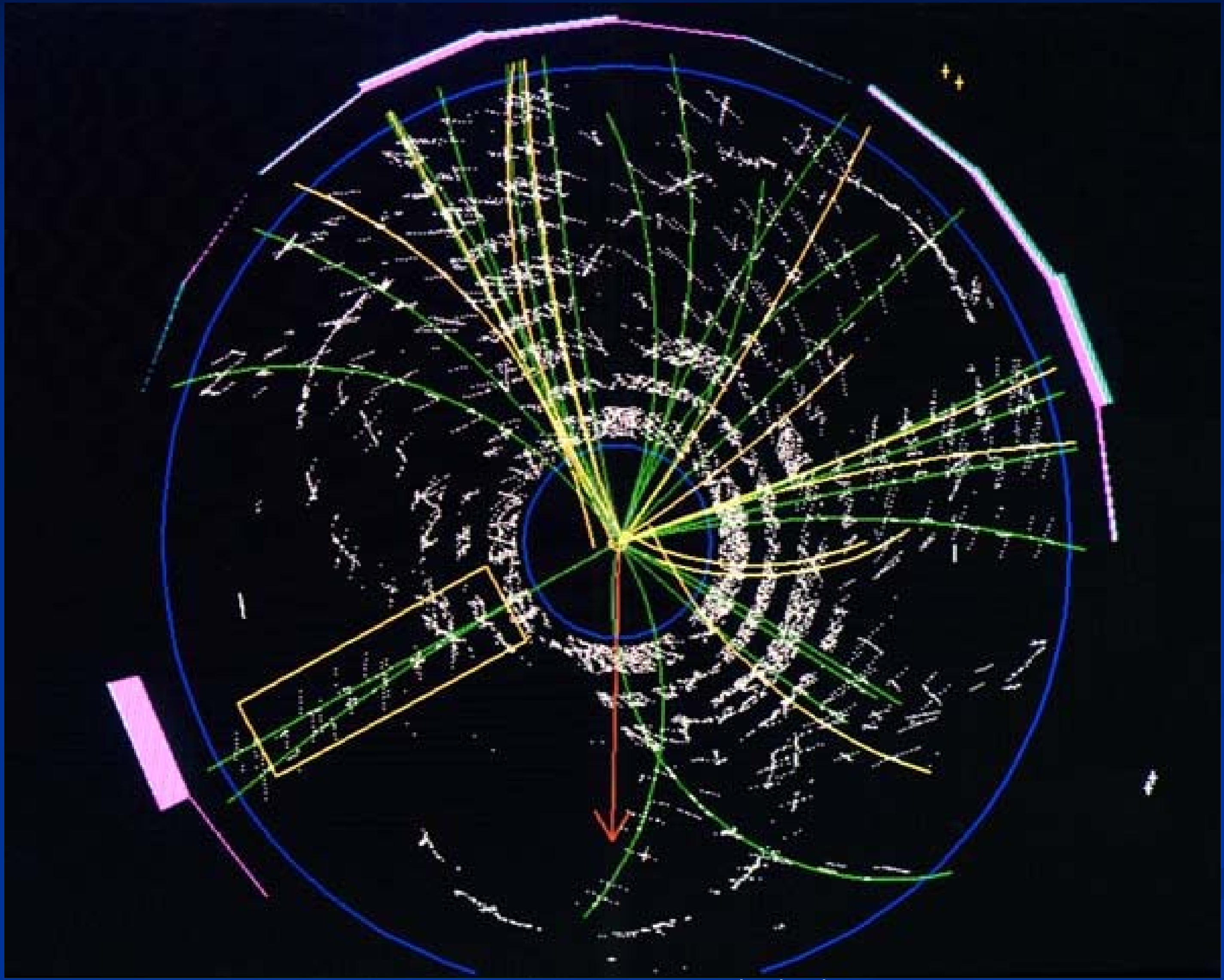



Lambda-b serves as calibration – who woulda thunk it that at 1.96 TeV you could do this? Shows the power of the SVT!

# Summary of Lecture 2: Present Status

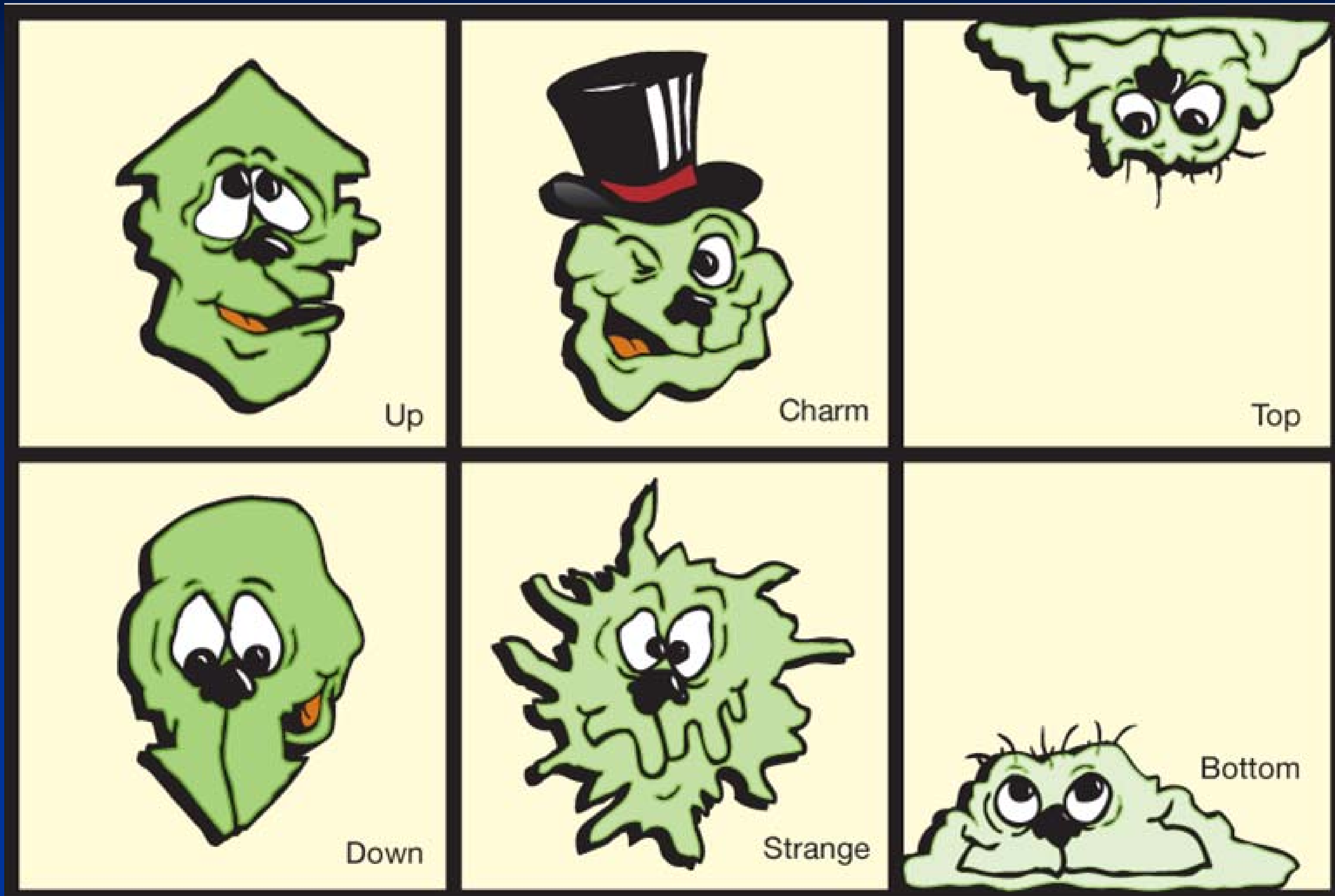
1. Tevatron running well – expect >= 1.5-2 fb-1/yr/expt of all goes well (could even be somewhat better- there are more pbars).
2. We have entered the era of precision top physics (working at the % level, and are learning how to deal with systematics at that level (e.g. jet-energy scale from the W-> jj decays). Many theoretical problems are being worked on – Njet matching, …
3. Remarkable low-mass hadron reconstruction from CDF SVT- precision B-physics..
4. Entering Higgs search era- need more luminosity, and a much higher degree of sophistication for jet resolution, trigger usage strategy, … CDF L2 upgrade, e.g.

# THE END



"You could be up to your belly-buttons in (SUSY) and not know it.."- C. Prescott

# The Quarks
The Quarks

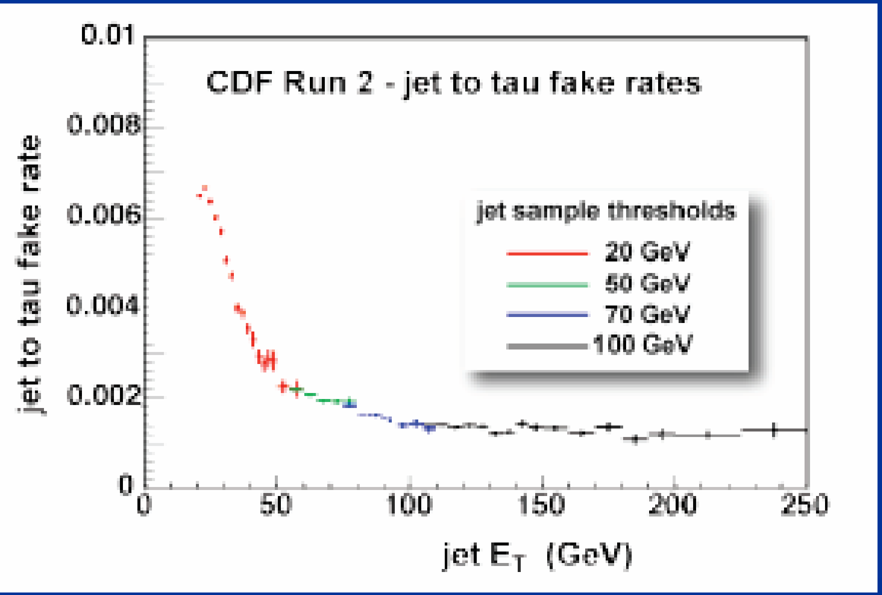


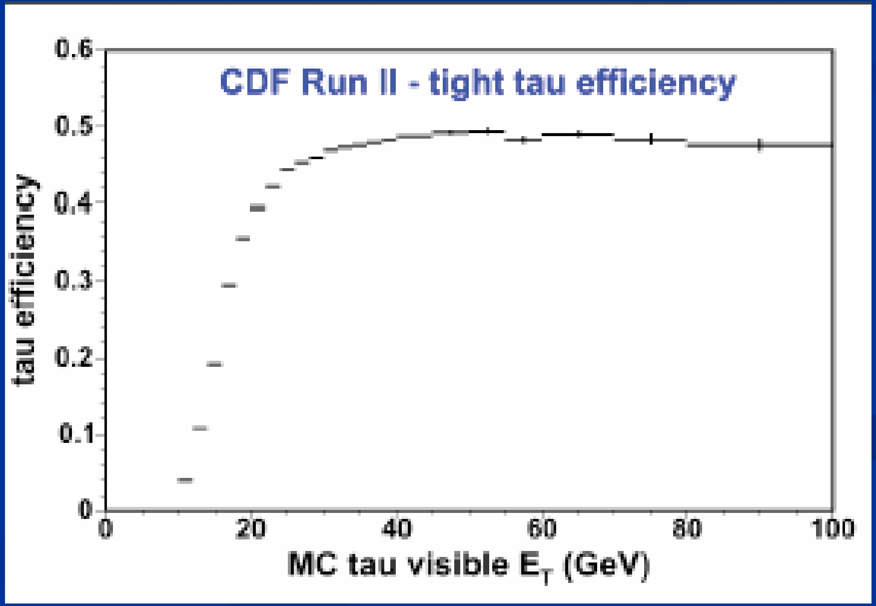
# BACKUP SLIDES

# New CDF Higgs to taus result:

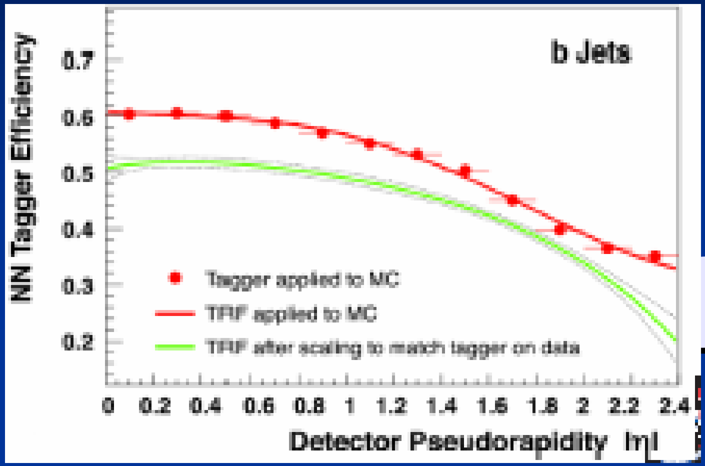
Tau ID depends on good tracking, photon ID- clean environment (all good at the Tevatron). Key numbers are efficiency and jet rejection:

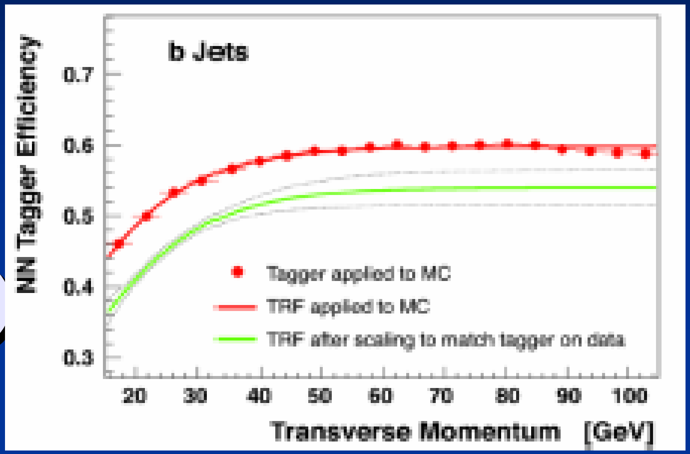
This may be an area in which the Tevatron is better.

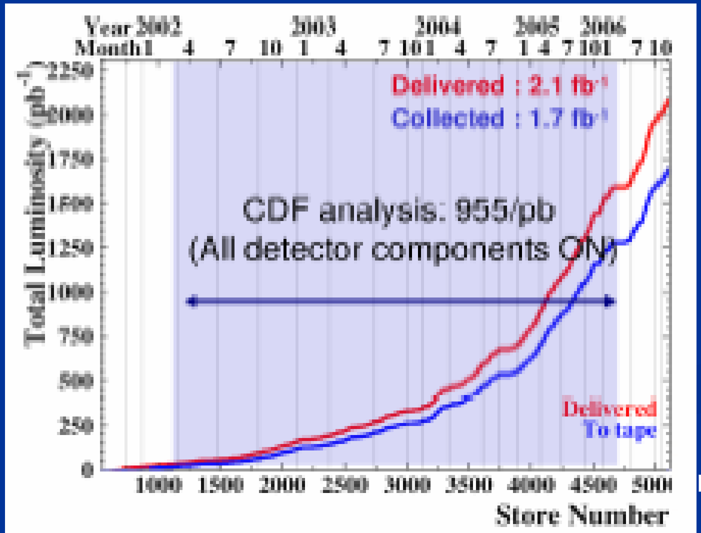


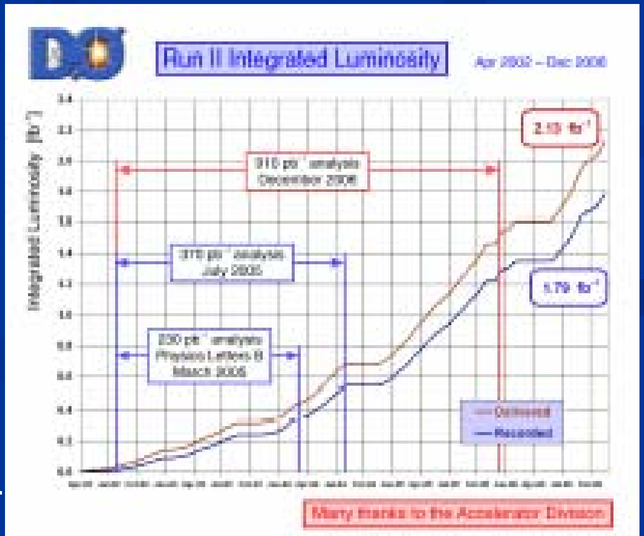



# Backup- lum on tape



# Precision Msremnt* of the Top Mass

*like Mrenna

## CDF Lepton+4jets:

## Systematics:

Jet Energy Scale (JES)

Now set by MW (jj)

| Systematic uncertainties (GeV/$c^2$) | | |
|---|---|---|
| JES residual | 0.42 | 4 |
| Initial state radiation | 0.72 | 2 |
| Final state radiation | 0.76 | 1 |
| Generator | 0.19 | |
| Background composition and modeling | 0.21 | |
| Parton distribution functions | 0.12 | |
| b-JES | 0.60 | 3 |
| b-tagging | 0.31 | |
| Monte Carlo statistics | 0.04 | |
| Lepton $p_T$ | 0.22 | |
| Multiple Interactions | 0.05 | |
| Total | 1.36 | |

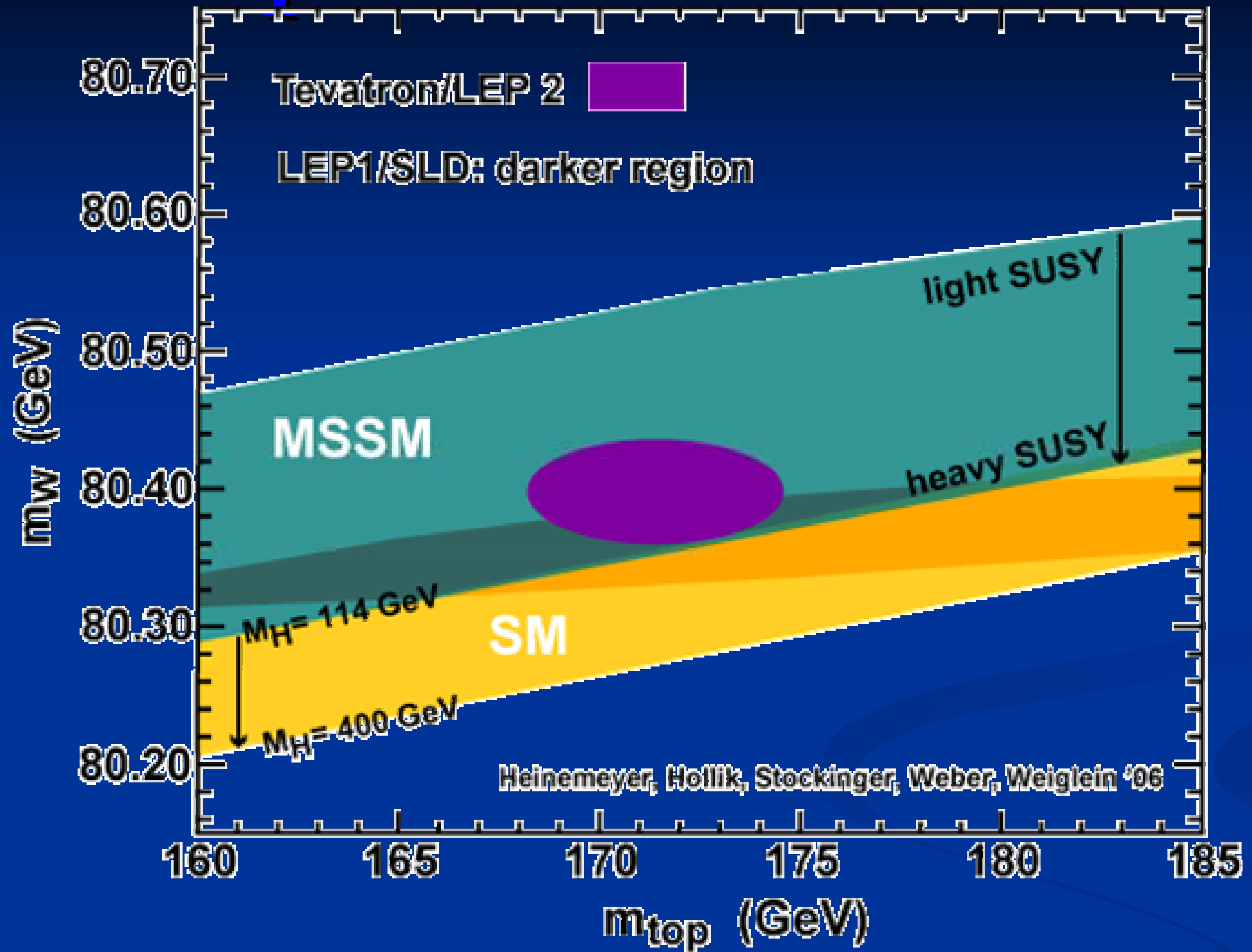
Note FSR, ISR, JES, and b/j JES dominate- all measurable with more data, at some level…

Again- systematics go down with statistics- no `wall' (yet).

# The Importance of the $M_W$ - $M_{Top}$-$M_{Higgs}$ Triangle

- Much as the case for Babar was made on the closing of the CKM matrix, one can make the case that closing the $M_W$ - $M_{Top}$-$M_{Higgs}$ triangle is an essential test of the SM.
- All 3 should be measured at the LHC- suppose the current central values hold up, and the triangle doesn't close (or no H found!). Most likely explanation is that precision $M_W$ or $M_{Top}$ is wrong. Or, H -> 4tau or worse, or, …? (low Et, met sigs)
- The systematics at the Tevatron are completely different from those at the LHC- much less material, known detectors, qbarq instead of gg, # of interactions, quieter events (for $M_W$).
- =>Prudent thing to do is don't shut off until we see $M_W$ - $M_{Top}$-$M_{Higgs}$ works.

# MW-Mtop Plane with new CDF #'s



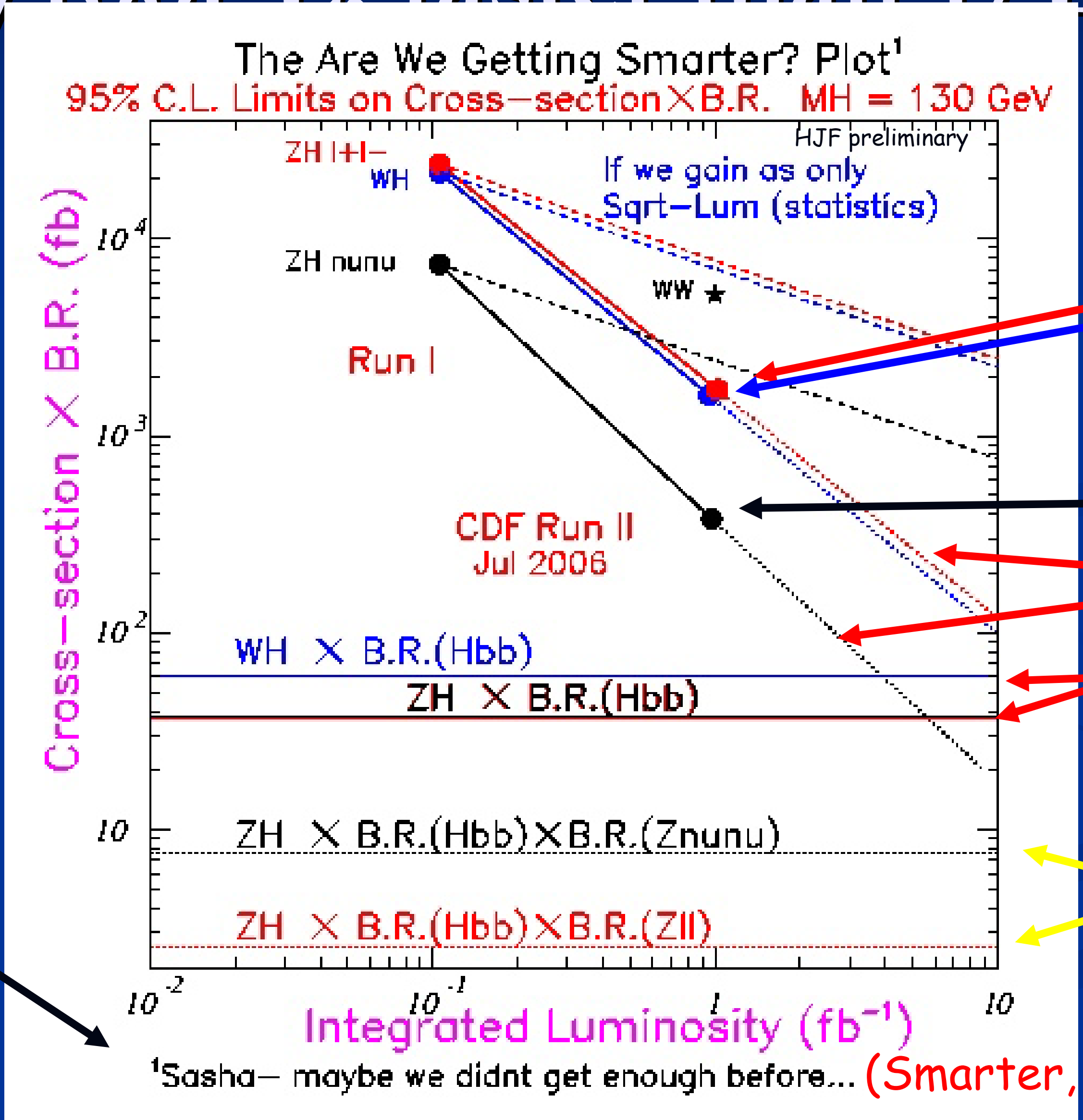

$M_W$= 80.398 \pm 0.025 GeV (inc. new CDF 200pb$^{-1}$)

$M_{Top}$ = 171.4 \pm 2.1 GeV (ICHEP 06)

=> MH =80+36-26 GeV; MH<153 GeV (95% C.L.)

MH < 189 GeV w. LEPII limit (M. Grunewald, Pvt.Comm.)

# Higgs Limits have gone faster than 1/root-L; faster than 1/L,even




Comment from already smart Russian grad student on seeing plot

# Precision Measurements, Small Crossections, and Non-Standard Signatures: The Learning Curve at a Hadron Collider

Henry Frisch
Enrico Fermi Institute and Physics Dept
University of Chicago

Lecture 1: Introduction to Collider Physics

Lecture 2: Tevatron Jets; W,Z,$\gamma$; Top, Bottom

Lecture 3:

1) Searching for Higgs and Not-SM

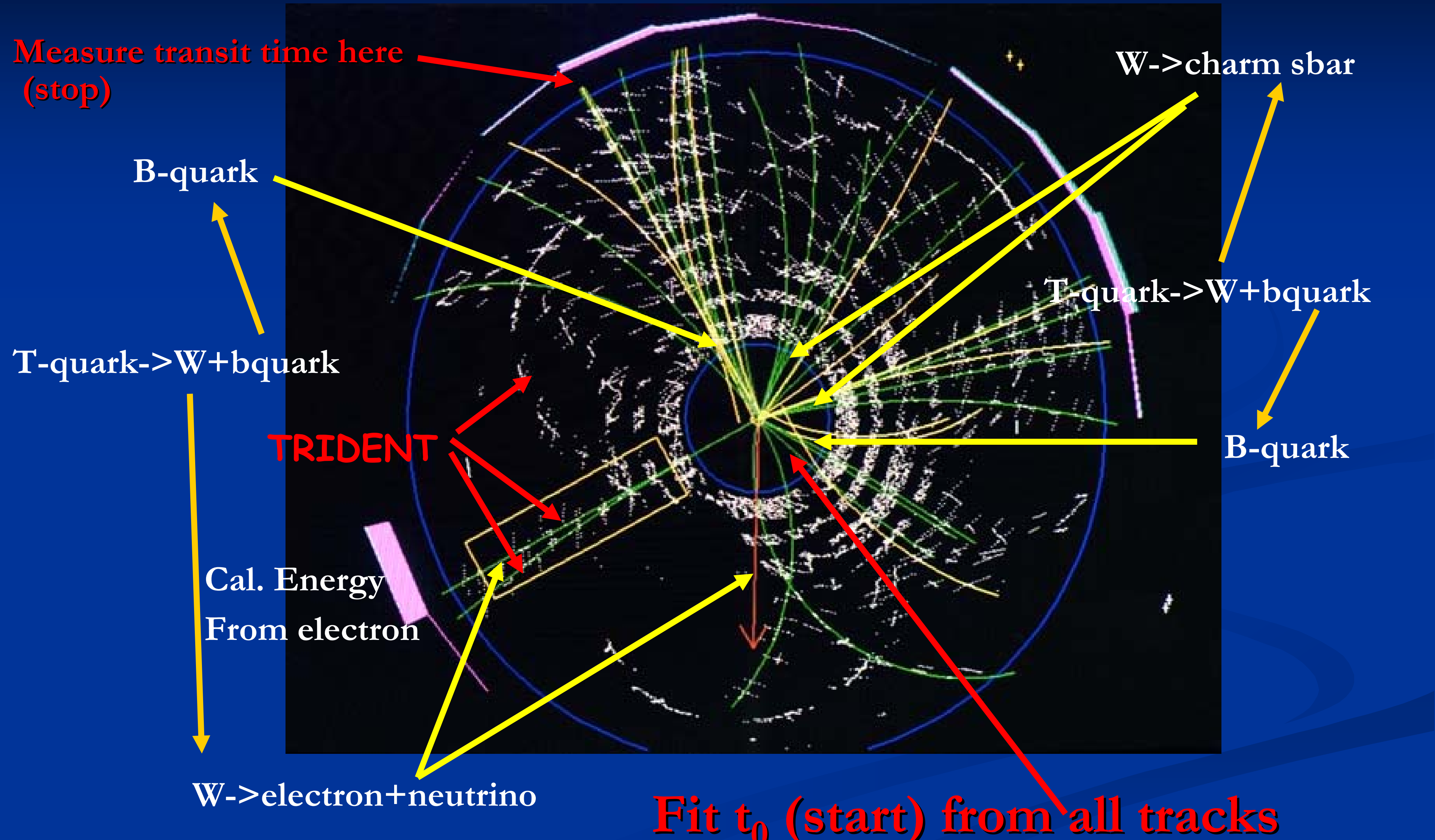
2) The Learning Curve at a Collider

3) Unsolved Problems

Note-These lectures are frankly pedagogical- apologies to the experts in advance..

# A real CDF Top Quark Event

T-Tbar -> W$^+$bW$^-$bbar




Can we follow the color flow through kaons, charm, bottom? TOF!

# Precision Measurements, Small Crosssections

# Precision Measurements, Small Crosssections

# Precision Measurements, Small Crosssections

# Precision Measurements, Small Crosssections