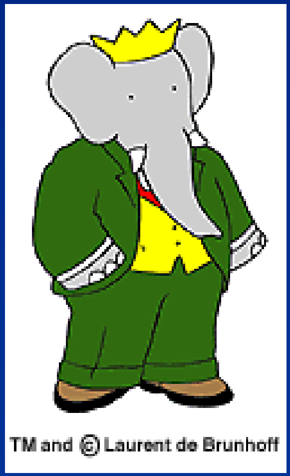
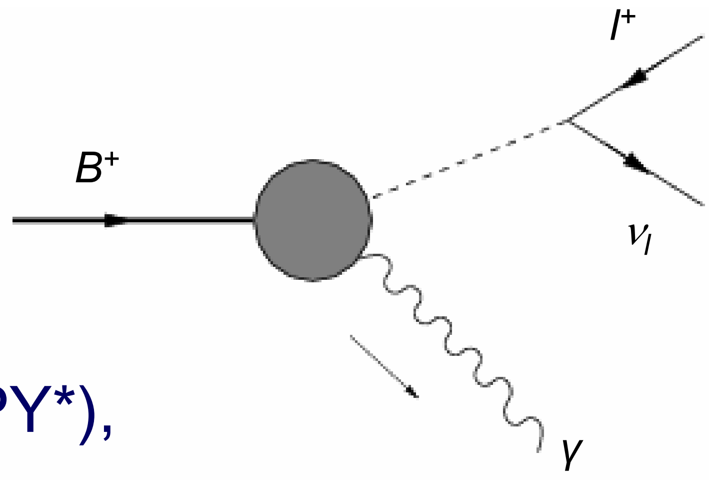
Searches for the Rare Decays $B^+ \to l^+ \nu\gamma$ and $B^0 \to l^+ l^- \gamma$ $(l = e, \mu)$



Edward Chen
BaBar Collaboration
DPF 2006
November 1, 2006

Radiative leptonic decays $B^+ \to l^+ \nu\gamma$



- Radiative leptonic decay is not helicity suppressed, unlike the purely leptonic decay
  - BF: predicted to be ~(1–5)×10^{-6}
    - Previous exp. limits ~<10^{-5}
  - Additional theoretical uncertainty
- Using a factorization approach (KPY*), the tree-level decay width is:

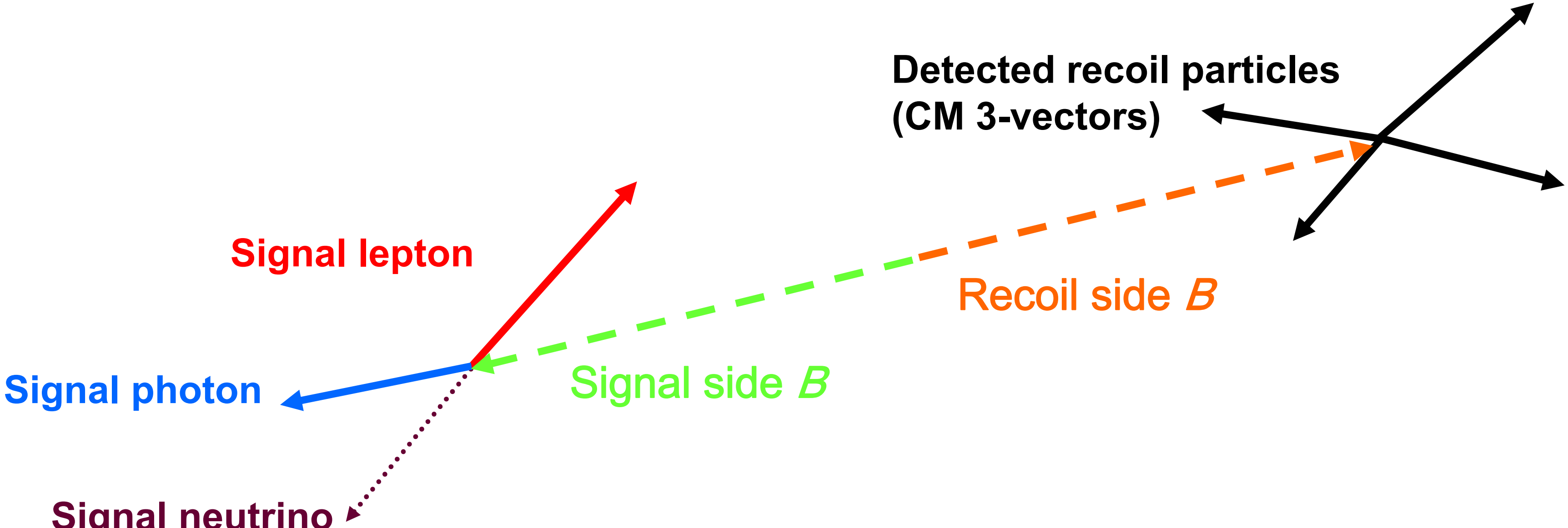
$$\Gamma(B^+ \to l^+\nu\gamma) = \alpha \frac{G_F^2 |V_{ub}|^2 m_B^5}{288\pi^2} f_B^2 \left(\frac{Q_u}{\lambda_B} - \frac{Q_b}{m_b} \right)^2$$

- The variable λ_B is the first inverse moment of the *B* light-cone distribution amplitude
  - It shows up in *B* to two-body hadronic decays such as $B \to \pi\,\pi$.
    - Not measured, and taken to be on the order of λ_{QCD}
  - Thus, a measurement of the radiative leptonic BF could be useful in constraining λ_B

*Korchemsky, Pirjol, and Yan, PRD 61 114510, '00 (Thanks to Dan Pirjol, in particular, for his help)

Analysis scheme

- Use 232M $B\bar{B}$ pairs on-peak data (+off-peak, MC)
- Signal MC generated using KPY model
- Reconstruction:
  - Signal side *B*: Highest CM E lepton, photon
  - "Recoil" side *B*: Sum up the remaining 4-momenta
    - Loose reconstruction
  - Signal neutrino is assumed to be only missing particle



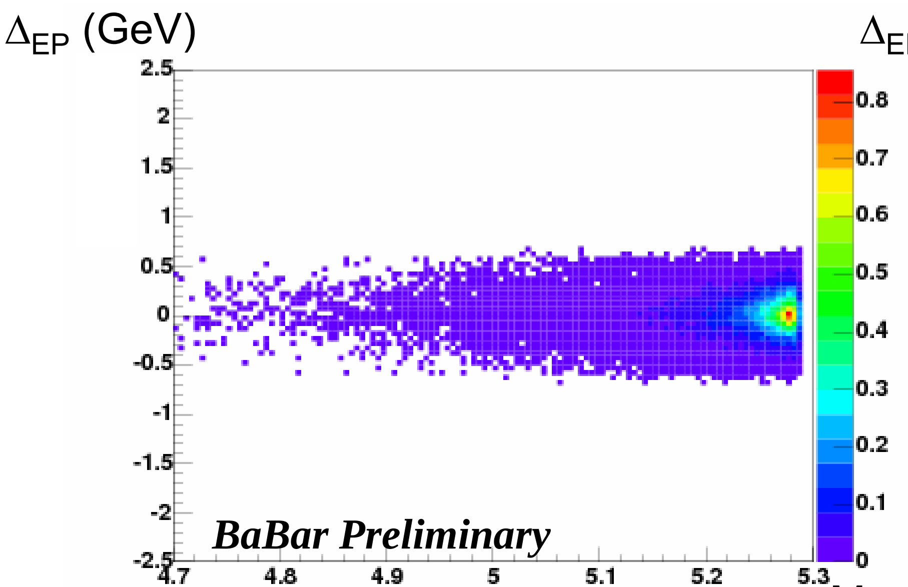
Analysis scheme II

- Event selection criteria:
  - Signal side: lepton, photon energies, angle, cos θ_{BY}
  - Recoil *B* side: total recoil energy and momentum
  - Neutrino reconstruction: missing E – missing |p|
  - Miscellaneous: Event shape, π^0 veto
  - Two-photon rejection: longitudinal momentum, etc.
- Iterative cut optimization procedure
- Binned ML fit to extract signal count

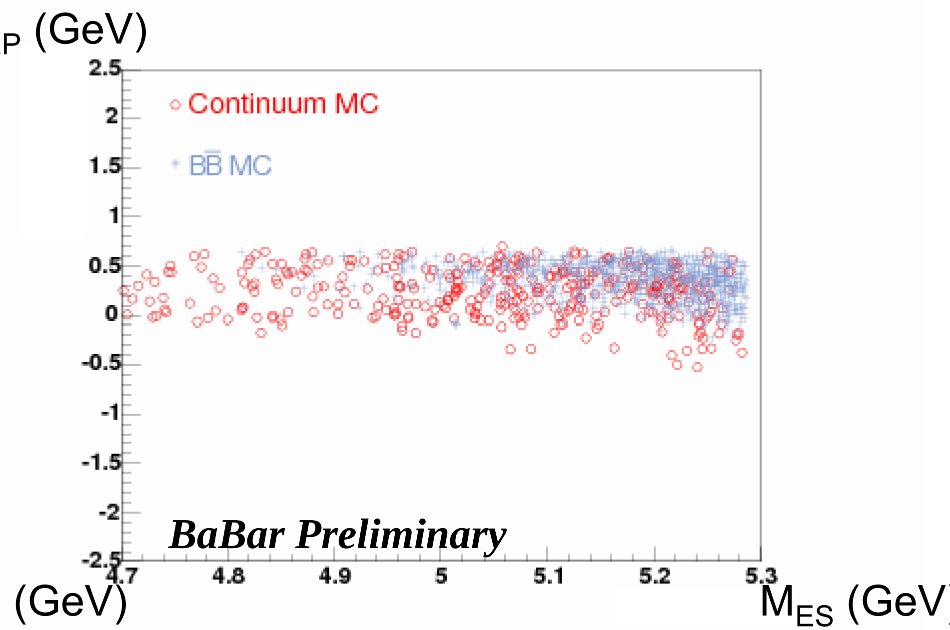
Backgrounds

- Model backgrounds with MC if possible
  - $B\bar{B}$ background
    - $b \to c\, l\, \nu$
    - $b \to u\, l\, \nu$
      - Treat 7 exclusive modes separately ($\pi^+ \pi^0, \rho^+ \rho^0, \omega\ \eta, \eta'$)
    - Other $B\bar{B}$ background
  - Continuum background
    - $e^+e^- \to q\bar{q}$ (where $q = udsc$)
    - $e^+e^- \to \tau^+\tau^-$
    - $e^+e^- \to \mu^+\mu^-\gamma$ (Radiative dimuon, muon mode)
    - Generic two-photon background (*unmodeled by MC!*)
      - $e^+e^- \to e^+e^- X$
      - Forced to use a low-statistics off-peak data sample in our fit!

Signal extraction fit



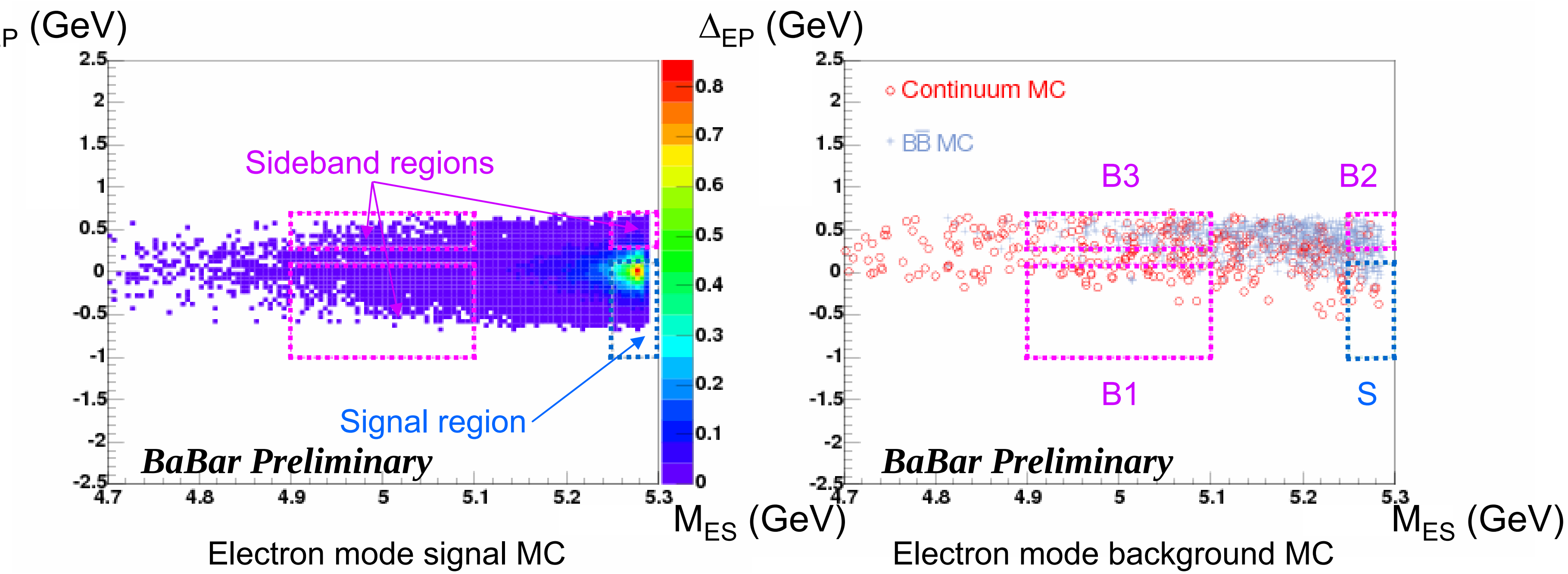
Electron mode signal MC



Electron mode background MC

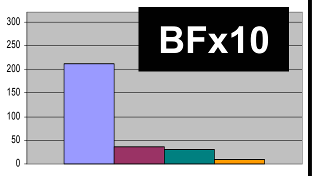
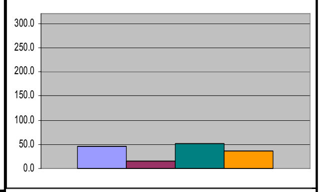
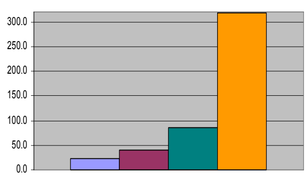
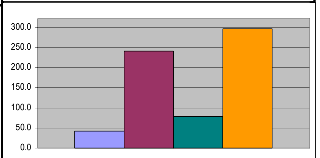
- After all event selections:
  - Use recoil *B* m_{ES} and neutrino E-|p| (Δ_{EP}) to separate signal from remaining background
    - $m_{ES} \equiv \sqrt{(E_{beam}^2 - p_B^2)}$

Signal extraction fit II



- Define a signal region (S) and three sideband regions (B1,B2,B3)
- Signal, continuum, and $B\bar{B}$ background have different relative counts (shapes) in these regions
- Signal efficiency in S region: 3% (2%) for electron (muon)

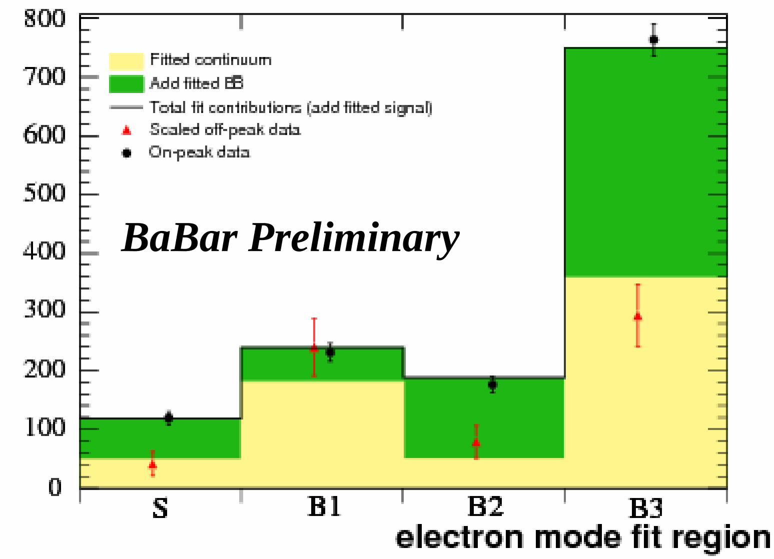
Signal extraction fit III

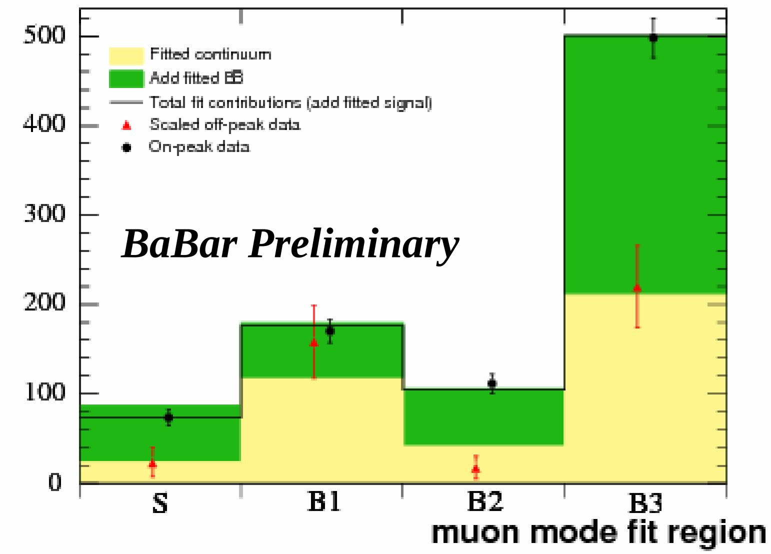
	Region event counts, electron mode (on-peak lumi)				Sample shapes
Δ_{EP} m_{ES}	S sig sig	B1 sig side	B2 side sig	B3 side side	
Signal (BF = 3×10^{-6})	21.2	3.7	3.1	0.9	
b→ulν 7-mode MC	45.5	15.9	51.3	37.1	
Gen *B* MC	22.4	40.2	85.7	317.3	
Off-peak (Cont MC)	41.4 (14.1)	239.7 (67.8)	79.0 (10.5)	294.5 (117.4)	

*Offpeak data was kept blinded, with continuum MC used for cut optimization

Signal extraction fit IV

- Perform ML fit to extract event counts for signal and each type of background
  - Based on four-region shapes for each type
  - Include the statistical uncertainties on the shapes
    - Important for off-peak subtraction
- Also perform a joint fit to both modes





Systematics

- Experimental systematics
  - Tracking efficiency (signal lepton only)
  - PID (signal lepton only)
  - Neutral reconstruction (signal photon)
  - Cut efficiencies
  - Shape (Δ_{EP}/M_{ES})
- Number of *B*'s
  - *B* counting
  - Charged to neutral *B* ratio
- *B* background-specific
  - $b \rightarrow u\, l\nu$ theoretical uncertainties (7 exclusive SL modes)
  - $X_u l\nu$ BF systematic
- Theoretical model for signal

Results

- We present the final measurements in terms of ΔBF, rather than BF, the total branching fraction
  - ΔBF is the branching fraction for the accepted region:
    - Lepton CM energy between 1.875 and 2.85 GeV
    - Photon CM energy between 0.45 and 2.35 GeV
    - Lepton-photon angle cosine less than -0.36
  - Largely eliminates any systematic due to choice of signal model
- In addition to two-sided limits, we quote 90% Bayesian CL upper limits
  - Prior flat in positive BF
  - Prior flat in positive amplitude, i.e. flat in sqrt(BF)

Results for ΔBF

	Central value	Statistical uncertainty	Systematic uncertainty	Theory
Muon mode ($\times 10^{-6}$)	-1.33	+1.74 -2.20	+0.80 -0.87	0.03
Electron mode ($\times 10^{-6}$)	0.11	+1.73 -2.13	+0.61 -0.59	0.08
Joint fit ($\times 10^{-6}$)	-0.25	+1.33 -1.53	+0.60 -0.64	0.07

- As stated in the previous slide, the region is:
  - Lepton CM energy between 1.875 and 2.85 GeV
  - Photon CM energy between 0.45 and 2.35 GeV
  - Lepton-photon angle cosine less than -0.36

Results for ΔBF UL's

	Muon	Electron	Joint
Prior flat in BF	$<2.10\times10^{-6}$	$<2.84\times10^{-6}$	$<2.25\times10^{-6}$
Prior flat in amplitude	$<1.47\times10^{-6}$	$<2.18\times10^{-6}$	$<1.71\times10^{-6}$

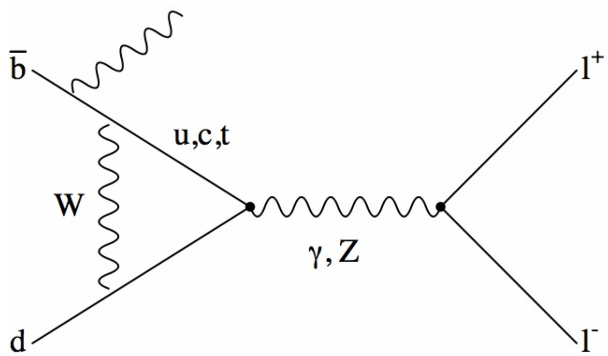
Constraints on λ_B

- In the KPY model, we can obtain full BF measurements
- Use full BF UL to constrain λ_B , and:
  - $|V_{ub}|$: Use PDG 2006 result:
    - $(4.31 \pm 0.30)\times10^{-3}$
  - f_B: HPQCD collab lattice result (2005):
    - 0.216 ± 0.22 (GeV)
- Paper will provide full BF results only for the **joint** fit

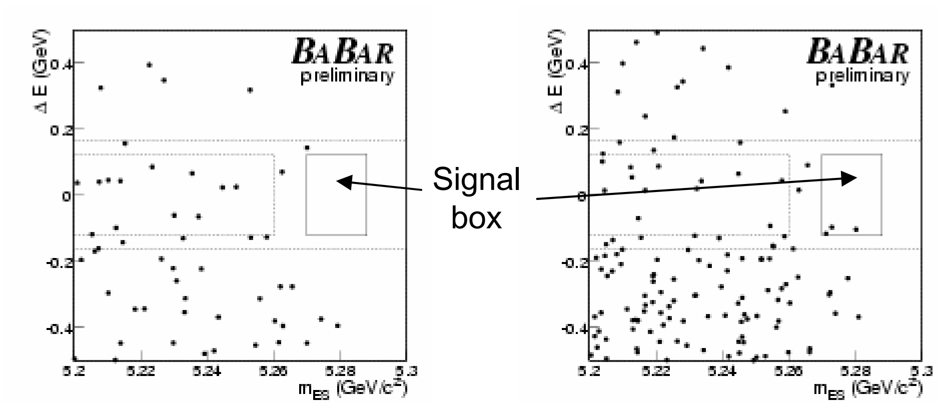
Mode (prior)	UL on full BF	Lower limit on λ_B (MeV)*
Muon (flat BF)	$<5.2\times10^{-6}$	>541
Muon (flat amp)	$<3.7\times10^{-6}$	>655
Electron (flat BF)	$<5.9\times10^{-6}$	>508
Electron (flat amp)	$<4.5\times10^{-6}$	>585
Joint (flat BF)	$<5.0\times10^{-6}$	>554
Joint (flat amp)	$<3.8\times10^{-6}$	>641

*Using central values for $|V_{ub}|$ and f_B

A Search for $B^0 \to l^+ l^- \gamma$



- SM BF prediction: $8(6)\times10^{-10}$ for e(μ) mode
  - G. Eilam, et al. Phys.Lett.B391:461-464,1997



Electron mode

Muon mode

- Reconstruct B^0 candidate using lepton pair and a photon.
- Count number of signal events in a signal box of ΔE and m_{ES}
- Background estimated from sideband areas.
- Set world's first upper limit @ 90% CL:

$BR(B^0 \to e^+ e^- \gamma) < 0.7\times10^{-7}$

$BR(B^0 \to \mu^+ \mu^- \gamma) < 3.4\times10^{-7}$

ICHEP 06 (hep-ex/0607058)

Conclusions

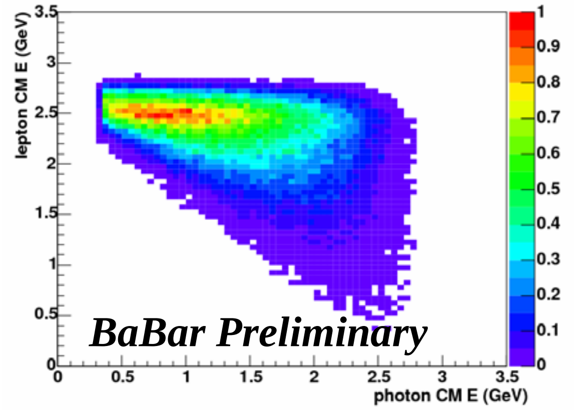
- $B^+ \to l^+ \nu\gamma$:
  - Some of our BF UL's are tighter than the upper end of SM predictions
    - e.g. 3.7×10^{-6} for muon mode (flat amp prior)
    - Standard model BF predictions: $1\text{-}5\times10^{-6}$
  - Future prospects ($\sim$1 ab^{-1}):
    - Our best BF stat. uncertainty (joint fit): $\sim3\times10^{-6}$
      - At $\sim$1 ab^{-1}, this would be $\sim1\times10^{-6}$
    - Should be able to make a SM observation with a Super *B* factory data set
    - Generic two-photon MC generator?
- $B^0 \to l^+ l^- \gamma$:
  - First limits set for these decay modes
  - At $\sim$1 ab^{-1}, expect limit to improve by a factor of 3

Backup

- Backup slides follow here

Signal side variables

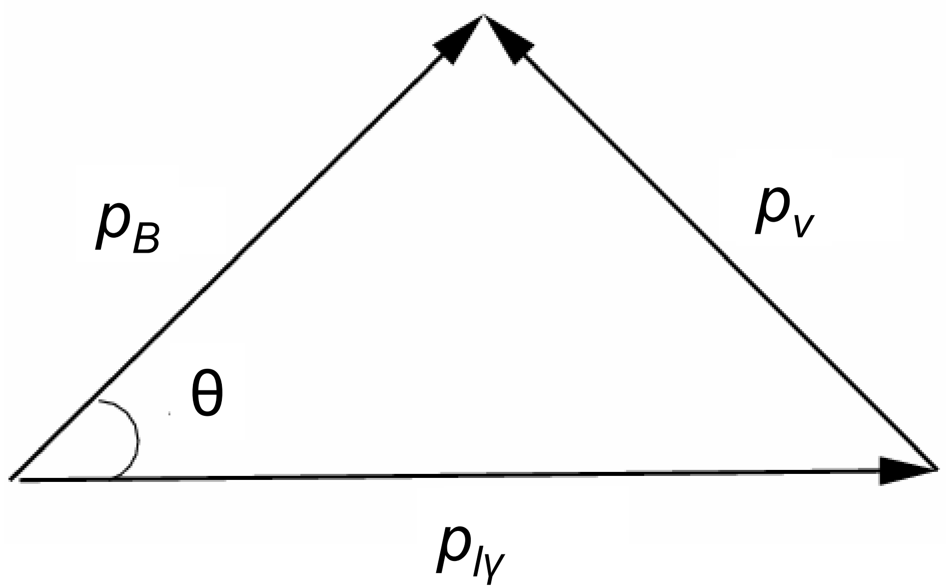
- In Υ(4S) CM frame: take highest energy lepton and highest energy photon in event.
  - GL accuracy studies of signal show this selection yields: Correct electron 99% of time, correct photon 91%, both 90%
    - Slightly higher when analysis cuts are applied to the energies
- Signal lepton CM energy
- Signal photon CM energy
- cos $\theta_{l\gamma}$: CM angle between lepton, photon
- cos θ_{BY}: implied angle between signal "*B*" and LP combo



Generator-level truth-matched electron-mode MC

- gLAT: lateral moment of signal photon shower shape
- Fiducial cut on photon lab angle

$\cos\theta_{BY}$



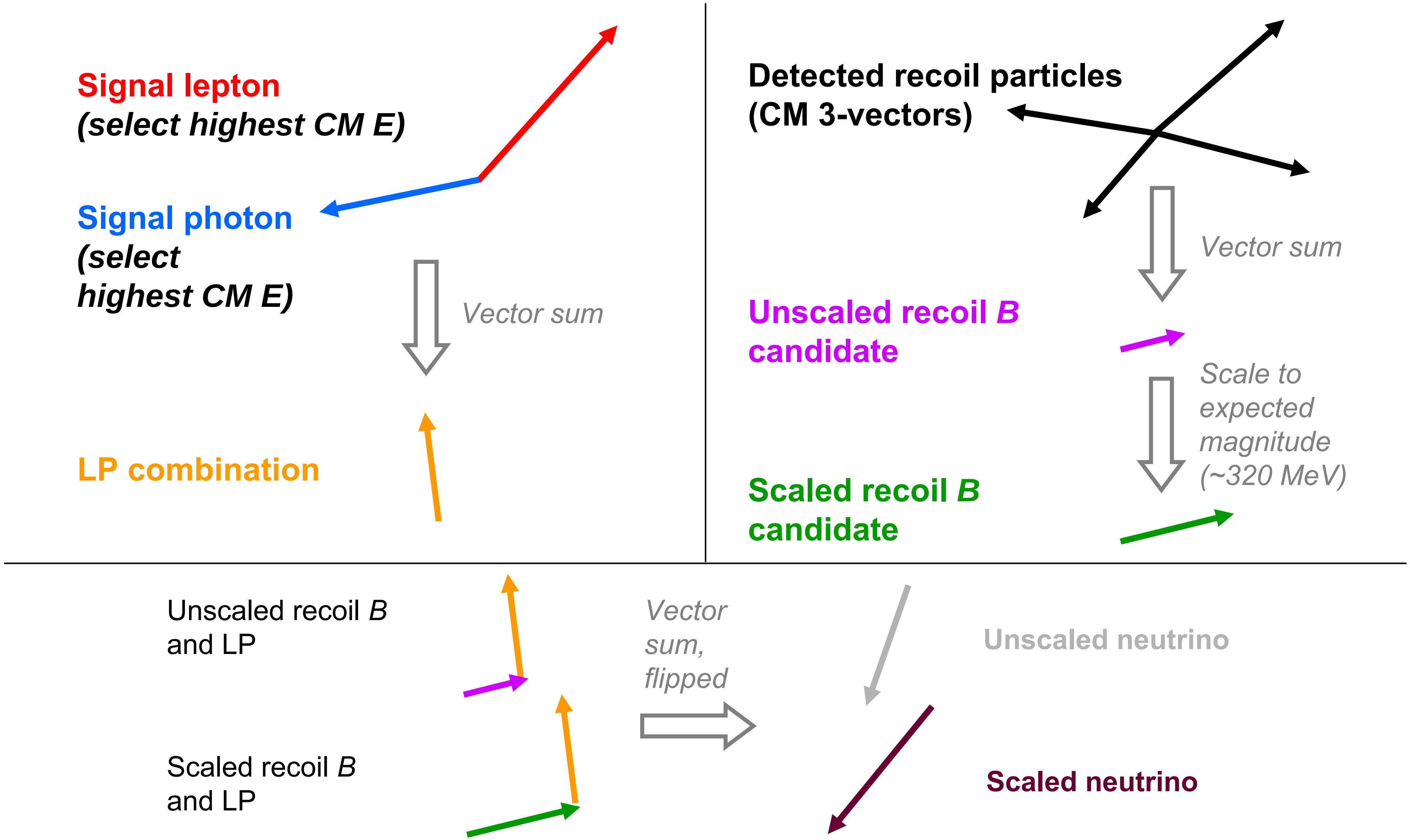
- θ_{BY} is the angle between the lepton-photon and the implied signal B:

$$\cos\theta_{BY} = \frac{(E_{\text{beam}}/2 - E_\ell - E_\gamma)^2 - |\vec{p}_{\ell\gamma}|^2 - |\vec{p}_B|^2}{-2|\vec{p}_B||\vec{p}_{\ell\gamma}|}$$

Recoil *B* reconstruction

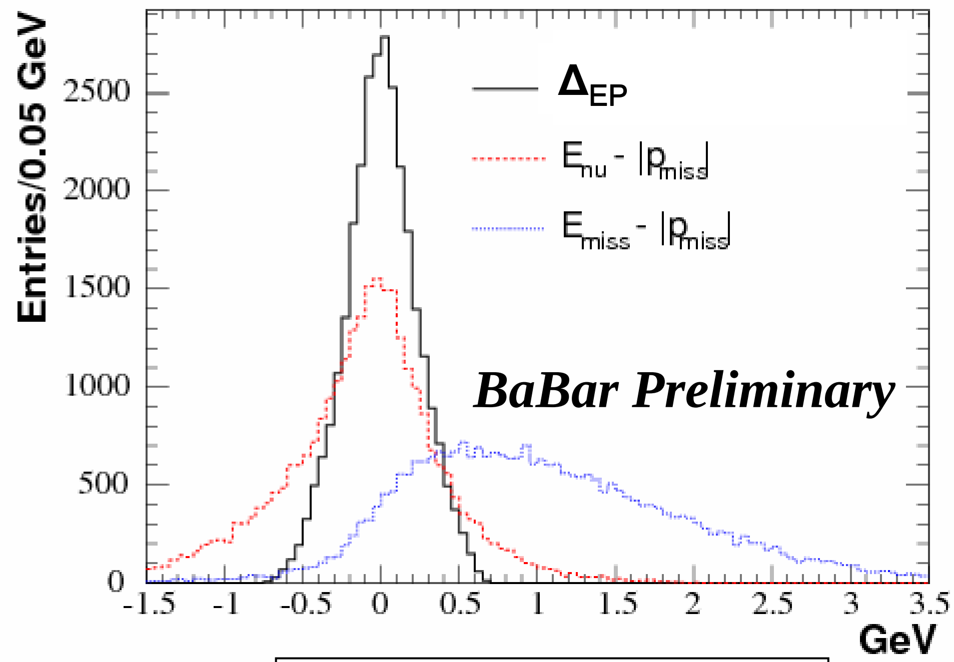
- After choosing signal lepton and photon, remaining particles are assigned to the recoil *B* candidate
  - Charged tracks: pion mass
  - Calorimeter clusters: photons
- Compute standard kinematic variables for this inclusively reconstructed *B* :
  - m_{ES}: Beam-constrained recoil *B* mass
  - ΔE: Total recoil *B* energy – beam energy
  - Both of these variables are standard for exclusive analyses

Neutrino reconstruction



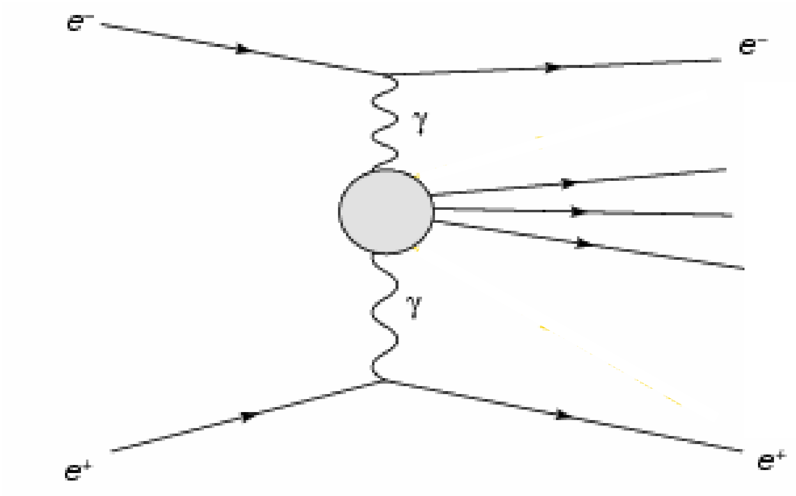
Neutrino reconstruction II

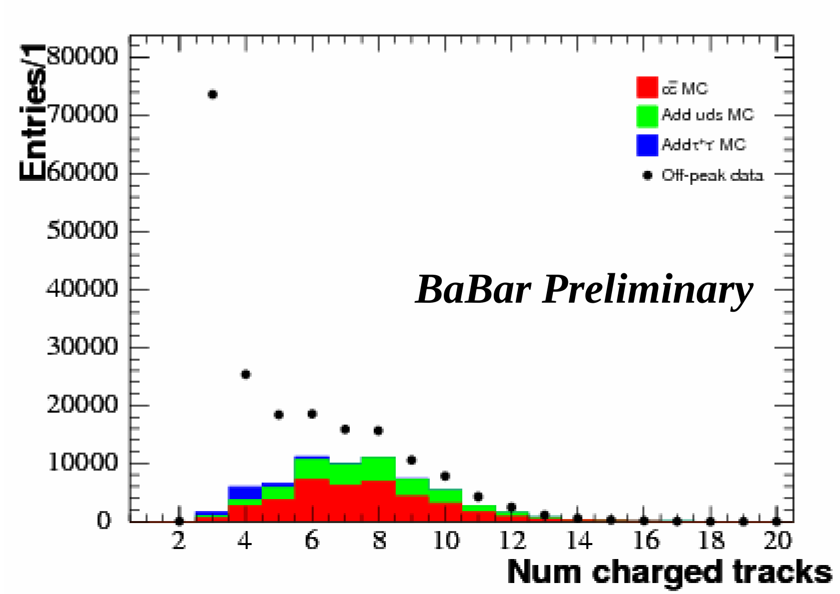
- Beam-constrained neutrino energy: $E_{nu} \equiv E_{beam} - (E_{LP})$
  - Compare with: $E_{miss} \equiv 2*E_{beam} - E_{LP} - E_{recoil}$
- $\Delta_{EP} \equiv E_{nu} - |\text{scaled } p_{nu}|$ is a useful variable for identifying the presence of a signal neutrino
  - Using scaled quantities yields improved resolution
- We require the reconstructed neutrino to point into the detector
  - Fiducial cuts on the lab polar angles of both the scaled and unscaled neutrino vectors.



Electron signal MC, loose cuts

Two-photon background





- Studies showed *excess* events in off-peak data vs. continuum MC (esp. in the electron mode)
  - Suspected to be predominantly from a high-multiplicity tail of two-photon events
  - Difficult to confirm precisely, or model, because we don't have a generic-two-photon generator

Two-photon background II

- Plan of attack:
  - Define additional selection variables sensitive to qualitative characteristic features of two-photon physics
    - Longitudinal momentum imbalance, low overall invariant mass
    - Use sidebands to study the effect
  - In the signal extraction fit, use *off-peak* data to measure the contribution of continuum background in the *on-peak* data
    - Sacrifices considerable statistical precision due to low off/on-peak luminosity ratio (1 to 10)
      - In contrast:
        - » Continuum MC : ~1 to 1.5
        - » Generic B background: ~ 2-2.5 to 1
    - **Also – this means that our off-peak data was blinded as well!**

Final cuts

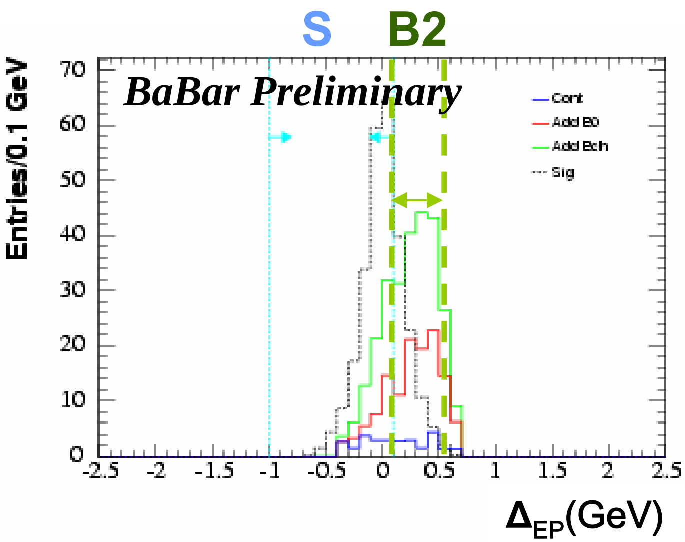
Cut variable	Muon	Electron
Signal photon lab angle	[0.326,2.443]	[0.326,2.443]
Scaled neutrino lab angle	[0.3,2.443]	[0.3,2.443]
Unscaled neutrino lab angle	[0.3,2.443]	[0.3,2.443]
Signal lepton cos lab angle (+ charge)	(-1.0,0.78)	(-0.74,0.78)
Signal lepton cos lab angle (- charge)	(-1.0,0.78)	(-0.94,0.7)
$\|$cos (thrust angle)$\|$	<0.86	<0.98
$R2_{All}$	<0.5	<0.5
Fisher discriminant (electron mode)	---	>-2.7
Fisher discriminant (muon mode)	>-2.8	---
Cosine (lepton-photon angle)	>-0.36	<-0.42
Cosine (B-Y angle) (Y = lepton-photon)	(-1.05,1.0)	(-1.1,1.1)
Signal lepton CM Energy (GeV)	(1.875,2.775)	(2,2.85)
Signal photon CM Energy (GeV)	(0.45,2.35)	(0.65,2.35)
Signal photon shower shape lateral moment	<0.55	<0.55
Electron two-photon parameter	---	<2.34
Muon two-photon parameter	<2.88	---
ΔE (GeV)	(-2.5,0.7)	<0.9
Signal photon π^0 veto region (GeV)	(<=116) || (>=148)	(<=123)||(>=147)
Δ_{EP}, m_{ES}	Fit	Fit

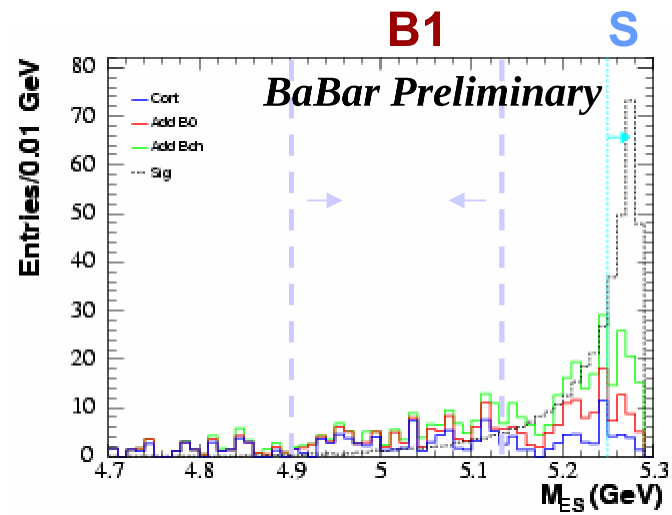
Monte Carlo sample breakdown

- In a “signal” region, # of exp. events (on-peak lumi):

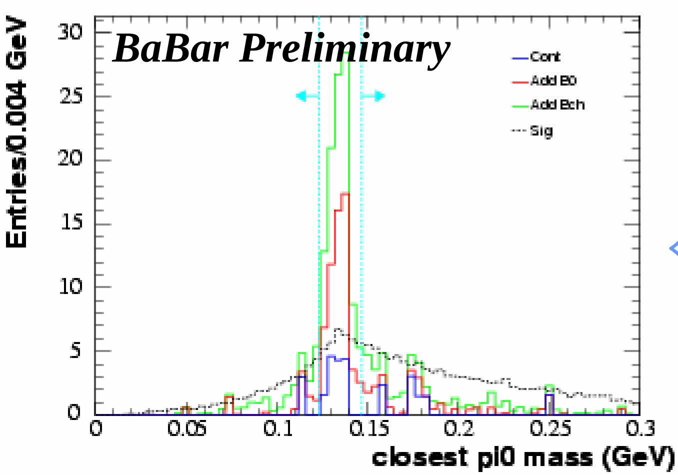
Monte Carlo sample	Electron mode		Muon mode	
Signal (BF = 3×10^{-6})	21.2	3% efficiency	13.1	1.9% efficiency
Total background	82.0		93.0	
Total exclusive $b \to u l\nu$	45.5		35.3	
$B^0 \to \pi^- l^+ \nu_l$	1.5		1.5	
$B^0 \to \rho^- l^+ \nu_l$	6.5		6.4	
$B^+ \to \eta\, l^+ \nu_l$	12.6		12.9	
$B^+ \to \eta' l^+ \nu_l$	0.4		0.1	
$B^+ \to \omega\, l^+ \nu_l$	0.7		1.2	
$B^+ \to \pi^0 l^+ \nu_l$	23.2		12.9	
$B^+ \to \rho^0 l^+ \nu_l$	0.7		0.3	
Other B background	22.4	0% fakes, 55% $X_u l\nu$, 40% $b \to cl\nu$, 5% misc	21.7	32% fakes, 35% $X_u l\nu$, 33% $b \to cl\nu$
cc	12.9	0% fakes	9.6	70% fakes
uds	1.3	0% fakes	26.4	91% fakes
$\tau^+\tau^-$	0.0		0.0	

Selection variable marginal distributions

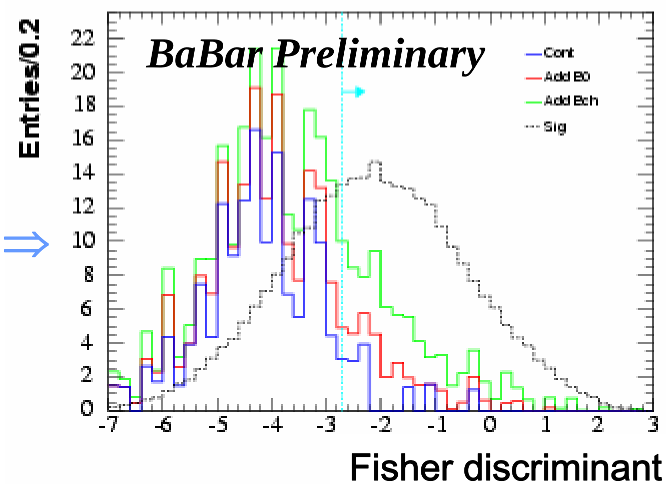




electron mode sample



⇐S region⇒ only



Signal extraction fit V

- Unblinding: fit for the total measured event counts in each of the four regions
- Fit parameters:
  - Signal BF
  - Magnitude of generic *B* background, freely floated
  - Three SL BF's, constrained to measurements:
    - $B^0 \to \pi^0 l^+ \nu_l$, $B^0 \to \rho^0 l^+ \nu_l$, $B^+ \to \eta\, l^+ \nu_l$
    - The other four BF's are related by isospin and SU(3) factors
  - Continuum background scale is **fixed**.

Systematics results

Systematic	Muon	Electron	Joint
Multiplicative			
Tracking eff.	1.3%	1.3%	1.3%
Particle ID	3.5%	2.2%	2.1%
Neutral reco.	1.6%	1.6%	1.6%
B counting	1.1%	1.1%	1.1%
B ratio (f_{+-}/f_{00})	9.4%	9.4%	9.4%
Selection eff.	6.0%	5.0%	6.0%
Additive ($\times 10^{-6}$) [units of full BF]			
Shape	0.8	0.5	0.6
η mode BF	0.7	0.3	0.4
π,ρ mode theory	0.8	0.9	0.8
$X_u l\nu$ BF	1.1	0.5	0.7
Total (on full BF)	$^{+1.74}_{-2.16}$	$^{+1.28}_{-1.23}$	$^{+1.34}_{-1.32}$