Electroweak Penguin B Decays at BaBar: $b \to s\gamma$ and $b \to sll$

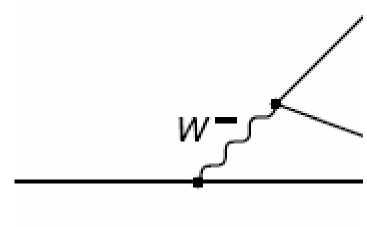
TM

LNS Journal Club Seminar
April 1, 2005

Three Paths to Flavor Violation

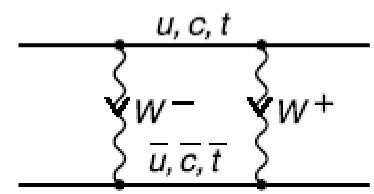
1. Tree diagram decay: down → up ($b \to c$, $b \to u$)

Not generally sensitive to new physics

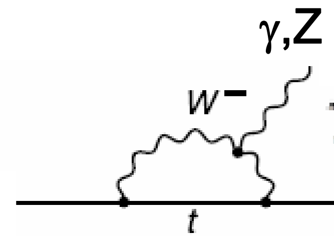


2. Box diagram: neutral meson mixing (K^0,B_d^0,B_s^0)

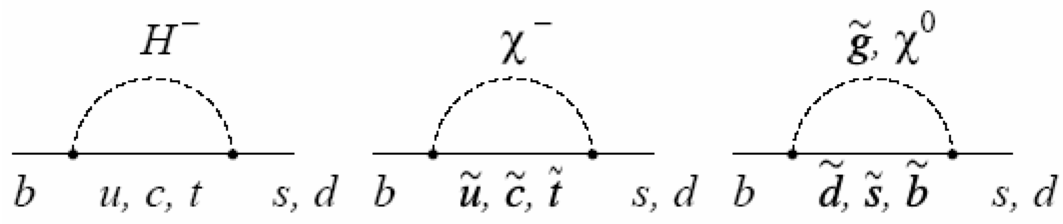
down-type → anti-down type ($b \to \bar{b}$)
via double W exchange



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!



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

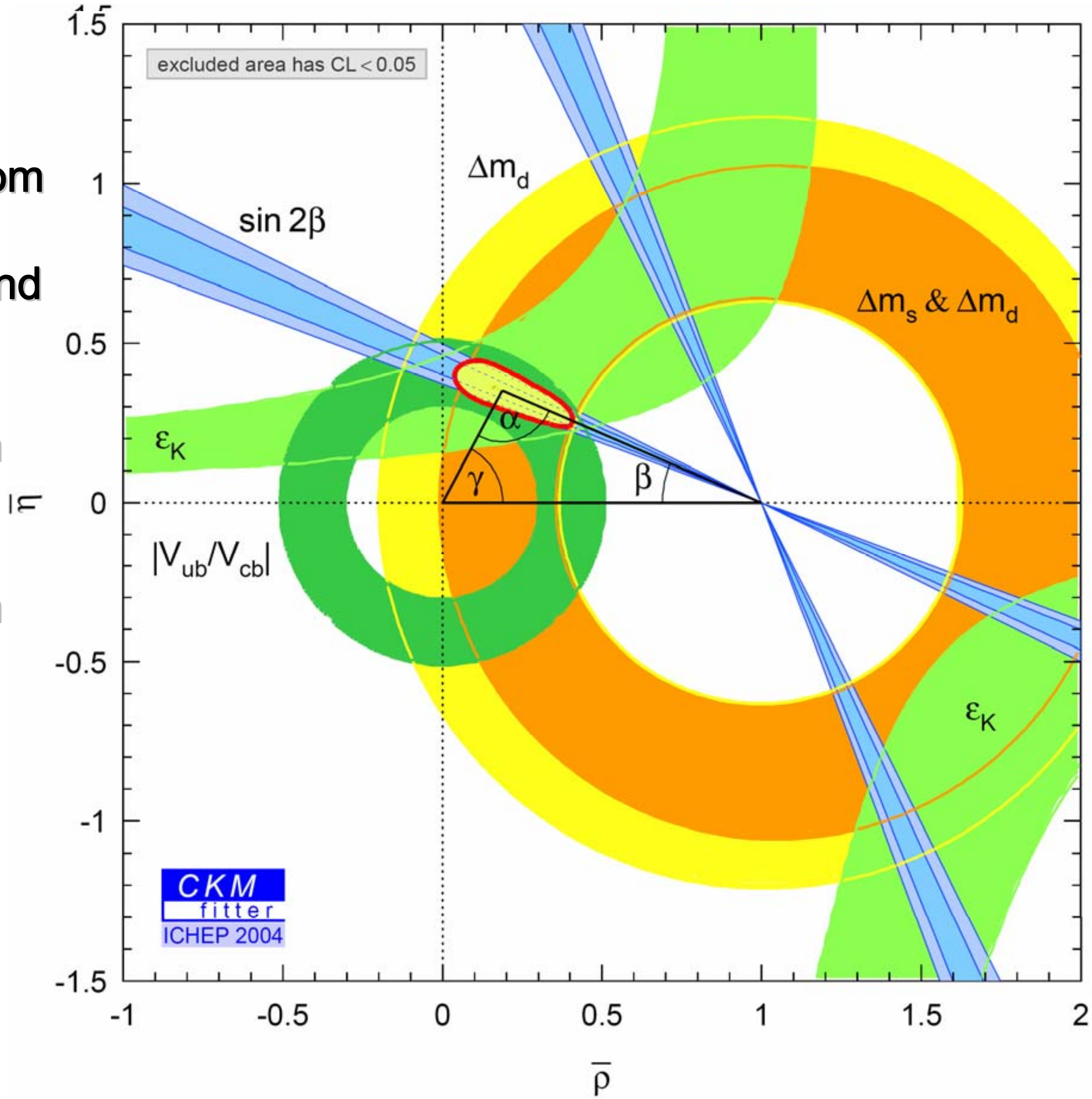
CKM Unitarity Triangle: Experimental Constraints

Constraints from

Decay rates and Mixing Rates

CP violation in kaon decay

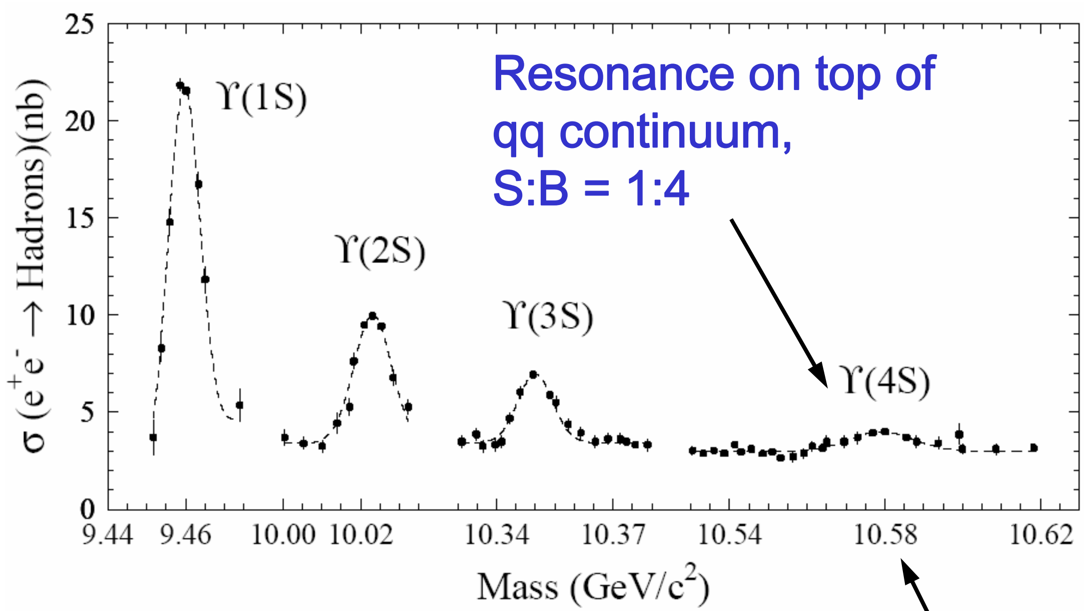
CP violation in $b \rightarrow ccs$

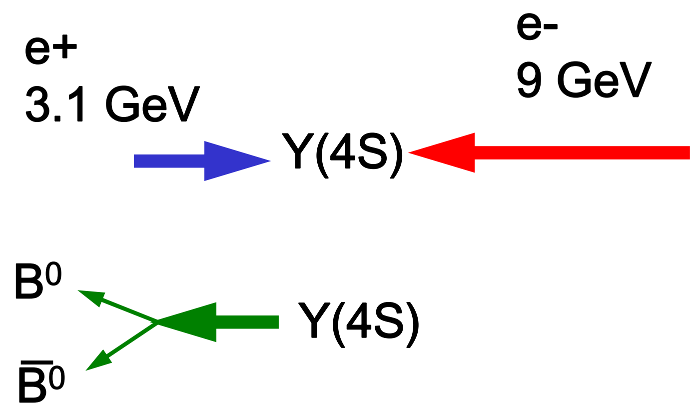


Remarkable validation of the CKM mechanism for both flavor violation and CP violation!

Do penguin decays agree with this picture??

Asymmetric B Factories





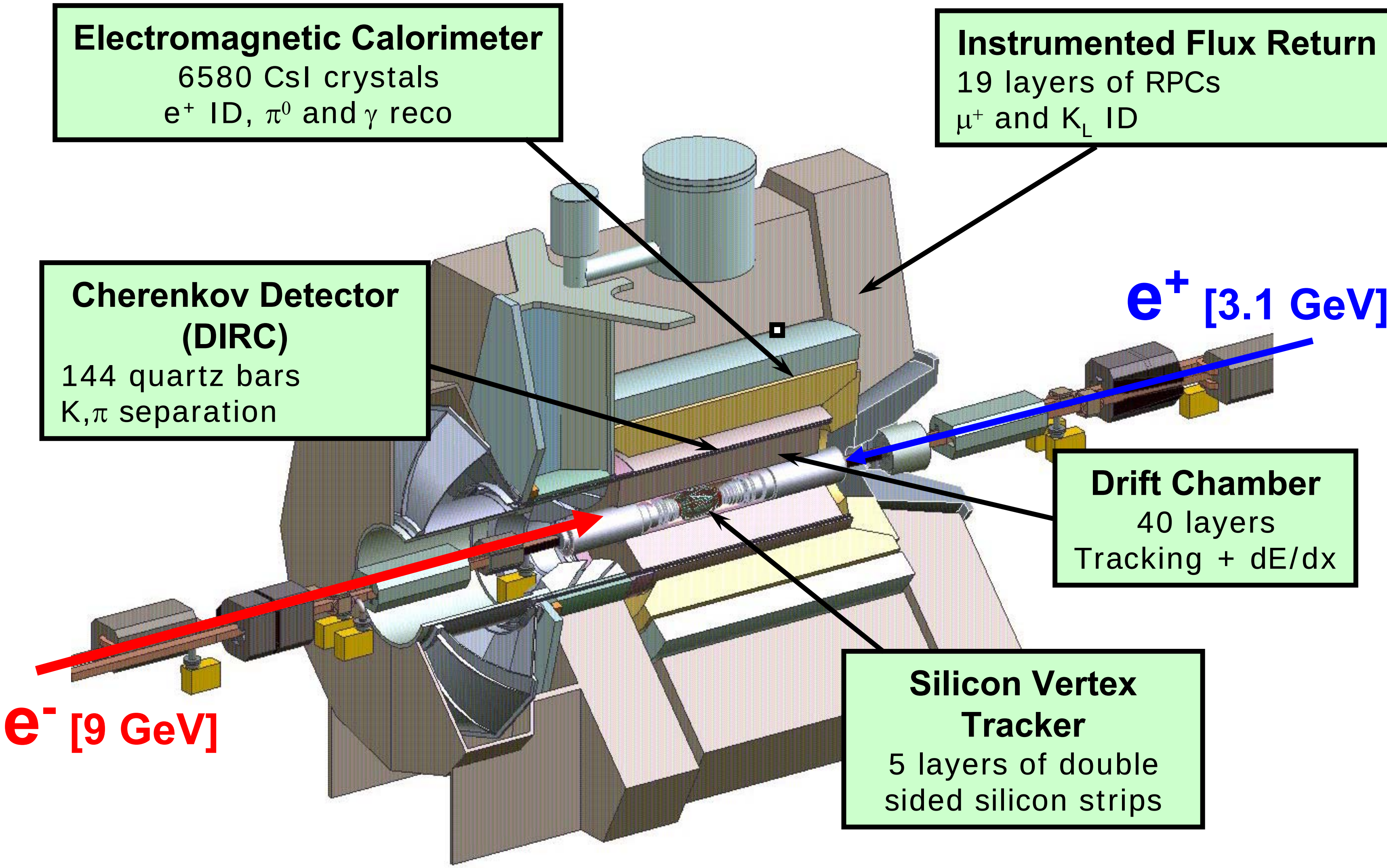
Y(4S) meson: $b\bar{b}$ bound state with mass 10.58 GeV/c^2

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)

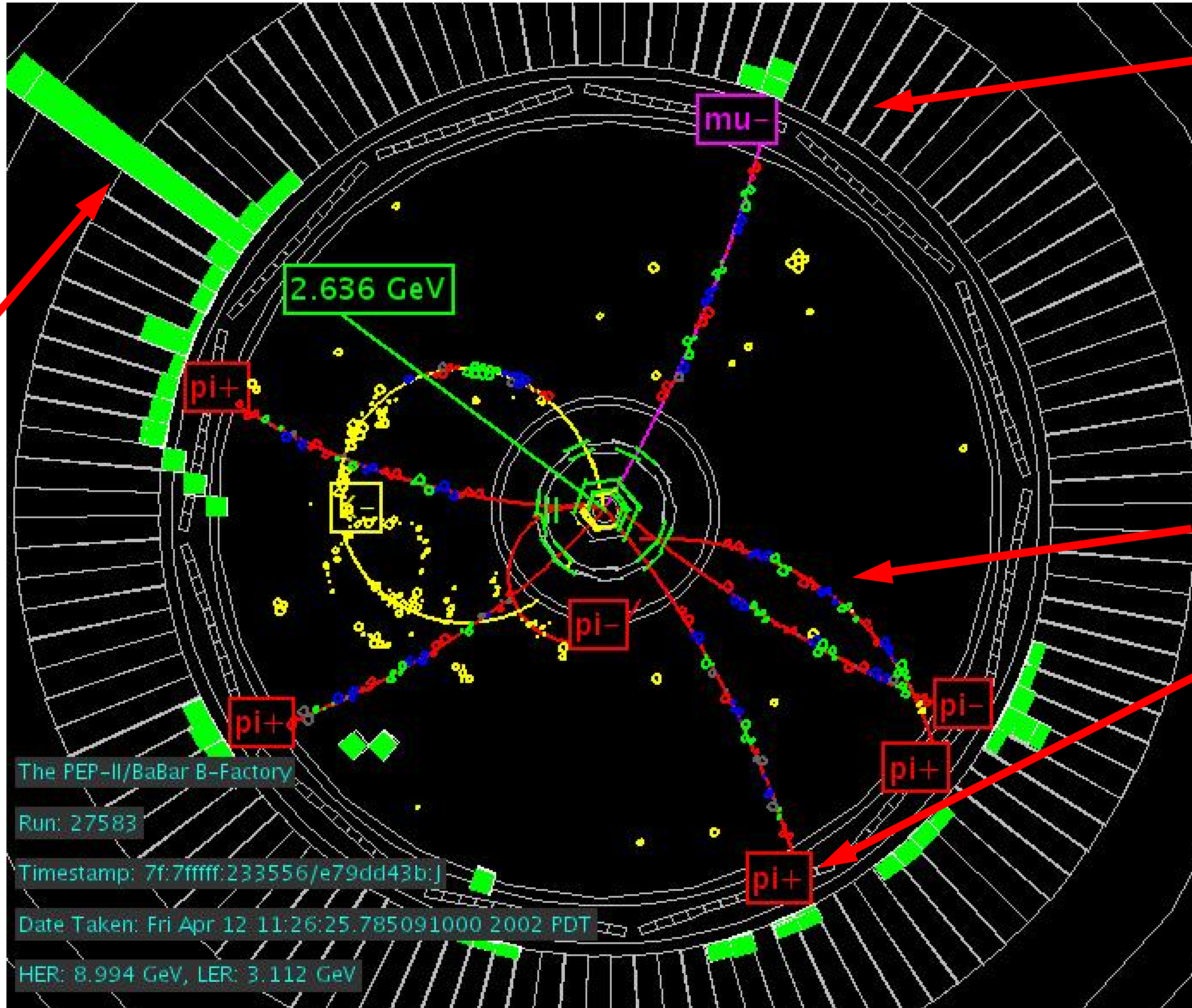
The BaBar detector



Penguin Portrait

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

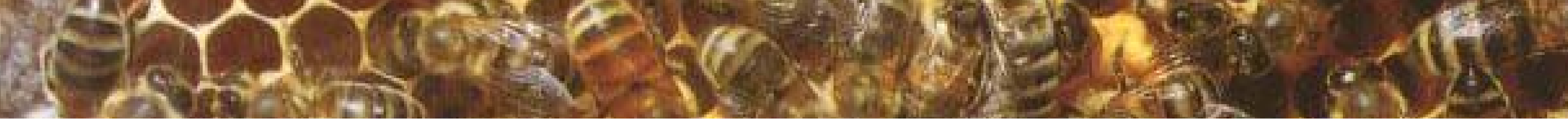
High energy photon

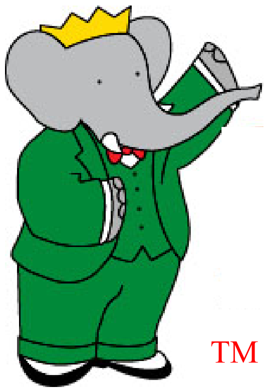


Muon from other B decay

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

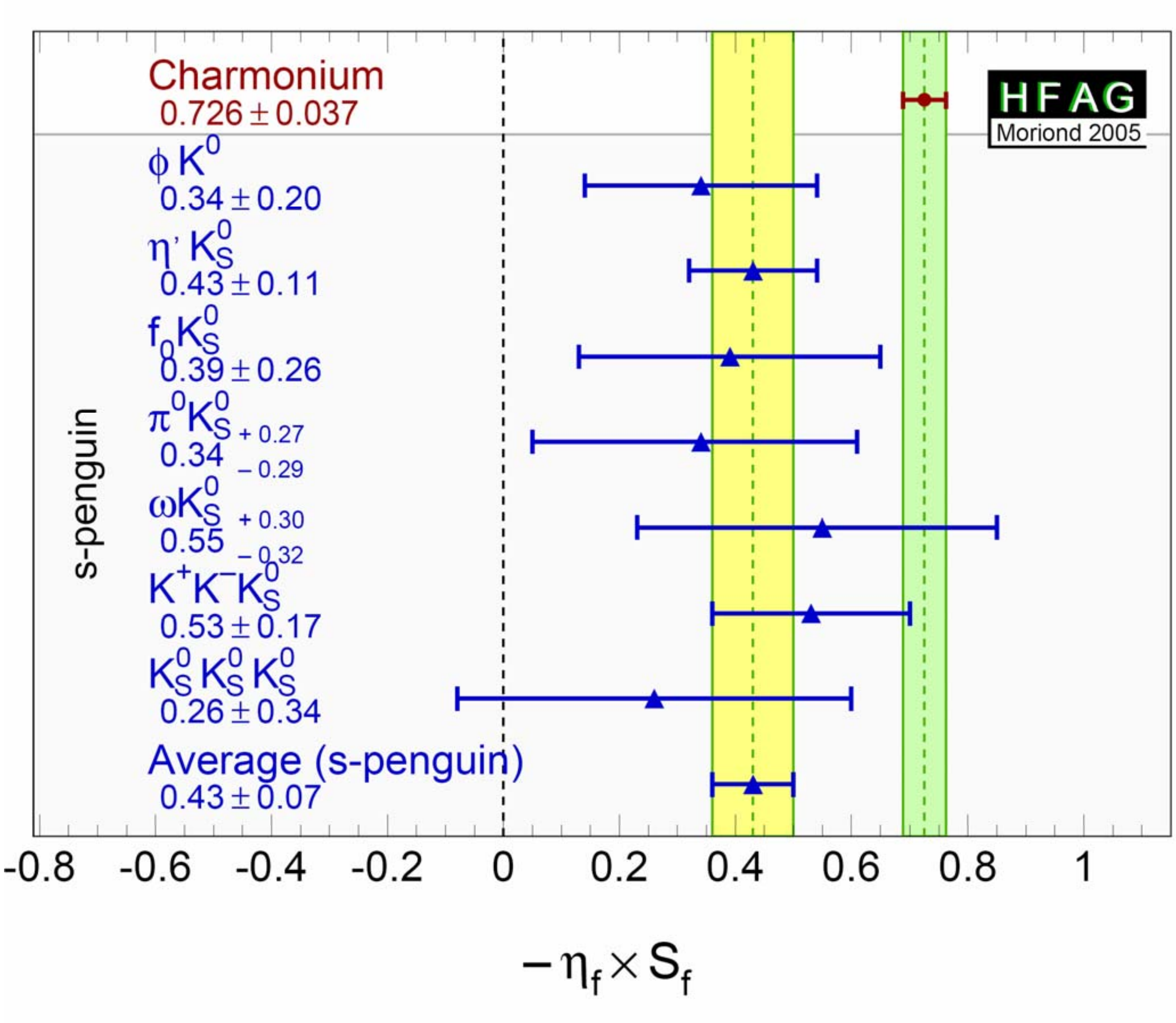
and π+





Gluon Penguins and CP Violation

Sin 2β: Trees(green) vs. Penguins(yellow) World Average

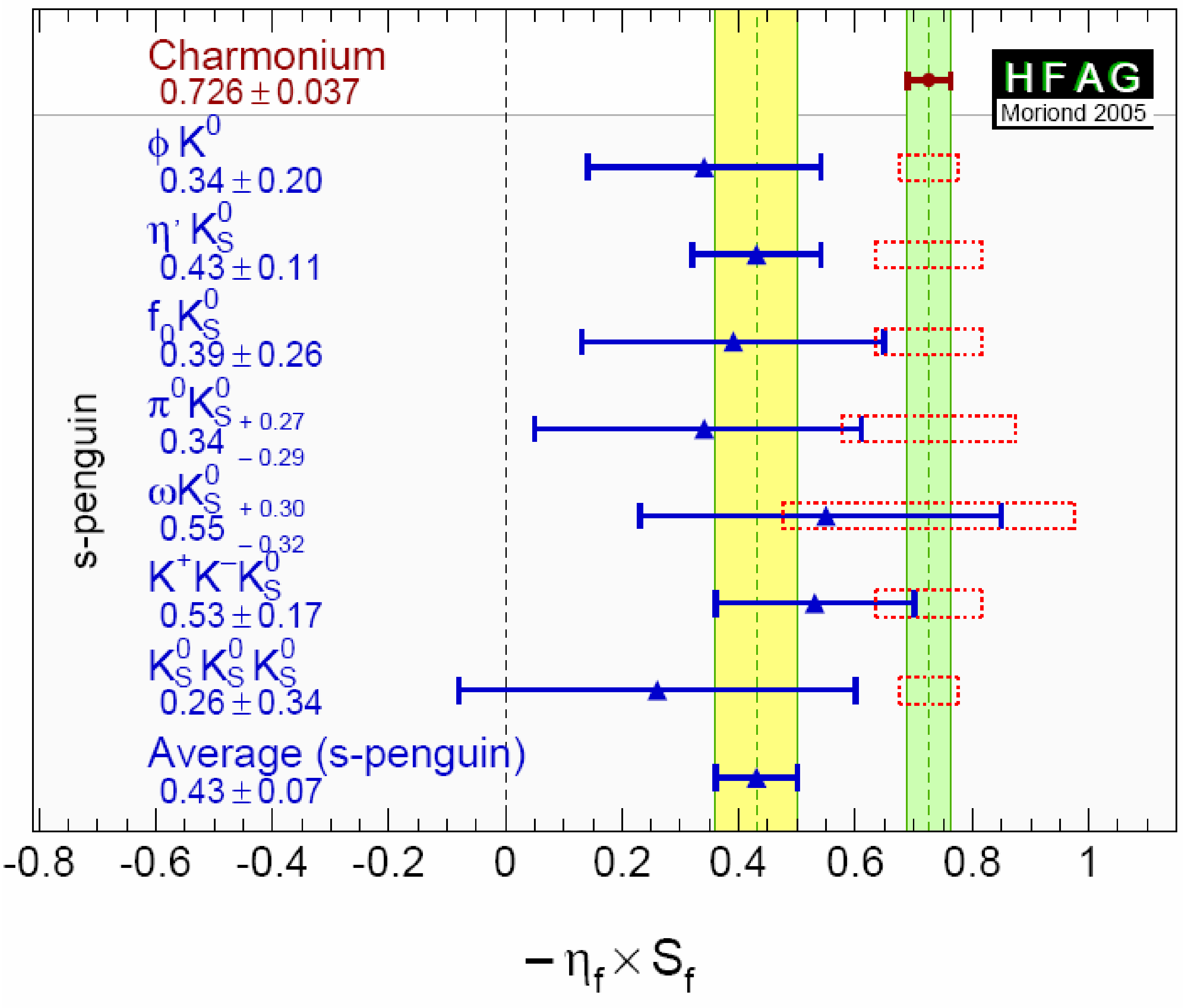


Averaging over many penguin decays:

World discrepancy with tree decays

= -3.7 σ

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



Averaging over many penguin decays:

World discrepancy with tree decays

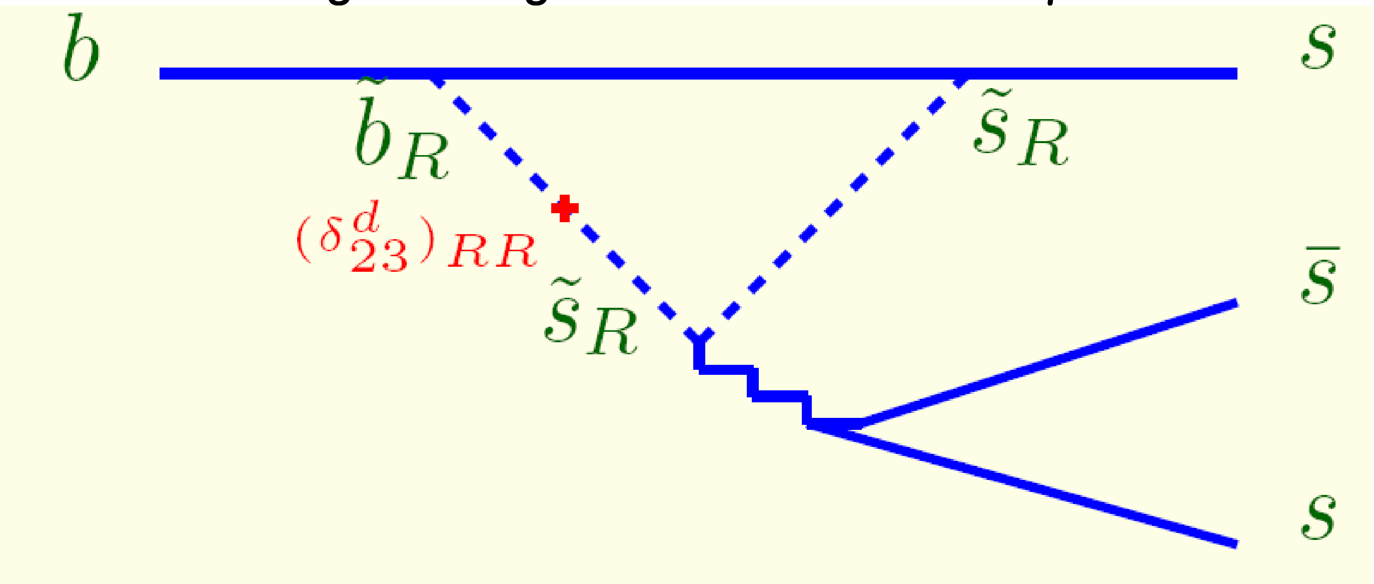
= -3.7 σ

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

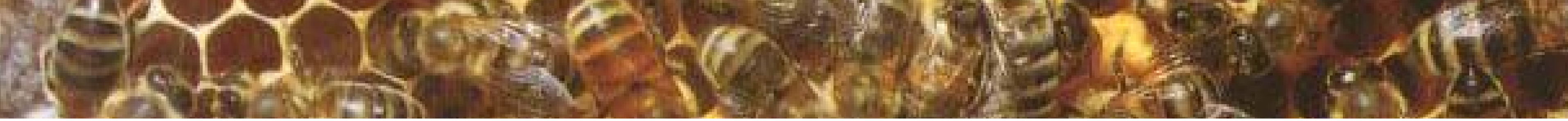
New Physics Scenarios

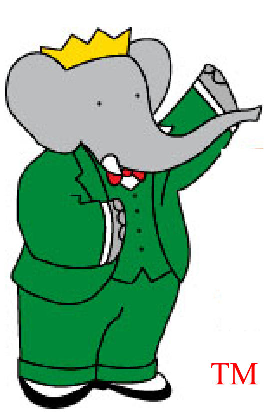
•**New physics at the electroweak scale generically introduces many new large flavor-violating or CP-violating couplings to quarks**

Ex: Isosinglet (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>

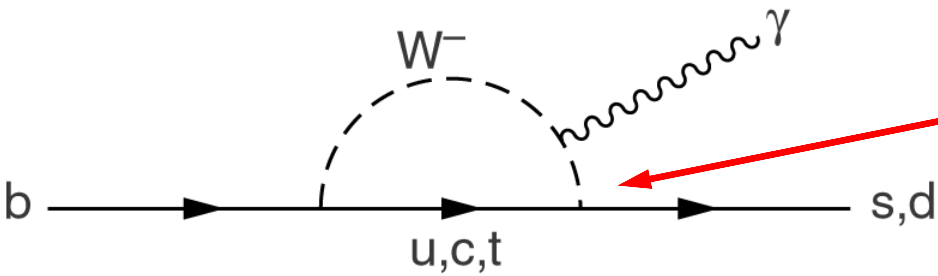




Photon Penguins

Photon Penguin Decays and New Physics

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



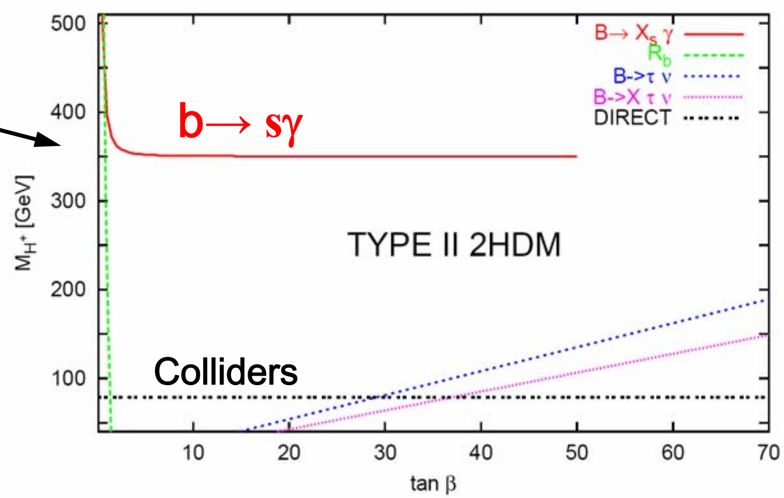
SM leading order = one EW loop

V_{ts}, V_{td} dependent

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

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

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

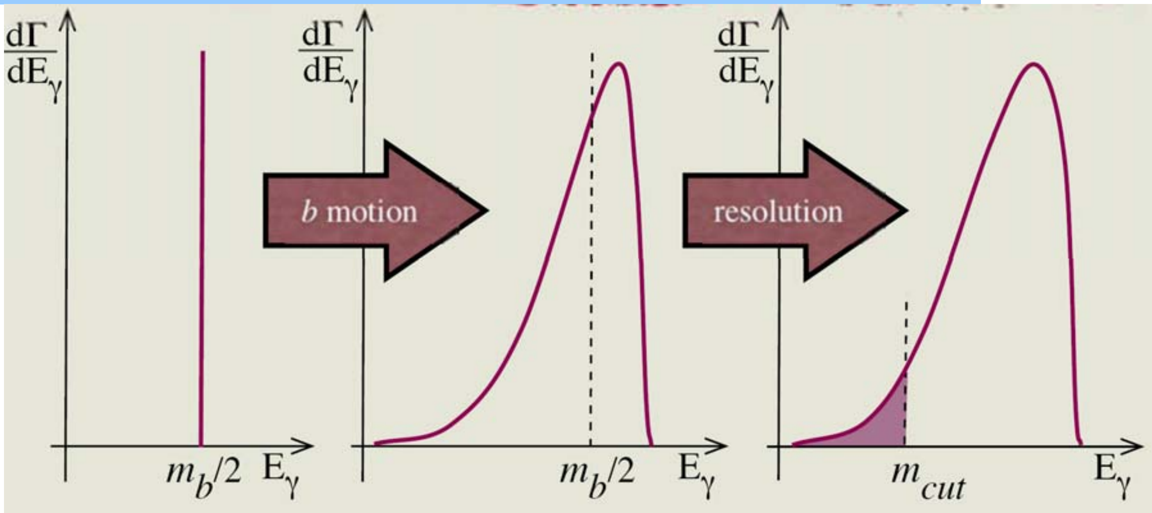


ALSO:
Direct CP asymmetry << 1% in SM
Could be O(1) beyond SM

Photon Penguin Decays and Heavy Quark Physics

$b \to s\gamma$ photon is DIS microscope of the b quark within the B meson

Trivial delta function spectrum modified by non-trivial b quark wave function



Close relationship with semileptonic B decays:

$b \to c l \nu$:
Lepton energy and hadronic mass spectral moments depend on non-perturbative parameters of a Heavy Quark Expansion (HQE)

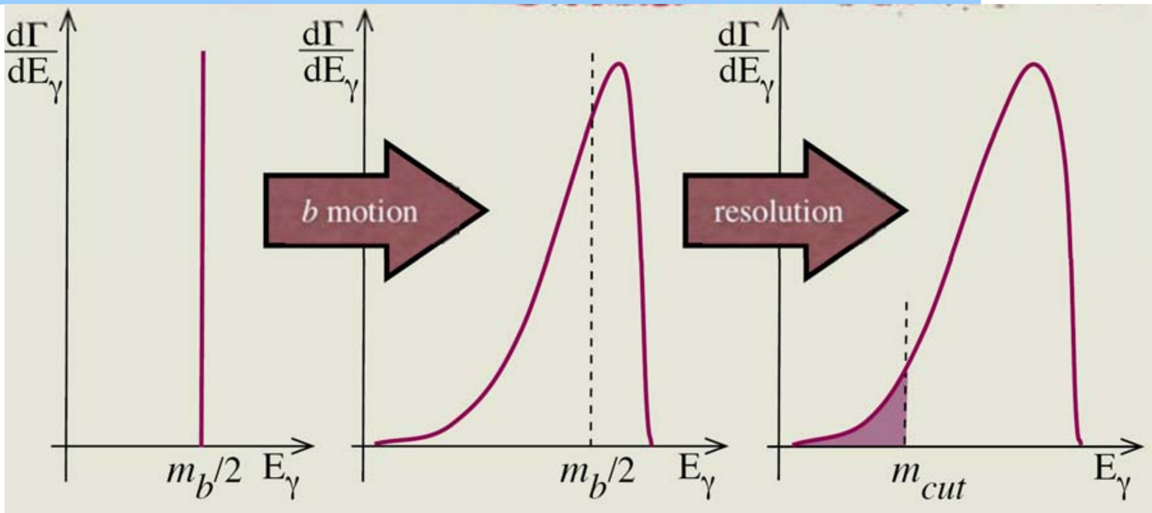
$b \to s\gamma$ photon energy spectral moments help constrain HQE parameters (especially b quark mass)

HQE technology necessary for high-precision $|V_{cb}|$ measurement
(currently ~2% and falling)

Photon Penguin Decays and Heavy Quark Physics

$b \to s\gamma$ photon is DIS microscope of the b quark within the B meson

Trivial delta function spectrum modified by non-trivial b quark wave function



$b \to ul\nu$:

HQE also relates $b \to ul\nu$ rates and moments with $|V_{ub}|$

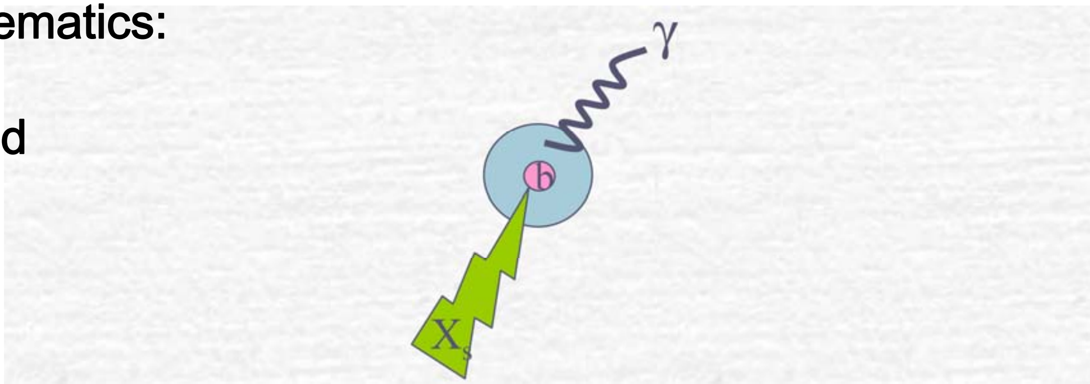
Experimental cuts generally spoil HQE and introduce other non-perturbative effects

At LO, $b \to s\gamma$ spectrum measures "shape function" independently, increases $|V_{ub}|$ precision

$$B(B \to X_u l\nu) = \frac{\Delta B}{f_u}, \text{ where } f_u \propto \iiint_{Sel} H(E_l, M_X, q^2) \otimes f(k_+; \Lambda^{SF}, \lambda_1^{SF})$$

b→sγ : Decay Model

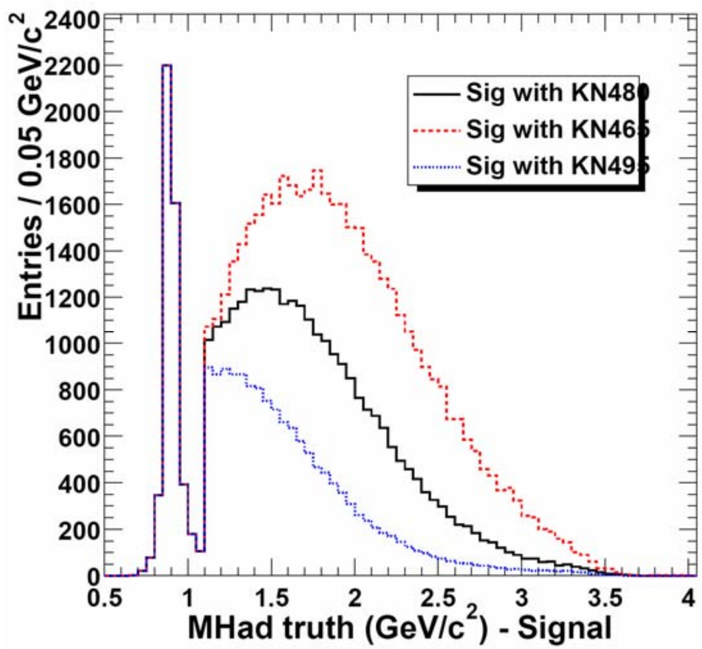
At parton level, two-body decay kinematics:



In B rest frame, M(Xs) and E_γ related

$$E_\gamma = \frac{m_B^2 - m_{Xs}^2}{2m_B}$$

Hybrid of inclusive and exclusive decays



<u>Below M(Xs) = 1.1 GeV</u>:

K* dominates

Breit-Wigner line shape assumed

<u>Above M(Xs) = 1.1 GeV</u>:

many overlapping resonances

quark-hadron duality applies

inclusive photon spectrum assumed

Xs fragmented by JETSET

$b \to s\gamma$: Shape Functions

Inclusive spectral shape (and relative amount of K*) from a shape function model

Kagan-Neubert (KN): Old ansatz with two parameters

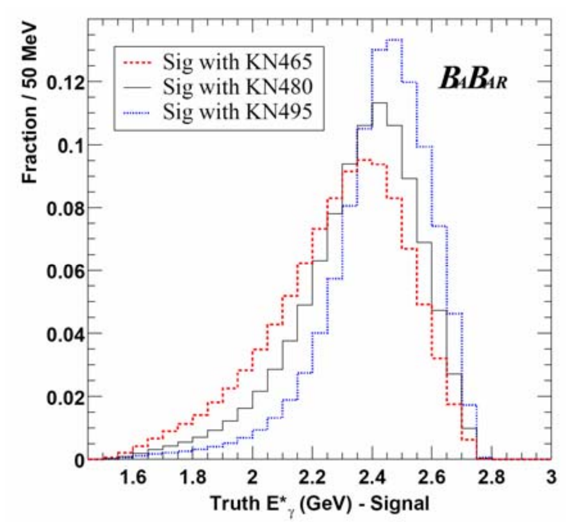
$\Lambda \approx m_B - m_b$ (correlated w/1st moment) $\mu_\pi^2 = \lambda_1 \approx$ - kinetic energy^2 (2nd moment)

<u>Two modern schemes</u>: correlate shape function with modern HQE parameters

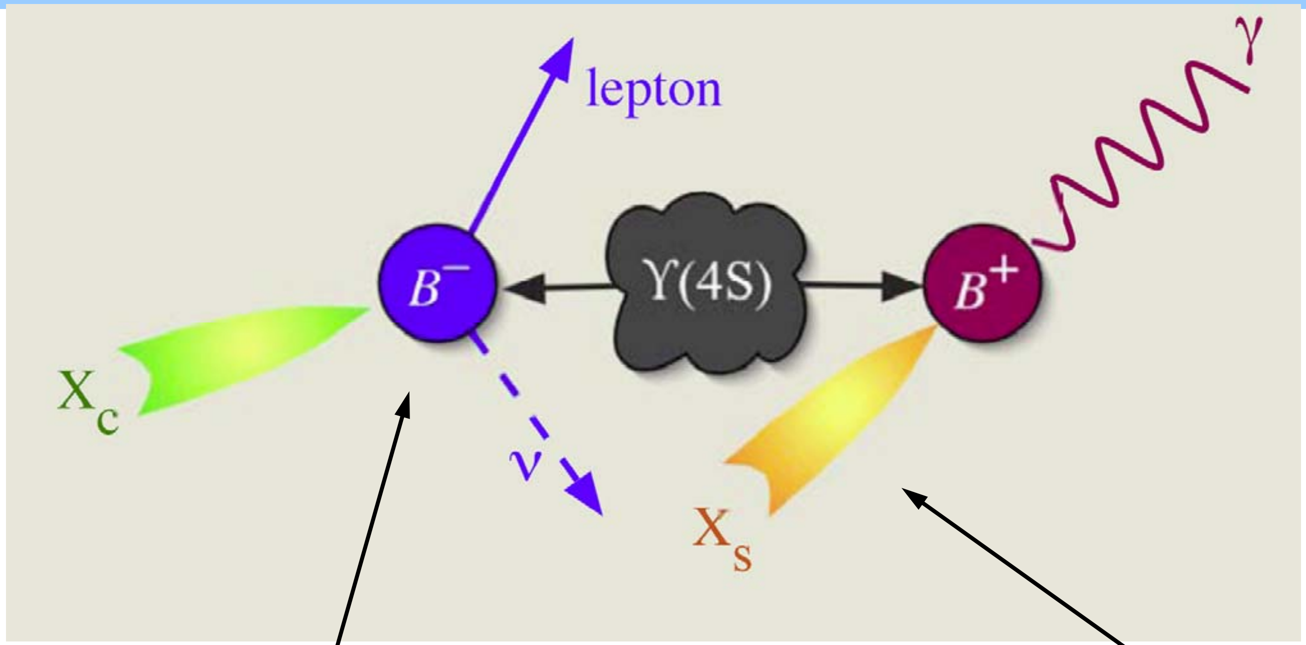
Benson-Bigi-Uraltsev (kin): based on "kinetic scheme" for HQE (hep-ph/0410080)
(m_b (kin), μ_π^2(kin))

Neubert (SF): based on "shape function scheme" with multi-scale OPE (hep-ph/0412241)
(m_b(SF), μ_π^2(SF))

Parameters to be determined empirically from photon spectrum



$b \to s\gamma$: Two Measurement Methods



"Inclusive Lepton-tagged"

Signal side: reconstruct photon only

Tag side: reduce qq background with high energy lepton, et al.

Pro: Least model dependent
Con: Large background subtraction

"Sum of exclusive"

Signal side: reconstruct photon + X_s

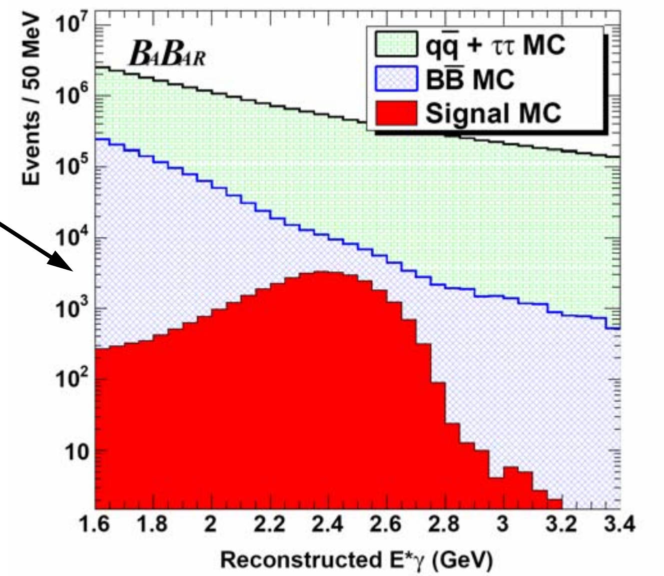
fit B mass distribution for signal + background

Pro: good resolution, low background
Con: Large model dependence at low $E\gamma$

$b \rightarrow s\gamma$: Inclusive Measurement (82 fb^{-1})

Event Selection:

Inclusive photon reconstruction: E^*_γ = 1.6-3.4 GeV
Energy in Y(4S) frame (B rest frame unknown)
Shower shape and/or extra photons consistent with π^0 or η vetoed

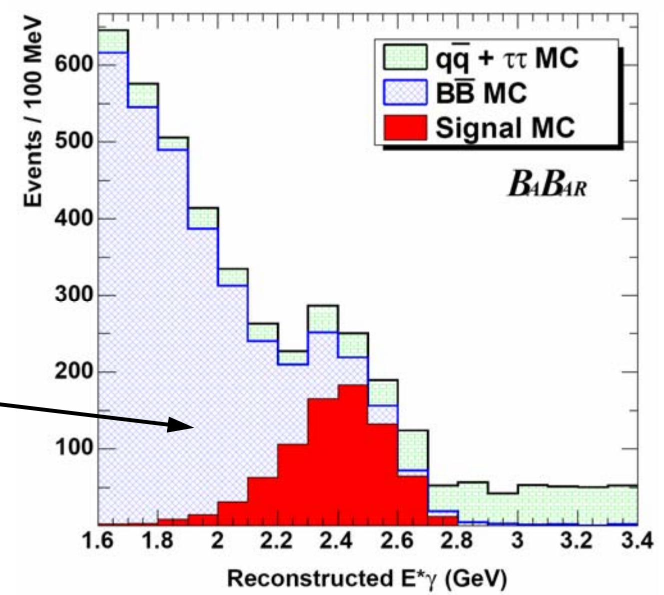


Lepton tag: reduces large continuum background
Semileptonic B decays have lepton and missing energy:

e (or μ) with P* > 1.25 (1.5) GeV
$\cos(\theta(l,\gamma))$ > -0.7 , E(miss) > 0.8 GeV

5% signal efficiency, 0.07% continuum efficiency
(also tags B flavor for CP measurement)

Event shape: further continuum reduction
Fisher discriminant distinguishes jet-like continuum from spherical signal



Inclusive Measurement: Background Subtraction

Remaining continuum background:
Subtraction estimated from data taken below Y(4S) (10 fb^{-1})
Tested by high E_γ data (> 2.7 GeV)

B background:

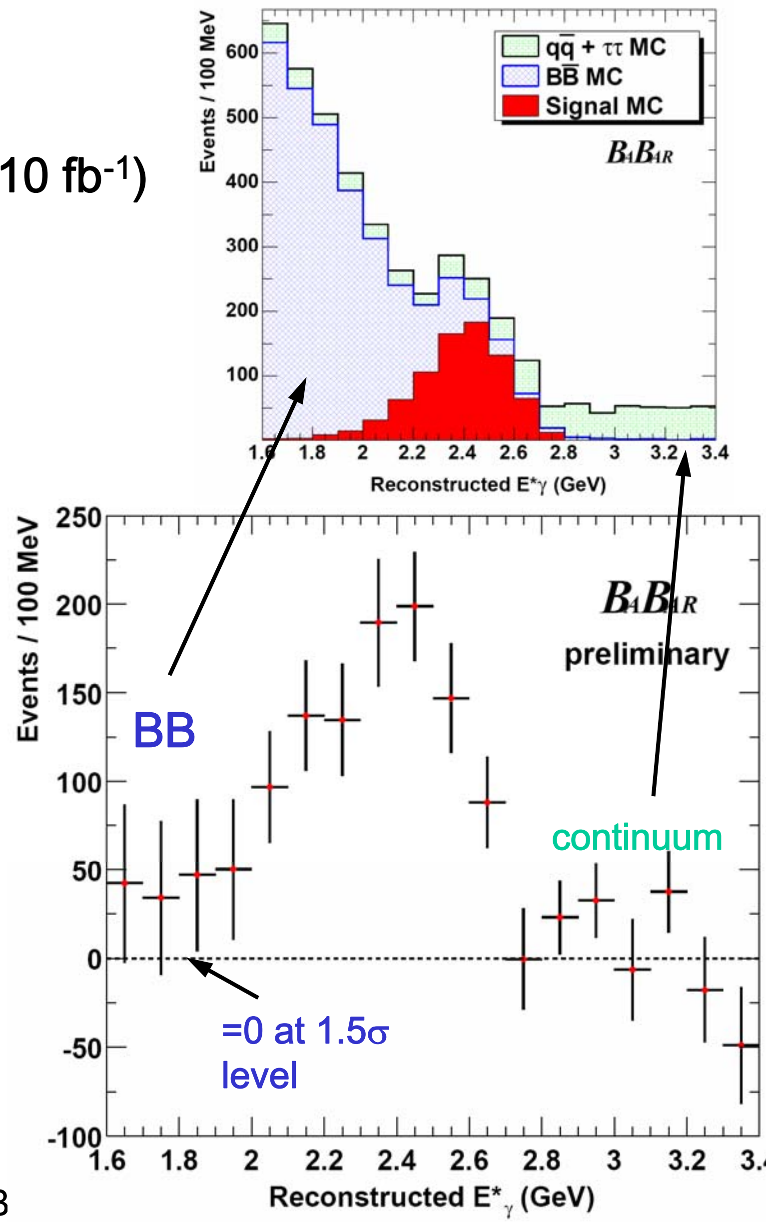
Mostly B decays to π^0 and η which escape veto
(also anti-n, electrons, and other mesons)

Inclusive spectrum of each component measured
in data, MC reweighted to match it

Subtraction from reweighted Monte Carlo simulation

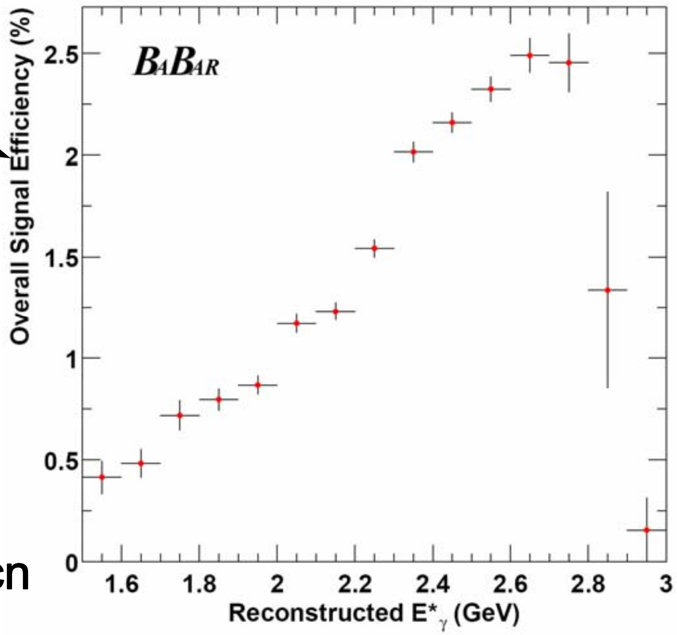
Tested by low E_γ data (1.6-1.9 GeV)

Signal = 1042 ± 84 ± 62 events, E_γ = 1.9-2.7 GeV



Inclusive Measurement: Efficiency Correction

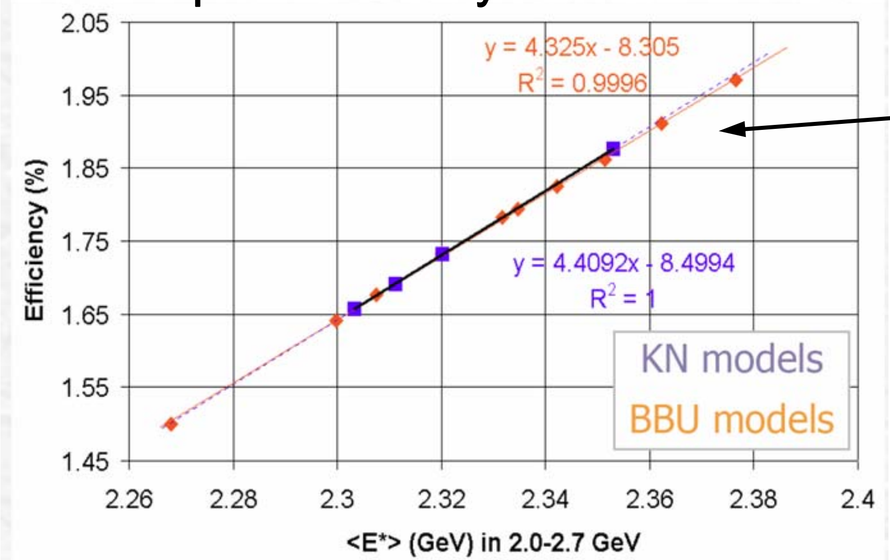
Event shape cuts induce E_γ dependence in efficiency (varies by a factor of 3)



Total branching fraction (BF) depends on assumed photon spectrum model

“Bootstrapping”: use first moment of observed Spectrum to infer shape function

then recompute efficiency with measured shape fcn



Total efficiency linearly correlated with first moment

Range of allowed moments bounds Model-dependence of efficiency

5% uncertainty from spectral model

Inclusive Measurement: Photon Spectrum

Partial branching fraction vs. E_γ (min) in B rest frame

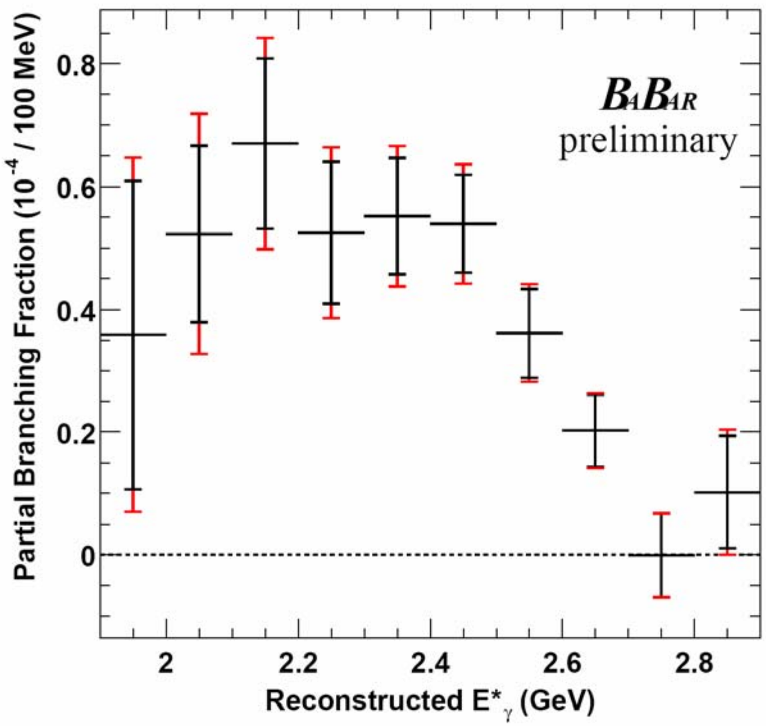
Corrected for B momentum and photon energy resolution

Errors: stat ± syst ± model

Energy range (GeV)	Corrected PBF ($\times 10^{-4}$) for true E_γ range, B frame
1.9 to 2.7	$3.67 \pm 0.29 \pm 0.34 \pm 0.29$
2.0 to 2.7	$3.41 \pm 0.27 \pm 0.29 \pm 0.23$
2.1 to 2.7	$2.97 \pm 0.24 \pm 0.25 \pm 0.17$
2.2 to 2.7	$2.42 \pm 0.21 \pm 0.20 \pm 0.13$

Systematic errors for E_γ (min) = 2.0 GeV

Systematic	Uncertainty
Photon Detection and Quality	3.3%
Topological Cuts	3.0%
Fragmentation-Dependence	1.4%
Lepton ID	2.2%
Tag Efficiency	3.0%
$B\overline{B}$ Background	5.7%
Miscellaneous	1.7%
Total Experimental	8.4%
Signal-model-dependence	4.8%

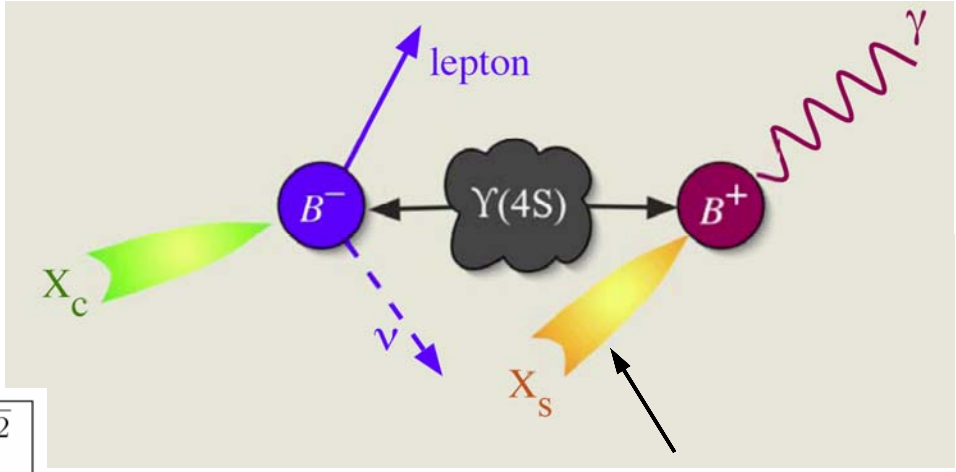


First moment vs. E_γ (min) also computed

TO DO:
Shape function fit and final bootstrapping
Second moment

"Total BF" from extrapolating best fit shape function

$b \to s\gamma$: Sum of Exclusive States Measurement (82 fb^{-1})



For completely reconstructed B meson decay, can use kinematic constraints of Υ(4S) to severely reduce background:

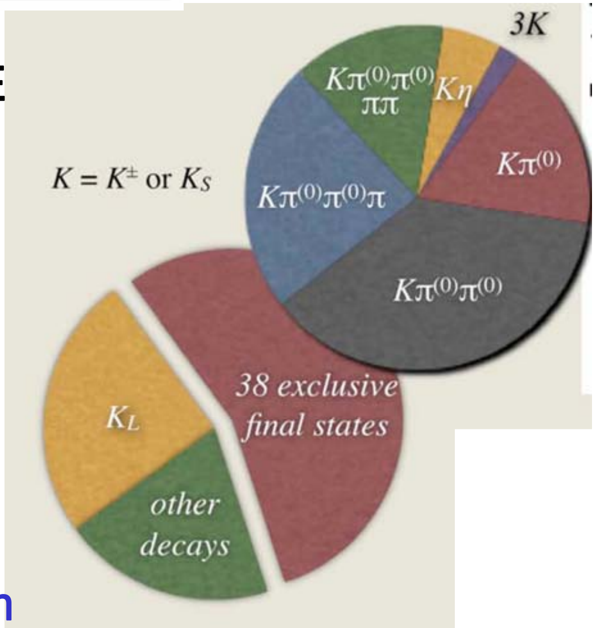
B energy = beam energy in Υ(4S) frame

$$\Delta E \equiv E_B^* - \sqrt{s}/2 \quad \text{and} \quad m_{ES} \equiv \sqrt{(\sqrt{s}/2)^2 - {p_B^*}^2}$$

Signal has narrow peaks in m_{ES}, ΔE
Background is flat → extract signal with a likelihood fit

Branching fraction measurement
Sensitive to fragmentation model and fraction of missing states

Photon spectrum inferred from precisely measured M(Xs) spectrum



38 distinct Xs states
(K^+ or K_S) + 1-4 π (≤ 2 π^0)
(K^+ or K_S) + 0-2 π + η
(K^+ or K_S) + 0-2 π + φ

Missing states:

K_L + X (25%)
K + >4 π
Baryonic decays
Other

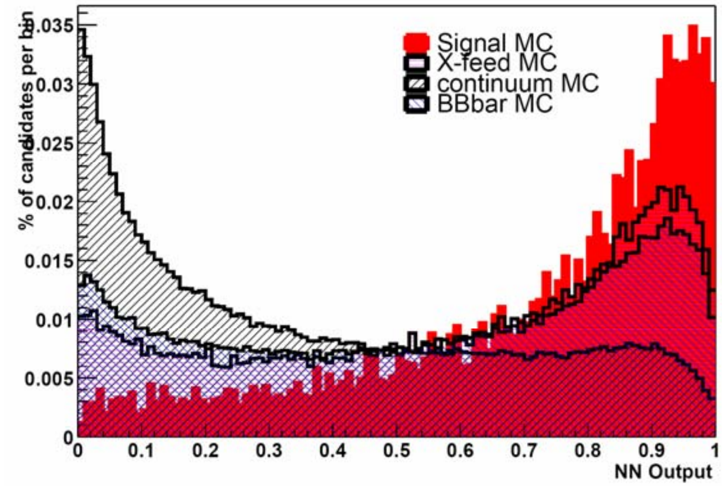
Sum of Exclusive: Event Selection

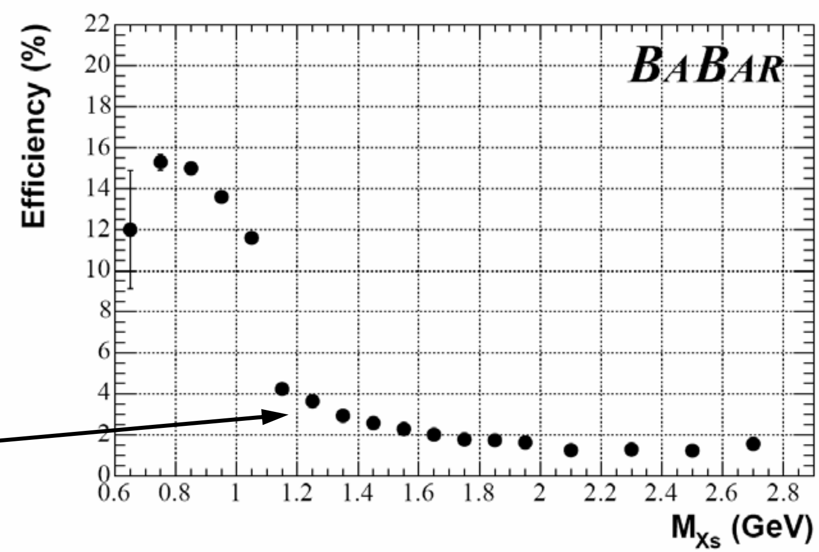
Event Selection:

Photon reconstruction: E_γ = 1.9-2.6 GeV
Energy in B rest frame
Shower shape and/or extra photons consistent with π^0 or η or ρ meson vetoed

Event shape: further background reduction
Neural net distinguishes jet-like continuum from spherical signal (validated by measuring $K^*\gamma$ branching fraction)

ΔE cut: reduces background of continuum + misreconstructed B decays
(especially "cross-feed" from $b \rightarrow s\gamma$)
$|\Delta E|$ < 70-80 MeV





Tighter selection at low E_γ

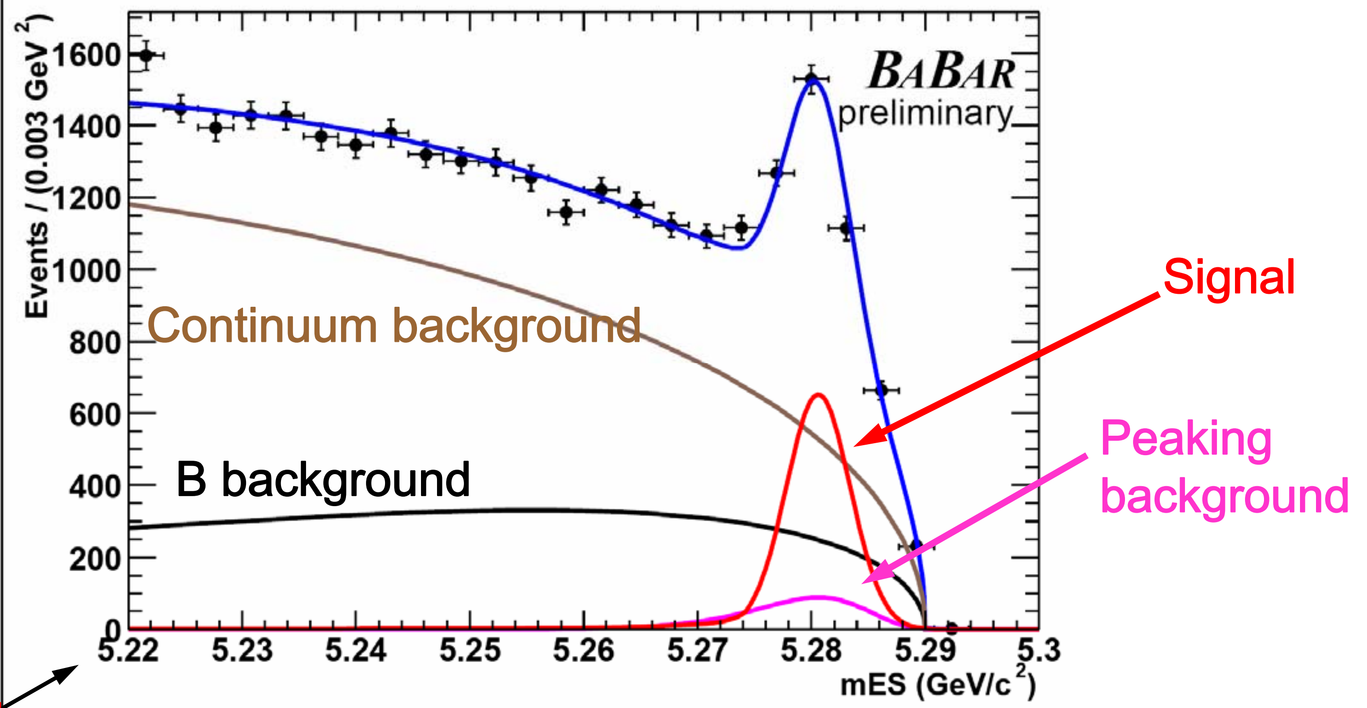
Sum of Exclusive: Signal Extraction

Binned maximum likelihood fit of m_{ES} distribution
Performed separately in 100 MeV bins of M(Xs) (and integrated over all M(Xs))

3 background components
(continuum, peaking fixed from MC)

$M(X_s)$ GeV	Data Signal yield	Data Fit χ^2/dof
0.6-0.7	6.5 ± 7.7	2.2
0.7-0.8	5.6 ± 14.1	0.8
0.8-0.9	416.2 ± 23.2	1.5
0.9-1.0	355.6 ± 24.9	0.9
1.0-1.1	51.2 ± 19.0	1.0
1.1-1.2	33.2 ± 12.9	1.2
1.2-1.3	83.2 ± 15.7	1.1
1.3-1.4	101.5 ± 16.8	0.8
1.4-1.5	72.0 ± 15.8	0.8
1.5-1.6	82.4 ± 16.5	1.1
1.6-1.7	66.1 ± 16.9	1.0
1.7-1.8	54.6 ± 16.5	1.3
1.8-1.9	76.6 ± 18.2	1.1
1.9-2.0	13.5 ± 19.5	1.1
2.0-2.2	47.5 ± 21.8	0.7
2.2-2.4	52.1 ± 24.0	0.7
2.4-2.6	44.7 ± 25.6	0.8
2.6-2.8	-6.2 ± 31.9	1.0

All 38 decay modes, E_γ = 1.9-2.6 GeV



Sum of Exclusive: Efficiency Correction

Fragmentation correction:
Admixture of reconstructed Xs states in JETSET tuned to match that observed in data

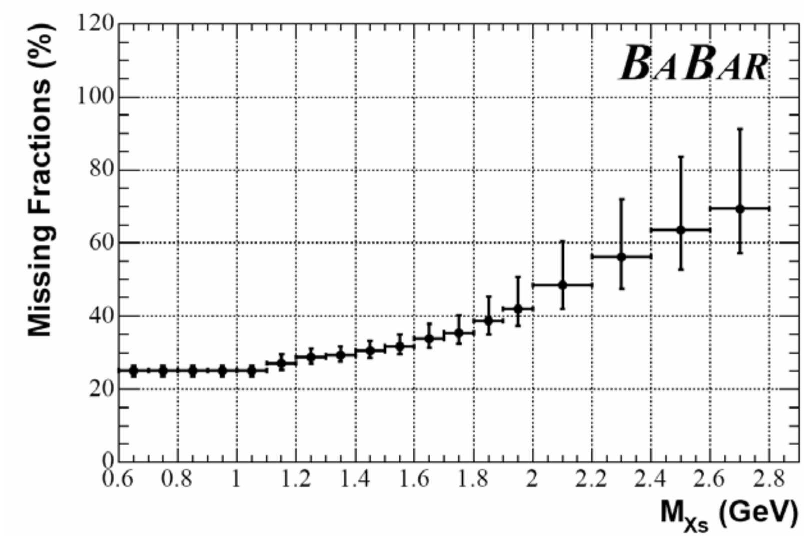
corrections up to 100%

Bootstrapped into efficiency calculation

Missing modes correction:
Fragmentation to non-K_L missing modes poorly known (50-100% errors)

~20% systematic at low Eg (high M(Xs))

Final States	Data/Monte Carlo
$K_S\pi^-$, $K^-\pi^+$	0.50 ± 0.07
$K_S\pi^0$, $K^-\pi^0$	0.19 ± 0.12
$K_S\pi^+\pi^-$, $K^-\pi^+\pi^-$	1.02 ± 0.14
$K_S\pi^-\pi^0$, $K^-\pi^+\pi^0$	1.34 ± 0.24
$K_S\pi^+\pi^-\pi^-$, $K^-\pi^+\pi^-\pi^+$	2.67 ± 0.96
$K_S\pi^+\pi^-\pi^0$, $K^-\pi^+\pi^-\pi^0$	1.29 ± 0.61
$K + 2\pi^0$ modes	1.89 ± 1.33
$K + 4\pi$	$1.32^{+1.55}_{-1.32}$
$K + \eta$ modes	$0.83^{+1.00}_{-0.83}$
3 Kaon modes	$0.27^{+0.54}_{-0.27}$



Sum of Exclusive: Photon Spectrum

Photon spectrum (binned BF) fit to BBU and Neubert shape function models

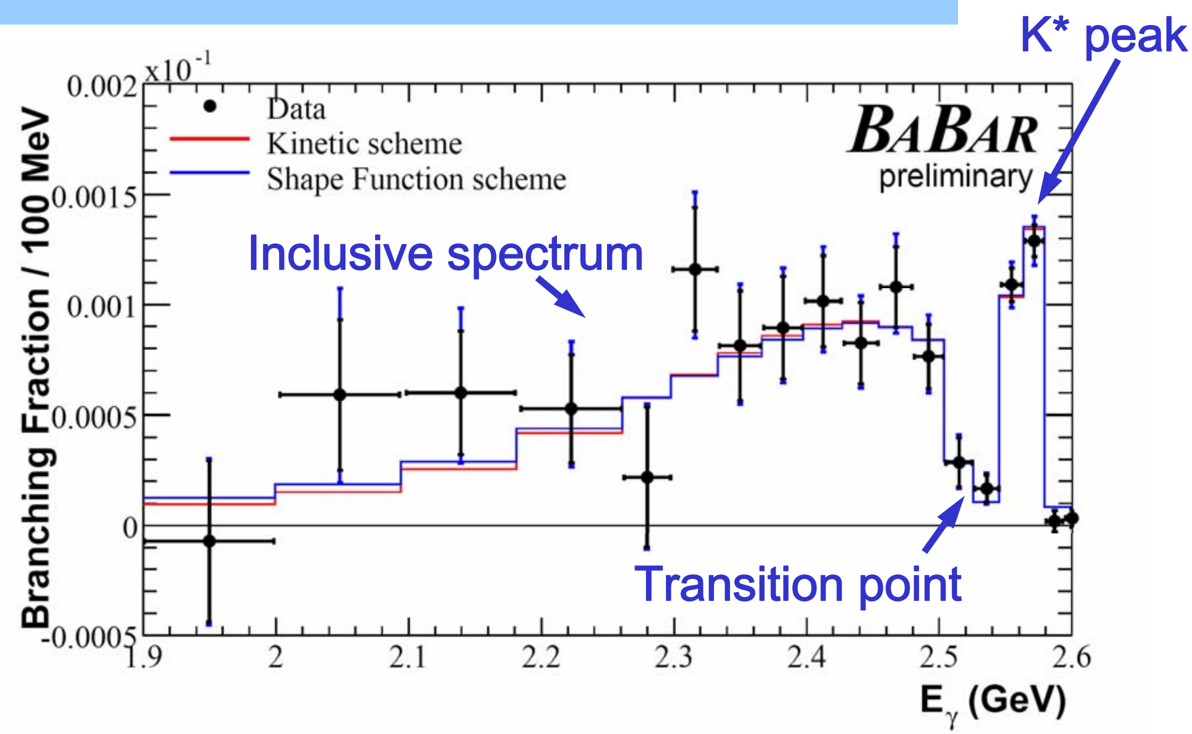
Total BF fixed

Breit-Wigner for K* above transition point

3 parameter fit:
m_b, μ_π^2, transition point

Total BF recomputed from shape function and fit reiterated

Total BF computed again, errors bound systematic on shape function parameters



Shape functions describe data well with good χ^2

Scheme	$\bar{\Lambda}$ (GeV)	μ_π^2 (GeV^2)	PBF (10^{-4}), $E_\gamma > 1.9$ GeV
Kinetic	$0.59^{+0.05}_{-0.04}$	$0.30^{+0.07}_{-0.05}$	$3.27 \pm 0.18^{+0.62}_{-0.39}{}^{+0.12}_{-0.12}$
Shape Func.	$0.63^{+0.04}_{-0.04}$	$0.19^{+0.06}_{-0.05}$	$3.31 \pm 0.18^{+0.63}_{-0.40}{}^{+0.02}_{-0.03}$

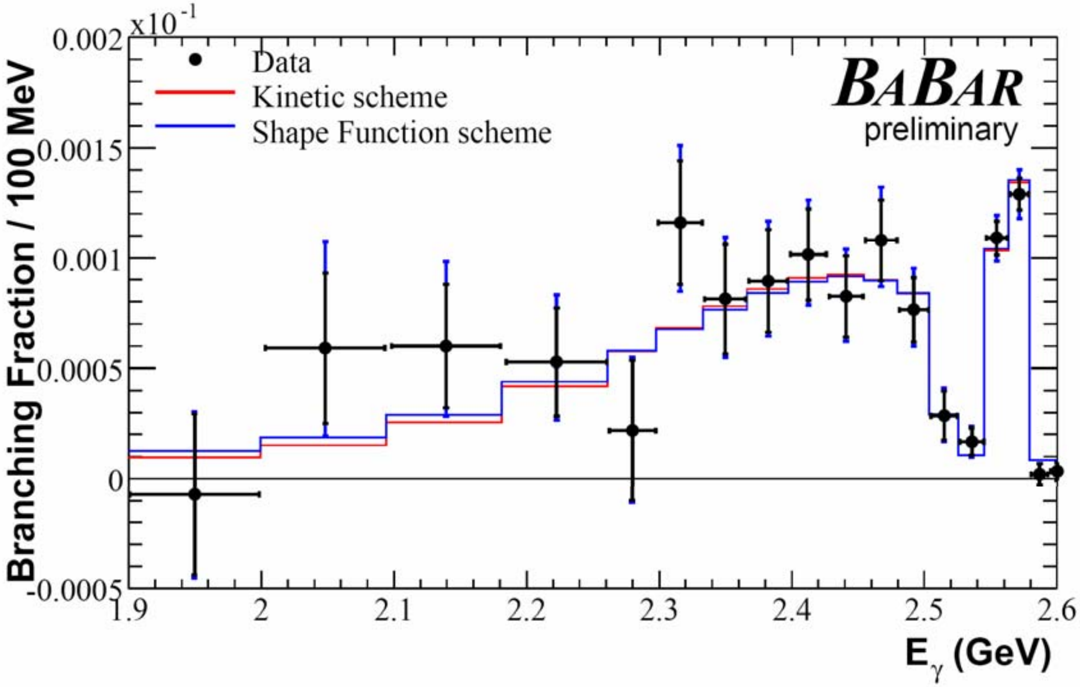
Kinetic scheme parameters agree with $b \to c l \nu$ HQE measurements!

Sum of Exclusive: Branching Fractions

Average of two schemes
gives partial BF for $E_\gamma > 1.9$ GeV

$$(3.29 \pm 0.18^{+0.62+0.07}_{-0.40+0.08}) \times 10^{-4}$$

Systematic	Uncertainty
Particle Detection	6.1%
Fitting	+9.5% -2.9%
Peaking Background	1.6%
Fragmentation	5.9%
Missing States	+13.8% -7.6%
Miscellaneous	2.0%
Total Experimental	+19.0% -12.0%
Signal-model-dep.	+2.1% -2.4%



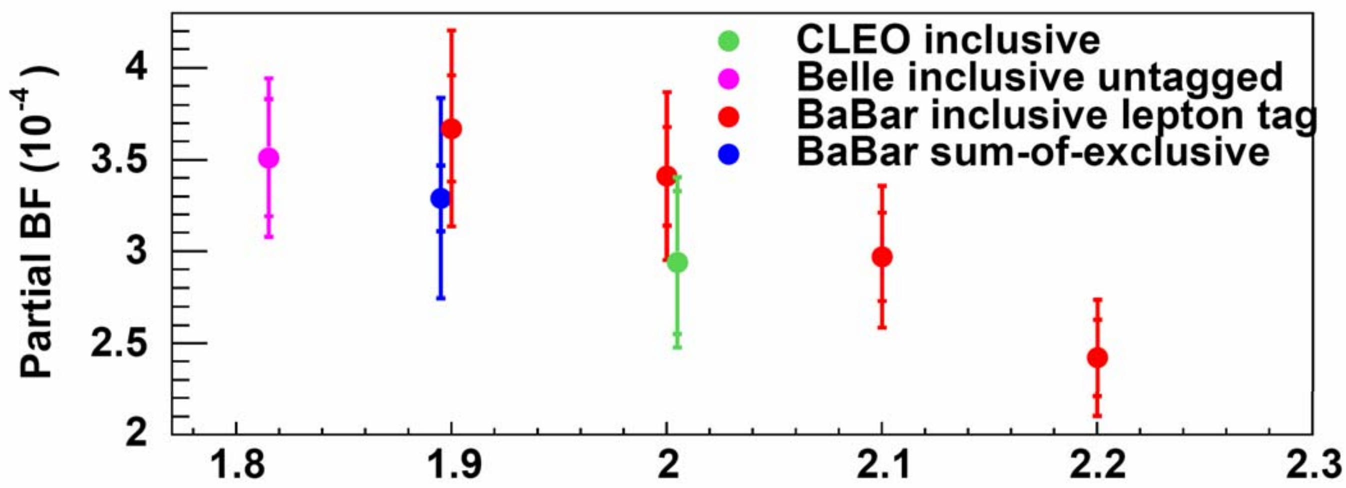
Dominant error from missing states

Use measured shape functions
to extrapolate down to partial BF for $E_\gamma > 1.6$ GeV ("Total Branching Fraction")

Average of two schemes gives total BF

Partial Branching Fractions: Summary

PBF vs. minimum photon energy in B rest frame



Consistency across measurements with common E_{γ}(min)

Systematics limited

Shape function model required to compare PBF's for different E_{γ} (min) (in progress)

Photon Spectral Moments: Summary

Comparisons

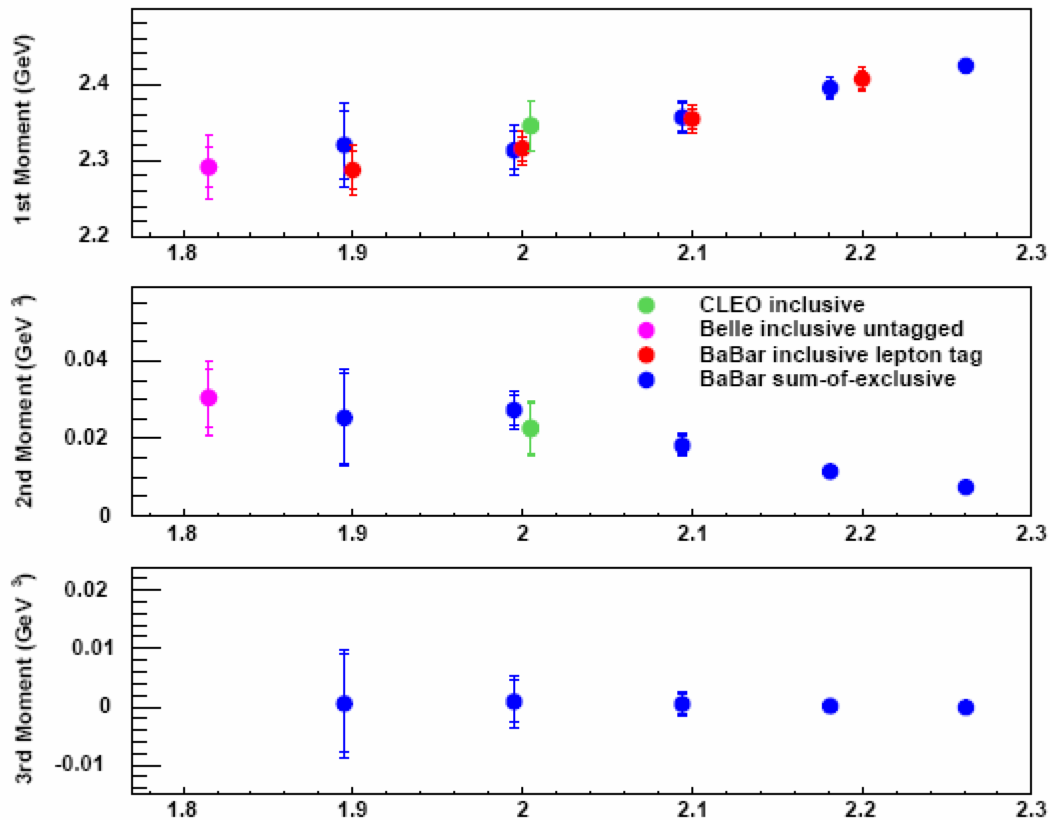
Truncated Moments in $B \to X_s\gamma$ vs. minimum E_γ in B rest frame

$1\text{st} \equiv \langle E \rangle$

2nd $\equiv \langle (E - \langle E \rangle)^2 \rangle$

3rd $\equiv \langle (E - \langle E \rangle)^3 \rangle$

BaBar data preliminary



Consistency across measurements with common E_γ(min)

Use moments and PBFs (0^{th} moment) to extract HQE parameters and/or shape function (in progress)

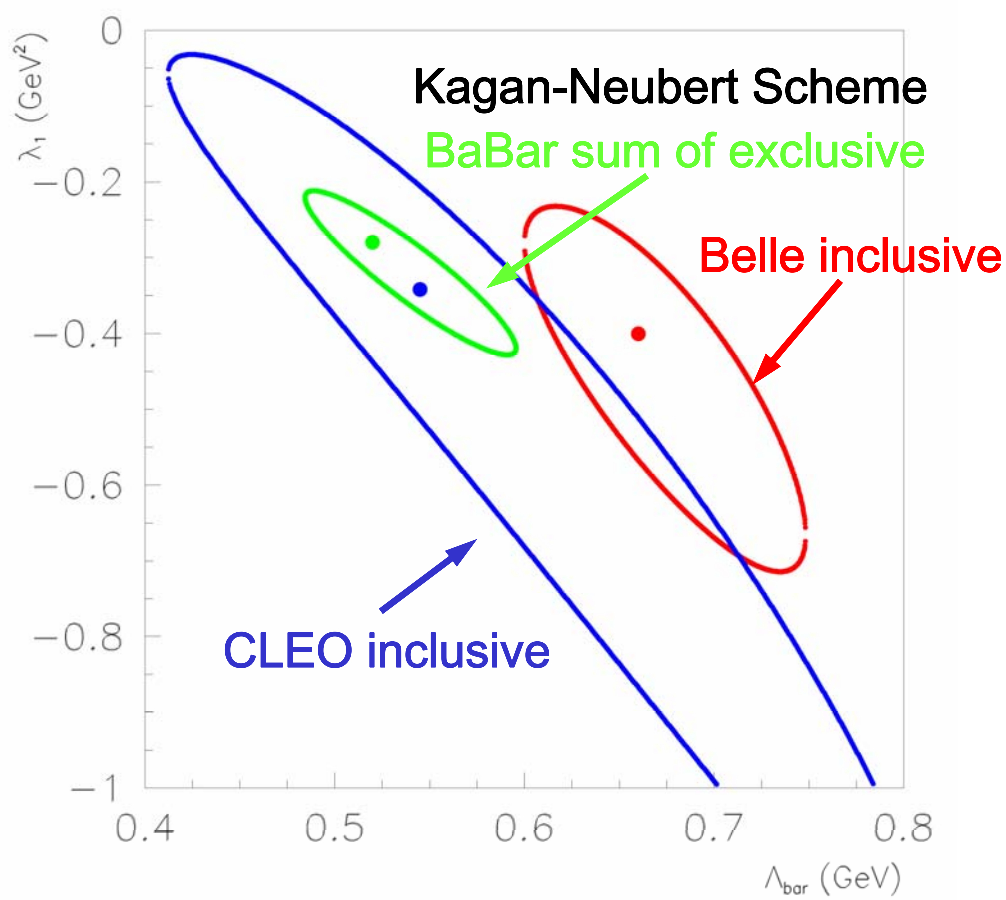
Shape Function Comparison

No significant disagreement

BaBar prefers larger m_b

High BaBar SF precision from good measurement at high E_γ

To avoid possible duality violating effects, BaBar SF fit method may sacrifice some of this precision (in progress)

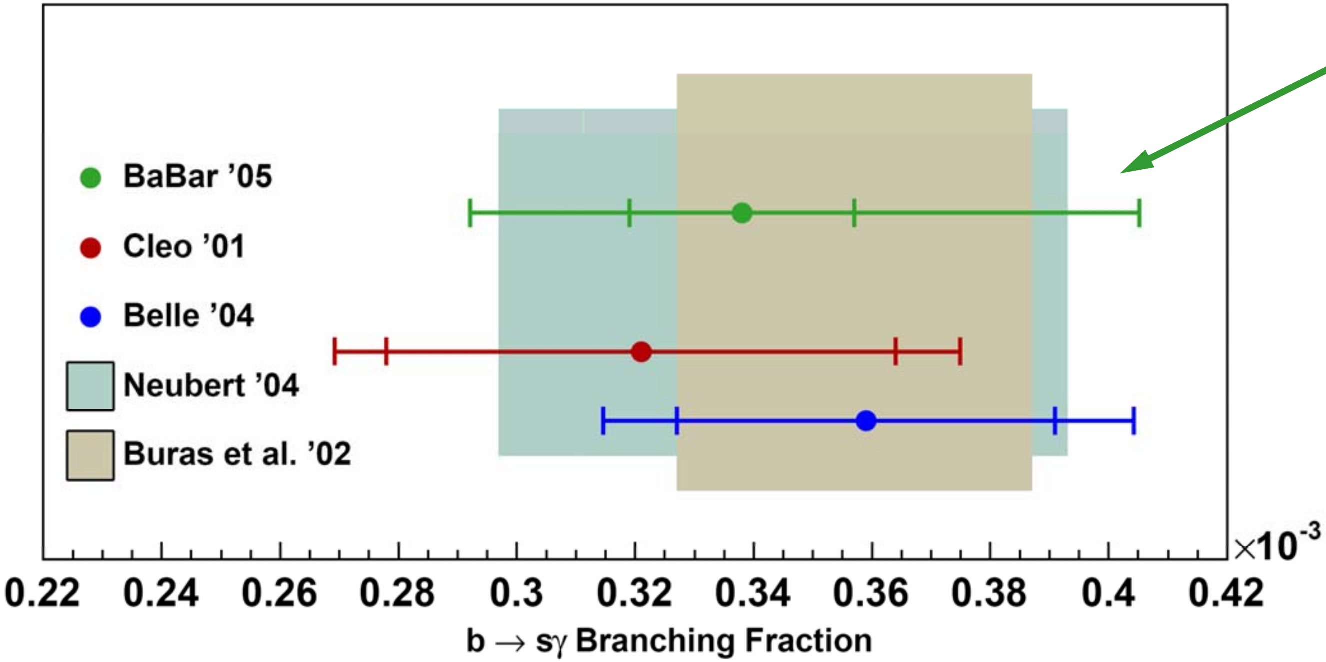


Total Branching Fractions: Summary

"Total Branching Fraction" → PBF at $E\gamma$ (min) = 1.6 GeV

Requires (model-dependent) extrapolation of spectral shape

Excellent agreement with Standard Model predictions at 10% level



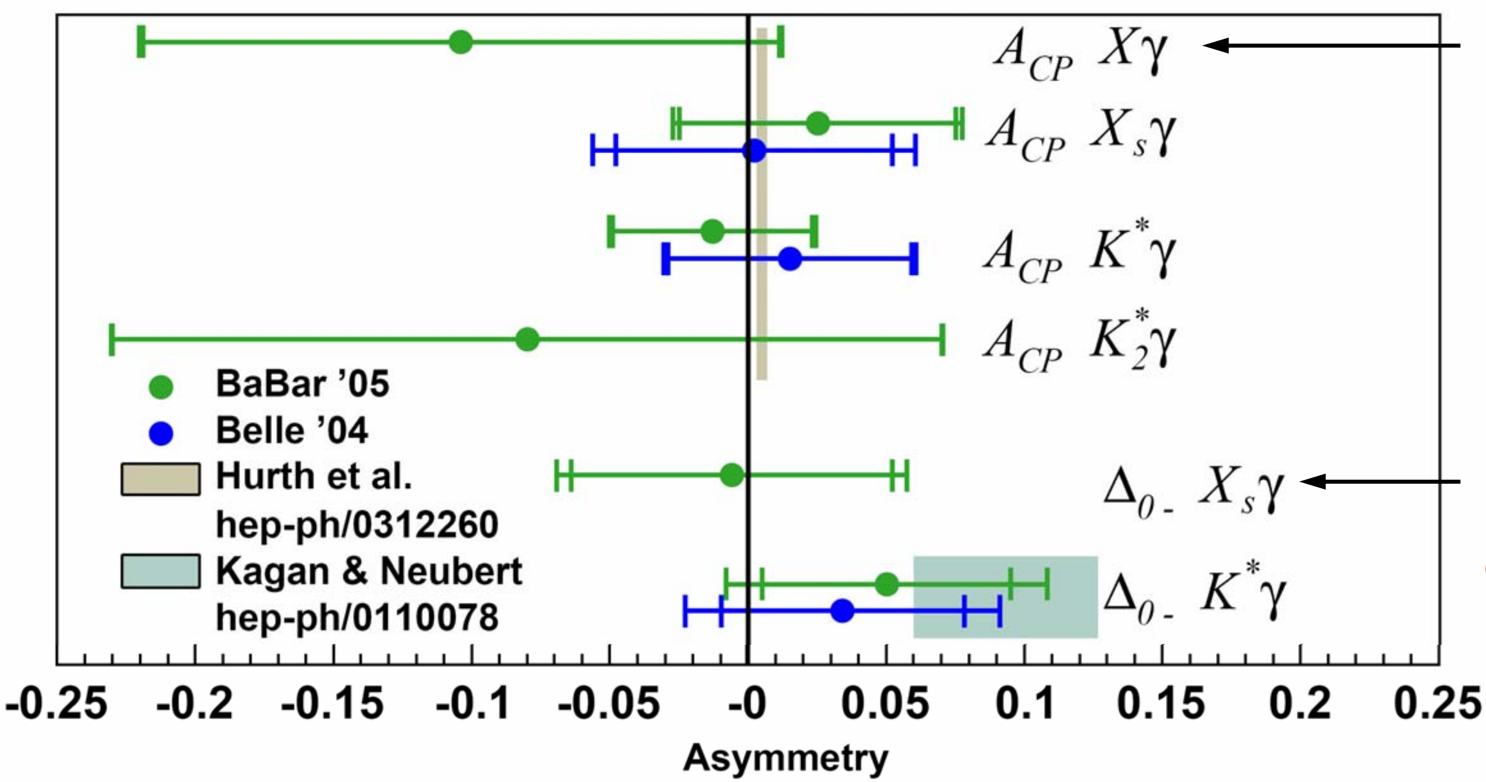
BaBar sum of exclusive (82 fb^{-1}, preliminary)

Experiment, theory uncertainty could each improve to ~5%

Total BF from BaBar inclusive measurement in progress (spectral fits)

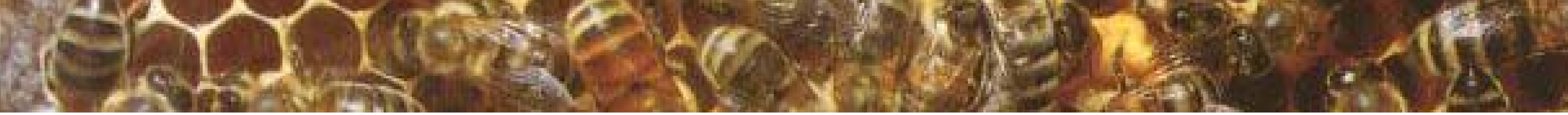
Asymmetries: Summary

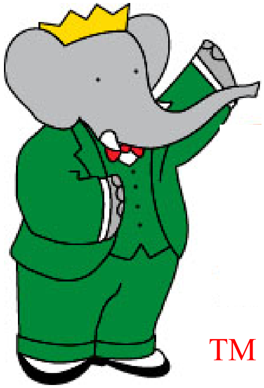
Direct CP asymmetry generally constrained to < 5%
Isospin asymmetry precision ~5%
All measurements statistics limited for forseeable future



First ever CP asymmetry measurement of b→(s+d) γ

First ever isospin breaking measurement of b→s γ



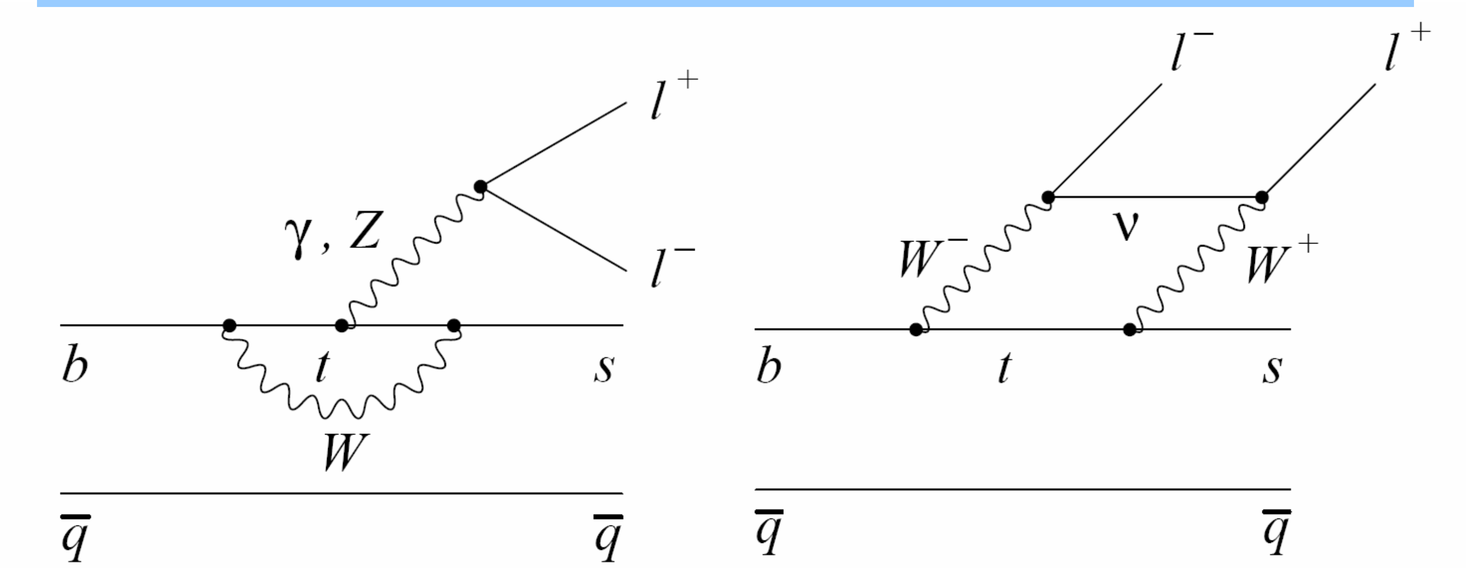


TM

The Ultimate Electroweak Penguin Decay:

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

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 $b \rightarrow s\, l\, l$

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

general Hamiltonian of $b \rightarrow s$ transitions

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

Wilson coefficients C_i encode short distance physics (order α_s)

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

C_9 (mostly) Z penguin

C_{10} (mostly) W box

unique to $b \rightarrow s\, ll$

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

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

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

15% uncertainty in inclusive rate

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

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

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

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

3 $B \rightarrow K$ form factors

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

7 $B \rightarrow K^*$ form factors

BF($B \rightarrow K\mu\mu$) = 0.35 ± 0.12 10^{-6}

BF($B \rightarrow K^*\mu\mu$) = 1.2 ± 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

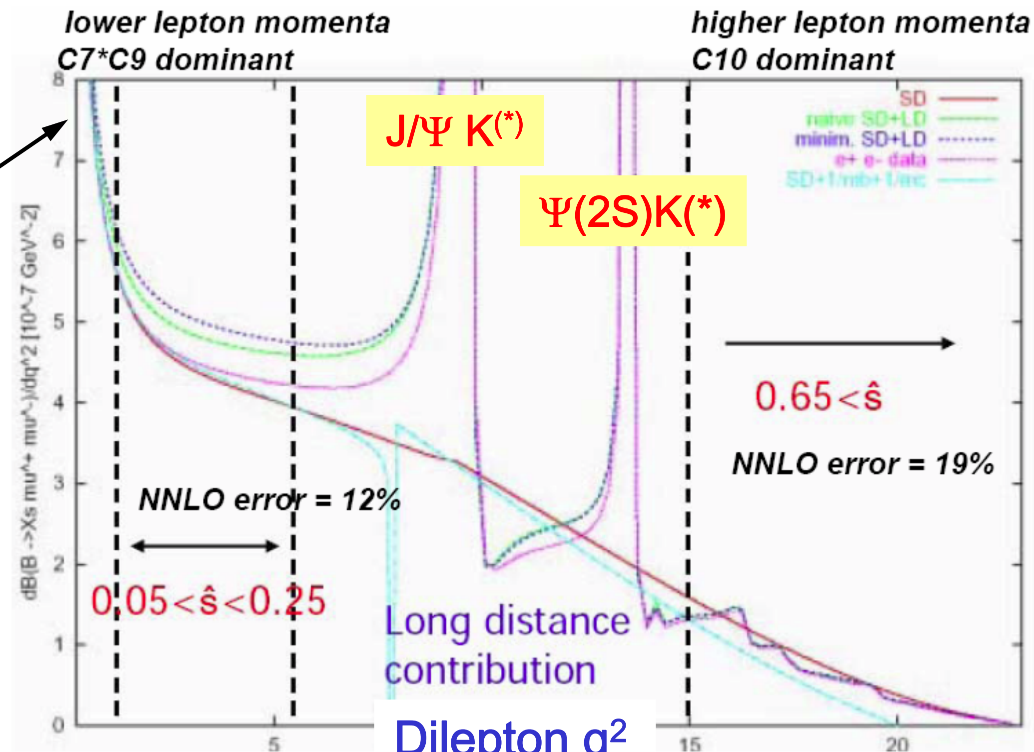
Dilepton Mass Distribution

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



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

Generally decreases with s

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

SUSY Higgs physics at a B Factory

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

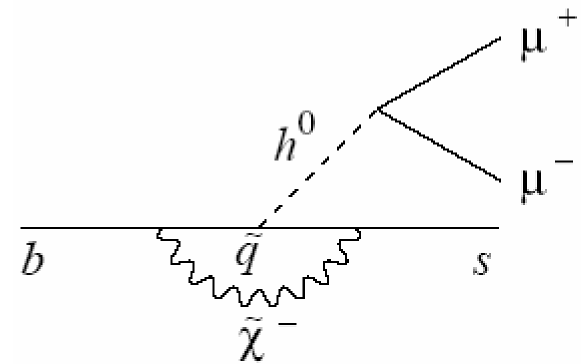
Sensitive to "neutral Higgs penguin" for SUSY with large tan β

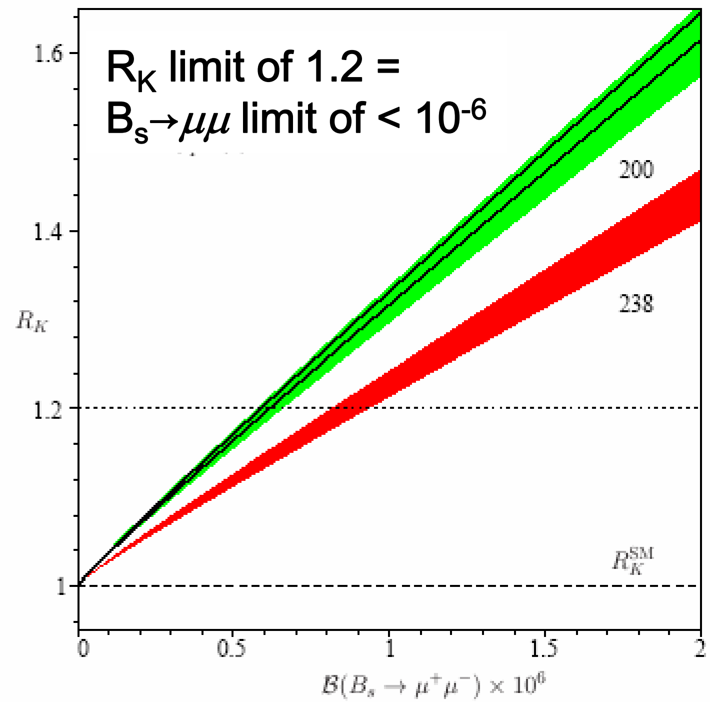
Ratio $R(K) = BF(B\to K\mu\mu)/BF(B\to Kee)$ isolates Yukawa enhancement in muon mode

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

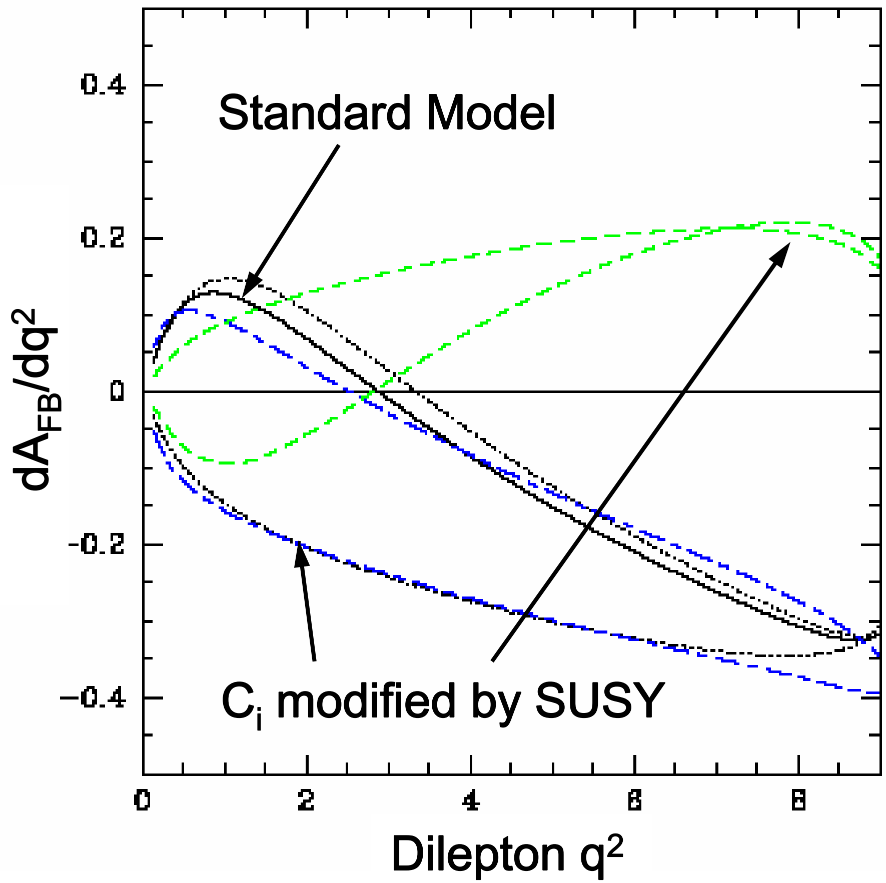
Forward-Backward Asymmetry

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)

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

$B \rightarrow K l l$, $K^* l l$ Measurement (208 fb^{-1})

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)

$B \to K^* ll$

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

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 Y(4S): precision kinematic constraints

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

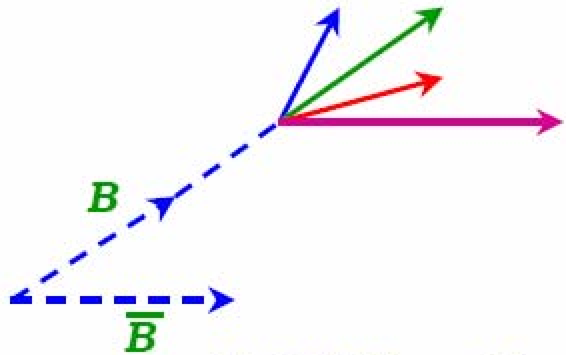
$$m_{ES} = \sqrt{E_{beam}^{*\,2} - (\sum_i p_i^*)^2}$$

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

Typical resolutions:

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

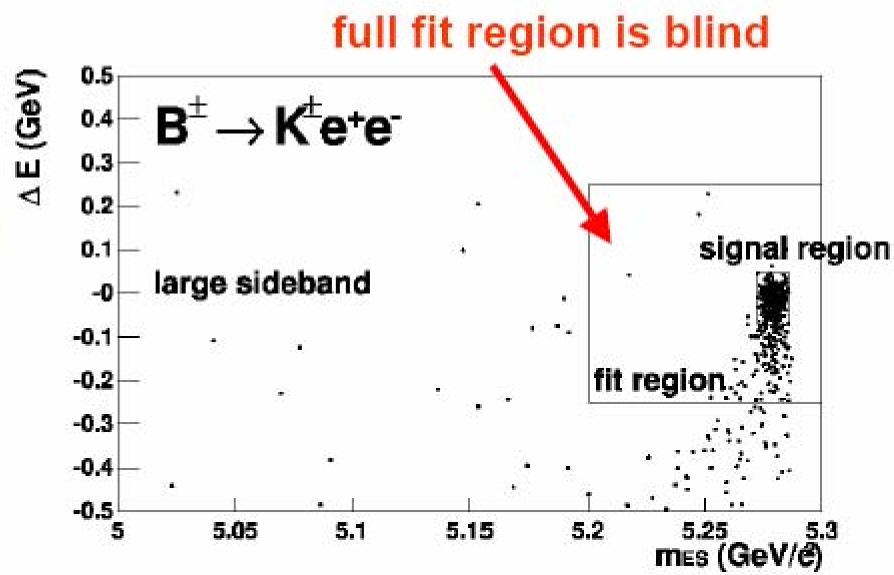
$\sigma(\Delta E) \approx$ 25 - 40 MeV



(*) ≡ measured in Υ(4S) rest frame

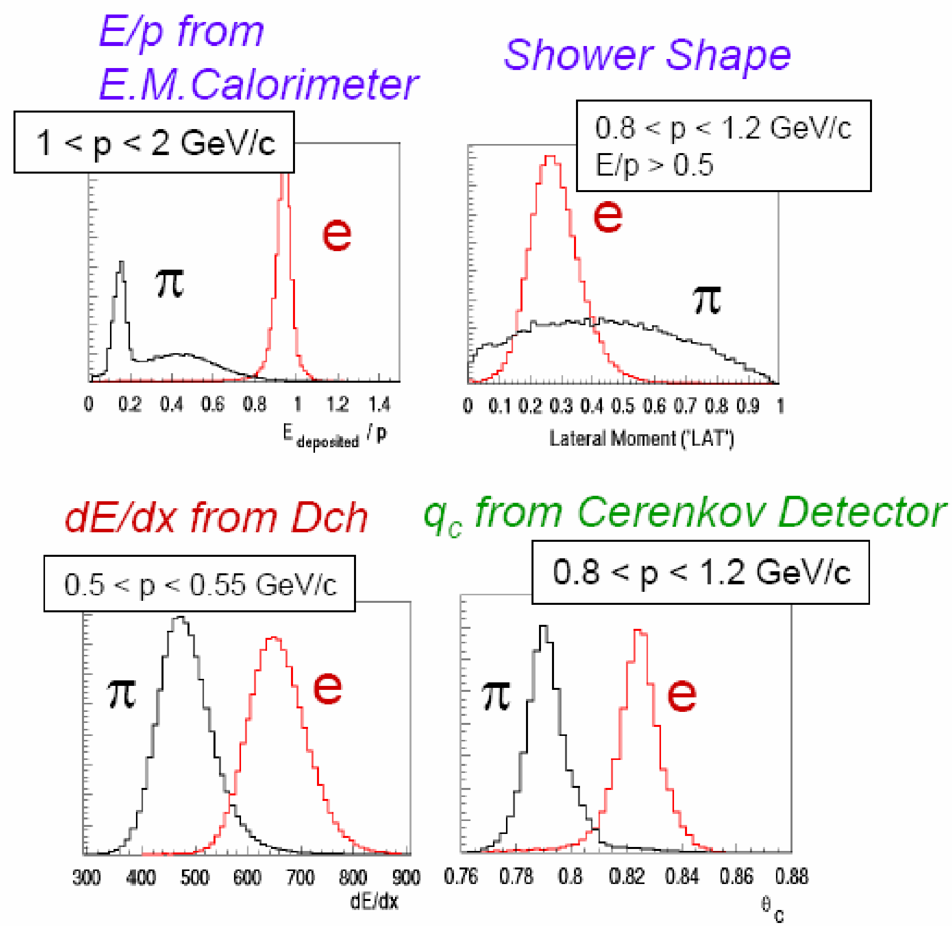
$E_i \longleftrightarrow E^*_{beam}$ ➔ Improve resolution

- **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

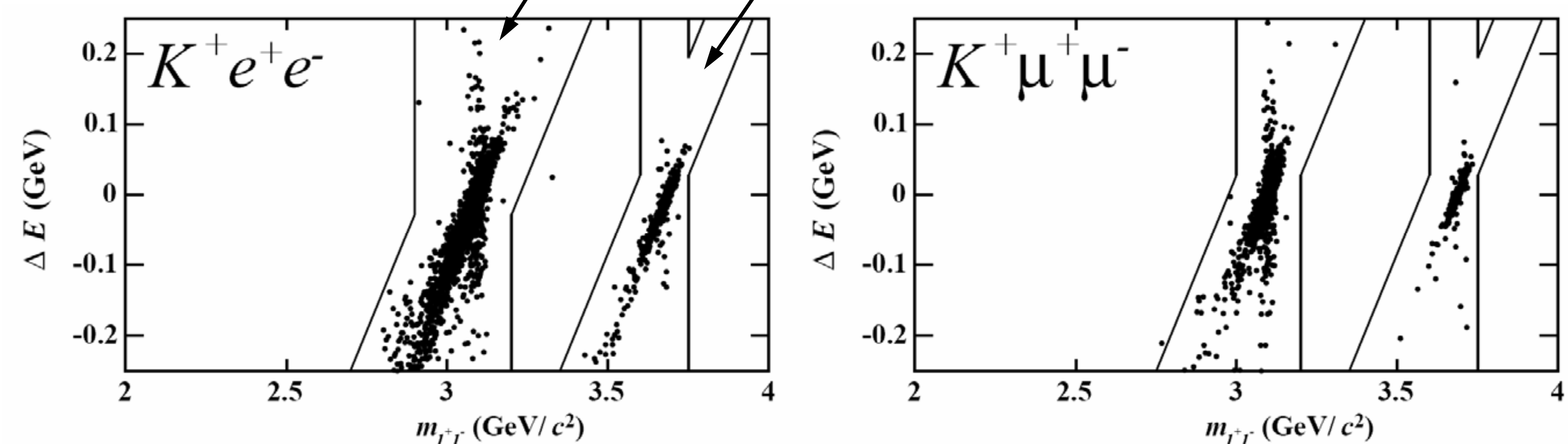


μ, K fake rates < 2%
e fake rate < 0.1 %

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 μμ samples)

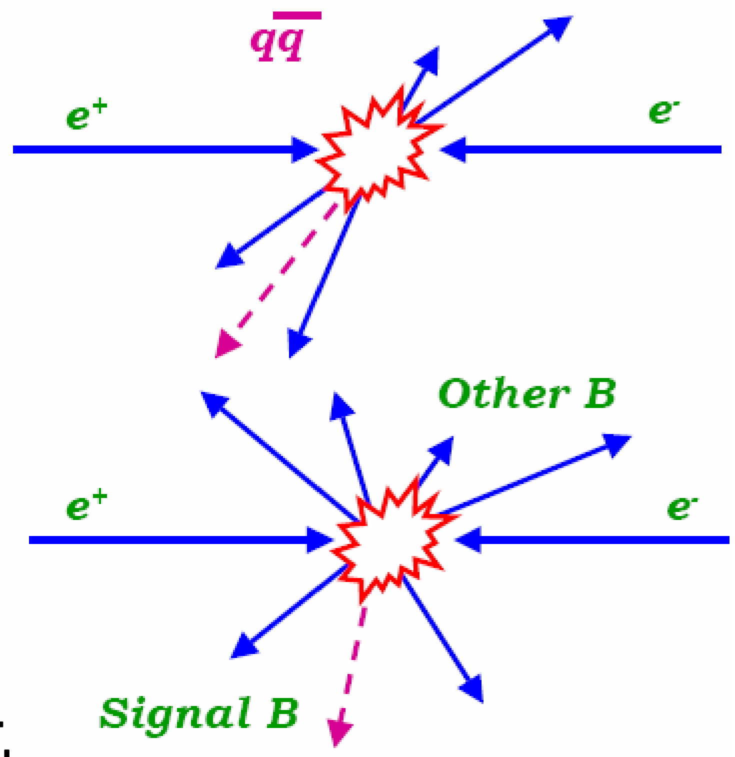
Reduced to < 1 event expected per mode

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 2^{nd} 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

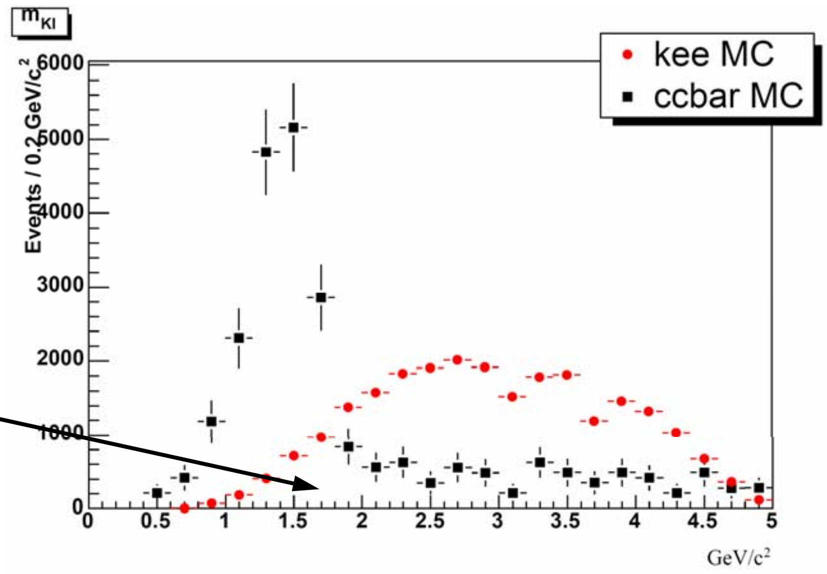


Signal shape from MC; background shape from off-resonance data

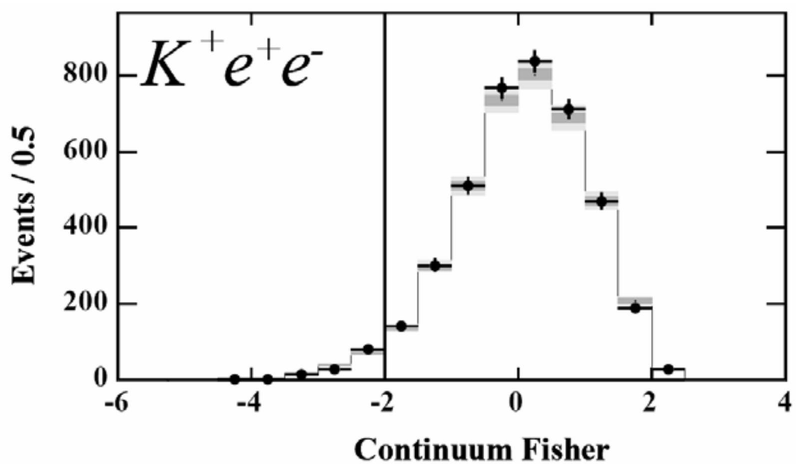
Continuum Suppression

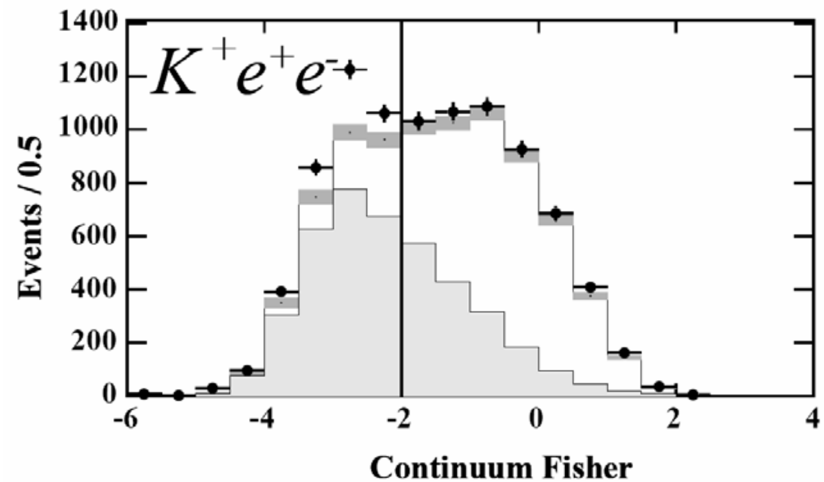
Kaon-lepton mass in Fisher reduces large background from semileptonic D decays

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

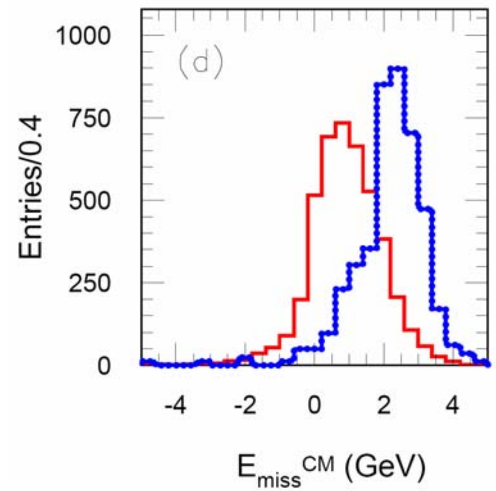
Separation of B background from signal using likelihood function (product of shapes):

Missing energy

B production angle

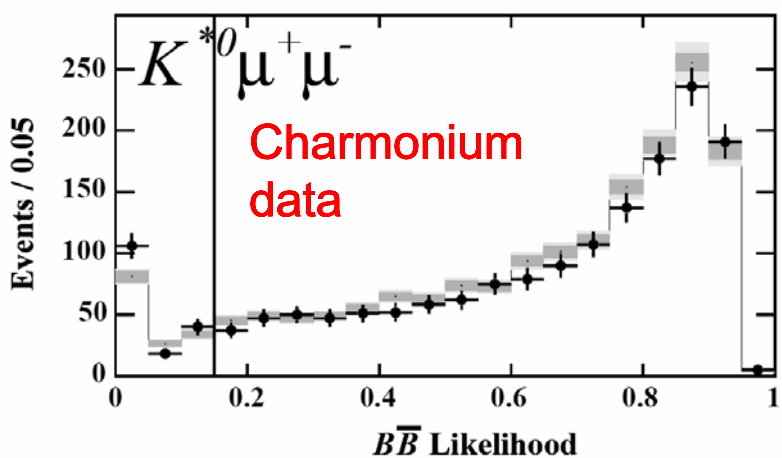
Vertex probability

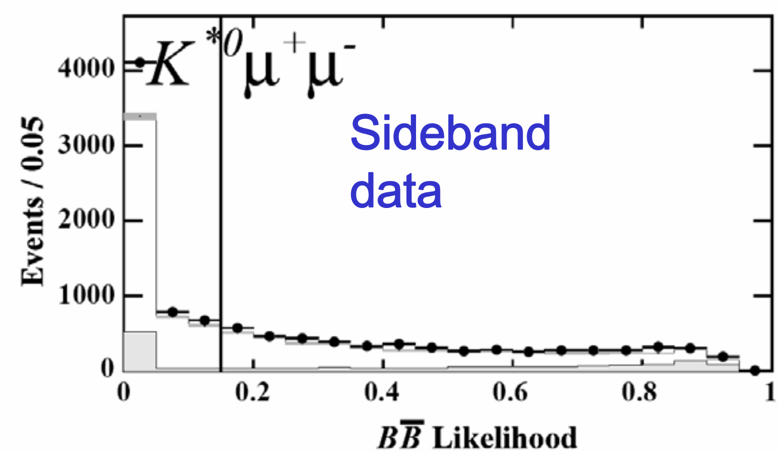
Likelihood shapes from MC



Signal vs.
Background
missing energy

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





Hadronic B Decay Background

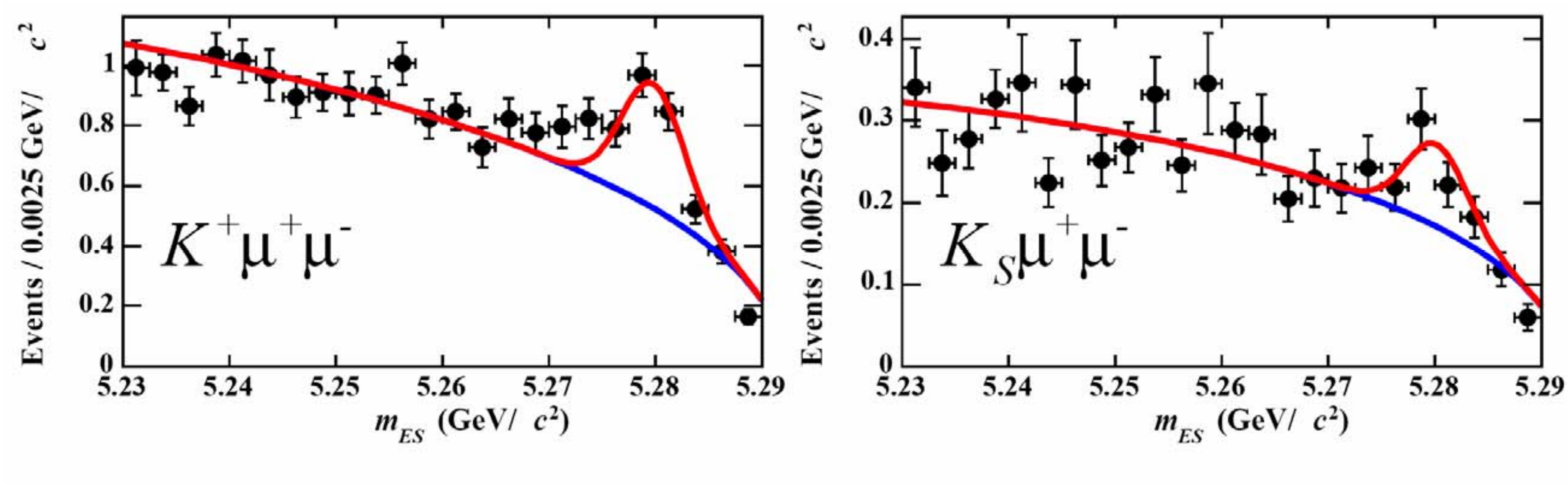
B decays to hadrons misidentified as leptons will have same kinematics as signal
Electron modes: misid ~0.1%, negligible
Muon modes: misid ~1-2% for pions and kaons
Misid rate calibrated from large $B \to D^*\pi$, $D^* \to D\pi$, $D \to K\pi$ samples

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

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

Convolve misid rates with $B \to K(^*)\mu\pi$ 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)

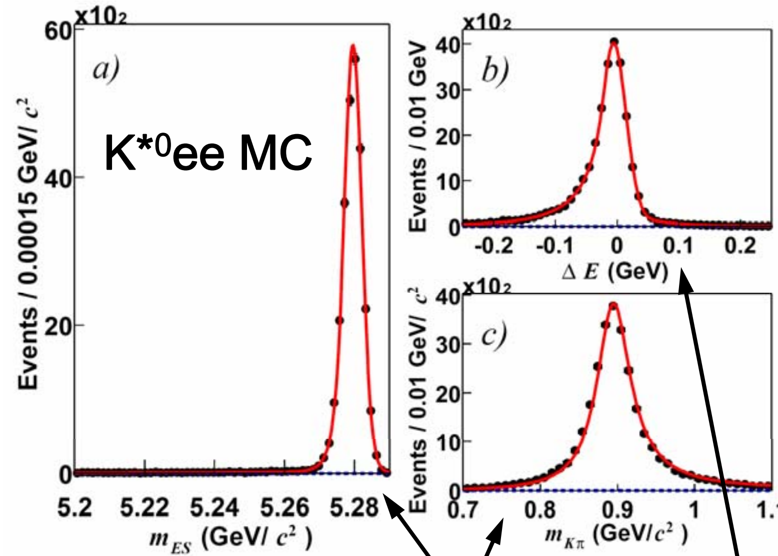
Signal shape parameters fixed from charmonium data

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

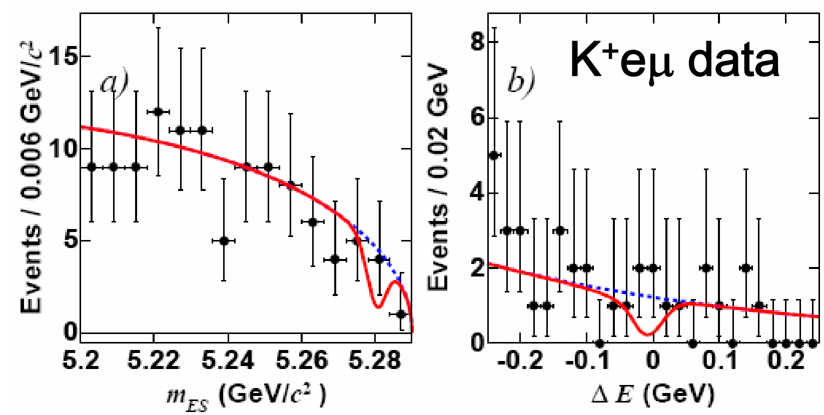
m_{ES}: "ARGUS function" models phase space cutoff at M_B

ΔE: linear or quadratic

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



Signal shapes (narrow peaks)

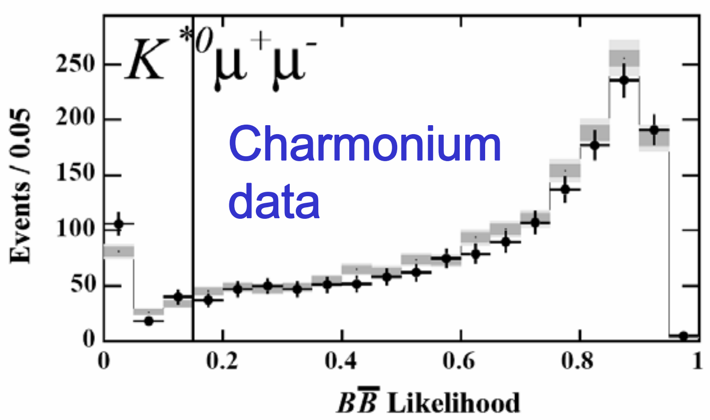


Background shapes (not peaked)

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

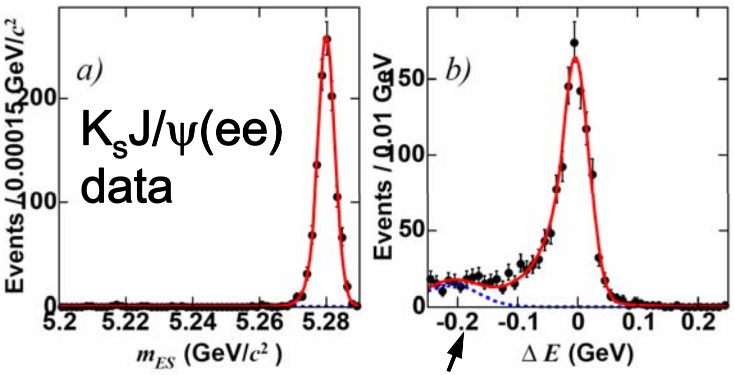
Dominant systematic on efficiency (4-7%) is model dependence
(form factor models change q^2 distribution)

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



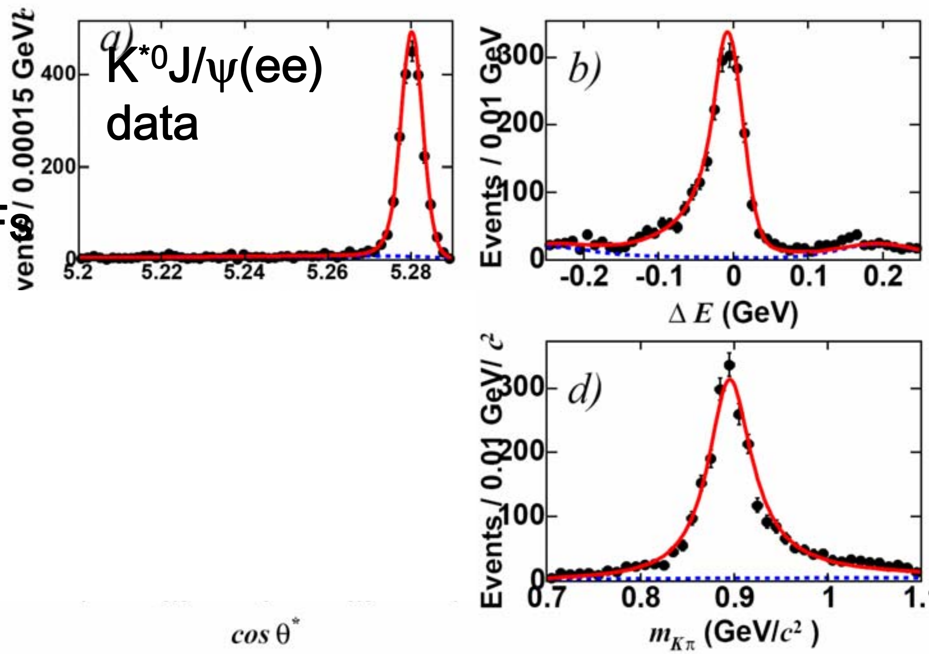
Feed-down from $J/\psi\ K^{*+}$

Test fit procedure on charmonium

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

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

Signal and background well-modeled by PDFs



Also:

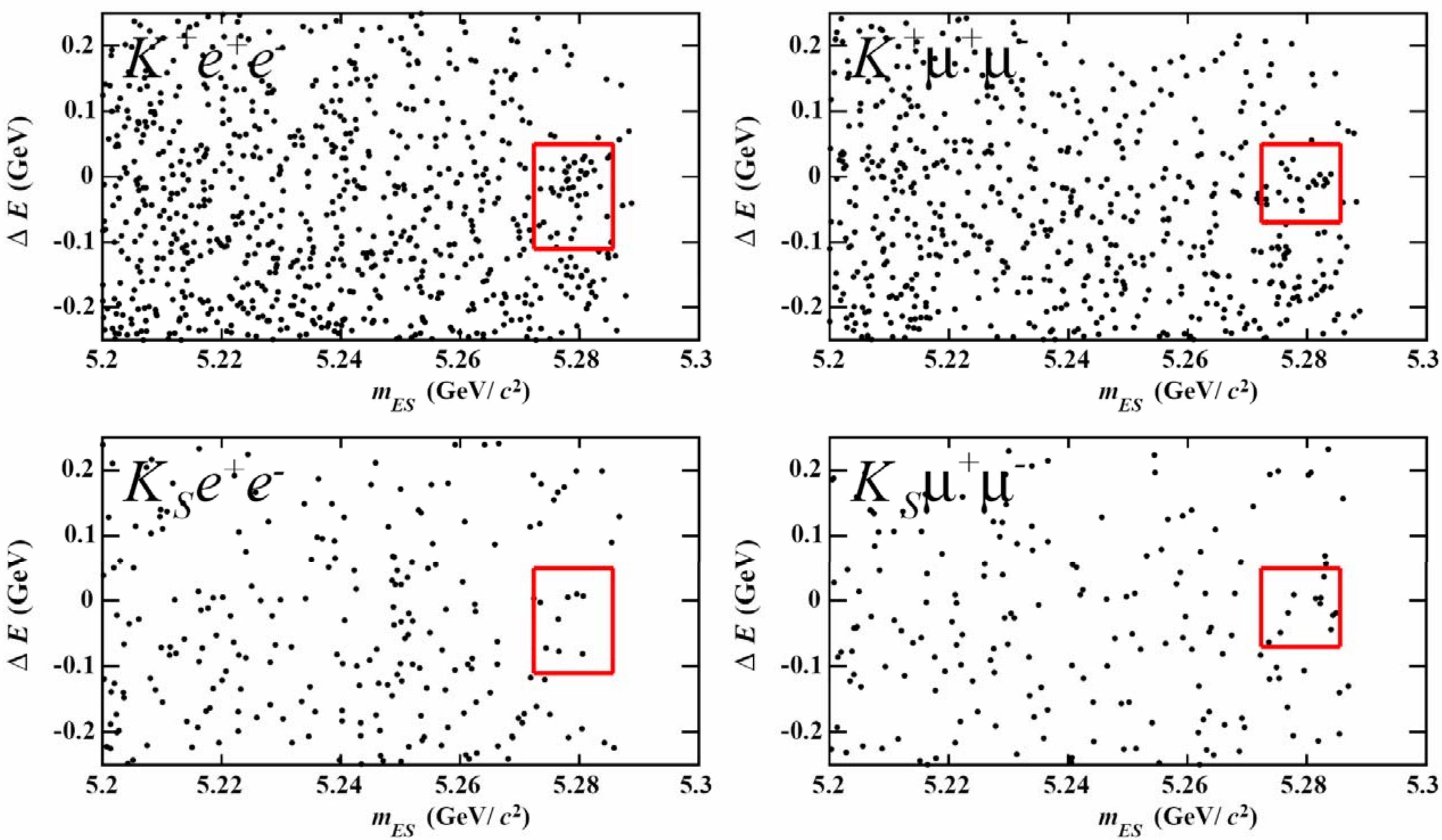
Ψ(2S) K(*) branching fractions

K(*)eμ

Lower-dimensional and/or smaller range fits

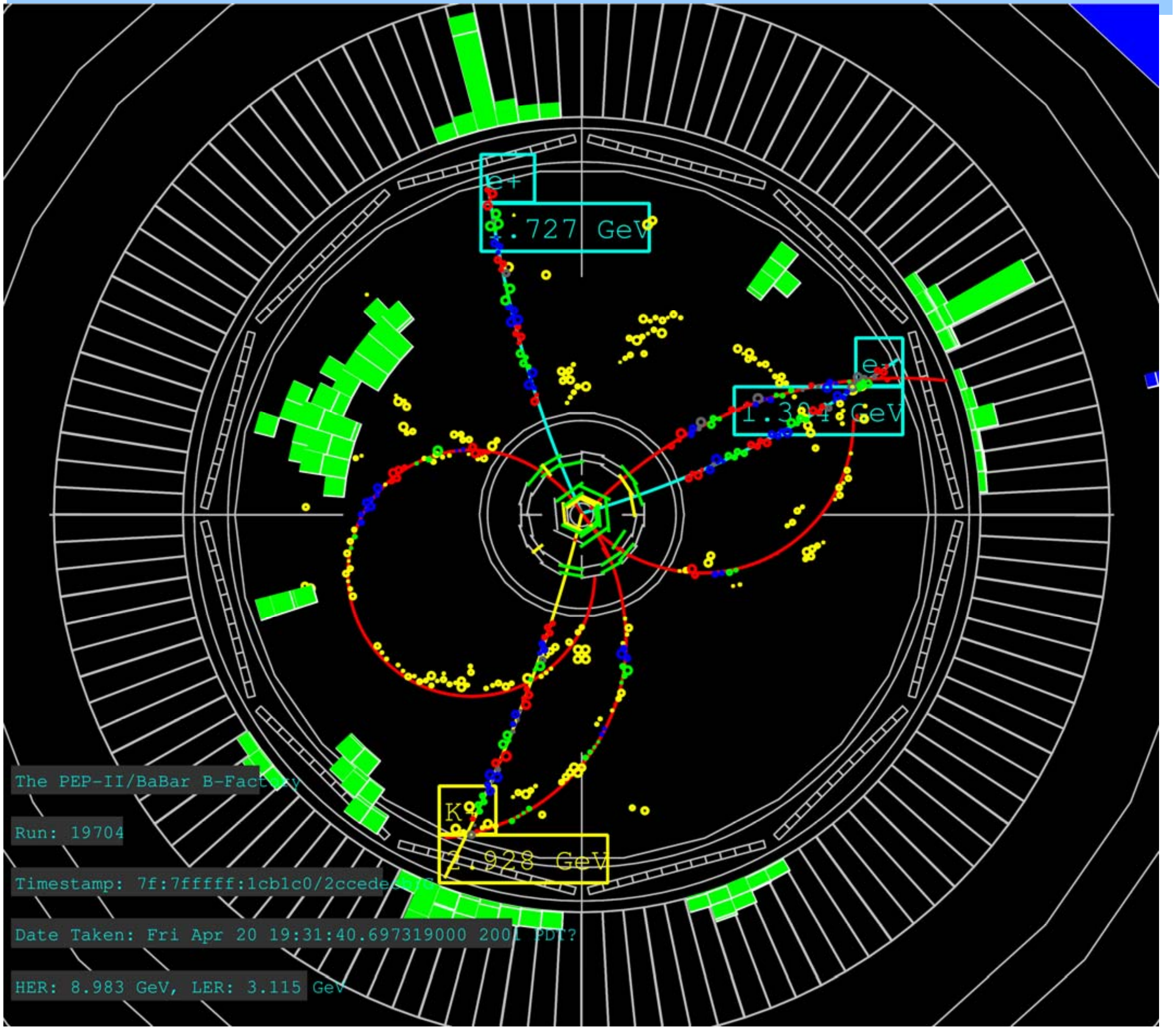
Sideband yields agree with MC

Kll Fits

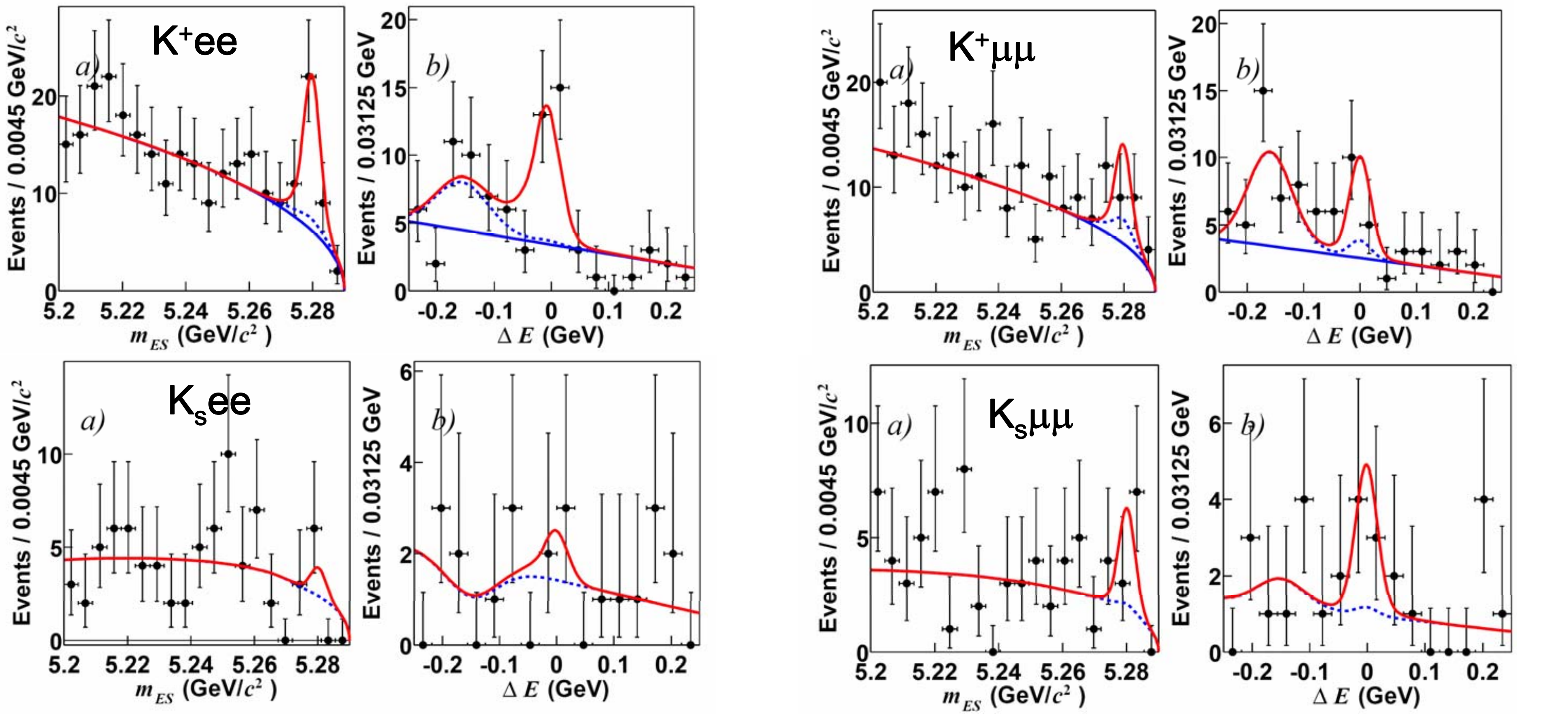


$K^+e^+e^-$
$K^+\mu^+\mu^-$
$K_S e^+e^-$
$K_S \mu^+\mu^-$
ΔE (GeV)
m_{ES} (GeV/ c^2)
0.2
0.1
0
-0.1
-0.2
5.2
5.22
5.24
5.26
5.28
5.3

$K^+e^+e^-$ Candidate



K*ll* Fits



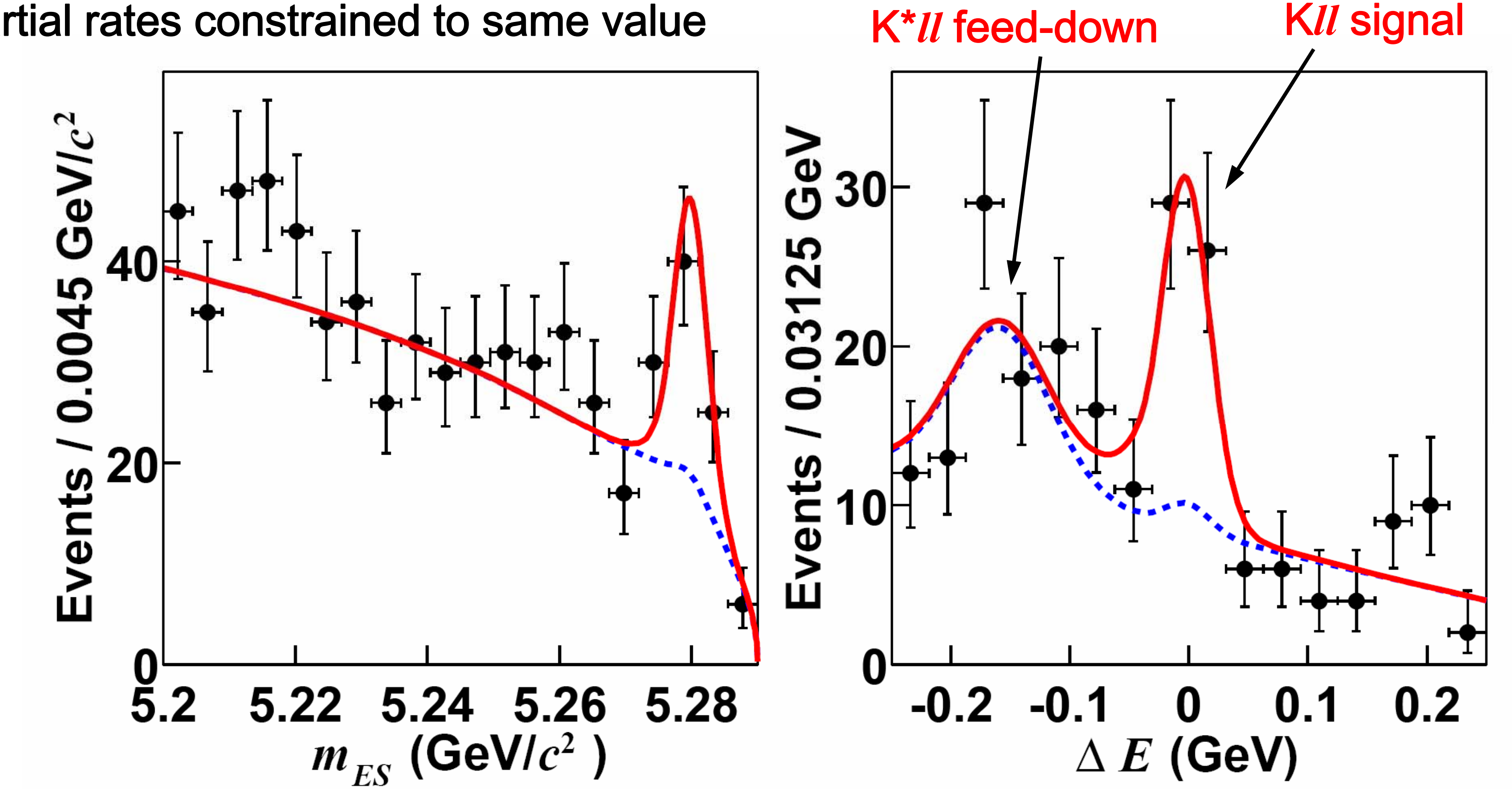
Mode	Signal yield	Eff.	Eff. Syst. $(\Delta\mathcal{B})(\times 10^{-6})$	Fit Syst. $(\Delta\mathcal{B})(\times 10^{-6})$	$\mathcal{B}(\times 10^{-6})$	Significance(σ)
$B^+ \to K^+ e^+ e^-$	$25.9^{+7.4}_{-6.5}$	$(26.4 \pm 0.1)\%$	± 0.02	± 0.02	$0.43^{+0.12}_{-0.11} \pm 0.03$	5.3
$B^+ \to K^+ \mu^+ \mu^-$	$10.9^{+5.1}_{-4.3}$	$(15.2 \pm 0.1)\%$	± 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

K*ll* Combined BF

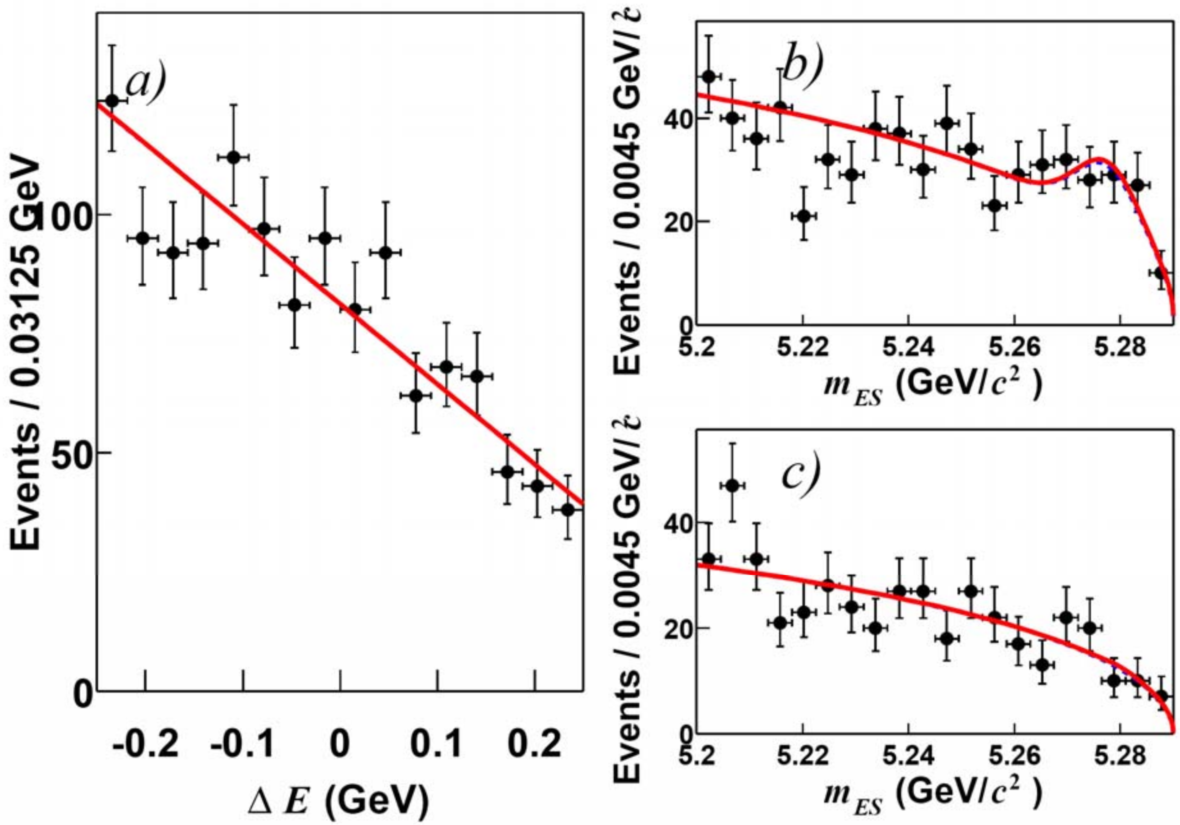
Mode	$(\Delta\mathcal{B})(\times 10^{-6})$	$(\Delta\mathcal{B})(\times 10^{-6})$	$\mathcal{B}(\times 10^{-6})$	Significance(σ)
$B \to K e^+ e^-$	± 0.02	± 0.01	$0.33^{+0.09}_{-0.08} \pm 0.02$	5.3
$B \to K \mu^+ \mu^-$	± 0.02	± 0.02	$0.35^{+0.13}_{-0.11} \pm 0.03$	3.8
$B \to K \ell^+ \ell^-$	± 0.02	± 0.01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

Simultaneous fit to four individual decay modes
Partial rates constrained to same value

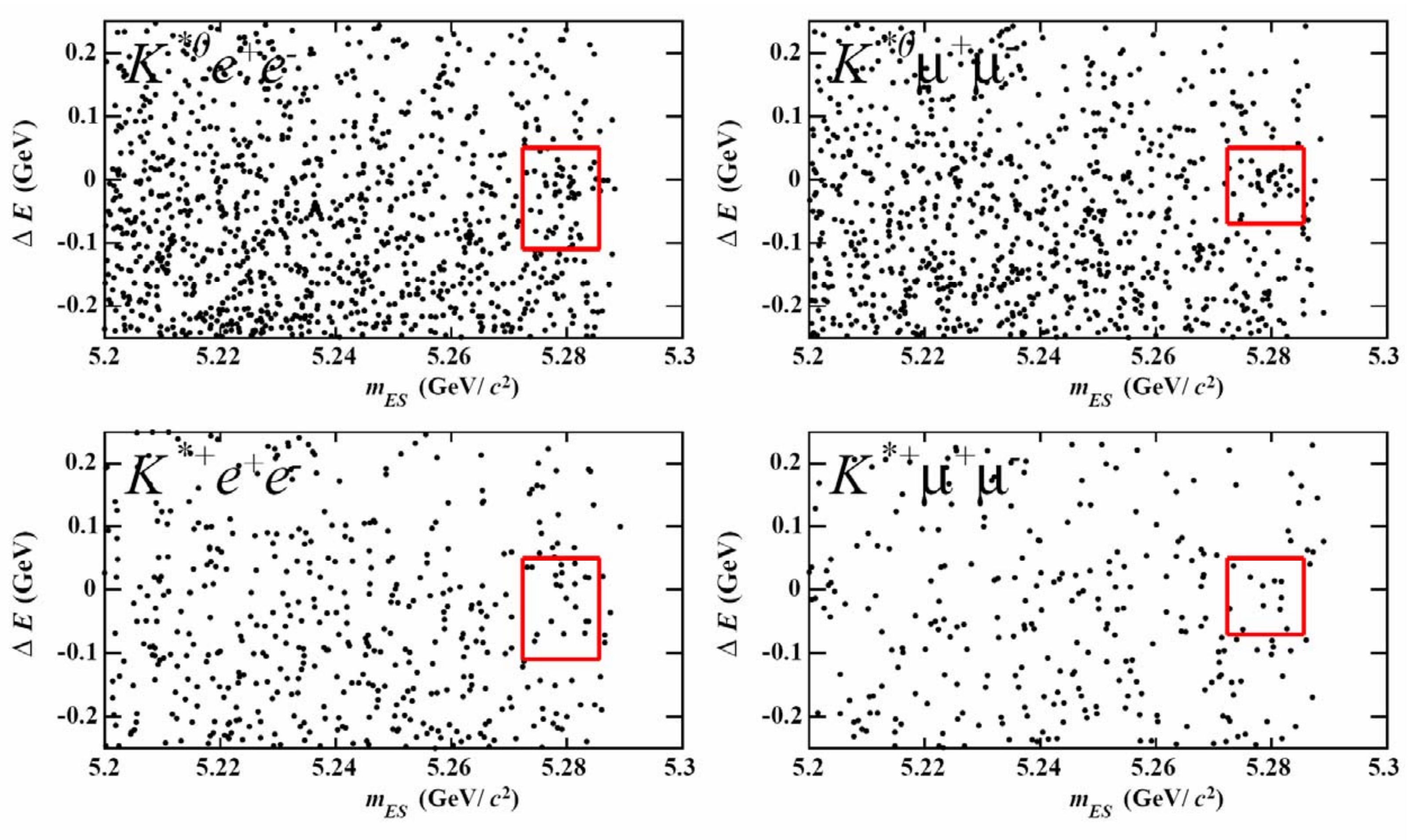


Kll Sidebands

Fit describes background shape well

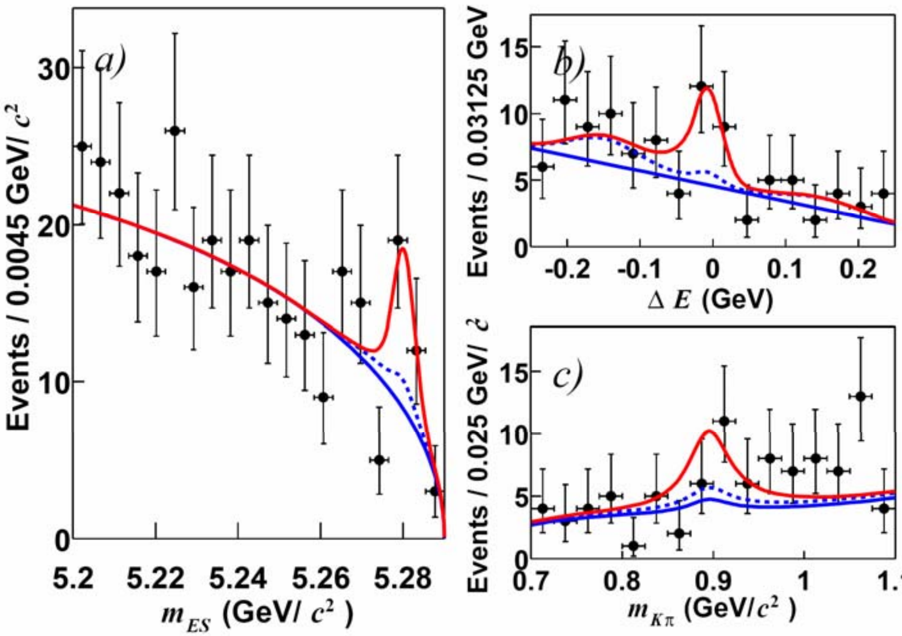


K*ll Fits

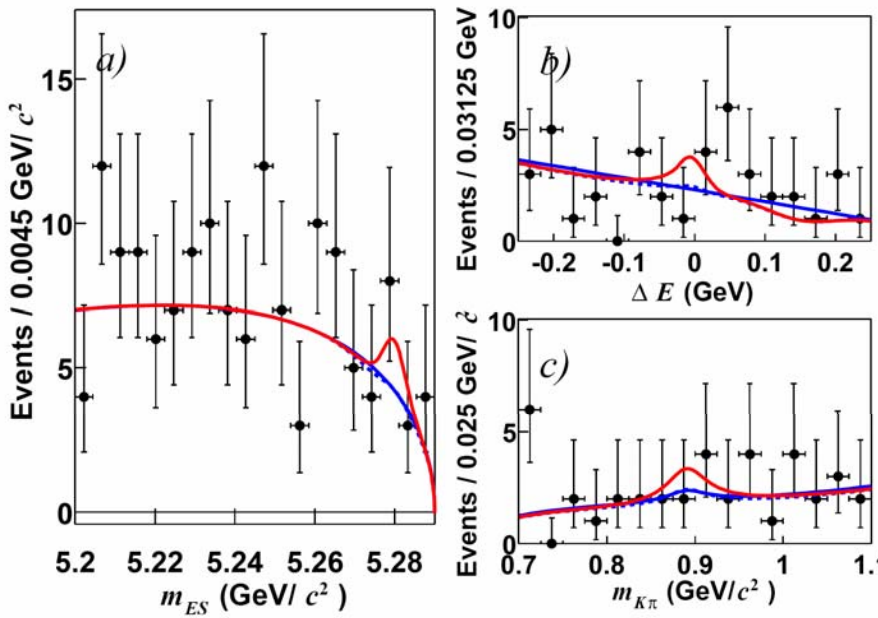


$K^{*0}e^+e^-$
$K^{*0}\mu^+\mu^-$
$K^{*+}e^+e^-$
$K^{*+}\mu^+\mu^-$
ΔE (GeV)
m_{ES} (GeV/ c^2)
0.2
0.1
0
-0.1
-0.2
5.2
5.22
5.24
5.26
5.28
5.3

K*ll Fits



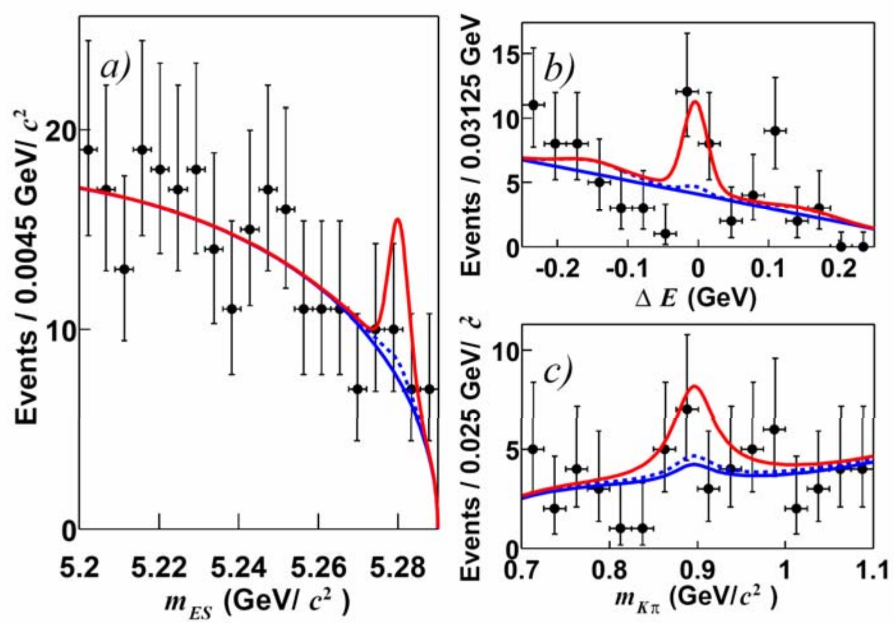
K*^{0}ee



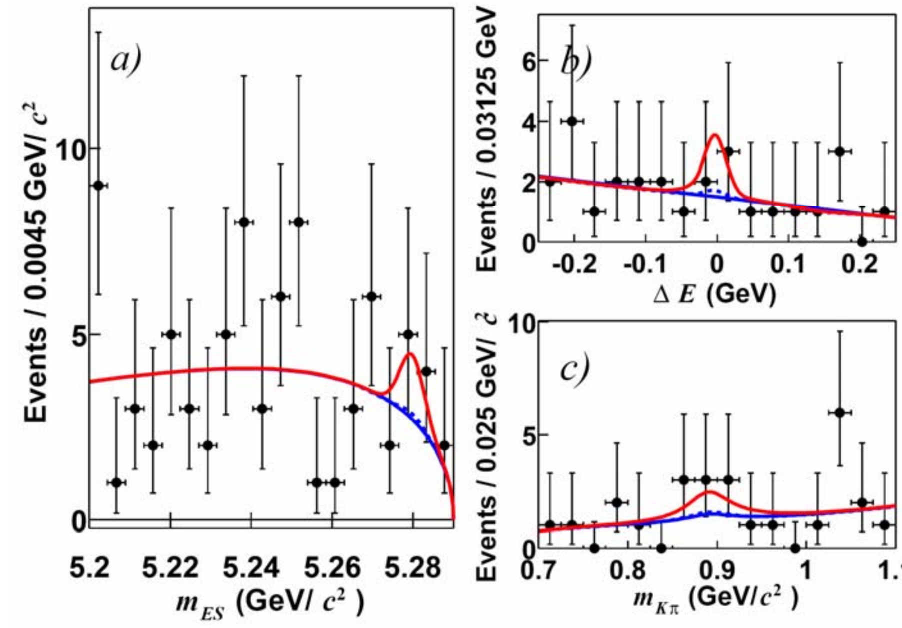
K*$^+$ee

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*⁰μμ



K*⁺μμ

Mode	Signal yield	Eff.	$(\Delta\mathcal{B})(\times10^{-6})$	$(\Delta\mathcal{B})(\times10^{-6})$	$\mathcal{B}(\times10^{-6})$	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	$0.78^{+0.19}_{-0.17} \pm 0.12$	

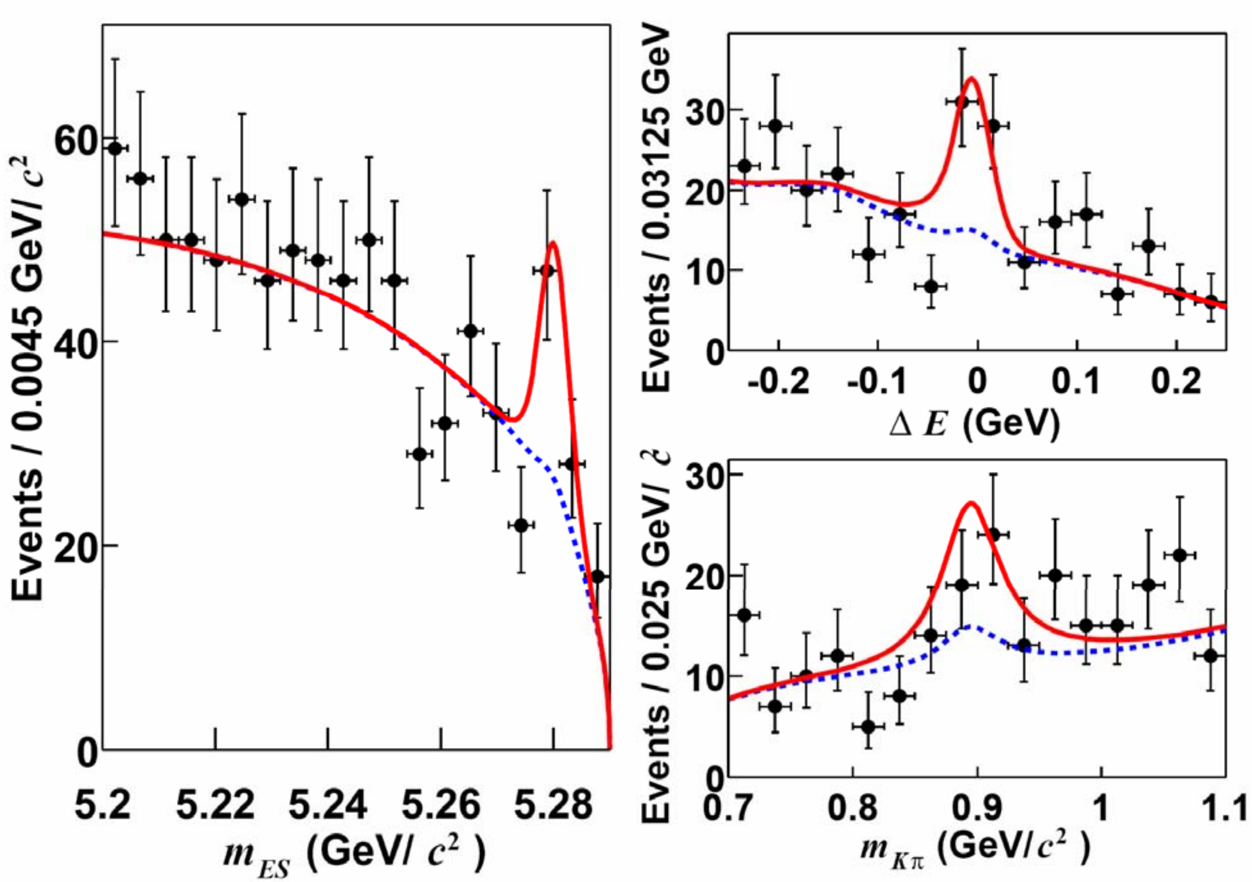
Simultaneous fit with constraint

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

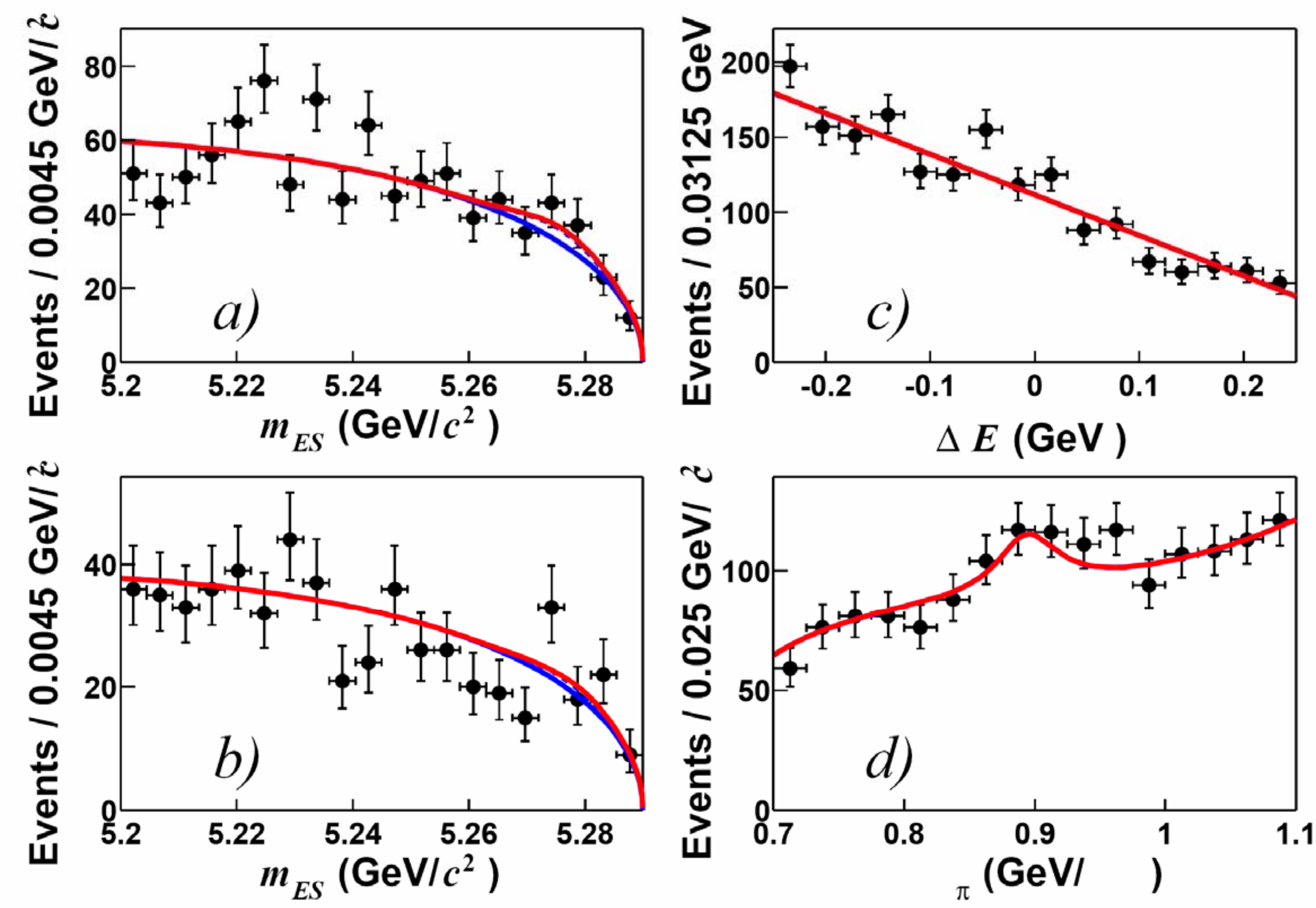
Alternatively, with pole region removed and equal partial rates:

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

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



K*ll Sidebands



Ratios of BFs and A_{CP}

Ratio of Kμμ/Kee BFs consistent with unity:

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

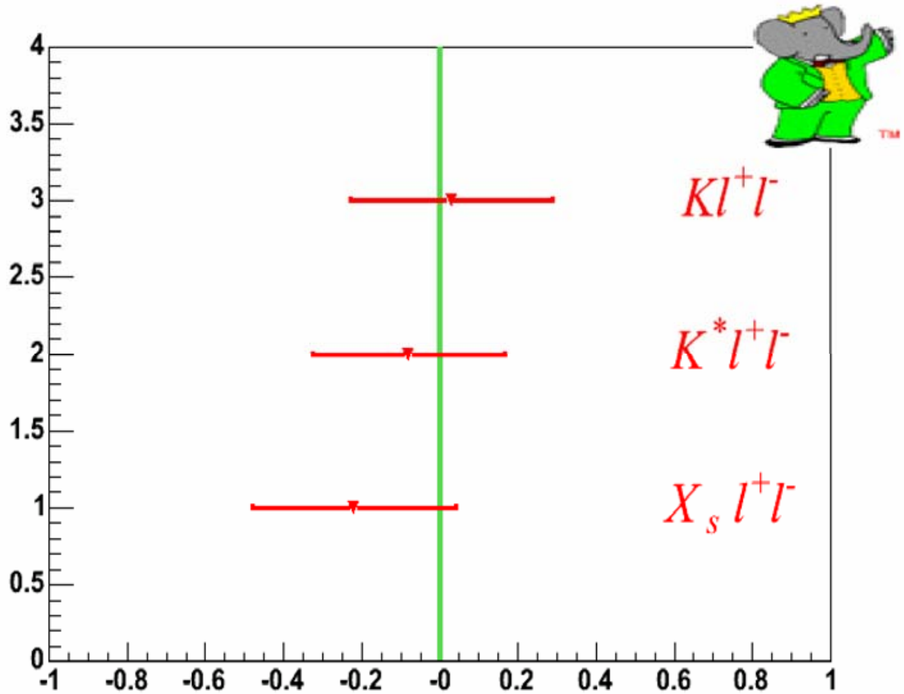
Ratio of K*μμ/K*ee BFs consistent with SM (=0.752):

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

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



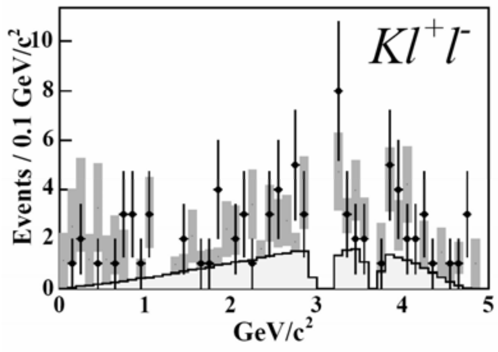
$$A_{CP}(B^+ \to K^+\ell^+\ell^-) = -0.08 \pm 0.22 \pm 0.11$$

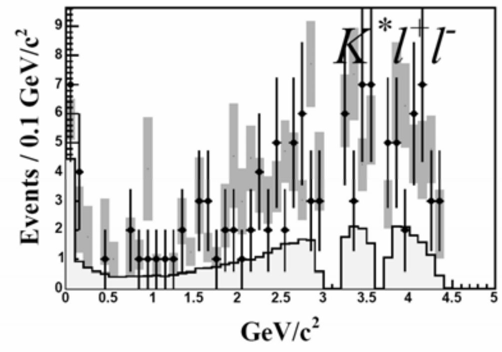
$$A_{CP}(B \to K^*\ell^+\ell^-) = 0.03 \pm 0.23 \pm 0.12,$$

Dominant systematic from unknown asymmetry of peaking background

Towards A_{FB}

First, need partial BF measurement vs. q^2





Signal candidates span entire range

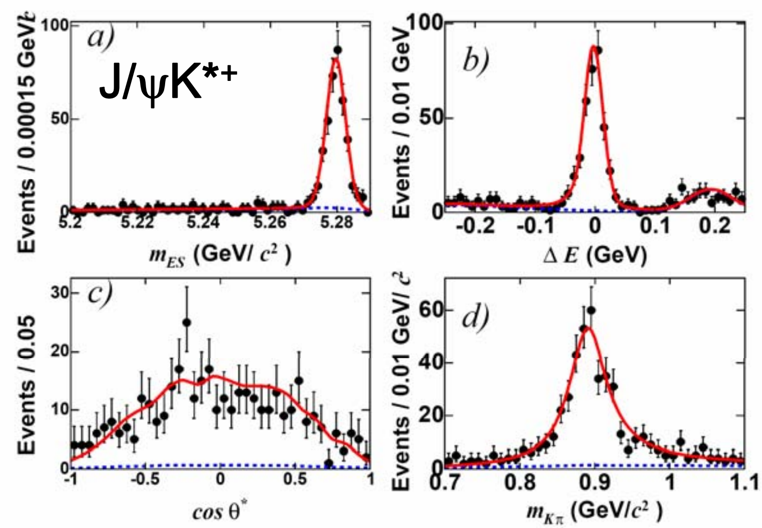
Separate fits for optimal q^2 bins

Fit method for cosθ*: 4D LH fit

$$\Gamma^{-1} d\Gamma/d\cos\theta^* = 0.5\times(1.0-2.0\times C/3.0) + \quad \times\cos\theta^* + C\times\cos^2\theta^*$$

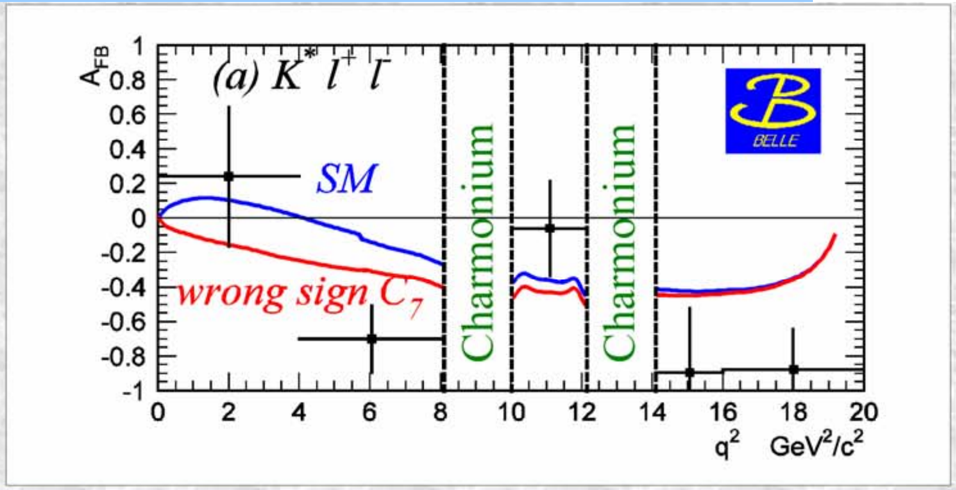
Check with charmonium and K*ll*

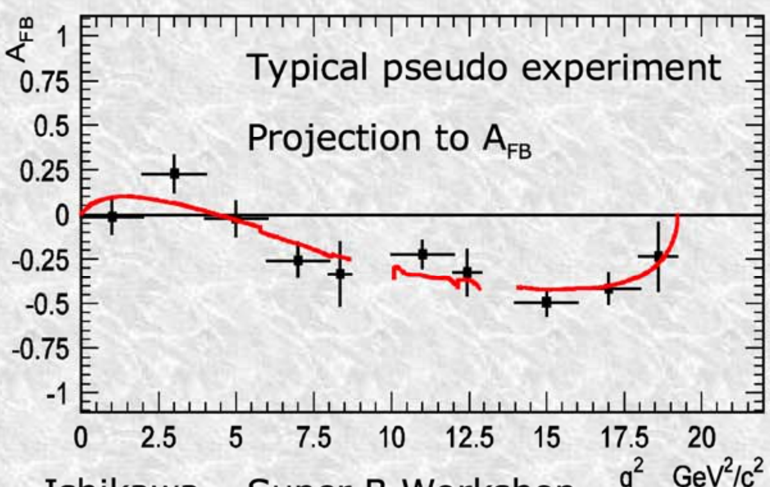
Need asymmetric efficiency and background PDFs



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

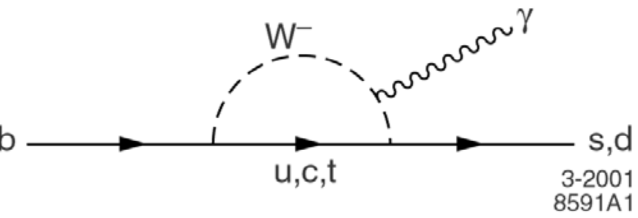
•**Strong penguins beginning to crack the standard model?**

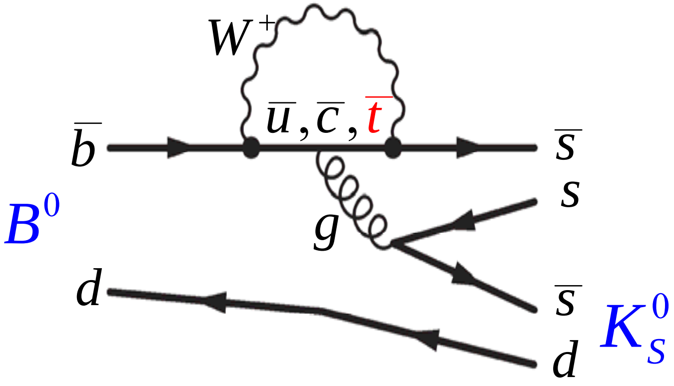
•**Decay rate measurements of $b \rightarrow s\gamma$ penguins** are well into the precision era.

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

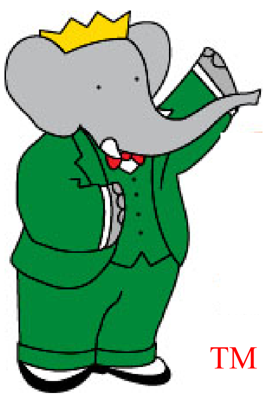
"Ultimate" $b \rightarrow sll$ penguin will ultimately disentangle all electroweak penguin effects, SM or not.

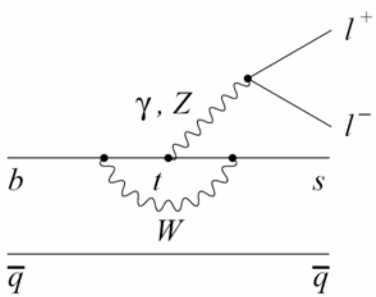
$B \rightarrow Kll$ ratios and K^*ll angular asymmetries are high precision tests of the electroweak scale and beyond

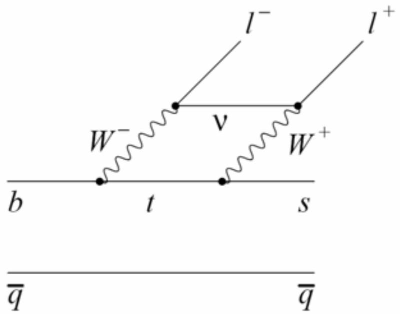


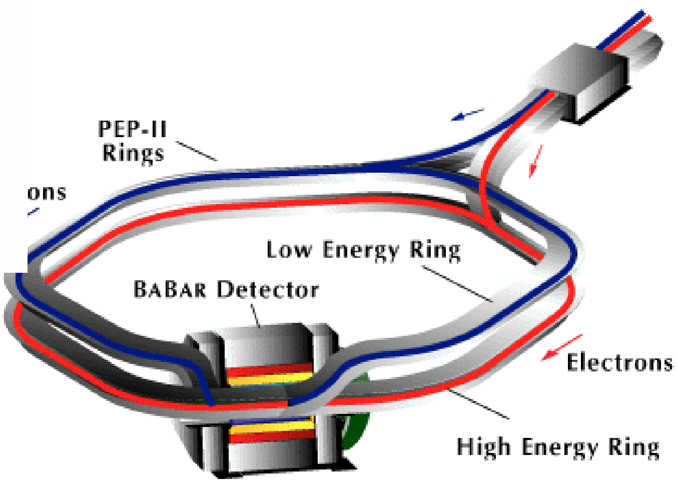


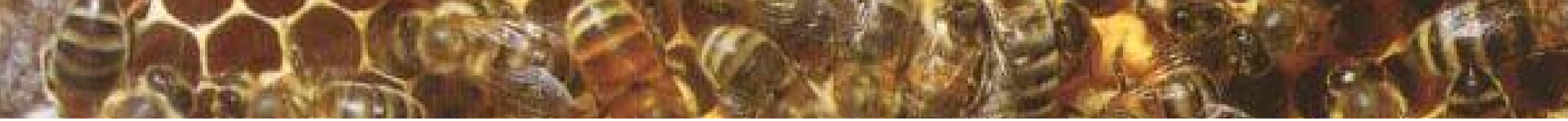
Penguin decays are strongly challenging the Standard Model!

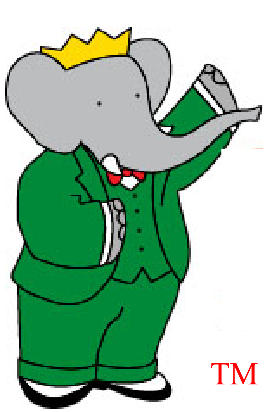












Quarks, Flavor Violation, and CP Violation

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

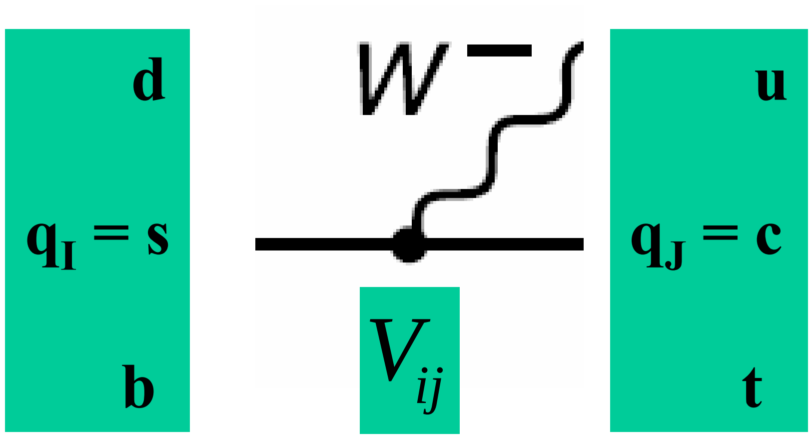
The origin of different fermion generations, masses, flavor violation, and CP violation are all arbitrary parameters of electroweak symmetry breaking.

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

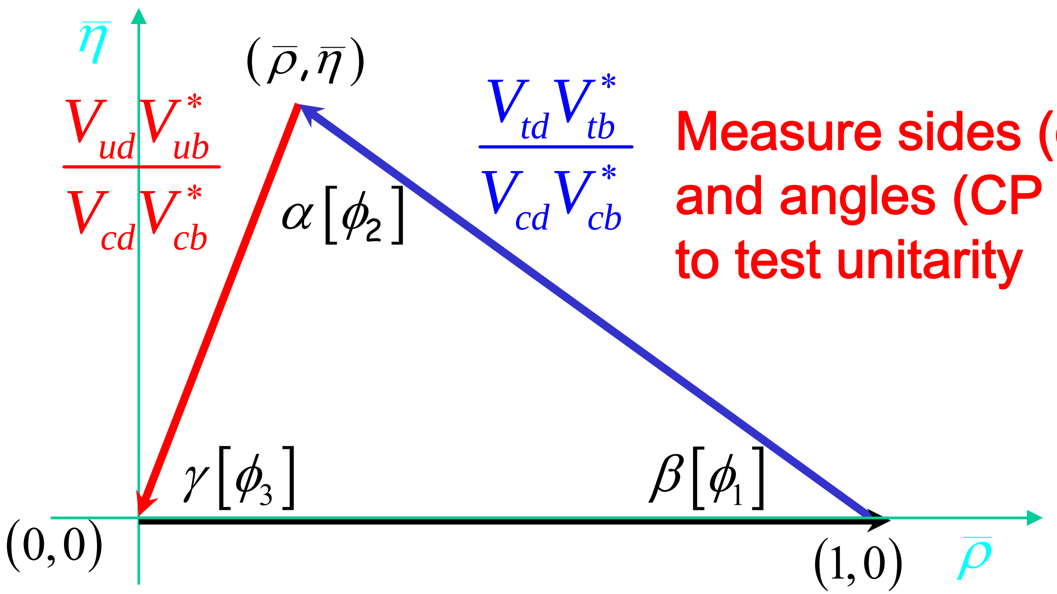
3X3 unitary matrix has (effectively) four degrees of freedom:
3 angles + 1 complex phase

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



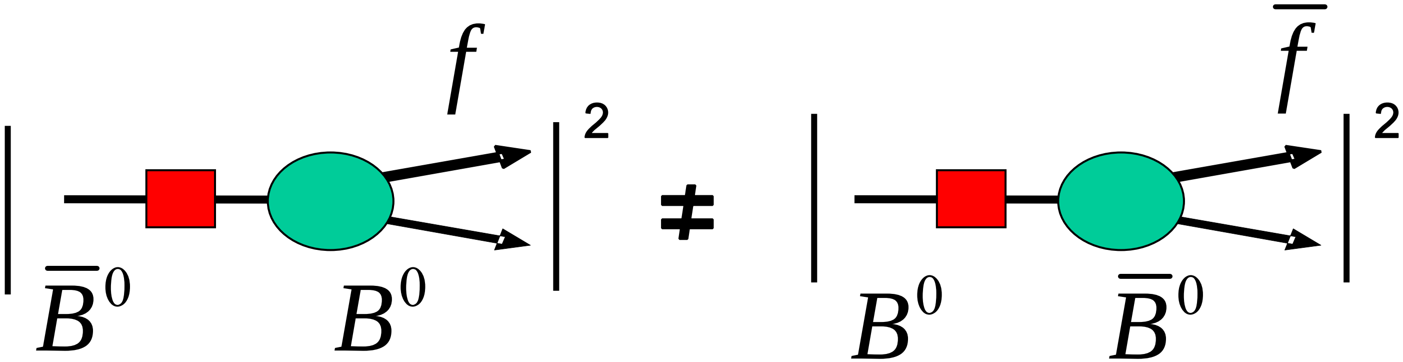
Measure sides (decay rates) and angles (CP violation) to test unitarity

Three Paths to CP Violation

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

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

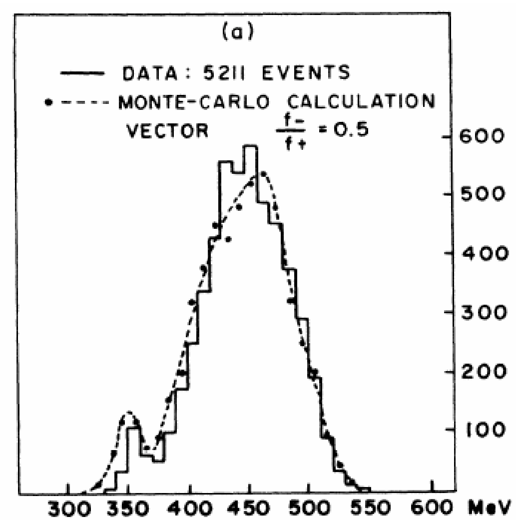
1. CP violation in meson mixing



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

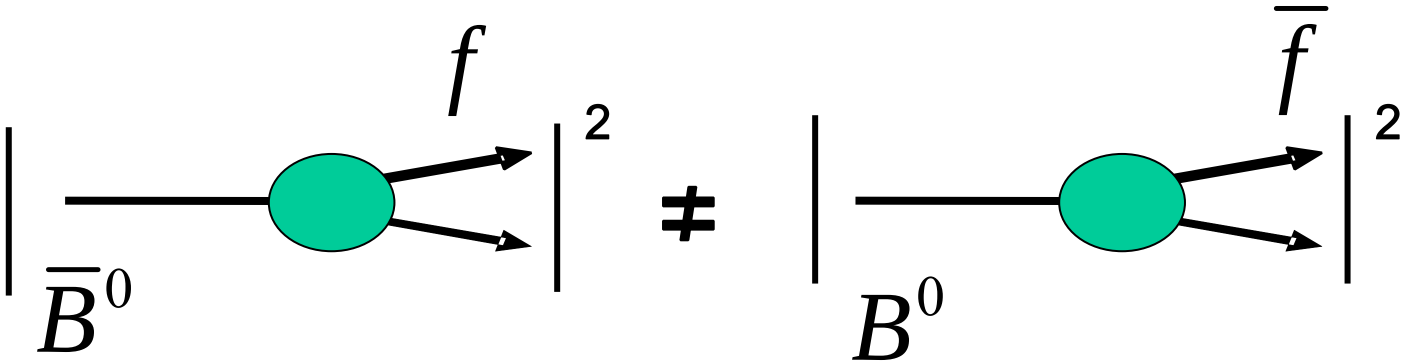
In the Standard Model, very small $\sim 10^{-3}$

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



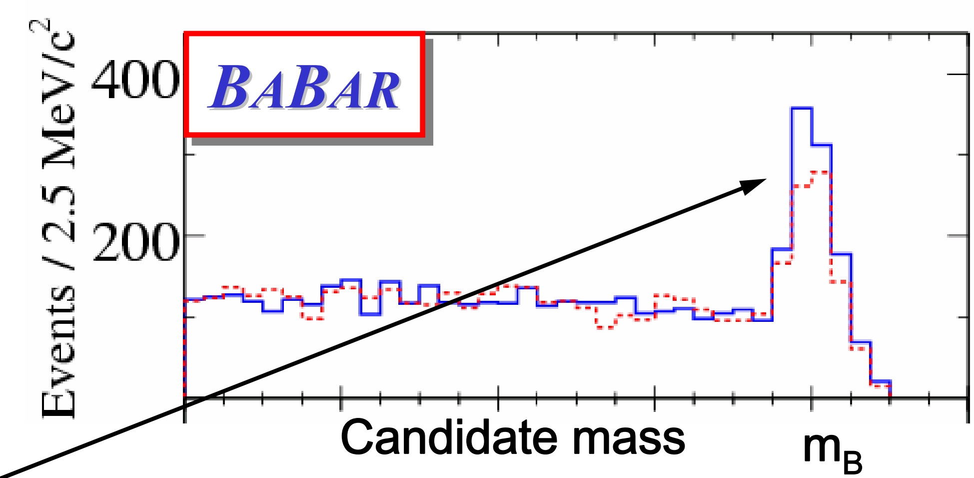
Three Paths to CP Violation

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

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

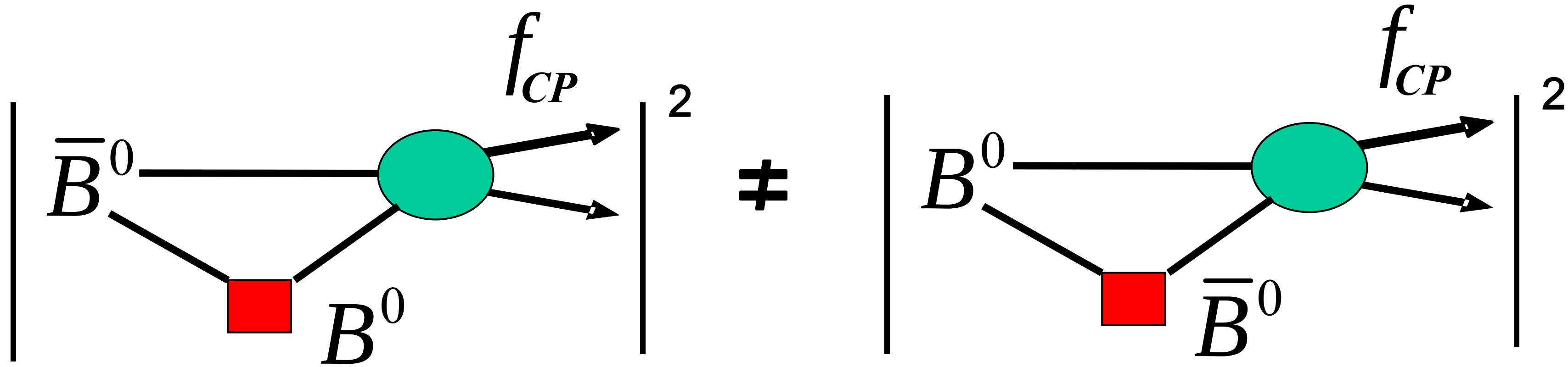


Blue $B^0 \to K^+\pi^-$

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

Three Paths to CP Violation

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

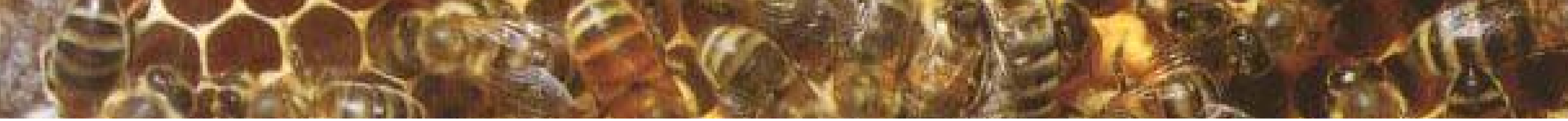


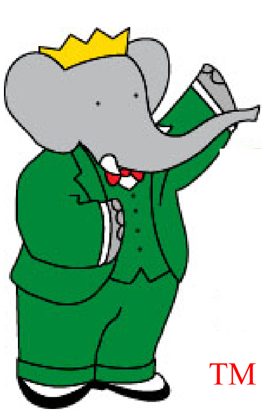
If $\overline{B}^0$ and B^0 decay to the same final state f_{CP}, there is interference between
amplitude of direct decay and
amplitude of mixing followed by decay

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!

<u>Triangle sides:</u>

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

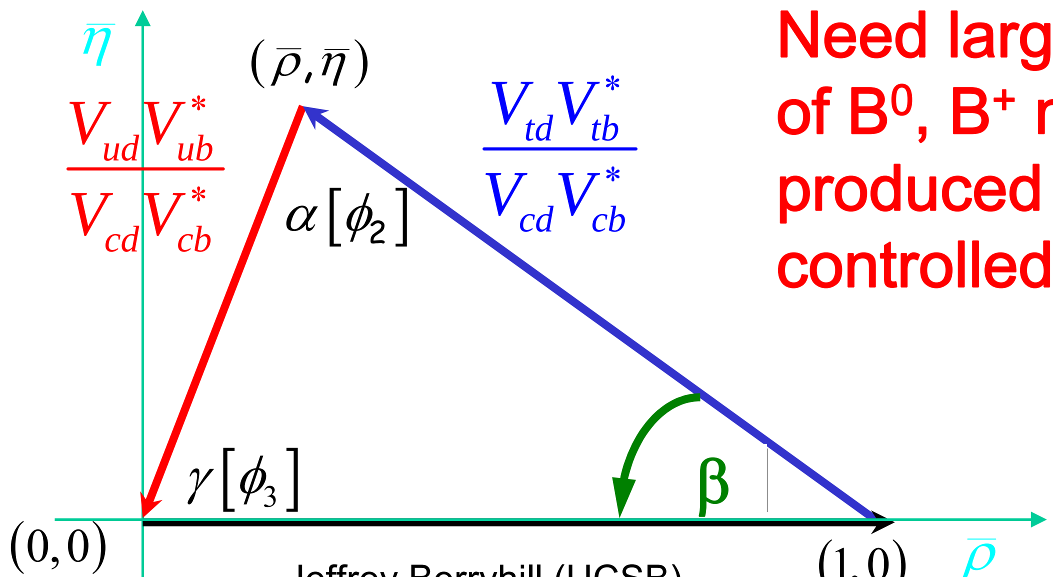
B^0 mixing rate measures $|V_{td}|$

<u>Angles:</u>

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

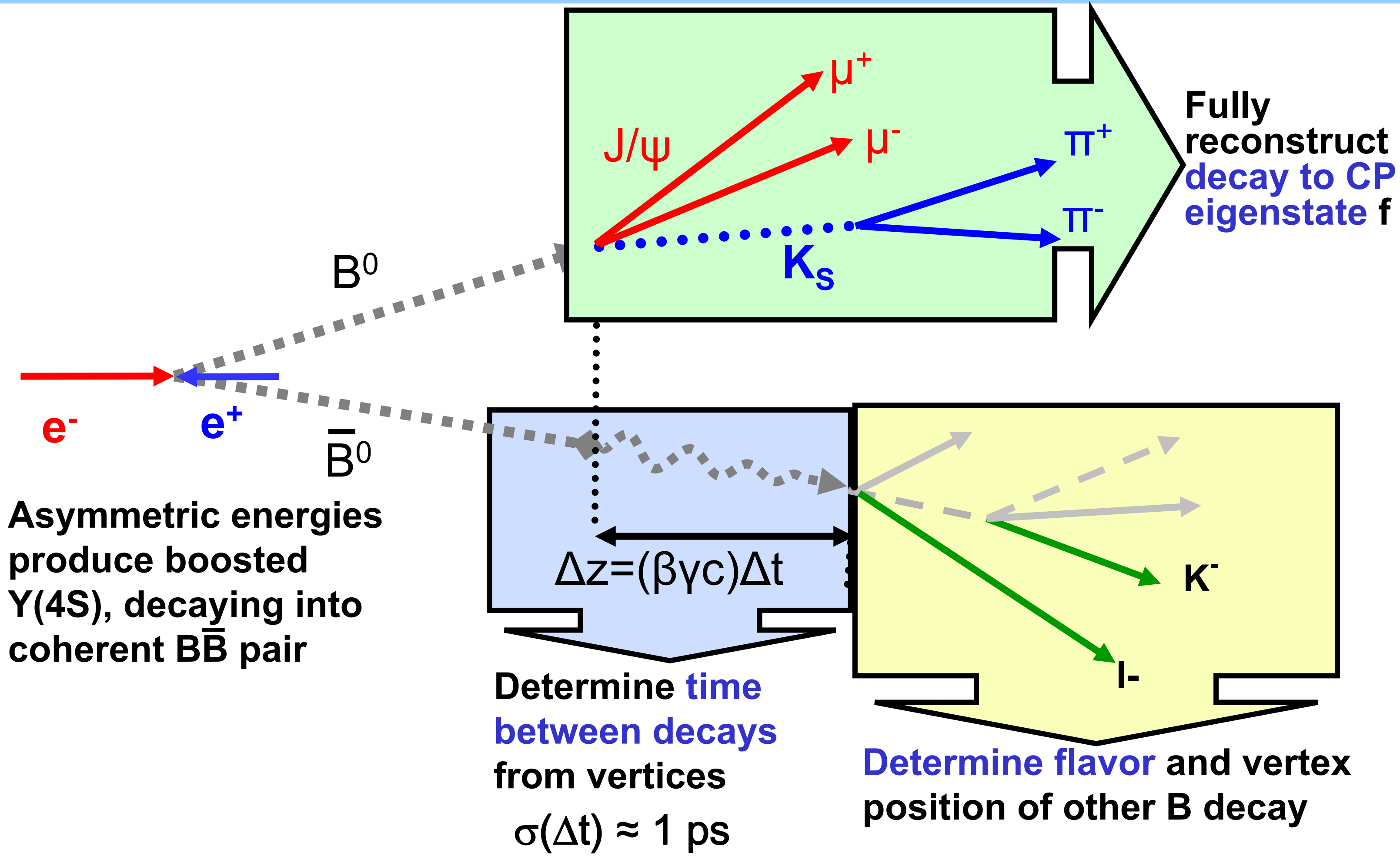
$B^0 \to J/\psi \, K_S^0$ time dependent CP asymmetry measures sin 2β

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



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

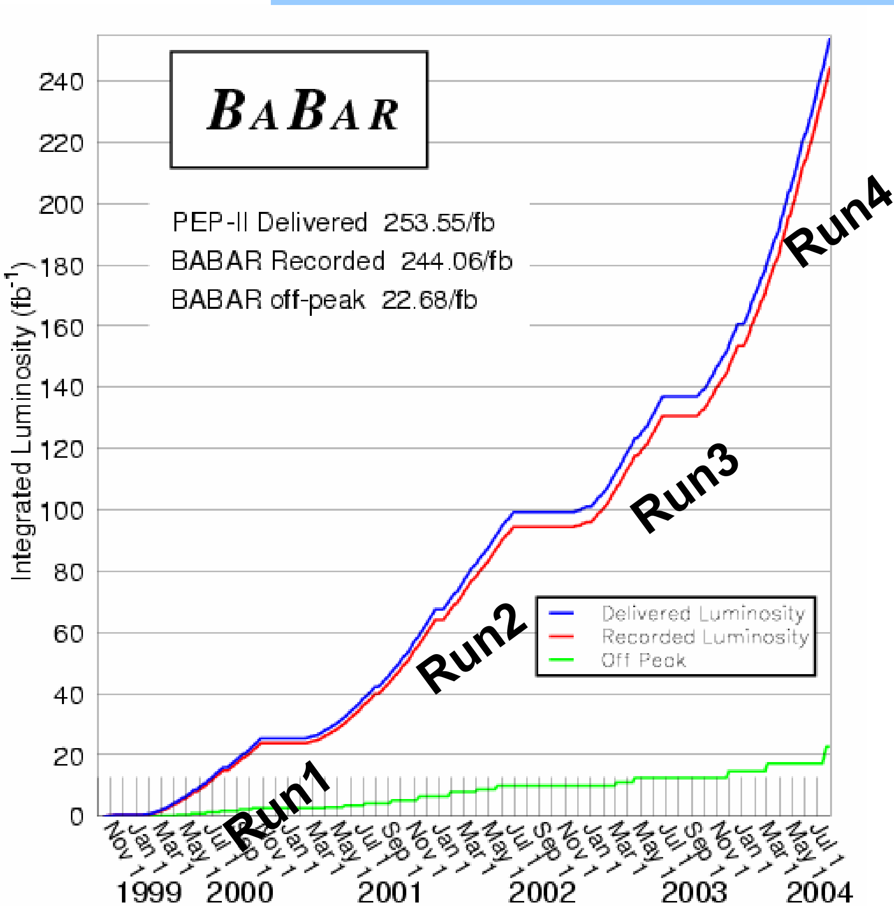
Time-Dependent CP Violation: Experimental technique



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



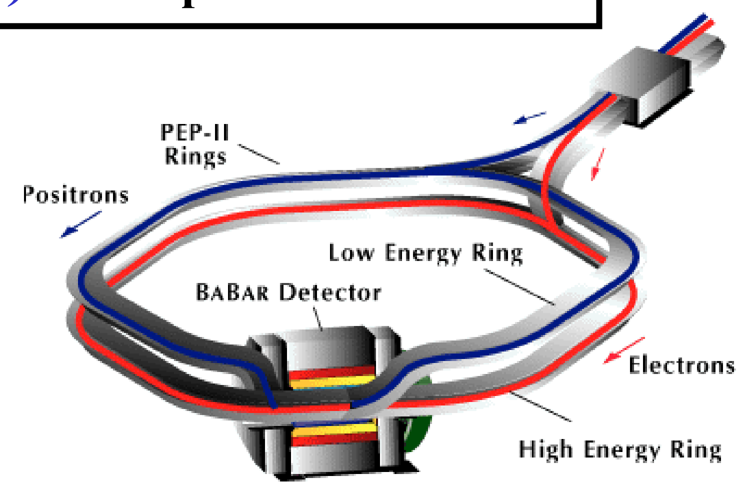
PEP-II top luminosity:
9.2 x 10^{33}cm^{-2}s^{-1}
(more than 3x design goal 3.0 x 10^{33})

1 day record : 681 pb^{-1}

About 1 Amp of current per beam, injected continuously

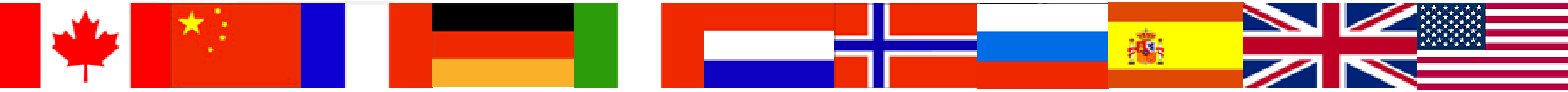
Run1-4 data: 1999-2004
On peak 211 fb^{-1}

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

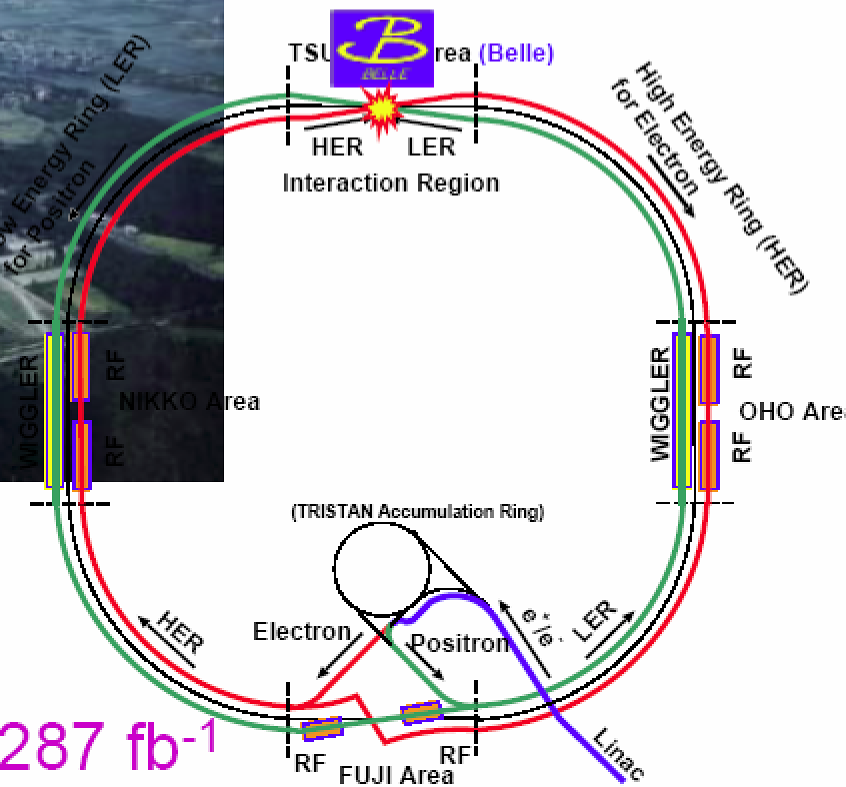
United Kingdom [10/66]

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

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 Υ(4S)   274M $B\bar{B}$
28 fb^{-1} below Υ(4S)

~287 fb^{-1}