Exploring Matter-Antimatter Asymmetries in Radiative Penguin Decays at Belle

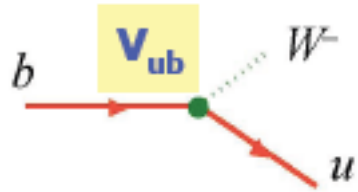
Himansu Sahoo
University of Hawaii
Fermi National Accelerator Laboratory
October 18, 2011

CP violation in SM

Standard Model quark mixing

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

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$



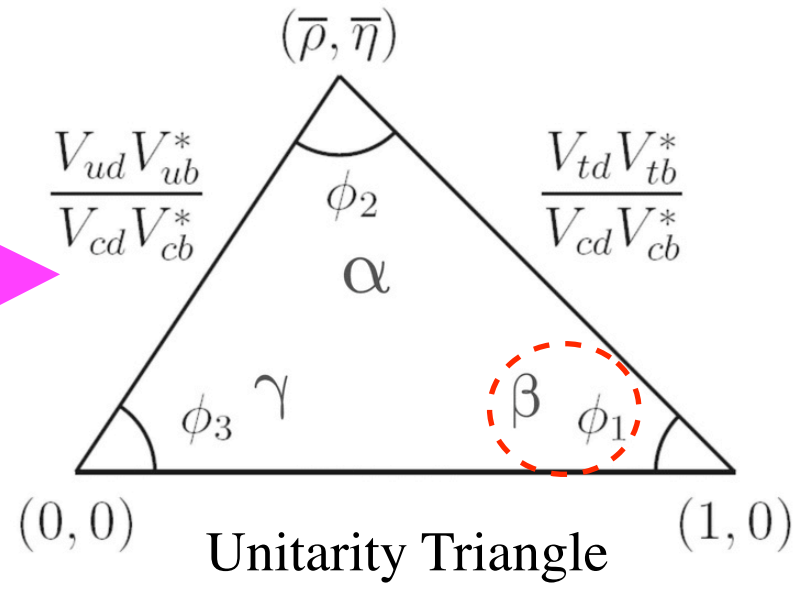
Cabibbo-Kobayashi-Maskawa (CKM) matrix (V_{CKM})

CP violation enters the SM through the complex phase in the CKM matrix

Unitarity relation ($V_{CKM}\, V^{+}_{CKM} = 1$)

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

The B factories (Belle and BaBar) measure the angles/sides precisely in different B decays

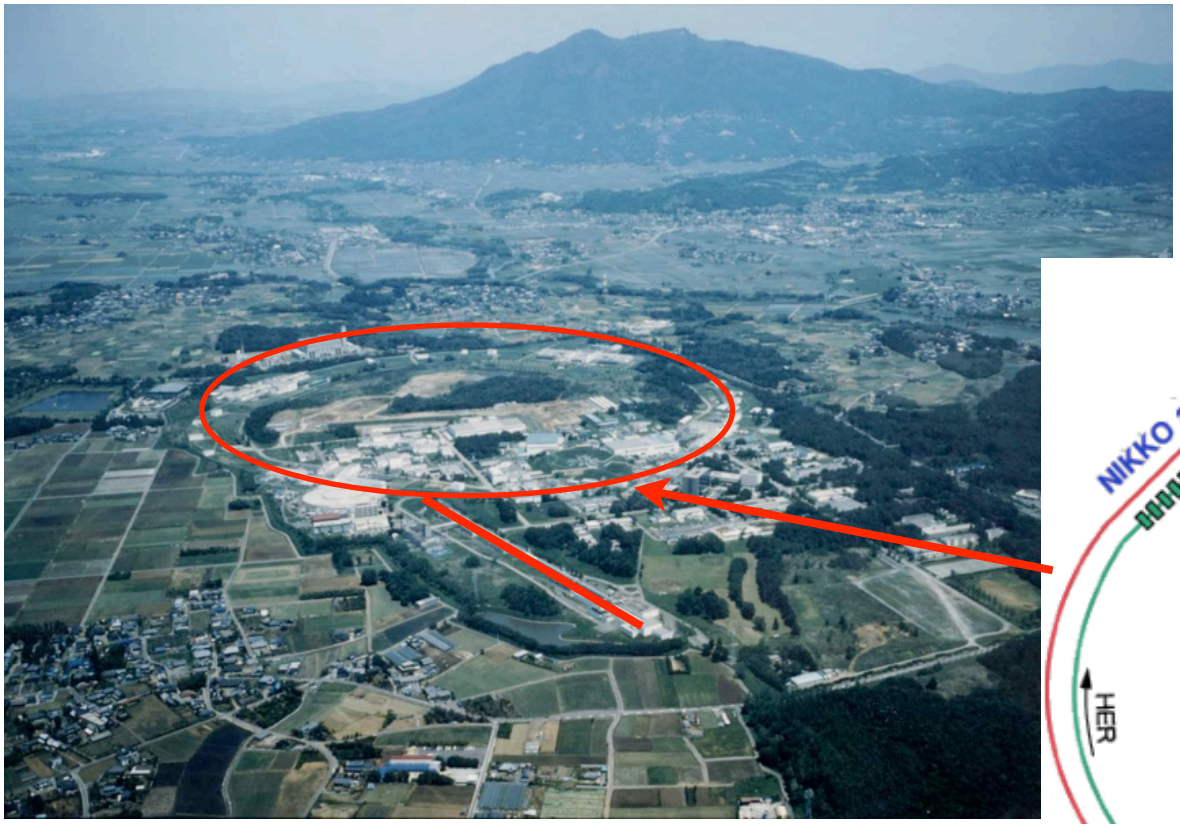


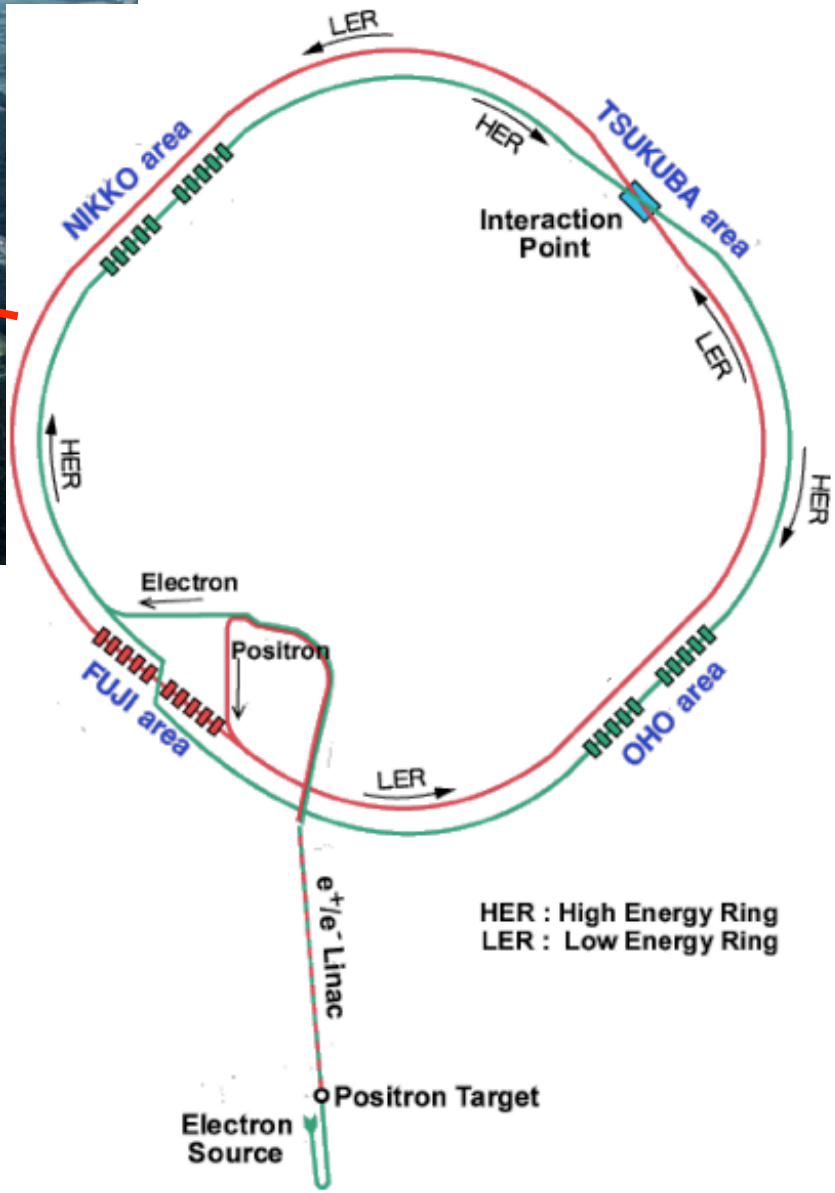
Unitarity Triangle

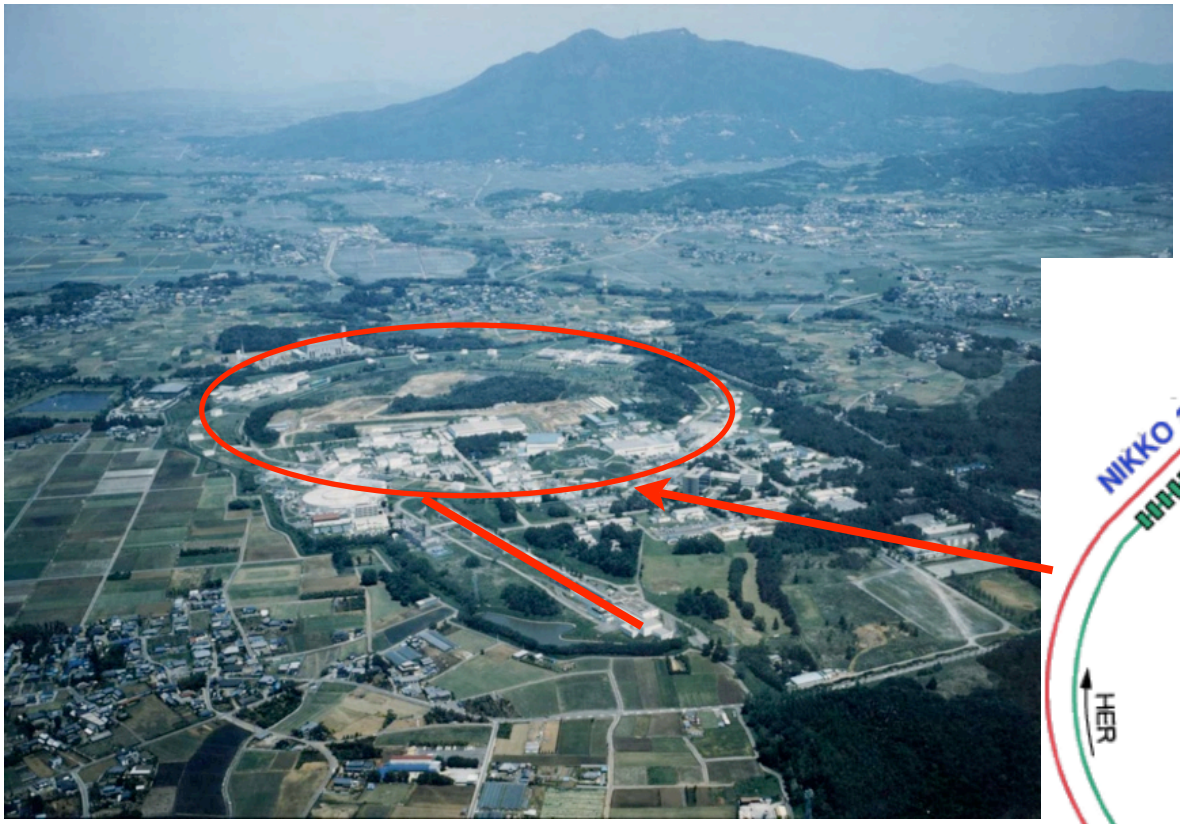
KEKB Asymmetic e^+e^- Collider

8 GeV e^- on 3.5 GeV e^+

boost $\beta\gamma=0.425$



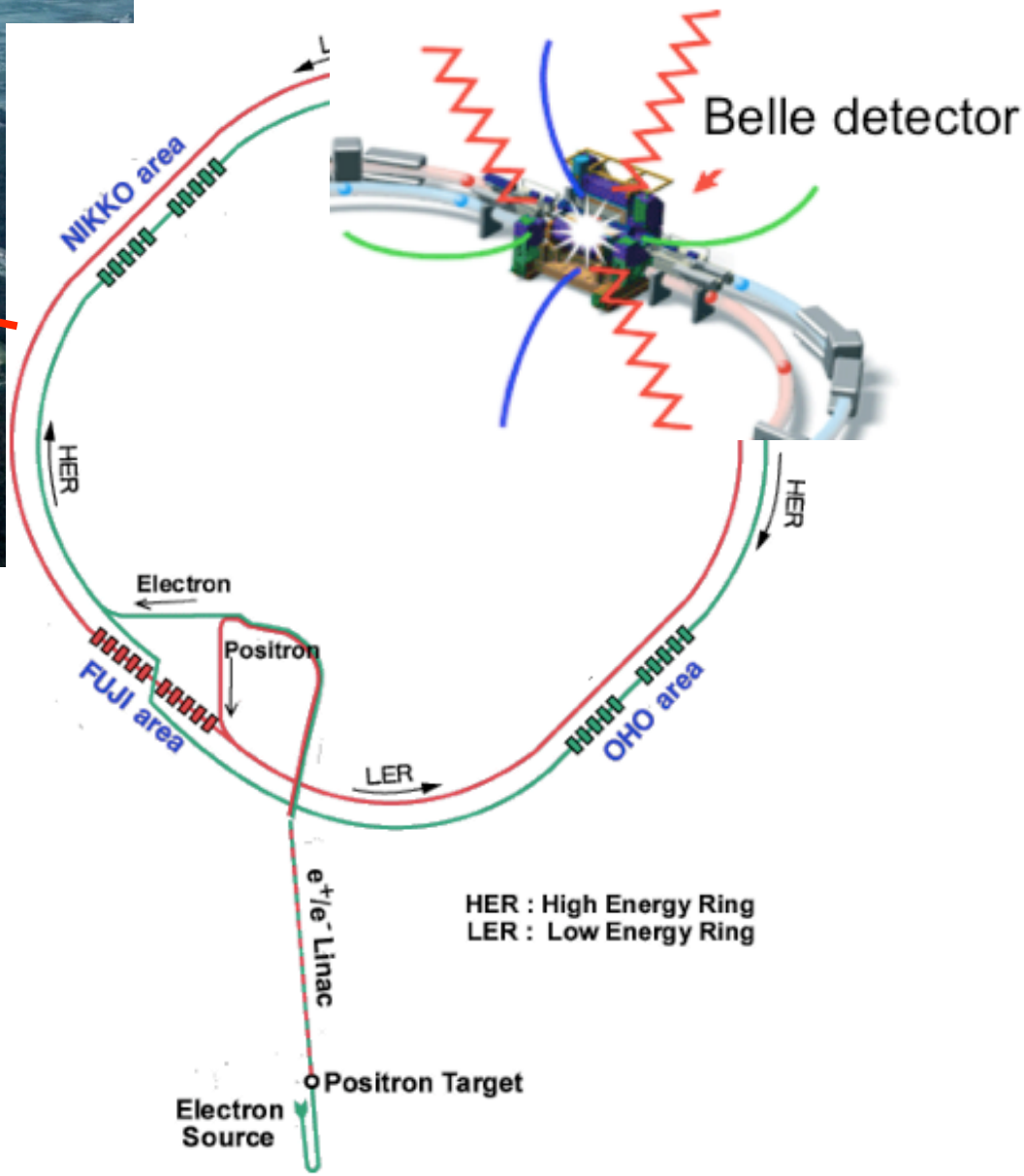


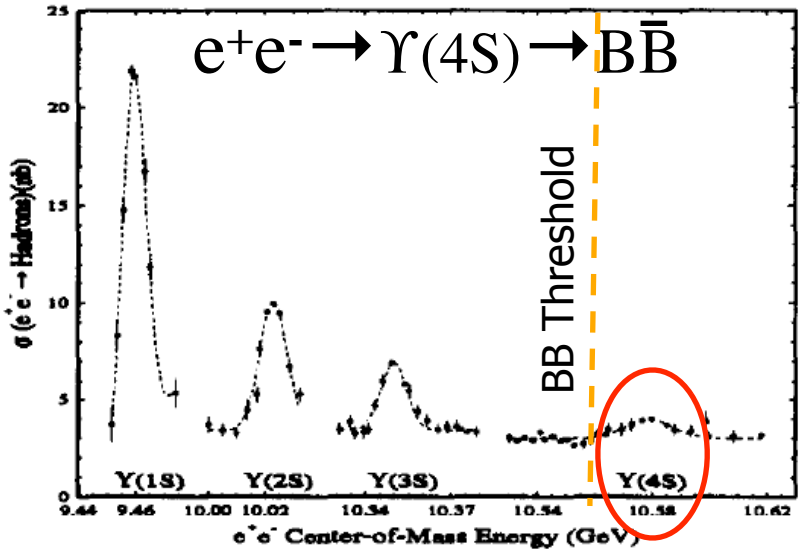


KEKB Asymmetic e^+e^- Collider

8 GeV e^- on 3.5 GeV e^+

boost $\beta\gamma=0.425$





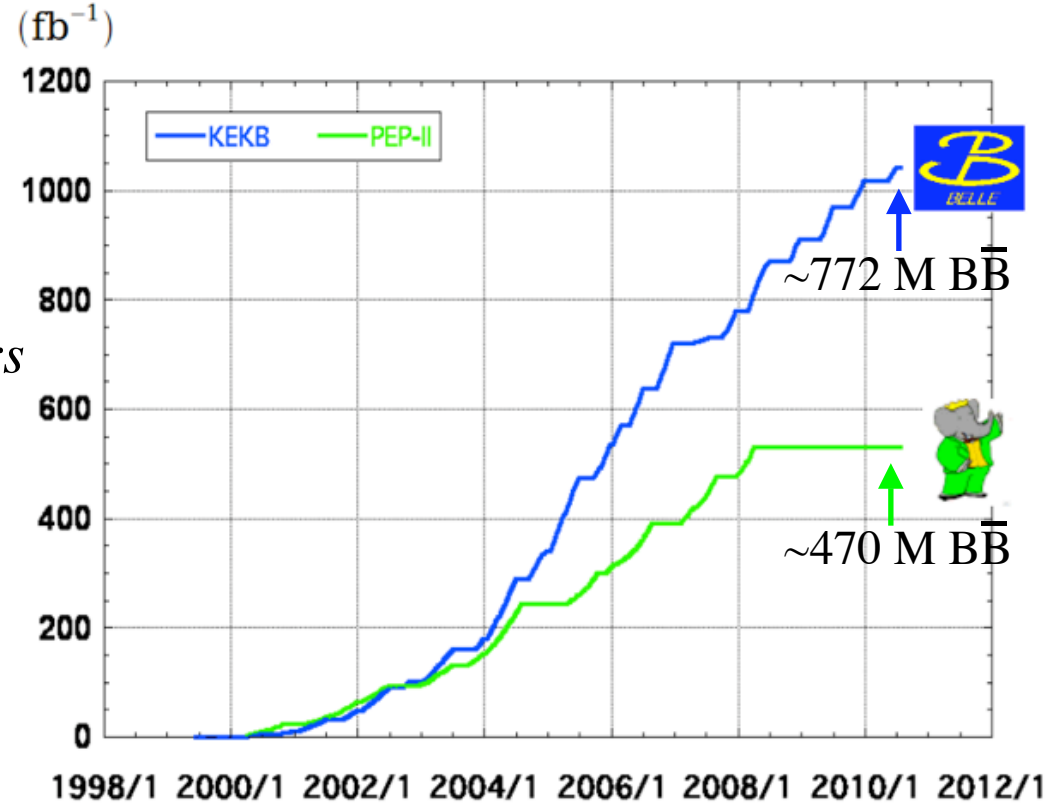
Luminosity

World record for integrated luminosity (1 ab^{-1})

Large Statistics of B meson pairs are available (772 M $B\bar{B}$)

11 years of operation of Belle (May 1999-June 2010)

Integrated luminosity of B factories

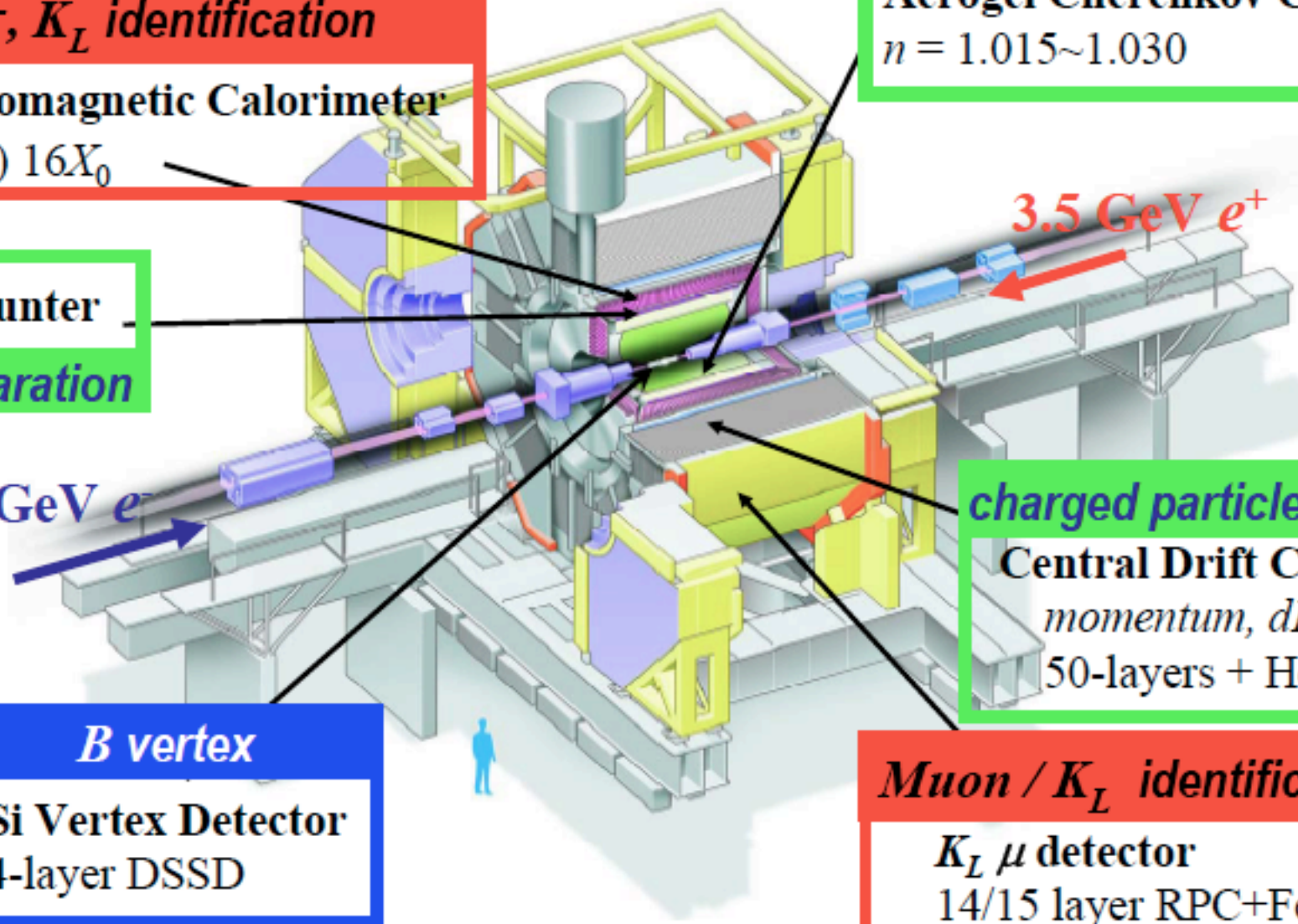


> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

KEKB Control room

Belle Detector



γ, π^0 reconstruction
e^{+-}, K_L identification

Electromagnetic Calorimeter
CsI(Tl) $16X_0$

K/π separation

Aerogel Cherenkov Counter
$n = 1.015 \sim 1.030$

TOF counter

K/π separation

3.5 GeV e^+

8.0 GeV e^-

charged particle tracking

Central Drift Chamber
momentum, dE/dx
50-layers + He/C_2H_6

B vertex

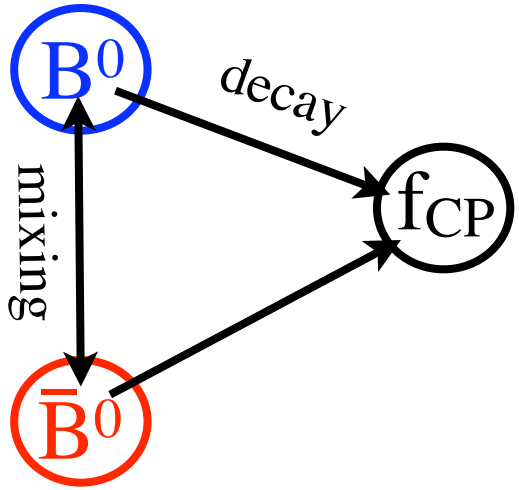
Si Vertex Detector
4-layer DSSD

Muon / K_L identification

K_L μ detector
14/15 layer RPC+Fe

Time-dependent CP asymmetry

Interference between $B^0 \to f_{CP}$ and $B^0 \to \bar{B}^0 \to f_{CP}$



- B^0-$\bar{B}^0$ mixing : A neutral B meson can transform into its own anti-particle
- Both the B^0 and its anti-particle $\bar{B}^0$ can decay to the same state final state.
- CP violation arises from interference between mixing and decay amplitudes.

Time dependent CP asymmetry

$$\mathcal{A}(\Delta t) = \frac{\Gamma(\bar{B}^0(\Delta t) \to f_{cp}) - \Gamma(B^0(\Delta t) \to f_{cp})}{\Gamma(\bar{B}^0(\Delta t) \to f_{cp}) + \Gamma(B^0(\Delta t) \to f_{cp})}$$

$$= \underbrace{\frac{2Im\lambda}{1+|\lambda|^2}}_{\mathcal{S}} \sin(\Delta m \cdot \Delta t) - \underbrace{\frac{1-|\lambda|^2}{1+|\lambda|^2}}_{\mathcal{A}} \cos(\Delta m \cdot \Delta t)$$

$$\lambda = \frac{q}{p}\frac{A(\bar{B}^0 \to f)}{A(B^0 \to f)}$$

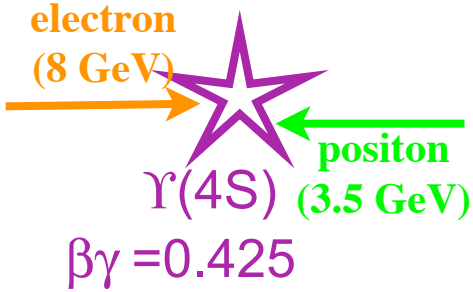
$$\mathcal{A}(\Delta t) = -\eta_{cp} \sin 2\phi_1 \sin(\Delta m \cdot \Delta t)$$

(for $b \to c\bar{c}s$ decays)

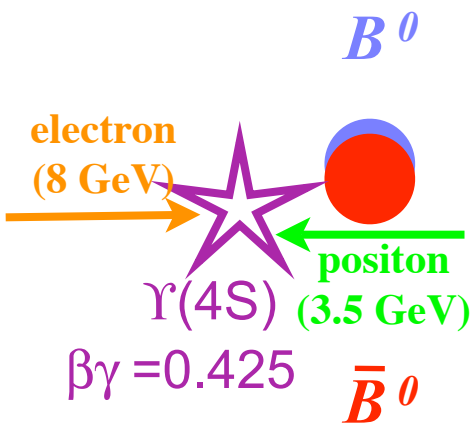
Mixing-induced CPV Direct CPV

How to measure Δt in experiment?

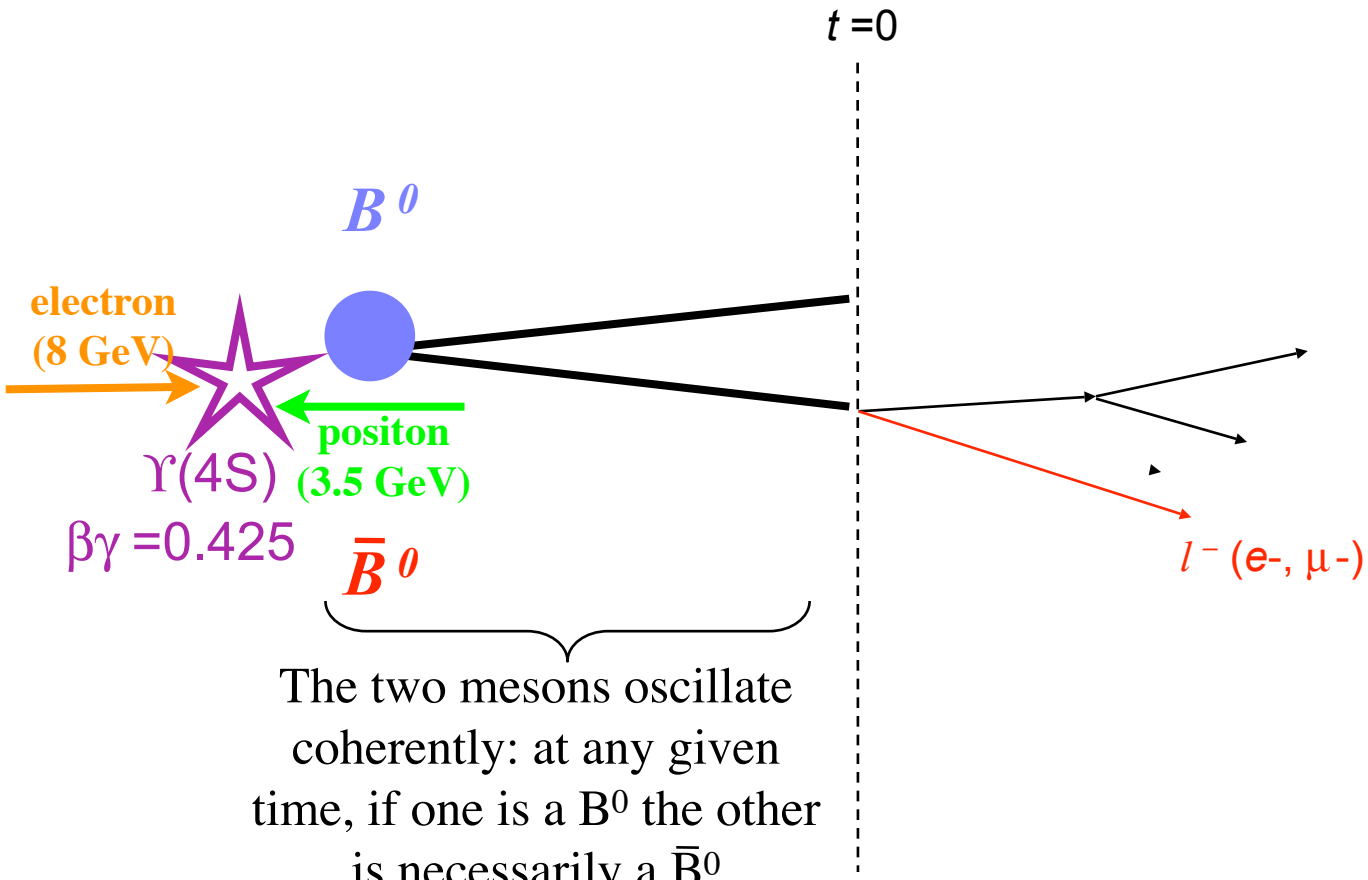
We need to know the flavor of the B at a reference t=0.



How to measure Δt in experiment?

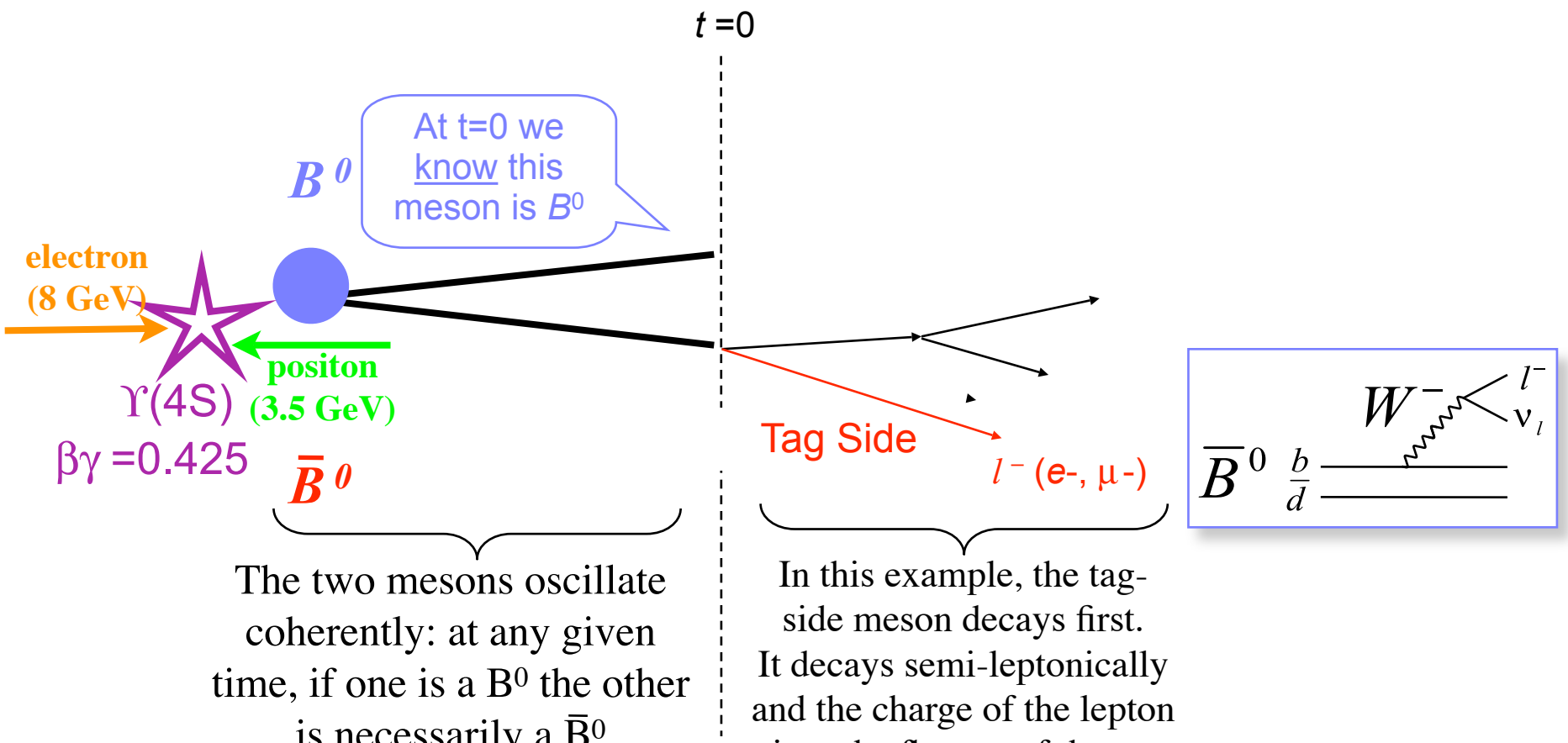


How to measure Δt in experiment?



The two mesons oscillate coherently: at any given time, if one is a B^0 the other is <u>necessarily</u> a $\bar{B}^0$

How to measure Δt in experiment?



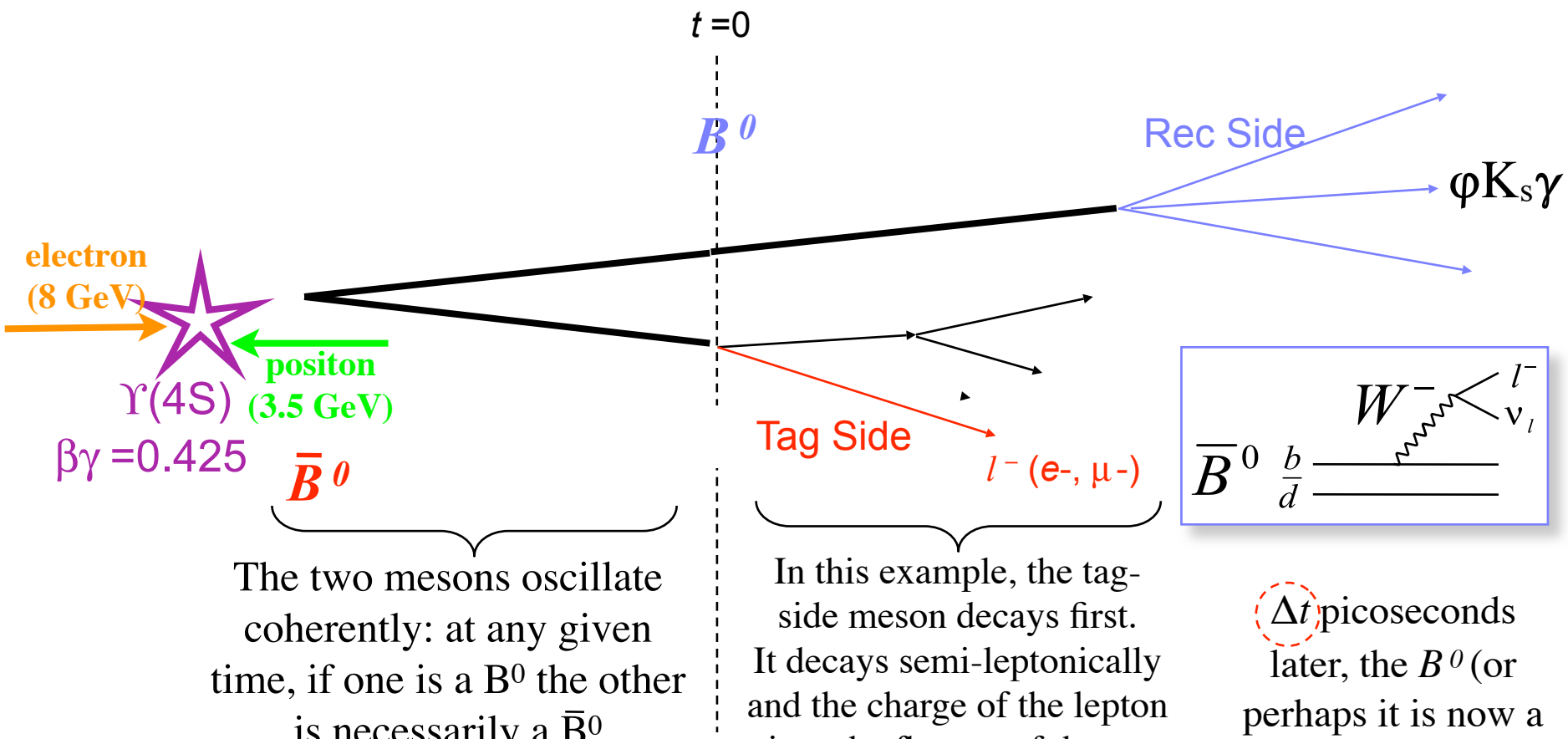
The two mesons oscillate coherently: at any given time, if one is a B^0 the other is necessarily a $\bar{B}^0$

In this example, the tag-side meson decays first. It decays semi-leptonically and the charge of the lepton gives the flavour of the tag-side meson :

$l^- = \bar{B}^0 \qquad l^+ = B^0$.

Kaon tags also used.

How to measure Δt in experiment?



The two mesons oscillate coherently: at any given time, if one is a B^0 the other is necessarily a $\bar{B}^0$

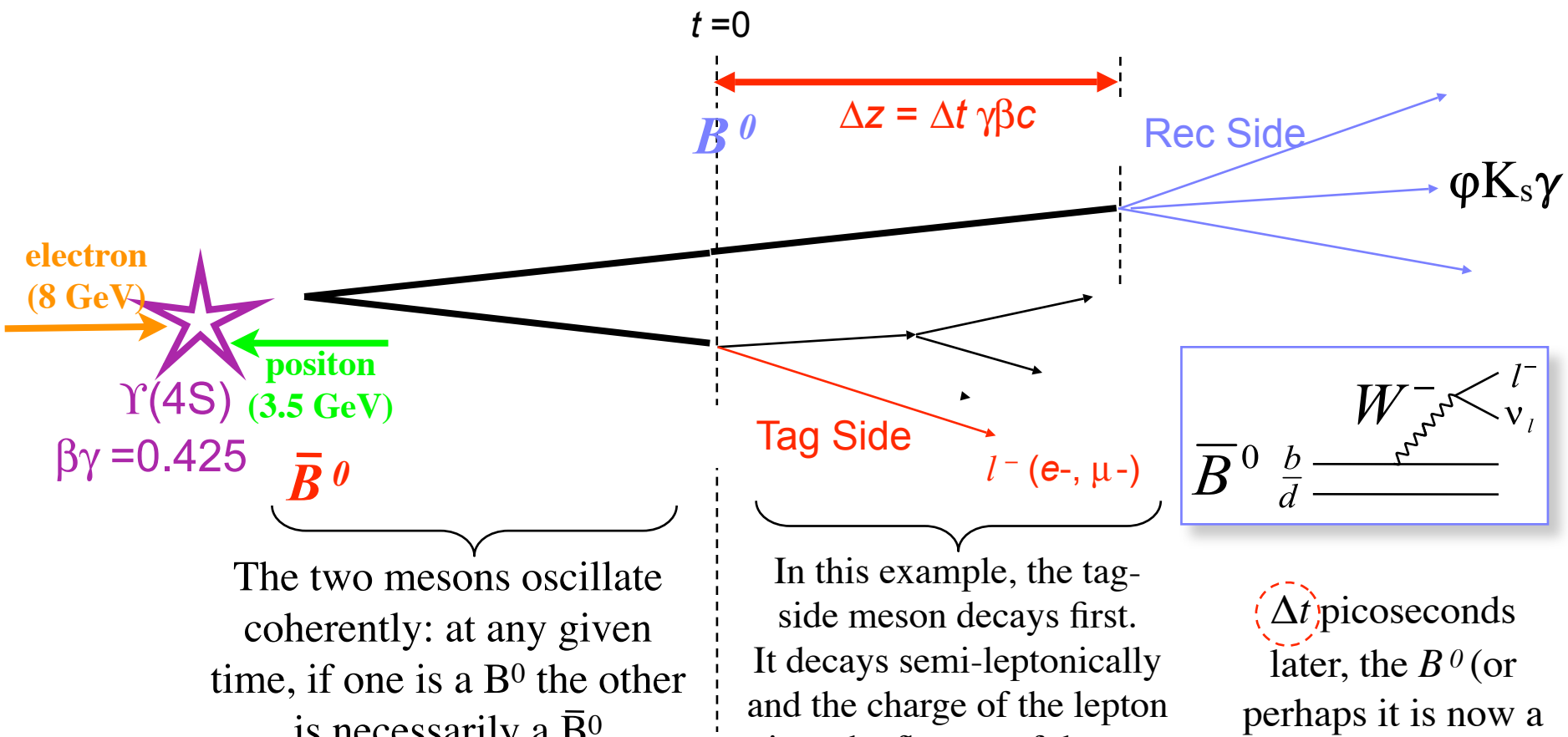
In this example, the tag-side meson decays first. It decays semi-leptonically and the charge of the lepton gives the flavour of the tag-side meson :

$l^- = \bar{B}^0 \quad l^+ = B^0$.

Kaon tags also used.

Δt picoseconds later, the B^0 (or perhaps it is now a $\bar{B}^0$) decays.

How to measure Δt in experiment?



The two mesons oscillate coherently: at any given time, if one is a B^0 the other is necessarily a $\bar{B}^0$

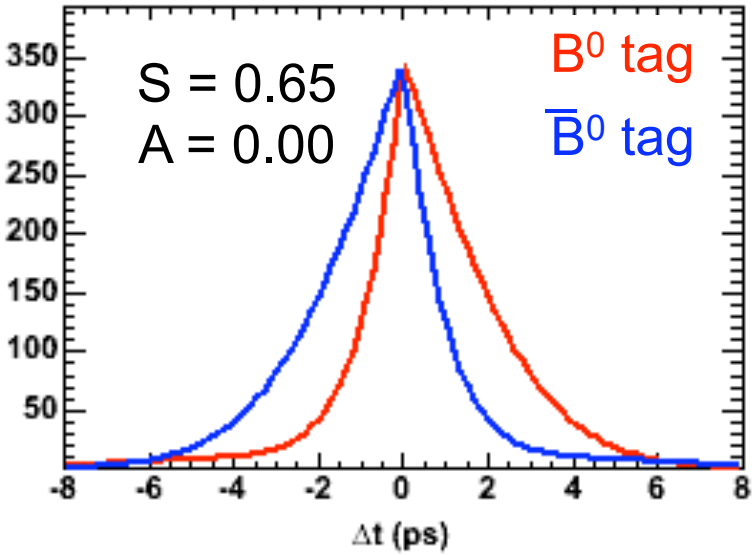
In this example, the tag-side meson decays first. It decays semi-leptonically and the charge of the lepton gives the flavour of the tag-side meson :

$l^- = \bar{B}^0 \quad l^+ = B^0$.

Kaon tags also used.

Δt picoseconds later, the B^0 (or perhaps it is now a $\bar{B}^0$) decays.

Expected experimental distribution

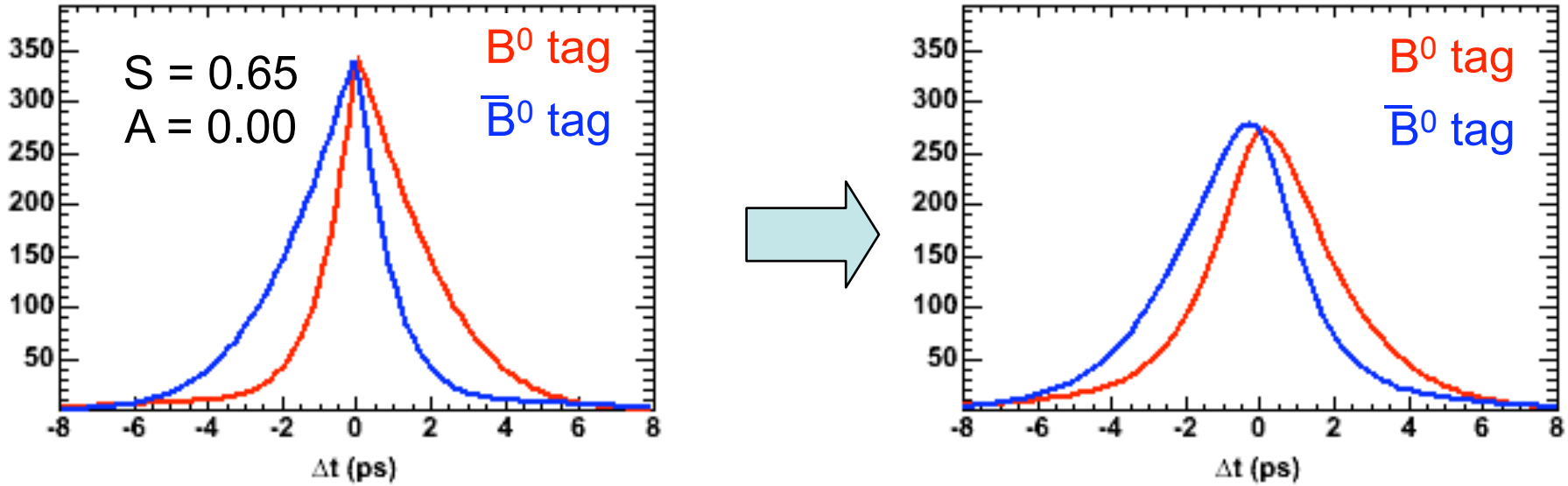


q = +1 (-1) for tagging

$$\mathcal{P}(q,\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left\{1 + q\left[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)\right]\right\}$$

q = +1 (-1) for tagging B^0 ($\bar{B}^0$)

Expected experimental distribution

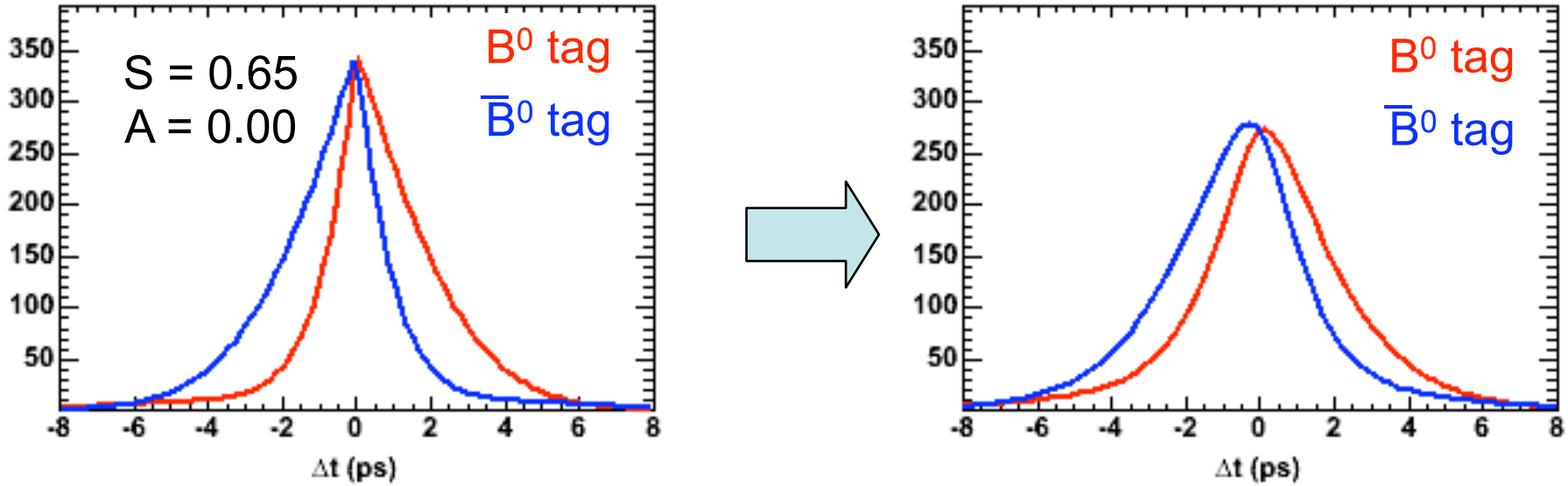


q = +1 (-1) for tagging

$$\mathcal{P}(q,\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left\{1 + q\left[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)\right]\right\}$$

q = +1 (-1) for tagging B^0 ($\bar{B}^0$)

Expected experimental distribution



q = +1 (-1) for tagging

$$\mathcal{P}(q,\Delta t) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left\{1 + q\left[\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)\right]\right\} \otimes R$$

$-q\Delta w$

$(1-2w)$

q = +1 (-1) for tagging B^0 ($\bar{B}^0$)

R : detector resolution
w : wrong tag fraction
(misidentification of flavor)
⇔ (1-2w) quality of flavor tagging
These are well determined by using data control samples: $D^* l\nu$, $D^{(*)}\pi$ etc…

$B \to (c\bar{c})K^0$ decay modes

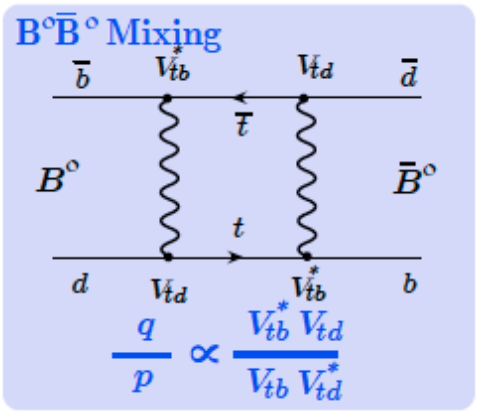
$B \to$ Charmonium K^0 : Golden modes for CP Violation measurements

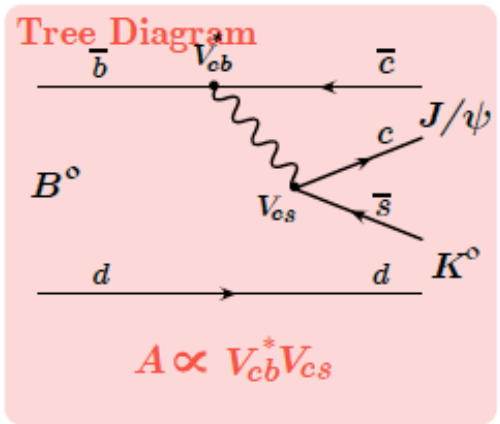
- Clean Experimental Signature
  - Many accessible modes with (relatively) Large BFs
  - Low Background Levels, high efficiency
- Clean Extraction of CKM angle
  - Dominated by tree diagram
  - Leading penguin diagram has the same weak phase as tree

$B^0 \to J/\psi K^0 \sim 8.7\times10^{-4}$
$B^0 \to \psi' K^0 \sim 6.2\times10^{-4}$
$B^0 \to \chi_{c1} K^0 \sim 3.9\times10^{-4}$
$B^0 \to \eta_c K^0 \sim 8.9\times10^{-4}$

$$B^0 \to \psi' K^0_S \begin{cases} \psi' \to l^+l^-, K^0_S \to \pi^+\pi^- \\ \psi' \to J/\psi\pi^+\pi^-, J/\psi \to l^+l^- \end{cases}$$

l^+l^- is e^+e^- or $\mu^+\mu^-$ four decay channels





SM expectation

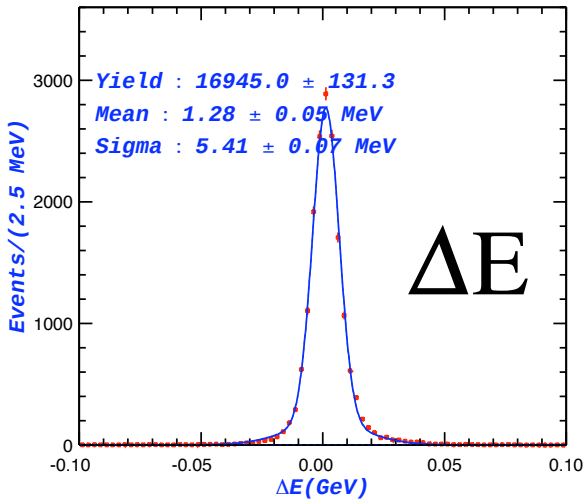
$$\lambda = \frac{q}{p}\frac{\bar{A}}{A} = \eta_{cp} e^{-i2\phi_1} \Rightarrow \begin{cases} \mathcal{S} = -\eta_{cp}\sin 2\phi_1 \\ \mathcal{A}(-\mathcal{C}) = 0 \end{cases}$$

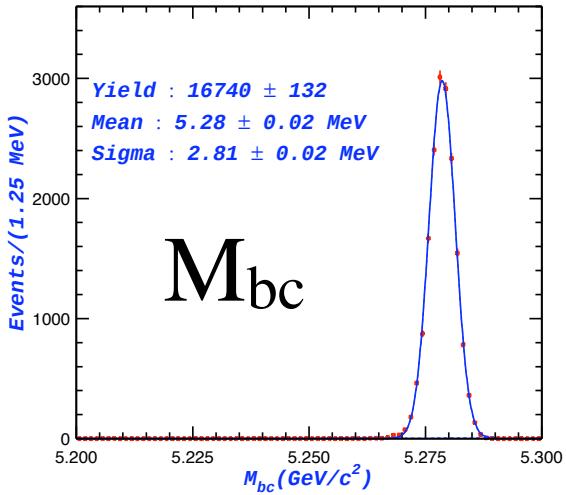
$$\mathcal{A}(\Delta t) = -\eta_{cp}\sin 2\phi_1 \sin(\Delta m \cdot \Delta t)$$

B candidate selection (ΔE and M_{bc}) MC

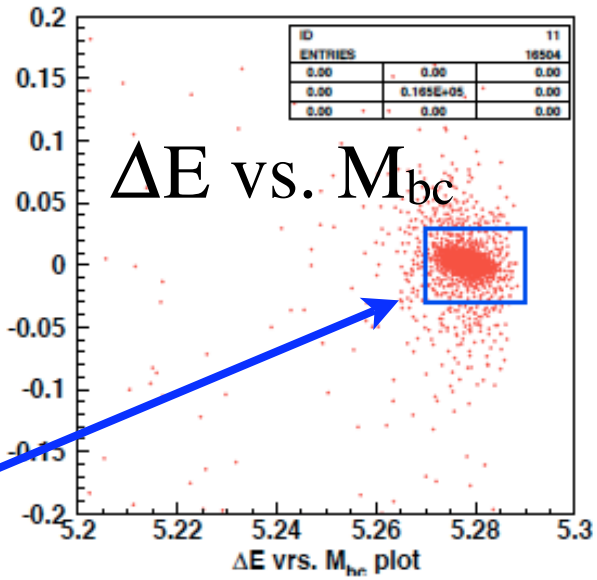
B candidates selection based on two kinematically uncorrelated variables.

$$\Delta E \equiv E^*_{\rm B} - E^*_{\rm beam}$$
$$M_{\rm bc} \equiv \sqrt{(E^*_{\rm beam})^2 - (p^*_{\rm B})^2}$$





- ΔE : Energy difference
- M_{bc} : beam-energy-constrained mass
- E_B^* (p_B^*) : Energy (momentum) of B in center-of-mass
- E_{beam}^* : Beam energy

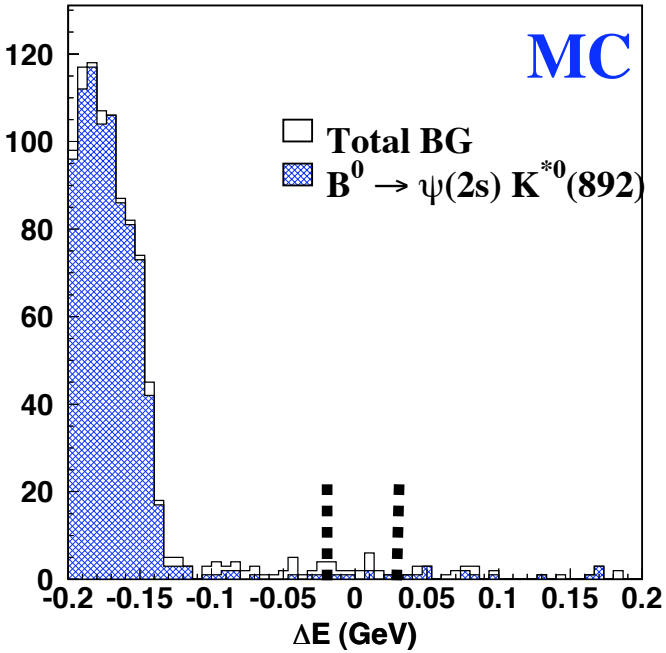


Signal region :

$|\Delta E| < 0.03$ GeV && $(5.27 < M_{bc} < 5.29$ GeV/$c^2)$

$B\bar{B}$ Backgrounds in $\psi' K_S$ mode

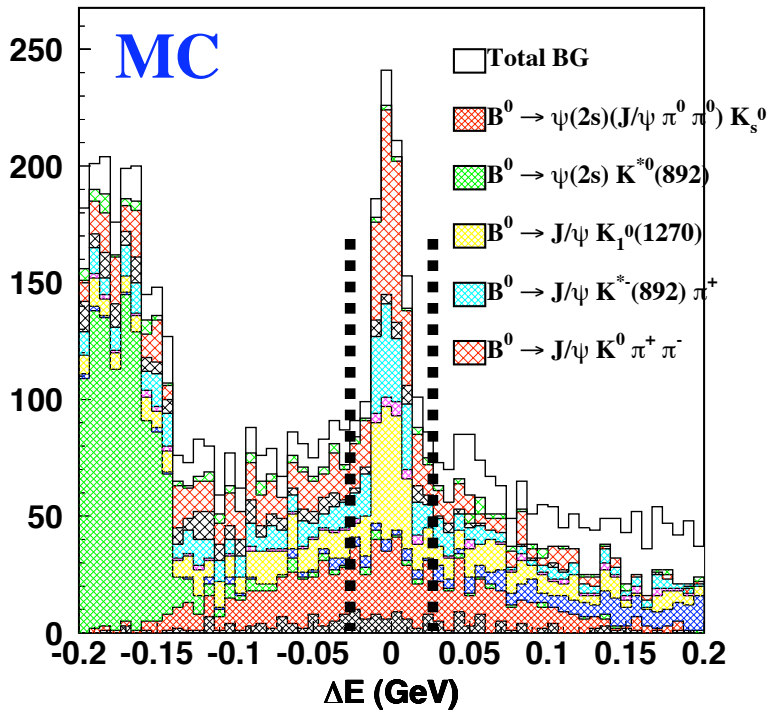
$\psi' \to ll$



$B^0 \to \psi' K^{*0}$

$\hookrightarrow K^0_S \pi^0$

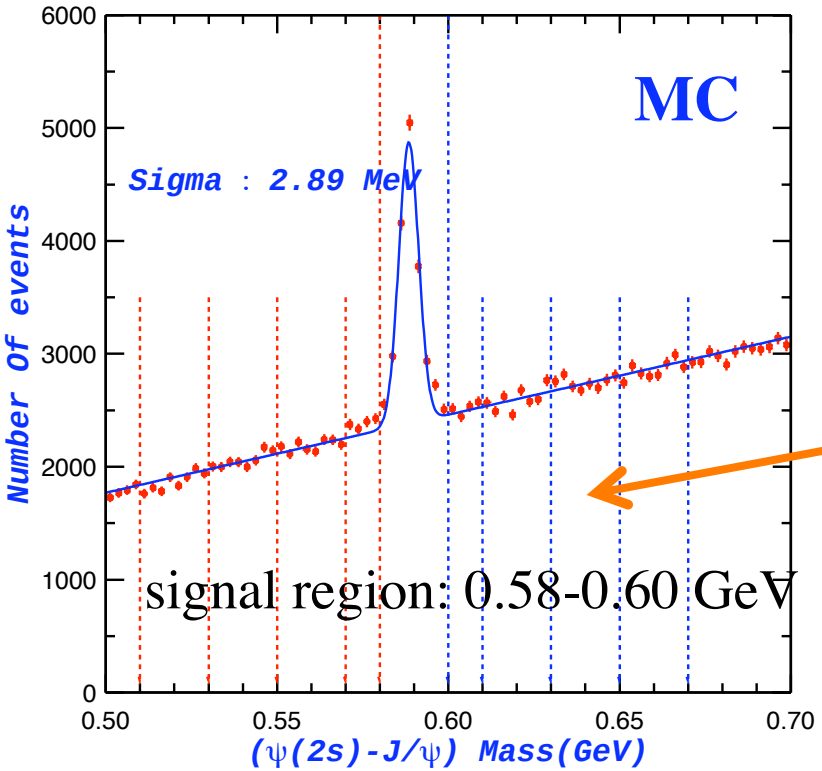
$\psi' \to J/\psi\pi\pi$



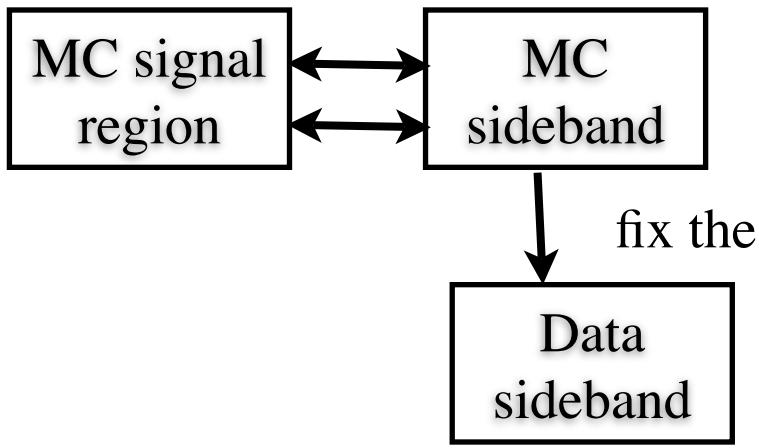
(100 times data)

Many peaking backgrounds (having same final state as signal $B^0 \to \psi' K_S$), but overall level in tiny (~1%) compared to signal

How to estimate the peaking bkgs using data?



- Peaking modes do not have real $\psi' \rightarrow J/\psi\pi^+\pi^-$
- They do not peak at the ψ' mass => estimate from sidebands of $[\psi'\text{-}J/\psi]$ mass
- Six sidebands are used, each having same width as signal region



peaking is ~1% of the signal

H. Sahoo *et al.*, PRD 77, 091103 (2008)

(657 M $B\bar{B}$)

$B \to (c\bar{c})K^0$ signals

- Belle's new result with full data sample (772 M $B\bar{B}$).
- More data and improved tracking ⇒ nearly 50% more signal than previous analysis.

$B^0 \to J/\psi\, K^0$

$J/\psi \to ee, \mu^+\mu^-$

$K_S \to \pi^+\pi^-$

K_L : clusters

$B^0 \to \psi' K_S$

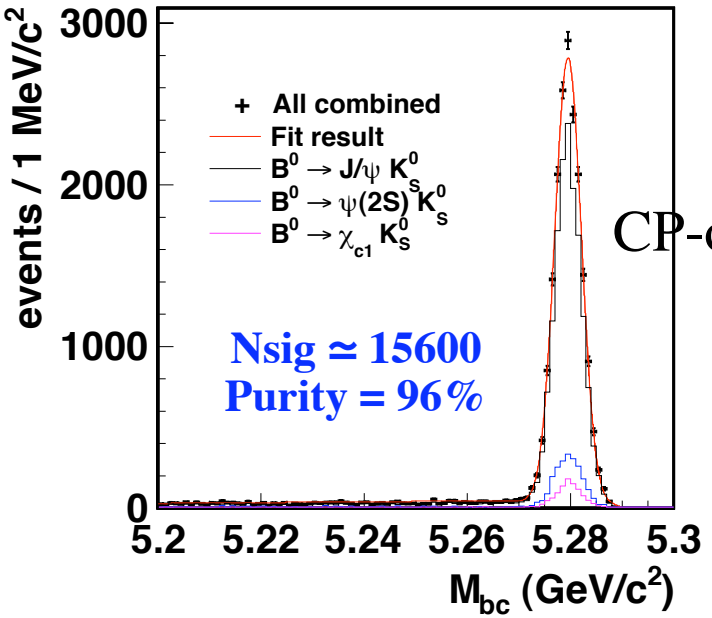
$\psi' \to ee, \mu^+\mu^-, J/\psi\pi^+\pi^-$

$B^0 \to \chi_{c1}\, K_s$

$\chi_{c1} \to J/\psi\gamma$

P_B^* for K_L : only K_L direction is measured; missing momentum is calculated using known B energy and K_L direction.

772 M $B\bar{B}$



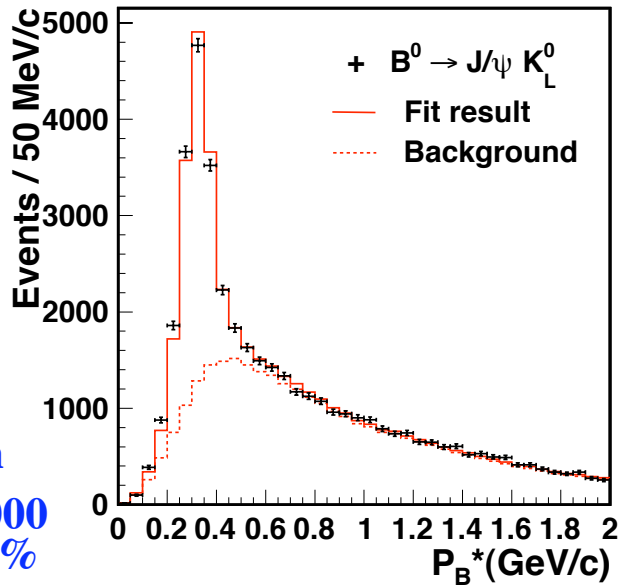
CP-odd

decay modes	signal Yield
$B^0 \to J/\psi\, K_S$	12681±114
$B^0 \to \psi' K_S$	1981±46
$B^0 \to \chi_{c1}\, K_s$	943±33
$B^0 \to J/\psi\, K_L$	10041±154

CP-even

Nsig ≃ 10000

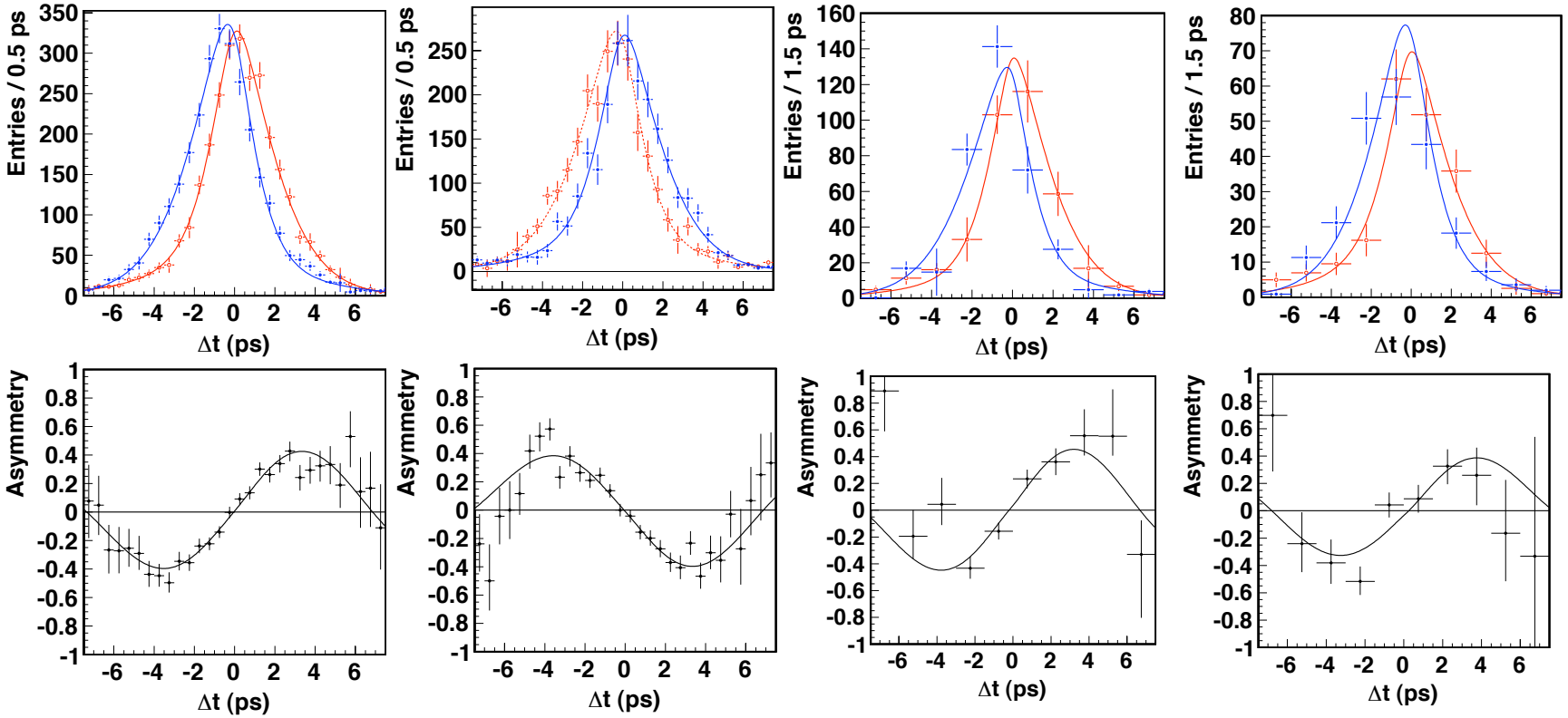
purity=63%



$\sin 2\phi_1$ in $B \to (c\bar{c})K^0$ decays

772 M $B\bar{B}$

Background subtracted, good tagged (r>0.5) only



B^0

$\bar{B}^0$

$$\frac{N(B^0)-N(\bar{B}^0)}{N(B^0)+N(\bar{B}^0)}$$

$B^0 \to J/\psi\, K_S$	$B^0 \to J/\psi\, K_L$	$B^0 \to \psi' K_S$	$B^0 \to \chi_{c1}\, K_S$
$\mathcal{S} = 0.671 \pm 0.029$	$\mathcal{S} = -0.641 \pm 0.047$	$\mathcal{S} = 0.739 \pm 0.079$	$\mathcal{S} = 0.636 \pm 0.117$
$\mathcal{A} = -0.014 \pm 0.021$	$\mathcal{A} = 0.019 \pm 0.026$	$\mathcal{A} = 0.103 \pm 0.055$	$\mathcal{A} = -0.023 \pm 0.083$

(stat errors only)

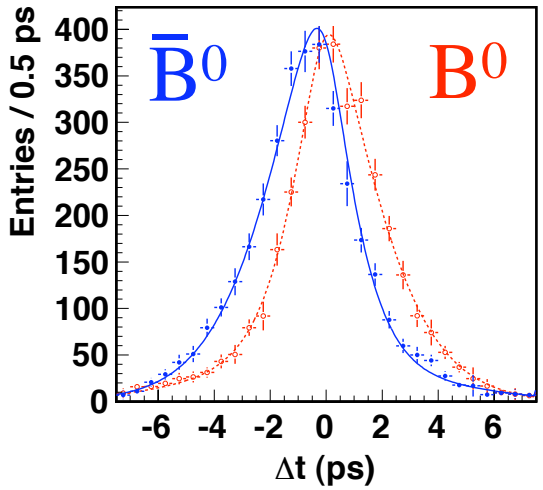
CP Violation is observed in all modes

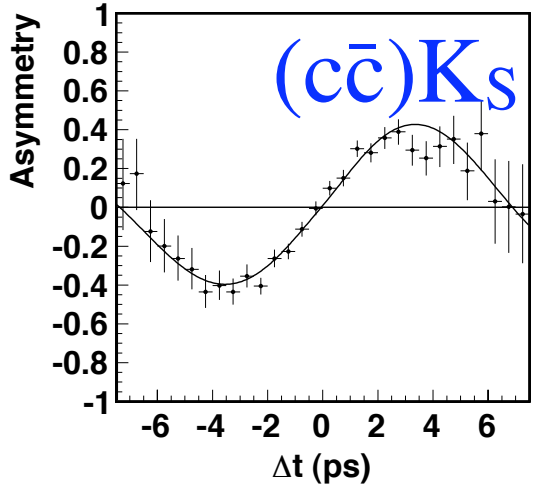
2011 measurement of $\sin 2\phi_1$ at Belle

772 M $B\bar{B}$

CP-odd (η_{cp}=-1)

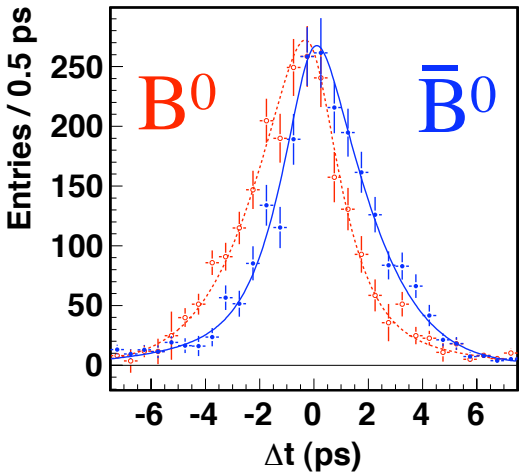
$B^0 \to J/\psi\, K_S$
$B^0 \to \psi' K_S$
$B^0 \to \chi_{c1}\, K_S$

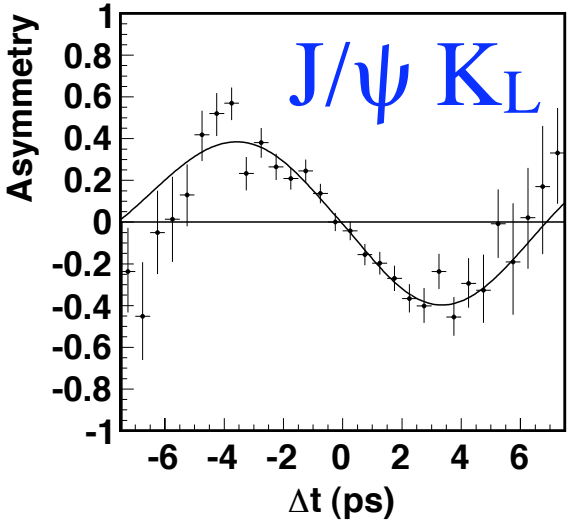




CP-even (η_{cp}=+1)

$B^0 \to J/\psi\, K_L$



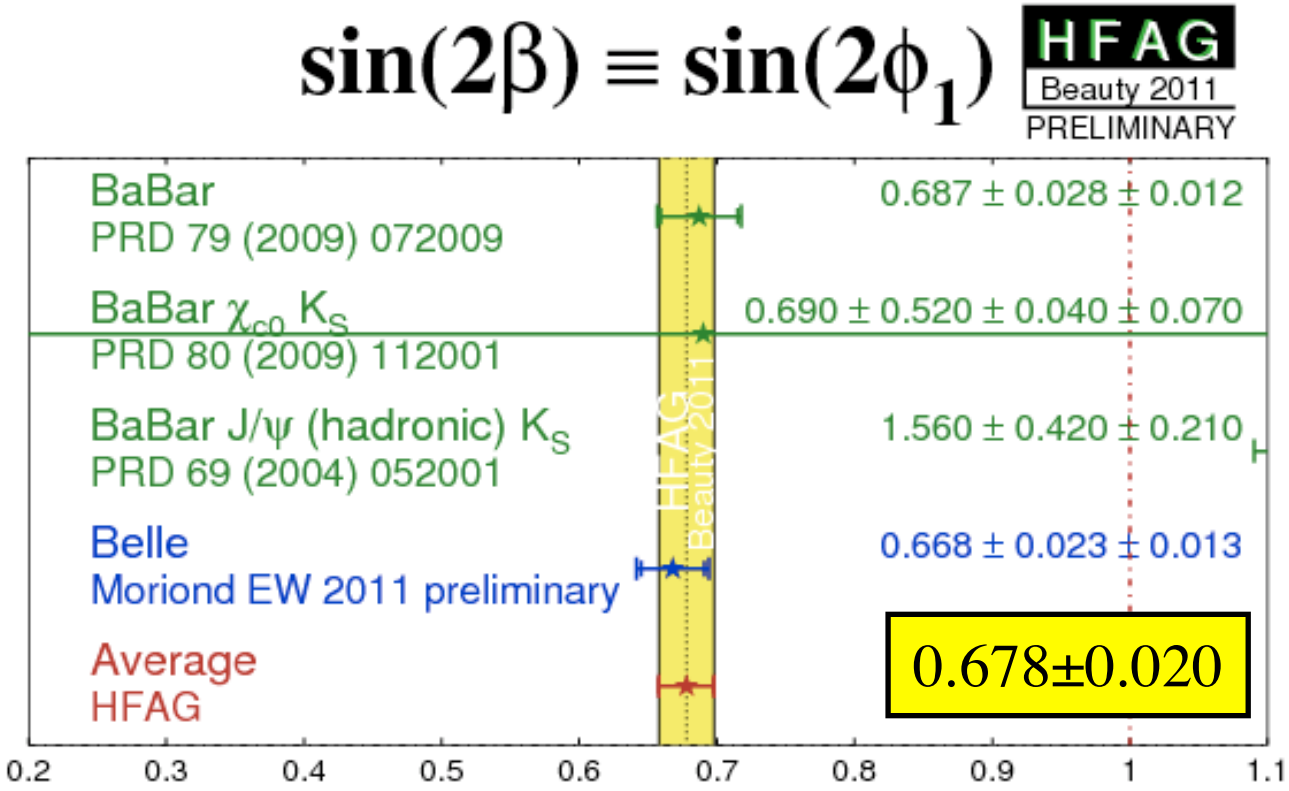


Combined result for all charmonium modes

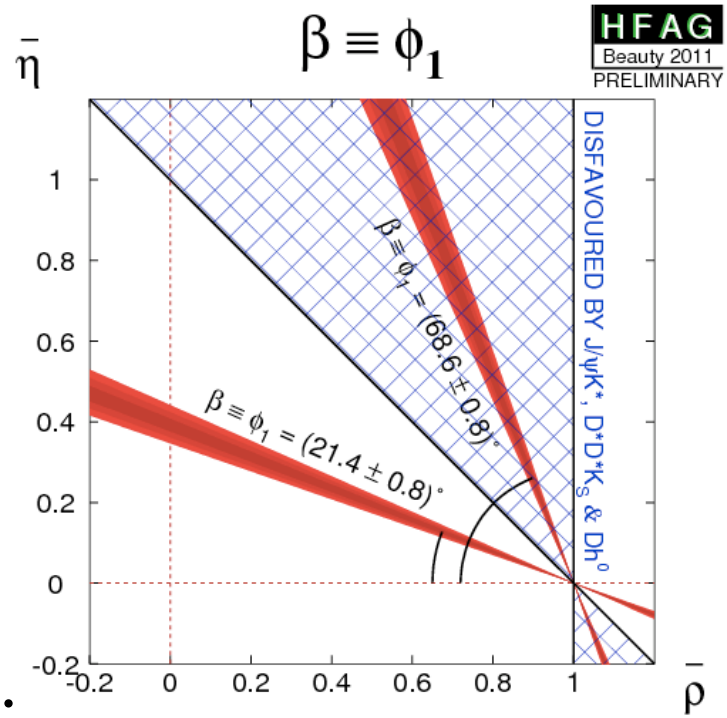
$$\sin 2\phi_1 = 0.668 \pm 0.023(\text{stat}) \pm 0.013(\text{syst})$$
$$\mathcal{A} = 0.007 \pm 0.016(\text{stat}) \pm 0.013(\text{syst})$$

World's most precise measurements

sin2ϕ_1: 2011 World Average



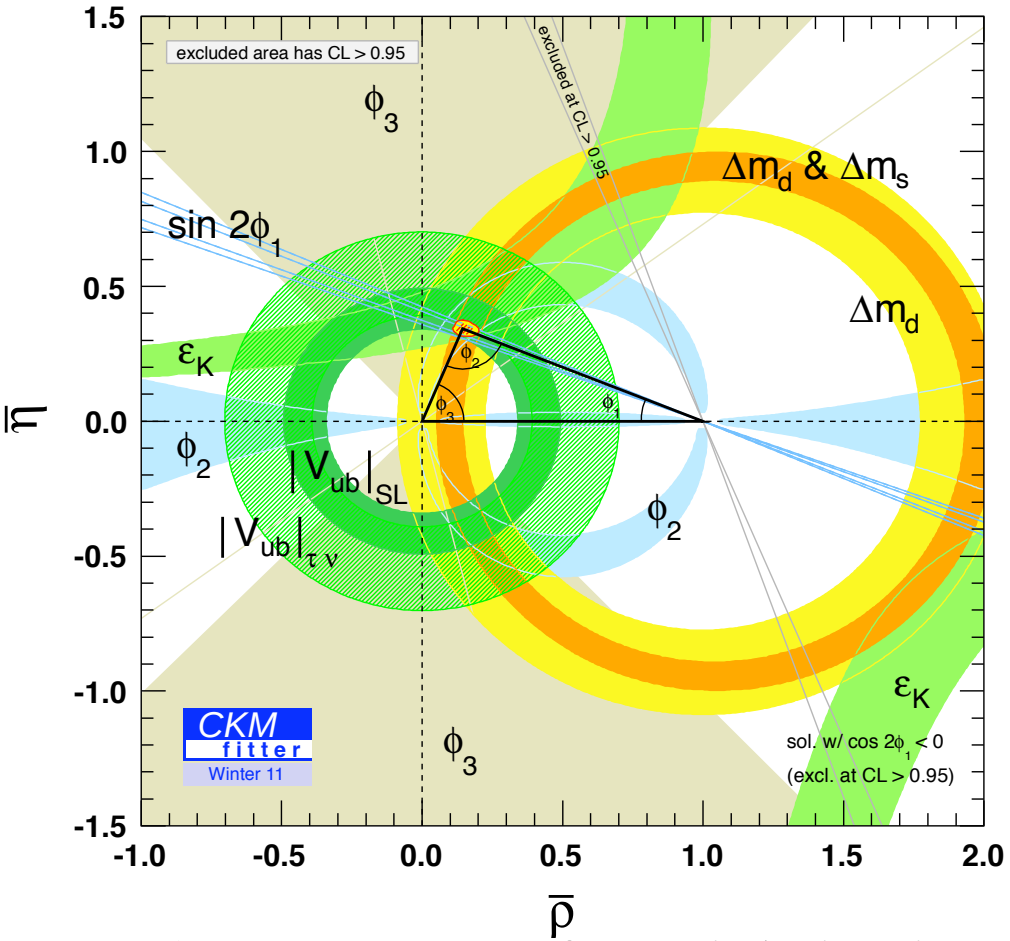
CP violating effect is $\mathcal{O}(1)$ in B meson instead of $\mathcal{O}(10^{-3})$ in K meson system



- Experimental uncertainty on sin2ϕ_1 ~3%.
- $\mathcal{A}$ value is consistent with zero ($\mathcal{A} = -0.013 \pm 0.017$).
- CKM angle $\phi_1(\beta)$ is measured with < 1° precision.

reference point for new physics search

UT from sin2ϕ_1 & indirect constraints



Global fit result by CKM fitter

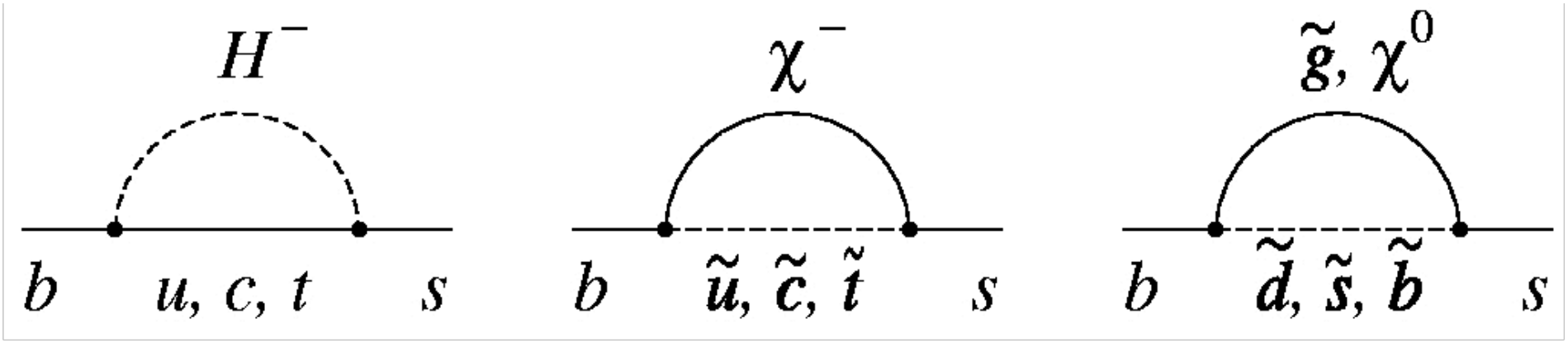
All independent measurements overlap at a single apex of the triangle => consistent with CKM picture

- The SM source of CP violation is not sufficient (10 orders of magnitude less) to explain the matter anti-matter imbalance.
- New sources are required to explain the matter dominance.

Look for New Physics beyond SM

Radiative penguin B decays

- Flavor Changing Neutral Current processes.
- Forbidden at tree-level in the SM, but allowed through loop (penguin) diagrams.
- Non-SM particles may contribute to the loop.



b→sγ spectrum

Many exclusive b→sγ modes have been observed by CLEO, Belle and BaBar

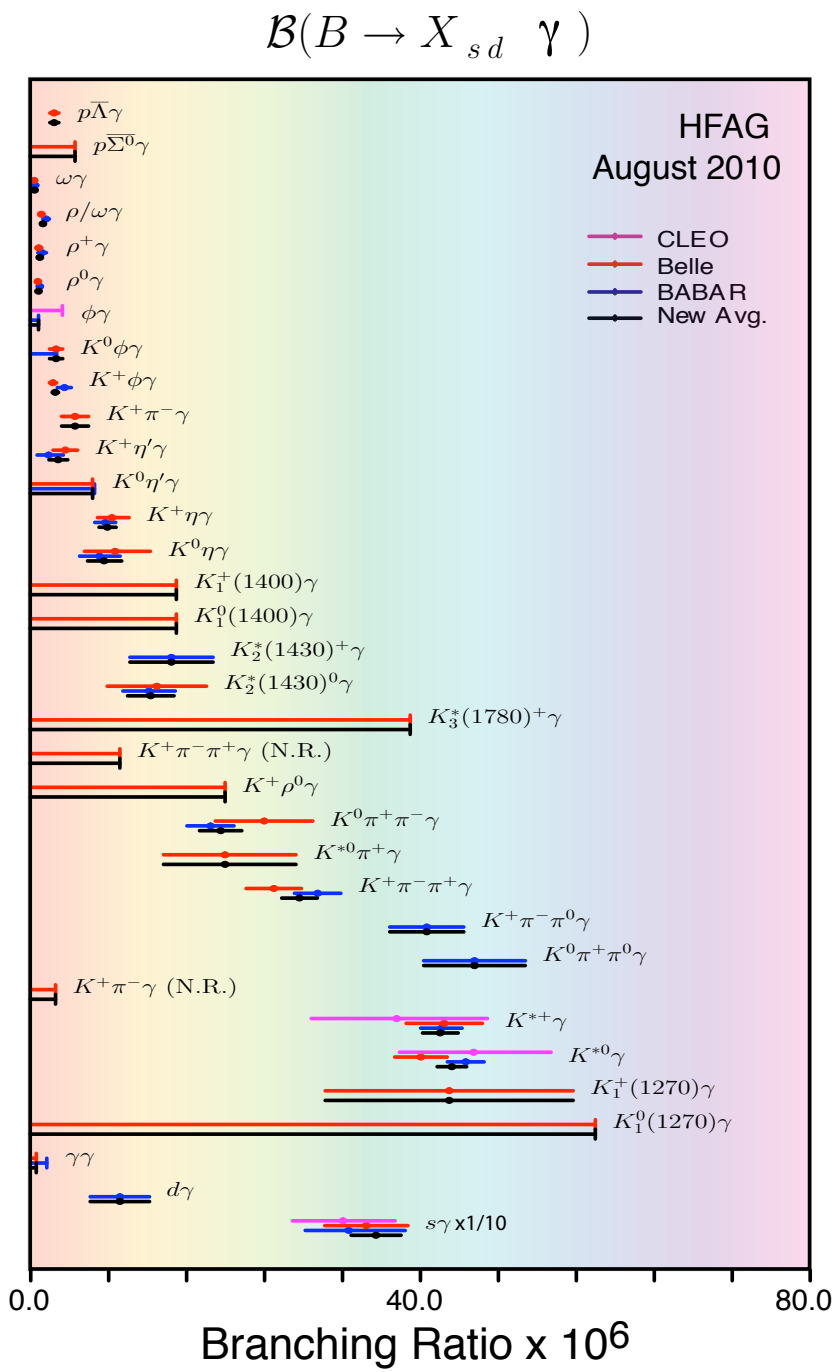
Inclusive B→Xsγ branching fraction

$(3.55 \pm 0.26) \times 10^{-6}$ experimentally measured

$(3.15 \pm 0.23) \times 10^{-6}$ theory prediction NNLO

Sum of all measured exclusive b→sγ decays is only 44% of the inclusive rate

room for new exclusive decays



b→sγ spectrum

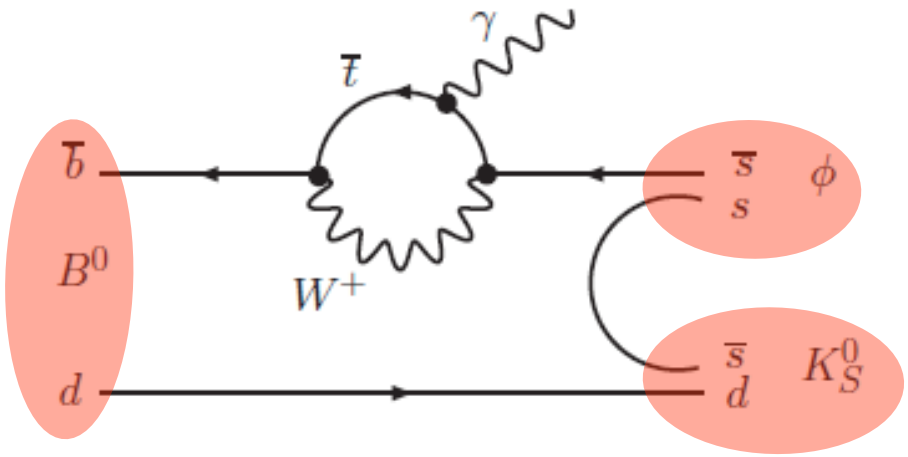
Many exclusive b→sγ modes have been observed by CLEO, Belle and BaBar

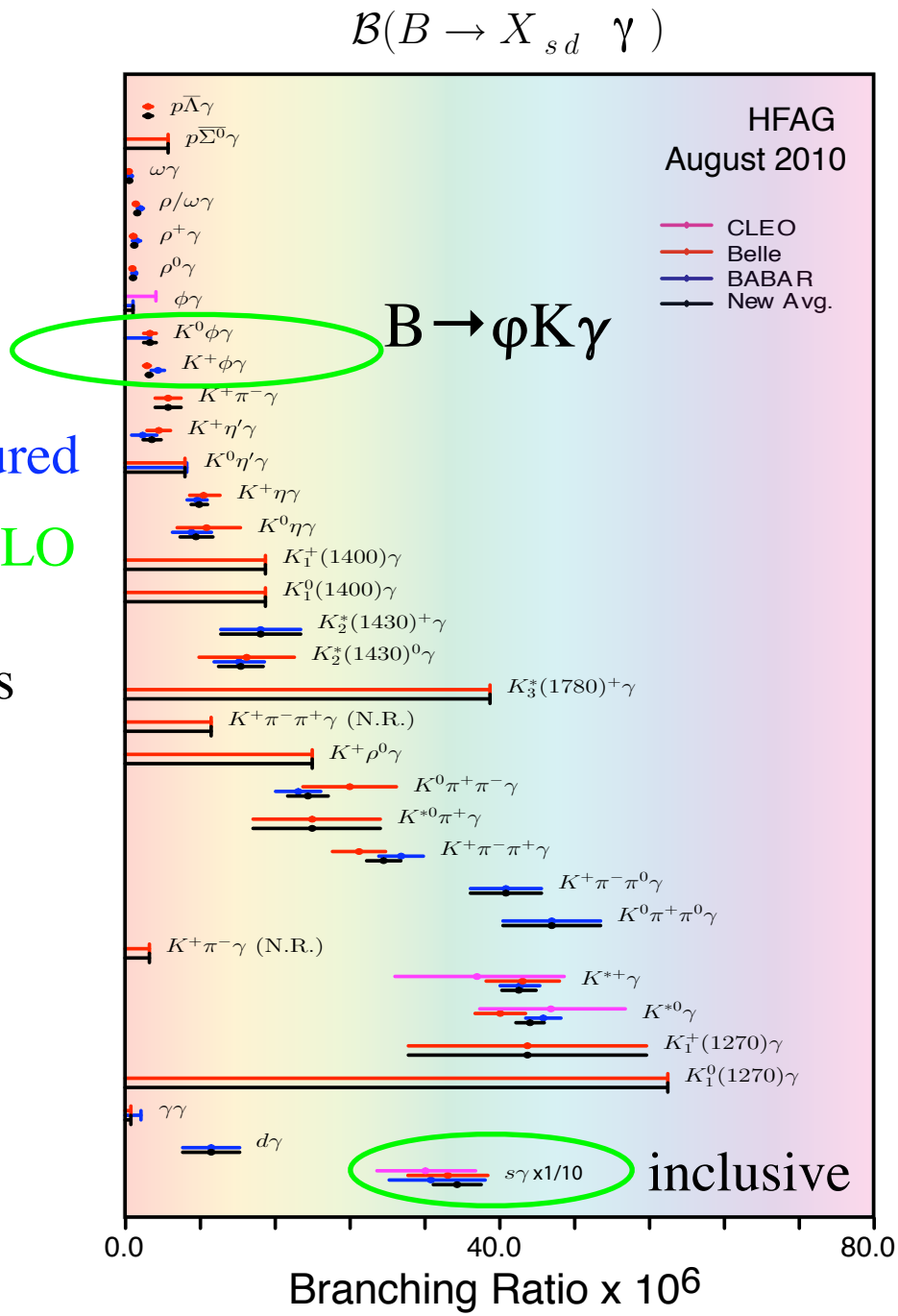
Inclusive B→Xsγ branching fraction

$(3.55 \pm 0.26) \times 10^{-6}$ experimentally measured

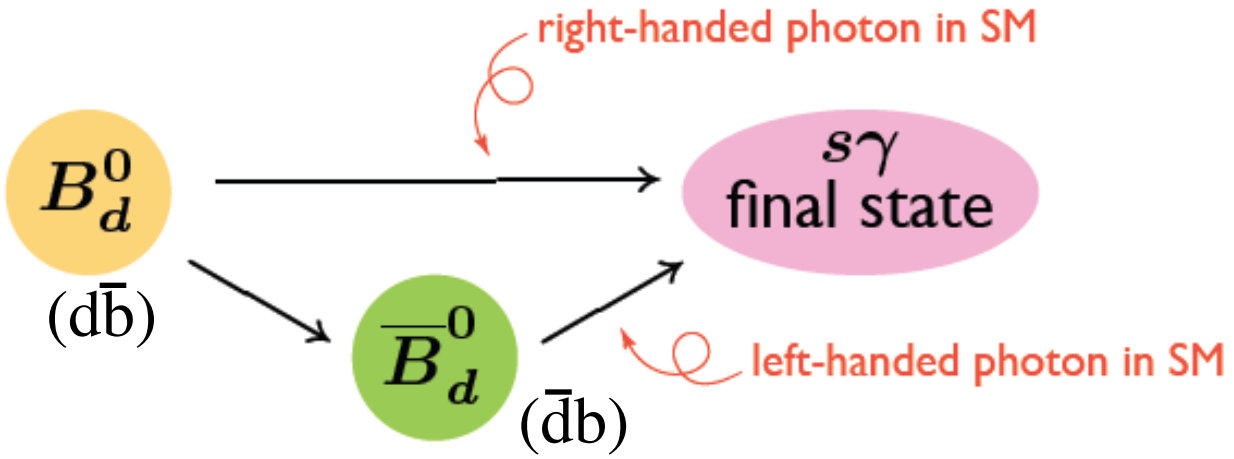
$(3.15 \pm 0.23) \times 10^{-6}$ theory prediction NNLO

Sum of all measured exclusive b→sγ decays is only 44% of the inclusive rate





D. Atwood, M.Gronau, A.Soni,
PRL 79, 185 (1997)



- In SM, radiative photon in b→sγ ($\bar{b}$→$\bar{s}\gamma$) is flavor-specific.
- $B^0 \leftrightarrow \bar{B}^0$ interference can occur only through a helicity flip.
- The CP asymmetry in SM is suppressed by the quark mass ratio.

$$S \approx -2(m_s/m_b)\sin(2\phi_1) \sim 0.03$$

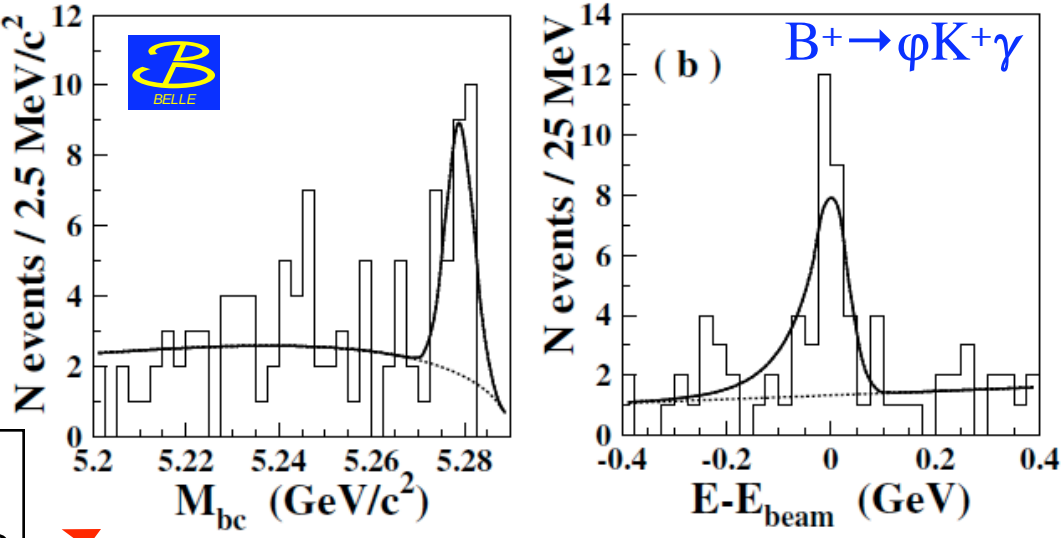
- A large CP asymmetry will be clear hint of new physics (e.g. LRSM model).
- With enough statistics in neutral mode, we can do a time-dependent measurement.

CPV in b→sγ requires right-handed currents rather than a mixing phase

Seven years ago...

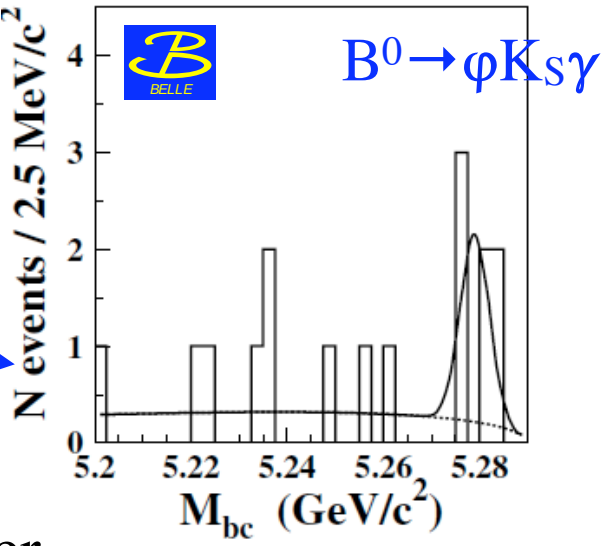
96 M $B\bar{B}$

PRL 92, 051801 (2004)



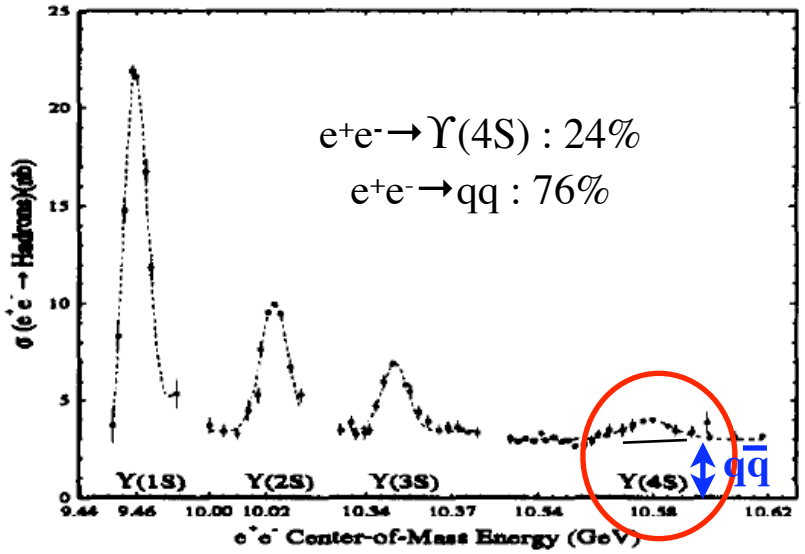
- First observation of $B^+ \to \varphi K^+ \gamma$ by Belle
- Events: 21.6±5.6, significance: 5.5σ

- Neutral mode is not observed yet!
- Upper limit, $\mathcal{B}(B^0 \to \varphi K^0 \gamma) < 2.7 \times 10^{-6}$, using 5.8±3.0 events

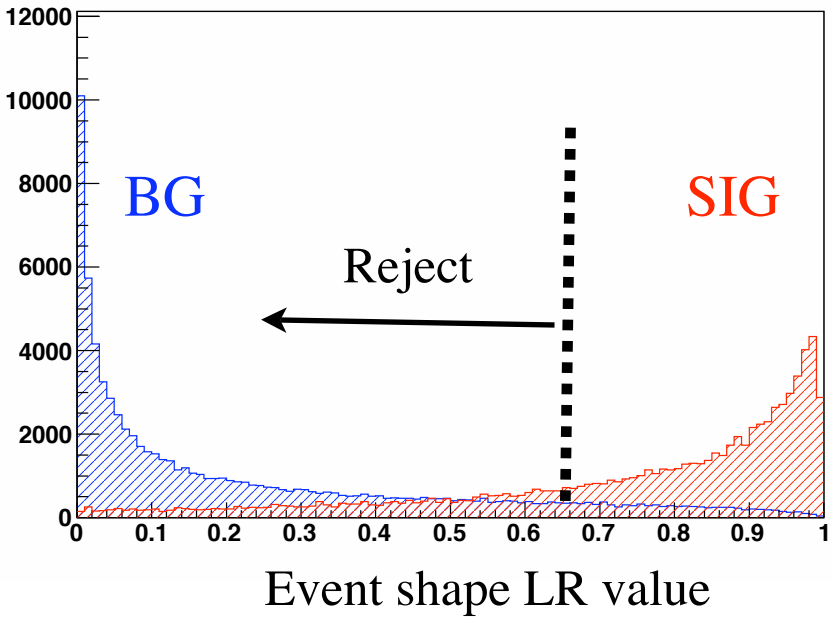


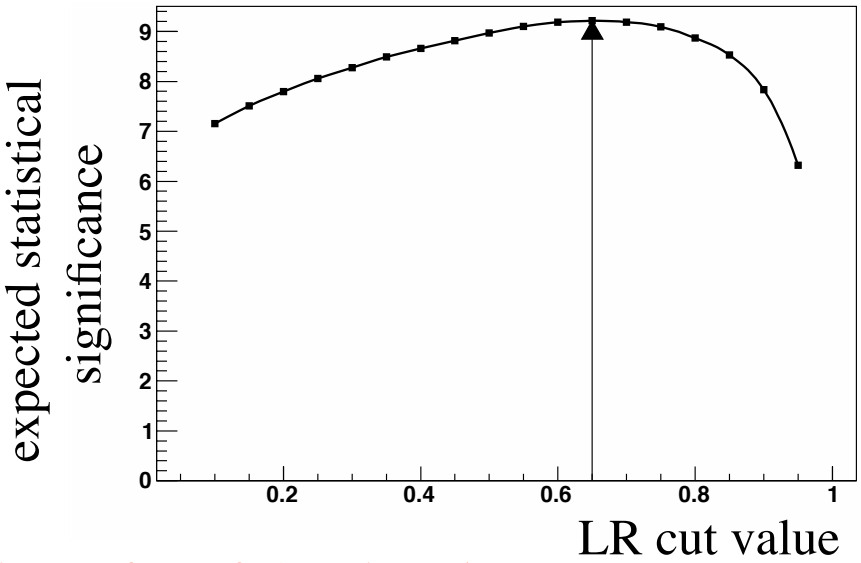
☑ Now Belle has a data sample nearly eight times larger

Continuum backgrounds in $B \to \phi K \gamma$



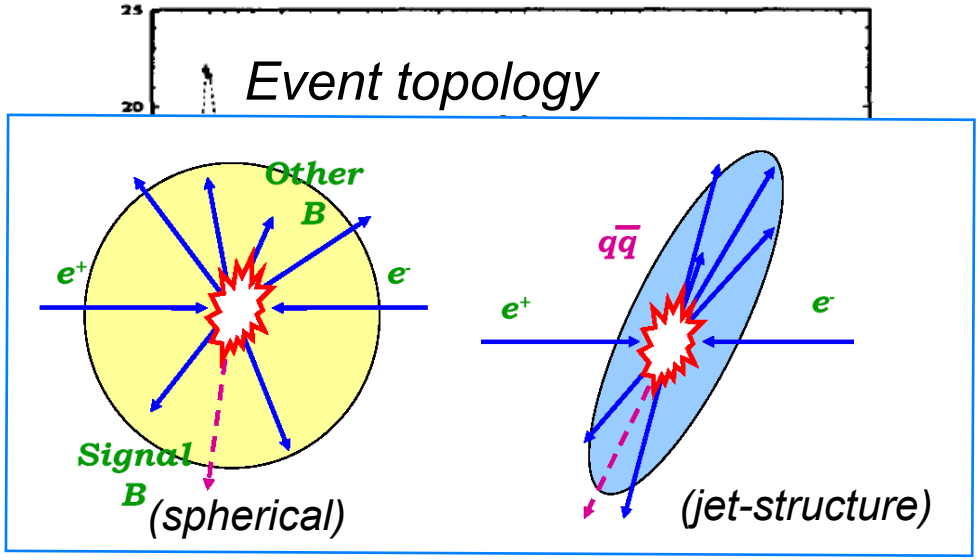
- Dominant background : $e^+e^- \to q\bar{q}$ events are separated using a likelihood derived from event shape variables and the B flight direction
- Signal : spherical as B mesons are almost at rest
- Continuum : hadronized particles are high-momentum and jet-like



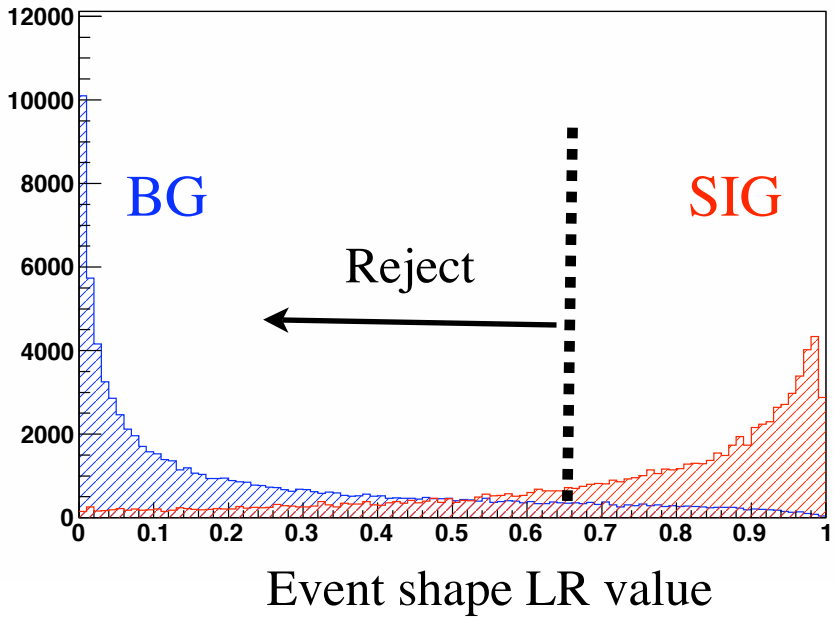


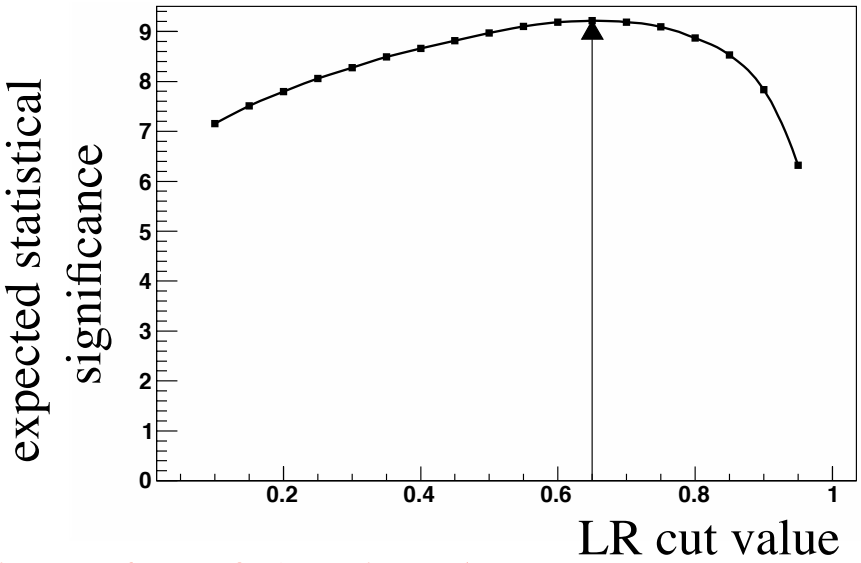
Removes 91% of the continuum while retaining 76% of the signal.

Continuum backgrounds in $B \to \phi K \gamma$



- Dominant background : $e^+e^- \to q\bar{q}$ events are separated using a likelihood derived from event shape variables and the B flight direction
- Signal : spherical as B mesons are almost at rest
- Continuum : hadronized particles are high-momentum and jet-like

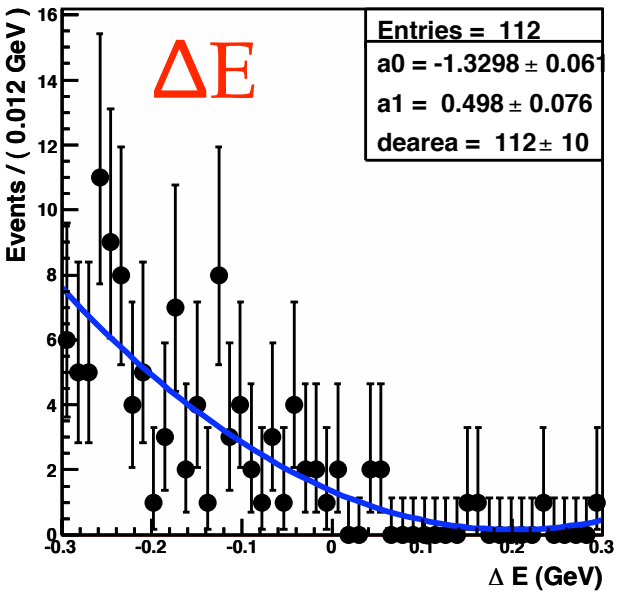


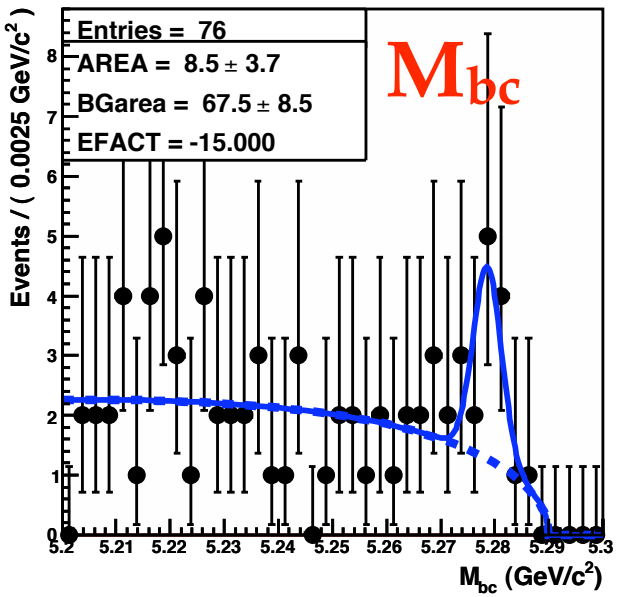


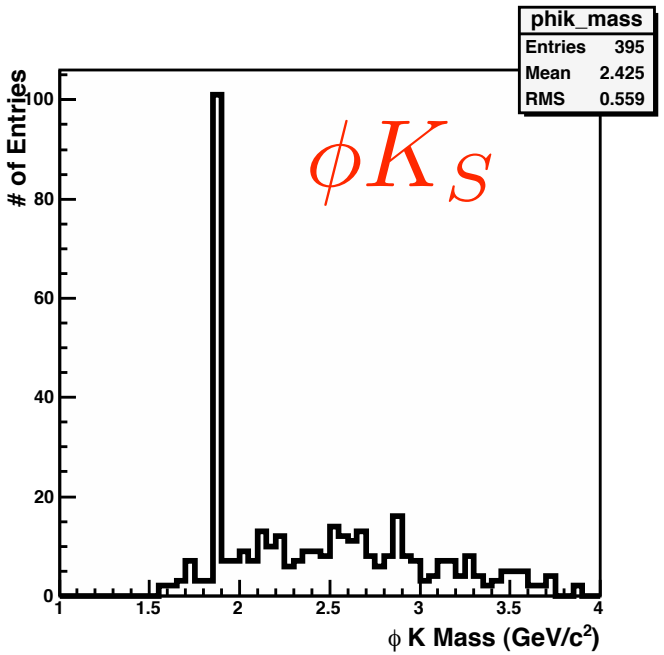
Removes 91% of the continuum while retaining 76% of the signal.

Backgrounds from b→c decays

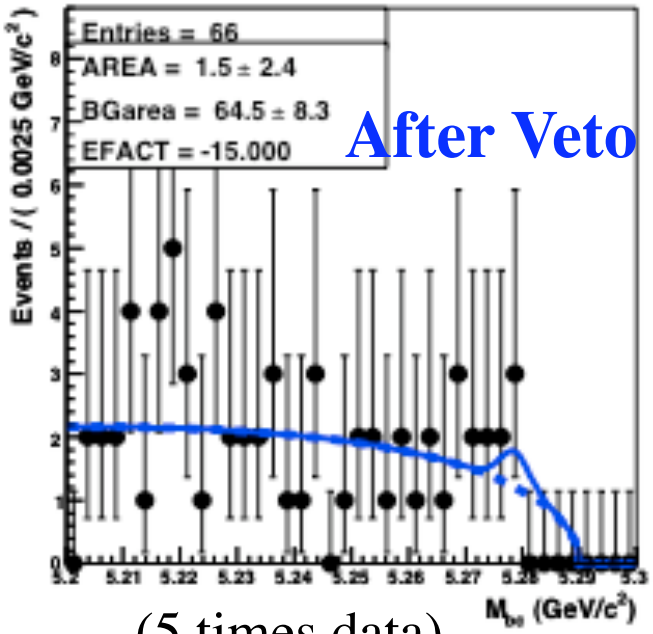
$B^0 \to \phi K_S \gamma$







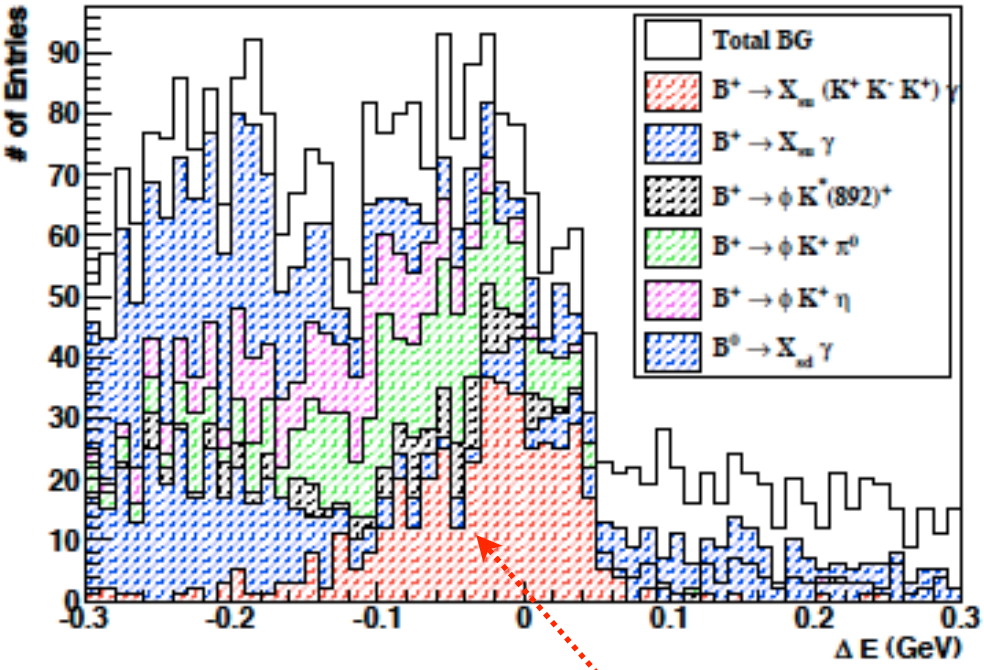
- b→c Backgrounds ($D^0\pi^0$, $D^0\eta$) peak at M_{bc} (4% of the signal yield)
- D^0 decays to φK_s => also peak at D mass in φK_s invariant mass.
- Remove those by veto on φKs mass [1.842< M(φKs) <1.878 GeV] (2% efficiency loss)

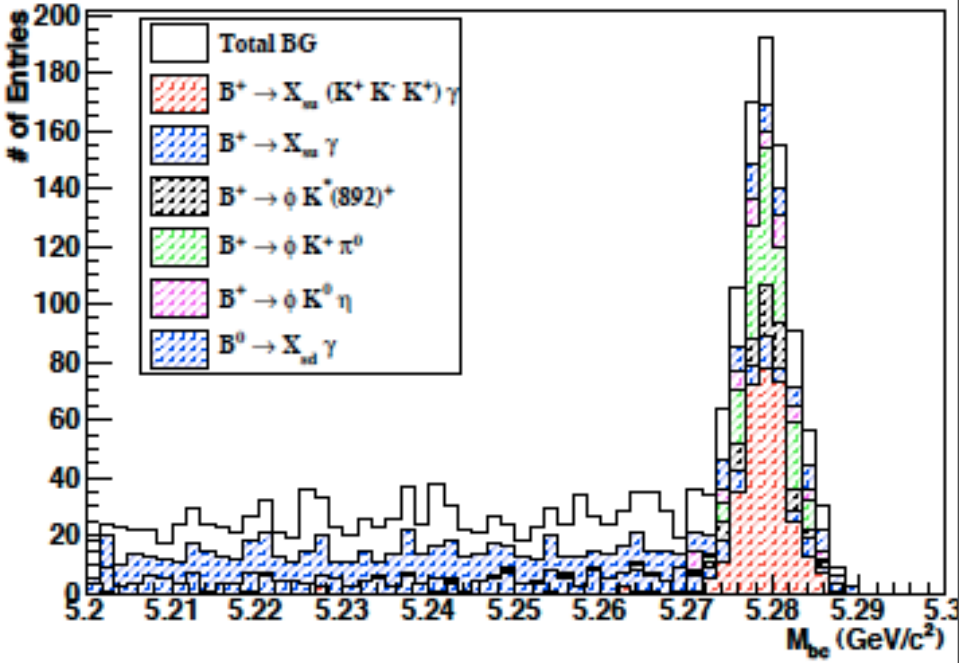


(5 times data)

Backgrounds from rare B decays

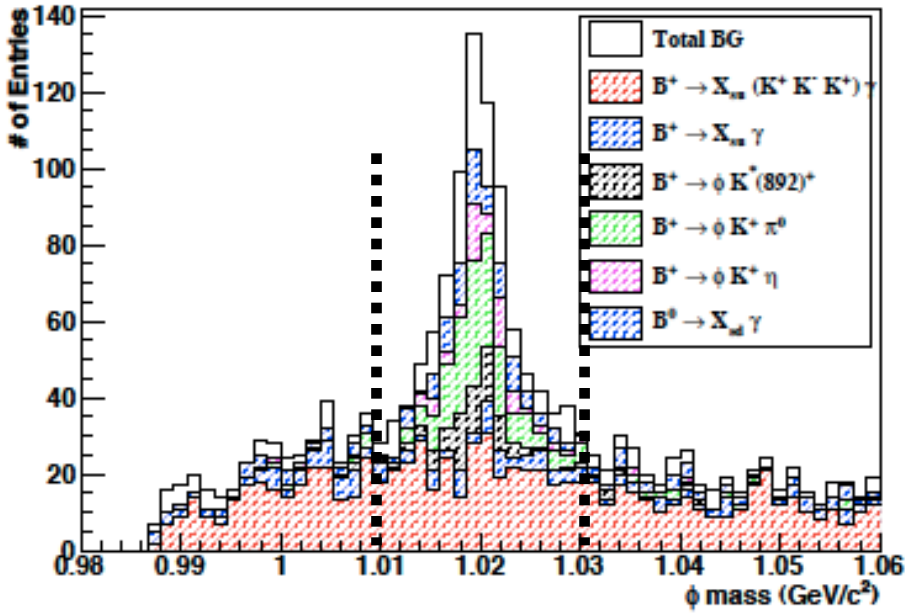
$B^0 \to \varphi K_S \gamma$





(50 times data)

- Dominant background : $B^0 \to K^+K^- K_S\gamma$
- Others : $\varphi K^*, \varphi K\pi^0$, $\varphi K\eta$ also peak at M_{bc}, but separated in ΔE
- Nonresonant $K^+K^- K_S\gamma$ is determined to be 13% of the signal using the φ mass sideband in data [1.05-1.3 GeV]



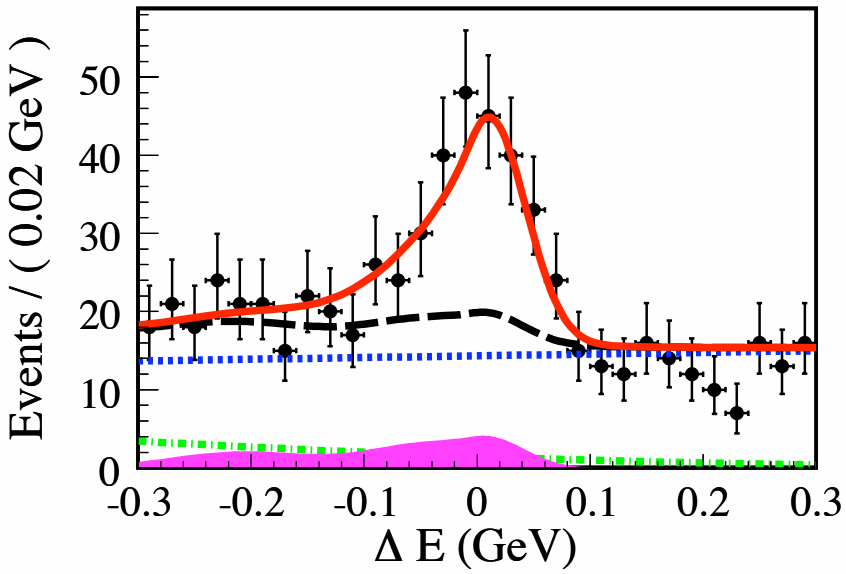
Signal in charged mode

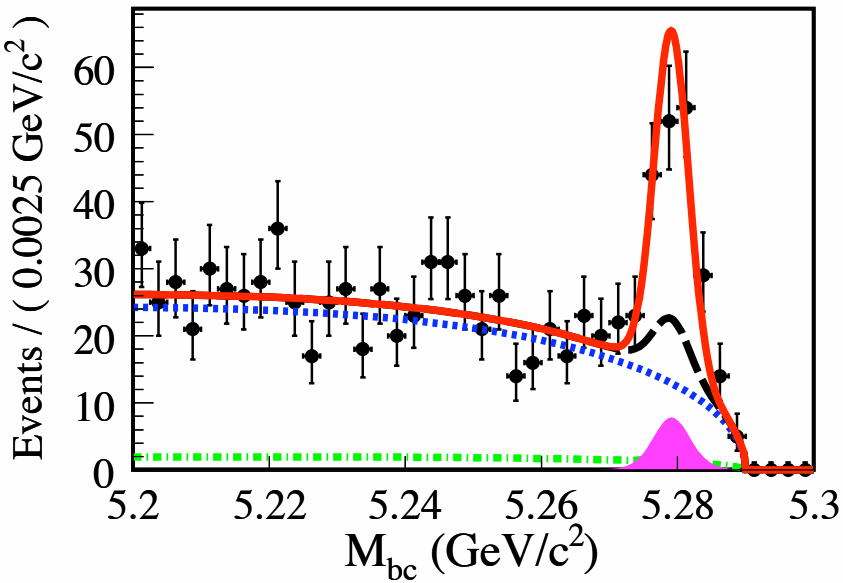
$B^+ \to \varphi K^+ \gamma$

772 M $B\bar{B}$

Unbinned maximum-likelihood fit to the 2D ΔE-M_{bc} fit region

$|\Delta E| < 0.3$ GeV && $(5.2\ \text{GeV}/c^2 < M_{bc})$





- Data
- Signal
- Total BG
- qq BG
- b→c BG
- Nonres+Charmless

144±17 Events

Efficiency : (15.3±0.1)%

Significance : 9.6σ

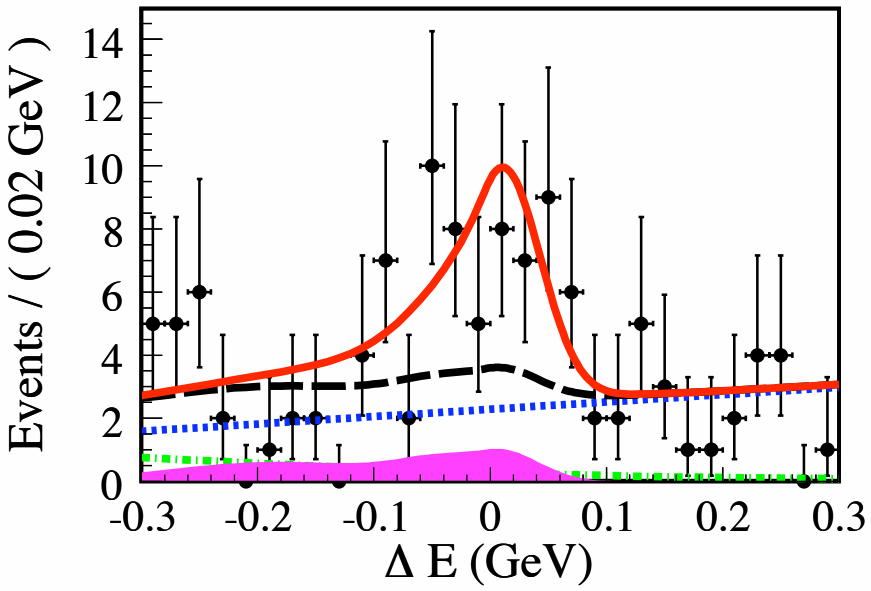
$$\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{max})}$$

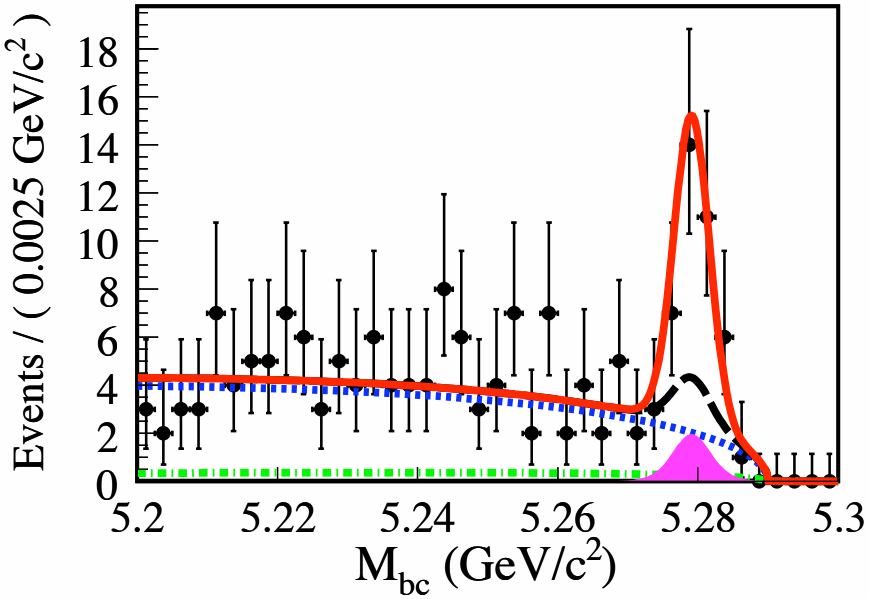
Signal shape is fixed using kinematically similar mode, $B \to K^*(\to K^+\pi^-)\gamma$

Signal in neutral mode

772 M $B\bar{B}$

$B^0 \to \varphi K_S \gamma$





37±8 Events

Significance : 5.4σ

Efficiency : (10.0±0.1)%

- **Data**
- **Signal**
- **Total BG**
- **qq BG**
- **b→c BG**
- **Nonres+Charmless**

The neutral mode now has enough statistics for a time-dependent CPV study

Branching Fraction

$$\mathcal{B} = \frac{N_{\rm sig}}{\epsilon \times N_{B\overline{B}} \times \mathcal{B}_{\rm sec}}$$

(product of daughter branching fractions)

$\mathcal{B}(B^+ \to \varphi K^+ \gamma) = (2.48 \pm 0.30 \pm 0.24) \times 10^{-6}$ Significance : 9.6σ

$\mathcal{B}(B^0 \to \varphi K^0 \gamma) = (2.74 \pm 0.60 \pm 0.32) \times 10^{-6}$ Significance : 5.4σ

First observation of the neutral mode

- Each fixed fitting parameter is varied by its ±1σ error
- Largest contribution from non-resonant yield (8%)
- Adding all other sources : total systematics 9.5% (11.7%) for charged (neutral) mode.

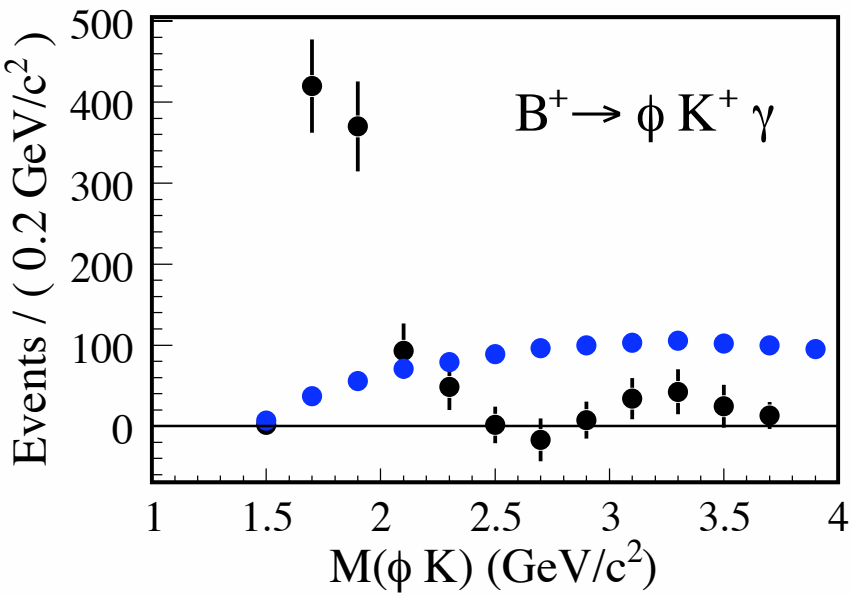
Systematic error sources	Uncertainties(%)	
	$B^+ \to \phi K^+ \gamma$	$B^0 \to \phi K^0_S \gamma$
Signal PDF shape	0.2	0.2
Generic PDF shape	0.2	0.4
Rare PDF shape	0.5	1.0
Generic yield	0.6	1.0
Rare yield	0.7	1.6
Fudge factor	1.3	1.1
Non-resonant yield	8.0	8.0
Fit bias	0.2	2.7
Total	**8.19**	**9.00**

M(φK) distributions

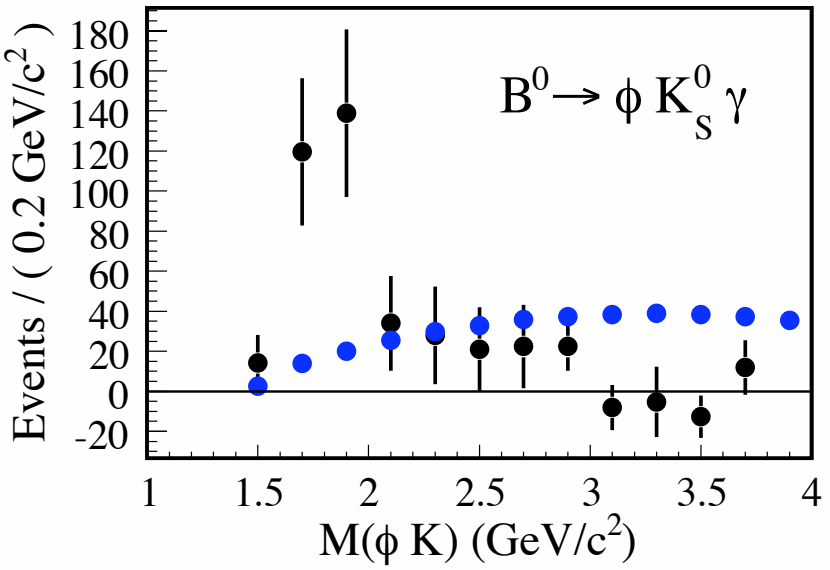
- Background-subtracted and efficiency-corrected M(φK) distributions
- Yield in each bin of φK mass is from ΔE-M_{bc} 2D-fit
- Nearly 72% events are concentrated in the low mass region (1.5-2.0 GeV/c^2)
- Re-weighted efficiency is used for branching fraction measurement.

φK mass spectrum is different from 3-body phase-space

Is this due to a resonance in φK mass or something else?

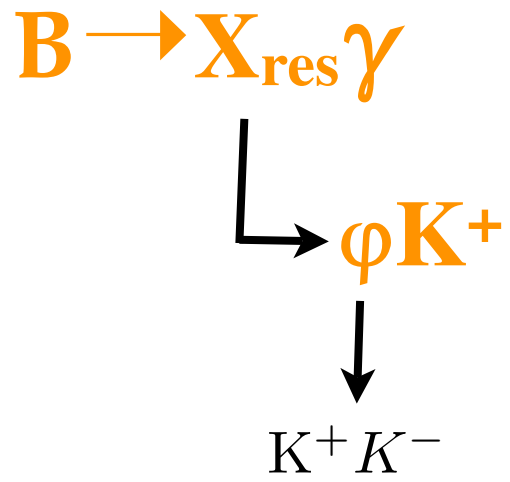


- **Data**
- **Phase-space from MC**

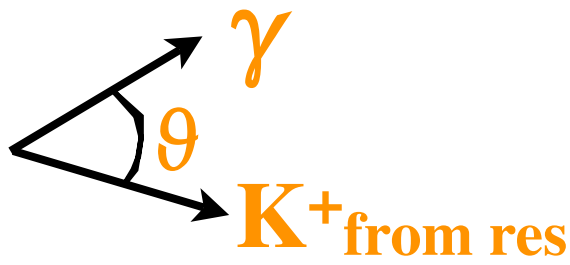


Any resonance??

- If the peak is due to a Resonance around 1.8 GeV...
  - ✓ Decay to φK should have large BF
  - ✓ Two resonances (charged, neutral), could be isospin doublet



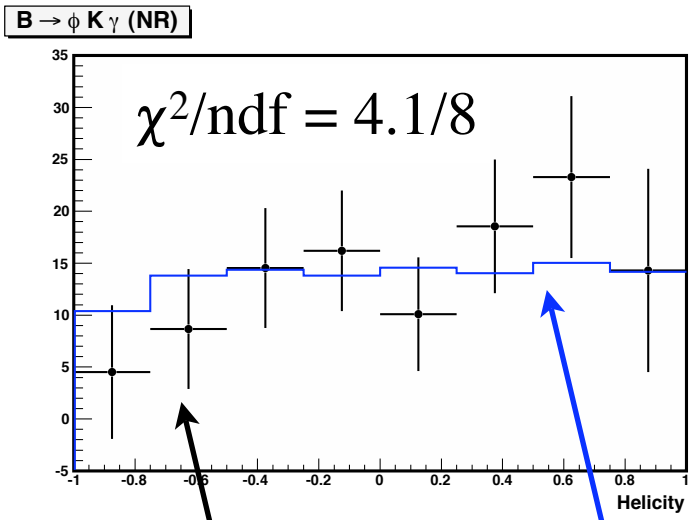
- Helicity : cosine of the angle between photon and K^+ from the resonance in the rest frame of the resonance



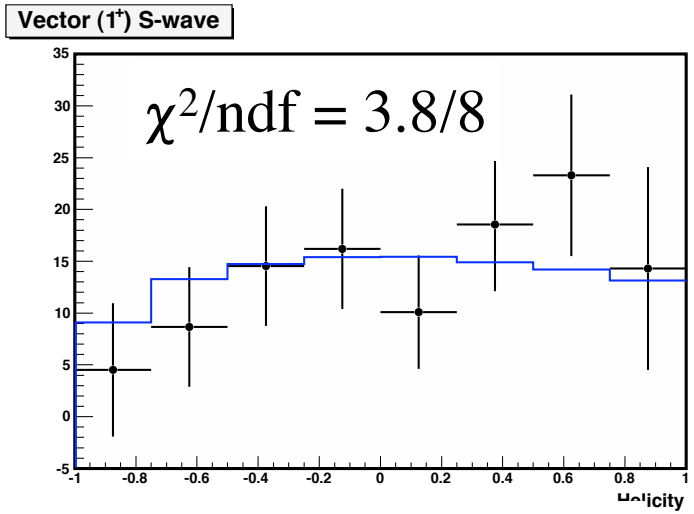
We have checked for the Monte Carlo models : (in the rest frame of resonance)

Non-resonant $B^+ \to \varphi K^+\gamma$ (NR)
Axial Vector (1^+) : l=0 (S-wave)
Axial Vector (1^+) : l=2 (D-wave)
Axial Tensor (2^+) : l=2 (D-wave)

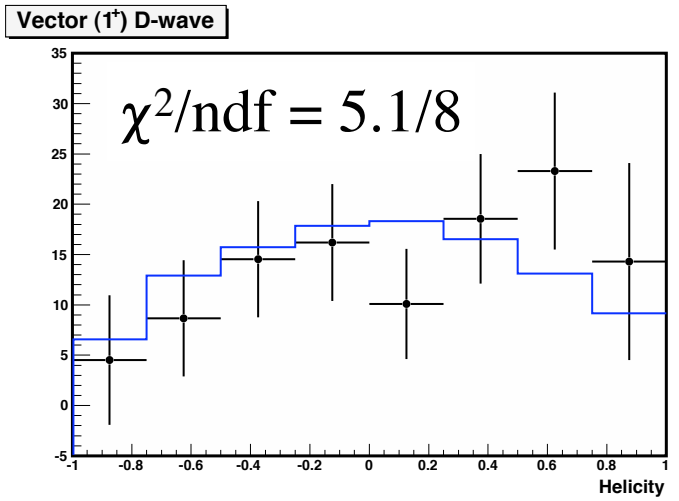
Helicity study



NR



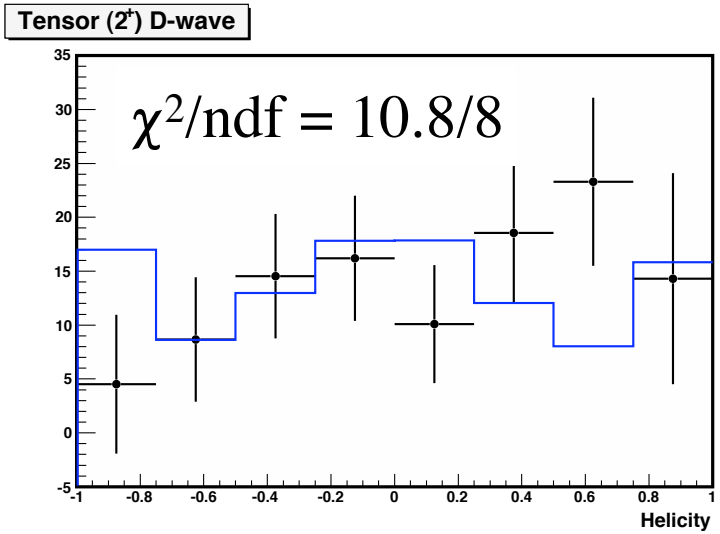
Vector (1^+) S-wave



Vector (1^+) D-wave

Models from MC after reconstruction

background-subtracted data points



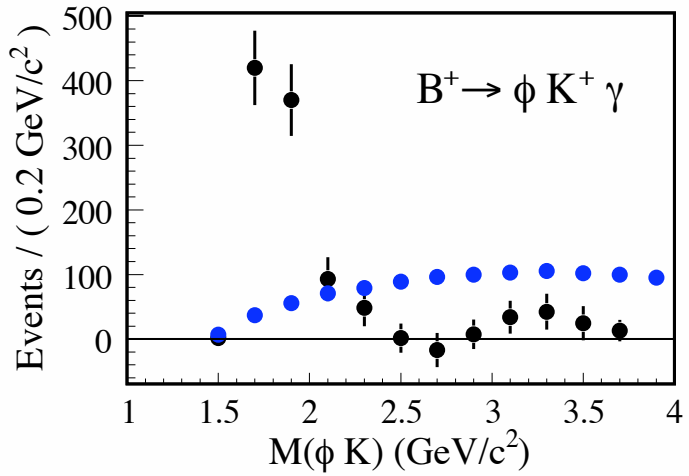
Tensor (2^+) D-wave

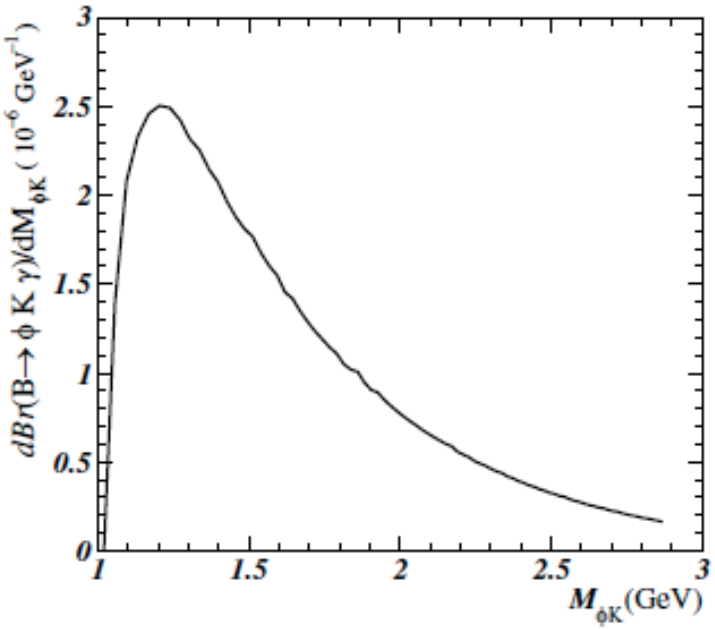
No clear evidence for the existence of a kaonic resonance decaying to φK.

Form Factor effects in the mass spectrum

Hsiang-nan Li
PRD 70, 054006 (2004) [hep-ph/0404097]

- Two-meson distribution amplitude in a three-body decay (neglecting the resonant contribution).
- The peak at threshold can be explained by form factor effects.
- The spectra is in qualitative agreement with expectation from pQCD model for non-resonant decays.

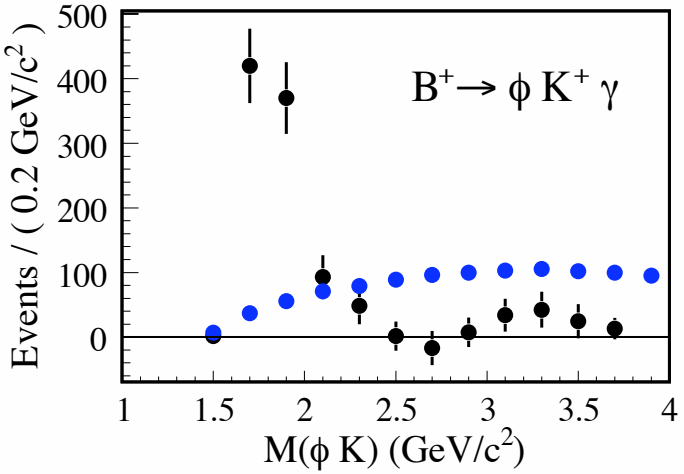


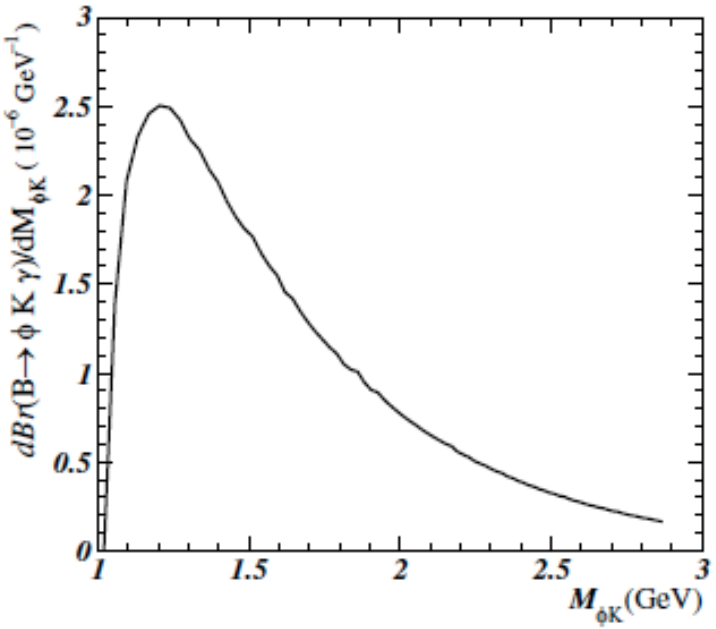


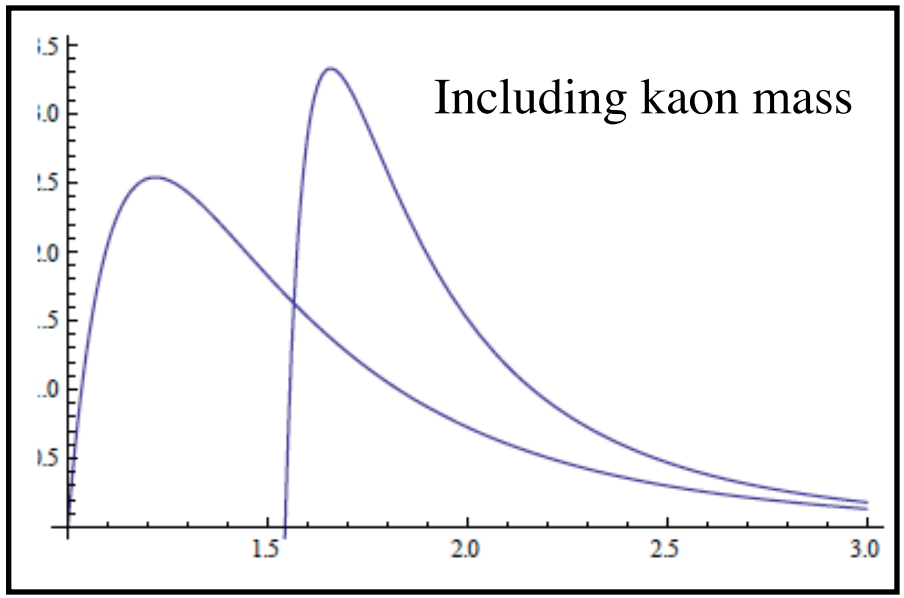
Form Factor effects in the mass spectrum

Hsiang-nan Li
PRD 70, 054006 (2004) [hep-ph/0404097]

- Two-meson distribution amplitude in a three-body decay (neglecting the resonant contribution).
- The peak at threshold can be explained by form factor effects.
- The spectra is in qualitative agreement with expectation from pQCD model for non-resonant decays.







Time-dependent Measurement

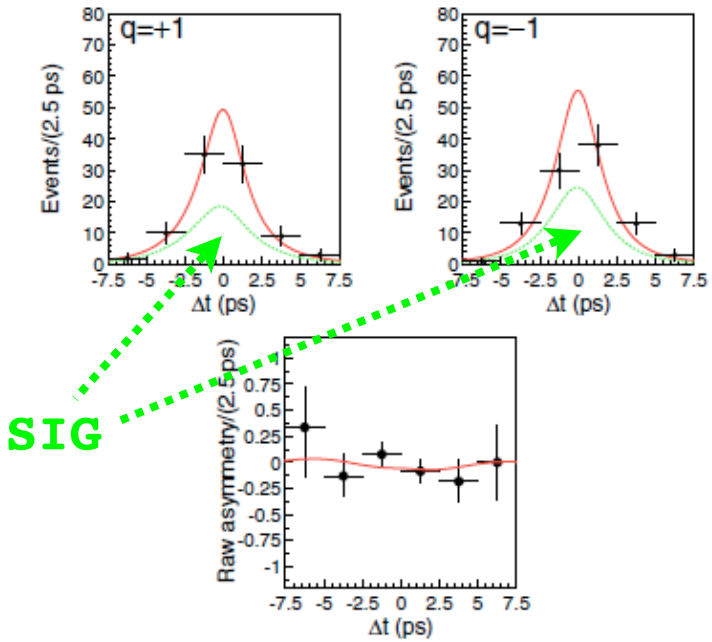
TCPV in b→sγ modes

$B^0 \to K_S\pi^0\gamma$

PRD 74, 1111(R) (2006)
535 M $B\overline{B}$

Vertex is from Ks →$\pi^+\pi^-$ (K_S must decay inside silicon detector)

$$\mathcal{S}_{K_S\pi^0\gamma} = -0.10 \pm 0.31 \pm 0.07$$
$$\mathcal{A}_{K_S\pi^0\gamma} = -0.20 \pm 0.20 \pm 0.06$$

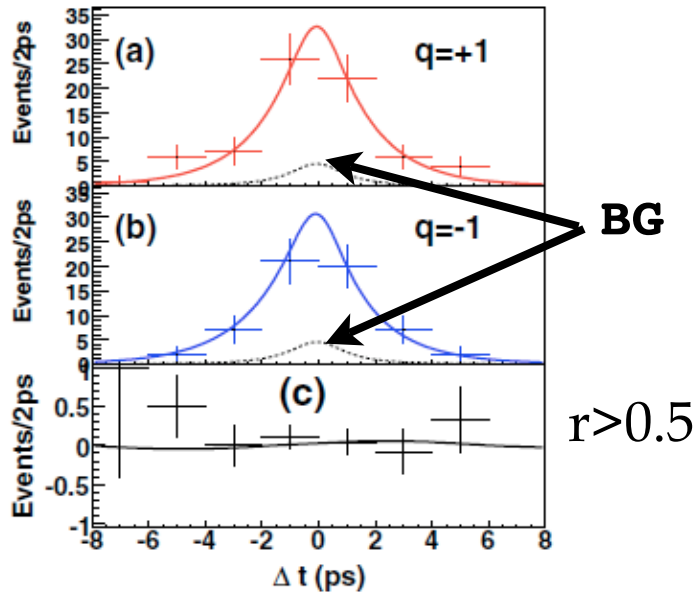


$B^0 \to K_S\rho^0\gamma$

PRL 101, 251601 (2008)
657 M $B\overline{B}$

Vertex is from ρ⁰→$\pi^+\pi^-$ (no K_S vertex is needed)

$$\mathcal{S}_{K_S\rho^0\gamma} = 0.11 \pm 0.33^{+0.05}_{-0.09}$$
$$\mathcal{A}_{K_S\rho^0\gamma} = 0.05 \pm 0.18 \pm 0.06$$



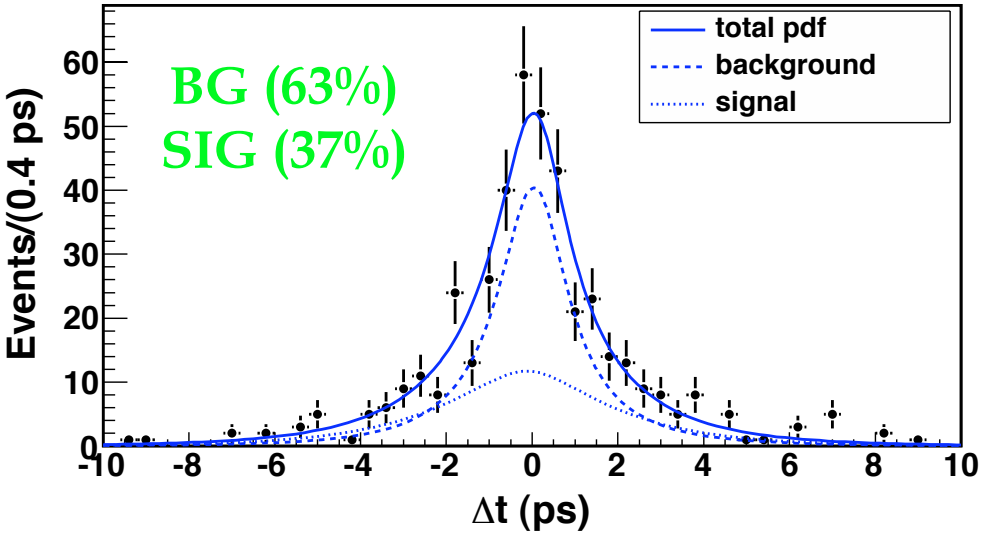
Consistent with the SM expectation

Checks for B lifetime in Data

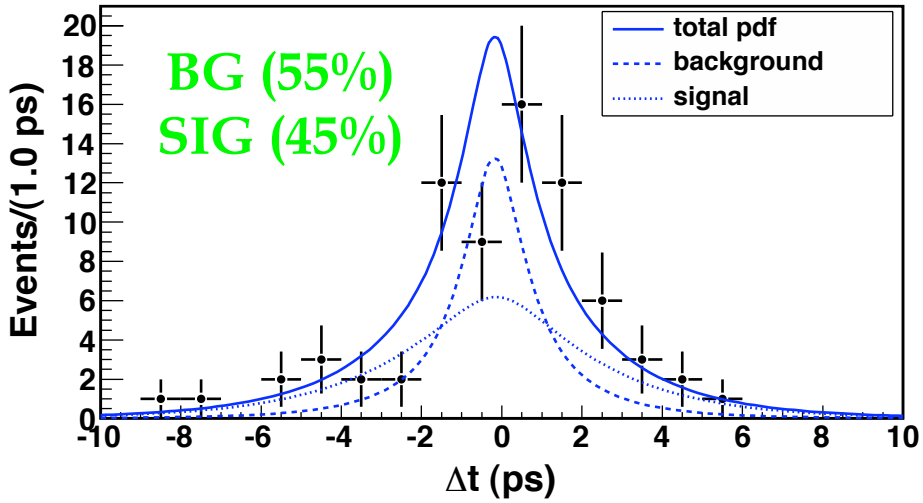
TCPV to the events in the ΔE-M_{bc} signal box => $(-0.2<\Delta E< 0.1\ \text{GeV}) \&\& (5.27\ \text{GeV}/c^2 < M_{bc})$

Vertex is from $\varphi \to K^+K^-$ (no K_S vertex is needed)

$B^+ \to \varphi K^+ \gamma$



$B^0 \to \varphi K_S \gamma$



Non-resonant $K^+K^-K\gamma$ has same new physics as signal $B \to \varphi K\gamma$ => treated as signal for the TCPV study [A. Soni]

$\tau(B^+) = 1.70 \pm 0.20$ (stat) ps

$\tau(B^+) = 1.64 \pm 0.01$ ps (PDG)

$\tau(B^0) = 2.09 \pm 0.45$ (stat) ps

$\tau(B^0) = 1.53 \pm 0.01$ ps (PDG)

Consistent with the PDG charged and neutral B lifetimes

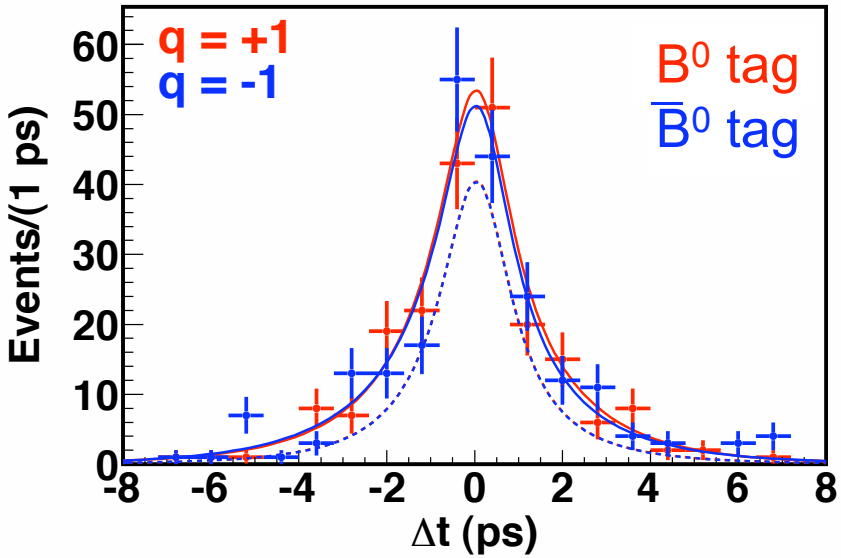
CP fit in charged mode (Data)

Fit to 160 signal events in the ΔE-M_{bc} signal box

SM expectation for S = 0 for a charged B mode

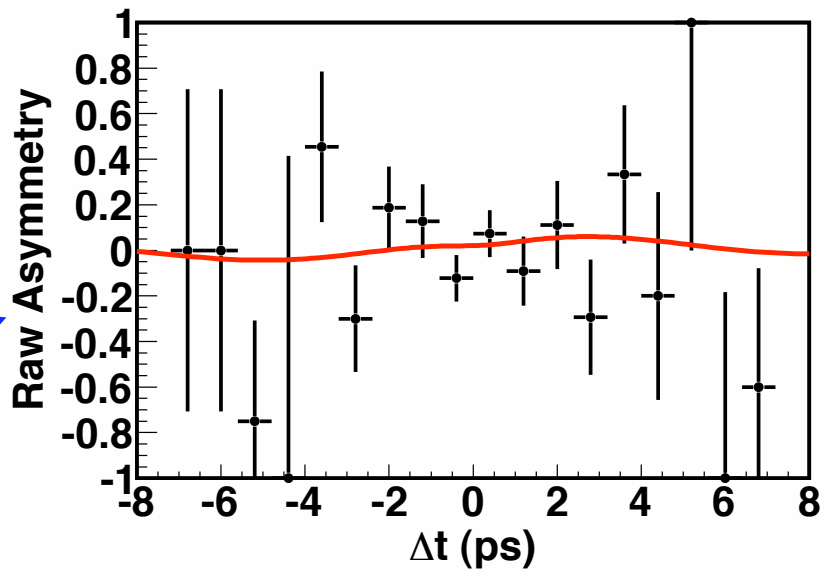
S = 0.25±0.33 (stat)

A= 0.18±0.26 (stat)



Consistent with no CP asymmetry

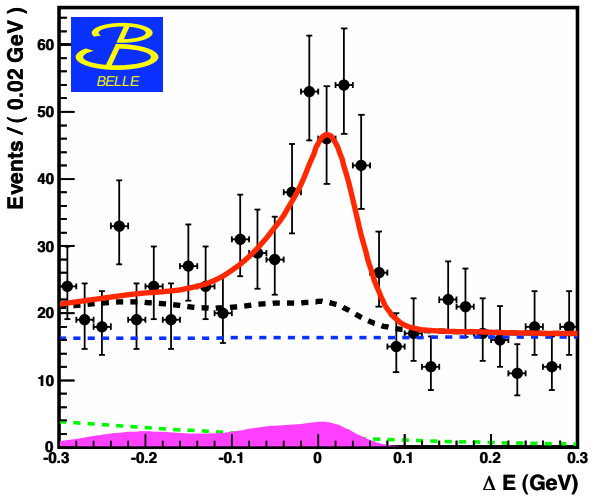
$$\frac{N(q=+1)-N(q=-1)}{N(q=+1)+N(q=-1)}$$

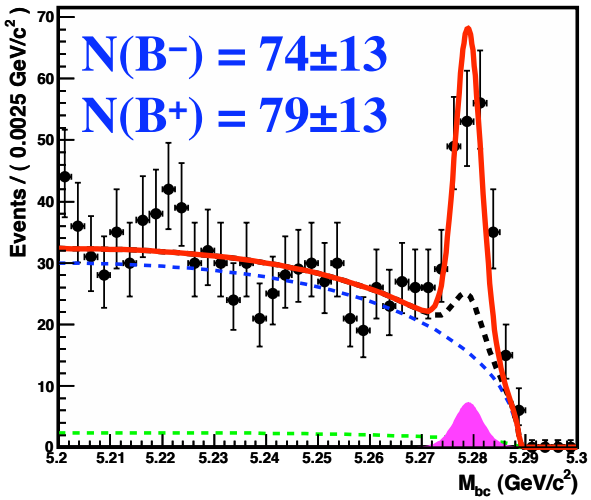


Charge Asymmetry in Data

Decay rate asymmetry between B^+ and B^- decays to $\varphi K\gamma$ final state

$$A_{CP} = \frac{N(B^- \to \phi K^- \gamma) - N(B^+ \to \phi K^+ \gamma)}{N(B^- \to \phi K^- \gamma) + N(B^+ \to \phi K^+ \gamma)}$$





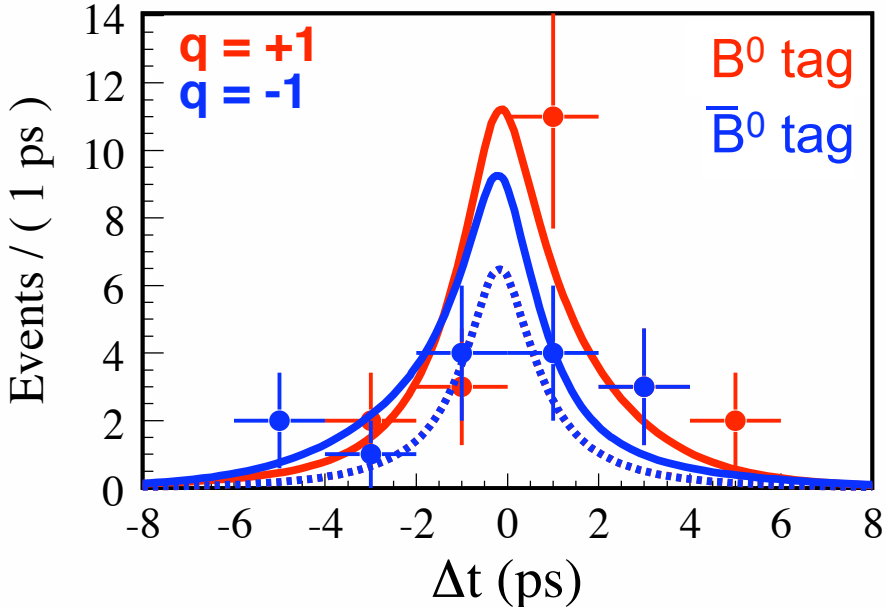
simultaneous fit to both B^+ and B^- data samples

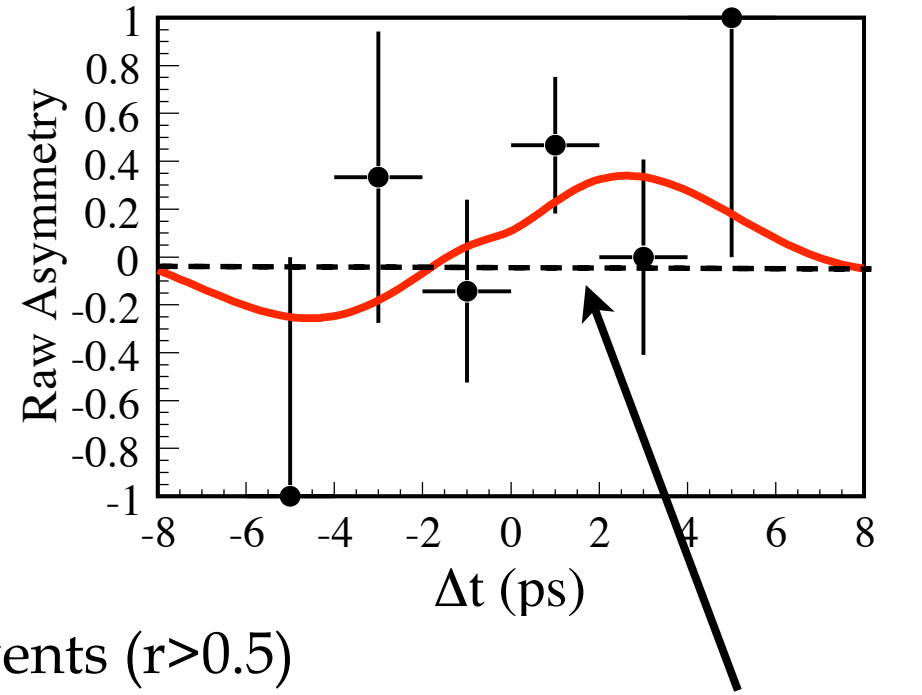
$N(B^- \to \varphi K^- \gamma)$	$N(B^+ \to \varphi K^+ \gamma)$	A_{cp}
74±13	79±13	−0.03±0.11±0.08

Consistent with no CP asymmetry

$B^0 \to \phi K_S \gamma$ CP fit in Data

First TCPV measurement in neutral mode with 35 signal events.





Good tagged events (r>0.5)
48% of total events

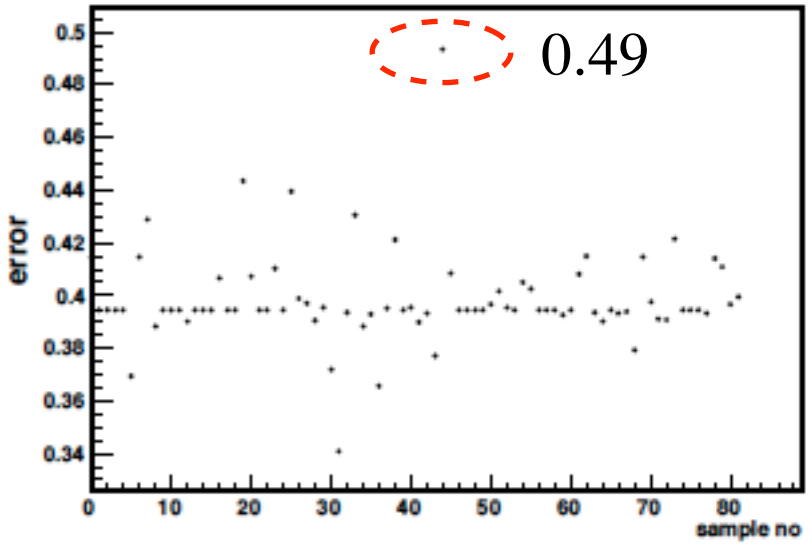
$S = 0.74^{+0.32}_{-0.45}$ (stat)
$A = 0.35 \pm 0.45$ (stat)

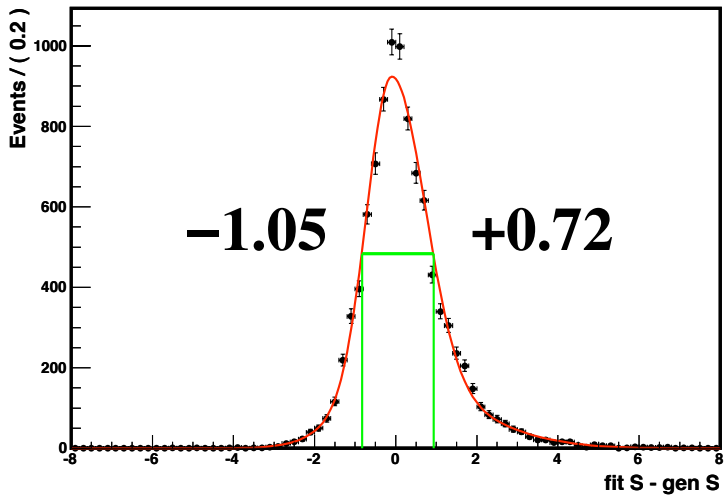
(The stat errors are from data fit)

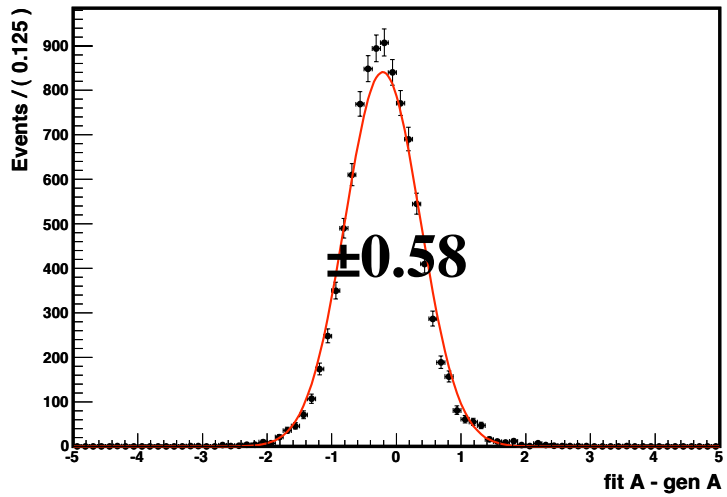
The error on S is from data fit is much smaller than the expectation from MC simulation and has a probability of only 0.6%.

Statistics Issues for $B^0 \rightarrow \varphi K_S \gamma$

- The low probability is due to small statistics and a special signal event (Good-tagged event, r~0.96)
- We use the ±68% CL's from the residual distributions of the toy pesudo-experiments as statistical errors.
- This approach is similar to Belle's early $B^0 \rightarrow \pi^+\pi^-$ TCPV measurements [**PRD 68, 012001 (2003)**]







Systematic Errors

Parameter	$\Delta S_{\phi K^0_S \gamma}$	$\Delta A_{\phi K^0_S \gamma}$
Vertexing	0.08	0.04
ResolutionFunction	0.02	0.03
WrongTagFraction	0.01	0.01
PhysicsParameter	0.05	0.03
PDFShape	0.01	0.01
SignalFraction	0.03	0.07
BackgroundDTShape	0.01	0.02
FitBias	0.00/−0.22	+0.21/0.00
TSI	0.00	0.03
Total	0.10/−0.24	0.23/0.10

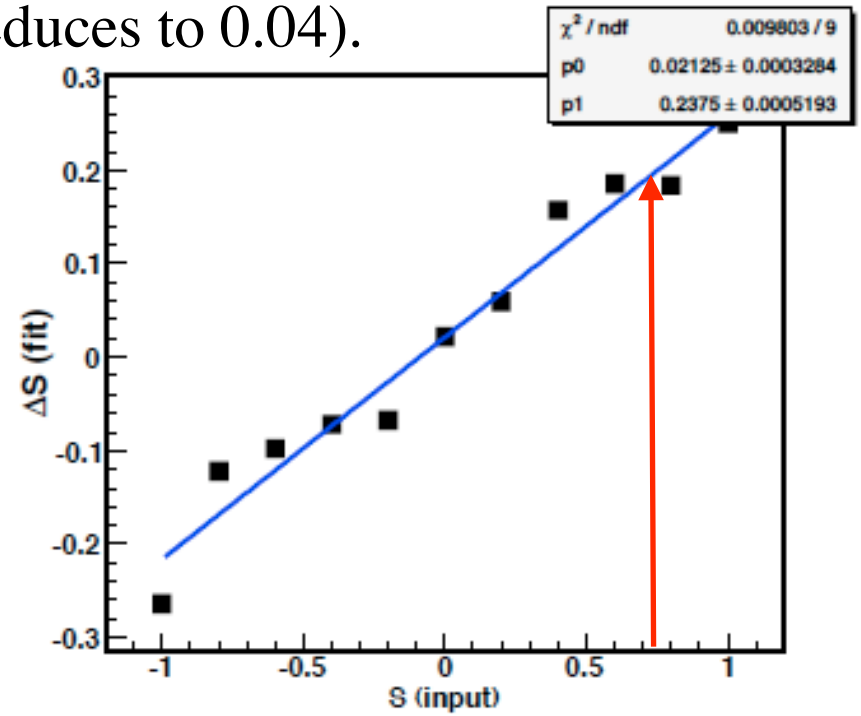
$$S = 0.74^{+0.72\ +0.10}_{-1.05\ -0.24}$$

$$C=-A= -0.35\pm0.58\ ^{+0.10}_{-0.23}$$

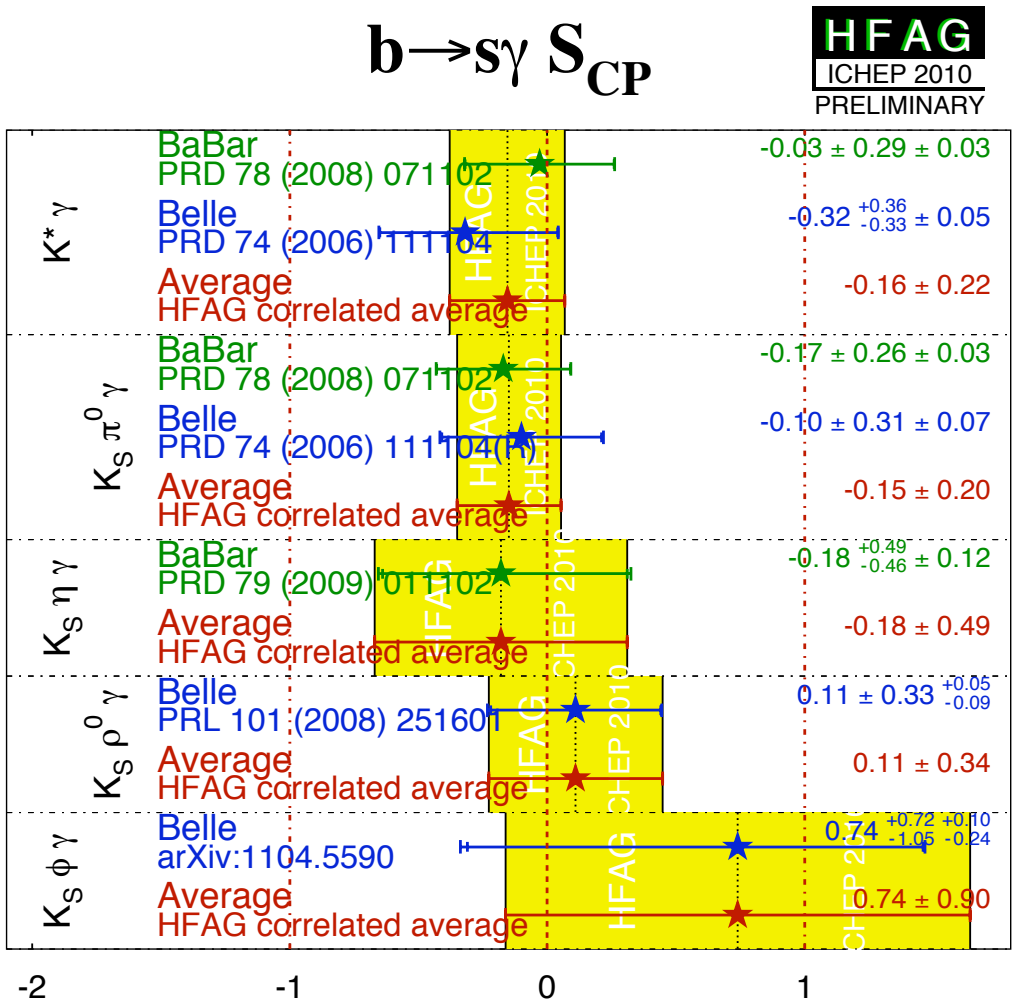
Results are published in Physical Review D.

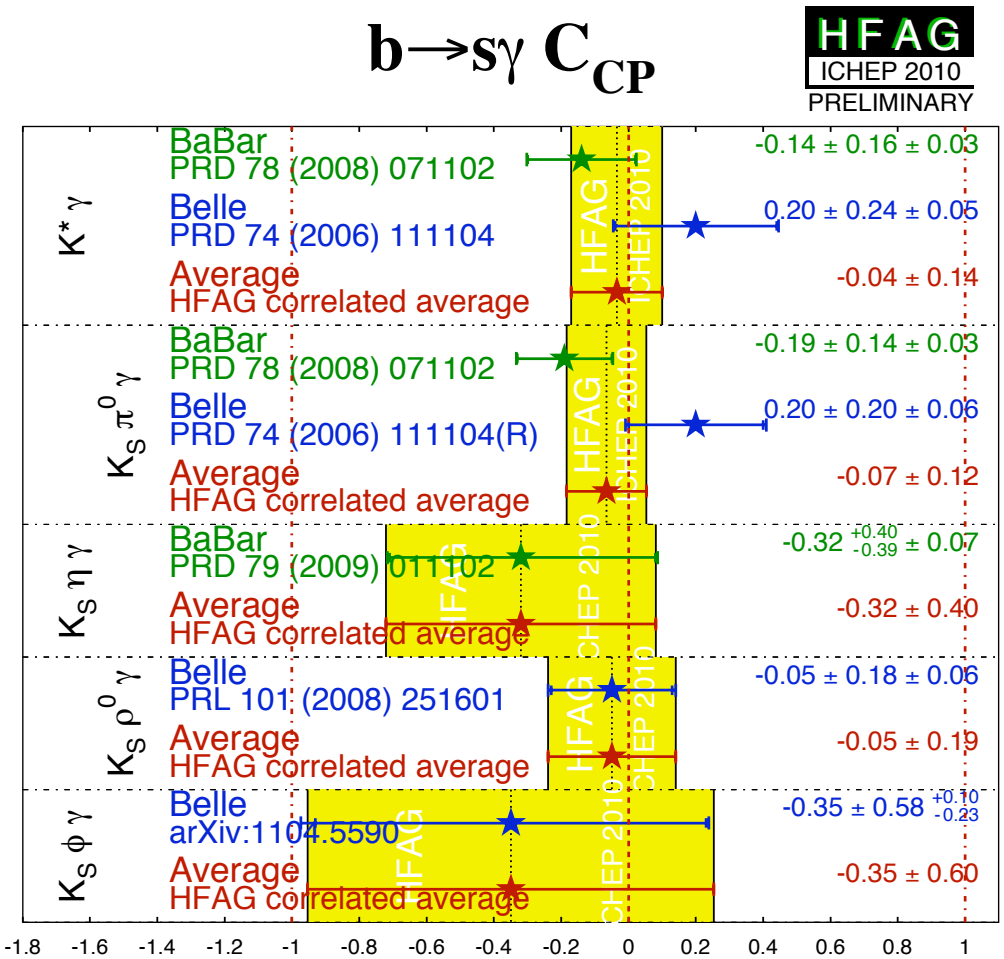
H. Sahoo *et al.*, PRD 84, 071101 (2011)

- Largest contribution : Fit bias (+0.22 for S and -0.21 for A)
- This is due to small statistics (35 signal events) and the high central value.
- MC simulations show that this bias significantly reduces as in statistics increase(with twice the signal it reduces to 0.04).



HFAG Average of b→sγ measurements





Only weak constraints on RH current with the present statistics.

We have established a new mode for future high-luminosity e^+e^- and hadronic facilities

Summary

- Most precise measurement of $\sin 2\phi_1$ in $B \to (c\bar{c})K^0$ decays using Belle's full data sample (772 M $B\bar{B}$).

  $S = +0.668 \pm 0.023 \pm 0.013$ $\quad$ $A = +0.007 \pm 0.016 \pm 0.013$

- First observation of $B^0 \to \varphi K_S \gamma$ signal with 5.4 significance using Belle's full data sample (772 M BB).

  $\mathcal{B}(B^0 \to \varphi K^0 \gamma) = (2.74 \pm 0.60 \pm 0.32) \times 10^{-6}$ $\quad$ $\mathcal{B}(B^+ \to \varphi K^+ \gamma) = (2.48 \pm 0.30 \pm 0.24) \times 10^{-6}$

- First measurements of time-dependent CP violation parameters in $B^0 \to \varphi K_S \gamma$

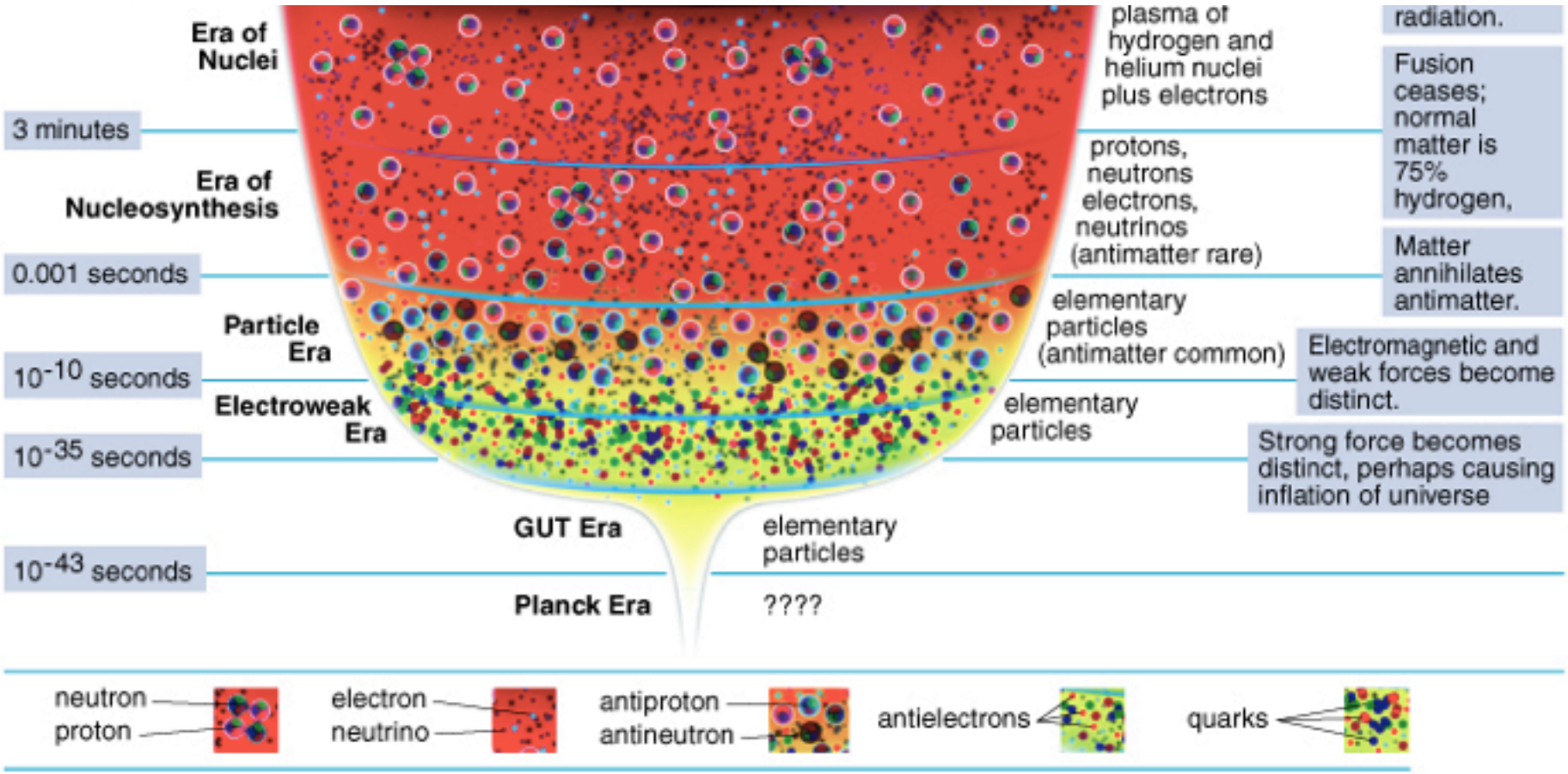
  $S = +0.74^{+0.72\ +0.10}_{-1.05\ -0.24}$ $\quad$ $A = +0.35 \pm 0.58^{+0.23}_{-0.10}$

BACK UP

A fundamental cosmological question?

Why the universe is now matter dominated (*what happened to all anti-matters*)?

$n_B/n_\gamma \sim 10^{-10}$



Implies 10^{-10} matter-antimatter asymmetry at 0.001s after the big bang

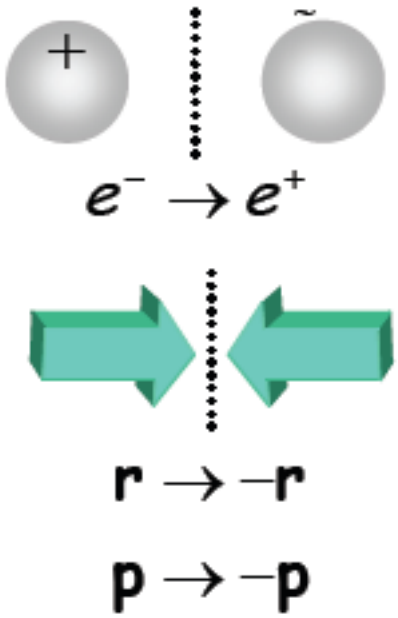
CP symmetry

(photo circa 1943)

One of the conditions required to explain this process -
properties of particles and anti-particles must be different
(Violation of CP symmetry)

A. D. Sakharov, 1967

- CP violation : Laws of nature are not invariant under simultaneous operation of charge conjugation (C) and parity (P).
- Charge conjugation (C) : transforms a particle into its anti-particle
- Parity transformation (P) : mirror reflection (space inversion)



Is CP a good symmetry of nature?

- Strong and electromagnetic interactions conserve parity.
- Parity is maximally violated in weak interaction. [*C. S. Wu et al, 1956*]
- Is the combined operation of C and P (i.e. CP) a good symmetry?

Dominant decay modes for neutral kaons:

$$K_S^0 \to \pi^+\pi^- \qquad CP = +1$$

$$K_L^0 \to \pi^+\pi^-\pi^0 \qquad CP = -1$$

In 1964, Christenson et al. observed:

CP=-1 CP=+1

$$B(K_L \to \pi^+\pi^-) = (2.0 \pm 0.4) \times 10^{-3}$$

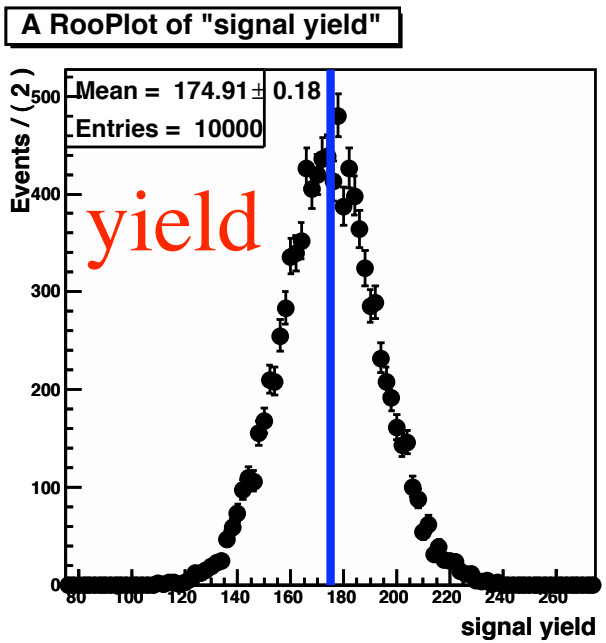
CP symmetry is violated at a tiny in the decays of neutral kaons.

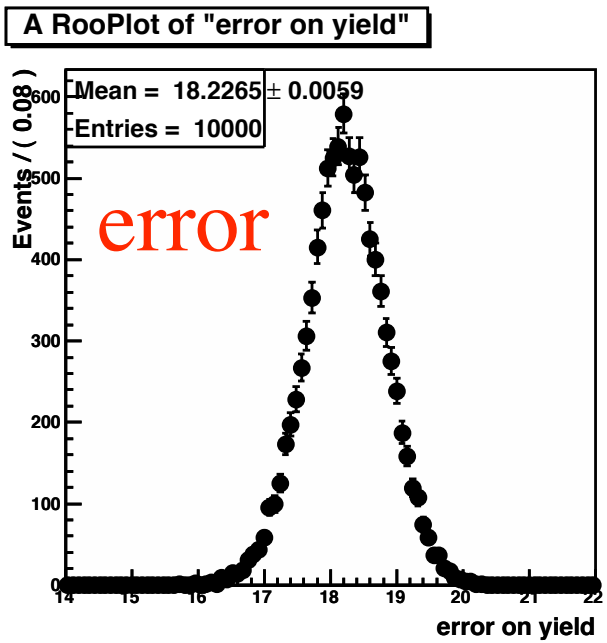
Is this the origin of the asymmetry?

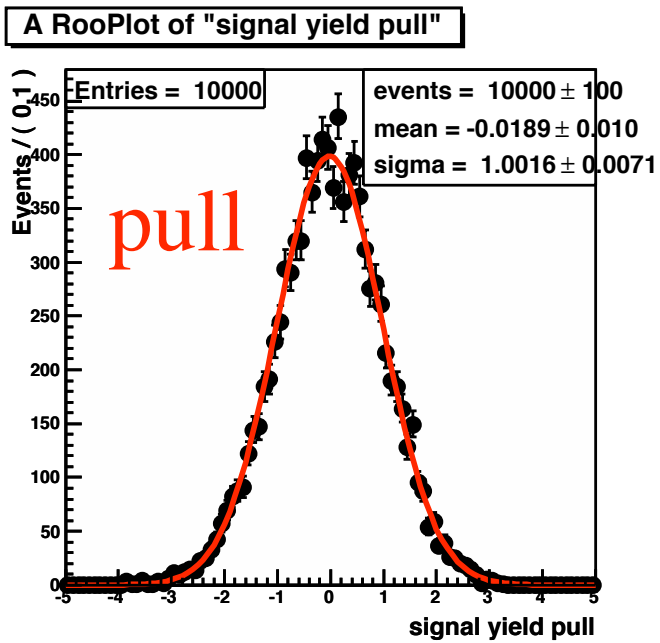
Fit Validation

Consistency of the fitter is checked using ensemble tests (10,000 statistically independent samples).

$$\text{Pull} = \frac{N_i^{fit} - N_i^{exp}}{\sigma_i^{fit}}$$







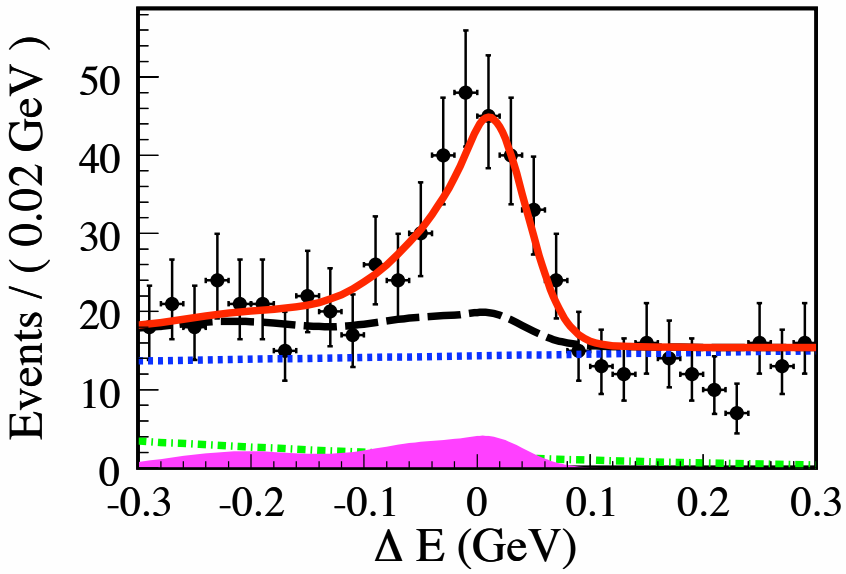
No significant bias is found...

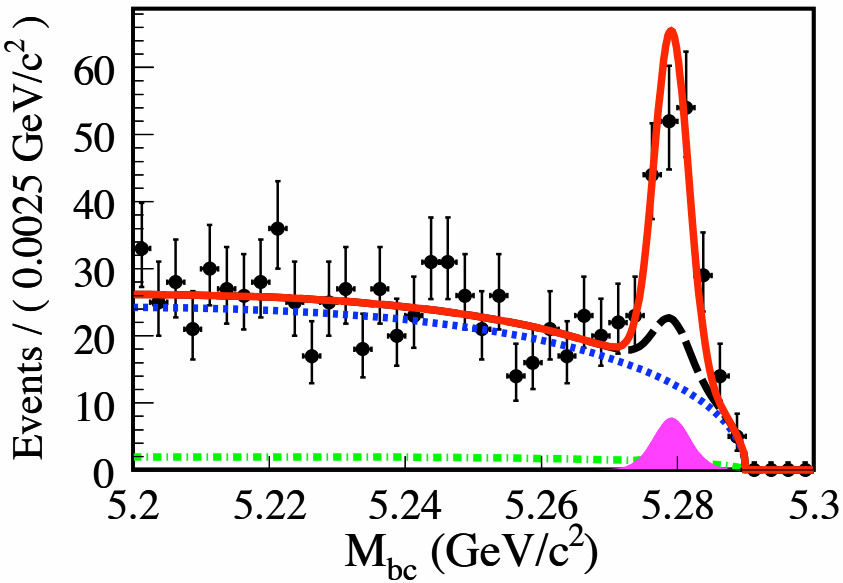
Signal in charged mode

$B^+ \to \varphi K^+ \gamma$

Unbinned maximum-likelihood fit to the 2D ΔE-M_{bc} fit region.

$|\Delta E| < 0.3$ GeV && $(5.2\ \text{GeV}/c^2 < M_{bc})$





	PDF	ΔE	M_{bc}
1	**Signal**	**Crystal Ball**	**Gauss**
2	**Continuum**	**1st Polynomial**	**Argus**
3	**b→c**	**2nd polynomial**	**Argus**
4	**Rare**	**Gauss+Gauss**	**Gauss**
5	**non-resonant**	**Crystal Ball**	**Gauss**

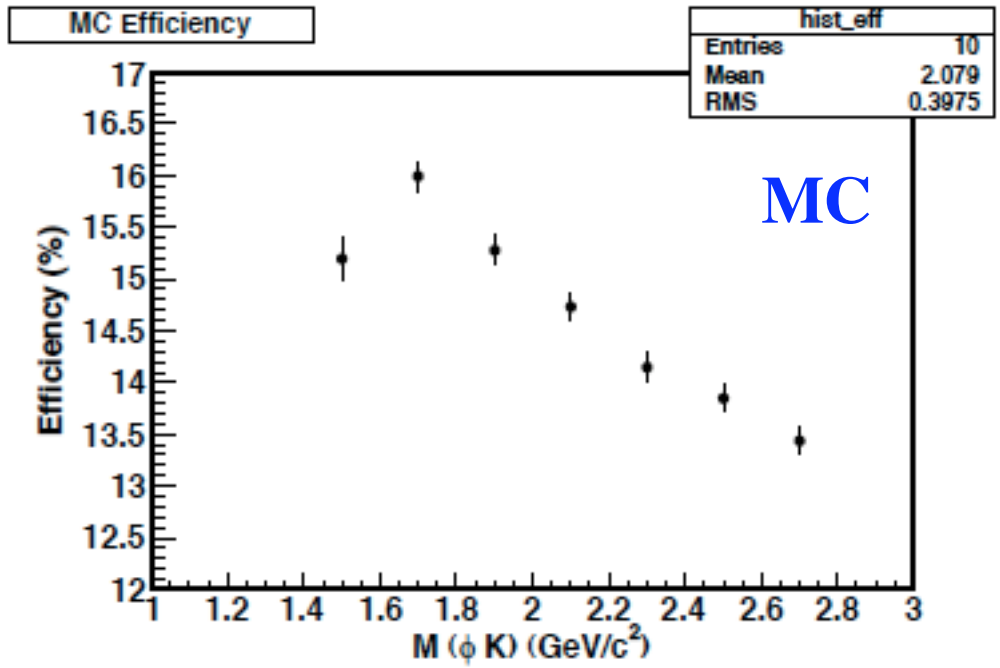
144±17 Events

Signal shape is fixed using kinematically similar mode, $B \to K^*(\to K^+\pi^-)\gamma$

Efficiency calibration

efficiency (ε_i) = (Events reconstructed)/(Events generated)

$$\epsilon_{avg} = \frac{\sum_i \epsilon_i * N_i}{N}$$



MC efficiency is re-weighted according to this M(φK) dependence in data and are used in branching fraction measurement.

20% relative change across the spectrum

Efficiency : (15.3±0.1)% for charged and (10.0±0.1)% neutral mode

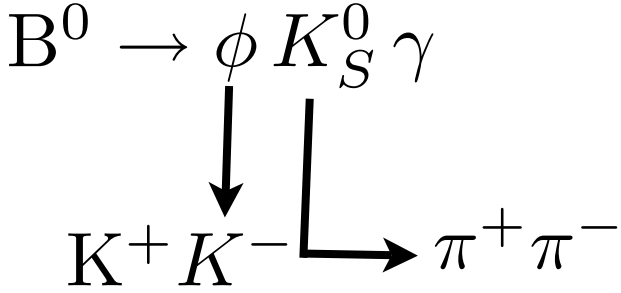
Analysis Method

Event reconstruction

Background rejection — three types
continuum,b->c,rare

Fitting strategy

Signal Extraction



- B candidates are selected using ΔE and M_{bc}

$$\Delta E \equiv E^*_{\rm B} - E^*_{\rm beam} \qquad M_{\rm bc} \equiv \sqrt{(E^*_{\rm beam})^2 - (p^*_{\rm B})^2}$$

- 2D fitting method to ΔE-M_{bc} (unbinned extended maximum likelihood) fit region :

(–0.3 GeV<ΔE<0.3 GeV) && (5.2 GeV/c^2 < M_{bc}<5.29 GeV/c^2)

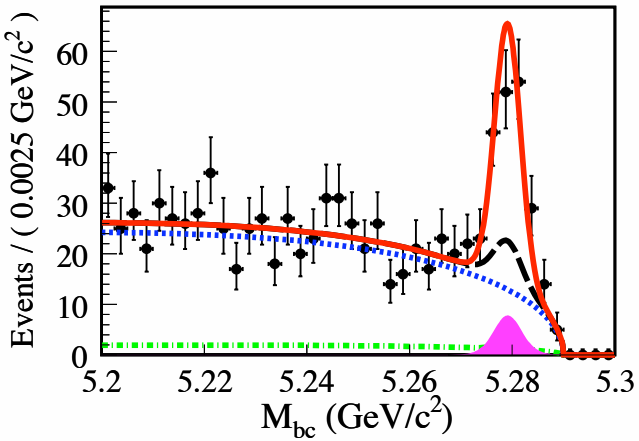
mention the selection criteria for phi, K_S,gamma

put DE Mbc plot here

and show 2D fit region

Branching Fraction

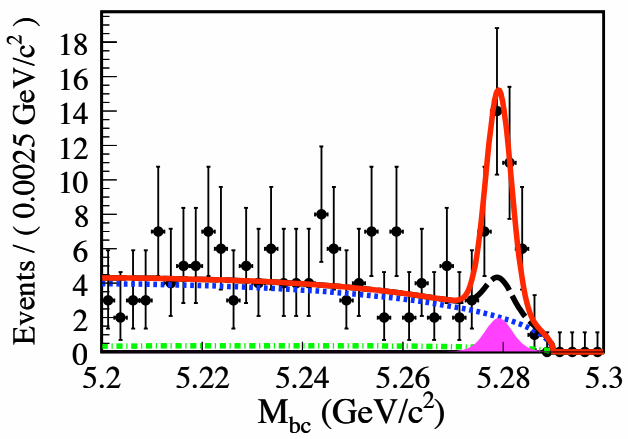
$B^+ \to \varphi K^+ \gamma$



N_{sig}=144±17 events

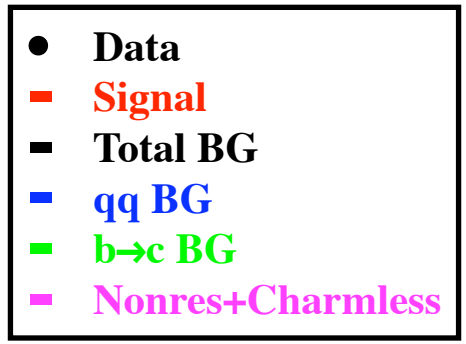
eff = (15.3±0.1)%

$B^0 \to \varphi K_S \gamma$



N_{sig}=37±8 events

eff = (10.0±0.1)%



Signal Extraction : ΔE-M_{bc} 2D fit

Non-resonant $K^+K^-K\gamma$ is obtained from φ mass sideband in data (13% of signal)

$\mathcal{B}(B^+ \to \varphi K^+ \gamma) = (2.48 \pm 0.30 \pm 0.24) \times 10^{-6}$ (9.6σ)

$\mathcal{B}(B^0 \to \varphi K^0 \gamma) = (2.74 \pm 0.60 \pm 0.32) \times 10^{-6}$ (5.4σ)

First observation in neutral mode

Charged Asymmetry

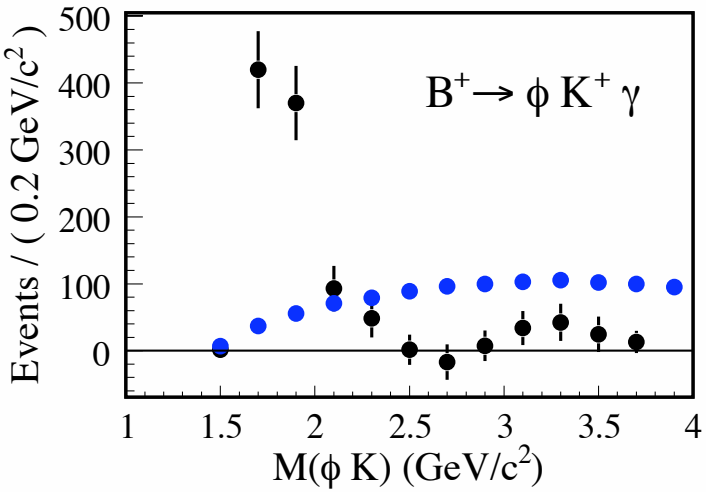
$$A_{CP} = \frac{N(B^- \to \phi K^- \gamma) - N(B^+ \to \phi K^+ \gamma)}{N(B^- \to \phi K^- \gamma) + N(B^+ \to \phi K^+ \gamma)} = (-0.03 \pm 0.11 \pm 0.08)$$

(consistent with no CP asymmetry)

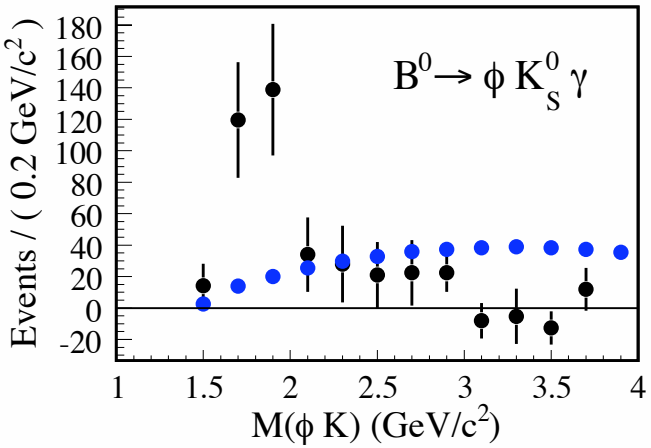
M(φK) mass distribution

- Background-subtracted and efficiency-corrected M(φK) mass distributions
- Yield in each bin of M(φK) mass is from ΔE-M_{bc} 2D-fit
- Nearly 72% events are concentrated in the low mass region (1.5-2.0 GeV/c^2)
- No clear evidence is found for the existence of a kaonic resonance decaying to φK.
- The spectra are in qualitative agreement with expectation from pQCD model for non-resonant decays (the peak at threshold can be explained by form factor effects).

C.H.Chen and H.-n.Li, PRD 70, 054006 (2004) [hep-ph/0404097]



- **Data**
- **Phase-space from MC**

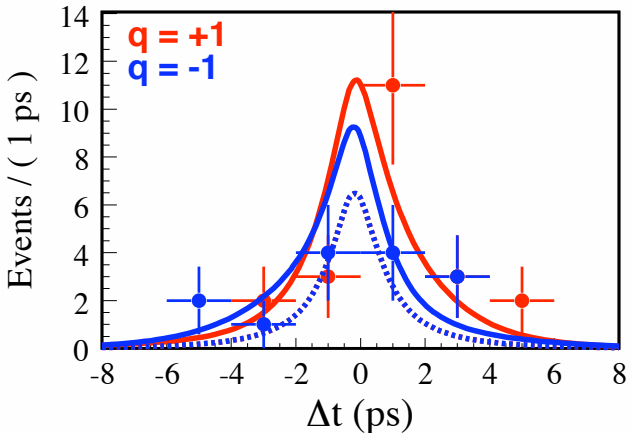


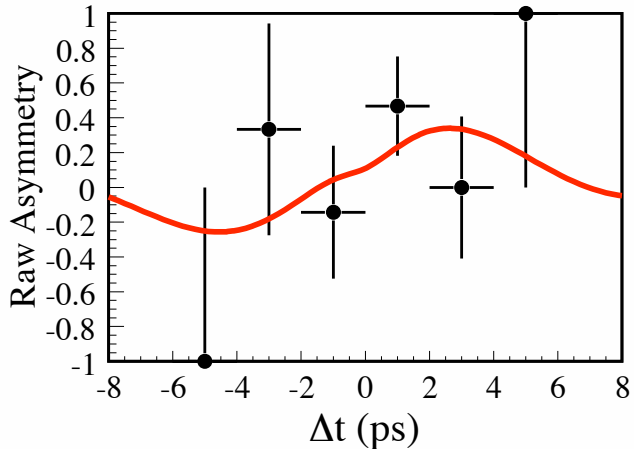
TCPV in $B^0 \to \varphi K_S \gamma$

First TCPV measurement in neutral mode with 35 signal events.

(vertexing from $\varphi \to K^+K^-$ tracks, K_S vertexing is not required)

Nonresonant $K^+K^-K\gamma$ is included in the signal for TCPV study

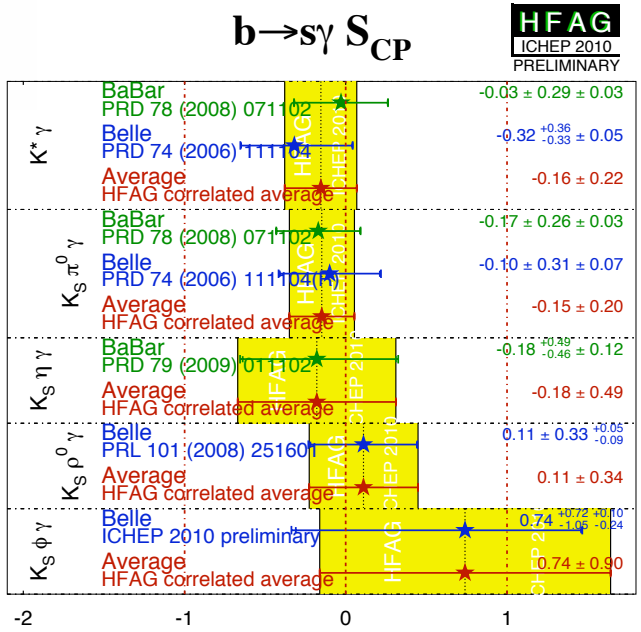




772M $B\bar{B}$
arXiv:1104.5590

submitted to PRL

$$S = 0.74^{+0.72}_{-1.05}\ (\text{stat})\ ^{+0.10}_{-0.24}\ (\text{syst})$$
$$A = 0.35 \pm 0.58\ (\text{stat})\ ^{+0.23}_{-0.10}\ (\text{syst})$$



➔ We have established a new mode for future high-luminosity e^+e^- and hadronic facilities

Summary

- Many new results from Belle on CP violation with full data sample.
- Most precise measurement of $\sin 2\phi_1$ in $B \to (cc)K^0$ decays

  $\sin 2\phi_1 = 0.668 \pm 0.023 \pm 0.013$, $\mathcal{A} = 0.007 \pm 0.016 \pm 0.013$
- TCPV in $B \to D^+D^-$ decays (NEW!)

  $\mathcal{S} = -1.06 \pm 0.21 \pm 0.07$, $\mathcal{A} = +0.43 \pm 0.17 \pm 0.04$
- TCPV in $B \to D^{*+}D^{*-}$ decays (NEW!)

  $\mathcal{S} = -0.79 \pm 0.13 \pm 0.03$, $\mathcal{A} = +0.15 \pm 0.08 \pm 0.02$
- CPT Violation (NEW!)

  $\mathrm{Re}(z) = (+1.9 \pm 3.7 \pm 3.2) \times 10^{-2}$, $\mathrm{Im}(z) = (-5.7 \pm 3.3 \pm 6.0) \times 10^{-3}$, $\Delta\Gamma_d/\Gamma_d = (-1.7 \pm 1.8 \pm 1.1) \times 10^{-2}$
- First TCPV in radiative $B^0 \to \varphi K_S \gamma$ decays

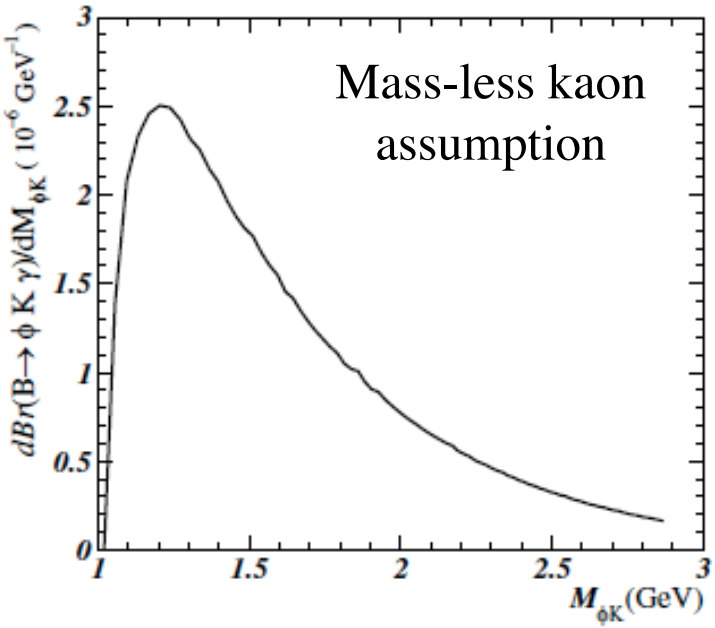
  $\mathcal{S} = 0.74^{+0.72+0.10}_{-1.05-0.24}$, $\mathcal{A} = 0.35 \pm 0.58^{+0.23}_{-0.10}$

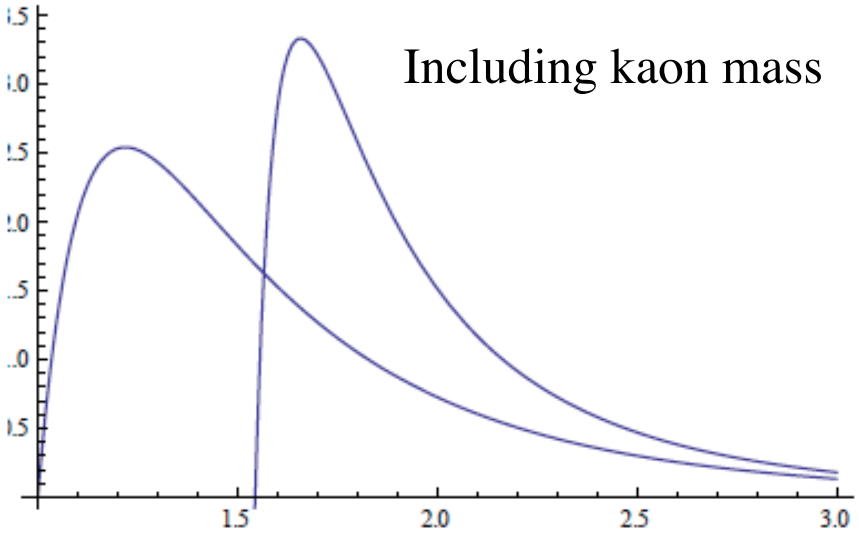
  (submitted to PRL)

Theoretical Prediction

- Two-meson distribution amplitude in a three-body decay (neglecting the resonant contribution).
- Predicted $B \to \varphi K \gamma$ decay spectrum exhibits maximum at φK invariant mass around 1.3 GeV.

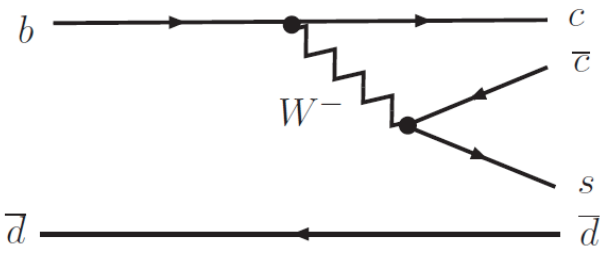
Hsiang-nan Li
PRD 70, 054006 (2004) [hep-ph/0404097]





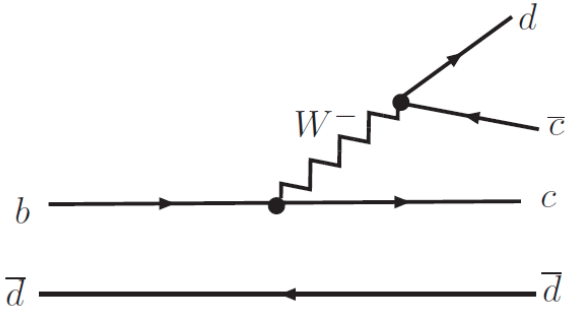
$B \to \varphi K \gamma$ decay spectrum in the φK invariant mass

Other ways to measure sin2$\phi_1(\beta)$



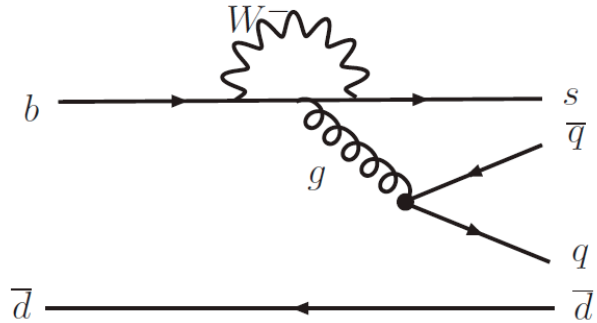
Charmonium
"Tree-dominated"

$B^0 \to J/\psi\, K_S$, $\psi' K_S$
$B^0 \to \chi_{c1}\, K_s$, $\eta_c K_s$
$B^0 \to J/\psi\, K_L$, $J/\psi\, K^*(\to K_S\pi^0)$



Open charm or Charmonium
Tree-dominance, Loop may contribute

$B^0 \to J/\psi\pi^0$
$B^0 \to D^{(*)} + D^{(*)-}$, $D^+ D^-$



Charmless, b→s loop decays
"penguin-dominance"

$B^0 \to \phi K_S$, $K^+ K^- K_S$, $K_S K_S K_S$
$B^0 \to K_S\pi^0$, $\eta' K_S$, ωK_S, $f_0 K_S$

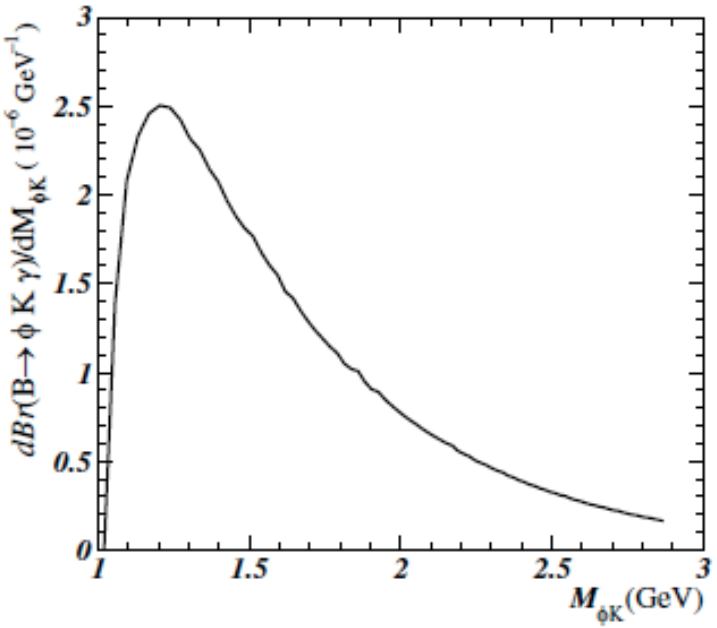
Increase tree diagram contribution

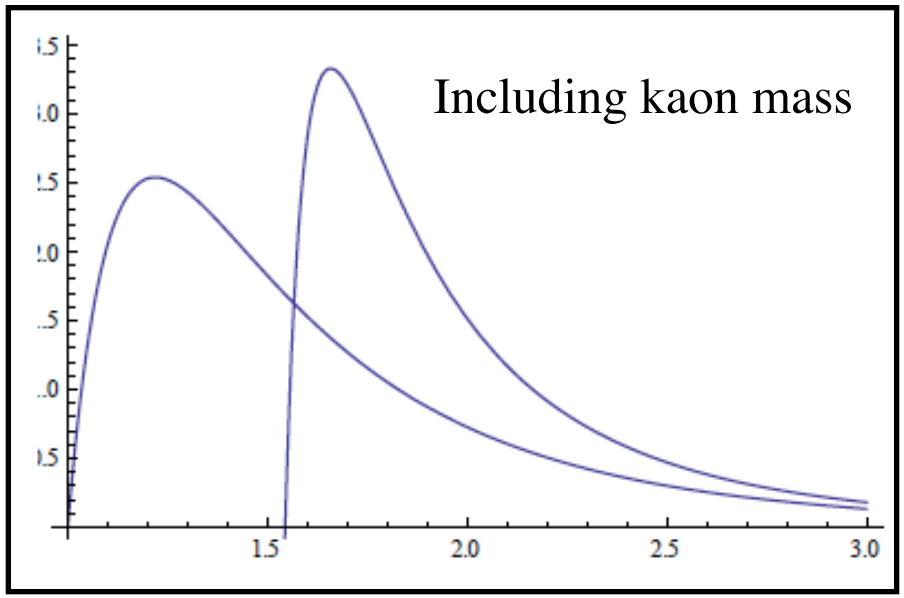
Increase sensitivity to new physics

Theoretical Prediction

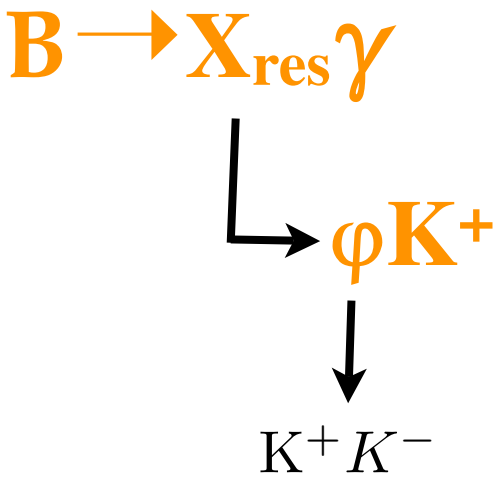
- It may also possible that this is not a resonance.
- Two-meson distribution amplitude in a three-body decay (neglecting the resonant contribution).
- Predicted $B \to \varphi K \gamma$ decay spectrum exhibits maximum at φK invariant mass around 1.3 GeV.

Hsiang-nan Li
PRD 70, 054006 (2004) [hep-ph/0404097]





$B \to \varphi K \gamma$ decay spectrum in the φK invariant mass



$B \to X\gamma$

B is pesudo-scalar and gamma is transversely polarized.
X can't be spin 0. X has m_j = ±1

$X \to \varphi K$

phiK system has spin S=1, m_s = 0, ±1
Since X has m_j = ±1, allowed values of m_*l* for phiK system = 0, ±1, ±2

allowed values of relative orbital angular momentum for the phiK system:
If X is spin 1 : *l* values = 0, 1, 2 (6 different states are possible)
If X is spin 2 : *l* values = 1, 2, 3 (8 different states are possible)

Strong decay : Parity is conserved $J^p = 1^- 0^- (-1)^l$

Polar Vector (1^-) : *l*=1 (P-wave)
Axial Vector (1^+) : *l*=0 (S-wave), l=2 (D-wave)
Polar Tensor (2^-) : *l*=1 (P-wave), l=3 (F-wave)
Axial Tensor (2^+) : *l*=2 (D-wave)

Angular distribution will be proportional to $|Y_l\hat{}m\_l|^2$

EvtGen models : PHSP for $B^+ \to \varphi K^+ \gamma$ (NR), VVS_PWAVE for Vector, TVS_PWAVE for Tensor

ERROR : 1^- and 2^- models aren't yet implemented in EvtGen!!