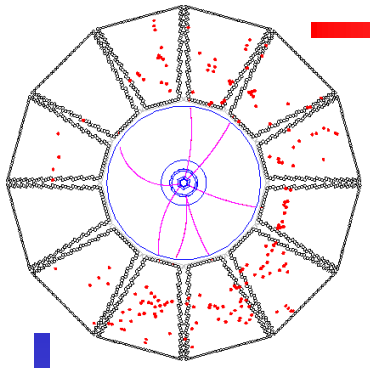


DIRC - The Particle Identification System for BaBar

Outline:

- DIRC Concept and Design
- Operational Experience
  - Performance Highlights
  - Photon Detection Efficiency
  - Background Sensitivity
  - Longevity Issues

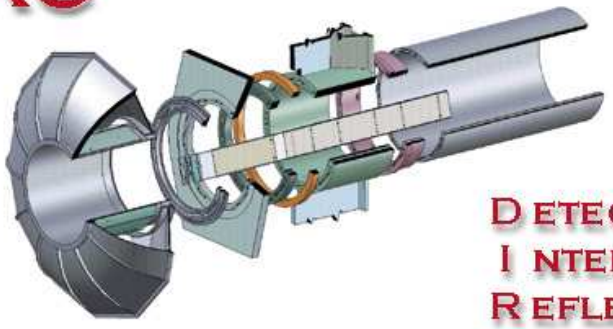
Blair Ratcliff

Stanford Linear Accelerator Center

A national laboratory funded by the Department of Energy

BABAR-DIRC COLLABORATION

DIRC



DETECTION OF
INTERNALLY
REFLECTED
CHERENKOV LIGHT

DIRC combines with dE/dx from CDC and SVT (mostly in the $1/\beta^2$ region) as hadronic particle identification system for BABAR.

The BABAR-DIRC Collaboration

I.Adam,[a] R.Aleksan,[b] D.Aston,[a] D. Bernard,[e] G.Bonneaud,[e] P.Bourgeois,[b]
F. Brochard,[e] D.N.Brown,[f] J.Chauveau,[c] J.Cohen-Tanugi,[c] M.Convery,[a] S.Emery,[b]
S.Ferrag,[e] A.Gaidot,[b] T.Haas,[a] T.Hadig,[a] G.Hamel de Monchenault,[b] C.Hast,[d]
A.Höcker,[d] R.W.Kadel,[f] J.Kadyk,[f] M. Krishnamurthy,[h] H. Lacker,[c] G.W.London,[b]
A.Lu,[g] A.-M.Lutz,[d] G.Lynch,[f] G.Mancinelli,[i] B.Mayer,[b] B.T.Meadows,[i] D.Muller,[a]
J.Ocariz,[c] I. Ofte,[i] S.Plaszczynski,[d] M.Pripstein,[f] B.N.Ratcliff,[a] L.Roos,[c]
M.-H.Schune,[d] J.Schwiening,[a] V.Shelkov,[f] M.D.Sokoloff,[i] S.Spanier,[a] J.Stark,[c]
A.V.Telnov,[f] Ch.Thiebaux,[e] G.Vasileiadis,[e] G.Vasseur,[b] J.Va'vra,[a] M.Verderi,[e]
W.A.Wenzel,[f] R.J.Wilson,[h] G.Wormser,[d] Ch.Yéche,[b] S.Yellin,[g] M.Zito.[b]

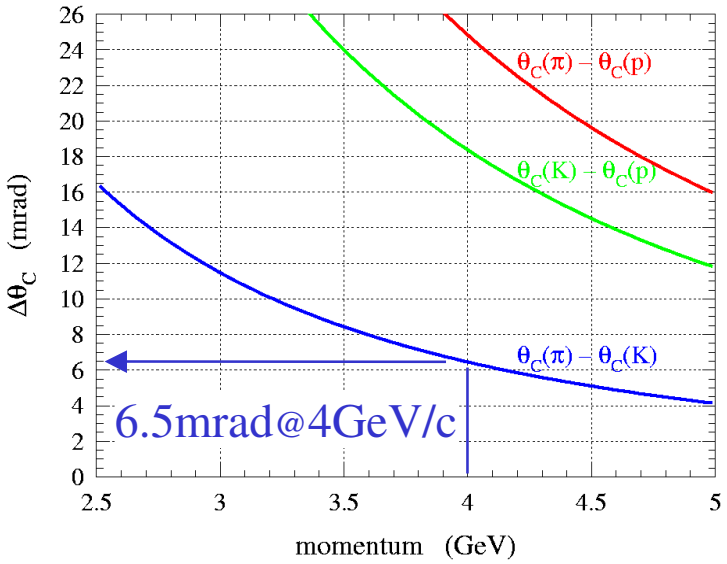
[a] Stanford Linear Accelerator Center
[b] CEA-Saclay,
[c] LPNHE des Universités Paris 6 et Paris 7
[d] LAL, Universite Paris Sud
[e] Ecole Polytechnique, LPNHE
[f] Lawrence Berkeley National Laboratory
[g] University of California, Santa Barbara
[h] Colorado State University
[i] University of Cincinnati

THE BABAR DIRC

Covering all B Decays at BABAR requires Particle Identification (PID) up to 4.2 GeV/c momentum.

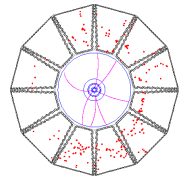
- $1.7 < |p| \lesssim 4.2$ GeV/c
  Pion/Kaon separation in rare charmless decays, e.g., $B \to \pi^+\pi^-$ / $B \to \pi^\pm K^\mp$
  time dependent decay asymmetry measures $\sin(2\alpha)$
- $|p| < 2$ GeV/c
  B/B flavor tagging with Kaons
  via $b \to c \to s$ cascade

PID using dE/dx of the BABAR
Vertex Detector and Drift Chamber
is only effective for $|p| < 0.7$ GeV/c



Design Constraints:

- CsI Calorimeter needs to detect photons down to 20 MeV,
  thus small radiation length (<20%) and small radial size required.
- Radiation robustness (expect 10 krad within 10 year lifetime).
- π/K separation at 4 GeV/c: 6.5 mrad
  $\to 3\sigma$ separation requires 2.2 mrad resolution



DIRC PRINCIPLE, PART I

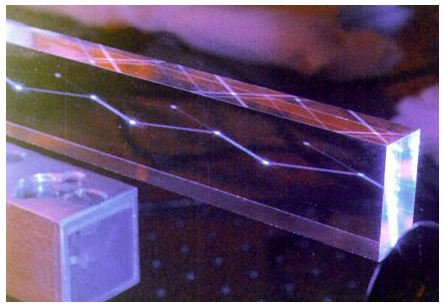
- A charged particle traversing a radiator with refractive index n with $\beta = v/c > 1/n$ emits Cherenkov photons on cone with half opening angle $\cos\theta_c = 1/n\beta$.
- If $n>\sqrt{2}$ some photons are always totally internally reflected for $\beta\approx 1$ tracks.

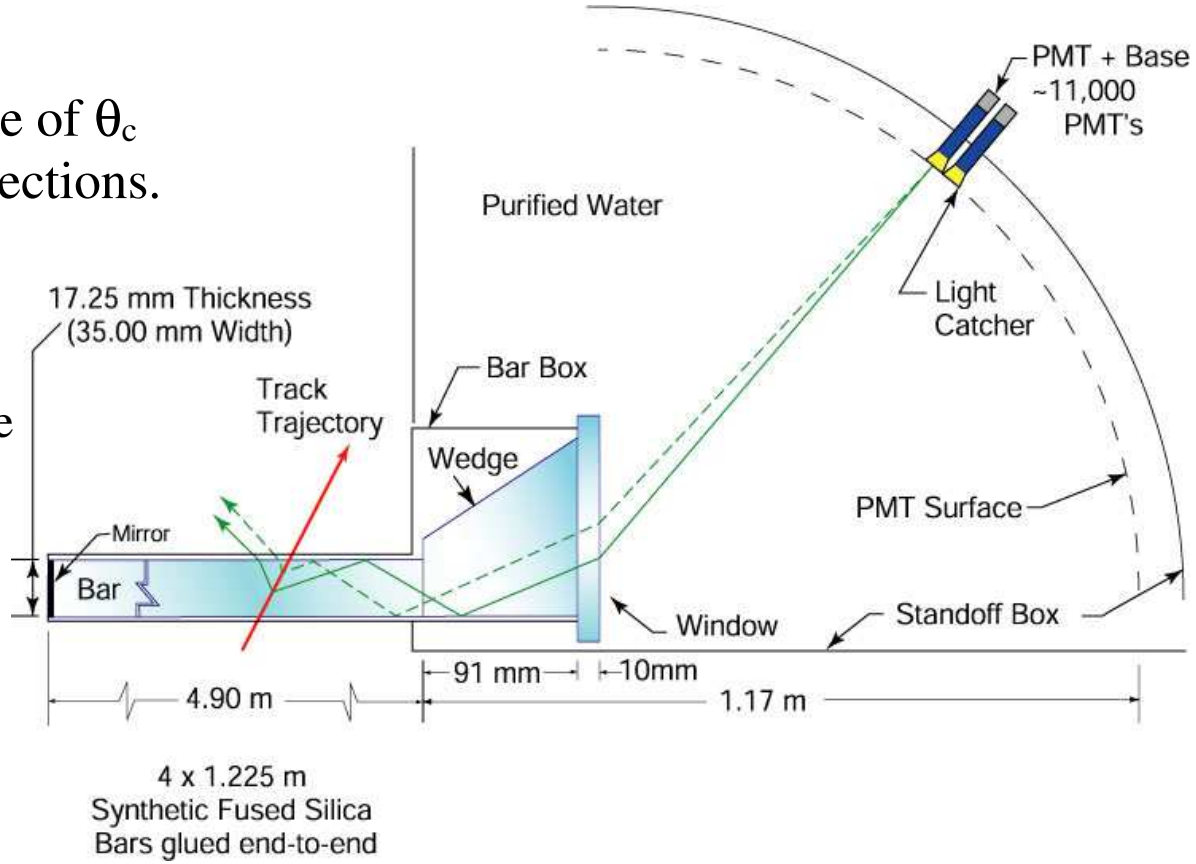
- Radiator and light guide: Long, rectangular Synthetic Fused Silica ("Quartz") bars

  (*Spectrosil:* average $\langle n(\lambda)\rangle \approx 1.473$, radiation hard, homogenous, low chromatic dispersion; 144 bars: 490×1.7×3.5 cm^3, polished to surface roughness <5Å (*rms*); square to better than 0.3 mrad.)

- Square radiator bar → magnitude of θ_c preserved during internal reflections.

  Typical DIRC photon:
  - $\lambda \approx 400$ nm,
  - ~ 200 bounces,
  - ~ 10-60 ns propagation time
  - ~ 5 m average path in bars.



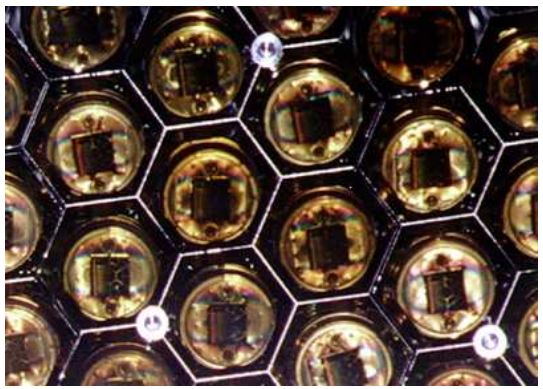


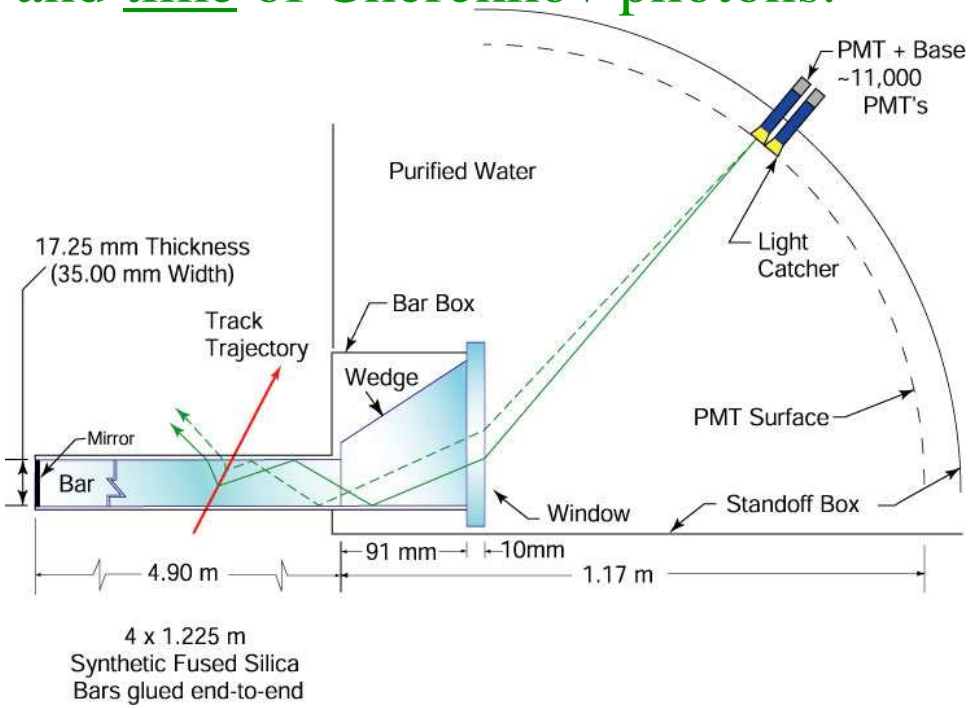
DIRC PRINCIPLE, PART II

- Only one end of bar instrumented; mirror attached to other (forward) end.
- Spectrosil wedge glued to readout end reduces required number of PMTs by ~ factor 2 and improves exit angle efficiency for large angle photons .
- Photons exit from wedge into expansion region (filled with 6m^3 pure, de-ionized water).

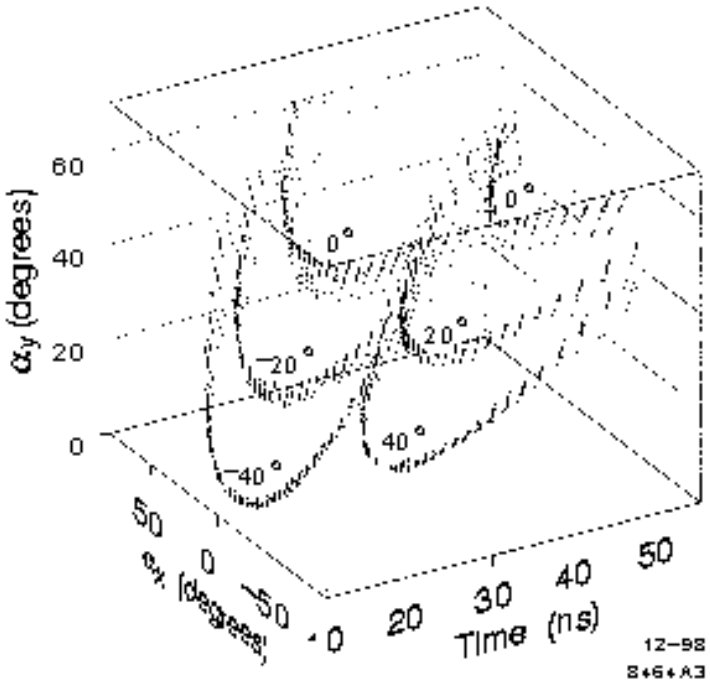
  ($<n_{water}(\lambda)> \approx 1.346$, Standoff distance ≈ 120 cm, outside main magnetic field; shielding: B < ~ 1 Gauss)
- Pinhole imaging on PMT array (bar dimension small compared to standoff distance).

  (10,752 traditional PMTs ETL 9125, immersed in water, surrounded by hexagonal "light-catcher", transit time spread ~1.5nsec)
- DIRC is a 3-D device, measuring: x, y and time of Cherenkov photons.
- PMT / radiator bar combination plus track direction and location from tracking define θ_c, ϕ_c, $t_{propagation}$ of photon.

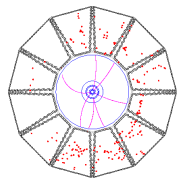




DIRC Is a 3-D Device



Need to take full advantage of all three dimensions for best performance and background rejection.



Digression- Some Issues of Principle

Basic Cherenkov Equations-I

Cherenkov radiation is emitted at polar angle (θ_c), uniformly in azimuthal angle (φ_c), with respect to the particle path

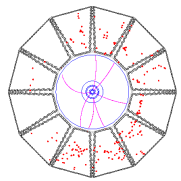
$$\cos\theta_c = \frac{1}{\beta\, n(\lambda)}$$

Since n is a function of the the photon wavelength lambda, there is a "intrinsic" chromatic production dispersion term of ~5.4 mrad for a normal bi-alkali photocathode.

The number of photo-electrons in Cherenkov radiation is always limited.

$$N_{pe} = 370L\int \varepsilon \sin^2\theta_c dE = LN_0 \sin^2\theta_c$$

In practice, Npe ~20 min. (more typically 30)



Digression- Some Issues of Principle

Basic Cherenkov Equations-II

A DIRC photon propagates a length (L_p) in a time (t_p) down a bar of length L (with speed of light c, group index n_g, , and z direction cosine k_z.

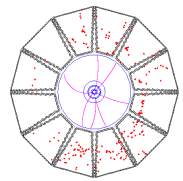
$$t_p = \frac{L_p n_g}{c} = \frac{L n_g}{c k_z}$$

Note that the group index must be used here since in a dispersive medium, energy propagates at the photon group velocity.

The relationship between group and phase index is

$$n_g(\lambda) = n(\lambda) - \lambda \, dn(\lambda)/d\lambda \, .$$

It is important to note that the group velocity averages about 3% less than the phase velocity for the BaBar DIRC. More importantly for DIRC performance in the time dimension, it is about 3 times more dispersive (relative dispersion ~1.5% rather than ~0.5%).



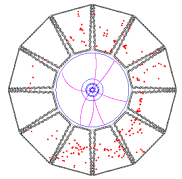
Digression- Some Issues of Principle

Basic Cherenkov Equations-III

Because the governing indices for Cherenkov angle and photon propagation speed are not quite the same in a dispersive medium, it turns out that the conical Cherenkov radiation shell (the Mach cone) is not quite perpendicular to the Cherenkov photon propagation angle. The half-angle of the cone opening (η) is given by

$$\cot\eta = \left[(n(\omega_0)\beta)^2 - 1\right]^{1/2} + \omega_0 n(\omega_0)\beta^2 (dn/d\omega)_0 \left[(n\beta)^2 - 1\right]^{-1/2},$$

This is only perpendicular to the directions of photon propagation when the second term is zero (the non-dispersive case).



DIRC Measurements

- ***DIRC measures photon arrival time at PMT position***

$$\left.\begin{array}{l} x_{PMT} \\ y_{PMT} \\ t_{arrival} \end{array}\right\} \rightarrow \left\{\begin{array}{l} \theta_c, \\ \varphi_c \\ \Delta t = t_{arrival} - t_{propagation} \end{array}\right.$$

consistency!

- ***expected uncertainties***

per photon:

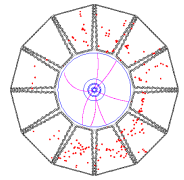
$$\Delta\theta^2_C = \Delta\theta^2_{C,track} + \Delta\theta^2_{C,dispersion} + \Delta\theta^2_{C,transport} + \Delta\theta^2_{C,imaging} + \Delta\theta_{PMT}{}^2 \sim (9.6\ \text{mrad})^2$$

~1-2 mrad; ~5.4 mrad; ~1-4 mrad; ~7.0 mrad

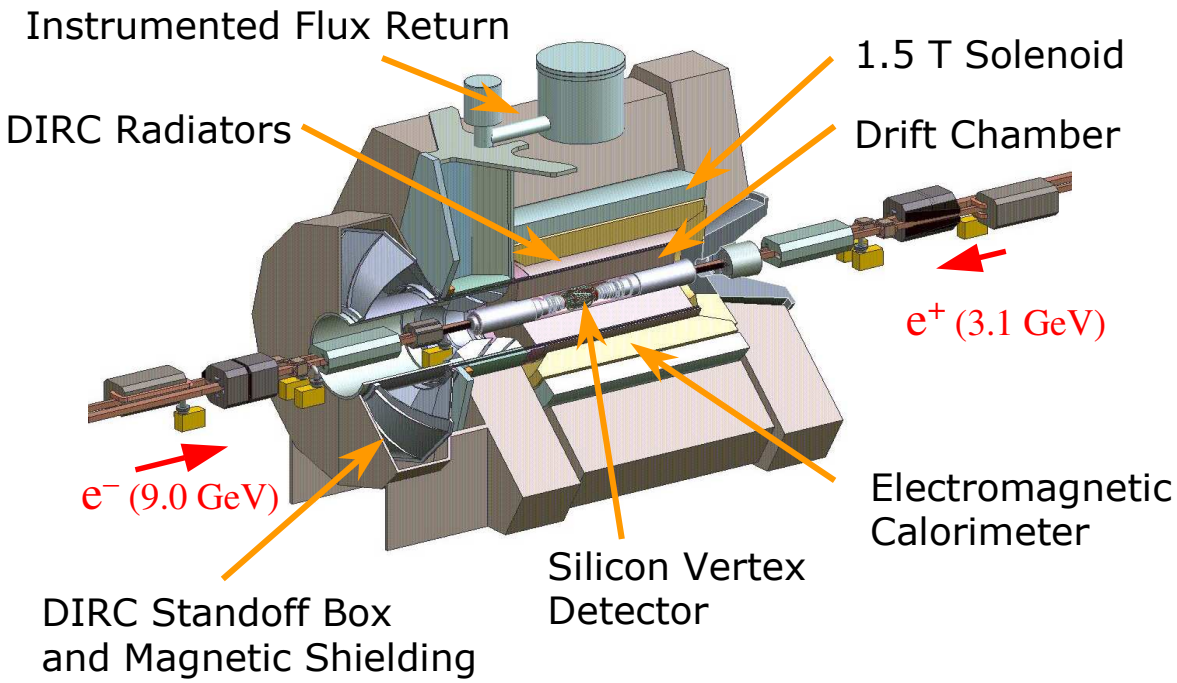
$$\Delta t^2 \sim \Delta t^2_{PMT} \sim (1.7\ \text{ns})^2$$

per track:

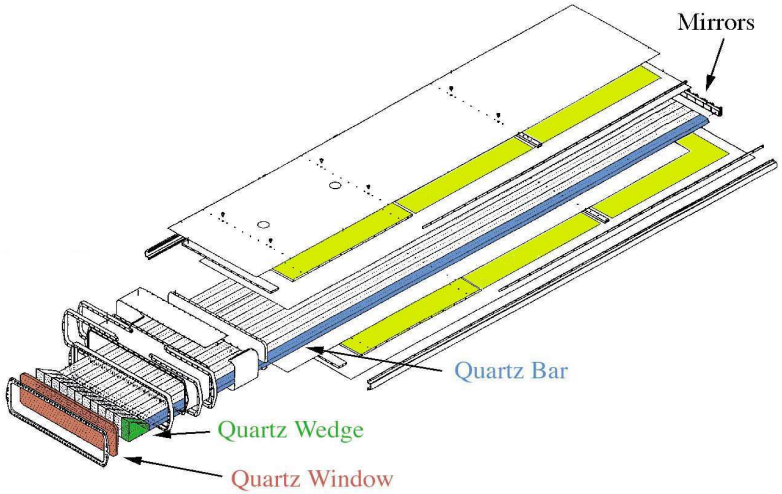
$$\Delta\theta^{track}_C \sim \Delta\theta^{photon}_C/\text{sqrt}(N_{photons\text{-}per\text{-}track}) \oplus \Delta\theta^2_{C,track}$$

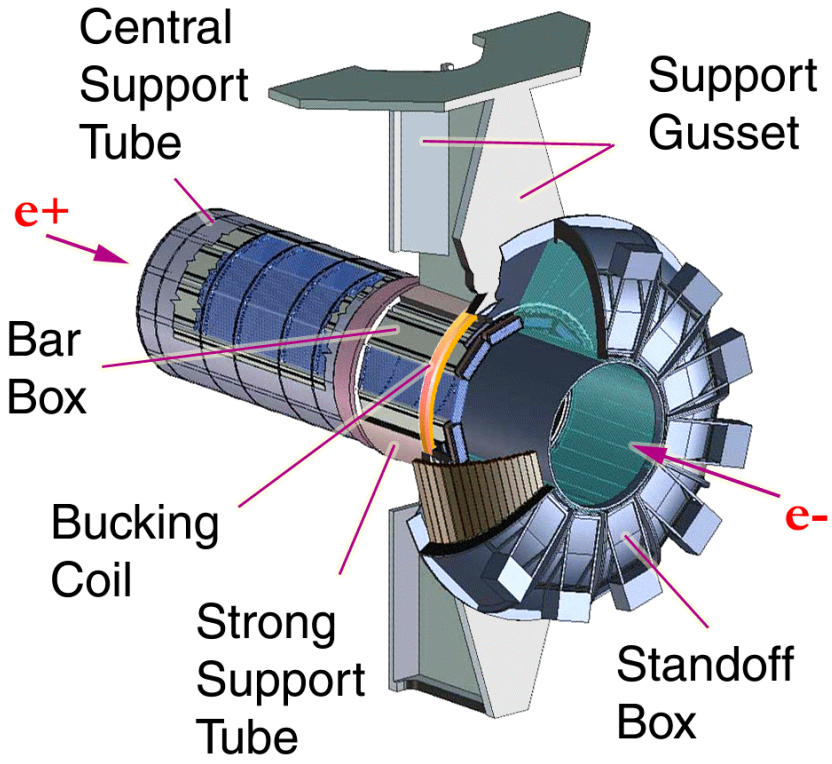


THE DIRC IN BABAR



DIRC thickness:
8 cm radial incl. supports
19% radiation length
at normal incidence
DIRC radiators cover:
94% azimuth,
83% c.m. polar angle





DIRC RECONSTRUCTION

DIRC "Ring" images:

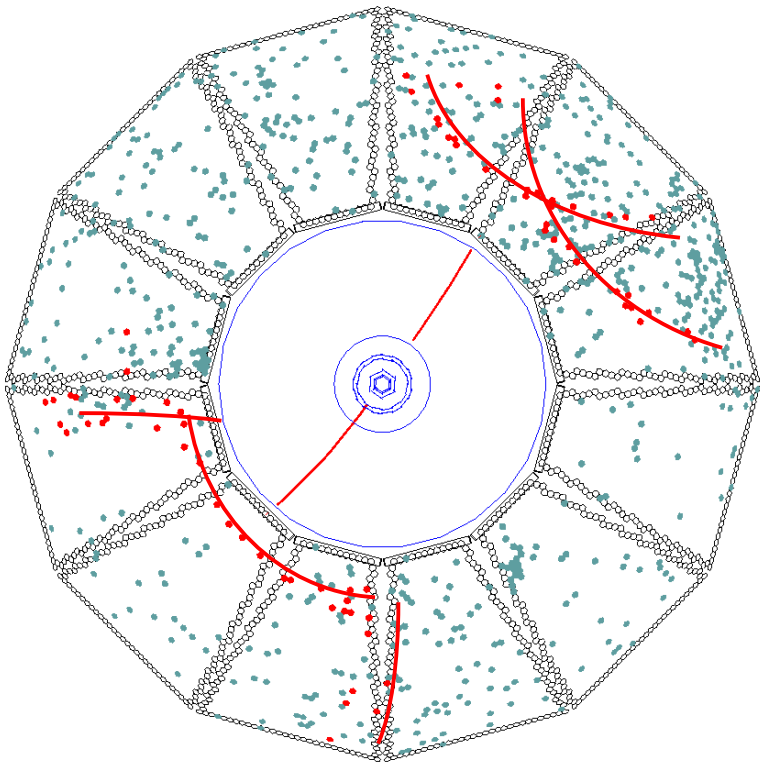
- limited acceptance for total internal reflection,
- reflection ambiguities (initial reflection up/down, left/right, reflection off mirror, wedge

→ up to 16 nominal (θ_c, ϕ_c) ambiguities per PMT hit),

- toroidal detection surface,

→ Cherenkov ring images are distorted:

complex, disjoint images



Low energy photons from accelerator hit Standoff Box.

At current luminosity this causes rates of ~80-100 kHz/tube.

80-100 kHz ⊗ 10,752 PMTs ⊗ ± 300 nsec trigger window

→ 500-600 background hits (~5-10% occupancy)

compared to

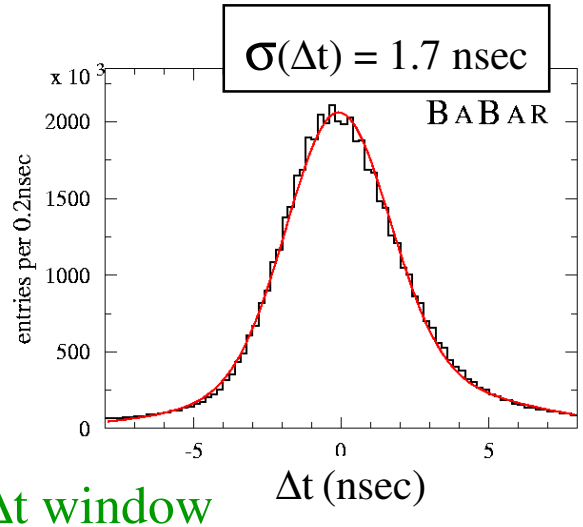
50-300 Cherenkov photons

DIRC RECONSTRUCTION

Time information provides powerful tool to reject accelerator and event related background.

Calculate expected arrival time of Cherenkov photon based on

- track TOF
- photon propagation in radiator bar and in water

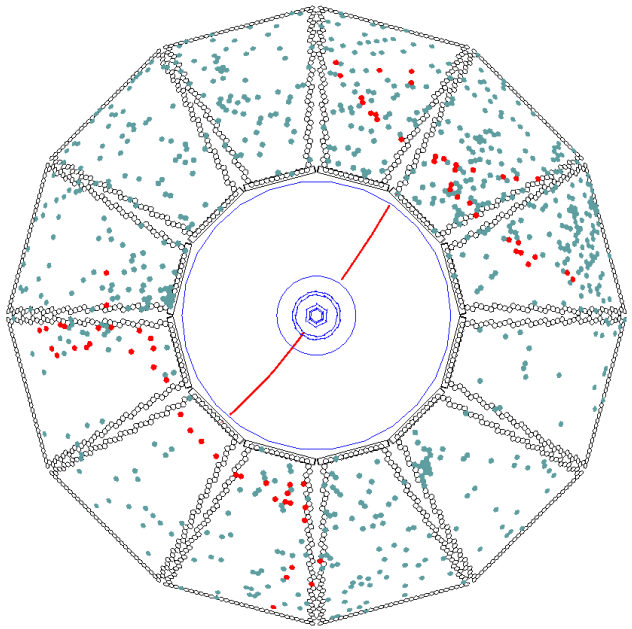


Δt: difference between measured and expected arrival time

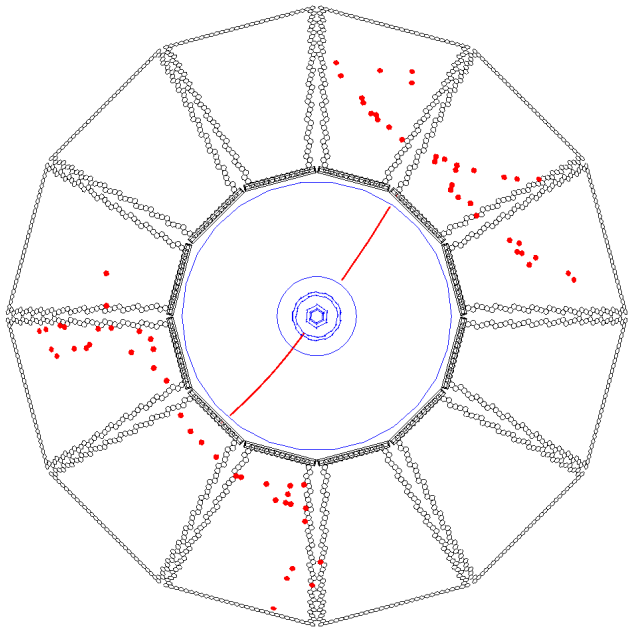
± 300 nsec trigger window
(~500-1300 background hits/event)

→

± 8 nsec Δt window
(1-2 background hits/sector/event)



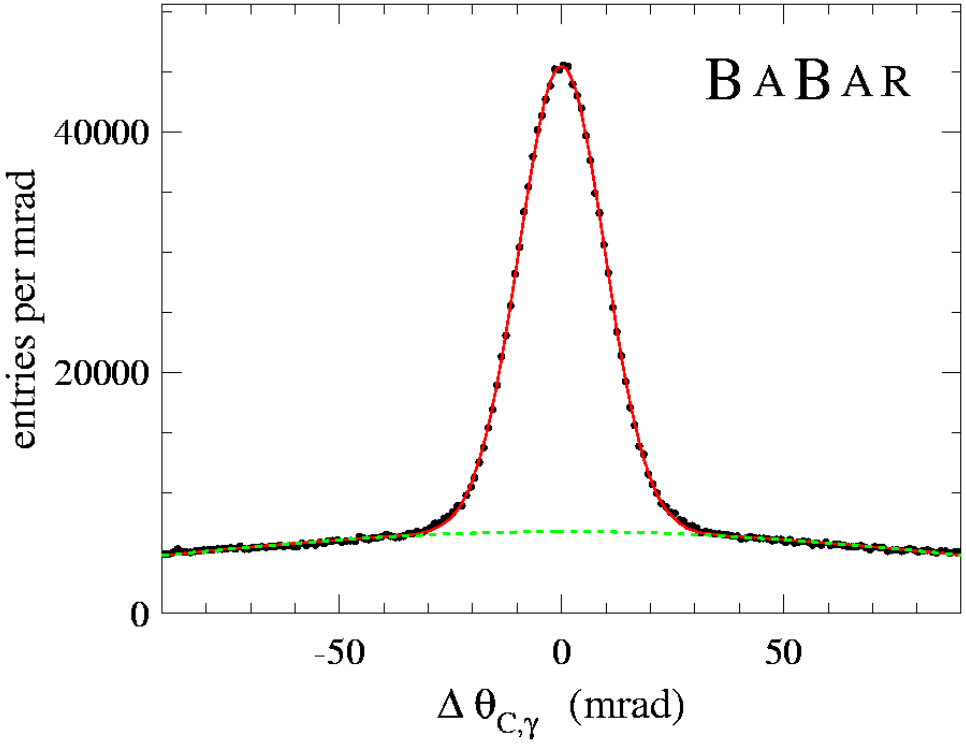
→



DIRC PERFORMANCE

Single Photon Cherenkov angle resolution:

$\Delta\theta_{c,\gamma}$: difference measured $\theta_{c,\gamma}$ per photon solution and θ_c of track fit (di-muons)



$\sigma(\Delta\theta_{c,\gamma}) = 9.6$ mrad

Expectation: ~9.5 mrad

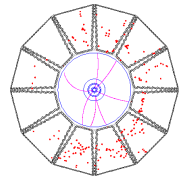
dominated by:

7mrad from PMT/bar size,
5.4mrad from chromatic term,
2-3mrad from bar imperfections.

~10% Background under $\Delta\theta_{c,\gamma}$ peak:

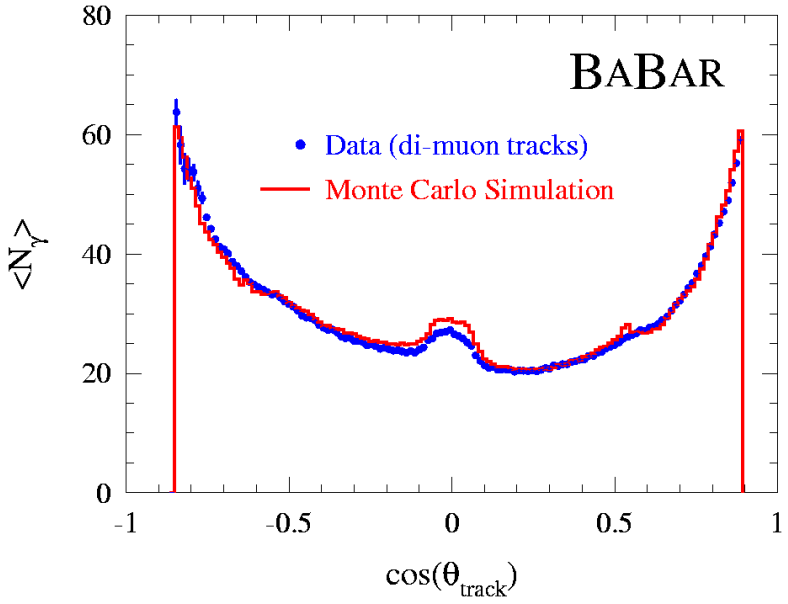
combinatoric background, track overlap, accelerator background,

δ electrons in radiator bar, reflections at fused silica/glue interface, ...



DIRC PERFORMANCE

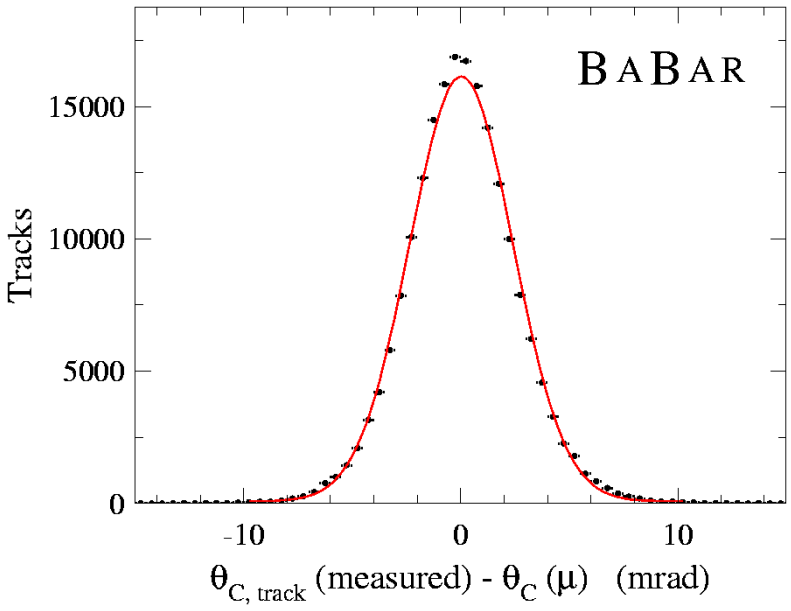
Number of Cherenkov photons per track (di-muons) *vs.* polar angle:



Between 20 and 60 signal photons per track.

Very useful feature in BABAR environment:
higher momentum correlated with larger polar angle values
→ more signal photons, better resolution (~ $1/\sqrt{N}$)

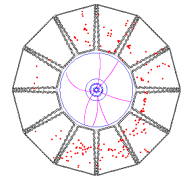
Resolution of Cherenkov angle fit per track (di-muons):



$\sigma(\Delta\theta_{c,}) = 2.4$ mrad

Track Cherenkov angle resolution is within ~10% of design.

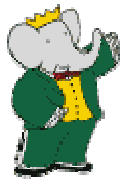
Should improve with advances in track- and DIRC-internal alignment.

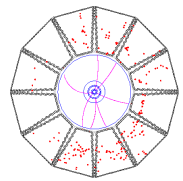


DIRC is Stable and Robust

Two Most Significant Operational Issues That Have Emerged During Two Years of Running:

- Sensitivity of the DIRC DAQ to machine background interacting in the SOB.
- Concerns about PMT longevity due to PMT window degradation.





DIRC OPERATIONAL EXPERIENCE: PMT STABILITY

PMT front window corrosion

•Discovered after ~ 1 year immersion Oct. 99.

•Status Oct. 99: ~ 50 *frosty* tubes and ~ 2/3 visibly *milky*.

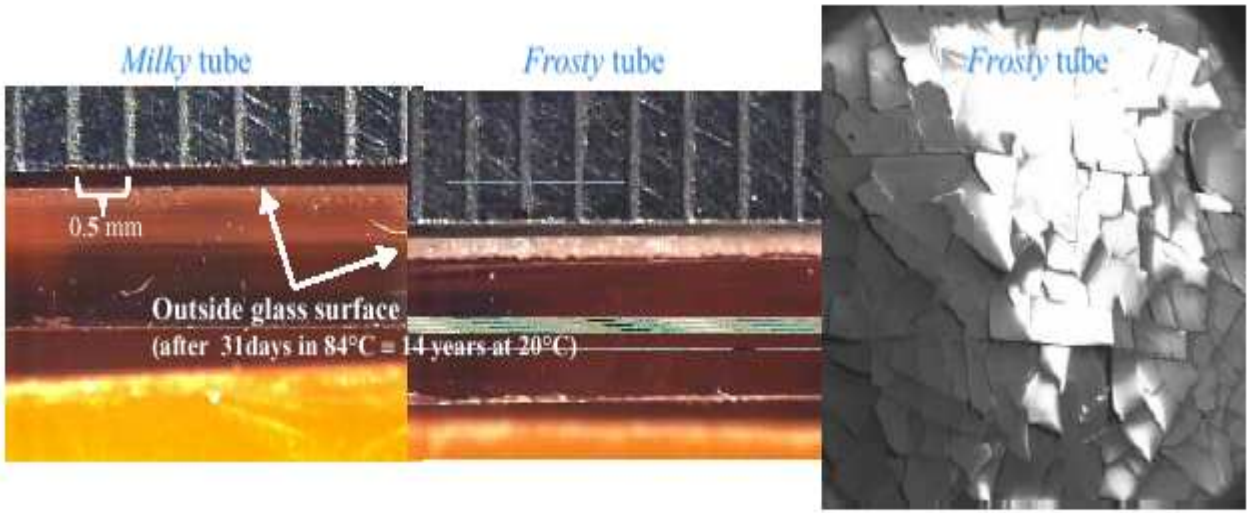
•Studies => -Strongly corroded (*frosty*) tubes are a bad batch of PMT glass (no zinc)

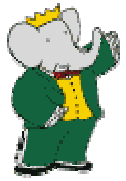
-*Milki*ness results from sodium depletion in near surface

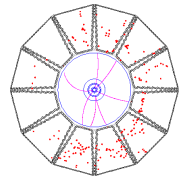
NO obvious immediate effect but……

⇒Might lose PMT efficiency with time.

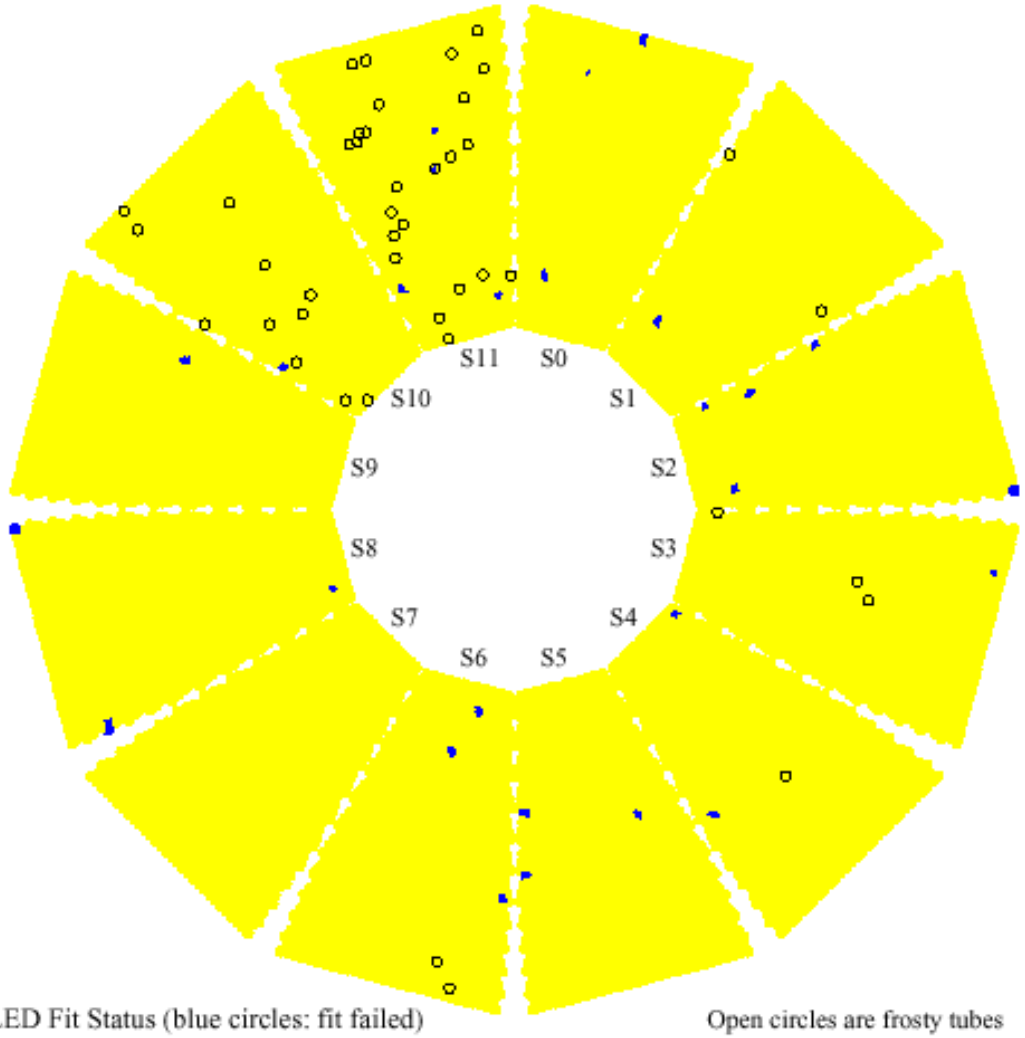
⇒Might lose vacuum in some of the ~ 50 *frosty* tubes on 10 year time scale.







Status of PMTs in DIRC



LED Fit Status (blue circles: fit failed)

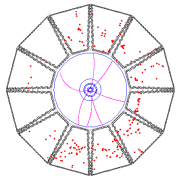
Open circles are frosty tubes

PMT STATUS

OBTAINED FROM CALIBRATION

Blue circles are dead channels

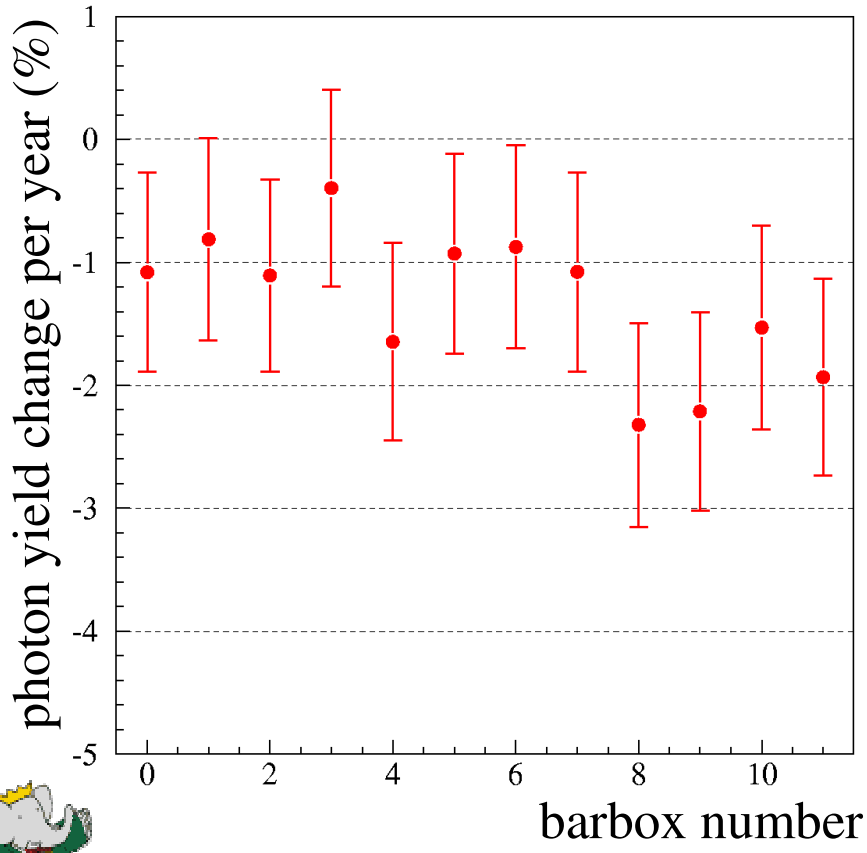
Open circles are frosty tubes



DIRC OPERATIONAL EXPERIENCE: PHOTON YIELD

Concern: stability of photon yield

- Observed PMT front glass corrosion;
- No direct experience with maintaining high (>0.999) radiator reflection coefficient for 10 years.



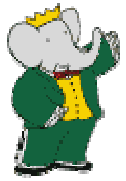
Detailed study of photon yield using:

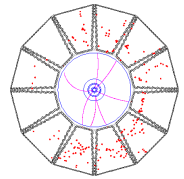
- LED pulser calibration,
- PMT aging tests,
- comparison of photon yield in real Bhabha and di-muon events separately for every radiator bar (box).

Consistent result:

1-2% photon yield loss per year.

→ very minor impact on PID performance over 10 year lifetime of DIRC.





DIRC OPERATIONAL EXPERIENCE: BACKGROUNDS

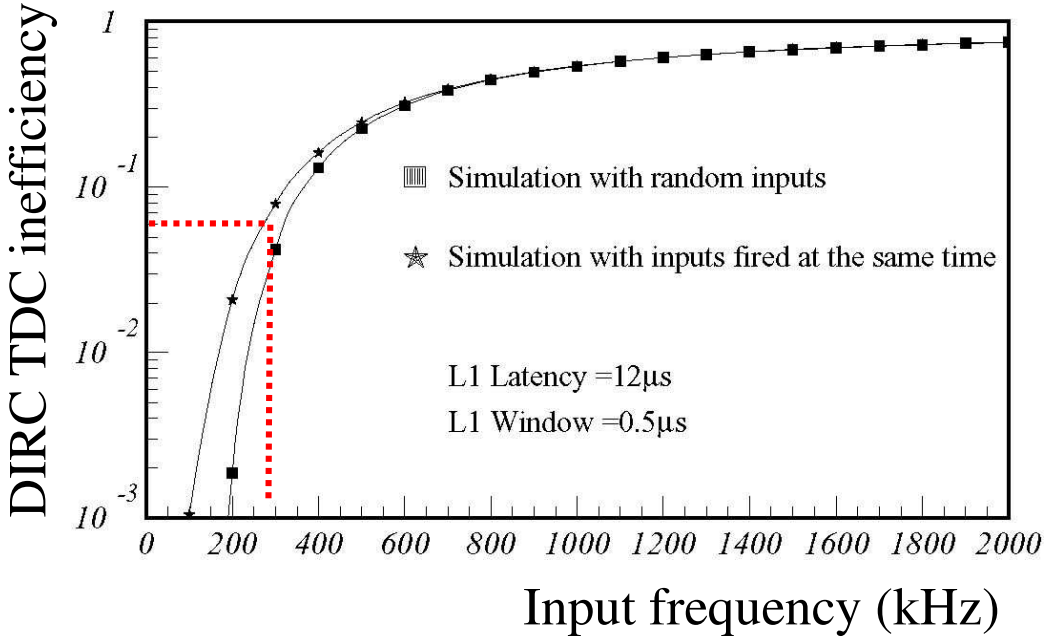
PEP-II Luminosity and currents are rapidly increasing

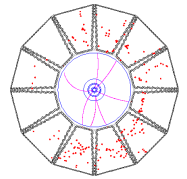
- $4*10^{33}$ /cm^2·s now,
- expect $>5*10^{33}$ /cm^2·s at the end of the 2001/2002 run,
- 1-2 $*10^{34}$ /cm^2·s in 2004/5;
- 10^{35} - 10^{36} /cm^2·s discussed ("SuperBABAR").

Δt cut very effective in removing accelerator induced background from reconstruction.

But high counting rates cause inefficiency of present DIRC DAQ:

~5% inefficiency at 250 kHz

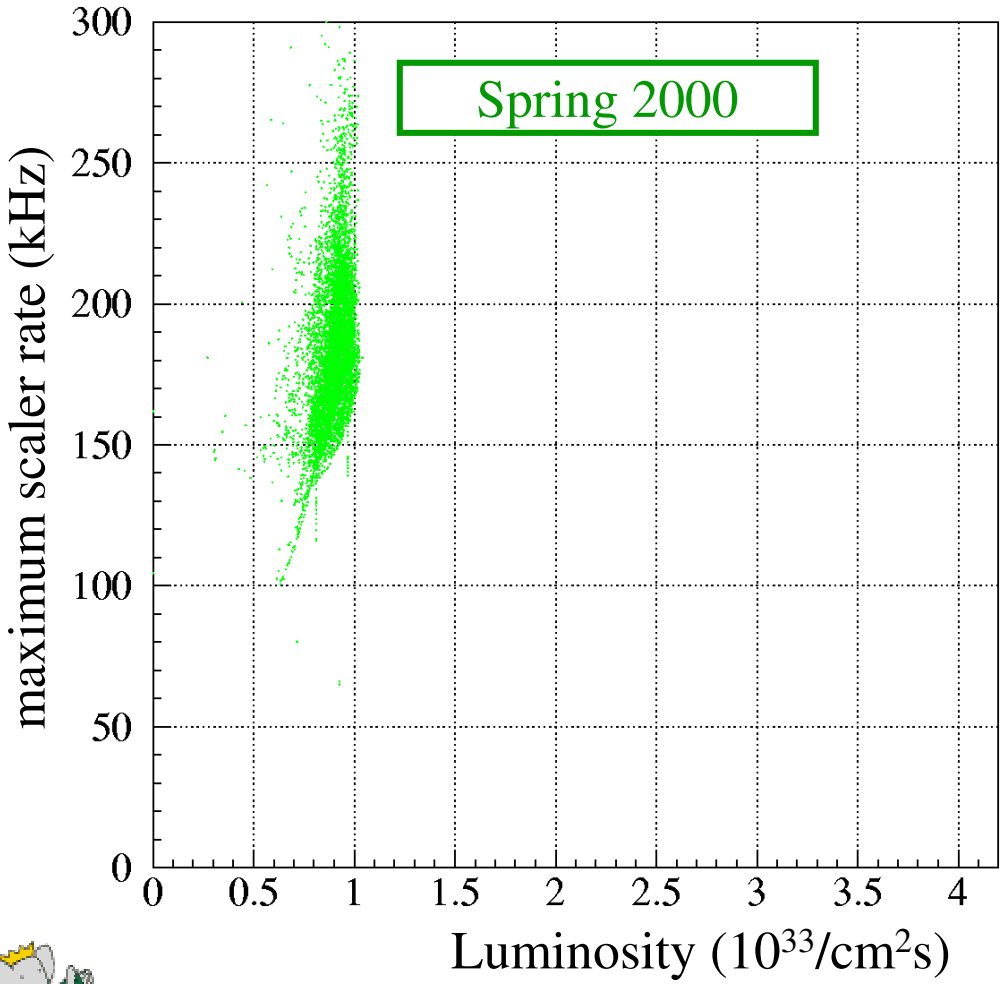




DIRC OPERATIONAL EXPERIENCE: BACKGROUNDS

Monitor background rates:

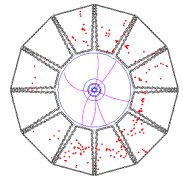
one PMT/sector is read out via scaler, available online,
used in slow control (current operational limit 400kHz).



Status during early BABAR running:

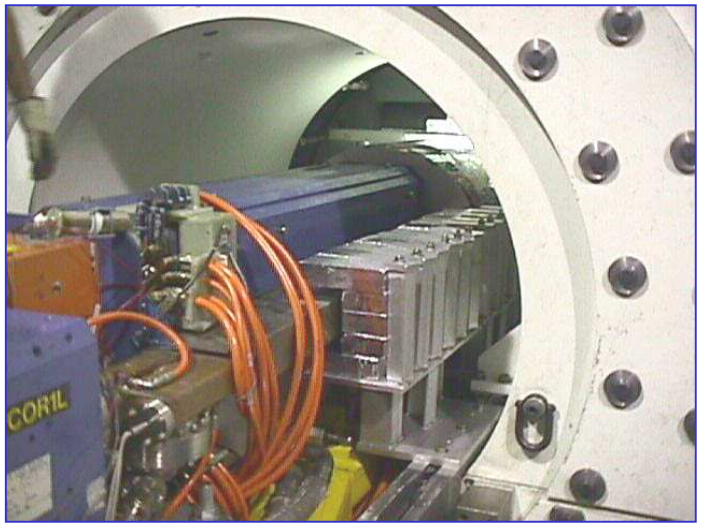
rates of >250kHz causing
noticeable TDC deadtimes
at 1/3 of design luminosity

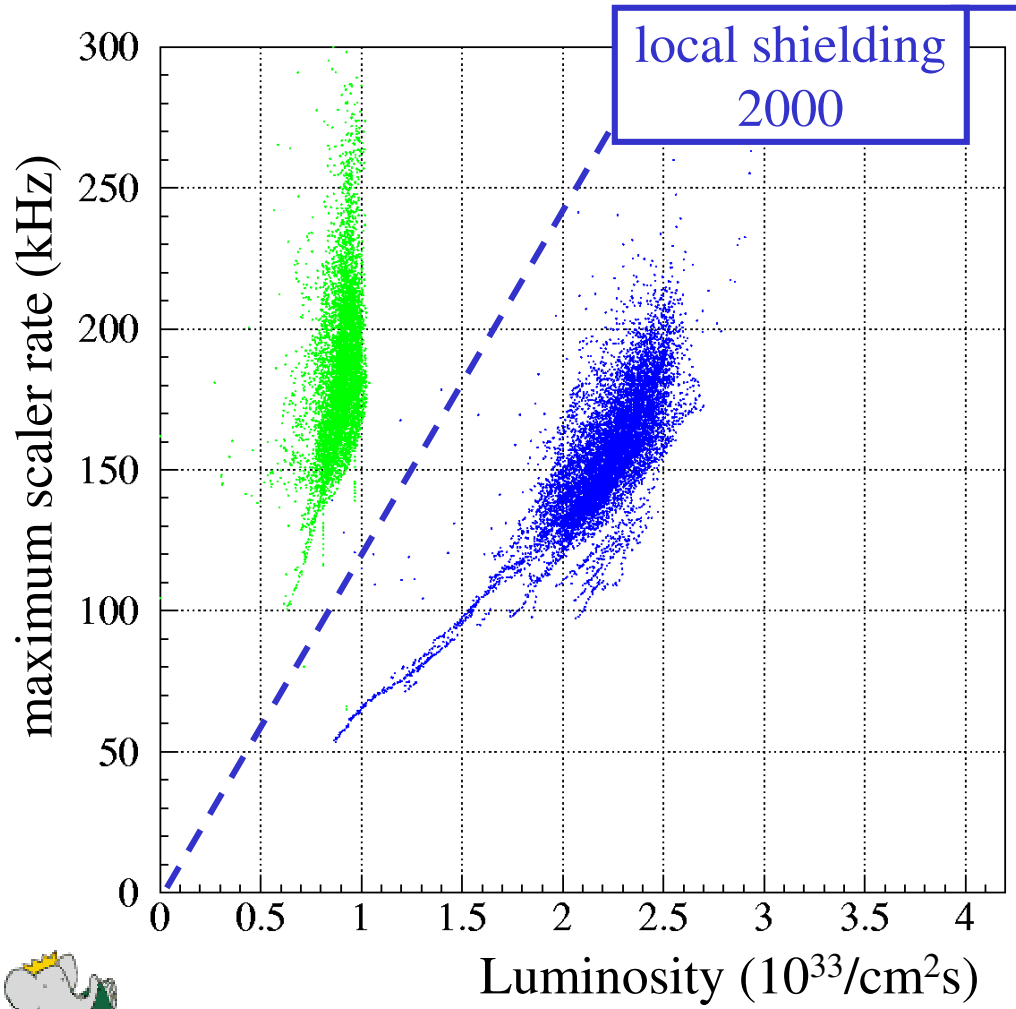
Started to install localized lead brick shielding to block potential background sources.



DIRC OPERATIONAL EXPERIENCE: BACKGROUNDS

Summer 2000 - 2000/2001 shutdown:
localized lead brick shielding around
beampipe and quadrupoles in BABAR





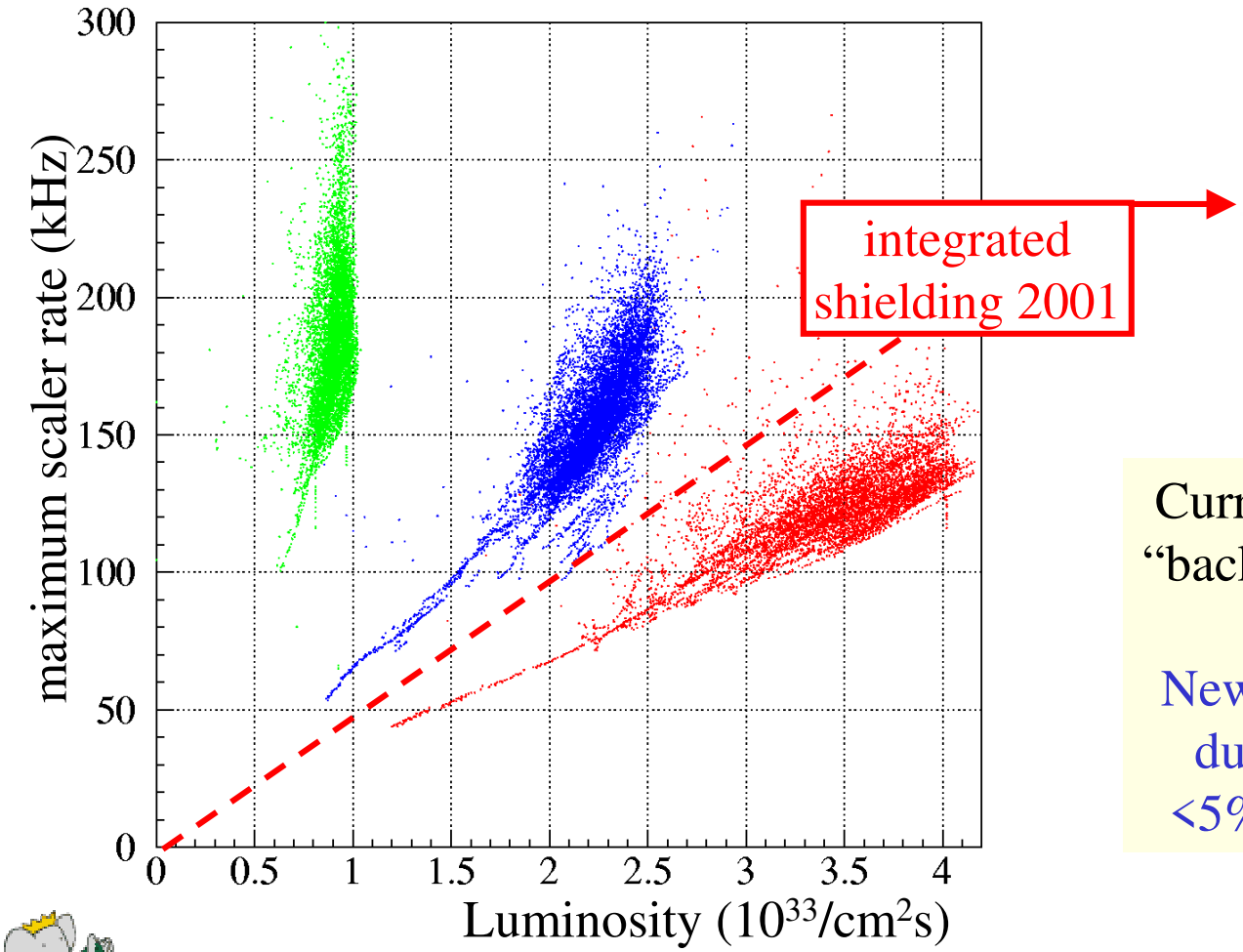
Rate vs. Luminosity showed that lead shielding essential in protecting DIRC from few MeV photon accelerator induced background.

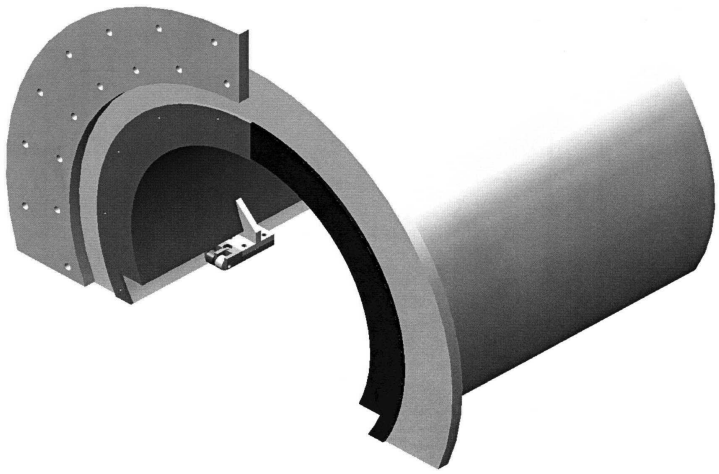
More uniform, complete shielding and easier access to detector required.

DIRC OPERATIONAL EXPERIENCE: BACKGROUNDS

In January 2001, installed new, more homogenous lead shielding (5-7cm of lead in upper 2/3, 2-3cm in lower 1/3 of shield).

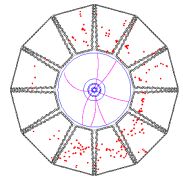
Scaler rates acceptable even above design lumi.



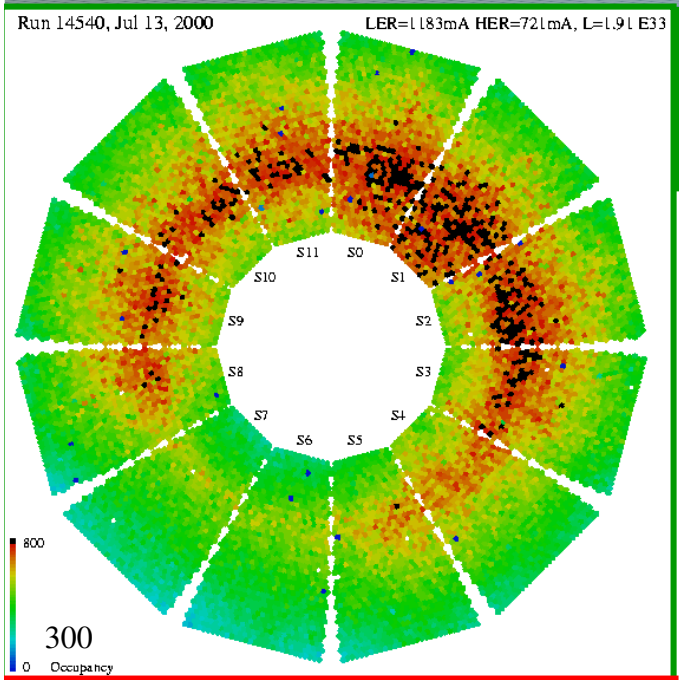


Current shielding configuration "background safe" through 2002.

New TDC chips to be installed during shutdown Fall 2002: <5% deadtime at 2.5MHz rate.

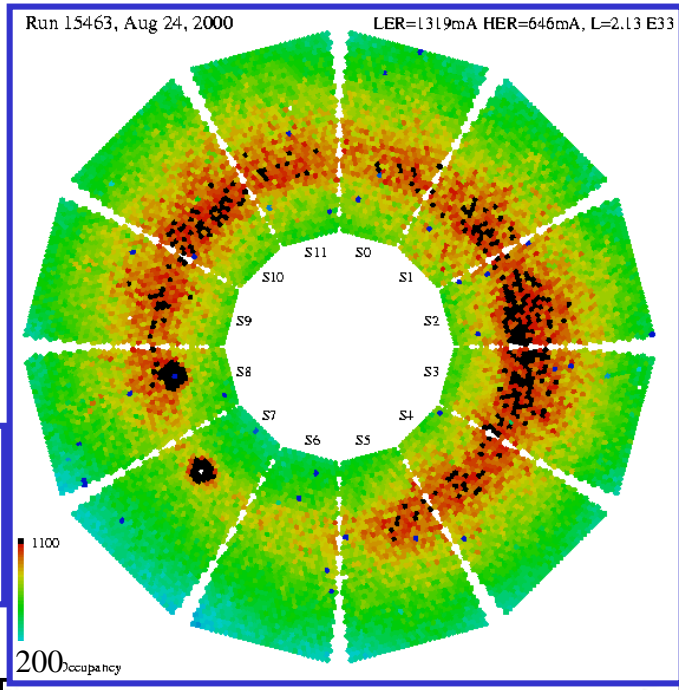


DIRC OPERATIONAL EXPERIENCE: OCCUPANCY

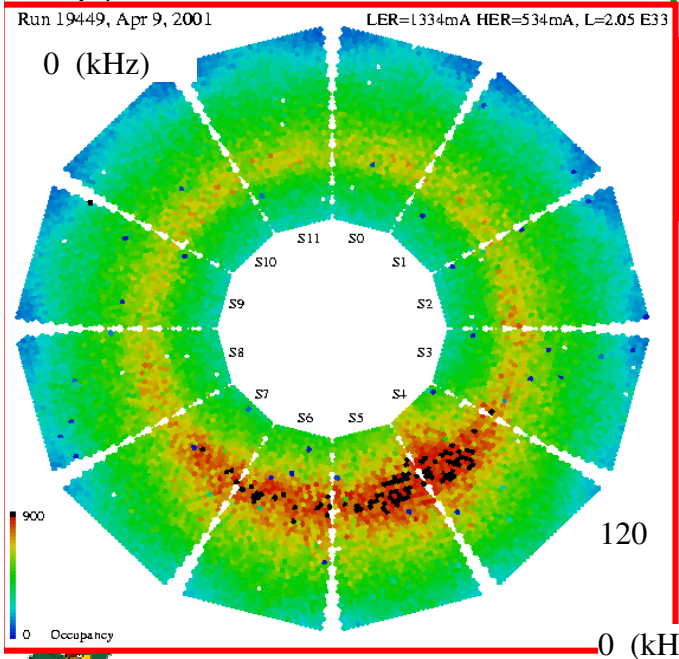


Early 2000.. No special shielding

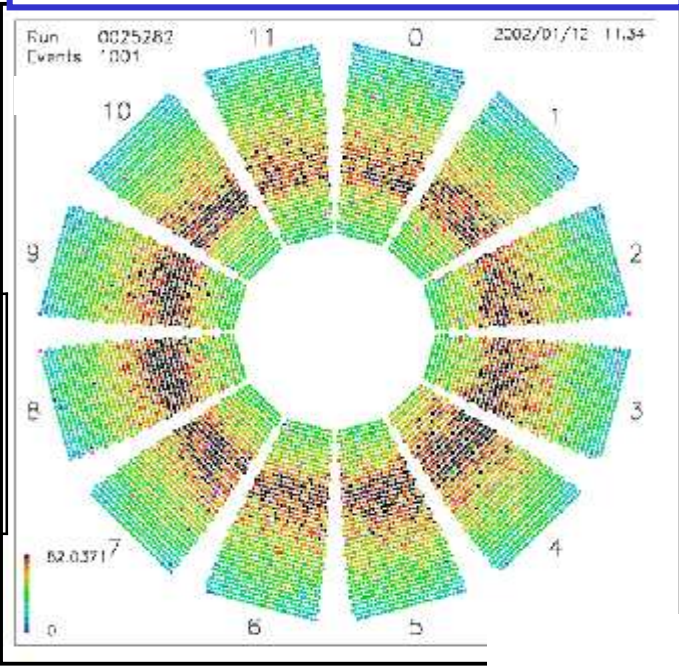
hot-cold scale: rate per PMT



Fall 2000 localized shielding



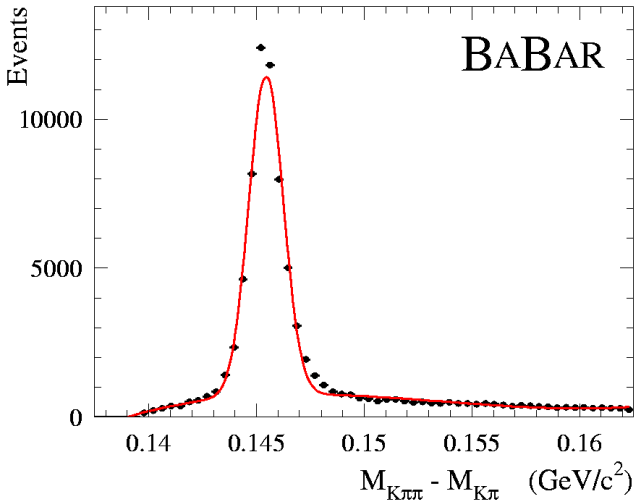
2001 integrated shielding

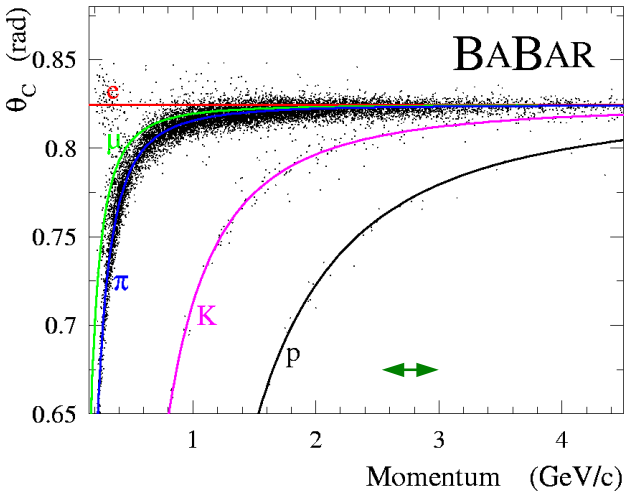


2002 integrated Shielding

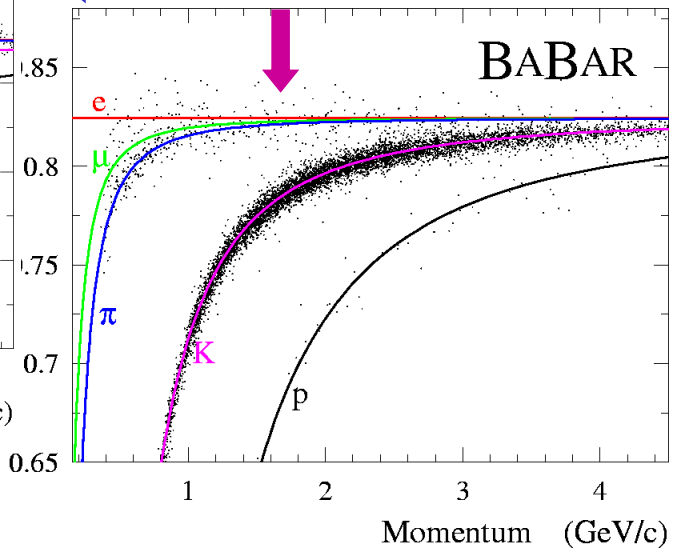
DIRC PARTICLE ID PERFORMANCE

$D^{*-} \rightarrow D^0 \pi^-$
$\hookrightarrow K^- \pi^+$

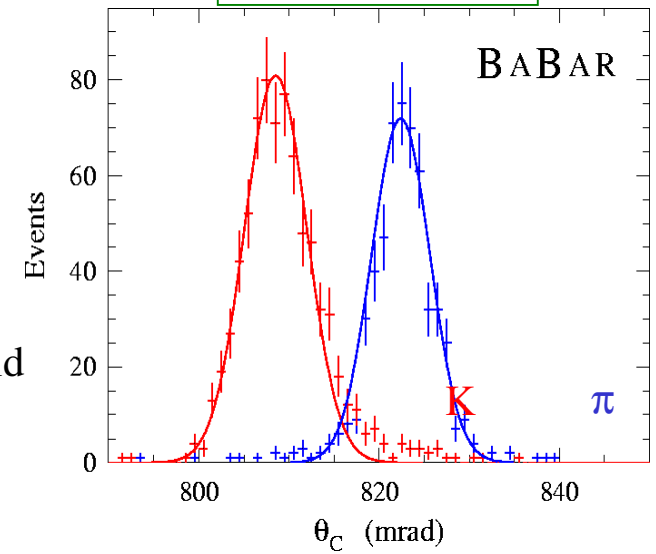


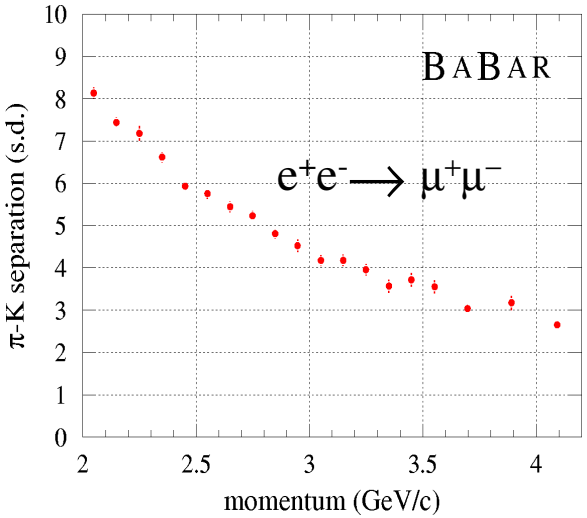


kinematically identified
π and K

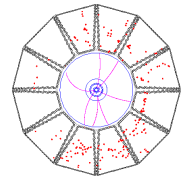


example:
2.5<|p|≤3GeV/c



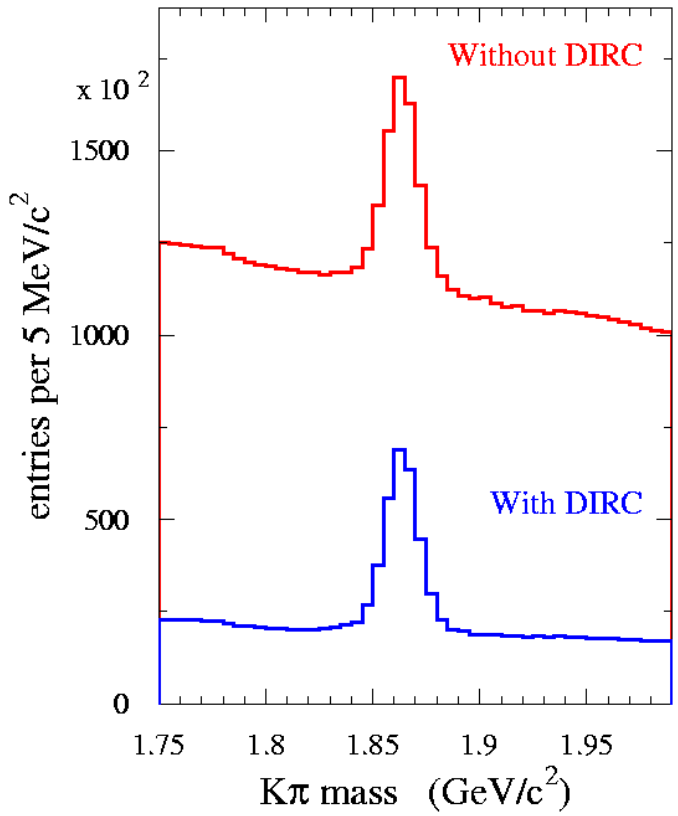


- Select D^0 candidate control sample with mass cut (±0.5 MeV/c^2)
- π and K are kinematically identified
- calculate selection efficiency and mis-id
- Correct for combinatorial background (avg. 6%) with sideband method.

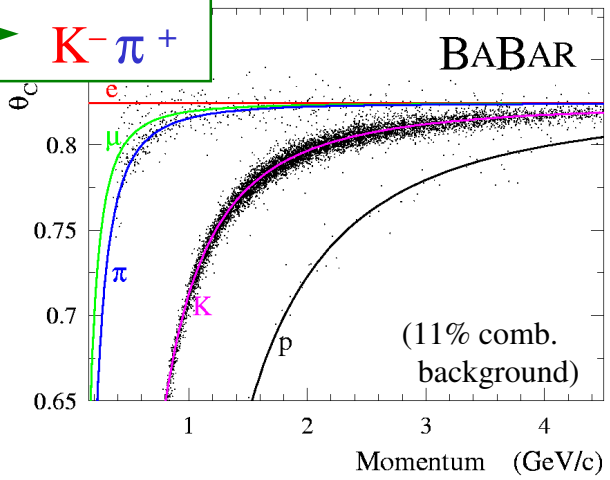


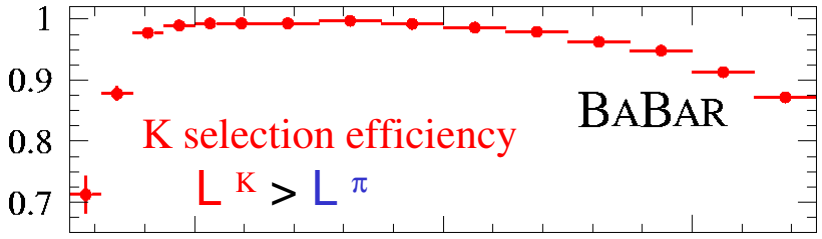
DIRC PARTICLE ID PERFORMANCE

$D^0 \rightarrow K^- \pi^+$

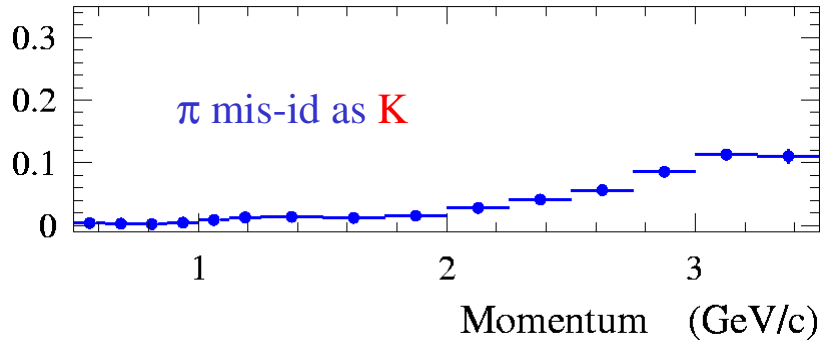


$D^{*-} \rightarrow D^0 \pi^-$
$\hookrightarrow K^- \pi^+$



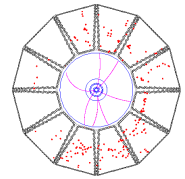


(track in DIRC fiducial, comb. background corrected)



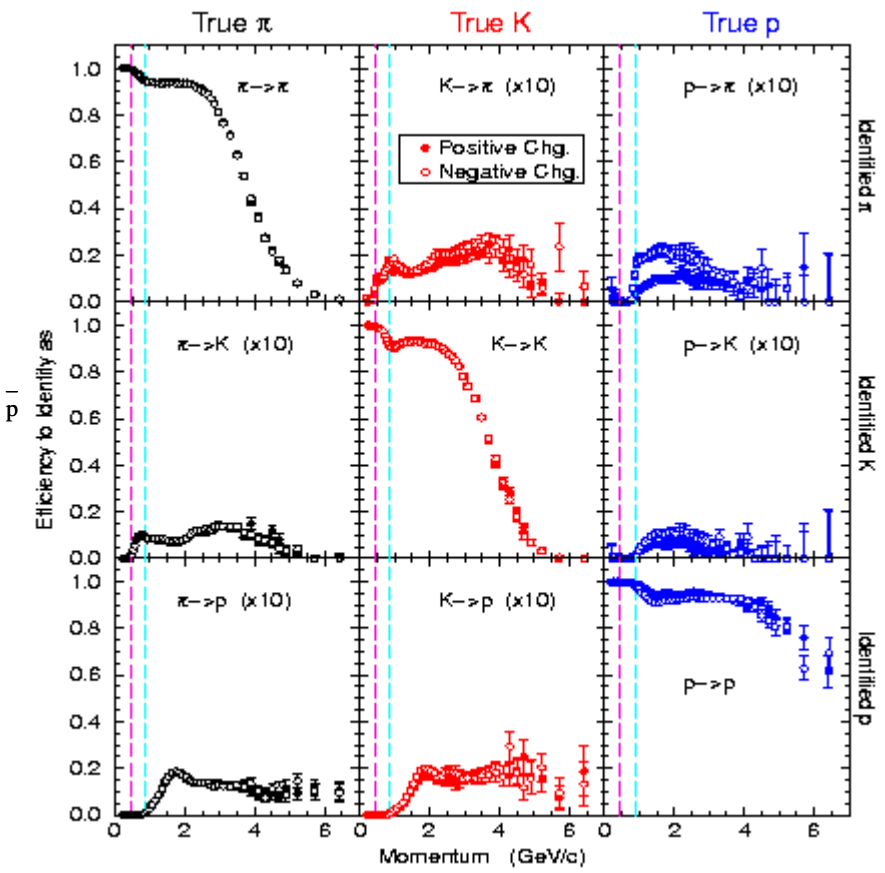
~200,000 D^0 reconstructed from 9 fb^{-1} of data.

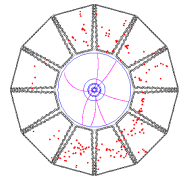
average K selection efficiency:	88%
average π mis-id:	2%
average rejection factor:	44



DIRC PERFORMANCE-Another View

- MC from Charged Hadron Spectra analysis.
- Cuts different than the "standard"….designed to keep Mis-ID <1-2% everywhere.
- In return, must accept somewhat lower ID efficiency especially a high momenta
- Note that $\bar{p}$ mis-ID> p mis-ID due to different interaction prob.?





CONCLUSIONS

•>30 months of experience in PEP-II/BABAR B-factory mode: DIRC hardware is robust and easy to operate.

•Performance is near design. Photon yields are stable.

• Machine backgrounds at $5 \cdot 10^{33}/cm^2 \cdot s$ no problem for reconstruction;
will install new TDC chips during Fall 2002 shutdown (to allow > 2 x $10^{34}/cm^2 \cdot s$ luminosity).

•Upgrade path to very high Luminosity under study.