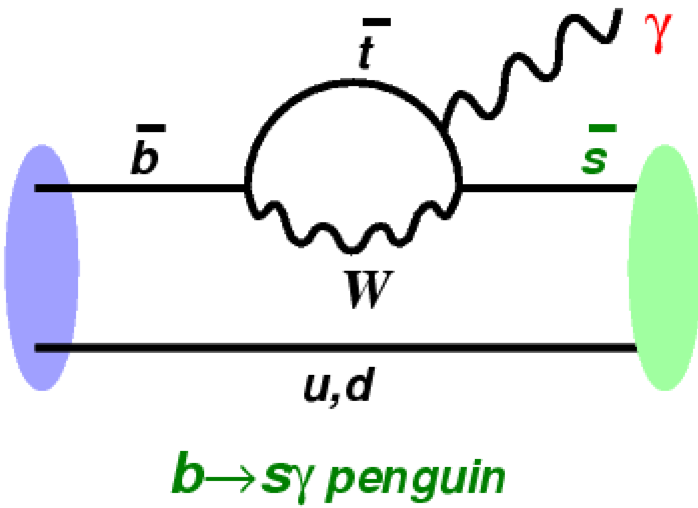
Observation of $b \to d\gamma$ and Determination of $|V_{td}/V_{ts}|$ at Belle

Fermilab, 04/04/2006

Debabrata Mohapatra
Virginia Tech

Radiative B decays directly probe the Standard Model for new Physics in Flavor Changing Neutral Current processes



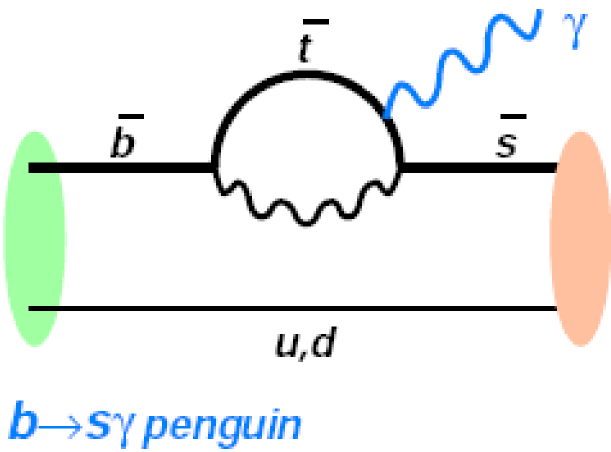
Feynman diagram for $b \to s\gamma / B \to K^{*}\gamma$

Flavor-changing-neutral-current (FCNC) processes

◦ *allowed in the Standard Model via penguin loop*

◦ *inclusive branching fraction* $\sim 3.5 \times 10^{-4}$ (*theory*)

This excited journey started at CLEO a decade ago



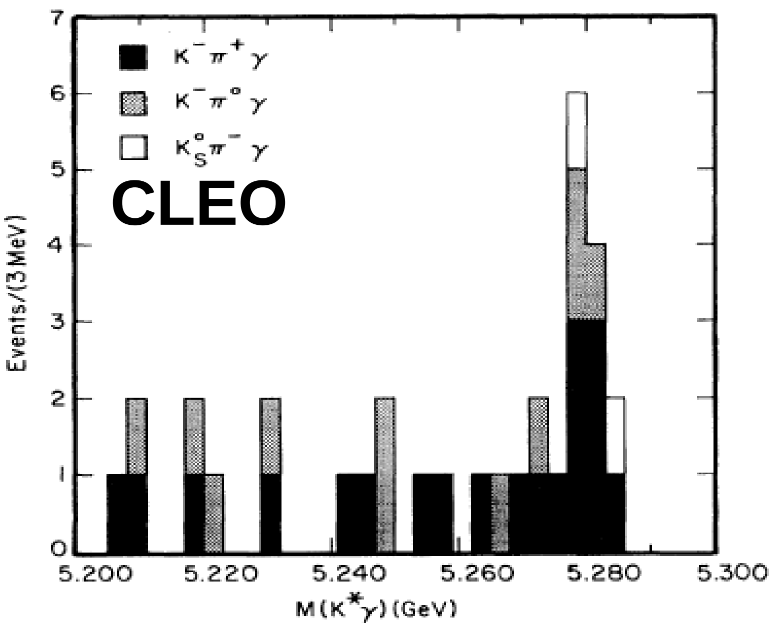
Feynman diagram for $b \to s\gamma / B \to K^* \gamma$

○ $B \to K^* \gamma$ was observed CLEO (1993)

Observation of $K^* \gamma$

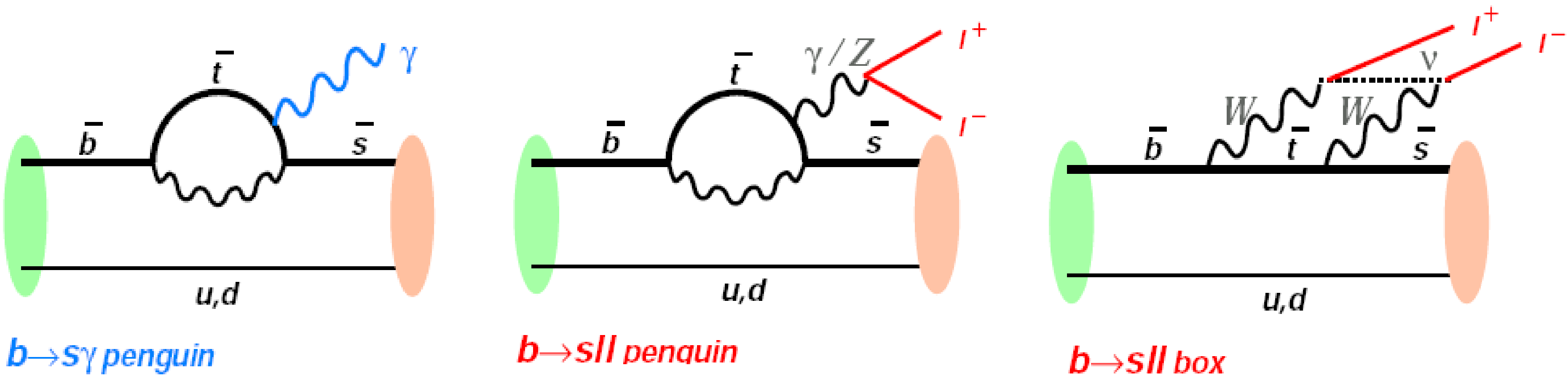
PRL 71, 674 (1993)

(cited more than 500 times !)



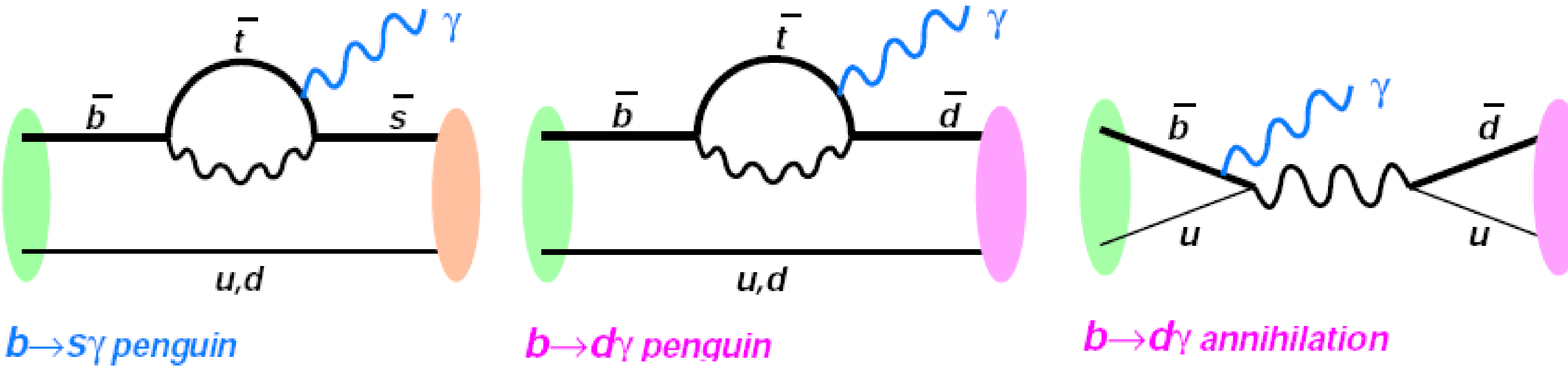
Now with higher luminosity,

We can access further suppressed decays: $b \to s\, l^+ l^-$



- $b \to s\, l^+ l^-$ suppressed by α
- Additional contribution from BOX diagram

$b \to d\,\gamma$



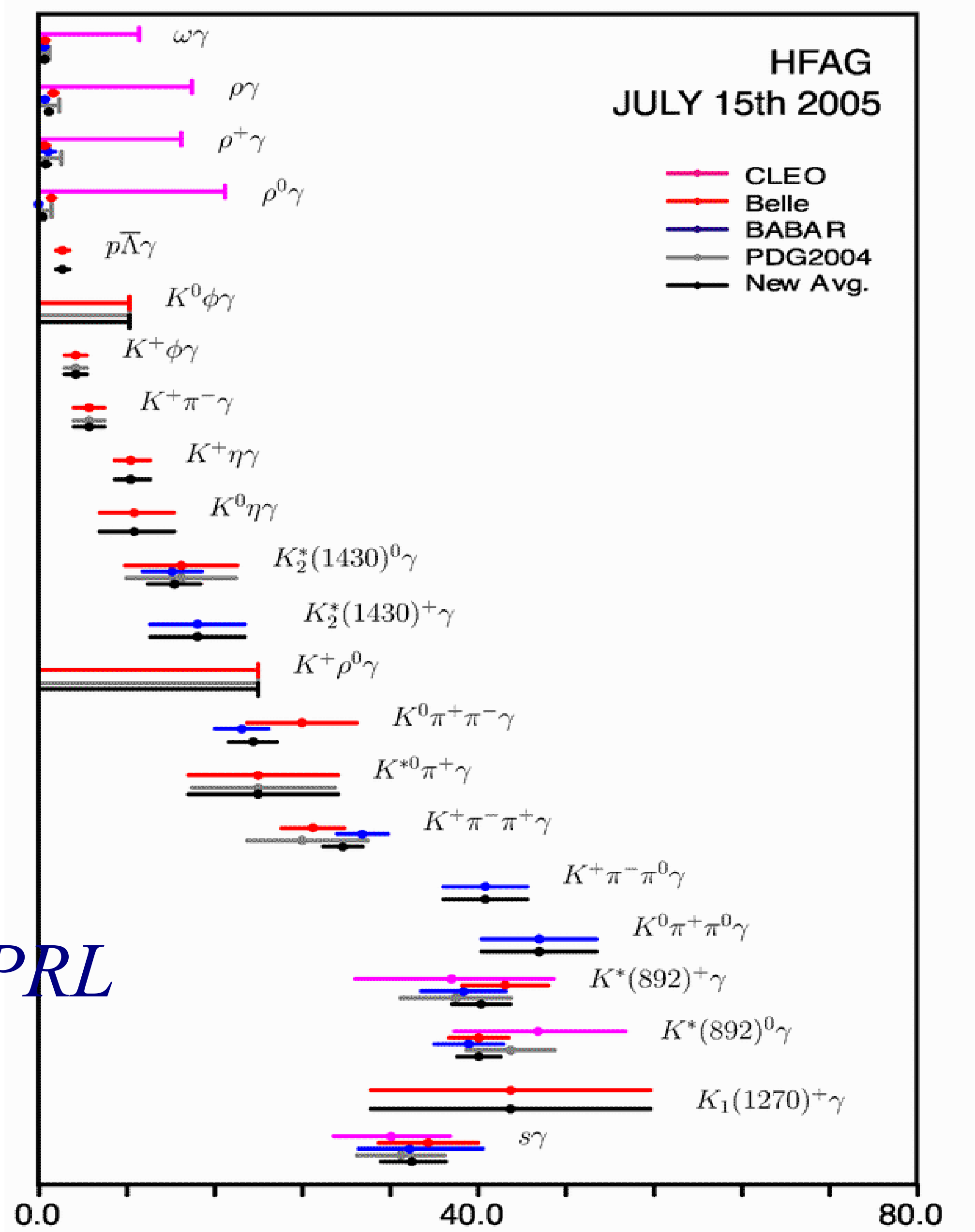
- $b \to d\,\gamma$ suppressed by $\left|V_{td}/V_{ts}\right|^2$
- Annihilation contributes to $B^- \to \rho^- \gamma$

Dedicated programs for radiative decays at Belle and BaBar

- *Inclusive* $b \to s\gamma$
- $B \to K^{*}\gamma$
- $B \to K_{2}^{*}\gamma$, $B \to K_{1}(1270)\gamma$
- $B \to K\phi\gamma$, $B \to K\eta\gamma$
- $B \to p\bar{\Lambda}\gamma$ *and more ...*

- $B \to \rho\gamma$ *and* $B \to \omega\gamma$

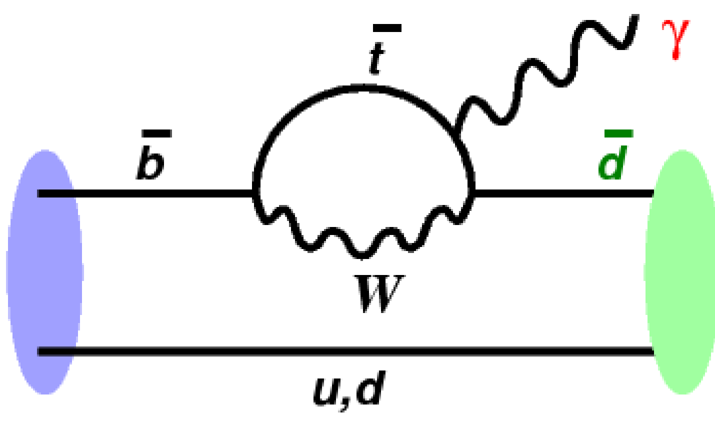
(First observation by Belle)
hep-ex/0506079 submitted to PRL



Introduction

Major roles of $b \to d\gamma$: ΔM_s of B -factories

- *Sensitive to* $|V_{td}/V_{ts}|^2$
- *CP violation as large as 10% is expected*



$b \to d\gamma$ penguin

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

- *Inclusive* $b \to d\gamma$ *with luminosity* $> 1\,ab^{-1}$
- *Exclusive decays* $B \to \rho\gamma$ *and* $B \to \omega\gamma$ *are now accessible*

Exclusive decays: $B \to \rho\gamma$ *and* $B \to \omega\gamma$

- *Branching fraction* $\sim 10^{-6}$ *(theory)*
- $\dfrac{B \to \rho(\omega)\gamma}{B \to K^{*}\gamma}$ *can be used to measure* $\left|\dfrac{V_{td}}{V_{ts}}\right|$

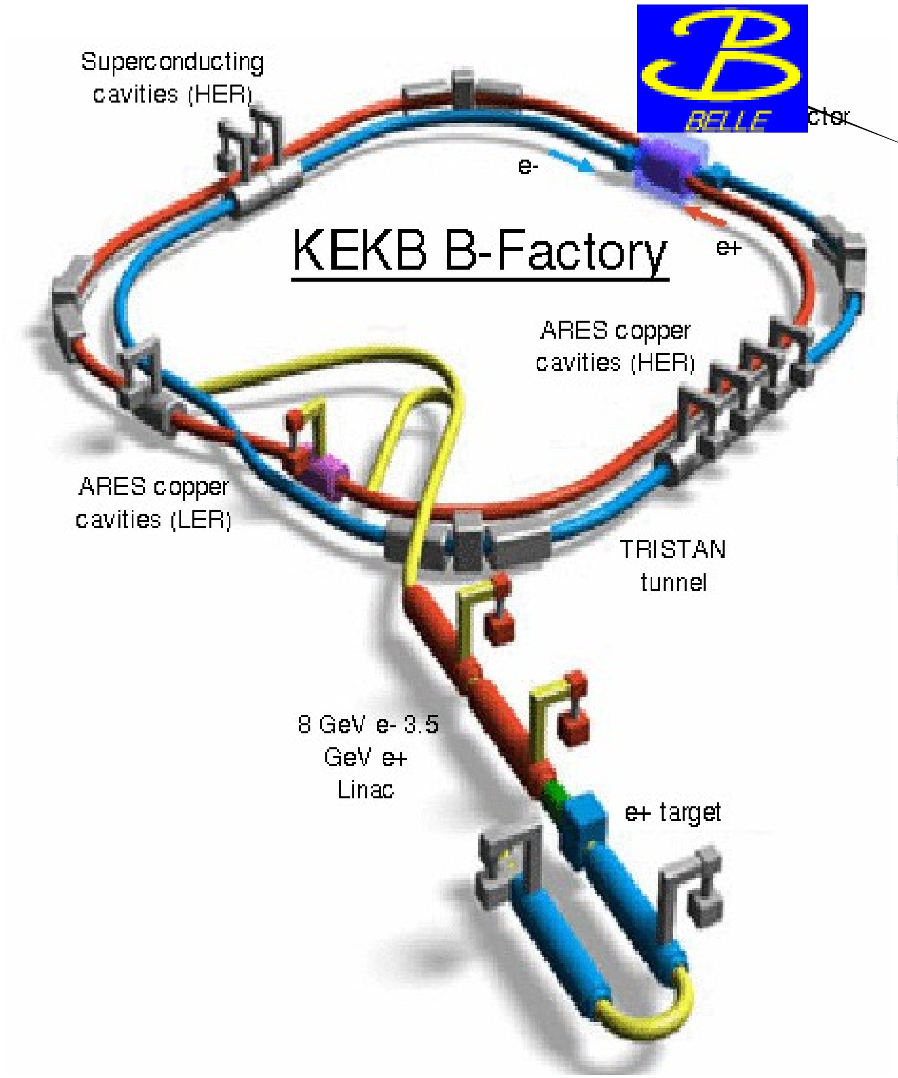
$$\frac{B(\overline{B} \to (\rho, \omega)\gamma)}{B(B \to K^{*}\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - M_{\rho}^2 / M_B^2}{1 - M_{K^*}^2 / M_B^2}\right) \zeta^2 [1 + \Delta R]$$

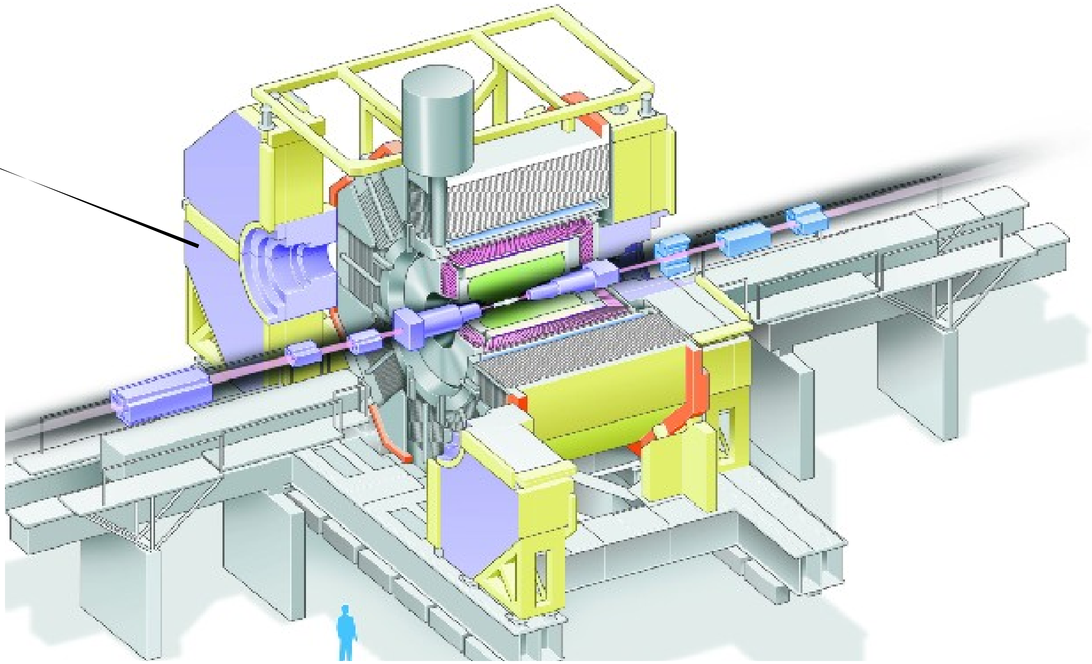
Form factor ratio $\zeta = 0.85 \pm 0.10$

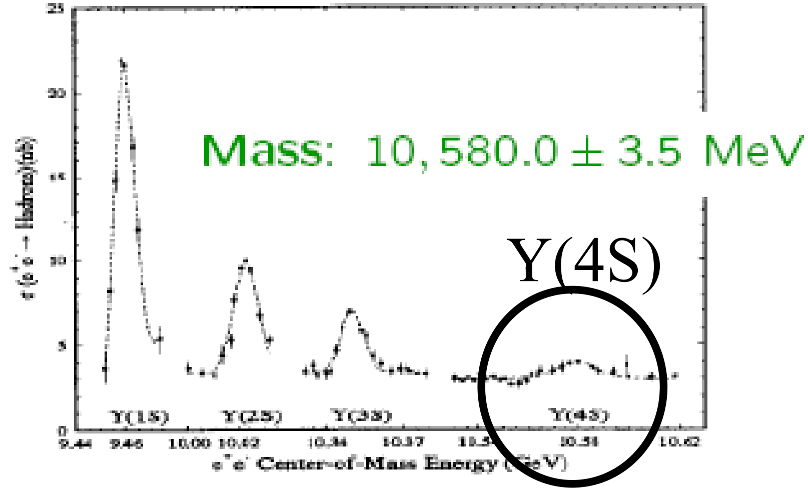
SU(3)-breaking effect $\Delta R = 0.1 \pm 0.1$

KEKB and Belle Detector

KEKB electron-positron collider (8 Gev on 3.5 GeV)

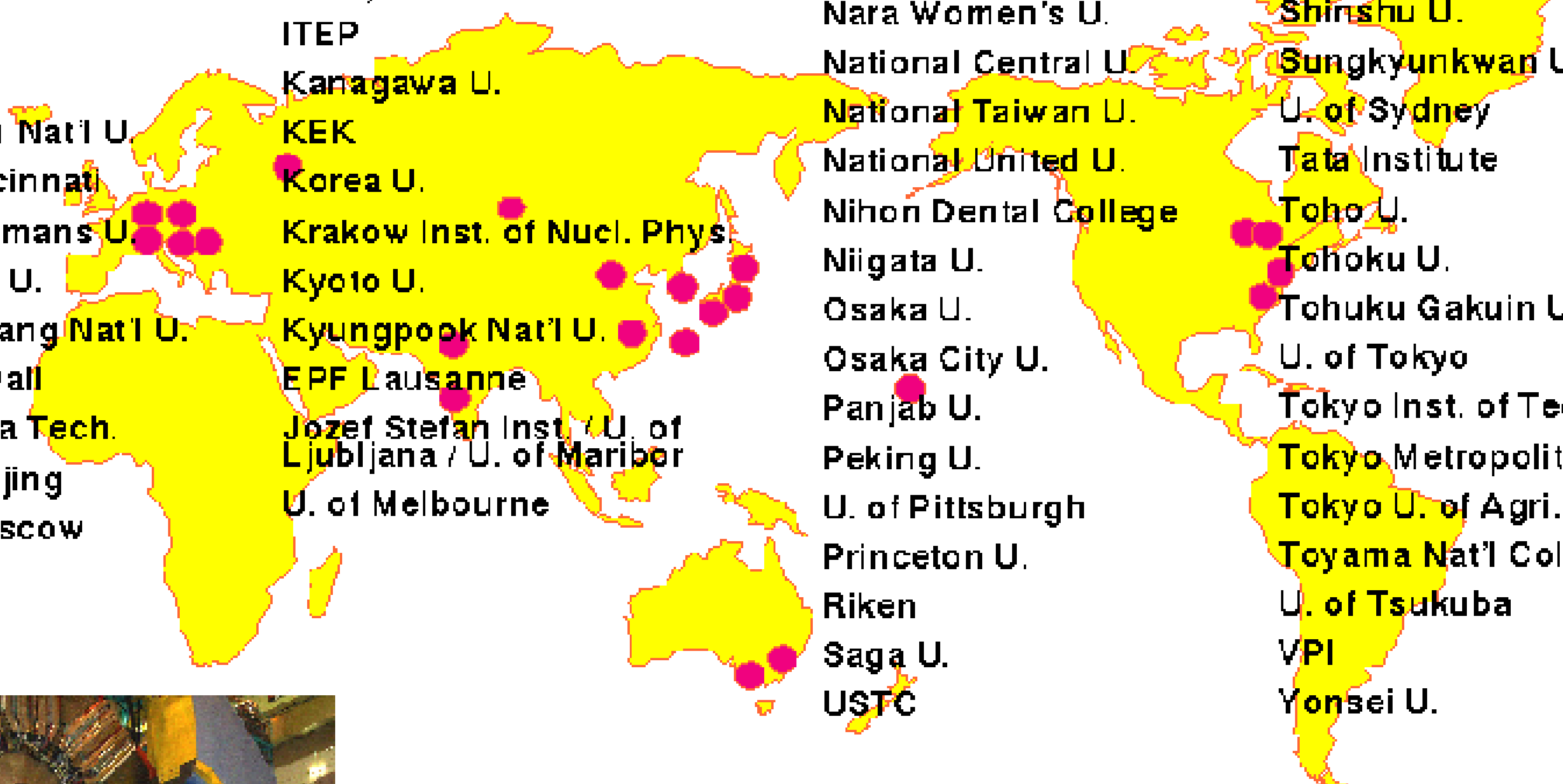






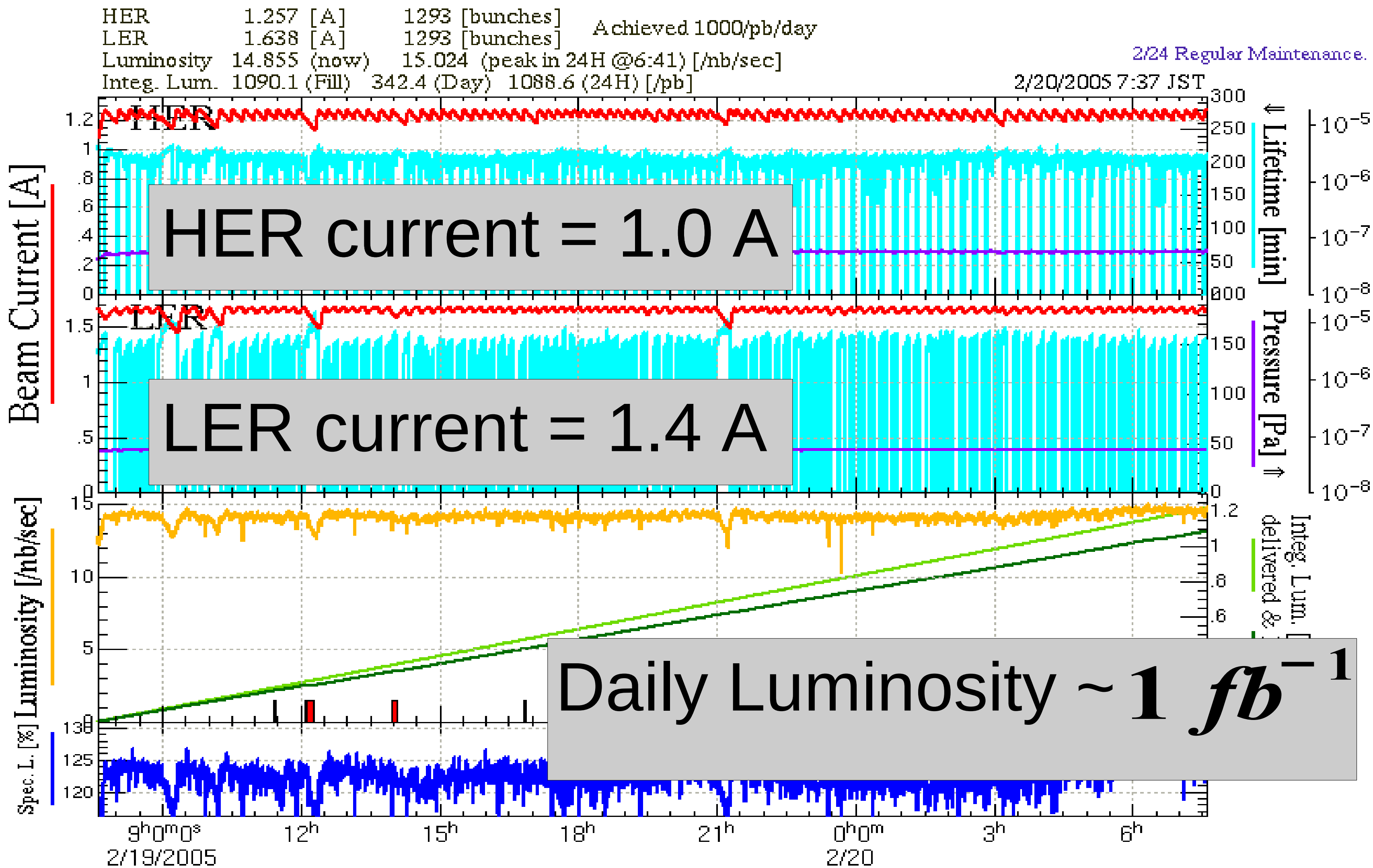
International Collaboration: Belle

Aomori U.
BINP
Chiba U.
Chonnam Nat'l U.
U. of Cincinnati
Ewha Womans U.
Frankfurt U.
Gyeongsang Nat'l U.
U. of Hawaii
Hiroshima Tech.
IHEP, Beijing
IHEP, Moscow
IHEP, Vienna
ITEP
Kanagawa U.
KEK
Korea U.
Krakow Inst. of Nucl. Phys.
Kyoto U.
Kyungpook Nat'l U.
EPF Lausanne
Jozef Stefan Inst. / U. of Ljubljana / U. of Maribor
U. of Melbourne
Nagoya U.
Nara Women's U.
National Central U.
National Taiwan U.
National United U.
Nihon Dental College
Niigata U.
Osaka U.
Osaka City U.
Panjab U.
Peking U.
U. of Pittsburgh
Princeton U.
Riken
Saga U.
USTC
Seoul National U.
Shinshu U.
Sungkyunkwan U.
U. of Sydney
Tata Institute
Toho U.
Tohoku U.
Tohuku Gakuin U.
U. of Tokyo
Tokyo Inst. of Tech.
Tokyo Metropolitan U.
Tokyo U. of Agri. and Tech.
Toyama Nat'l College
U. of Tsukuba
VPI
Yonsei U.



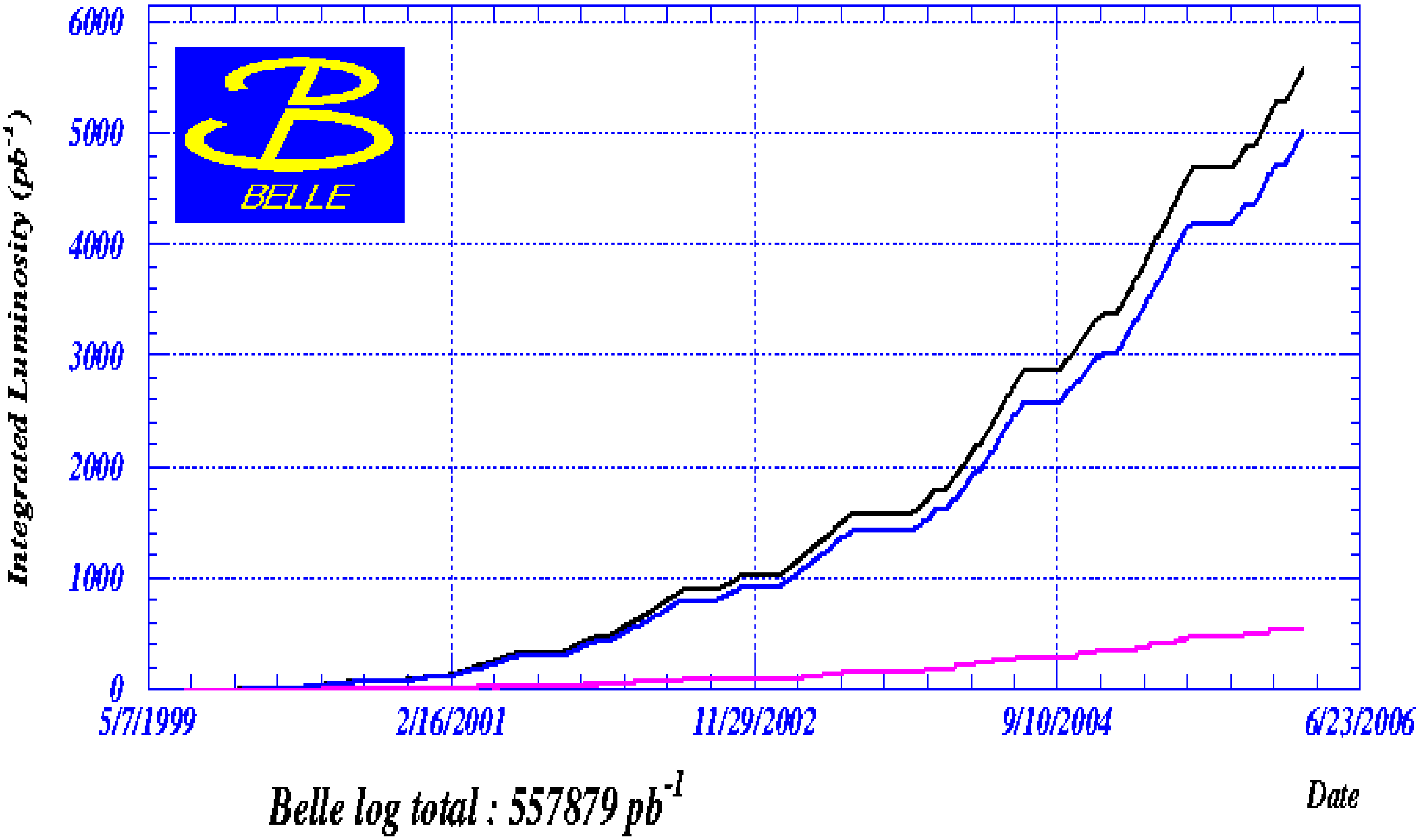
13 countries, 55 institutes, ~400 collaborators

KEKB performance has been excellent with many luminosity records



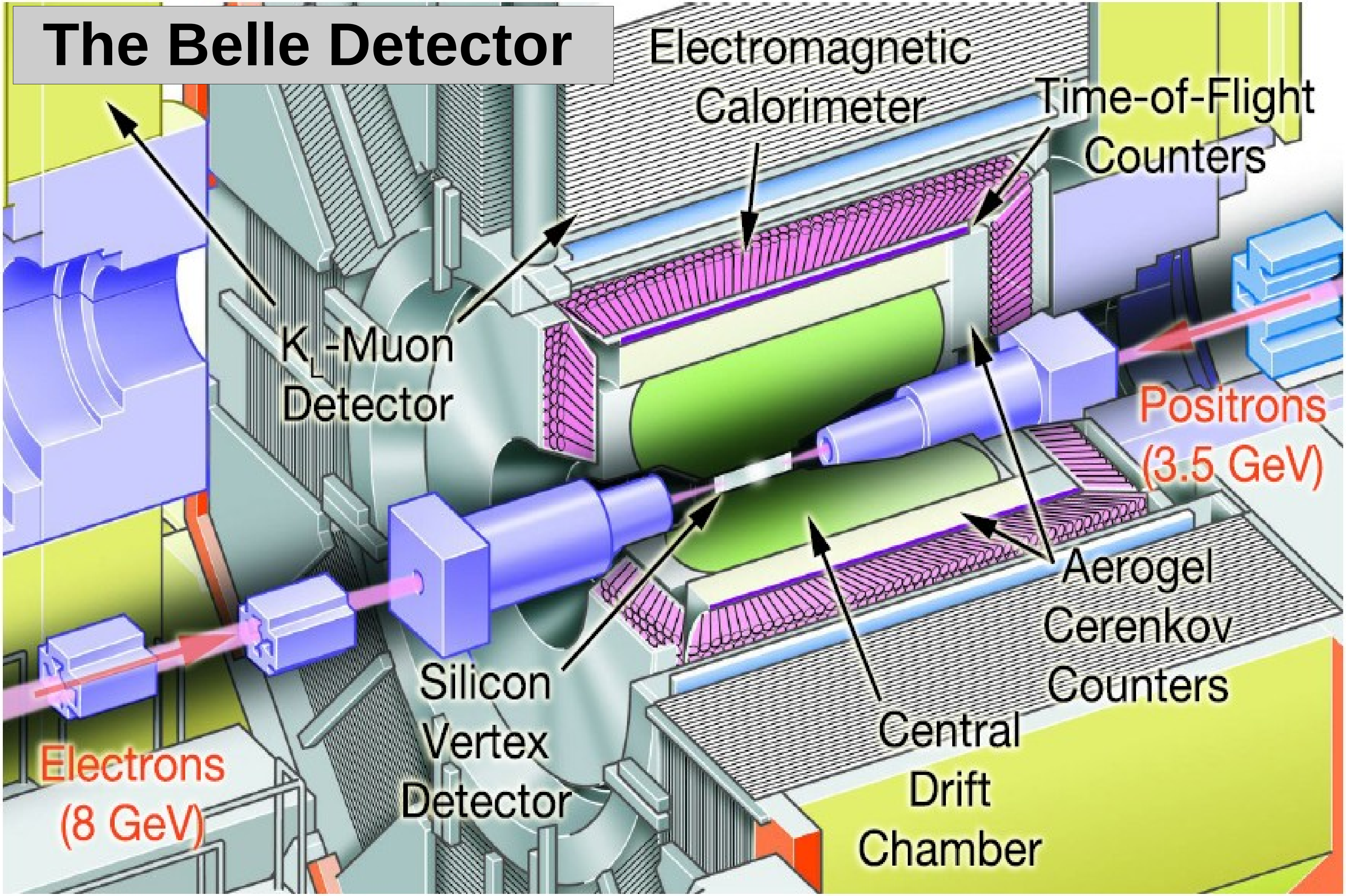
Integrated Luminosity: ~560 fb^{-1}

A subset of data sample is analyzed for summer 2005



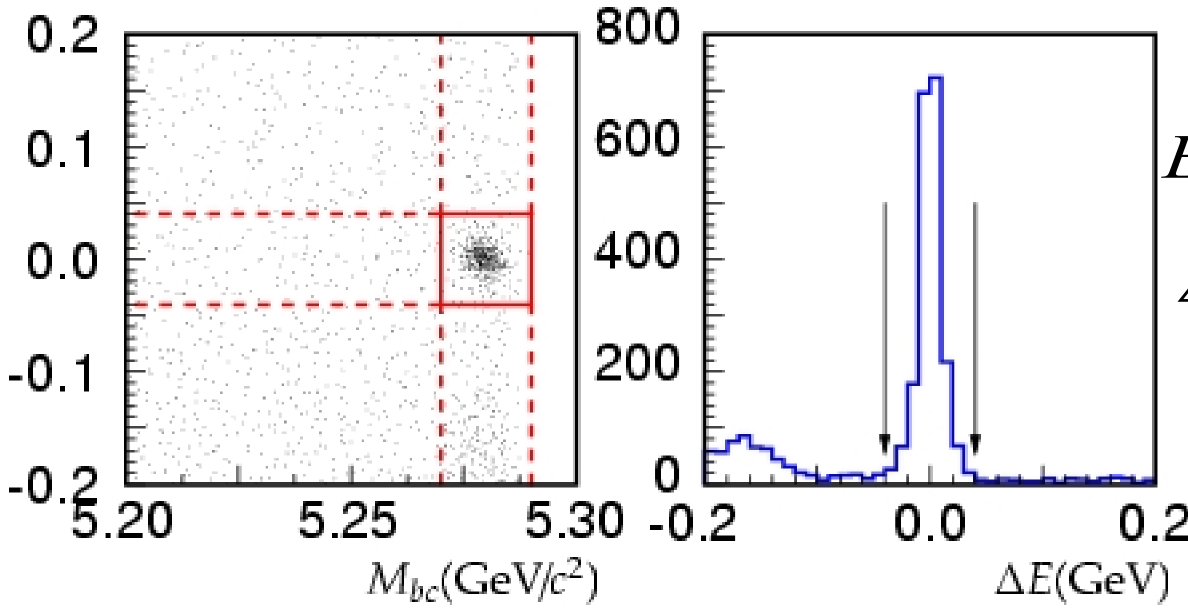
Data set used: $357\ fb^{-1} \equiv 386 \times 10^6\ B\overline{B}$

Aerogel based PID system plays an important role in background reduction



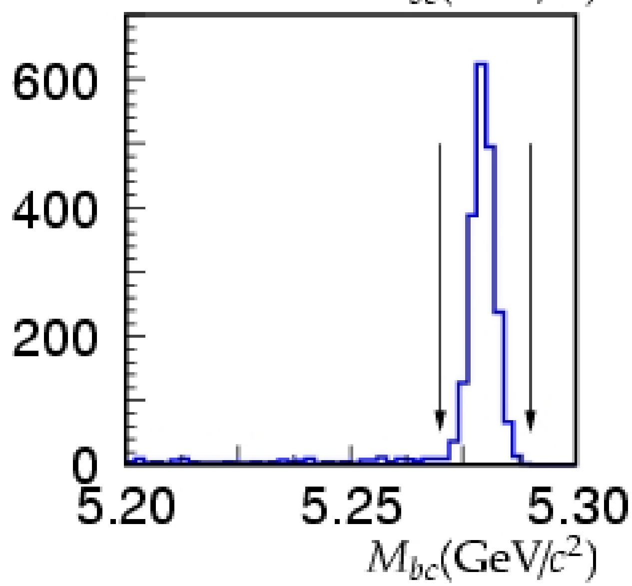
Reconstruction of B

B-meson Reconstruction: Kinematic variables



Energy difference:

$$\Delta E \equiv \sum E_i - E_{CM}/2$$

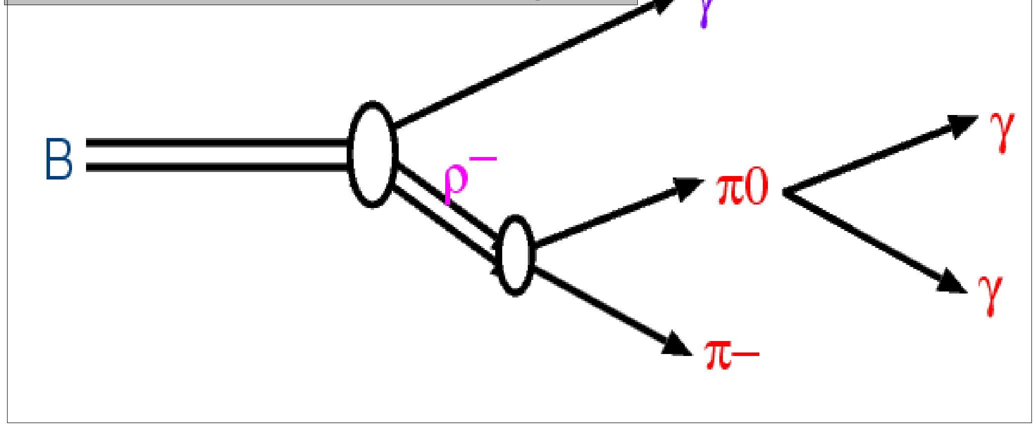


Beam-constrained mass:

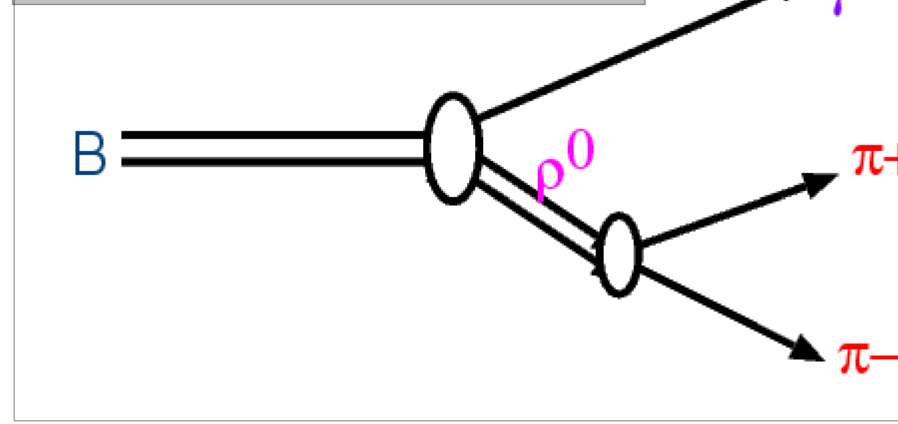
$$M_{bc} = \sqrt{(E_{CM}/2)^2 - (\sum \vec{p}_i)^2}$$

B-meson reconstruction in $b \to d\gamma$

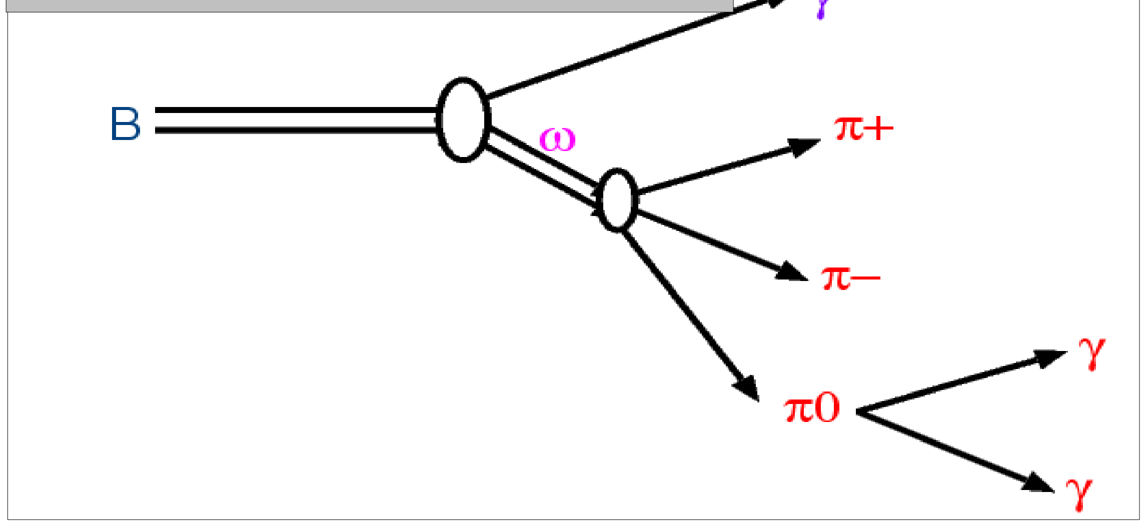
$B^- \to \rho^-(\pi^0, \pi^-)\gamma$



$B^0 \to \rho^0(\pi^+, \pi^-)\gamma$



$B^0 \to \omega(\pi^+, \pi^-, \pi^0)\gamma$



B-meson reconstruction; cont' d

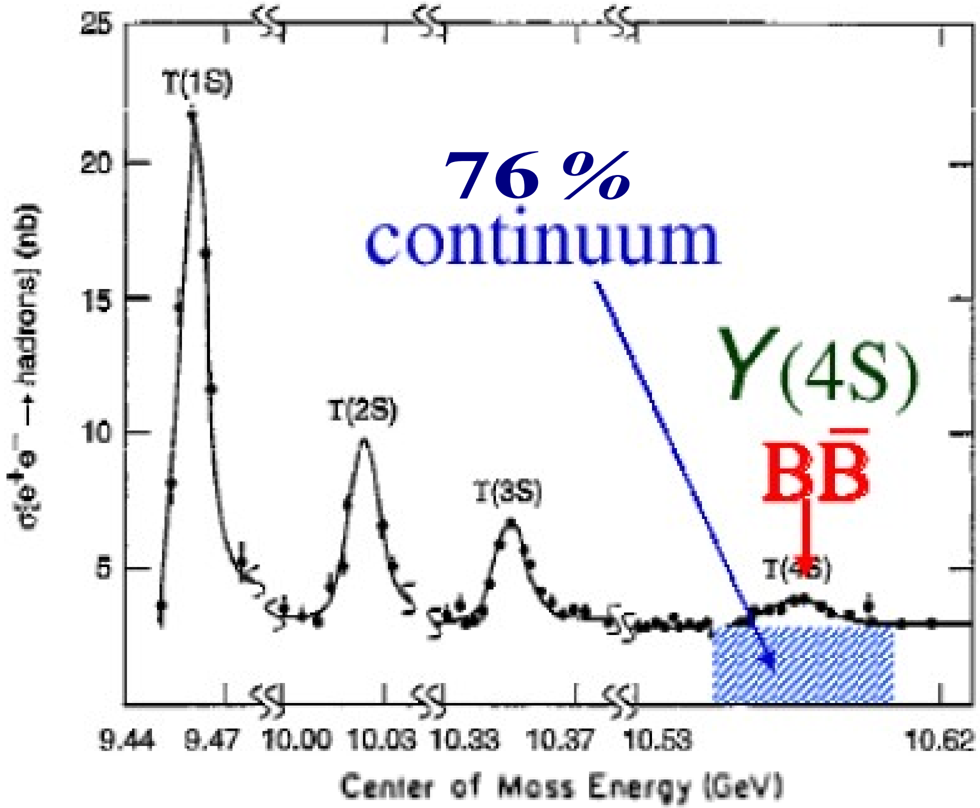
Photon selection	$1.8\,GeV < E^*_\gamma < 3.4\,GeV$ & $33^o < \theta_\gamma < 128^o$ *Electromagnetic shower shape* π^0 & η *veto based on likelihood*
Neutral pion selection $\pi^0 \to \gamma\gamma$	$E_\gamma > 50(100)\,MeV$ *for barrel (endcap)* $\cos\theta_{\gamma_1,\gamma_2} > 0.7$ $118\,MeV < M_{\gamma,\gamma} < 150\,MeV$
Reconstruction of ρ & ω $\rho^- \to \pi\pi$ $\omega \to \pi\pi\pi^0$	*Tracks close to IP* $(dr < 0.5\,cm\,\&\,\lvert dz\rvert < 3\,cm)$ & *tracks from* K_s *are removed* $\frac{L_K}{L_K + L_\pi} < 0.15$ & $0.620\,GeV < M_\rho < 0.920\,GeV$ $\frac{L_K}{L_K + L_\pi} < 0.40$ & $0.752\,GeV < M_\omega < 0.812\,GeV$
Reconstruction of B *Beam const. mass* *Energy difference*	$B^- \to \rho^-\gamma$, $\overline{B^0} \to \rho^0\gamma$ & $\overline{B^0} \to \omega\gamma$ $5.2\,GeV < M_{bc} < 5.3\,GeV$, $M_{bc} = \sqrt{E^{*2}_{beam} - P^{*2}_B}$ $\lvert\Delta E\rvert < 0.5\,GeV$, $\Delta E = E^*_{\rho,\omega} + E^*_\gamma - E^*_B$

Background suppression

$b \to d\gamma$ modes are highly background dominated

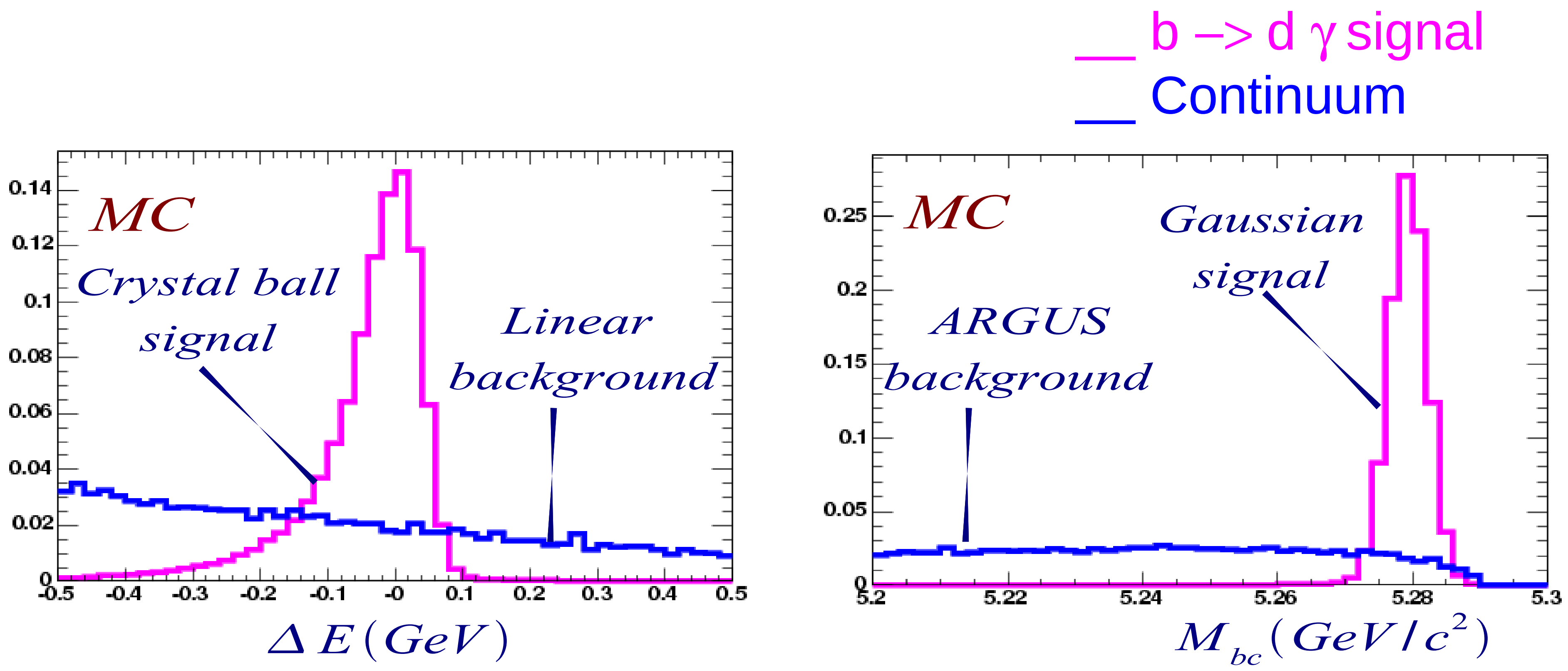
- Continuum: $e^+e^- \to q\bar{q},\ q = u, d, s, c$
- $B \to K^*\gamma$
- other $b \to s\gamma$ modes
- $B \to \rho\pi^0(\eta),\ B \to \omega\pi^0(\eta)$
- and other charmless rare B modes

Huge Continuum background under the Y(4S)

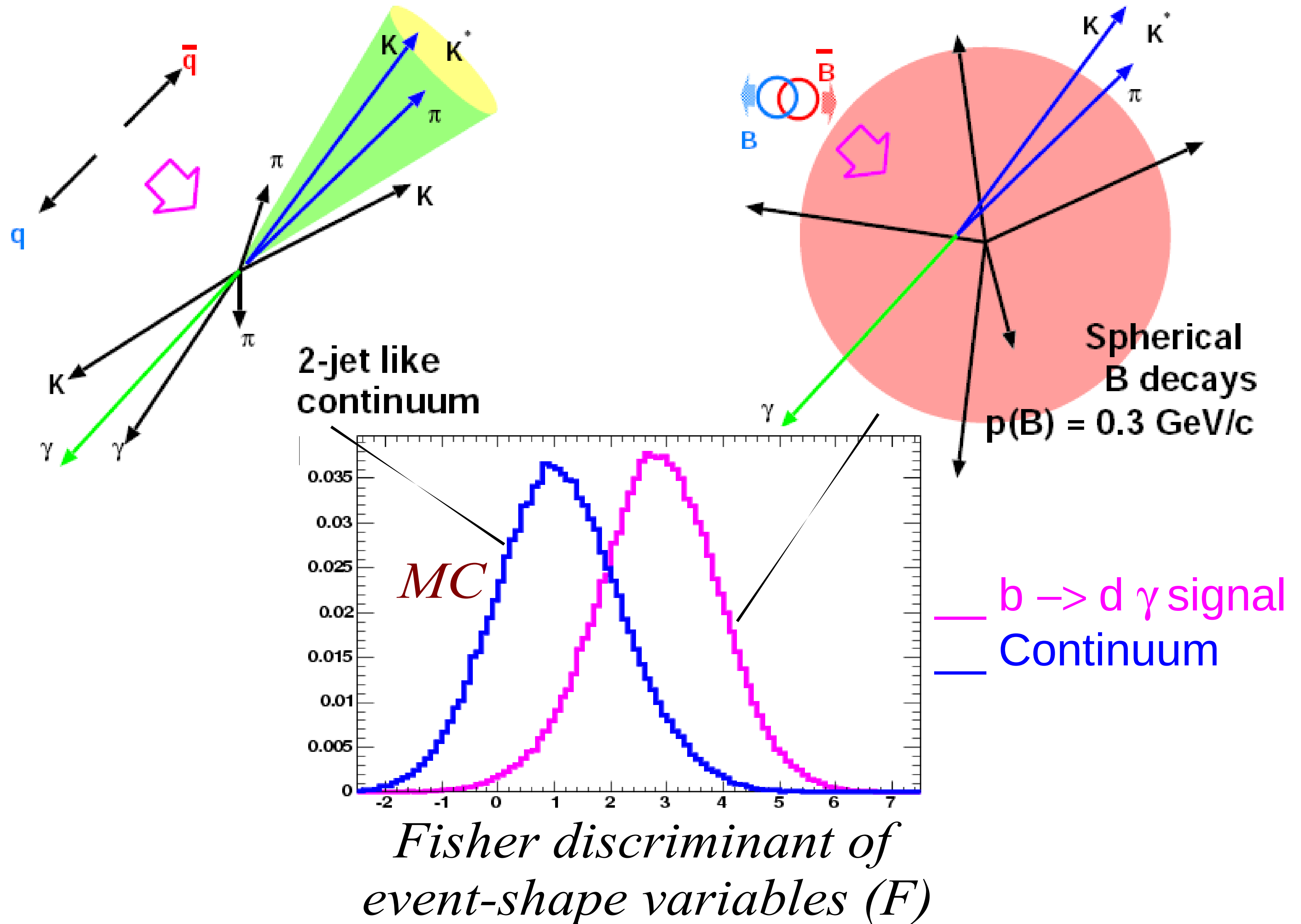


$$Continuum:\ e^+ e^- \rightarrow q\,\overline{q}\ (q = u, d, s, c)$$

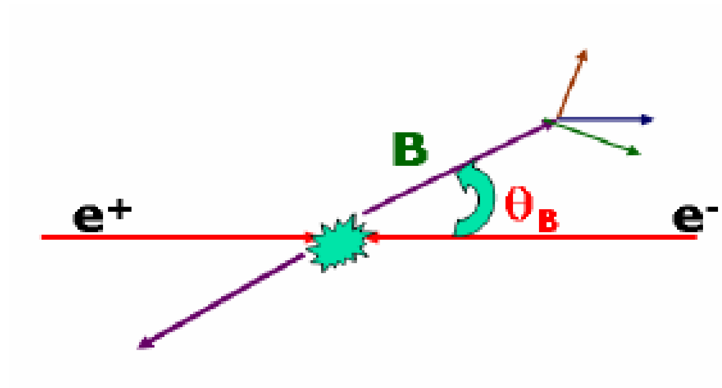
Signal and Continuum background shapes

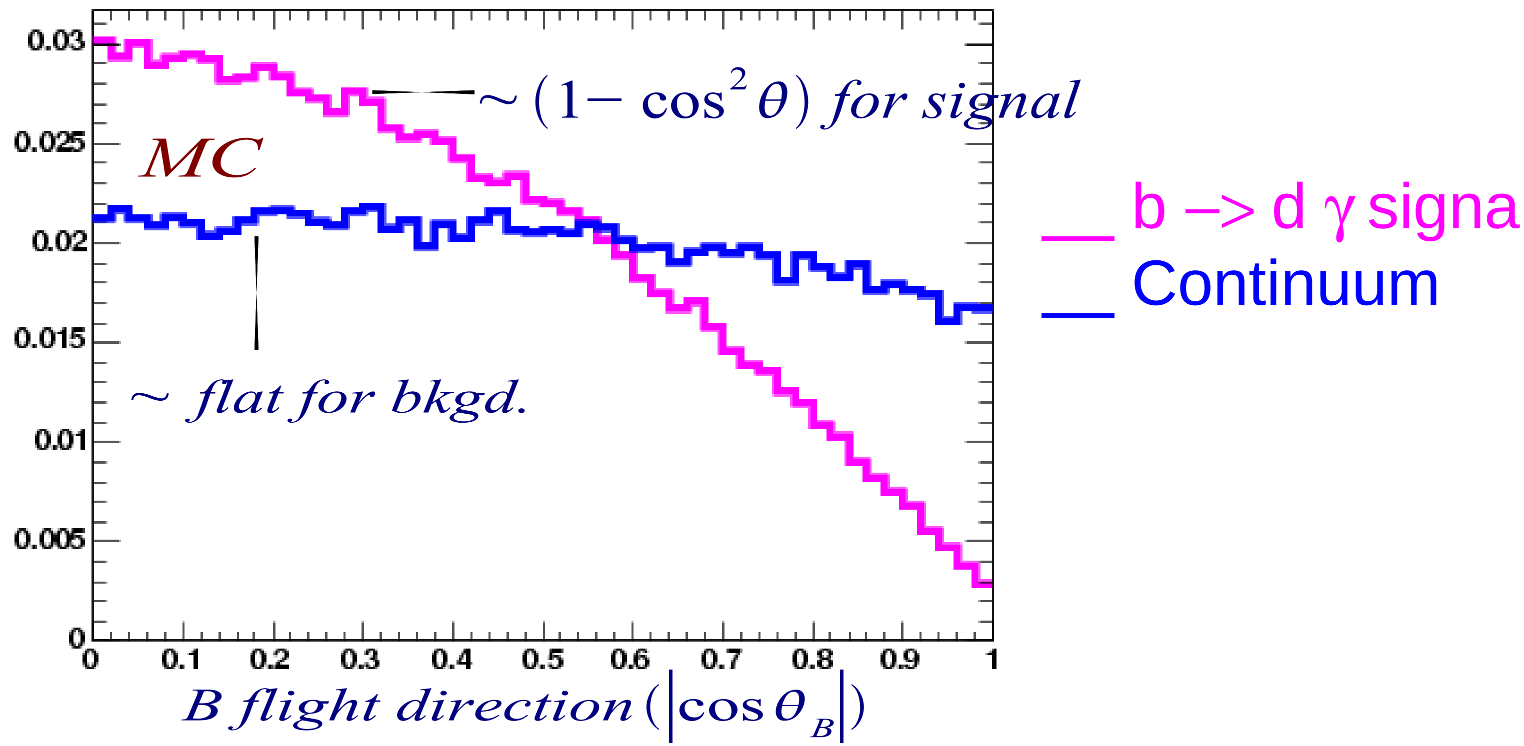


Fisher discriminant of event-shape variables is used to separate spherical B decays from jet-like continuum

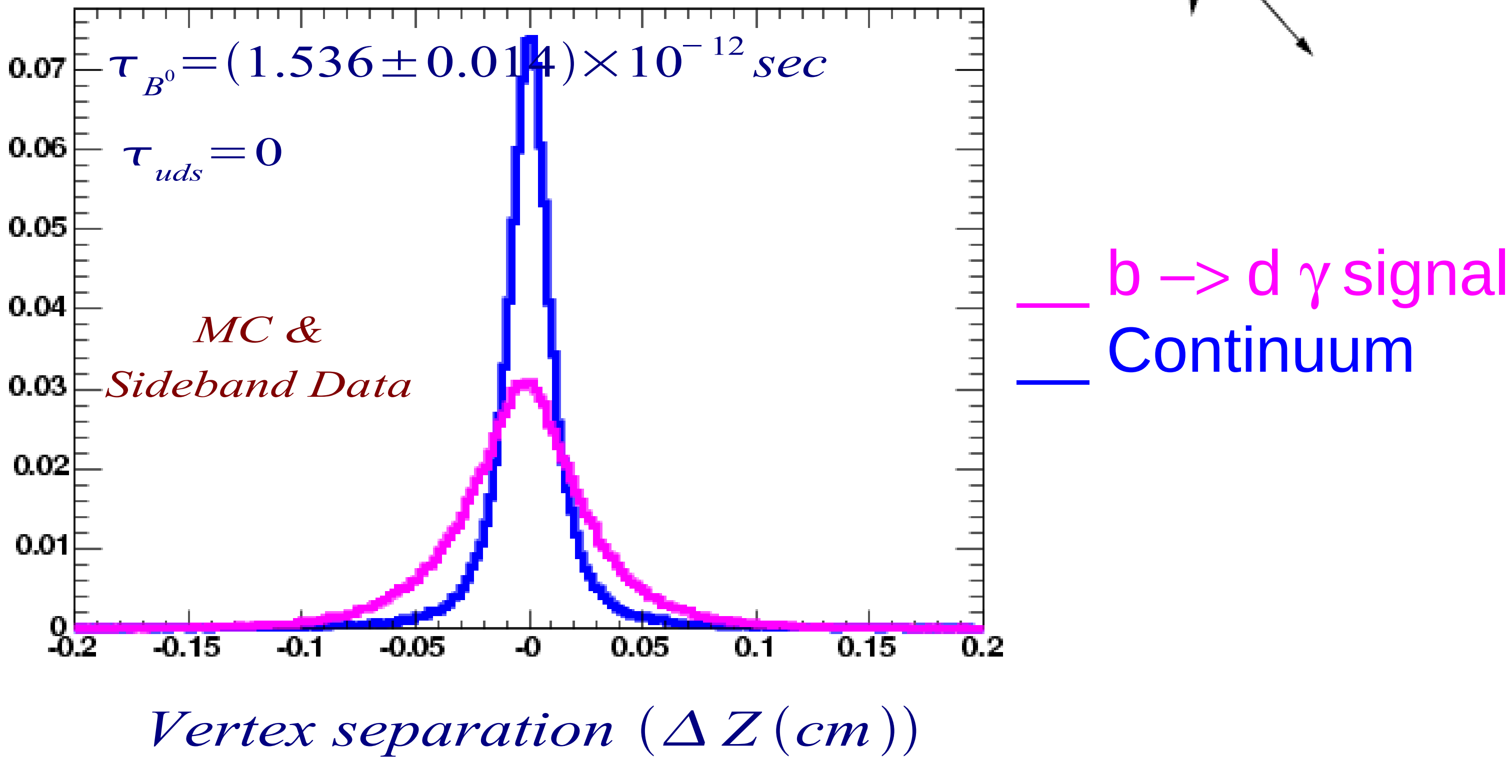


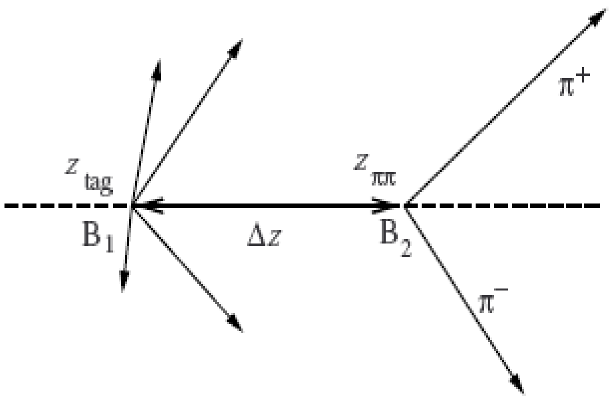
B flight direction in CM frame also discriminates B events from that of continuum





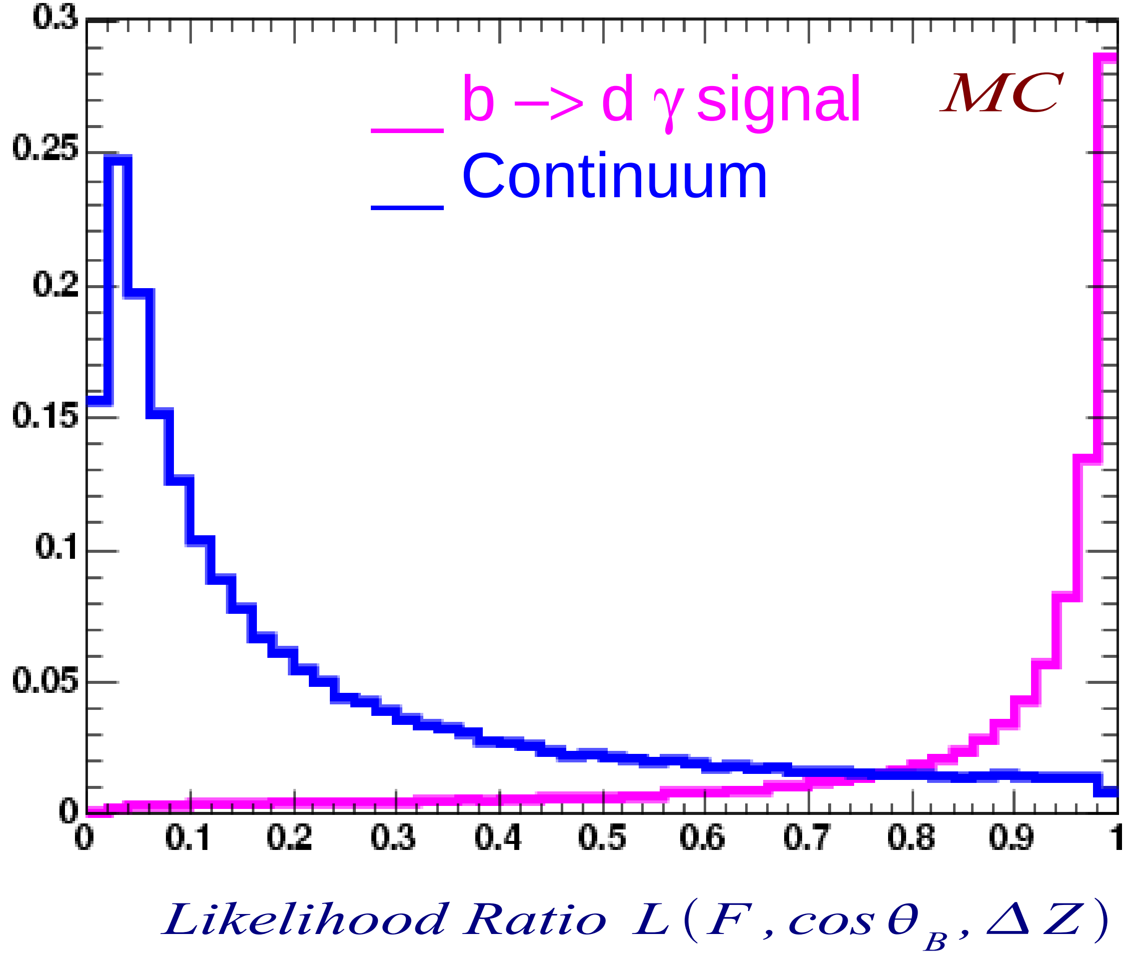
The vertex separation variable is introduced in $b \to d\gamma$ analysis for continuum suppression



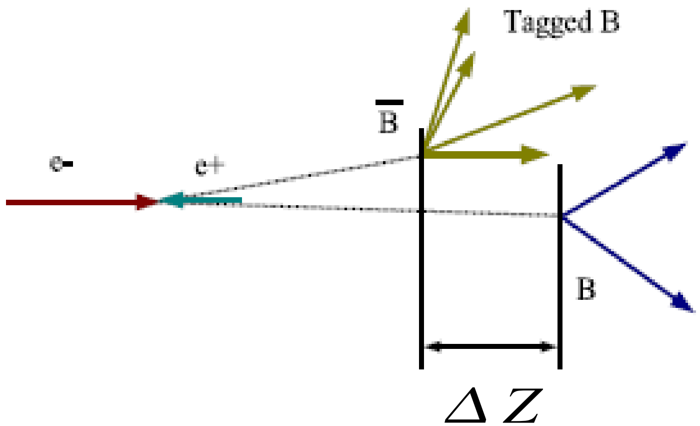


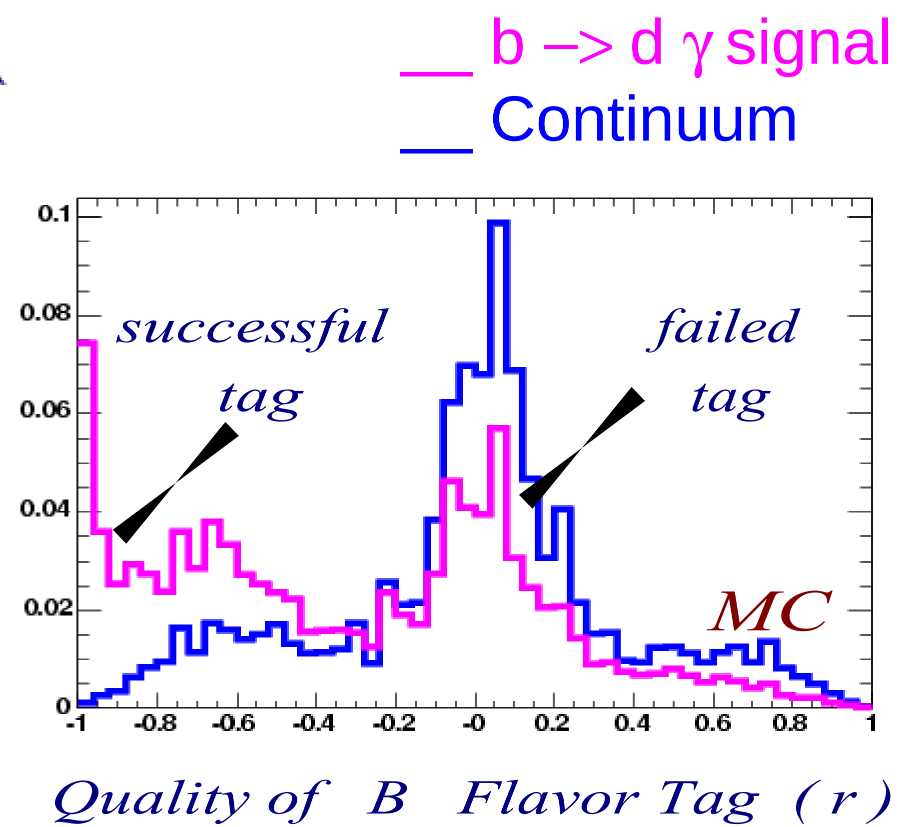
Two vertices are reconstructed in 80% of $b \to d\gamma$ events

Using Fisher discriminant, B flight direction and Vertex separation, a Likelihood Ratio is formed.

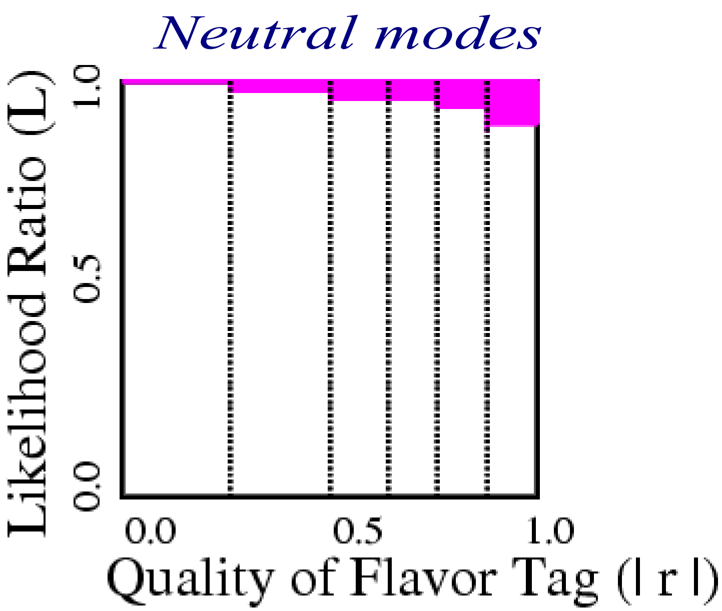


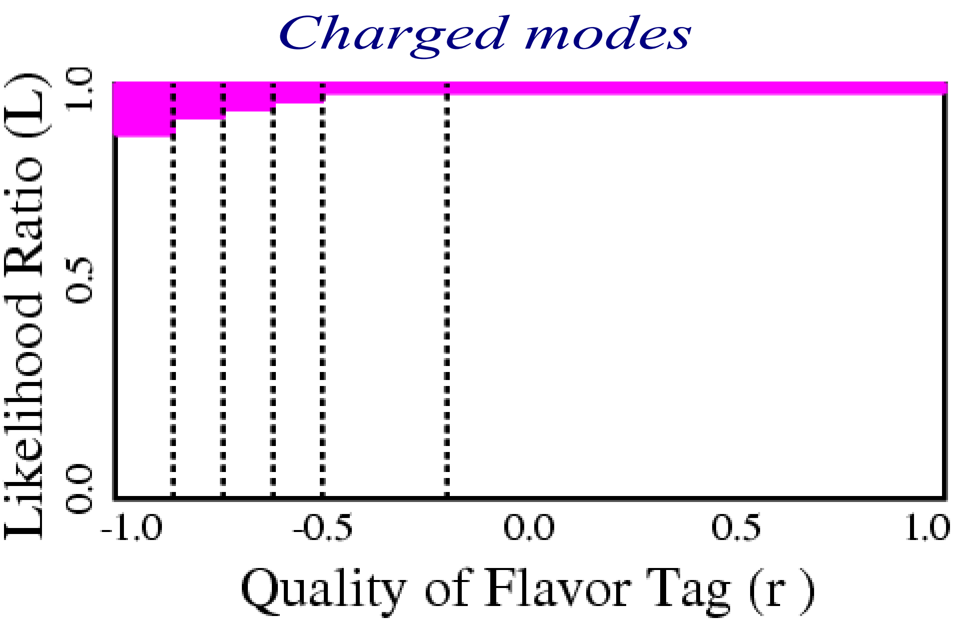
Additional discrimination is gained from "Quality of B Flavor Tag"





~ 95 % of Continuum background is rejected by a cut on likelihood ratio vs. flavor tag





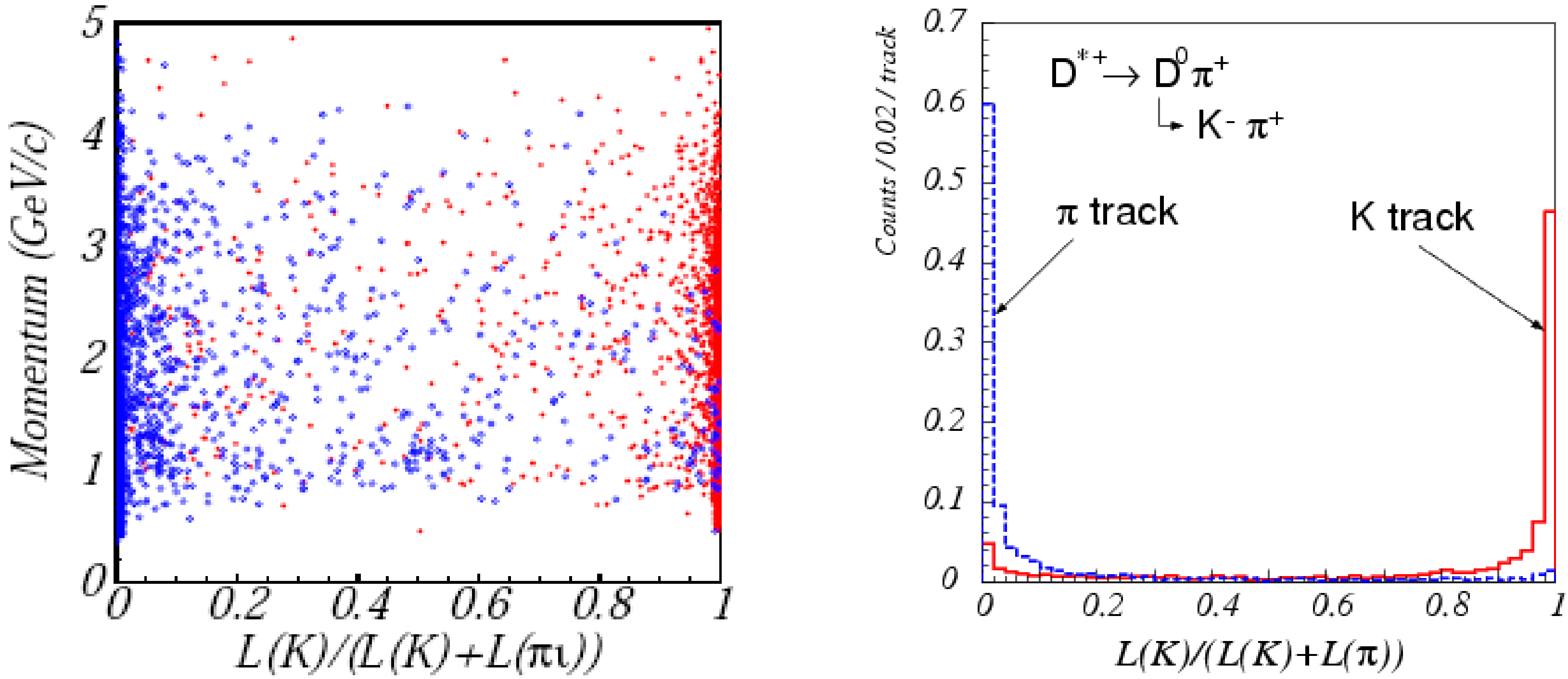
Neutral modes $\Rightarrow$ *cut in* $|r|$*-L*

Charged modes $\Rightarrow$ *cut in r-L*

Multidimensional scan uniquely determines the best $S/\sqrt{B}$

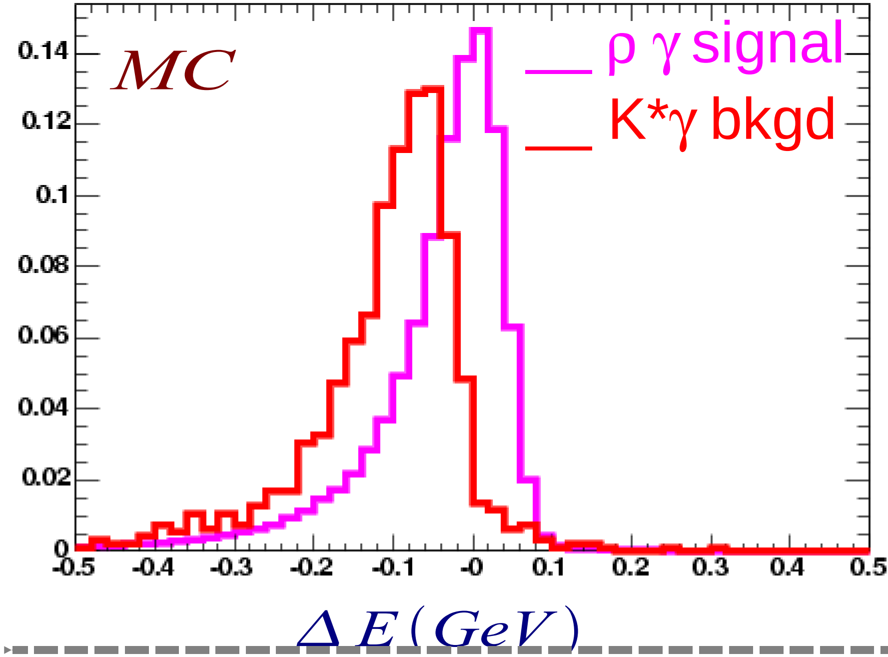
	$\rho^{-}\gamma$	$\rho^{0}\gamma$	$\omega\gamma$
ϵ_{sig}	38%	45%	32%
ϵ_{uds}	4%	8%	3%

$K/\pi -$ *misidentification* $\Rightarrow B \rightarrow K^{*}\gamma$ *background*

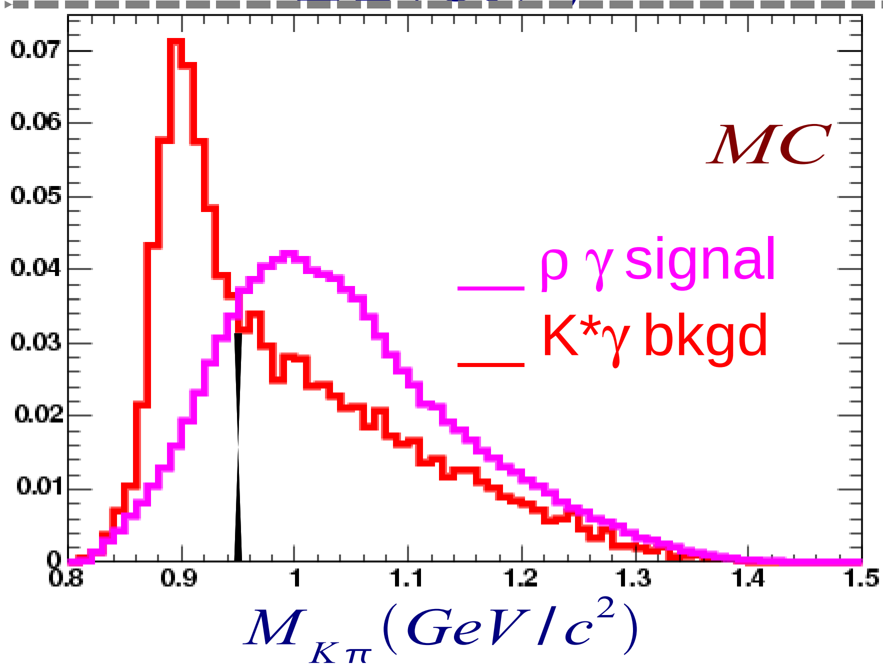


With KID < 0.15 , K/π fake rate ~ 5-10 %

Rejection of $B \to K^* \gamma$ events that failed the particle ID cut



The $K^* \gamma$ events peak at ~ -100 MeV and overlap with $\rho\gamma$ signal

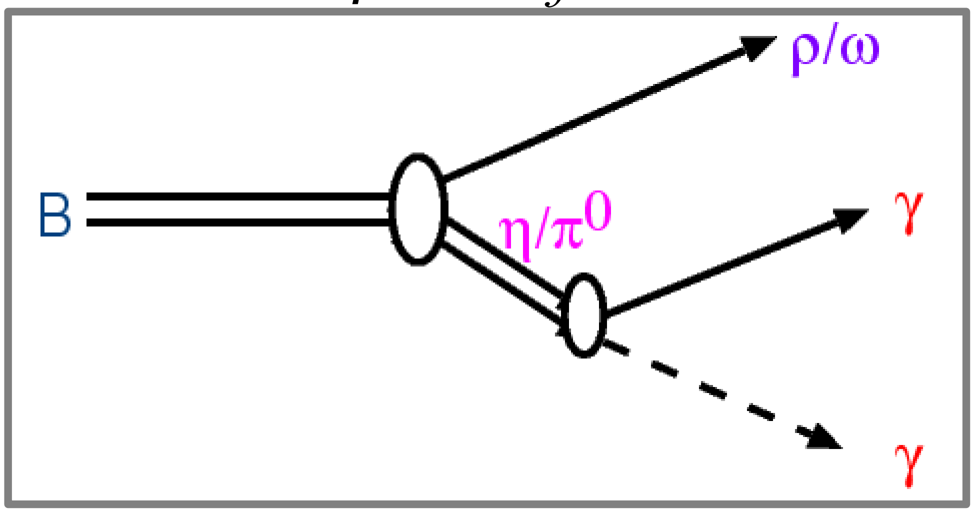


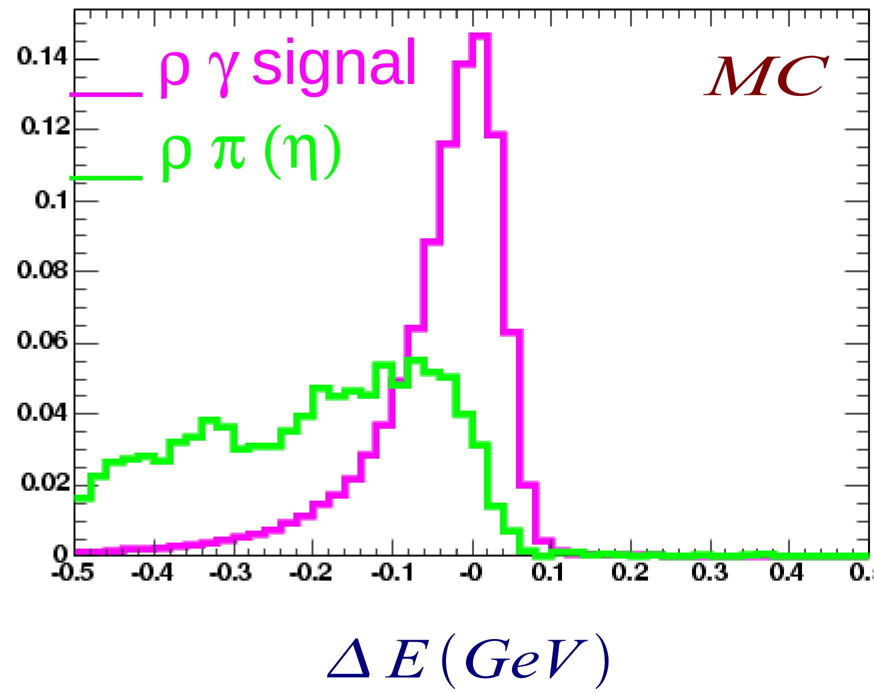
With $M_{K/\pi}$ cut we reject ~80% of $K^* \gamma$ events

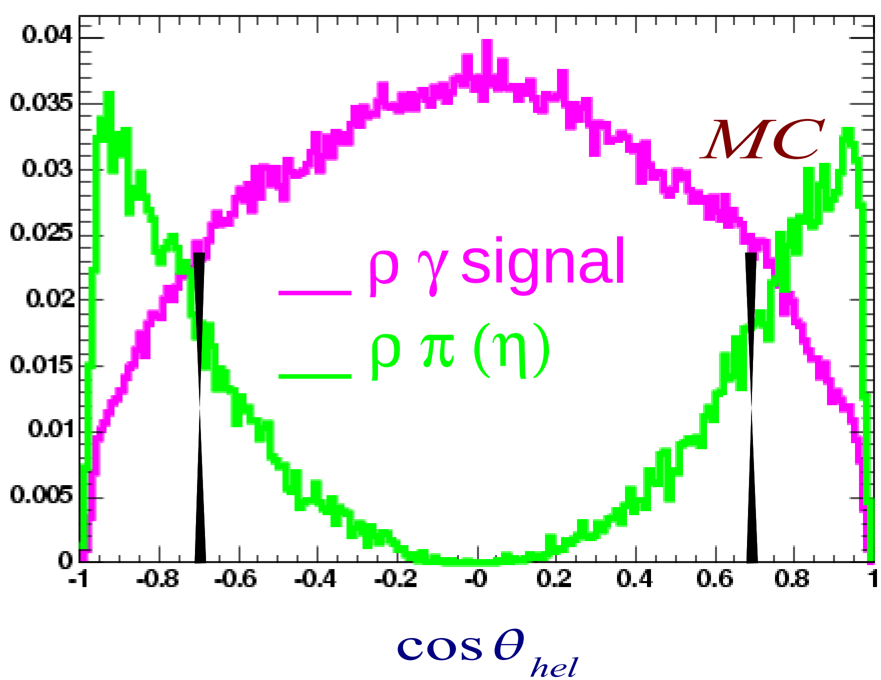
	$\rho^- \gamma$	$\rho^0 \gamma$
ϵ_{sig}	87 %	63 %
$\epsilon_{K^*\gamma}$	36 %	18 %

Asymmetric $\pi^0(\eta)$ *decay (with a missing soft photon)* $\Rightarrow B\to\rho(\omega)\pi^0$ & $B\to\rho(\omega)\eta$ *background*

When $\pi^0/\eta-$ *veto fails*







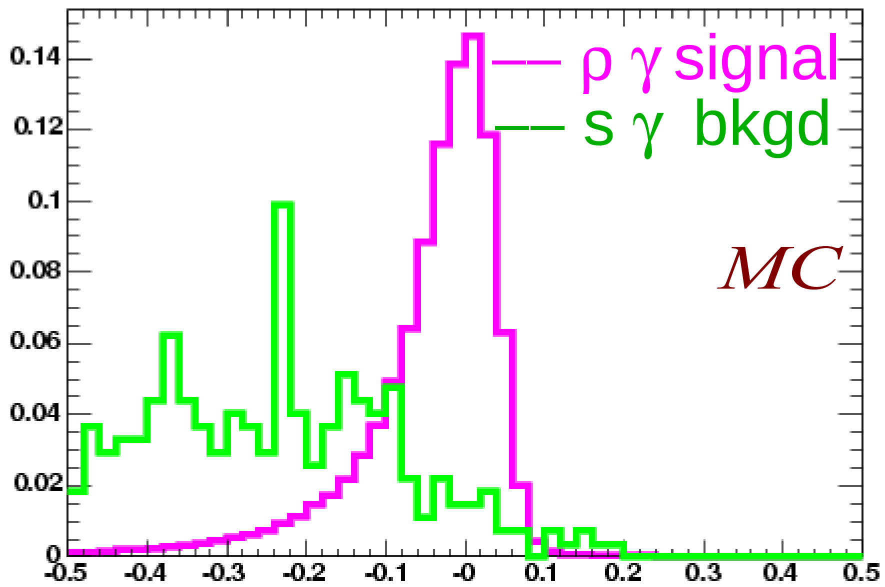
$\cos\theta_{hel}$ *optimized for* $\frac{S}{\sqrt{B}}$

$B^-\to\rho^-\gamma : |\cos\theta_{hel}| < 0.75$

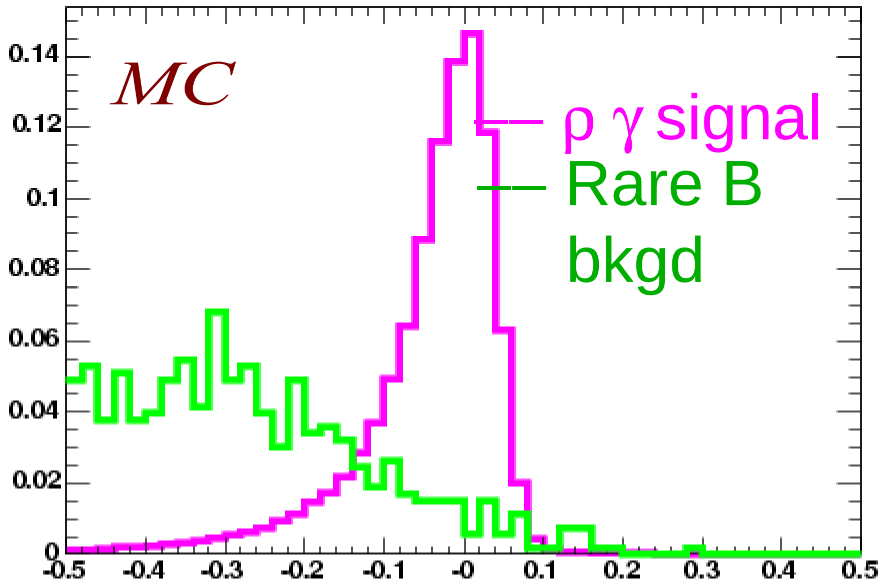
$\overline{B^0}\to\rho^0\gamma : |\cos\theta_{hel}| < 0.70$

$\overline{B^0}\to\omega\gamma : |\cos\theta_{hel}| < 0.8$

$b \to s\gamma$ background other than $B \to K^{*}\gamma$



Charmless rare B background other than $B \to \rho(\omega)\pi^0$ & $B \to \rho(\omega)\eta$



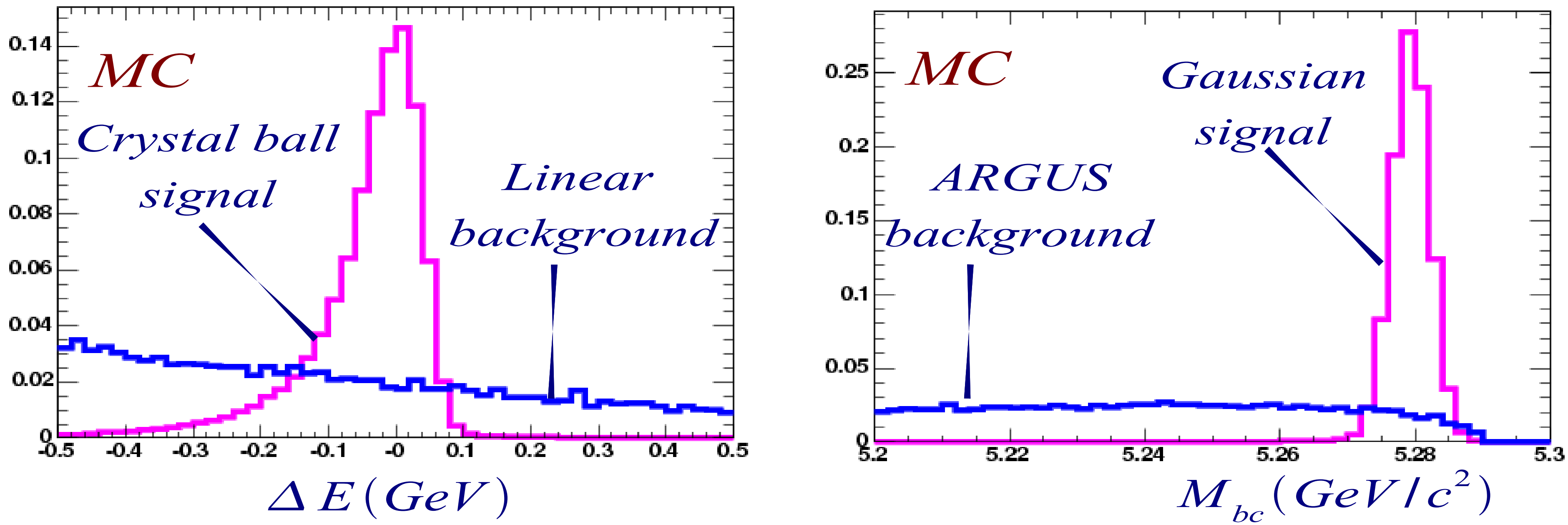
$\Delta E\,(GeV)$

Very small fraction of total background

Signal Extraction & Results

Signal and Continuum background shapes

__ b –> d γ signal
__ Continuum



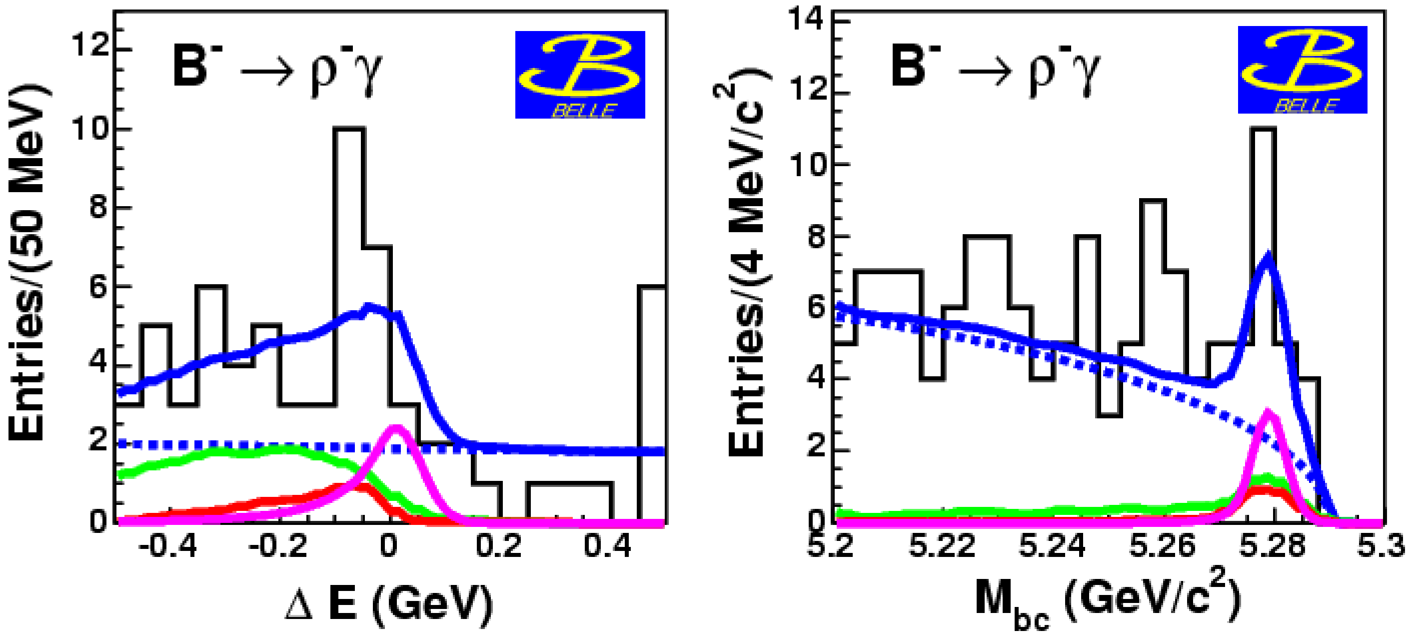
2D unbinned extended maximum likelihood fit is used for signal extraction

1. Shapes of Signal & Background

	M_{bc}	ΔE
$B \to \rho^{-}(\omega)\gamma$	Crystal Ball	Crystal Ball
$B \to \rho^{0}\gamma$	Gaussian	Crystal Ball
Continuum	ARGUS	Linear
$B \to K^{*}\gamma$	2D Histogram	
$B \to (\rho^{-}, \rho^{0}, \omega)\pi^{0}$ & $B \to (\rho^{-}, \rho^{0}, \omega)\eta$	2D Histogram	
$B \to X_{s}\gamma$	2D Histogram	
Charmless Rare B	2D Histogram	

2. Floated parameters: * Shape parameters of continuum background
* Signal and continnum background yields

Fit results: $B \to \rho^- \gamma$ **386 M $B\bar{B}$**



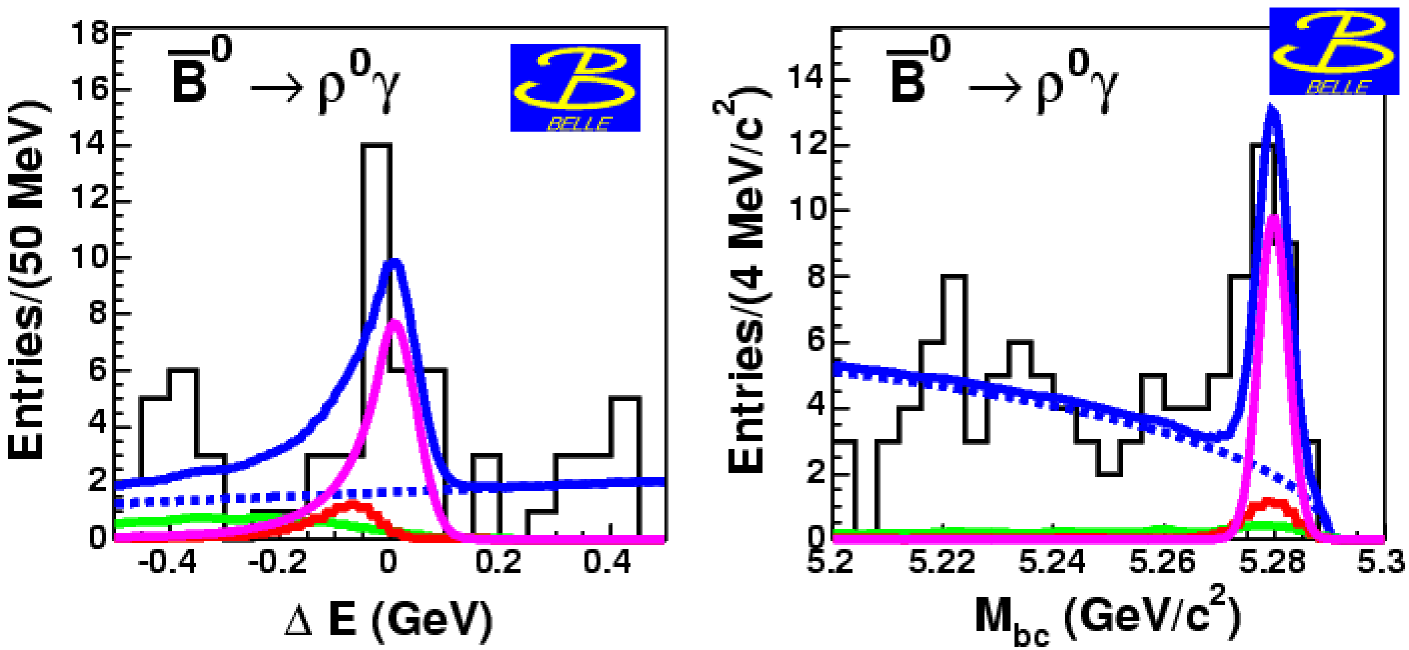
$$Signal\ Yield = \quad 8.5\ events$$

$$Significance = \quad 1.6\,\sigma\,(incl.\ syst.\ )$$

$$\mathcal{B}(B \to \rho^- \gamma) = \quad (0.55^{+0.42}_{-\ 0.36}(stat.)^{+0.09}_{-\ 0.08}(syst.)) \times 10^{-\ 6}$$

— ρ γ -- Continuum — K*γ — remaining B background

Fit results: $\overline{B^0} \rightarrow \rho^0 \gamma$ **386 *M B $\overline{B}$***

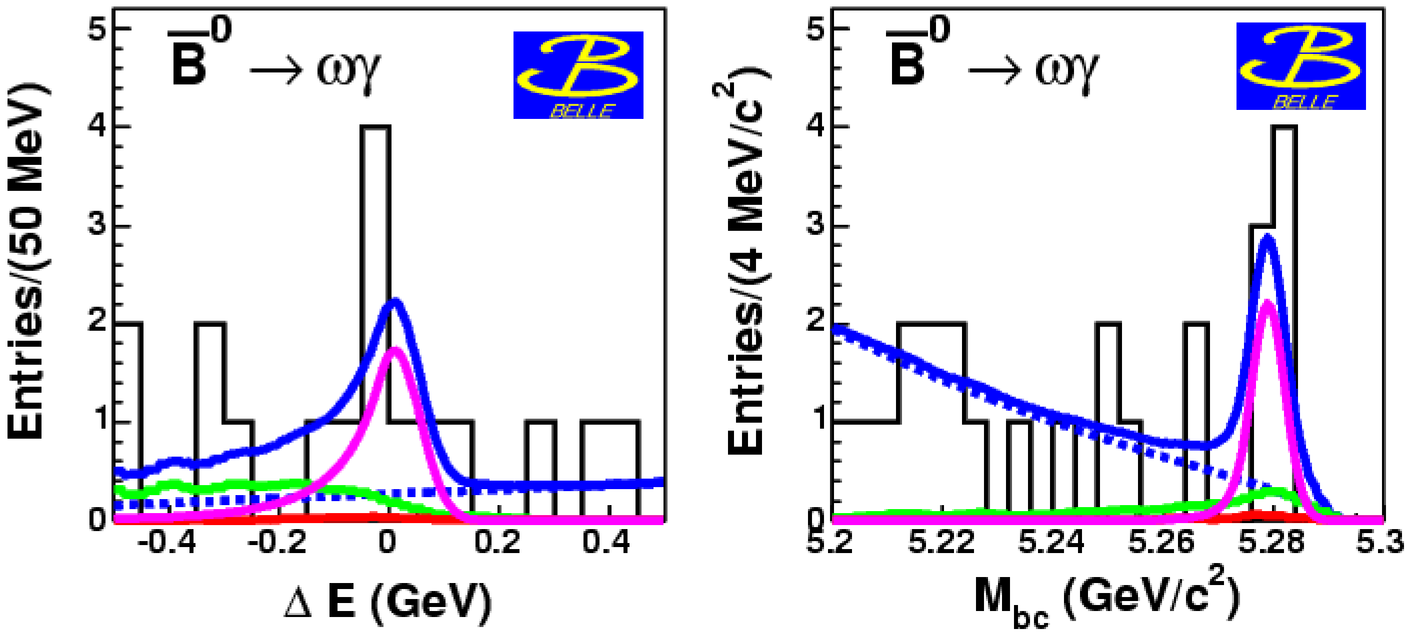


$$Signal\ Yield = \quad 20.7\ events$$

$$Significance = \quad 5.2\,\sigma\,(incl.\ syst.)$$

$$B(\overline{B^0} \rightarrow \rho^0 \gamma) = \quad (1.25^{+0.37}_{-0.33}(stat.)^{+0.07}_{-0.06}(syst.)) \times 10^{-6}$$

Fit results: $\overline{B^0} \to \omega\gamma$ **386 M $B\overline{B}$**



$$Signal\ Yield = \quad 5.6\ events$$

$$Significance = \quad 2.3\,\sigma\,(incl.\ syst.)$$

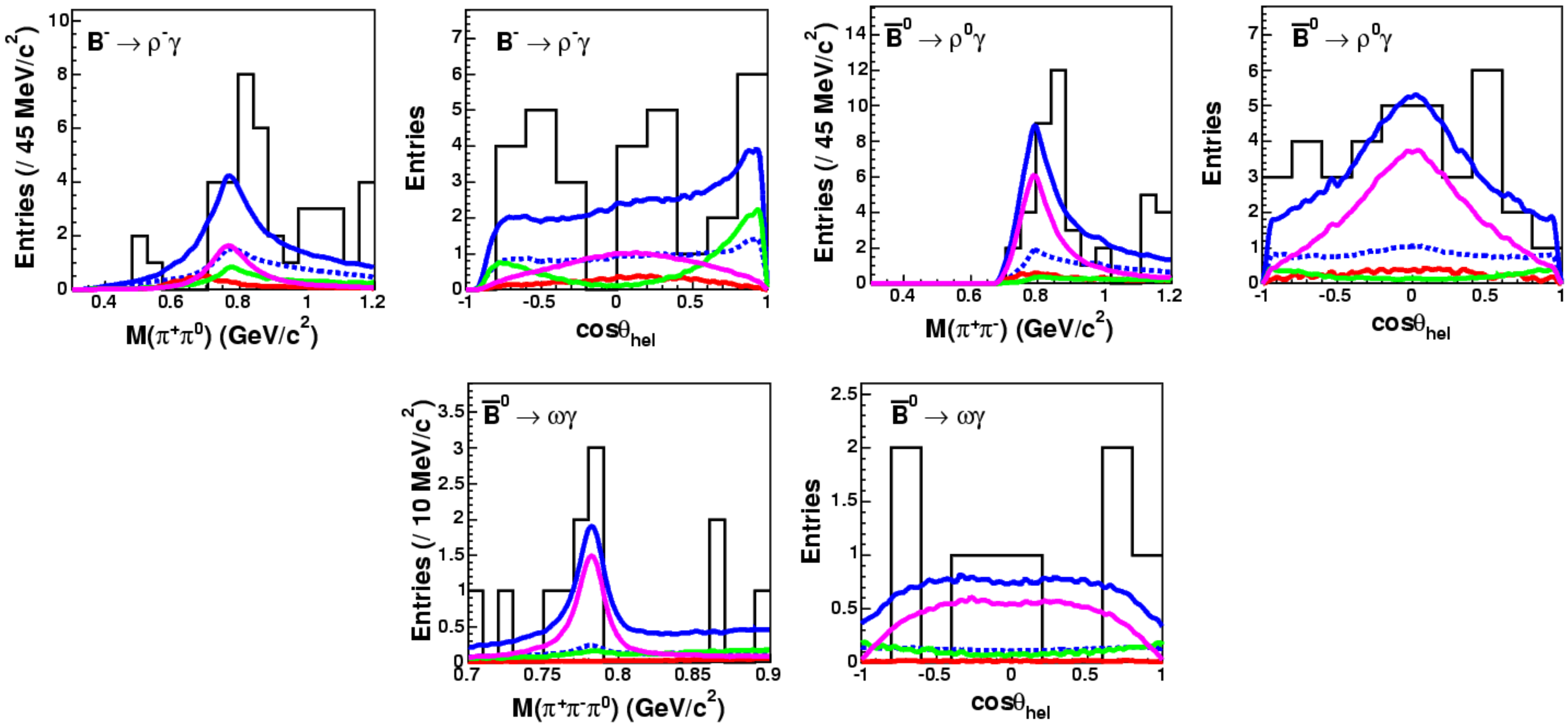
$$B(\overline{B^0} \to \omega\gamma) = \quad (0.56^{+0.34}_{-0.27}(stat.)^{+0.05}_{-0.10}(syst.)) \times 10^{-6}$$

¿

Fit results are consistent with Mass and Helicity

Results from fit are superimposed on Mass and Helicity

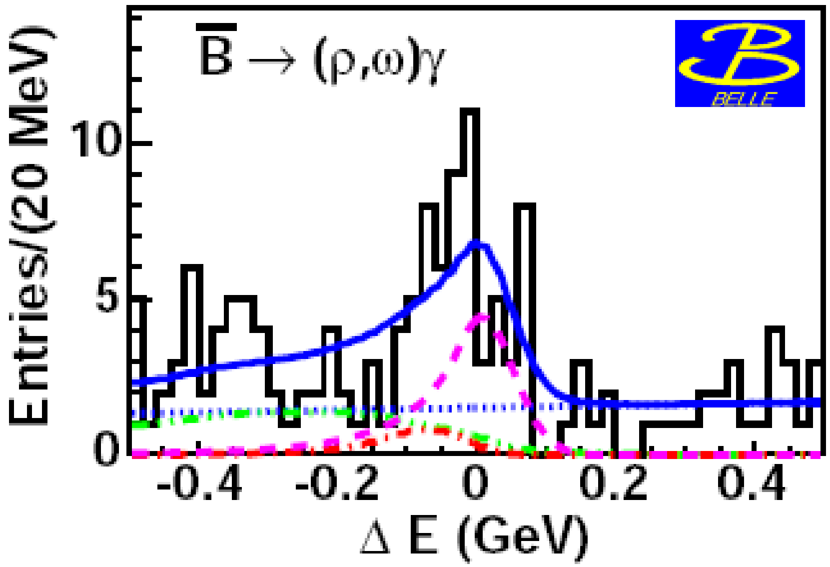
$M_{\pi\pi}$ & $\cos\theta_{hel}$ *deformed by* $M_{K\pi}$ ($K^* \gamma$ *veto variable*)

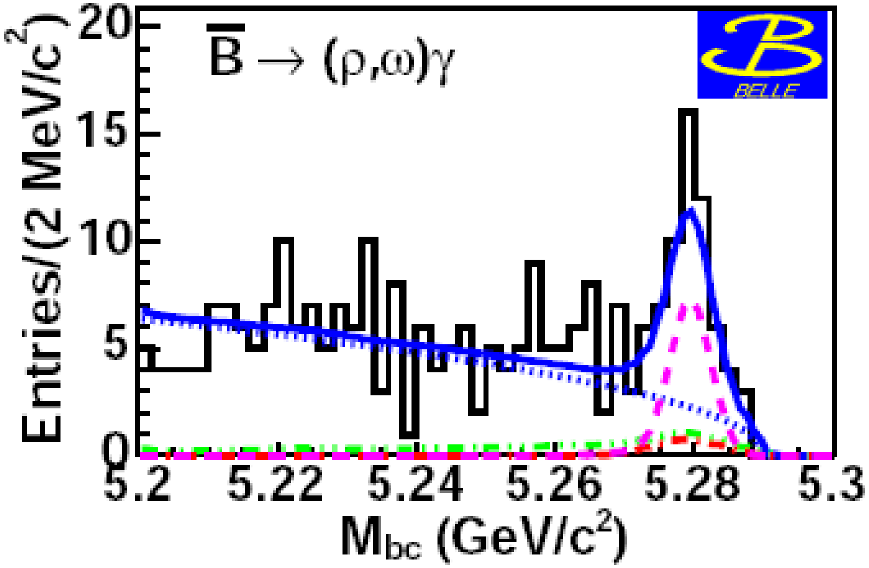


Combined fit: $\bar{B} \to (\rho, \omega)\gamma$ 386 M $B\bar{B}$

$$B(\bar{B}\to(\rho,\omega)\gamma) \equiv B(B^- \to \rho^- \gamma) = 2\times\frac{\tau_{B^+}}{\tau_{B^0}} B(\overline{B^0}\to\rho^0\gamma) = 2\times\frac{\tau_{B^+}}{\tau_{B^0}} B(\overline{B^0}\to\omega\gamma)$$

$$\text{using } \frac{\tau_{B^+}}{\tau_{B^0}} = 1.076 \pm 0.008$$





$$B(B\to(\rho,\omega)\gamma) = (1.32^{+0.34}_{-0.31}(stat.)^{+0.10}_{-0.09}(syst.))\times 10^{-6}$$

$$Significance = 5.1\,\sigma\,(incl.\ syst.)$$

Extraction of $\left|V_{td}/V_{ts}\right|$

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

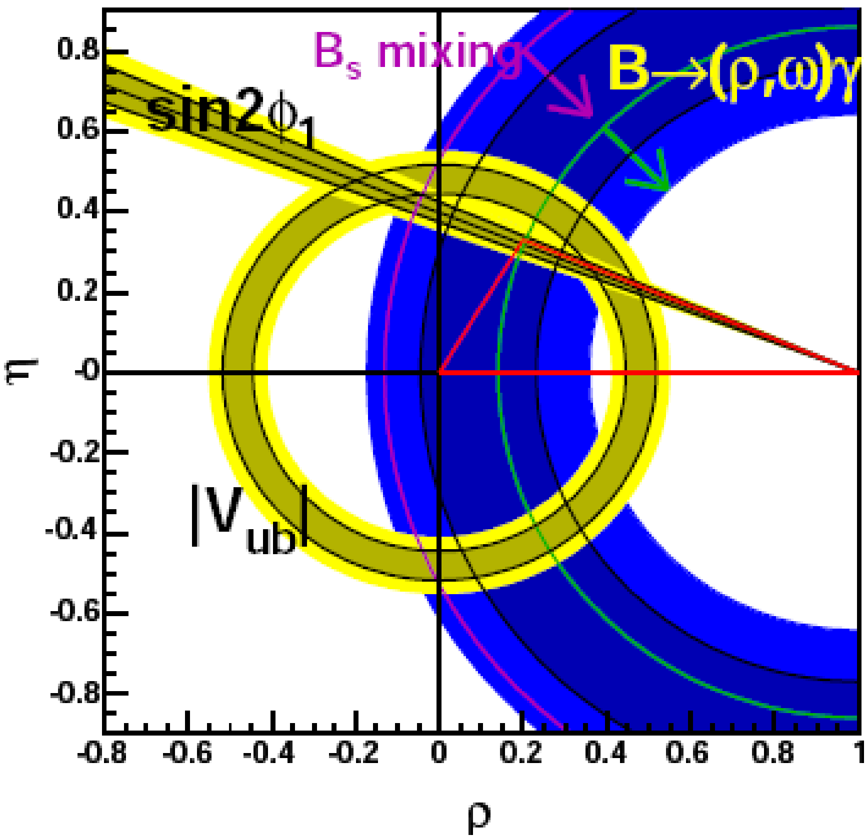
Form factor ratio $\zeta = 0.85 \pm 0.10$

SU(3)-breaking effect $\Delta R = 0.1 \pm 0.1$

$$\frac{B(B\to(\rho,\omega)\gamma)}{B(B\to K^*\gamma)} = 0.032 \pm 0.008^{+0.003}_{-0.002}$$

$$0.142 < \left|\frac{V_{td}}{V_{ts}}\right| < 0.259$$

(95 % C.L. interval)



$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.199^{+0.026}_{-0.025}(\textit{expt.})^{+0.016}_{-0.015}(\textit{theo.})$$

Discussion

Comparison of Belle results with SM predictions

	Theory (Ali et. al)	Belle Results
$B(B\to(\rho,\omega)\gamma)$	$(1.38\pm0.42)\times10^{-6}$	$(1.32^{+0.34+0.10}_{-0.31-0.09})\times10^{-6}$
$B(B^-\to\rho^-\gamma)$	$(0.90\pm0.34)\times10^{-6}$	$(0.55^{+0.42+0.09}_{-0.36-0.08})\times10^{-6}$
$B(\overline{B}^0\to\rho^0\gamma)$	$(0.49\pm0.18)\times10^{-6}$	$(1.25^{+0.37+0.07}_{-0.33-0.06})\times10^{-6}$
$B(\overline{B}^0\to\omega\gamma)$	$(0.49\pm0.18)\times10^{-6}$	$(0.56^{+0.34+0.05}_{-0.27-0.10})\times10^{-6}$
	$0.16<\left\|\frac{V_{td}}{V_{ts}}\right\|<0.29$	$0.14<\left\|\frac{V_{td}}{V_{ts}}\right\|<0.26$
	(68 % CL)	*(95 % CL)*

Comparison of Belle and BaBar results

	$386\ M\ B\overline{B}$ ¿ **Belle**	$221\ M\ B\overline{B}$ **BaBar**
$B(B\to(\rho,\omega)\gamma)$	$(1.32^{+0.34}_{-0.31}{}^{+0.10}_{-0.09})\times10^{-6}$	$<1.2\times10^{-6}$
$B(B^-\to\rho^-\gamma)$	$(0.55^{+0.42}_{-0.36}{}^{+0.09}_{-0.08})\times10^{-6}$	$<1.8\times10^{-6}$
$B(\overline{B^0}\to\rho^0\gamma)$	$(1.25^{+0.35}_{-0.31}{}^{+0.07}_{-0.06})\times10^{-6}$	$<0.4\times10^{-6}$
$B(\overline{B^0}\to\omega\gamma)$	$(0.56^{+0.34}_{-0.27}{}^{+0.05}_{-0.10})\times10^{-6}$	$<1.0\times10^{-6}$
	$0.14<\left\lvert\frac{V_{td}}{V_{ts}}\right\rvert<0.26$	<0.19
	(95 % CL)	*(90 % CL)*
	hep-ex/0506079 [submitted to PRL]	PRL 94, 011801 (2005)

Summary

- *Belle observes* $b \to d\gamma$ *with* 5.5σ *significance*

$$B(B \to (\rho,\omega)\gamma) = (1.32^{+0.34+0.10}_{-0.31-0.09}) \times 10^{-6}$$

$$B(B^- \to \rho^-\gamma) = (0.55^{+0.42+0.09}_{-0.36-0.08}) \times 10^{-6}$$

$$B(\overline{B^0} \to \rho^0\gamma) = (1.25^{+0.37+0.07}_{-0.33-0.06}) \times 10^{-6}$$

$$B(\overline{B^0} \to \omega\gamma) = (0.56^{+0.34+0.05}_{-0.27-0.10}) \times 10^{-6}$$

and determines

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.199^{+0.026}_{-0.025}(expt.)^{+0.018}_{-0.015}(theo.)$$

- *Uncertainties will be reduced with additional data*
- *CP violation will become measurable in few years*
- $b \to d\,\gamma$ *inlcusive measurement will be ready soon*

References

1. Belle Collaboration, K. Abe et al, hep-ex/0507036
2. Belle Collaboration, K. Abe et al, hep-ex/0506079
3. Belle Collaboration, D. Mohapatra et al, PRD72, 011101(R)(2005)
4. BaBar Collaborartion, B. Aubert et al, PRL92, 111801(2004)
5. LP05 Talk, Francesco Forti, CKM parameters and rare B decays
6. Susy2005, Shohei Nishida, Recent Results from Belle
7. EPS2005, D. Mohapatra, Observation of $b \to d\gamma$ and search for $\overline{B}^0 \to \gamma\gamma$
8. PANIC' 05, D. Mohapatra, Observation of $b \to d\gamma$ decays

and references therein...

Thank you all

We can test Isospin violation with the following approach

This is the isospin relation we use

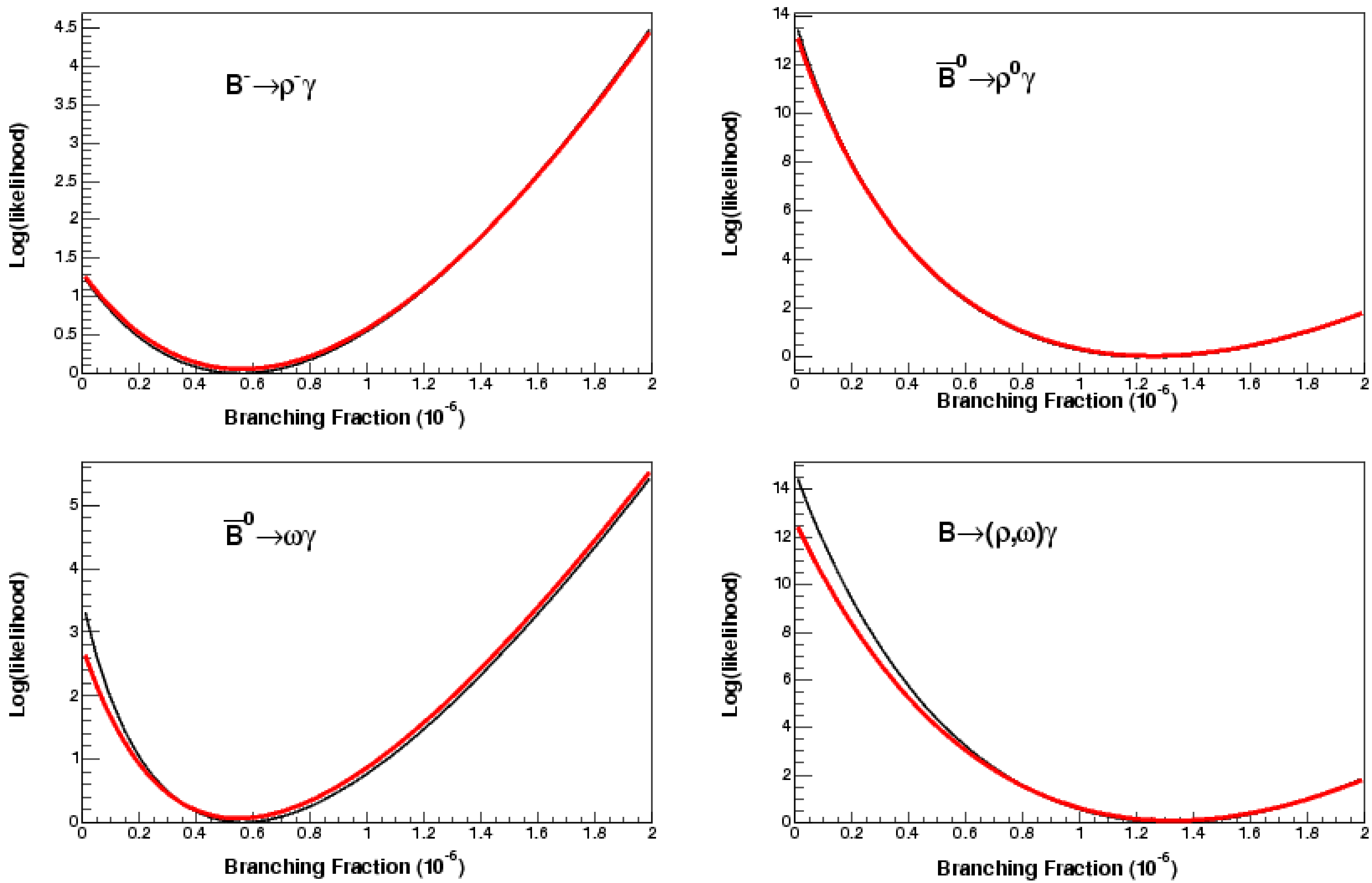
$$\mathcal{B}(B^- \to \rho^- \gamma) = 2 \times \frac{\tau_{B^+}}{\tau_{B^0}} \mathcal{B}(\overline{B^0} \to \rho^0 \gamma) = 2 \times \frac{\tau_{B^+}}{\tau_{B^0}} \mathcal{B}(\overline{B^0} \to \omega \gamma)$$

Isospin violation parameters are defined as,

$$\beta = \frac{\mathcal{B}(\overline{B}^0 \to \rho^0\gamma) + \mathcal{B}(\overline{B}^0 \to \omega\gamma)}{2\mathcal{B}(B^- \to \rho^-\gamma)} \frac{\tau_{B^+}}{\tau_{B^0}}$$

$$\gamma = \frac{2}{1 + \mathcal{B}(\overline{B}^0 \to \omega\gamma)/\mathcal{B}(\overline{B}^0 \to \rho^0\gamma)} - 1.$$

	Isospin	*Belle Results*
β	0.5	$1.75^{+0.83}_{-0.82}(2.1\sigma)$
γ	0.0	$0.36^{+0.25}_{-0.26}(0.9\sigma)$

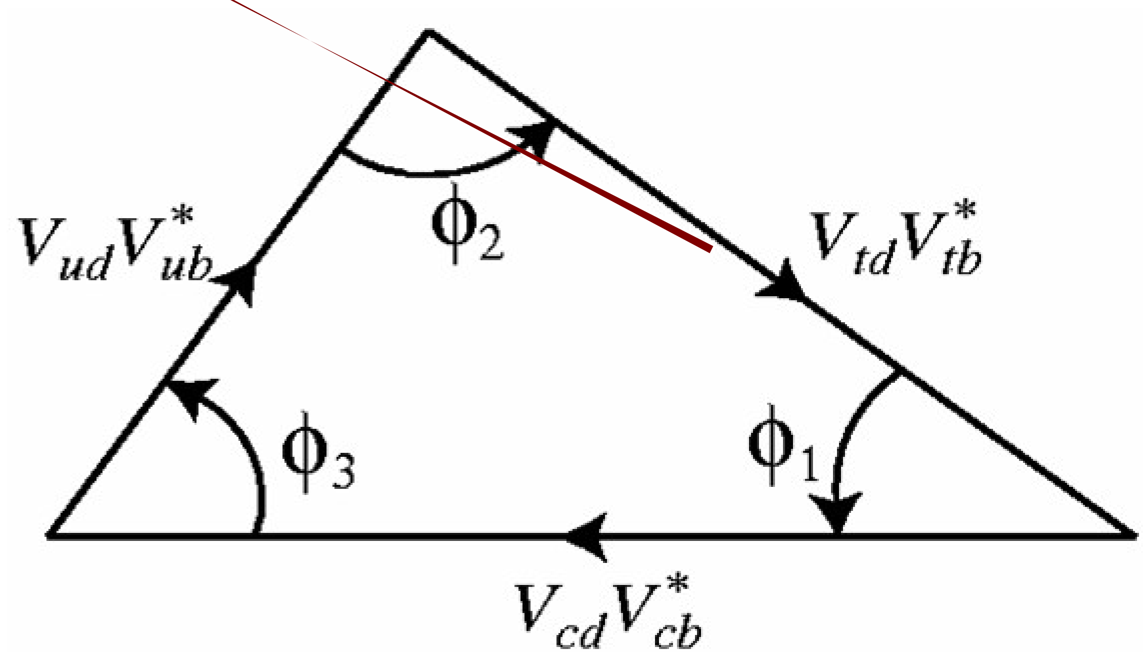


B⁻→ρ⁻γ
B̄⁰→ρ⁰γ
B̄⁰→ωγ
B→(ρ,ω)γ
Log(likelihood)
Branching Fraction (10⁻⁶)

Cabibbo-Kobayashi-Maskawa (CKM) Matrix and the Unitarity triangle

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

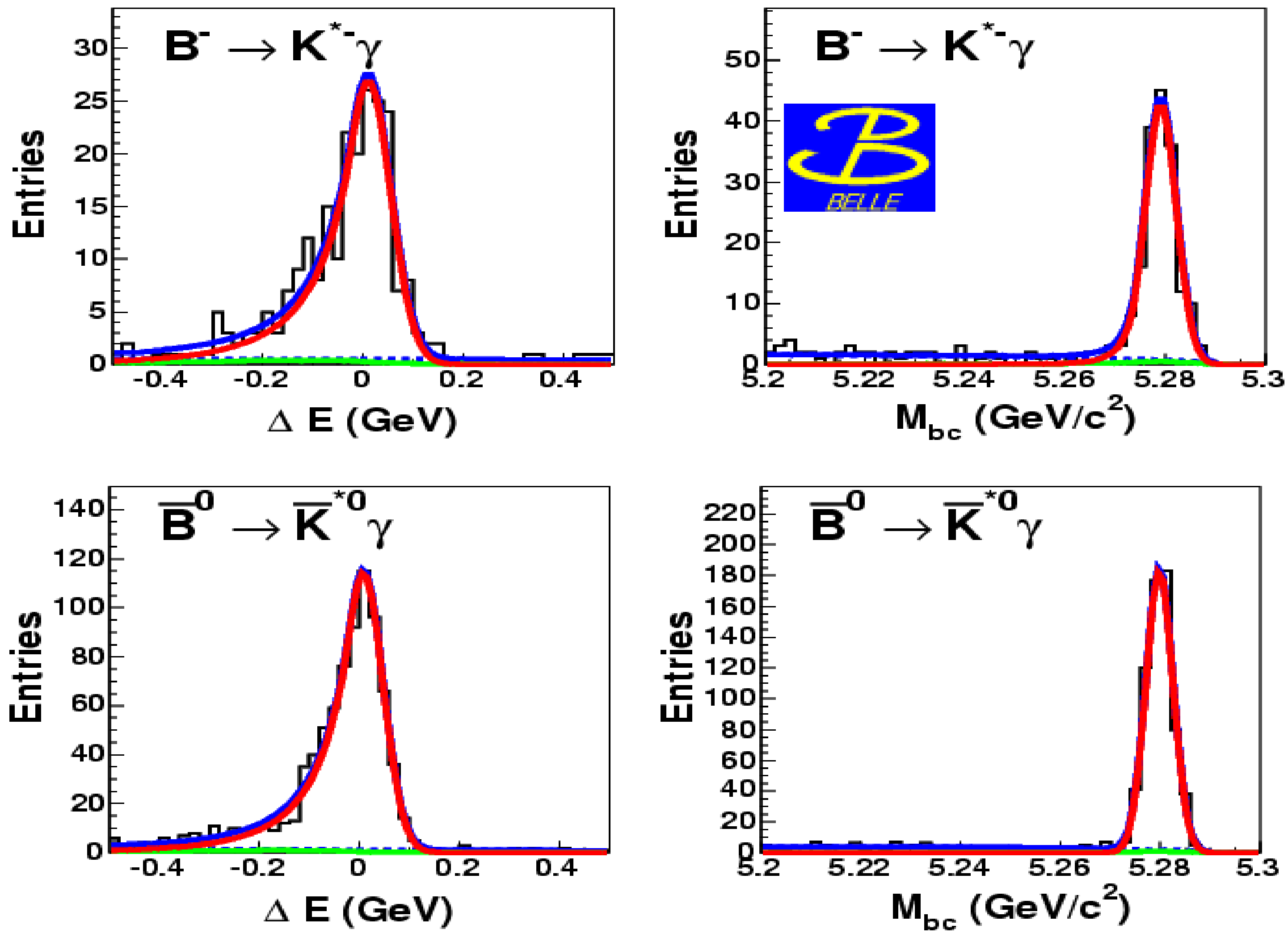
$$Unitarity \Rightarrow V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$



CKM Angles

$$(\phi_1, \phi_2, \phi_3) = (\beta, \alpha, \gamma)$$

Fit Results: $B \to K^* \gamma$ 386 $M\, B\bar{B}$



$$\mathcal{B}(B \to K^* \gamma) = (41.3 \pm 1.4) \times 10^{-6}$$

BaBar 211 M $B\overline{B}$

Mode	n_{sig}	n_{cont}	n_{peak}	Significance (σ)	ϵ(%)	$\mathcal{B}(10^{-6})$	$\mathcal{B}(10^{-6})$ 90% C.L.
$B^+ \to \rho^+\gamma$	26^{+15+2}_{-14-2}	6850 ± 90	18 ± 4	1.9	13.2 ± 1.4	$0.9^{+0.6}_{-0.5} \pm 0.1$	< 1.8
$B^0 \to \rho^0\gamma$	$0.3^{+7.2+1.7}_{-5.4-1.6}$	4269 ± 73	18 ± 7	0.0	15.8 ± 1.9	$0.0 \pm 0.2 \pm 0.1$	< 0.4
$B^0 \to \omega\gamma$	$8.3^{+5.7+1.3}_{-4.5-1.9}$	1378 ± 37	$2.6^{+0.8}_{-1.2}$	1.5	8.6 ± 0.9	$0.5 \pm 0.3 \pm 0.1$	< 1.0
Combined	$269^{+126+40}_{-120-45}$	—	—	2.1	—	$0.6 \pm 0.3 \pm 0.1$	< 1.2

Belle 275 M $B\overline{B}$

Mode	Yield	Significance	Efficiency	Branching Fraction Central Value	Branching Fraction Upper Limit
$B^- \to \rho^-\gamma$	$18.7^{+10.1}_{-9.2}$	1.7σ	$(5.5 \pm 0.4)\%$	$(1.24^{+0.67}_{-0.61} \pm 0.26) \times 10^{-6}$	2.2×10^{-6}
$\overline{B}^0 \to \rho^0\gamma$	$1.9^{+2.8}_{-2.7}$	0.3σ	$(3.9 \pm 0.3)\%$	$(0.18^{+0.88}_{-0.25} \pm 0.10) \times 10^{-6}$	0.8×10^{-6}
$\overline{B}^0 \to \omega\gamma$	$0.9^{+4.2}_{-3.8}$	0.1σ	$(3.9 \pm 0.4)\%$	$(0.08^{+0.89}_{-0.81} \pm 0.19) \times 10^{-6}$	0.8×10^{-6}
Combined	—	1.2σ	—	$(0.72^{+0.48}_{-0.89} \pm 0.28) \times 10^{-6}$	1.4×10^{-6}

Belle 386 M $B\overline{B}$

TABLE I: Yield, significance with (without) systematic uncertainty, efficiency, and branching fraction ($\mathcal{B}$) for each mode.

Mode	Yield	Signif.	Efficiency (%)	$\mathcal{B}$ (10^{-6})
$B^- \to \rho^-\gamma$	8.5	1.6 (1.6)	3.86 ± 0.23	$0.55^{+0.42}_{-0.36}{}^{+0.09}_{-0.08}$
$\overline{B}^0 \to \rho^0\gamma$	20.7	5.2 (5.2)	4.30 ± 0.28	$1.25^{+0.37}_{-0.33}{}^{+0.07}_{-0.06}$
$\overline{B}^0 \to \omega\gamma$	5.7	2.3 (2.6)	2.61 ± 0.21	$0.56^{+0.34}_{-0.27}{}^{+0.05}_{-0.10}$
$\overline{B} \to (\rho,\omega)\gamma$	36.9	5.1 (5.4)	—	$1.32^{+0.34}_{-0.31}{}^{+0.10}_{-0.09}$

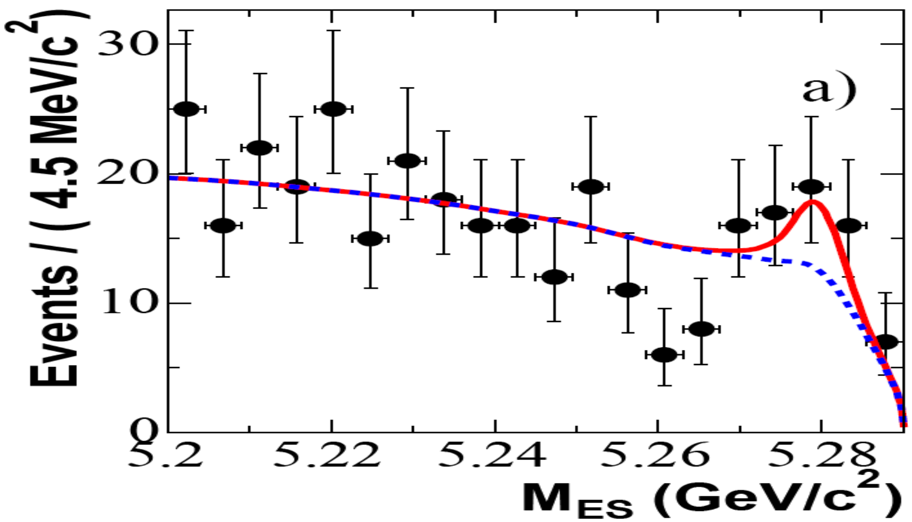
Table 14: Summary of the fit results to full- and sub-samples. The number in the parenthesis is the statistical significance (no systematic error).

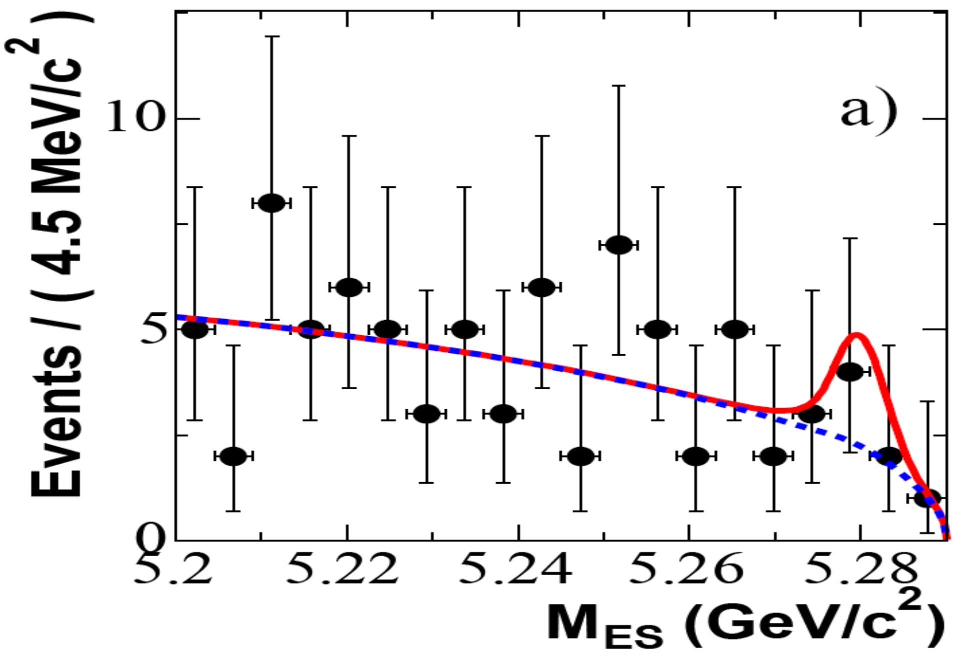
	$\rho^-\gamma$ $\mathcal{B}(\times10^{-6})$	$\rho^0\gamma$ $\mathcal{B}(\times10^{-6})$	$\omega\gamma$ $\mathcal{B}(\times10^{-6})$	$(\rho,\omega)\gamma$ $\mathcal{B}(\times10^{-6})$
I.	1.77 ± 0.80 (2.8)	0.61 ± 0.45 (1.8)	0.26 ± 0.38 (0.9)	1.32 ± 0.54 (3.2)
II.	0.08 ± 0.46 (0.2)	1.28 ± 0.63 (3.1)	-0.10 ± 0.50 (0.2)	0.79 ± 0.46 (2.1)
I+II.	0.80 ± 0.47 (2.0)	0.92 ± 0.38 (3.5)	0.17 ± 0.27 (0.7)	1.04 ± 0.35 (3.7)
PRD	$1.24^{+0.67}_{-0.61}$ (2.1)	$0.18^{+0.33}_{-0.25}$ (0.7)	$0.08^{+0.39}_{-0.31}$ (0.2)	$0.72^{+0.43}_{-0.39}$ (2.?†)
III.	-0.48 ± 0.77 (0.6)	2.00 ± 0.76 (4.1)	1.49 ± 0.82 (3.1)	2.05 ± 0.70 (4.2)
Full	$0.55^{+0.42}_{-0.36}$ (1.6)	$1.25^{+0.37}_{-0.33}$ (5.2)	$0.56^{+0.34}_{-0.27}$ (2.6)	$1.32^{+0.34}_{-0.31}$ (5.4)

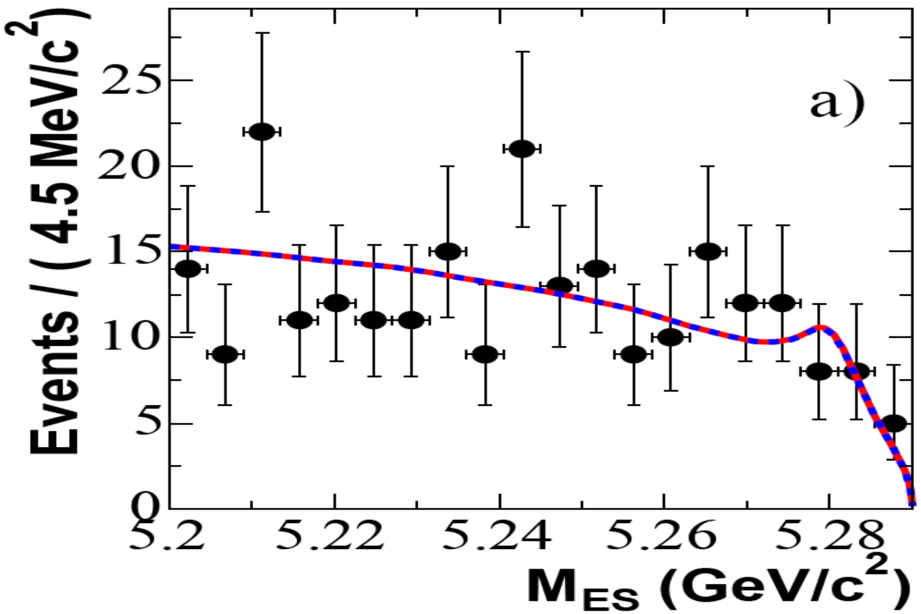
† The significance without the systematic error for this result is lost somewhere.

Table 16: Comparison of results between two analyses.

	DM results			SN results		
	$\mathcal{B}$ (10^{-6})	$N_{\rm sig}$	*sig.*	$\mathcal{B}$ (10^{-6})	$N_{\rm sig}$	*sig.*
$B^- \to \rho^-\gamma$	$0.55^{+0.42}_{-0.36}{}^{+0.09}_{-0.08}$	8.5	1.5	$1.19^{+0.51}_{-0.44}{}^{+0.11}_{-0.07}$	$12.5^{+5.4}_{-4.7}{}^{+1.0}_{-0.4}$	3.1
$\overline{B}^0 \to \rho^0\gamma$	$1.25^{+0.37}_{-0.33}{}^{+0.07}_{-0.06}$	20.7	5.2	$1.04^{+0.37}_{-0.32}{}^{+0.07}_{-0.06}$	$16.0^{+5.6}_{-4.9}{}^{+0.9}_{-0.8}$	4.1
$\overline{B}^0 \to \omega\gamma$	$0.56^{+0.34}_{-0.27}{}^{+0.05}_{-0.10}$	5.7	2.2	$0.53^{+0.32}_{-0.26}{}^{+0.06}_{-0.04}$	$7.2^{+4.4}_{-3.6}{}^{+0.8}_{-0.4}$	2.2
$\overline{B} \to (\rho,\omega)\gamma$	$1.32^{+0.34}_{-0.31}{}^{+0.10}_{-0.09}$	—	5.2	$1.47^{+0.36}_{-0.33}{}^{+0.12}_{-0.13}$	—	5.5







similar analysis by BaBar (211M $B\bar{B}$, PRL94,011801(2005)):

$\mathcal{B}(B \to (\rho, \omega)\gamma) = (0.6 \pm 0.3 \pm 0.1) \times 10^{-6}$ (2.1σ) $< 1.2 \times 10^{-6}$ (90%CL)