B Physics at the Tevatron and the *B* Factories

Physics Motivation and Experimental Setup

Lecture I

Christoph Paus
Massachusetts Institute of Technology

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The Caveats Slide

Who is the lecturer?

- I am a CDF member and working on *B* physics
- My main interest is measuring B_s mixing at CDF

A word on *B Physics*

- there are 1001 topics
- I have picked a very small selection
- *B* Factories and Tevatron can do much more

My selection of plots

- CDF and BaBar plots came easy
- .... does not mean that I do not like DØ and/or Belle

Overview

Motivation and History

- Why do we measure the *CKM* matrix?
- First important *B* physics measurements

Introduction to the Experimental Setup

- *b* production mechanisms as motivation
- *B* Factories versus Tevatron
- BaBar/Belle versus CDF/DØ

Two Stories in some Detail

- Tools for the measurement
- Observation of *CP* violation in *B* systems, $\sin 2\beta$
- How Tevatron will measure B_s mixing, Δm_s

Web Pointers

The experiments

+ Tevatron: http://www-cdf.fnal.gov/, http://www-d0.fnal.gov/
+ *B* Factories: http://www.slac.stanford.edu/BFROOT, http://belle.kek.jp/

Overview reports

+ The BaBar Physics Book

  http://www.slac.stanford.edu/pubs/slacreports/slac-r-504.html
+ *B* Physics at the Tevatron: Run II and Beyond

  http://arXiv.org/pdf/hep-ph/0201071

Excellent live videos / transparencies on the Web

+ SLAC summer school 2002:

  http://www-conf.slac.stanford.edu/ssi/2002/
+ MIT Course: Heavy Flavor Physics (F. Würthwein)

  http://mit.fnal.gov/ ˜ fkw/teaching/mit8.881.html

Symmetries in Particle Physics

Lewis Carrol's (1872)

Through the Looking Glass

+ Alice climbs through the mirror and .... finds a world very different from the expected reversed world
+ clocks had actual faces, chess pieces walked about, flowers talked *etc*.

+ this seems to be the theme for symmetries in particle physics in the last century
+ broken symmetries had a deep impact on the consciousness of physicists

Symmetries in Particle Physics

Electromagnetism basics understood by 1900

- Maxwell's equations

Quantum Electro Dynamics understood by 1950

- Renormalization of QED

Electromagnetism conserves 3 symmetries

- *P* parity – reversal of the three spatial dimensions
- *C* charge conjugation – particle ⇔ anti–particle
- *T* time reversal

Symmetries in Particle Physics

Weak Interaction violates P, C, T and CP:

P: asymmetric β ray spectrum in polarised Co^{60}

1957 C.S. Wu et al.

C: asymmetry of μ^+ and μ^- polarization from $\pi^\pm$ decay

1957 R.L. Garwin, L.M. Lederman, M. Weinreich

1957 J. Friedman, V. Telegdi

CP: in the neutral kaon system (K_S, K_L decays)

1964 J.H. Christenson, J.W. Cronin, V.L. Fitch, R. Turlay

T: rate difference for $K^0 \rightarrow \overline{K}^0$ as a function of propert time

1998 CPLEAR Collaboration

CP: in the neutral B system ($B^0 \rightarrow J/\psi K_S$ decays)

2000 BaBar and Belle Collaborations

Matter-Antimatter Asymmetry

Big Bang theory

- matter and antimatter are created in equal amounts
- see mostly matter .... where is the antimatter?

Sakharov explanation needs three conditions (1966)

- proton must decay
- universe passed a phase of thermal non-equilibrium
- *CP* violation must exist

Opinions from theorists

- Standard Model *CP* violation too small
- good chance for new physics in *CP* violation

First B Physics Measurements: Lifetime (MAC/Mark II)

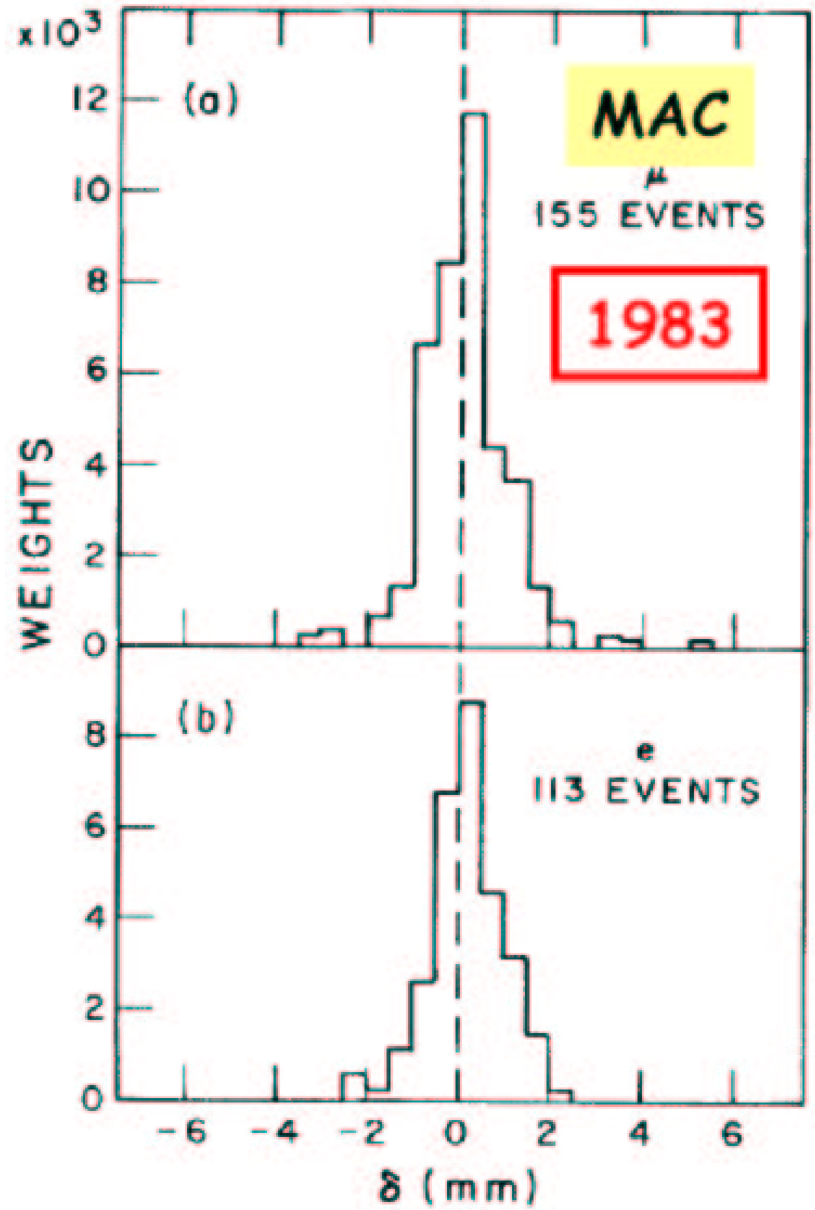
Sample of high p_T leptons

- p_T – transverse to thrust axis
- use track impact parameter, δ
- sign determined by jet direction
- 155 – muon events
- 113 – electron events

B lifetime governed by V_{cb}

MAC	$1.8 \pm 0.8 \pm 0.4$ ps	PRL **51** (1983) 1022
Mark II	$1.2 \pm 0.4 \pm 0.3$ ps	PRL **51** (1983) 1316

- larger than expected
- large $c\tau_B$ means small V_{cb}



Experimental details

- e^+e^- at $\sqrt{s} = 29$ GeV
- 109 pb^{-1} integrated luminosity
- about 3,500 $b\bar{b}$ pairs

First B Physics Measurements: Mixing (Argus)

At $\Upsilon(4S)$ resonance

- $m_{\Upsilon(4S)}(10.580\ \text{GeV}) >$
  $> 2 \times m_B(5.279\ \text{GeV})$
- $\Upsilon(4S) \to B^0\overline{B}^0 \to B_1^0 B_2^0$
- 25 like sign events
- 270 opposite sign events

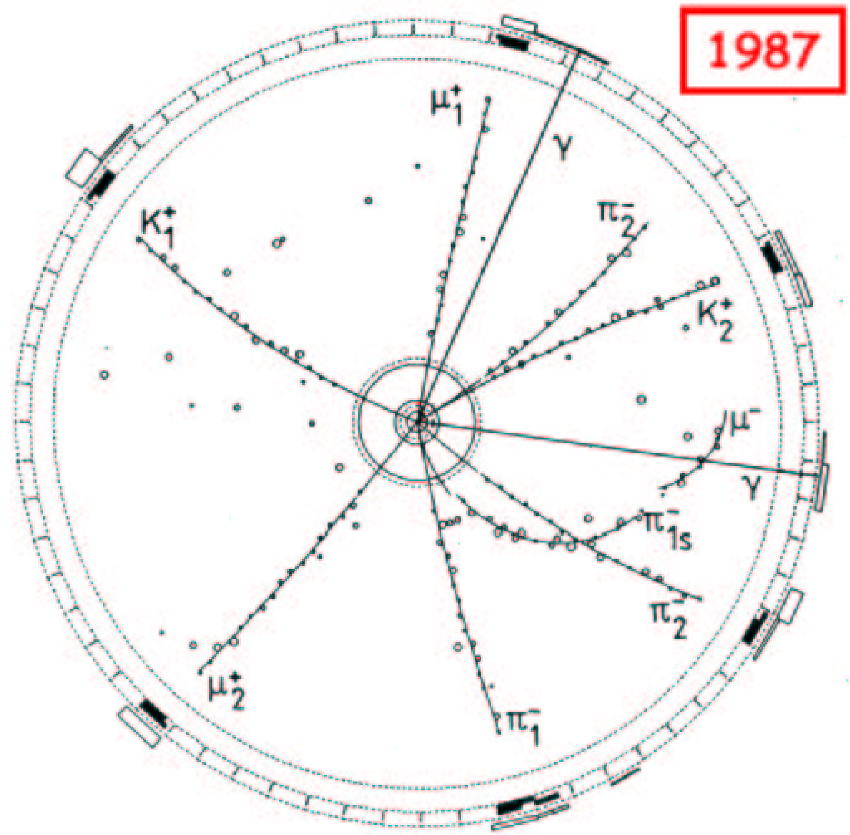
Time integrated mixing

Argus $\chi_b = 0.17 \pm 0.05$ PL B **192** (1987) 245

- slower than expected
- indication for heavy top

Experimental details

- e^+e^- at $\sqrt{s} = 10.58$ GeV
- 113 pb^{-1} integrated luminosity
- about 110,000 $b\overline{b}$ pairs



A like sign event!!

$$B_1^0 \to D_1^{*-}\mu_1^+\nu_1; D_1^{*-} \to \overline{D}^0\pi_{1s}^-$$
$$B_2^0 \to D_2^{*-}\mu_2^+\nu_2; D_2^{*-} \to D^-\pi^0$$

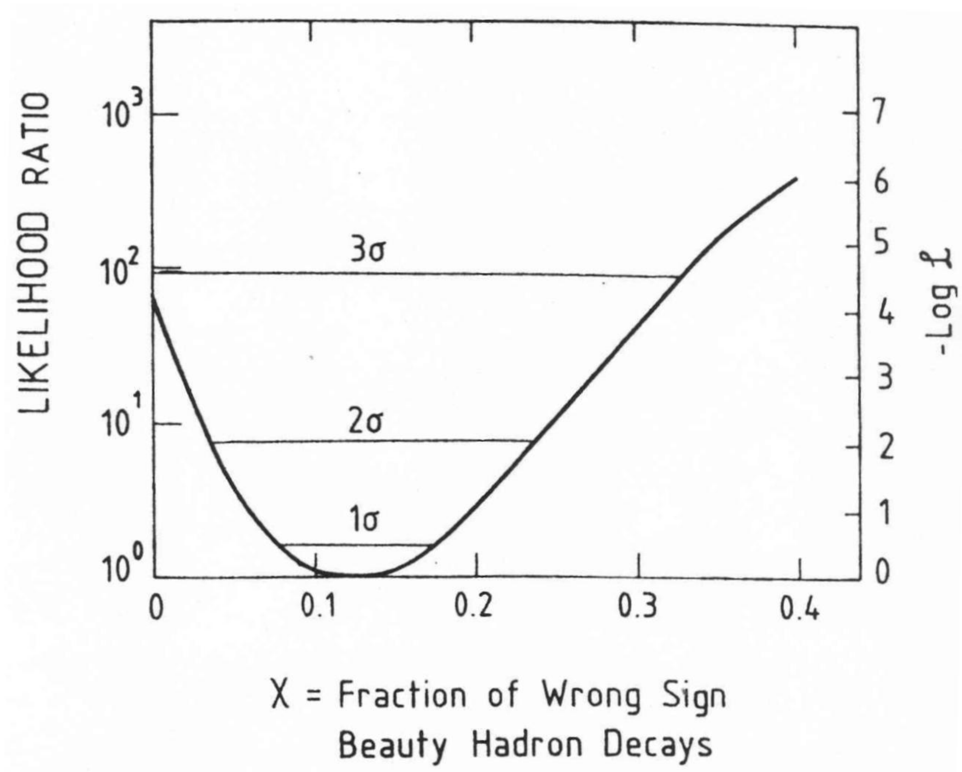
Start of the $\Upsilon(4S)$ success story

First B Physics Measurements: Mixing (UA1)

Inclusive measurement at $p\bar{p}$ collider

PL B **186** (1987) 247

- signature: like sign high p_T leptons; UA1 got it first: 3 sigma

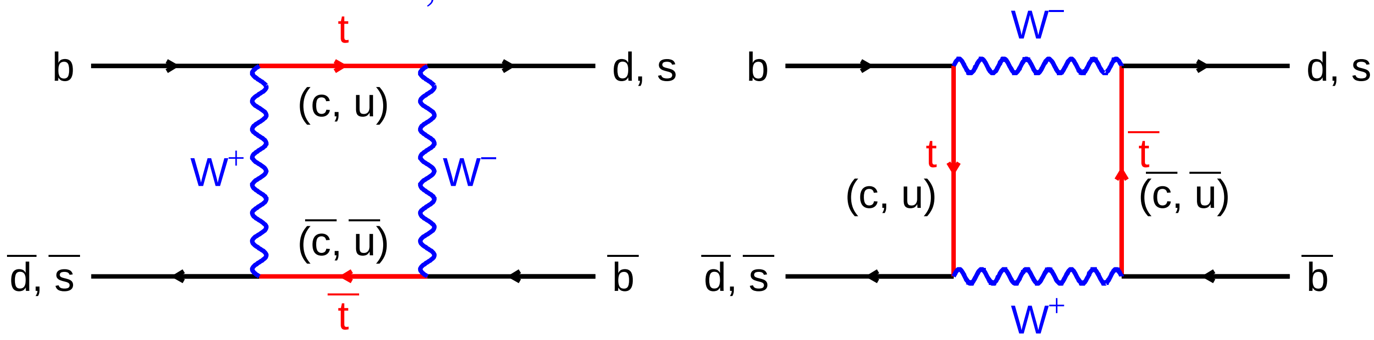


Argus at the time excluded this value at 90% CL

Start of the $p\bar{p}$ B physics success story

Advanced Measurements: B_s Mixing

Feynman diagram of $B^0_{d,s}$ mixing:



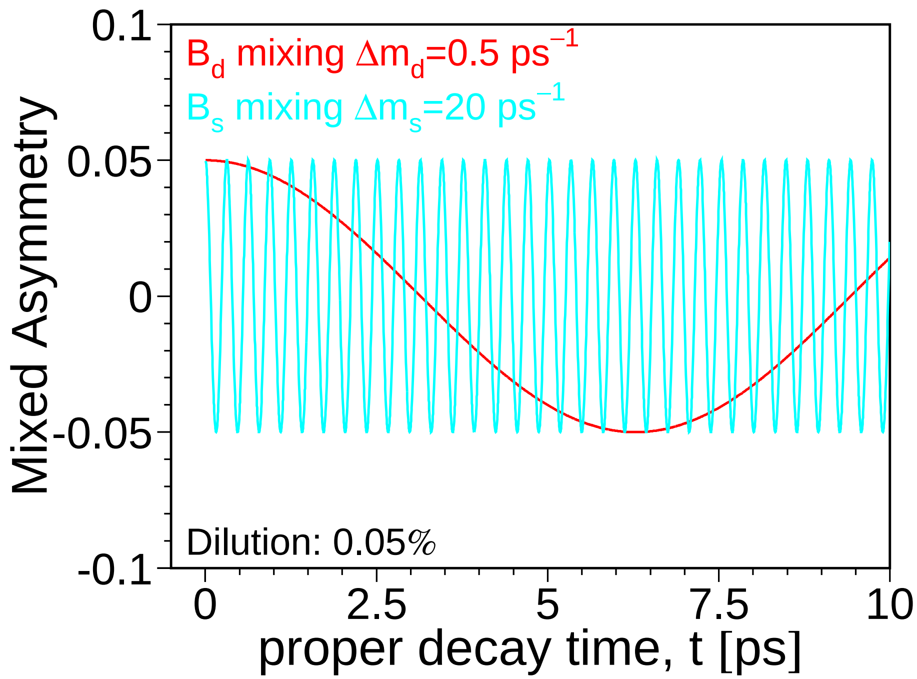
Differences

- + B^0_d crosses two families
- + B^0_s crosses one family
- + faster B^0_s mixing (≈ 40)

Experimental challenge

- + *ct* resolution critical
- + fully hadronic decays:

$$B_s \to D_s^- \pi^+ (\pi^+ \pi^-)$$

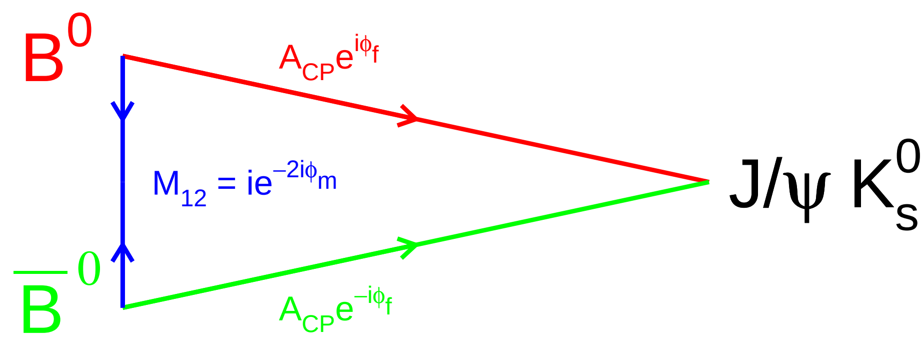


To be done at Tevatron

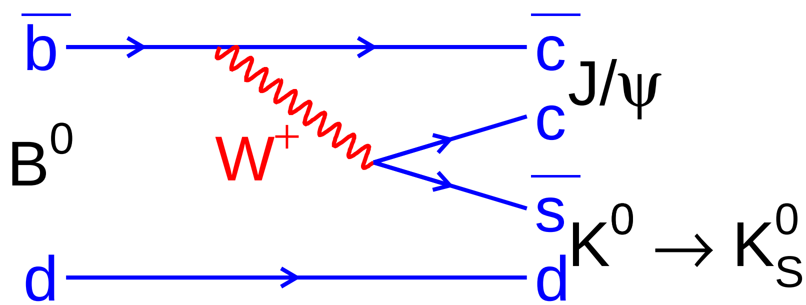
Advanced Measurements: *CP* Violation – $\sin 2\beta$

CP Violation mechanisms

- + interference of decay amplitudes
- + interference of mixing diagram
- + interference between mixing and decay amplitude



Golden mode: $B^0 \to J/\psi K_S$



CP eigenstate: $\eta_{f_{CP}} = -1$

$$\mathcal{Im}\lambda_{b\to c\bar{c}s} = \eta_{f_{CP}}\,\mathcal{Im}\left[\frac{V_{tb}V_{td}^*}{V_{tb}^*V_{td}}\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\frac{V_{cd}^*V_{cs}}{V_{cd}V_{cs}^*}\right]$$

$$= \eta_{f_{CP}} \sin 2\beta$$

$$A_{f_{CP}}(t) = \frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})} = -\mathcal{Im}\lambda_{f_{CP}} \sin \Delta m_d t$$

CKM Measurements from *B*

Unitarity triangle and what measures it

CP Violation parameter, $\sin 2\beta$

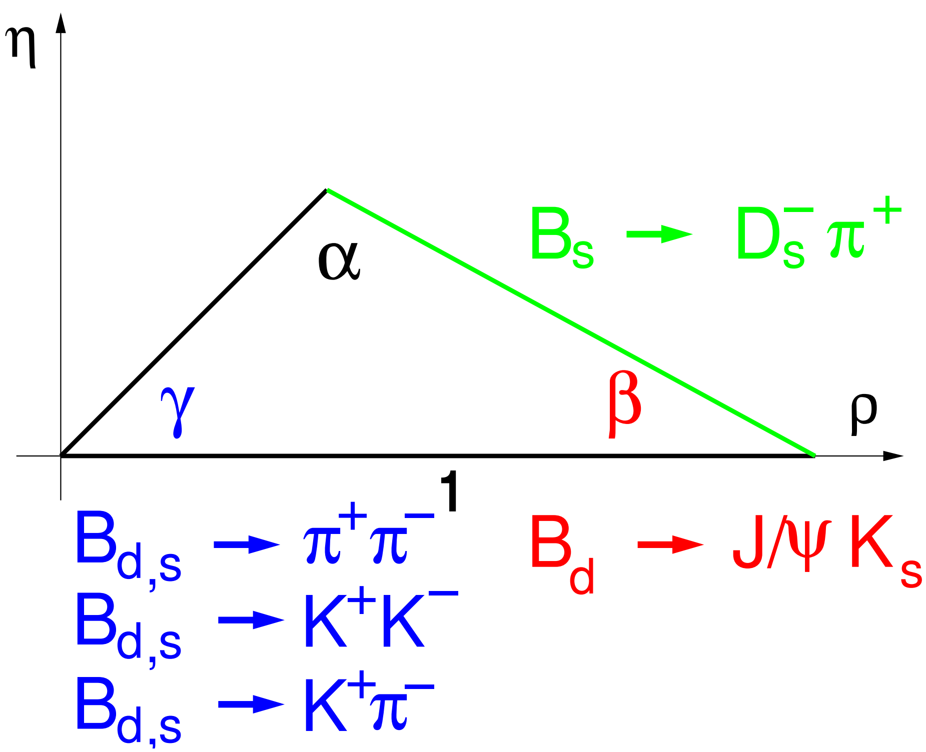
- $B^0 \to J/\psi K_S$
- simple signature
- relatively large branching

Mixing parameter, Δm_s

- $B_s^0 \to D_s^- \pi^+$
- needs hadronic trigger
- clean signature
- relatively large branching

CP Violation parameter, γ

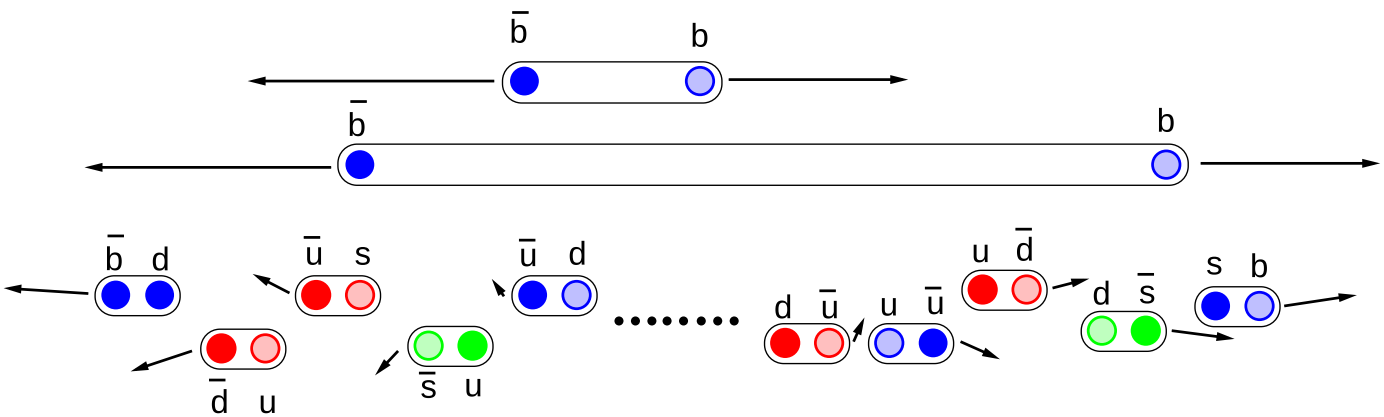
- $B_{s,d}^0 \to \pi\pi, K\pi, KK$
- tricky.. for later



Producing *b* Quarks / *b* Hadrons

Quark confinement

+ color string between quarks and gluons
+ to the outside: quark ensemble colorless
+ meson: color+anticolor; baryons: blue+green+red, ..
+ energy stored in string increases with distance
+ string breaks up and new quarks are created
+ controlled process (one pair) at $\Upsilon(4S)$ = clean
+ uncontrolled process in $p\bar{p}$ collisions = dirty

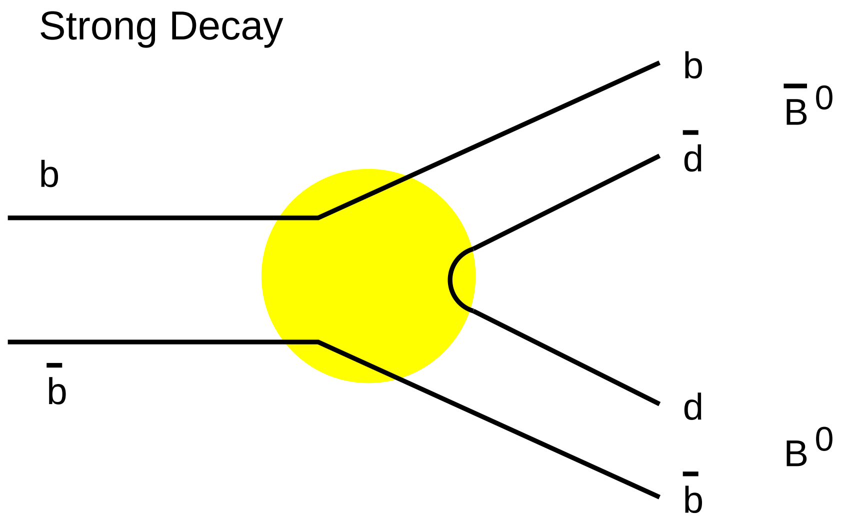


Simplistic but instructive fragmentation model

$\Upsilon(4S)$ versus $p\overline{p}$

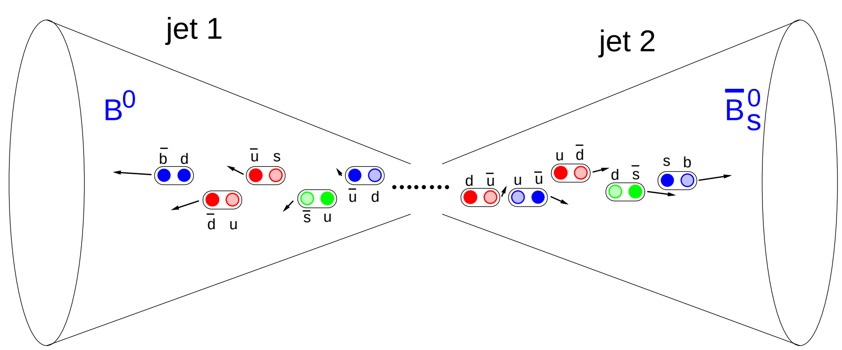
At $\Upsilon(4S)$

- \+ simple e^+e^- as input
- \+ *CM* energy enough for B^0, B^+
- \+ minimal fragmentation
- \+ asymmetric beams cause boost
- \+ coherent $B^0\overline{B}^0$ pair



At $p\overline{p}$ colliders

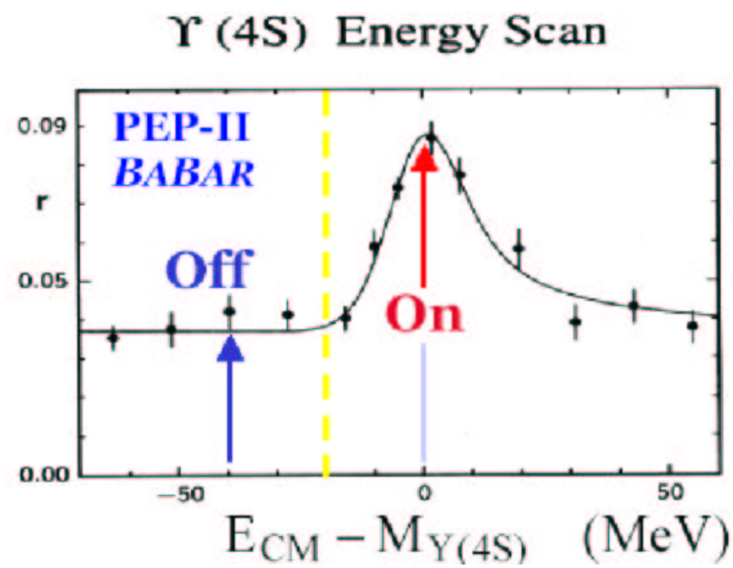
- \+ complicated $p\overline{p}$ as input
- \+ *CM* energy varies tremendously
- \+ always fragmentation
- \+ boost intrinsic: hadrons not at rest
- \+ incoherent $b\overline{b}$ pair

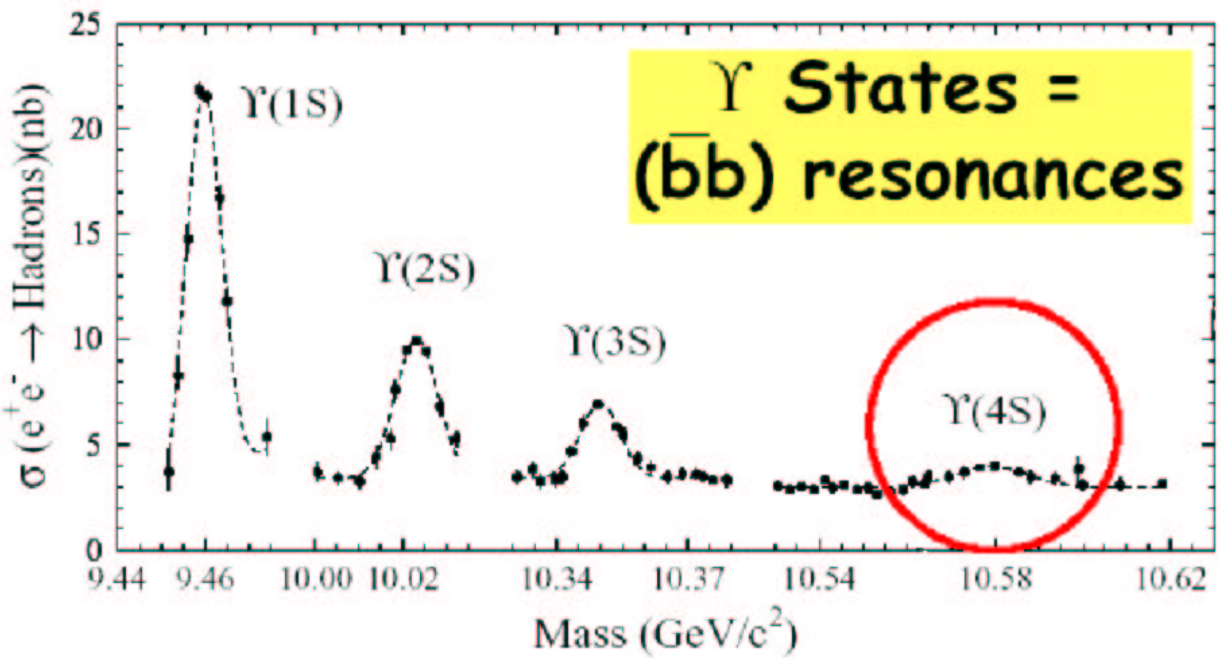


$\Upsilon(4S)$ Resonance

Available CM energy $\Upsilon(4S)$

+ $m_{\Upsilon(4S)} = 10.580$ GeV
+ $2 \times m_{B^0,B^+} \approx 10.54$ GeV 4
+ $m_{B_s} + m_{B^0} \approx 10.64$ GeV 8
+ B_s, B_c^+, Λ_b, Ξ_b .. not accessible





$\Upsilon(4S)$ Cross Sections

+ $\sigma(b\bar{b}) \approx 1.1$ nb
+ $\sigma(c\bar{c}) \approx 1.3$ nb
+ $\sigma(d\bar{d}, s\bar{s}) \approx 0.3$ nb
+ $\sigma(u\bar{u}) \approx 1.4$ nb

Coherent Production of $B^0\bar{B}^0$

Coherent state from $\Upsilon(4S)$ with $L = 1$ with $S(t_f, t_b) =$

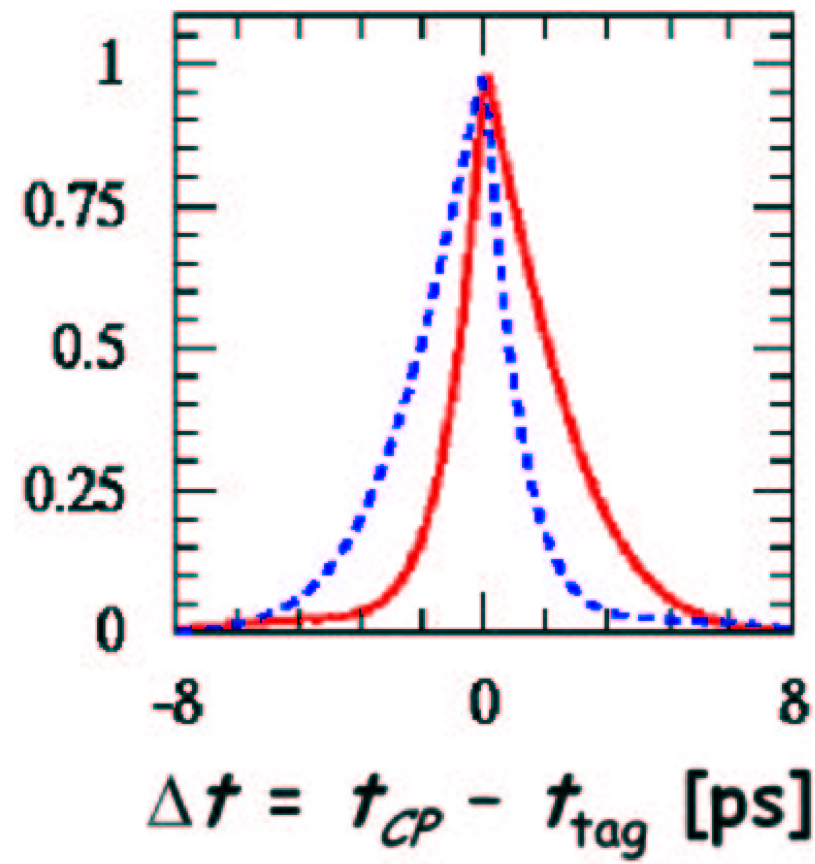
$$\frac{\sin\theta}{\sqrt{2}}\left[B^0_{phys}(t_f,\theta,\phi)\bar{B}^0_{phys}(t_b,\pi-\theta,\phi+\pi) - \bar{B}^0_{phys}(t_f,\theta,\phi)B^0_{phys}(t_b,\pi-\theta,\phi+\pi)\right]$$

Coherent development means

+ exactly one B^0 and one $\bar{B}^0$
+ at decay of any, coherence breaks

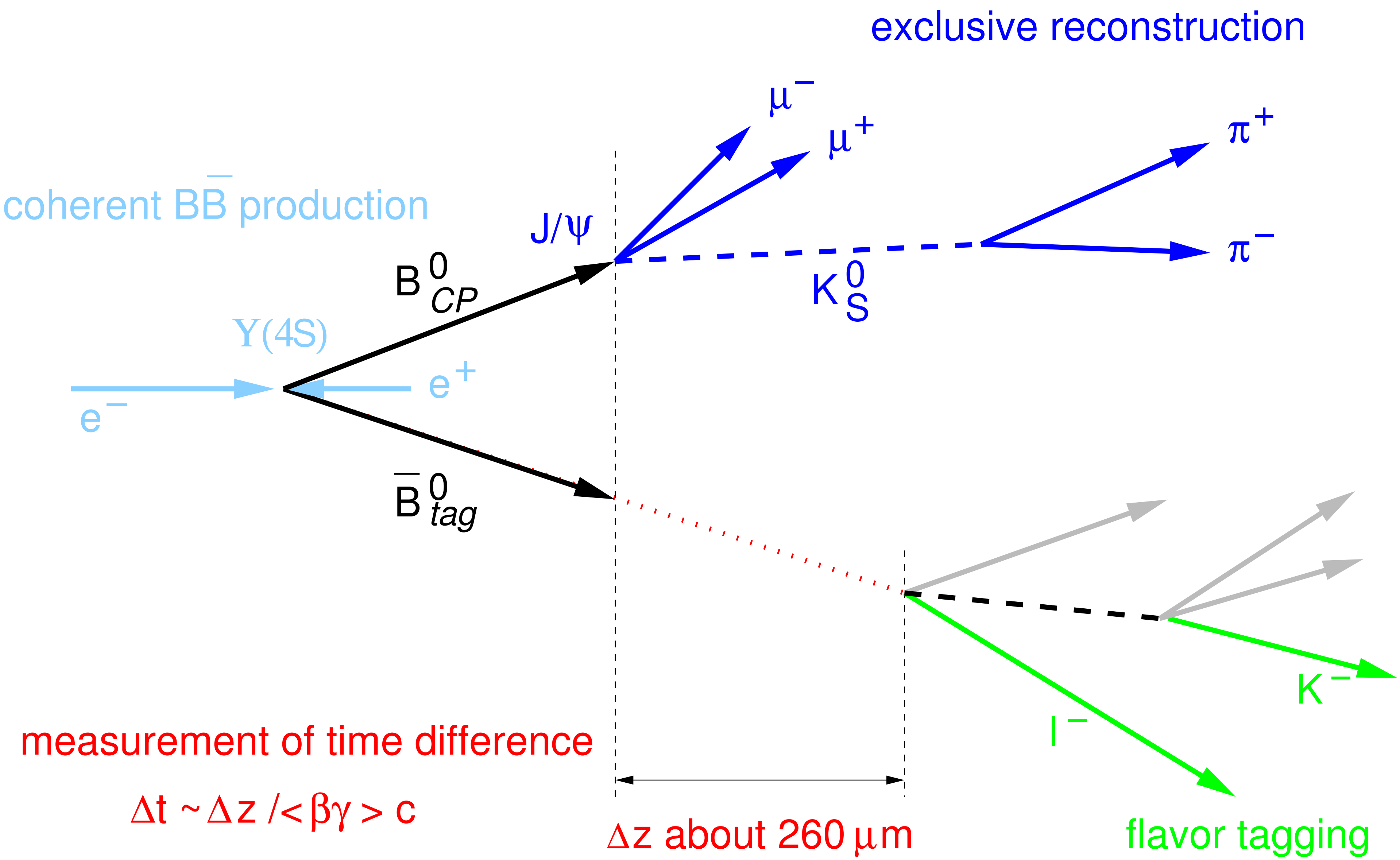
Consequences for measurement

+ mixing measurable after first decay
+ measure Δt between both decays
+ half of the time B_{CP} decays first, t_{CP}
+ other meson decay for tag, t_{tag}
+ symmetric behavior
+ integrated mixing is zero



B^0, $\bar{B}^0$ mesons with $t_{CP} = 0$

Detailed Cartoon of *B* Decays at $\Upsilon(4S)$



Tevatron Bottom Production - Overview

Cross Section:

$\sigma(b\bar{b}) \quad \approx 100\ \mu b$

Light quark σ(inelastic) 10^3 larger

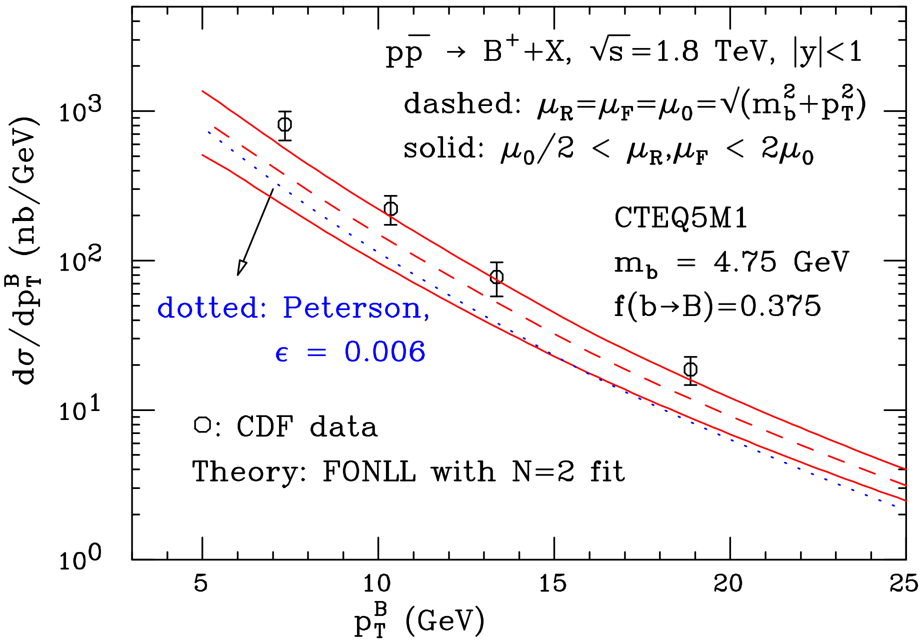
b-hadron triggers required

Triggers in Run I

- based on leptons ($\mu^\pm$, $e^\pm$)
- taus are not included
- typically single 8 GeV lepton
- typically two 2-4 GeV lepton
- semilept. decays or $J/\psi \rightarrow \mu\mu$

Triggers in Run II

- all the lepton triggers
- also displaced tracks
- typically two 2 GeV tracks
- hadronic modes available



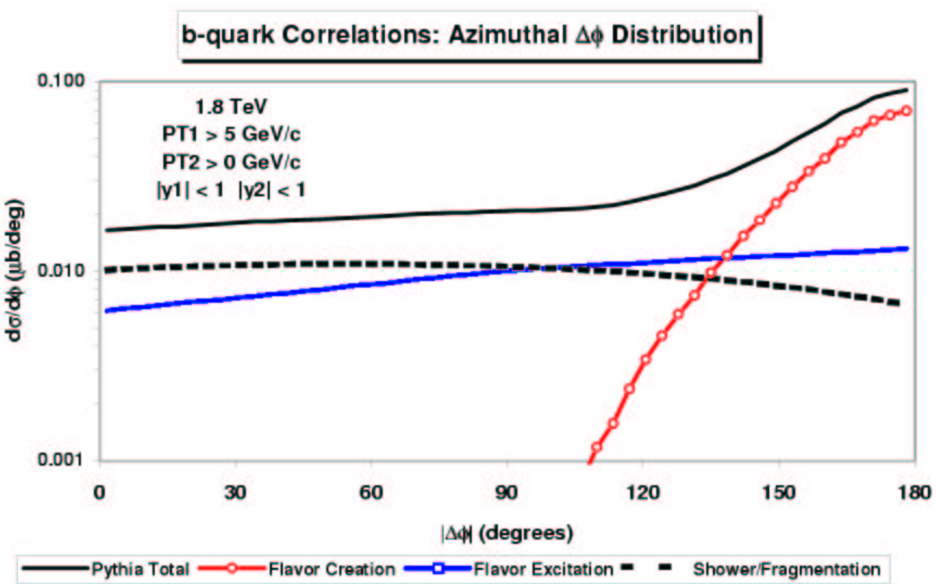
CDF Run I analysis: $B^+ \rightarrow J/\psi K^+$

- single inclusive *B* cross section
- theory update FONLL Cacciari, Nason
- $\sigma_{data}/\sigma_{theory} = 1.7$
- data do not contradict theory

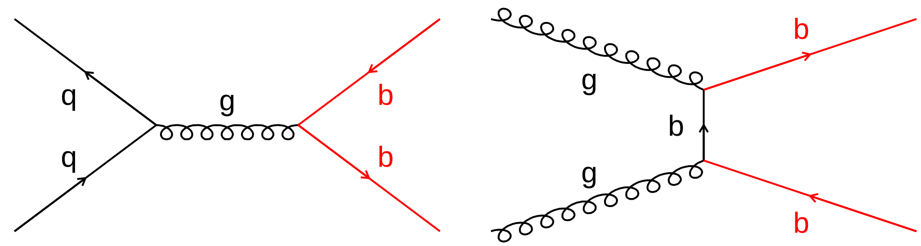
b Quarks / *b* Hadrons at the Tevatron

$p\bar{p}$ collisions

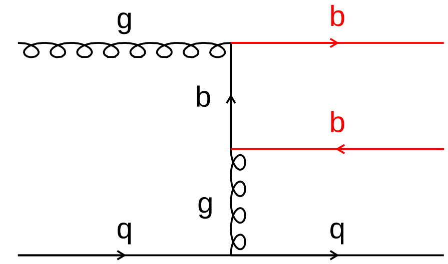
- 1 TeV beam energy
- proton is complicated beast
- collisions quite imbalanced
- large σ(forward,backward)
- often second *b* not in acceptance
- $b\bar{b}$ production not coherent
- always refer to primary vertex



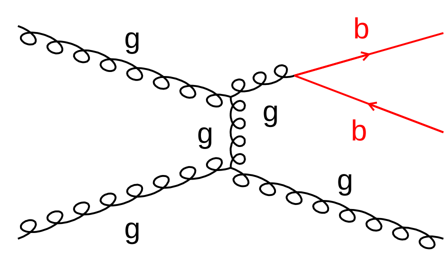
Lowest order



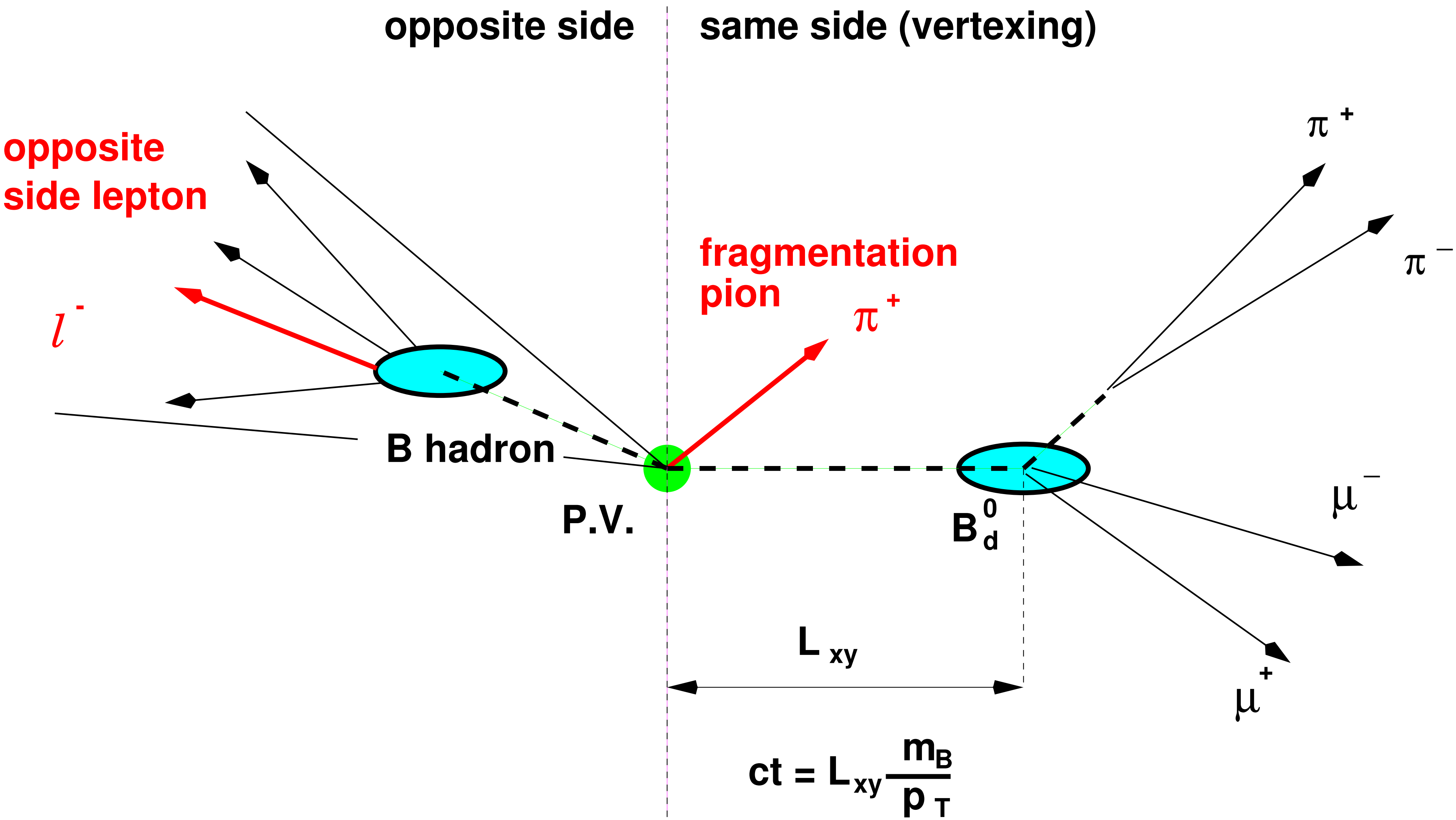
Flavor excitation



Gluon splitting



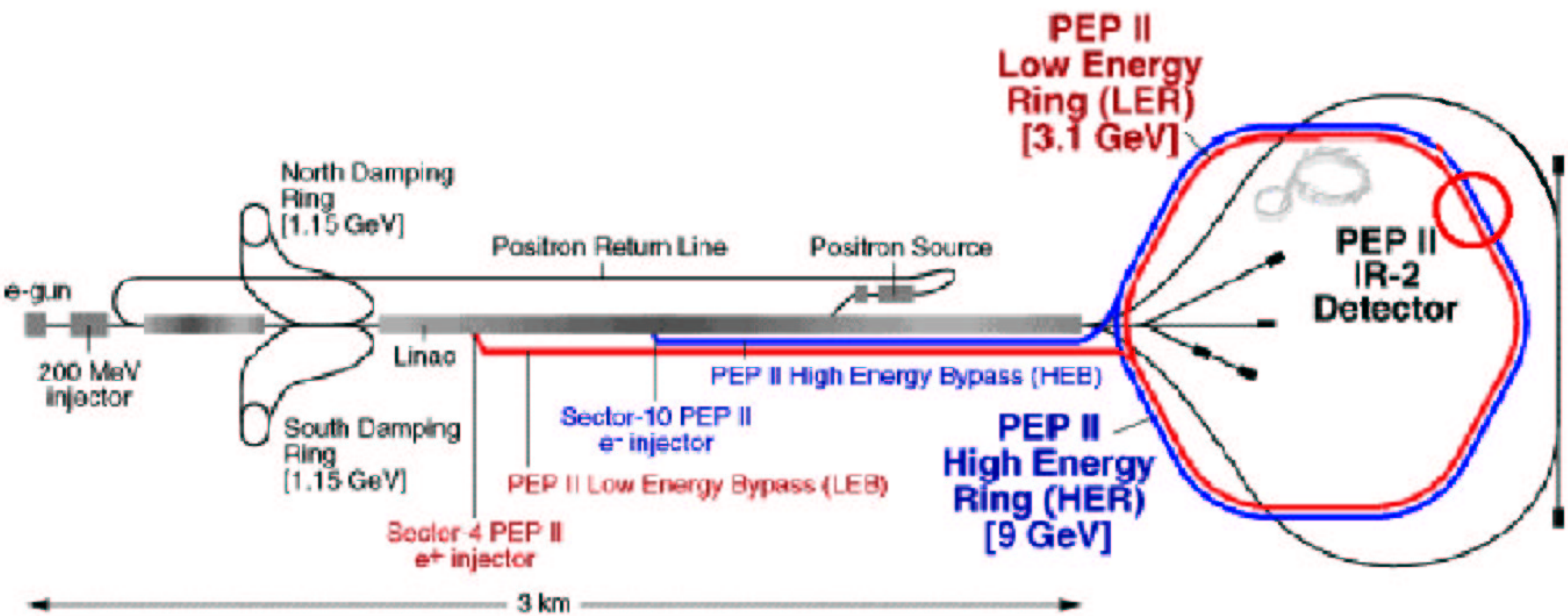
Detailed Cartoon of B Decays at Tevatron



PEP II Machine

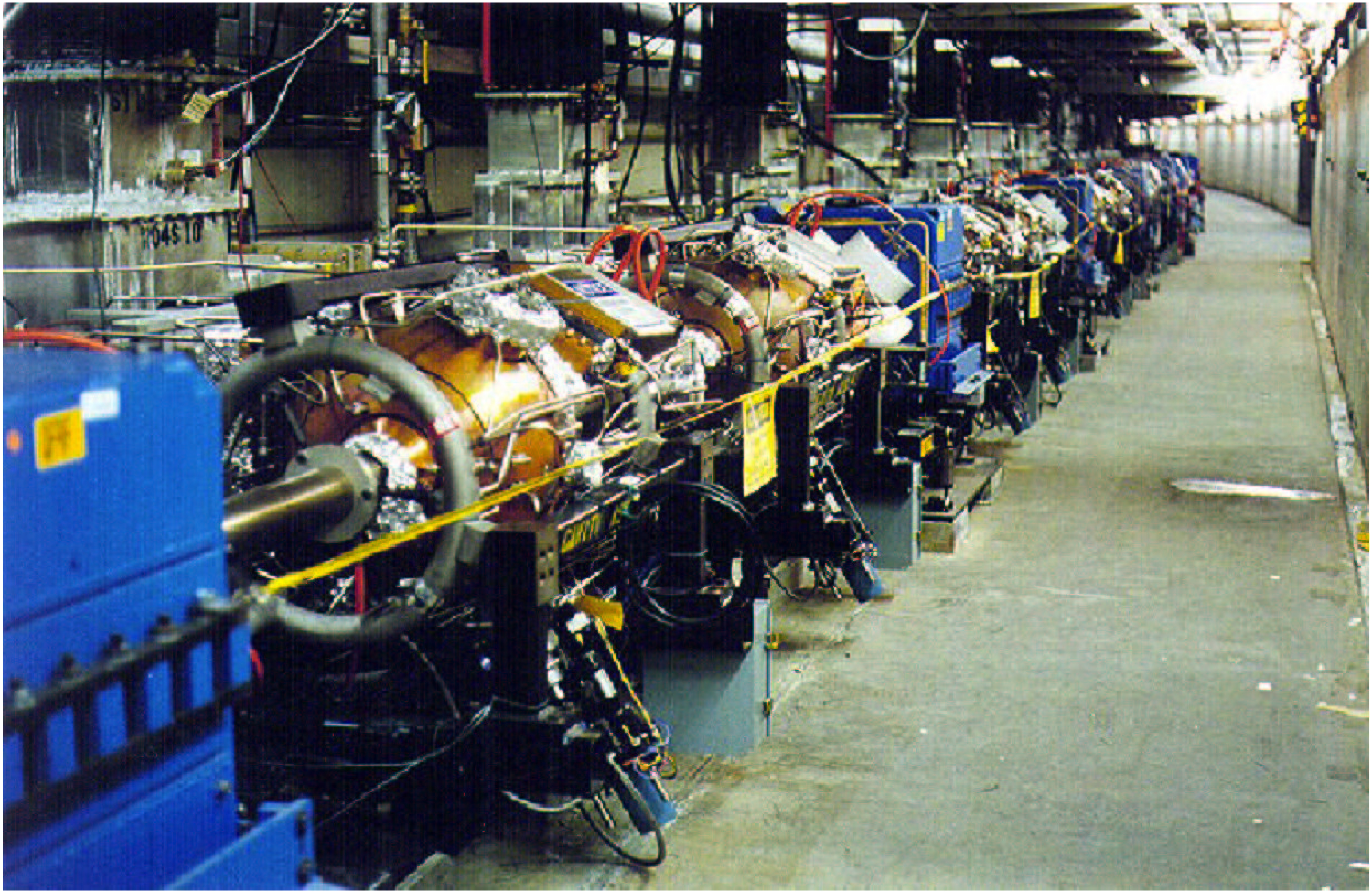
PEP II is located in the 2.2 km PEP tunnel

- 9 GeV electrons on 3.1 GeV positrons
  $\rightarrow \Upsilon(4S)$ boost: $\beta\gamma = 0.55$



PEP II Machine – The Rings

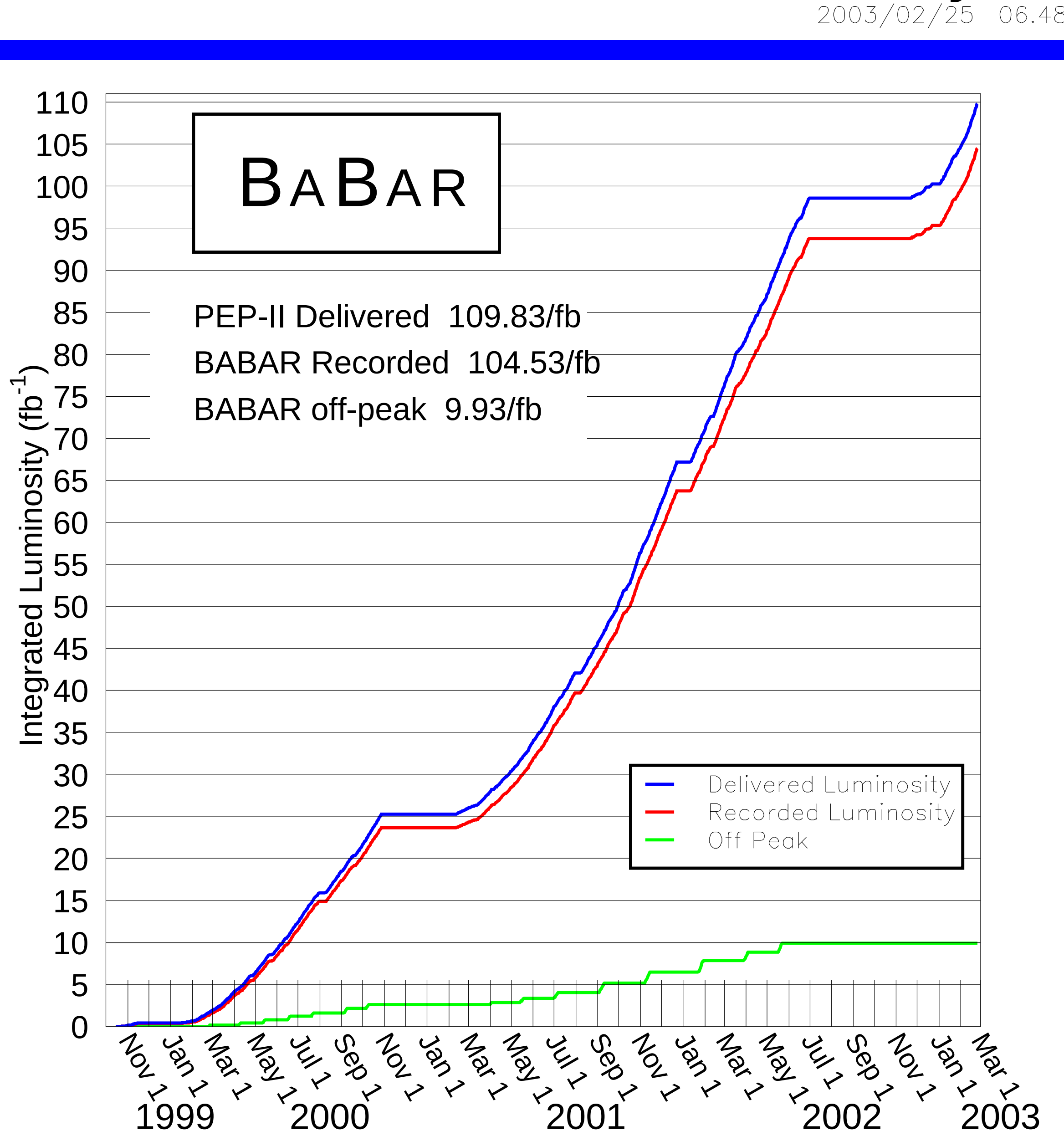
PEP II – The RF Clystrons



PEP II / KEKB Machine Performance

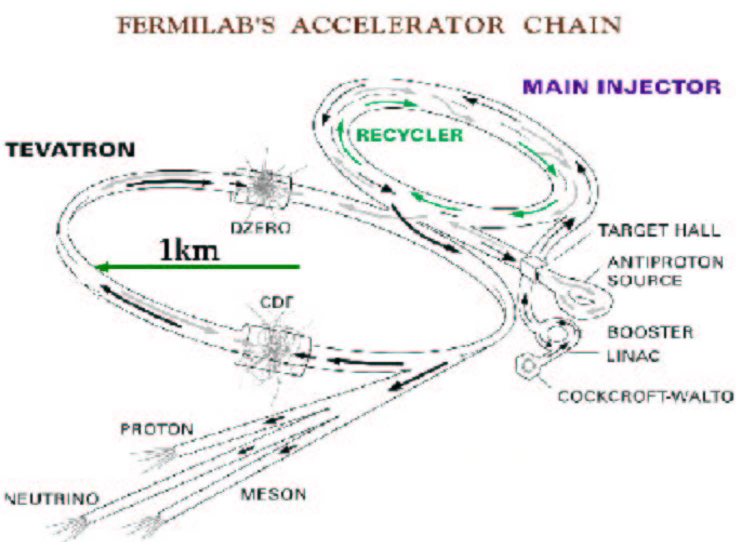
	PEP II		KEKB	
	e^-	e^+	e^-	e^+
Beam energies [GeV]	9	3.1	8	3.5
Currents [A]	1.05	2.14	0.92	1.37
Number of bunches	830		1223	
Luminosity [$\times 10^{33}/\text{cm}^2/\text{sec}$]	4.6		7.35	
Bunch spacing [m]	2.52		2.4	
Bunch currents [mA]	1.28	2.20	0.71	1.14
Beam stored energy [kJ]	69	41	73	49
Beam power [GW]	9.4	5.6	7	5
Beam RF power [GW]	2.5	1.4	3.2	2.4

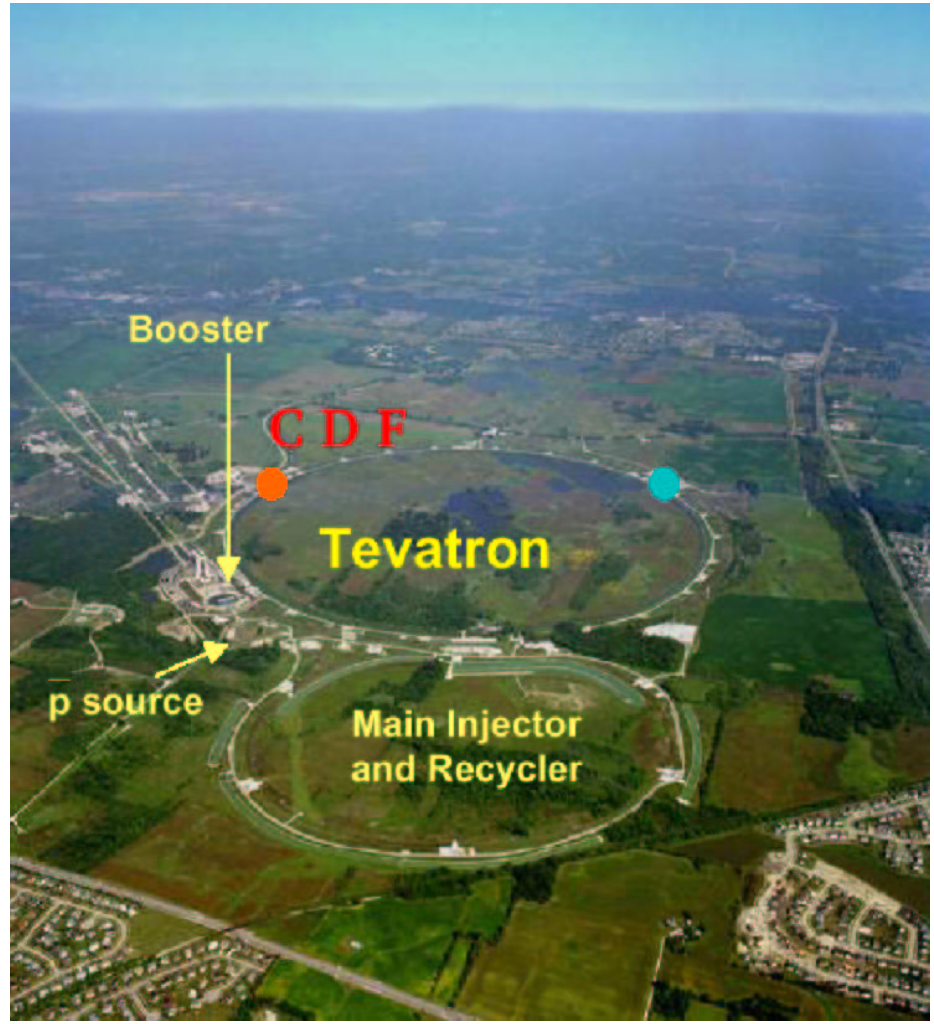
PEP II Machine – Luminosity



Accelerator Setup at Fermilab

Complex accelerator system





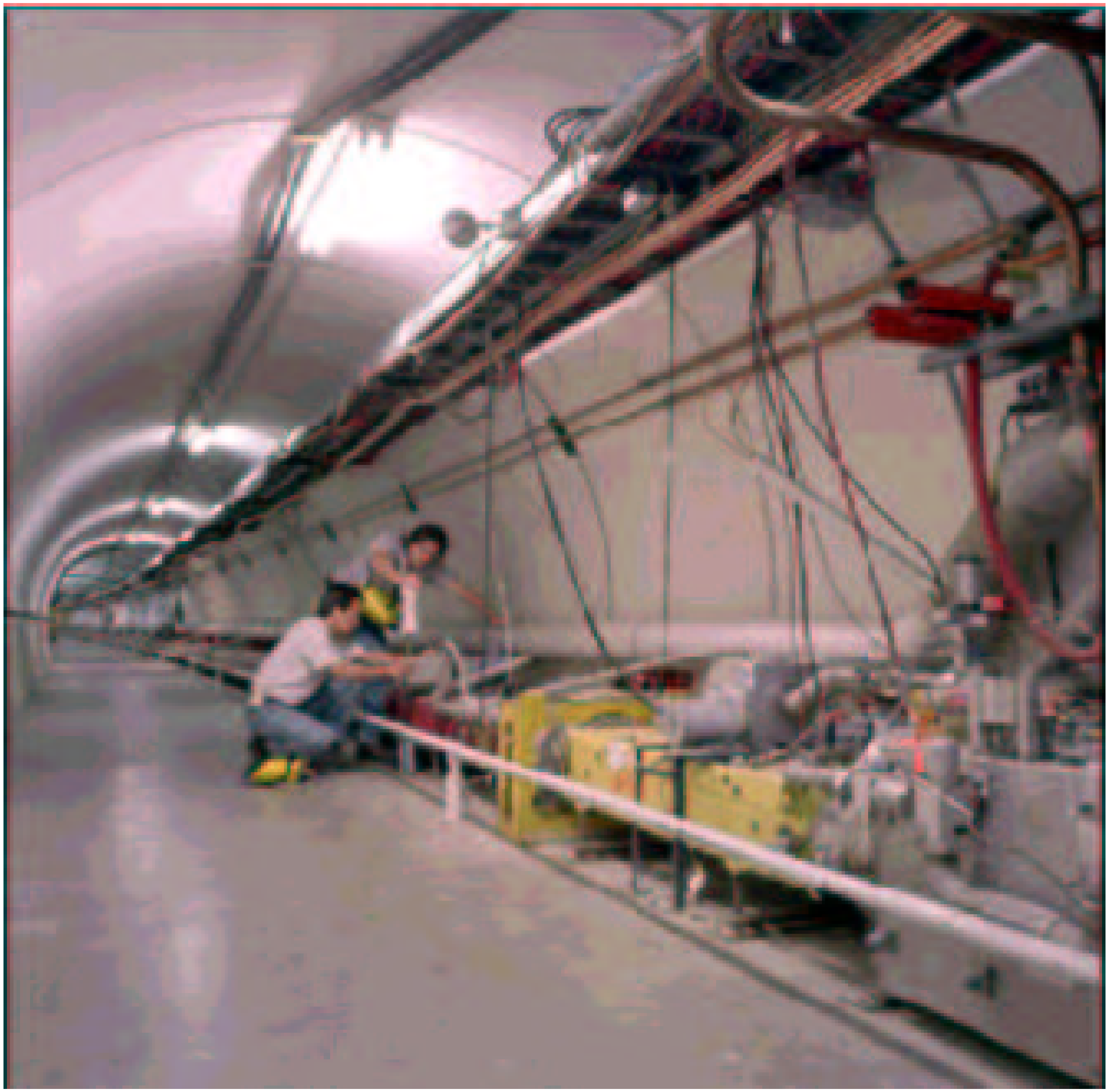
Tevatron Collider

+ Tevatron 1 km ring radius
+ $10^{11}(10^{10})$ $p(\bar{p})$ per bunch
+ 36x36 colliding p, $\bar{p}$ bunches

Goal

+ high beam-beam crossing but few events per crossing

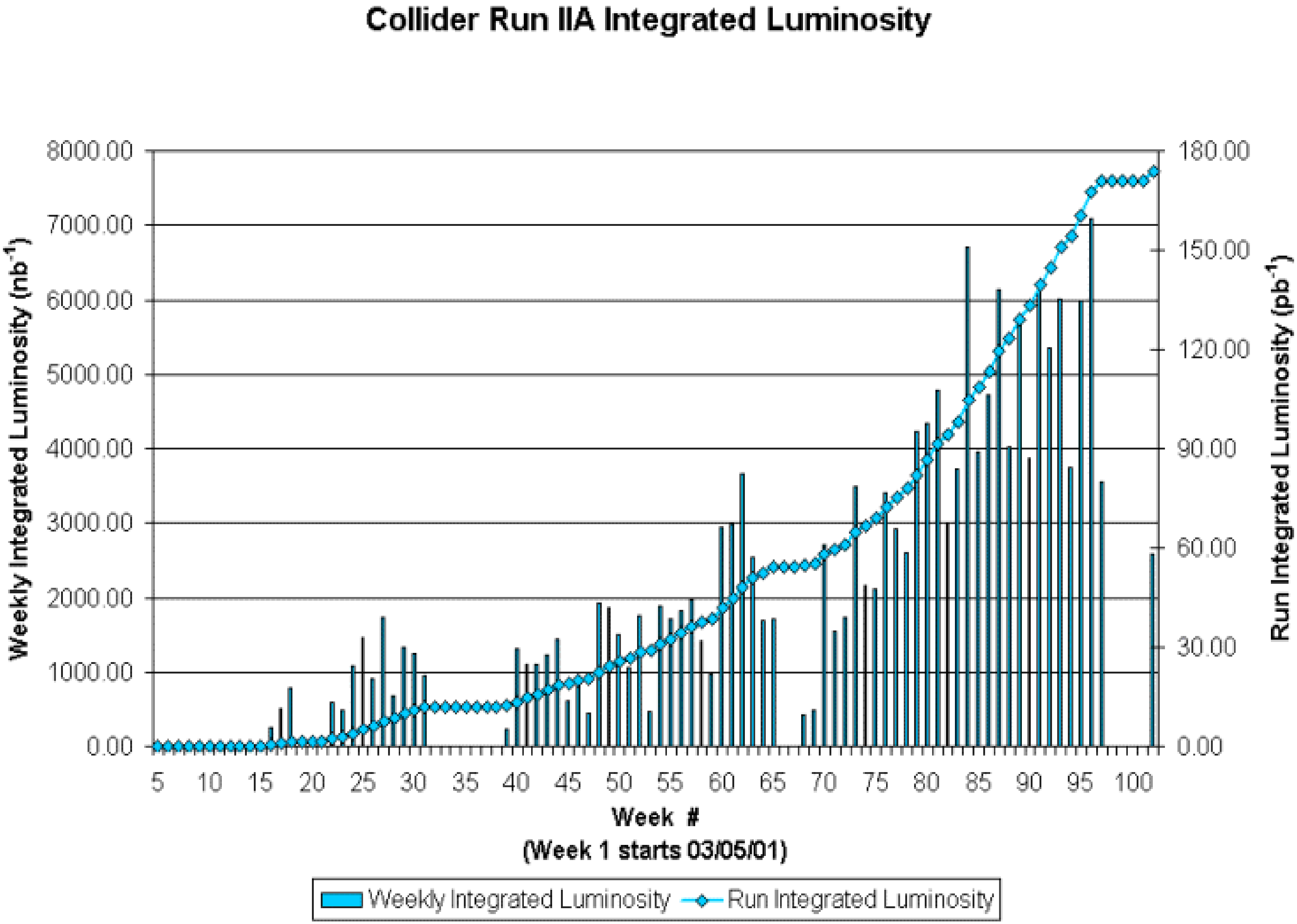
Tevatron – The Ring



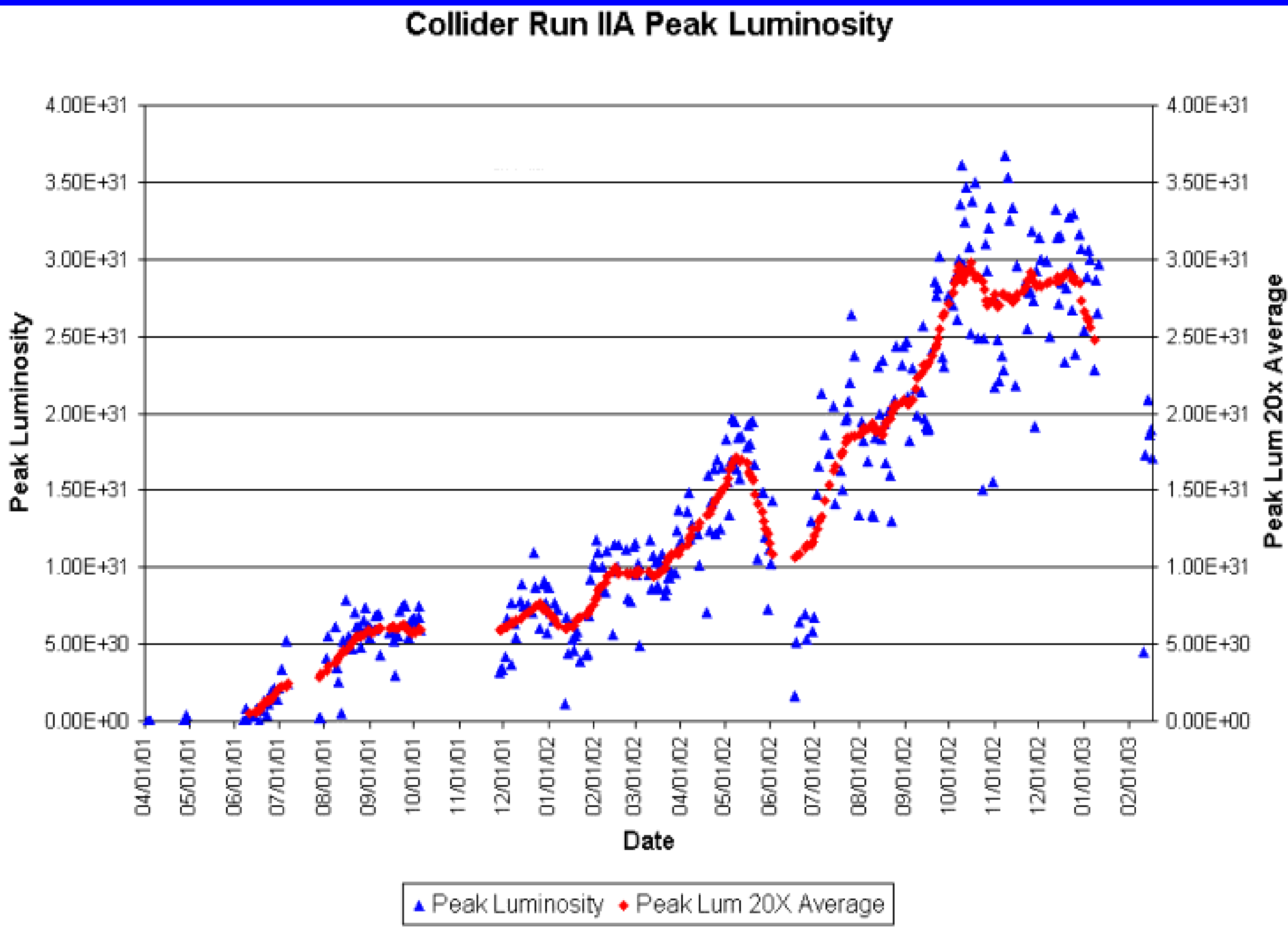
Tevatron Machine Performance

	acchieved	Run IIa goal
Beam energies [TeV]	1	1
Protons/bunch $\times 10^{10}$	20	27
AnitProtons/bunch $\times 10^{10}$	2.6	3.0
Number of bunches	36	36
Luminosity [$\times 10^{31}/cm^2/sec$]	3.2	8.1
Bunch spacing [ns]	396	396
Bunch length proton [cm]	61	37
Bunch length antiproton [cm]	54	37
Integrated Lumi [pb^{-1}/week]	5-7	16

Tevatron Machine Performance – Luminosity



Tevatron Machine Performance – Peak Luminosity



Detector Design – Considerations

Main design elements

- + solid angle coverage
- + vertex measurement
- + momentum measurement
- + particle identification: K vs π
- + Tevatron: trigger

Drift chambers, Momentum

- + resolution $\propto Br^2$
- + radius limited by cost of ECAL
- + minimize material in front of calorimeters
- + solid angle limited by IP setup

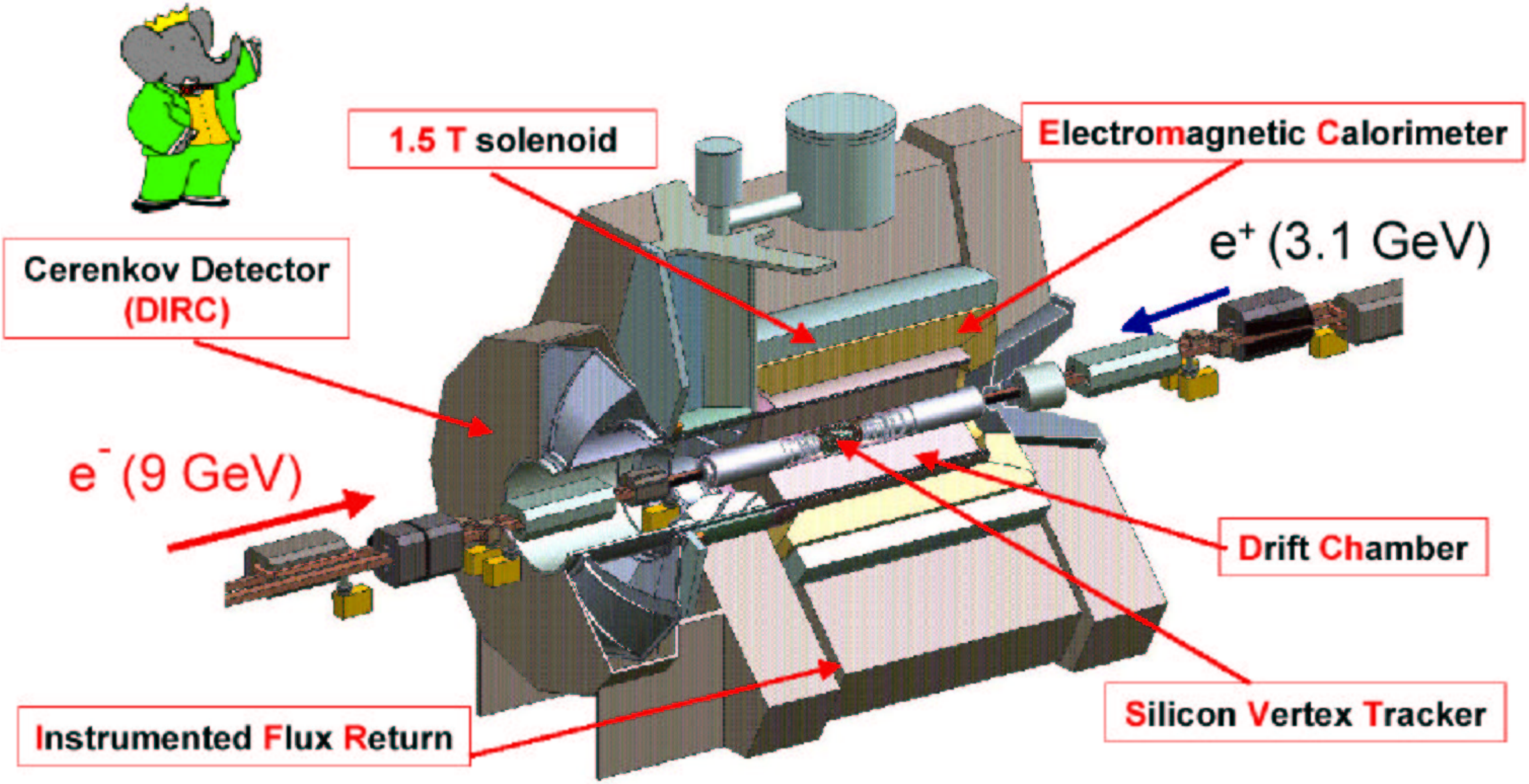
Silicon detectors, Vertex

- + close to the interaction point
- + little material: avoid MS
- + radiation hard
- + not to expensive
- + $\Upsilon(4S)$: z vertex res. $<$ oscillation
- + Tevatron: L_{xy} resolution crucial

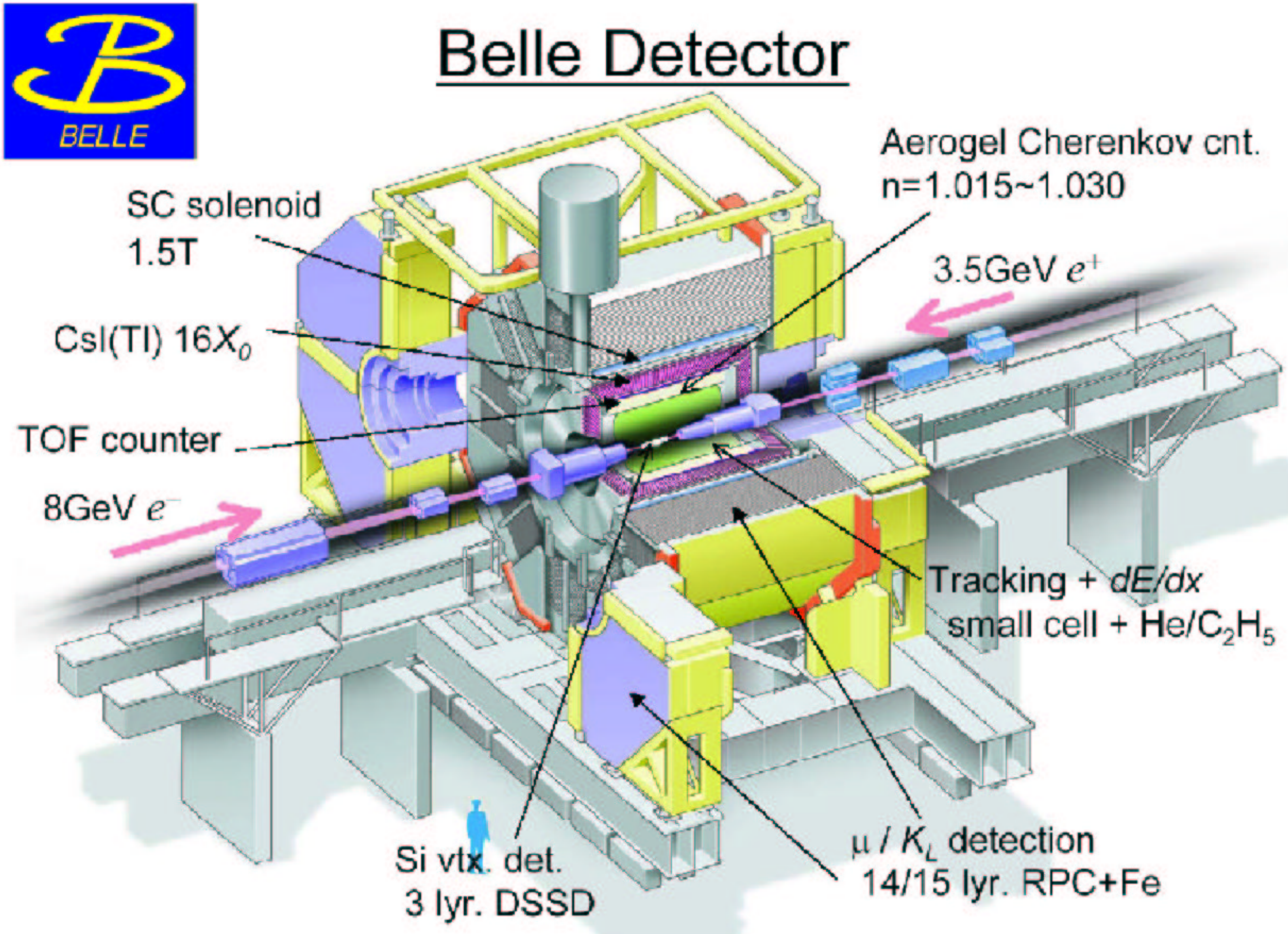
Particle Id detectors

- + cover given spectrum
- + kaon tagging: 0.6 – 2.0 GeV
- + 2 body B decays: up to 4.4 GeV
- + various implementations:
  TOF, Transition Radiation, DIRC

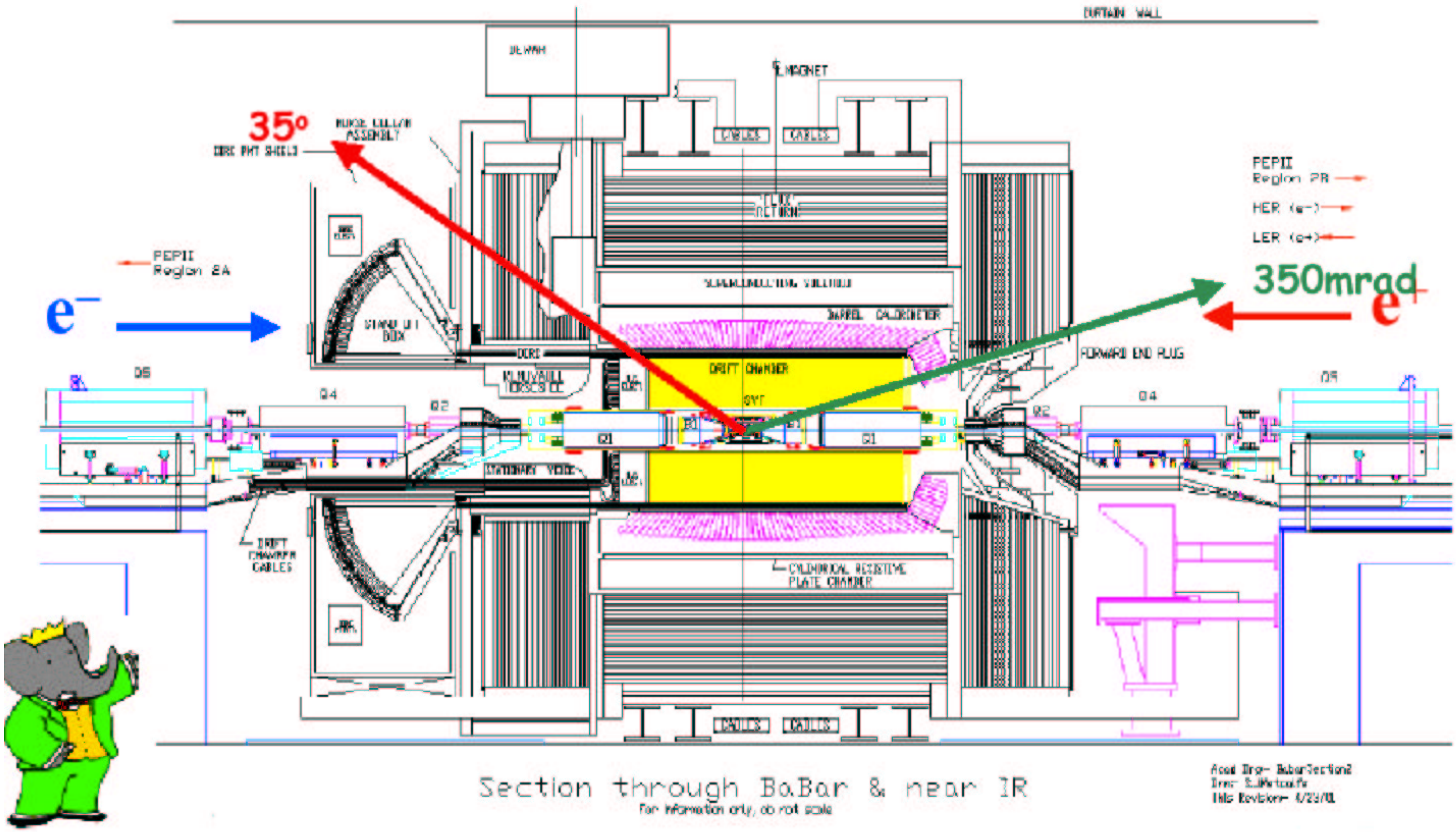
Detector – BaBar



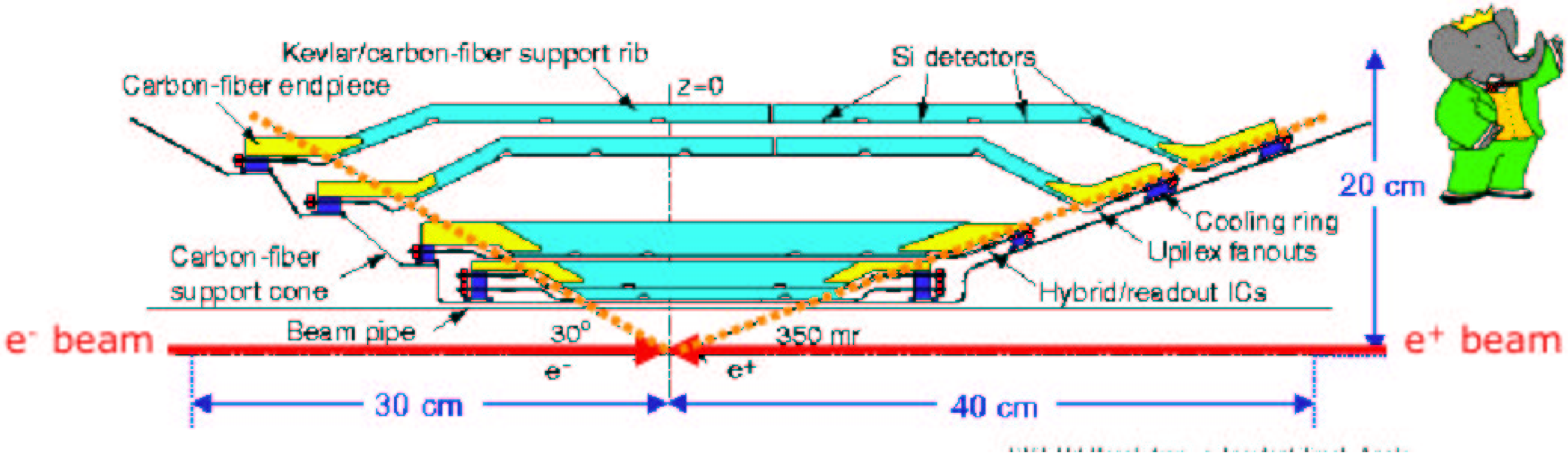
Detector – Belle



BaBar – Asymmetric Design

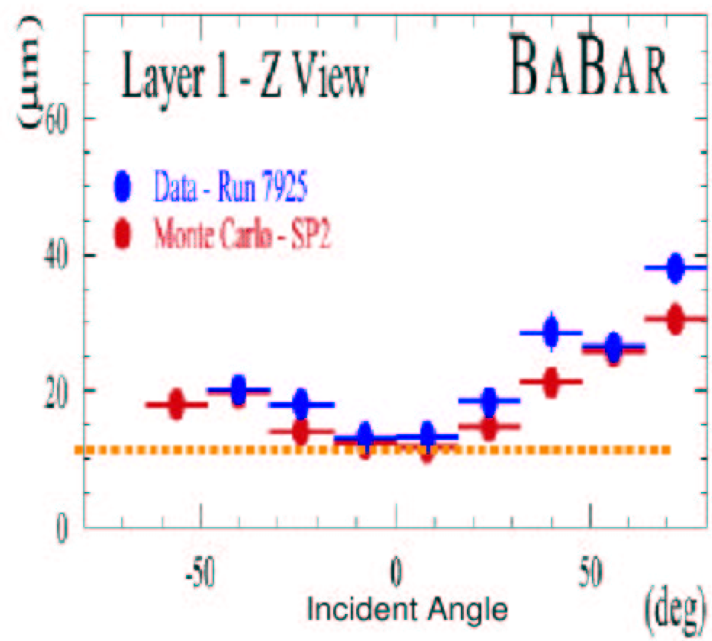


BaBar - Silicon Vertex Detector



Properties

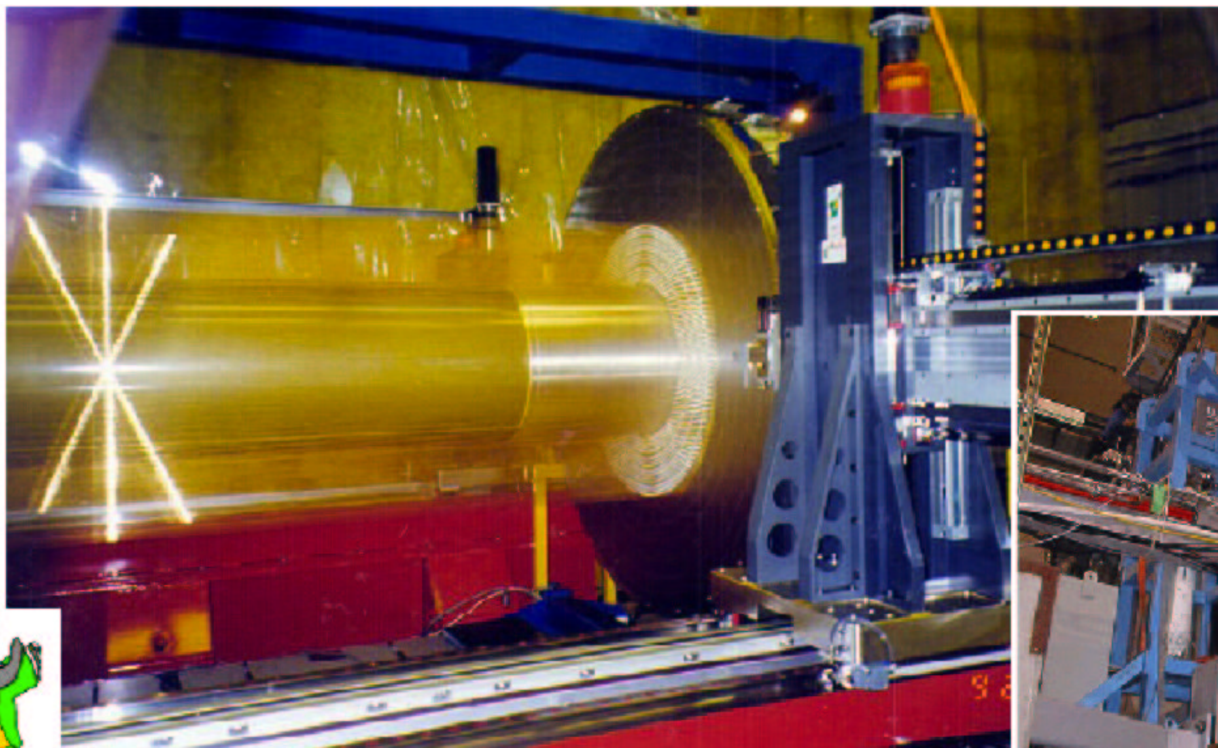
- 5 double sided layers
- AC coupled
- 97% hit reconstr. efficiency
- hit resolution ≈ 15 μm at 90°



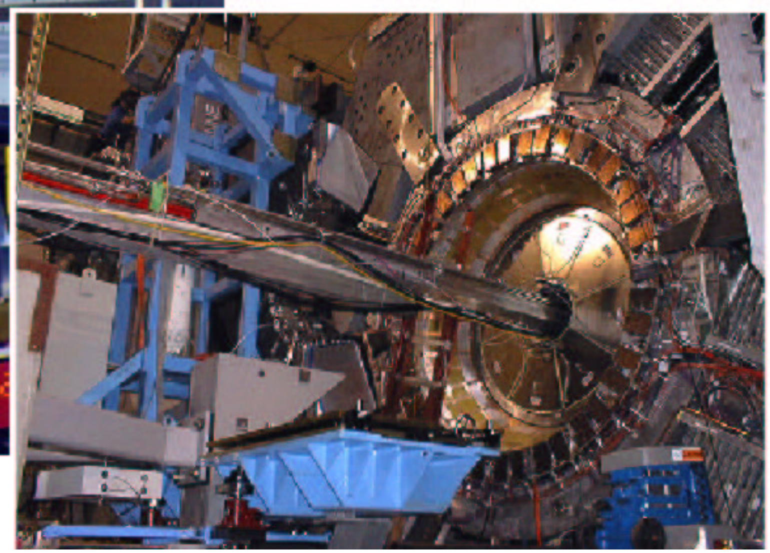
BaBar - Drift Chamber

Properties

- \+ 40 layers of wires in 1.5 Tesla magnetic field
- \+ Helium,Isobutane (80:20) gas, Al field wires
- \+ Beryllium inner wall
- \+ dE/dx particle id with 7% resolution



$$\frac{\sigma(p_T)}{p_T} = 0.13\% \times p_T + 0.45\%$$

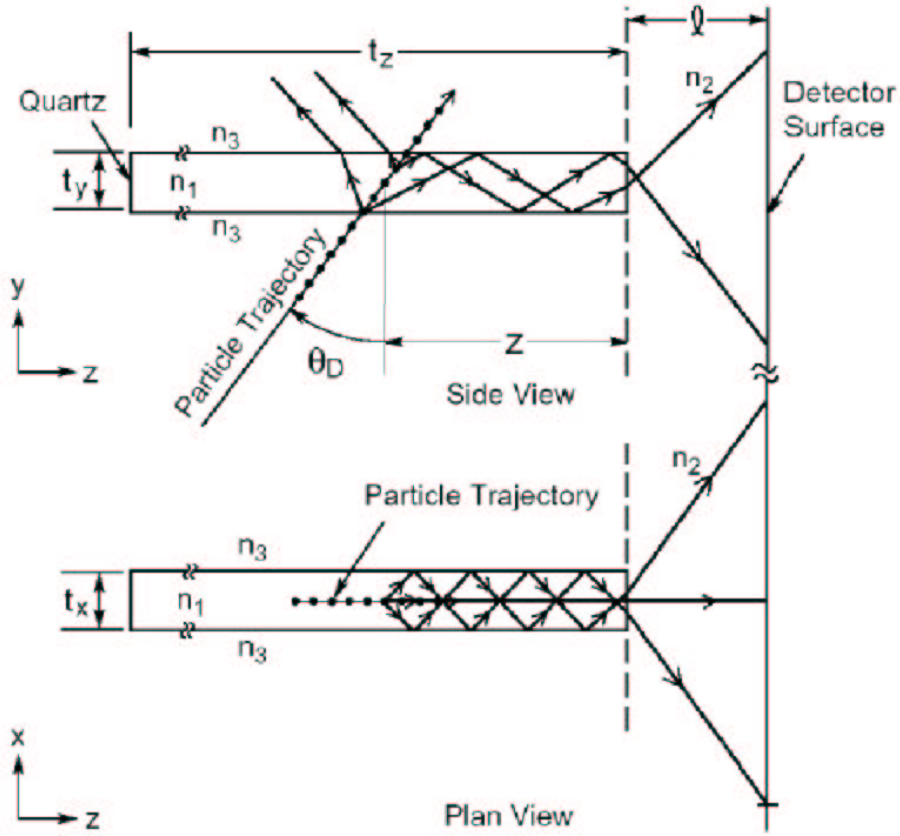


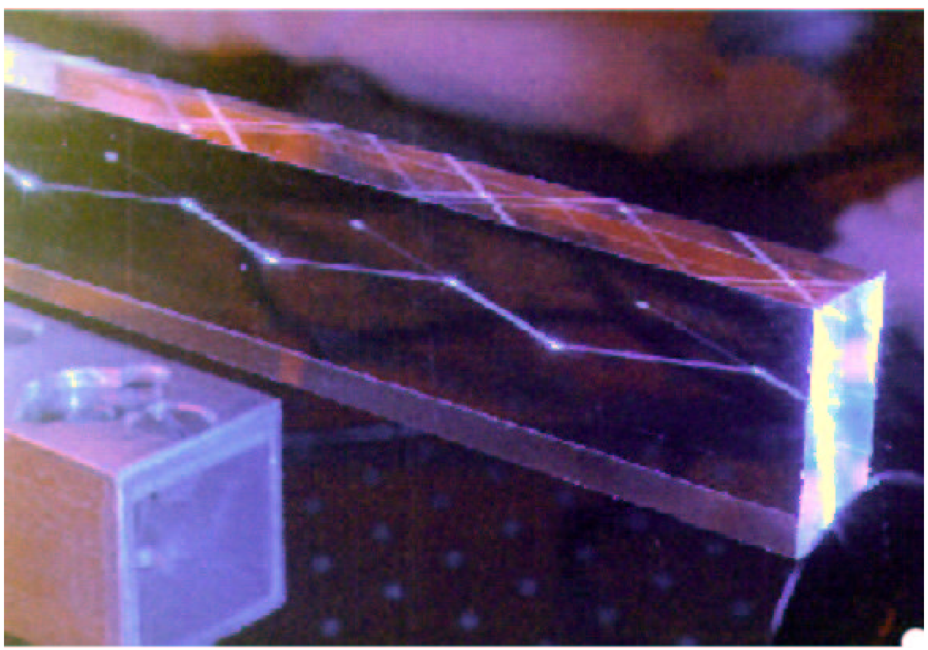
16 axial, 24 stereo layers

Principle of the DIRC

Particle identification

- DIRC consists of quartz bars
- particles emit Cherenkov light
  with $1/\beta$ opening angle
- light transmission via internal reflection
- opening angle is preserved on the precision surfaces
- rings projected in water tanks

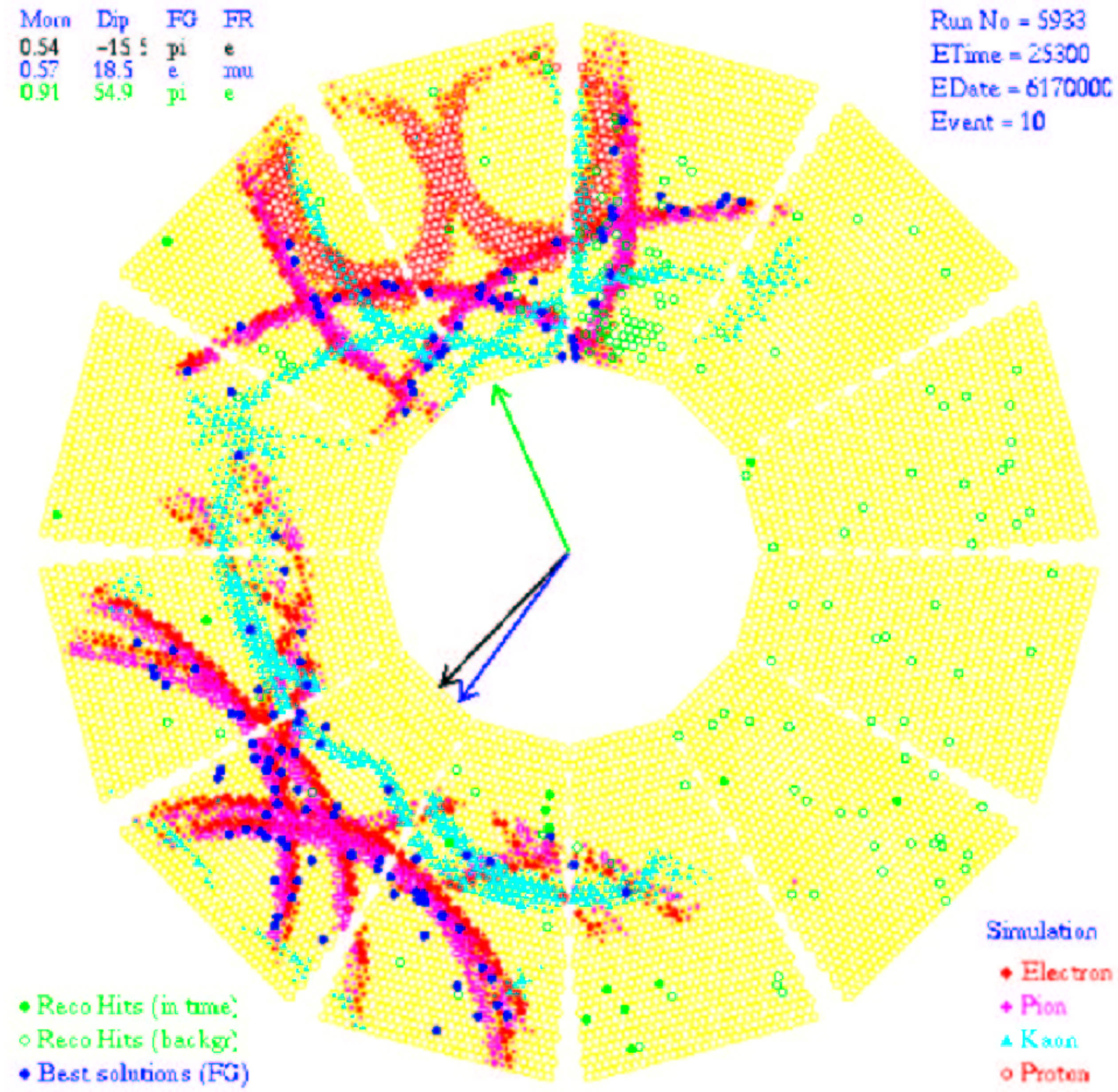




Water tank readout

- about 10k photomultipliers

DIRC Detector Pictures – BaBar



Particle Id Summary – BaBar

Particle identification

- drift chamber dE/dx
- DIRC particle Id system

Drift chamber

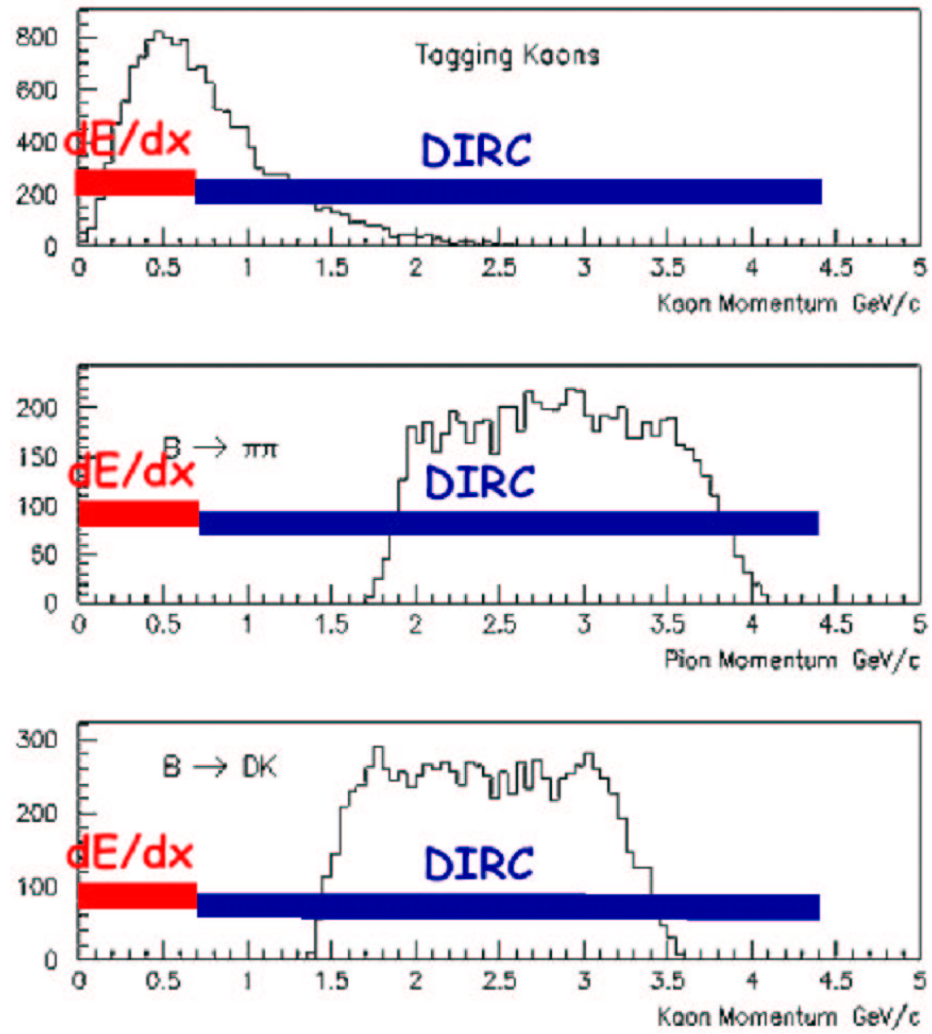
- dE/dx for $p < 1.4$ GeV

DIRC system

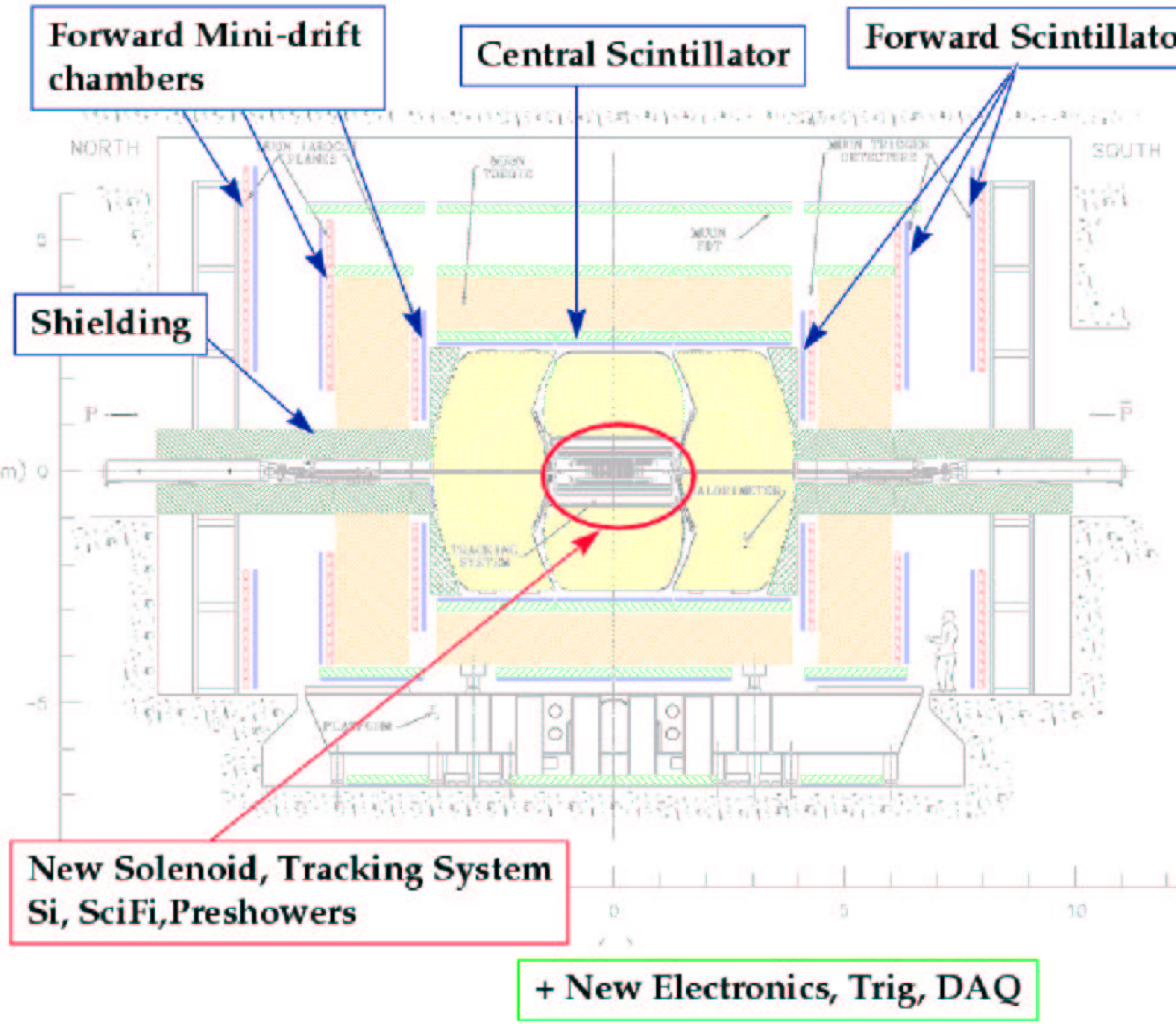
- for 1.4 GeV $< p <$ 4.4 GeV

Combined perfomance

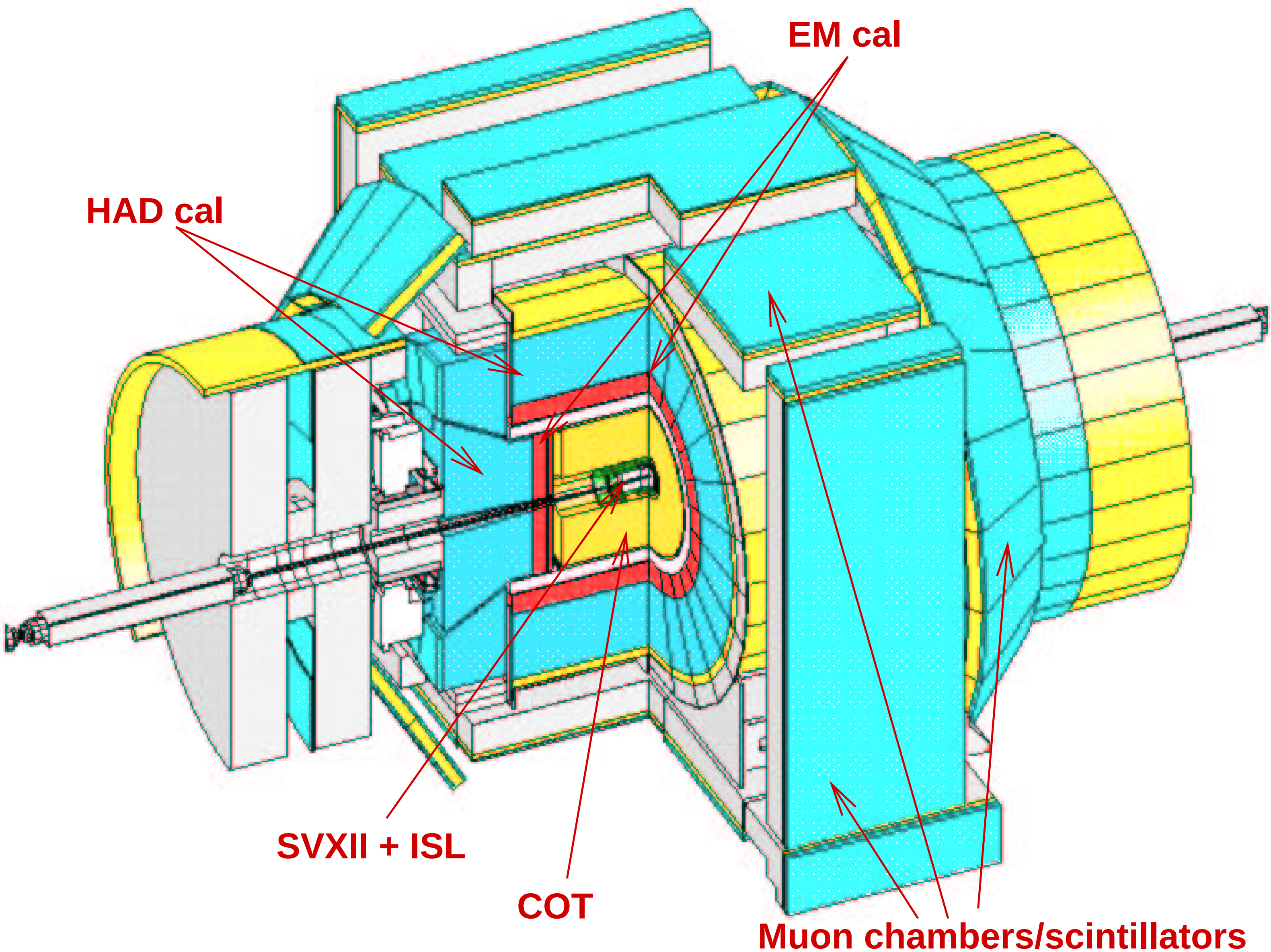
- Kaon identification 85%
- pion misidentified 5%



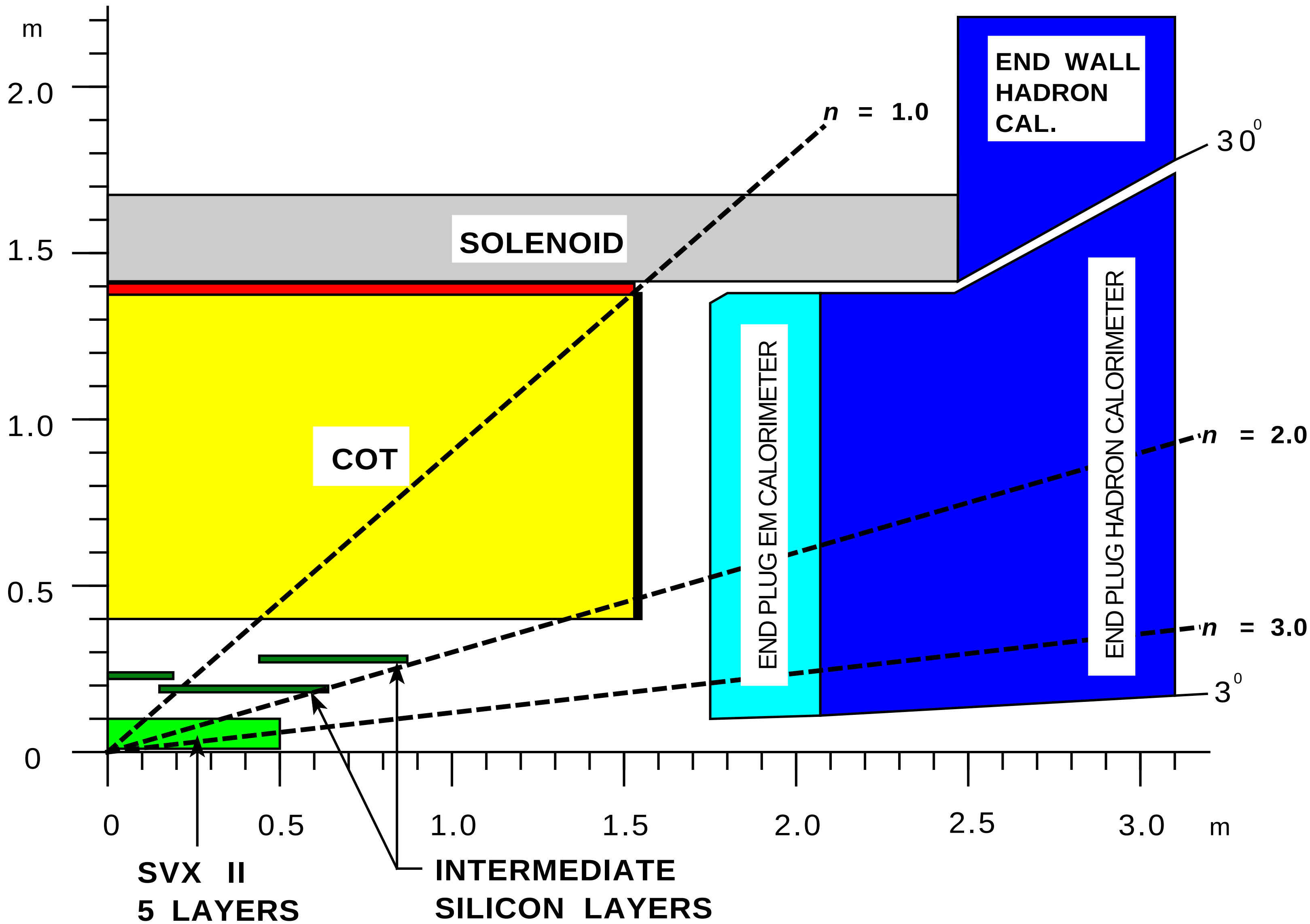
Detector Design – DØ



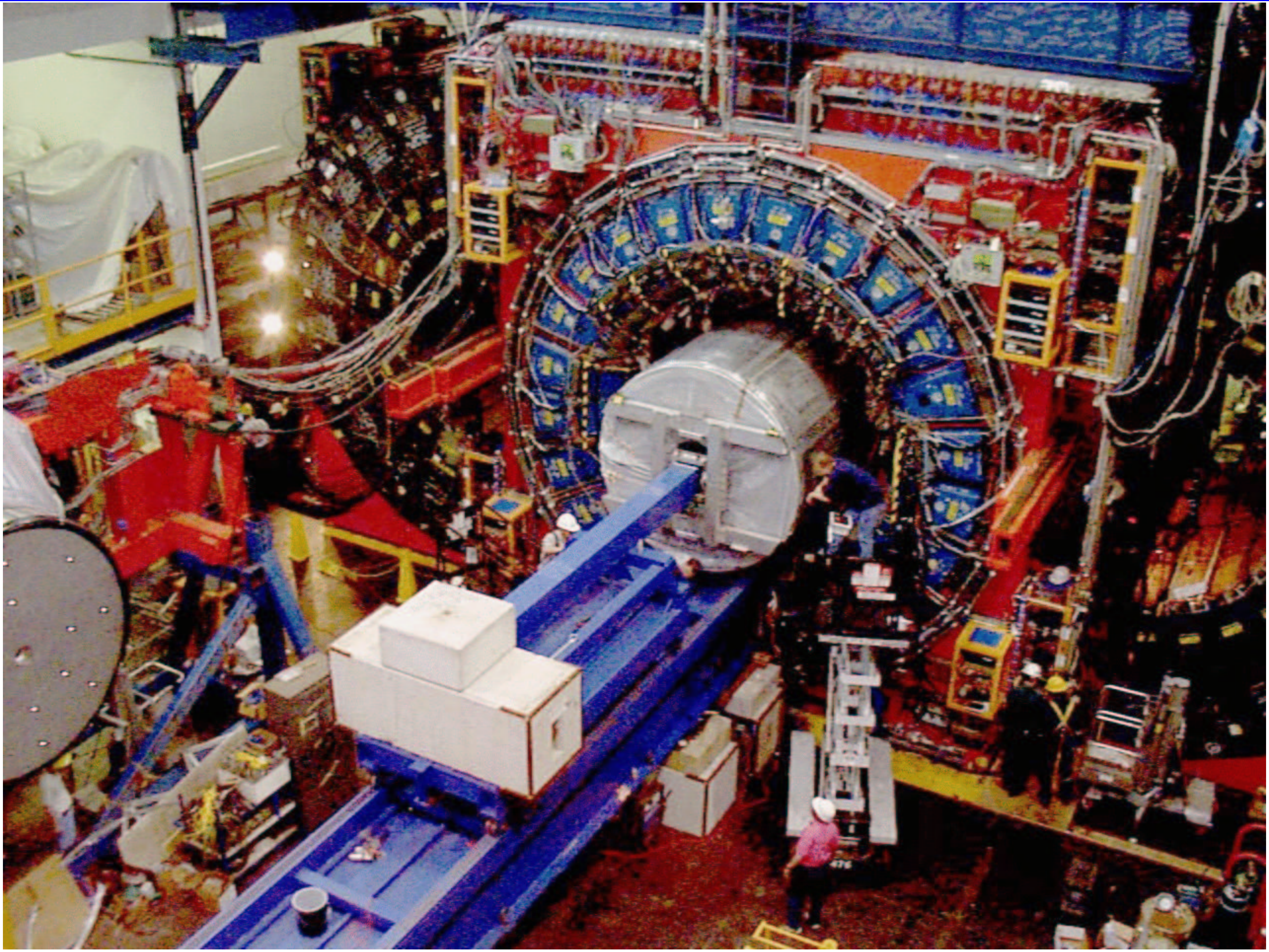
Detector Design – CDF



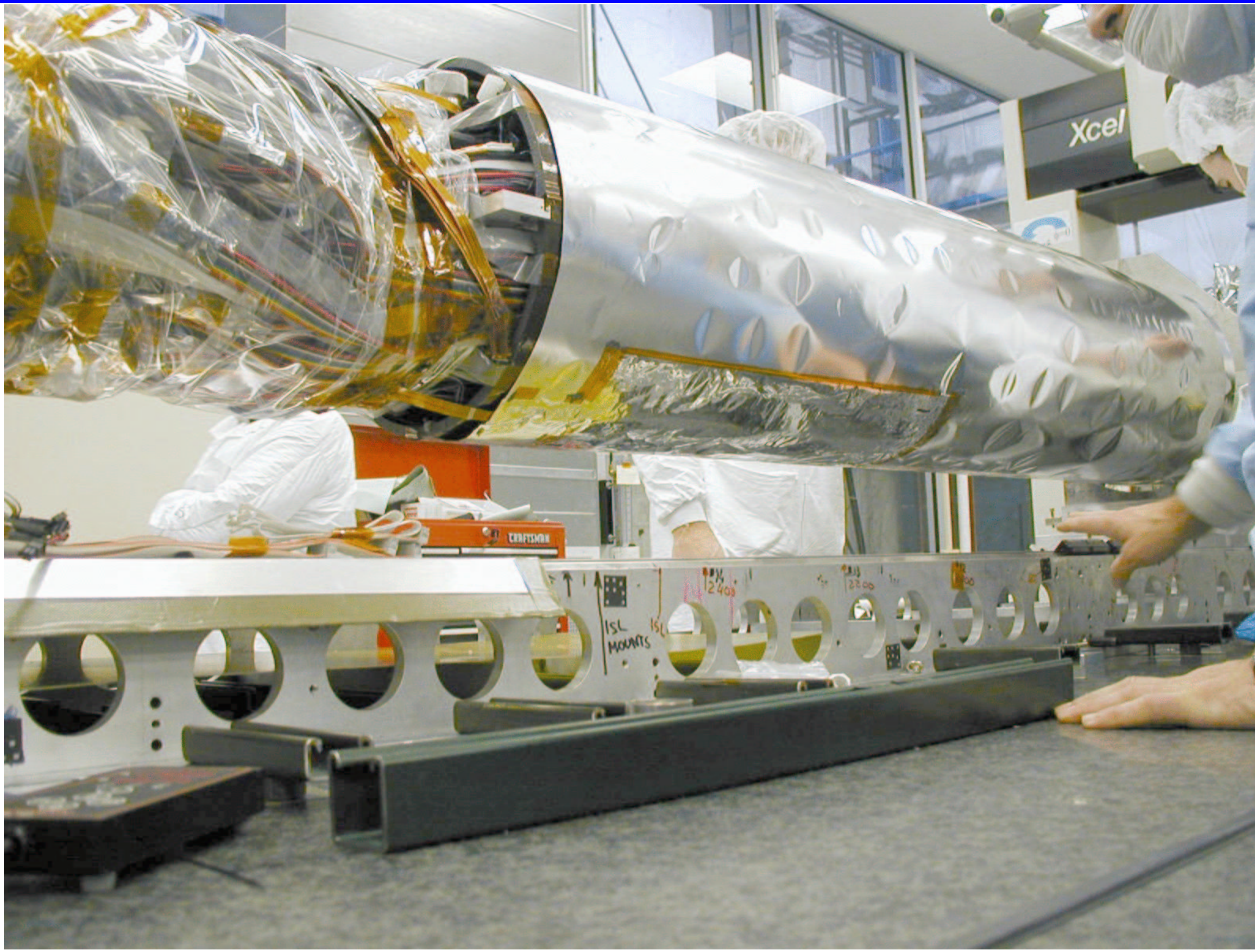
Detector Design – CDF



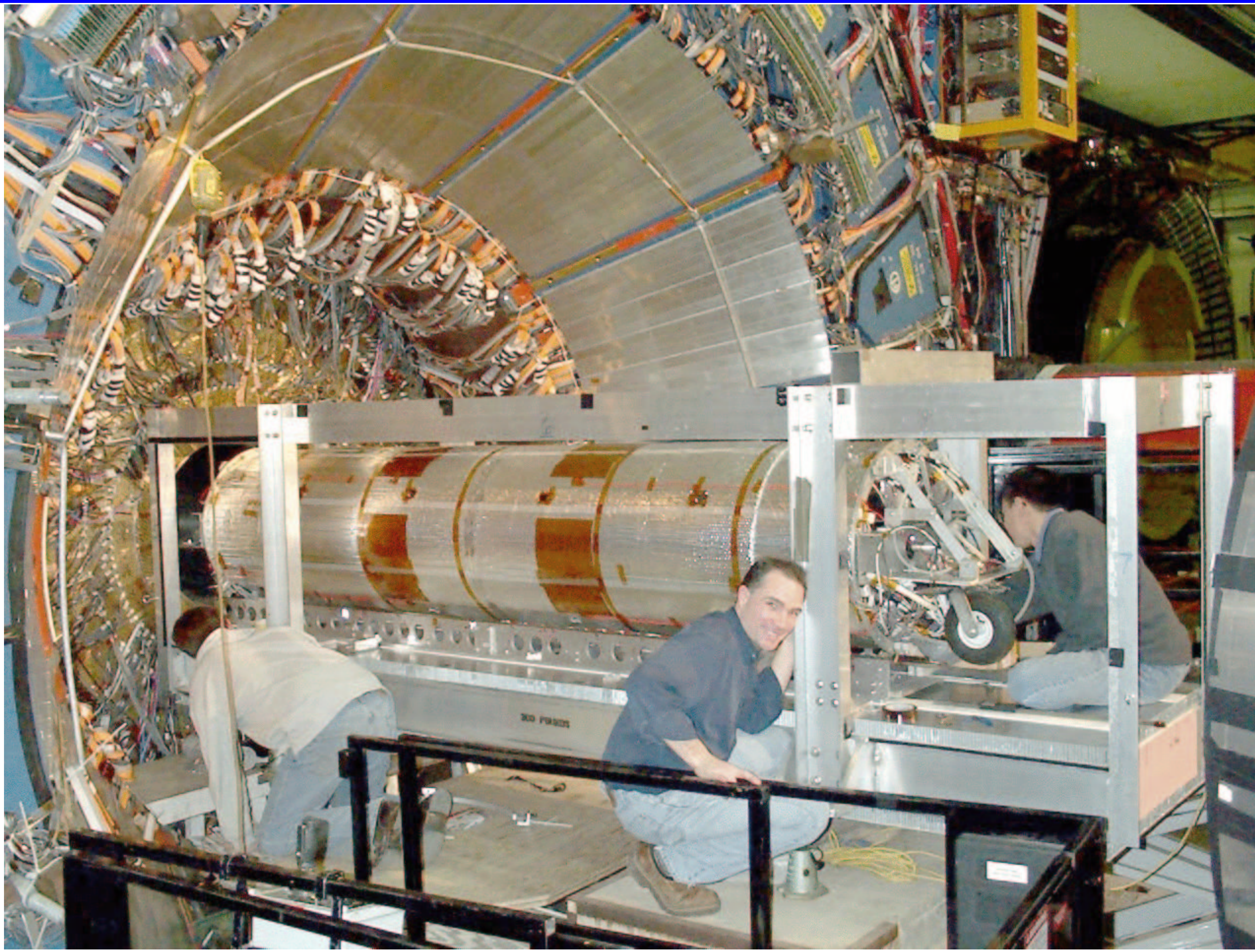
CDF – Drift Chamber – COT



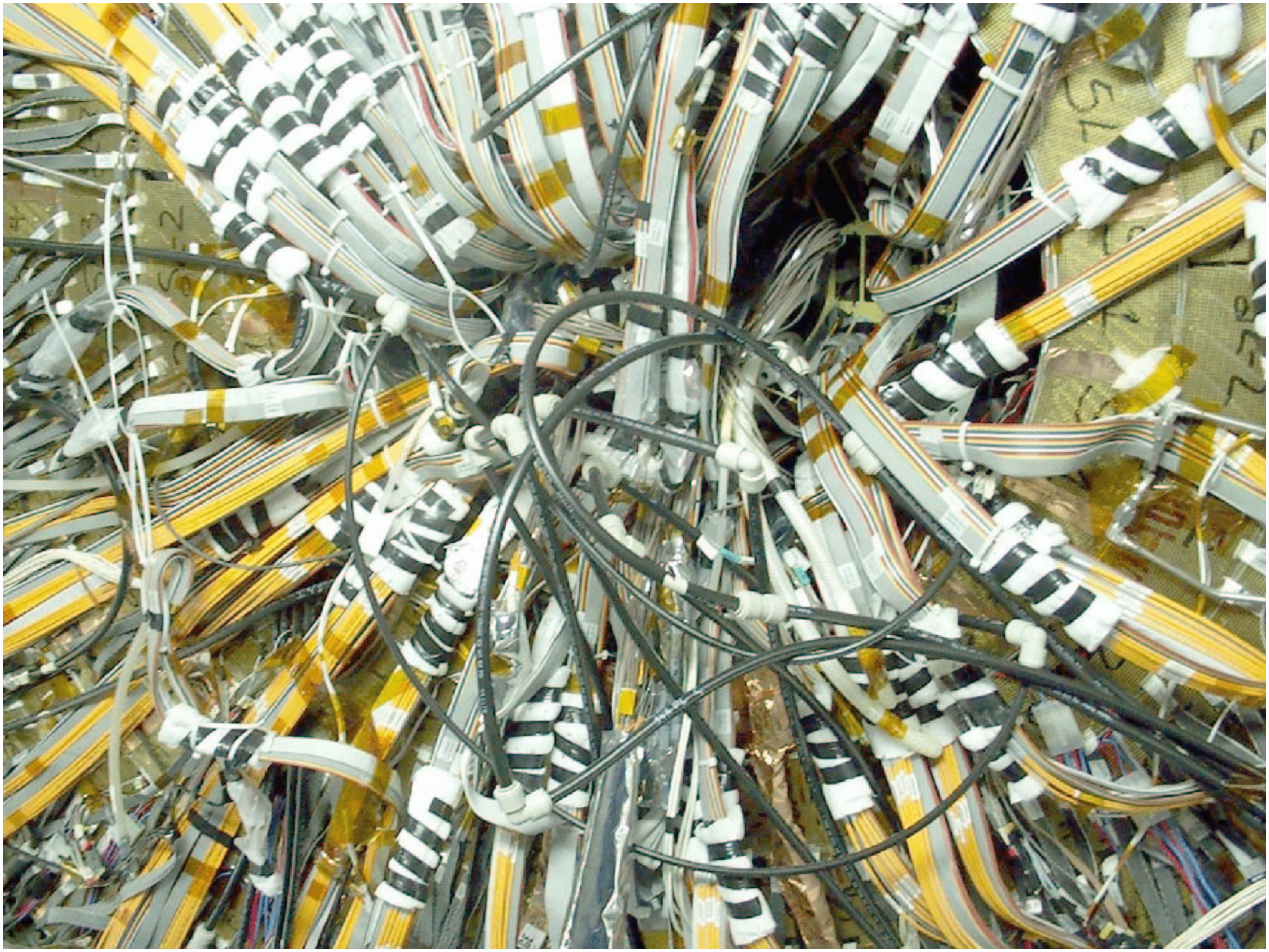
CDF – Silicon Vertex Detector – SVX



CDF – Silicon Vertex Detector – SVX



Cabling Up



Run II Upgrades: Hadronic Trigger

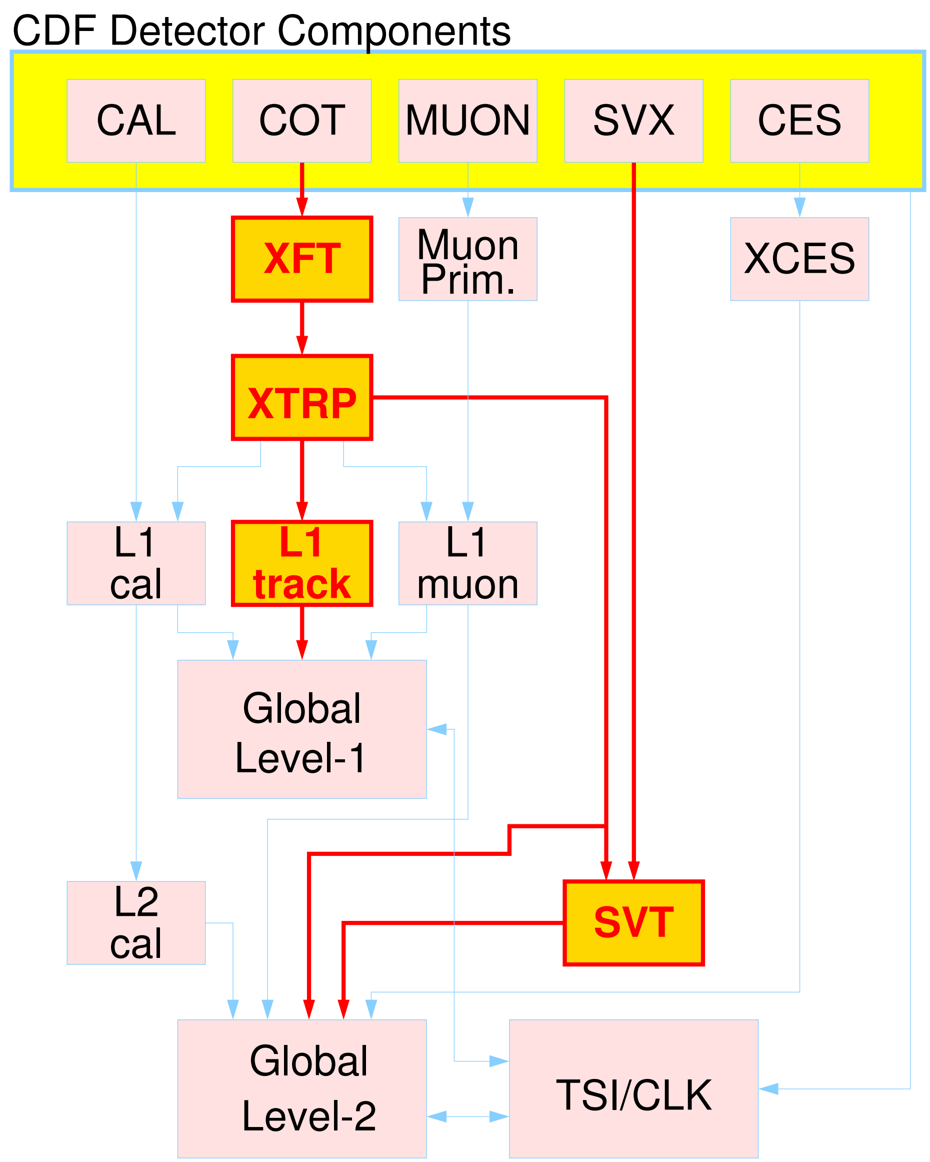
Level 1 track trigger

- based on chamber: $r - \phi$
- opposite charged track pair with $p_T > 2$ GeV each
- sum of $p_T > 5.5$ GeV
- $\Delta\phi < 135^o$

Level 2 track trigger

- based on silicon: $r - \phi$
- repeat level 1
- two large impact par. tracks

Improves sensitivity by 5 orders of magnitude over Run I



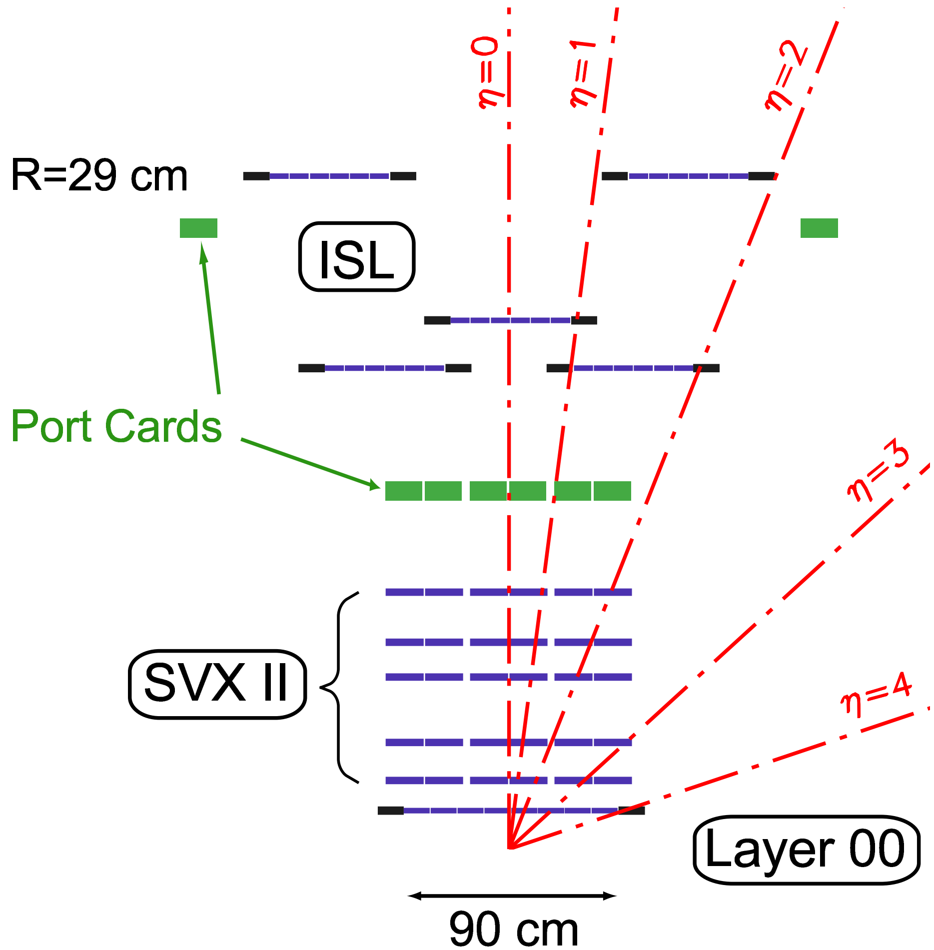
Run II Upgrades: Silicon Detector

Inner Silicon: L00 and SVX

Number of Layers	6
Number of Barrels	3
Active length	29 cm
Readout	$\phi + z/\phi + \phi'$
Inner Radius	$\approx$ 1 cm
Outer Radius	10.6 cm

Outer Silicon: ISL

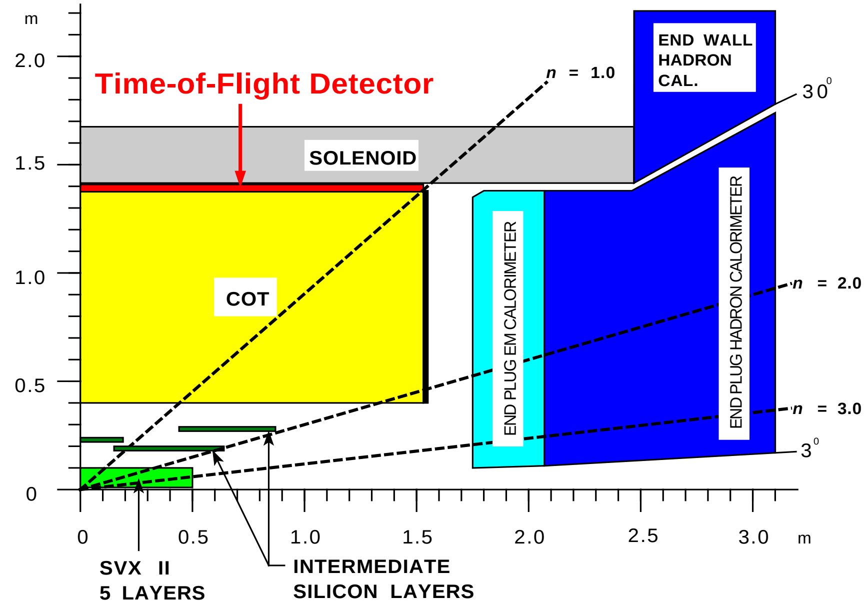
Number of Layers	1 or 2
Number of Barrels	3
Readout	$\phi + z$
Inner Radius	$\approx$ 20 cm
Outer Radius	$\approx$ 30 cm



Run II Upgrades: Time-of-Flight Detector

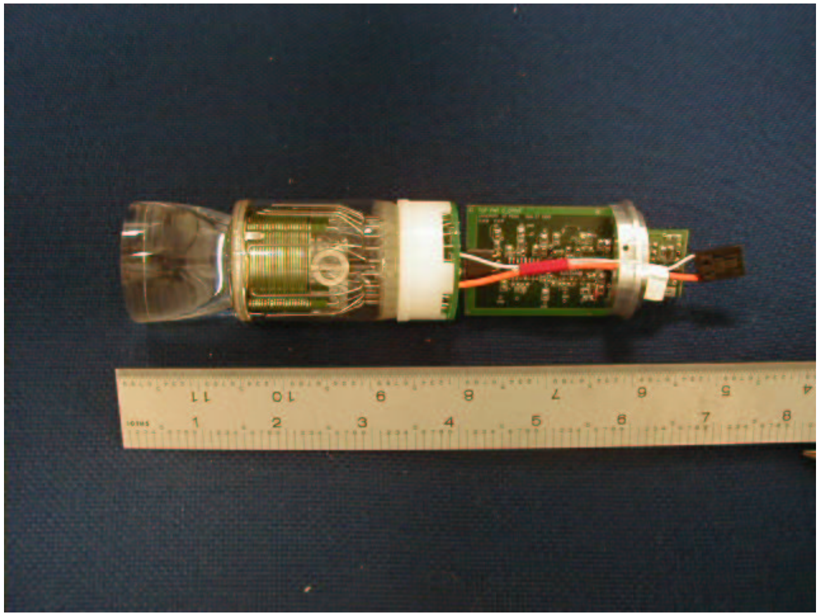
Characteristics of the system

Scintillator Bars	216 (1.7°)
Radius	140 cm
Bar Cross Section	4×4 cm^2
Bar Length Bar	300 cm
Coverage	$\lvert\eta\rvert < 1$
Scintillator Material	Bicron–408
Photomultipliers	Hamamatsu
Readout of the Bars	two–sided
Design Resolution	100 ps



Hamamatsu photomultiplier

Type	fine mesh, R7761
Stages	19
Geometry	1.5 inch diam.



PMT operates in 1.4 T B field

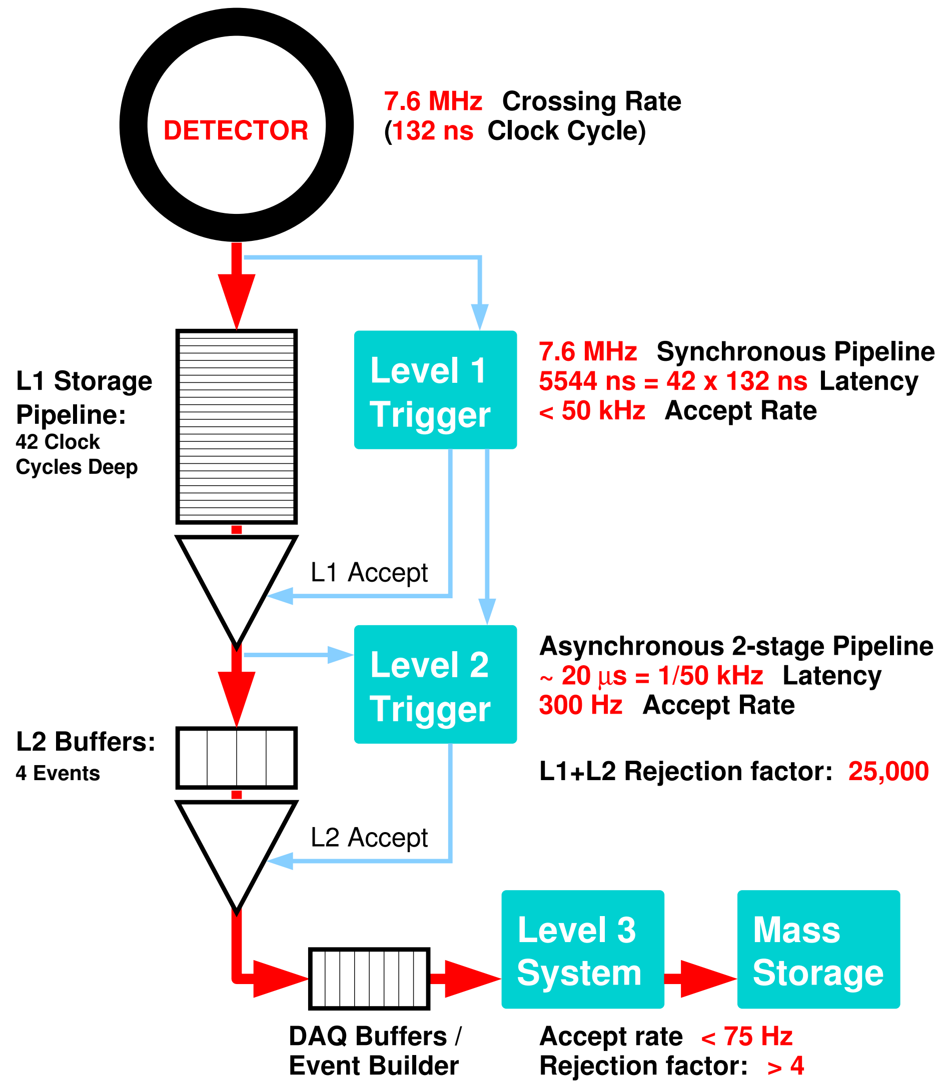
Run II Upgrades: DAQ System

Event Building in Run II

ATM switch	32 ports
input rate [kHz]	0.3 (1)
event size [kB]	150 (250)
total flow [MB/s]	44 (244)

Level-3 Processing for Run II

PC farm (Linux)	250 PCs
input rate [kHz]	0.3 (1)
output rate [Hz]	30 (75)
rejection rate	≈ 10
logging flow [MB/s]	4.4 (18)



Comparisons of B Experiments

Accelerator	CESR,DORIS	LEP,SLC	PEPII,KEKB	Tevatron
Detector	Argus,CLEO	ADLO,SLD	BaBar,Belle	CDF,DØ
$\sigma(b\bar{b})$	$\approx$ 1 nb	$\approx$ 6 nb	$\approx$ 1 nb	$\approx$ 50 μb
$\sigma(b\bar{b}) : \sigma(had)$	0.26	0.22	0.26	0.001
b hadrons	B^0, B^+	all	B^0, B^+	all
Boost $< \beta\gamma >$	0.06	6	$\approx$ 0.5	2-4
Production	Bs at rest	$b\bar{b}$ btb	forward boost	$b\bar{b}$ not btb
Event pile-up	no	no	no	yes
Trigger	inclusive	inclusive	inclusive	selective

Comments

- + experimentally LEP/SLC at Z looks ideal – but expensive
- + Babar and Belle can cheaply produce although not all
- + Tevatron has the highest cross section and can do all but lots of background
- + nice complementary setup

Conclusions

Physics Motivation

+ *CKM* physics exciting: potential discrepancy with SM
+ amount of *CP* violation well predicted but too small
+ additional measurements tests consistency of SM

Comparison of $\Upsilon(4S)$ and $p\bar{p}$

+ beautifully complementary programs
+ high precision B^0, B^+ at the *B* Factories
+ all other *b* hadrons at Tevatron

Detector Design Issues

+ detector at *B* factory take all events
+ complete analysis: neutral, Pid (K/π) full spectrum
+ detector at Tevatron filter out the interesting events
+ focus on: charged particles, minimal Pid (K/π)