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,γ; Top, Bottom

Lecture 3:

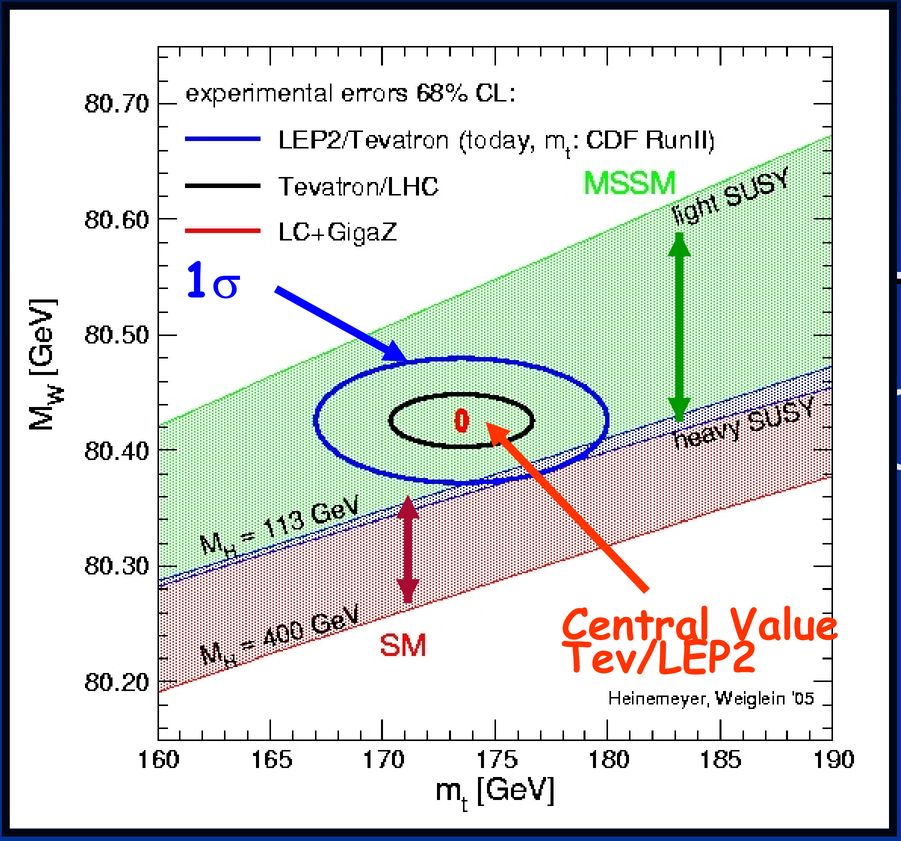
1) Searching for the Higgs
2) Searching for Not-SM events
3) The Learning Curve at a Collider
4) Unsolved Problems

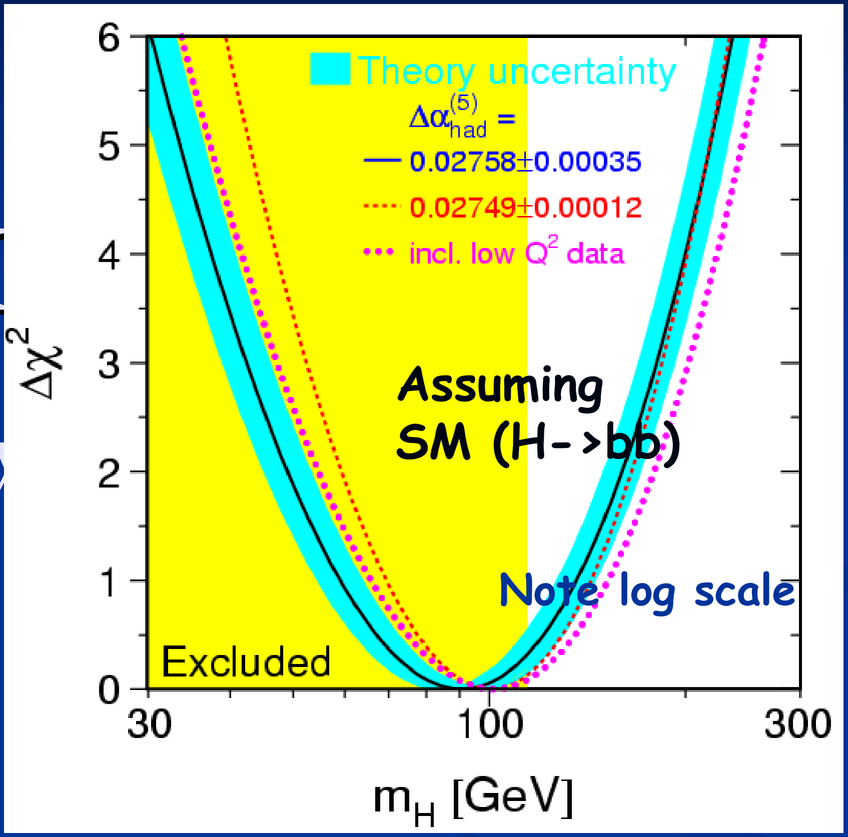
Theme of Lecture

- We know the SM is incomplete- an `effective FT', which breaks down at ~1 TEV, where W_L-W_L scattering violates unitarity (see the Higgs Hunter's Guide, e.g.);
- We have a number of models of NP- e.g. the MSSM, NMSSM, LED,Bjorken-Pakvasa-Tuan, Hidden Valleys, but many free parameters
- There are some obvious NP phenomena to look for- Z', W', heavy squarks, gravitinos,…- but there are many ways that new physics can hide in the haystack of SM hadron collisions-
- All of which implies developing better tools- flavor ID, better understanding of fake rates, lower threshold triggers, ….
- Lastly, rather than try to be encyclopedic, I've chosen only certain topics- apologies if I've left out your favorite.

Searching for the (a!?) Higgs

- Cross-sections for a light SM Higgs are ~0.2 pb (vs 8 pb vs top, e.g.), and fall with mass- need more lum, more acceptance, more jet resolution
- While the SM Higgs has known decays, all bets are off outside the SM, I believe. It is easy to make a model with a Higgs sector very hard to detect (e.g. NMSSM with a light a_0 (Gunion et al.), SUSY+R-parity Violation (D. Kaplan et al.,…).
- A big and coordinated effort on Higgs searches has begun now that there is ~2 invfb recorded/expt.





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

Central value prefers a light (too light) Higgs

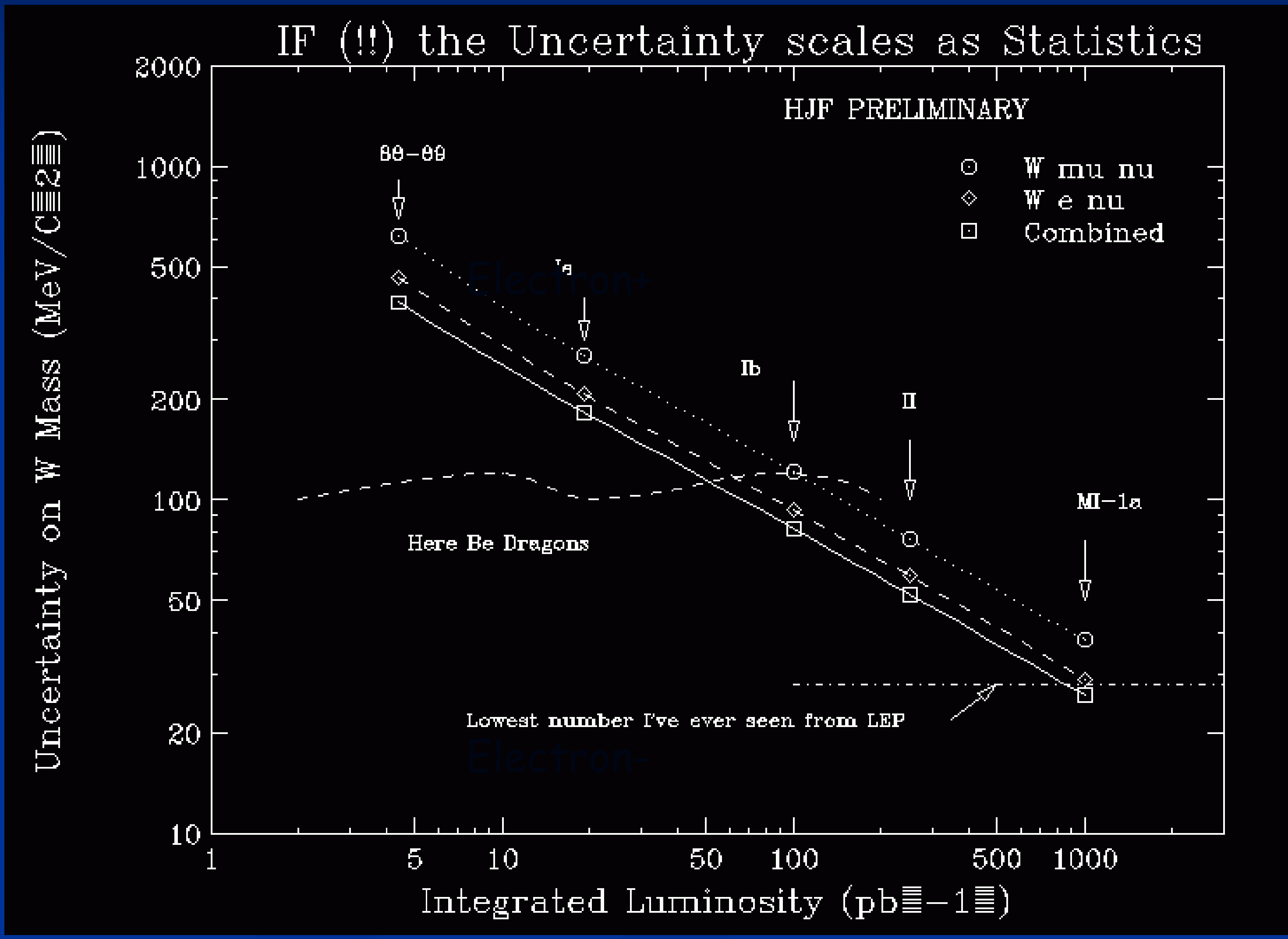
Puts a High Premium on Measuring Mtop and MW precisely, no matter what happens at the LHC (really diff. systematics at Tevatron.)

The Learning Curve at a Hadron Collider

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

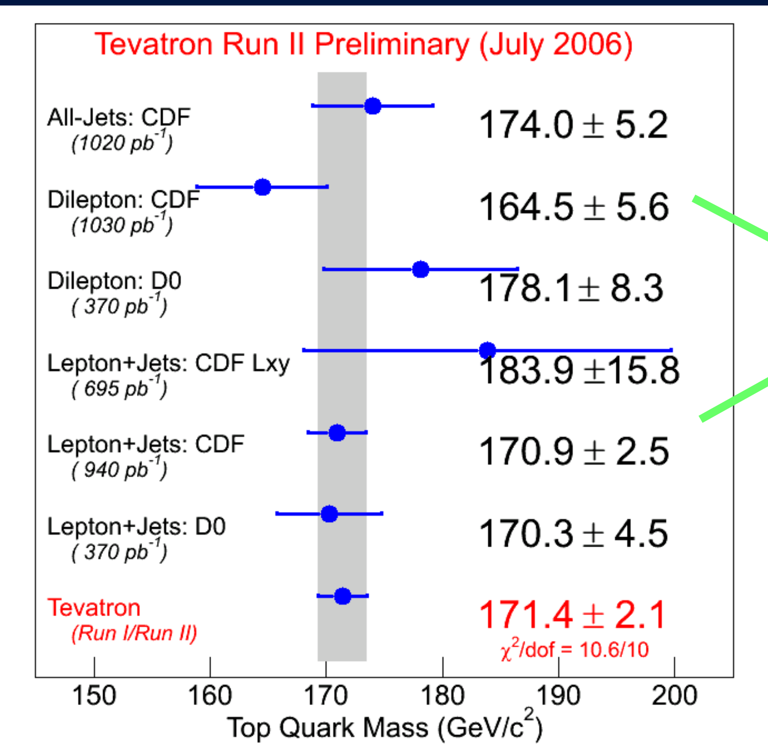
Dec 1994 (12 yrs ago)-

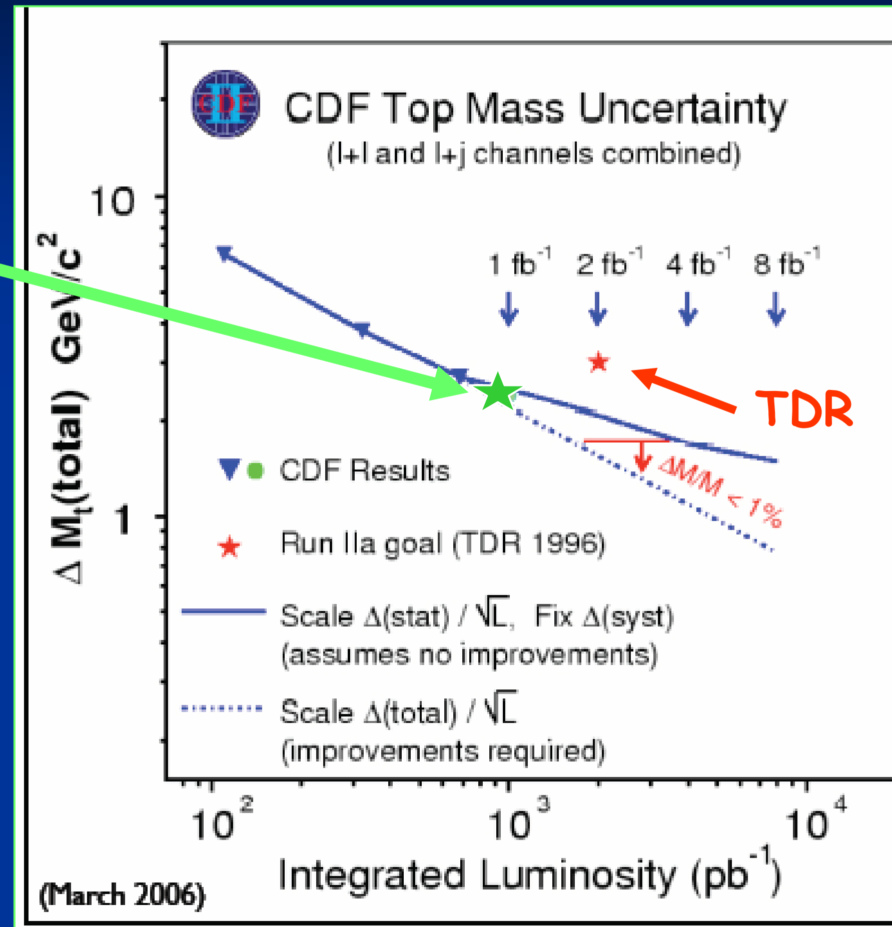
` Here Be Dragons' Slide: remarkable how precise one can do at the Tevatron (MW,Mtop, Bs mixing, …)- but has taken a long time- like any other precision measurements requires a learning process of techniques, details, detector upgrades….



Theorists too(SM)

Precision Measurement of the Top Mass





Aspen Conference Annual Values
(Doug Glenzinski Summary Talk)

Jan-05: ΔMt = +/- 4.3 GeV

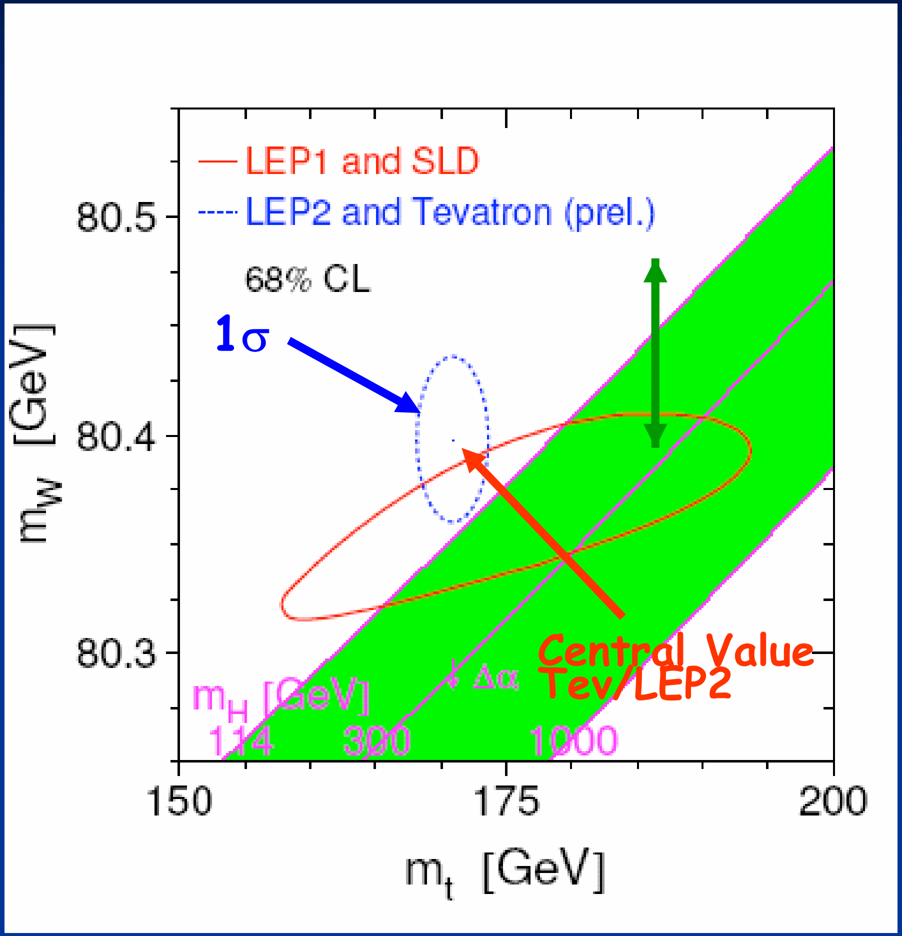
Jan-06: ΔMt = +/- 2.9 GeV

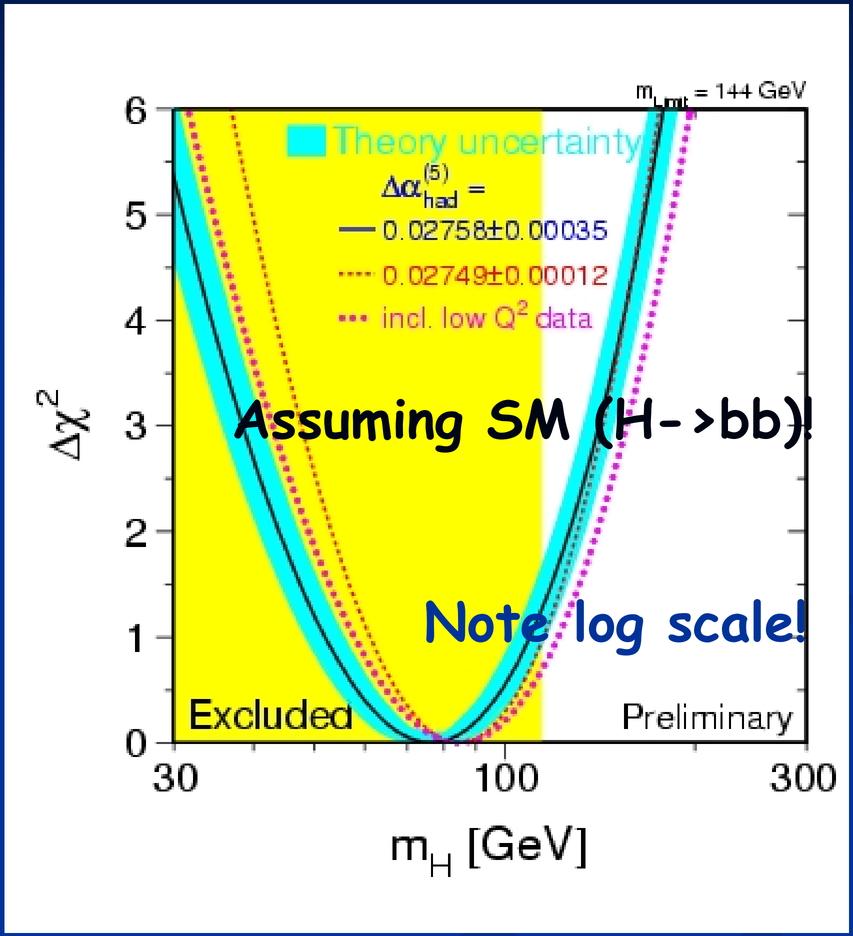
Jan-07: ΔMt = +/- 2.1 GeV

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.)

Where is the Higgs? M_{top} vs M_W

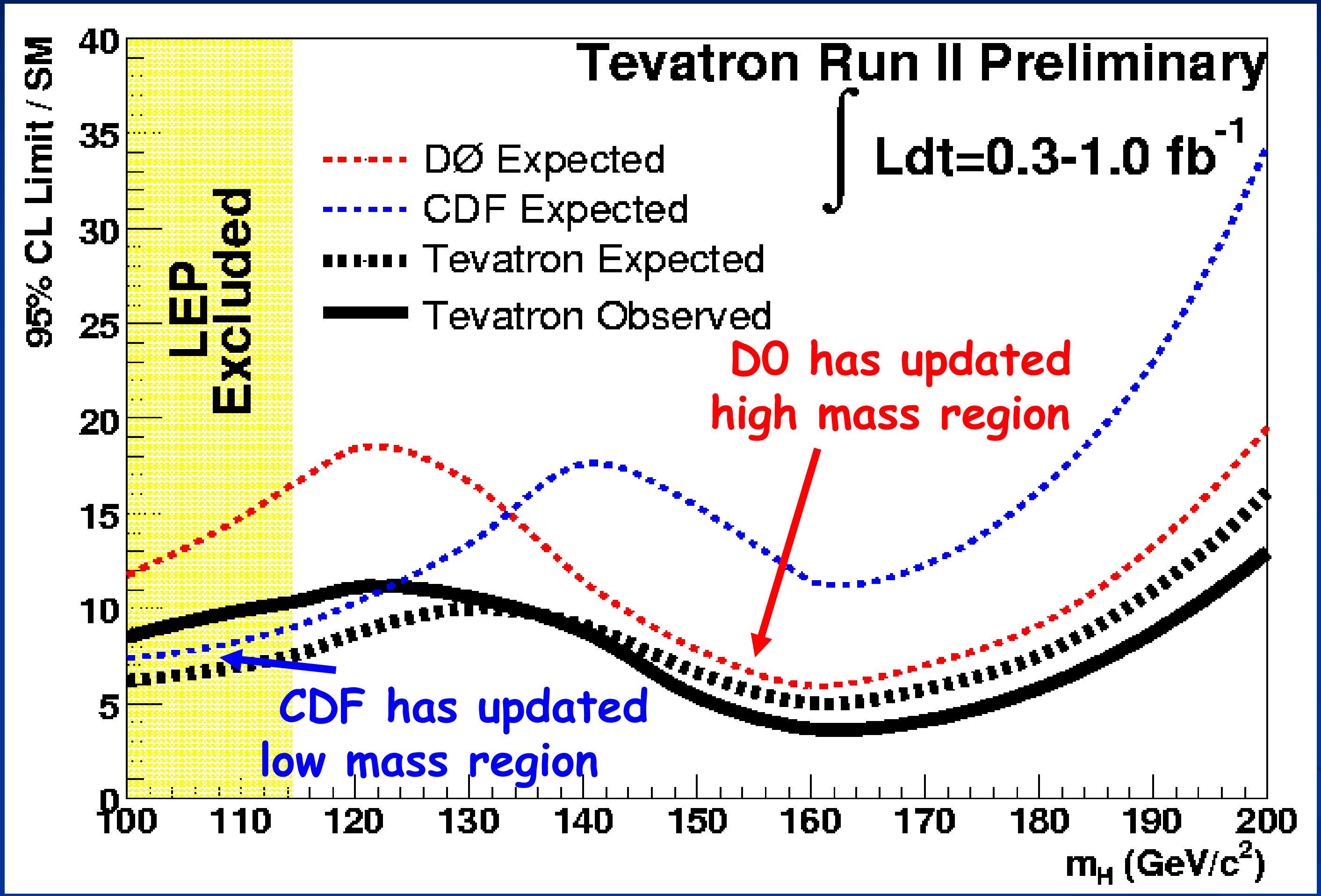




Central value prefers a light (too light) SM Higgs

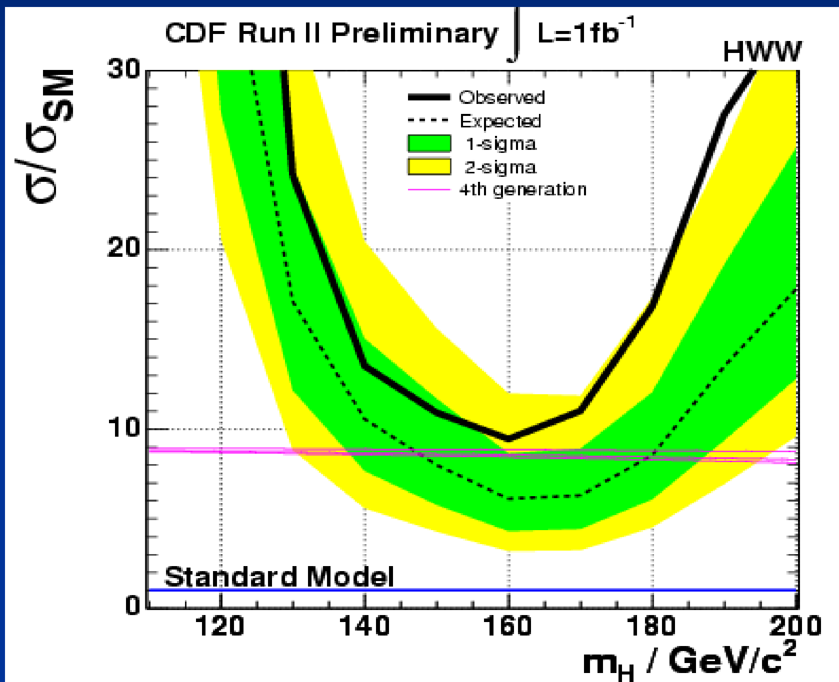
Puts a High Premium on Measuring Mtop and MW precisely, no matter what happens at the LHC (really diff. systematics at Tevatron.)

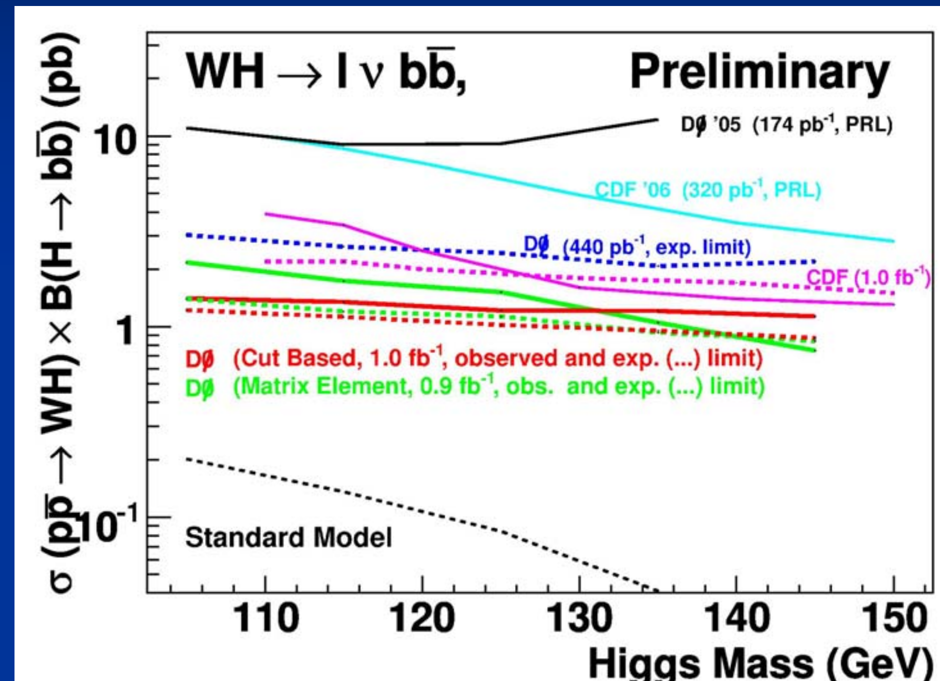
Direct Limits on SM Higgs



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

Direct Limits on SM Higgs-cont.





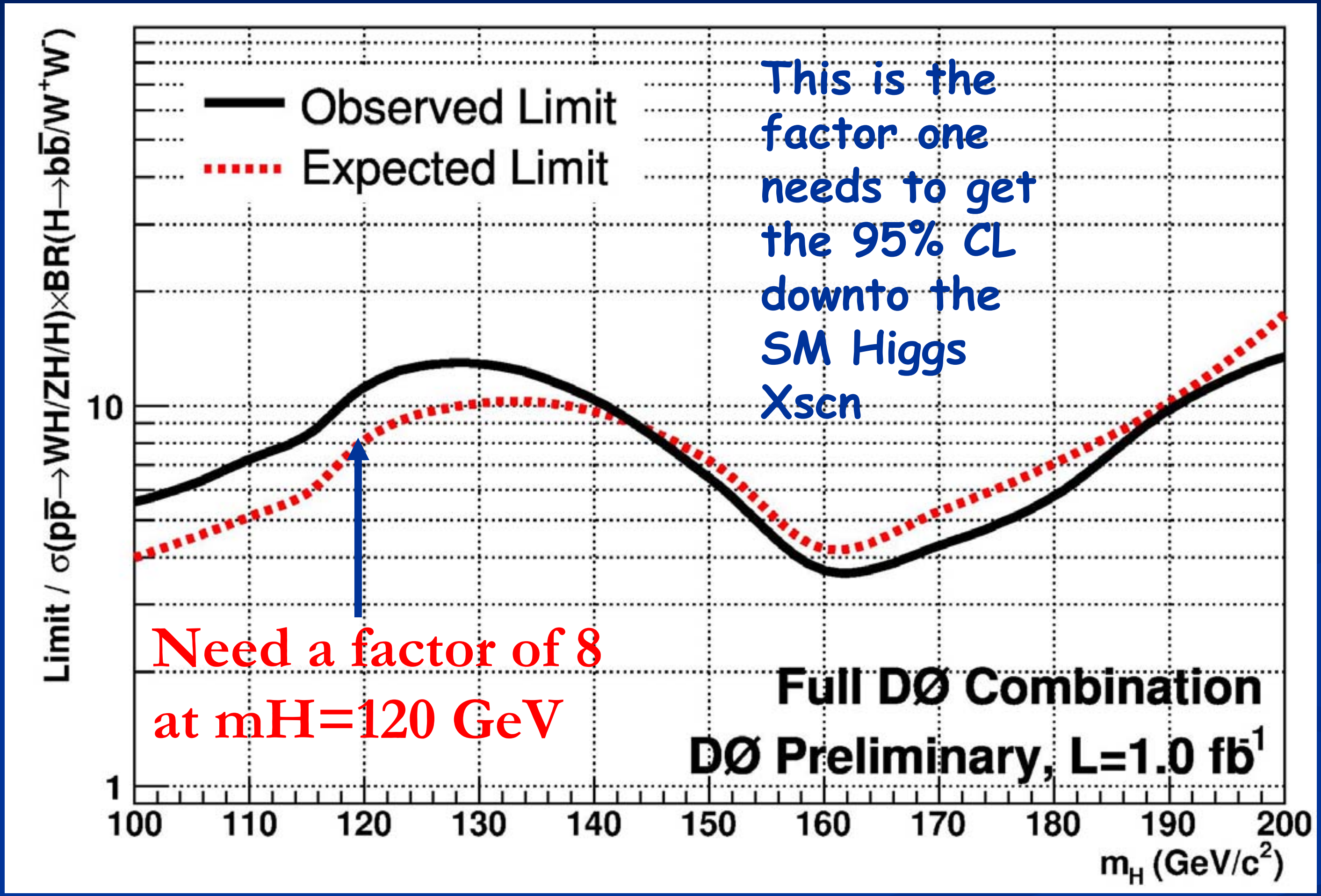
CDF has recently (1/31/07) updated high mass region

D0 has recently (3/12/07) updated low mass region

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,…

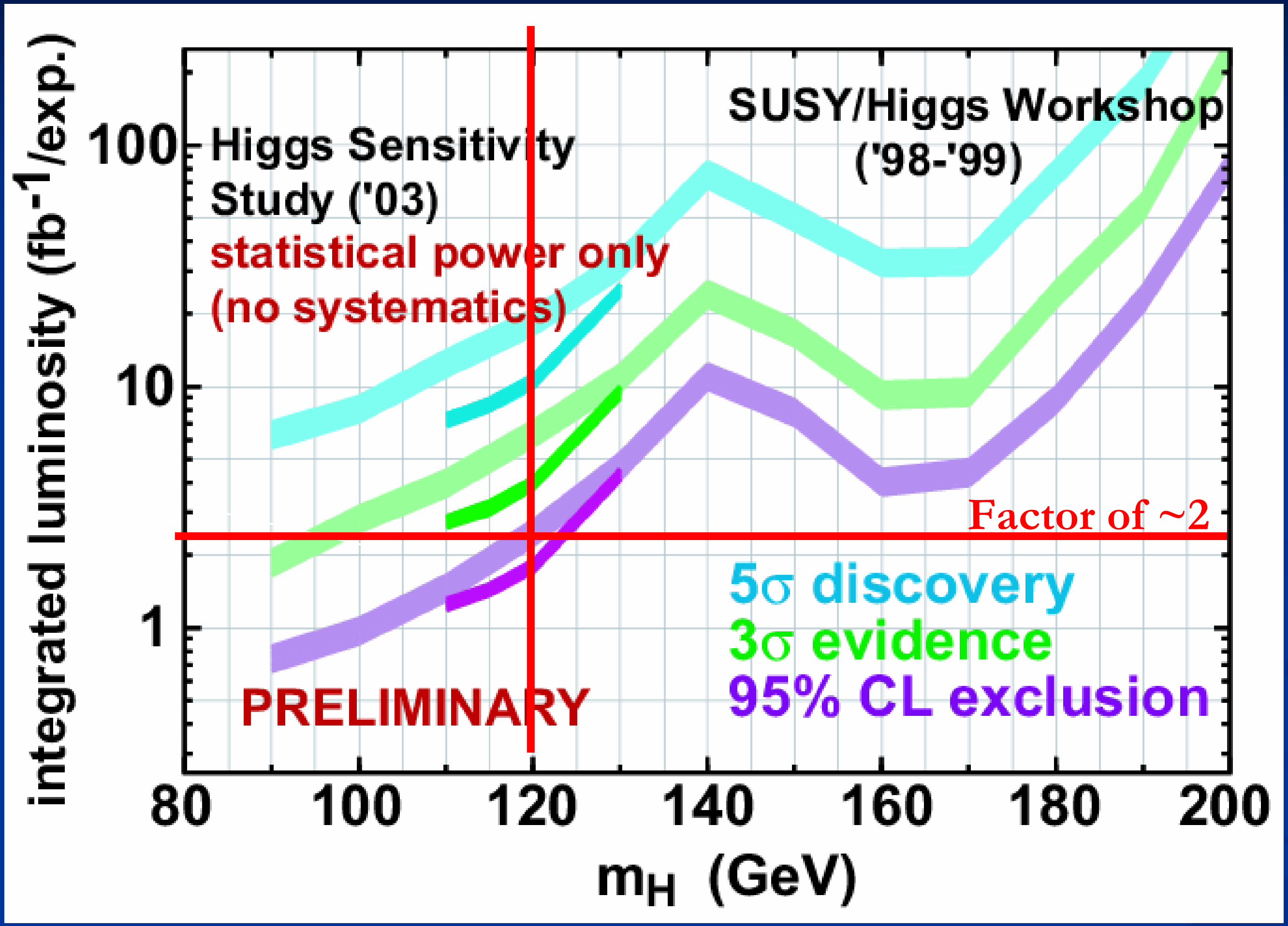
Direct Limits on SM Higgs-cont.

New (April 6) D0 combined limit (no CDF/D0 comb. yet)



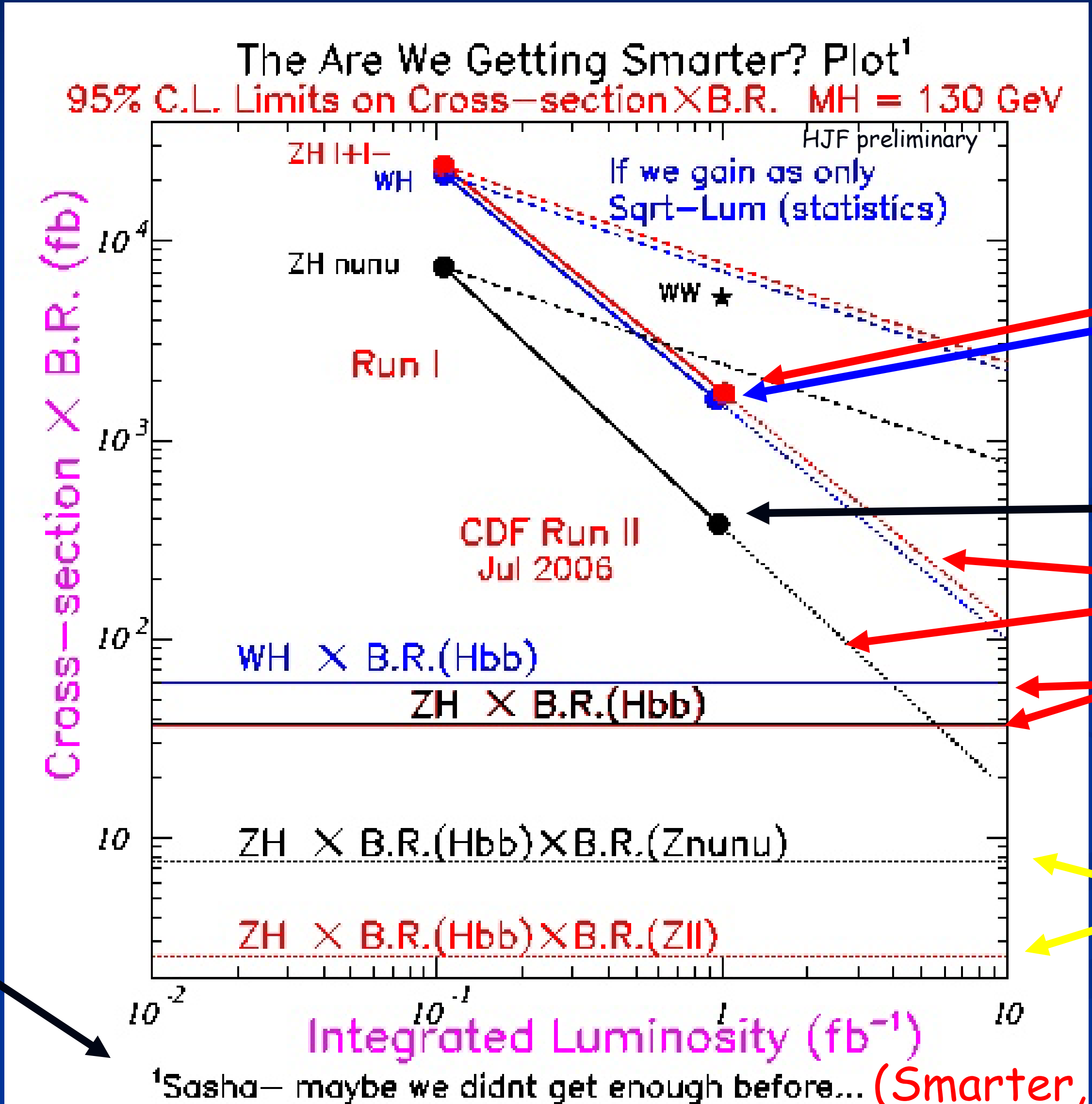
With 5X the data and X 2 Expts the expected limit covers the entire region up to 190 GeV even with no improvements in tools.We expect to improve the tools..

Compare to Early Higgs Estimates



Overly optimistic given present state-of-the-art-
There are possibly large factors to be gained, however
(jet resolution, triggers,…)- this is the present challenge at the Tev.

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



(Smarter, that is)

Z Hll, WH *BR(Hbb)

Z Hnunu

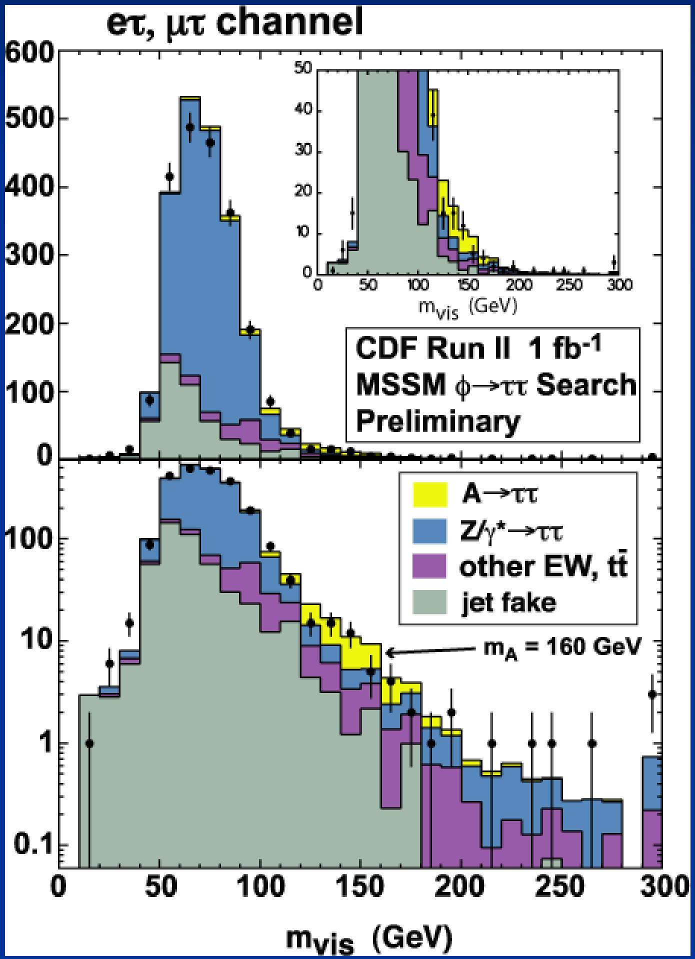
Not guaranteed!!

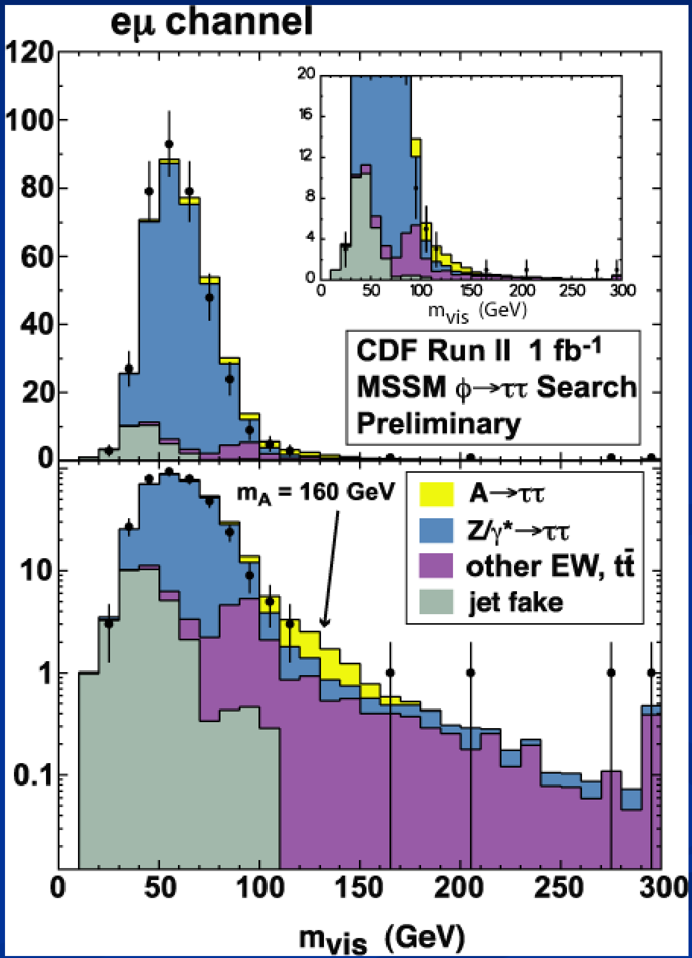
Xsctns to compare to

ev/fb produced

Comment from already smart Russian grad student on seeing plot

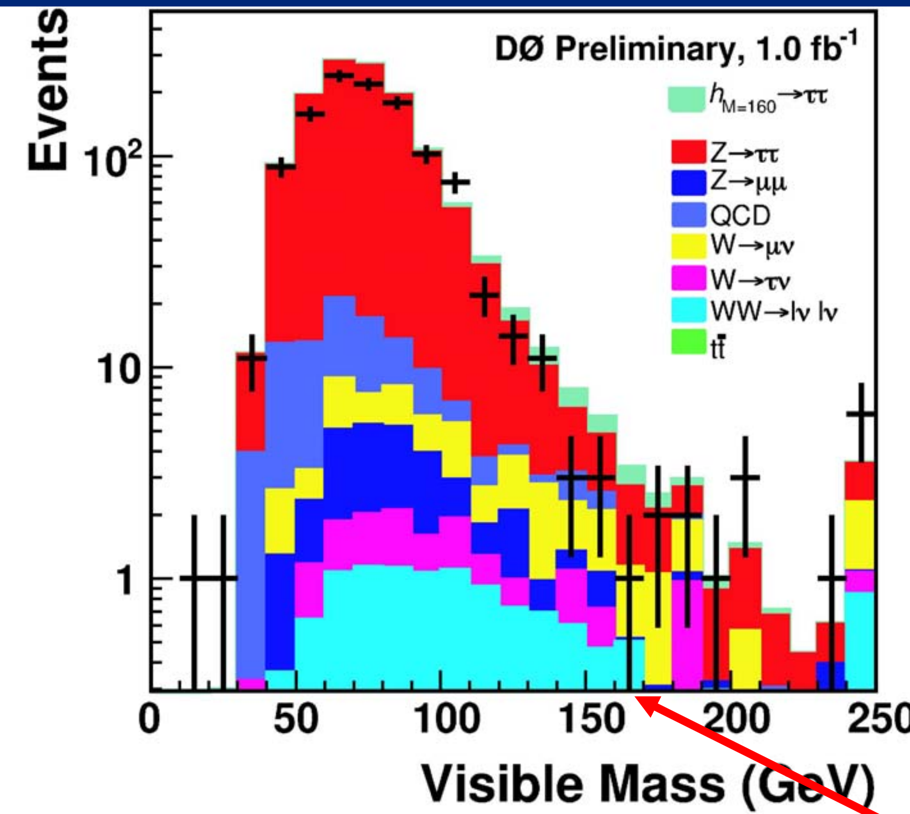
Recent Measurement in τ–τ Channel- CDF

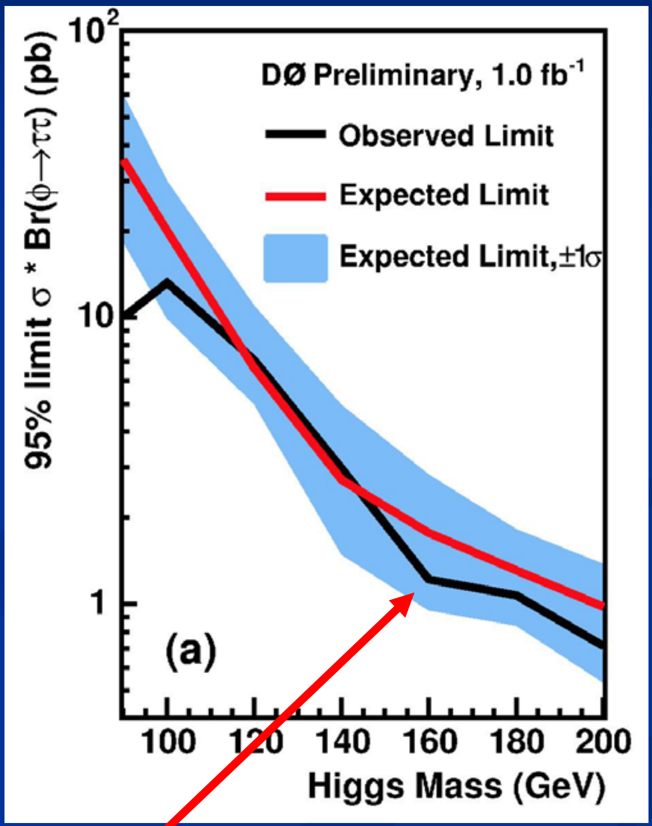




"The Excess is not Statistically Signficant- We need more data…before we draw any conclusions"- CDF

Recent Measurement in τ–τ Channel- D0

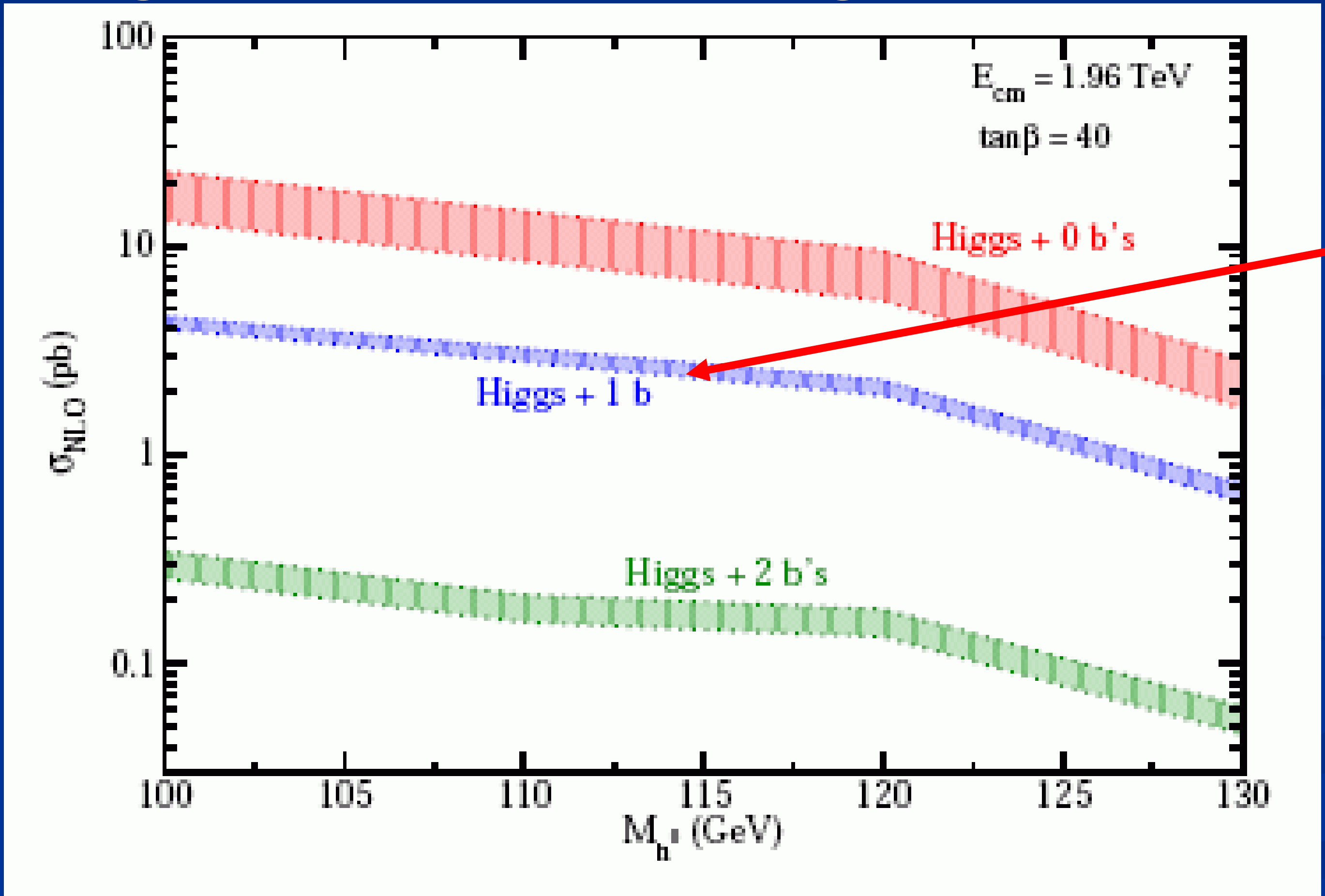




D0 has a dip at 160 in the same channel. (It pays to be patient and hang in there on the Higgs- a learning process…)

Pbar-p ->bbh, -> 4b's

MSSM Higgs Sector is complicated, but in many regions of space get a SM-like H, but with a possibly larg tan(β)-squared enhancement (see, e.g. Carena, Menon, and Wagner- arXiv:0704.1143 (Apr. 07)

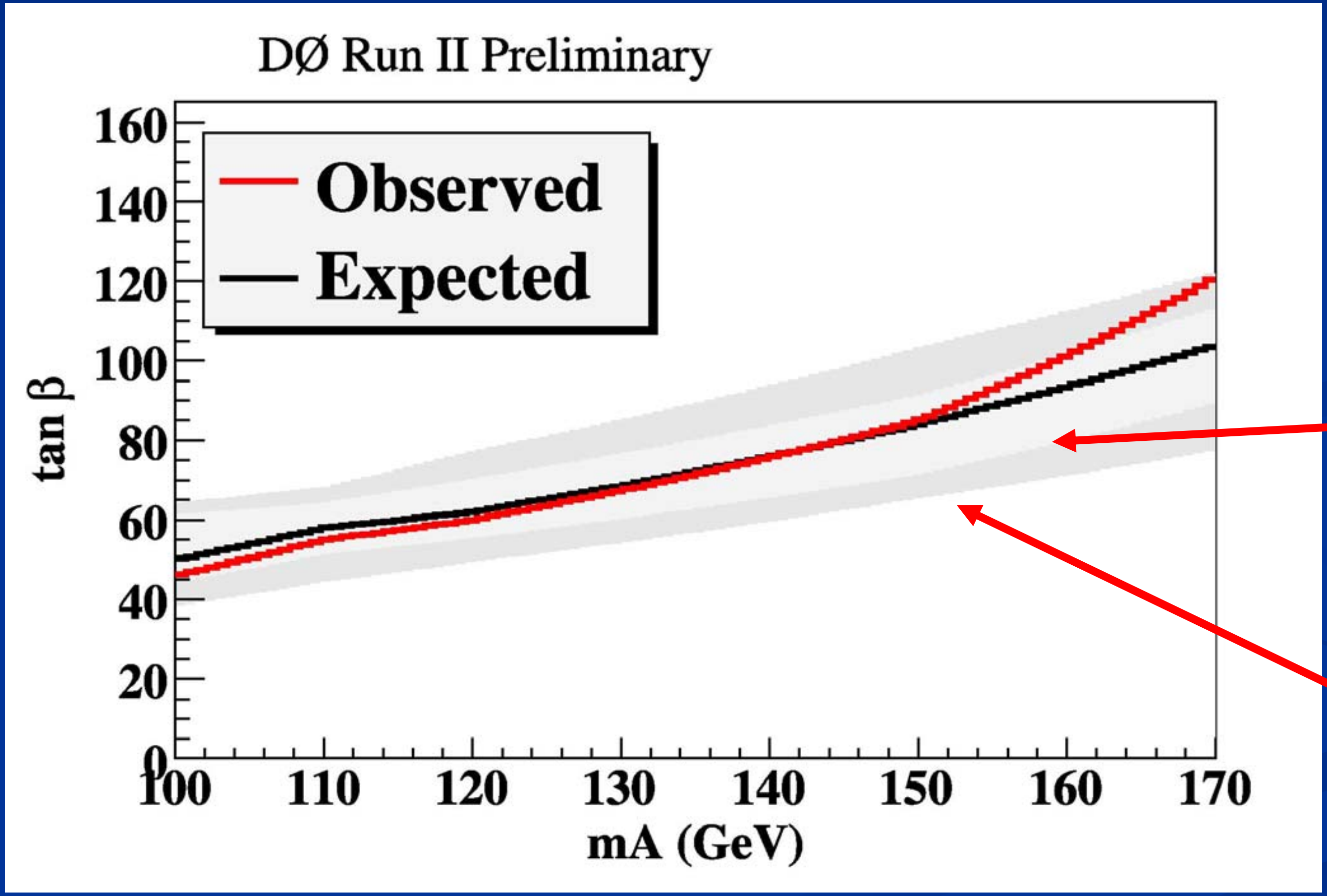


Tag the 1 b from production- look for 2 b's from the Higgs

Dawson, Jackson, Reina, and Wackeroth; hep-ph/0603112

Pbar-p ->bbh, -> 4b's

MSSM Higgs Sector is complicated, but in many regions of space get a SM-like H, but with a possibly large tan(β)-squared enhancement



D0 limit (old) from July 2006

1σ on 95% limit (??)

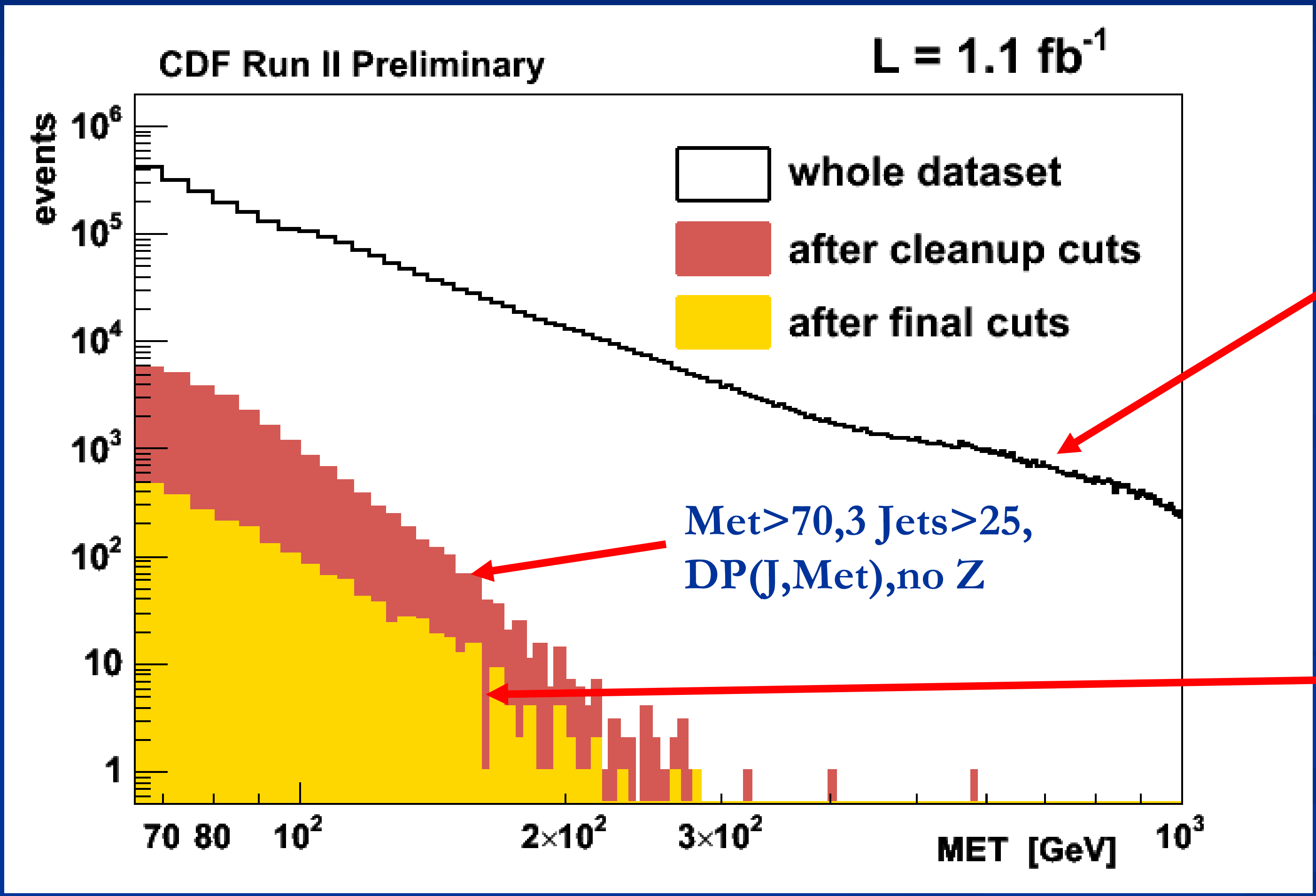
2σ on 95% limit (??)

Searching for SUSY

- See `A Supersymmetry Primer’ by S. Martin; hep-ph/9709356 for a really nice intro to SUSY
- Many (>100) parameter space- decay chains of heavy sparticles have many possibilities (e.g. the photon story)- `You could be up to your navels in SUSY and never know it’- C. Prescott
- However there are popular `golden’ modes-
  - squark and gluino (strongly produced) into met+jets
  - Chargino-neutralino (weakly produced) into trileptons

Met+Jets Squark/Gluino Searches

Select Events with Missing Et (Met), 3 jets, and large HT (total Et of the jets)-

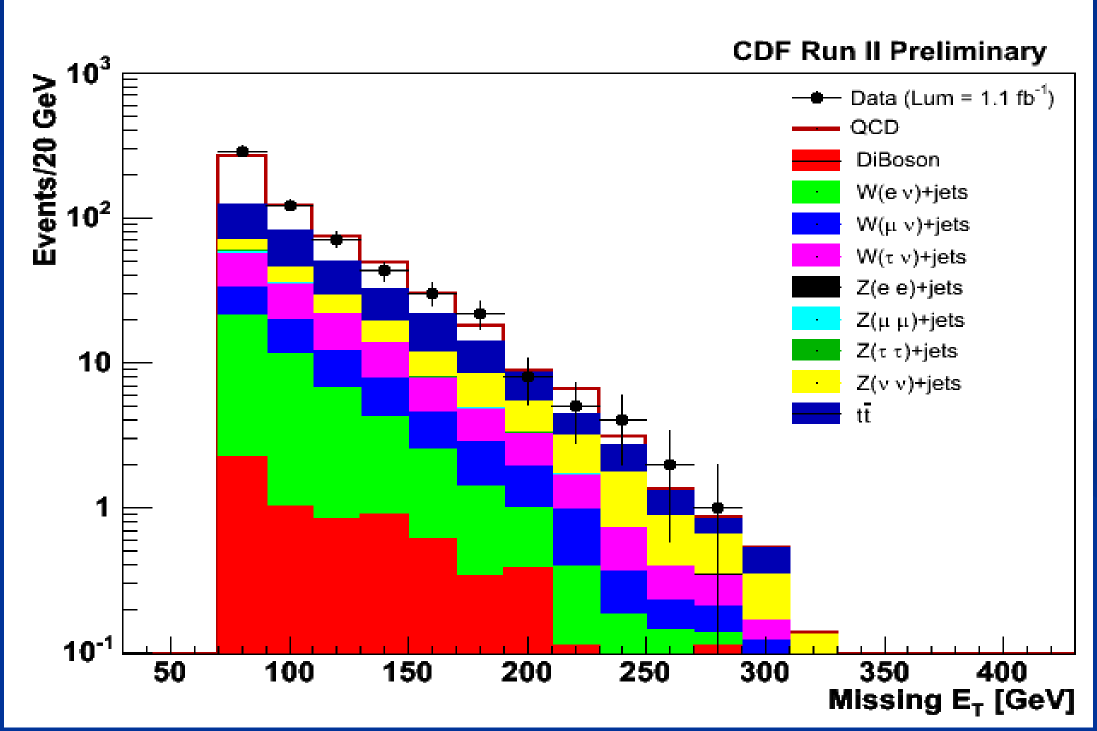


Jet Triggers

Met	HT	Jet1	Jet2
75	230	95	55
90	280	120	70
120	330	140	100

Met+Jets Squark/Gluino Searches

Data vs Expectations(SM theory only)

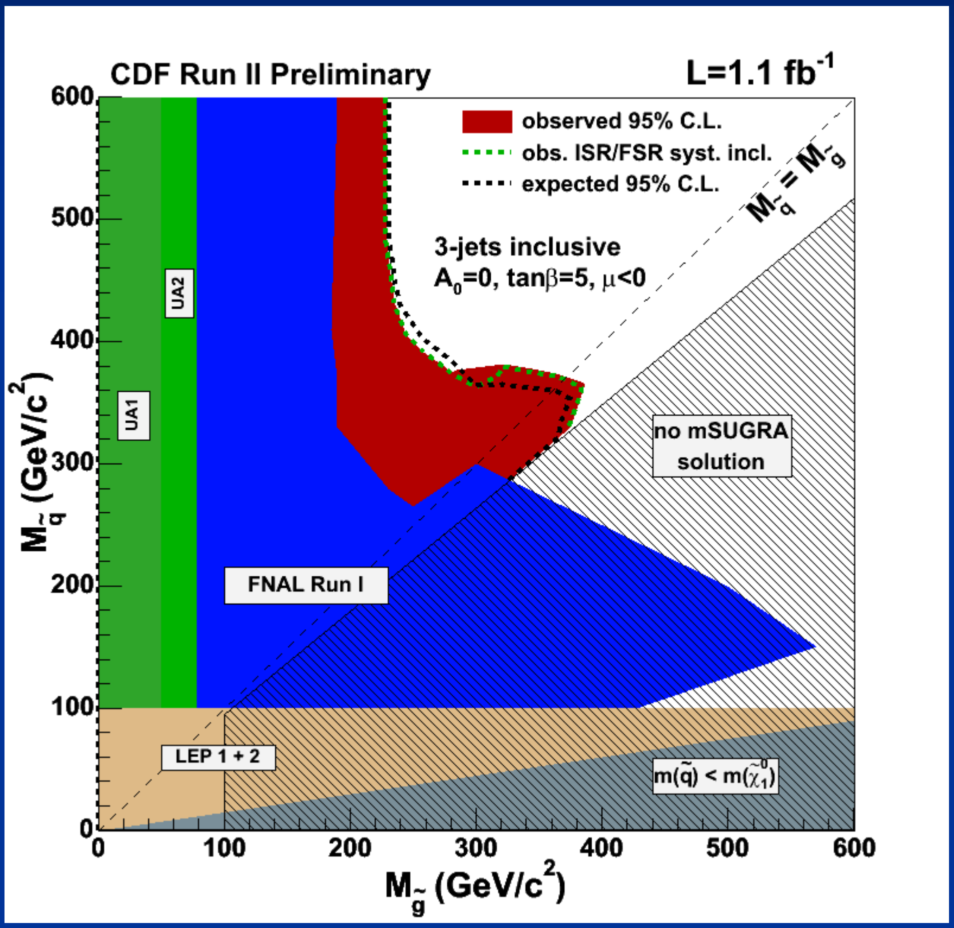


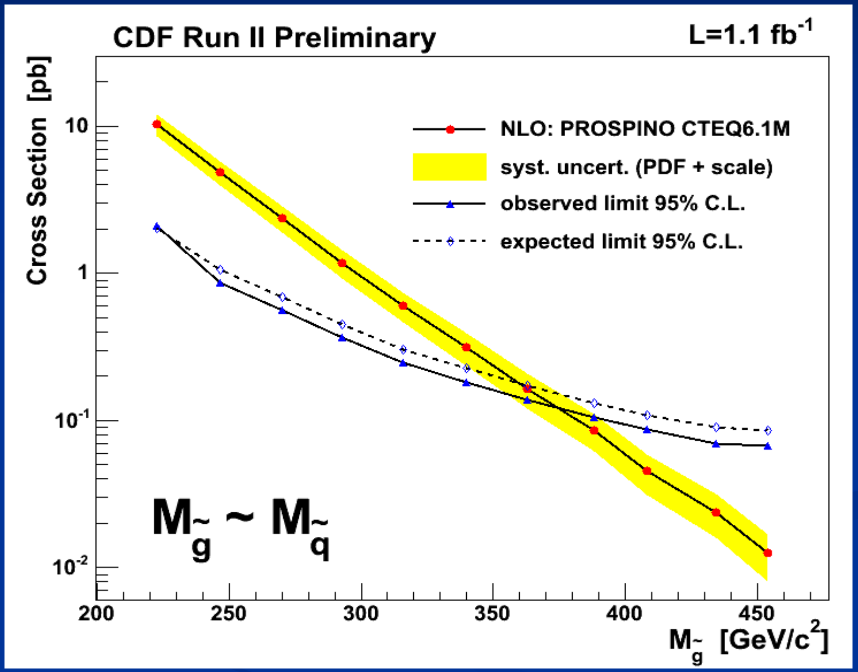
events in 1.1 fb^{-1}	DATA	SM Expected
Type A	494	486 ± 17 (stat.) ± 101 (syst.)
Type B	136	129 ± 8 (stat.) ± 31 (syst.)
Type C	17	20 ± 2 (stat.) ± 5 (syst.)

Missing Et spectrum vs SM expectations

Expected (SM) vs Observed in 3 regions)

Met+Jets Squark/Gluino Searches





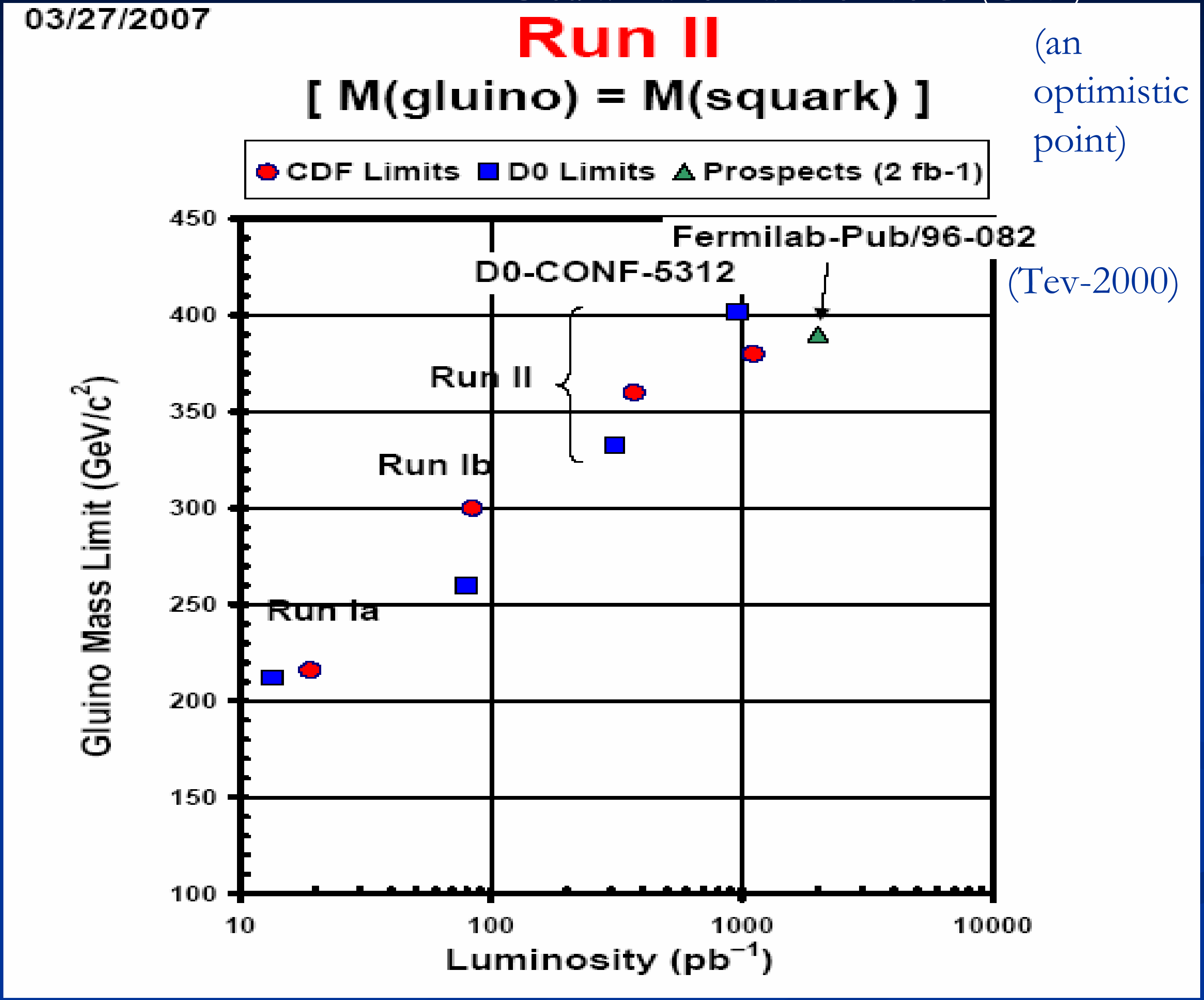
Limit Plot at one point (the diagonal)

One Point in a 100+ dimensional space

(I don't understand such plots… much prefer simpler comparisons, e.g. vs the pair QCD cross-section for heavy quarks..)

2 fb^{-1} Prospects (caveat emptor)

Credit: Mario Martinez-Perez (CDF)



(an optimistic point)

(Tev-2000)

Chargino/Neutralino Searches

Signature is 3 leptons (think W-Z, with twiddles: one (of many searches) is for 2 same-sign leptons

Ask for 2 SS leptons, Et>20,10, Mll>25

Met>15, no Z(ee) or Z(mumu)

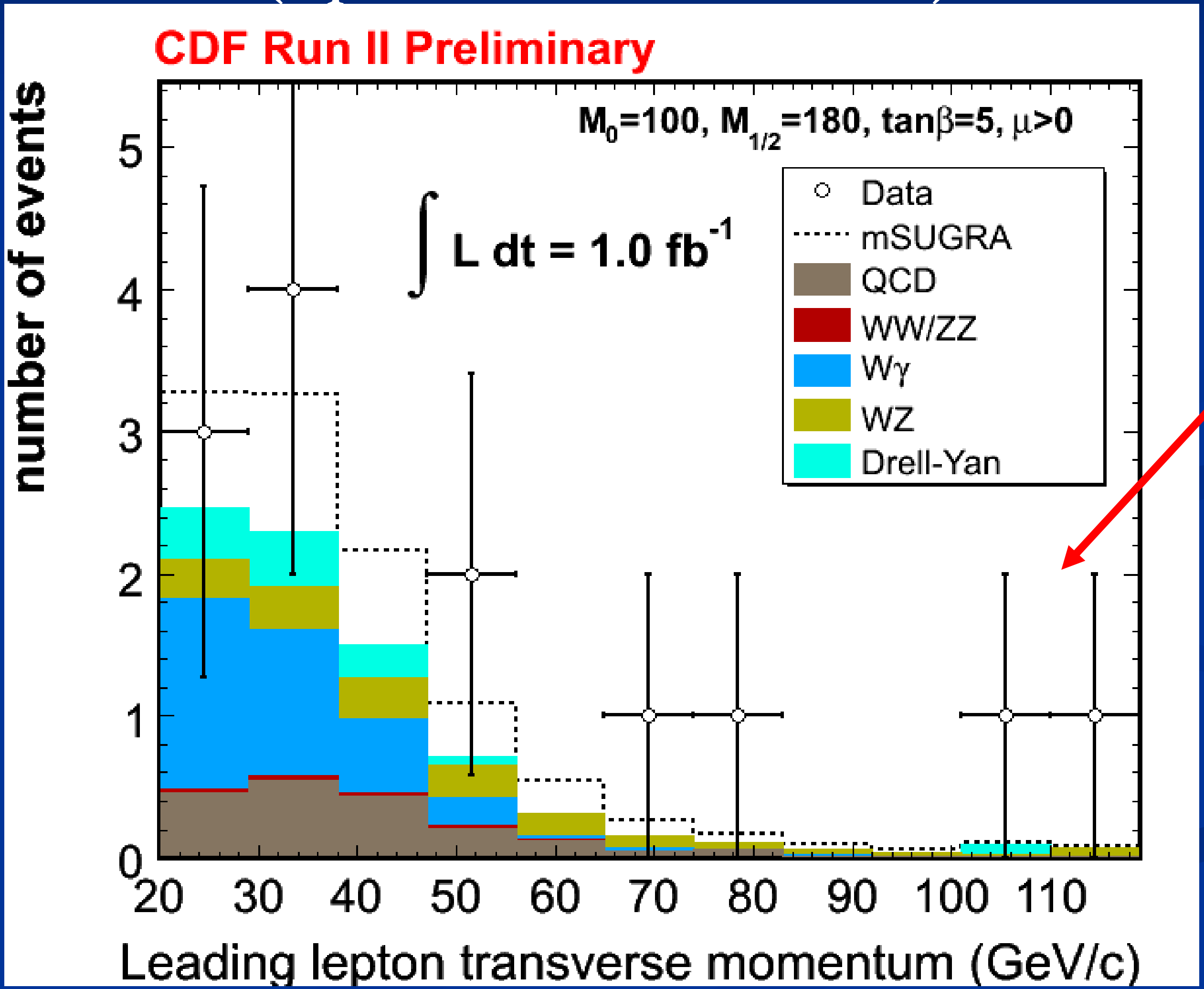
Expect 8, see 13

Category	Observed	Predicted	±σ	Drell Yan	Wγ	Diboson	ttbar	Fakes
e_si e_si	1	1.3	0.2	0.4	0.6	0.0	0.0	0.4
ee	1	0.1	0.0	0.0	0.1	0.0	0.0	0.0
e_si e	2	1.5	0.2	0.1	1.2	0.0	0.0	0.2
e_si μ	4	1.7	0.2	0.0	1.0	0.1	0.0	0.7
e μ	4	2.3	0.4	0.6	1.4	0.0	0.0	0.2
μ μ	1	0.9	0.1	0.0	0.5	0.1	0.0	0.4
sum	13	7.9	1.0	1.1	4.7	0.2	0.0	1.9

Tighter: Results for two leptons of the same sign, with a MET>15 GeV and Z veto requirement. Errors are statistical and systematic, combined.

Chargino/Neutralino Searches

Pt of leading lepton has some events on tail - electrons- interesting, and now cuts are set… (a priori better than blind!)

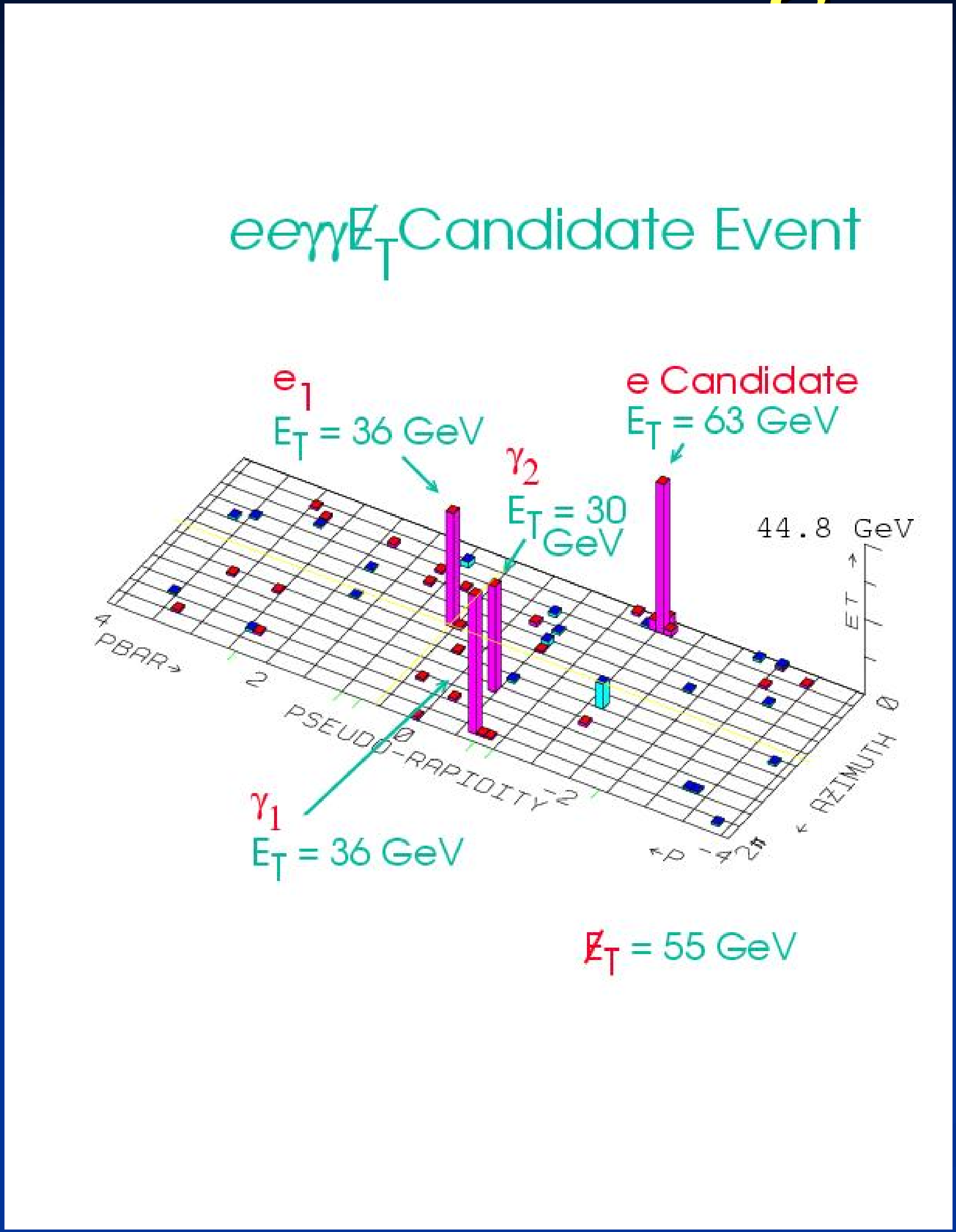


Note Events on tail…

Searching for GMSB

- Photons (gammas) from Photino decay are characteristic- LSP is typically a light Gravitino
- Have diphoton and single photon trigger paths, so one has event samples with $\gamma\gamma$+X, γ+X.
- Photon identification relies on an EM cluster, shower shape (transverse and longitudinal), and no track
- Backgrounds are from pizeros, etas, photons in jets => use isolation
- Pure background samples don't exist- Compton diagram gives photon+jet events in jet samples.

Searching for GMSB



\`Famous' eeggmet Event from CDF- way out on tail of many distributions- 2e, 2gamma, and met distributions. Large Ht too..

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

RunI eegammagamma+met event;

also,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…"

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

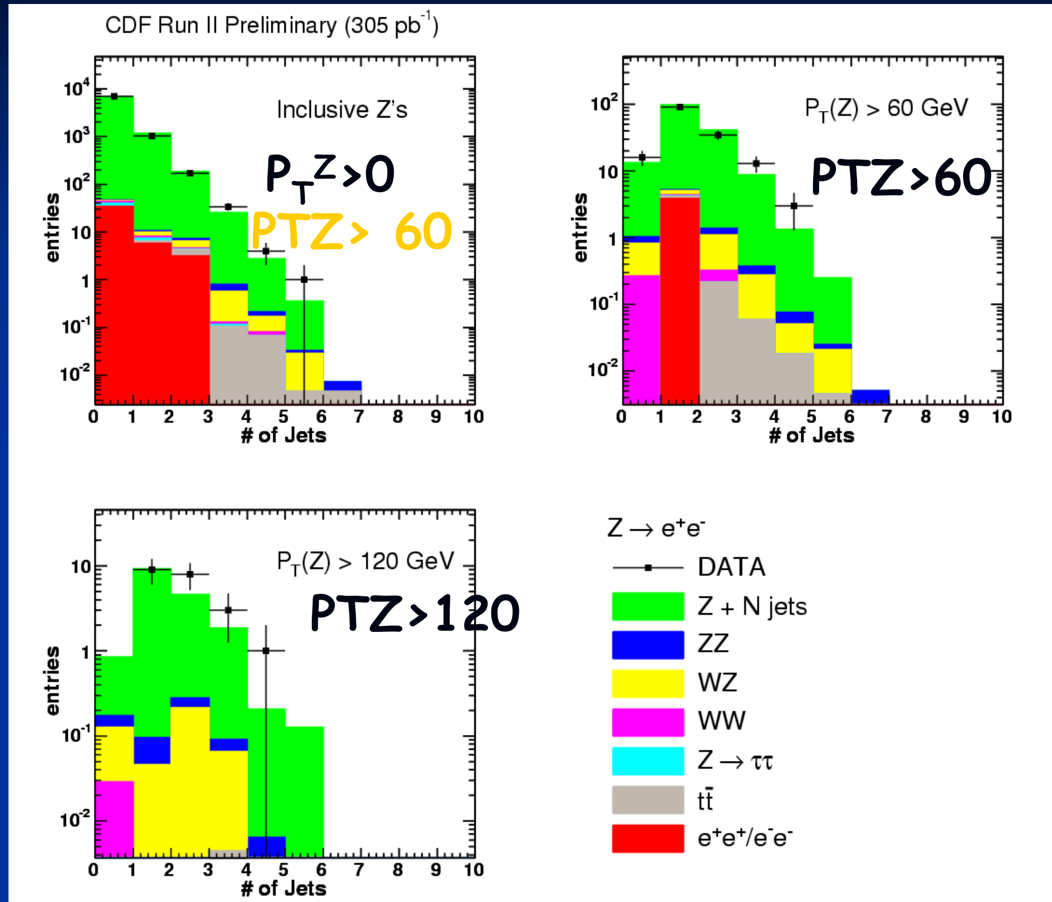
CDF Run II Preliminary, $929pb^{-1}$

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
$Z^0 \rightarrow e^+e^-, e \rightarrow \gamma$	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



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).

Signature-Based High Pt Z+X+Y

Simple Counting Expt- ask for a Z + one object, or Z+ 2objects

One Object

X	Observed	Expected
Lepton	3	1.6
Photon	14	12.4
Missing Energy	97	85.4
Ht	45	36

Z+X+anything

Two Objects

X+Y	Observed	Expected
Lepton+Photon	0	0.001
Lepton+Missing Energy	0	0.8
Lepton+Ht	0	0.14
Photon+Missing Energy	0	0.19
Photon+Ht	0	0.28
Missing Energy+Ht	6	3.5

Z+X+Y+anything

Communicating results of searches to Theorists

Proposal (R. Culbertson et al, Searches for new physics in events with a photon and b-quark jet at CDF. Phys.Rev.D65:052006,2002. hep-ex/0106012)- Appendix A:

3 Ways:

- A. Object Efficiencies (give cuts and effic. for e, mu, jets,b's. met,....
- B. Standard Model Calibration Processes (quote $W\gamma$, $Z\gamma$, $W\gamma\gamma$ in $l\gamma$met,e.g..)
- C. Public Monte Carlos (e.g. John Conway's PGS)

True Acceptnce | **Ratios to True (ABC)**

Model	M_s	BR(%)	A	$A\cdot\epsilon$	R_{obj}	R_{WW}	R_{SHW}
GMSB $M_s = M_{\tilde\chi_1^\pm}$	130	3	65.0	27.50	2.79	3.03	1.07
	147	20	49.8	7.45	0.91	1.00	0.70
	170	23	51.7	8.35	0.97	1.00	0.87
	186	18	54.7	11.44	1.26	1.22	1.11
$\tilde\chi_2^0 \to \gamma\tilde\chi_1^0$ $\tilde q, \tilde g$ production $M_s = M_{\tilde g}$	185	30	17.0	1.97	0.91	0.68	0.48
	210	30	22.0	2.98	1.04	0.73	0.90
	235	30	24.0	3.23	1.01	0.68	0.90
	260	30	24.5	2.69	0.82	0.52	0.75
	285	30	19.7	2.16	0.84	0.48	0.72
$\tilde\chi_2^0 \to \gamma\tilde\chi_1^0$ $\tilde q, \tilde g$ production $M_s = M_{\tilde\chi_2^\pm}$	110	100	13.5	0.93	0.54	0.54	0.59
	130	100	12.6	1.41	0.88	0.80	0.87
	140	100	14.8	1.29	0.68	0.60	0.66
	150	100	13.7	1.34	0.77	0.65	0.78
	170	100	11.5	1.27	0.85	0.68	0.65

TABLE XIX. The results of comparing the methods of calculating $A\epsilon$ using the model-independent methods and the rigorously-derived $A\epsilon$. Each row is a variation of a model of supersymmetry as indicated by the label in the first column and the mass of a supersymmetric particle listed in column two (GeV). The column labeled A is the acceptance of the model in % and the next column is the rigorously-derived $A\epsilon$. The columns labeled with R are the ratios of the rigorously-derived $A\epsilon$ to $A\epsilon$ found using the model-independent method indicated.

Comparison of full MC with the 3 methods:

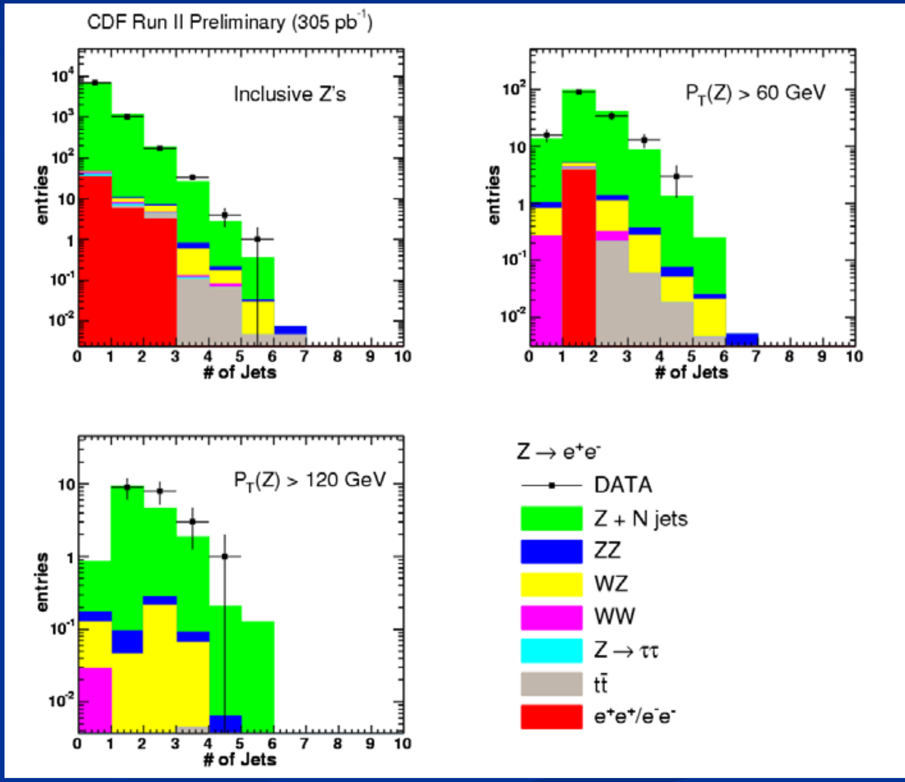
Conclusion- good enough for most applications, e.g. limits…

Case for gamma+b-quark+met+x (good technisig)

Tools needed at the Tevatron (20 yrs later)

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…')

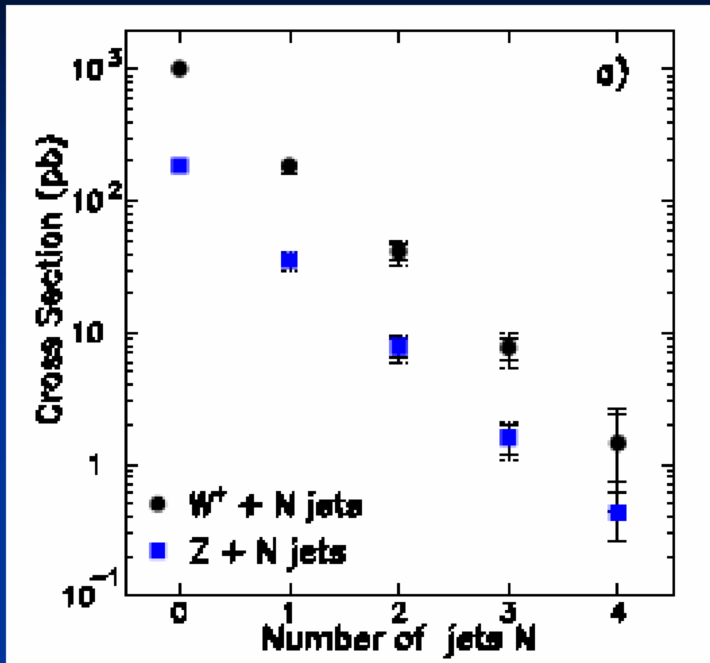


HT for P_T^Z>0, P_T^Z> 60, and P_T^Z>120 GeV Z's: ee (Left) and $\mu\mu$ (right)

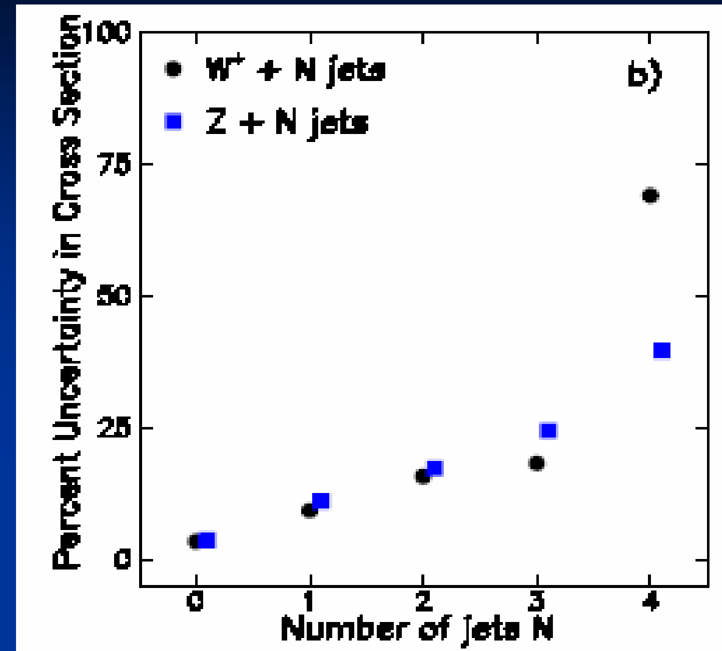
Really hard Problems (among many) my ideosyncratic and arguable list

1. How to get the systematics of W+jets and Z+jets (and γ+jets) predictions down to SUSY levels (pb from nb)
2. QED and QCD ISR together at high accuracy
3. Luminosity book-keeping- a nightmare
4. Orthogonal sensible object ID
5. Underlying event, trigger biases, …
6. Following the quark (flavor) flow by particle ID

Problem of Njets (W+Nj,Z+Nj)



Crossection vs number of jets in W and Z events



% uncertainty vs number of jets in W and Z events

Event and W Properties		W/Z Ratio Method Reach	
N(Jets)	σ_W	σ_{new} 2 fb^{-1}	σ_{new} 15 fb^{-1}
0	1896 pb	20 pb (1.0%)	20 pb (1.0%)
1	370 pb	4.4 pb (1.2%)	3.7 pb (1.0%)
2	83 pb	1.5 pb (1.8%)	0.9 pb (1.1%)
3	15 pb	0.5 pb (3.5%)	240 fb (1.6%)
4	3.1 pb	230 fb (7.5%)	95 fb (2.9%)
5	650 fb	100 fb (16%)	40 fb (6%)
6	140 fb	50 fb (36%)	18 fb (13%)
7	28 fb	20 fb (78%)	8 fb (29%)
8	6 fb	——	4 fb (63%)

So, switch to a measurable that is more robust: look for new physics by precise measurements of (W+Njets)/(Z+Njets)

Systematics at few % level (PRD68,033014;hep-ph/030388

The attraction of hardware upgrades

- 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

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

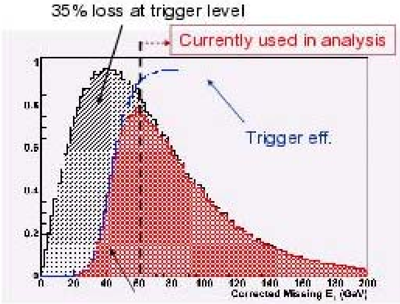


Figure 12: Expected signal shape as a function of corrected $\not{E}_T$ of the SM Higgs assuming $M_H = 120$ GeV for the Higgs search in the $ZH \rightarrow \nu\nu bb$ channel. The blue curve shows the efficiency of the trigger requiring MET and two jets currently used, and the red histogram shows the 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.

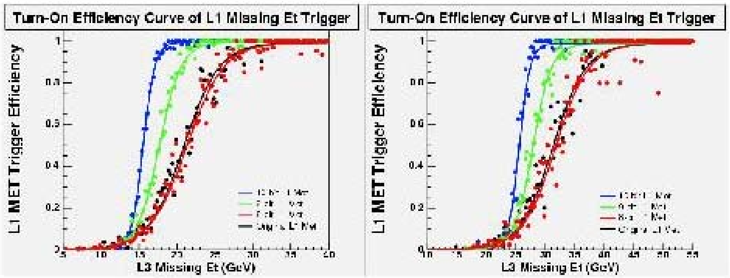
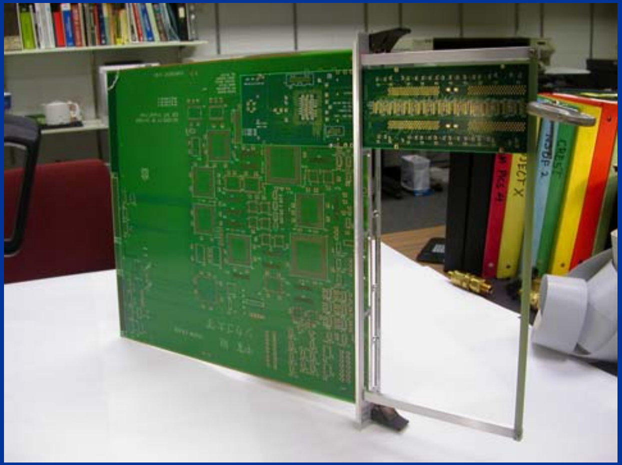


Figure 13: L1 MET trigger efficiency of (*left*) $\not{E}_T > 15$ GeV and (*right*) $\not{E}_T > 25$ GeV cuts for 8 (current), 9, and 10 bit precision of the MET calculation. L1 MET25 is currently used in the MET+2JET and inclusive MET triggers. The proposed upgrade will provide 10-bit precision at Level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

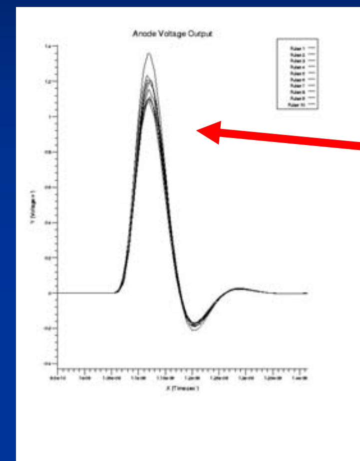


L2Cal Upgrade Group – new Cluster finder algorithm/hdwre

The attraction of hardware upgrades

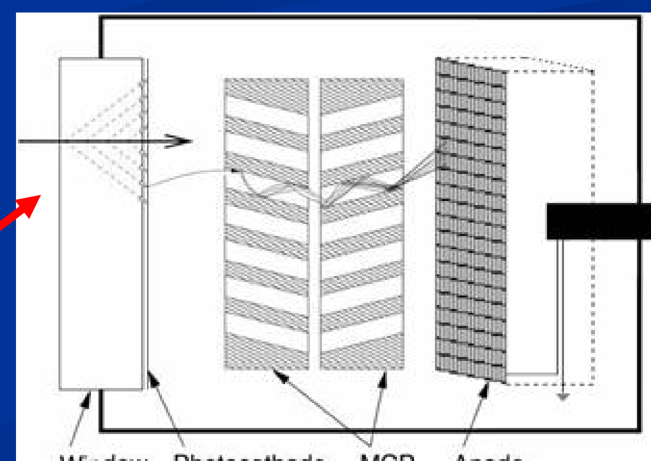
(this is a little over the top- ignore it if you want to, please)

- 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 $\sigma <=$ 1 psec:



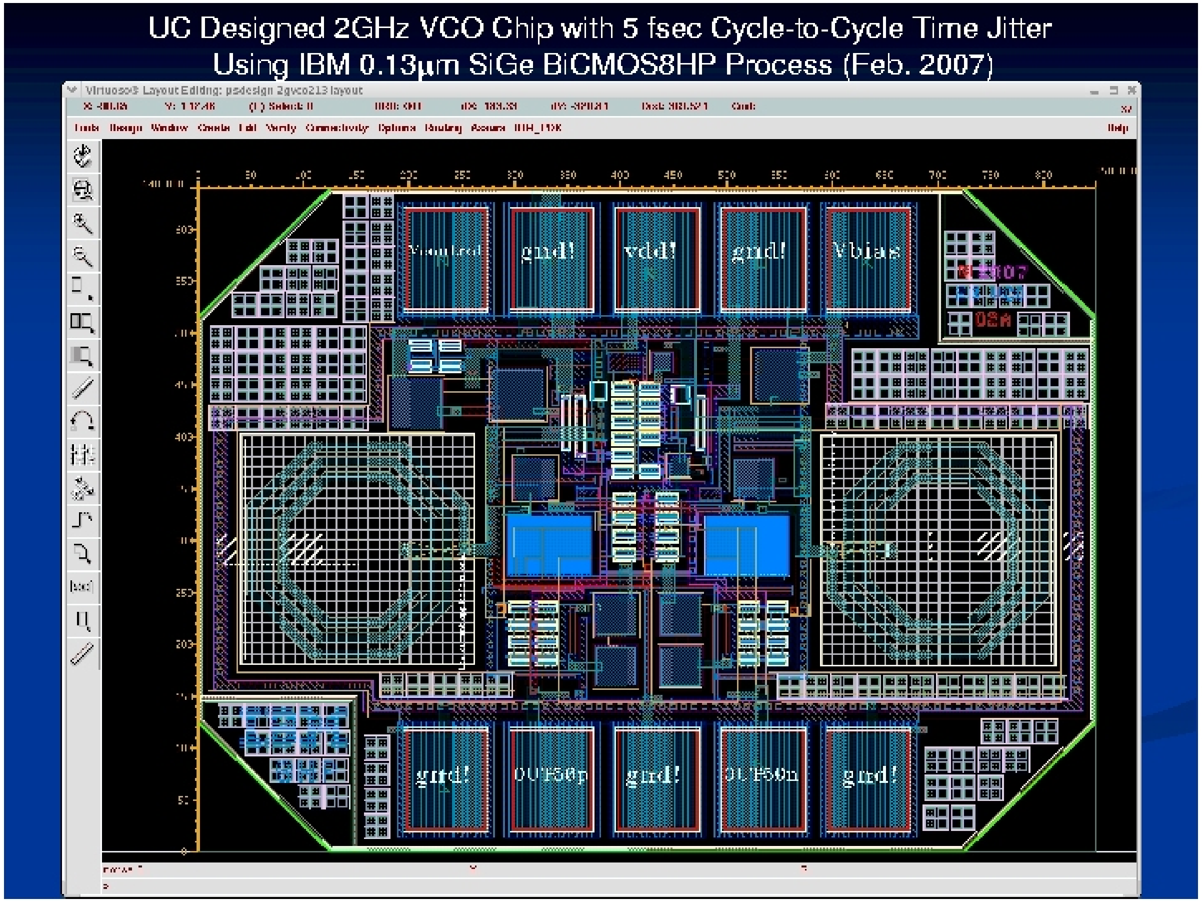
Collect signal here

Incoming particle makes light in window:



Micro-channel Plate/Cherenkov Fast Timing Module

Electronics for TOF measurements:

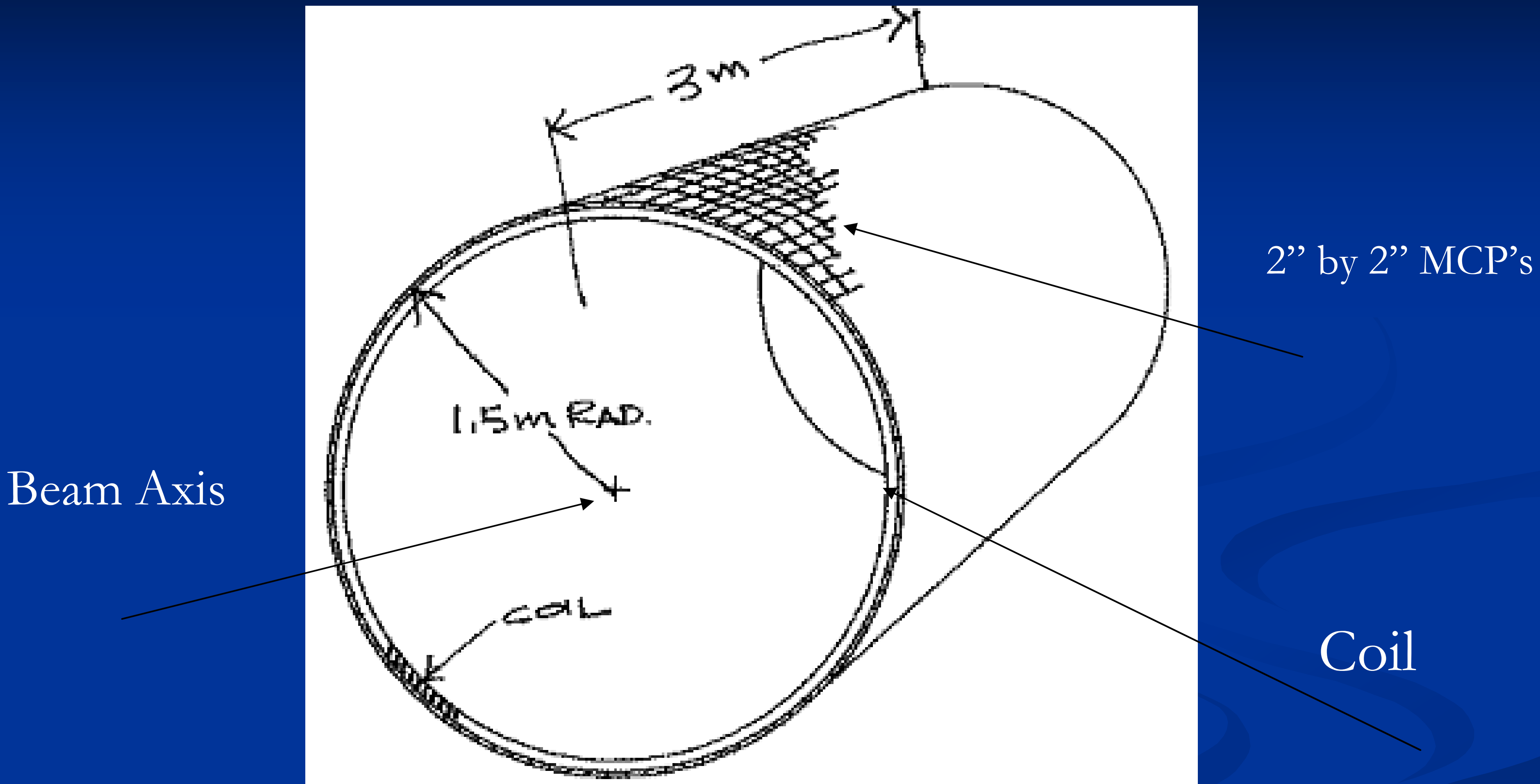


Most Recent work-

IBM 8HP SiGe process Fukun Tang (EFI-EDG)

3a. Oscillator with predicted jitter ~5 femtosec (!) (basis for PLL for our 1-psec TDC) .

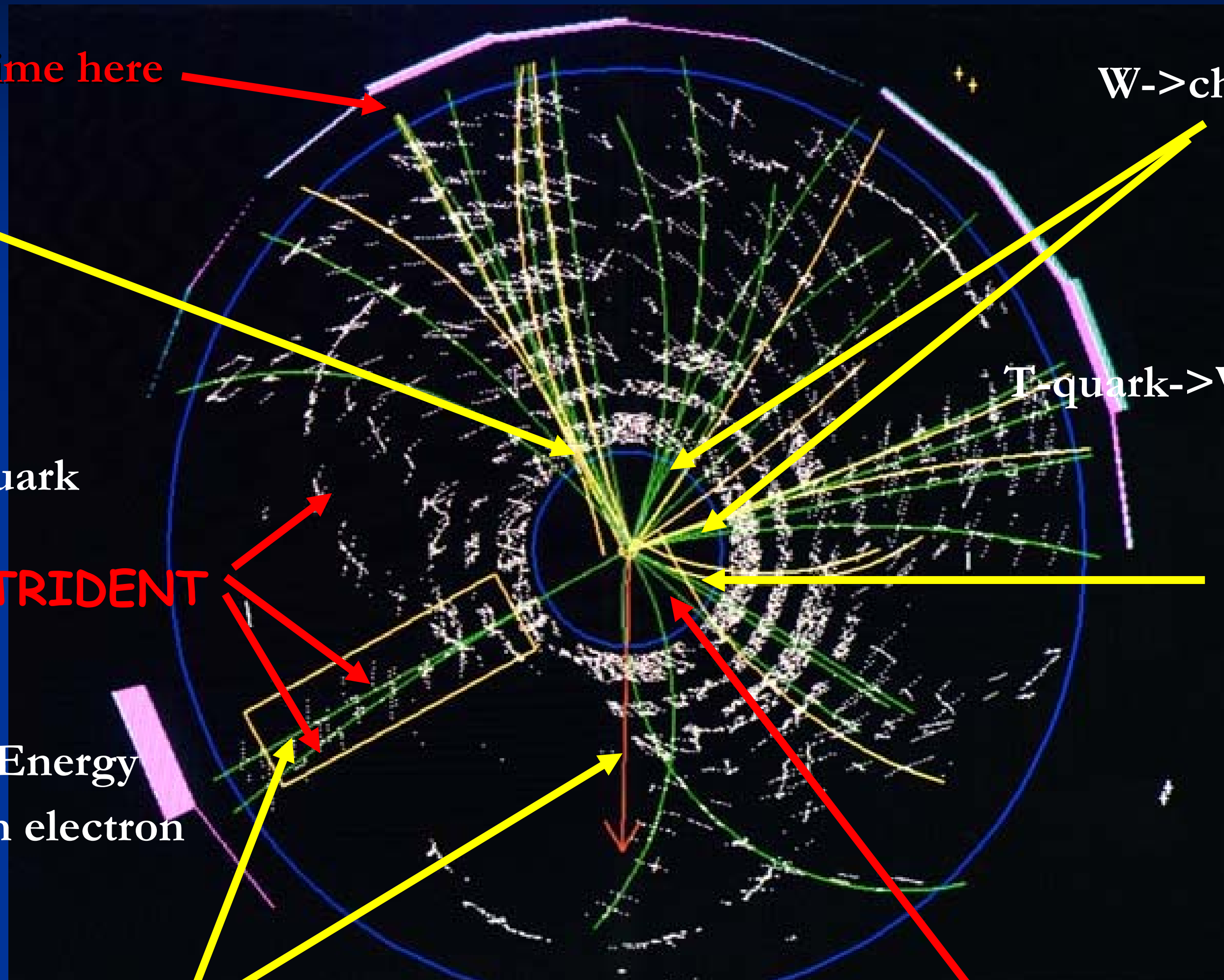
Geometry for a Collider Detector



"r" is expensive- need a thin segmented detector

A real CDF Top Quark Event

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



Fit t_0 (start) from all tracks

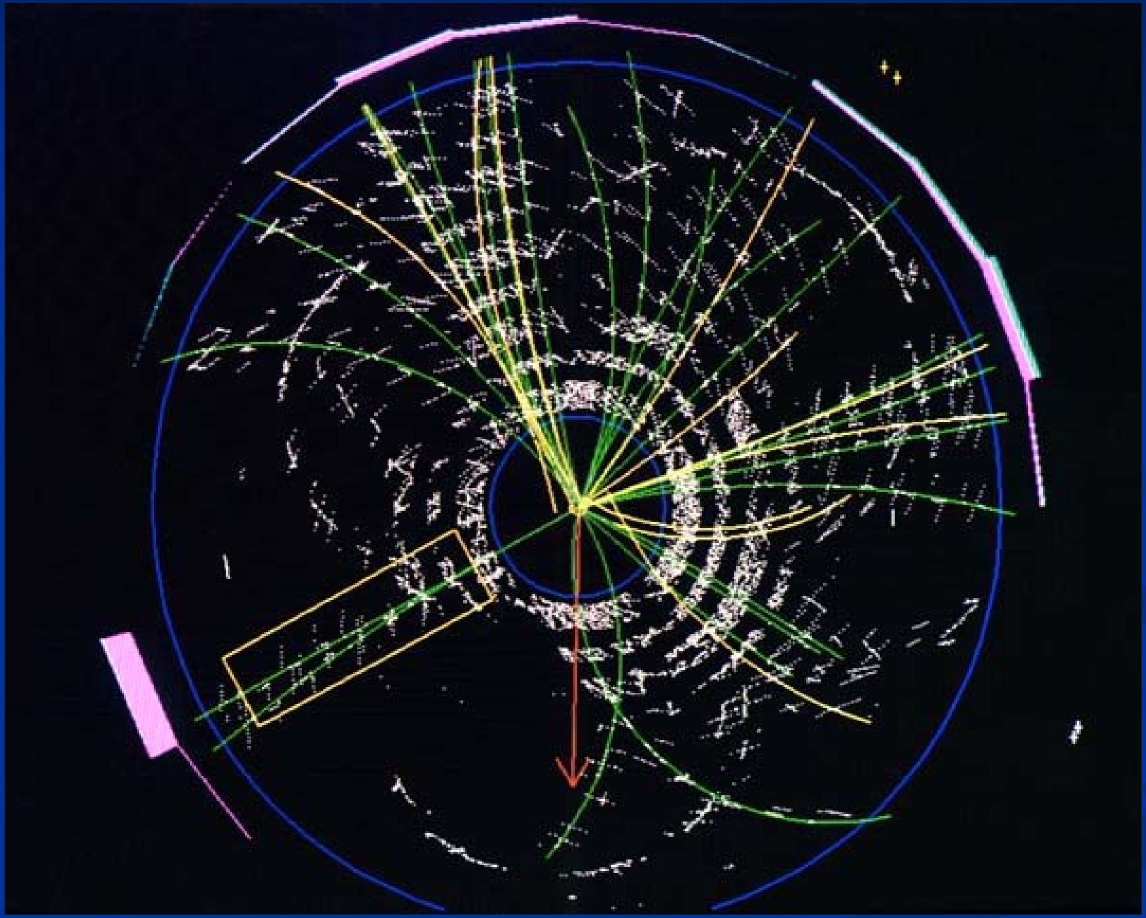
Can we follow the color flow through kaons, charm, bottom? TOF!

Summary of Tevatron Now

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 statistics-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!)

The End

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

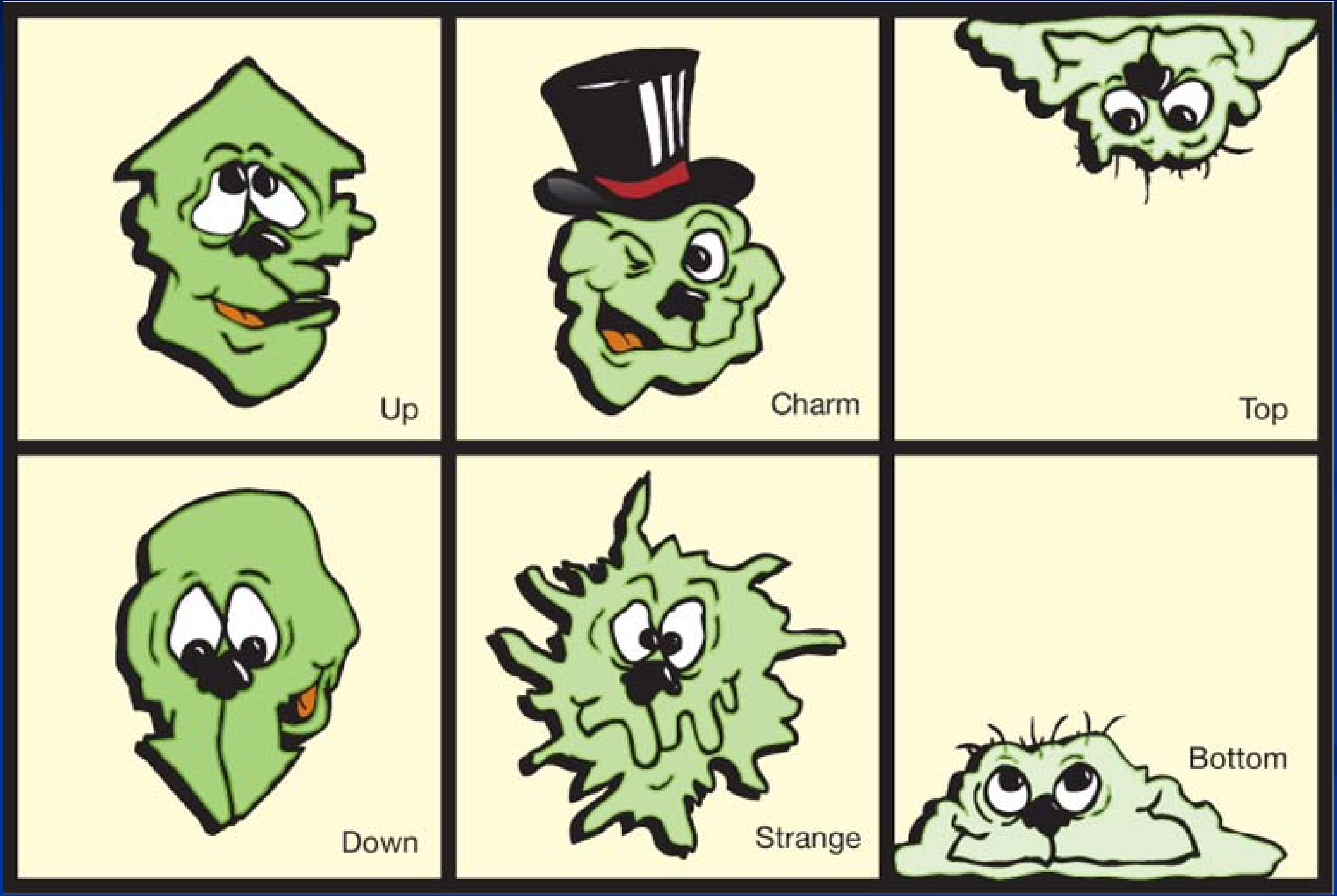


Come join us looking- at least for a while it's still the best place in town to learn the trade with real data- complements the (tremendous) fun of commissioning a new detector…

Referemces:

And Many Thanks to the Organizers for a wonderful meeting!

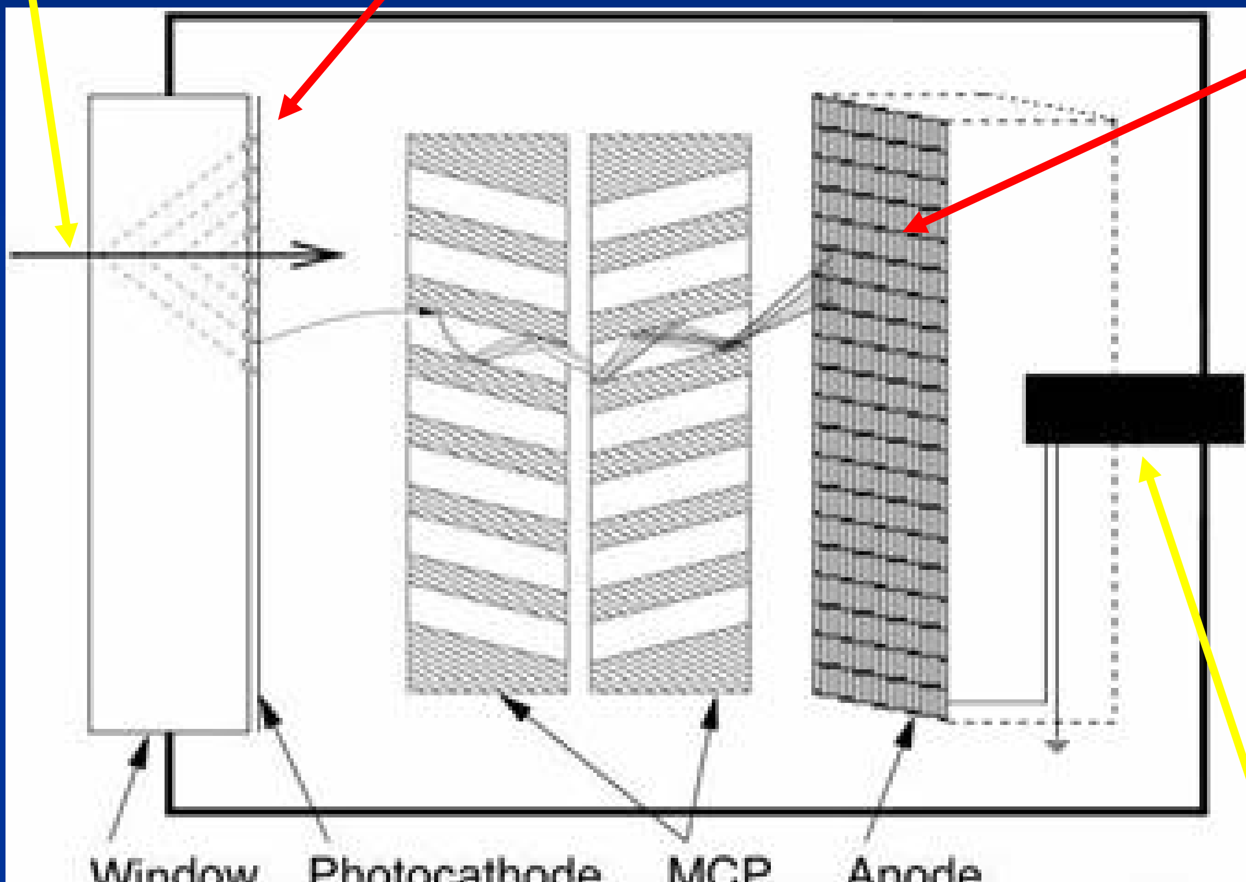
The Quarks- Follow the Flavor….



BACKUP SLIDES

Use Cherenkov light - fast
ignal

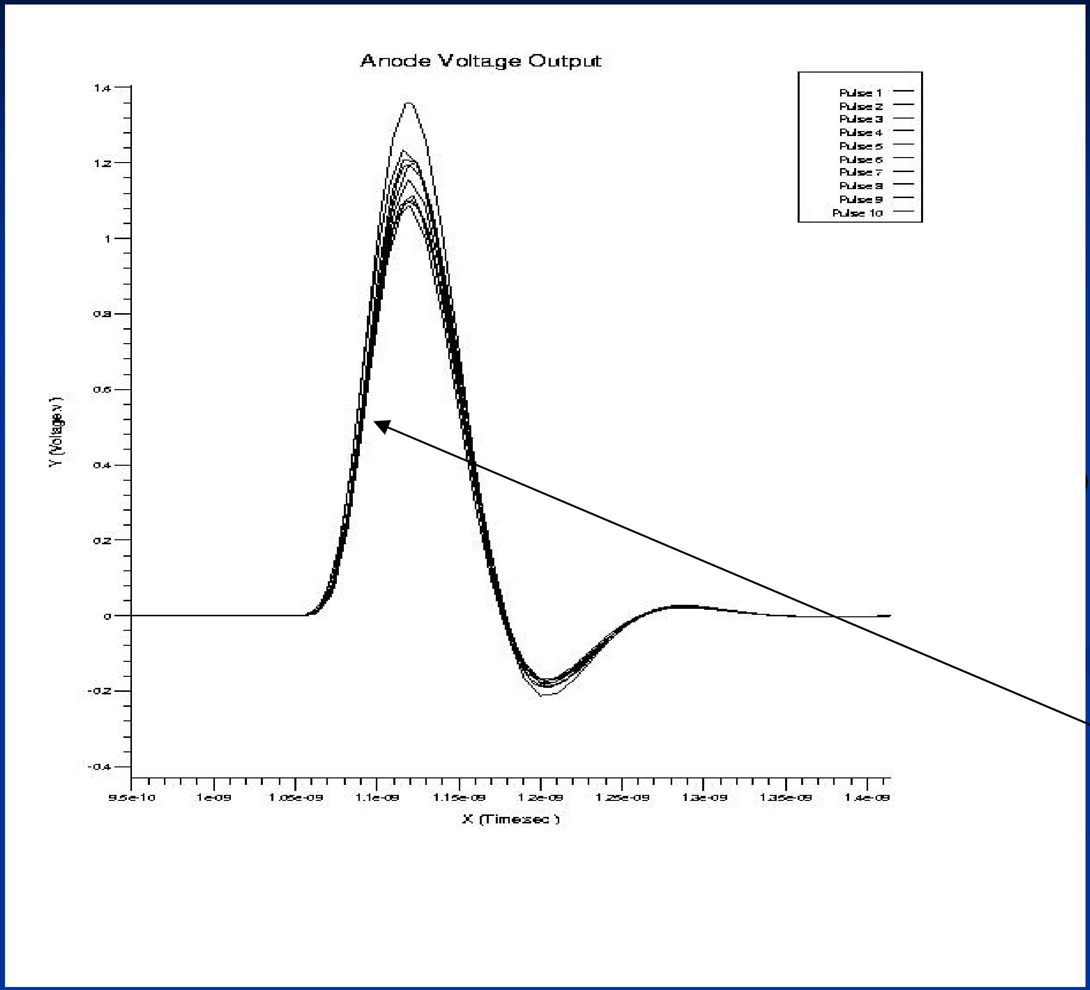
Incoming rel. particle



Custom Anode with Equal-Time Transmission Lines + Capacitative. Return

- A 2" x 2" MCP- actual thickness ~3/4"
- e.g. Burle (Photonis) 85022- with mods per our work

Collect charge here-differential Input to 200 GHz TDC chip



TOF

:

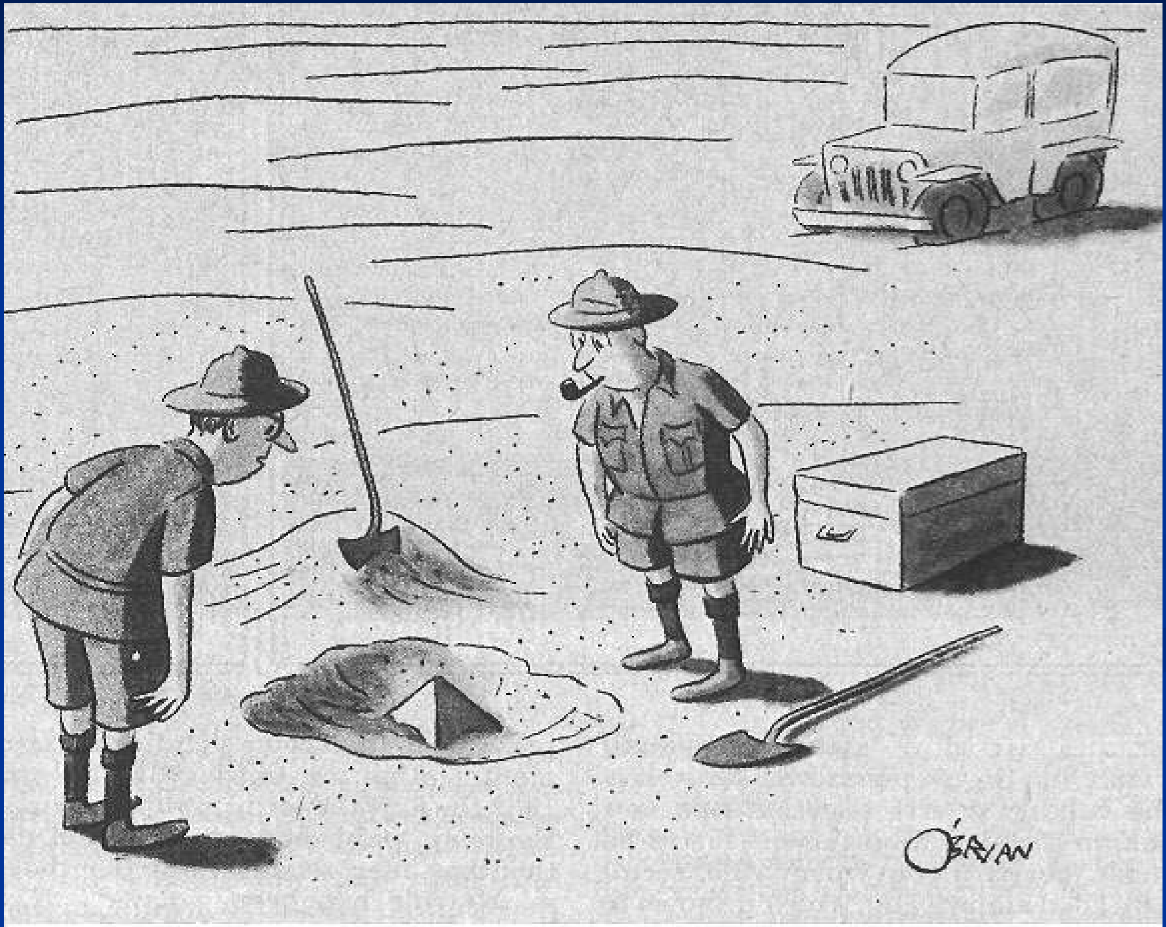
Output at anode from simulation of 10 particles going through fused quartz window- T. Credo, R. Schroll

Jitter on leading edge 0.86 psec


MATTER
ANTIMATTER
DOESN'T MATTER

High Pt Photons as New Physics Signature:

(e.g. CDF Run1 $ee\gamma\gamma$, $\mu\mu\gamma\gamma$ events)



"This could be the discovery of the century. Depending, of course, on how far down it goes."

Are anomalies real? Experiments see only upward fluctuations- can estimate luminosity needed to get to the mean (though huge uncert.)- wonderful to be getting more data

'Understanding Objects' and their limitations

Example- electro-magnetic (em) cluster

Identify an em cluster as one of 3 objects: (CDF)

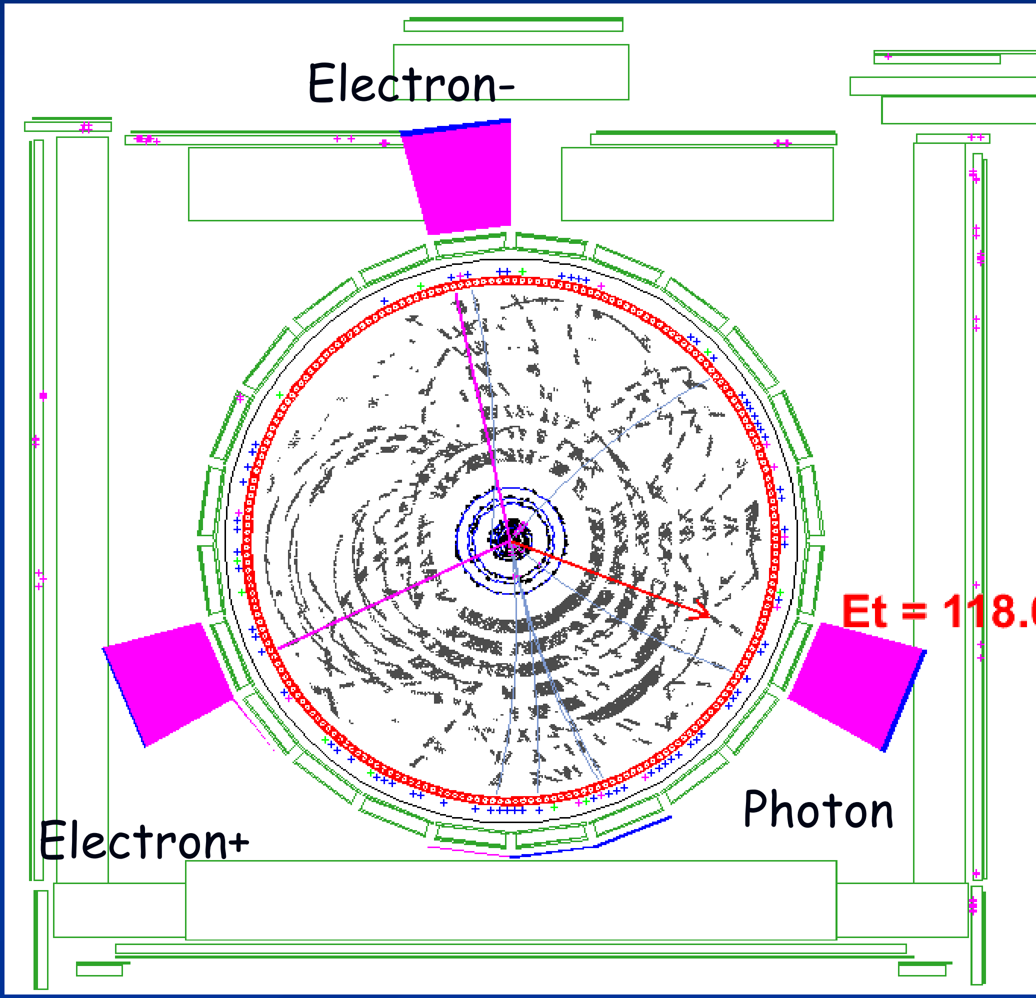
E/p < 2: Electron

E/p> 2: Jet

P <1: Photon

Where p is from track, E is from cal

E/p measures bremsstrahlung fraction



Recent 'typical' zoo event (only an example)