BTeV: Status and physics prospects

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Talk Outline

I. Physics Motivation

II. Detector Description

III. Physics Prospects

IV. Project Status

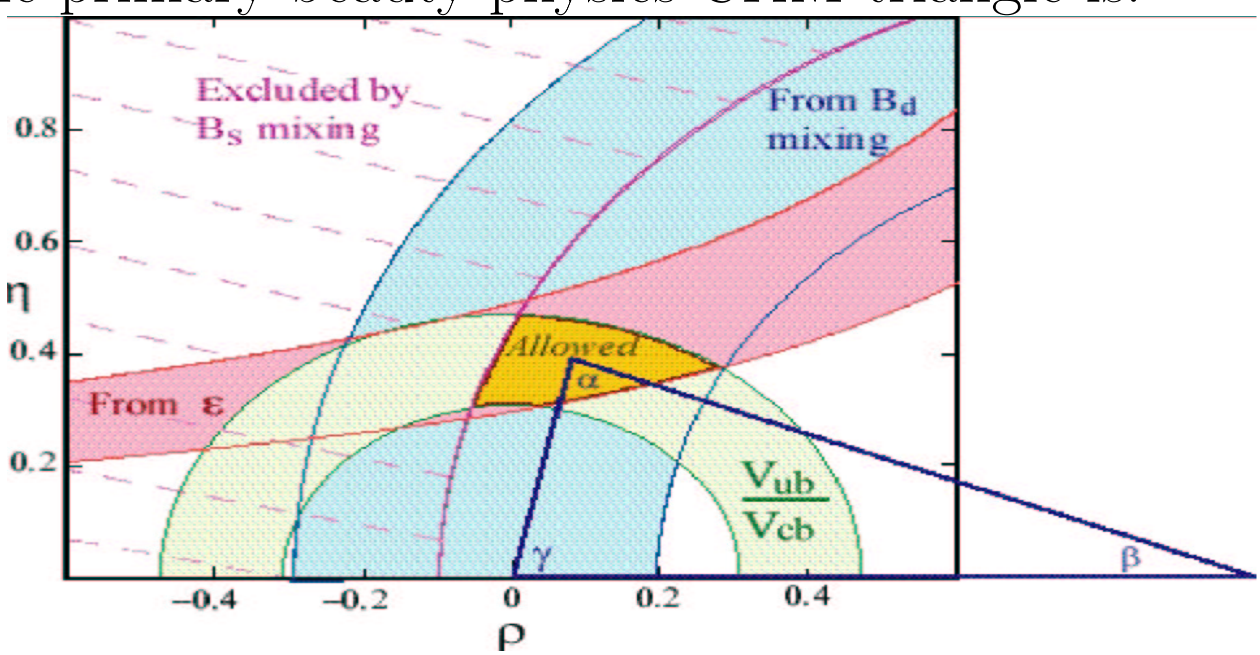
V. Summary

Quick Recap of Beauty Physics Theory

CKM matrix and triangles:

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta(1-\lambda^2/2)) \\ -\lambda & 1-\lambda^2/2-i\eta A^2\lambda^4 & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- $\lambda \approx 0.22$ and $A \approx 0.8$
- All Standard Model CP violation comes from η so CP violation from different particles and different decays are all related and thus CP violation is a good place to search for physics beyond the Standard Model
- The primary beauty physics CKM triangle is:



- Prime goal is measuring α, β, and γ in many ways
- Measuring the side lengths is also very important
- Measuring other independant angles (χ, χ') also crucial

- Finding the "right" decays is a thriving cottage industry

Physics	Decay Mode
$\sin(2\alpha)$	$B^0 \to \rho\pi$ or $B^0 \to \pi\pi$
$\cos(2\alpha)$	$B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$
$\mathrm{sign}(\sin(2\alpha))$	$B^0 \to \rho\pi$ & $B^0 \to \pi^+\pi^-$
$\sin(\gamma)$	$B_s \to D_s^\pm K^\mp$
$\sin(\gamma)$	$B^- \to \overline{D}^0 K^-$
$\sin(\gamma)$	$B^0 \to \pi^+\pi^-$ & $B_s \to K^+K^-$
$\sin(2\chi)$	$B_s \to J/\psi\,\eta'$, $J/\psi\eta$
$\sin(2\beta)$	$B^0 \to J/\psi\, K_S$
$\cos(2\beta)$	$B^0 \to J/\psi\, K^0$, $K^0 \to \pi\ell\nu$
$\cos(2\beta)$	$B^0 \to J/\psi\, K^{*o}$ & $B_s \to J/\psi\,\phi$
x_s (side length)	$B_s \to J/\psi\, K^*, D_sK$
$\|V_{cb}\|$ (side length)	$B^0 \to D^{*+}\mu^-\nu$
$\|V_{ub}\|$ (side length)	$B^- \to \rho^0\mu^-\nu$

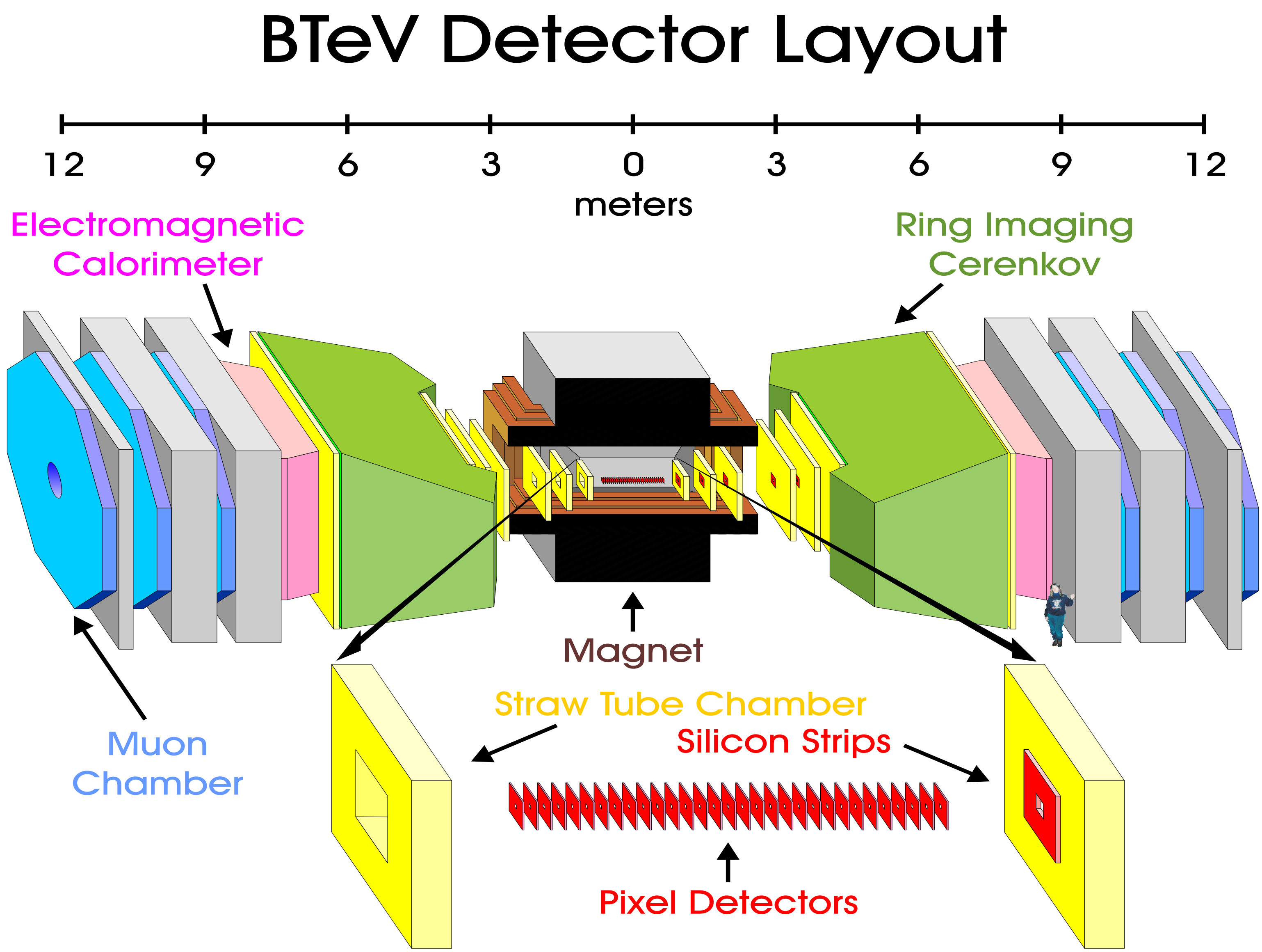
- $\sin(2\beta)$ is measured; α and γ are much more difficult.
- CP violation measurements generally have:
  - Suppressed decays ⇒ low rates
  - Many contributions (from different Feynman diagrams) to particular final state ⇒ complicated theoretically
  - Interferences between contributions ⇒ complicated theoretically
  - Mixing of neutral states⇒complicated experimentally
  - Time dependent effects⇒complicated experimentally

The BTeV Experiment

BTeV is designed to make a high-statistics study of decays of hadrons containing b and/or c quarks and is scheduled to start in 2008.

Basic idea

- Two-arm spectrometer in C0 region of Tevatron
- Forward coverage ($10\,\text{mrad} < \theta < 300\,\text{mrad}$, $1.9 < \eta < 5.3$)



Design Justifications

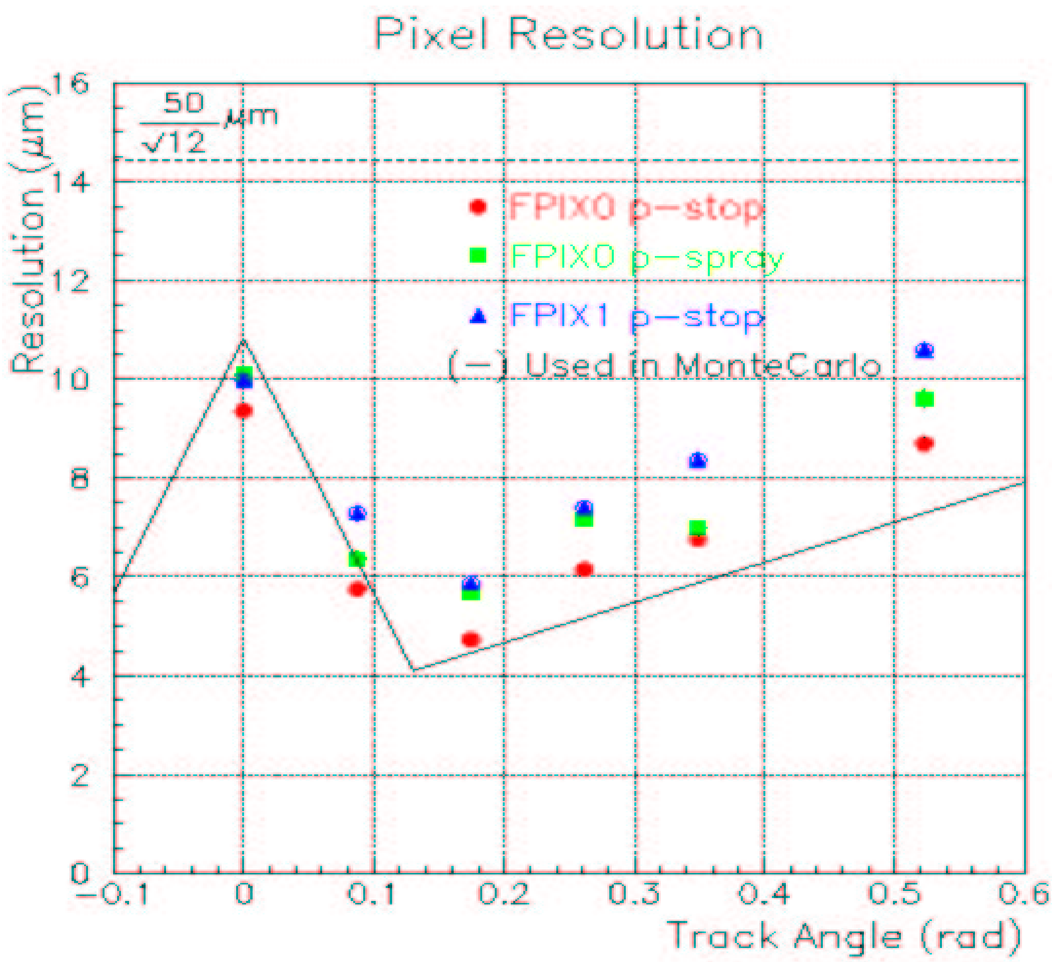
- Forward produced $\Rightarrow$ higher momentum
  - Significant vertex separation between production and decay
  - Less sensitive to multiple Coulomb scattering
  - Excellent lifetime resolution
  - Stellar particle ID of μ, π, K, p, e, γ
- Hadron colliders $\Rightarrow$ more statistics and particles
  - 20,000 $b\bar{b}$ per second at Tevatron compared to 10/s at $\mathcal{L}$=$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ e^+e^- collider
  - $p\bar{p}$ produces B_s, b-baryons, B_c, Ξ_{cc}, Ω_{ccc}, Ξ_{bc}

Design Challenges

- Minimum bias (u,d,s) backgrounds are produced $\sim$750 times more often than b events
  - Need trigger to reduce background rate and good DAQ to handle event rate
  - High radiation, especially near beam

Pixels are key to trigger & experiment

- 30 million 50 $\times$ 400 μm^2 n^+np^+ type pixels
- 10$\times$10 cm^2 transverse with 1.2 $\times$1.2 cm^2 beam hole
- 30 x-y doublets separated by 4.25 cm
- FPIX2 (amp/ADC/readout) fabricated with intrinsically rad-hard .25μm CMOS process & bump bonded to pixels
- 2-D spacepoint reduces tracking combinatorics
- Beam test of pixels in Fall, 1999
  - Measured noise: 200–400 e^-
  - Signal of non-shared track >20,000 e^-
  - ADC+charge-sharing algorithm $\Rightarrow$ excellent resolution



Forward tracking for momentum and projection

- 7 stations/arm with silicon strips inside ($24 \times 24\,\mathrm{cm}^2$) and straw tubes outside
- Straws: 4 mm diameter, 3 views/station, 3 layers/view
- Silicon strips: 100 μm pitch with 3 views/station
- 100K channels each of straws (TDC) and strips (latch)
- Momentum resolution better than 1%

EM calorimeter for e-ID & γ/π^0 reconstruction

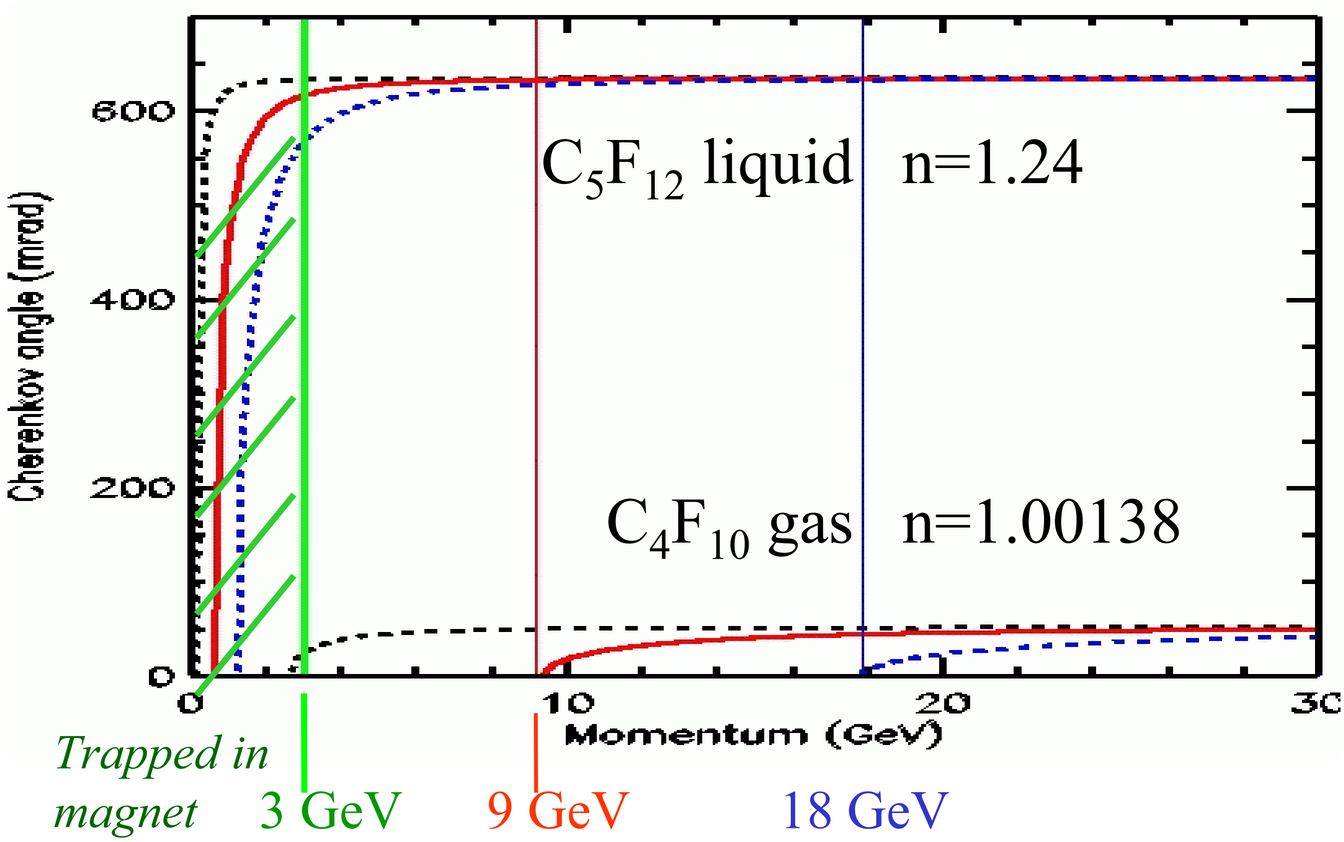
- 20,000 $PbWO_4$ crystals (rad hard CMS development)
- 2.72×2.72 cm^2 in front and 2.8×2.8 cm^2 in back
- 22 cm long = 25 radiation lengths = 1 interaction length
- Geant energy resolution $\sim 0.55\% \oplus 1.6\%/\sqrt{E}$
- Readout with photomultiplier tubes

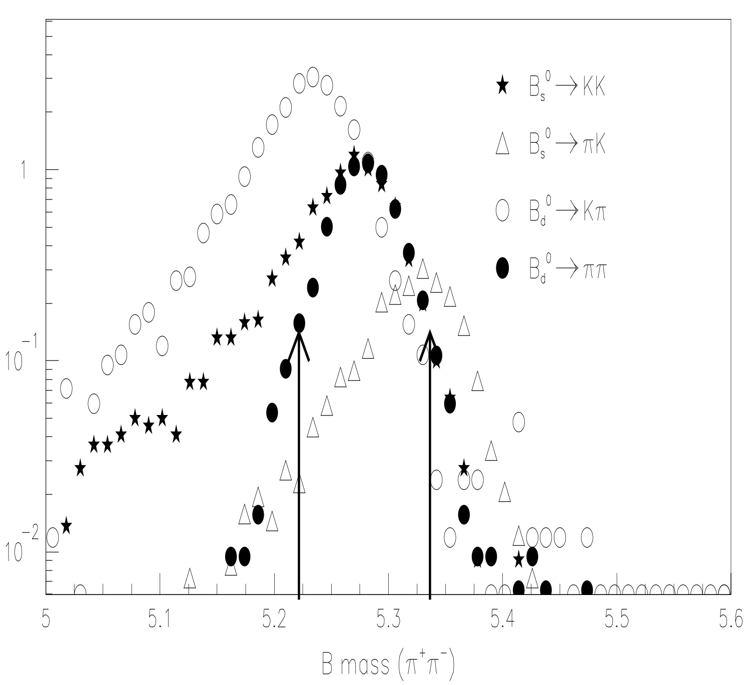
Muon detector for μ-ID and trigger

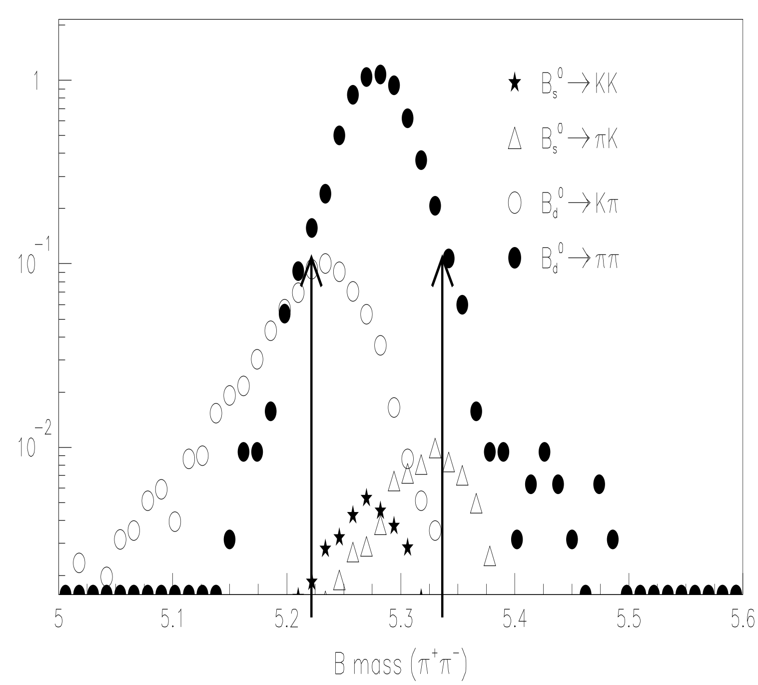
- Two 1 m magnetized iron filters per arm
- 74K 1 cm diameter proportional tubes (latch readout)
- Arranged in octants $\Rightarrow$ reduce occupancy near beam
- 3 stations/arm, 4 views (r-u-v-r)/station, 2 layers (picket fence)/view, 192 tubes/layer
- Gas: $Ar/CF_4/CO_2$ (88%/10%/2%) $\Rightarrow$ fast (90 μm/ns)

Hadron Particle ID is crucial (RICH):

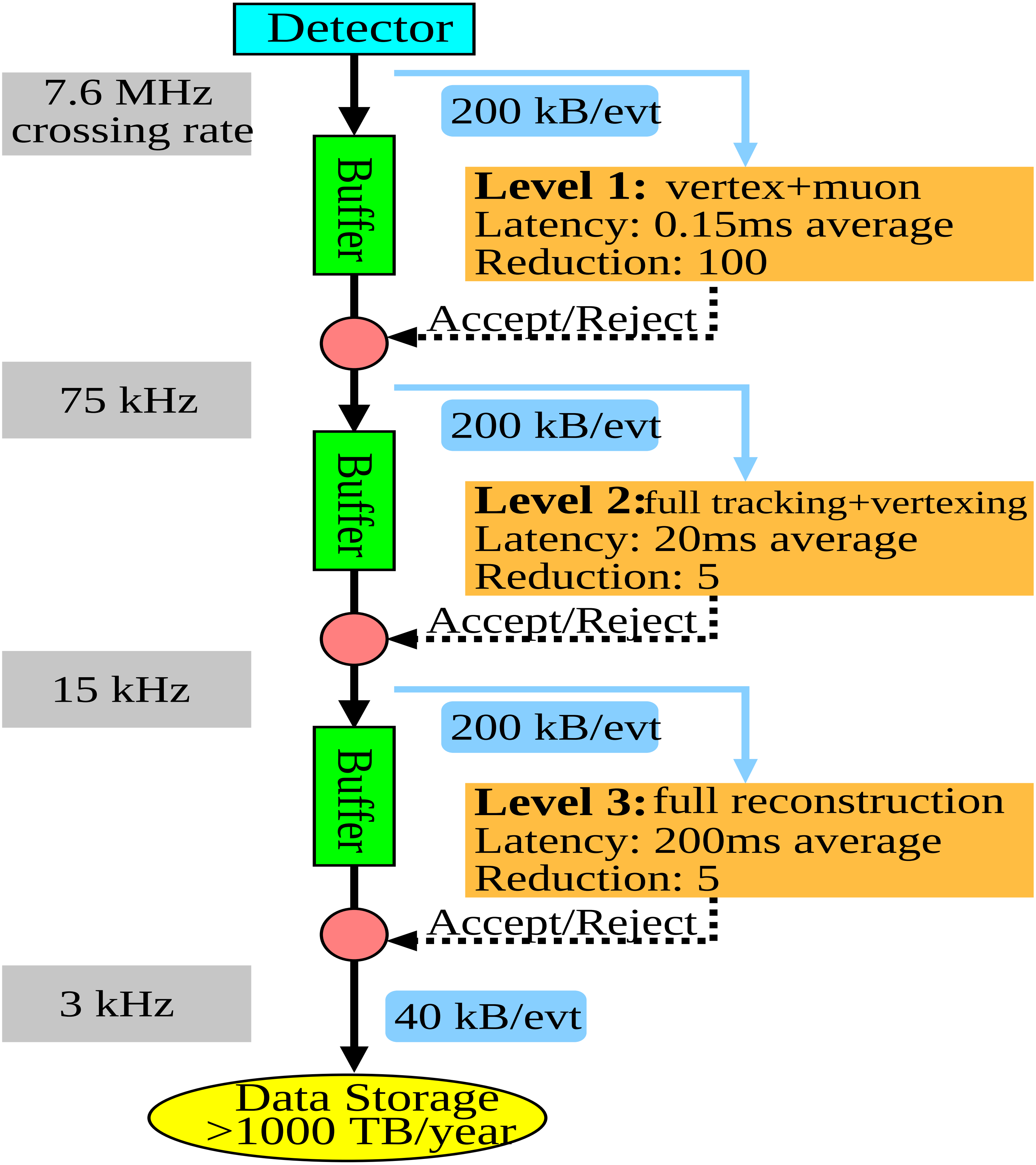
- C_4F_{10} gas provides $\pi/K/p$ separation from 9–70 GeV
- Considering C_5F_{12} liquid for particles in 3–9 GeV range
- Detect gas photons with 300,000 channels of hybrid photo-diodes
- Detect liquid photons with 10,000 channels of photomultiplier tubes





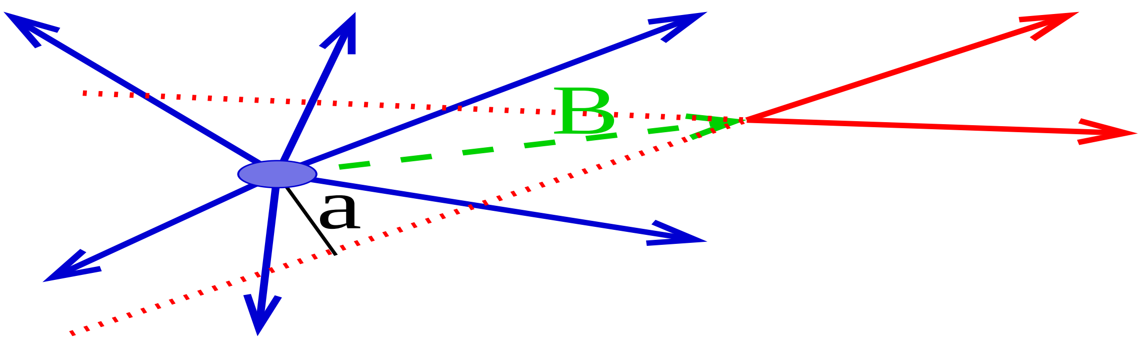


Trigger/Data Acquisition (DAQ)

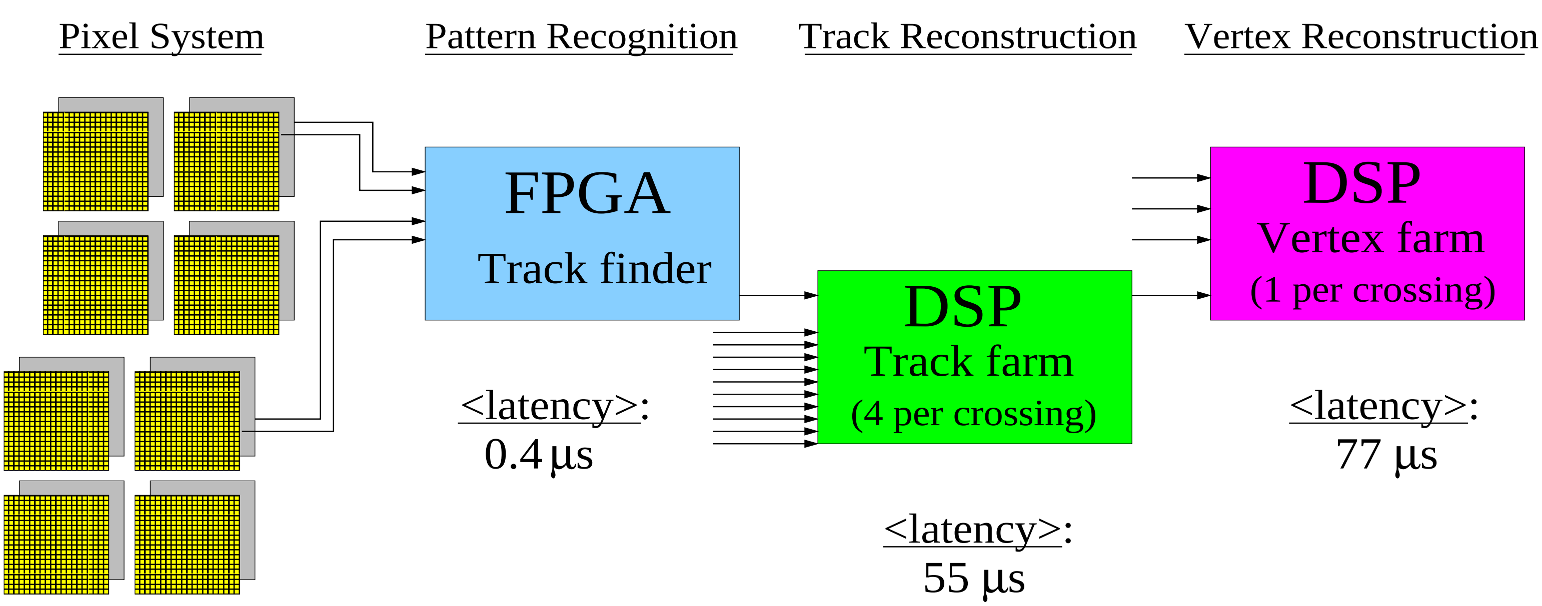


Vertex Trigger

- Algorithm
  - Reconstruct tracks using pixel information
  - Verticize tracks to find production vertex
  - Look for tracks which miss production vertex
  - Make cut (currently ≥ 2 tracks miss production vertex (a) by $> 6\sigma$)



- Implementation
  - Use Field Programmable Gate Arrays (FPGA) to time-order and cluster hits
  - Use Digital Signal Processors (DSP) to reconstruct tracks, verticize, and obtain primitive information



Examples of new physics searches

New phases can be introduced from new physics:

In SM, $B^0 \to J/\psi\, K_S^0$ and $B^0 \to \phi\, K_S^0$ both measure $\sin 2\beta$ but in MSSM they measure $\sin 2(\beta + \theta_D)$ and $\sin 2(\beta + \theta_D + \theta_A)$, respectively. BTeV can collect 200 tagged $B^0 \to \phi\, K_S^0$ events/year.

The rate and structure of $B^0 \to K^{*0} \ell^+ \ell^-$

- Rare decays are good window for new physics
- Compare branching ratio with SM (BR $\approx 1.5 \times 10^{-6}$)
- Zero of forward-backward asymmetry of dilepton mass (A_{FB}) well defined in SM
- Other theories (some SUSY and SUGRA models) can have different (or no) zero
- BTeV can collect 4400 $B^0 \to K^{*0} \mu^+ \mu^-$ events/10^7 s

Measuring the CKM angle χ

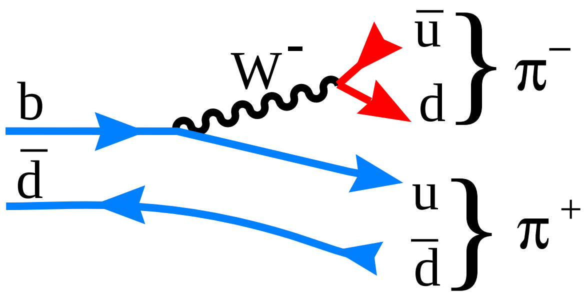
- $\chi \equiv arg\left(-\frac{V_{cs}^* V_{cb}}{V_{ts}^* V_{tb}}\right)$ is independant from α, β, and γ
- Need to check SM predictions of:

$$\sin \chi \;=\; \left|\frac{V_{us}}{V_{ud}}\right|^2 \frac{\sin\beta \sin\gamma}{\sin(\beta+\gamma)} \;=\; \left|\frac{V_{ub}}{V_{cb}}\right|^2 \frac{\sin\gamma \sin\beta+\gamma}{\sin(\beta)} \;=\; \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{\sin\beta \sin\beta+\gamma}{\sin(\gamma)}$$

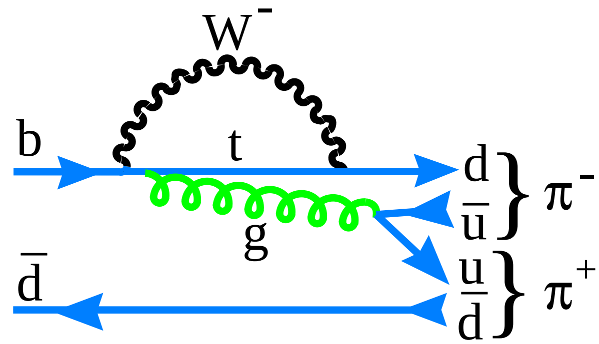
Comparing side lengths to angles

- CKM unitarity triangle side lengths are given by CKM matrix elements (*e.g.* V_{ub}), using semileptonic decays
- CKM unitarity triangle angles are given by α, β, and γ
- Discrepancies indicate new physics

α measurement study



Tree diagram



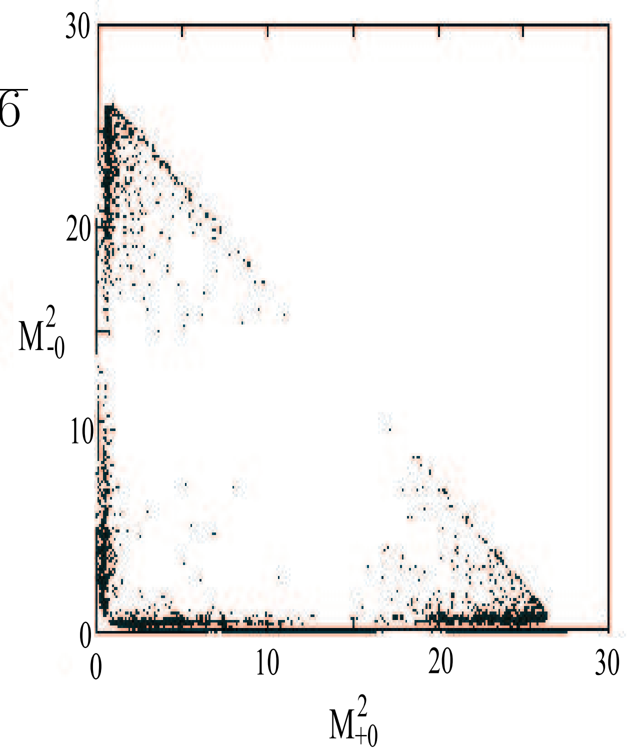
Penguin diagram

- Need decay of form $b \rightarrow du\bar{u}$
- Traditionally $B^0 \rightarrow \pi^+\pi^-$ has been the favored decay for $\sin(2\alpha)$
- $\Upsilon(4S)$ results $\Rightarrow$ "Penguin pollution" large
- In this case, extracting α requires isospin analysis
- For $B^0 \rightarrow \pi^+\pi^-$ this requires measuring $B^0 \rightarrow \pi^0\pi^0$ which has smaller branching ratio and very difficult (impossible at BTeV) to reconstruct
- A solution in 3-body modes?

$B^0 \to \rho\pi \to \pi\pi\pi$

- Three decays: $B^0 \to \rho^+\pi^-$, $B^0 \to \rho^-\pi^+$, $B^0 \to \rho^0\pi^0$
- Requires time-dependent Dalitz plot tagged analysis
  - Dalitz plot analysis measures contributions of resonances as well as their interferences
  - The lifetime of each B^0 is determined to allow time-dependent measurement
  - "Tag" B flavor to distinguish B^0 from $\overline{B^0}$
  - Opposite side tagging tags the flavor of the B which we do not reconstruct by looking at signatures ($\mu/e/K$/jet charge)
- Interferences can allow resolution of all ambiguities of α
- Snyder & Quinn find robust solutions with 2,000 background-free events

Quantity	$\rho^{\pm}\pi^{\mp}$	$\rho^0\pi^0$
BR	2.8×10^{-5}	$\sim5\times10^{-6}$
Effic.	0.44%	0.36%
Trigger effic.	50%	50%
S/B	4.1	0.3
Signal/year	8,700	1,250
ϵD^2	0.10	0.10
Tagged/year	870	125



CKM and rare decay sensitivities

	BTeV-2arm 10^7 s	LHC-b 10^7 s	b-factory $500\,\mathrm{fb}^{-1}$	$\mathcal{L}=10^{36}$ 10^7 s
$\sin 2\beta$ $(B^0 \to J/\psi K^0_S)$	0.013	0.02	0.037	0.008
$\sin 2\alpha_{\rm eff}$ $(B^0 \to \pi^+\pi^-)$	0.05	0.05	0.14	0.032
$\alpha_{\rm eff} - \alpha$ $(B^0 \to \pi^0\pi^0)$	—	—	$<18^\circ$	$<7^\circ$
α $(B^0 \to \rho\pi)$	10°			
γ $(B^0_s \to D_s K)$	$\sim 7^\circ$	$\sim 10^\circ$	—	—
γ $(B^- \to \overline{D^0} K^-)$	$\sim 10^\circ$	$\sim 10^\circ$	$\sim 20^\circ$	2.5°
$\sin 2\chi$ $(B^0_s \to J/\psi \eta^{(\prime)})$	0.021		—	—
$x_s (B^0_s \to D^+_s \pi^-)$	up to 75	up to 75	—	—
V_{ub} $(B \to \rho \ell \nu)$	?	?	2.3%	<1%
$Y(B^0 \to \mu^+\mu^-)(8\times 10^{-11})$	2 evt	2 evt		
$Y(B^0_s \to \mu^+\mu^-)(10^{-9})$	10 evt	11 evt		
$Y(B \to X_s \mu^+\mu^-)(6\times 10^{-6})$	7.2k evt		.3k evt	6k evt
$Y(B \to K^* \mu^+\mu^-)(2\times 10^{-6})$	4.4k evt		.12k evt	2.4k evt
$Y(B \to K^* e^+ e^-)(2\times 10^{-6})$	4.4k evt		.12k evt	2.4k evt

For a 1-arm BTeV, errors will increase by $\sim\sqrt{2}$ and yields will decrease by ~ 2.

BTeV project status and future

- BTeV received PAC & Fermilab approval in June, 2000
- Budget constraints prompted negotiations between Fermilab, DOE, & BTeV which resulted in the following goals (contingent on passing reviews):
  - Support for BTeV R&D
  - Most BTeV construction money for the rescoped (one arm) detector in 2005-2007
  - Parasitic data-taking can begin for debugging and commissioning as soon as major components are available for installation
  - Start physics data taking with one arm in 2008
  - Until CDF or DØ end, will have low intensity collisions or wire target to bring up systems
  - To reduce cost, existing magnets will be used for the BTeV interaction region
- PAC will review new plan in April, 2002 followed by an outside "P5"-style review in Fall, 2002

The BTeV Outlook

- The era of beauty physics has only just begun
- The B factories (and CDF & DØ) should obtain:
  - $\sin(2\beta)$ from $J/\psi K_s^0$
  - V_{ub} (V_{cb}) from semileptonic decays $B \to \rho\mu\nu$ ($B \to D^{(*)}\mu\nu$)
  - Rare decays (probably limits if Standard Model)
  - x_s from B_s mixing (if Standard Model)
  - Charm mixing and rare decays (limits if Standard Model)
- In 2008 many questions will still be open
- BTeV can answer these questions by measuring:
  - $\sin(2\beta)$ to ± 0.013 using $B^0 \to J/\psi K_S$
  - α to $\pm 10°$ using $B^0 \to \rho\pi$
  - γ to $\pm 7°$ using $B_s \to D_s^{\pm} K^{\mp}$
  - $\sin(2\chi)$ to ± 0.021 using $B_s \to J/\psi\eta^{(\prime)}$
  - Rare decay rates and distributions
  - Semileptonic decays of B^0, B^+, Λ_b, B_s, ...
  - Properties of B_c, Ξ_{cc}, Ω_{cc}, Ξ_{bc}, Ω_{bc}, Ω_{ccc}
  - Charm mixing and rare decays
- The BTeV features which make this possible are:
  - The massive statistics available at a hadron collider
  - A flexible and open trigger which allows us to look for things not even dreamed up during design
  - Excellent particle ID of e,μ,π,K,p
  - Great π^0 and γ reconstruction
  - Superb vertex and mass resolution