DESY Seminar
Hamburg, April 29, 2008

The CDF Silicon Detector: Design – Operations – Studies

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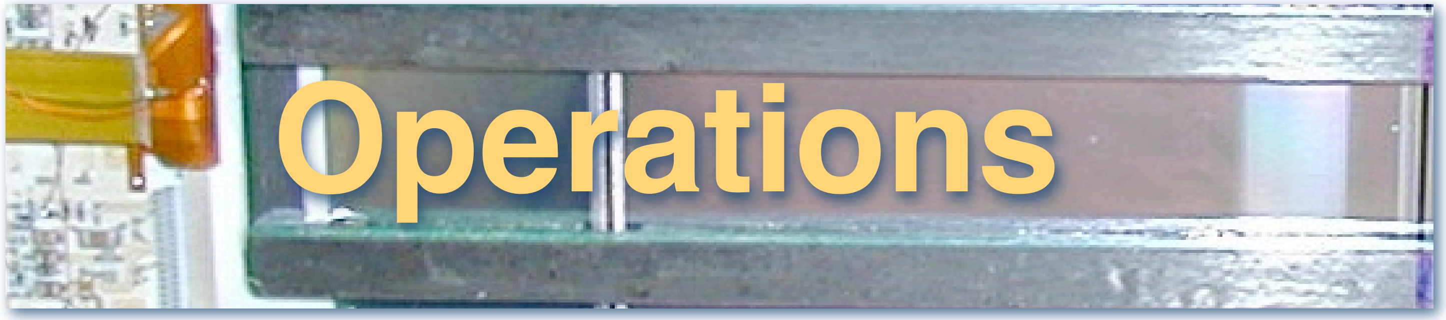
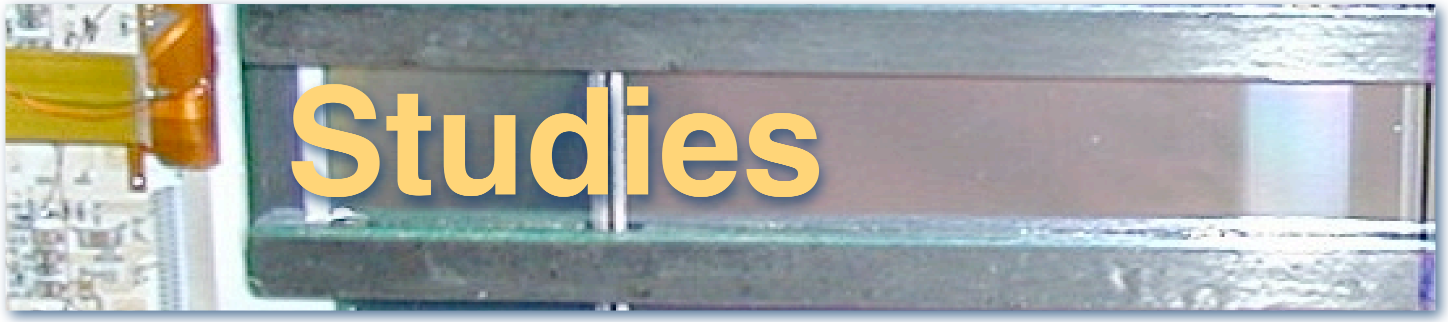
Design


Commissioning


Operations


Studies

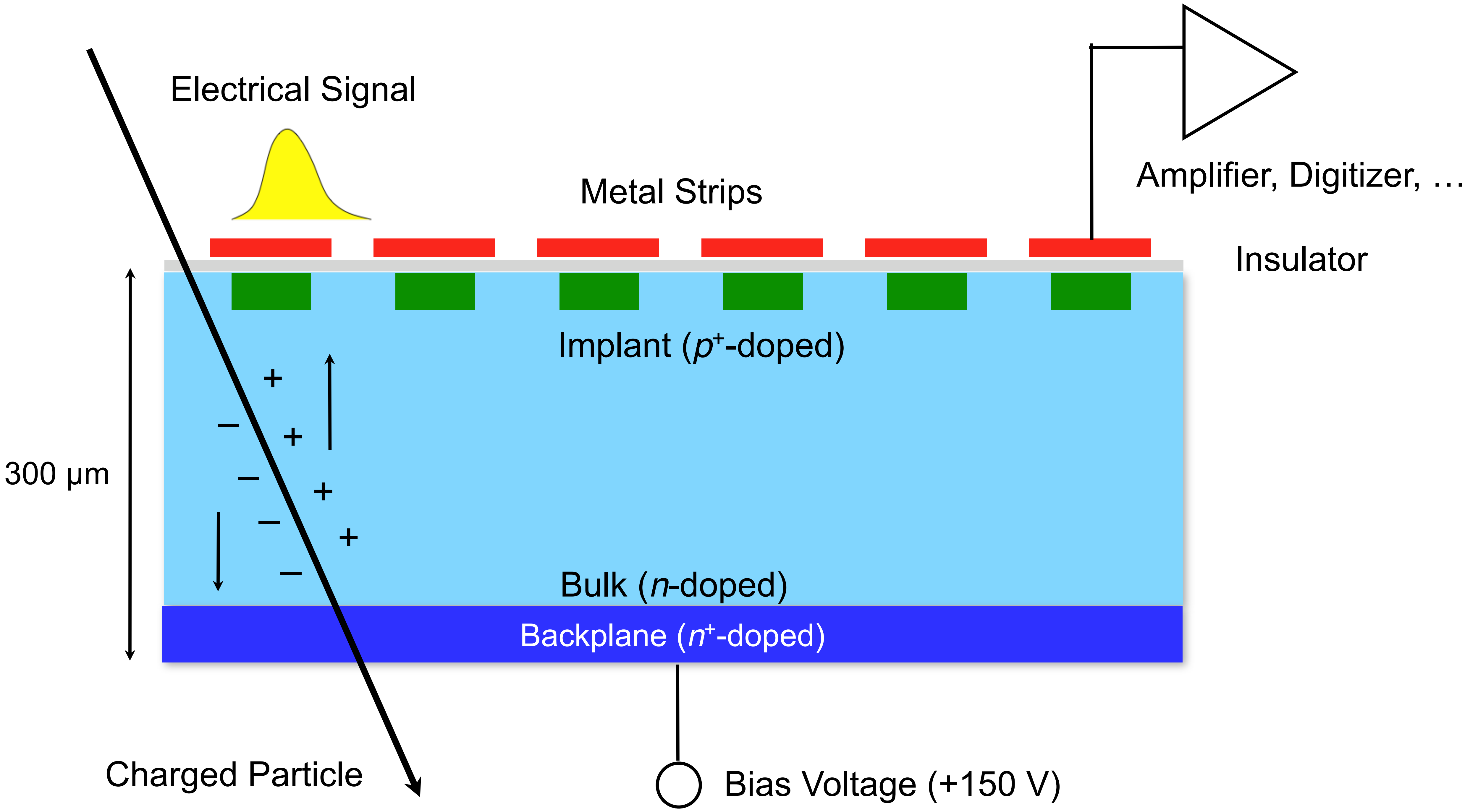

Design


Commissioning


Operations


Studies

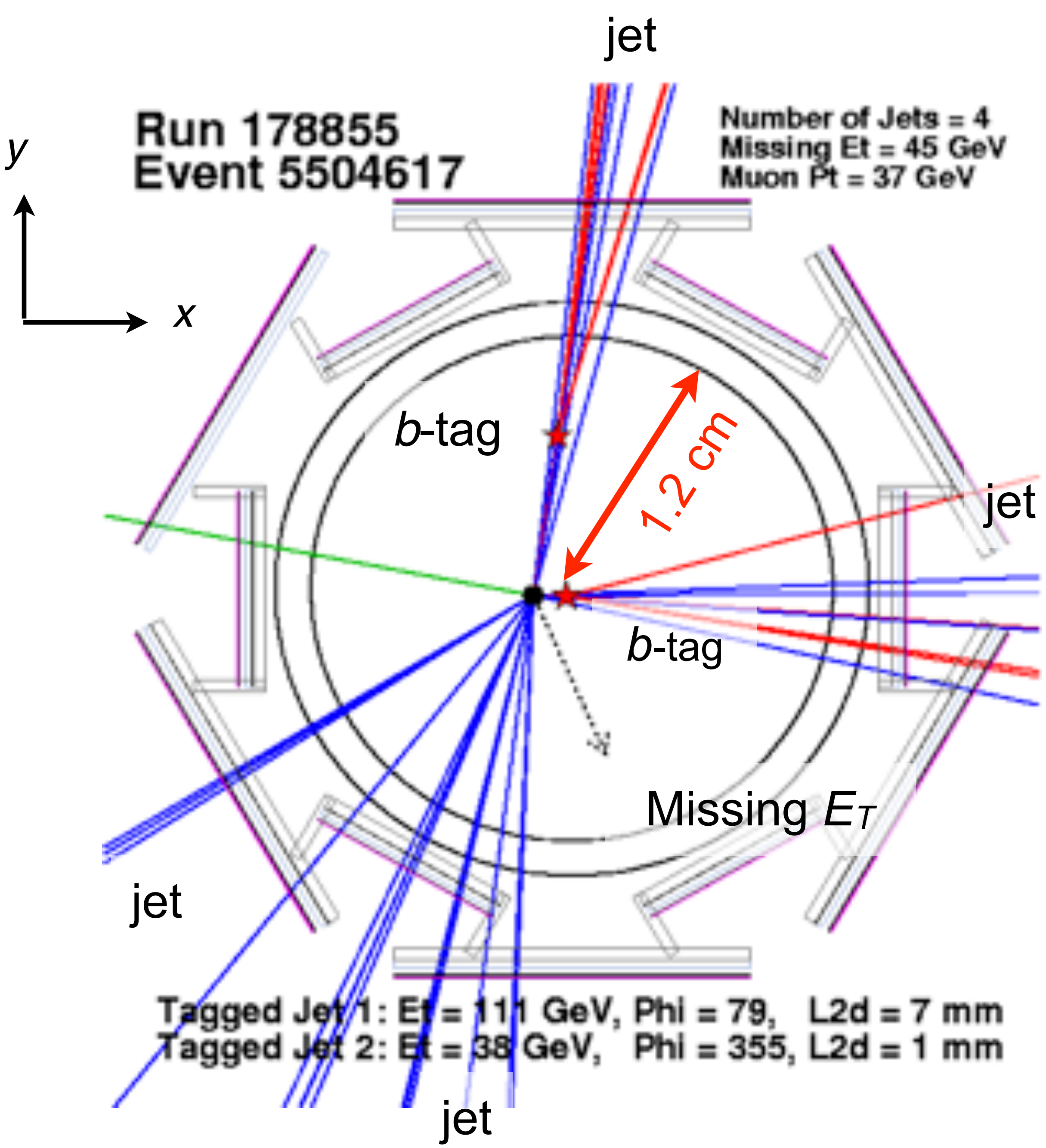
How a Silicon Detector Works



Making Use of Silicon Detectors

- Precision tracking
  - Momentum measurement = measurement of track curvature: dominated by larger tracking device, e.g. drift chamber
  - Impact parameter = closest distance between track helix and beam axis: need precision tracking point close to primary interaction
- *B*-tagging
  - Decays of long-lived *B* mesons ($c\tau \approx 500$ μm) lead to displaced vertices
  - Identification of *b*-jets: displaced secondary vertex (cut on decay length significance)

Double-Tag Event in Layer 00 of CDF Silicon Detector



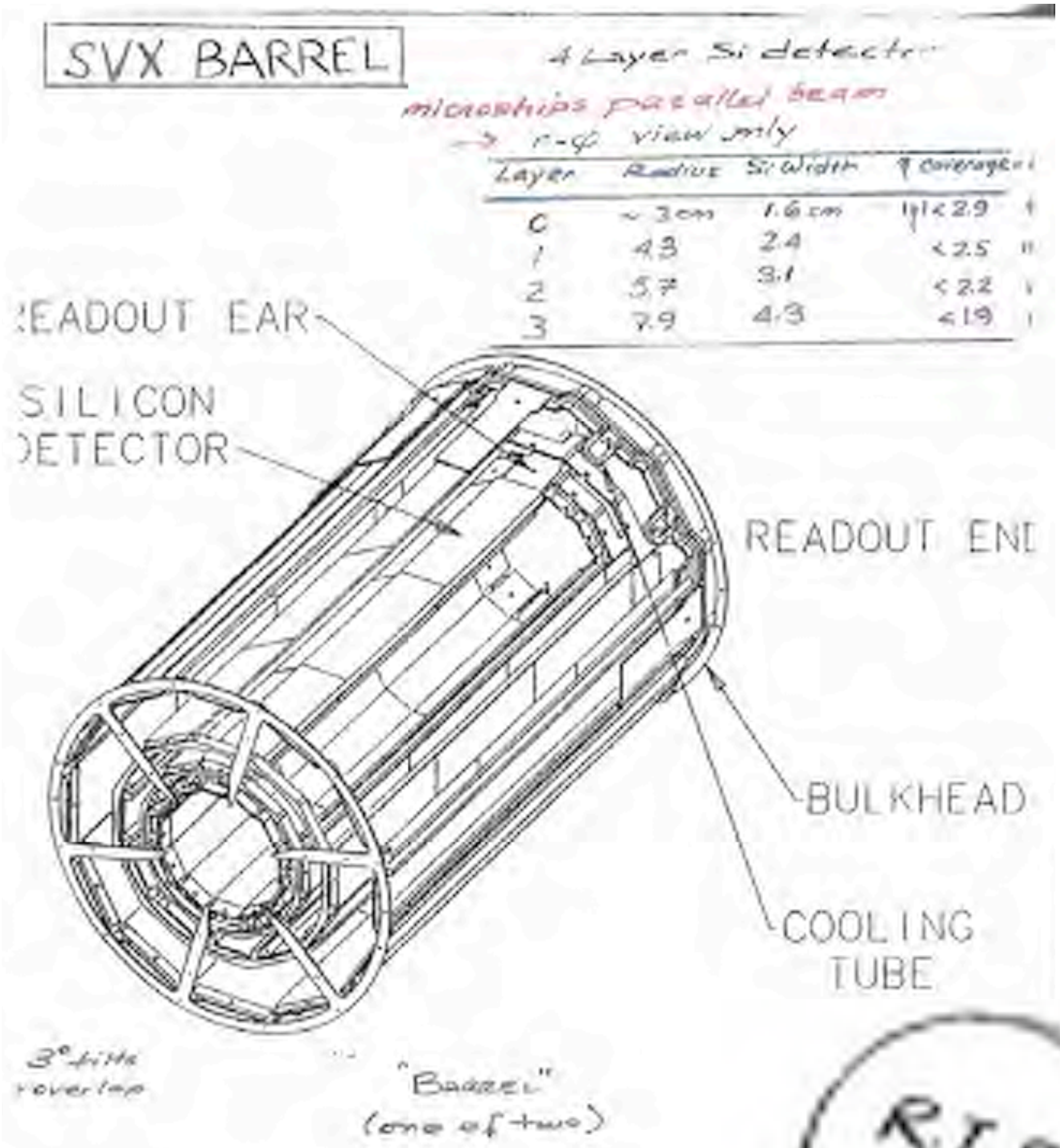
Silicon in HEP: A Little History

- Today: Silicon detectors standard tool for precision tracking and vertexing (esp. secondary vertex heavy flavor tagging)
- First particle physics application of silicon detectors: high-rate fixed target experiments for charm physics (esp. *D* meson lifetimes)
  - CERN NA11 (ACCMOR Collaboration): ~1983
  - Fermilab E691 (Tagged Photon Spectrometer): ~1985
- Silicon microstrip vertex trackers at electron-positron colliders (1990s)
  - All LEP detectors, Mark-II at SLC
  - *B* factories

- First application in a hadron collider (CERN $Sp\bar{p}S$): UA2 (1987)
  - Single cylinder of silicon pads ($8.7 \times 40\ mm^2$): 60 cm long, 14.7 cm radius, 1 m^2 of sensor surface, mounted directly on the beam pipe

Silicon Detector in CDF Run I a

- First ideas in 1983
- Concept of silicon detectors at hadron colliders controversial within CDF (e.g.: occupancy of inner layers too high?)
- First design: SVX (operated 1992–1993)
  - 2 barrels with 4 layers each, 51.1 cm long, radii: 3–8 cm
  - Single sided sensors (60 µm pitch), DC-coupled readout
  - Short lifetime mainly due to radiation damage to the readout chip: increased occupancy, reduced efficiency



PHYSICAL REVIEW D VOLUME 50, NUMBER 5 1 SEPTEMBER 1994

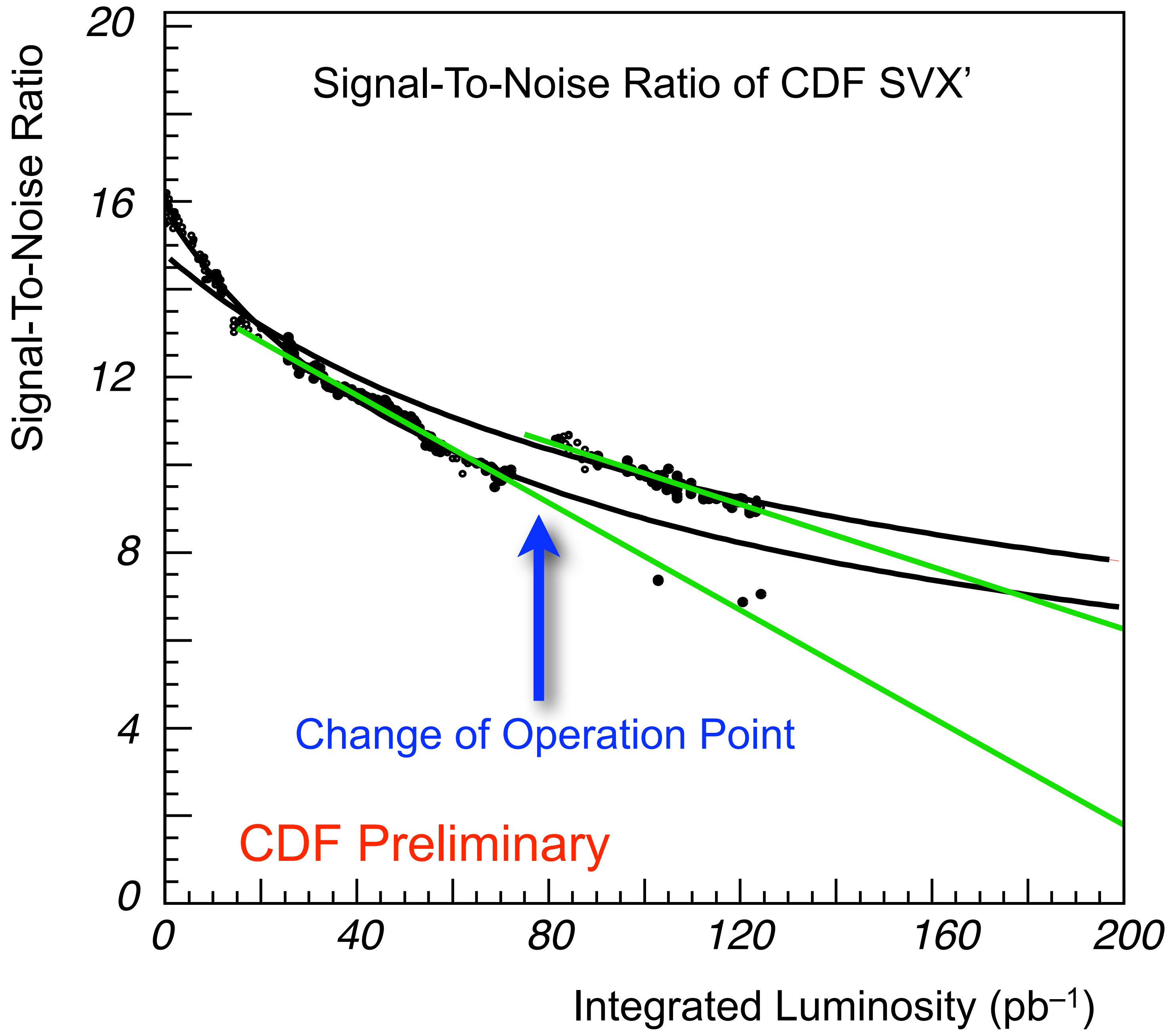
ARTICLES

Evidence for top quark production in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV

F. Abe,[13] M. G. Albrow,[7] S. R. Amendolia,[23] D. Amidei,[16] J. Antos,[28] C. Anway-Wiese,[4] G. Apollinari,[26] H. Areti,[7] P. Auchincloss,[25] M. Austern,[14] F. Azfar,[21] P. Azzi,[20] N. Bacchetta,[18] W. Badgett,[16] M. W. Bailey,[24] J. Bao,[34] P. de Barbaro,[25] A. Barbaro-Galtieri,[14] V. E. Barnes,[24] B. A. Barnett,[12] P. Bartalini,[23] G. Bauer,[15] T. Baumann,[9] F. Bedeschi,[23] S. Behrends,[2] S. Belforte,[23] G. Bellettini,[23] J. Bellinger,[33] D. Benjamin,[32] J. Benlloch,[15] J. Bensinger,[2] D. Benton,[21] A. Beretvas,[7] J. P. Berge,[7] S. Bertolucci,[8] A. Bhatti,[26] K. Biery,[11] M. Binkley,[7] F. Bird,[29] D. Bisello,[20] R. E. Blair,[1] C. Blocker,[29] A. Bodek,[25] V. Bolognesi,[23] D. Bortoletto,[24] C. Boswell,[12] T. Boulos,[14] G. Brandenburg,[9] E. Buckley-Geer,[7] H. S. Budd,[25] K. Burkett,[16] G. Busetto,[20] A. Byon-Wagner,[7] K. L. Byrum,[1] C. Campagnari,[7] M. Campbell,[16] A. Caner,[7] W. Carithers,[14] D. Carlsmith,[33] A. Castro,[20] Y. Cen,[21] F. Cervelli,[23] J. Chapman,[16] M.-T. Cheng,[28] G. Chiarelli,[8] T. Chikamatsu,[31] S. Cihangir,[7] A. G. Clark,[23] M. Cobal,[23] M. Contreras,[5] J. Conway,[27] J. Cooper,[7] M. Cordelli,[8] D. P. Coupal,[29] D. Crane,[7] J. D. Cunningham,[2] T. Daniels,[15] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[23] M. Dell'Orso,[23] L. Demortier,[26] B. Denby,[23] M. Deninno,[3] P. F. Derwent,[16] T. Devlin,[27] M. Dickson,[25] S. Donati,[23] R. B. Drucker,[14] A. Dunn,[16] K. Einsweiler,[14] J. E. Elias,[7] R. Ely,[14] E. Engels, Jr.,[22] S. Eno,[5] D. Errede,[10] S. Errede,[10] Q. Fan,[25] B. Farhat,[15] I. Fiori,[3] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[9] M. Frautschi,[18] J. Freeman,[7] J. Friedman,[15] H. Frisch,[5] A. Fry,[29] T. A. Fuess,[1] Y. Fukui,[13] S. Funaki,[31] G. Gagliardi,[23] S. Galeotti,[23] M. Gallinaro,[20] A. F. Garfinkel,[24] S. Geer,[7] D. W. Gerdes,[16] P. Giannetti,[23] N. Giokaris,[26] P. Giromini,[8] L. Gladney,[21] D. Glenzinski,[12] M. Gold,[18] J. Gonzalez,[21] A. Gordon,[9] A. T. Goshaw,[6] K. Goulianos,[26] H. Grassmann,[6] A. Grewal,[21] G. Grieco,[23] L. Groer,[27] C. Grosso-Pilcher,[5] C. Haber,[14] S. R. Hahn,[7] R. Hamilton,[9] R. Handler,[33] R. M. Hans,[34] K. Hara,[31] B. Harral,[21]

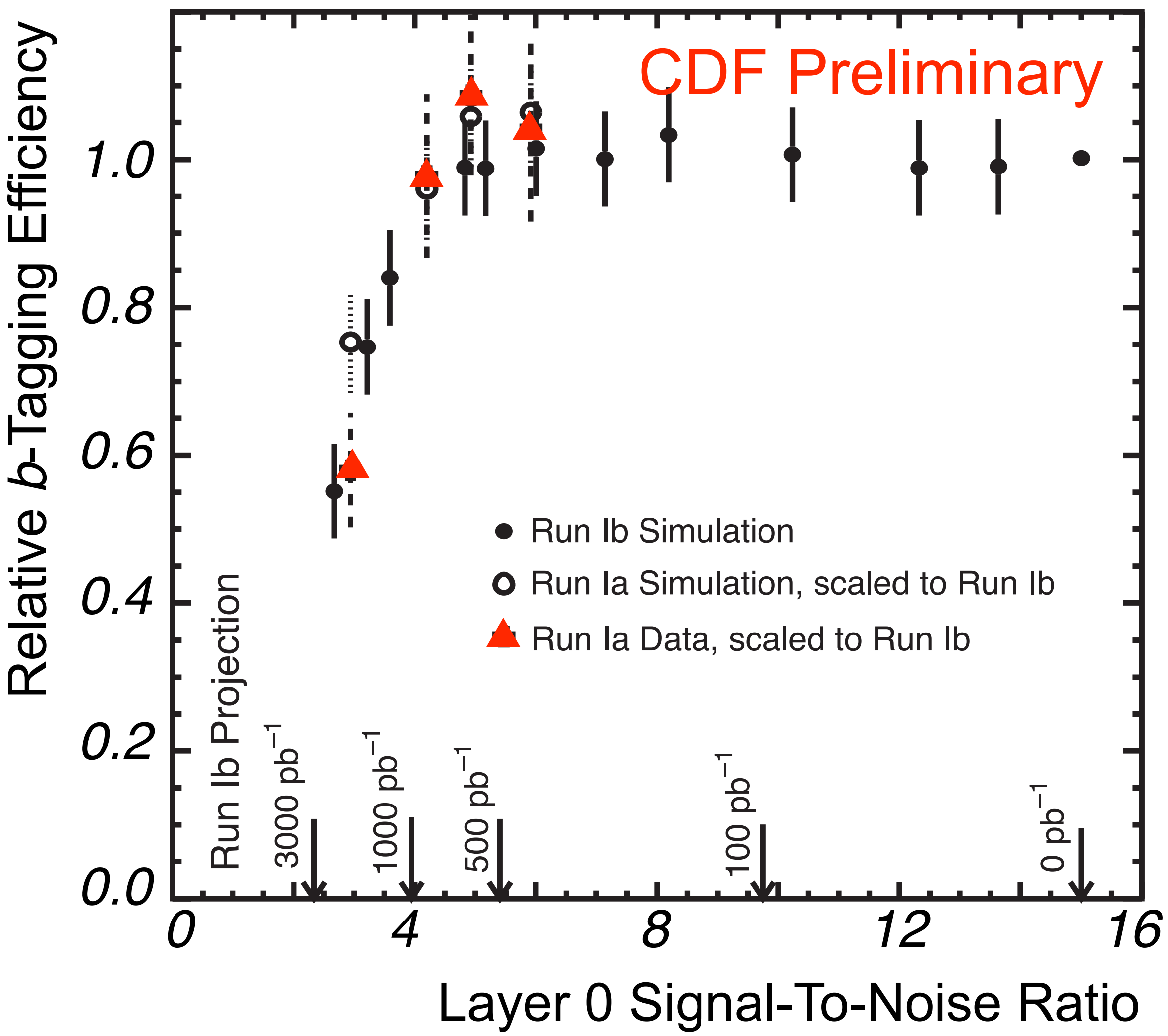
…The Top!

- Second attempt: SVX' (operated 1993–1996)
  - Mechanical design similar to SVX, slightly smaller inner radius (2.8 cm)
  - Radiation hard readout chip
  - AC-coupled readout with FOXFET (Field Oxide FET) biasing
  - Signal-to-noise ratio (SNR) decreases faster than expected (attributed to FOXFET biasing)
  - Reduction of SNR partly compensated by changes in detector operation (integration time, temperature, bias voltage)



CDF Run I: Lessons Learnt

- Secondary vertex *b*-tagging:
  - Efficiency drops quickly for SNR smaller than approx. 3
  - But: top quark discovery with data taken with SNR of 6 → 3
- Detector resolution:
  - Great impact parameter resolution (SVX' only: 35 μm, 46 μm including beam spot)
  - Poor p_T resolution: short lever arm, radii: 3–8 cm → additional layer at larger radius (~20 cm)
- Some limitations can be overcome by clever software (and people)

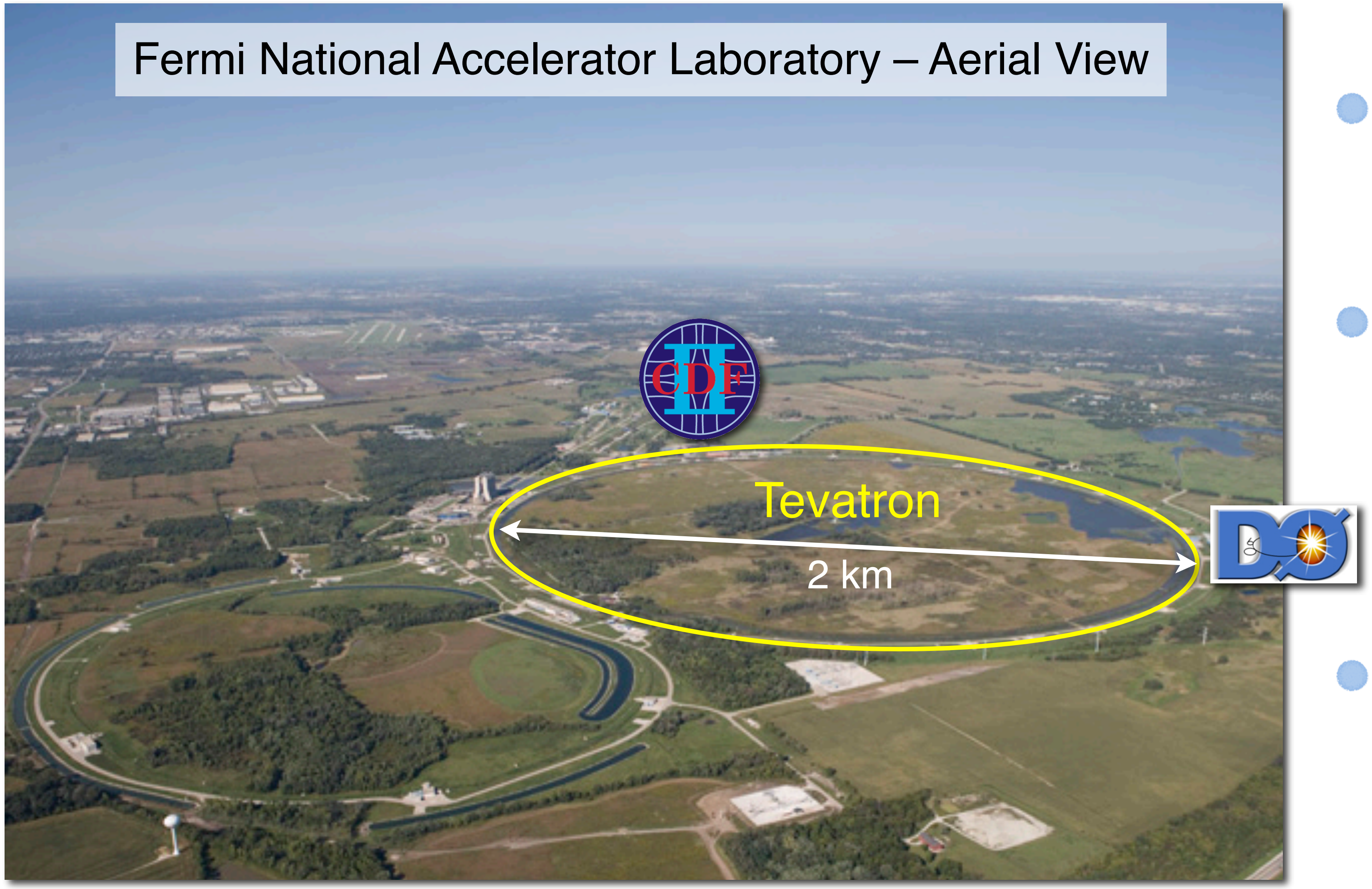


For more details on the history of Silicon detectors in CDF (and CMS):

J. Incandela, *Life on the Critical Path*

(talk given at the 6th International "Hiroshima" Symposium, Carmel, CA, September 11–15, 2006)

Tevatron Run II: 2001–2009 (2010?)

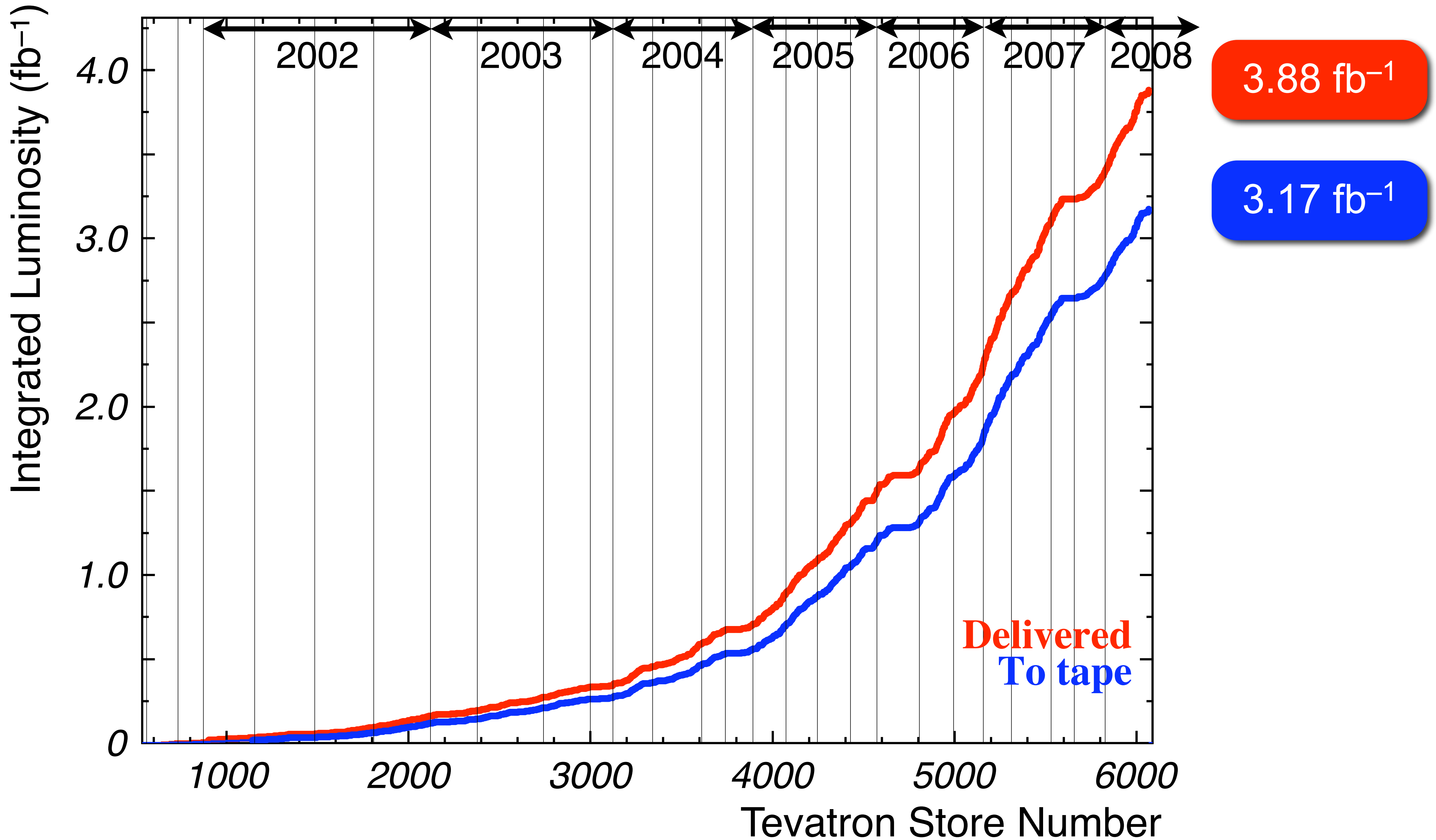


[Fermilab Visual Media Service]

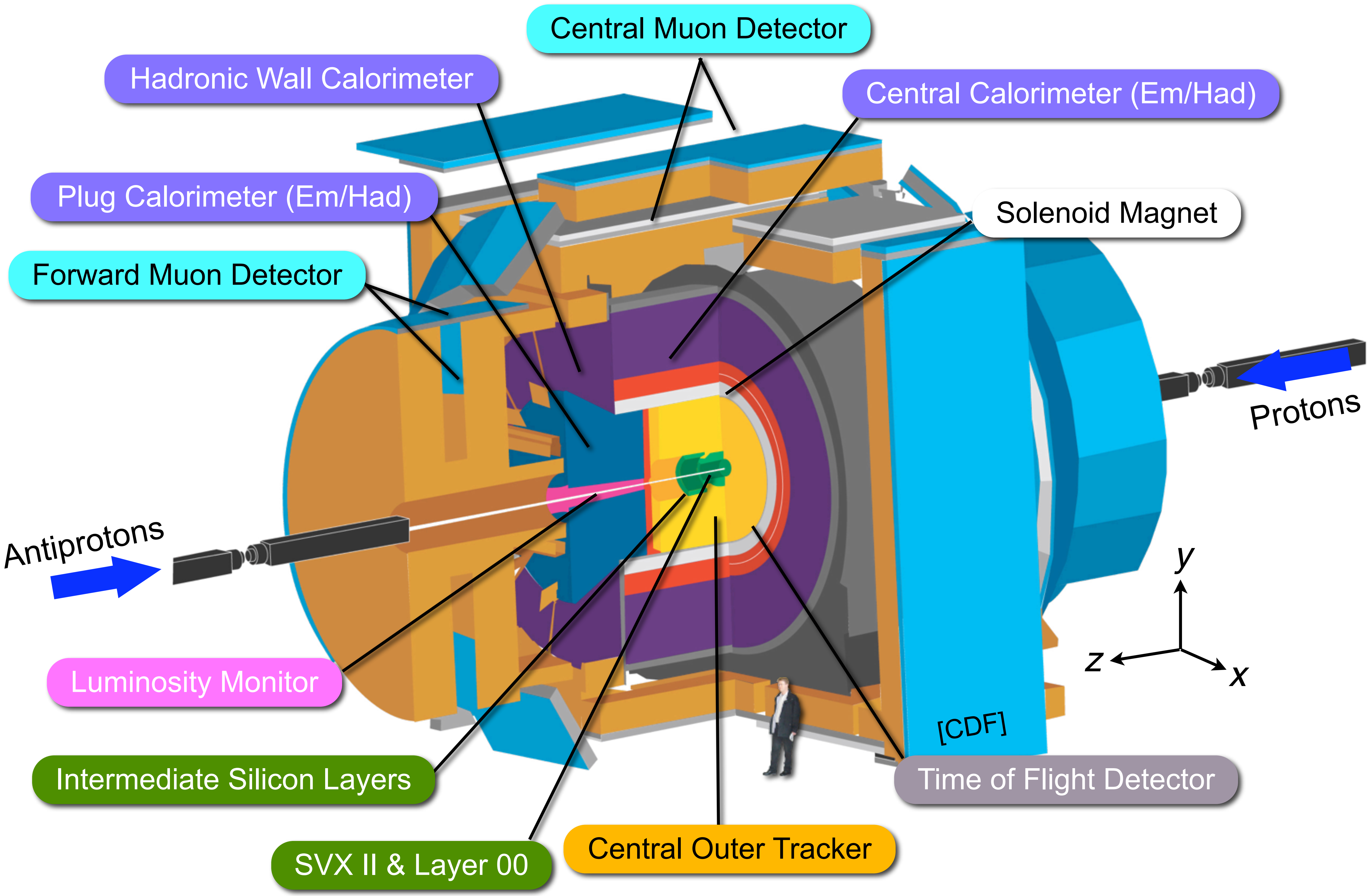
- Proton-antiproton collider: $\sqrt{s}$ = 1.96 TeV
- 36×36 bunches, collisions every 396 ns
- Record instantaneous peak luminosity: 316 $\mu b^{-1} s^{-1}$ (1 $\mu b^{-1} s^{-1} = 10^{30} cm^{-2} s^{-1}$)
- Luminosity goal: 5.5–6.5 fb^{-1} of integrated luminosity by 2009, running in 2010 currently under discussion
- Two multi-purpose detectors: CDF and DØ

Tevatron Performance

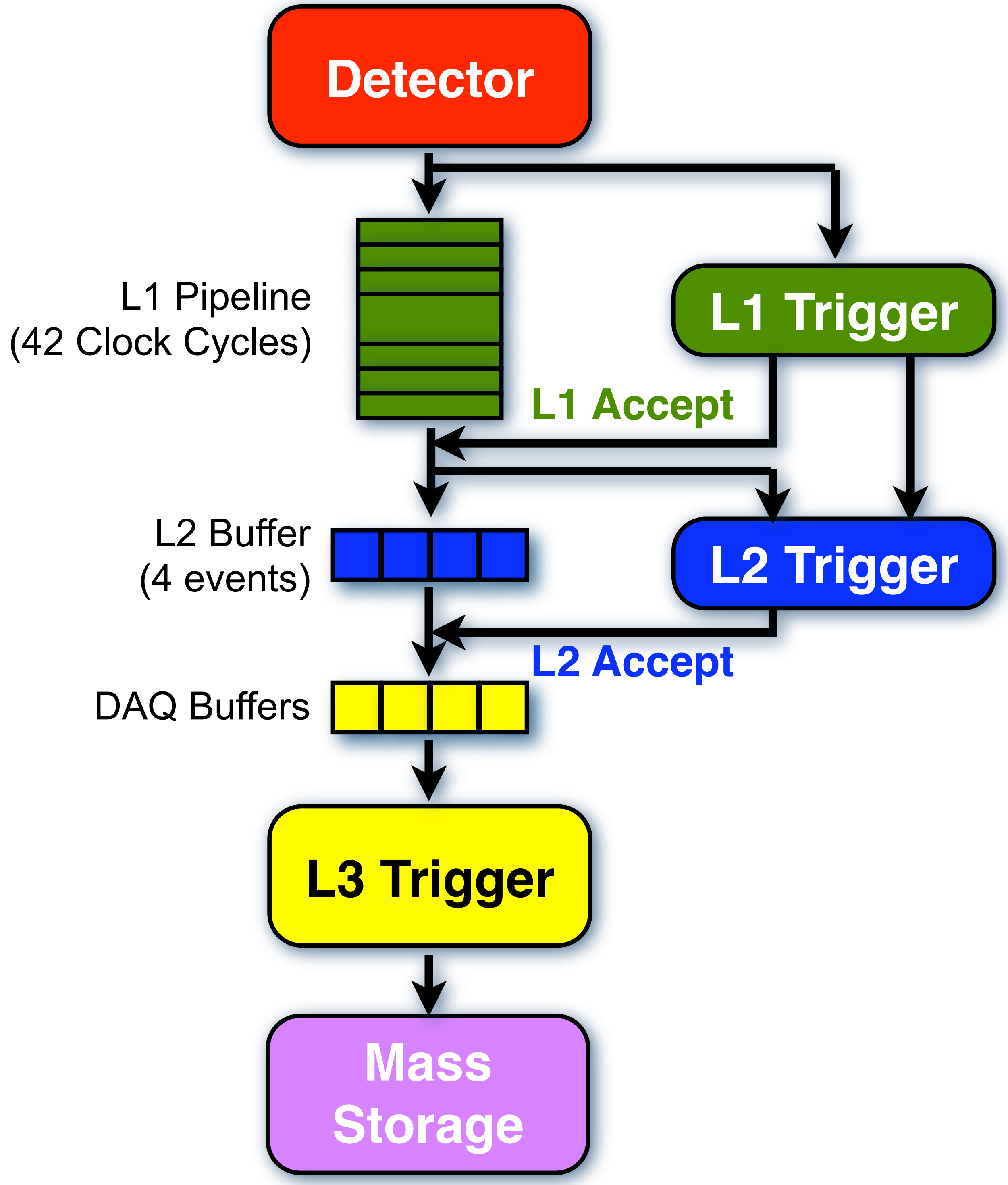
- Tevatron continues to perform very well:
  - Almost 4 fb^{-1} delivered by Tevatron as of April 2008
  - More than 3 fb^{-1} recorded by CDF



The CDF II Detector



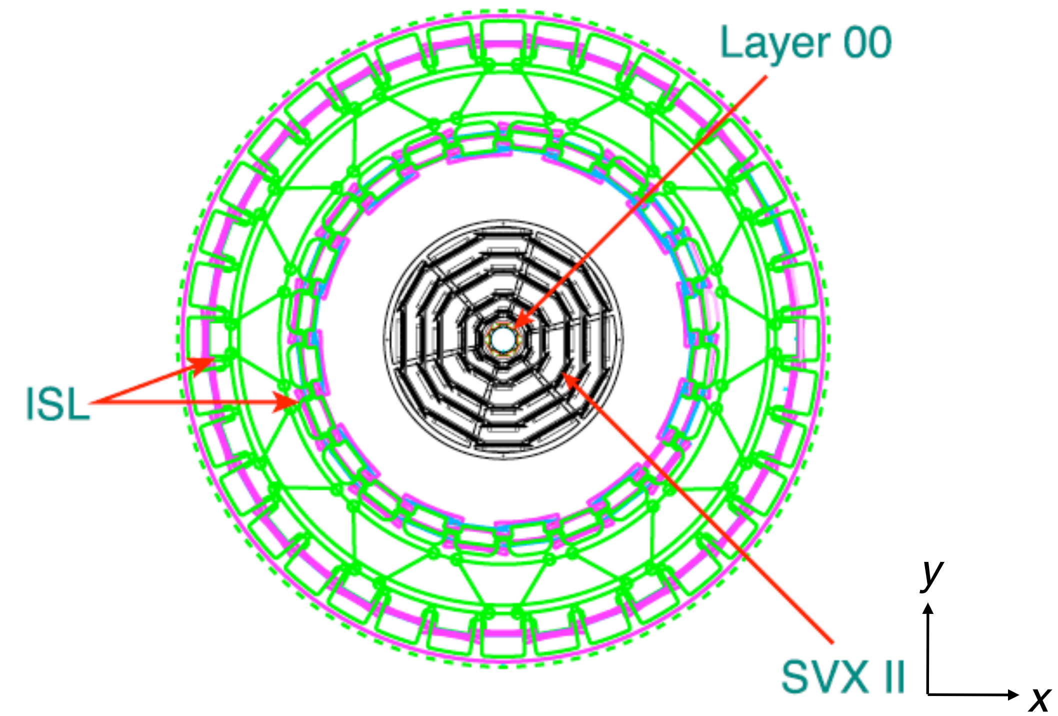
CDF Trigger Overview

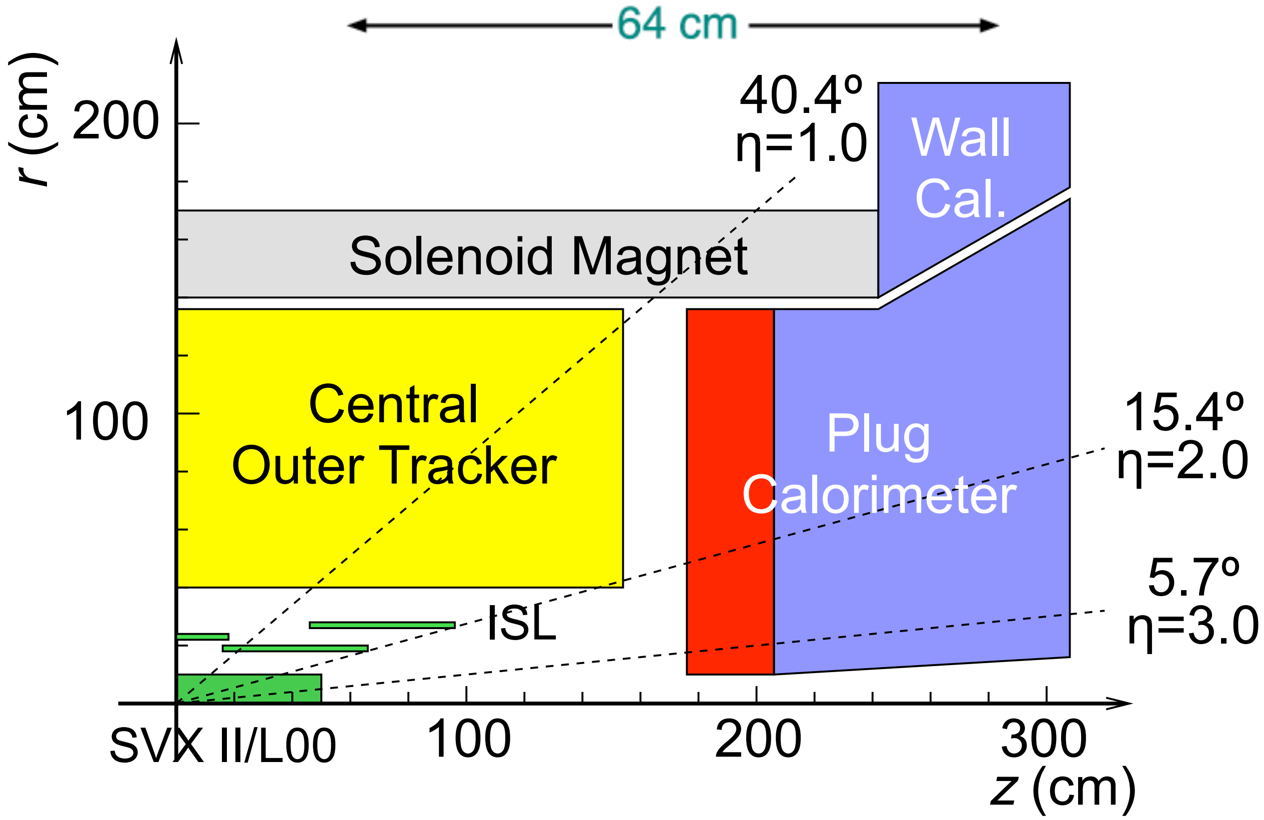


- Level 1 Trigger:
  - Synchronous hardware trigger
  - Input rate: 1.7 MHz
- Level 2 Trigger:
  - Hardware & software triggers
  - Input rate: up to 35 kHz
- Level 3 Trigger:
  - PC farm
  - Input rate: up to 1 kHz
- Special role of Silicon detector due to Silicon Vertex Trigger (SVT)
  - Silicon information used in SVT, i.e. at Level 2
    → must be read out at Level 1

Silicon Detectors in CDF

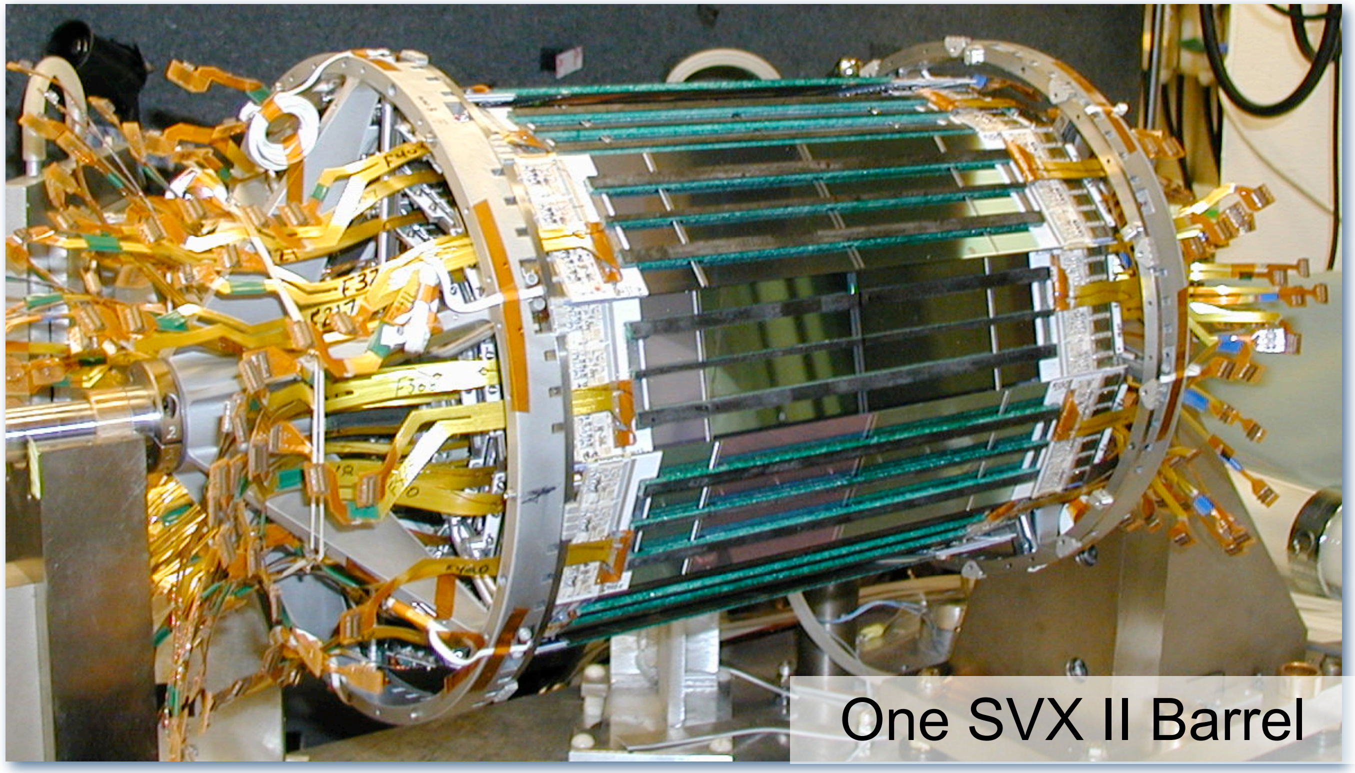
- 7–8 silicon layers (6 m^2)
- 722,432 readout channels
  on 5,456 readout chips
- Three sub-detectors:
  - SVX II
  - Intermediate Silicon Layers (ISL)
  - Layer 00 (L00)
- Purpose:
  - Precision tracking
  - Reconstruction of primary and secondary vertices





SVX II: The Core Detector

- Mechanical structure:
  3 barrels with 6 bulkheads,
  12 wedges each (1m long)
- 5 layers of double-sided silicon sensors at radii of 2.5–10.6 cm
  - Layers 0, 1, 3 (Hamamatsu): axial and 90º strips
  - Layers 2 and 4 (Micron): axial and 1.2º stereo strips
  - Strip pitch: 60–140 µm
  - AC-coupled readout: micro-discharges limit bias voltage to 170 V (Hamamatsu) and 80 V (Micron)

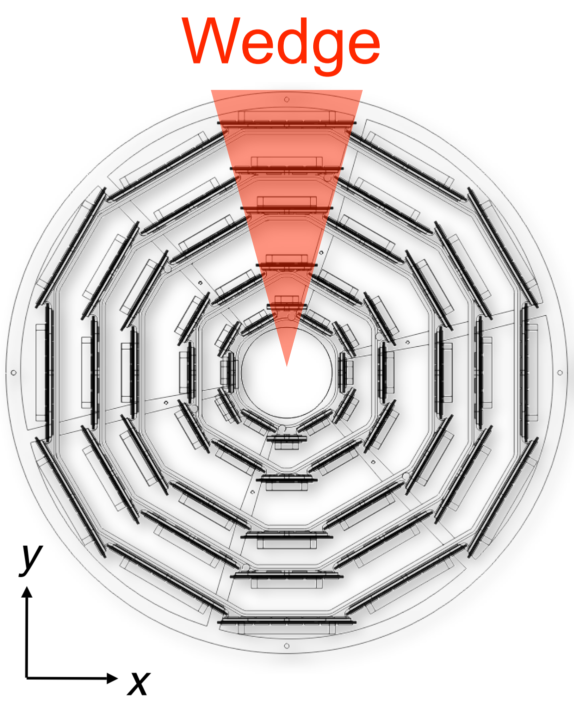


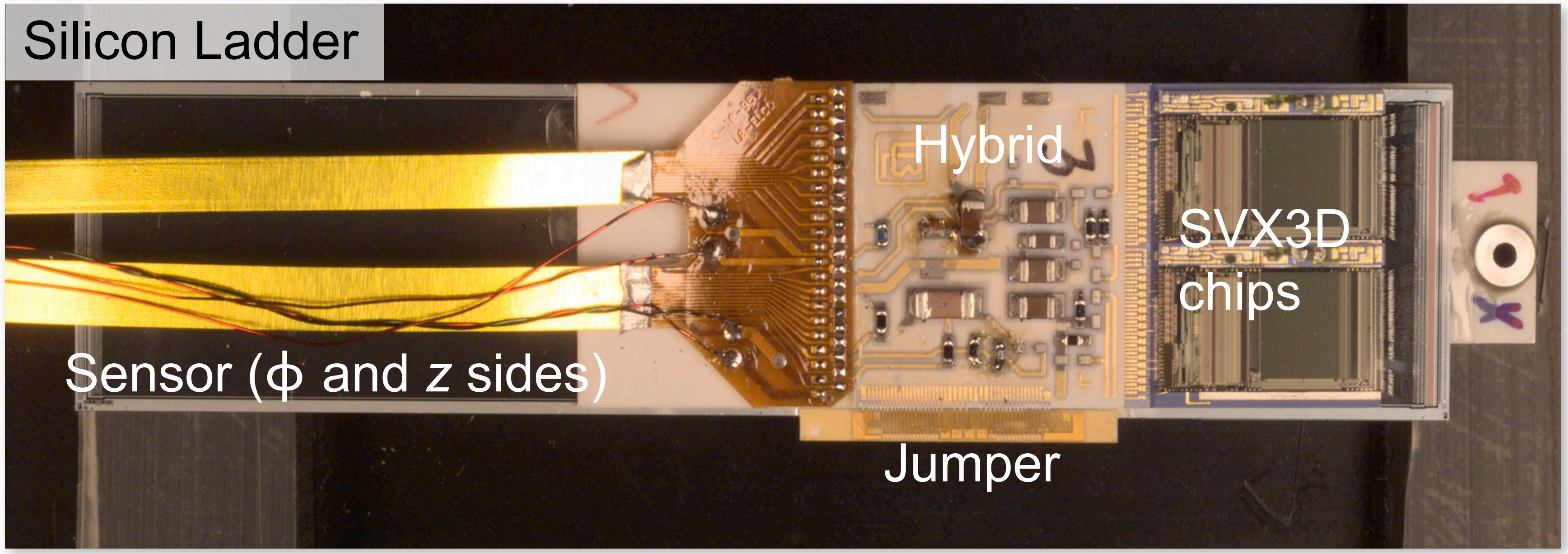
One SVX II Barrel

SVX II Ready for Installation

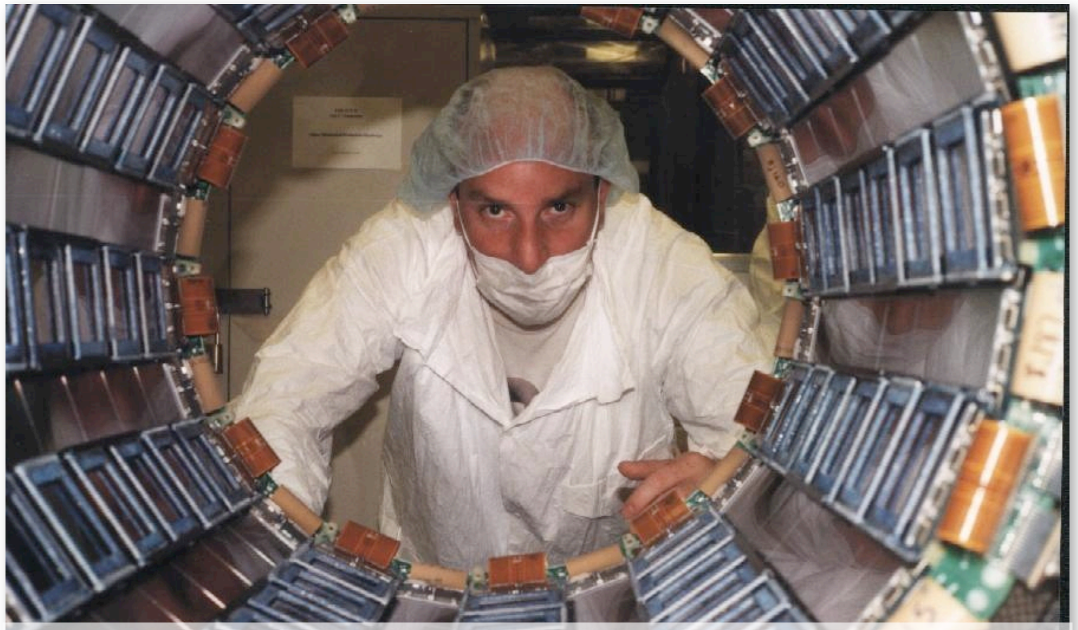
SVX and SVT

- Silicon Vertex Trigger (SVT):
  - Fast track reconstruction and cut on impact parameter at trigger level
  - Essential for trigger on hadronic *B* decays
- Requirements for using SVX II in the SVT:
  - Easy geometrical mapping: symmetric 12-fold wedge structure
  - Full SVX II data available at L2: fast readout
  - Tight alignment constraints: SVX II must be parallel to the beam to within 100 μrad



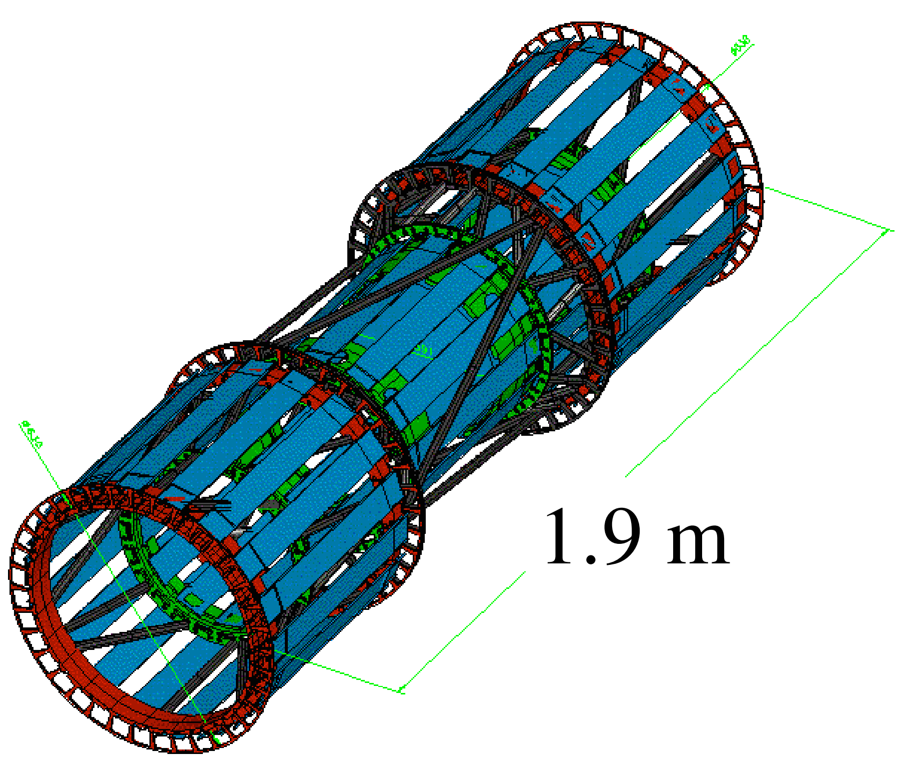


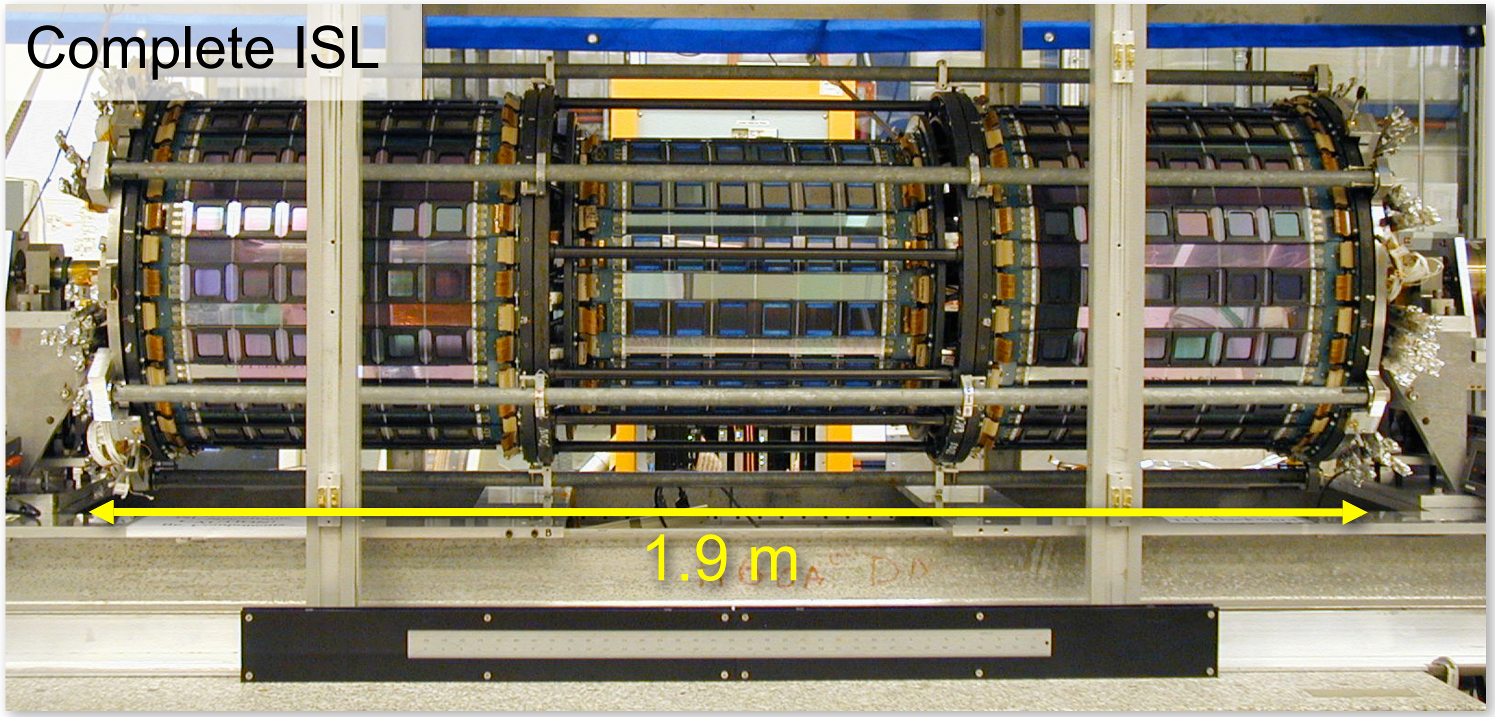
ISL: The Extension



J. Goldstein: “Don’t mess with my detector!”

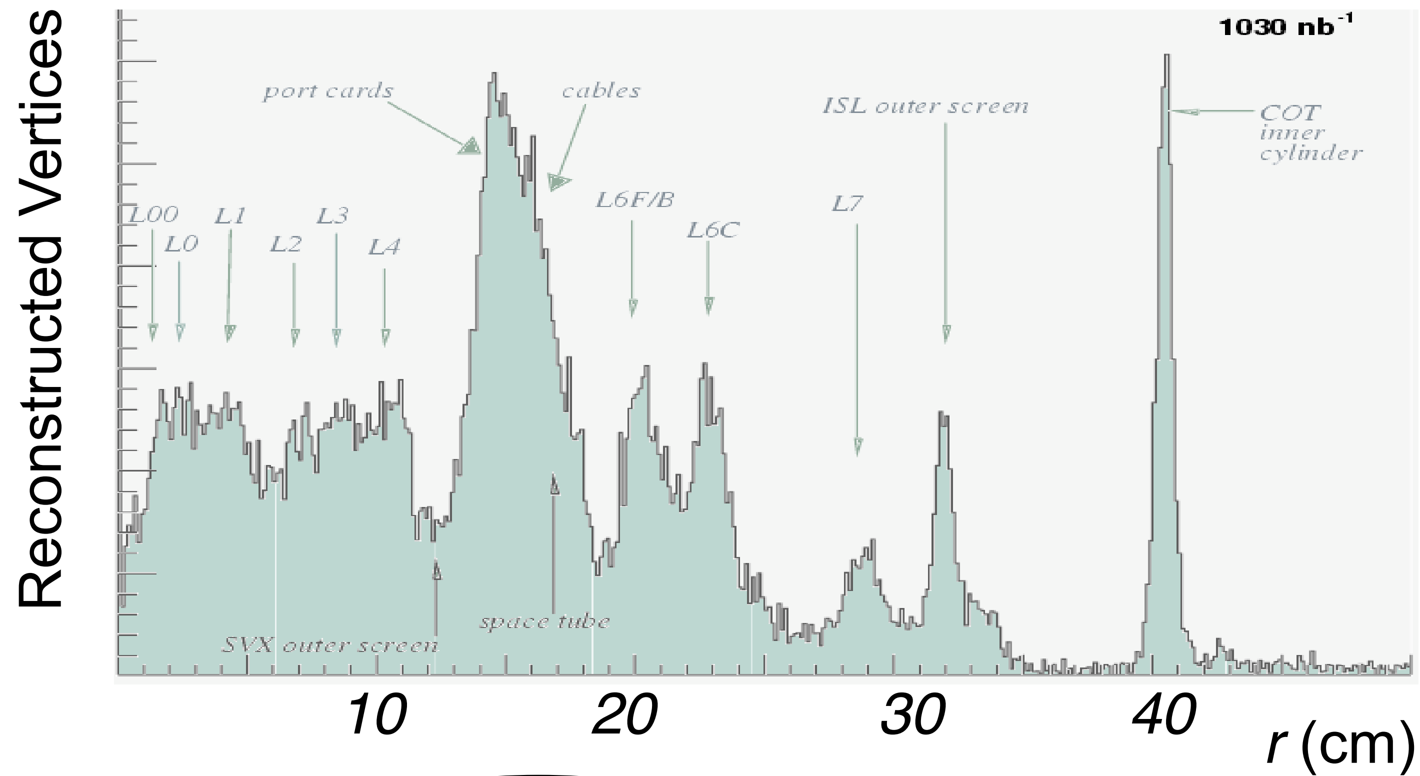
- One central layer (|η| < 1): link tracks from SVX II to wire chamber
- Two forward layers (1 < |η| < 2): tracking at large pseudorapidities
- Strip pitch: 112 μm



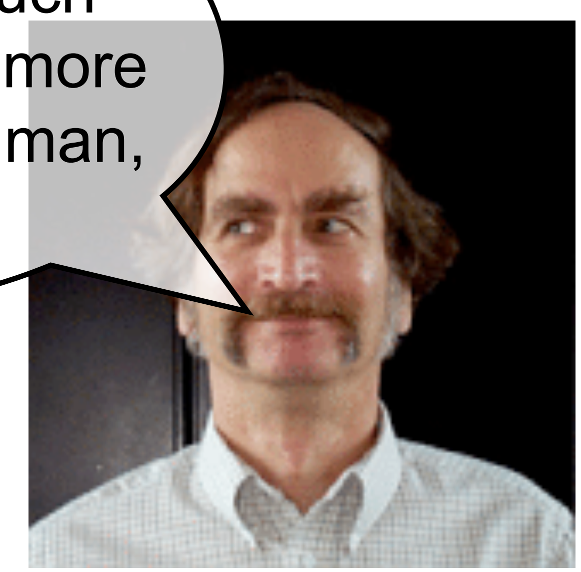


Material Budget and Longevity

- SVX II: cables, hybrids, portcards, and beryllium bulkheads introduce a lot of material
  - Poor impact parameter resolution for low-p_T tracks
  - Affects also high-p_T physics: need low-p_T tracks for *b*-tagging
- LHC-style radiation-hard silicon not yet available when SVX II was designed
  - Inner layers may die of radiation damage
- Solution: Layer 00
  - New low-mass layer directly on the beam pipe
  - Use radiation-hard silicon

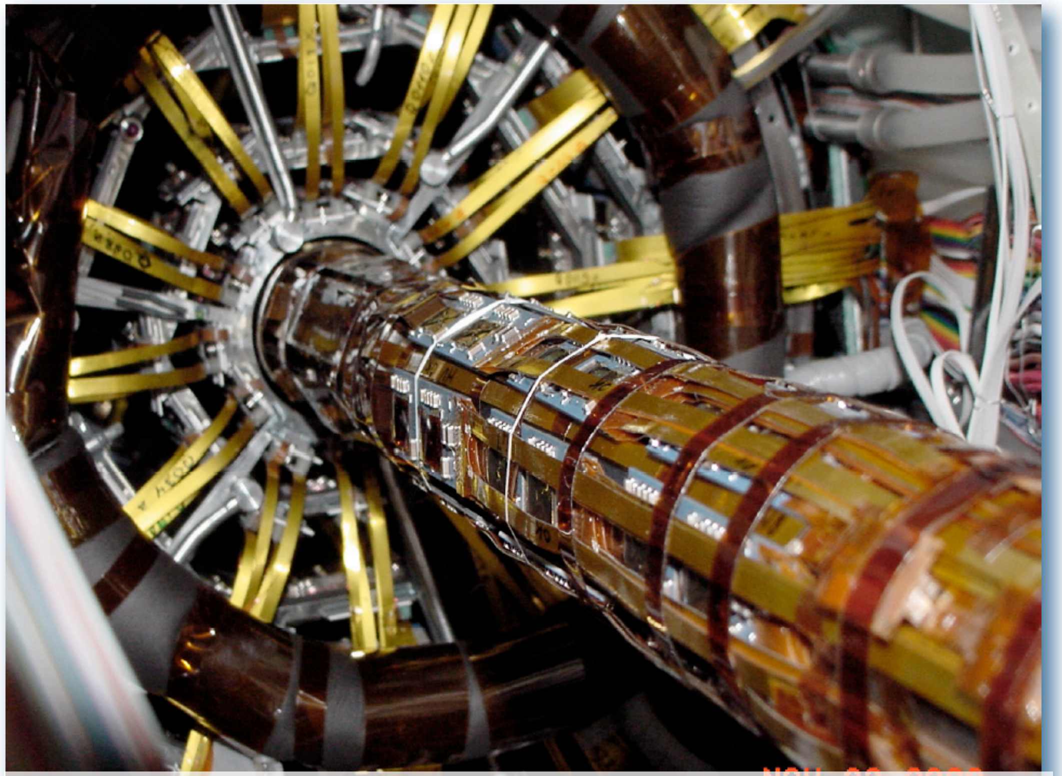


How do you fix a problem of too much material by adding more material? (L. Nodulman, 1997)

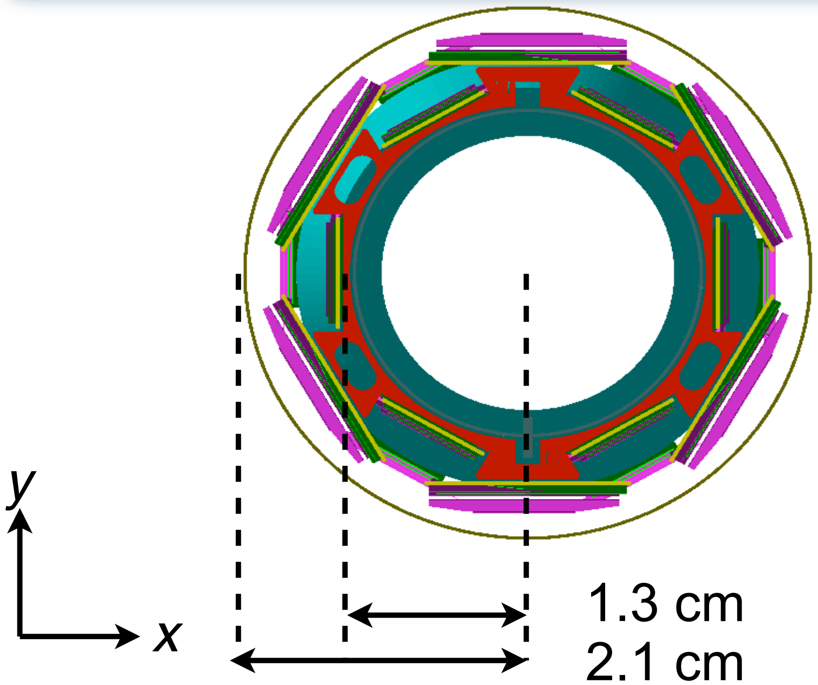


L00: The Beam Pipe Layer

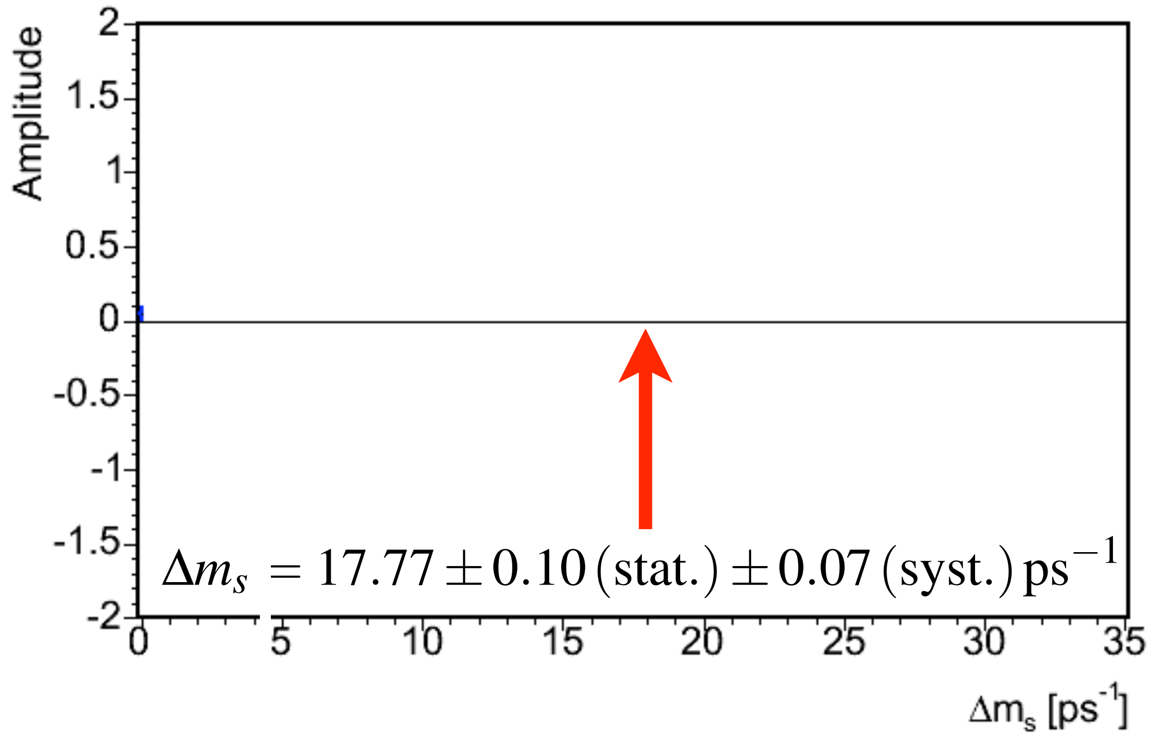
- Material budget:
  - Goal: 0.01 X_0 (achieved)
  - Below r = 2 cm, 0.01 X_0 of additional material does not matter
- Material and radiation:
  - Remove readout electronics from tracking volume
  - Transmit analog signals to chips
- Single-sided “LHC style” sensors:
  - Non-oxygenated (Hamamatsu, SGS Thomson)
  - Oxygenated (Micron)
- Actively cooled support structure
- Strip pitch: 25 μm, every second strip read out



Insertion of L00: 300 μm clearance!



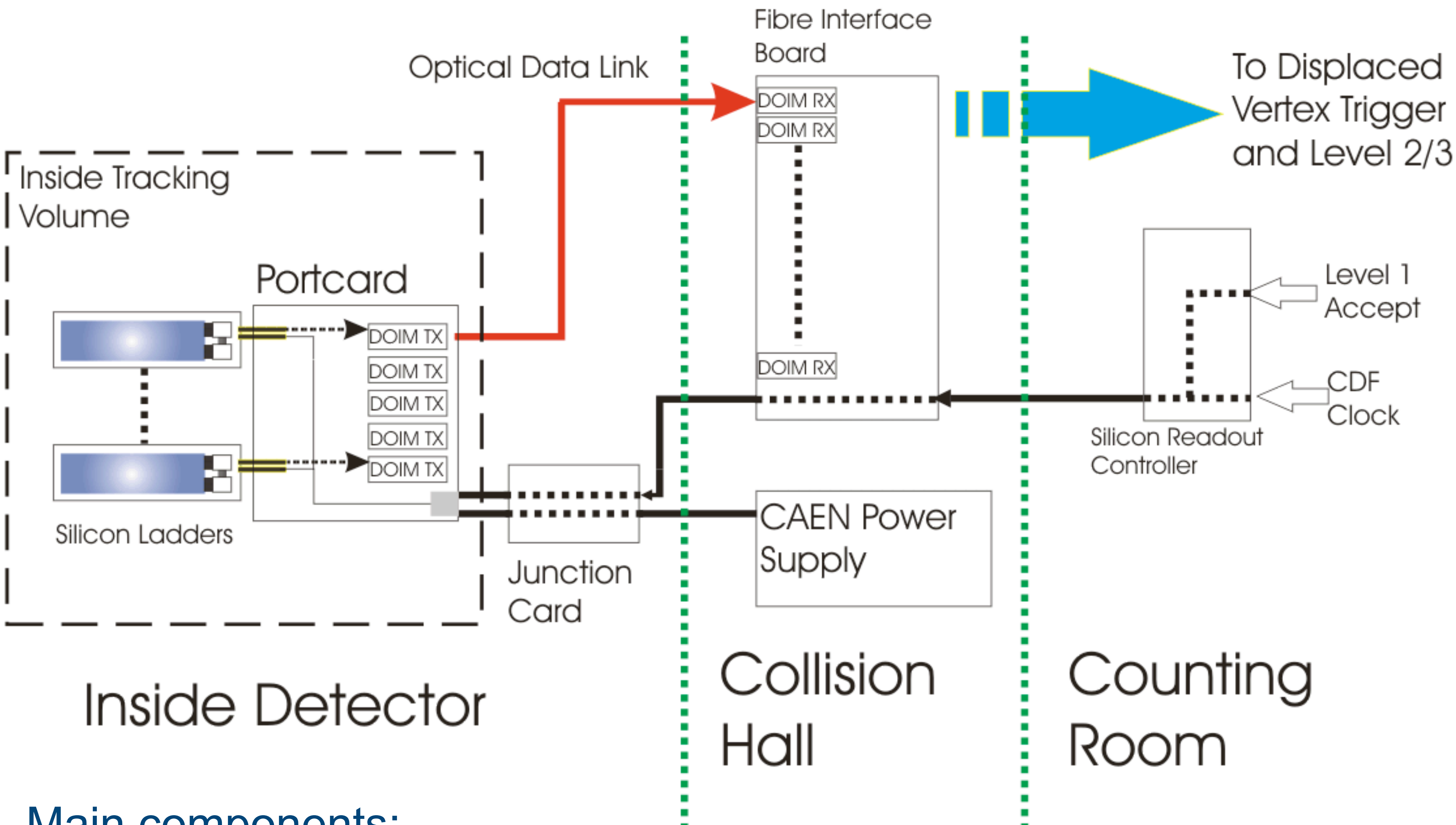
B_s Oscillations



[Aart Heijboer, U. of Pennsylvania]

- Discovery of B_s oscillations: Phys. Rev. Lett. **97** (2006) 242003
- Layer 00 makes the difference: uncertainty on oscillation amplitude reduced by factor of >2
  → 5σ discovery instead of 3σ evidence
- Achieved decay time resolution of σ_t = 90 fs (1/4 of measured oscillation period)
- Resolution corresponds to approx. 27 μm decay length resolution

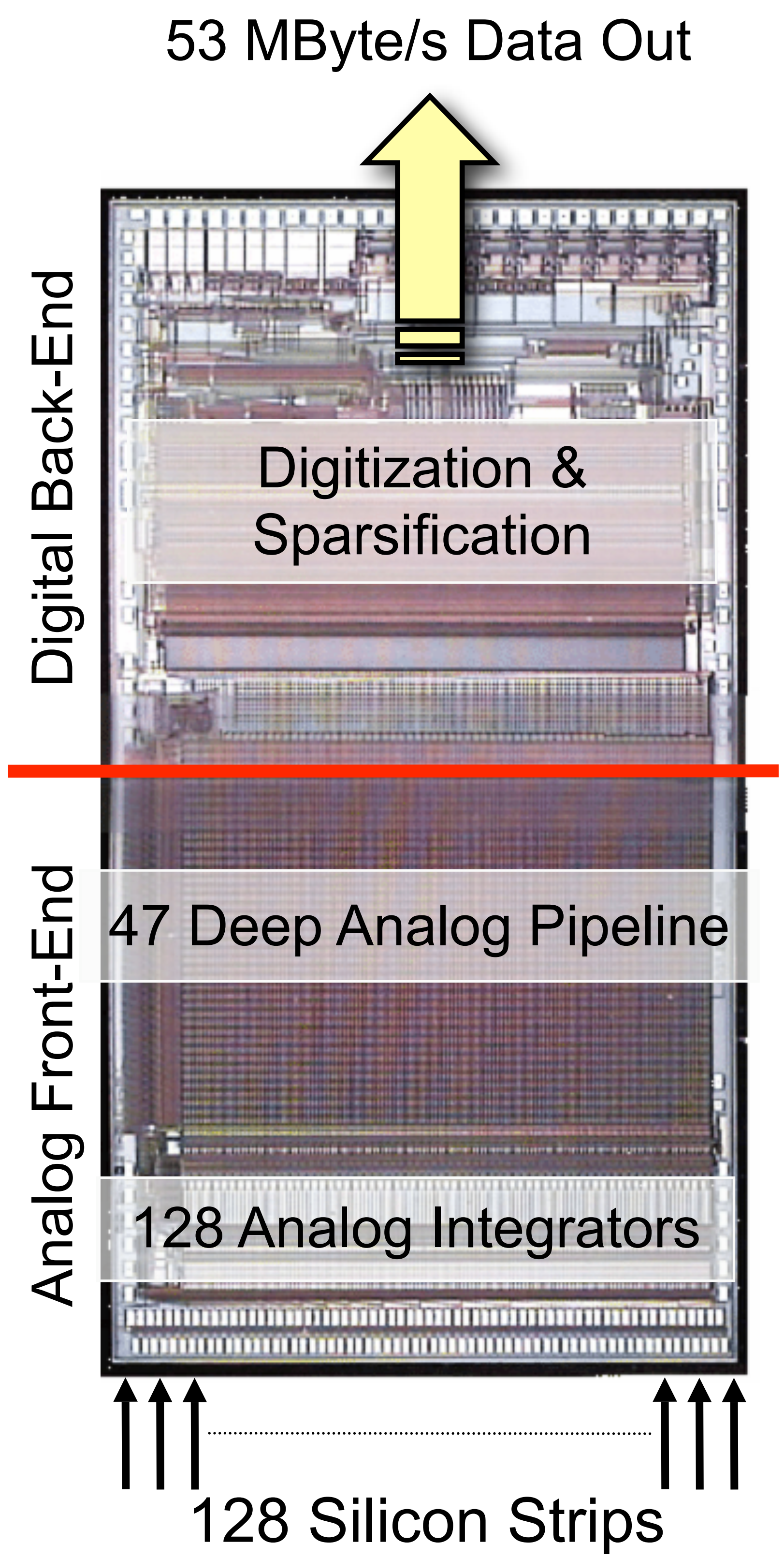
Silicon DAQ: A Simplified View



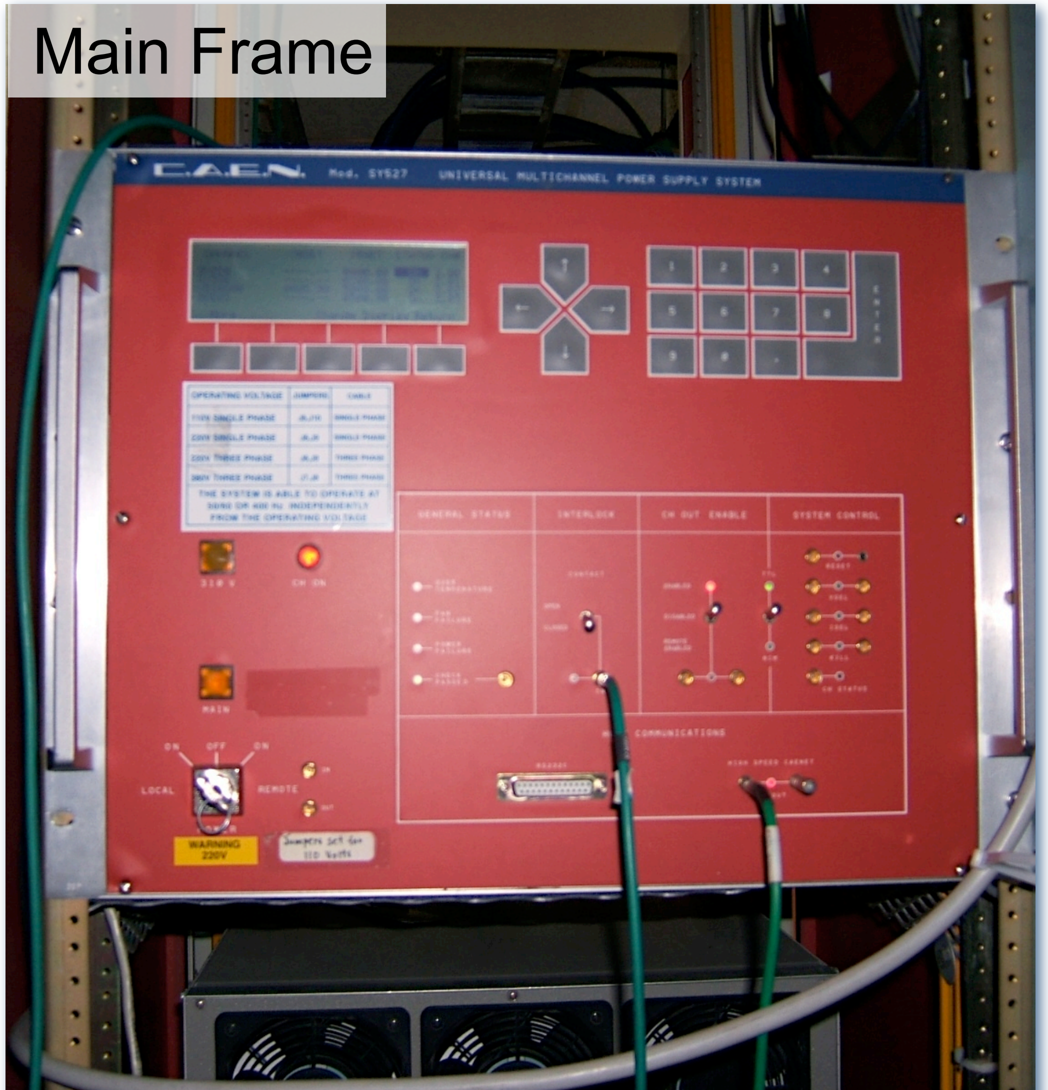
- Main components:
  - Silicon Readout Controller (SRC): "brain" of the system
  - Fiber Interface Board (FIB): control signals and optical readout
  - Portcard: chip commands and optical transmitters (DOIMs)

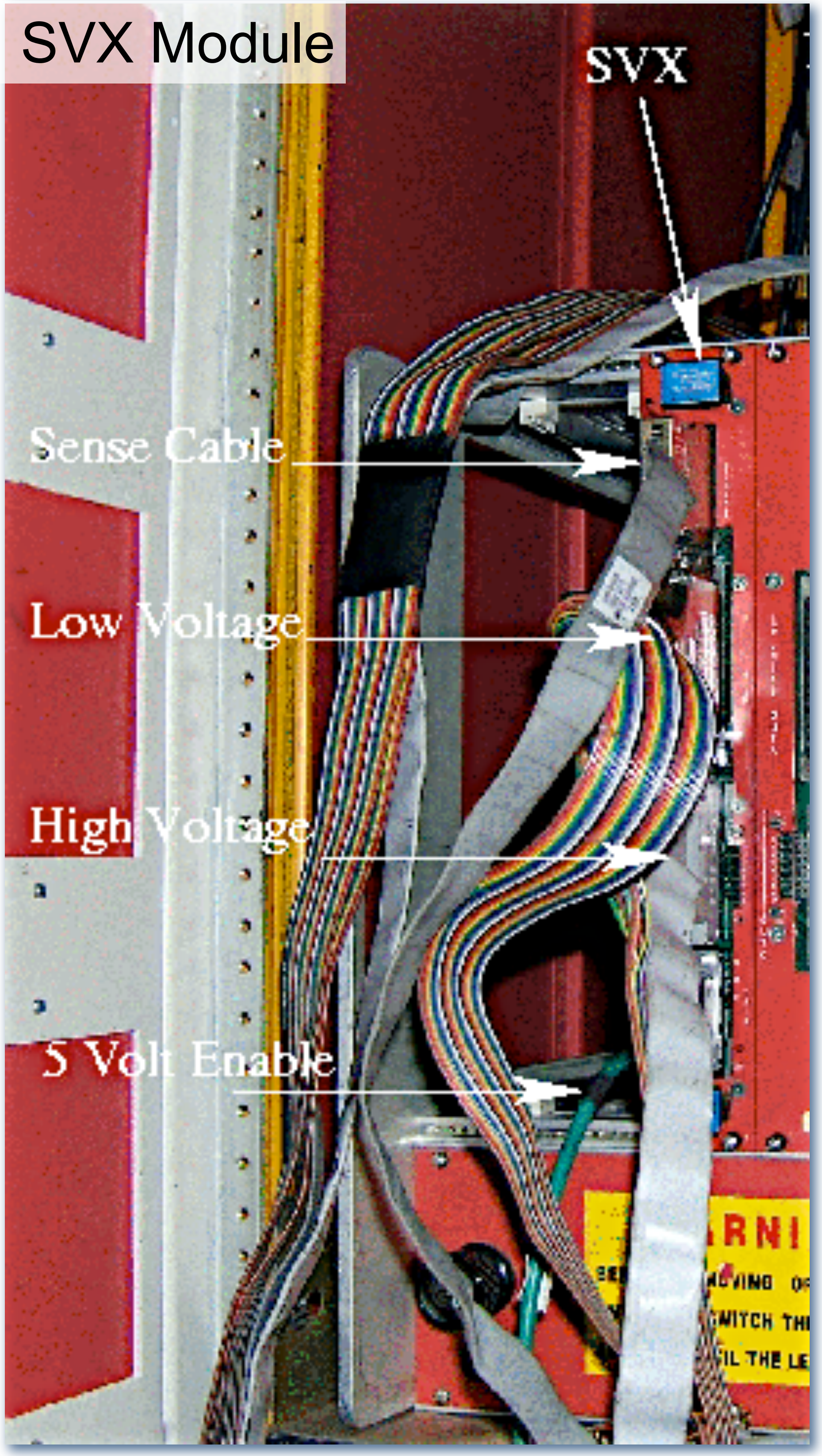
SVX3D Readout Chip

- Integrated analog front-end and digital back-end
- Fast: capable of running at 132 ns clock rates
- Deadtimeless: can collect charge and digitize simultaneously
- Dynamic pedestal subtraction
  - On-chip subtraction of common mode noise (defined as number of ADC counts measured in 31st lowest channel)
- On-chip sparsification
  - Removes channels below programmable threshold
  - Reduces data rate and readout time
- Honeywell radiation-hard CMOS 0.8 μm process, irradiated with:
  - 40 kGy with ^{60}Co source: 17% chip noise increase
  - 150 kGy with 55 MeV Proton source



Power Supplies

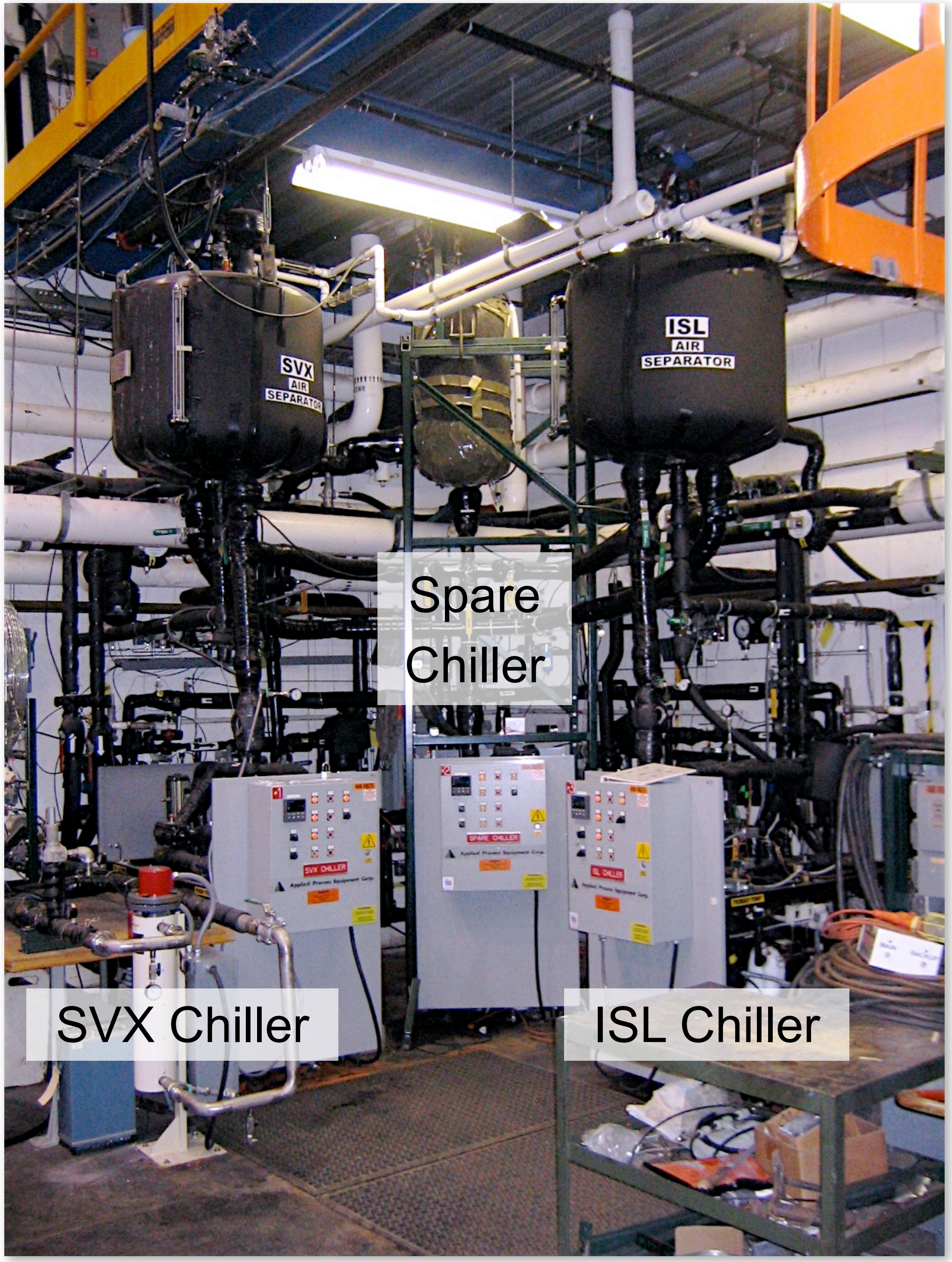




- Standard CAEN SY527 main frame & custom modules
- Installed in collision hall
- CAENet communication

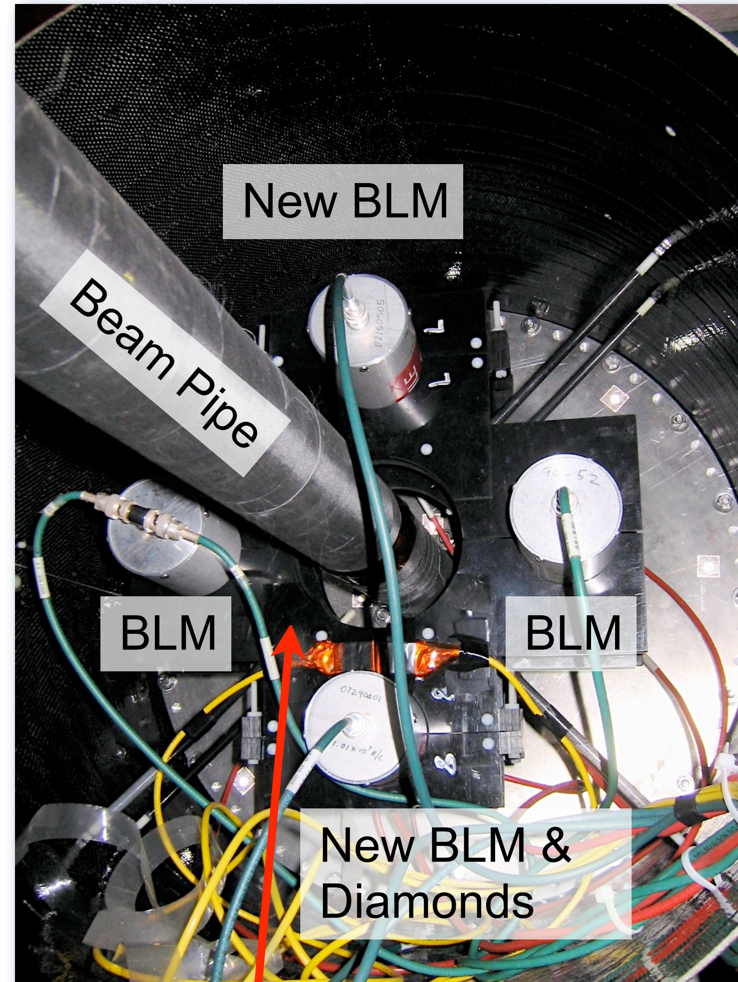
Cooling & Interlocks

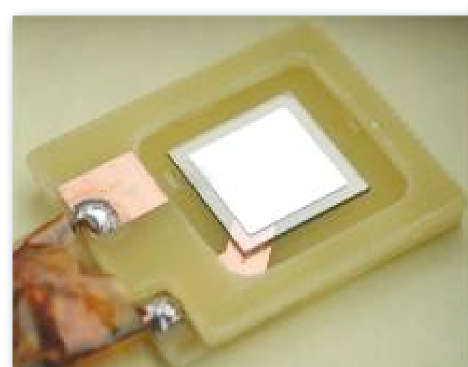
- Readout electronics develops 3.5 kW of heat
- Low temperatures are beneficial for Silicon sensors:
  - Reduction of thermal noise
  - Mitigation of radiation damage
- Solution: operate Silicon detectors at –10 ºC (SVX II/L00) and +6 ºC (ISL, electronics)
- System runs sub-atmospheric
- Protect Silicon by interlock system based on Programmable Logic Controller
  - Monitor several 100 process parameters: temperatures, pressures, dew points, …
  - Trip chillers & power supplies in unsafe situations

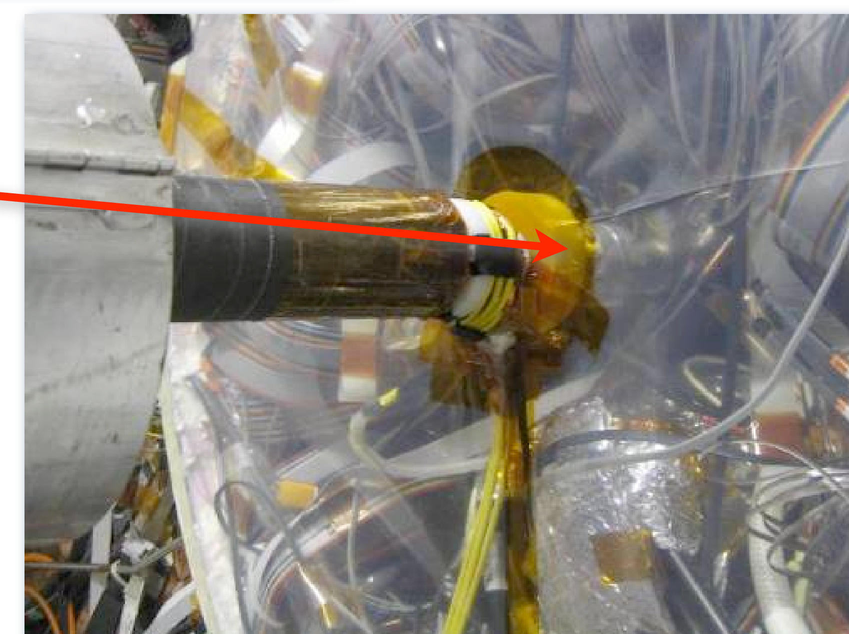


Diamond Beam Abort System

- Traditional system:
  - 4 Beam Loss Monitors (BLMs)
  - CAMAC logic triggers beam abort if dose rate > 0.12 Gy/s
  - Time resolution (210 μs = 10 Tevatron revolutions) too slow for some beam incidents
- Diamond/BLM upgrade (operational since Summer 2007)
  - Faster VME electronics: 21 μs = 1 revolution
  - Smaller & closer to Silicon real estate: polycrystalline CVD diamond detectors








Design

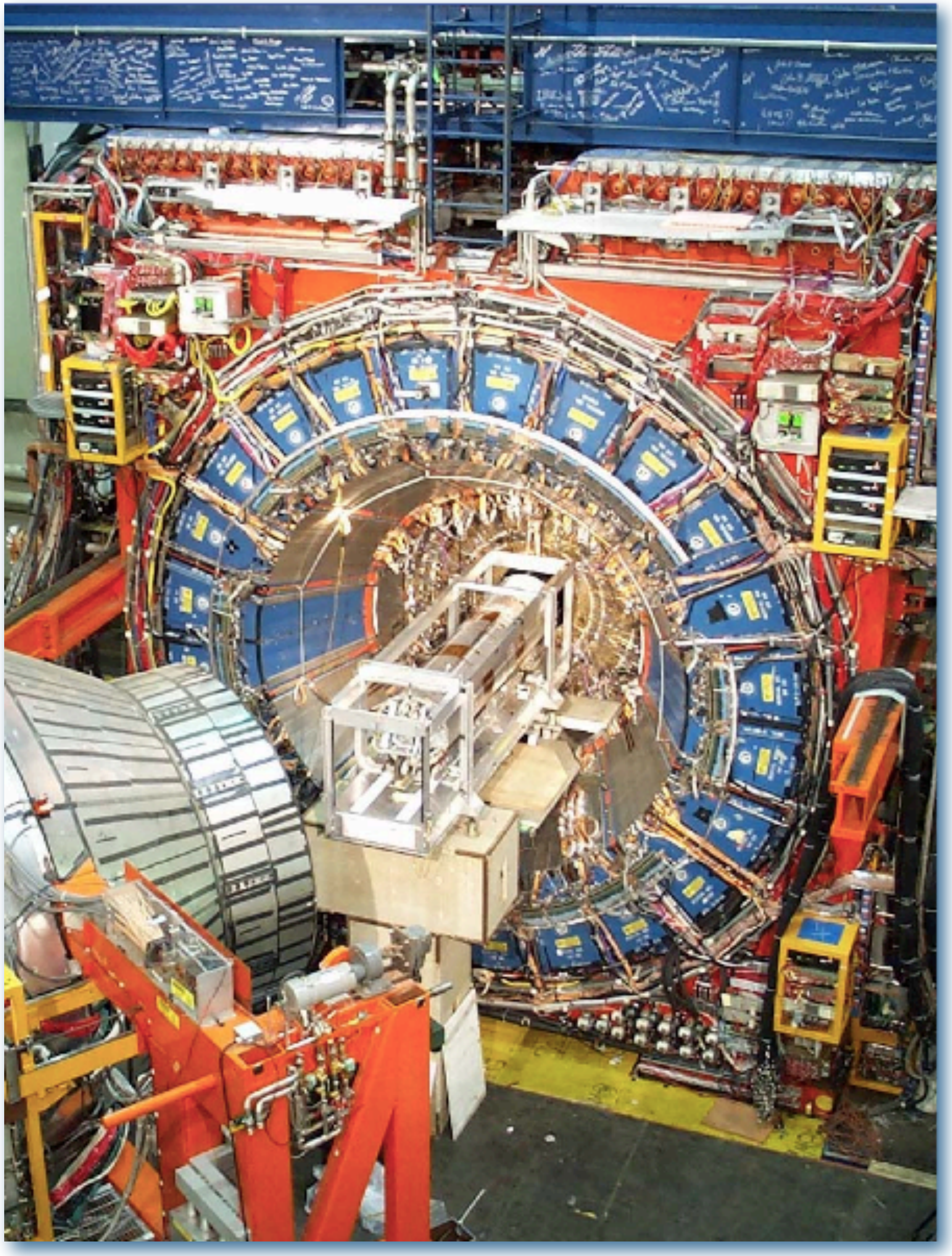

Commissioning


Operations


Studies

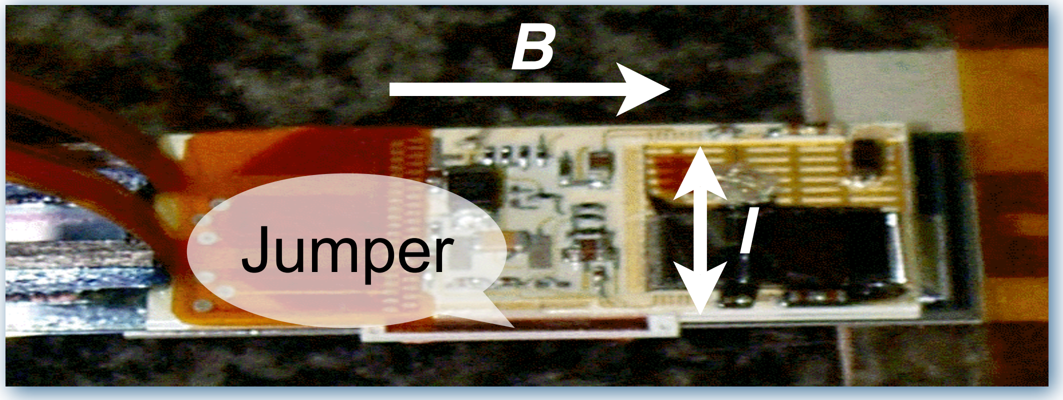
Expect the Unexpected

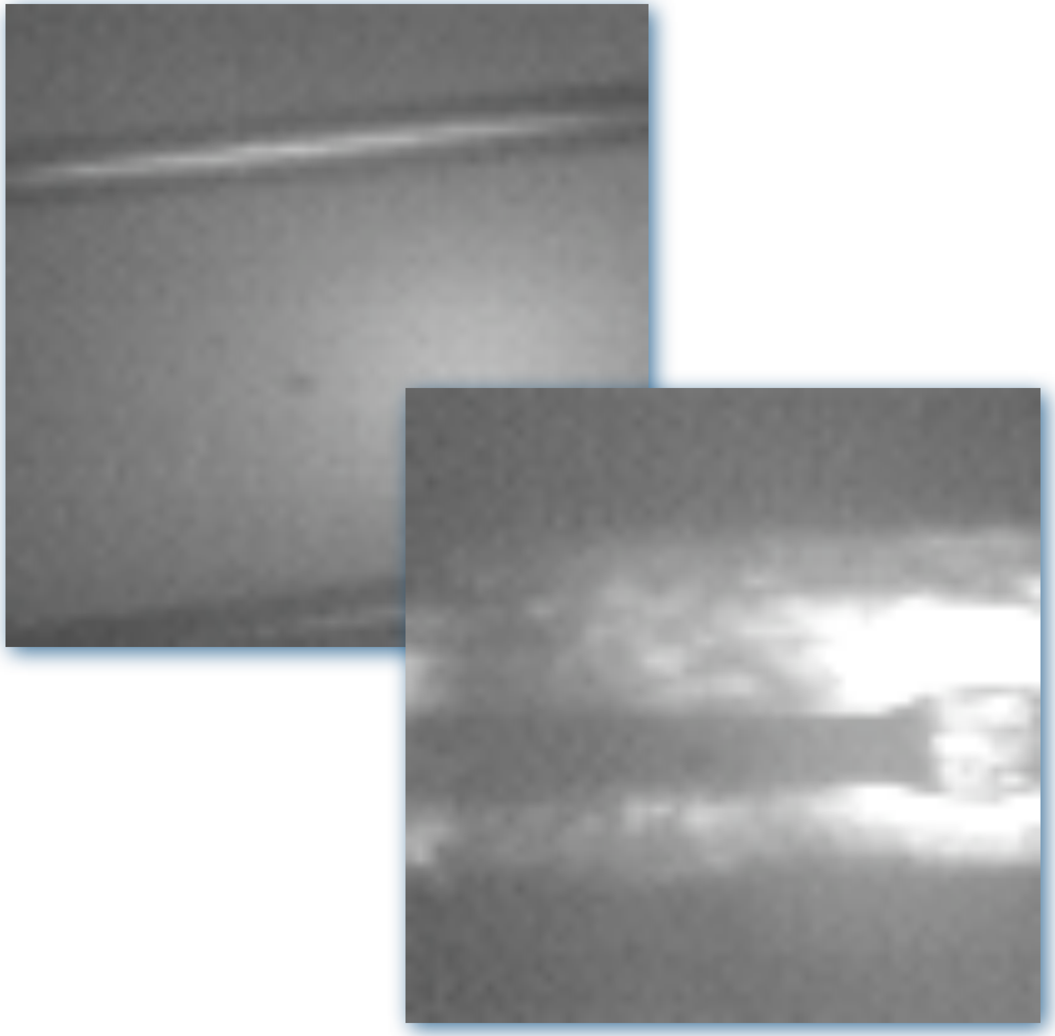
- Timeline:
  - R&D: 4 years
  - Production & Installation: 1 year
  - Commissioning: 1.5 years
- Various problems encountered initially:
  - Power supply burn-out
  - Blocked cooling lines in ISL
  - Noise pickup on L00
  - Wirebond resonance problems
  - Beam incidents
- All of the above problems have been addressed: detector in good shape for Run II



Wirebond Resonances

- Symptom: mysterious loss of *z* sides
- Reason (reproduced on test bench):
  - Wires in jumper to connect *r*–ϕ and *z* sides are perpendicular to magnetic field → Lorentz force
  - Highest current during readout
  - Resonance frequency around 20 kHz
- Preventing further losses:
  - Dedicated VME board to measure Δ*t* between subsequent readout commands → stop data-taking if more than 13 readout commands with the same Δ*t* occur
  - Limit L1 trigger rate to < 35 kHz
- ATLAS and CMS learnt the lesson:
  - Resonance protection board (ATLAS)
  - Potted wires (CMS)






Design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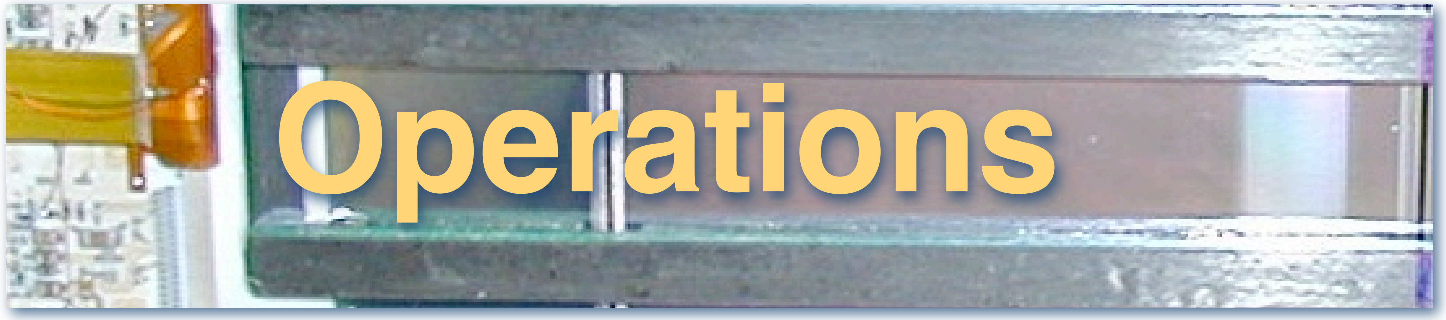
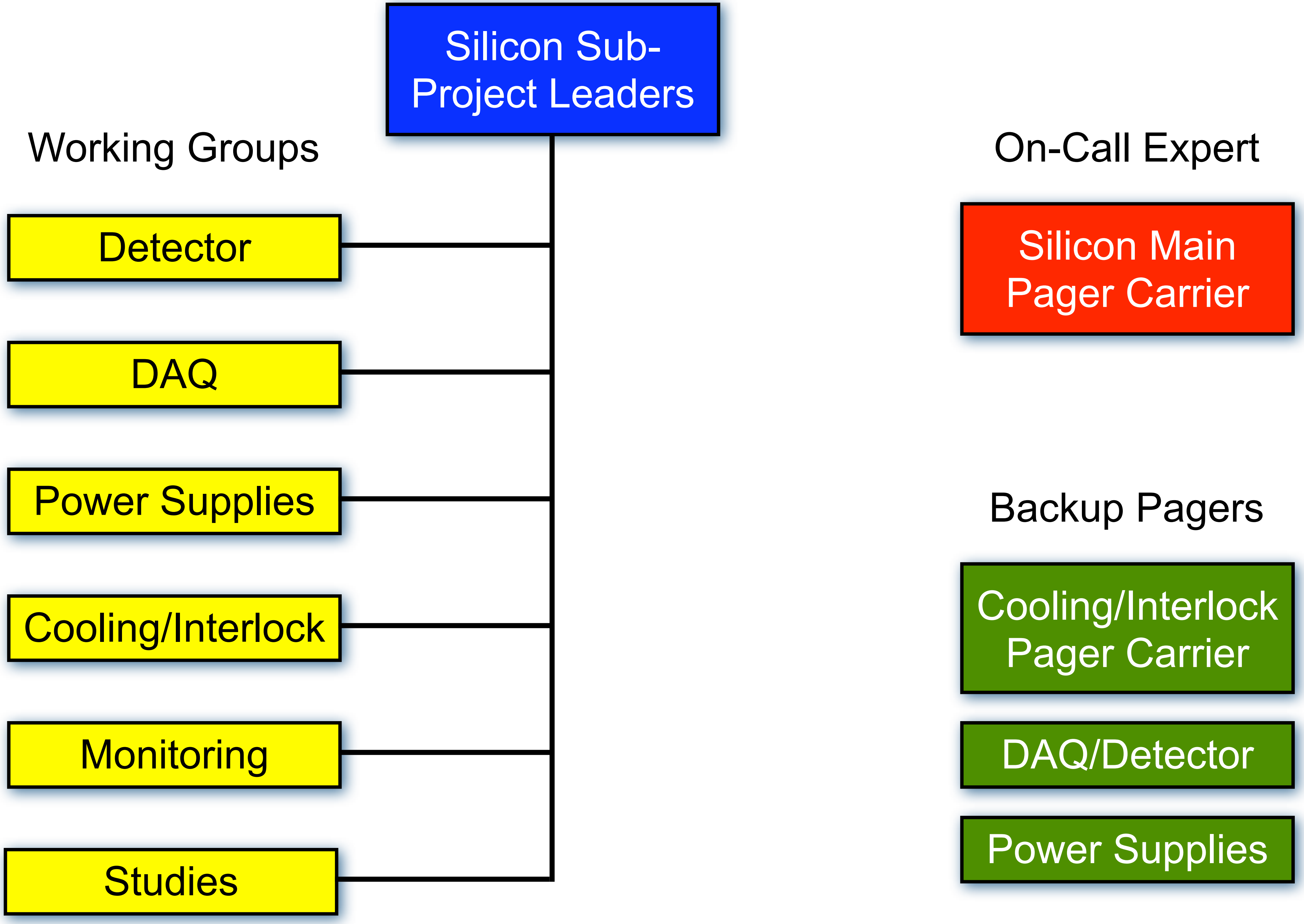

Operations

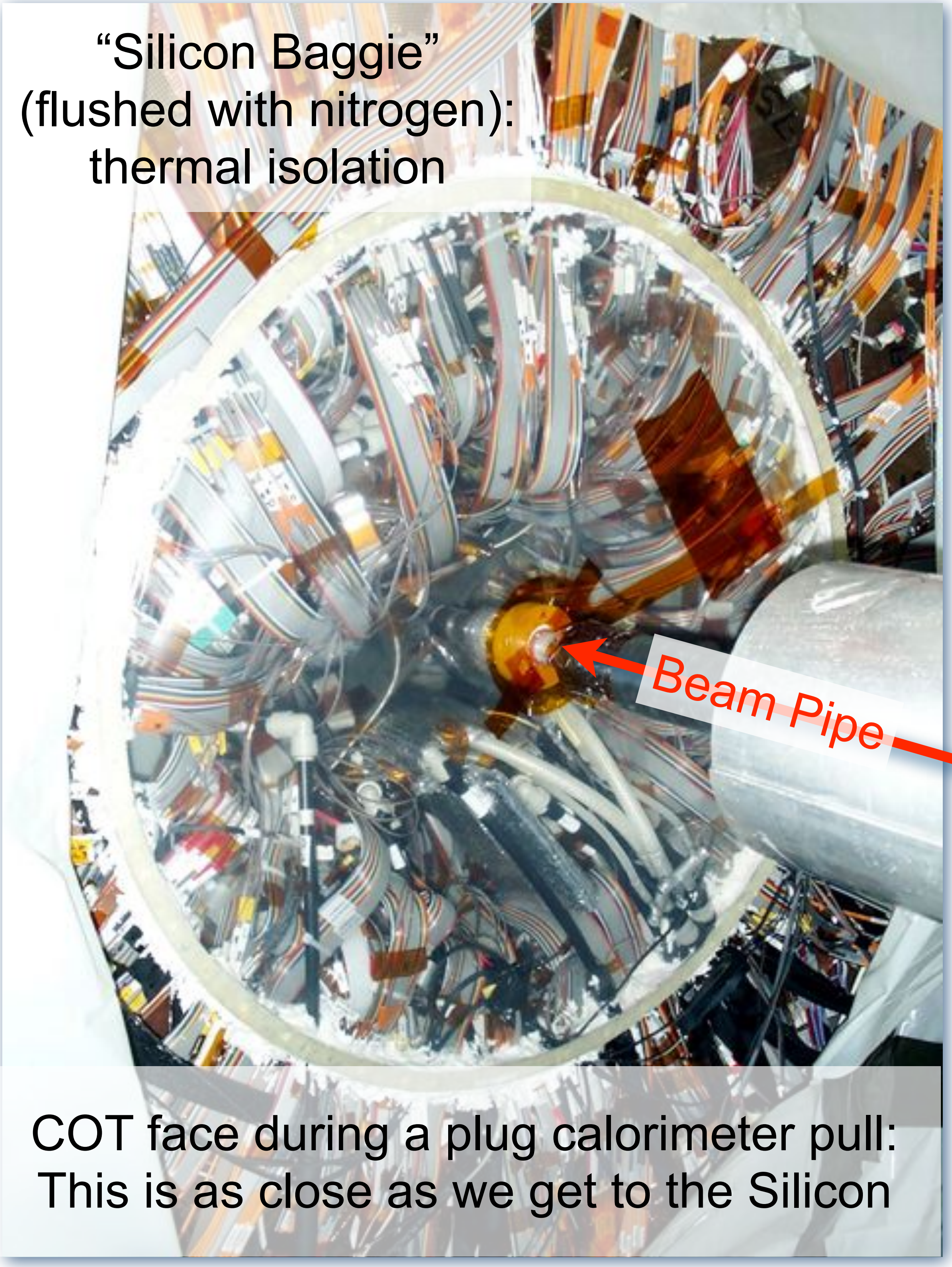

Studies

Silicon Operations Group



Maintenance is a Challenge

- A complex system…
  - 722,000 channels
  - 5,400 chips
  - 135 VME boards in 17 crates
  - 114 power supplies in 16 crates
  - Cooling & interlocks
  - Lots of cables
- … and not very accessible:
  - Power supplies and part of DAQ in collision hall
  - Detector and portcards: inaccessible



No Ladder Left Behind*

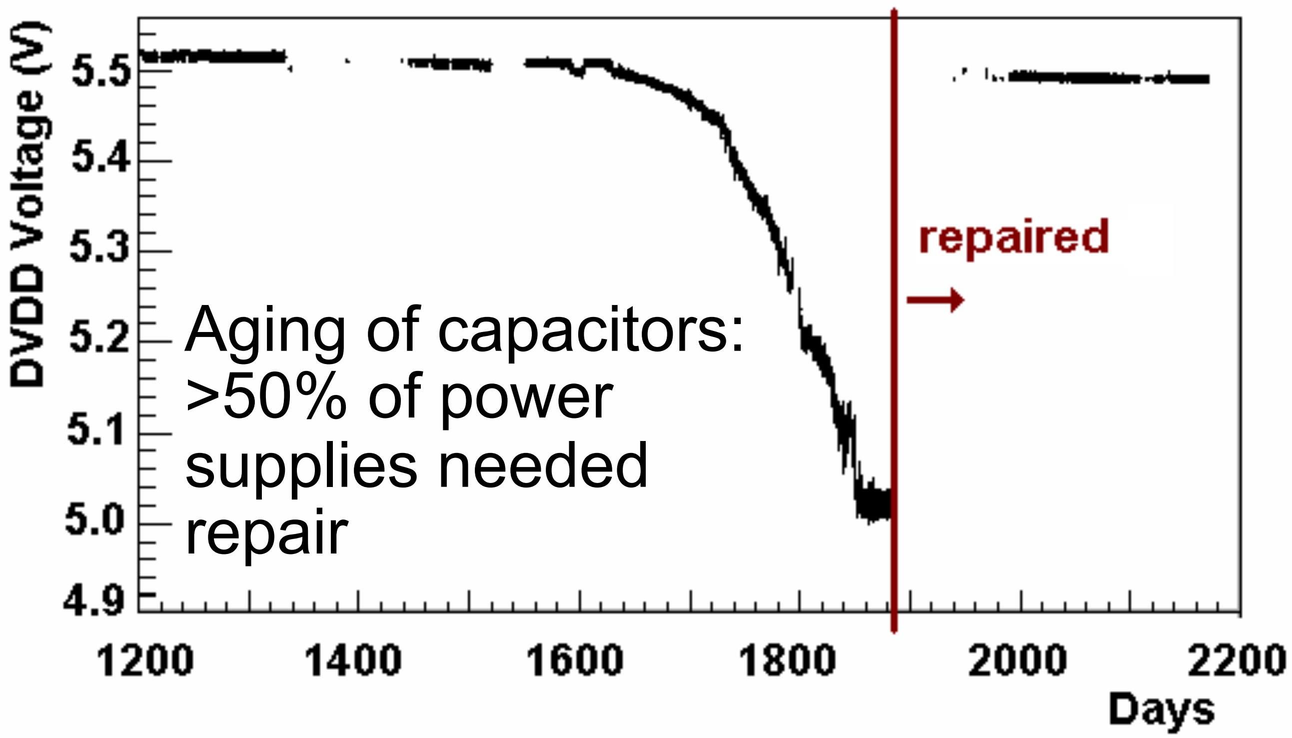
- Maintain constant high efficiency due to aggressive "No Ladder Left Behind" policy:
  - Vigilant monitoring: spot problems early (digital errors, ADC spectra, …)
  - Detailed logging of problems occurring
  - "Quiet time studies": diagnose problems a.s.a.p. → fix or mitigate
  - Collision hall access between stores: diagnosis and exchange of broken equipment
  - Extremely successful, but person-power intensive: need 4–6 FTE
- Since 2006: focus on automatic recovery of most common failure modes → higher efficiency with fewer people

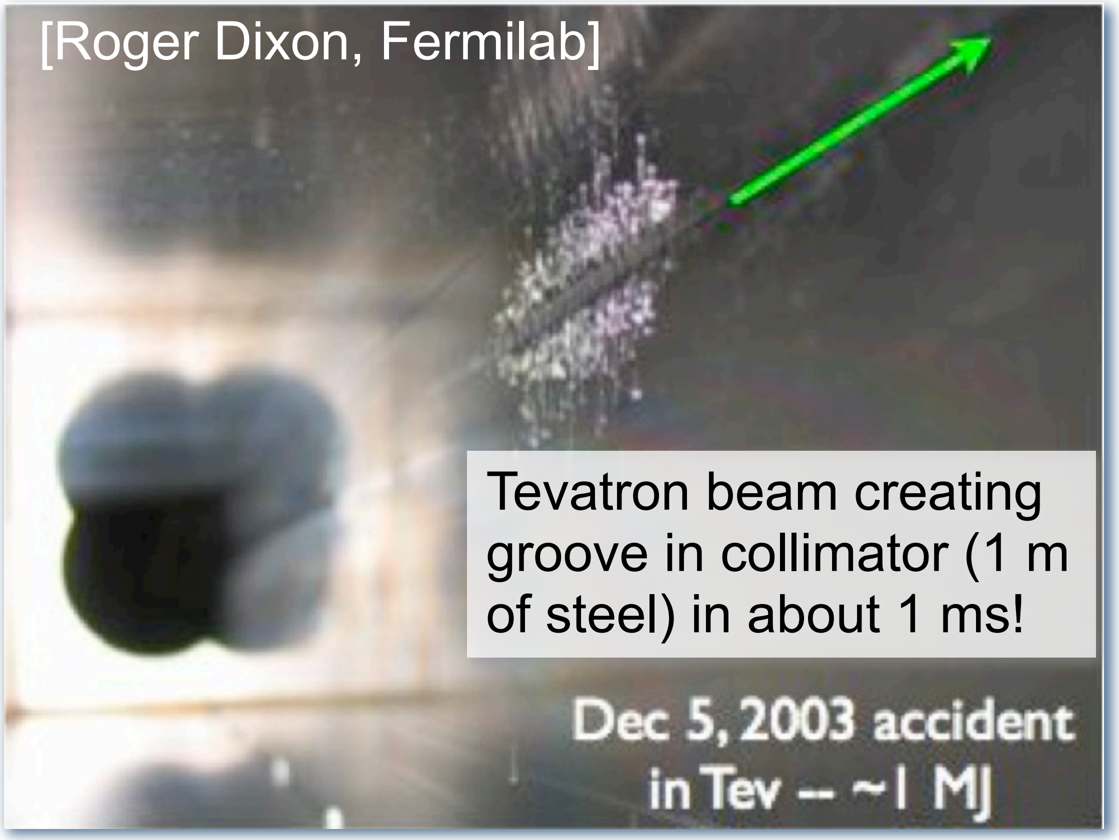
Ankush working on DAQ rack in the collision hall

*see: *No Child Left Behind Act* of 2001 (US Public Law 107-110), also: US Marine Corps motto

There are Problems, too…

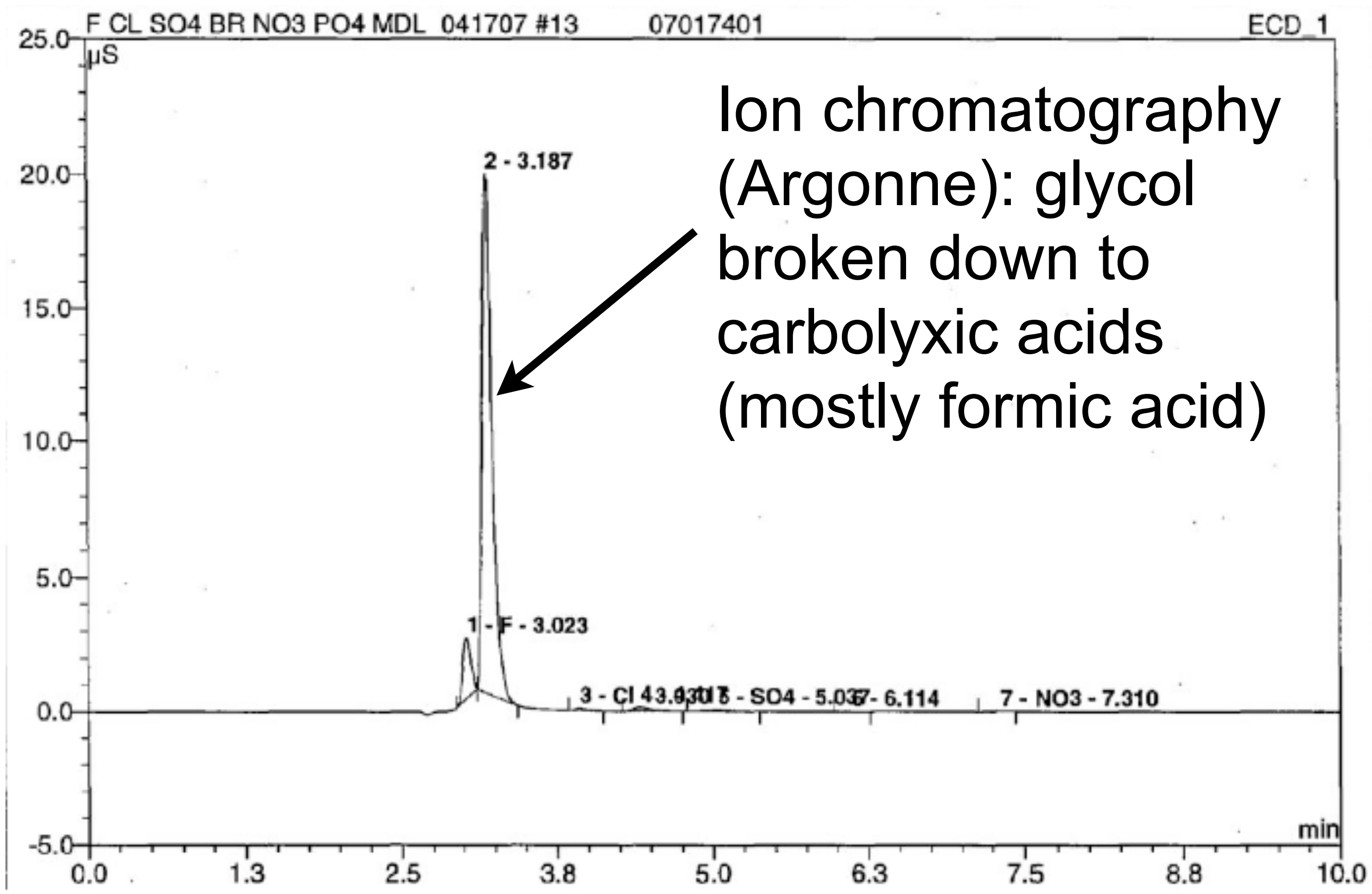
- Radiation-related:
  - Single-event upsets in collision hall DAQ boards (approx. 1 per day)
  - FPGA burnout (1–2 per year)
- Power supply failures: corrupted read-back, drooping voltages, spontaneous switch-offs, loss of CAENet communication
- Beam incidents:
  - Examples: magnet quenches, RF station loss, beam separator sparks, spontaneous ramping of abort kicker magnets
  - Close collaboration with Tevatron group: reduced to a minimum now
- Cooling and interlocks: chiller wear and tear, frozen cooling lines, humidity sensor problems, leaks

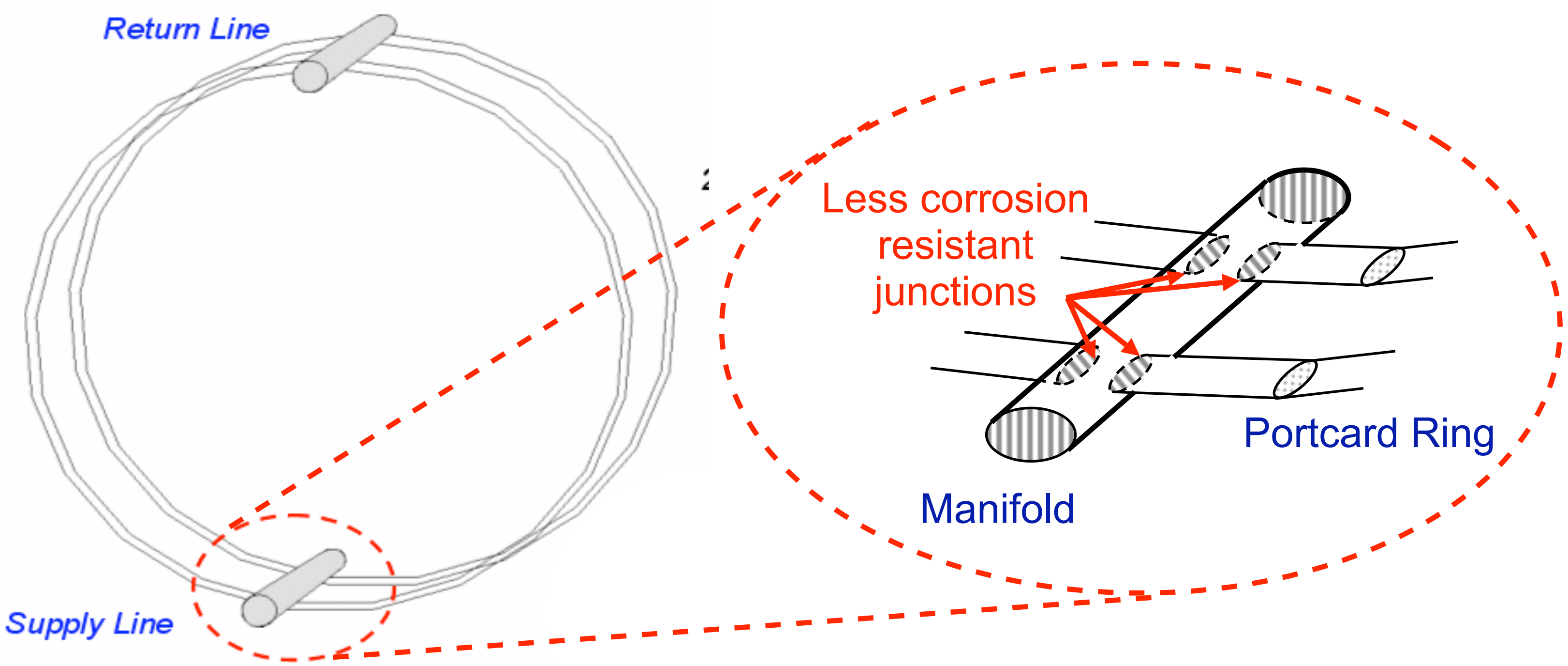




ISL Cooling Leak: The Problem

- First symptoms: electronic valve failures (early 2007)
- Problem: ISL coolant (10% ethylene glycol in water) became acidic (pH ≥ 2 = vinegar) during 2006 shutdown
- Solution: coolant neutralized by drain and flush procedure and large de-ionizers, unfortunately too late…
- … May 2007: leaks in heat affected zone around aluminum welds in ISL Portcard ring (alloy: 6061-Al)

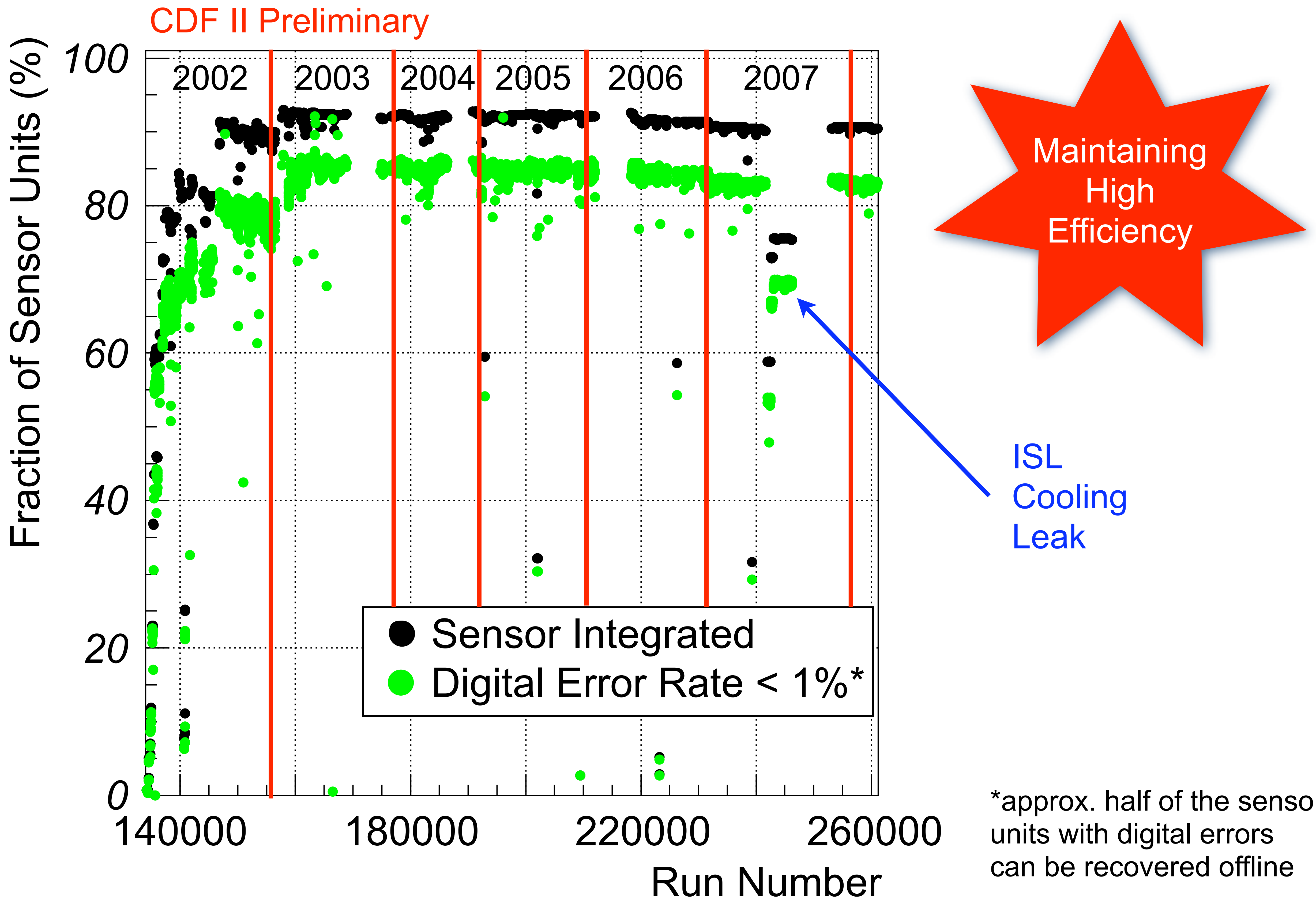




ISL Cooling Leak: The Fix

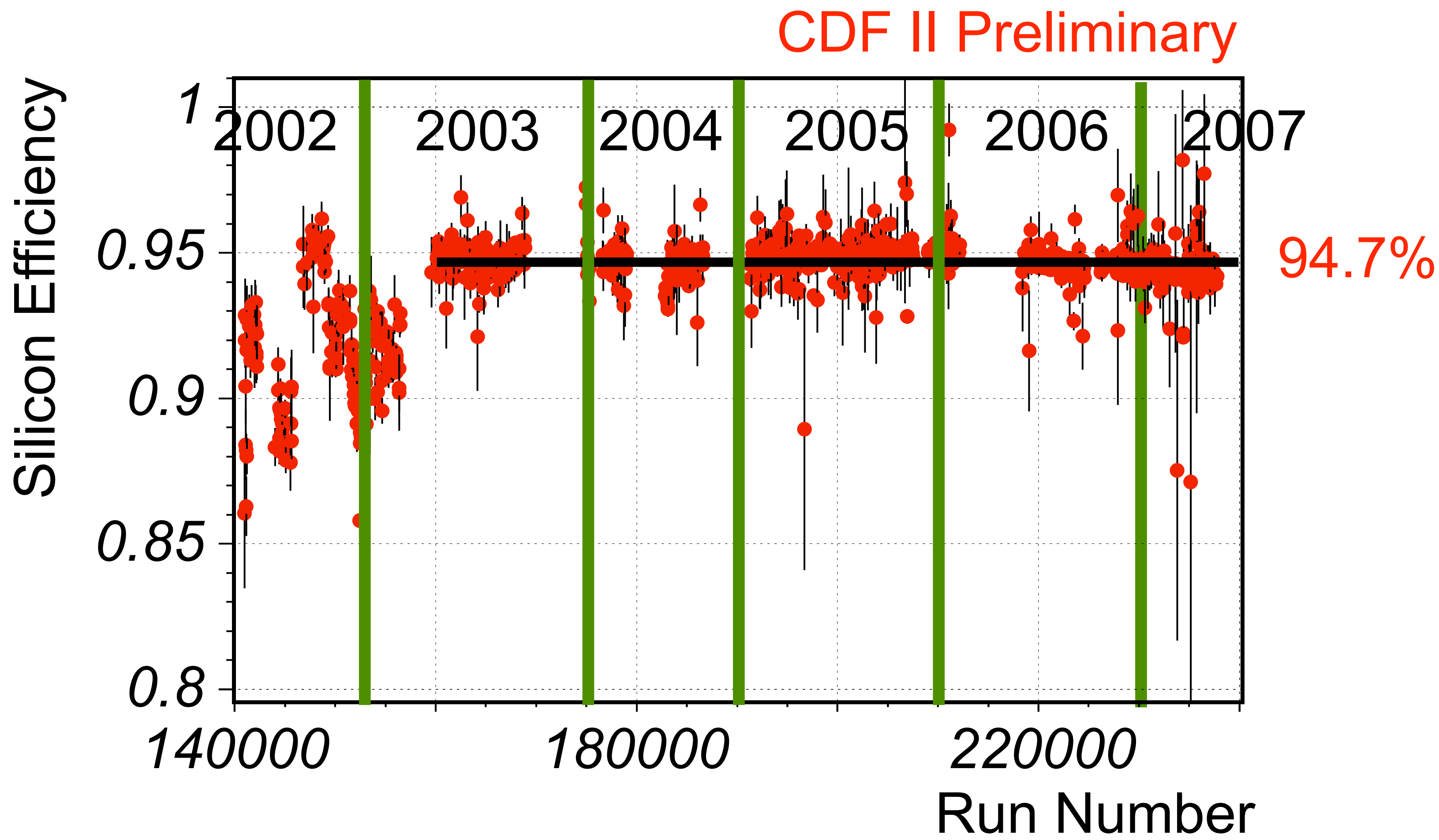
- Repair during 2007 shutdown (1 month of work for 4–5 people)
- Challenge #1: radiation damage
  - Must keep Silicon cold (and dry)
  - Solution: set up plastic tent, use air dryer to keep dew point below –10ºC at all times
- Challenge #2: Portcard ring inaccessible from outside
  - Inside detector, approx. 1 m away from COT face
  - Repair through cooling tubes using borescopes, catheters, syringes, …
  - Cover holes with epoxy using 0.75 mm brass tube
- Result: all leaks fixed, stable running since October 2007

History of Detector Status



*approx. half of the sensor units with digital errors can be recovered offline

Tracking Efficiency



- Very stable efficiency after commissioning, average: 95%
- Define efficiency as close as possible to standard CDF tracking:
  - Denominator: muons from $J/\psi \rightarrow \mu\mu$ with muon ID and COT track which cross at least 3 layers of SVX II
  - Numerator: Silicon added to COT track by standard pattern recognition, at least 3 layers with hits in SVX II/L00

Lessons Learnt

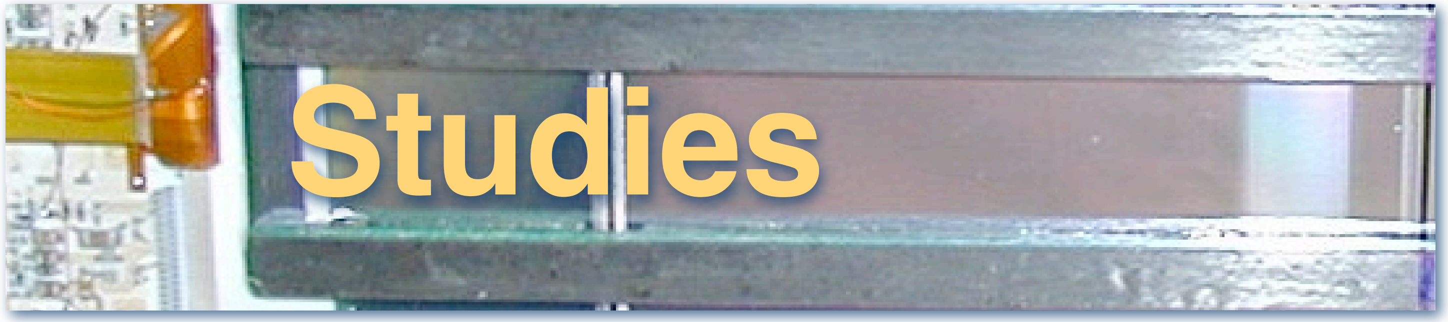
[...] because as we know, there are known knowns;
there are things we know we know.
We also know there are known unknowns;
that is to say we know there are some things we do not know. But there are also unknown unknowns —
the ones we don't know we don't know.
(D. Rumsfeld, 2002)

- Expect surprises during commission and operation
- Keep expertise around, good documentation
- Eliminate single points of failure: what can break will break
- Spares, spares, spares…
- It’s a hadron collider, dude! Don’t underestimate radiation-induced failures and beam incidents
- Don’t forget infrastructure: cables, power supplies, cooling, …


Design


Commissioning


Operations


Studies

Silicon Detector Longevity

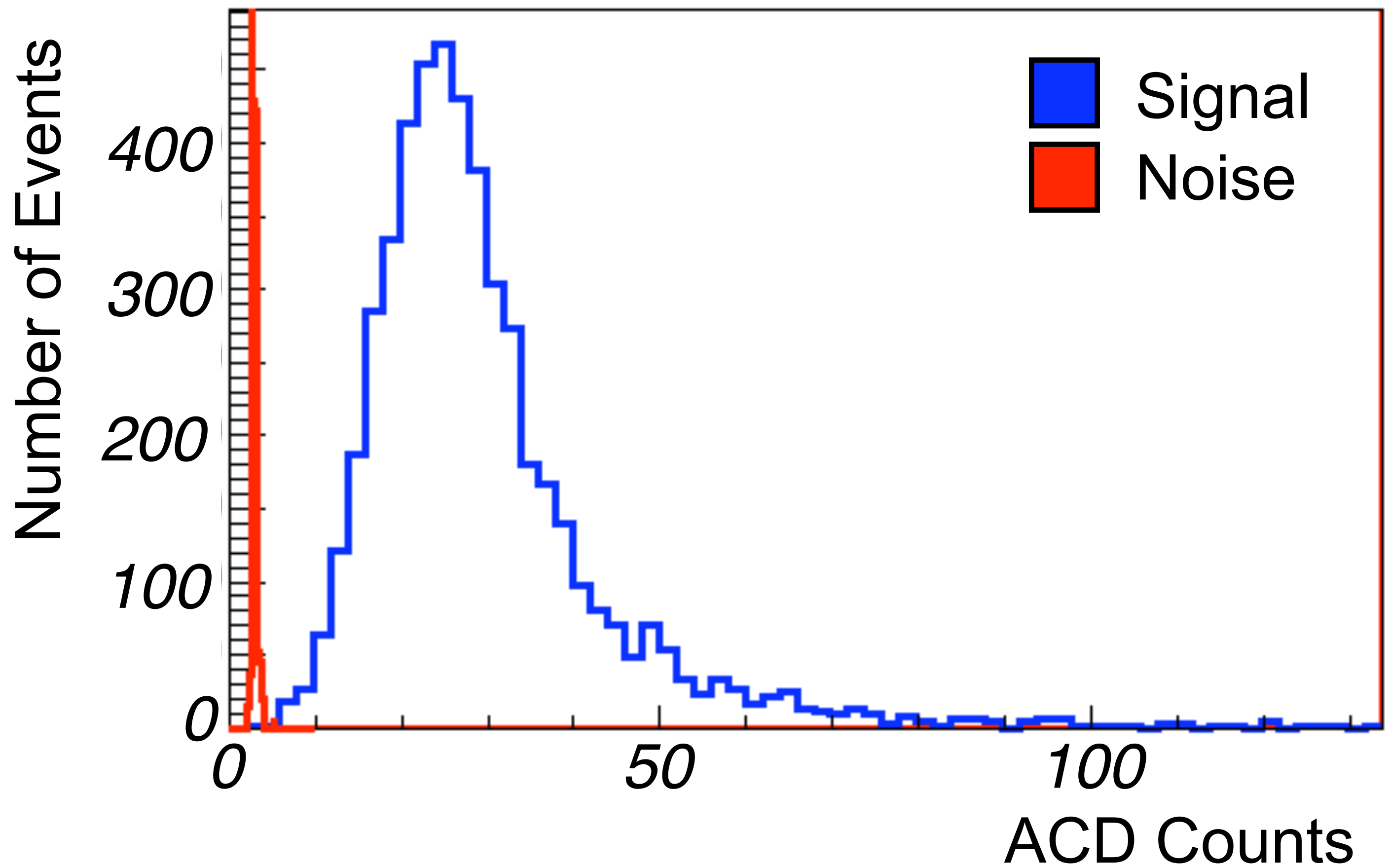
- Performance of key components decreases with irradiation, main concern: inner detector layers
- Noise increase
  - Bulk damage of sensors: increased leakage currents & capacitance
  - Electronics: chip damage, capacitance
- Signal degradation
  - Charge trapping in crystal defects: decreased charge collection efficiency
  - Bias voltage limited: under-depletion of sensors

Component	Performance after 8 fb^{-1}
Optical Transmitters	10% degradation of light level, no change in wave form
SVX3D Readout Chip	17% noise increase
Silicon Sensors	This talk

Signal-to-Noise Ratio

- Two main sources of noise:
  - Sensor shot noise (I_{leak} = leakage current): $Q_{\text{shot}} = 900\,e^{-}\sqrt{I_{\text{leak}}(\mu\text{A})}$
  - Chip noise (C_{chip} = chip capacitance): $Q_{\text{chip}} = f_1(\Phi) + f_2(\Phi)\,C_{\text{chip}}$
    Test beam data: 17% increase of chip noise after 8 fb^{-1}
- Direct measurement from data:

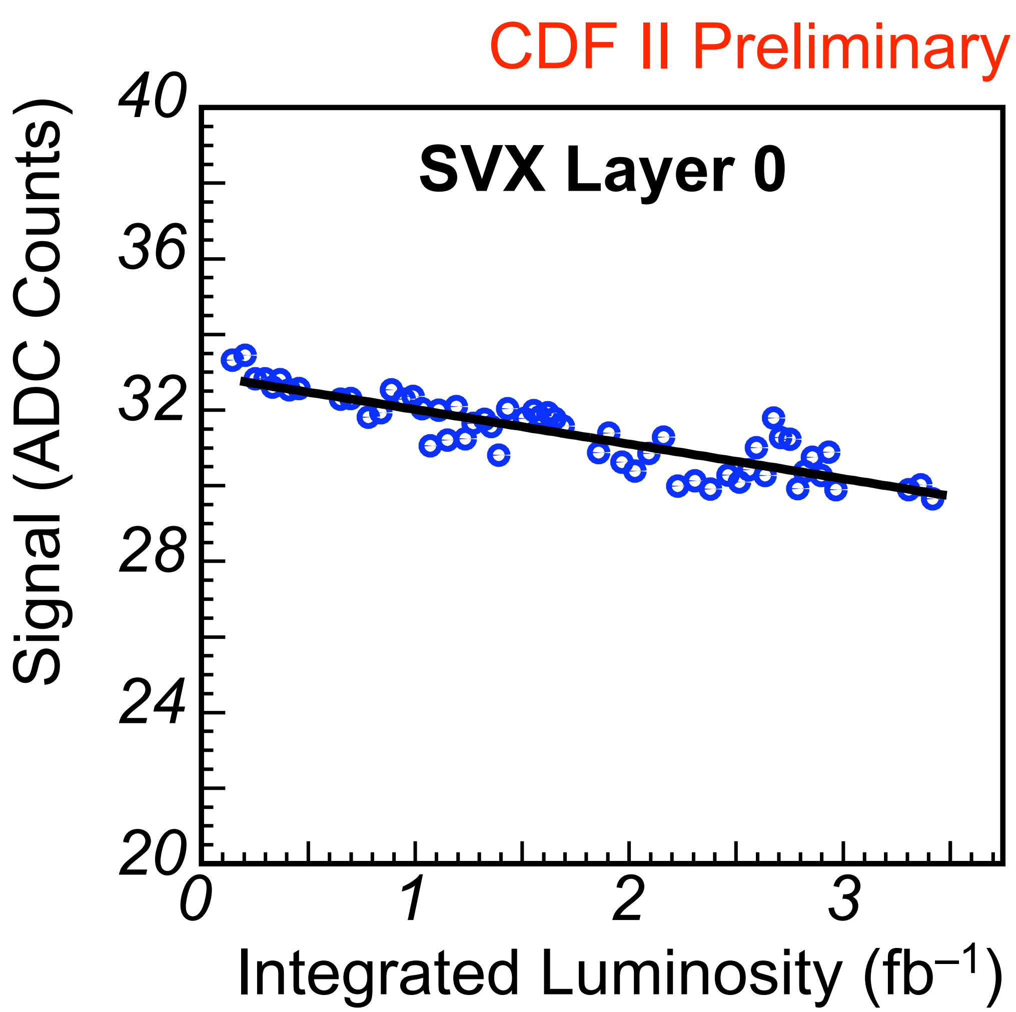
CDF II Preliminary

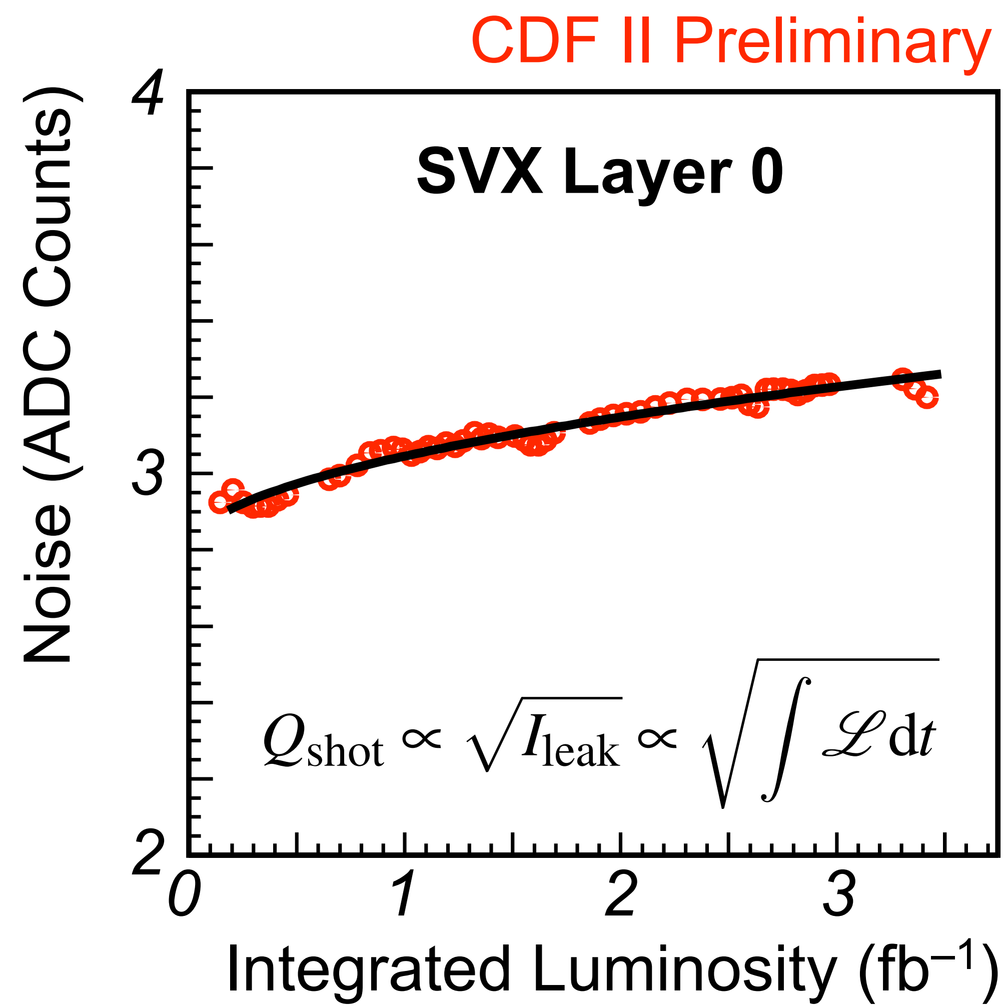


- Dataset: full 3.1 fb^{-1} (164 pb^{-1} from commissioning period excluded)
- Signal: path-length corrected charge sum of clusters using hits on tracks (J/ψ data)
- Noise: single-channel noise (calibration data)

Signal and Noise Models

- Signal definition: most probably value of fit to ADC spectrum (Landau distribution convoluted with Gaussian)
- Data suggest linear decrease with luminosity

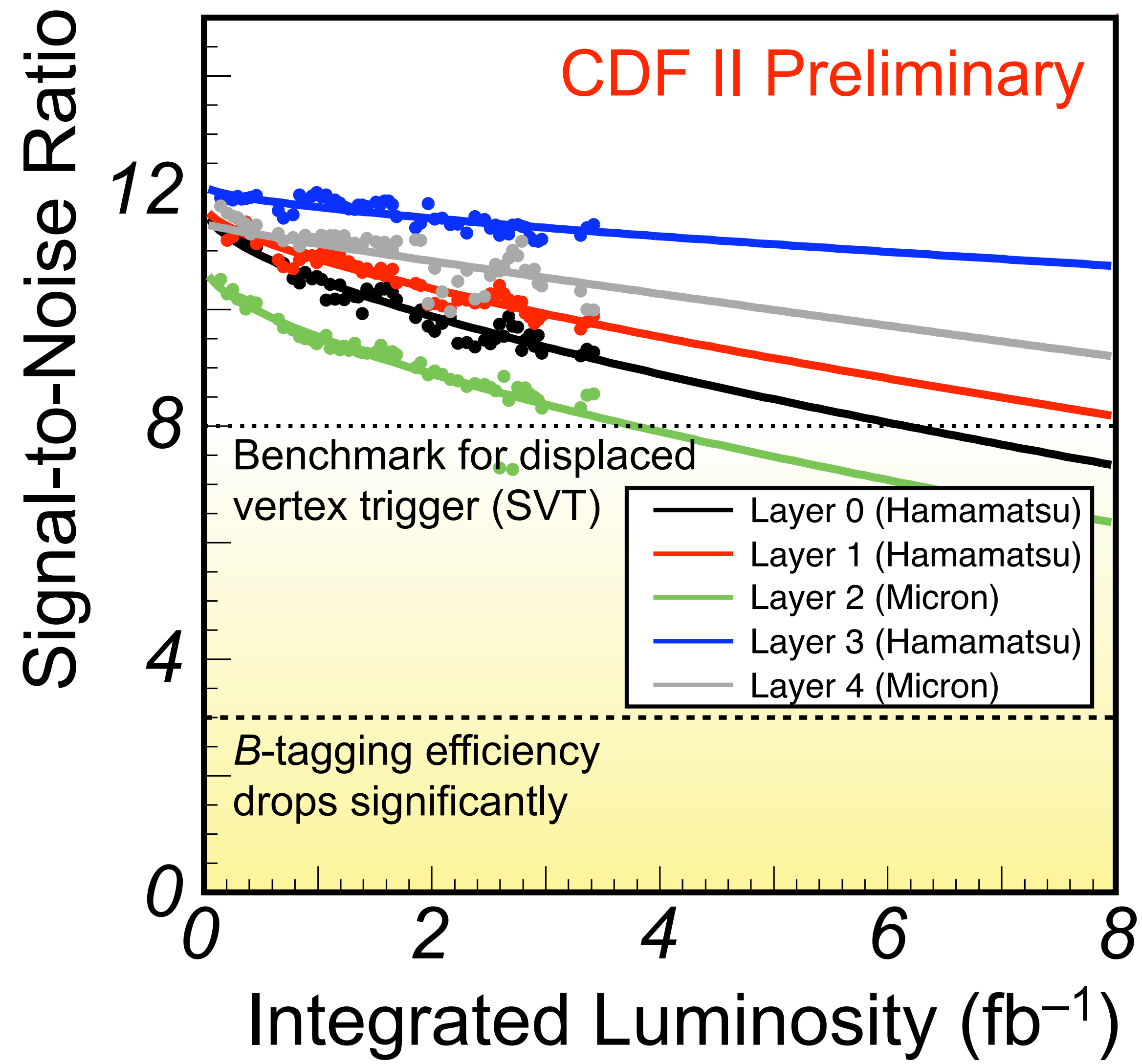




- Noise definition: mean strip noise obtained from calibration runs (taken every two weeks)
- Assumption: shot noise dominant source of noise: square-root increase with luminosity

SNR & Lifetime Projections

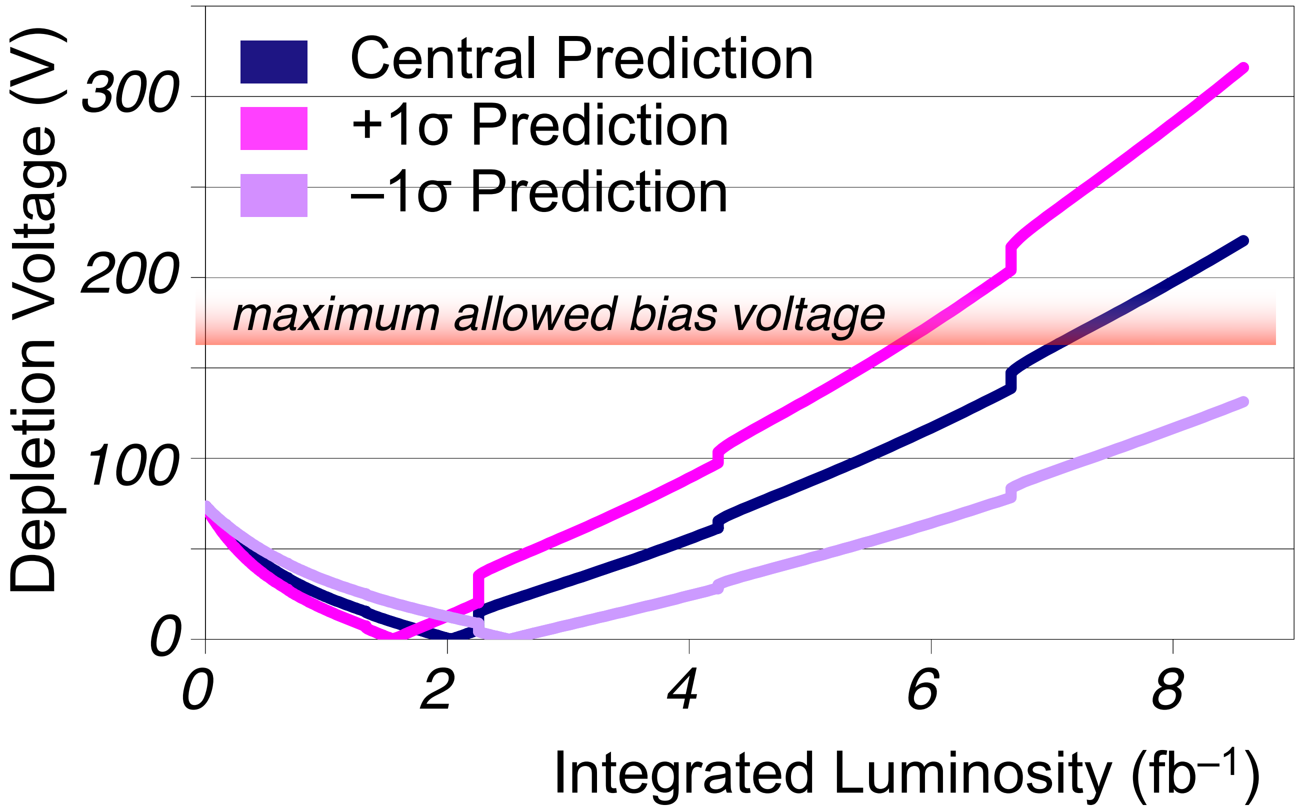
- Fit with signal & noise model and extrapolation
  - Limit I: *SNR* = 8 (SVT efficiency drops by 5% for SNR = 6)
  - Limit II: *SNR* = 6–3 (*b*-tagging efficiency degraded)
- Conclusions:
  - SVX Layers 1, 3, 4 most probably not limited by SNR degradation
  - Need careful monitoring of Layer 0 and Layer 2



Depletion Voltage

- Due to radiation damage: evolution of voltage needed to fully deplete sensor
  - Effective number of charge carriers N_{eff} reduced until type inversion: decreasing depletion voltage
  - Increasing depletion voltage after type inversion, eventually reaching maximum allowed bias voltage

Depletion Voltage Evolution in SVX II Layer 0



S. Worm, *Lifetime of the CDF Run II Silicon,* VERTEX 2003

Predictions: modified Hamburg model: $\Delta V_{dep} \propto \Delta N_{eff} = N_A + N_C + N_Y$

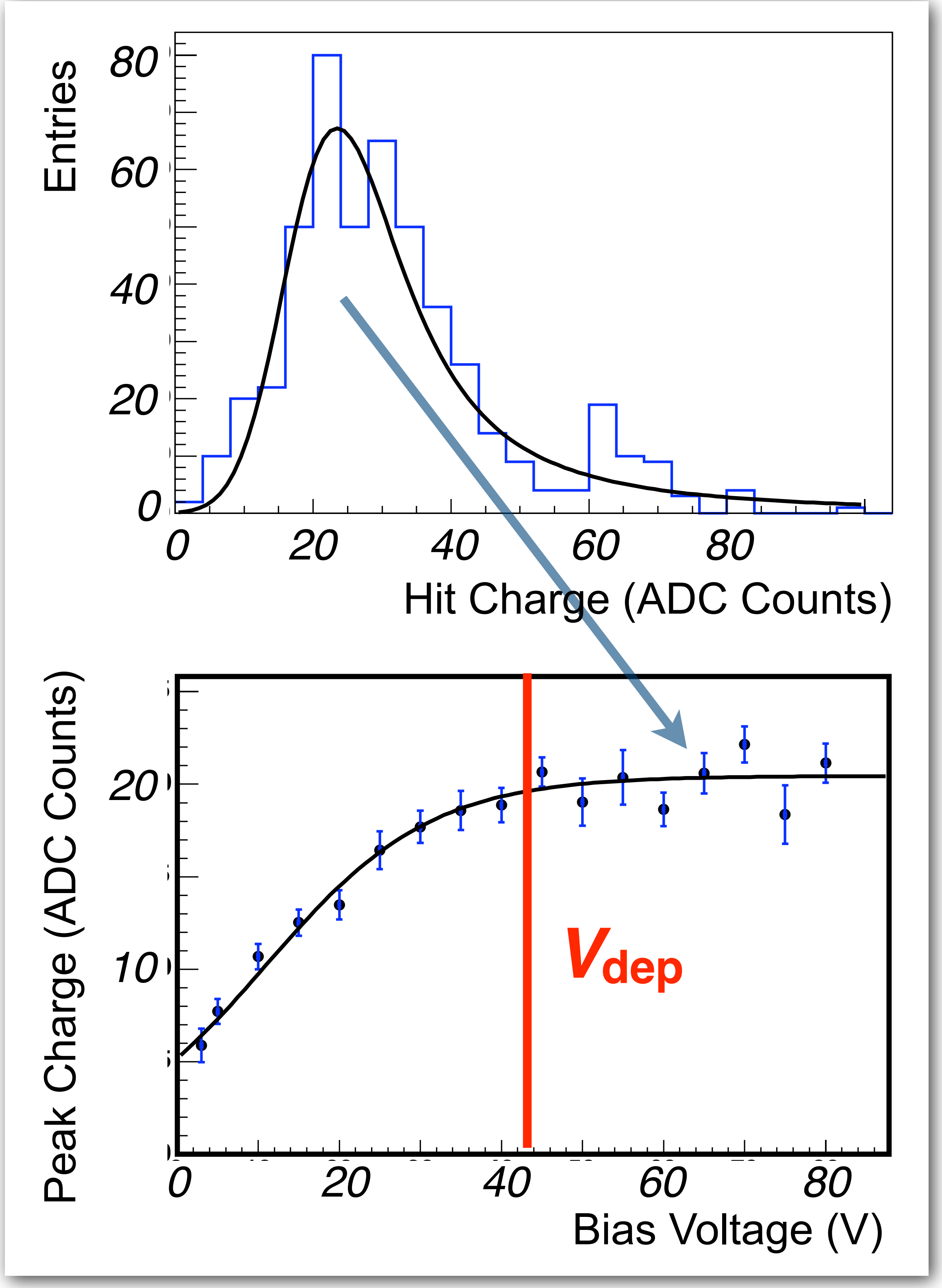
$$N_A = \Phi \sum_i g_{0,i} \exp[-c_{A,i}(T)\,t]$$ Beneficial Annealing

$$N_C = N_{C,0}\,(1 - \exp[-c\Phi]) + g_c \Phi$$ Stable Component

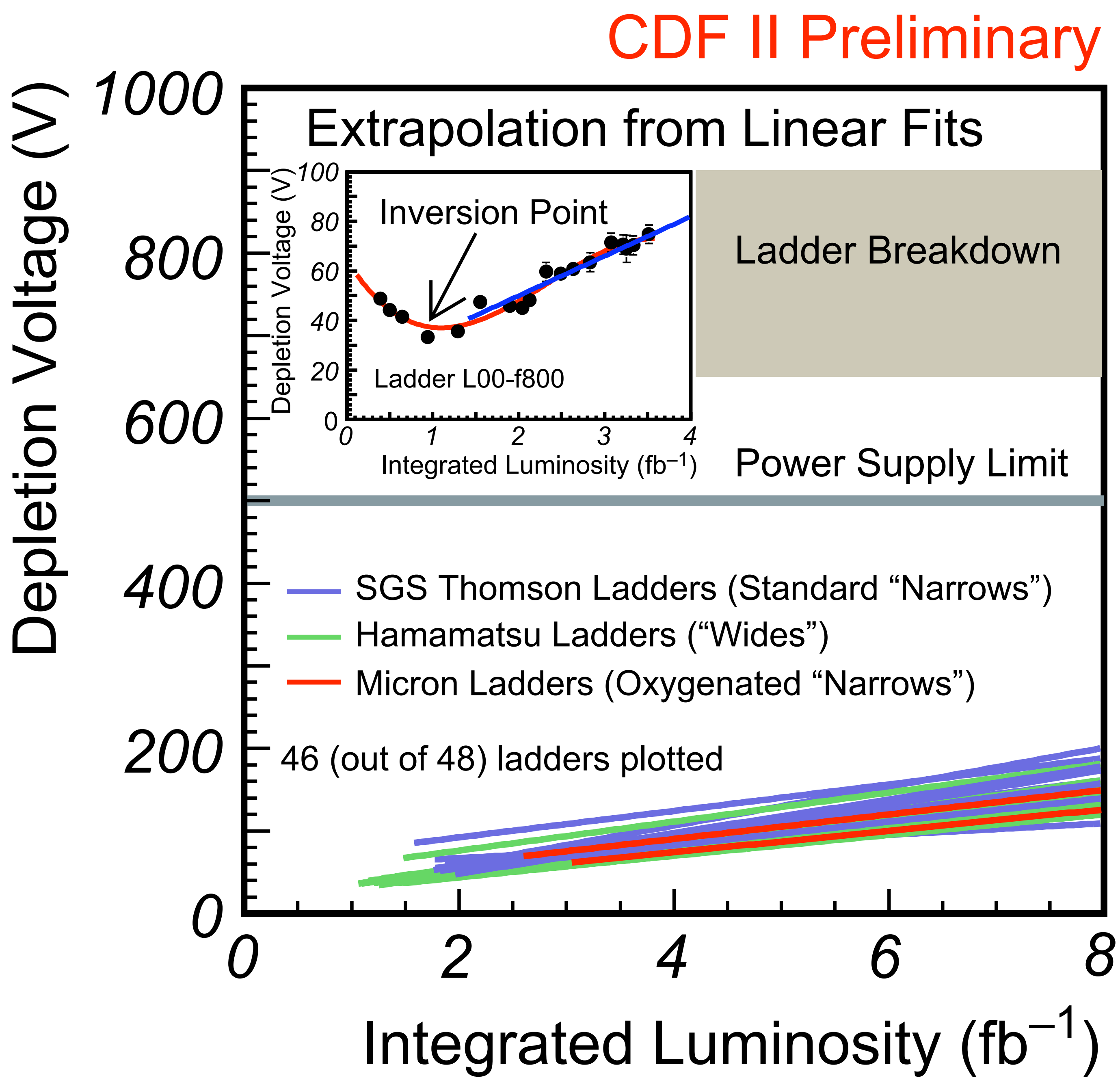
$$N_Y = g_Y \Phi \left(1 - \frac{1}{1 + g_Y \Phi c_Y(T)\,t}\right)$$ Reverse Annealing

Signal Bias Scans

- Dedicated data-taking runs ("Signal Bias Scans")
  - Study collected charge of silicon hits from good tracks during colliding beams operation
  - Find peak of ADC spectrum as a function of bias voltage (fit: Landau ⊗ Gaussian)
  - Determine V_{dep} as 95% amplitude of sigmoid fit
  - Operational problem: consumes valuable beam time



Lifetime Projection for Layer 00



- Layer 00: very close to the beam, but built from "radiation-hard" silicon
- Evolution of depletion voltage:
  - Type inversion around 1 fb^{-1} (except oxygenated sensors)
  - Minimum depletion voltage around 35 V
  - Very consistent increase after type inversion
- Layer 00 will outlast CDF Run II

Summary and Conclusions

- Silicon detectors in CDF: SVX II, ISL, and L00
  - Large and complex system: 6 m^2 of sensors, 722k channels
  - Essential for CDF's physics program
  - Stable performance after long commissioning period
- LHC detectors have profited (and will further profit) from Tevatron experience, especially for Silicon detectors
- The CDF Silicon group is very active:
  - Detector maintenance and day-to-day operations: large effort!
  - Fixing unexpected operational issues (e.g. ISL cooling leak)
  - Detailed studies of performance and longevity
- Tevatron runs until 2009 (or 2010):
  CDF will go for the Higgs, and the Silicon is ready to go!

Let’s go for the Higgs!
The CDF Silicon is Ready!

[CDF Silicon Workshop 2006, Santa Barbara]