CP Physics With b Quarks At e^+e^- Colliders

Lecture Two

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Outline

- Rare decays
  - $K\pi/\pi\pi$
- Event selection at the Y(4s)
  - Decay kinematics
  - Continuum suppression
  - Yield estimates
- Program at Asymmetric Machines
  - BaBar/BELLE
    - Effects of boost
    - Reconstructing K_L's
    - Particle ID

B Physics at the Υ(4s)

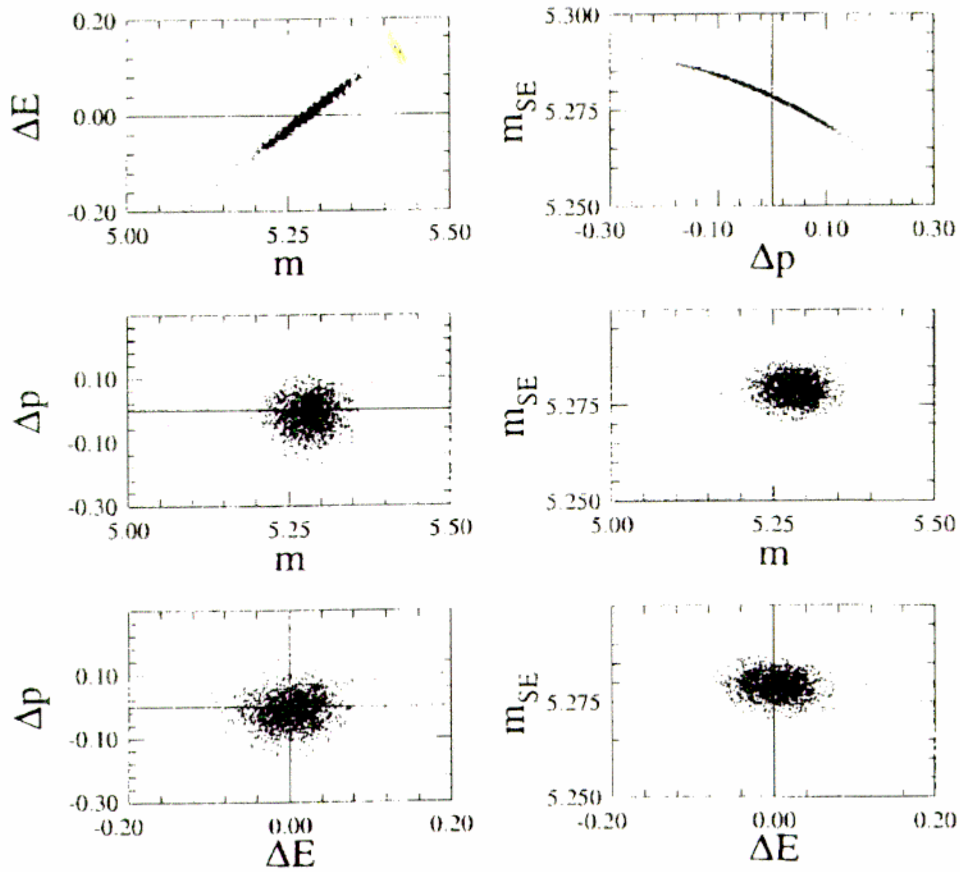
- Many important branching fractions for CP measurements have already been studied
- Many of them involve two-body or quasi-two body (two body via resonances) decays
  - These decays have very nice kinematic signatures in the B rest frame - two back to back particles
- Depending on the cleanliness of the channel there are a variety of techniques which can be used to isolate the signal at the Υ(4s)
  - Kinematic variables such as ΔE, substitute energy mass
  - Continuum suppression tools
    - » Shape variables
    - » Continuum subtraction using scaled off resonance data (from below Υ(4s))
      - No B mesons so can only accidentally make a “signal” event
  - We will see the importance of particle ID and track momentum resolution……

Technique - kinematic constraints (Υ(4s))

- Knowing that B's come from the decay $\Upsilon(4s) \rightarrow \bar{B}B$ adds information
  - Energy of B in Υ(4s) CM is same as single beam energy in CM
  - If a B meson is fully reconstructed, know the particle types and therefore the masses of decay products and so can uniquely boost these into the Υ(4s) CM to get the four momentum of the B
    - » $P=(p_x,p_y,p_z,E)$
      - Can use these components to suppress background
      - $\cos\theta = p_z/p$ ($p=|\mathbf{p}|$, z is along beam axis) weakly suppresses background since signal is distributed as $(1-\cos^2\theta)$ and continuum background follows a $(1+b\cos^2\theta)$ distribution where typically $b \sim 1$
      - Strongest background suppression comes from using E,p - can select functions to reduce correlations...

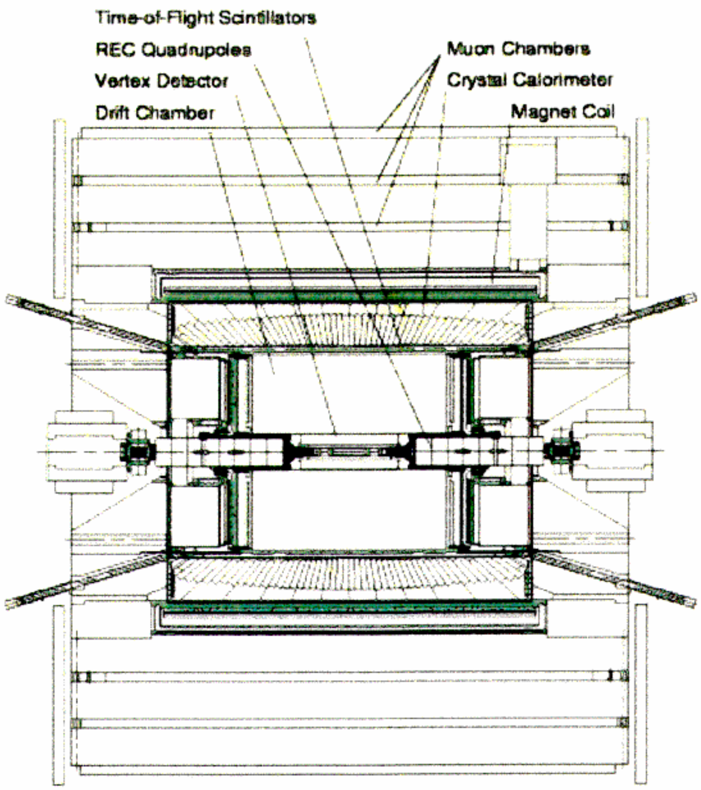
- E,p depend on beam energy (E_{beam})
  - Experience at Doris,CESR is that E_{beam} can shift with time
    - » intentionally, e.g. during scans of peak
    - » unintentionally, e.g. due to hardware changes, fluctuations in run conditions
  - Can avoid the need to know the beam energy by transforming $E \rightarrow \Delta E \equiv E - E_{beam}$ which gives a distribution centered around zero and easy to understand.
  - Have the choice of one more independent variable - choose one that is not strongly correlated
    - » Beam-constrained mass (though not using a constrained fit) or better, Substituted Energy mass (m_{SE}). Since momentum so small, the resolution is dominated by the beam energy spread (about 2.7MeV at CESR)

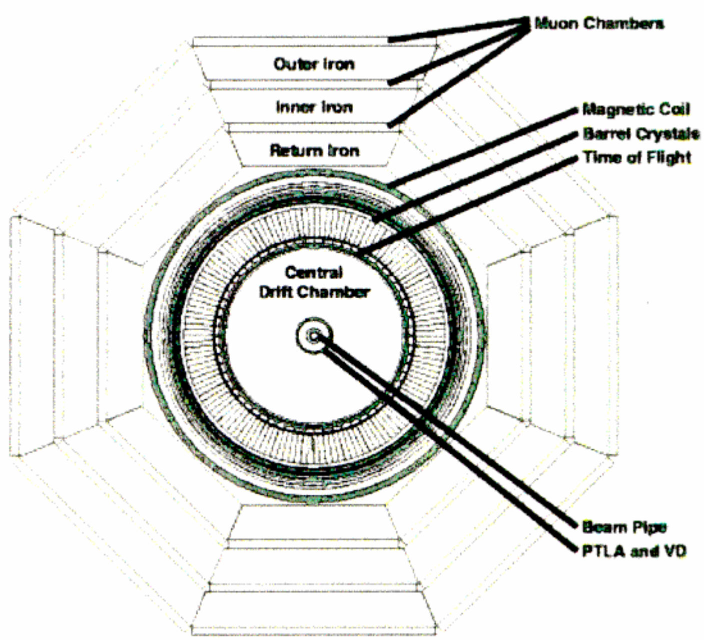
$$m_{SE} = \sqrt{E_{beam}^2 - p^2}$$



Correlations between possible kinematic variables

CLEO detector views





P. Rankin, SSI 1999

9 - 95 Cleo $\overline{\underline{II}}$ → 5 fb^{-1}

2:1 ~ 1.4 fb^{-1} 10^6 $B^{\pm}$

10^6 $\overset{(-)}{B}{}^0$

50-50 Ar - Ethane

5-98 Cleo II.V 9 fb^{-1}

60-40 He - Propane C_3H_8

SVT

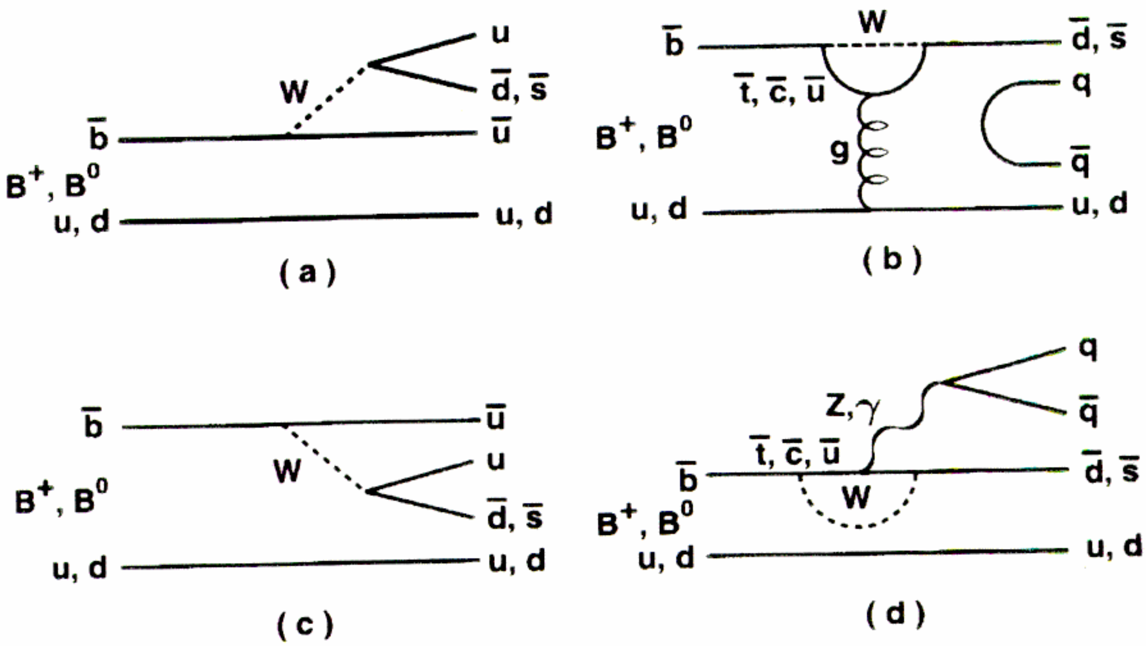
22 pb^{-1} / 440 pb^{-1} month.

↓

Cleo $\overline{\underline{III}}$ RICH → Sept '99

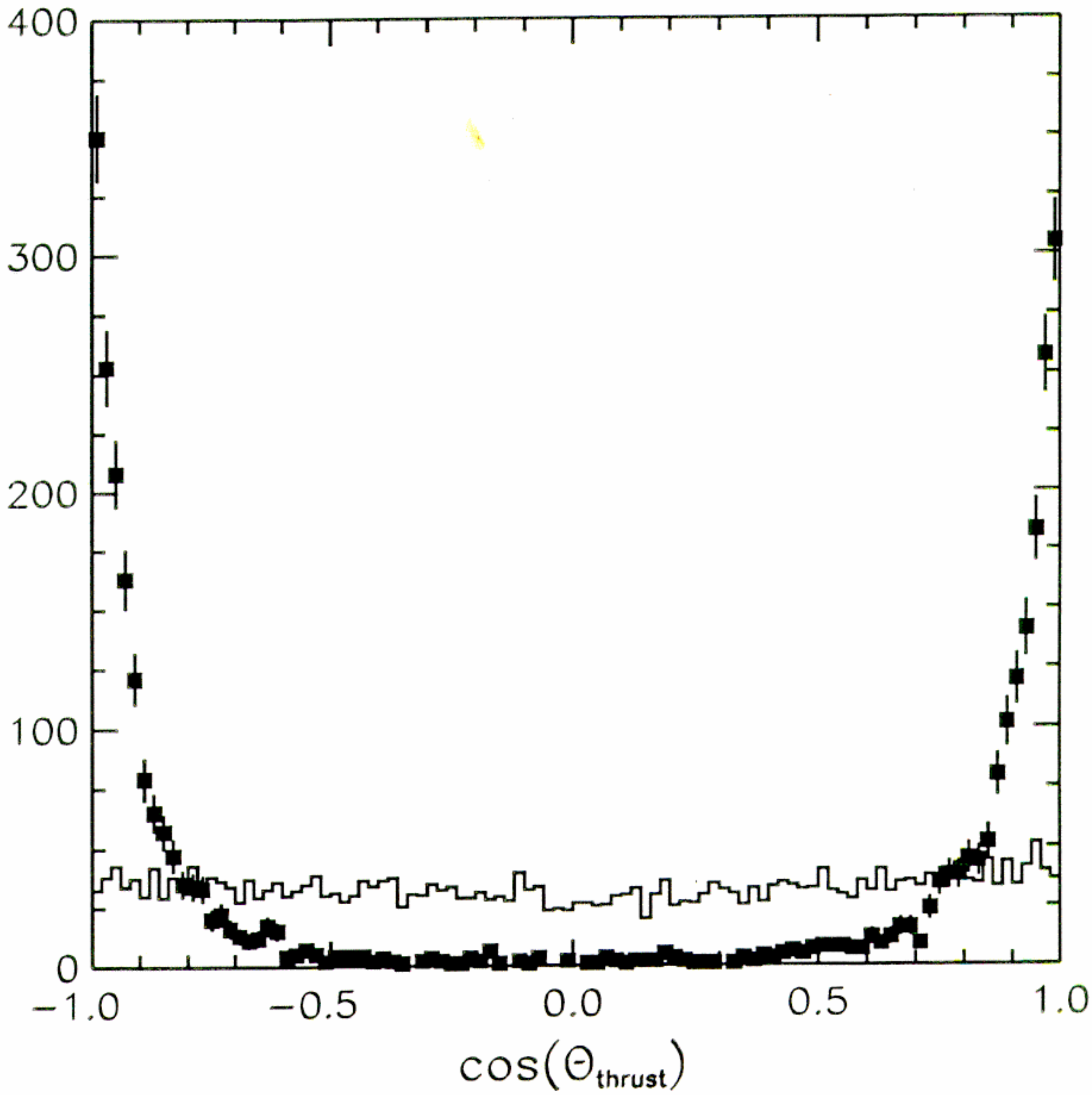
B→ Kπ/ππ

- Possible Decay Processes
  - (a) external W emission
  - (b) gluonic penguin
  - (c) internal W emission
  - (d) external electroweak penguin



$K\pi/\pi\pi$ Which Dominates?

- Easy to use shape cuts to separate signals from the background
- Hard to separate signals
  - Kinematic separation of these two decay modes is difficult
    - » For CLEO II and CLEO II.5 resolutions, the separation of the two mass peaks corresponds to about 1.6σ and 1.9σ respectively for two charged tracks
      - Harder if decay involves a π^0 since ΔE resolution is about a factor of two worse and is asymmetric because of energy loss out of the back of the CsI crystals
  - Particle ID using dE/dx for tracks at 2.6 GeV/c (Relativistic rise region) gives some separation between $K^{\pm}/\pi^{\pm}$
    - » About 1.7σ for CLEO II, about 15% better for the upgraded detector (uses a helium-propane based gas in drift chamber)



8''

$B \to K^{\pm}\pi^{\mp}$, CLEO

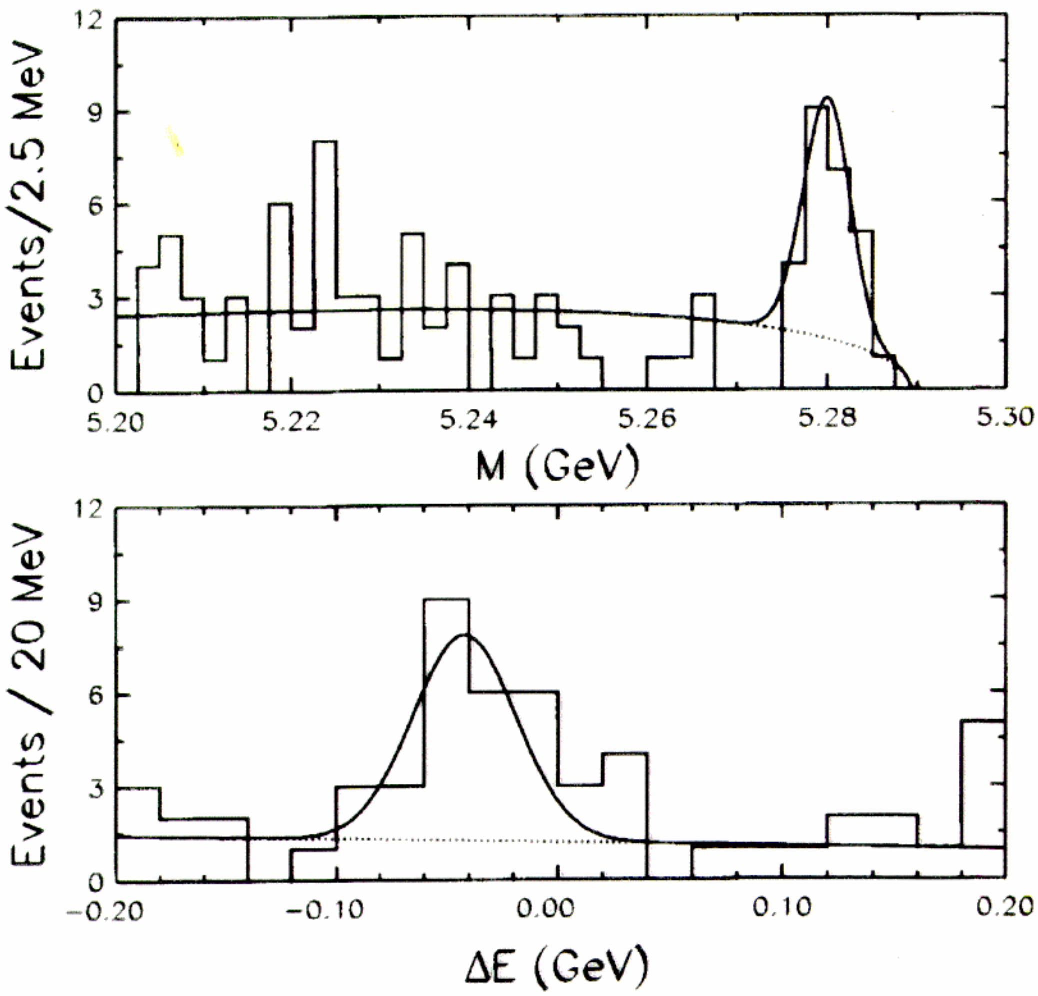


FIG. 5. Projection plots in $B \to K^+\pi^+$.

(What mass hypotheses where used to make ΔE plot?)

$B \to K_s\pi^\pm$, CLEO

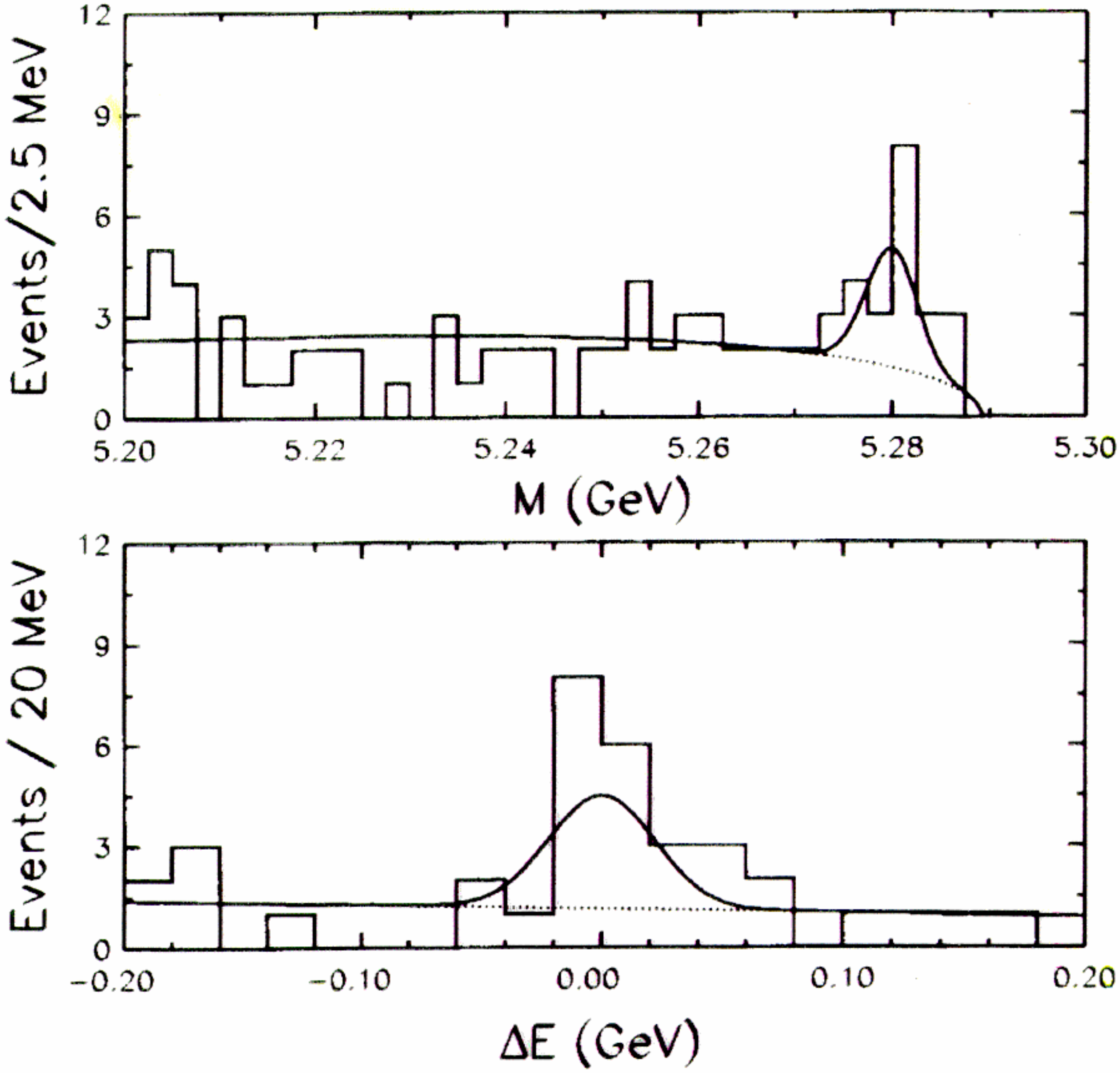


FIG. 7. Projection plots in $B^\pm \to K_S^0\pi^\pm$.

$B \to K^{\pm}\pi^{0}$, CLEO

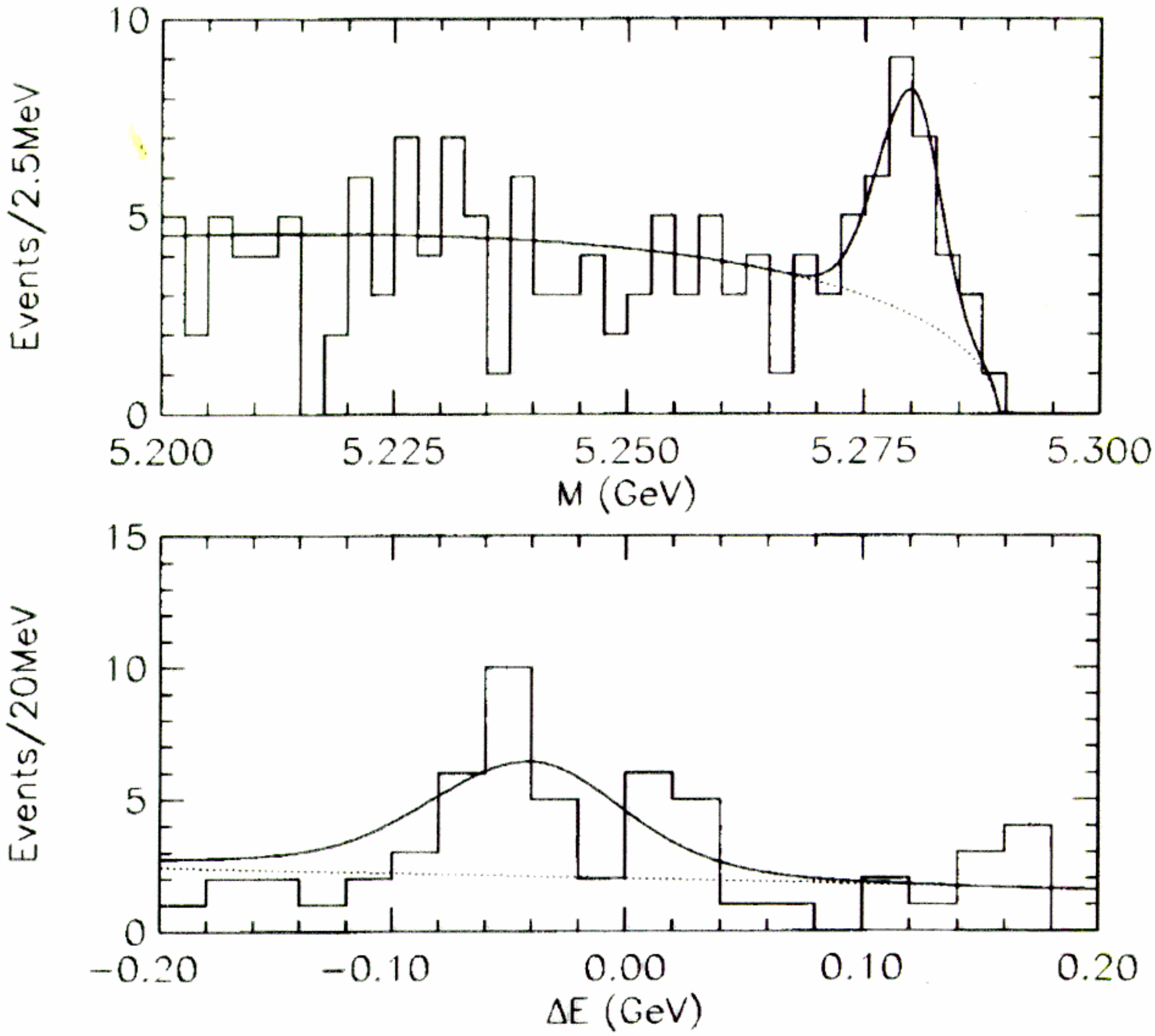
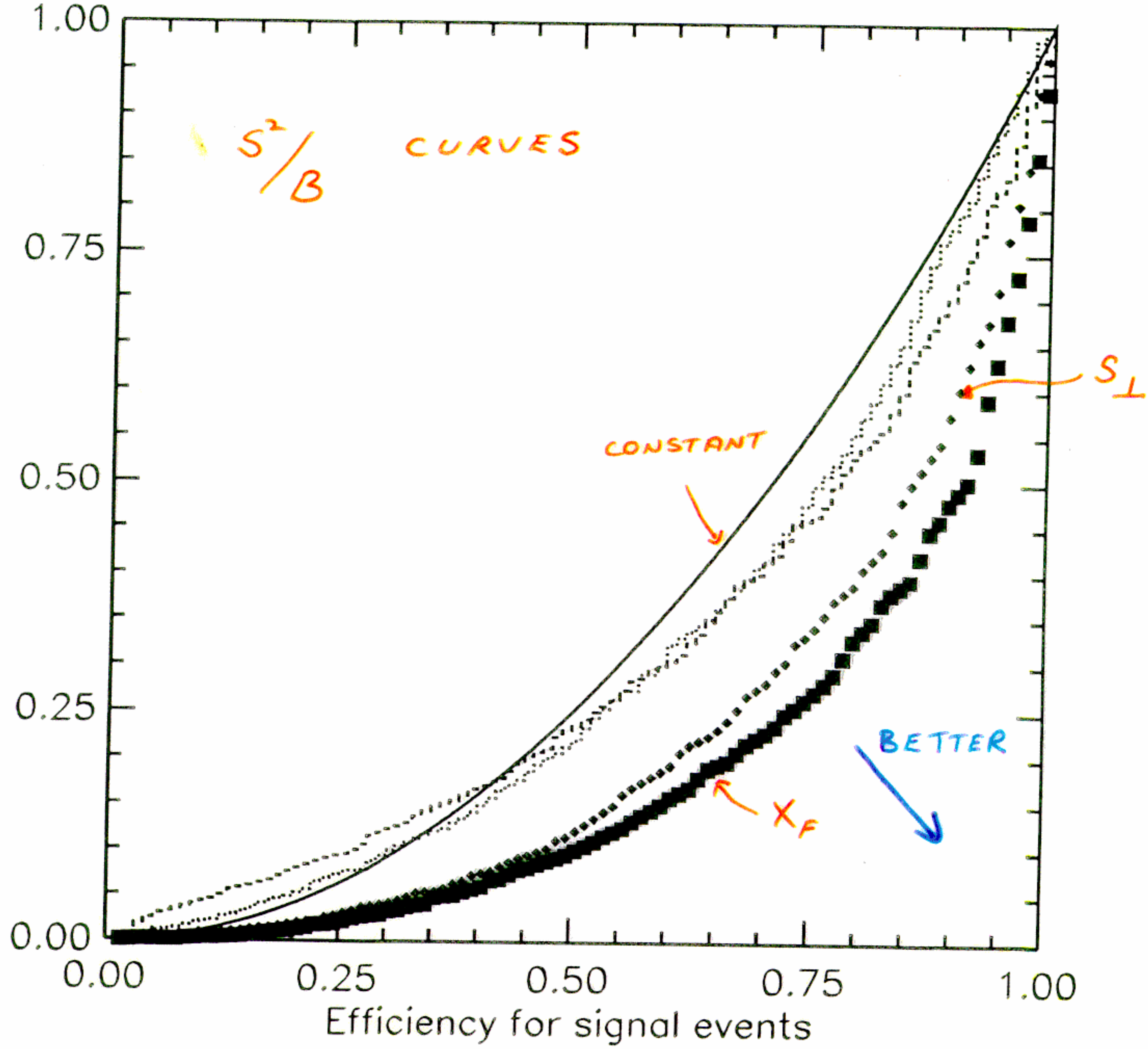


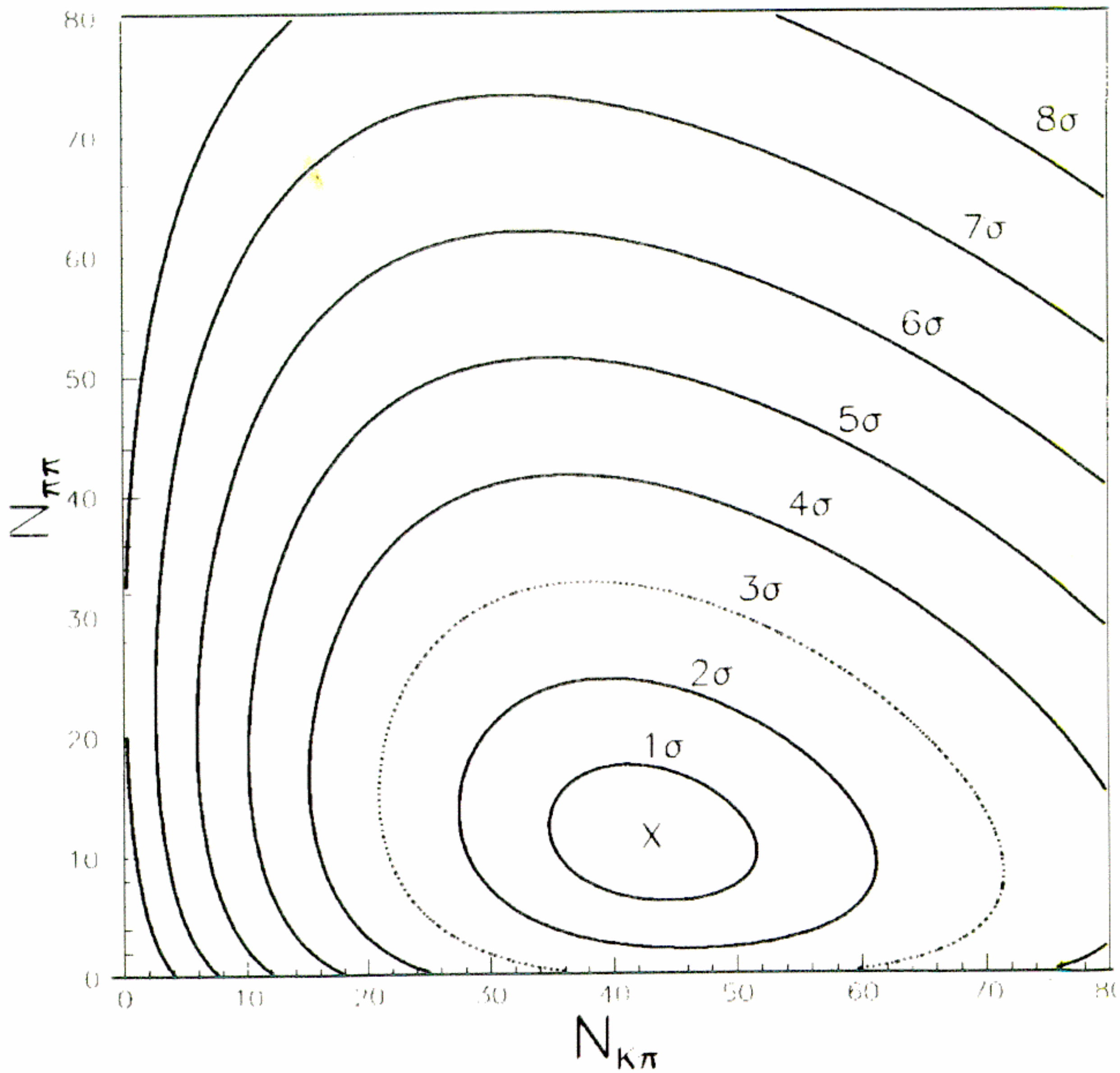
FIG. 6. Projection plots in $B^{\pm} \to K^{\pm}\pi^{0}$.

Technique - Signal Yield Extraction

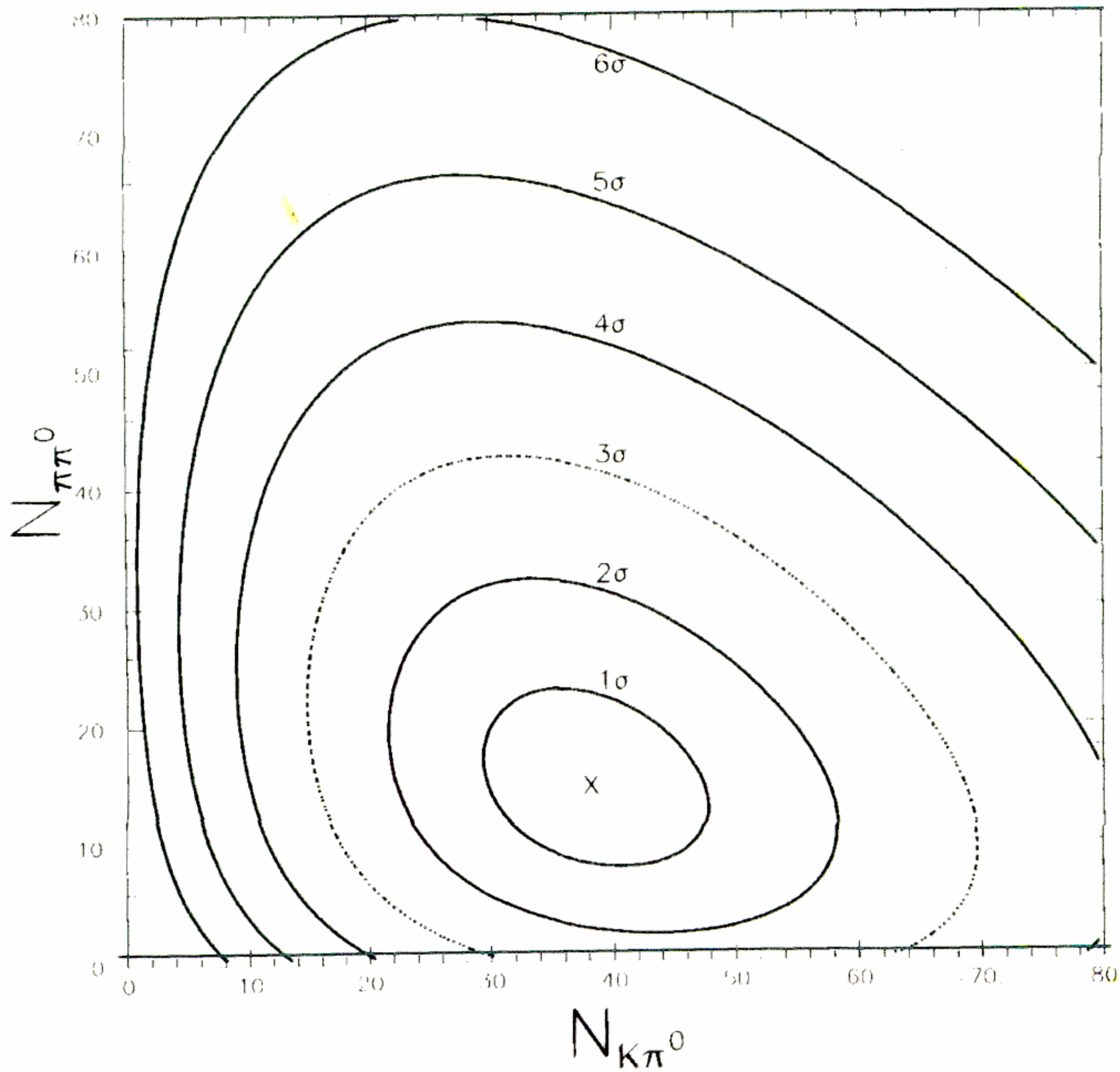
- Extraction of signal yield is done by performing an unbinned maximum-likelihood (ML) fit using
  - ΔE, M and dE/dx
  - Angle between B meson momentum and beam axis - $|\cos\theta_B|$
  - F, Fisher discriminant, - a variable chosen to maximize the separation of signal and continuum background
- Fit for each charged topology
  - likelihood of event parameterized by the sum of the probabilities for all relevant signal and background hypotheses
    - » Relative weights determined by maximizing the likelihood function (L)
    - » Probability of a particular hypothesis the product of the probability density functions (PDF) for input variables, estimated using MC, independent data samples (limited statistics dominate uncertainties)

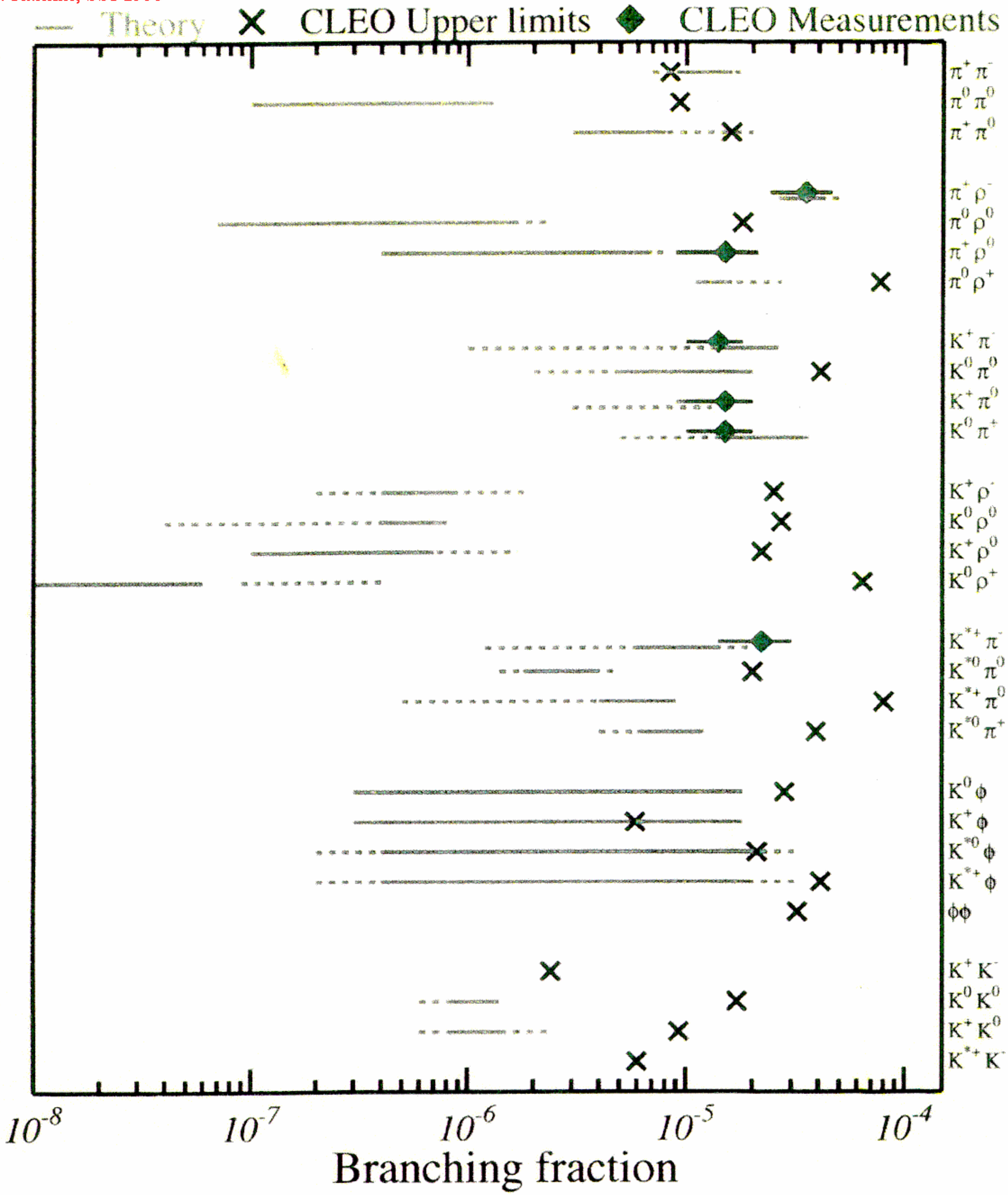

1.00
0.75
0.50
0.25
0.00
0.00
0.25
0.50
0.75
1.00
Efficiency for signal events
S²/B CURVES
CONSTANT
S⊥
X_F
BETTER

Contour of the -2ln L for the ML fit to $N(K^{\pm}\pi^{\mp})$ and $N(\pi^{\pm}\pi^{\mp})$



Contour of the -2ln L for the ML fit to $N(K^{\pm}\pi^0)$ and $N(\pi^{\pm}\pi^0)$





Theory
CLEO Upper limits
CLEO Measurements
$\pi^+\pi^-$
$\pi^0\pi^0$
$\pi^+\pi^0$
$\pi^+\rho^-$
$\pi^0\rho^0$
$\pi^+\rho^0$
$\pi^0\rho^+$
$K^+\pi^-$
$K^0\pi^0$
$K^+\pi^0$
$K^0\pi^+$
$K^+\rho^-$
$K^0\rho^0$
$K^+\rho^0$
$K^0\rho^+$
$K^{*+}\pi^-$
$K^{*0}\pi^0$
$K^{*+}\pi^0$
$K^{*0}\pi^+$
$K^0\phi$
$K^+\phi$
$K^{*0}\phi$
$K^{*+}\phi$
$\phi\phi$
K^+K^-
K^0K^0
K^+K^0
$K^{*+}K^-$
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
Branching fraction

Technique - More Continuum Discriminators

- In addition to the variables already discussed ($\Delta E, m_{SE}$, angle between thrust axis and B momentum) several other variables can be used
- The sum of the transverse components of the momenta for the tracks not used to reconstruct the B candidate w.r.t. the B candidate direction is small for jetty (background) events, uncorrelated for true B decays
- Fox-Wolfram Moments (H_l)
  - These are defined by

$$H_l = \sum_{i,j} \frac{|p_i| \bullet |p_j|}{E_{vis}^2} P_l(\cos\theta_{ij})$$

  - where P_l are the Legendre polynomials, $p_{i,j}$ are particle momenta, θ_{ij} is opening angle between the particles and E_{vis} is total visible energy in event
  - Neglecting particle masses, energy-momentum conservation gives $H_0 = 1$
  - For two-jet events $H_{odd} = 0$, $H_{even} = 1$
  - Use ratio of Fox-Wolfram 2nd to 0th moments as discriminator (tends to 0 for spherical (B) events)

Technique - Sphericity / Aplanarity

- Sphericity is defined as $S = \frac{3}{2}(\lambda_2 + \lambda_3)$
  - where λ_2, λ_3 are the two larger eigenvalues of the diagonalized sphericity tensor

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha \cdot p_i^\beta}{\sum_i p_i^2}$$

  - where α,β=1,2,3 correspond to x,y,z components respectively
    - » Isotropic events have sphericity ~ 1
    - » Jetty events have sphericity ~ 0
- Sphericity axis is direction of eigenvector with largest eigenvalue (c.f thrust axis)
- Aplanarity measures component of transverse momentum out of event plane $A = \frac{3}{2}\lambda_3$
  - A= 0 for a planar event (λ_3= 0), and has maximum value of 0.5 for an isotropic event (all three eigenvalues equal)

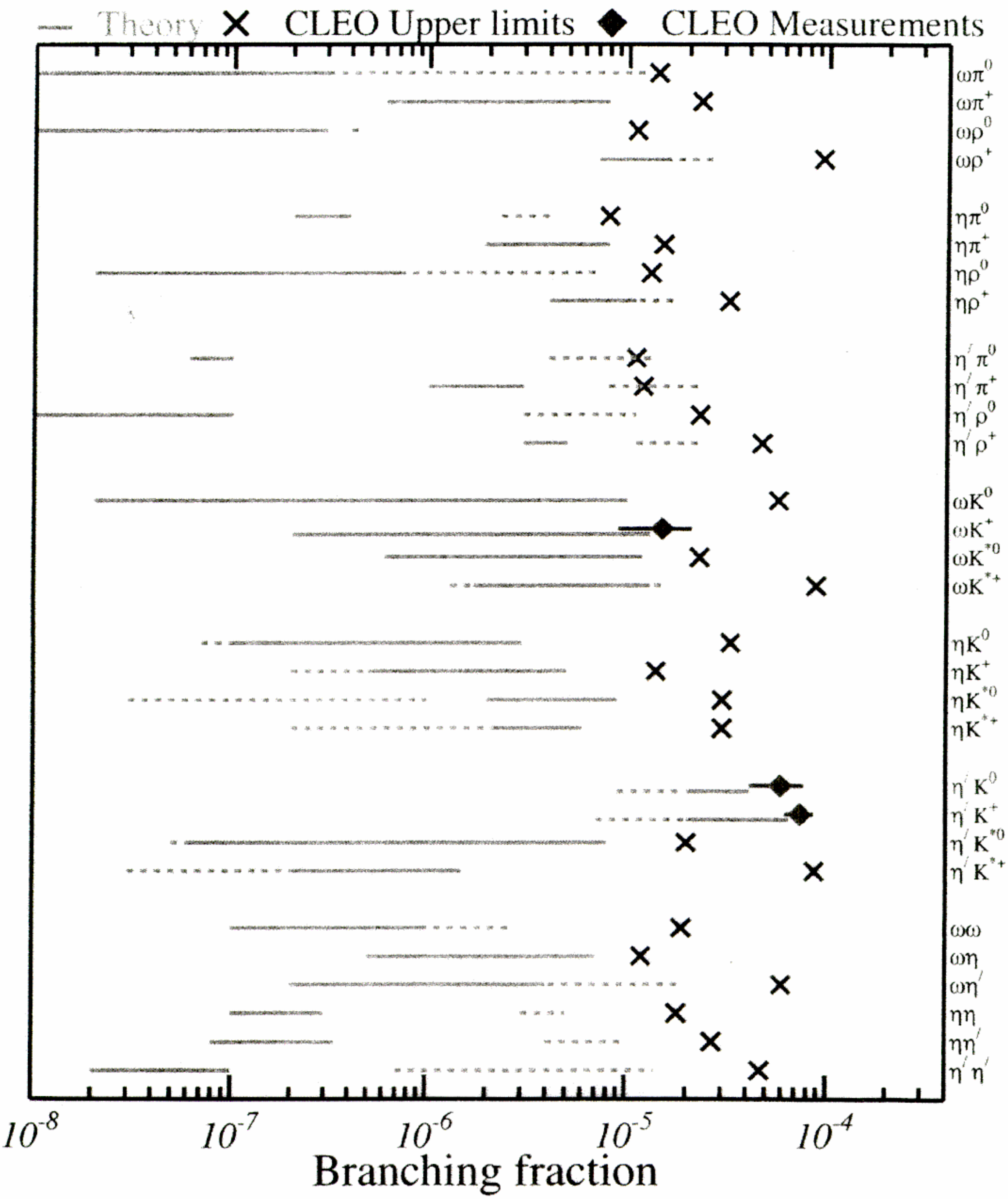
The (Near?) Future

- Studies limited by
  - Statistics - observability goes as $Br \bullet (A_m)^2$
    - » For Branching fraction of 2×10^{-5}, 50% reconstruction efficiency, 10% background, require $n(fb^{-1}) > 1/(A^2)$, for a 3σ effect
  - ΔE resolution
  - Particle Identification
- CESR/CLEO are almost finished upgrading
  - Current CLEO II.V data set is about $9 fb^{-1}$ (2:1 split on:off resonance)
  - Upgrade luminosity goal is $10^{33} cm^{-2} s^{-1}$
  - Much improved particle ID
- New Asymmetric B-Factories are online
  - High statistics (5:1 on:off split?)
  - Time evolution .....

Two Body Decays Via Resonances

- CLEO has published branching ratios or limits on many of these modes
  - η' higher than (some?) theorists had predicted
  - Many additional discriminators
    - » Mass of resonance
    - » Decay amplitude ($\omega \rightarrow \pi\pi\pi$)
    - » Helicity cuts
      - pseudoscalar → pseudoscalar+vector
        - Use angle between direction of vector meson and normal to decay plane, signal goes as $\cos^2\theta$, background is flat.
- These channels, and $K\pi$, open up the possibility for measurements of direct CP violation by looking for asymmetries in partial decay rates where the interference is between penguin and tree diagrams

$$A_m = \frac{N(B^+ \rightarrow f) - N(B^- \rightarrow \bar{f})}{N(B^+ \rightarrow f) + N(B^- \rightarrow \bar{f})}$$


Theory
CLEO Upper limits
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$\omega\pi^0$
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$\eta\rho^+$
$\eta'\pi^0$
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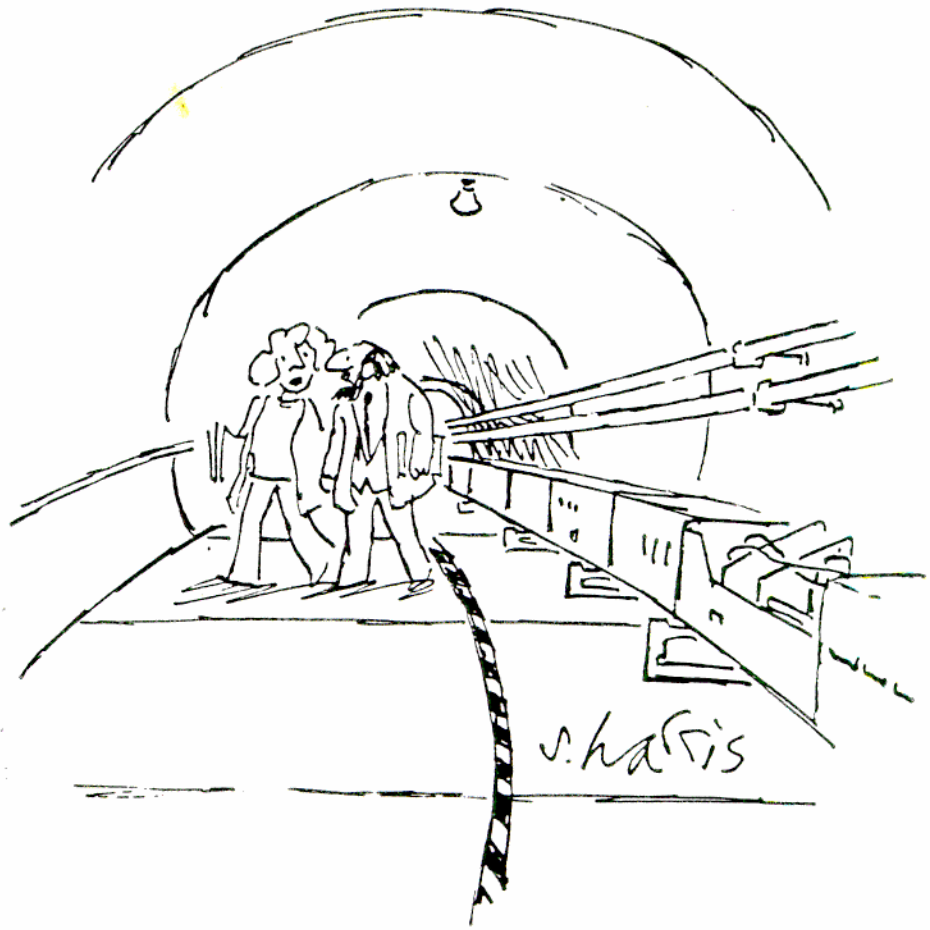
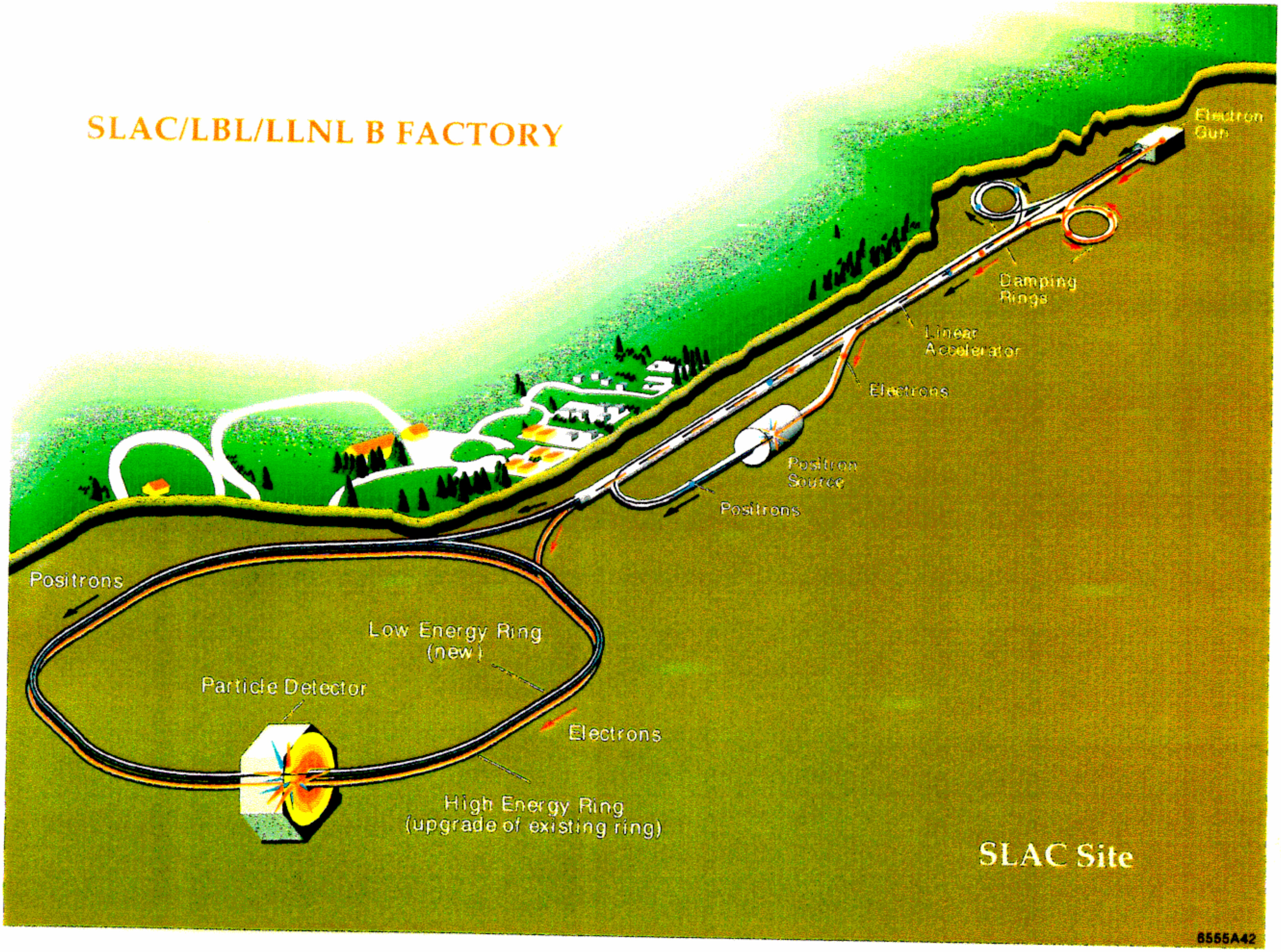
ωK^0
ωK^+
ωK^{*0}
ωK^{*+}
ηK^0
ηK^+
ηK^{*0}
ηK^{*+}
$\eta' K^0$
$\eta' K^+$
$\eta' K^{*0}$
$\eta' K^{*+}$
$\omega\omega$
$\omega\eta$
$\omega\eta'$
$\eta\eta$
$\eta\eta'$
$\eta'\eta'$
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
Branching fraction

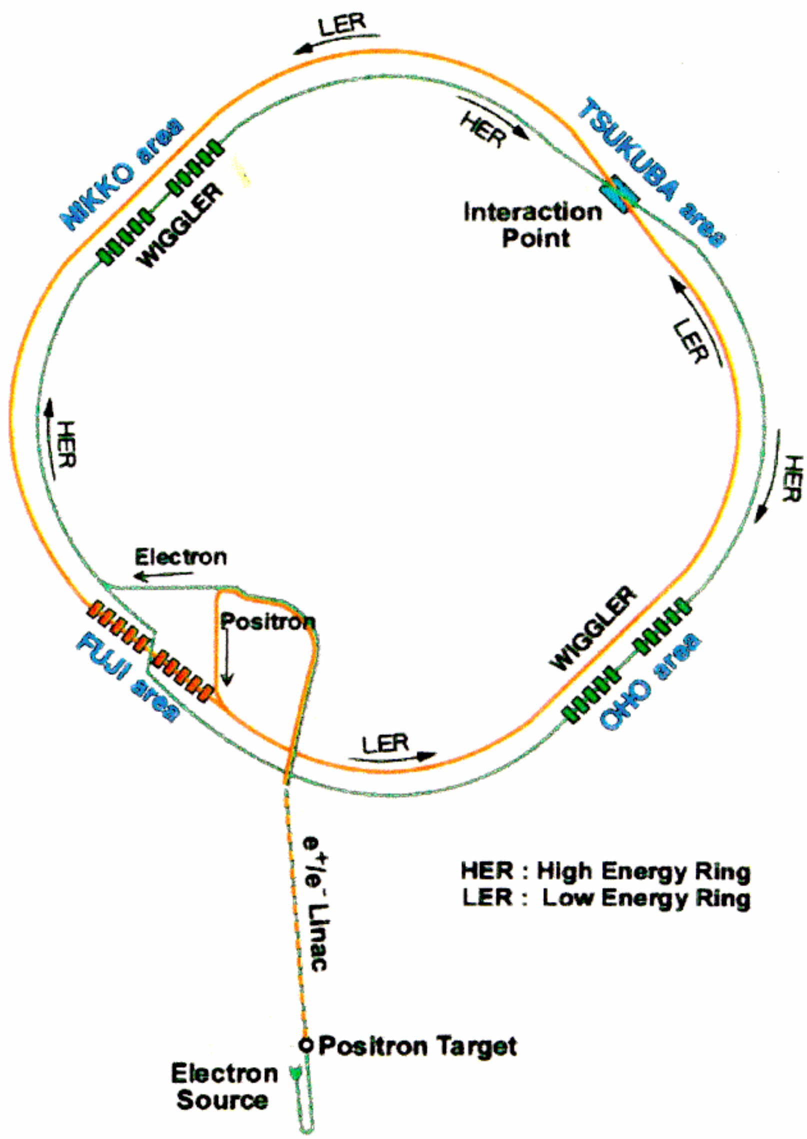


"What if we spend all these billions, and there just *aren't* any more particles to find?"

SLAC/LBL/LLNL B FACTORY

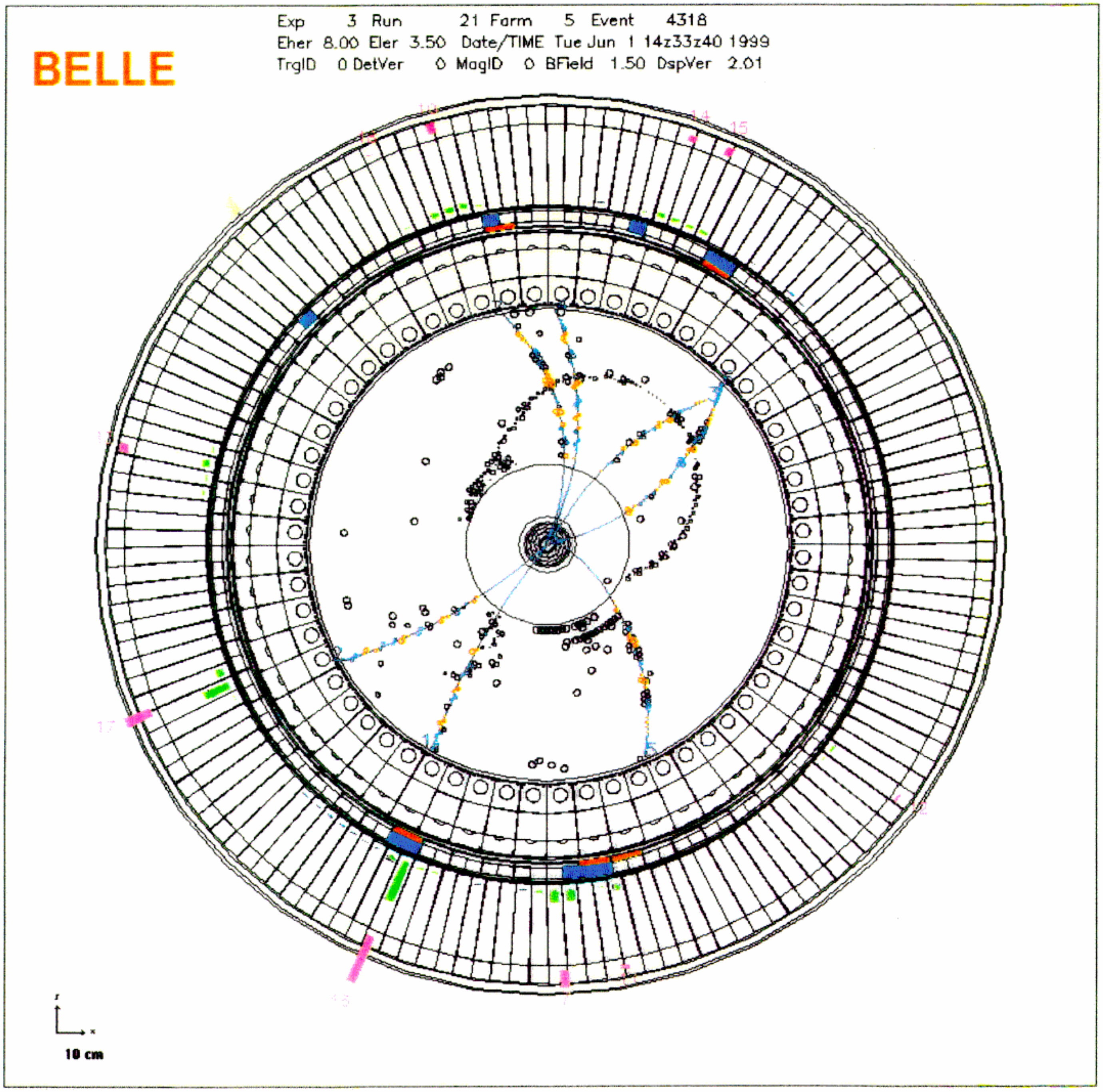


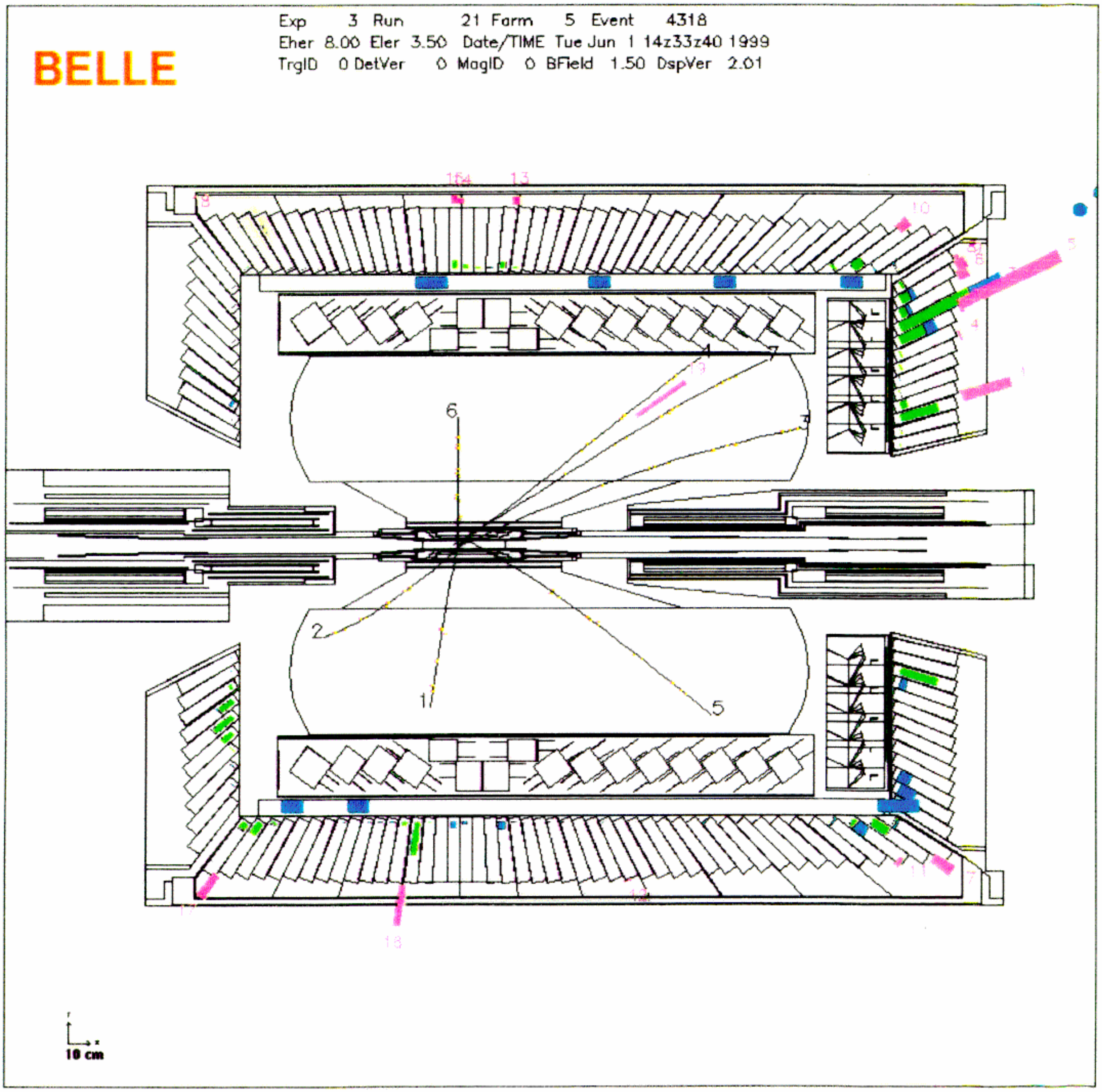
KEK-B Rings


LER
HER
TSUKUBA area
Interaction Point
NIKKO area
WIGGLER
LER
HER
HER
Electron
Positron
FUJI area
WIGGLER
OHO area
LER
e^+/e^- Linac
HER : High Energy Ring
LER : Low Energy Ring
Positron Target
Electron Source

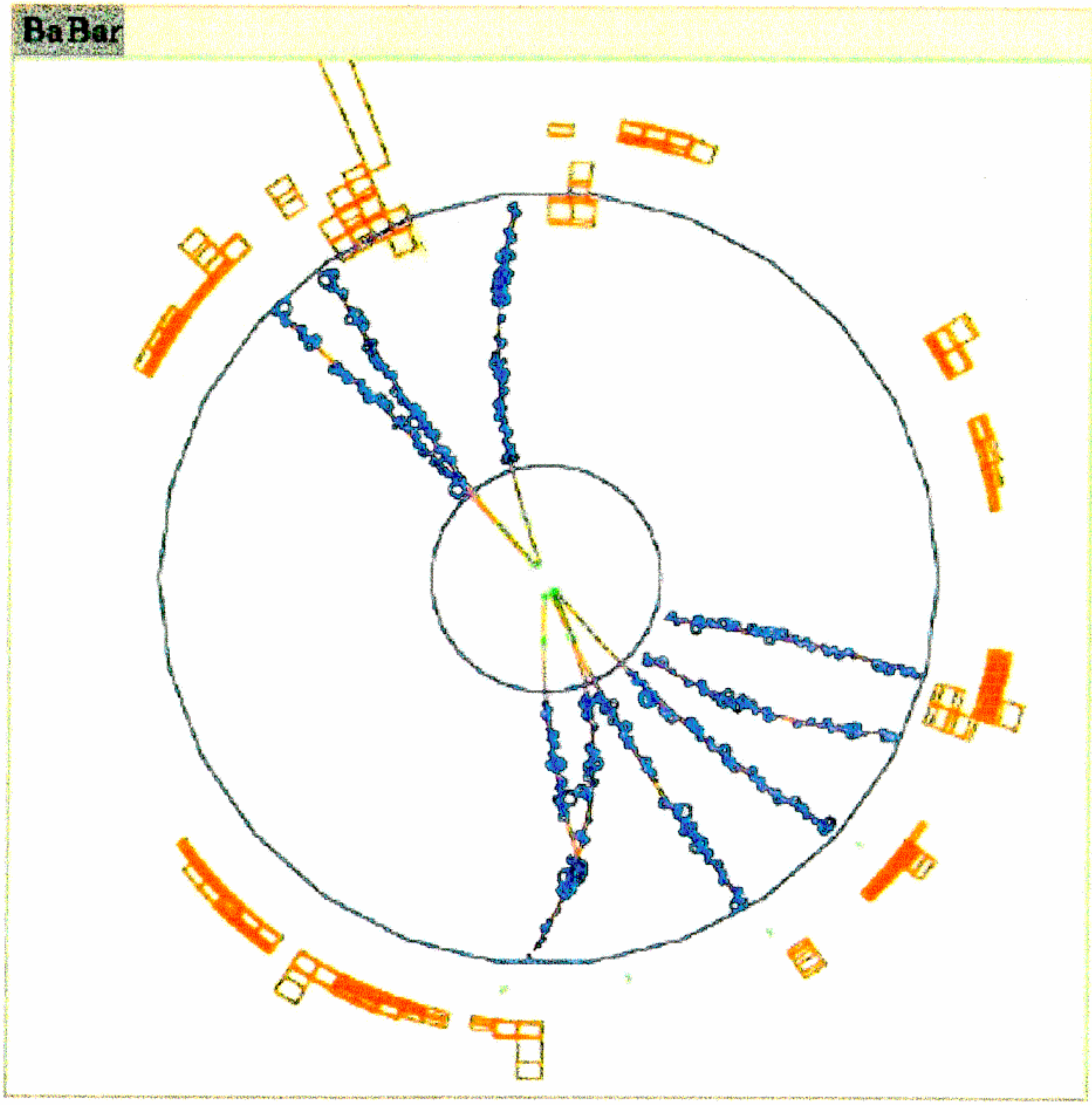
KEK-B/PEP-II

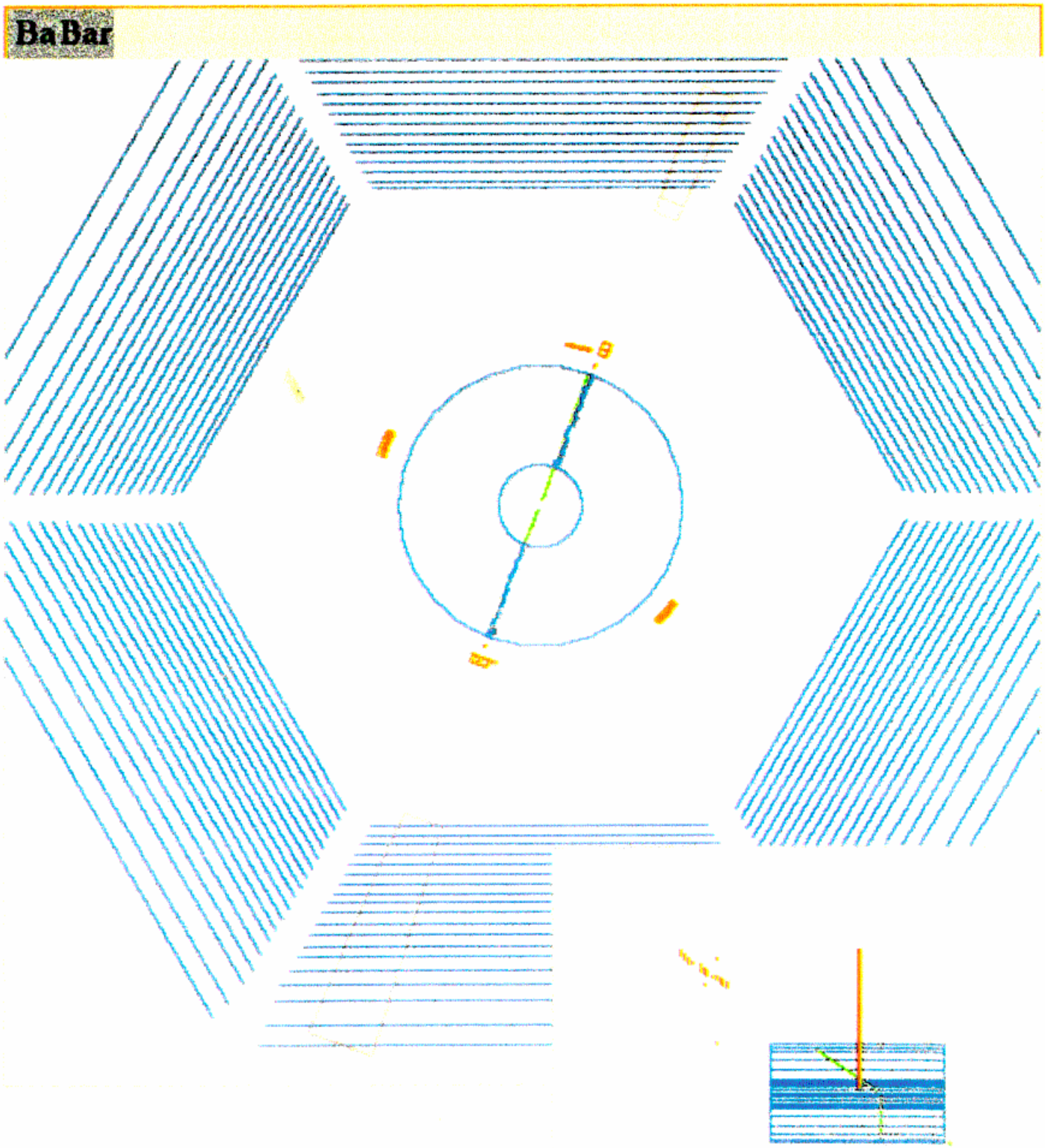
- Both have begun providing collisions to experiments (end of May/start of June)
  - KEK-B has 8.0GeV electrons and 3.5 GeV positrons
    - » $\gamma\beta = 0.42$
  - PEP-II has 9.0GeV electrons and 3.1 GeV positrons
    - » $\gamma\beta = 0.56$, mean separation between B decays is about 260μm
- CM Boost
  - Helps continuum background suppression by making it easier to find separated vertices
  - Folds tracks forward
  - Increases momentum range must cover with particle ID


Exp 3 Run 21 Farm 5 Event 4318
Eher 8.00 Eler 3.50 Date/TIME Tue Jun 1 14z33z40 1999
TrgID 0 DetVer 0 MagID 0 BField 1.50 DspVer 2.01
BELLE
10 cm

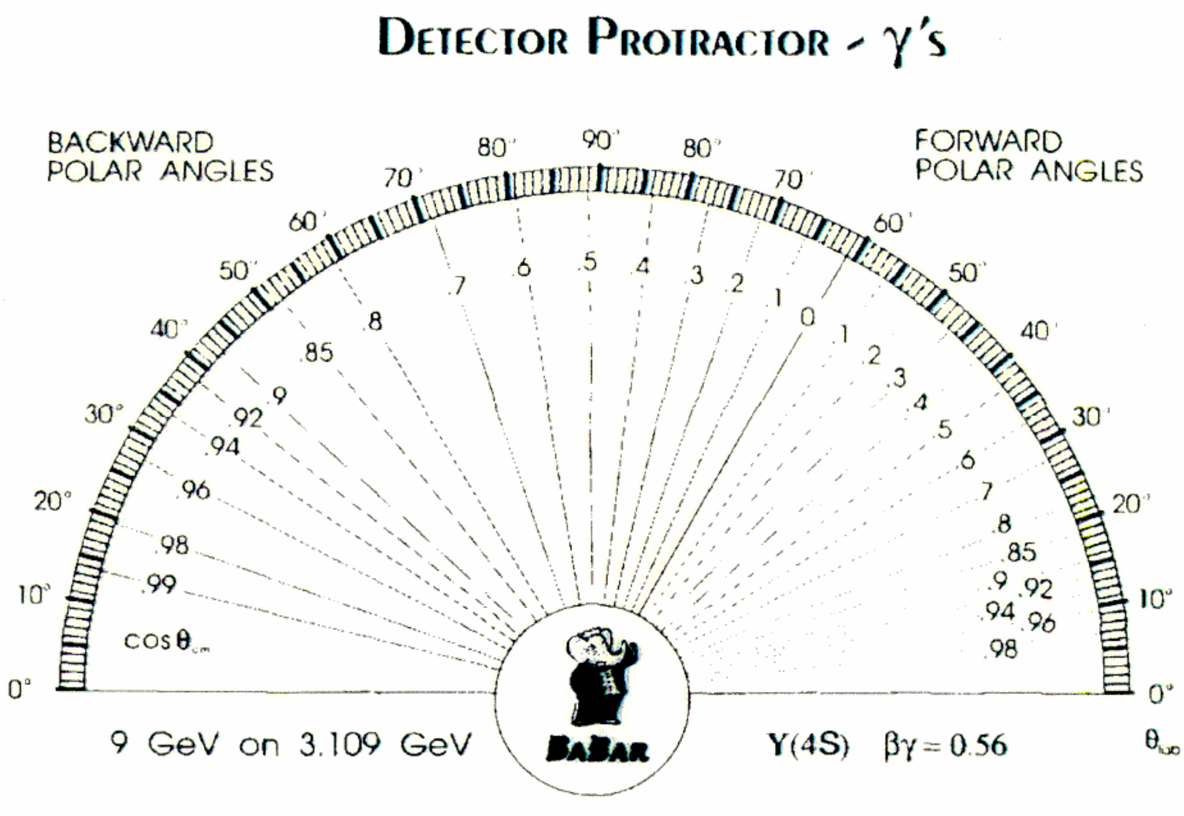


BELLE
Exp 3 Run 21 Farm 5 Event 4318
Eher 8.00 Eler 3.50 Date/TIME Tue Jun 1 14z33z40 1999
TrgID 0 DetVer 0 MagID 0 BField 1.50 DspVer 2.01
10 cm

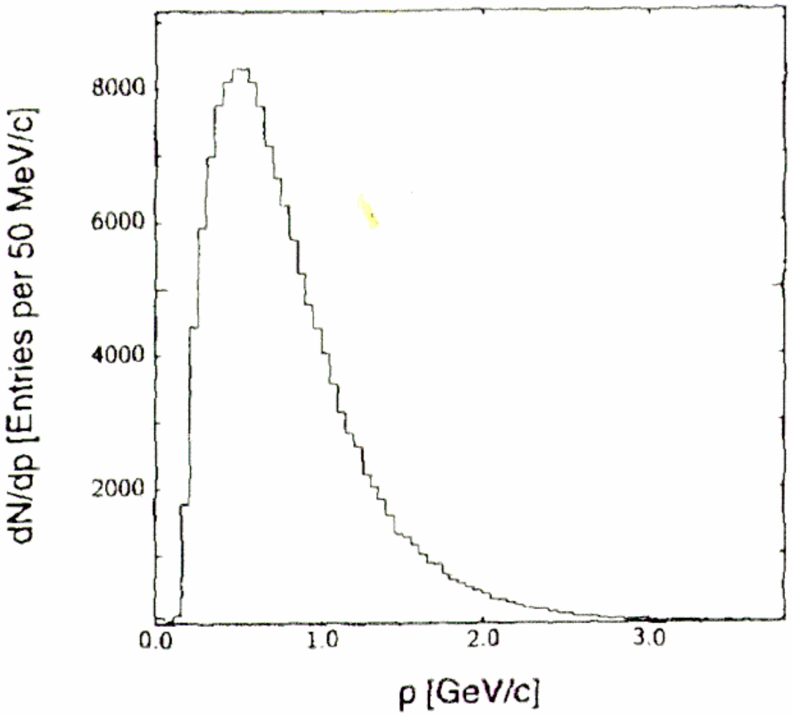

BaBar


BaBar

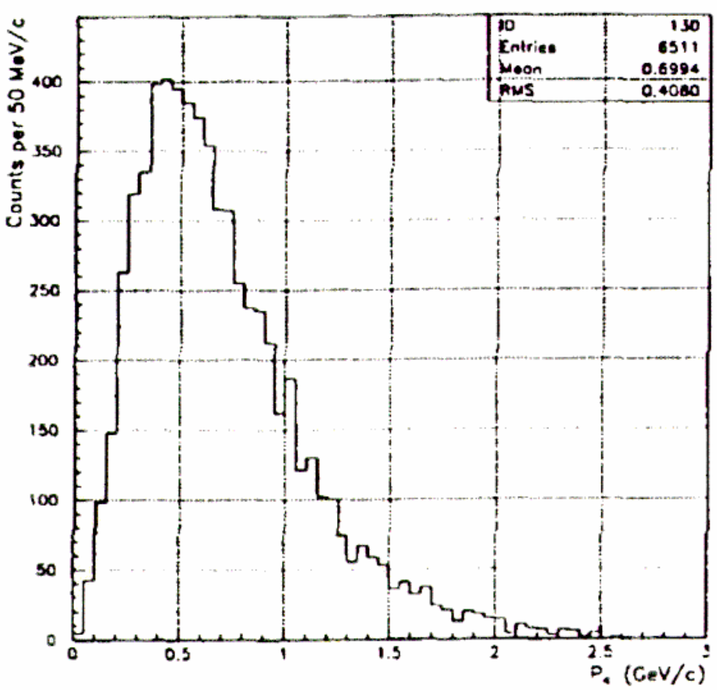
CM/LAB angle for γ's (PEP-II)



Spectra for tagging

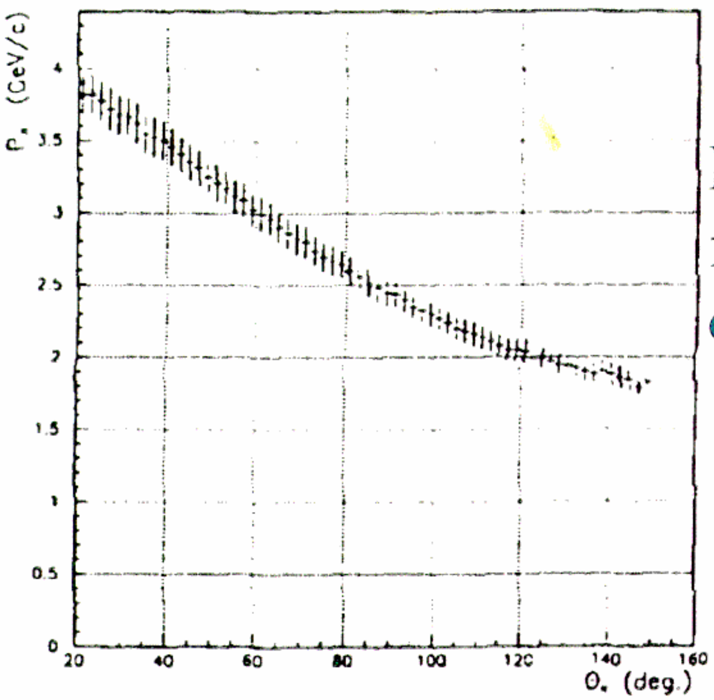


BaBar, kaon spectra



BELLE, kaon spectra

Spectra for $B \to K^{\pm}\pi^{\mp}$



BELLE, kaon spectra from $B \to K\pi$ as a function of lab polar angle

- Note, to separate $k\pi$ and $\pi\pi$ decays (very important for physics) with good efficiency need to cover high end of momentum range
- These decays give back to back tracks in CM

  At BaBar get 4.2 GeV/c K at $\cos\theta_{lab} \sim 0.95$

  At BaBar get 1.5 GeV/c K at $\cos\theta_{lab} \sim =-0.69$
- Tagging requires good particle identification at low momenta

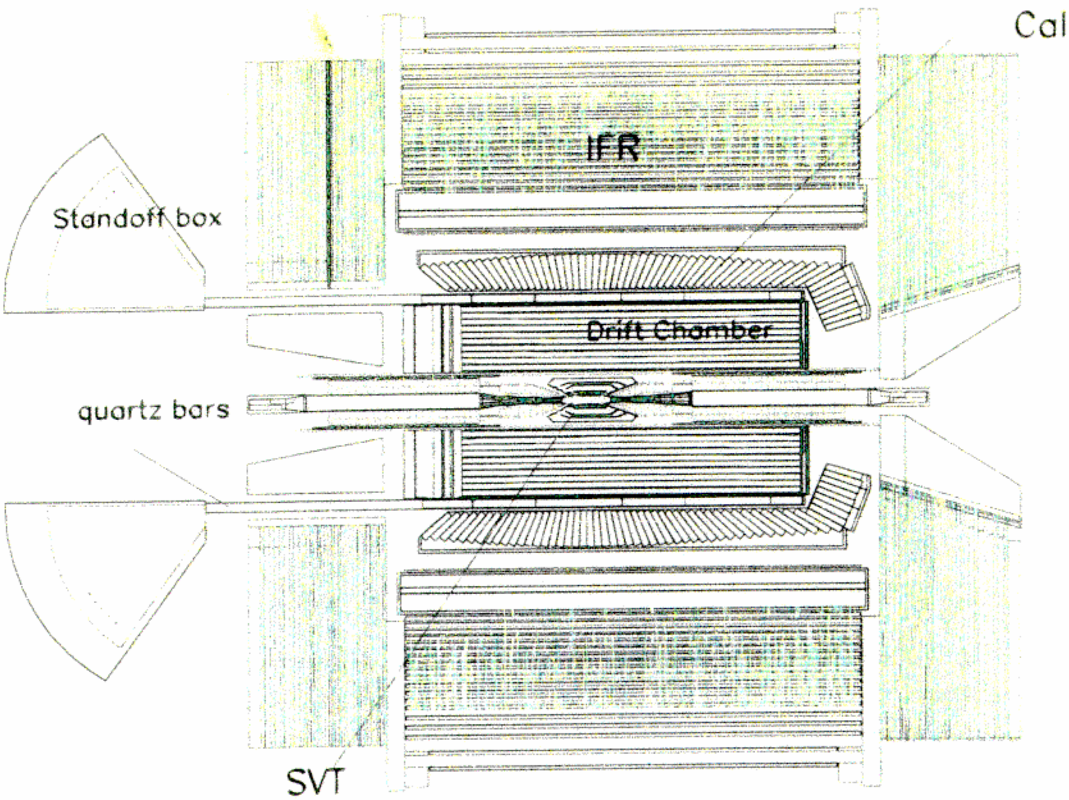
Lab→ CM Boost Effects

- Though the lab frame momentum is measured directly, the lab frame B candidate energy depends on the mass hypothesis used for tracks
  - For $B^0 \rightarrow \pi^+\pi^-$ taking one p to be a K shifts the B energy by 40MeV, with a spread of about 11 MeV
- At CESR,DORIS cm and lab frames the same, at KEK-B, PEP-II they aren't which is an additional complication
  - $E_{cm} = \gamma(E-\beta p_z) \Rightarrow \delta E_{,cm} = \gamma\delta E$
  - p_x, p_y stay the same
  - $p_{z,cm} = \gamma(p_z-\beta E) \Rightarrow \delta p_{z,cm} = -\beta\Delta E_{cm}$
    - » $\delta p_{cm} \approx \delta p_{z,cm}/\sqrt{3}$
    - » For PEP-II, $\beta \approx 0.48$, $\gamma \approx 1.14$
      - implies a net broadening of the p distribution by about 12MeV/c

BaBar Detector - tasks

- From beam pipe, radially outwards
  - A five layer Silicon Vertex Detector
    - » B^0-$\overline{B}^0$ vertex separation
    - » Track finding for p_t below 100 MeV/c
    - » Particle identification via dE/dx
  - A low density He-based Drift Chamber
    - » Track reconstruction
    - » Particle identification via dE/dx
    - » Small radiation length (preserve σ_{pt}, DIRC, EMC)
  - A DIRC (Detection of Internally Reflected Cerenkov light)
    - » K/π separation up to 4.0 GeV/c and at large dip angles, important for tagging and reconstruction

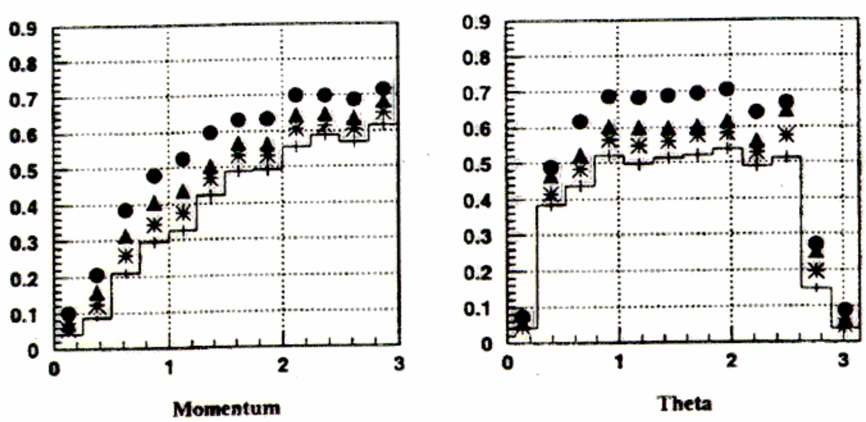
BaBar



- A CsI (Tl) Electromagnetic Calorimeter with high granularity
  - » High efficiency for low energy photons
  - » Reconstruct π^o
  - » Good energy, angular resolution to help π^0,B^0 mass resolutions
  - » lepton identification e/π, μ/π, e/μ
- A 1.5T Superconducting coil
- An Instrumented Flux Return
  - » μ/π separation
  - » K_L detection

Technique - Using K_L Decays

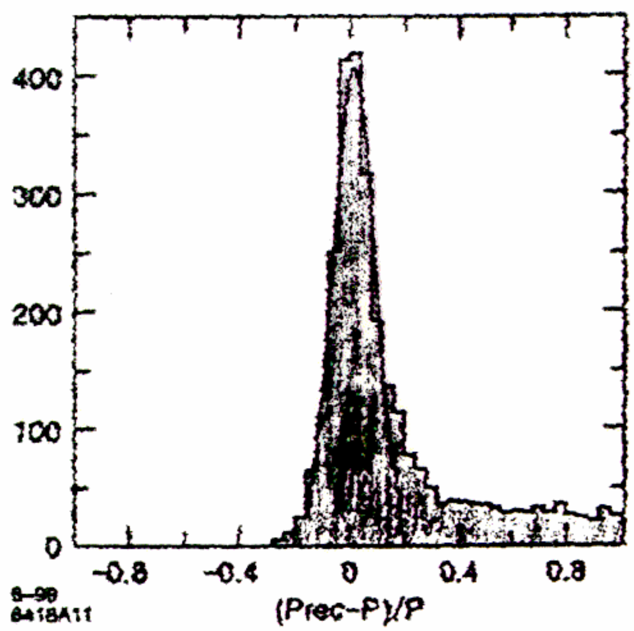
- Get a good detection efficiency for K_L's if require a minimum of four IFR layers hit ($\approx$55% of $B \rightarrow J/\psi K_L$)
- IFR does not give information on energy, only on direction
  - Improve resolution if have interaction which starts in EMC
  - In about 1/3rd of cases only get hits in IFR
- Reconstruction efficiency studies currently rely on MC, vary in results for low momenta K_L's although agree on general features



- Can estimate the momentum of the K_L using the momentum of the K_S and the opening angle (α)

$$M_\phi^2 = 2m_K^2 + 2[E_L E_S - P_L P_s \cos\alpha]$$

- Two solutions for P_L
  - » Only use events with one solution of too low a momentum to be detected
  - » Correct solution has a fairly flat distribution in ϕ center of mass, wrong solution is highly peaked so if one solution in backward hemisphere, one in forward hemisphere probably correct
    - Tail (~ 10% of events) due to selecting wrong solution, get about 8% resolution on K_L momentum



BaBar Performance - TDR Parameters

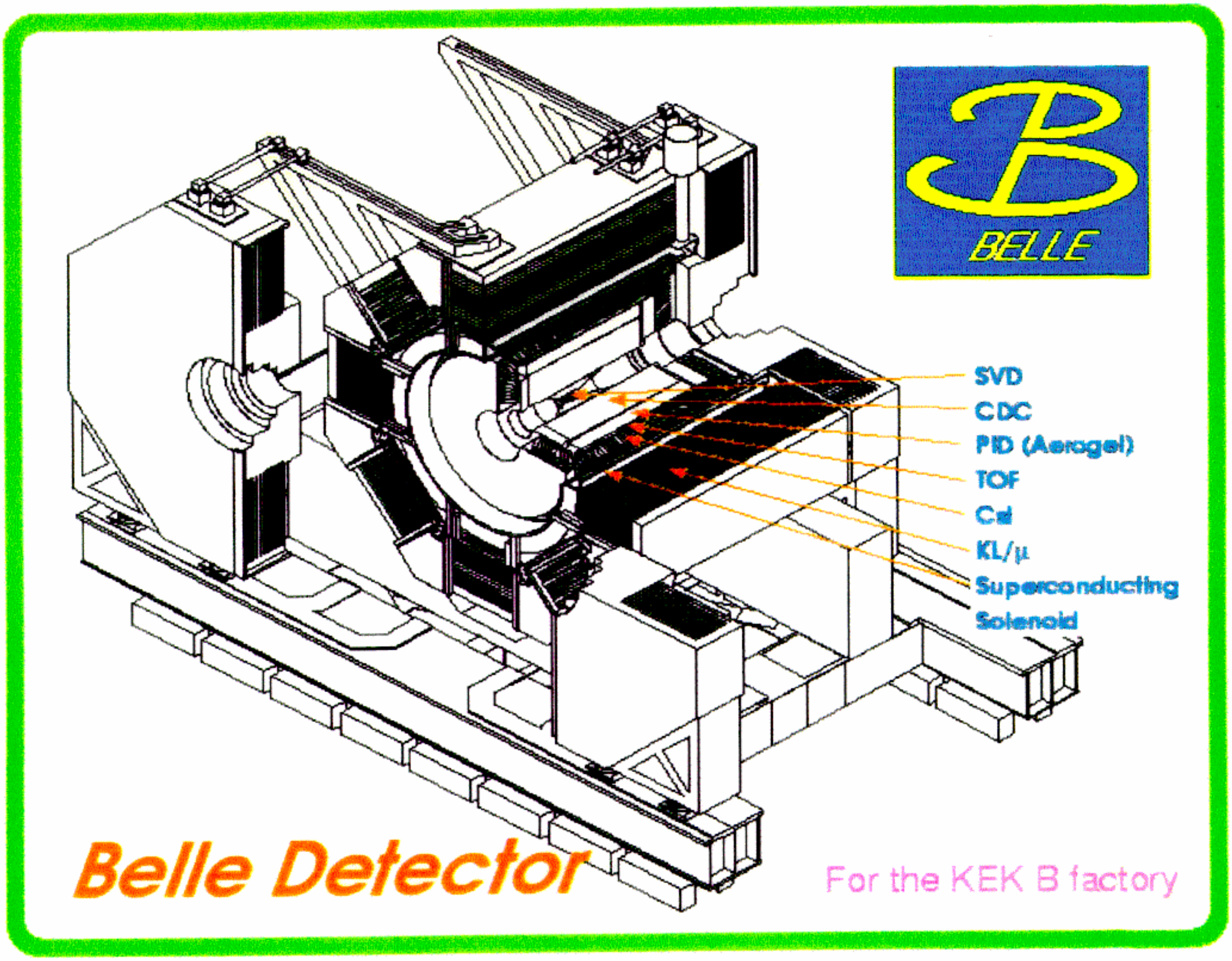
- Acceptances quoted for CM system

Parameter	Value [2]
Tracking coverage ($/4\pi$)	0.92
σ_{p_t}/p_t (%) (1 GeV pions at 90°)	0.36
σ_{z_0} (μm) (1 GeV pions at 90°)	52
Calorimetry coverage ($/4\pi$)	0.90
X_0 in front of Calorimeter (at 90°)	0.25
σ_E/E (%) (1 GeV γ at all angles)	1.8
γ efficiency within acceptance (at100 MeV)	0.92
Charged Hadron ID coverage ($/4\pi$)	0.84

Babar/Belle

- Collaboration
  - BaBar - 630 people from 73 institutions
  - BELLE- 240 people from 44 institutions
- Inner tracker
  - Both use double sided silicon
  - BaBar has 5 layers, r=3.2-14.4cm, $16.3° < \theta < 150.5°$
  - BELLE has 4 layers, r=2.8- 4.8cm, $17° < \theta < 150°$, estimated resolution of B separation is $75.8 \pm 0.5 \mu m$
- Outer tracker
  - drift chambers
  - BELLE has small cells, 50 anode layers, 3 cathode layers, r=8.0-88 cm, $-77 < z < 160$cm
  - BaBar has hex cells, 10 superlayers of 4 layers (AUVAUVAUVA), r=22.5-80cm, $-111 < z < 166$cm

BELLE


BELLE
SVD
CDC
PID (Aerogel)
TOF
CsI
KL/μ
Superconducting
Solenoid
Belle Detector
For the KEK B factory

Particle Identification

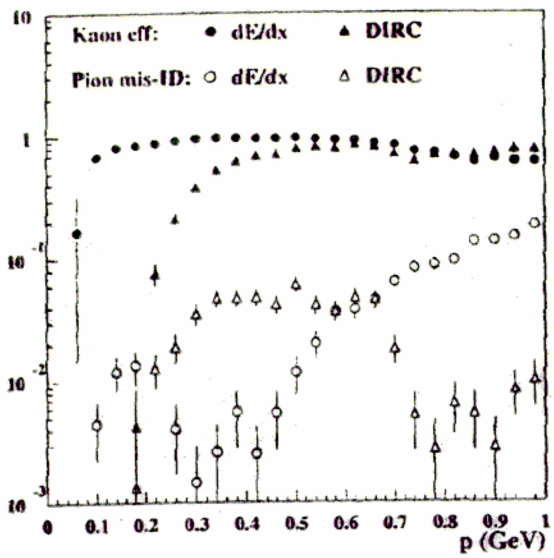
- This is one area in which BELLE/BaBar made very different choices
- BaBar - DIRC
  - Uses a cylindrical arrangement of quartz bars (n=1.472)
    - Cerenkov light is emitted when particle travels through quartz bar. Uses the component of light captured in the radiator which propagates to end of bar by internal reflection, *preserving* its characteristic angle
    - Photon propagates into a large volume of water (stand-off box or SOB) and reaches array of 11000 photomultipliers (PMT)
    - Reconstruction of angle between PMT and bar gives the Cerenkov angle and hence the particle id

  » Covers 87% of polar angle, 93% of ϕ in CM

  » K efficiency >95% with π misid <3%, up to 3GeV/c, rising to 97% for $B^0 \rightarrow K^+\pi^-$

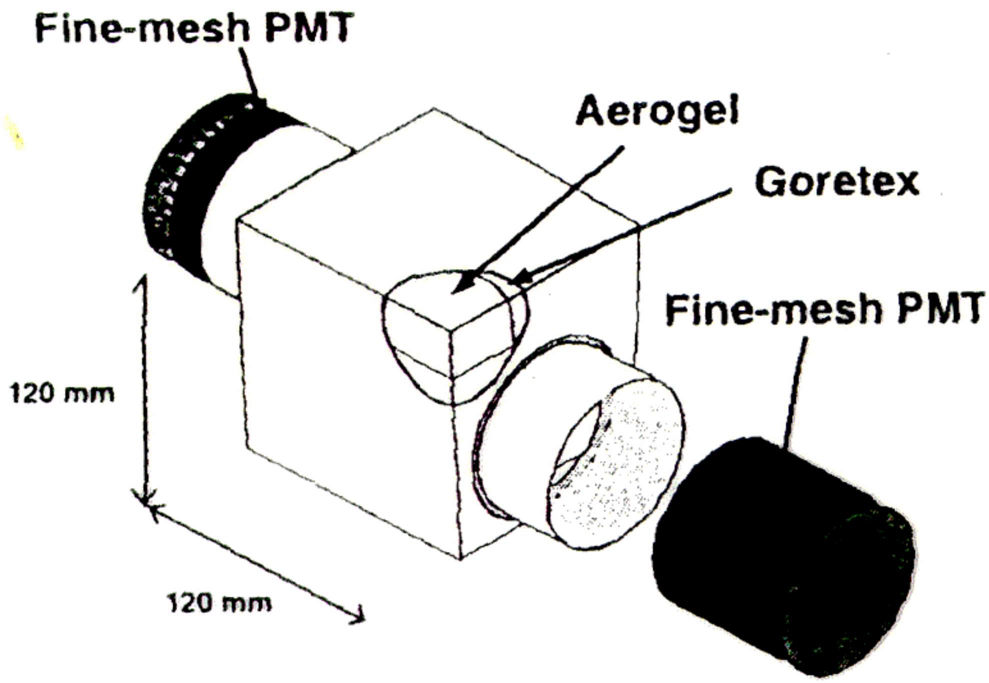
  » μ efficiency>80% below 750 MeV/c, 95% below 500 MeV/c

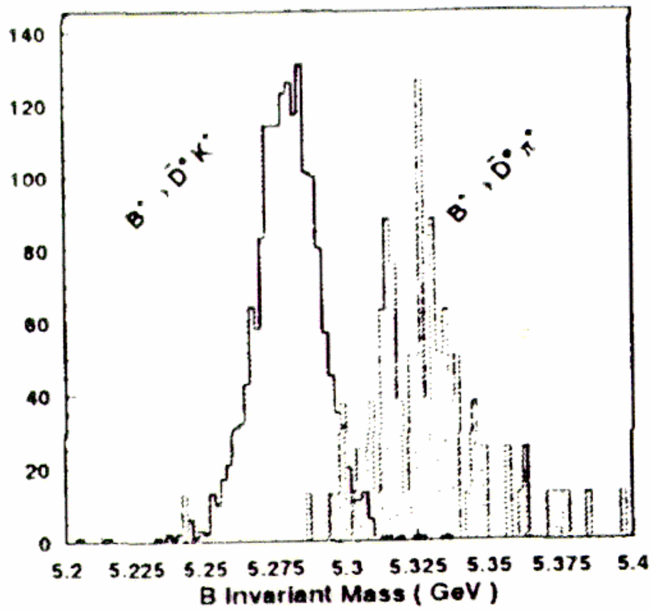
BaBar - Particle ID Performance



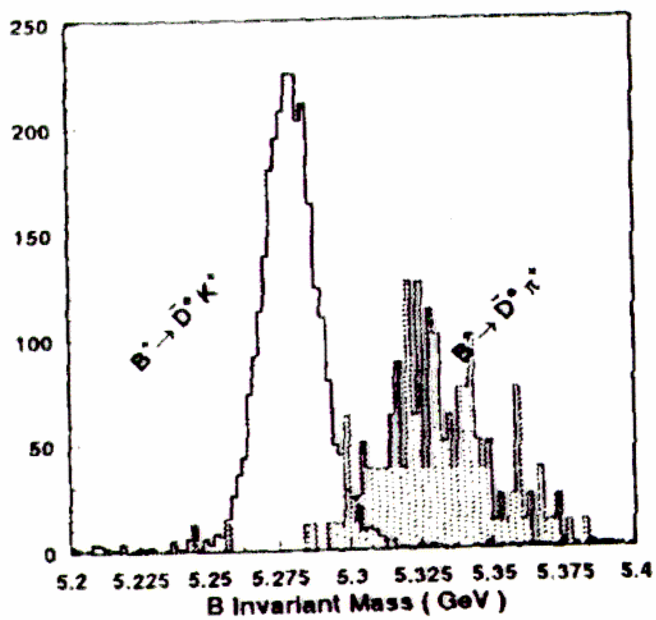
- BELLE
  - Scintillator Time-of-flight (TOF) to cover momenta below 1.2 GeV/c
    - » designed for 6σ π/k separation at 1 GeV/c
  - Silica Aerogel
    - » 960 element arrays divided into a barrel and forward end-cap system.
      - Barrel aerogel has a varying refractive index to take account of dependence of hadron momentum spectrum on polar angle (n=1.01-1.028)
        - K threshold is about 3.5GeV/c for n=1.01
      - Forward end cap counters all use n=1.03 aerogel

Belle - Particle ID unit





A) B→ DK/B→Dπ for D→Kπ (BELLE)



B) B→ DK/B→Dπ for D→Kπππ (BELLE)

- EM Calorimeter
  - Both use CsI, BELLE has BGO crystals in the extreme forward part of the detector
  - BELLE 5.5x5.5 cm^2 crystals, 16.1 rad lengths
  - BaBar 4.8x4.8 cm^2 crystals, 16-17.5 rad lengths
- Magnet
  - Both have super-conducting magnets, 1.5T
  - BaBar - inner radius 140cm
  - BELLE - inner radius 170 cm
- Outer Calorimeter/Muon/K_L
  - Both use resistive plate chambers (RPC) interleaved with iron to form the inside return yoke
  - BELLE - 14 layers
  - BaBar - 18 layers

Summary

- Lots of advantages to running on the Y(4s)
  - Know the B kinematics
    - » m_{SE}, ΔE
  - If have one B reconstructed know remaining tracks come from another B
- Experimental indications are that Penguins will need to be taken into account
  - Direct CP?
- More techniques
  - Shape variables
  - K_L reconstruction