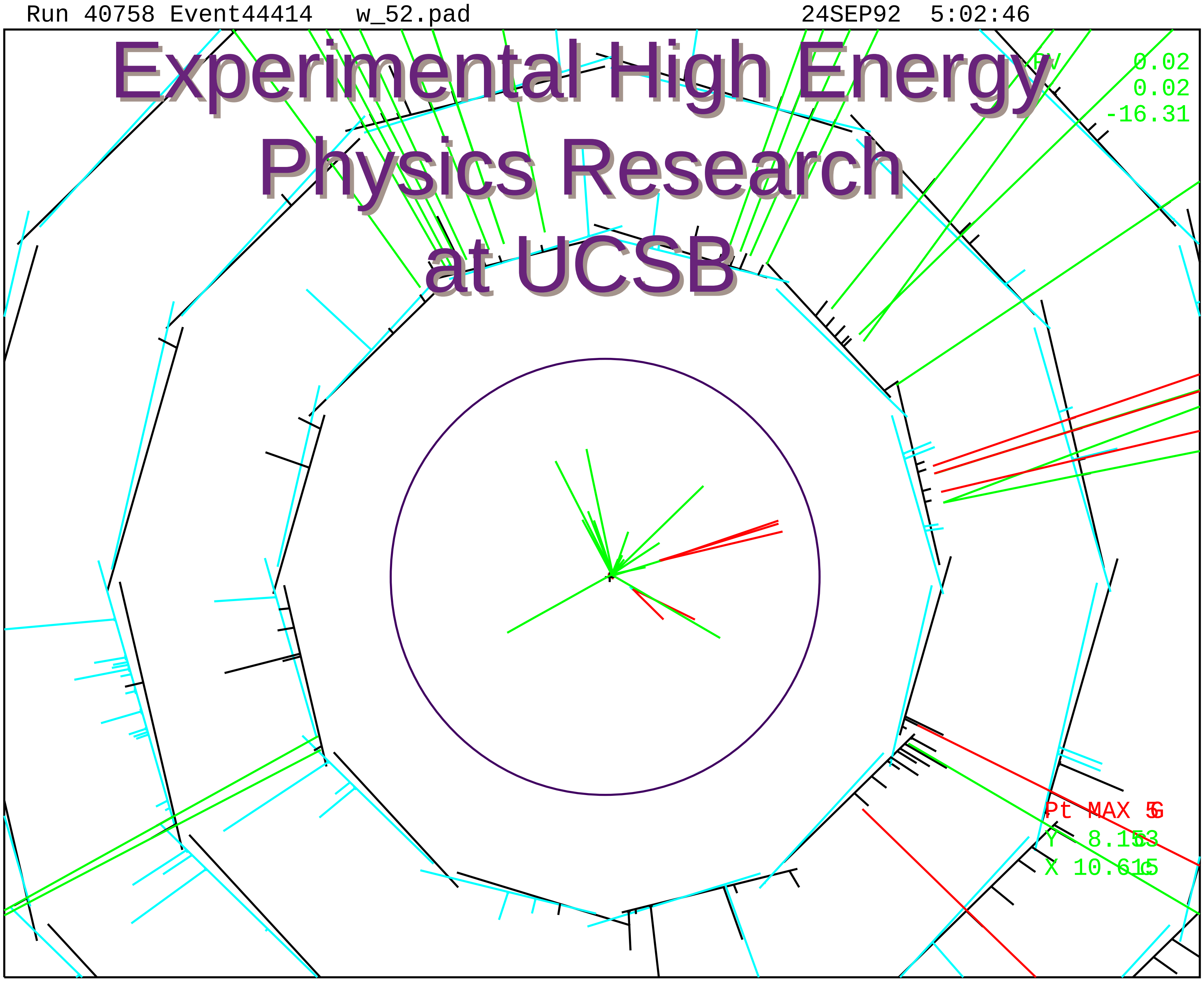
Experimental High Energy Physics Research at UCSB



Joe Incandela, for the UCSB High Energy Group; May 24, 2002

Gauge Fields

- EM: field potentials ⇒ gauge freedom

  $\partial_\mu F^{\mu\nu} = j^\nu = (\rho, \mathbf{j})$ ($F^{\mu\nu} \equiv \partial^\nu A^\mu - \partial^\mu A^\nu$)

  $\partial^\mu \partial_\mu A^\nu - \partial^\nu (\partial_\mu A^\mu) = j^\nu$

  → *Maxwell eqns. invariant for*

  $$A^\mu \rightarrow A'^\mu = A^\mu + \partial^\mu \chi$$

- QM: phase invariance ↔ gauge invariance

  $\partial_\mu \rightarrow D_\mu = \partial_\mu + iq A_\mu$ ≡ *covariant derivative*

- QFT: Fields become operators
  - QED Free massless photon Lagrangian

  $L_{em} = -1/4\, F^{\mu\nu} F_{\mu\nu}$

  $L_{em} = -1/4\, F^{\mu\nu} F_{\mu\nu} + (m^2/2) A^\mu A_\mu$ ***not* gauge invariant!**

  - Covariant derivative → particle interactions
    - *Lagrangian for free Dirac spinors:*

    $L_D = \underline{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi$

    - *Gauge/phase invariance* $\partial_\mu \rightarrow D_\mu = \partial_\mu + ie A_\mu$

    $L_D \rightarrow L_D' = L_D + j^\mu A_\mu$ where $j^\mu = e\, \underline{\Psi}\, \gamma^\mu \Psi$

    $L = -1/4\, F^{\mu\nu} F_{\mu\nu} + \underline{\Psi}(i\gamma^\mu \partial_\mu - m)\Psi + j^\mu A_\mu$

    Euler-Lagrange→ $\partial^\mu \partial_\mu A^\mu - \partial^\mu(\partial_\nu A^\nu) = j^\mu$

- Gauge theories
  - Classical EM Gauge Invariance
  - Quantum Mechanics Phase Invariance
    - presence of A_μ
  - Quantum Field Theory
    - QED - U(1)
      - gauge invariance ⇒massless photon
    - QCD - $SU(3)_c$
      - Gauge invariance implies massless gauge quanta (8 gluons)
      - Quark confinement → jet production

- The weak nuclear force ?

Weak Force

- Weak Nuclear Force
  - Hints of SU(2) gauge symmetry
    - Doublets
    - Universal Coupling G_F
  - But short-ranged $\Rightarrow$ massive gauge quanta
    - Interactions only observed over short distances (effectively contact interactions)
    - Coupling $G_F \sim 1/M^2$
  - How to reconcile ?

- An example from Nature: Superconductivity

$$j^\mu = (-q^2/m)\,|\psi|^2 A^\mu \quad \text{(London)}$$

$$\partial^\mu \partial_\mu A^\nu - \partial^\nu(\partial_\mu A^\mu) = (-q^2/m)\,|\psi|^2 A^\nu \equiv -M^2 A^\nu$$

Cooper pair (boson) wavefunction ψ with non-zero constant ground state

$\rightarrow$ massive photon!

Supercurrents screen the EM field making it effectively short-range

$\therefore$ Massive gauge quanta are possible when gauge symmetry is broken!

EWK Symmetry Breaking

- Glashow Weinberg Salam SU(2) ⊗U(1)

  $L = -\frac{1}{4} \mathbf{W}^{\mu\nu} \cdot \mathbf{W}_{\mu\nu} - \frac{1}{4} \mathbf{B}^{\mu\nu} \mathbf{B}_{\mu\nu}$

  $W^{\mu\nu}_i = \partial^\nu W^\mu_i - \partial^\mu W^\nu_i + g\varepsilon^{ij\kappa} W^\mu_j W^\nu_k$ $\quad B^{\mu\nu} = \partial^\nu B^\mu - \partial^\mu B^\nu$

- Add a scalar doublet field

  $\phi^\dagger = 2^{-1/2} (\phi_1 - i\phi_2, H - i\phi_o)$ with potential $V(\phi) = \mu^2 \phi\phi^\dagger + \lambda |\phi\phi^\dagger|^2 \quad (\lambda > 0)$

  - This is the most general SU(2) invariant and renormalizable potential
  - (e.g. Gibb's free energy in ferromagnetism)
  - $\mu^2 > 0$ symmetry retained $\quad (T > T_c)$
  - $\mu^2 < 0 \Rightarrow \langle\phi\rangle_o \neq 0.0$ $\quad (T < T_c)$

  $L_\phi = (D_\mu \phi)^\dagger (D_\mu \phi) - V(\phi)$

  - where $D_\mu = \partial_\mu + ig (\tau/2) \cdot \mathbf{W}_\mu + ig'/2 \; B_\mu$
  - choose gauge with $\phi^\dagger = 2^{-1/2} (0, v+H)$, $\langle H\rangle_o = 0$

⇒ Lagrangian now has 3 Massive Vector Gauge Bosons and massless photon:

$W_\mu^\pm = 2^{-1/2} (W_\mu^1 \pm W_\mu^2)$ $\quad M_W^2 = \frac{1}{4} g^2 v^2$

$Z_\mu^o = (g^2 + g'^2)^{-1/2} (-g' B_\mu + g W_\mu^3)$ $\quad M_Z^2 = \frac{1}{4} (g^2 + g'^2) v^2$

$A_\mu = (g^2 + g'^2)^{-1/2} (g B_\mu + g' W_\mu^3)$ $\quad M_A^2 = 0$

The Higgs & its couplings

- Electroweak Couplings satisfy

  $g\sin\theta_W = e = g'\cos\theta_W \quad (M_Z = M_W/\cos\theta_W)$

  From μ decay $G_F/2^{1/2} = g^2 / 8M_W^2 = 1 / 2v^2$

  $\Rightarrow M_W \sim 80$ GeV
  $M_Z \sim 91$ GeV

  – In the process, also generate masses for fermions:

  $L = \lambda_d \underline{Q}_L \phi d_R$

  $\lambda_d = 2^{1/2} m_d/v \sim m_d/M_W$

  – The coupling is proportional to the fermion mass

  e.g. top quark:

  $\lambda_t = 2^{1/2} m_t/v = 2^{1/2} (174.1)/(246) = 1$

$\Gamma(H \rightarrow f\underline{f}) = (N_c g^2/32\pi)(m_f^2 / M_W^2)(1-4m_f^2/M_H^2)M_H$

$\Gamma(H \rightarrow W^+W^-) = (g^2/128\pi)(M_H^2/M_W^2) f(x) M_H$

where $f(x) = (1-x)^{1/2}(1-x+3x^2/4)$
and $x = 4\, M_W^2 / M_H^2$

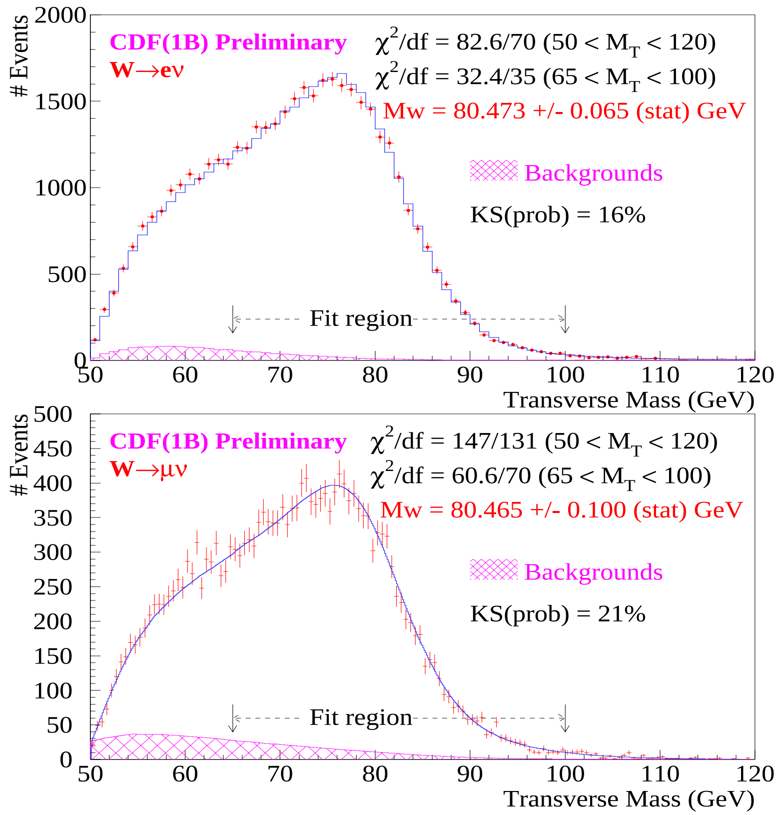
$\Gamma(H \rightarrow W^+W^-) / \Gamma(H \rightarrow ff) \sim M_H^2 / m_f^2$

And the Higgs term itself:

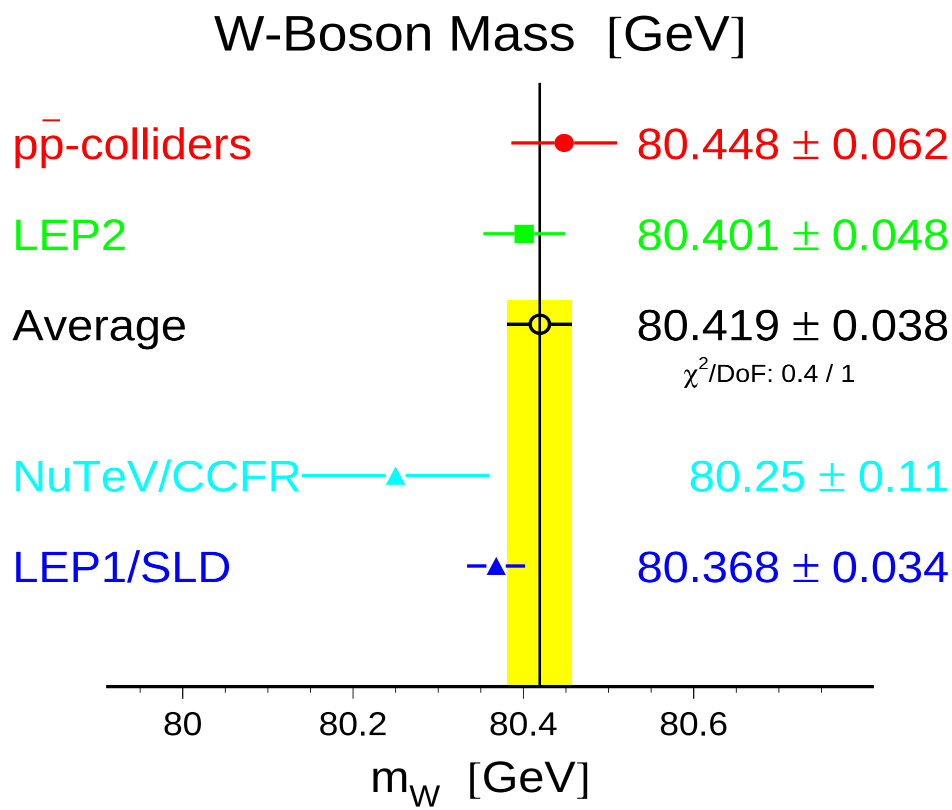
$2v^2\lambda H^2 \quad \Rightarrow \quad M_H = (2\lambda)^{1/2} v$

- We know everything about the Standard Model Higgs except
  – its mass
  – whether or not it exists

W

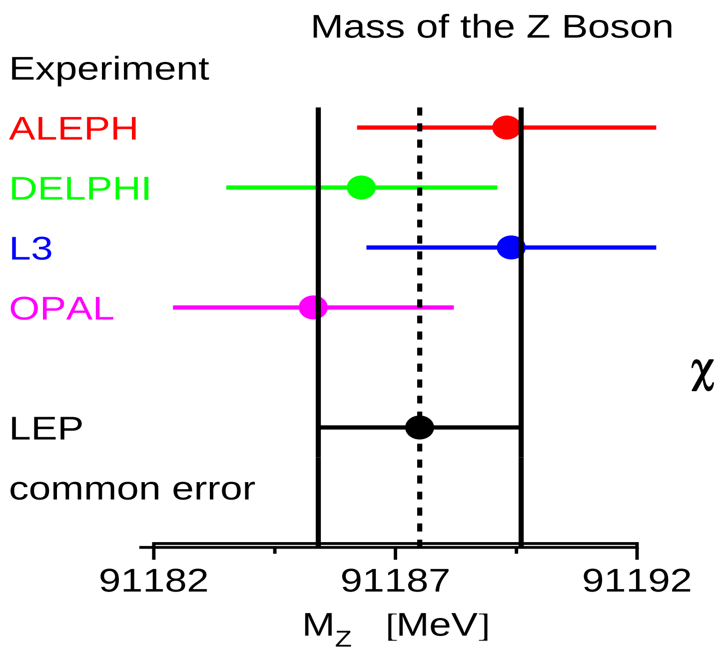


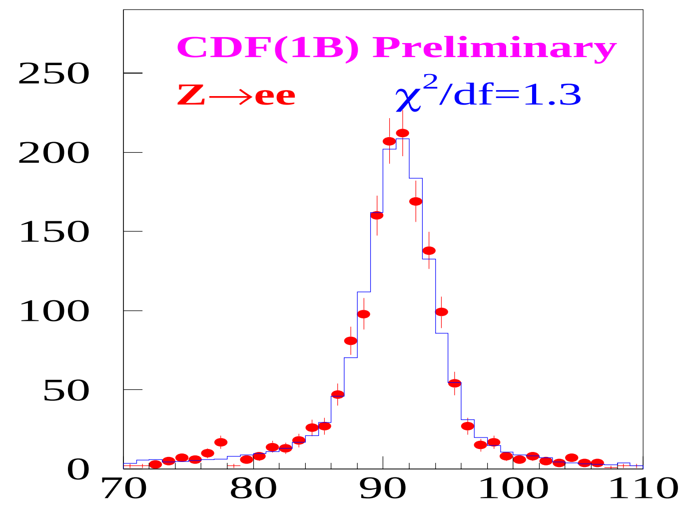
CDF(1B) Preliminary
W→eν
χ²/df = 82.6/70 (50 < M_T < 120)
χ²/df = 32.4/35 (65 < M_T < 100)
Mw = 80.473 +/- 0.065 (stat) GeV
Backgrounds
KS(prob) = 16%
Fit region
Events
Transverse Mass (GeV)
CDF(1B) Preliminary
W→μν
χ²/df = 147/131 (50 < M_T < 120)
χ²/df = 60.6/70 (65 < M_T < 100)
Mw = 80.465 +/- 0.100 (stat) GeV
Backgrounds
KS(prob) = 21%
Fit region
Events
Transverse Mass (GeV)

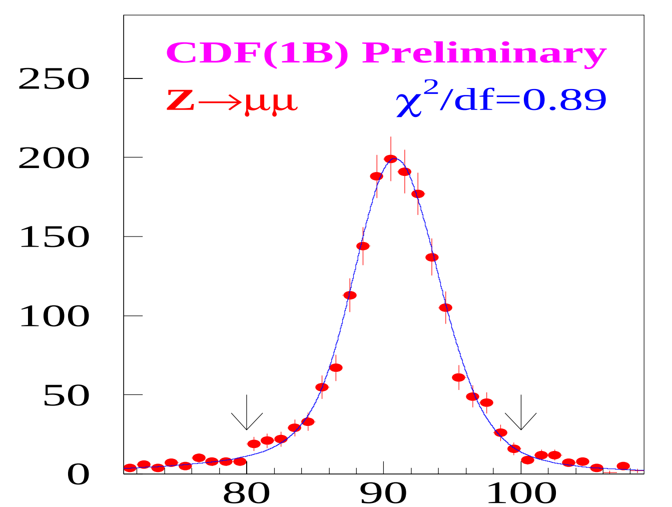


W-Boson Mass [GeV]
pp̄-colliders 80.448 ± 0.062
LEP2 80.401 ± 0.048
Average 80.419 ± 0.038
χ²/DoF: 0.4 / 1
NuTeV/CCFR 80.25 ± 0.11
LEP1/SLD 80.368 ± 0.034
80 80.2 80.4 80.6
m_W [GeV]

Z

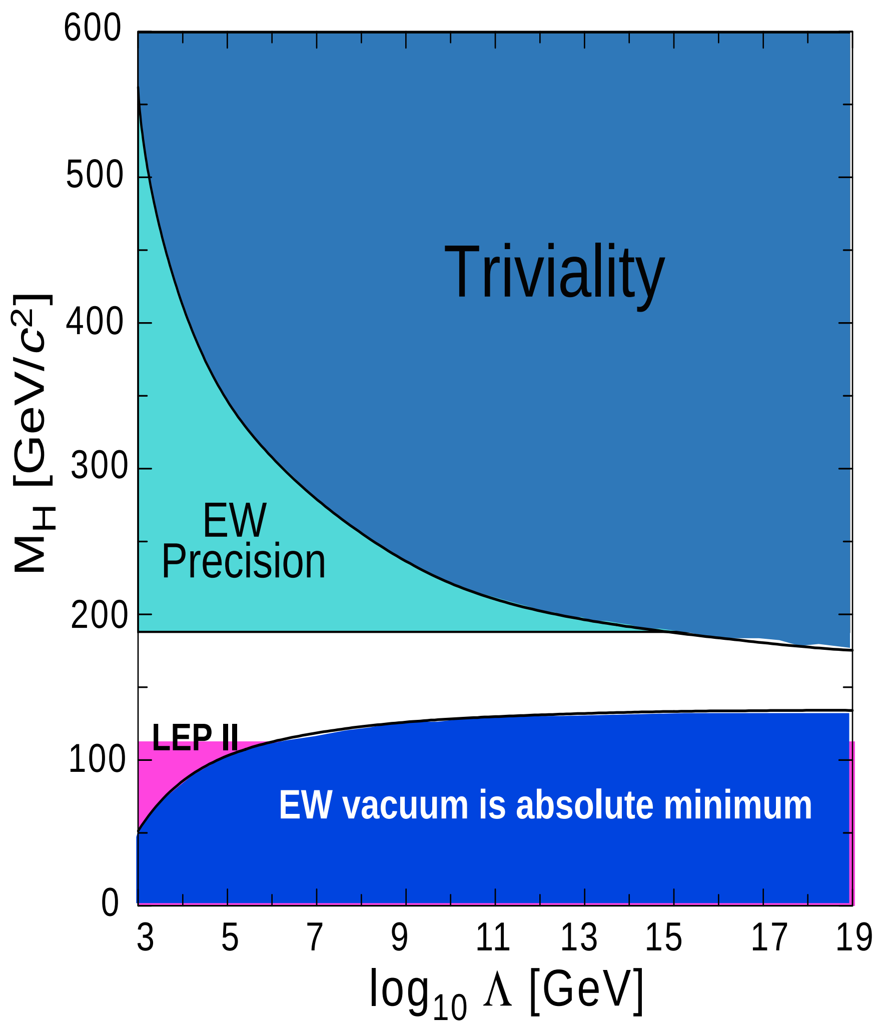






The W and Z were discovered by UA1 and UA2 at CERN

SM Higgs Mass Bounds



- Triviality:
  - To avoid having the higgs self-coupling vanish, you need a cut-off L at which new physics occurs.
- Vacuum stability:
  - Require $V(\phi_o) < V(0)$ - i.e. symmetry breaking takes place. For some masses this requires new physics above a scale L.
- Fits to EWK Precision Measurements:
  - MH < 188 GeV at 95% CL
- LEP II direct searches:
  - MH ≥ 114 GeV at 95% CL

Standard Model Flaws

- Problems
  - Hierarchy Problem: How did we get here when the only known fundamental scale is the Planck scale ($M_p \sim 10^{19}$ GeV) ?
    - What is the underlying reason for EWK symmetry breaking and why at this low energy ?
  - Fermion and Higgs Masses ?
  - How do we include Gravity ?
  - Fundamental Scalar Theories are Fundamentally pathological
    - Quadratic divergences

Beyond Standard Model

- Many other ways to break the symmetry
  - Fermion composite (cf. cooper pairs)
    - Technicolor $\rightarrow$ Topcolor-Assisted Walking Technicolor
    (a.k.a. “ Stumbling drunk …”)
  - Supersymmetry (SUSY)
    - $\forall$ Standard Model particle $\exists$ a SUSY partner with spin shifted by 1/2
      Fermions $\leftrightarrow$ Bosons
      At least two Higgs doublets required
    - Appealing for several reasons
      - Superpartners cancel divergent terms in higher order corrections to the Higgs mass.
      - Formulated as a local symmetry, spin-2 graviton must be introduced
      - Appears in superstrings
      - Gauge coupling unification at ~10^{16} GeV if there are exactly 2 higgs doublets (and possibly some number of singlets)

Supersymmetric Higgs

- Minimal Case of 2 doublets:
  - $\tan\beta = v_2/v_1$ and $v_1^2 + v_2^2 = v^2$
  - After W,Z masses, 5 remaining d.o.f.
    - **5 physical higgs bosons h_o, H_o, A_o, $H^{\pm}$**
    - Scalar potential has one free parameter
      - masses are expressed in terms of

        m_A and $\tan\beta$
  - Large radiative corrections (at one-loop)

    $M_h^2 < M_Z^2 + (3G_F/(2^{1/2}\pi^2))\ M_t^4 \ln(1+m^2/M_t^2)$

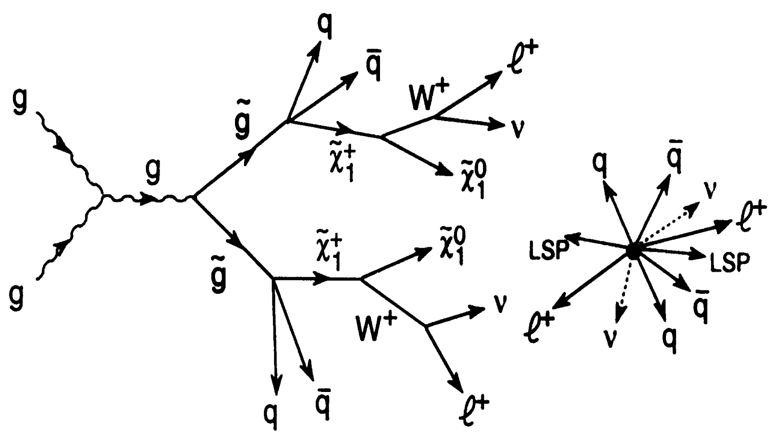
    M_h < 130 GeV

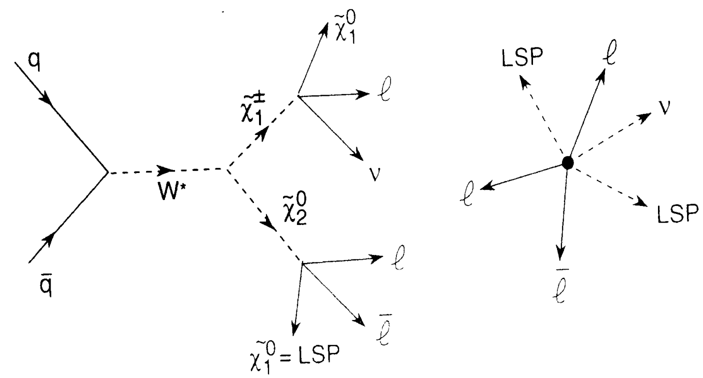
    < 150 GeV (w/Higgs singlets)
  - Some Important features
    - Couplings to W,Z now shared

      $$g_{h_oVV}^2 + g_{H_oVV}^2 = g_{HVV}^2 \text{ (SM)}$$

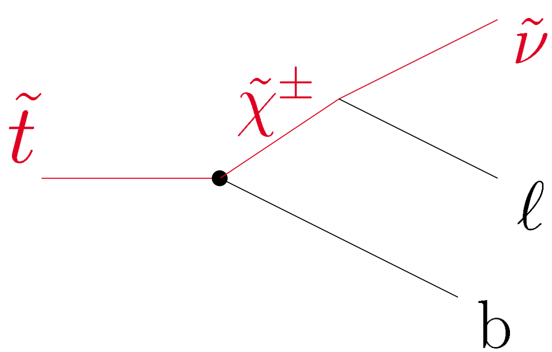
•Fermion couplings also (S.Dawson hep-ph/9411325)

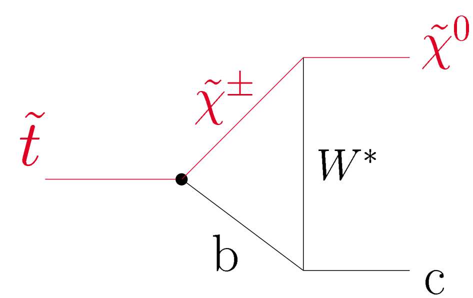
Feynmann Diagrams for SUSY





gluino pair production w/ cascade to like sign di-leptons or gauginos to tri-leptons

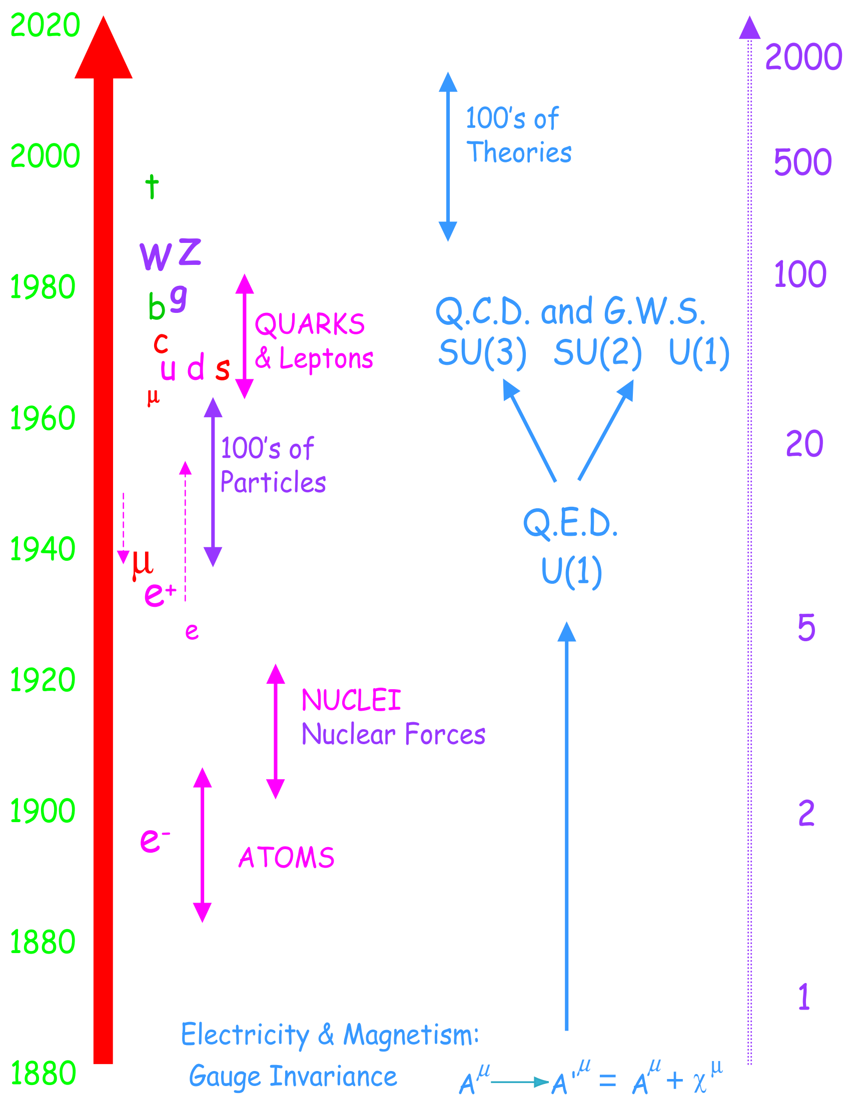




$$\Rightarrow c\bar{c}\not{E}_T$$

stop pair production to top-like decays with bottom or cascades to charm

History of particle physics



- Parallel experimental and theoretical developments
  - Discovery of several layers of fundamental particles
  - Realization of the importance of Gauge symmetries

And some accidental symmetries…

Experimental focus today

- Some Questions at the leading edge where UCSB hopes to help shed some light…
  - Why is the universe predominantly matter?
    - What is and what causes CP violation ?
  - What is the composition of galactic dark matter ?
    - Weak scale SUSY ?
  - Why do particles have mass ?
    - (I.e. what is the origin spontaneous symmetry breaking ?)
  - What is there beyond the standard model ?
    - Is the universe super symmetric ?

Outline

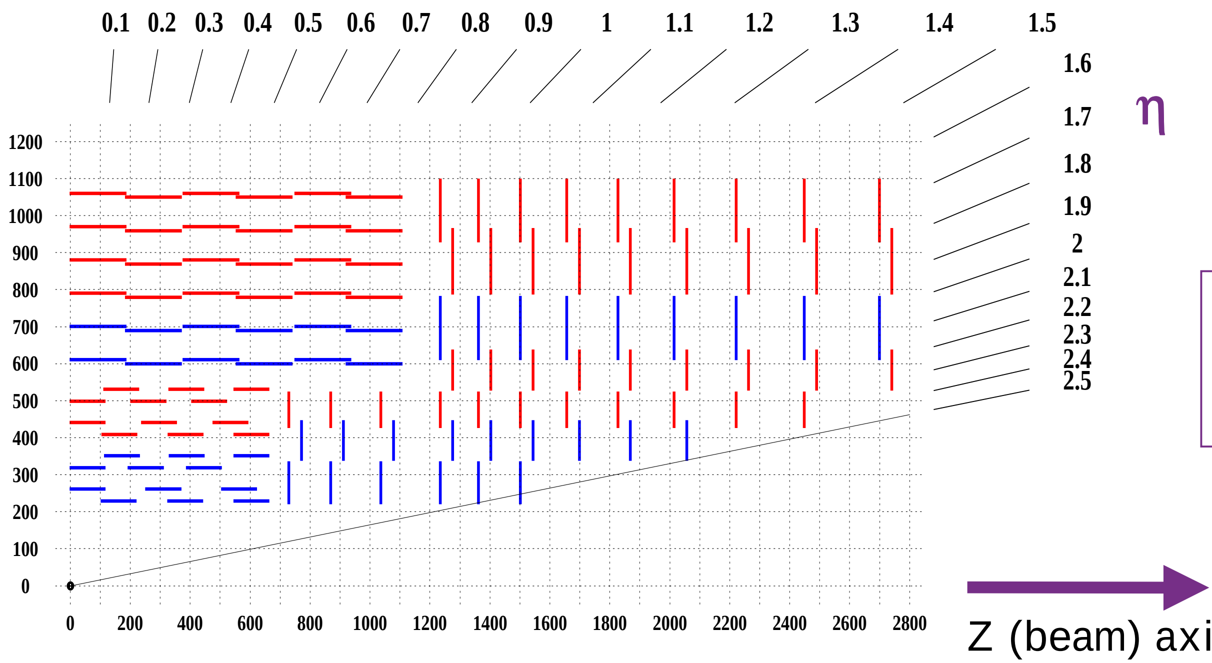
- Hadron Colliders *(Campagnari,Incandela,Stuart)*
  - Some Basics
  - History
  - CDF Experiment at the Tevatron
  - CMS Experiment at LHC
- Cold Dark Matter Search *(Caldwell,Nelson)*
  - The common thread
  - Listening out for WIMPs
- Babar Experiment at SLAC* *(Campagnari, Richman)*
  - Rare b decays and CP violation

  *(covered in Tuesday's colloquium)

Hadron Collider Jargon:PDF's, P_T, and η

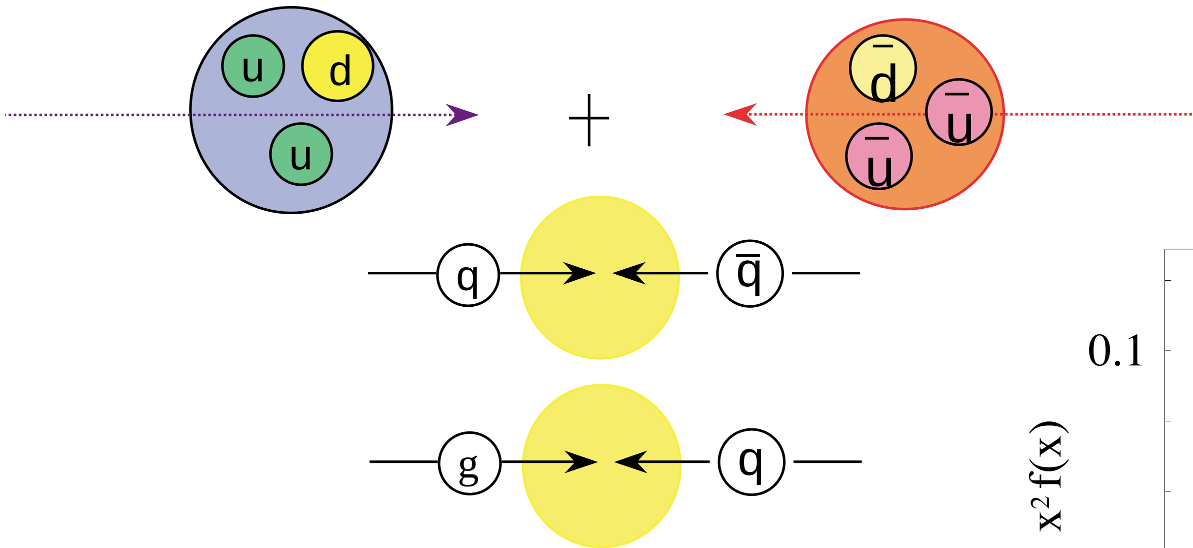
- Really colliding 'partons':**qg, qq, gg**
  - q can be a valence (u,d) or a sea (virtual) quark (..,s,c,b…).
- Momenta given by Parton Distribution Functions (PDF's)

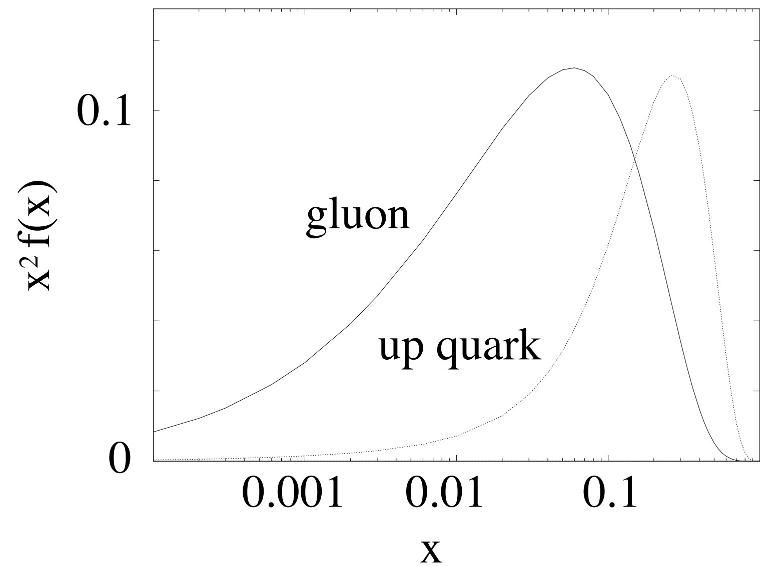
  ⇒ Can't balance all components
    - **P_T** ≡ Transverse Momentum must balance.
    - Pz ≡ Longitudinal Momentum (along the beam) unknown.
  - Coordinates (r,η,ϕ) with **$\eta = -\ln(\tan(\theta/2))$**
  - Distributions (dN/dη) invariant under boosts in z



Quadrant of the CMS silicon tracker

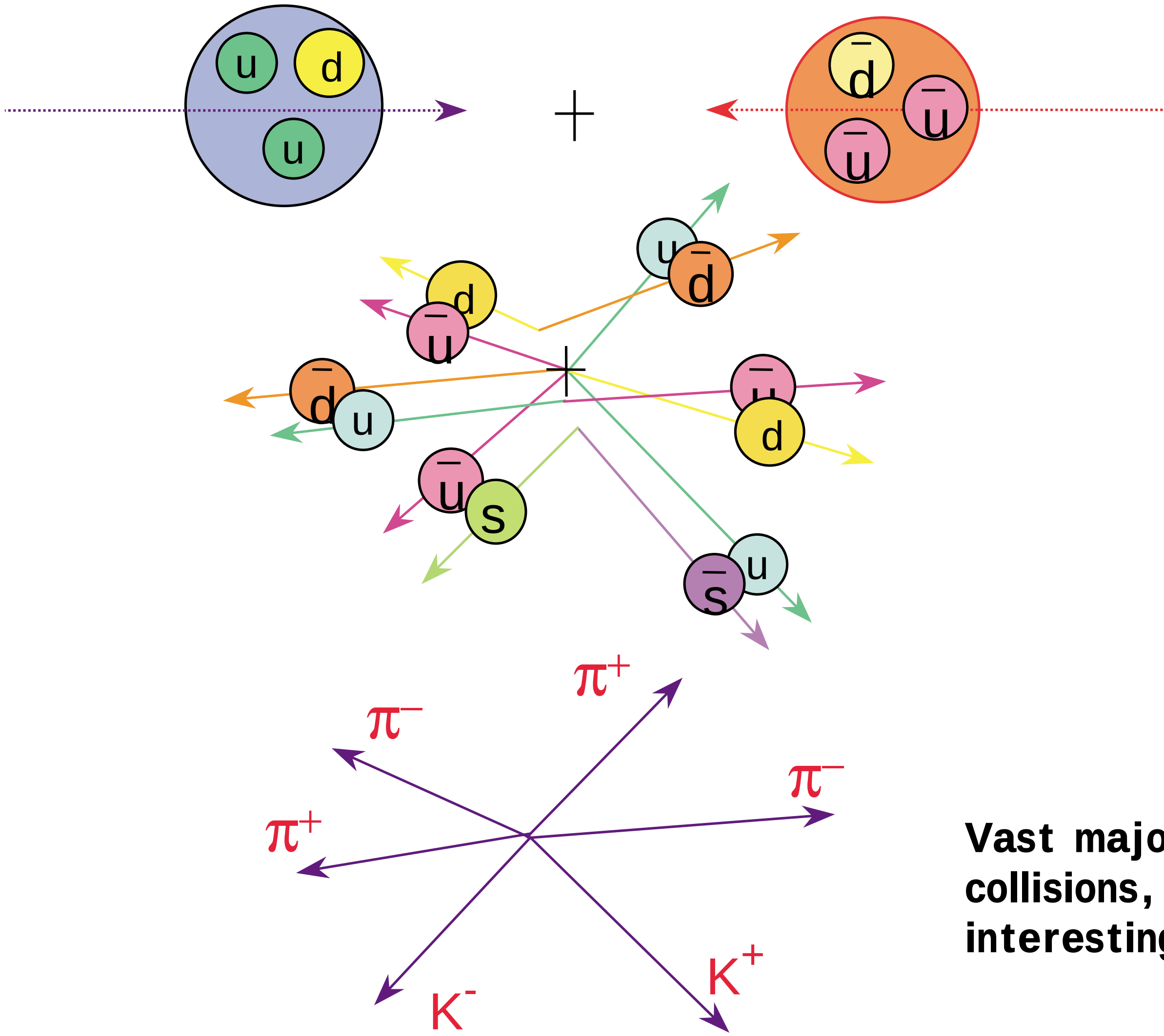
Colliding Partons





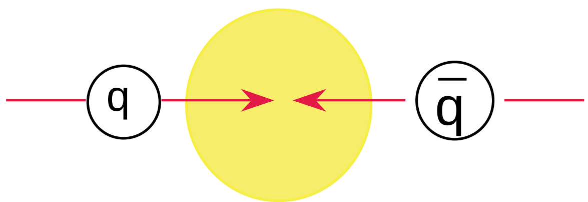
⇒Broadband: Production of particle states
with cm energies ranging from a few to 100's of GeV

“Minimum Bias” Events

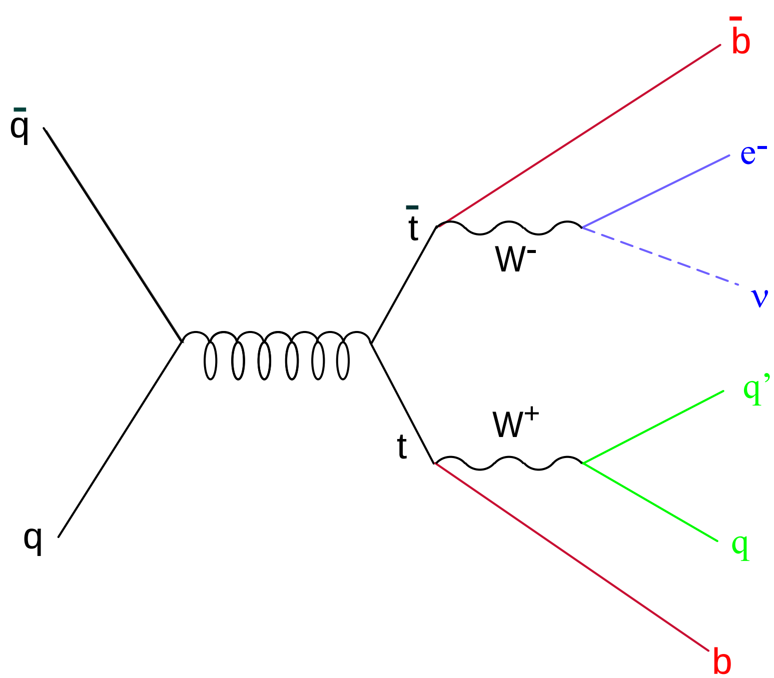


Vast majority of collisions, but not interesting…

Hard Collisions

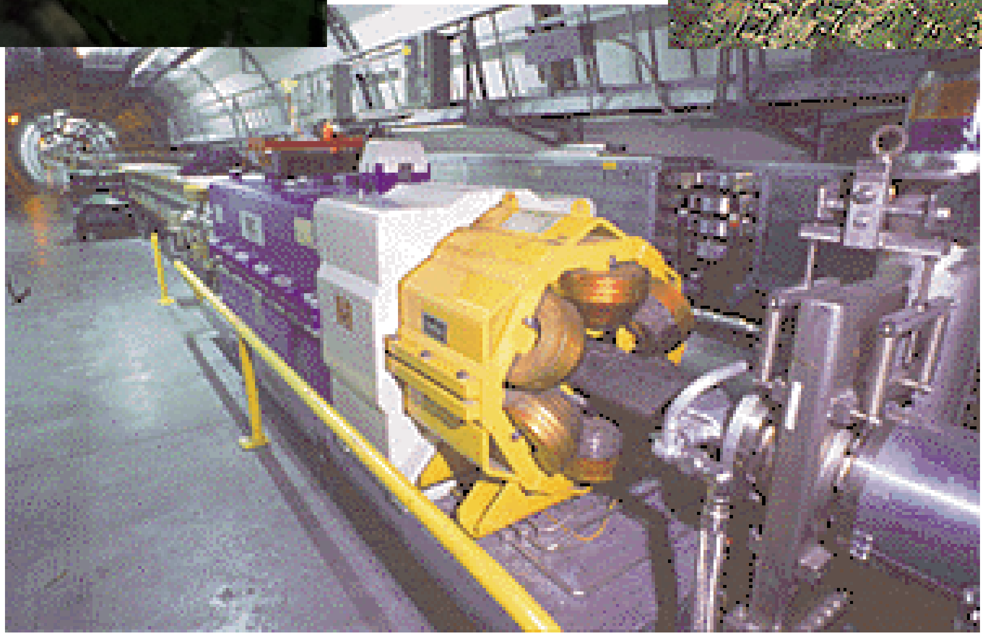


Quark-Antiquark Annihilation

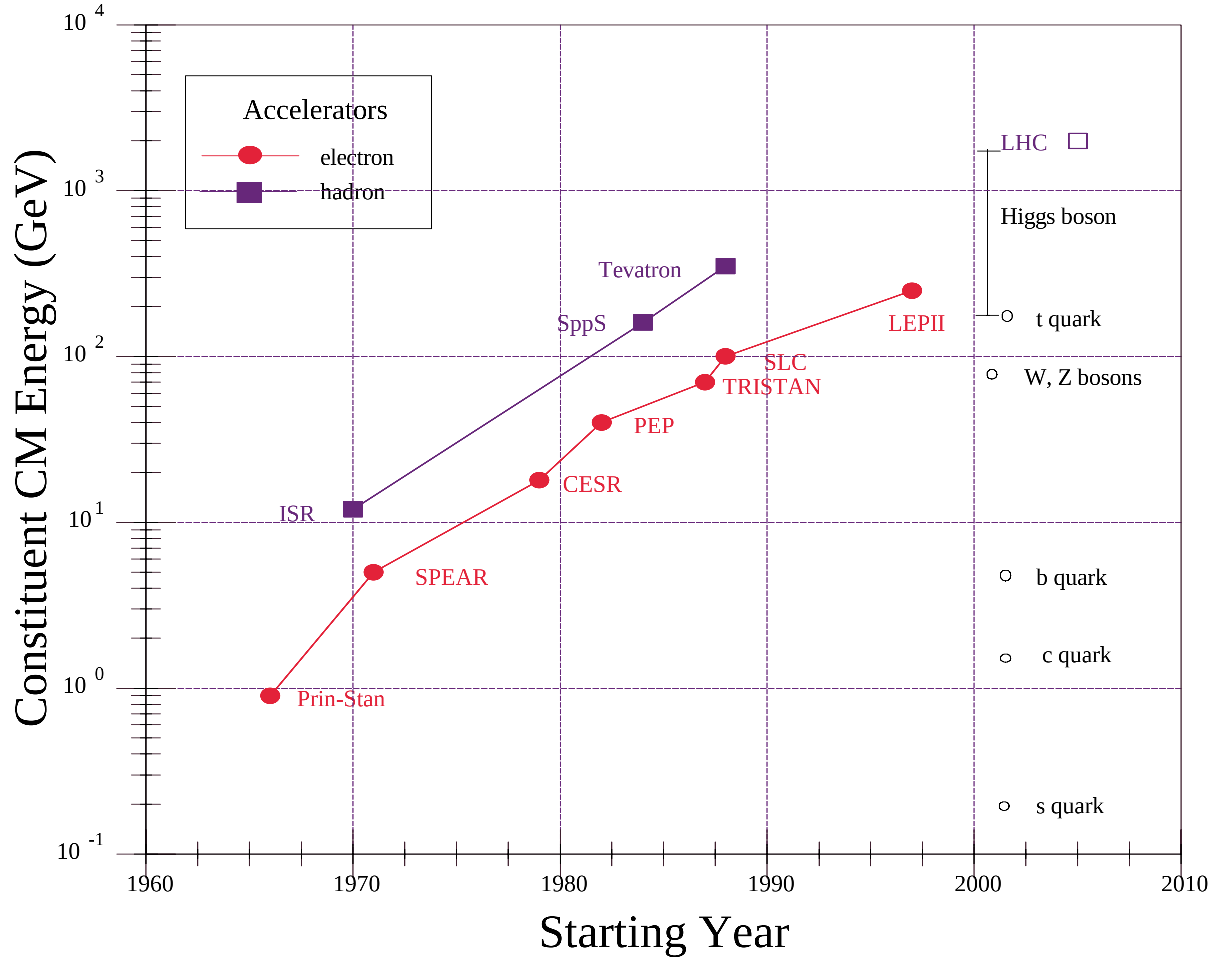


Example: top quark pair production

FNAL and CERN



Why Collide Hadrons ?

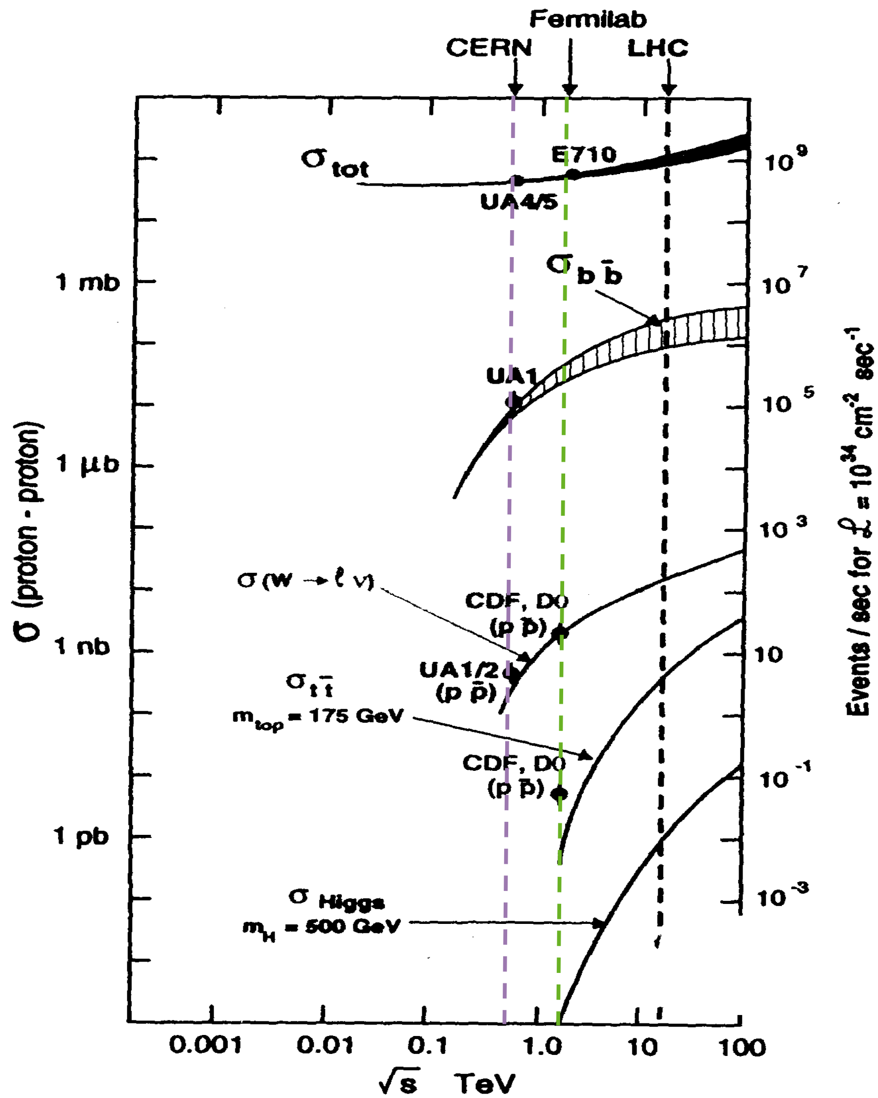


Challenge and Reward

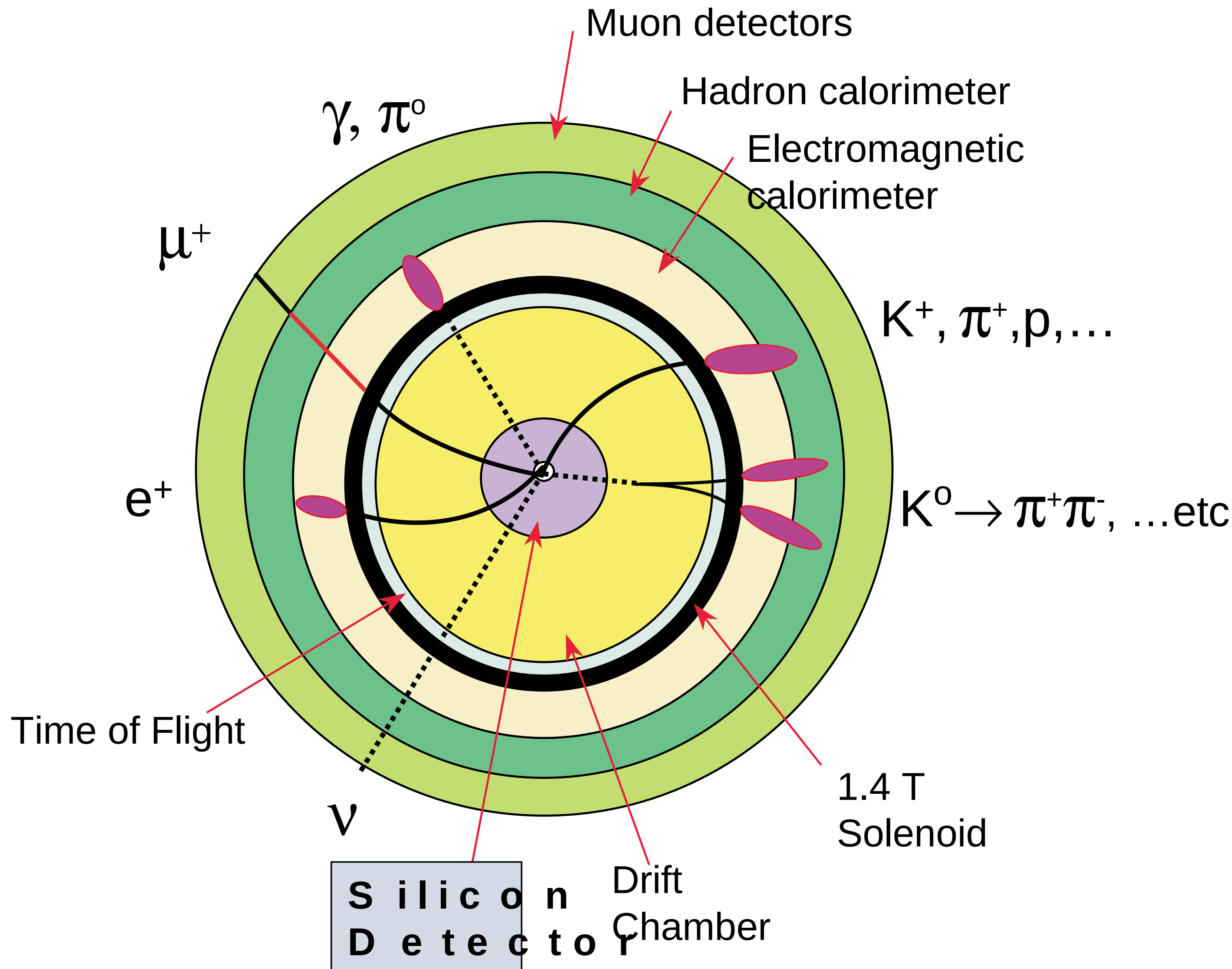
- Higher Energy
- Broadband production

⇒ Discovery machines

- Physics cross-section high
- What's interesting is rare
- The ability to find rare events is a consequence of evolved detector design and technological innovations
  - Multi-level trigger systems and high speed pipe-lined electronics
  - Precision, high rate, calorimetry
  - High rate wire tracking detectors
  - Highly radiation-tolerant Silicon microstrip and Pixel detectors

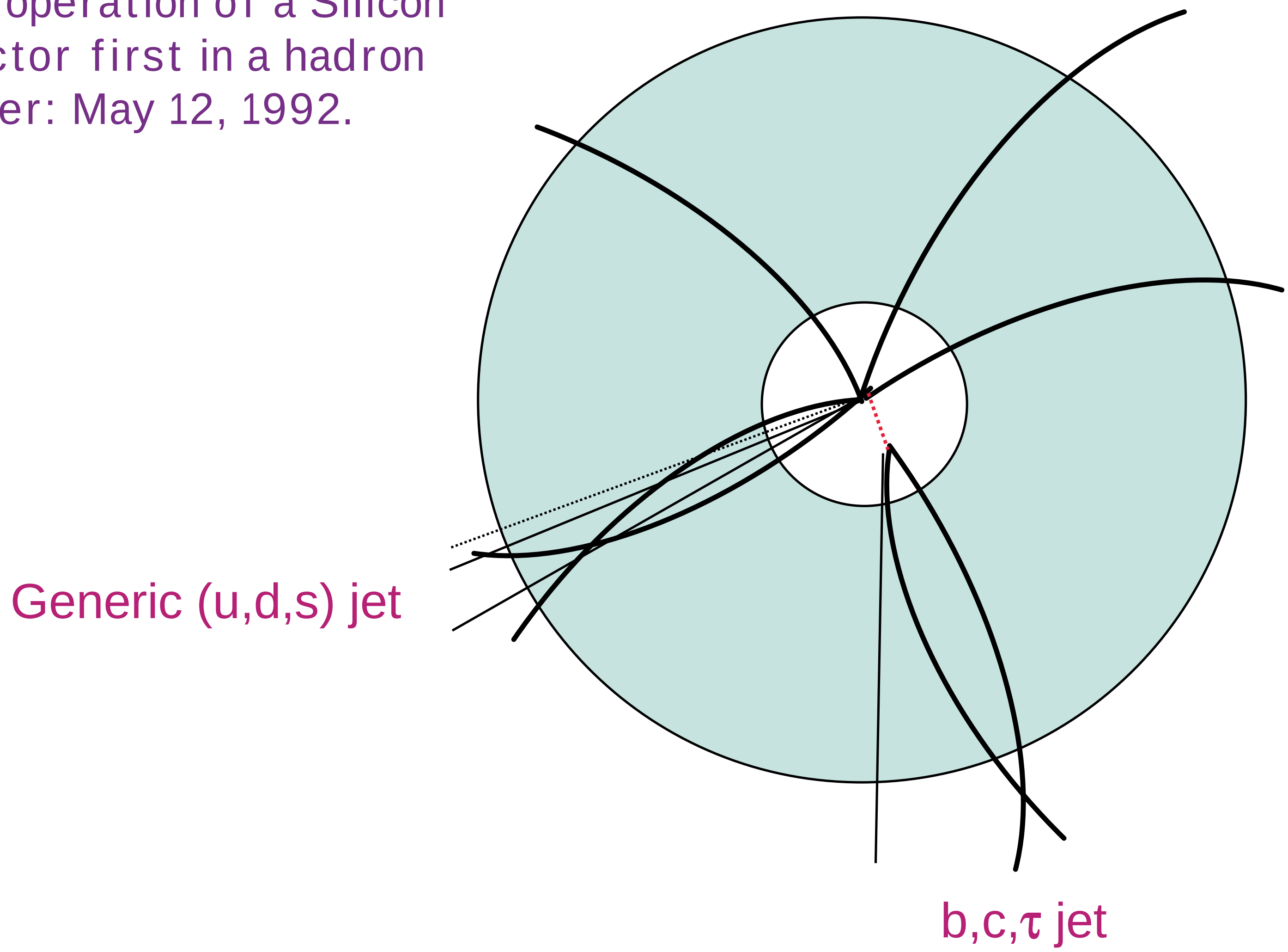


Hadron Collider Detectors



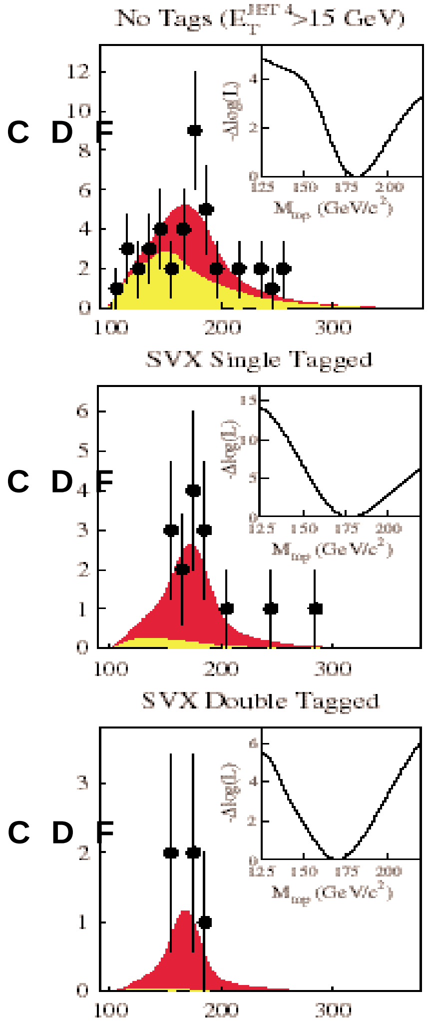
Micro-Vertexing

First operation of a Silicon detector first in a hadron collider: May 12, 1992.

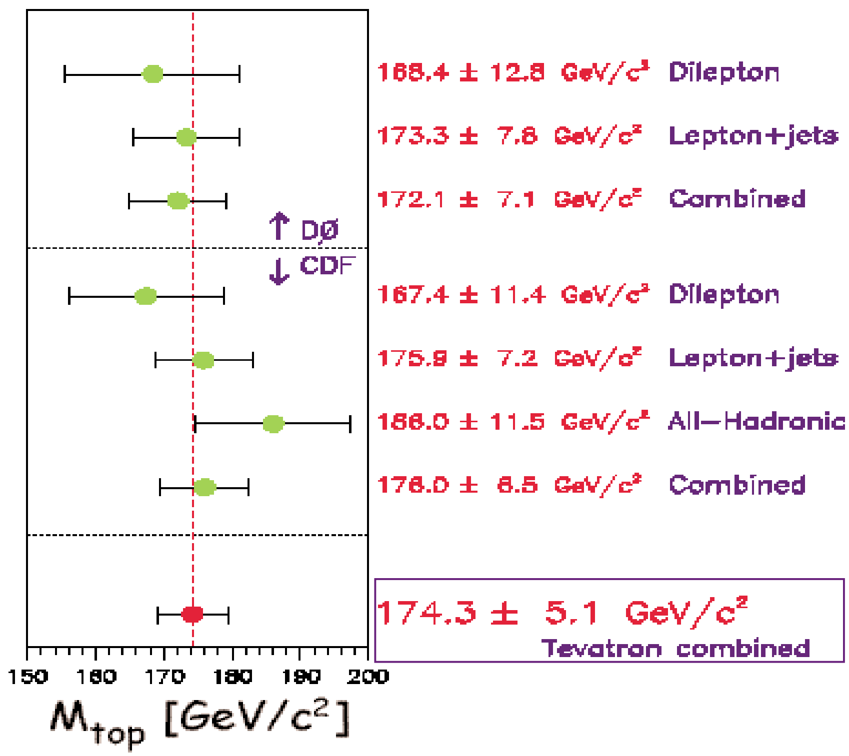


Tevatron: Top Discovery

Displaced Vertex b tagging



- CDF and DØ successfully found the top quark with a cross section of ~ 10^{-10} σ_{tot}



What's Next ?

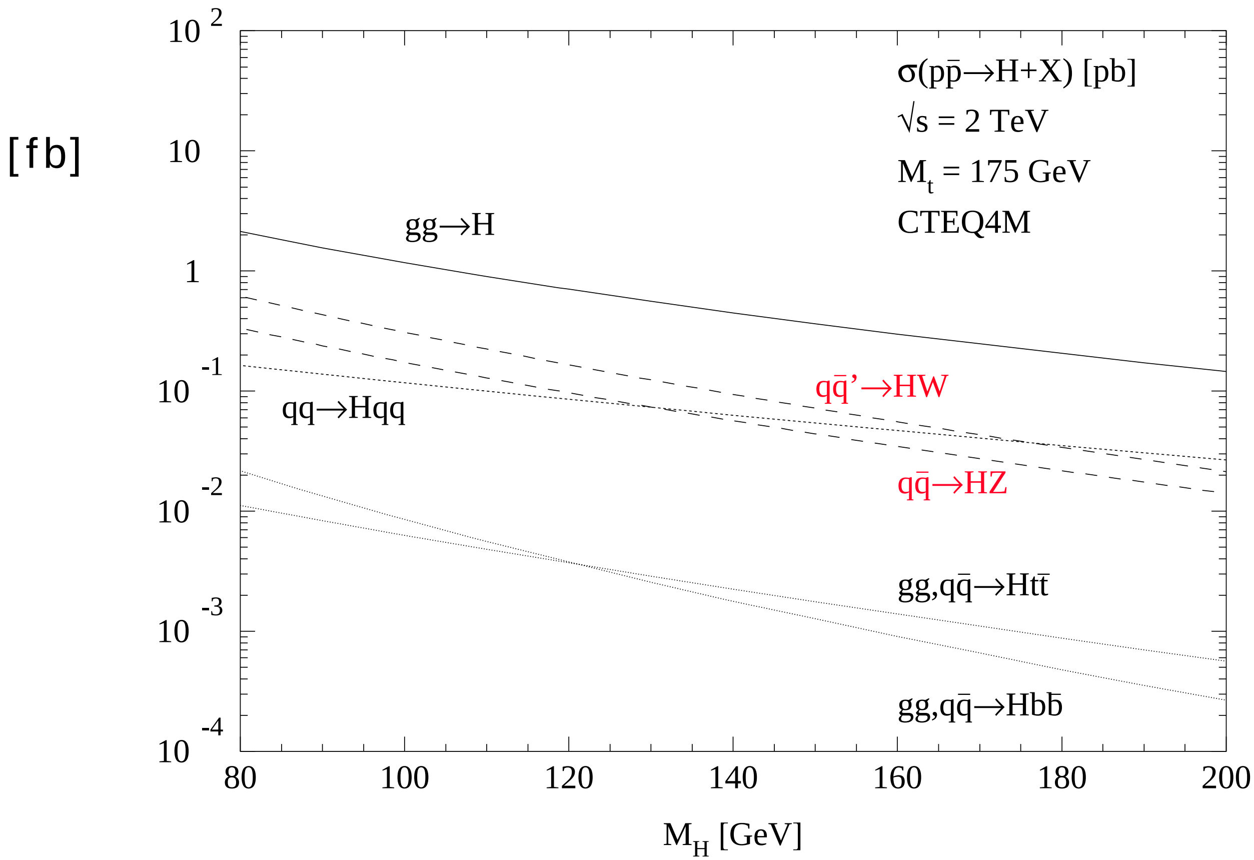
- Hadron Colliders have 2 main goals.

  1. Find the Higgs
  2. Direct evidence of something beyond the standard Model

     e.g. SUSY partners

- Plus… more work on the Standard Model:
  - Precision electroweak measurements
    - M_W, M_{top}
  - B Physics
    - **CKM and CP Violation**
    - B_s mixing
- … as well as more exotic fare…
  - Large extra dimensions
  - Mini-black holes (Giddings UCSB)

Tevatron: SM Higgs Production

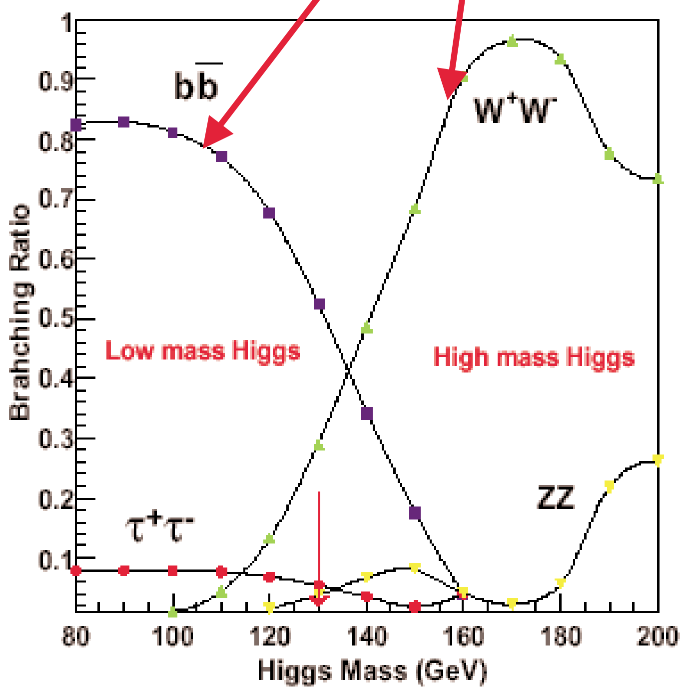


- gg→ H dominates but swamped by dijets
- qq′ → HV factor 5-10 lower but backgrounds are more rare (tt,Wbb,Zbb,WZ)

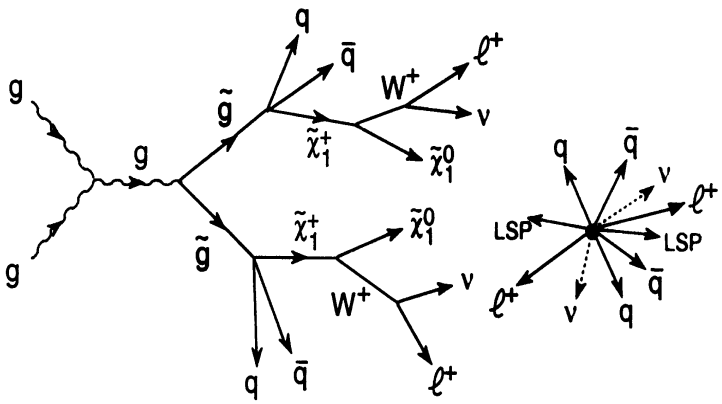
Tevatron: SM Higgs Decays

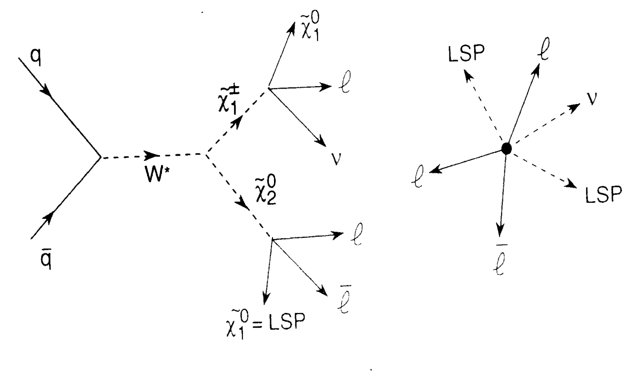
- m_H < 130: H→bb̲ dominant:
  - ⇒ W(lν,qq')bb̲, Z(νν,ll,qq̲)bb̲ final states
- m_H > 140: H→WW dominant:
  - ⇒ W^+W^-,$W^+W^-W^\pm$, W^+W^- Z : **$l^+l^-\nu\nu$, $l^+l'^+\nu\nu jj$, $l^+l^-l'^\pm$** final states
- MSSM Higgs: many of the same channels as SM and enhanced association to bb̲ at large tanβ

Lepton id, b tagging and $\not{E}_T$ are crucial

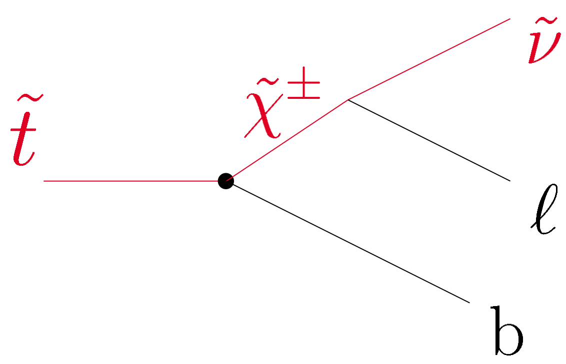


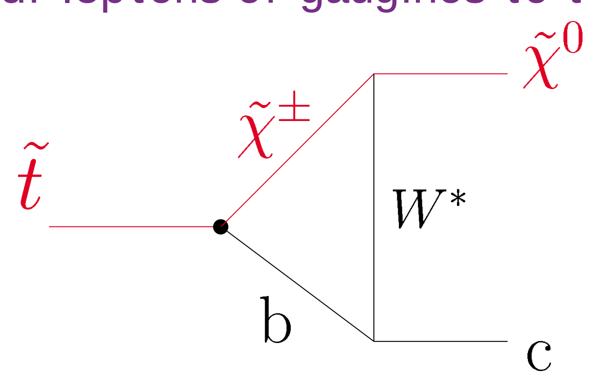
SUSY





gluino pair production w/ cascade to like sign di-leptons or gauginos to tri-leptons





$$\Rightarrow c\bar{c}\not{E}_T$$

stop pair production to top-like decays with bottom or cascades to charm

Colliding Beams

- FNAL Tevatron

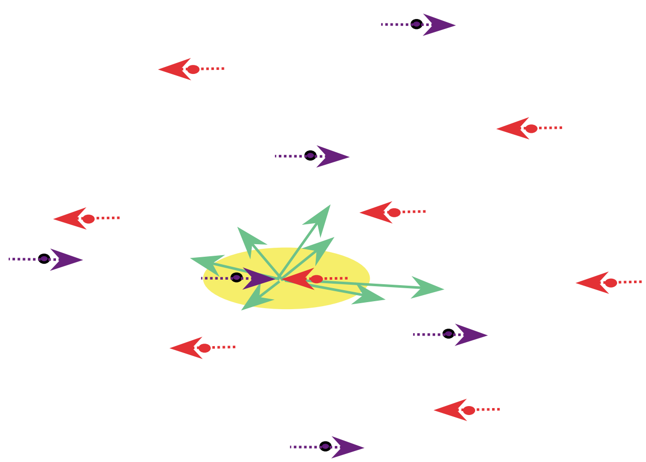
  R = 1 km, E_{beam} = 1 TeV, B = 4.5 Tesla
- Bunch structure:

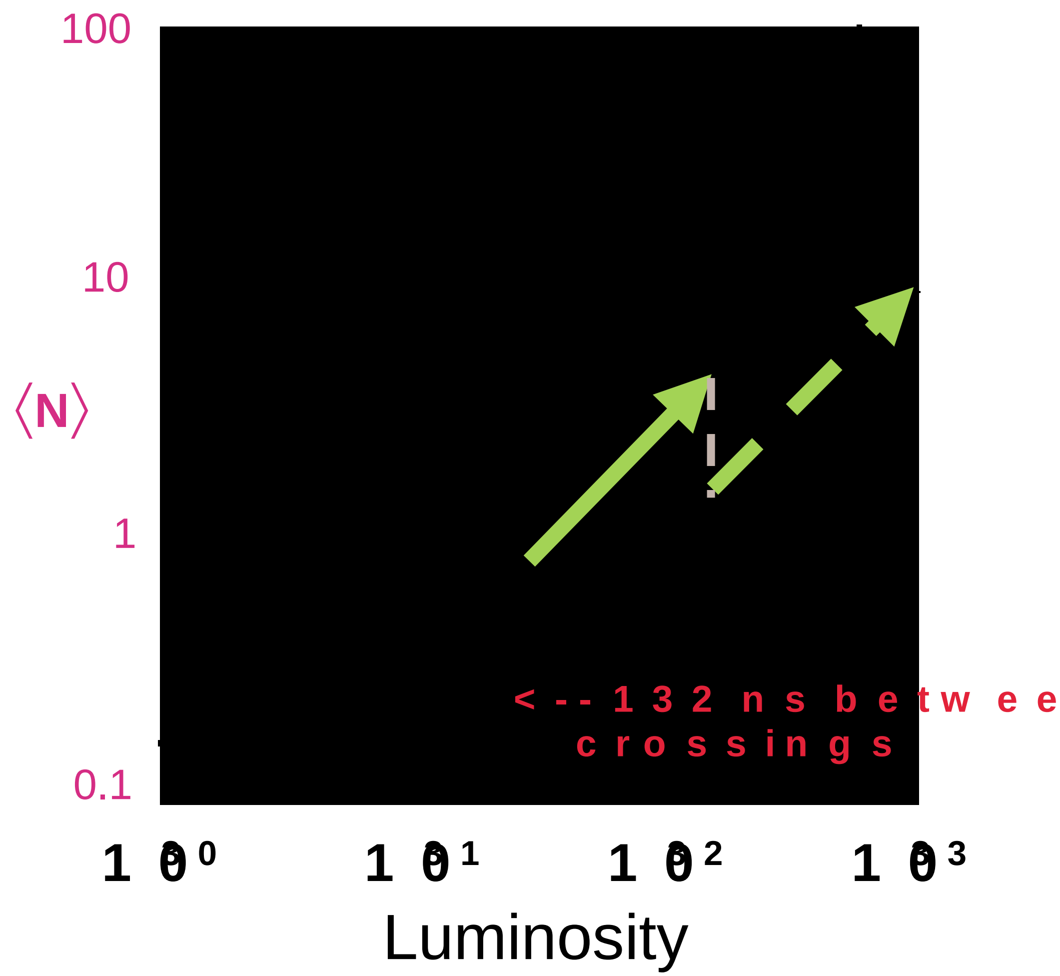
  36 x 36 will be 141 x 121 bunches

  ~ 10^{11} (10^{9}) p (pbar) per bunch

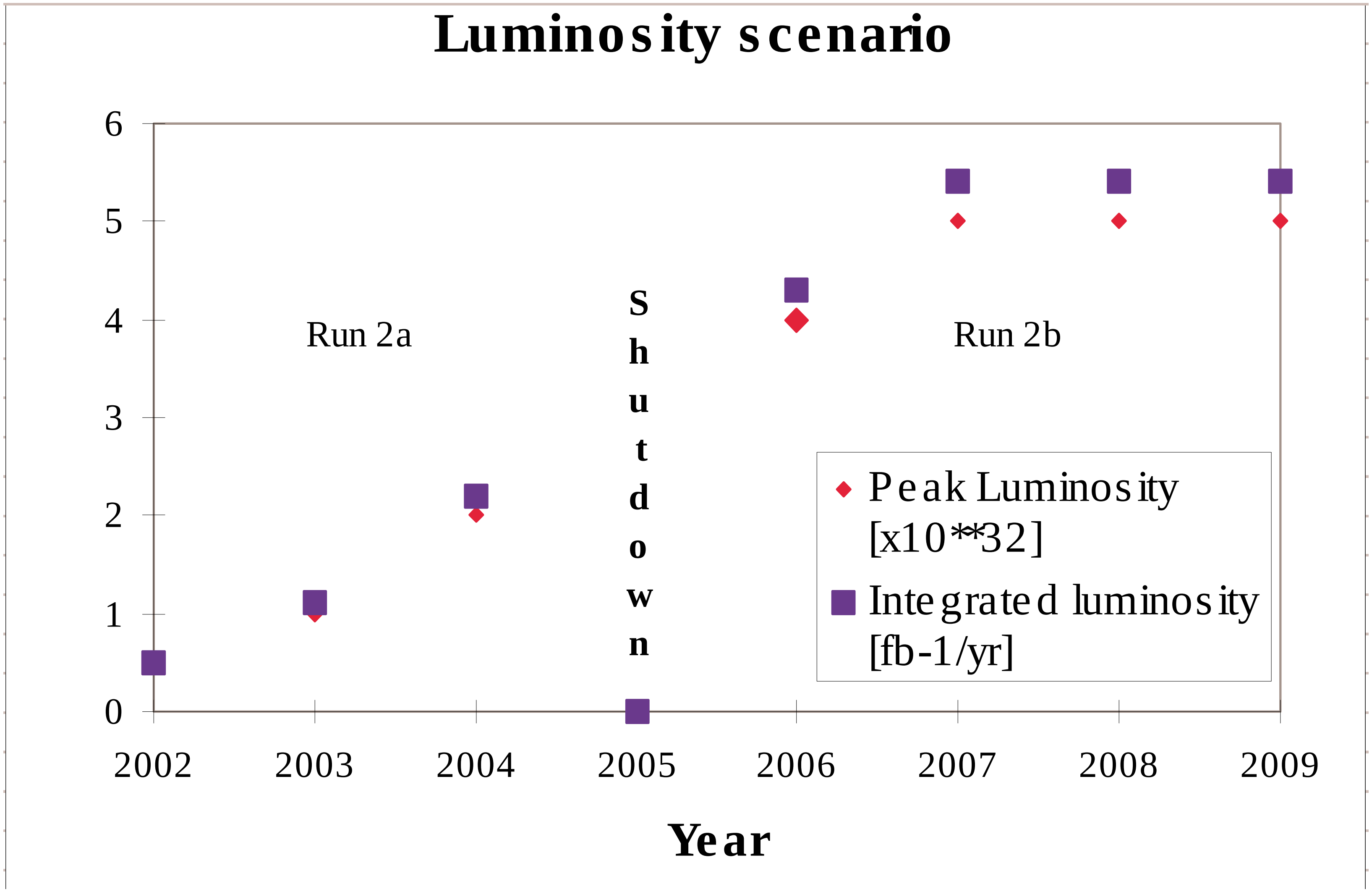
  - Interaction rate is ~ 7Mhz (beams collide every 132 ns)

  – Goal: A high beam-beam crossing rate but with ⟨**N**⟩ ~ 1 collision per crossing (expect 1 – 10)





Luminosity Profile*



* Likely to change once we have more operational experience.

Some Numbers

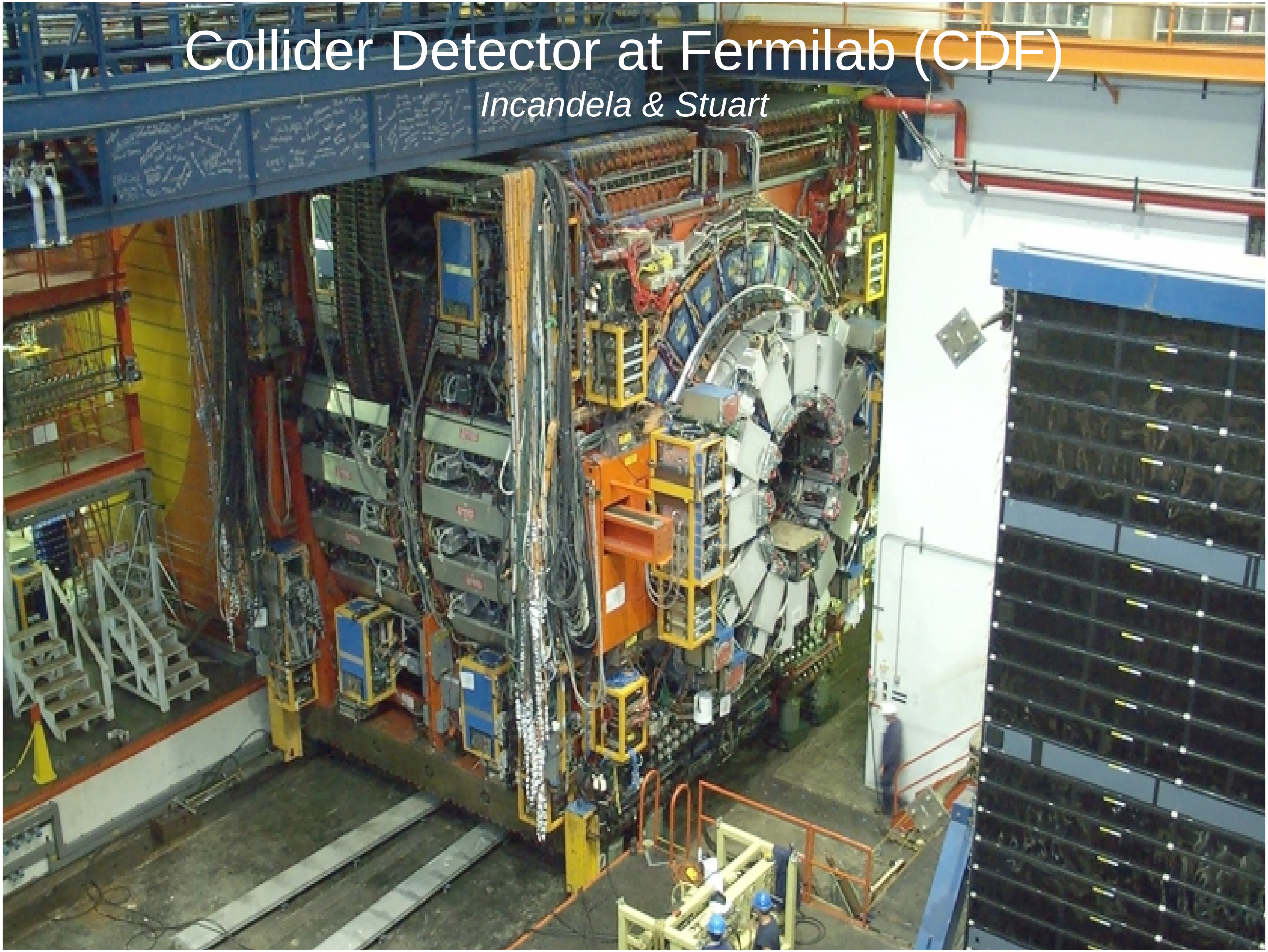
- Collisions are frequent (~ 7 million per second) but interesting collisions are rare.
  - 10^{12} collisions allowed us to observe ~ 50 top quark events

- We can only write ~50 events to tape per second.
  - Three decision ('trigger') levels:
    - A first analysis is done in ~4 μs
    - A second quick analysis takes ~ 20 μs
    - The third and final analysis takes ~ 0.1 second

- We collect 1 Terabyte of data per day and our total data set will be ~10 Petabytes

Collider Detector at Fermilab (CDF)

Incandela & Stuart



The 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

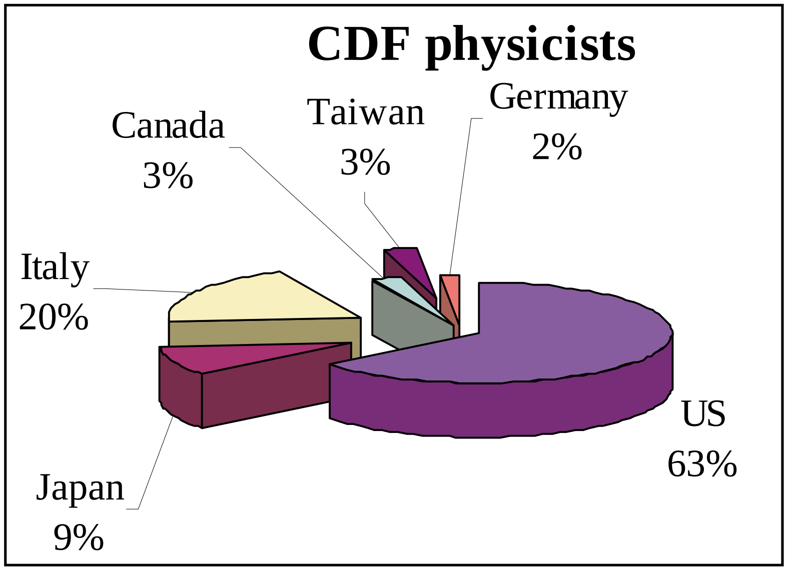
1 Research Lab
4 Universities

1 University

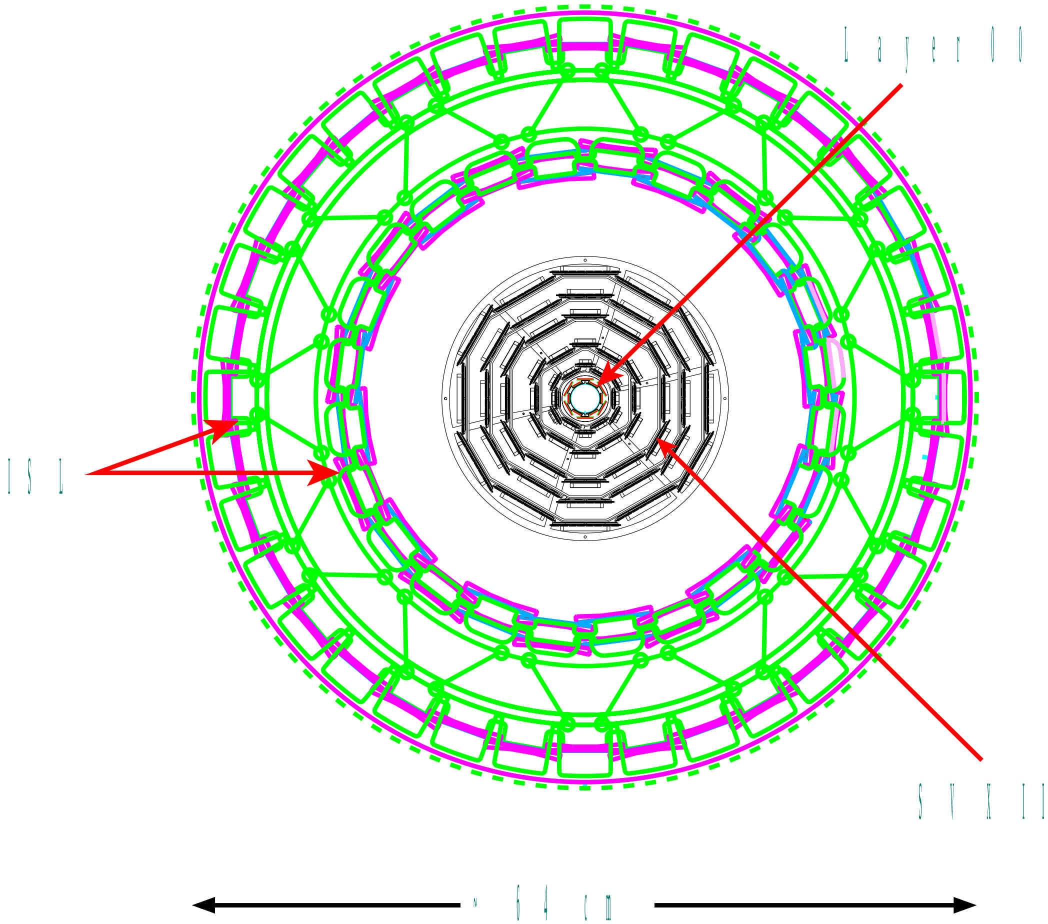
1 University
consortium

- **11 countries**
  - **52 institutions**
  - **525 physicists**
    (140 students)

195 PhD theses since 1985

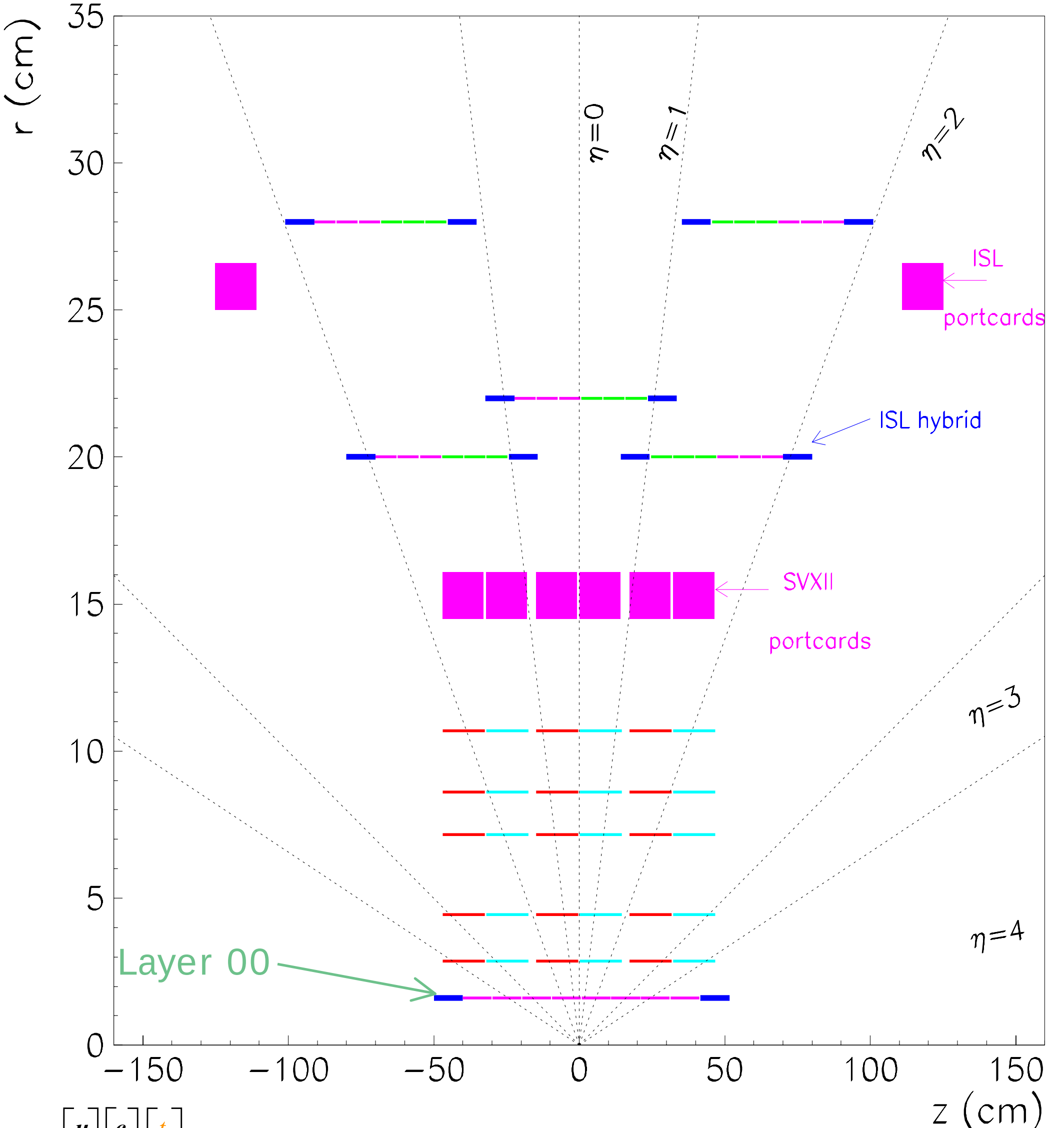


CDF II Silicon



- SVXII (SVX)
  - Originally the only Silicon in the upgrade w/ Main Goals:
    - 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
- Layer 00 (L00)
  - Improve impact parameter resolution to increase B tag efficiency
  - In the Level 2 trigger
  - Outlive inner layers of SVX

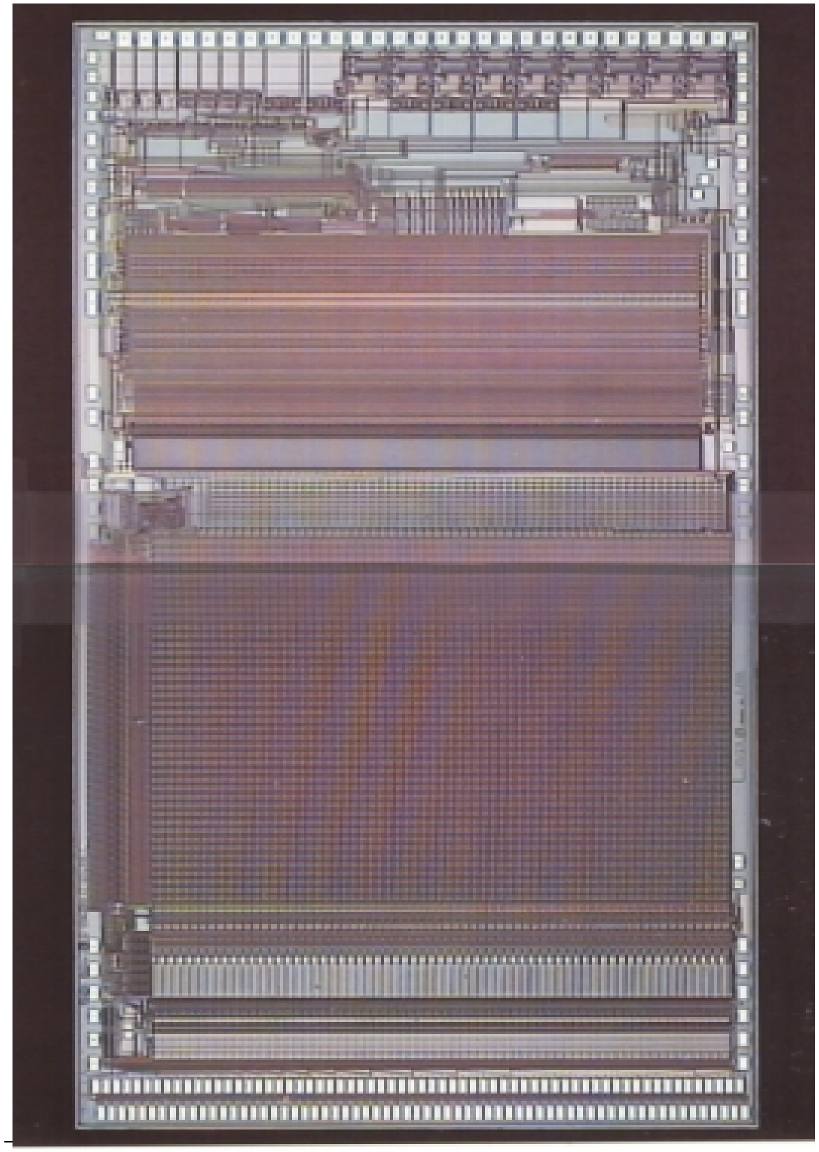
Layout



Layer	Inner/Outer Radii [cm]	Axial Pitch [μm]	Stereo Angle	Stereo Pitch [μm]
1	1.35/1.62	25	-	-
2	2.5/3.0	60	90	141
3	4.1/4.6	62	90	125.5
4	6.5/7.0	60	1.2	60
5	8.2/8.7	60	90	141
6	10.1/10.6	65	1.2	65
7 Forward	19.7/20.2	112	1.2	112
7 Central	22.6/23.1	112	1.2	112
8 Forward	28.6/29.0	112	1.2	112

- All silicon is p/n
- All layers except Layer 1 are double-sided silicon
- 90 degree: Double Metal

SVX3 Chip

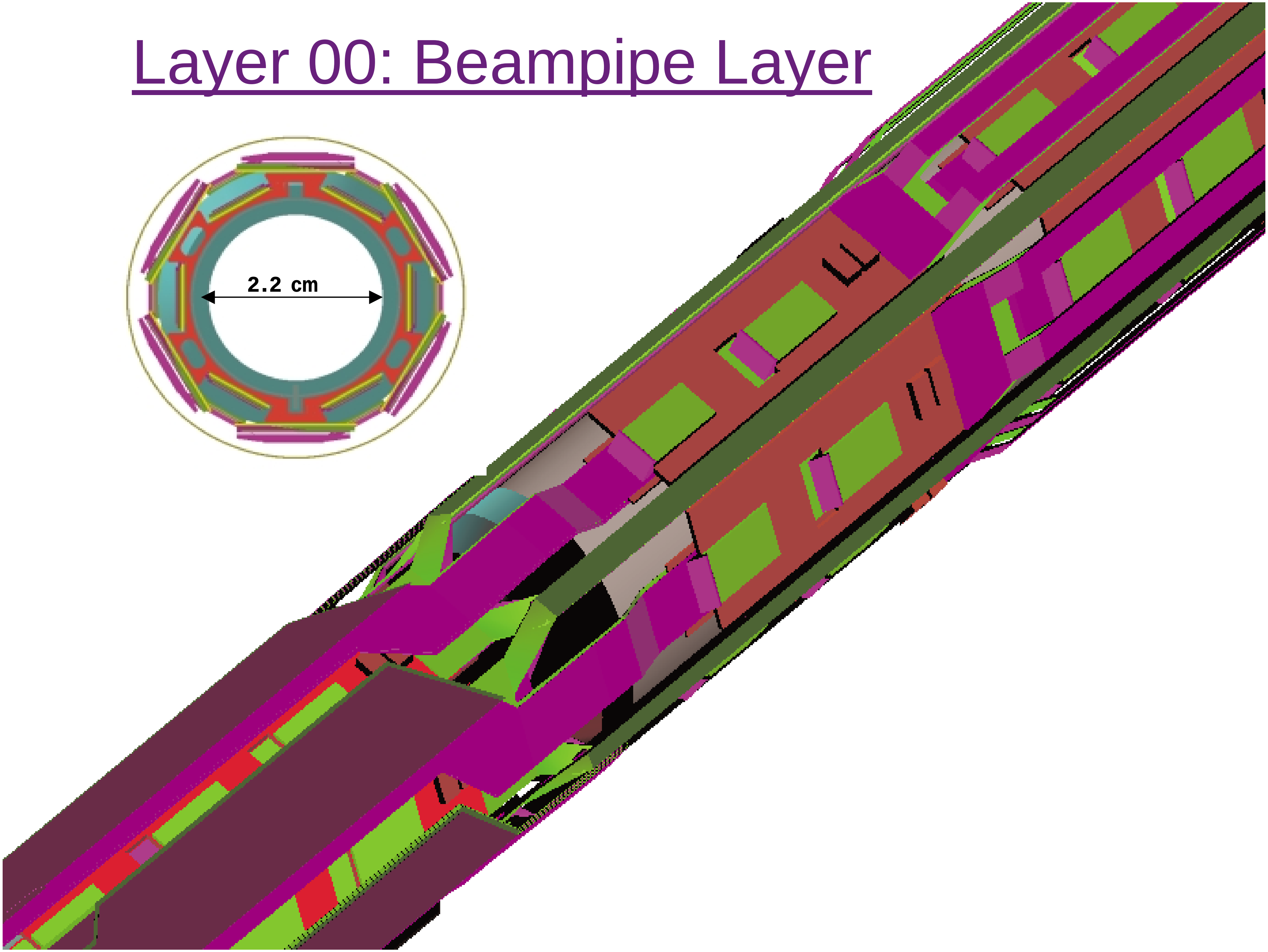


- Analog Front End (FE) and Digital Back End (BE)
  - FE has relatively low noise integrator and 42 cell analog pipeline with 4 buffer cells
  - BE has comparator, ADC, and sparse readout
- Deadtimeless:
  - Capable of analog operations during digitization and readout
- Dynamic pedestal subtraction (DPS)
  - Enables common mode noise suppression

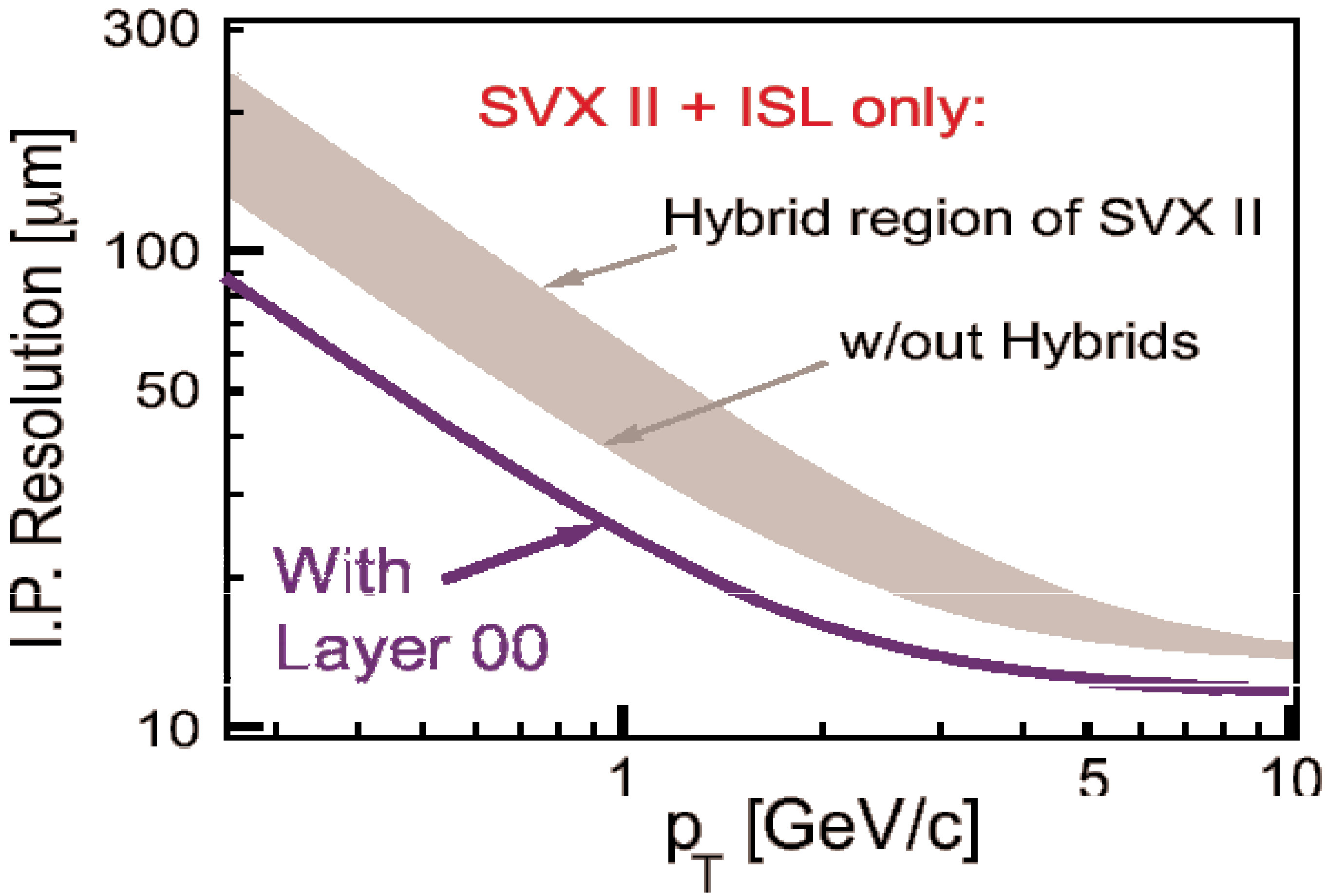
CDF Run 2 Silicon Table

CDF	Layer 00	SVX II	ISL	Totals
Layers	1	5	2	8
Length	0.9 m	0.9 m	1.9 m	
Channels		**13824**	**405504**	**303**
Modules	48 SS	360 DS	296 DS	704
Readout Length	14.8 cm	14.5 cm	21.5 cm	
Inner Radius	1.35 cm	2.5 cm	20 cm	1.35 cm
Outer Radius	1.65 cm	10.6 cm	28 cm	28 cm
Power	~100 W	1.4 kW	1.0 kW	2.5 kW

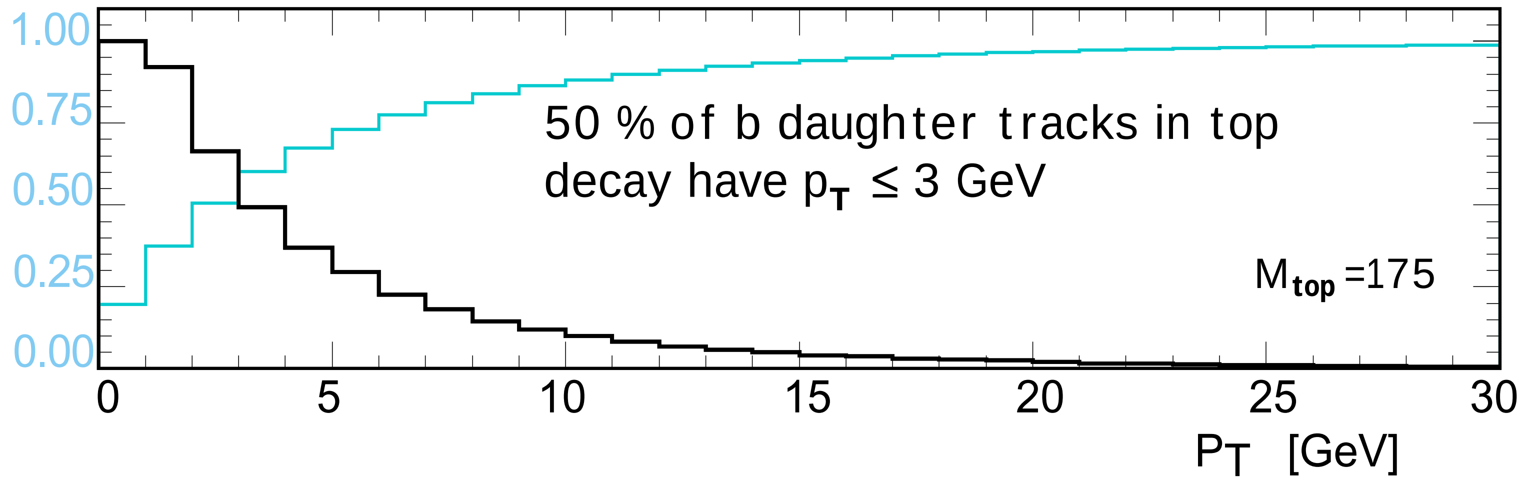
Layer 00: Beampipe Layer

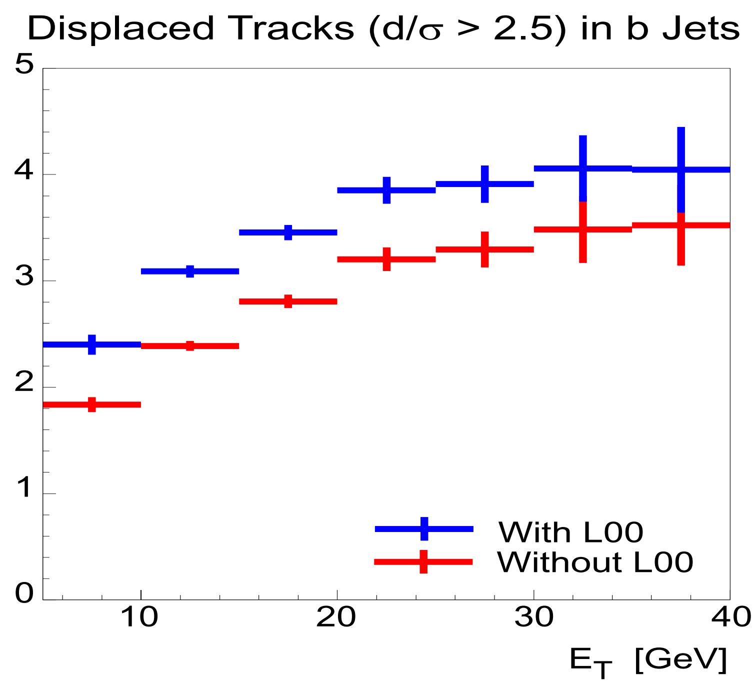


Impact Parameter Resolution



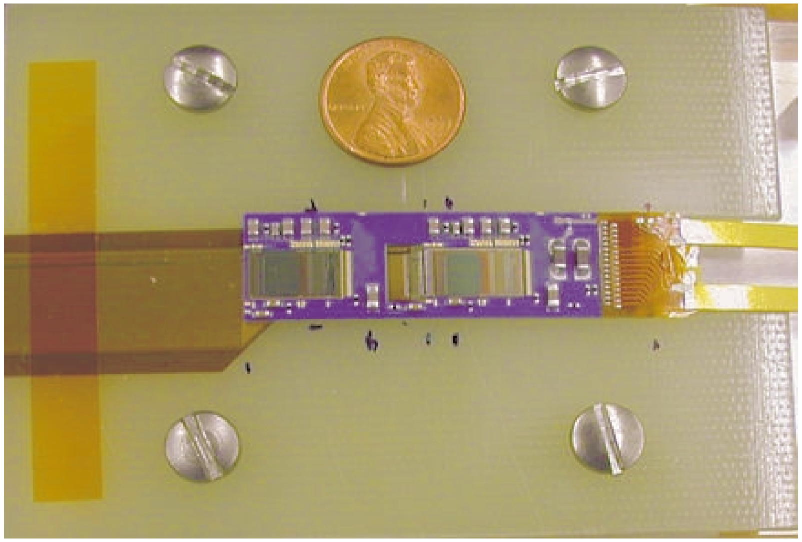
B tagging

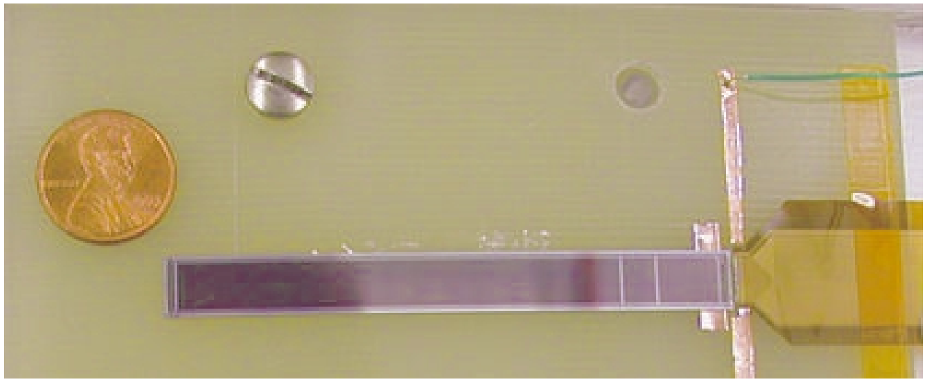


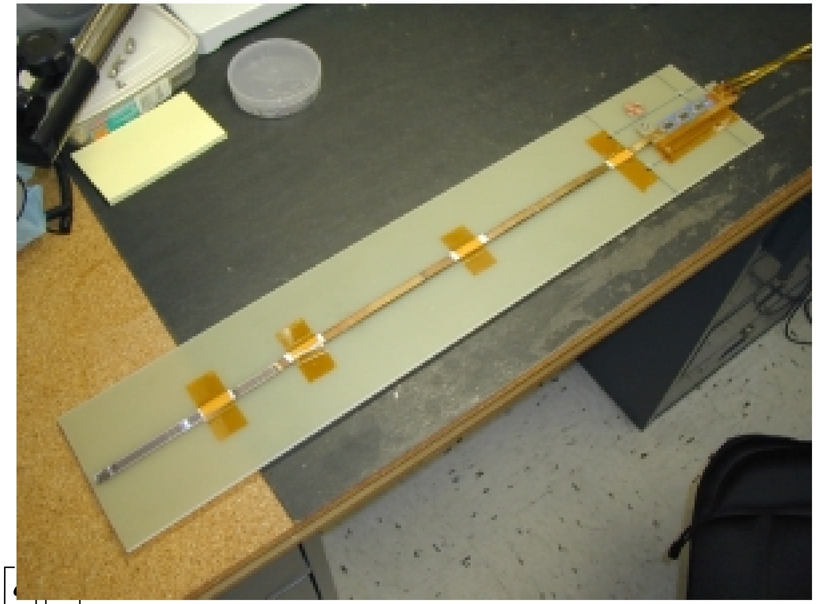


- Layer 00 increases the number of observed displaced tracks and hence b tagging and flavor tagging are improved.

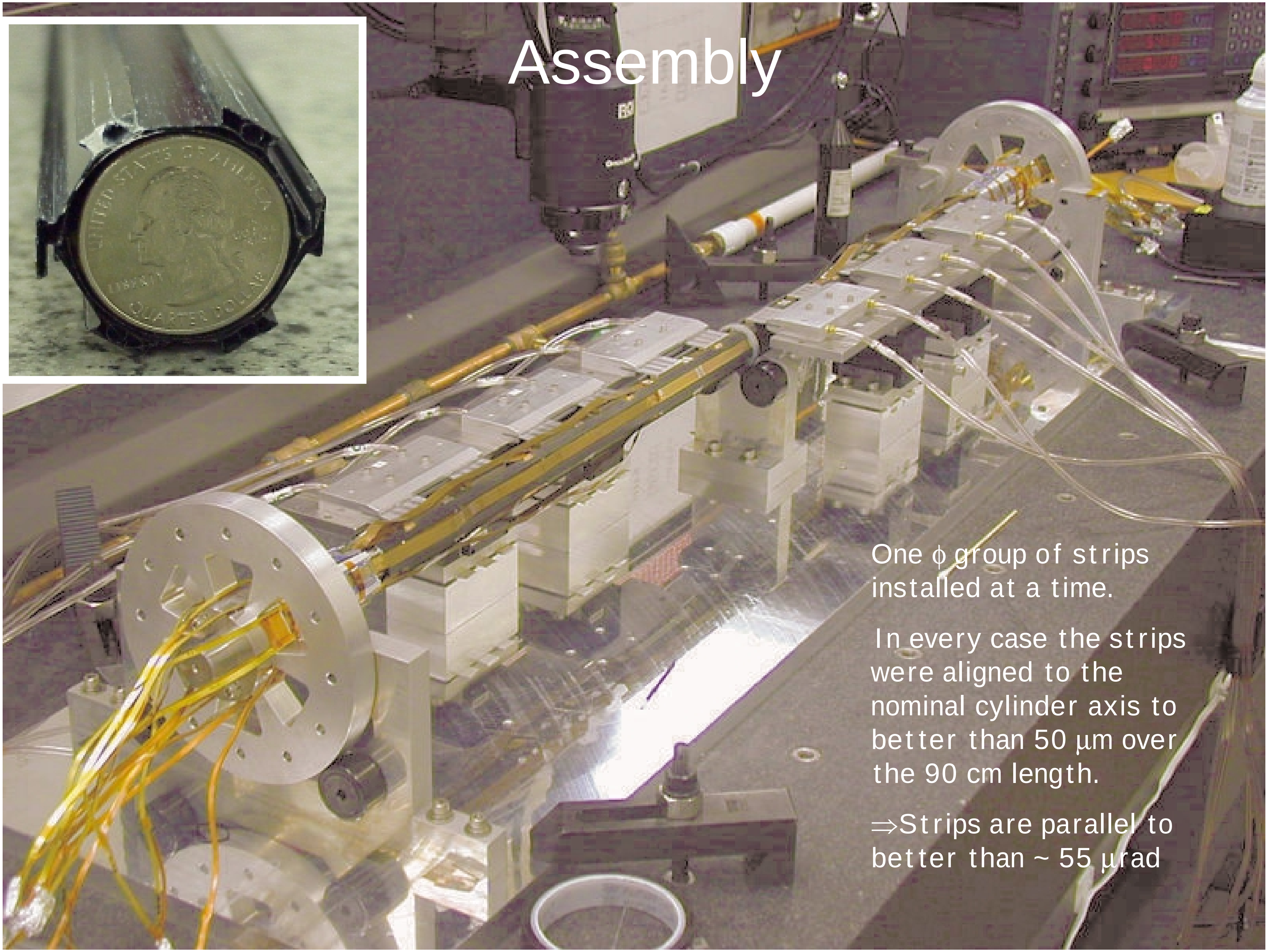
Components







Assembly



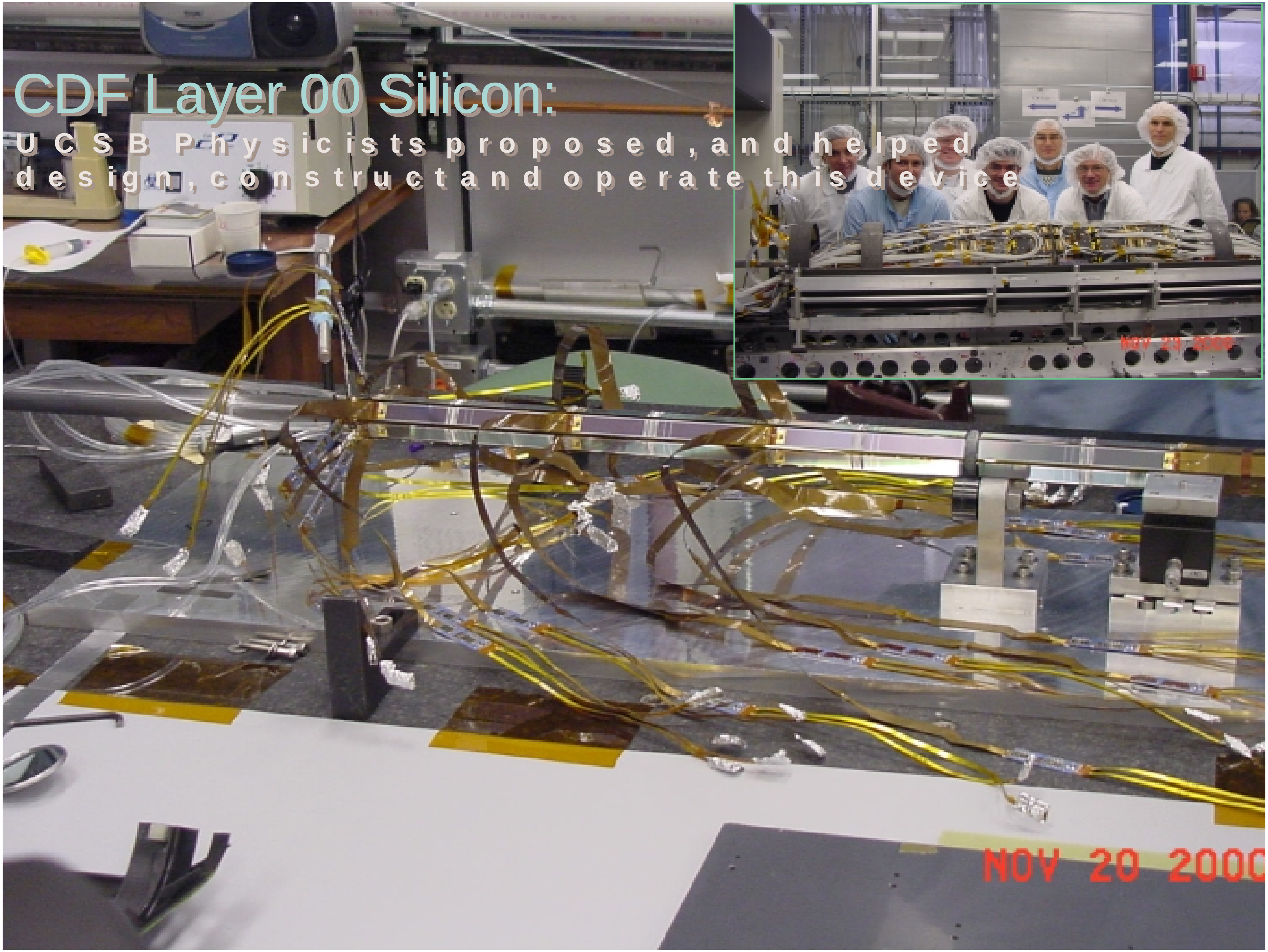
One ϕ group of strips installed at a time.

In every case the strips were aligned to the nominal cylinder axis to better than 50 μm over the 90 cm length.

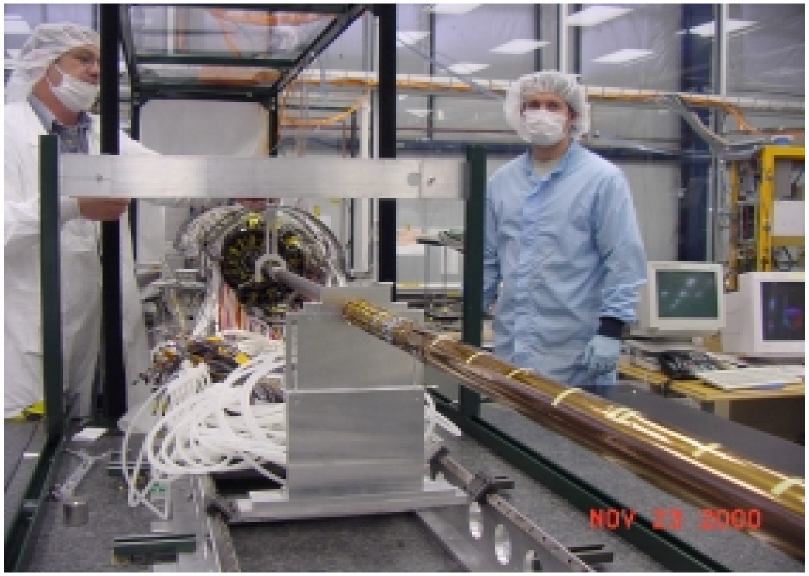
⇒Strips are parallel to better than ~ 55 μrad

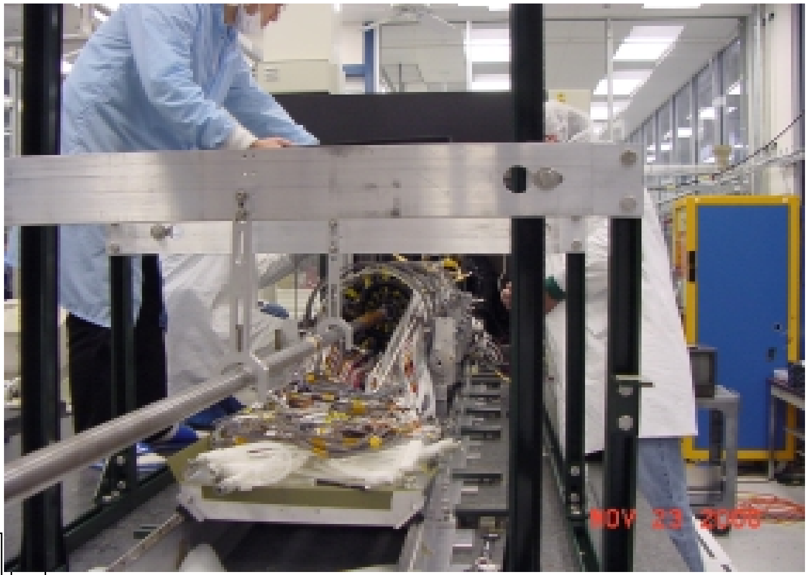
CDF Layer 00 Silicon:

UCSB Physicists proposed, and helped design, construct and operate this device



Installation



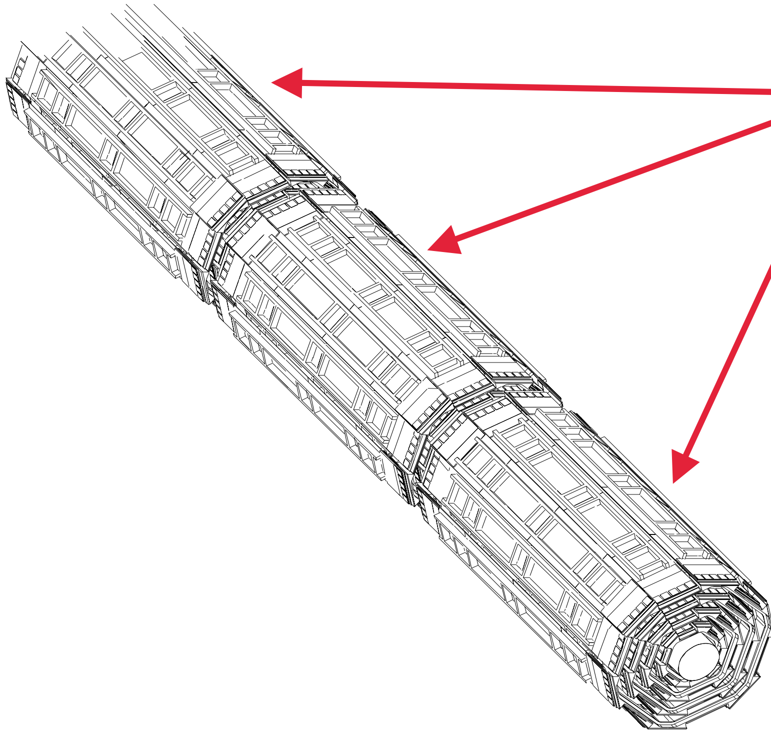


Inside SVX

Installation clearance: 300 - 450 μm over ~ 2 m

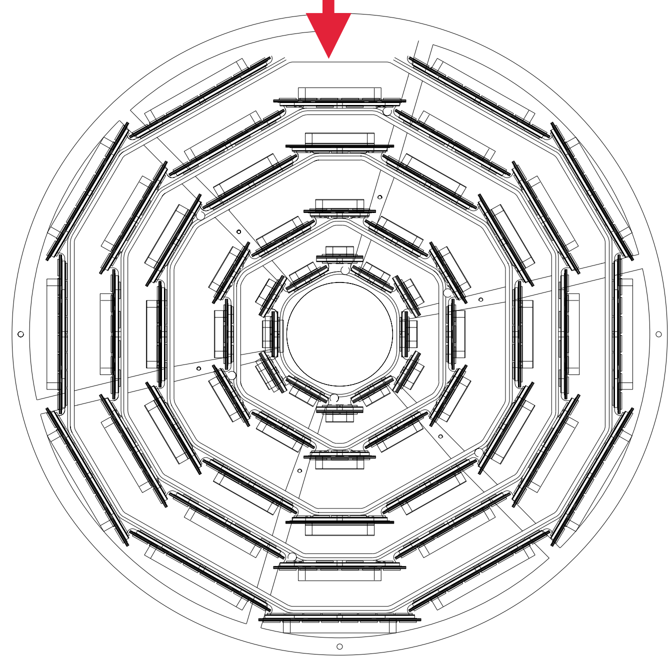
Final alignment*: L00 parallel to SVX to ~ 25 μrad

CDF SVX II

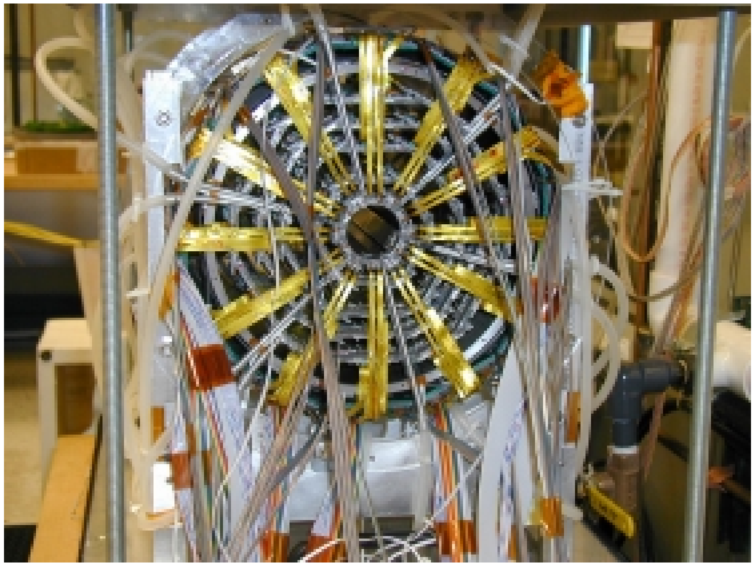


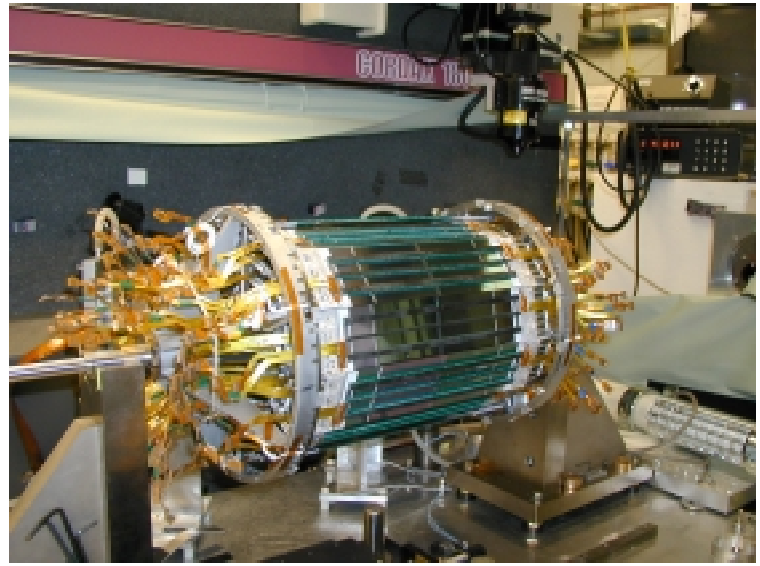
3 Barrels: Very Compact design:

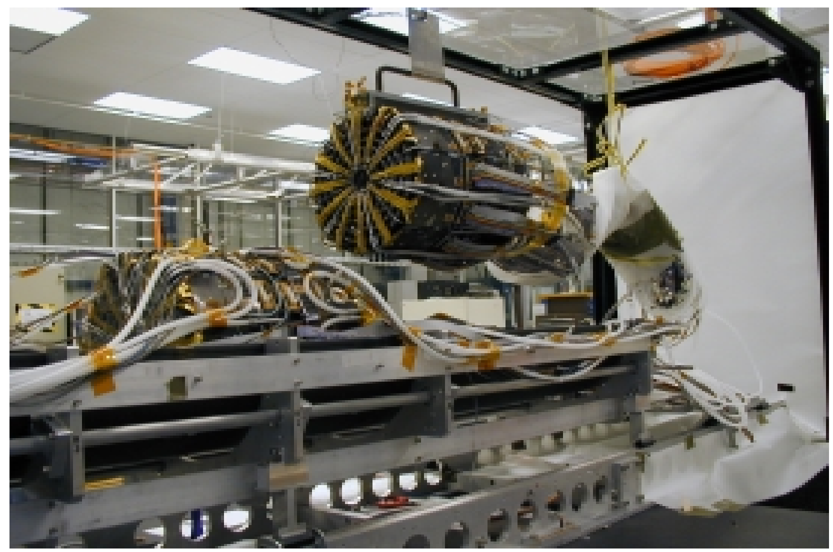
- Electronics mounted directly on silicon to avoid longitudinal gaps.
- Overlaps in ϕ
- Radial span ~8 cm for 5 layers !



SVXII Barrels



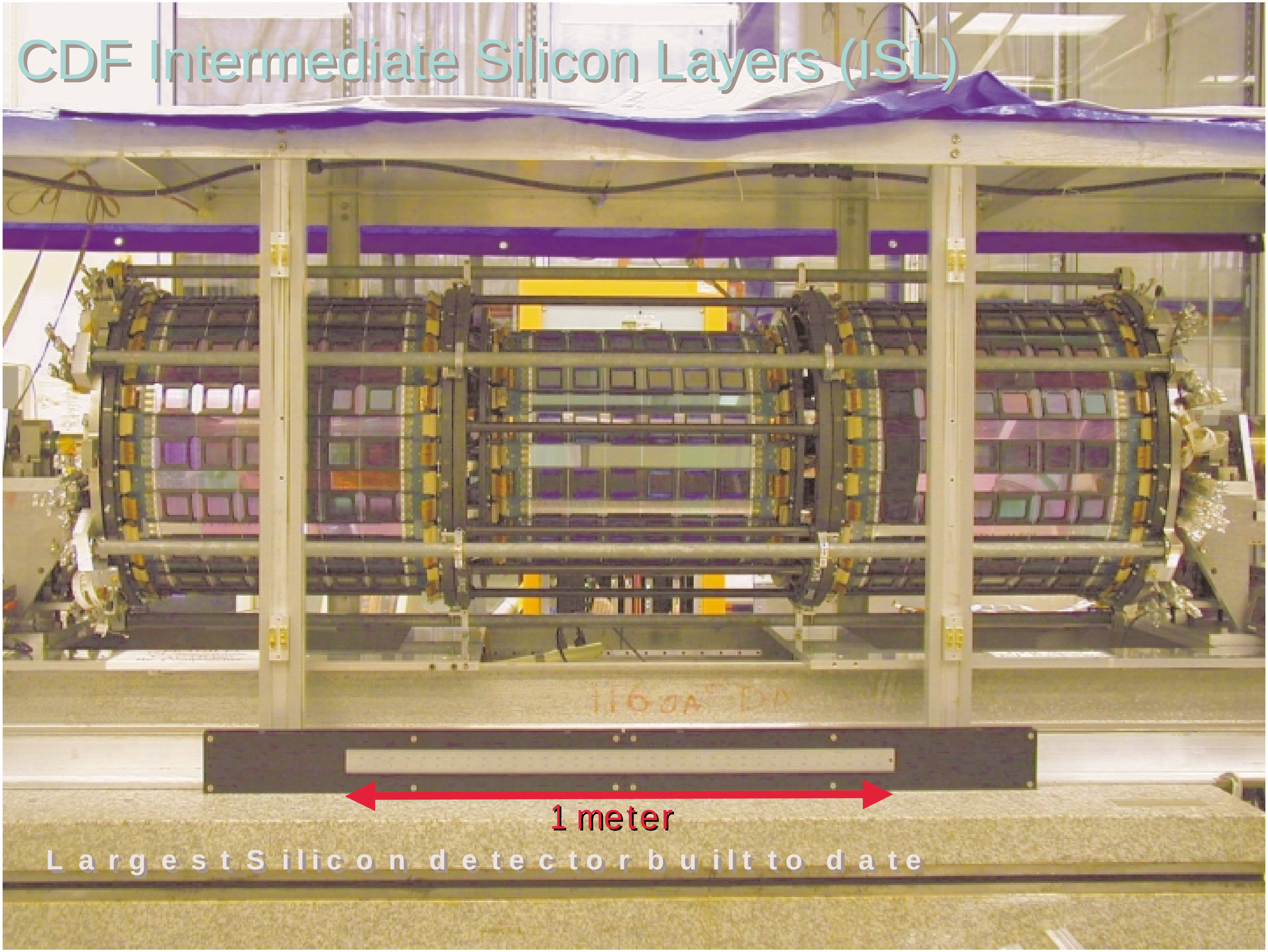




Preparation for Installation in ISL

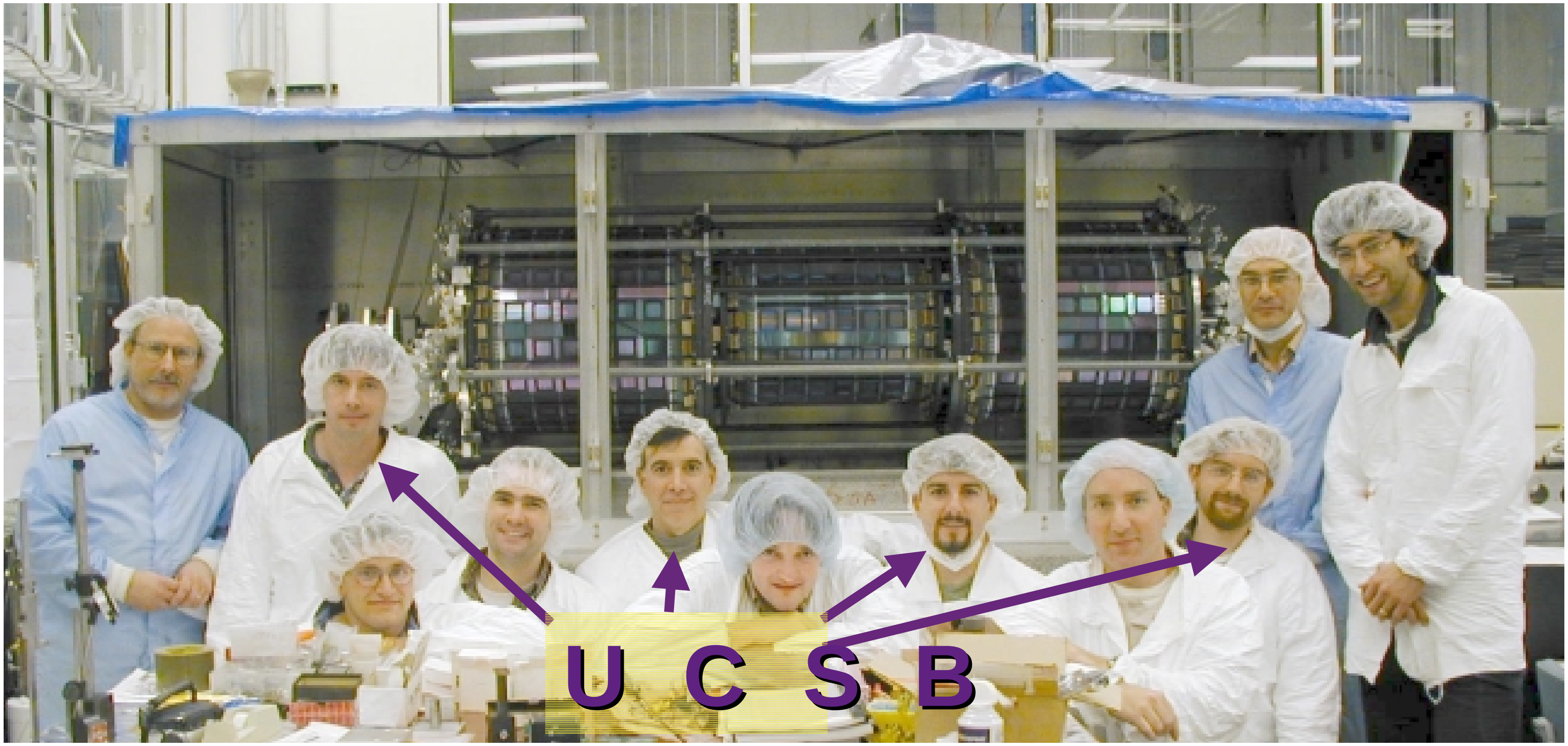
David Stuart (UCSB) Inside the ISL

CDF Intermediate Silicon Layers (ISL)



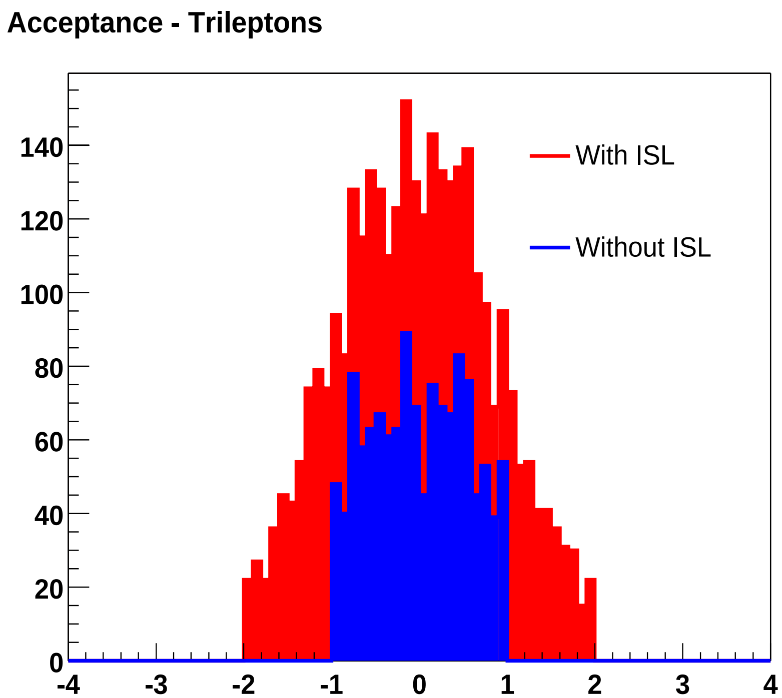
Largest Silicon detector built to date

UCSB involvement in CDF Silicon



- UCSB CDF physicists
  - Joe Incandela , David Stuart (Faculty)
  - Tony Affolder, Chris Hill, (Post-docs)
  - Cigdem Issever, Russell Taylor (Post-docs – not in picture)

CDF Run 2 Silicon

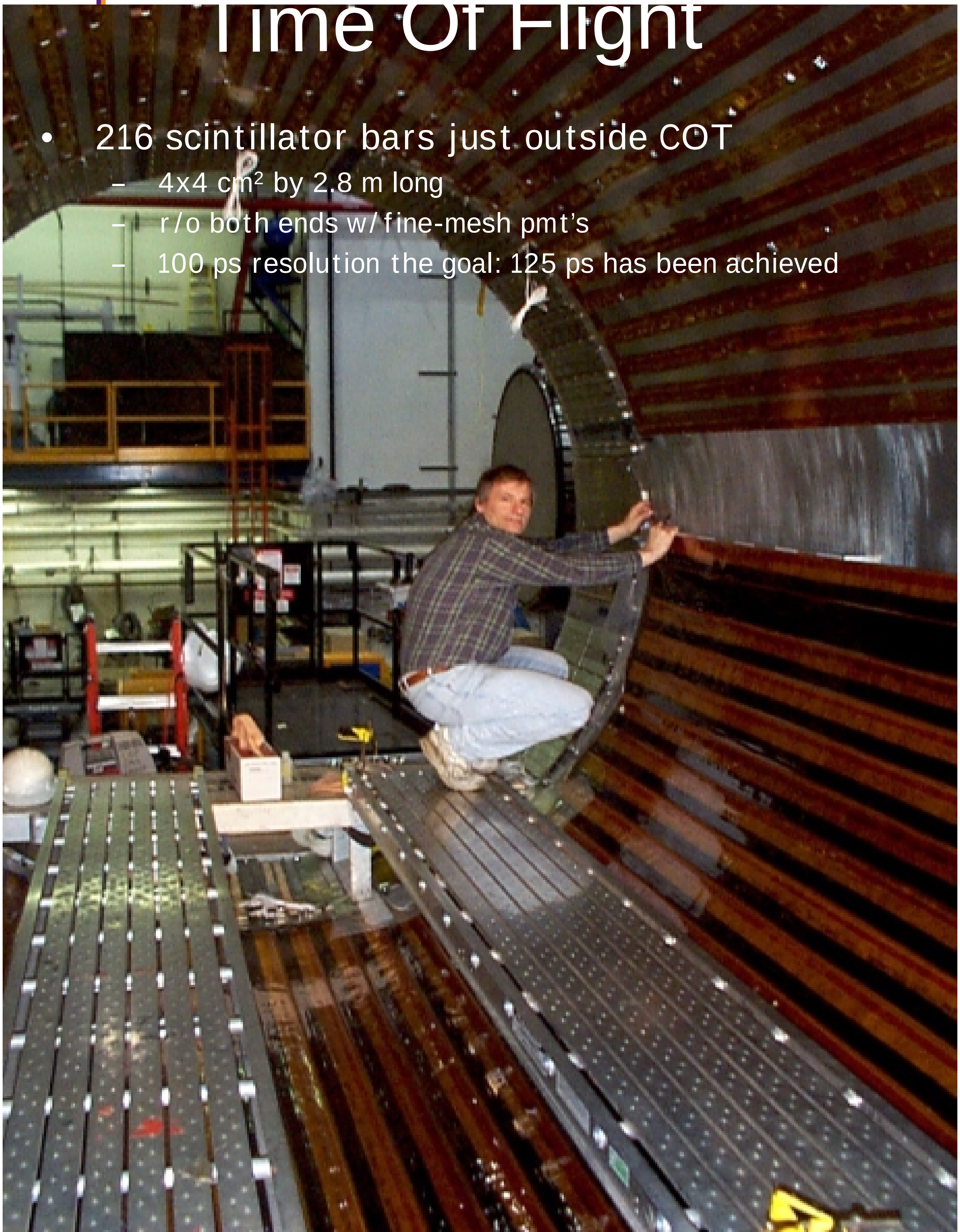


- Goal: maximum sensitivity to Higgs and SUSY in 15 fb^{-1}
- Depends mainly upon 3 things:
  - B Tagging
    - For W/Z+H, H $\rightarrow$ $b\bar{b}$ the ability to tag b jets in $1 \leq |\eta| \leq 2$ accounts for roughly 2/3 of our sensitivity in this channel.
    - We need the highest possible b tag efficiency while also maintaining low tag rates for charm, light quark, and gluon jets.
  - Lepton id
    - For SUSY channels with 3 leptons the ability to track and determine particle momenta in $1 \leq |\eta| \leq 2$ accounts for the majority of our sensitivity.
  - Energy resolution
    - Jet energy and missing E_T resolution need to be optimal.

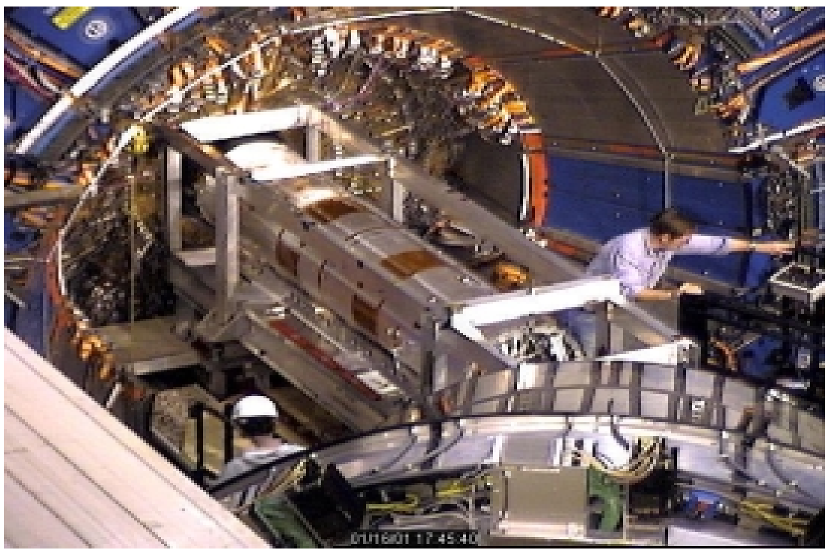
Central Outer Tracker (COT)

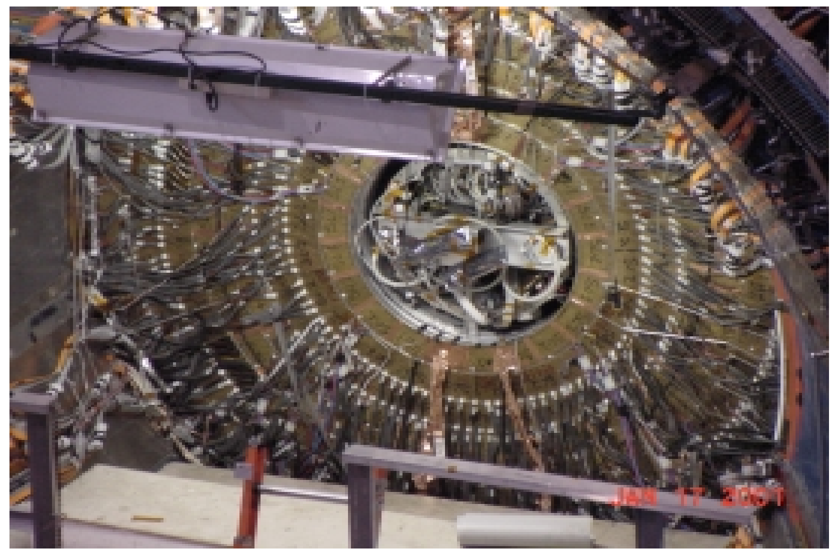
Time Of Flight

- 216 scintillator bars just outside COT
  - 4x4 cm^2 by 2.8 m long
  - r/o both ends w/ fine-mesh pmt's
  - 100 ps resolution the goal: 125 ps has been achieved

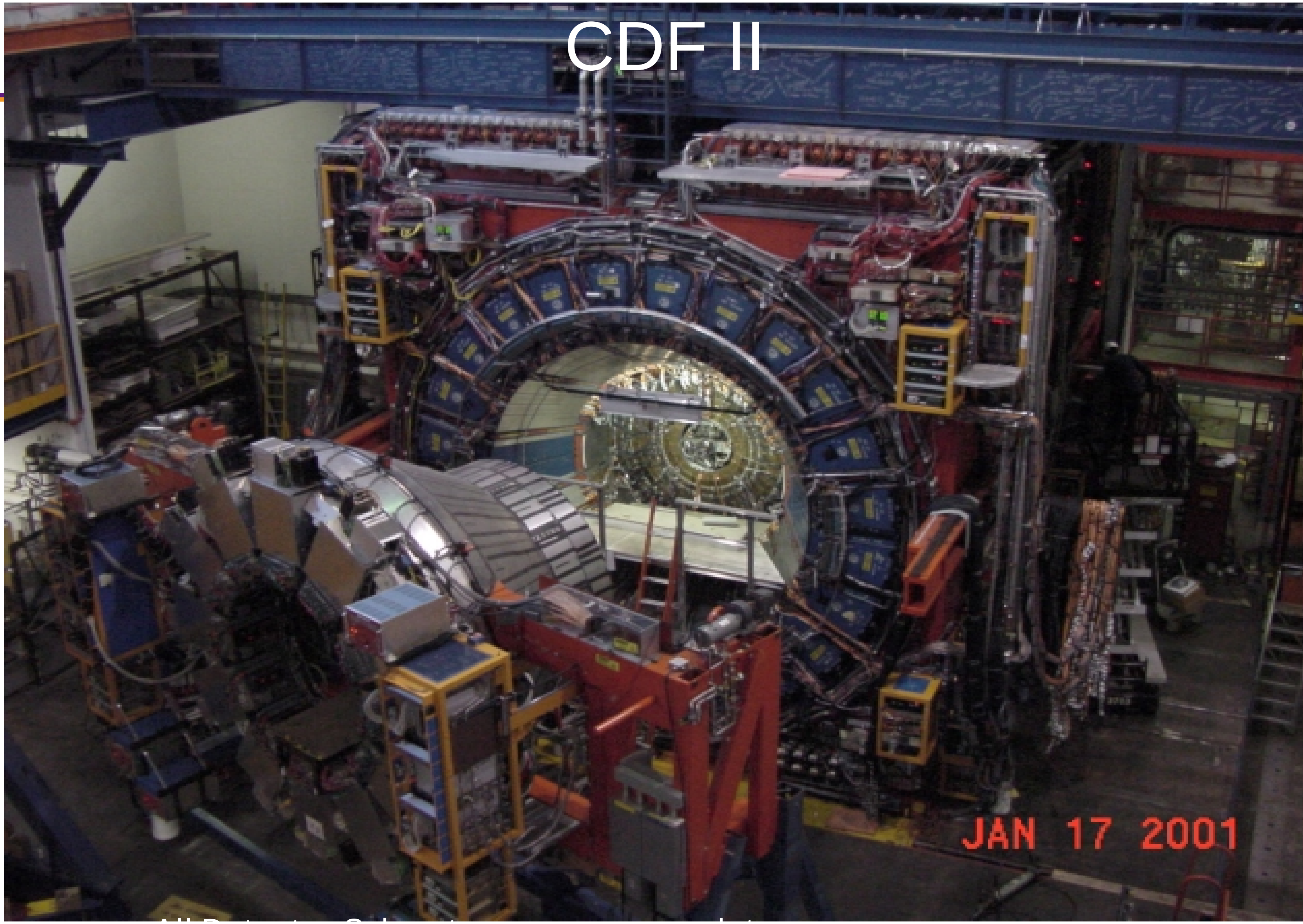


Installation in CDF

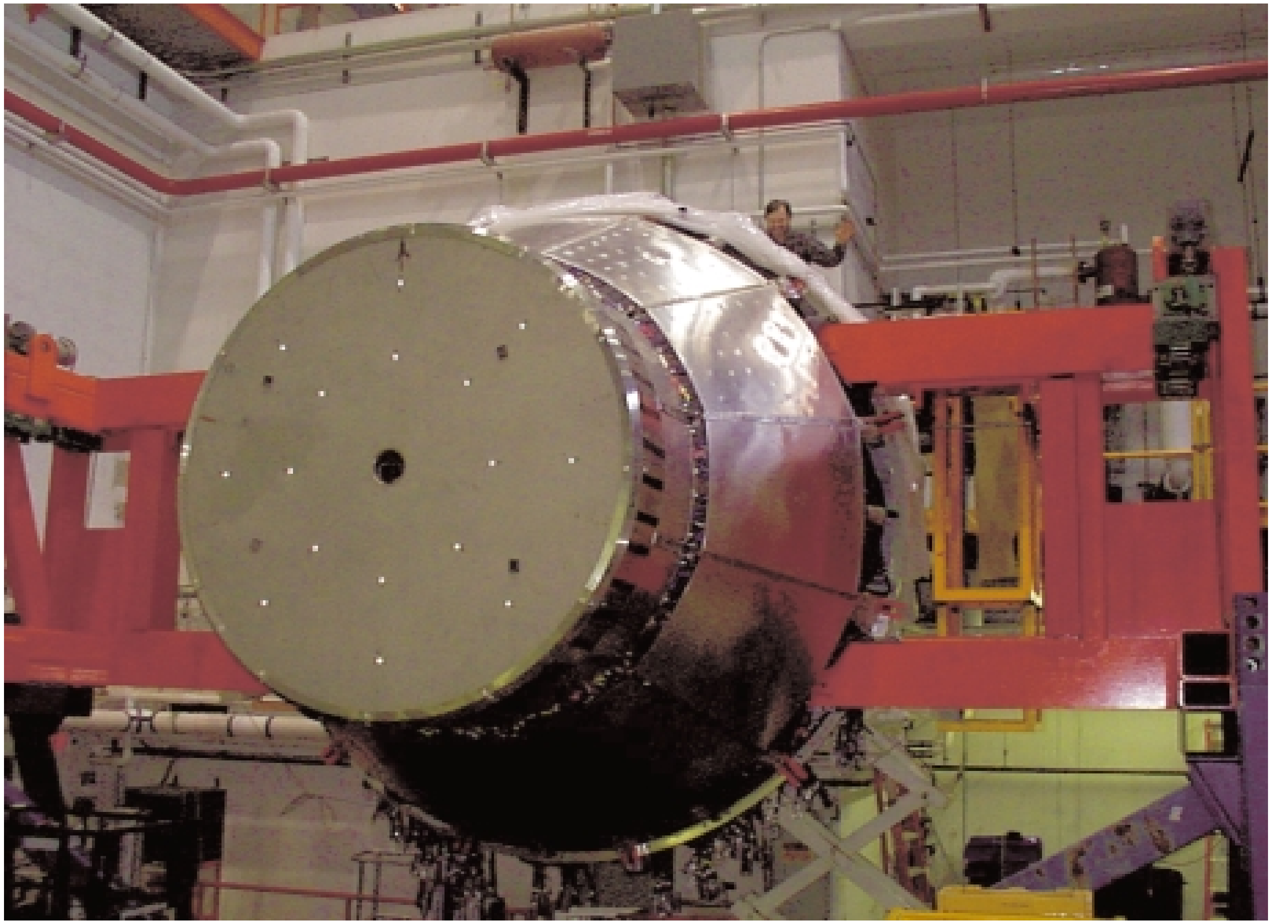




CDF II

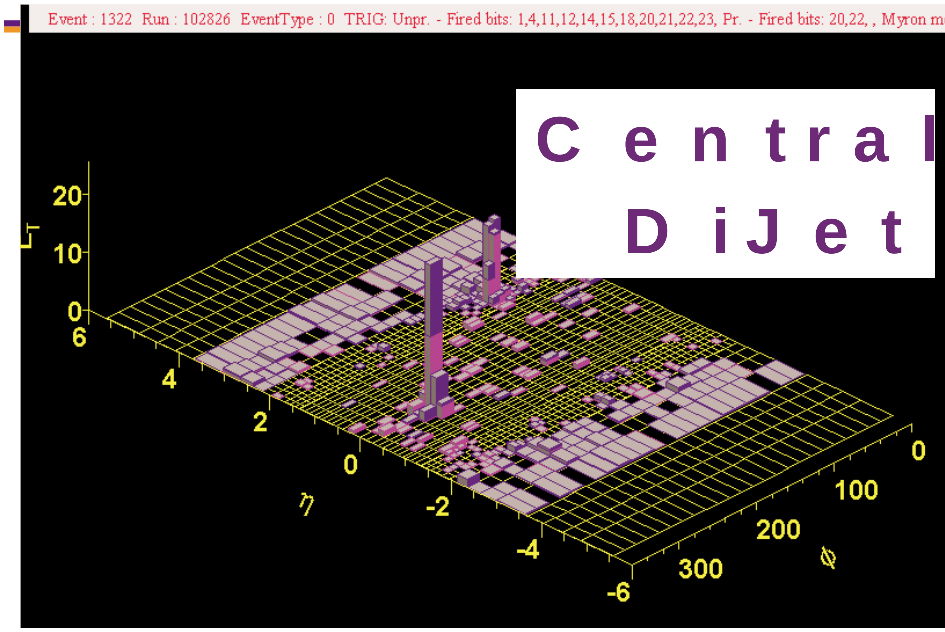


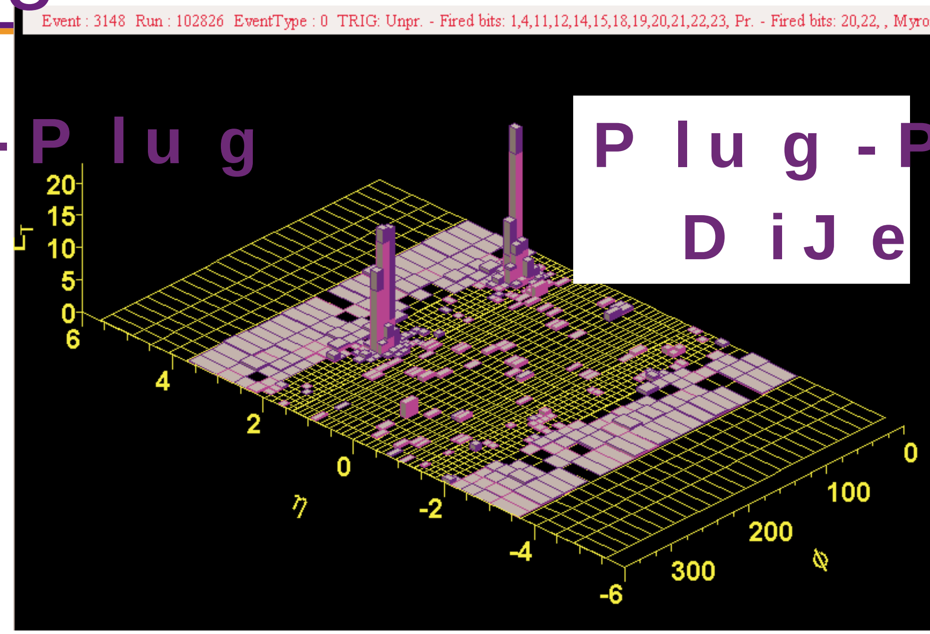
CDF Calorimeters

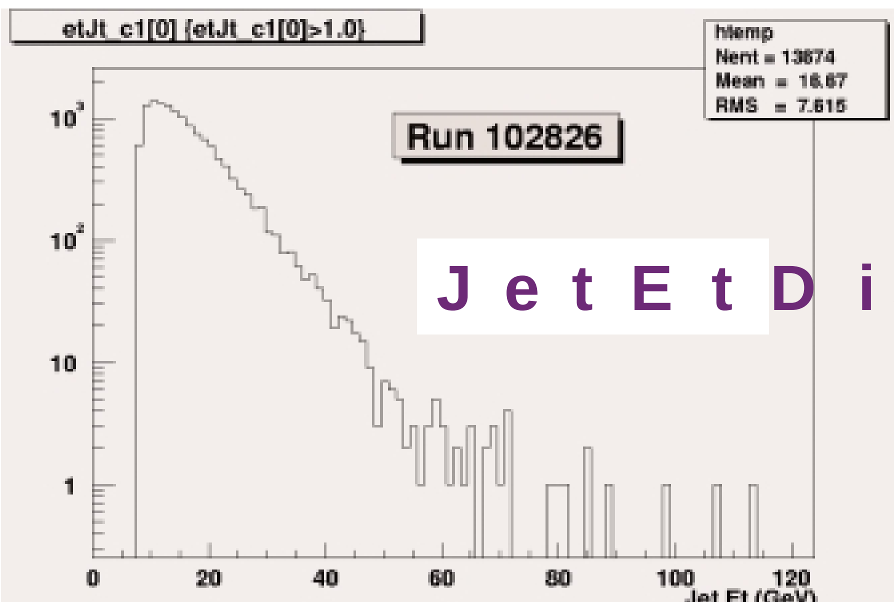


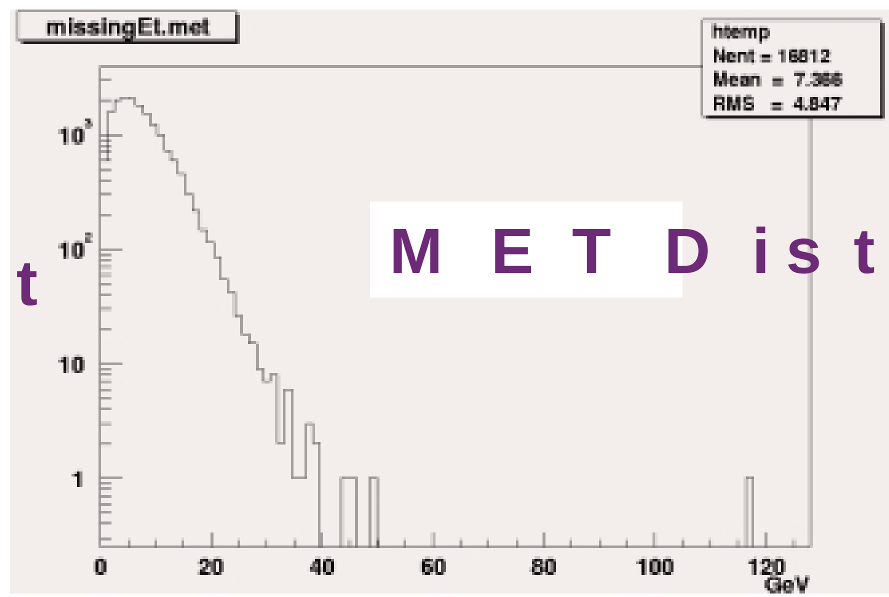
- New Plug Calorimeters
  - Scintillator tile design

Jets in the Plug Calorimeters



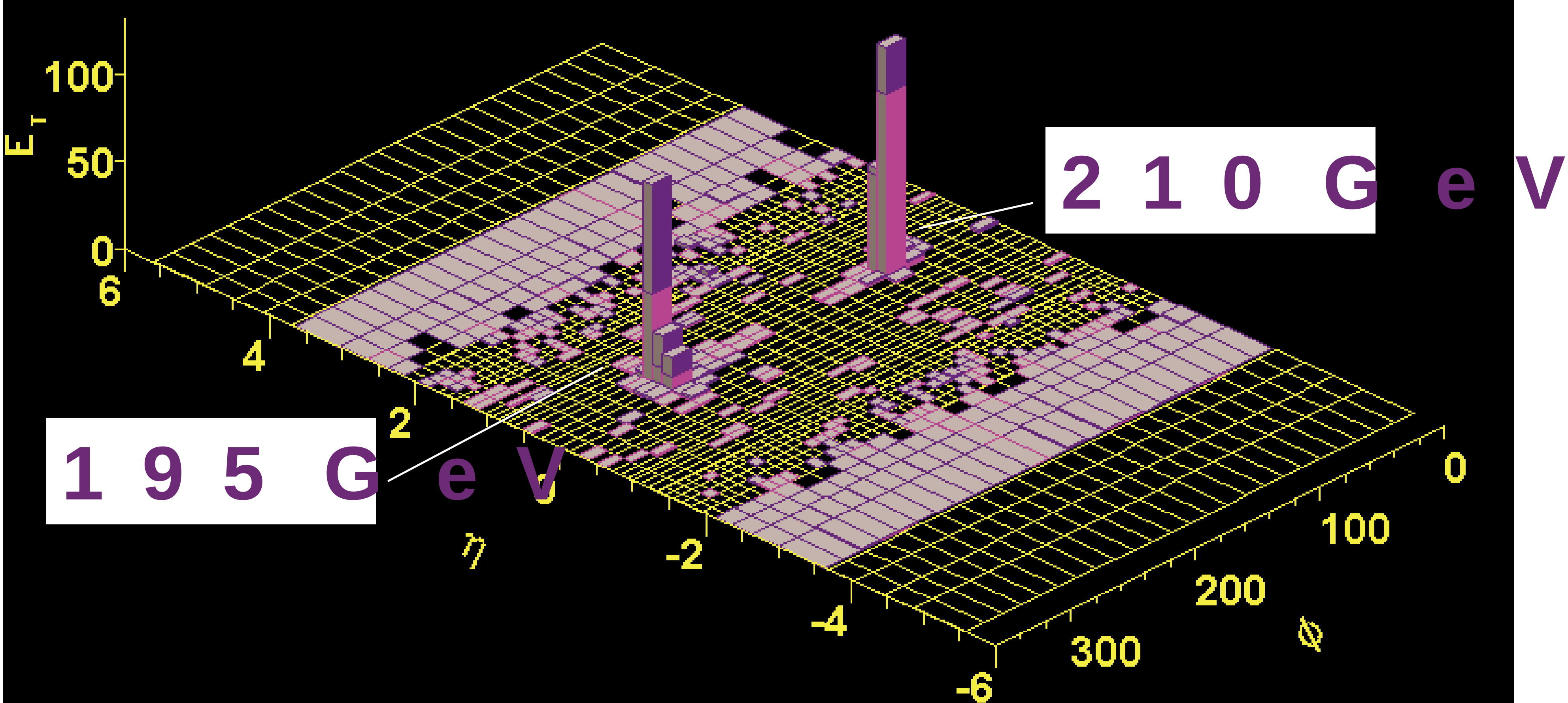




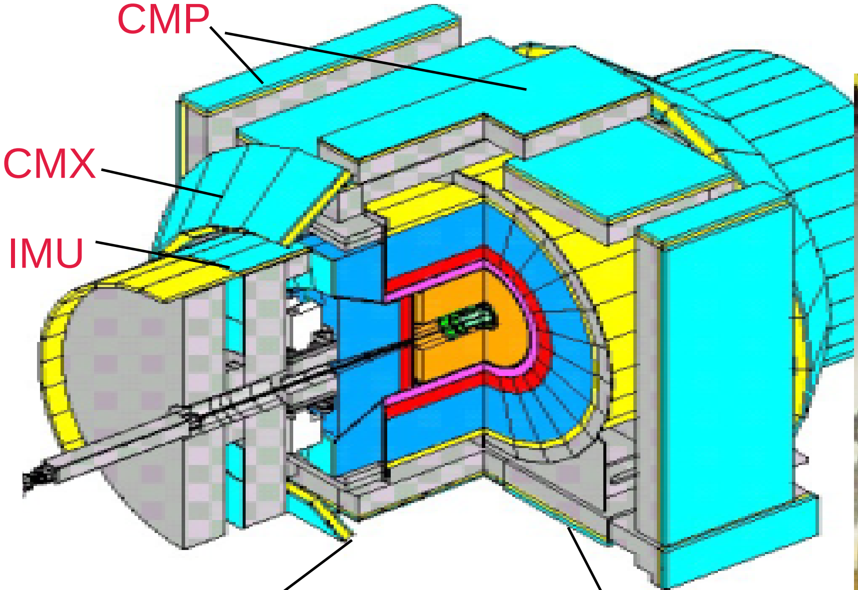


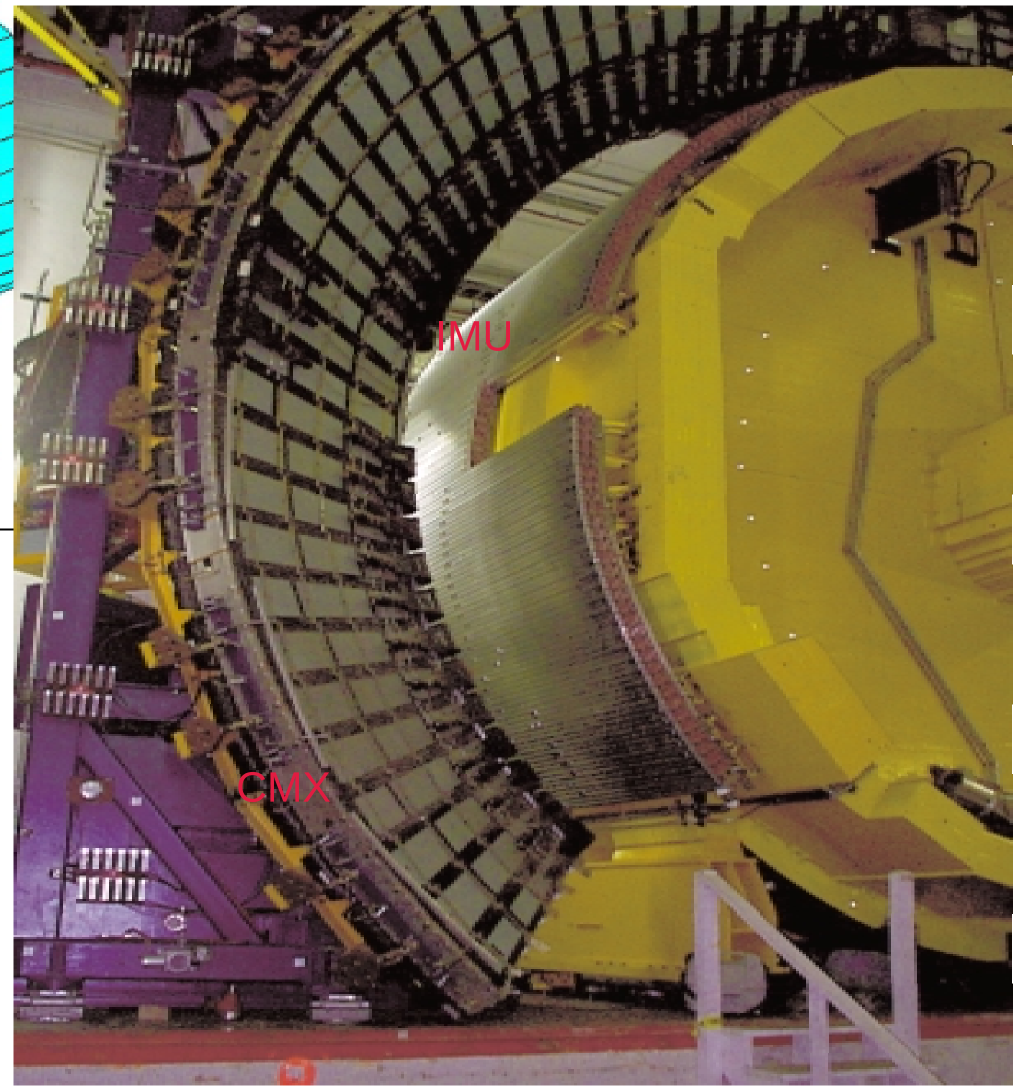
Event : 7973 Run : 102837 EventType : 0 TRIG: Unpr. - Fired bits: 1,41,14,15,21,22,23,24,26,30, Pr. - Fired bits: 22, , Myron mode 0

Central Calorimeter Dijet Event

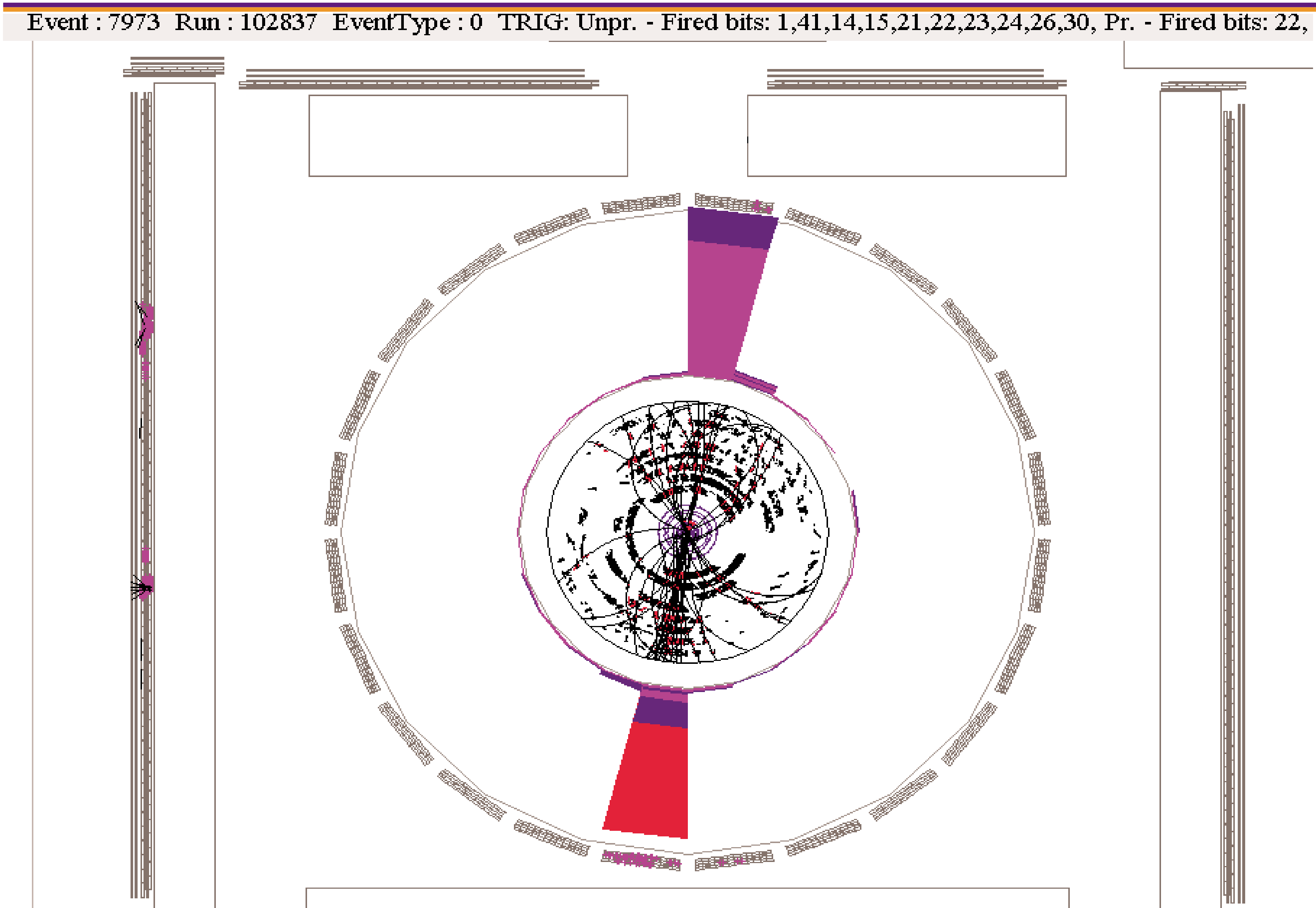


CDF Muon System

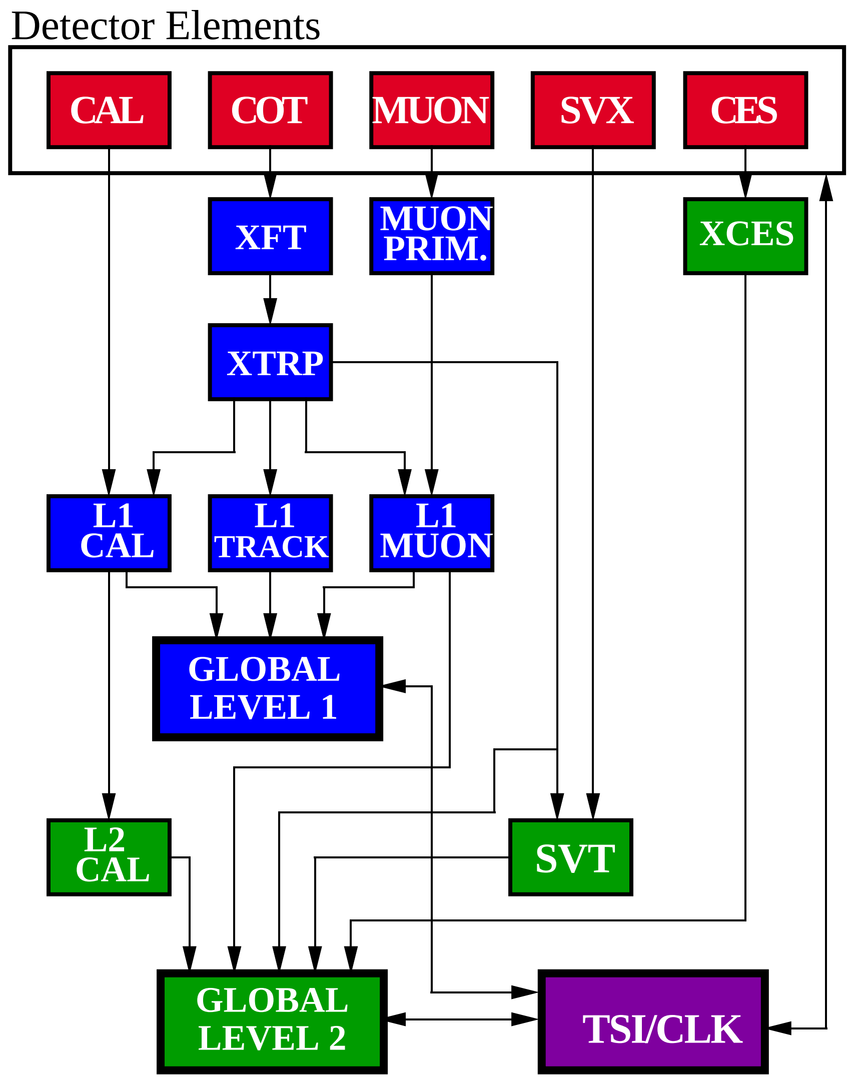




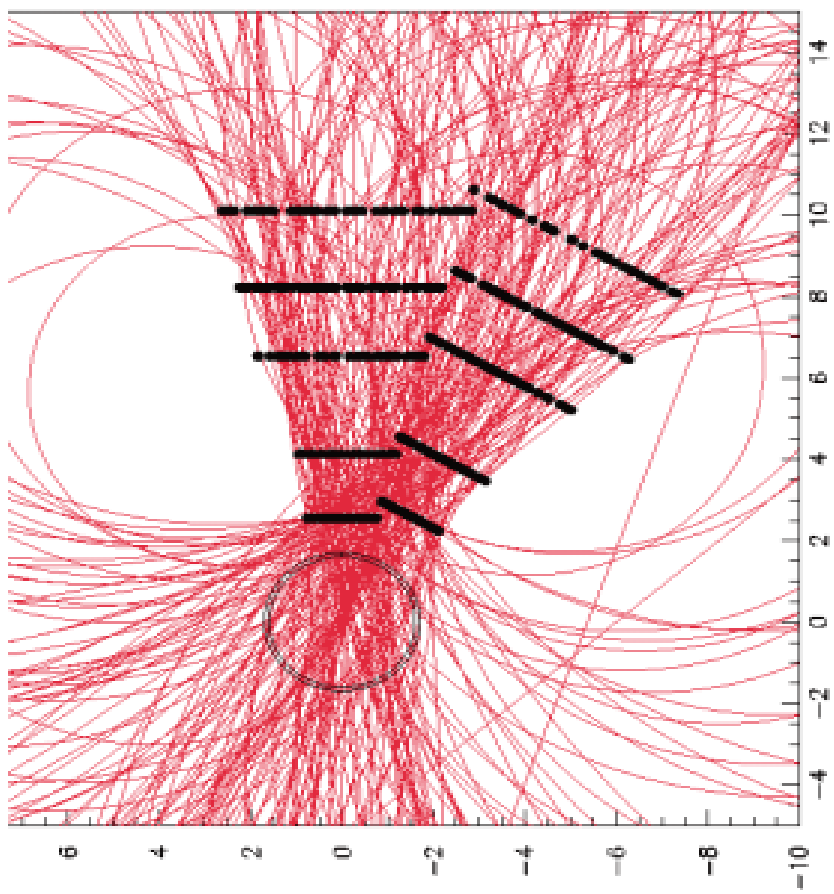
First Collisions

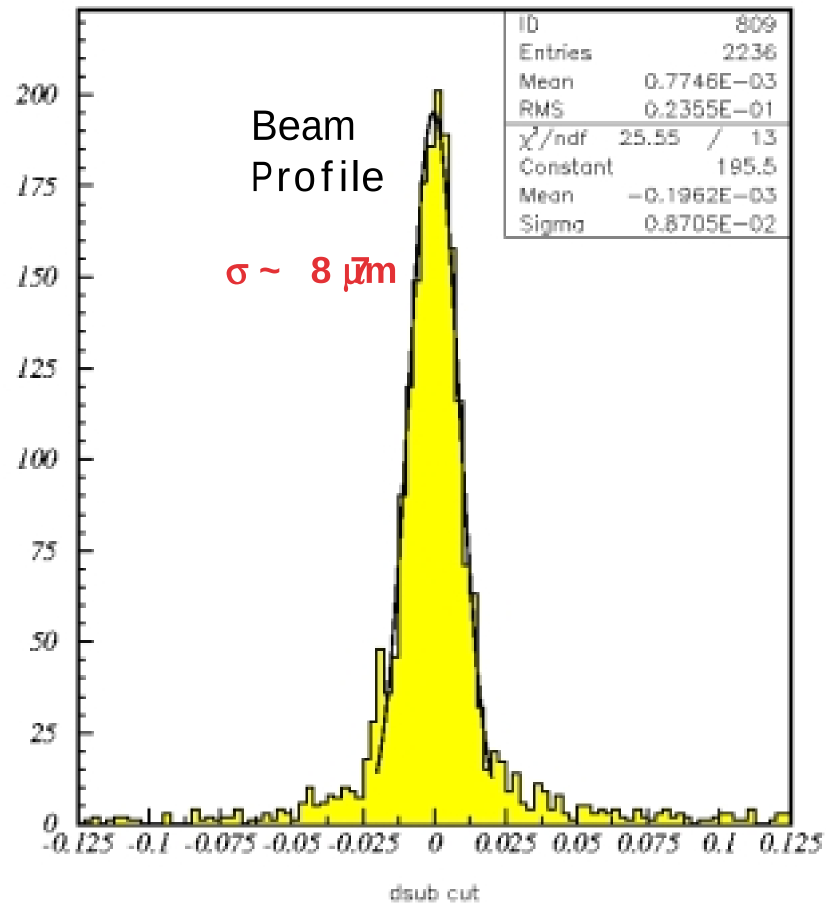


CDF Trigger Scheme



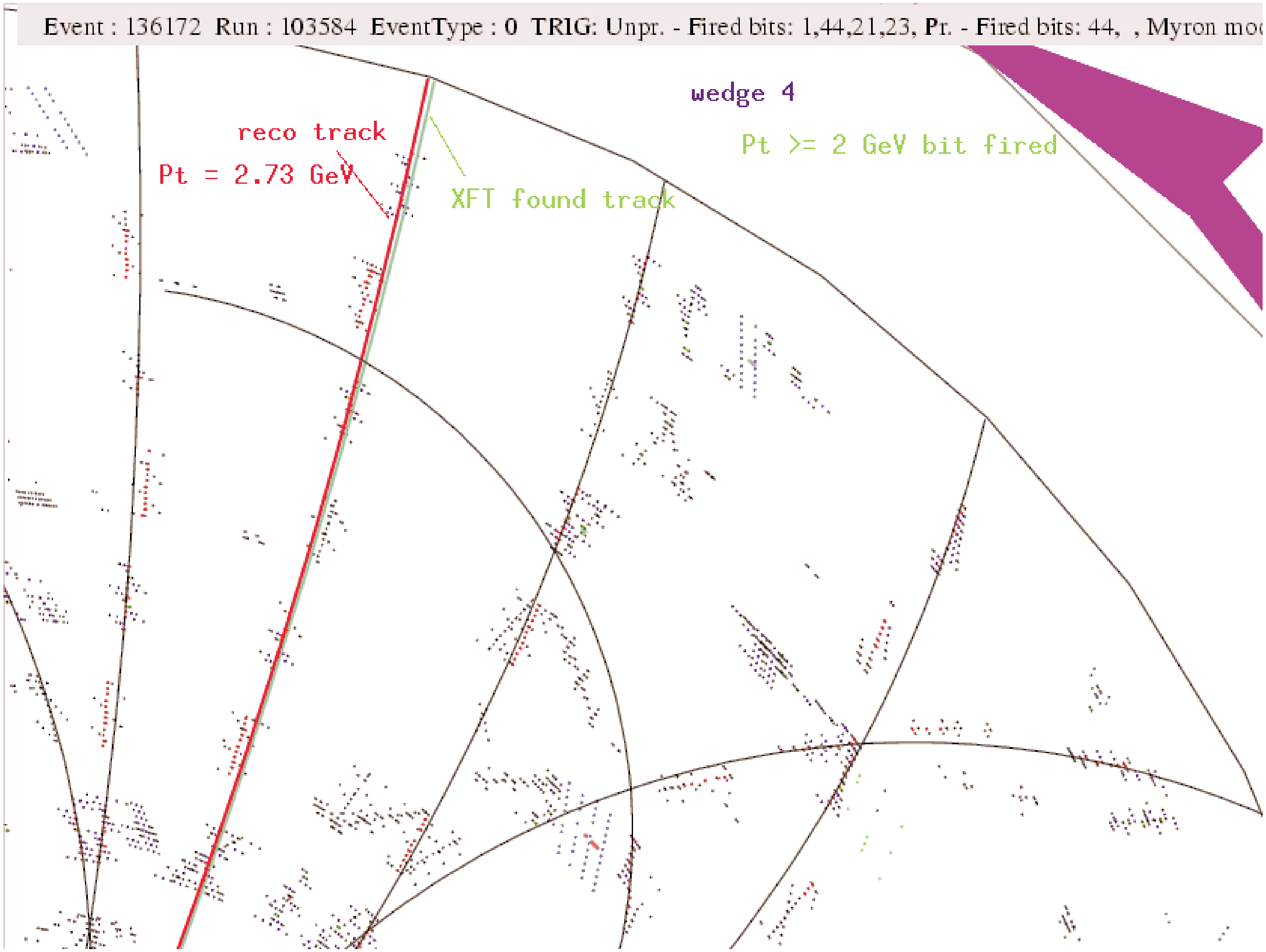
Very First Tests



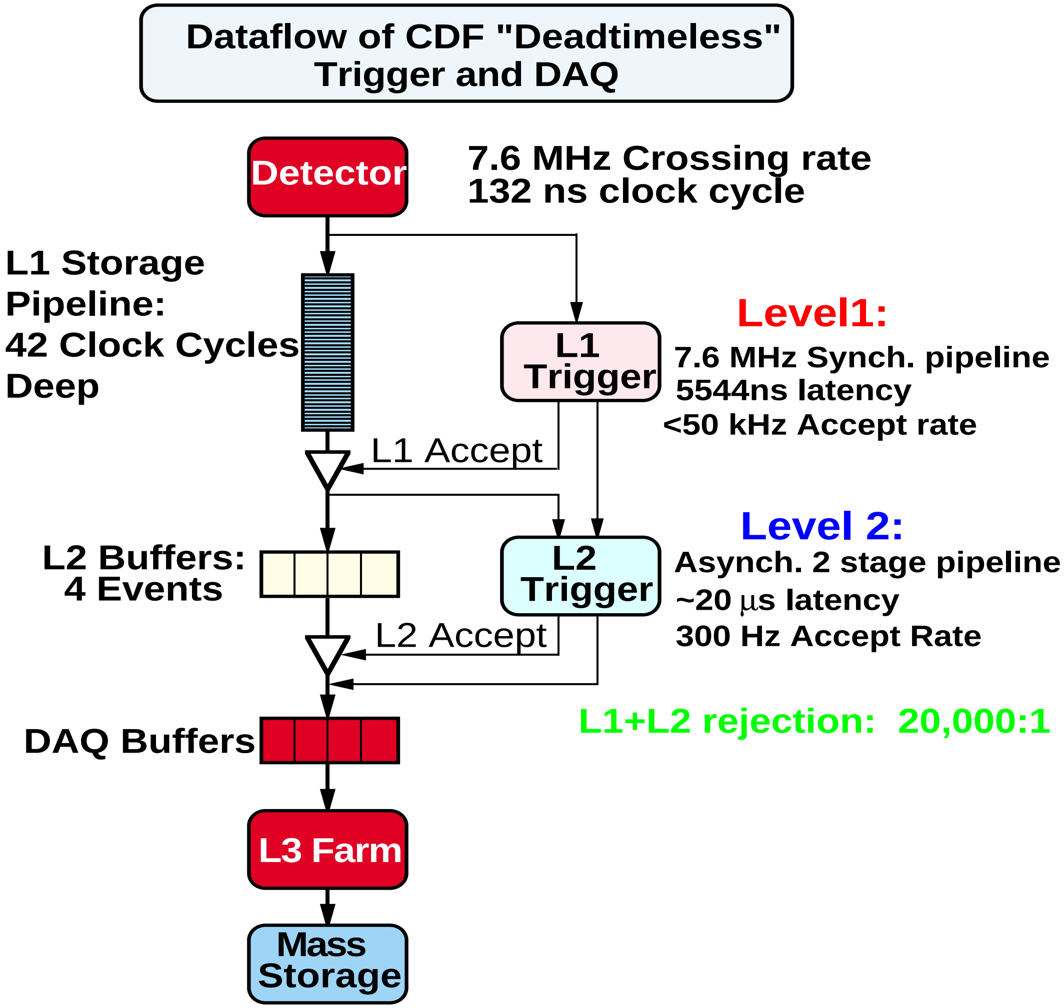


Measured online – with level 2 trigger!

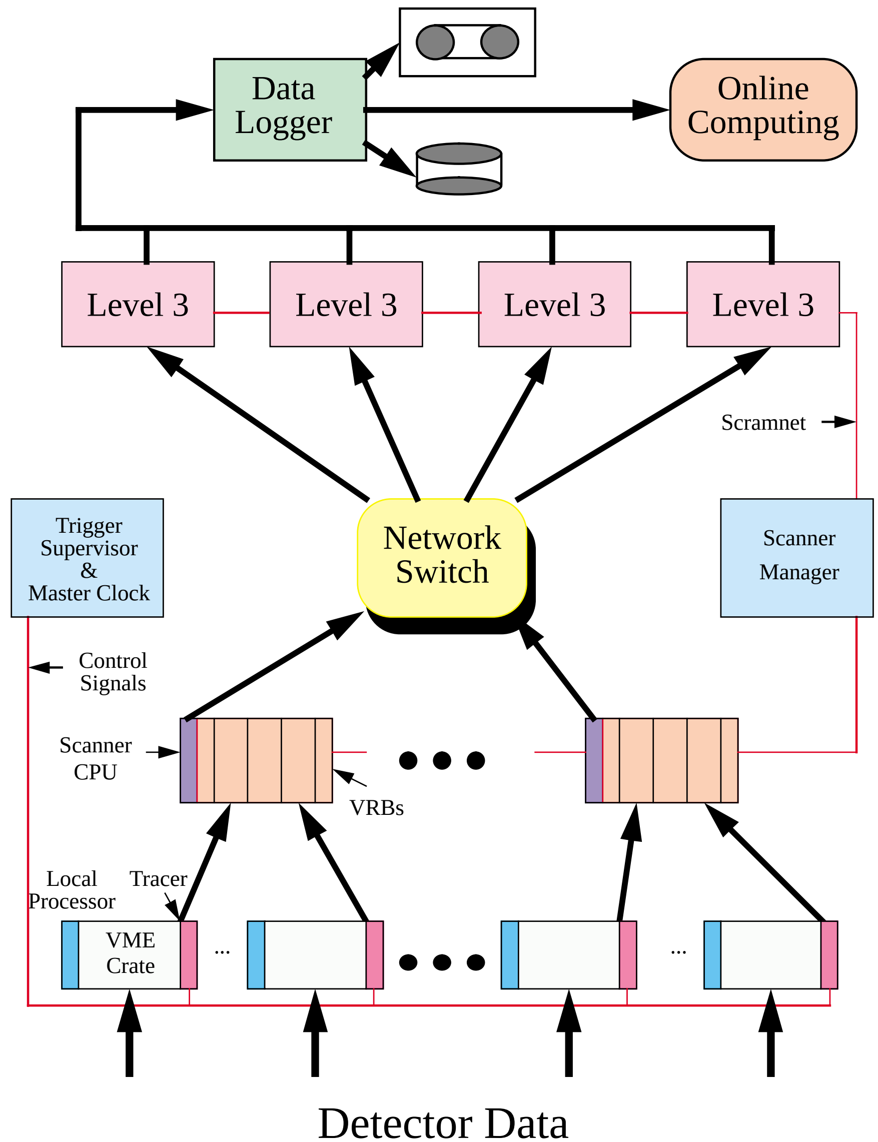
Particle Tracks



CDF Deadtimeless Trigger&DAQ



CDF DAQ

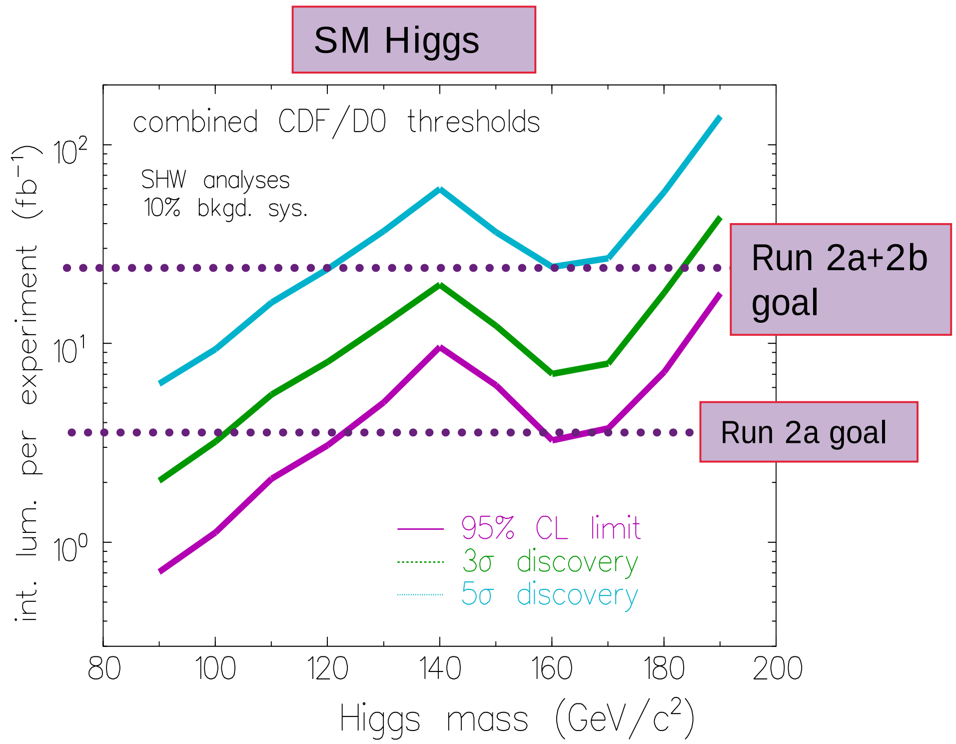


Data Logger
Online Computing
Level 3
Level 3
Level 3
Level 3
Scramnet
Trigger Supervisor & Master Clock
Network Switch
Scanner Manager
Control Signals
Scanner CPU
VRBs
Local Processor
Tracer
VME Crate
...
...
Detector Data

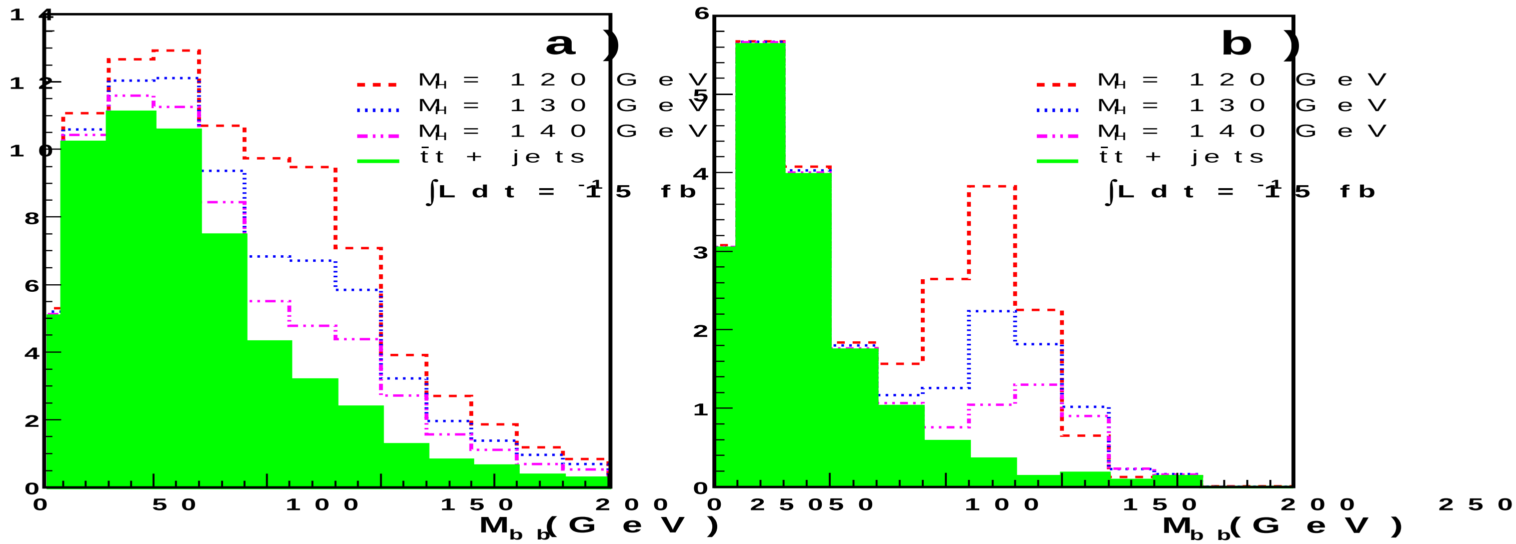
Tevatron Expectations

- SM Higgs: CDF ⊕ DØ
  - Exclude M_H < 180 GeV (10 fb^{-1}/exp)
  - 3σ : M_H < 180 GeV (20 fb^{-1}/exp)
  - 4σ : M_H < 125 and 150 < M_H < 170 GeV

    (20 fb^{-1}/exp)
- SUSY Higgs
  - many of the same channels as SM, enhanced association to b$\underline{b}$ at large tanβ



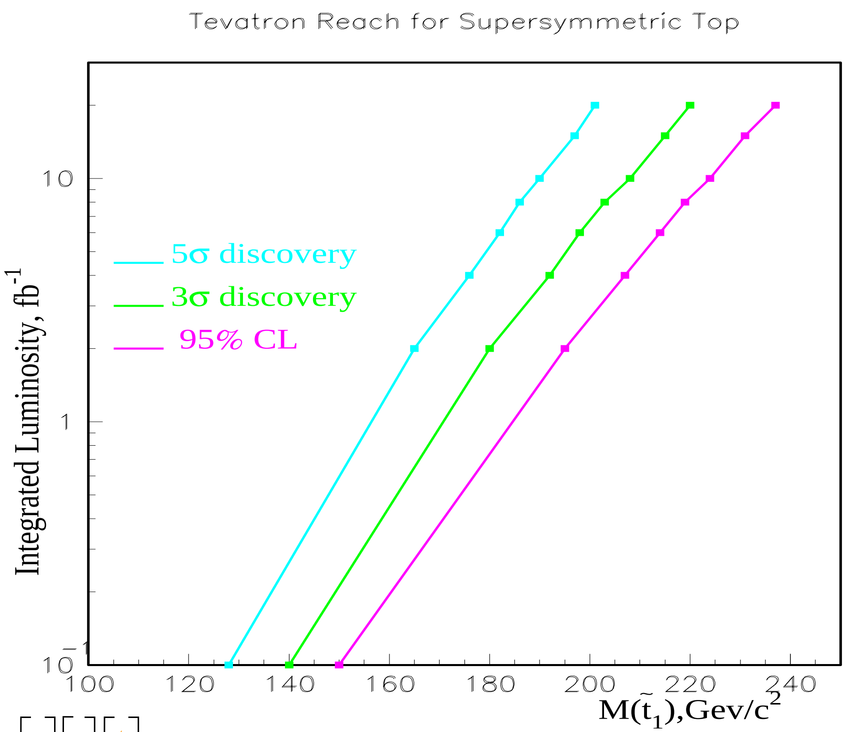
Higgs in Top

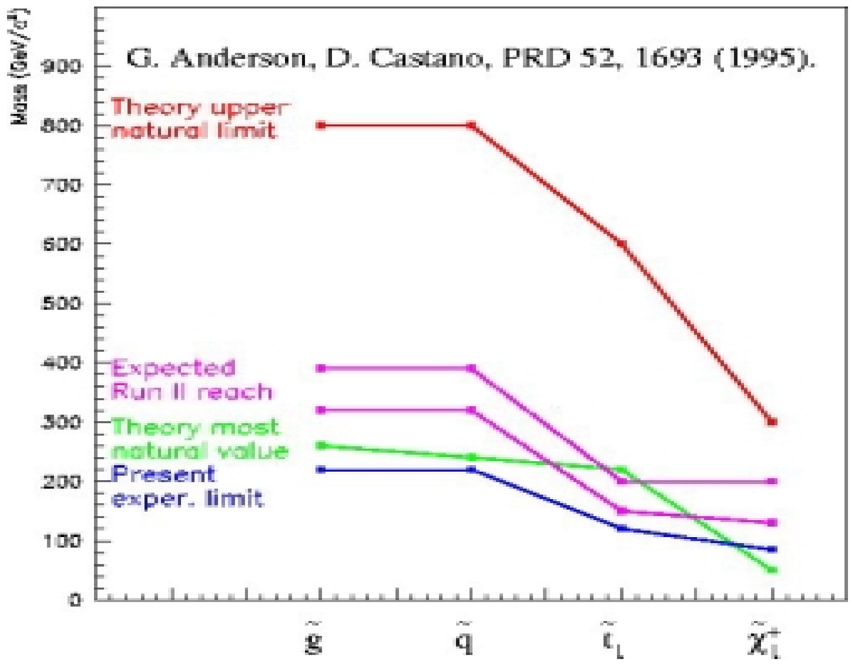


- The main background is from tt+jets.
  - Select events with a lepton, , 3 b tags
- Reconstruct the hadronic top decay.
  - Distribute mass for all remaining jet pairs in which at least one jet is b tagged
    - This elimates most tt+light quark jets.
    - Majority of what remains are the irreducible backgrounds from tt+bb and tt+cc remain.
- Reconstructing both top quarks leaves only one pair of jets. Signal is very clear.

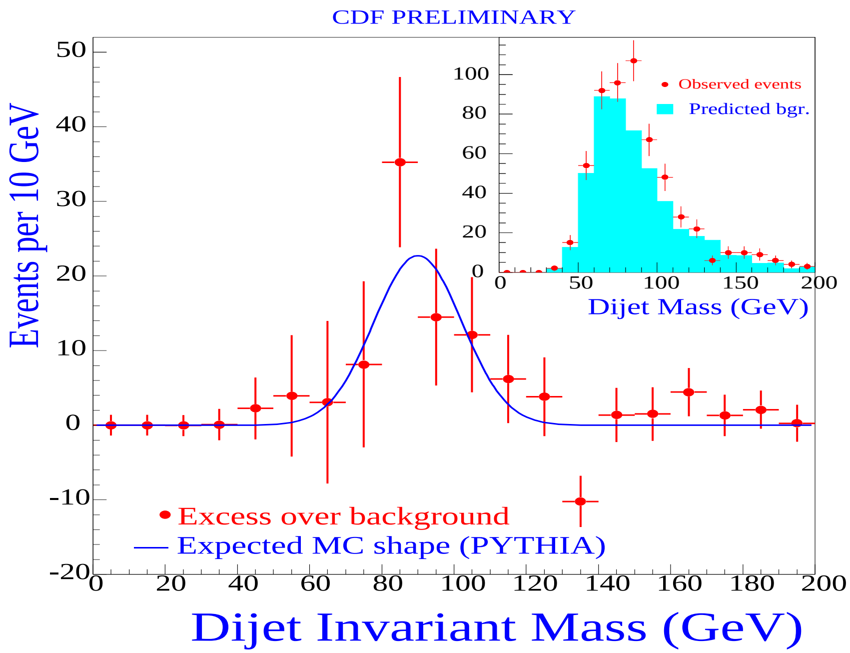
SUSY at the Tevatron

SUSY will really begin to be tested in Run 2!

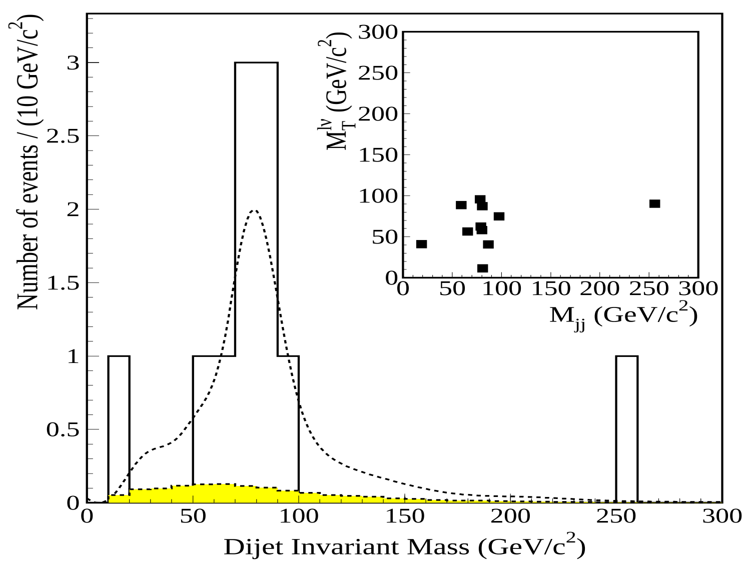




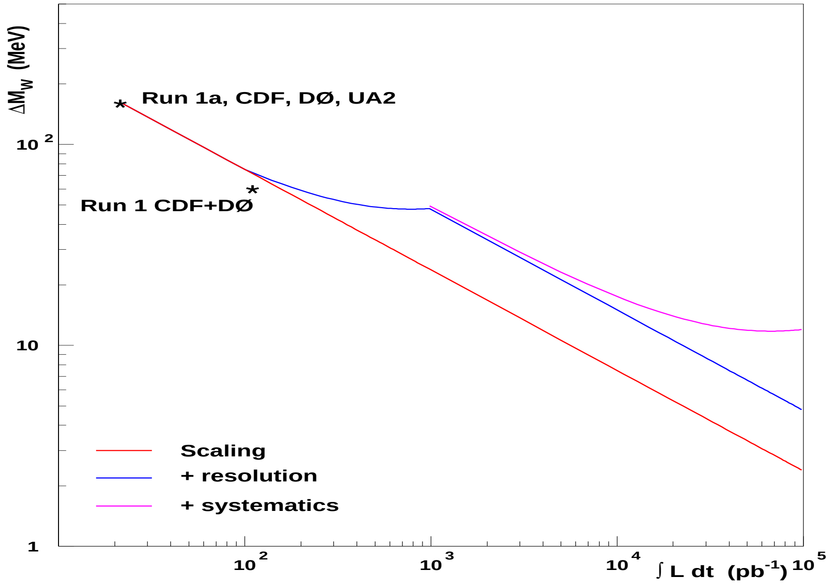
M_t Systematics



Better control of the jet energy scales in top events using samples of Z→ b$\underline{b}$ events and by reconstructing hadronic W decays inside top events themselves.



Pre cis ion EWK in Run 2

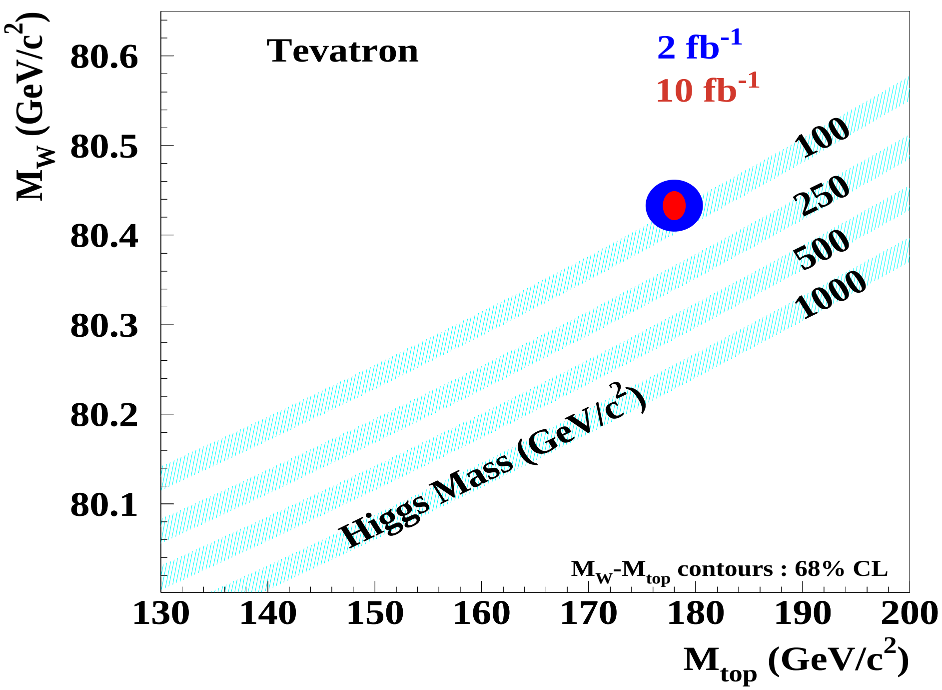


M_W: CDF ⊕ DØ

- σ_M ~ 35 MeV (2 fb^{-1}/)
- σ_M ~ 20 MeV (10 fb^{-1}/)

M_t: CDF or DØ

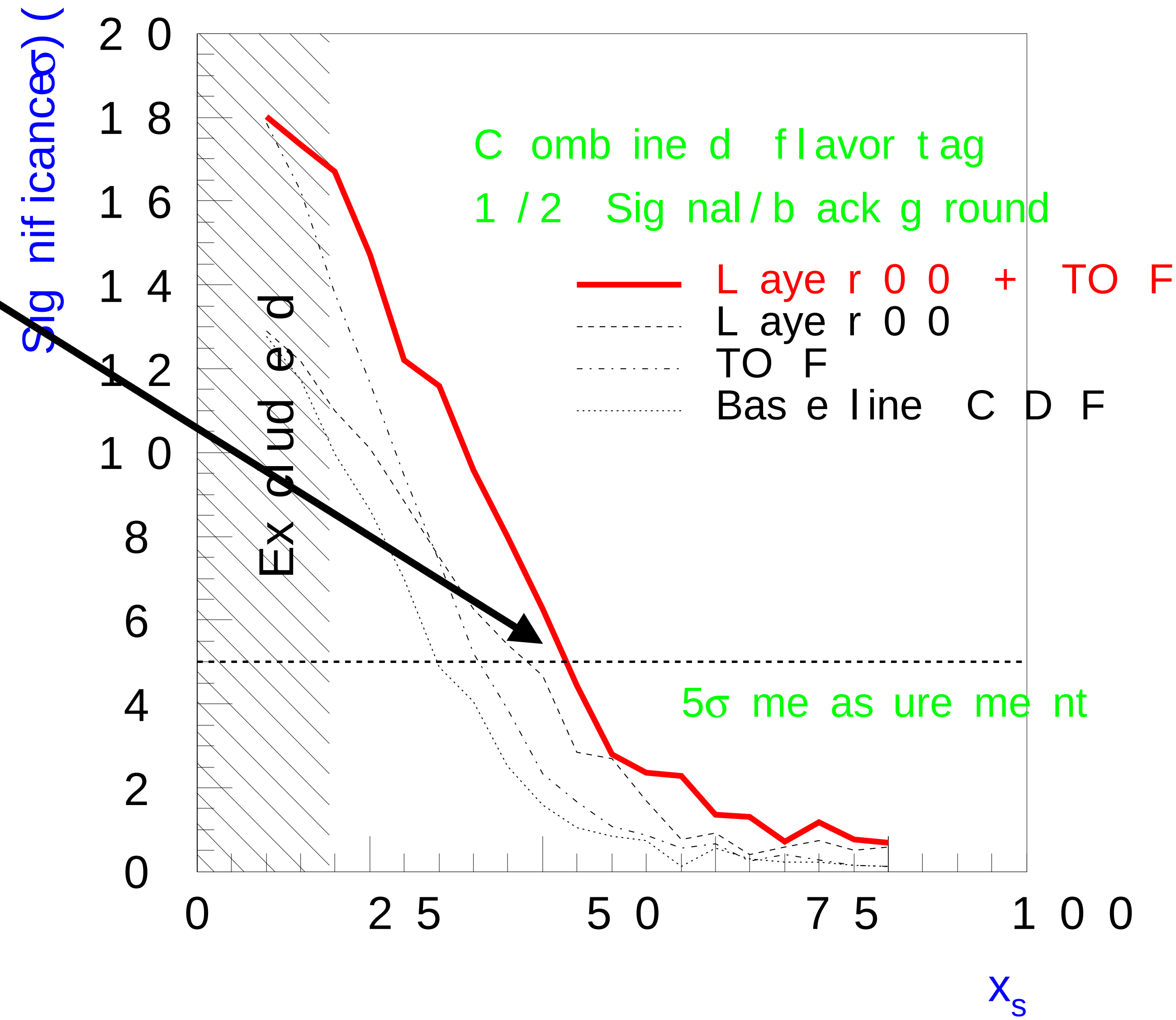
- σ_M < 4 GeV (2 fb^{-1}/)
- σ_M < 2 GeV (10 fb^{-1}/)



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

Tevatron B Physics

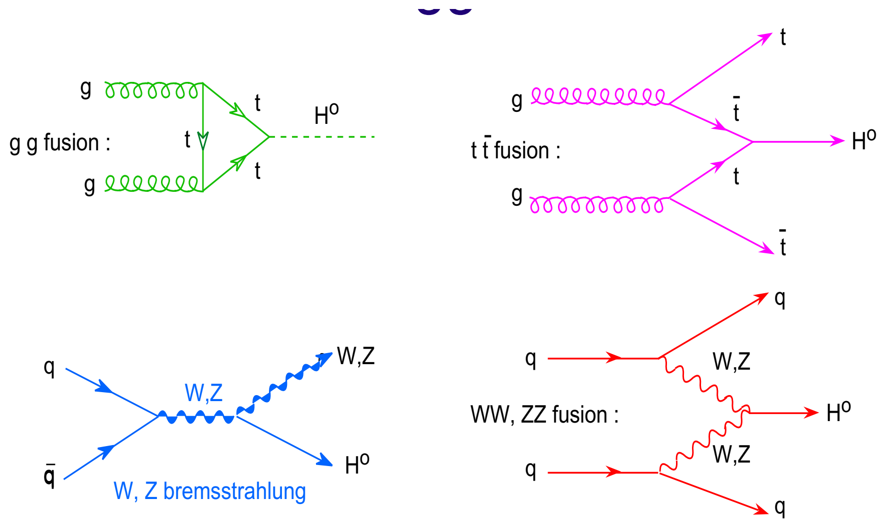
- x_s with very high precision
- Run 1 CDF:
  $\sin 2\beta = 0.8 \pm 0.4$
- Run 2 CDF:
  ± 0.07 (0.02)
  for 2 (15) fb^{-1}
- $\sin 2\alpha$ w/$B \rightarrow \pi\pi$ and γ w/$B \rightarrow DK$

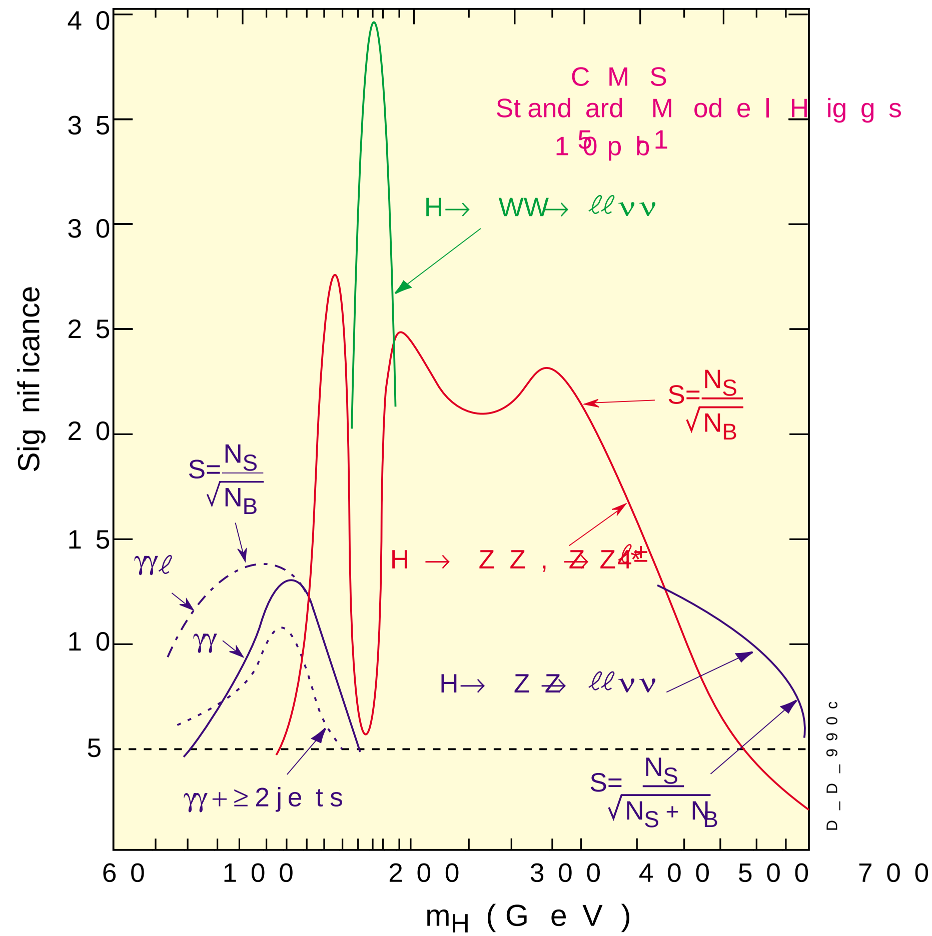


UC SB Program on CDF

- Two – pronged Attack
  1. Physics beyond the standard model (e.g. SUSY) via multiple high energy leptons:
     - Start by developing special lepton identification tools to enable us to extend our sensitive range
     - With initial low-luminosity we'll measure W decay asymmetry:
       - Determines the quark content of the proton which is a major uncertainty in the W mass determination
     - Having developed a high degree of expertise, start searching for new physics as data comes in
  2. Higgs and top physics
     - Start studying tracking and b tagging. In combination with lepton identification, use these tools to study top quark events:
     - With initial low-luminosity we'll begin to study the rate at which additional jets are produced with top quarks:
       - Determines strong coupling at the top mass which is a major source of uncertainty in the top mass determination
       - This is also the main background to top+Higgs
     - Having developed a high degree of expertise, start searching Higgs decaying to b jets in a variety of channels as data comes in.

Higgs at the CERN Large Hadron Co

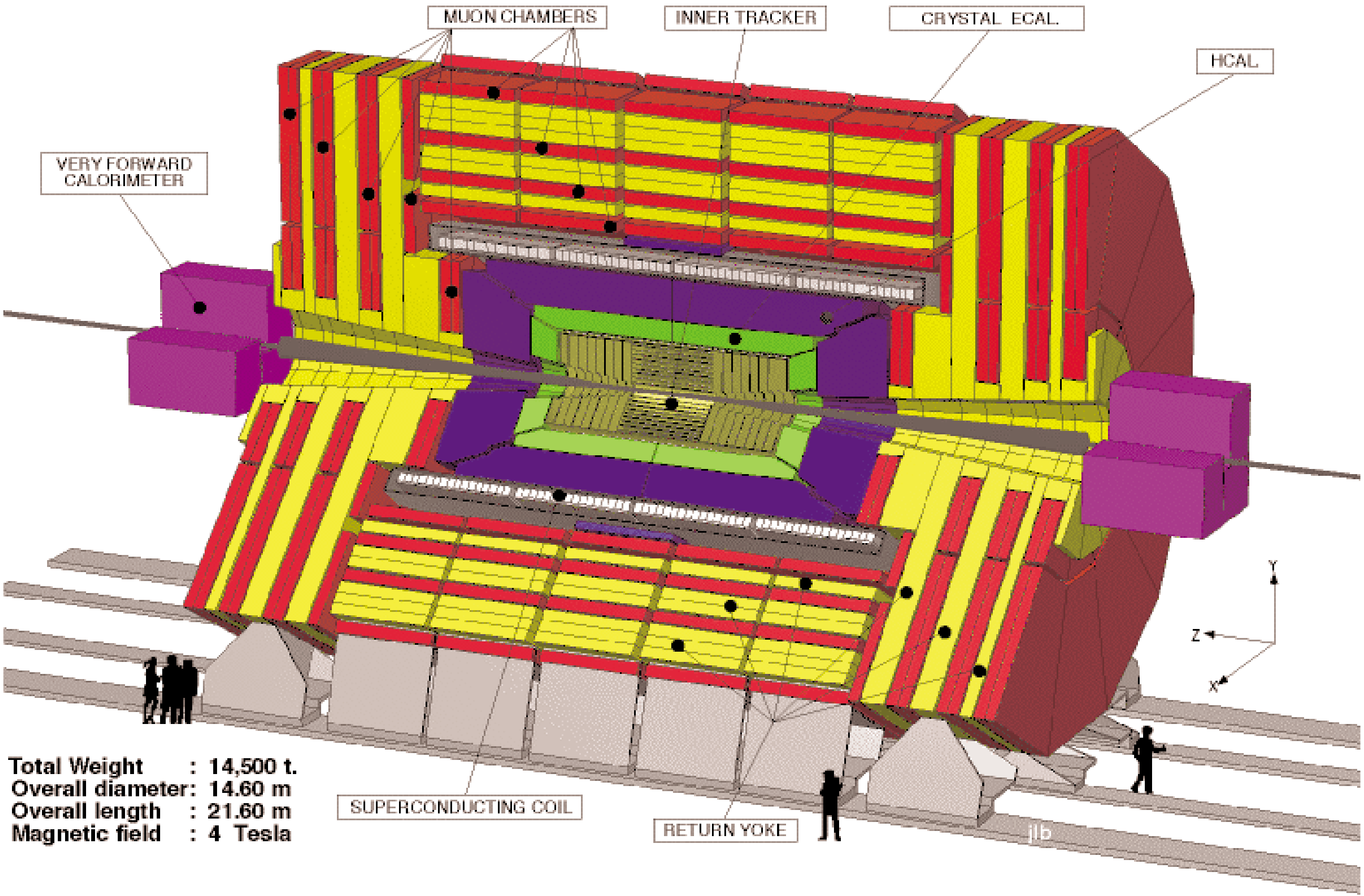




- SM Higgs Search strategies
  - $H \to b\bar{b}$ $\quad 90 \leq m_H \leq 120$ GeV/c^2
  - $H \to \gamma\gamma$ $\quad 100 \leq m_H \leq 140$ GeV/c^2
  - $H \to ZZ^* \to 4l^\pm$ $\quad 130 \leq m_H \leq 200$ GeV/c^2
  - $H \to WW \to l\nu l\nu$ $\quad 140 \leq m_H \leq 200$ GeV/c^2
  - $H \to ZZ \to 4l^\pm$ $\quad 200 \leq m_H \leq 750$ GeV/c^2

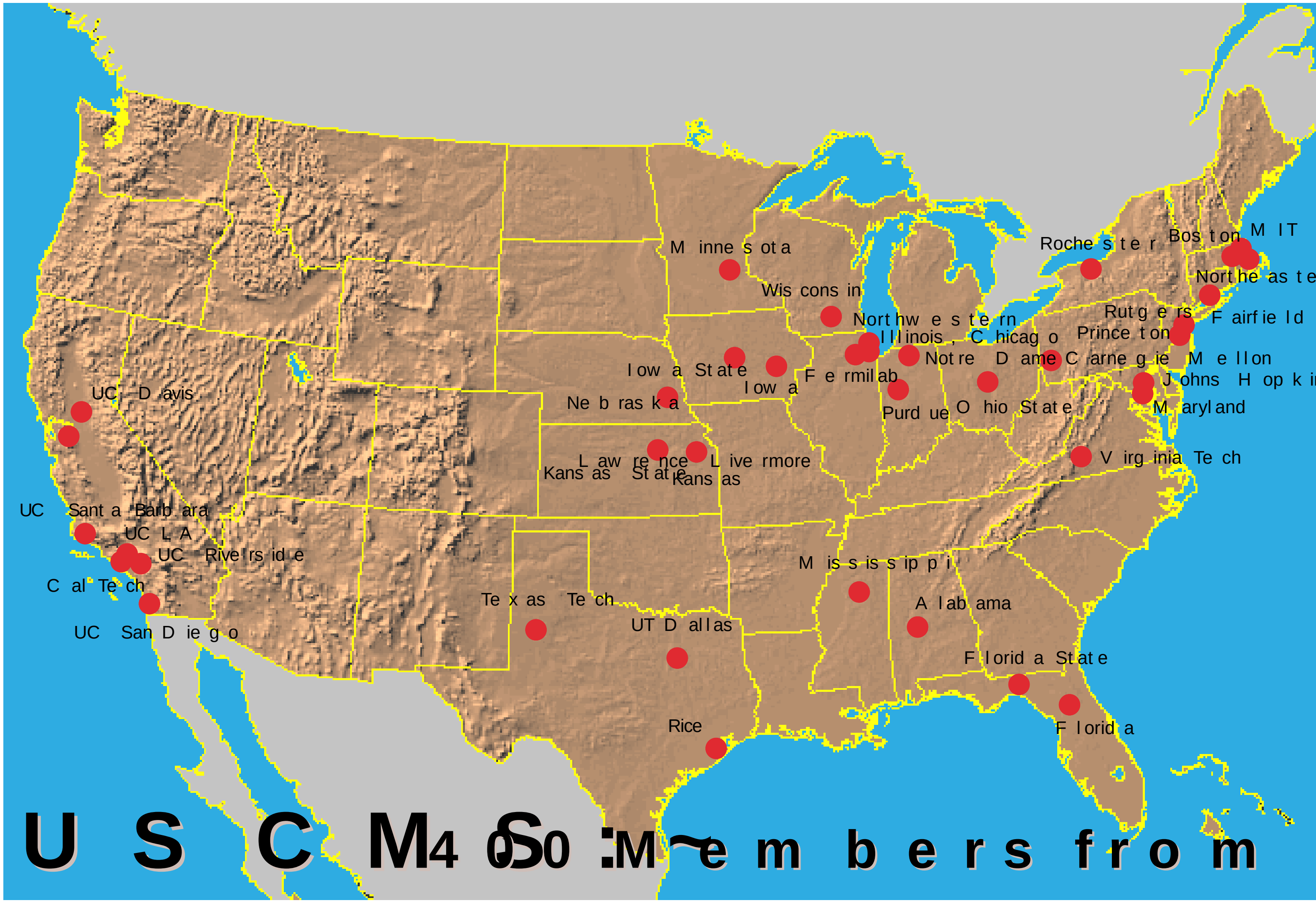
C M S Ex p e rime nt at C ERN

Campagnari & Incandela



Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

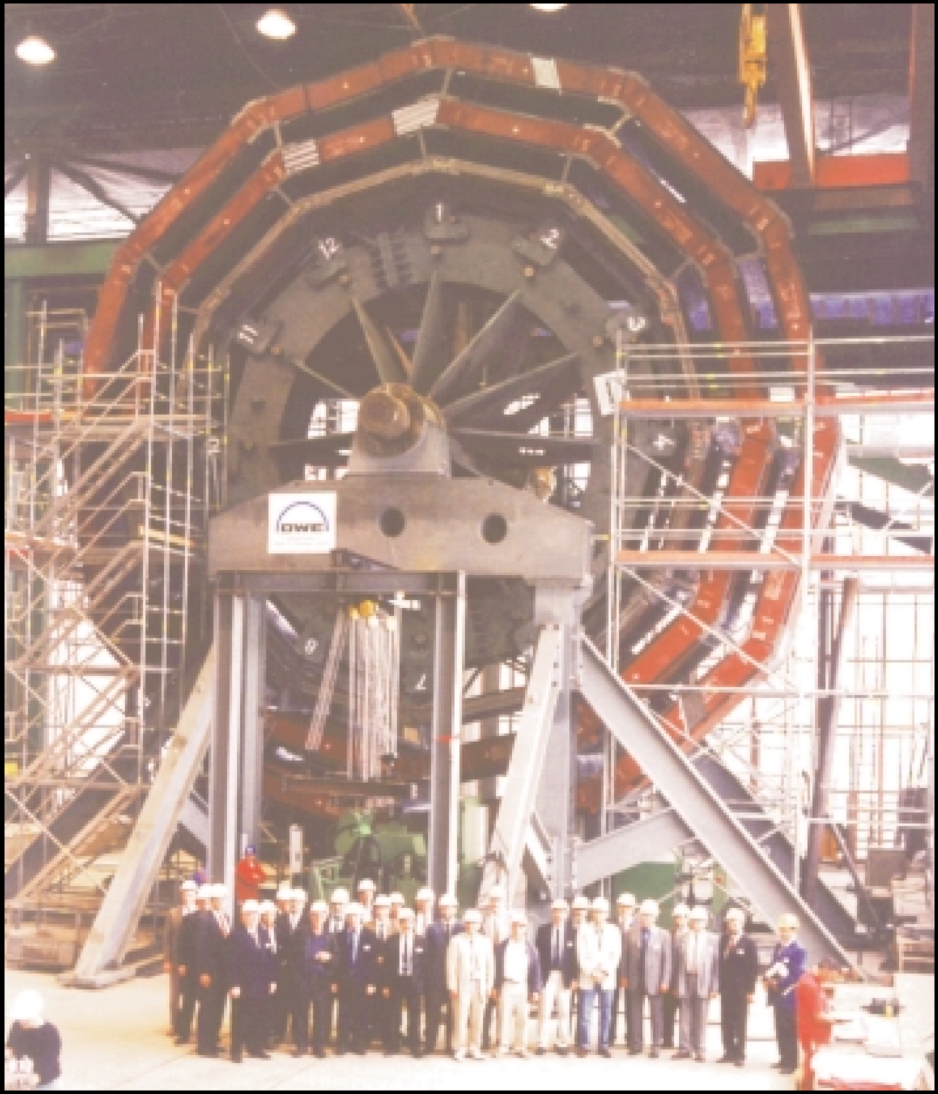
~2000 scientists from 31 cou

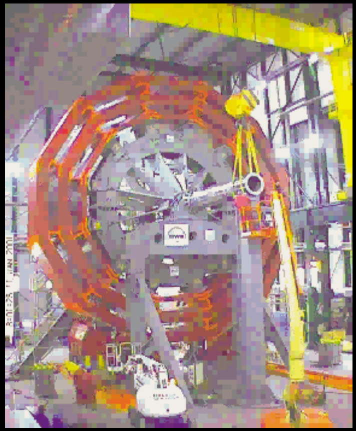


November 10, 2000

High Energy Physics

Construction is underway

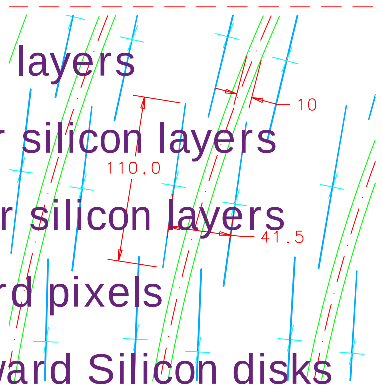


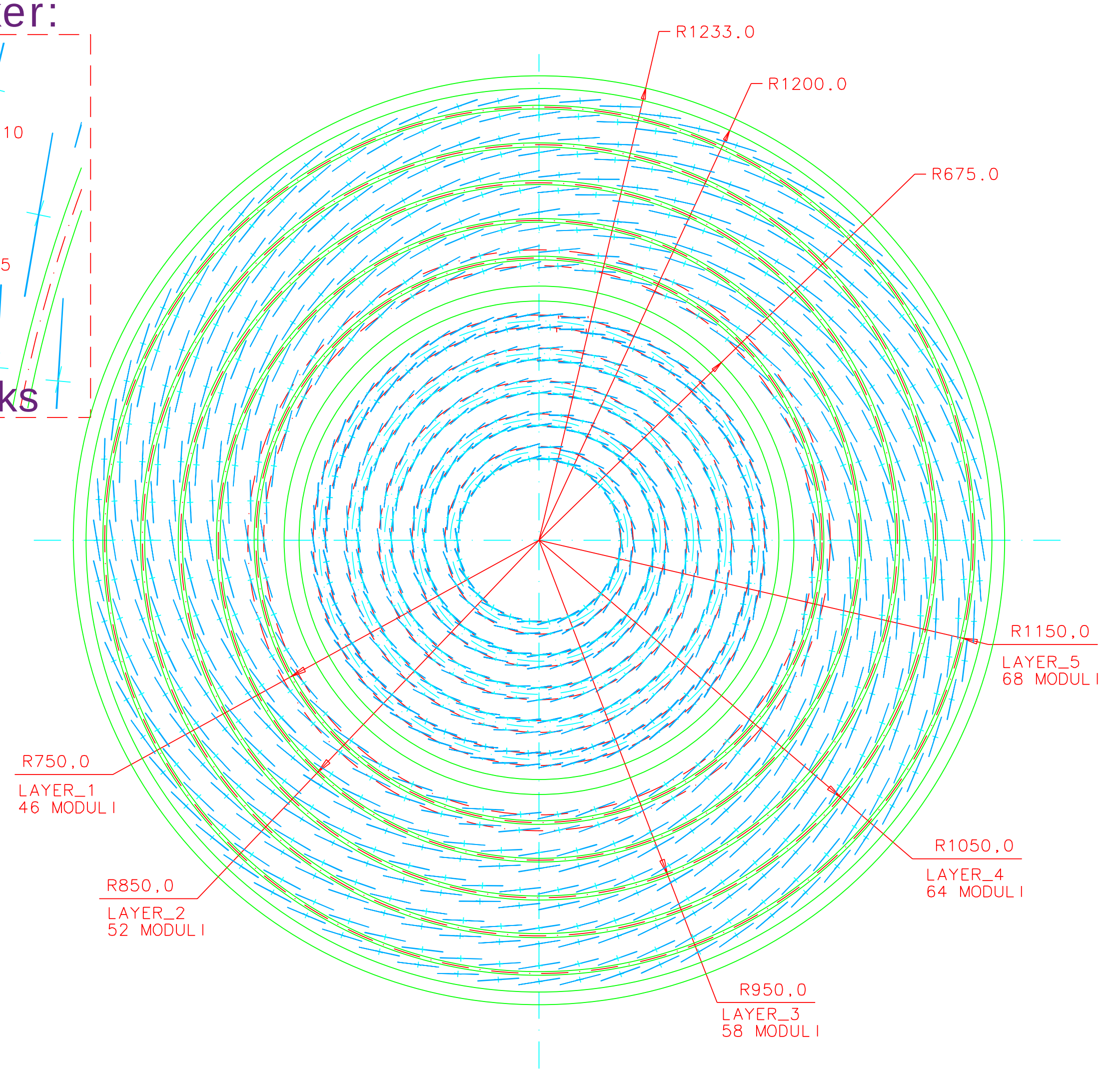


All Silicon Tracker

The CMS Silicon Tracker:

- 2 pixel layers
- 4 inner silicon layers
- 6 outer silicon layers
- Forward pixels
- 9 Forward Silicon disks

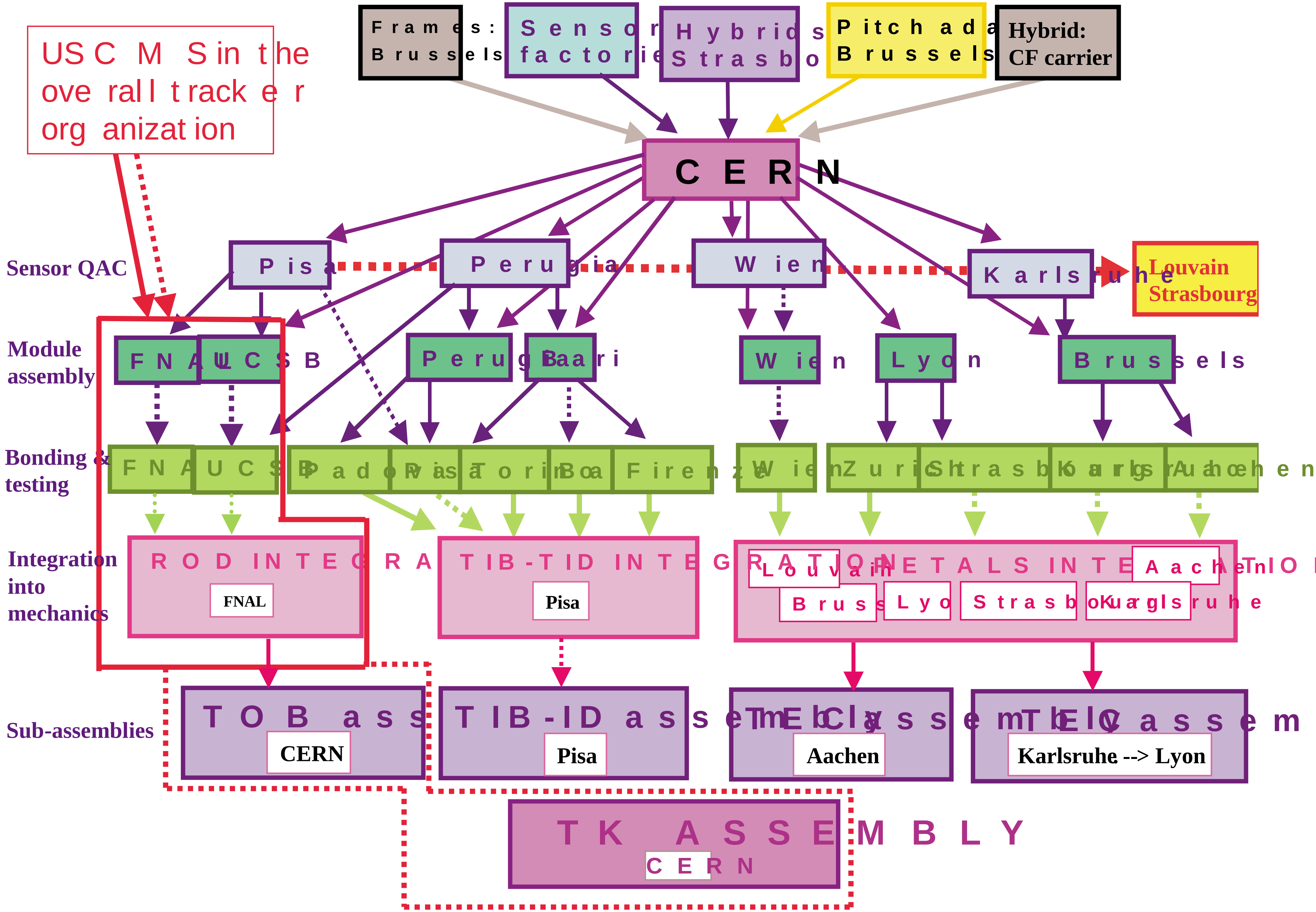




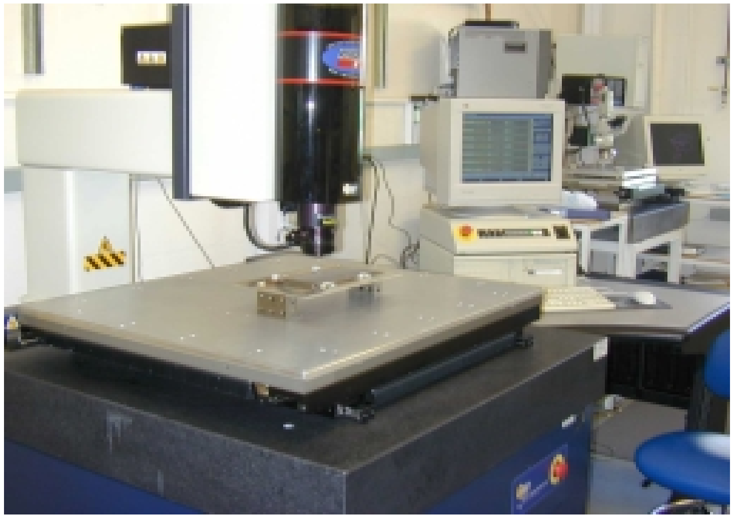
Total of 230 m^2 of Silicon microstrips

Of this ~110 m^2 will be built by US CMS.

UCSB will build 30-50 m^2

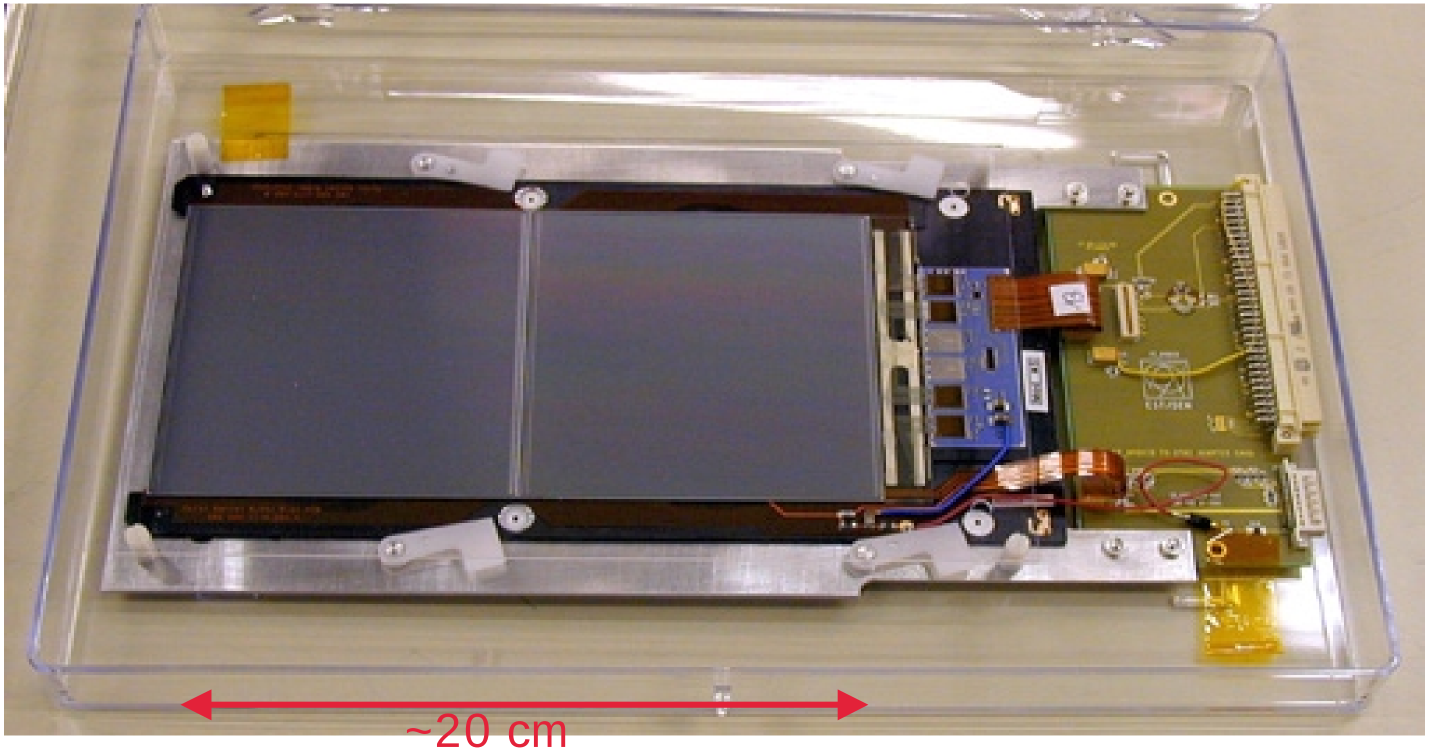

US CMS in the overall tracker organization
Frames: Brussels
Sensor factories
Hybrids Strasbourg
Pitch adapter Brussels
Hybrid: CF carrier
CERN
Sensor QAC
Pisa
Perugia
Wien
Karlsruhe
Louvain
Strasbourg
Module assembly
FNAL
UCSB
Perugia
Bari
Wien
Lyon
Brussels
Bonding & testing
FNAL
UCSB
Padova
Pisa
Torino
Bari
Firenze
Wien
Zurich
Strasbourg
Karlsruhe
Aachen
Integration into mechanics
ROD INTEGRATION
FNAL
TIB-TID INTEGRATION
Pisa
PETALS INTEGRATION
Louvain
Aachen
Brussels
Lyon
Strasbourg
Karlsruhe
Sub-assemblies
TOB assembly
CERN
TIB-ID assembly
Pisa
TEC assembly
Aachen
TEC assembly
Karlsruhe --> Lyon
TK ASSEMBLY
CERN

UCSB Production line



- **Significant progress.**
  - **Clean room expanded.**
  - **K&S 8090 wirebonder up and running, practicing on Babar modules.**
  - **OGP functioning – for automated mechanical inspection of modules.**
  - **Gantry arrived in March, now being setup.**
- **New groups (UCR, and TTU) will support production line at UCSB.**

Our Job

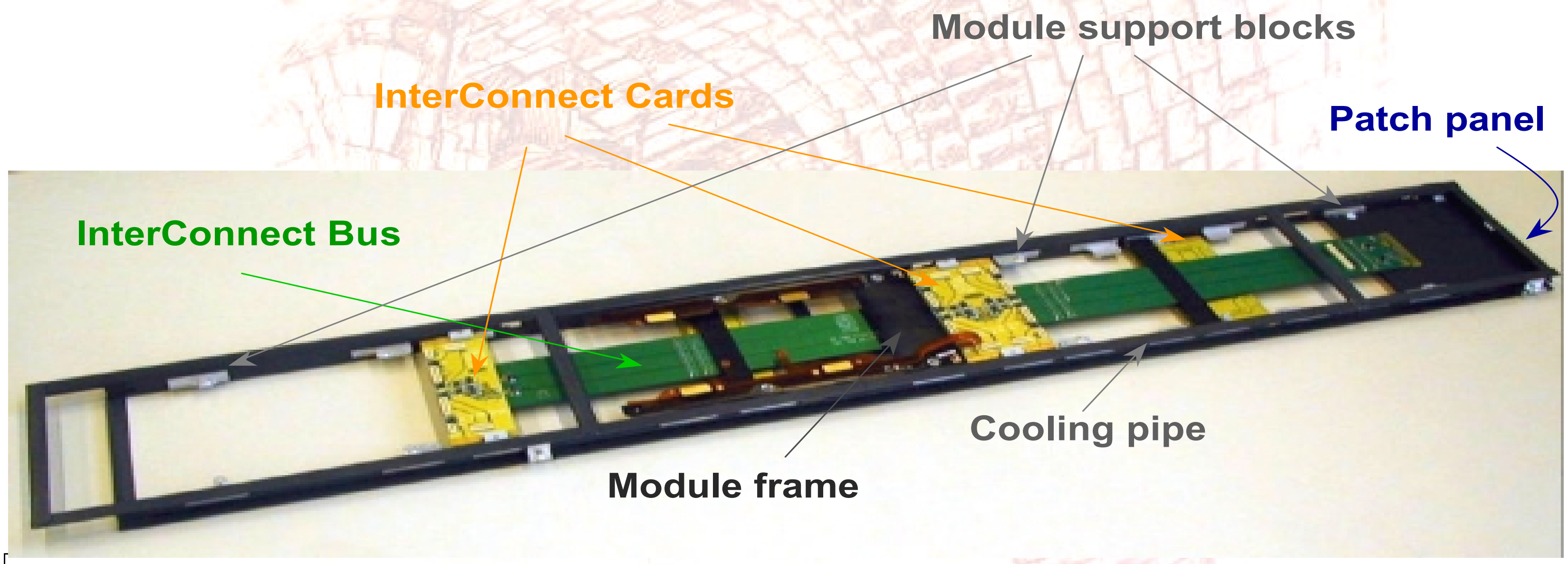


~6,000 Tracker Outer Barrel (TOB) modules

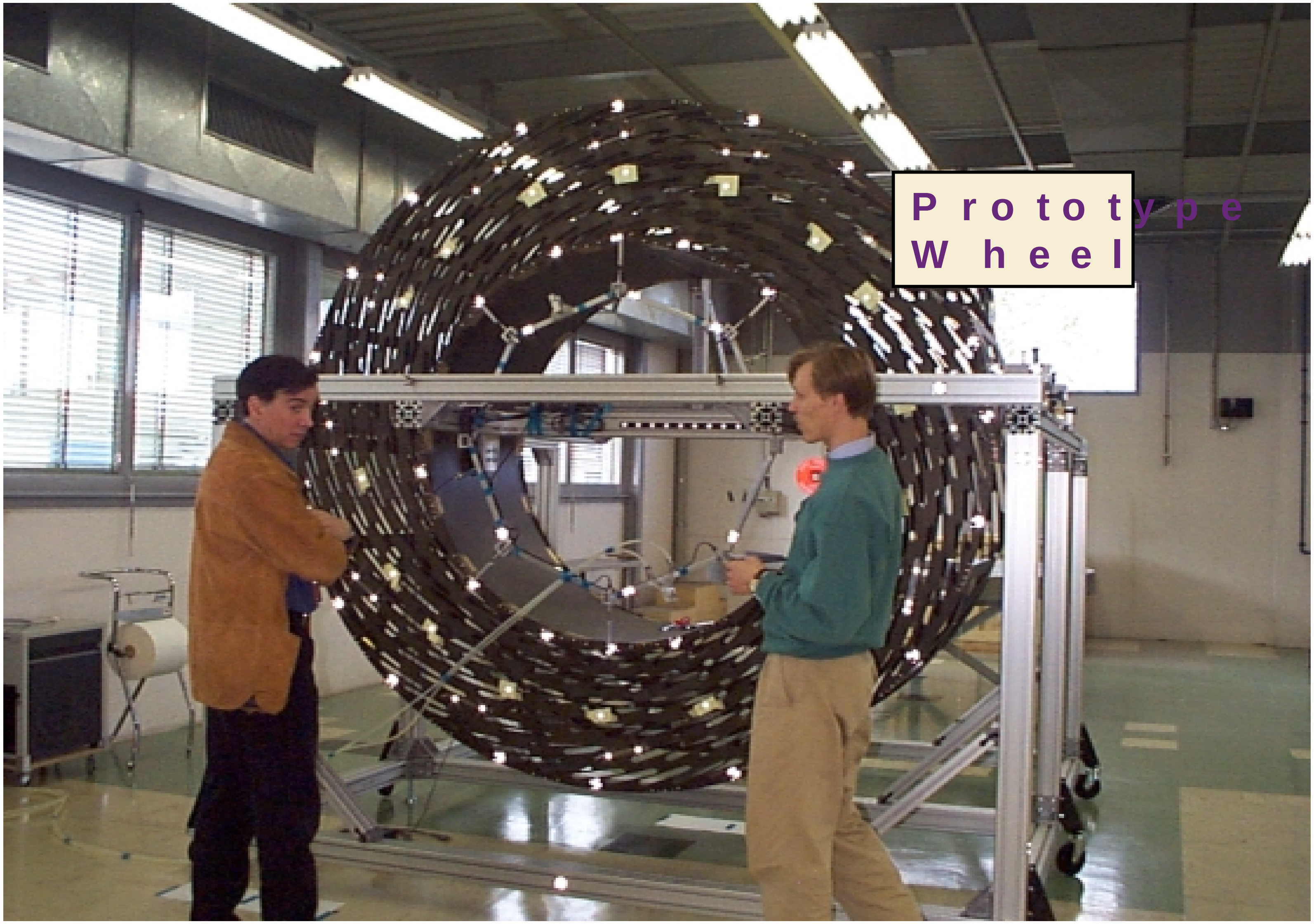
Current plan 2/3:1/3 constructed at FNAL:UCSB

Rod s

- 6 (12) Modules per single (double) sided rod
- Preliminary tests complete
  - Interconnect bus and cards tested with 1 hybrid and 1 opto-hybrid
    - **Nice results: Signals are extremely clean**
    - **Conclusive test requires full load (12 hybrids and opto-hybrids) planned for later this Spring**



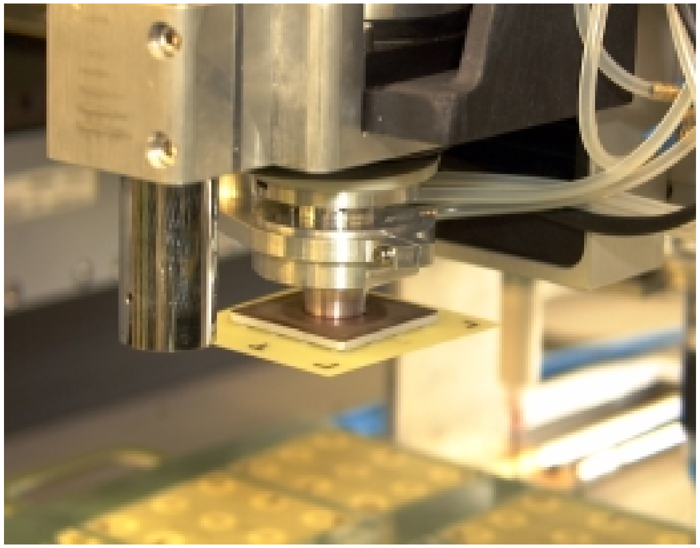
Support Structure for Rods

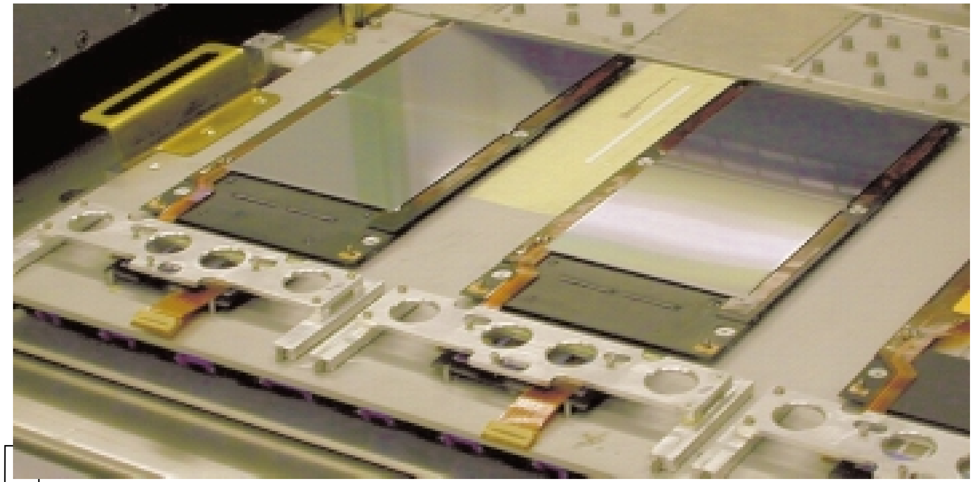


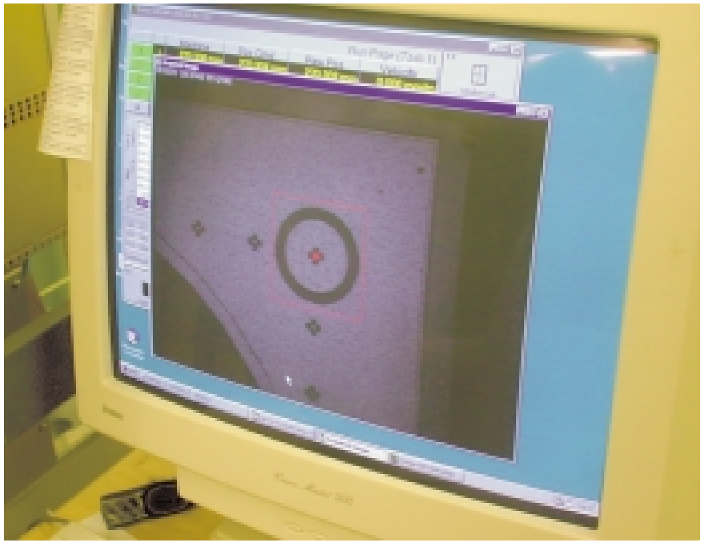
Automation

Special robot - GANTRY - was developed for assembling CMS Silicon tracker components.

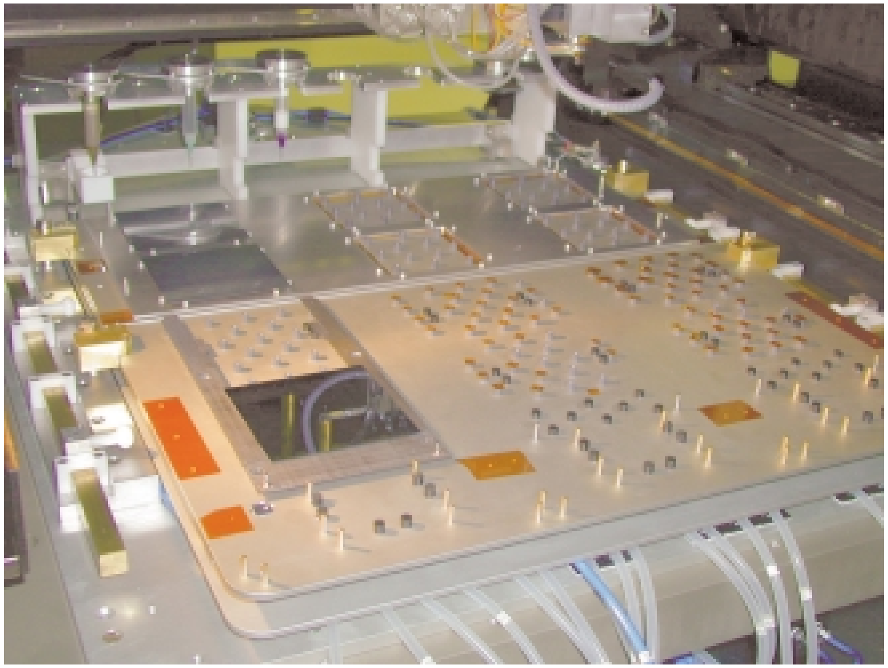
Positioning accuracy $\pm 1.6\ \mu m$
Production time 10 min/module

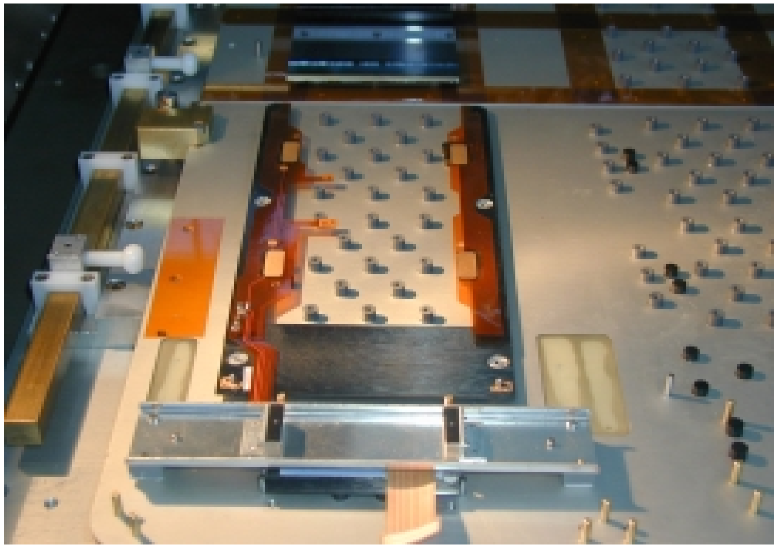






F NA L Rob ot

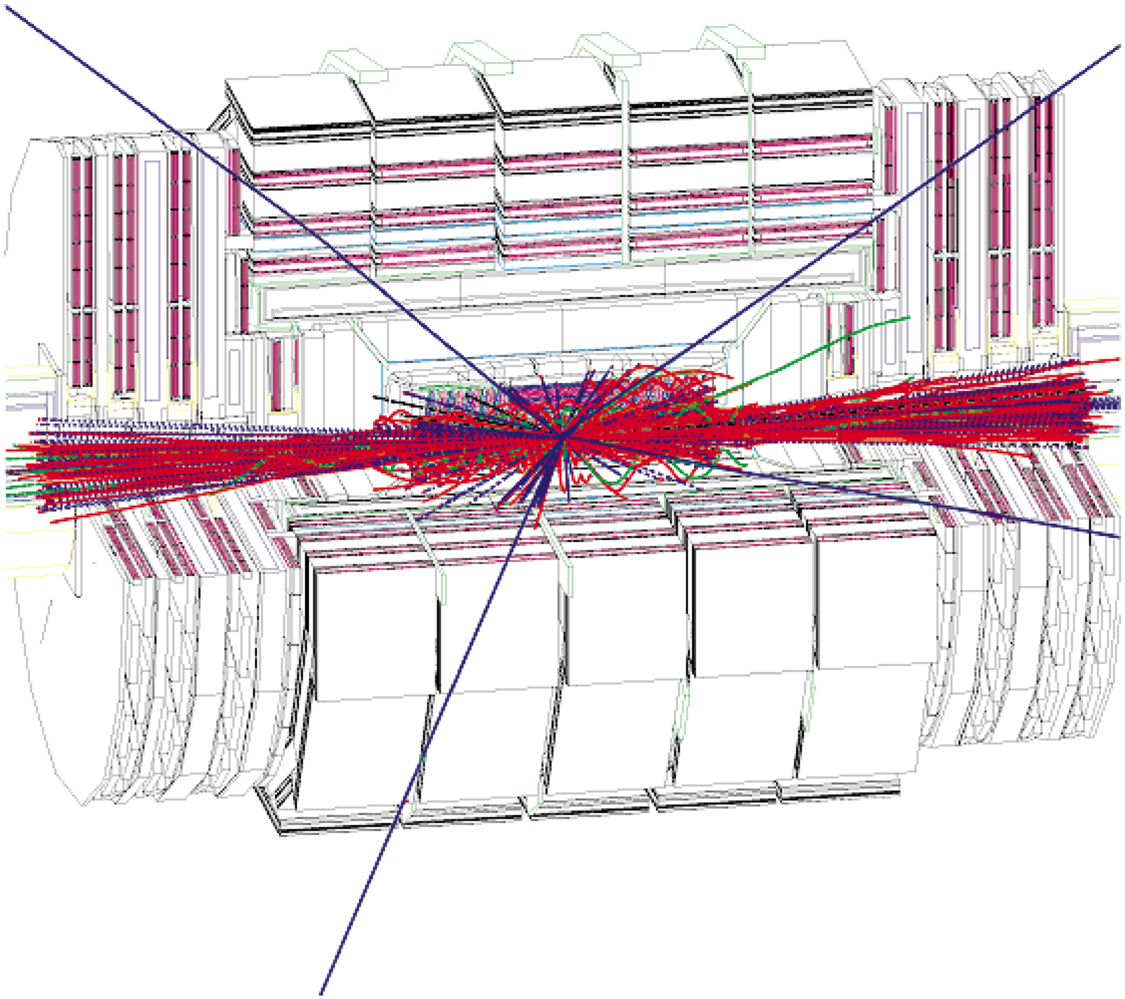




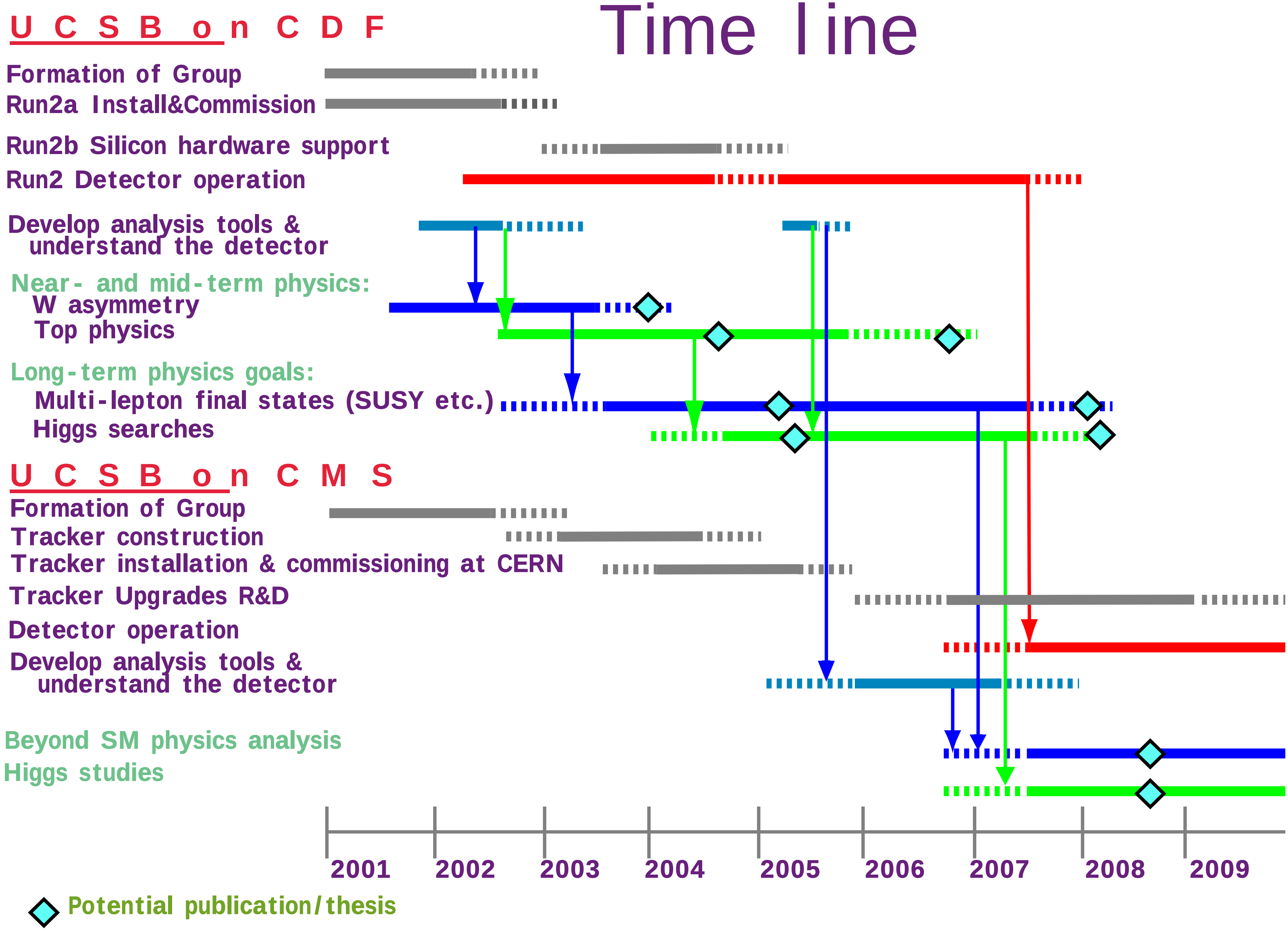
- **FNAL pick and place gantry for automated module assembly**
  - **Made 10 pre-series TOB modules (for May test beam studies)**

C M S Event

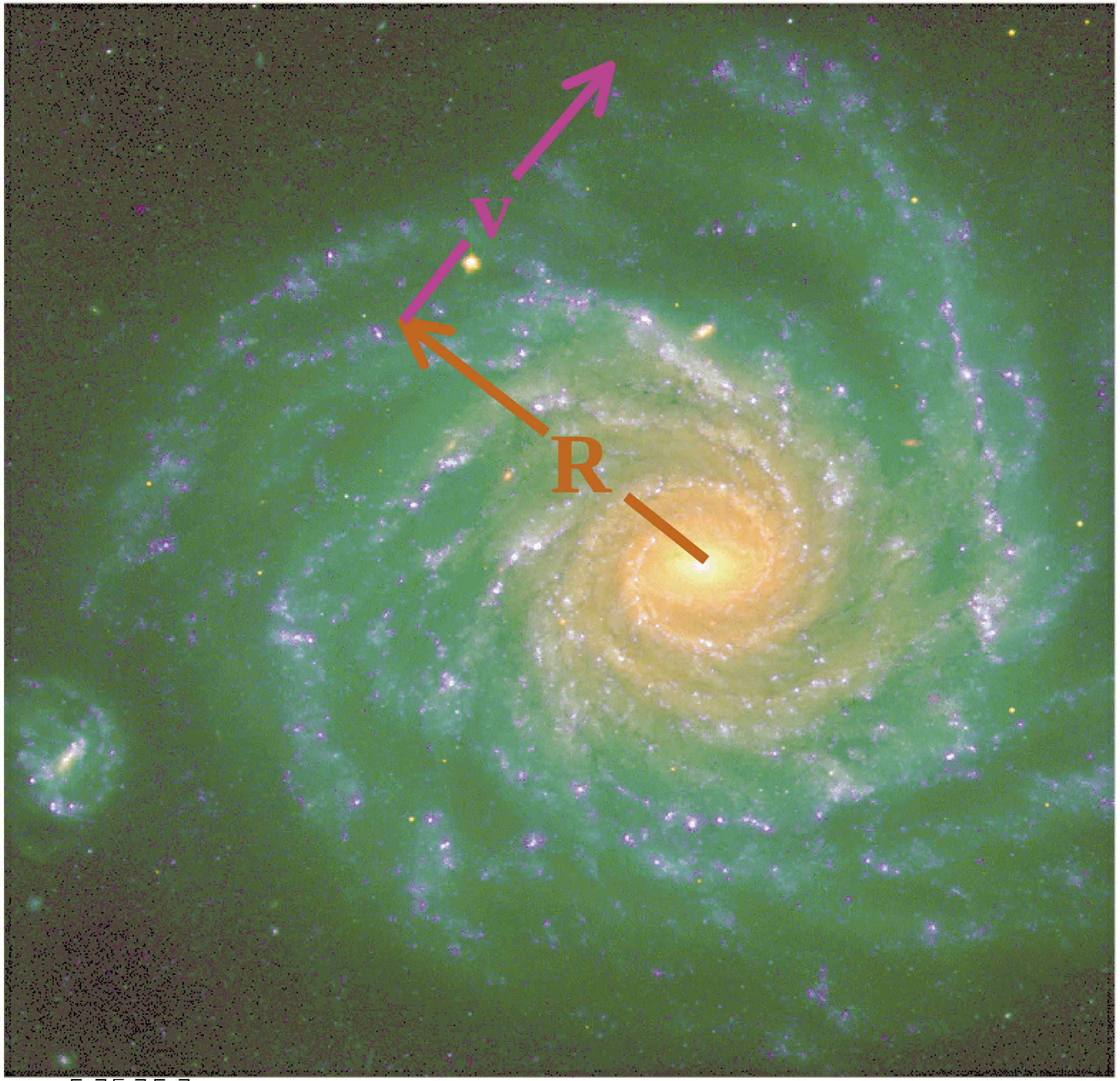
H (150 GeV) → $Z^o Z^{o*}$ → 4μ

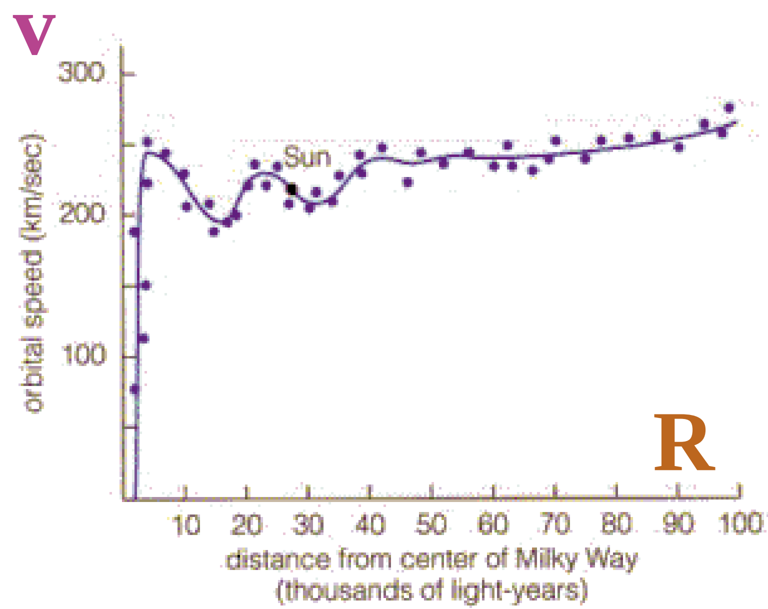


Time line


UCSB on CDF
Formation of Group
Run2a Install&Commission
Run2b Silicon hardware support
Run2 Detector operation
Develop analysis tools & understand the detector
Near- and mid-term physics:
W asymmetry
Top physics
Long-term physics goals:
Multi-lepton final states (SUSY etc.)
Higgs searches
UCSB on CMS
Formation of Group
Tracker construction
Tracker installation & commissioning at CERN
Tracker Upgrades R&D
Detector operation
Develop analysis tools & understand the detector
Beyond SM physics analysis
Higgs studies
2001
2002
2003
2004
2005
2006
2007
2008
2009
Potential publication/thesis

The Milky Way has Dark Matte

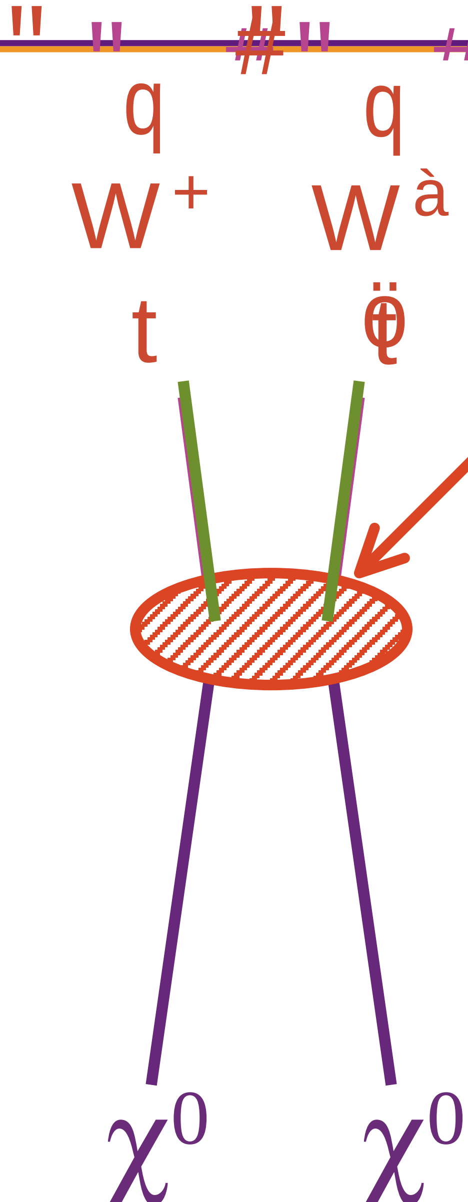




χ^0

Heavy neutral Particle

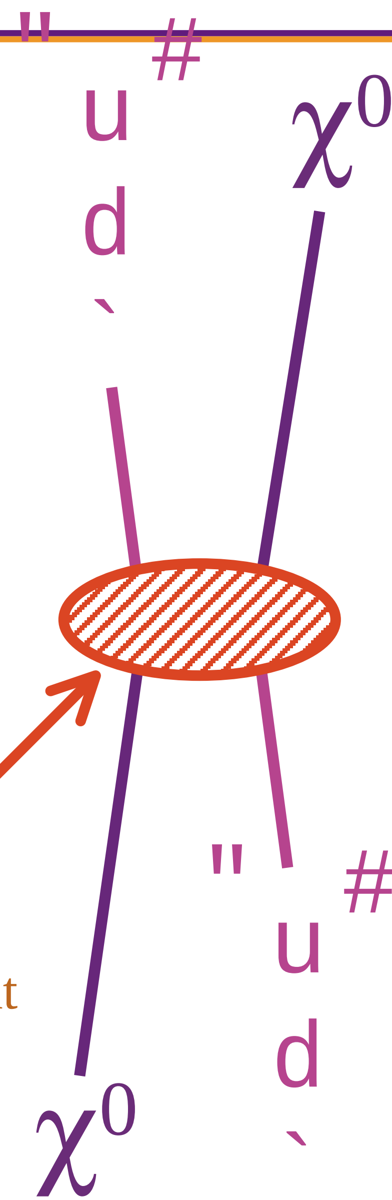
Does the χ^0 have weak interactions?



Weak coupling just right to explain the ratio of dark to baryonic matter

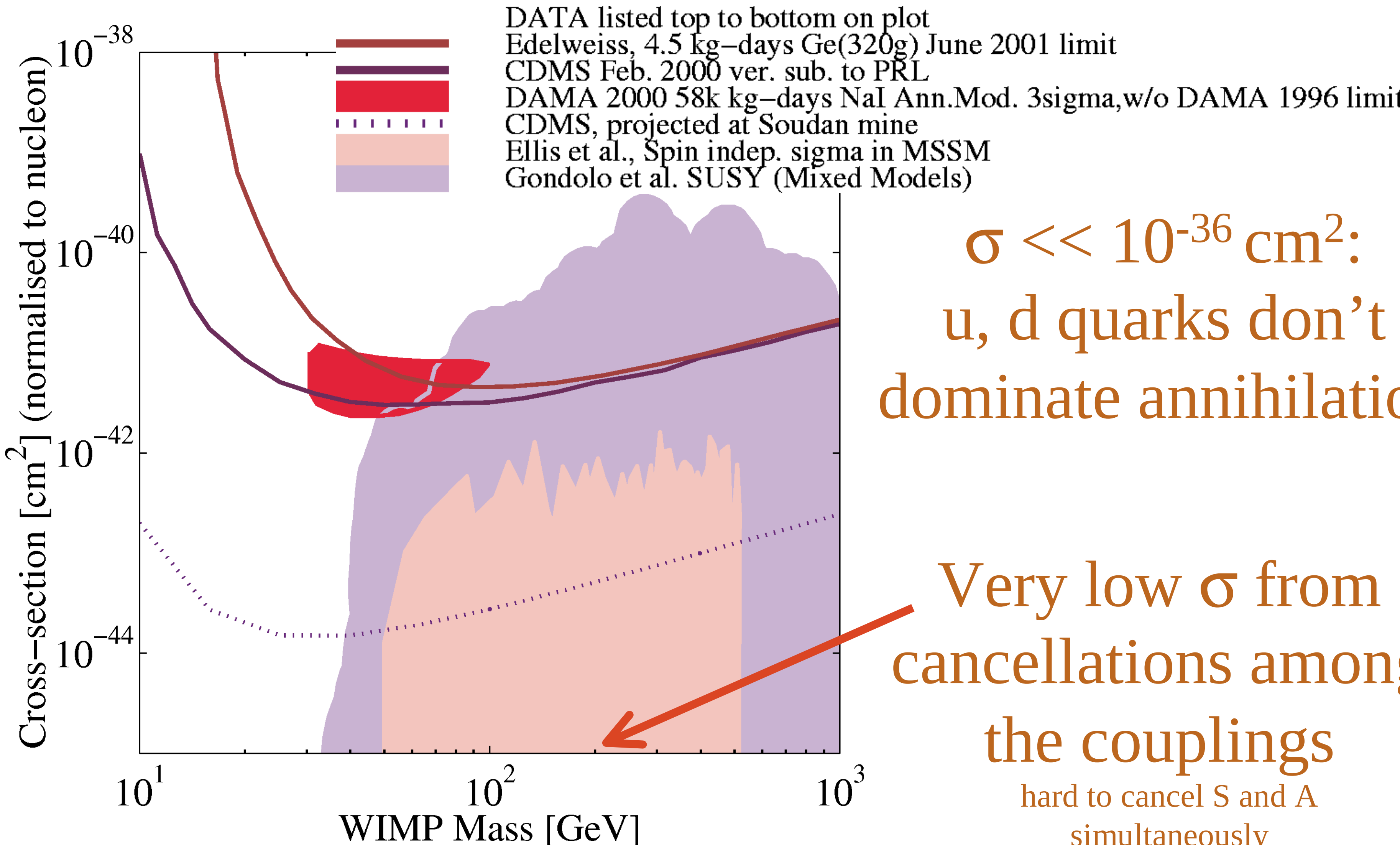
-42 or less

û ø 10^{à36} cm^{2}



S(calar) - spin independent
A(xial Vector) - spin dependent

Weak scale SUSY: χ^0 is the LSP

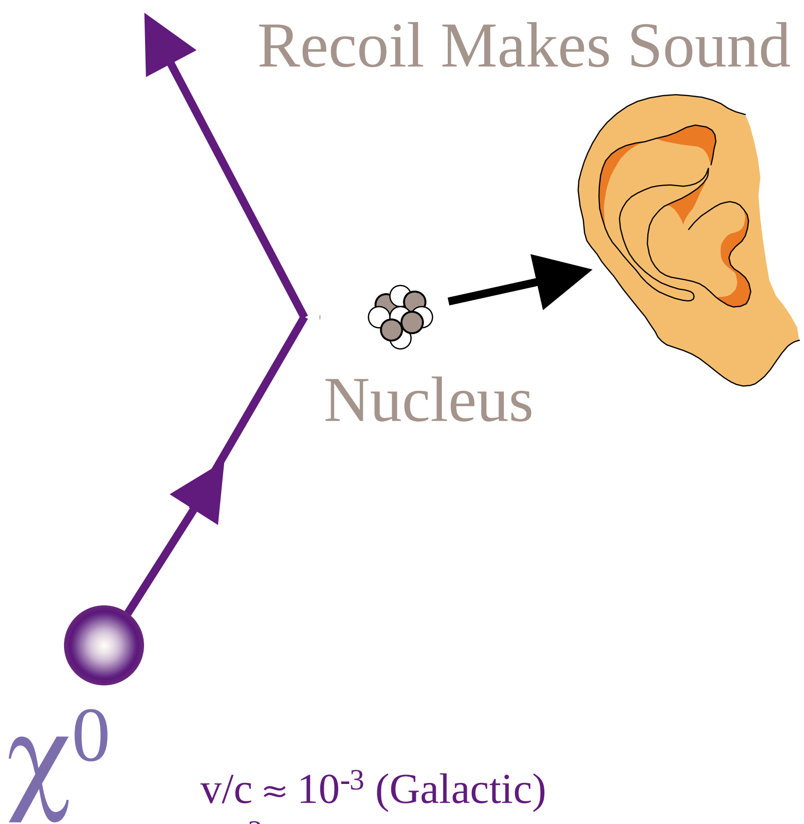


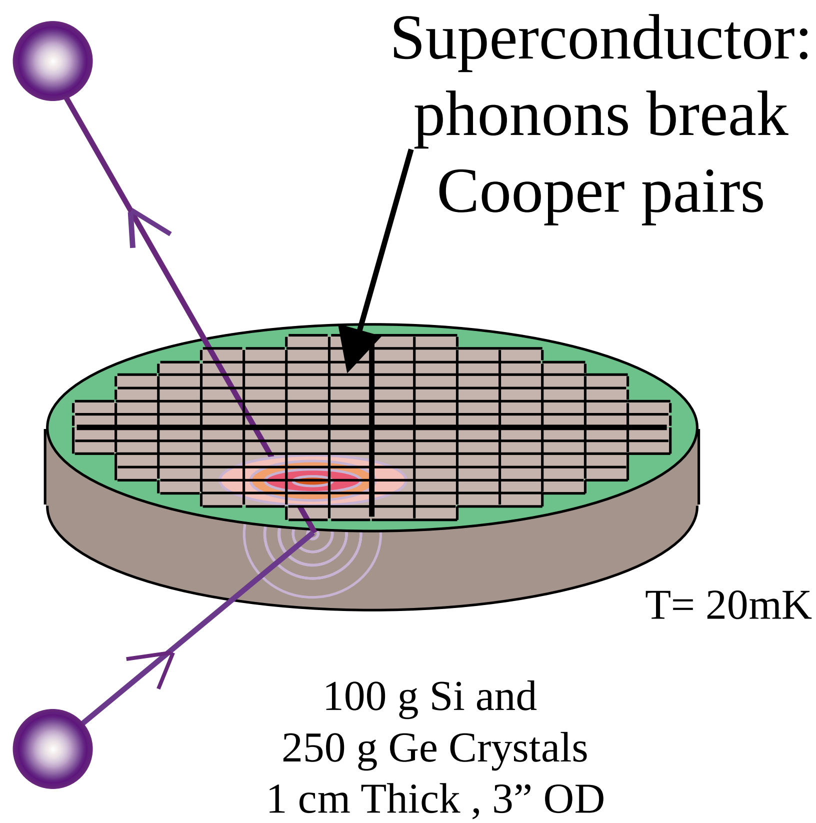
$\sigma << 10^{-36}$ cm^2: u, d quarks don't dominate annihilation

Very low σ from cancellations among the couplings

hard to cancel S and A simultaneously

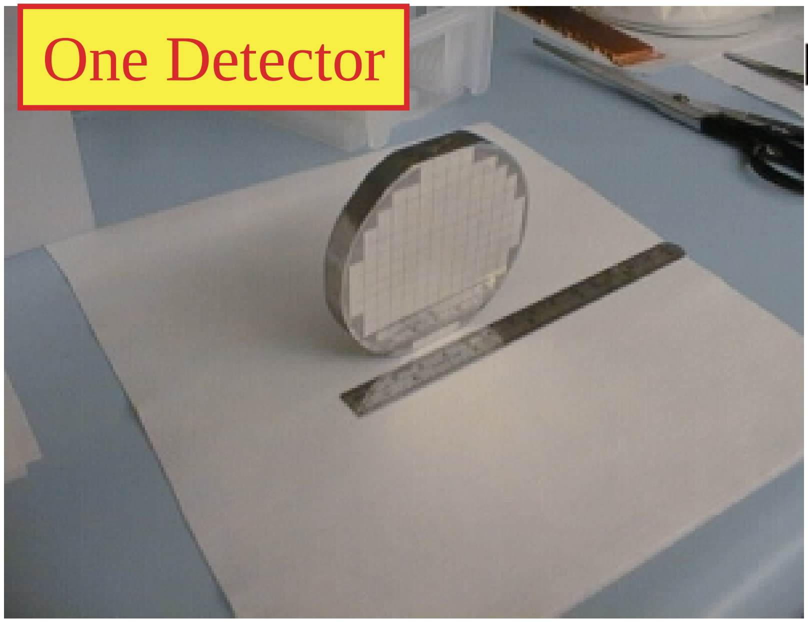
Direct Detection





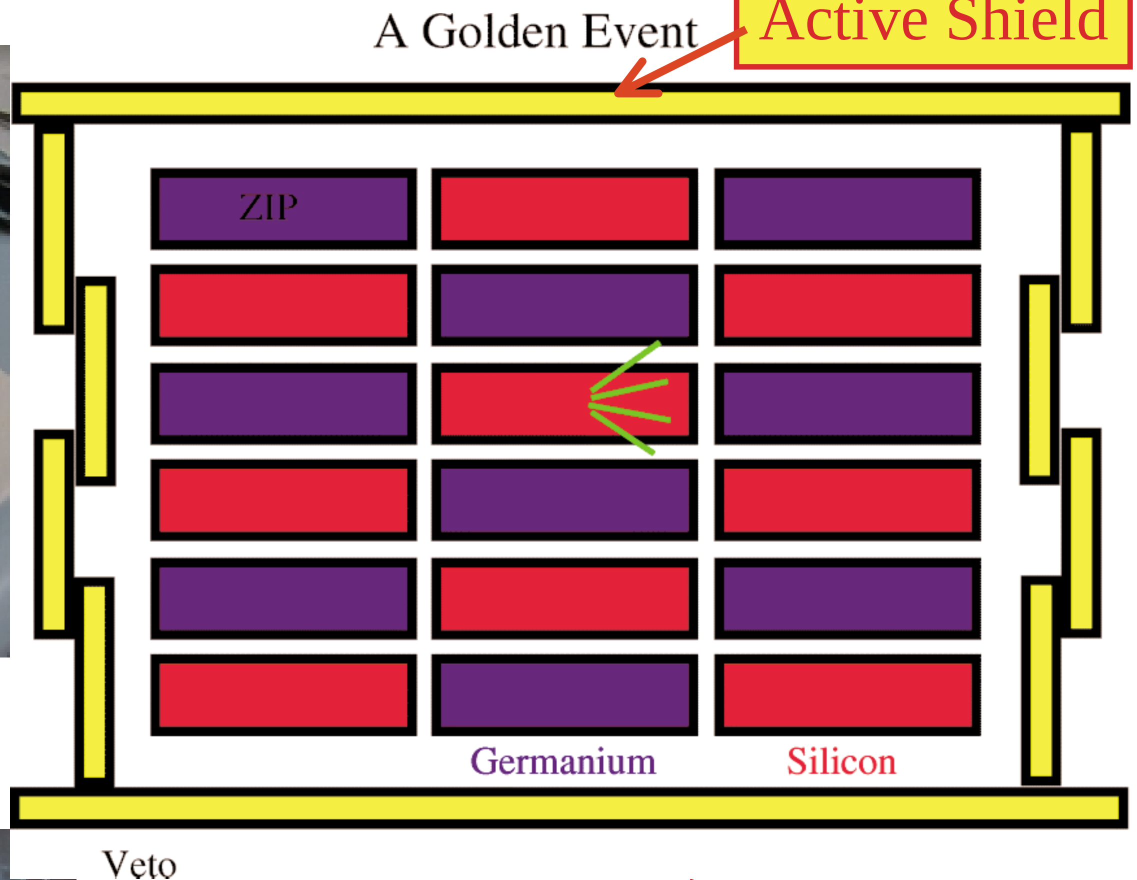
$v/c \approx 10^{-3}$ (Galactic)
$Mc^2 \approx 50 - 500$ GeV)

One Detector



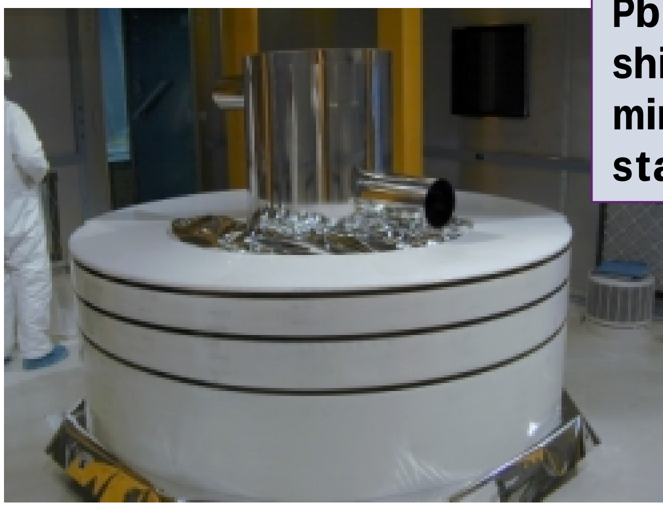
Icebox and
Shielding There Now

Active Shield

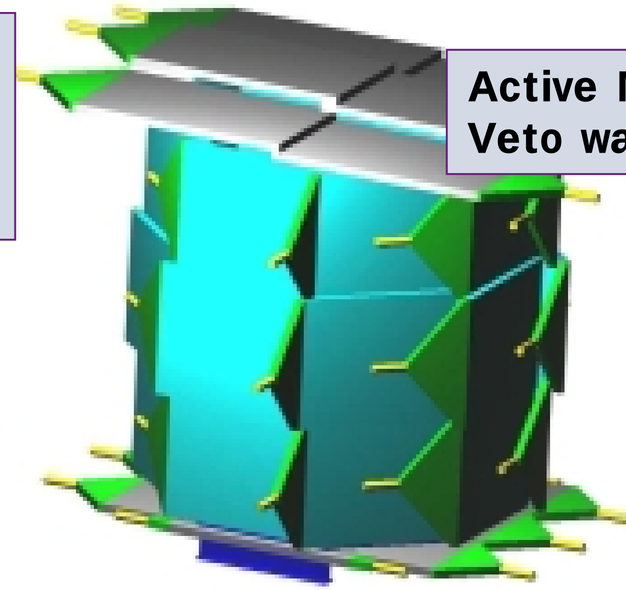


Soudan Mine
Northern Minnesota
690 meters underground

UCSB Responsibilities on CD



Pb/Poly/Pb passive shielding in Soudan mine. Operation to start in 2004



Active Muon Veto walls

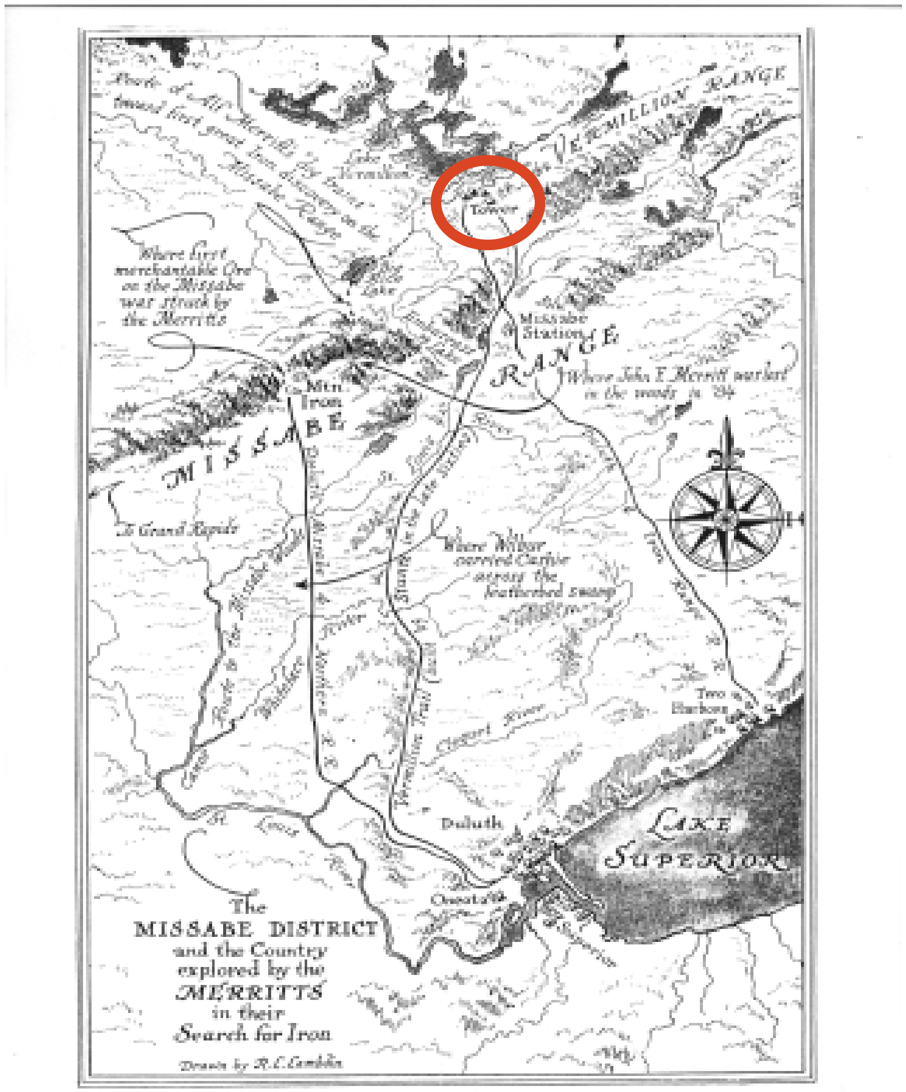
UCSB Background Veto and Shielding: From outside to inside

- **Cosmic ray muons detected via scintillators and photomultipliers**
- **Neutrons and Gammas moderated and attenuated with 15 cm Pb,25 cm Polyethylene, 3 cm Cu, 1 cm of ancient low activity Pb**

Scintillator panel

UCSB is also responsible for the Data Acquisition system for the experiment

Location, location



UCSB Contributions to CDM

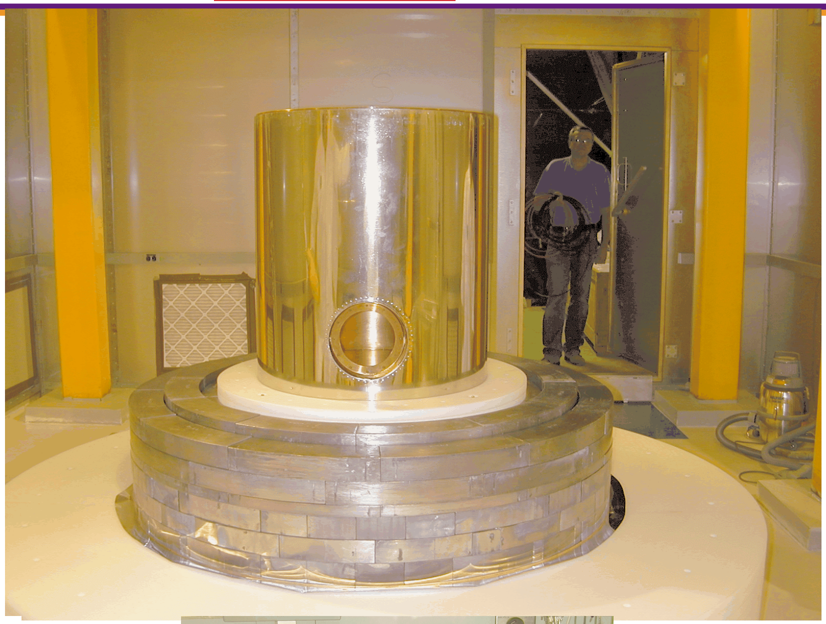
- Inception - Dave Caldwell
- Shielding - both I and II
  - Hale, Kyre, Callahan (Technical)
  - Yellin (Design)
  - Bauer, Bunker (Grad),
    R. Nelson (Ugrad) (Implementation)
  - Crucial for the discovery of WIMPs
- Data Acquisition
  - Soudan Underground Facility (SUF):
  - CDMS I - largely the work of Dan Bauer
  - CDMS-II a new challenge –
    - scale up
    - remote operations
    - conversion and overhaul to more modern practices
      - trigger electronics (Sam Burke)
      - software: Java, Corba, event-builder
  - Rupak Mahapatra, Dan Bauer, Don Holmgren (FNAL)
    - UCSB Grads Ron Ferril, Joel Sander, Chris Savage
- Management
  - Dave Caldwell - chair of the Executive Committee
  - Dan Bauer - chair of the Experiment Integration and Coordination committee; subsystem manager (Shield)
  - Harry Nelson - subsystem manager (DAQ)
  - Steve Yellin - chair of the Monte Carlo group
- Operations
  - Dan Bauer coordinates at SUF Steve Yellin is computer system manager
- Analysis
  - Steve Yellin Background simulation
    - Statistical Analyses
  - Ray Bunker
    - Veto
    - Ph. D. Thesis - Soudan or SUF/new run

Shie l d s

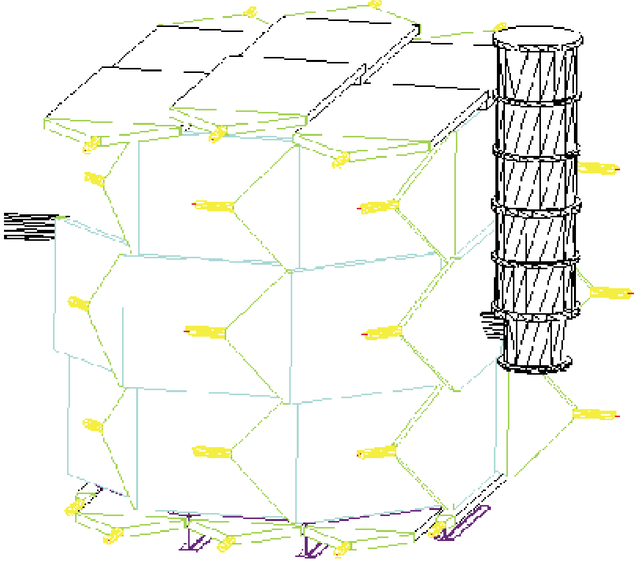
UCSB

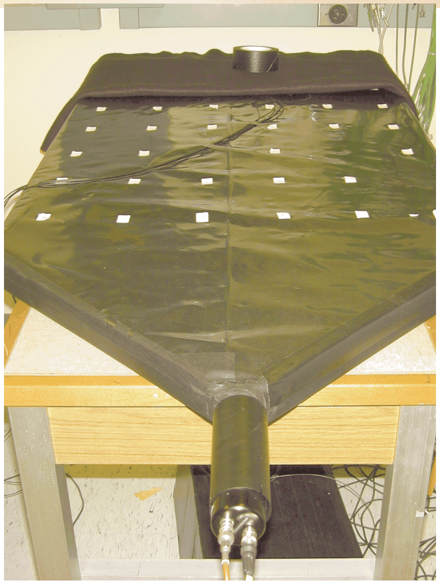
Soudan

Passive

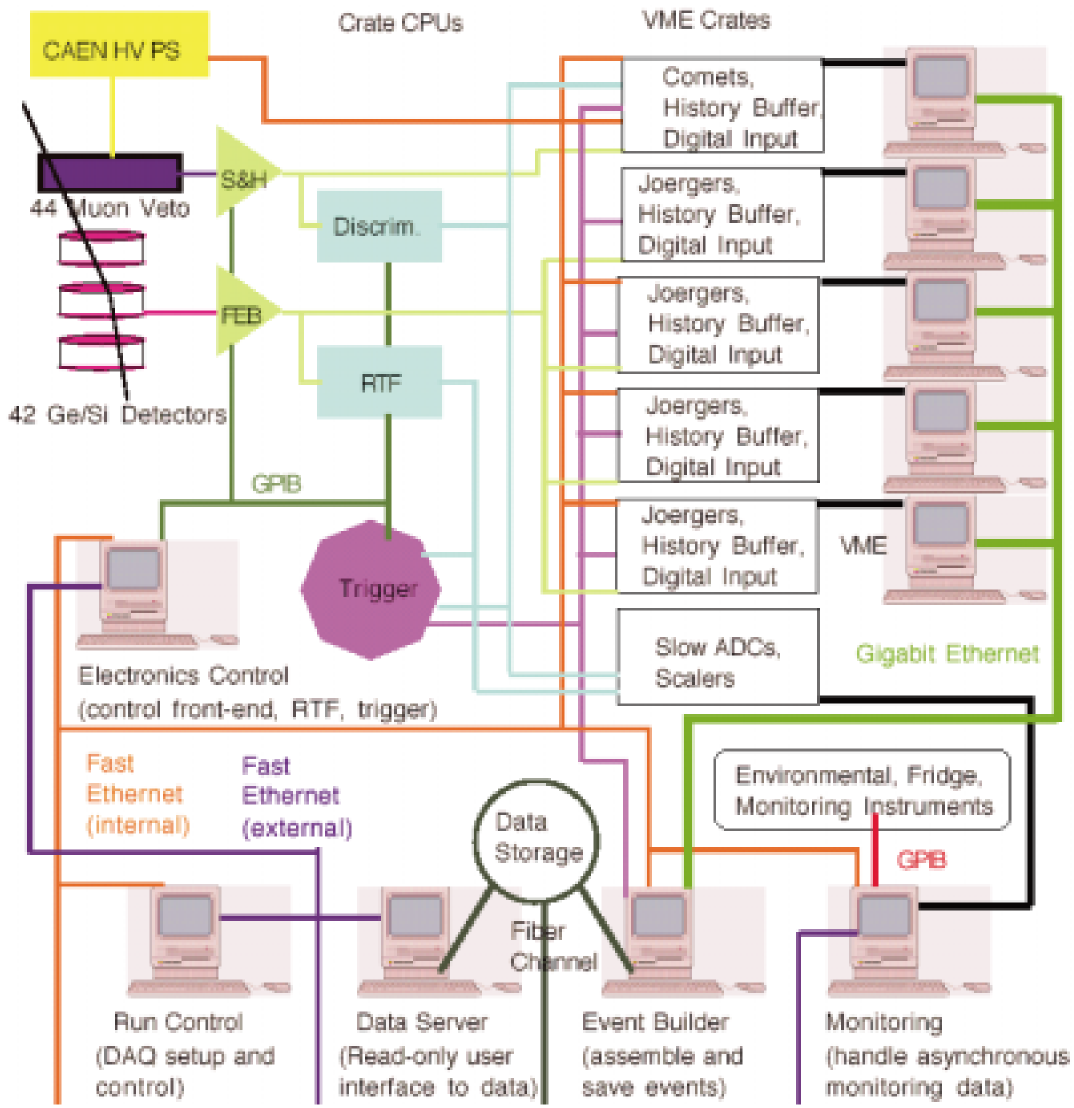


Active





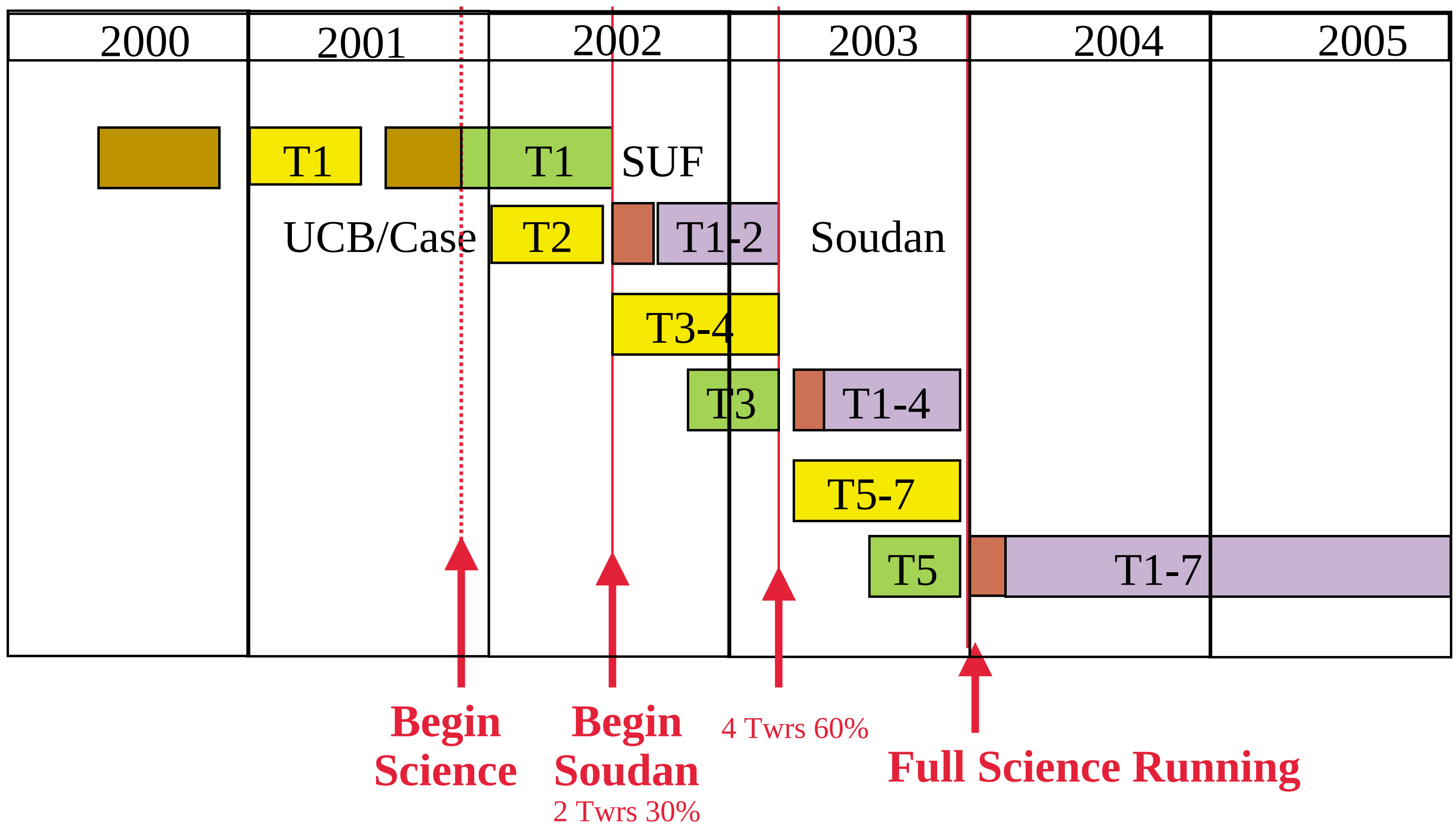
D at a A cquis it ion: D A Q



The Future

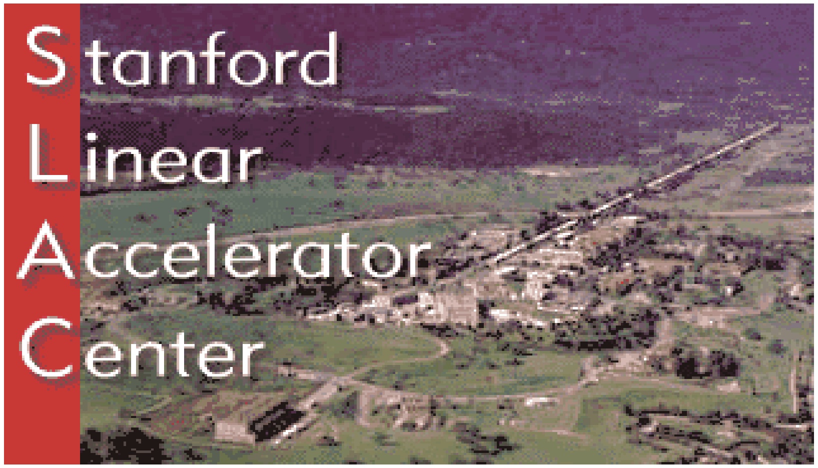
- CDMS-II
  - SUF Run underway - all positive - Dan Bauer will talk
  - Soudan - Crunch Time -
    - DAQ, shield operational this spring
    - Summer - running commences (Towers in July) (next)
    - 3-4 Dissertations from UCSB
  - 2003 - CDMS-II/Soudan measured (expect internal backgrounds about twice Soudan neutrons)
- Next step?
  - Desire for sensitivity as far as we can go
  - Background experience at CDMS-II crucial

New Scenario 2 - 4 - 7

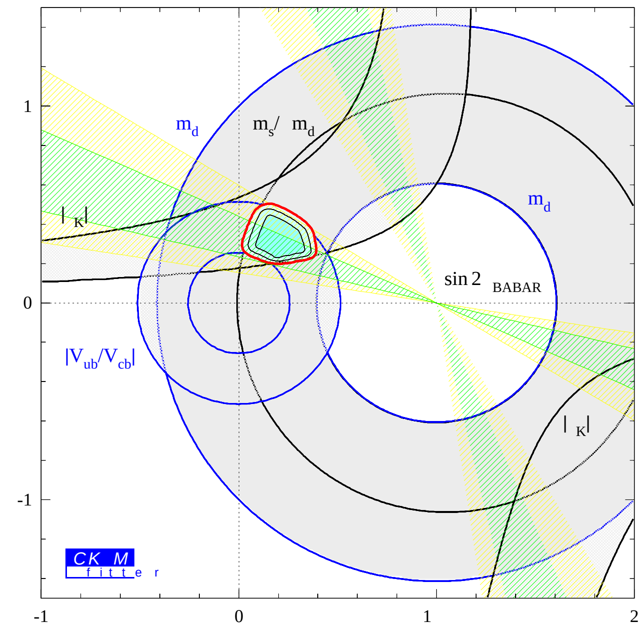


The Babar Experiment at SL A

Campagnari, Richman



- Babar experiment looks at b and b-bar mesons produced in e+e- collisions.
  - Primary goal of this experiment and its competition (the Belle experiment at KEK in Japan) is the observation of CP violation in the b quark sector
  - CP violation was Recently Observed at both experiments !
- UCSB played a major role in both the construction of the detector and the data analysis

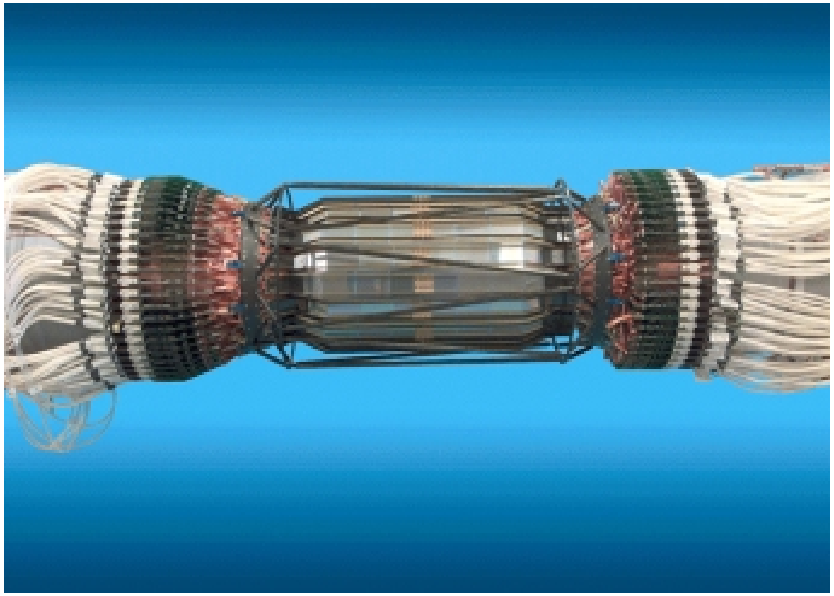


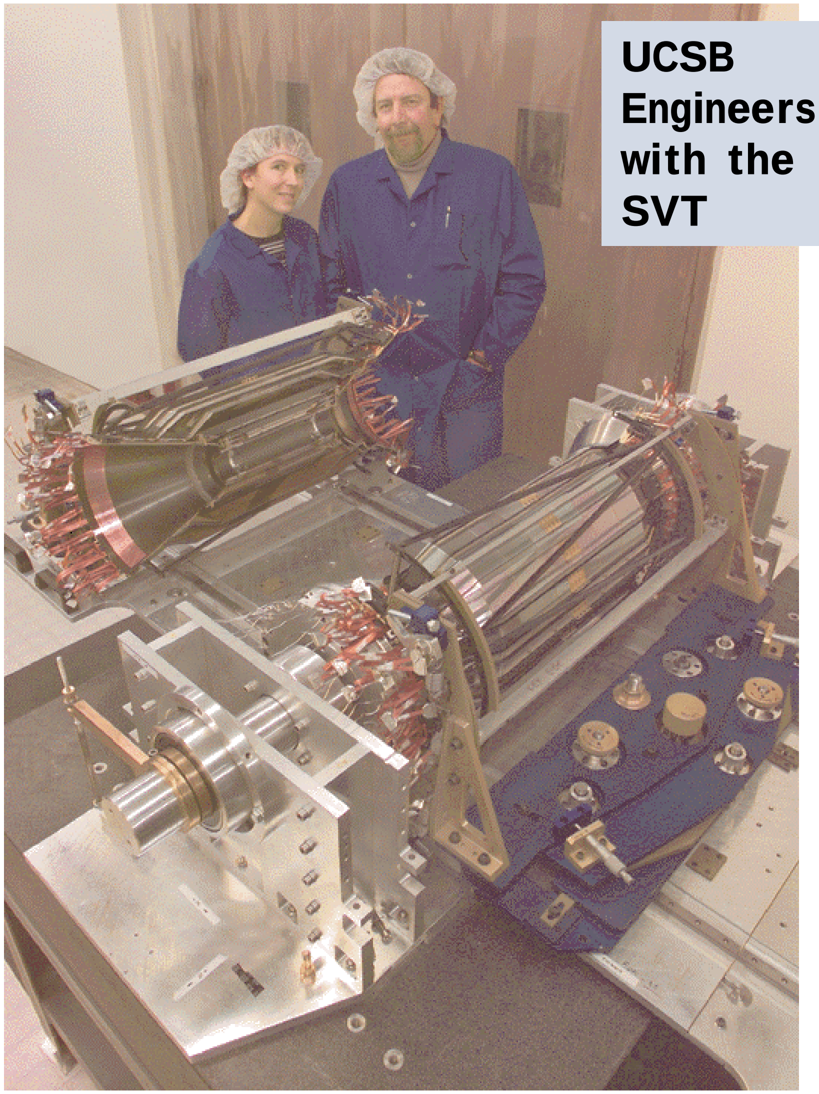
Sin2β is a relative measure of the asymmetry of neutral B and Bbar meson decay rates to $\Psi + K_S$. A non-zero value means CP is violated

The Babar result is shown above in the ρ–η plane.

Bab ar SV T

The Babar Silicon Vertex Tracker (SVT) is crucial to the sin 2b measurement. Much of the design and construction of this detector was the responsibility of the UCSB HEP group and was performed at UCSB.





UCSB Engineers with the SVT

The UCSB HEP Group

- Faculty
  - Claudio Campagnari (Babar,CMS)
  - Joe Incandela (CDF,CMS)
  - Harry Nelson (CDMS)
  - Jeff Richman (Babar)
  - David Stuart (CDF)
- Senior Research Physicists
  - Dan Bauer (CDMS)
  - Steve Yellin (CDMS)
- Post-doctoral Research Assoc.
  - Anthony Affolder (CMS)
  - Jeff Berryhill (Babar)
  - Philip Hart (Babar)
  - Chris Hill (CDF)
  - Cigdem Issever (CDF)
  - Owen Long (Babar)
  - Rupak Mahapatra (CDMS)
  - Russell Taylor (CMS)
  - Wouter Verkeke (Babar)
- Old Graduate Students
  - Ray Bunker
  - Brian Dahmes
  - Ron Ferril
  - Steven Levy
  - Michael Mazur
  - Joel Sander
- Undergraduates
  - Robert Nelson
  - Aviva Shackell
- Technical Staff
  - Sam Burke (Electrical Engineer)
  - Dave Hale (Senior Engineer)
  - Suzanne Kyre (Mechanical Engineer)
  - Dan Callahan (Technician)
  - Julie Stoner (Wirebonder operator)
  - Lap-Yan Leung (Computer systems)
  - Currently hiring another engineer…

How do students fit in?

- These experiments depend heavily on graduate students.
- Each analysis topic generally involves only a very small fraction of the collaboration.
  - Students can and regularly do make enormous individual contributions to major measurements and major discoveries
    - e.g. top quark
  - The advantages of a large collaboration far outweigh any disadvantages
    - Experts of all stripes are available
    - Work daily with excellent physicists from every great physics department and institute worldwide
    - Truly an international undertaking

Conclusions

- The UCSB group is playing key roles in key experiments
  - The search for Dark Matter
  - CP violation in the b quark sector
  - Search for the Higgs and SUSY
- Key contributions to the Babar, CDF and CDMS and CMS
- We have pretty exciting times ahead…

C M S The M ovie

C M S