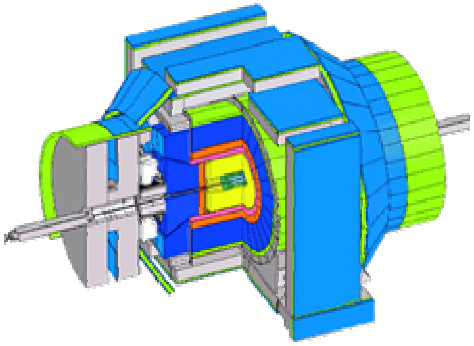


CDF at the Tevatron Collider Run 2

On the Energy Frontier

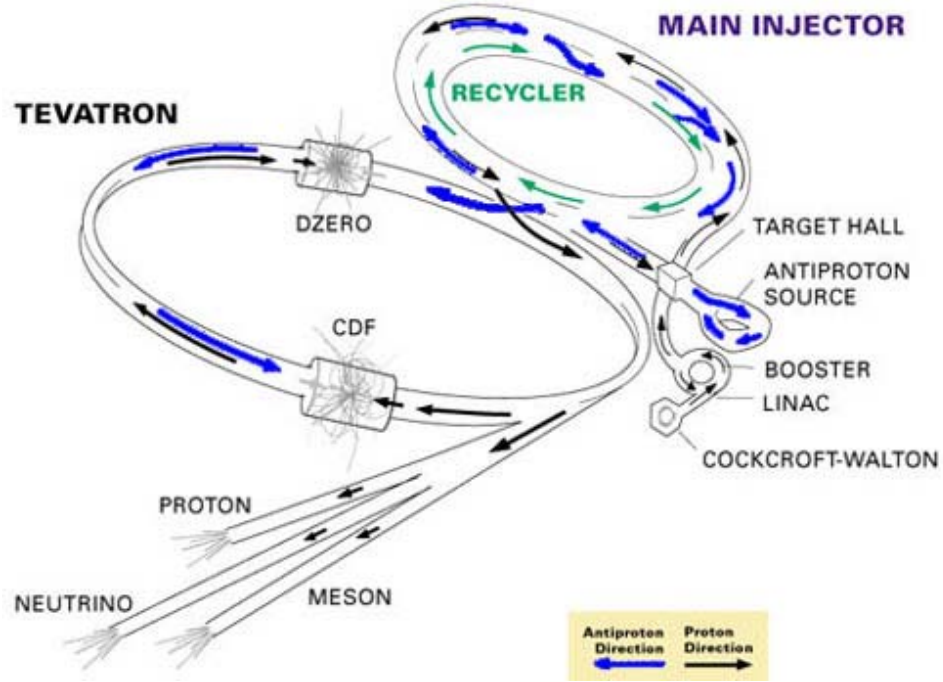
Robin Erbacher

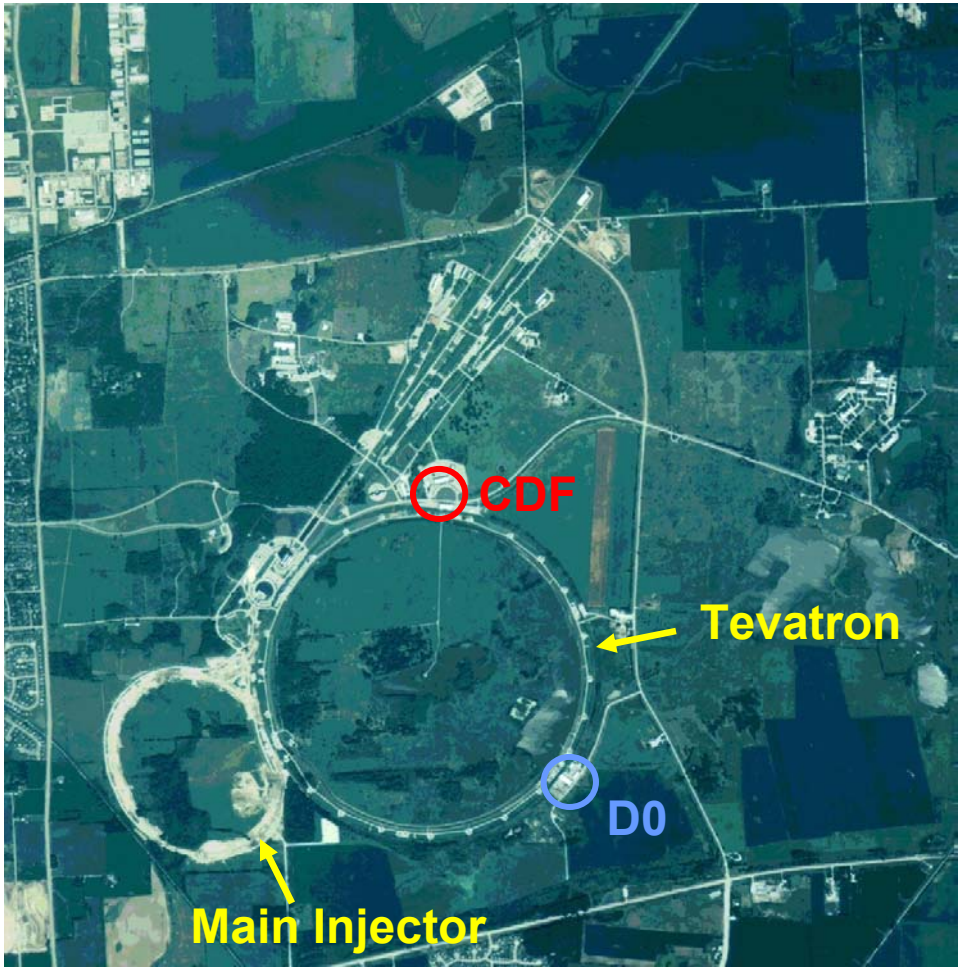
Fermilab-- Batavia, Illinois U.S.A.

Prospects and Status of CDF

Michigan State University, September 2002

Fermilab Tevatron Upgrade





- **New Main Injector:**
  - Improve p-bar production
- **Recycler ring:**
  - Reuse p-bars!

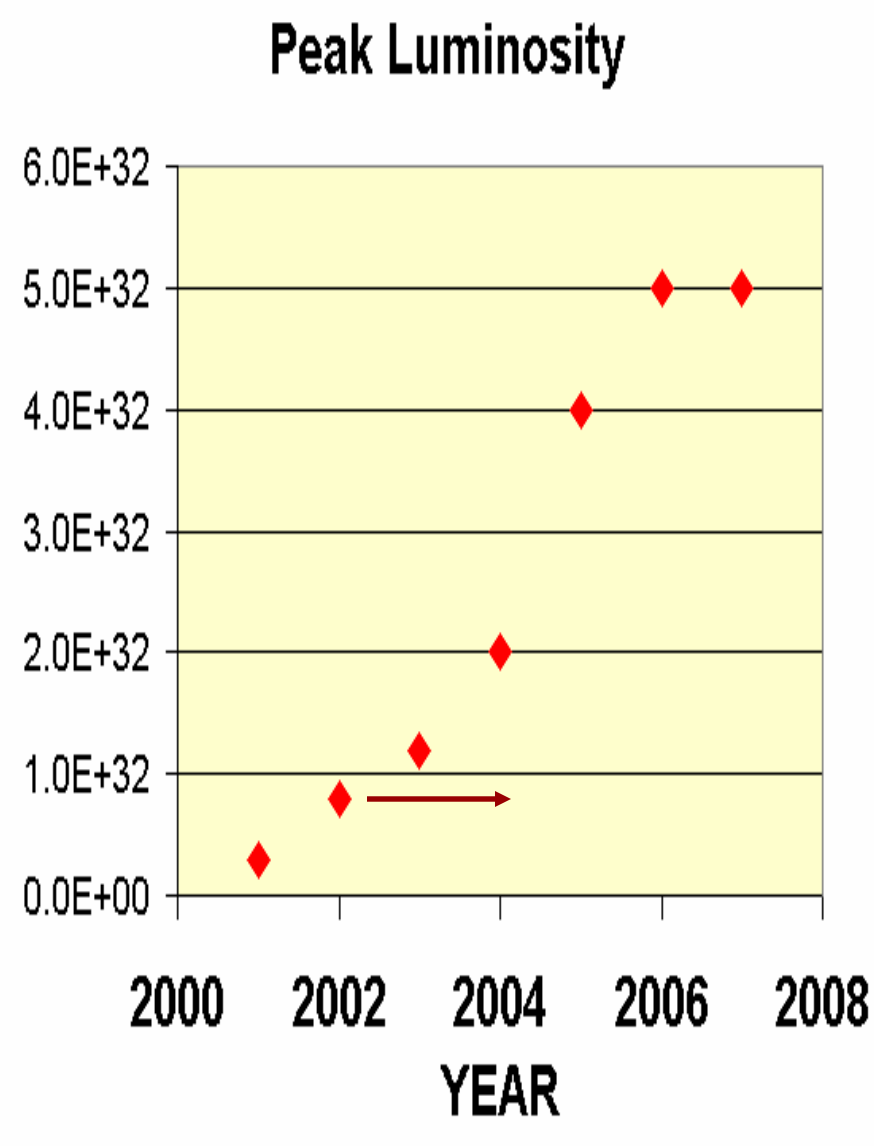
Tevatron Upgrade Details

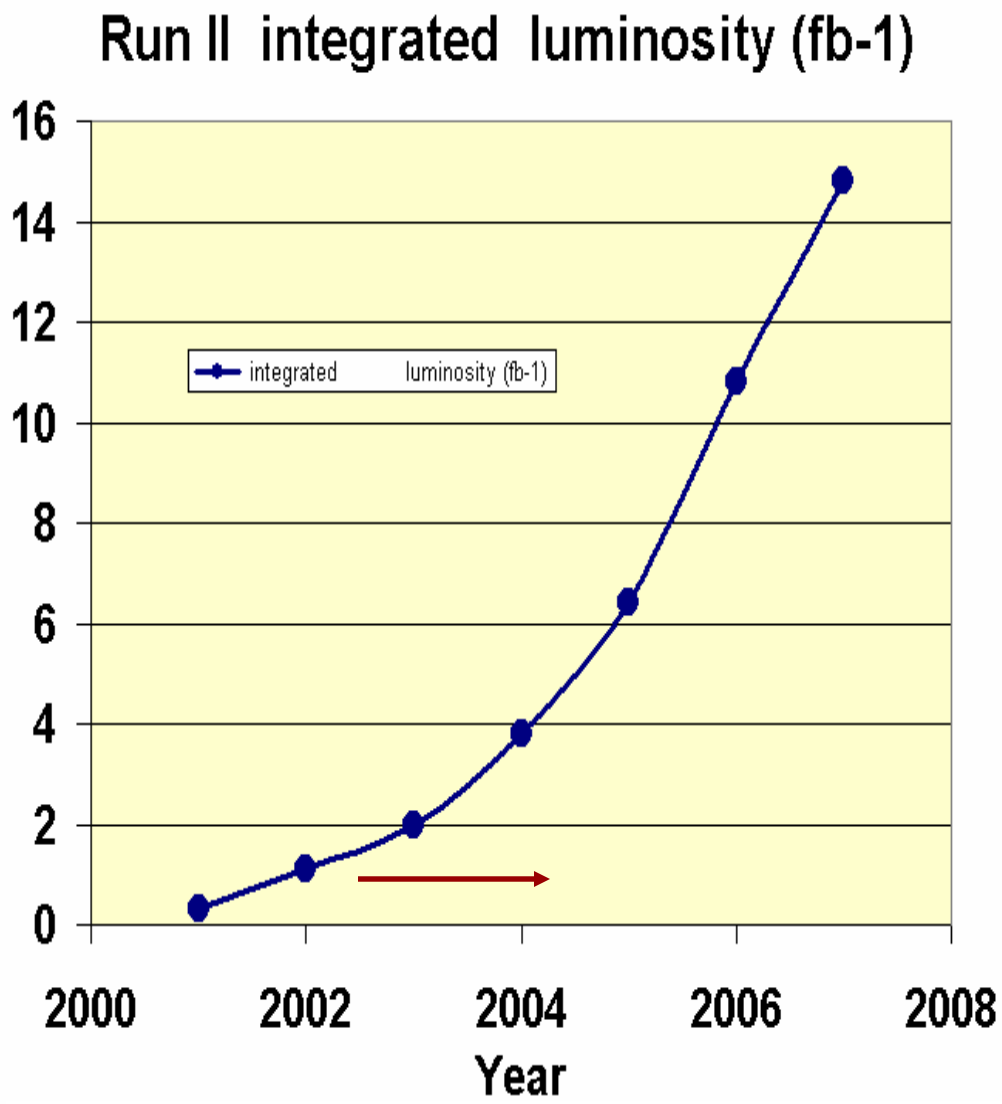
- **Run 1 (ended Feb '96):**
  - CDF integrated 110 pb^{-1}
  - Lum > 10^{31} $cm^{-2}s^{-1}$
- **Run 2 Upgrades:**
  - Main Injector : (factor of ~5)
    - Goal: ~O(10^{32} cm^{-2} s^{-1})
  - Recycler : (factor of ~2)
    - Re-cool antiprotons from the Tevatron
- **Bunches**
  - Initially 36x36 at 396 ns
  - ~~Ultimately 141x121 at 132ns~~
- **$\sqrt{s}$ = 1.98 TeV**
  - Ultimately >2 TeV?

RUN	Ib (1993-95) (6x6)	Run IIa (36x36)	Run IIa (140x103)	Run IIb (140x103)	
Protons/bunch	2.3×10^{11}	2.7×10^{11}	2.7×10^{11}	2.7×10^{11}	
Antiprotons/bunch*	5.5×10^{10}	3.0×10^{10}	4.0×10^{10}	1.0×10^{11}	
Total Antiprotons	3.3×10^{11}	1.1×10^{12}	4.2×10^{12}	1.1×10^{13}	
Pbar Production Rate	6.0×10^{10}	1.0×10^{11}	2.1×10^{11}	5.2×10^{11}	hr^{-1}
Proton emittance	23π	20π	20π	20π	mm-mrad
Antiproton emittance	13π	15π	15π	15π	mm-mrad
β^*	35	35	35	35	cm
Energy	900	1000	1000	1000	GeV
Antiproton Bunches	6	36	103	103	
Bunch length (rms)	0.60	0.37	0.37	0.37	m
Crossing Angle	0	0	136	136	μrad
Typical Luminosity	0.16×10^{31}	0.86×10^{32}	2.1×10^{32}	5.2×10^{32}	$cm^{-2}sec^{-1}$
Integrated Luminosity†	3.2	17.3	42	105	pb^{-1}/week
Bunch Spacing	~3500	396	132	132	nsec
Interactions/crossing	2.5	2.3	1.9	4.8	

Total Run 1 data = 1 week running in Run 2b

Run 2 Luminosity Goals

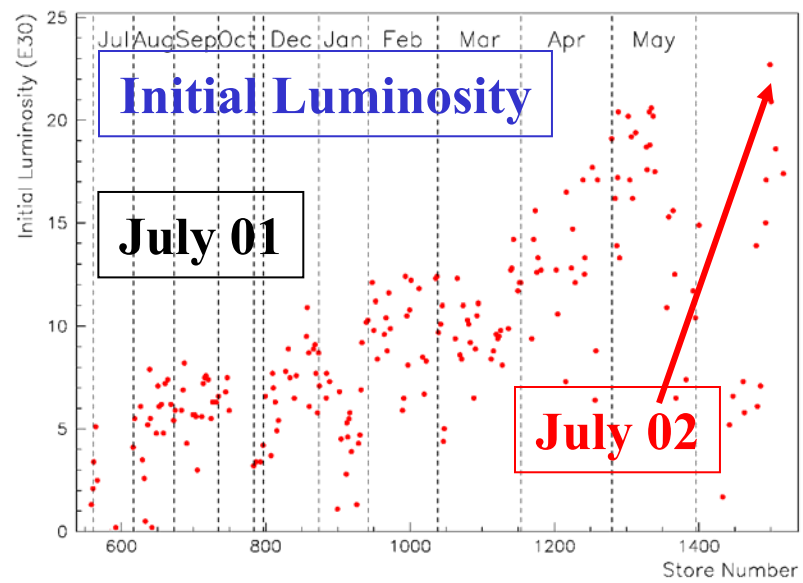


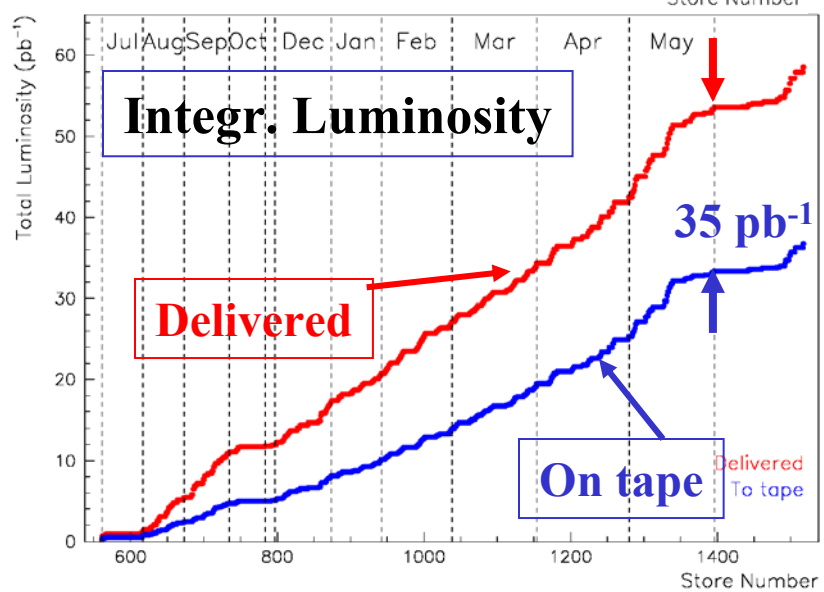


Tevatron Status

- Tev operations began 3/01:
- Luminosity goals for Run 2a:
  - ✓ 5-8x10^{31} cm^{-1}s^{-1} w/o recycler
  - ✓ 2x1032 cm^{-2}s^{-1} w/ recycler
- Achieved so far:
  - ✓ 2.2x10^{31} cm^{-2} s^{-1} in July

- June shutdown- pbar cooling:
- 54 pb^{-1} delivered to early July
  - ✓ 35 pb^{-1} are on tape
  - ✓ 10-20 pb^{-1} were used for ICHEP analyses this summer





CDF Run 2 Collaboration

North America

3 Natl. Labs
25 Universities

2 Universities

Europe

1 Research Lab
6 Universities

1 University

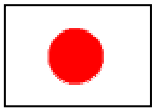
4 Universities

2 Research Labs

1 University

1 University

Asia

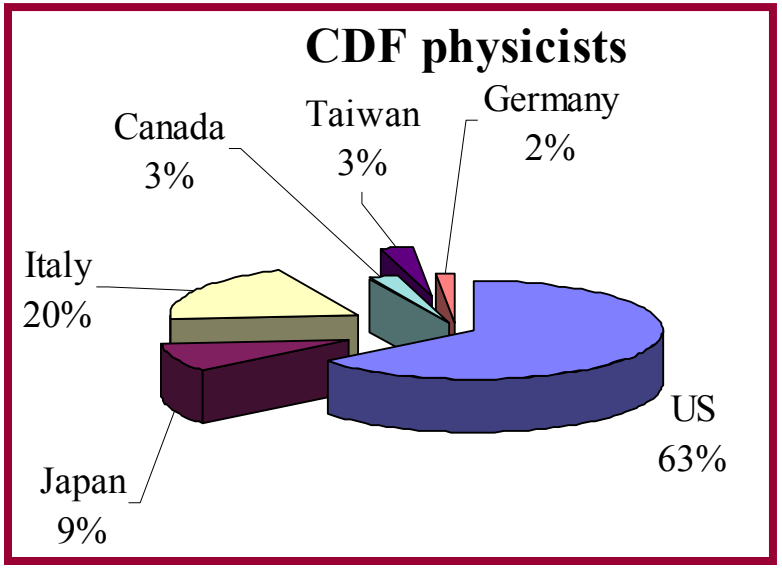


1 Research Lab
4 Universities

1 University

1 University consortium

- **11 countries**
  - 52 institutions
  - 525 physicists
  - 140 students:
    - More than 195 theses since 1985



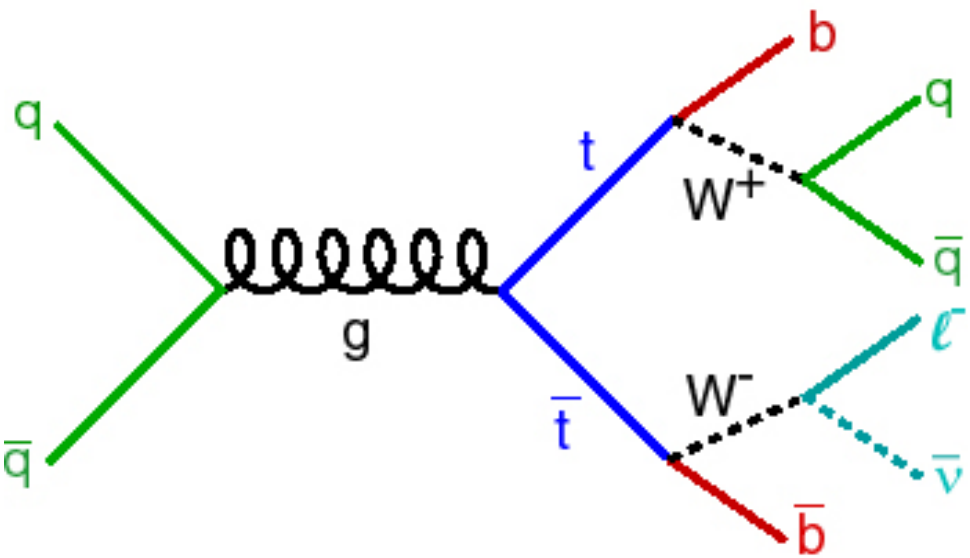
Run 2 Physics Potential

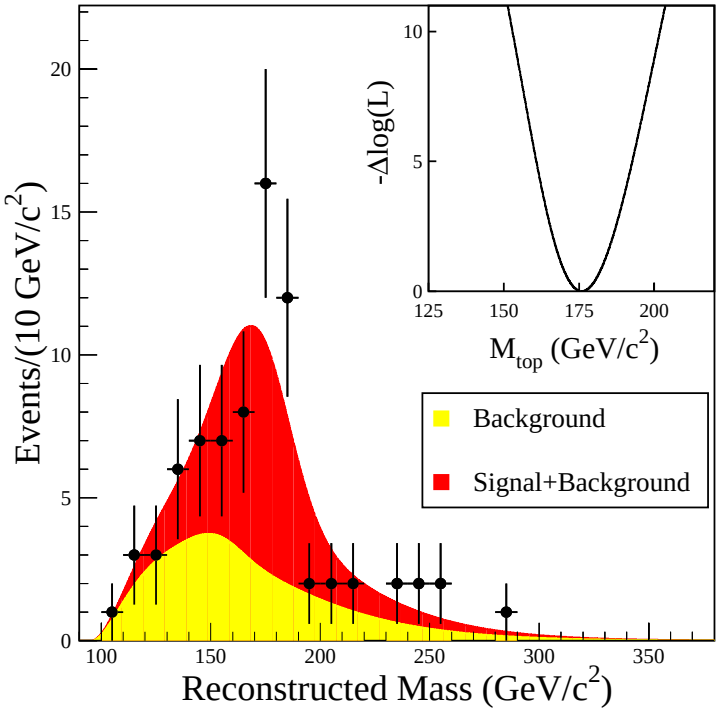
- **Top physics**
  - Top quark properties
  - Single and pair top production
- **Electroweak physics**
  - W boson properties
  - Triboson coupling
  - Drell-Yan, W', Z' searches
- **QCD Physics**
  - QCD jets, photons, PDFs, α_s
  - Compositeness
  - Diffraction
- **B physics**
  - B lifetimes, rare decays
  - B mixing
  - CP violation, CKM parameters
  - B_c spectroscopy
- **Theory-driven searches**
  - Higgs bosons
  - SUSY particles
  - Technicolor, leptoquarks, LED
- **The unexpected surprises**
  - Signals from Nature we haven't thought of!

Top Physics

- **Discovered in 1995**

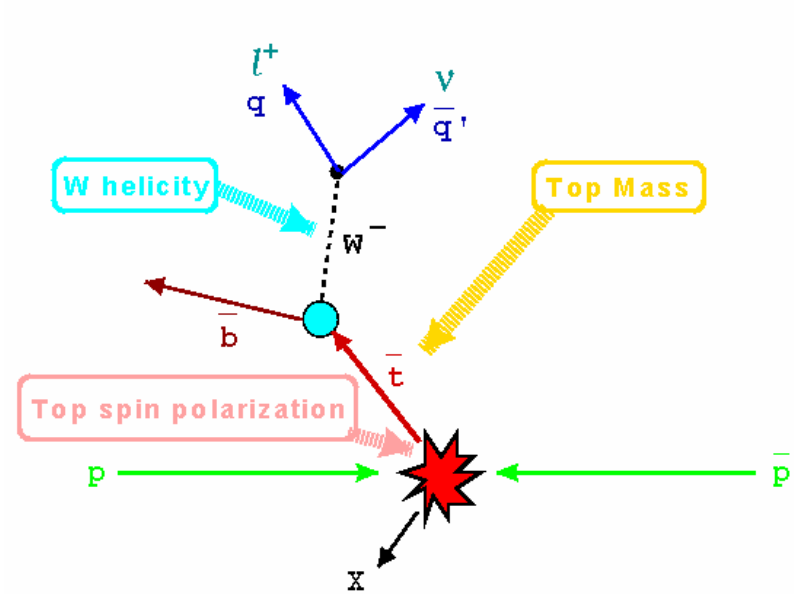
  CDF+D0 combined:
  m_t=174.3± 5.1 GeV/c^2

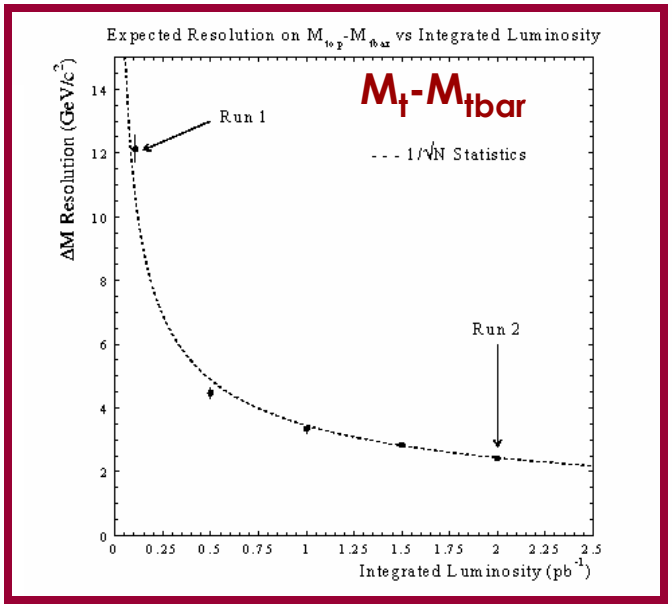




- **Main "usable" top event topologies:**
  - **tt → ℓνℓνbb** **di-lepton** **5% e+μ**
  - **tt → ℓνqqbb** **lepton+jets** **30% e+μ**
  - **tt → qqqqbb** **all hadronic** **45%**

Top Quark Understanding





Top Production

(~ 2x10⁵ tt plus tb produced in 15 fb⁻¹)

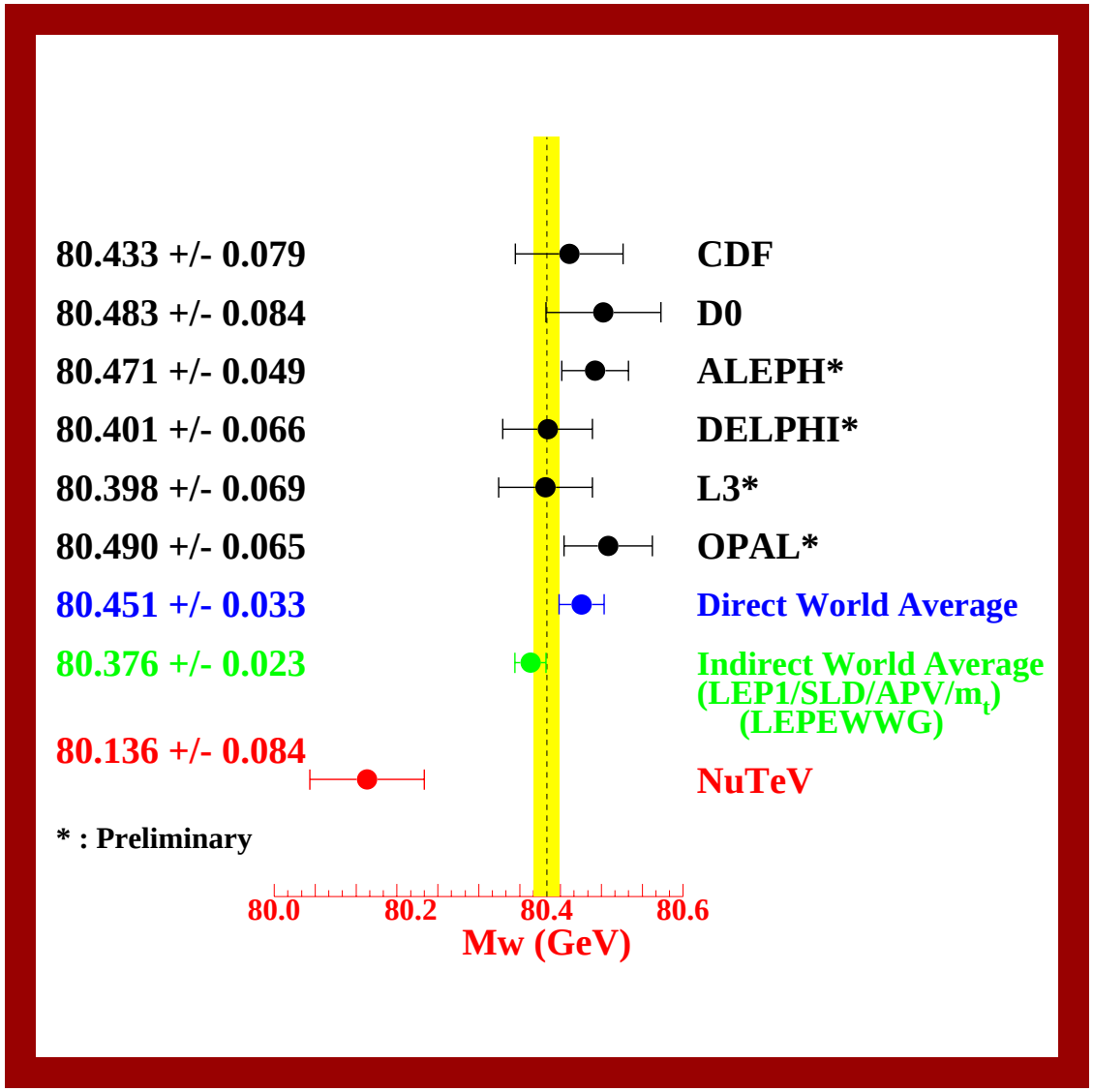
- Top pairs: $\sigma(tt) \sim 7.0$ pb
  - QCD tests
  - Anomalous couplings, new particles
- Differential production properties
  - t-tbar spin correlations
  - Top P_t
  - Top Drell-Yan via $d\sigma/dM$ of t-tbar
  - New Physics in $X \rightarrow tt$
- Single top: σ (tb) ~ 1.6 pb
  - QCD tests
  - $|V_{tb}|$, top form factor

Precision EW Physics

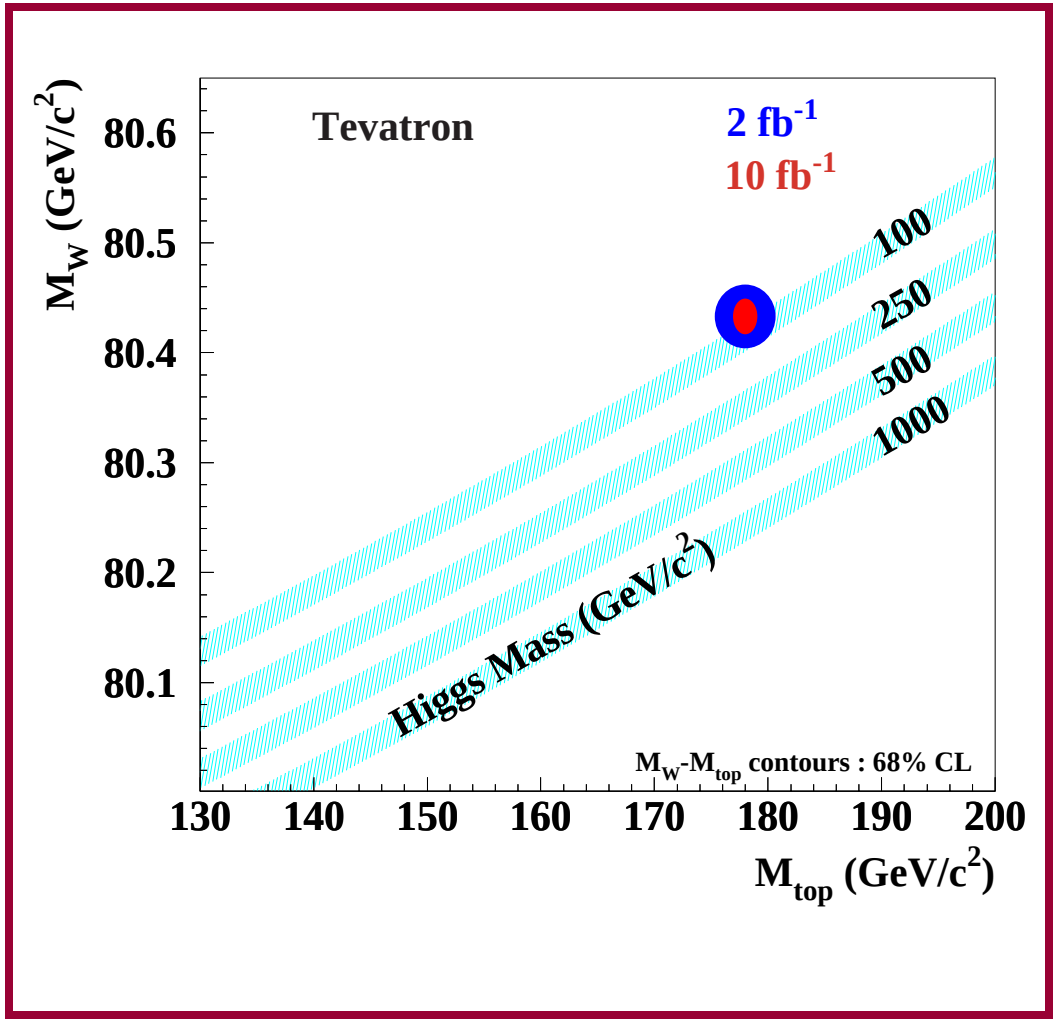
- The Tevatron will make the most accurate W measurements until the LHC or the LC

- Run 2 combined CDF and D0 prospects for 2 (10) fb^{-1} :
  - δM_W = 30 (20) MeV/c^2
  - $\delta \Gamma_W$ ~ 40 MeV (direct)

- Searches for rare decay processes:
  - $W \rightarrow \pi + \gamma$, $D_s + \gamma$, …
  - ~250 million W bosons in 10 fb^{-1} of data



EWSB Constraints

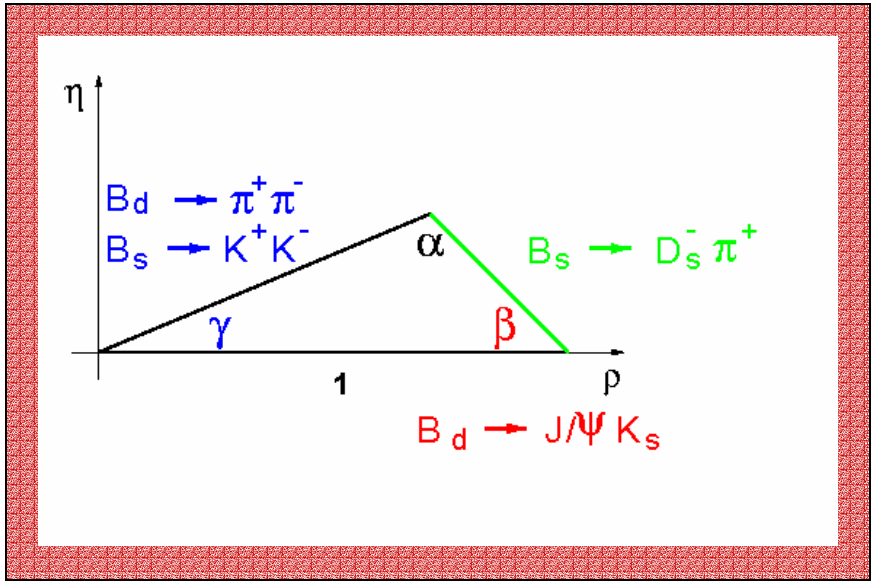


Precision measurements of top and W masses constrain the mass of the Standard Model Higgs

- M_W : CDF ⊕ DØ
  - σ_M ~ 30 MeV (2 fb^{-1})
  - σ_M ~ 20 MeV (10 fb^{-1})
- M_t : CDF or DØ
  - $\sigma_M <$ 4 GeV (2 fb^{-1})
  - $\sigma_M <$ 2 GeV (10 fb^{-1})

Tevatron as a B Factory

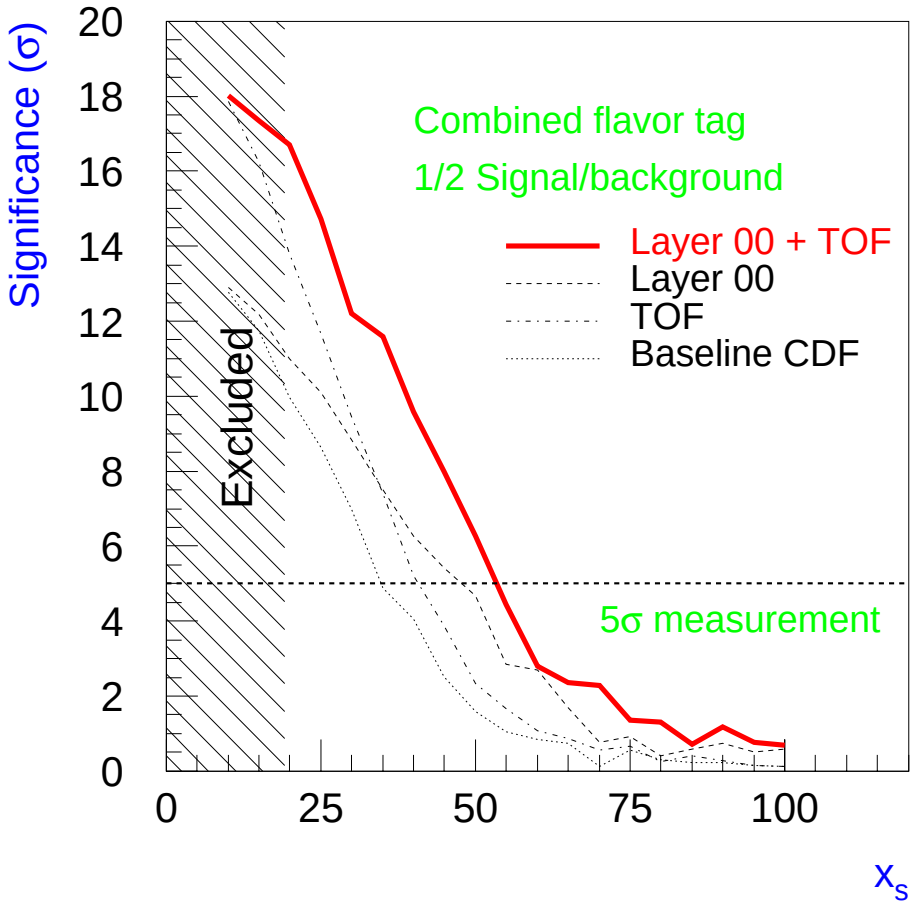
- B production rate is high: ~ 20 KHz @ L = 2 x 10^{32} $cm^{-2}s^{-1}$
  - Data collection is limited by offline bandwidth of ~50Hz
  - All B species are produced
- B mixing measurements:
  - B_d , B_s access to $|V_{td}|/|V_{ts}|$
- CP violation:
  - $B^o \rightarrow J/\psi\ K_s$, $B_s \rightarrow J/\psi\ \phi$, …
- Rare decays
- B hadron spectroscopy with B_c
- QCD production studies



B Physics at CDF

The Improved Tool Kit

- **Better decay vertex measurements with 3d silicon trackers**
- **Better tracking of decay particles**
- **Better particle ID**
- **Ability to trigger on all hadronic decays at level 2**
- **Improved flavor tagging**
- **B detection efficiency will be improved in Run 2 with level 2 displaced vertex triggers**



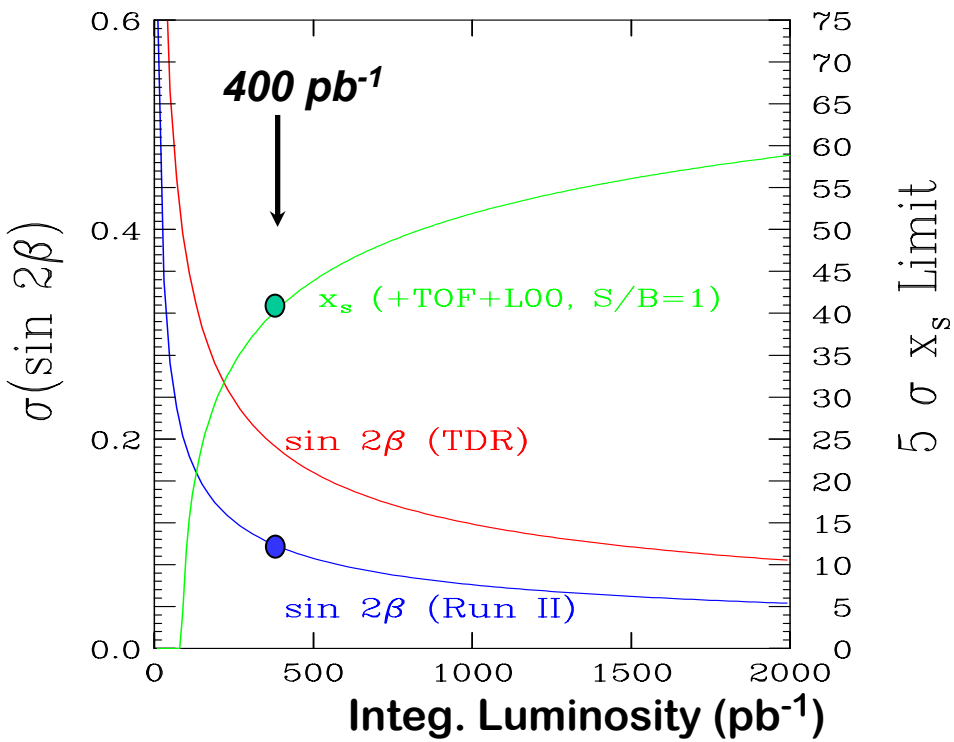
B Physics with 2 fb^{-1}

CP violation

- $\sin 2\beta$ from $B^o \to J/\psi\ K_s$
  - 20,000 events ($J/\psi \to \mu\ \mu$)
  - σ ($\sin 2\beta$) ~ 0.05
  - additional 10,000 $J/\psi \to ee$
- γ from $B^o \to \pi^+ \pi^-$ / $B_s \to K^+ K^-$
  - ~ 5,000/~10,000 events
  - σ (γ) ~ 7°
  - Assuming S/B ~½; x_s = 40
- Aim for first $\sin 2\beta$ results by summer 2003 conferences

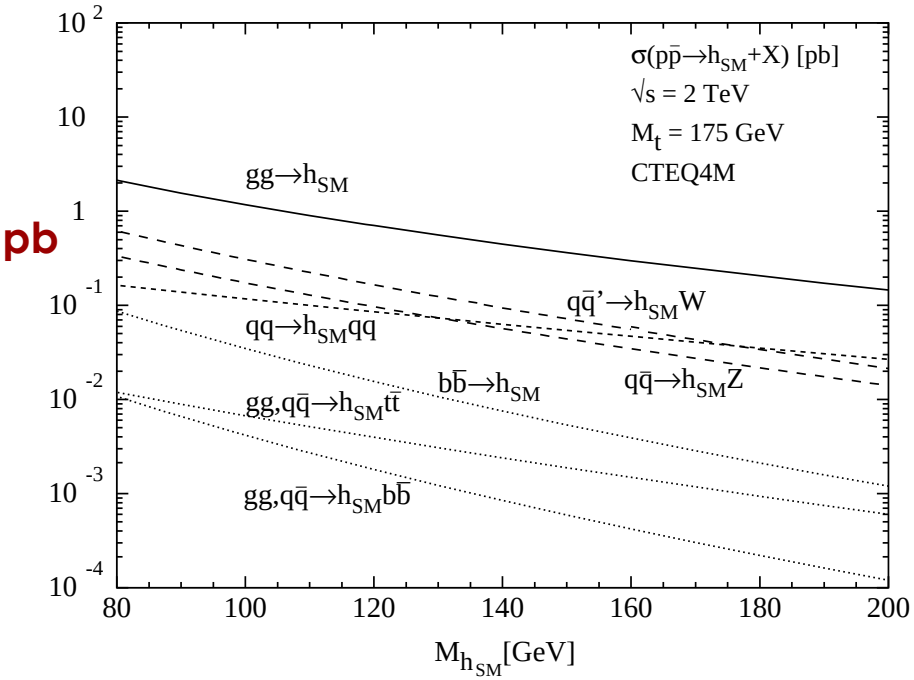
Mixing in B_s decay

- Use $B_s \to D_s\ \pi$ and $D_s\ 3\pi$
  - ~ 75,000 events (50% uncert.)
- Standard Model expectation:
  - $x_s = \Delta m_s / \Gamma_s$ ~ 30
  - $\Delta\Gamma_s/\Gamma_s$ ~ 0.15

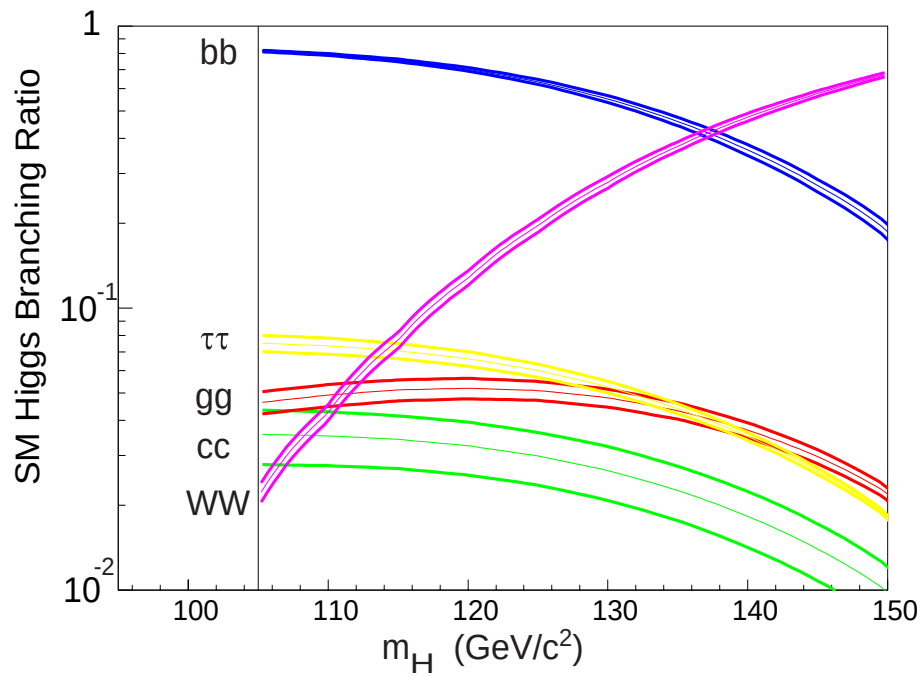


The Standard Model Higgs

Cross Section for Tevatron Production



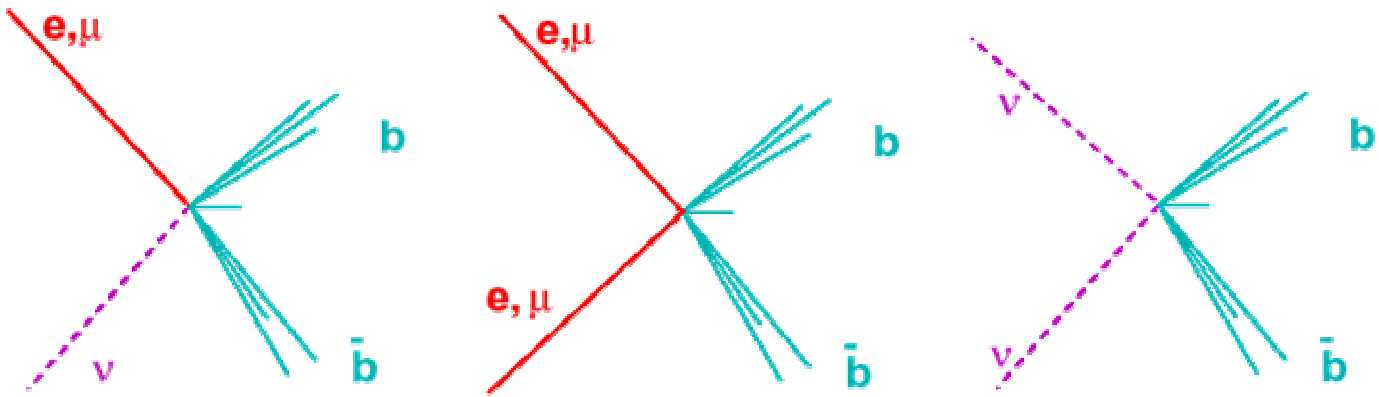
- **gg → H rate large but too much bb dijet background**
  - **bb background ~6μb**
- **Main modes: WH, ZH**



- **Best search channels:**

M_H<135GeV	***M_H>135GeV***
$\ell\nu bb$	$\ell\ell\nu\nu$
$\nu\nu bb$	$\ell\ell jj$
$\ell\ell bb$	

Main Higgs Channels



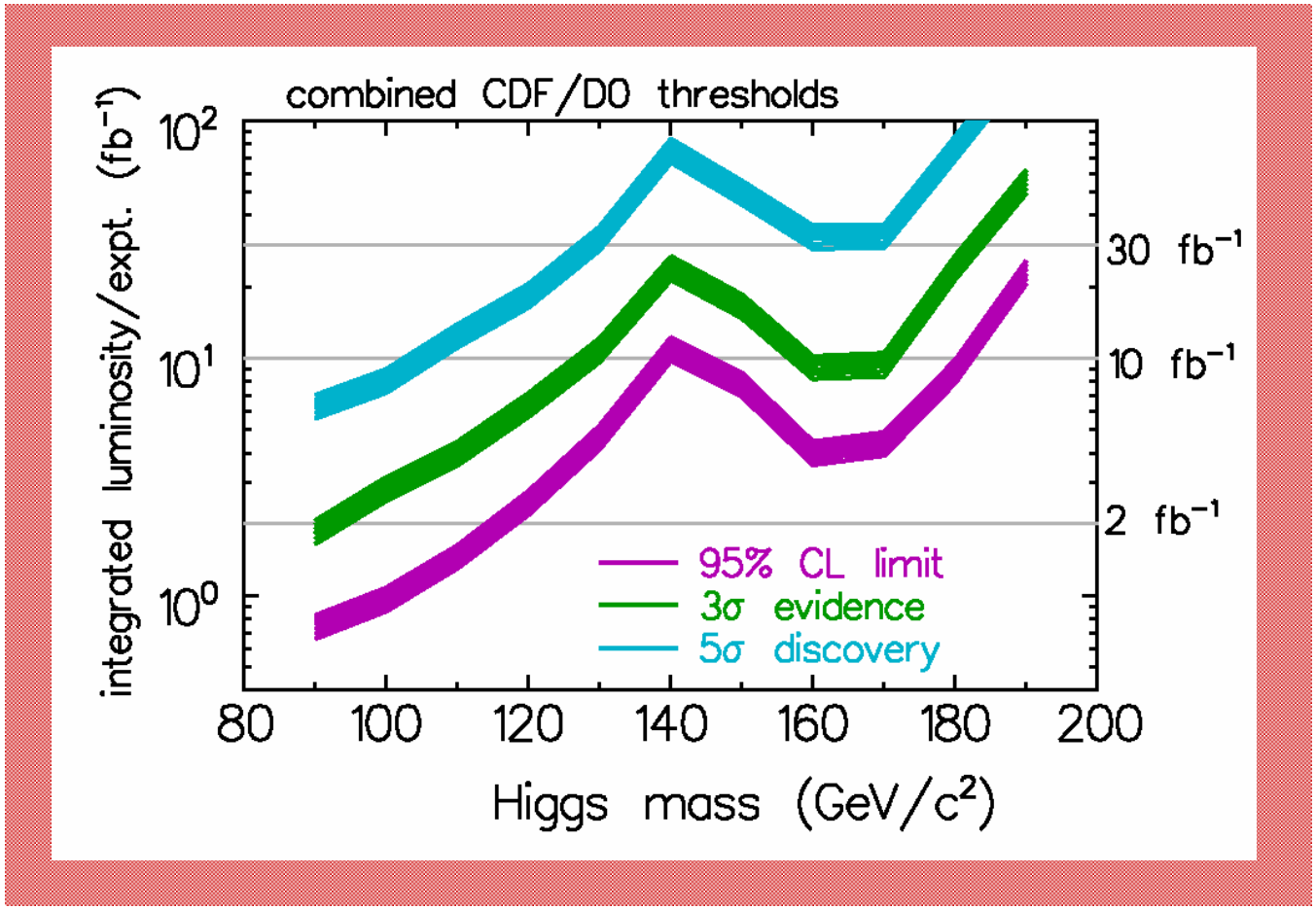
$\ell\nu$bb

- lepton trigger (e,μ)
- $E_T(\ell) > 20$ GeV
- missing $E_T > 20$ GeV
- 2 jets (E_T >15, 10 GeV)
- b tag (tight/loose)
- cos$\Delta\phi$ (jet-MET) …
- reconstruct bb mass

$\nu\nu$bb

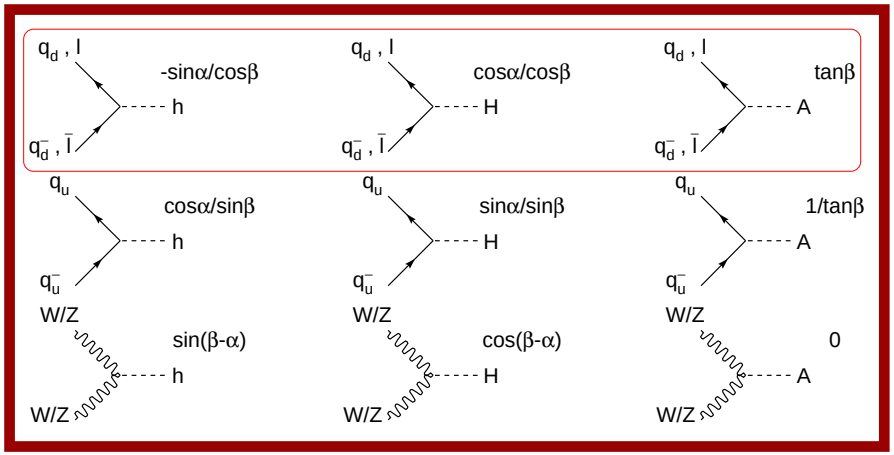
- missing E_T trigger
- 2 jets (E_T > 20, 15 GeV)
- b tag (tight/loose)
- p_T(bb), …
- reconstruct bb mass

SM Higgs Reach

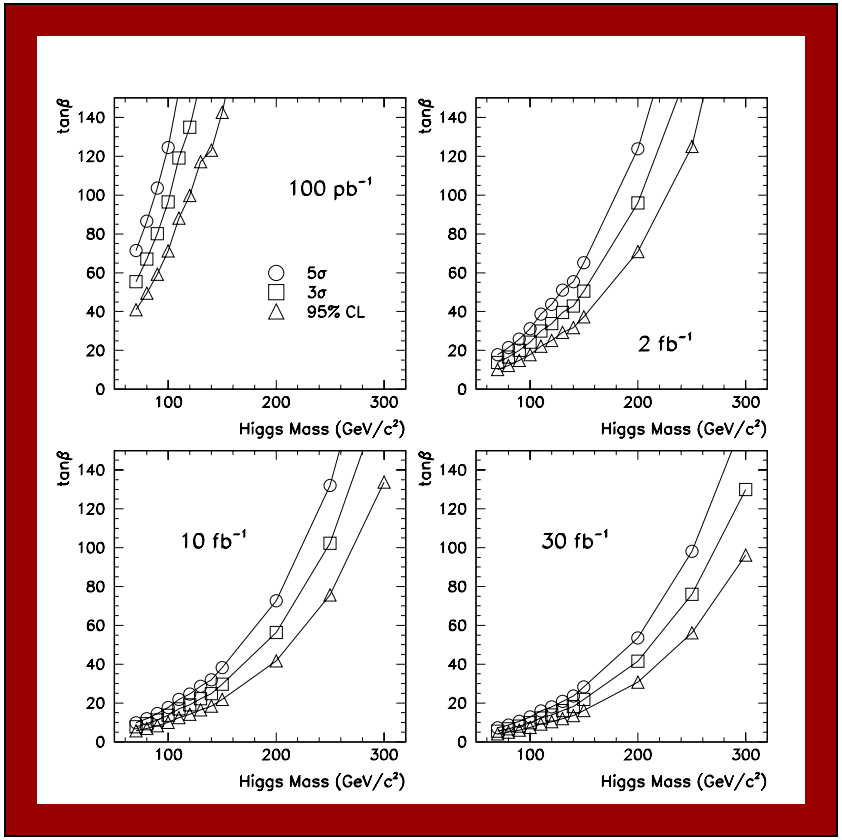


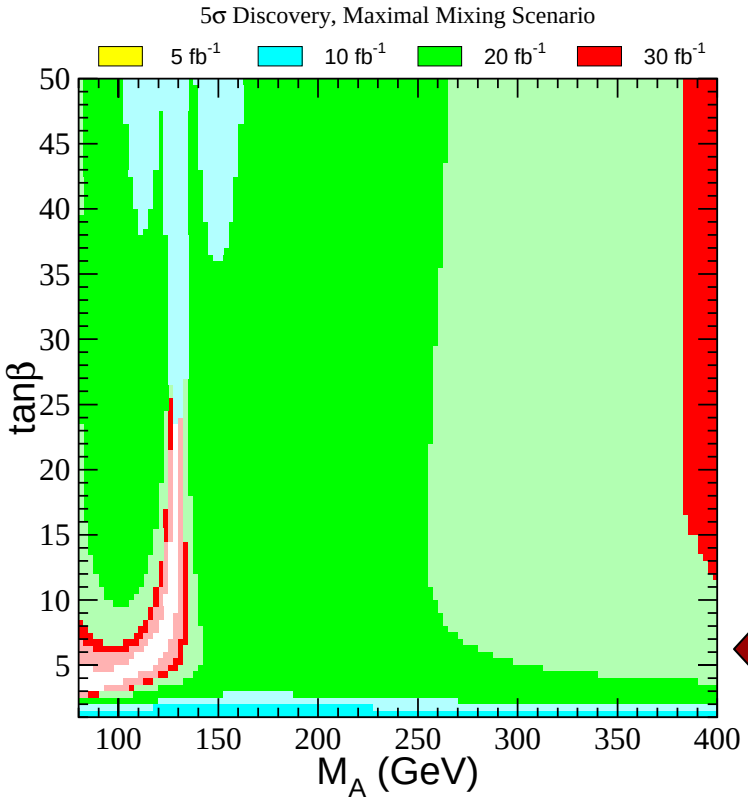
CDF+D0 combined integrated luminosity thresholds assuming 10% mass resolution, NN selection, nominal systematics

MSSM Higgs



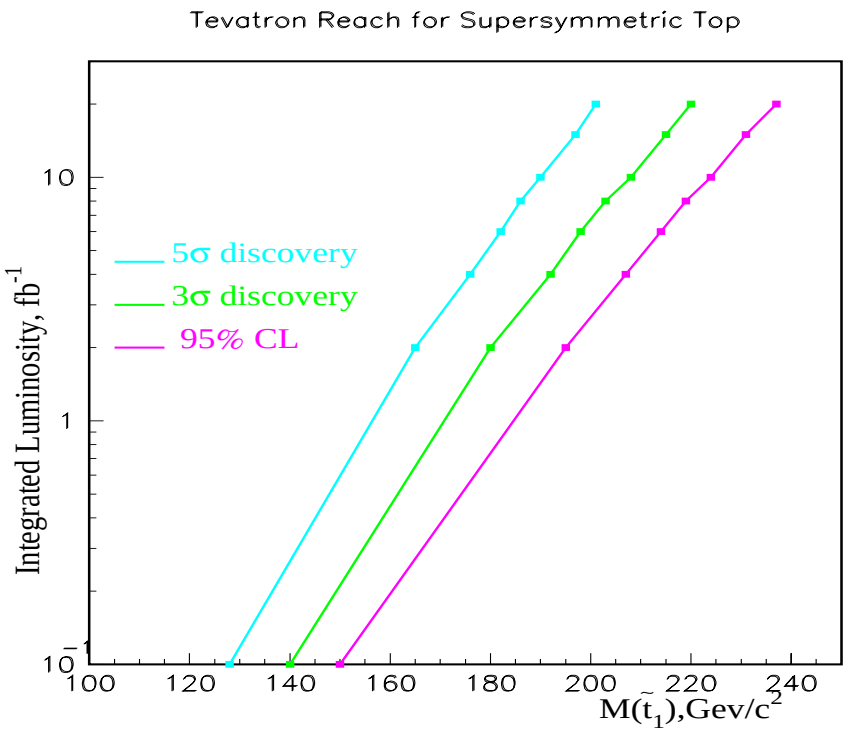
Enhanced production of bbϕ at high tanβ





Apply SM Higgs search in MSSM parameter plane

SUSY Searches

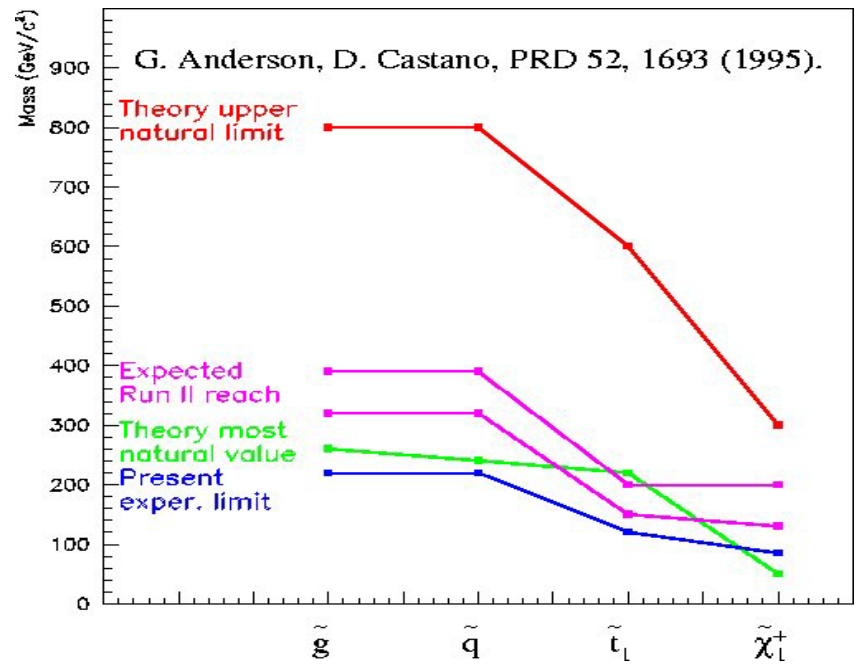


Reach for stop squark with $\mathcal{L}$:

- **We'll begin to be fairly sensitive with 2fb^{-1} of data**

The most natural ranges for SUSY can be explored early:

- **With more data we move further into the parameter space.**

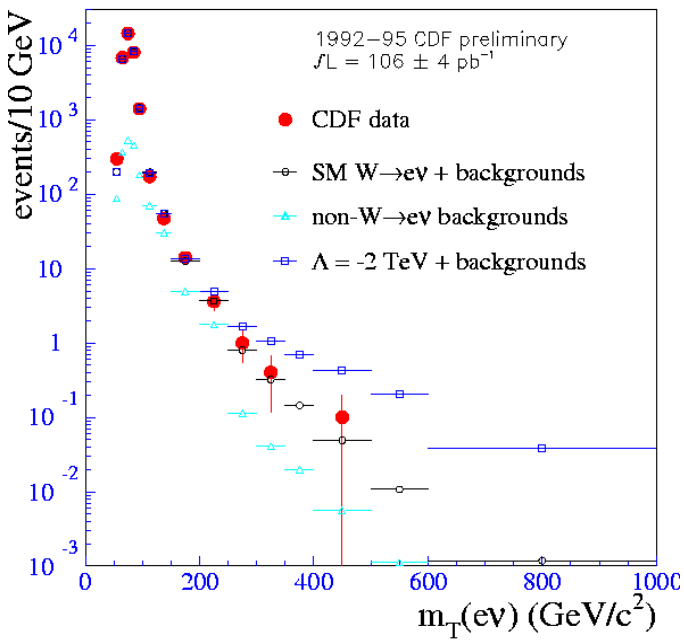


Other New Phenomena

Search for new W' and Z' bosons

- $M_{Z'} > 690$ GeV/c^2
- $M_{W'} > 786$ GeV/c^2
- Run 2 projections:

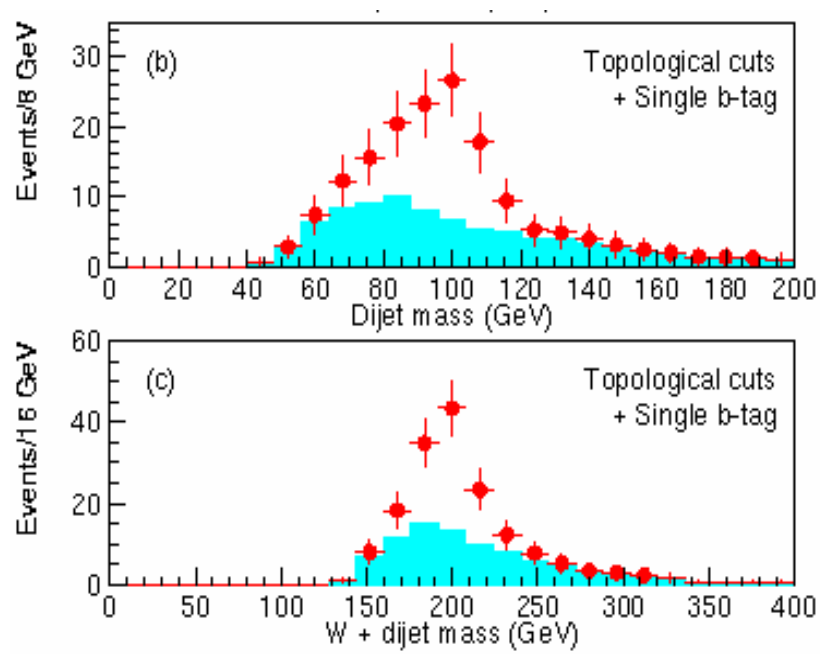
  $M_V > \sim 1$ TeV (for SM couplings)



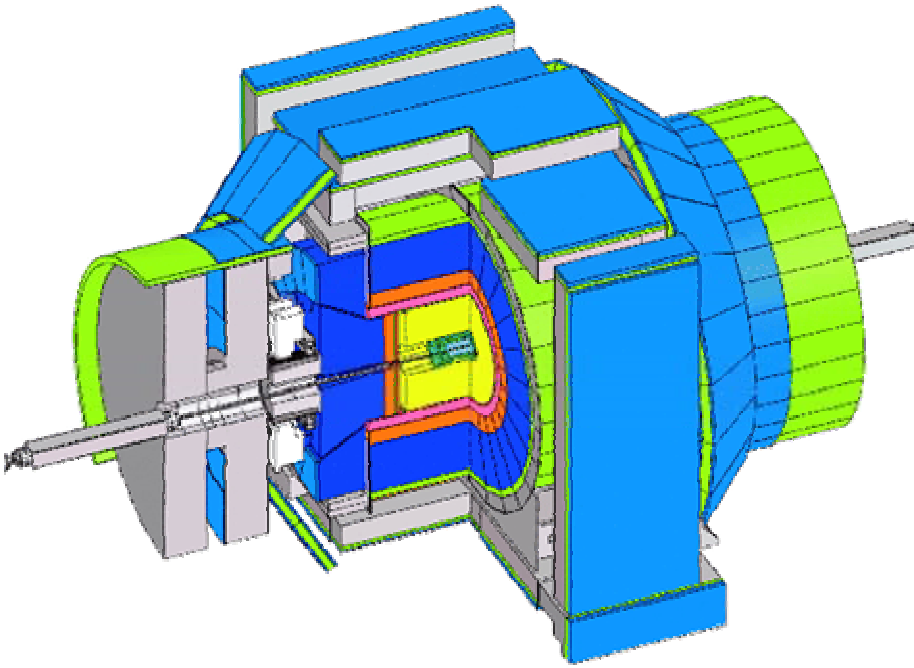
Search for Technicolor

- Higgs is composite
- New particles decaying to vector bosons and fermions

Technicolor $\rho_T \rightarrow W\pi_T \rightarrow \ell\nu bb$
Tevatron, 1fb^{-1}



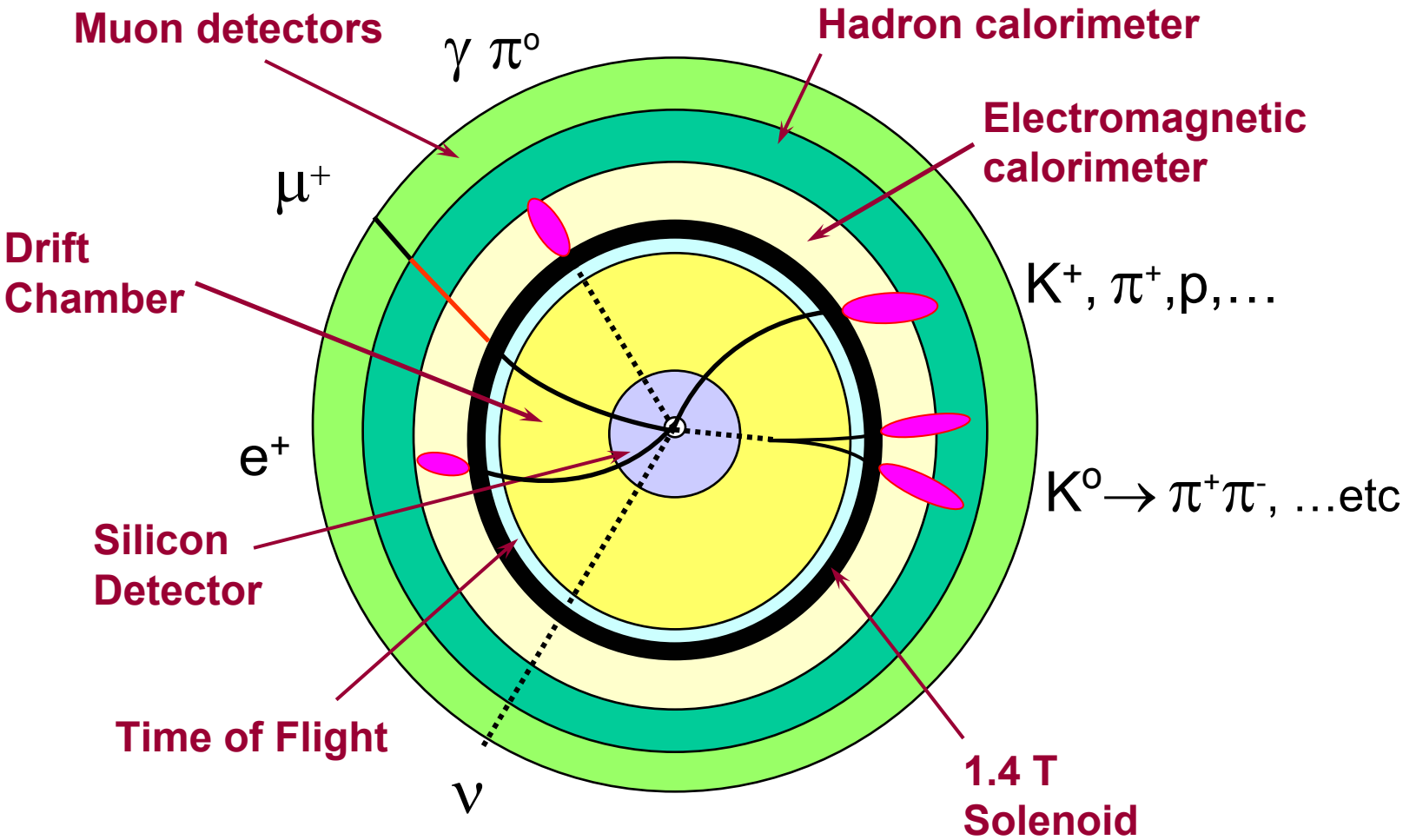
CDF Detector Upgrade



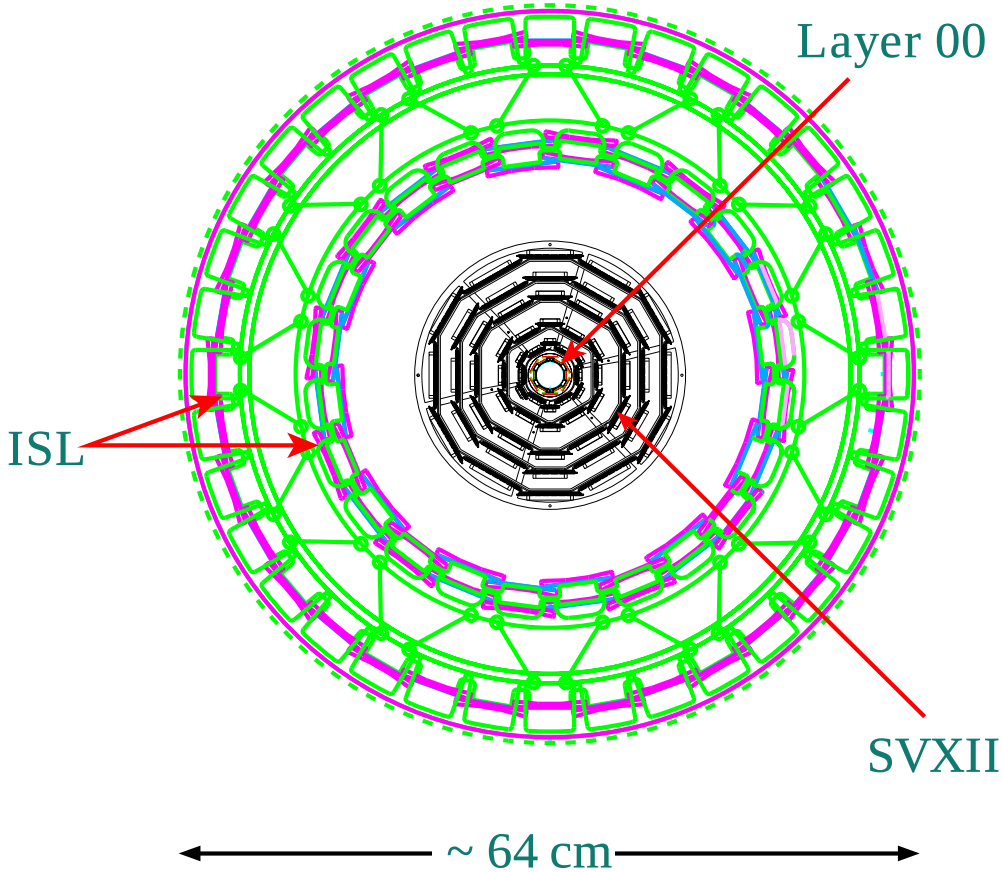
- **Most of the detector is new!**
  - Tracking
    - Silicon Tracker (L00, SVXII, ISL)
    - Central Outer Tracker
    - Time of Flight
  - Endplug Calorimeters
  - Intermediate muon detectors
  - Front End Electronics (132ns)
  - Trigger (pipelined)
  - DAQ (L1,L2,L3)
  - Online and Offline software

- **What did we keep?**
  - Solenoid
  - Central Calorimeters
  - Portions of muon detector

CDF Functionality

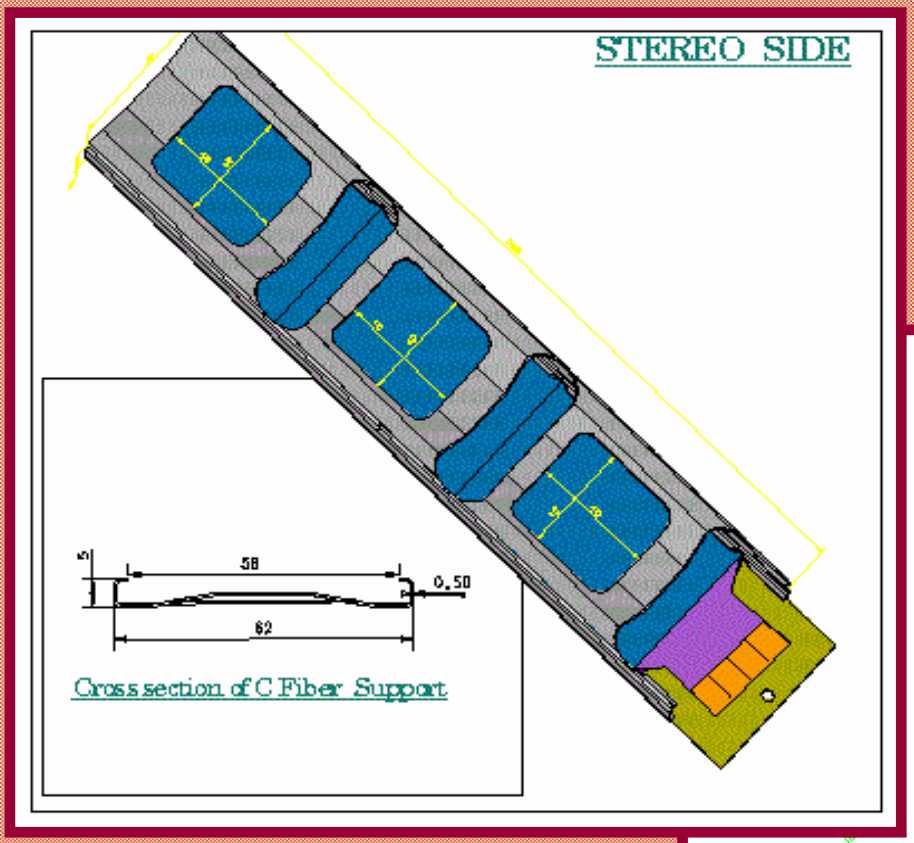


CDF Run 2 Silicon Trackers

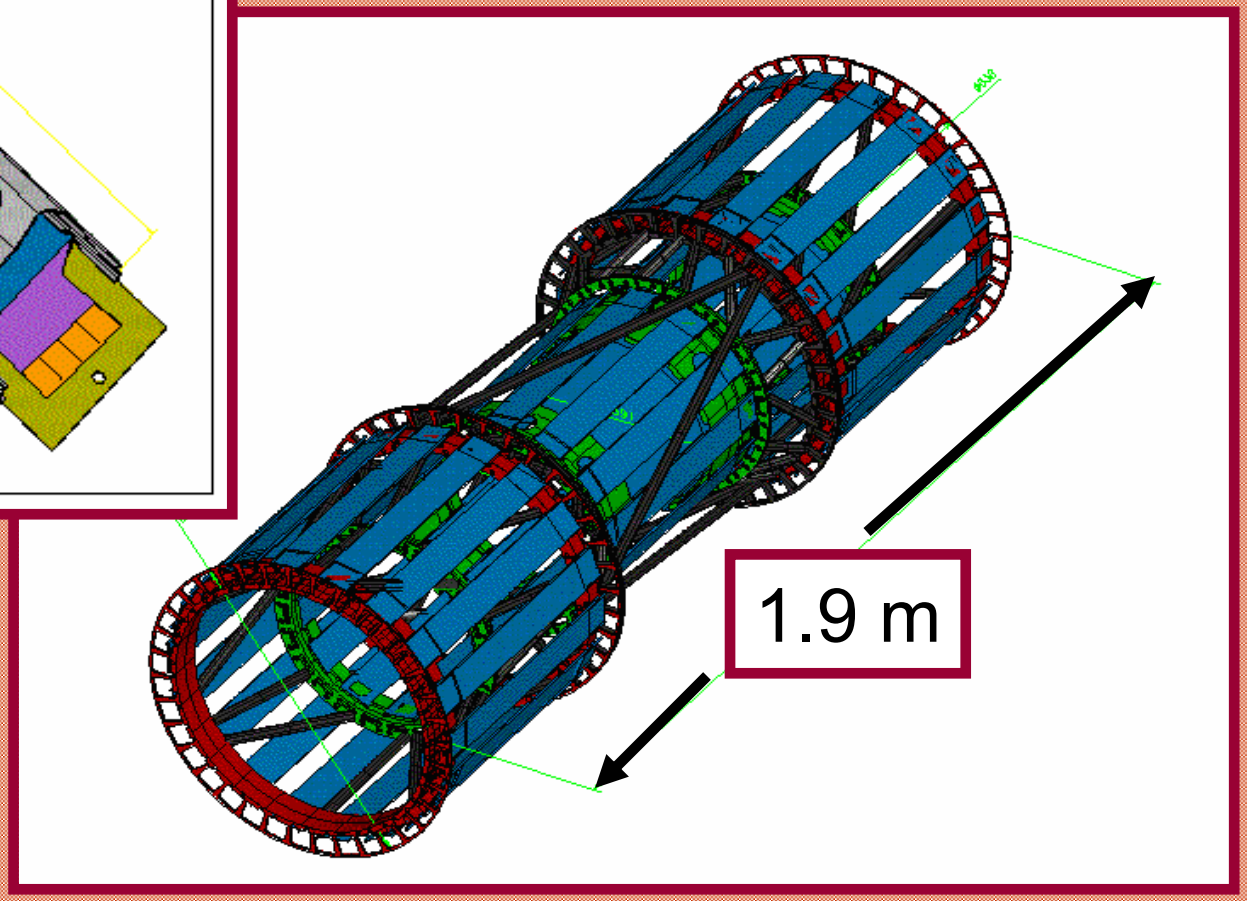


- **Layer 00 (L00)**
  - Improve impact parameter resolution to increase B tag efficiency
  - Use in Level 2 trigger
  - Extend CDF lifetime
- **SVX II (SVX)**
  - Extended coverage with smaller gaps in z and ϕ
  - 3D vertexing
  - Triggering at Level 2 on 2D displaced tracks
- **ISL**
  - Extend b-tagging to $|\eta| = 2$
  - Help link tracks found in the drift chamber to SVX

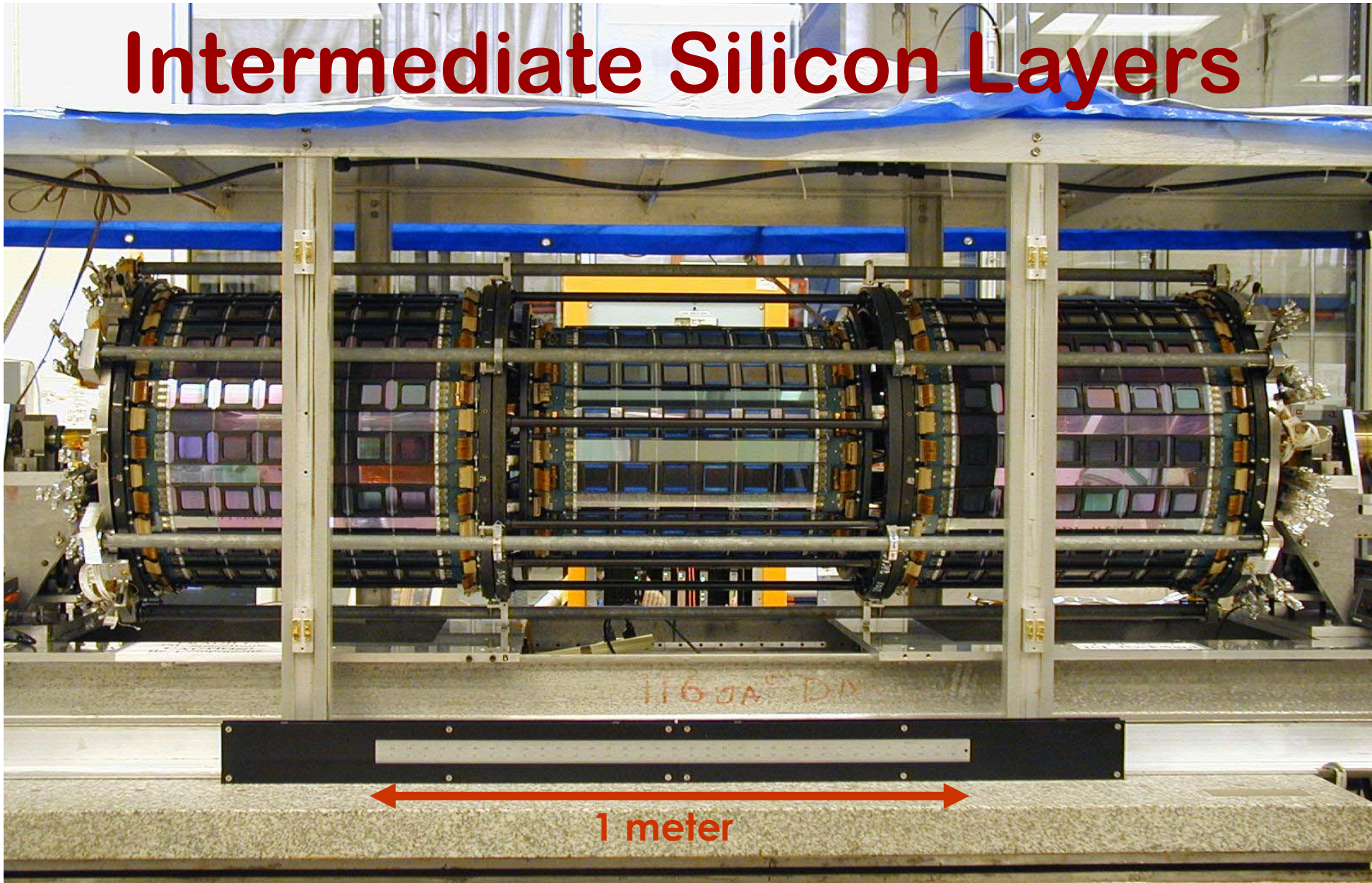
Intermediate Silicon Layers



ISL



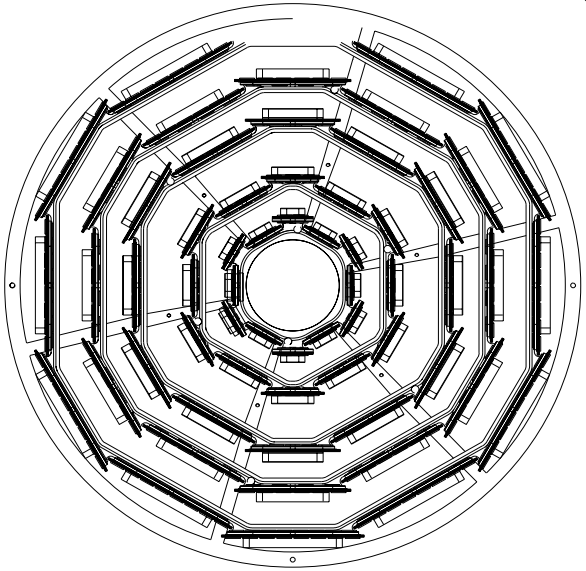
Intermediate Silicon Layers

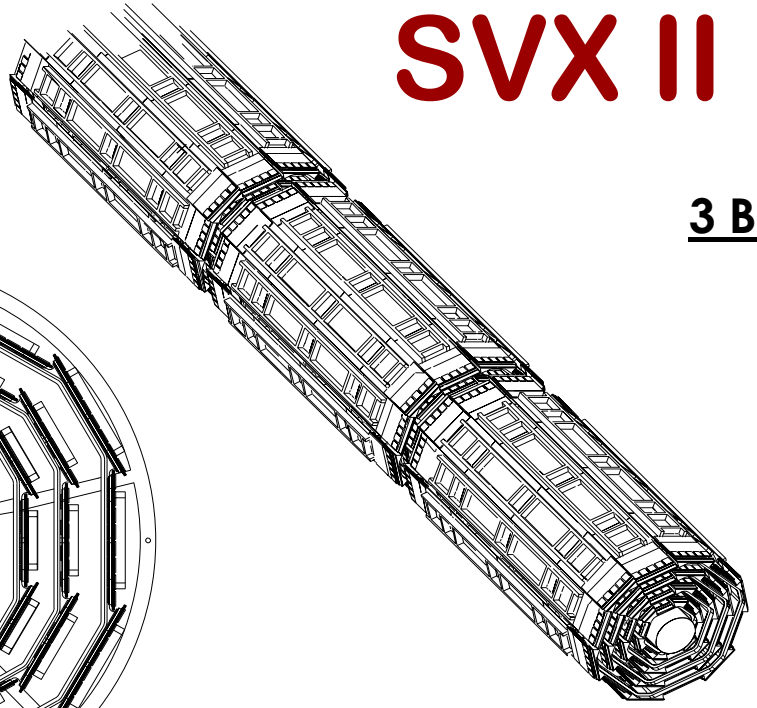


The ISL doubles the pseudorapidity range for b tagging and lepton id.

Inside the ISL

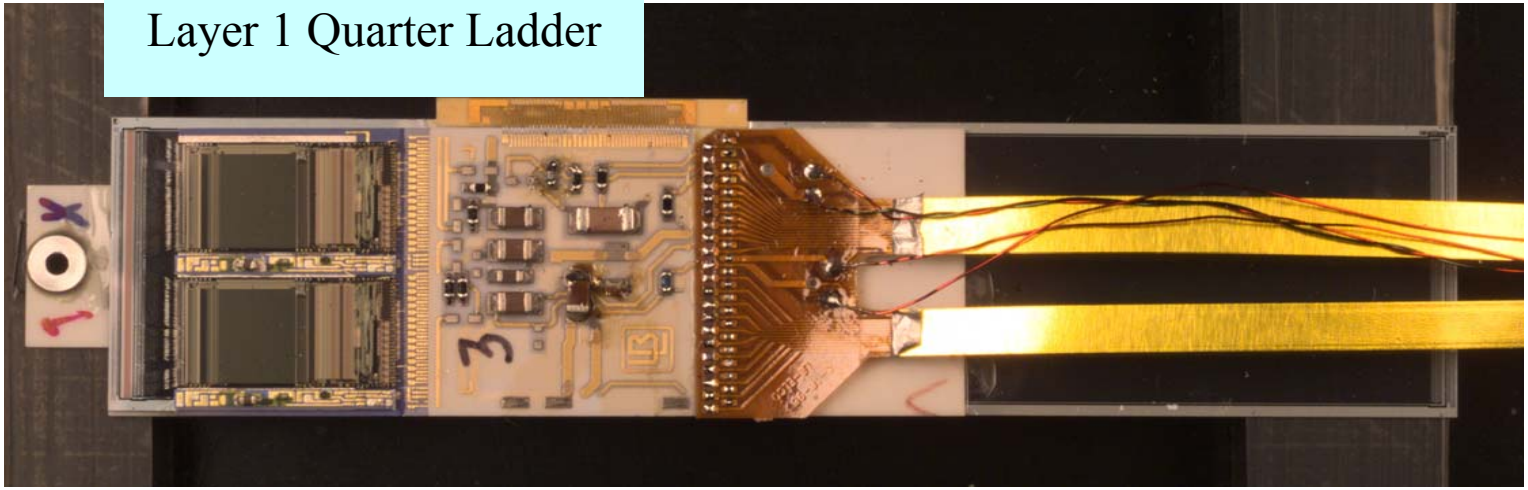
SVX II



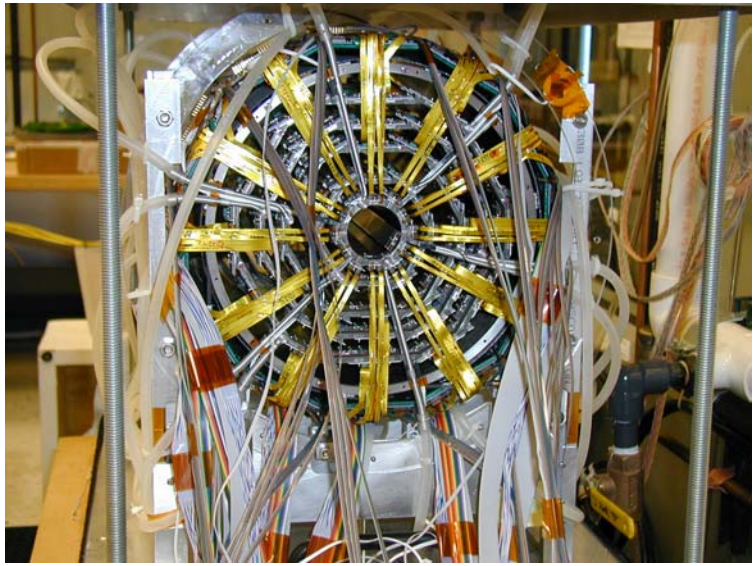


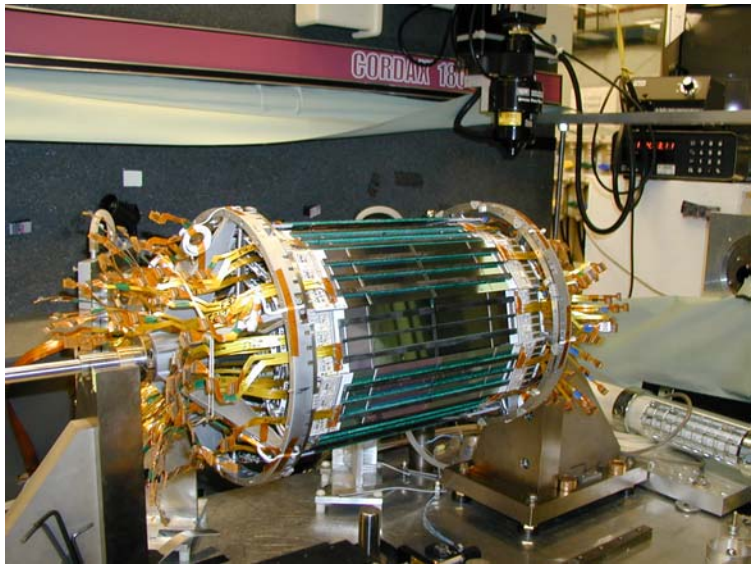
3 Barrels: Very compact design:

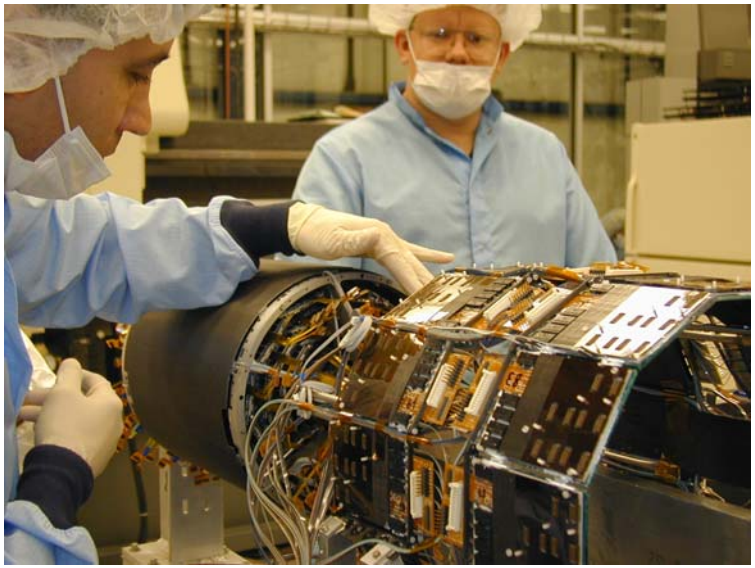
- Electronics mounted directly on silicon to avoid longitudinal gaps.
- Overlaps in Φ
- Radial span ~8 cm for 5 layers!

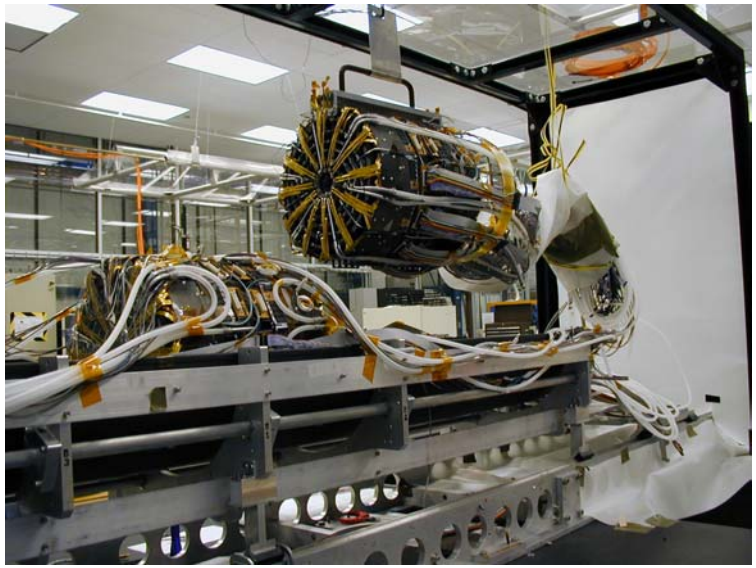


Barrel Preparation SVX II



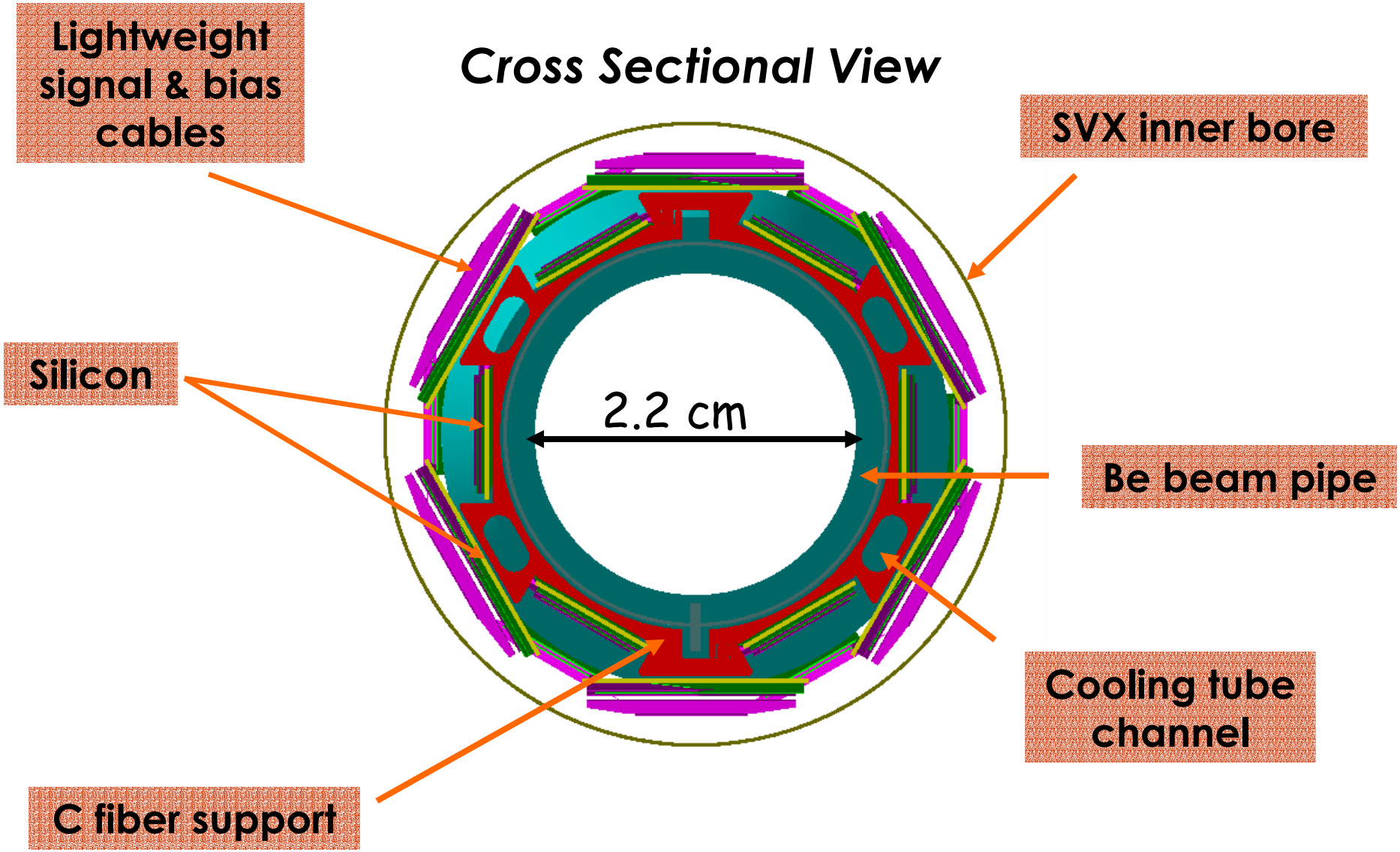




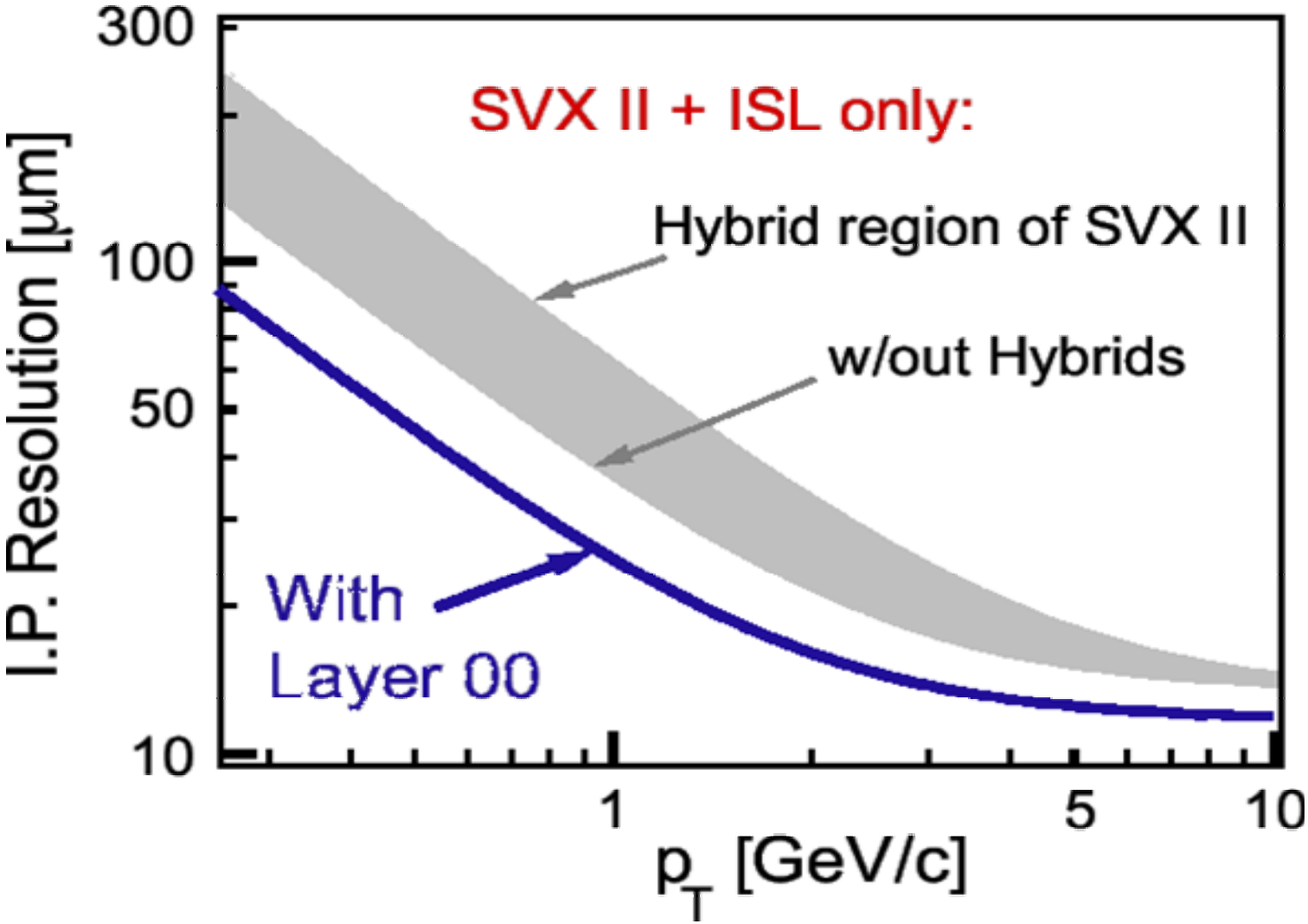


Silicon Layer 00

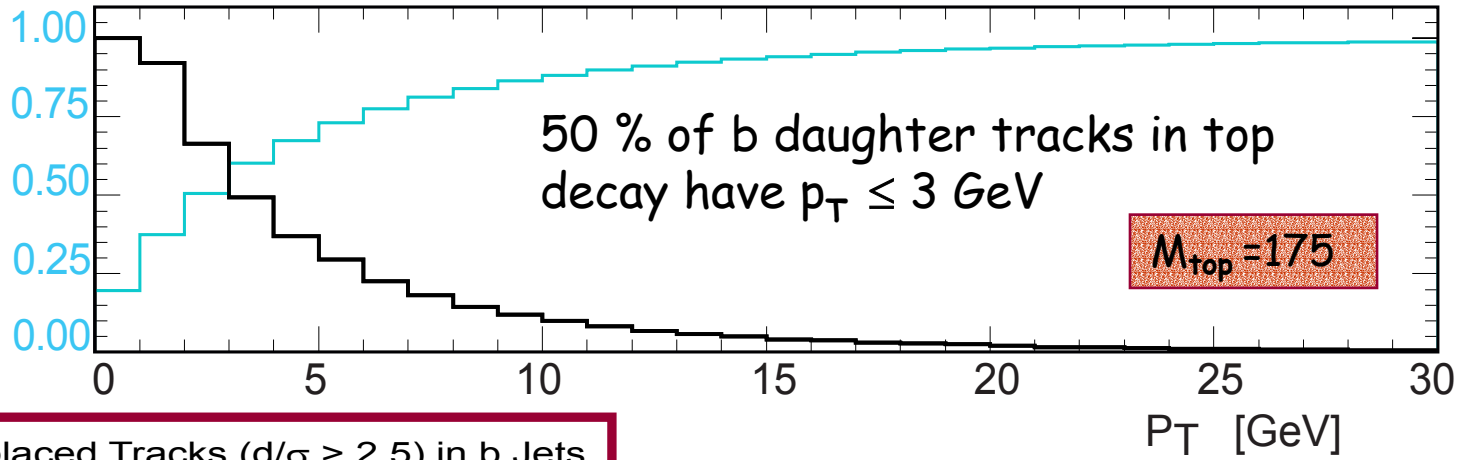
Cross Sectional View

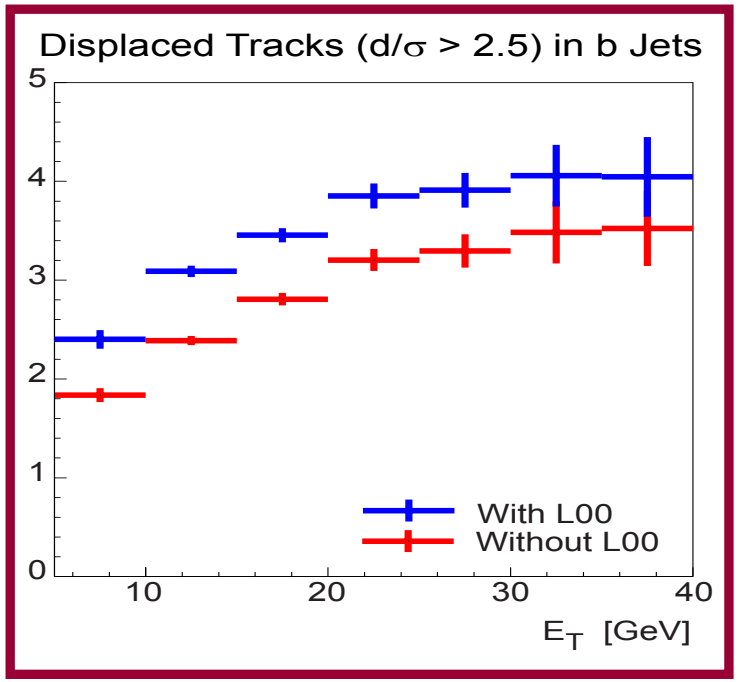


Impact Parameter Resolution



B Tagging with L00



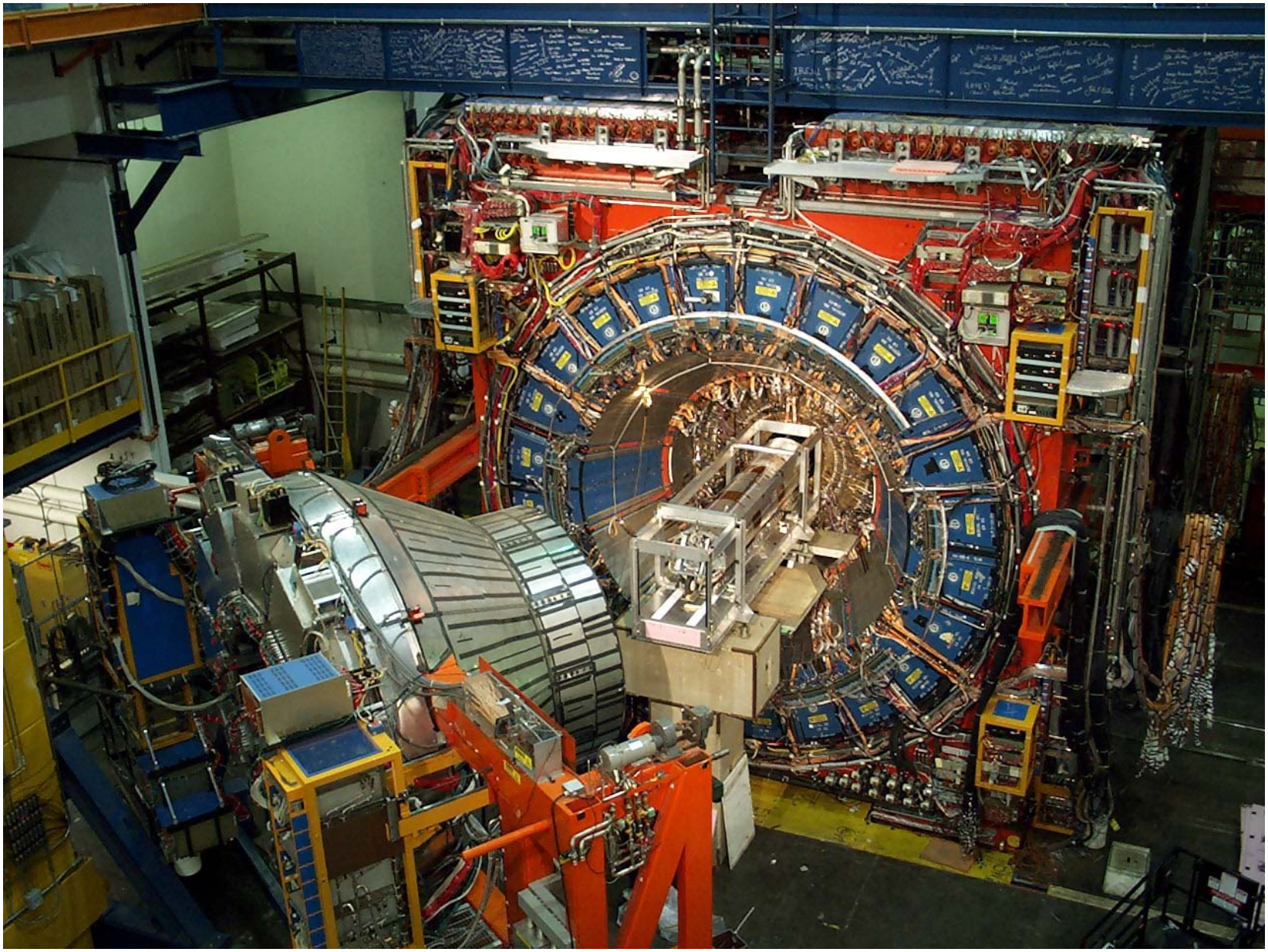


Layer 00 increases the number of observed displaced tracks and hence b tagging and flavor tagging are improved.

L00 Inside SVX

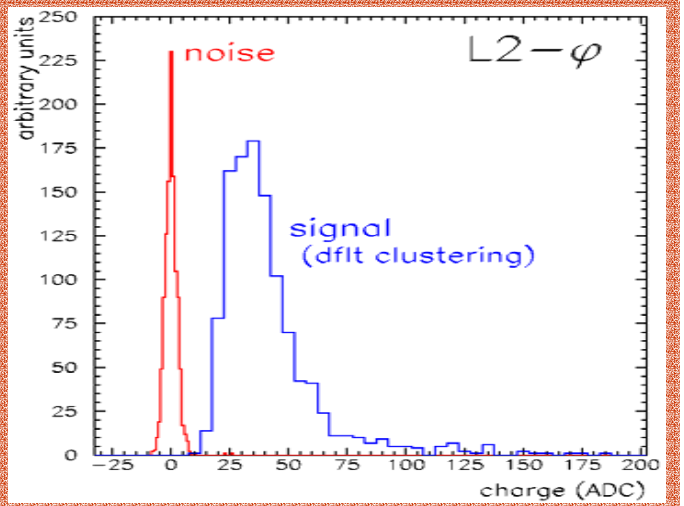
Installation clearance: 300 - 450 mm over ~ 2 m
Final alignment: L00 parallel to SVX to ~ 25 mrad

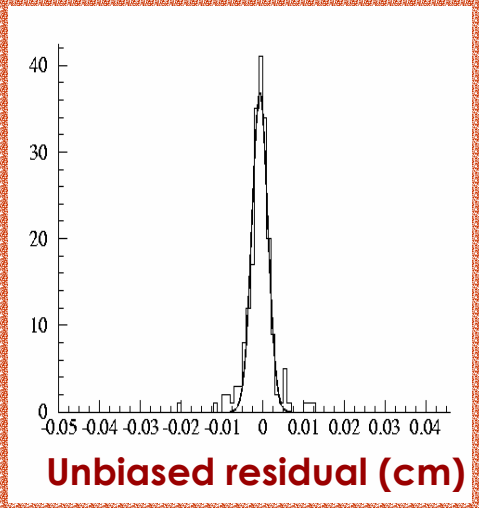
Installation into CDF

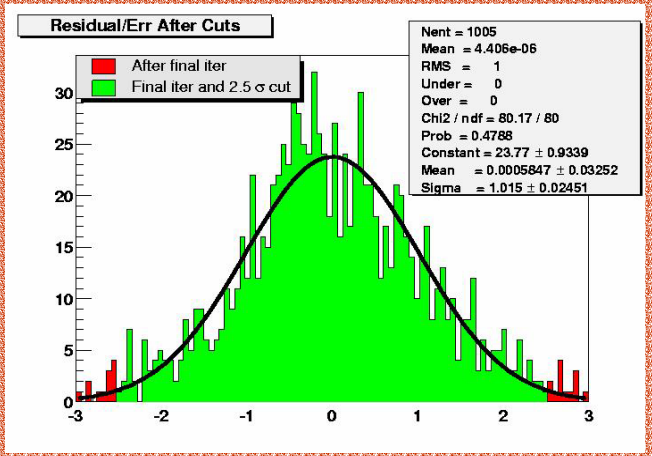


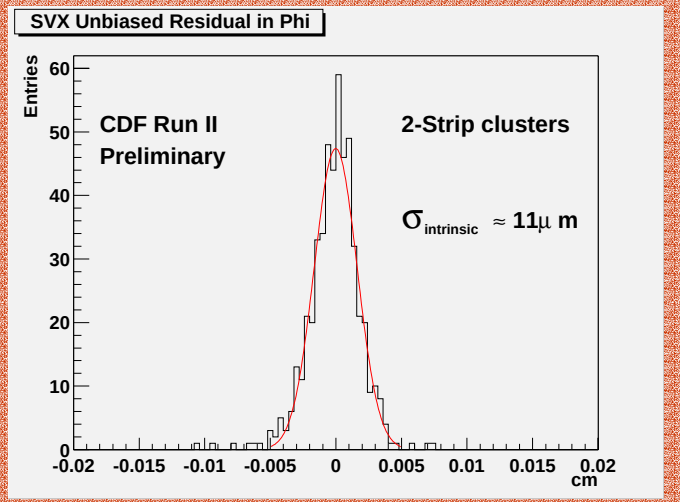
Silicon Tracking Status

- After June shutdown we have:
  - > 95% L00 (beam pipe) operational
  - > 90% of SVXII operational for tracking
  - > 80% of ISL ladders operational (cooling)
- Single hit efficiency > 99%; S/N ~12
- Construction alignment tolerances for L2 impact parameter trigger have been met
- SVXII 2-strip resolution:
  - Track-by-track pull has σ~1; Resolution~11μm

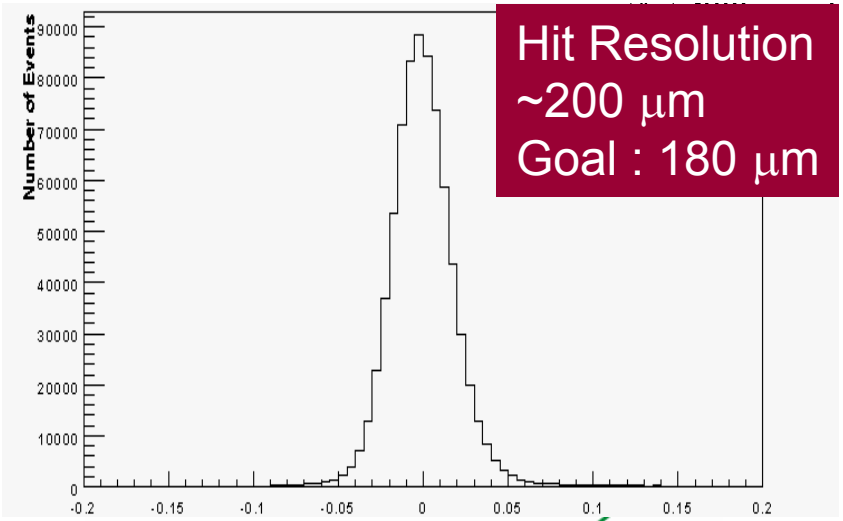




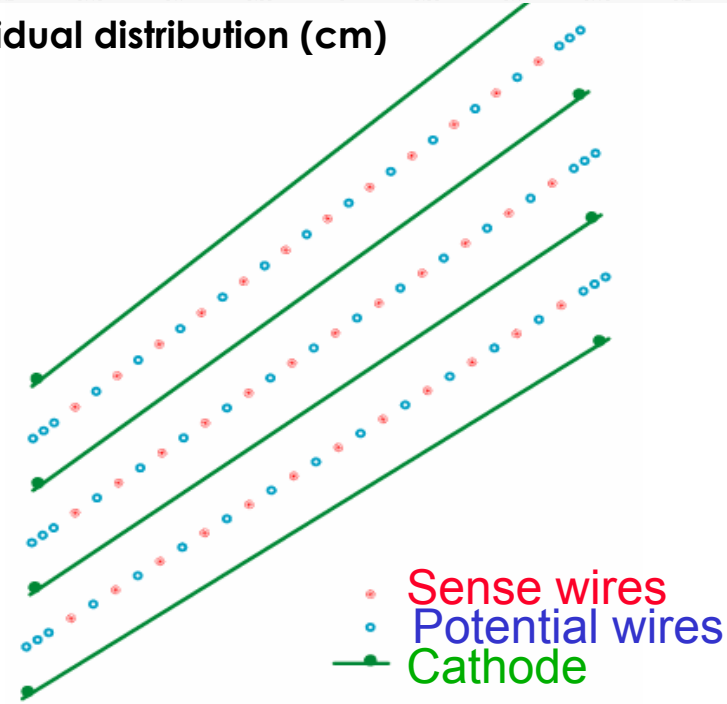




Central Outer Tracker (COT)

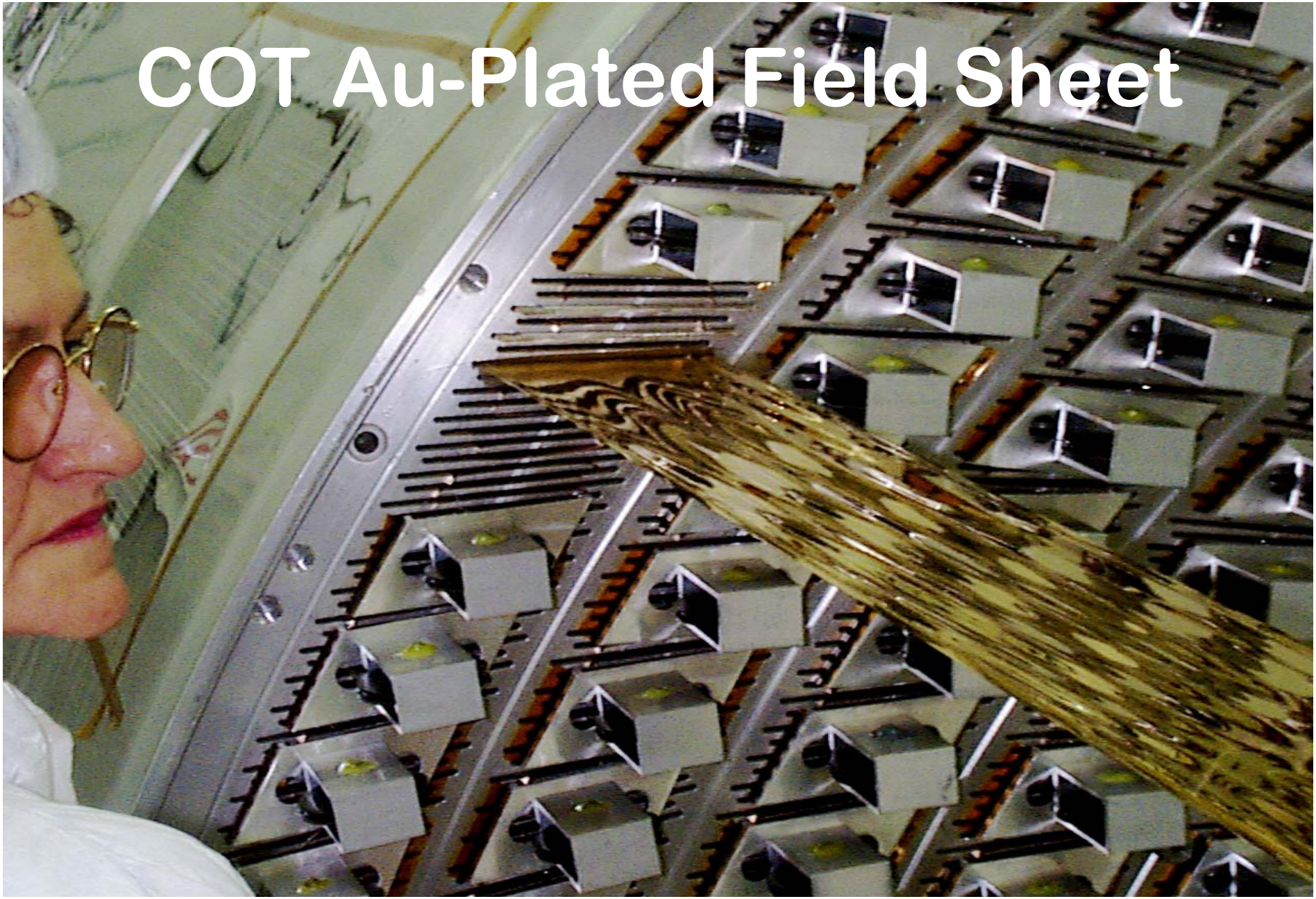


Residual distribution (cm)



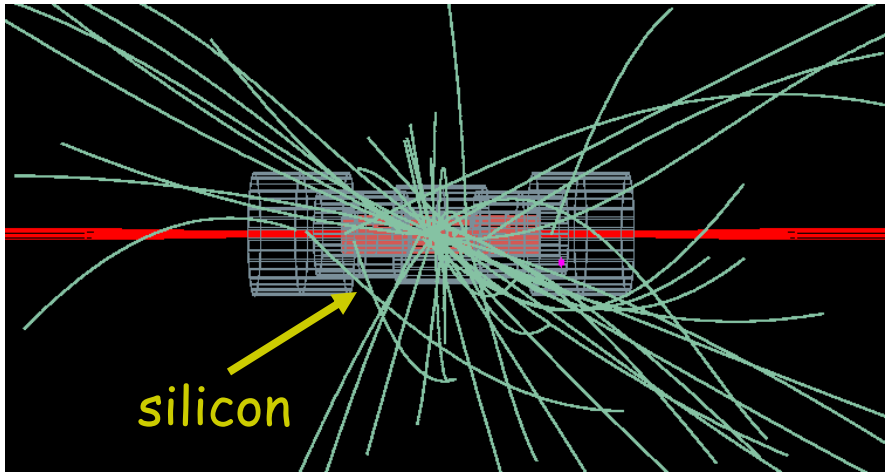
- 96 wire planes
  - (8 superlayers)
  - 50% are 3° stereo
  - Uniform drift (0.88 cm cell)
  - 30,240 sense wires

COT Au-Plated Field Sheet

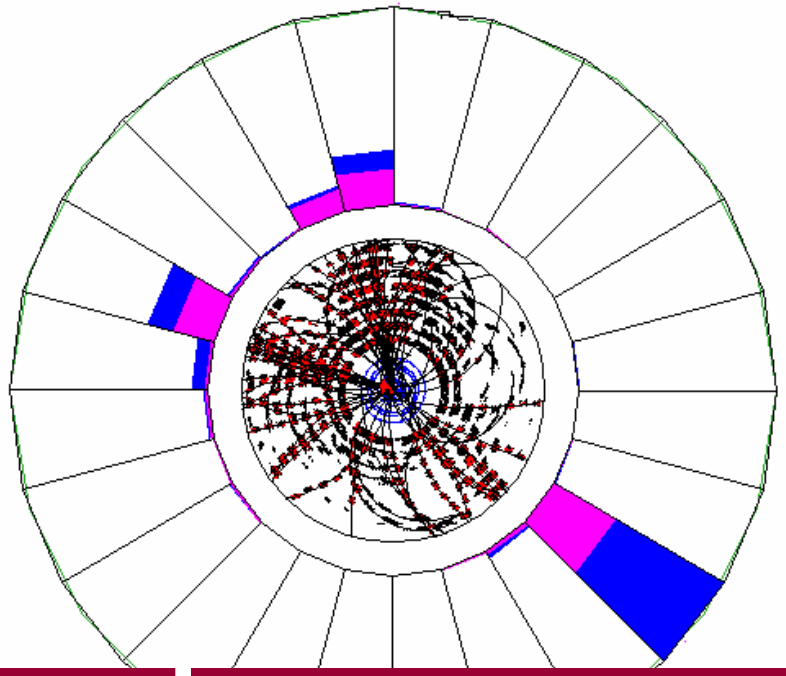


COT Installation

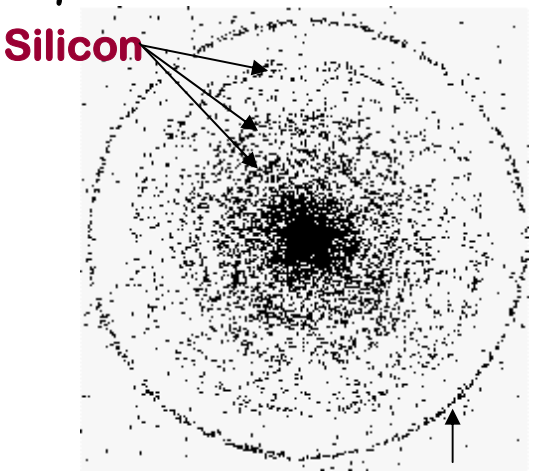
Tracker Performance



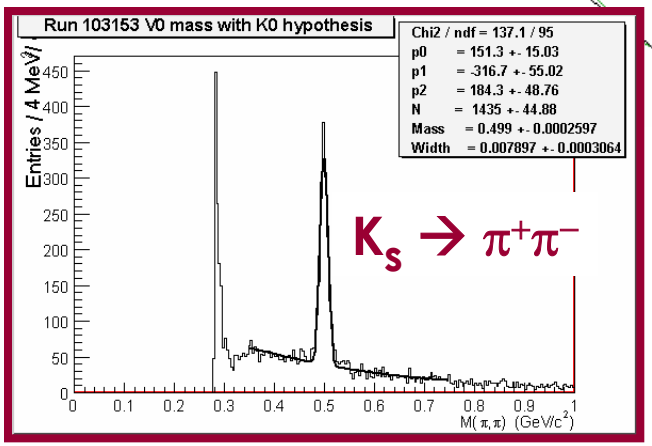
(COT tracks)



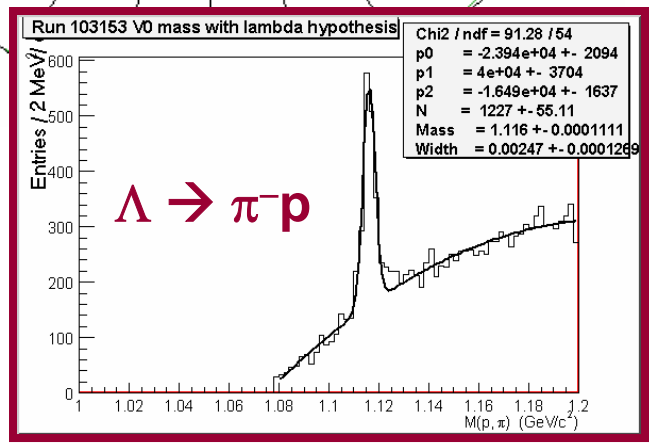
X-ray the detector with
$\gamma \rightarrow e^+e^-$ conversions



COT inner cylinder

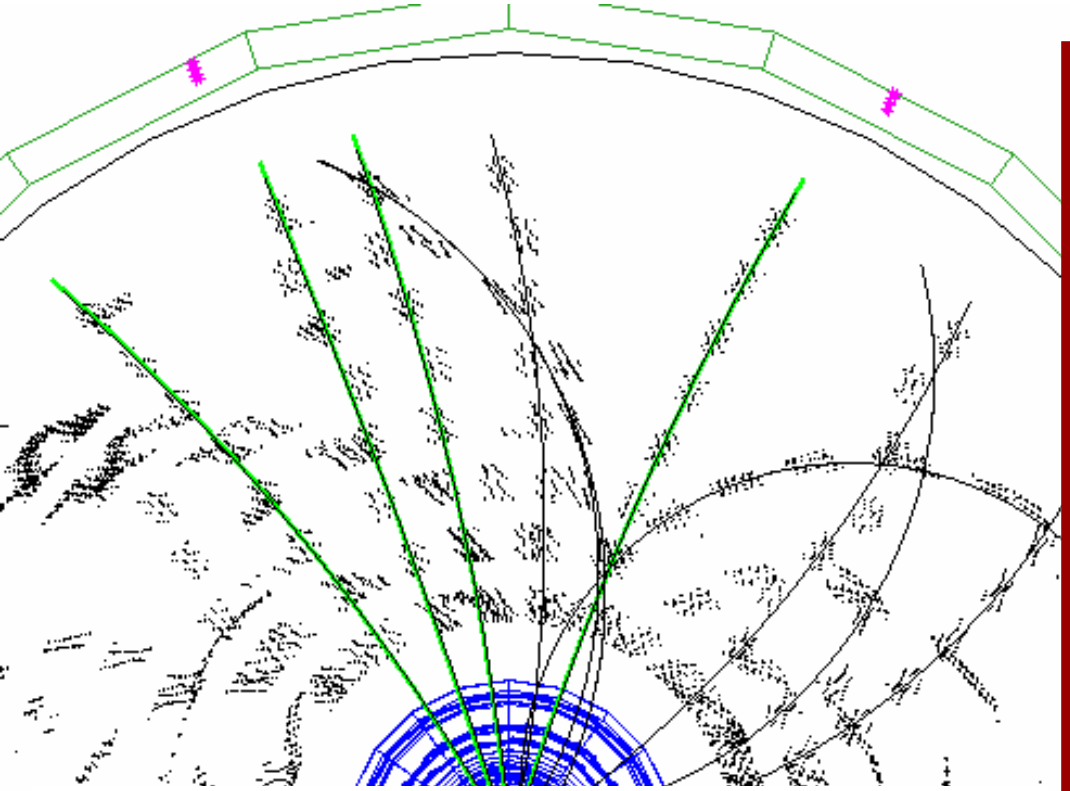


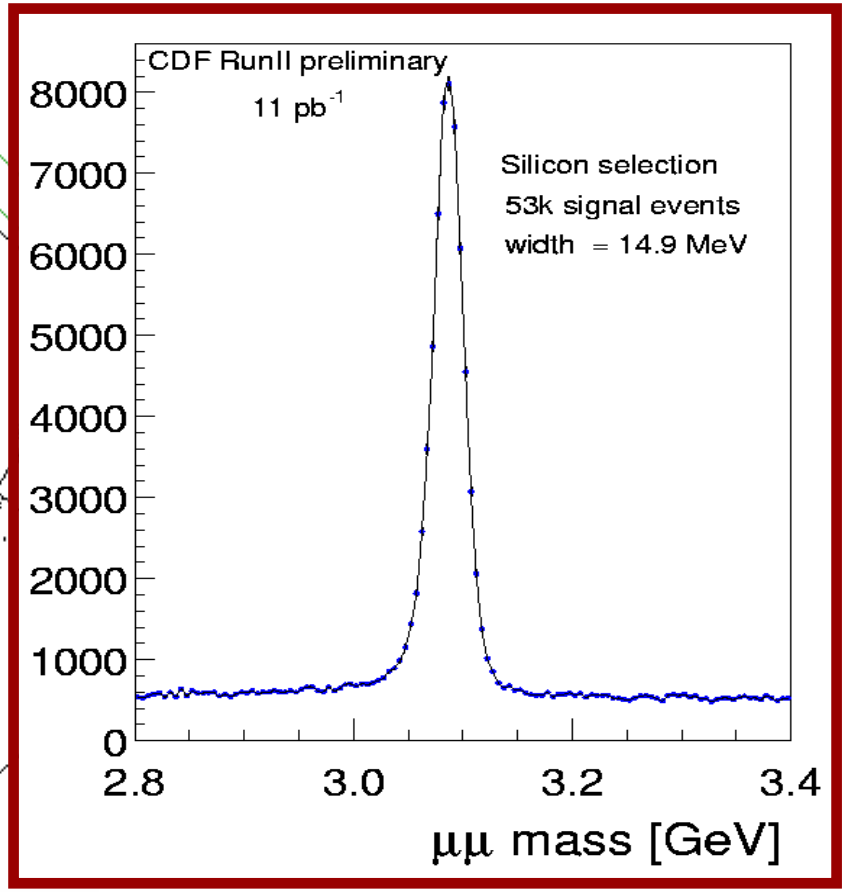
$M(K_s)$=499 ± 0.2 (stat) MeV/c^2



$M(\Lambda)$=1116 ± 0.1 (stat) MeV/c^2

Precision Momentum Measurement





COT tracking (measured)

ε = 99±1% (L3/offline reco)

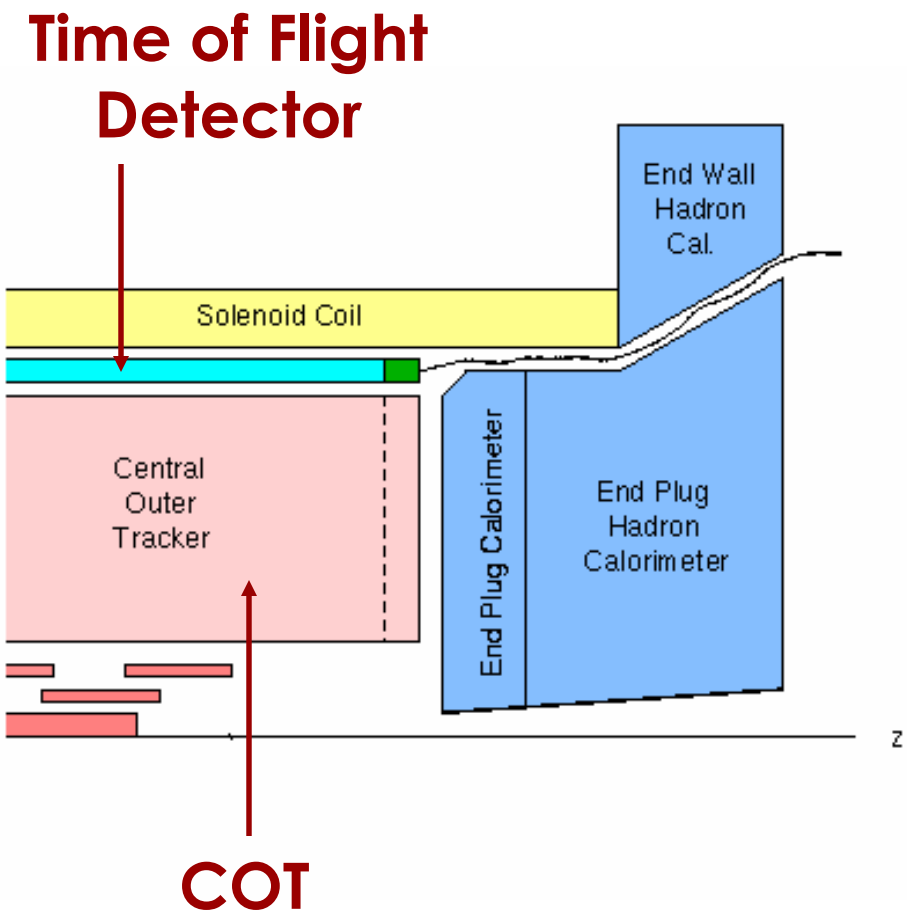
ε = 96.1±0.1% (L1 trigger)

$\sigma(1/p_T) < 0.13\%/\text{GeV}$ (offline)

$\sigma(1/p_T) = 1.74\%/\text{GeV}$ (L1 trigger)

Run II trigger efficient down to $p_T(\mu)$=1.5 GeV

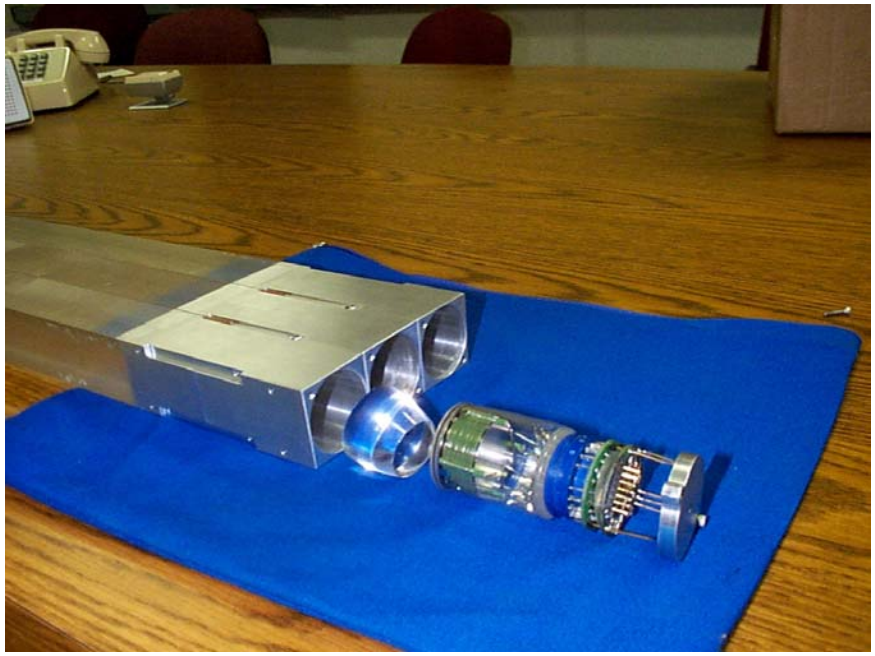
Particle ID Upgrade

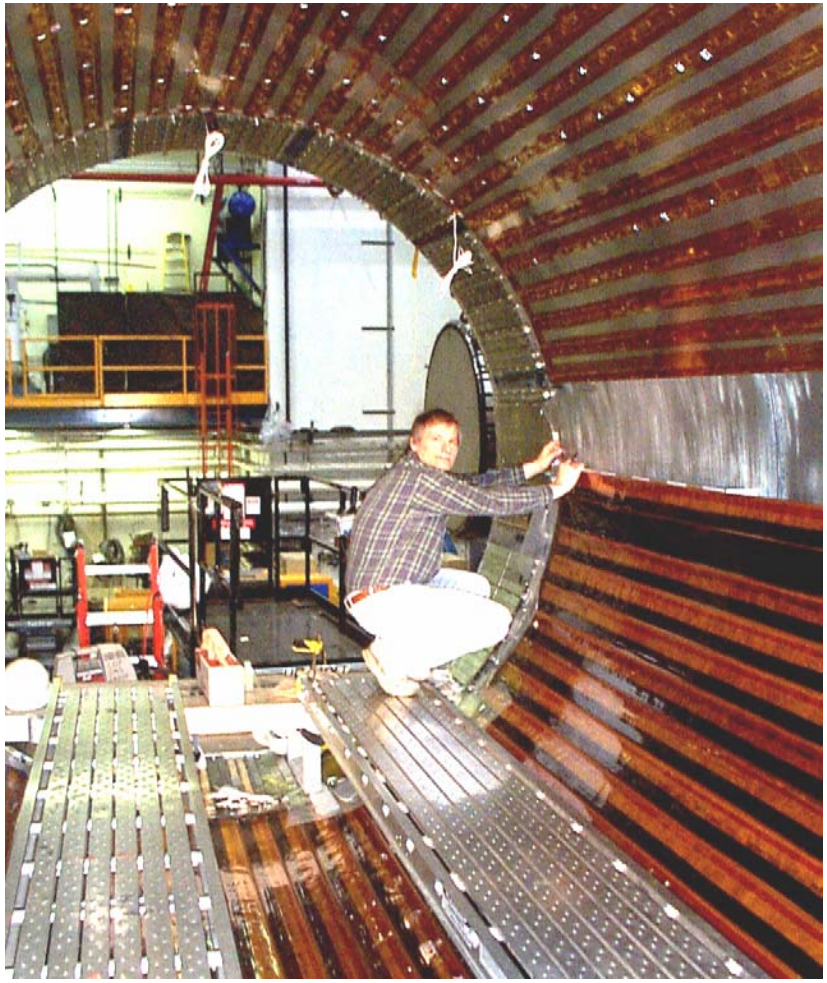


- **COT wires**
  - 96 pulse height measurements
  - dE/dx measured from pulse width via new ASD + TDC electronics
- **TOF scintillator bars**
  - 216 x 2 PMT channels
  - 100ps timing resolution

Time of Flight Detector

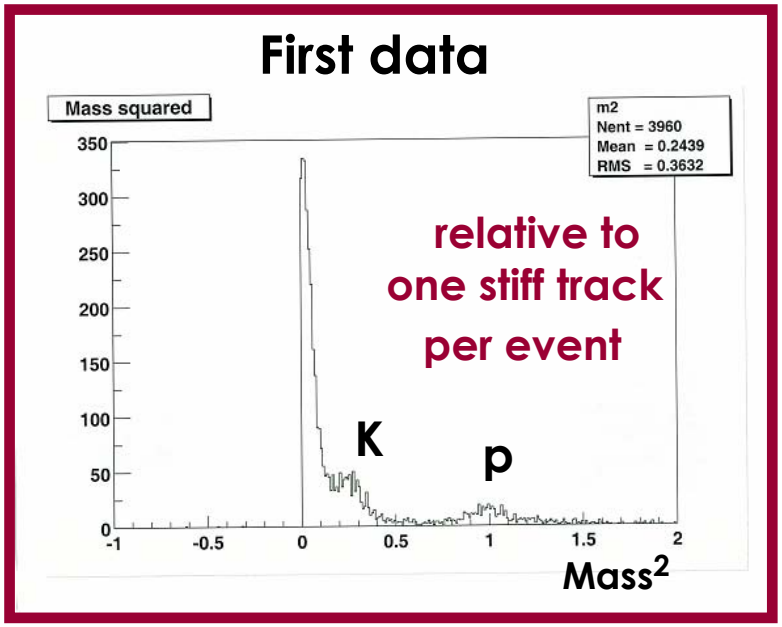
- 216 scintillators
- Fine mesh PMTs

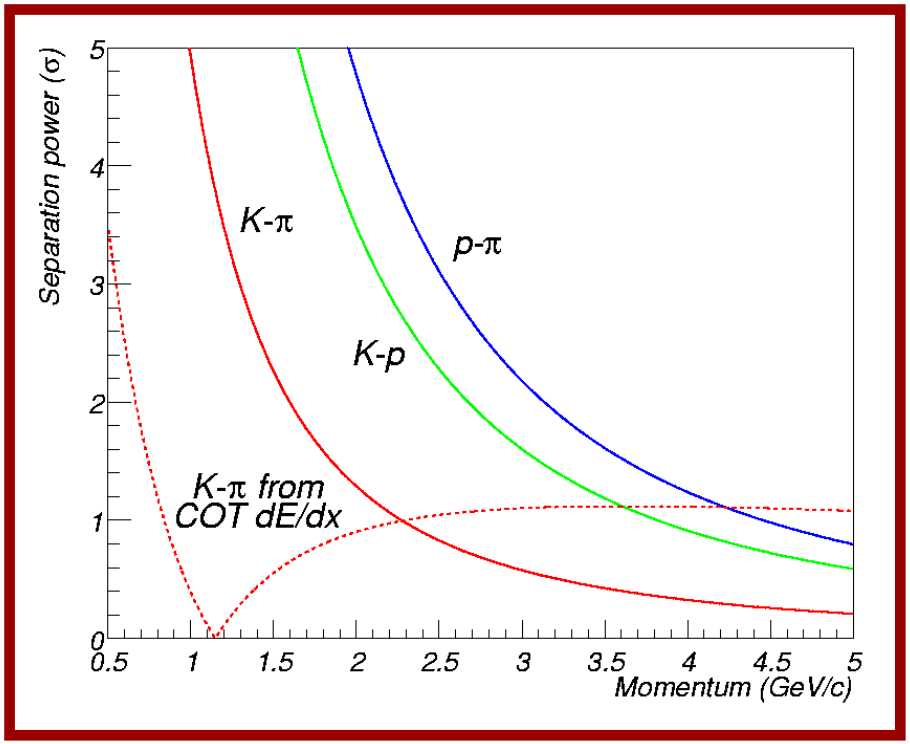


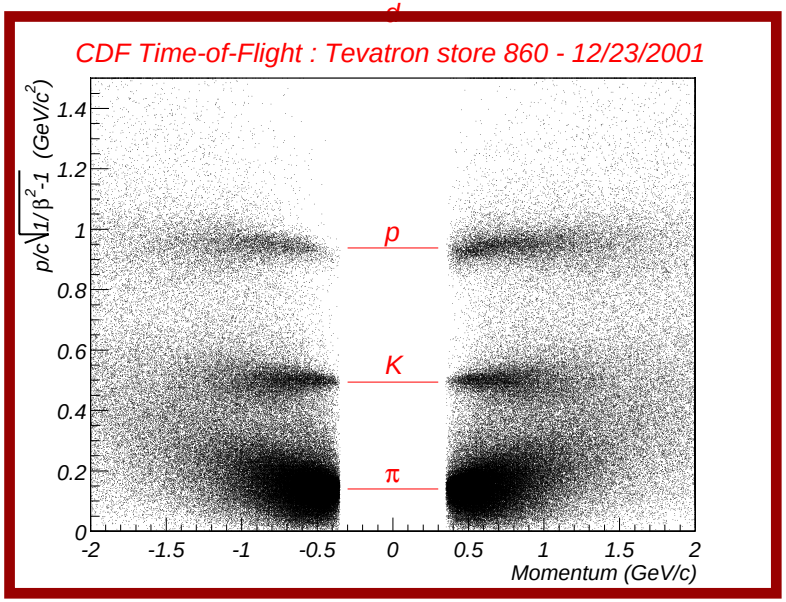


Particle ID with TOF & COT

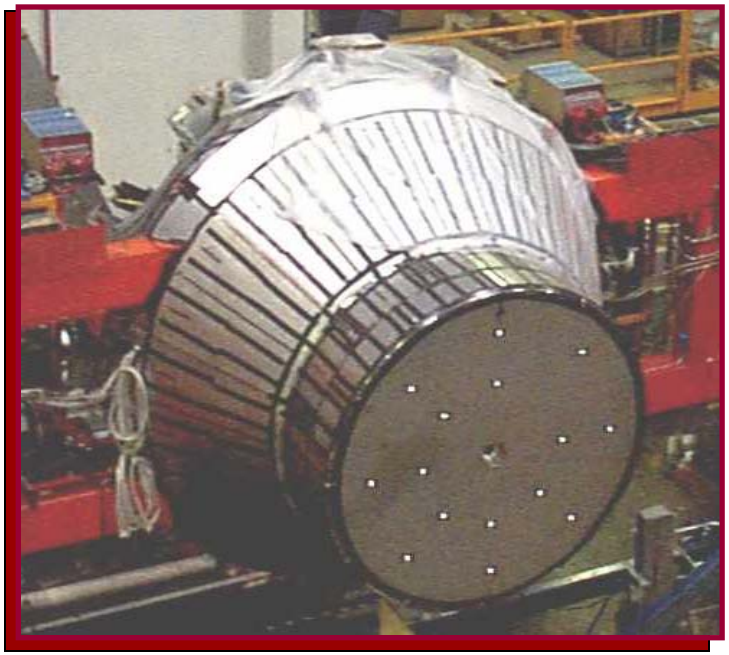
- **TOF: 100 ps resolution →**
  2σ separation for:
  - **K/π for p < 1.6 GeV**
  - **K/p for p < 2.7 GeV**
  - **p/π for p < 3.2 GeV**
- **COT dE/dx is complementary**





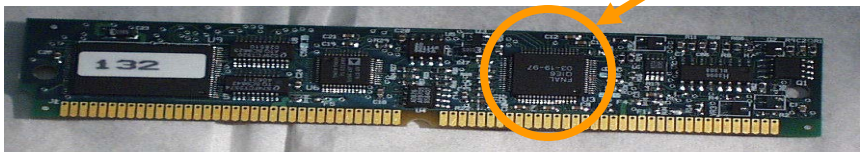


CDF Calorimeters

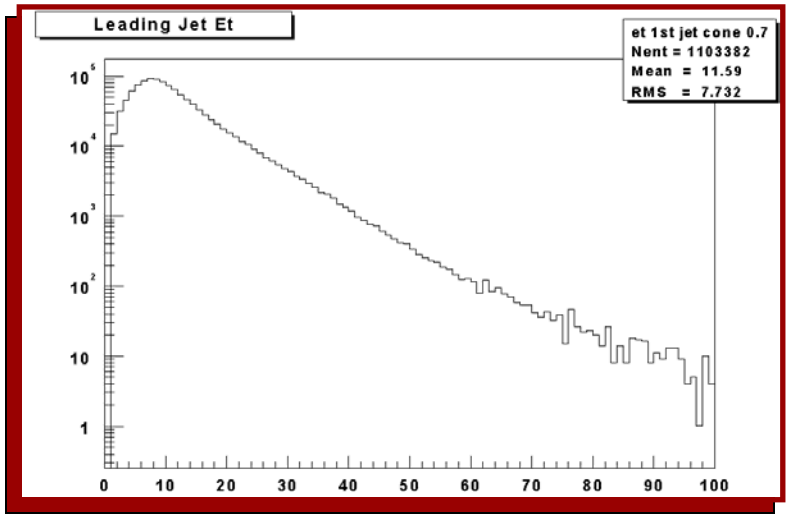


- **Central Calorimeters**
  - Kept Run I detectors
  - Scintillator based→fast
  - New readout electronics
  - QIE chip→18 bits dynamic range
  - Fully pipelined
  - Digital trigger

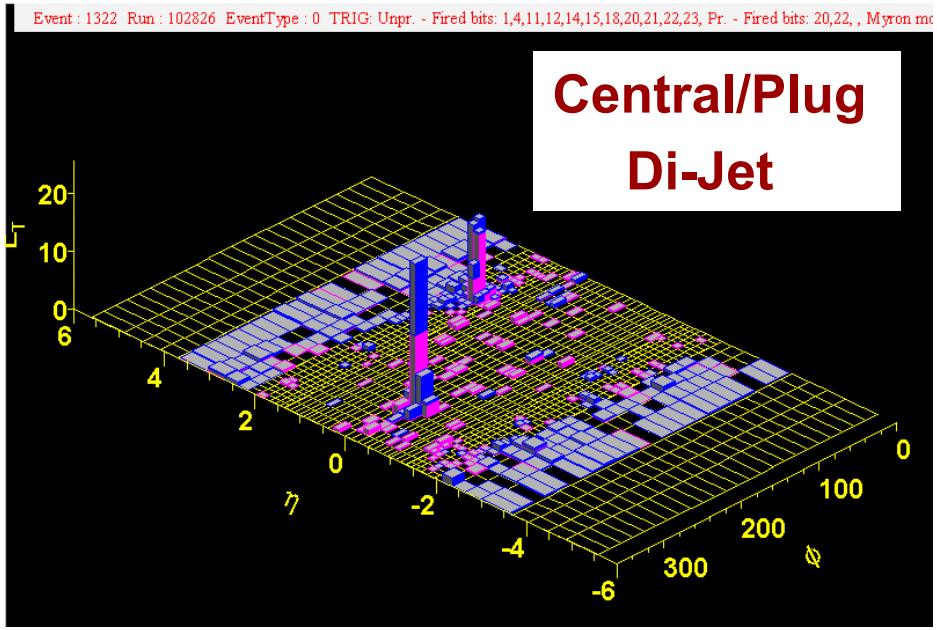
QIE chip

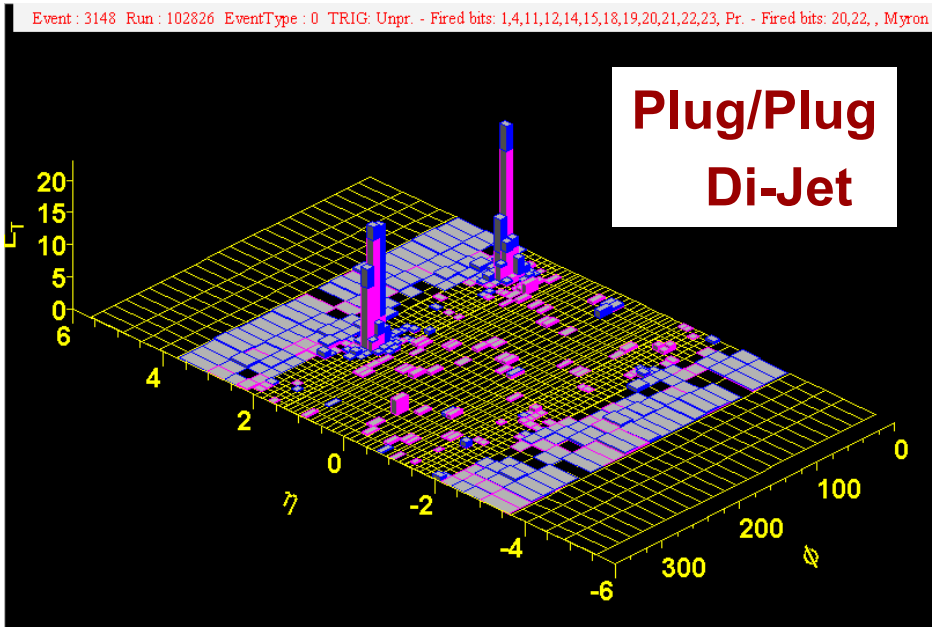


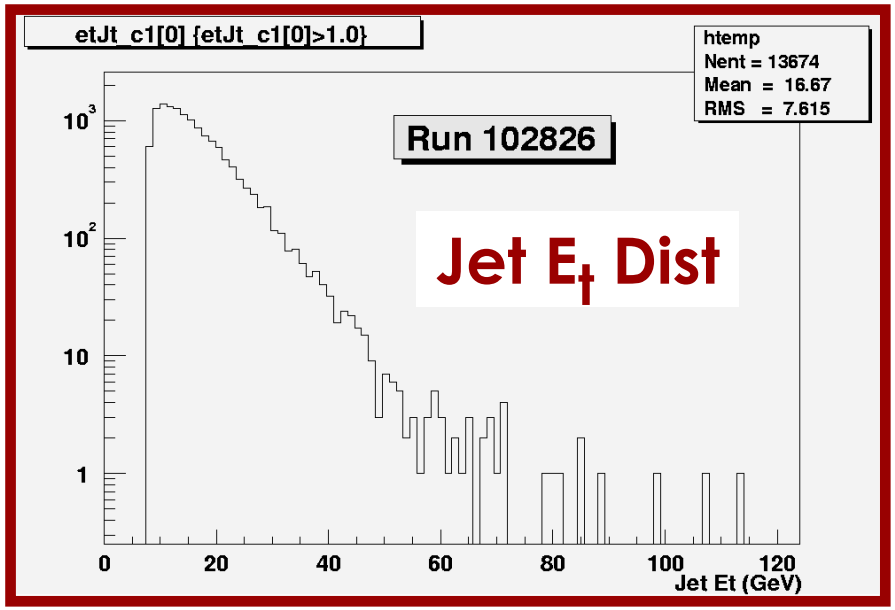
- **New Plug Calorimeters**
  - Scintillator tile design: Fast ! plus better sampling fraction than Run I gas cal.
  - Same technology over full solid angle to $|\eta| = 3.6$
  - More hermetic: 10° fwd gap gone, 30° reduced

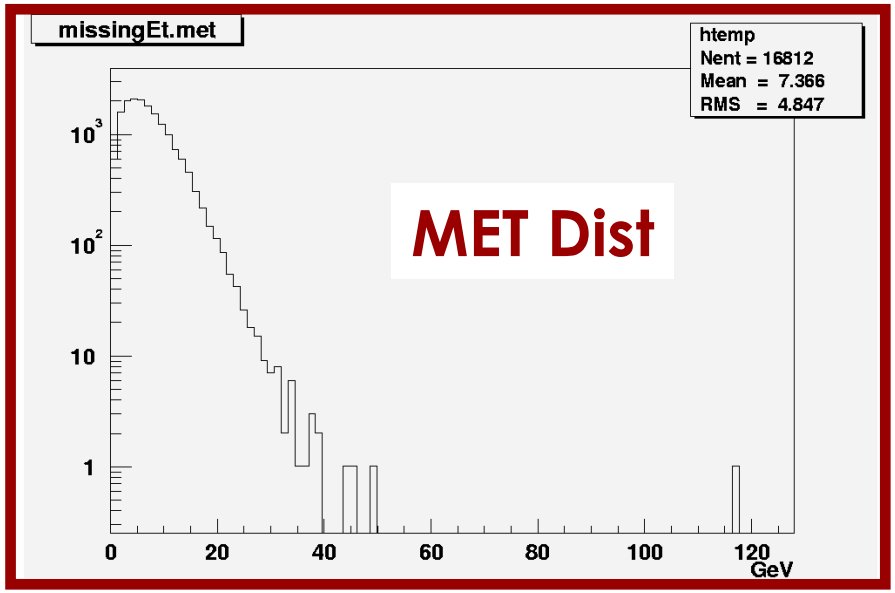


Jets in the Endplug Cal



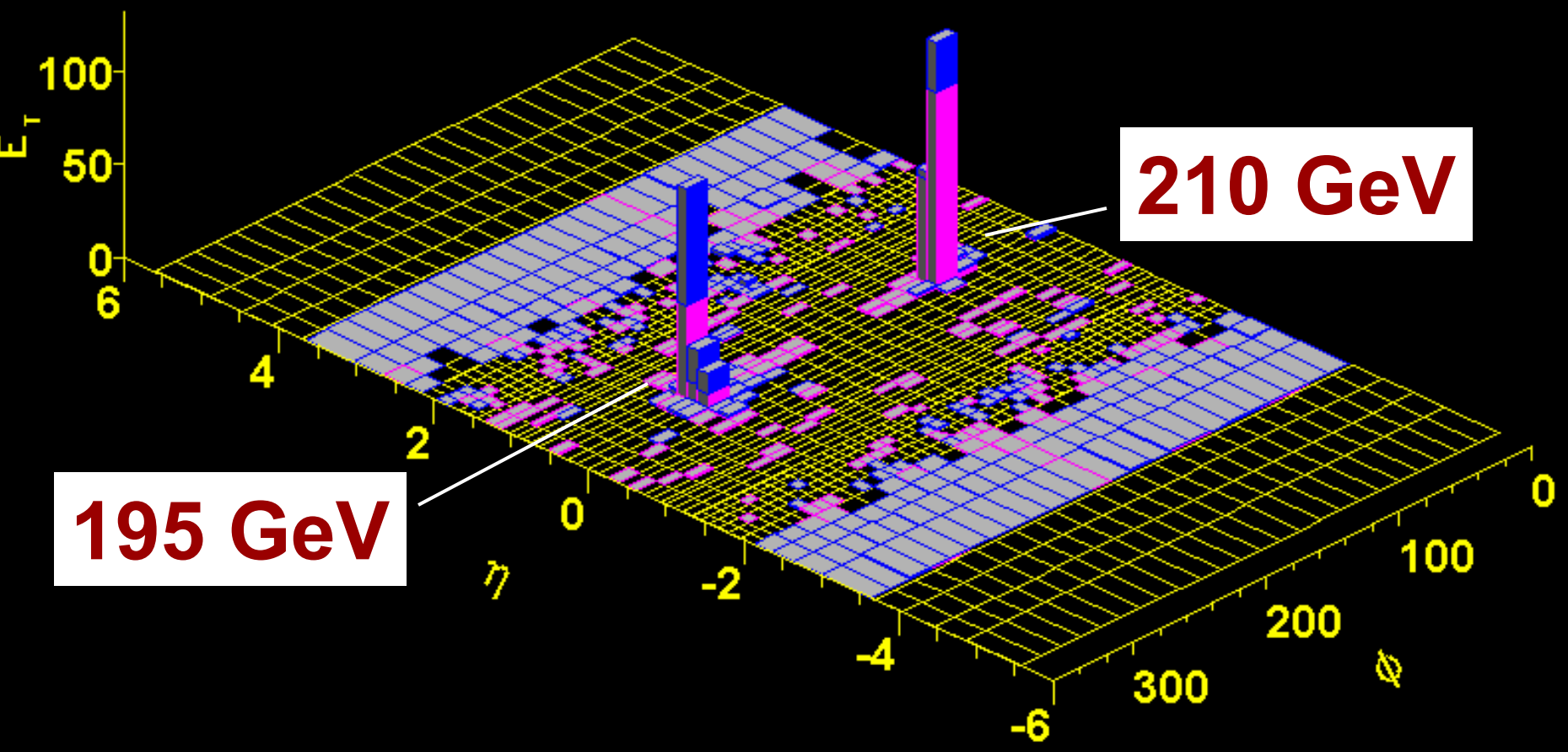






Event : 7973 Run : 102837 EventType : 0 TRIG: Unpr. - Fired bits: 1,41,14,15,21,22,23,24,26,30, Pr. - Fired bits: 22, , Myron mode 0

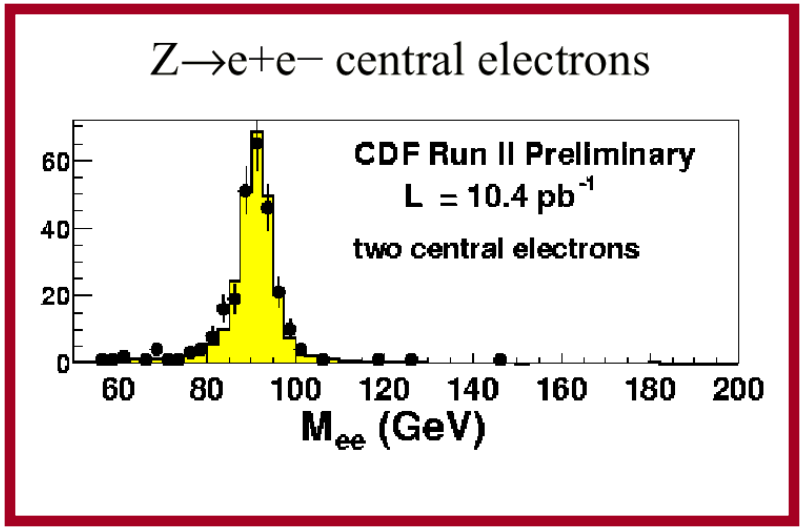
Central Calorimeter Di-Jet

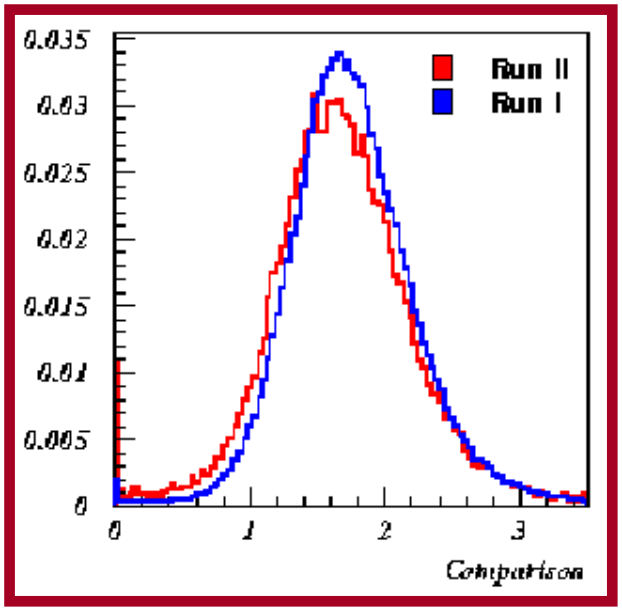


Energy Scales and Jets

Use M(Z) and M(W) to verify EM energy scale

M(Z) ~ 91 GeV





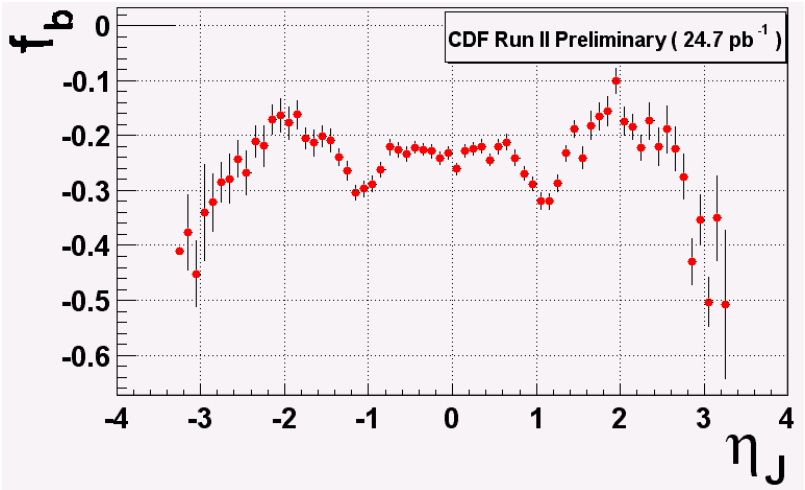
Check HAD energy scale with MIPs

MIP_2/MIP_{1b}=0.96 ± 0.005

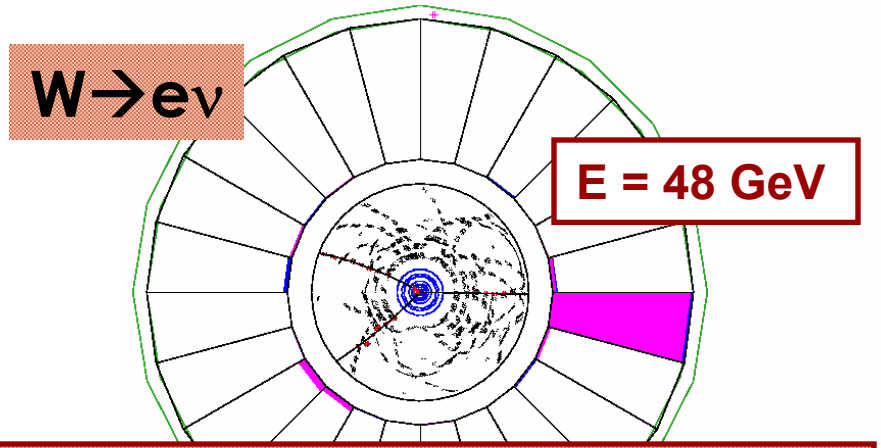
Use γ-jet p_T balancing to find jet scale wrt Run 1

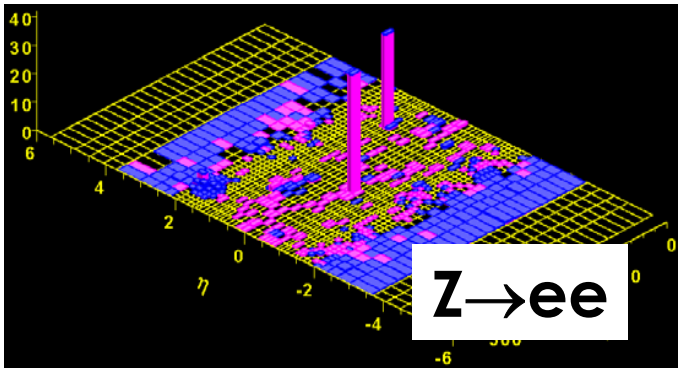
$f_b = (P_T^{Jet}-P_T^{\gamma})/P_T^{\gamma}$

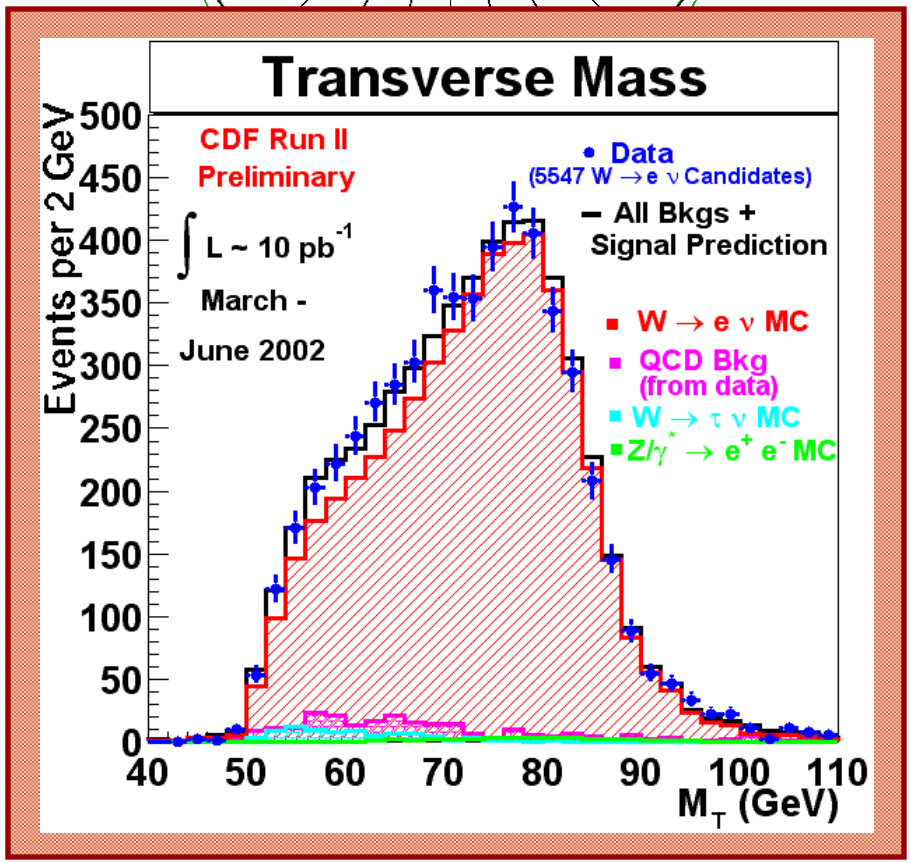
$\Delta f_b = (4.0 \pm 0.4)\%$

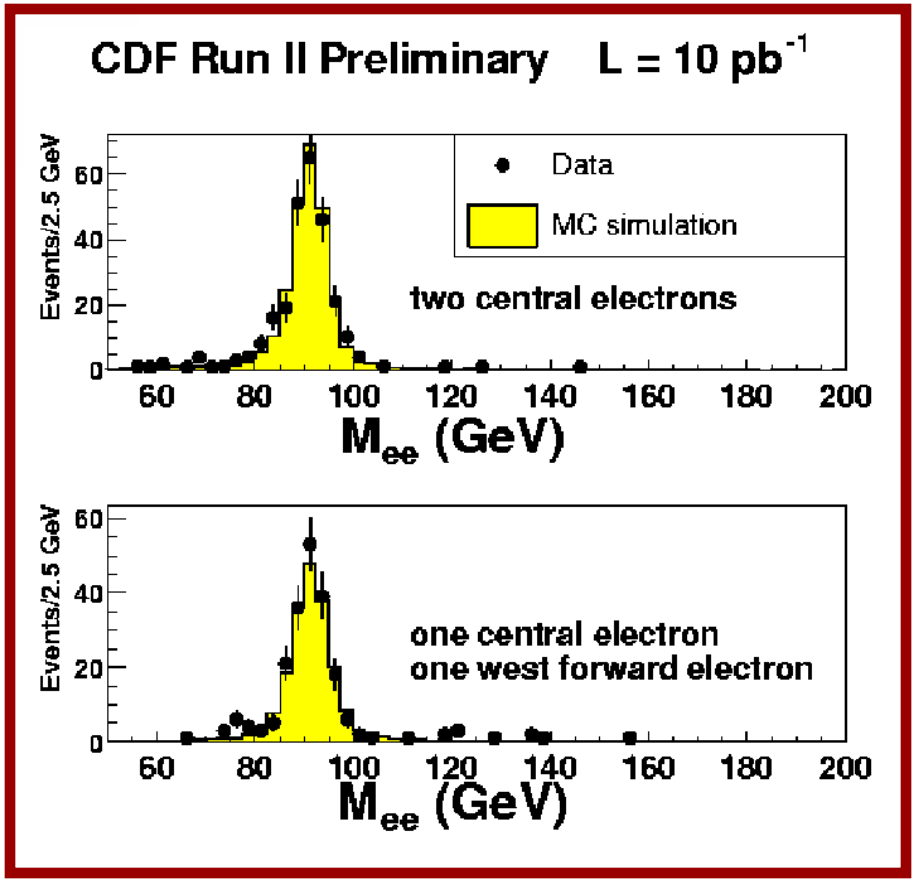


W and Z Candidates



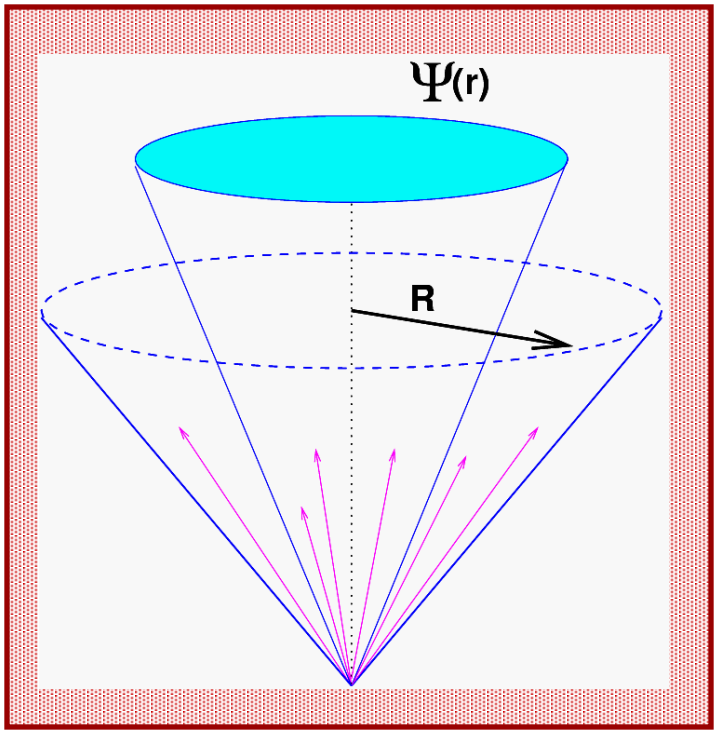


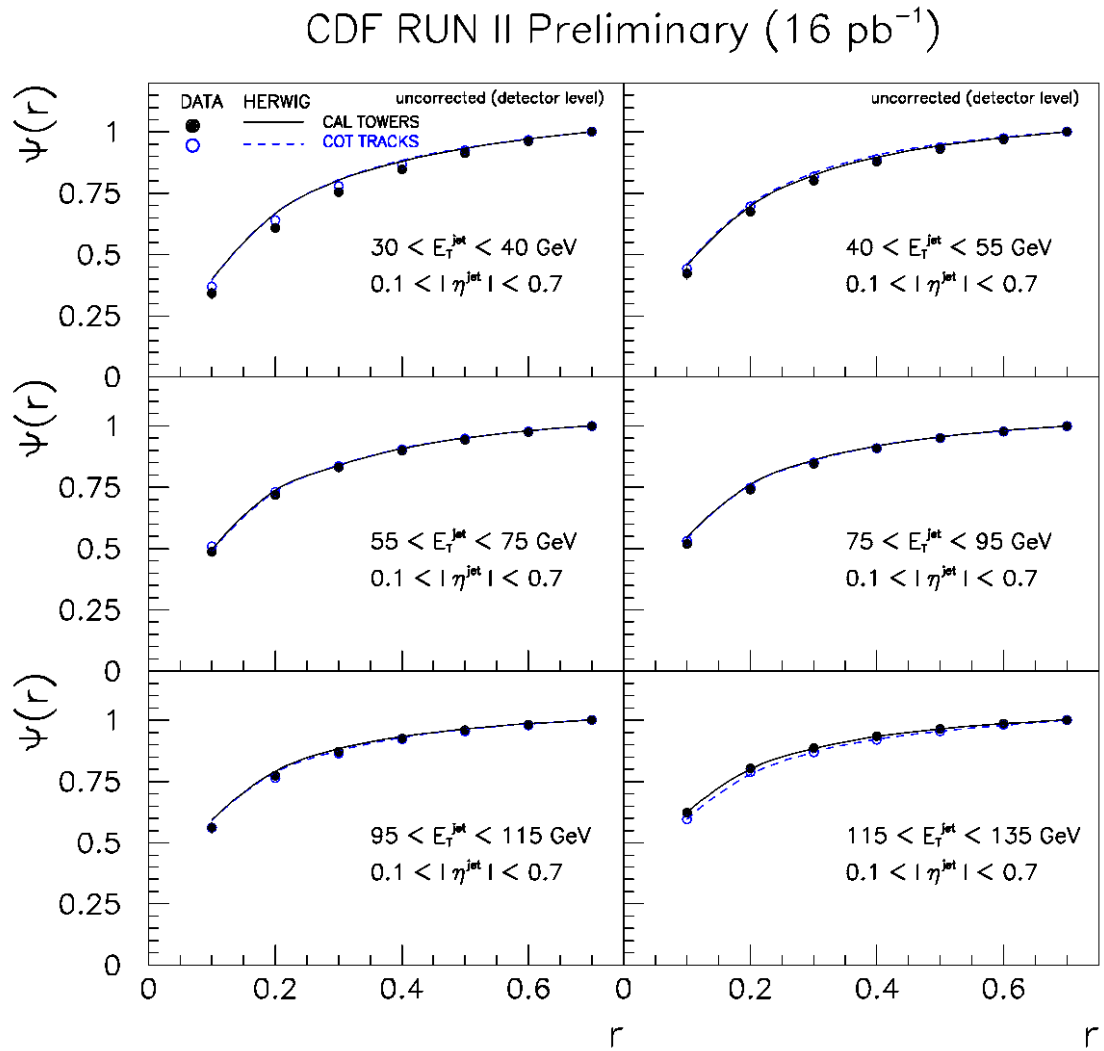




Analysis of Run 2 Jet Shapes

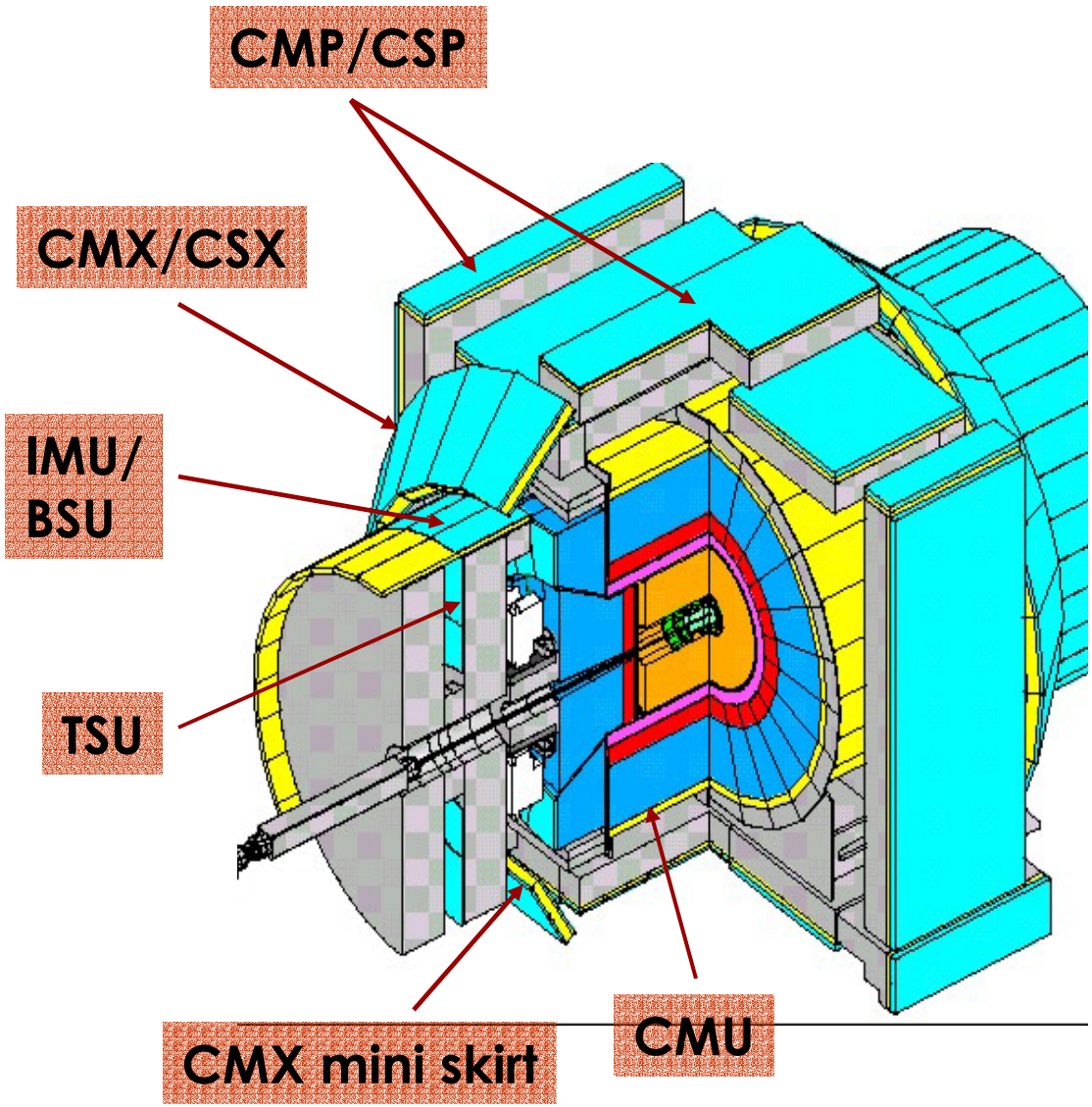
- **Jet Shapes:**
  - Narrower at higher E_T
  - Calorimeter and tracking consistent
  - Herwig modeling OK



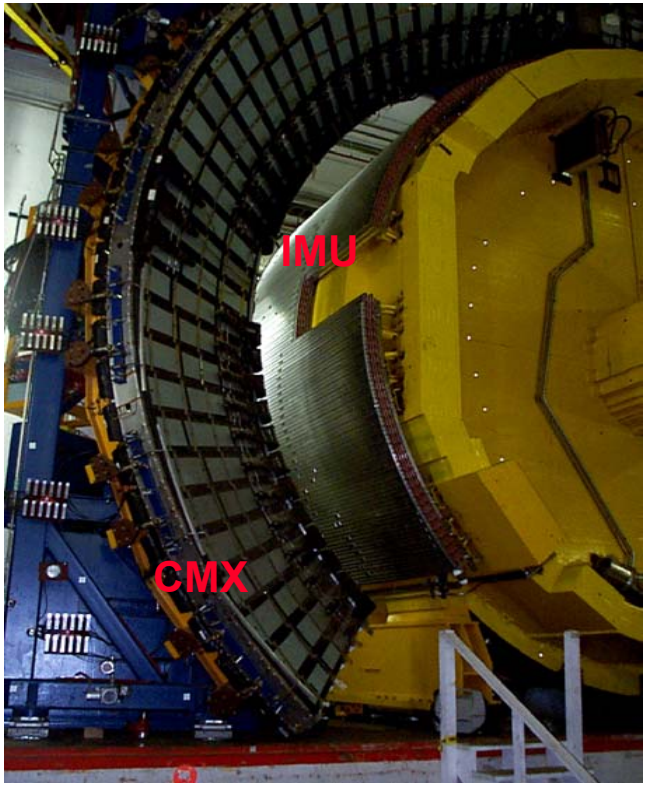


16 pb^{-1} used for this study

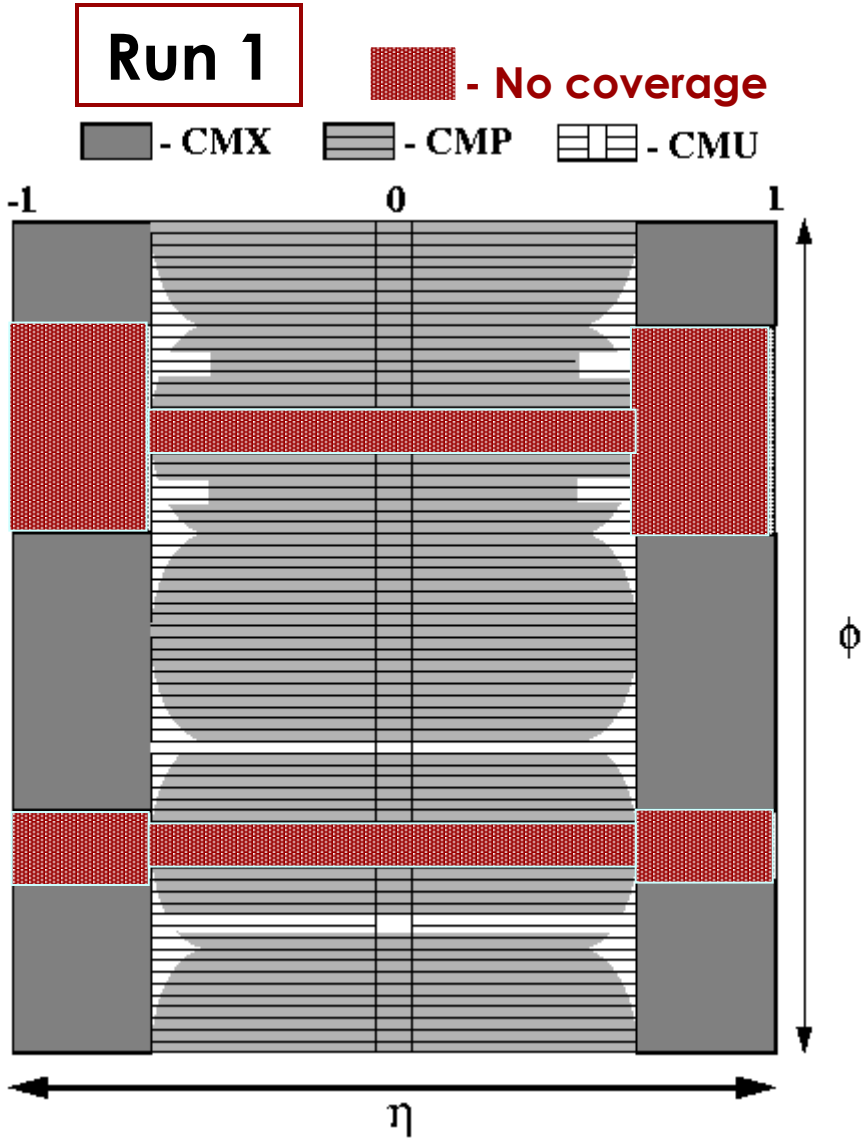
CDF Muon System

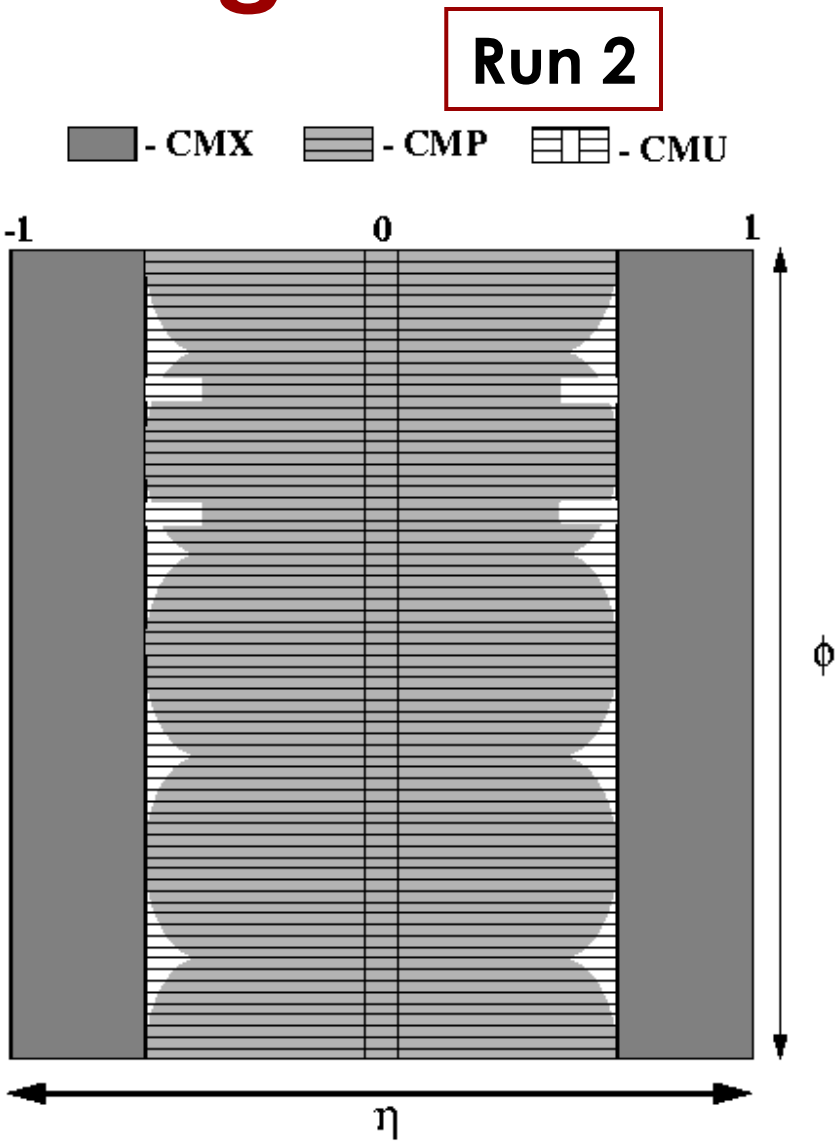


Muon coverage has been increased for Run 2 and old portions have been refurbished.



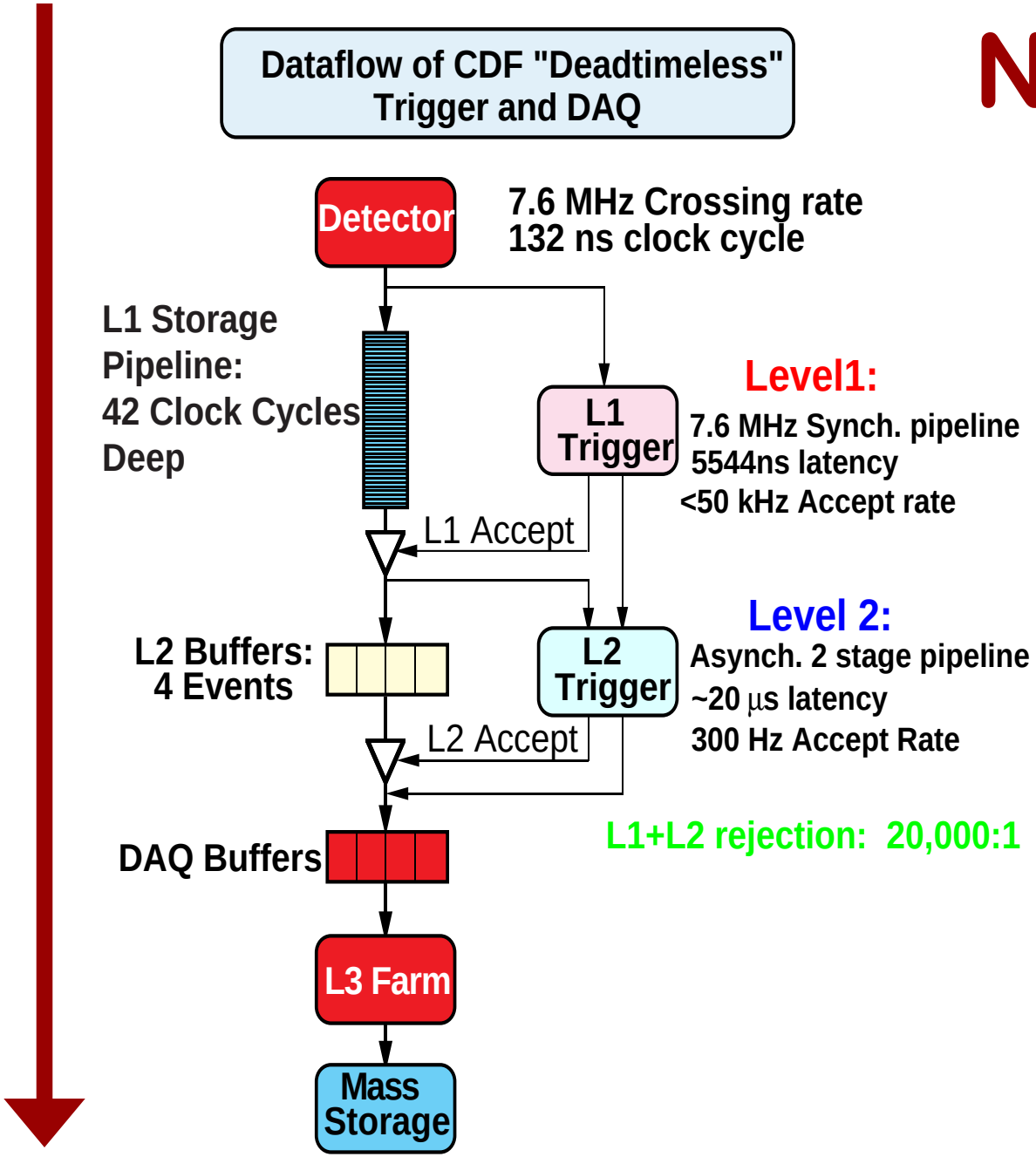
Muon Coverage





Additional coverage now out to $|\eta| = 1.5$

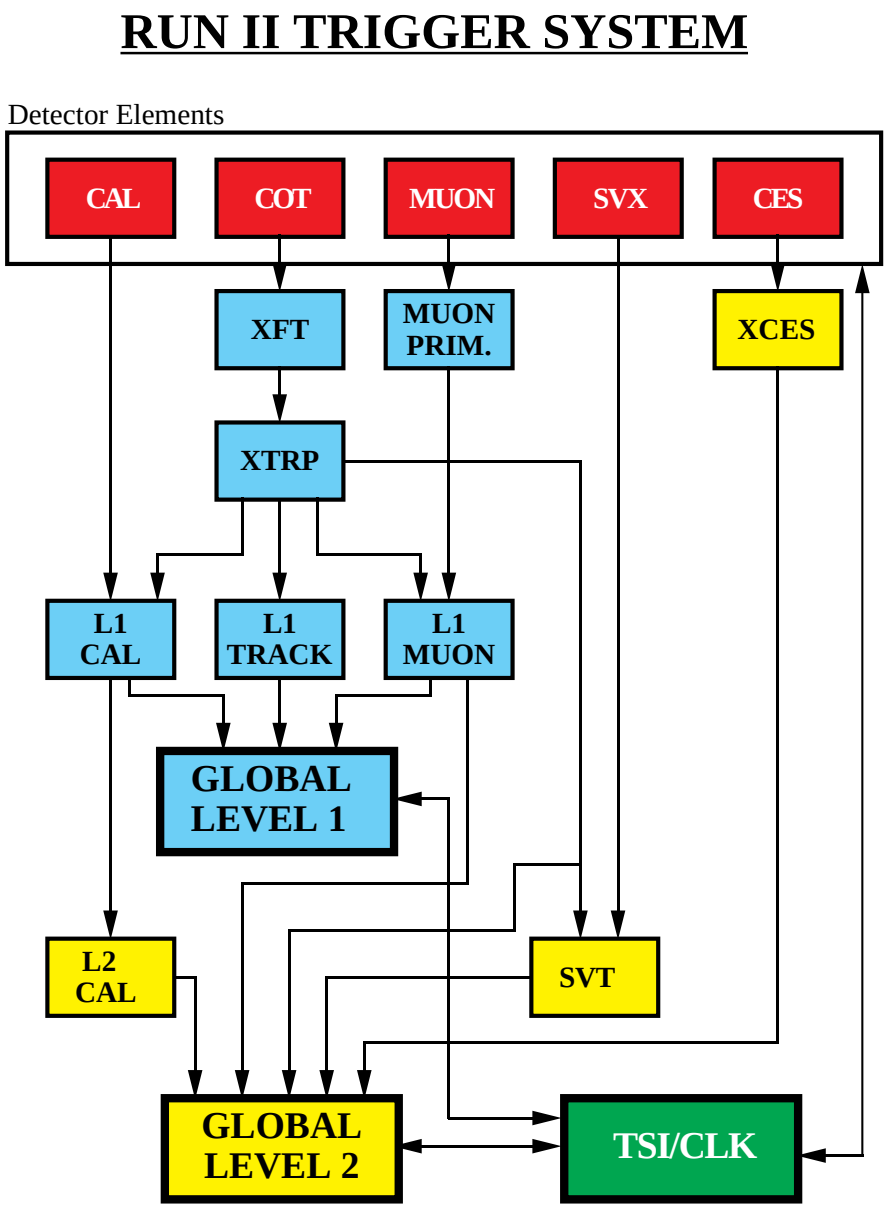
New Trigger Hardware



L1: Calorimeter energy Central Tracker (P_t,ϕ) muon stubs

L2: Cal energy-track match E/P, EM shower max, secondary vertex, multi-object triggers

L3: Farm of PC's Running fast versions of offline code → more sophisticated selections



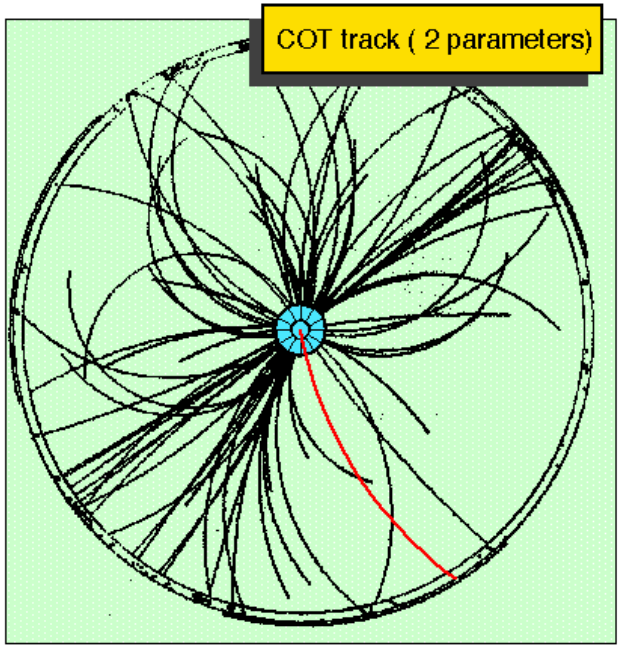
Trigger Paths

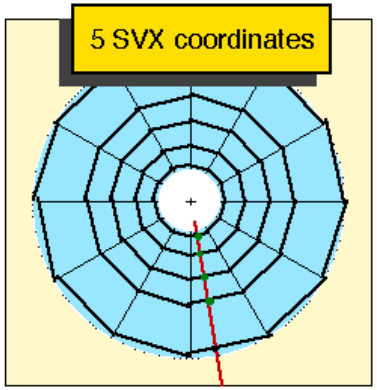
- Level 1combines COT, muon, and calorimeter information:
  - eXtremely Fast Tracker (XFT) and track extrapolator (XTRP) combines tracks, energy, and muon stubs to form objects: e,μ,γ,MET
- Level 2 adds secondary vertex info from SVT
  - L2 decision made in custom alpha processors
  - Four consecutive buffers→ >90% live time

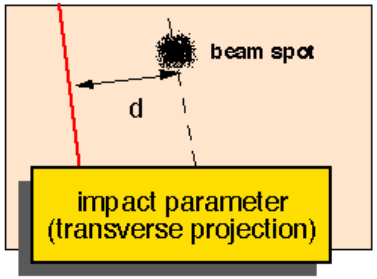
Impact Parameter at L2

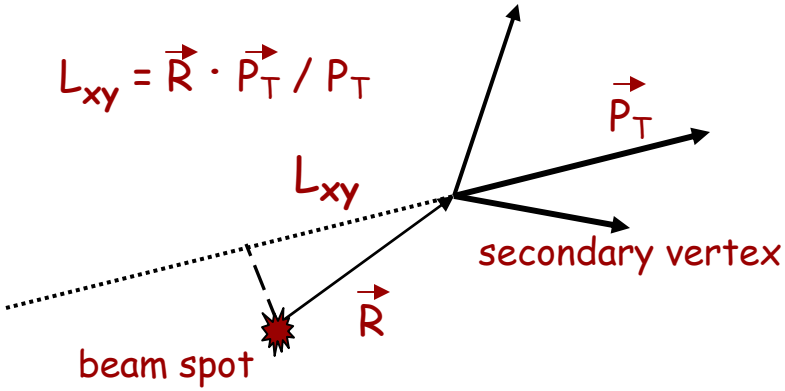
COT defines track momentum cut at level 1 (XFT)

SVX measures impact parameter cut at level 2 (SVT)



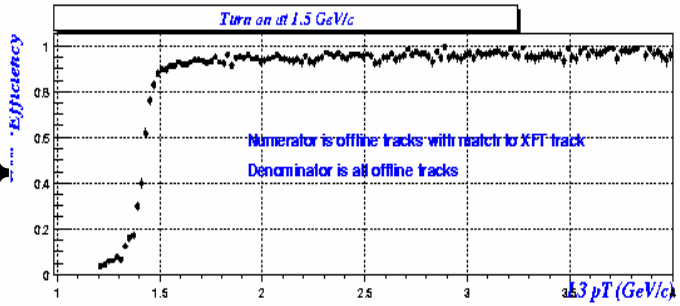




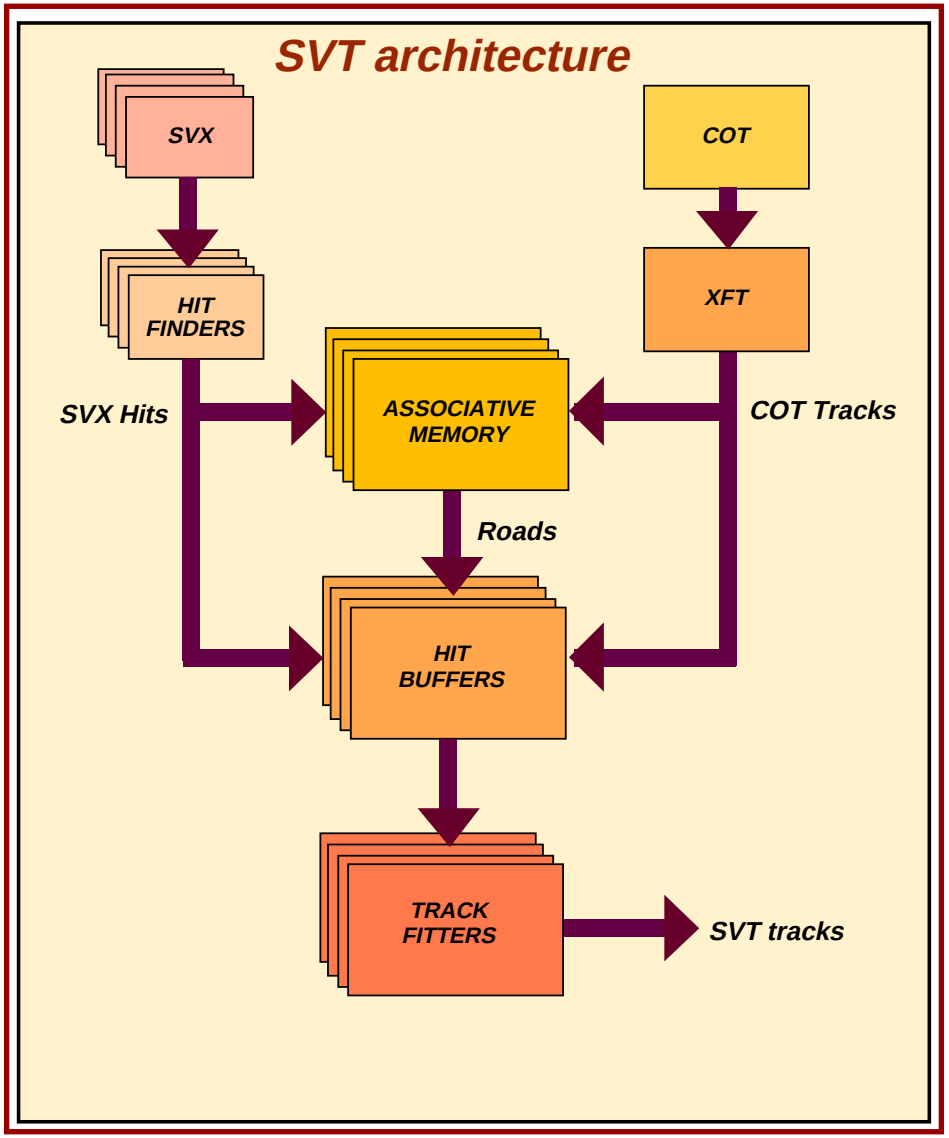


Hadronic B decays:
Select 2 tracks with P_t > 2.0 GeV/c using level 1 trigger (XFT), and having impact parameter between 120μm and 1mm using SVT data…

XFT cut at P_T = 1.5 GeV/c

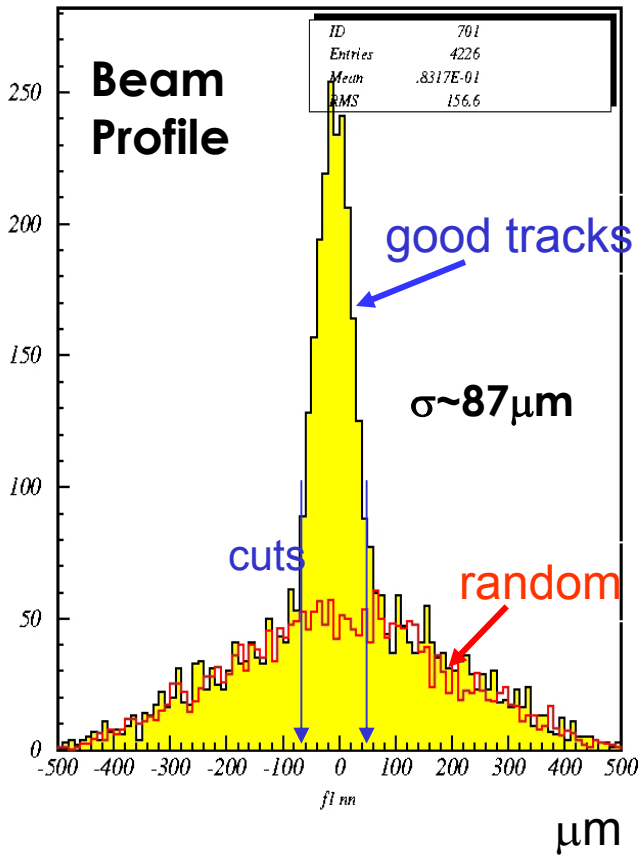


Secondary Vertex Trigger



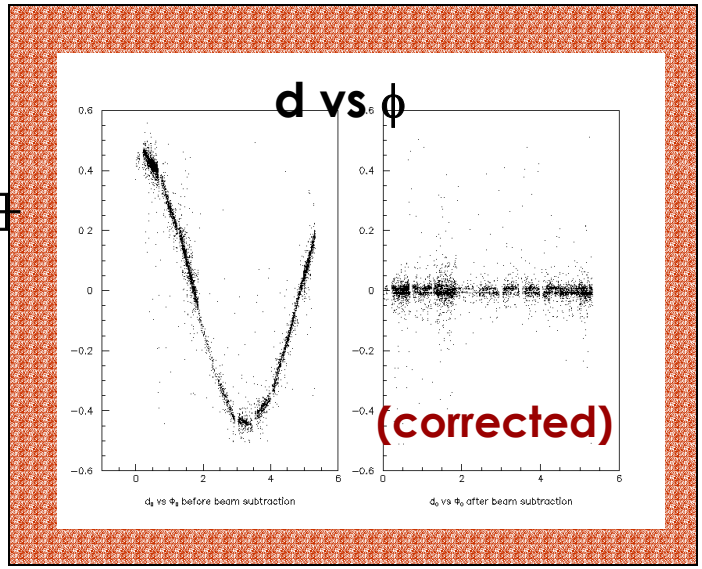
- EXtremely Fast Tracker (XFT) finds tracks in the Drift Chamber (COT)
- Silicon Vertex Tracker (SVT) combines COT tracks with SVX hit information
  - Associative memory checks track info to see if consistent with possible preset "road" list
  - When matches are found, the data are output to track fitters
  - Final track quality is comparable to offline!
- Effectively an impact parameter trigger at L2
  - Can trigger on hadronic B decays

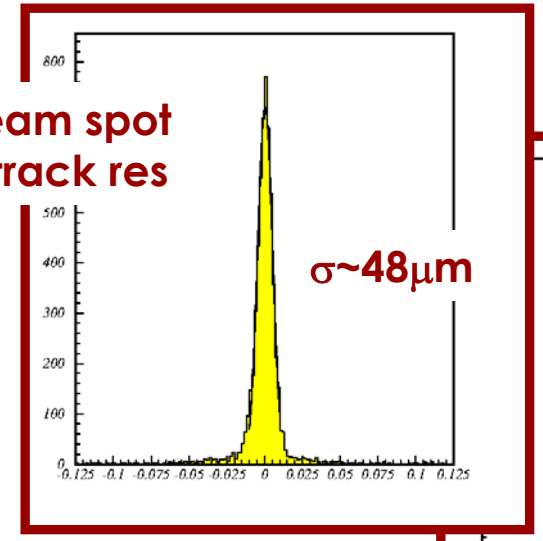
SVT Performance

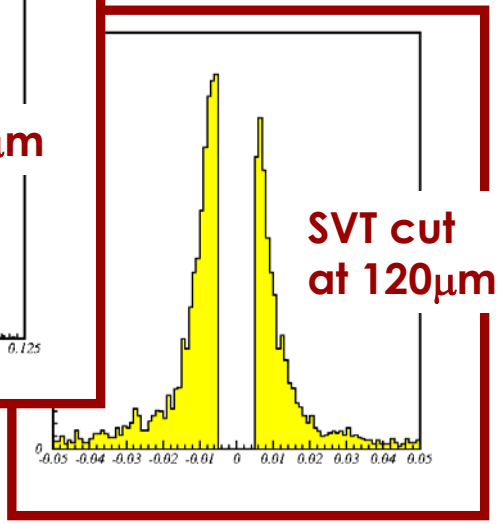


Commissioning performance good (above): using all tracks, no alignment or beam position correction, σ~87μm

Beam offset ~4mm

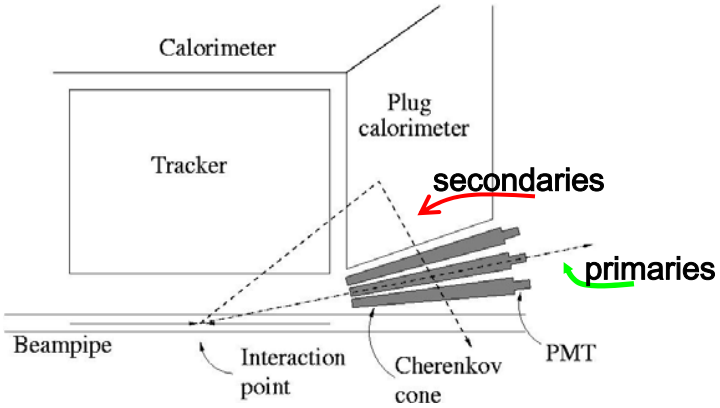






Other Upgrade Projects

- New Cherenkov counter for luminosity measurement

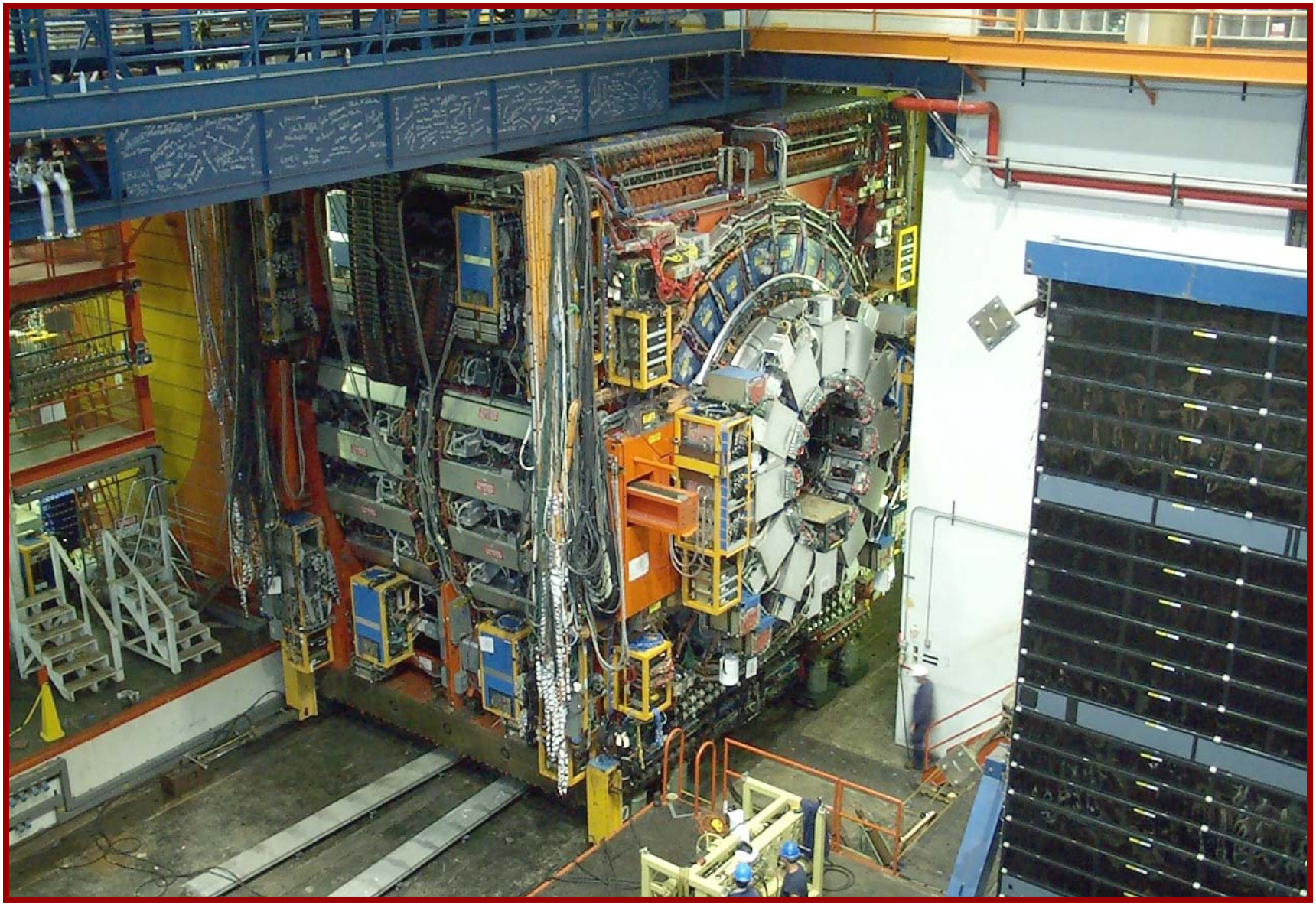


- Status of level 1, 2, and 3 triggers
  - L1 and L3 performing well
  - L2 not complete but sufficient for expected Tevatron luminosity profile

- DAQ system performance
  - working as designed
  - established 50 Hz, 20Mbyte/s out of L3 to offline data handling

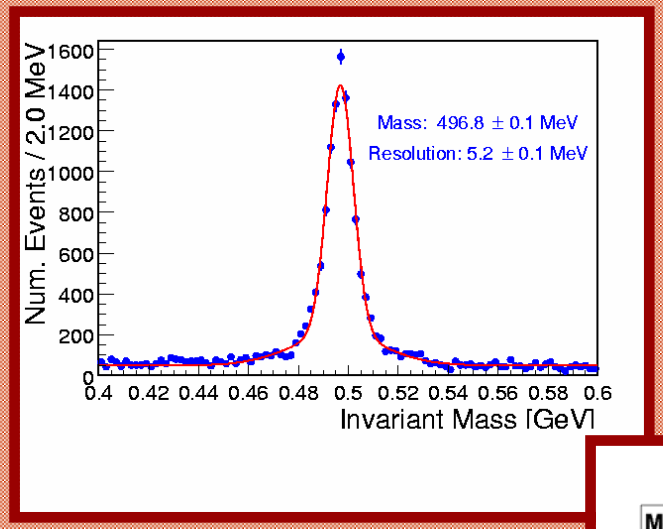
- Offline data handling and event reconstruction
  - Have recorded and reconstructed 78M events
  - 50 TB of data stored in 1000Tb tape robot
  - Secondary dataset handling and Monte Carlo event generation in development

Rolling in for Collisions

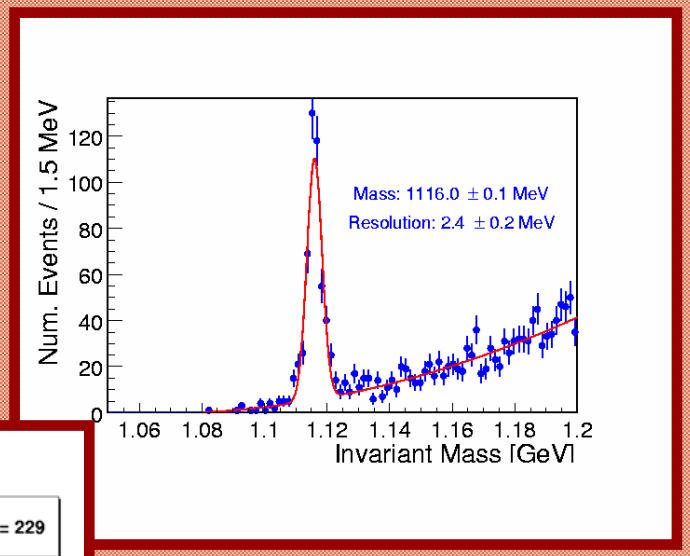


Preparing for Physics

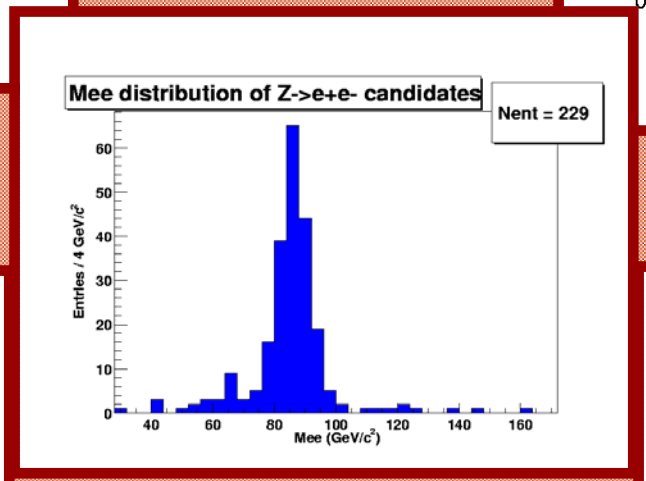
$K^o \rightarrow \pi^+ \pi^-$



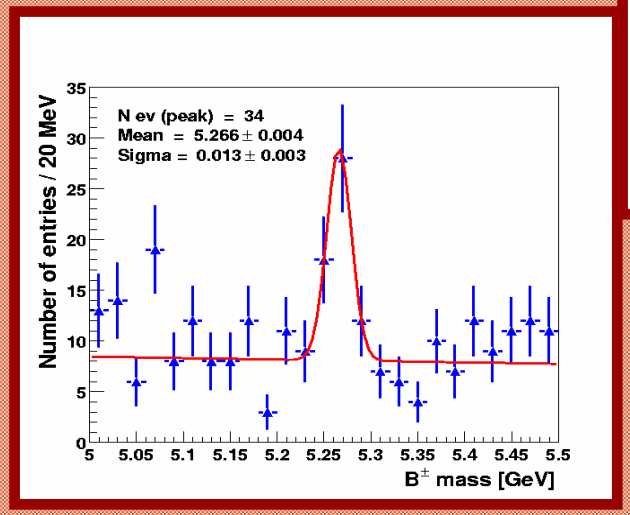
$\Lambda \rightarrow p\, \pi$



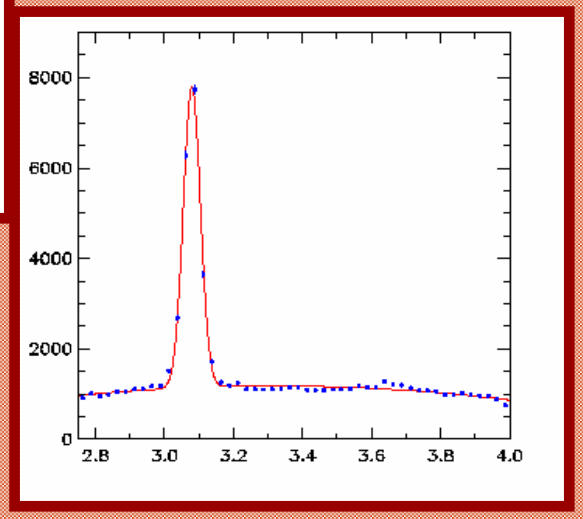
$Z \rightarrow e^+ e^-$



$B^{\pm} \rightarrow J/\psi\, K^{\pm}$



$J/\psi \rightarrow \mu^+ \mu^-$



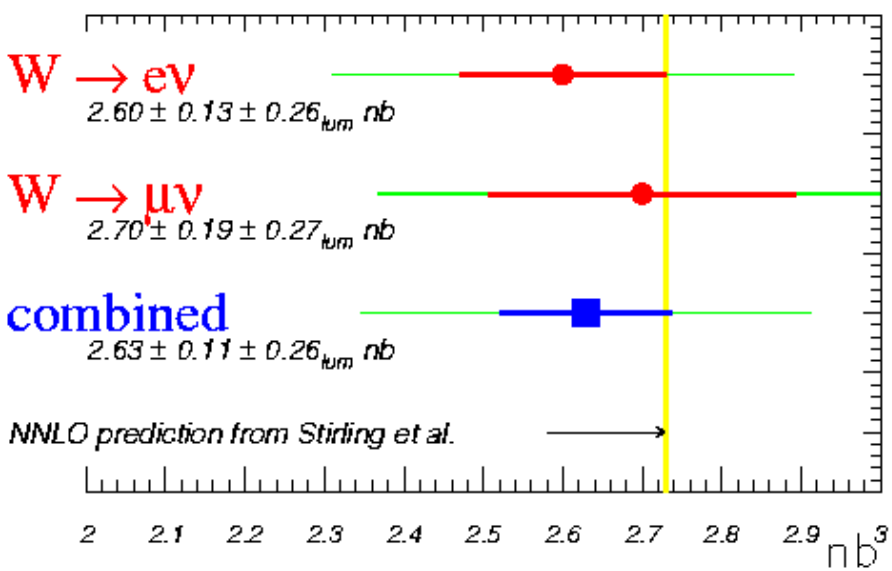
First Results from CDF Run2

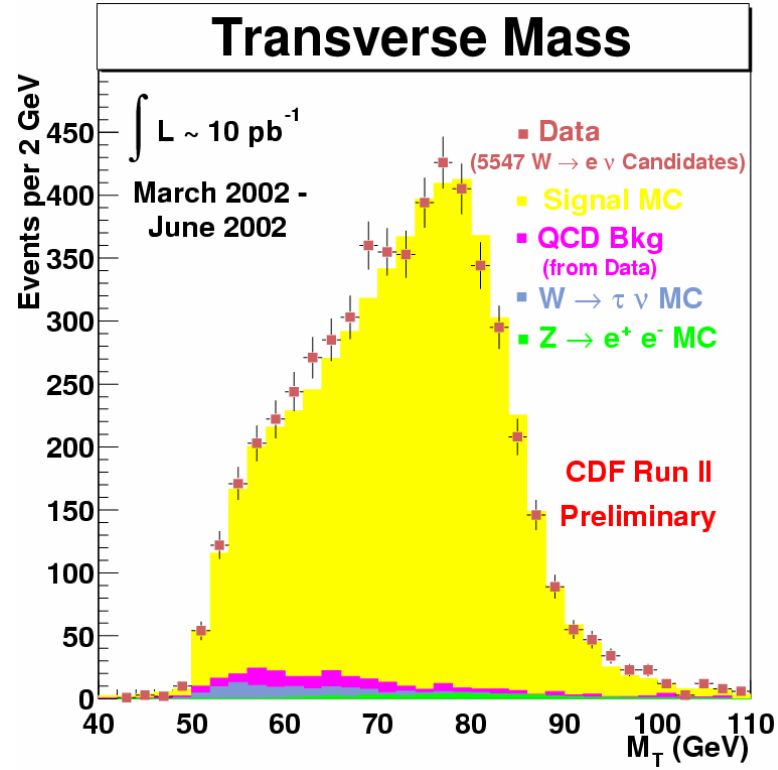
- **Re-establish Run I physics signals**
  - Reconstruct and model leptons, W's, Z's, jets, b's, …
  - Essential feedback for detector/trigger/reconstruction/simulation
  - Measure $\sigma(W)/\sigma(Z)$; Measure D-Y angular distributions
  - Prepare for high-P_T program: M_{top}, M_W, Higgs, SUSY, Z', LED
- **Calibrate precision track measurements**
  - Exploit high cross-section signals; Measure B lifetimes, masses
  - Begin B physics program (lifetimes, masses, B_s mixing, CP, L_b, B_c, …)
  - Provides calibration/tools for M_W, M_{top}, b jet tagging
- **Exploit new trigger capabilities**
  - Measure $\Delta M(D_s, D^+)$; Measure $B(D^0 \to KK, \pi\pi) / B(D^0 \to K\pi)$
  - Learn to model trigger for physics signals (later $\Rightarrow Z \to bb$, $H \to bb$)
  - Reconstruct fully hadronic B decays

Measurements with High E_T electrons

- **W cross section:** 0.16 soon!
- σ_W*BR(W→eν) = $2.60 \pm 0.07_{stat} \pm 0.11_{syst} \pm 0.26_{lum}$
- **Consistent with Run 1 results rescaled for higher energy:** $2.72 \pm 0.02_{stat} \pm 0.08_{syst} \pm 0.09_{lum}$

(use Sterling et al. NNLO predictions)





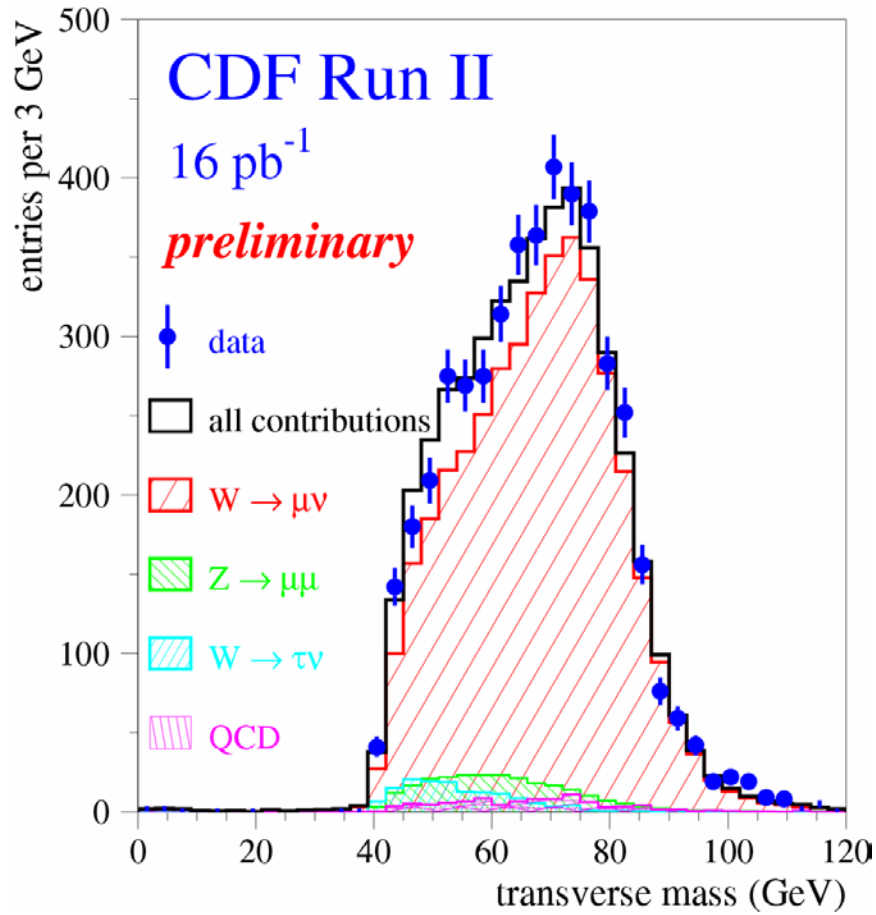
Number of Candidates:
- **5547 in 10 pb^{-1}**

Background (8%):
- QCD: 260 ±34±78
- Z →ee: 54 ± 2 ± 3
- W→τν: 95 ± 6 ± 1

Measurements with High E_T muons

- **W cross section:**
- σ_W*BR(W→μν) = $2.70 \pm 0.04_{stat} \pm 0.19_{syst} \pm 0.26_{lum}$
- **Consistent with Run 1 results rescaled for higher energy:** $2.41 \pm 0.08_{stat} \pm 0.15_{syst} \pm 0.16_{lum}$

(use Sterling et al. NNLO predictions)



Number of Candidates:

- **4561 in 16 pb^{-1}**

Background (12.5%) :

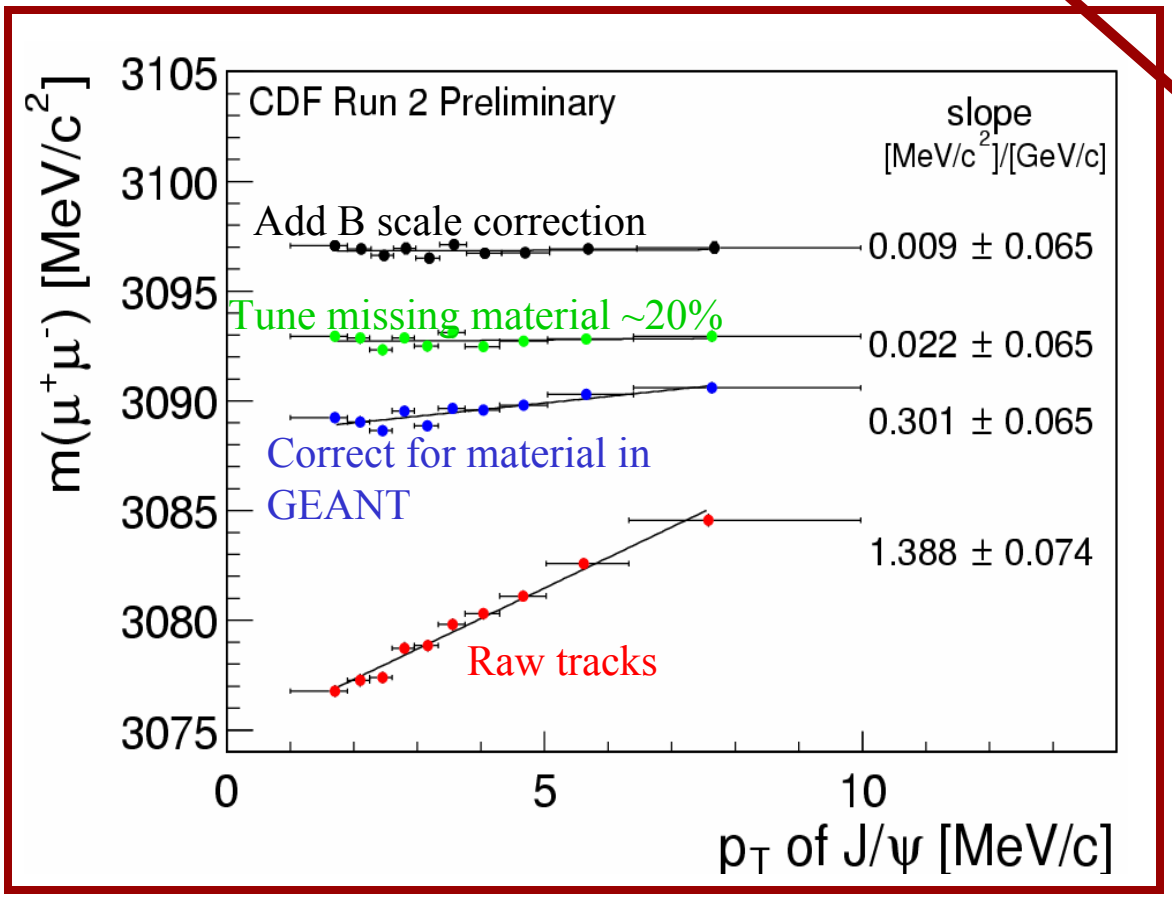
- QCD: 104 ± 53
- cosmics: 73 ± 30
- Z →ee: 247 ± 13
- W→τν: 145 ± 10

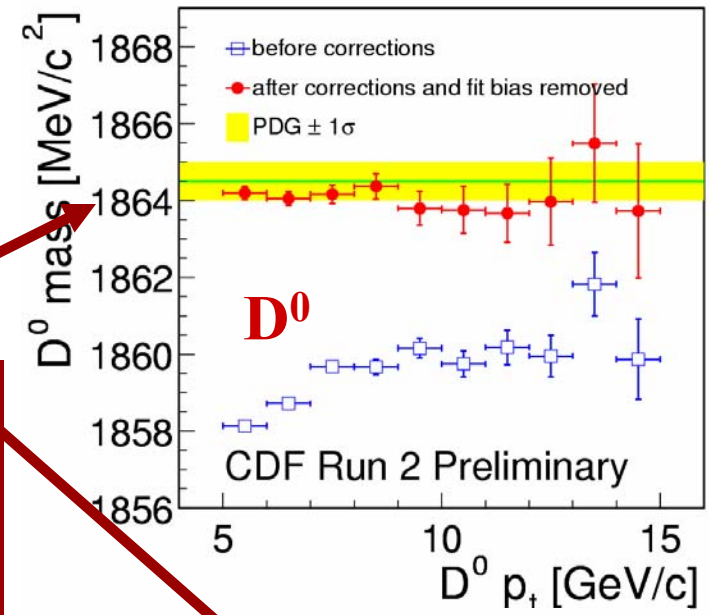
$R = \sigma(W \to \mu\nu)/\sigma(Z \to \mu\mu) = 13.66 \pm 1.94_{stat} \pm 1.12_{syst}$

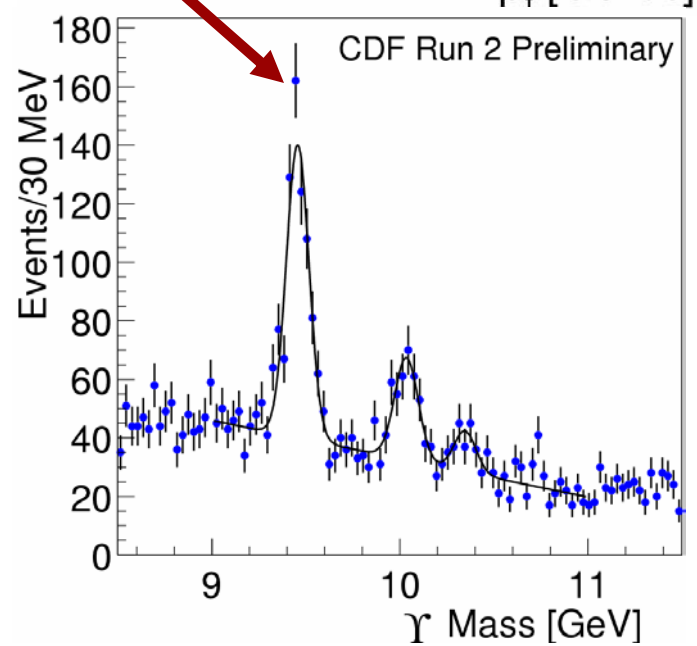
(Consistent with Run 1 results)

Measurements with Low E_T muons

- Use ψ's to understand E-loss and B-field corrections
- Check with other known signals





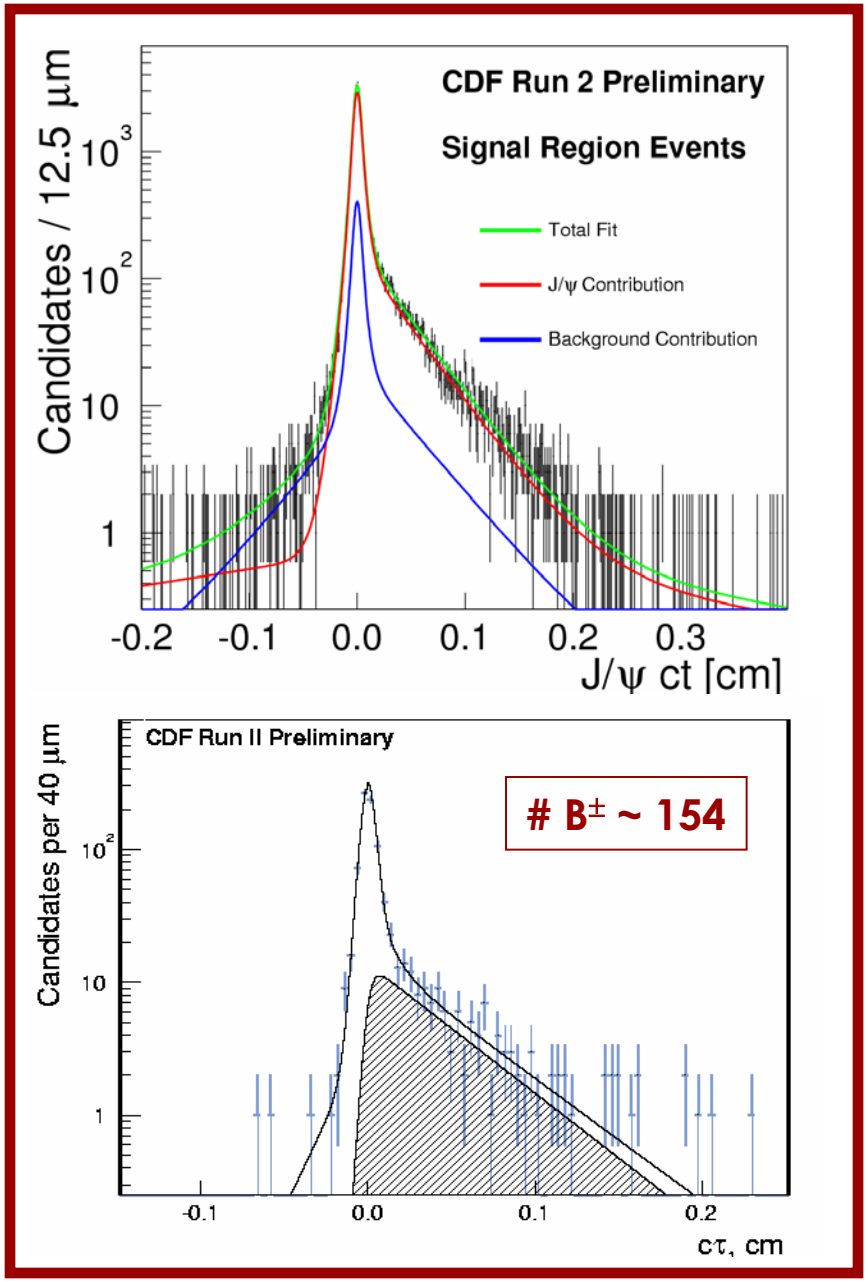


B Hadron Lifetimes with Low E_T muons

- ψ trigger improved
  - $p_T^m > 2.0 \rightarrow 1.5$ GeV;
  - $\Delta\phi > 5° \rightarrow 2.5°$

- Inclusive B lifetime with ψ's
- Fit pseudo $c\tau = L_{xy}^{\psi} * F_{MC} * M^{\psi}/p_T^{\psi}$ distn
- Output: B lifetime; fraction of ψ from B
  - $c\tau = 458 \pm 10_{stat} \pm 11_{syst}$ μm (PDG: 469 ± 4 μm)
  - ψ from B = 17% ($p_T^{\psi} > 4$ GeV)

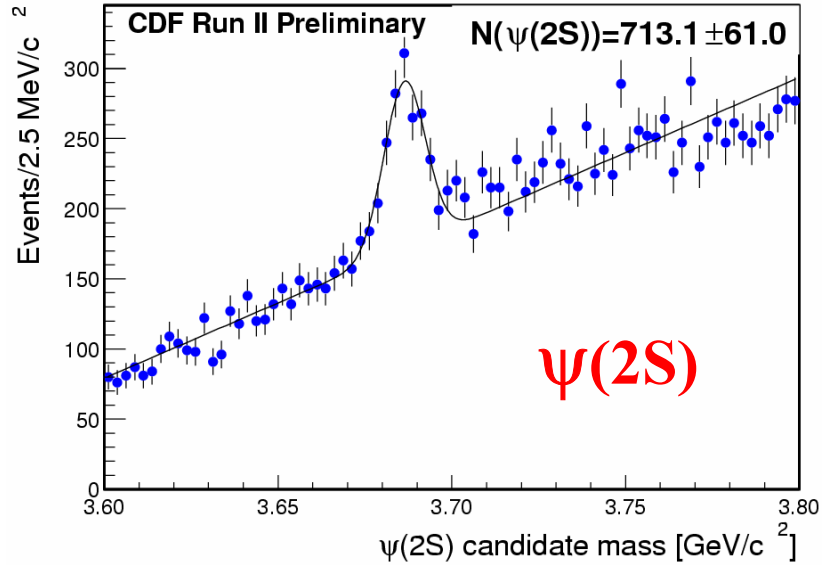
- Exclusive $B^+ \rightarrow J/\psi K^+$ lifetime
  - $c\tau = 446 \pm 43_{stat} \pm 13_{syst}$ μm (PDG: 502 ± 5 μm)



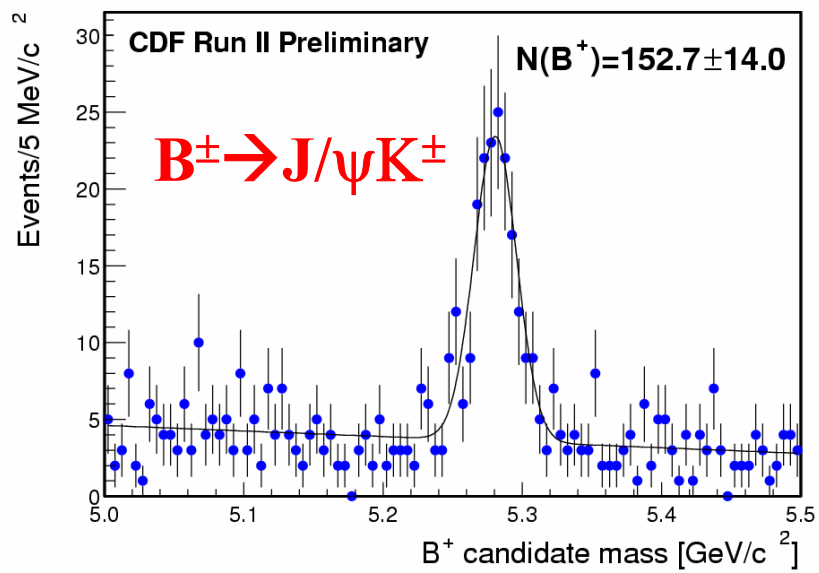
B Meson Mass Measurements

B masses:

- $\psi(2s) \rightarrow J/\psi\ \pi^+\pi^-$ (control)
- $B_u \rightarrow J/\psi\ K^+$
- $B_d \rightarrow J/\psi\ K^{0*}$ ($K^{0*} \rightarrow K^+\pi^-$)
- $B_s \rightarrow J/\psi\ \phi$ ($\phi \rightarrow K^+K^-$)

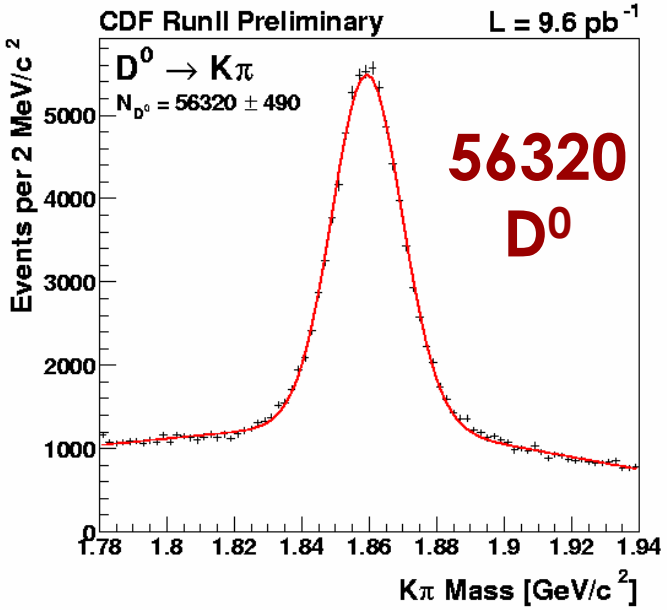


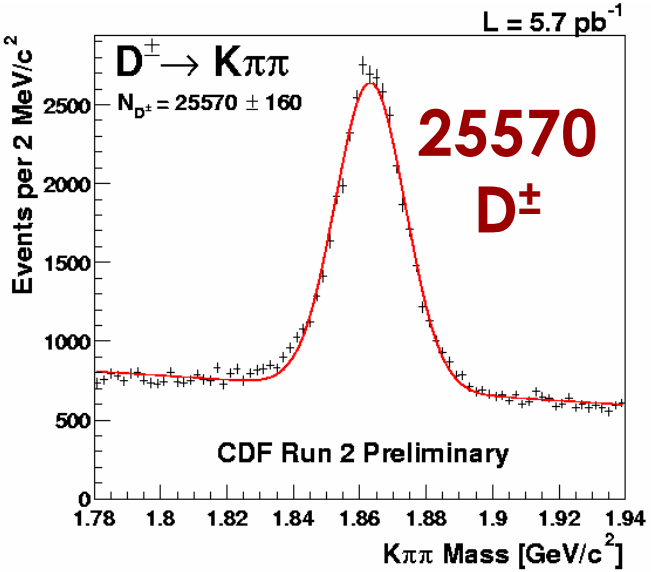
	CDF 2002	ΔPDG/σ	σ(CDF)/σ(PDG)
ψ(2S)	3686.43±0.54	0.9	6.00
Bu	5280.60±1.70±1.1	0.8	4.05
Bd	5279.80±1.90±1.4	0.2	4.72
Bs	5360.30±3.80± 2.10 2.90	-2.1	1.90



SVT Selects Huge Charm Samples

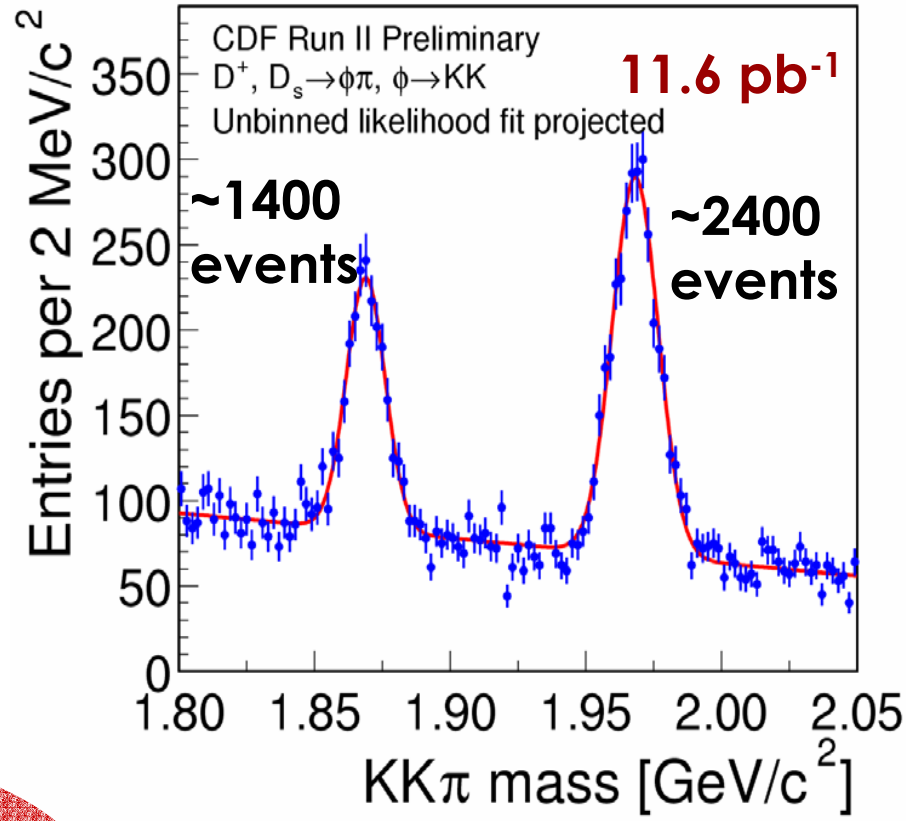
- L2 trigger on 2 tracks:
  - pt > 2 GeV
    - |D| > 100 mm (2 body)
    - |D| > 120 mm (multibody)
- Large amounts of charm:
  - Will have O(10^7) fully reconstructed decays in 2/fb data set
    - FOCUS = today's standard for huge: 139k $D^0 \rightarrow K^- \pi^+$, 110k $D^+ \rightarrow K^- \pi^+ \pi^+$
- A substantial fraction come from B decays





Measure D_s, D^+ Mass Difference

- $D_s^{\pm}$-$D^{\pm}$ mass difference
  - Both $D \rightarrow \phi\pi$ ($\phi \rightarrow KK$)
    - $\Delta m = 99.28 \pm 0.43 \pm 0.27$ MeV
      - PDG: 99.2 ± 0.5 MeV (CLEO2, E691)
  - Systematics dominated by background modeling

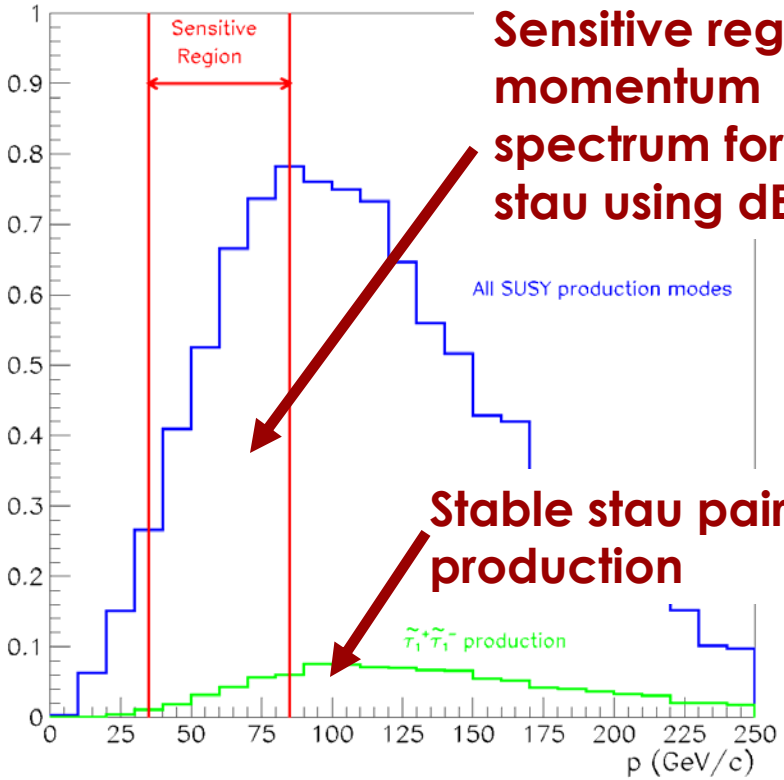


Brand new CDF capability

CHAMP Searches in Run 2

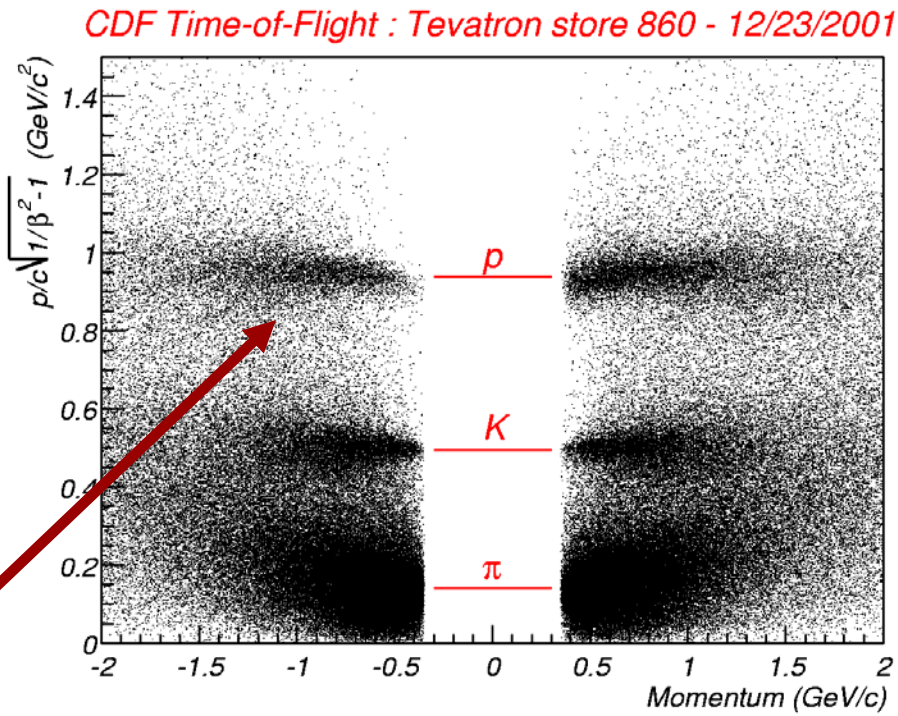
Charged Massive Particles, long-lived, leaves detector

Heavy, slow moving particle
- **Large time-of-flight (TOF)**
- **Large dE/dx**



Sensitive region of momentum spectrum for 100 GeV stau using dE/dx

Stable stau pair production



Separation at higher values Of $\beta\gamma$ using time of flight

Summary

- The long upgrade of the Fermilab accelerator and the CDF detector is finished.
  - The Tevatron start-up is slow but improvements are steady.
  - The CDF detector upgrades are extensive and the detector is performing very well.
  - Engineering data sets have been used to understand our detector, its performance, as well as our simulation of it.
- We have many analyses underway, and some are competitive!
  - Our large charm and B samples have led to early measurements.
  - High pt tools are being developed via W and Z cross-section measurements, asymmetries, and ratios.
  - DY bump searches, new bosons, CHAMPS, new photon physics.
  - Expect first top cross-sections in winter, and B->ΨKs by summer.
- The sensitivity of the Fermilab Run 2 physics program will be ~500x that of Run 1 for complex events with B hadrons (at 15 fb^{-1}).

CDF is back in business!