Radiative B decays at Belle

Wine and Cheese Seminar, Femilab

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International Collaboration: Belle

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Kyoto U.
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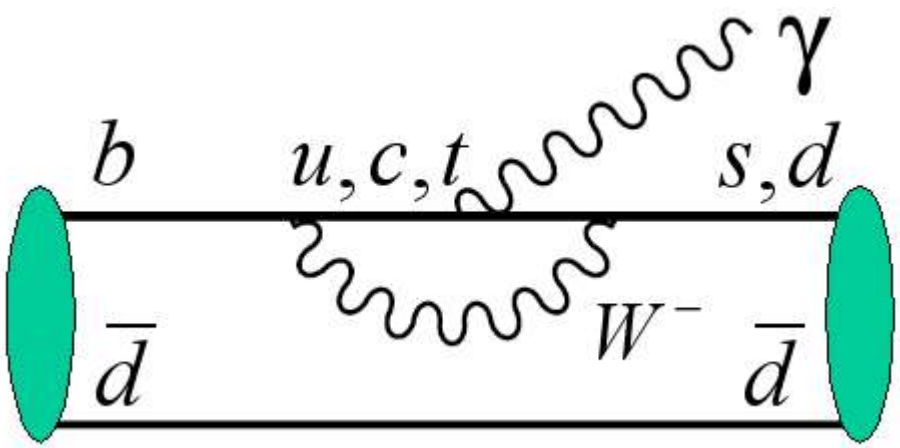
Jozef Stefan Inst. / U. of Ljubljana / U. of Maribor
U. of Melbourne
Nagoya U.
Nara Women's U.
National Central U.
National Taiwan U.
National United U.
Nihon Dental College
Niigata U.
Osaka U.
Osaka City U.
Panjab U.
Peking U.
U. of Pittsburgh
Princeton U.
Riken
Saga U.
USTC
Seoul National U.
Shinshu 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.

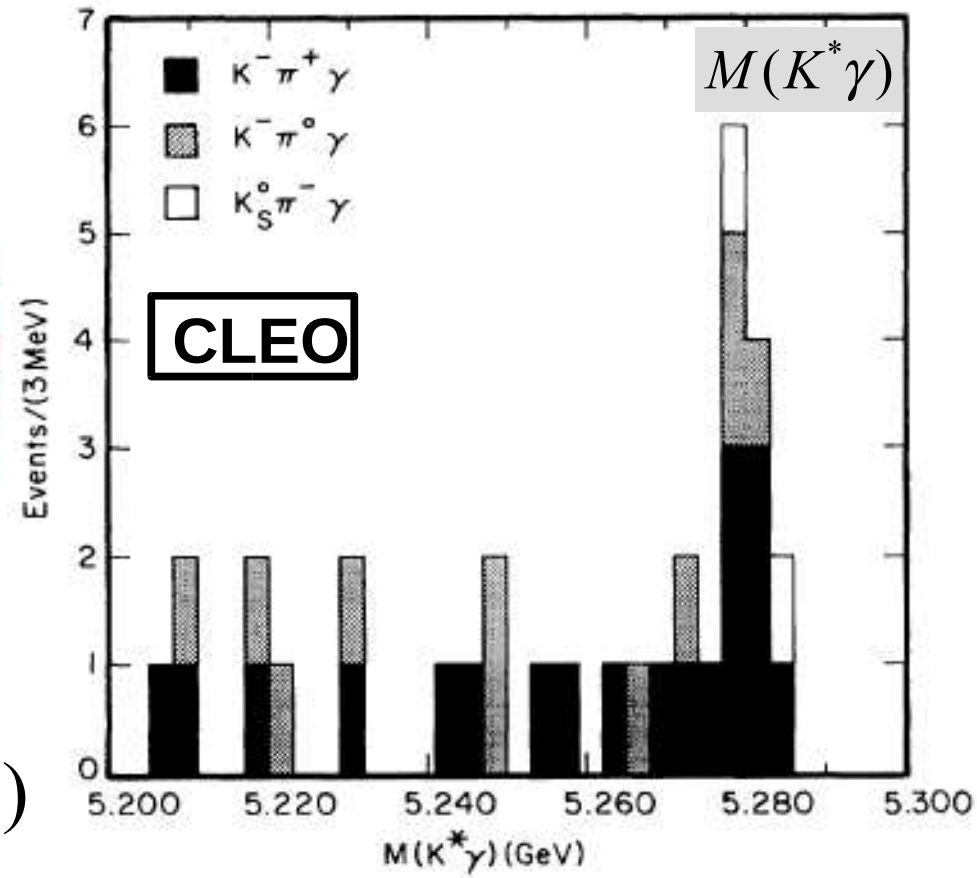
13 countries, 55 institutes, ~400 collaborators

Introduction

First observation of radiative penguin decays by CLEO, 12 years ago

$b \to s\,\gamma$ process





Observation of $K^*\gamma$

PRL 71, 674 (1993)

(cited more than 500 times !)

- 8 events
- Branching fraction $\sim 4.5 \times 10^{-5}$

Belle has a dedicated Physics program for radiative penguin decays

$b \to s\gamma$ and $b \to d\gamma$

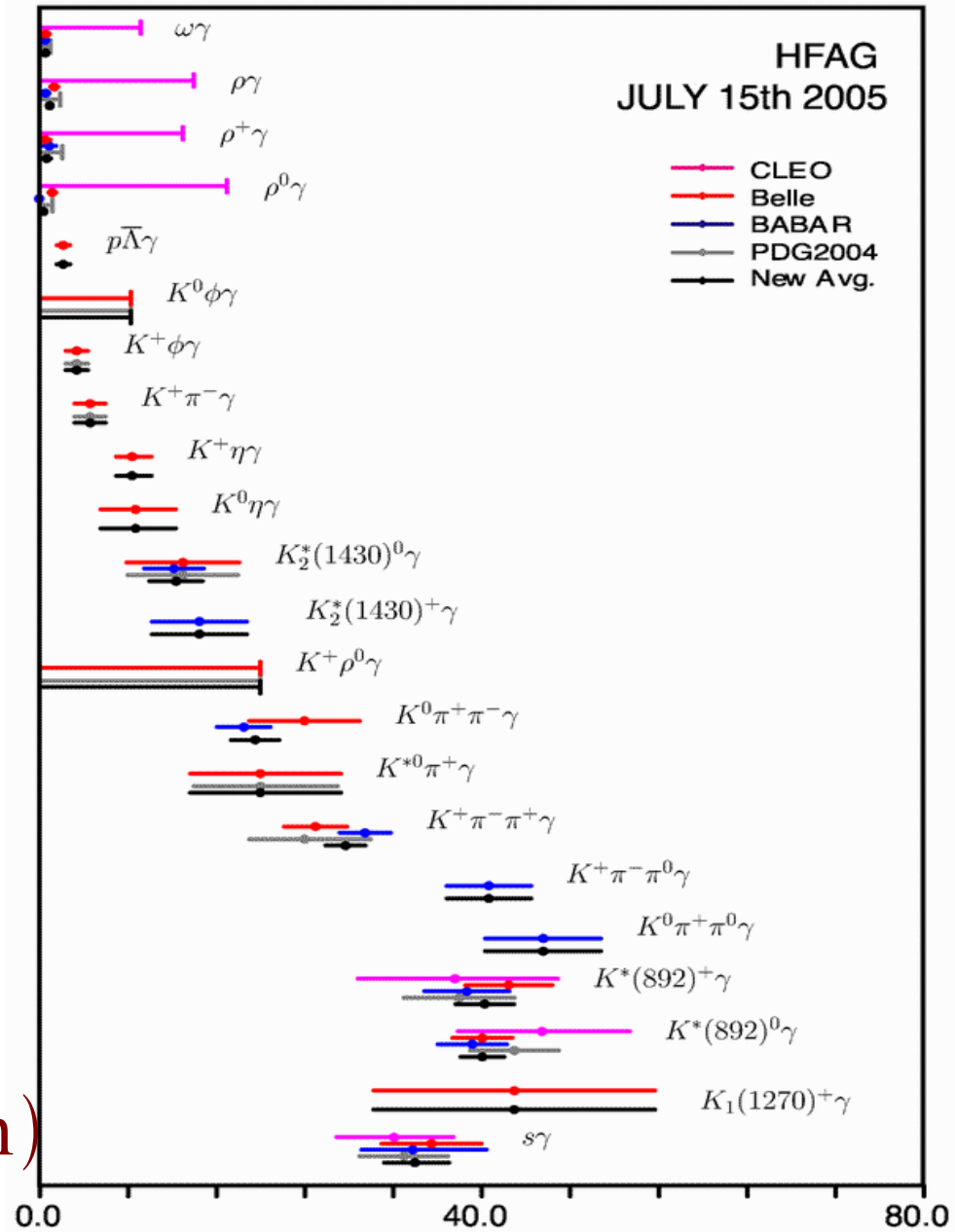
- Inclusive $b \to s\gamma$
- $B \to K^* \gamma$
- $B \to K_2^* \gamma$, $B \to K_1(1270)\gamma$
- $B \to K\phi\gamma$, $B \to K\eta\gamma$
- $B \to p\bar{\lambda}\gamma$ and more ...

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

(First observation by Belle)

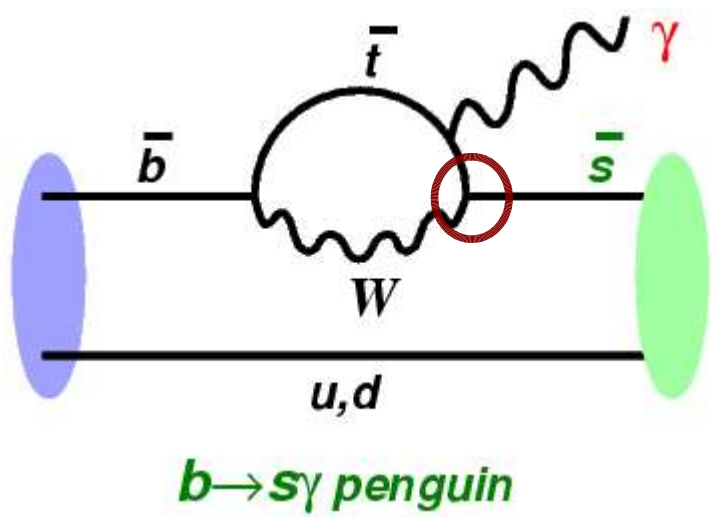
[to be submitted to PRL]

(Today's topic of discussion)



Radiative B decays: $b \to s\gamma$

Flavor-changing-neutral-current (FCNC) processes
- allowed in the Standard Model via penguin loop
- inclusive branching fraction $\sim 3.5 \times 10^{-4}$ (theory)

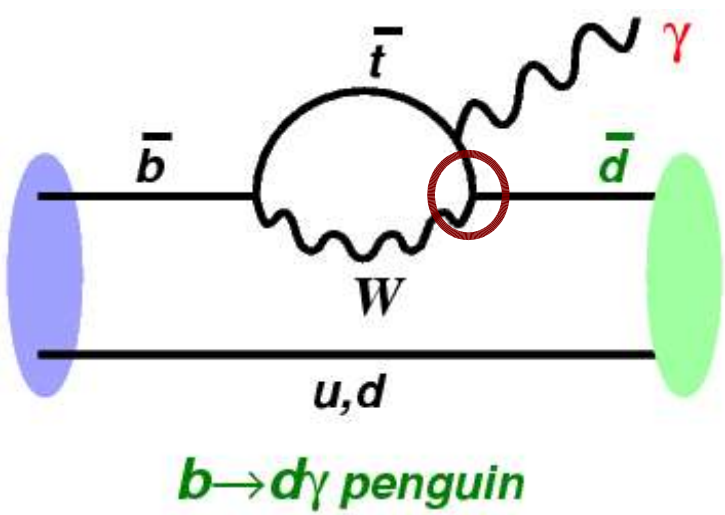


$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Radiative B decays: $b \to d\gamma$

- suppressed by $|V_{td}/V_{ts}|^2 (\sim 0.04)$ relative to $b \to s\gamma$
- branching fraction $\sim 10^{-6}$ (theory)
- $\dfrac{B \to \rho(\omega)\gamma}{B \to K^* \gamma}$ can be used to measure $\left|\dfrac{V_{td}}{V_{ts}}\right|$,

  complementary to B_s mixing $\left(\dfrac{\Delta M_d}{\Delta M_s}\right)$ @ Fermilab



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

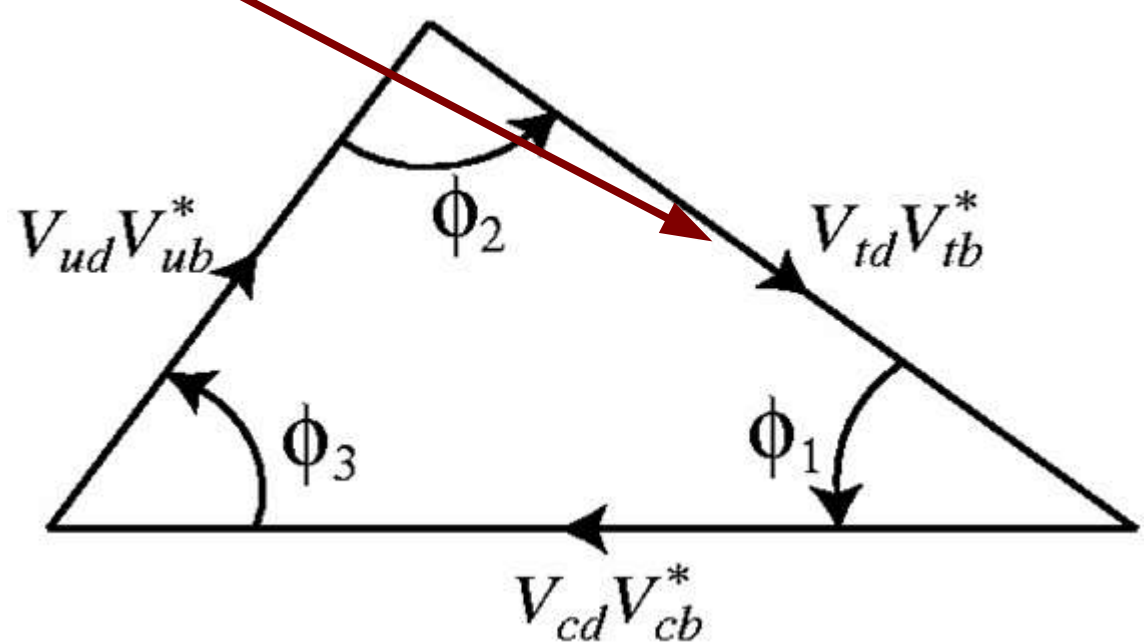
Cabibbo-Kobayashi-Maskawa (CKM) Matrix and the Unitarity triangle

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

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

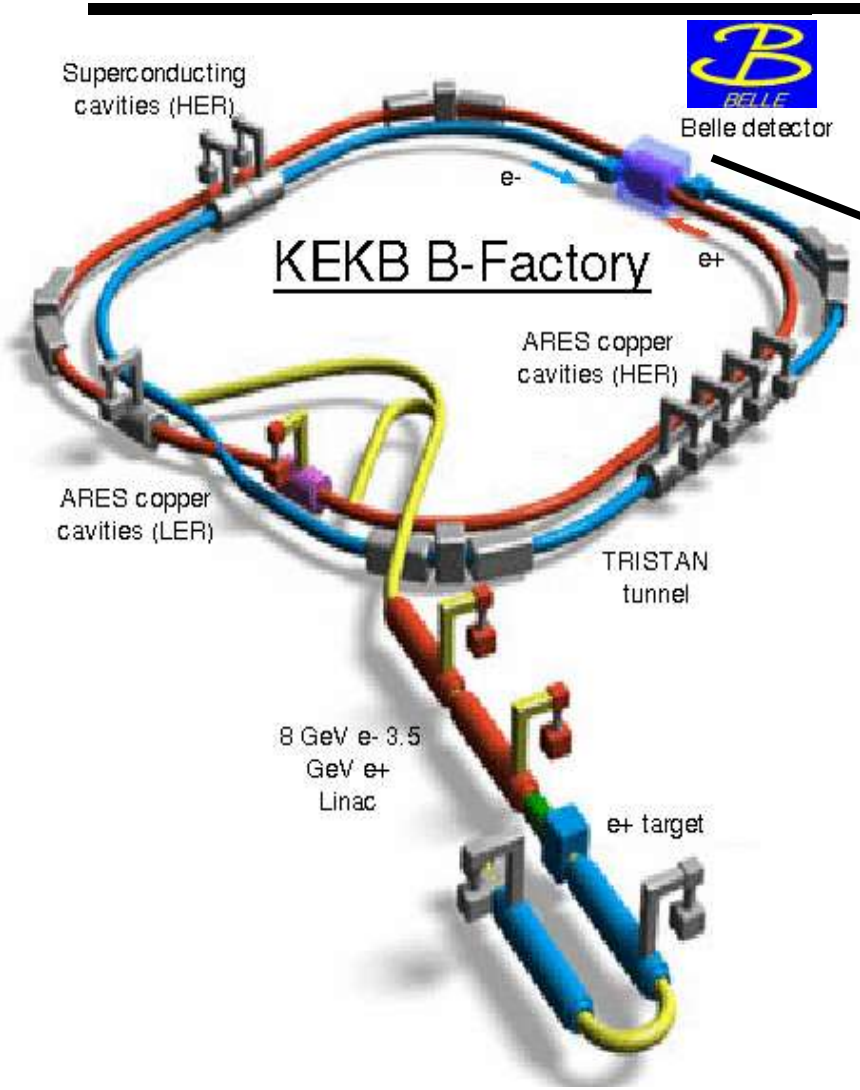
CKM Angles

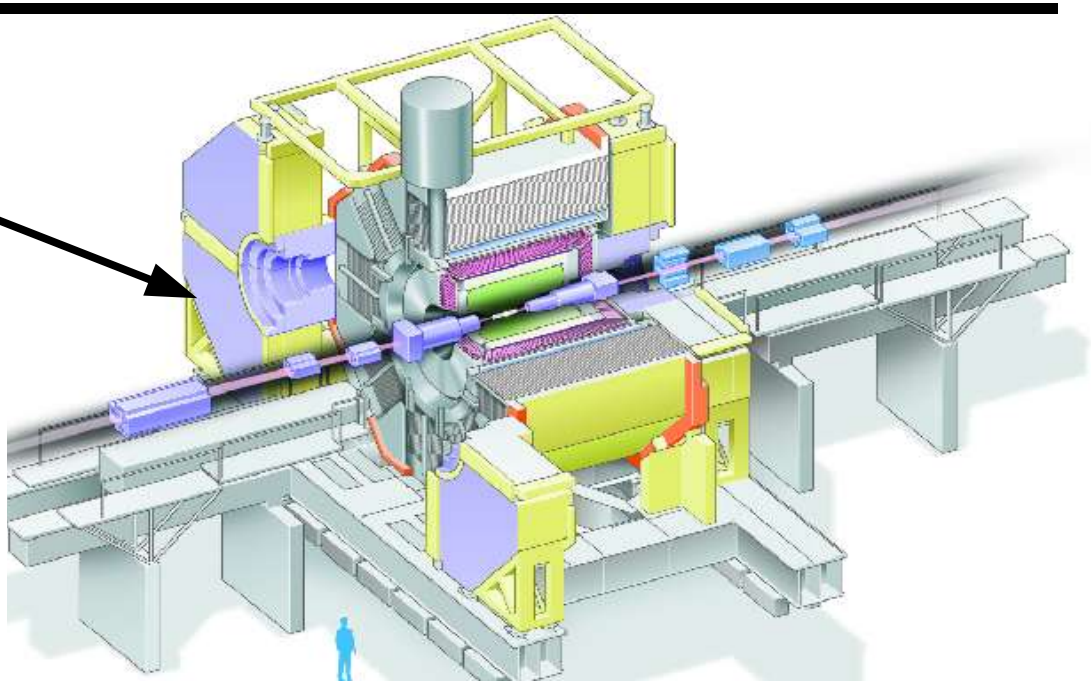
$$(\phi_1, \phi_2, \phi_3) = (\beta, \alpha, \gamma)$$

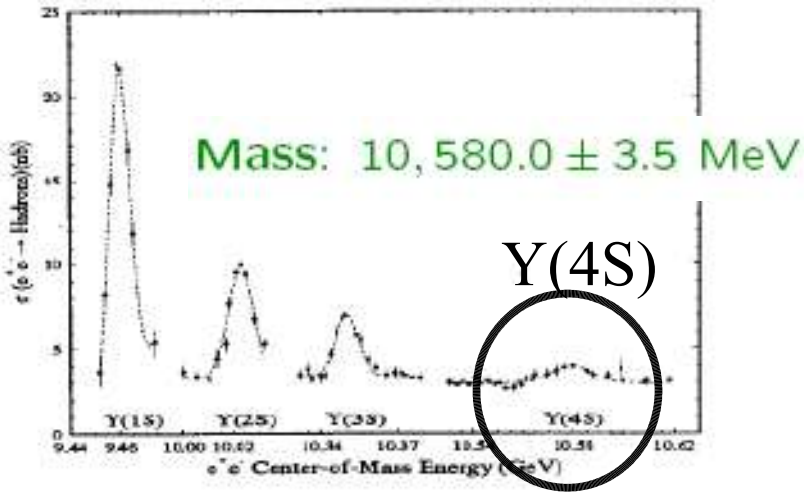


KEKB and Belle Detector

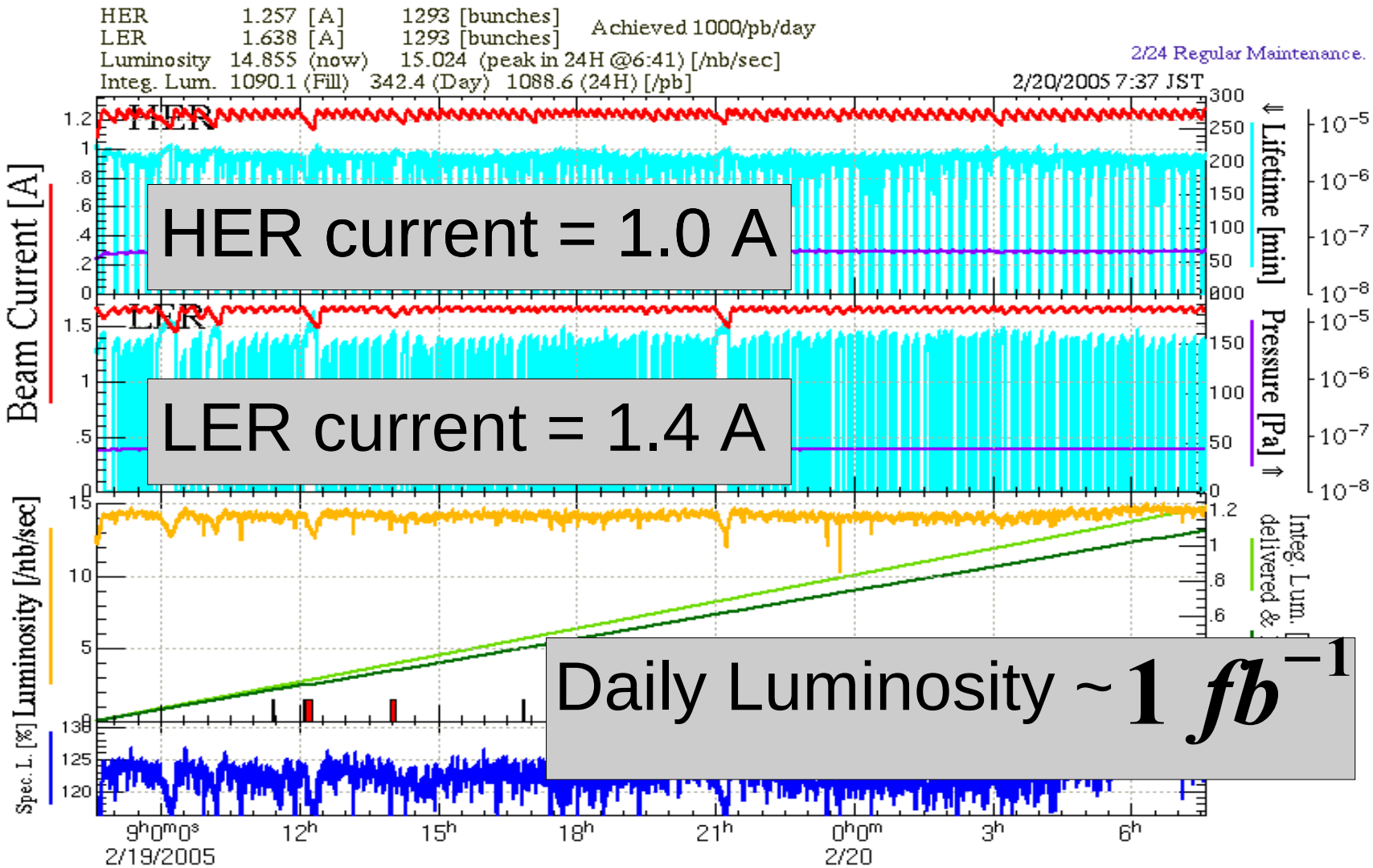
KEKB electron-positron collider (8 Gev on 3.5 GeV)







KEKB performance has been excellent with many luminosity records



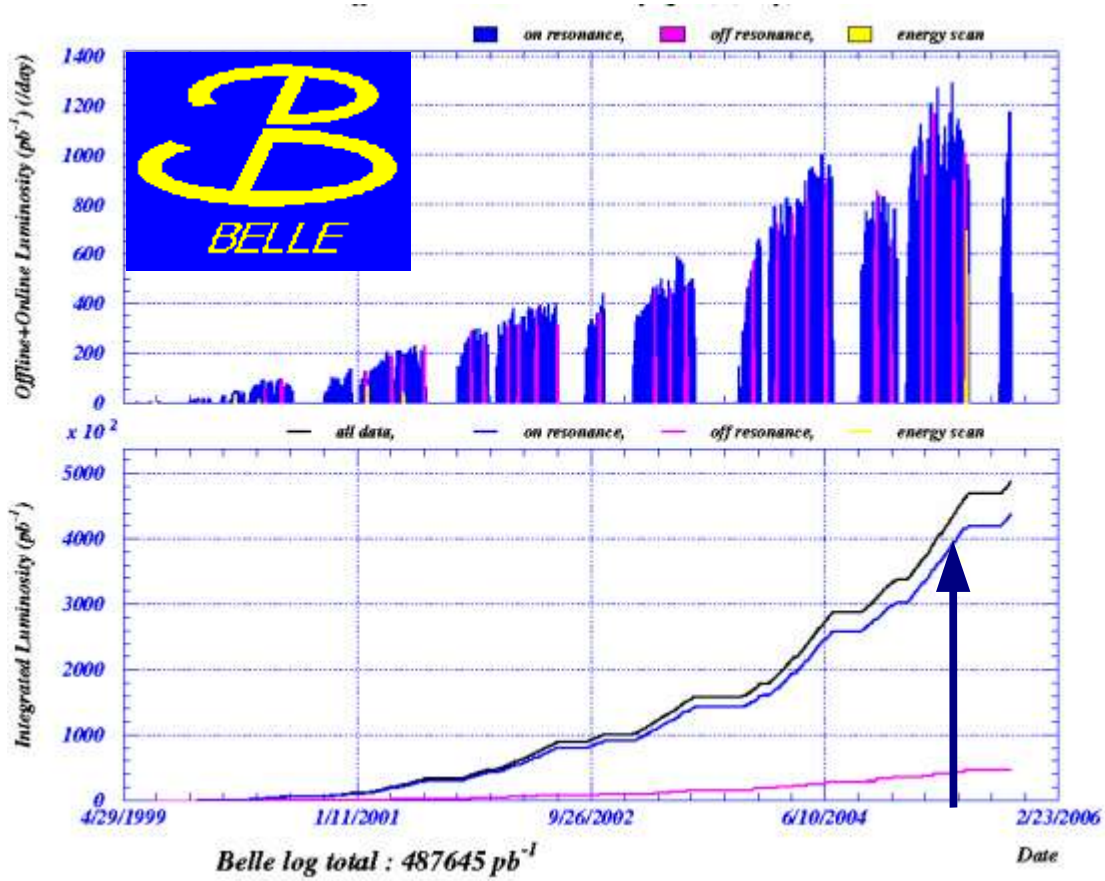
HER current = 1.0 A

LER current = 1.4 A

Daily Luminosity ~ $1\ fb^{-1}$

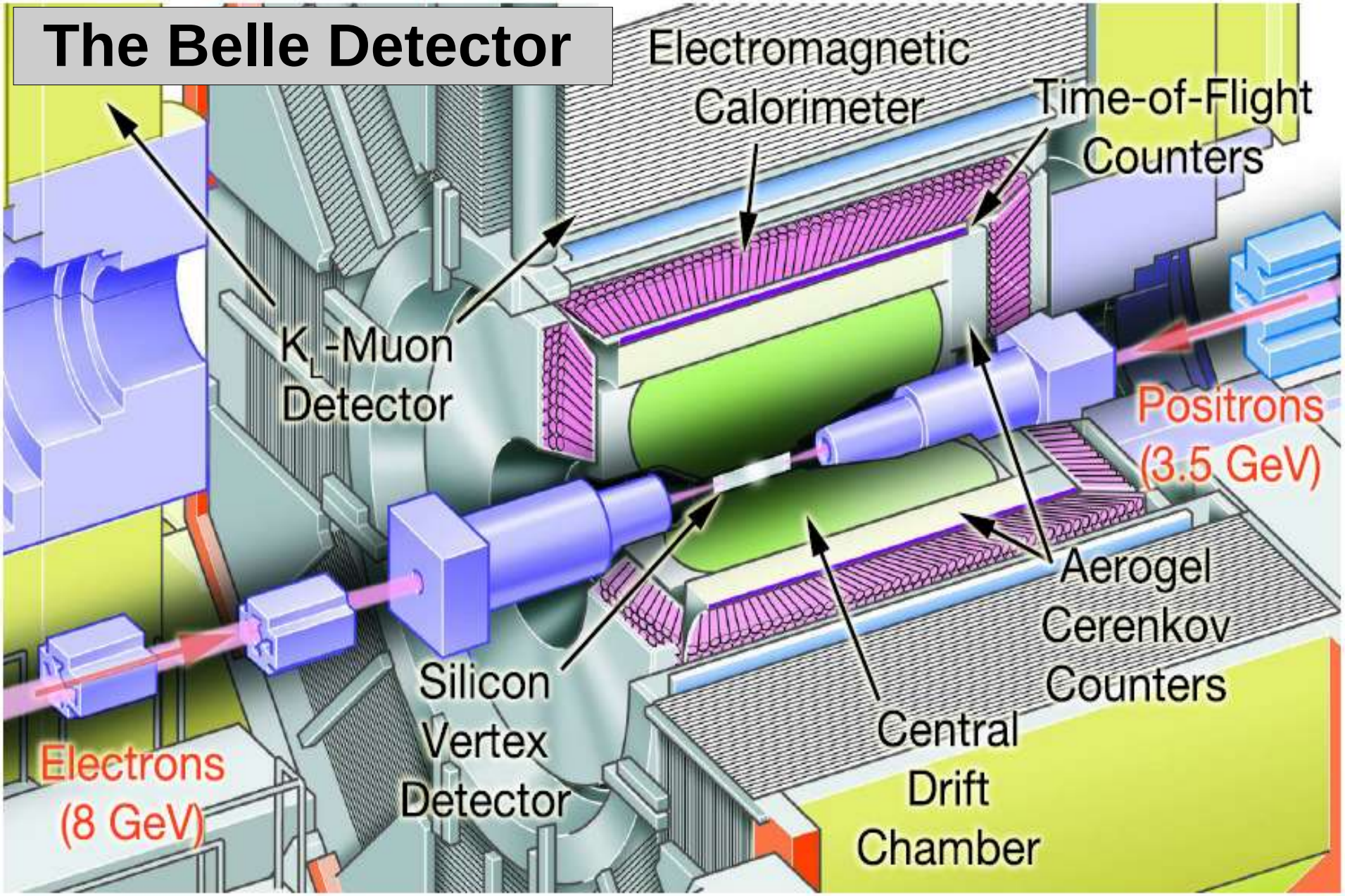
Integrated Luminosity: $487\ fb^{-1} (500 \times 10^6\ B\overline{B})$

A subset of data sample is analyzed for summer 2005



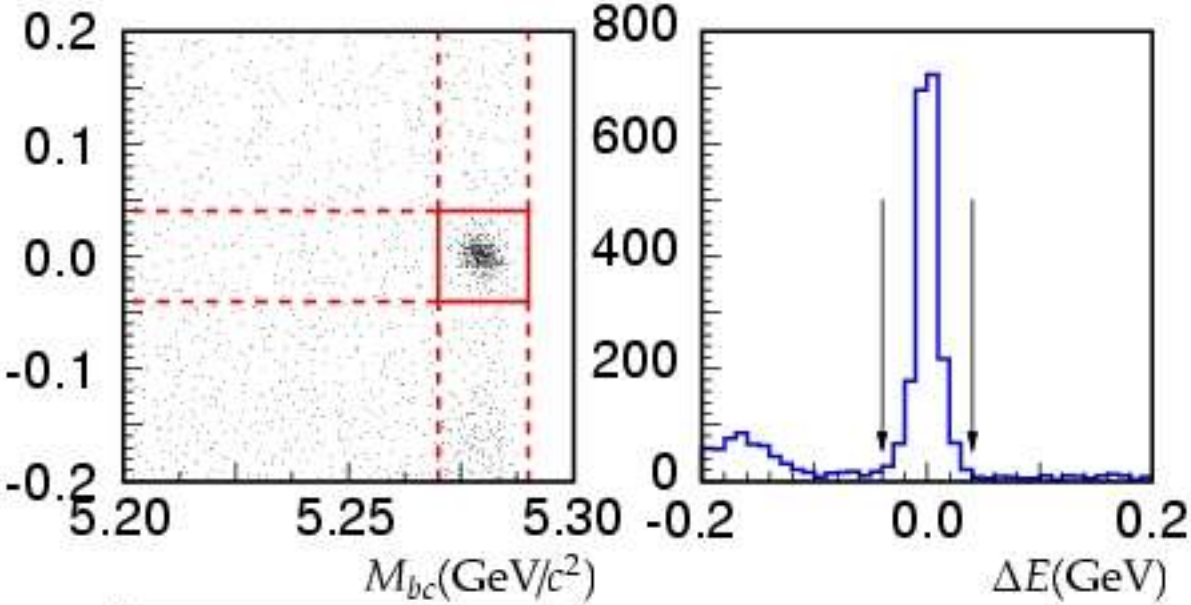
$$357\ fb^{-1} \equiv 386 \times 10^{6}\ B\,\overline{B}$$

Aerogel based PID system plays an important role in background reduction



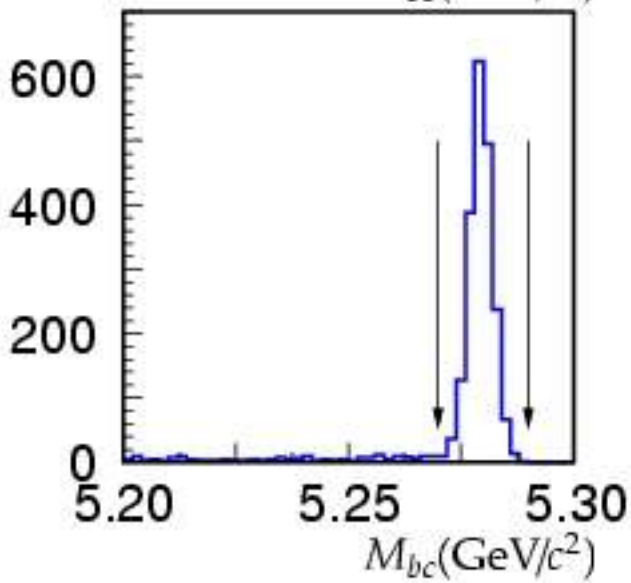
Reconstruction of B

B-meson Reconstruction: Kinematic variables



Energy difference:

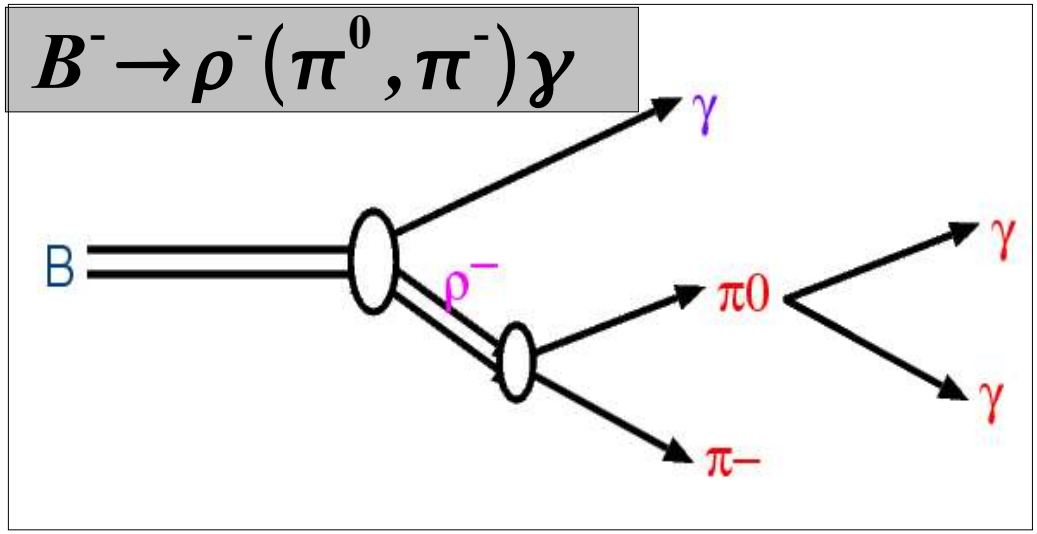
$$\Delta E \equiv \sum E_i - E_{CM}/2$$

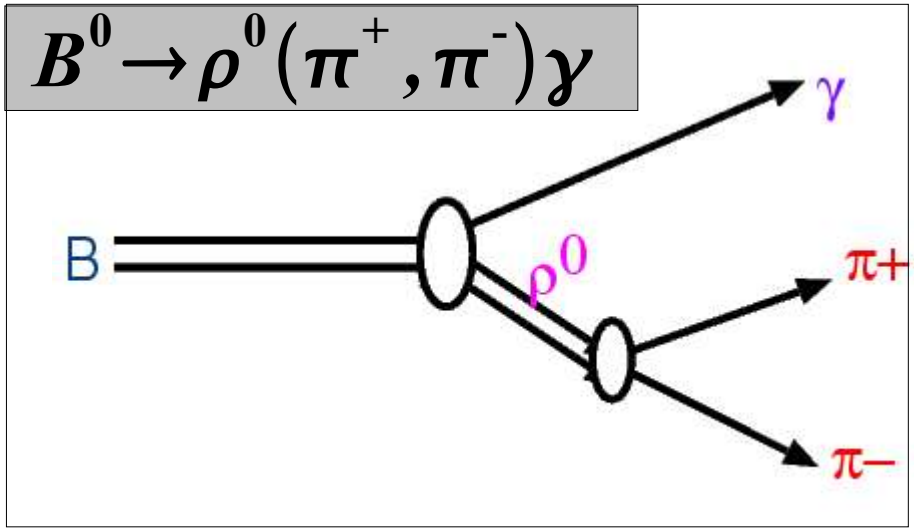


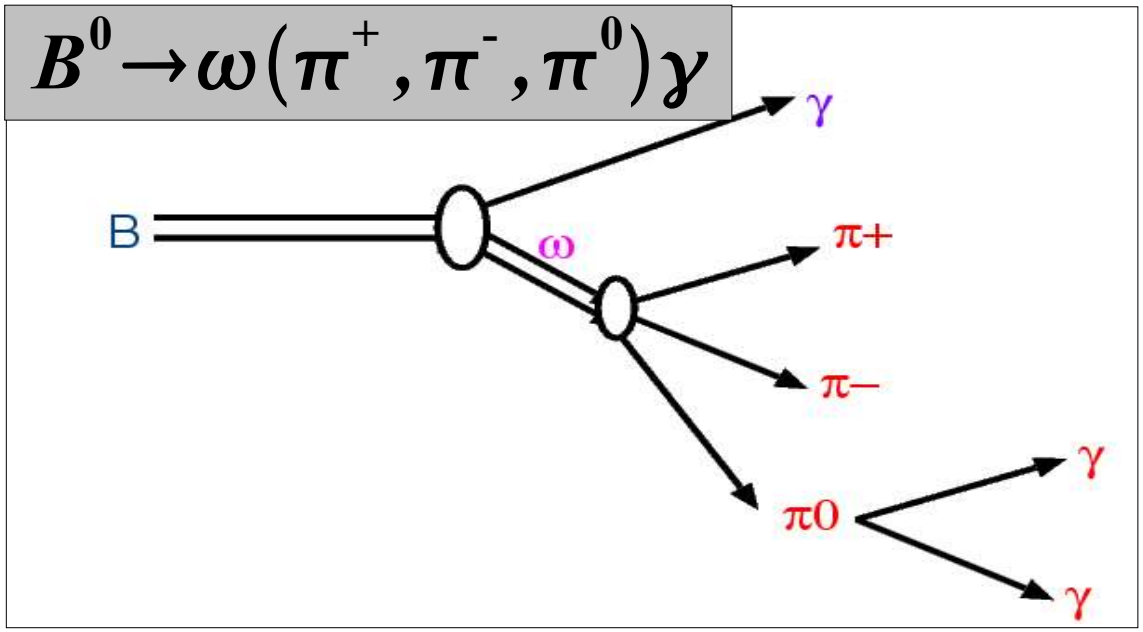
Beam-constrained mass:

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

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







B-meson reconstruction; cont' d

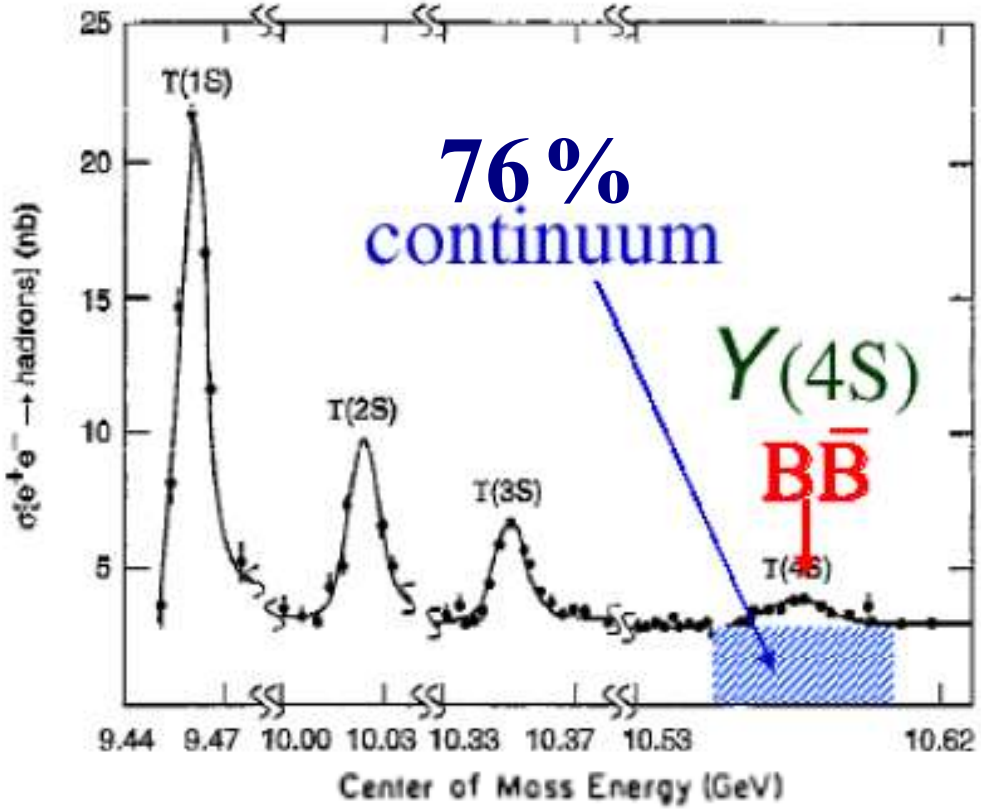
Photon selection	$1.8\,\mathrm{GeV} < E^*_\gamma < 3.4\,\mathrm{GeV}$ & $33^\circ < \theta_\gamma < 128^\circ$ Electromagnetic shower shape π^0 & η veto based on likelihood
Neutral pion selection $\pi^0 \to \gamma\gamma$	$E_\gamma > 50(100)\,\mathrm{MeV}$ for barrel (endcap) $\cos\theta_{\gamma_1,\gamma_2}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

Background suppression

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

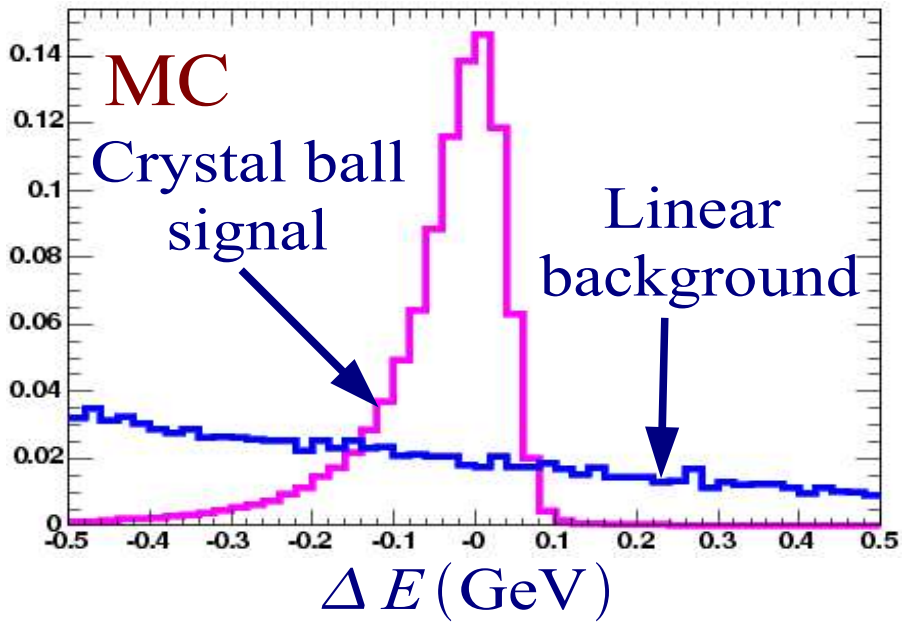
- Continuum: $e^+ e^- \to q\bar{q},\ q = u, d, s, c$
- $B \to K^* \gamma$
- other $b \to s\gamma$ modes
- $B \to \rho\pi^0(\eta), B \to \omega\pi^0(\eta)$
- and other charmless rare B modes

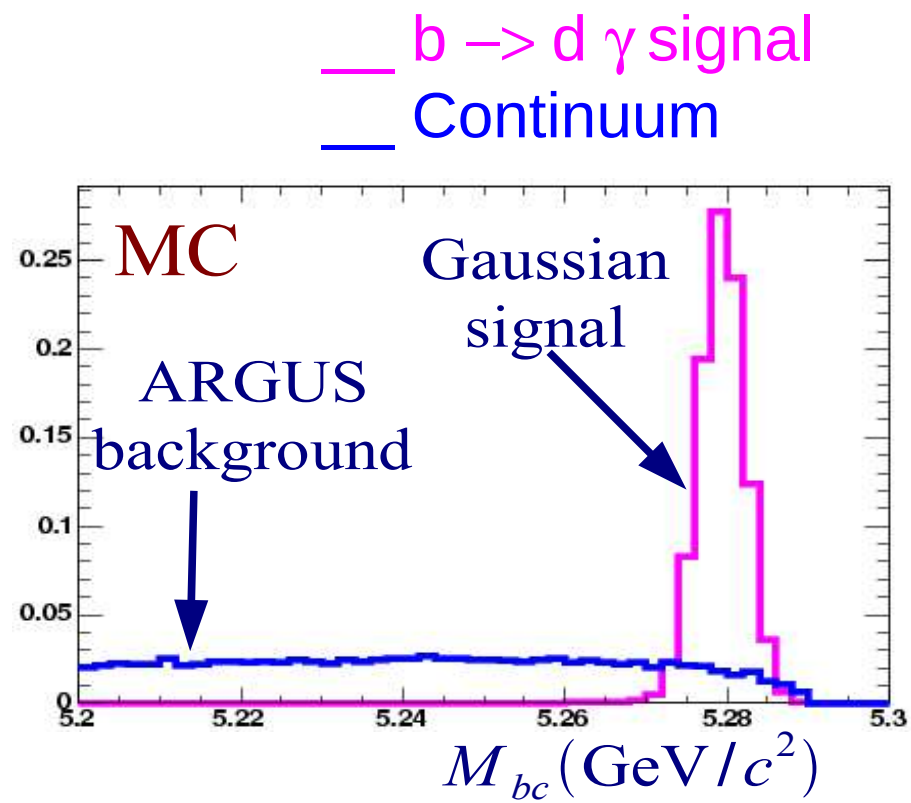
Huge Continuum background under the Y(4S)



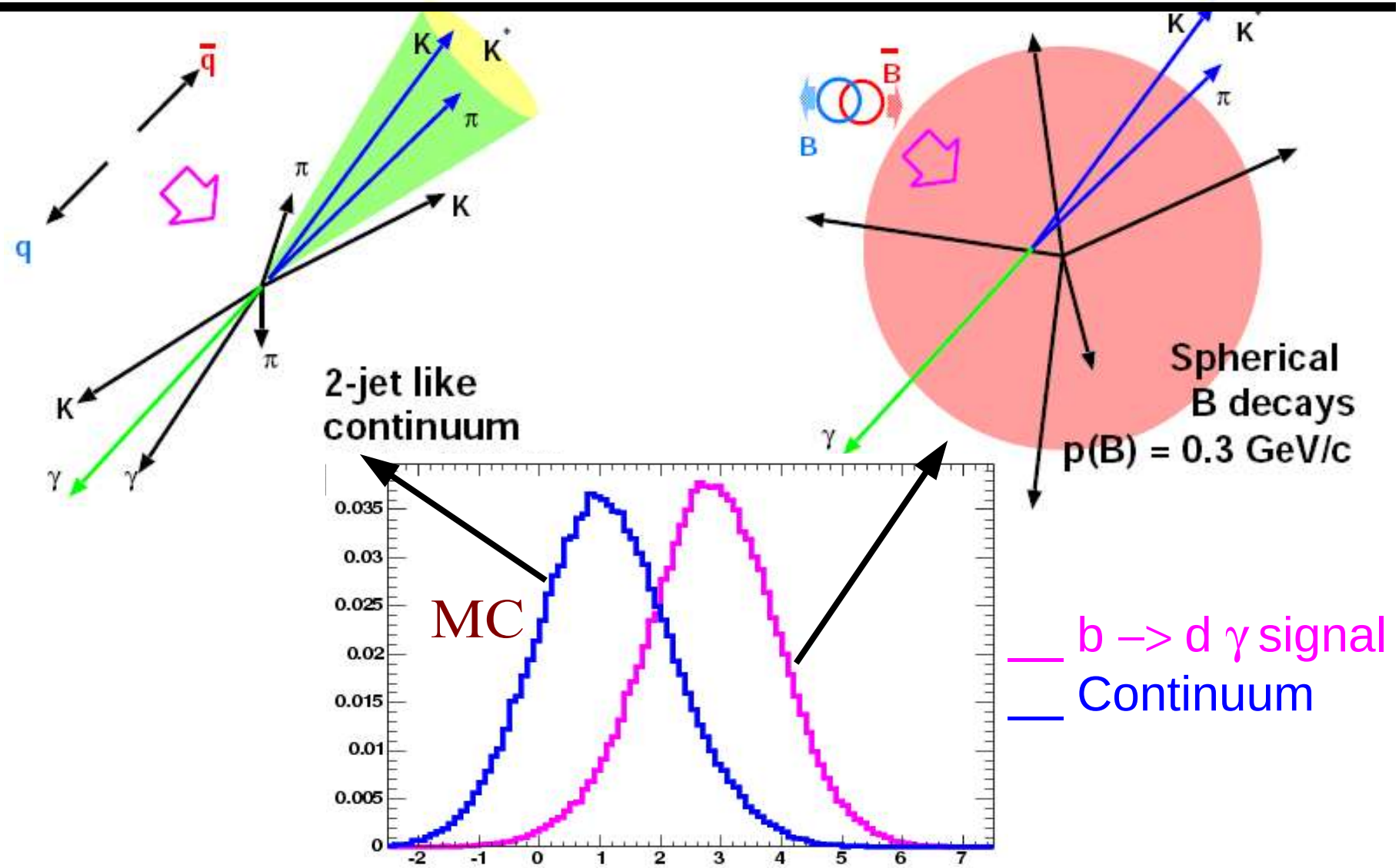
Continuum: $e^+e^- \rightarrow q\bar{q}\,(q = u, d, s, c)$

Signal and Continuum background shapes



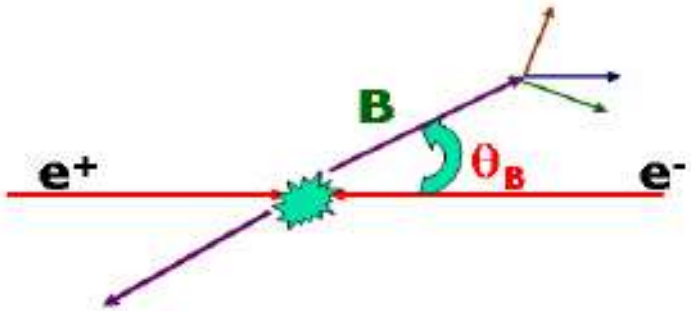


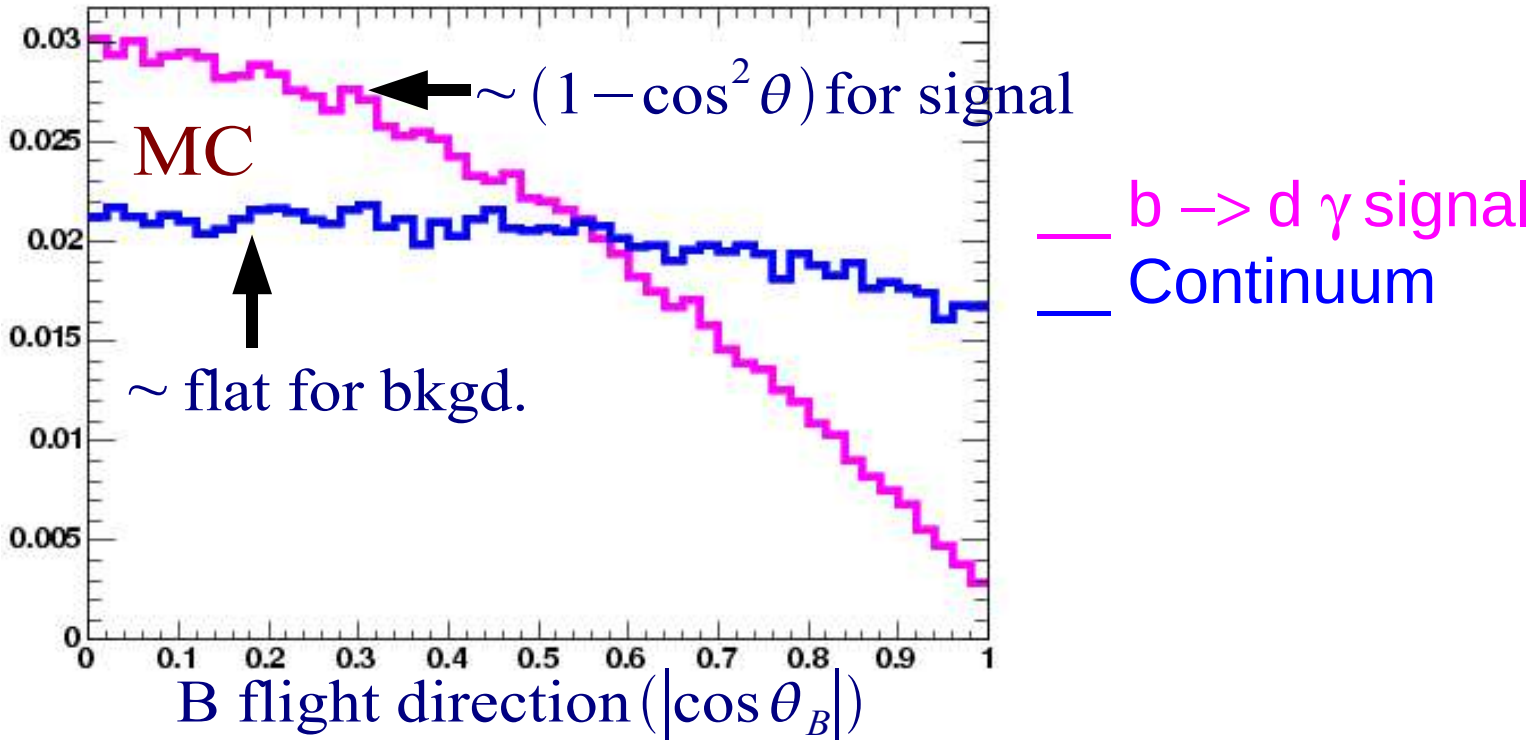
Fisher discriminant of event-shape variables is used to separate spherical B decays from jet-like continuum



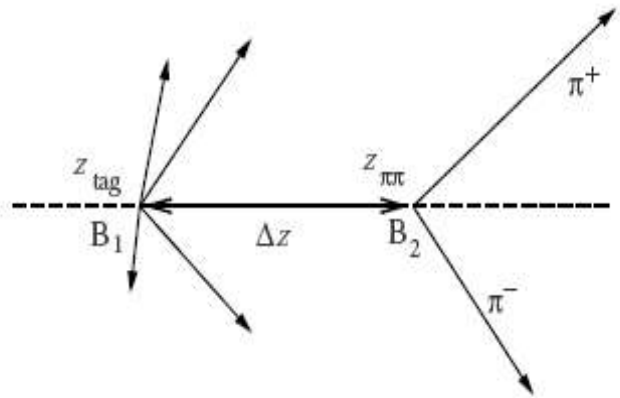
Fisher discriminant of event-shape variables (F)

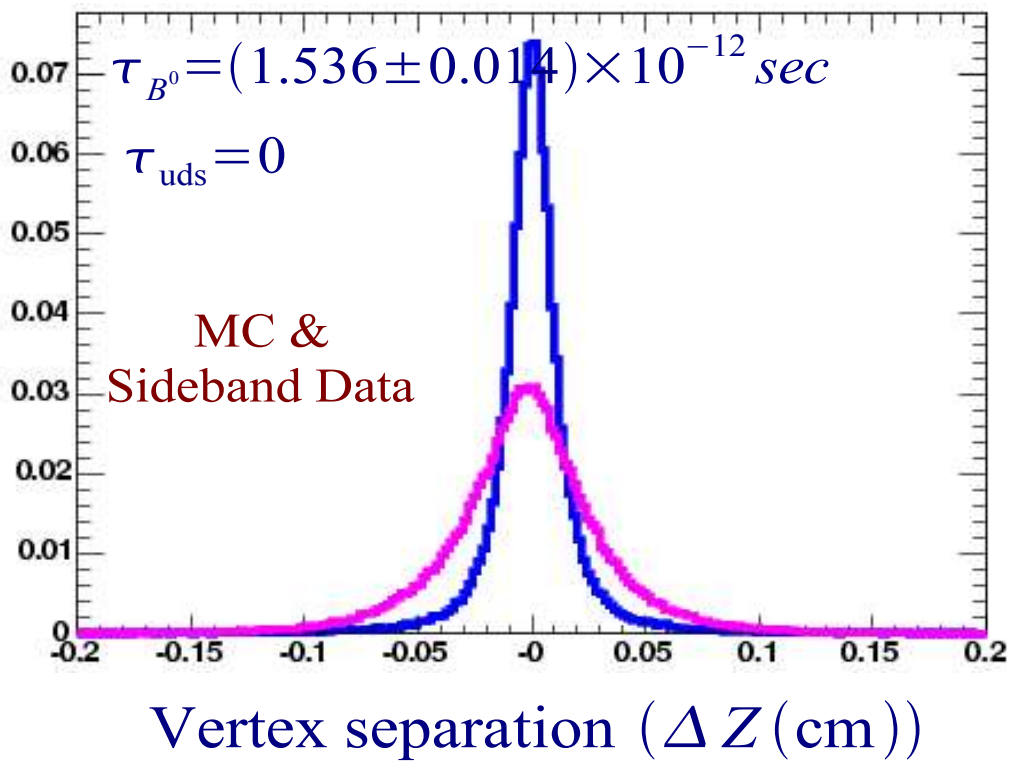
B flight direction in CM frame also discriminates B events from that of continuum





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



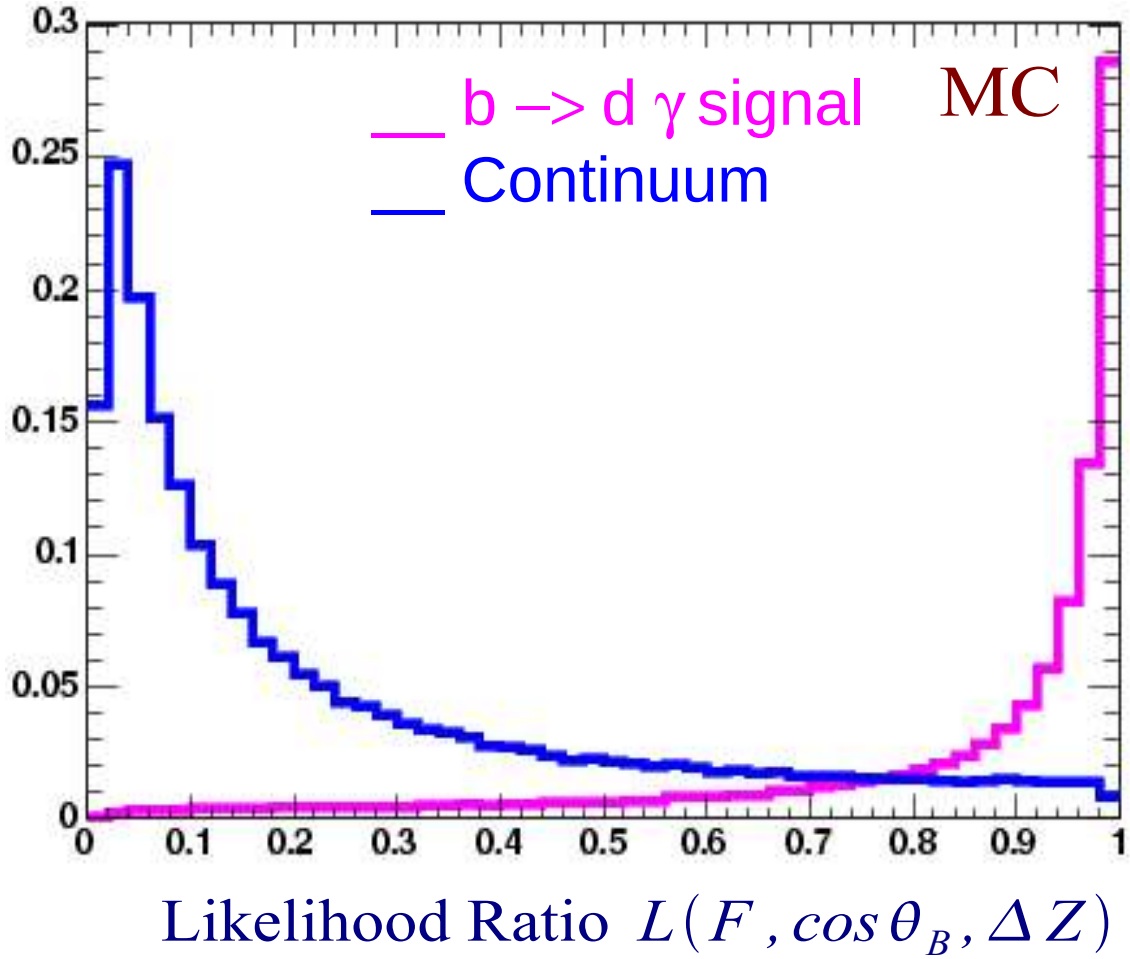


___ b –> d γ signal

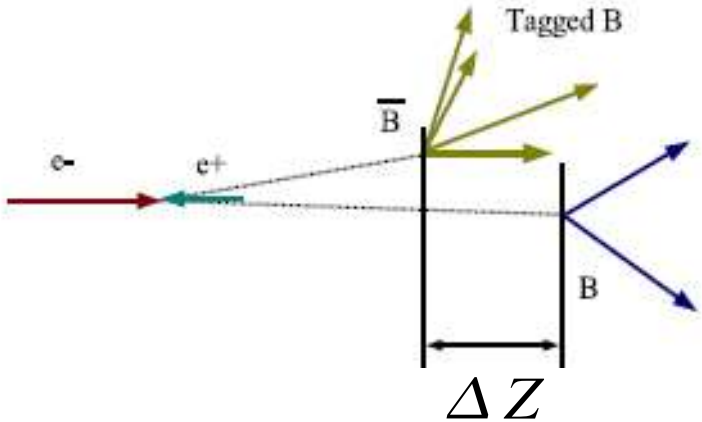
___ Continuum

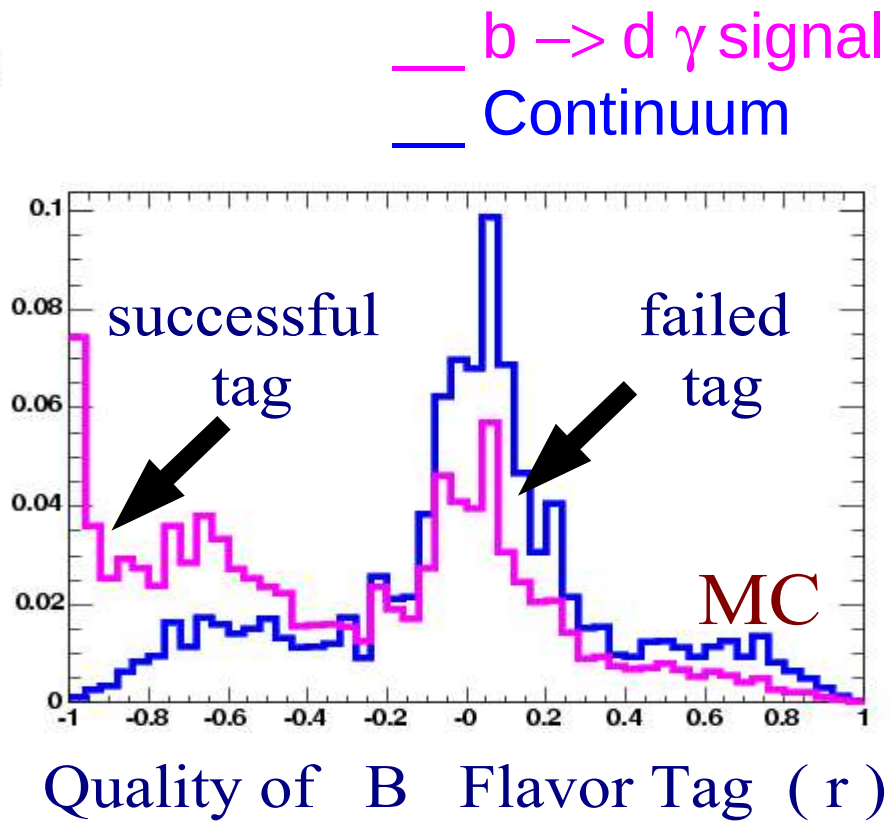
Two vertices are reconstructed in 80% of $b \to d\gamma$ events

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

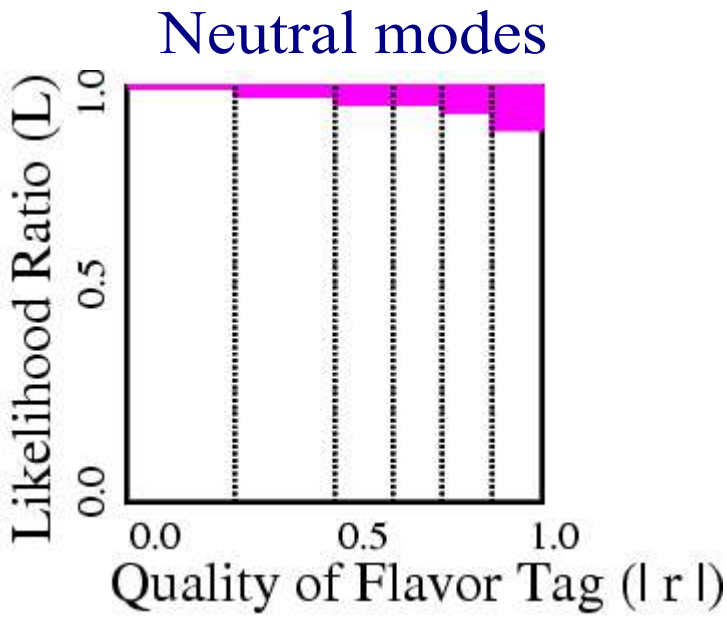


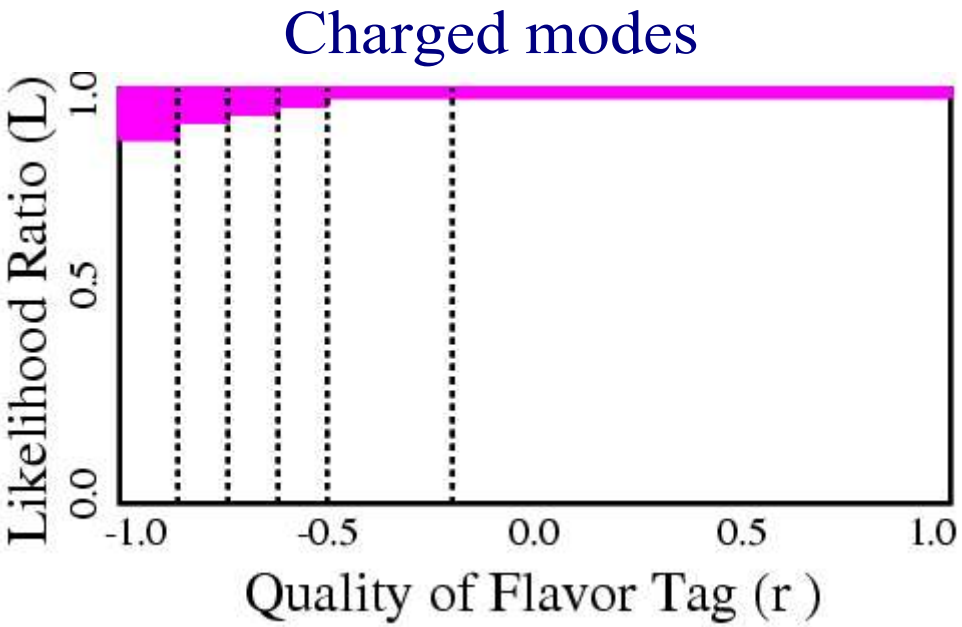
Additional discrimination is gained from "Quality of B Flavor Tag"





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





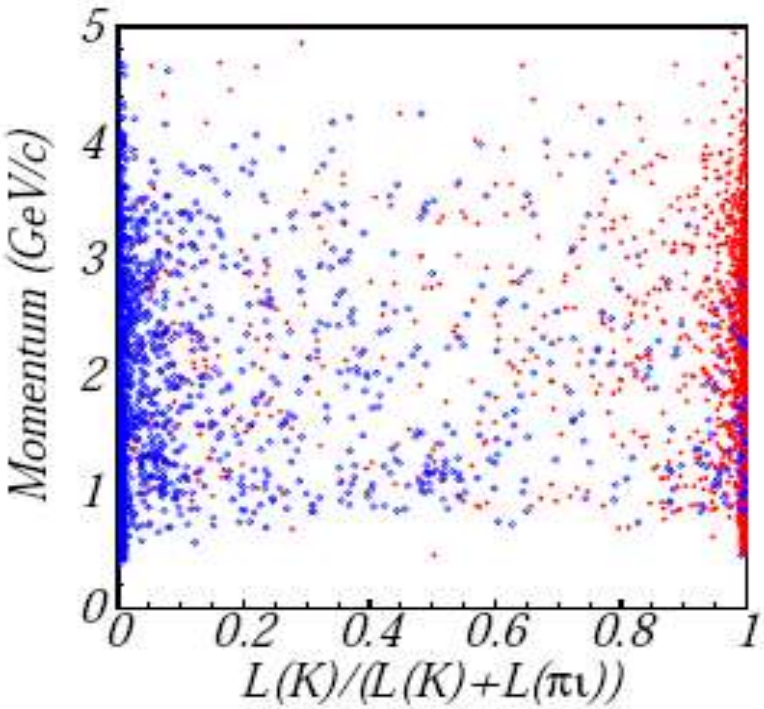
Neutral modes $\Rightarrow$ cut in |r|-L

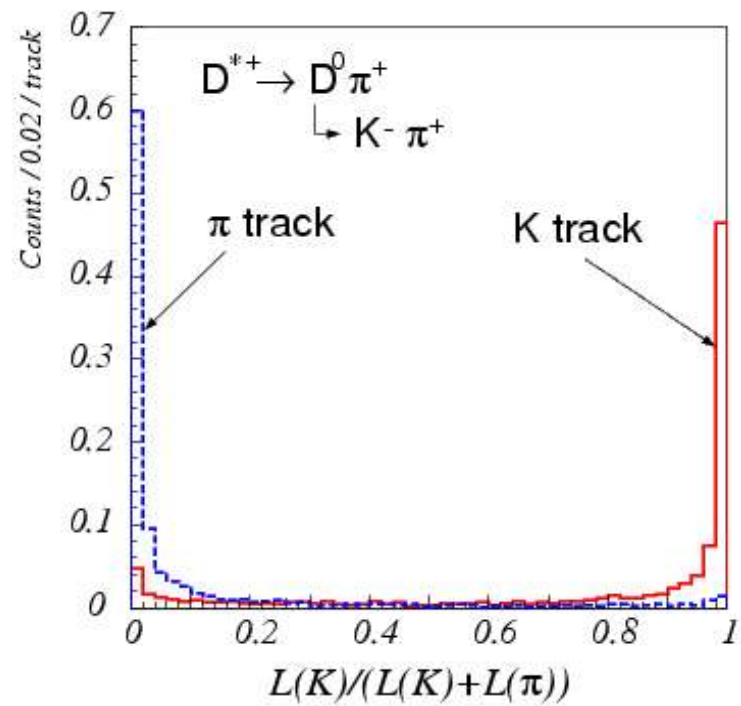
Charged modes $\Rightarrow$ cut in r-L

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 %

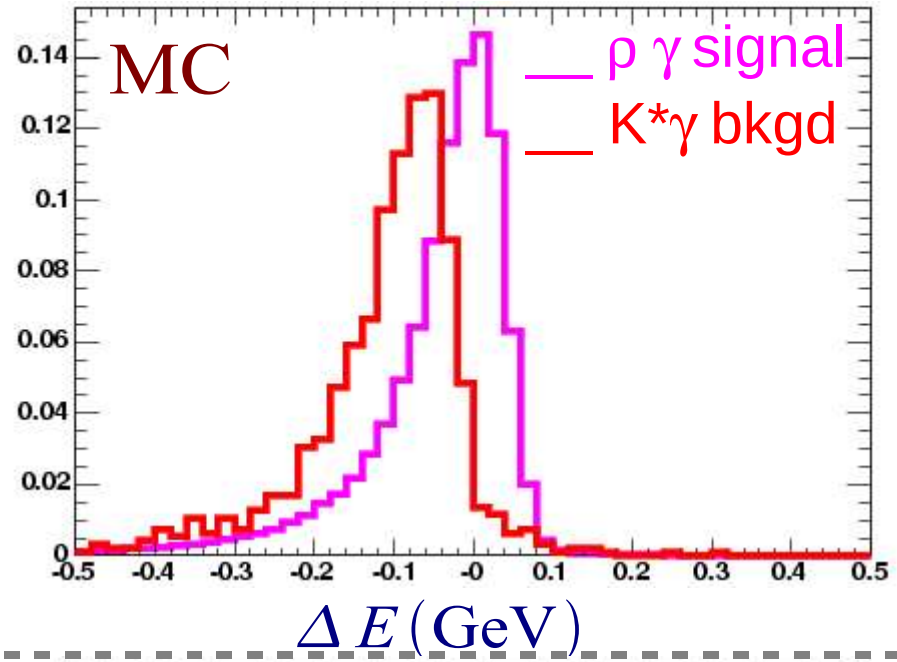
K/π − misidentification ⇒ $B \to K^* \gamma$ background



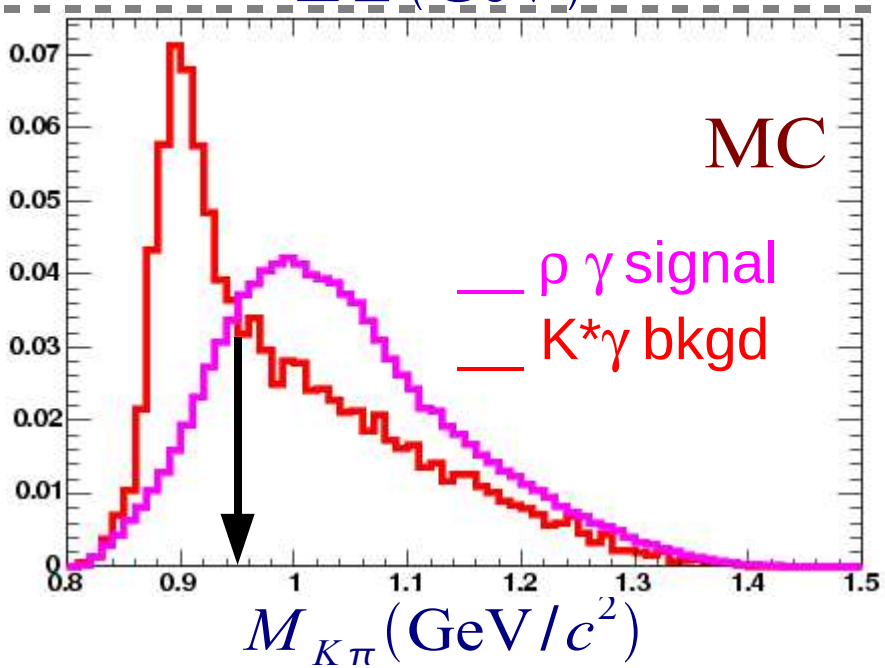


With KID < 0.15 , K/π fake rate ~ 5-10 %

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

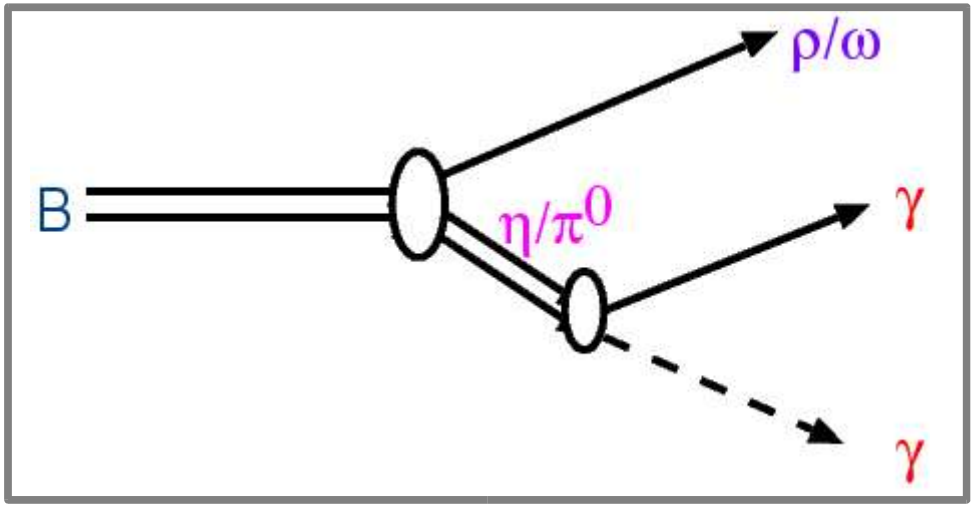


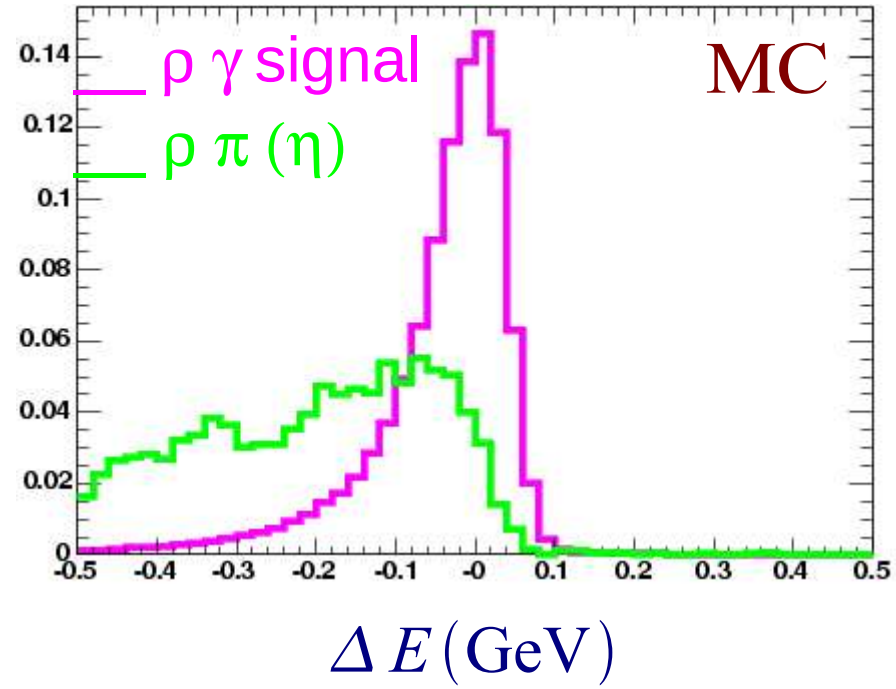
With $M_{K/\pi}$ cut we reject ~80% of $K^* \gamma$ events

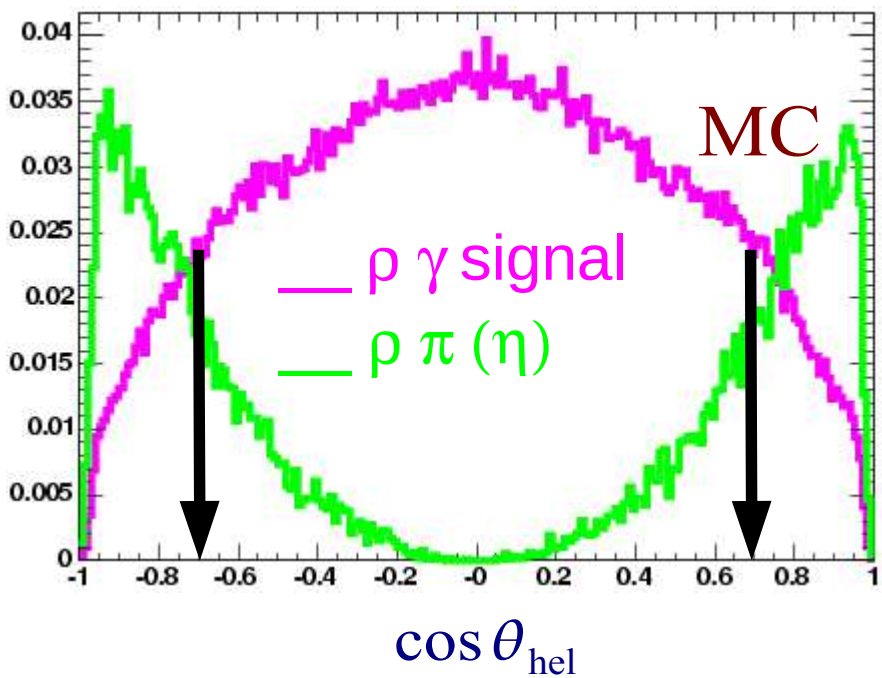
	$\rho^- \gamma$	$\rho^0 \gamma$
ϵ_{sig}	87%	63%
$\epsilon_{K^* \gamma}$	36%	18%

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







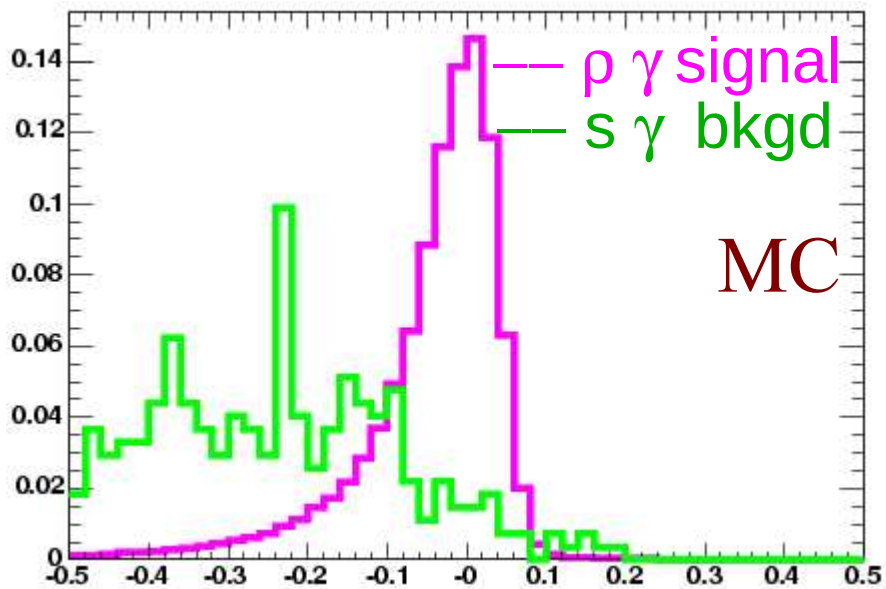
$\cos\theta_{\rm hel}$ optimized for $\frac{S}{\sqrt{B}}$

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

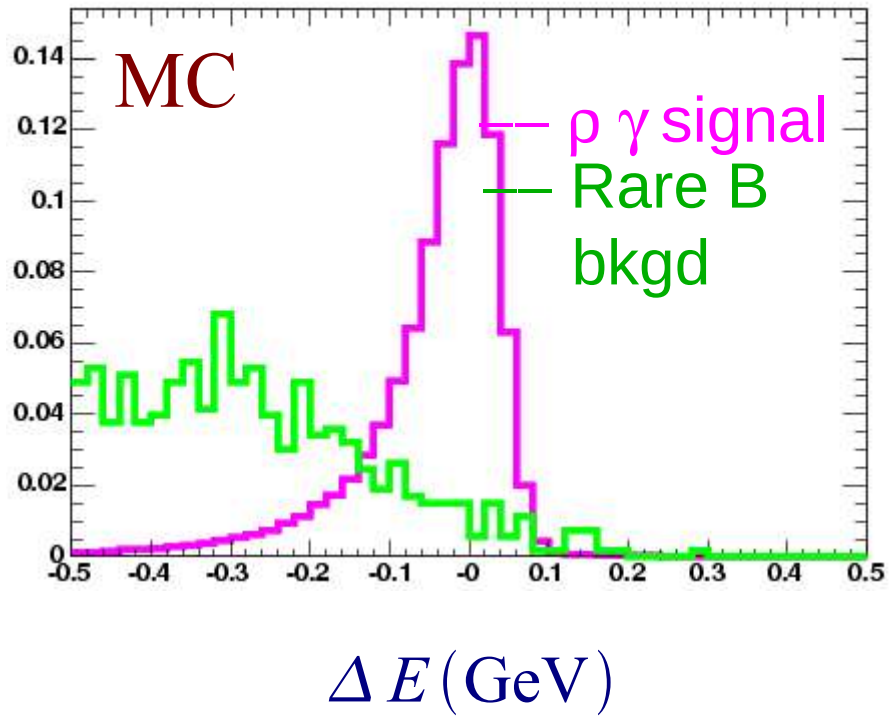
$\overline{B}^0 \to \rho^0 \gamma : |\cos\theta_{\rm hel}| < 0.70$

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

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



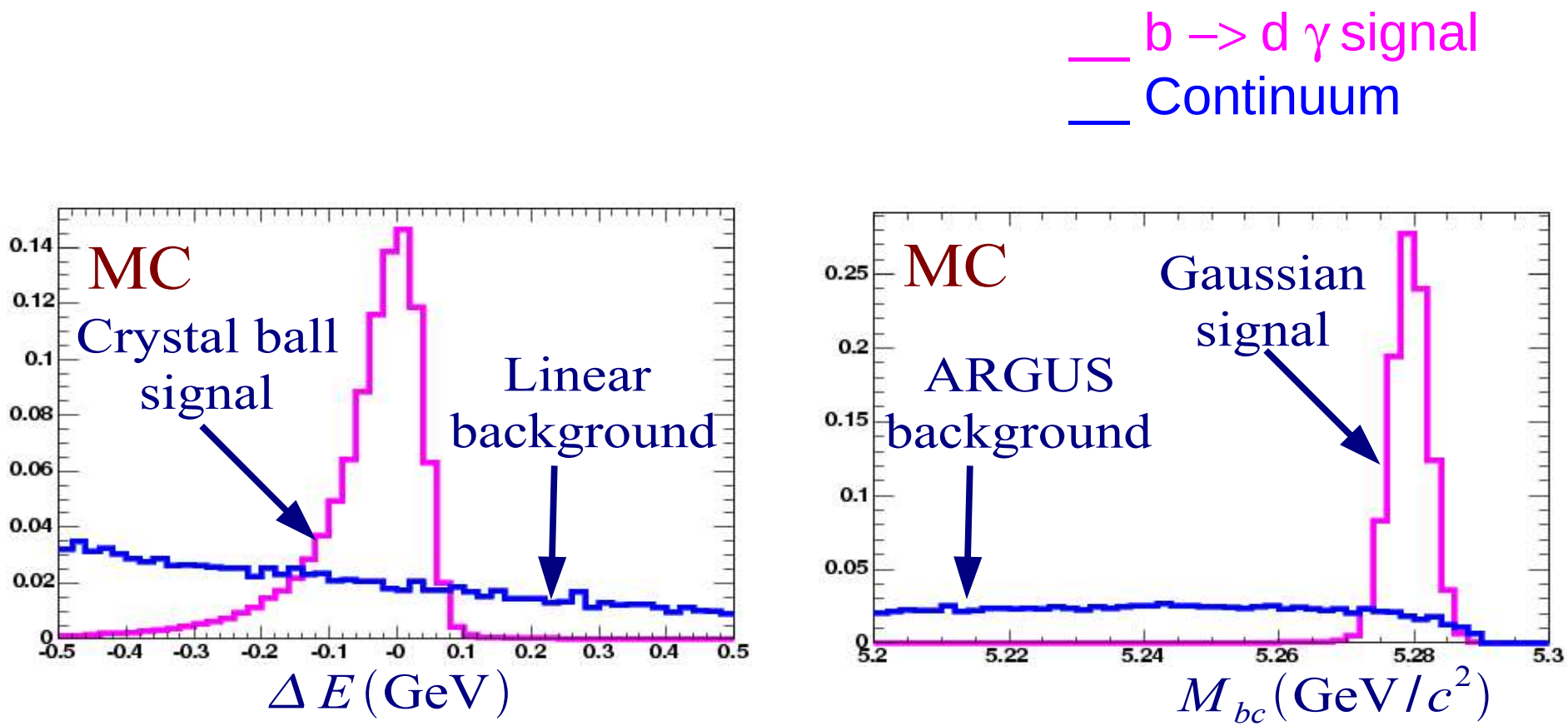
Charmless rare B background other than $B \to \rho(\omega)\pi^0$ & $B \to \rho(\omega)\eta$



Very small fraction of total background

Signal Extraction & Results

Signal and Continuum background shapes



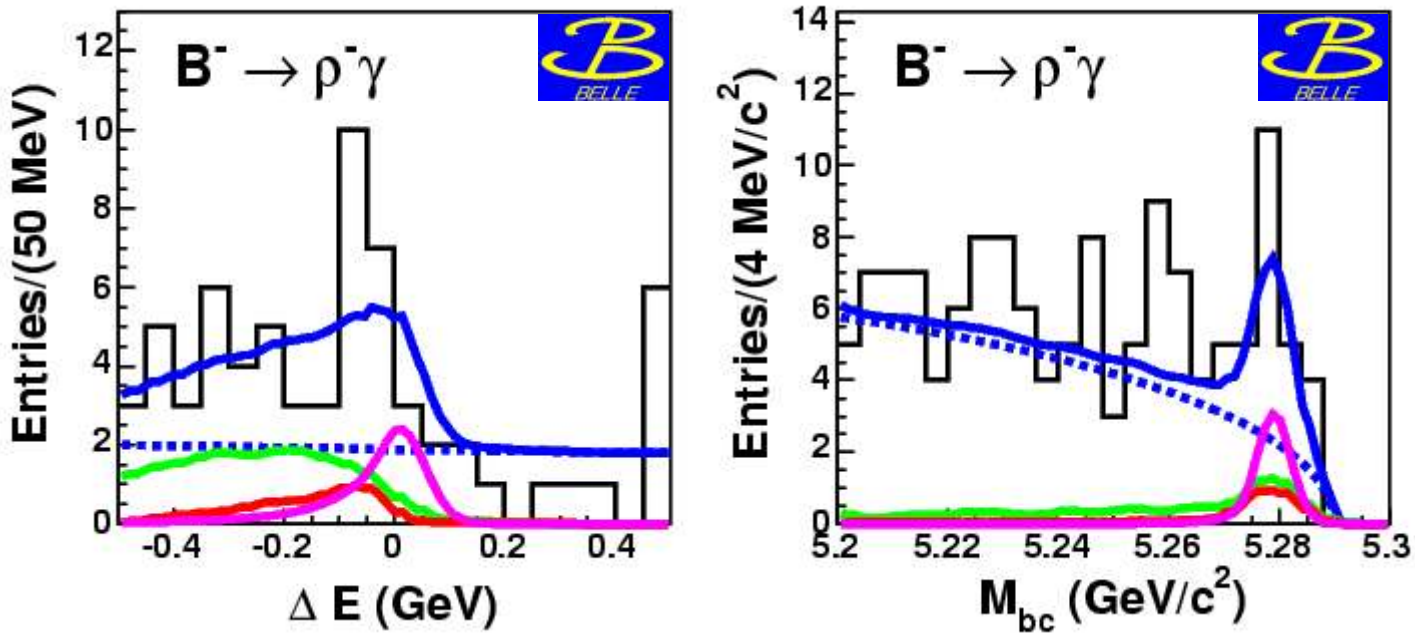
2D unbinned extended maximum likelihood fit is used for signal extraction

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 $B\bar{B}$



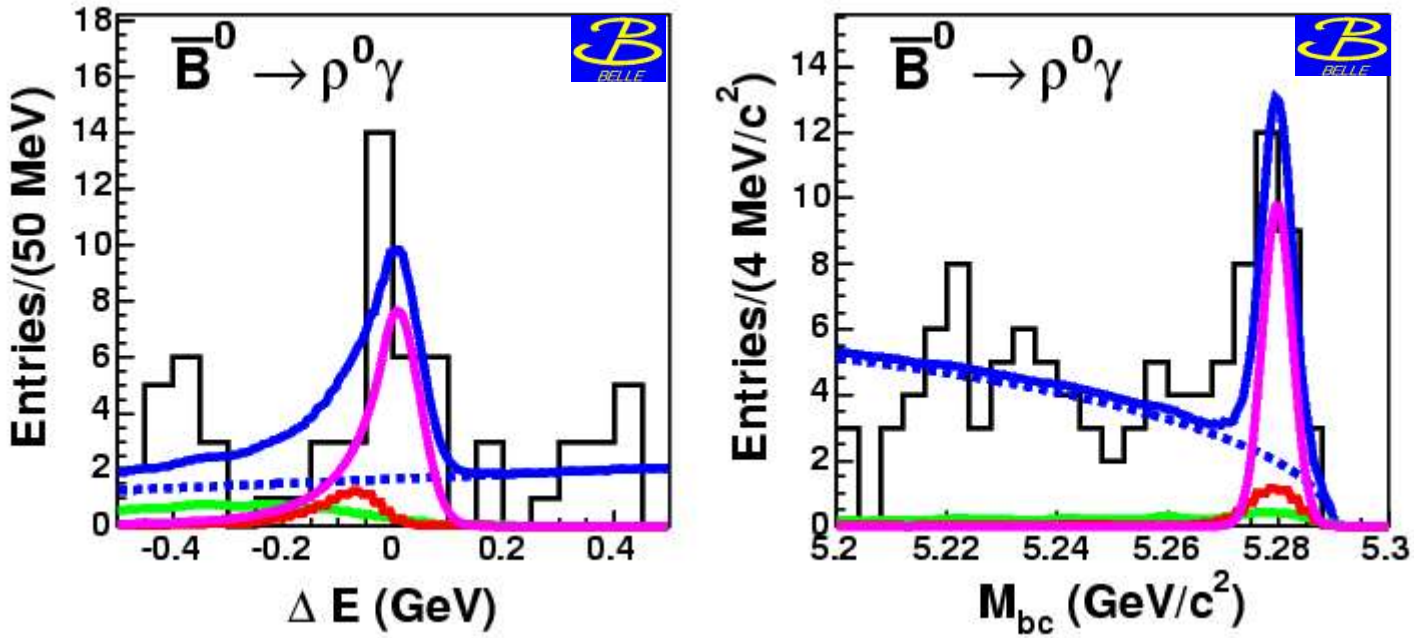
$$\text{Signal Yield} = 8.1^{+6.4}_{-5.5}(\text{stat.})^{+1.8}_{-1.6}(\text{syst.})$$

$$\text{Significance} = 1.5\sigma(\text{incl. syst.})$$

$$B(B \to \rho^- \gamma) = (0.55^{+0.43}_{-0.37}(\text{stat.})^{+0.12}_{-0.11}(\text{syst.}))\times 10^{-6}$$

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

Fit results: $\overline{B^0} \to \rho^0 \gamma$ 386 M $B\,\overline{B}$

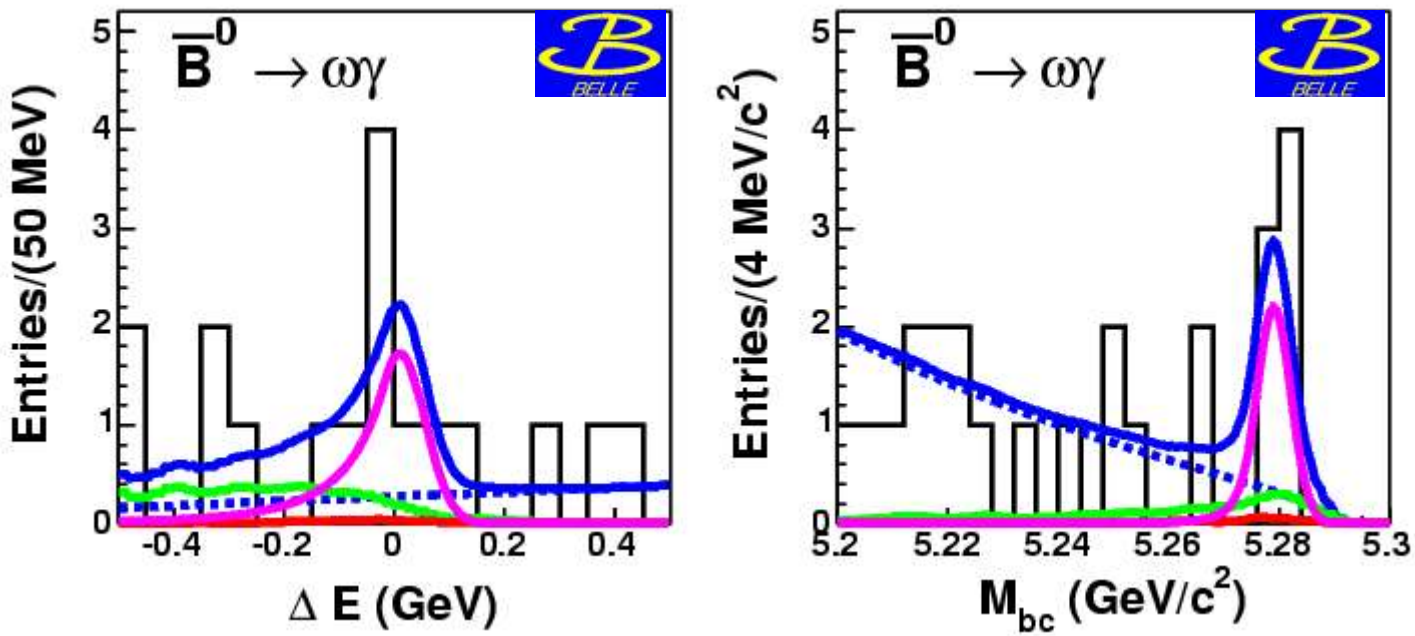


$$\text{Signal Yield} = 20.8^{+6.2}_{-5.5}(\text{stat.})^{+1.2}_{-1.4}(\text{syst.})$$

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

$$B(\overline{B^0} \to \rho^0 \gamma) = (1.17^{+0.35}_{-0.31}(\text{stat.})^{+0.09}_{-0.08}(\text{syst.}))\times 10^{-6}$$

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



$$\text{Signal Yield} = 8.9^{+3.5}_{-2.7}(\text{stat.})^{+0.7}_{-0.8}(\text{syst.})$$

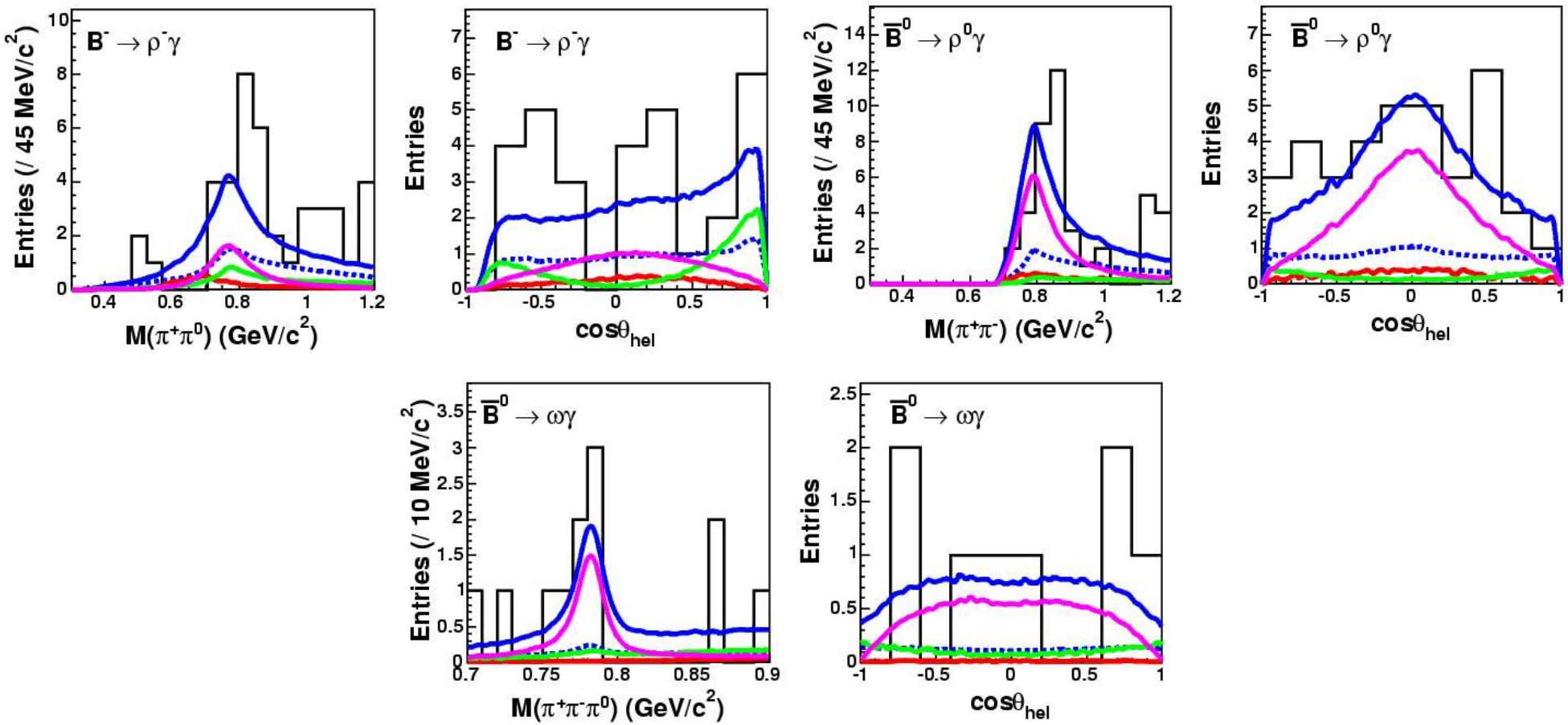
$$\text{Significance} = 2.6\,\sigma(\text{incl. syst.})$$

$$B(\overline{B}^0 \to \omega\gamma) = (0.58^{+0.35}_{-0.27}(\text{stat.})^{+0.07}_{-0.08}(\text{syst.}))\times 10^{-6}$$

Fit results are consistent with Mass and Helicity

Results from fit are superimposed on Mass and Helicity

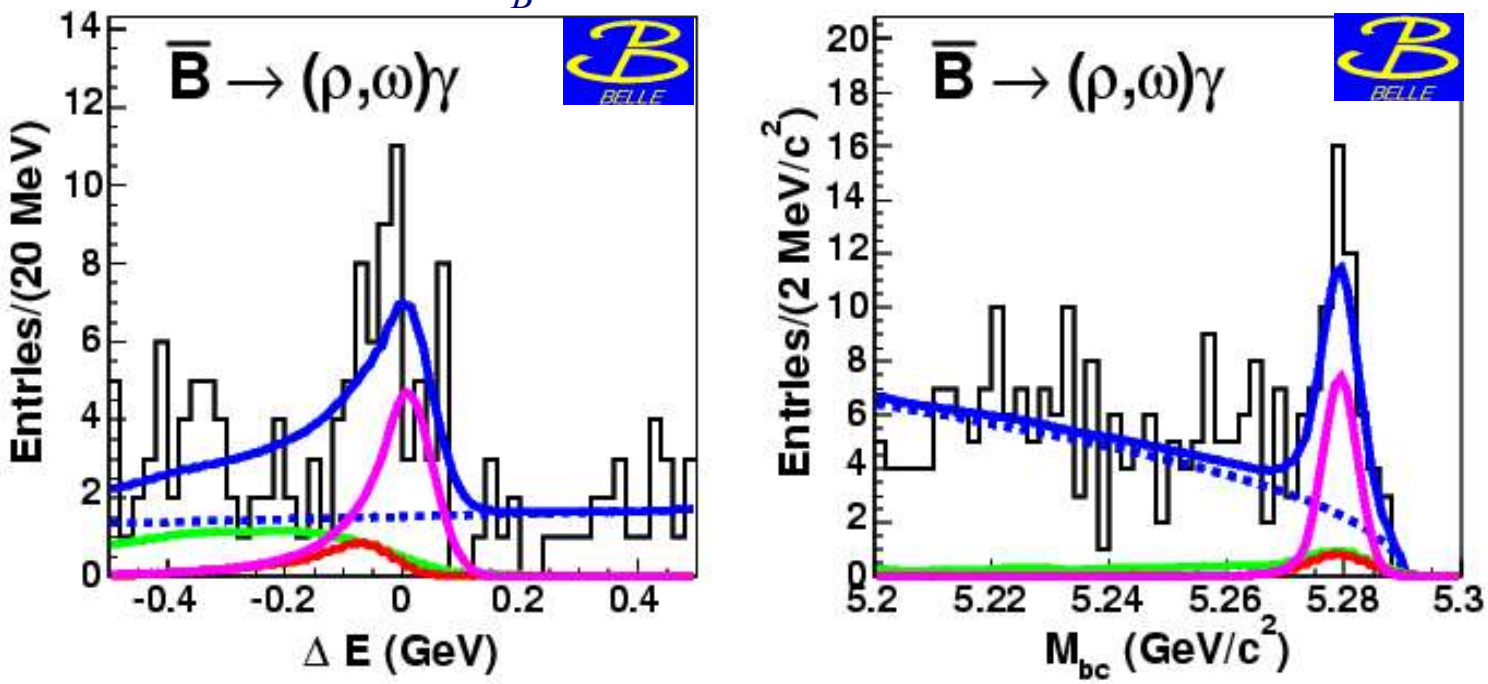
$M_{\pi\pi}$ & $\cos\theta_{\rm hel}$ deformed by $M_{K\pi}$ ($K^*\gamma$ veto variable)



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

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

using $\frac{\tau_{B^+}}{\tau_{B^0}}=1.076\pm0.008$



$$B(B\to(\rho,\omega)\gamma)= \quad (1.34^{+0.34}_{-0.31}(\text{stat.})^{+0.14}_{-0.10}(\text{syst.}))\times10^{-6}$$

$$\text{Significance}= \quad 5.5\,\sigma(\text{incl. syst.})$$

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

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

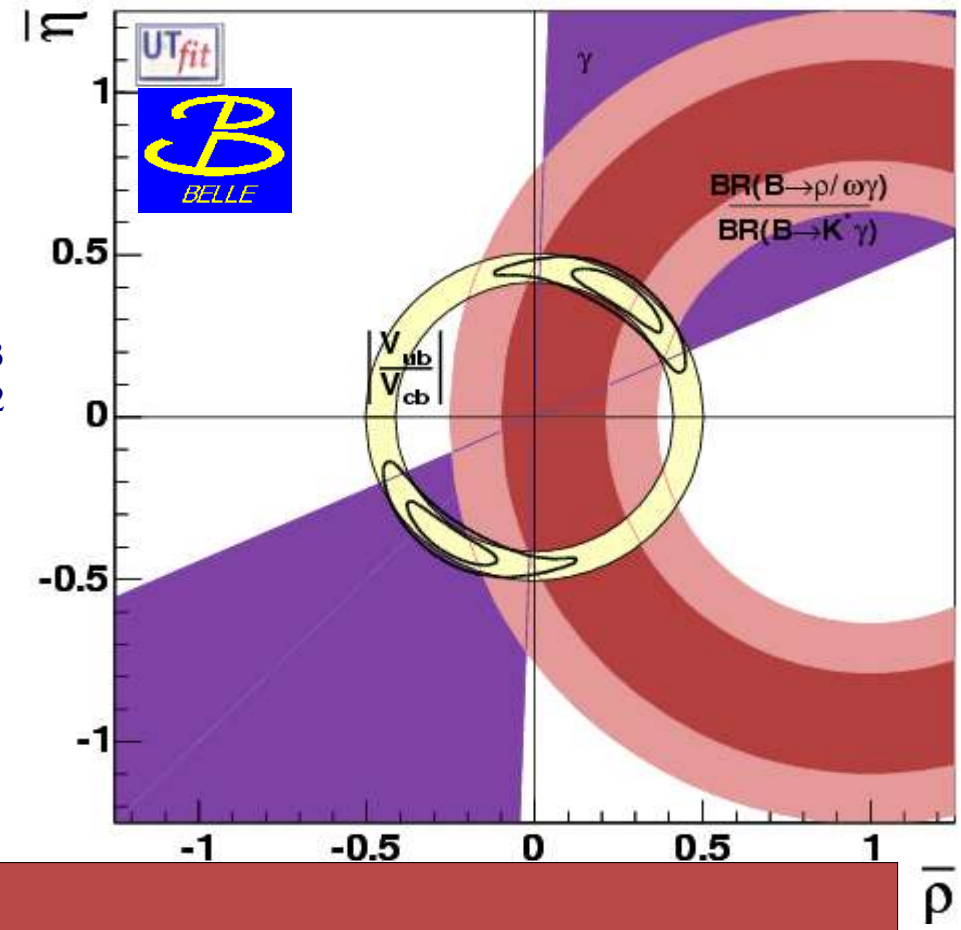
Form factor ratio $\zeta=0.85\pm0.10$

SU(3)-breaking effect $\Delta R=0.1\pm0.1$

$$\frac{B(B\to(\rho,\omega)\gamma)}{B(B\to K^*\gamma)}=0.032\pm0.008^{+0.003}_{-0.002}$$

$$0.143<\left|\frac{V_{td}}{V_{ts}}\right|<0.260$$

(95 % C.L. interval)



$$\left|\frac{V_{td}}{V_{ts}}\right|=0.200^{+0.026}_{-0.025}(\text{expt.})^{+0.038}_{-0.029}(\text{theo.})$$

Discussion

Comparison of Belle results with SM predictions

	Theory (Ali et. al)	**Belle Results**
$B(B \to (\rho, \omega)\gamma)$	$(1.38 \pm 0.42) \times 10^{-6}$	$(1.34^{+0.34}_{-0.31}{}^{+0.14}_{-0.10}) \times 10^{-6}$
$B(B^- \to \rho^- \gamma)$	$(0.90 \pm 0.34) \times 10^{-6}$	$(0.55^{+0.43}_{-0.37}{}^{+0.12}_{-0.11}) \times 10^{-6}$
$B(\overline{B}^0 \to \rho^0 \gamma)$	$(0.49 \pm 0.18) \times 10^{-6}$	$(1.17^{+0.35}_{-0.31}{}^{+0.09}_{-0.08}) \times 10^{-6}$
$B(\overline{B}^0 \to \omega \gamma)$	$(0.49 \pm 0.18) \times 10^{-6}$	$(0.58^{+0.35}_{-0.27}{}^{+0.07}_{-0.08}) \times 10^{-6}$
	$0.16 < \left\lvert \frac{V_{td}}{V_{ts}} \right\rvert < 0.29$	$0.14 < \left\lvert \frac{V_{td}}{V_{ts}} \right\rvert < 0.26$
	(68 % CL)	(95 % CL)

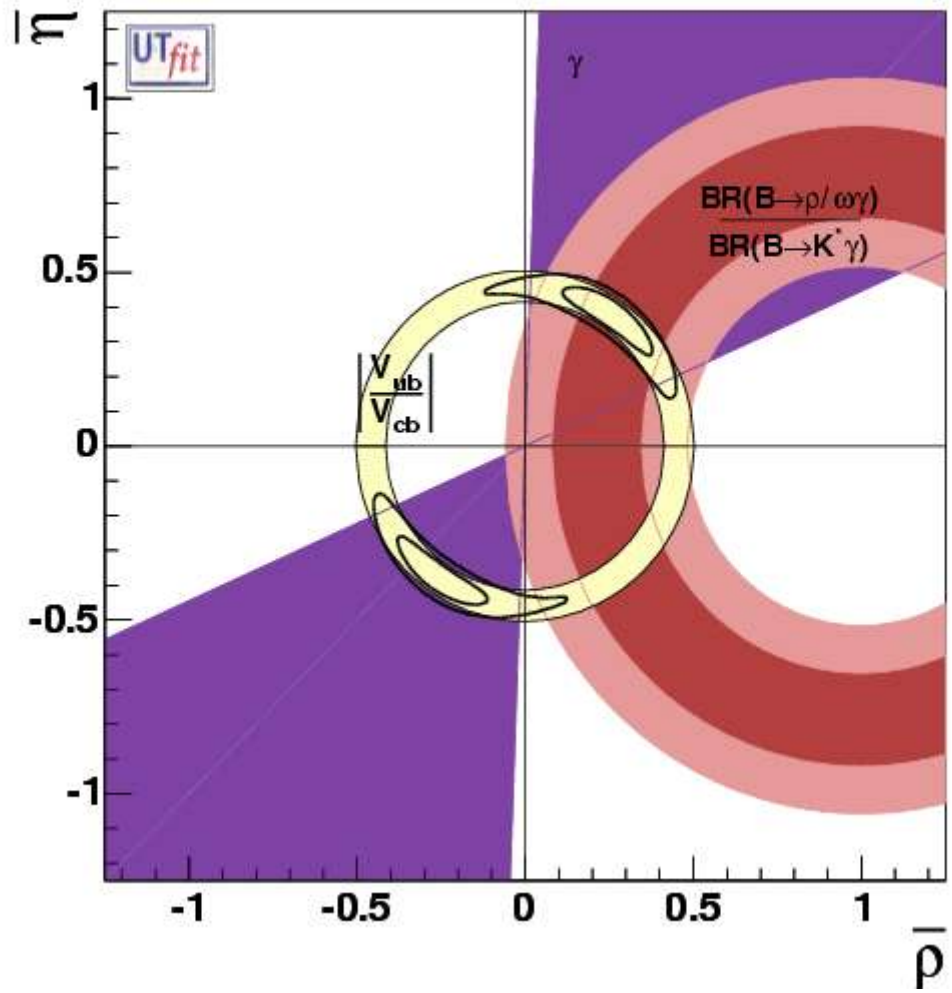
Comparison of Belle and BaBar results

	$386\,\mathrm{M}\,B\overline{B}$ **Belle**	$221\,\mathrm{M}\,B\overline{B}$ **BaBar**
$B(B\to(\rho,\omega)\gamma)$	$(1.34^{+0.34+0.14}_{-0.31-0.10})\times10^{-6}$	$<1.2\times10^{-6}$
$B(B^-\to\rho^-\gamma)$	$(0.55^{+0.43+0.12}_{-0.37-0.11})\times10^{-6}$	$<1.8\times10^{-6}$
$B(\overline{B}^0\to\rho^0\gamma)$	$(1.17^{+0.35+0.09}_{-0.31-0.08})\times10^{-6}$	$<0.4\times10^{-6}$
$B(\overline{B}^0\to\omega\gamma)$	$(0.58^{+0.35+0.07}_{-0.27-0.08})\times10^{-6}$	$<1.0\times10^{-6}$
	$0.143<\left\lvert\frac{V_{td}}{V_{ts}}\right\rvert<0.26$	<0.19
	(95 % CL)	(90 % CL)

hep-ex/0506079
[to be submitted to PRL]

PRL 94, 011801 (2005)

Belle and BaBar results combined



(Belle's 386M + BaBar's 211M) $B\,\overline{B}$

assuming isospin symmetry

We can test Isospin violation with the following approach

This is the isospin relation we use

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

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	$0.36^{+0.25}_{-0.26}(0.9\sigma)$

Summary

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

$$B(B \to (\rho, \omega)\gamma) = (1.34^{+0.34}_{-0.31}{}^{+0.14}_{-0.10}) \times 10^{-6}$$

$$B(B^- \to \rho^- \gamma) = (0.55^{+0.43}_{-0.37}{}^{+0.12}_{-0.11}) \times 10^{-6}$$

$$B(\overline{B}^0 \to \rho^0 \gamma) = (1.17^{+0.35}_{-0.31}{}^{+0.09}_{-0.08}) \times 10^{-6}$$

$$B(\overline{B}^0 \to \omega \gamma) = (0.58^{+0.35}_{-0.27}{}^{+0.07}_{-0.08}) \times 10^{-6}$$

and determines

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.200^{+0.026}_{-0.025}(\text{expt.})^{+0.038}_{-0.029}(\text{theo.})$$

- 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

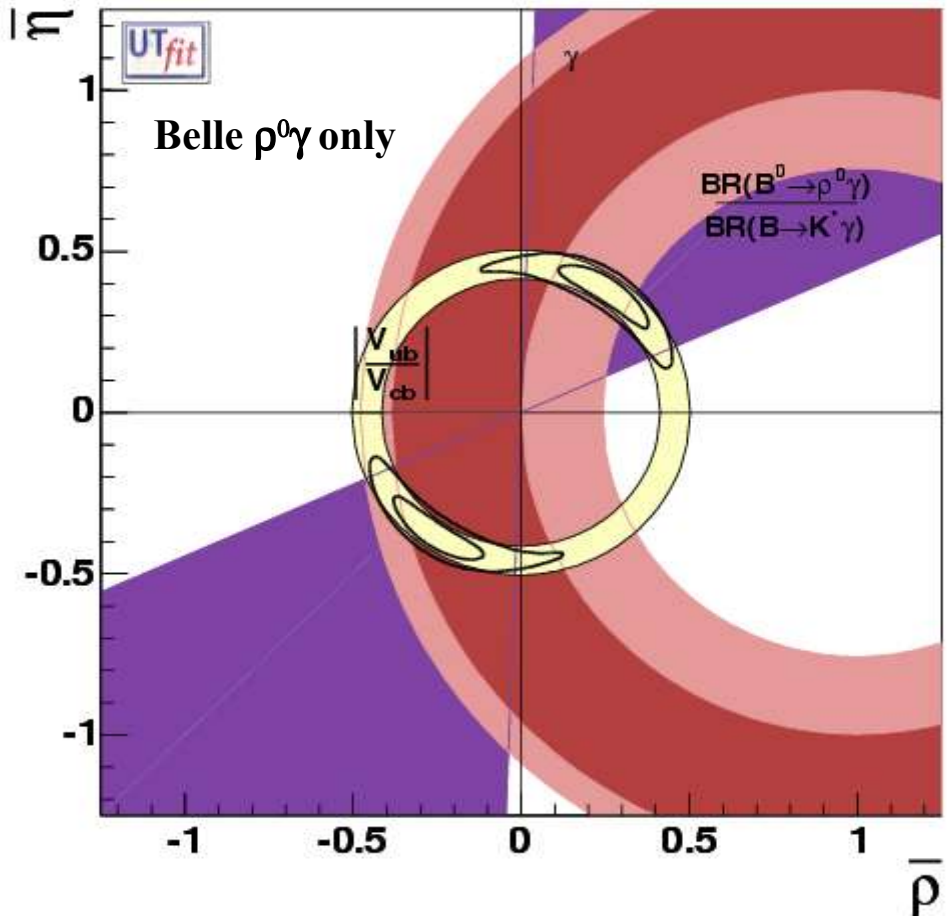
References

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

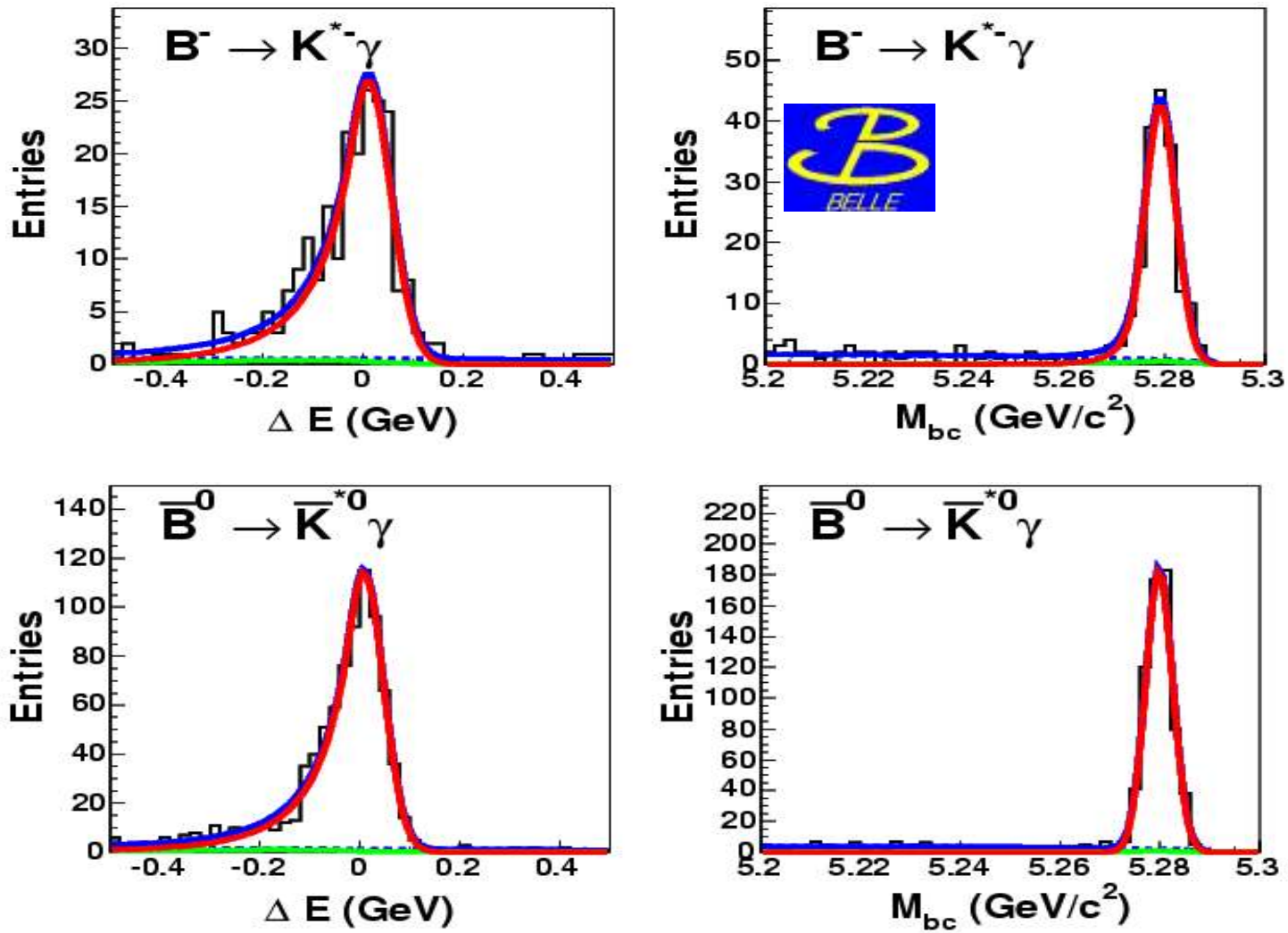
and references therein...

Thank you all

$|V_{td}/V_{ts}|$ from $B \to \rho^0 \gamma$



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



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

BaBar 211 $M\ B\overline{B}$

Mode	n_{sig}	n_{cont}	n_{peak}	Significance (σ)	$\epsilon(\%)$	$\mathcal{B}(10^{-6})$	$\mathcal{B}(10^{-6})$ 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	—	$(0.72^{+0.48}_{-0.39} \pm 0.28) \times 10^{-6}$	1.4×10^{-6}

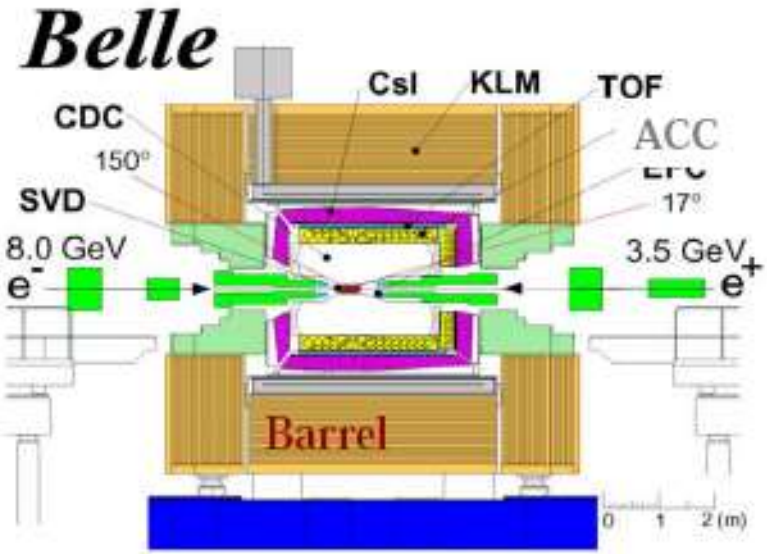
Belle 386 $M\ B\overline{B}$

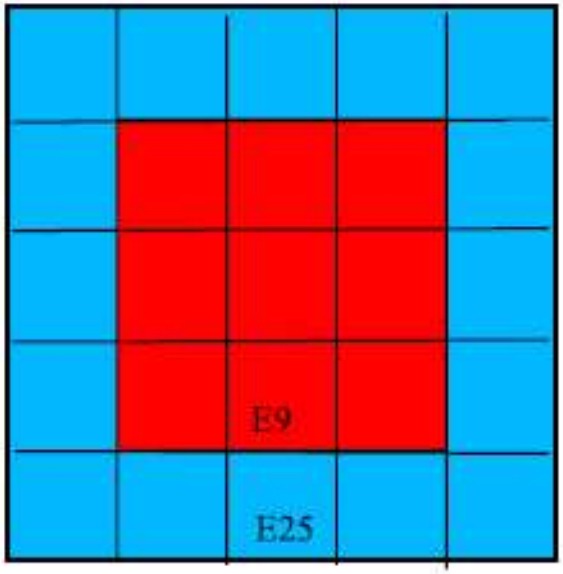
Mode	Yield	Σ	Efficiency (%)	$\mathcal{B}$ $(\times 10^{-6})$
$B^- \to \rho^-\gamma$	8.2	1.5	3.83 ± 0.23	$0.55^{+0.43}_{-0.37}{}^{+0.12}_{-0.11}$
$\overline{B}^0 \to \rho^0\gamma$	20.8	5.1	4.61 ± 0.29	$1.17^{+0.35}_{-0.31}{}^{+0.09}_{-0.08}$
$\overline{B}^0 \to \omega\gamma$	5.9	2.6	2.61 ± 0.21	$0.58^{+0.35}_{-0.27}{}^{+0.07}_{-0.08}$
$B \to (\rho, \omega)\gamma$	37.2	5.5	—	$1.34^{+0.34}_{-0.31}{}^{+0.14}_{-0.10}$

(BF in $\times 10^{-6}$ (stat only) and significance (with syst))

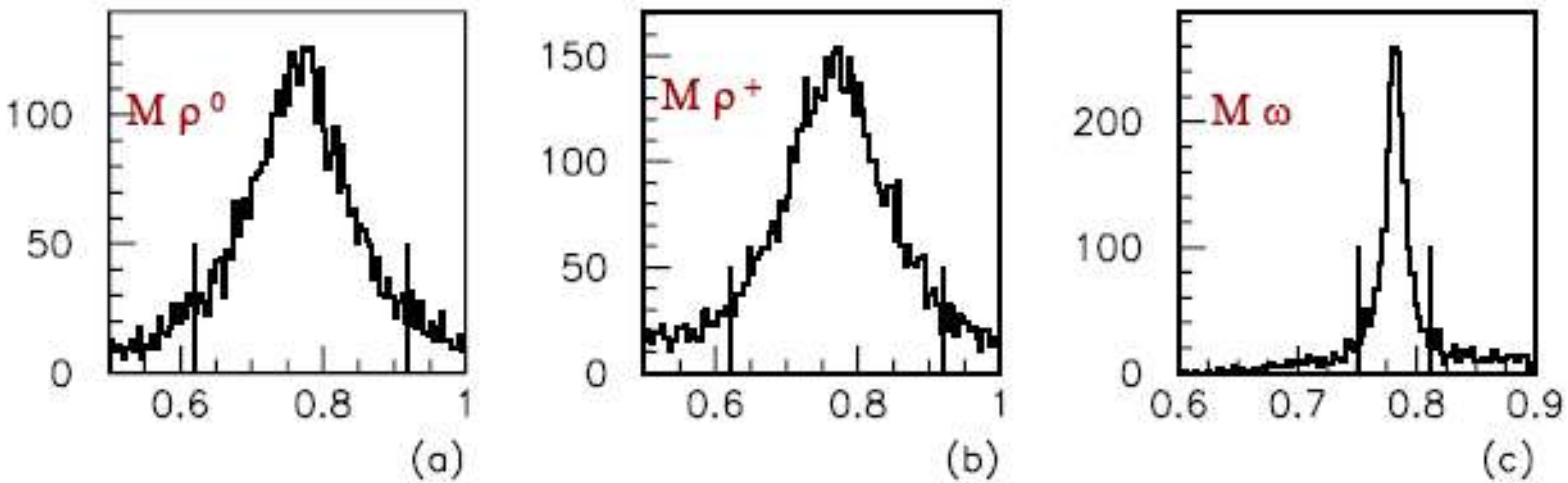
mode	140 fb^{-1}	110 fb^{-1}	100 fb^{-1}	250 fb^{-1}	350 fb^{-1}
$\rho^+\gamma$	$1.77^{+0.90}_{-0.76}$ 2.6	$0.11^{+0.57}_{-0.40}$ 0.1	$-0.58^{+0.90}_{-0.70}$ 0.5	$0.79^{+0.53}_{-0.44}$ 1.9	$0.55^{+0.43}_{-0.37}$ 1.5
$\rho^0\gamma$	$0.58^{+0.48}_{-0.37}$ 1.7	$1.21^{+0.66}_{-0.53}$ 3.1	$1.87^{+0.78}_{-0.64}$ 4.0	$0.87^{+0.38}_{-0.33}$ 3.4	$1.17^{+0.35}_{-0.31}$ 5.1
$\omega\gamma$	$0.27^{+0.47}_{-0.29}$ 0.8	$-0.20^{+0.61}_{-0.39}$ 0.2	$1.51^{+0.97}_{-0.71}$ 3.1	$0.16^{+0.33}_{-0.22}$ 0.5	$0.58^{+0.35}_{-0.27}$ 2.6
$(\rho,\omega)\gamma$	$1.31^{+0.56}_{-0.49}$ 3.1	$0.80^{+0.52}_{-0.43}$ 2.0	$2.07^{+0.74}_{-0.63}$ 4.2	$1.04^{+0.38}_{-0.33}$ 3.7	$1.34^{+0.34}_{-0.31}$ 5.5

Selection of Photon Candidates





- Energetic photon candidate: $E_\gamma^{cm} > 1.8\mathrm{GeV}$
- Electromagnetic shower shape : $E9/E25 > 0.95$
- Barrel photons only: $33^o < \theta_\gamma^{lab} < 128^o$



$$0.62 < M_{\rho^0} < 0.92, 0.62 < M_{\rho^+} < 0.92, 0.752 < M_{\omega} < 0.812$$

$$\mathcal{L}_u(\mathbf{p}) = \frac{A(\mathbf{p})^N e^{-A(\mathbf{p})}}{N!} \prod_{i=1}^{N} \frac{f(x_i;\mathbf{p})}{A(\mathbf{p})}$$

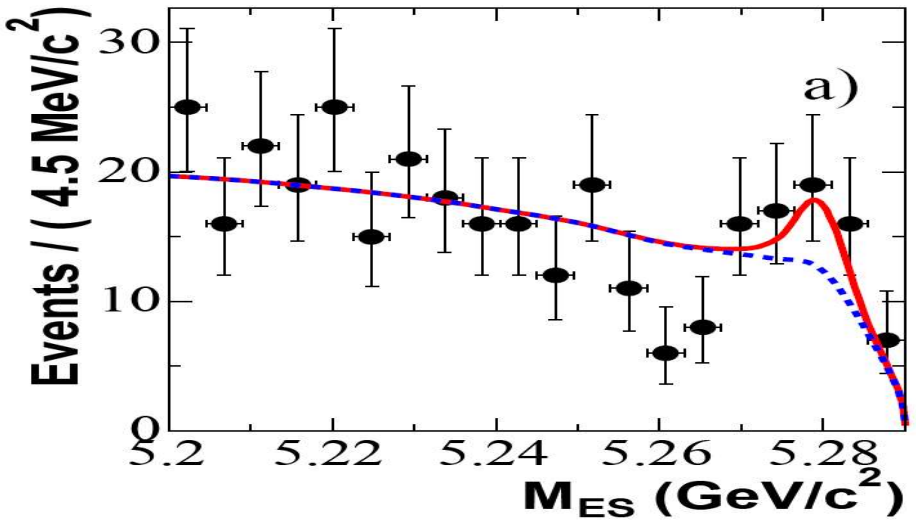
$$\mathcal{F}_u(\mathbf{p}) \equiv -\ln \mathcal{L}_u(\mathbf{p}) = -\sum_{i=1}^{N} \ln\left(\frac{f(x_i;\mathbf{p})}{A(\mathbf{p})}\right) - N \ln A(\mathbf{p}) + A(\mathbf{p}) + \ln N!$$

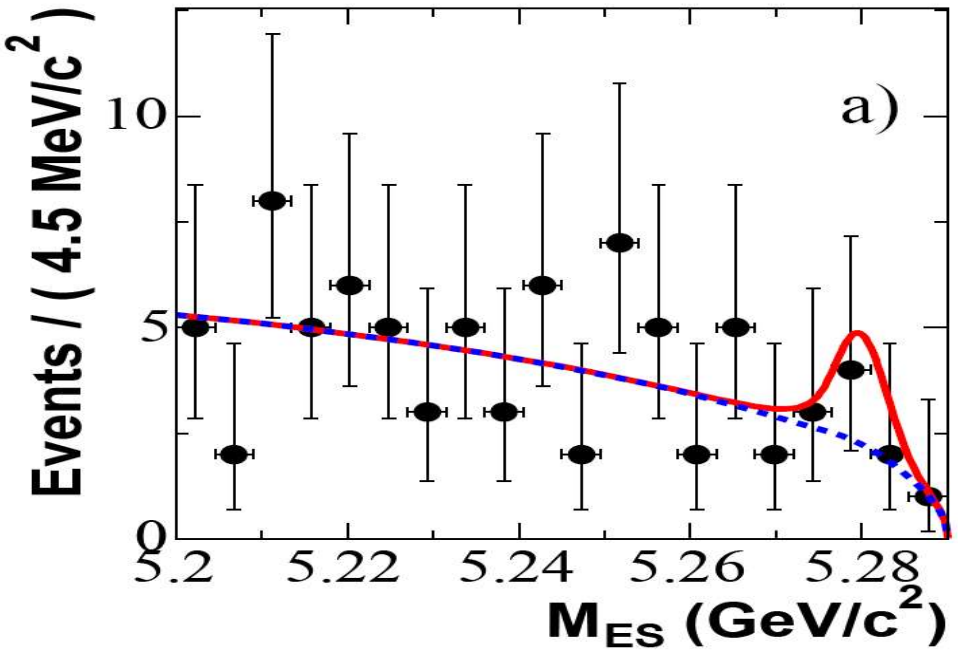
$$F_{gaussian} = \frac{1}{\sqrt{(2\pi\sigma^2)}} \times e^{\frac{-(M_{\mathrm{bc}}-\mu)^2}{2\sigma^2}}$$

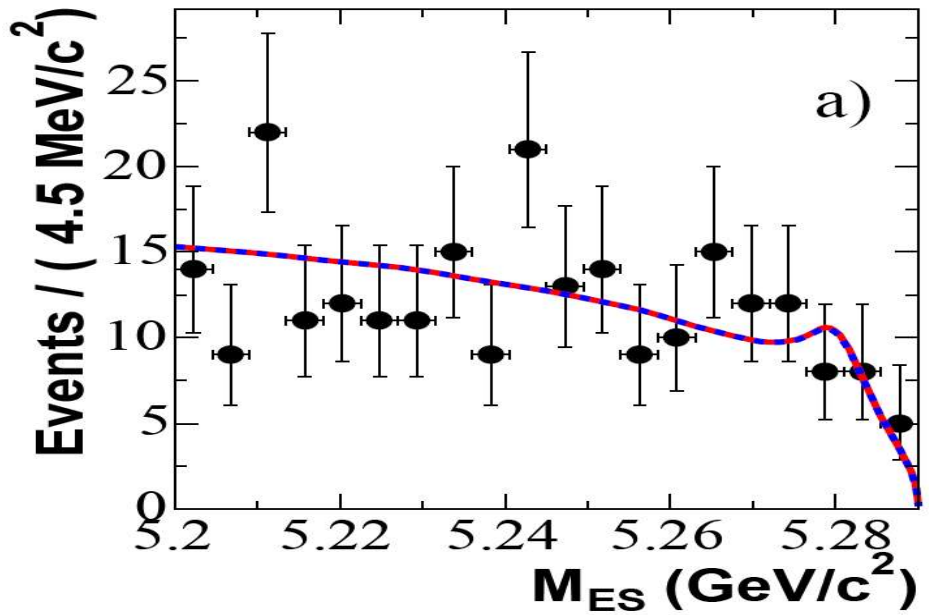
$$F_{cbls} = e^{-(\Delta E-\Delta E_0)^2/2\sigma_E^2} \qquad \Delta E > \Delta E_0 - \alpha\sigma_E$$

$$= e^{-\alpha^2/2} / \left(1 - \frac{\alpha}{N} \frac{\Delta E - \Delta E_0 + \alpha\sigma_E}{\sigma_E}\right)^N, \qquad \Delta E \leq \Delta E_0 - \alpha\sigma_E$$

$$F_{argus} = M_{\mathrm{bc}}\sqrt{1 - (M_{\mathrm{bc}}/M_0)^2)} \times e^{-\lambda[1-(M_{\mathrm{bc}}/M_0)^2]}$$


a)
Events / (4.5 MeV/c^2)
M_{ES} (GeV/c^2)


a)
Events / (4.5 MeV/c^2)
M_{ES} (GeV/c^2)


a)
Events / (4.5 MeV/c^2)
M_{ES} (GeV/c^2)