Review of rare *B* decay results from *BABAR* and Belle

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Overview

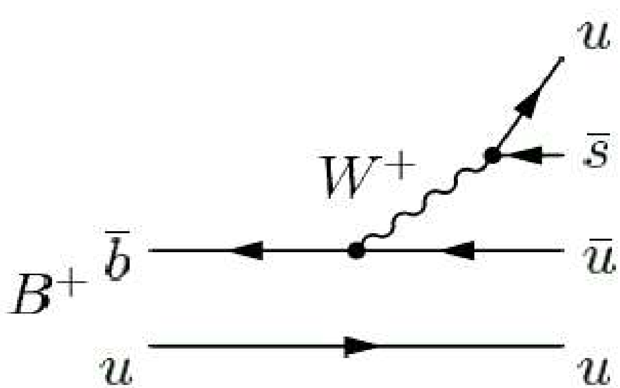
- Introduction
- The *BABAR* and Belle experiments
- Charmless hadronic *B* decays:
  - branching fractions
  - charge asymmetries
- Radiative *B* decays
- *B* charmless decays to pairs of vector mesons
- Summary & conclusion

Brief historical perspective

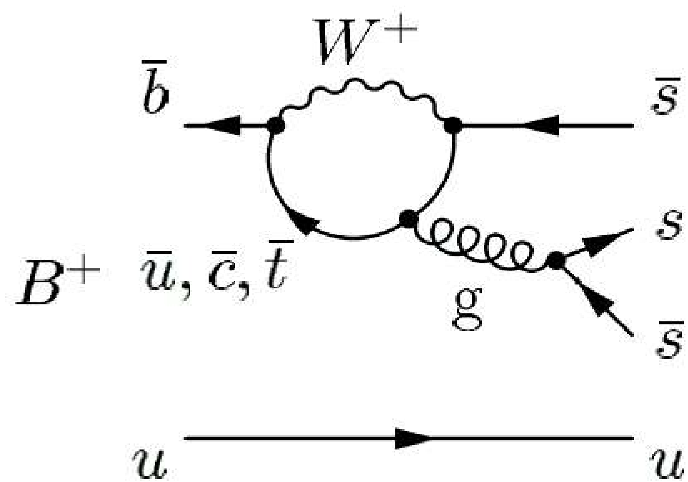
- **1990's:**
  CLEO (and ARGUS) started to explore rare B decays:
  - observation of $b \to u$ transitions (semileptonic)
  - $b \to s\gamma$
  - $B^0 \to h^+ h^- \to B \to K^+\pi^-$ (~17×10^{-6})
    $\to B \to \pi^+\pi^-$ (~4×10^{-6})
  - $B \to \eta' K$ larger than first expected (~70×10^{-6})
- **1999:** *BABAR* and Belle start data taking
  - high luminosity B factories
  - in ~5 years, accumulated a combined sample of >500M $B\bar{B}$
  - **ideal for the study of rare decays**

What do we call rare B decays?

- B decays suppressed relative to $b \to c$ transitions:
  - they occur mostly via ***b→u* (tree)** or ***b→s*(*d*) (penguin loop)** transitions => BF <10^{-4}
  - competing tree and penguin amplitudes
- Examples of possible diagrams:



Tree



Penguin

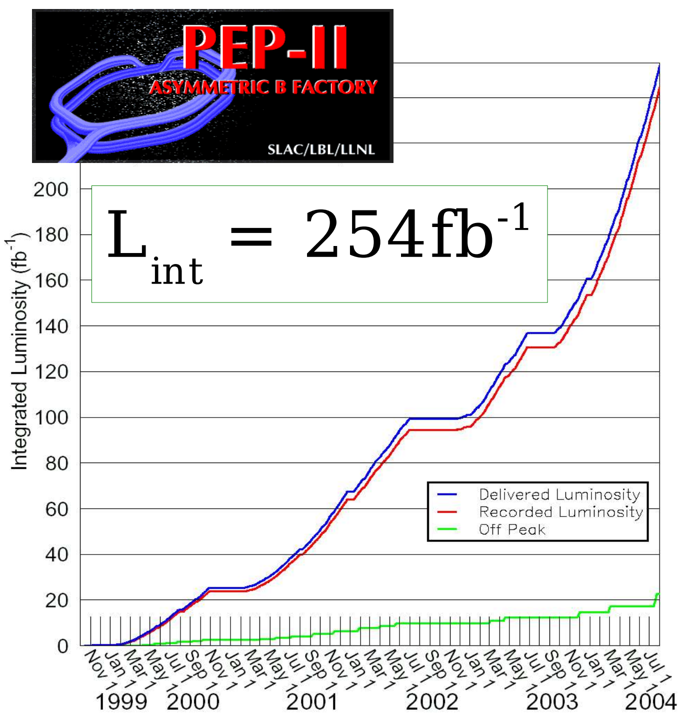
Why are rare B decays interesting?

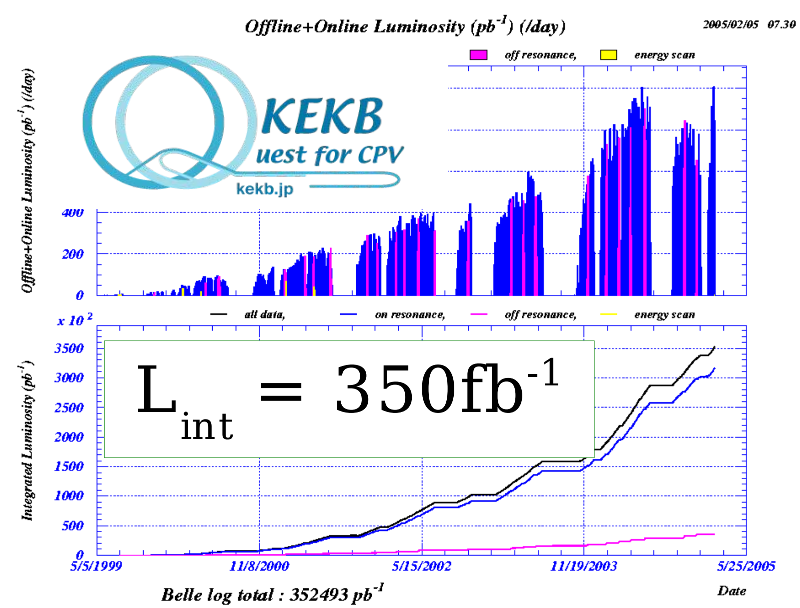
1) Tests of the standard model (SM)
   - small amplitude processes
   - sensitivity to **CP violation** (phases in mixing and decay)
   - constraints on **CKM parameters**: <u>sides & angles</u>

2) Sensitivity to physics beyond the SM
   - heavy (non-SM) particles can enter the loop
   - put constraints on theoretical models (e.g. SUSY)

PEP-II and KEK-B

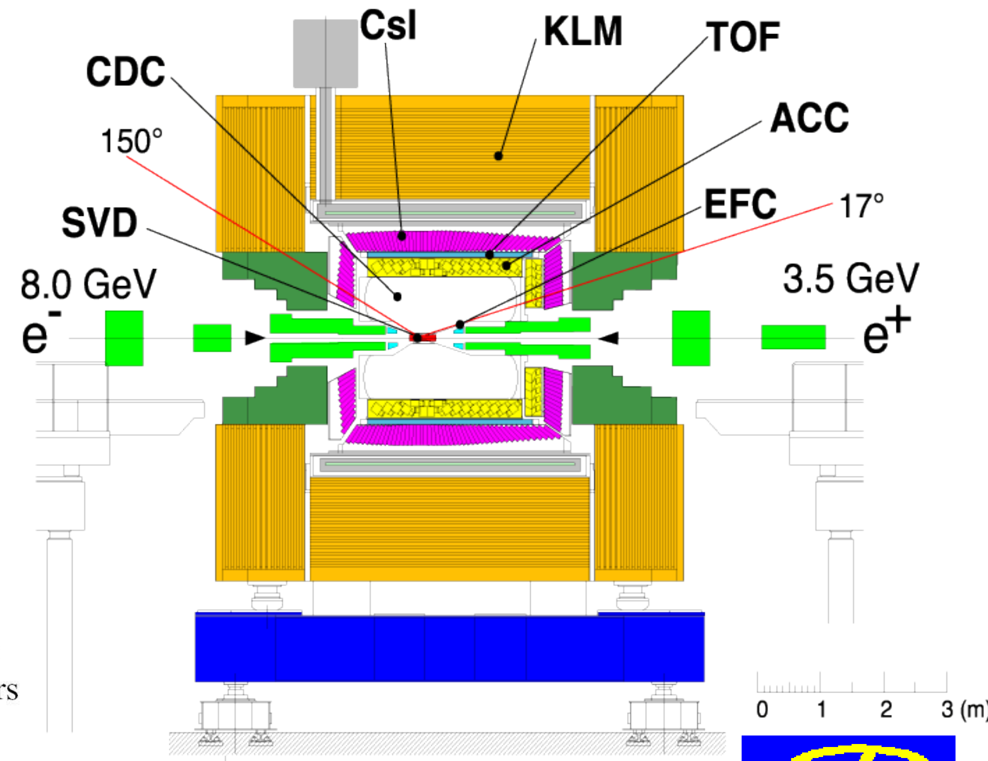
- Asymmetric B factories
- Run at ϒ(4S) CM energy (10.58GeV)
- Peak luminosities:
  PEP-II: $9.2 \times 10^{33} cm^{-2}s^{-1}$ KEK-B: $14.2 \times 10^{33} cm^{-2}s^{-1}$

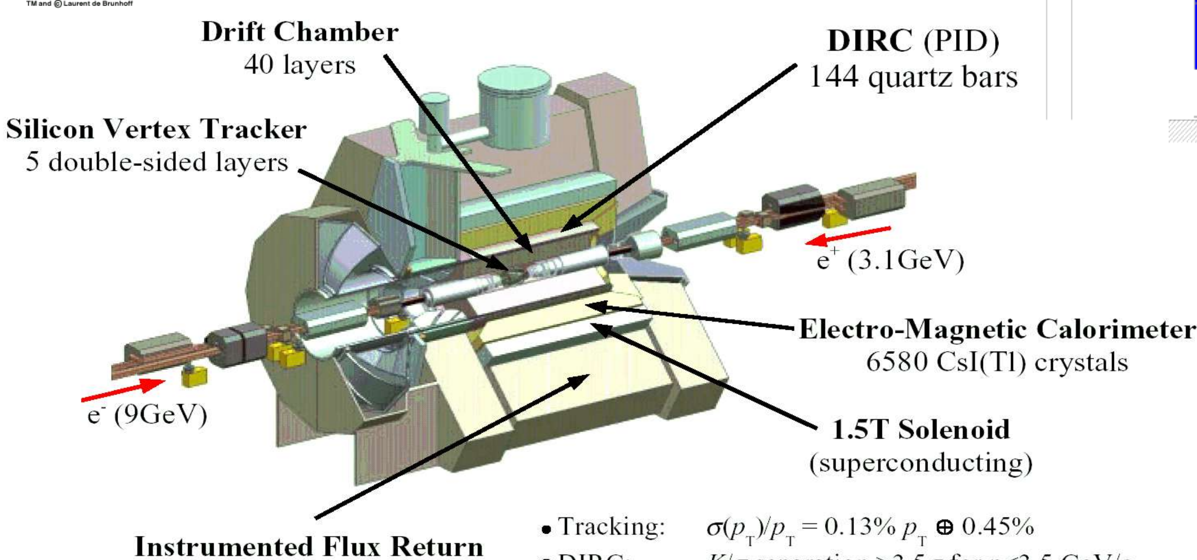




BABAR and Belle detectors

- Multipurpose detectors:
  - Tracking
  - PID
  - Calorimeter
  - Muon/KL detector





- Tracking: $\sigma(p_T)/p_T = 0.13\%\ p_T \oplus 0.45\%$
- DIRC: K/π separation $>3.5\sigma$ for $p<3.5$ GeV/c
- EMC: $\sigma_E/E = 2.3\%\ E^{-1/4} \oplus 1.9\%$

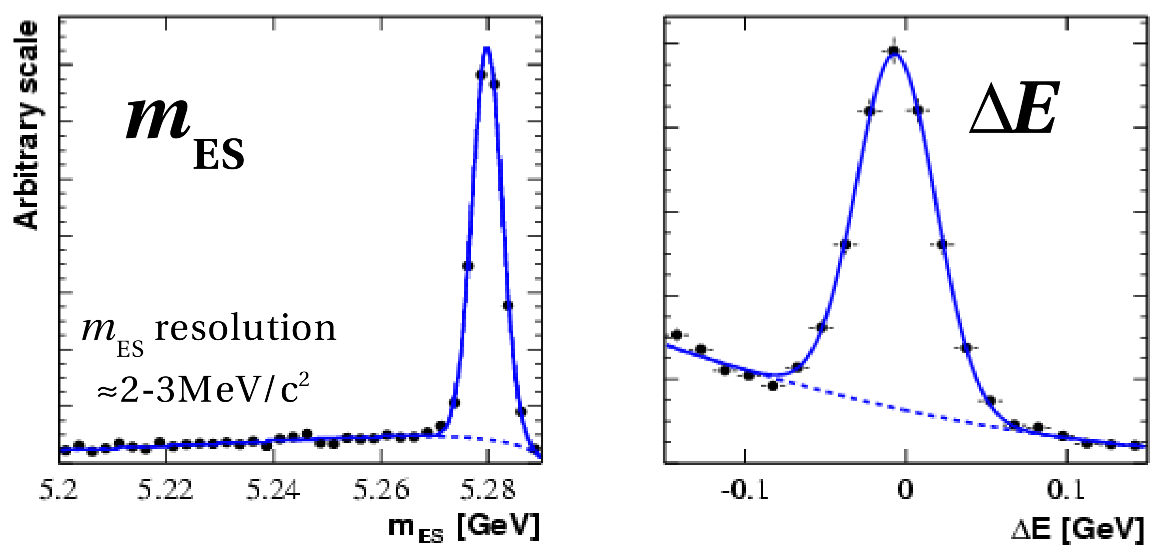
Analysis techniques (I)

- Experimental challenge: isolate tiny signal in very large background (100s M events)
- Variables used to identify the signal:
  - *B* kinematics (exploit the known total energy of the *B* candidate)

***B* mass:** $\boxed{m_{ES} = \sqrt{\frac{1}{4}s - |\mathbf{p}_B|^2}}$ **Energy:** $\boxed{\Delta E = E_B^* - \frac{1}{2}\sqrt{s}}$

B candidate energy CM energy

$m_{ES}(BABAR) = m_{bc}(\text{Belle})$



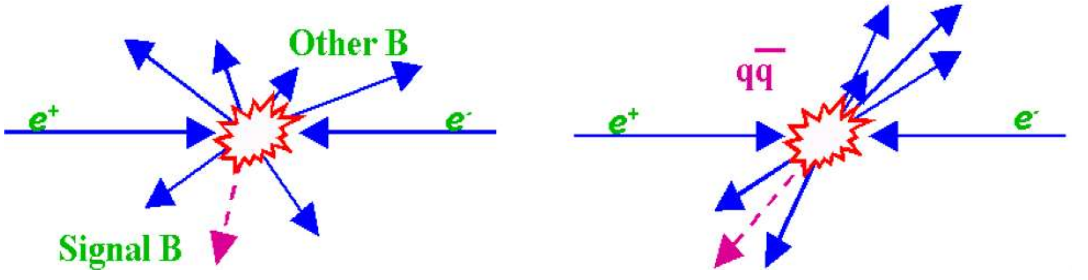
m_{ES} resolution $\approx$2-3MeV/c^2

ΔE resolution $\approx$20-50MeV

  - secondary resonance mass(es), etc...

Analysis techniques (II)

- **Backgrounds:**
  - combinatoric $e^+e^- \to q\overline{q}$ $(q=u,d,s,c)$ (dominant background)
    - ➔ event shape variables

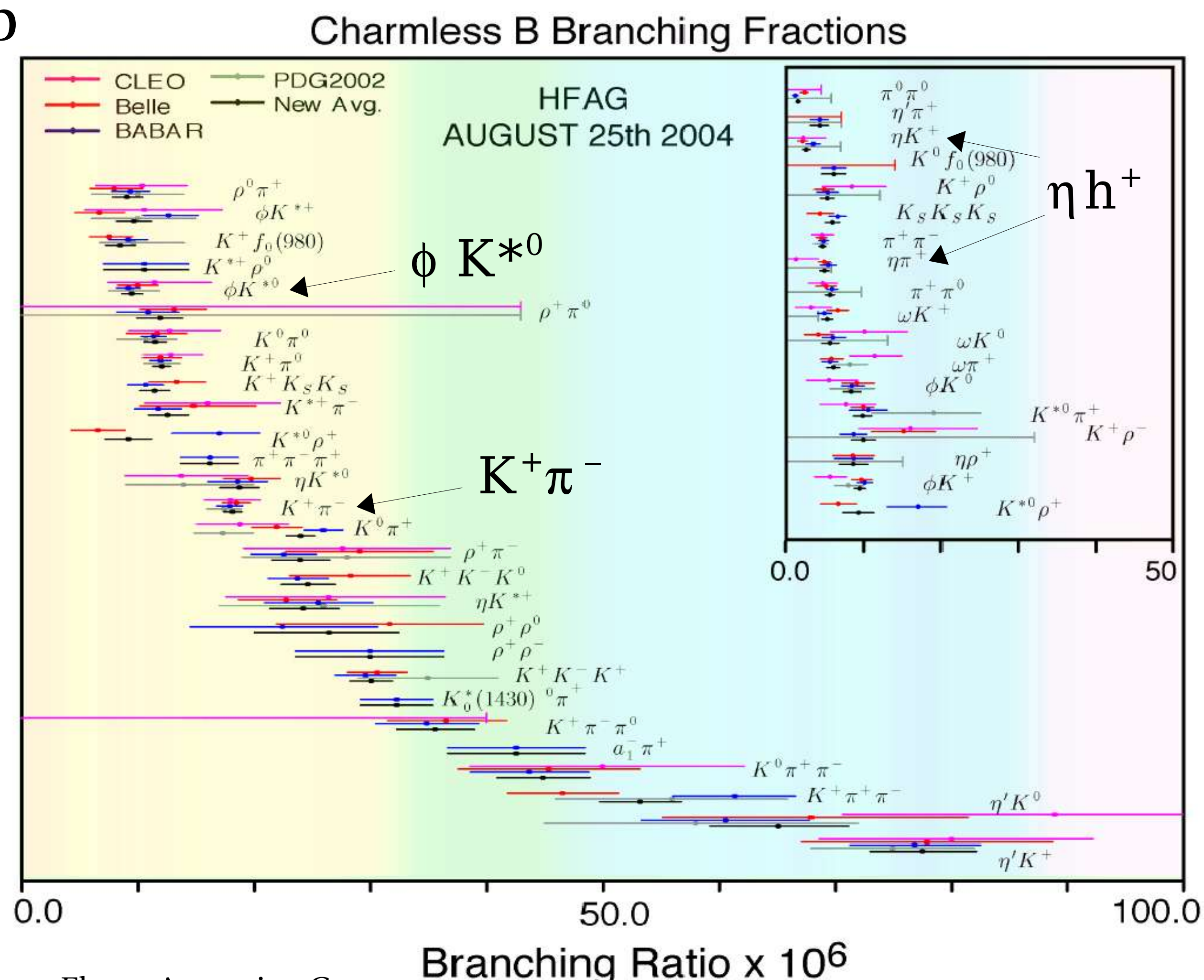


  - other B decays

- **Signal extracted with ML fit on discriminating variables**

Branching fractions (BF)

- ~50 charmless hardonic B decays have been observed
- Useful to test and help develop phenomeno-logical models
- Examples:
  - flavor SU(3)
    e.g. Chiang etal.
    PRD68,074012
    PRD69, 034001
  - QCD factorization
    e.g. Beneke&Neubert
    Nucl.Phys. B675,333
  - …

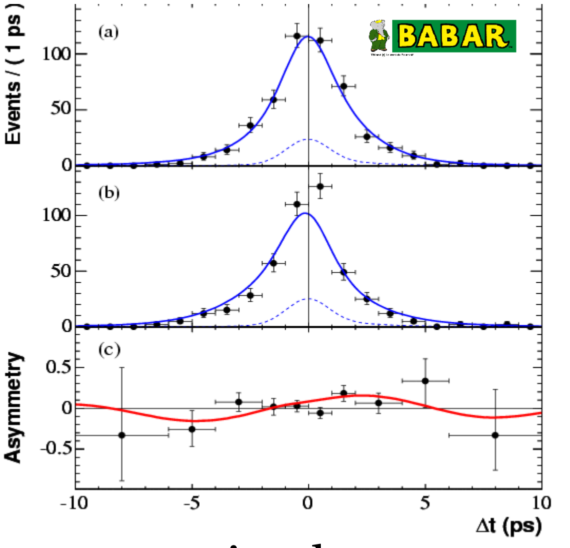


Plots from Heavy Flavor Averaging Group:
http://www.slac.stanford.edu/xorg/hfag/

Setting bounds on the tree contribution in $B^0 \to \eta' K_S$

- Time-dependent results in $B^0 \to \eta' K_S$

	BABAR (232M)	Belle (275M)	Average
S	0.30±0.14±0.02	0.65±0.18±0.04	**0.43±0.11**
C	-0.21±0.10±0.02	0.19±0.11±0.05	-0.04±0.08



- Compare with charmonium value: $\sin 2\beta = 0.73 \pm 0.04$
  => difference $\Delta S_{exp} = S - \sin 2\beta = -0.30 \pm 0.12$

- Estimate of the tree contribution in $B^0 \to \eta' K_S$ is necessary in the interpretation of the time-dependent results

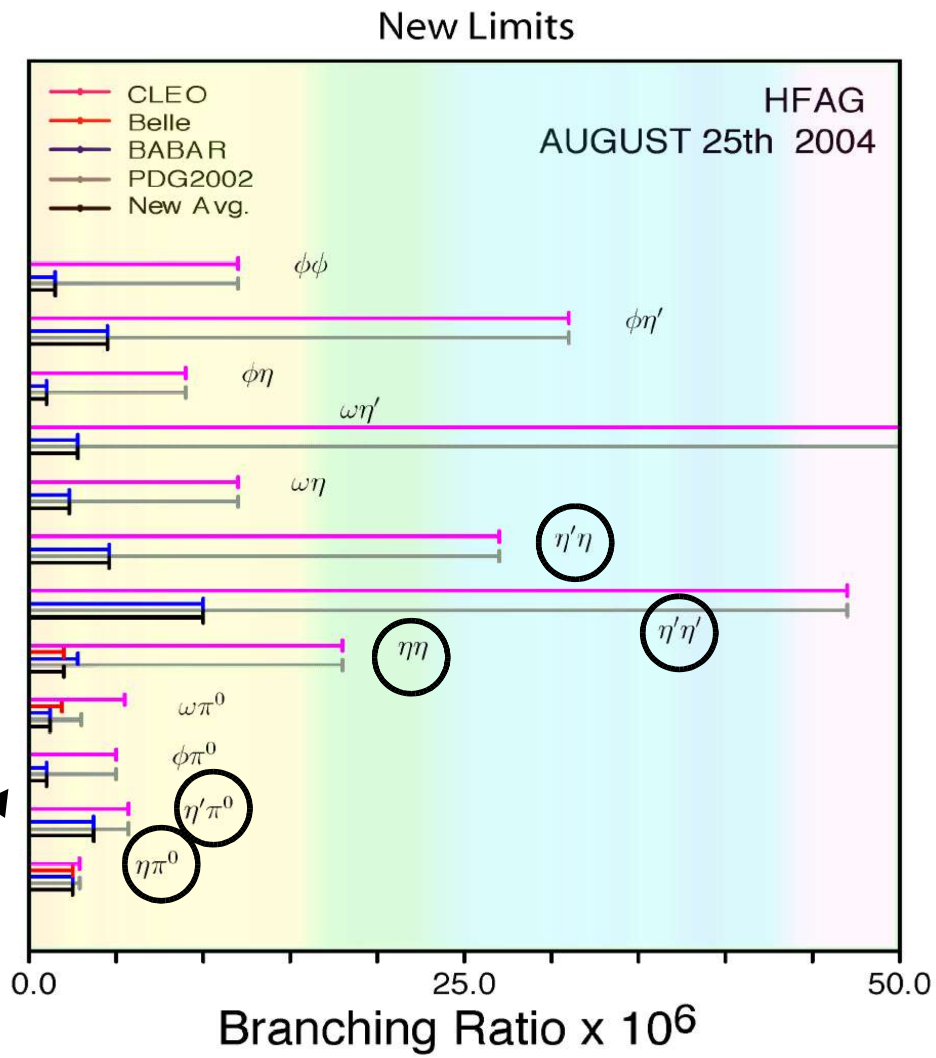
- Flavor SU(3) is used to set bounds on time-dependent CP asymmetry in $B \to \eta' K_S$:

$$\Delta S_{th} = S(\eta' K_S) - \sin 2\beta < |\xi_{\eta' Ks}|$$

- $\xi_{\eta' Ks}$ **function of BF for related decay modes**

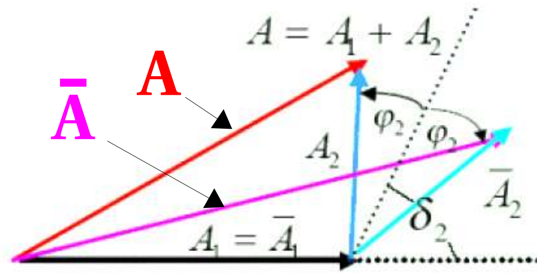
B decays to pairs of light isoscalar mesons

- $\Delta S_{th} = S(\eta' K_S) - \sin 2\beta < |\xi_{\eta' K_S}|$
- $\xi_{\eta' K_S}$ function of the BF for flavor SU(3) related decay modes $B^0 \rightarrow \eta'\eta', \eta'\eta, \eta\eta, \eta'\pi^0, \eta'\pi^0$, etc...
  [Grossman et.al., PRD68 (2003) 015014]
  [Gronau et.al., PLB596 (2004) 107]
- Current limit: $\Delta S_{th} <\sim 0.1$ (compare to $\Delta S_{exp} \sim 0.3$)
- If measure $\Delta S_{exp} >> 0.1$ => signature for new physics
- **ΔS_{th} will improve with better BF measurements**



Charge asymmetries (direct CP)

- Many self-tagging (i.e. B flavor identified by final state) rare decays have competing tree and penguin amplitudes
- Interference between two decay amplitudes can lead to direct CP violation A_{CP}:



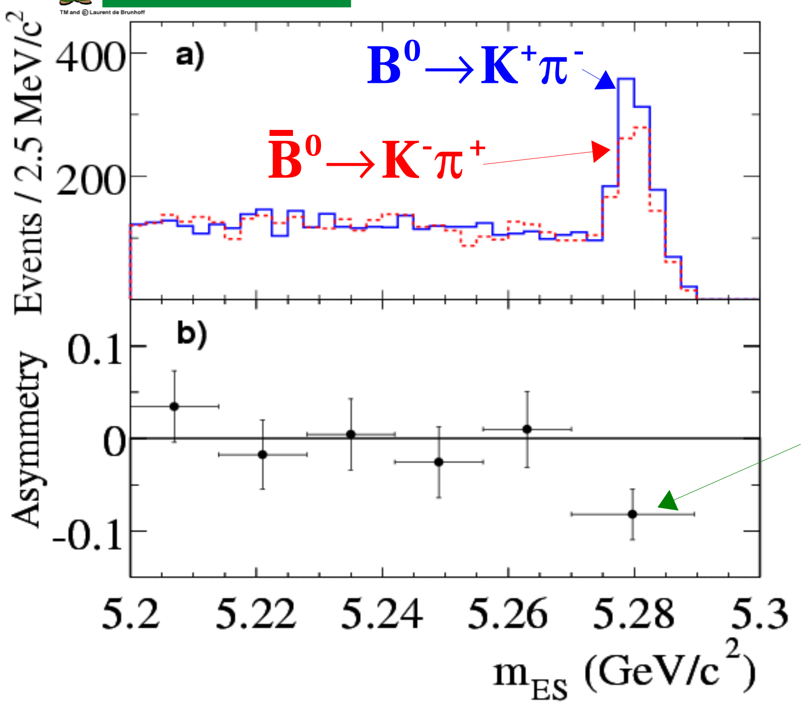
$$A_{CP} = \frac{\Gamma(\bar{B}\to\bar{f})-\Gamma(B\to f)}{\Gamma(\bar{B}\to\bar{f})+\Gamma(B\to f)} \sim \sin\Delta\phi_{\text{weak}} \sin\Delta\delta_{\text{strong}}$$

- A_{CP} can be sizable if both weak and strong phases ≠0
- Strong phases difficult to estimate
  => large theoretical uncertainties on predictions

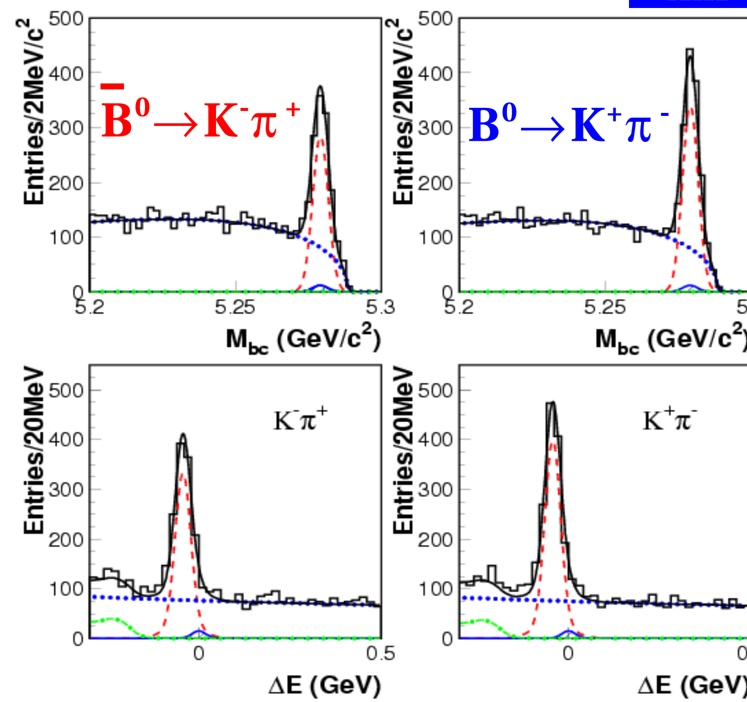
$B^0 \to K^+\pi^-$

- Observation of direct CP in $B^0 \to K^{\pm}\pi^{\mp}$ decays

	N_{BB}	$N_{K\pi}$	A_{CP}	signif.
BABAR	227M	1606±51	**-0.133±0.030±0.009**	4.2σ
Belle	275M	2140±53	**-0.101±0.025±0.005**	3.9σ



Significant asymmetry in signal region



$B^{\pm}\to\eta^{(\prime)}h^{\pm}$

- Why A_{CP} in $B^{+}\to\eta K^{+}/\pi^{+}$ may be large:
  - η-η' mixing enhances $B\to\eta' K$ and suppresses $B\to\eta K$
    => in ηK interference between amplitude can be sizable
    => possible source of large direct CP violation
  - predicted in 1979! [Bander, Silverman, Soni, PRL 43, 242]
- Based on 89M $B\bar{B}$ pairs, *BABAR* saw ~2σ significant A_{CP} :

  $A_{CP}(\eta K^{+})$=-0.52±0.24 and $A_{CP}(\eta\pi^{+})$=-0.44±0.18 [PRL 92, 061801]
- BABAR and Belle obtained new preliminary measurements:

	N_{BB}	$A_{CP}(\eta K^{+})$	$A_{CP}(\eta\pi^{+})$	$A_{CP}(\eta'\pi^{+})$
Belle	152M	-0.49±0.31±0.07	+0.07±0.15±0.03	--
BABAR	232M	-0.20±0.15±0.01	-0.13±0.12±0.01	+0.14±0.16±0.01
My average		**-0.25±0.14**	**-0.05±0.09**	

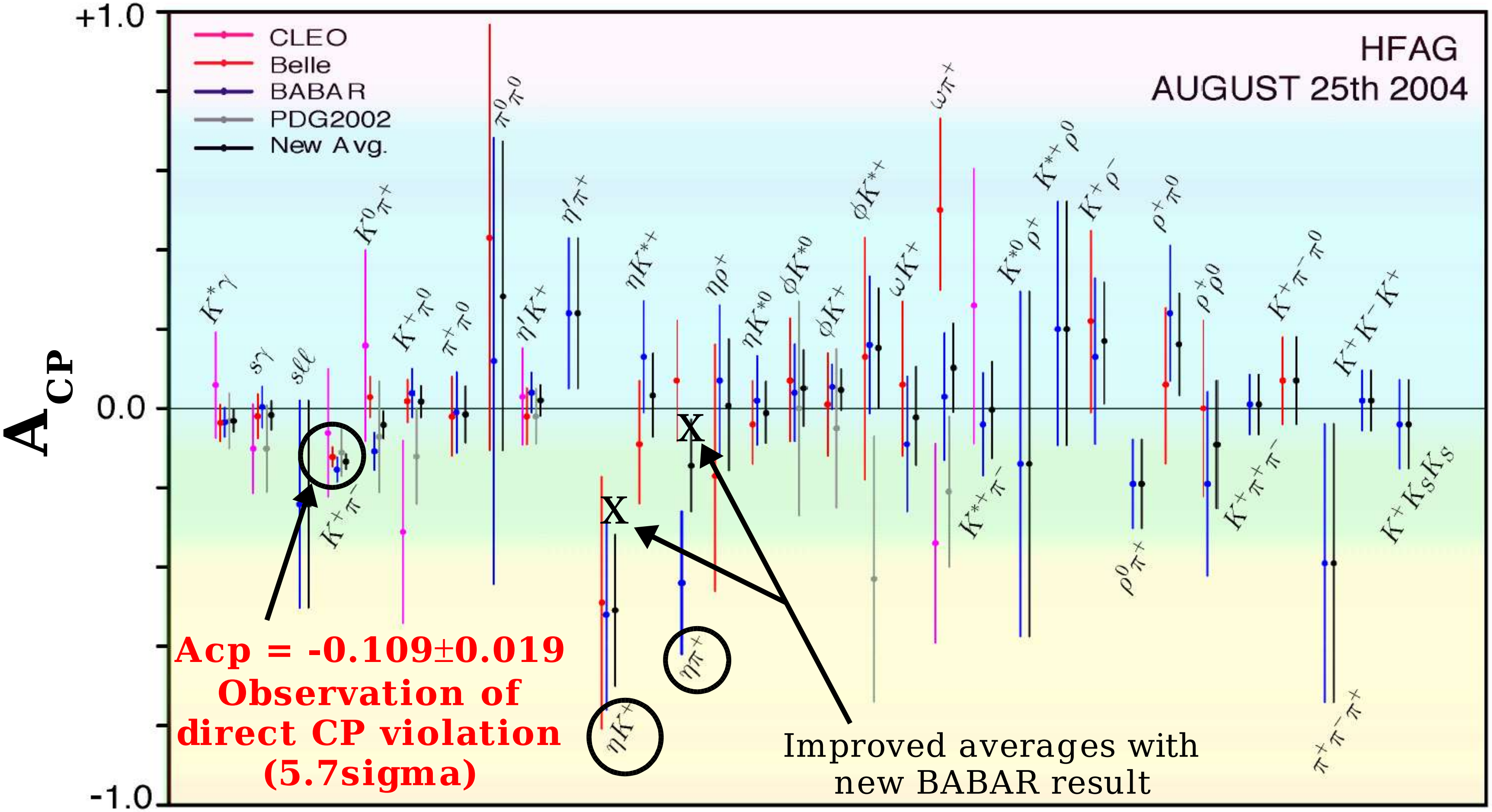
New results (preliminary)

(BABAR: BF($B\to\eta'\pi^{+}$)=(4.0±0.8±0.4)x10^{-6} signif. 5.4σ)

=> Results compatible with no asymmetry (and with large A_{CP})

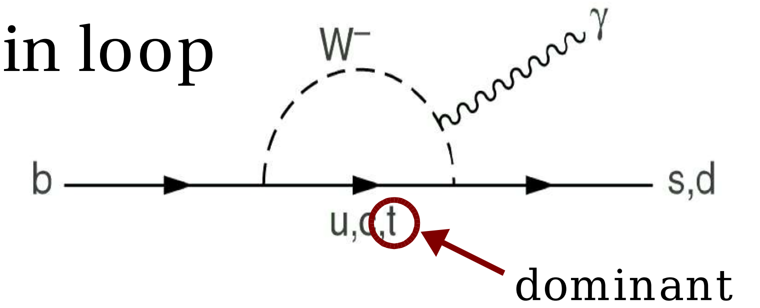
Charge asymmetries: summary

- Several modes used to look for direct CP violation
- Errors as low as ±0.02



Radiative penguin decays

- $b \to s(d)\gamma$ proceed through EW penguin loop



- **Inclusive decays**
  - <u>Branching fractions:</u>
    - theoretically clean (no hadronization) $BF_{th} = (3.6 \pm 0.3) \times 10^{-4}$
    - experimentally difficult (fight background)

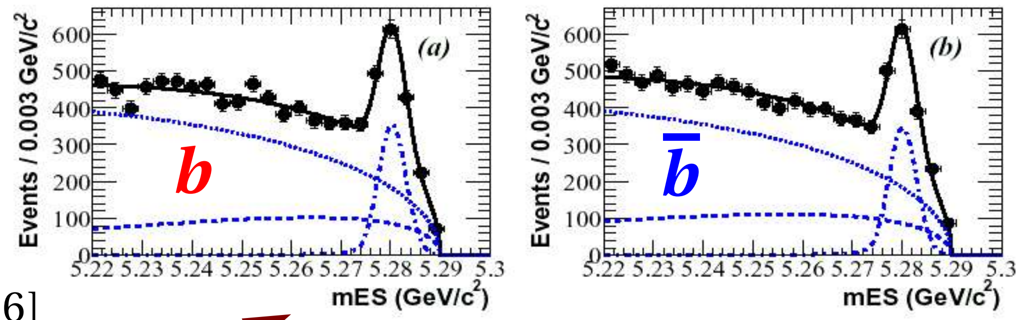
good agreement

=> $BF_{exp} = (3.5 \pm 0.3) \times 10^{-4}$

    - sensitive to new physics entering the loop
  - <u>Charge asymmetries:</u>
    - experimental errors cancel
    - sensitive to new physics in loop and to new phases
- **Exclusive decays**
  - experimentally easier
  - theoretical uncertainites from hadronization

A_{CP} in inclusive $b \to s\gamma$

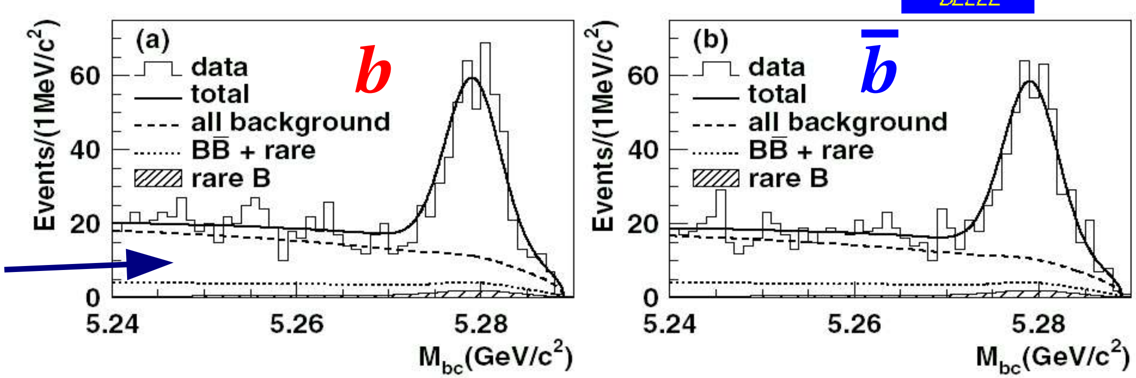
- Theory prediction (SM):
  - small due to single dominant amplitude => sensitive to new physics
  - $A_{CP} = 0.0044{+0.0024 \atop -0.0014}$
    [Hurth et.al., Nucl.Phys.B704(2005)56]



- Results:

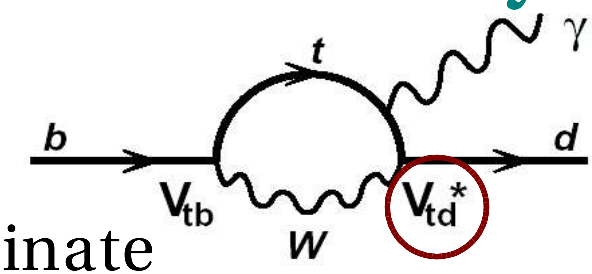
BABAR (89M BB):
$A_{CP} = 0.025 \pm 0.050 \pm 0.015$

Belle (152M BB):
$A_{CP} = 0.002 \pm 0.050 \pm 0.030$



- **Results statistics limited, and in agreement with SM**

Search for $b \to d\gamma$ exclusive decays

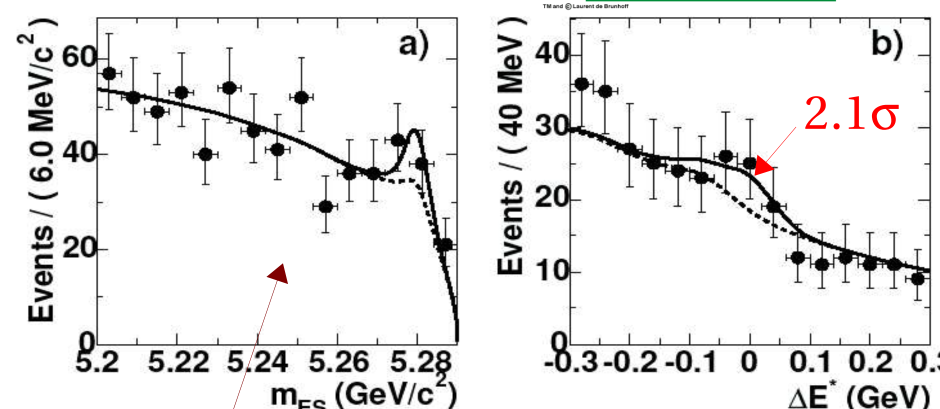


- **Used in determination of Vtd**
- $B^0 \to \omega\gamma$ and $B \to \rho\gamma$ expected to dominate
  - SM predictions: BF~(0.9-2.7)x10^{-6}
- Results (x10^{-6})
  (upper limits at 90% C.L.)

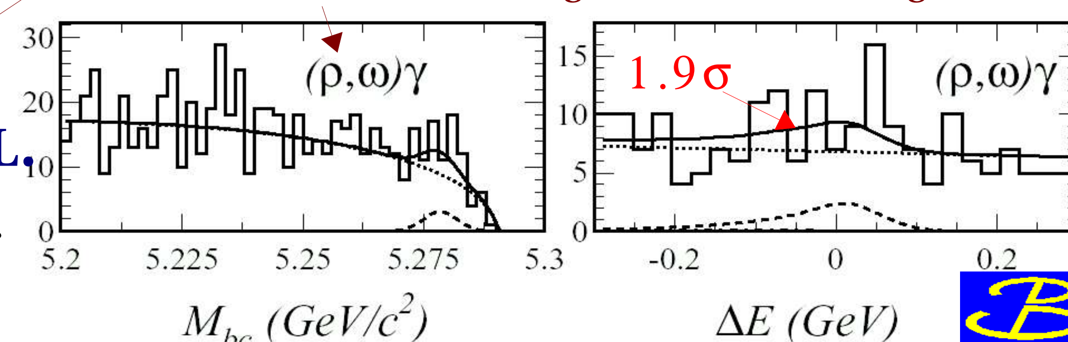
	BABAR	Belle
	(211M BB)	(274M BB)
$\rho^+\gamma$	<1.8	<2.2
$\rho^0\gamma$	<0.4	<0.8
$\omega\gamma$	<1.0	<0.8
$(\rho,\omega)\gamma$	<1.2	<1.4

➔ **|Vtd|/|Vts|<0.19 @90%C.L.**

- Upper limits in range of SM predictions

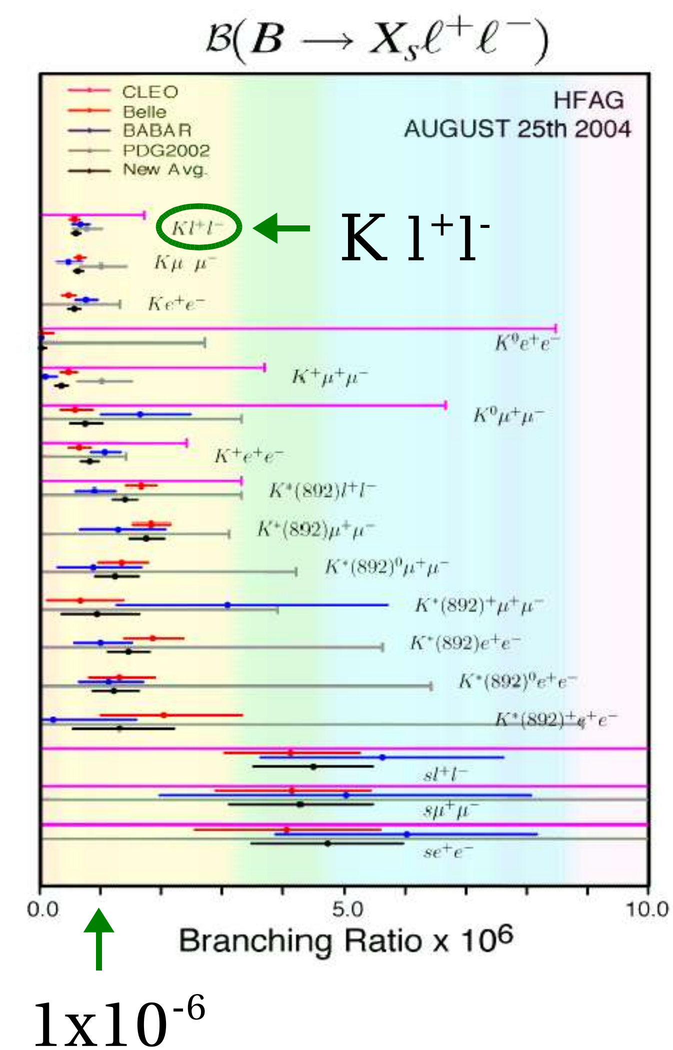


combined modes (non-significant hint of signal)



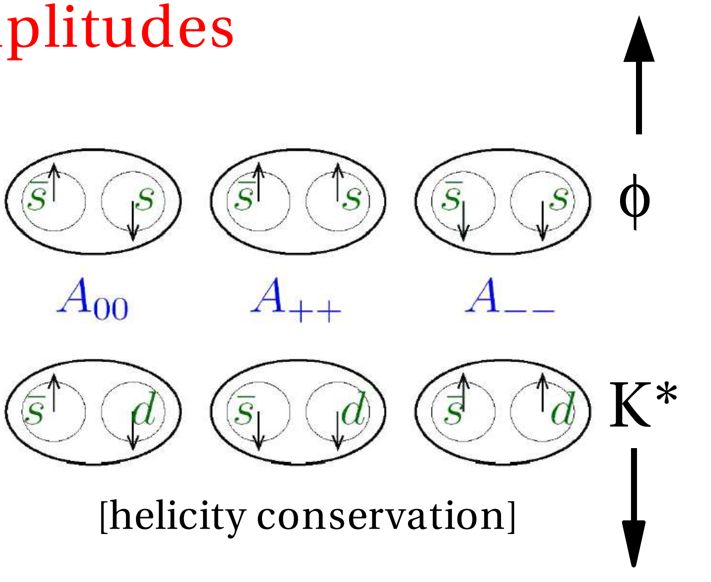
Other radiative decay results

- Other radiative decay results not covered in this talk:
  - inclusive photon spectrum => *b*-quark mass
  - $B \rightarrow K^*\gamma$
    - direct CP
    - time-dependent CP
  - $b \rightarrow s l^+ l^-$
    - BF & A_{CP} results in agreement with SM predictions
    - $BF(B \rightarrow K\, l^+ l^-) = (0.57 +- 0.07) \times 10^{-6}$ smallest BF measured in B decays



Polarization in charmless B→VV

- *B* (spin-0) decays to two spin-1 particles:
  - spin-related configurations => 3 amplitudes
  - 11 observables:
    - **Polarization** fractions
    - Direct CP asymmetries
    - triple product asymmetries



[helicity conservation]

- In SM
  - A_{00} is the natural spin configuration
  - A_{++} and A_{--} suppressed by m_{res}/m_B (one for each spin flip)
  - ➔ expect strong longitudinal polarization

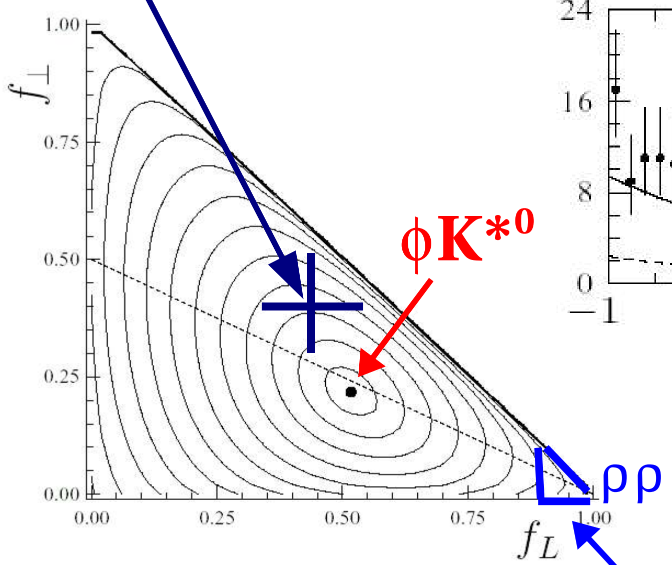
$$\boxed{\mathbf{f_L = |A_{00}|^2/(|A_{00}|^2+|A_{++}|^2+|A_{--}|^2) \sim 1}}$$

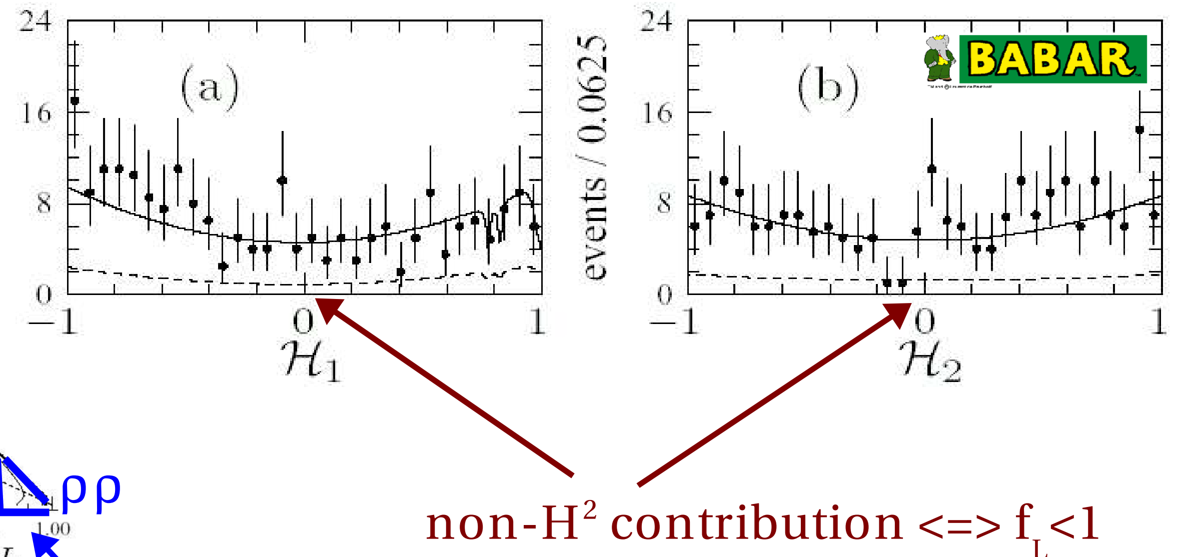
$B^0 \to \phi K^{*0}$

- In $B^0 \to \phi K^{*0}$ decays, measure

  BABAR (227M BB) $f_L = 0.52 \pm 0.05 \pm 0.02$ (PRL93, 231804)

  Belle (86M BB) $f_L = 0.43 \pm 0.09 \pm 0.04$ (PRL91, 201801)





- But $f_L \sim 1$ for tree-dominated $B \to VV$ decays (ρρ, ωρ$^+$)
- Other penguin dominated modes still statistics limited

Polarization in $B \to VV$: summary

- The polarization puzzle in $B^0 \to \phi K^{*0}$ remains: $f_L(\phi K^{*0}) \sim 0.5$
- For tree-dominated VV mode: $f_L(\text{tree}) \sim 1$
- Currently no convincing explanation
- Possible scenarios:
  - poorly understood SM strong interaction effects?
  - effects from new physics?
- Additional measurements will help solve this problem

Summary

- We have presented recent highlights of the study of rare *B* decays:
  - several measurements of branching fractions
    - useful to contraint phenomenological models
  - Search for direct CP violation in *B* decays:
    - Direct CP observed in $B^0 \to K^{\pm}\pi^{\mp}$ decays
    - many other measurements (non significant)
  - Radiative decays
  - $B \to VV$ decays
    - rich program, and puzzle in polarization results

Conclusion

- Rare *B* decays are a very rich source of information on
  - the standard model
  - physics beyond the standard model
- The experiments at the *B* factories have produced many new results with their current data samples
- Many more rare-*B* decay results to come with a combined **>1000fb^{-1}** by 2006!