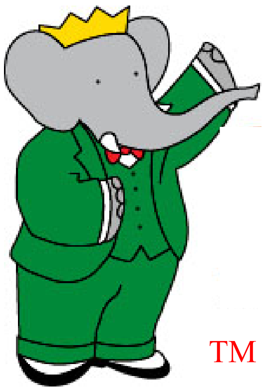


The Penguin & The Elephant: Half a Billion b Quarks at BaBar

Jeffrey Berryhill
University of California, Santa Barbara
For the BaBar Collaboration

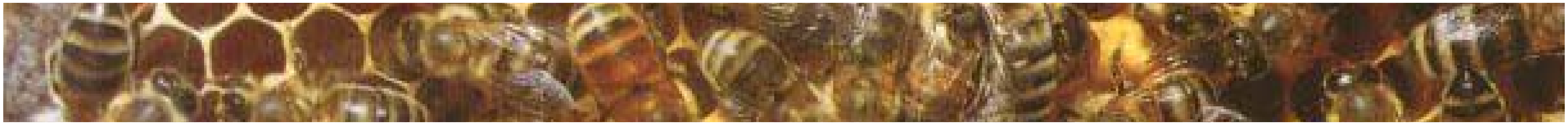
Rutgers High Energy Physics Seminar
March 21, 2005

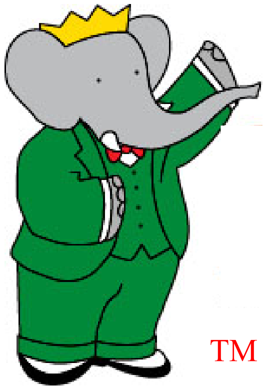
Outline

- Quark Flavor and CP Violation
- B Factories
- Gluon Penguin B Decays
- Photon Penguin B Decays

- The Electroweak Penguin B Decay $b \to sll$

  Brand new results for $B \to Kll, K^*ll$





Quarks, Flavor Violation, and CP Violation

Quarks and the problem of mass

Standard Model “explanation” of quark mass:
Six quark species with unpredicted masses
Spanning almost six orders of magnitude

Up type (q=+2/3)	Mass (GeV/c^2)
Up u	10^{-3}
Charm c	1
Top t	175

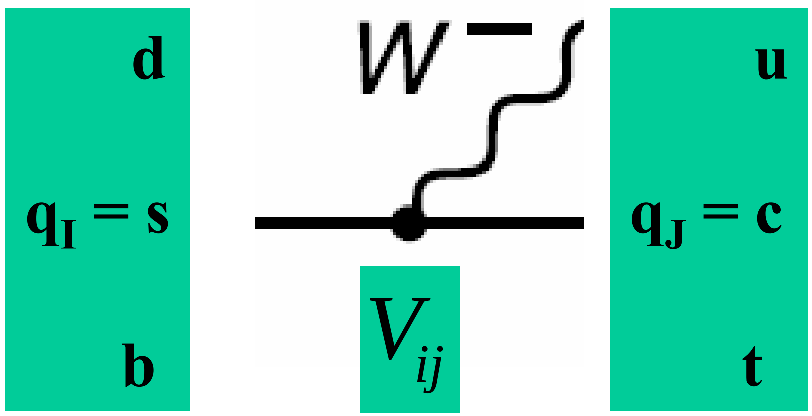
Down type (q=-1/3)	Mass (GeV/c^2)
Down d	5 10^{-3}
Strange s	10^{-1}
Bottom b	5

The origin of different fermion generations, masses, flavor violation, and CP violation are all arbitrary parameters of electroweak symmetry breaking.
A comparative physics of the quark flavors directly probes this little-known sector.

Quarks and Flavor Violation

Photon, gluon or Z boson: quark flavor conserving interactions

W boson: changes any down type flavor to any up type flavor



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

The (Cabibbo-Kobayashi-Maskawa) CKM matrix: complex amplitude of each possible transition

Conservation of probability → CKM matrix is unitary

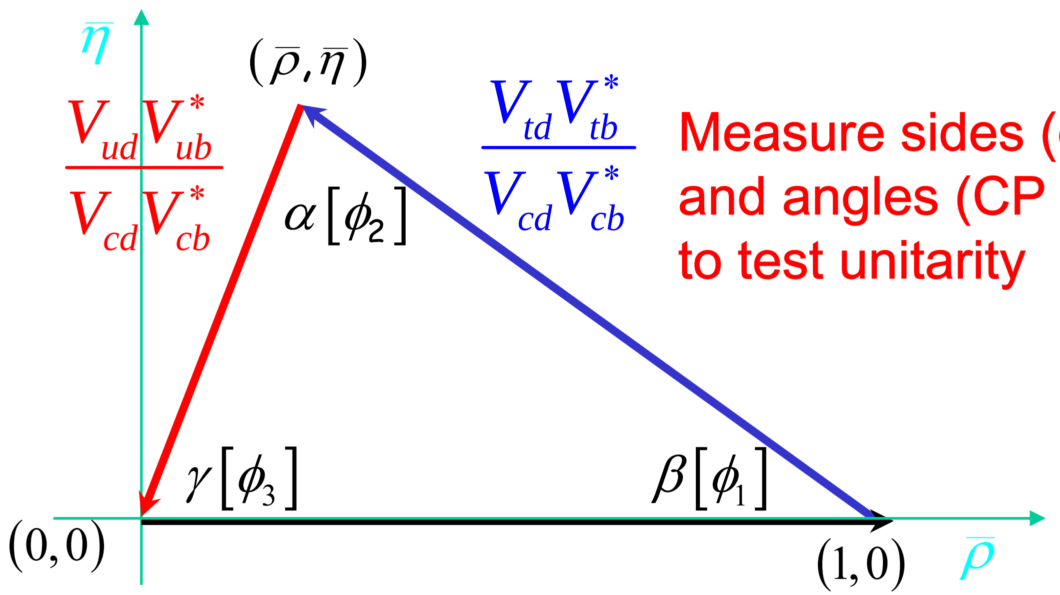
3X3 unitary matrix has (effectively) four degrees of freedom:
3 angles + 1 complex phase

CKM Unitarity

Inner product of first and third columns of CKM matrix is zero:

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

Rescale, rotate and reparameterize to describe a Unitarity Triangle in the complex plane

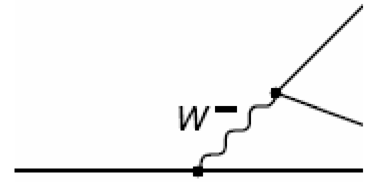


Measure sides (decay rates) and angles (CP violation) to test unitarity

Three Paths to Flavor Violation

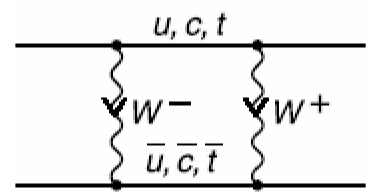
1. Tree diagram decay: down → up ($b \to c$, $b \to u$)

Not generally sensitive to new physics

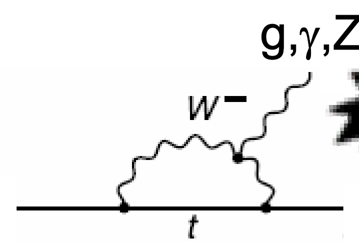


2. Box diagram: neutral meson mixing (K^0,B_d^0,B_s^0)

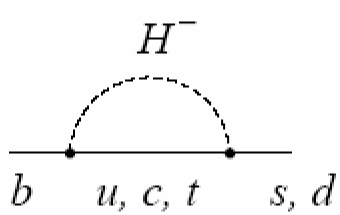
down-type → anti-down type ($b \to \bar{b}$)
via double W exchange

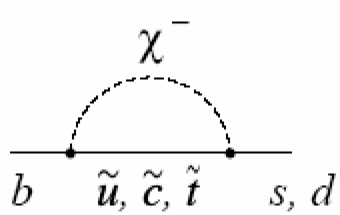


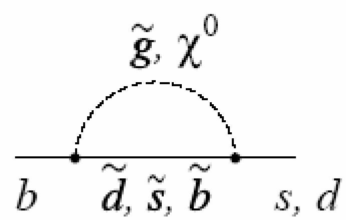
3. Penguin diagram: ($b \to s$, $b \to d$)
down-type → down-type
via emission & reabsorption of W;
top-quark couplings V_{td}, V_{ts} dominate



SM penguins are suppressed; new physics can compete directly!







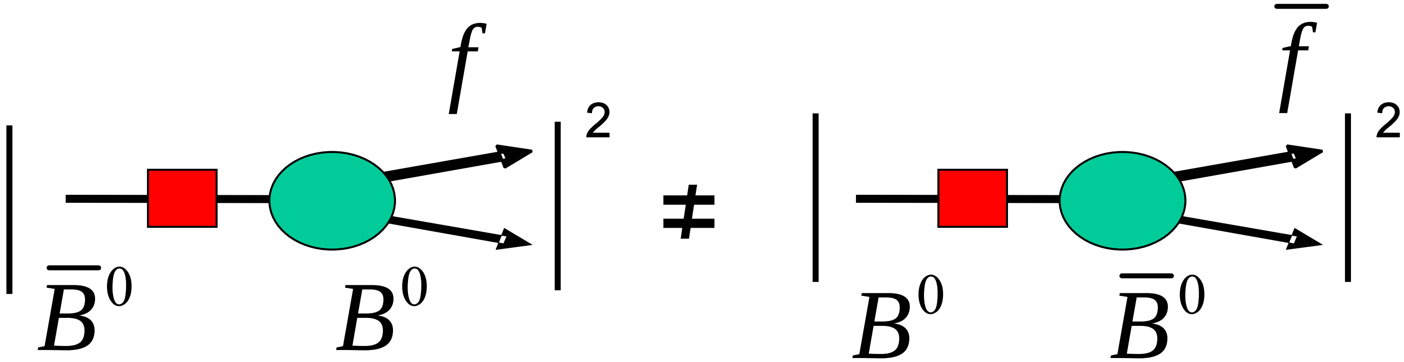
+ 4^{th} gen. quarks, technicolor, LED, etc., etc., with possible enhanced flavor couplings

Three Paths to CP Violation

CP violation → an observable O of particles (f1,f2,…) such that

$O(f1,f2,\ldots) \neq O(CP(f1,f2,\ldots)) = O(\overline{f1}, \overline{f2}, \ldots)$

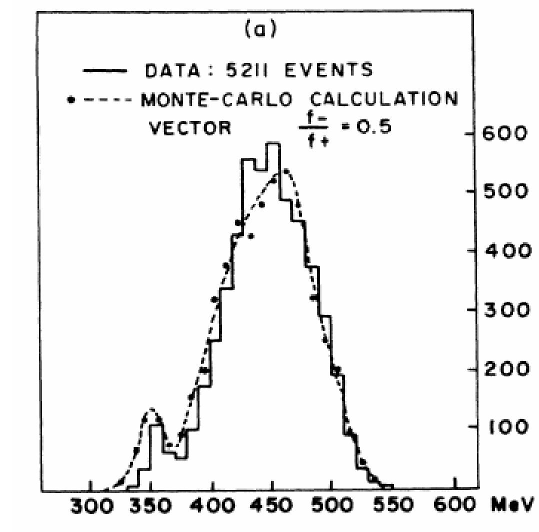
1. CP violation in meson mixing



Mixing rate of meson to final state f not the same as
Mixing rate of anti-meson to same final anti-state

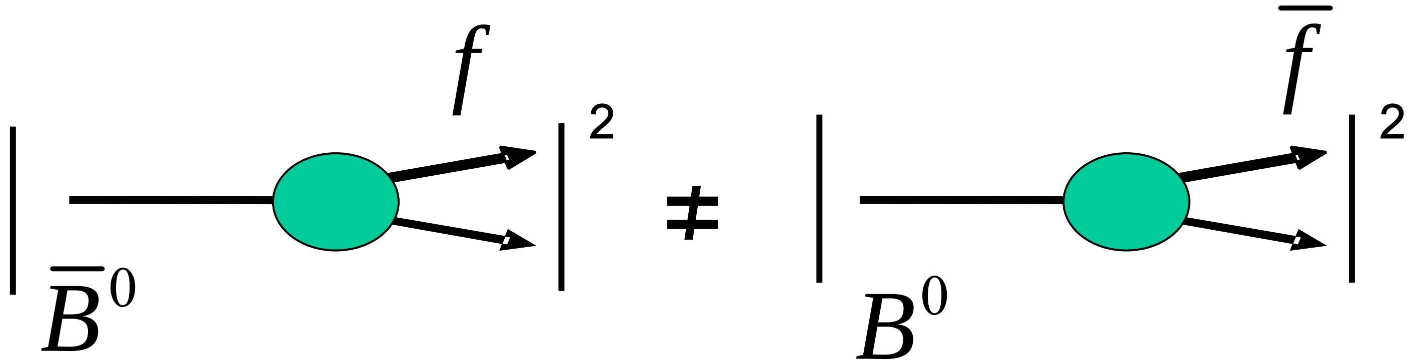
In the Standard Model, very small ~10^{-3}

CP violation in K^0 decays first observed through this path forty years ago!

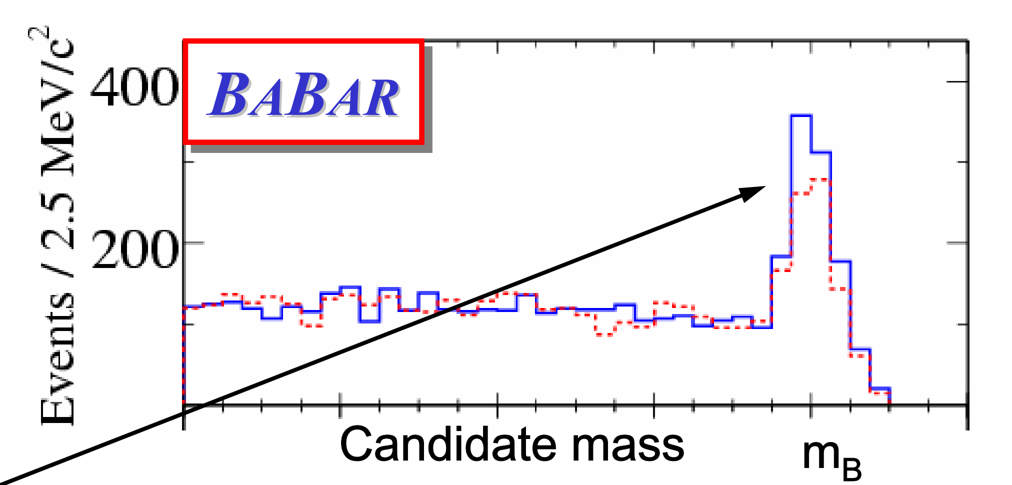


Three Paths to CP Violation

2. CP violation in meson decay → "Direct CP violation"



Decay rate of meson to final state f not the same as Decay rate of anti-meson to same final anti-state

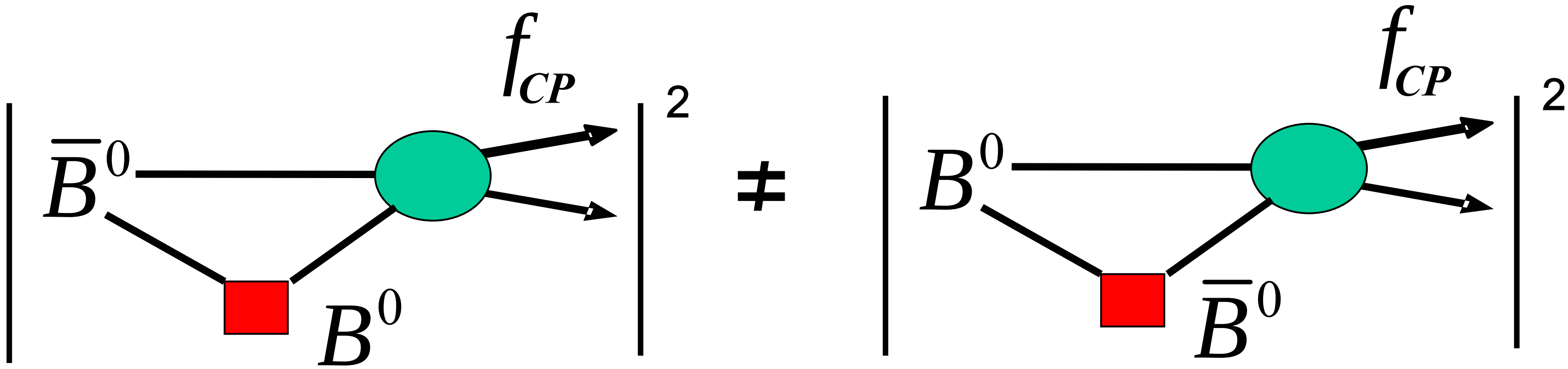


Blue $B^0 \to K^+\pi^-$
Red $\overline{B}^0 \to K^-\pi^+$

Recently observed in $B^0 \to K^+ \pi^-$ at the 10% level!

Three Paths to CP Violation

3.Time dependent asymmetry of meson/anti-meson decay rate to a common final state

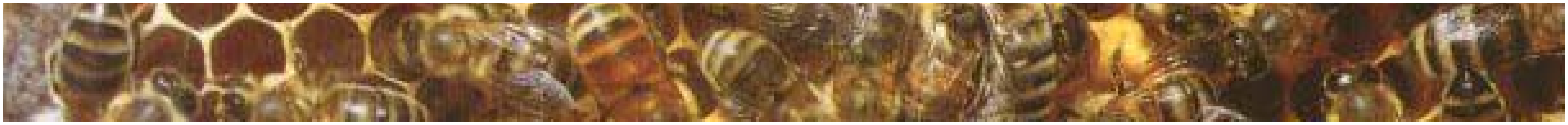


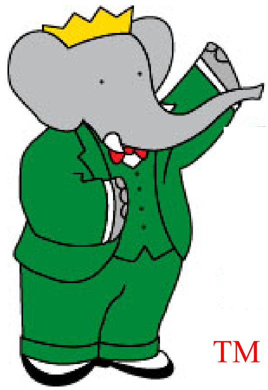
If $\overline{B}^0$ and B^0 decay to the same final state f_{CP}, there is interference between
amplitude of direct decay and
amplitude of mixing followed by decay

In the presence of CP violating phases in these amplitudes, can induce large time-dependent asymmetry with frequency equal to mixing frequency:

$$A_{f_{CP}} = -C_{f_{CP}} \cos(\Delta m t) + S_{f_{CP}} \sin(\Delta m t)$$

$C_{f_{CP}} \neq 0$ implies Direct CP Violation





B Factories

b Quarks and CKM Unitarity

B decay rates, CP asymmetries measure the entire triangle!

Triangle sides:

$B^+ \to \rho^0 l^- \nu$ decay rate measures $b \to u$ transition ($|V_{ub}|$)

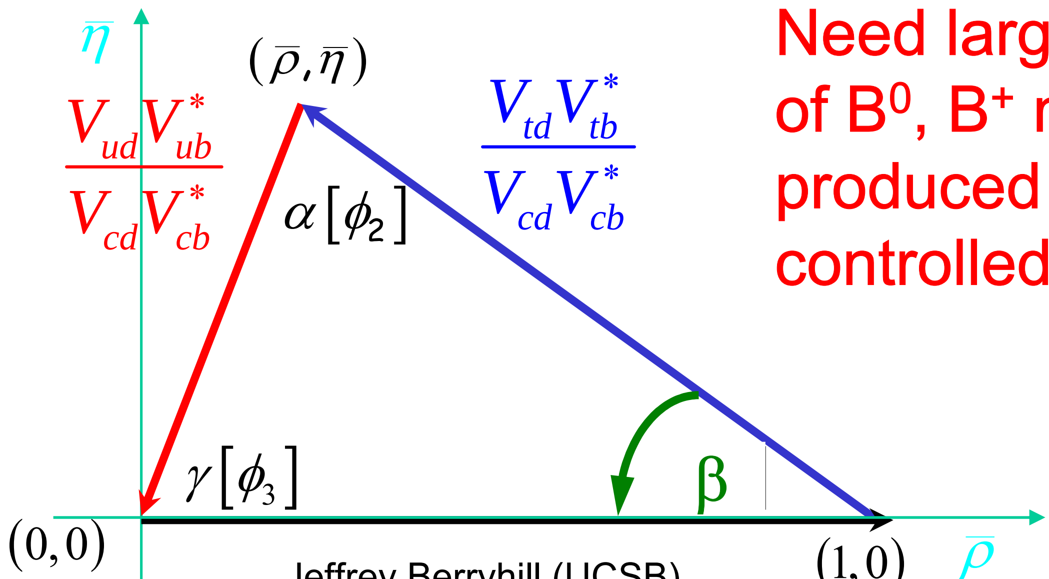
B^0 mixing rate measures $|V_{td}|$

Angles:

$B^0 \to \rho^+ \rho^-$ time dependent CP asymmetry measures sin 2α

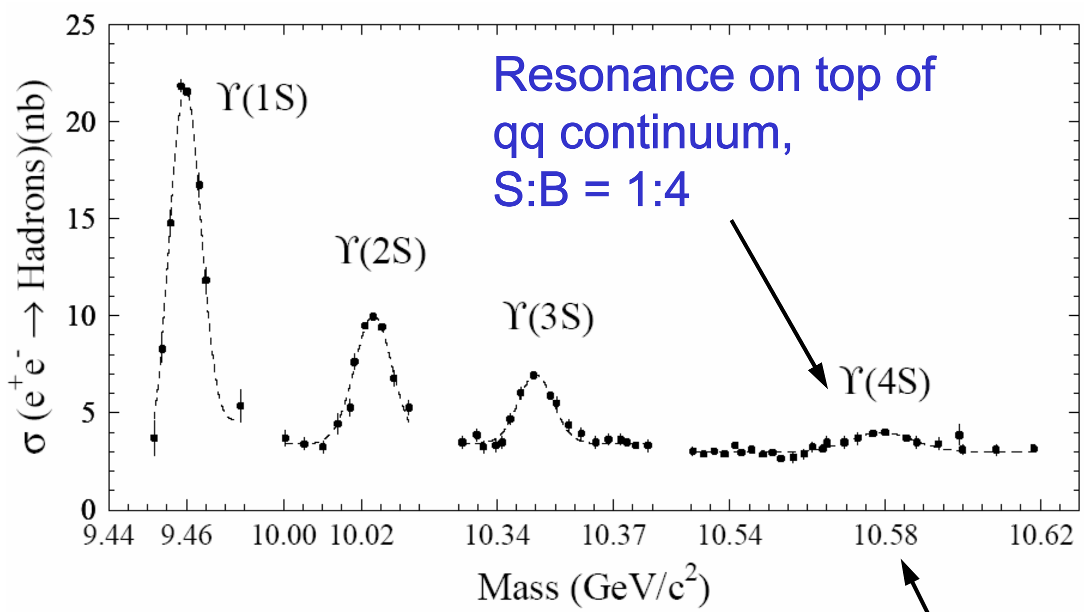
$B^0 \to J/\psi K_S^0$ time dependent CP asymmetry measures sin 2β

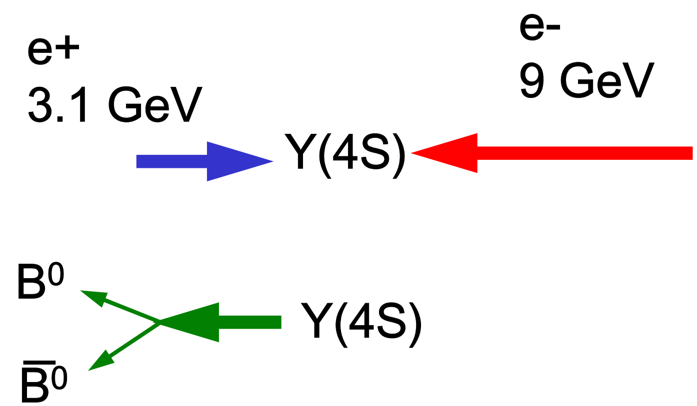
$B^+ \to D(^*)K^+$ decay rates measure γ



Need large sample of B^0, B^+ mesons produced under controlled conditions

Asymmetric B Factories





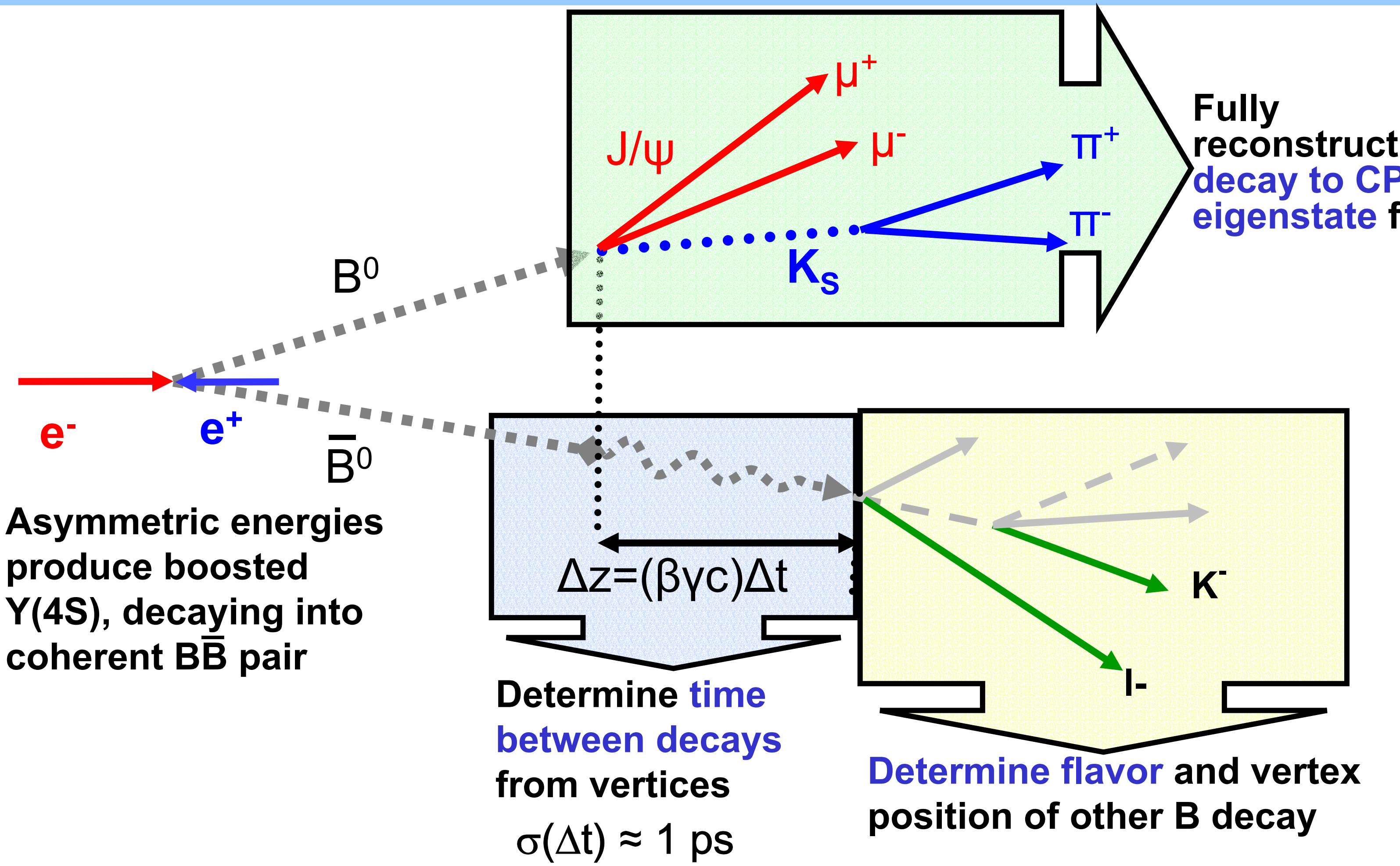
Y(4S) meson: $b\bar{b}$ bound state with mass 10.58 GeV/c^2

Just above 2 × B mass → decays exclusively to $B^0\,\bar{B}^0$ (50%) and $B^+\,B^-$ (50%)

B factory: intense e+ and e- colliding beams with E_{CM} tuned to the Y(4S) mass

Use e beams with asymmetric energy → time dilation due to relativistic speeds keeps B's alive long enough to measure decay time (decay length ~0.25mm)

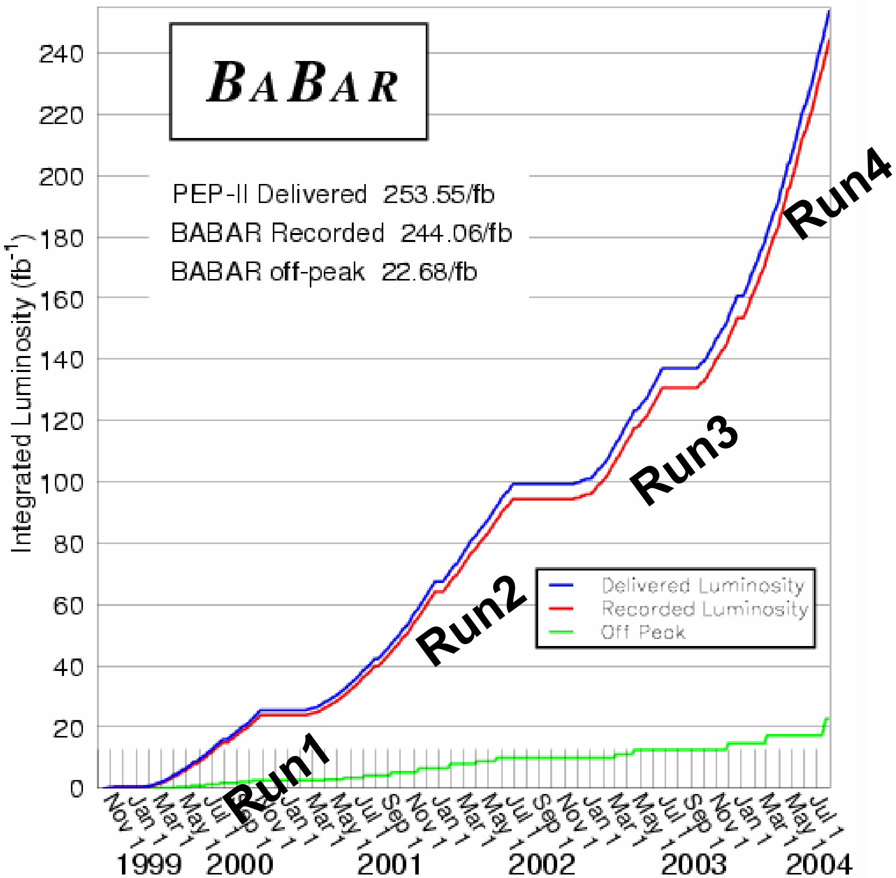
Time-Dependent CP Violation: Experimental technique



Compute CP violating asymmetry $A(\Delta t) = \dfrac{N(\bar{f}\,;\Delta t) - N(f\,;\Delta t)}{N(\bar{f}\,;\Delta t) + N(f\,;\Delta t)}$

PEP-II at the Stanford Linear Accelerator Center

PEP-II performance



PEP-II top luminosity:
9.2 x 10^{33}cm^{-2}s^{-1}
(more than 3x design goal 3.0 x 10^{33})

1 day record : 681 pb^{-1}

About 1 Amp of current per beam, injected continuously

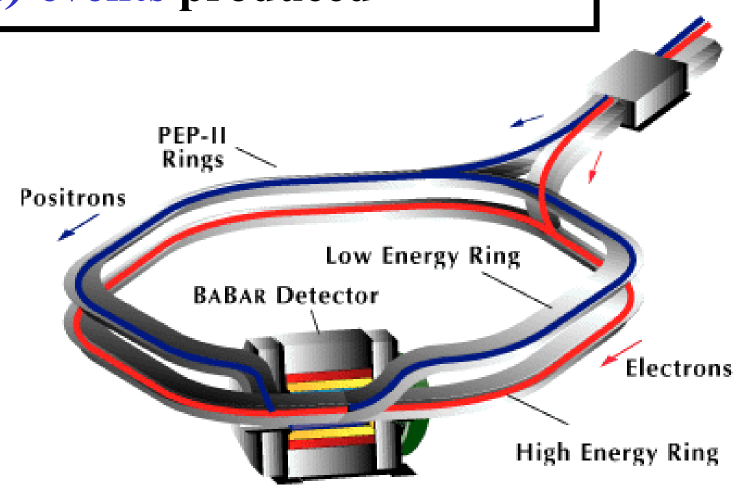
Run1-4 data: 1999-2004

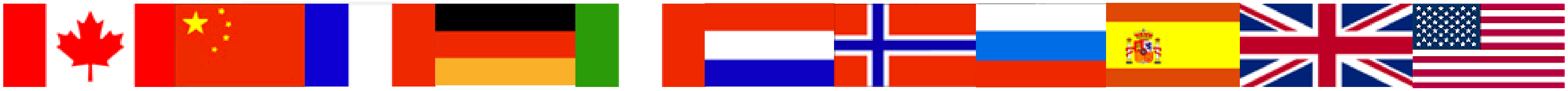
On peak 211 fb^{-1}

σ(e+e- →Υ(4S)) = 1.1 nb →
229M *Υ(4S)* events produced

458 million b quarks produced!

Also ~10^8 each of u, d, s, c, and τ





The *BABAR* Collaboration

11 Countries

80 Institutions

593 Physicists

USA [38/300]

California Institute of Technology
UC, Irvine
UC, Los Angeles
UC, Riverside
UC, San Diego
UC, Santa Barbara
UC, Santa Cruz
U of Cincinnati
U of Colorado
Colorado State
Florida A&M
Harvard
U of Iowa
Iowa State U
LBNL
LLNL
U of Louisville
U of Maryland
U of Massachusetts, Amherst
MIT
U of Mississippi
Mount Holyoke College
SUNY, Albany
U of Notre Dame
Ohio State U
U of Oregon
U of Pennsylvania
Prairie View A&M U
Princeton U
SLAC
U of South Carolina
Stanford U
U of Tennessee
U of Texas at Austin
U of Texas at Dallas
Vanderbilt
U of Wisconsin
Yale

Canada [4/20]

U of British Columbia
McGill U
U de Montréal
U of Victoria

China [1/5]

Inst. of High Energy Physics, Beijing

France [5/51]

LAPP, Annecy
LAL Orsay
LPNHE des Universités Paris VI et VII
Ecole Polytechnique, Laboratoire Leprince-Ringuet
CEA, DAPNIA, CE-Saclay

Germany [5/31]

Ruhr U Bochum
U Dortmund
Technische U Dresden
U Heidelberg
U Rostock

Italy [12/101]

INFN, Bari
INFN, Ferrara
Lab. Nazionali di Frascati dell' INFN
INFN, Genova & Univ
INFN, Milano & Univ
INFN, Napoli & Univ
INFN, Padova & Univ
INFN, Pisa & Univ & ScuolaNormaleSuperiore
INFN, Perugia & Univ
INFN, Roma & Univ "La Sapienza"
INFN, Torino & Univ
INFN, Trieste & Univ

The Netherlands [1/5]

NIKHEF, Amsterdam

Norway [1/3]

U of Bergen

Russia [1/11]

Budker Institute, Novosibirsk

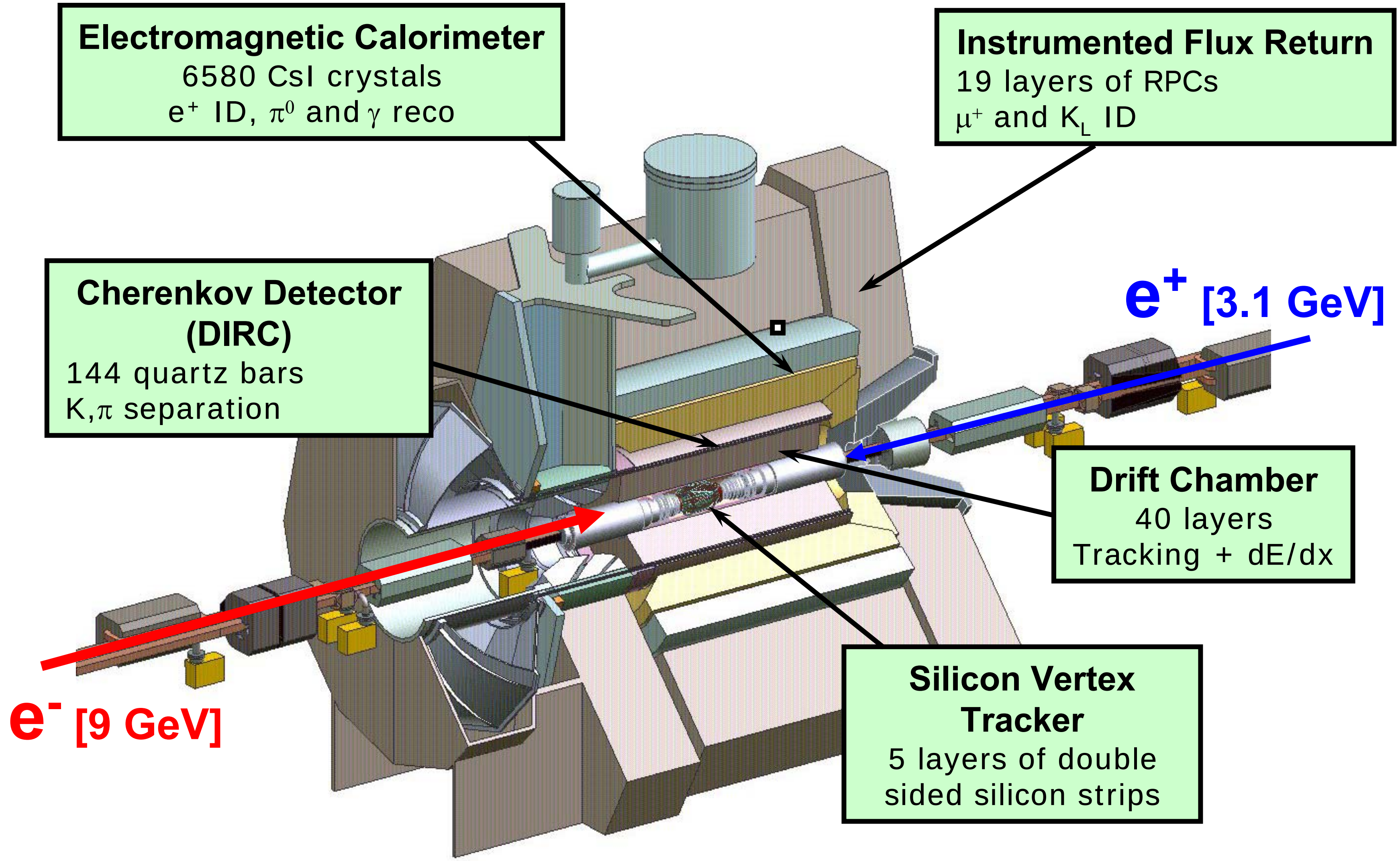
Spain [2/2]

IFAE-Barcelona
IFIC-Valencia

United Kingdom [10/66]

U of Birmingham
U of Bristol
Brunel U
U of Edinburgh
U of Liverpool
Imperial College
Queen Mary , U of London
U of London, Royal Holloway
U of Manchester
Rutherford Appleton Laboratory

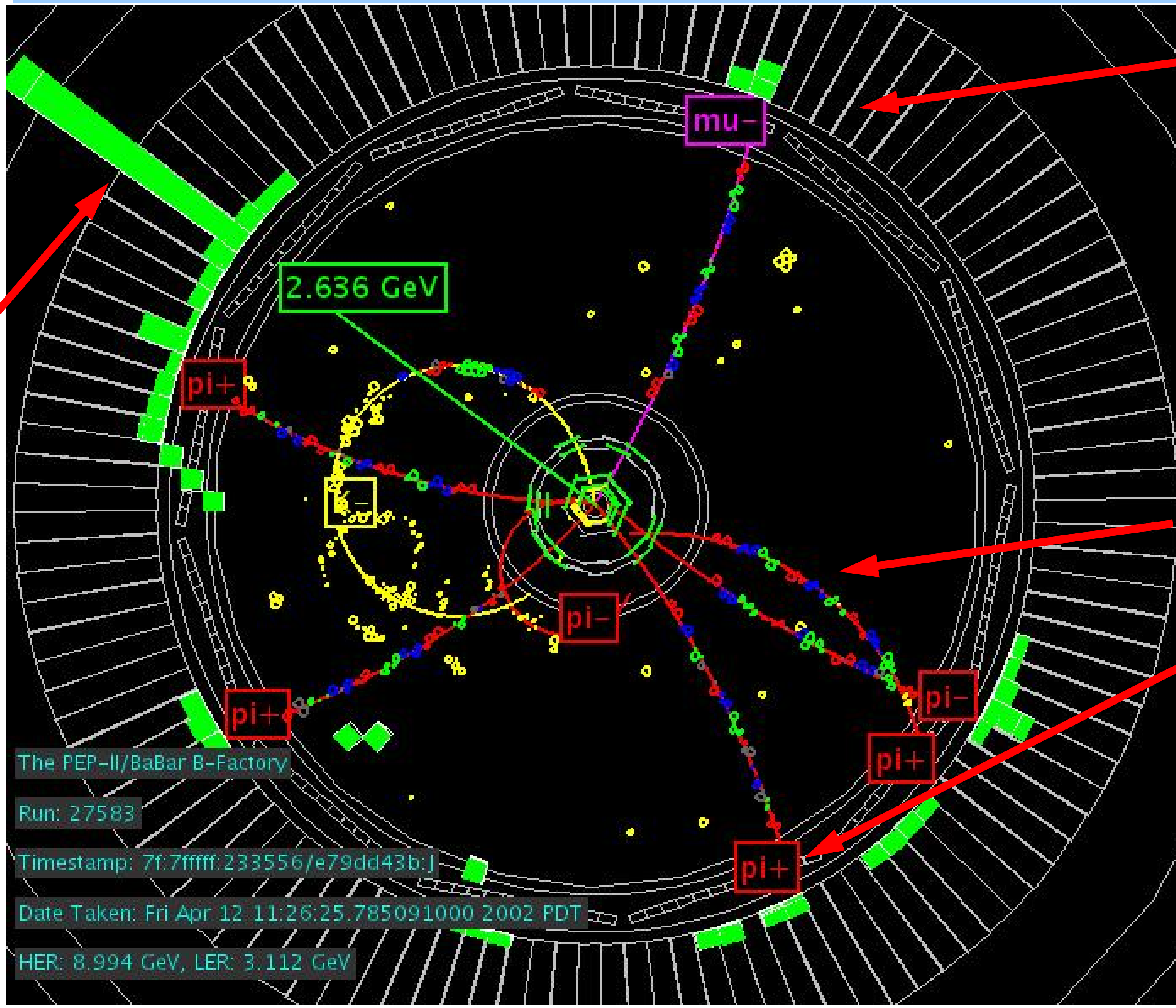
The BaBar detector



Penguin Portrait

$B^+ \to K_s\, \pi^+\, \gamma$
Candidate

High energy
photon



Muon
from
other
B decay

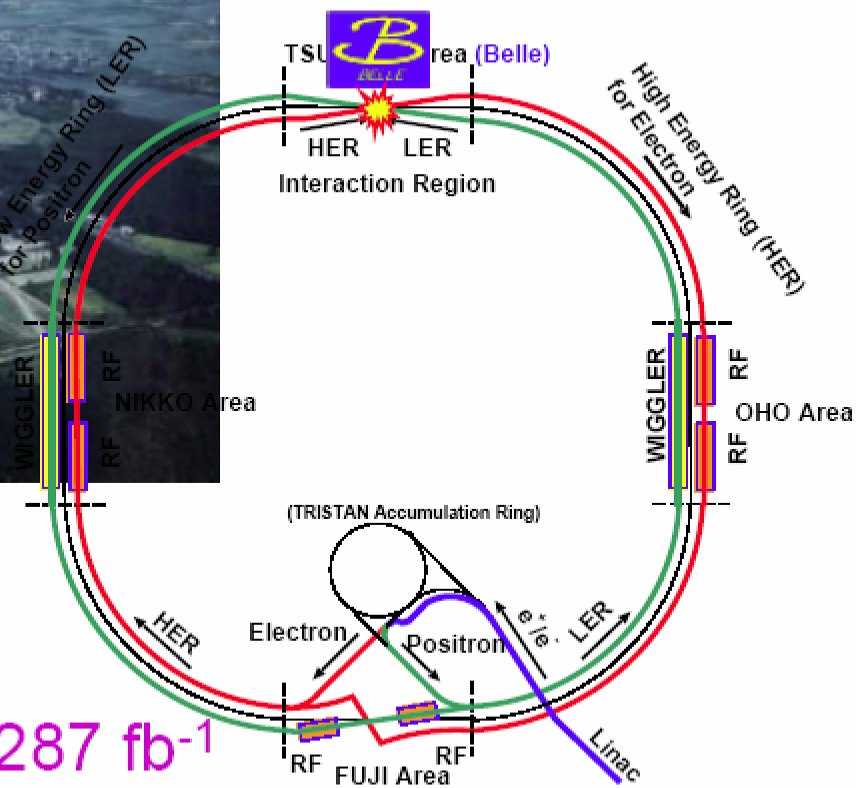
$K_s \to \pi^+\pi^-$

and π+

Our Friendly Competitors

8 GeV e^- x 3.5 GeV e^+

±11mrad crossing



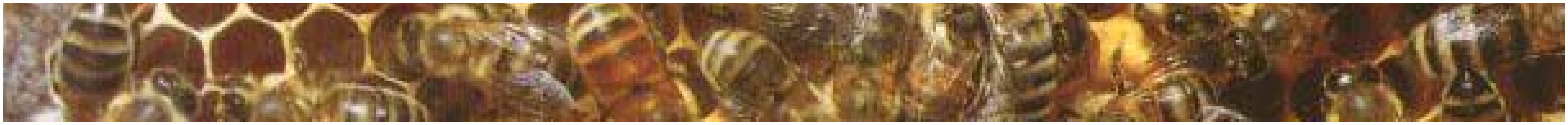
$L_{peak} = 1.39 \times 10^{34}\ sec^{-1}cm^{-2}$

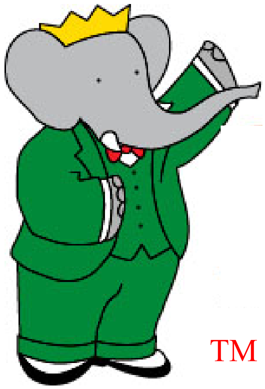
@ 1.2A x 1.6A

253 fb^{-1} on Y(4S)   274M $B\bar{B}$

28 fb^{-1} below Y(4S)

~287 fb^{-1}





Gluon Penguins and CP Violation

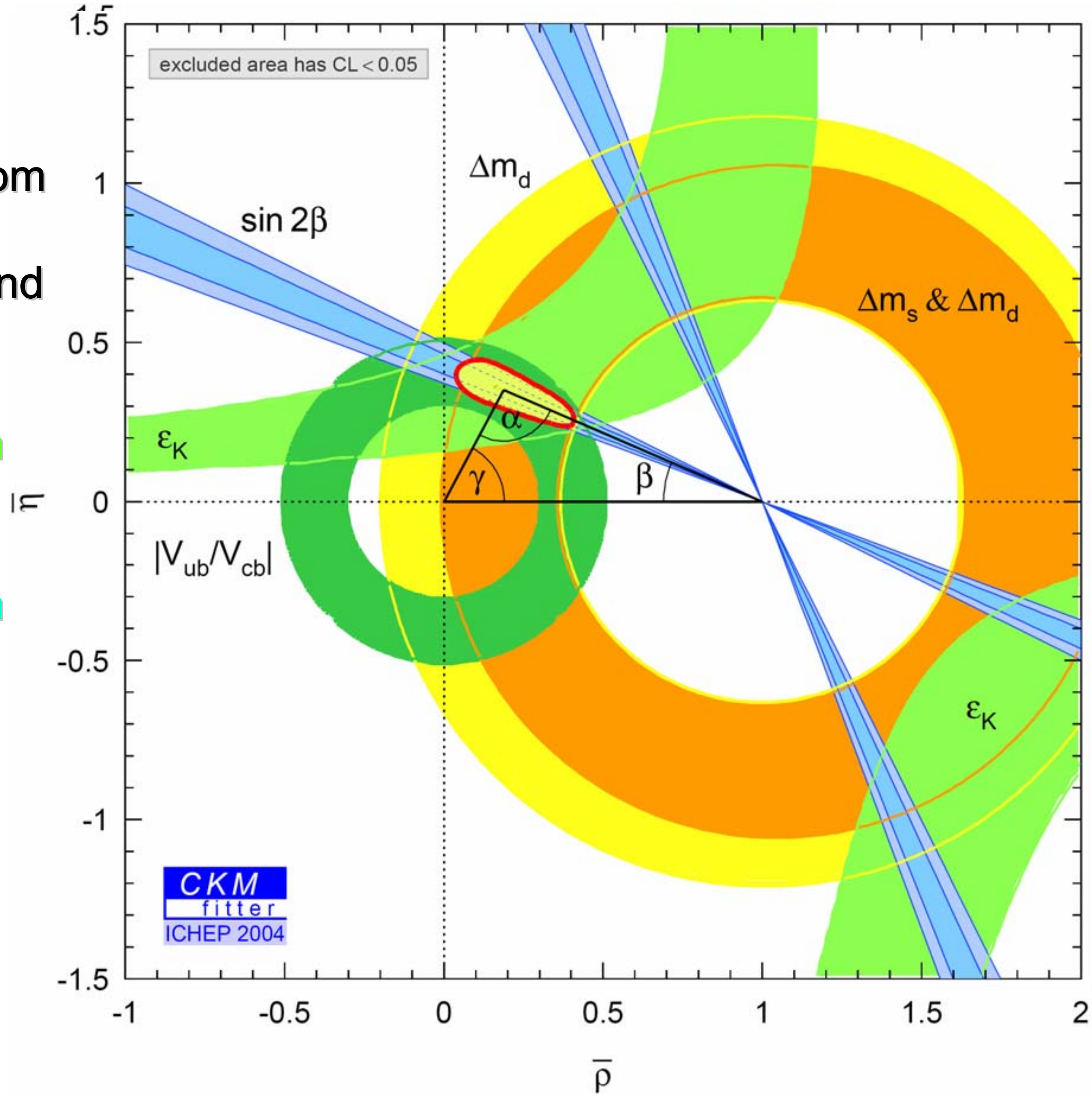
CKM Unitarity Triangle: Experimental Constraints

Constraints from

Decay rates and
Mixing Rates

CP violation in
kaon decay

CP violation in
$b \to ccs$

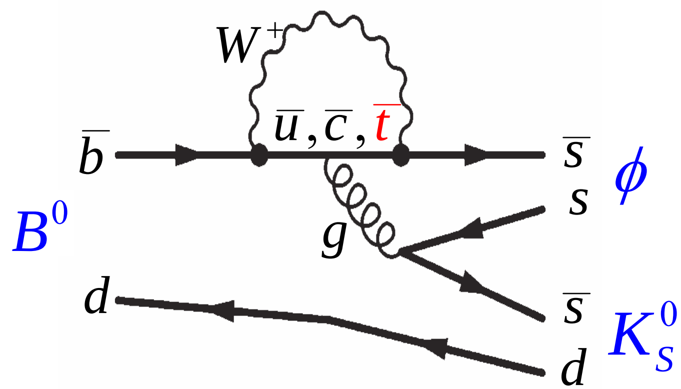


Remarkable validation of the CKM mechanism for both flavor violation and CP violation!

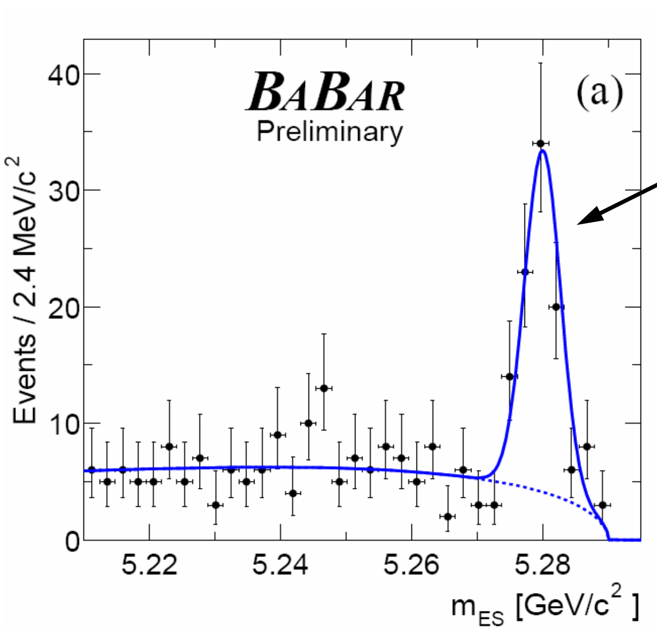
Do penguin decays agree with this picture??

$B^0 \rightarrow \phi K_S^0$ and sin 2β

Decay dominated by a single "gluonic penguin"
Feynman diagram: $b \rightarrow s\bar{s}s$



Decay rate 100X smaller than $J/\psi K_S$
→ small signal, large background

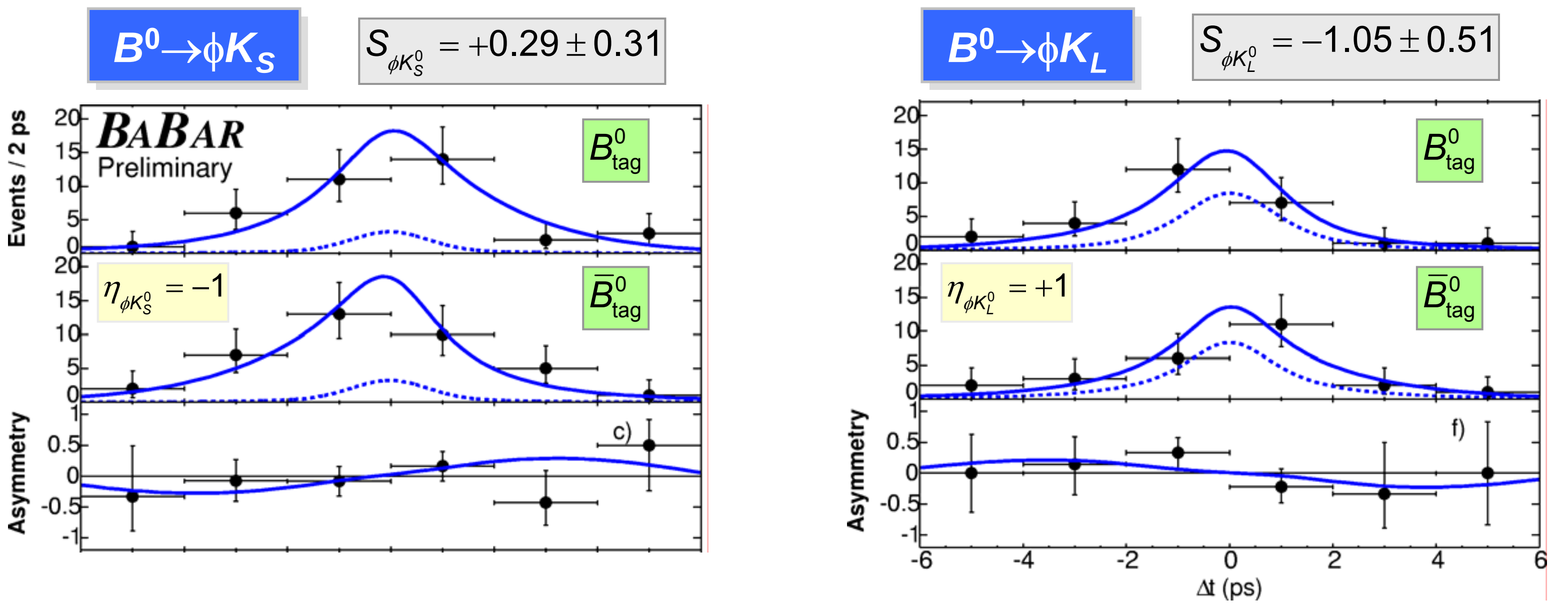


114 ± 12 $B^0 \rightarrow \phi K_S$ events out of ½ billion b quarks produced!

Time-dependent CP violating asymmetry A can be measured in the same way as $J/\psi K_S$

Same combination of CKM complex phases as $J/\psi K_S$ → same relation between A and sin 2β

$B^0 \to \phi K^0$ and sin 2β

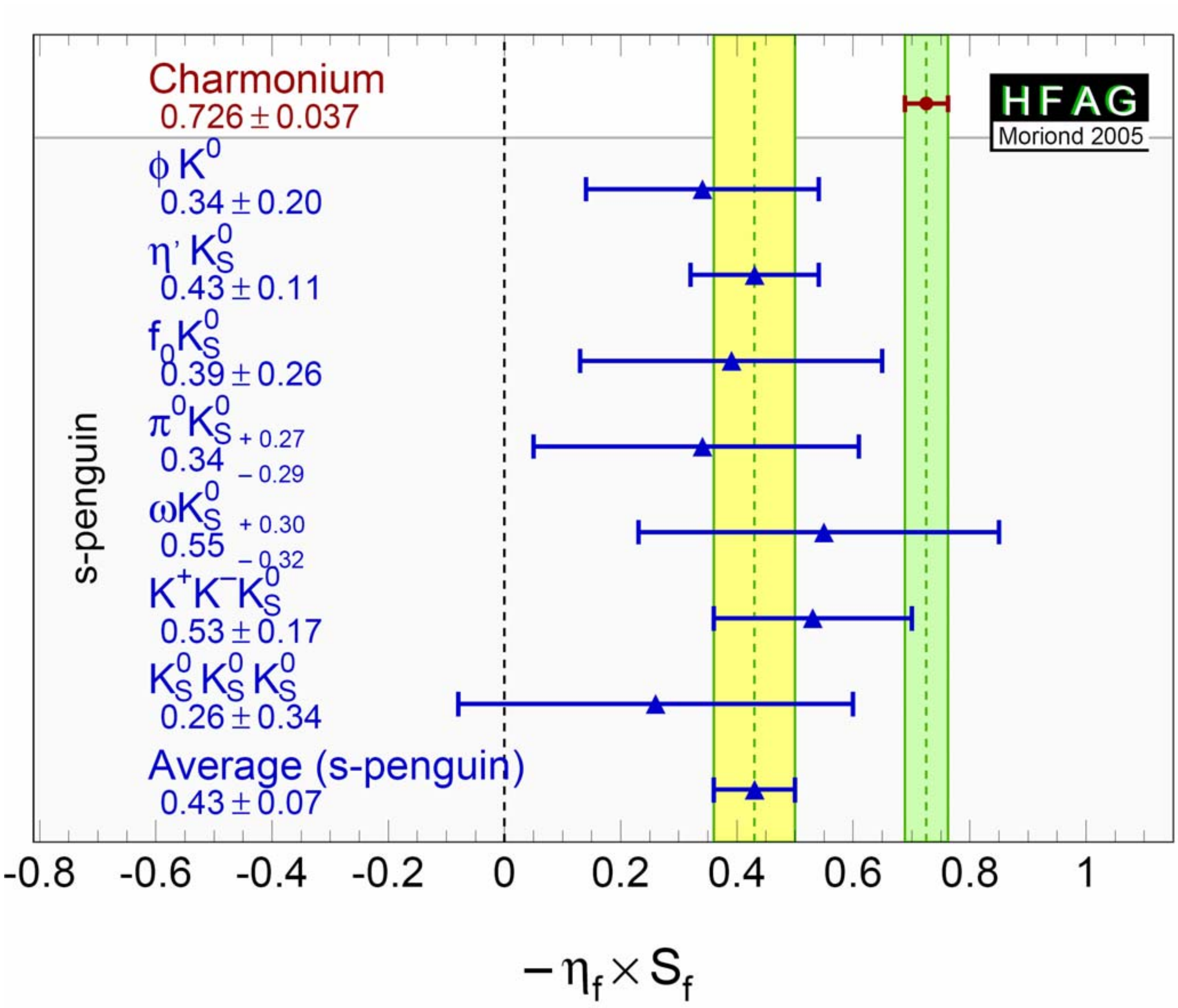


sin 2β = S(ϕ K^0) = +0.50 ± 0.25 ±0.07

vs. S(ψ K^0) = +0.72 ± 0.04 ±0.02

Penguin decay consistent with tree decays, about 1 σ low

Trees(green) vs. Penguins(yellow): World Average

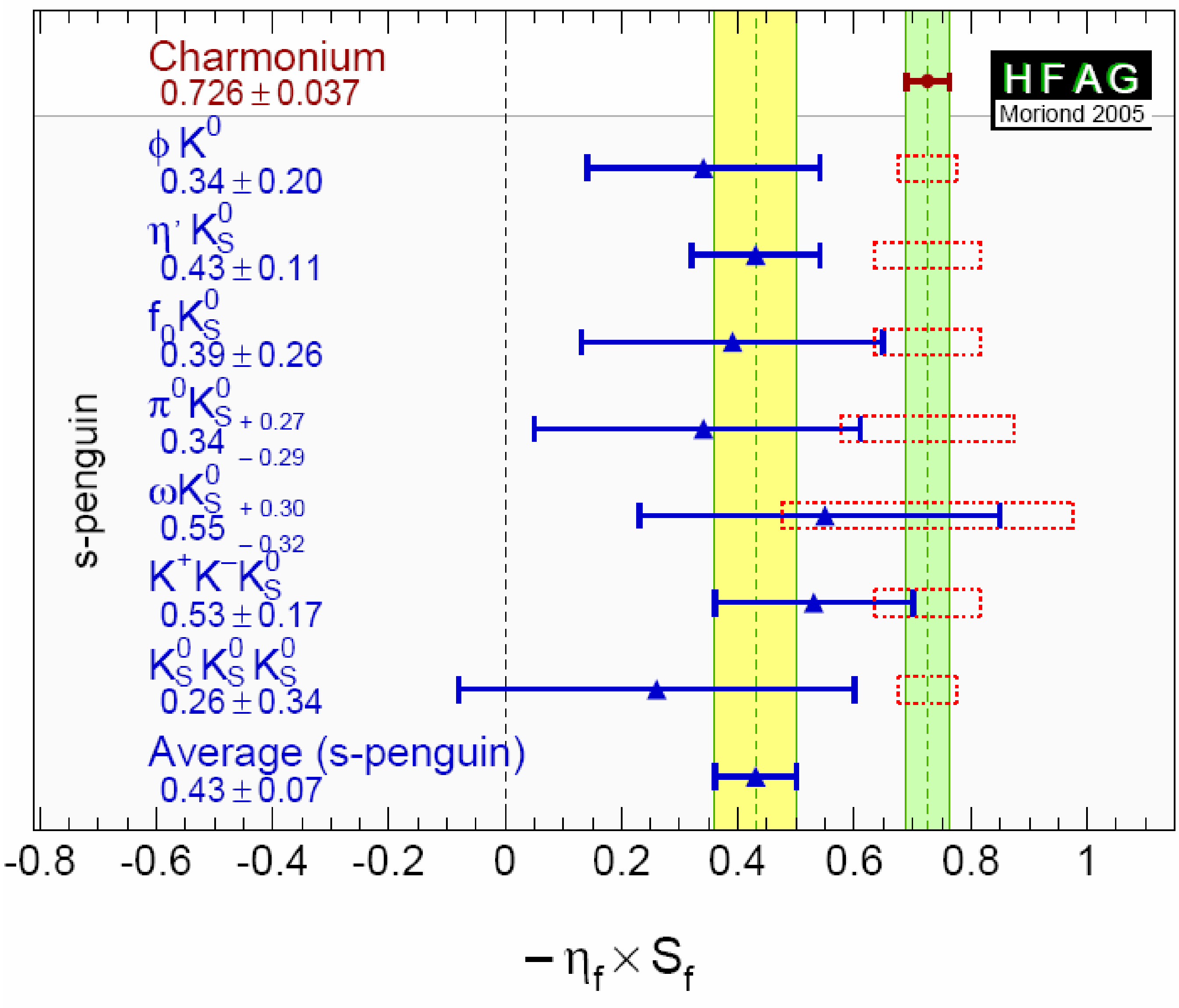


Averaging over many penguin decays:

World discrepancy with tree decays

= $-3.7\ \sigma$

Trees(green) vs. Penguins(yellow): World Average



Averaging over many penguin decays:

World discrepancy with tree decays

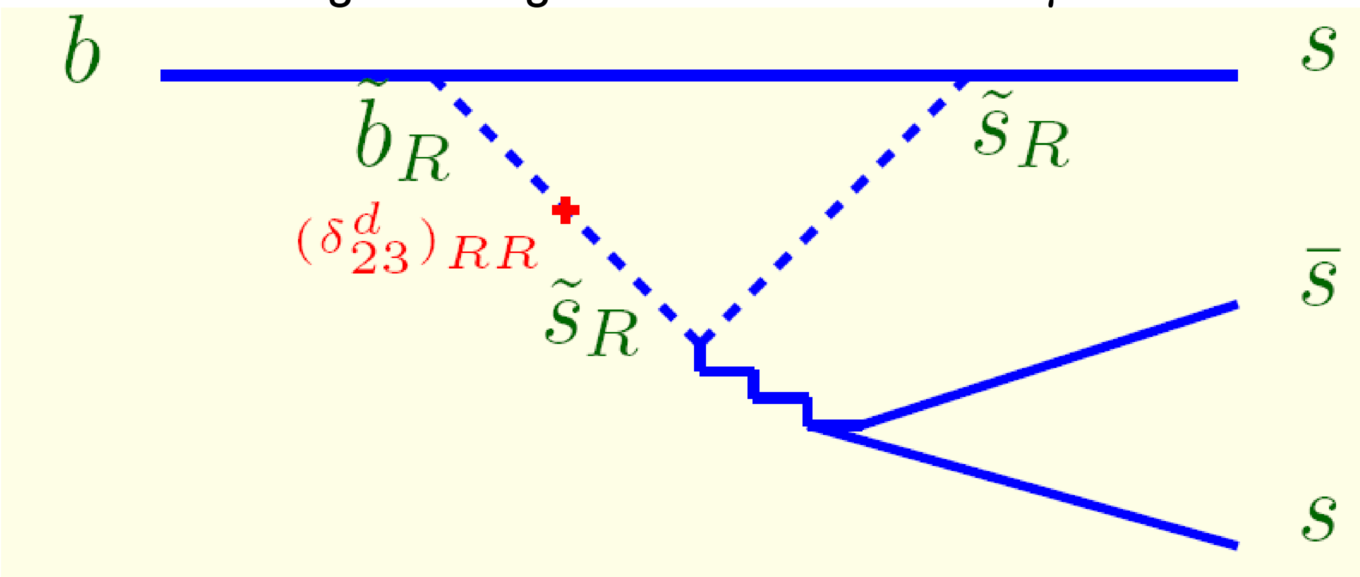
= $-3.7\ \sigma$

Red boxes: estimate from theory of errors due to neglecting other decay amplitudes

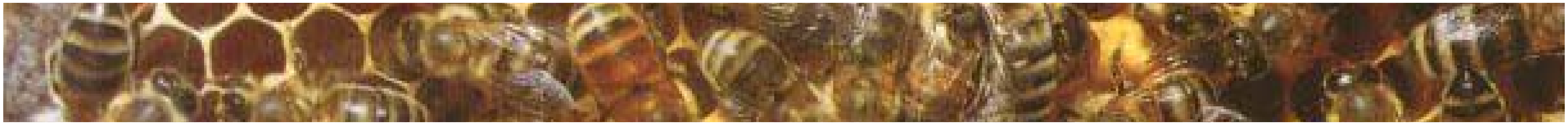
New Physics Scenarios

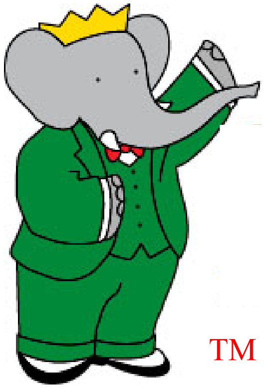
•**New physics at the electroweak scale generically introduces many new large flavor-violating or CP-violating couplings to quarks**

Ex: Right handed (b →s) squark mixing in gluino penguins could introduce a new phase in b → sss penguins
without affecting B mixing nor b → ccs nor b → sγ



Effects in gluon penguins should generically produce effects in <u>electroweak penguins</u>

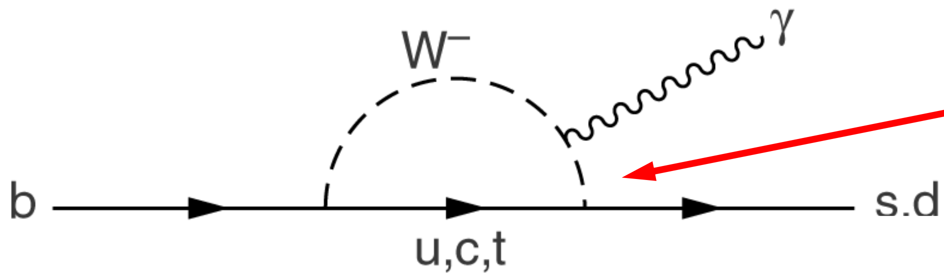




Photon Penguins

Photon Penguin Decays

Radiative penguin decays: $b \rightarrow s\gamma$ and $b \rightarrow d\gamma$ FCNC transitions



SM leading order = one EW loop

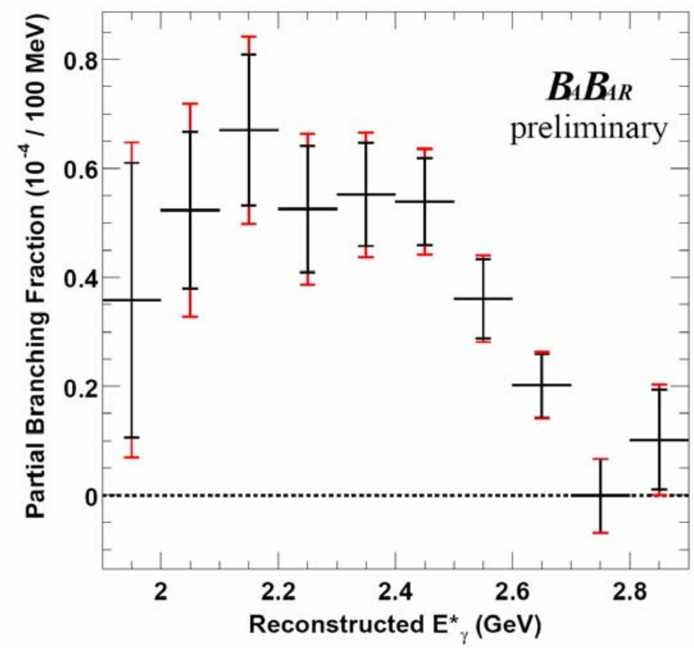
V_{ts}, V_{td} dependent

precise SM prediction:

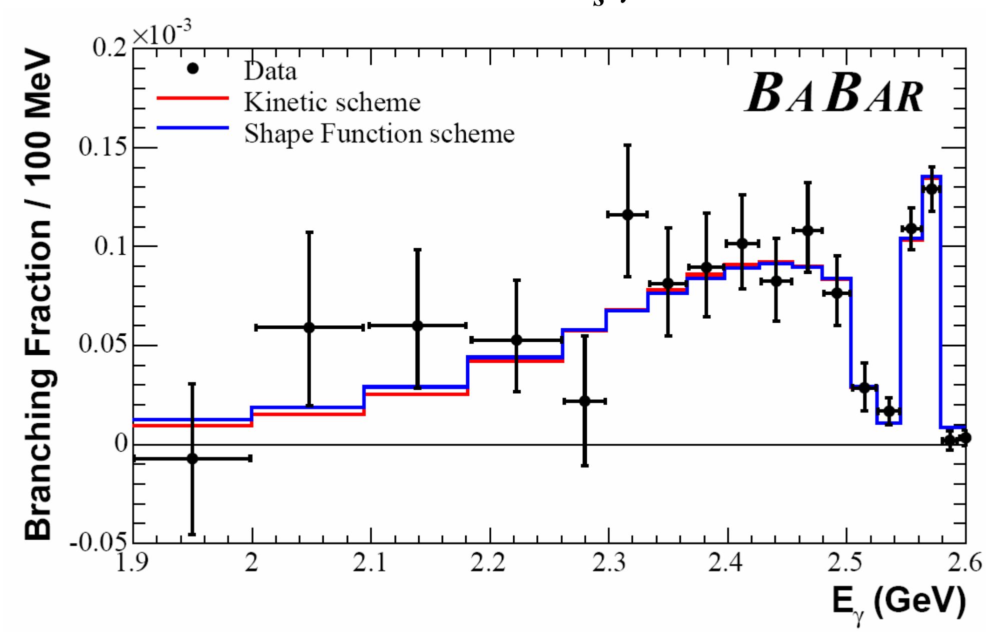
$BF(b\rightarrow s\gamma)_{TH} = 3.57 \pm 0.30 \times 10^{-4}$ (SM NLO)

Measured two different ways:

Inclusive photon spectrum



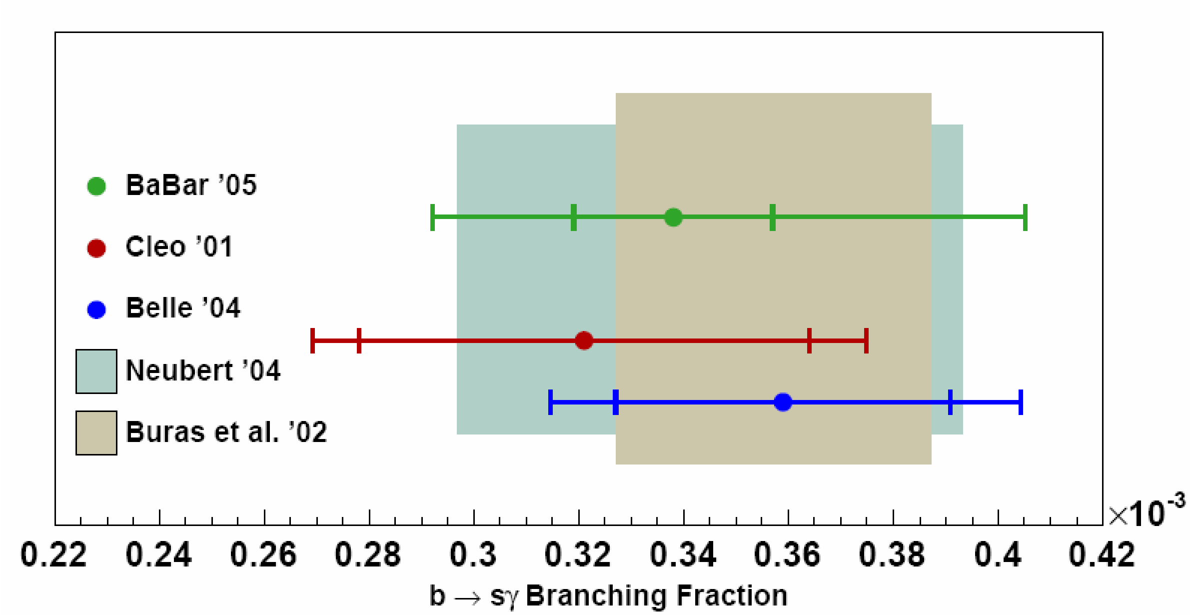
Sum of $B \rightarrow X_s\,\gamma$ exclusive states



$b \rightarrow s\,\gamma$ Branching Fractions

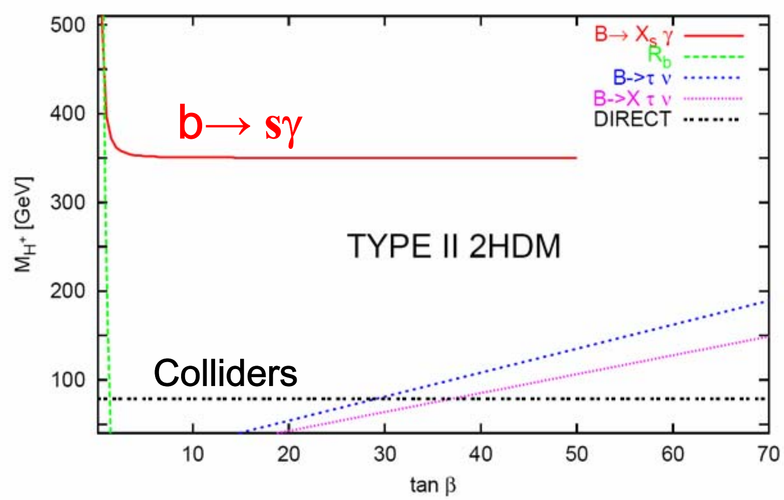
Excellent agreement with SM

Systematics, theory limited:
both could improve
to 5% precision



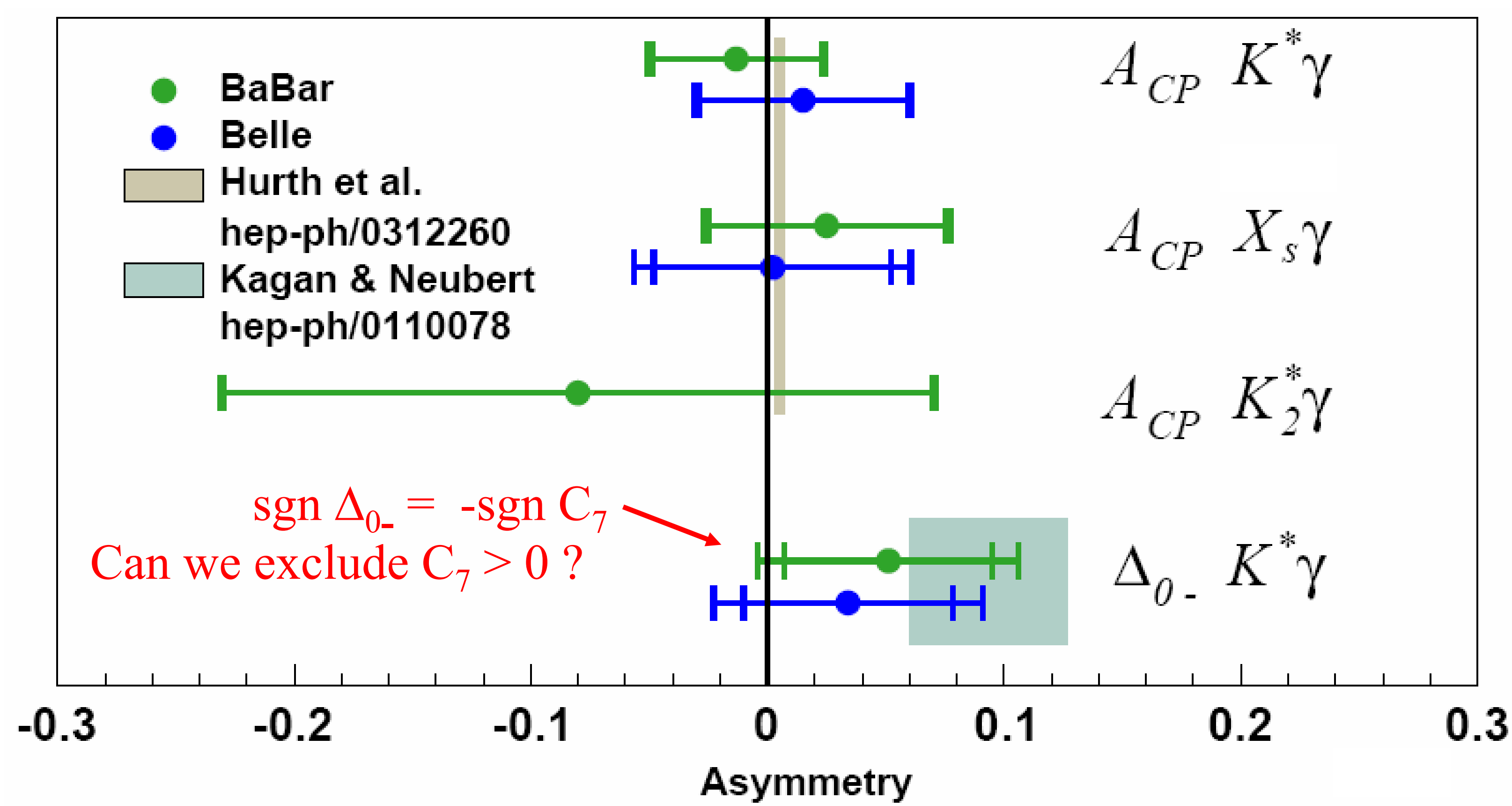
"Standard Candle" of flavor physics

Constrains numerous models
Strongest bound on H^+



$b \rightarrow s\,\gamma$ Asymmetries

•CP asymmetries consistent with SM (0.4%) at the ~5% level
•$K^*\gamma$ isospin asymmetry Δ_{0-} consistent with $C_7 < 0$
•Statistics limited up to ~1 ab^{-1}

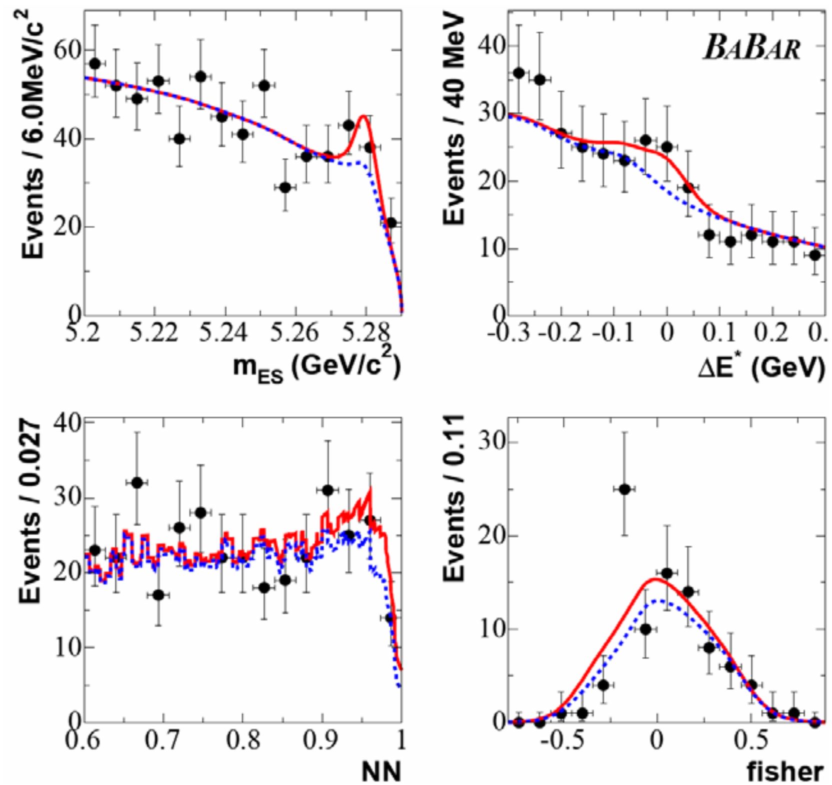


Search for b → d γ Penguins: B → ρ, ω γ

Simplest and most "common" b → dγ exclusive decays are $\rho\gamma$ and $\omega\gamma$:

$B^+ \rightarrow \rho^+ \gamma,\ \rho^+ \rightarrow \pi^+ \pi^0$
$B^0 \rightarrow \rho^0 \gamma,\ \rho^0 \rightarrow \pi^+ \pi^-$
$B^0 \rightarrow \omega \gamma,\ \omega \rightarrow \pi^+ \pi^- \pi^0$

$BF \approx BF\ K^*\gamma \times |V_{td}/V_{ts}|^2 \approx 1.6 \times 10^{-6}$



Huge backgrounds suppressed by
neural net
multi-dimensional likelihood fit
excellent K-pi separation

$BF = (0.6 \pm 0.3 \pm 0.1) \times 10^{-6}$

significance = 2.1σ

$\boxed{BF < 1.2 \times 10^{-6}\ \ 90\%\ CL}$

b→dγ CKM matrix constraint

SU(3) breaking of
form factors $\zeta^2 = 0.85 \pm 0.10$

weak annhilation
correction $\Delta R = 0.1 \pm 0.1$

Ali et al. hep-ph/0405075

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

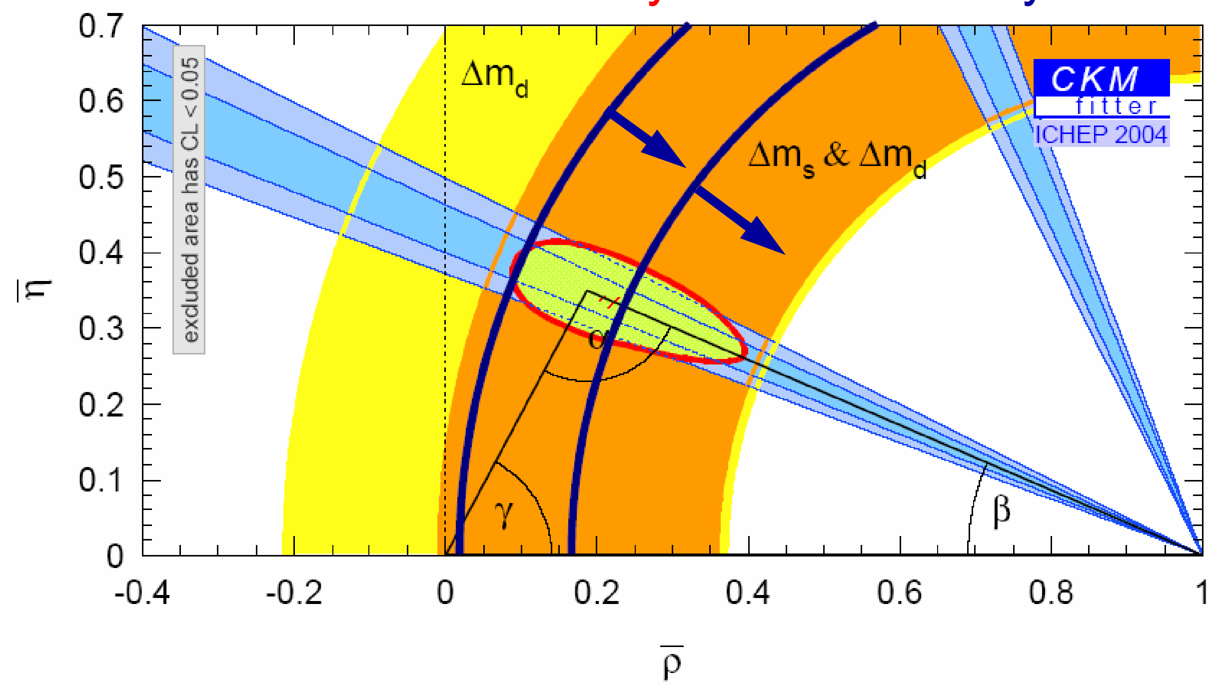
$(\zeta^2,\Delta R) = (0.75,0.00)$
theory error

$(\zeta^2,\Delta R) = (0.85,0.10)$
no theory error

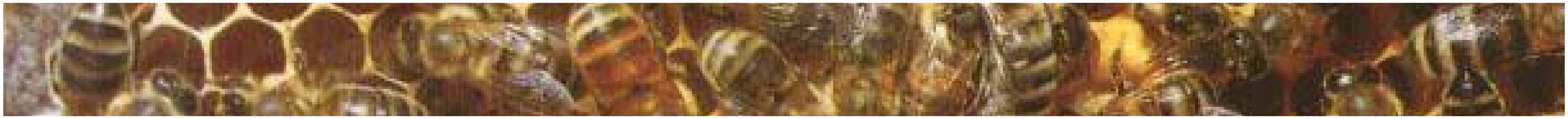
Penguin data now provide strong CKM constraint

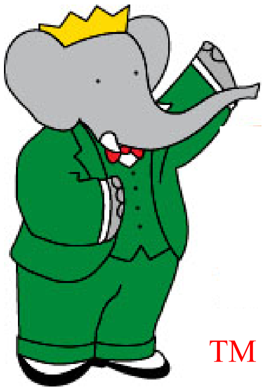
Direct competitor with B_s mixing

Reduction of theory errors needed!



ργ 95% C.L. BaBar allowed region (inside the blue arc)

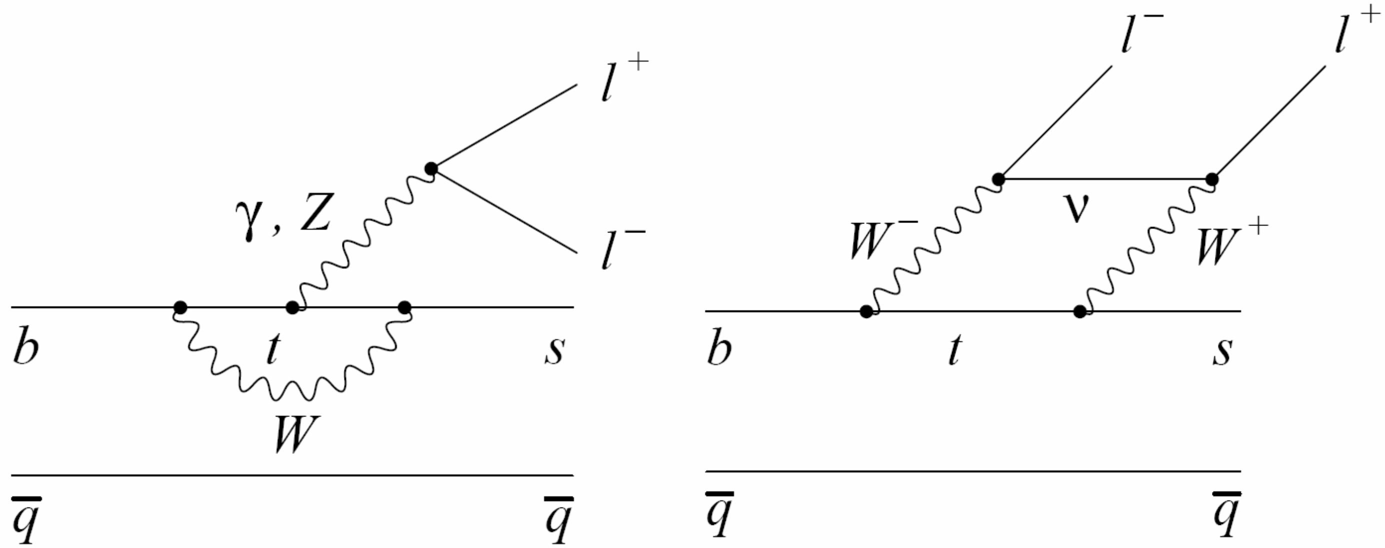




The Ultimate Electroweak Penguin Decay:

$$b \to s\, l^+ l^-$$

The Physics of $b \rightarrow s\, l\, l$



Three separate FCNC diagrams contribute→ multiple ways for new physics to interfere

Three body decay→ non-trivial kinematic and angular distributions sensitive to magnitude and phase of different amplitudes

Rare decay→ 10^{-6} branching fractions approach limits of B-factory sensitivity

The Physics of $b \to s\, l\, l$

$b \to s\, ll$ rate computed from operator product expansion with α_s and Λ/m_b corrections

general Hamiltonian of $b \to s$ transitions

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu)\, O_i(\mu)$$

Wilson coefficients C_i encode short distance physics (order α_s)

C_7 photon penguin ← from $b \to s\, \gamma$

C_9 (mostly) Z penguin

C_{10} (mostly) W box ← unique to $b \to s\, ll$

$$\mathcal{M}(b \to s\ell^+\ell^-) = \frac{G_F \alpha}{\sqrt{2}\pi} V_{ts}^* V_{tb} \left\{ C_9^{\rm eff} \left[\bar{s}\gamma_\mu L b\right] \left[\bar{\ell}\gamma^\mu \ell\right] + C_{10} \left[\bar{s}\gamma_\mu L b\right] \left[\bar{\ell}\gamma^\mu \gamma_5 \ell\right] \right.$$

$$\left. -2\hat{m}_b C_7^{\rm eff} \left[\bar{s} i \sigma_{\mu\nu} \frac{\hat{q}^\nu}{\hat{s}} R b\right] \left[\bar{\ell}\gamma^\mu \ell\right] \right\} .$$

$$\boxed{\mathrm{BF}(b \to s\mu\mu) = 4.2 \pm 0.7\ 10^{-6}}$$

15% uncertainty in inclusive rate

The Physics of $B \to K\,l\,l,\ K^*l\,l$

Dominant exclusive decays are $B \to Kll,\ K^*ll$

$K\,ll,\ K^*ll$ rates computed from (perturbative) $b \to s\,ll$ amplitude convolved with (non-perturbative) $B \to K,\ K^*$ form factors for each O_i

$\langle K(p)|\bar{s}\gamma_\mu b|B(p_B)\rangle$ et al.

3 $B \to K$ form factors

$$\boxed{\text{BF}(B \to K\mu\mu) = 0.35 \pm 0.12\ 10^{-6}}$$

$\langle K^*(p)|(V-A)_\mu|B(p_B)\rangle$ et al.

7 $B \to K^*$ form factors

$$\boxed{\text{BF}(B \to K^*\mu\mu) = 1.2 \pm 0.4\ 10^{-6}}$$

30% form factor uncertainty
(Light-cone QCD sum rules)

Exclusive branching fractions not a precision test of the SM →

Asymmetries and distributions are higher precision tests
(form factor uncertainty cancels)

EX: Direct CP asymmetry $A_{CP} \approx 10^{-4}$ in SM, could be order 1 beyond SM

Dilepton Mass Distribution

Dilepton mass distribution probes Wilson coeffcients

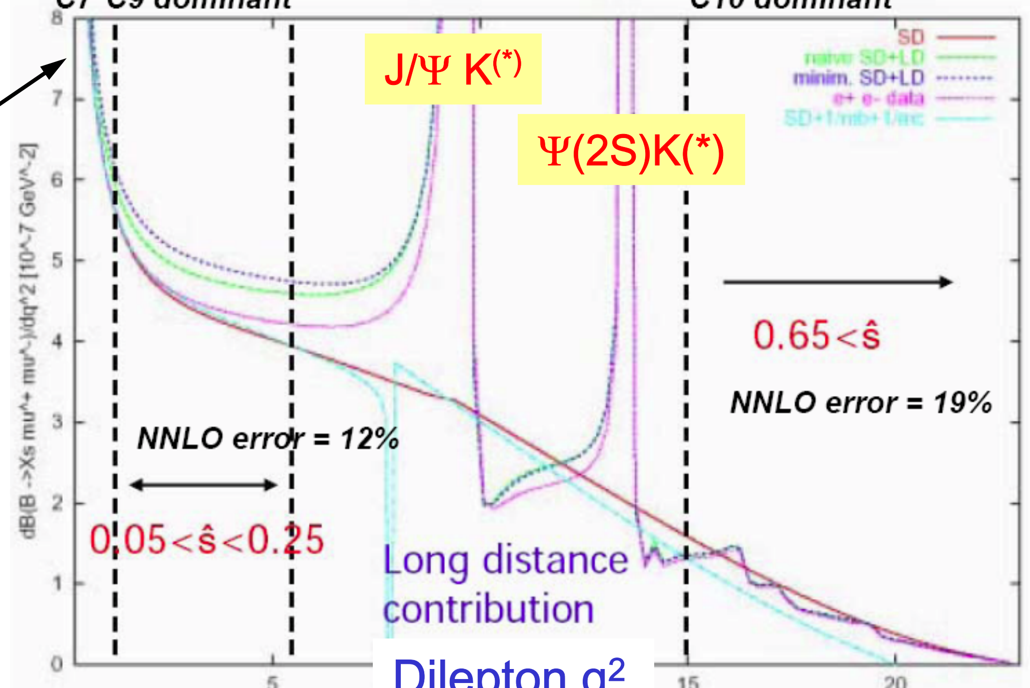
Pole at $q^2 \approx 0$ for K*ee (nearly on-shell B→K*γ)

$$\frac{\mathcal{B}(B\to K^*e^+e^-)}{\mathcal{B}(B\to K^*\mu^+\mu^-)} = 1.33$$

Huge long-distance contribution from B →charmonium decays

lower lepton momenta
*C7*C9 dominant*

higher lepton momenta
C10 dominant



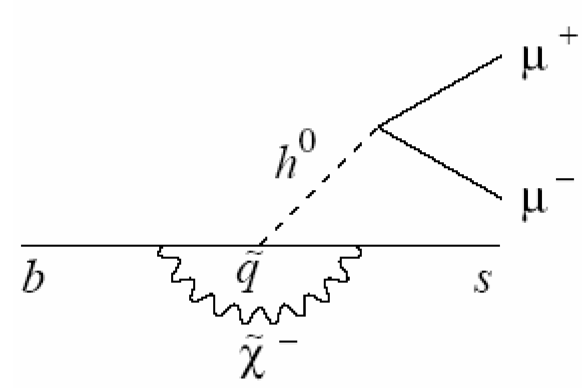
C9,C10 dominant at high s, C7 dominant at low s, sign of C7 matters

Generally decreases with s

$$\frac{d\Gamma(b\to X_s\ell^+\ell^-)}{d\hat{s}} = \left(\frac{\alpha_{em}}{4\pi}\right)^2 \frac{G_F^2 m_{b,pole}^5 \left|V_{ts}^*V_{tb}\right|^2}{48\pi^3}(1-\hat{s})^2 \times$$
$$\left((1+2\hat{s})\left(\left|\tilde{C}_9^{\rm eff}\right|^2+\left|\tilde{C}_{10}^{\rm eff}\right|^2\right)+4\left(1+2/\hat{s}\right)\left|\tilde{C}_7^{\rm eff}\right|^2+12{\rm Re}\left(\tilde{C}_7^{\rm eff}\tilde{C}_9^{\rm eff*}\right)\right)$$

SUSY Higgs physics at a B Factory

$b \to s\mu\mu$ = $B_s \to \mu\mu$ turned sideways



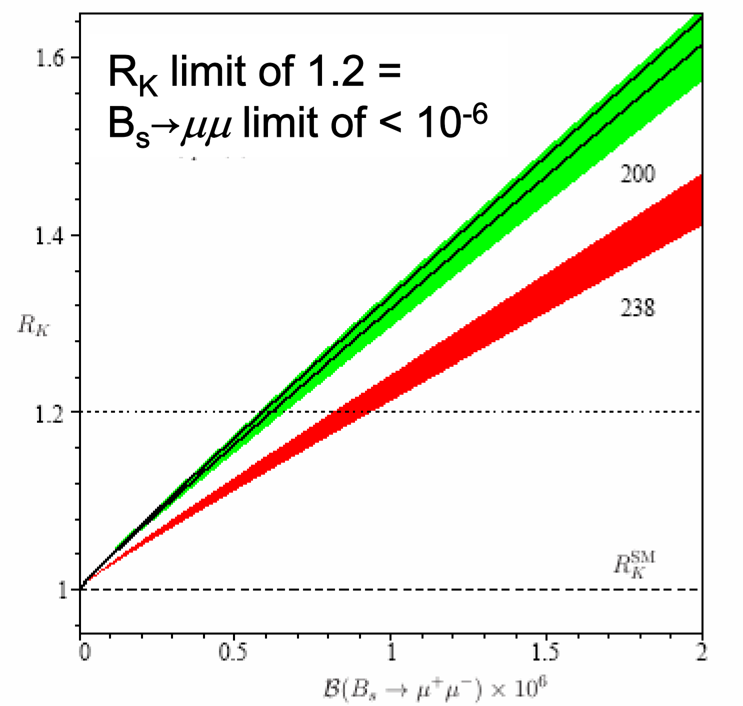
Sensitive to "neutral Higgs penguin"
for SUSY with large tan β

Ratio R(K) = BF($B \to K\mu\mu$)/BF($B \to Kee$)
isolates Yukawa enhancement in muon mode

In SM, equal to unity with very high precision

Also contributes to R(K*)
(=1 above the photon pole)

Complementary to Tevatron $B_s \to \mu\mu$ limit



Hiller & Kruger hep-ph/0310219

Forward-Backward Asymmetry

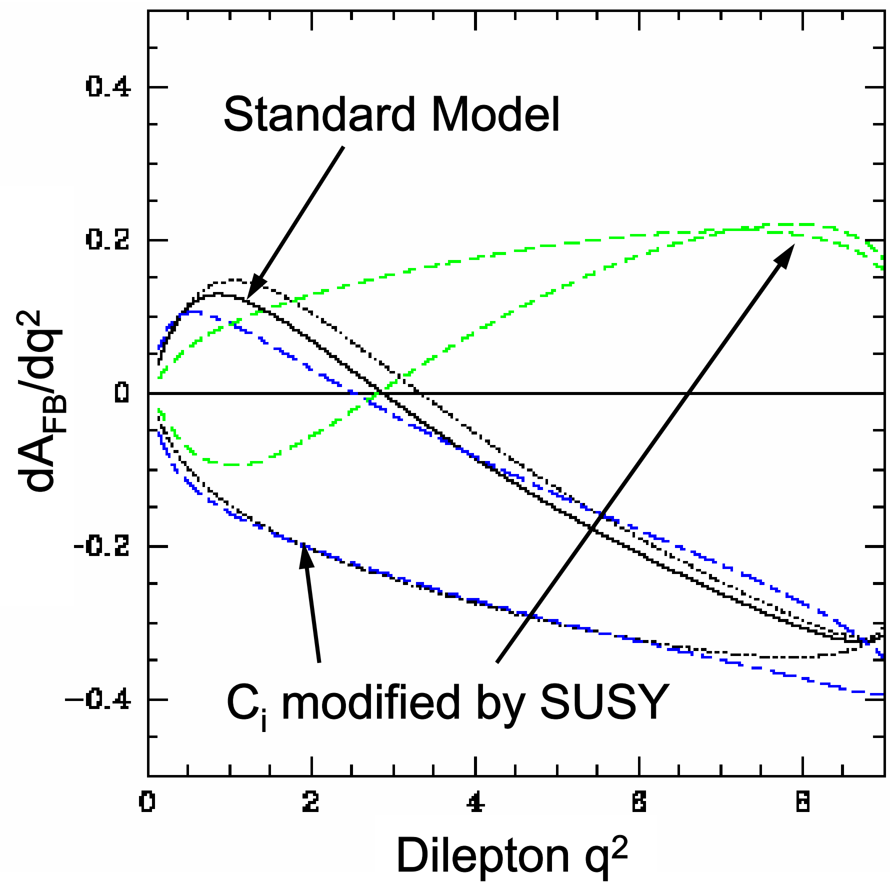
Angular asymmetry of lepton (anti-lepton) angle with B (anti-B) momentum in dilepton rest frame

Varies with dilepton q^2

Theoretically clean probe of relative size and phase of $C_7/C_9/C_{10}$

Can be dramatically modified by new physics

Zero of A_{FB} provides simple, precise (15%) relation between C_7 and C_9 (for LHCb)



$$\frac{\mathrm{dA_{FB}}}{\mathrm{d}q^2} \propto -\widetilde{C}_{10}^{\mathrm{eff}}\left[\mathrm{Re}(\widetilde{C}_9^{\mathrm{eff}})VA_1 + \frac{m_b}{q^2}\widetilde{C}_7^{\mathrm{eff}}(VT_2(1-m_{K^*}/m_B)+A_1T_1(1+m_{K^*}/m_B))\right]$$

$B \rightarrow K\,l\,l,\ K^{*}l\,l$ Measurement

Find ~50 needles in a haystack of 500 million B's + 2 billion light quarks

Full B decay reconstruction to charged tracks: (brem photons added for ee modes)

$B \rightarrow Kll$	
$B^+ \rightarrow K^+ e^+ e^-$	$B^0 \rightarrow K_s e^+ e^-$
$B^+ \rightarrow K^+ \mu^+ \mu^-$	$B^0 \rightarrow K_s \mu^+ \mu^-$
	$K_s \rightarrow \pi^+ \pi^-$

$B \rightarrow K^*ll$	
$B^+ \rightarrow K^{*+} e^+ e^-$	$B^0 \rightarrow K^{*0} e^+ e^-$
$B^+ \rightarrow K^{*+} \mu^+ \mu^-$	$B^0 \rightarrow K^{*0} \mu^+ \mu^-$
$K^{*+} \rightarrow K_s \pi^+$	$K^{*0} \rightarrow K^+ \pi^-$

BLIND ANALYSIS

Strict particle ID requirements

Veto “peaking” backgrounds of B decays similar to signal

Construct multivariate discriminants to suppress “combinatorial” backgrounds

Signal yield extraction via multi-dimensional unbinned maximum likelihood fit

B Meson Reconstruction at Υ(4s)

"Killer App" of the Υ(4S): precision kinematic constraints

$$\boxed{e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}}$$

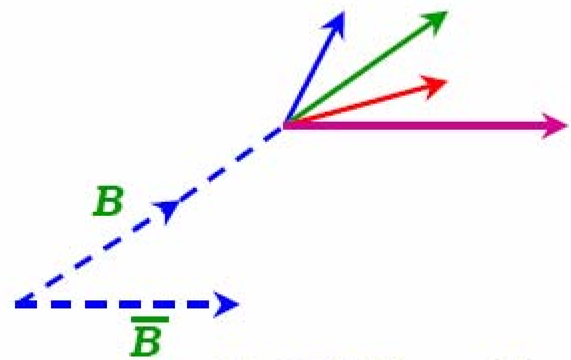
$$m_{ES} = \sqrt{E_{beam}^{*\,2} - (\sum_i p_i^*)^2}$$

$$\Delta E = \sum_i \sqrt{p_i^{*\,2} + m_i^2} - E_{beam}^*$$

Typical resolutions:

$\sigma(m_{ES}) \approx$ 2.5 MeV

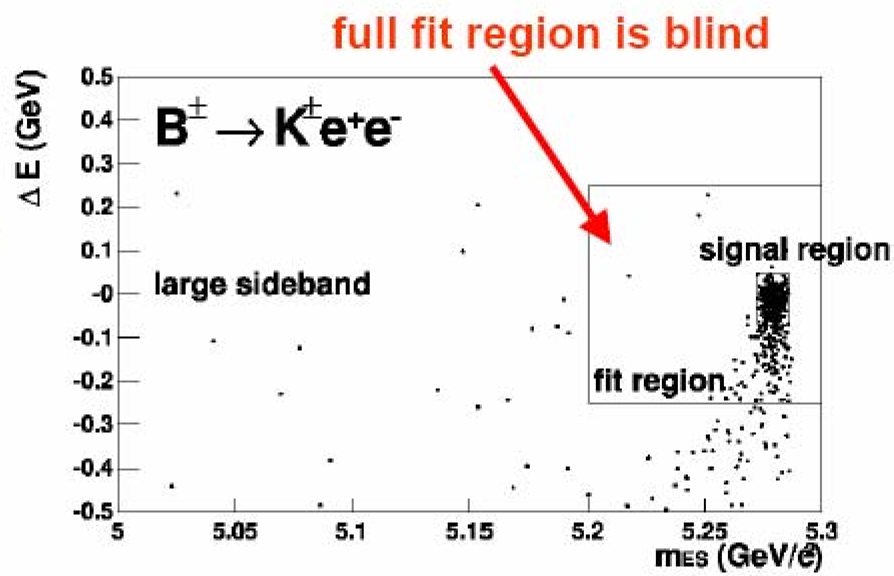
$\sigma(\Delta E)$ $\approx$ 25 - 40 MeV



(*) ≡ measured in Υ(4S) rest frame

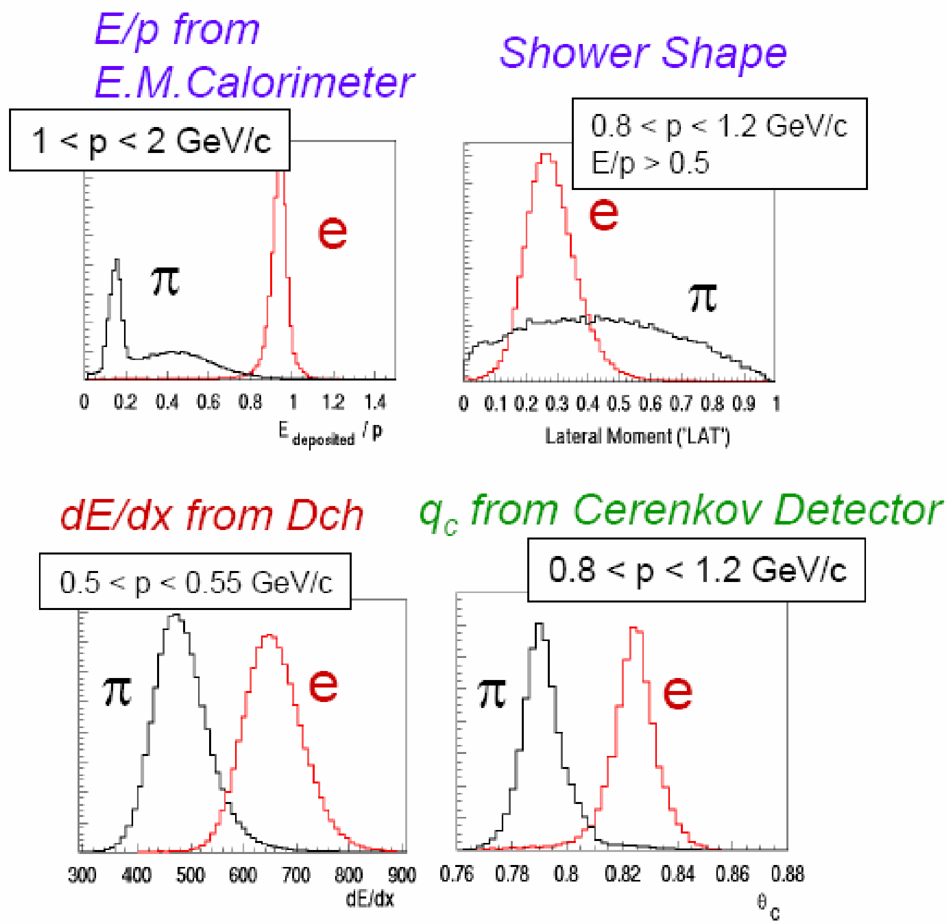
$E_i \longleftrightarrow E^*_{beam}$ ➔ Improve resolution

- Define 3 regions in ΔE, m_{ES} plane:
  - A – Signal region
  - B –Fit region
  - C – Large Sideband region



Particle Identification

- Electrons – p* > 0.3 GeV
  - •shower shapes in EMC
  - •E/p match
- Muons – p* > 0.7 GeV
  - Penetration in iron of IFR
- Kaons
  - dE/dx in SVT, DCH
  - θ_C in DRC

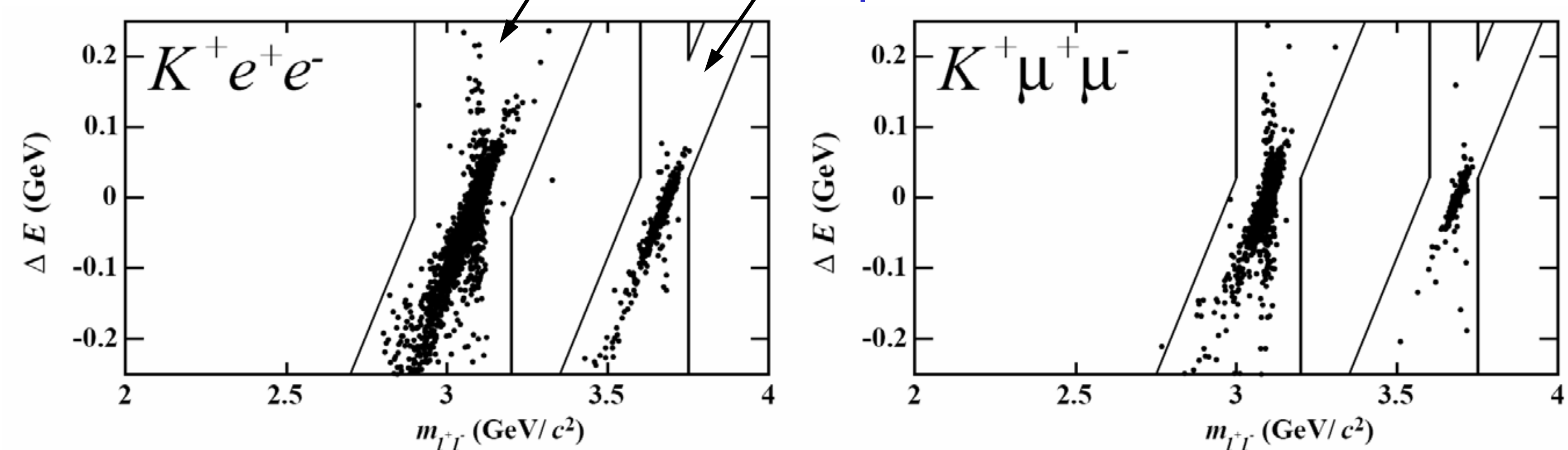


μ, K fake rates < 2%
e fake rate < 0.1 %

Huge control samples for efficiency and misid studies

Charmonium Background

Huge (100 times signal) J/ψ K(*) and ψ(2S) K(*) background eliminated with 2D veto on dilepton mass and ΔE



Mismeasured mass correlated with ΔE

Bigger veto for electron modes (Bremsstrahlung tail)

Energy loss and tracking response to leptons well-calibrated in MC (checked with huge radiative Bhabha and $\mu\mu$ samples)

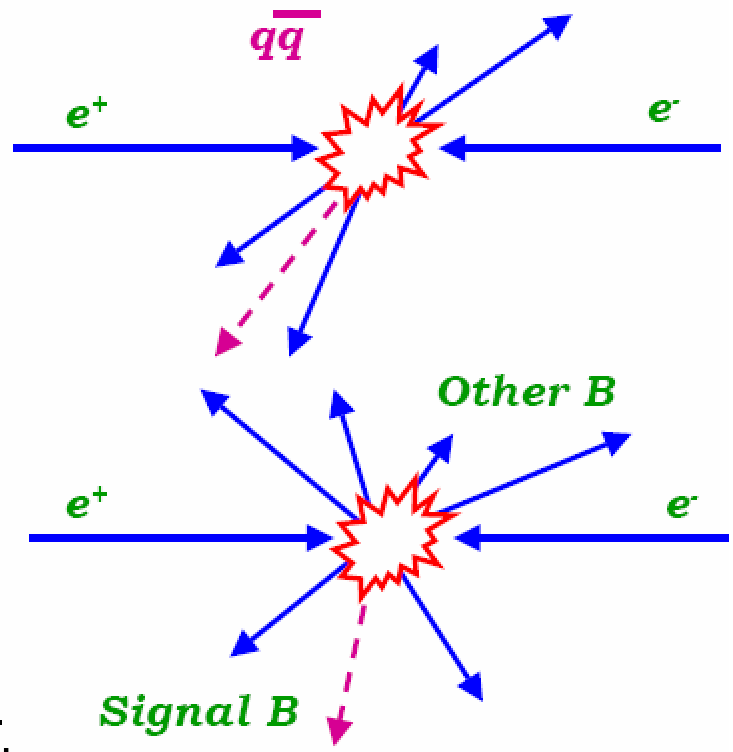
Reduced to < 1 event expected per mode

Veto sample is huge control sample for validating signal efficiency!

Continuum Background Suppression

- **Continuum suppression: exploit fact that continuum events are more jet-like than BB events**
  - R_2: W-F 2nd moment
  - Cos θ_{thrust}: angle of candidate thrust axis
  - Cos θ_B : angle of B in CM
  - m_{Kl} : Kl invariant mass
- **Combine optimally using Fisher discriminant**

  linear combination of variables for which multi-dimensional gaussian dist. of signal and background are maximally separated

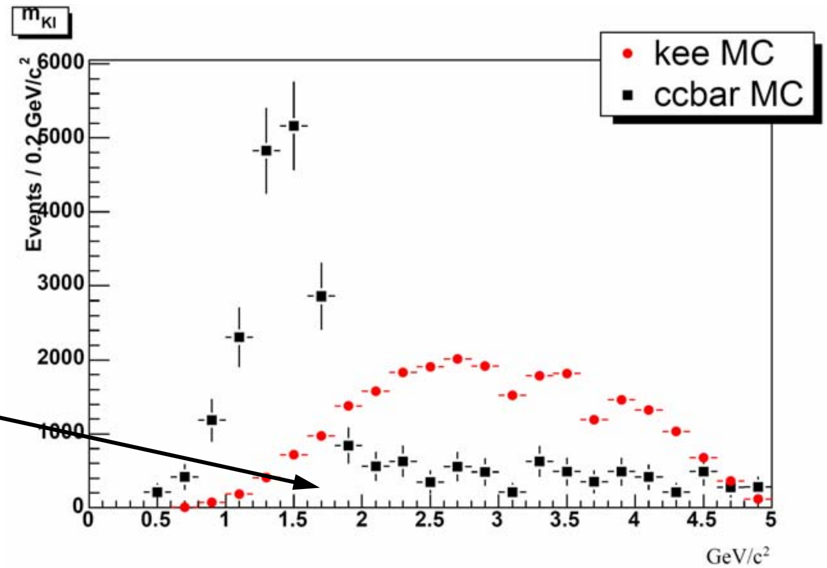


Signal shape from MC; background shape from off-resonance data

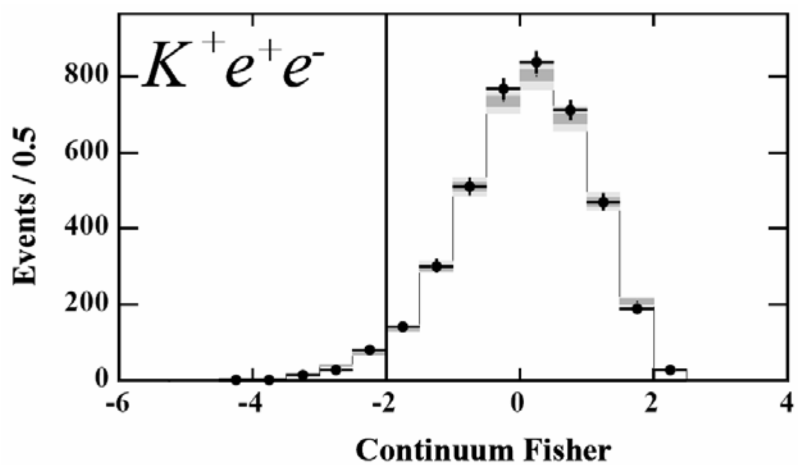
Continuum Suppression

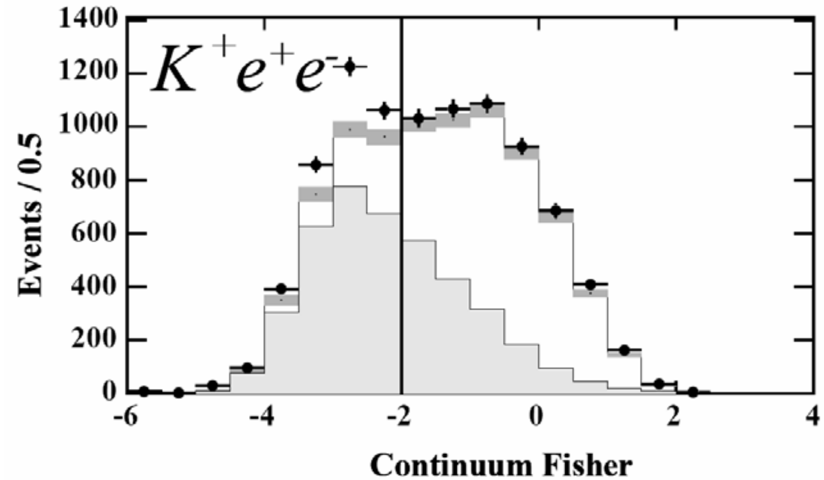
Kaon-lepton mass in Fisher reduces large background from semileptonic D decays

Background cuts off at D mass



Large charmonium samples validate signal shape; sidebands validate background shape





Semileptonic B Decay Background

Large fraction (10%) of B's decay to leptons→ large "combinatorial" B background

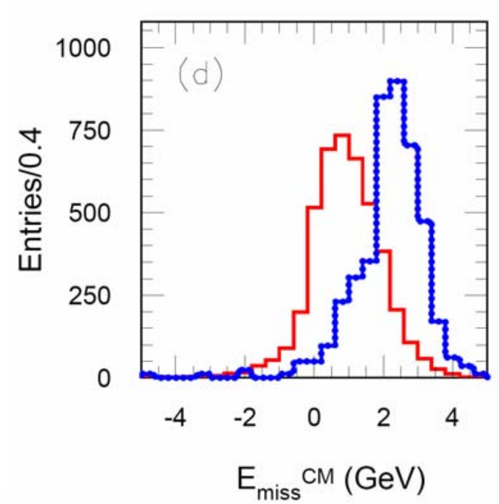
Separation of B background from signal using likelihood function (product of shapes):

Missing energy

B production angle

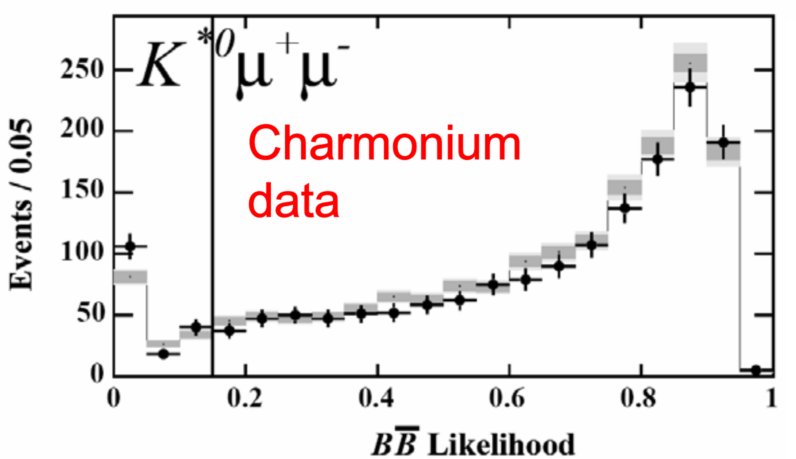
Vertex probability

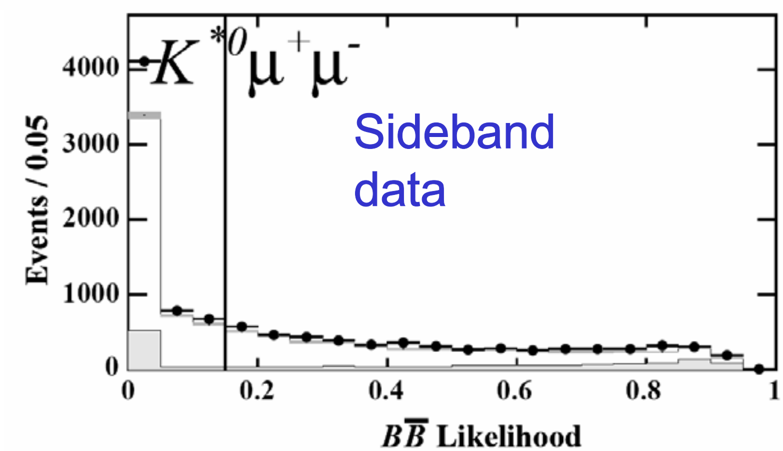
Likelihood shapes from MC



Signal vs.
Background
missing energy

Cut values scanned
For maximal $S^2/(S+B)$





Hadronic B Decay Background

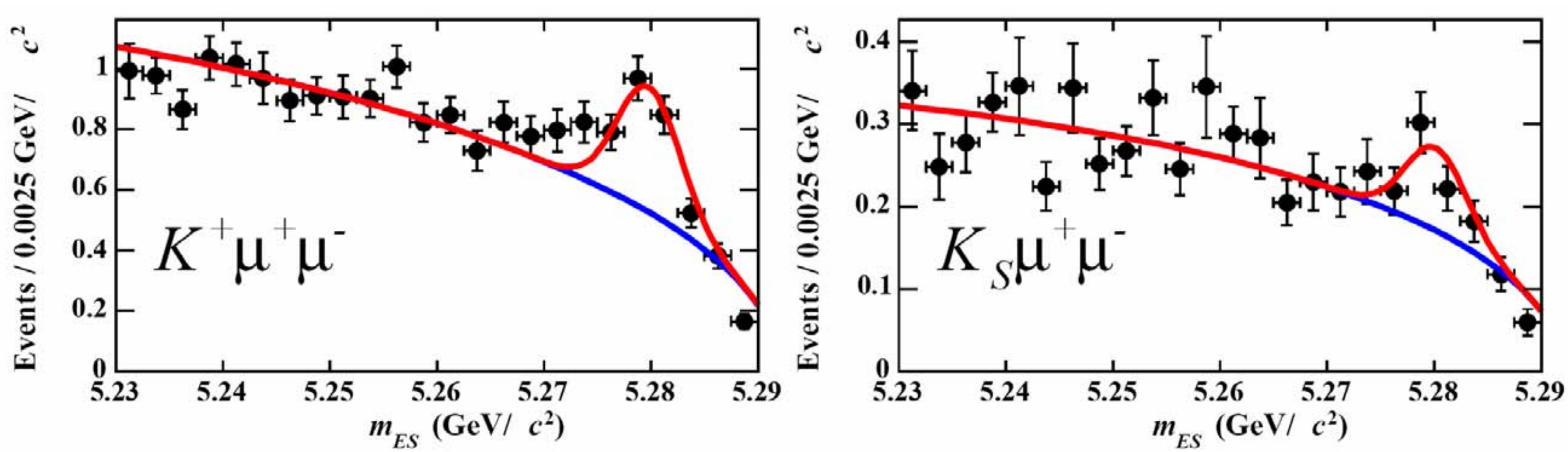
B decays to hadrons misidentified as leptons will have same kinematics as signal
Electron modes: misid ~0.1%, negligible
Muon modes: misid ~1-2% for pions and kaons
Misid rate calibrated from large $B \rightarrow D^* \pi$, $D^* \rightarrow D \pi$, $D \rightarrow K \pi$ samples

$K \mu\mu$, $K^* \mu\mu$ events with $K\mu$ mass consistent with D decay vetoed

Non-resonant $B \rightarrow K^{(*)} \pi\pi$ background estimated from data:

Convolve misid rates with $B \rightarrow K^{(*)} \mu\pi$ events in data

Extract background from a binned fit to m_{ES} distribution



Maximum Likelihood Fit

Unbinned maximum likelihood fit of (m_{ES}, ΔE, $m(K\pi)$): maximizes LH function

$$\mathcal{L} = \frac{e^{-(n_{\rm sig}+n_{B\bar{B}}+n_{\rm cont})}}{N!}\prod_{i=1}^{N}(n_{\rm sig}P_{\rm sig}+n_{B\bar{B}}P_{B\bar{B}}+n_{\rm cont}P_{\rm cont})_i$$

Components: signal, peaking backgrounds, combinatorial background

$P_i = P_i(m_{ES})^*P_i(\Delta E)^*P_i(m(K\pi))$ (negligible correlation)

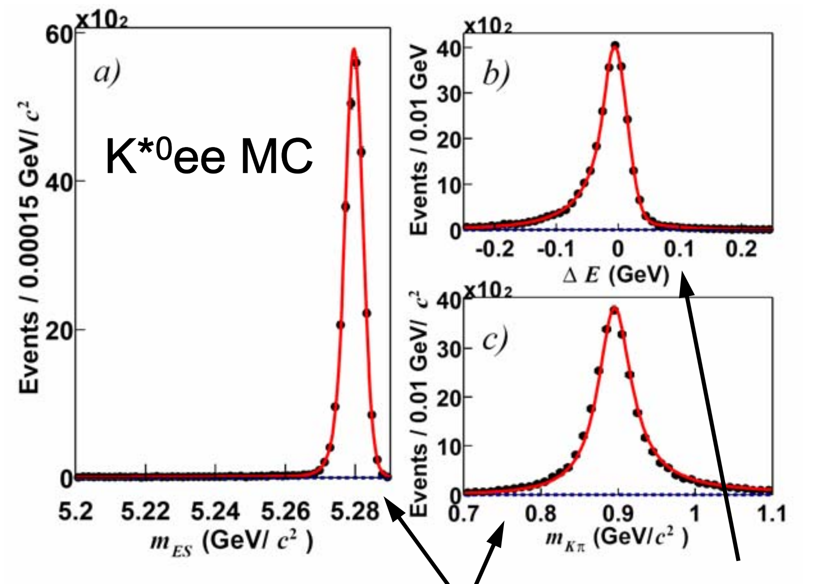
Signal shape parameters fixed from charmonium data

Signal yield, background yield and background shape parameters are floating in fit

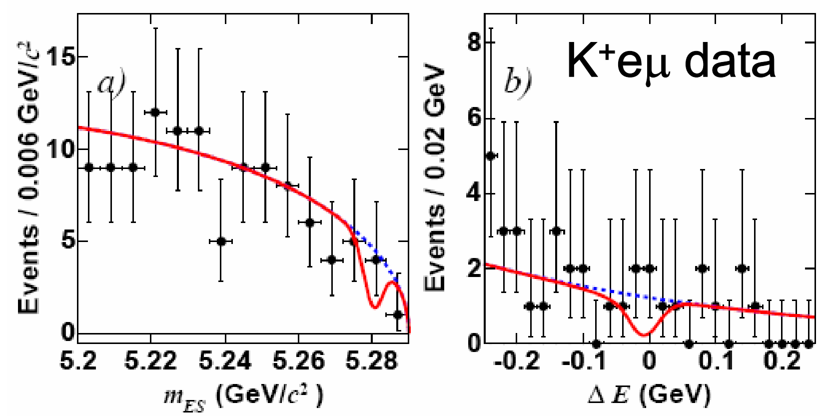
m_{ES}: "ARGUS function" models phase space cutoff at M_B

ΔE: linear or quadratic

$M(K\pi)$: quadratic (+ small 5% K* fraction)



Signal shapes (narrow peaks)

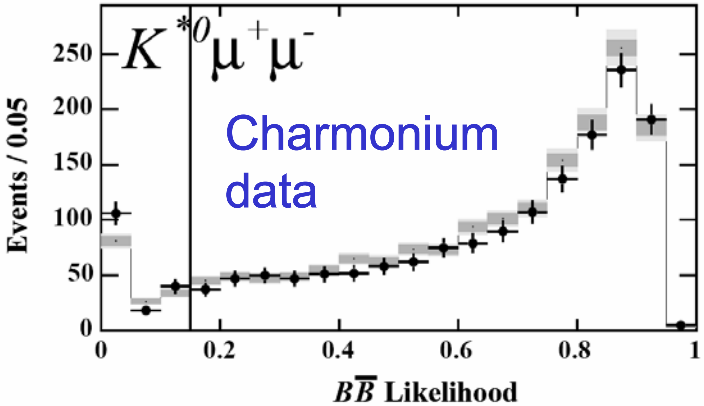


Background shapes (not peaked)

Branching Fraction Systematics

Measure single cut efficiencies for particle ID, Fisher, likelihood directly from data using vetoed charmonium events

Ex: B background likelihood cut, data vs. MC



Mode	Data Eff.	SP5/6 Eff.	$C = (Data/MC)$
$B^+ \to K^+ e^+ e^-$	$(91.58 \pm 0.46)\%$	$(91.57 \pm 0.22)\%$	$(100.0 \pm 0.6)\%$
$B^+ \to K^+ \mu^+ \mu^-$	$(90.84 \pm 0.51)\%$	$(93.55 \pm 0.23)\%$	$(97.1 \pm 0.6)\%$
$B^0 \to K^0_S e^+ e^-$	$(91.17 \pm 0.86)\%$	$(92.56 \pm 0.05)\%$	$(98.5 \pm 0.9)\%$
$B^0 \to K^0_S \mu^+ \mu^-$	$(92.76 \pm 0.90)\%$	$(94.63 \pm 0.05)\%$	$(98.0 \pm 0.9)\%$
$B^0 \to K^{*0} e^+ e^-$	$(88.42 \pm 0.71)\%$	$(88.82 \pm 0.29)\%$	$(99.6 \pm 0.9)\%$
$B^0 \to K^{*0} \mu^+ \mu^-$	$(91.01 \pm 0.75)\%$	$(92.65 \pm 0.32)\%$	$(98.2 \pm 0.9)\%$
$B^+ \to K^{*+} e^+ e^-$	$(88.68 \pm 1.40)\%$	$(86.75 \pm 0.36)\%$	$(102.2 \pm 1.7)\%$
$B^+ \to K^{*+} \mu^+ \mu^-$	$(86.66 \pm 1.71)\%$	$(85.52 \pm 0.48)\%$	$(101.3 \pm 2.1)\%$

Systematic uncertainty on cut efficiency reduced to a few percent

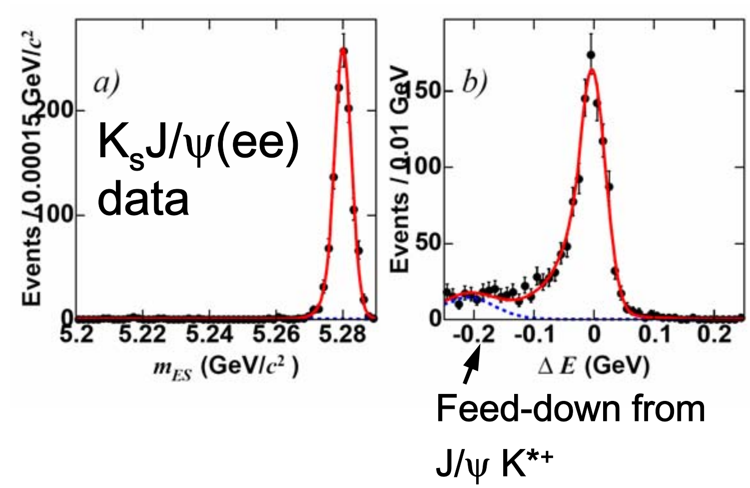
Dominant systematic on efficiency (4-7%) is model dependence
(form factor models change q^2 distribution)

Fit systematics: change in signal yield from choices of

- Signal shape parameters (m_{ES}, ΔE, $m(K\pi)$ mean and width)
- Background shape scheme (introduce correlations, higher polynomial terms)
- Peaking background mean rates (total varied within uncertainty)

Fit Validation: Charmonium

Mode	A_{CP} (%)	$\mathcal{B}/10^{-6}$	PDG $\mathcal{B}/10^{-6}$
$B^+ \to K^+e^+e^-$	-0.2 ± 1.5	1016 ± 15	1000 ± 40
$B^+ \to K^+\mu^+\mu^-$	0.4 ± 1.8	1038 ± 22	1000 ± 40
$B^0 \to K^0_S e^+e^-$	—	869 ± 26	850 ± 50
$B^0 \to K^0_S \mu^+\mu^-$	—	895 ± 32	850 ± 50
$B^0 \to K^{*0}e^+e^-$	1.9 ± 2.0	1346 ± 28	1310 ± 70
$B^0 \to K^{*0}\mu^+\mu^-$	3.0 ± 2.4	1326 ± 33	1310 ± 70
$B^+ \to K^{*+}e^+e^-$	1.4 ± 3.8	1404 ± 58	1350 ± 100
$B^+ \to K^{*+}\mu^+\mu^-$	0.2 ± 4.7	1558 ± 76	1350 ± 100



<u>Test fit procedure on charmonium</u>

J/ψ K(*) branching fractions agree with PDG

A_{CP} consistent with 0 (bounds detector bias)

Signal and background well-modeled by PDFs

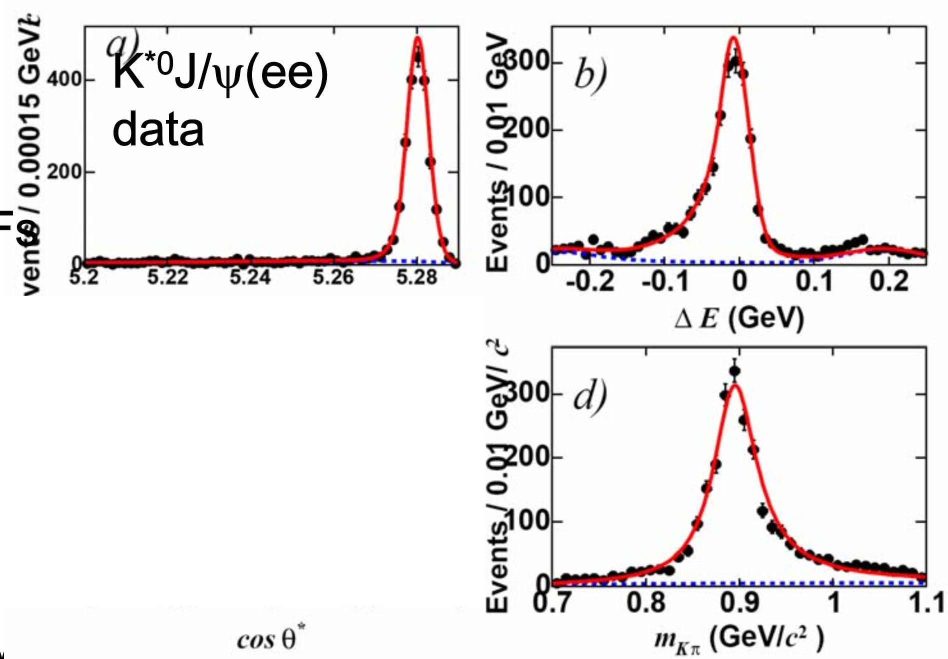
<u>Also:</u>

Ψ(2S) K(*) branching fractions

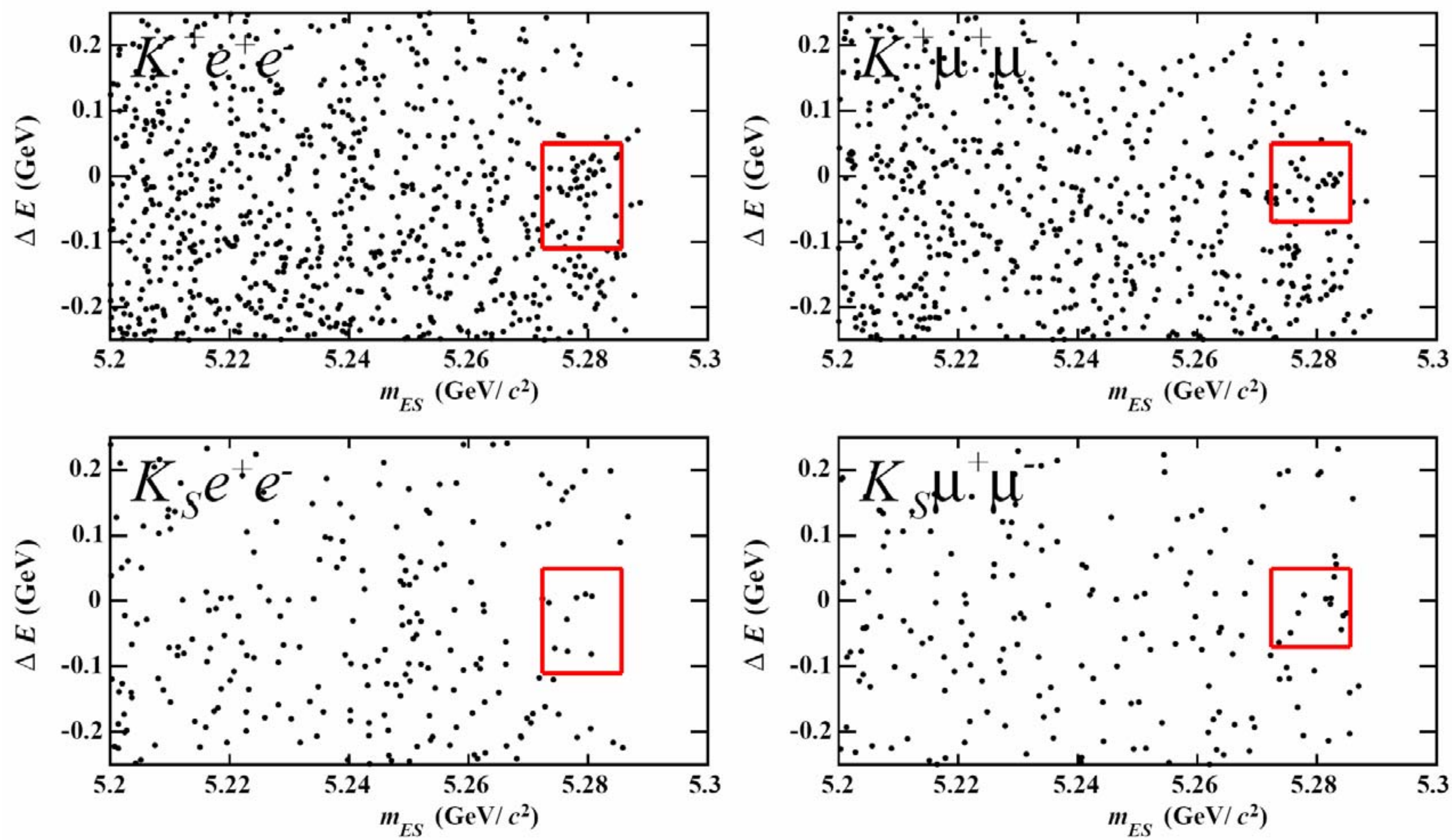
K(*)eμ

Lower-dimensional and/or smaller range fits

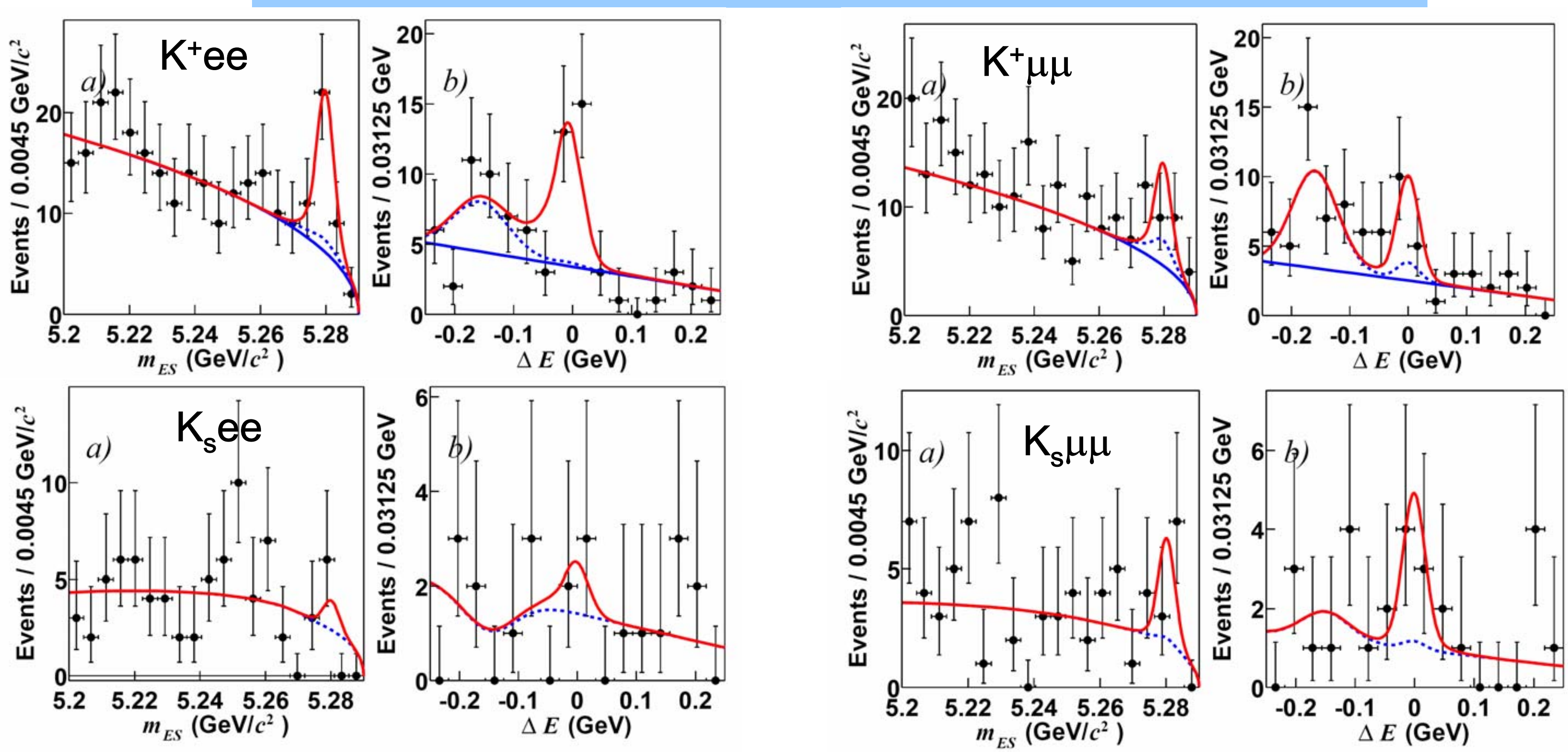
Sideband yields agree with MC



$K\ell\ell$ Fits



K*ll* Fits



Mode	Signal yield	Eff.	Eff. Syst. $(\Delta\mathcal{B})(\times 10^{-6})$	Fit Syst. $(\Delta\mathcal{B})(\times 10^{-6})$	$\mathcal{B}(\times 10^{-6})$	Significance(σ)
$B^+ \to K^+ e^+ e^-$	$25.9^{+7.4}_{-6.5}$	$(26.4 \pm 0.1)\%$	± 0.02	± 0.02	$0.43^{+0.12}_{-0.11} \pm 0.03$	5.3
$B^+ \to K^+ \mu^+ \mu^-$	$10.9^{+5.1}_{-4.3}$	$(15.2 \pm 0.1)\%$	± 0.02	± 0.04	$0.31^{+0.15}_{-0.12} \pm 0.04$	3.0
$B^0 \to K^0 e^+ e^-$	$2.4^{+2.8}_{-2.0}$	$(22.6 \pm 0.1)\%$	± 0.01	± 0.01	$0.14^{+0.16}_{-0.11} \pm 0.02$	1.2
$B^0 \to K^0 \mu^+ \mu^-$	$6.3^{+3.6}_{-2.8}$	$(13.3 \pm 0.1)\%$	± 0.04	± 0.03	$0.60^{+0.34}_{-0.27} \pm 0.05$	2.8

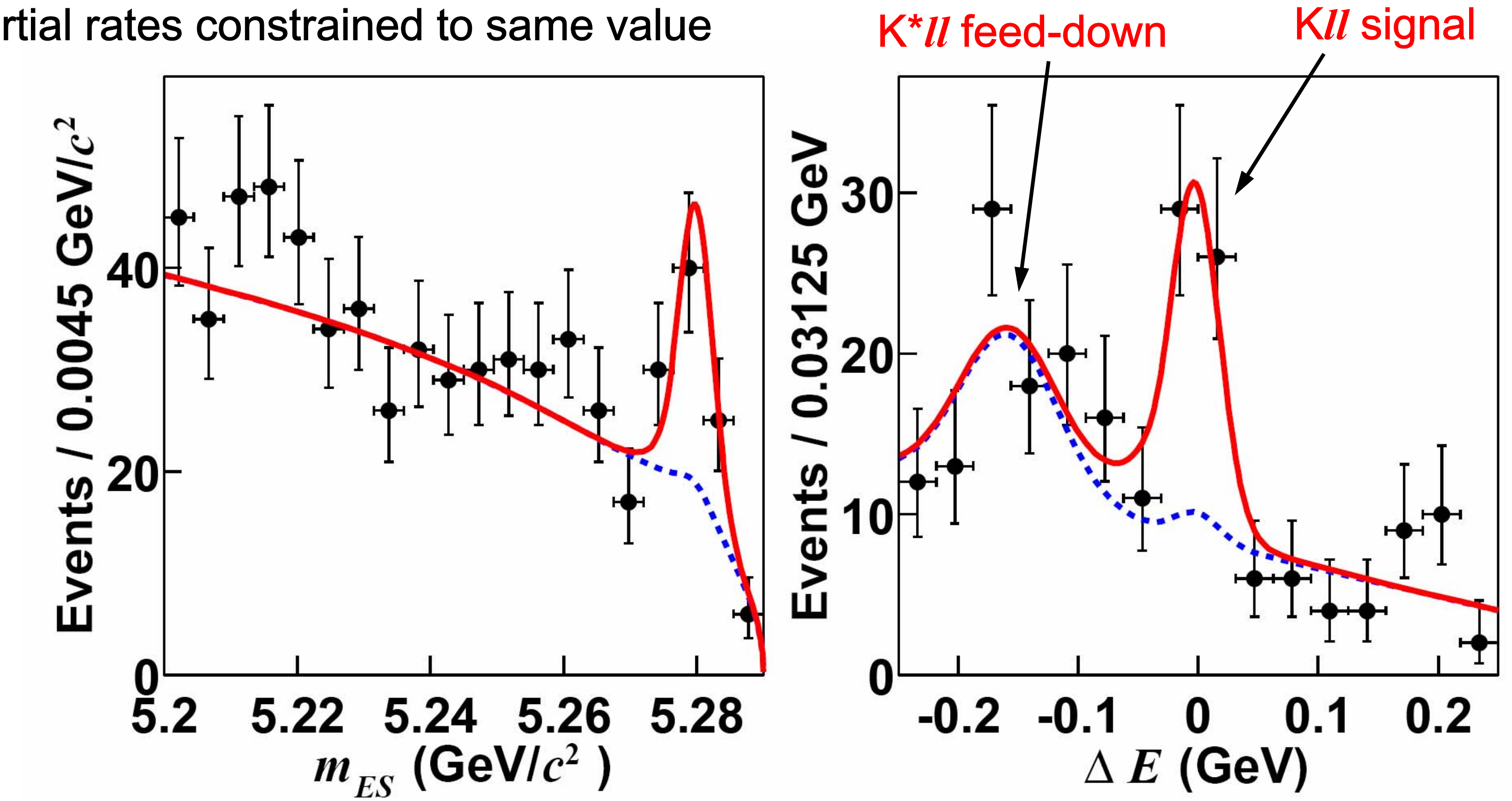
K*ll* modes consistent

Kll Combined BF

Mode	$(\Delta\mathcal{B})(\times 10^{-6})$	$(\Delta\mathcal{B})(\times 10^{-6})$	$\mathcal{B}(\times 10^{-6})$	Significance(σ)
$B \to K e^+ e^-$	± 0.02	± 0.01	$0.33^{+0.09}_{-0.08} \pm 0.02$	5.3
$B \to K \mu^+ \mu^-$	± 0.02	± 0.02	$0.35^{+0.13}_{-0.11} \pm 0.03$	3.8
$B \to K \ell^+ \ell^-$	± 0.02	± 0.01	$0.34^{+0.07}_{-0.07} \pm 0.02$	6.6

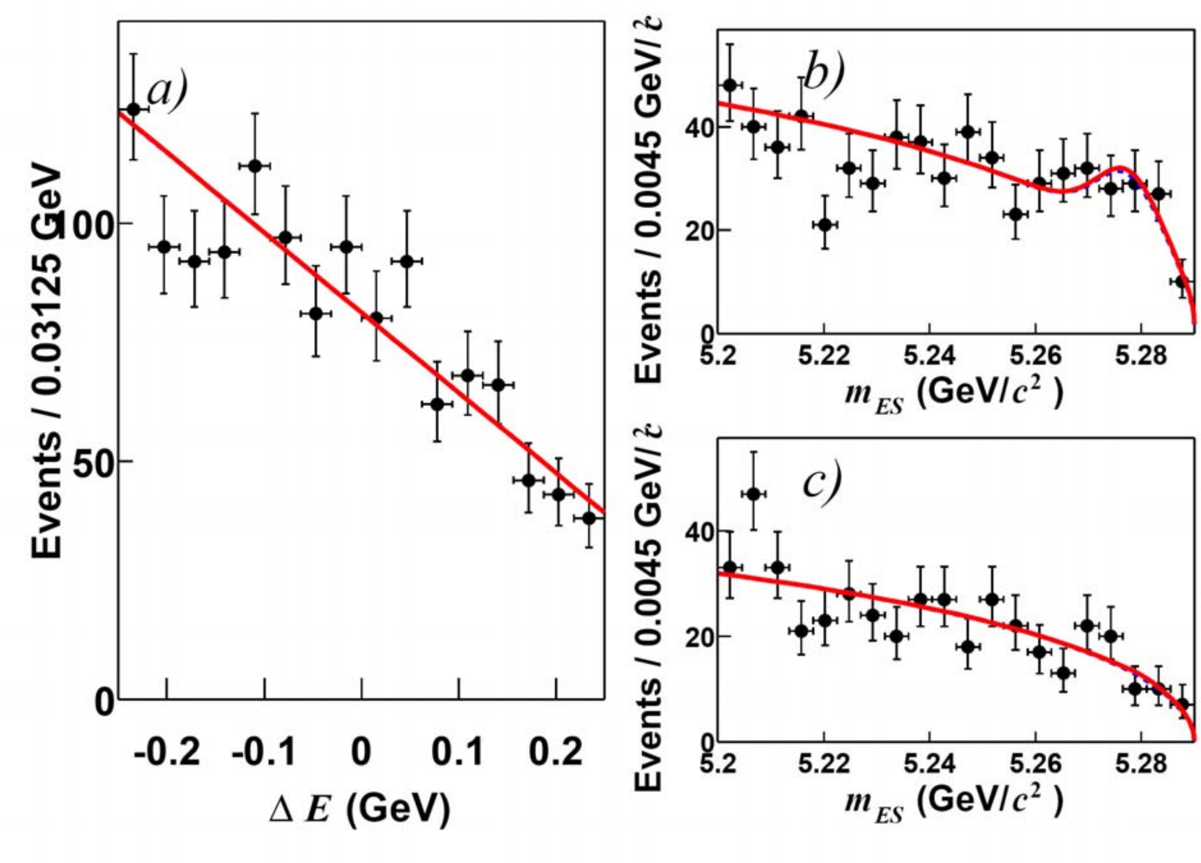
Simultaneous fit to four individual decay modes

Partial rates constrained to same value

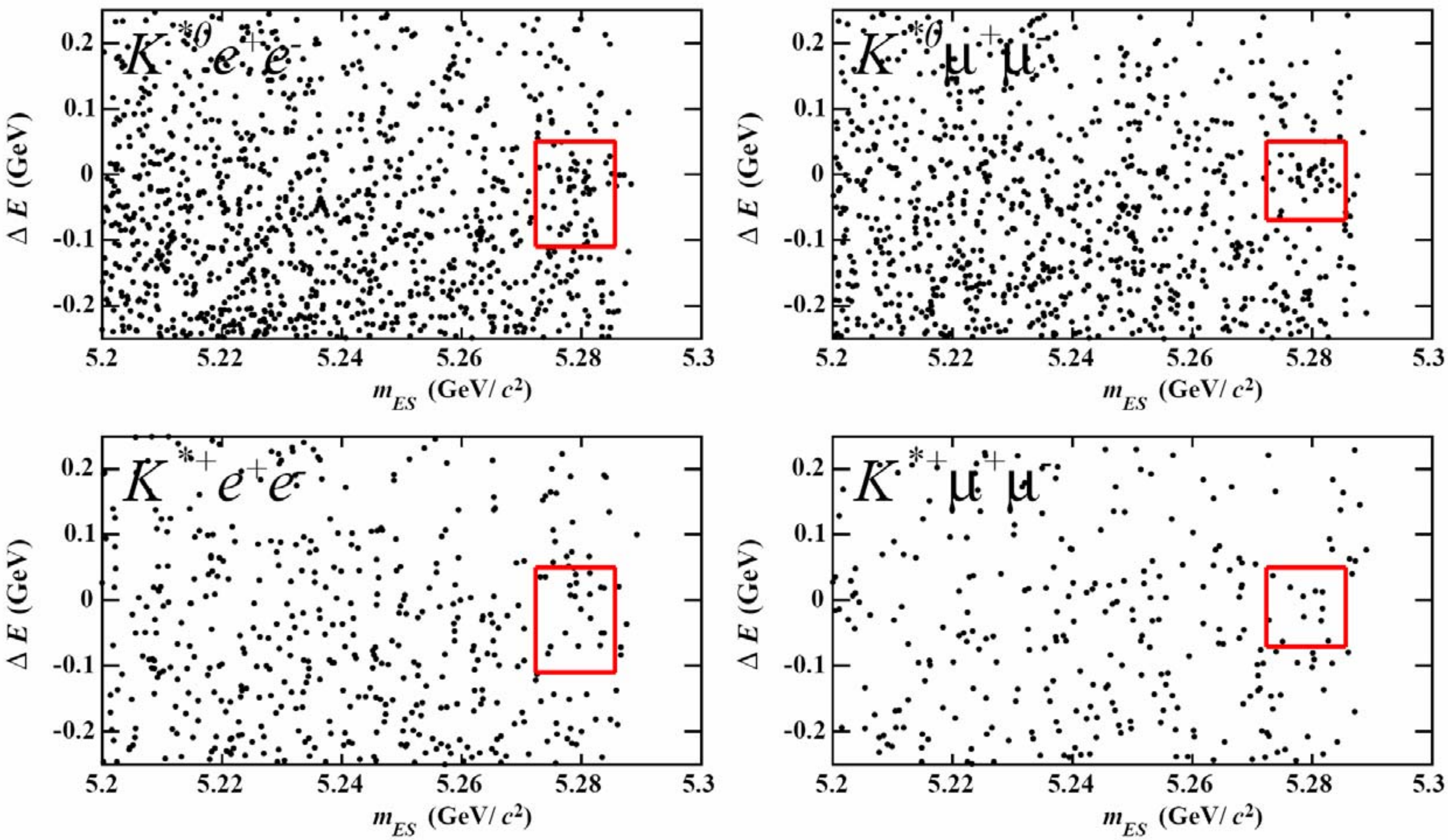


Kll Sidebands

Fit describes background shape well

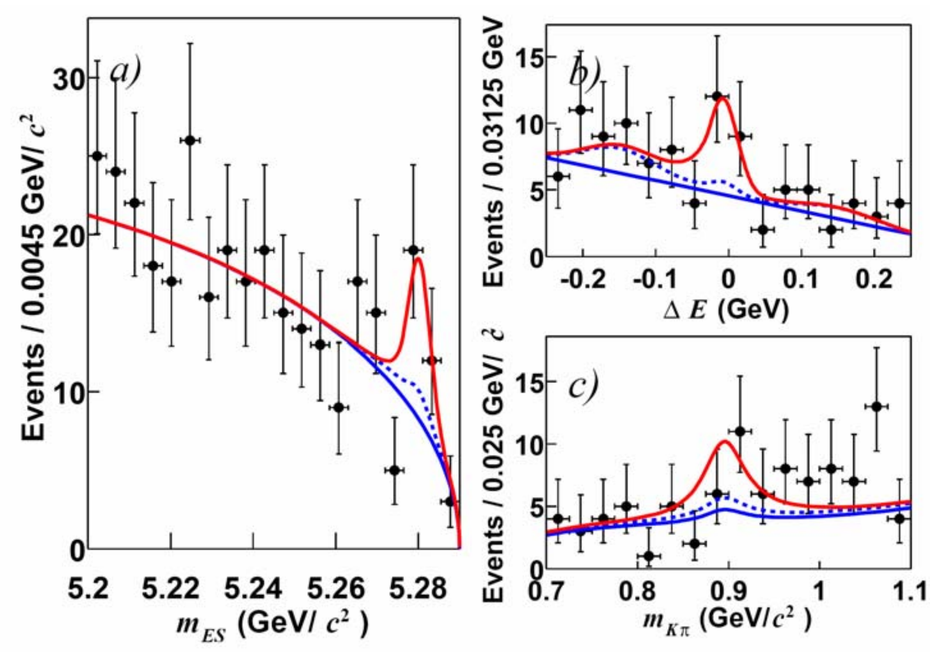


K*ll Fits

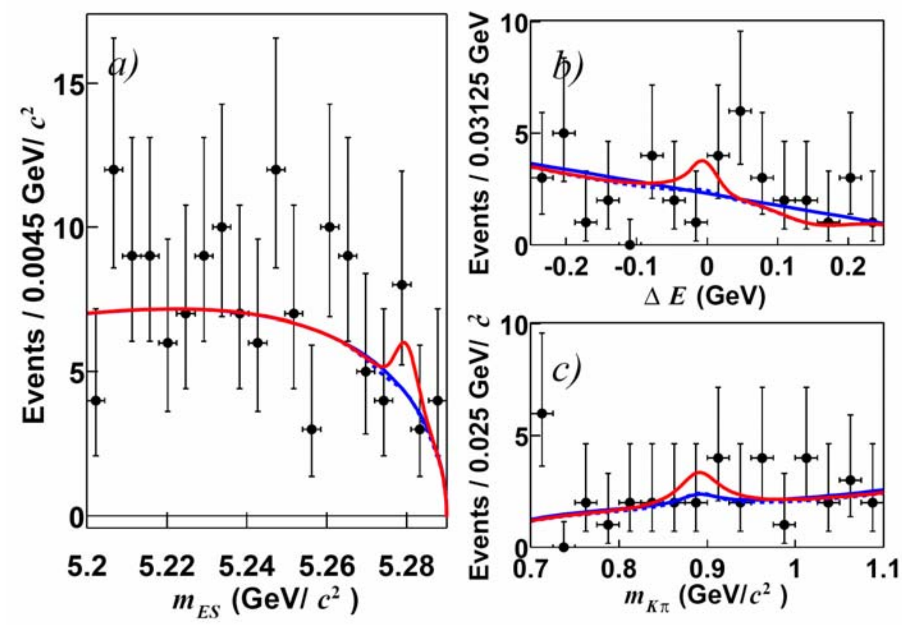


$K^{*0}e^+e^-$
$K^{*0}\mu^+\mu^-$
$K^{*+}e^+e^-$
$K^{*+}\mu^+\mu^-$
ΔE (GeV)
m_{ES} (GeV/ c^2)
0.2
0.1
0
-0.1
-0.2
5.2
5.22
5.24
5.26
5.28
5.3

K*ll Fits



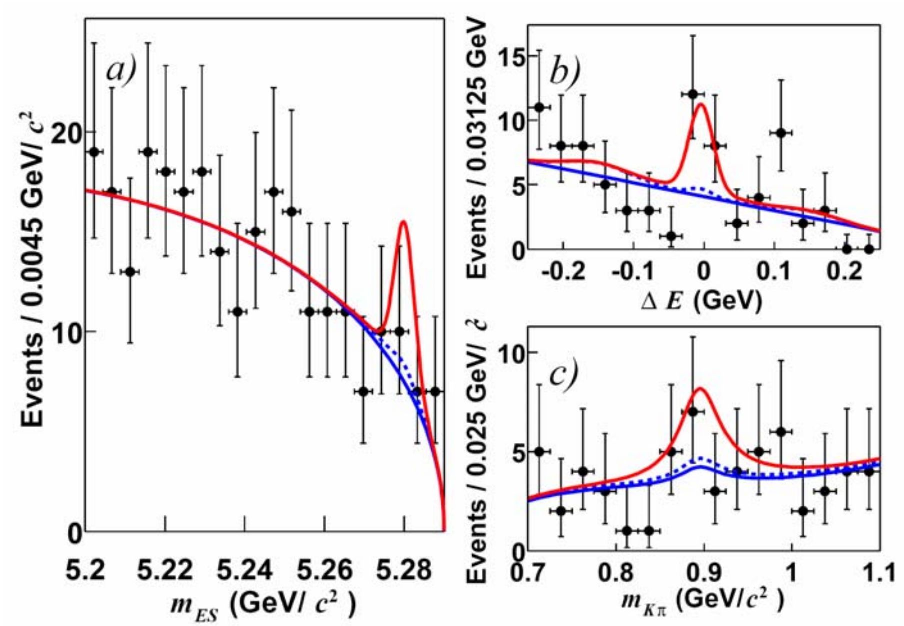
K*⁰ee



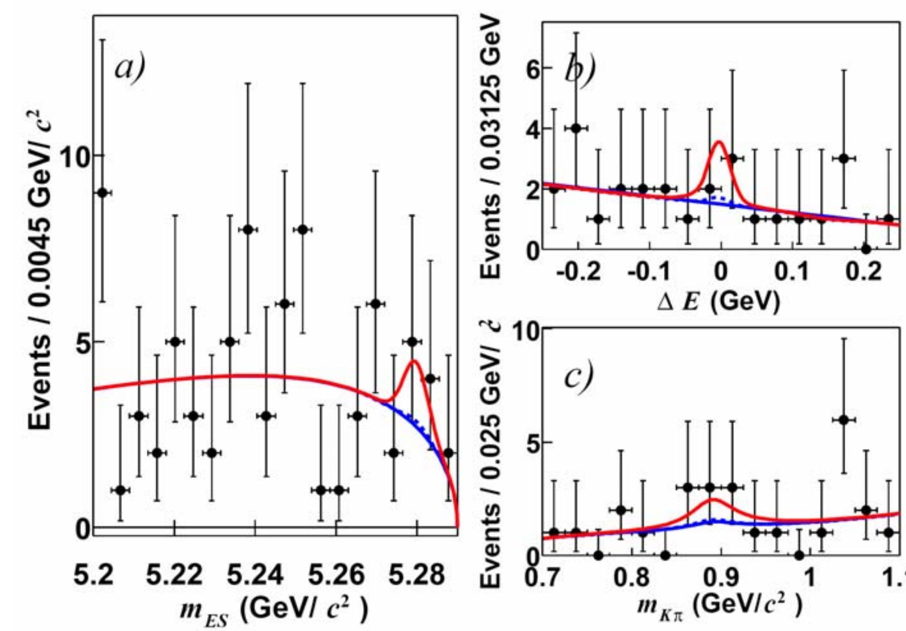
K*⁺ee

Mode	Signal yield	Eff.	$(\Delta\mathcal{B})(\times 10^{-6})$	$(\Delta\mathcal{B})(\times 10^{-6})$	$\mathcal{B}(\times 10^{-6})$	Significance(σ)
$B^0 \to K^{*0}e^+e^-$	$29.4^{+9.5}_{-8.4}$	$(18.7 \pm 0.1)\%$	± 0.06	± 0.10	$1.03^{+0.33}_{-0.29} \pm 0.12$	4.4
$B^0 \to K^{*0}\mu^+\mu^-$	$15.9^{+7.0}_{-5.9}$	$(11.7 \pm 0.1)\%$	± 0.08	± 0.11	$0.89^{+0.39}_{-0.33} \pm 0.14$	3.3
$B^+ \to K^{*+}e^+e^-$	$6.2^{+7.0}_{-5.6}$	$(15.4 \pm 0.1)\%$	± 0.07	± 0.60	$0.77^{+0.87}_{-0.70} \pm 0.60$	1.0
$B^+ \to K^{*+}\mu^+\mu^-$	$4.7^{+4.6}_{-3.4}$	$(9.0 \pm 0.1)\%$	± 0.10	± 0.13	$1.00^{+0.96}_{-0.71} \pm 0.16$	1.6

K*ll Fits



$K^{*0}\mu\mu$



$K^{*+}\mu\mu$

Mode	Signal yield	Eff.	$(\Delta\mathcal{B})(\times 10^{-6})$	$(\Delta\mathcal{B})(\times 10^{-6})$	$\mathcal{B}(\times 10^{-6})$	Significance(σ)
$B^0 \to K^{*0}e^+e^-$	$29.4^{+9.5}_{-8.4}$	$(18.7 \pm 0.1)\%$	± 0.06	± 0.10	$1.03^{+0.33}_{-0.29} \pm 0.12$	4.4
$B^0 \to K^{*0}\mu^+\mu^-$	$15.9^{+7.0}_{-5.9}$	$(11.7 \pm 0.1)\%$	± 0.08	± 0.11	$0.89^{+0.39}_{-0.33} \pm 0.14$	3.3
$B^+ \to K^{*+}e^+e^-$	$6.2^{+7.0}_{-5.6}$	$(15.4 \pm 0.1)\%$	± 0.07	± 0.60	$0.77^{+0.87}_{-0.70} \pm 0.60$	1.0
$B^+ \to K^{*+}\mu^+\mu^-$	$4.7^{+4.6}_{-3.4}$	$(9.0 \pm 0.1)\%$	± 0.10	± 0.13	$1.00^{+0.96}_{-0.71} \pm 0.16$	1.6

$K^*\ell\ell$ Combined Branching Fraction

Mode	$(\Delta\mathcal{B})(\times 10^{-6})$	$(\Delta\mathcal{B})(\times 10^{-6})$	$\mathcal{B}(\times 10^{-6})$	Significance(σ)
$B \to K^* e^+ e^-$	± 0.06	± 0.13	$0.97^{+0.30}_{-0.27} \pm 0.15$	4.5
$B \to K^* \mu^+ \mu^-$	± 0.08	± 0.11	$0.90^{+0.35}_{-0.30} \pm 0.13$	3.5
$B \to K^* \ell^+ \ell^-$	± 0.05	± 0.10	$0.78^{+0.19}_{-0.17} \pm 0.12$	5.7

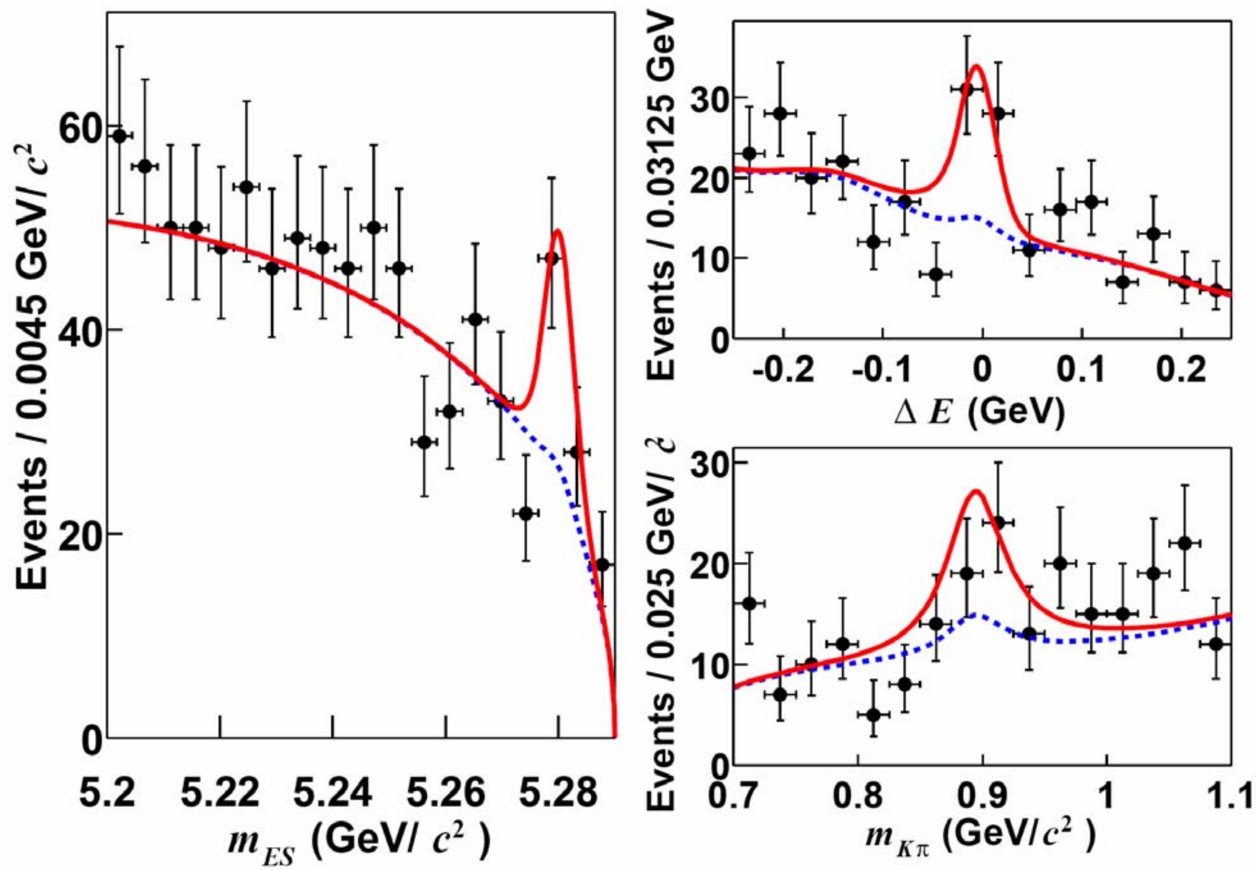
Simultaneous fit with constraint

$\Gamma(B \to K^*\mu\mu)/\Gamma(B \to K^*ee) = 0.752$
("$K^*\ell\ell$ BF" ≡ $K^{*0}\mu\mu$ BF)

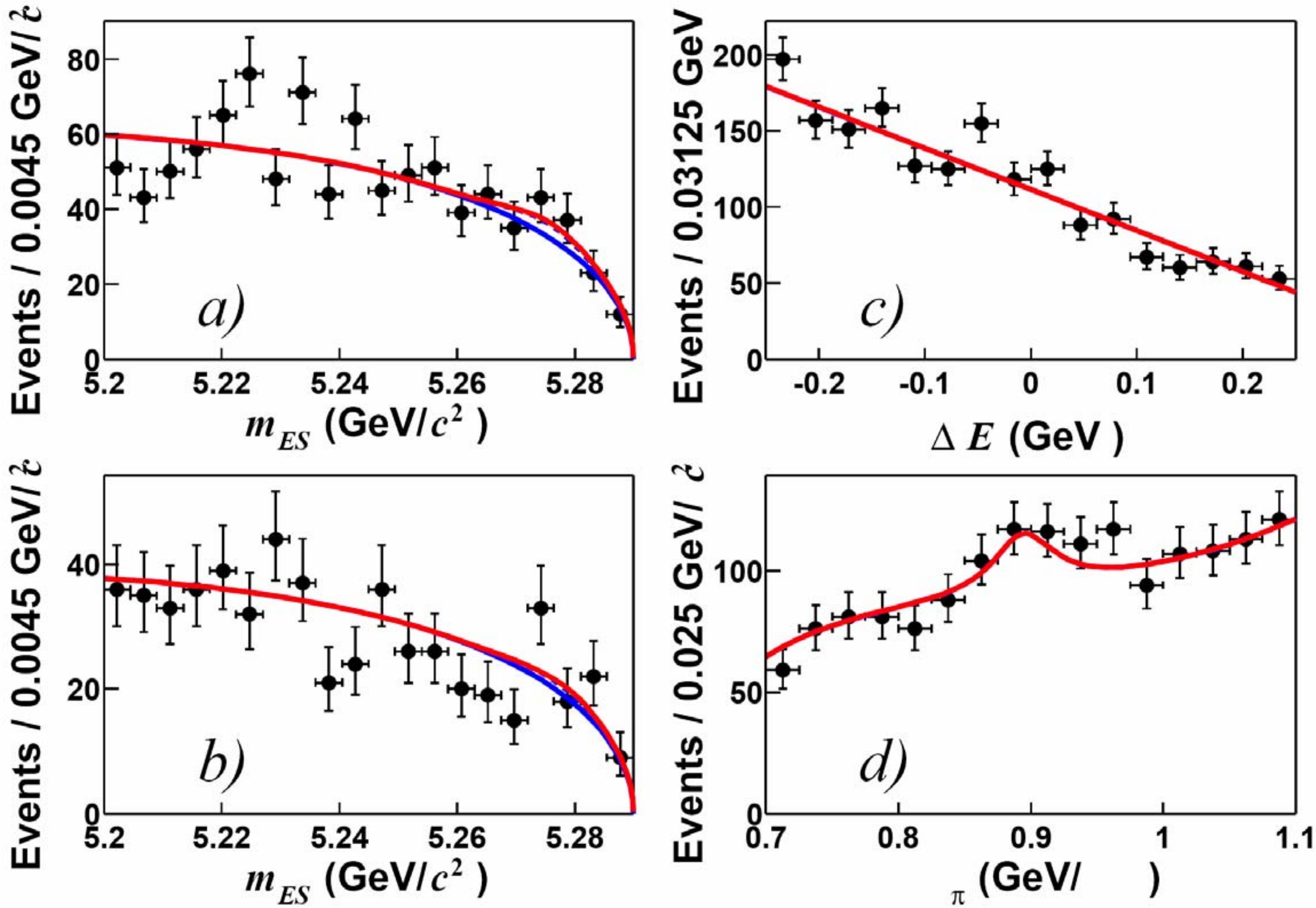
Alternatively, with pole region removed and equal partial rates:

$$\mathcal{B}(B \to K^*\ell^+\ell^-, q^2 > 0.10\,\mathrm{GeV}^2/c^4) =$$

$$(0.74^{+0.20}_{-0.18} \pm 0.12) \times 10^{-6}$$



K*ll Sidebands



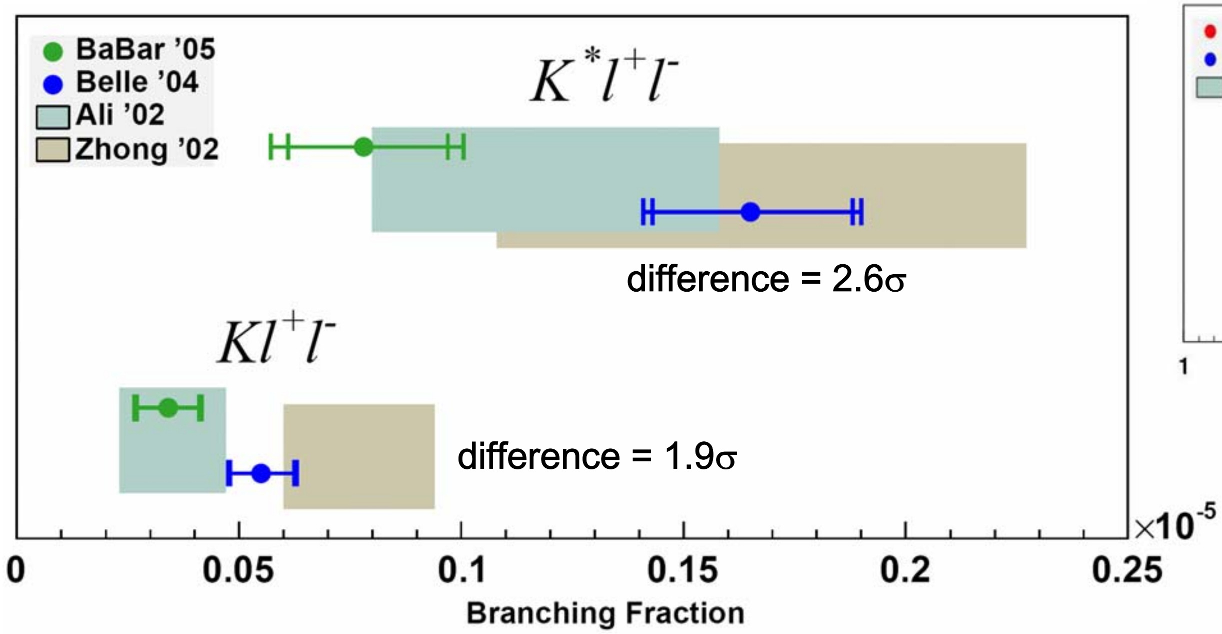
BF Summary

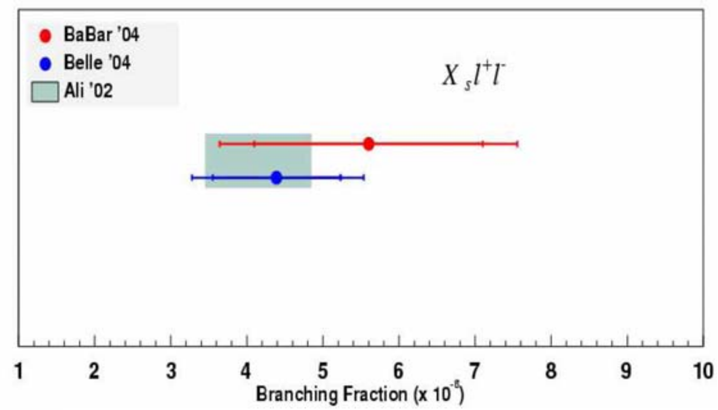
BaBar and Belle branching fractions agree with SM predictions

Experimental uncertainty already better than theory

Difference between BaBar and Belle becoming significant?

Smallest B branching fractions ever measured!!





"Sum-of-exclusive" b→sll BF also agrees with SM

Ratios of BFs and A_{CP}

Ratio of Kμμ/Kee BFs consistent with unity:

$$R_K = 1.06 \pm 0.48 \pm 0.05$$

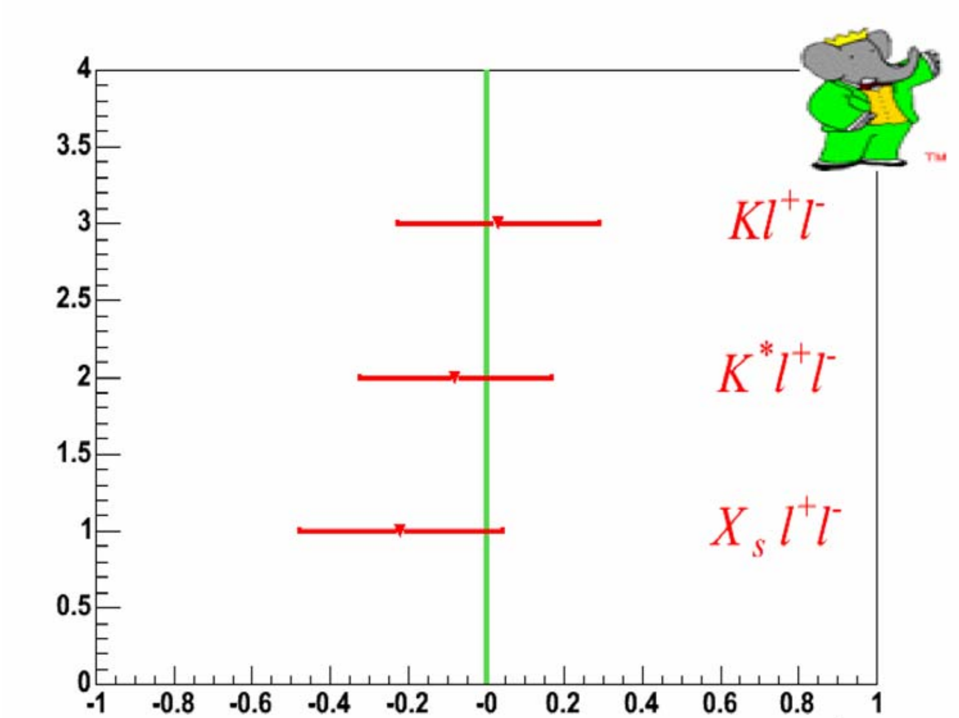
Ratio of K*μμ/K*ee BFs consistent with SM (=0.752):

$$R_{K^*} = 0.98 \pm 0.46 \pm 0.06$$

Ratio of K*μμ/K*ee BFs (excluding pole) consistent with unity:

$$R_{K^*}(q^2 > 0.10\,\mathrm{GeV}^2/c^4) = 1.37 \pm 0.74 \pm 0.11$$

A_{CP} measurements consistent with 0



$$A_{CP}(B^+ \to K^+\ell^+\ell^-) = -0.08 \pm 0.22 \pm 0.11$$

$$A_{CP}(B \to K^*\ell^+\ell^-) = 0.03 \pm 0.23 \pm 0.12,$$

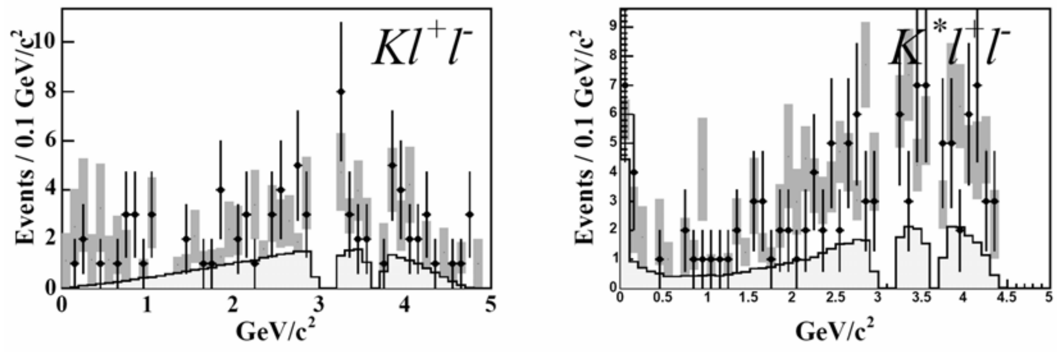
Dominant systematic from unknown asymmetry of peaking background

Towards A_{FB}

First, need partial BF measurement vs. q^2

Signal candidates span entire range

Separate fits for optimal q^2 bins

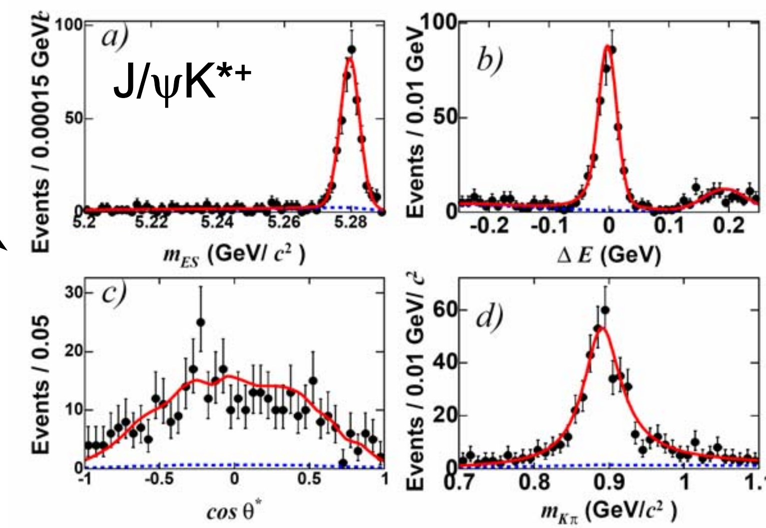


Fit method for $\cos\theta^*$: $\Gamma^{-1} d\Gamma/d\cos\theta^* \;=\; 0.5\times(1.0-2.0\times C/3.0)+A_{FB}\times\cos\theta^*+C\times\cos^2\theta^*$

4D LH fit

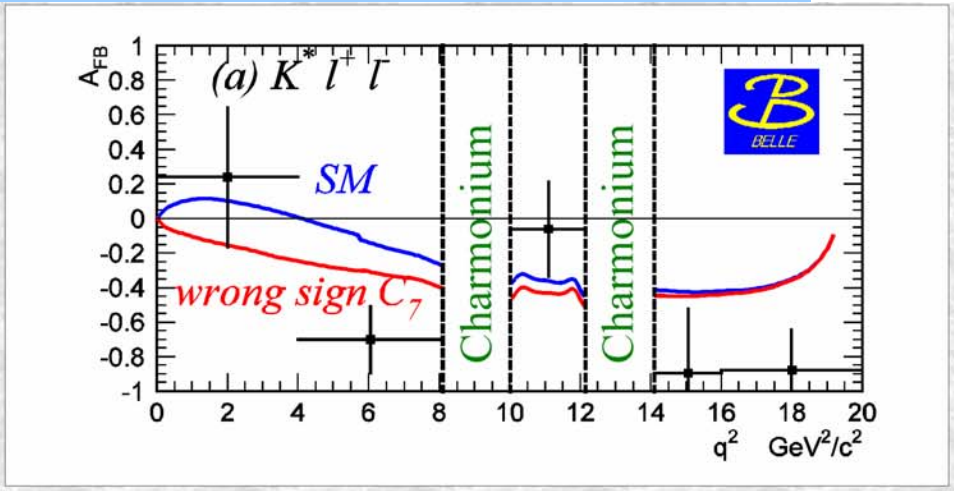
Check with charmonium and K*ll*

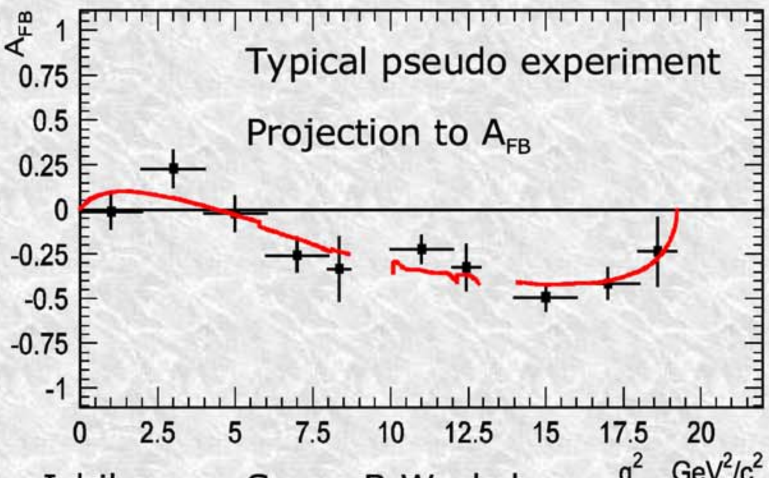
Need asymmetric efficiency and background PDFs



Towards A_{FB}

- First raw A_{FB} distribution in *B –> K*ll* from Belle
  - Consistent with SM or wrong sign C_7





Ishikawa – Super B Workshop

- Belle projections to 5 ab^{-1} with simultaneous fit to q^2, $\cos(\theta^*)$ distributions
  - Extract A_9, A_{10} directly
  - For SM input values, mean errors:

$$\boxed{\begin{array}{l}\delta A_9/A_9 = 11\% \\ \delta A_{10}/A_{10} = 13\%\end{array}}$$

$A_i = q^2$ independent term of C_i

Summary

•**Strong penguins beginning to crack the standard model?**

•**Decay rate measurements of $b \rightarrow s\gamma$ penguins** are well into the precision era.

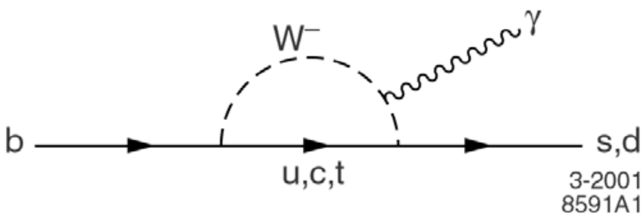
•**CP asymmetries of $b \rightarrow s\gamma$ penguins** are statistics limited and will continue to test the SM

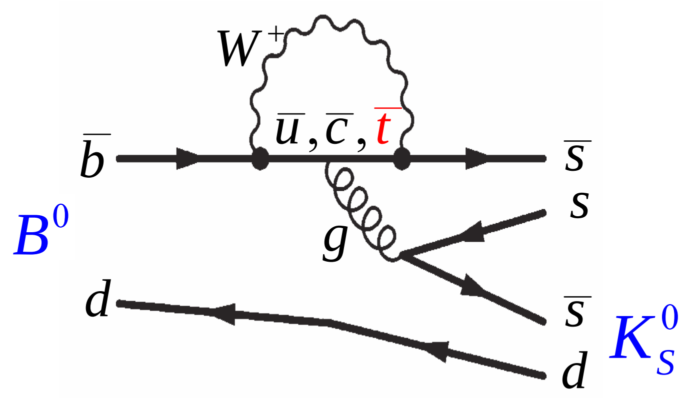
$b \rightarrow d\gamma$ penguins are only now beginning to reveal themselves in B-factory data. They could also uncover new physics, or measure the poorly known $|V_{td}|$.

$BF(B \rightarrow \rho,\omega\,\gamma) < 1.2 \times 10^{-6}$ $|V_{td}/V_{ts}| < 0.19$ (90% CL)

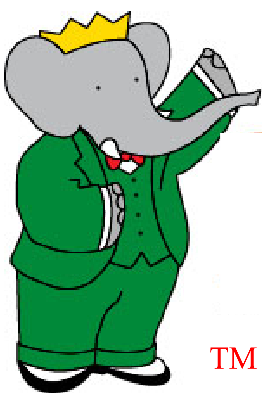
"Ultimate" $b \rightarrow sll$ penguin will ultimately disentangle all electroweak penguin effects, SM or not.

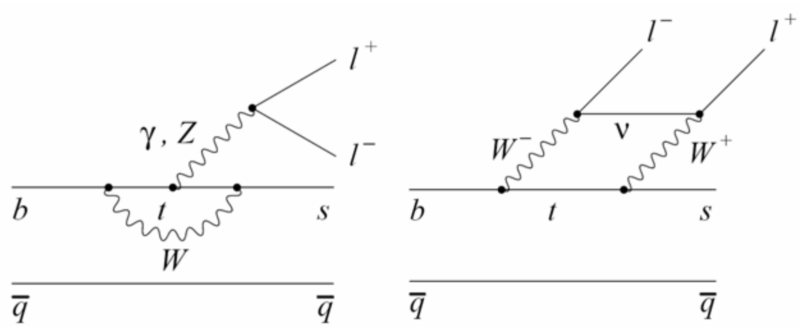
$B \rightarrow K\mathit{ll}$ ratios and $K^*\mathit{ll}$ angular asymmetries are high precision tests of the electroweak scale and beyond

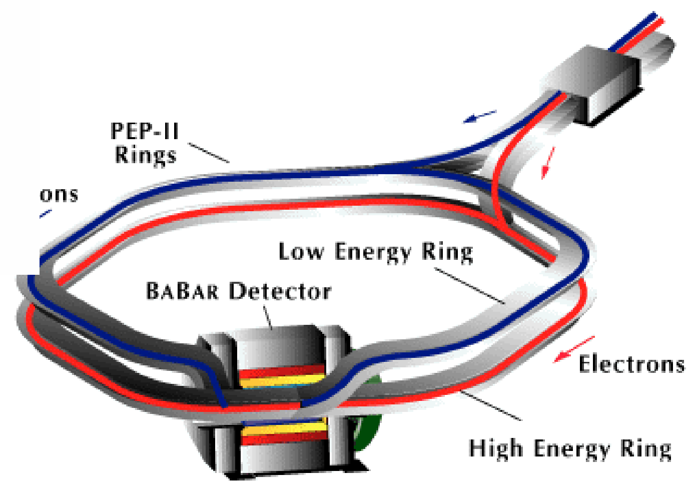




Penguin decays are strongly challenging the Standard Model!







Search for $B \to \rho\gamma, \omega\gamma$ (191 fb^{-1})

Simplest and most "common" $b \to d\gamma$ exclusive decays are $\rho\gamma$ and $\omega\gamma$:

$B^+ \to \rho^+ \gamma,\ \rho^+ \to \pi^+ \pi^0$ BF ≈ BF $K^*\gamma$ x $|V_{td}/V_{ts}|^2 \approx 1.6 \times 10^{-6}$
$B^0 \to \rho^0 \gamma,\ \rho^0 \to \pi^+ \pi^-$ BF ≈ ½ BF $\rho^+\gamma$
$B^0 \to \omega \gamma,\ \omega \to \pi^+ \pi^- \pi^0$ BF ≈ ½ BF $\rho^+\gamma$

Comparable to rarest B decays measured!

Previous BaBar limit: BF $\rho^+\gamma < 1.9 \times 10^{-6}$ 90% CL (78 fb^{-1})
Preliminary Belle evidence (3.5σ): BF $\rho^+\gamma = 1.8 \pm 0.6 \pm 0.1 \times 10^{-6}$ (140 fb^{-1})

Ratio of exclusive $b \to d\gamma$ and $b \to s\gamma$ decay rates measures $|V_{td}/V_{ts}|$ via

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

Ali et al. hep-ph/0405075

ΔR weak annhilation correction
ζ^2 SU(3) symmetry breaking of exclusive form factors

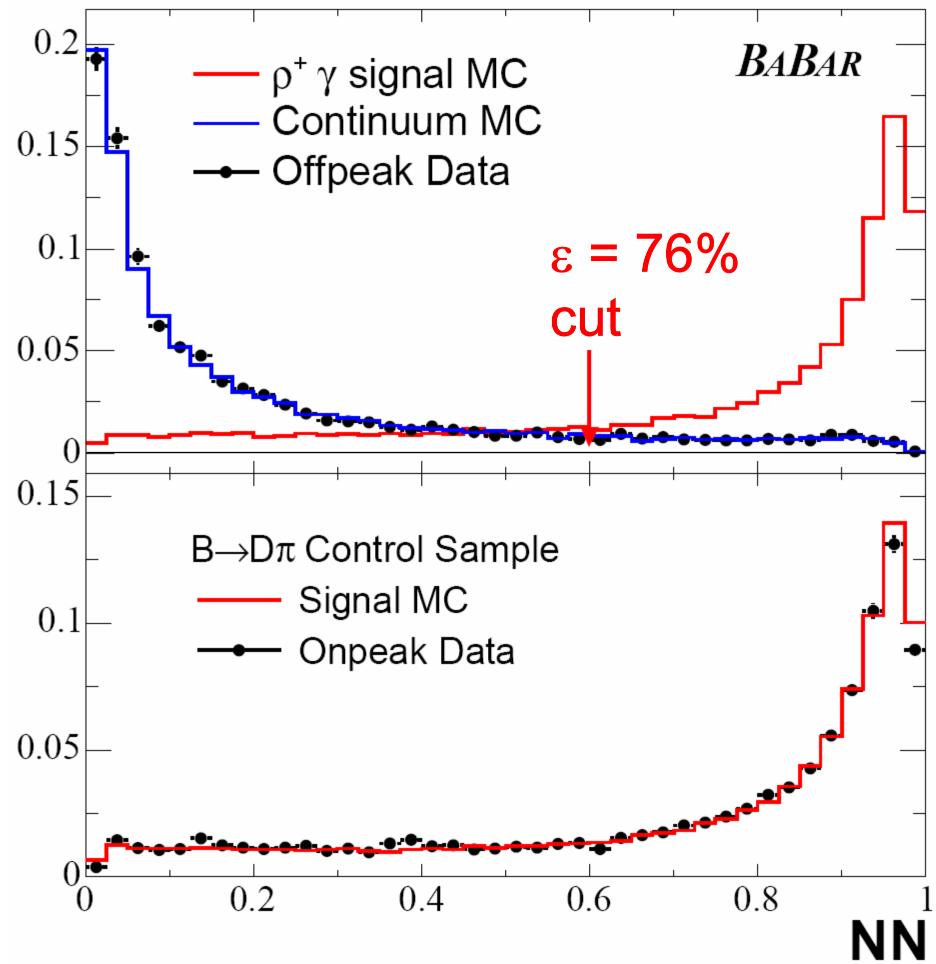
Continuum Background Suppression

$e^+e^- \rightarrow q\bar{q}$ continuum events are the dominant background

Combine properties discriminating $B \rightarrow \gamma + X$ from continuum into a single-output neural net:

- Event shape variables: spherical B vs. jet-like continuum
- B flavor tagging variables: kaons and leptons in the rest of the event
- B candidate vertex separation from rest of the event

Neural net trained on simulated signal and continuum samples

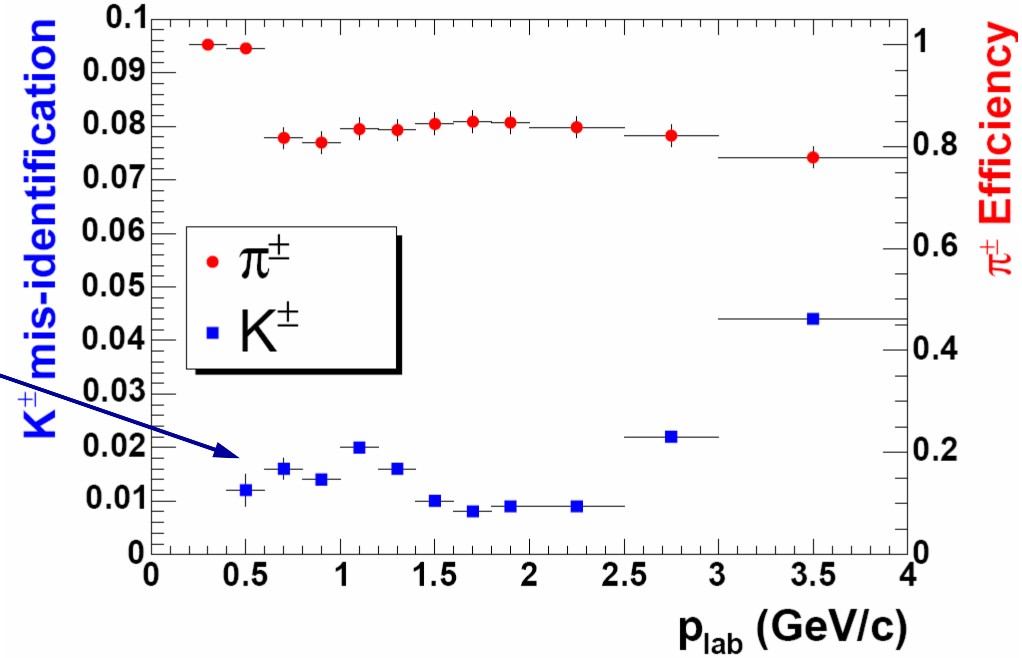


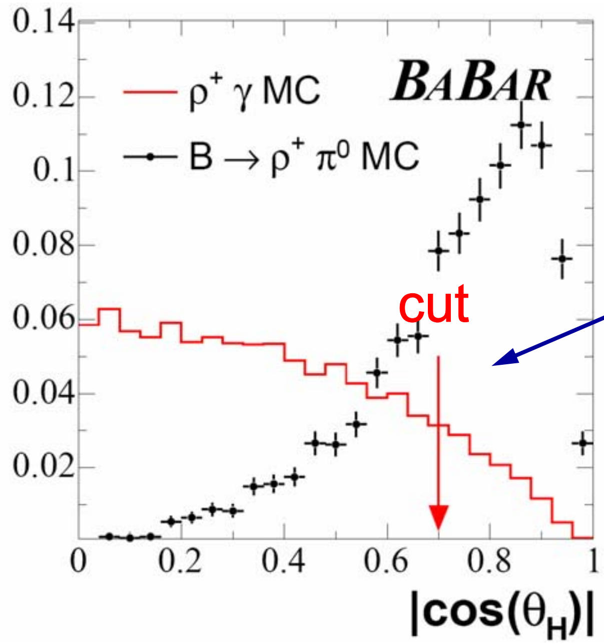
Neural net distribution for both signal and background described well by simulation

B Background Suppression

Large (40 x signal) $K^* \gamma$ background reduced by strict π^+ PID requirements (track dE/dx, DIRC θ_c , DIRC N_γ)

K^+ misid 1-2% for most of acceptance
ΔE provides additional separation of $K^*\gamma$ from $\rho\gamma$





B decays to $\rho\pi^0$, $\rho\eta$, $\omega\pi^0$, $\omega\eta$ suppressed by cut on helicity angle

Combine helicity angle, B production angle, Dalitz angle (ω only) into B Fisher discriminant for additional background separation in signal fit

Signal Fit: K*γ Control Sample

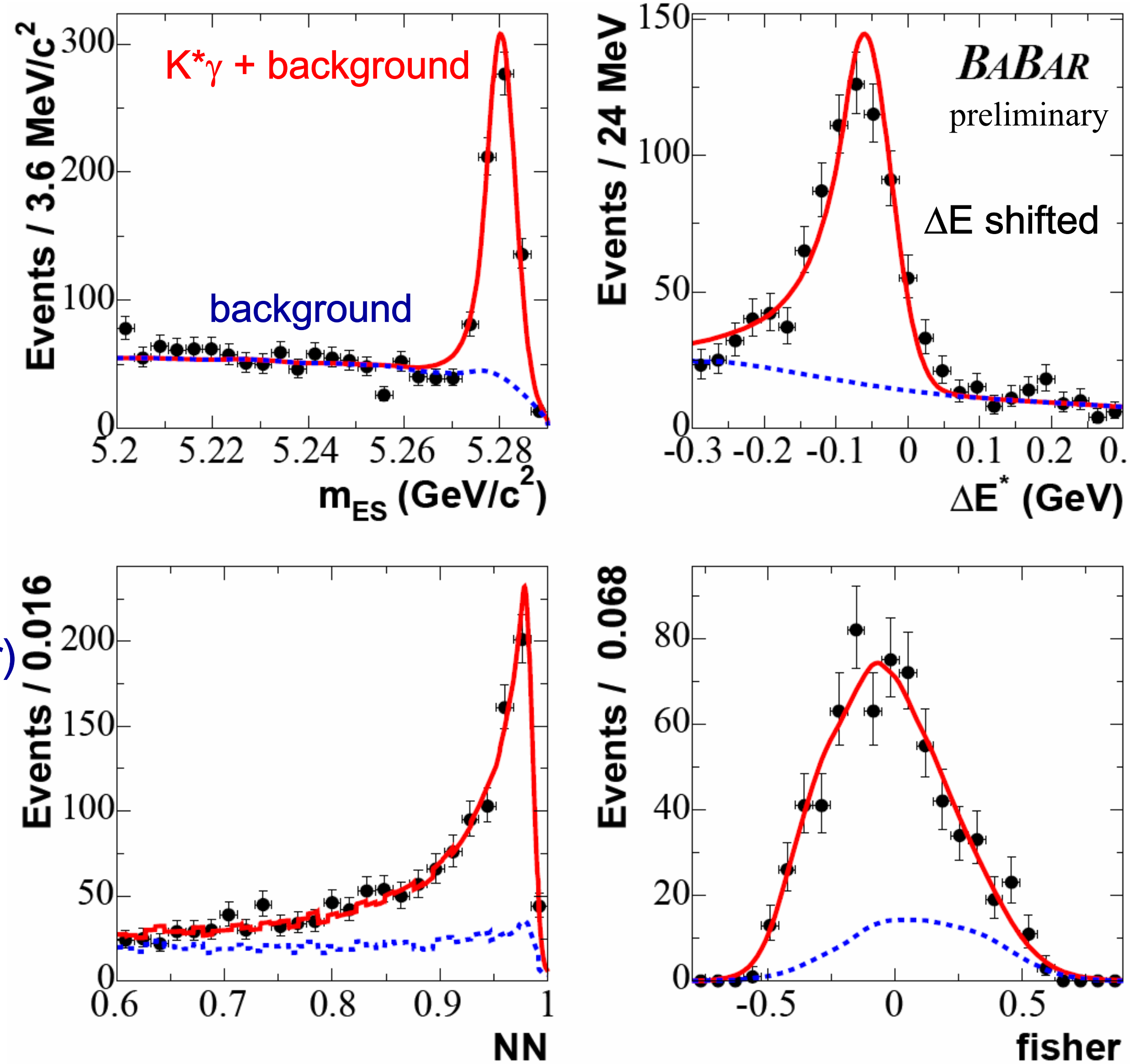
Validate fit procedure on data with K*γ sample ($\rho^0\gamma$ candidates with no PID requirement)

Unbinned extended ML fit of three background components ($q\bar{q}$, $X_s\,\gamma$, $\rho^0(\pi^0/\eta)$) and K*γ component

to 4D data (m_{ES},ΔE,NN,Fisher)

qq, $X_s\,\gamma$, K*γ yield are free parameters

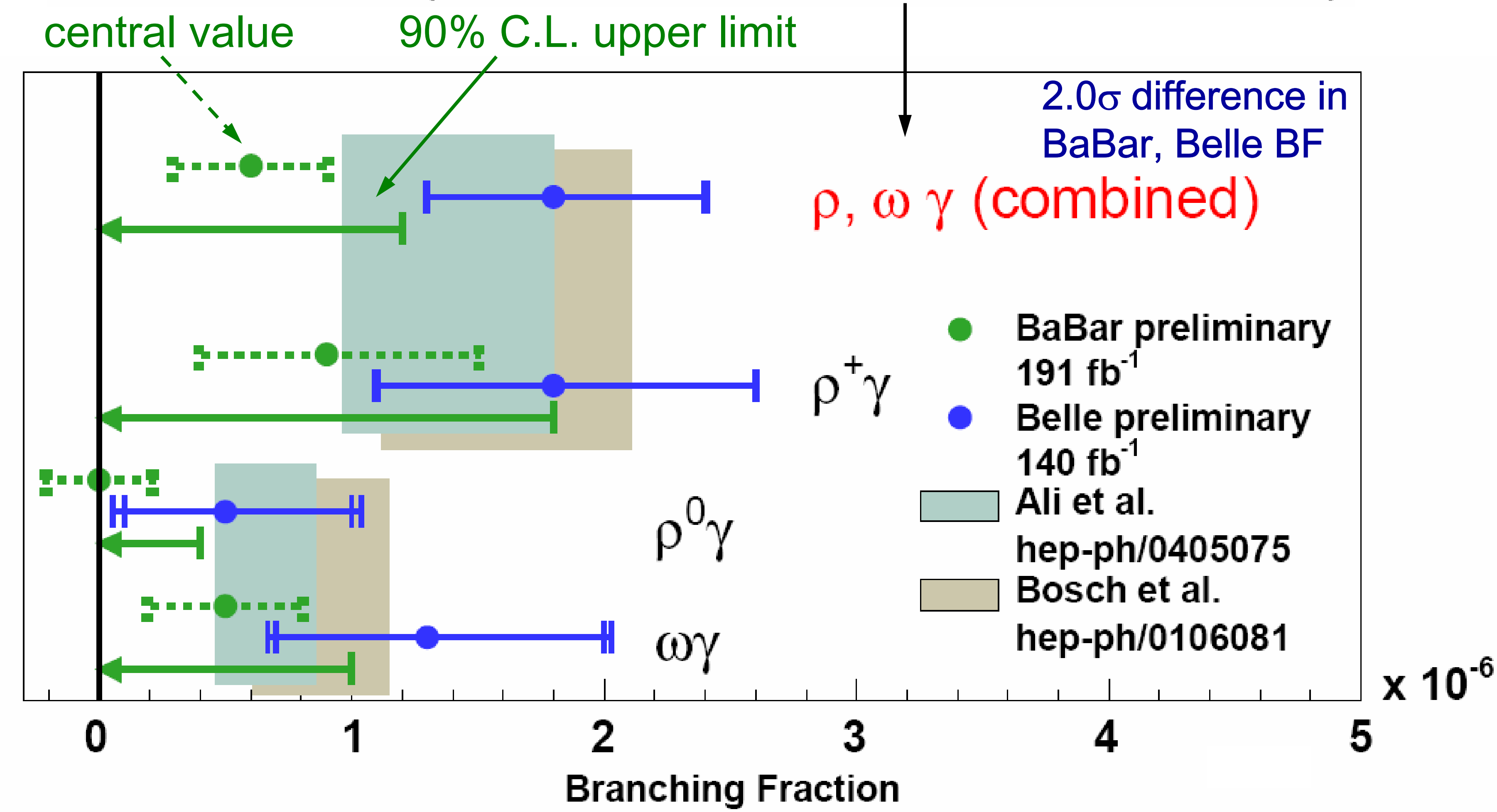
Large K*γ signal yield consistent with BaBar BF measurement



$b \rightarrow d\,\gamma$ Branching Fractions: Summary

Comparison of measurements with predictions for individual modes and combined BF

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



CKM matrix constraint

BaBar BF ratio upper limit < 0.029 → $|V_{td}/V_{ts}| < 0.19$ (90% CL)

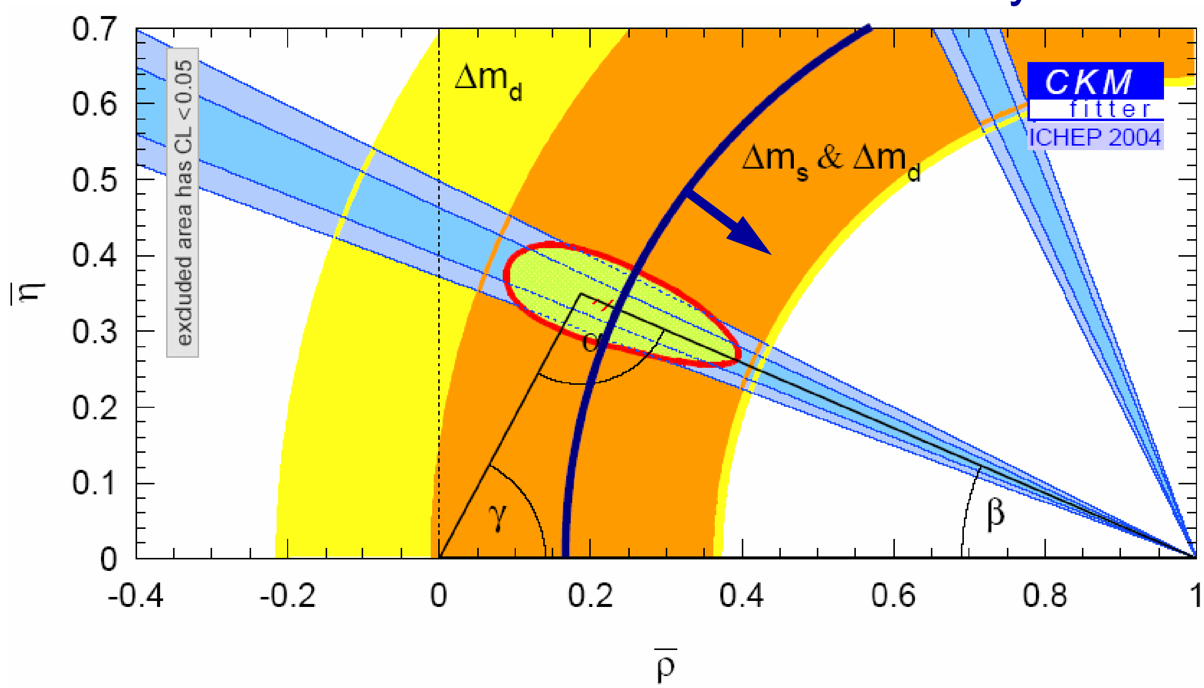
Ali et al. hep-ph/0405075

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

$(\zeta^2, \Delta R) = (0.85, 0.10)$

no theory error

Penguins are starting to provide meaningful CKM constraint



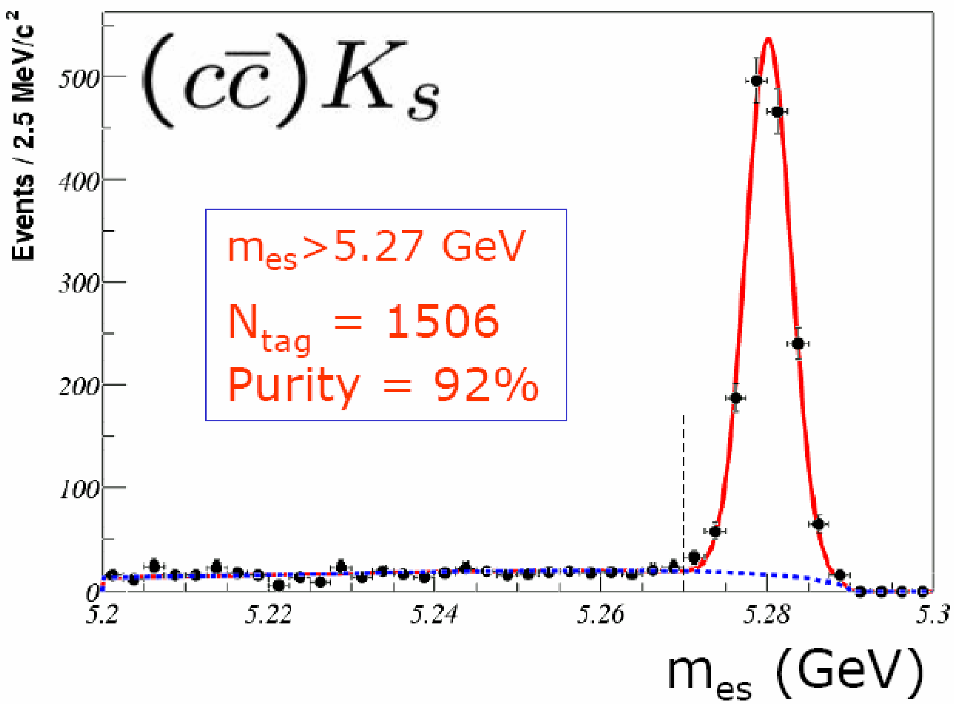
ργ 95% C.L. BaBar allowed region (inside the blue arc)

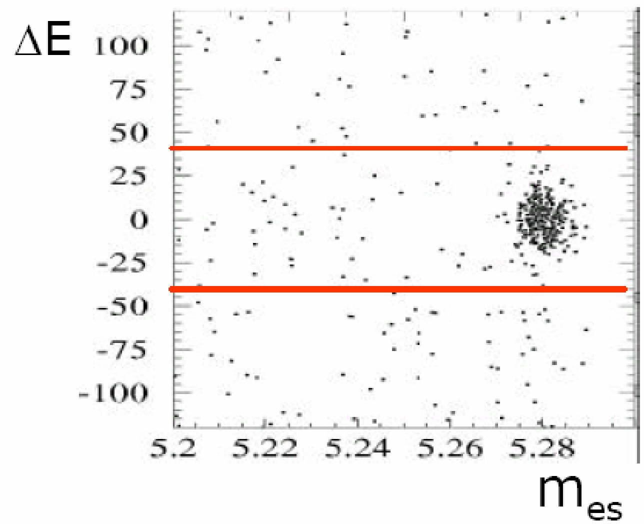
Kinematic variables at the $\Upsilon(4S)$

Variables for signal/BG discrimination

$$m_{es} = \sqrt{E^{*2}_{\text{beam}} - \sum \vec{p}^{*\,2}_i}$$

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





$\sigma m_{es} \approx 3$ MeV

$\sigma\ \Delta E \approx 15$ MeV

J/ψ Ks ($\pi^+\pi^-$)
m_{es} > 5.27 GeV
N_{tag} = 974
Purity 97%

Quarks and their Strong Interactions

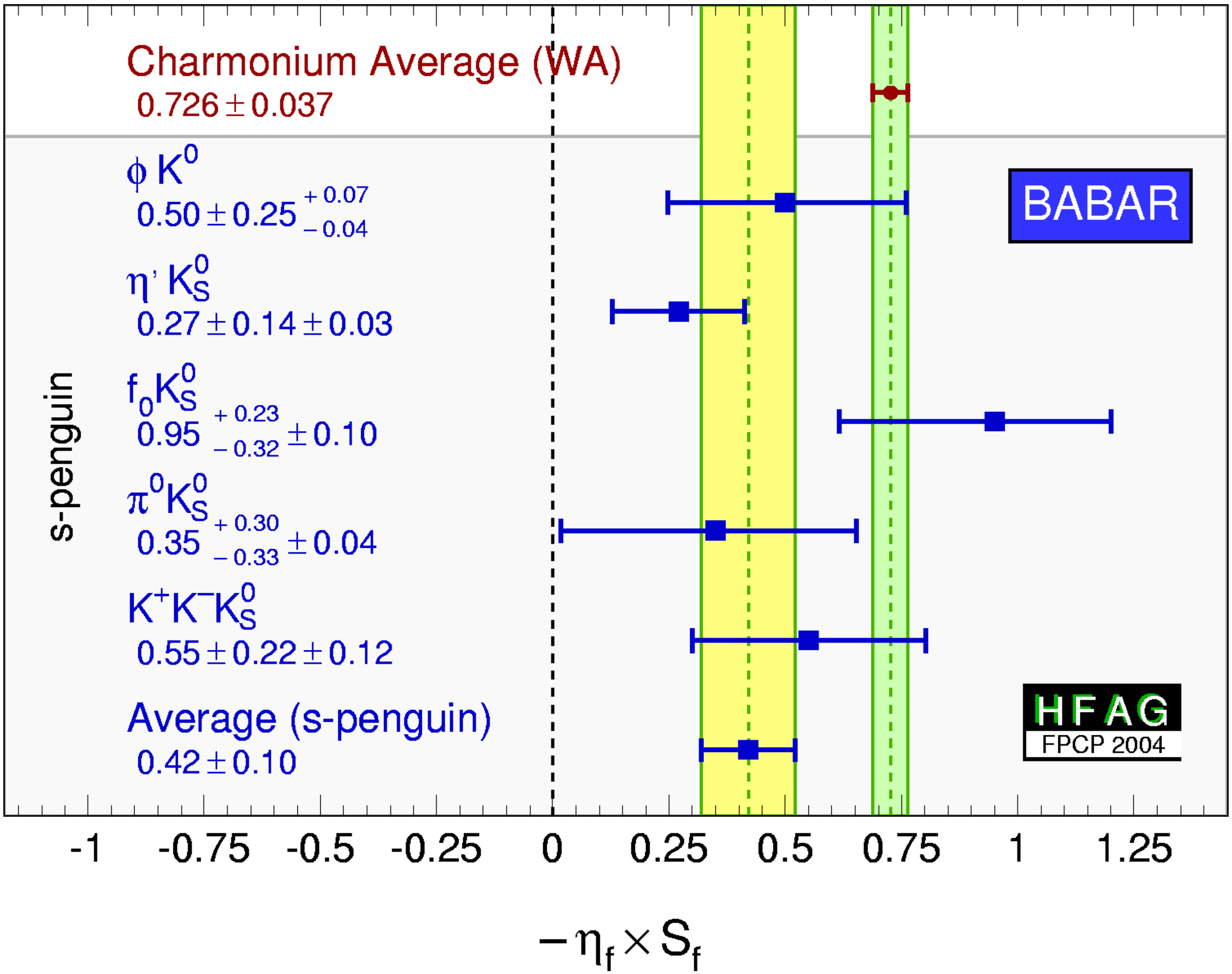
Quarks cannot be detected in isolation, only as bound states
A quark/anti-quark pair forms a bound state (mesons)

Flavor	u,d	s	c	b	t
spin 0 mesons	π^+ $(u\bar{d})$ π^0 $(u\bar{u}-d\bar{d})$	K^+ $(u\bar{s})$ K_S^0 $(d\bar{s}+s\bar{d})$	D^+ $(c\bar{d})$ D^0 $(c\bar{u})$	B^0 $(d\bar{b})$ B^+ $(u\bar{b})$	none
spin 1 mesons	ρ^+ $(u\bar{d})$ ρ^0 $(u\bar{u}-d\bar{d})$ ω $(u\bar{u}+d\bar{d})$	K^{*+} $(u\bar{s})$ K^{*0} $(d\bar{s})$ ϕ $(s\bar{s})$	D^{*+} $(c\bar{d})$ D^{*0} $(c\bar{u})$ J/ψ $(c\bar{c})$	Υ $(b\bar{b})$	none

b quarks are the heaviest flavor with measureable bound states→

B mesons are a natural starting point for studying the other flavors

Trees(green) vs. Penguins(yellow): BaBar Data



Averaging over many penguin decays:

BaBar discrepancy with tree decays

= $-2.7\ \sigma$

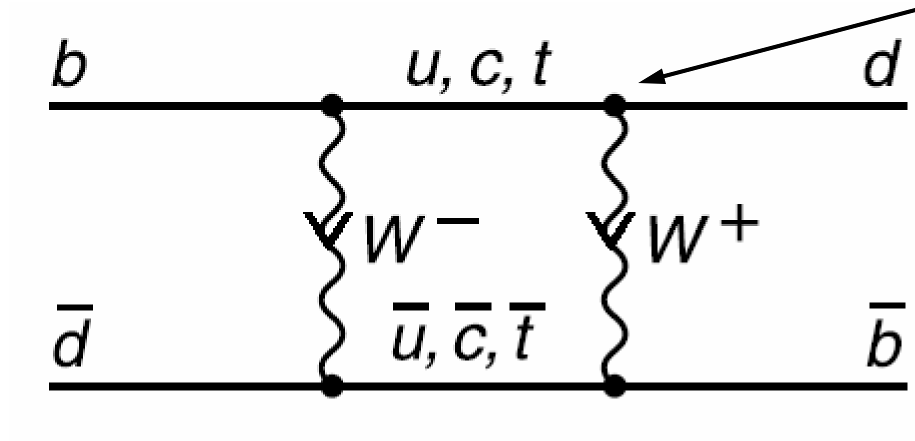
Quarks and Flavor Violation: Mixing

Pairs of down (or pairs of up) type quarks can spontaneously swap flavor for anti-flavor via two flavor-violating exchanges

"Meson Mixing" aka "Flavor oscillation"

Sensitive to $V_{td,}$ top quark!

$\overline{B}^0$



B^0

$$\mathrm{Prob}(\overline{B}^0 \rightarrow B^0) \approx \exp(-\Gamma\, t)/2 * (1 - \cos(\Delta m\, t))$$

Similar to neutrino oscillation, except decay term added

Mixing time ~few ps

Quarks and CP Violation

For a particle(s) f with momentum p and helicity λ

C : Charge conjugation operator $\quad C\ f(p, \lambda) = \bar{f}(p, \lambda)$

P : Parity reversal operator $\quad P\ f(p, \lambda) = f(-p, -\lambda)$

$CP\ f(p, \lambda) = \bar{f}(-p, -\lambda)$

CP eigenstate: particle = anti-particle (Ex: $q\bar{q}$ mesons)

CP conservation → left-handed particles have the same physics as right-handed anti-particles

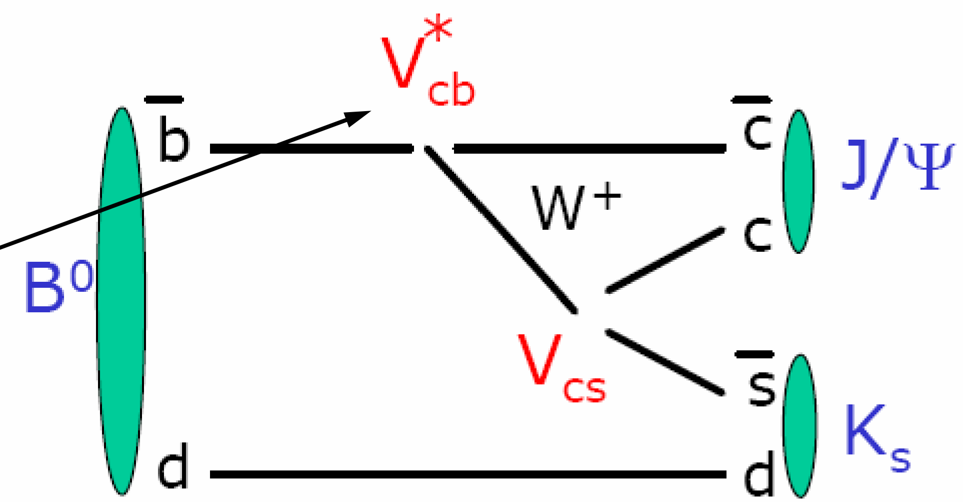
Obviously violated for our (baryon-asymmetric) local universe!

In the Standard Model CP violation originates from complex phase in CKM matrix → in general, $V_{ij} \neq V_{ij}^*$

$B^0 \to J/\psi\, K_S{}^0$ and sin 2β

Decay dominated by a single "tree-level" Feynman diagram: $b \to c\bar{c}s$

$$\beta \equiv \varphi_1 \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$



J/ψ identified cleanly by decay to a lepton pair;
K_S identified cleanly by decay to pion pair.
Both particles are CP eigenstates → both B^0 and $\bar{B}^0$ decay to them

Time-dependent CP violation has amplitude sin 2β and frequency Δm

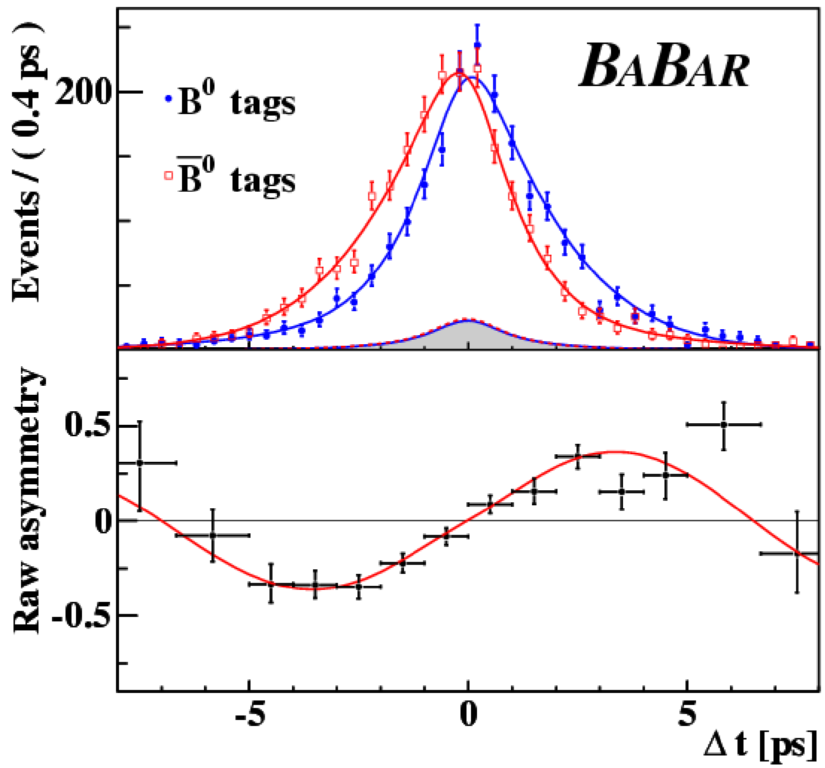
$$A_{CP}(J/\psi K_s;t) = \sin 2\beta \, \sin \Delta m_d\, t$$

Works for several other $b \to c\bar{c}s$ decays as well; results can be combined

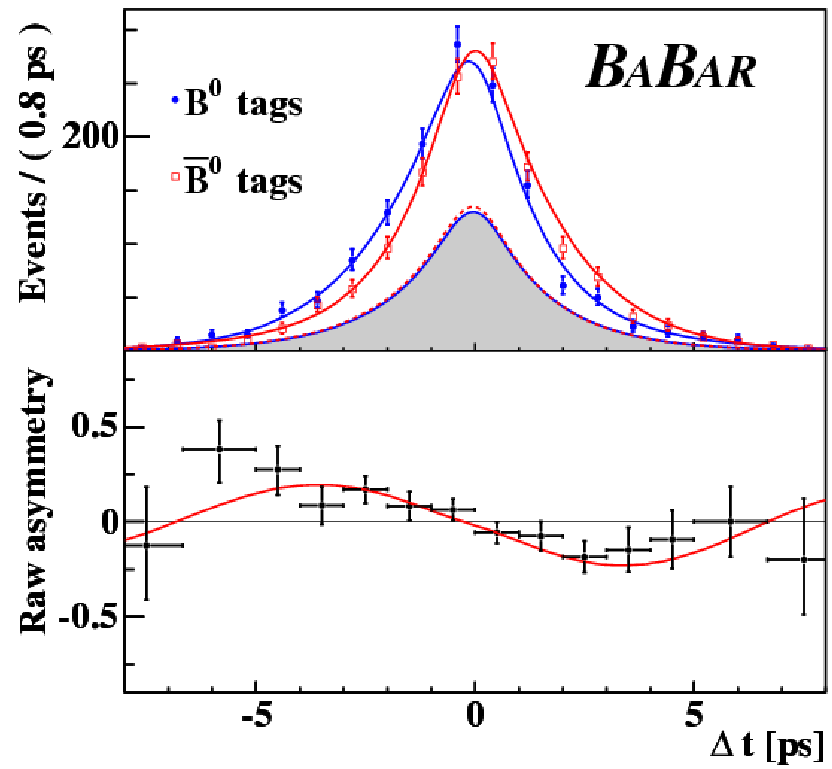
sin 2β fit results

Raw asymmetry $A(\Delta t) \approx (1 - 2w)\ \sin 2\beta\ \ \sin \Delta m \Delta t$

$(c\bar{c})\ K_S$ (CP odd) modes



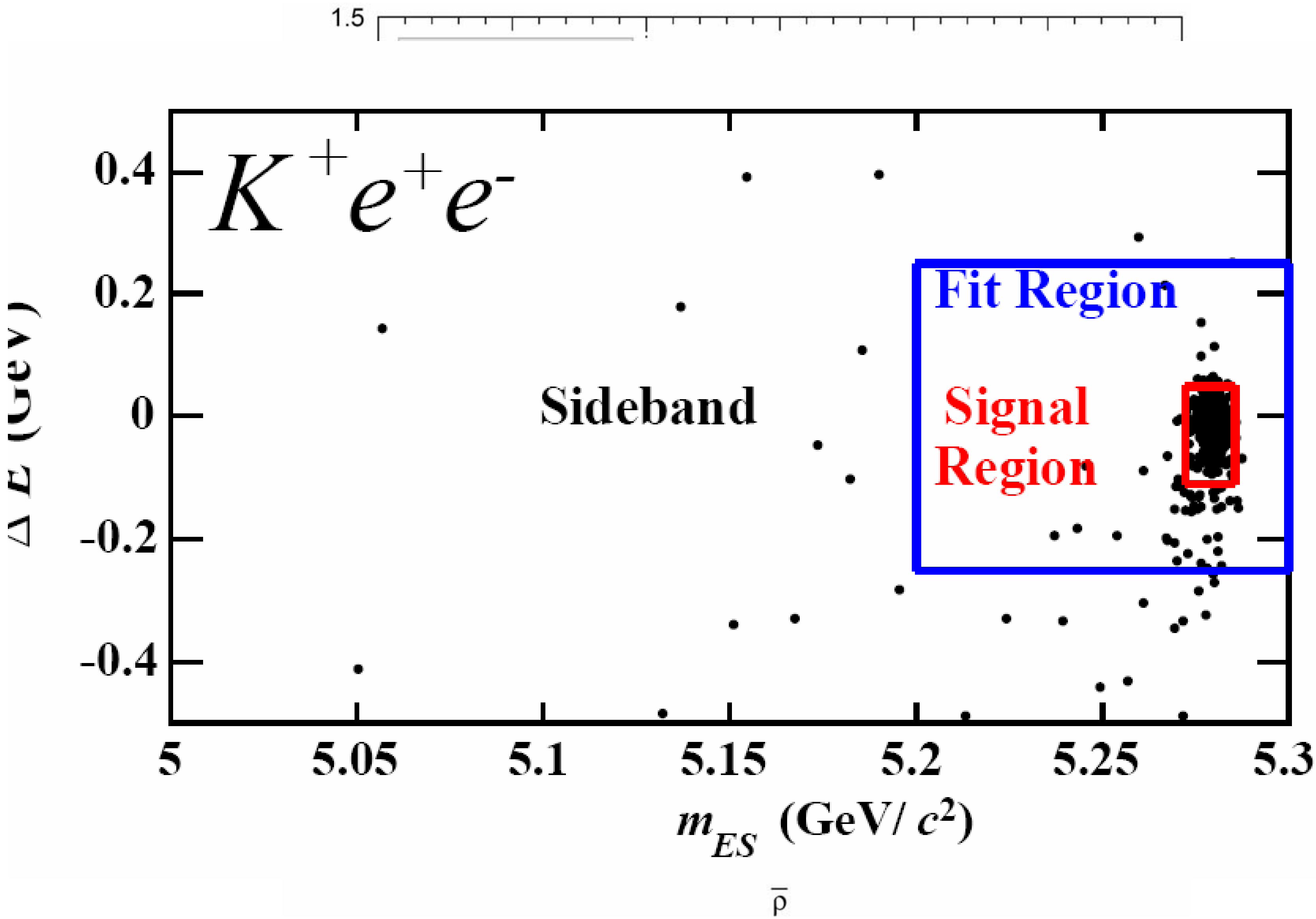
$J/\psi\ K_L$ (CP even) mode



Signal yield, background yield, sin 2β, flavor tagging, Δt resolution function all from simultaneous maximum likelihood fit to signal+control samples

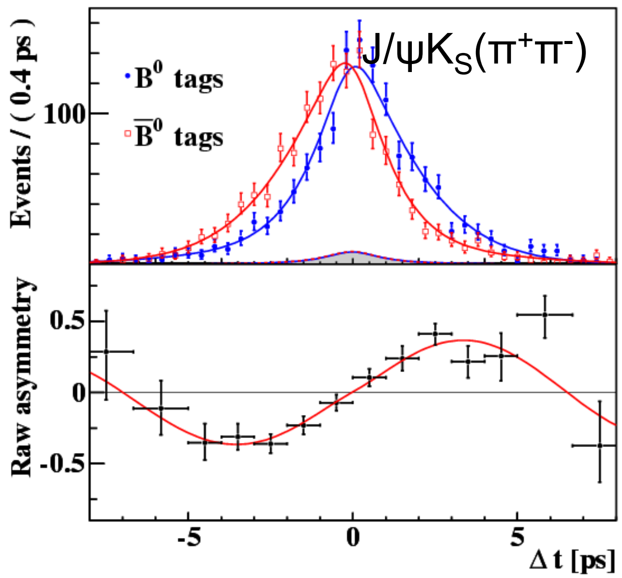
$\sin 2\beta = 0.722 \pm 0.040\ (\text{stat}) \pm 0.023\ (\text{sys})$

CKM Unitarity Triangle: Experimental Constraints

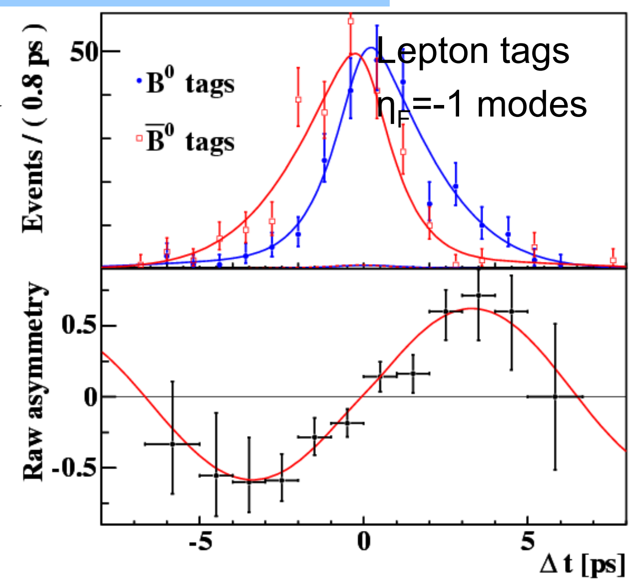


Consistency checks

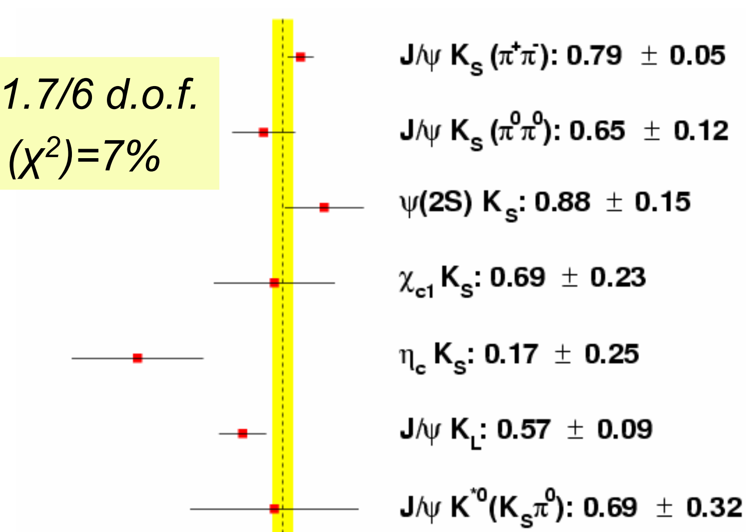
Cleanest charmonium sample



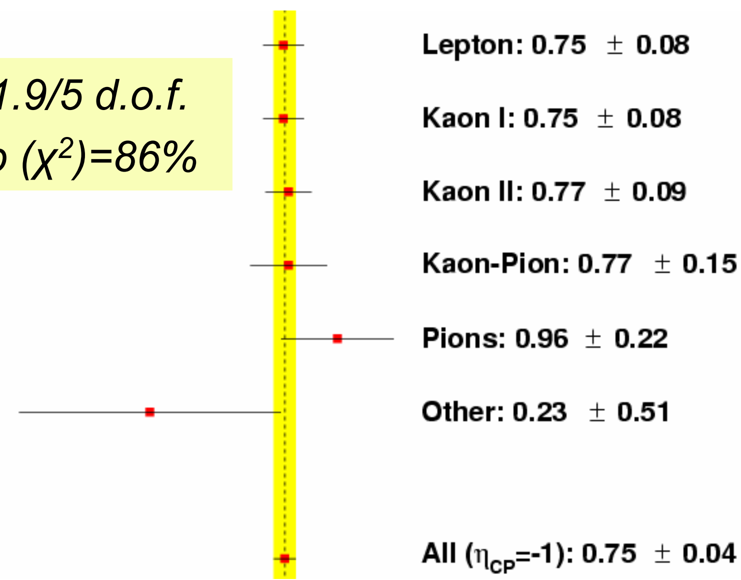
Purest flavor tagging mode



X^2=11.7/6 d.o.f.
Prob (χ^2)=7%



X^2=1.9/5 d.o.f.
Prob (χ^2)=86%

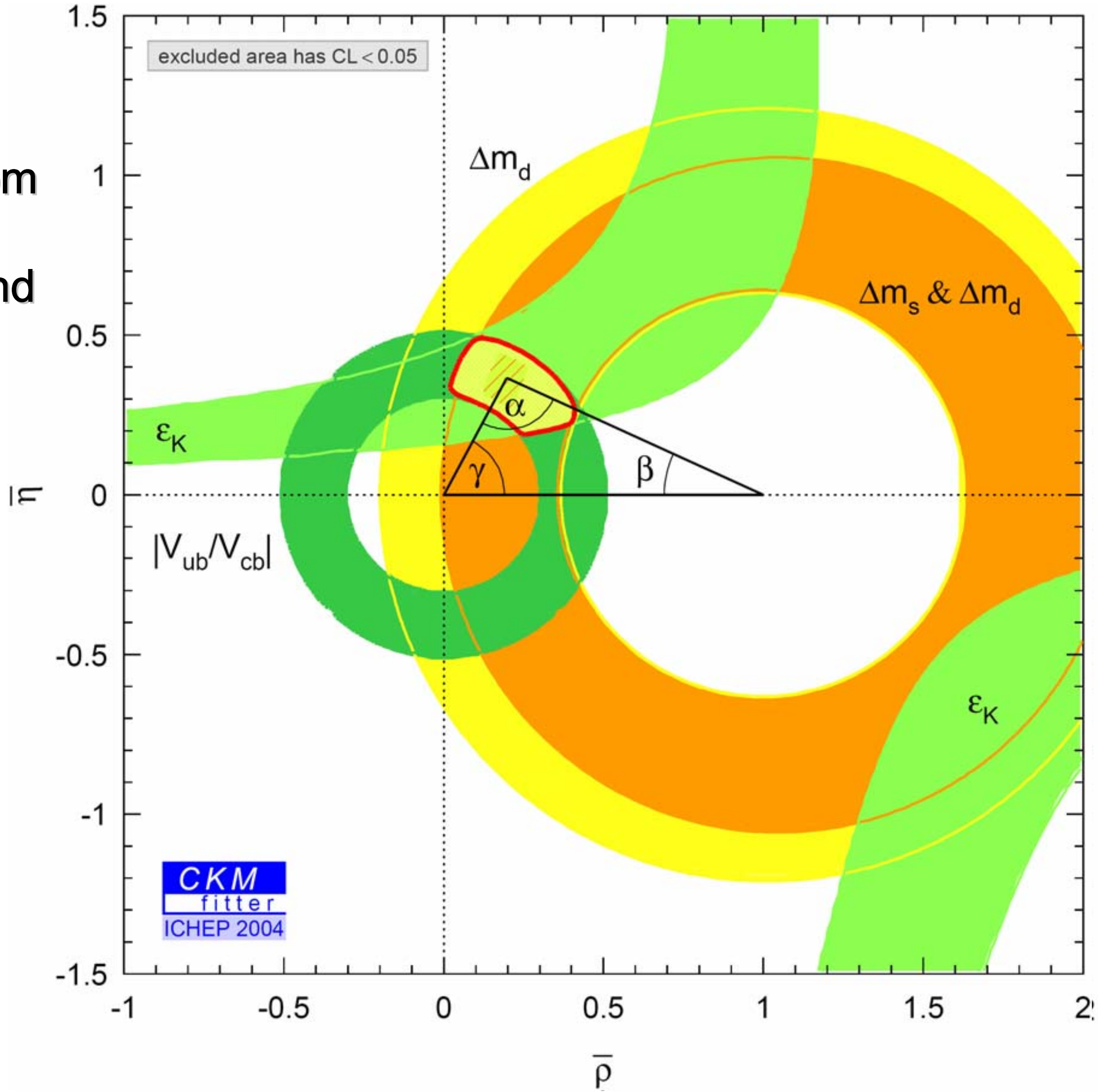


CKM Unitarity Triangle: Experimental Constraints

Constraints from

Decay rates and
Mixing Rates

CP violation in
Kaon decay



Future and Follow-up Measurements

- Both B factories hope to collect 4-5 X more data over the next 4-5 years
  - Significance of the penguin problem could double and unambiguously falsify the Standard Model!

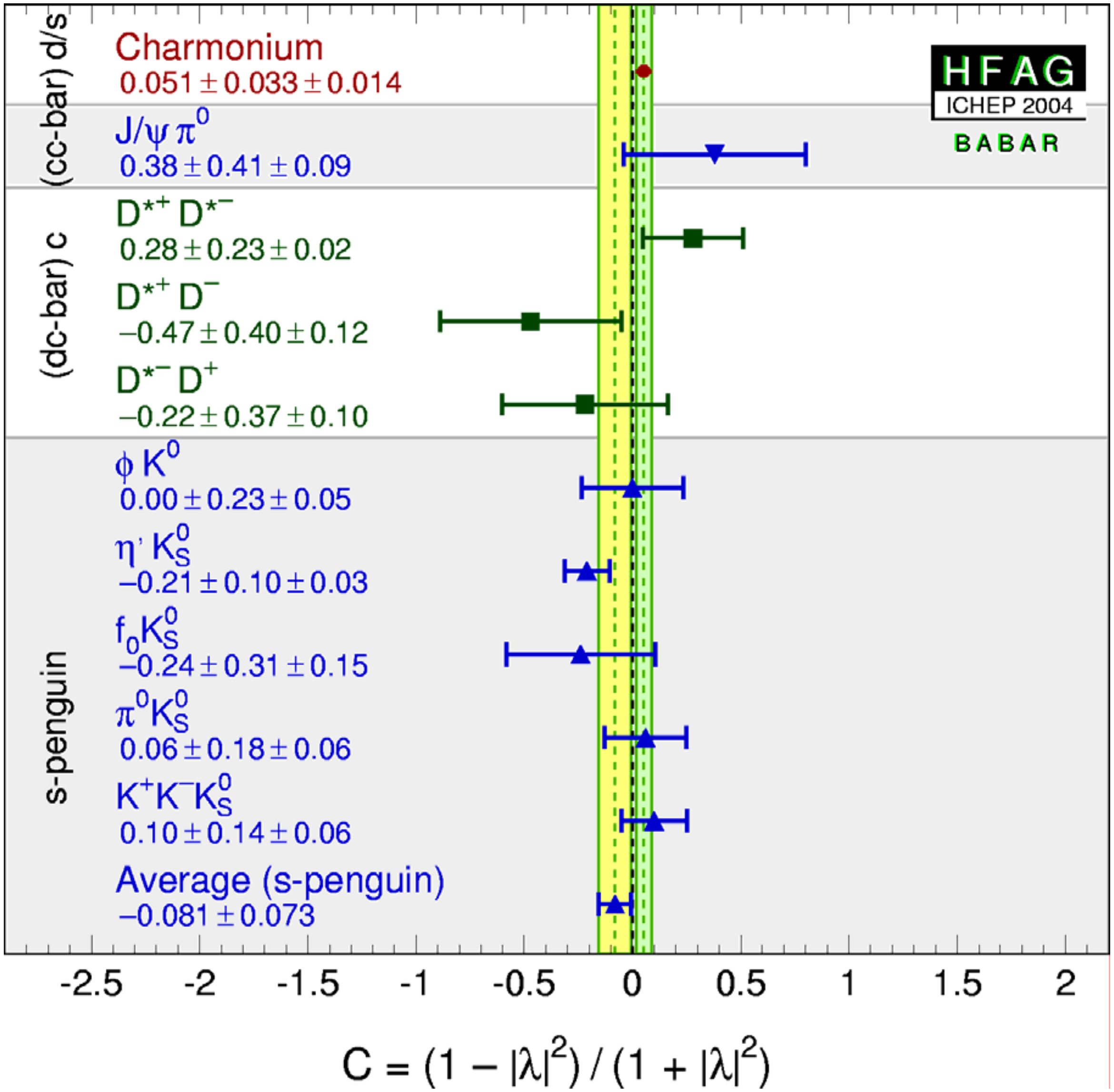
- Improved measurements of rates and asymmetries in other penguin decays ($b \rightarrow s\,\gamma$, $b \rightarrow d\,\gamma$, $b \rightarrow s\,l\,l$, $B \rightarrow \phi\,K^*$, ……)

- Fermilab Tevatron can measure B_s , Λ_b decays

- LHCb, BTeV: scheduled to produce billions of B's in pp collisions

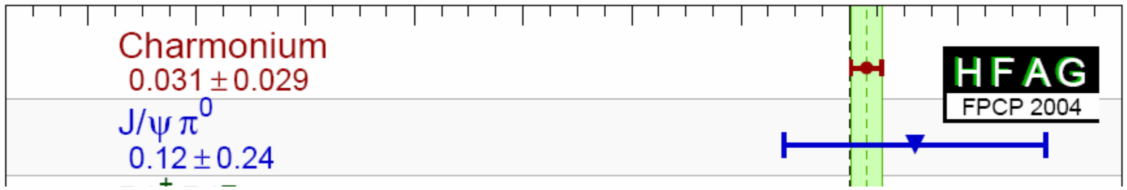
- Super B Factory: 50X version of B factories

Direct CP Violation: BaBar Data



Direct CP violation consistent with 0 for all modes

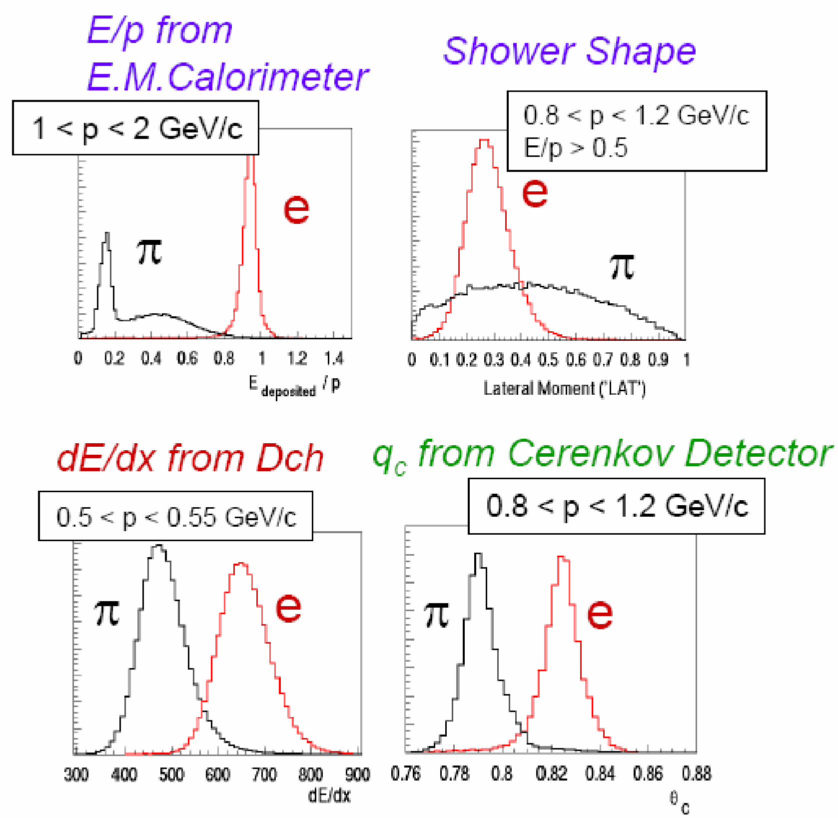
Direct CP Violation: World Average



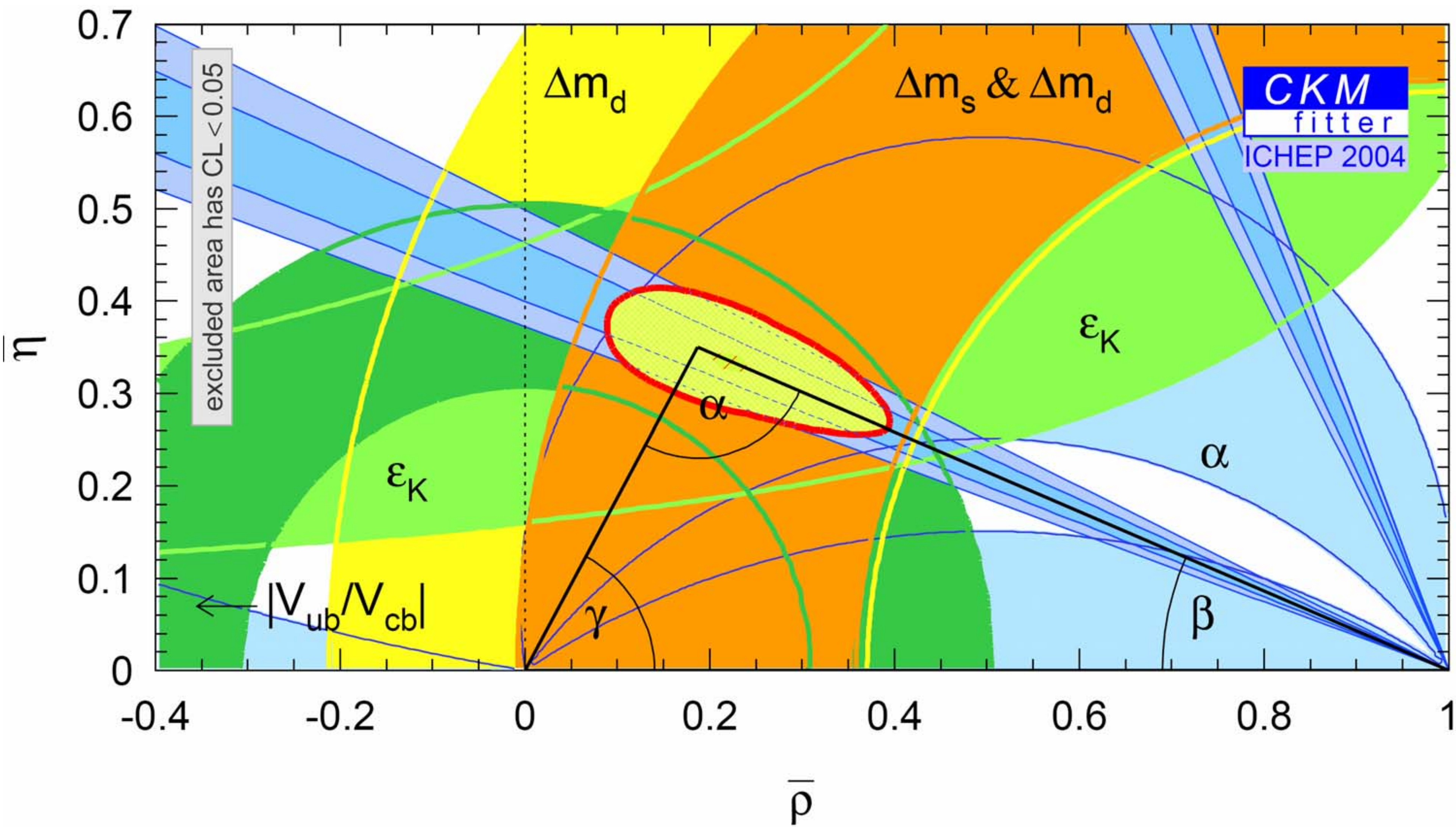
Electrons – p* > 0.5 GeV

- •shower shapes in EMC
- •E/p match

- Muons – p* > 1 GeV
  - Penetration in iron of IFR
- Kaons
  - dE/dx in SVT, DCH
  - θ_C in DRC



CKM Constraints



Direct CP Asymmetry: b →sγ and $B \rightarrow K^* \gamma$

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Either inclusive or exclusive decays could reveal new physics

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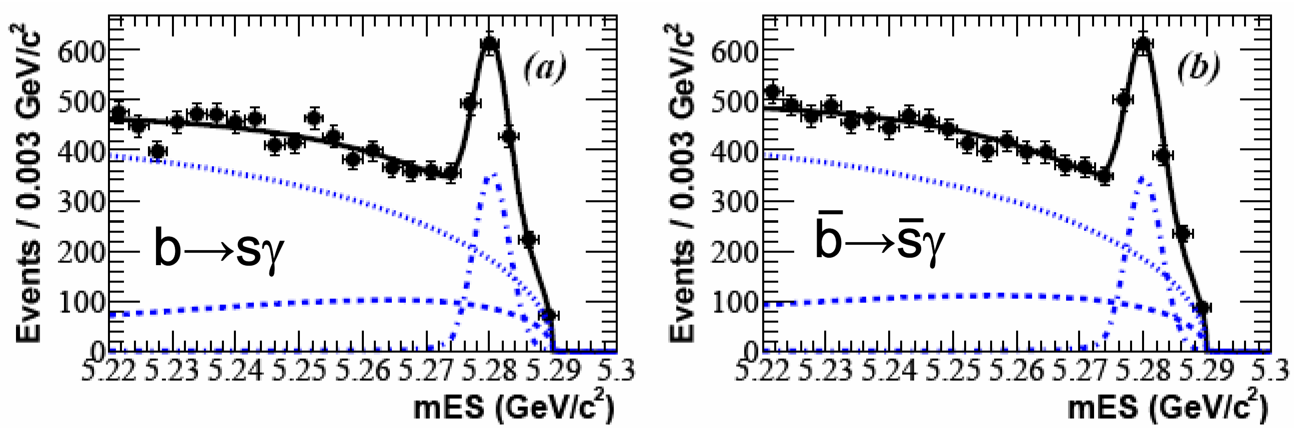


Sum of 12 exclusive, self-tagging $B \rightarrow X_s\ \gamma$ final states

$X_s = K/K_s$ + 1-3 pions
$E\gamma^* > 2.14$ GeV

b →sγ $A_{CP} = (N - \bar{N})/(N + \bar{N}) = 0.025 \pm 0.050 \pm 0.015$

PRL 93 (2004) 021804, hep-ex/0403035

Asymmetries also measured precisely in exclusive K*γ decays:

B →K*γ $A_{CP} = -0.013 \pm 0.036 \pm 0.010$

submitted to PRL, hep-ex/0407003

$$\Delta_{0-} = \frac{\Gamma(\bar{K}^{*0}\gamma) - \Gamma(K^{*-}\gamma)}{\Gamma(\bar{K}^{*0}\gamma) + \Gamma(K^{*-}\gamma)} = 0.050 \pm 0.045 \pm 0.028 \pm 0.024$$

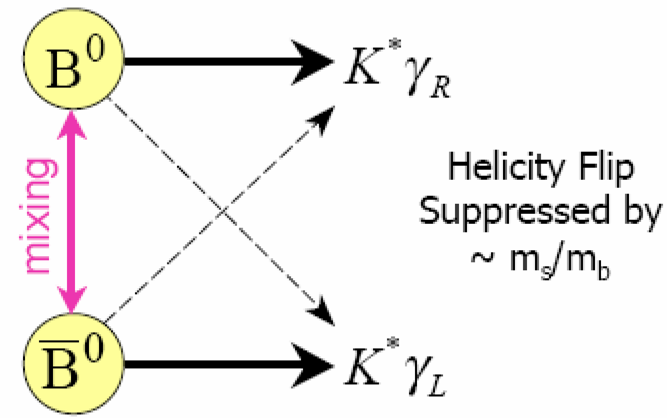
preliminary

Time-Dependent CP Asymmetry in $B \to K^*\gamma$ (113 fb^{-1})

As in $B^0 \to J/\psi\ K_S$, interference between mixed and non-mixed decay to same final state required for CPV.

In the SM, mixed decay to $K^*\gamma$ requires wrong photon helicity, thus CPV is suppressed:

In SM: $C = -A_{CP} \approx -1\%$ $S \approx 2(m_s/m_b)\sin 2\beta \approx 4\%$



Measuring Δt of $K^*(\to K_S\pi^0)\ \gamma$ events requires novel beam-constrained vertexing techinque:

Vertex signal B with intersection of K_S trajectory and beam-line

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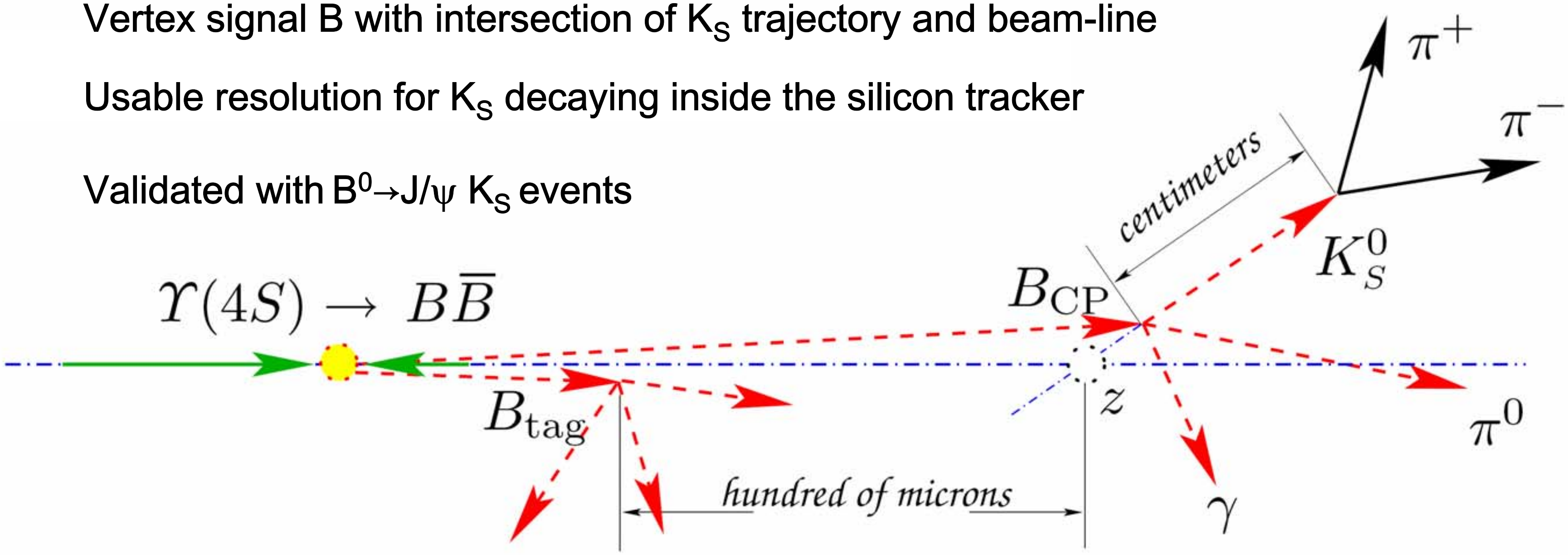
Validated with $B^0 \to J/\psi\ K_S$ events



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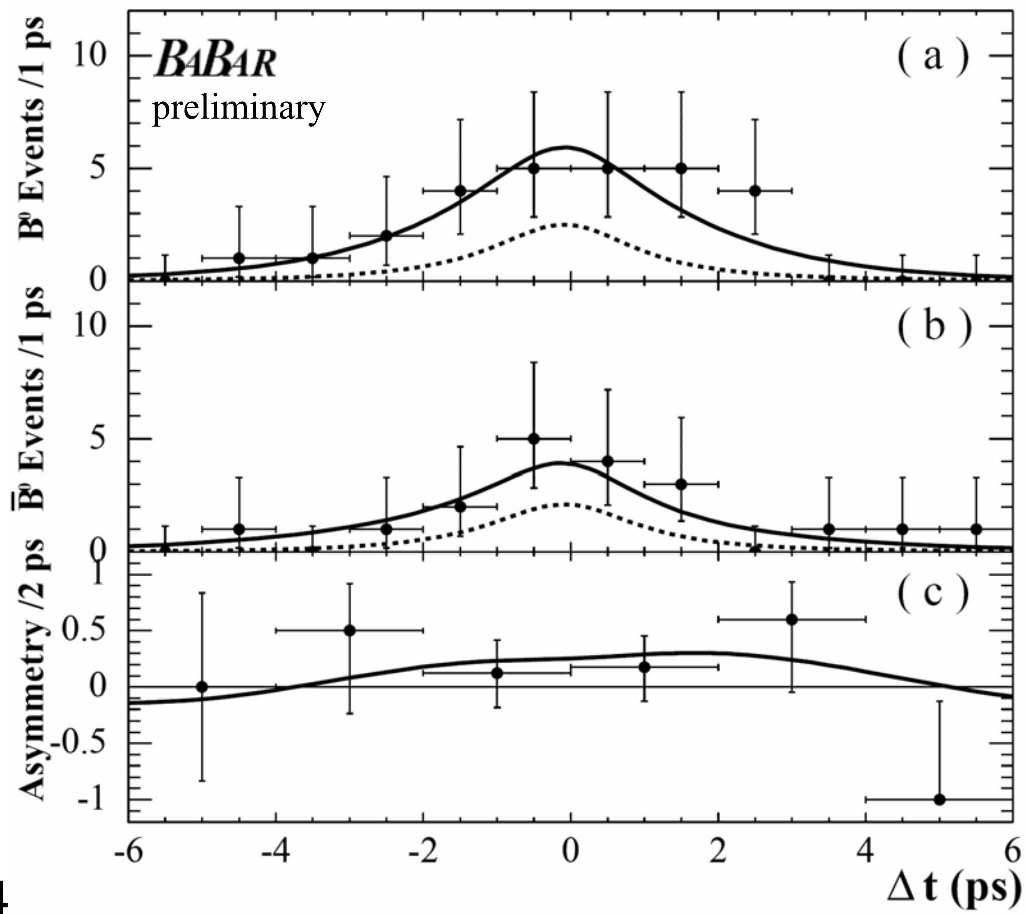
Likelihood fit of three components
($q\bar{q}$, $B\bar{B}$, $K^*\gamma$)
to 5D data
(m_{ES},ΔE,Fisher,m_{K^*},Δt)

$K^*\gamma$ signal = 105 ± 14 events



S = +0.25 ± 0.63 ± 0.14

C = -0.57 ± 0.32 ± 0.09

submitted to PRL, hep-ex/0405082

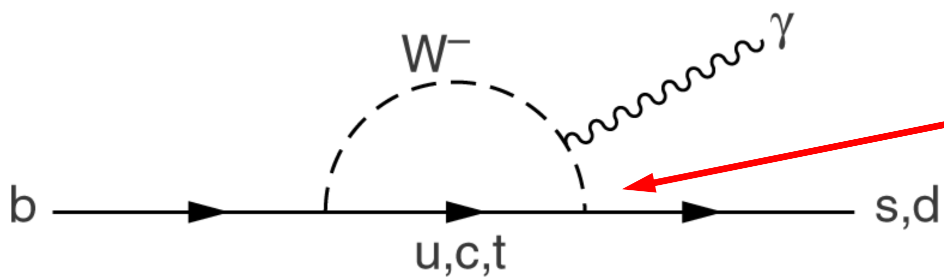
Consistent with SM

For C fixed to 0, S = 0.25 ± 0.65 ± 0.14

First ever measurement of time-dependent CP asymmetries in radiative penguins!

Radiative Penguin Decays and New Physics

Radiative penguin decays: $b \to s\gamma$ and $b \to d\gamma$ FCNC transitions



SM leading order = one EW loop
V_{ts}, V_{td} dependent

FCNCs probe a high virtual energy scale comparable to high-energy colliders
Radiative FCNCs have precise SM predictions:

$$BF(b\to s\gamma)_{TH} = 3.57 \pm 0.30 \times 10^{-4} \text{ (SM NLO)}$$
$$BF(b\to s\gamma)_{EXP} = 3.54 \pm 0.30 \times 10^{-4} \text{ (HFAG)}$$

Multiple new $BF(b\to s\gamma)$ measurements coming soon from BaBar

Decay rate agreement highly constrains new physics at the electroweak scale!

Further tests presented here:
- Exclusive $b\to s\gamma$ decay rates
- $b\to s\gamma$ CP asymmetries
- $b\to d\gamma$ penguins

Measuring Exclusive Radiative Penguin Decays

Small rates (BF < 10^{-4}) on top of large backgrounds

Common strategy :

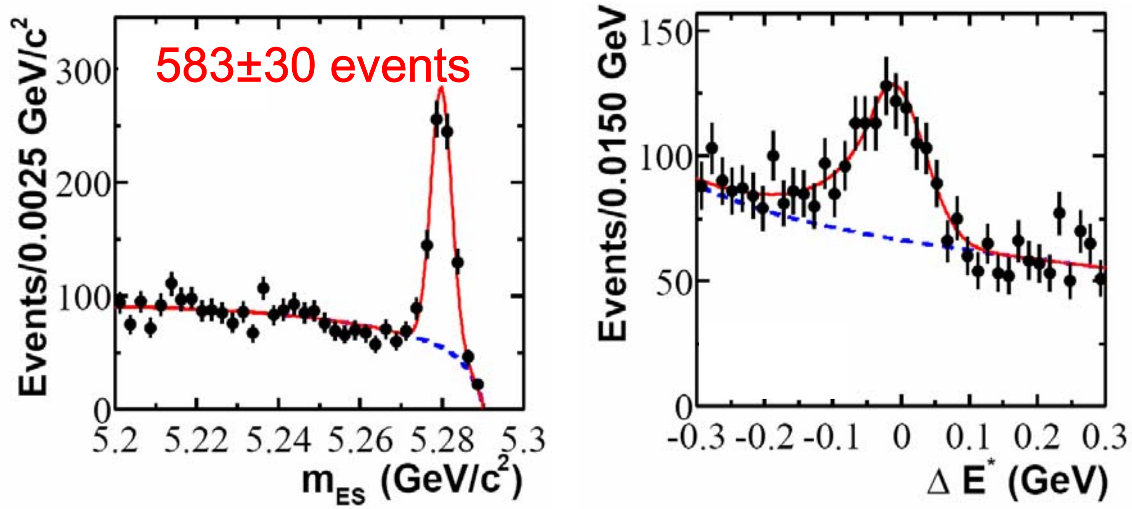
- select photon + hadrons with strict particle ID
- cut when possible on meson masses
- reduce continuum background with multivariate methods
- extract signal with multi-dimensional maximum likelihood fit

Best kinematic constraints from B candidate momentum and energy, compared with E_{beam}:

$$m_{\mathrm{ES}} \equiv \sqrt{E_{\mathrm{beam}}^{*2} - \mathrm{p}_B^{*2}}$$
$$\Delta E^* \equiv E_B^* - E_{\mathrm{beam}}^*$$

* denotes CM frame

Ex: signal fit for $B \to K^{*0}\gamma$, $K^{*0} \to K^+\pi^-$

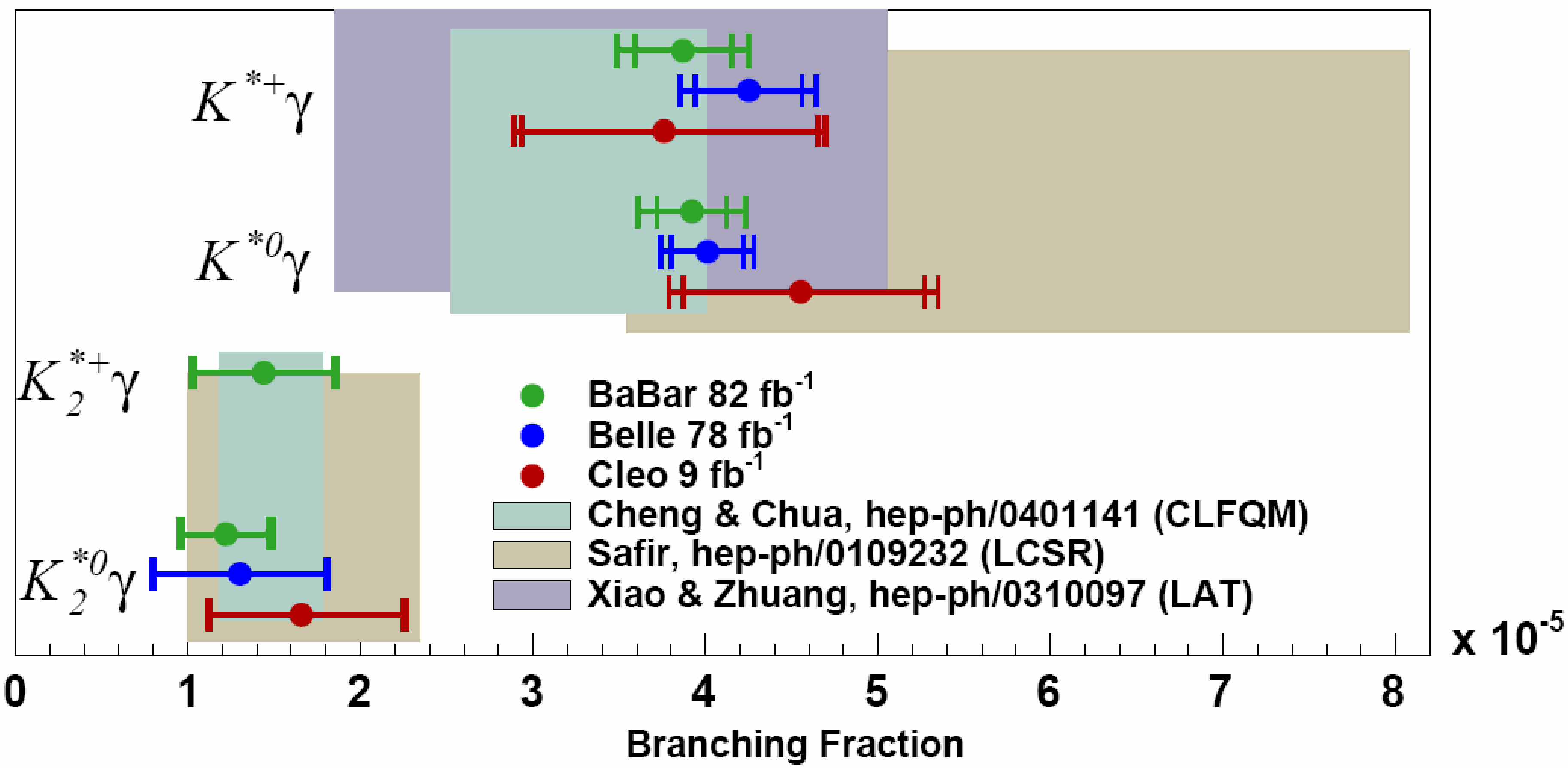


For signal, $m_{ES} \approx m_B$, $\sigma(m_{ES}) \approx 3$ MeV

$\Delta E^* \approx 0$, $\sigma(\Delta E^*) \approx 50$ MeV

$B \rightarrow K^* \gamma$ Branching Fractions: Summary

- BaBar preliminary measurements on 82 fb^{-1}
- Becoming systematics limited
- Exp. vs. theory: data more accurate than form factor predictions!



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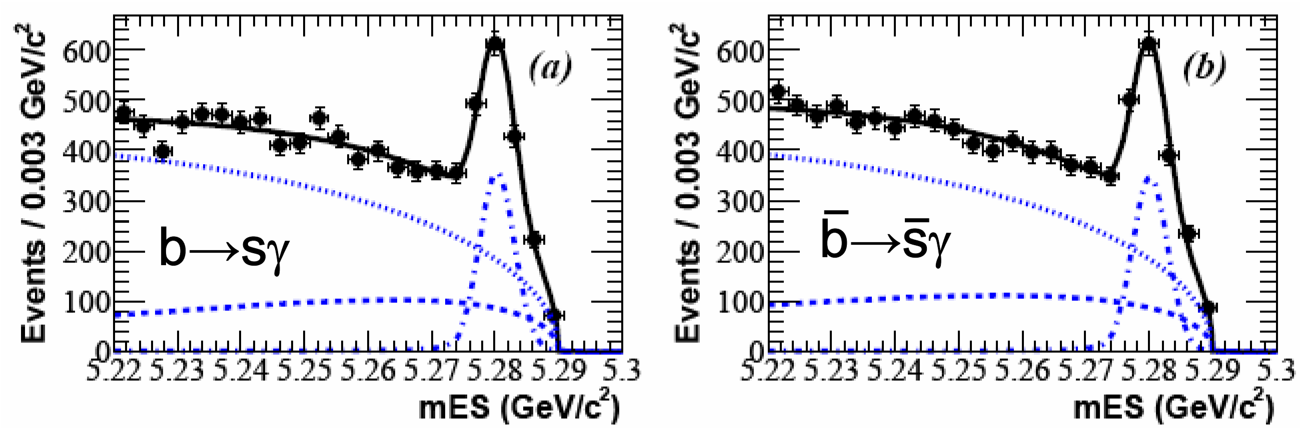

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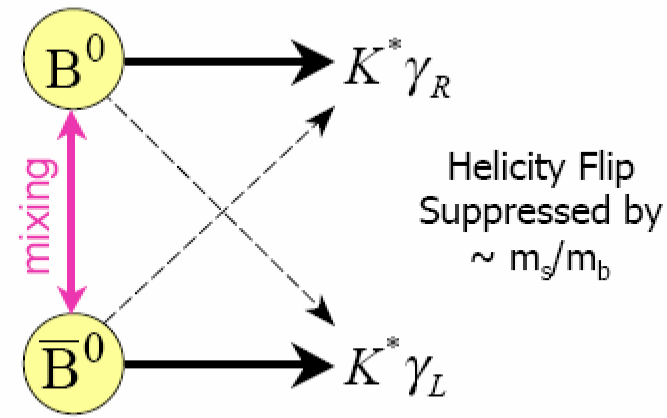

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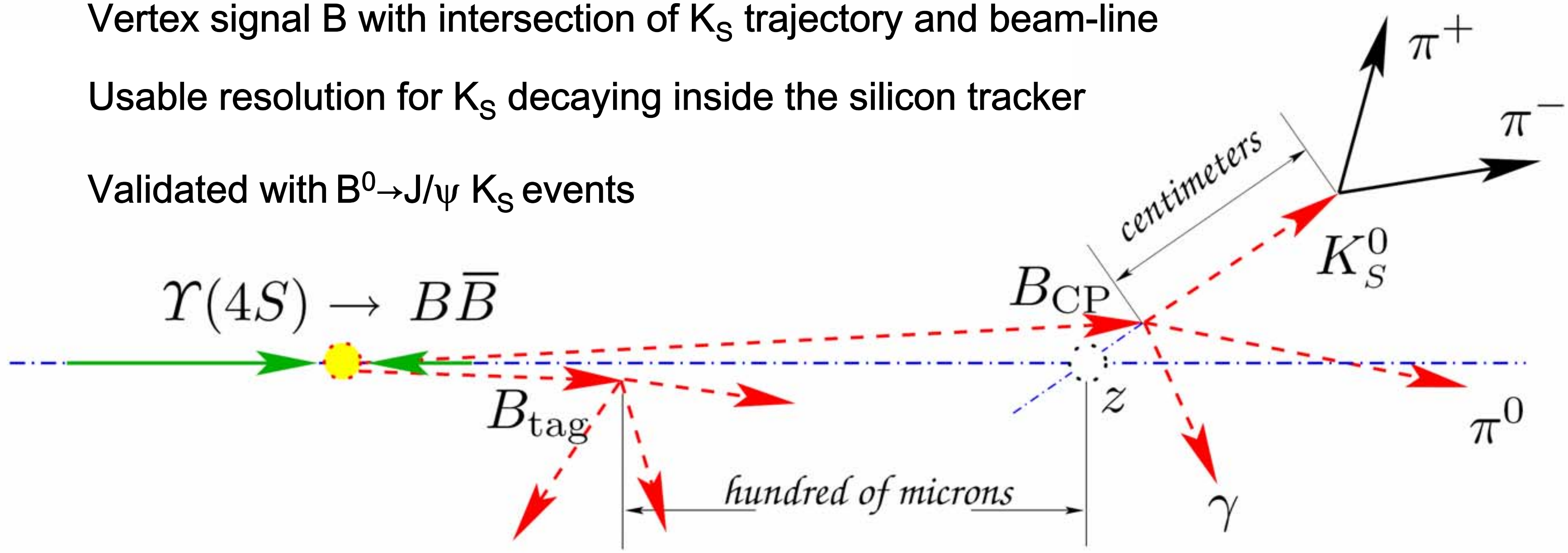

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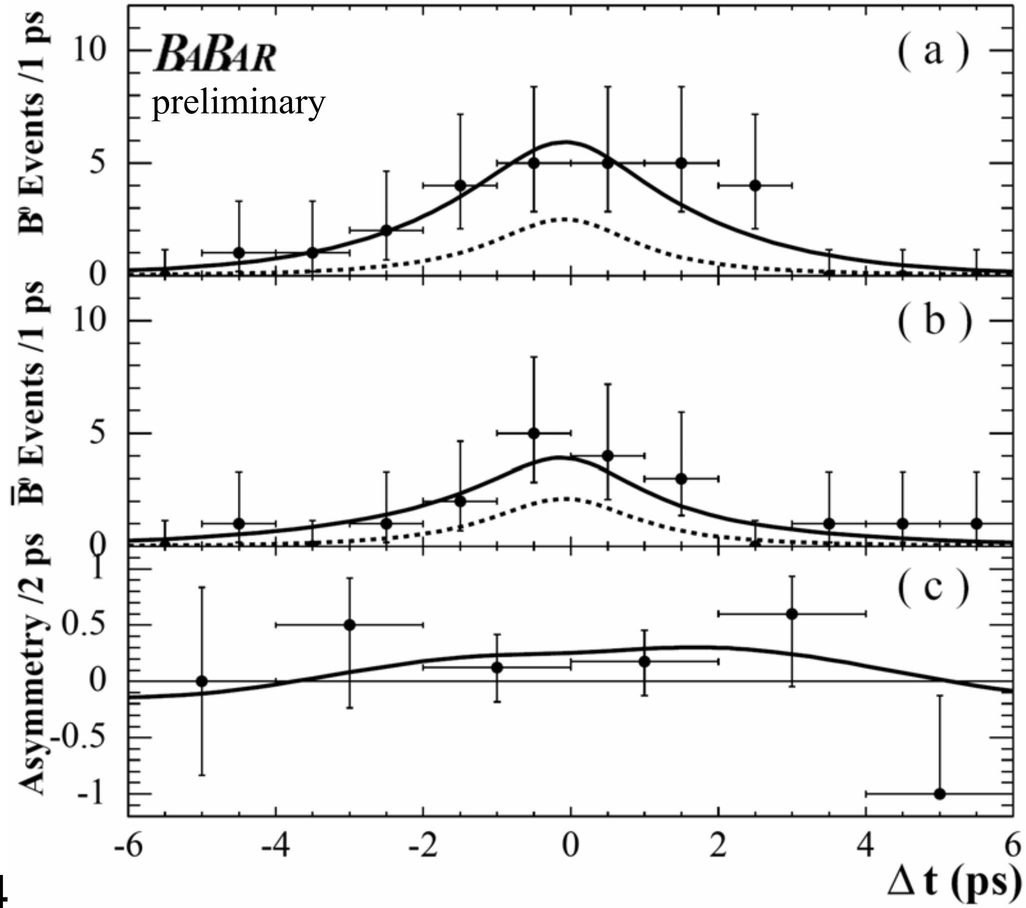

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submitted to PRL, hep-ex/0405082

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First ever measurement of time-dependent CP asymmetries in radiative penguins!

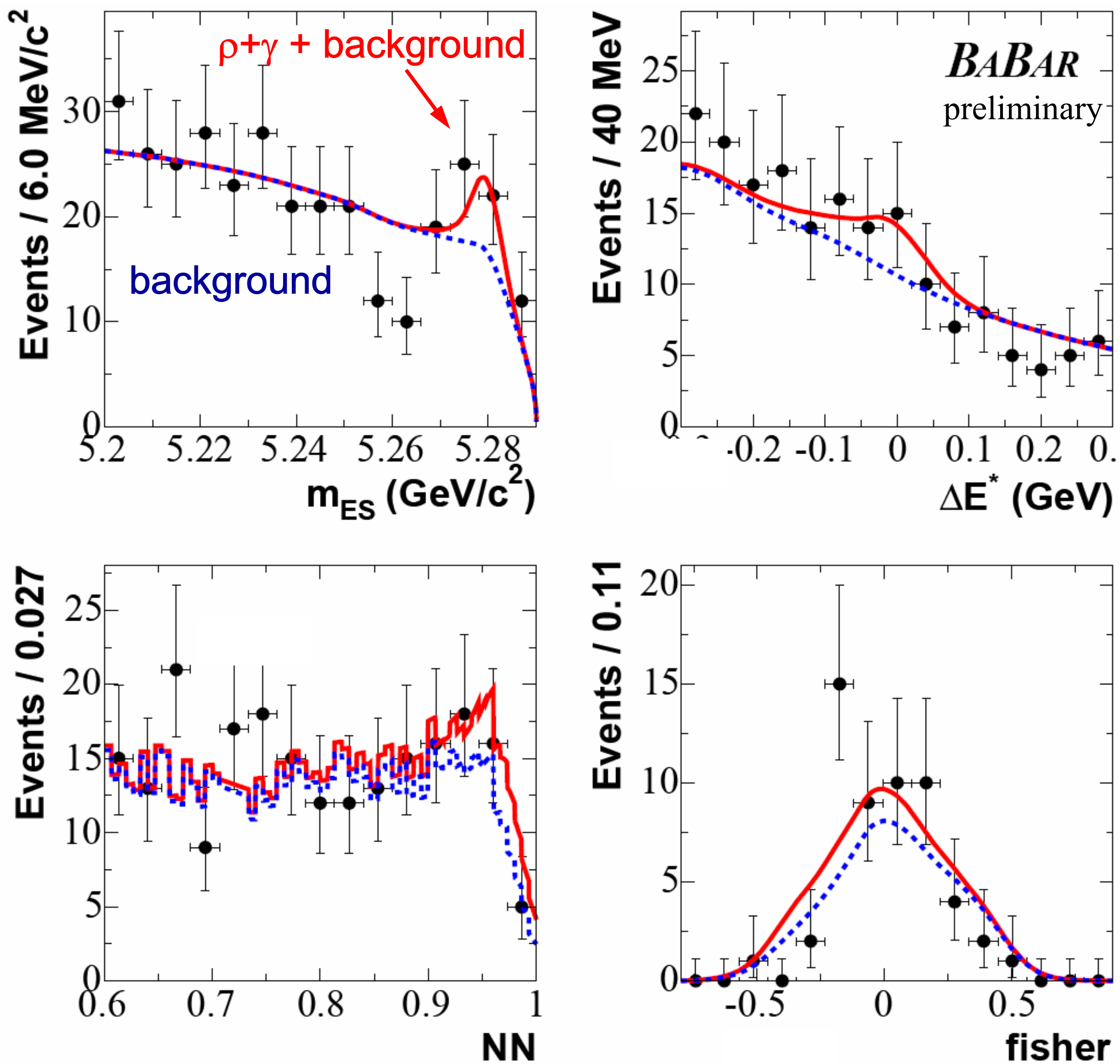
Signal Fit: $B^+ \rightarrow \rho^+ \gamma$

N(signal) = 26 ± 15 ± 2
significance = 1.9 σ

ε = 13.2 ± 1.4 %

BF = (0.9 ± 0.6 ± 0.1) x10^{-6}

BF < 1.8 x10^{-6} 90% CL



Fit of four backgrounds ($q\bar{q}$, $X_s\,\gamma$, $\rho^+(\pi^0/\eta)$, $K^*\gamma$) and ρ+γ signal

$q\bar{q}$, $X_s\,\gamma$, $\rho^+\gamma$ yield are free parameters

Signal Fit: $B^0 \to \rho^0 \gamma$

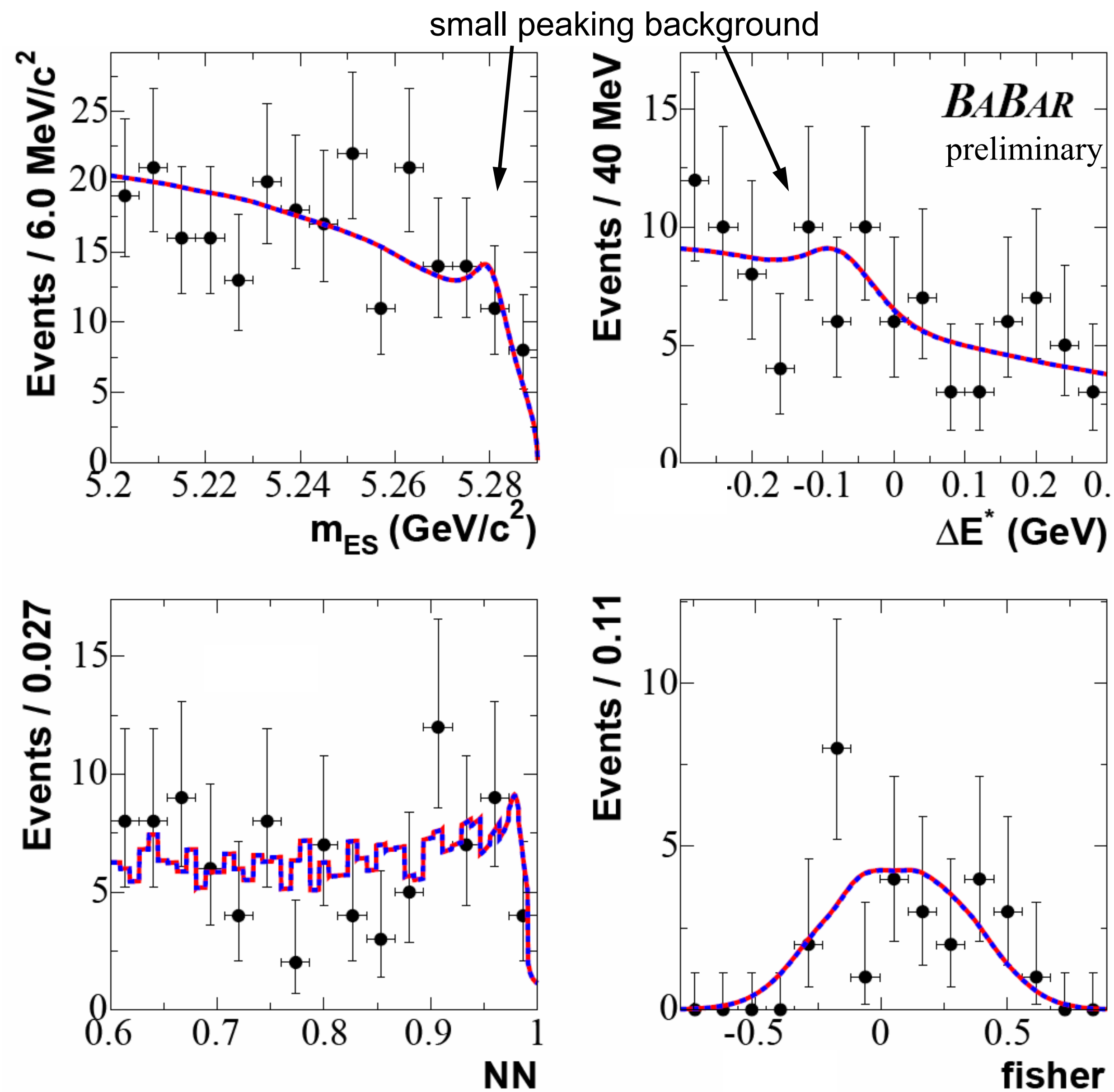
N(signal) = $0.3^{+7.2\ +1.7}_{-5.4\ -1.6}$

significance = 0.0 σ

ε = 15.8 ± 1.9 %

BF = (0.0 ± 0.2 ± 0.1) x10^{-6}

BF < 0.4 x10^{-6} 90% CL



Fit of four backgrounds ($q\bar{q}$, $X_s\,\gamma$, $\rho^0(\pi^0/\eta)$, $K^*\gamma$) and $\rho^0\gamma$ signal

$q\bar{q}$, $X_s\,\gamma$, $\rho^0\gamma$ yield are free parameters

Signal Fit: $B^0 \rightarrow \omega\,\gamma$

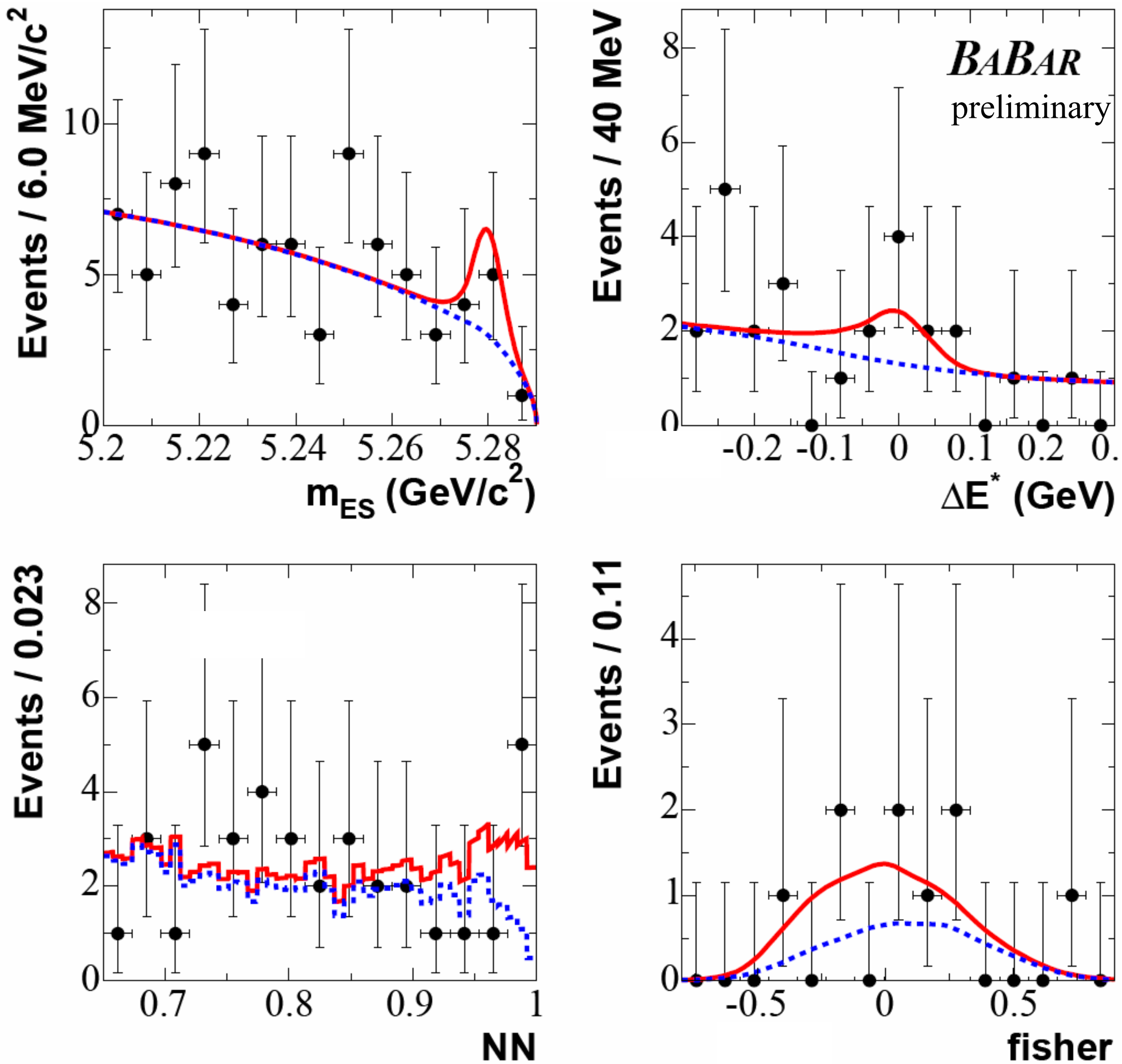
N(signal) = $8.3^{+5.7\ +1.3}_{-4.5\ -1.9}$

significance = 1.5 σ

ε = 8.6 ± 0.9 %

BF = (0.5 ± 0.3 ± 0.1) x10^{-6}

BF < 1.0 x10^{-6} 90% CL



Fit of two backgrounds
($q\bar{q}$, $\omega(\pi^0/\eta)$)
and $\omega\gamma$ signal

$q\bar{q}$, $\omega\gamma$ yield are free parameters

Summary

•**Decay rate measurements of b→ sγ penguins** are well into the precision era.

•**CP asymmetries of b→ sγ penguins** are statistics limited and will continue to test the SM

A_{CP} in B → X_s γ PRL 93 (2004) 021804, hep-ex/0403035
BF, A_{CP}, and Isospin asymmetry in B→ K*γ submitted to PRL, hep-ex/0407003
time-dependent CPV in $B^0 \rightarrow K^{*0}\gamma$ submitted to PRL, hep-ex/0405082 **First measurement!**

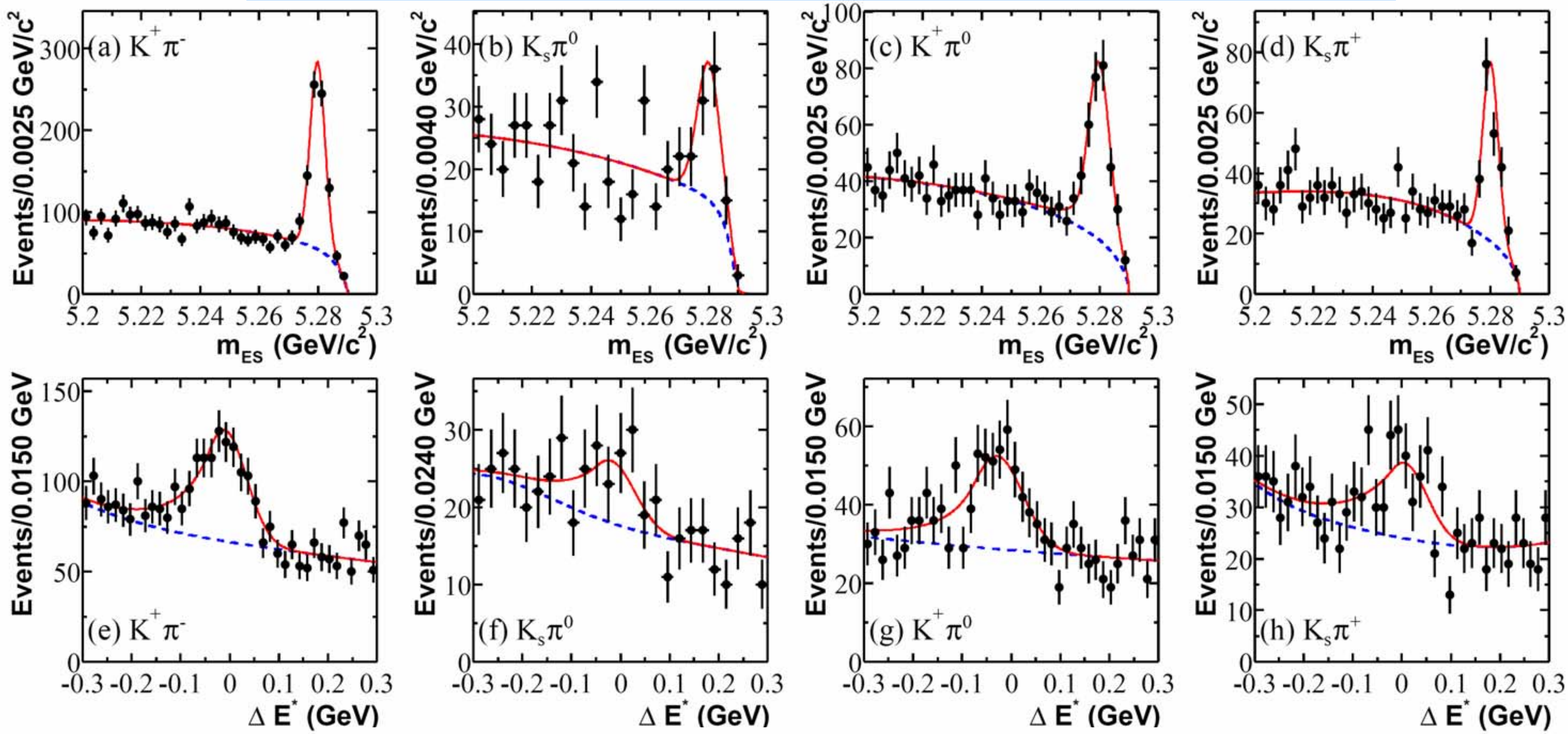
b→ dγ penguins are only now beginning to reveal themselves in B-factory data. They could also uncover new physics, or measure the poorly known $|V_{td}|$.

BaBar finds no evidence for B → ργ in 211 million $B\bar{B}$ events

submitted to PRL, hep-ex/0408034

$BF(B \rightarrow \rho,\omega\,\gamma) < 1.2 \times 10^{-6}$ $|V_{td}/V_{ts}| < 0.19$ (90% CL)

B → K*γ (82 fb^{-1}): Signal fits



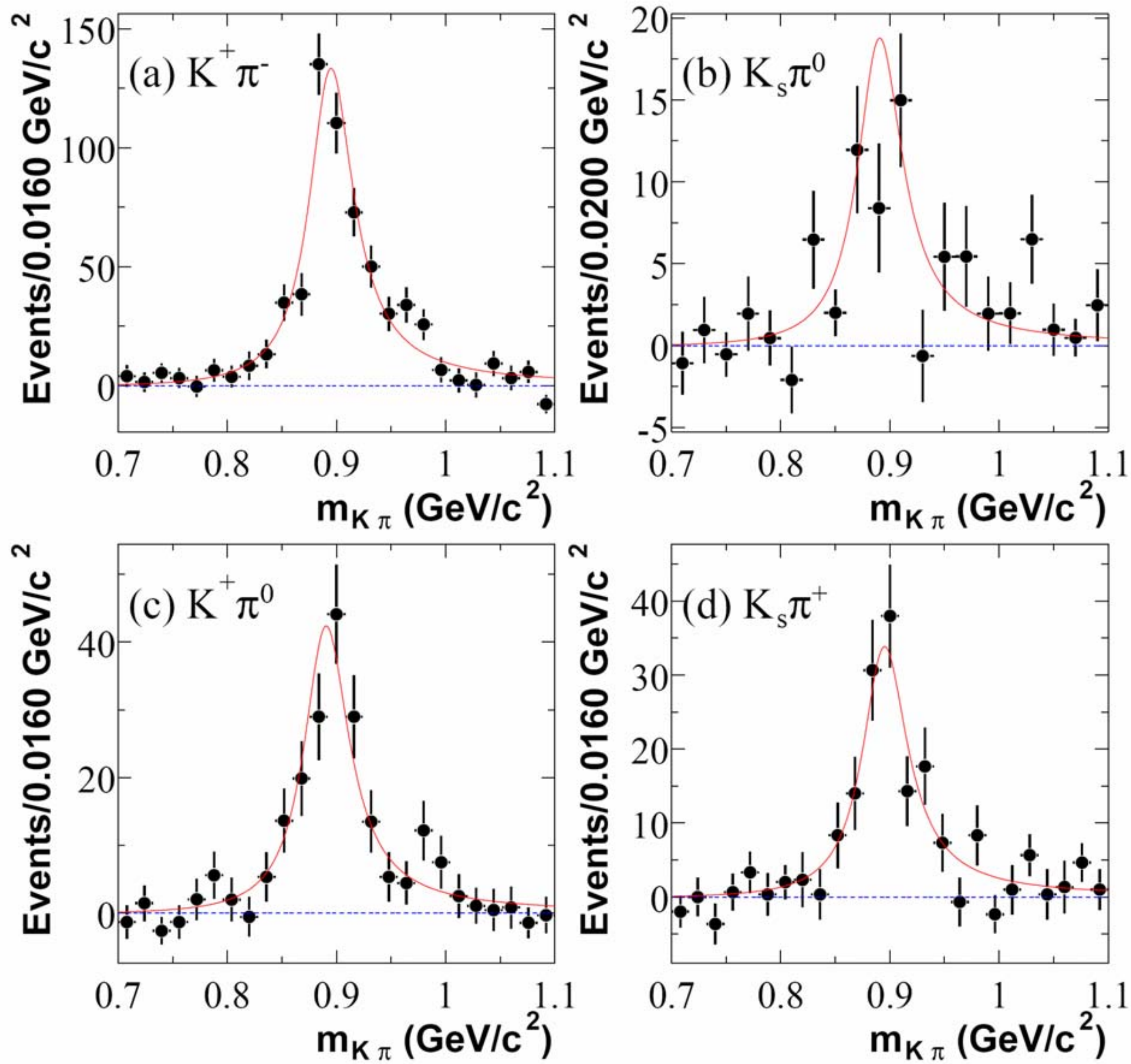
Mode	$\epsilon(\%)$	N_S	$\mathcal{B}(\times 10^{-5})$
$K^+\pi^-$	24.4±1.4	583±30	3.92±0.20±0.23
$K_s\pi^0$	15.3±1.9	62±15	4.02±0.99±0.51
$K^+\pi^0$	17.4±1.6	251±23	4.90±0.45±0.46
$K_s\pi^+$	22.1±1.4	157±16	3.52±0.35±0.22

$B \to K^*\gamma$ (82 fb^{-1}): $K^*\gamma$ lineshape

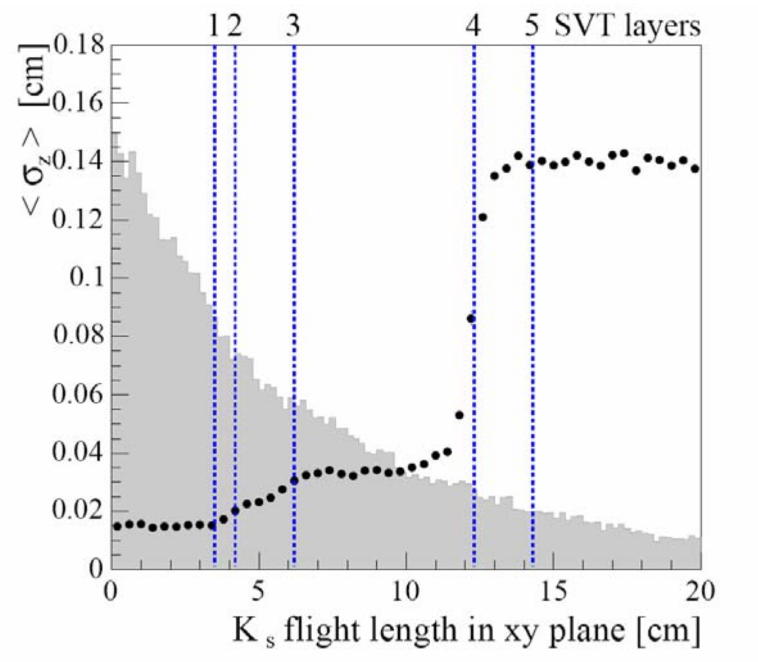
K^* lineshape for events with:
$m_{ES} > 5.27$ GeV/c^2
-0.2 GeV < ΔE < 0.1 GeV

Background subtracted with shape from m_{ES} sideband

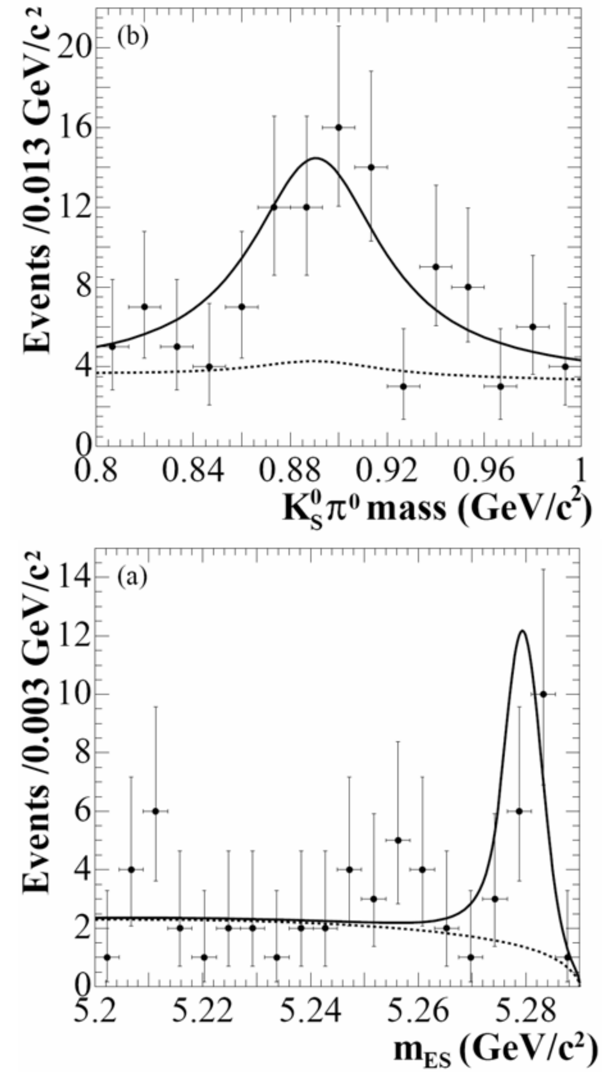
Fit to relativistic Breit-Wigner with PDG $\Gamma(K^*)$, m_{K^*}



Time-Dependent CP Asymmetry in $B \to K^*\gamma$

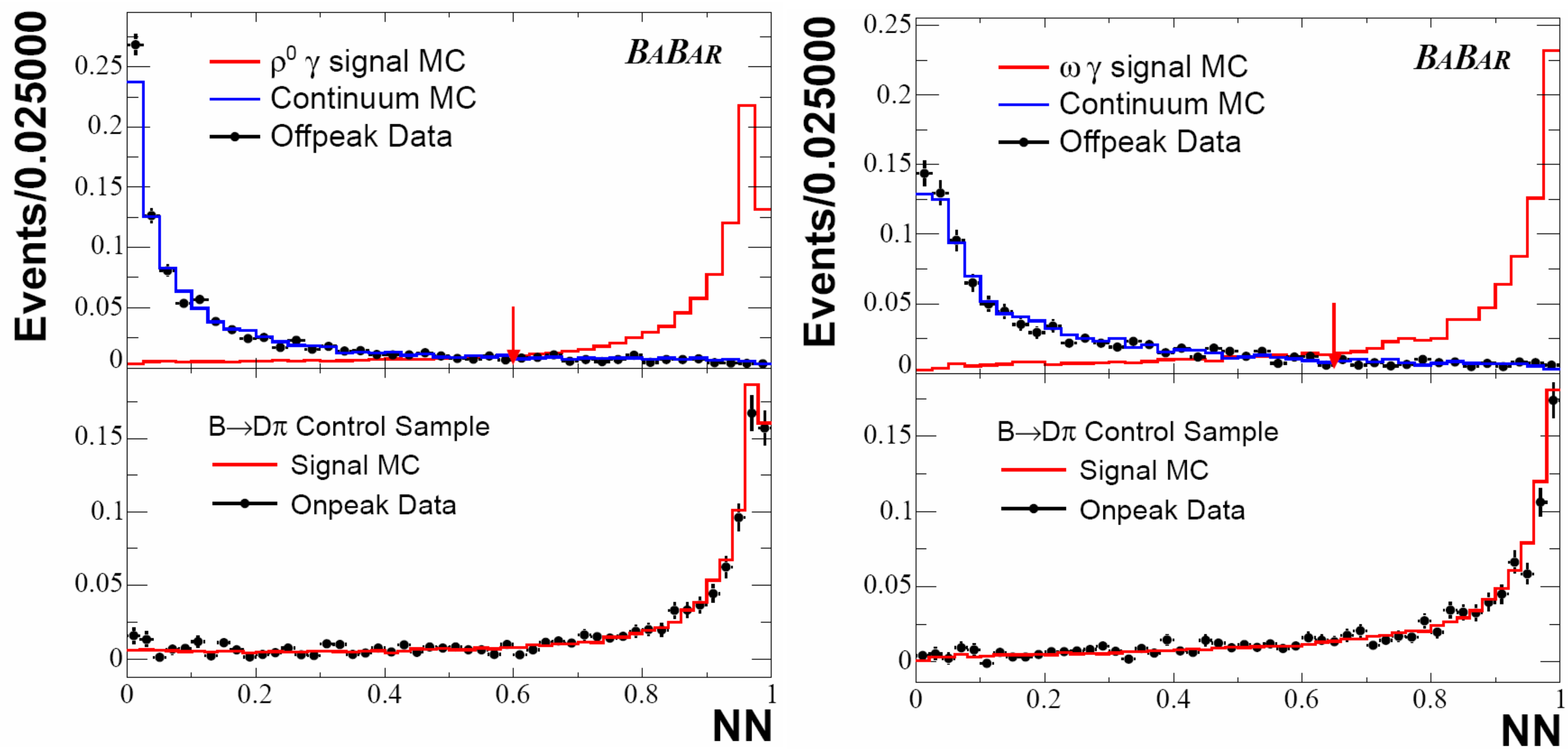


Z resolution vs. K_S decay radius

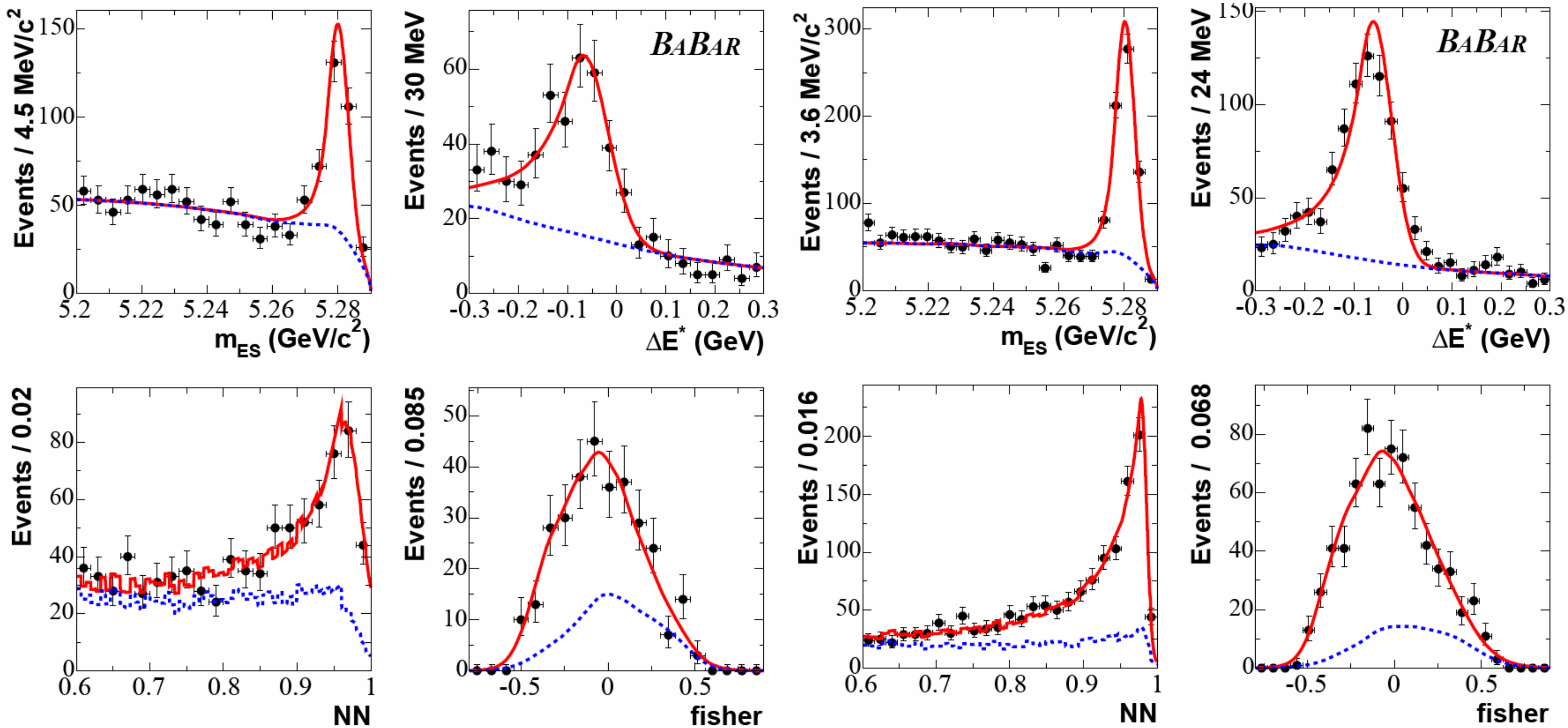


Projection of fit with likelihood cut

$B \to \rho\gamma$: Neural net performance



$B \to \rho\gamma$: $K^*\gamma$ Control Sample



$\rho^+\gamma$, no PID

$\rho^0\gamma$, no PID

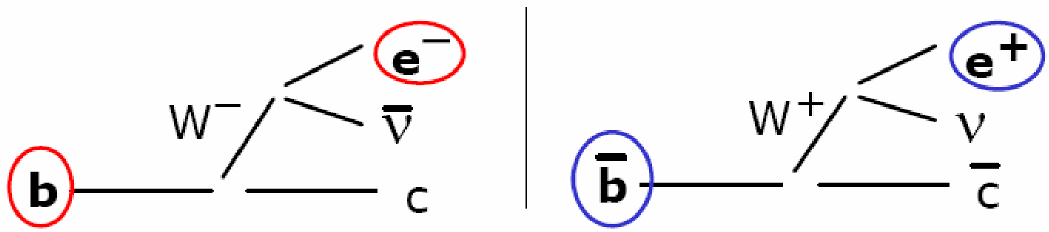
Flavor tagging

CP asymmetry is between $B^0 \to f$ and $\overline{B^0} \to f$

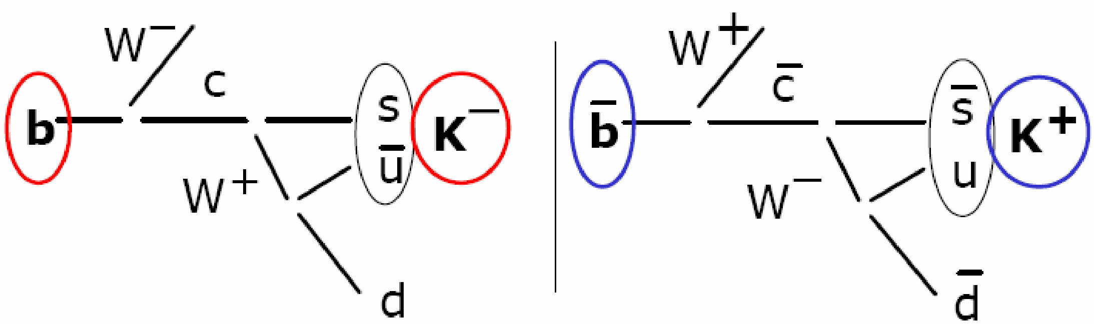
Must tag flavor at $\Delta t=0$ (when we know flavor of two Bs is opposite).

Use decay products of *other* (tag) B.

Leptons : Cleanest tag. Correct >95%



Kaons : Second best. Correct 80-90%



Full tagging algorithm combines all in neural network

Four categories based on particle content and NN output.

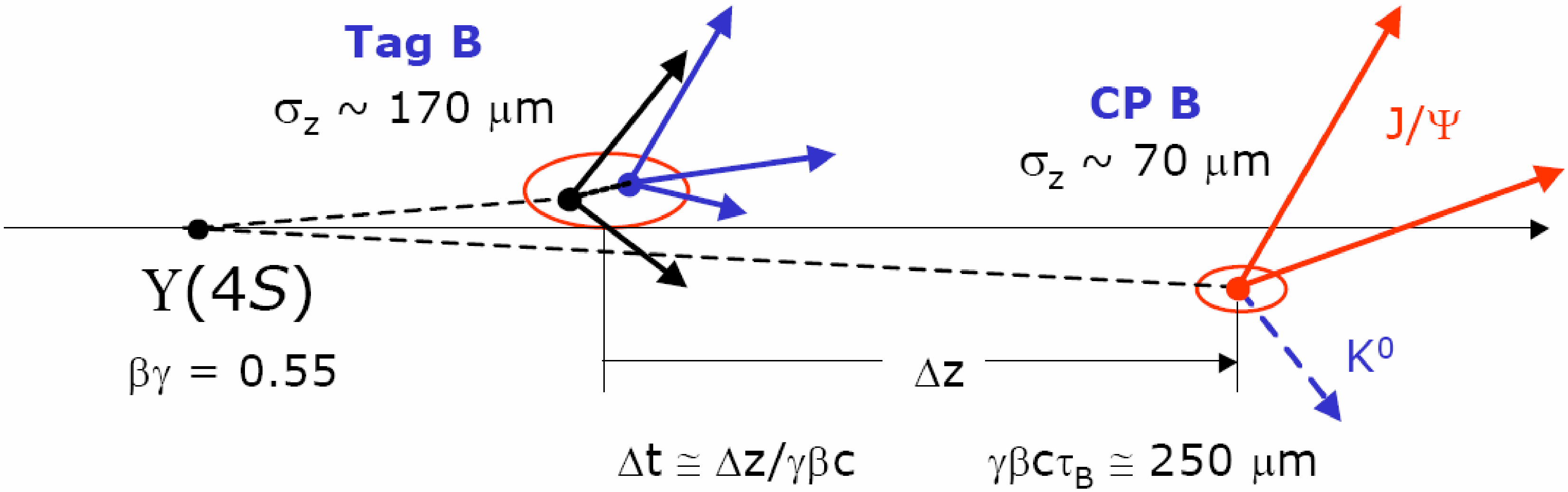
Tagging performance

$$\sum_i \epsilon_i (1 - 2\omega_i)^2$$

= 28% !

Measurement of Δt

- $J/\Psi \rightarrow l^+l^-$ dominates in determination of CP vertex.
- Tracks not from CP B combined to form tag vertex.
  - Tracks with large χ^2 iteratively removed.
  - Long-lived particles (K_s , Λ) explicitly reconstructed.
  - Photon conversions ($\gamma \rightarrow e^+e^-$) removed.
- Vertex incorporates constraint from average beam position.
- Efficiency for CP sample 97 % (95% after $|\Delta t|<20$ ps, $\sigma_{\Delta t}<2.5$ ps)



CKM matrix constraint

SU(3) breaking of form factors $\zeta^2 = 0.85 \pm 0.10$

weak annhilation correction $\Delta R = 0.1 \pm 0.1$

Ali et al. hep-ph/0405075

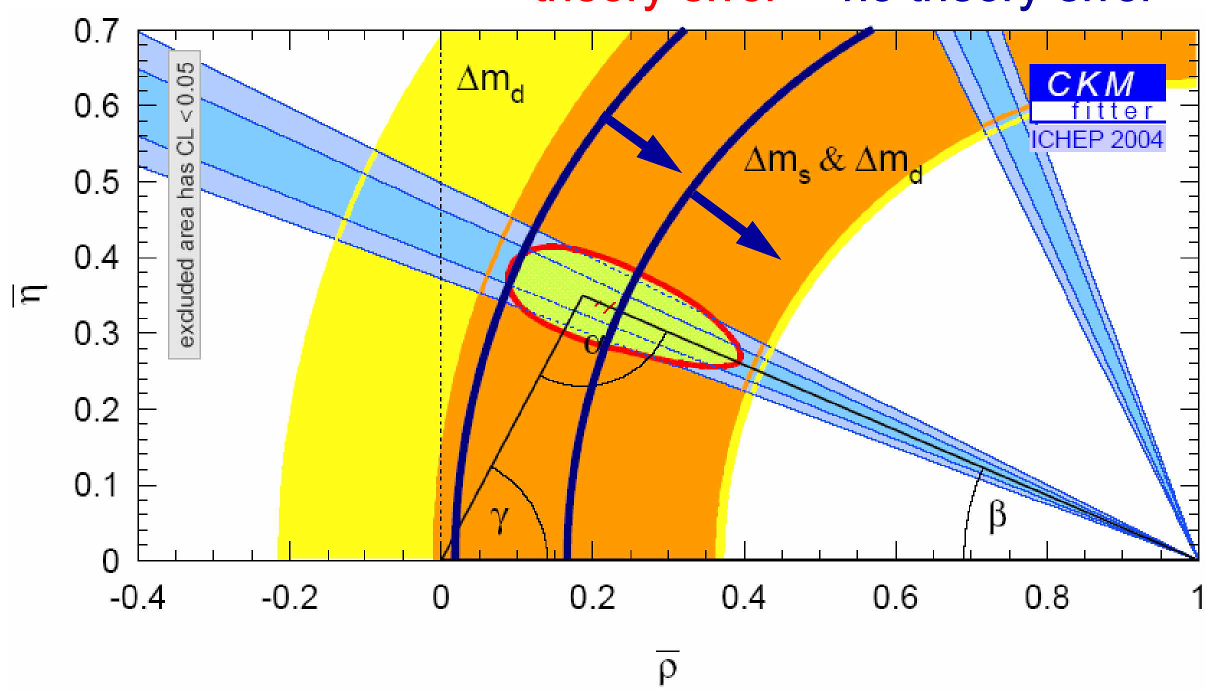
$$\frac{\overline{\mathcal{B}}[B \to (\rho/\omega)\gamma]}{\mathcal{B}(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1 - m_\rho^2/M_B^2}{1 - m_{K^*}^2/M_B^2}\right)^3 \zeta^2[1 + \Delta R]$$

$(\zeta^2, \Delta R) = (0.75, 0.00)$ theory error

$(\zeta^2, \Delta R) = (0.85, 0.10)$ no theory error

Penguins are starting to provide meaningful CKM constraint

Reduction of theory errors necessary to be competitive with B_d,B_s mixing



ργ 95% C.L. BaBar allowed region (inside the blue arc)