Silicon Detectors at CDF:
Performance and Importance for Physics Discovery

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Outline

- Motivation
- Introduction to CDF and the Tevatron
- Silicon Detectors at CDF
- Physics impact from silicon detectors
- Performance of the Silicon System now at CDF
- Conclusions and outlook

Motivation

At the 2004 Fermilab User's meeting, it was quoted (by Chris Hill of the Fermilab theory division):

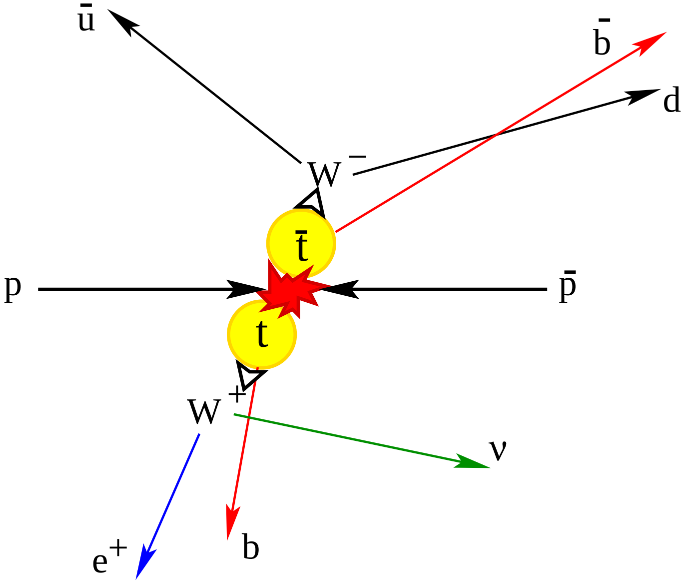
"In 10 years the written laws of Physics will be different than they are now"

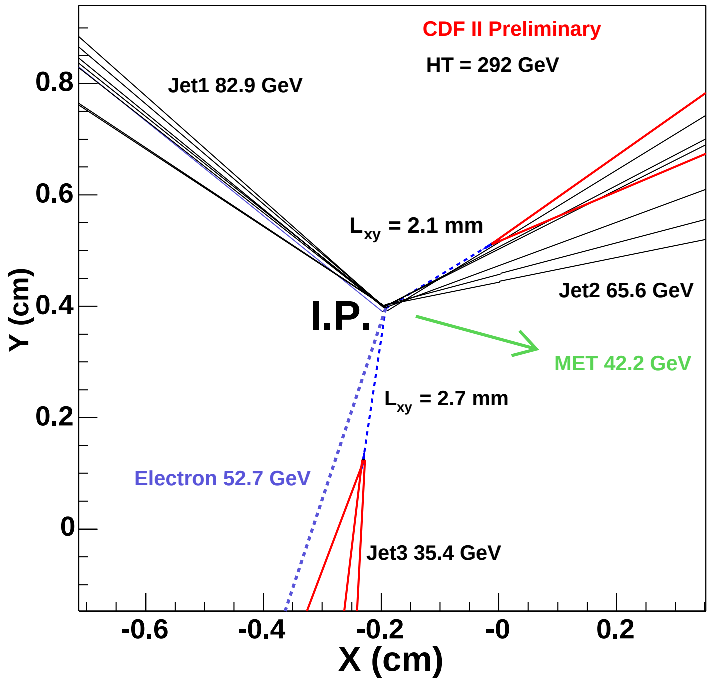
- ▶ Run 2 at the Tevatron until ∼2009
- ▶ LHC from ∼2008
- ▶ BaBar, Belle, B-TeV
- ▶ neutrino programs
- ▶ astrophysics (SNAP, Sloan, ...)
- ▶ many other expts......

At the Tevatron and LHC, new physics discoveries are almost certainly going to rely heavily on silicon detectors

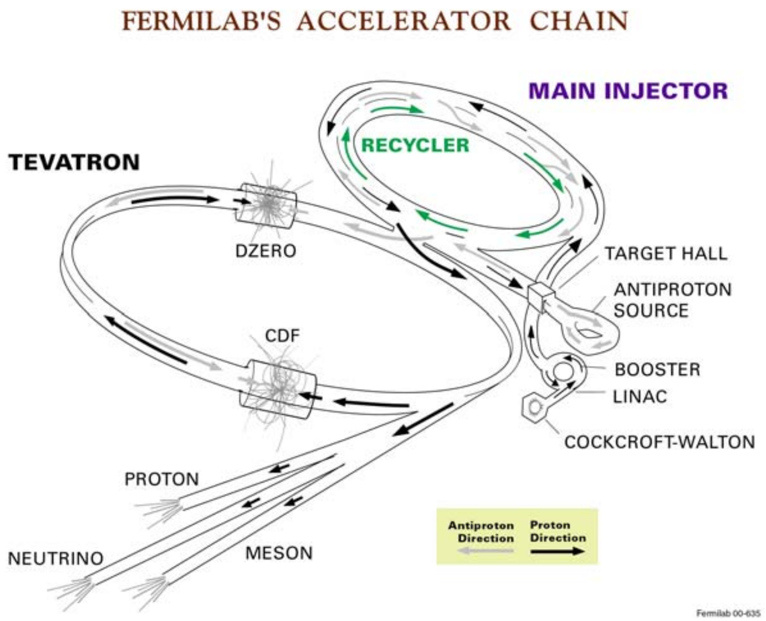
Why ?

- In High Energy Physics(HEP) experiments many interesting (and new) physics processes involve b-quarks
- b-quarks can travel a couple of mm before decaying
- Identifying this decay through extremely precise tracking, identifies the b-quark, and exposes the interesting physics
- E.g. top quark pair production:





The Tevatron at Fermilab



- proton bunches on antiproton bunches in a 1 km radius ring at a collison energy of 1.96 TeV $\Longrightarrow \; v-c \;\sim\; 150\, km/h \; (1\times10^{-7}c)$!!
- Protons travel the $\sim$4 mile ring about 50 000 times a second
- About $\sim 3\times10^{6}\; p\bar{p}$ “events” occur every second
- “Run 1”: 1992 - 1996 : Integrated luminosity $\sim 100\,\mathrm{pb}^{-1}$
  “Run 2”: 2002 - 200? : Integrated luminosity goal $\sim 5\,\mathrm{fb}^{-1}$

Tevatron Performance in Run II

- Rare processes require high luminosity:

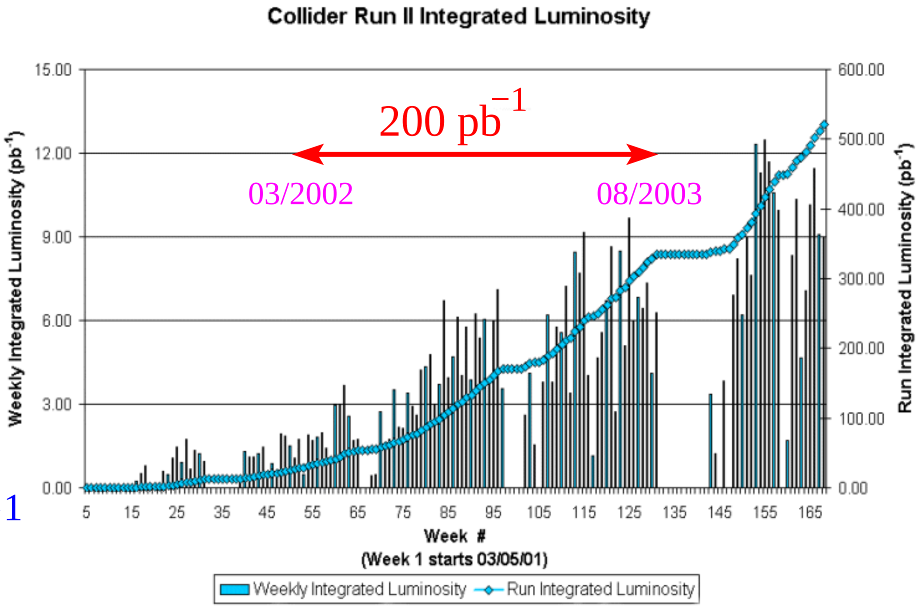
$$N = \varepsilon \sigma L$$

number observed

efficiency for detection

cross–section (pb)

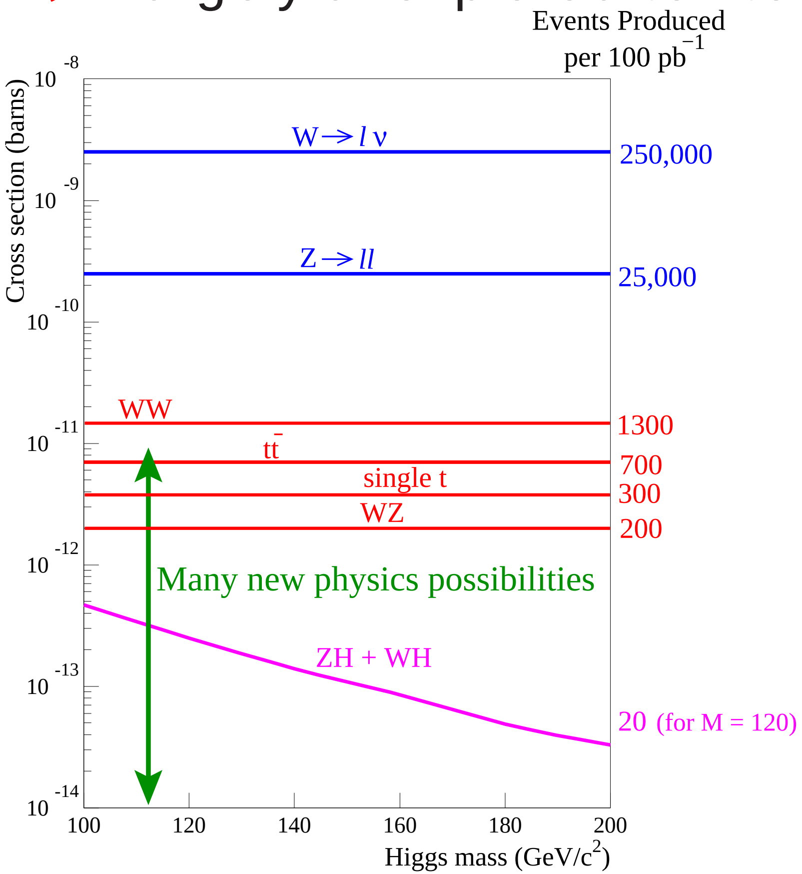
integrated luminosity (pb^{-1})



- Tevatron delivered $\sim 500\,\mathrm{pb}^{-1}$
- Data taking efficiency $\sim 85\%$
- Recent CDF analyses based on $\sim 200\,\mathrm{pb}^{-1}$ (about twice that from “Run 1”)
- Expect another $\sim 400\,\mathrm{pb}^{-1}$ within next year
- Run II will accumulate more than 10× current data → silicon system will require dedicated ongoing effort

The Tevatron Environment

- At 2 TeV we are creating the conditions of the universe after about 10^{-12} s ! (after about 10^{-14} s at the LHC)
- Largely unexplored territory → could be many surprises

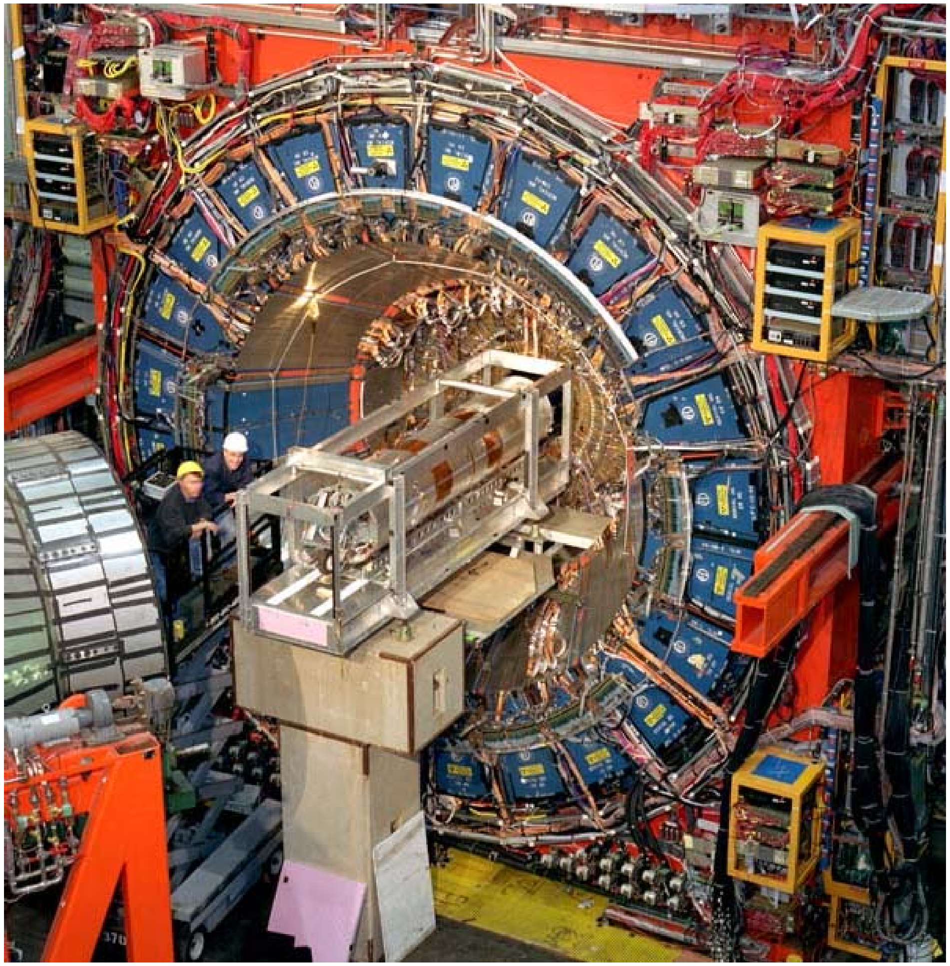


- W's, Z's: Large cross sections ⇒ precision measurements
- Top: Cross section ∼ 7 pb ⇒ soon entering phase of highly anticipated precision measurements
- Higgs, new physics: optimizing searches

Mark Kruse, Duke University, 21 June 2004

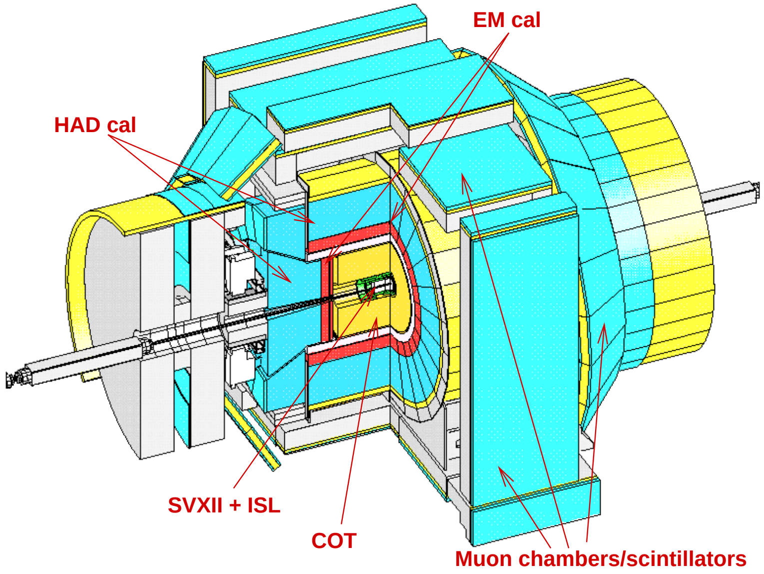
The CDF Collaboration

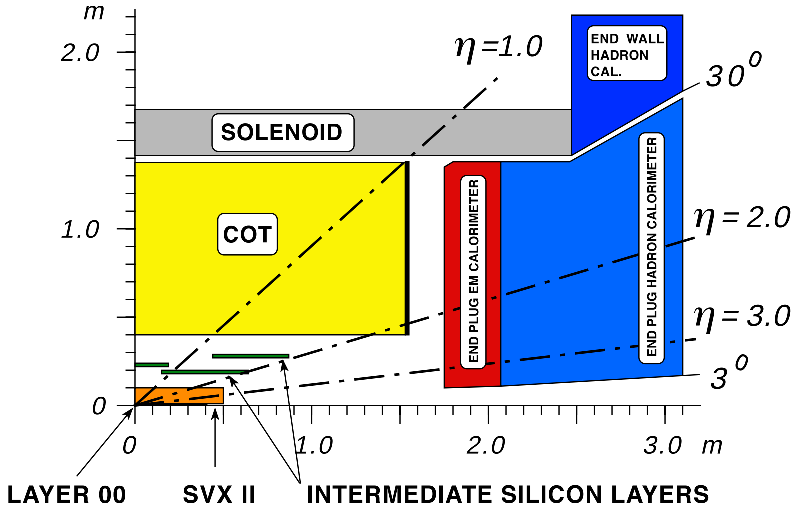
- About 600 physicists from 57 institutions and 11 countries



The CDF Detector

- Current and near future HEP detectors are necessarily general purpose: tracking system, calorimetry, muon system.

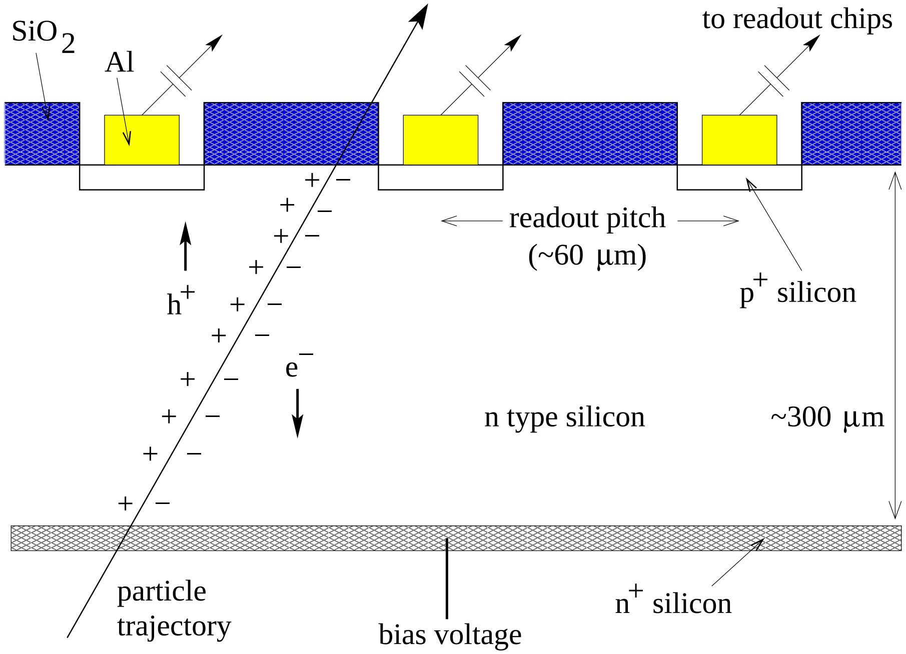




- Tracking system consists of a silicon system (L00 + SVXII + ISL) and a Multiwire Drift Chamber (COT)

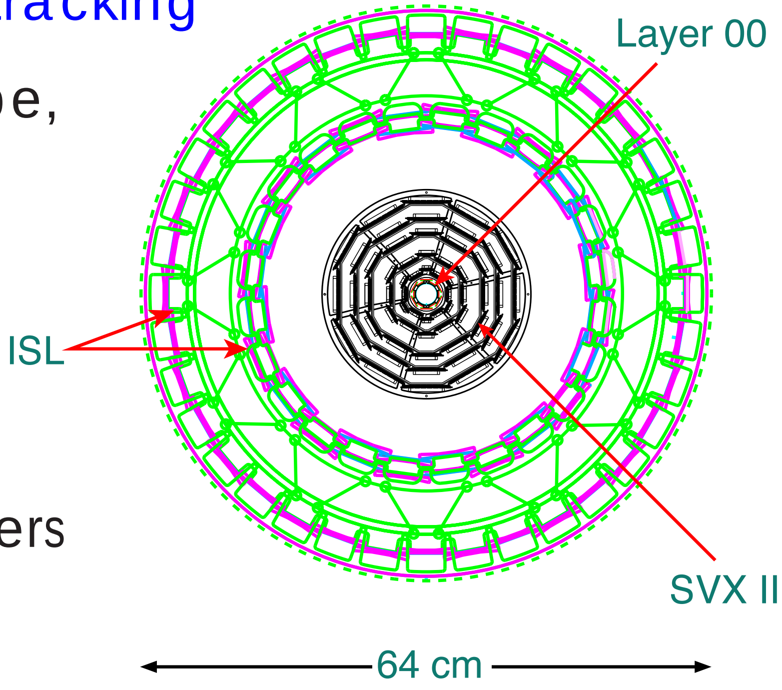
Silicon detector basics

- Si Properties:
  - 3.6 eV to release e-hole pair
  - particles lose ~400 eV/μm (~ 100 e-h/μm)
- Consequences:
  - Good signal for little material (~30,000 e-h pairs in 300 μm, while energy loss ~100 keV → ~0.01% for 1 GeV particle)
  - detectors close to interaction region, σ_{d0} preserved
- Particle Detection ⟹

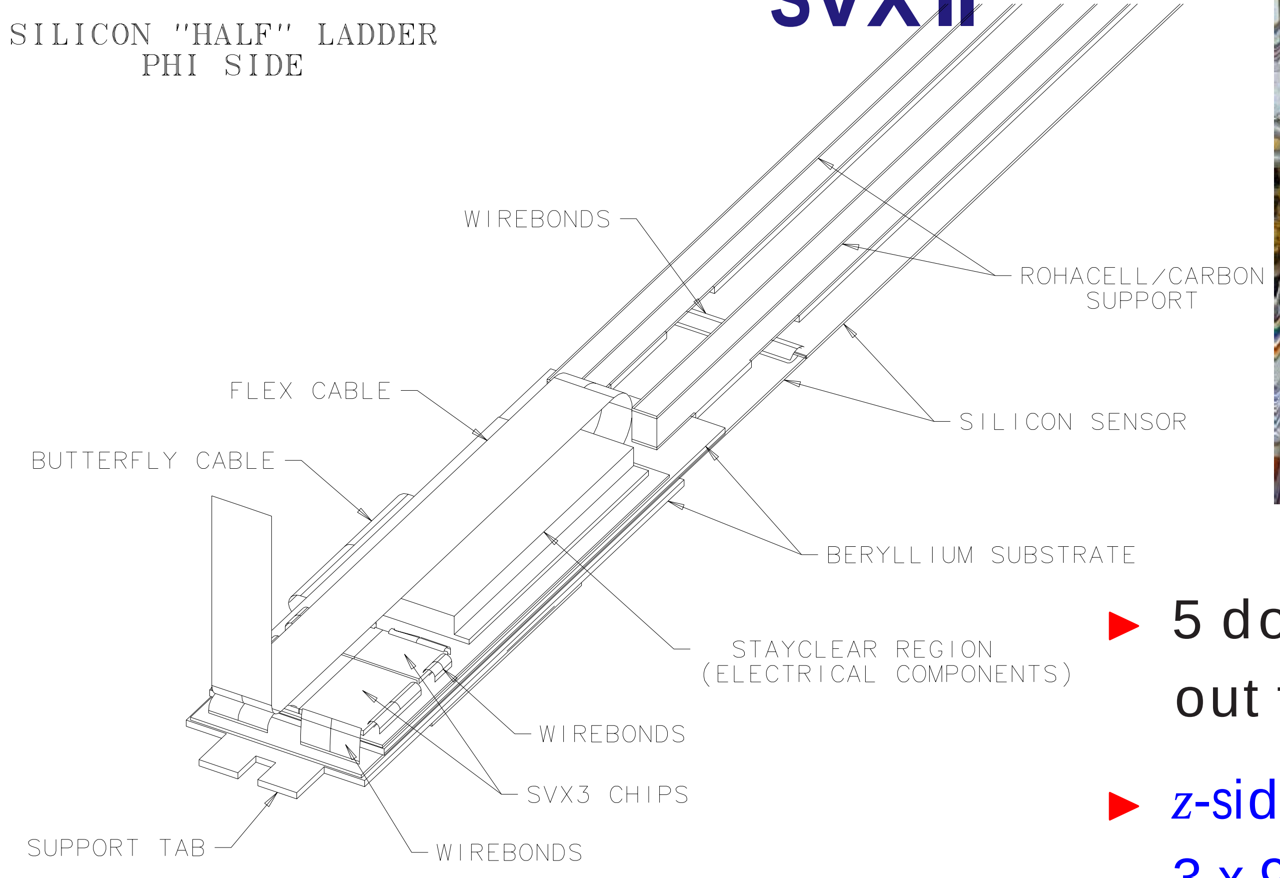


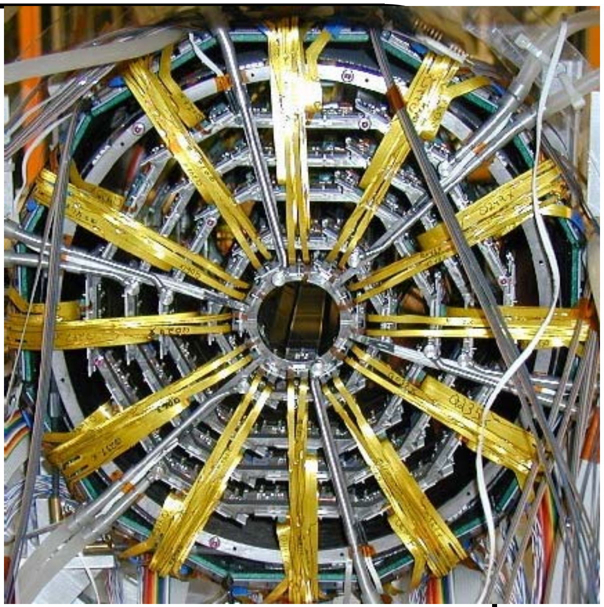
Silicon Detectors at CDF: Run 1 vs Run 2

- Run 1
  - 4 layers of silicon sensors, total length ∼50 cm
  - Crucial for discovery of the *top* quark in 1995
- Run 2: 3 systems → improved tracking
  - L00: layer built on beampipe, R 1.4 - 1.6 cm
  - SVX II: 5 layers, double-sided sensors, 90 cm long, $3 < R < 10$ cm
  - ISL: intermediate silicon layers 3 outer layers, 2 m long, $20 < R < 30$ cm



SVX II

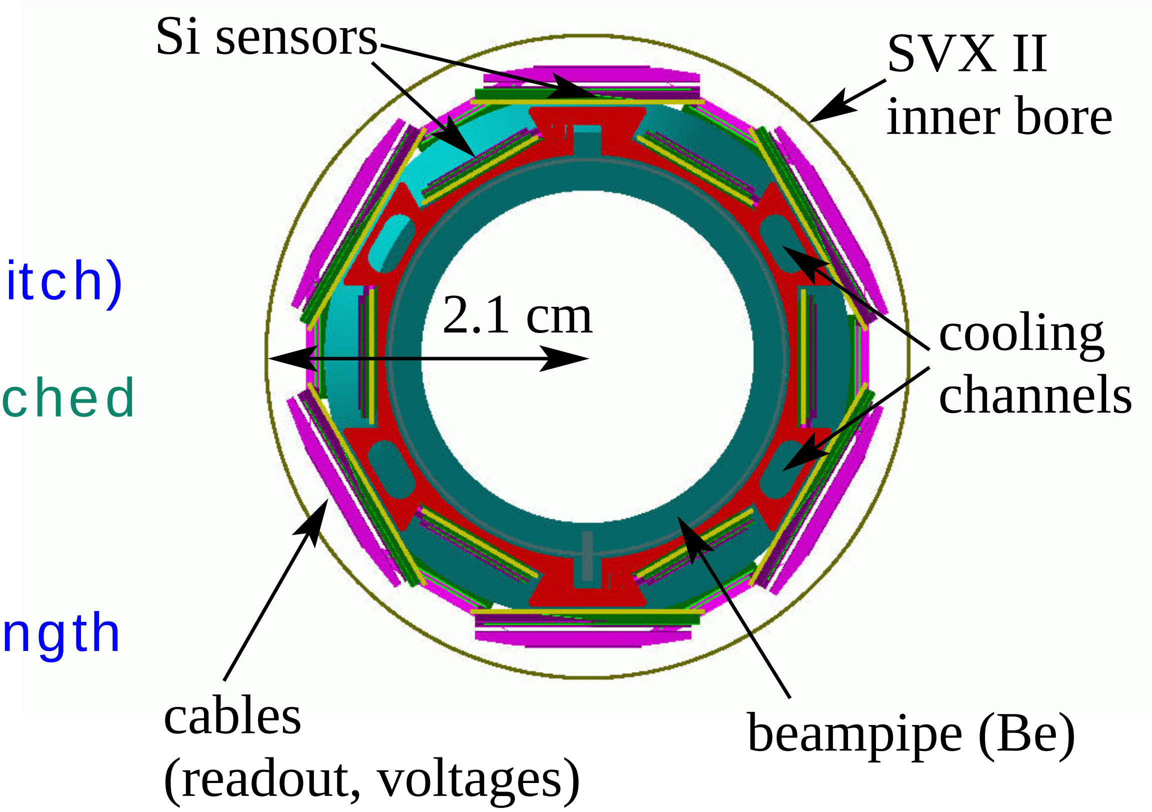




- 5 double-sided layers out to R ∼10 cm
- z-side for 3-D tracking: 3 x 90^o, 2 x 1.2^o
- 3 “barrels” → 12 “wedges” → 360 “half-ladders” → 3168 readout chips → ∼400,000 channels
- $r-\phi$ pitch $\sim 60\,\mu m$, $r-z$ pitch $\sim 140\,\mu m$ ($\sim 60\,\mu m$ for 1.2^o)

Layer 00

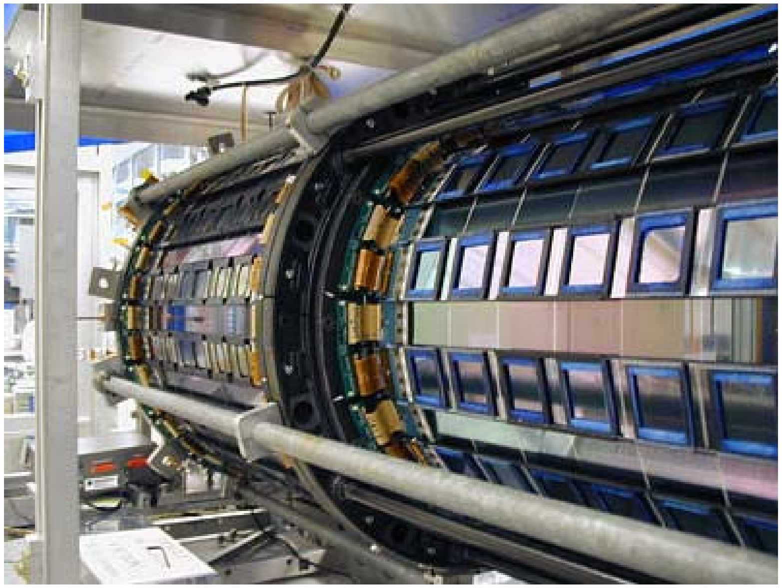
- Single-sided
- 25 μm pitch (50 μm readout pitch)
- Electronics detached
- Active cooling
- $<$1% radiation length
- Bias voltage up to 500 V
  $\Rightarrow$ will outlast SVX II layer 0
- Provides improved IP resolution (especially at low P_T)

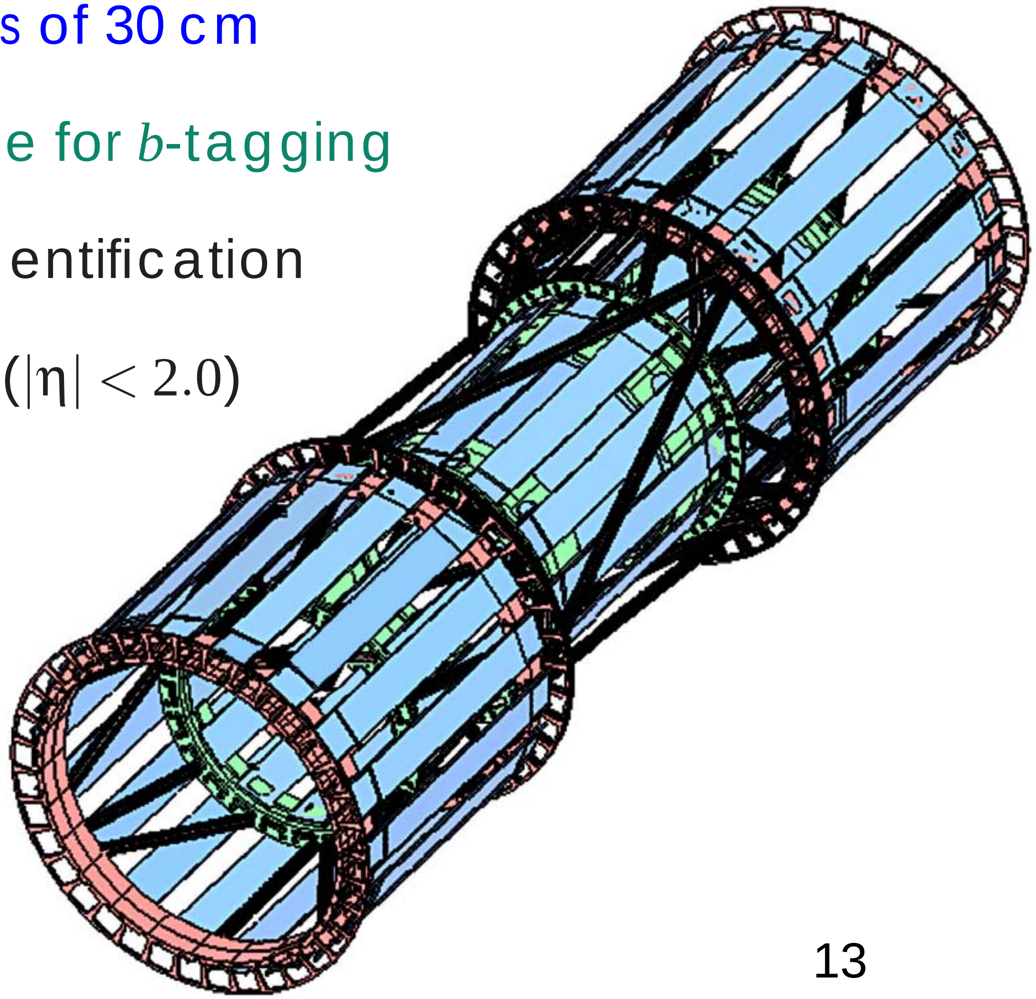


ISL: intermediate silicon layers

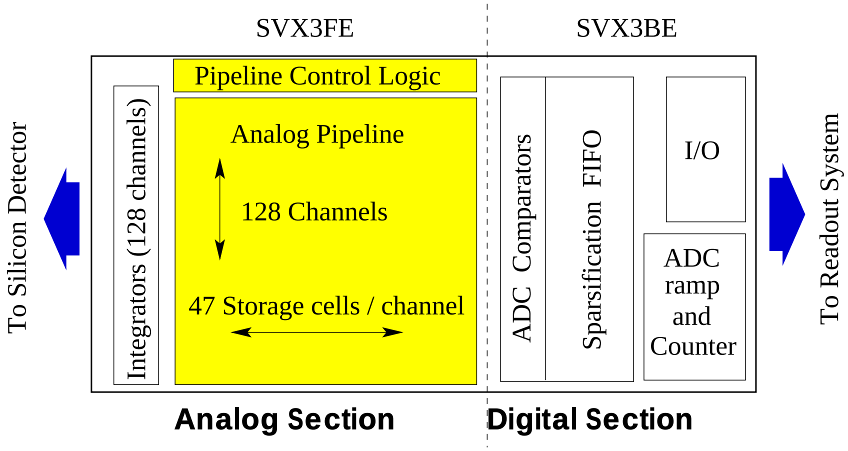
- 2 double-sided layers (296 half-ladders, 2368 chips, $\sim$300,000 channels)
- $\sim$2 m long with outer radius of 30 cm
- Allows greater acceptance for b-tagging
- useful for forward lepton identification

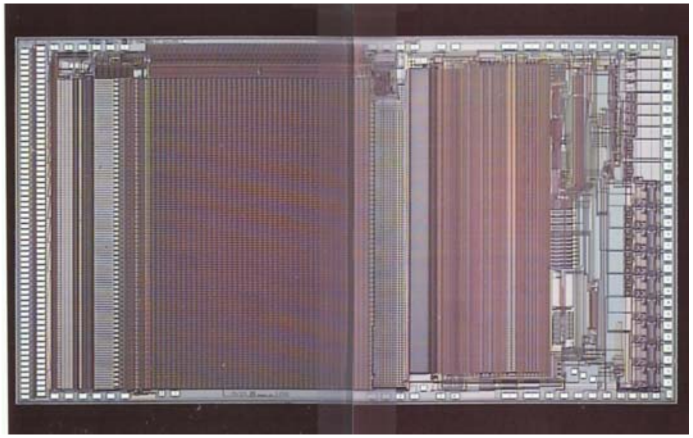
$(|\eta| < 2.0)$





Readout chips





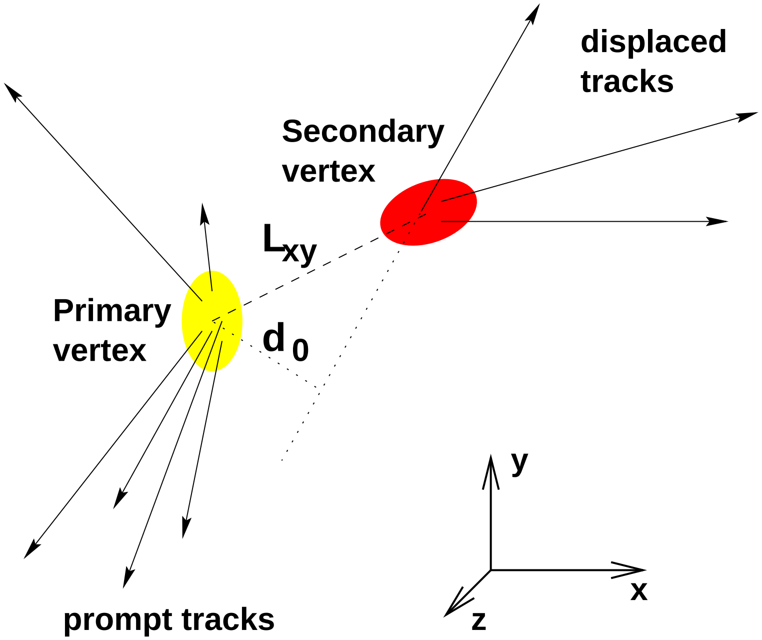
- Detector Signals → SVX3D readout chips
- Radiation hard:
  - 0.8μm technology
  - tested to $\sim$4 MRad
- Deadtimeless
- Dynamic common mode noise suppression
- Sparsified readout
- $\sim 2\mu s$ readout per “event”
- Same readout chip used for SVX-II, ISL and L00
- Readout chips(5644 total) → Hybrids → Portcards → various readout boards/controllers → event builder

Impact on physics

- Precision tracking →
  detection of displaced vertices from b quarks
- Many important physics signatures contain b-quarks
- Precision tracking from silicon detectors is crucial for:
  - Precision *top* quark measurements
  - Beauty and Charm physics: precision tests, new observations
  - Searches for $H^0 \rightarrow b\overline{b}$
  - Many new physics processes

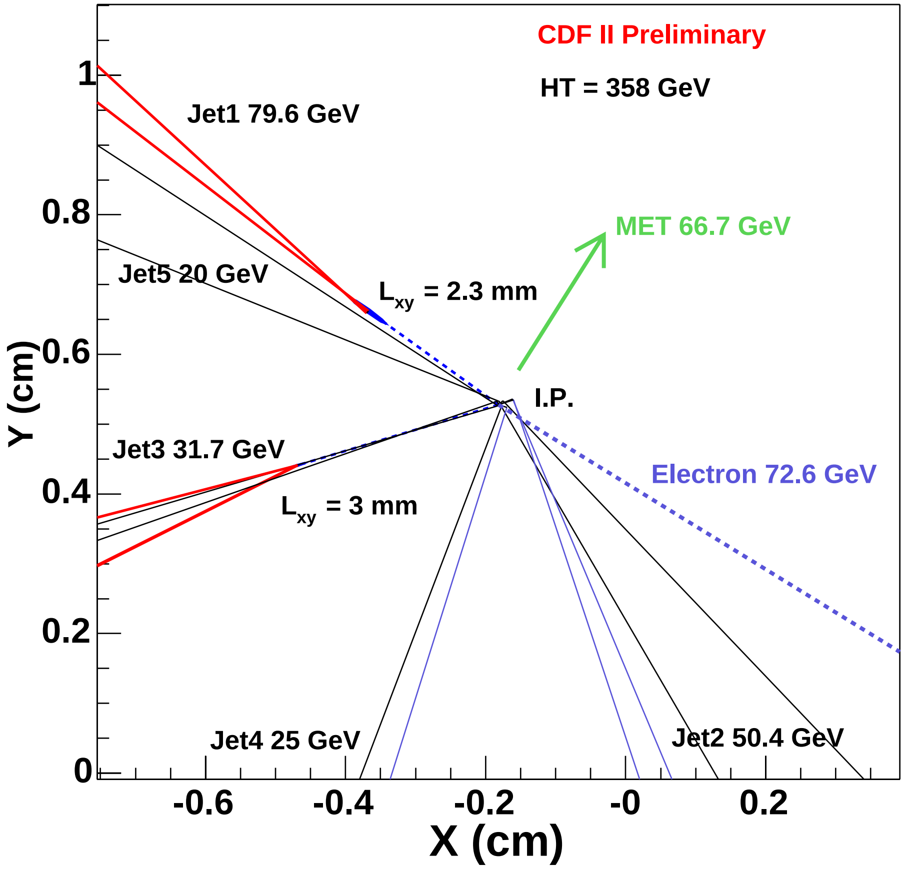
“b-tagging”

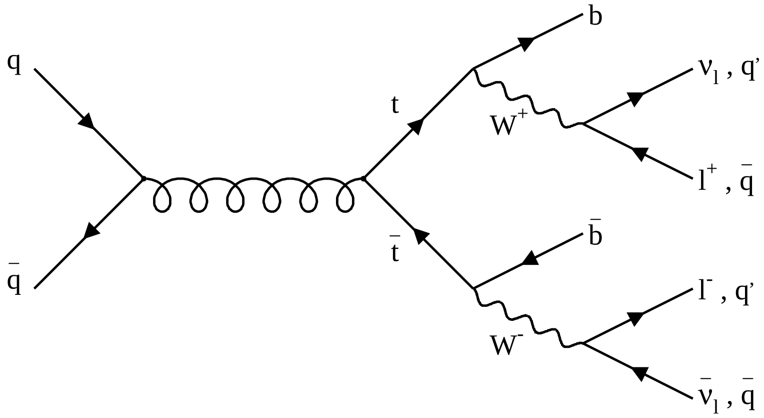
- b-quarks have a long lifetime : $\tau(b) \sim 1.5$ ps ($c\tau \sim 450\,\mu$m)
  $\Longrightarrow$ B hadrons travel $L_{xy} \sim 3$ mm before decay.
- Silicon detectors “b-tag” jets by measuring displaced vertices in the transverse plane:
  - Uses SVX tracks
  - Secondary vertex $\geq$ 2 tracks
  - Tagged if $L_{xy}/\sigma_{L_{xy}} > 3.0$
    (typically $\sigma_{L_{xy}} \sim 150\,\mu$m)

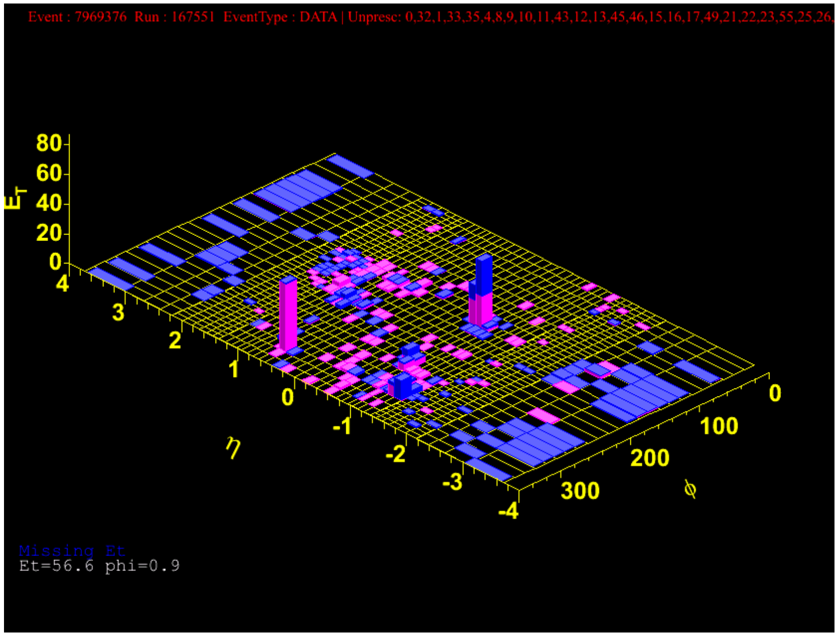


- $\varepsilon_b \sim 35\%$ ($\varepsilon_{fake} \sim 0.5\%$ per jet)
- Much more challenging at the LHC → pixels, rad-hard materials/electronics, ...

Example: $p\bar{p} \rightarrow t\bar{t}$







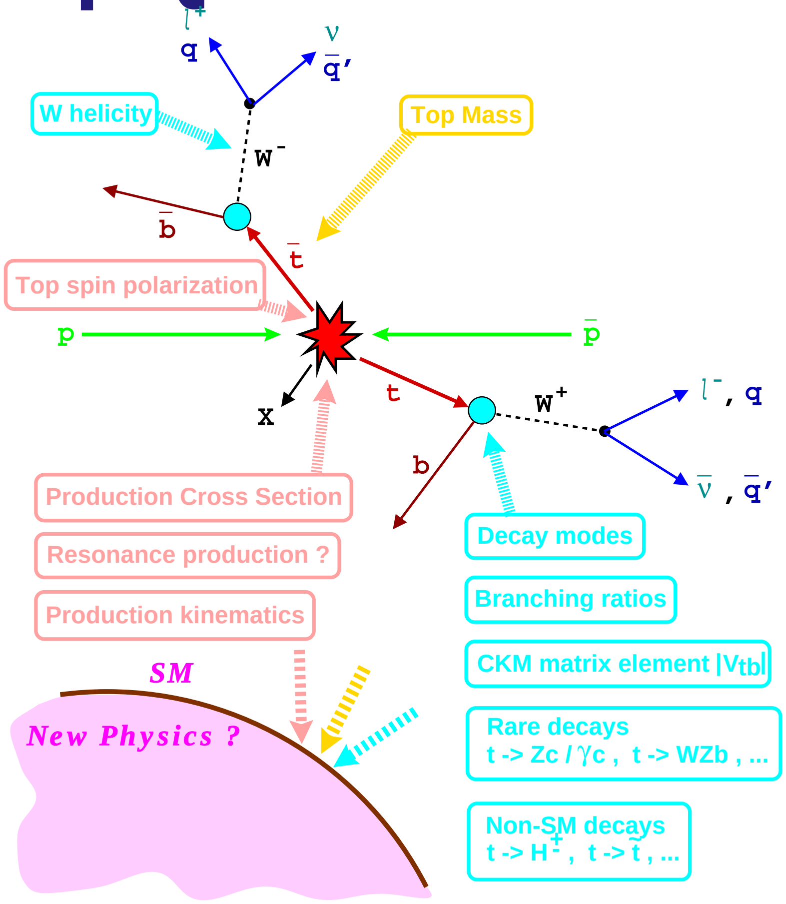
SVX b-tagging:

~55% efficient for $t\bar{t}$

~1% efficient for non-b/c

Measuring the Top Quark

- *top* remains the most intriguing particle we have discovered
- Large Mass ⇒ intimate connection with EWSB ?
- Top measurements still statistically limited
- Main Run II priority to measure as many top quark properties, in as many ways, and as best we can, not only as a test of the SM, but to exploit the top quark potential to lead us to new physics



W helicity

Top Mass

Top spin polarization

Production Cross Section

Resonance production ?

Production kinematics

SM

New Physics ?

Decay modes

Branching ratios

CKM matrix element $|V_{tb}|$

Rare decays
t -> Zc / γc , t -> WZb , ...

Non-SM decays
t -> H^+ , t -> $\tilde{t}$, ...

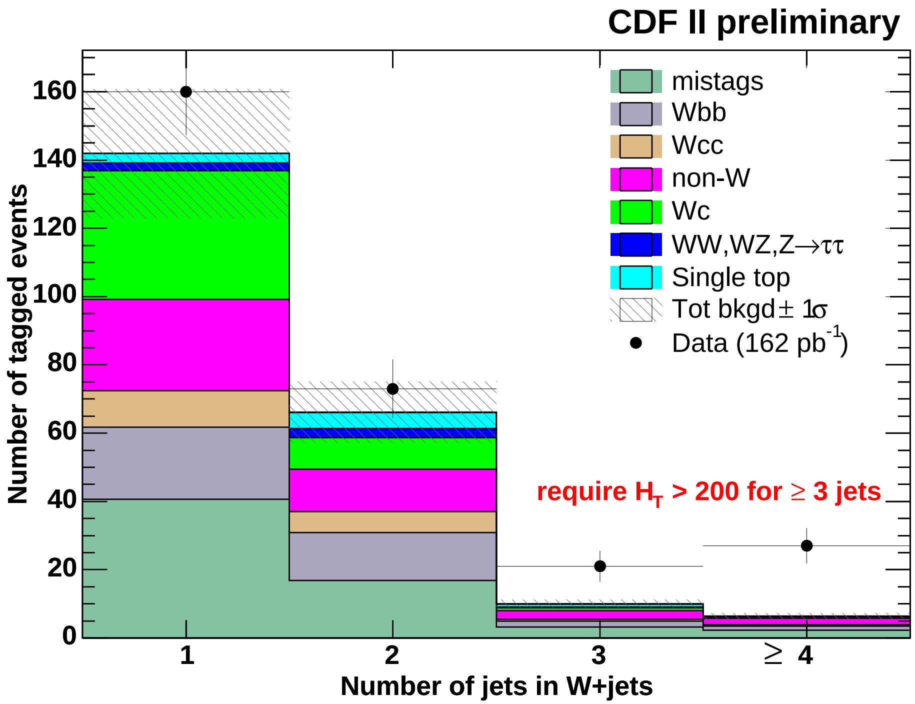
- This can not be achieved without an excellent silicon system and the Tevatron is the only place to do this for several more years

Progress on top measurements in Run 2

- Many analyses well under way. *One* example: $t\bar{t}$ cross-section using SVX tagged events:

  Measure $\sigma(p\bar{p} \rightarrow t\bar{t}) = 5.6^{+1.2}_{-1.0}(\text{stat})\ ^{+1.0}_{-0.7}(\text{syst})$ pb (162 pb^{-1})

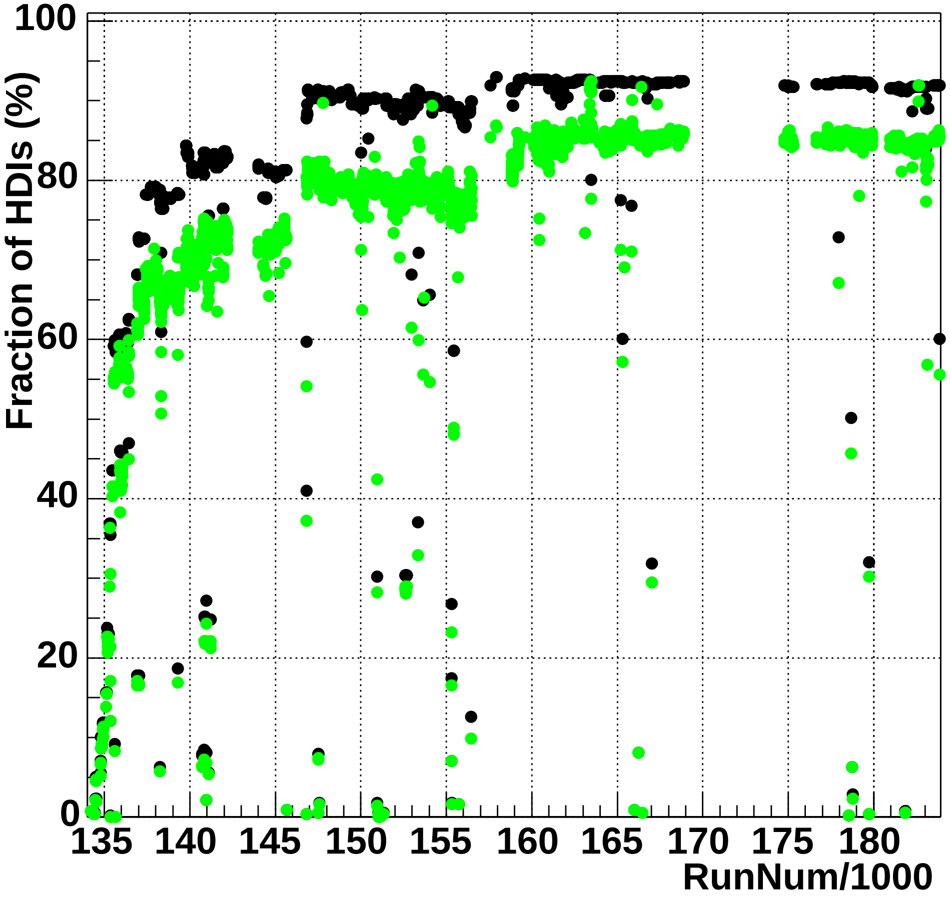
  (goal to measure to 10% in Run II) (c.f. $\sigma_{theory} = 6.7 \pm 0.3$ pb)



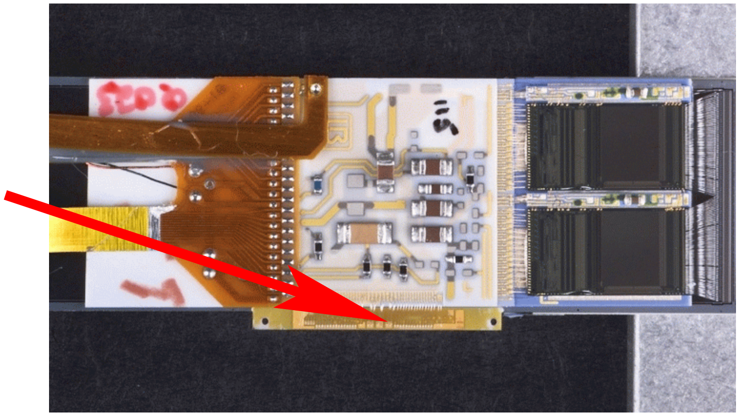
- A **lot** more to come, and not only in *top*

Current silicon status

- Silicon stable and taking good data after arduous commissioning effort
  - Powered ladders
  - Good ladders
- 92.5% powered
- good data from 86%
- Maintaining ~90% ladders providing good data requires dedicated ongoing effort



Operational experience (what doesn't kill you makes you stronger)



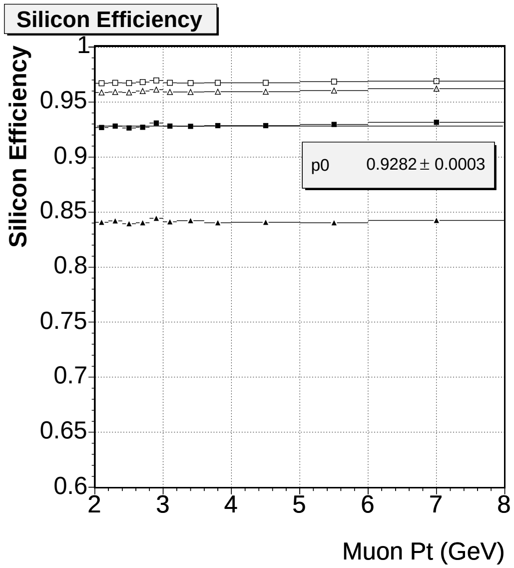
- Wire-bond failures:
  - connect ϕ and z sides of hybrids
  - 1.4T B-field $\rightarrow$ resonant Lorentz forces $\rightarrow$ bonds break
  - Reproduced in subsequent tests
  - $\Rightarrow$ minimize Lorentz forces, triggers inhibited if resonance conditions detected
- High dose incidents:
  - some readout chips damaged at time of 2 separate Tevatron incidents resulting in high instantaneous particle flux
  - damage cannot be reproduced under controlled conditions
  - countered with fast interlock at start of failure sequence; collimator installed to protect against uncontrolled aborts

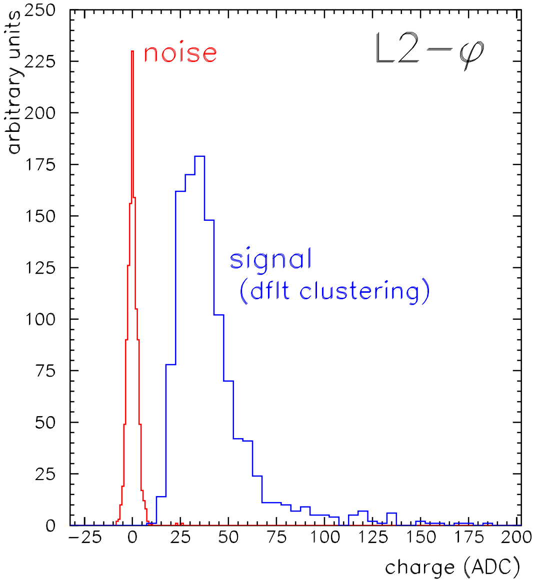
- Blockage of ISL cooling lines:
  - epoxy glue blocked lines at some elbows
  - unable to cool central part of ISL
  - laser surgery successfully opened lines

- Other hurdles overcome:
  - Power supply failures
  - Noise pickup on L00 analog cables
- Quick understanding and reaction to problems is critical to maintaining the high performance necessary for continued good physics

Silicon performance

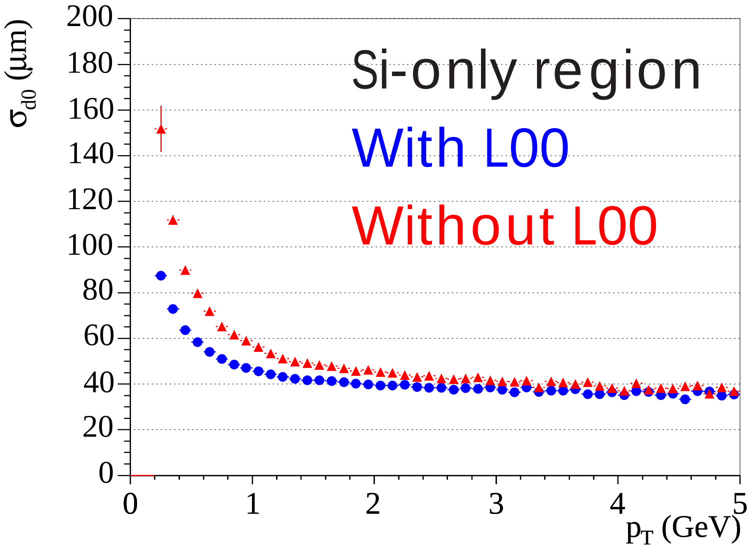
- Silicon detector performing to expectations
- Track efficiency $\sim$ 93%
- S:N $\sim$ 12:1
- Position resoluton $\sim$9 μm
- Already giving higher b-tag efficiency than in Run 1 $\longrightarrow$ will increase further when full potential realised

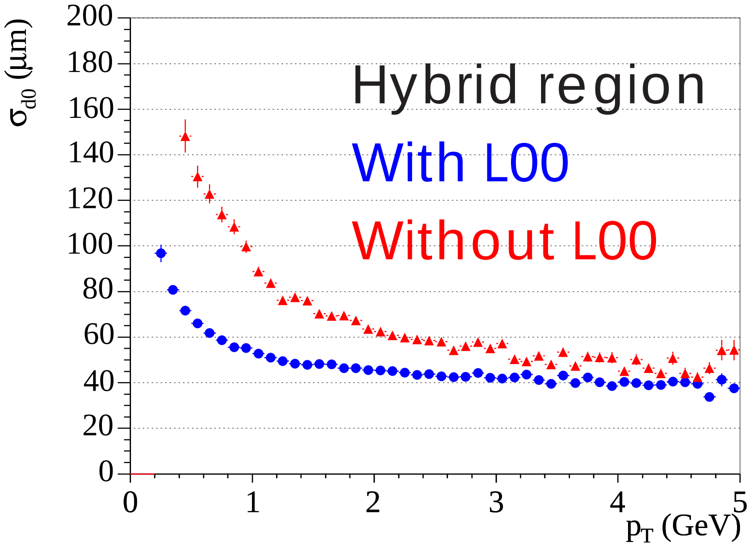




Silicon performance: adding L00

- L00 recovers degraded IP resolution due to multiple scattering off passive SVX II material
- Particularly effective at low P_T
- Hit efficiency $\sim$ 65%
- Not yet included in *b*-tagging → one of the future improvements to *b*-tag efficiency



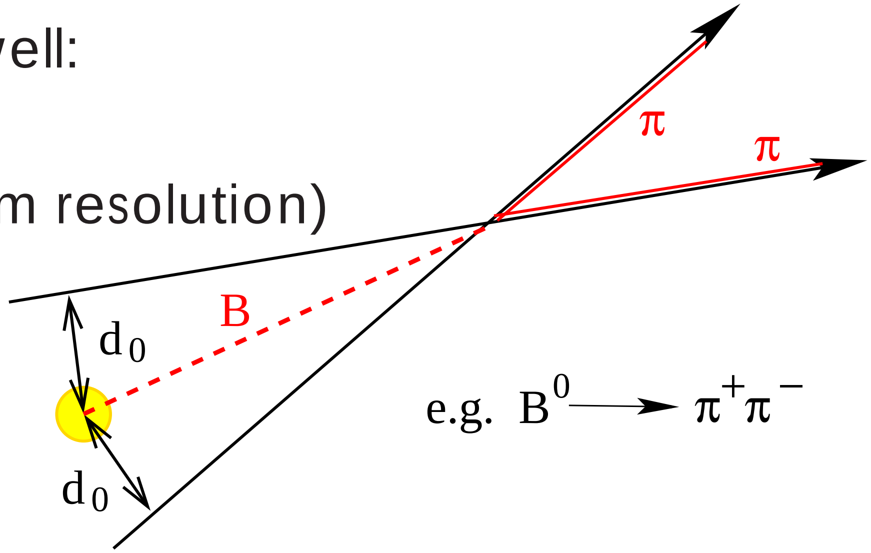


Triggering on Silicon Information (SVT)

- CDF has a 3-tiered trigger system:

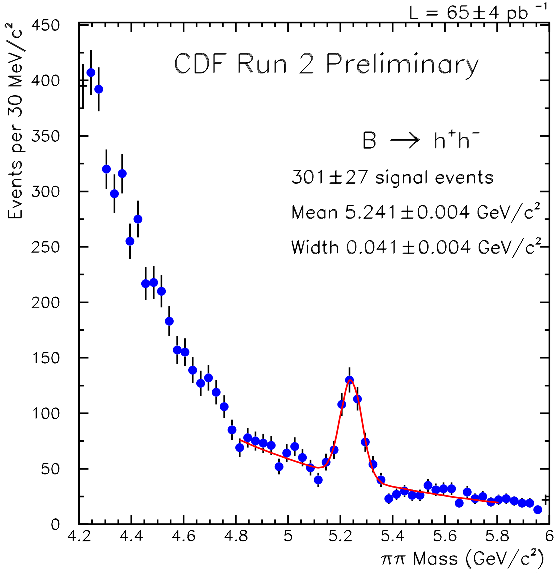
  2.5 MHz → L1 → 30 kHz → L2 → 300 Hz → L3 → 50 Hz → tape

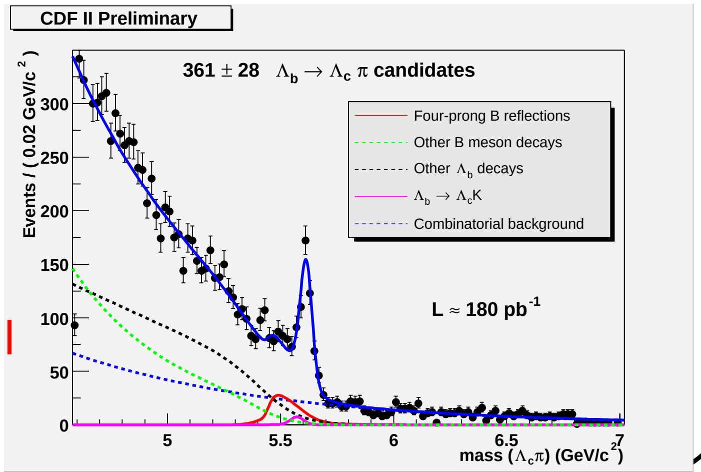
- In Run 2 silicon information being used at level-2
  - looks for 2 tracks with impact parameters (d_0) $> 120\,\mu m$
  - working extremely well:
    IP resolution $\sim 40\ \mu m$
    (includes 30 μm beam resolution)



SVT → significant impact on Run II physics

- top physics and Higgs searches → able to select large $Z \to b\overline{b}$ sample → important for b-jet calibrations
- Will revolutionize Beauty and Charm studies at a Hadron collider → allows triggering on hadronic B decays
- Many nice results early in Run II: First observations of : $\Lambda_b \to \Lambda_c \pi$ $B_s^0 \to K^{\pm}K^{\pm}$, $B_s^0 \to D_s^{\pm}\pi^{\pm}$
- CP violation in $B \to hh$, B_s mixing, B_c properties
- Triggering on silicon will greatly enhance discovery potential in Run II





Summary

- Silicon detectors have greatly extended the physics potential at the Tevatron
- The CDF Run II silicon system is performing well and producing excellent physics results. This is just the beginning of a very rich program of physics involving in the silicon system
- The complexity of the system demands a constant vigilance to maintain this performance throughout Run II (we have less than 10% of the projected luminosity!)
- Future physics discoveries in HEP will rely heavily on the precision tracking afforded by silicon detectors → will be fascinating to observe the next decade unfold