BTeV – A Dedicated B Physics Experiment at the Tevatron Collider

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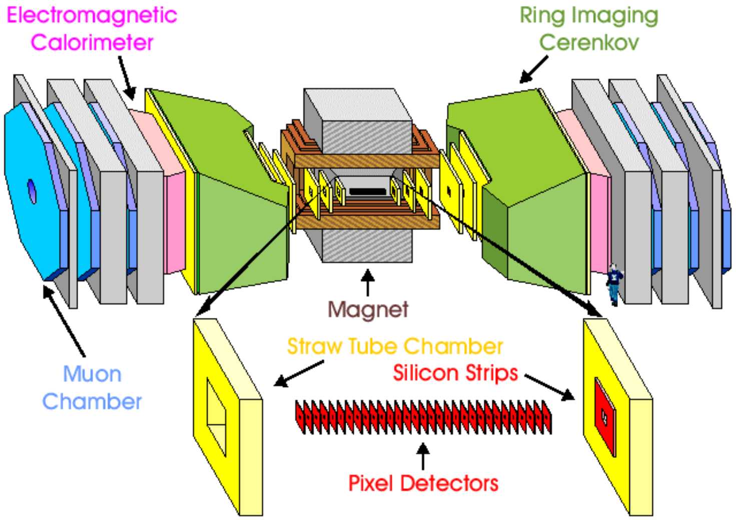
July 13, 2001



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Some crucial measurements

Physics Quantity	Decay Mode	Vertex Trigger	K/π sep	γ det	Decay time σ
$\sin(2\alpha)$	$B^o \to \rho\pi \to \pi^+\pi^-\pi^o$	✓	✓	✓	
$\cos(2\alpha)$	$B^o \to \rho\pi \to \pi^+\pi^-\pi^o$	✓	✓	✓	
$\mathrm{sign}(\sin(2\alpha))$	$B^o \to \rho\pi$ & $B^o \to \pi^+\pi^-$	✓	✓	✓	
$\sin(\gamma)$	$B_s \to D_s K^-$	✓	✓		✓
$\sin(\gamma)$	$B^+ \to D^o K^+$	✓	✓		
$\sin(\gamma)$	$B \to K \pi$	✓	✓	✓	
$\sin(\gamma)$	$B^o \to \pi^+\pi^-$ & $B_s \to K^+K^-$	✓	✓		✓
$\sin(2\chi)$	$B_s \to J/\psi\eta'$, $J/\psi\eta$	✓	✓	✓	✓
$\sin(2\beta)$	$B^o \to J/\psi K_s$				
$\sin(2\beta)$	$B^o \to \phi K_s, \eta' K_s$, $\psi\pi^o$	✓	✓	✓	
$\cos(2\beta)$	$B^o \to J/\psi K^*$ & $B_s \to J/\psi\phi$				
x_s	$B_s \to D_s\pi^-$	✓	✓		✓
$\Delta\Gamma$ for B_s	$B_s \to J/\psi\eta'$, K^+K^-, $D_s\pi^-$	✓	✓	✓	

B Physics at Hadron Colliders

- **The Opportunity**
  - **Lot's of b's (a few times 10^{11} b-pairs per year at the Tevatron)**
  - **"Broadband, High Luminosity B Factory" (B_d, B_u, B_s, b-baryon, and B_c)**
  - **Tevatron luminosity will increase to at least $5x10^{32}$**
  - **Cross sections at the LHC will be 5 times larger**
  - **Because you are colliding gluons, it is intrinsically asymmetric so time evolution studies are possible (and integrated asymmetries are nonzero)**

- **The Challenge**
  - **Lot's of background (S/N 1:500 to 1:1000)**
  - **Complicated underlying event**
  - **No stringent kinematic constraints that one has at an e^+e^- machine**
  - **Multiple interactions**

These lead to questions about the triggering, tagging, and reconstruction efficiency and the background rejection that can be achieved at a hadron collider

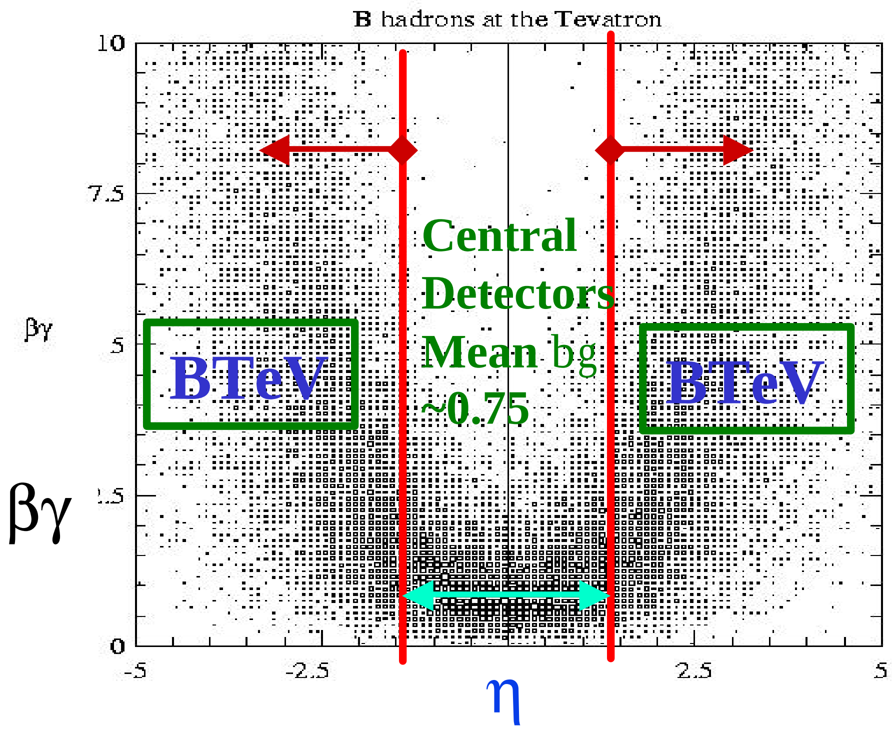
btev

The Tevatron as a b & c source

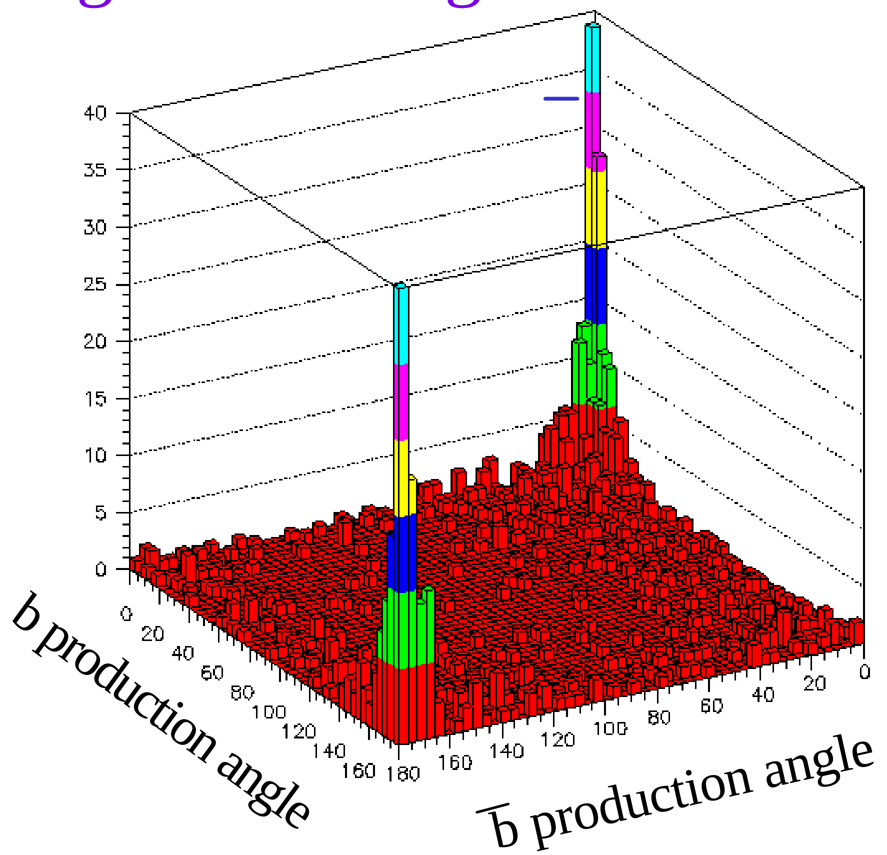
property	Value
Luminosity	2 x 10^{32}
b cross-section	100 mb
# of b-pairs per 10^7 sec	2 x 10^{11}
b fraction.	10^{-3}
c cross-section	>500 mb
Bunch Spacing	132 ns
Luminous region length	s_z = 30 cm
Luminous region width	$s_x \sim s_y \sim$ 50 mm
Interactions/crossing	<2.0>

Characteristics of hadronic b production

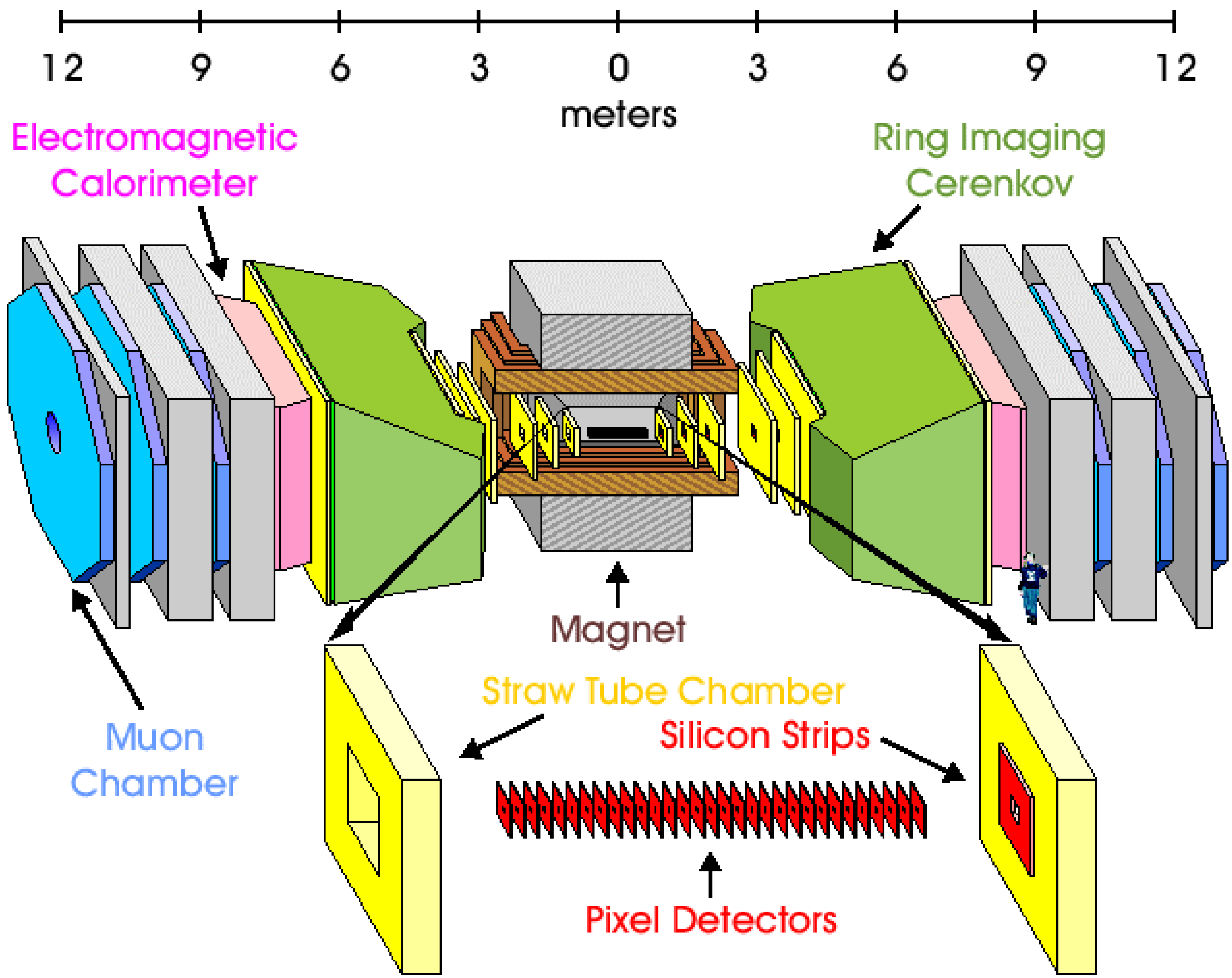
The higher momentum b's are at larger η's



b production peaks at large angles with large bb correlation



BTeV Detector Layout

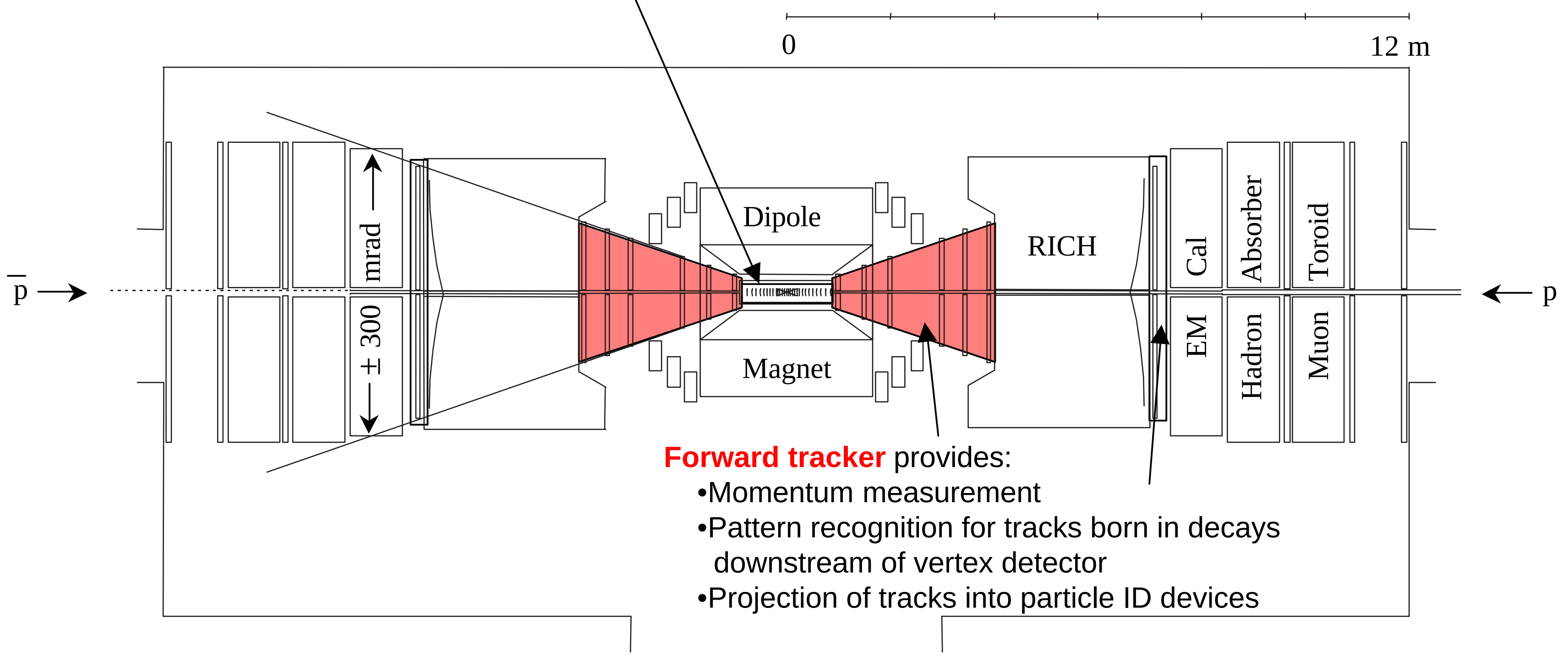


Key Design Features of BTeV

- A dipole magnet (1.6 T) and 2 spectrometer arms
- A precision vertex detector based on planar pixel arrays
- A detached vertex trigger at Level I
- High resolution tracking system (straws and silicon strips)
- Excellent particle identification based on a Ring Imaging Cerenkov counter.
- A lead tungstate electromagnetic calorimeter for photon and π^0 reconstruction
- A very high capacity data acquisition system which frees us from making excessively specific choices at the trigger level

BTeV Tracking System Overview

Silicon pixel vertex detector provides:
- Pattern recognition power
- Very good position resolution (~7μ)
- Radiation hardness



Forward tracker provides:
- Momentum measurement
- Pattern recognition for tracks born in decays downstream of vertex detector
- Projection of tracks into particle ID devices

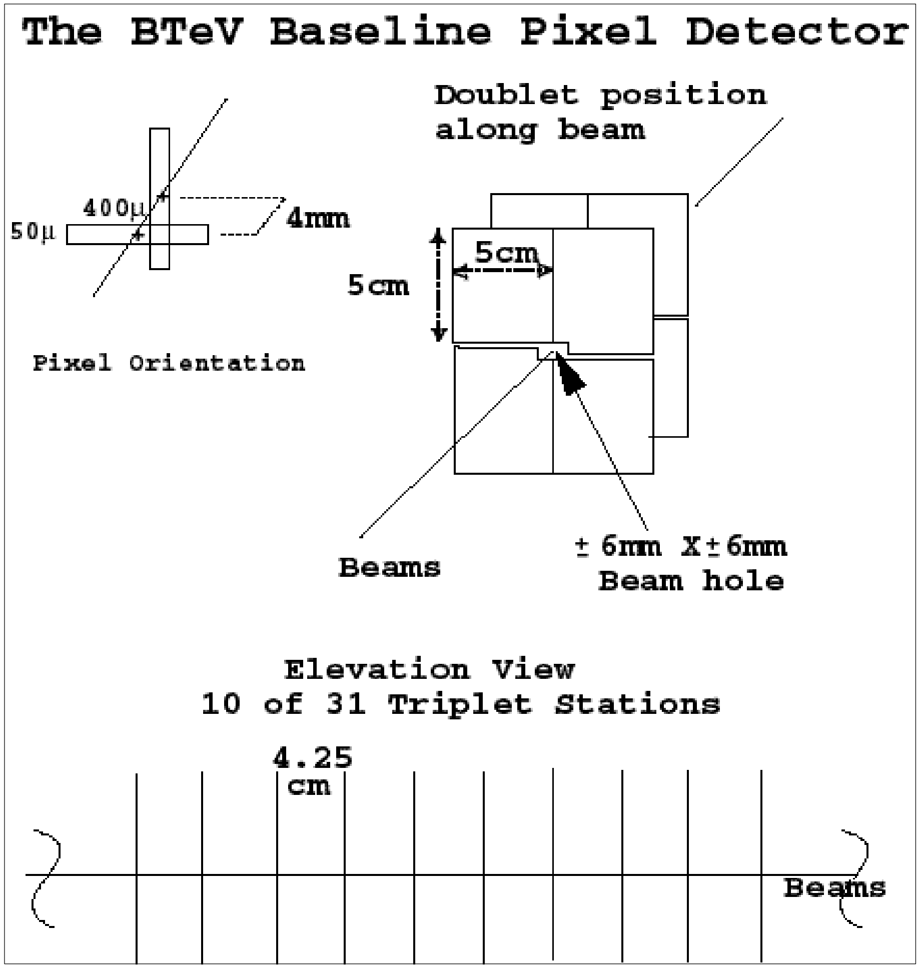
Pixel Vertex Detector

Reasons for Pixel Detector:

- Superior signal to noise
- Excellent spatial resolution -- 5-10 microns depending on angle, etc
- Very Low occupancy
- Very fast
- Radiation hard

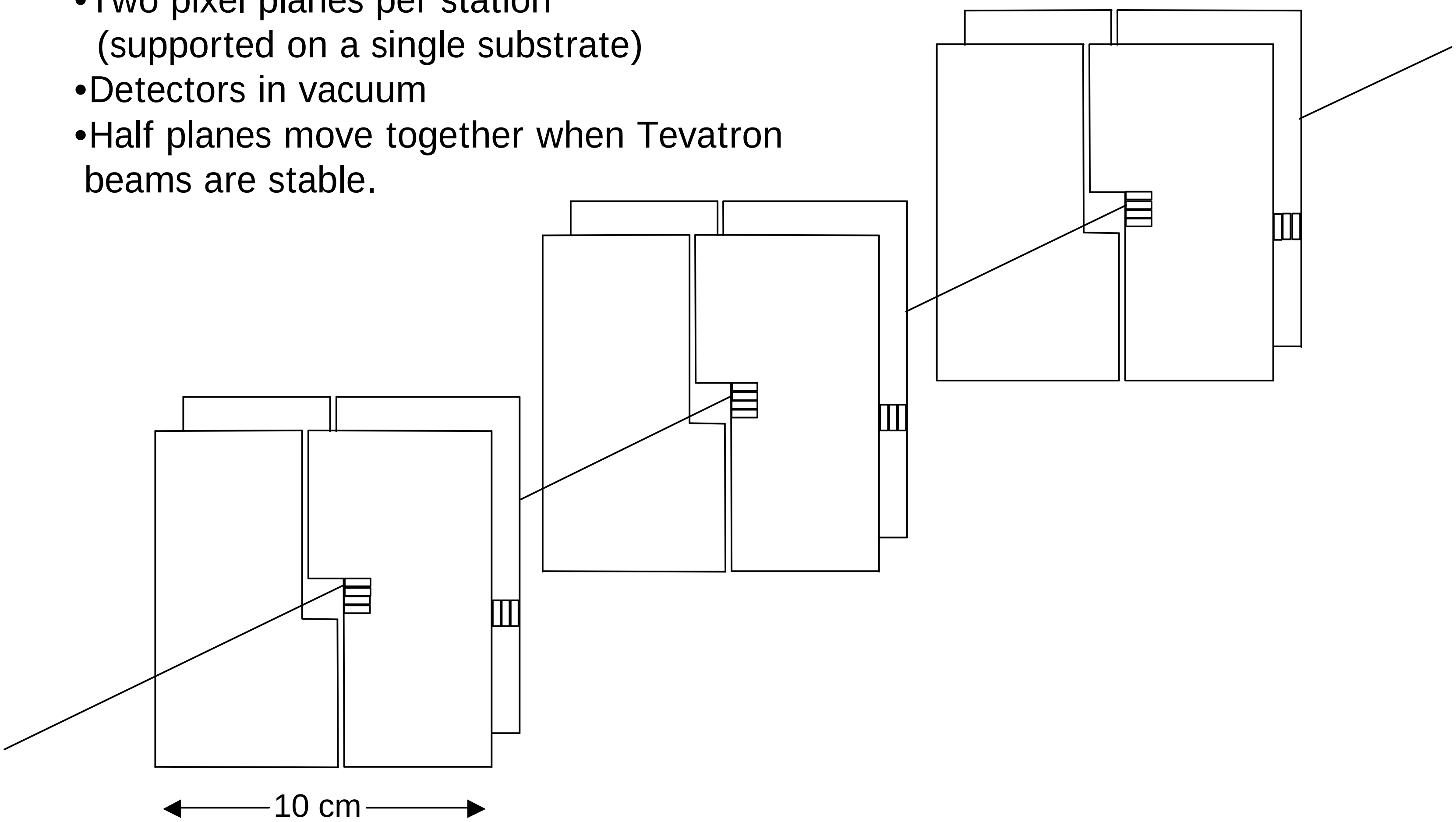
Special features:

- It is used directly in the L1 trigger
- Pulse height is measured on every channel with a 3 bit FADC
- It is inside a dipole and gives a crude standalone momentum



Pixels – Close up of 3/31 stations

- 50µm x 400µm pixels - 30 million total
- Two pixel planes per station
  (supported on a single substrate)
- Detectors in vacuum
- Half planes move together when Tevatron
  beams are stable.



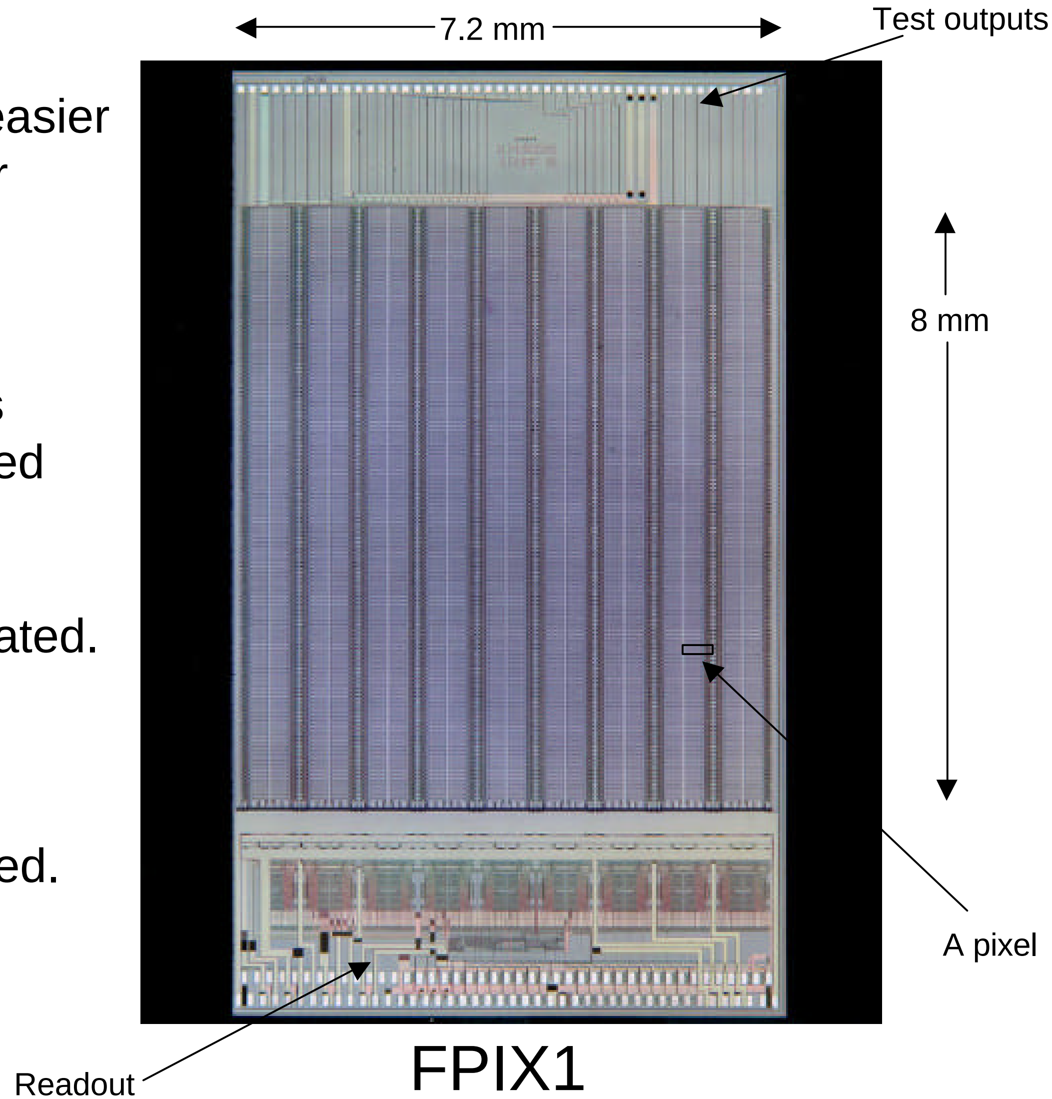
Pixel Readout Chip

•Different problem than LHC pixels:
132 ns crossing time (vs. 25ns) → easier
Very fast readout required → harder

•R&D started in 1997

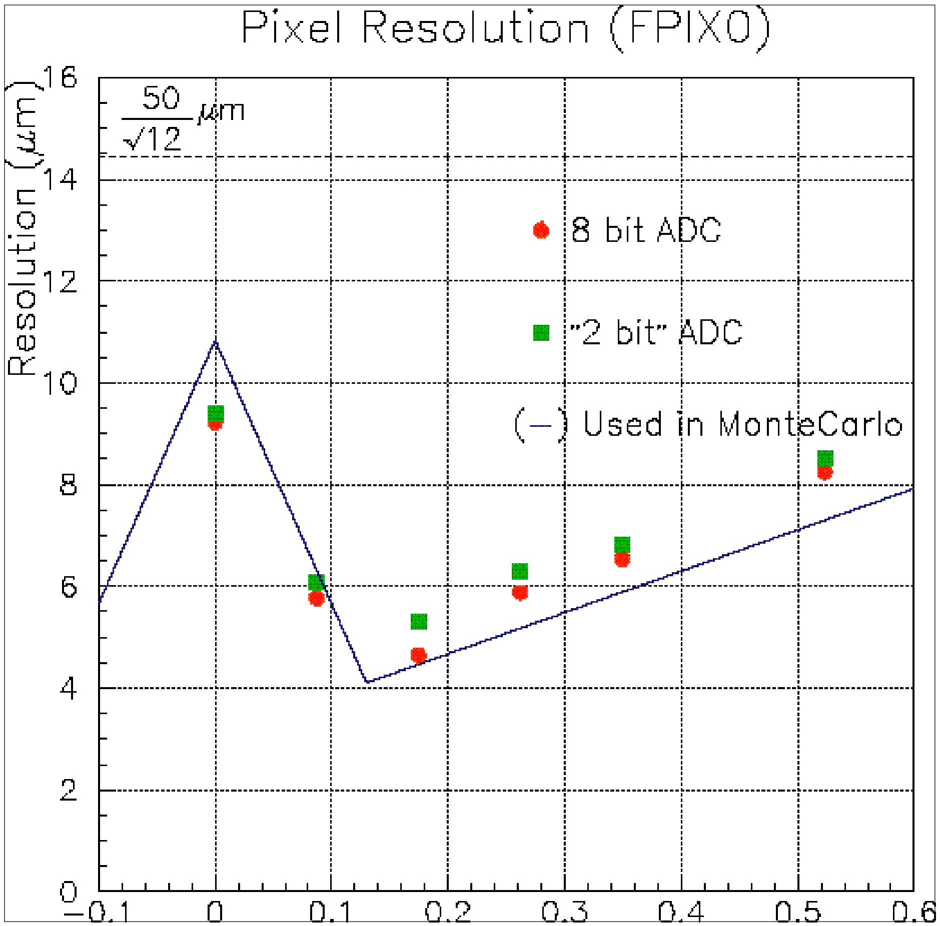
•Two generations of prototype chips (FPIX0 & FPIX1) have been designed & tested, with & without sensors, including a beam test (1999) in which resolution <9μ was demonstrated.

•New "deep submicron" radiation hard design (FPIX2):Three test chip designs have been produced & tested. Expect to submit the final design ~Dec. 2001



FPIX1

Pixel Test Beam Results

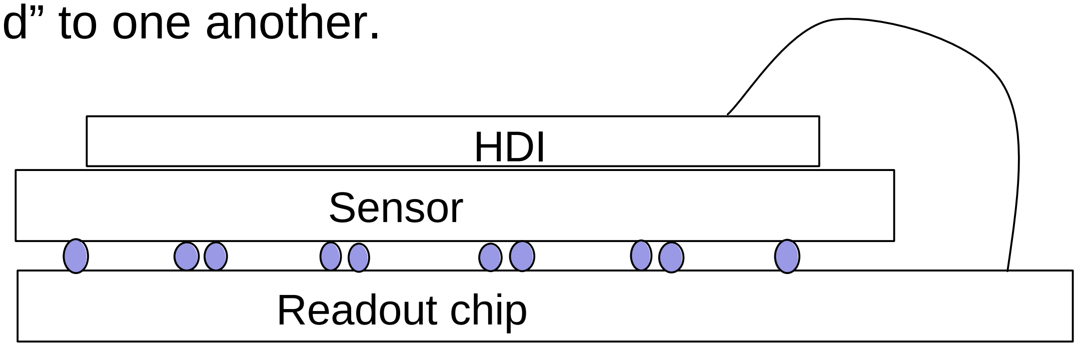


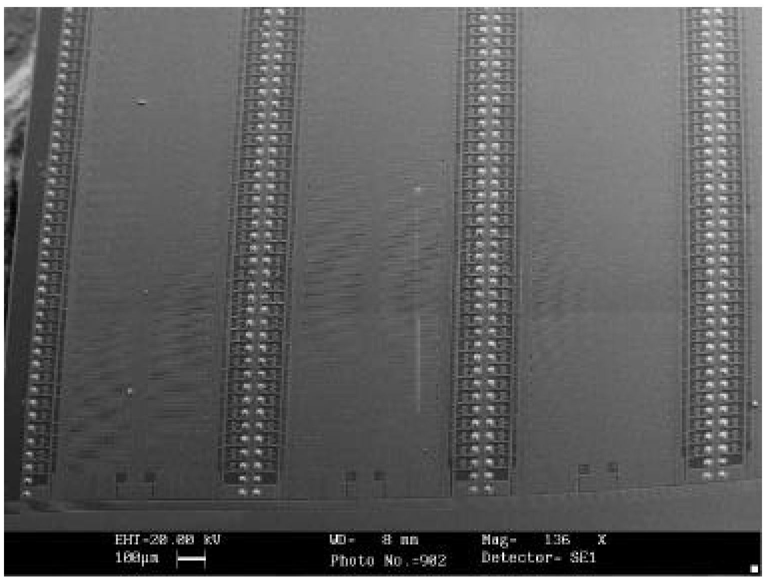
Track angle (mr)

Analog output of pixel amplifier before and after 33 Mrad irradiation.
0.25μ CMOS design verified radiation hard with both γ and protons.

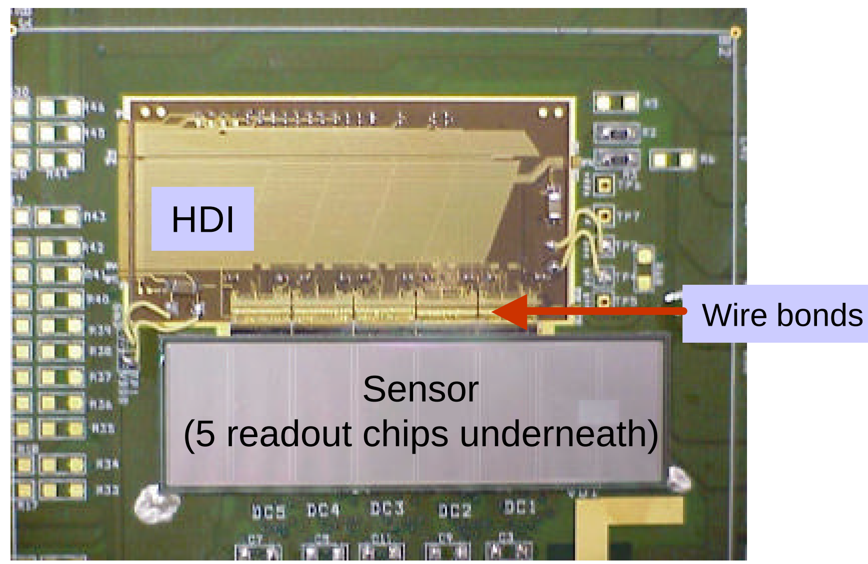
Pixel detectors are hybrid assemblies

- Sensors & readout "bump bonded" to one another.
- Readout chip is wire bonded to a "high density interconnect" which carries bias voltages, control signals, and output data.





Micrograph of FPIX1: bump bonds are visible



The BTeV Level I Detached Vertex Trigger

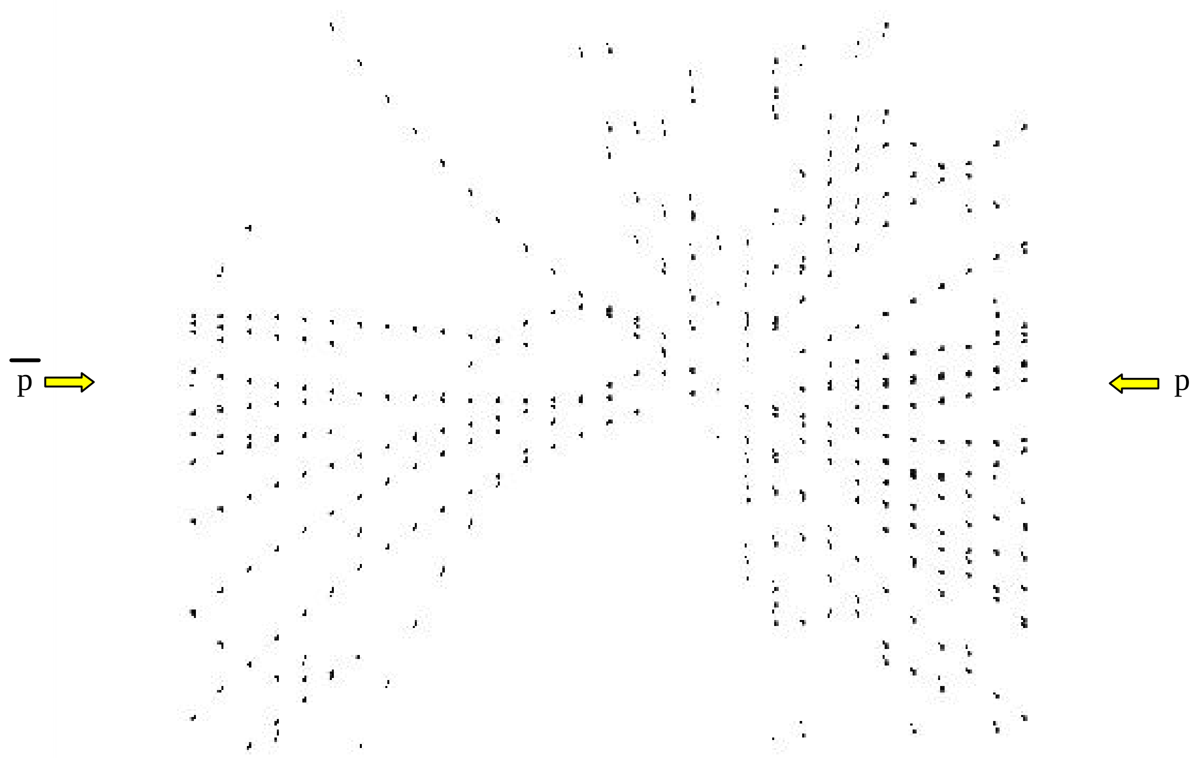
Three Key Requirements:

- Reconstruct every beam crossing, run at 7.6 MHz
- Find primary vertex
- Find evidence for a B decaying downstream of primary vertex

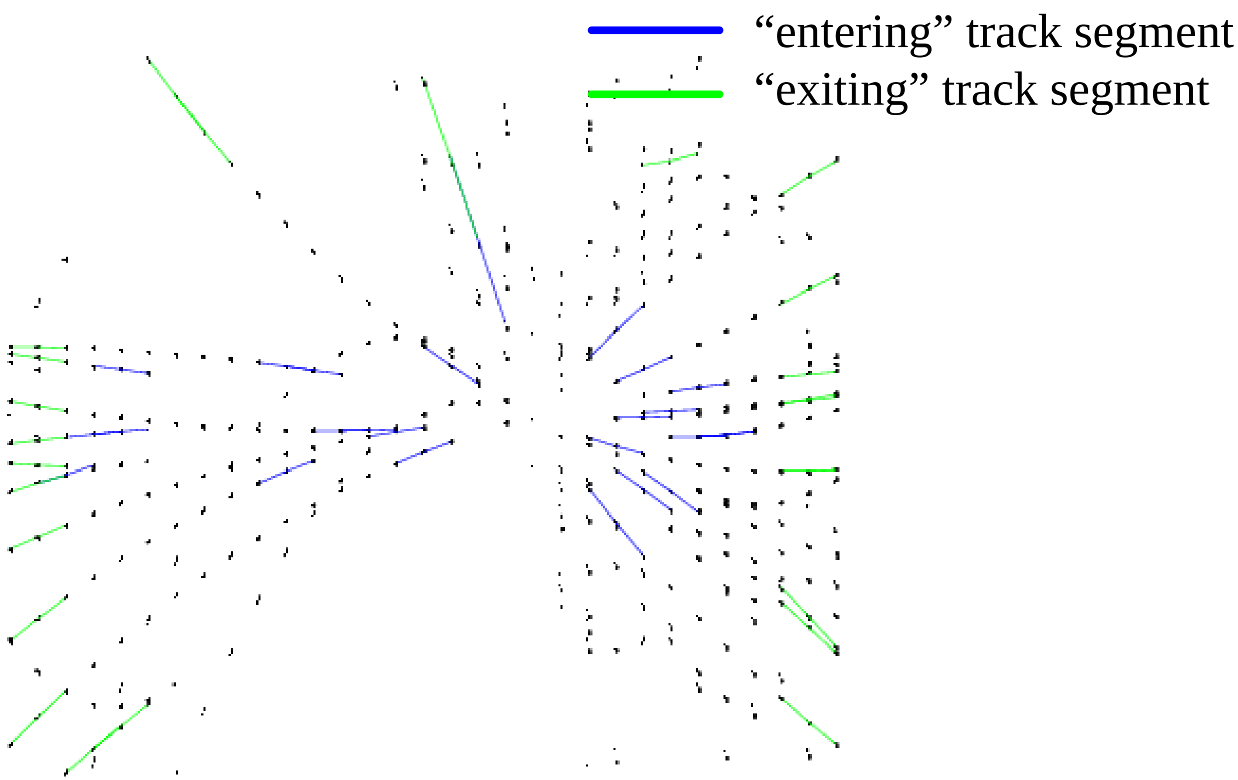
Five Key Ingredients:

- A vertex detector with excellent spatial resolution, fast readout, and low occupancy
- A heavily pipelined and parallel processing architecture well suited to tracking and vertex fining
- Inexpensive processing nodes, optimized for specific tasks within the overall architecture ~3000 CPUs
- Sufficient memory to buffer the vent data while calculations are carried out ~1 Terabyte
- A switching and control network to orchestrate the data movement through the system

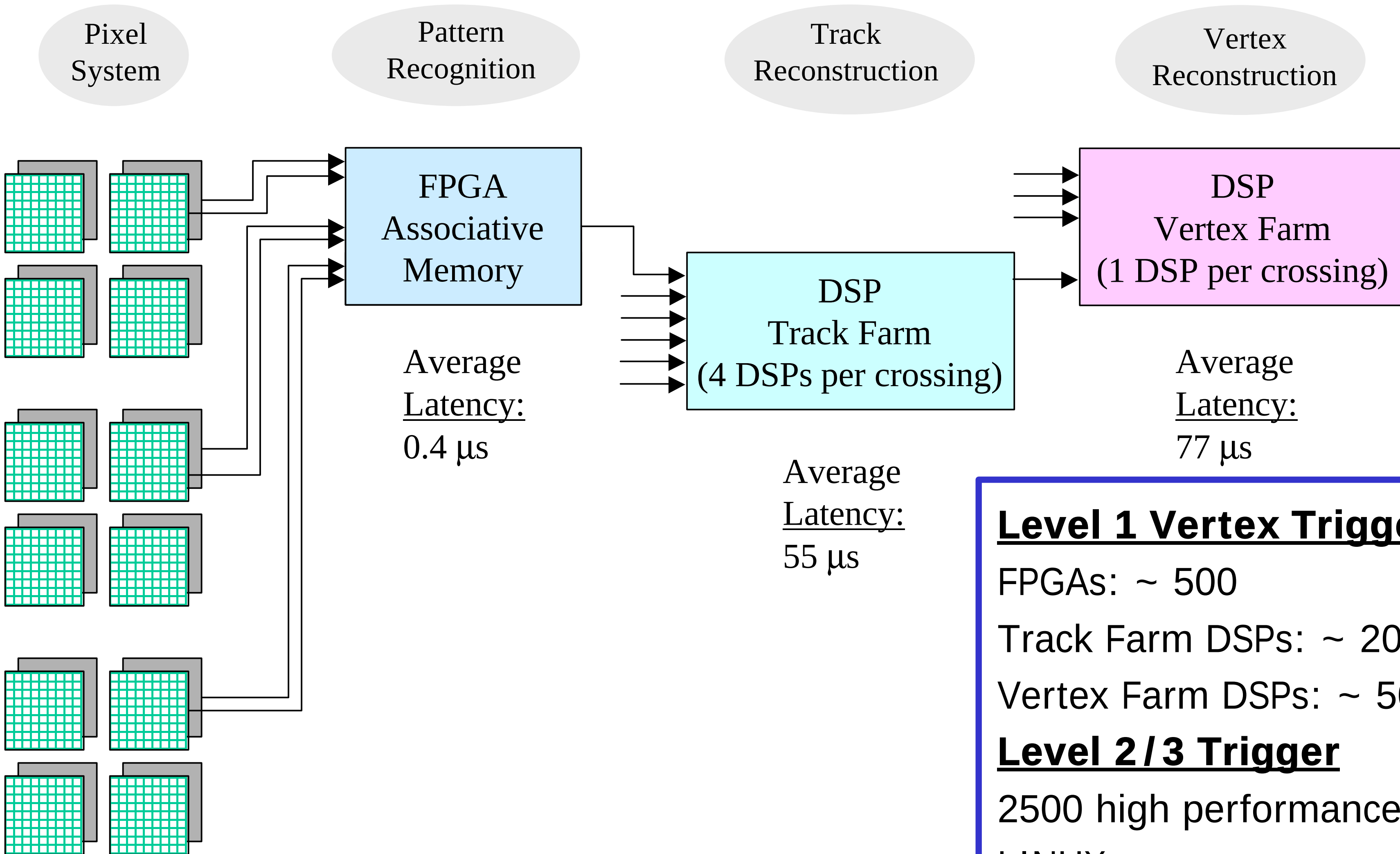
Information available to the L1 vertex trigger



Track segments found by the L1 vertex trigger



Block Diagram of the Level 1 Vertex Trigger



Level 1 Vertex Trigger:

FPGAs: ~ 500

Track Farm DSPs: ~ 2000

Vertex Farm DSPs: ~ 500

Level 2 / 3 Trigger

2500 high performance LINUX processors

Pixel Trigger Performance

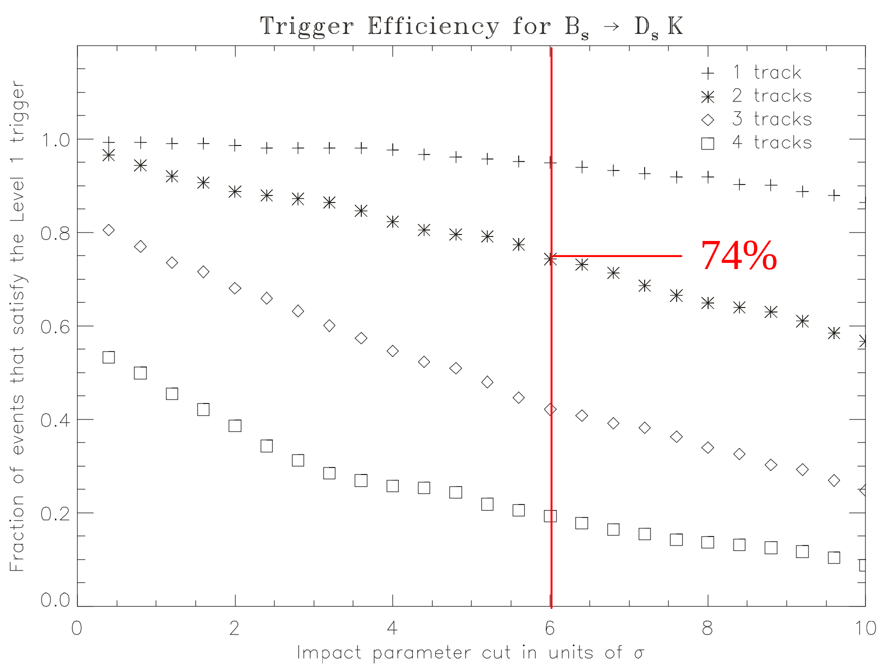
Select number (N) of detached tracks

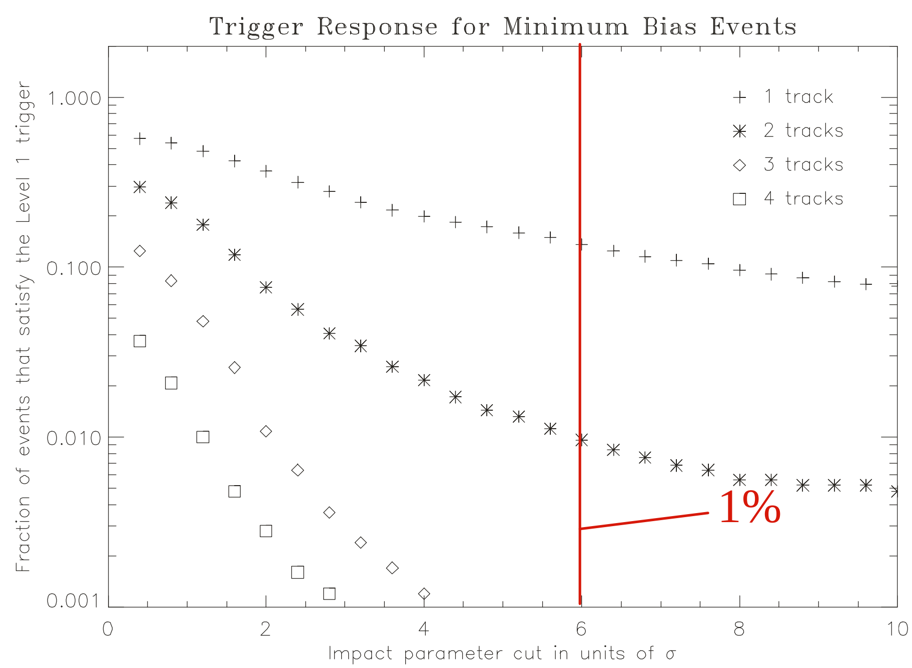
typically pt> 0.5 GeV, N = 2

Select impact parameter (b) w.r.t. primary vertex

typically σ(b) = 6

Options include cuts on vertex, vertex mass etc.





Trigger Simulation Results

- L1 acceptance: 1%
- Profile of accepted events
  - 4 % from b quarks including
    50-70% of all “analyzable” b events
  - 10 % from c quarks
  - 40 % from s quarks
  - 45 % pure fakes
- L2/L3 acceptance: 4 %
  - 4000 Hz output rate
  - 200 Mbytes/s

Level 1 Efficiency on Interesting Physics States

Process	Eff. (%)	Monte Carlo
Minimum bias	1	BTeVGeant
$B_s \to D_s^+ K^-$	74	BTeVGeant
$B^0 \to D^{*+}\rho^-$	64	BTeVGeant
$B^0 \to \rho^0\pi^0$	56	BTeVGeant
$B^0 \to J/\psi K_s$	50	BTeVGeant
$B_s \to J/\psi K^{*o}$	68	MCFast
$B^- \to D^0 K^-$	70	MCFast
$B^- \to K_s\pi^-$	27	MCFast
$B^0 \to$ 2-body modes $(\pi^+\pi^-, K^+\pi^-, K^+K^-)$	63	MCFast

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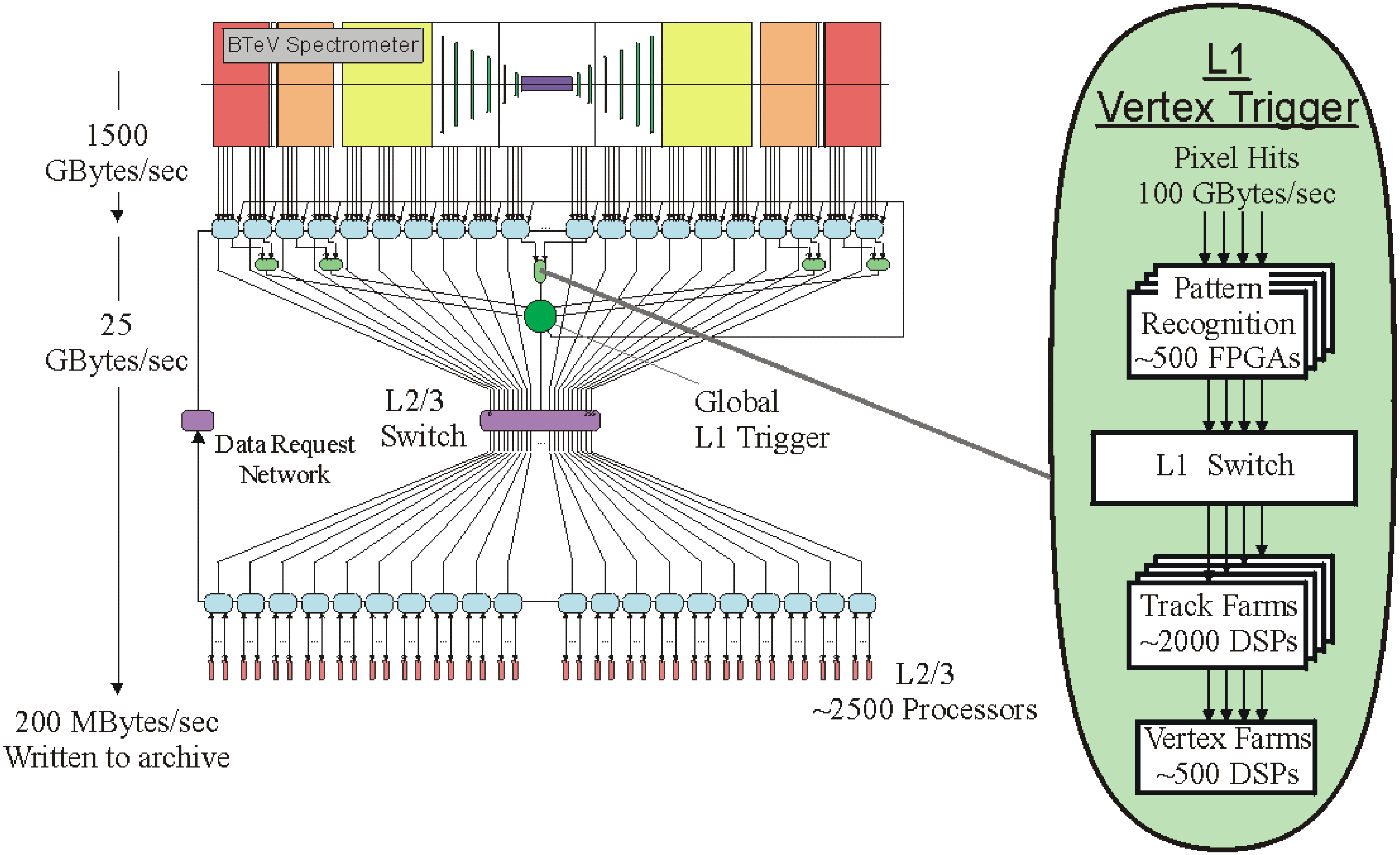
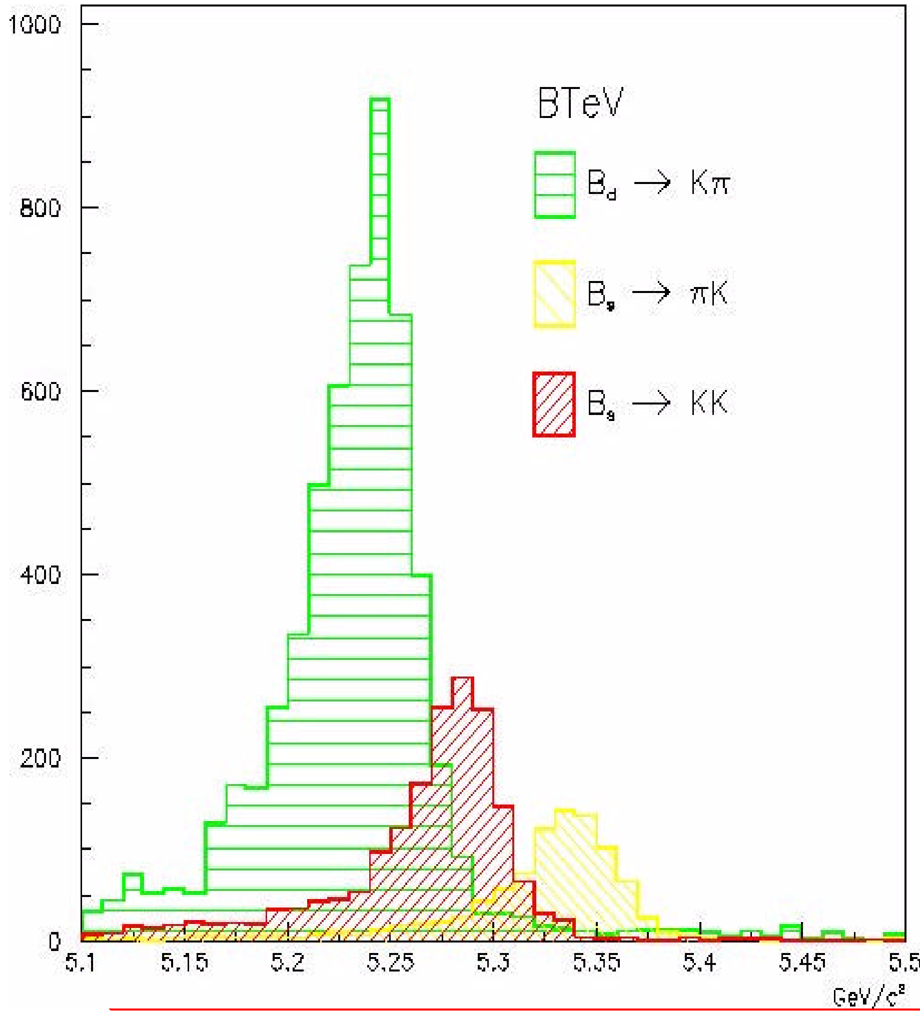
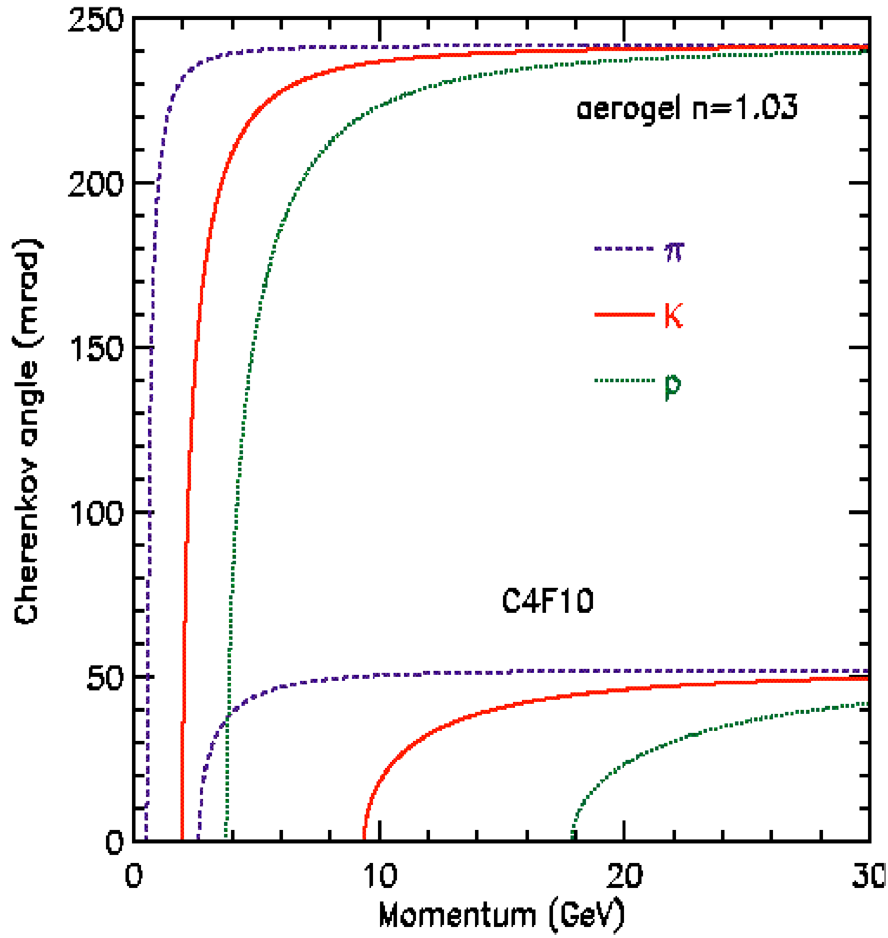
BTeV Data Acquisition Overview



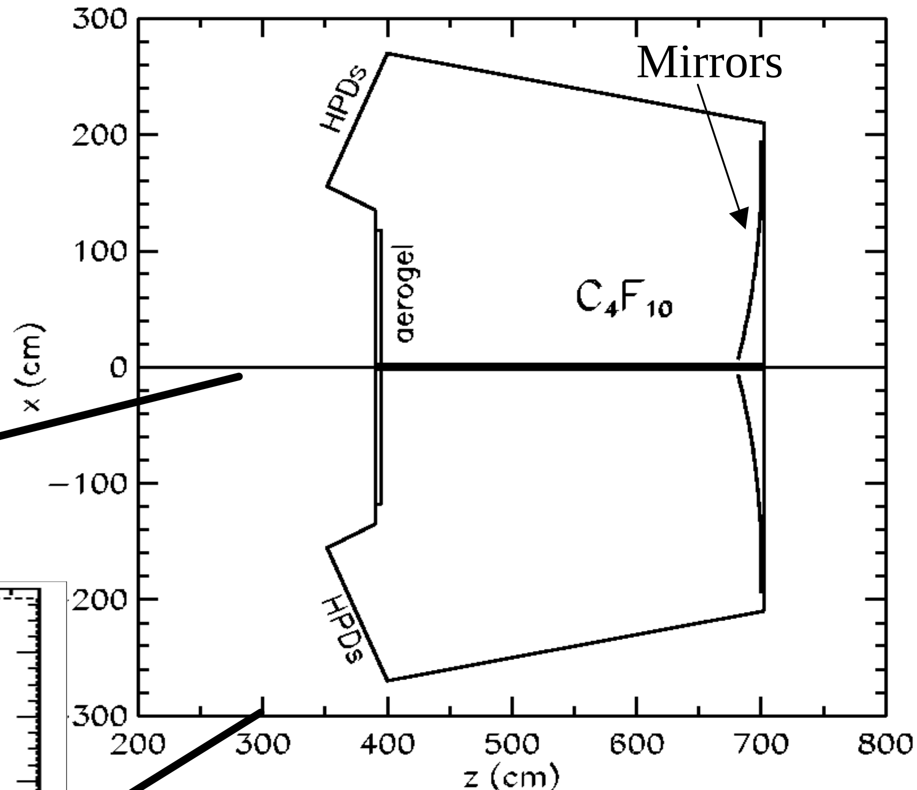
Importance of Particle Identification

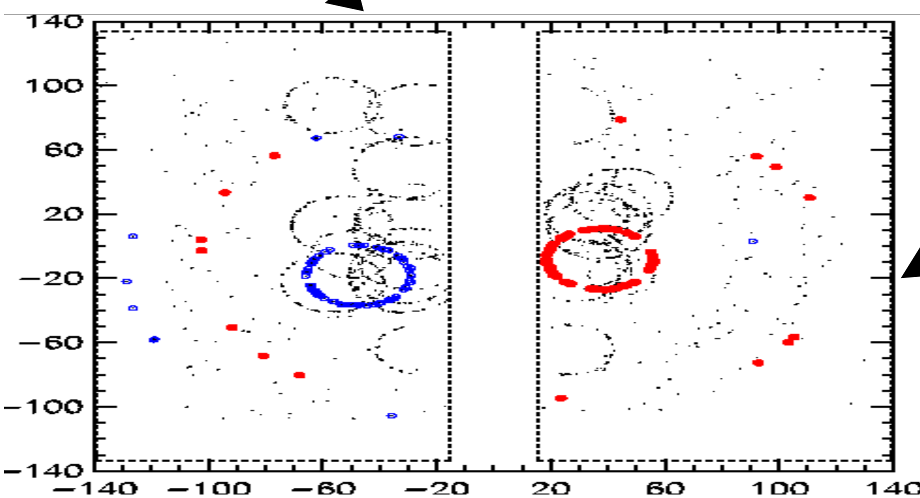




Ring Imaging Cherenkov (RICH)

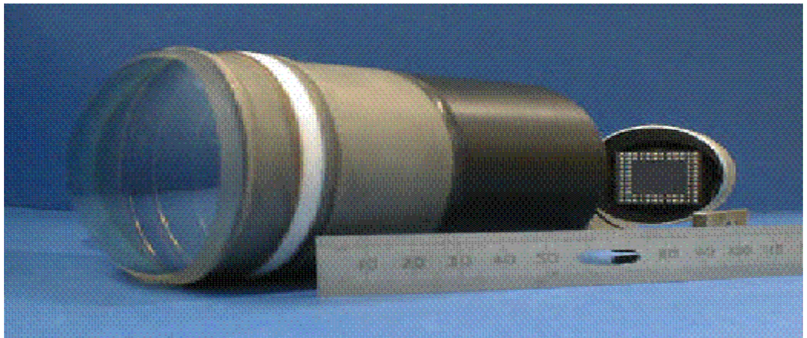
- Two identical RICH detectors
- Components:
  - Gaseous radiator (C_4F_{10})
  - Aerogel (?) radiator
  - Spherical mirrors
  - Photo-detectors
  - Vessel to contain gas volume

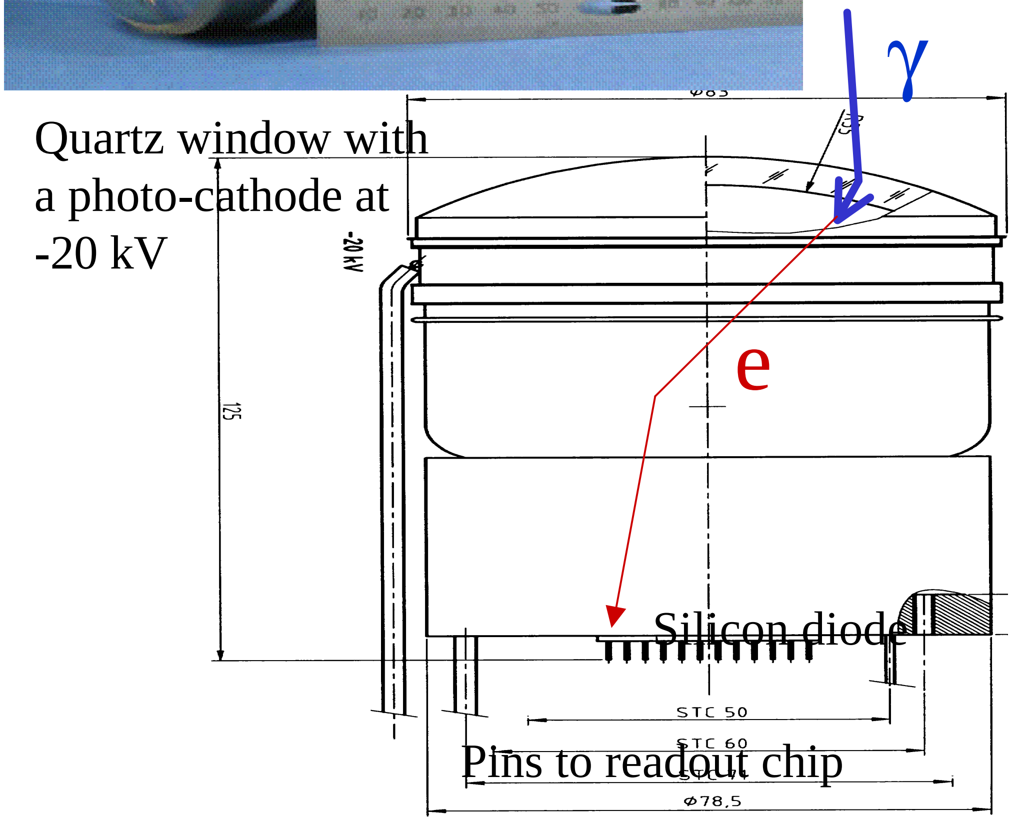




Cherenkov photons from B^{o} ® $p^{+}p^{-}$ and rest of the beam collision

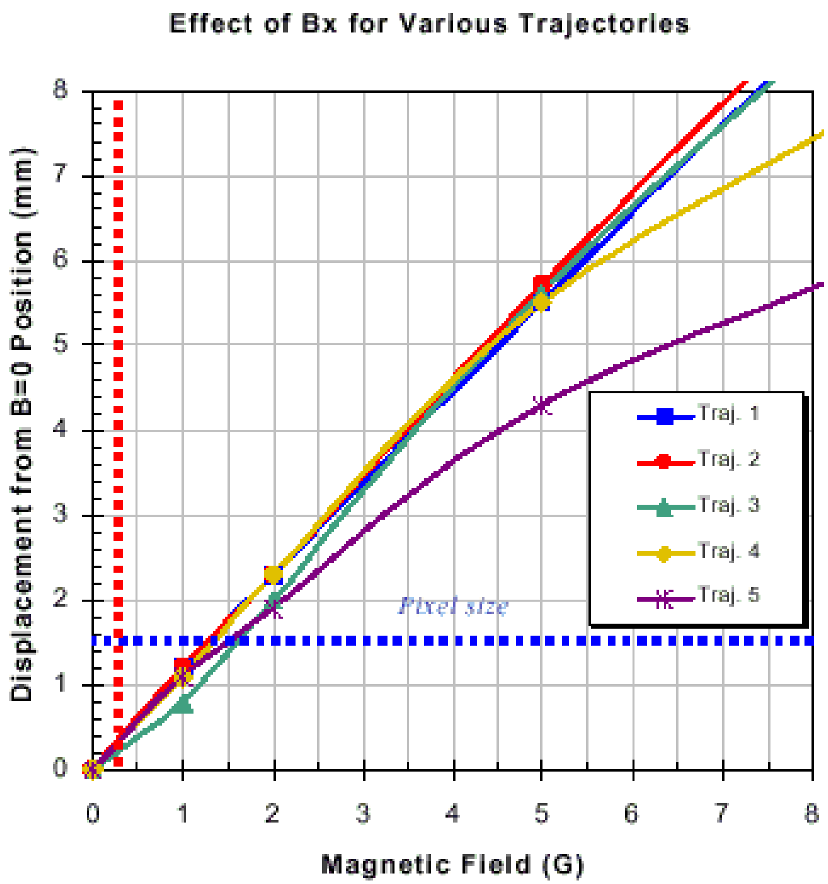
RICH Readout: Hybrid Photodiodes (HPD)





- Commercial supplier from Holland (DEP)
- A number of prototypes was successfully produced and tested for CMS
- New silicon diode customized for BTeV needs is under development at DEP (163 pixels per HPD); on schedule for prototype delivery at the end of the summer
- Challenges:
  - high voltages (20 kV!)
  - Signal ~5000e^- α need low noise electronics (Viking)
  - In the hottest region up to 40 channels fire per tube
  - About 2000 tubes total (cost)

Displacement vs B-Field



- Transverse B-Field
- Plot shows displacement of electron trajectory at the diode
- B-Field to displace 1 pixel (1.5 mm): B ~ 1.2 G (⊥)
- To make loss of efficiency at the edge and position corrections small want:

  $B_{crit} < 0.25$ G (⊥)

Electromagnetic Calorimeter

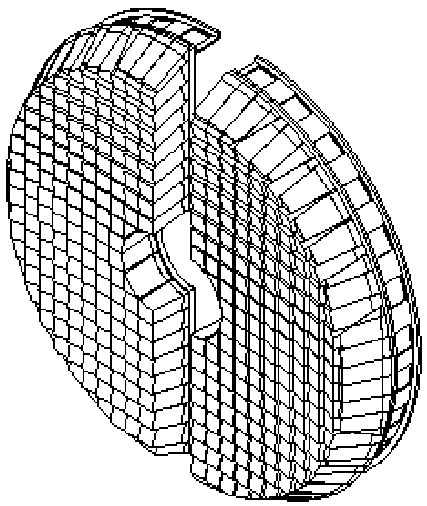
The main challenges include

- Can the detector survive the high radiation environment ?
- Can the detector handle the rate and occupancy ?
- Can the detector achieve adequate angle and energy resolution ?

BTeV now plans to use a $PbWO_4$ calorimeter

- Developed by CMS for use at the LHC
- Large granularity
  - Block size 2.7 x 2.7 x 22 cm^3 (25 X_o)
  - ~23000 crystals
- Photomultiplier readout (no magnetic field)
- Pre-amp based on QIE chip (KTeV)
- Energy resolution
  - Stochastic term 1.6%
  - Constant term 0.55%
- Position resolution

$$s_x = 3526\, m\mathrm{m} / \sqrt{E} \oplus 217 m\mathrm{m}$$

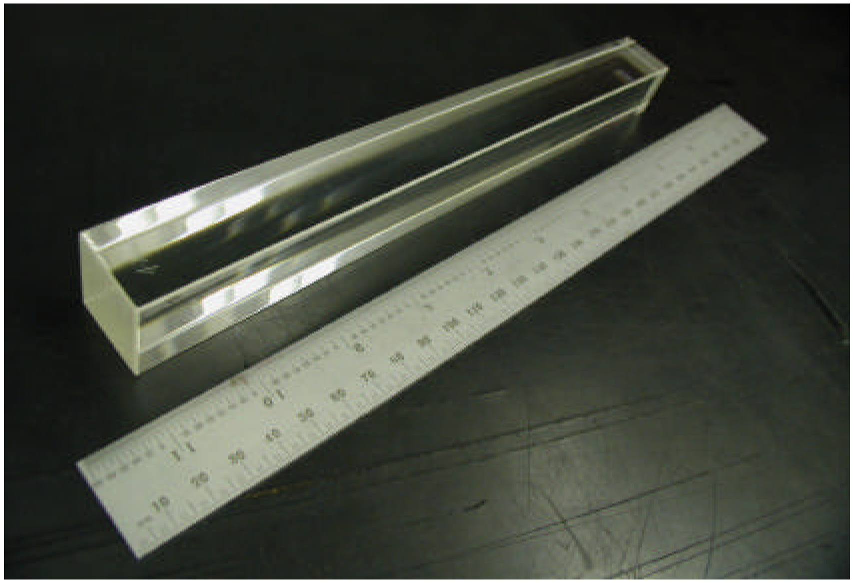


$PbWO_4$ Calorimeter Properties

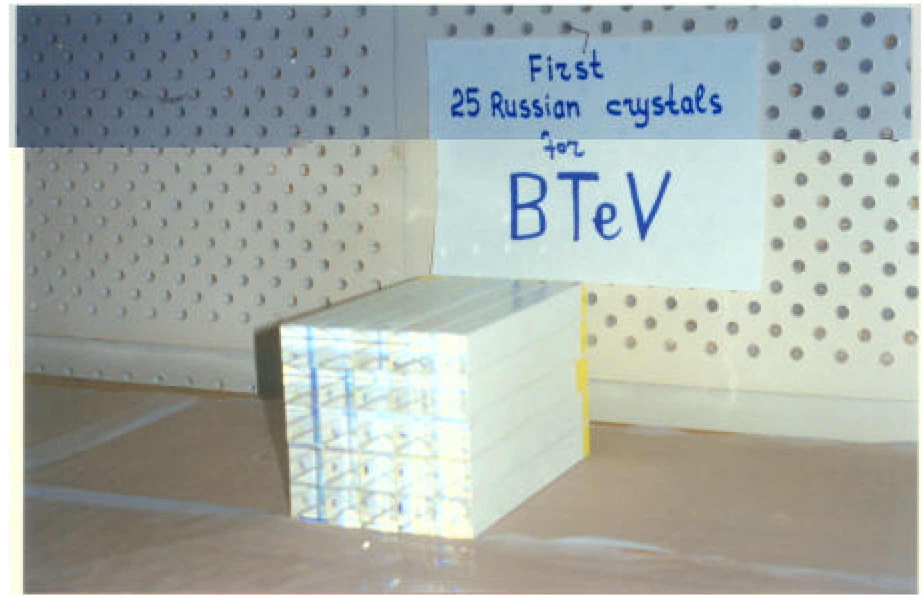
Property	Value
Density(gm/cm^2)	8.28
Radiation Length(cm)	0.89
Interaction Length(cm)	22.4
Light Decay time(ns) (3components)	5(39%) 15(60%) 100(1%)
Refractive index	2.30
Max of light emission	440nm
Temperature Coefficient (%/^{o}C)	-2
Light output/Na(Tl)(%)	1.3
Light output(pe/MeV) into 2” PMT	10

Property	Value
Transverse block size	2.7cm X 2.7 cm
Block Length	22 cm
Radiation Length	25
Front end Electronics	PMT
Inner dimension	+/-9.8cm (X,Y)
Energy Resolution:	
Stochastic term	1.6% (2.3%)
Constant term	0.55%
Spatial Resolution:	$s_x = 3526\, mm / \sqrt{E} \oplus 217 mm$
Outer Radius	140 cm--215 cm $ driven
Total Blocks/arm	11,500

Electromagnetic Calorimeter Tests



Block from China's Shanghai Institute

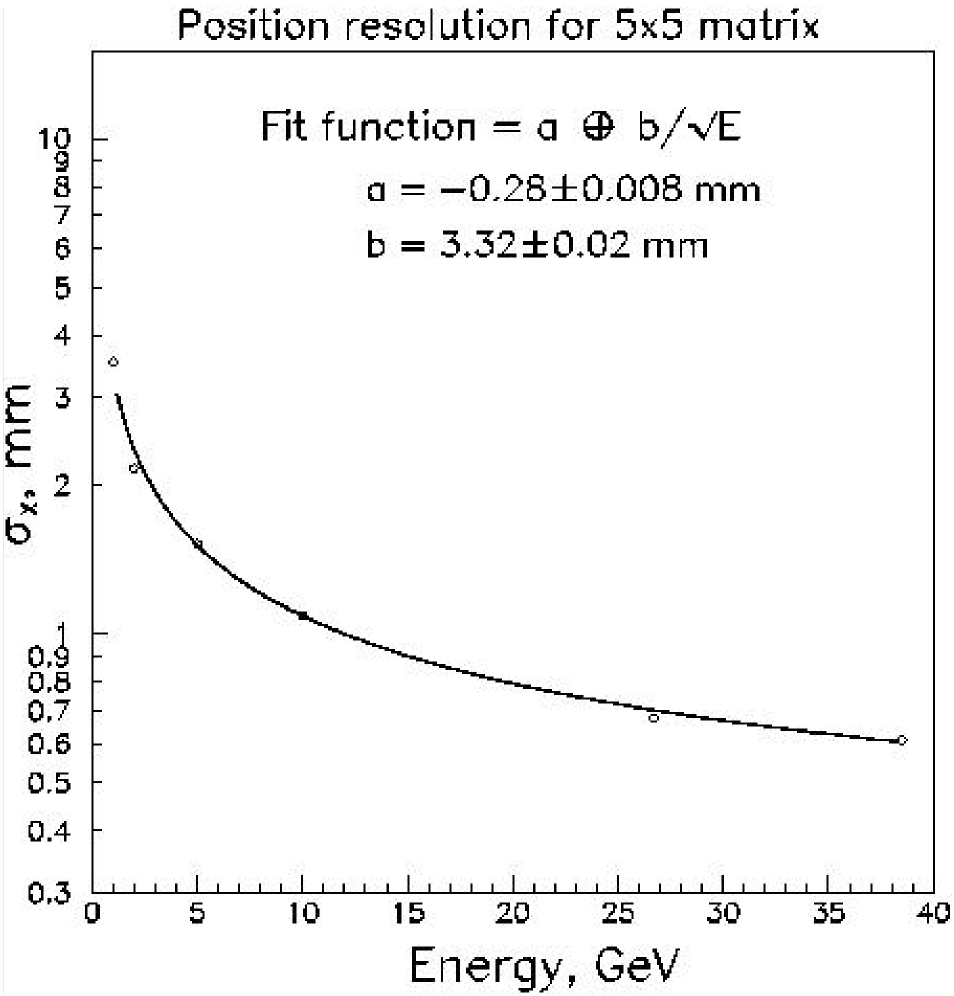


5X5 stack of blocks from Russia ready for testing at Protvino

- Lead Tungstate Crystals from Shanghai, Bogoroditsk, other vendors
- Verify resolution, test radiation hardness (test beam at Protvino)
- Test uniformity

Preliminary Testbeam Results

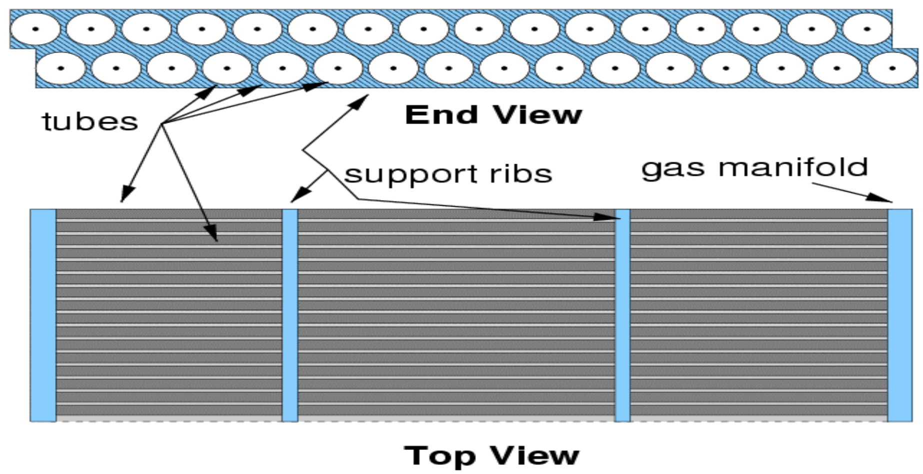
- Resolution (energy and position) close to expectations
- Some non-uniformity in light output
- Radiation Hardness studies in November

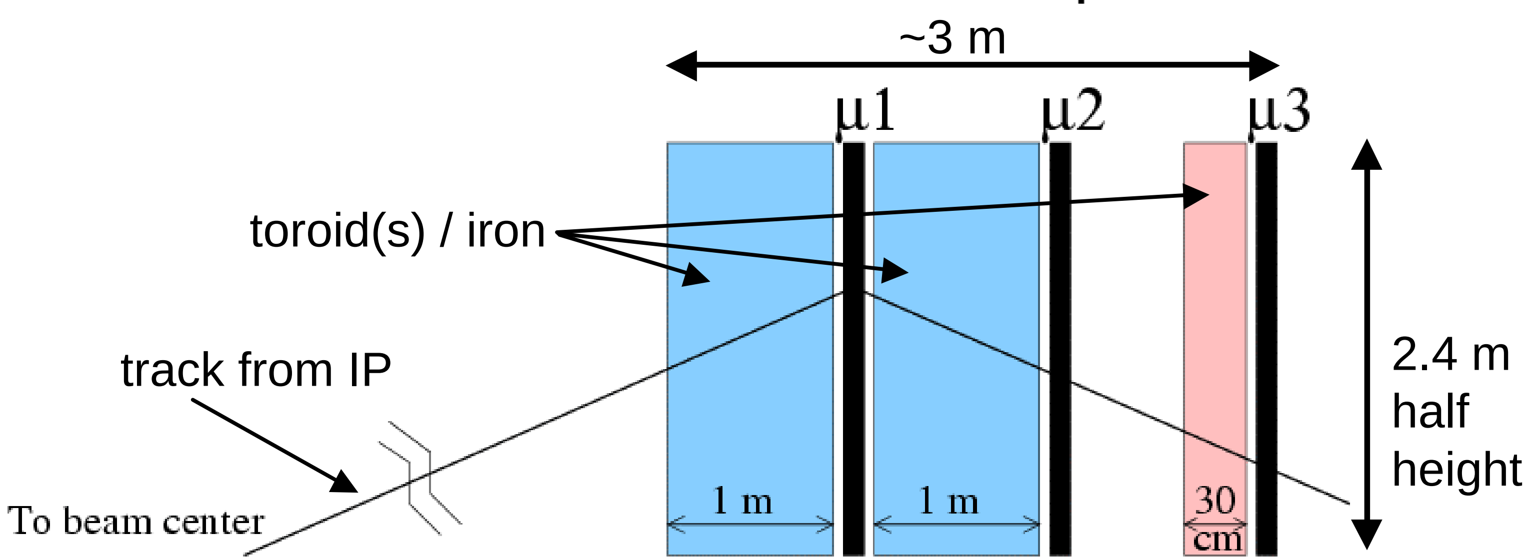


btev

Muon System

- Provides Muon ID and Trigger
  - Trigger for interesting physics states
  - Check/debug pixel trigger
- fine-grained tracking + toroid
  - Stand-alone mom./mass trig.
  - Momentum “confirmation”
- Basic building block: Proportional tube “Planks”





Physics Reach (CKM) in 10^7 s

Reaction	*B* (B)($\times 10^{-6}$)	# of Events	S/B	Parameter	Error or (Value)
$B^o \to \pi^+\pi^-$	4.3	24,000	3	Asymmetry	0.024
$B_s \to D_s K^-$	300	13,100	7	γ	7^o
$B^o \to J/\psi K_S$, $J/\psi \to \mu^+\mu^-$	445	80,500	10	$\sin(2\beta)$	0.025
$B_s \to D_s \pi^-$	3000	103,000	3	x_s	(75)
$B^- \to D^o (K^+\pi^-) K^-$	0.17	300	1		
$B^- \to D^o (K^+K^-) K^-$	1.1	1,800	>10	γ	10^o
$\overline{B}^- \to K_S \pi^-$	12.1	8,000	1		
$B^o \to K^+\pi^-$	18.8	108,000	20	γ	$<5^o$
$B^o \to \rho^+\pi^-$	28	9,400	4.1		
$B^o \to \rho^o\pi^o$	5	1,350	0.3	α	$\sim 10^o$
$B_s \to J/\psi\, \eta$,	330	1,920	15		
$B_s \to J/\psi\, \eta'$	670	7,280	30	χ	0.033

Concluding Remarks

C0 Detector Hall at the Tevatron

"The Committee believes that BTeV has the potential to be a central part of an excellent Fermilab physics program in the era of the LHC. With excitement about the science and enthusiasm for the elegant and challenging detector, the Committee unanimously recommends Stage I approval for BTeV."