Prospects for DØ Beauty Physics Measurements in Run II

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IV International Conference on Hyperons, Charm and Beauty Hadrons

Valencia Spain
June 27-30 2000

The Tevatron is a B factory

- **Large production cross section**
- **Even larger inelastic cross section**

(S/B≈10^{-3}) ⇒ specialized triggers:

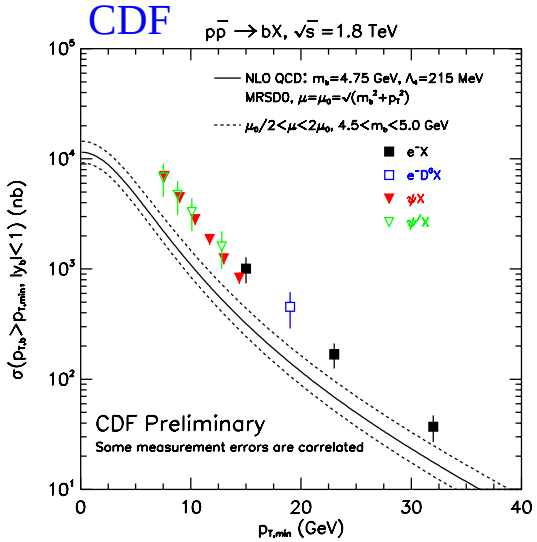
- **Single lepton triggers**
- **Dilepton triggers such as $J/\psi \to \mu^+\mu^-$**
- **Track triggers moved to L1 (RunII)**
- **In Run II, L2 trigger on displaced tracks using SVX will allow CDF/DØ to trigger purely hadronic B decays and study such as $B^0 \to \pi^+\pi^-$, $B_s \to D_s^-\pi^+$ ...**

- **Precise 2nd vertex reconstruction**

$$\sigma(p\bar{p} \to b\bar{b}) \approx 100\,\mu b \quad \text{At 1.8 TeV}$$

$$\sigma(e^+e^- \to b\bar{b}) \approx 7nb \quad \text{At } Z^0$$

$$\sigma(e^+e^- \to B\bar{B}) \approx 1nb \quad \text{At } \Upsilon(4S)$$



DØ Run II B Physics Goals

QCD tests

- cross sections
- correlations
- charmonium polarization

CP violation and CKM angles

- $\sin(2\beta)$ $\quad B \to J/\psi + K_s$
- $\alpha + \gamma$ $\quad B \to \pi^+\pi^-$, $B_s \to K^+K^-$
- possibly γ $\quad B_s \to D_s^{\pm} K^{\mp}$

Non SM CP violation

- $B_s \to J/\psi + \varphi$

B_S mixing

- $B_s \to D_s + n\pi$
- $B_s \to J/\psi + K^*$

Spectroscopy and lifetimes

- $B^0, B^+, B_s, B_c, \Lambda_b$

Rare and radiative decays

- $B \to l^+l^-$ $\quad B \to l^+l^- X_s$
- $B_s \to K^*\gamma$

The Cabibbo-Kobayashi-Maskawa Matrix

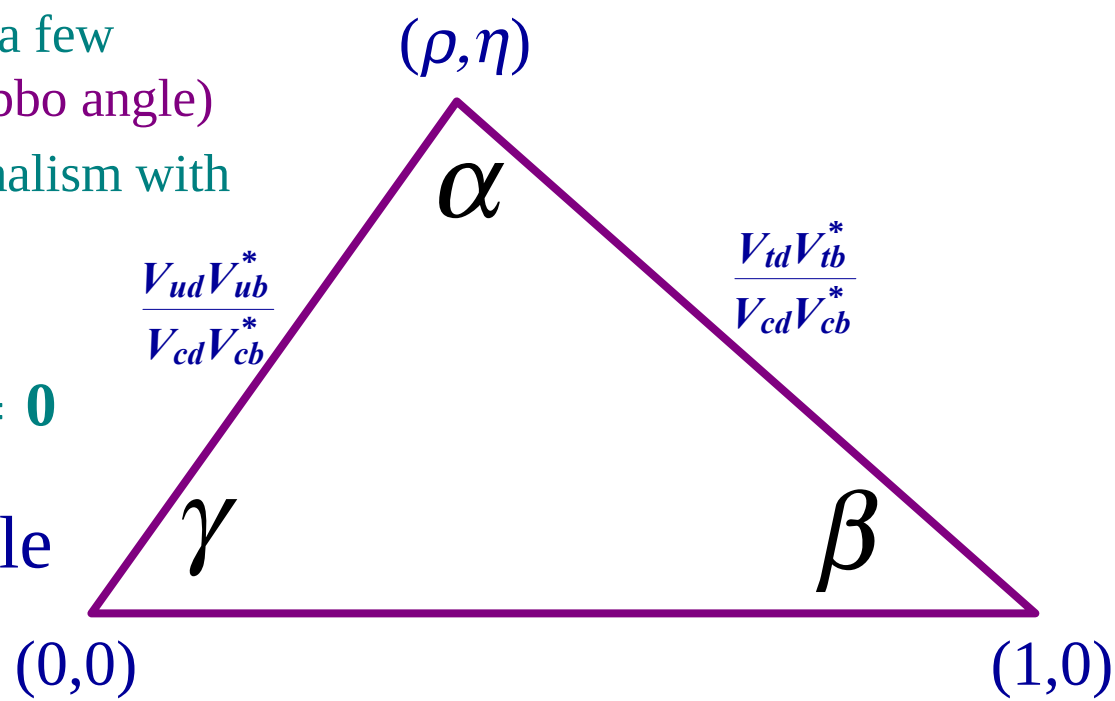
The CKM matrix rotates quark mass eigenstates into their weak counterparts

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- A and λ have been measured to a few percent (λ is the sin of the Cabibbo angle)
- CP violation is put into the formalism with the complex phase η
- unitarity condition:

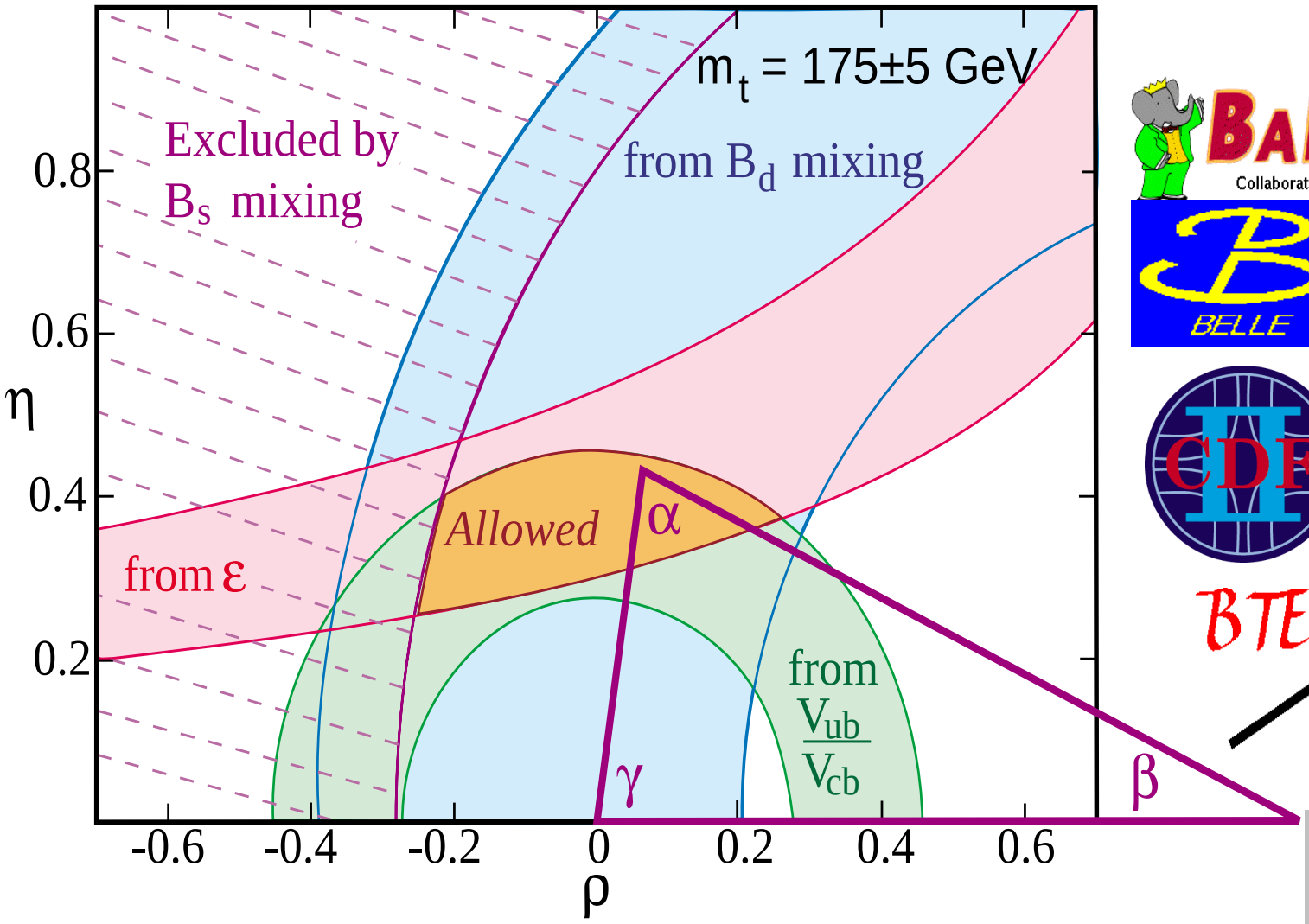
$$V_{tb}^* V_{td} + V_{cb}^* V_{cd} + V_{ub}^* V_{ud} = 0$$

gives the unitarity triangle



B Physics in the 21st Century

Experiments will confront the Standard Model interpretation of CP violation



KTEV Kaons at the Tevatron

BaBar Collaboration Ho

BELLE

CLEO III

CDF II

DØ

BTEV

Co

LHCb

ATLAS

CMS

The DØ Upgrade

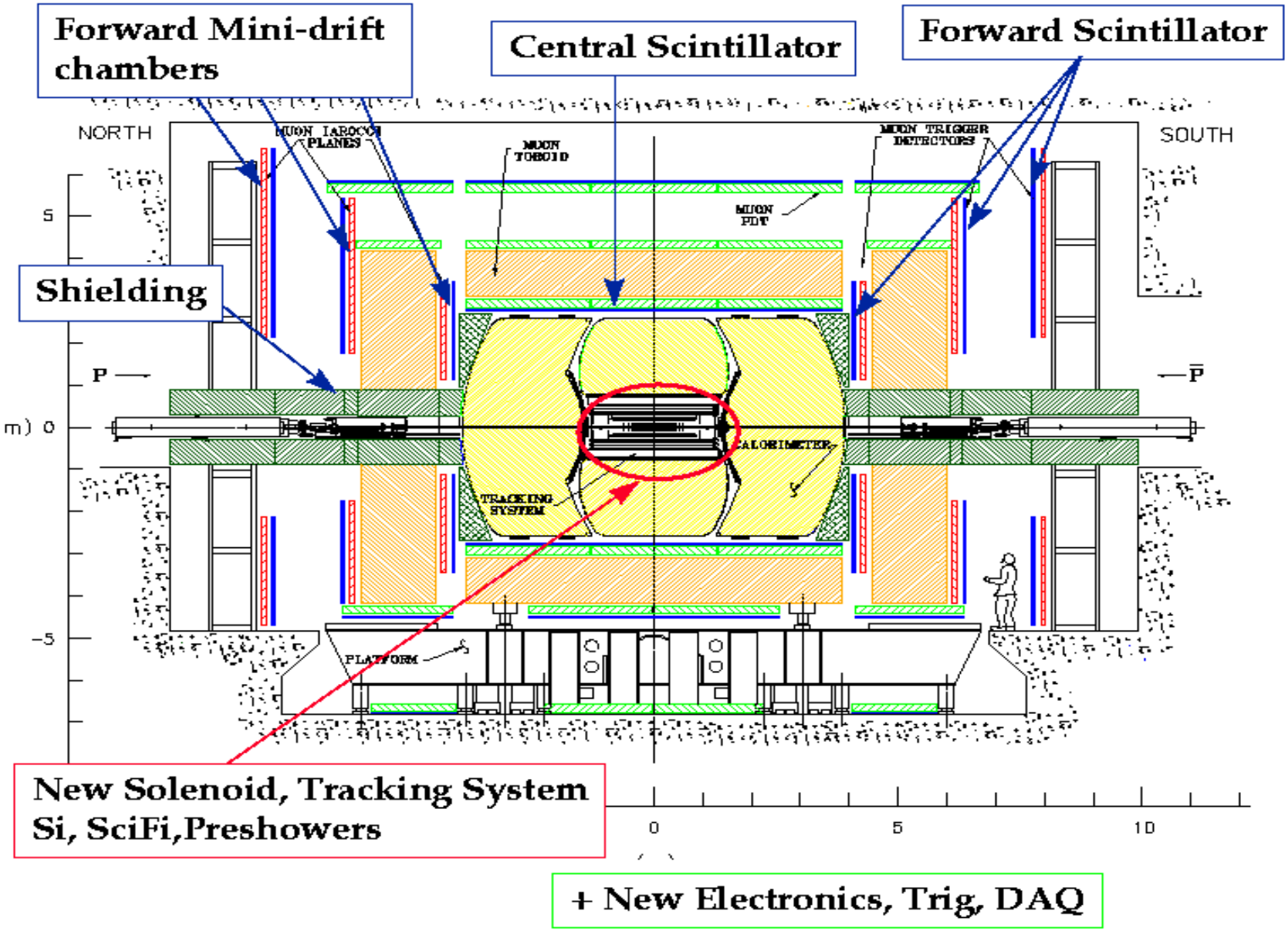
Built on previous strengths:

- excellent calorimetry
- good muon coverage and purity

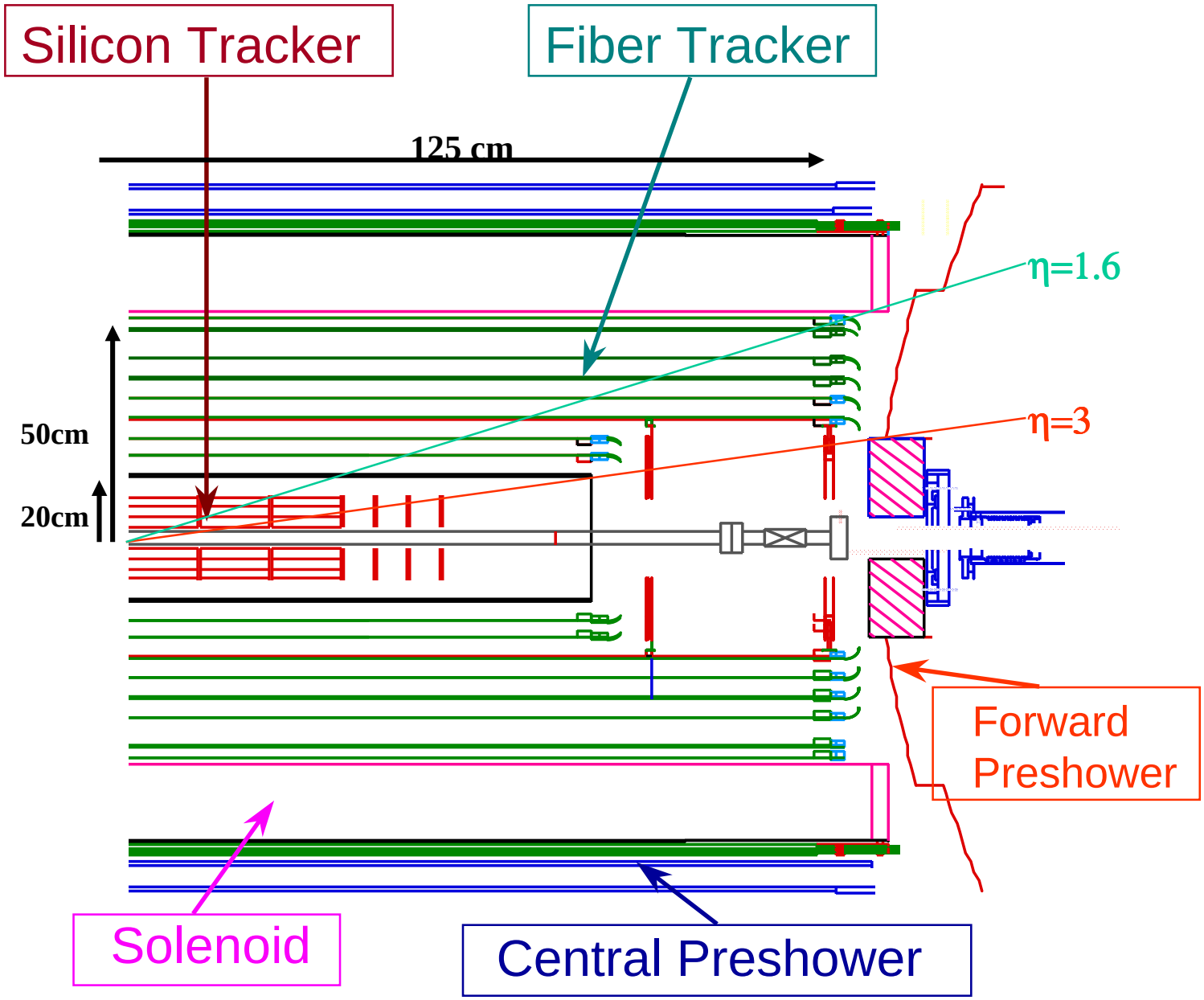
Significantly improved tracking and triggering capabilities:

- new inner tracker with silicon vertex detector and scintillating fiber tracker
- 2 Tesla magnetic field
- enhanced muon triggering
- pre-shower detectors for electron ID and triggers
- level II impact parameter trigger

The DØ Upgrade

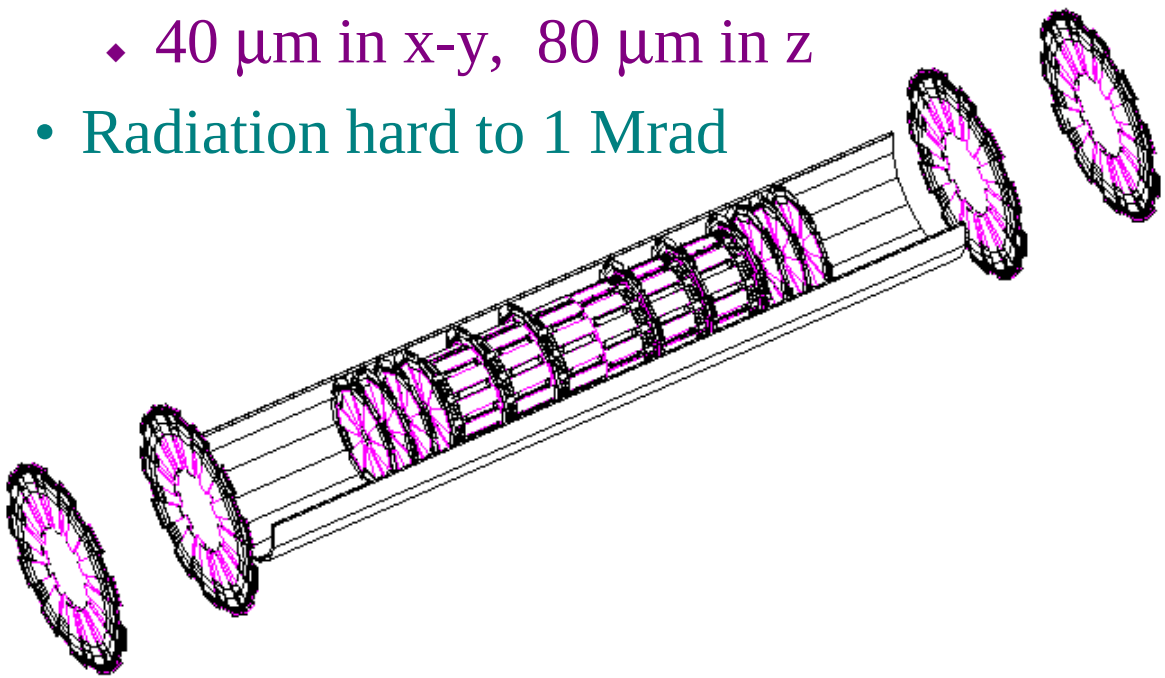


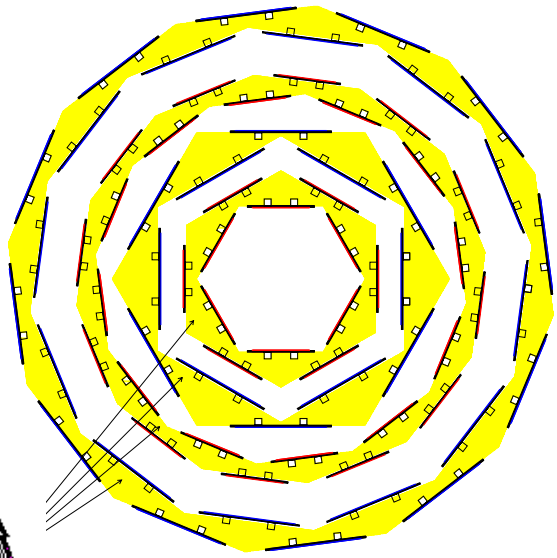
The DØ Inner Tracking System

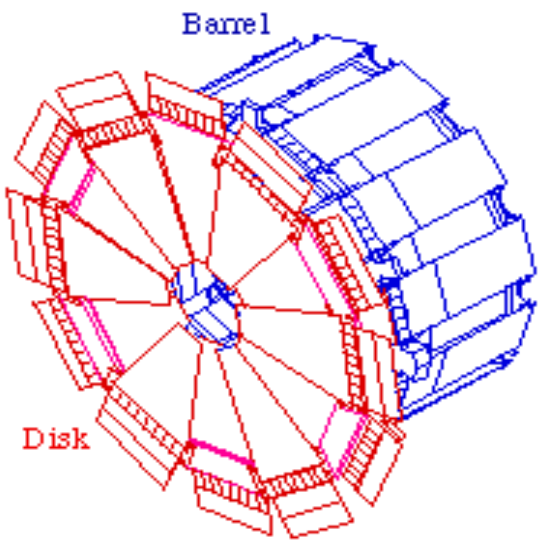


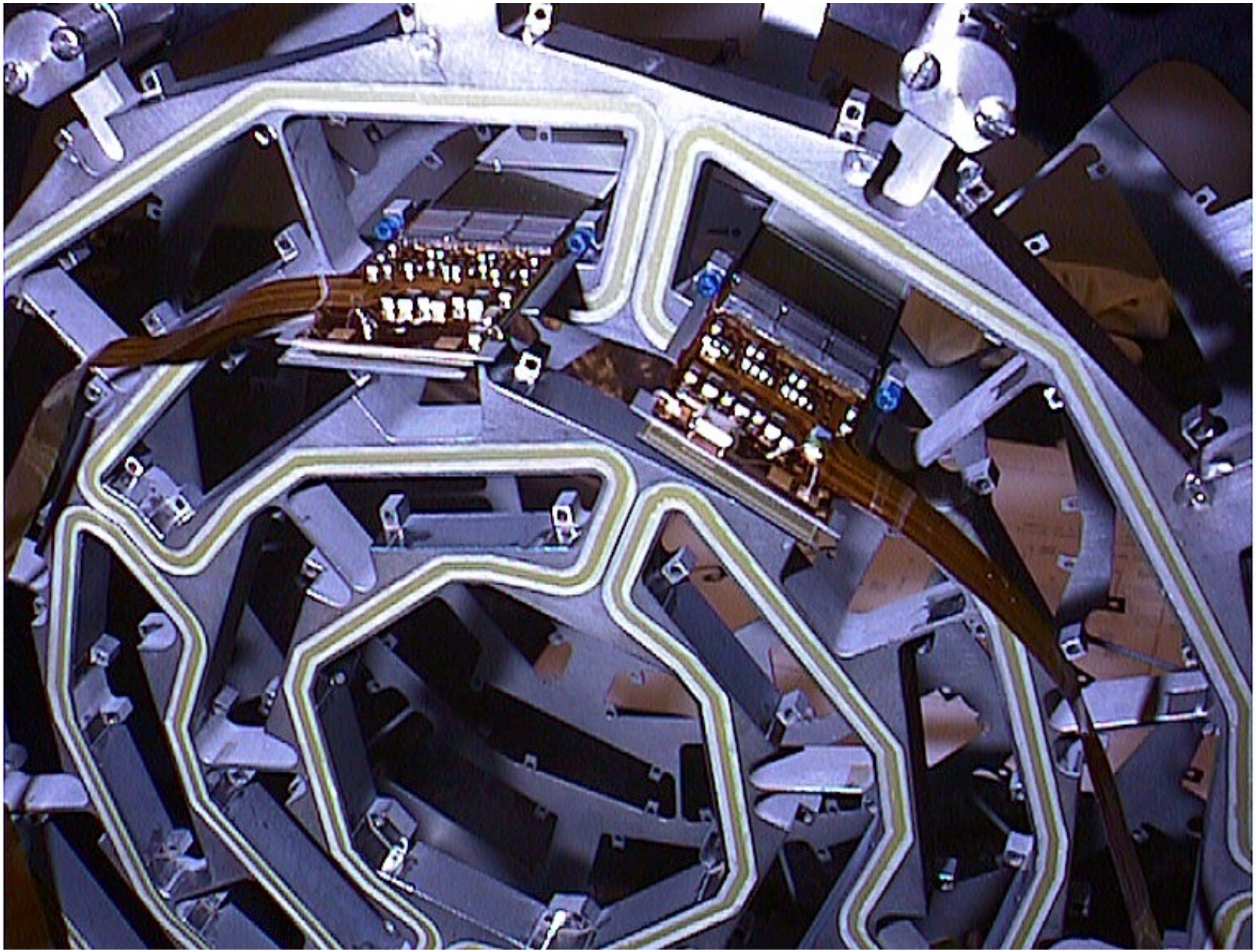
The DØ Silicon Detector

- 6 barrels (12cm) with 4 layers each
- 16 disks
- Hit resolution: 10 μm
- vertex resolution:
  - 40 μm in x-y, 80 μm in z
- Radiation hard to 1 Mrad

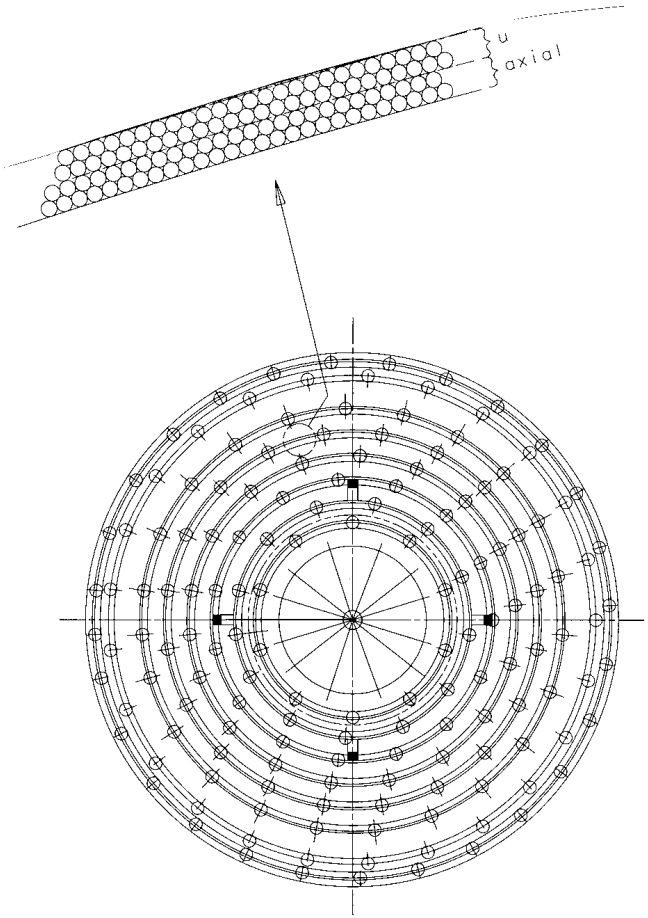


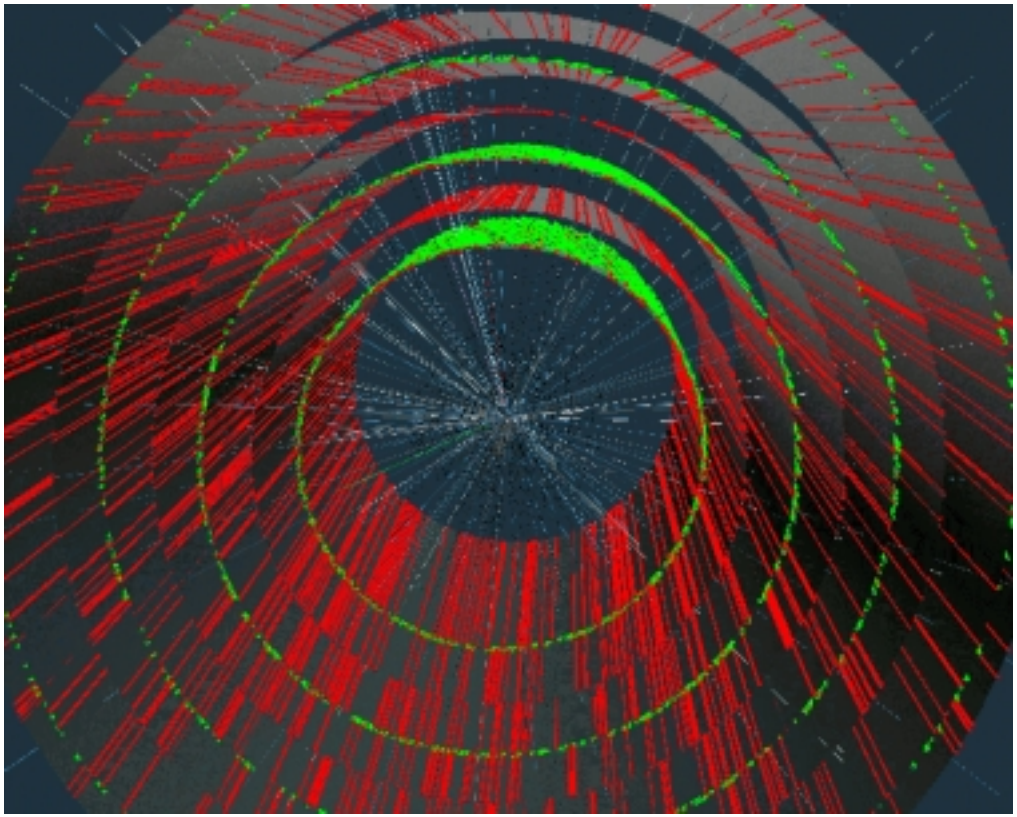






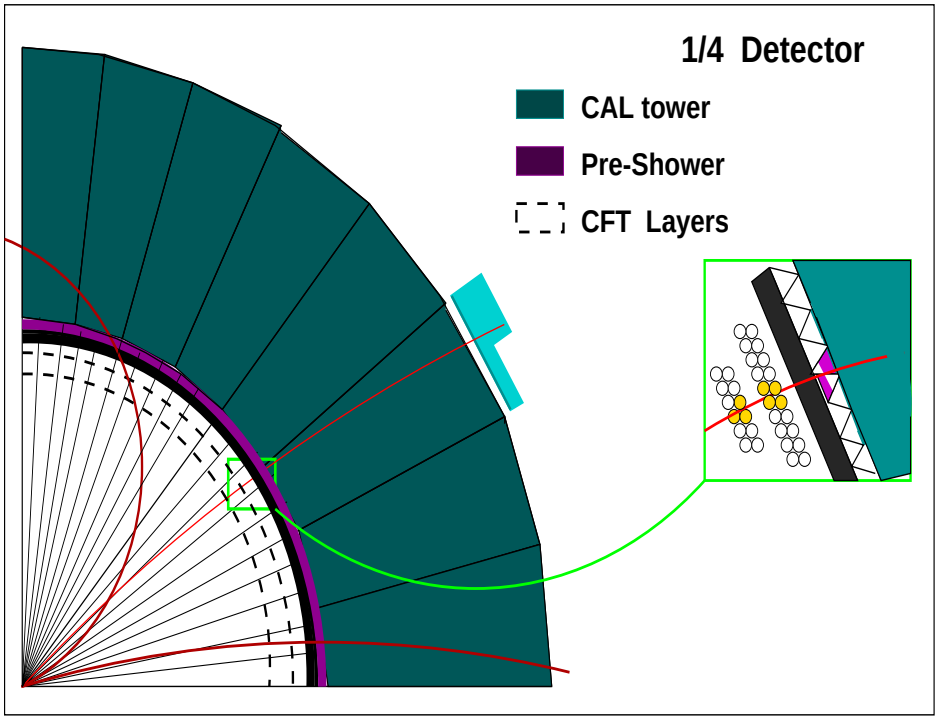
The DØ Fiber Tracker

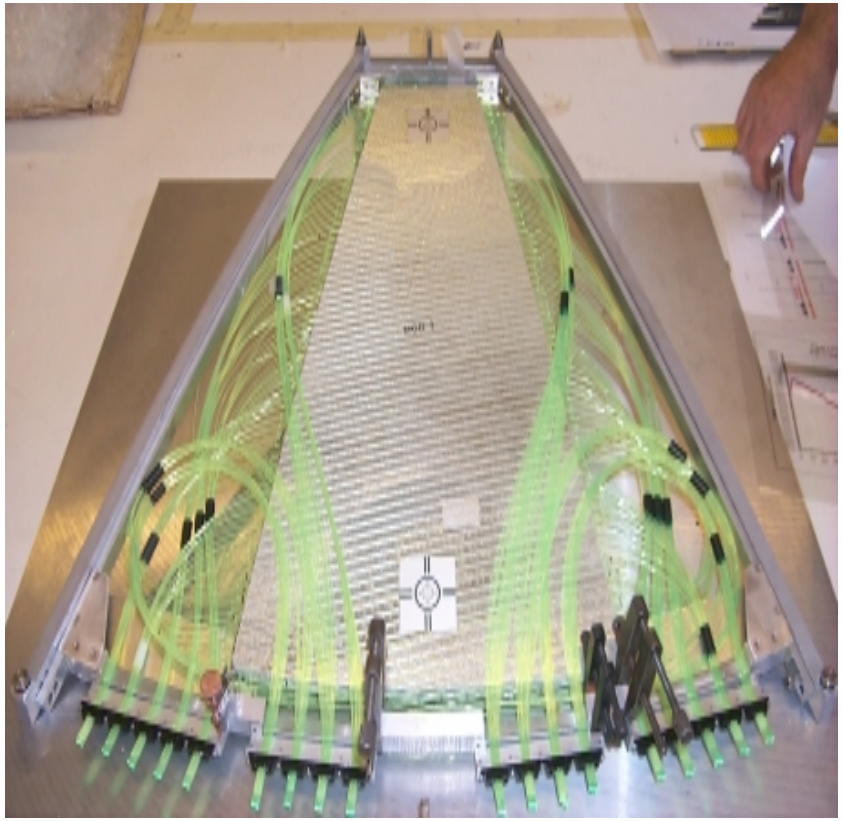




- 8 cylinders with 4 layers of 830 μm scintillating fibers each
- Radial and alternating u v (2°) stereo doublets
- Fast response, good resolution, low mass

The DØ Pre-shower Detectors





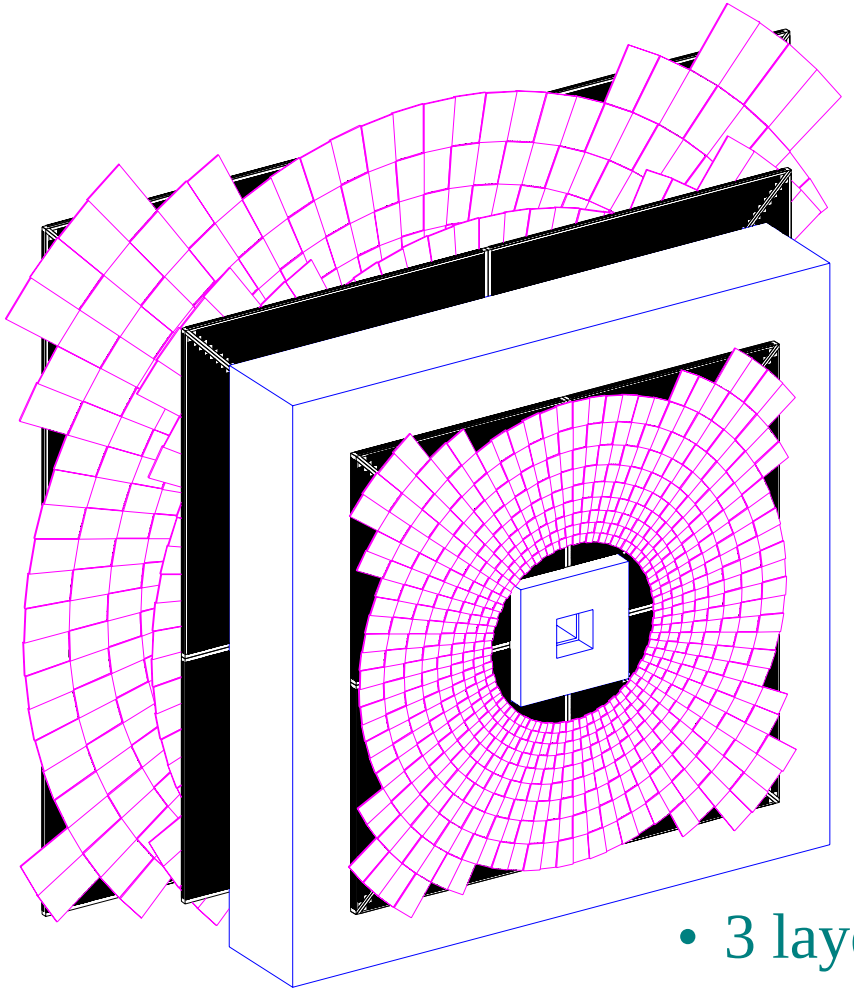
- 2 X_0 pre-radiator (solenoid + lead)
- Triangular scintillator strip layers
  - central: 3 layers (axial + 20° stereo u-v)
  - forward: 4 layers (22.5^o stereo u-v)

DØ Central Muon Scintillators

A-ϕ Counters

- 630 scintillation counters
- ($\Delta\eta$ x $\Delta\phi$ = 0.2 x 4.5°)
- full coverage in the central region
- allow low p_T muon triggers
  - pT > 1.5 GeV/c

The DØ Forward Muon System



- 3 layers of high granularity mini drift tubes
  - position resolution of ~ 350 μm
- 3 scintillator pixel layers
  - ($\Delta\eta$ x $\Delta\phi$ = 0.1 x 4.5°)

DØ Upgraded Detector Performance

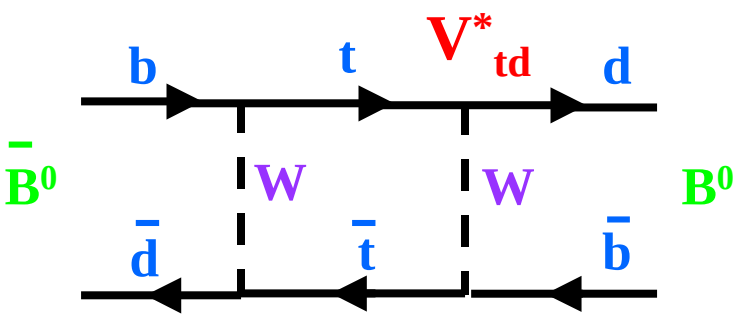
- Good Momentum resolution:
  - $dp_T/p_T^2 = 0.002$ (Silicon + Fiber tracker)
- High tracking efficiency:
  - at least 95 % $|\eta| < 3$ (Silicon disks)
- Vertex Reconstruction:
  - primary vertex: $\sigma^{vertex} = 15\text{-}30\ \mu m$ (r-ϕ)
  - secondary vertex: $\sigma^{vertex} = 40\ \mu m$ (r-ϕ) , $80\ \mu m$ (r-z)
- Excellent lepton coverage trigger and ID efficiency:
  - muons: $p_T > 1.5$ GeV, $|\eta| < 2$
  - electrons: $p_T > 1$ GeV, $|\eta| < 2.5$
- Impact parameter trigger

CP Violation in *B* Decays

Flavor oscillations in the neutral *B* system

$$B^0 = \bar{b}d \qquad |B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle \qquad \Delta M_B = M_H - M_L \qquad \frac{\Delta\Gamma_B}{\Gamma_B} \approx O(10^{-2})$$

$$\bar{B}^0 = b\bar{d} \qquad |B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle \qquad \Delta\Gamma_B << \Delta M_B$$

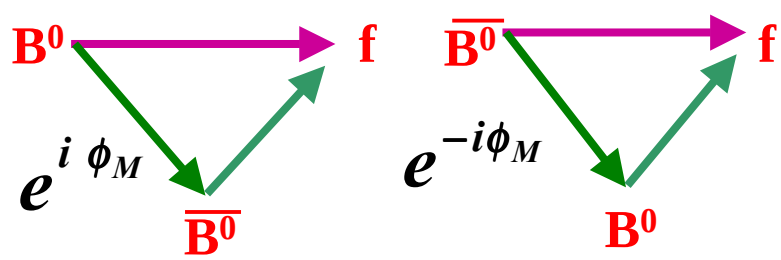


$$A(B_d \to \bar{B}_d) \propto m_t^2 V_{td}^2 \approx |A|\, e^{i2\beta}$$

$$A(\bar{B}_d \to B_d) \propto m_t^2 V_{td}^{*2} \approx |A|\, e^{-i2\beta}$$

Direct and mixed decays interfere with different amplitudes - leading to different decay rates into the same CP eigenstate:

CP VIOLATION



Sin(2β) via $B \to J/\psi + K_S$

Asymmetry is directly related to sin2β:

$$A_{CP}(t) = \frac{\Gamma\left(\overline{B^0} \to J/\psi K_S^0\right) - \Gamma\left(B^0 \to J/\psi K_S^0\right)}{\Gamma\left(\overline{B^0} \to J/\psi K_S^0\right) + \Gamma\left(B^0 \to J/\psi K_S^0\right)}$$

$$= \sin[2(\phi_M - \phi_D)]\sin \Delta m_d t = \sin(2\beta)\sin(\Delta m_d t)$$

$$\sin 2\beta = \mathrm{Im}\left[-\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*}\right)\left(\frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}\right)\right] = \frac{2\eta(1-\rho)}{\eta^2(1-\rho)^2}$$

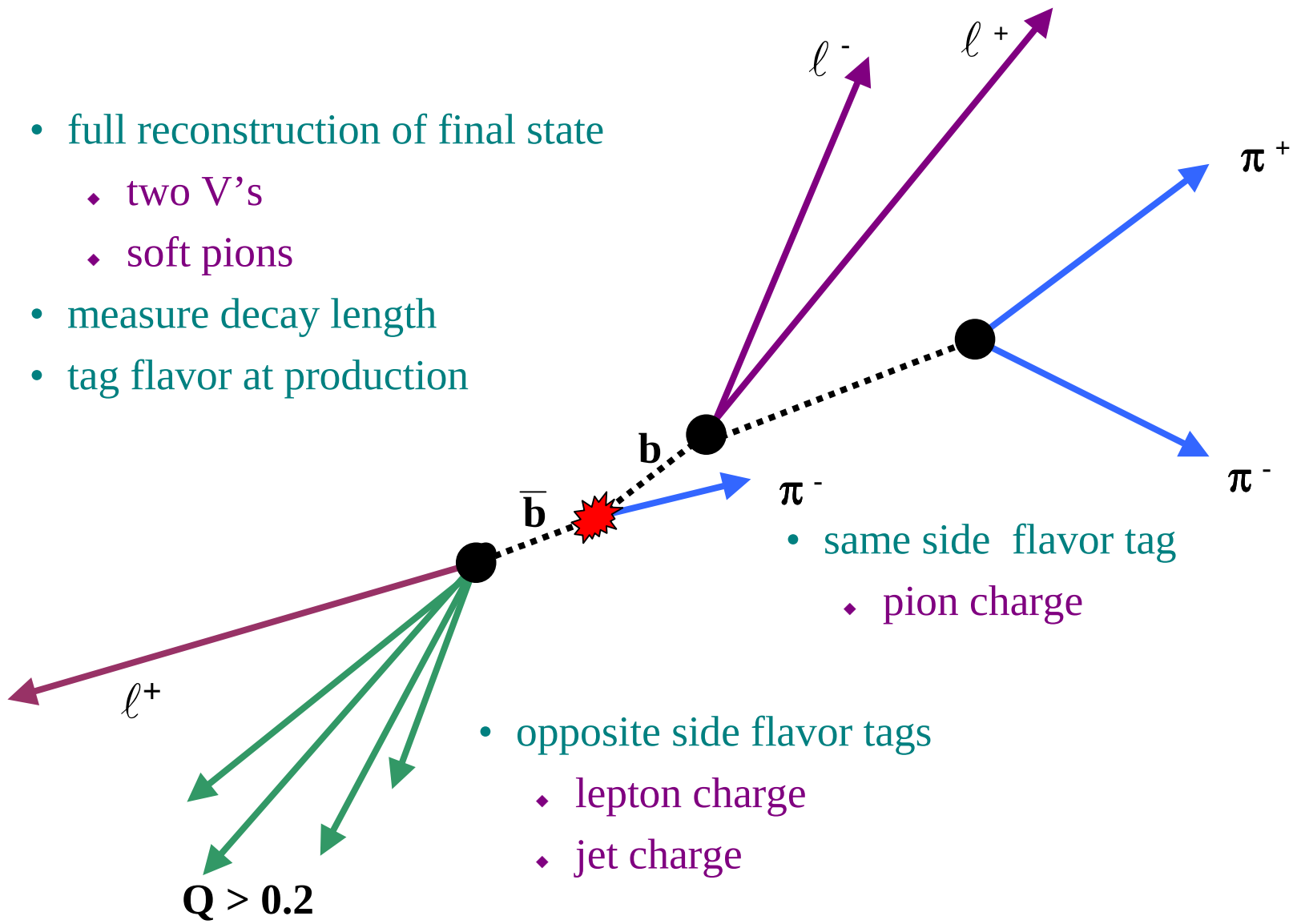
B^0 $\overline{B}^0$ Mixing

Ratio of $\frac{\overline{A}(f)}{A(f)}$

K^0-$\overline{K}^0$ mixing

Sin(2β) via $B \rightarrow J/\psi + K_S$

- full reconstruction of final state
  - two V's
  - soft pions
- measure decay length
- tag flavor at production



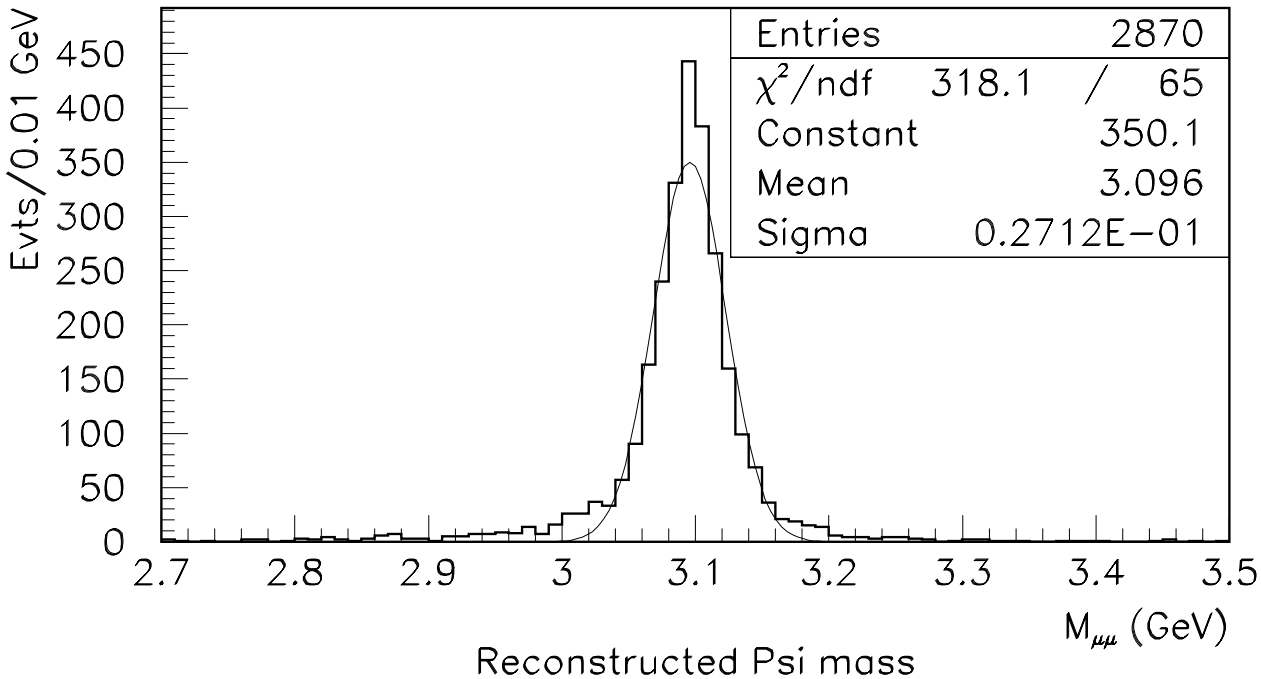
- same side flavor tag
  - pion charge

- opposite side flavor tags
  - lepton charge
  - jet charge

$B \rightarrow J/\psi K_S$ Reconstruction

$J/\psi \rightarrow \mu^+\mu^-$

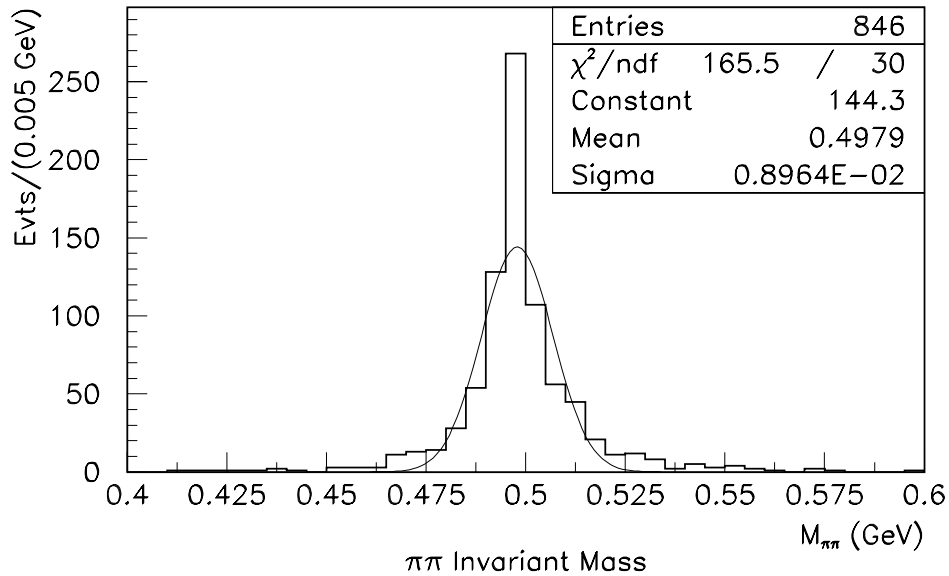
- two muon tracks
  - $p_T > 1.5$ GeV/c
  - $|\eta| < 2$



$B \rightarrow J/\psi K_S$ Reconstruction

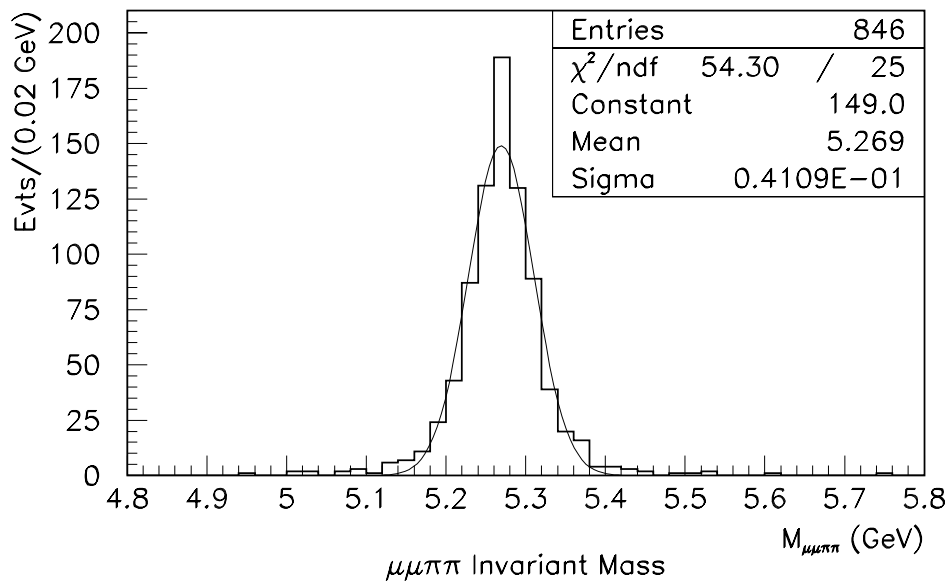
$K_S \rightarrow \pi^+\pi^-$

- $p_T(\pi) > 0.45$ GeV/c
- $p_T(K_S) > 0.75$ GeV/c
- $|\eta_\pi| < 1.8$
- $L_{xy}/\sigma > 5$



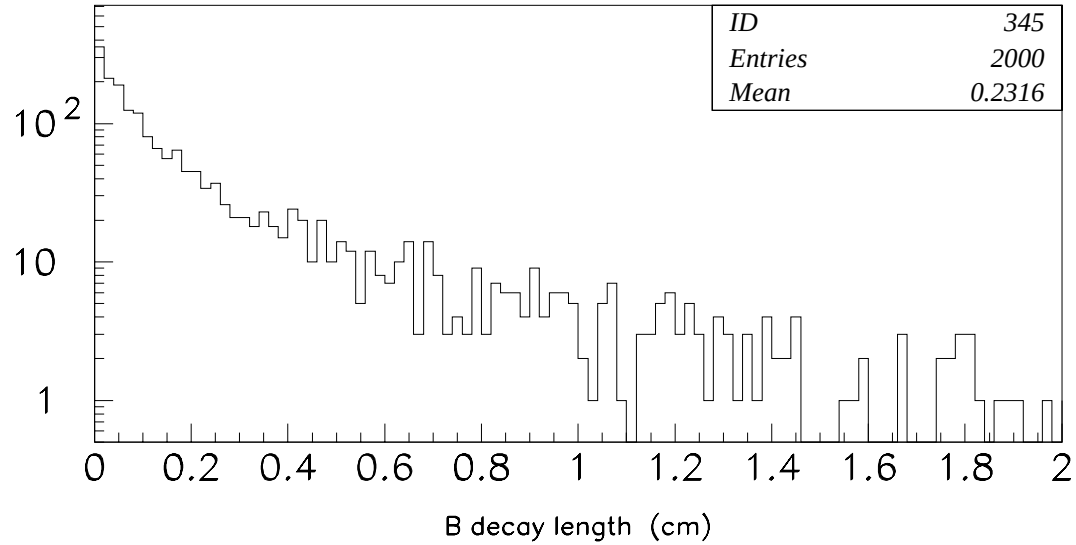
Combined $\mu^+\mu^-\pi^+\pi^-$ *invariant mass*

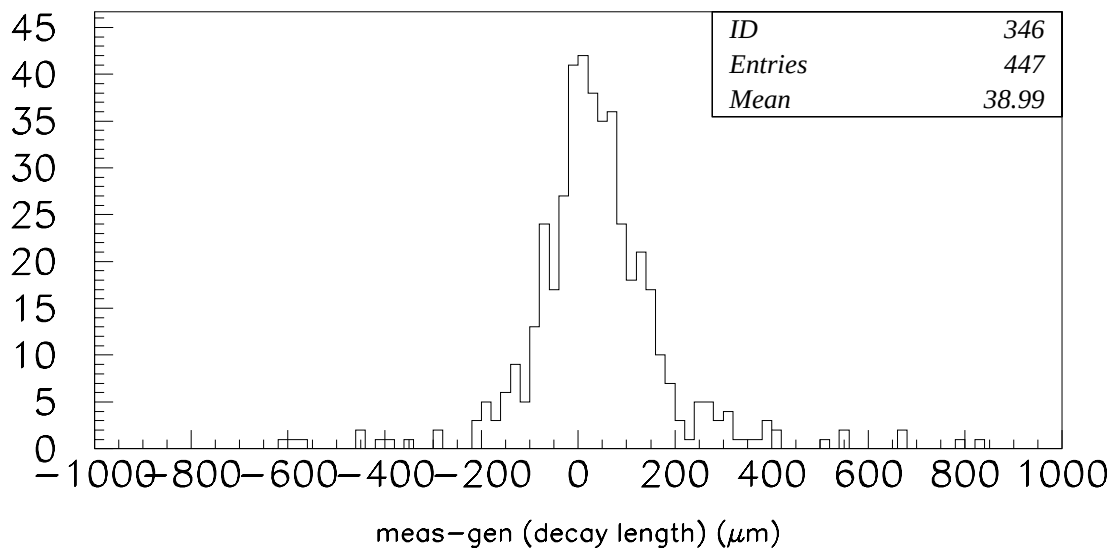
(before fit)



$B \rightarrow J/\psi K_s$ decay length reconstruction

- Two secondary two-track vertices
- Average B decay length: 2.3 mm
- Measured decay length resolution: 100 μm



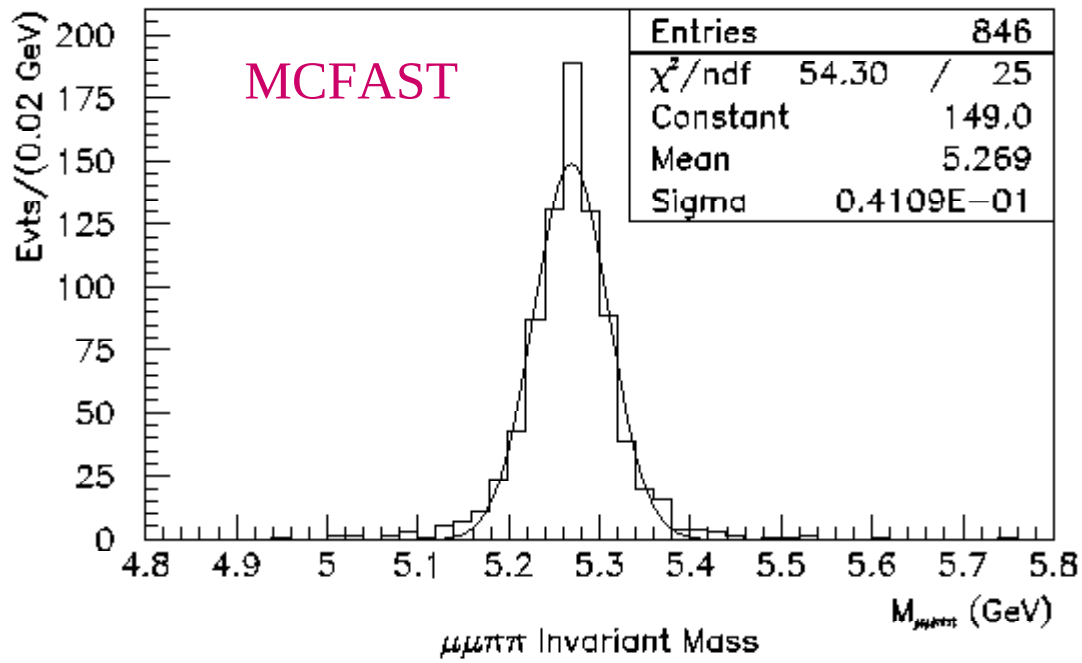


$B \rightarrow J/\psi\ K_S$ Reconstruction

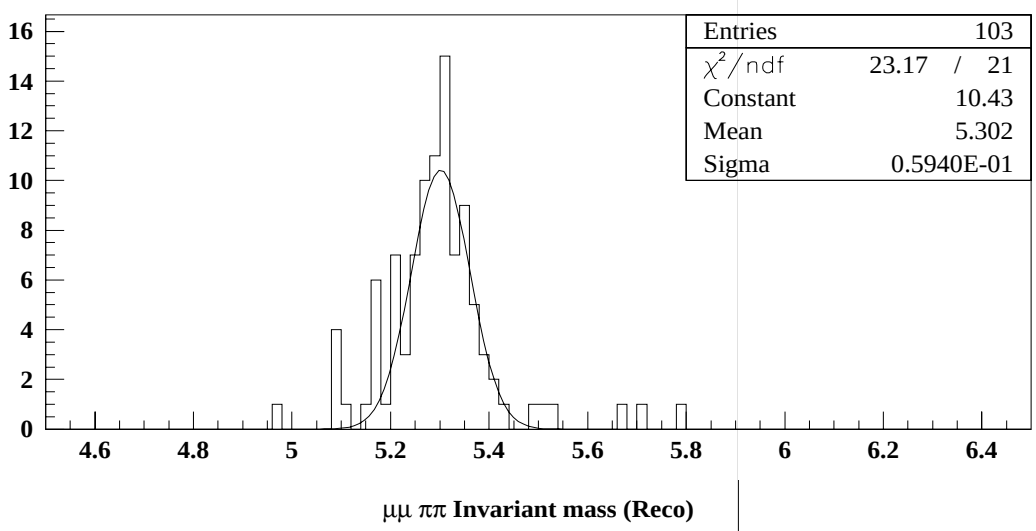
Combined $\mu^+\mu^-\pi^+\pi^-$ *invariant mass*

(before fit)

MCFAST

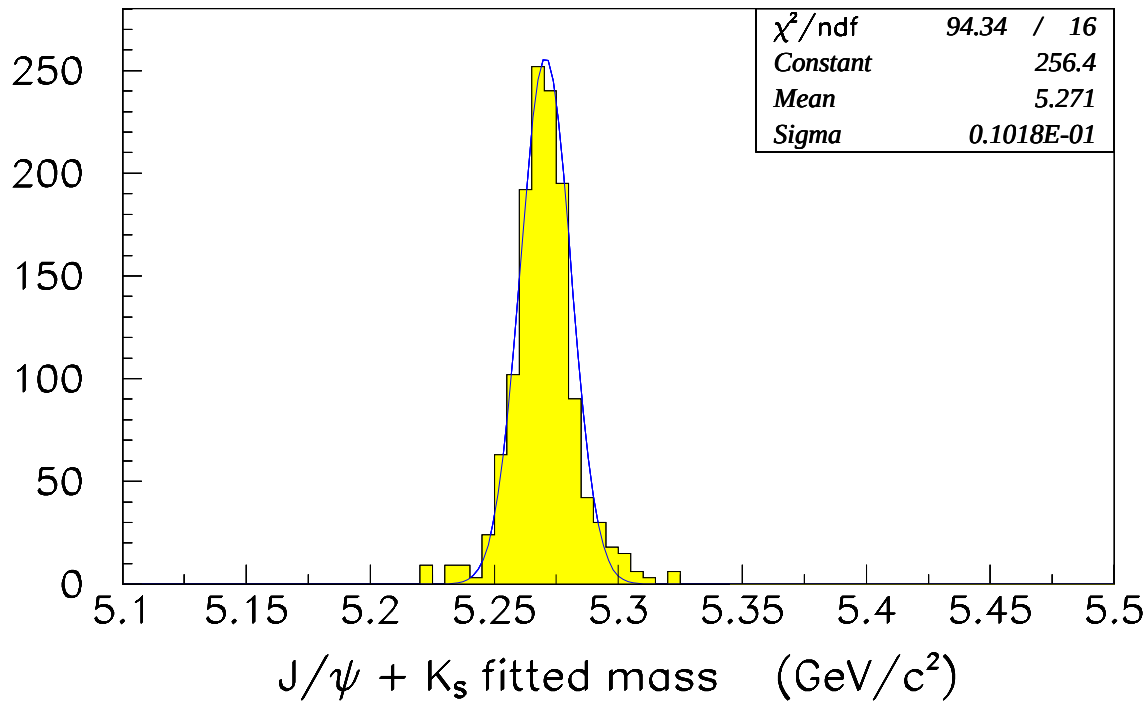


RECO



$B \rightarrow J/\psi K_S$ Reconstruction

- $J/\psi \rightarrow \mu^+\mu^-$ require two central tracks with $p_T > 1.5$ GeV/c
- $K_S \rightarrow \pi^+\pi^-$ use long lifetime to reject background: $L_{xy}/\sigma > 5$
- Perform 4-track fit assuming $B \rightarrow J/\psi + K_S$
  - constrain $\pi\pi$ and $\mu\mu$ to mass of K_S and J/ψ respectively
  - force K_S to point to B vertex and B to point to primary



Flavor Tagging

Opposite side tags:

- identify the flavor of the other B in the event
  - soft lepton tags $b \rightarrow l^- + X$
  - jet charge tags $Q_{jet} < 0$ for b

Efficiency (ε) and dilution factor (D)

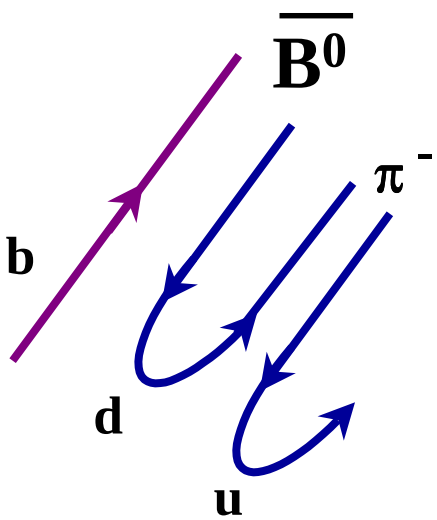
$D = 2P - 1$

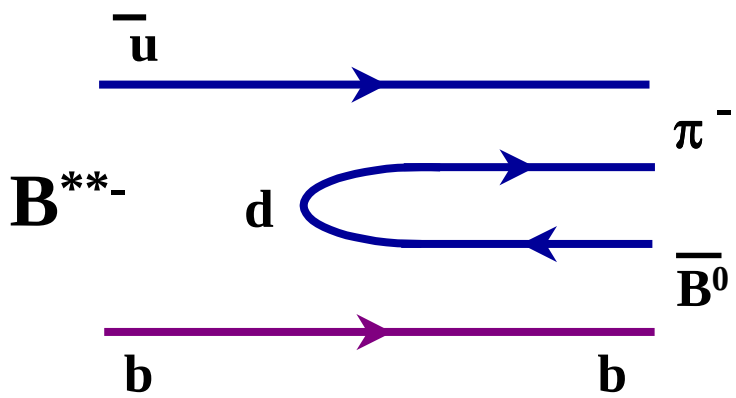
P is the correct tag probability

εD^2 is the tag's effectiveness

Same side tags:

- correlation of flavor and charge of closest particle produced in fragmentation or decay





Flavor Tagging

Tag	εD^2 (%) measured CDF Run I	εD^2 (%) expected CDF Run II	Relevant DØ difference	DØ capabilities
Same side	$1.8 \pm 0.4 \pm 0.3$	2.0	same	2.0
Soft lepton	$0.9 \pm 0.1 \pm 0.1$	1.7	μ , e ID coverage	3.1
Jet charge	$0.8 \pm 0.1 \pm 0.1$	3.0	forward tracking	4.7
Opp. side *K*		2.4	no K ID	none
Combined		9.1		9.8

How many events will we get ?

$$\sigma_{b\bar{b}} = 3.3 \times 48\,\mu b = 158\,\mu b$$

$$f(b \to B_d) = 0.42$$

$$\text{Acceptance} \quad : \mathrm{P}_T(B) > \mathbf{4\ GeV/}\ \boldsymbol{c}\ , |\, y(B) \,| < 3.0 = 31\%$$

$$\sigma_B = \boldsymbol{\sigma}_{b\bar{b}} \cdot f \cdot \boldsymbol{Acc} = 21\mu b$$

$$BR = BR(B \to J/\psi + K_s, J/\psi \to \mu^+\mu^-, K_s \to \pi^+\pi^-)$$

$$= (5 \times 10^{-4})(0.06)(0.68) = (2 \times 10^{-5})$$

$$\varepsilon_{trigger} = 0.27$$

$$\varepsilon_{reco} = 0.09$$

$$N = L \cdot 2 \cdot \sigma_B \cdot BR \cdot \varepsilon_{\text{trigger}} \cdot \varepsilon_{reco} = 40\mathbf{K}$$

assuming luminosity ~ 2 fb^{-1}

Sin(2β) Expectations for 2 fb^{-1}

For a ***time dependent*** analysis:

$$\sigma(\sin 2\beta) \approx e^{x_d^2 \Gamma^2 \sigma_t^2} \sqrt{\frac{1+4x_d^2}{2x_d}} \frac{1}{\sqrt{\varepsilon D^2 N}} \sqrt{1+\frac{B}{S}}$$

DØ:

- **(S/B ~ 0.75)**
- **εD^2 ~ 9.8 %**
- **Time resolution**

  σ_t ~ 100 fs

mode	$J/\psi \to \mu^+\mu^-$	$J/\psi \to e^+e^-$
trigger eff. (%)	**27**	**20**
reco'd events	**40,000**	**30,000**
$\sigma(\sin 2\beta)$	**0.04**	**0.05**
	0.03	

- assuming luminosity ~ 2 fb^{-1}
- DØ and CDF have similar precisions

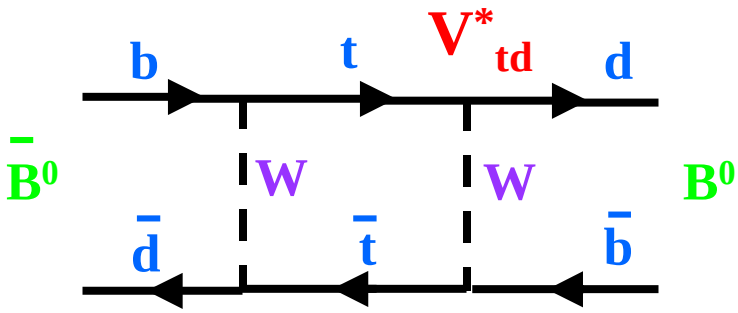
New Director - New Run II Plan

- No long shutdowns
- Gradual luminosity improvements as we run
- Run until LHC results tell us to stop
- 3 (or more) fb^{-1} per year at peak

L (fb^{-1})	Number of $B \rightarrow J/\psi K_S$	$\sigma(\sin 2\beta)$
2	34 K	0.04
5	85 K	0.03
10	170 K	0.02
20	340 K	0.01

Neutral B Meson Flavor Oscillations

Neutral *B* meson oscillates due to 2nd order weak interaction:



If initial state is B_q,

$$P(B_q) = \tfrac{1}{2}\Gamma e^{-\Gamma t}(1+\cos\Delta m_q t)$$

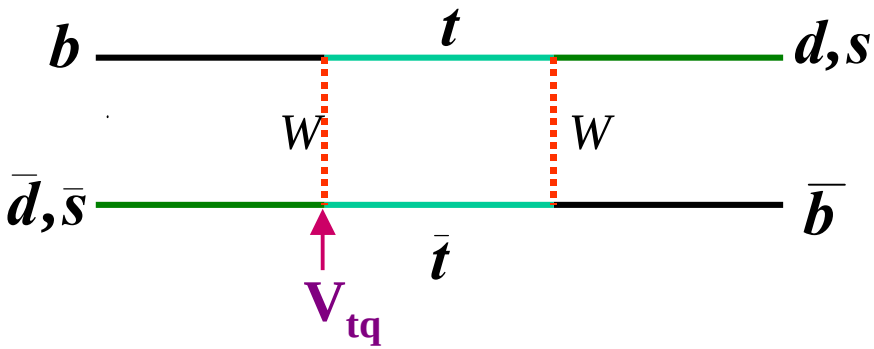
$$P(\overline{B}_q) = \tfrac{1}{2}\Gamma e^{-\Gamma t}(1-\cos\Delta m_q t)$$

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle \qquad \Delta M_B = M_H - M_L \qquad \Delta\Gamma_B = \Gamma_L - \Gamma_H$$

$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle \qquad \Delta\Gamma_B << \Delta M_B \qquad \frac{\Delta\Gamma_B}{\Gamma_B} \approx O(10^{-2})$$

- The mixing of B_q and $\overline{B}_q$ is governed by Δm_B and $\Delta\Gamma_B$
- Mixing parameter $x_B = \Delta m_B/\Gamma_B$

Neutral B Meson Flavor Oscillations



- oscillation frequency $\Delta m_q \propto |V_{tb}^* V_{tq}|^2$
- since $V_{ts} >> V_{td}$, B_s oscillates faster than B_d
- $$\frac{|V_{td}|}{|V_{ts}|} = (1.16 \pm 0.06) \bullet \sqrt{\frac{\Delta m_d \bullet m(B_S)}{\Delta m_S \bullet m(B_d)}}$$

- An observable value of $\Delta\Gamma_{B_S}$ is expected in SM
- Since B_s mesons are not produced on the $\Upsilon(4s)$, this physics will be unique to hadron colliders;

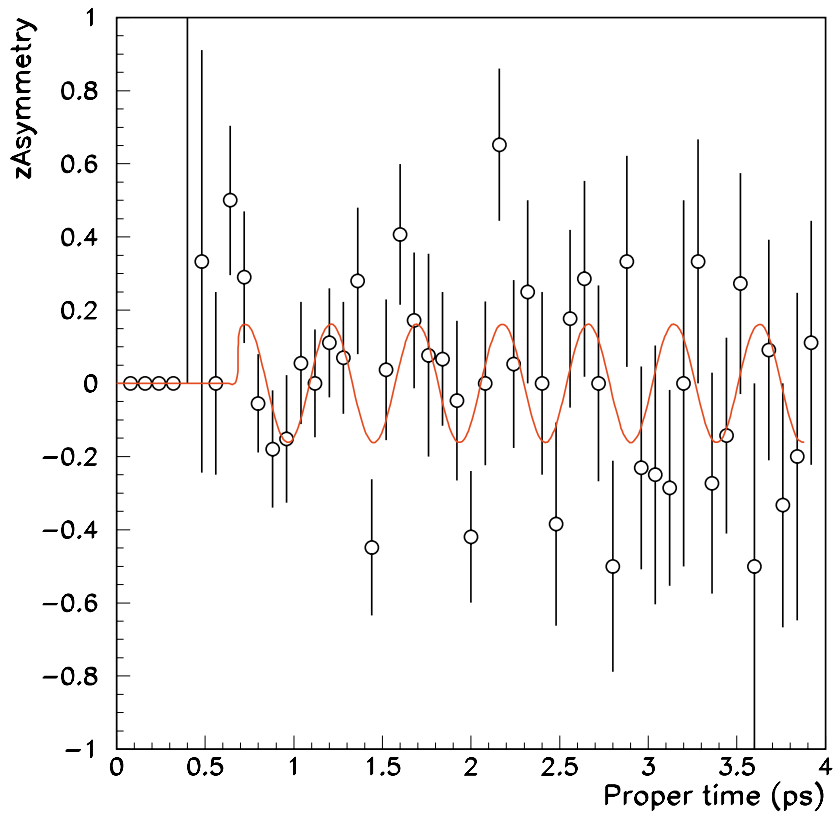
B_S Mixing at DØ

Use fully reconstructed events

- $B_S \rightarrow D_S \pi^+$ 100 - 300 events
- $B_S \rightarrow D_S \pi^+\pi^-\pi^+$ 300 - 900 events
  - $D_S \rightarrow \phi\pi \rightarrow KK\pi$
  - final flavor tagged by charge of the D_S
  - hadronic modes require lepton from opposite b for trigger - sign gives initial flavor
- $B_S \rightarrow J/\psi + K^*$ 300 - 1000 events
  - easier trigger
  - initial flavor tag $\varepsilon D^2 \sim 7$ %
  - final flavor tagged by charge of K in $K^* \rightarrow K^+\pi^-$ - $\varepsilon D^2 \sim 90$ %

Amplitude fit of B_S oscillation frequency

Generated x_s = 20, smeared



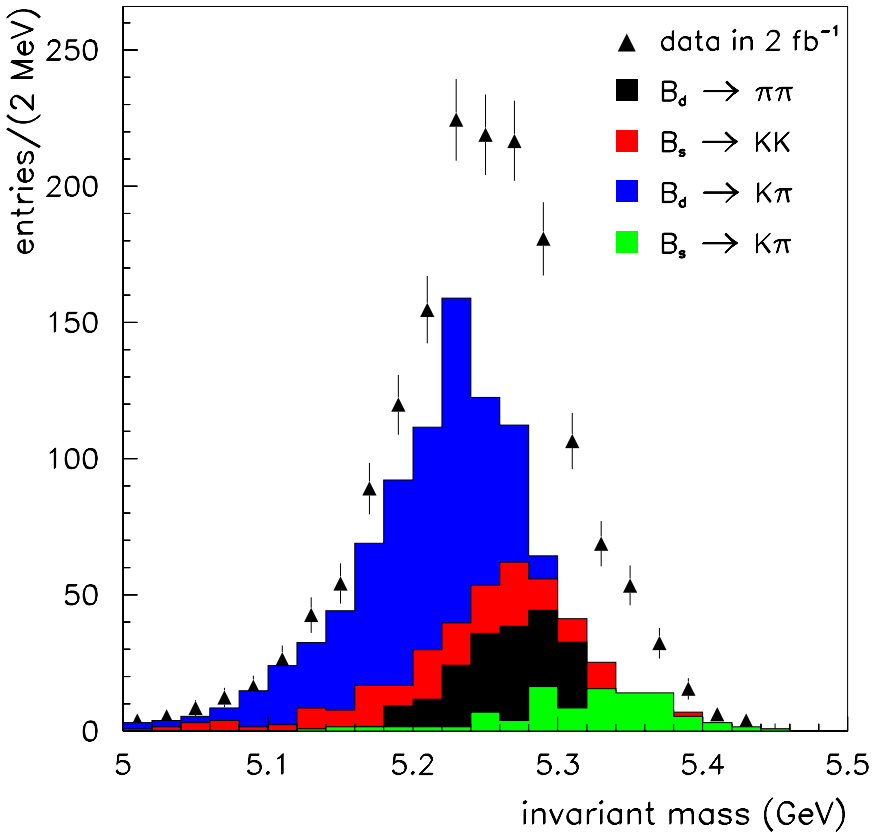
- DØ can measure x_S values up to 20 - 30 in 2 fb^{-1}
- further study is needed to determine our maximum reach

$B \rightarrow \pi^+ \pi^-$ at DØ

- We must trigger on a lepton from the other B in the event
  - require: 1 lepton pT > 3 GeV and two other tracks with pT > 1.5 GeV
  - total detection efficiency is between 0.25 - 0.5 %

expected tagged events:

$B_d \rightarrow \pi^+ \pi^-$	300 - 600
$B_s \rightarrow K^+ K^-$	650 - 1300
$B_d \rightarrow K^+ \pi^-$	1300 - 2600
$B_s \rightarrow K^+ \pi^-$	150 - 300



Conclusions

DØ is poised to make significant beauty physics measurements in Run II. We will begin to take data in the spring of 2001 and in 2 years (2 fb^{-1}) we will:

- continue QCD studies
- measure $\sin 2\beta$ to an accuracy of 0.04
- measure (or put a limit on) Bs mixing up to $x_s \sim 30$
- put limits on other CKM angles α , γ
- measure Λ_b lifetime in exclusive decays
- rare decays, heavy baryons, ...