A search for the radiative penguin decays $B \to \rho\gamma$ and $B^0 \to \omega\gamma$ at BABAR

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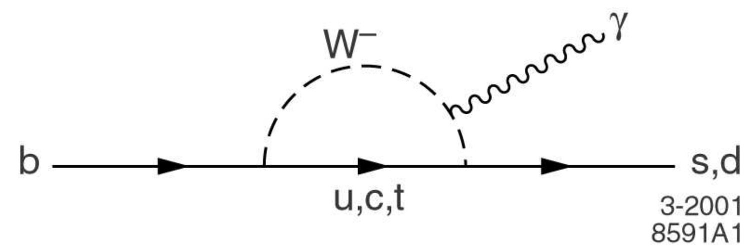
Outline

- Physics motivation
- *BABAR* experiment
- Analysis overview
- Backgrounds and their suppression
- Likelihood fits
- Individual results
- Combined $B \to \rho\gamma$, $B^0 \to \omega\gamma$

Published in B. Aubert et al. Search for the radiative penguin decays $B^+ \to \rho^+\gamma$, $B^0 \to \rho^0\gamma$, and $B^0 \to \omega\gamma$. *Phys. Rev. Lett.*, 94:011801, 2005.

Rare decays, new physics

- Rare decay
- Loop sensitive to new physics/constrains the SM
- Large theory uncertainties



Leading Feynman diagram

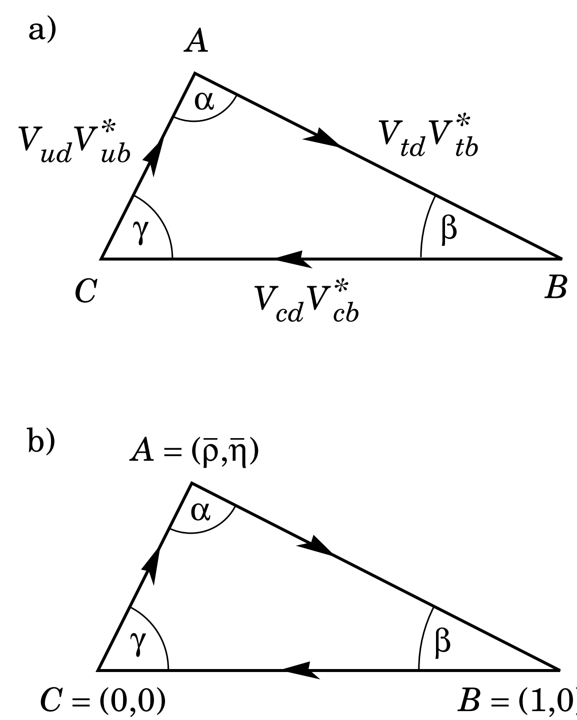
Calculations	Ali, Lunghi, ('04) Parkhomenko	Bosch, ('02) Buchalla	Ali, ('02) Parkhomenko
$\mathcal{B}(B^0 \to \rho^0\gamma)(\times 10^{-6})$	0.66 ± 0.20	$0.76^{+0.26}_{-0.23}$	0.49 ± 0.18(th) ± 0.04(ex)
$\mathcal{B}(B^+ \to \rho^+\gamma)(\times 10^{-6})$	1.35 ± 0.42	$1.58^{+0.53}_{-0.46}$	0.90 ± 0.33(th) ± 0.10(ex)
$\lvert V_{td}/V_{ts}\rvert$	Limit from $\Delta M_{B_d}/\Delta M_{B_s}$		< 0.25

$|V_{td}/V_{ts}|$ and the unitarity triangle

- CKM matrix unitarity

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- Graphically represented by unitarity triangle
- $|V_{td}/V_{ts}|$ from ratio of penguin branching fractions
- Independent of mass splitting $\Delta M_{B_d}/\Delta M_{B_s}$ measurement



$$\frac{\Gamma(B^+ \to \rho^+\gamma)}{\Gamma(B^+ \to K^{*+}\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - m_\rho^2/M_B^2}{1 - m_{K^*}^2/M_B^2}\right)^3 \zeta^2[1 + \Delta R]$$

Current Measurements

Value	BaBar 2004 (this) $(211 \times 10^6\ B\overline{B})$	Belle 2005 $(386 \times 10^6\ B\overline{B})$
$\mathcal{B}(B^0 \to \rho^0\gamma)$	$< 0.4 \times 10^{-6}$	$(1.17^{+0.35}_{-0.31}{}^{+0.09}_{-0.08}) \times 10^{-6}$
$\mathcal{B}(B^+ \to \rho^+\gamma)$	$< 1.8 \times 10^{-6}$	$< 1.3 \times 10^{-6}$
$\mathcal{B}(B^0 \to \omega\gamma)$	$< 1.0 \times 10^{-6}$	$< 1.1 \times 10^{-6}$
$\mathcal{B}(B \to (\rho/\omega)\gamma)$	$< 1.2 \times 10^{-6}$	$(1.35^{+0.34}_{-0.31}{}^{+0.14}_{-0.10}) \times 10^{-6}$
$\lvert V_{td}/V_{ts}\rvert$	< 0.190	$0.200^{+0.026}_{-0.025}(\text{exp})^{+0.038}_{-0.029}(\text{theo})$

- Combined BF reduces exp. uncertainty

$$\mathcal{B}(B \to (\rho,\omega)\gamma) \equiv \frac{1}{2} \cdot [\mathcal{B}(B^+ \to \rho^+\gamma) + \frac{\tau_{B^+}}{\tau_{B^0}} \cdot (\mathcal{B}(B^0 \to \rho^0\gamma) + \mathcal{B}(B^0 \to \omega\gamma))]$$

(Isospin symmetry $\Rightarrow \Gamma(B^0 \to \rho^0\gamma) = \Gamma(B^0 \to \omega\gamma) = \frac{1}{2}\Gamma(B^+ \to \rho^+\gamma)$)

PEP-II B meson factory

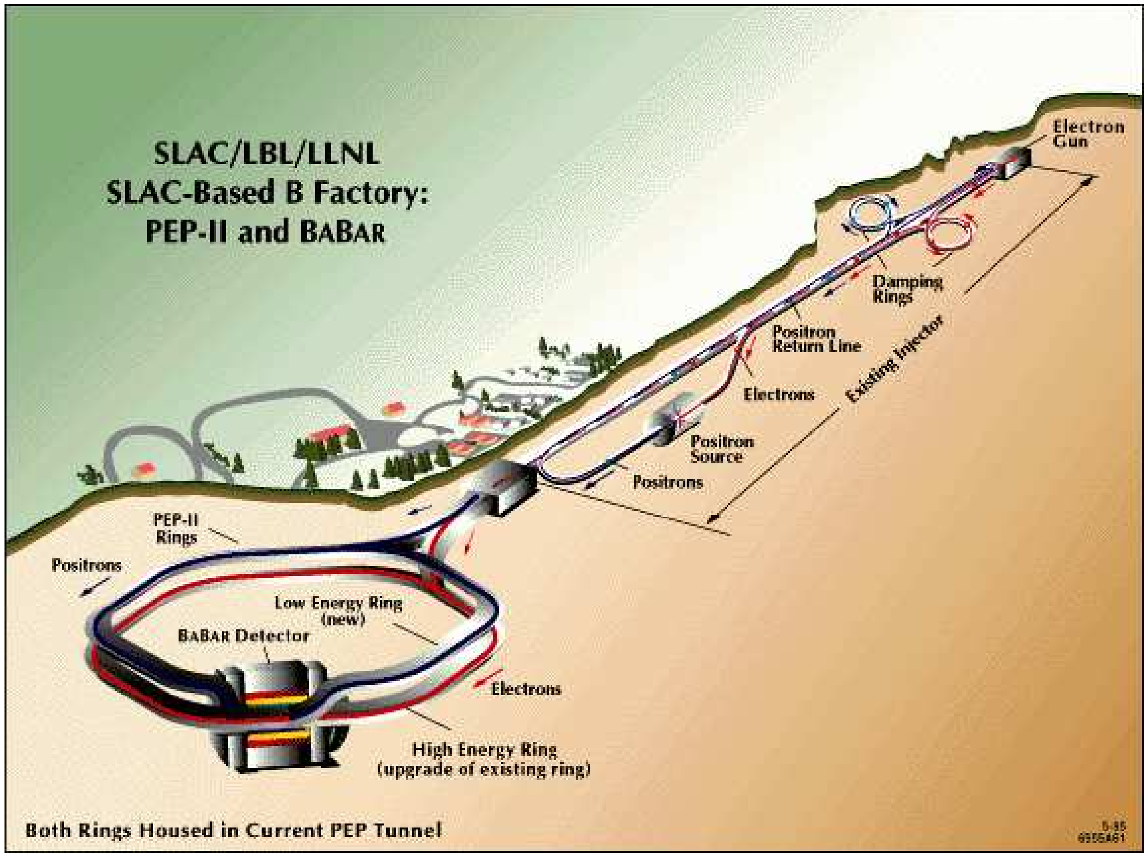
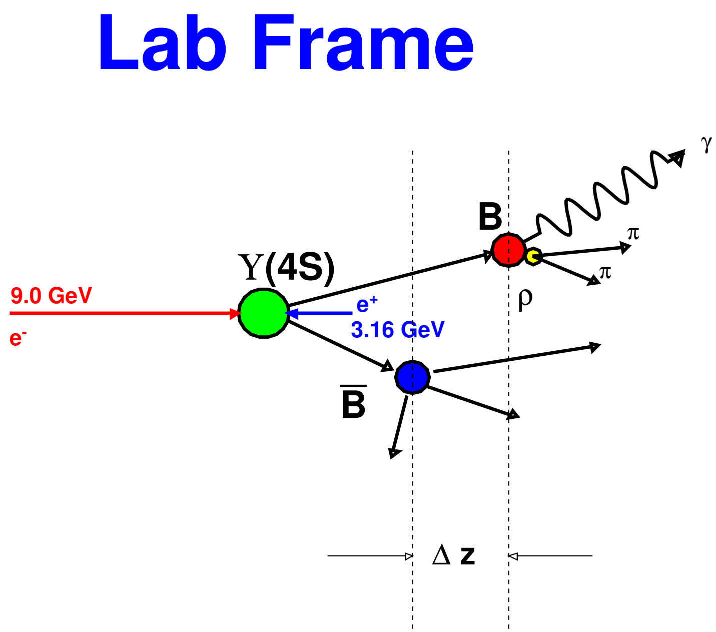


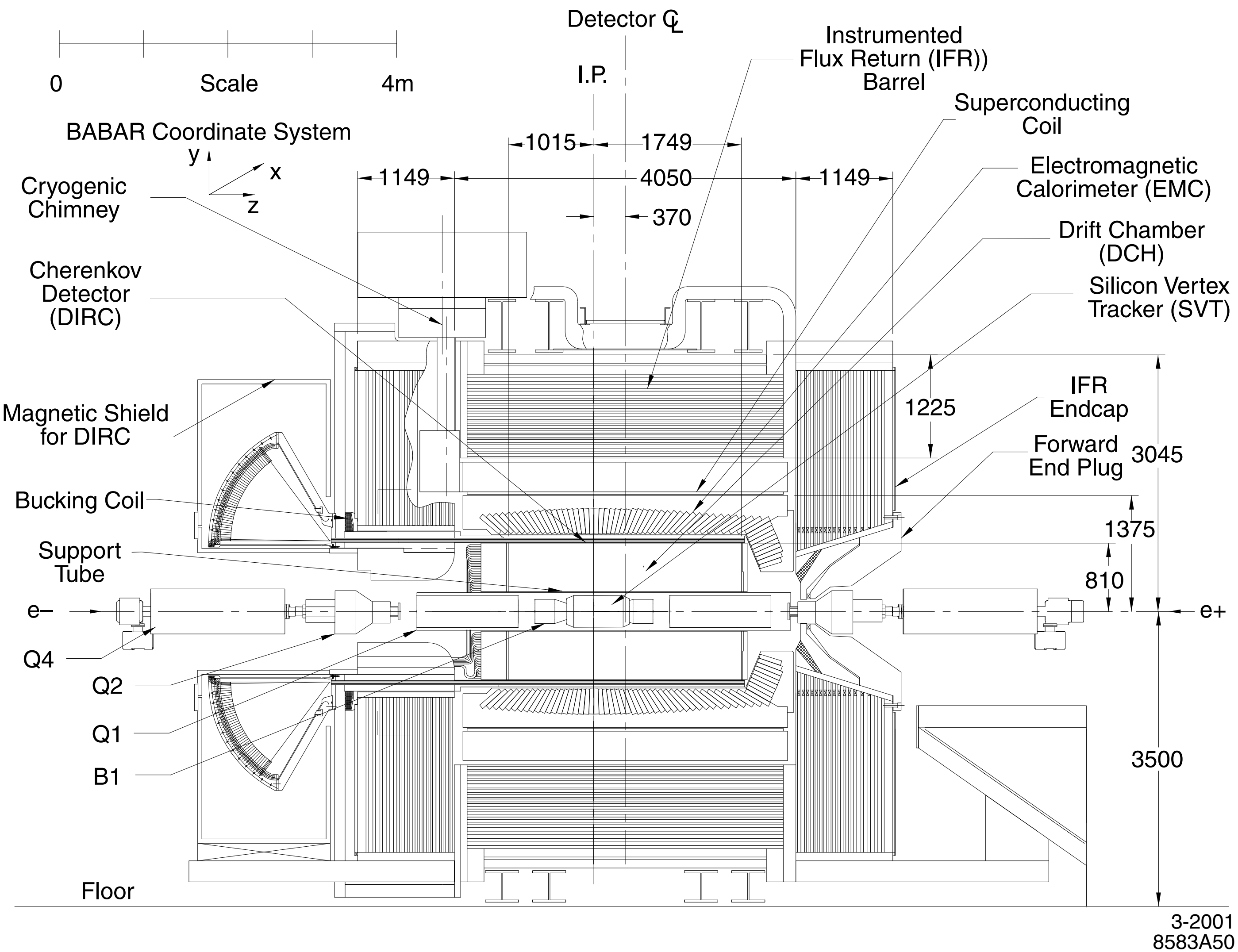
Figure 2.1: Illustration of SLAC and PEP-II

B production at PEP-II



- Asymmetric e^-e^+ collisions $\Rightarrow$ boosted CM frame
- 10.58 GeV CM energy–the $\Upsilon(4S)$ resonance
- $Prob(\Upsilon(4S) \rightarrow B\bar{B}) \approx 1$
- $m_B = 5.279GeV \Rightarrow$ B's are almost at rest in CM frame
- Production cross-section $\sigma(e^+e^- \rightarrow b\bar{b}) = 1.09\mathrm{nb}$
- Luminosity is usually quoted in fb^{-1} : $1\mathrm{fb}^{-1} \approx 1.09 \times 10^6\ B\bar{B}$ pairs.

BABAR detector diagram



Detector summary (I)

- Cylindrical coaxial array of specialized subdetectors
- Boosted CMS: Asymmetric, higher component density in the forward direction in the lab frame.
- SVT: Silicon Vertex Tracker
  - Precise position information for charged tracks
  - Sole tracking device for very low momentum charged particles
  - Position resolution $\approx 30\ \mu\mathrm{m}$

Detector summary (II)

DCH: Drift Chamber

- Main momentum measurement for charged particles
- dE/dx part of PID system
- Estimated tracking efficiency: $\approx 87\%$ (GTL) ($\approx 99\%$ within acceptance)
- Very small charge asymmetry in tracking efficiency: $\epsilon^{+} - \epsilon^{-} = 0.24\%$

Tracking performance

- Kalman filter track parameter estimates
- Resolution of POCA to z axis

$$\sigma_{d_0} = 23\ \mu\mathrm{m}, \sigma_{z_0} = 29\ \mu\mathrm{m}$$

- Parameterized momentum resolution

$$\sigma_{p_t}/p_t = (0.13 \pm 0.01)\% \cdot p_t + (0.45 \pm 0.03)\%$$

Detector summary (III)

- DIRC: Detector of Internally Reflected Cherenkov light
  - Designed and optimized for charged hadron PID
  - $B^0 \to K^{*0}\gamma$ relies heavily on the DIRC for $K^\pm$ selection
  - 4.2σ $\pi - K$ separation for 3 GeV tracks
- EMC: Cesium Iodide Electromagnetic Calorimeter
  - Calorimeter acceptance: $-0.74 < \cos\theta_{\gamma,\mathrm{lab}} < 0.93$
  - Photon energy resolution $\sigma_{E_\gamma} \approx 2.3\%$ at signal energies
- Superconducting coil: 1.5 T solonoid magnetic field.
- IFR: Instrumented Flux Return: muon ID

Analysis strategy

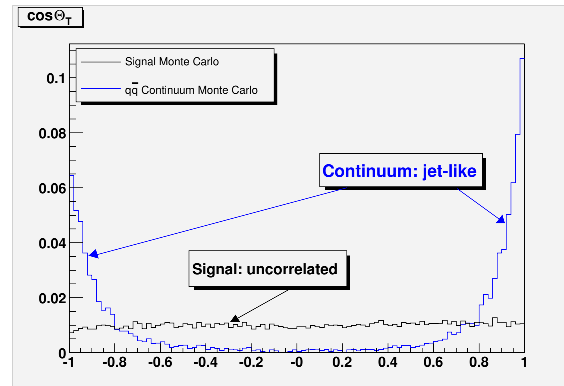
- Explicitely reconstruct B decays
  - $B^+ \to \rho^+\gamma(\rho^+ \to \pi^+\pi^0)$
  - $B^0 \to \rho^0\gamma(\rho^0 \to \pi^+\pi^-)$
  - $B^0 \to \omega\gamma(\omega \to \pi^+\pi^-\pi^0)$
- High energy γ signature
- $\pi^\pm$ PID and K_S^0 rejection
- Neural network and Fisher discriminant for further background discrimination
- Likelihood fit to measure signal yield

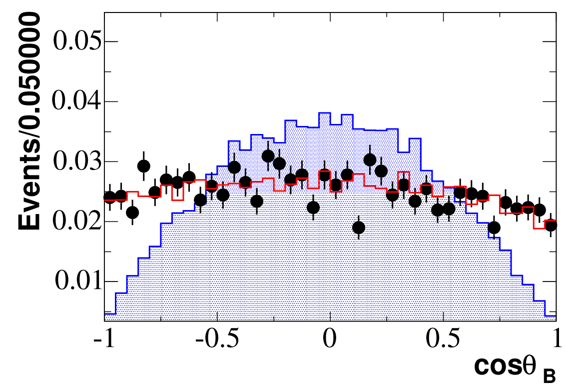
Sources of backgrounds

- Continuum with high energy γ
  - Dominant background
  - Initial State Radiation γ
  - Asymmetric π^0/η decays
  - Suppressed with event shape variables
- $B \longrightarrow K^*\gamma$
  - $\mathcal{B}(B^+ \to K^{*+}\gamma) = (38.7 \pm 2.8(\text{stat.}) \pm 2.6(\text{syst.})) \times 10^{-6}$,
    $\mathcal{B}(B^0 \to K^{*0}\gamma) = (39.2 \pm 2.0(\text{stat.}) \pm 2.4(\text{syst.})) \times 10^{-6}$
  - Decays very similar to signal
- $B \longrightarrow (\rho/\omega)(\pi^0/\eta)$
- Other B decays with high energy γ
  - Mostly from $B \longrightarrow X_s\gamma$

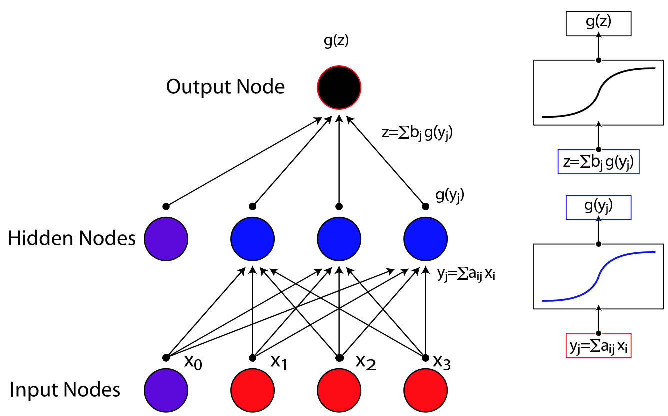
Selection variables

- Basic sufficiency and quality criteria
- Event shape variables
  - Discriminate against jet-like continuum
  - Event shape moments, photon-thrust axis angle
- Standard *BABAR* B-Tagging
  - Characterize classes of B decays
  - Also discriminate B decays from continuum
- Physics signatures
  - Discriminate signal from other B decays
  - Decay angle signatures of Vector $\longrightarrow$ 2 Pseudoscalar transitions





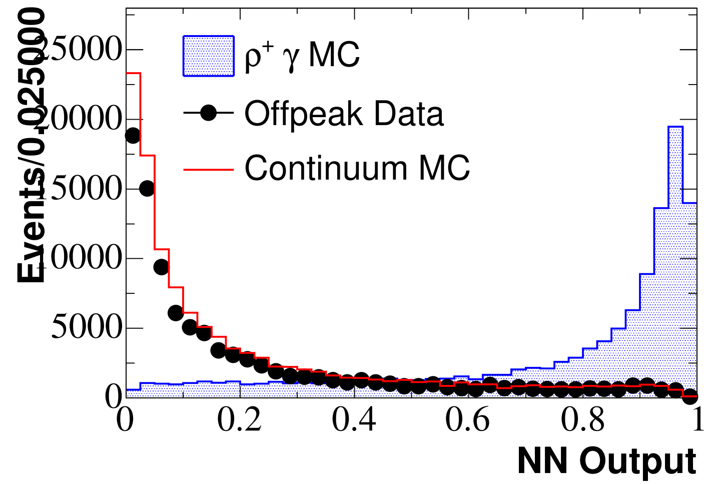
Neural networks

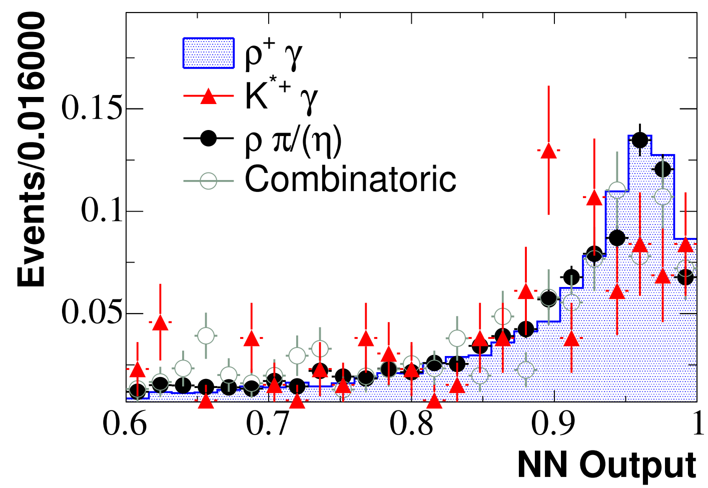


- Nonlinear combination of input variables
- Information is distributed in weighted connections
- Optimally treats correlations among input variables
- Trained with Monte Carlo simulated data
- Output: 0 (bkgrnd) to 1 (sig)

Continuum discrimination

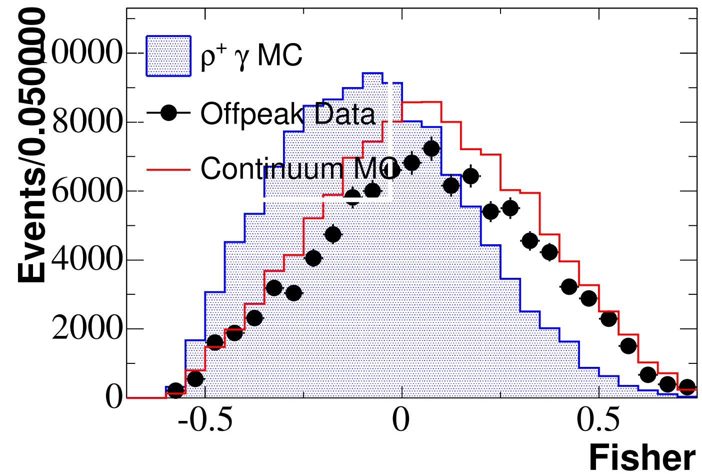
- NN output used as likelihood fit variable
- Loose cut on neural network output
  - $NN(B^0 \to \rho^0\gamma) > 0.6$
  - $NN(B^+ \to \rho^+\gamma) > 0.6$
  - $NN(B^0 \to \omega\gamma) > 0.65$
- Event shape variables similar for all true B decays

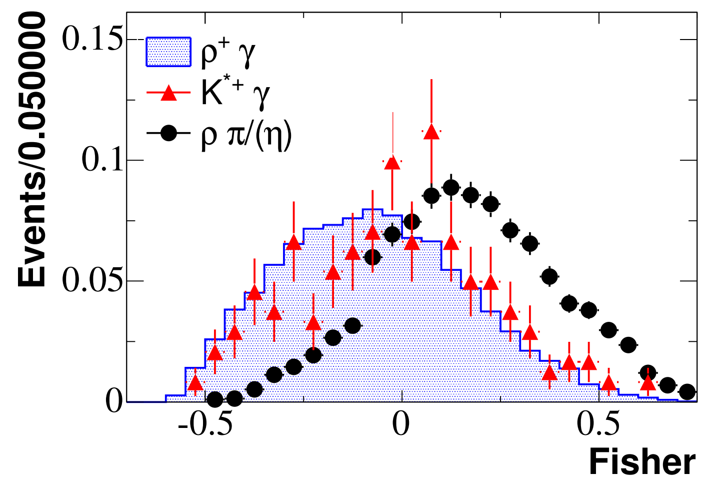




Fisher discriminant

- Linear combination of discriminating variables
- Used in likelihood fit
- Signal shape variables
  - $|\cos(\theta_H)|$
  - $|\cos(\theta_B)|$
  - $|\cos(\theta_D)|$ $(B^0 \to \omega\gamma)$



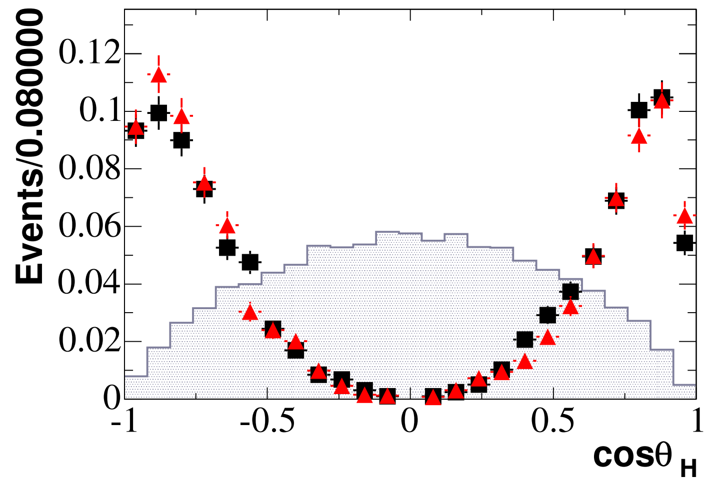


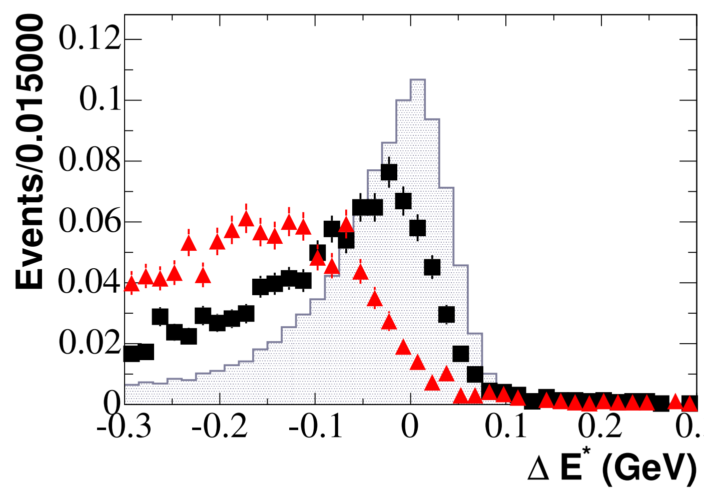
Suppressing $B \to K^*\gamma$

- Peaks in signal region
- Misidentified charged Kaon in $B \to K^*\gamma$
  - Pion PID : pion likelihood selector veryTight (all modes)
  - Optimized $m_{\pi\pi}$ cut
  - Discriminate with ΔE^* and Fisher in fit
- Shared final state in $B^0 \to \omega\gamma$
  - From $B^0 \to K^{*0}\gamma, K^{*0} \to K_s^0\pi^0, K_s^0 \to \pi^+\pi^-$
  - Vertex $\pi^+\pi^-$
  - Veto flight distance $> 0.3cm$ ($B^0 \to \omega\gamma$ only)

Suppressing $B \to (\rho/\omega)(\pi^0/\eta)$

- Helicity angle cut: $|\cos\Theta_H| < 0.75$
- Physics variable differences $\to$ Fisher discriminant differences
- ΔE differences
- Distributions for $B^0 \to \rho^0\gamma$
  - triangles: $\rho^0\eta$
  - squares: $\rho^0\pi^0$





Likelihood fits

- Set of discriminating variables $\vec{x}$ (m_{ES}, ΔE^*, neural network, Fisher)
- Parameterized PDF of data over variables
  - Weighted sum of PDFs of classes of events
  - Floating parameters $\vec{\alpha}$ estimated in fit
- Maximize likelihood function over data

$$\mathcal{L}(\vec{n}, \vec{\alpha}) = \exp\left(-\sum_{i=1}^{N_{class}} n_i\right) \cdot \left[\prod_{j=1}^{N_{cand}} \left(\sum_{i=1}^{N_{class}} n_i \mathcal{P}_i(\vec{x}_j; \vec{\alpha}_i)\right)\right]$$

PDFs for $B \to \rho\gamma$, $B^0 \to \omega\gamma$

Five component PDFs:

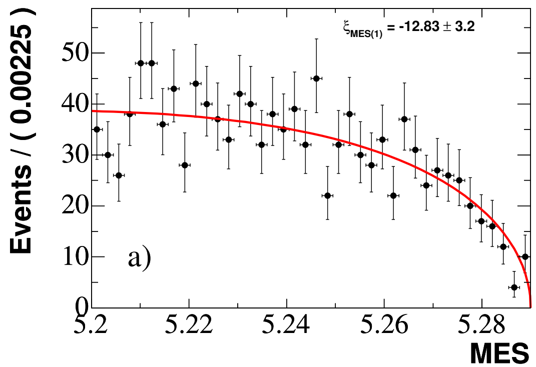
- Signal
- Continuum $q\bar{q}$
- $B \to (\rho/\omega)(\pi^0/\eta)$
- Other B decays with high energy γ ($B \to X_s\gamma$) ($B \to \rho\gamma$ modes)
- $B \to K^*\gamma$ ($B \to \rho\gamma$ modes)

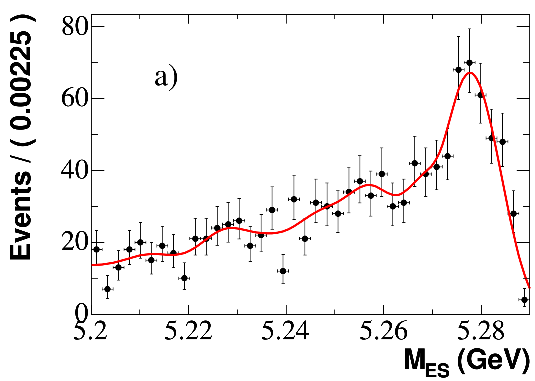
Over four variables:

- m_{ES}
- ΔE^*
- Neural Network
- Fisher Discriminant

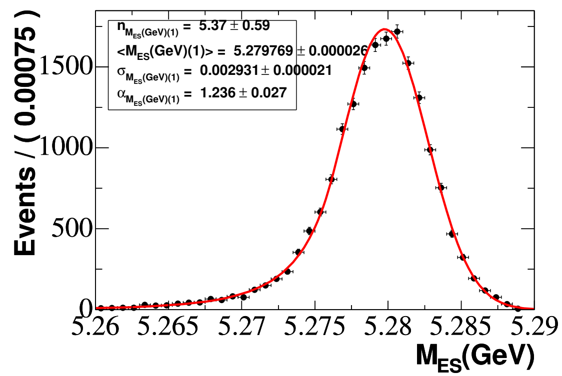
PDFs for $B^0 \to \rho^0\gamma$: m_{ES}

Continuum



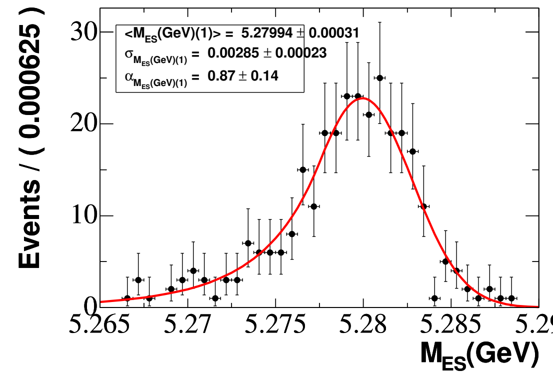


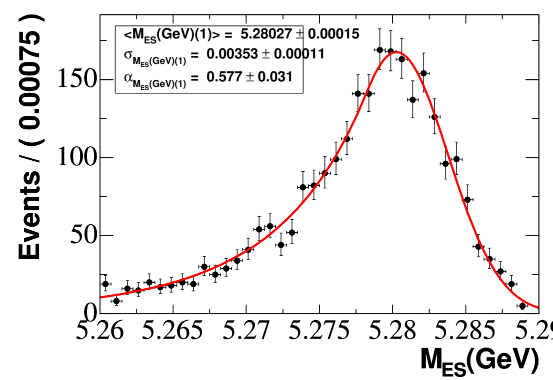
$B\overline{B}$



Signal

$K^*\gamma$

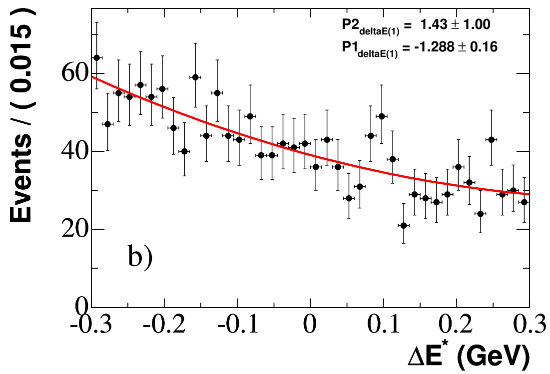


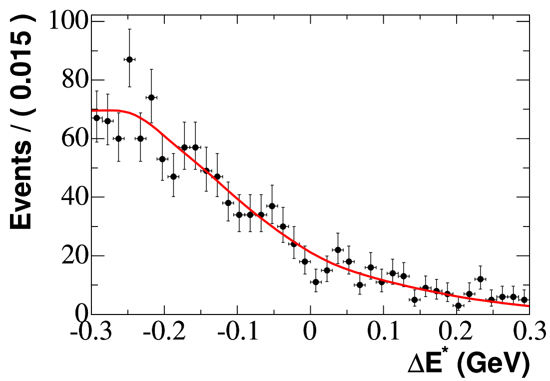


$\rho^0(\pi^0/\eta)$

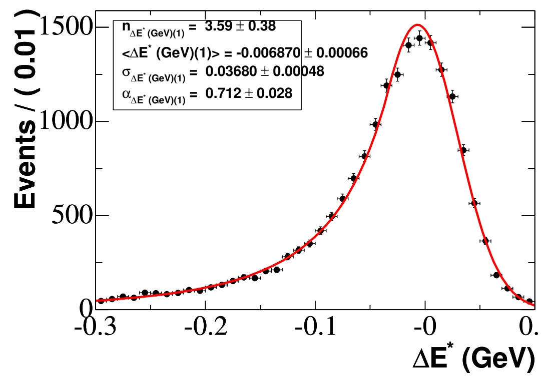
PDFs for $B^0 \to \rho^0\gamma$: ΔE^*

Continuum



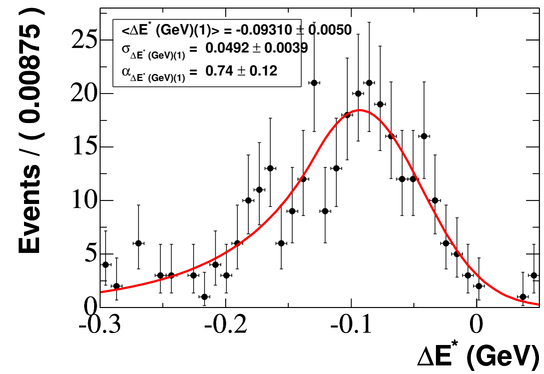


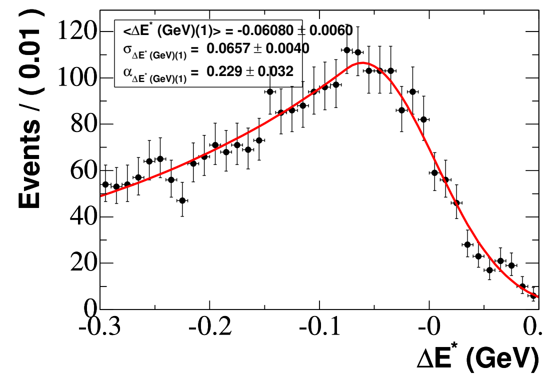
$B\overline{B}$



Signal

$K^*\gamma$

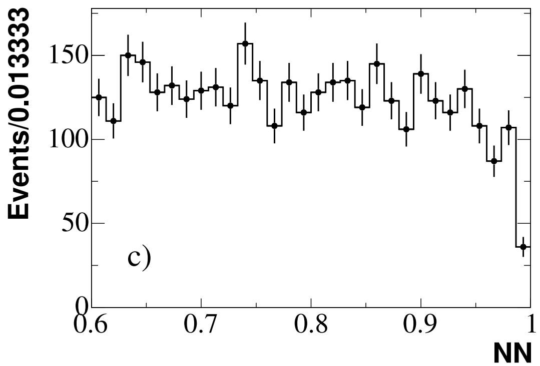




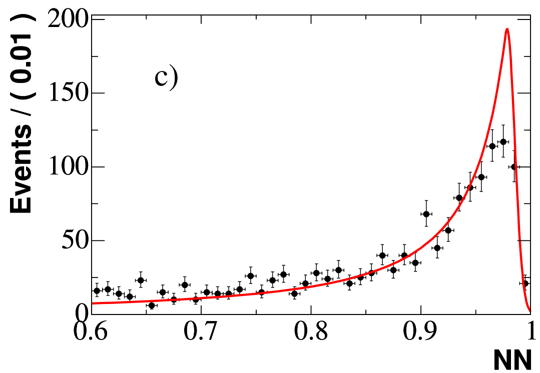
$\rho^0(\pi^0/\eta)$

PDFs for $B^0 \to \rho^0\gamma$: neural network

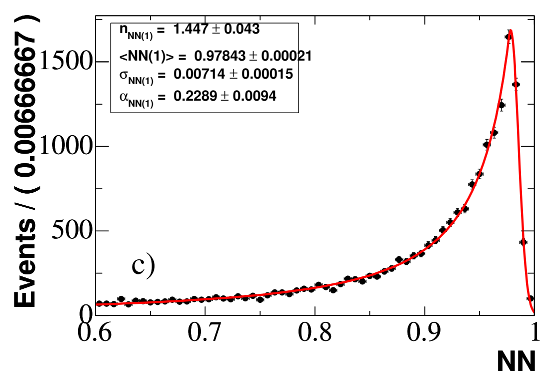
Continuum



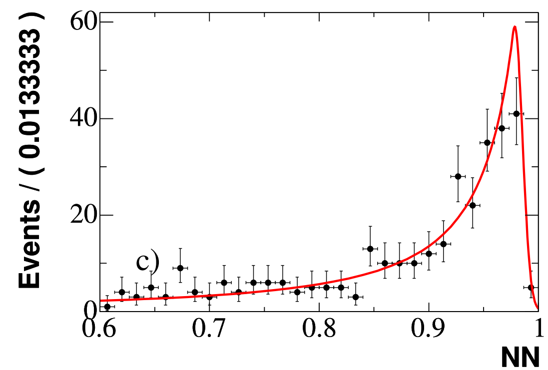
$B\overline{B}$



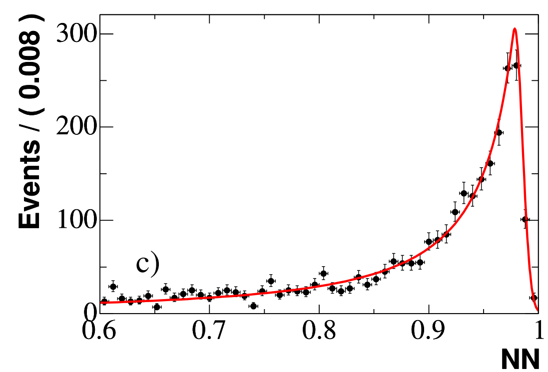
Signal



$K^*\gamma$

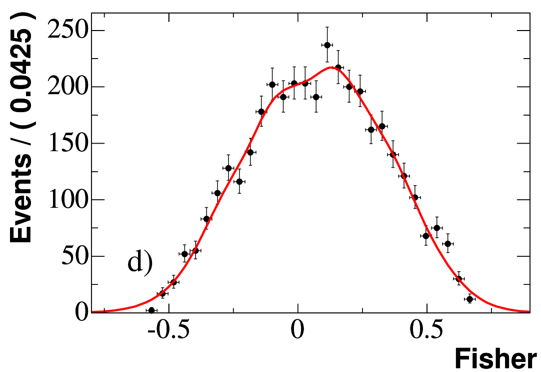


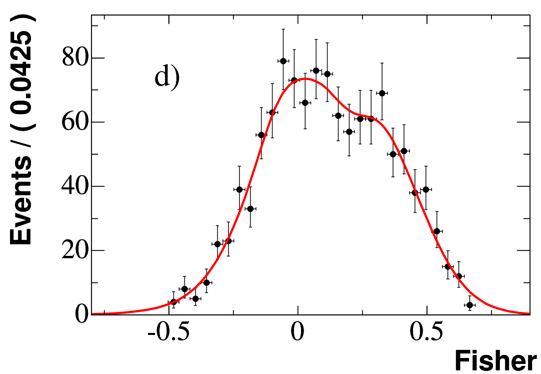
$\rho^0(\pi^0/\eta)$



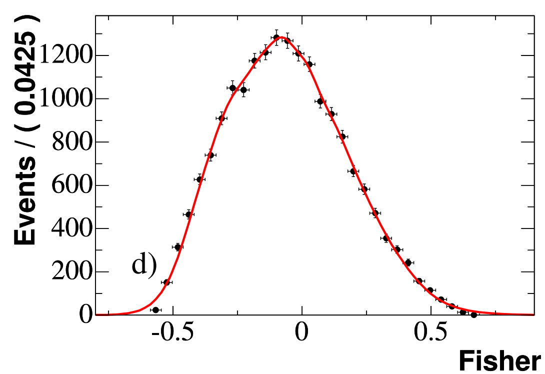
PDFs for $B^0 \to \rho^0\gamma$: Fisher

Continuum



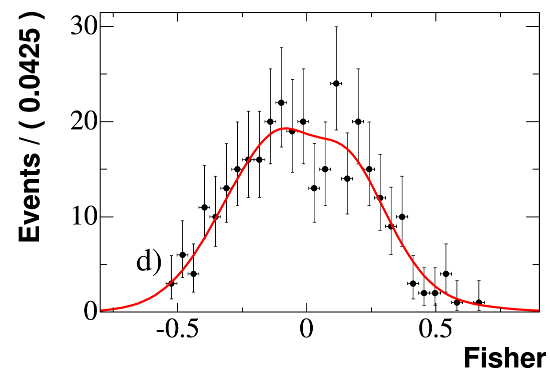


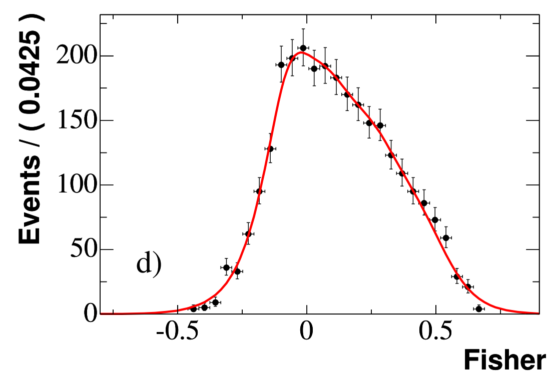
$B\overline{B}$



Signal

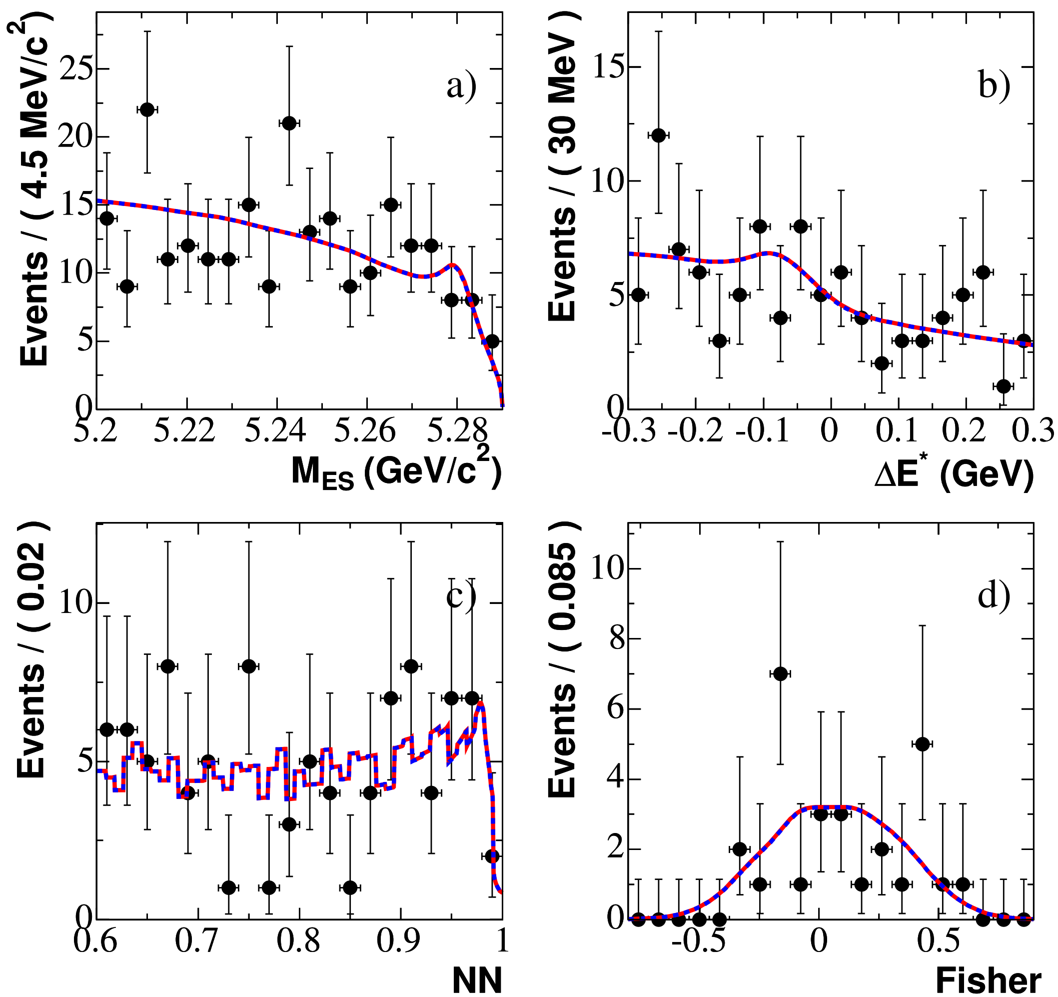
$K^*\gamma$





$\rho^0(\pi^0/\eta)$

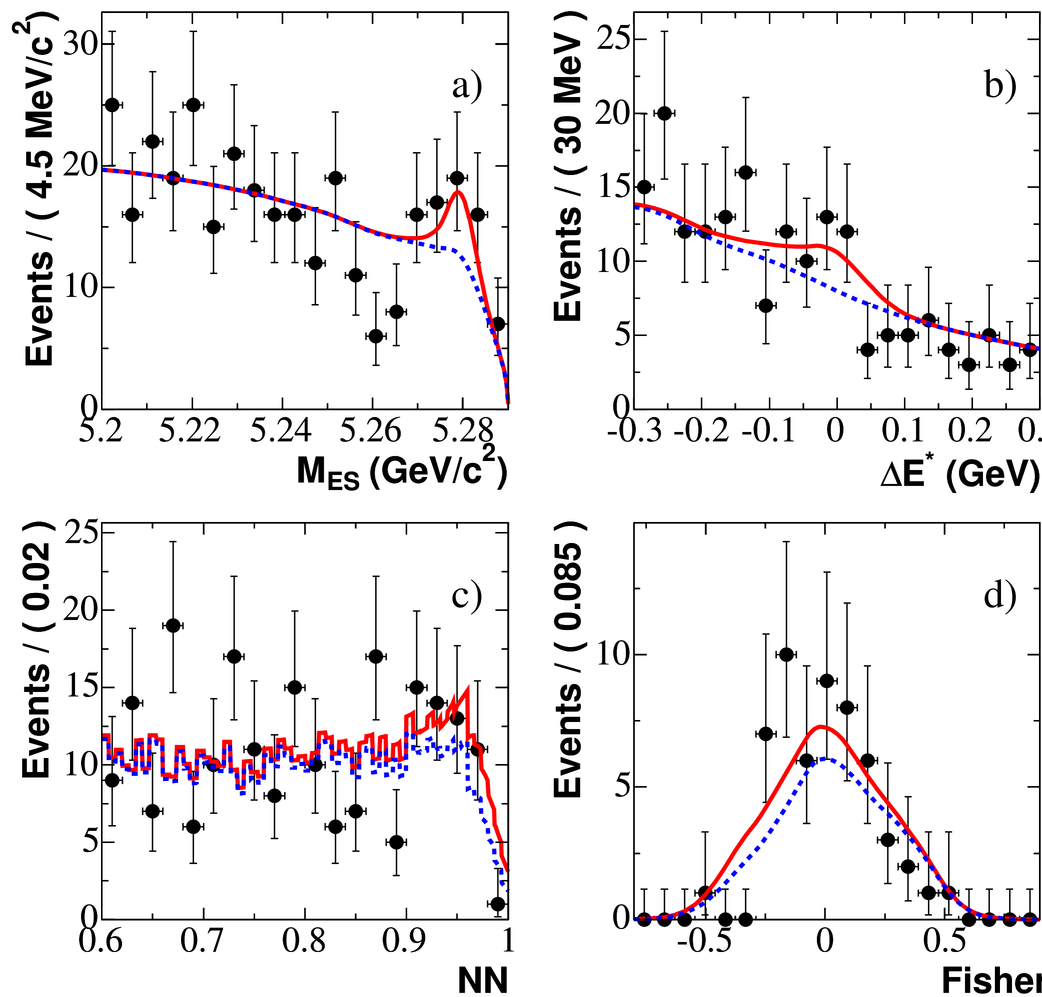
Projection plots of results: $B^0 \rightarrow \rho^0\gamma$



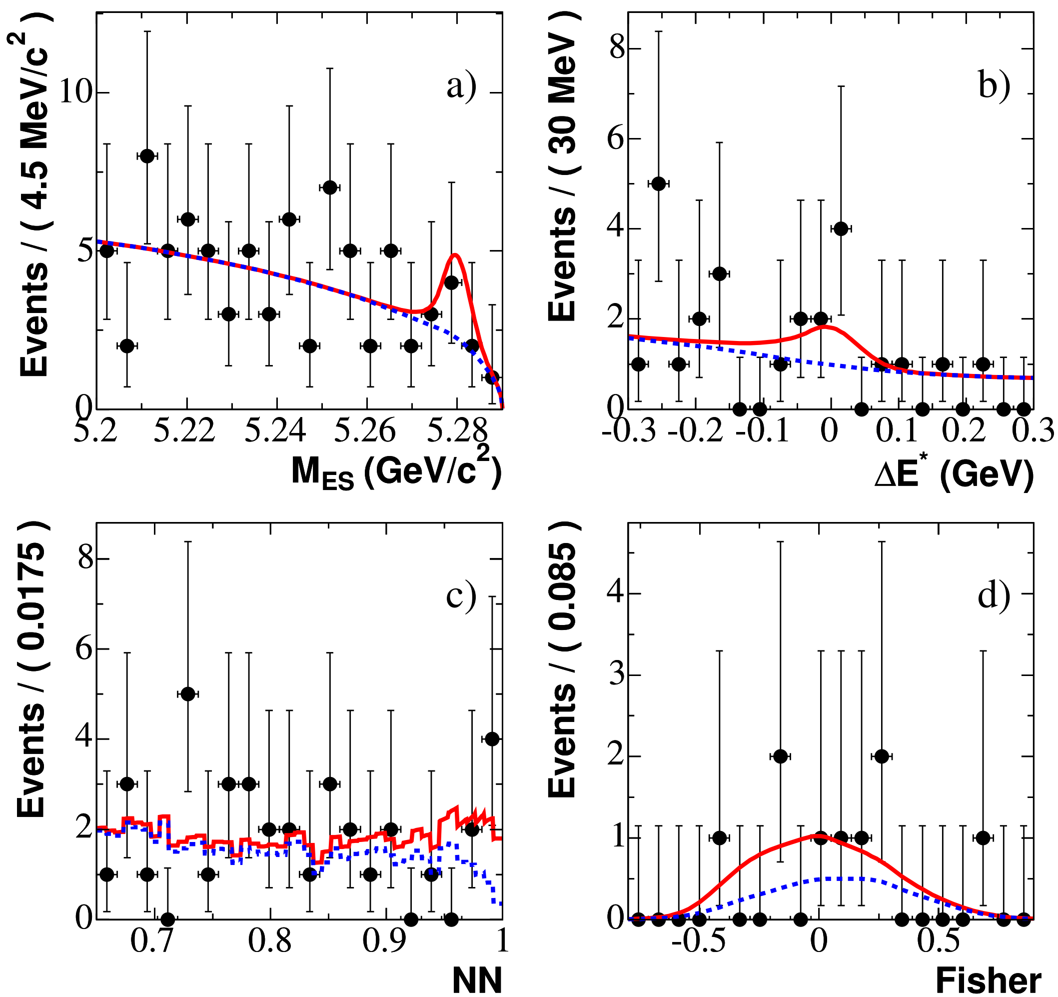
- $N_{\rm sig} = 0.3^{+7.2}_{-5.4}$
- $N_{\rm cont} = 4269 \pm 73$
- $N_{B\rm bkg} = 80 \pm 36$

Projection plots of results: $B^+ \to \rho^+$

- $N_{\rm sig} = 25.6^{+15.3}_{-13.9}$
- $N_{\rm cont} = 6850 \pm 90$
- $N_{B{\rm bkg}} = 175 \pm 40$



Projection plots of results: $B^0 \to \omega\gamma$



- $N_{\rm sig} = 8.3^{+5.7}_{-4.5}$
- $N_{\rm cont} = 1378 \pm 37$

Systematic uncertainties: $B \to \binom{\rho}{\omega}\gamma$

	$B^0 \to \rho^0\gamma$		$B^+ \to \rho^+\gamma$		$B^0 \to \omega\gamma$	
Description	factor	error	factor	error	factor	error
Number of B events	1.000	0.011	1.000	0.011	1.000	0.011
Tracking eff.	0.988	0.016	0.996	0.008	0.986	0.016
PID	1.000	0.020	1.000	0.020	1.000	0.020
Photon(π^0/γ) eff.	1.000	0.030	0.971	0.060	0.966	0.060
π^0, η veto	1.000	0.010	1.000	0.010	1.000	0.010
Photon isolation cut	1.000	0.020	1.000	0.020	1.000	0.020
$m_{\pi\pi(\pi)}$ mass cut	1.000	0.000	1.000	0.000	1.000	0.000
Neural net	1.000	0.046	1.000	0.018	1.000	0.046
MC statistics/bias	1.000	0.102	1.000	0.081	1.000	0.054
Total multiplicative	0.988	0.121	0.967	0.108	0.952	0.100
fit bias/systematic	0.0	$^{+1.7}_{-1.6}$	0.0	$^{+2.2}_{-2.2}$	-1.05	$^{+1.3}_{-1.9}$

Individual BF measurements

Description	N_{sig}	fit sys.	ϵ	$\mathcal{B}$(±stat. ± sys.) ($\times 10^{-6}$)	90%C.L. UL ($\times 10^{-6}$)
$B^0 \to \rho^0\gamma$	$0.3^{+7.2}_{-5.4}$	$^{+1.7}_{-1.6}$	0.158 ± 0.019	$0.01^{+0.22+0.05}_{-0.16-0.05}$	0.36
$B^+ \to \rho^+\gamma$	$25.6^{+15.3}_{-13.9}$	$^{+2.2}_{-2.2}$	0.132 ± 0.014	$0.92^{+0.55+0.13}_{-0.50-0.13}$	1.76
$B^0 \to \omega\gamma$	$8.3^{+5.7}_{-4.5}$	$^{+1.3}_{-1.9}$	0.086 ± 0.009	$0.46^{+0.31+0.08}_{-0.25-0.12}$	0.97

- Significance evaluated by analyzing likelihood function
  - $B^+ \to \rho^+\gamma$: 1.9σ significance
  - $B^0 \to \omega\gamma$: 1.5σ significance
- No individual mode meets the 3σ significance criteria for claiming evidence of $b \to d\gamma$

Combined $\mathcal{B}(B \to (\rho, \omega)\gamma)$

- Simultaneous fit to all 3 modes
- Assume isospin relationship

$$\Gamma(B^0 \to \rho^0\gamma) = \Gamma(B^0 \to \omega\gamma) = 0.5 \cdot \Gamma(B^+ \to \rho^+\gamma)$$

- Measure combined average $\mathcal{B}$

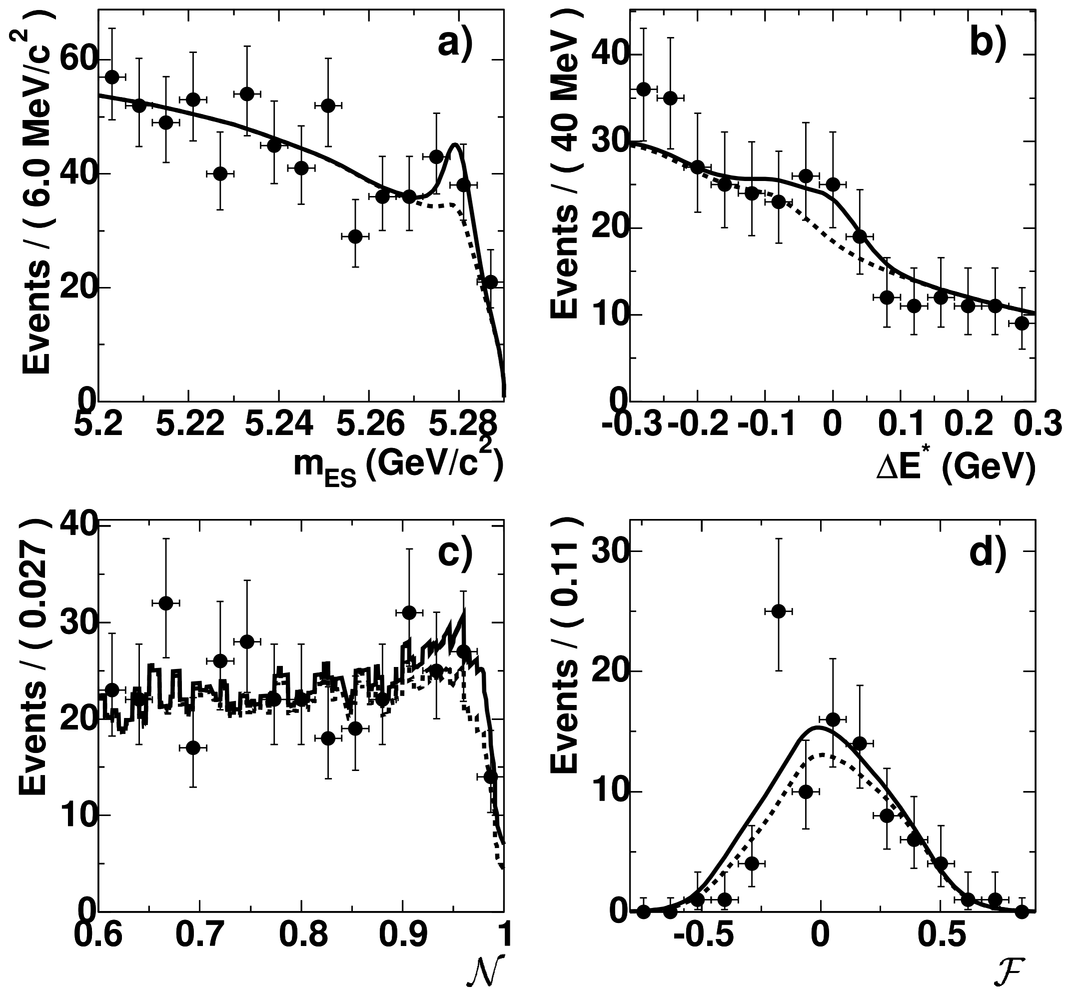
$$\begin{aligned} \mathcal{B}(B \to (\rho, \omega)\gamma) &\equiv \frac{1}{2} \cdot \{\mathcal{B}(B^+ \to \rho^+\gamma) + \frac{\tau_{B^+}}{\tau_{B^0}} \cdot [\mathcal{B}(B^0 \to \rho^0\gamma) + \mathcal{B}(B^0 \to \omega\gamma)]\} \\ &= \mathcal{B}(B^+ \to \rho^+\gamma) \end{aligned}$$

- Fit for effective number of $B^+ \to \rho^+\gamma$ decays

$$N_{\text{eff}} = 2 \cdot N_{B\bar{B}} \cdot \mathcal{B}(B \to (\rho, \omega)\gamma)$$

Projection plots of results: combine

- $N_{\mathrm{sig,eff}} = 269^{+126}_{-120}$



Calculation of $|V_{td}/V_{ts}|$

- Relation

$$\frac{\mathcal{B}(B^+ \to \rho^+\gamma)}{\mathcal{B}(B^+ \to K^{*+}\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - m_\rho^2/M_B^2}{1 - m_{K^*}^2/M_B^2}\right)^3 \zeta^2[1 + \Delta R] \quad (1.6)$$

- Experimental mean BF ratio

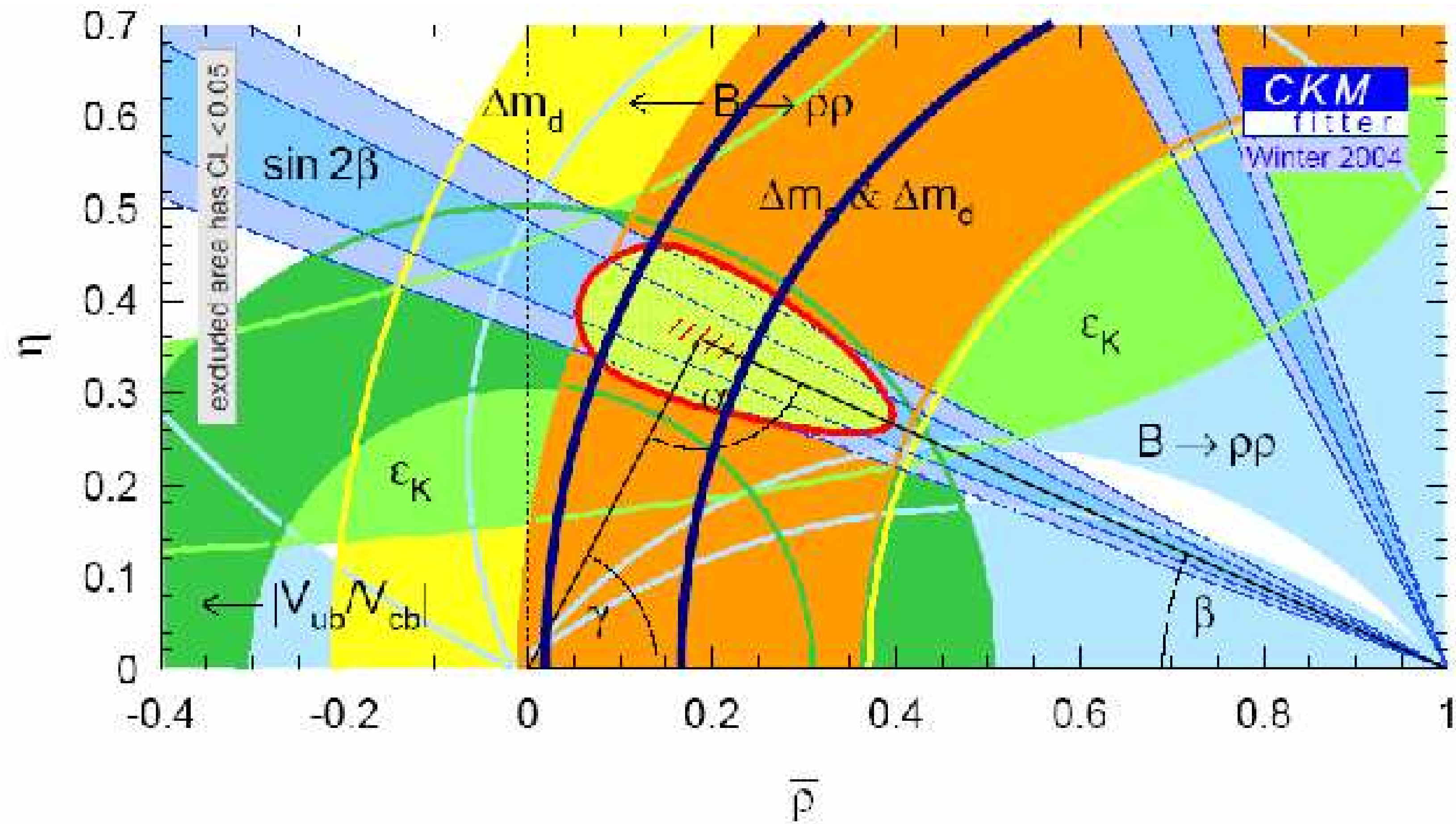
$$\frac{\mathcal{B}(B \to (\rho/\omega)\gamma)}{\mathcal{B}(B \to K^*\gamma)} = \frac{(0.64 \pm 0.34) \times 10^{-6}}{(3.930 \pm 0.262) \times 10^{-5}} = 0.0163 \pm 0.0087$$

- Uncertain theoretical terms

$$\zeta = 0.85 \pm 0.10,\ \Delta R = 0.10 \pm 0.10$$

- $\left|\frac{V_{td}}{V_{ts}}\right| = 0.142 \pm 0.038(\text{exp}) \pm 0.017(\zeta) \pm 0.006(\Delta R)$
- 90% CL UL: $\left|\frac{V_{td}}{V_{ts}}\right| < 0.195$ (< 0.190 w/only σ_{exp})

$|V_{td}/V_{ts}|$



inner: $(\zeta, \Delta R) = (0.85, 0.10)$; outer: $(0.75, 0.10)$

Summary of results: $B \to (\rho, \omega)\gamma$

Measurements

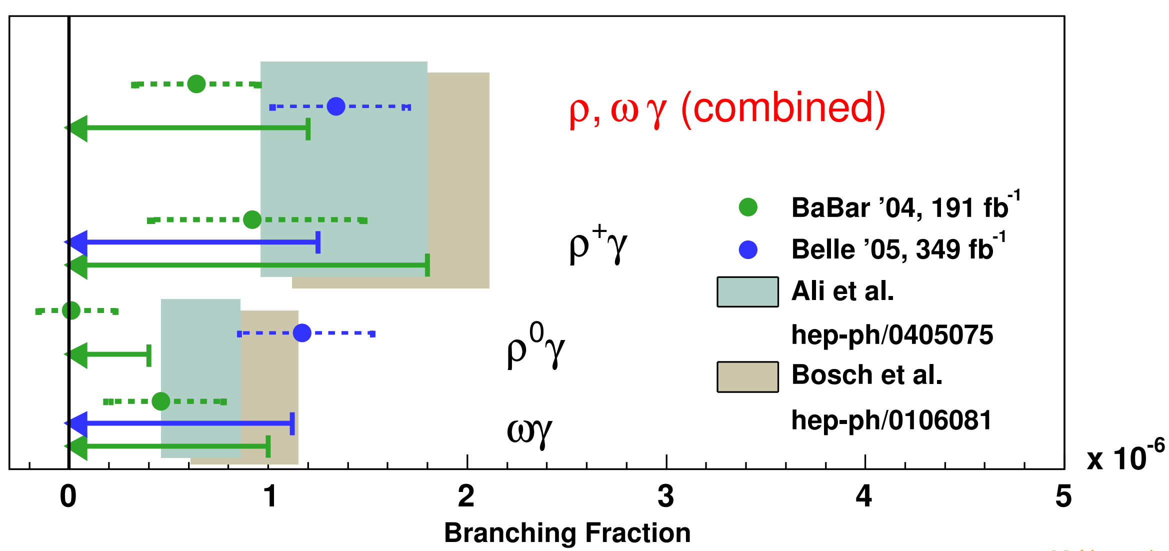
Value	BaBar 2004 (this) $(211 \times 10^6\ B\overline{B})$	Belle 2005 $(386 \times 10^6\ B\overline{B})$
$\mathcal{B}(B^0 \to \rho^0\gamma)$	$< 0.4 \times 10^{-6}$	$(1.17^{+0.35}_{-0.31}{}^{+0.09}_{-0.08}) \times 10^{-6}$
$\mathcal{B}(B^+ \to \rho^+\gamma)$	$< 1.8 \times 10^{-6}$	$< 1.3 \times 10^{-6}$
$\mathcal{B}(B^0 \to \omega\gamma)$	$< 1.0 \times 10^{-6}$	$< 1.1 \times 10^{-6}$
$\mathcal{B}(B \to (\rho/\omega)\gamma)$	$< 1.2 \times 10^{-6}$	$(1.35^{+0.34}_{-0.31}{}^{+0.14}_{-0.10}) \times 10^{-6}$
$\|V_{td}/V_{ts}\|$	< 0.190	$0.200^{+0.026}_{-0.025}(\mathrm{exp})^{+0.038}_{-0.029}(\mathrm{theo})$

Theoretical calculations

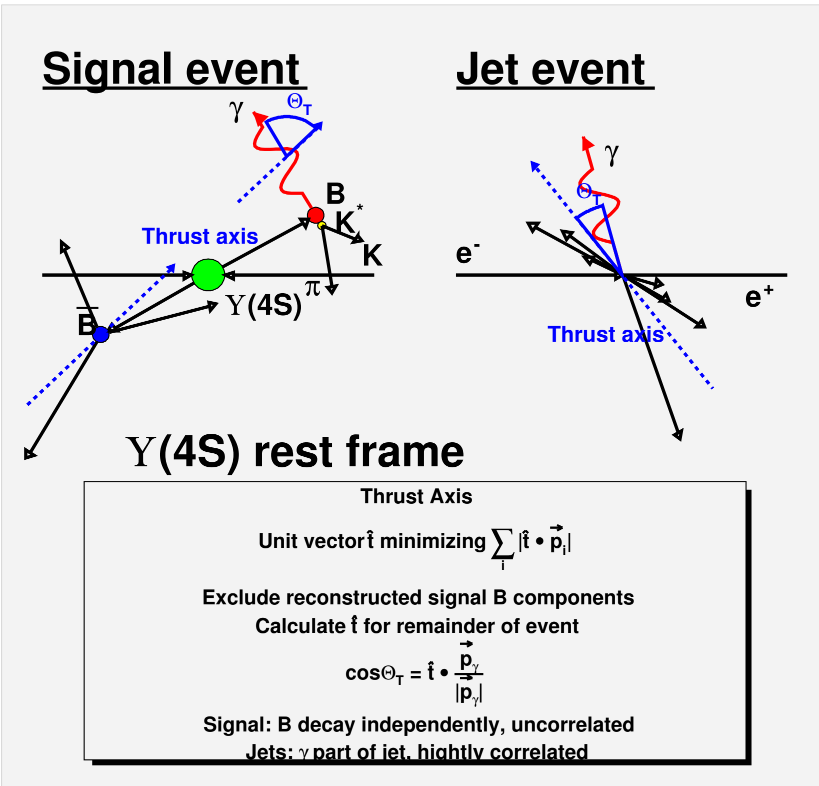
Calculations			
$\mathcal{B}(B^0 \to \rho^0\gamma)(\times 10^{-6})$	0.66 ± 0.20	$0.76^{+0.26}_{-0.23}$	0.49 ± 0.18(th) ± 0.04(ex)
$\mathcal{B}(B^+ \to \rho^+\gamma)(\times 10^{-6})$	1.35 ± 0.42	$1.58^{+0.53}_{-0.46}$	0.90 ± 0.33(th) ± 0.10(ex)
$\|V_{td}/V_{ts}\|$	Limit from $\Delta M_{B_d}/\Delta M_{B_s}$		< 0.25

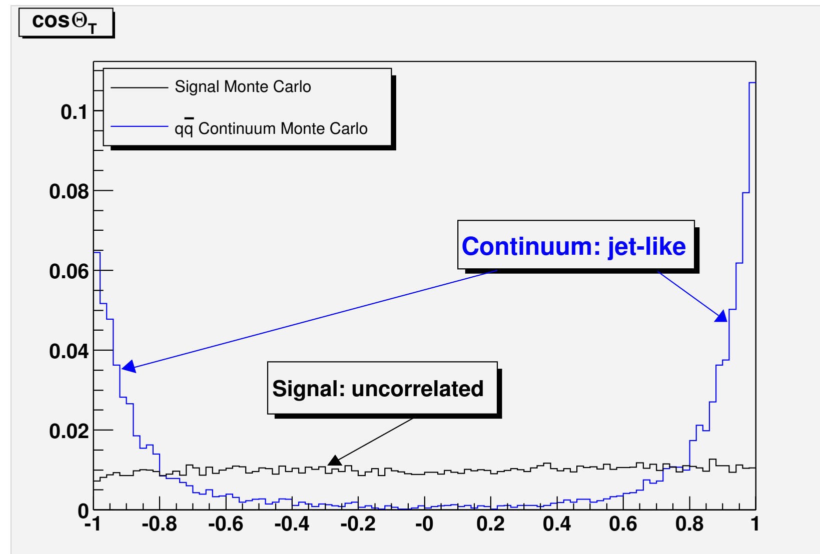
Immediate future

- Still seeking first *BABAR* observation of $B \to \rho\gamma$
- Examination of possible disagreement with Belle's recent observations
- Direct determination of $|V_{td}/V_{ts}|$ with improved $B \to \rho\gamma$ measurements



Event shape: Θ_T



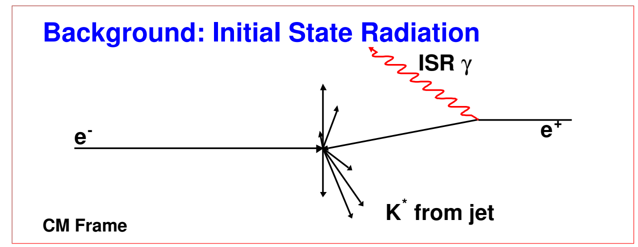


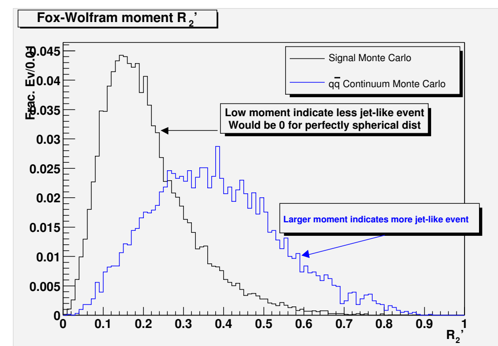
Distributions for $B^0 \to K^{*0}\gamma$

Event shape: Fox-Wolfram moment

- Event shape moments
  - $\vec{p}_{i,j}$: particle momenta
  - θ_{ij}: $\vec{p}_i - \vec{p}_j$ opening angle
  - P_ℓ: the Legendre polynomials
  - E_{vis}: total visible event energy
- $R_0 = 1,\ R_1 = 0$
- R_0 normalization
- Jets: $R_{2k} \approx 1,\ R_{2k+1} \approx 0$
- R_2 whole event, CMS: 2 jet
- R_2' evaluated in γ_{sig} recoil frame: ISR

$$R_\ell = \sum_{i,j} \frac{|\vec{p}_i||\vec{p}_j|}{E_{vis}^2} P_\ell(\cos\theta_{ij})$$





Distributions for $B^0 \to K^{*0}\gamma$

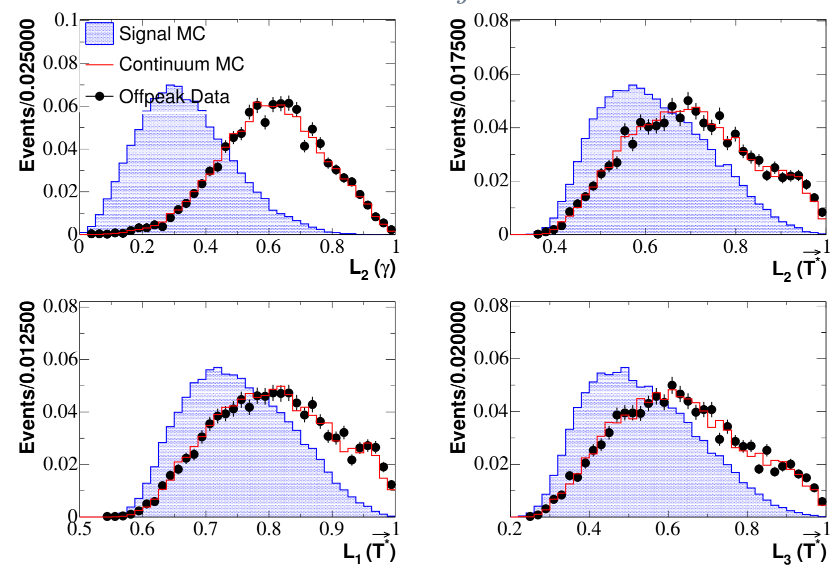
Event shape: L-moments

- Characterize event shape
- Defined w.r.t. an axis $\hat{a}$
- Four moments used:

$$\{L_2(\gamma_B), L_1(\hat{t}^*), L_2(\hat{t}^*), L_3(\hat{t}^*)\}$$

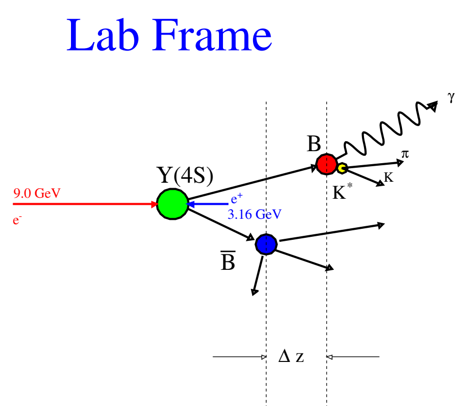
- Neural network input in $B \to \rho\gamma$ and $B^0 \to \omega\gamma$
- Provide as much continuum discriminating power as 18 energy cones

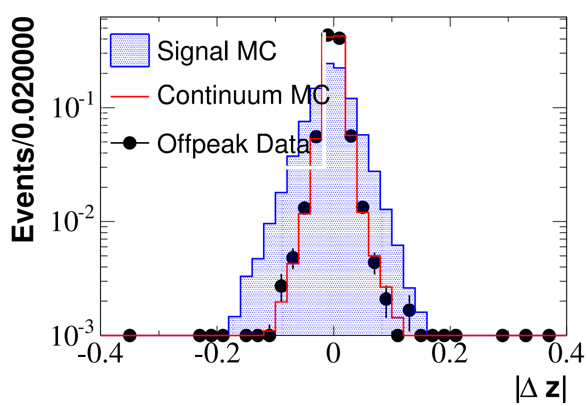
$$L_i(\hat{a}) = \frac{\sum_{j=1}^{N} |\vec{p}_j| \times \left|\frac{(\vec{p}_j \cdot \hat{a})}{|\vec{p}_j|}\right|^i}{\sum_{j=1}^{N} |\vec{p}_j|}$$



Distributions of L-moments for $B^0 \to \rho^0\gamma$

Physics: Δz

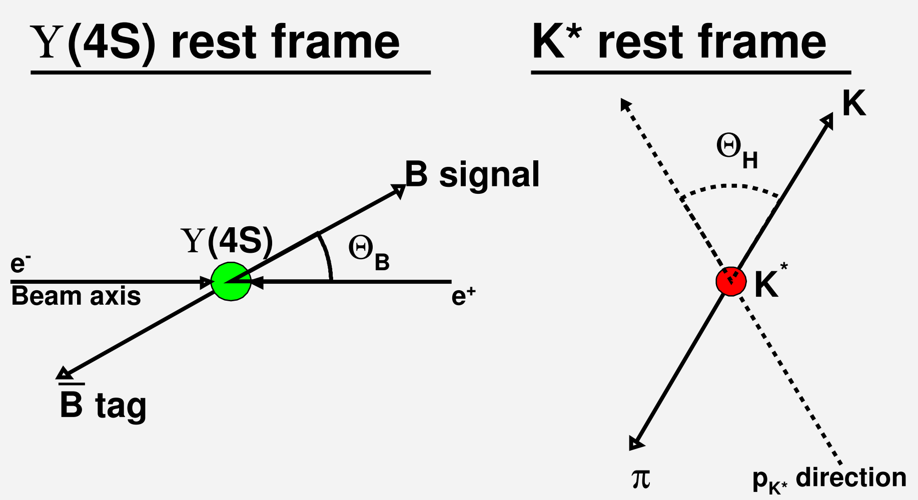




$B^0 \rightarrow \rho^0\gamma$ Monte Carlo

- Lab frame displacement between signal candidate vertex and ROE vertex
- Continuum: vertices should nearly coincide
- $B\overline{B}$ events: vertices separated by boost

Physics: $\cos\Theta_B, \cos\Theta_H$



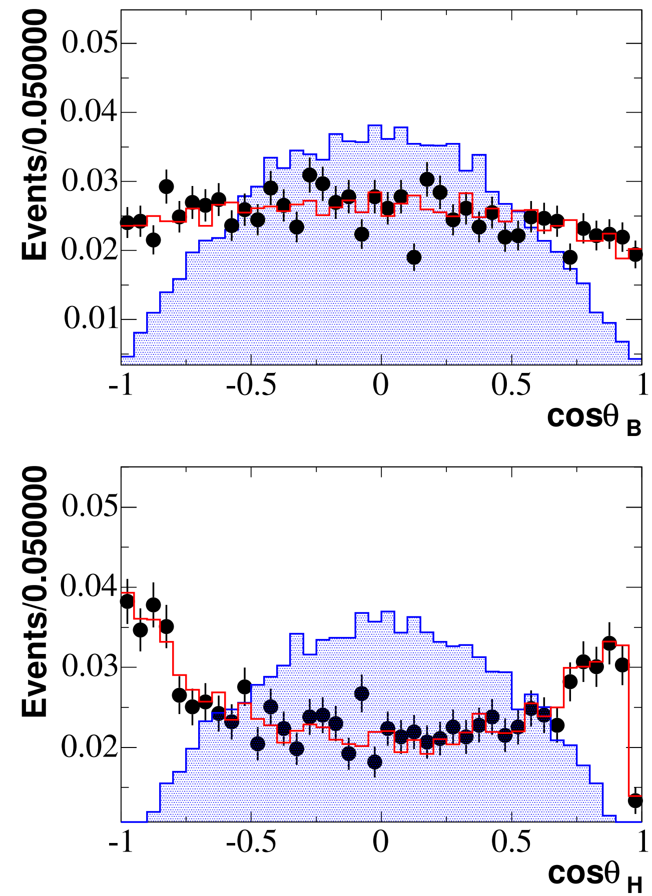
Angular Momentum

Vector → Pseudoscalar + Pseudoscalar

Transition amplitude $\propto \sin^2\Theta_{B,H}$

Backgrounds: randomly associated candidates

No angular correlation in particle rest frame



Physics: $\cos\Theta_D$

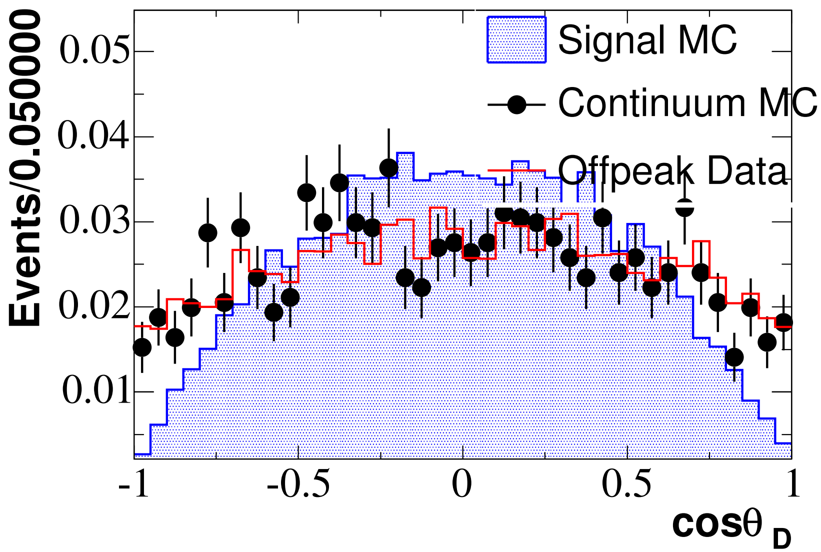


Figure 5.13: Distribution of $\cos\Theta_D$ for $B^0 \to \omega\gamma$

- Dalitz angle of ω for $B^0 \to \omega\gamma$ mode
- Angle in $\pi^+\pi^-$ rest frame between π^+ and π^0 momenta
- $\sin^2\Theta_D$ by simultaneous isospin and angular momentum conservation

ROE flavor information

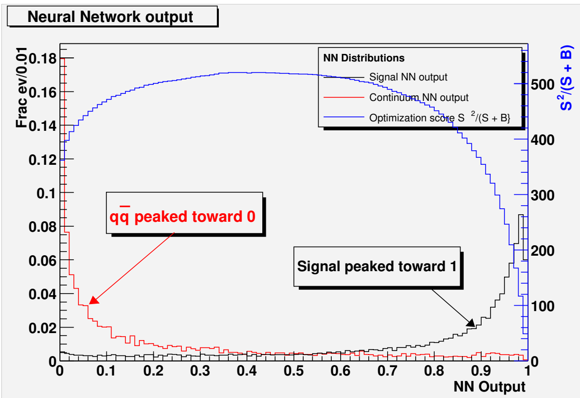
- Standard *BABAR* B-Tagging
  - Set of variables characterizing classes of B decays
  - Developed to discriminate B^0 and $\overline{B}^0$
  - Also effective at discriminating true B decays from continuum

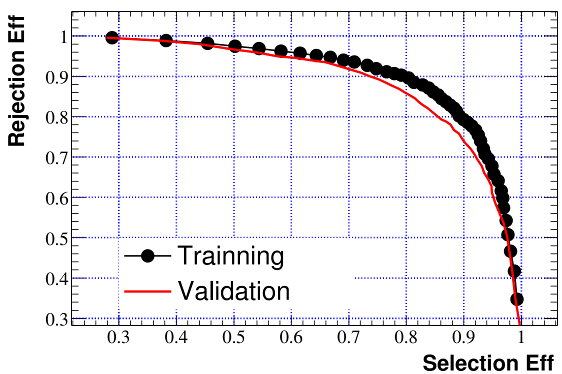
Neural network inputs

Modes	Variables	Configuration
$B^0 \to \rho^0\gamma$	$\|\cos(\Theta_T)\|$, R_2', $L_2(\gamma)$, L_1, L_2, L_3, $\|\Delta z\|$, e-tag, μ-tag, π_S-tag, K-π_S-tag, P^*_{max}-tag, Num. of Kaons, kaon P^*_{max}	14:5:1
$B^+ \to \rho^+\gamma$	$\|\cos(\Theta_T)\|$, R_2', $L_2(\gamma)$, L_1, L_2, L_3, e-tag, μ-tag, π_S-tag, K-π_S-tag, P^*_{max}-tag, Num. of Kaons, kaon P^*_{max}	13:6:1
$B^0 \to \omega\gamma$	$\|\cos(\Theta_T)\|$, R_2', $L_2(\gamma)$, L_1, L_2, L_3, $\|\Delta z\|$, e-tag, μ-tag, π_S-tag, K-π_S-tag, P^*_{max}-tag, Num. of Kaons, kaon P^*_{max}	14:5:1

Table 1: Neural net configurations

Continuum discriminant





- Applied after event γ quality control, signal reconstruction, and PID
- Likelihood fit variable for $B \to \rho\gamma$ and $B^0 \to \omega\gamma$
- Optimize a cut for $B \to K^*\gamma$:
  - Maximize significance

$$S/\sqrt{S+B}$$

  - S signal yield in 82fb^{-1}
  - B background yield in 82fb^{-1} in m_{ES}–ΔE^* signal box
  - Optimized value: $nn_{out} > 0.425719$
- Signal acceptance: 0.825
- Background rejection: 0.805

Fisher discriminant

- Linear combination of discriminating variables $\vec{x}$
- Maximize distance d between populations

$$d = \frac{(\vec{a} \cdot (\vec{\mu}_1 - \vec{\mu}_2))^2}{\sum_{i,j} a_i V_{ij} a_j}$$

  - $\vec{a}$: coefficients of $\vec{x}$ defining discriminant
  - $\vec{\mu}_1, \vec{\mu}_2$: population means of $\vec{x}$
  - V_{ij}: joint covariance matrix of $\vec{x}$ over populations
- Used in likelihood fit for $B \to \rho\gamma$ and $B^0 \to \omega\gamma$

Estimated background levels (200 fb

Mode	$B^0 \to \rho^0\gamma(200\ \text{fb}^{-1})$		$B^+ \to \rho^+\gamma(200\ \text{fb}^{-1})$		$B^0 \to \omega\gamma(200\ \text{fb}^{-1})$	
	fit reg	signal reg	fit reg	signal reg	fit reg	signal reg
Signal Eff	16.0%		13.7%		9.0%	
Signal Yield	16.8	15.6 ± 0.2	28.7	25.3 ± 0.2	9.5	8.5 ± 0.1
$B \to K^*\gamma$	11.4	9.2 ± 0.6	4.4	3.0 ± 0.3	5.0	1.6 ± 0.2
$B \to (\rho/\omega)\pi^0$	1.60	1.20 ± 0.02	7.0	4.7 ± 0.1	0.50	0.35 ± 0.03
$B \to (\rho/\omega)\eta$	0.99	0.58 ± 0.02	6.5	3.5 ± 0.2	2.2	1.3 ± 0.1
Sum	2.59	1.77 ± 0.03	13.5	8.2 ± 0.2	2.7	1.7 ± 0.1
$other B^0\overline{B^0}$	33.3	8.6 ± 2.2	74.7	16.6 ± 3.0	11.5	1.7 ± 1.0
$other B^+B^-$	43.2	3.5 ± 2.0	95.6	19.8 ± 4.8	14.0	1.2 ± 1.2
Sum	76.5	12.1 ± 3.0	170.3	36.5 ± 5.7	25.5	2.8 ± 1.5
Continuum	4025	300 ± 61	7050	400 ± 70	1763	175 ± 46

PDFs for $B \to \rho\gamma$, $B^0 \to \omega\gamma$

Floated parameters

- N_{sig}
- $N_{continuum}$
- $N_{b \to s\gamma}$ (only for $B \to \rho\gamma$ modes)
- Continuum Argus $\xi_{m_{ES},cont}$
- Continuum Polynomial $P1_{\Delta E^*,cont}$
- Continuum Polynomial $P2_{\Delta E^*,cont}$

Combined results $\mathcal{B}(B \to (\rho, \omega)\gamma)$ (II

- Individual mode yields related by
  - $N_{sig}(B^+ \to \rho^+\gamma) = N_{\text{eff}} \cdot \epsilon(B^+ \to \rho^+\gamma)$
  - $N_{sig}(B^0 \to \rho^0\gamma) = 0.5\frac{\tau_{B^0}}{\tau_{B^+}} N_{\text{eff}} \cdot \epsilon(B^0 \to \rho^0\gamma)$
  - $N_{sig}(B^0 \to \omega\gamma) = 0.5\frac{\tau_{B^0}}{\tau_{B^+}} N_{\text{eff}} \cdot \epsilon(B^0 \to \omega\gamma)$
- Results

$$N_{\text{eff}} = 269^{+126}_{-120} \Rightarrow \begin{array}{rcll} N_{sig}(\rho^+\gamma) & = & 35.5^{+16.6}_{-15.8} & (25.6^{+15.3}_{-13.9}) \\ N_{sig}(\rho^0\gamma) & = & 19.8^{+9.3}_{-8.9} & (0.3^{+7.2}_{-5.4}) \\ N_{sig}(\omega\gamma) & = & 10.8^{+5.1}_{-4.8} & (8.3^{+5.7}_{-4.5}) \end{array}$$