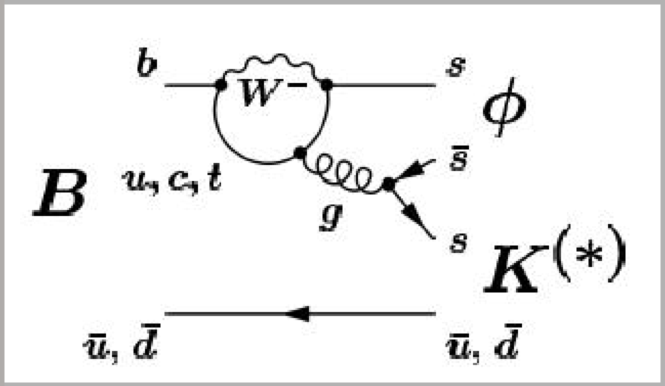
Rare B Decays at BABAR

Paul C. Bloom
University of Colorado
SLAC Summer Institute

What this talk will cover

- B decays with Penguins, Penguins and more Penguins
  - No, not that kind of penguin
  - This kind of penguin



- Electromagnetic Penguins
  - $K^*\gamma$, $\rho/\omega\ \gamma$, $b \to s\gamma$
- Electroweak Penguins
  - $K^{(*)}l^+l^-$, Dileptons, $K\nu\bar{\nu}$, $\gamma\gamma$
- QCD Penguins (charmless hadronic decays)
  - Two and three-body final states

What this talk won't cover

- Vast breadth of physics from the B-Factories
  - 45 minutes is about right to list them all
- You already heard about CP physics at BABAR in David Lange's talk on Wednesday
- Still, some things will have to go uncovered
  - Tau physics
  - Charm physics
  - B mixing and lifetime
  - Semileptonic B decays and CKM matrix elements
  - B decays to charm and charmonium

CKM - Quark Couplings in the Standard Model

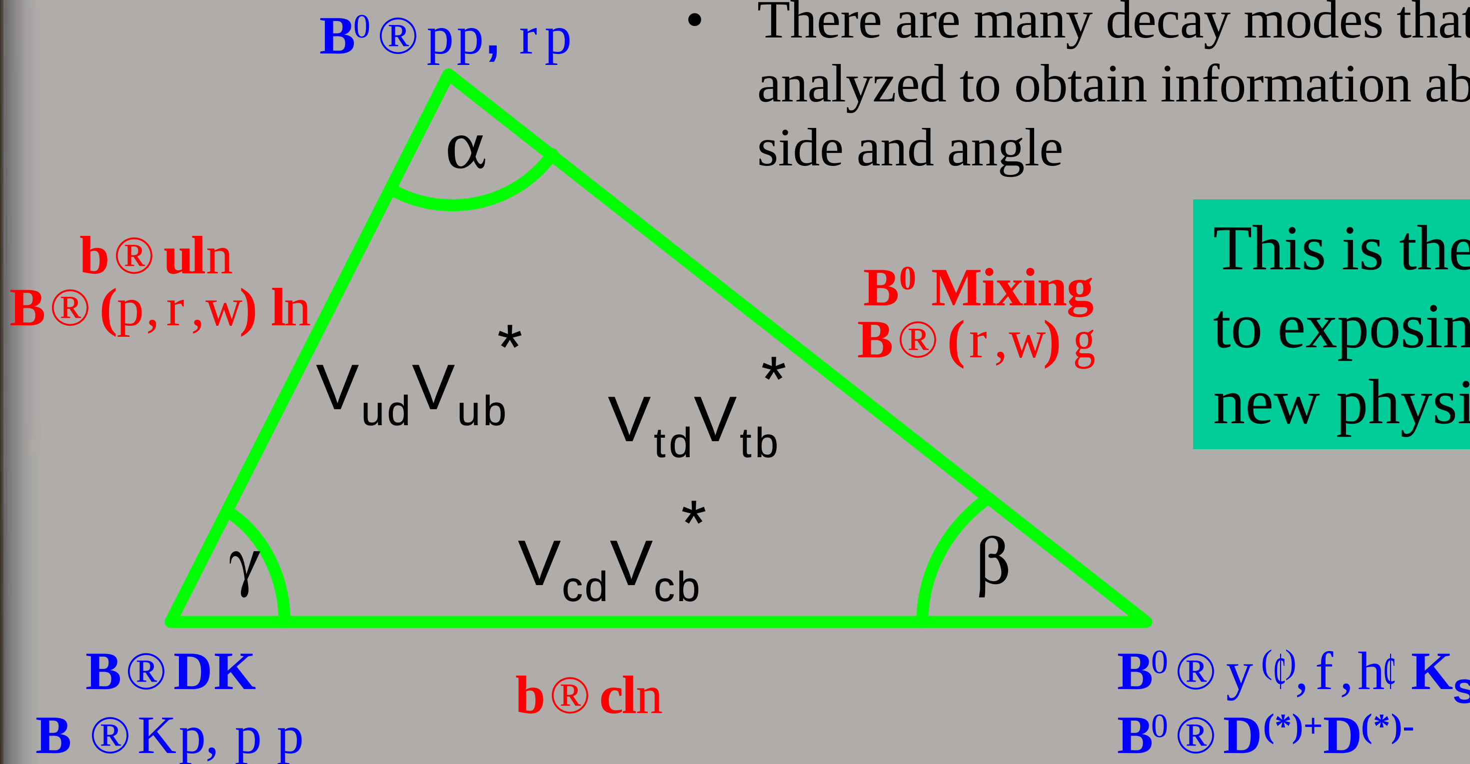
- Weak isospin doublet members (b´, s´, d´) are states of mixed flavor

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- The transformation between mass eigenstates (which we observe) and flavor eigenstates is the matrix of Cabbibo, Kobayashi and Maskawa
- Unitarity implies 4 free parameters, one of which is a phase. One requirement of this condition is: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, which can be represented geometrically as a triangle…

The Unitarity Triangle: Getting at all the Angles – and Sides

- The B sector provides many options to learn about and (over-) constrain this triangle

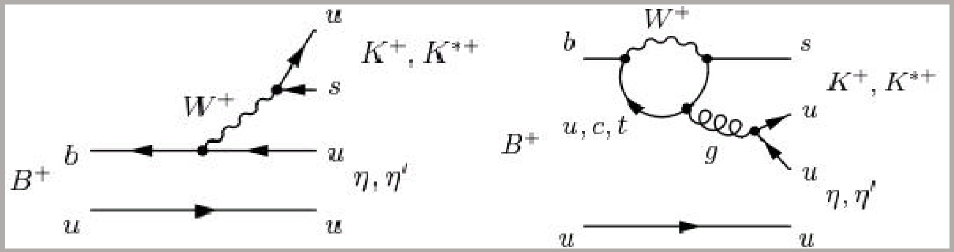


- There are many decay modes that can be analyzed to obtain information about each side and angle

This is the path to exposing new physics

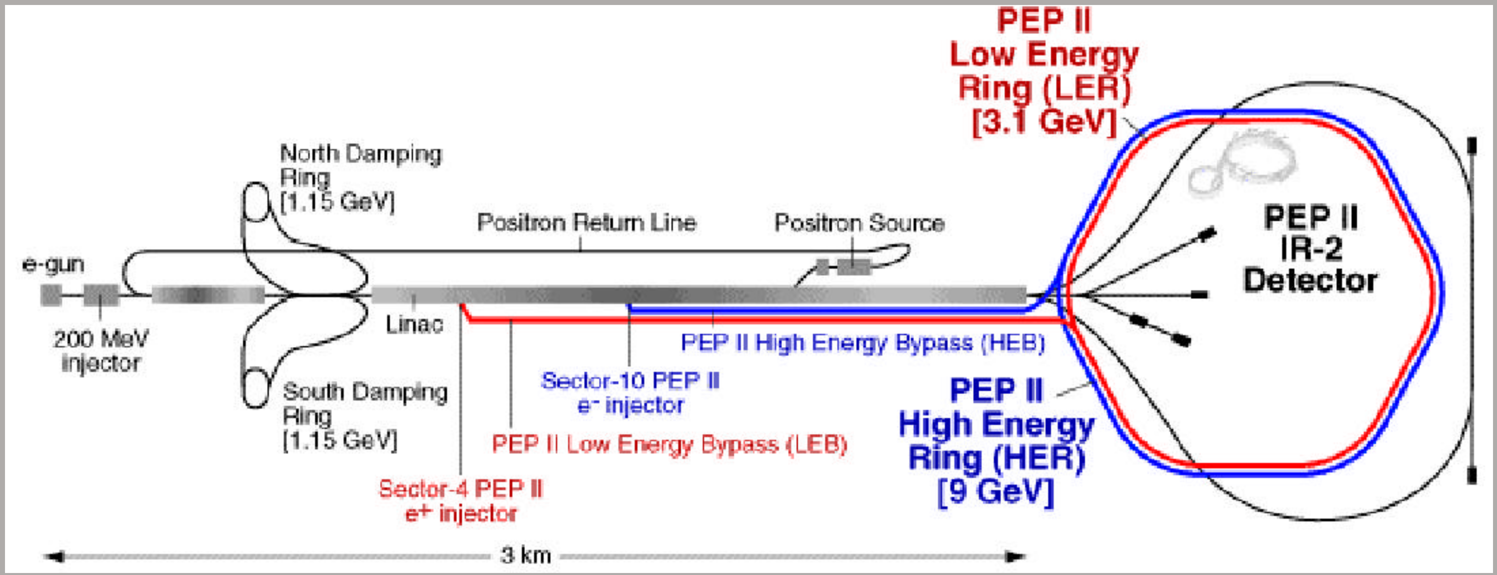
Defining "rare", and Why these Decays are Interesting

- By rare, we mean decays in which there is neither open nor hidden charm
  - $b \to u$ is CKM suppressed: $\left| V_{ub} / V_{cb} \right| < 0.10$
  - $b \to s, d$ proceed only via higher order diagrams (penguins!)
  - Basically, anything that does not involve a $b \to c$ transition
- Processes with tree diagrams that are CKM suppressed or forbidden are sensitive to Penguin amplitudes
  - Example: $B^+ \to \eta' K^+$



- Particles that can't appear on-shell can appear in loops
  - Top, Higgs, SUSY, ???
- Interfering amplitudes can expose new phases - they also complicate the interpretation of CP measurements

The PEP-II Asymmetric B-factory



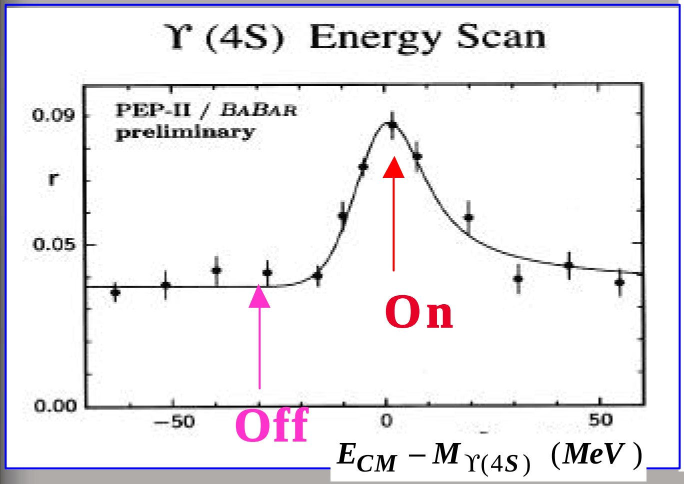
3.1 GeV e^+ on 9 GeV e^-, produce the

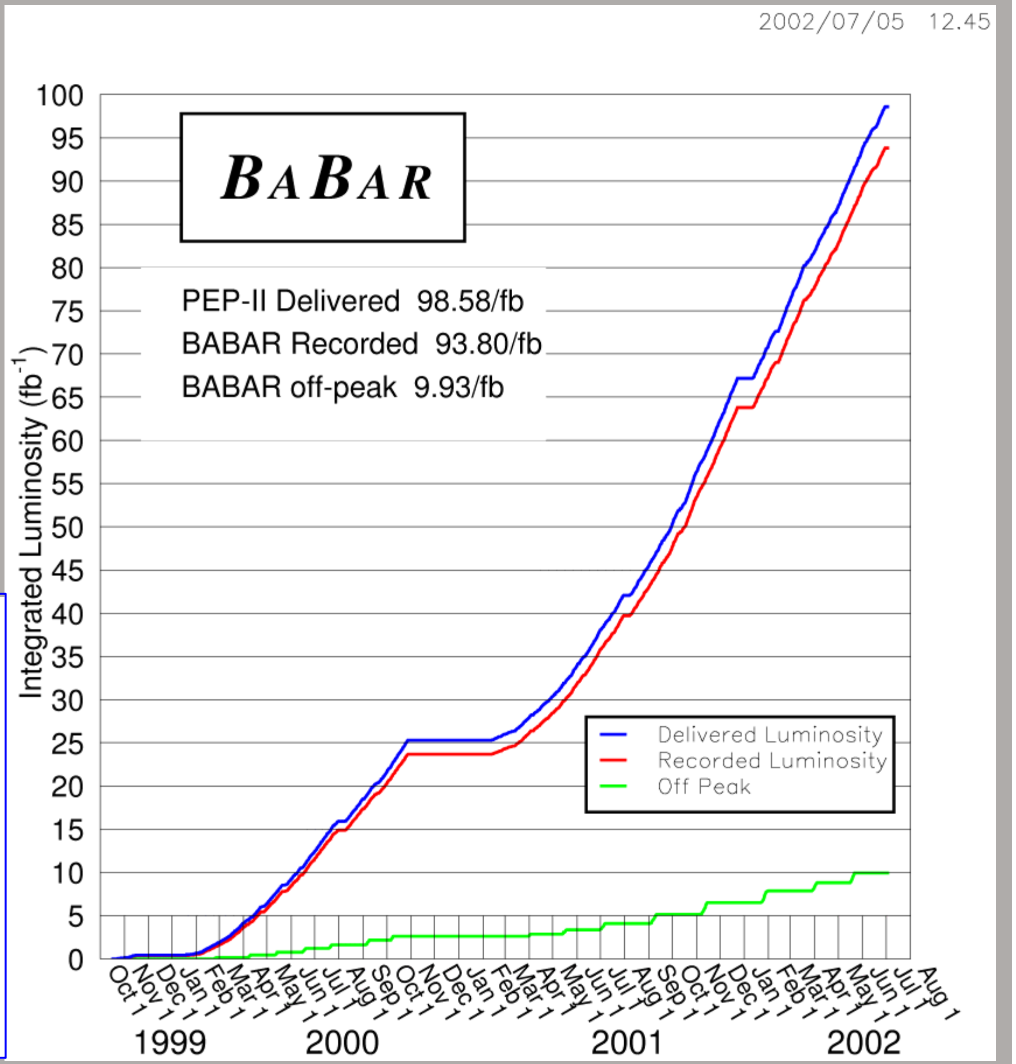
Υ(4S) with a CM boost $<\beta\gamma>$ = 0.55

- Peak Luminosity = 4.60×10^{33} cm^{-2} s^{-1} (3×10^{33} cm^{-2} s^{-1} design)
- Positron current = 1775 mA
- Electron current = 1060 mA
- Number of bunches = 800
- IP beam sizes = 147 mm $\times$ 5 mm

Data Sample(s)

- Full data set
  - – 81.2 fb^{-1} onpeak
  - – ~88M $B\bar{B}$ pairs
  - – 9.6 fb^{-1} offpeak
- Most analyses use only a subset for now





The BABAR Detector

SVT: 5 double side layers, 97% efficiency, 15 mm z hit resolution

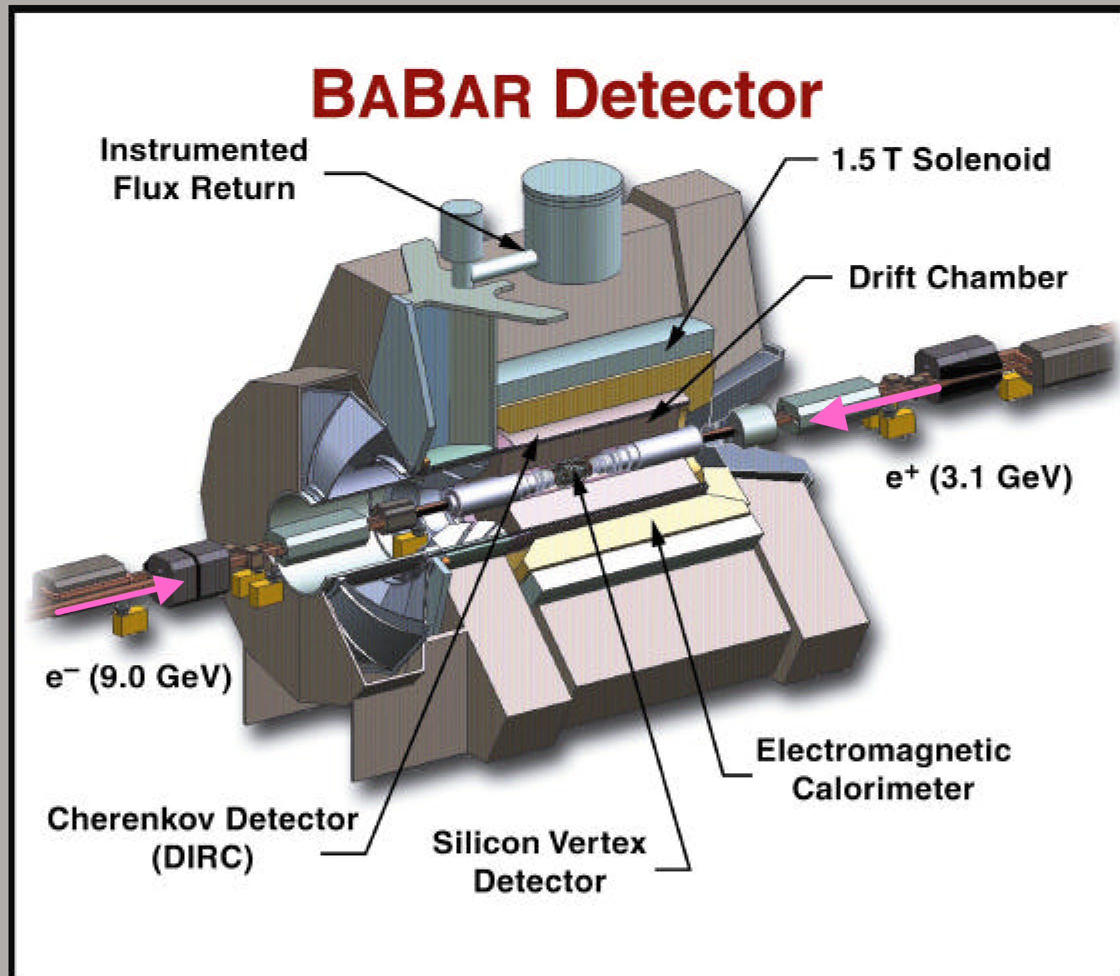
DCH: 40 axial and stereo layers, $\sigma(dE/dx) = 7.5\%$

Tracking: $\sigma(p_T)/p_T = 0.13$ % ´ p_T + 0.45 %, s(z_0) = 65m @ 1 GeV/c

DIRC: 144 quartz bars

EMC: 6580 CsI(Tl) crystals σ_E/E = 2.3 % ·$E^{-1/4}$ Å 1.9 %

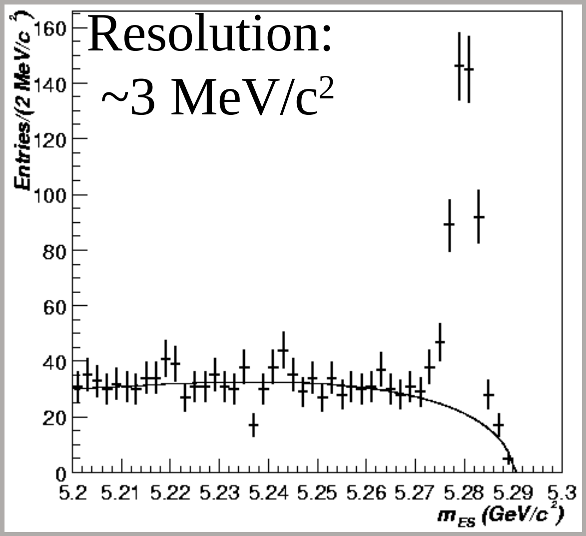
IFR: 19 RPC layers, muon and K_L id

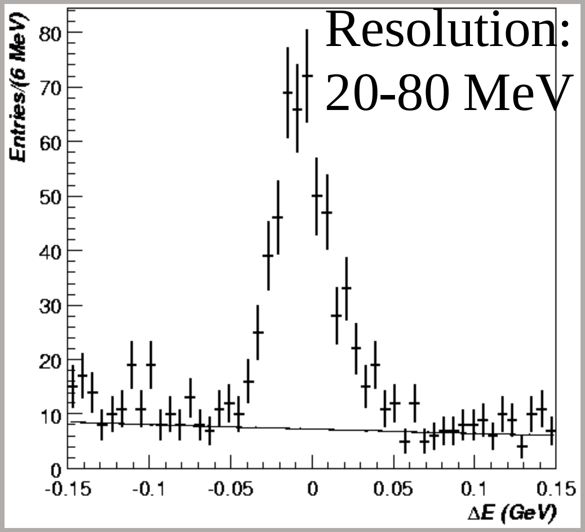


B Decays at the $\Upsilon(4S)$

- $\Upsilon(4S) \rightarrow B^0\bar{B}^0$, B^+B^- ~100% with $p^*_B \cong 325$ MeV/c
  - In a two body B decay, daughters are produced back to back in the CM with $E^* \cong 2.6$ GeV, p = 1.0 to 4.4 GeV/c in the lab, depending on the daughter masses
- Kinematic signature for B decays - express energy and momentum conservation (within resolution) as:

$$m_{\mathrm{ES}} \equiv \sqrt{E^{*2}_{\mathrm{beam}} - p^{*2}_B} = m_B \qquad \Delta E \equiv E^*_B - E^*_{\mathrm{beam}} = 0$$





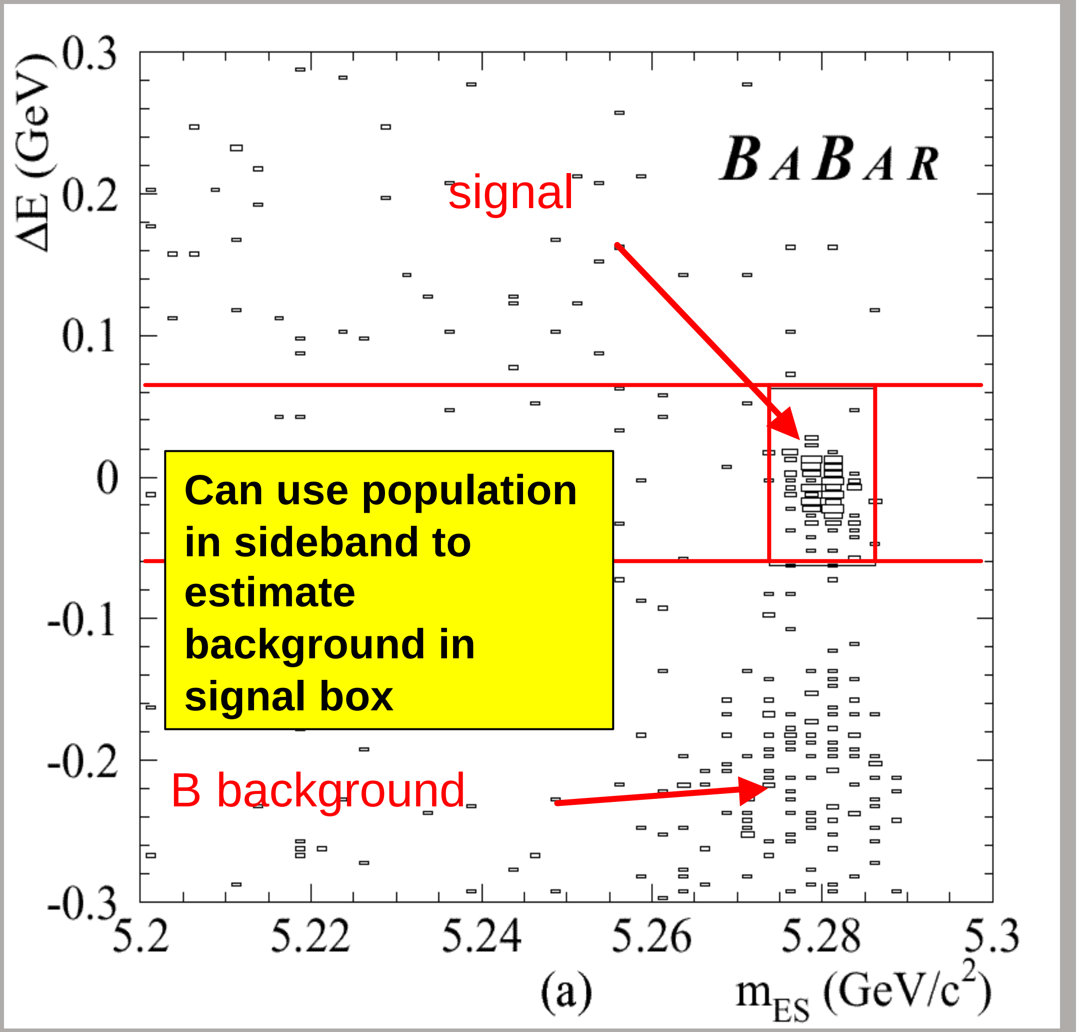
- E^*_{beam} is more precisely measured than ΣE^*_i

Backgrounds

- Generic $b \to c$ backgrounds not a problem for most rare decay modes
  - Heavier daughters $\Rightarrow$ lower recoil energy
  - Exception is modes with high multiplicity
  - Some modes suffer from specific backgrounds, which can be controlled via selection criteria (e.g. ψK^* in $K^* l^+ l^-$)
- Principal backgrounds to rare decays originate from $q\bar{q}$ (q=u,d,s,c) production in the continuum
  - Cross section for udsc ~3.5 nb, Υ ~1 nb
  - Fake signal arises from random track/neutral combinations
  - Topology is "jet-like" as $q\bar{q}$ produced well above threshold
  - B decays spherical in the CM, so…
- Exploit topological variables to suppress continuum background
  - Fox Wolfram moments, B decay axis correlation with jet axis

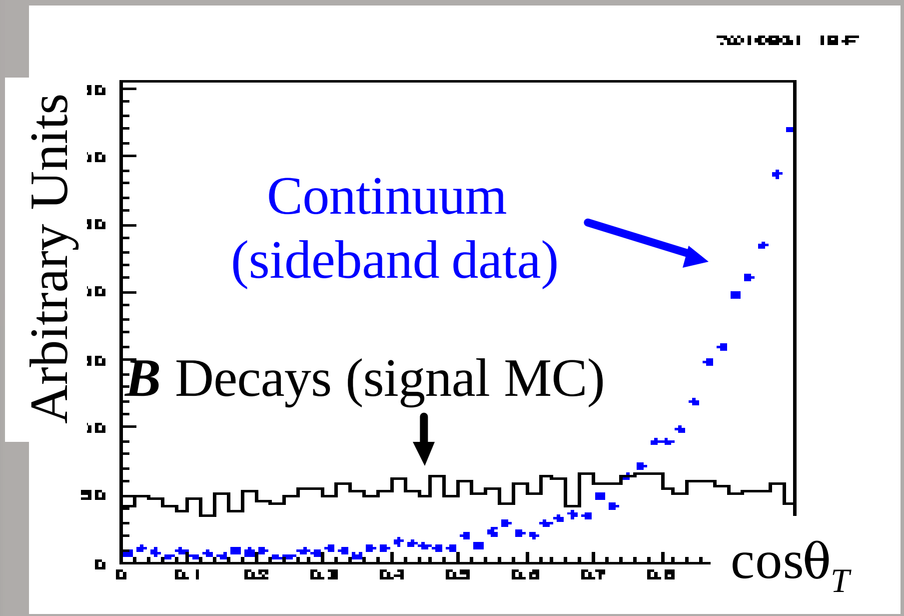
m_{ES} vs ΔE

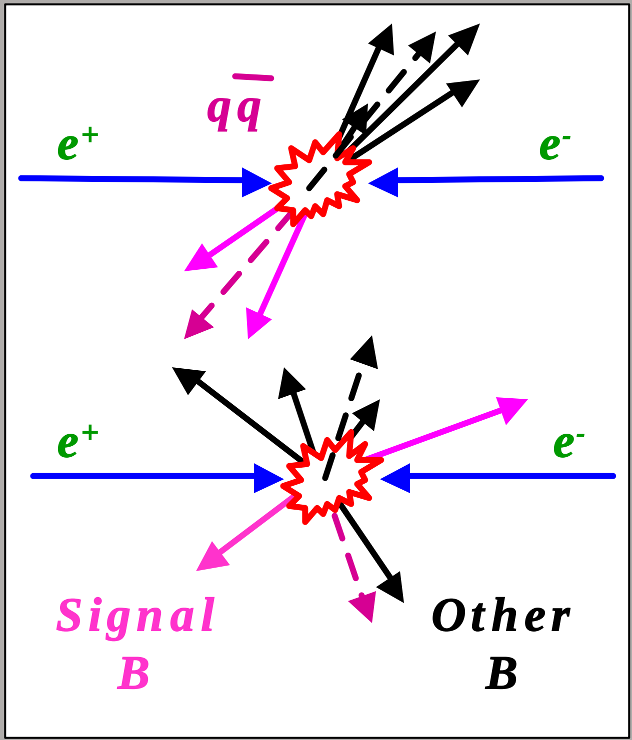
- Signal clusters around $\Delta E=0$ and $m_{ES}=m_B$
- Continuum background is more or less isotropic over the plane
  - m_{ES} – "Argus" shape
  - ΔE – linear with negative slope
- B background populates the sidebands of ΔE
  - Lose or gain a particle to "manufacture" the final state of interest



Event Shape

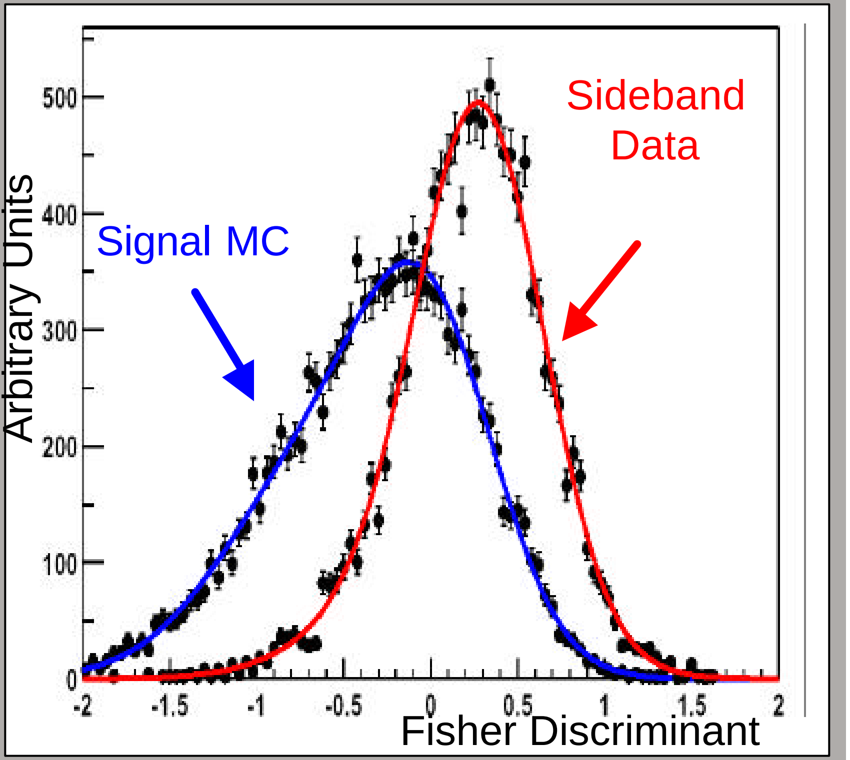
- Exploit spherical decay of the B vs "jettiness" of $q\bar{q}$ background
- Thrust, sphericity provide powerful separation between true B's and continuum background





More on Event Shape

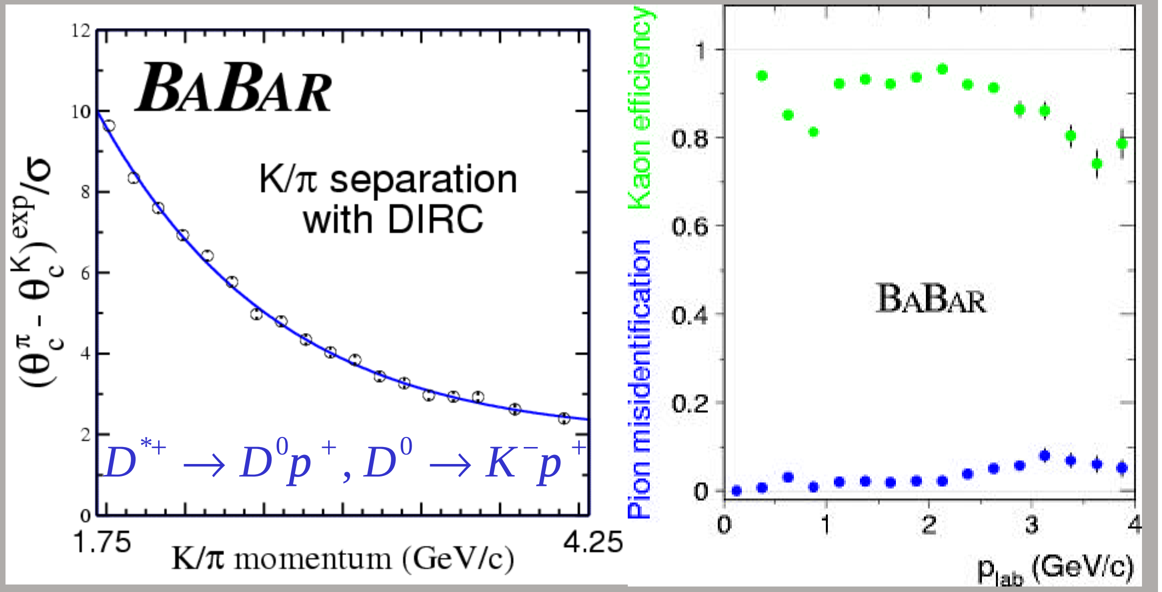
- Additional information available if further continuum suppression is needed - and it often is
  - Direction of B flight and B decay wrt the beam axis
  - Angular energy flow
- Use of this and other information can be optimized via neural network or a Fisher discriminant



Separation after thrust cut

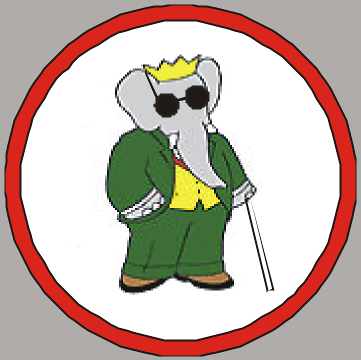
Particle Identification

- Separation of charged kaons and pions is crucial to most rare analyses – especially at high momentum
  - Pions outnumber kaons in the continuum 7 to 1
- The DIRC measures the Cherenkov angle θ_C associated a track passing through a quartz radiator
- Well behaved pulls can be cut on, included in fits, or made part of a global selection which includes dE/dx from the tracking systems



Extracting a Signal (I)

- All rare analyses at BABAR are performed blind
  - Don't look at the answer until the analysis is "finalized"
  - Avoid experimenter's bias



- Event counting analysis
  - Tune selection to optimize expected signal wrt estimated background (the experimental sensitivity or upper limit)
  - Count events in $m_{ES} - \Delta E$ signal box
  - Estimate continuum background from sidebands and subtract to obtain signal yield
  - Best suited for analyses where large yields or good signal to background is expected

Extracting a Signal (II)

- In cases where a small yield is expected, or the backgrounds are large (or both), the technique of choice is an extended maximum likelihood fit

$$L = \frac{e^{-\sum n_j}}{N!} \prod_{i=1}^{N} L_i \qquad L_i = \sum_{j=1}^{m} n_j P_j(\vec{x}_i)$$

  - n_j : population for each species (signal and background)
  - $P_j(x_i)$: Probability density function evaluated with a set of observables x_i (m_{ES}, ΔE, Fisher, etc …)
  - Statistical error on the event yield:

$$\Delta(-2 \ln L) = 1$$

  - Statistical significance ~ difference in $\Delta(-2 \ln L)$ when forced to null signal hypothesis (typically require a 4σ effect to claim an observation

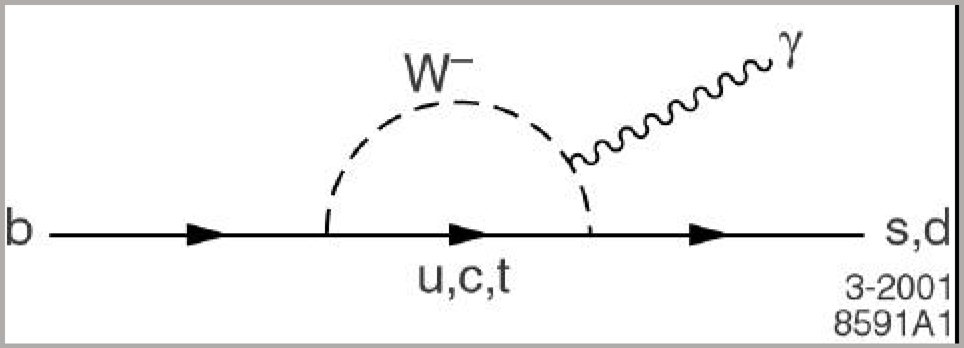
Extracting a Signal (III)

- Key ingredient to ML fit are the Probability Density Functions
  - PDFs <u>must</u> describe the data
- Determine signal PDFs from Monte Carlo
  - Use control samples to study Data/MC agreement and adjust PDFs as necessary
    - e.g. study inclusive samples of resonances in offpeak data to understand resonance line-shapes and resolutions
    - Use plentiful $B \rightarrow$charm modes with useful topologies to understand m_{ES}, ΔE and event shape variables.
  - $\Rightarrow$ signal PDFs effectively derived from data
- Determine background PDFs from sideband and off-peak data

All results are preliminary unless reference cited

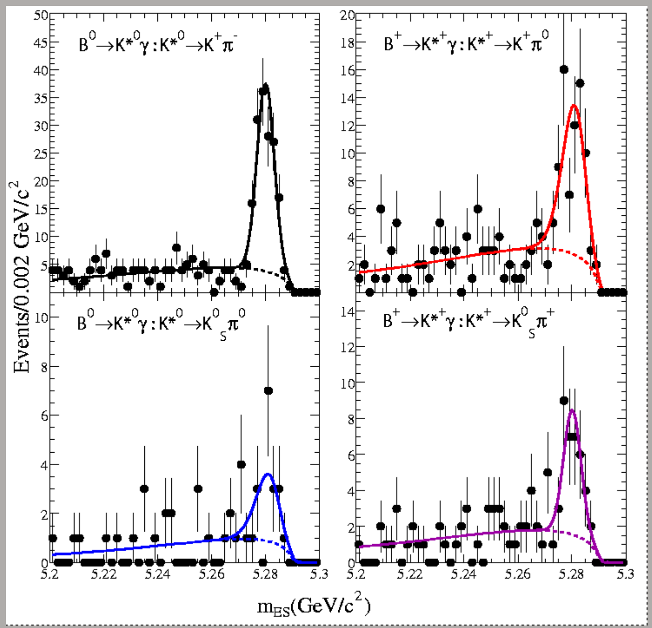
Electromagnetic Penguins

- B $\rightarrow$K*γ was the first penguin to be observed (CLEO)
  - Measurement of branching fraction tests QCD
  - Direct CP violation would indicate new physics
- Ratio of *B*(B $\rightarrow\rho\gamma$) to *B*(B $\rightarrow$K*γ) sensitive to $|V_{td}/V_{ts}|$
- Inclusive measurement of B(b $\rightarrow s\gamma$) constrains new physics
- The E_γ spectrum from b $\rightarrow$sγ provides information on the mass and Fermi motion of the b quark within the B meson



$B \to K^*\gamma$

- All analyses require
  - an isolated high energy photon with $1.5 < E\gamma^* < 3.5$ GeV
  - Require EM-like shower profile
  - Veto photons from π^0, η
- Reconstruct all K* decay modes
- Suppress continuum with cuts on thrust angle, B flight angle and K* helicity, kaon ID



	$B(B^0 \to K^{0*}\gamma)$ /10^{-5}	$B(B^+ \to K^{+*}\gamma)$/10^{-5}	Acp
Theory(avg.)	7.5 ± 3.0	7.5 ± 3.0	|Acp|< 0.005
PRL 88, 161805(2002)	4.23 ± 0.40(stat.) ± 0.22(sys.)	3.83 ± 0.62(stat.) ± 0.22(sys.)	-0.17 < Acp < 0.08 (90% C.L.)

theory=hep-ph/0106081,0106067,0105302

22M BB pairs

Searches for $B\rightarrow\rho\gamma$ and $\omega\gamma$

- Goal is to measure $|V_{td}/V_{ts}|$ and compare to result from mixing analysis of B_d and B_s systems
- More challenging than $K^*\gamma$
  - Predicted branching fraction smaller by x50
  - ρ is very broad resonance
  - Backgrounds from $B\rightarrow K^*\gamma$, $B\rightarrow\rho\pi^0$, $b\rightarrow s\gamma$
  - Significant theoretical errors (15-35%) in extracting $|V_{td}/V_{ts}|^2$
- Continuum background rejection with neural net
  - Event shape, Δz, flavor tag
- Kaon ID to veto $K^*\gamma$
- Estimate signal with Maximum Likelihood fit

Results for $B \rightarrow \rho\gamma$ and $\omega\gamma$

- Analyzed sample of 84 million BB pairs
  - No significant signals observed, so set 90% C.L. upper limits

	$\mathcal{B}(B \rightarrow \rho^0\gamma)$	$\mathcal{B}(B \rightarrow \rho^+\gamma)$	$\mathcal{B}(B \rightarrow \omega\gamma)$
Theory	$0.5\text{-}0.75 \times 10^{-6}$	$0.8\text{-}1.5 \times 10^{-6}$	Same as $\rho^0\gamma$
BABAR	$<1.4\times10^{-6}$	$<2.3\times10^{-6}$	$<1.2\times10^{-6}$

Preliminary

Theory: hep-ph/0105302,0106081

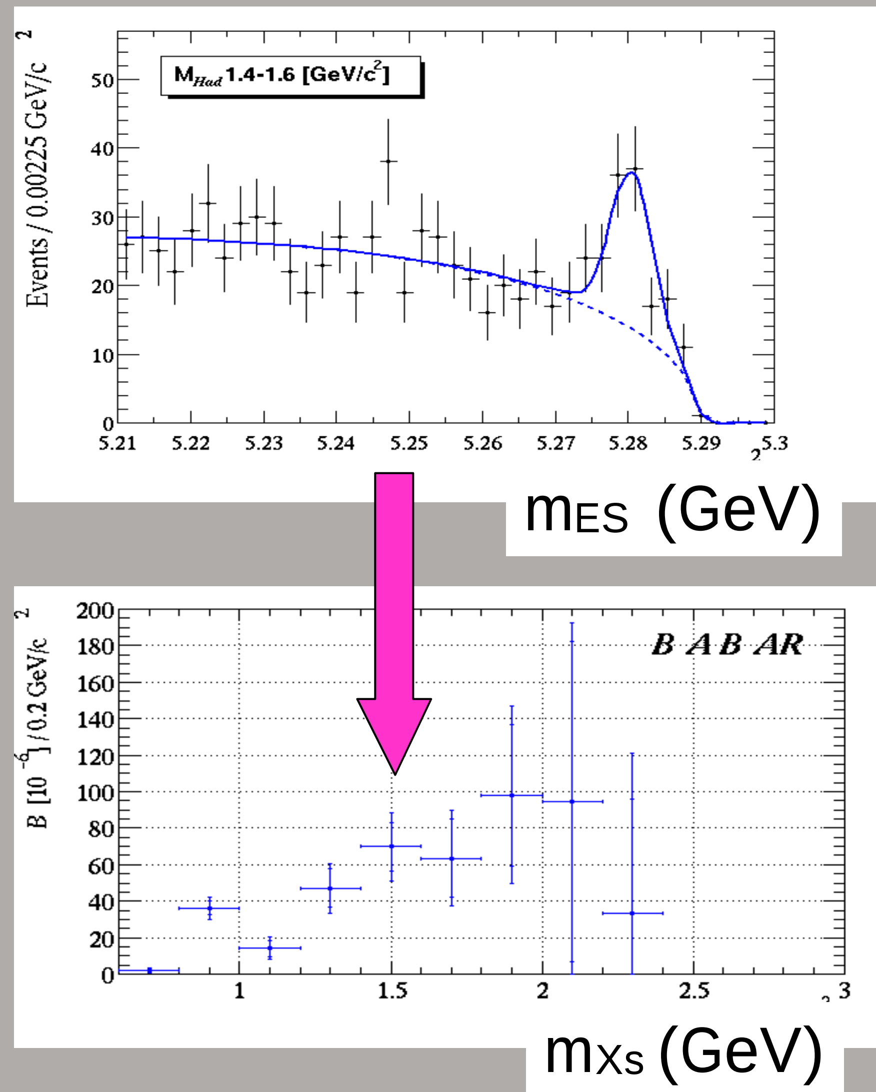
- Combined limit $\mathcal{B}(B \rightarrow \rho\gamma) < 1.9 \times 10^{-6}$ @ 90% C.L.
  - Assume $(\mathcal{B}(B^0 \rightarrow \rho^0\gamma) = \mathcal{B}(B^0 \rightarrow \omega\gamma) = 2^*\mathcal{B}(B^+ \rightarrow \rho^+\gamma))$
- Limit on CKM - $|V_{td}/V_{ts}| < 0.036$ @ 90% C.L.
- For discussion of theory errors, see *Ali & Parkhomenko (Eur Phys. J. C23:89 (2002))*

Inclusive $b \rightarrow s\gamma$

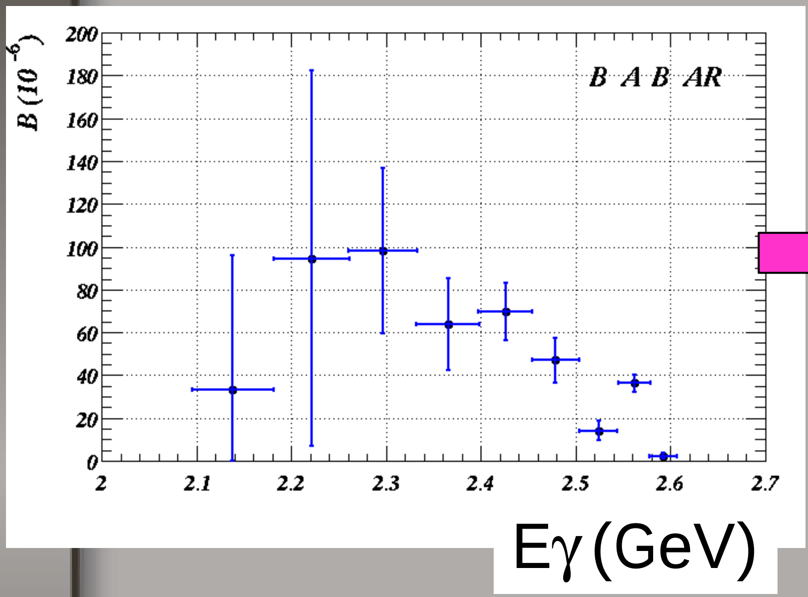
- HQET: Quark-Hadron duality $\Rightarrow$ $B(b \rightarrow s\gamma) = B(B \rightarrow X_s\gamma)$
- Theory: NLO $B(b \rightarrow s\gamma) = 3.57 \pm 0.30 \times 10^{-4}$
  - *(hep-ph/0207131)*
- Models of E_γ spectrum parameterized in m_b and λ_1
- JETSET used to model X_s fragmentation
- Two approaches to the analysis
  - Semi-inclusive (Σ exclusive states)
  - Fully-inclusive
- In both cases, challenge is to reduce backgrounds while controlling systematic and theoretical uncertainties

Semi-Inclusive $b \to X_s \gamma$

- Sum over exclusive final states
  - K^+/K^0_S + up to 3π ($1\pi^0$)
  - total of 12 final states
- 22M BB pairs
- Continuum from sideband, cross feed and BB background from MC
- MC efficiency corrected for observed discrepancy in X_s fragmentation

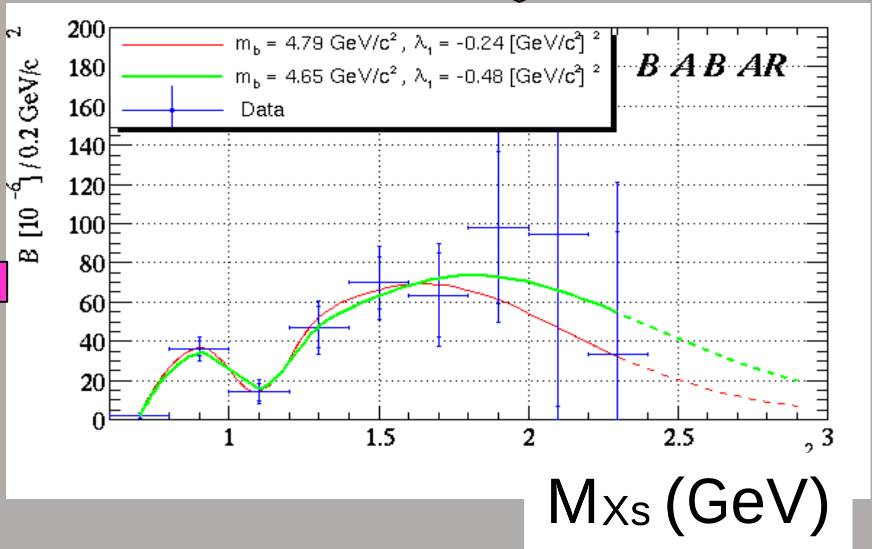


Semi-Inclusive $b \to X_s\gamma$ - Results



$<E_\gamma>=2.35 \pm 0.04$ (stat.) ± 0.04(sys.)

Determine $\Lambda \to m_b$. Fix m_b, Fit spectrum of Kagan & Neubert (Euro.Phys.J.C 75(1999)



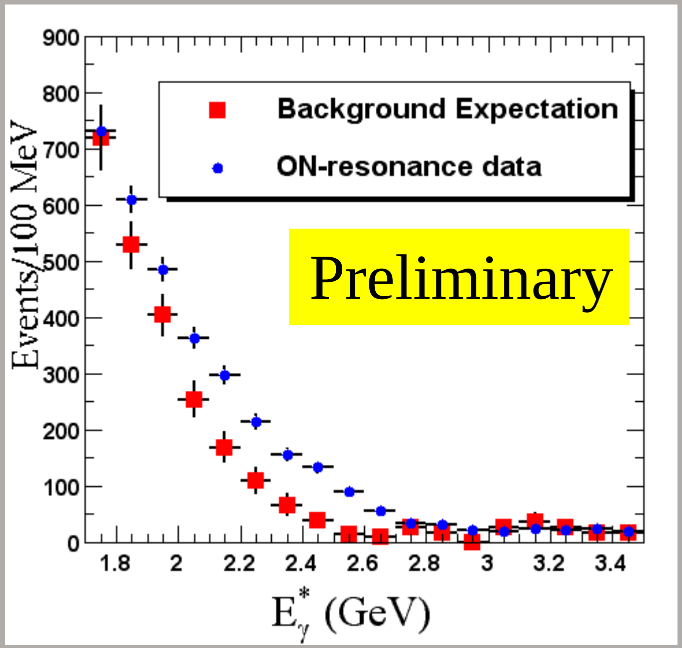
$B(B \to X_s\gamma) = (\ 4.3 \pm 0.5$ (stat) ± 0.8 (sys) ± 1.3 (theory)) $\times 10^{-4}$

Preliminary

Fully Inclusive $b \rightarrow X_s\gamma$

- Suppress continuum by requiring fast lepton tag, angular separation between tag lepton and photon, missing E to suppress $B \rightarrow Xl\nu$
  - Results in 5% efficiency with x1200 reduction in background
- Consider E_γ in range 2.1 – 2.7 to reduce model dependence
- Dominant systematic from BB backgrounds with fast π^0,η
- Continuum subtraction using off-peak data (6.4 fb-1)
- 61M BB pairs (54.6 fb^{-1})

$$\mathcal{B}(B \rightarrow X_S g) = (3.88 \pm 0.36(\text{stat}) \pm 0.37(\text{sys})^{+0.43}_{-0.23}(\text{theory})) \times 10^{-4}$$

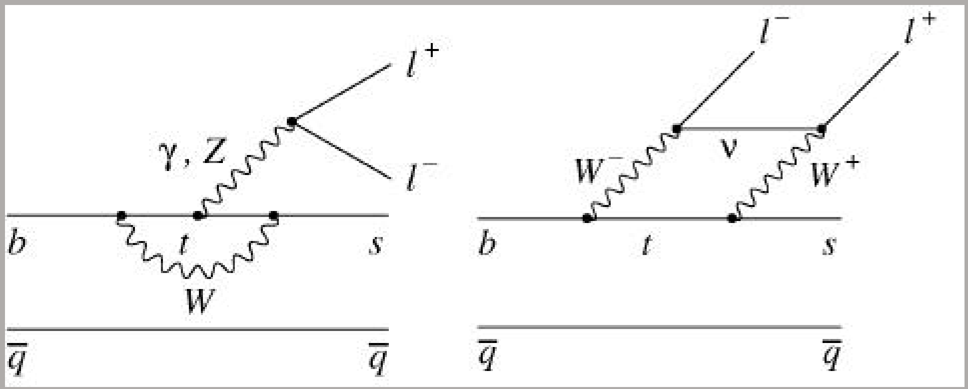


Electroweak Penguins

- Processes that proceed via photons and ($W^{\pm}$, Z^0)
- Strongly suppressed in the SM
- For many of these processes, theory errors are well controlled
- All are very sensitive to new physics

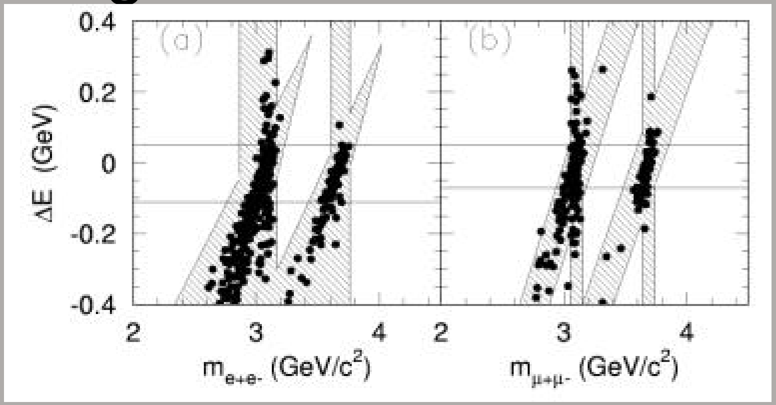
Measurement of $B \to K^{(*)} l^+ l^-$

- Branching fraction very sensitive to new physics
  - Rate can vary by factor of two with some SM extensions
- m^2_{ll} ($=q^2$) distribution, forward-backward asymmetry also of considerable interest
  - q^2 distributions vary substantially for SM+
  - Constructive and destructive interference effects
  - Less model dependence than overall rate



$B \to K^{(*)} l^+ l^-$

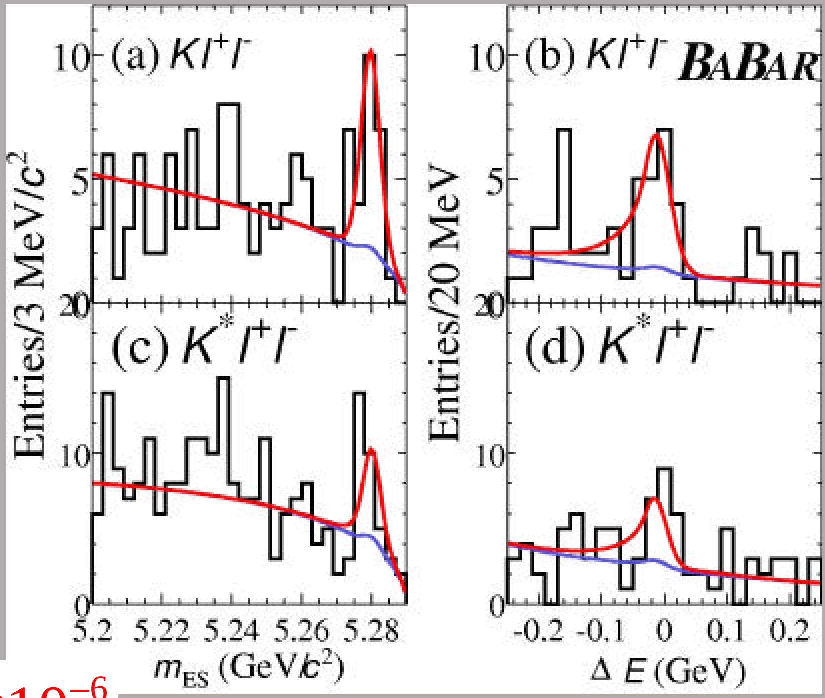
- Many sources of background to control
- Charmonium $K^{(*)}$
  - Veto regions in ΔE vs m_{ll}



- Continuum
  - Fisher with event shape and M(Kl) (veto $D \to Kl\nu$)
- Combinatorics from $B \to Xl$
  - Use B-likelihood built from E_{miss}, vertex, B production angle
- Peaking backgrounds from particle misID
  - Veto $K^{(*)}\pi$ in D mass region and include in fit

$B \to K^{(*)} l^+ l^-$

- Extract signal with likelihood fit to m_{ES} and ΔE
- 85M BB pairs
- 4.4σ effect in Kll
- 2.8σ effect in K*ll
- Results:



$$B(B \to K l^+ l^-) = (0.78^{+0.24+0.11}_{-0.20-0.18}) \times 10^{-6}$$

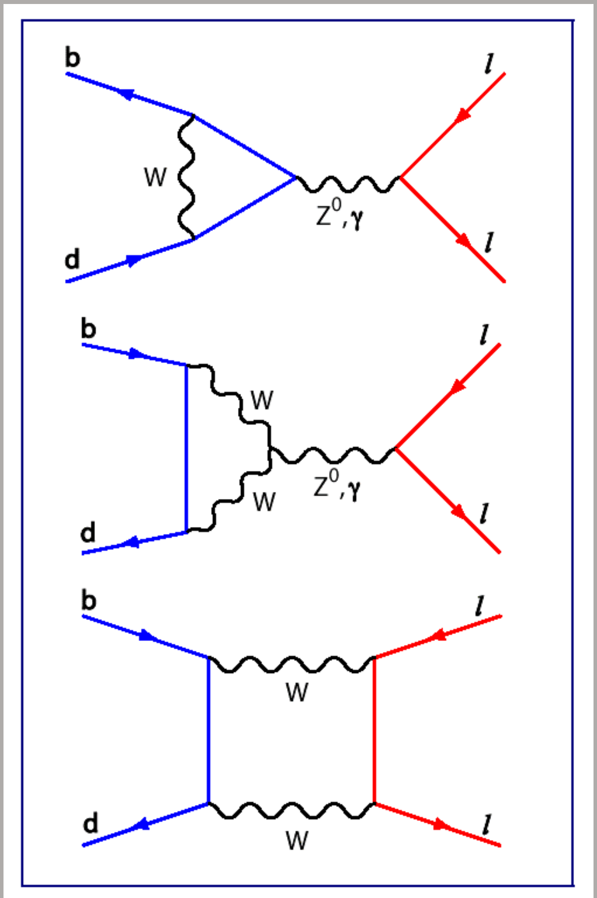
$$B(B \to K^* l^+ l^-) = (1.68^{+0.68}_{-0.58} \pm 0.28) \times 10^{-6}$$

$$< 3.0 \times 10^{-6} \text{ @ } 90\% \text{ C.L.}$$

Preliminary

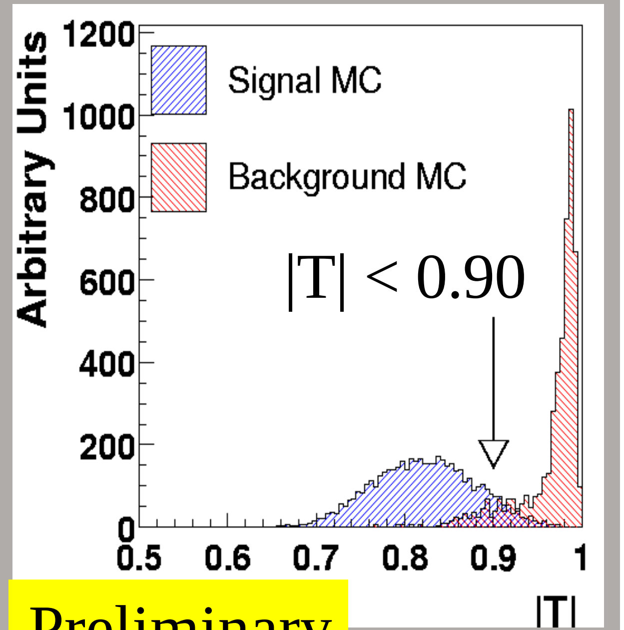
Search for $B \rightarrow l^+ l^-$

- Highly suppressed in SM
  - CKM suppression: $b \rightarrow d$ transition
  - Helicity suppressed $(m_l/m_B)^2$
- SM predictions for:
  $e^+e^- \sim 10^{-15}$, $\mu^+\mu^- \sim 10^{-10}$
- Require two high momentum leptons (lepton ID) with good vertex information



Search for $B \to l^+l^-$

- Backgrounds from real leptons in cc decays, $\pi \to \mu$ misidentification, 2 photon processes
- Suppress continuum background with thrust angle and magnitude
- Cuts optimized for best upper limit
- Results from ~60M BB events

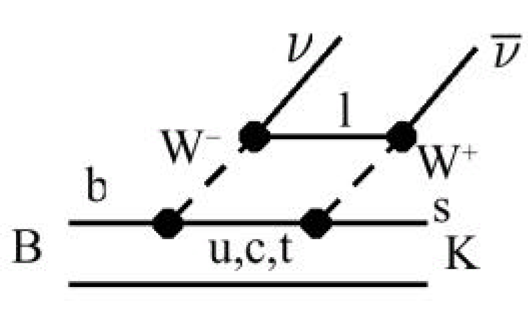


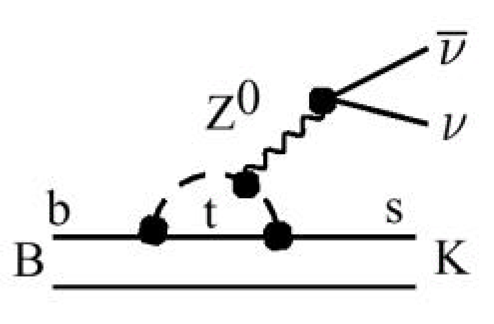
Preliminary

	N_{GSB}	N_{SigBox}	N_{BG}	90% CL Upper Limit
$B \to e^+e^-$	25	1	0.60±0.24	3.3×10^{-7}
$B \to \mu^+\mu^-$	26	0	0. 49±0.19	2.0×10^{-7}
$B \to e^\pm\mu^\mp$	37	0	0.51±0.17	2.1×10^{-7}

Search for $B^+ \to K^+ \nu\bar{\nu}$

- Nearly pure EW flavor changing neutral current
  - Nearly free from strong interaction effects
  - Small theoretical uncertainties
  - SM Theory: $\mathcal{B}(B^+ \to K^+ \nu\nu) \approx 3.8 \times 10^{-6}$
- Final state has two neutrinos
  - Difficult to reconstruct - tag the other B and search for the signal in the recoil
  - Tag with $B^- \to D^0 l\nu(X)$ (i.e. D*, …)
  - Require high momentum K^+ in recoil (need PID!)
  - Cut on remaining neutral energy in recoil and angle between kaon and tag lepton

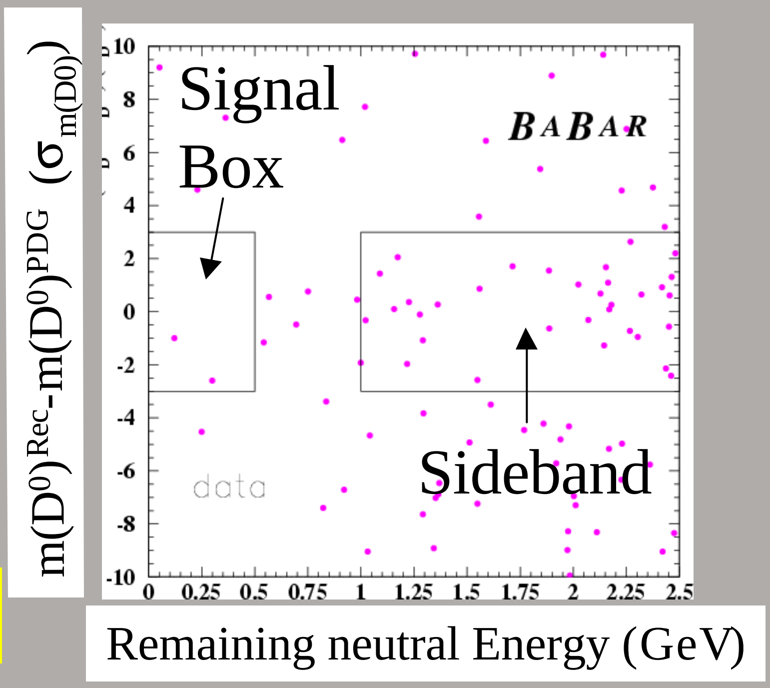




$B^+ \to K^+\nu\bar{\nu}$ Results

- Define signal and sideband regions in D^0 mass vs E_{left}
- Signal efficiency ~0.1%
- 60M BB pairs

2 events observed
in the data
(2.2 expected)

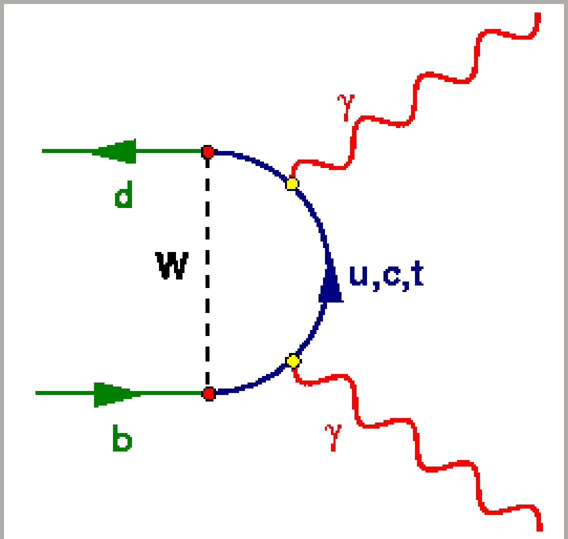


Preliminary

$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 9.4 \times 10^{-5}$ (90% CL)

Search for B→γγ

- Example of electroweak annihilation
- SM expectation *B*~0.1 to 2.3 x 10^{-8}
- Cuts on R2, thrust and B production angles to suppress background
- Select photon pairs not consistent with π^0 or η
- 22M BB pairs
- *B*(B→γγ) < 1.7 x 10^{-6}



PRL 87 241803(2001)

Charmless Hadronic B Decays

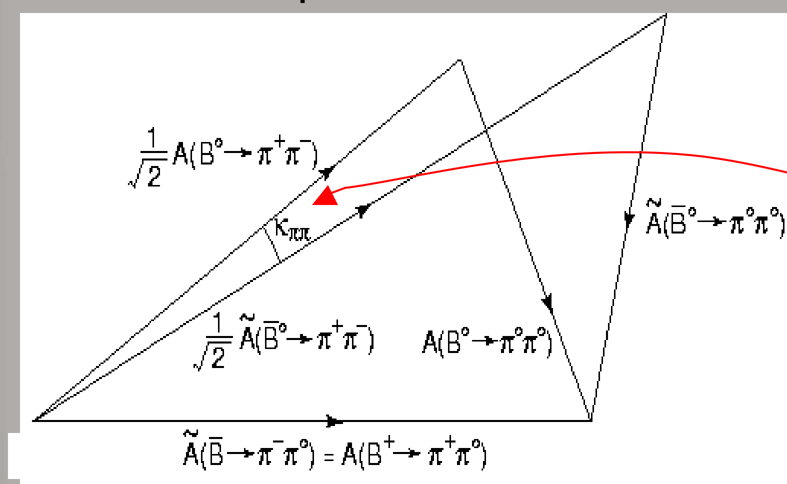
- Dominant amplitudes are CKM suppressed tree and gluonic penguins
- Continuum background dominates
  - Modes high multiplicity and those with π^0s (and other neutrals) also suffer from BB background
- Kinematic and topological variables reject continuum
- PID crucial to separate kaons and pions
- Most analyses use ML fit to extract signal
- Typical observables: m_{ES}, ΔE, Fisher, PID, resonance masses and helicities

Charmless 2-body Decays

- $B \rightarrow \pi^+\pi^-$ CP eigenstate – extract $\sin(2\alpha_{eff})$
- Need all the $\pi\pi$ final states to go from α_{eff} to α via isospin analysis
- $K\pi$ final states may yield information on CP phase γ (Fleischer-Mannel bound), and may have substantial direct CP violation
  - $A_{K\pi} \sim |P/T|\sin(\gamma)\sin(\delta)$ (δ=strong phase)
- Extract signal with ML fit using m_{ES}, ΔE, DIRC pulls, Fisher discriminant
  - Fit kaon and pion hypothesis yields (along with qq background) and rate asymmetries simultaneously

Contamination in B→ππ

- Penguin contamination of B→ππ means we measure sin2α_{eff} instead of sin2α
- Use isospin relations to "subdue" the penguins
  - All ππ states have either I=2 or 0
    - Gluonic penguins only contribute to I=0 (ΔI=1/2)
    - $\pi^+\pi^0$ is pure I=2 (ΔI=1/2) so has only tree amplitude → ($|A^{+0}| = |A^{-0}|$)
    - Requires measurement of all ππ decays each for B and $\overline{B}$



$$2a_{eff} = 2a + k_{pp}$$

Gronau and London, Phys. Rev. Lett. 65, 3381 (1991)

2-Body Results

Mode	N_{EVENTS}	Branching ratio (´ $\mathbf{10^{-6}}$)	A_{CP}
$B^0 \to \pi^+\pi^-$	157 ± 19	$4.7 \pm 0.6 \pm 0.2$	
$B^0 \to K^+\pi^-$	589 ± 30	$17.9 \pm 0.9 \pm 0.7$	$-0.102 \pm 0.050 \pm 0.016$
$B^0 \to K^+K^-$	1 ± 8	<0.6 (90% C.L.)	
$B^+ \to \pi^+\pi^0$	125 ± 22	$5.5 \pm 1.0 \pm 0.6$	$-0.03 \pm 0.18 \pm 0.02$
$B^+ \to K^+\pi^0$	239 ± 22	$12.8 \pm 1.2 \pm 1.0$	$-0.09 \pm 0.09 \pm 0.01$
$B^0 \to K^0\pi^0$	86 ± 13	$10.4 \pm 1.5 \pm 0.8$	$0.03 \pm 0.36 \pm 0.09$
$B^0 \to \pi^0\pi^0$	23 ± 10	<3.6 (90% C.L.)	
$B^+ \to K^+K^0$	< 10	<1.3 (90% C.L.)	
$B^+ \to K^0\pi^+$	172 ± 17	$17.5 \pm 1.8 \pm 1.3$	$-0.17 \pm 0.10 \pm 0.02$

$\sim 88 \times 10^6$ B pairs

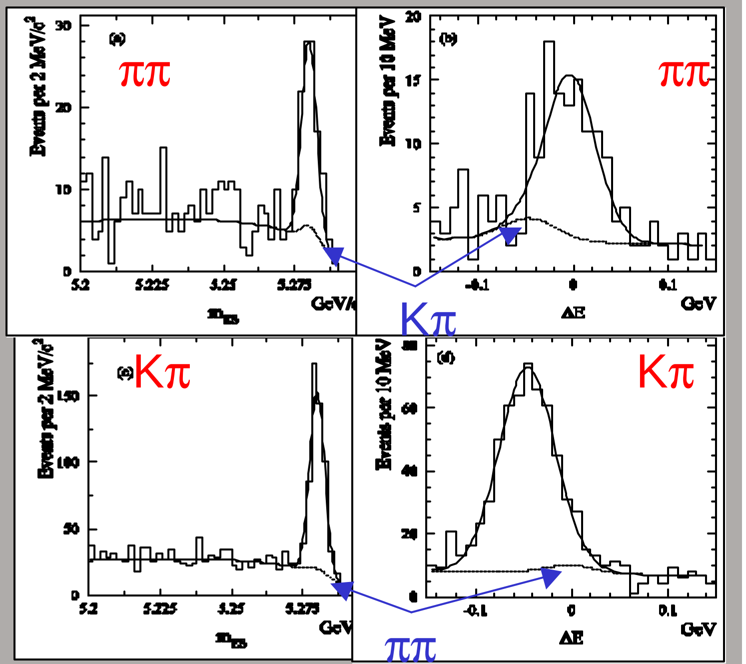
$\sim 60 \times 10^6$ B pairs

- Observe a 2.5σ effect (including systematics) in the search for $B^0 \to \pi^0\pi^0$

Preliminary

More on 2-Body results

- Projections in m_{ES} and ΔE
  - Few hundred signal events out of 26K 2-prongs (mostly continuum)
- Can still get information α from limit on $\pi^0\pi^0$
  - Grossmann-Quinn bound (assumes only isospin)



$$\sin^2(a_{\text{eff}} - a) < \frac{\frac{1}{2}\left[BR(B^0 \to p^0 p^0) + BR(\overline{B}^0 \to p^0 p^0)\right]}{BR(B^\pm \to p^\pm p^0)}$$

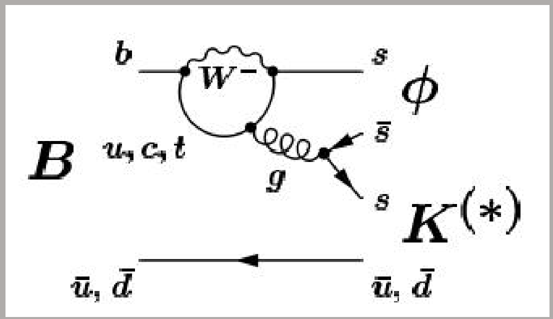
$$< 0.61 @ 90\% \text{ C.L.} \Rightarrow \left| a_{\text{eff}} - a \right| < 51^\circ @ 90\% \text{ C.L.}$$

“Quasi”-2-body Decays

- A 2-body B decay through one (or two) intermediate resonances
  - e.q. $B\rightarrow\phi K^*$
- ~70 combinations among the lowest lying vector and pseudoscalar nonets
  - All combinations of K, π, η, η' ρ, K^*, ϕ
- Analysis very similar to $\pi\pi$, $K\pi$
- Additional information from resonance masses, helicities (in pseudoscalar-vector decays)

$B \to \phi K^{(*)}$

- CKM forbidden $b \to s\bar{s}s$, proceeds via penguin only
- In SM, time-dependent asymmetry in ϕK^0_S measures sin2β
  - But since this is pure penguin, potentially very sensitive to non-SM effects



Results for B→ϕK$^{(*)}$

$\sim 22.7\times10^{6}\,B\ \ pairs$ PRL **87** 151801 (2001)

$$Br(B^{\pm}\rightarrow j\,K^{*\pm}) = (9.7\pm^{+4.2}_{-3.4}\pm1.7)\times10^{-6}$$

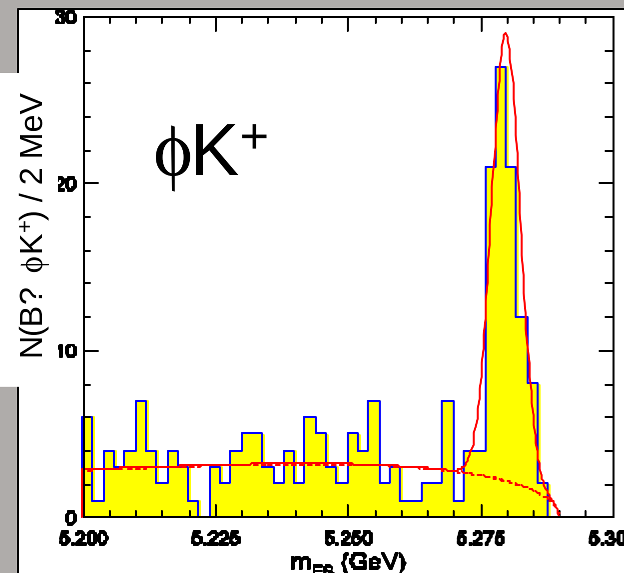
$$Br(B^{0}\rightarrow j\,K^{*0}) = (8.6^{+2.8}_{-2.4}\pm1.1)\times10^{-6}$$

$\sim 60\times10^{6}\,B\ \ pairs$ Preliminary

$$Br(B^{\pm}\rightarrow j\,K^{\pm}) = (9.2\pm1.0\pm0.8)\times10^{-6}$$

$$Br(B^{0}\rightarrow j\,K_{S}^{0}) = (8.7^{+1.7}_{-1.5}\pm0.9)\times10^{-6}$$

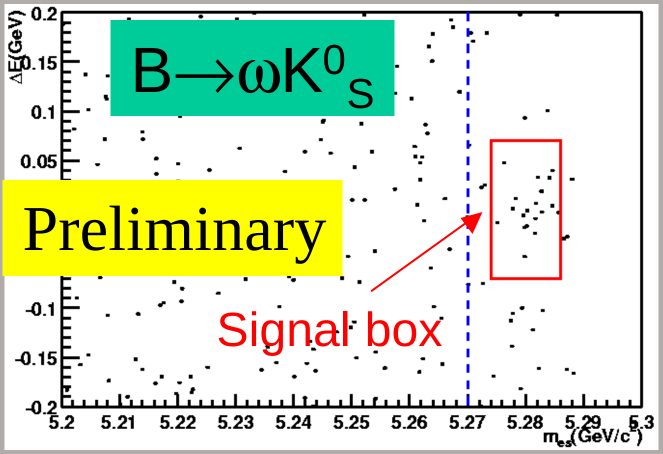
$$Br(B^{\pm}\rightarrow j\,p^{\pm}) < 0.56\times10^{-6}\,(90\%\ \ C.L.)$$



- (nearly) pure gluonic penguin observed
- B→ϕπ both CKM and color suppressed
  - Theory BF ~10^{-9}, a signal at these sensitivities could mean new physics

$B \to \omega h$ ($h = K, \pi$)

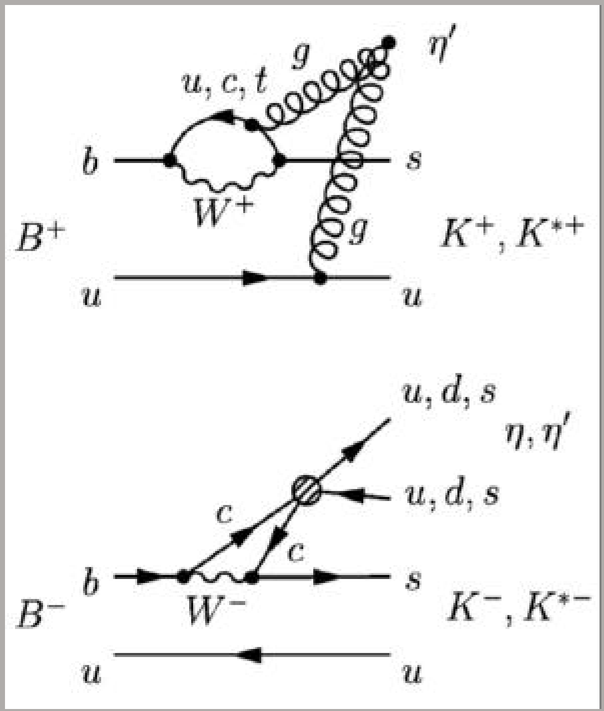
- Some mixture of CKM suppressed tree and penguin
  - Tree expected to dominate?
- Charged mode seems to be indecisive
  - First ωK observed (CLEO), then $\omega\pi$ (CLEO and BABAR)
- Results on 22M BB pairs PRL 87 21802(2001)
  - New result for ωK^0_S (60M BB pairs) – first observation
  - All yields from likelihood fits



Mode	N_{signal}	$S(\sigma)$	$B(\times 10^{-6})$
ωK^+	$6.4^{+5.6}_{-4.4}$	1.3	<4
ωK^0	$26.6^{+7.7}_{-6.6}$	6.6	$5.9^{+1.7}_{-1.5} \pm 0.9$
$\omega \pi^+$	$27.6^{+8.8}_{-7.7}$	4.9	$6.6^{+2.1}_{-1.8} \pm 0.7$
$\omega \pi^0$	$-0.9^{+5.0}_{-3.2}$	-	<3

Measurement $B \to \eta^{(\prime)} K^{(*)}$

- Penguin dominated, some tree
- First QCD penguin observed (by CLEO)
  - Observed because rates for η'K (and ηK*) much larger than expected
- Conjecture: interfering amplitudes
  - Enhance η'K, ηK*
  - Suppress η'K*, ηK
- Other hypotheses:
  - η' as an approximate flavor singlet
  - QCD anomaly, gluon couples directly to η'
  - "charming" penguins, c quark enhanced in loop

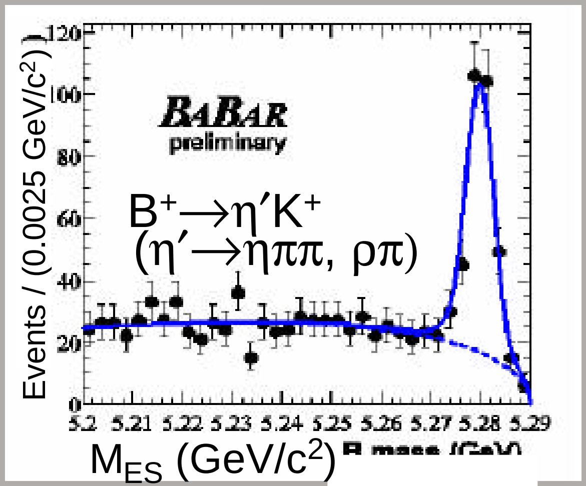


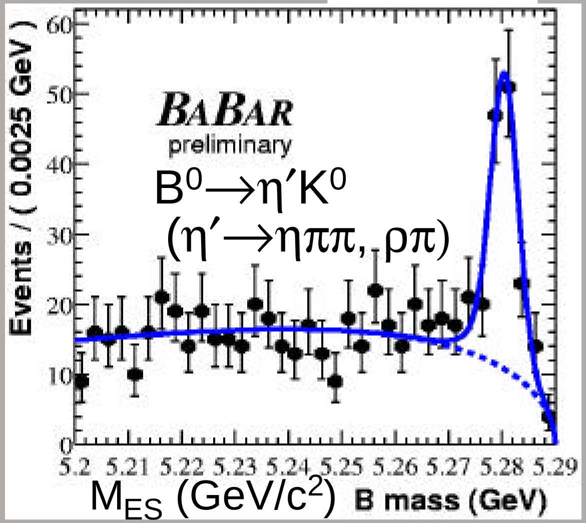
Results for $B \to \eta^{(\prime)} K^{(*)}$

- 60M BB pairs for η' analyses, 22M for η

Mode	N_{EVENTS}	Branching ratio (´ **10^{-6}**)
$B^+ \to \eta' K^+$	445 ± 26	67 ± 5 ± 5
$B^0 \to \eta' K^0$	135 ± 15	46 ± 6 ± 4
$B^0 \to \eta' K^{*0}$	5.2 ± 3.4	<13 (90% C.L.)
$B^+ \to \eta K^+$	12.9 ± 5.7	<6.4 (90%C.L.)
$B^+ \to \eta \pi^+$	8.0 ± 5.9	<5.2 (90%C.L.)
$B^0 \to \eta K^0$	5.7 ± 3.3	<12 (90%C.L.)
$B^0 \to \eta K^{*0}$	20.5 ± 6.3	$19.8^{+6.5}_{-5.6} \pm 1.5$
$B^+ \to \eta K^{*+}$	14.3 ± 6.6	$22.1^{+11.1}_{-9.2} \pm 3.2$

Preliminary





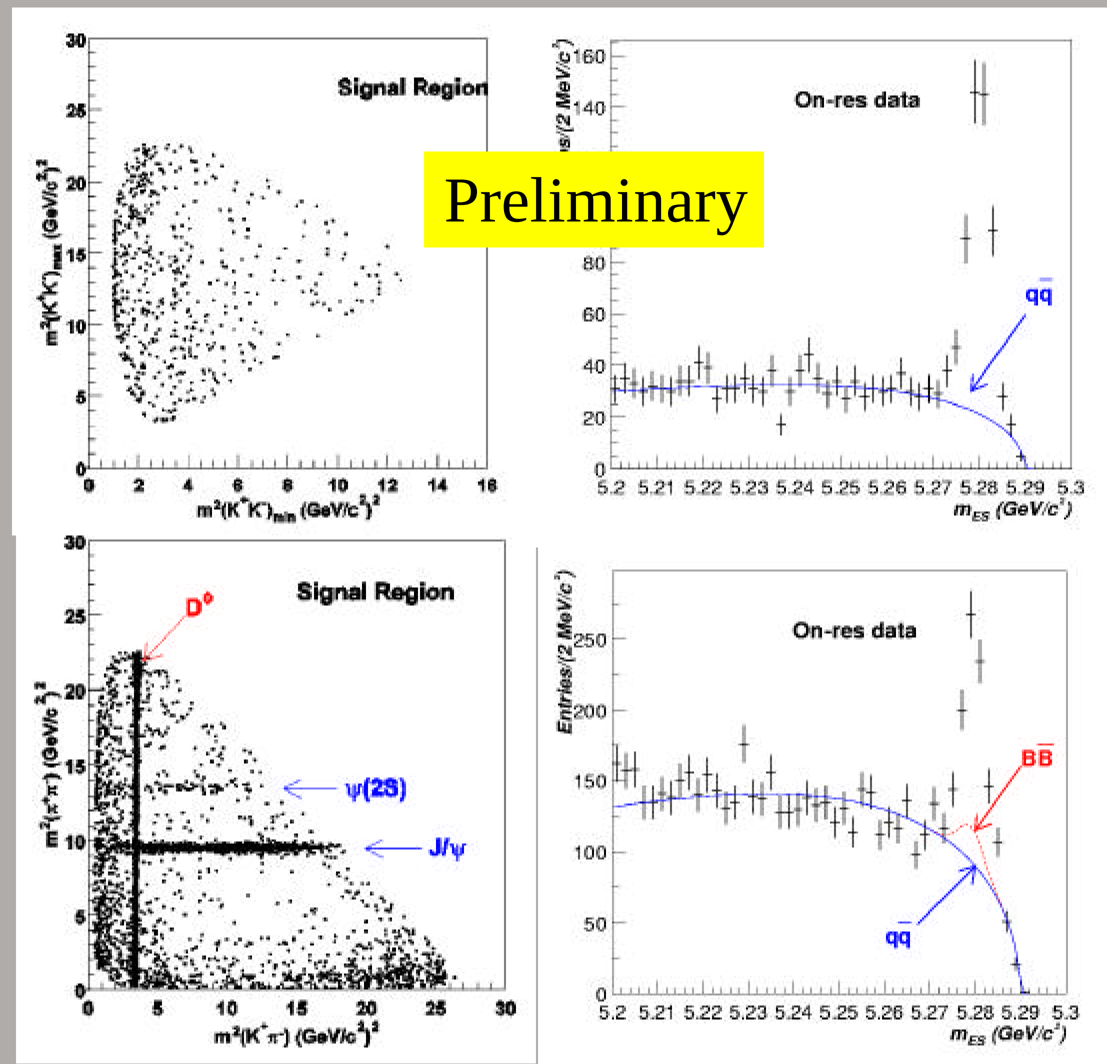
Three Body: $B \rightarrow hhh$, $h=\pi^{\pm}$, $K^{\pm}$

- Analysis over full dalitz plot
- Cut based analysis analysis
- Measure all final states simultaneously and unfold to obtain branching fractions
- In addition to continuum background, B background from $J/\psi K$, $D\pi/DK$, cross-feed
- Primary systematics in PID and tracking

3-Body Results

B→KKK

B→Kππ



3-Body Results

- In 56M BB pairs, measure branching fractions across the Dalitz plot

$$Br(B^{\pm} \rightarrow K^{\pm} p^{\mp} p^{\pm}) = (59.2 \pm 4.7 \pm 4.9) \times 10^{-6}$$

$$Br(B^{\pm} \rightarrow K^{\pm} K^{\mp} K^{\pm}) = (34.7 \pm 2.0 \pm 1.8) \times 10^{-6}$$

$$Br(B^{\pm} \rightarrow p^{\pm} p^{\mp} p^{\pm}) < 15 \times 10^{-6}$$

$$Br(B^{\pm} \rightarrow K^{\pm} K^{\mp} p^{\pm}) < 7 \times 10^{-6}$$

Preliminary

Outlook

- With ~90M BB events in hand, many analyses to be updated to the full data set
  - Now sensitive to branching fractions of better than x 10^{-6}
- Still much to be done to fill in the full spectrum of possible measurements
- Some "rare" analyses are becoming systematics limited – improved techniques will be needed to fully exploit the deluge of new data in the coming years
- Theoretical developments must keep pace
- The reward for continued efforts in this area could well be the first glimpse of new physics

Results I didn't have Time to Present

- B decays to DDK
  - $\mathcal{B}(B^0 \to D^{(*)}D^{(*)}K)$=[4.3 ± 0.3(stat) ± 0.6(sys)]%
  - $\mathcal{B}(B^+ \to D^{(*)}D^{(*)}K)$=[3.5 ± 0.3(stat) ± 0.5(sys)]%
- Color Suppressed B decays
  - $\mathcal{B}(B^0 \to D^0\pi^0)$=[2.9 ± 0.3(stat) ± 0.4(sys)]x10^{-4}
  - $\mathcal{B}(B^0 \to D^0\eta)$=[2.4 ± 0.4(stat) ± 0.3(sys)]x10^{-4}
  - $\mathcal{B}(B^0 \to D^0\omega)$=[2.5 ± 0.4(stat) ± 0.3(sys)]x10^{-4}

Preliminary

- B decays to $D_S^{(*)+}D^{*-}$
  - $\mathcal{B}(B^0 \to D_S^+D^{*-})$=[1.03 ±0.14(stat) ± 0.13(sys) ±0.26(meson B)]%
  - $\mathcal{B}(B^0 \to D_S^{*+}D^{*-})$=[1.97 ±0.15(stat) ± 0.30(sys) ±0.49(meson B)]%
  - Polarization with $D_S \to \phi\pi^+$: G_L/G = [51.9 ±5.0(stat) ±2.8(sys)]%
- $B^- \to D^0_{(CP)}K^-$

$$R \equiv \frac{Br(B^- \to D^0K^-)}{Br(B^- \to D^0p^-)} = (8.31 \pm 0.35 \pm 0.20)\%$$

$$A_{CP} = 0.17 \pm 0.23^{+0.09}_{-0.07}$$