The Ultimate Potential of the Tevatron[1]

Henry Frisch
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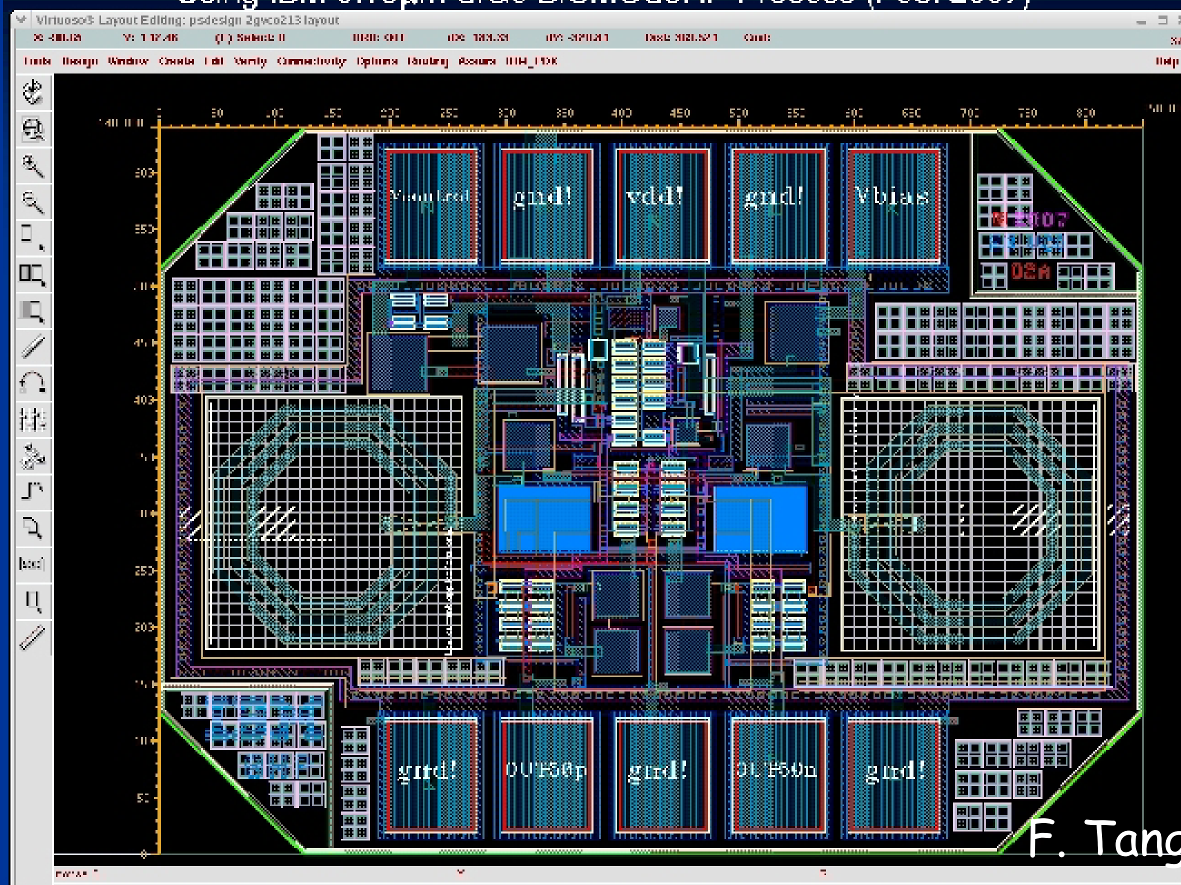
Some recent results, and some thoughts on the future
(“It’s hard to predict, especially the future”- Niels Bohr)

Oscillator with 5 fsec jitter cycle-to-cycle (predicted)

UC Designed 2GHz VCO Chip with 5 fsec Cycle-to-Cycle Time Jitter
Using IBM 0.13μm SiGe BiCMOS8HP Process (Feb. 2007)



[1] Not my choice of title, though I agreed, and will do my best…

Precision Measurements, Small Cross-sections, and Non-Standard Signatures: The Learning Curve at a Hadron Collider (τ_L)

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Including (esp.)
Some NittyGritty: e.g

`EM Clusters':

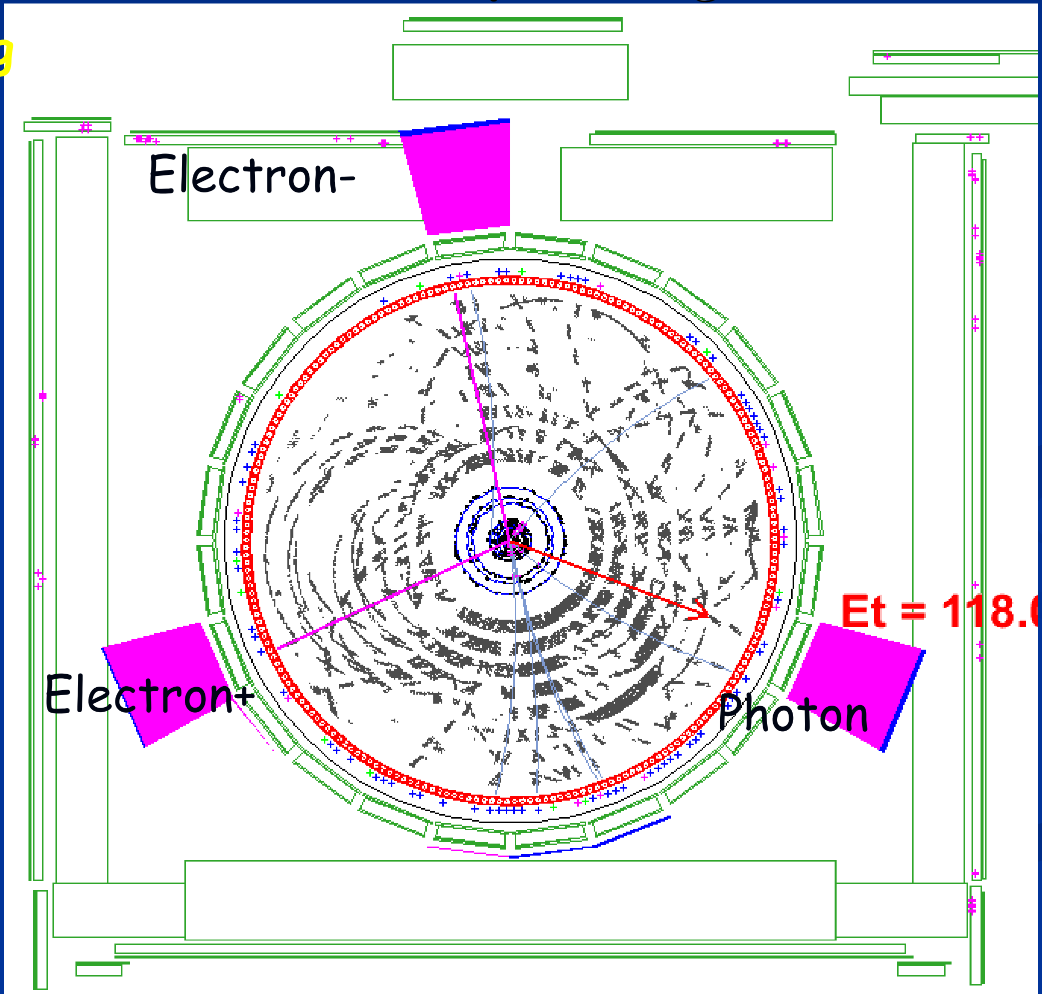
E/p < 2: Electron

E/p> 2: Jet

P <1: Photon

Where p is from track, E is from cal

E/p measures bremstrahlung fraction



Recent event emailed by the CDF detector,

Acknowledgements

- Thanks to many CDF and D0 colleagues whose work I'll show… Also SM MC generator folks!
- Apologies to D0- I tend to show much more CDF than D0 as I know it much better
- Opinions and some of the plots are my own, and do not represent any official anything.

OUTLINE

1. Weisskopf Panel's 3 Frontiers (1974 Woods Hole)
2. Luminosity and Reach of the Tevatron
3. Quick intro/status to some areas of opportunity:
   - A. Precision Mass Measurements: The Triangle of Mtop, M_W, and M_{Higgs}
   - B. Brief Summary of Progress on the Higgs Reach
   - C. Photon Signatures: (lgX and ggX) and GMSB
   - D. B_s mixing, other Precision tests
4. Tev/CDF/D0 `things' complementary to LHC strengths
5. Tools needed at the Tevatron (20 yrs later)
6. The attraction of hardware upgrades (and the ILC).

Summary- the Tevatron Opportunity at 1.5-2 fb^{-1} /year

Theme of Talk: Tevatron experience indicates:

It will not be luminosity-doubling time but systematics-halving time that determines when one will know that one no longer needs the Tevatron. We should NOT shut off the Tevatron until we have relatively mature physics results from the LHC (i.e. it's clear that we won't need the different systematics.)

<u>Have lots of hadron-collider experience now-</u>

1. remarkable precision in energy scales possible (e.g. MW to better than part per mil)

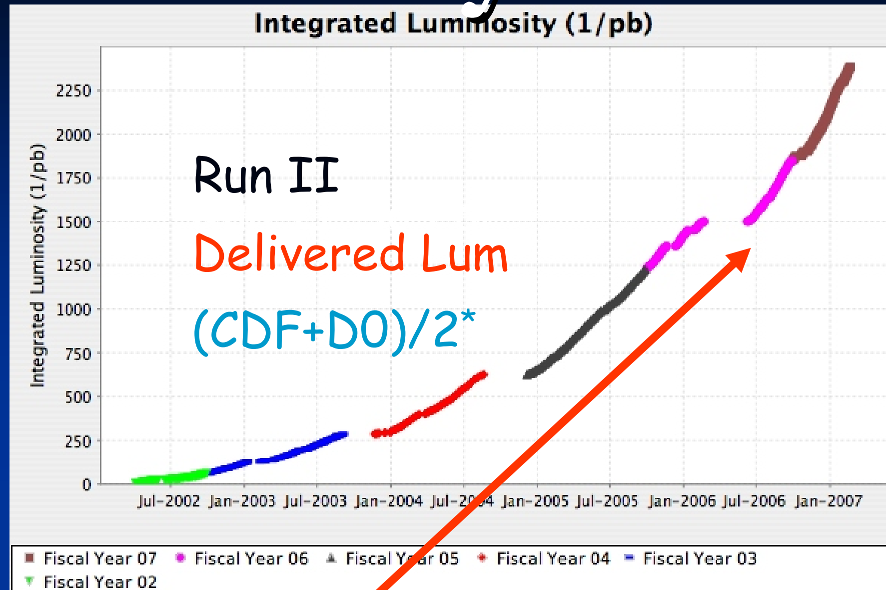
2. remarkable precision in real-time reconstruction and triggering (e.g. SVT triggering on B's at CDF);

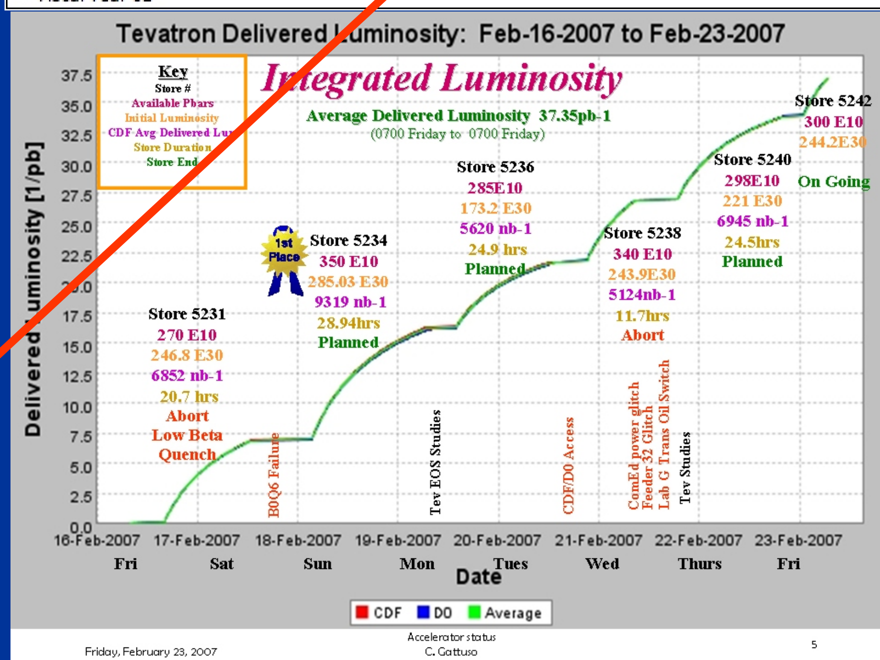
3. remarkably long and hard development of tools (e.g. jet resolution, fake rates, tau id, charm, strange id).

Weisskopf 1974 Woods Hole Panel

- Three frontiers in 1974- hold up pretty well in 2007:
- 1. Energy Frontier (now LHC, Auger, Anita,…)
- 2. e+e- (to be ILC, Super-B?)
- 3. Precision tests (EWK, flavor, FCNC,…) - could (should) be a role for the Tevatron at least until LHC is well-understood. (AGS/MR analog in 70's).

Luminosity vs Time



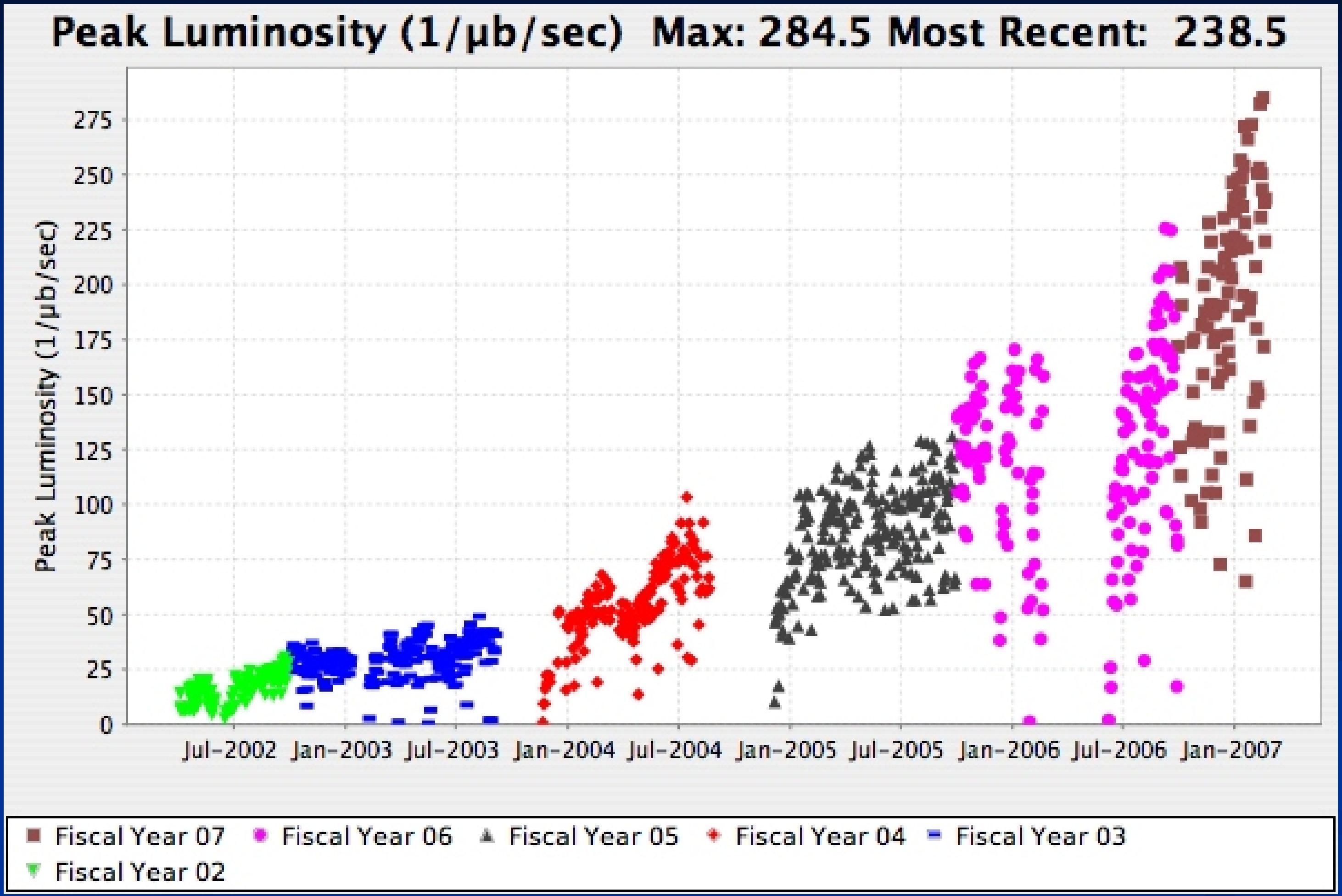


Note pattern-integral grows when you don't stop, with increasing slope

*(Protons are smaller on this side (joke))

> 40 pb^{-1}/wk/expt (x 40 wks/yr, e.g.)

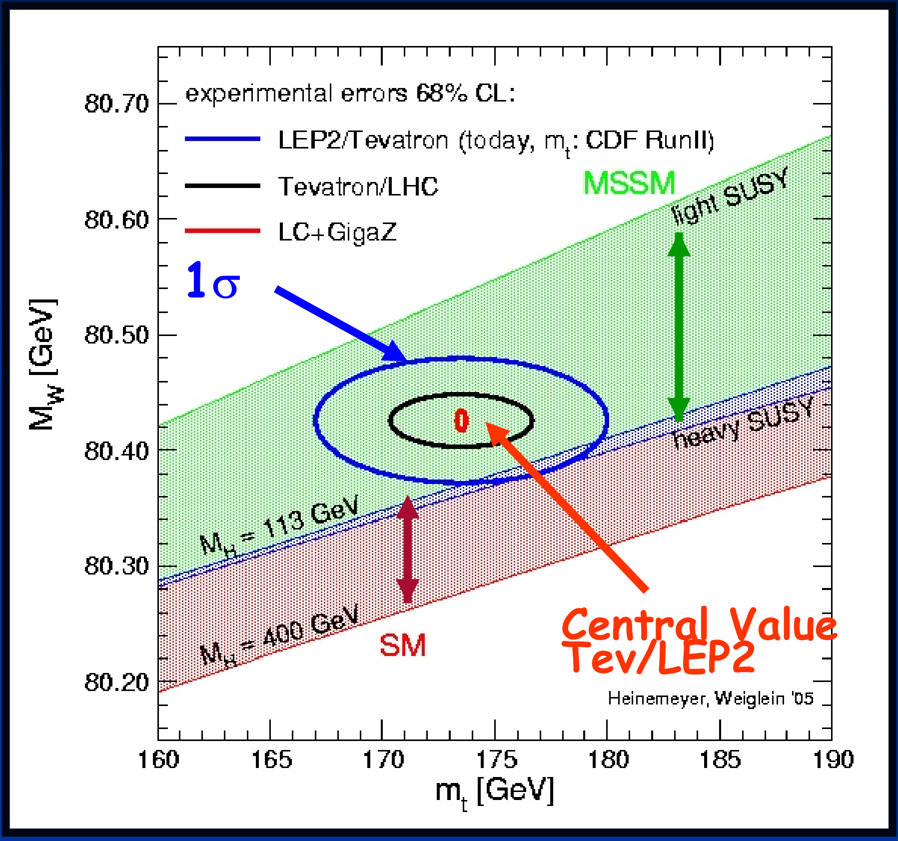
Peak Lum coming up on 3E32

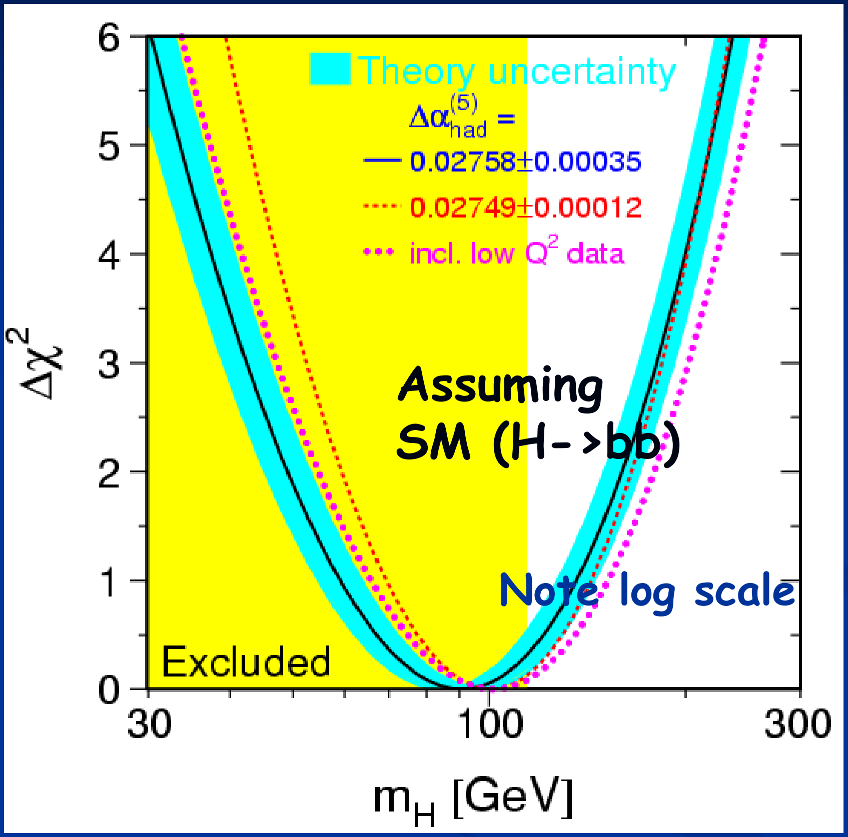


40-50 pb-1/wk times 40 weeks/yr = 2 fb-1/year delivered per expt-

There are more pbars even now. Peak lum problem =>Luminosity leveling?

Where is the Higgs? M_{top} vs M_W





M_{top} vs M_W Status as of Summer 2006 (update below)

Central value prefers a light (too light) Higgs

Puts a High Premium on Measuring Mtop and MW precisely, no matter what happens at the LHC (really diff. systematics at Tevatron.)

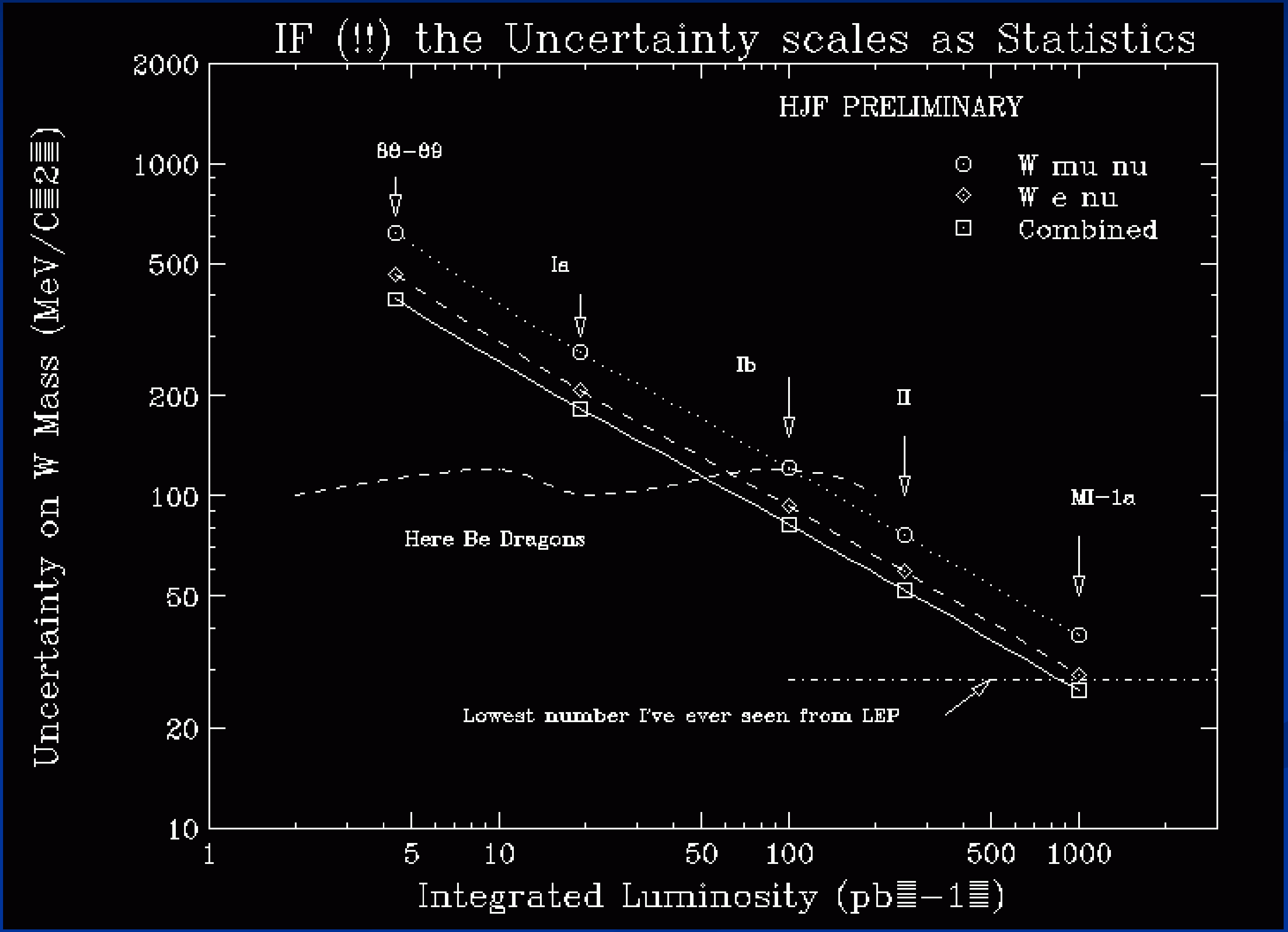
The Learning Curve at a Hadron Collider (τ_L)

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….

Theorists too(SM)



New (Jan. 5, 07) CDF W Mass

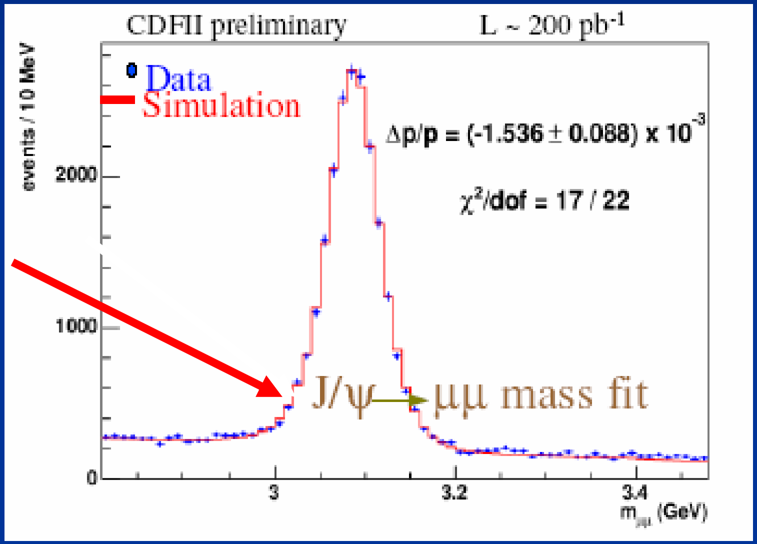
(See Willilam Trischuk's talk after coffee)

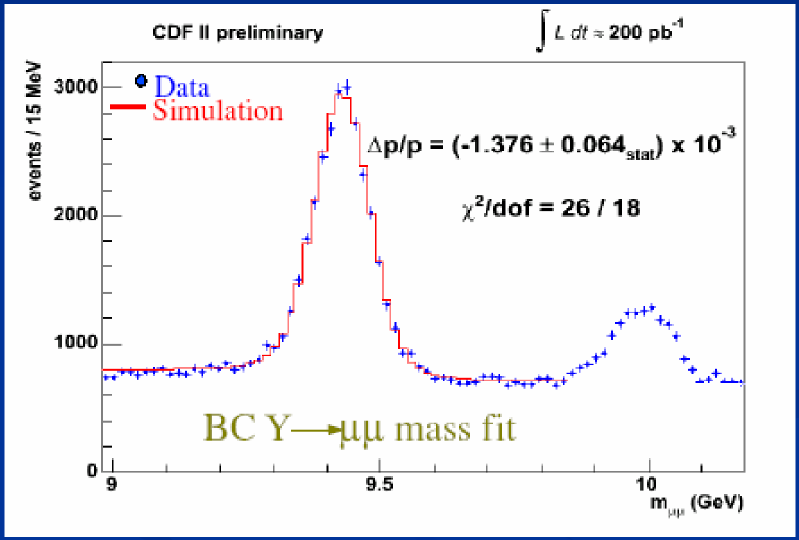
Data from Feb. 02-Sept 03

218 pb^{-1} for e; 191 pb^{-1} for μ

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

N.B.



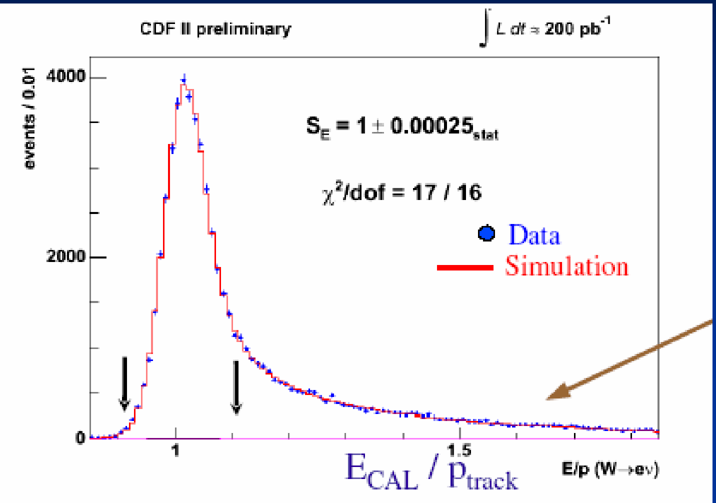


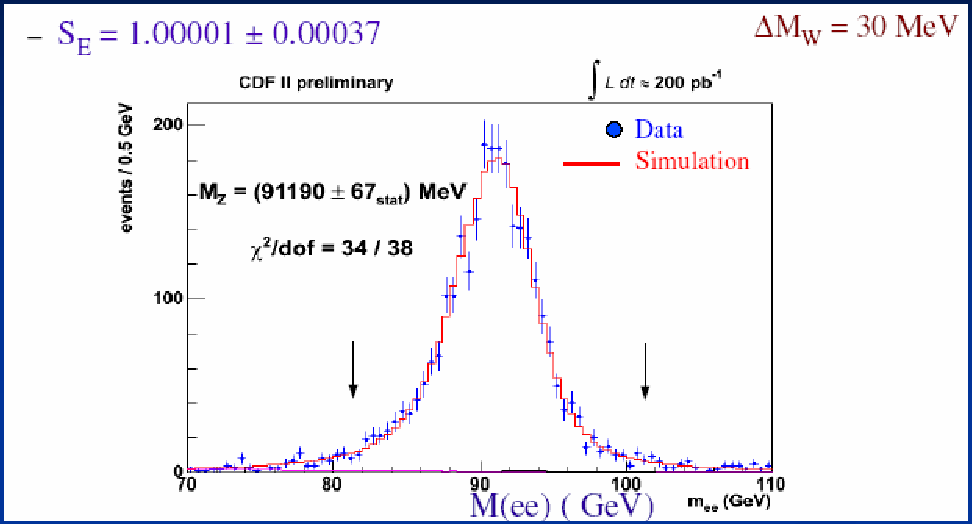
First, Calibrate the spectrometer momentum scale on the J/Psi and Upsilon- material traversed by muons really matters in electron Wmass measurement.

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

(See William's talk later this morning for much more)





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 ± 67
L3	80270 ± 55
OPAL	80416 ± 53
ALEPH	80440 ± 51
CDF-I	80433 ± 79
D0-I	80483 ± 84
LEP Average	80376 ± 33
Tevatron-I Average	80454 ± 59
Previous World Average	80392 ± 29
CDF-II (preliminary)	80413 ± 48
New Tevatron Average	80429 ± 39
New World Average	80398 ± 25

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

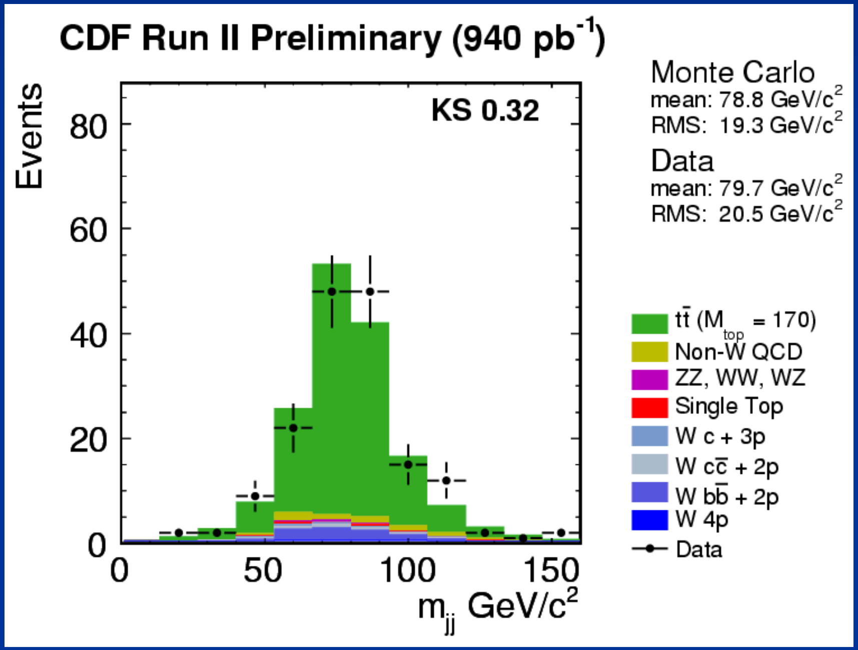
N.B. 48 Mev/80 GeV

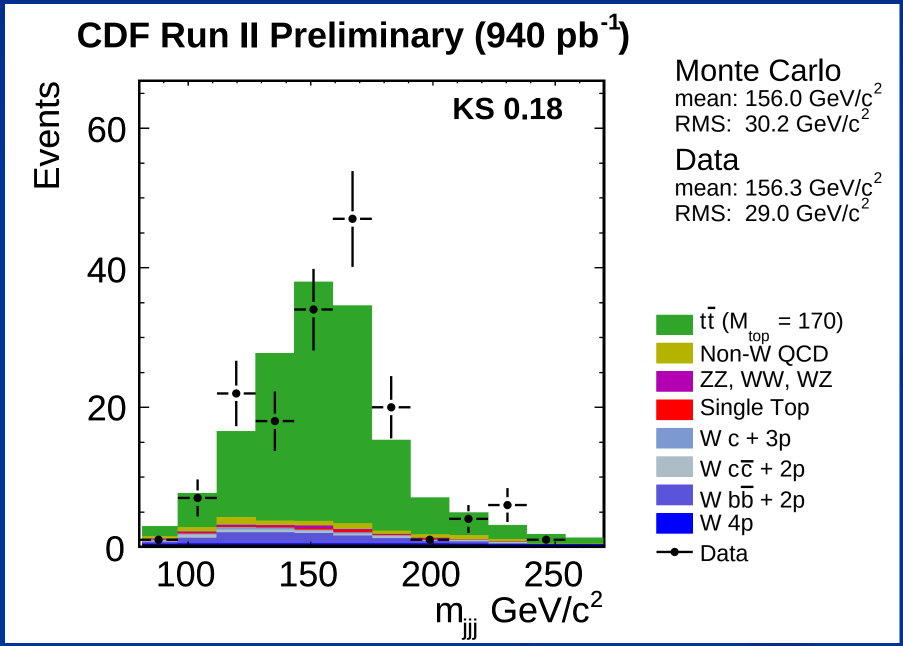
CDF Wmass group believes each systematic in green scales like a statistical uncertainty =>

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

Precision Measuremnt of the Top Mass

(See talk by Gaston Gutierrez later this morning)





M(2-jets)- should be M_W

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

CDF Lepton-Met+4 Jets (1b) - 0.94 fb-1, ~170 ttbar events (Florencia et al...)

Precision Msremnt* of the Top Mass

*like Mrenna

CDF Lepton+4jets:

Systematics:

Jet Energy Scale (JES)

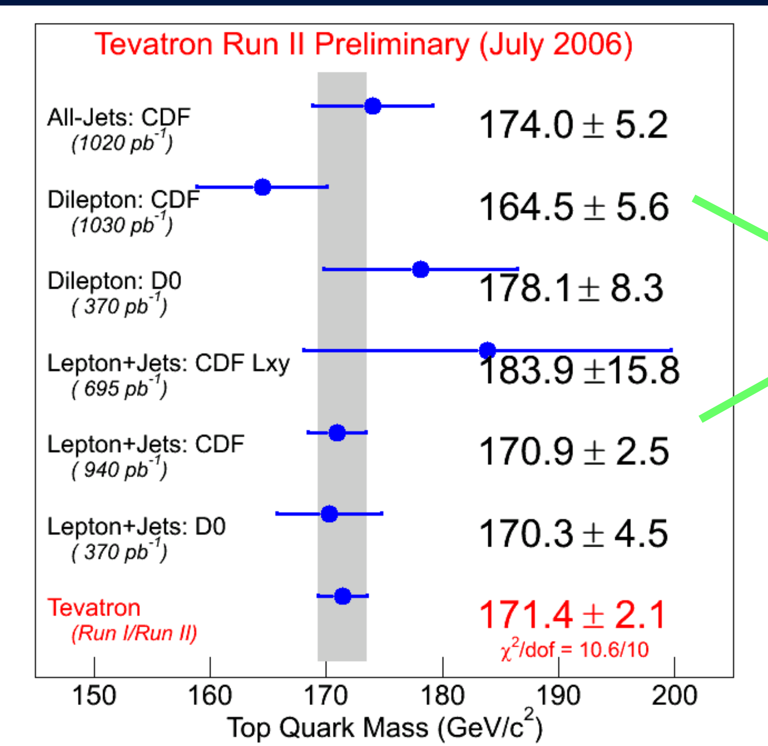
Now set by MW (jj)

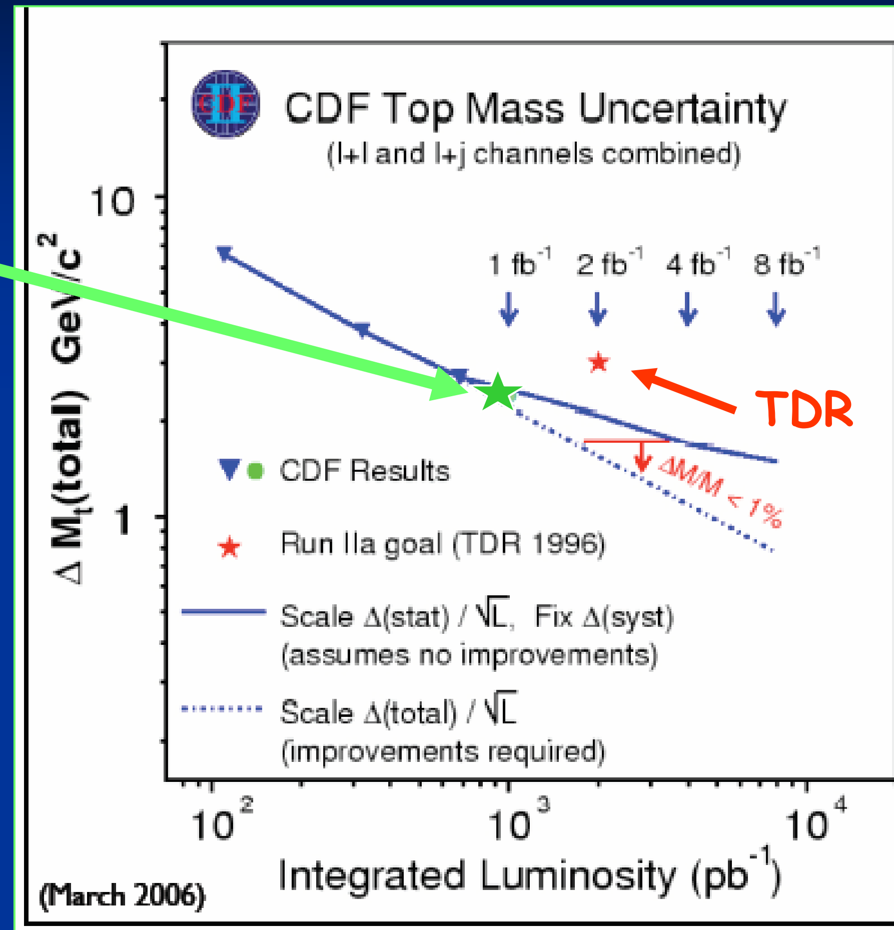
Note FSR, ISR, JES, and b/j JES dominate- all measurable with more data, at some level…

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	

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

Precision Measuremnt 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

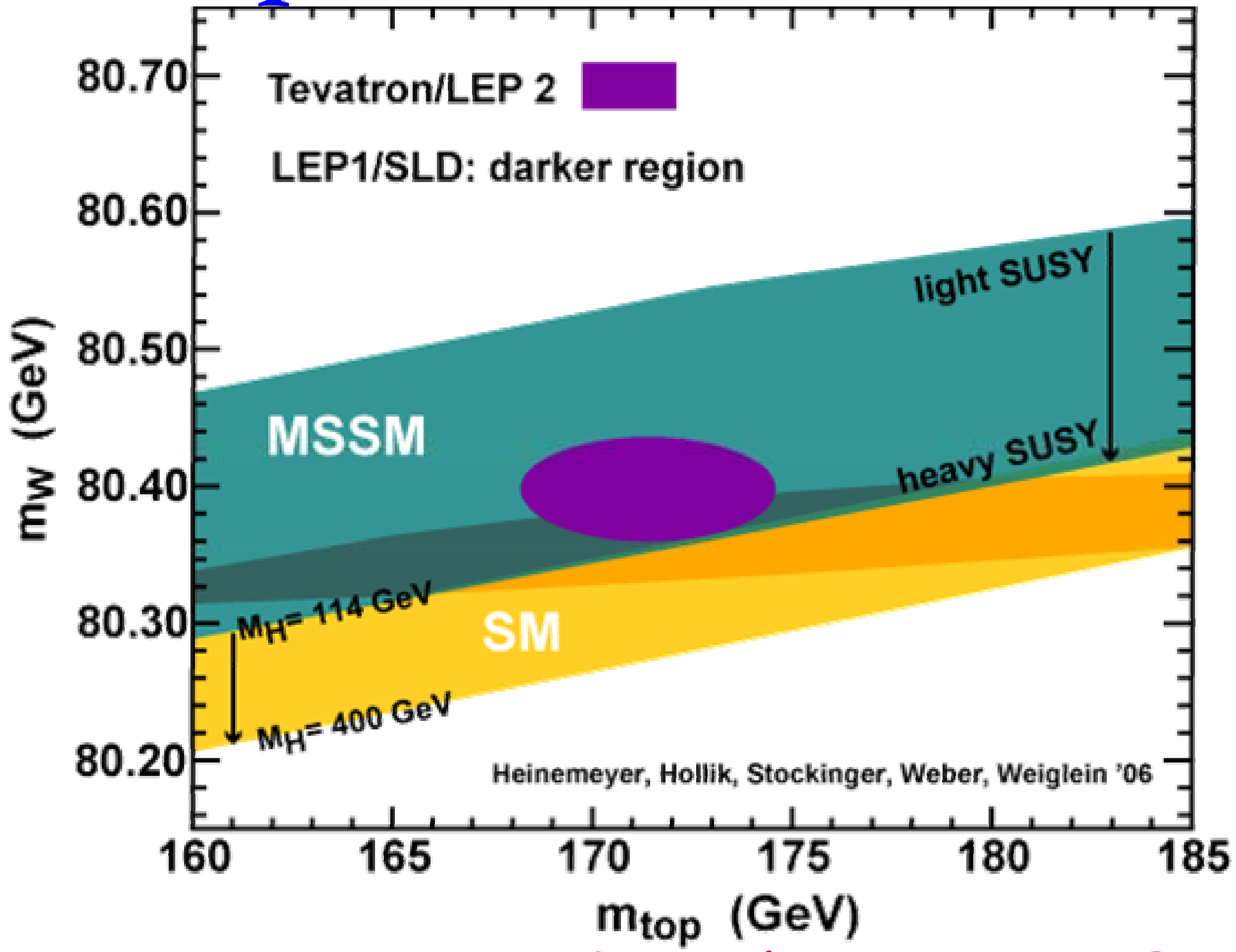
Note we are doing almost 1/root-L even now

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.)

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.)

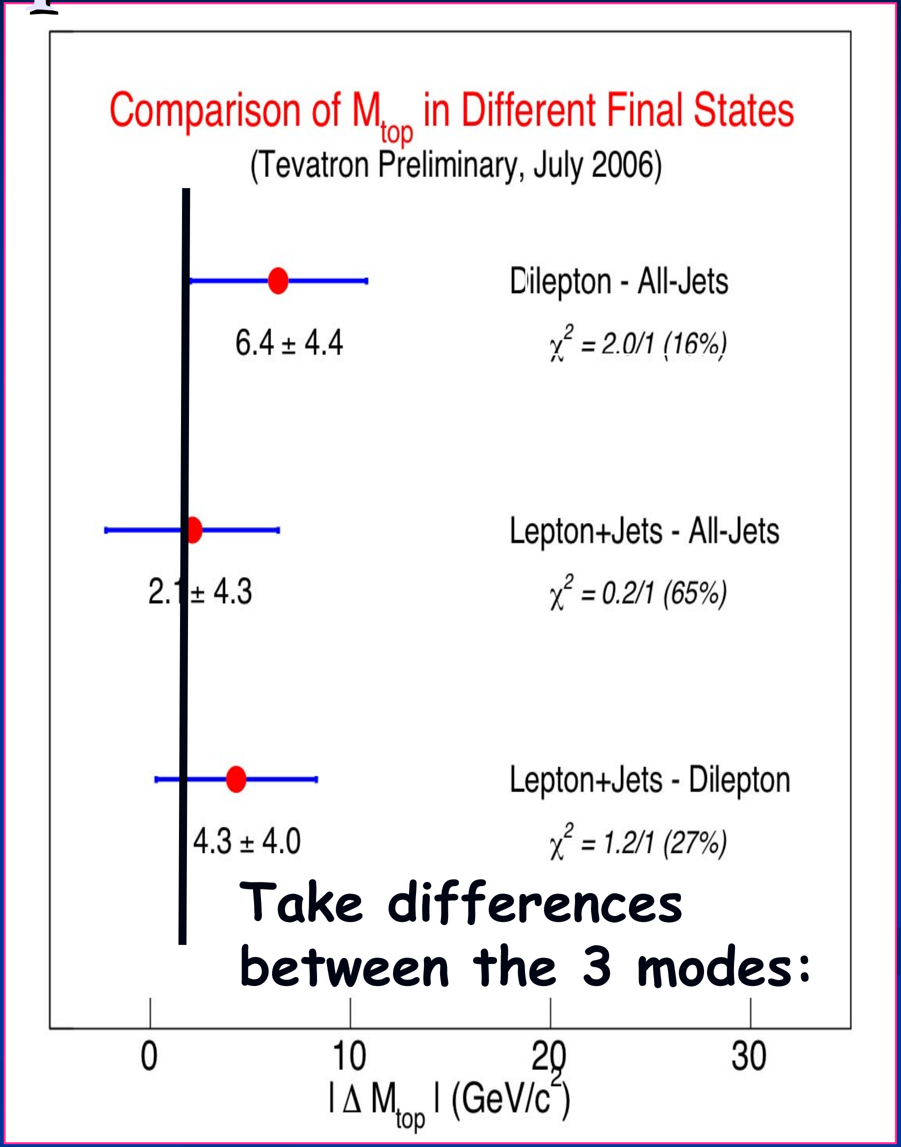
Aside- One old feature may be going away-top mass in dileptons was too low…

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

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

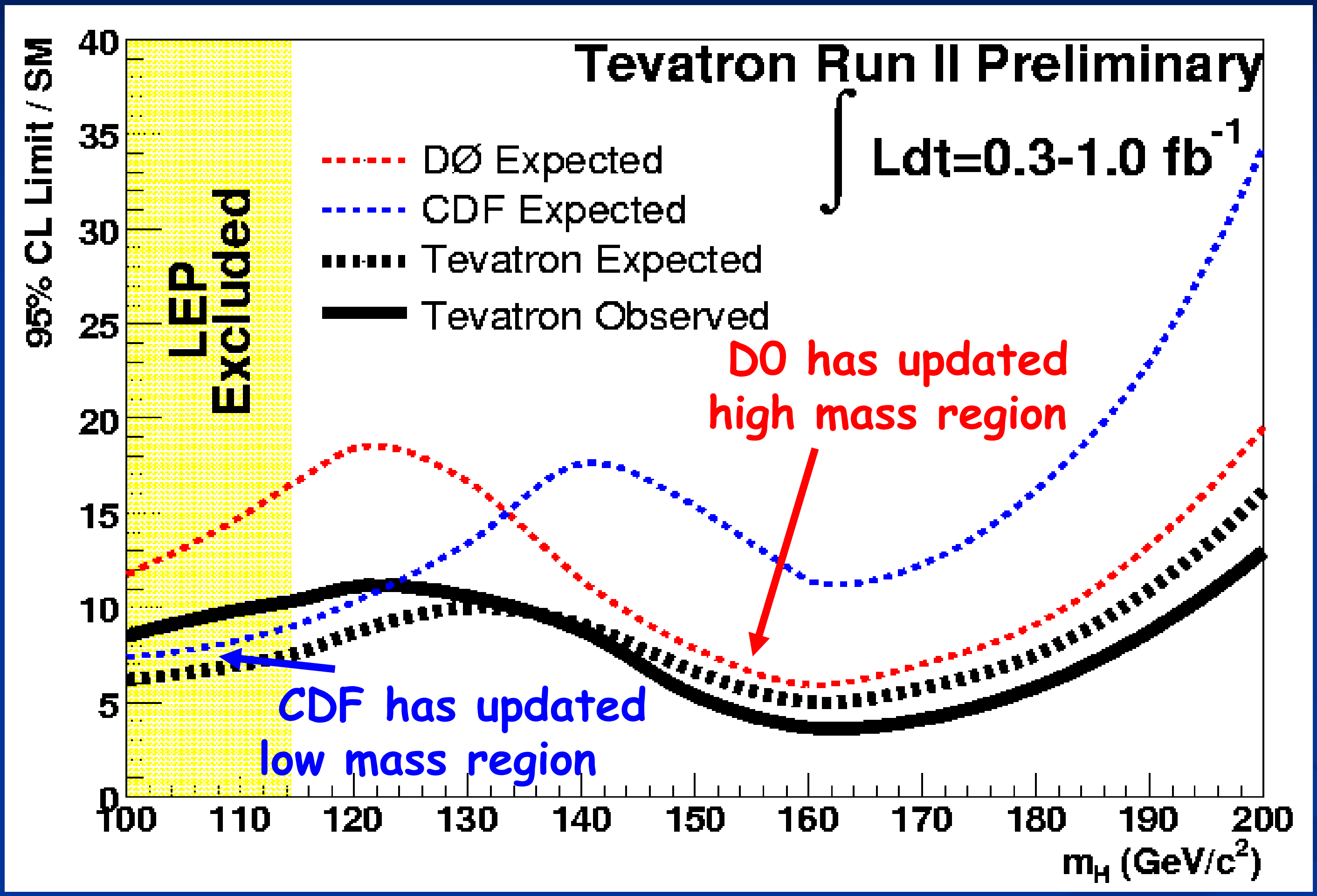
M_{top}(Lepton+Jets) = 171.3 ± 2.2 GeV/c^2

(Rainer Wallny, Aspen 07)



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

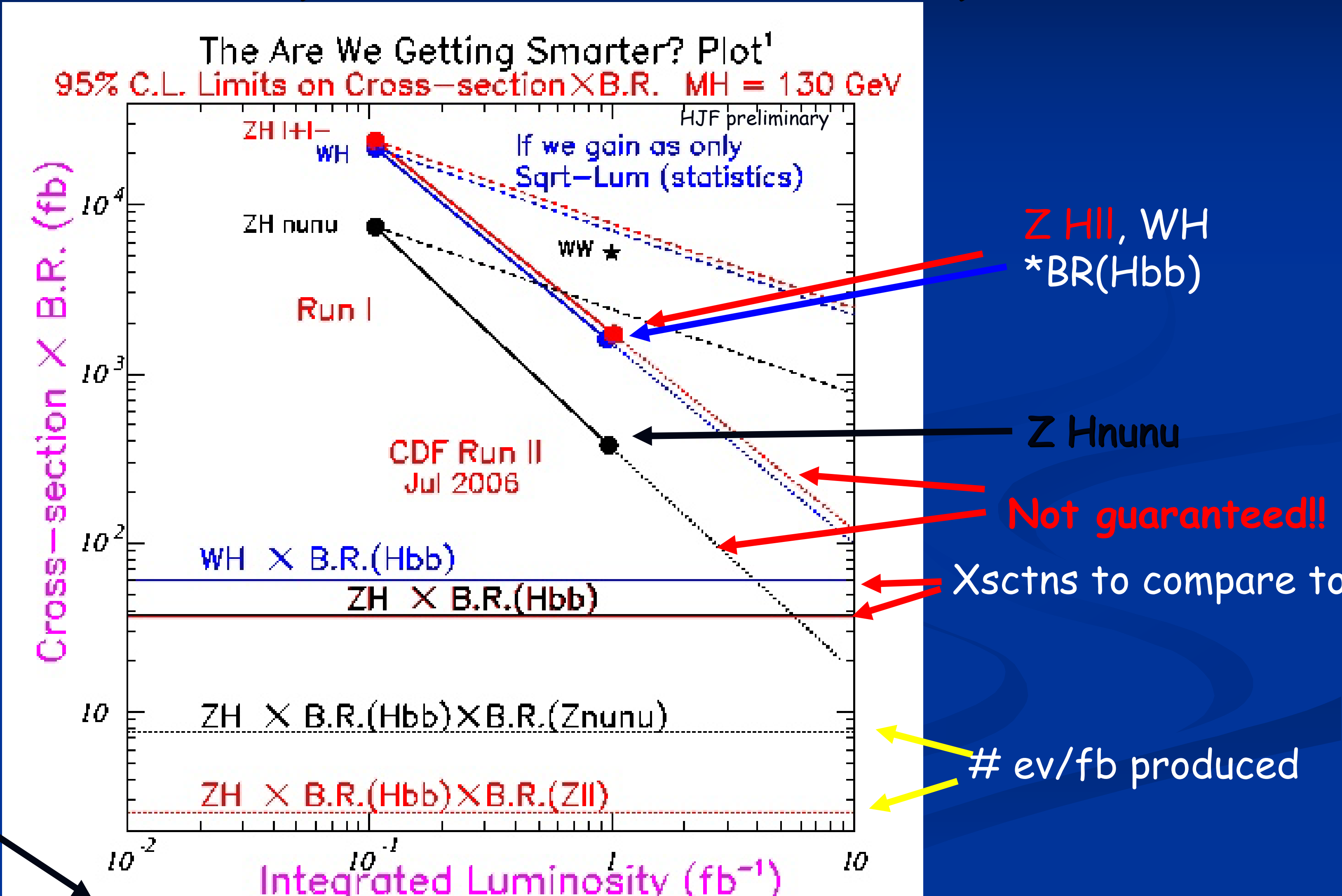
Direct Limits on SM Higgs



This is the factor one needs to get the 95% CL downto the SM Higgs Xscn

I'm not willing to prognosticate (other than to bet we don't see the SM Higgs)- would rather postnosticate. However, lots of tools not yet used- we're learning many techniques, channels,…

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



[1]Sasha– maybe we didnt get enough before...

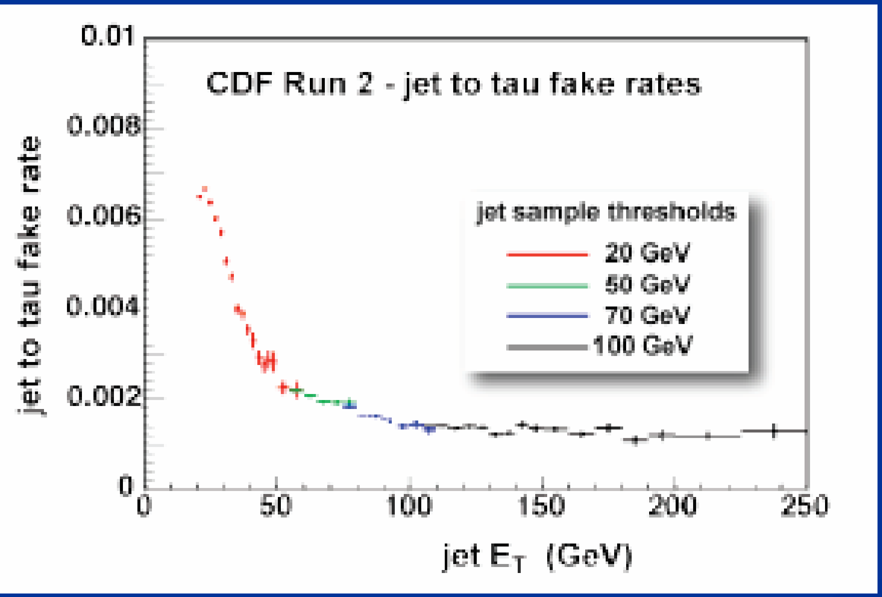
Comment from already smart Russian grad student on seeing plot

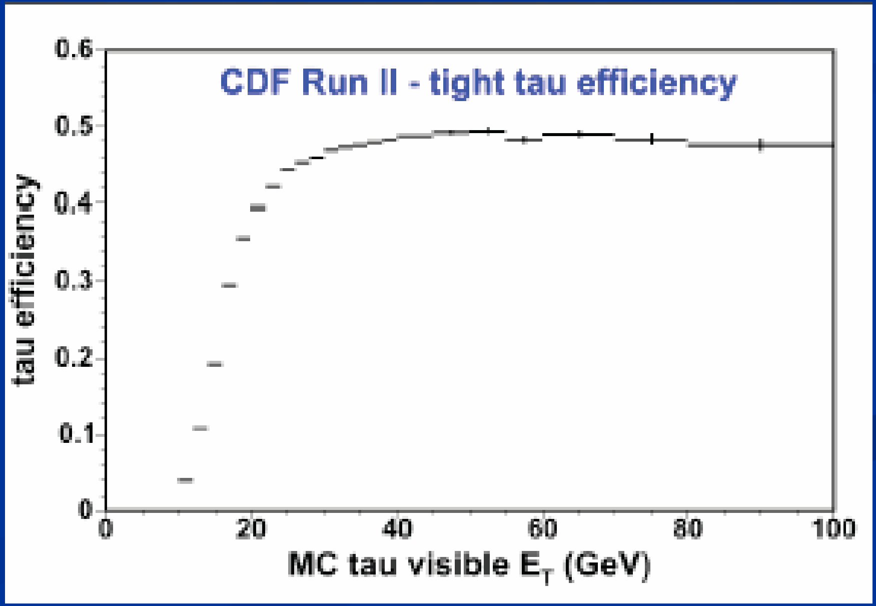
New CDF Higgs to taus result:

(See talk by Tom Junk later this morning)

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.





Low-mass/low met SM, ..e.g. eeggmet Event Followup (lg+X,gg+X)

One event from CDF in Run I: 2 high-Pt electrons, 2 high-Pt photons, large missing Et, and nothing else. Lovely clean signature- and very hard to do in the SM (WW$\gamma\gamma$).

Two Run I analyses looked for `cousins' in 86 pb-1 - spread a wide net: 2 photons+X (X=anything; Toback) and photon+lepton+X (Berryhill). In g-l+X found a 2.7s excess over SM. From PRL:

``CDF Run I PRL: ..an interesting result, but … not a compelling observation of new physics. We look forward to more data…"

LHC has much more reach- but there may be regions of rel. soft things (e.g. met~20) that will not be top priority at CERN and where XYZcan hide

eeggmet Event Followup

Andrei Loginov repeated the lgmet analysis- same cuts (no optimization- kept it truly a priori. Good example of SM needs…

Run II: 929 pb-1 at 1.96 TeV vs Run I: 86 pb-1 at 1.8 TeV

CDF Run II Preliminary, $929pb^{-1}$			
Lepton+ Gamma $+\not{E}_T$ Events			
Standard Model Source	$e\gamma\not{E}_T$	$\mu\gamma\not{E}_T$	$(e+\mu)\gamma\not{E}_T$
$W^{\pm}\gamma$	41.65 ± 4.84	29.85 ± 5.62	71.50 ± 10.01
$Z^0/\gamma + \gamma$	3.65 ± 1.31	14.10 ± 2.36	17.75 ± 3.65
$W^{\pm}\gamma\gamma$	0.32 ± 0.042	0.18 ± 0.025	0.50 ± 0.064
$Z^0/\gamma + \gamma\gamma$	0.087 ± 0.012	0.38 ± 0.048	0.47 ± 0.058
$t\bar{t}\gamma$	0.22 ± 0.029	0.13 ± 0.019	0.35 ± 0.045
$Z^0 \to e^+e^-, e \to \gamma$	9.59 ± 0.76	–	9.59 ± 0.76
Jet faking γ	21.5 ± 4.80	6.2 ± 3.60	27.7 ± 6.00
$\tau\gamma$ contribution	2.15 ± 0.56	0.76 ± 0.24	2.91 ± 0.65
QCD(Jets faking ℓ and $\not{E}_T$)	15.0 ± 4.12	0.0 ± 0.100	15.0 ± 4.12
DIF (Decays-In-Flight)	–	2.3 ± 0.72	2.3 ± 0.72
Total	$94.17 \pm 4.71(stat)$ $\pm 6.64(sys)$	$53.90 \pm 1.94(stat)$ $\pm 6.84(sys)$	$148.07 \pm 5.10(stat)$ $\pm 11.93(sys)$
	$94.17 \pm 8.14(tot)$	$53.90 \pm 7.11(tot)$	$148.07 \pm 12.97(tot)$
Observed in Data	96	67	163

Conclude that eeggmet event, l+g+met `excess', Run II Wgg event all were Nature playing with us- a posteriori searches show nothing with more data…

Signature-Based High Pt Z+X Searches

Look at a central Z +X, for Pt > 0, 60, 120 GeV, and at distributions…

Need SM predictions even for something as `simple' as this… (not easy-ask Rick

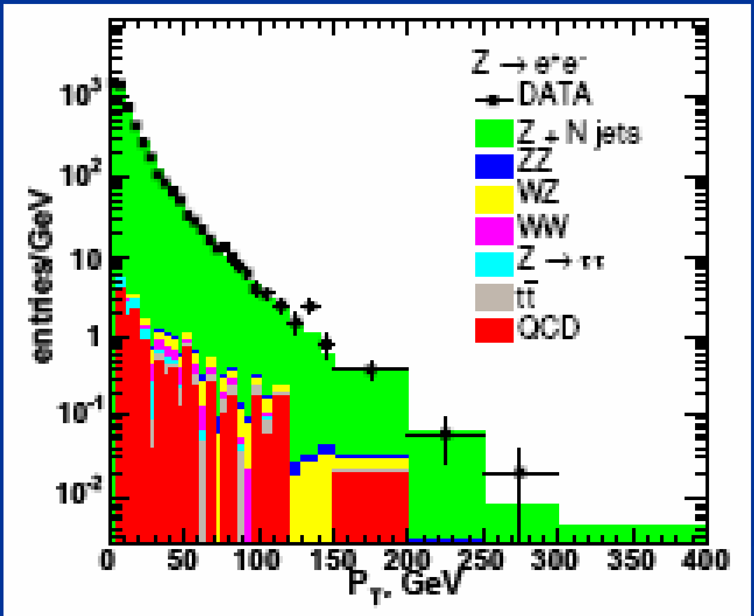
5 Observed and Expected events in each P_T-category

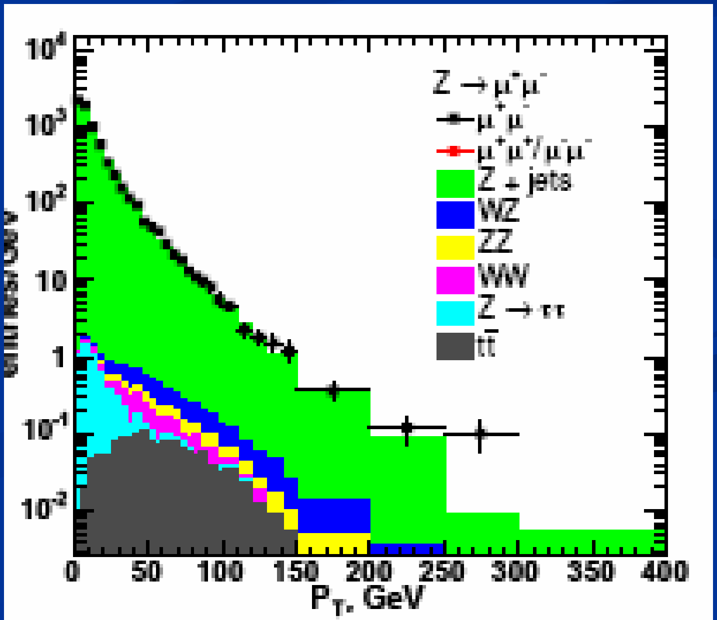
Z + X	Inclusive	$P_T(Z) > 60$ GeV	$P_T(Z) > 120$ GeV
$Z \to e^+e^-$	25079	587	70
$Z \to \mu^+\mu^-$	34222	721	74

Table 1: Number of Z + X events observed in each category.

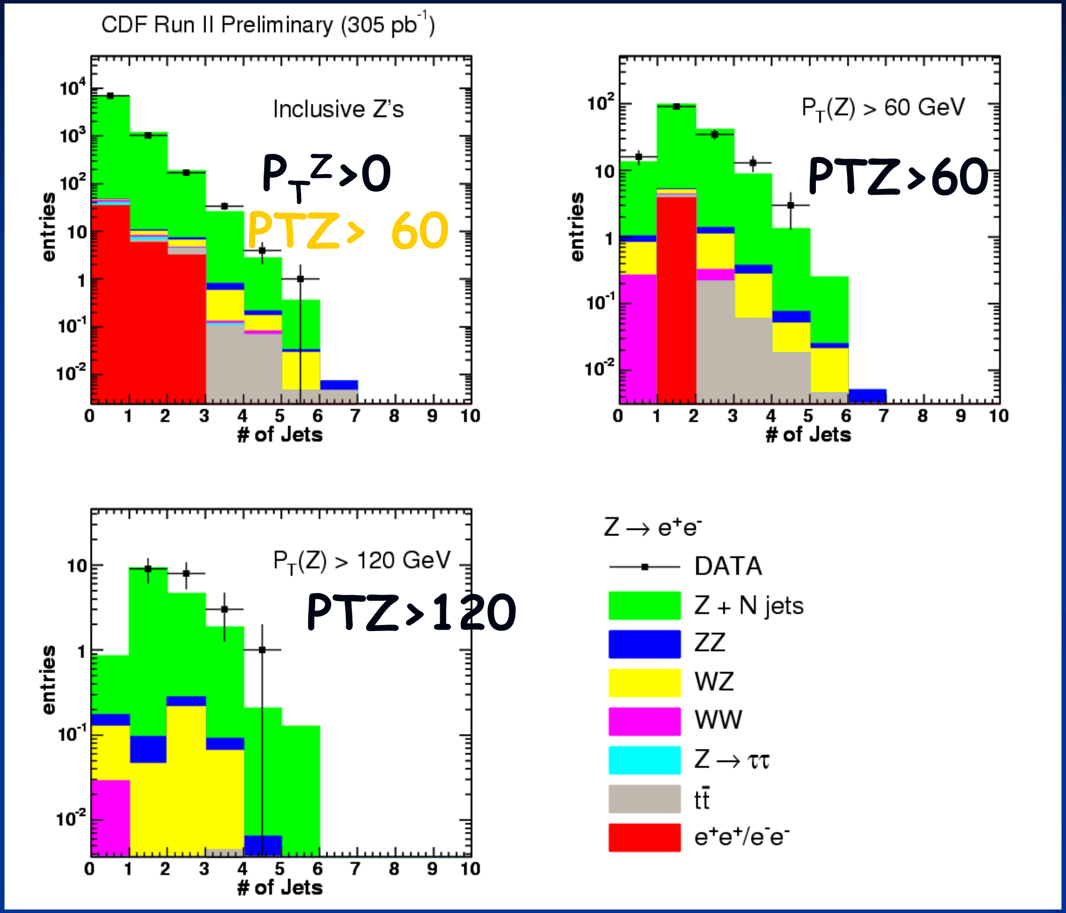
Z + X	Inclusive	$P_T(Z) > 60$ GeV	$P_T(Z) > 120$ GeV
$Z \to e^+e^-$	25079	500	53.7
$Z \to \mu^+\mu^-$	34222	650	61.8

Table 2: Number of Z + X events expected in each category.





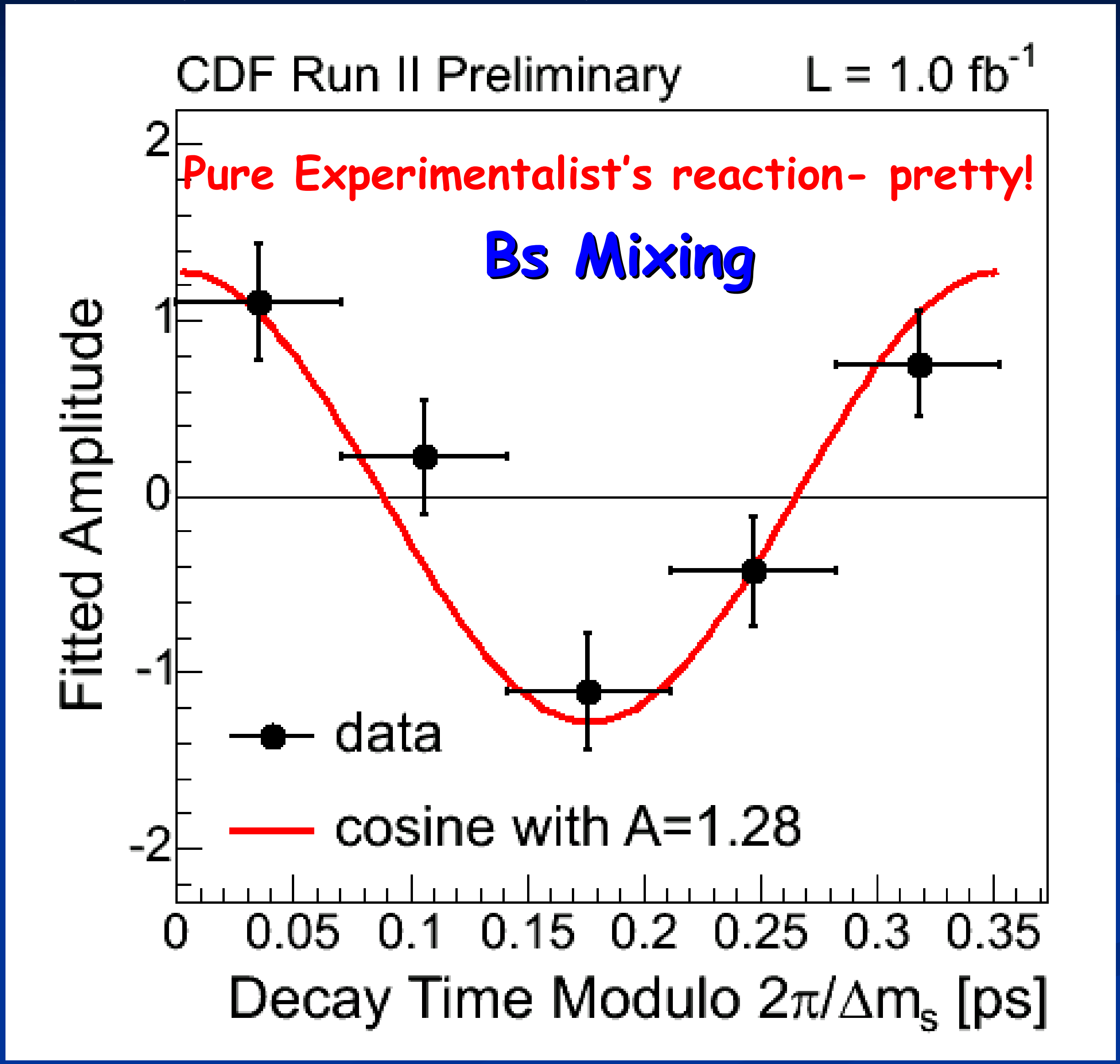
Signature-Based High Pt Z+X Searches



N_{jets} for P_T^Z>0, P_T^Z> 60, and P_T^Z>120 GeV Z's vs Pythia (Tune AW)- this channel is the control for Met+Jets at the LHC (excise leptons - replace with neutrinos).

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

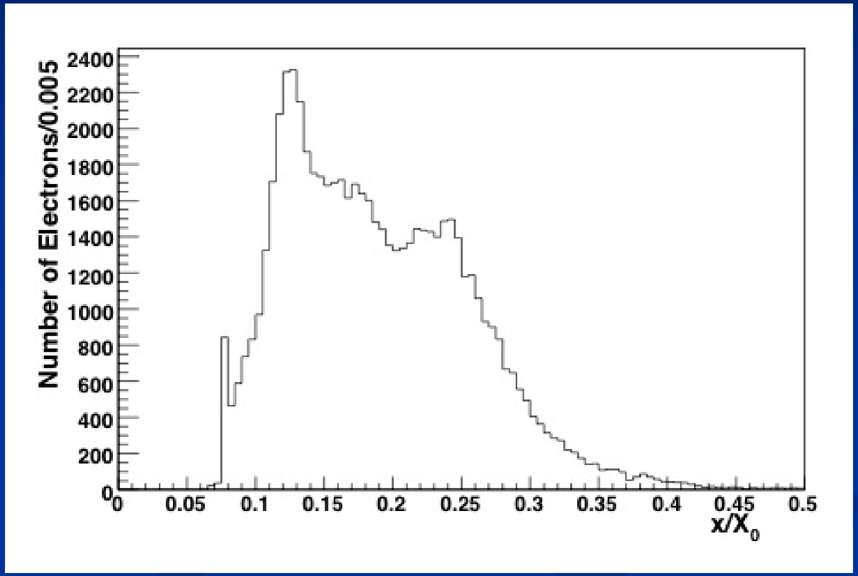
(See talk by Stephano Giagu Tuesday morning)



Note: 1 psec = 300 microns. SVT trigger is critical!!

Tevatron aspects complementary to LHC strengths to compare capabilities

- Obvious ones (pbar-p,..)
- Electron, photon, tau ID has much less material- ultimate M_W, H->taus,?
- Tau-ID; photon/pizero separation (shower max)
- Triggering at met~20GeV
- Triggering on b, c quarks (SVT)- also (?) hyperons,…



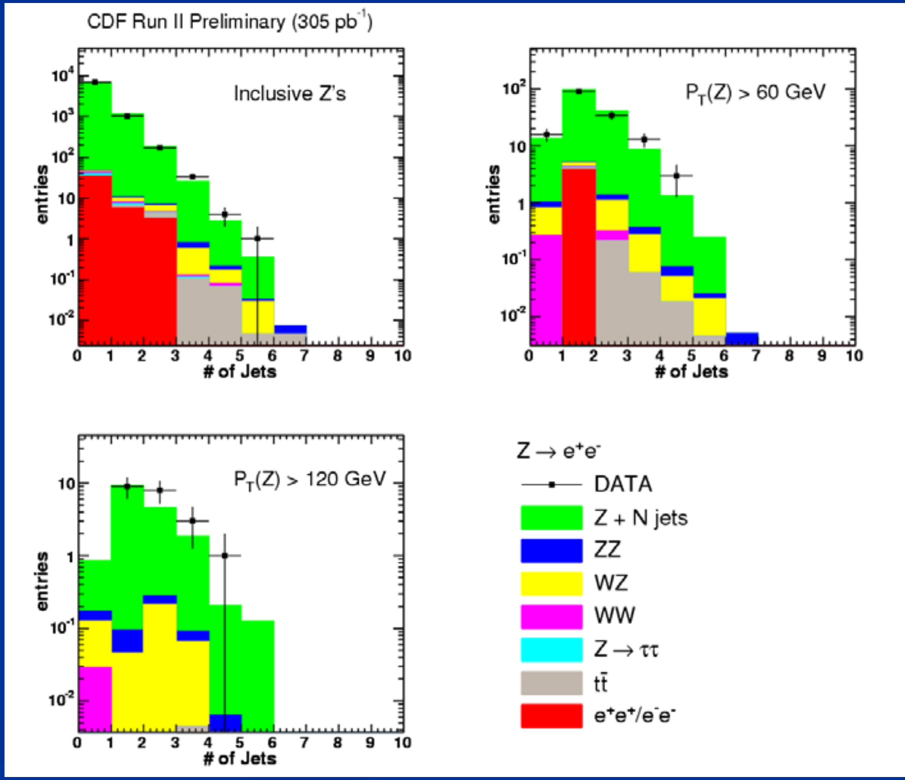
Fraction of a radiation length traversed by leptons from W decay (CDF Wmass analysis)- << 1 X_0

Tools needed at the Tevatron (20 yrs later)

Much SM/QCD work needed- See talk by Rick Field on Wed

Some topical typical examples:

- **Jet fragmentation in the Z=1 limit for photon, tau fake rates (see a difference in u,d,c,b, gluon jets)**
- **Njets >2,3,4,… for γ,W,Z**
- **W,Z, γ + Heavy Flavor (e.g. Zb,Zbj,Zbbar ,Zbbbarj,….- normalized event samples)**
- **Better, orthogonal, object ID**
- **Optimized jet resolution algorithms**
- **etc….** (tools get made when it becomes essential- `mother of invention…')



HT for $P_T^Z>0$, $P_T^Z> 60$, and $P_T^Z>120$ GeV Z's: ee (Left) and μμ (right)

The attraction of hardware upgrades

Met calculated at L2 only- design dates back to 1984. Losing 30% of ZHnunu…Upgrade (now)!

- Find grad students love building hardware-e.g CDF Level-2 trigger hardware cluster finder upgrade:
- Trigger is a place a small gp can make a big difference,
- E.g., Met trigger for ZH,.. at CDF

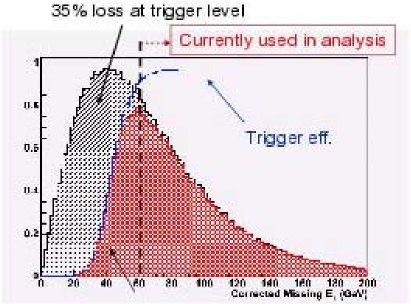


Figure 12: Expected signal shape as a function of corrected $\not\!\!E_T$ of the SM Higgs assuming $M_H = 120$ GeV for the Higgs search in the $ZH \to \nu\nu bb$ channel. The blue curve shows the efficiency of the trigger requiring MET and two jets currently used, and the red histogram shows the signal acceptance due to the trigger. Approximately 50% of the signal is lost after applying a an offline cut to avoid systematic uncertainties in the trigger turn-on.

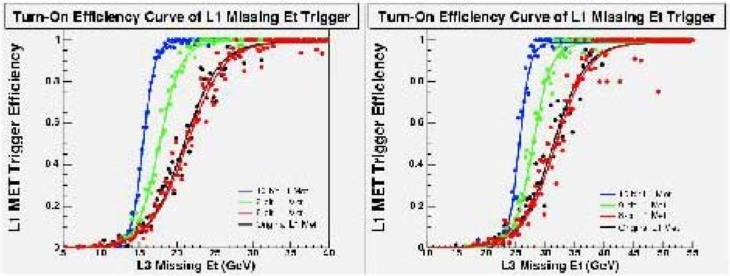
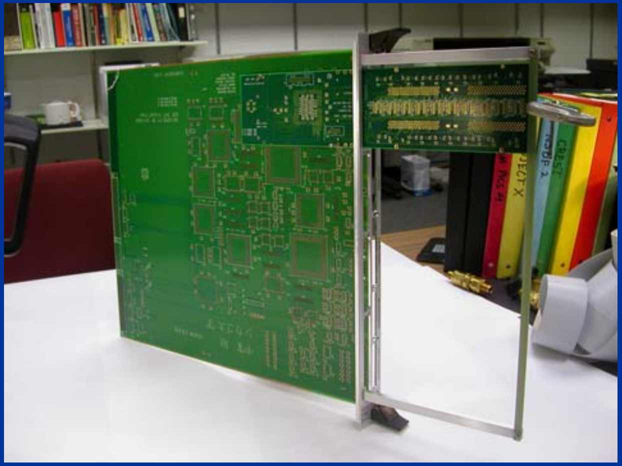


Figure 13: L1 MET trigger efficiency of (*left*) $\not\!\!E_T > 15$ GeV and (*right*) $\not\!\!E_T > 25$ GeV cuts for 8 (current), 9, and 10 bit precision of the MET calculation. L1 MET25 is currently used in the MET+2JET and inclusive MET triggers. The proposed upgrade will provide 10-bit precision at Level 2.

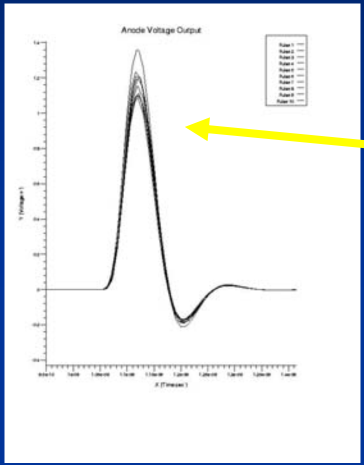
L2Cal Upgrade Group - new Cluster finder algorithm/hdwre



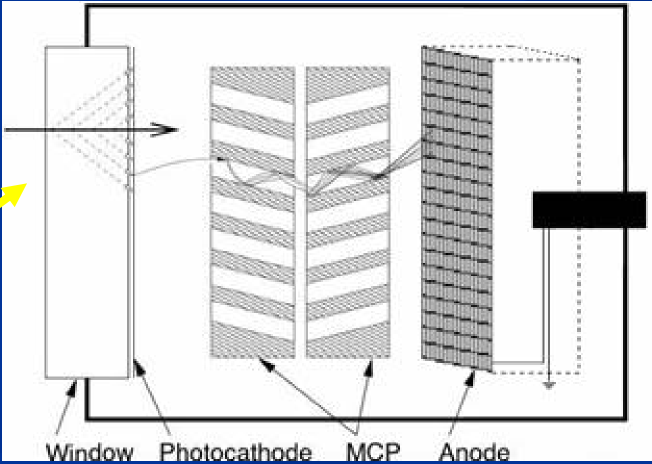
The attraction of hardware upgrades

(this is a little over the top- ignore it if you want to, please)

- Could even imagine bigger upgrades- e.g. may want to distinguish W->csbar from udbar, b from bbar in top decays, identify jet parents,..
- Outfit one of the 2 detectors with particle Id- e.g. TOF with σ <= 1 psec:



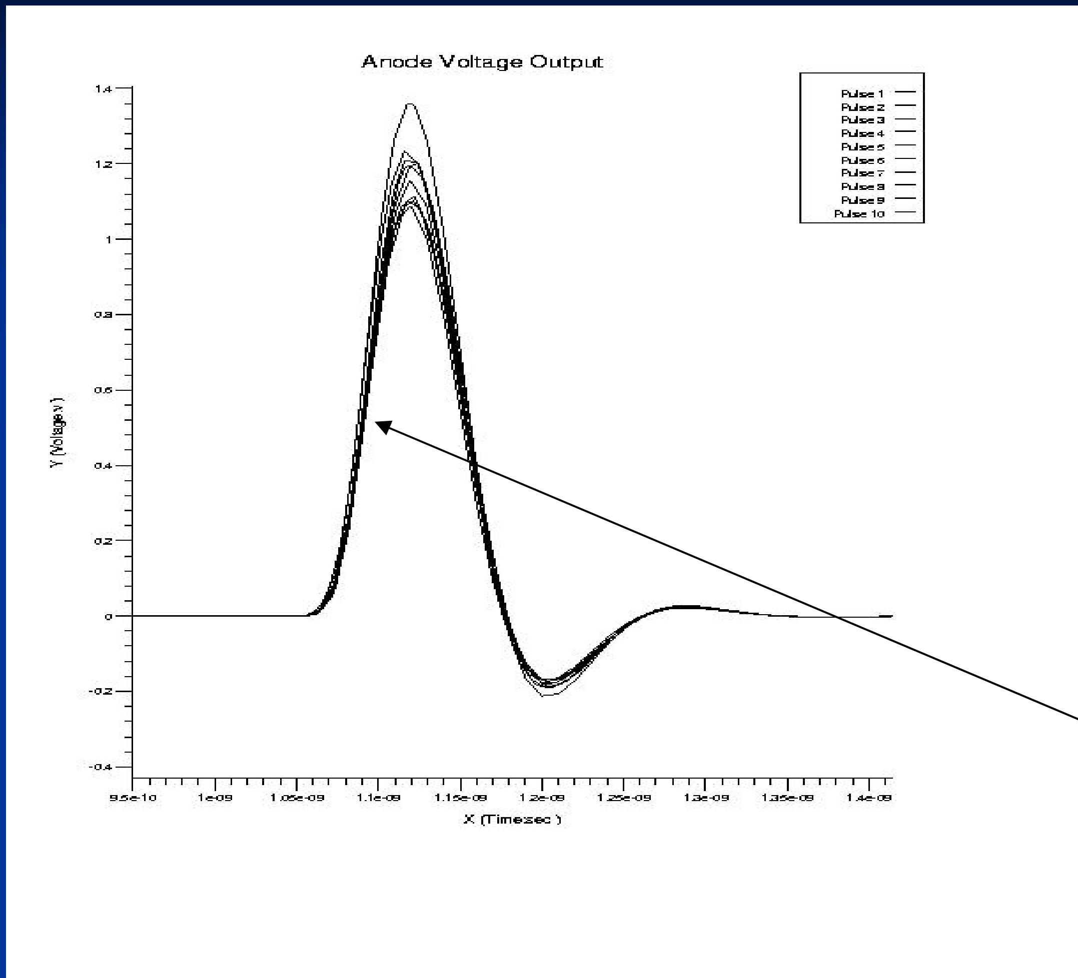
Collect signal here



Incoming particle makes light in window:

Micro-channel Plate/Cherenkov Fast Timing Module

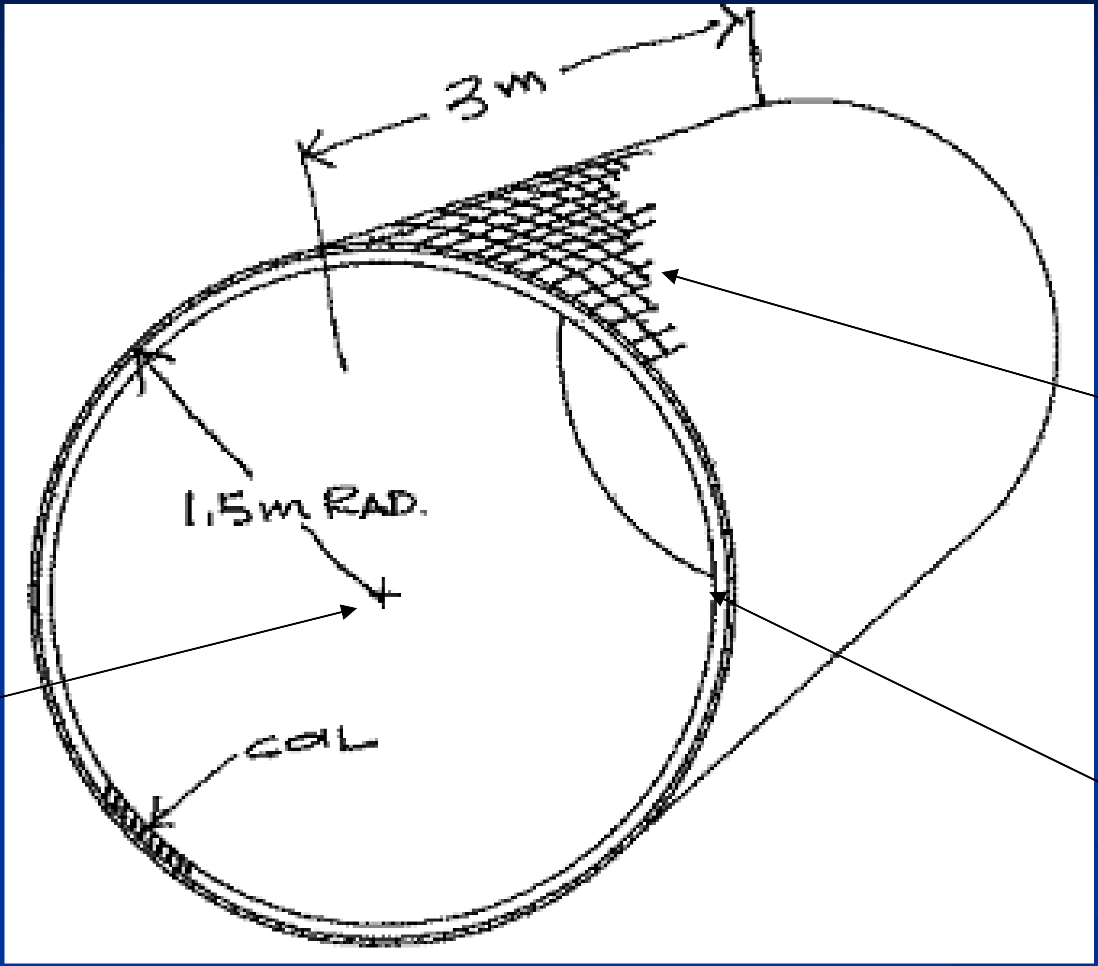
Major advances for TOF measurements:



Output at anode from simulation of 10 particles going through fused quartz window- T. Credo, R. Schroll

Jitter on leading edge 0.86 psec

Geometry for a Collider Detector



2" by 2" MCP's

Beam Axis

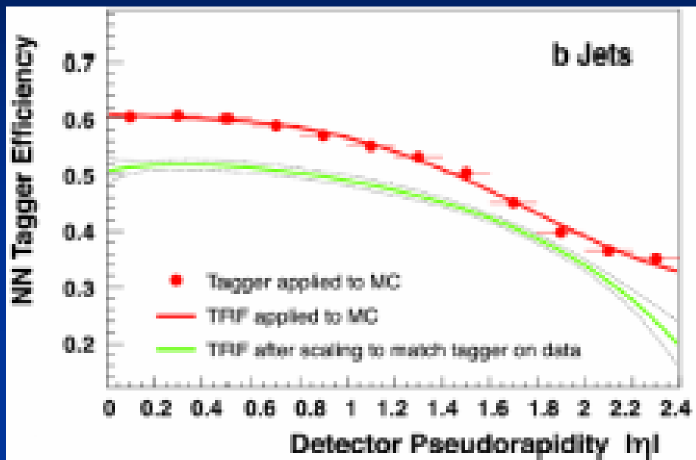
Coil

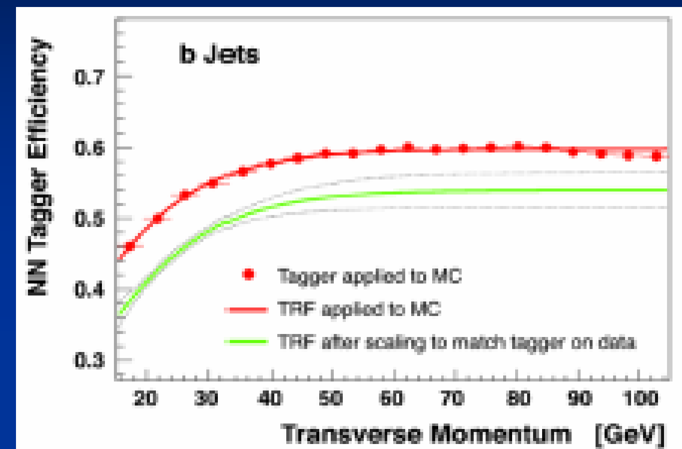
"r" is expensive- need a thin segmented detector

Summary

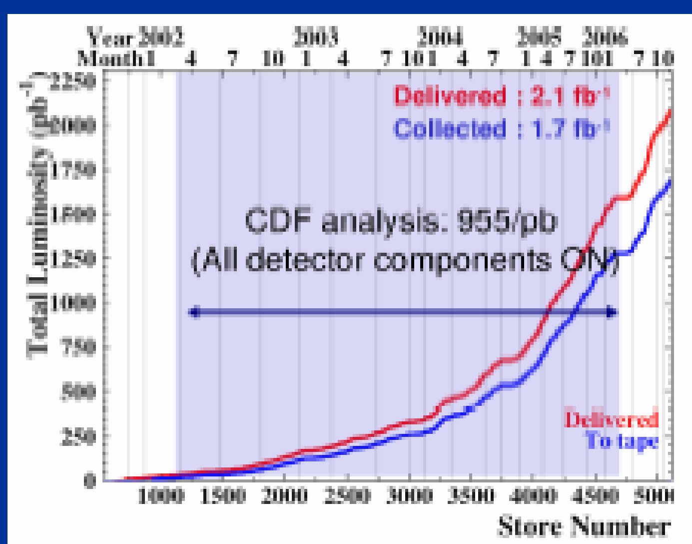
1. Tevatron running well – expect >= 1.5-2 fb-1/yr/expt of all goes well (could even be somewhat better- there are more pbars).
2. Experiments running pretty well and producing lots of hands-on and minds-on opportunities (lots of room for new ideas, analyses, and hardware upgrades (great for students!)
3. Doubling time for precision measurements isn't set by Lum- set by learning. Typical time constant ~ one grad student/postdoc.
4. Precision measurements- MW, Mtop, Bs Mixing, B states- MW and Mtop systematics statisics-limited
5. Can make a strong argument that pbar-p at 2 TeV is the best place to look for light SUSY, light Higgs,…; as met at EWK scale, (MW/2, Mtop/4) doesn't scale with mass, root-s, and tau's (maybe b's) are better due to lower mass in detector, and SVT and L1 tracking triggers,
6. All of which implies keep the Tevatron running until we know that we don't need it (and keep Fermilab strong for the ILC bid too!)

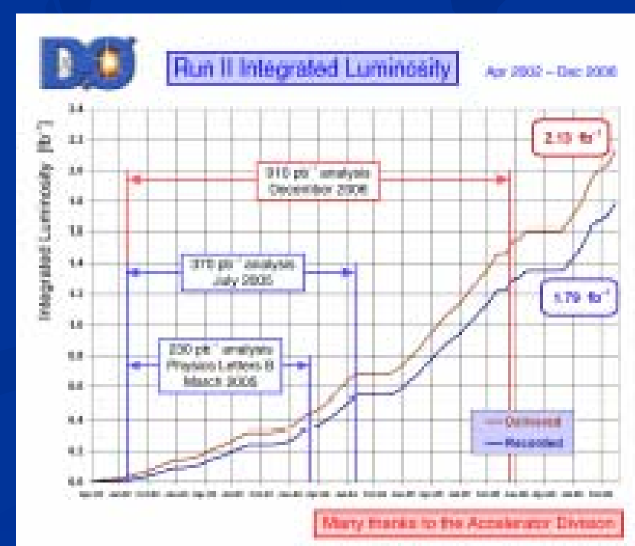
Backup- D0 btagging



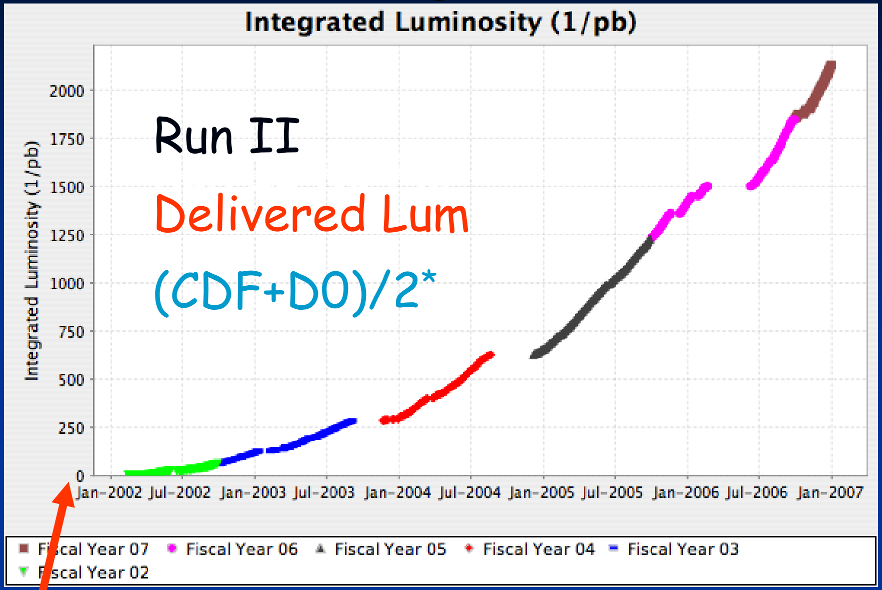


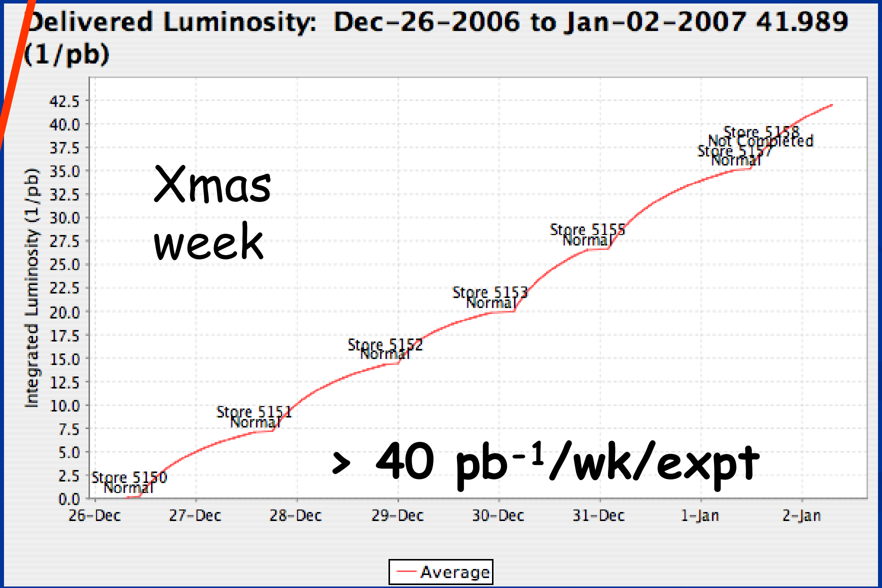
Backup- lum on tape





Luminosity vs Time





Note pattern- integral grows when you don't stop, with increasing slope

*(Protons are smaller on this side (joke))