Physics at the Tevatron
Part 1: Experience from Run 1
Part 2: Upgrades and Prospects for Run 2

Peter Wilson

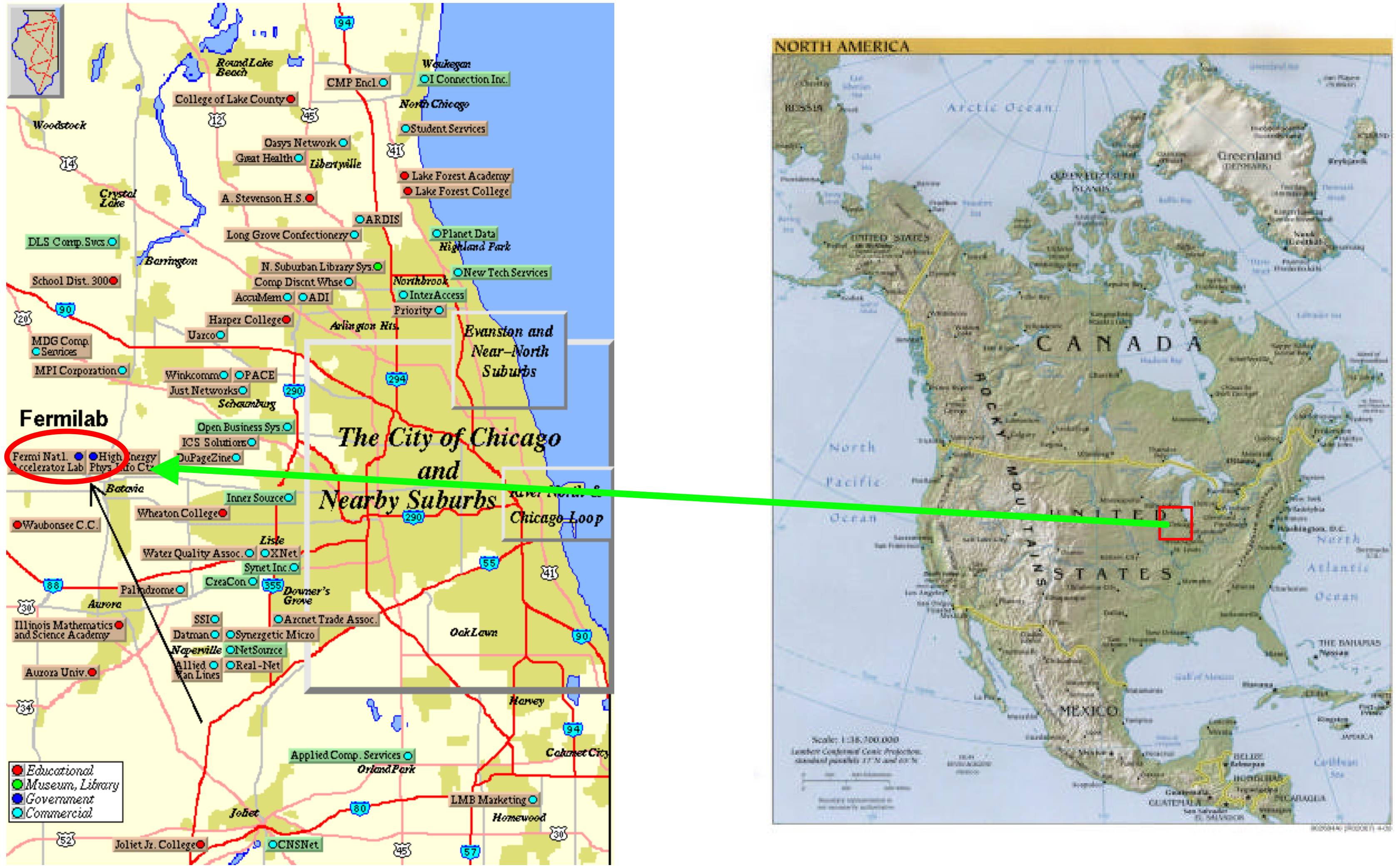
Fermilab

8 January 2002

Outline

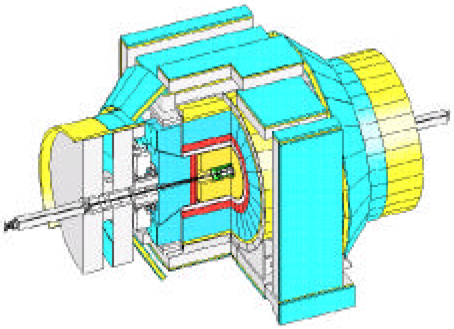
- **Part 1 Today: Experience from Run 1**
  - ➢ Run 1 Tevatron performance
  - ➢ Run 1 CDF and D0 detectors
  - ➢ Overview of Run 1 Tevatron Physics and techniques
    - Physics range of Tevatron
    - QCD physics
    - Electroweak
    - B-physics
    - Putting it all together: top physics
    - Putting it together again: searches for new phenomena
- **Part 2 Tomorrow: Physics at the Tevatron in Run II**
  - ➢ Improvements to Fermilab Accelerator Complex
  - ➢ CDF and D0 Detector Upgrades
  - ➢ Current accelerator and detector status
  - ➢ Projections for Run II physics

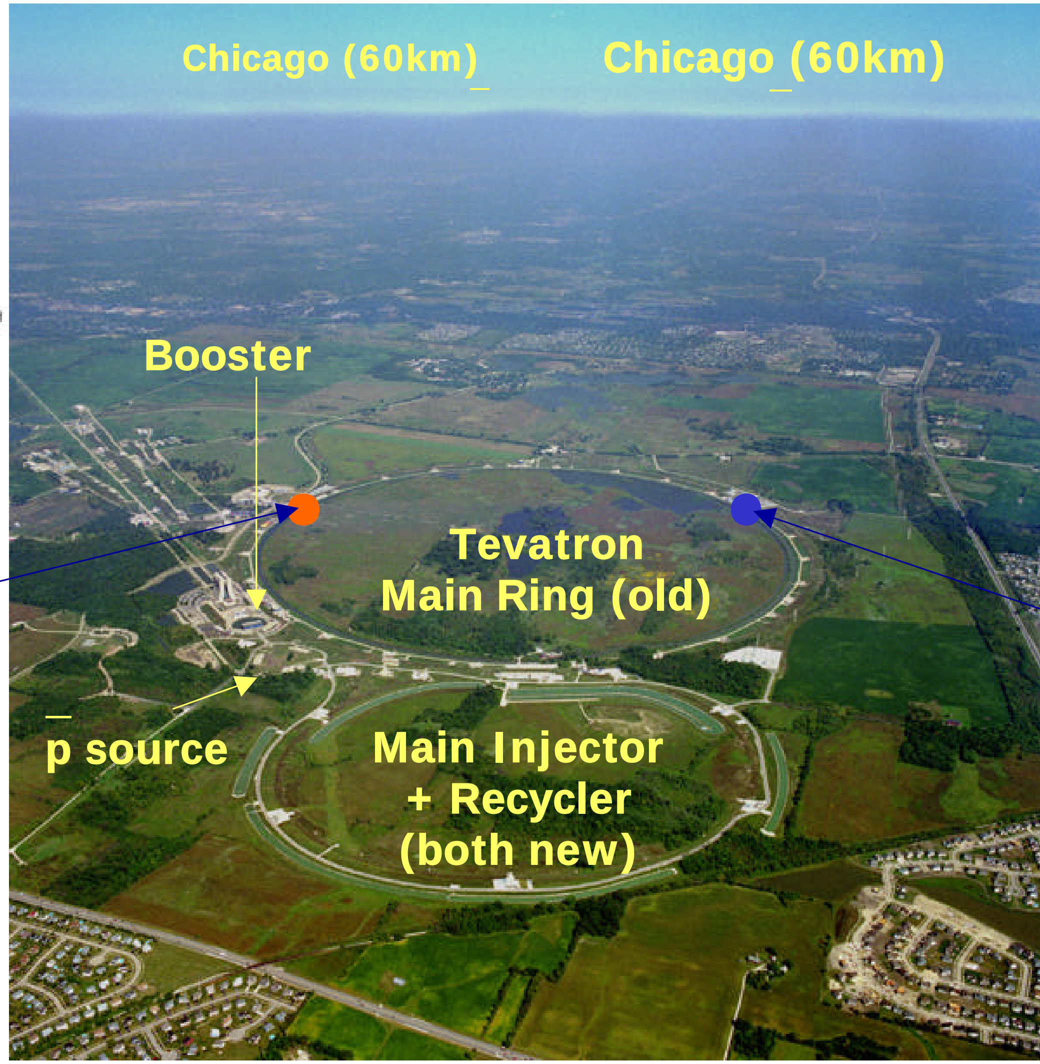
Fermilab

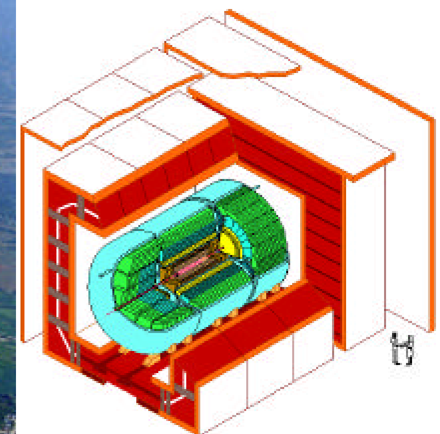


Fermilab
Fermi Natl. Accelerator Lab
High Energy Phys Info Ctr
Batavia
The City of Chicago and Nearby Suburbs
Evanston and Near–North Suburbs
Chicago Loop
Educational
Museum, Library
Government
Commercial
NORTH AMERICA
Arctic Ocean
Greenland
CANADA
ROCKY MOUNTAINS
UNITED STATES
MEXICO
North Pacific Ocean
North Atlantic Ocean

The Fermilab Tevatron Collider







D0 Collaboration

Totals

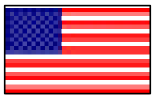
18 countries

79 institutions

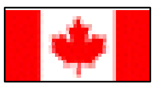
>500 physicists

CDF Collaboration

North America

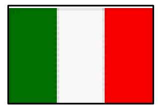


3 Natl. Labs
25 Universities



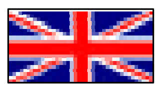
2 Universities

Europe

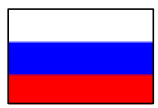


1 Research Lab
6 Universities

1 University

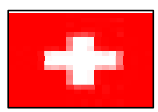


4 Universities



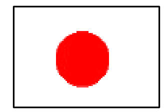
2 Research Labs

1 University

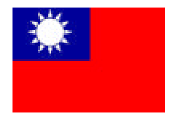


1 University

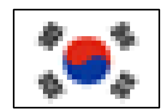
Asia



4 Universities
1 Research Lab



1 University



3 Universities

Totals

11 countries

55 institutions

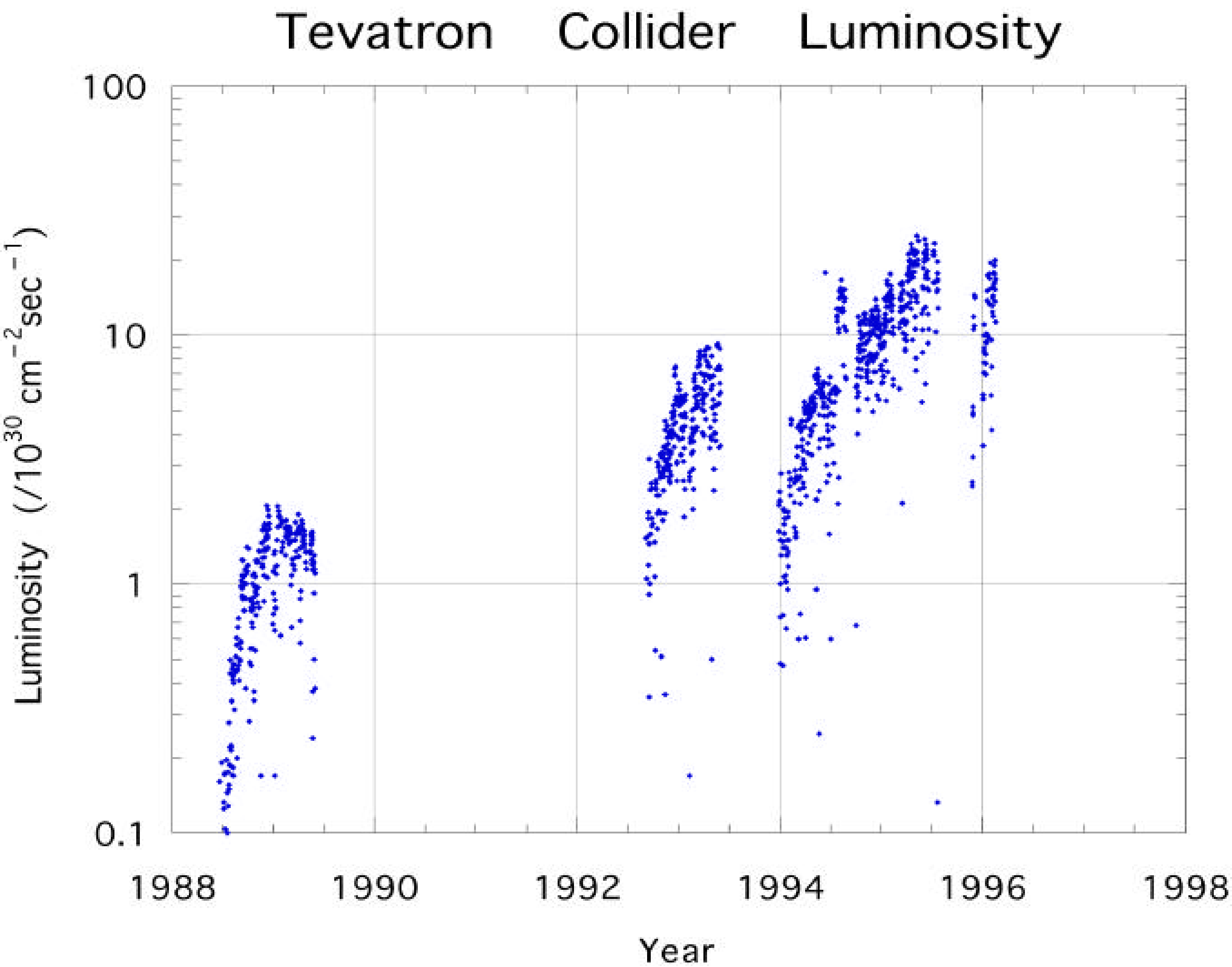
525 physicists

Tevatron Timeline

1985	First proton-antiproton collisions
1988-89	First physics run, CDF only
1992-96	**Run 1: 120 pb^{-1}, 1.8TeV, CDF and DØ**
	6 bunches, 3.5 μs between collisions; $L \sim 10^{31}\ cm^{-2}\ s^{-1}$ ($10 \mu b^{-1}\ s^{-1}$), $L_{peak} \sim 2 \times 10^{31}$, $<N_{int}> \sim 2.5$
1996-2001	Major detector upgrades
2001-04	Now **Run 2a: 2 fb^{-1}, 1.96 TeV**
	36 bunches, 396 ns between collisions; $L \sim 2 \times 10^{32}\ cm^{-2}\ s^{-1}$ ($0.2 nb^{-1}\ s^{-1}$)
2004	Short shutdown to install new silicon detectors (+ . . .)
2004-07	**Run 2b: ~ 15 fb^{-1} (total)**
	99 bunches, 132 ns between collisions; $L \sim 5 \times 10^{32}\ cm^{-2}\ s^{-1}$
2007?	LHC operation starts at CERN

- Top quark production cross section ~ 5 pb
- Higgs, supersymmetry, . . . ~ few × 100 fb

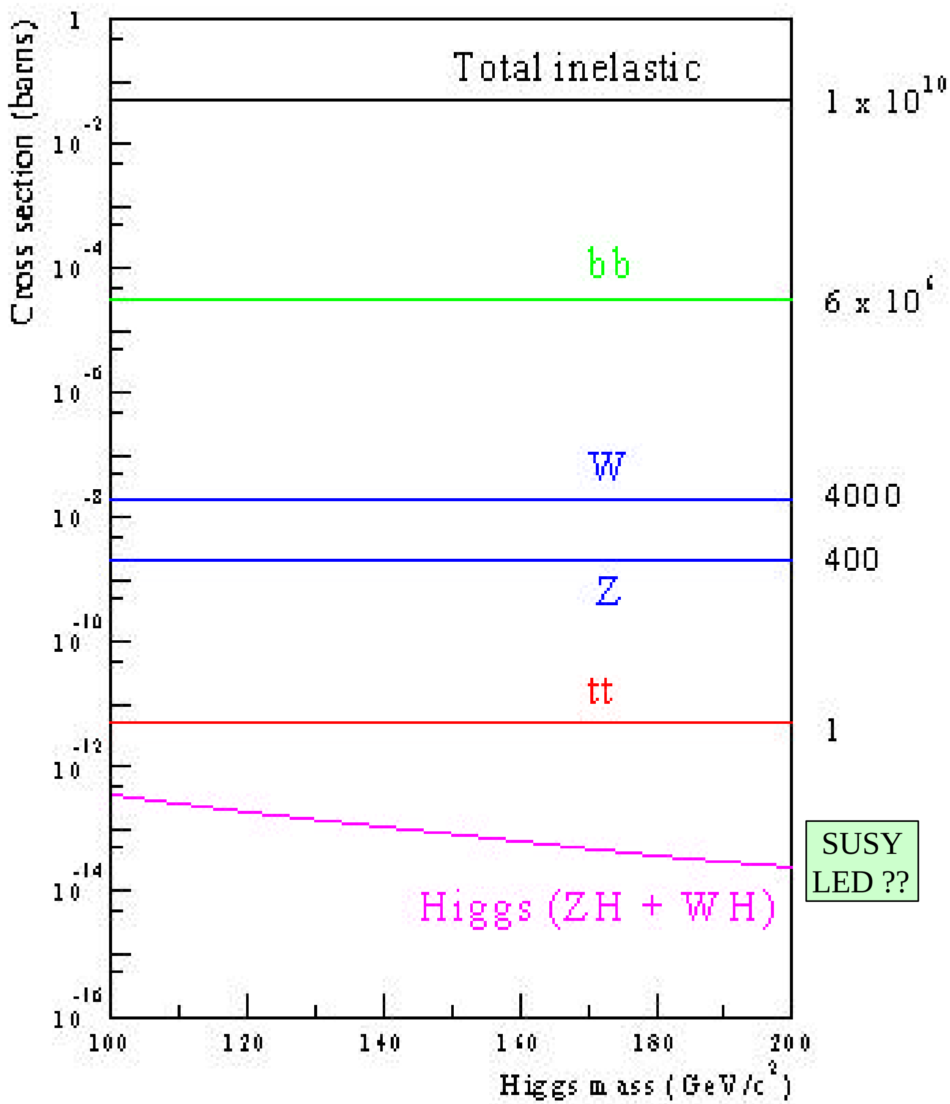
Tevatron Luminosity History



RUN 0 1A 1B 1C
(incl 630 GeV)

The Particle Menu at the Tevatron

- **pp collisions Tevatron provides a broad spectrum of physics: QCD, B's, W, Z, tt, new particle searches**
- **Cross sections for particle production vary by a factor of ~ 10^{10} (diffraction to Higgs)**
- **Enormous b rates ~ 10^3 - 10^4/s**
  - ➢ challenge: triggers, flavor tagging
- **Large W boson samples**
  - ➢ challenge: lepton, MET precision
- **Modest t t samples**
  - ➢ challenge: B's in jets, jet Et
- **Searches for Higgs, SUSY…**
  - ➢ challenge: backgrounds, statistics



Detector Needs

- **QCD – Jet, Photon, J/ψ… cross-sections angular distributions…**
  - ➢ Jet and photon reconstruction – good calorimeters
- **B's – lifetimes, cross-sections (really QCD), B_c, mixing, CP violation…**
  - ➢ Lepton ID (e and μ)
  - ➢ Displaced vertex measurements
  - ➢ Flavor tagging (leptons, particle ID)
- **Electroweak – M_W , Γ_W, W Asymmetry…**
  - ➢ Lepton ID (e and μ)
- **$t\bar{t}$ and new particle searches**
  - ➢ Use all of the above

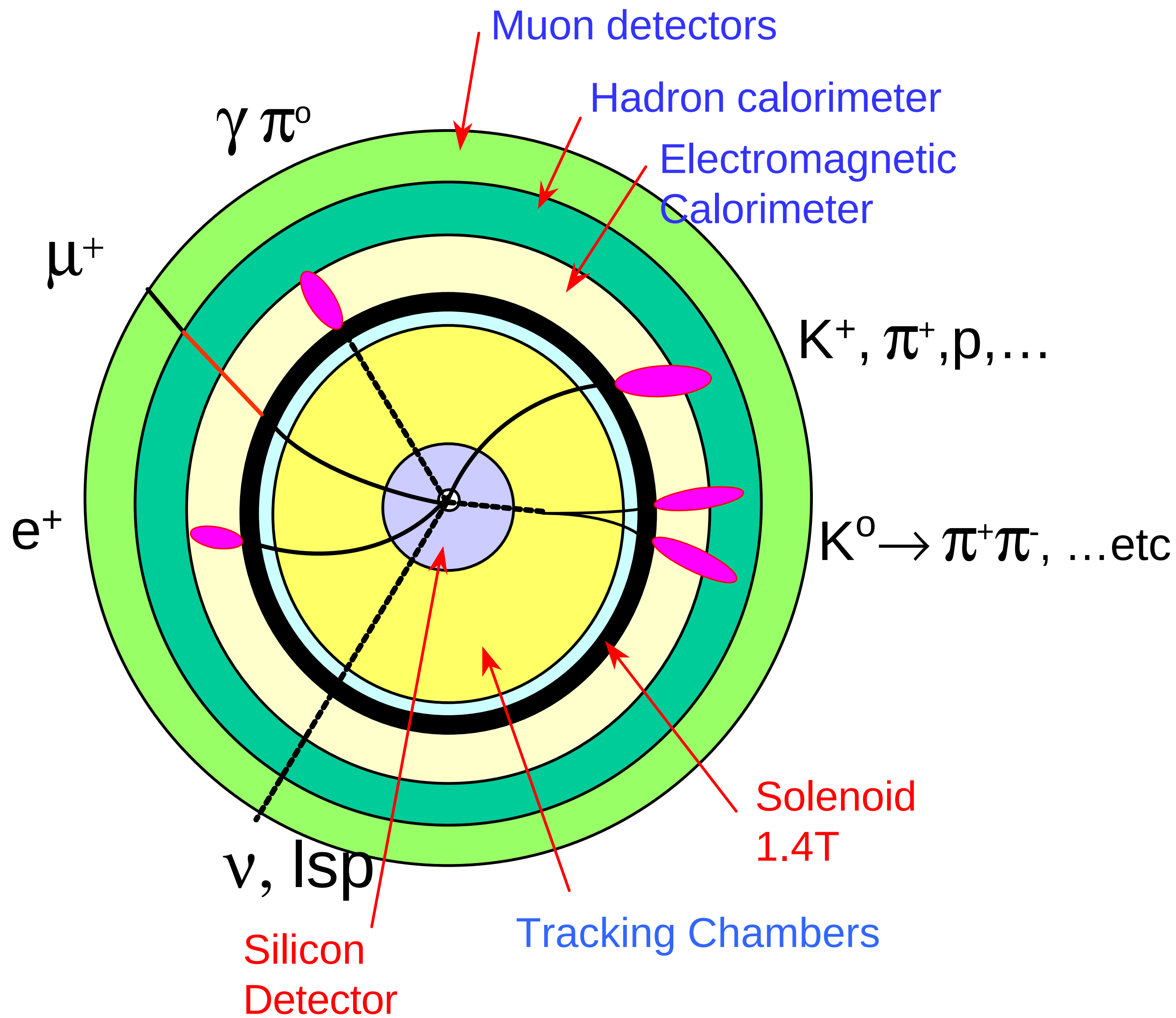
Run 1 Detector Schematic

Key

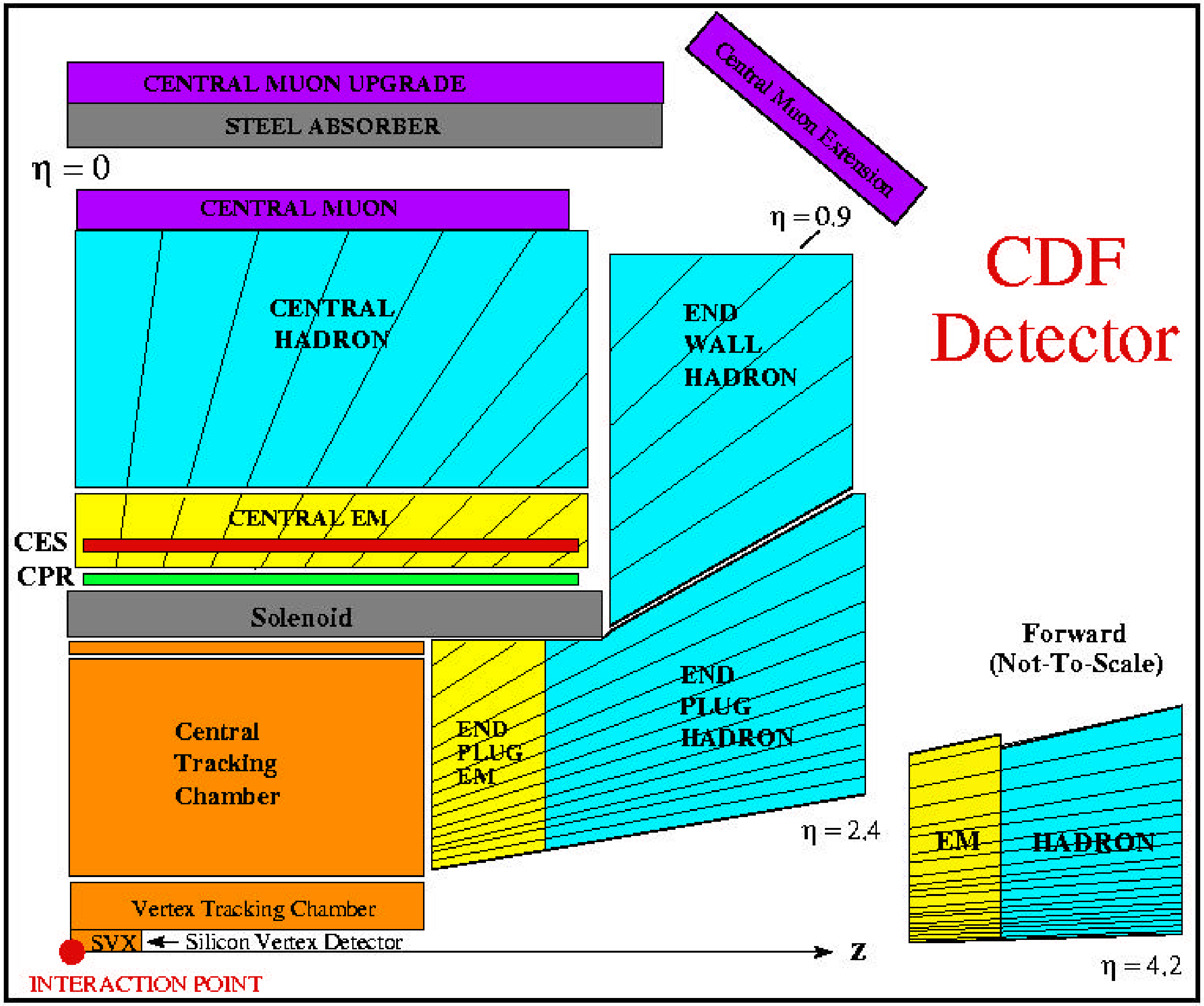
CDF and D0

CDF

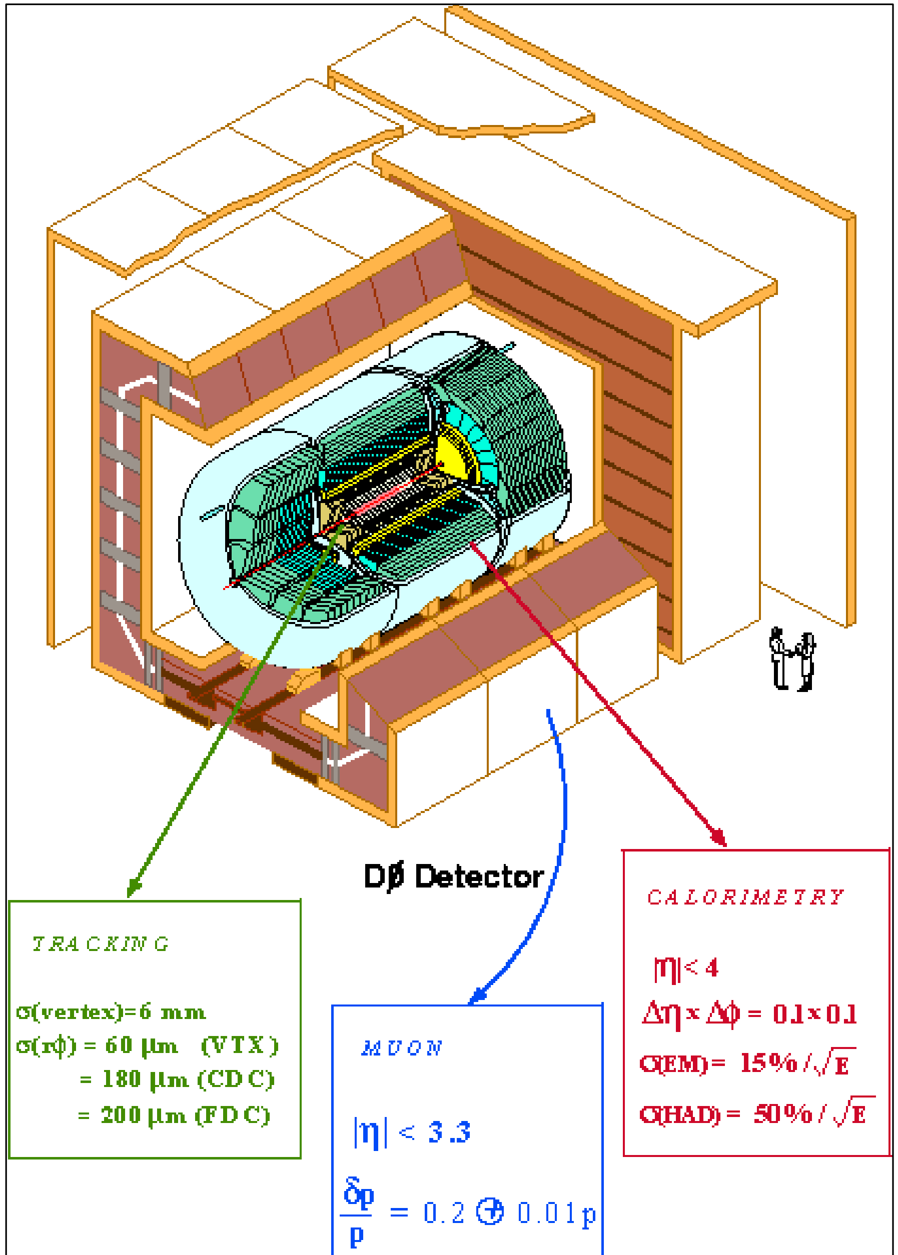
D0



Run 1 CDF Detector



Run 1 D0 Detector



Run 1 Triggering

Run 1 Triggering limited to (CDF example):

- Leptons (Electron or Muon)
  - ~20 GeV for EW work
  - ~8 GeV with some prescale for b->Xlν
  - Dimuon 2 GeV
- Jets - 20 GeV w/large prescale to 100 GeV un-prescaled
- Photons – 23 GeV un-prescaled
- Missing Et

Most heavy flavor physics done from lepton samples

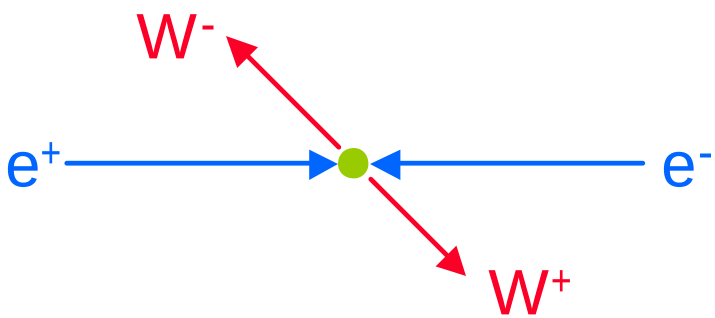
Level	Bandwidth	Trigger On
	300kHz	Beam Crossing
L1	1kHz	Cal Tower (EM or HAD), m stub, SEt, $\not{E}t$
L2	25Hz	Add Tracking, Cal clusters, processors
L3	5Hz	Offline type reconstruction in farm

Properties of the W and Z

- **Before LEPII the Tevatron was the center of measurements of properties of the W- Boson. This will again be true in Run 2**
- **Cross section for W+X on order of 20 nb**
- **Studies done almost exclusively with leptonic decays to e and** m. **A few studies done with** Z->nn (**eg** Zg **from D0**)
- **Properties measured in Run 1**
  - W Mass
  - W Width – both directly and indirectly
  - W/Z production asymmetries
  - Di-doson production (WW, WZ, ZZ, Wγ, Zγ)
  - W+n jets production
  - W/Z P_T
  - Drell-Yan production

Precision Measurement of M_W

LEP 2 (e^+e^-)



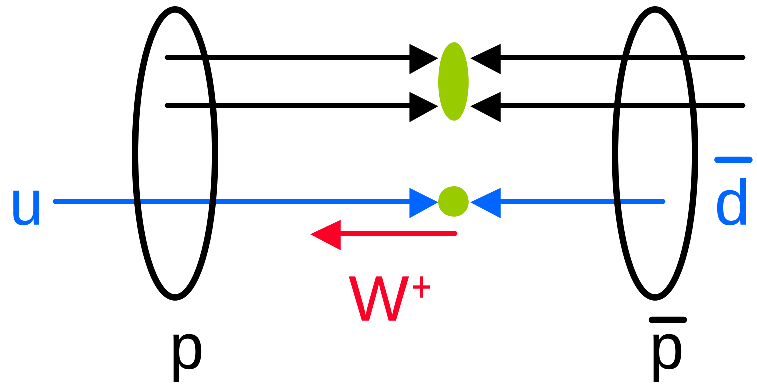
$W^+ \to e^+\nu$, $W^- \to u\bar{d}$

$P_i(W^+) + P_i(W^-) = 0$, i=1,2,3

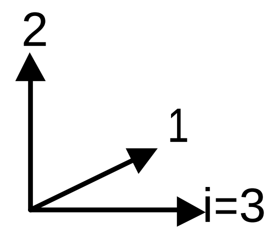
$E(W^+) + E(W^-) = E(e^+) + E(e^-)$

$$M^W = \sqrt{2P^eP^\nu(1-\cos\theta_{3D})}$$

Tevatron ($p\bar{p}$)



$W^+ \to e^+\nu$



$P_i(W^+) = 0$, i=1,2

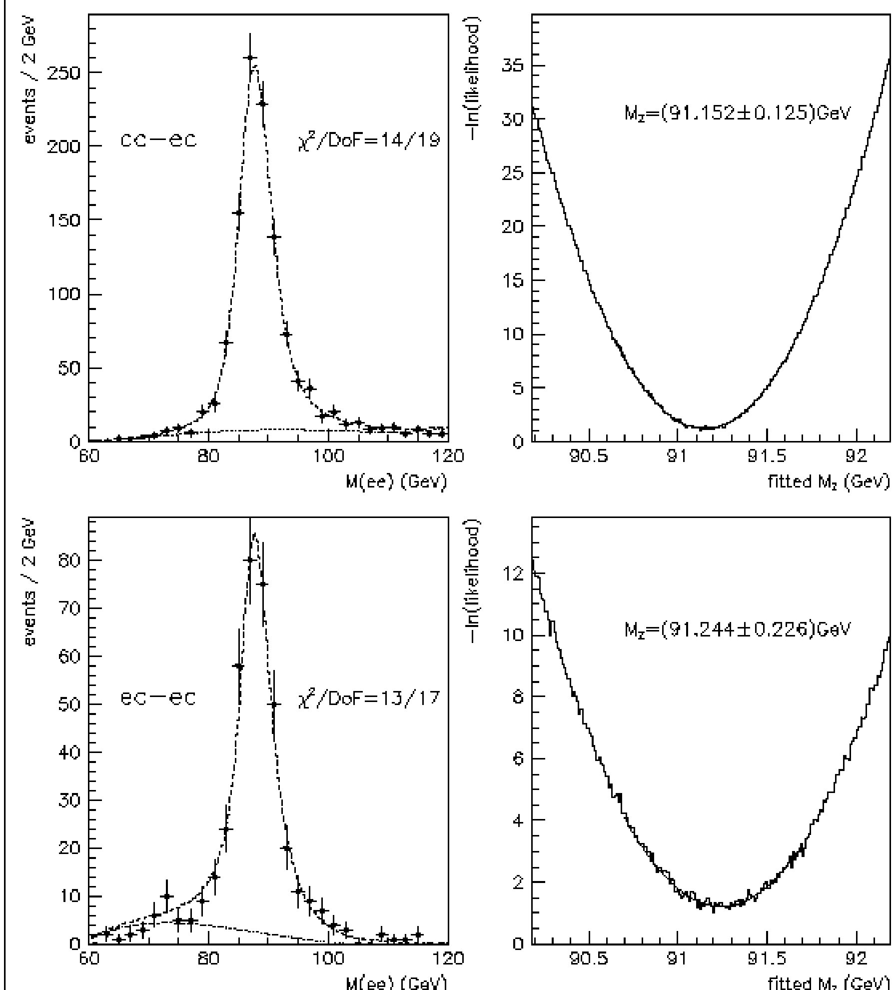
$$P_T = \sqrt{P_1^2 + P_2^2}$$

$$M_T^W = \sqrt{2P_T^eP_T^\nu(1-\cos\theta_{2D})}$$

Precision Measurement of M_W

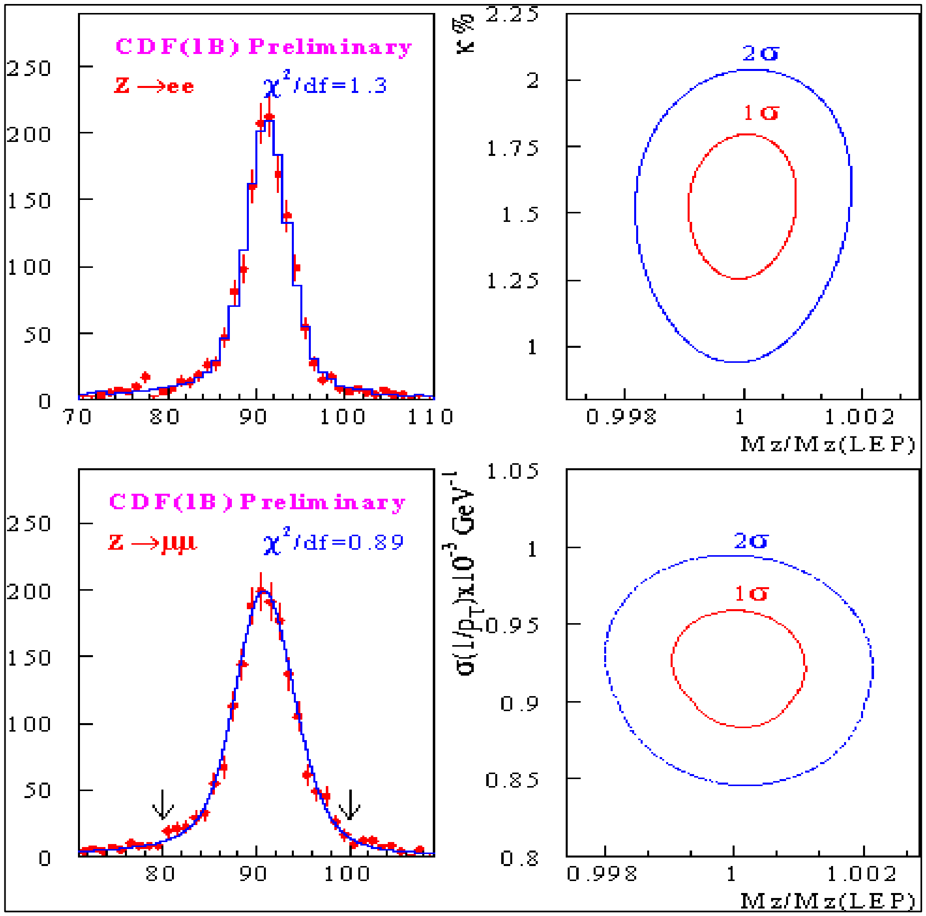
- **Clean low bias W samples:**
  - m + track in COT
  - EM shower w/minimal Had energy and narrow transverse shape + COT track
  - $\not{E}_T$ >~20 GeV
  - Exclude events with jets
- **Dominant systematics are data dependent -> decrease with higher statistics**
  - energy and momentum scales
  - PDFs (from W asymmetry)
  - ...
- **Energy scale:**
  - Testbeam data
  - from Z®ee (cross-check with E/P at CDF)
- **Momentum Scale (CDF):**
  - Z®mm, J/y ® mm, ϒ ® mm

D0 Z® e^+e^- fits

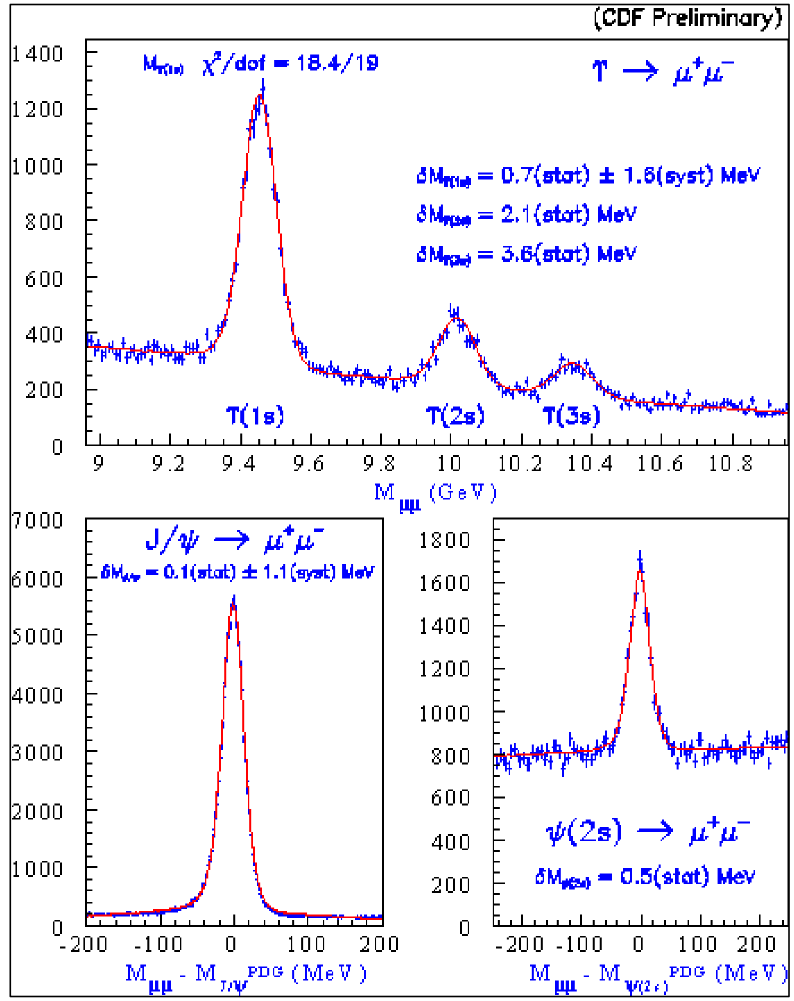


Energy and Momentum Scale

CDF Z ® ll



CDF ¡ and J/y ® mm

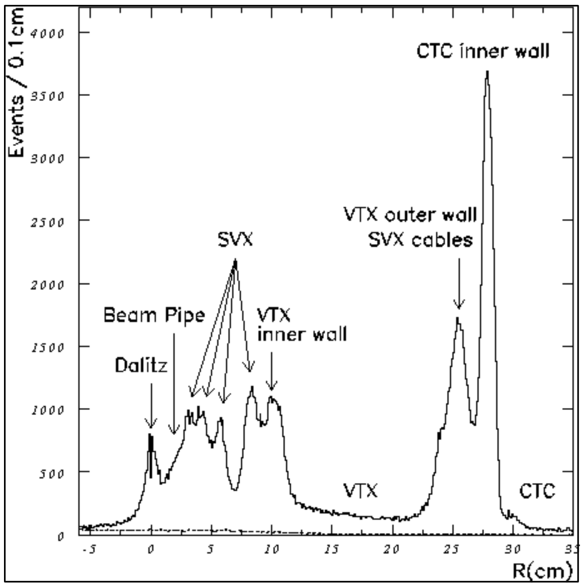


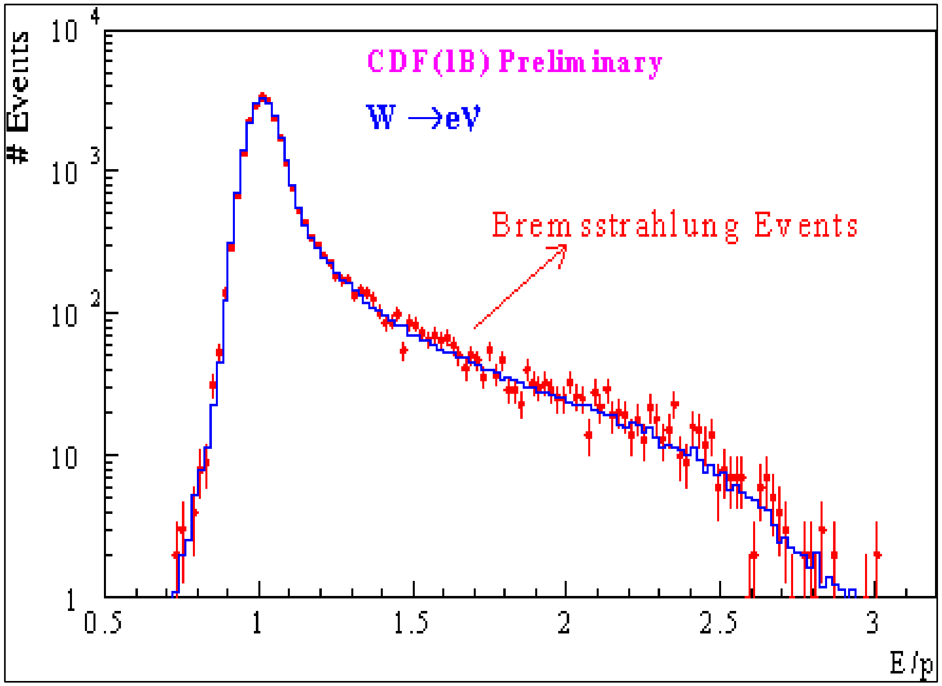
Energy Scale Check

Energy Scale Check

- ➢ E/P in W ® eν
- ✓ Check against material seen in conversions
- ➢ Get shift relative to Z ®ee, not explained by material. Apply as systematic. (Worked in 1A)

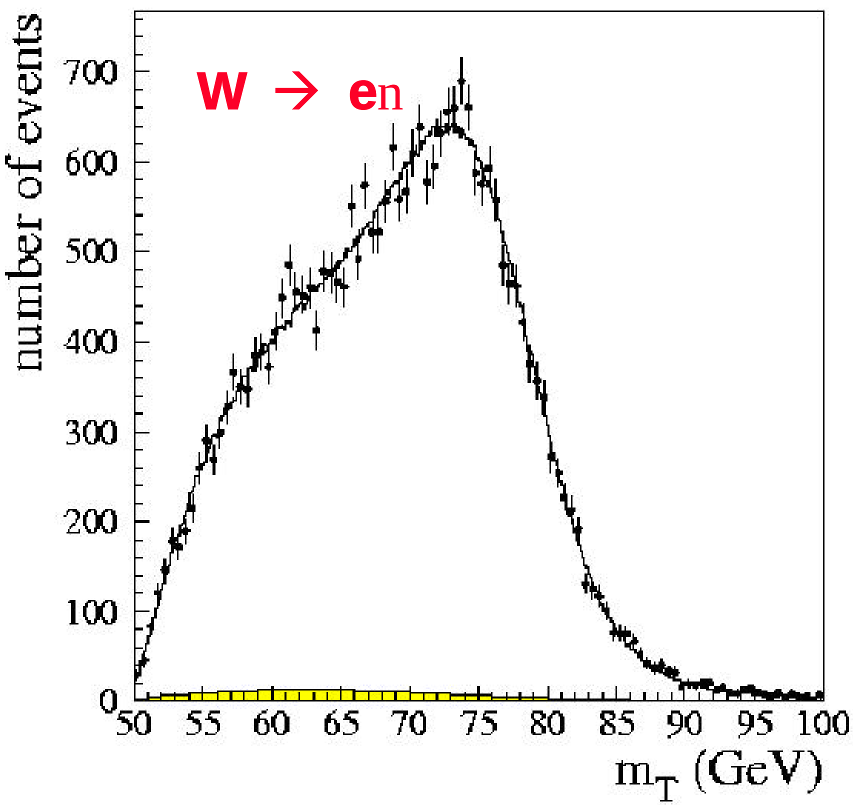
Material from Conversions





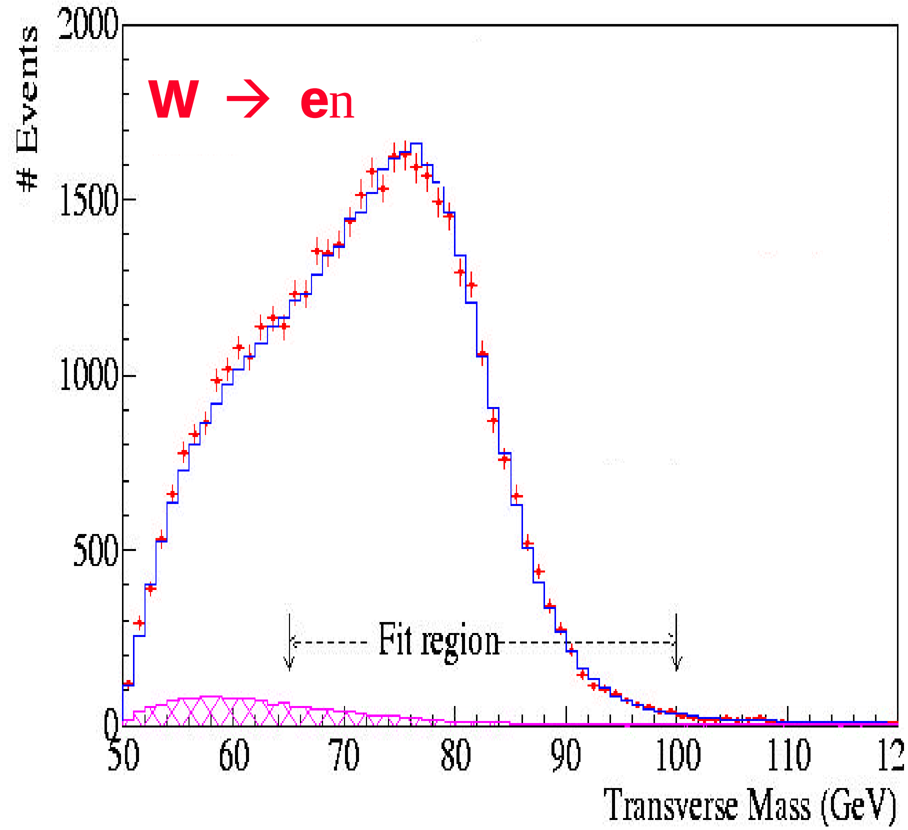
W mass: Fits to M_T

D0



m_W = 80.483 ± 0.084 GeV

CDF



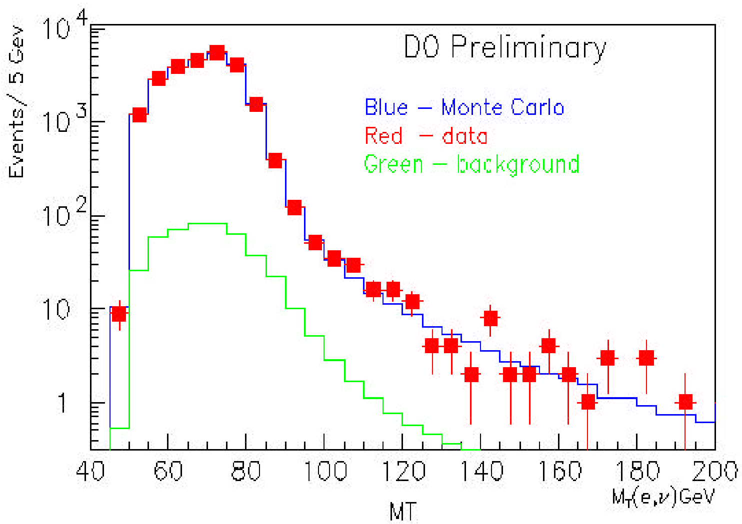
m_W = 80.433 ± 0.079 GeV Run 1 e and m

Mw(ALEPH+DELPHI+L3+OPAL)
= 80.450 +- 0.039 GeV

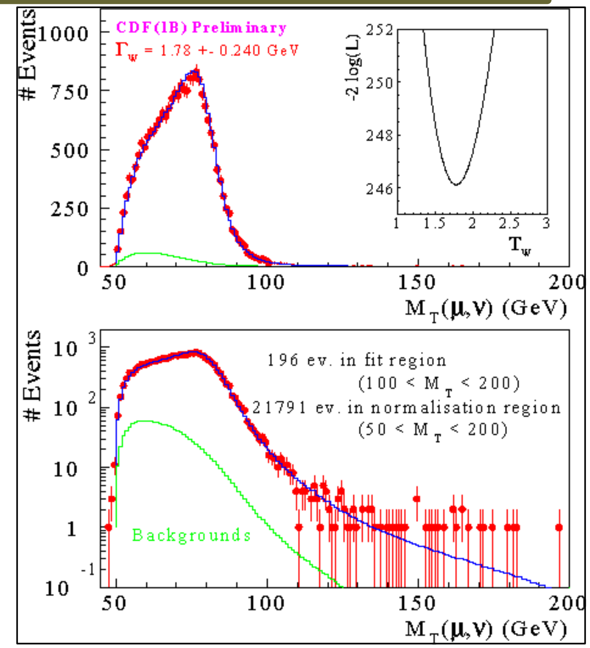
Mw(CDF+D0)
= 80.454 +- 0.060 GeV

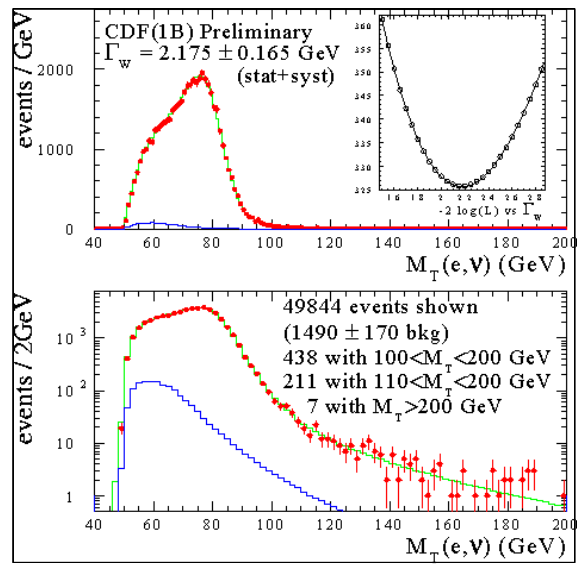
Width of the W

Γ(W) measured directly from tail of M_T distribution. Not sensitive to theory or other measurements.



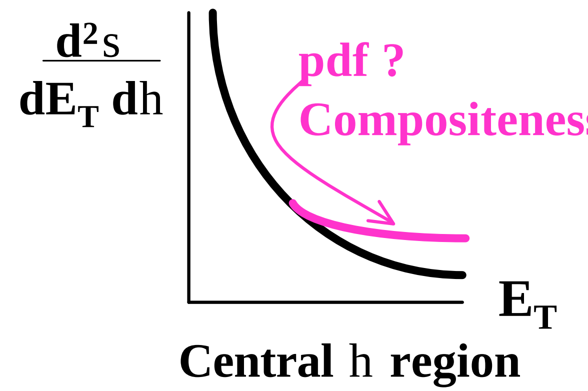
Experiment	Γ(W) (GeV)	Stat	Sys
CDF eν (1A)	2.11	0.28	0.16
CDF eν (1B)	2.17	0.125	0.105
CDF μν (1B)	1.78	0.195	0.135
CDF Comb	2.055	0.100	0.075
D0 eν (1B)	2.231	+0.145 -0.138	0.092
SM Pred	2.0937	0.0025	





QCD – Jets and Photons

- **Jet and Photon cross sections are used to probe the structure of the proton at very small scales**
  - Test perterbative QCD
  - Tests of the parton distribution functions
  - At large Et or Jet-Jet mass, sensitive to new physics such as quark substructure

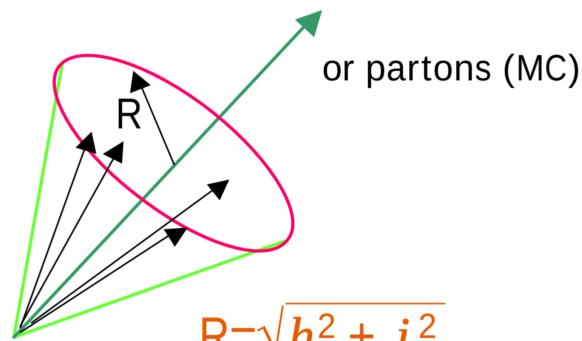


- **QCD measurements**
  - Jet and Photon x-sec
  - Di-jet, di-photon x-sec
  - Multi-jet x-sec
  - $\gamma\mu$ xsec (c and b in proton)
  - J/ψ, Upsilon, B cross-sections
  - Diffractive production of jest J/ψ…

Tevatron Jet Events

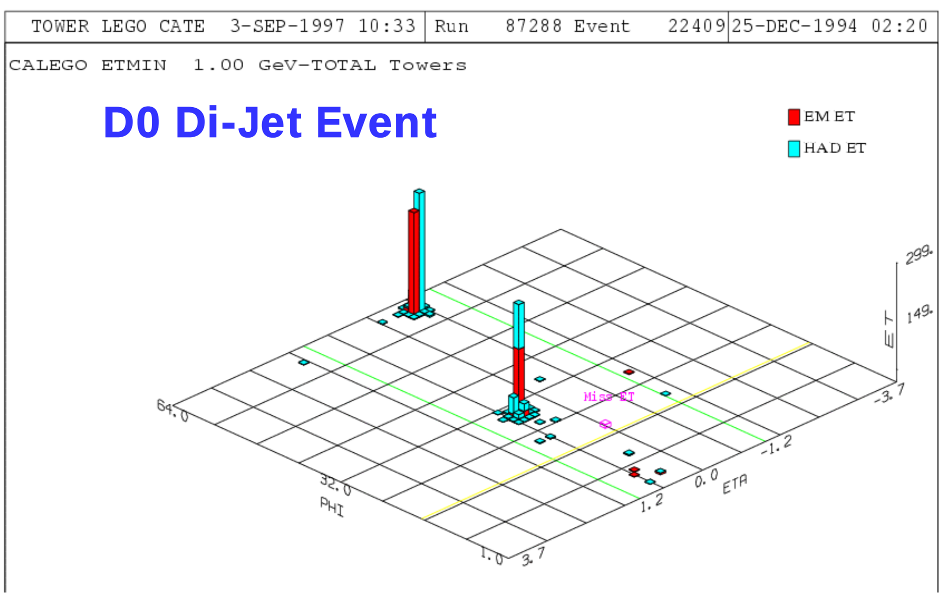
Jets are reconstructed in combination of Hadronic and Electromagnetic calorimeters

- Showers are wide due to fragmentation
- Reconstruct using fixed cone algorithm
  - Jet Cross sections: R=0.7
  - Top analysis: R=0.4 to reduce merging
  - R_{sep} used to separate jets
- Starting to use K_T algorithm
  - Cluster based on K_T relative to seed tower or parton (MC)
  - Avoid infared divergence

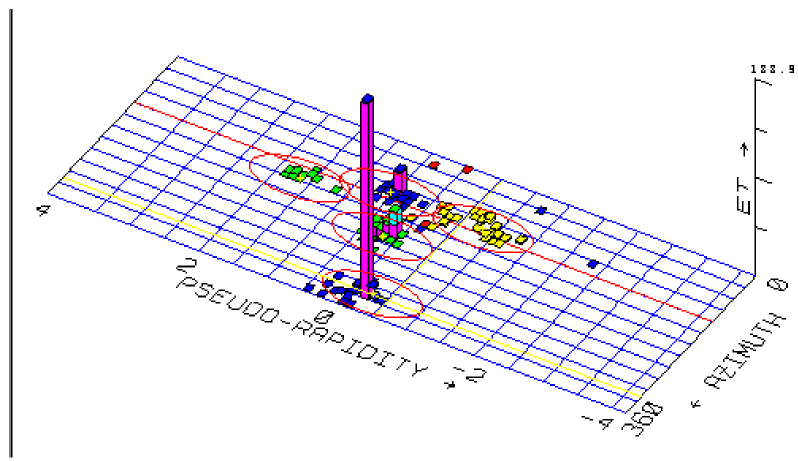


$R=\sqrt{\eta^2+\varphi^2}$

$\eta = -\ln[\tan(\theta/2)]$

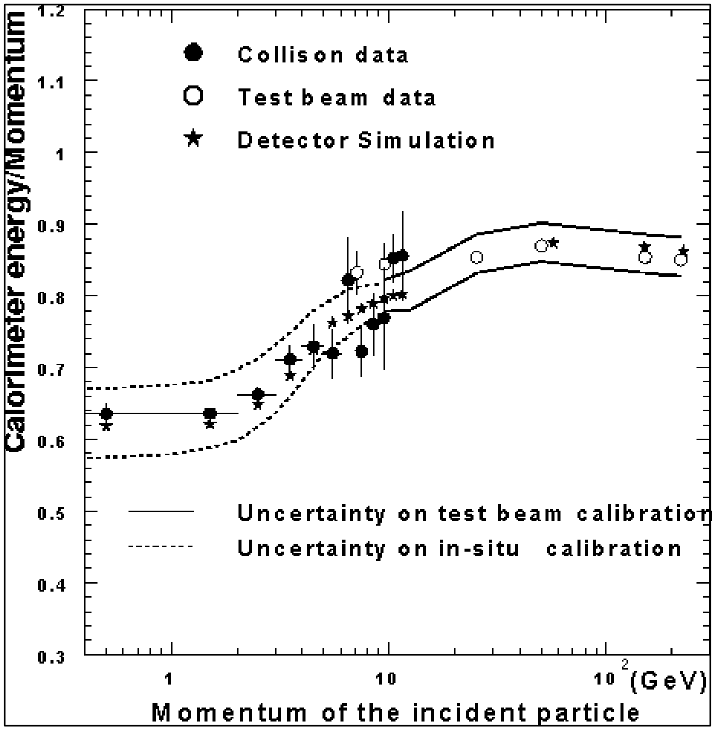


CDF 5 Jet Event



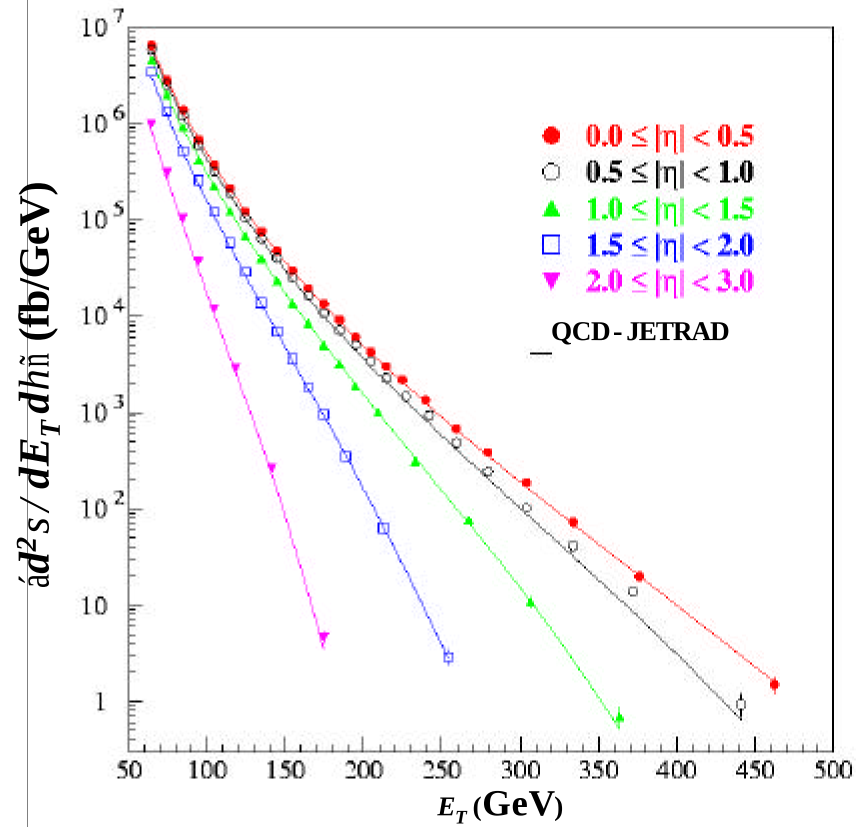
Jet Energy Calibrations

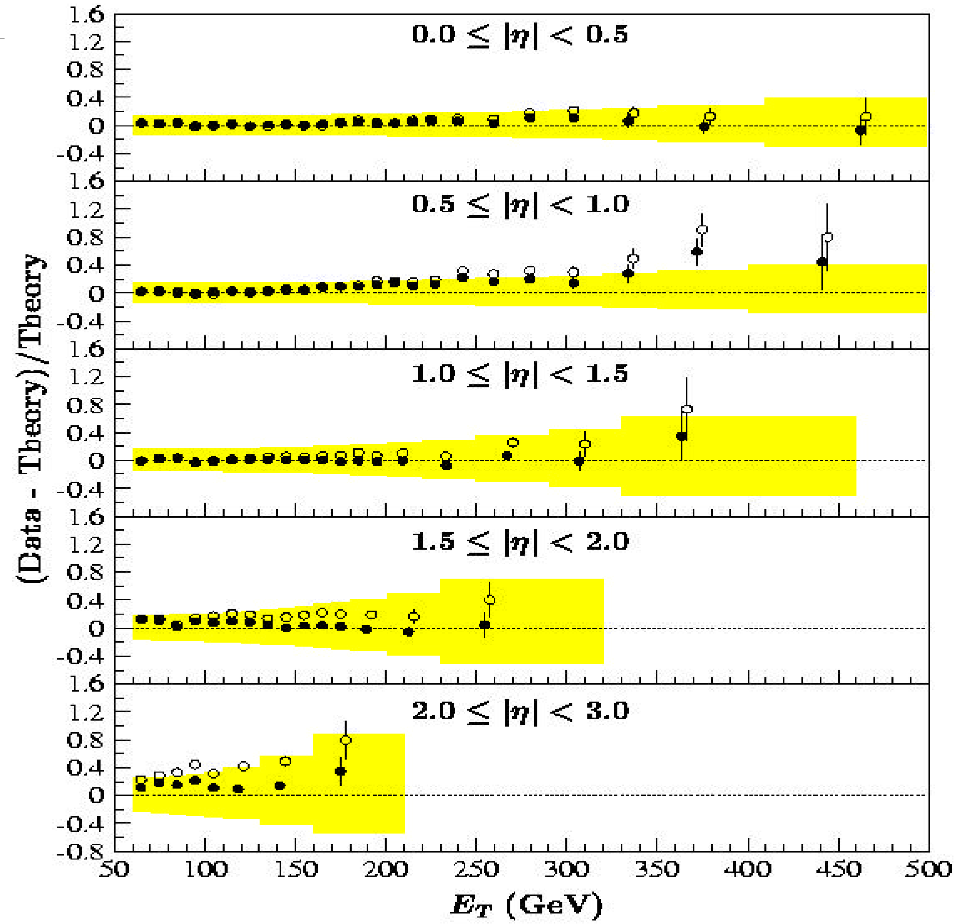
- **Need to account for:**
  - Detector response - Data
  - Different fragmentation (e.g. charge fraction) –Data + MC
  - Losses from cone to get back to original parton - MC
  - Underlying event – minimum-bias Data
- **D0 uses Jet-Photon to calibrate energy response and map region to region**
- **CDF uses**
  - single charged particle response and MC to determine response of central region:
    - Test beam data (single e/pi)
    - Single pion in colliding beam data
    - Use resolution in MC vs to tune MC
  - CDF uses Jet-Jet balancing to cross-calibrate regions
    - Jet-Z(->ll) and Jet-Photon balance as cross check



D0 Inclusive Jet Spectra

Phys. Rev. Lett. 86, 1707 (2001)

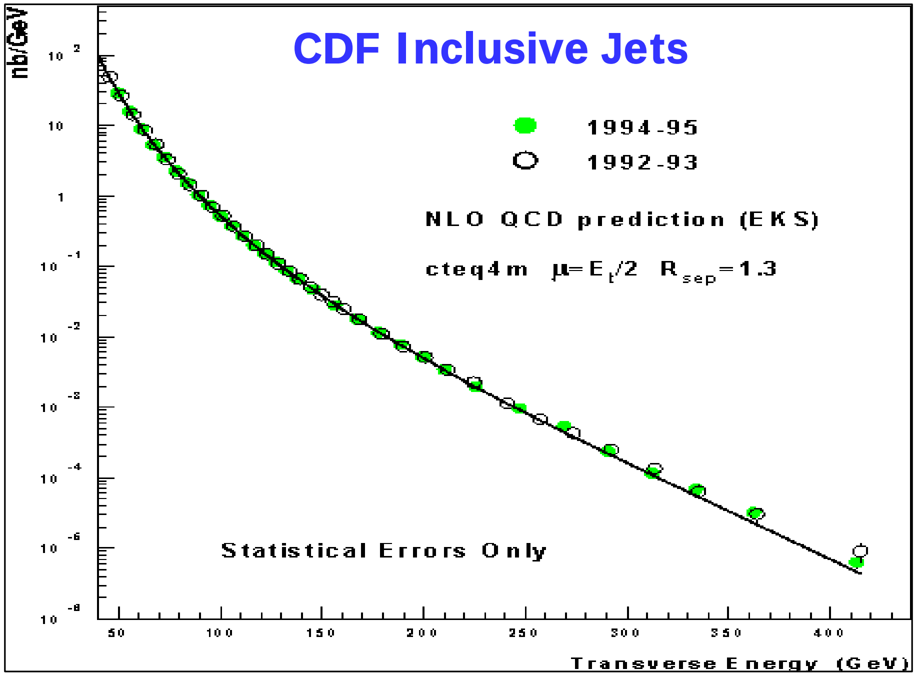


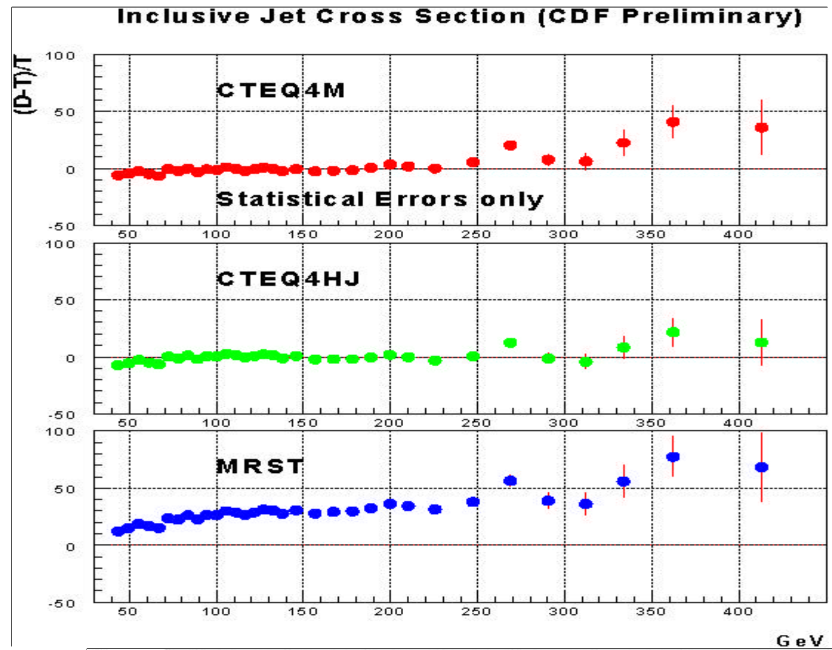


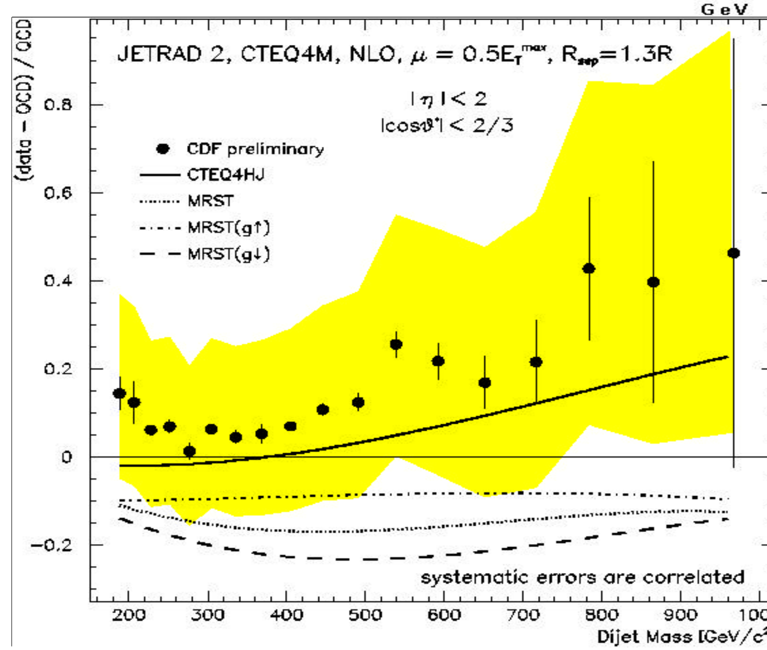
PDF	c2	c2/dof	Prob
CTEQ3M	121.56	1.35	0.01
CTEQ4M	92.46	1.03	0.41
CTEQ4HJ	59.38	0.66	0.99
MRST	113.78	1.26	0.05
MRSTgD	155.52	1.73	<0.01
MRSTgU	85.09	0.95	0.63

CTEQ4HJ ●
CTEQ4M ○

CDF Inclusive Jet Spectra





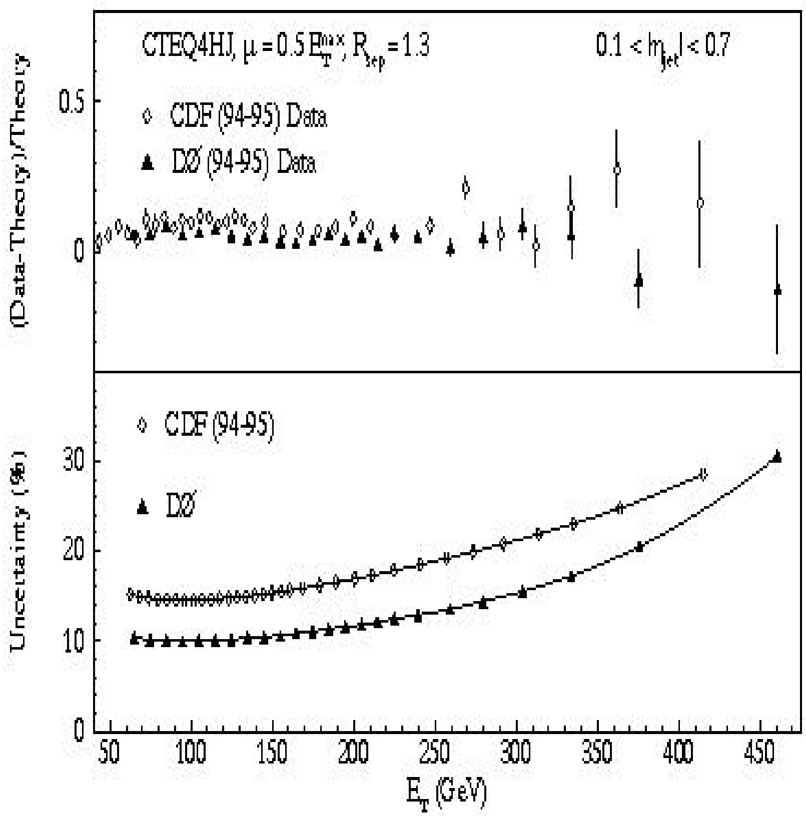


Amazing agreement over 7 orders of magnitude

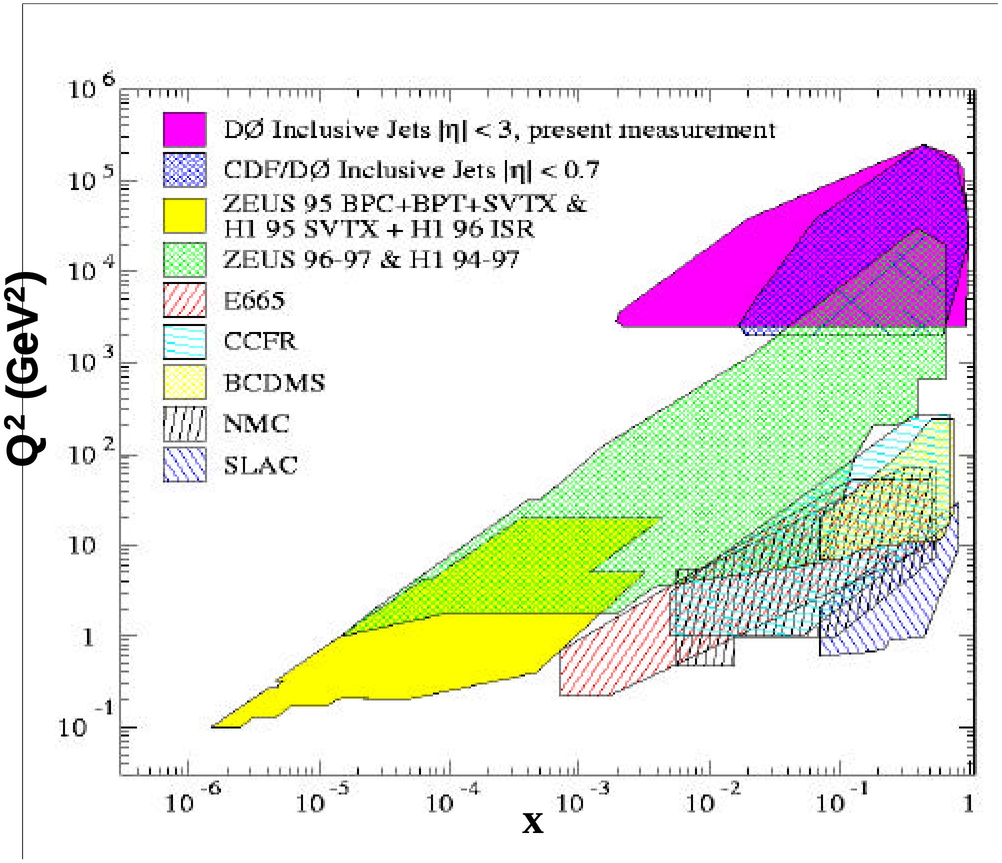
Best agreement with CTEQ4 pdf

Also good agreement for Di-Jets

CDF and D0 Jets Compared



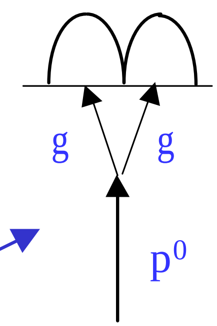
CDF and D0 Agree

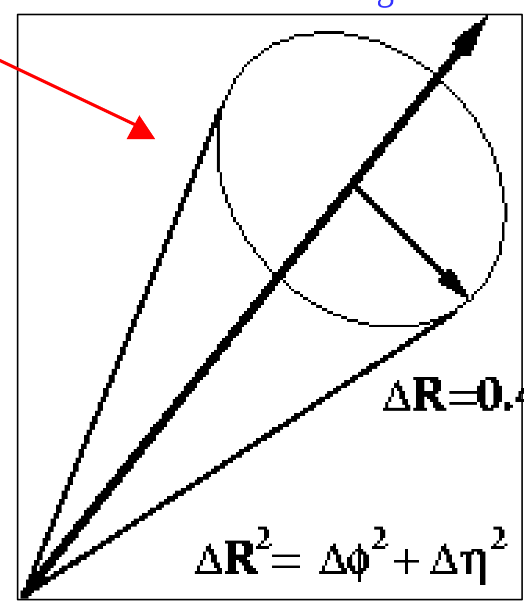


Kinematic Reach of Tevatron Jet Measurements

Photon Production

- **Sensitive to gluon content of the proton qg->qg**
- **Photons selected based on EM energy a small region of calorimeter**
  - minimal deposition in hadron compartment
  - absence of charge particle track match pointing at cluster
  - Narrow transverse shower shape
  - Isolated in calorimeter to reject against background from parton fragmented to single π^0 or η^0
- **Energy calibration based on Electron calibration – see Ws**
- **Direct g separated from p^0 decay through statistical measures based on transverse shower profile and conversion probability before cal (CDF)**



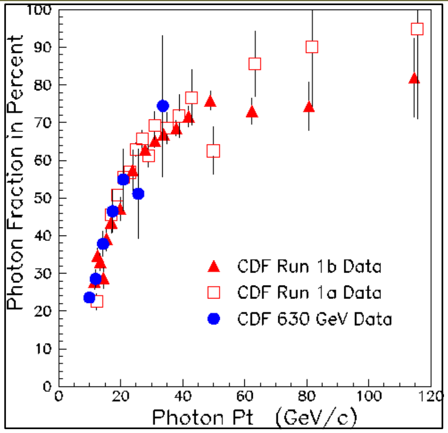


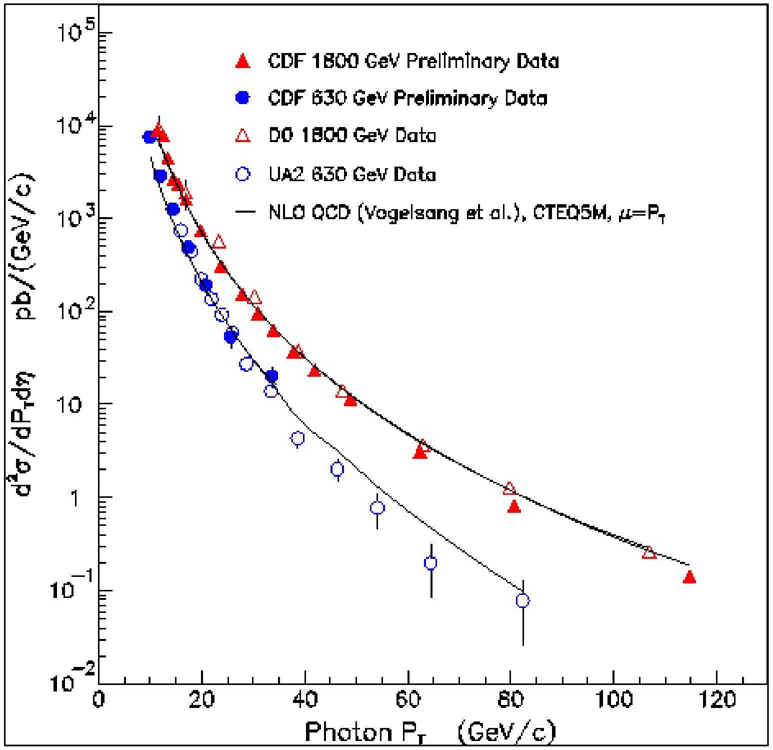
Isolation Cone

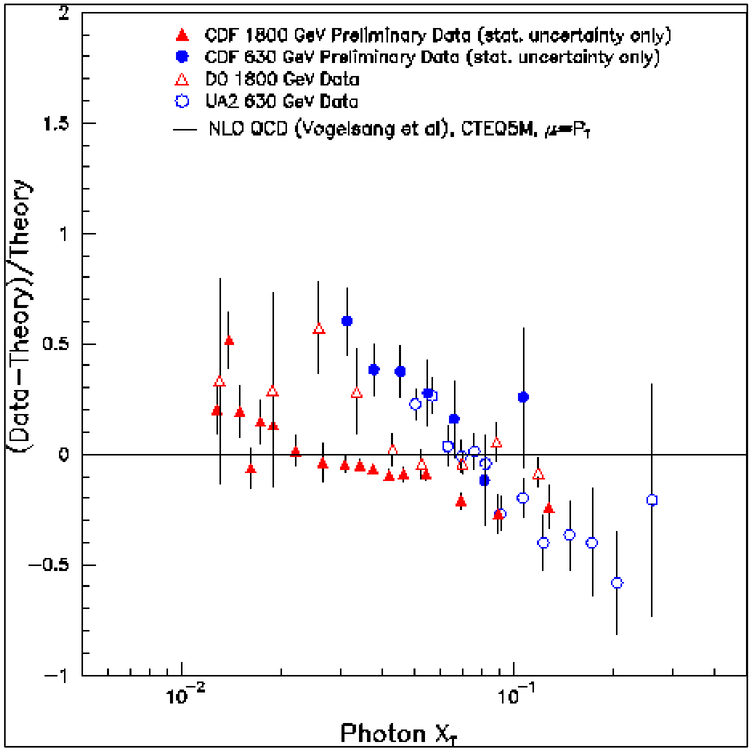
Prompt Photon Cross-sections

- **Good agreement with overall normalization but the shape does not quite work:**
  - ➢ Ratio between 630 GeV and 1800 GeV vs X_T implies not a PDF problem. New NLO models coming with K_T

Photon Purity



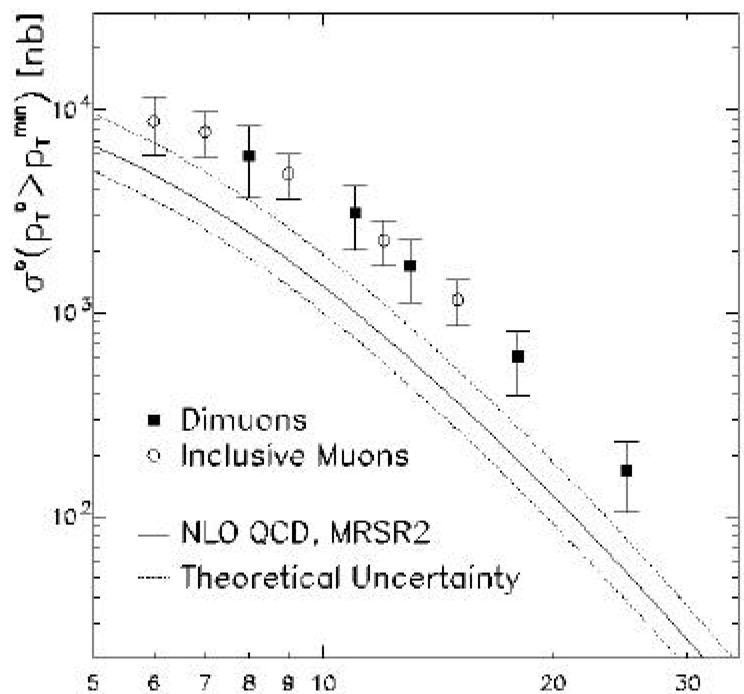




B Cross Sections not so good !

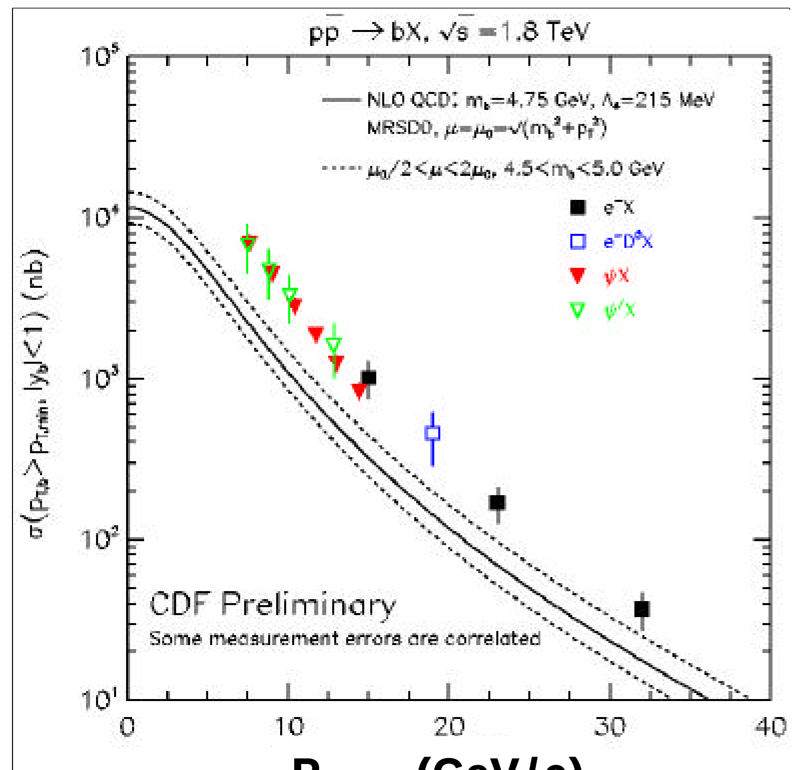
Inclusive B production properties |y| < 1.0

D0



P_{Tmin} (GeV/c)

CDF



P_{Tmin} (GeV/c)

Data/NLO QCD ~ 2.5

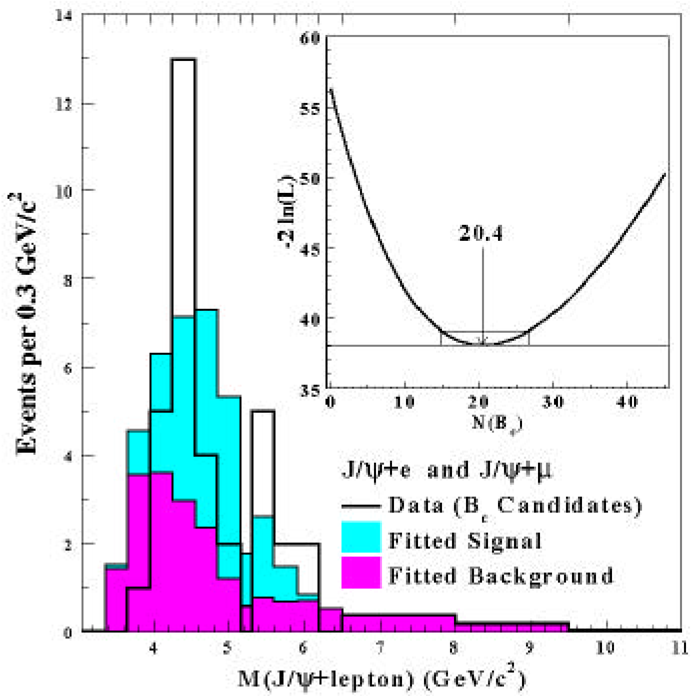
B Physics

- **Cross section for bb O(100μb)**
- **Run 1 Trigger limited to**
  - B-> J/ψ X, J/ψ -> $\mu\mu$
  - B-> X l ν (e or μ)
- **Key features of CDF for B's:**
  - SVX - lifetimes
    - 51 cm long, 2D, r-ϕ readout
    - $\sigma_d = [13 \oplus 40/p_T(\mathrm{GeV/c})]\mu m$
  - CTC – mass resolution and dE/dx
    - $(\delta p_T/p_T)^2 = (0.0009 \bullet p_T)^2$
- **Key measurements**
  - Inclusive and Exclusive (B^+, B^0_d, B_s, B_c, Λ_b) lifetimes
  - Mixing (Bs and Bd) -> probe of |Vtd|
  - Measurement of Sin 2β
  - Discovery of B_c
  - Mass measurements of Bd, B+, Bs...

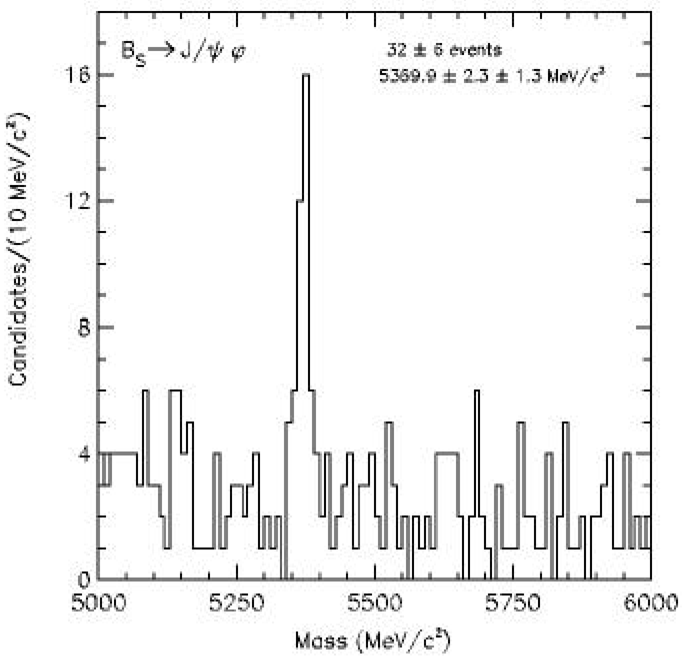
CDF B Physics: Masses

- **B hadron masses (MeV/c^2)**
  - B_s : 5369.9 ± 2.3 ± 1.3
  - Λ_B : 5621 ± 4 ± 3
  - B_c: 6400 ±390 ± 130

Discovery of B_c



$B_c \Rightarrow J/\psi l\nu$ (20 events)



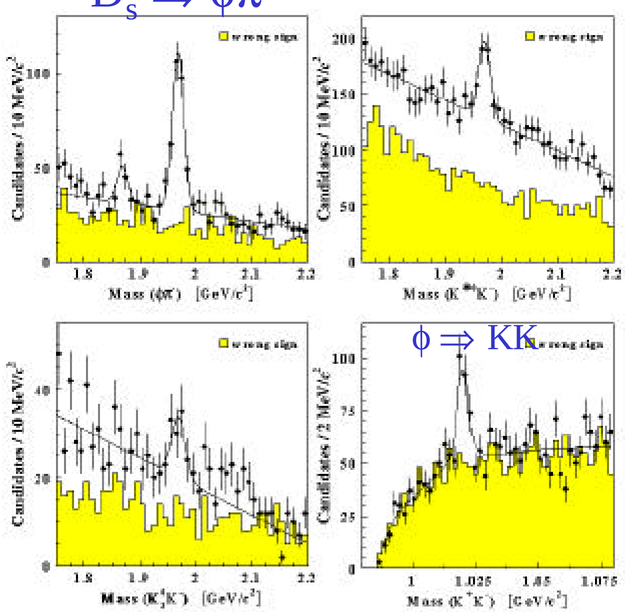
$B_s \Rightarrow J/\psi\ \phi$

(32 events)

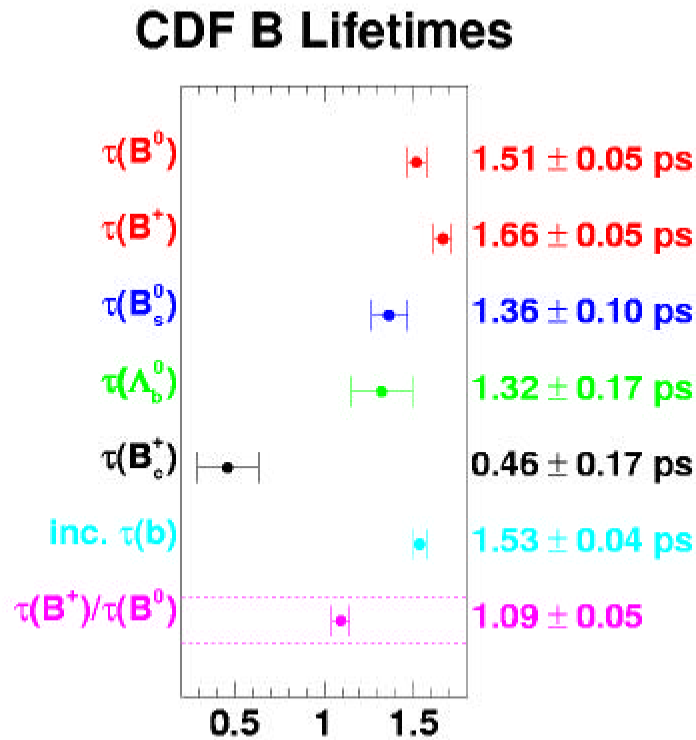
CDF B Physics: Lifetimes

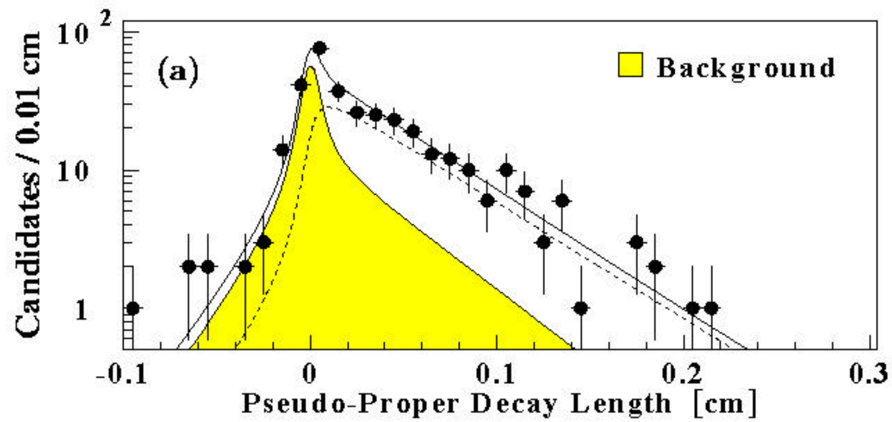
- **B hadron lifetimes**
  - Extract |Vcb| using $1/\Gamma$
  - Lifetimes are the same at 0^{th} order for all B hadrons
  - $\tau(B^+)/\tau(B^0) = 1.09 \pm 0.05$
  - $\tau(B_s) = 1.36 \pm 0.09\,^{+0.06}_{-0.05}$ ps
  - $\Delta\Gamma_s/\Gamma_s < 0.83$ at 95 % CL

$D_s \Rightarrow \phi\pi$



$B_s \Rightarrow D_s\, l\, \nu$
(600 events)

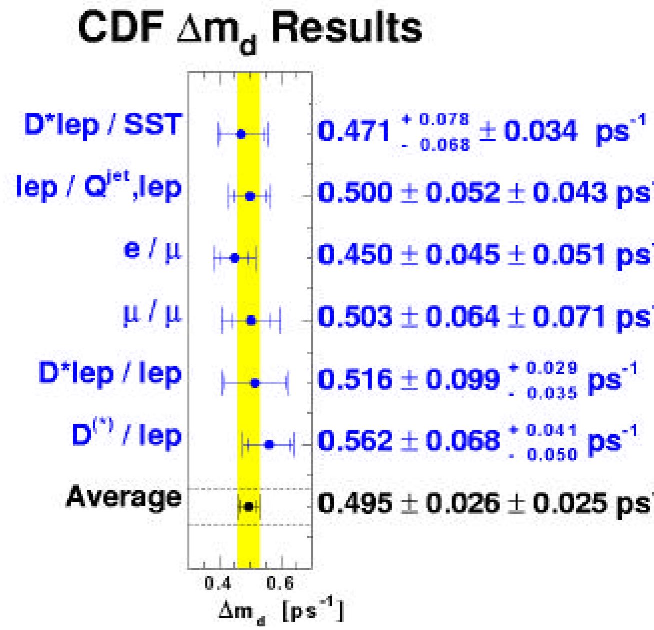




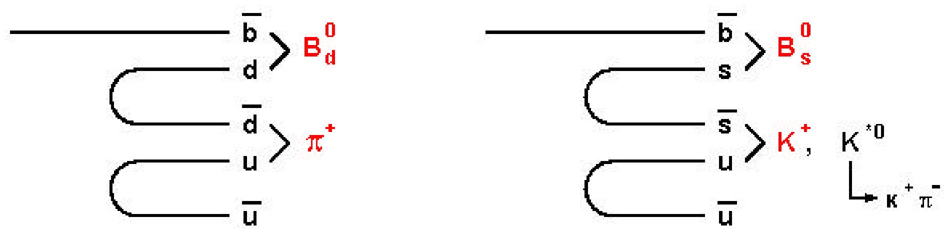
 P.J. Wilson, 8 Jan 2002

CDF B Physics: Mixing

- **$B^0/\overline{B^0}$ Flavor Oscillations**
  - ➢ Semileptonic $B^0/\overline{B^0}$ decays
  - ➢ Tag flavor at production
    - Soft Lepton Tagging
    - Jet Charge Tagging (Σ Q $P_T/\Sigma P_T$)
    - Same Side Tagging
  - ➢ $A(t) = D\cos(\Delta m_d t)$, $D \equiv (1-2w)$
- **Δm_d = 0.495 ± 0.026 ± 0.025 ps^{-1}**

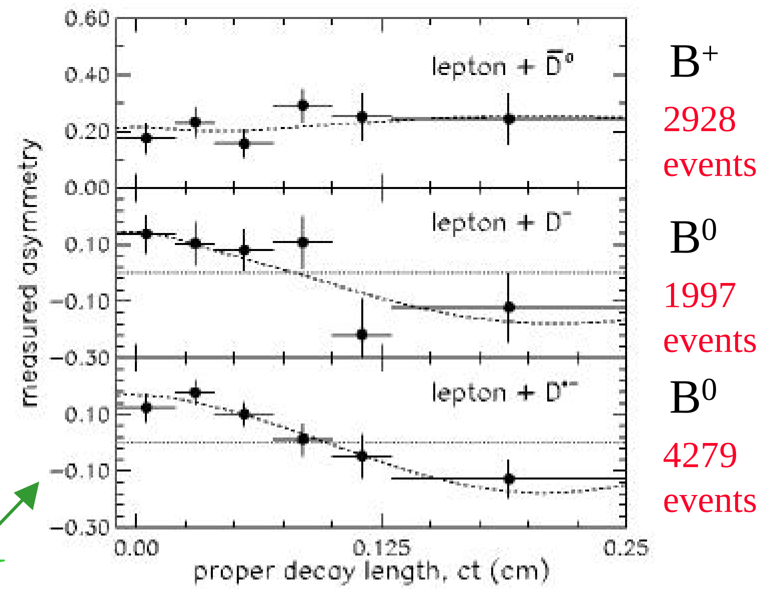


Same side tagger



☞ fragmentation particle likely to be pion (kaon)

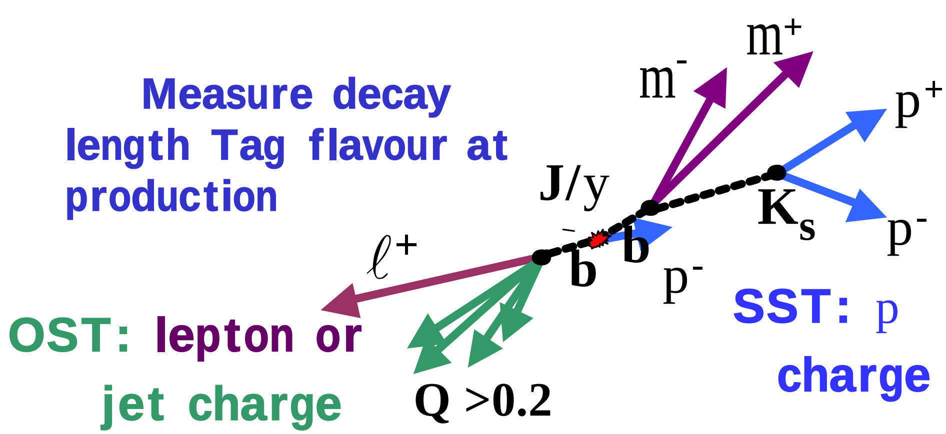
☞ charge identifies *b*-quark flavor

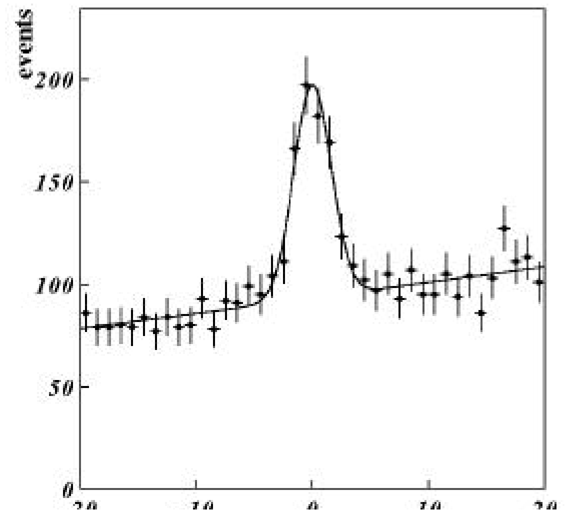


SST in $B^0 \Rightarrow l^+ D^{*-} X$

CDF B Physics: sin2b

- **Measurement of sin2b**
  - ➢ CP asymmetry in $B^0 \Rightarrow J/\psi K_s$
  - ➢ $A_{CP}(t) = \sin 2\beta \sin(\Delta m_d t)$
  - ➢ Combine taggers: εD^2 (%)
    - SLT: 2.2 ± 0.5
    - JCT: 2.2 ± 1.3
    - SST: 2.1 ± 1.0
  - ➢ Combined $\varepsilon D^2 = (6.3 \pm 1.1)\%$
  - ➢ Taggers calibrated on mixing
- **sin2b = 0.79 $^{+0.41}_{-0.44}$ (stat + sys)**

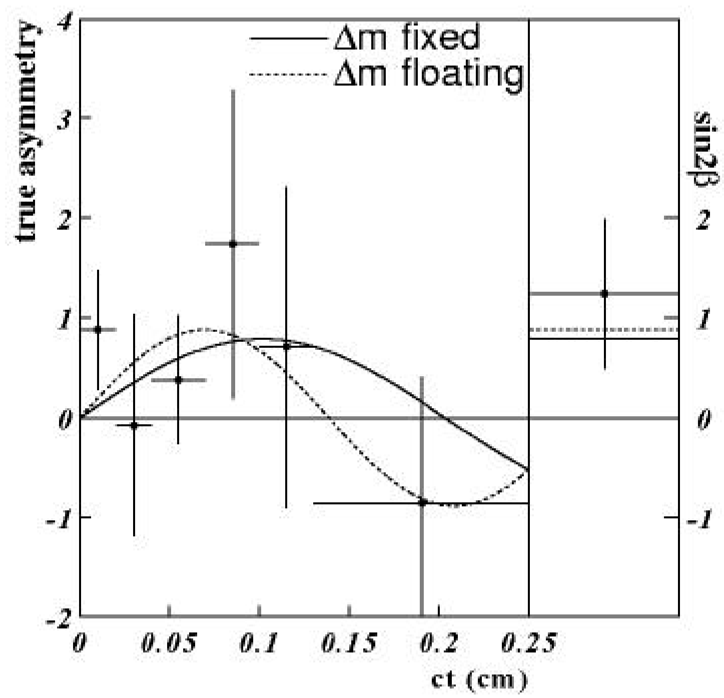




$B^0 \Rightarrow J/\psi K_s$

395 ± 31 events

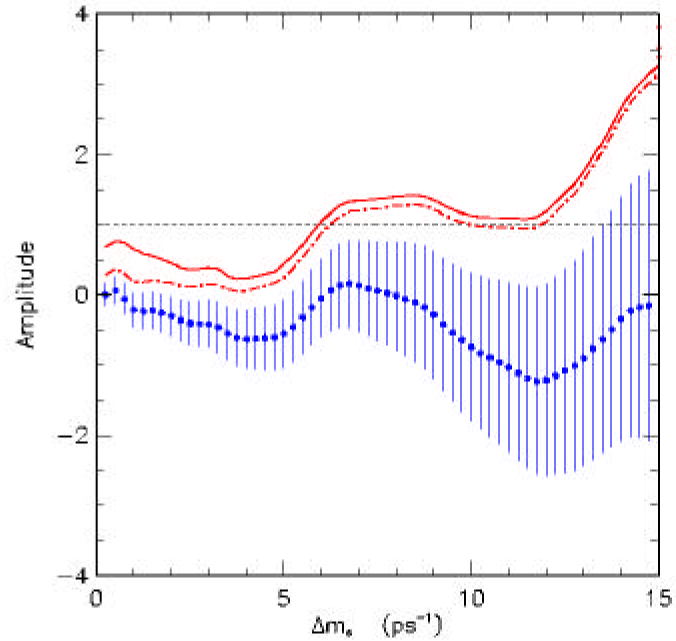
S/N = 0.7



CDF B Physics: Bs

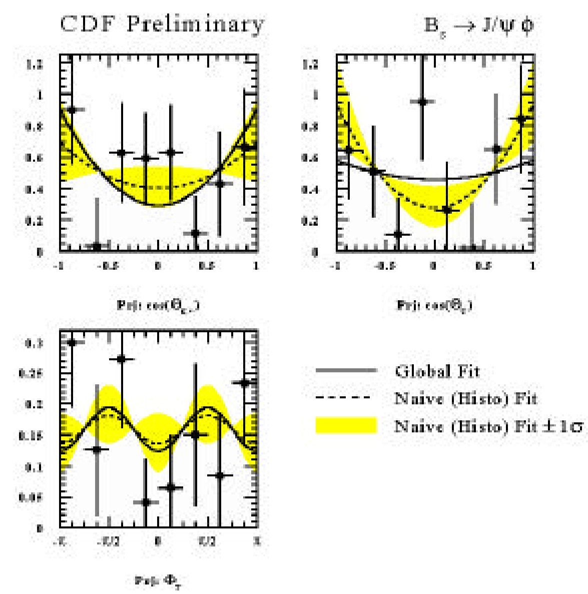
- **Limit on B_s mixing**
  - $B_s \Rightarrow \nu l^+ \phi X;\ \phi \Rightarrow K^+K^-$
  - Flavor tagging as in B^0
  - Amplitude fit method

$Dm_s > 5.8\ ps^{-1}$ at 95% CL



- CP fraction in $B_s \Rightarrow J/\psi\phi$
  - Angular fits in transversity basis
  - Find parity-odd contribution

$|A_\wedge|^2 = 0.23 \pm 0.19 \pm 0.04$



Top from Search to Studies

- **Top lifetime**

  t_{top} **~ 1/ M$^{3}_{top}$~10^{-24} sec**

  t_{qcd} **~** L^{-1} **~10^{-23} sec**

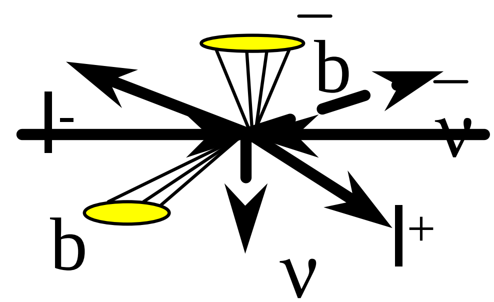
the top quark does not hadronize. It decays as a free quark!

- **BR(t ® Wb)** @ 100 %

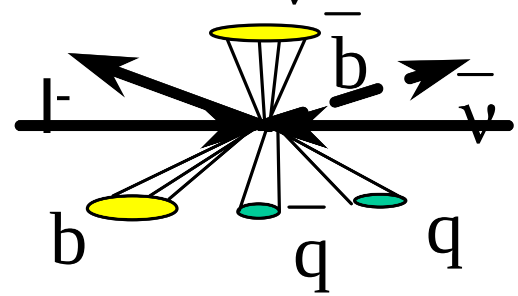
Decay channels:

More Signal

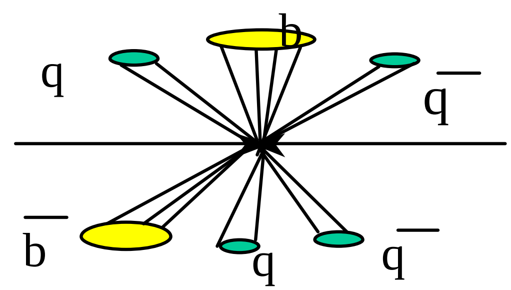
- **Dilepton**
  - Both W's decay leptonically
  - final state: ln ln **bb**



- **Lepton + Jets**
  - One W's decays leptonically
  - final state: ln qq **bb**

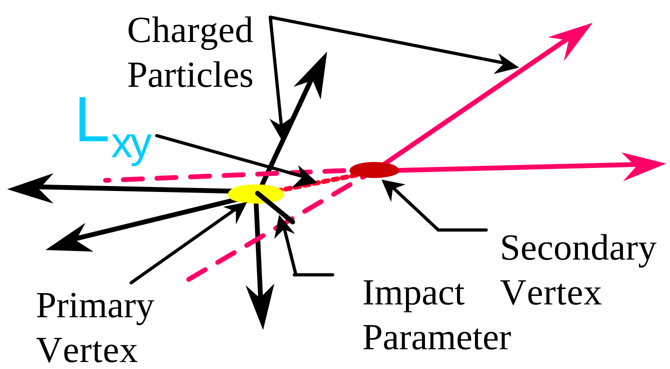


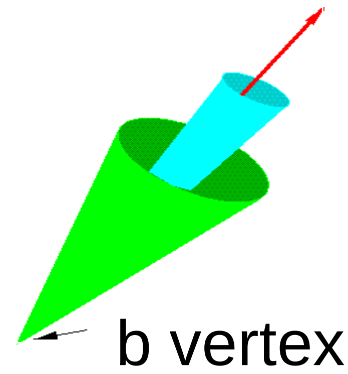
- **All-Hadronic**
  - Both W's decay hadronically
  - final state: qq qq **bb**



More Background

Finding b-Jets at CDF/D0



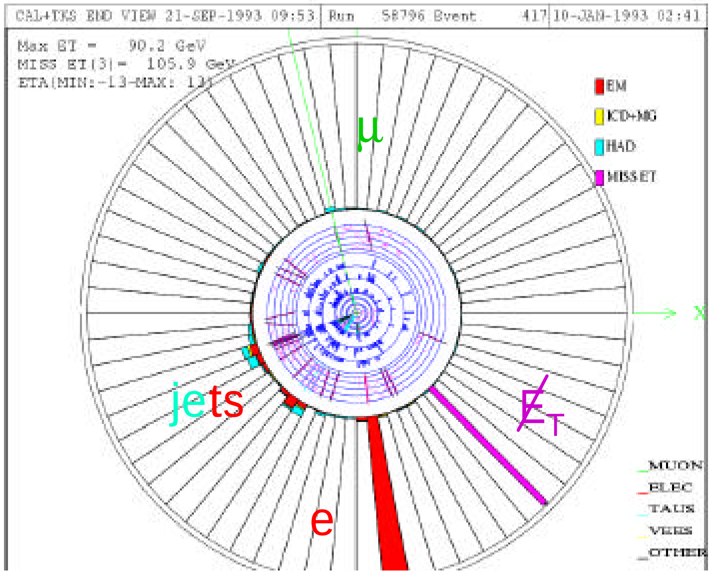


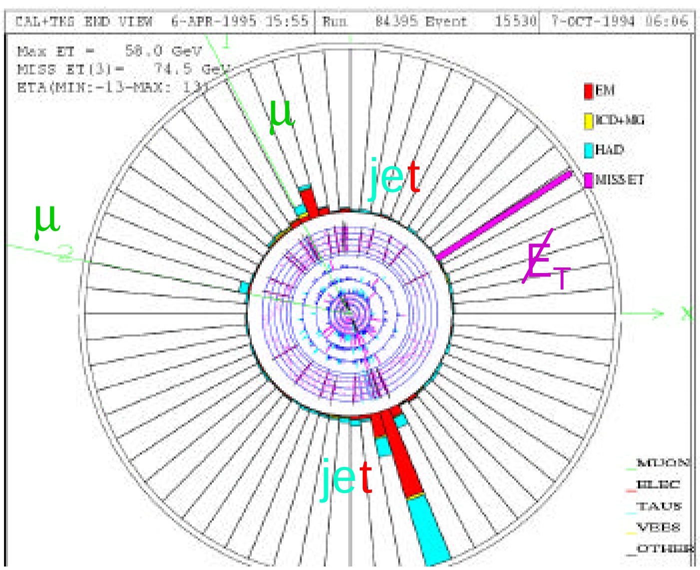
- **b-quark lifetime**
  ct ~ 450mm
  - b hadrons travel Lxy ~ 3 mm before decay
- **Secondary VerteX Tagging**
- **e(SVX) ~ 25%**

- **Identify semileptonic B decay**
  - $b \to l$, $b \to c \to l$
- **Soft Lepton Tagging**
- **e(SoftLeptonTagging) ~ 20%**

Top Events

D0 Diplepton Events





CDF Lepton + 4 Jet Event

e + 4 jet event

40758_44414

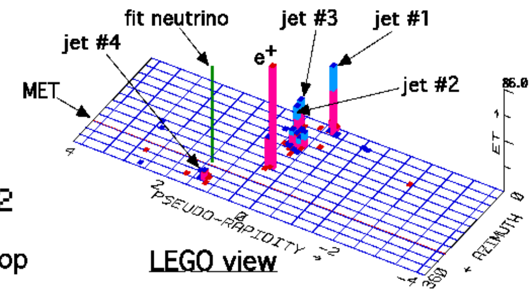
24-September, 1992

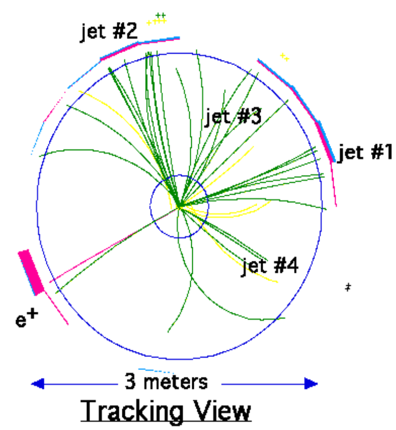
TWO jets tagged by SVX

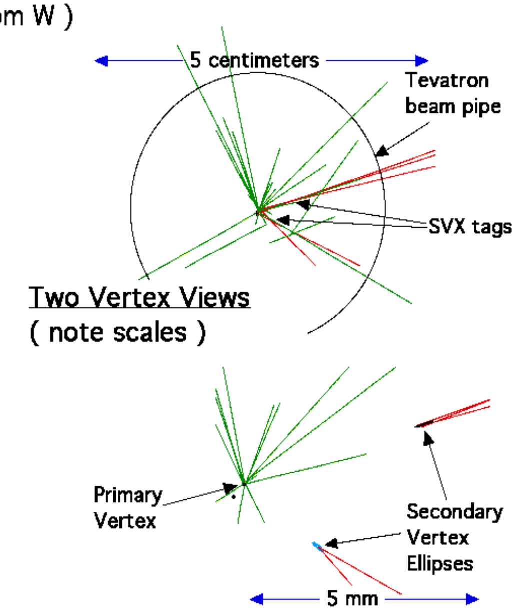
fit top mass is 175±10 GeV/c^2

e^+, Missing E_t, jet #4 from top

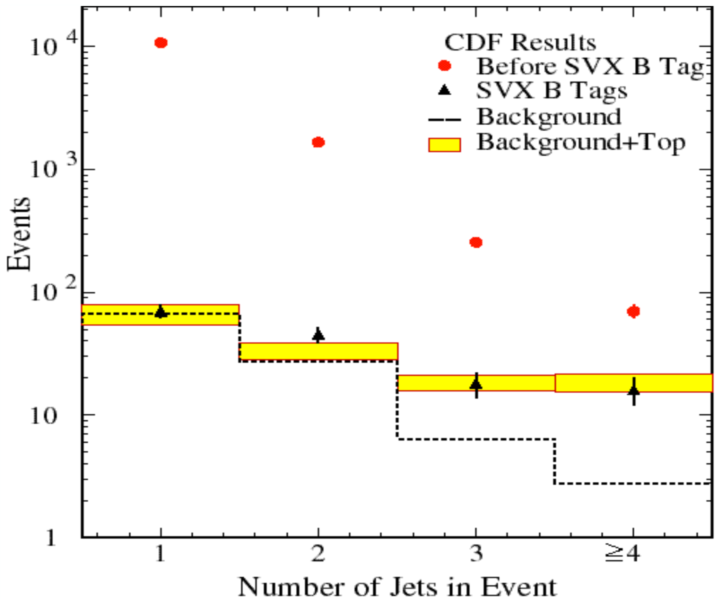
jets 1,2,3 from top (2&3 from W)

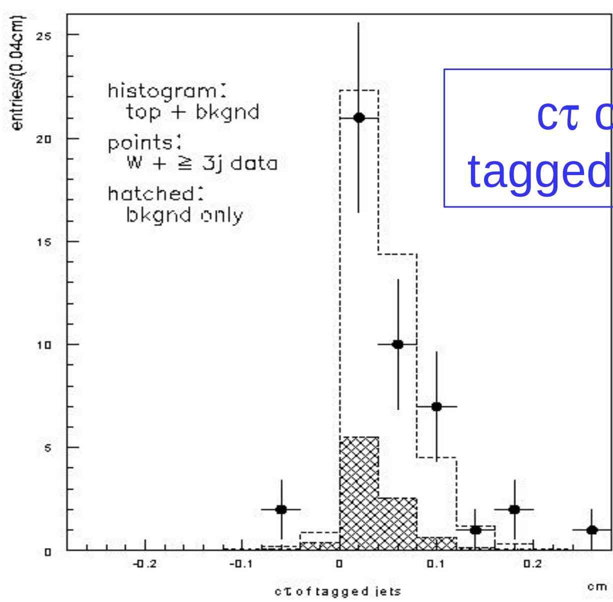




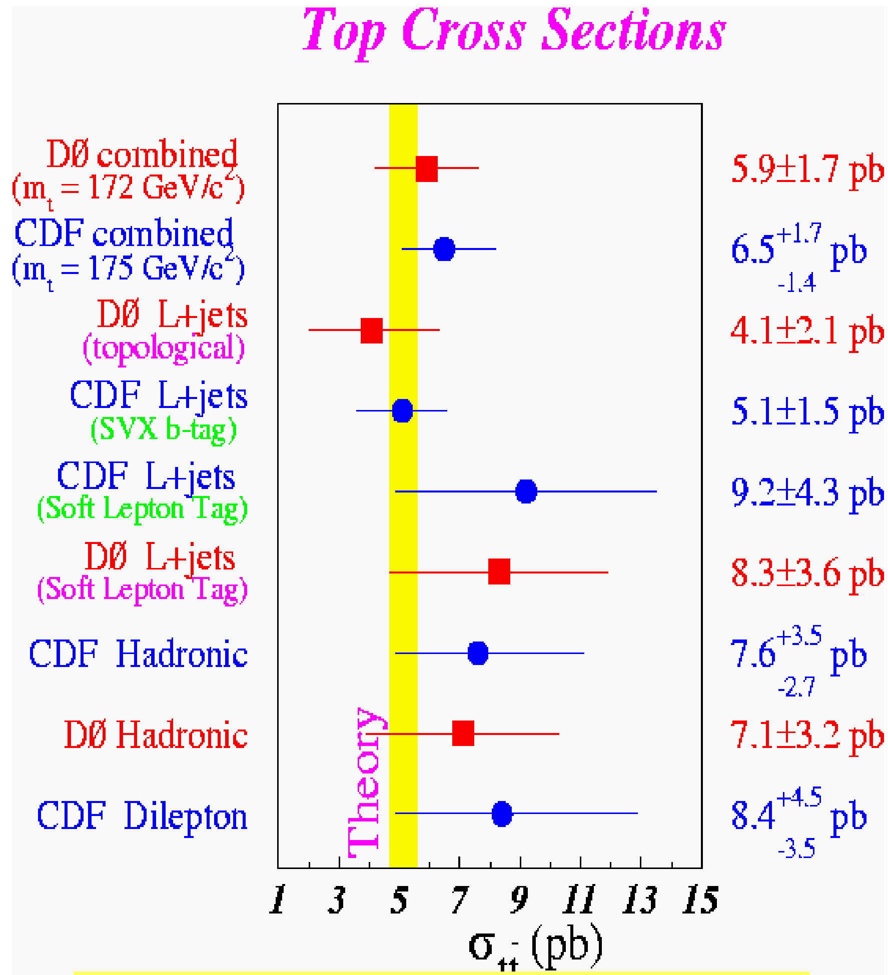


Top Discovery→Cross Section





cτ of tagged jets



CDF $s\,(t\bar{t}) = 6.5^{+1.7}_{-1.4}$

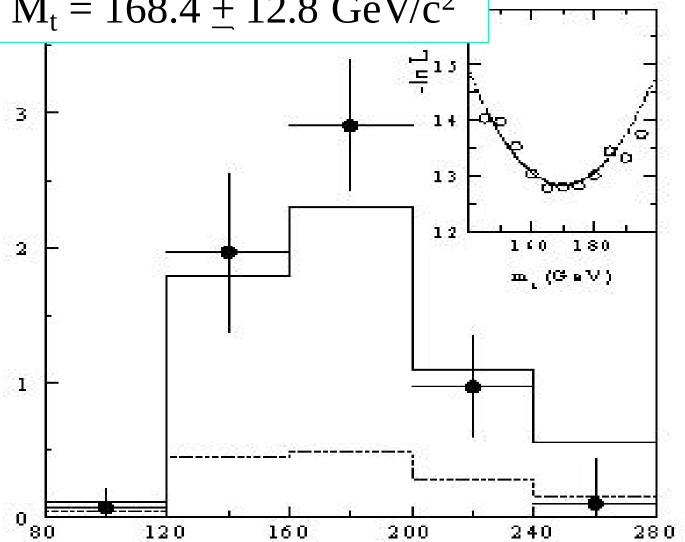
DØ $s\,(t\bar{t}) = 5.9 \pm 1.7$

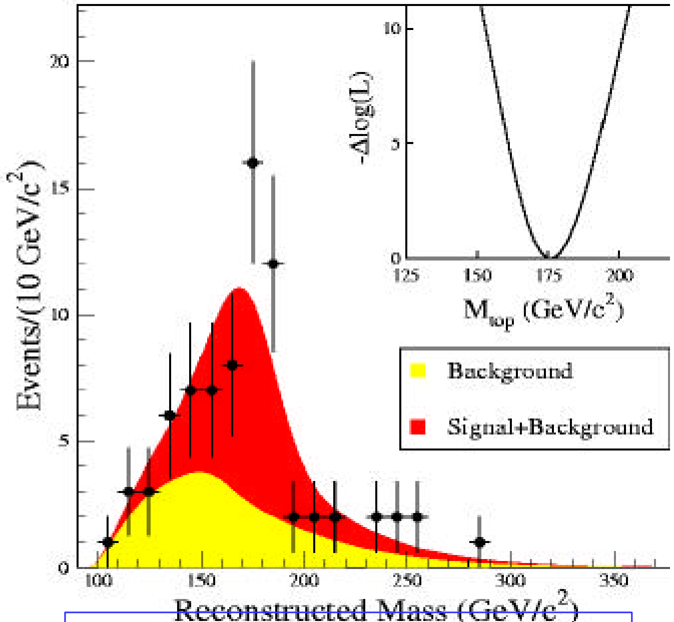
Measurement of M_{Top}

Likelihood Fits to MC templates (ala M_W)

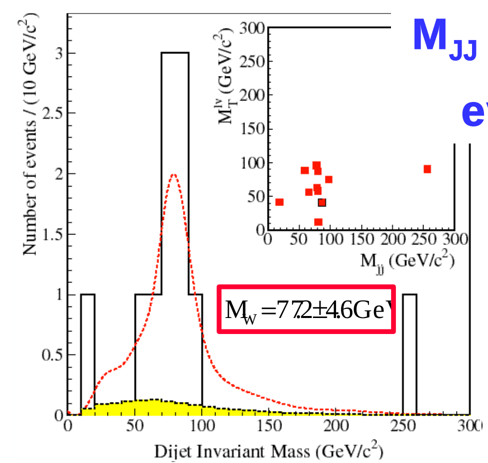
- **Use Jet, m, e calibration from EW/QCD**
- **Additional corrections for b-jets to account for m and n from b->cln (MC)**

D0: 6 dilepton events
$M_t = 168.4 \pm 12.8$ GeV/c^2





CDF: 76 l + jet events
$M_t = 176.1 \pm 7.4$ GeV/c^2



M_{JJ} in l+jet events

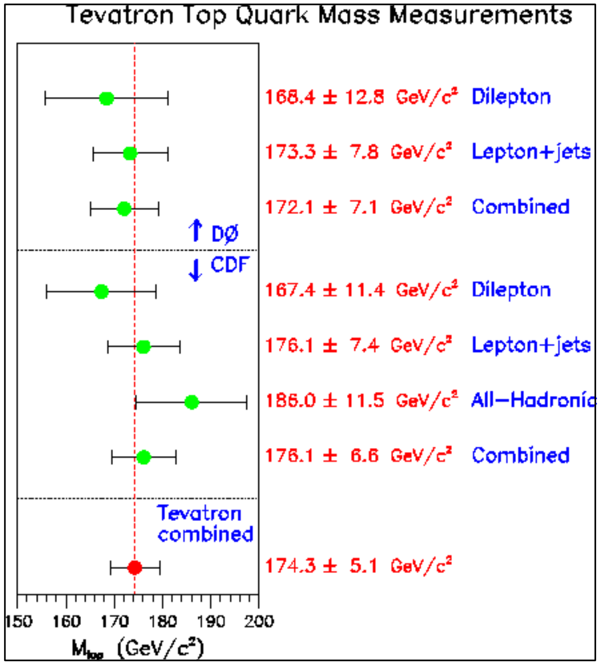
Comparable precision to b quark mass

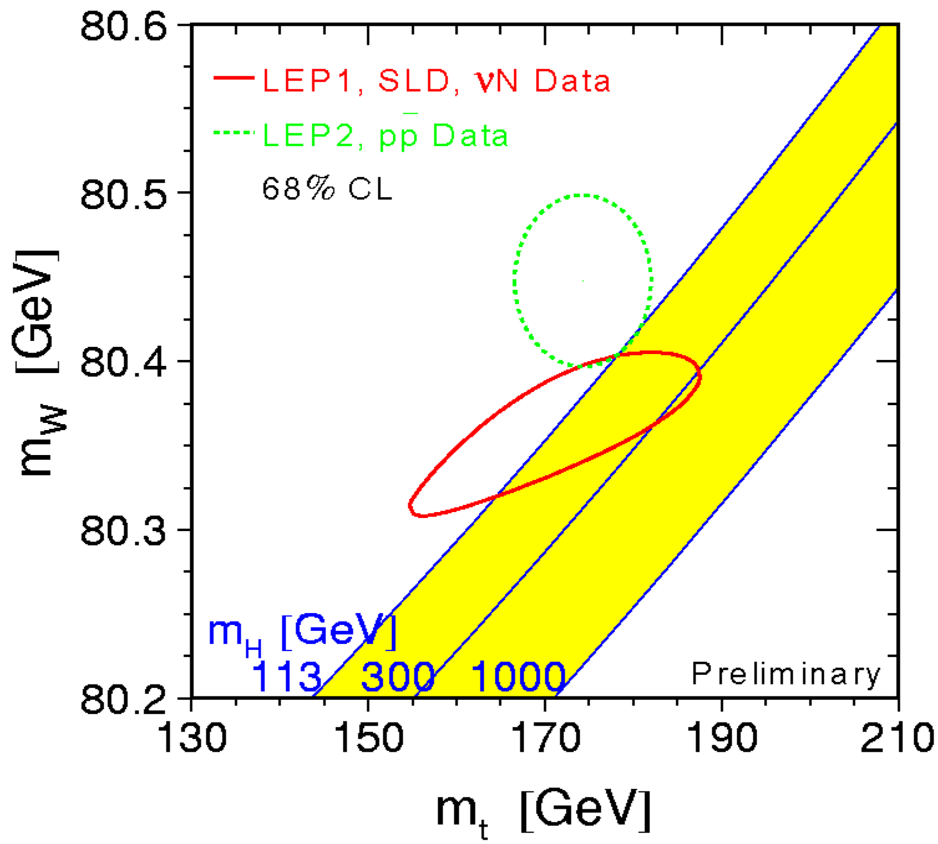
$M_t = 174.3 \pm 5.1$ GeV/c^2

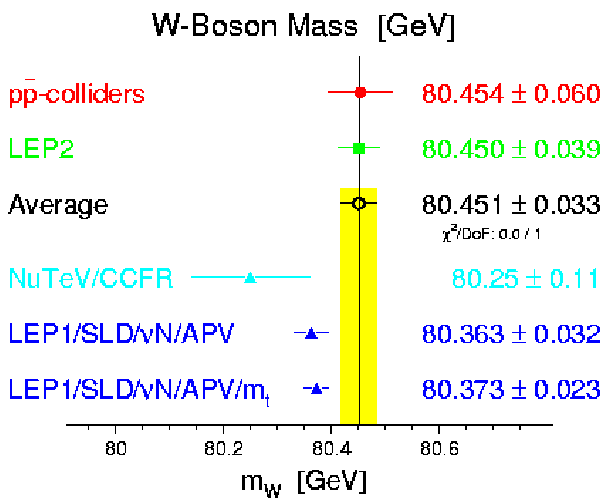
$M_t / M_b = 36 \pm 2$

$M_t \sim$ scale of EWSB $= (2\sqrt{2}\, G_F)^{-1/2} \sim 175$ GeV

M_{top} and $M_W \rightarrow M_{Higgs}$

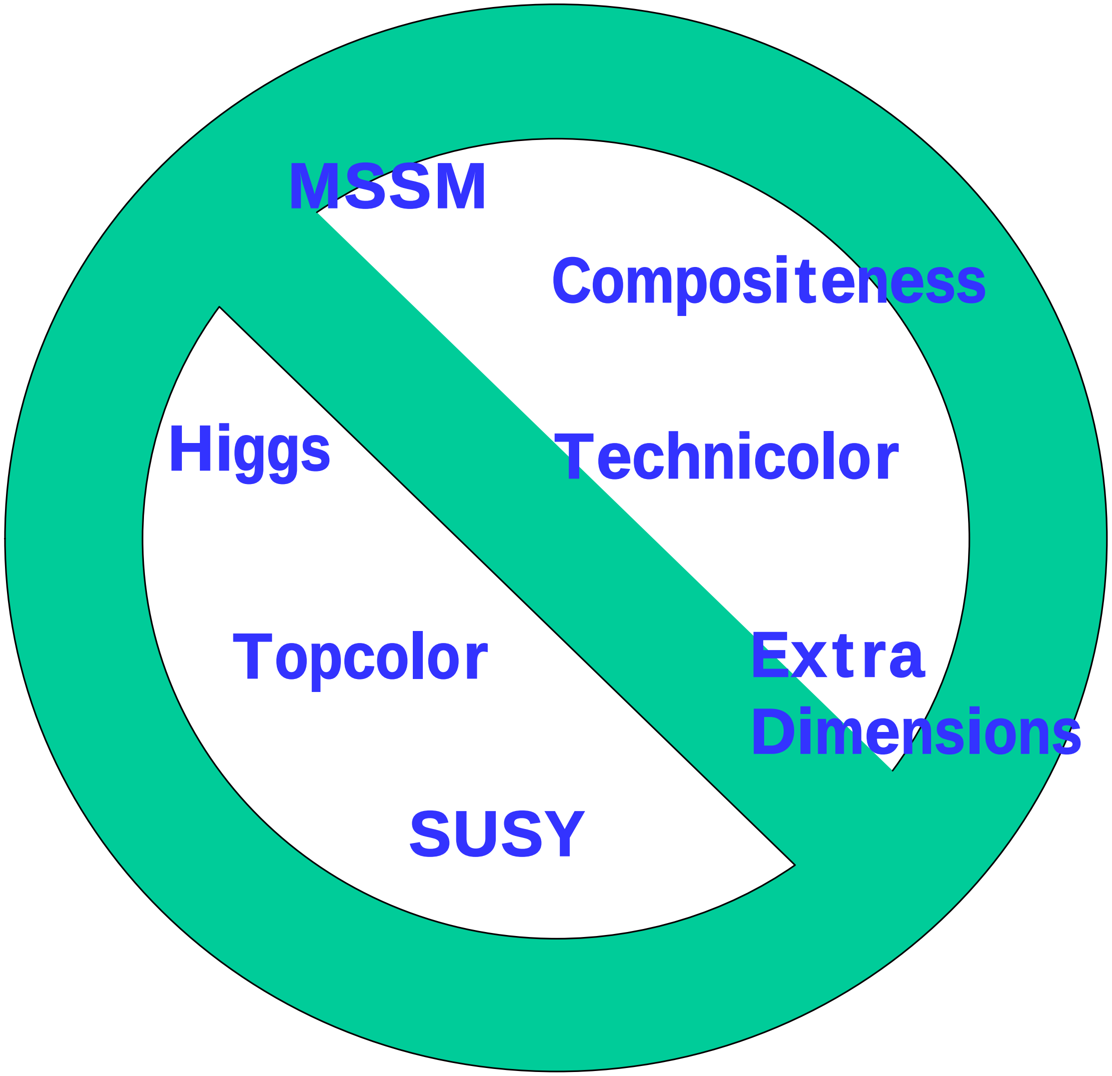






EW Meas : M_{Higg} <165 GeV @95%CL
LEP II Higgs Searches :
M_{Higg} > 113 GeV @95%CL
LEP II Hint @ M_{Higg}= 115 GeV
⇒ Run 2 Challenge

New Phenomena



NOT YET!

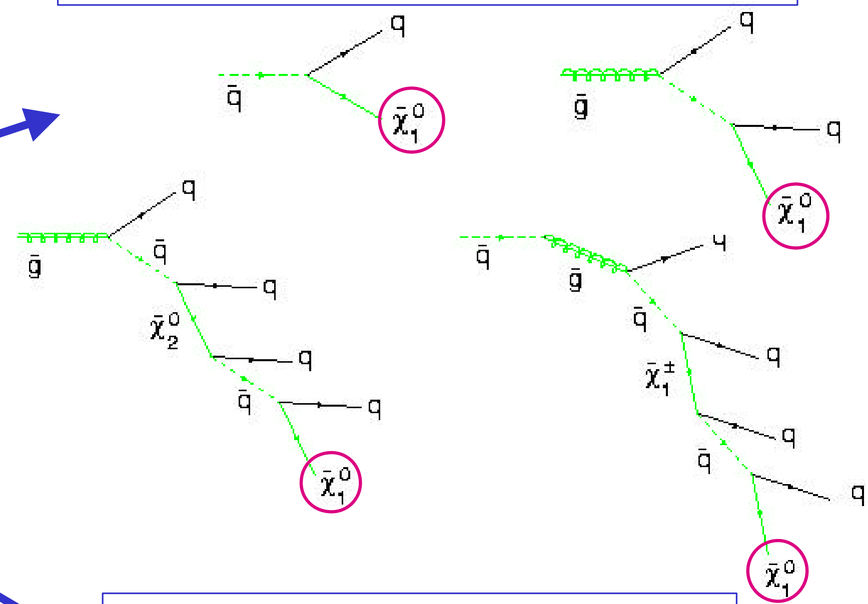
New Adventures - Basic Tools

- **Indirect searches:**
  - Deviations in comparisons of precision measurements with theory (e.g. width of W or Z)
  - Excess in High E_T or high Mass production (e.g. jets)
- **Direct searches**
  - Model driven (e.g. $\not{E}_T$ + jets for squarks and gluinos)
  - Signature based – not necessarily driven by a specific model
- **All use the tools of EW, QCD, b and t physics to classify events**

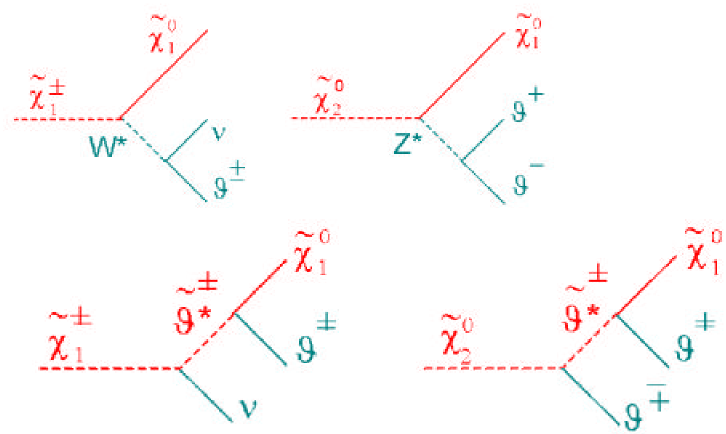
Supersymmetry

- **Run 1 focused on:**
  - ➢ Typically within the MSSM and minimal-supergravity
  - ➢ squarks and gluinos
  - ➢ stop and sbottom
    - stop ® b + $\chi^{+/-}$ or W
    - stop ® c + χ^{0}
    - sbottom ® 2 b jets + $\not{E}_T$
  - ➢ charginos and neutalinos
  - ➢ Moved into R-Parity violating models as well
- **Some excursions into other territory:**
  - ➢ Gauge mediated touched off by $ee\gamma\gamma\not{E}_T$ event from CDF
  - ➢ Gravitinos, sgoldstinos…

Squark and Gluino ® $\not{E}_T$ + n jets



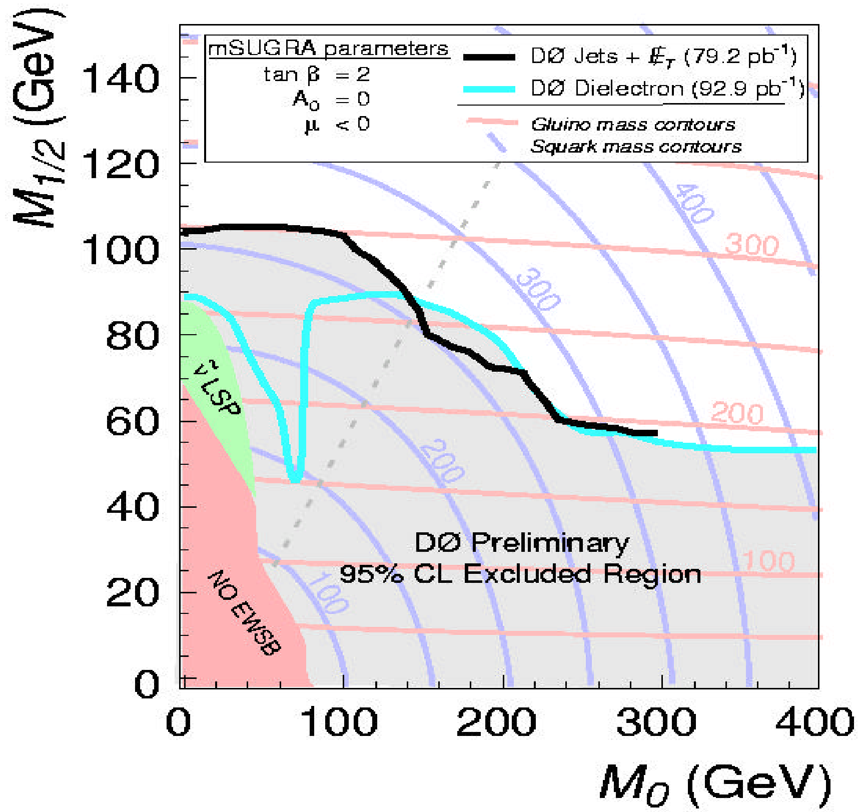
Gauginos ® $\not{E}_T$ + 3 leptons



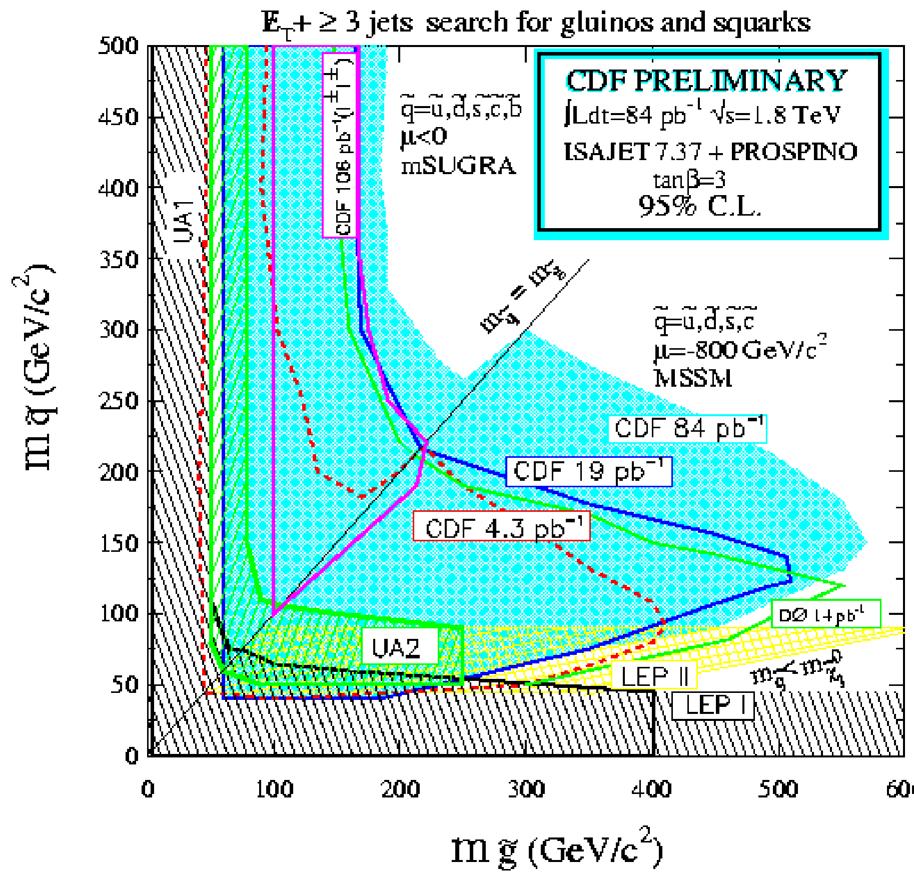
Squarks and Gluinos

D0 searches:

1. 2 electrons, 2 jets + Missing E_T
2. jets plus missing E_T and no electrons/muons



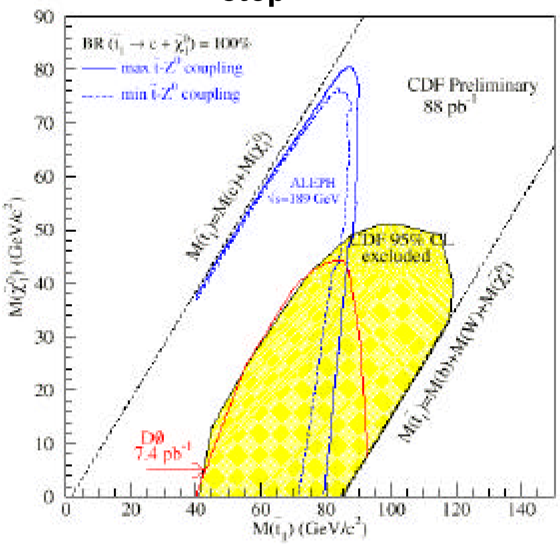
CDF search: 3 jets + Missing E_T



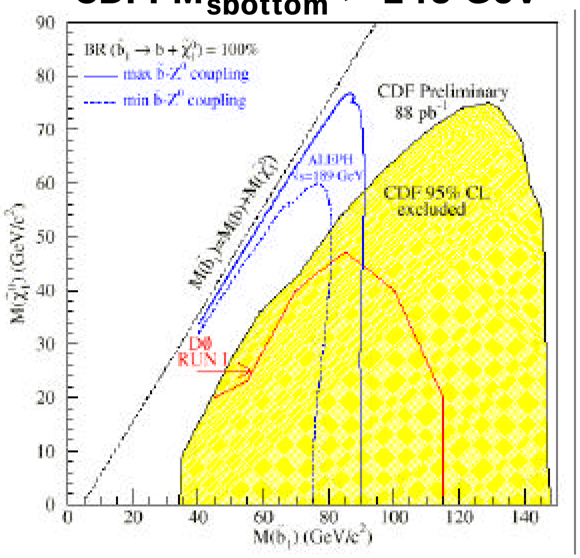
Run 1 reach
gluino ~ 200 GeV
squark ~ 250 GeV

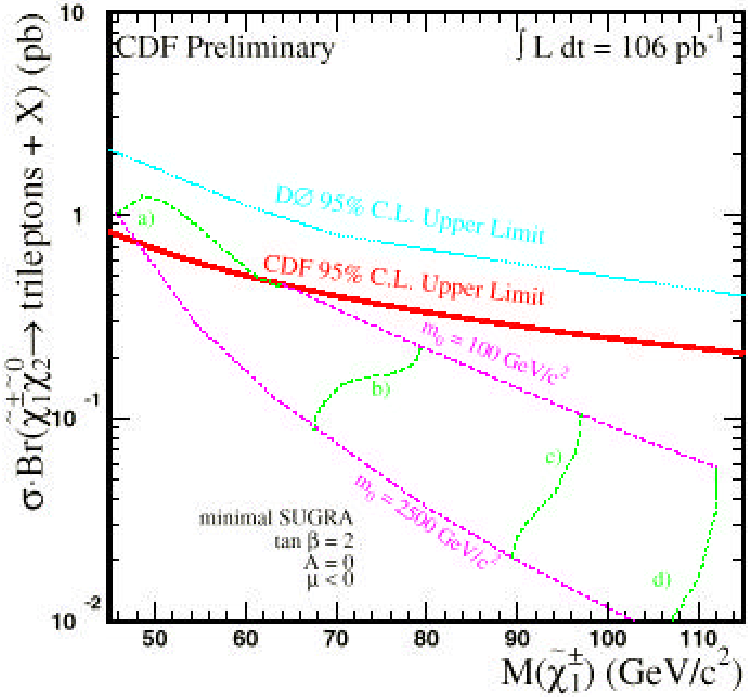
Stop, Sbottom and Gauginos

CDF: M_{stop} > 115 GeV



CDF: $M_{sbottom}$ > 145 GeV





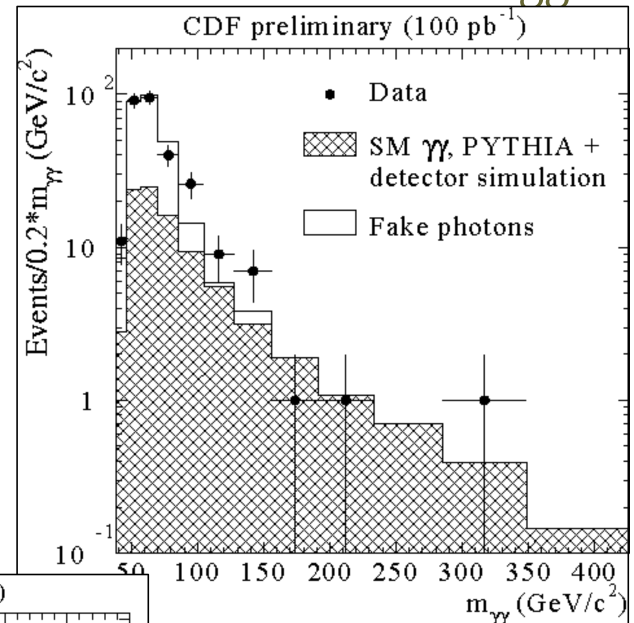
CDF Trilepton search: not competitive with LEP in Run 1.

Could be very interesting in Run 2

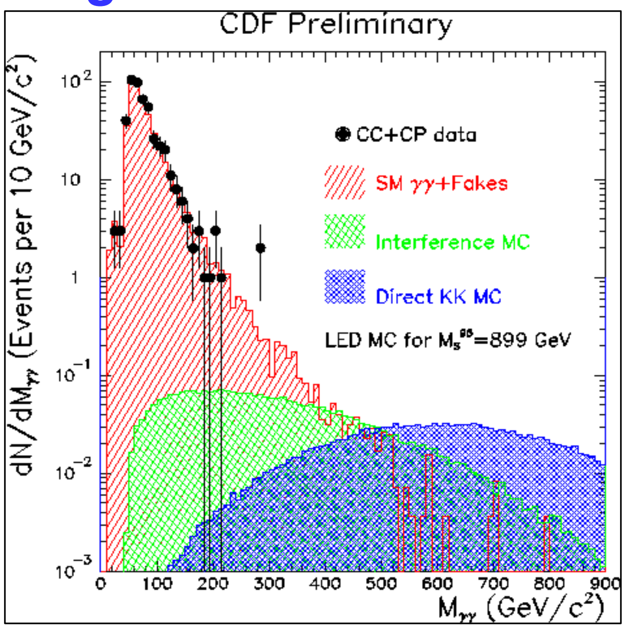
A Signature Based Search: M_{gg}

Searches for new physics involving two high E_T photons

- CDF $ee\gamma\gamma \not{E}_T$ event motivated searches for $l\gamma\not{E}_T$, $\gamma\gamma + X$ ® No new physics
- General search in $M_{\gamma\gamma}$ inclusively and $M_{\gamma\gamma}$ in $\gamma\gamma + W/Z$ results in limits on:

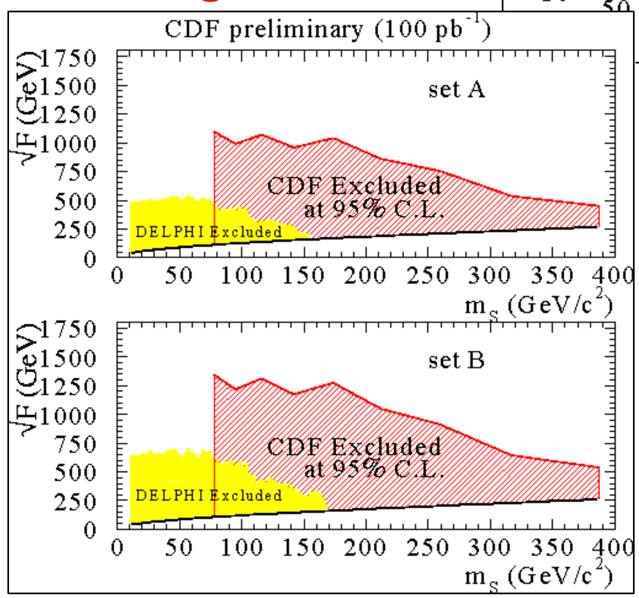


Large Extra Dimensions

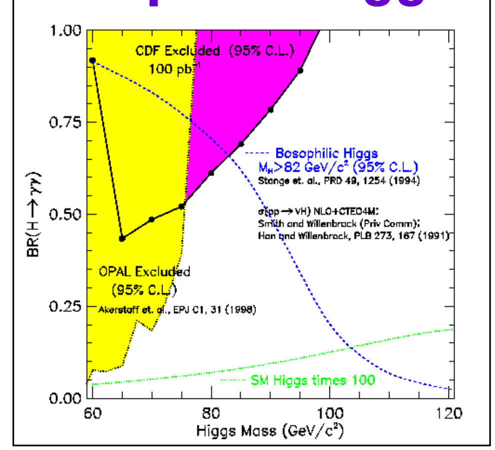


MS > 899 GeV (L_{Hewett} = -1)
MS > 797 GeV (L_{Hewett} = +1)

Sgoldstinos



Bosophilic Higgs



Best Limits now from LEPII

Summary

- **Tevatron Run 1 was a very successful program:**
  - ➢ Excellent accelerator performance
  - ➢ Discovery of top quark!
  - ➢ Top mass, cross section…
  - ➢ Precision W mass and width measurements
  - ➢ B hadron lifetimes
  - ➢ B_c meson discovered!
  - ➢ Measurement of $\sin 2\beta$
  - ➢ Many tests of perturbative QCD
  - ➢ …
- **CDF and D0 learned many techniques…**
  - ➢ b-tagging for top (and Higgs!) with soft leptons and Si
  - ➢ Flavor tagging for B-physics
  - ➢ Deficiencies of our experiments…

Summary

- **Deficiencies we wanted to correct after Run 1:**
  - More collisions !
  - CDF wanted:
    - more Si coverage – greater b tagging efficiency
    - Higher bandwidth trigger – more B physics
    - Greater lepton coverage – W's, b's, J/psi's
    - Better calorimetry at high eta – W's, jets
    - Particle ID for b-flavor tagging
  - D0 wanted:
    - Magnet + tracking for P_T measurement – leptons and b's
    - Si for b tagging – greater b-tagging, B physics
    - Improved muon systems:
    - Higher bandwidth trigger
  - See tomorrow what we got!