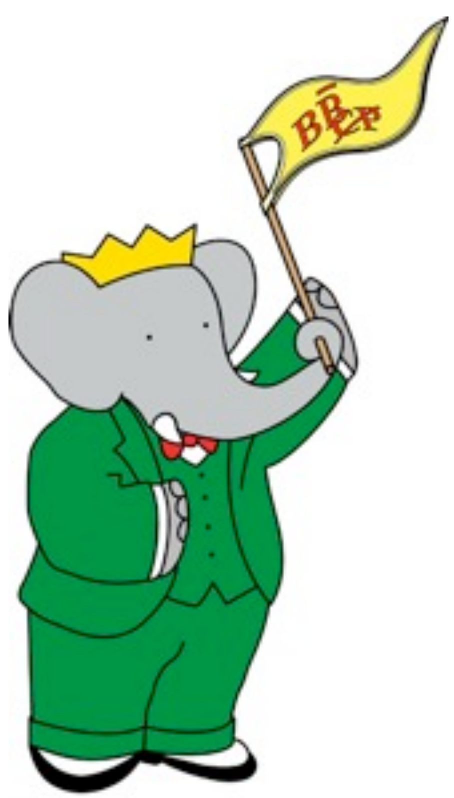
Searches for Flavor-Changing Neutral Currents and Rare B decays

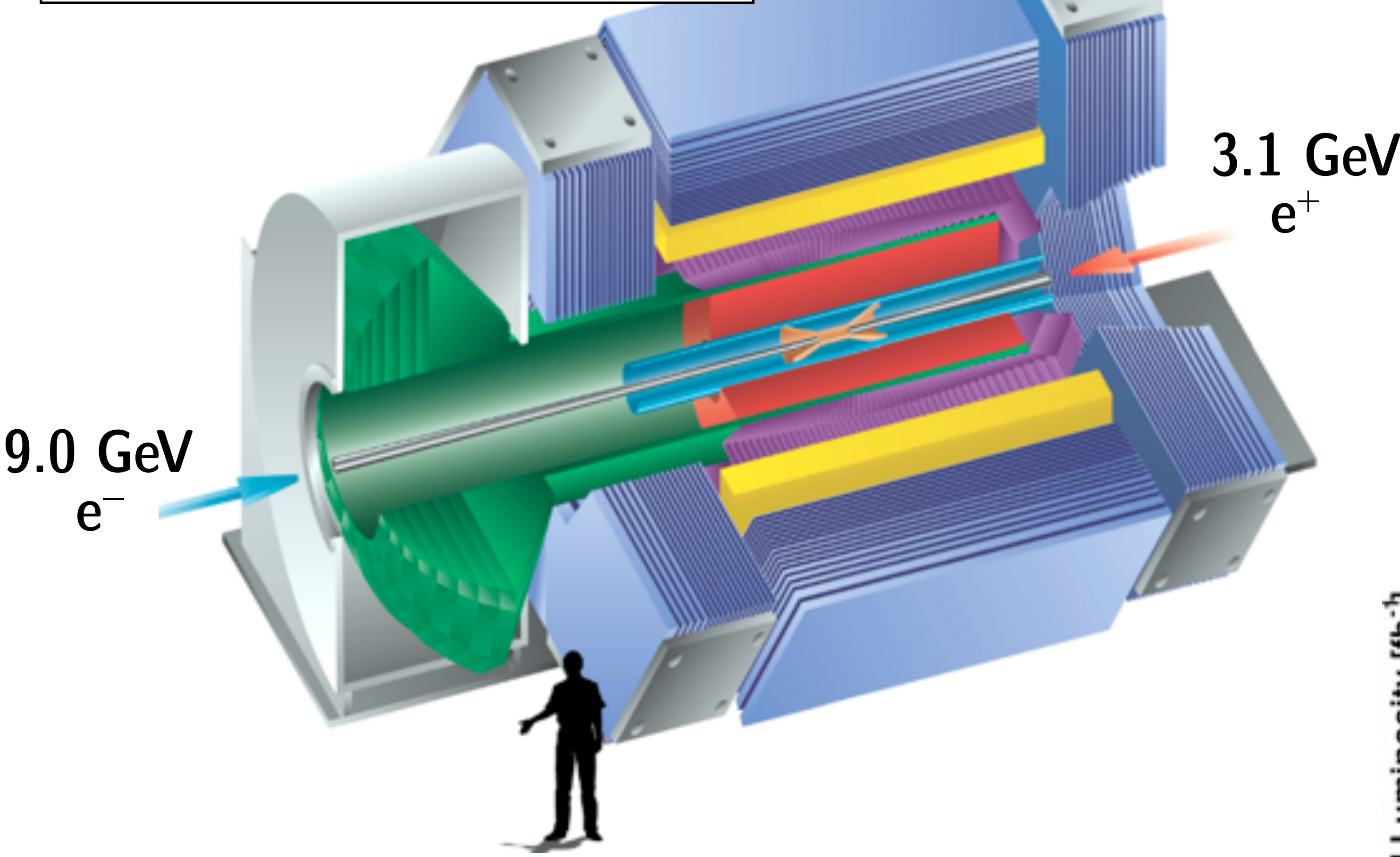


Andrew Ruland
The University of Texas at Austin
(For the BABAR Collaboration)

SUSY-2010
Bonn, Germany

The BaBar Detector & Dataset

$\Upsilon(4S)$ C.M. Energy = 10.58 GeV



SVT - tracking and precision vertex measurements

DCH - charged particle tracking

DRC - PID for K/π separation

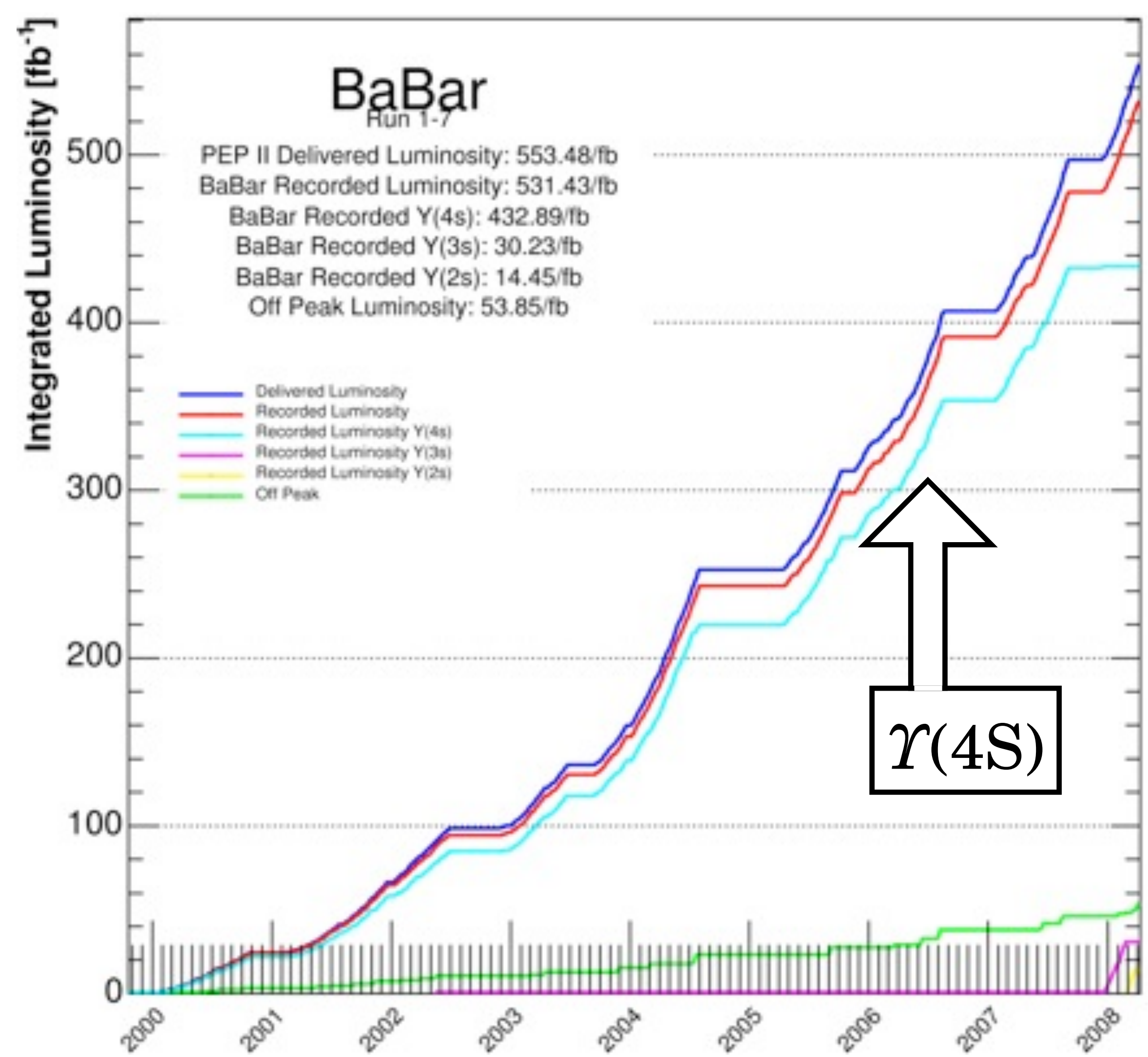
EMC - photon detection and e ID

Solenoid producing 1.5 T B field

IFR - μ/K_L ID

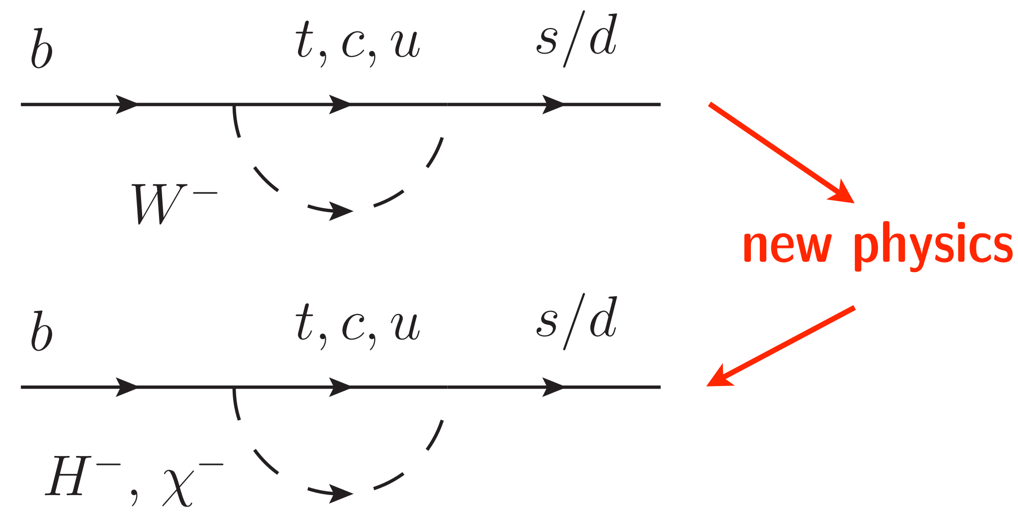
Inner radius → Outer radius

- Located at SLAC National Accelerator Lab
- Analyses presented here are based on the full $\Upsilon(4S)$ dataset
- Corresponds to 467 million $B\overline{B}$ pairs



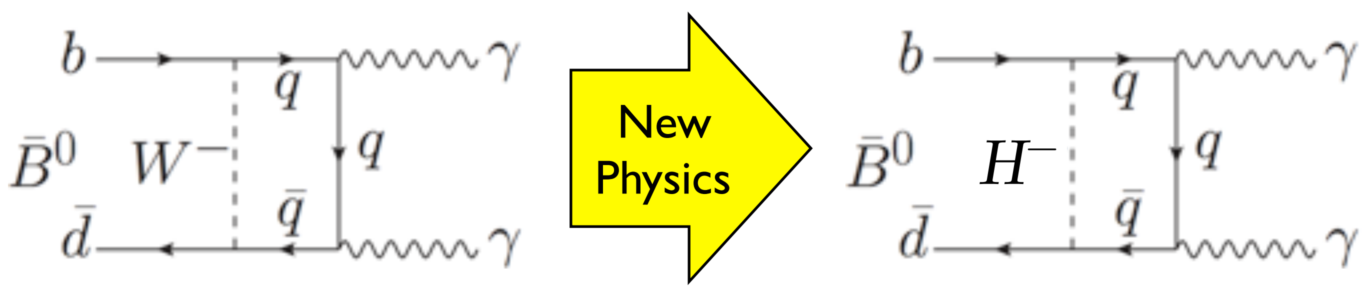
Flavor-Changing Neutral Currents and Rare B Decays

- Flavor-changing neutral currents are forbidden at tree level in the standard model (SM).
  - Excellent avenue for searches for new physics.
  - Non-SM particles can appear inside loops at same order as SM particles and enhance observables.



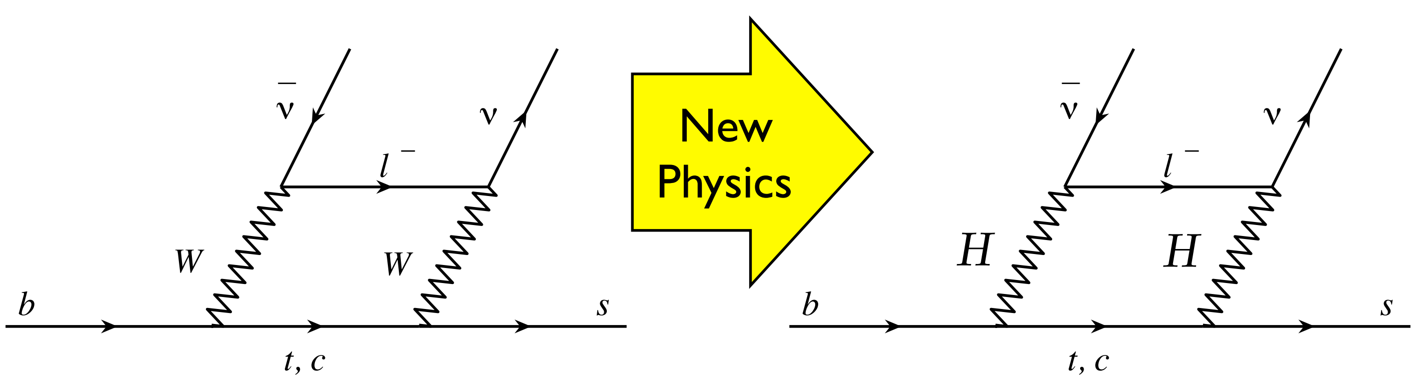
$B \to \gamma\gamma$

Occurs via "effective" FCNC transition $b \to d\,\gamma\,\gamma$



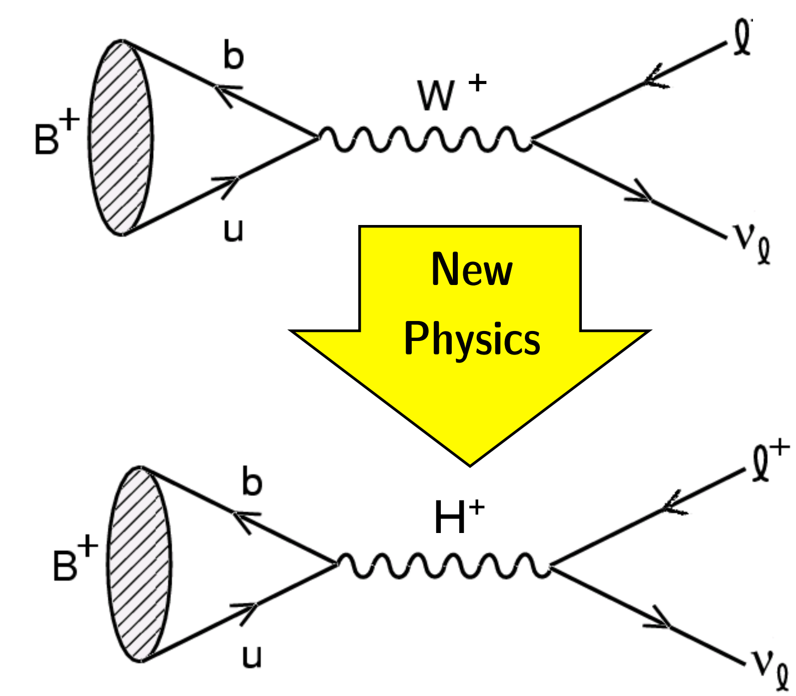
$B \to K\,\nu\,\bar{\nu}$

Occurs via FCNC transition $b \to s\,\nu\,\nu$



$B \to \tau\,\nu$

Rare B decay



Search for

$$B \to \gamma\gamma$$

Motivation and Event Selection

$B \to \gamma\gamma$

- SM theoretical prediction: $\mathcal{B}(B^0 \to \gamma\gamma) \simeq 3 \times 10^{-8}$

Bosch & Buchalla, JHEP 0208:054 (2002)

  - Heavy non-SM particles in loop can enhance BF up to order of magnitude

Aliev and Turin, PRD 48(3) 1993

- Previous searches

Experiment	B($B \to \gamma\gamma$)[1]	Dataset (fb^{-1})	Ref.
BaBar	$< 1.7 \times 10^{-6}$	19	Aubert et al. PRL 87, 24, 2001
Belle	$< 6.1 \times 10^{-7}$	104	Villa et al. PRD 73, 2006

1: limits are given at 90% CL

- Event Selection
  - Two high energy photons: $E_\gamma{}^* \in [1.15, 3.5]$ GeV
  - High energy γ background rejection
    - π^0 / η vetos
    - out-of-time photons
  - Continuum Rejection using neural network
    - 19 event shape variables

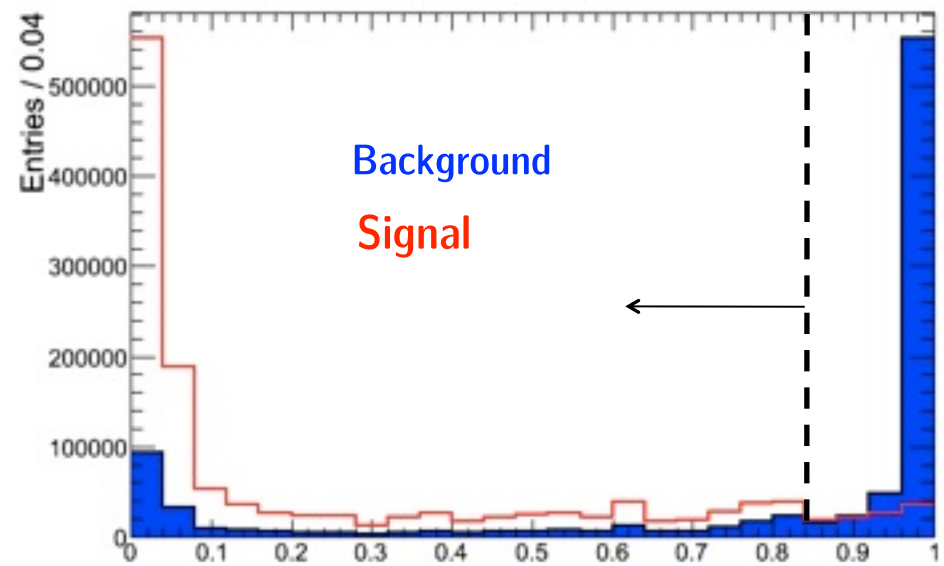
Variable	Cut Value
Number of Tracks / event	> 2
Total Event Energy	< 15.0 GeV
Cluster Time	150 ns window
Number of cluster crystals	> 10
Cluster isolation	> 25 cm
Cluster Lateral Moment	$0.15 \leq f_{LAT} \leq 0.5$
Photon momentum angle	$0.4 < \theta < 2.4$ radians
Merged π^0 consistency	< 0.01
π^0 LR	≤ 0.84
η LR	≤ 0.84
Neural Network	≥ 0.54

Background Suppression

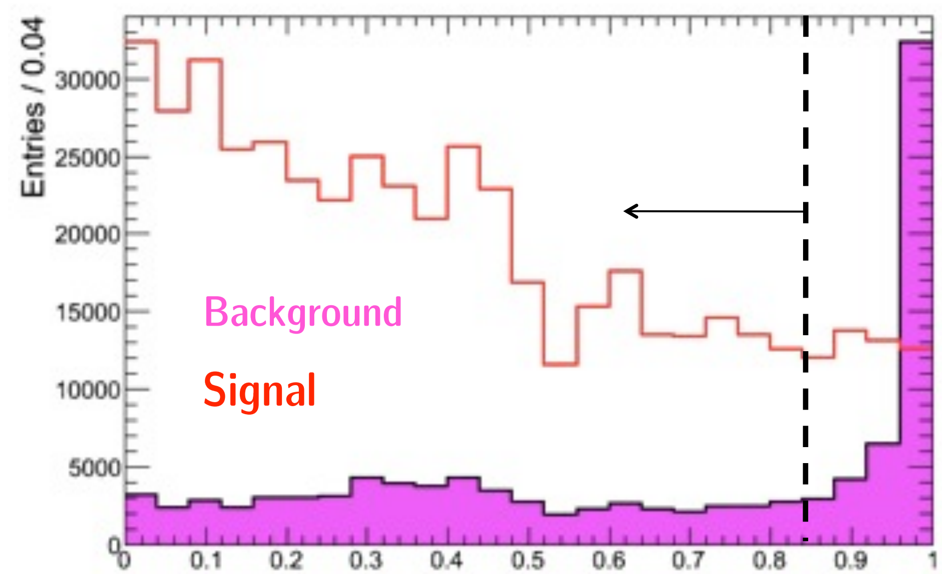
- Major source of backgrounds are photons produced in high-energy π^0 / η decays
  - Signal photons (γ) are paired with other photons in event (γ').
  - Invariant mass M(γγ') and energy of other photon $E_{\gamma'}$ are used to compute a likelihood

$$L_i = \frac{\mathcal{P}_i(m_{\gamma\gamma'}, E_{\gamma'})}{\mathcal{P}_{\mathrm{sig}}(m_{\gamma\gamma'}, E_{\gamma'}) + \mathcal{P}_i(m_{\gamma\gamma'}, E_{\gamma'})}$$

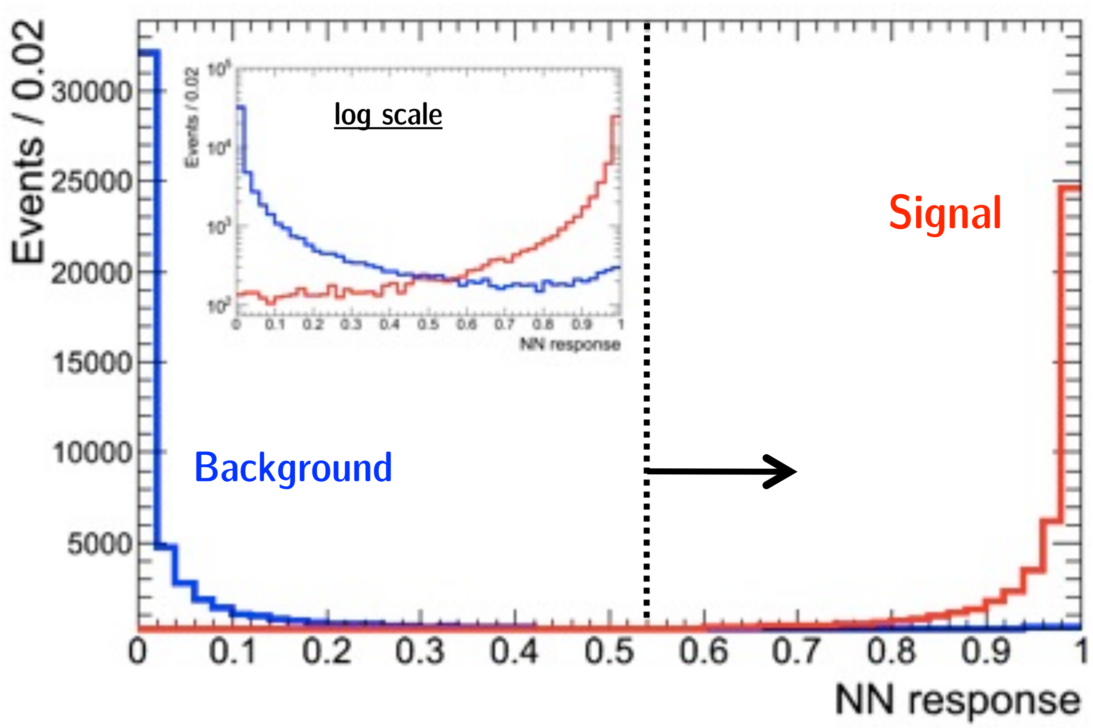
$$i = \pi^0/\eta$$



L_{π^0}



L_η



- Continuum background suppression done using a neural network with 19 event shape variables as inputs

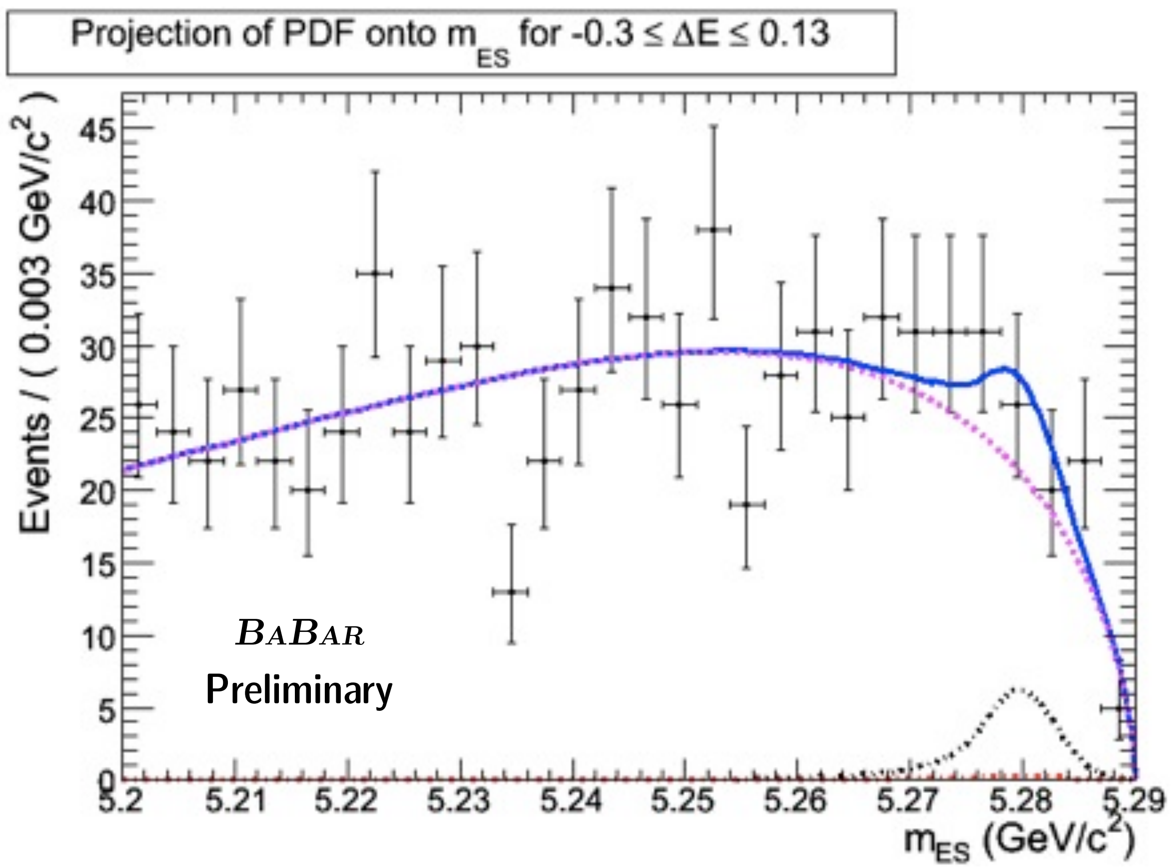
Maximum Likelihood Fit

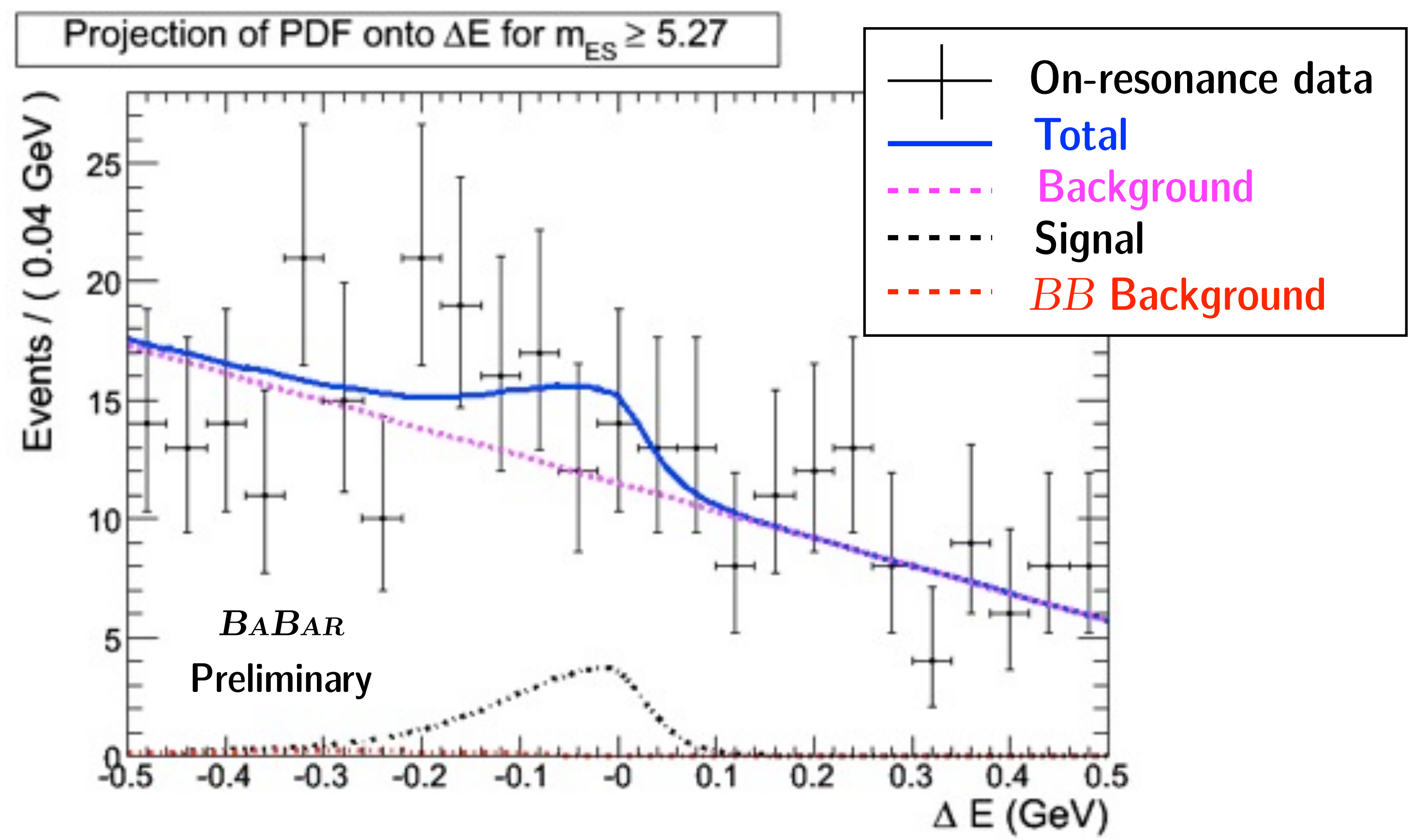
$B \to \gamma\gamma$

- Extract signal yield from on-resonance data using unbinned extended maximum likelihood fit.
- Signal and combinatoric background yields, slope and power of combinatoric m_{ES} ARGUS PDF are floated in the fit.

Component	m_{ES} Shape	ΔE Shape
Signal[1]	Crystal Ball	Asym. Gaussian
Continuum Bkg	ARGUS	Polynomial O(1)
$B\overline{B}$ Bkg	2D Histogram PDF	

1: Signal PDF parameters fixed from MC





- Signal Yield: $N_{\mathrm{sig}} = 21.3^{+12.8}_{-11.8}$

$$\boxed{\mathcal{B}(B \to \gamma\gamma) = (1.7 \pm 1.1) \times 10^{-7}} \implies \text{Statistical Sig.} = 1.9\,\sigma$$

Systematics and Upper Limit

$B \to \gamma\gamma$

- Systematic Uncertainties

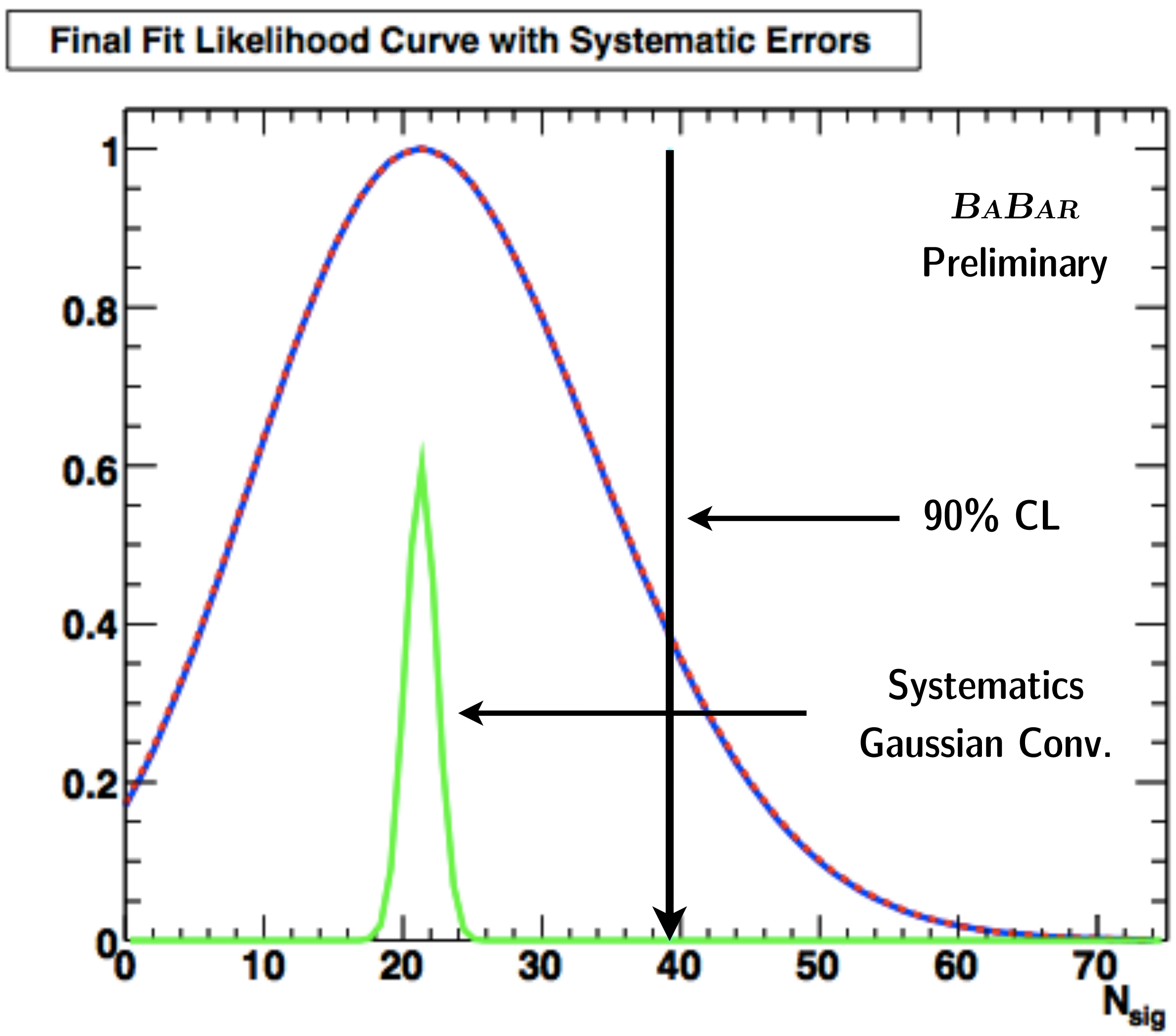
Source	Uncertainty on N_{sig} (%)
$B^0\overline{B}^0$ counting	1.7
Tracking efficiency	0.2
Photon efficiency	4.0
Cluster time	0.7
L_{π^0} and L_η	2.0
Neural network	3.0
Fit systematic	3.5
Sum in quadrature	6.7

$$\Longrightarrow \quad N_{\rm sig} = 21.3^{+12.8}_{-11.8}(stat.) \pm 1.4(syst.)$$

$$\mathcal{B}(B \to \gamma\gamma) = (1.7 \pm 1.1(stat.) \pm 0.1(syst.)) \times 10^{-7}$$

- Upper Limit
  - Convolve likelihood curve from ML fit with a Gaussian whose width equals systematic uncertainty
  - Integrate from zero up to 90% of the curve area

$$\mathcal{B}(B^0 \to \gamma\gamma) < 3.2 \times 10^{-7} \text{ (@ 90\% CL)}$$



Search for

$$B \to K \nu \overline{\nu}$$

Motivation and B Tagging

$B \to K\,\nu\,\overline{\nu}$

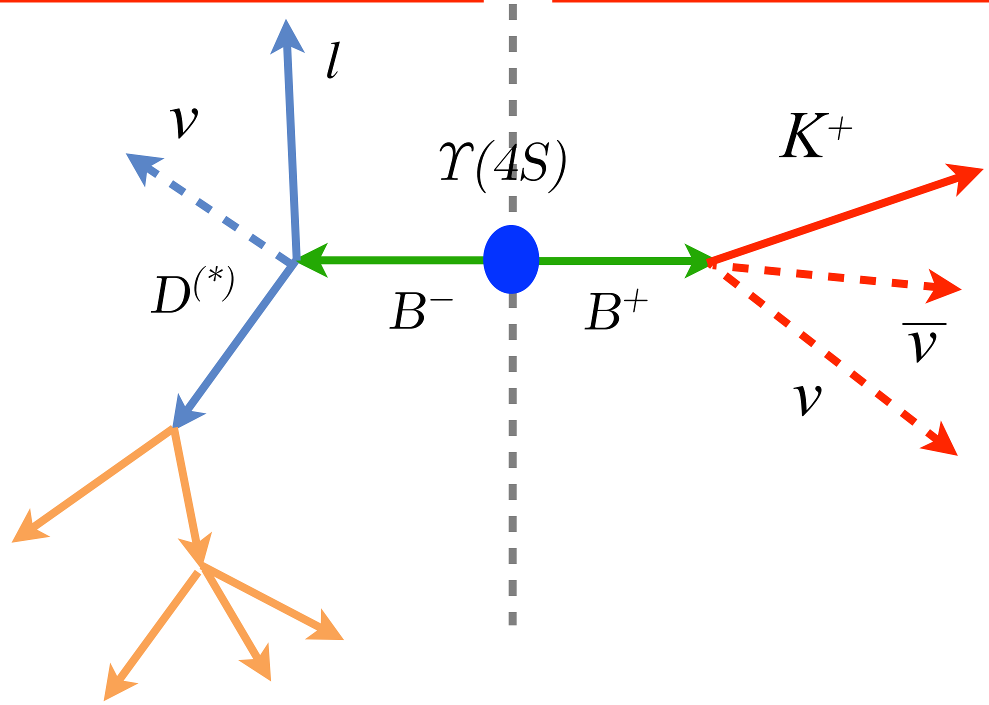
- SM prediction of branching fraction (summed over neutrino flavors)
  - $\mathcal{B}(B \to K\nu\bar{\nu}) = (4.5 \pm 0.7) \times 10^{-6}$
  - New particles can give BF enhancements up to 5× SM

W. Altmannshofer et al., JHEP 0904, 022 (2009)

Buchalla, PRD 63, 014015 (2001)

Semi-leptonic tag B | Signal B

- B_{tag} is reconstructed using the semi-leptonic tag $B \to D^{*}l\nu$
  - larger eff. than hadronic tag
- D is reconstructed from $K^-\pi^+$, $K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^-$ $K^-\pi^+\pi^0$, $K^0_s\pi^+$, $K^0_s\pi^+\pi^-$
  $\Rightarrow K^0_s \to \pi^+\pi^-$
- D^{*0} reconstructed as $D^0\pi^0$
- D^{*+} reconstructed as $D^0\pi^+$, $D^+\pi^0$
- Tag efficiency is ~1%.



- Look for signal B as
  - $B^+ \to K^+\,\nu\,\overline{\nu}$
  - $B^0 \to K_s^0\,\nu\,\overline{\nu}$ $(K_s^0 \to \pi^+\pi^-)$
- Signature is single K in rest of event
- Also measure partial BF in 2 regions of di-neutrino invariant mass

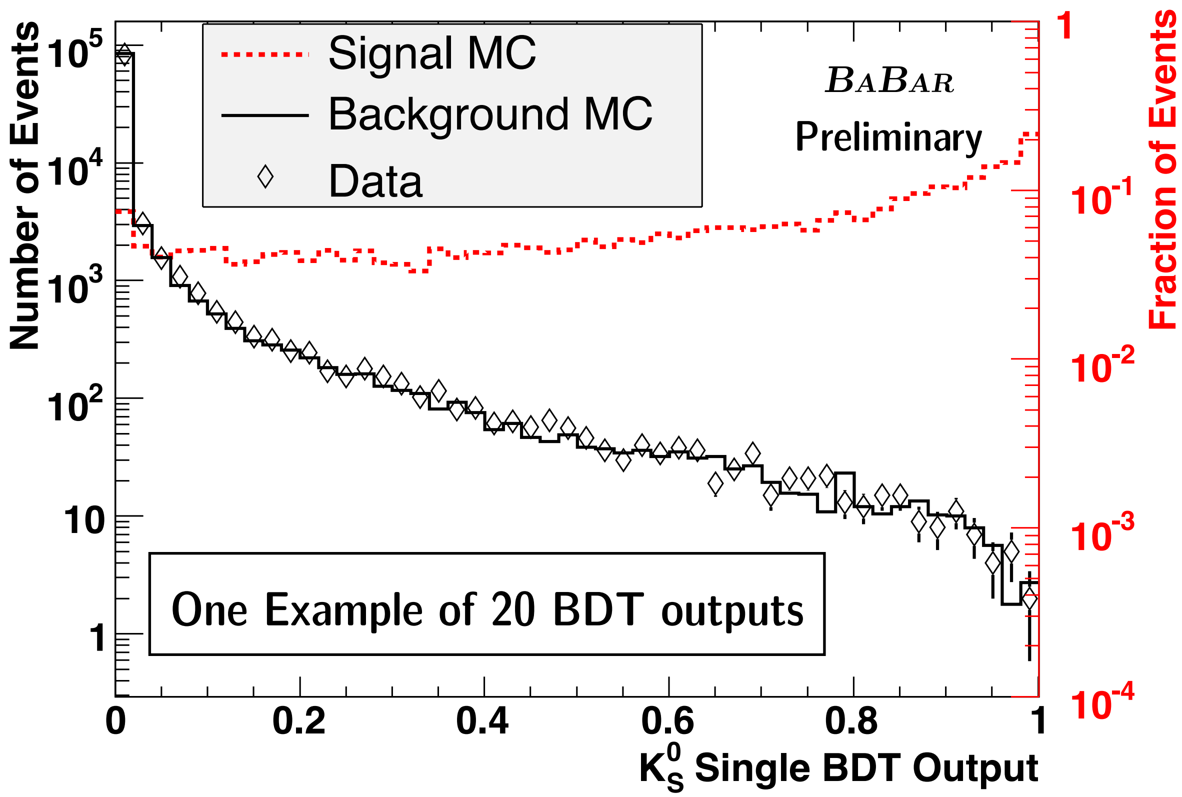
$$q^2_{high} > 0.4 m_B^2 > q^2_{low}$$

partial BF in high invariant mass bin could be enhanced by new physics

Background Suppression using BDT

$B \to K \nu \overline{\nu}$

- Background suppressed using 20 independent Bagged Decision Trees (BDT) for charged and neutral modes
- $K^+(K_s{}^0)$ tree utilizes 26(38) discriminating variables from 4 categories.
  - Missing Energy, Event Properties, Signal side kinematics, and $B_{\rm tag}$ reconstruction quality
- Strongest discriminating variable is extra energy, $E_{\rm extra}$
  - Sum of of neutral particle energy not associated with tag or signal B.



- Branching fraction is measured after optimum BDT selection using $\mathcal{B} = (N_{\rm obs} - N_{\rm bkg})/(\varepsilon \cdot N_{B\overline{B}})$
- $N_{\rm obs}$ is from on-resonance data, $N_{\rm bkg}$ is expected from MC, ε is signal efficiency derived from MC

Mode	$\epsilon(\%)$	N_{sig}	N_{bkg}	N_{obs}	N_{excess}
K^+	0.16	2.9 ± 0.4	$17.6 \pm 2.6 \pm 0.9$	$19.4^{+4.4}_{-4.4}$	$1.8^{+6.2}_{-5.1}$
K^0_s	0.06	0.5 ± 0.1	$3.9 \pm 1.3 \pm 0.4$	$6.1^{+4.0}_{-2.2}$	$2.2^{+4.1}_{-2.8}$
low-q^2	0.24	2.9 ± 0.4	$17.6 \pm 2.6 \pm 0.9$	$19.4^{+4.4}_{-4.4}$	$1.8^{+6.2}_{-5.1}$
high-q^2	0.28	2.1 ± 0.3	$187 \pm 10 \pm 46$	164^{+13}_{-13}	-23^{+49}_{-48}

Results

- **Systematics**

Category	Uncertainty
Signal efficiency	14%
K^+ background prediction	5%
High-q^2 K^+ background prediction	25%
K_S^0 background prediction	10%

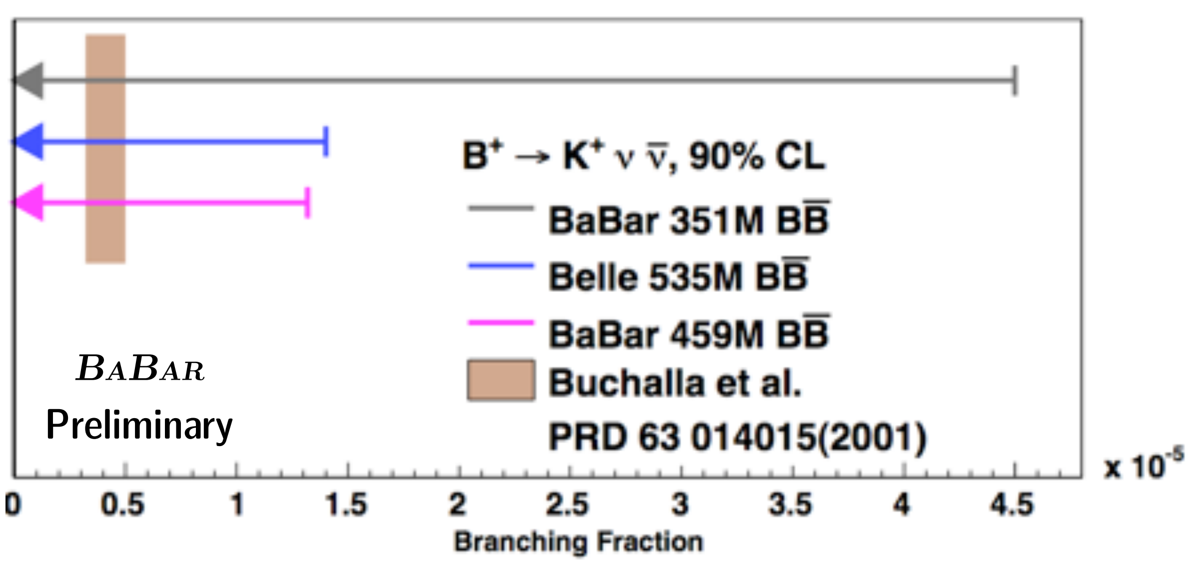
Results (limits are x10^{-5})

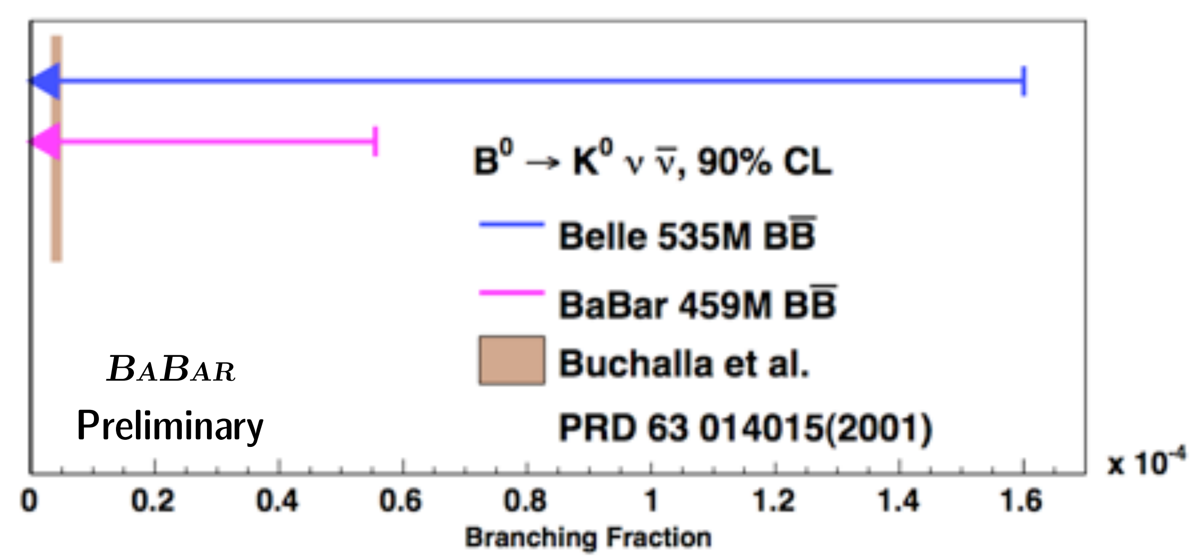
Mode	$\mathcal{B} \times 10^{-5}$	90% CL	95% CL
K^+	$0.2^{+0.8}_{-0.7}$	< 1.3	< 1.6
K_s^0	$1.7^{+3.1}_{-2.1}$	< 5.6	< 6.7
Comb. K^+, K_s^0	$0.5^{+0.7}_{-0.7}$	< 1.4	< 1.7
low-q^2	$0.2^{+0.6}_{-0.5}$	< 0.9	< 1.1
high-q^2	$-1.8^{+3.8}_{-3.8}$	< 3.1	< 4.6

- **Previous searches**

Experiment	$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$	Dataset	Ref.
BaBar	$< 5.2 \times 10^{-5}$	351×10^6 $B\bar{B}$	Moriond EW 08 Conference Proceedings
Belle	$< 1.4 \times 10^{-5}$	535×10^6 $B\bar{B}$	Villa *et al.*, PRL 99, 221802 (2007)

- **Comparison**





Measurement of

$B \to \tau \nu$

$B \to l\,\nu$ Decays

$B \to \tau\,\nu$

Standard Model

Helicity suppression term
$\tau : \mu : e \sim 1 : 5 \times 10^{-3} : 10^{-7}$

Sensitive to f_B and V_{ub}

$$\mathcal{B}(B \to \ell\nu) = \frac{G_F^2 m_B}{8\pi} \boxed{m_\ell^2} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 \boxed{f_B^2 |V_{ub}|^2} \tau_B$$

V_{ub} (exp+theory) and f_B (theory) uncertainties dominate SM uncertainty

$$\mathcal{B}(B \to \tau\nu) = (0.80 \pm 0.20) \times 10^{-4}$$

$f_B = 190 \pm 13$ MeV (HPQCD Collab) arXiv:0902.1815v2

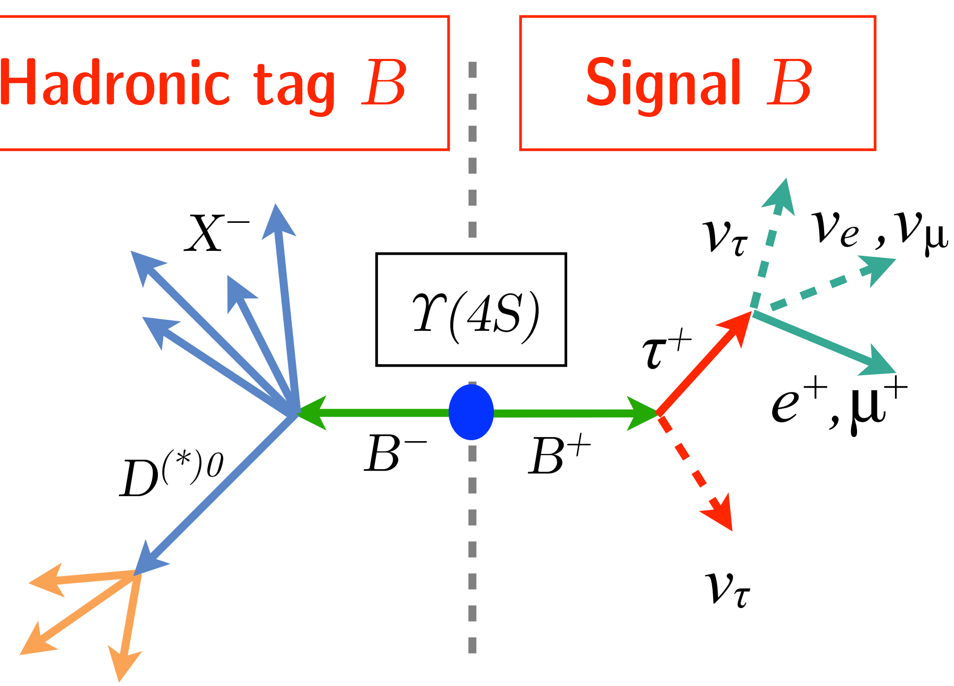
$V_{ub} = (3.5 \pm 0.4) \times 10^{-3}$ CKM/UT Fitter Collaboration

Beyond SM

$$\mathcal{B}(B \to \ell\nu)_{2HDM} = \mathcal{B}(B \to \ell\nu)_{SM} \times \left(1 - \tan^2\beta \frac{m_B^2}{m_H^2}\right)^2$$

W.S. Hou, Phys. Rev. D 48 (1993) 2342

- Reconstruct tag B through
  - $B \to D^{(*)0}X$, $B \to J/\psi X$
- X system contains up to 9 π^0, $\pi^\pm$, $K^\pm$, K_s^0
- In multi-B candidate events, smallest $|\Delta E|$ assigned as $B_{\rm tag}$



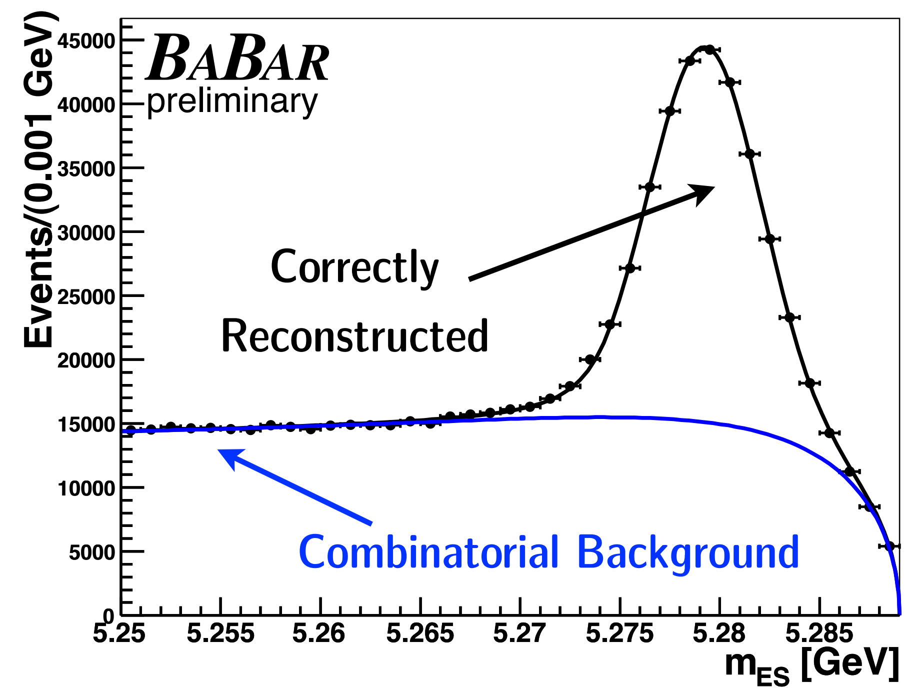
- τ reconstructed using ~70% of decay modes
  - $e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, $\pi\nu$, $\rho\nu$
- Require exactly 1 charged track
- ρ decay pairs $\pi^\pm$ with π^0
  - $M(\pi^0) \in [115,155]$ MeV$/c^2$

Analysis Overview

$B \to \tau\nu$

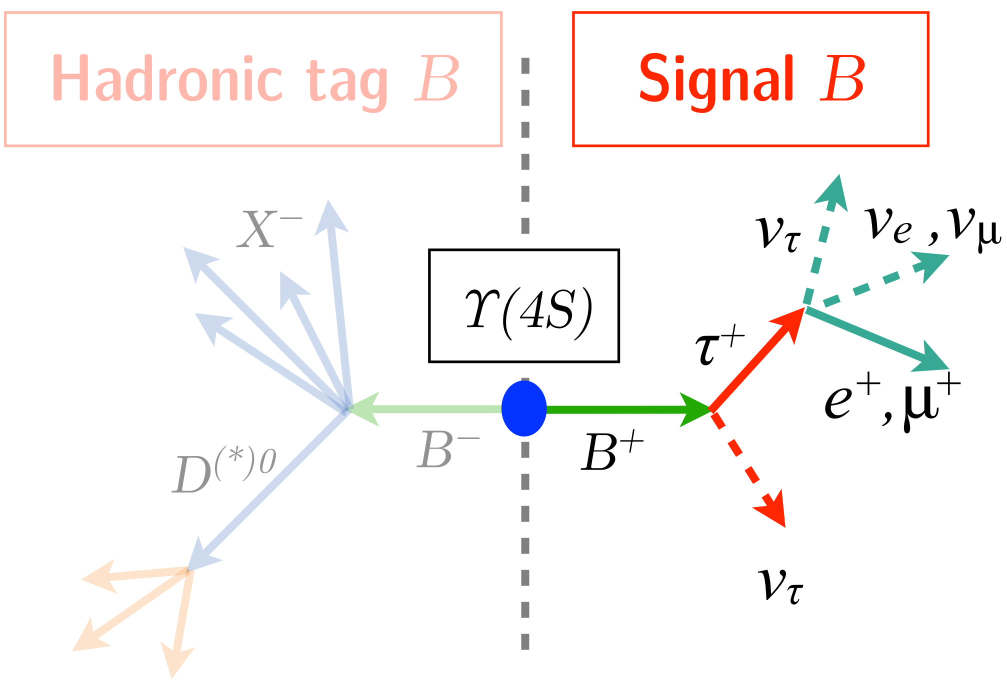
Tag B Selection

- Fit m_{ES} distribution tag B sample with a Crystal Ball shape (correctly reconstructed B) + ARGUS shape (combinatorial background).
- Tag B modes with purity P $>$ 10% are used for signal selection.



Signal B Selection

- Continuum + combinatorial bkg suppressed using likelihood ratio of 3 kinematic B variables.
  - $D^{(*)0}/J/\psi$ center-of-mass momentum,
  - cosine of angle, θ, between tag B thrust and rest-of-event thrust.
  - Magnitude of thrust of tag B
- Most discriminating variable is residual energy in the calorimeter: E_{extra}
  - Sum of all neutral particle energies ($>$ 60 MeV) not assigned to B_{tag} or B_{sig}.
- Optimize selections for smallest statistical + systematic BF uncertainty.

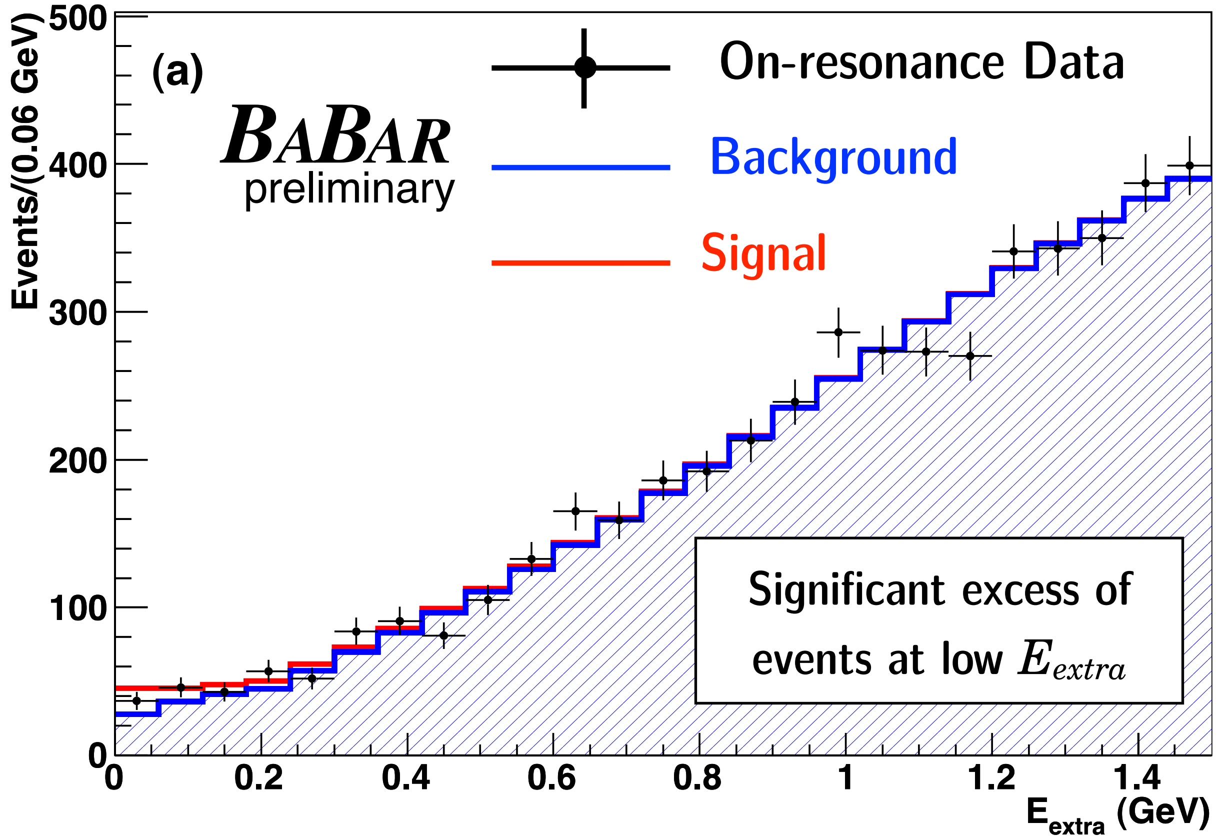


Branching Fraction Determination

$B \to \tau\, \nu$

- Extract branching fraction using an unbinned extended maximum likelihood fit of E_{extra} distribution.
  - Simultaneously fit in all 4 tau modes to calculate a common BF.
  - Signal PDF derived from simulated $B \to \tau\, \nu$ events.
  - Combinatoric background PDF derived from on-resonance sideband data.
  - Peaking background PDF derived from B^+B^- MC.

All τ modes fit simultaneously



Fit Results

Decay Mode	$\epsilon \times 10^{-4}$	$\mathcal{B}(\times 10^{-4})$	Significance (σ)
$\tau^+ \to e^+\nu\bar{\nu}$	2.97	$0.39^{+0.89}_{-0.79}$	0.5
$\tau^+ \to \mu^+\nu\bar{\nu}$	3.20	$1.23^{+0.89}_{-0.80}$	1.6
$\tau^+ \to \pi^+\nu$	1.71	$4.0^{+1.5}_{-1.3}$	3.3
$\tau^+ \to \rho^+\nu$	0.93	$4.3^{+2.2}_{-1.9}$	2.6
combined	8.81	$1.80^{+0.57}_{-0.54}$	3.6

Significance calculated as:

$$\sigma = \sqrt{2 \cdot \ln(\mathcal{L}_{\text{s+b}}/\mathcal{L}_{\text{b}})}$$

$\mathcal{L}_{\text{s+b}}$ = Max. likelihood value

$\mathcal{L}_{\text{b}}$ = Max. likelihood value assuming all no signal

Systematic Uncertainties

$B \to \tau\, \nu$

- Sources of systematic uncertainties

Source	$\mathcal{B}F$ uncertainty (%)
B counting	0.5
Tag B efficiency	5.0
Background PDF	12
Signal PDF	1.7
MC statistics	0.8
e ID	2.6
μ ID	4.7
K ID	0.4
Tracking	1.4
Total	14

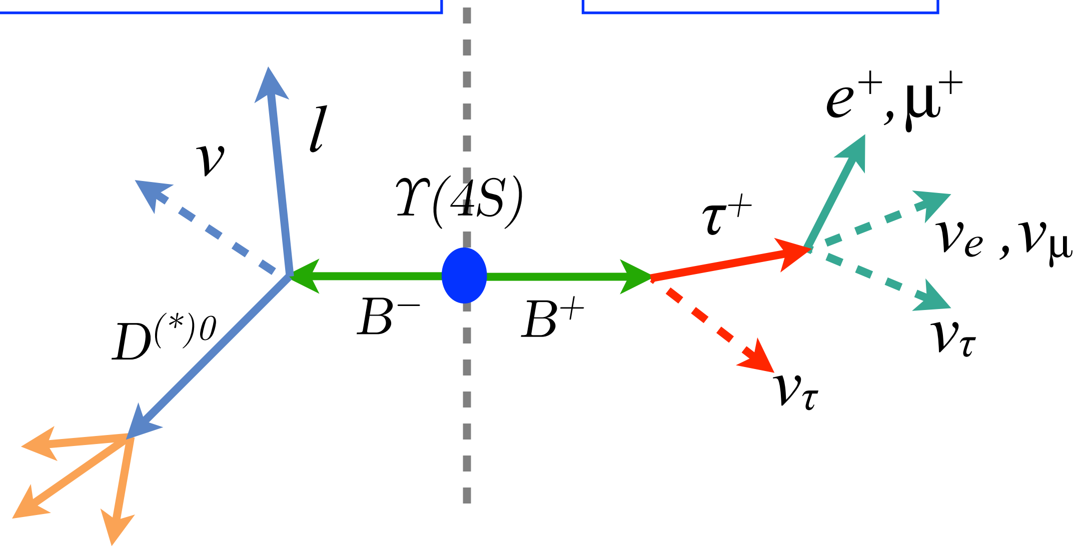
$$\mathcal{B}(B \to \tau\nu) = (1.80^{+0.57}_{-0.54} \pm 0.26) \times 10^{-4}$$

Exclusion of null hypothesis at 3.6 σ level

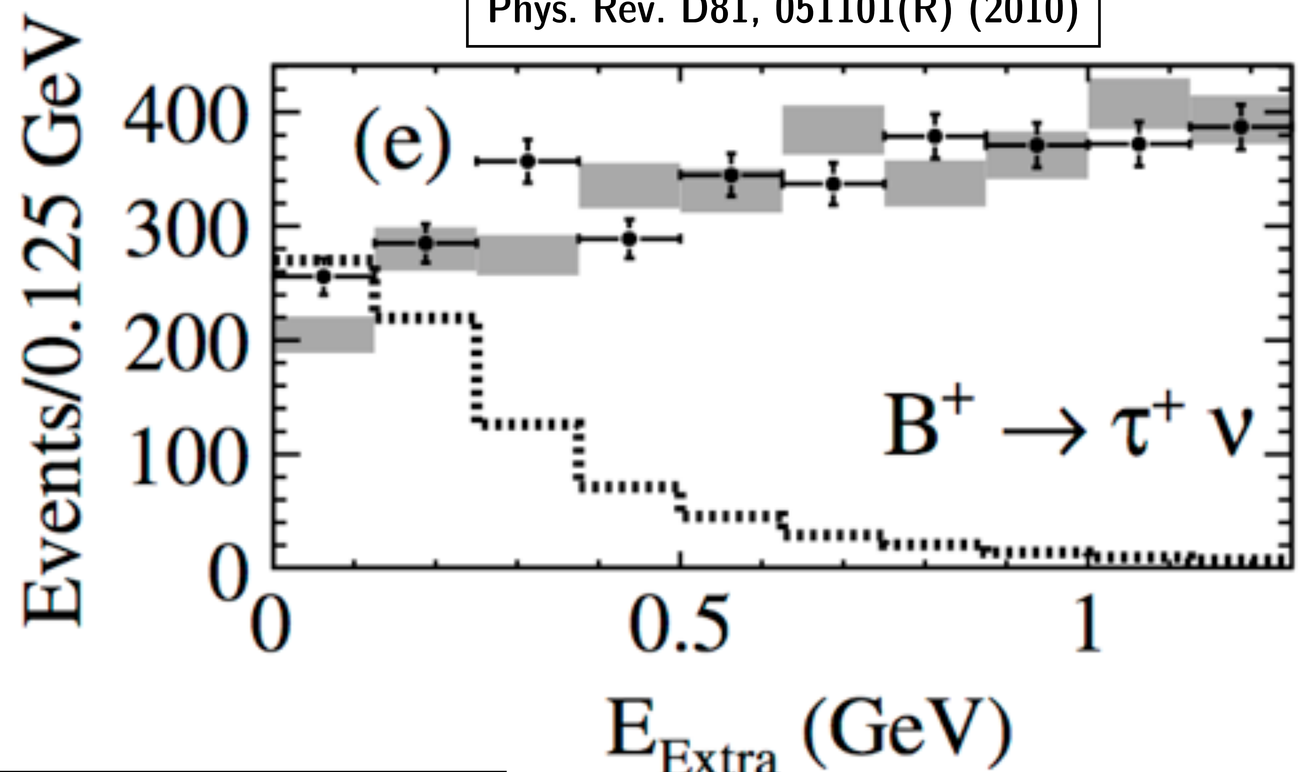
- Additional measurement from an independent dataset using a semi-leptonic tag.

Semi-leptonic tag B

Signal B



Phys. Rev. D81, 051101(R) (2010)



$$\mathcal{B}(B \to \tau\nu) = (1.7 \pm 0.8 \pm 0.2) \times 10^{-4}$$

Summary

- Search for FCNC and rare B decays $\rightarrow$ test of SM predictions and are a probe of new physics.
- B Factories provide high statistics and clean data samples
  - Indirect searches for NP and complementary to searches at high energy machines.
- Preliminary results of searches for FCNC rare B decays
  - $\boxed{\mathcal{B}(B \rightarrow \gamma\gamma) < 3.2 \times 10^{-7} \text{ (90\% CL)}}$ Preliminary
  - $\boxed{\mathcal{B}(B \rightarrow K\nu\bar{\nu}) < 1.4 \times 10^{-5} \text{ (90\% CL)}}$ Preliminary
- Updated measurement of $B \rightarrow \tau\,\nu$ using
  - Hadronic Tag $\boxed{\mathcal{B}(B \rightarrow \tau\nu) = (1.80^{+0.57}_{-0.54} \pm 0.26) \times 10^{-4}}$ Preliminary
  - Semi-leptonic Tag $\boxed{\mathcal{B}(B \rightarrow \tau\nu) = (1.7 \pm 0.8 \pm 0.2) \times 10^{-4}}$ Phys. Rev. D81, 051101(R) (2010)
  - Combining these measurements we present a single BABAR measurement

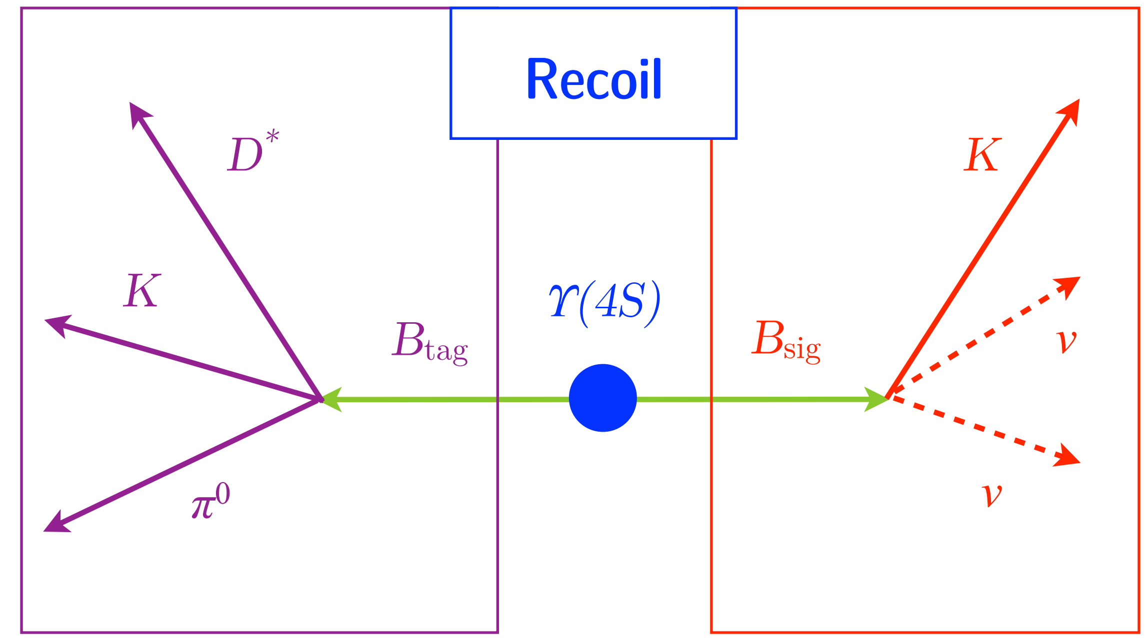
$$\boxed{\mathcal{B}(B \rightarrow \tau\nu) = (1.76 \pm 0.49) \times 10^{-4}}$$ Preliminary

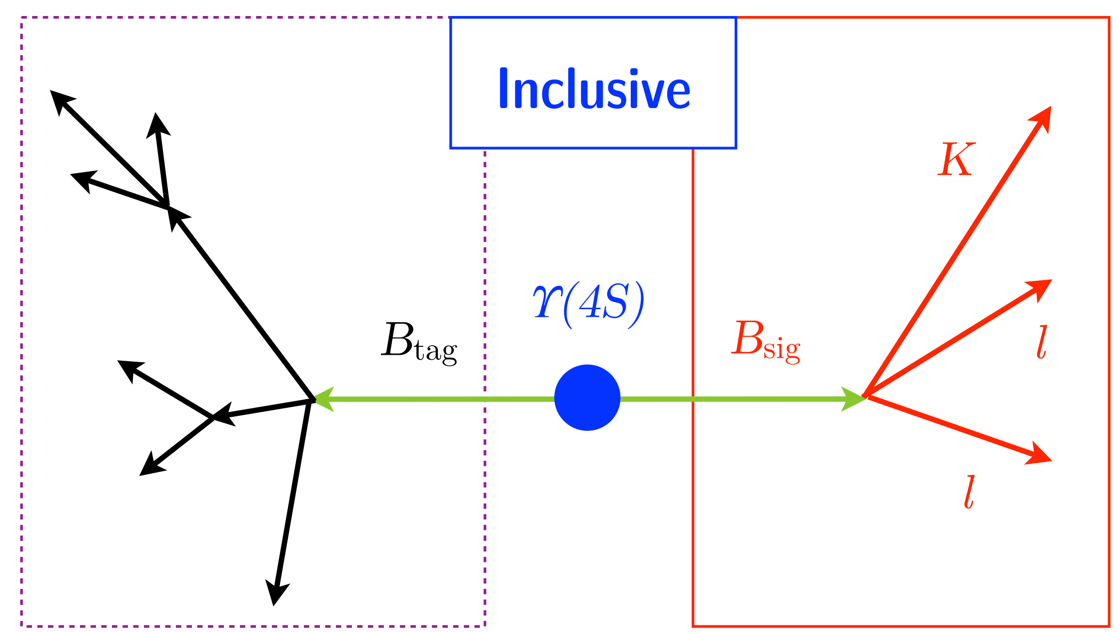
- Further progress in these modes possible at high luminosity B factory

Backup Slides

B Decay Analyses

- Two methods are used to reconstruct B decays
- Recoil Analysis
  - Fully reconstruct a B in the event using a semi-leptonic or hadronic tag ($B_{\rm tag}$) to constrain its kinematics
  - Search the rest of the event for the signature of the signal B ($B_{\rm sig}$)
  - Useful when there are undetectable particles in the signal side final state, e.g., ν.
  - $\boxed{B_{\rm tag} \text{ reco efficiency } \sim 10^{-2}/10^{-3}, \text{ clean sample}}$
- Inclusive Analysis
  - Reconstruct $B_{\rm sig}$ decay products and constrain kinematics
  - Use extra-tracks and neutrals to reconstruct $B_{\rm tag}$ (1 ν on signal side)
  - $\boxed{\text{Higher efficiency but larger backgrounds}}$





Useful B variables

$$m_{\rm ES} \equiv \sqrt{E^{*2}_{\rm beam} - p^{*2}_{\rm B}}$$

$$\Delta E \equiv E^{*}_{\rm beam} - E^{*}_{\rm B}$$

Fit Results individual modes

$B \to \tau\,\upsilon$

Decay Mode	$\epsilon \times 10^{-4}$	$\mathcal{B}(\times 10^{-4})$	Significance (σ)
$\tau^+ \to e^+\nu\bar{\nu}$	2.97	$0.39^{+0.89}_{-0.79}$	0.5
$\tau^+ \to \mu^+\nu\bar{\nu}$	3.20	$1.23^{+0.89}_{-0.80}$	1.6
$\tau^+ \to \pi^+\nu$	1.71	$4.0^{+1.5}_{-1.3}$	3.3
$\tau^+ \to \rho^+\nu$	0.93	$4.3^{+2.2}_{-1.9}$	2.6
combined	8.81	$1.80^{+0.57}_{-0.54}$	3.6