Radiative Penguin Decays at the B Factories

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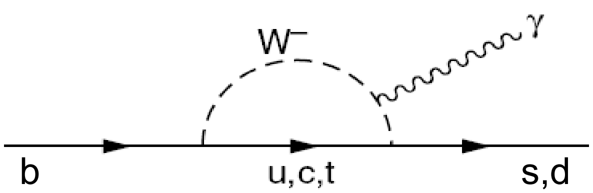
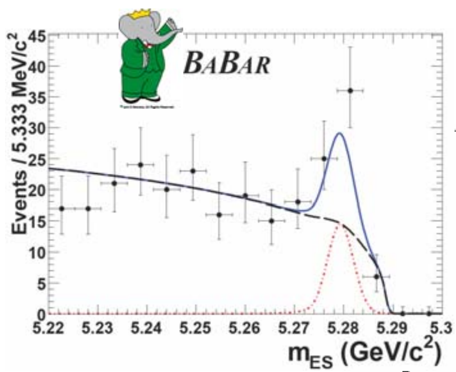
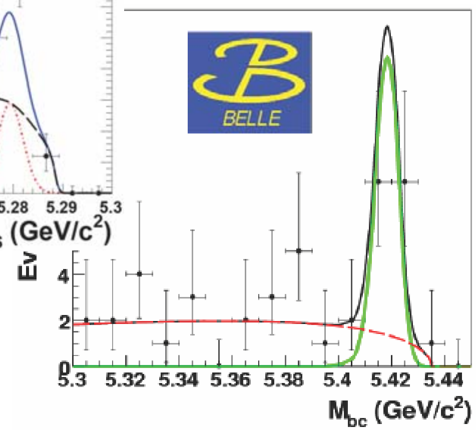
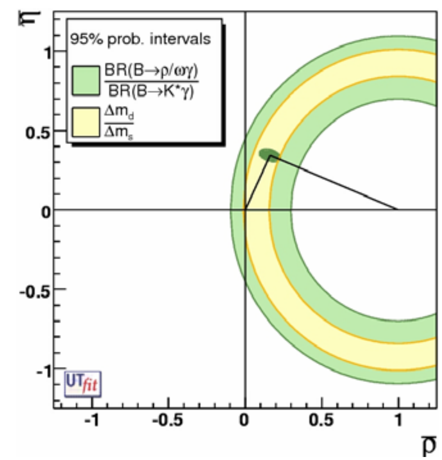






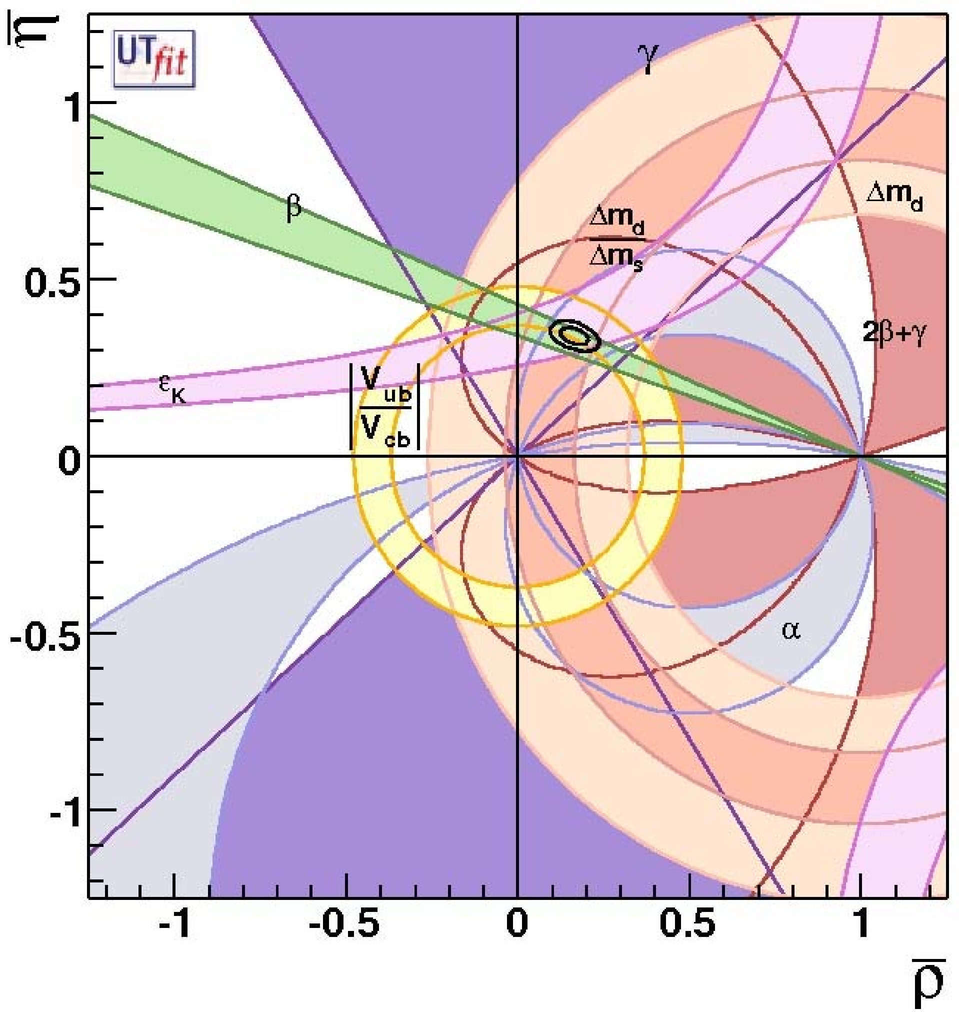


Outline:

- **Introduction** — *CKM, SM, New Physics, Belle and BaBar, Analysis*
- $B \rightarrow (\rho/\omega)\,\gamma$ — *Analysis, Results and the Tevatron*
- $b \rightarrow s\,\gamma$ — *A new technique*
- $B_s \rightarrow \varphi\,\gamma,\ \gamma\,\gamma$ — *The Y(5S) run at Belle*
- **Summary** — *...*

Current state of CKM Flavor Physics:

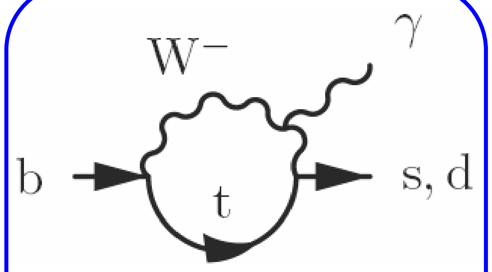
- **CP violation in the Standard Model is consistently accounted for by the CKM matrix:**



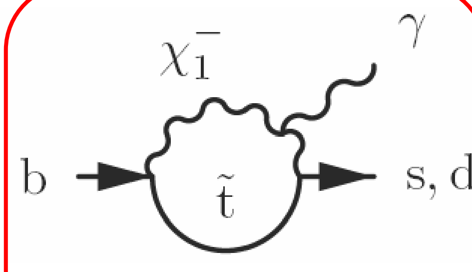
Radiative penguin decays:

Penguin = One loop effective FCNC

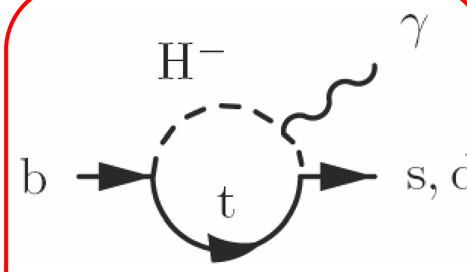
Decays where leading contribution is Penguin, thus BF ~ $10^{-4} – 10^{-7}$



SM radiative penguin

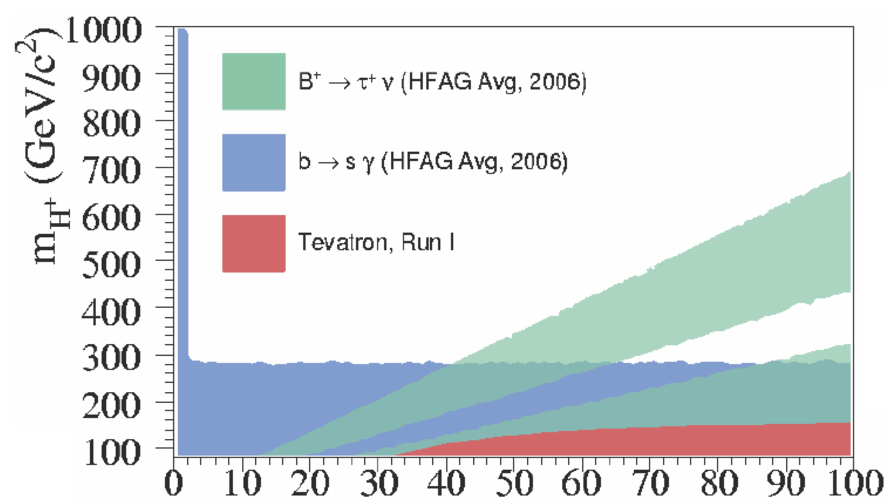


SUSY penguin



SUSY/2HDM penguin

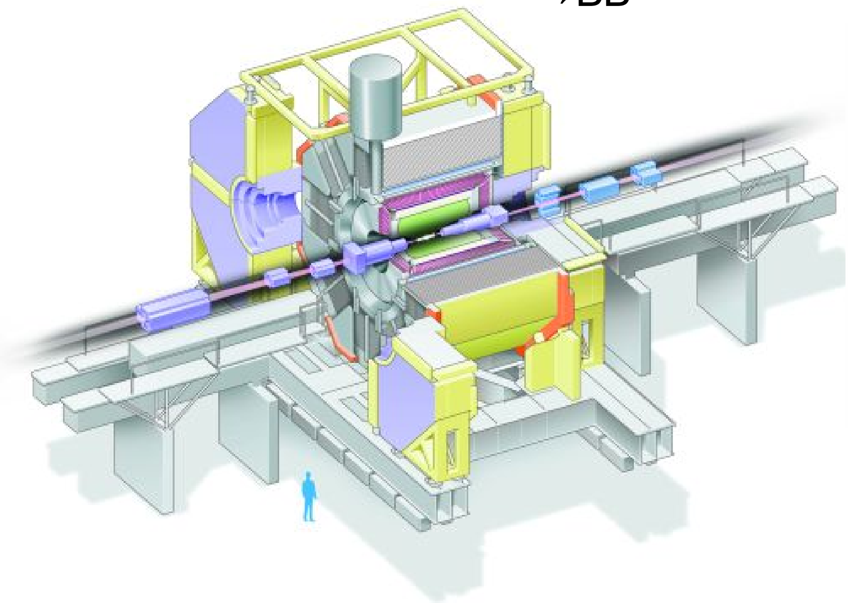
- **New physics contributions can enter at the same level as SM contributions!**
- **Thus, observables can shift w.r.t. the SM prediction.**
- **If no conclusive difference between measurements and SM predictions are found, constraints on new physics contributions can be extracted (e.g. exclusion regions in m_{H+} - tan β plane from b → s γ)**

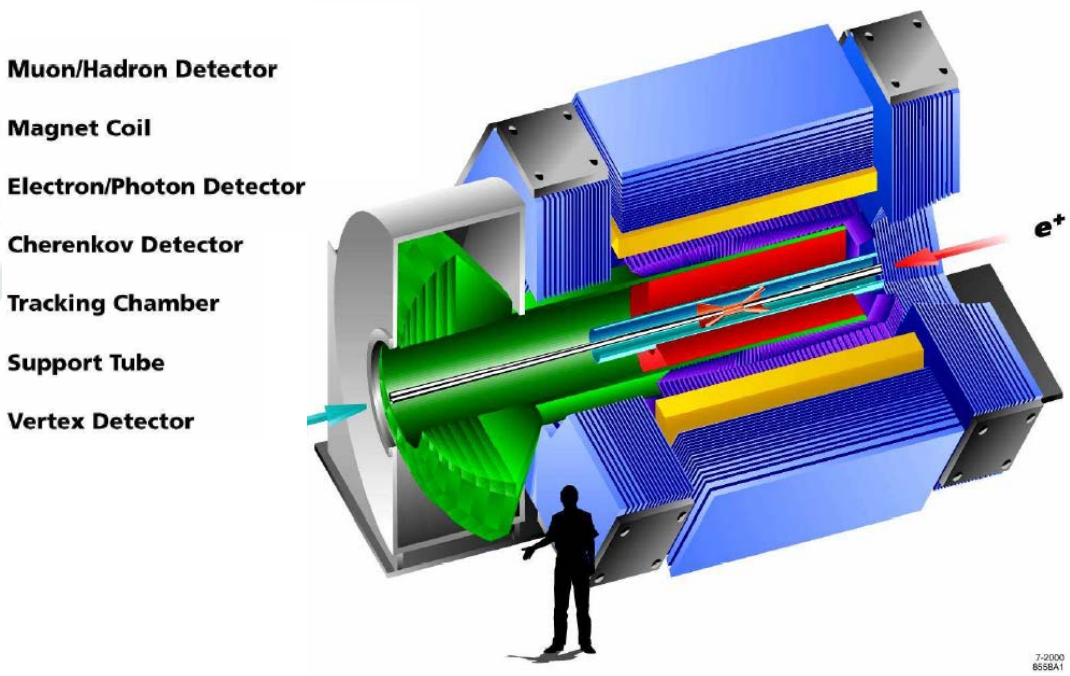


Excluded regions at 95% C.L. (colored) for MSSM 2-Higgs Doublet Model of type II (PRD 48, 2342 (1993))

Design Goal: Study time dependent CP-violation in the B-meson system

→ Run asymmetric at Υ(4S) resonance
↳ $B\bar{B}$

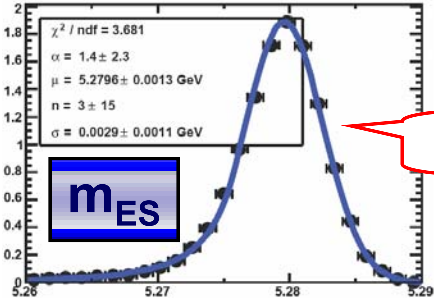




Basic Machine Parameters:

Beam energies	8 GeV electrons on 3.5 GeV positrons	9 GeV electrons on 3.1 GeV positrons
Integrated Luminosity	605 fb^{-1}	411 fb^{-1}
Peak Luminosity	17.1×10^{33} $cm^{-2}s^{-1}$	12.0×10^{33} $cm^{-2}s^{-1}$

B meson reconstruction: Use two standard variables:

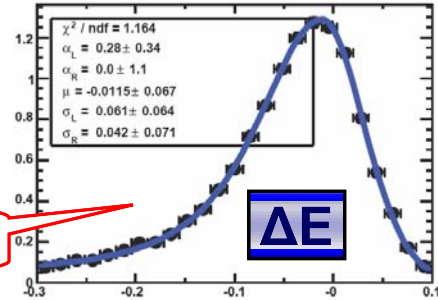


$$m_{ES} = M_{bc} = \sqrt{E^{*2}_{Beam} - \left|\vec{p}^{\,*}_B\right|^2}$$

Resolution ~ 3 MeV

$$\Delta E = E^*_B - E^*_{Beam}$$

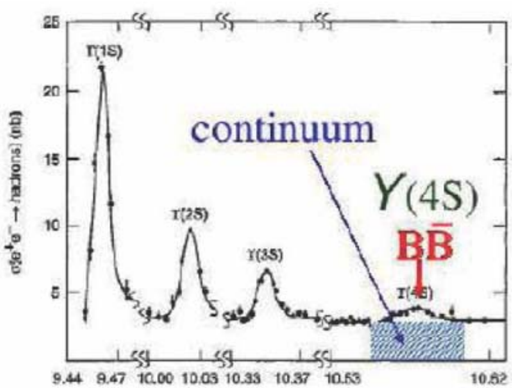
Resolution ~ 50 MeV

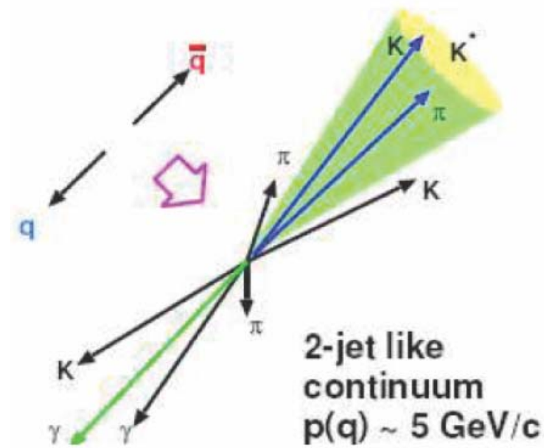


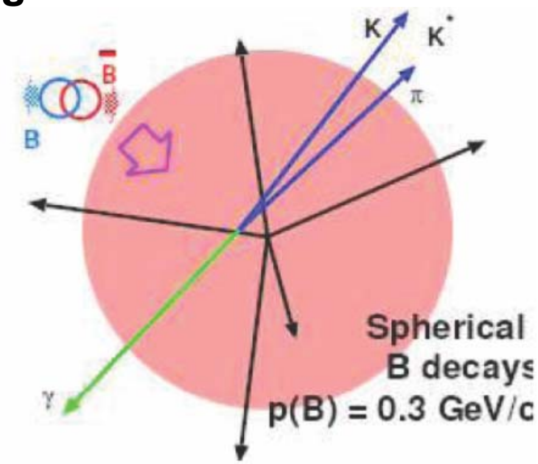
Background suppression – The Name of the Game!

$\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ suppression: High-energy photon usually comes from these decays in background events.

Continuum ($e^+e^- \to$ light quark): Event shape variables and angular information

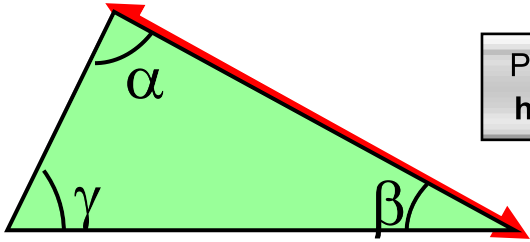






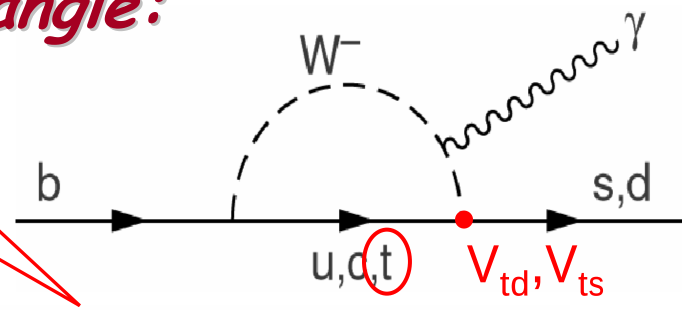
Also, use tagging information, i.e. Leptons, Kaons (…) from the other B

Sensitive to far side of Unitarity Triangle:



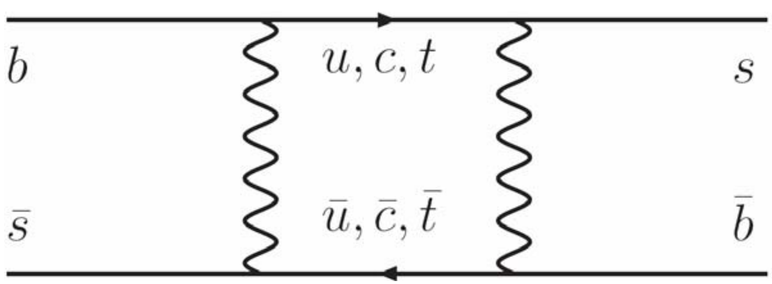
P. Ball, R. Zwicky
hep-ph/0603232

Form factor ratio
$(\xi = 1.17 \pm 0.09)^{-1}$



$$\frac{\mathcal{B}(B \to (\rho,\omega)\gamma)}{\mathcal{B}(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - m^2_{\rho,\omega}/m^2_B}{1 - m^2_{K^*}/m^2_B}\right)^3 \left(\frac{T_1^{\rho,\omega}(0)}{T_1^{K^*}(0)}\right)^2 [1 + \Delta R]$$

Measures same side of UT triangle as B_d/B_s mixing, but with rather different underlying physics:

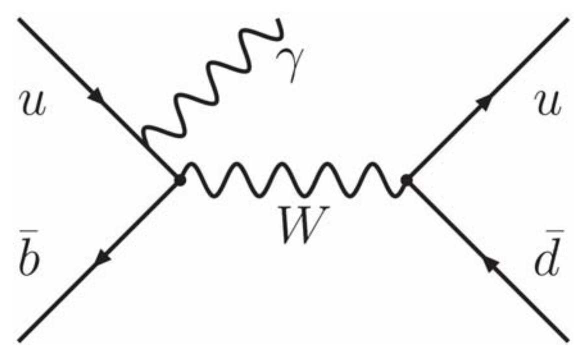


From the Tevatron:

CDF
hep-ex/0609040

$$\sqrt{\frac{\Delta m_d}{\Delta m_s}} \propto \left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007^{+0.0081}_{-0.0060}$$

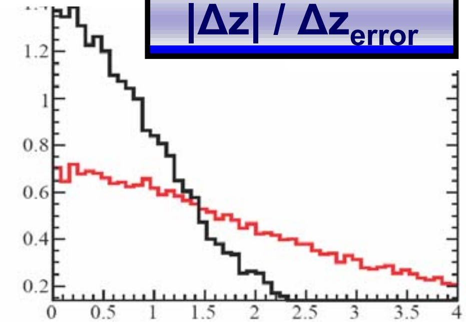
Difference in dynamics (such as W annihilation) $\Delta R \approx 0.1 \pm 0.1$



Continuum background rejection:

- **Shape variables:** Fox-Wolfram Moments, Legendre moments, thrust angle
- **B decay properties:** cosine of B decay angle $\cos\theta_B$, Δz
- **Tagging related variables:** Presence and properties of Leptons, Kaons, Pions in the rest-of-the-event

$|\Delta z| / \Delta z_{error}$



Signal MC
Background

BELLE

1) Construct Fisher from shape variables.
2) Build likelihoods for Fisher output, $\cos\theta_B$ and Δz, where available (not 1-track ρ^+ mode).
3) Depending on a tagging quality variable, cut on product likelihood ratio.

At ~40% signal efficiency, achieve ~95% continuum background rejection efficiency.

BABAR

Combine all variables with separating power into a neural network (including Δz – even for 1-track ρ^+ mode).

At ~50% signal efficiency, achieve ~98.5% continuum background rejection.

Signal extraction with an unbinned maximum likelihood fit:

- **Variables used:**
  - m_{ES} (M_{bc}),
  - ΔE,
  - Neural network ouput,
  - Cosine of the Helicity angle,
  - Second decay angle in the $B \to \omega\gamma$ decay,

***Based on theory assumptions, build simultaneous fit models*:**

e.g. in: A. Ali, A. Parkhomenko **hep-ph/0610149**

- For all three modes (ρ^+, ρ^0, ω):

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

- For the two ρ modes (ρ^+, ρ^0), since the inclusion of ω is controversial:

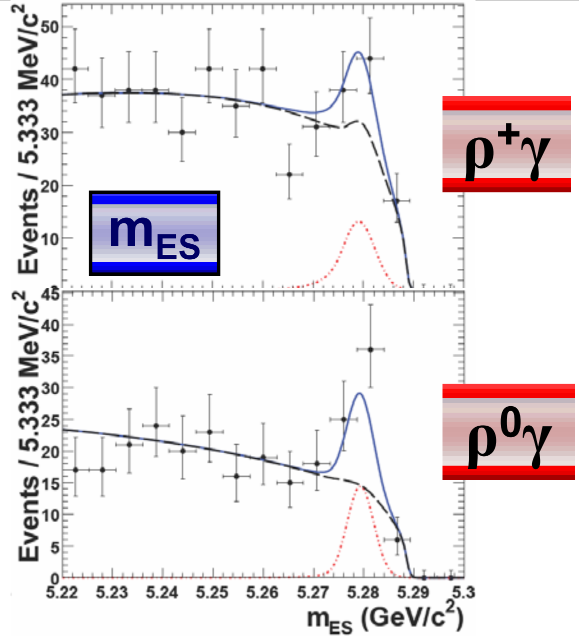
$$\mathcal{B}(B \to \rho\gamma) = \frac{1}{2} \cdot \left(\mathcal{B}(B^+ \to \rho^+\gamma) + 2 \cdot \frac{\tau_{B^+}}{\tau_{B^0}} \cdot \mathcal{B}(B^0 \to \rho^0\gamma) \right)$$

Fit datasets simultaneously, only 1 signal yield parameter instead of 2 or 3.

BABAR

PRL 98, 151802 (2007) — 316 fb^{-1}

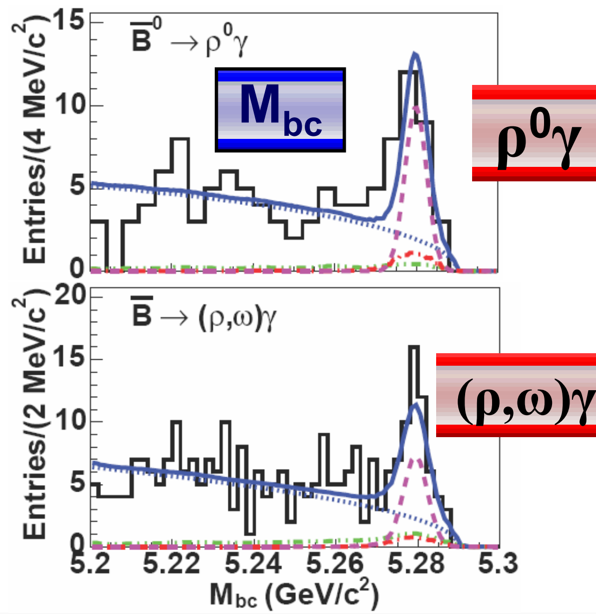
Mode	$n_{\rm sig}$	Signif.	$\epsilon(\%)$	$\mathcal{B}(10^{-6})$
$B^+ \to \rho^+\gamma$	$42.0^{+14.0}_{-12.7}$	3.8σ	11.0	$1.10^{+0.37}_{-0.33} \pm 0.09$
$B^0 \to \rho^0\gamma$	$38.7^{+10.6}_{-9.8}$	4.9σ	14.1	$0.79^{+0.22}_{-0.20} \pm 0.06$
$B^0 \to \omega\gamma$	$11.0^{+6.7}_{-5.6}$	2.2σ	7.9	$0.40^{+0.24}_{-0.20} \pm 0.05$
$B \to (\rho/\omega)\,\gamma$		6.4σ		$1.25^{+0.25}_{-0.24} \pm 0.08$
$B \to \rho\gamma$		6.0σ		$1.36^{+0.29}_{-0.27} \pm 0.09$



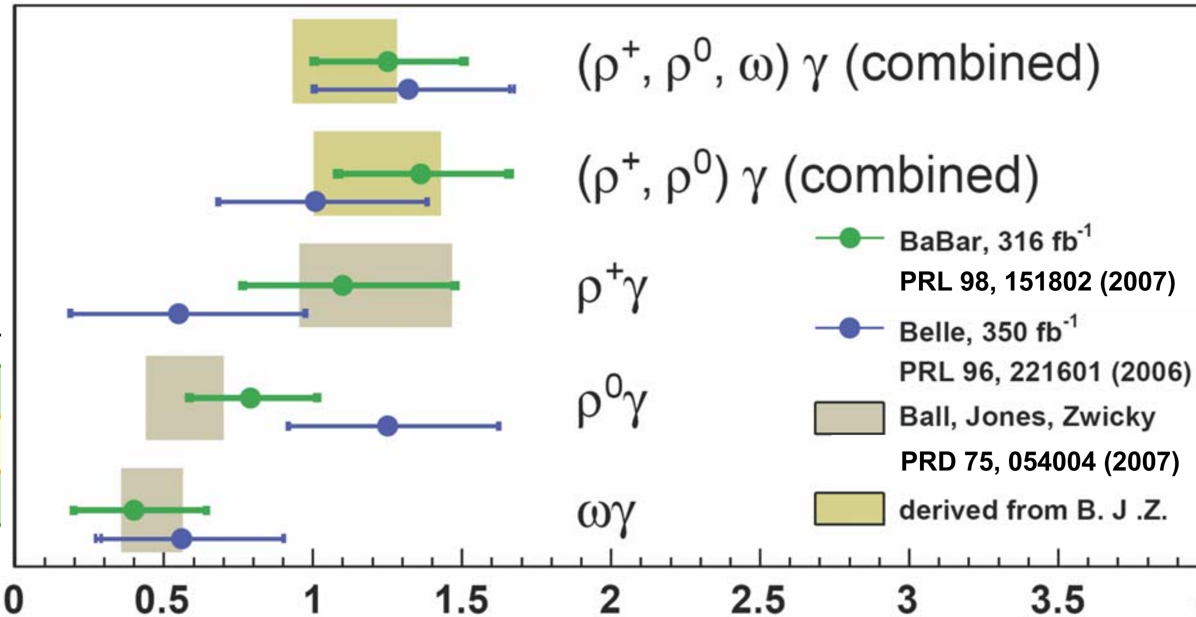
BELLE

PRL 96, 221601 (2006) — 350 fb^{-1}

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)	—	$1.32\,^{+0.34}_{-0.31}\,^{+0.10}_{-0.09}$

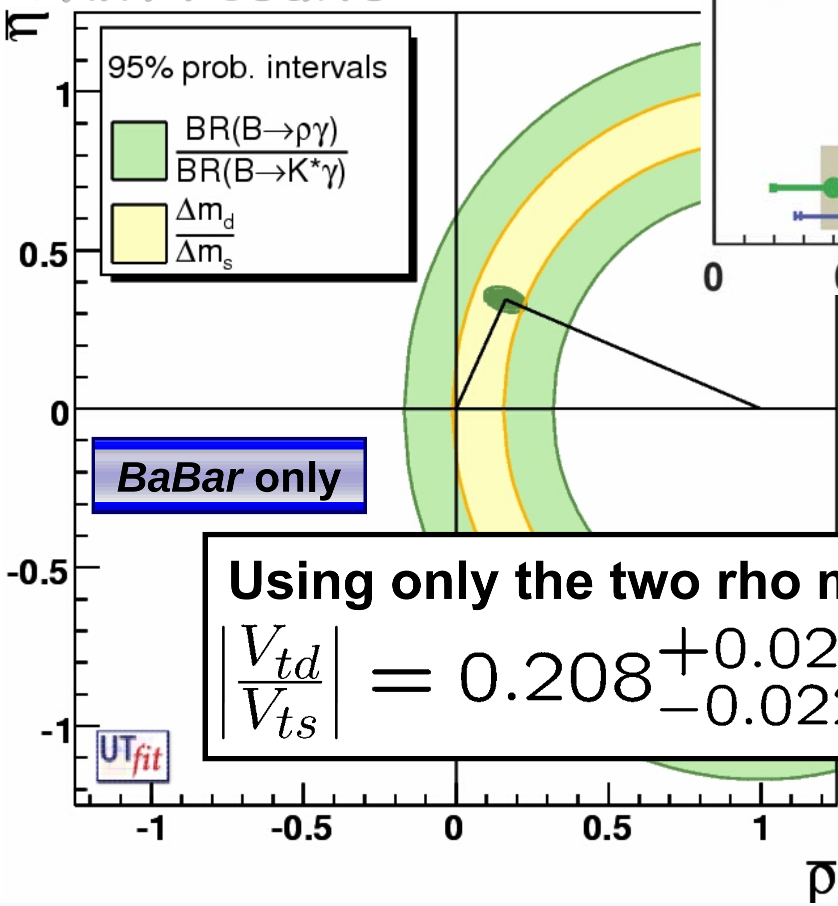


Comparison of Belle and BaBar with theory:



Branching Fraction (10^{-6})

CKM results:



BaBar only

Using only the two rho modes:

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.208^{+0.023}_{-0.022} \pm 0.016$$

First error experimental and second theoretical.

In excellent agreement with B_d/B_s mixing

Combining Belle and BaBar

Experiment	$\mathcal{B}(10^{-6})$
Babar	$1.25^{+0.25}_{-0.24} \pm 0.08$
Belle	$1.32^{+0.34+0.10}_{-0.31-0.09}$
Average	$1.28^{+0.20}_{-0.19} \pm 0.06$

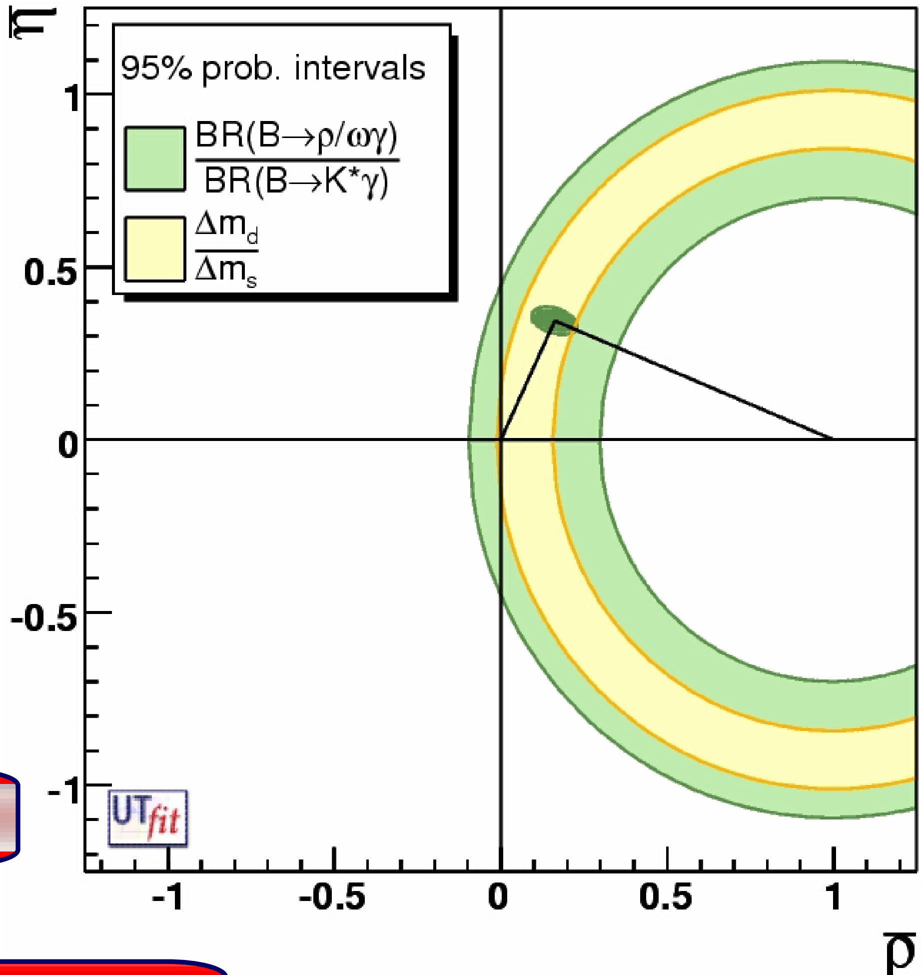
B factories average:

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.202^{+0.017}_{-0.016} \pm 0.015$$

8.4% exp. error

7.4% theo. error

First error experimental and second theoretical.



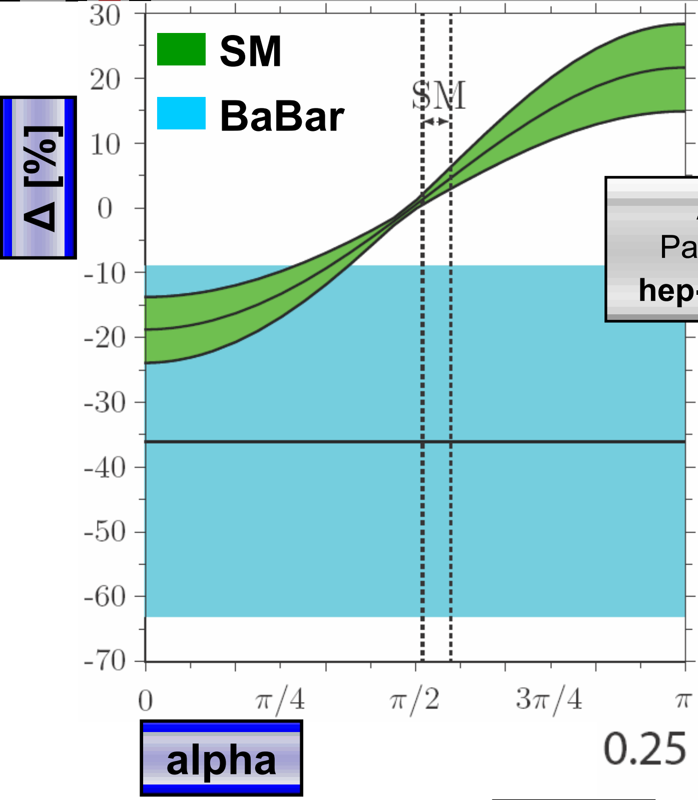
For comparison, from CDF:

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0007^{+0.0081}_{-0.0060}$$

4% total error

In excellent agreement with B_d/B_s mixing

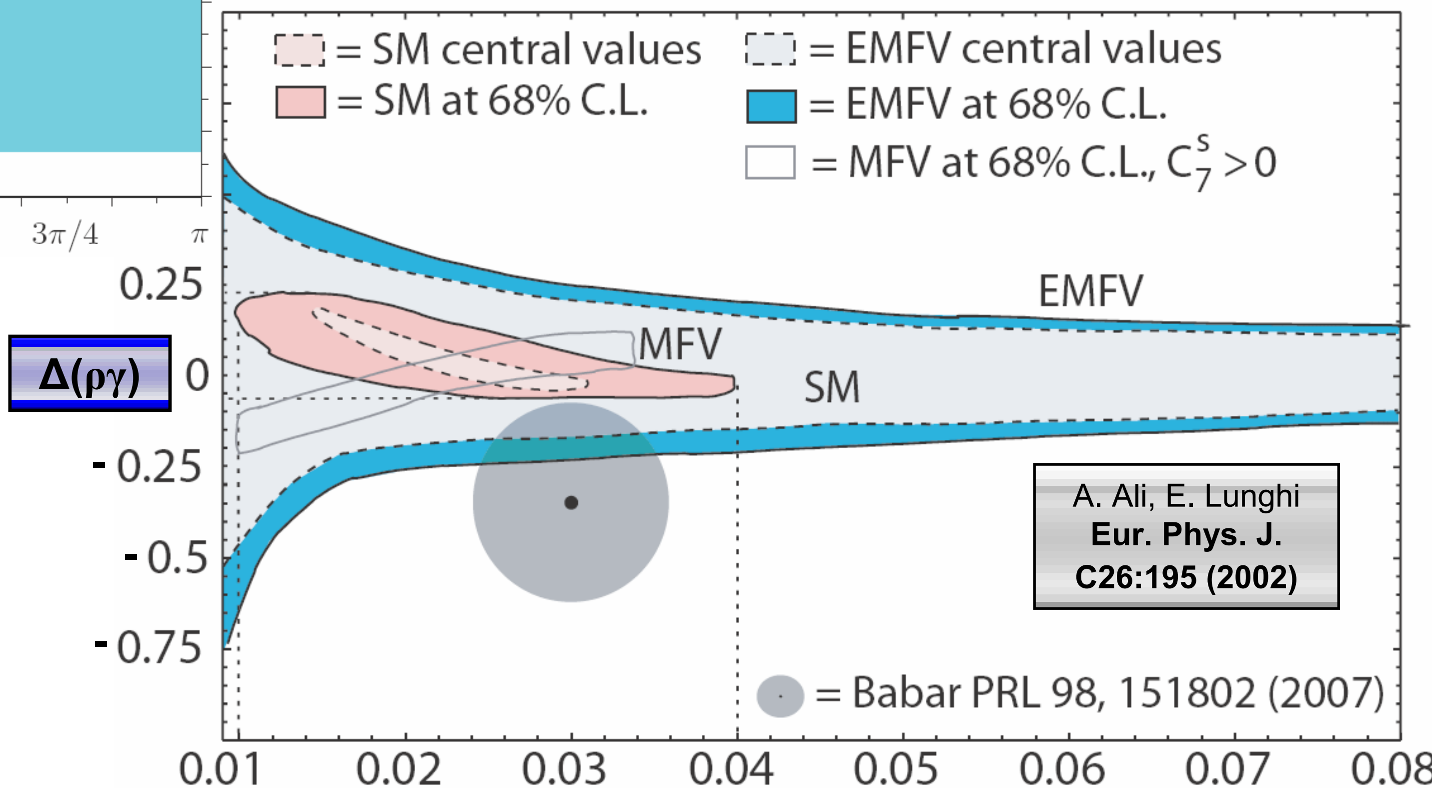
$B \to (\rho/\omega)\,\gamma$ Results



A. Ali, A. Parkhomenko
hep-ph/0610149

Measure the isospin violation between $\rho^+\gamma$ and $\rho^0\gamma$ ($\sim \cos\alpha$):

$$\Delta \equiv \frac{\Gamma(B^+ \to \rho^+\gamma)}{2\Gamma(B^0 \to \rho^0\gamma)} - 1 = -0.35 \pm 0.27$$



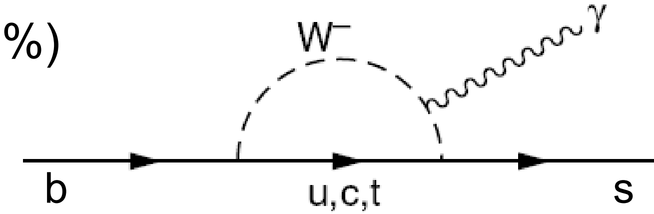
A. Ali, E. Lunghi
Eur. Phys. J. C26:195 (2002)

New Physics:

Misiak et. al., **hep-ph/0609232**

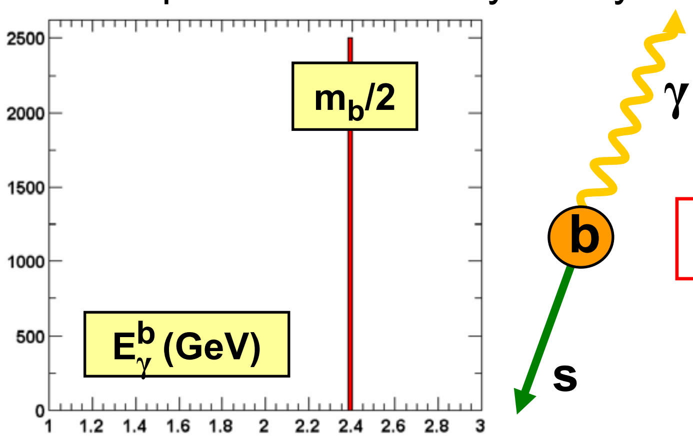
SM expectations (e.g.): $\mathcal{B}(B \rightarrow X_s\gamma)$ [E_γ > 1.6 GeV] = $(3.15 \pm 0.23) \times 10^{-4}$ (NNLO)

$A_{CP}(B \rightarrow X_s\gamma)$ < 1% (SUSY: up to 20%)

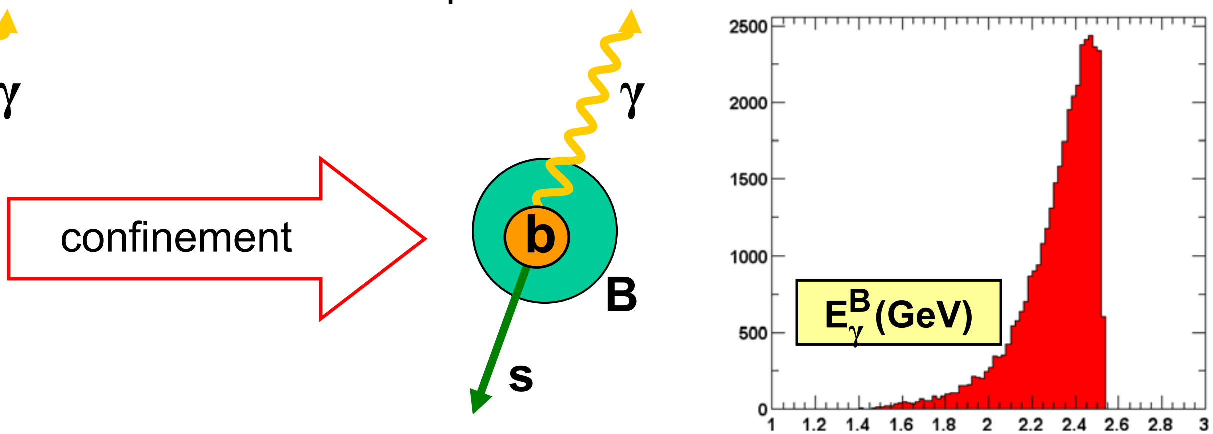


Photon Spectrum:

At the quark level: 2-body decay



b quark bound inside B meson:



Moments of Photon Energy Spectrum carry information:

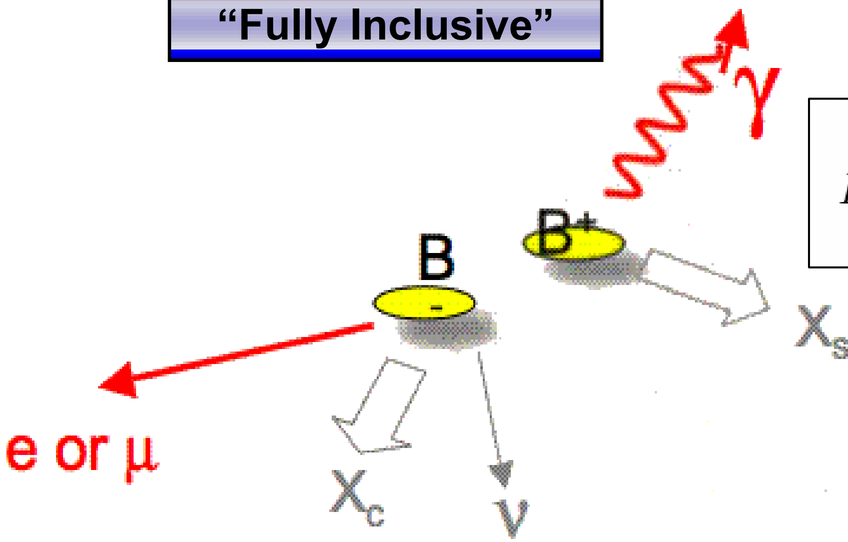
1st moment: $\left\langle E_\gamma^B \right\rangle \approx \frac{m_b}{2}$

2nd moment: $\left\langle \left(E_\gamma^B\right)^2 \right\rangle - \left\langle E_\gamma^B \right\rangle^2 \approx \mu_\pi^2 \approx E^2_{kin}(b)$

This information can be used to extract V_{cb} and V_{ub} from semileptonic $b \rightarrow c$ and $b \rightarrow u$ transitions

Two established experimental methods:

"Fully Inclusive"



- Ignore X_s system.
- Reconstruct only the γ.

Pros:

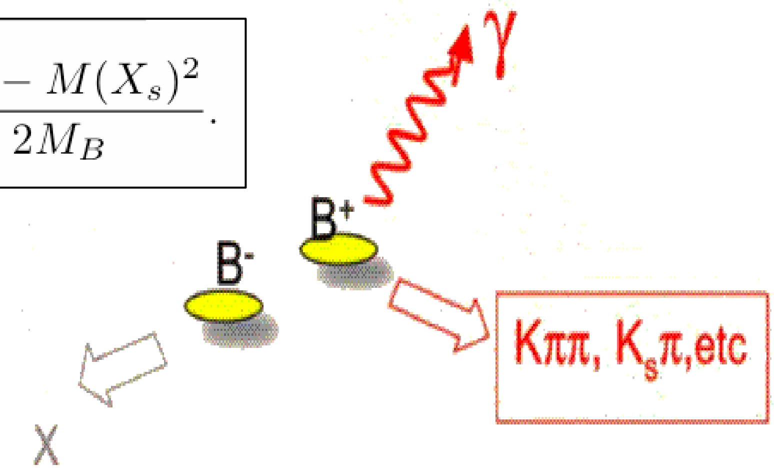
- No sensitivity to X_s fragmentation.
- Theoretically clean.

Cons::

- High background.
- E_γ measured in Y(4S) rest frame.

"Sum of Exclusive"

$$E_\gamma = \frac{M_B^2 - M(X_s)^2}{2M_B}.$$



- Fully reconstruct subset of all X_s final states.

Pros:

- Lower background.
- Good E_γ resolution in B rest-frame.

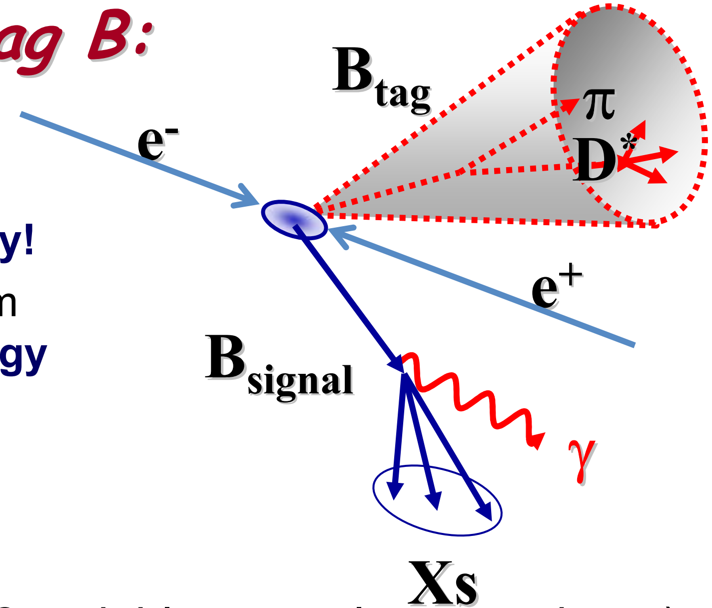
Cons::

- X_s fragmentation systematic.
- Missing X_s decay modes.

New approach: Fully reconstructed tag B:

Hadronic decay of one B meson fully reconstructed:

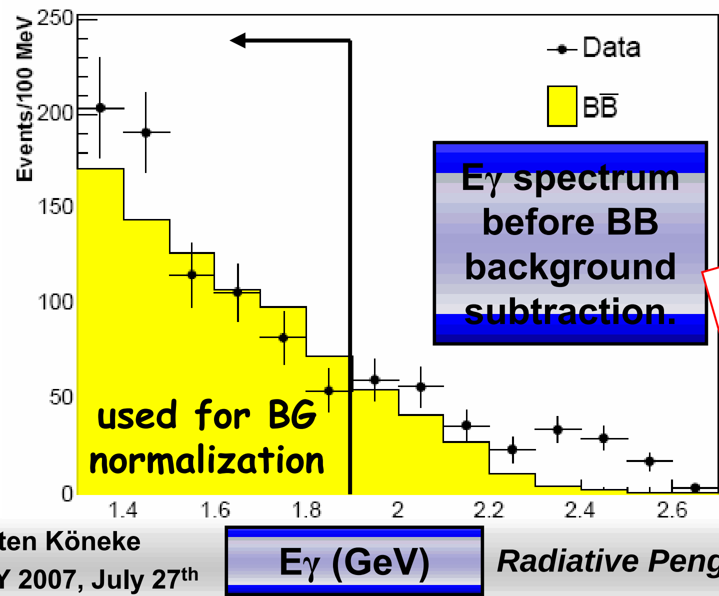
- 4-momentum, charge and flavor known, thus **measurement of Isospin and CP asymmetry!**
- With 4-momentum of Υ(4S), also 4-momentum of signal B meson known. Thus, **photon energy can be measured in signal B rest frame!**



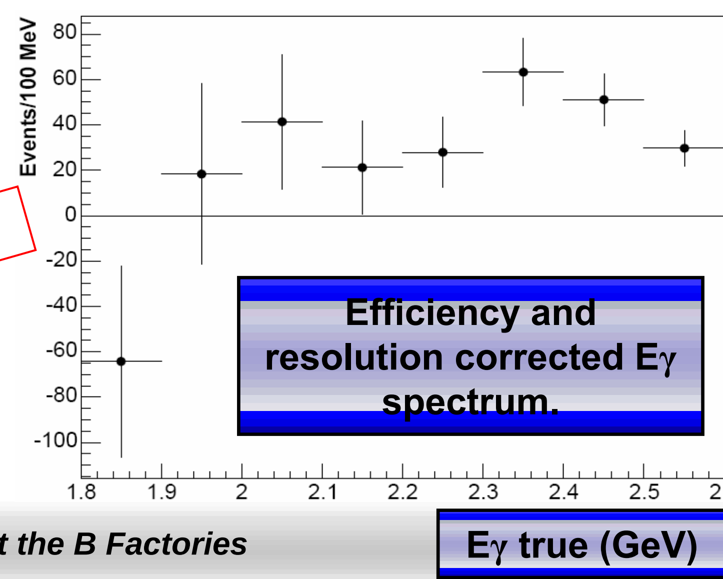
Analysis:

210 fb^{-1}

- Veto photons from π^0, η, ρ decays.
- Suppress continuum with a Fisher discriminant (12 variables, mostly event shape).
- Determine partial branching fractions in bins of E_γ, using fits to m_{ES}.

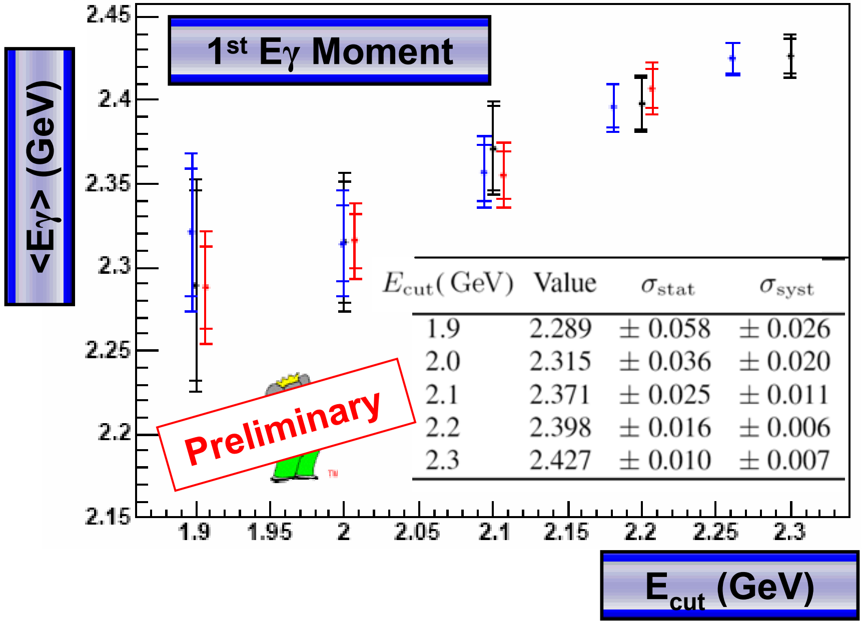


Preliminary

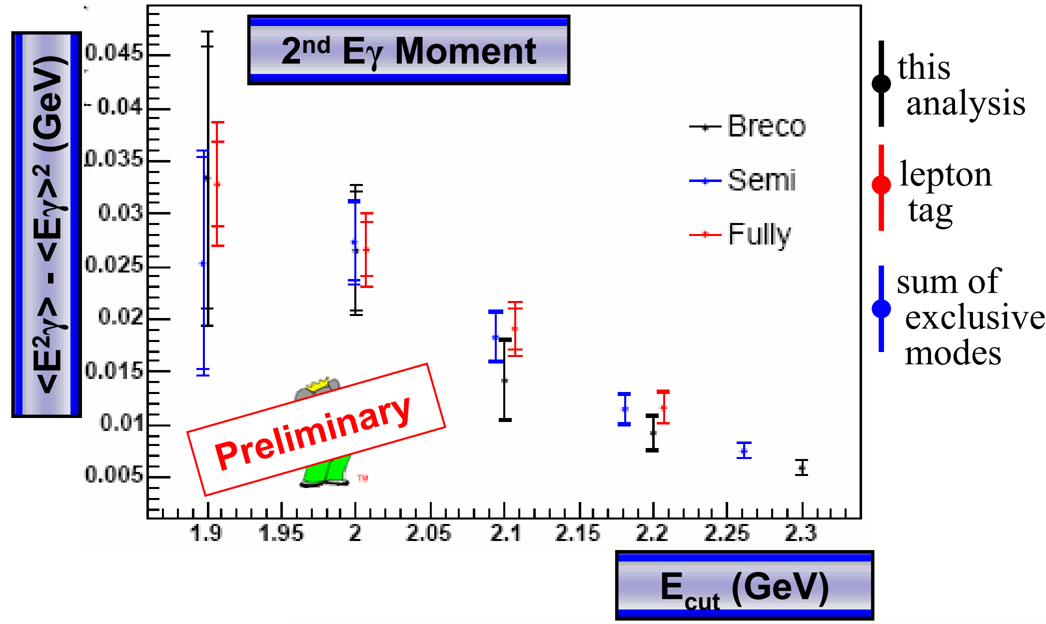


E_γ Moments:

- Measurement of photon energy moments as a function of minimum energy.
- Good agreement, different methods, independent data samples.



E_{cut}(GeV)	Value	σ_{stat}	σ_{syst}
1.9	2.289	± 0.058	± 0.026
2.0	2.315	± 0.036	± 0.020
2.1	2.371	± 0.025	± 0.011
2.2	2.398	± 0.016	± 0.006
2.3	2.427	± 0.010	± 0.007

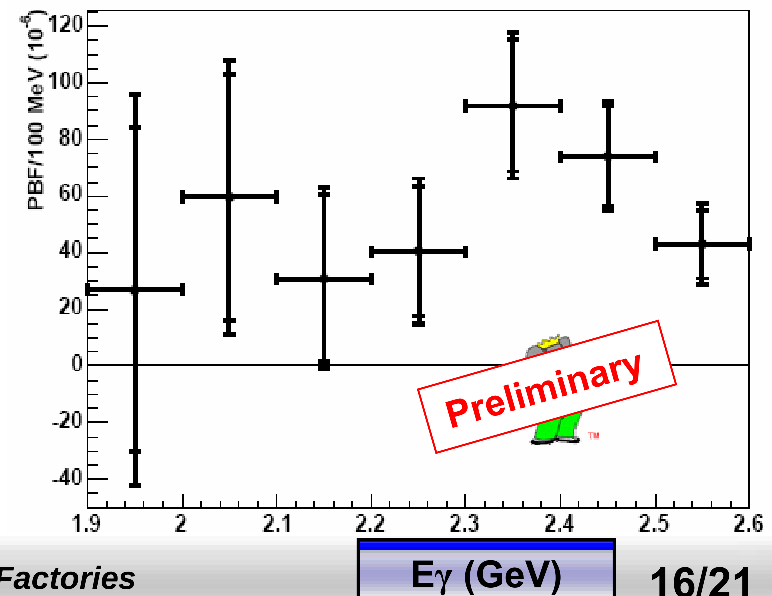


Partial Branching Fractions:

E_{cut}(GeV)	Value $BF[E_\gamma > E_{cut}]/10^{-6}$	σ_{stat}	σ_{syst}
1.9	366	± 85	± 59
2.0	339	± 64	± 47
2.1	278	± 48	± 34
2.2	248	± 38	± 26
2.3	207	± 30	± 19

Preliminary

- Statistical error dominates.
- Systematic error will shrink with more data.



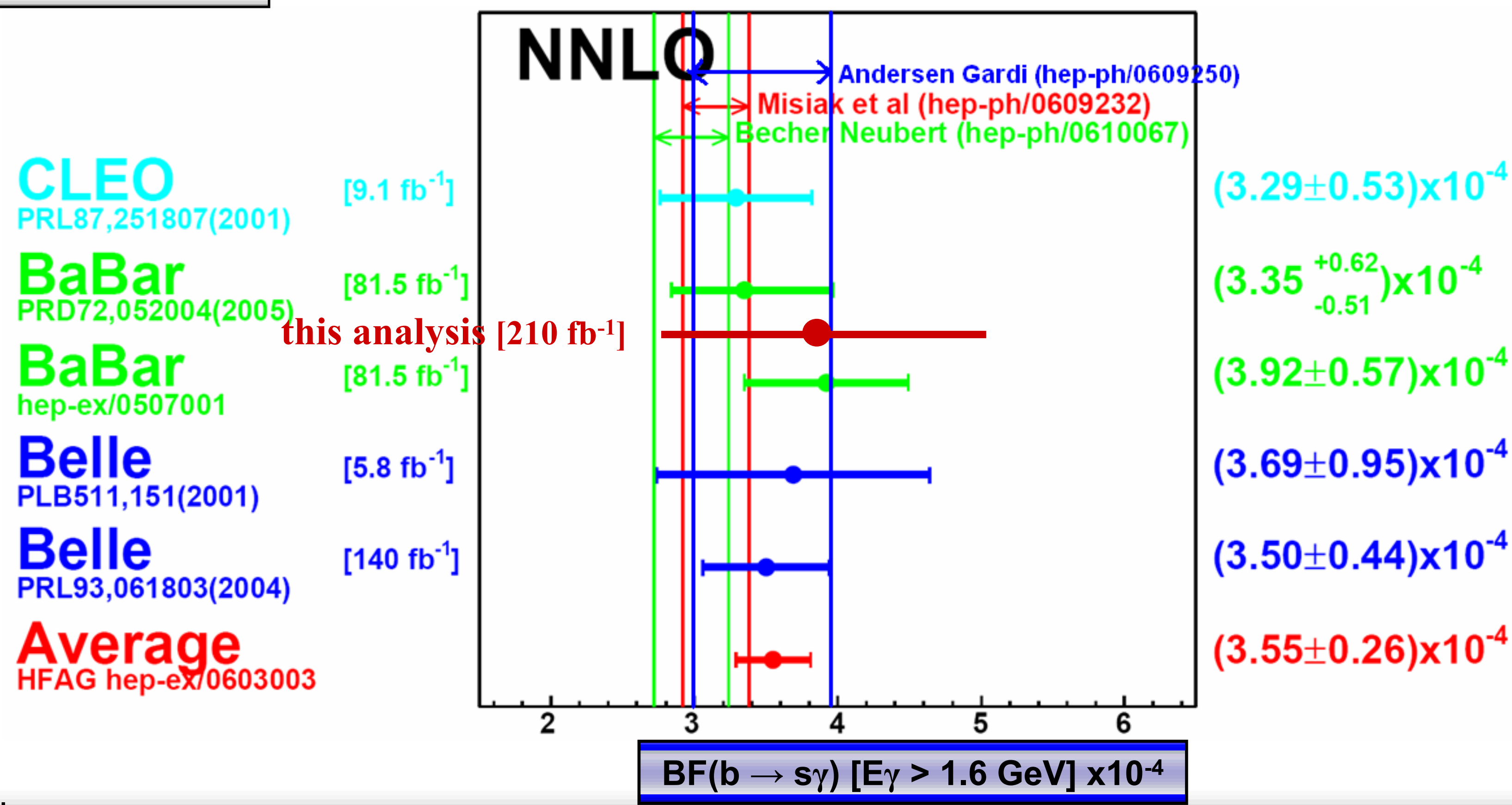
Branching Fractions:

Preliminary

Measured: $BF(B \rightarrow X_s\gamma)\ [E_\gamma > 1.9\ GeV] = (3.66 \pm 0.85 \pm 0.59) \times 10^{-4}$

Extrapolated: $BF(B \rightarrow X_s\gamma)\ [E_\gamma > 1.6\ GeV] = (3.91 \pm 0.91 \pm 0.63) \times 10^{-4}$

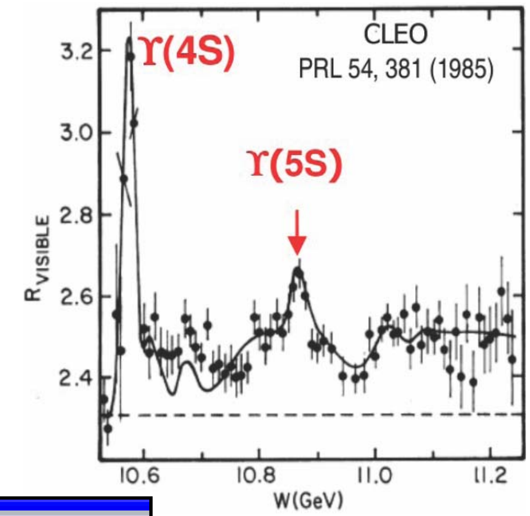
Using: **PRD 73, 073008 (2006)**



Producing B_s mesons:

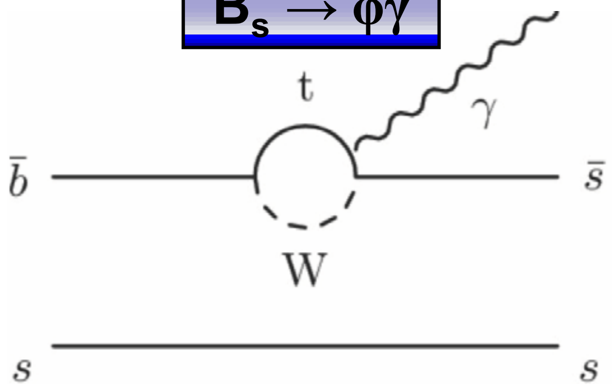
Belle collected 23.6 fb^{-1} running at the Υ(5S) resonance.

This corresponds to about 2.6×10^6 B_s mesons (~20% uncertainty)

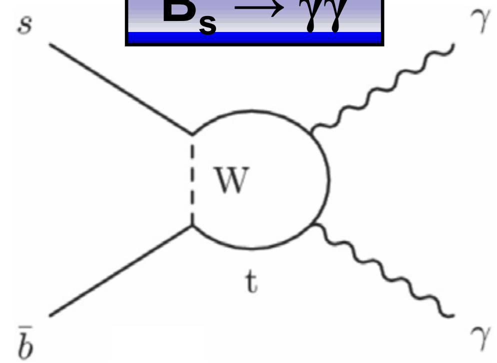


Two radiative penguin decays looked at:

$B_s \rightarrow \varphi\gamma$



$B_s \rightarrow \gamma\gamma$



SM prediction: BF = $(4 \pm 1) \times 10^{-5}$

PRD 75, 054004 (2007)

BF = $(0.5 - 1.0) \times 10^{-6}$

PRD 56, 5805 (1997)
JHEP 0208 054 (2002)

Can be enhanced by new physics by up-to an order of magnitude!

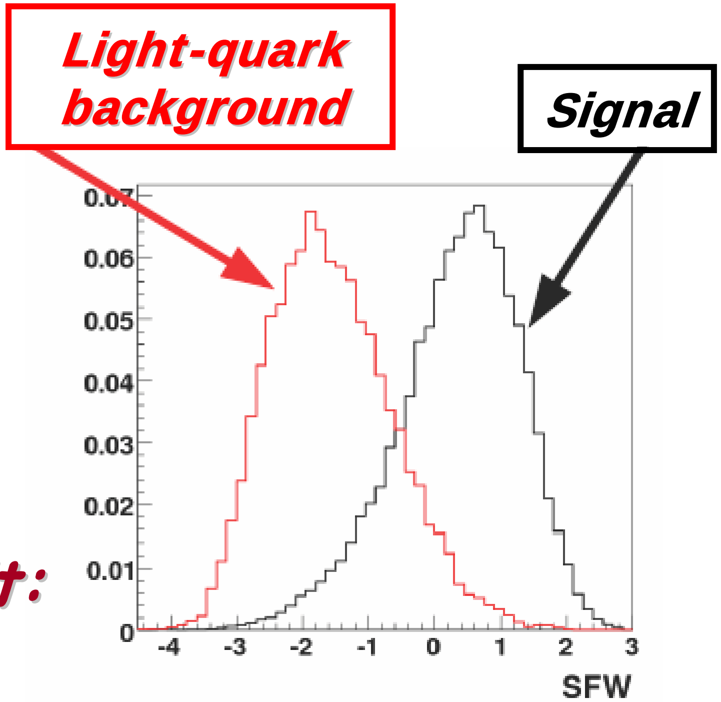
$B_s \to \varphi\gamma$

B_s meson reconstruction:

- **φ candidates:** Select $K^+ K^-$ pairs with invariant mass of 12 MeV around the nominal φ mass.
- **B_s candidates:** Standard m_{ES} (M_{bc}) and ΔE reconstruction.

Background suppression:

- **High-energy γ from π^0/η decays:** Veto by combining high energy photon candidate with other photons in the event.
- **Continuum background (e^+e^- to light quark pairs) suppression:** Use event topology by utilizing modified Fox-Wolfram moments:



Final unbinned maximum likelihood fit:

- **Use three variables:**

	m_{ES} (M_{bc}),	ΔE	$\cos(\theta_{Helicity})$
Signal:	Smoothed MC-histogram		$1 - \cos^2(\theta_{Helicity})$
Background:	ARGUS	1st order Polynomial	Constant

Preliminary

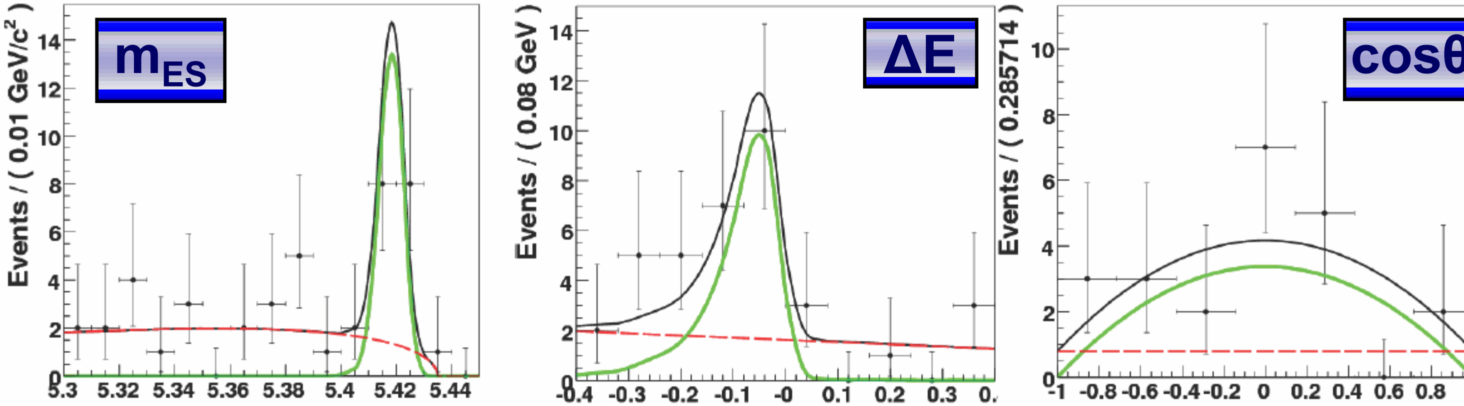
23.6 fb^{-1}

$B_s \to \phi\gamma$

Results:

- **(18 ± 6) signal events found:** $\mathcal{B}(B_s \to \phi\gamma) = \left(5.7^{+1.8}_{-1.5}\,{}^{+1.2}_{-1.7}\right) \times 10^{-5}$
- **Significance (including systematics):** 5.5σ.
- **Signal region projection plots:**

First observation of a radiative B_s penguin decay!



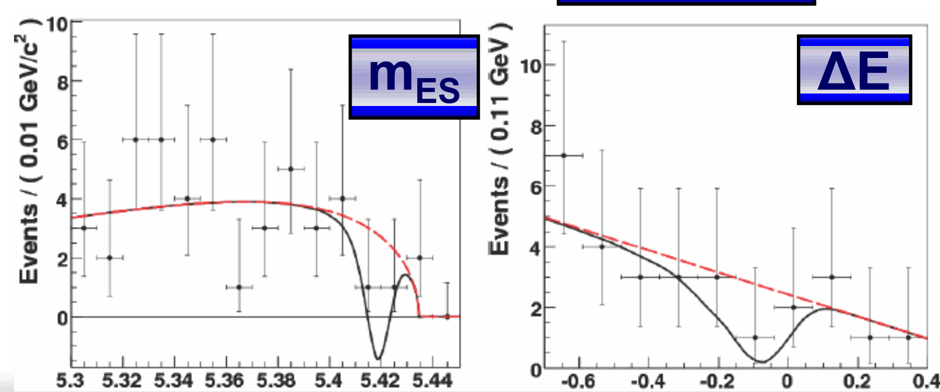
Final fit finds no signal:

23.6 fb^{-1}

$B_s \to \gamma\gamma$

	m_{ES} (M_{bc})	ΔE
Signal:	Smoothed MC-histogram	
Background:	ARGUS	1st order Polynomial

$$\mathcal{B}(B_s \to \gamma\gamma) < 8.6 \times 10^{-6} \quad (90\%\ \text{CL})$$



Summary

Very interesting results in $B \rightarrow (\rho/\omega)\gamma$:

- The BaBar and Belle measurements lead to a first extraction of $|V_{td}/V_{ts}|$ from penguin decays!

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.202^{+0.017}_{-0.016} \pm 0.015$$

- In excellent agreement with Tevatron measurement. With increased statistics:
  - More precise determination of $|V_{td}/V_{ts}|$, even theory limited if calculations don't improve…
  - Determination of $|V_{td}/V_{ts}|$ from single modes and measurements of other observables (direct CP violation, Isospin violation).

A promising new method for $b \rightarrow s\gamma$:

$BF(B \rightarrow X_s\gamma)$ $[E_\gamma > 1.9$ GeV$] = (3.66 \pm 0.85 \pm 0.59) \times 10^{-4}$

- Recent progress in both experiment and theory
  - Very good agreement between different experimental approaches.

Preliminary

- Photon energy spectrum measured in B rest frame.
- Soon: measurement of isospin and CP asymmetry.

The Y(5S) run at Belle produces interesting new results:

- First measurement of a radiative penguin decay of the B_s meson:

$$\mathcal{B}(B_s \rightarrow \phi\gamma) = \left(5.7^{+1.8}_{-1.5}\,^{+1.2}_{-1.7}\right) \times 10^{-5}$$

Preliminary

- Six times better upper limit on $\mathcal{B}(B_s \rightarrow \gamma\gamma) < 8.6 \times 10^{-6}$

More constraints on new physics to come before LHC!

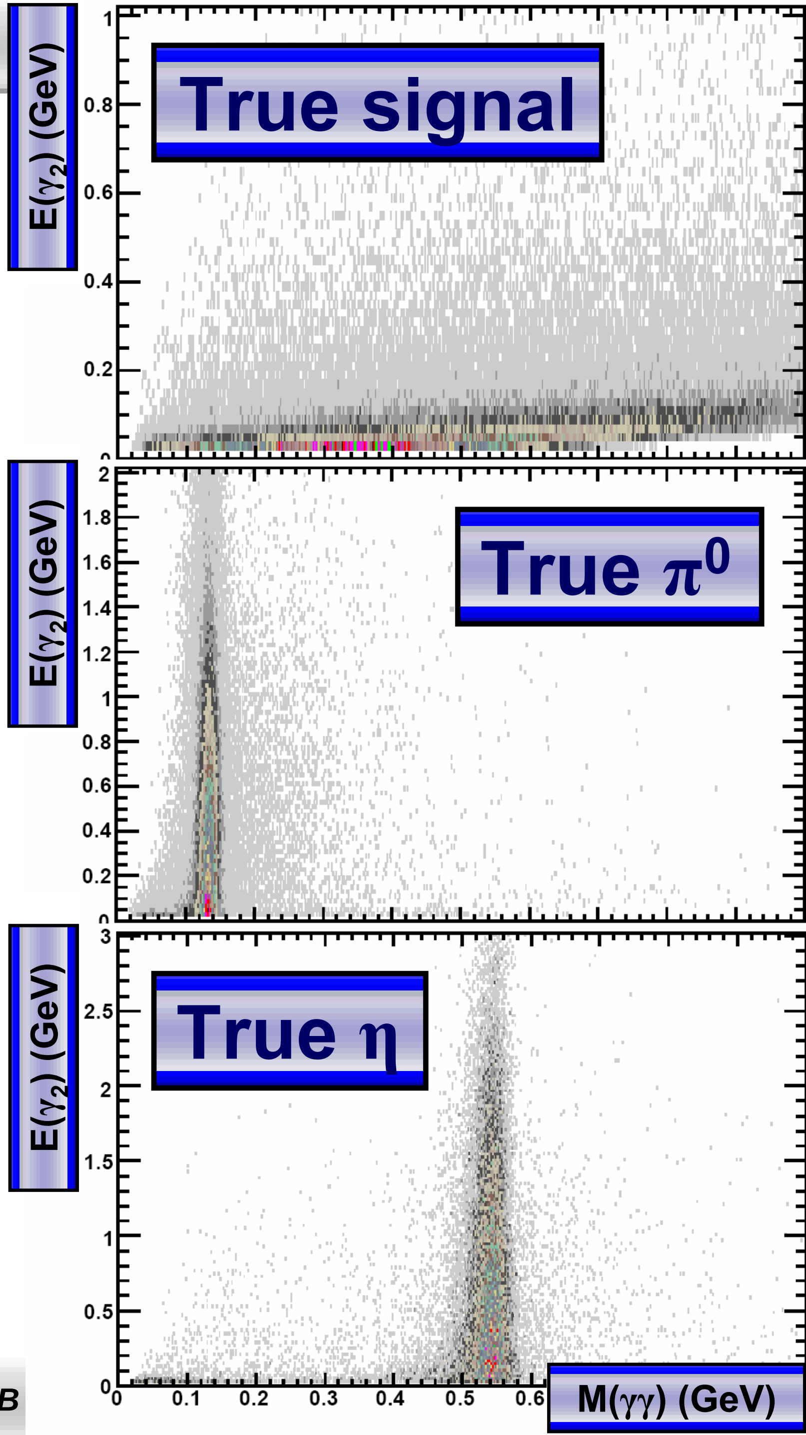
Backup slides

Likelihood based veto system:

In background events, the high energy photon comes mostly from ($\pi^0 \rightarrow \gamma\gamma$) or ($\eta \rightarrow \gamma\gamma$) decays!

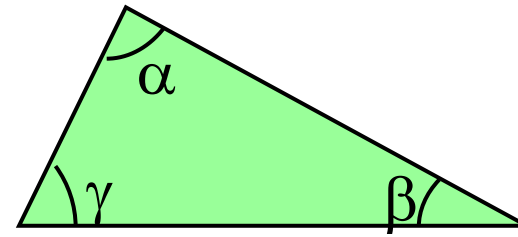
Strategy:

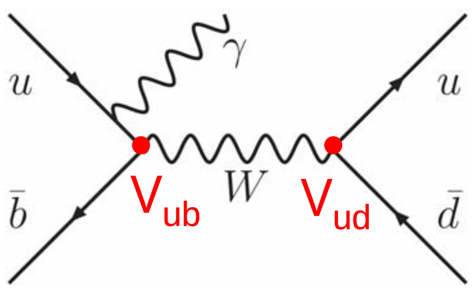
- **Combine high-energy photon with all other photons in the event.**
- **Build 2-dim PDF from invariant two-photon mass and second photon energy.**
- **Construct likelihoods for signal and background.**
- **Cut on likelihood ratios.**

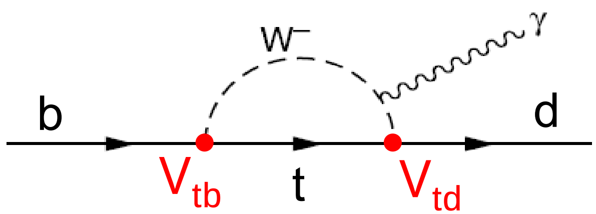


Sensitive to the Unitarity Triangle angle alpha:

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$$







$$\sim \frac{V_{ub}V_{ud}^*}{V_{tb}V_{td}^*} = -\left|\frac{V_{ub}V_{ud}^*}{V_{tb}V_{td}^*}\right| e^{i\alpha}$$

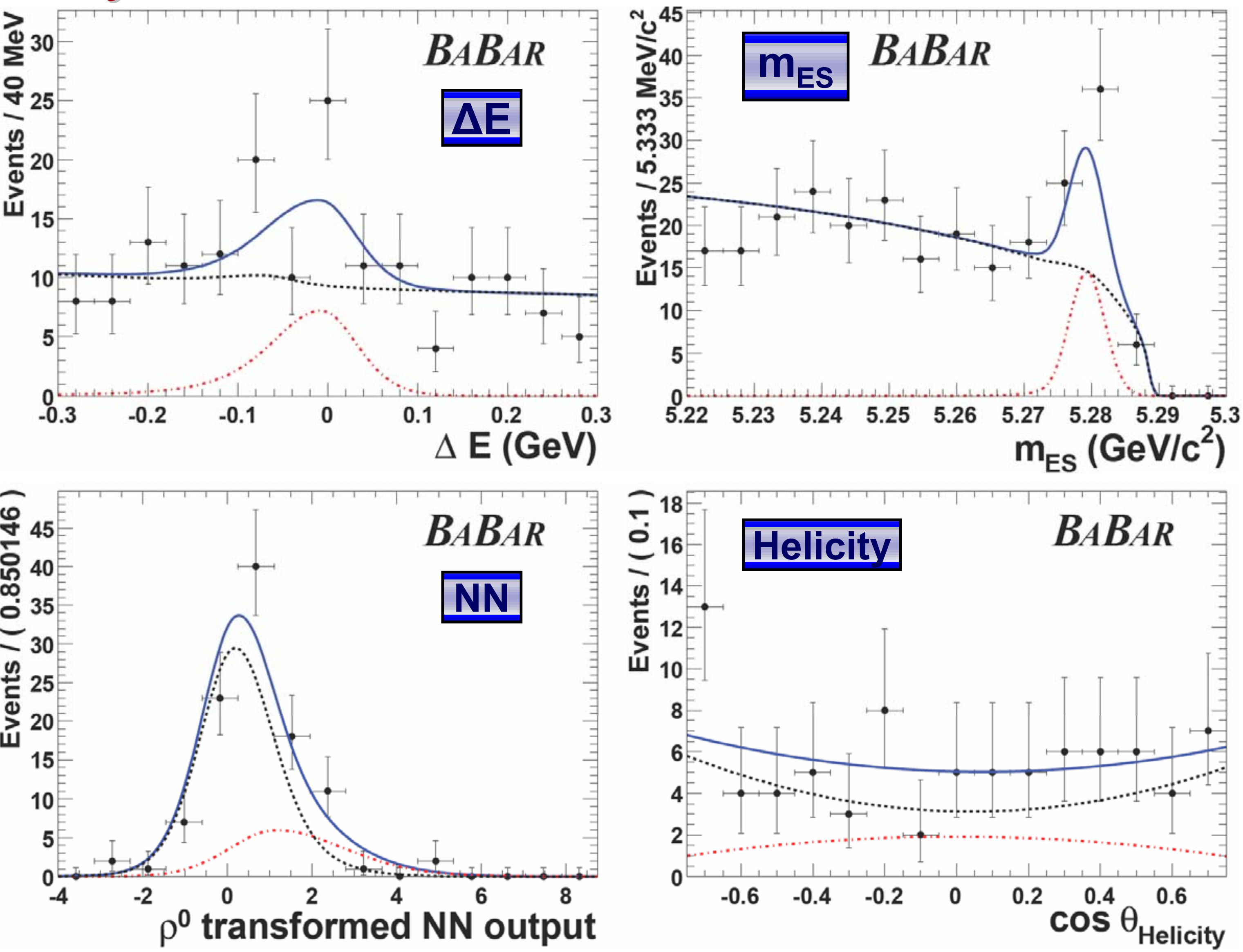
Thus:

Isospin violation between $\rho^+\gamma$ and $\rho^0\gamma$: $\frac{\Gamma(B^+\to\rho^+\gamma)}{2\Gamma(B^0\to\rho^0\gamma)} - 1 \sim \cos\alpha$

Systematics

Source of error	$\rho^+\gamma$	$\rho^0\gamma$	$\omega\gamma$	$\rho\gamma$	$(\rho/\omega)\gamma$
Tracking efficiency	1.0	2.0	2.0	1.4	1.5
Particle identification	2.0	4.0	2.0	2.9	2.7
Photon selection	1.9	2.6	1.7	2.2	2.1
π^0 reconstruction	3.0	-	3.0	1.9	2.5
π^0 and η veto	2.8	2.8	2.8	2.8	2.8
$\mathcal{NN}$ efficiency	1.0	1.0	1.0	1.0	1.0
$\mathcal{NN}$ shape	0.4	0.3	2.3	0.4	0.7
Signal PDF shapes	4.8	3.3	2.4	3.1	2.6
B background PDFs	3.9	2.9	9.7	2.6	2.7
$B\overline{B}$ sample size	1.1	1.1	1.1	1.1	1.1
$\mathcal{B}(\omega \rightarrow \pi^+\pi^-\pi^0)$	-	-	0.8	-	0.1
Sum in quadrature	8.1	7.4	11.6	6.7	6.7

Projections to all 4 dimensions:



$\rho^0\gamma$

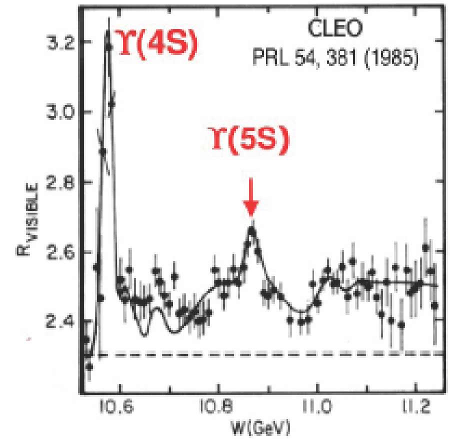
Full Fit
Background
Signal

Use 4 dimensions (5 for $\omega\gamma$)

Belle running at the Y(5S)

From: **J. Wicht, EPS HEP2007, Manchaster, UK**

- Beam energies increased by 2.7%
  - **smooth running!**
- Two samples :
  - June 2005 : 1.86 fb^{-1}.
  - June 2006 : 21.7 fb^{-1}.
- **Today's results : 23.6 fb^{-1}.**



$$\sigma_{b\bar{b}}^{\Upsilon(5S)} = (0.302 \pm 0.015)\ \mathrm{nb}$$

$$f_s = (19.5^{+3.0}_{-2.3})\%$$

PDG2007

$$f_{B_s^* B_s^*} = (93^{+7}_{-9})\%$$

PRL 98, 052001 (2007)
PRD 76, 012002 (2007)

N_{Bs}(23.6 fb^{-1}) = 2.6x10^6
~20% uncertainty