The Super$B$ Detector Confronts New Physics

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Elba Super$B$ Meeting

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- This talk will address general design considerations for detector for a 10^{36} collider like Super$B$ in light of the main physics goals of the experiment
  - Note that detector technology issues for Super$B$, a low-emittance, "low current" collider, may be quite distinct from those for a high current machine such as SuperKEKB
- The marquee physics goals are different from those of BABAR/Belle
- We are also not starting with a blank sheet of paper: rather, we are constrained to use BABAR as the basis of an upgrade
- Can we, with such an upgraded detector, reach the appropriate levels of sensitivity to be able to address the new, more demanding requirements of e^+e^- flavour physics in the LHC era?

The two other talks in this session, by Bill Wisniewski and Hassan Jawahery, will cover different aspects of the detector design

Primary physics questions for a Super Flavour Factory

- Are there new *CP*-violating phases ?
- Are there new right-handed currents ?
- Are there new loop contributions to flavour-changing neutral currents
- Are there new Higgs fields ?
- Is there charged lepton flavour violation ?
- Is there a new flavour symmetry that elucidates the CKM hierarchy ?

- What are the requirements for a detector that can address these questions in a 10^{36} asymmetric e^+e^- environment ?

Benchmark physics examples

- Rare CP-violating decays: $B^0 \to \phi K_S^0, \eta' K_S^0$
- Rare B decays containing leptons: $B \to \tau\nu$
- $D^0\bar{D}^0$ mixing events, search for CP asymmetry $\psi(3770)$

$$D^0 \to K^{\pm}\pi^{\mp}, K^{\pm}K^{\mp}, \pi^{\pm}\pi^{\mp} \leftarrow \bar{D}^0$$

running

- Rare leptonic τ decays $\tau \to \mu\gamma,\ \tau \to \ell\ell\ell$
- τ decays with a polarized electron beam
  - Most τ decay final states are useful for analyzing τ polarization
- New spectroscopy searches D^* efficiency

- Two approaches to optimization
  - Simulate specific channels
  - Abstract main characteristics of benchmark decays and their ascertain their influence on detector system components

Required functionality and detector attributes

Function	Requirement
Recoil technique efficiency	Solid angle coverage for tracking, photons with good resolution, particle ID. Hermeticity
Flavor tagging	K, μ, e ID (high efficiency, low misID)
m_{ES}, ΔE resolution	p resolution, at high and low p_T $\Rightarrow$ low multiple scattering π^0 mass, momentum resolution
Vertex resolution	A_{CP}, rejection of charm background
D^* reconstruction efficiency	Efficient low p track reconstruction
Lepton ID	High efficiency, low misID
K_S, reconstruction efficiency	At least five layer SVT, sophisticated tracking
K_L " "	Hadron calorimeter coverage, angular res.
Measurement of e^- polarization	Can it be done *in situ* with data?

Trigger rates and DAQ

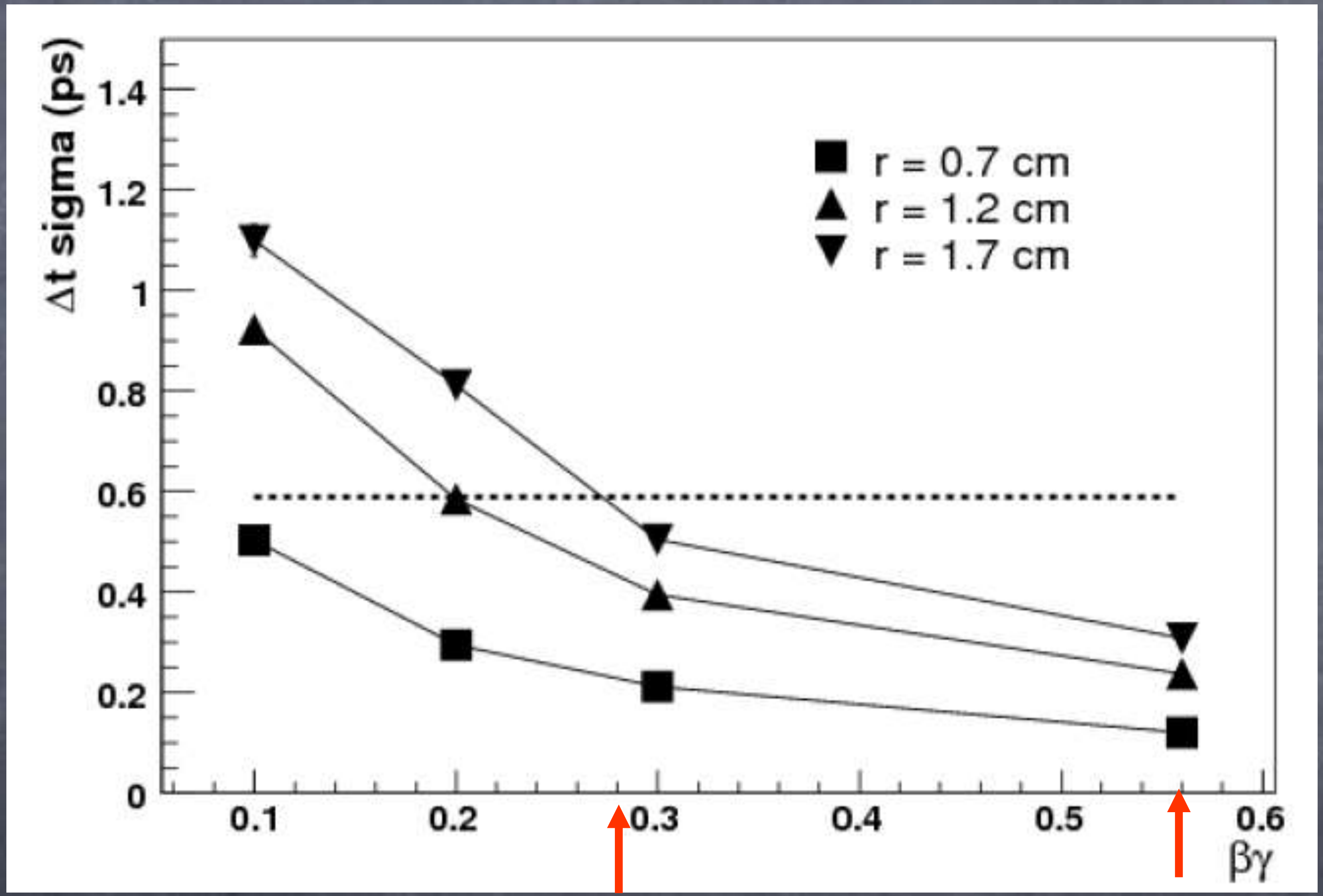
- Physics rates at 10^{36}

Process	Rate at $\mathcal{L} = 10^{36}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (kHz)
$\Upsilon(4S)\ to B\bar{B}$	1.1
$udsc$ continuum	3.4
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^- for $\lvert\cos\theta_{\mathrm{Lab}}\rvert < 0.95$	30

- Due to the low emittance design, a small radius beam pipe is feasible, allowing use of a reduced energy asymmetry
- Physics requirements are best met with an open trigger as is traditional in e^+e^-
- Demands on the trigger and DAQ are substantial, but can be met
- GPDF made a proposal on Saturday that meets the requirements

Choice of energy asymmetry

- Smaller Super*B* beam sizes at the IP allow the use of a smaller beam pipe
- This permits a thinner beam
- Smaller asymmetry improves solid angle coverage

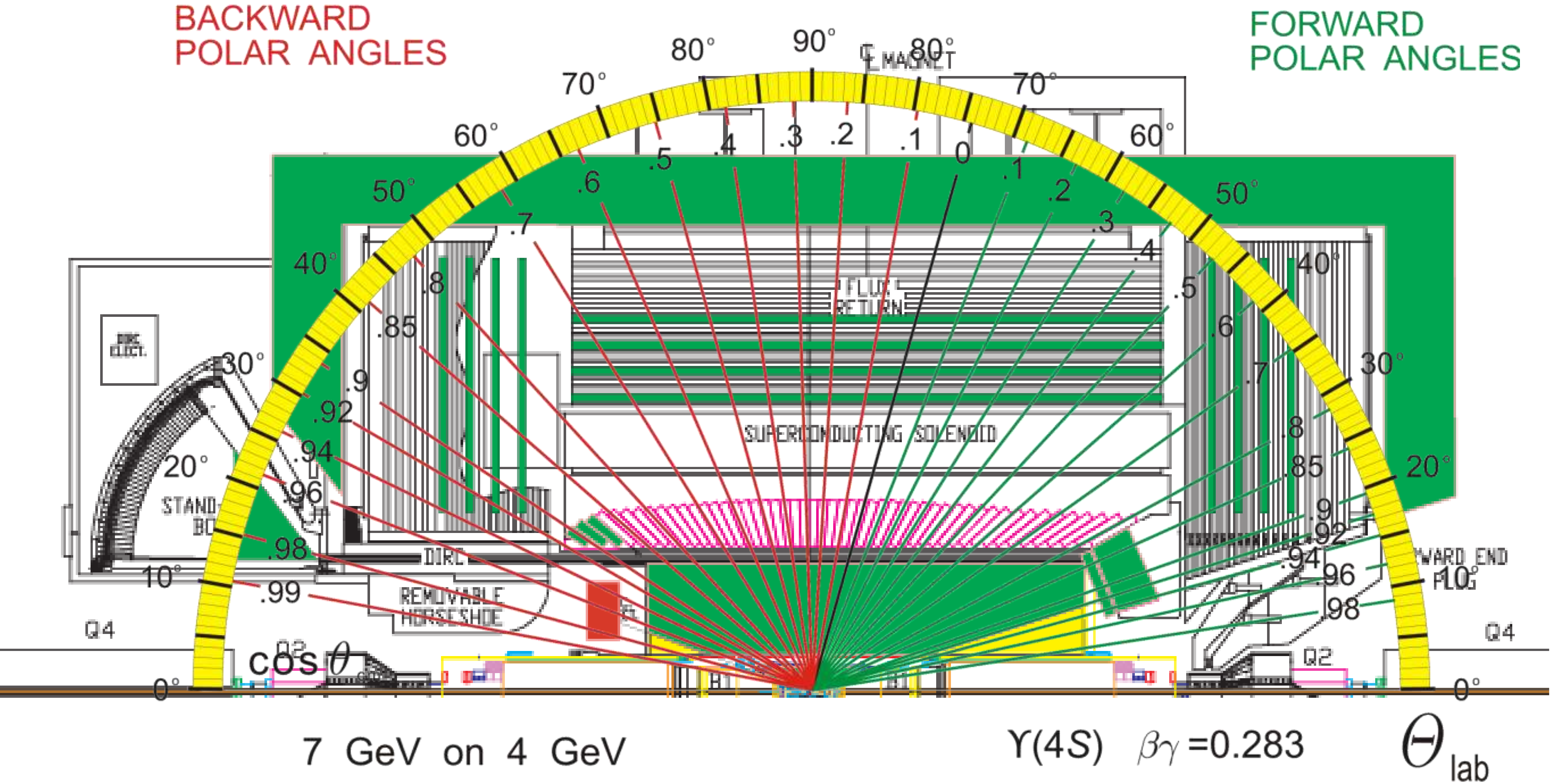


7x 4 GeV

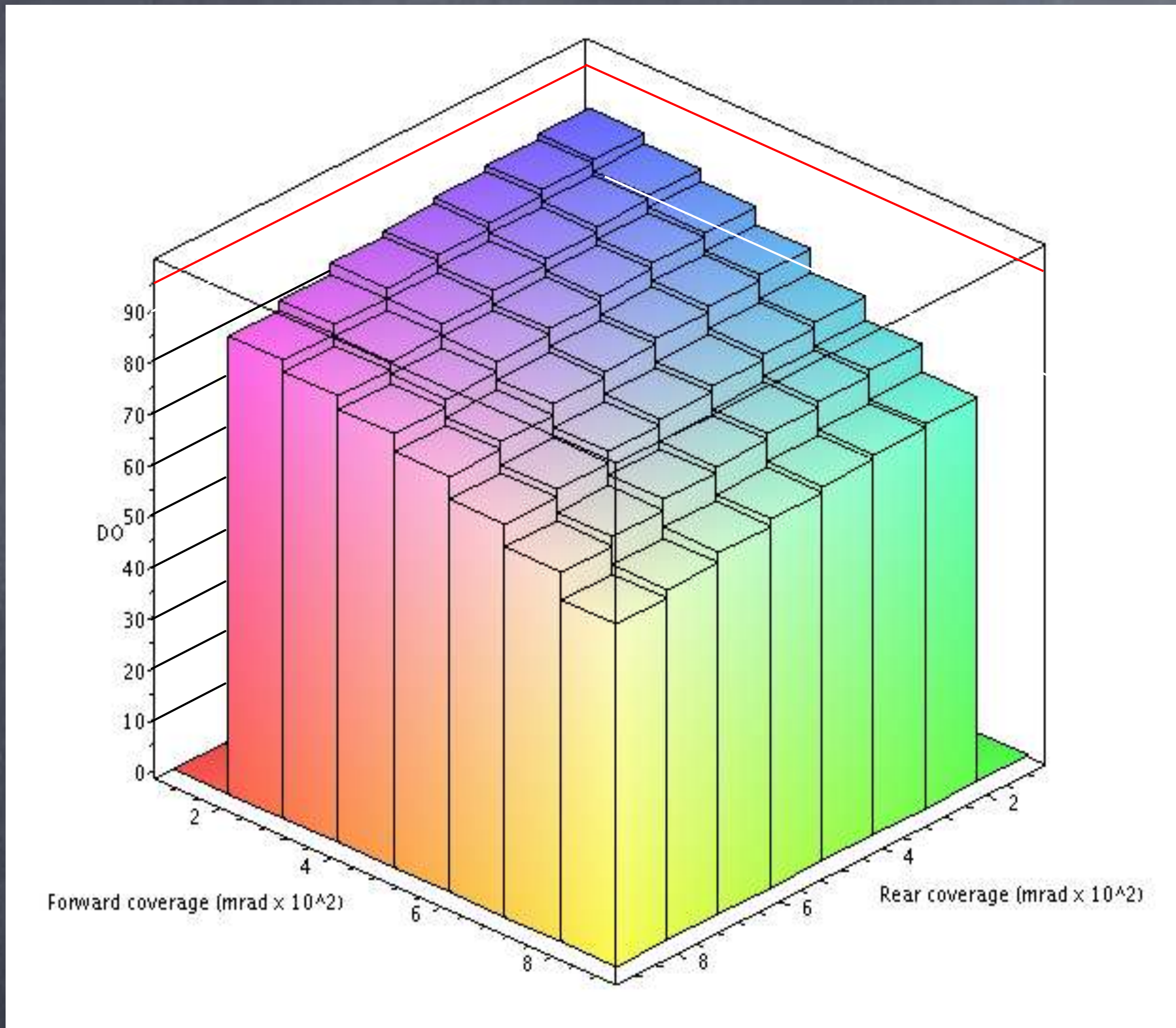
Boost $\beta\gamma$=.28

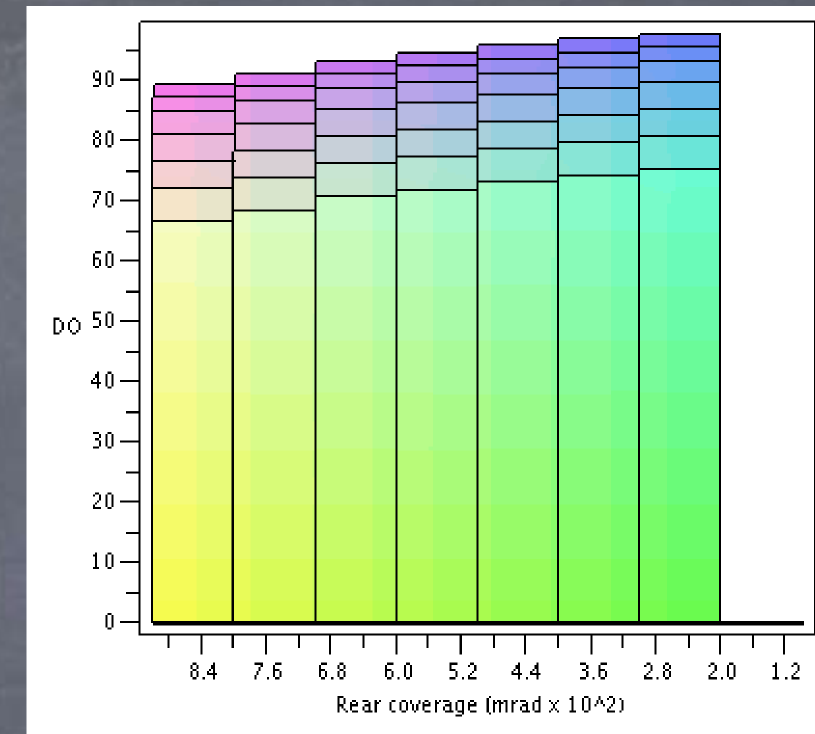
PEP-II: $\beta\gamma = 0.56$

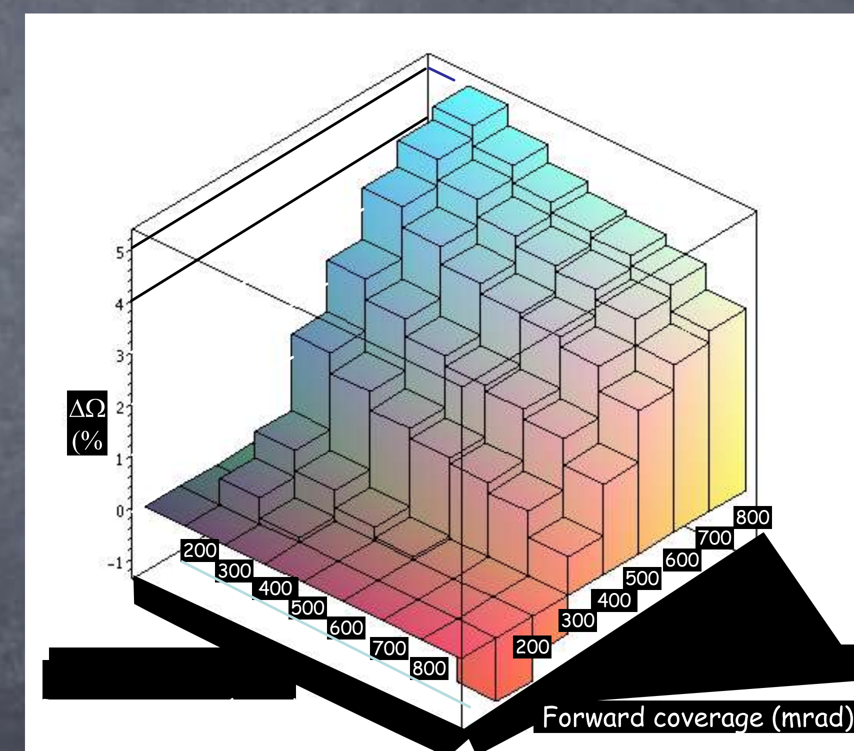
Detector Protractor - γ's



Solid angle (% of 4π)

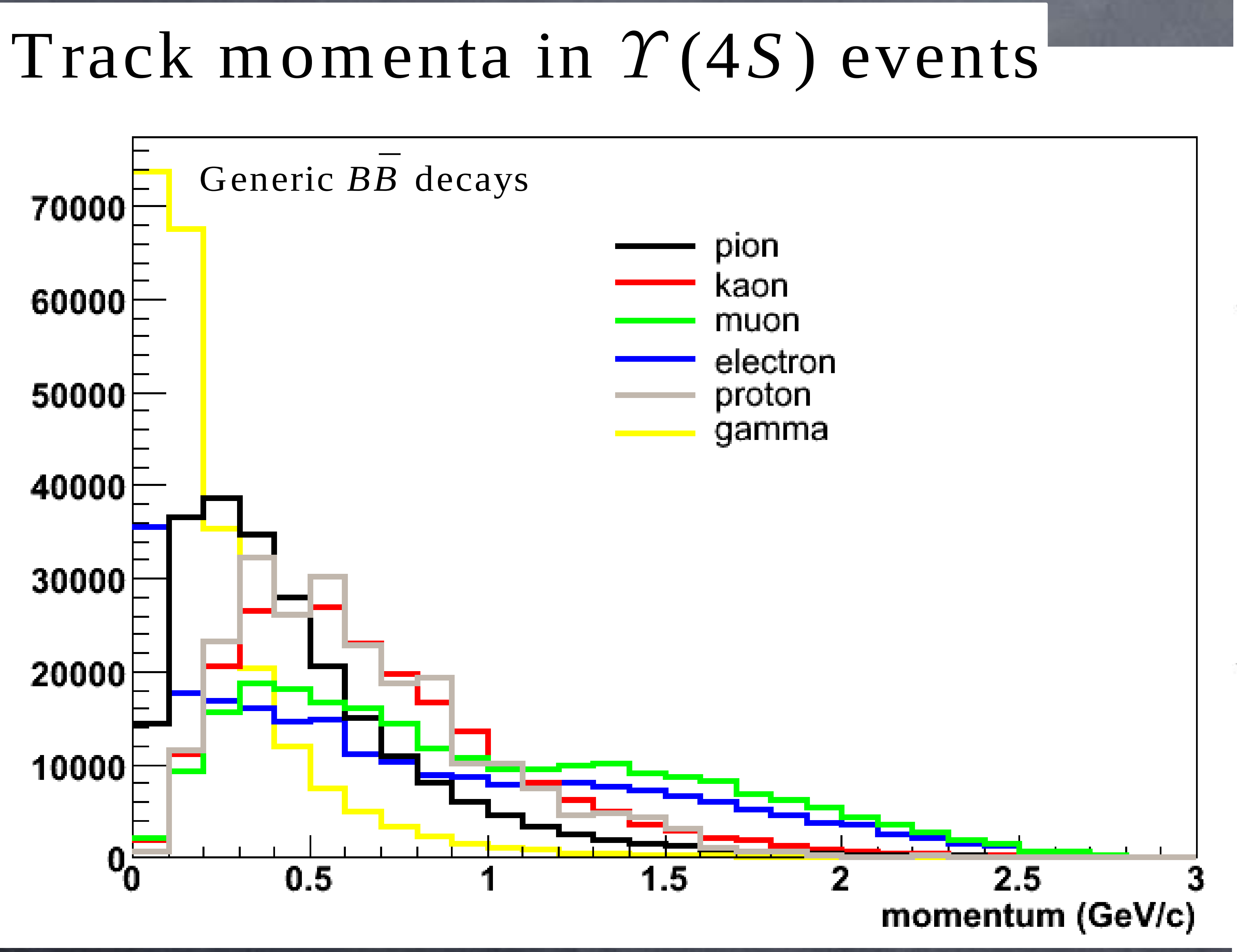


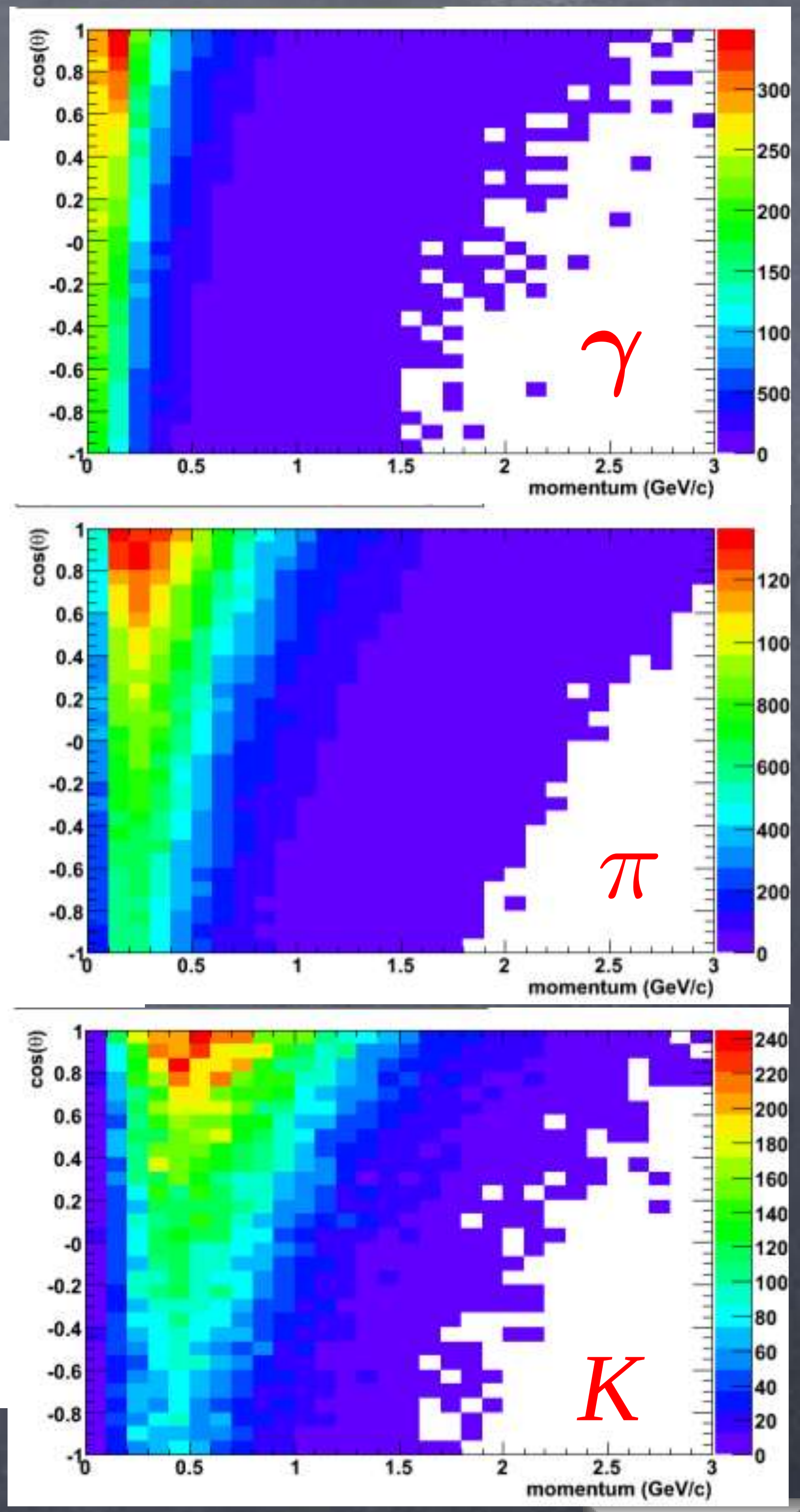




Coverage of *BABAR*: 300 mrad forward
600-700 mrad backward

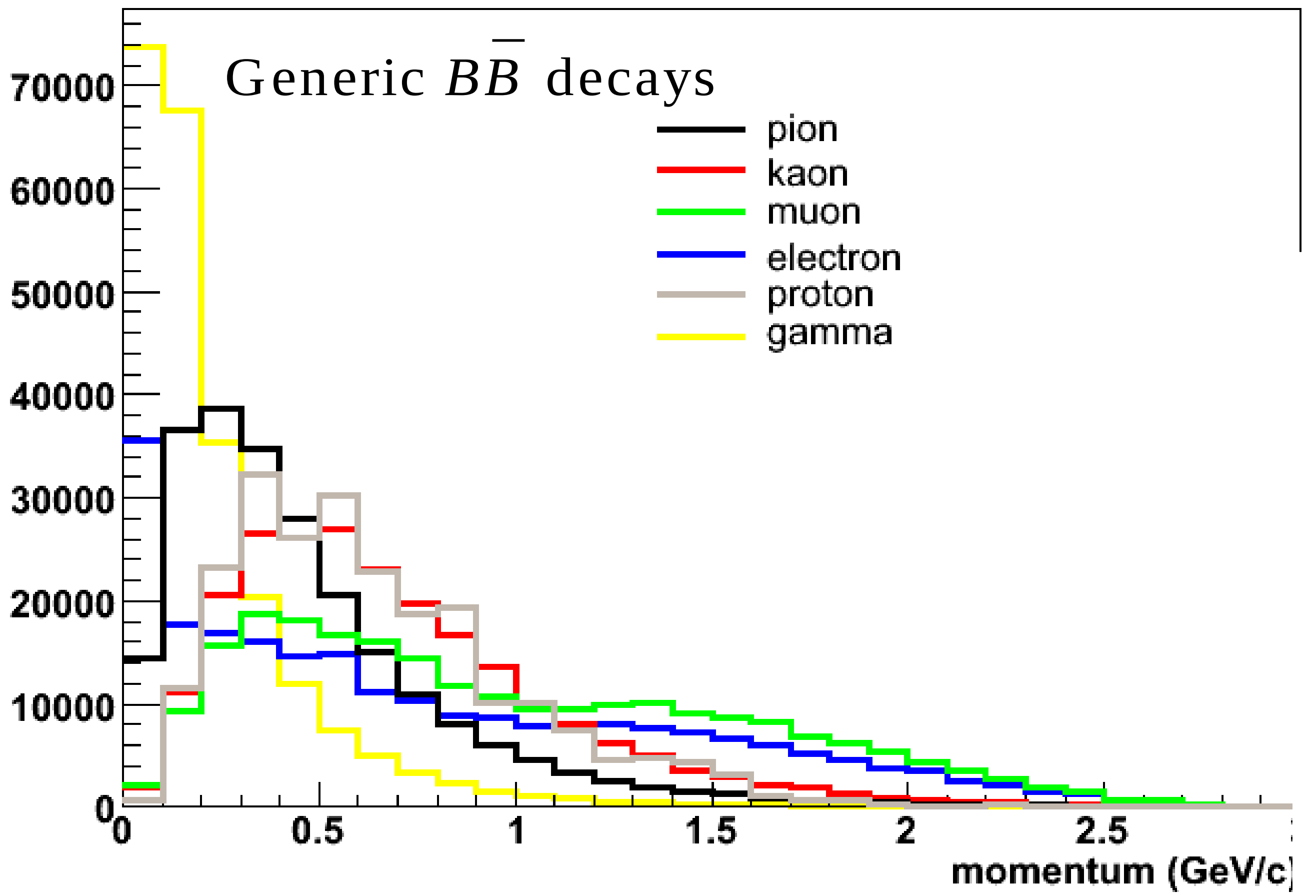
Track momenta and polar angle distribution





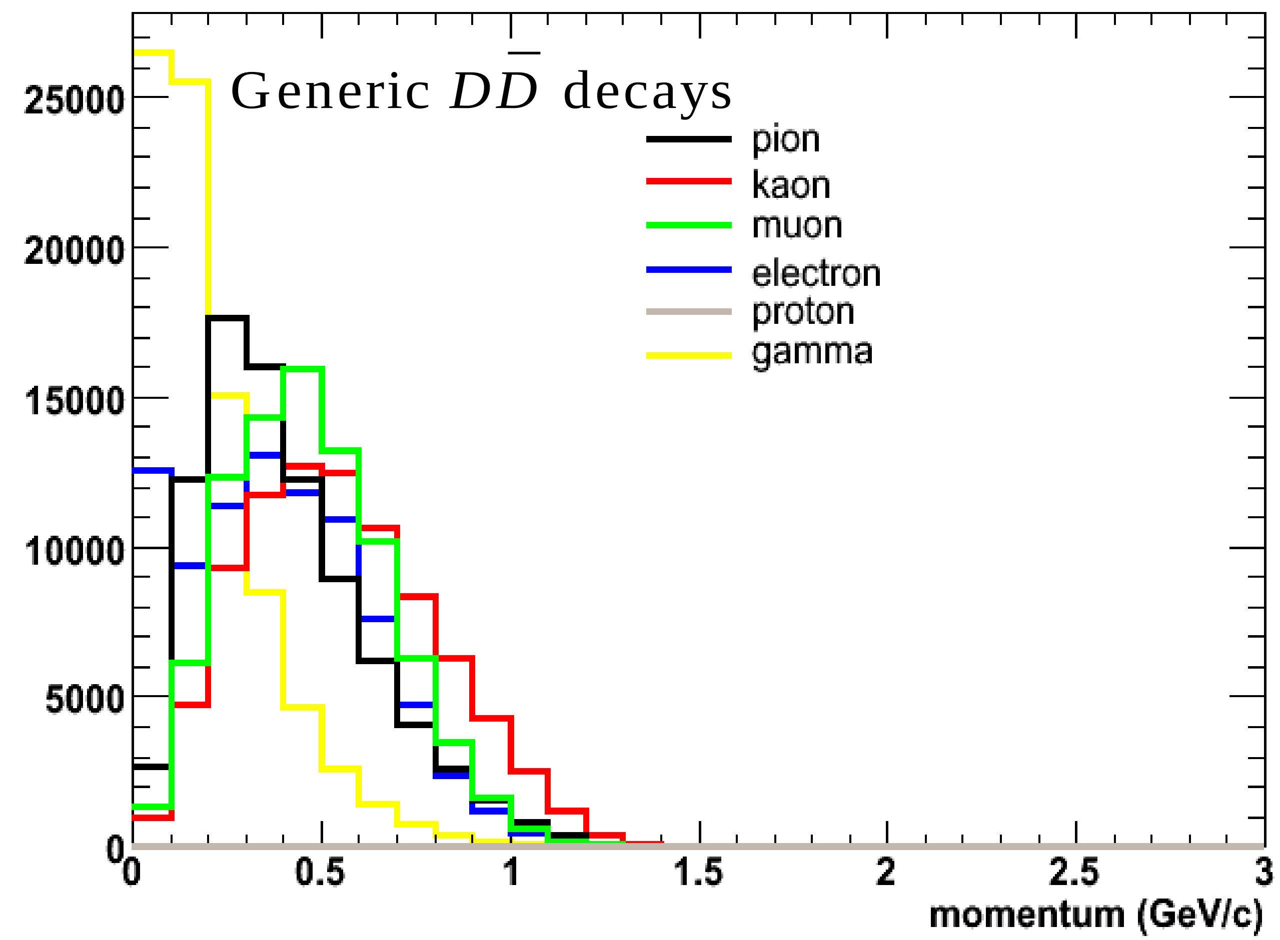
Track momenta at lower E_{cm} are substantially softer

Track momenta in $\Upsilon(4S)$ events



Super$B$ can run at lower E_{cm} for specific D and τ studies, as well as at the other Y resonances and above (with $\beta\gamma$ =0.28)

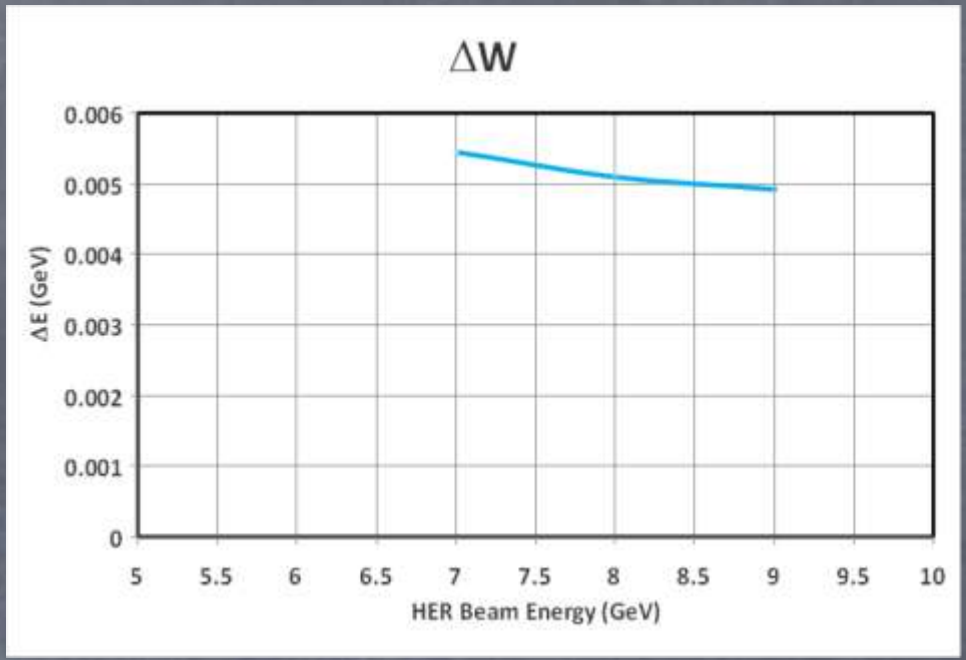
Track momenta in $\psi(3770)$ events

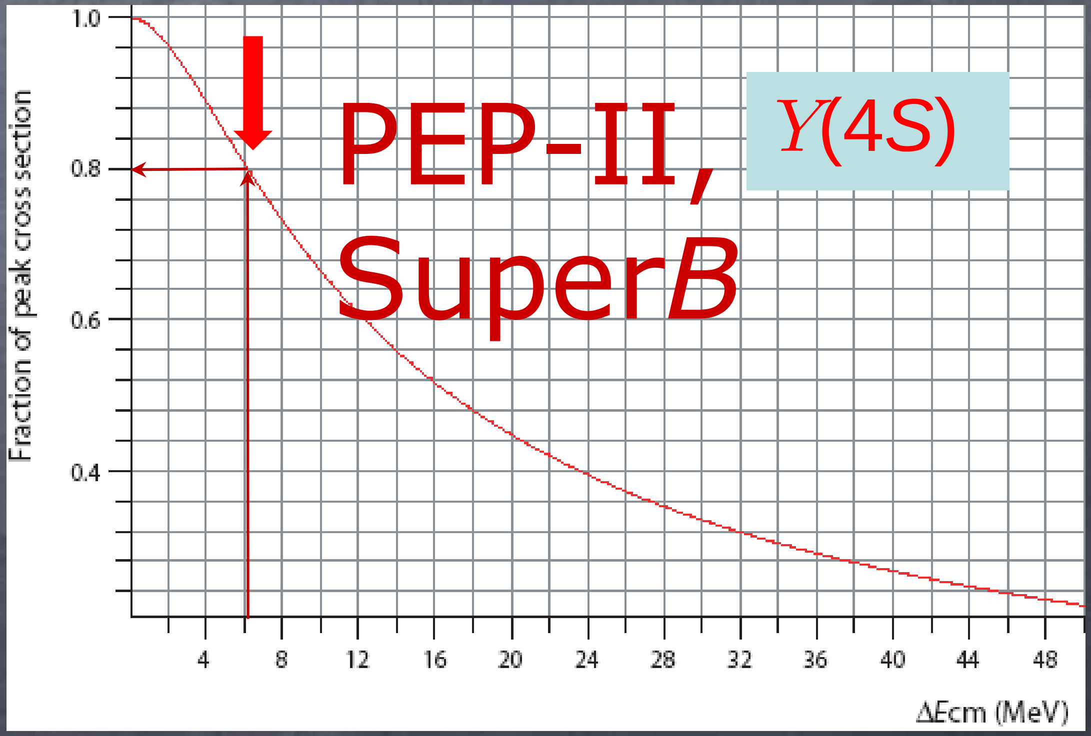


1 month of Super$B$ running at ψ(3770) or for $\tau\bar{\tau}$ below charm charm threshold yields 10X final BES-II data

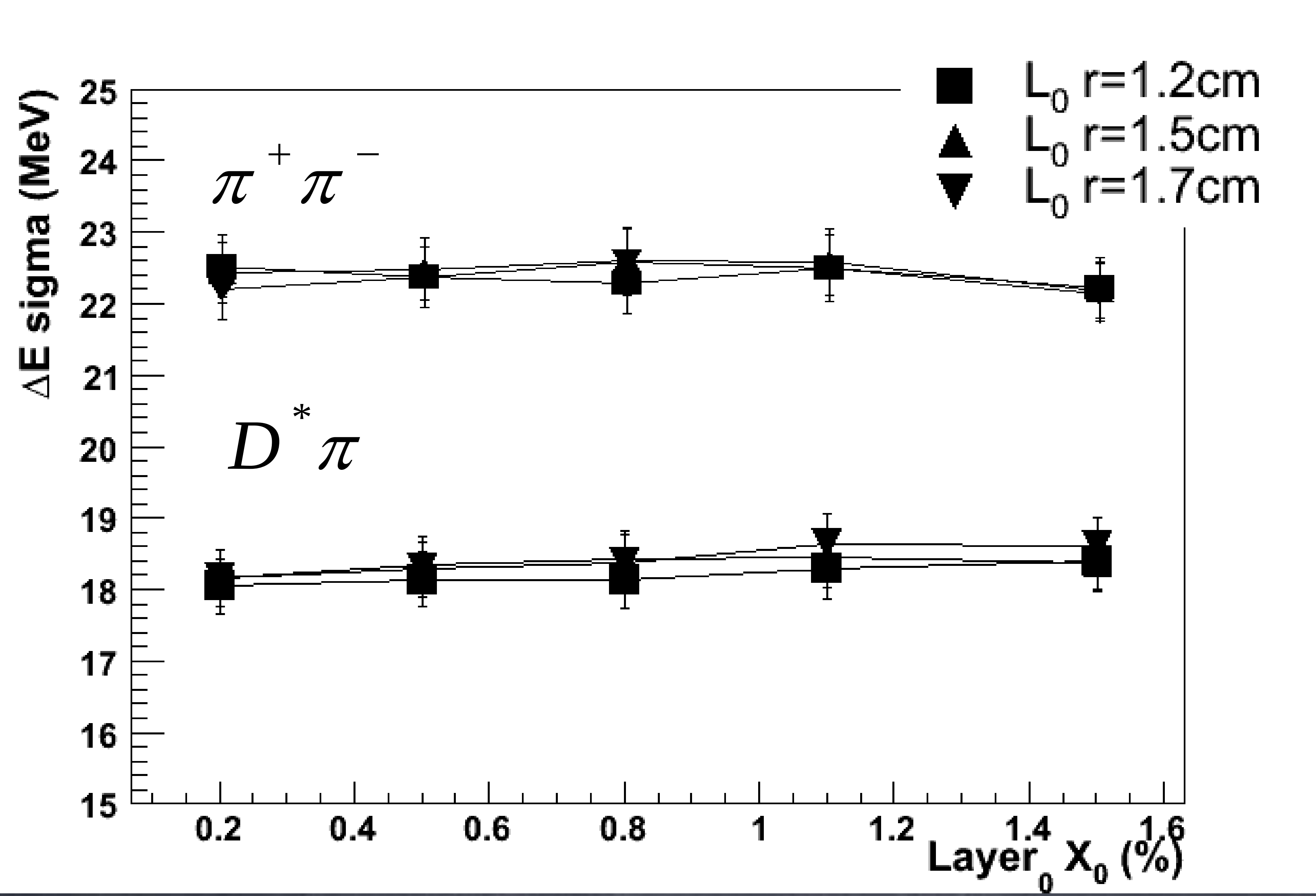
Center-of-mass energy spread

- Many analyses use cuts on Δm_{ES} and ΔE to extract a signal
- Center-of-mass energy spread determines Δm_{ES} and thus the signal-to-noise ratio in rare B decays
- Center-of -mass energy spread also determines the effective cross section on the $\Upsilon(4S)$, $\Upsilon(5S)$ or $\psi(3770)$ resonances
- This was a concern in earlier incarnations of Super$B$ which had highly disruptive collisions but is no longer an issue





ΔE resolution



Final state reconstruction efficiency

- In B meson decay <n$_{ch}$>=5, <n$_\gamma$>=5
- τ decay is dominated by 1 and 3 prong topologies
- We expect recoil physics to be a key technique
  - Both B mesons must, perforce, be reconstructed, or both τ's identified
- In most, but not all cases, important exceptions being, *e.g.*,

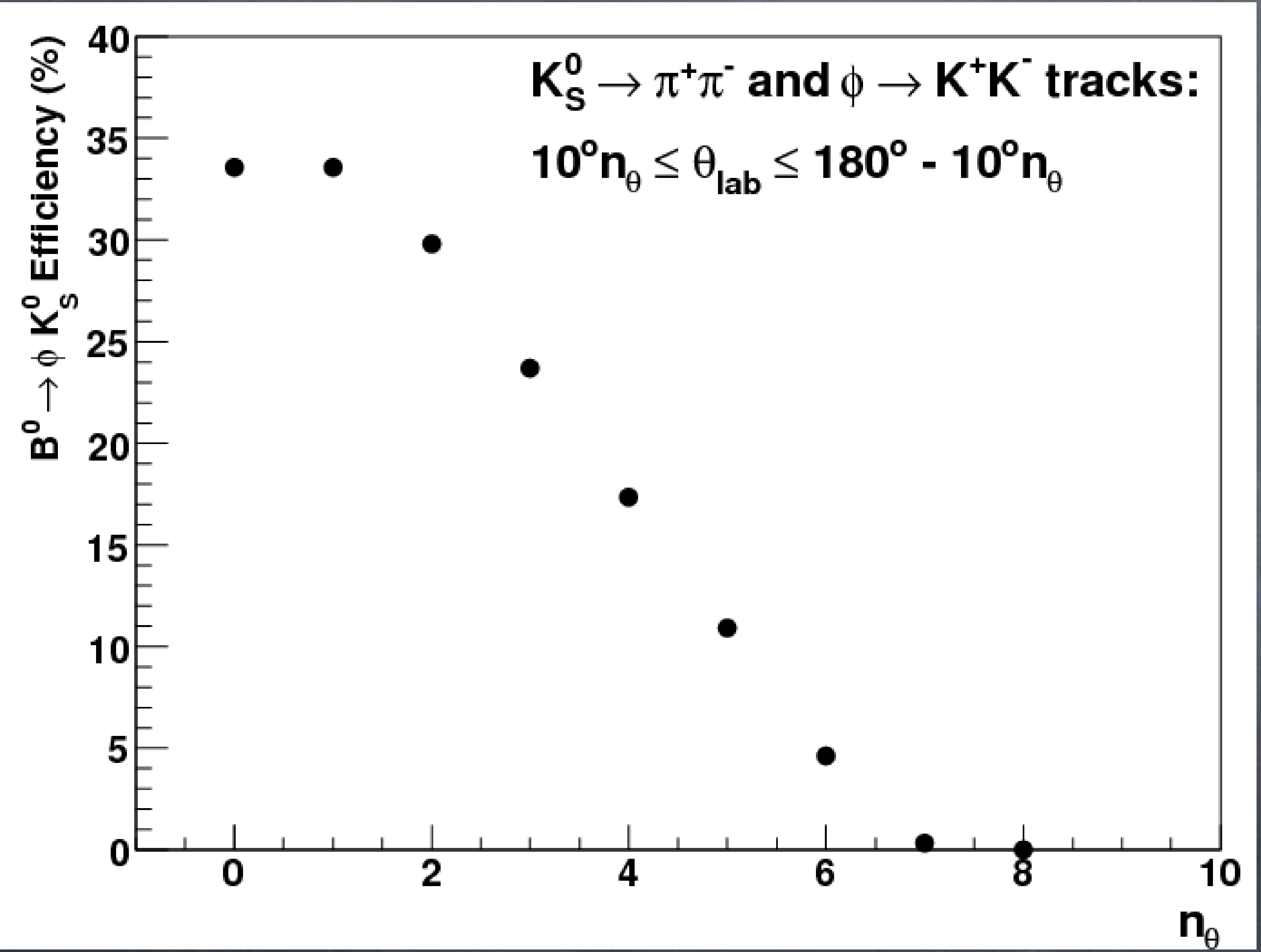
$$b \to s\gamma,\ \tau \to \mu\gamma,$$

the object of photon detection is π^0 reconstruction, in which case $\varepsilon_{\pi^0} \sim \varepsilon_\gamma^2$

- The effective solid angle for complete final state reconstruction is determined by the system which has the minimum solid angle coverage

$$\varepsilon_{vertex} \geq \varepsilon_{tracking} \geq \varepsilon_{PID} \geq \varepsilon_\gamma > \varepsilon_{\pi^0}$$

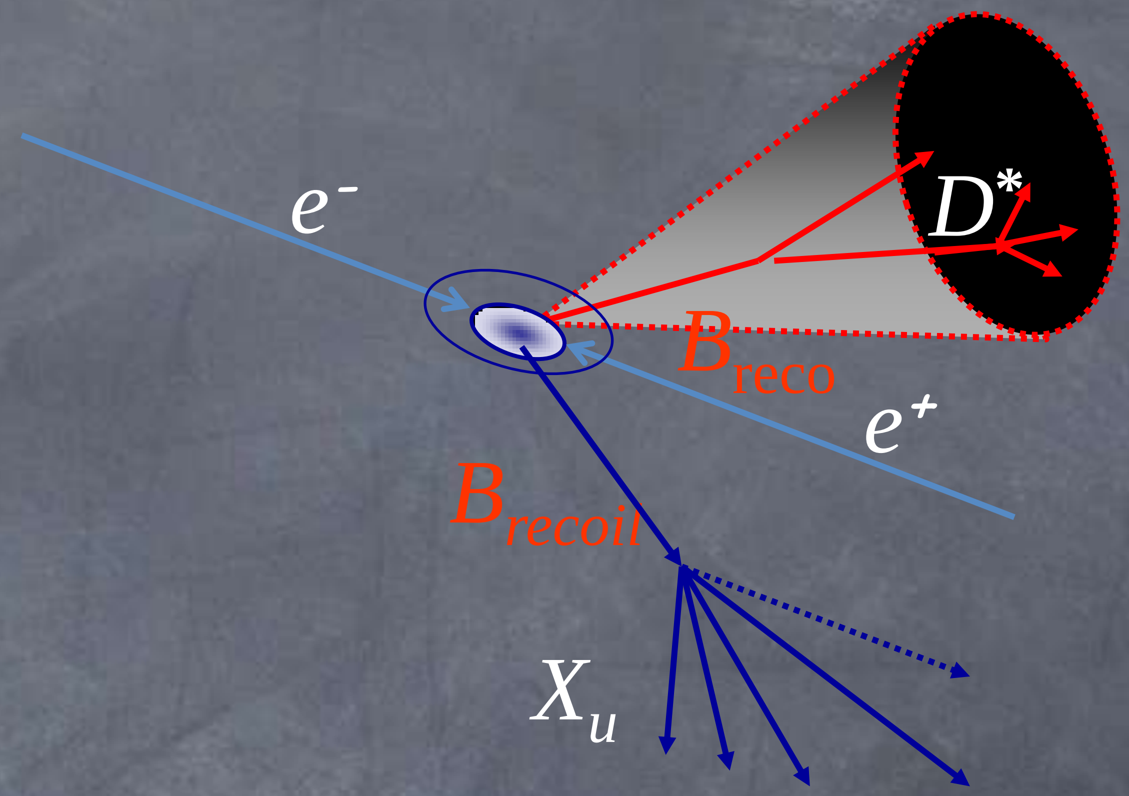
$B^0 \to \phi K_s$ reco efficiency *vs* solid angle coverage



J. Back

Recoil physics at the $\Upsilon(4S)$

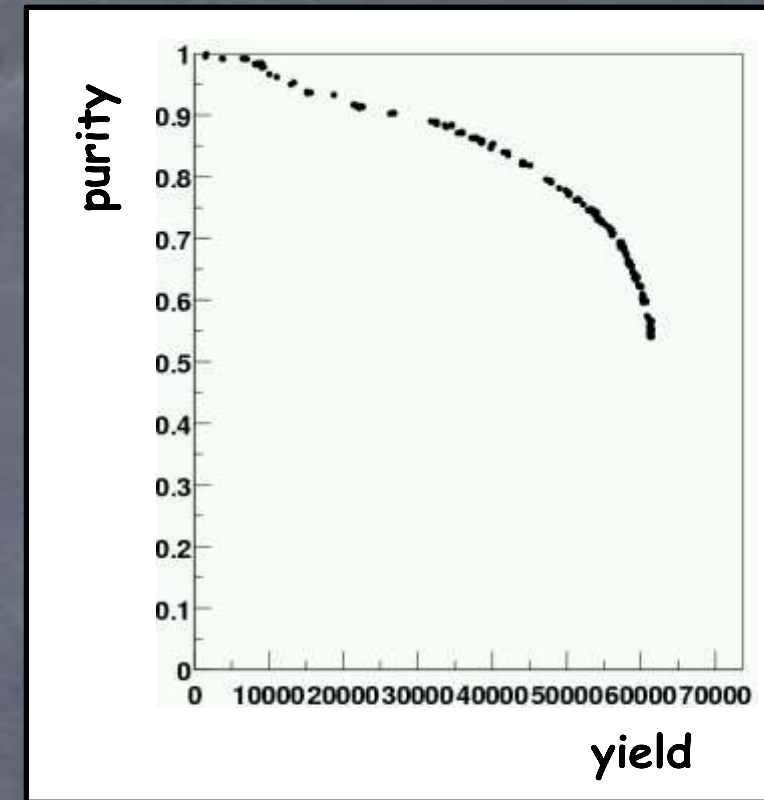
- "The Recoil Method " will be of increasing importance at Super$B$
  - Fully reconstruct one of the two B's in hadronic modes and/or semileptonic modes as well ....and do it with high efficiency
  - The rest of the event is the other B, whose four-momentum is known
  - You then have a single B beam:
    - reduced backgrounds for rare decay studies, especially those with neutrinos, and
    - reduced systematics for precision V_{cb}, V_{ub} studies

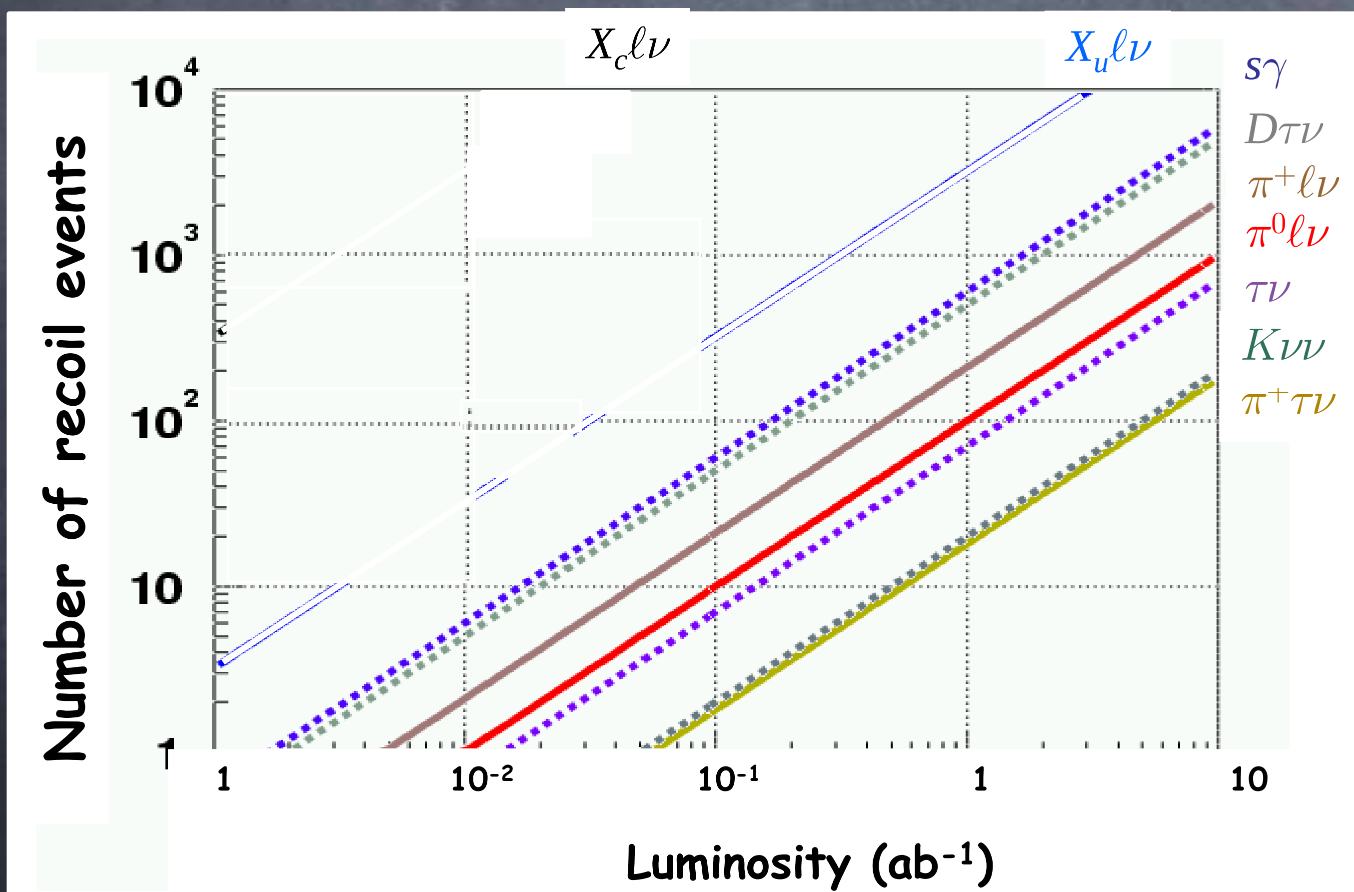


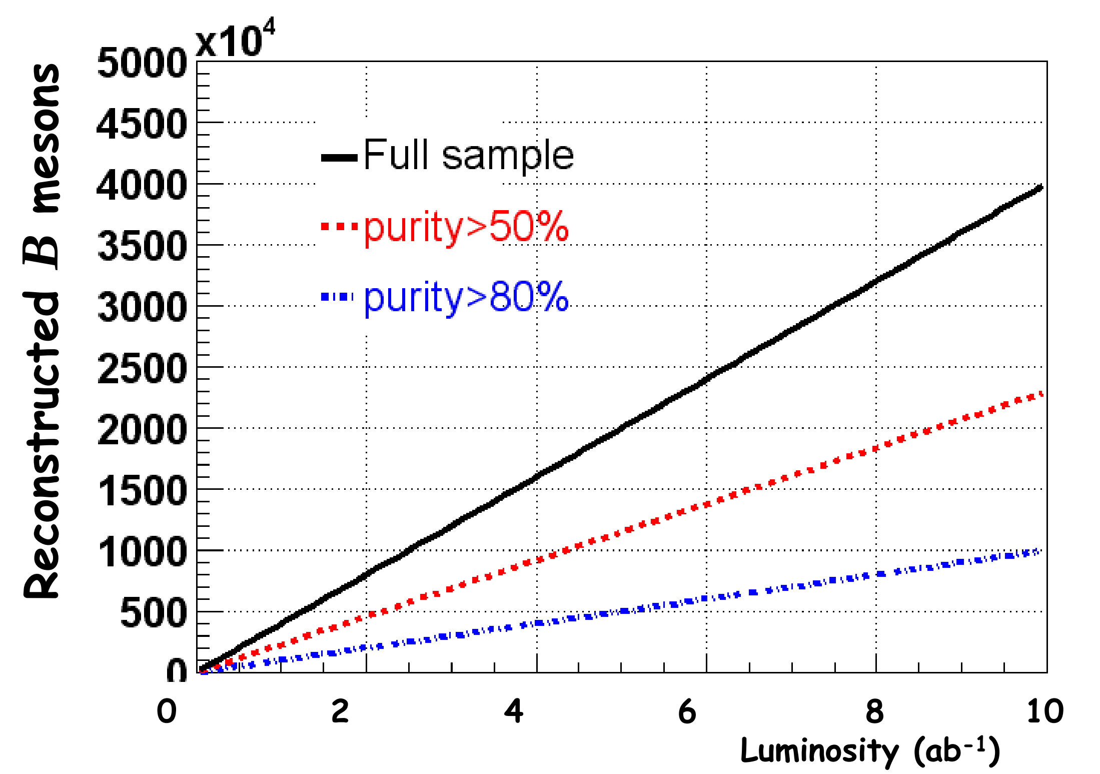
- Semileptonic decays
- $B\to D^{(*)}\ell\nu$, $B\to(\pi,\rho)\ell\nu$, $B\to X_{c,u}\ell\nu$
- $B\to D^{(*)}\tau\nu$ (sensitive to New Physics)
- Purely leptonic decays $B\to\tau\nu$, ...
- $B\to K\nu\nu$
- $B\to$ invisible
- $B\to X_s\gamma$

The recoil method

- Subtract combinatorial background
- B_{reco} (recoil) kinematics known with small uncertainties
- B_{reco} (recoil) flavor determined
- B_{reco} (recoil) charge (B^0- B^+ separation)
- Direct m_X reconstruction
- Lepton charge – B_{reco} (recoil) flavor correlation
- Kinematic constraints on recoil B
  - Low efficiency - can be tuned for purity

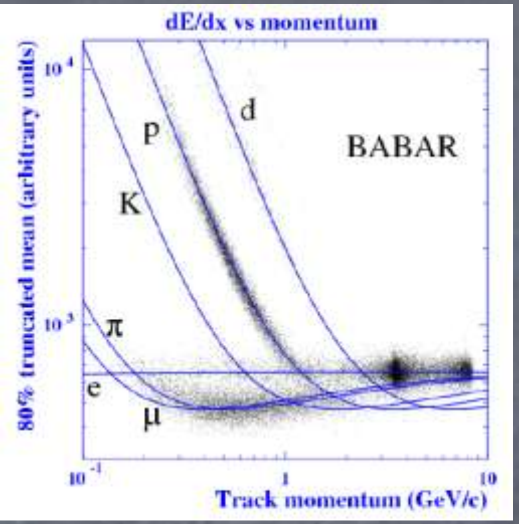






Particle ID coverage

- At 7 on 4 GeV, with the IP displaced, the DIRC $\pi/K/p$ separation coverage is ~70% of 4π
- Coverage is extended to >80% in a restricted momentum range with dE/dx in the SVT and DCH
- Can we improve this ?
- It is unlikely that tracking solid angle coverage can be increased in any meaningful way, but dE/dx resolution can perhaps be improved somewhat

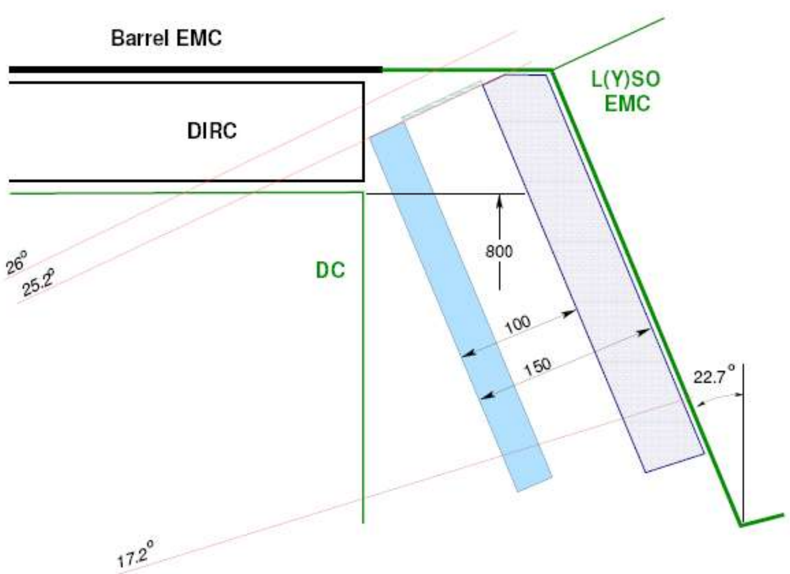


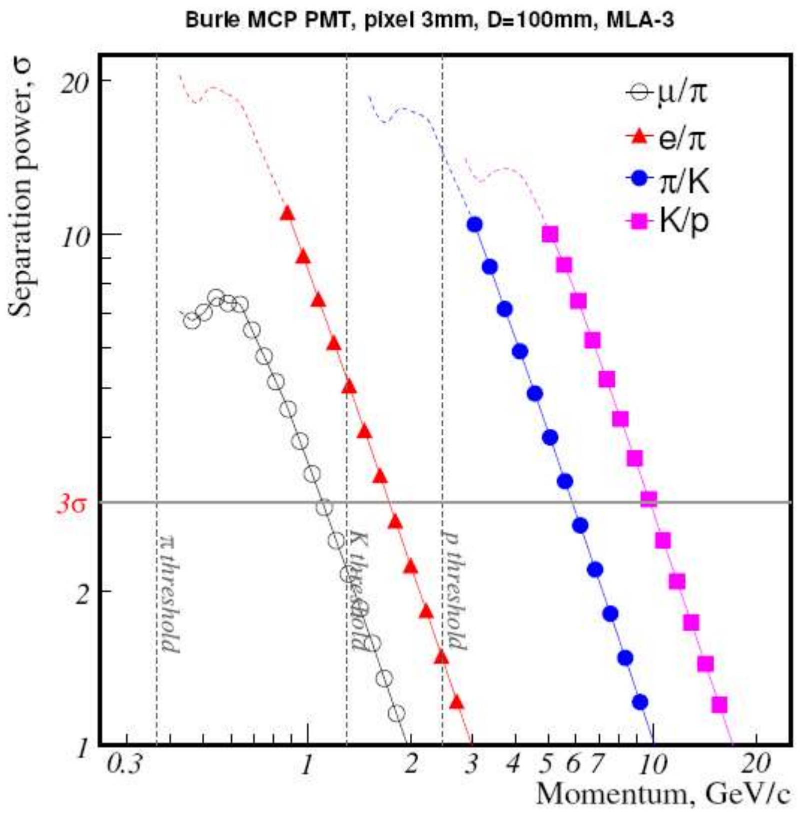
- It is possible, in principle, to add forward (and rear) PID systems
  - [A forward aerogel threshold Cerenkov endcap was considered for *BABAR*]
  - We need to confront our benchmark physics processes with potential new endcap PID systems to ascertain whether there is a worthwhile gain in physics capability
    - PID coverage is extended beyond that covered by dE/dx
    - Space is taken from tracking and/or EC calorimeter volumes
    - There is extra material in front of the calorimeter, which affects energy resolution and photon detection efficiency

FARICH Endcap PID

- Radiator to photodetector: 100 mm
- Photodetector: Burle MCP PMT (500)
  3mm pixels
  16x16 array
- 140K channels
- Three layer aerogel, n_{max} =1.07

A TOF option is also being considered



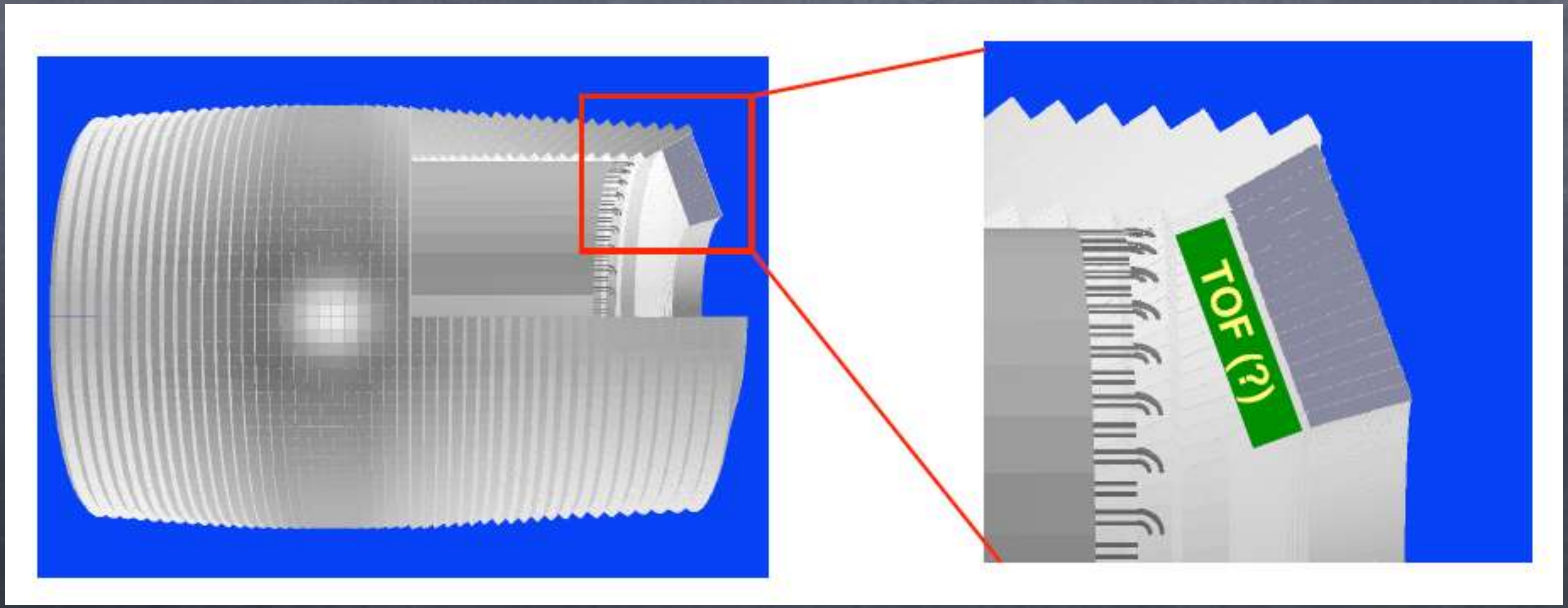


Barrel calorimeter projectivity

- *BABAR* was designed for an asymmetry of 9 an 3.1 GeV
  - In particular the IP was displaced -5 cm from the center of the magnet, and the projective calorimeter crystals do not point at the geometric center of the detector
  - Maximizing solid angle coverage for the Super*B* upgrade requires the magnet to be offset~ +5 cm on the other side of the IP
  - There is thus a small change in the degree of projectivity
  - We has, as yet, no quantitative understanding of the effect of lack of projectivity will have on
    - photon energy and position resolution
    - linearity of energy response
    - photon detection inefficiency
  - What is the effect on benchmark physics measurements?

The forward region

- While the CsI(Tl) barrel EM calorimeter can be retained in Super$B$ with minor modifications, the forward endcap must be replaced with a device having greater radiation hardness, faster decay time and smaller Molière radius
  - The leading candidate, LYSO (lutetium yttrium orthosilicate) has a shorter radiation length (1.14 *vs* 1.85 cm for CsI(Tl)), potentially leaving space for a forward PID system
  - A detailed benchmarking of several physics objectives, comparing gain for extended particle ID *vs* loss in γ energy resolution and efficiency, is required

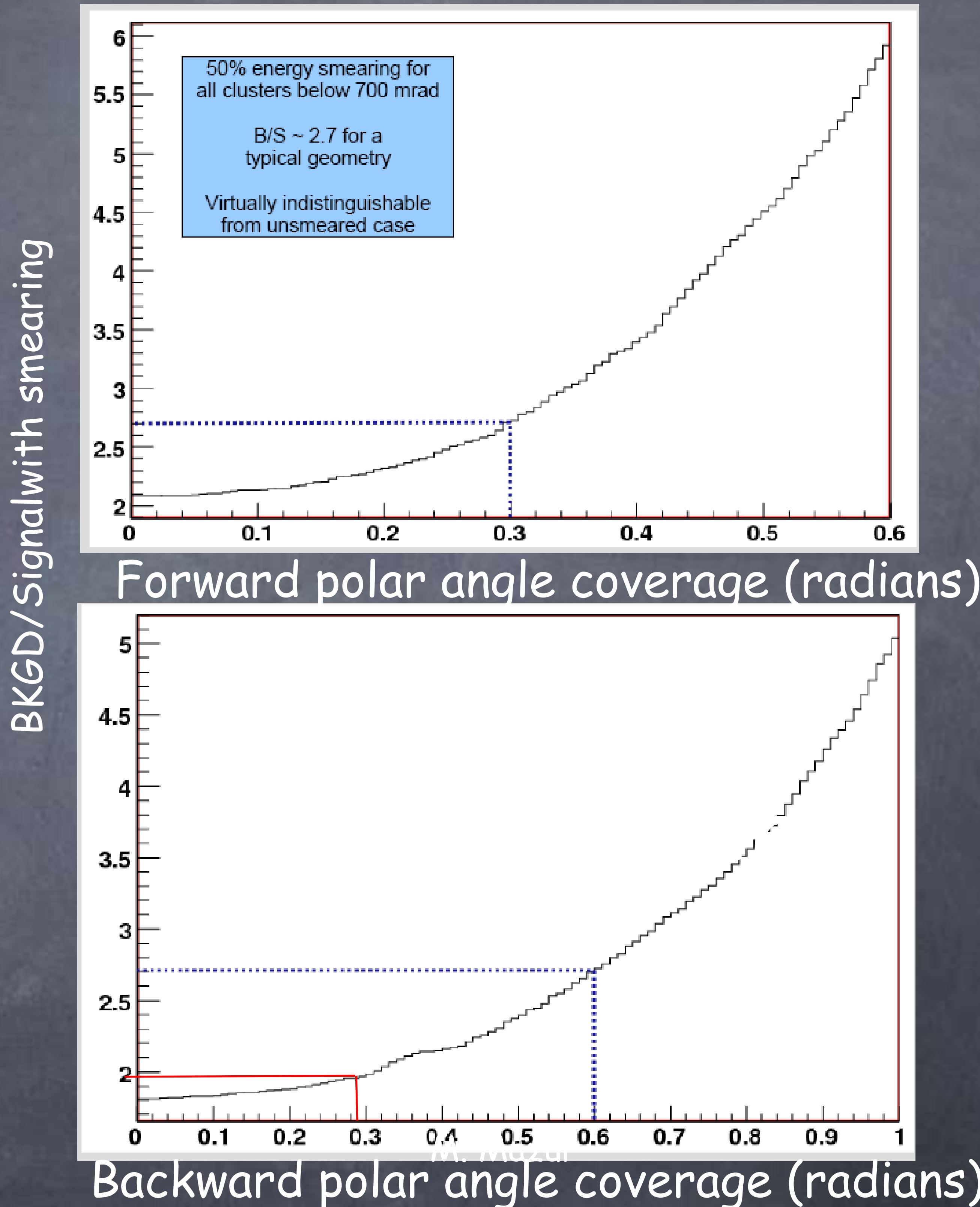


Acceptance studies

- Many of the main physics objectives of Super$B$ require the use of missing energy signatures

- Detector requirements
  - Use of the recoil technique
  - Excellent reconstruction efficiency for hadronic B decays, especially those involving D^*s
  - Excellent particle ID
  - Hermeticity

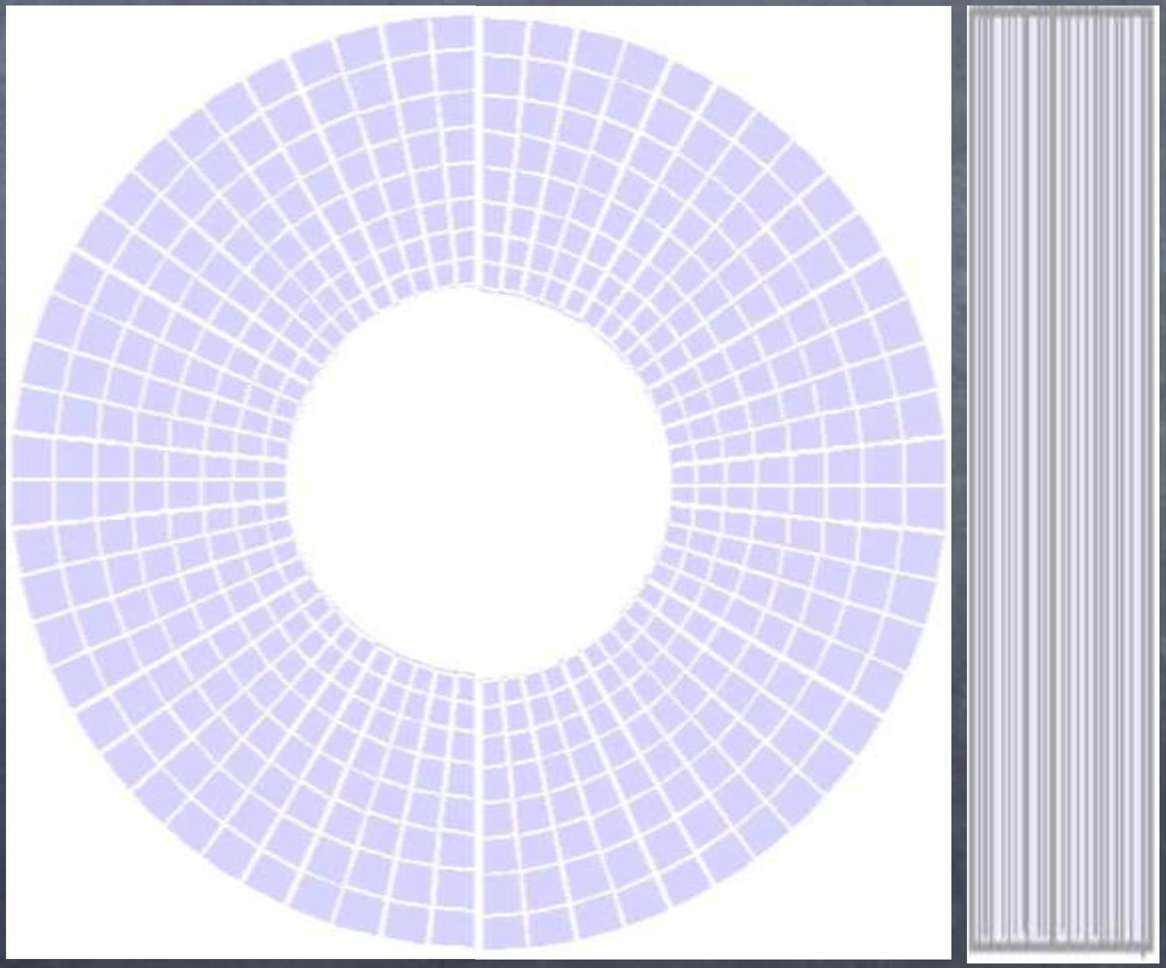
- Improving backward calorimeter coverage can pay large dividends in signal/background
- Study using $B \to \tau\nu$ benchmark



M. Mazur

Read endcap Pb/tile calorimeter concept

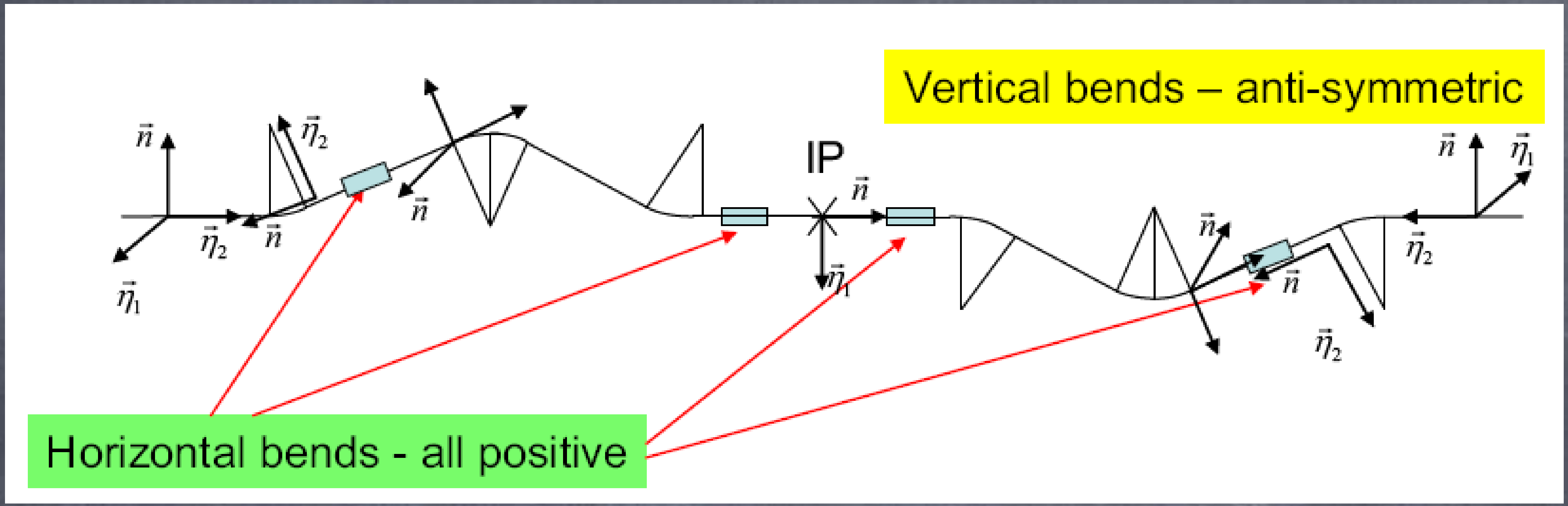
- An adequate rear endcap device can be realized with a Pb/scintillating tile device using SiPM readout, built as two D's to fit within the DIRC tunnel
- $12X_0$, with $0.5\ X_0$ sampling
- Energy resolution ~15%/$\sqrt{E}$ (GeV)



G. Eigen

The Super$B$ design has a longitudinally polarized e^- beam

- Several techniques of achieving longitudinal e^- polarization of >80% at the IP are discussed in the CDR
- Provides polarization in the 10 GeV CM region, not at lower E_{CM}



- Production of polarized positrons (~40%) is a substantial R&D project, and in fact, ~~a potential area of synergy with ILC R&D~~
- Super$B$ plans only a polarized e^-, which yields most of the physics benefits

CP violation in τ production and a τ EDM

- With a polarized electron beam, can define an azimuthal asymmetry in hadronic τ decays sensitive to to a τ EDM : d_τ^γ

$$A_N^{\mp} = \frac{\sigma_L^{\mp} - \sigma_R^{\mp}}{\sigma} = \alpha_{\mp} \frac{3\pi\gamma\beta}{8\left(3-\beta^2\right)} \frac{2m_\tau'}{e} d_\tau^\gamma$$

Bernabeu et al.

where

$$\sigma_L^{\mp} = \int_0^{2\pi} d\phi_{\pm} \left[\int_0^{\pi} d\phi_{\mp} \left. \frac{d^2\sigma^S}{d\phi_- d\phi_+} \right|_{Pol(e^-)} \right] =$$

$$Br(\tau^+ \to h^+\bar{\nu}_\tau) Br(\tau^- \to h^-\nu_\tau)\, \alpha_{\mp} \frac{(\pi\alpha\beta)^2\gamma}{8s} \frac{2m_\tau}{e} d_\tau^\gamma$$

$$\sigma_R^{\mp} = \int_0^{2\pi} d\phi_{\pm} \left[\int_{\pi}^{2\pi} d\phi_{\mp} \left. \frac{d^2\sigma^S}{d\phi_- d\phi_+} \right|_{Pol(e^-)} \right] =$$

$$-Br(\tau^+ \to h^+\bar{\nu}_\tau) Br(\tau^- \to h^-\nu_\tau)\, \alpha_{\mp} \frac{(\pi\alpha\beta)^2\gamma}{8s} \frac{2m_\tau}{e} d_\tau^\gamma$$

$$h^{\mp} = \pi^{\mp}, \rho^{\mp}$$

- Summing over τ^+ and τ^- yields a true CP-odd observable

$$A_N^{CP} = \frac{1}{2}\left(A_N^+ + A_N^-\right) = \alpha_h \frac{3\pi\gamma\beta}{8(3-\beta^2)} \frac{2m_\tau}{e} d_\tau^\gamma$$

- Sensitivity:

$$15 \text{ ab}^{-1} : \left|d_\tau^\gamma\right| \le 4.4 \times 10^{-19}\ e \text{ cm}$$

$$75 \text{ ab}^{-1} : \left|d_\tau^\gamma\right| \le 1.6 \times 10^{-19}\ e \text{ cm}$$

A three order of magnitude improvement over current bounds

CP Violation in τ decay

- Unpolarized τ's
- Measure $\mathcal{B}$'s of τ decays with two or more hadrons

$$\mathcal{B}(\tau^- \to \pi^-\pi^0\nu_\tau) \neq \mathcal{B}(\tau^+ \to \pi^+\pi^0\overline{\nu}_\tau)$$

Interpretation of any observed CPV requires understanding of inelastic final state interactions

- Measure CP or T-violating correlations in $\tau^+\tau^-$ decays
- Polarized τ's
- Search for T-odd rotationally invariant products, *e.g.*

$$w_{e^-} \cdot \left(p_{\pi^+} \times p_{\pi^0} \right)$$

in τ^+ and τ^- decays such as

$$\tau^- \to \pi^-\pi^0\nu_\tau,\ \tau^- \to K^-\pi^0\nu_\tau,\ \tau^- \to \pi^-\pi^+\pi^-\nu_\tau,\ \tau^- \to K^-\pi^+\pi^-\nu_\tau$$

- Search for T-odd correlation between τ polarization and μ polarization in $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ decay
- Sensitivity to asymmetries at the 10^{-3} level

Polarization systematics

- Effect of crabbed waist on longitudinal polarization
- Measurement of longitudinal polarization
  - Compton polarimeter
  - Møller scattering (gas jet?)
  - A_{LR} in $\mu^+\mu^-$
- Measurement of transverse polarization (Sokolov-Ternov)
  - Buildup/decay
  - Azimuthal asymmetry
- Randomization scheme – bunch by bunch?
- Detector asymmetries

Issues for a comprehensive detector design

- Shielding of IR components from showers due to off-energy beam particles
- Support/alignment of IR components without a support tube
- Can coverage be extended below 300mrad?
- Is it practical to extend backward barrel CsI calorimeter by three rings?
  - What is the effect on barrel calorimeter performance of shifting the collision point by 10 cm?
- Develop benchmarks to understand tradeoffs between extended polar angle coverage for PID and extra material in front of forward endcap calorimeter
- Determine actual available space for a rear endcap calorimeter
  - Estimate space required for current generation DCH electronics
    - Can at least a portion of the DCH electronics mass be placed outside the fiducial volume?
- Tradeoff between occupancy, spatial resolution and dE/dx resolution in DCH
- ....
- ....

Conclusions

- An excellent detector for Super*B* can be constructed using an existing detector such as *BABAR* as a base
- It is important to have a forum to allow comprehensive consideration of the inevitable trade-offs in optimizing the design
  - Data-taking at 4 as well as 10 GeV E_{cm}
  - Improved hermiticity
  - Improved vertex resolution to enable 7x4
  - Upgrade endcap calorimetry
  - Extended solid angle for PID
  - Better muon ID,
  - Higher bandwidth DAQ system
  - Improved trigger
  - Understanding of demands that a polarized electron beam places on the detector