Charmless *B* Decays in *B*-Factories

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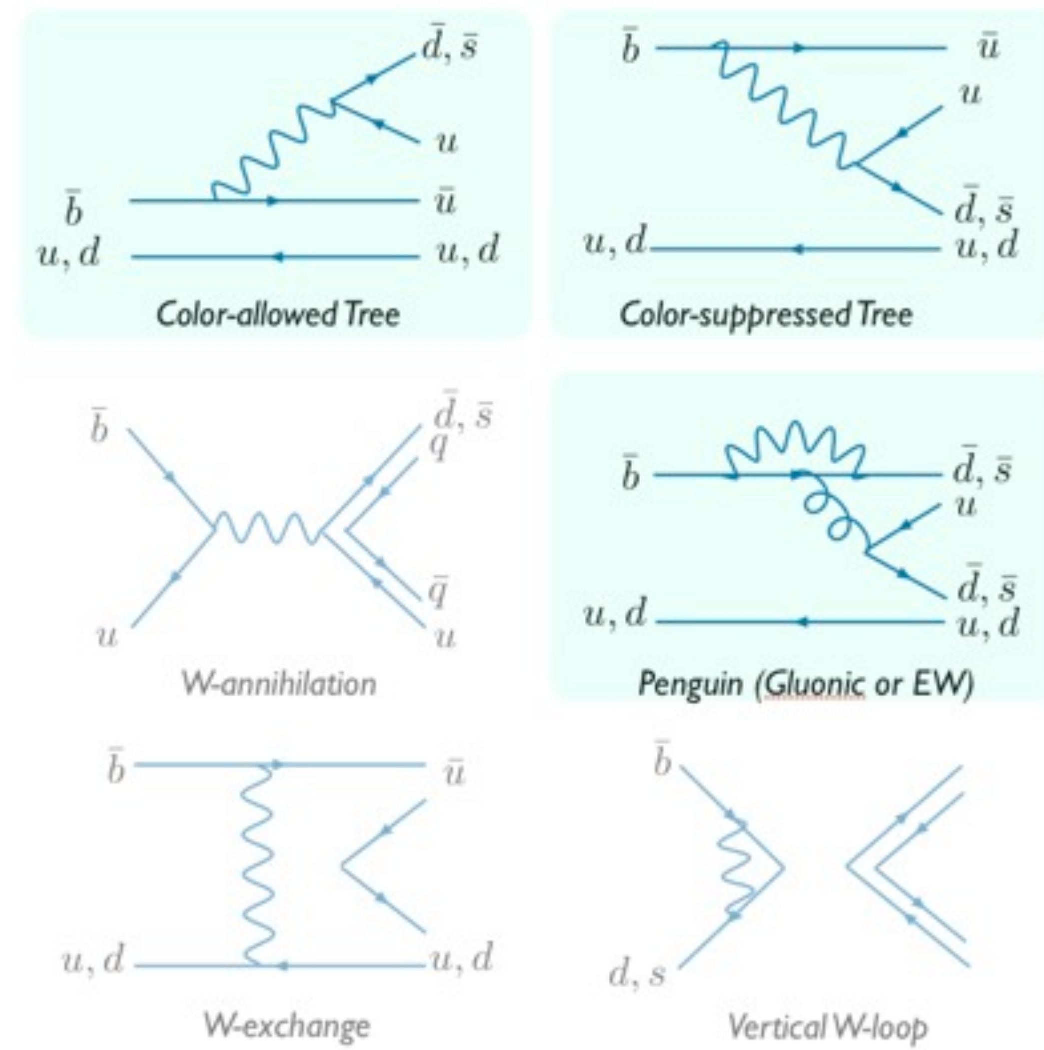
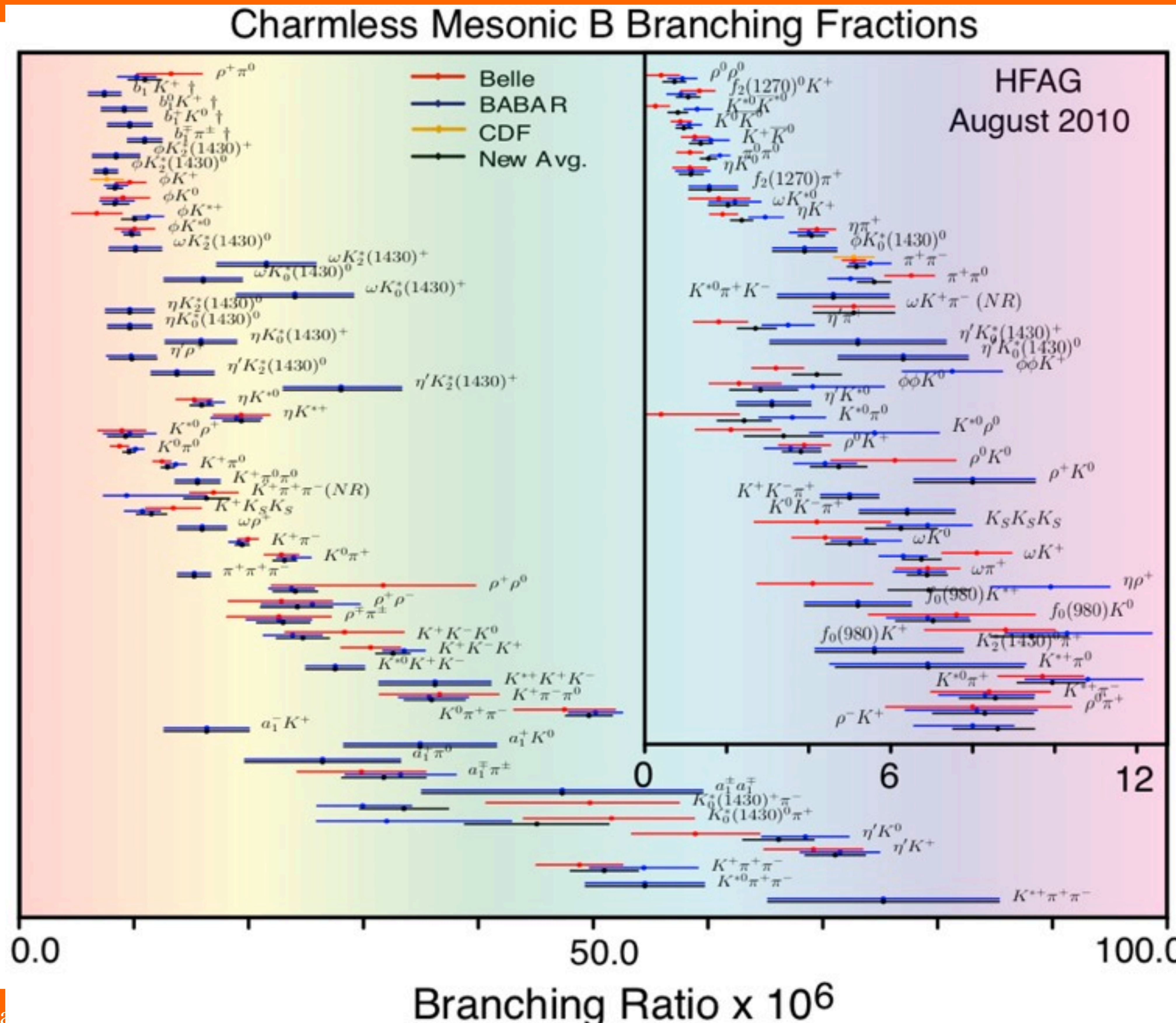
Overview

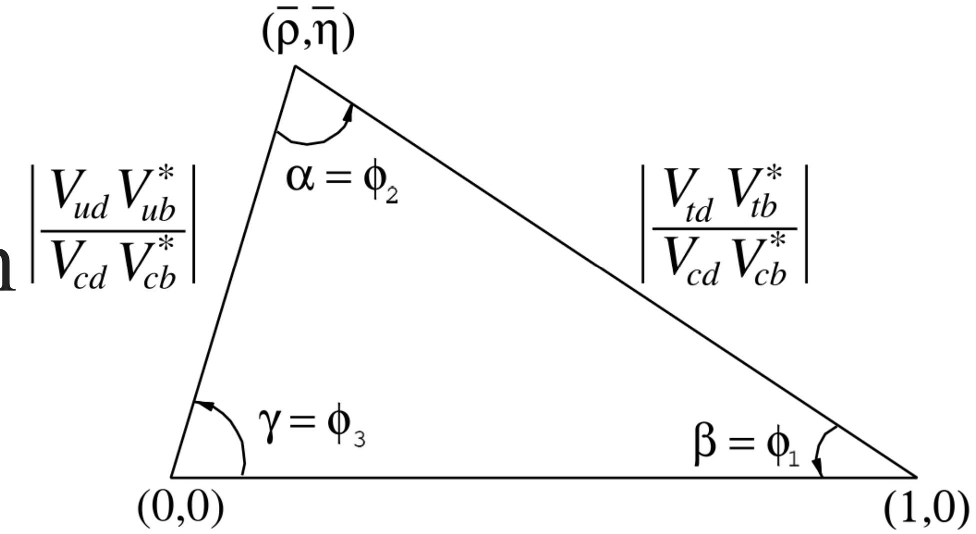
- *B* mesons decay predominately through tree level $b \to cW^*$, leaving a charm meson in the final states.
- In <u>charmless</u> hadronic *B* decays, other types of diagrams are enhanced. They provide a rich laboratory to study *CP-violations, long/short-distance QCD effects, hadronic phases,* and *New Physics search*.
- About 100 charmless *B* decay modes have been measured with >4σ significance, mostly from *BABAR* and Belle. Their BF's range from few×10^{-5} to 10^{-6}.



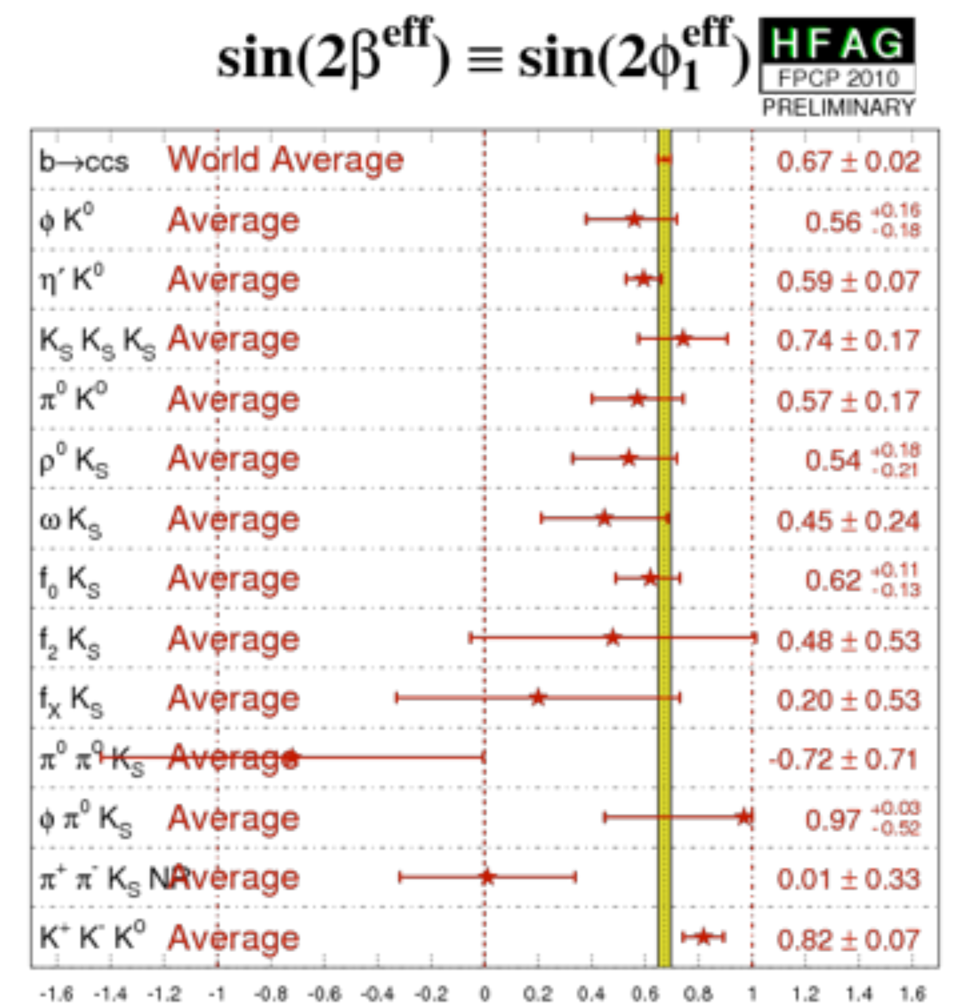
Large number of channels



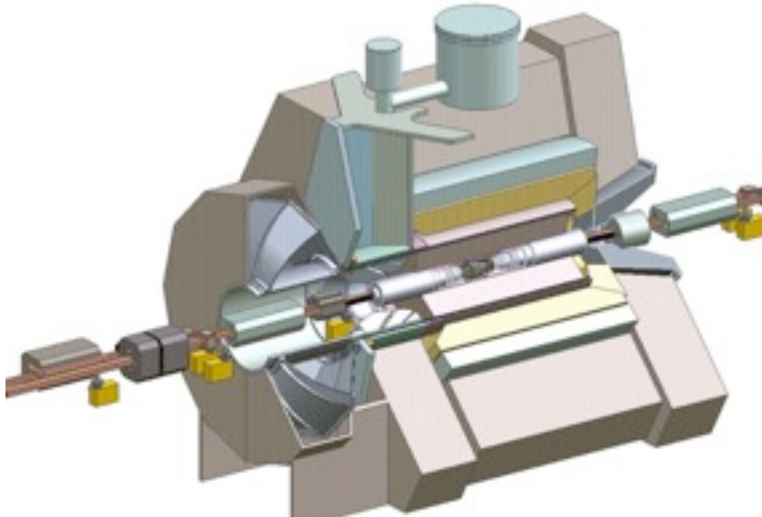
Charmless programs

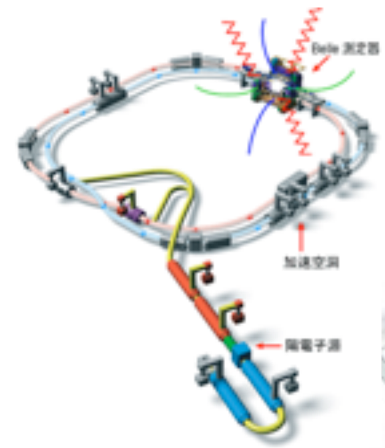


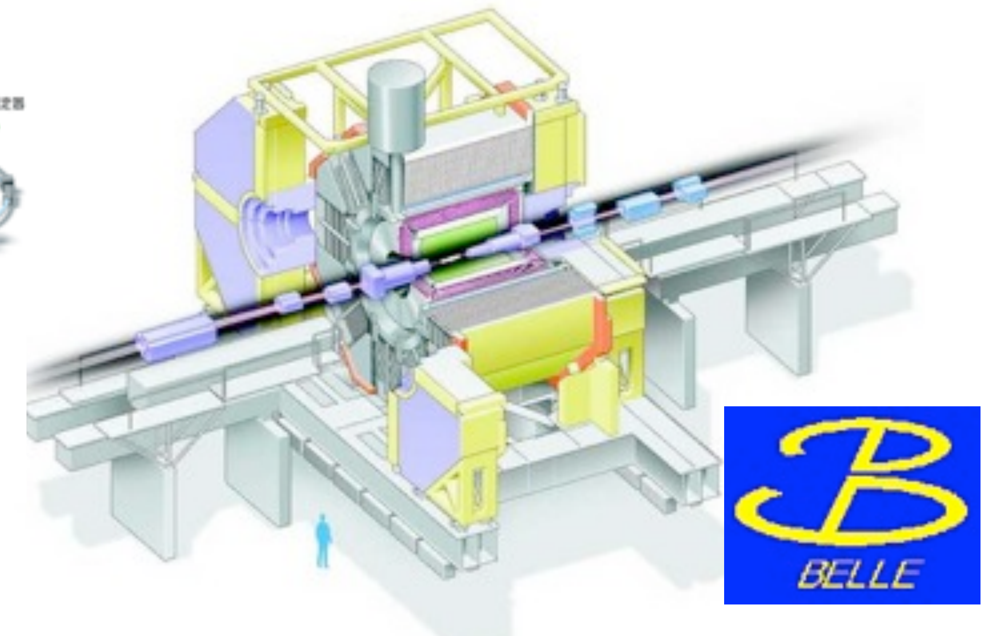
- CKM angle α (ππ, ρρ)
- CKM sin2β$_{eff}$: Hint of discrepancy from golden modes $B \to J/\psi K$.
- CKM angle γ
- Direct CP violation: $K\pi$ puzzle? $\Delta A_{K\pi} = A_{CP}(K^+\pi^0) - A_{CP}(K^+\pi^-) \neq 0$
- Polarization in $B \to VV,\ TV$
- Search for enhancement in b→s,d penguins
- Baryonic decays
- ...

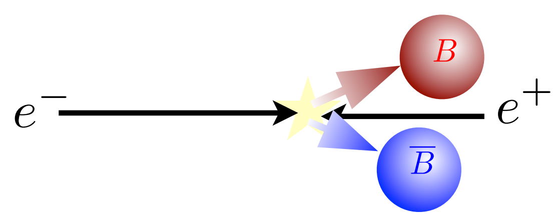


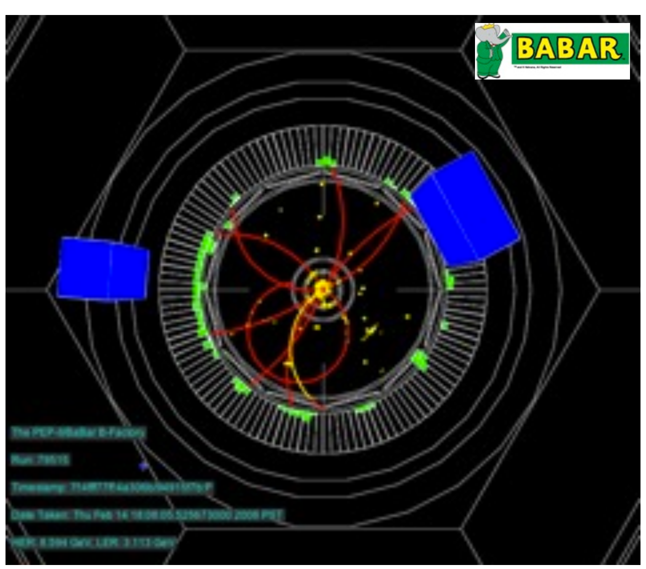
B factories

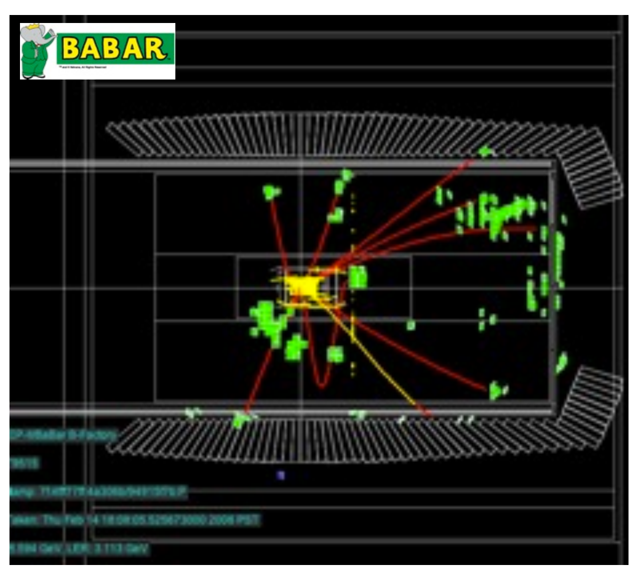




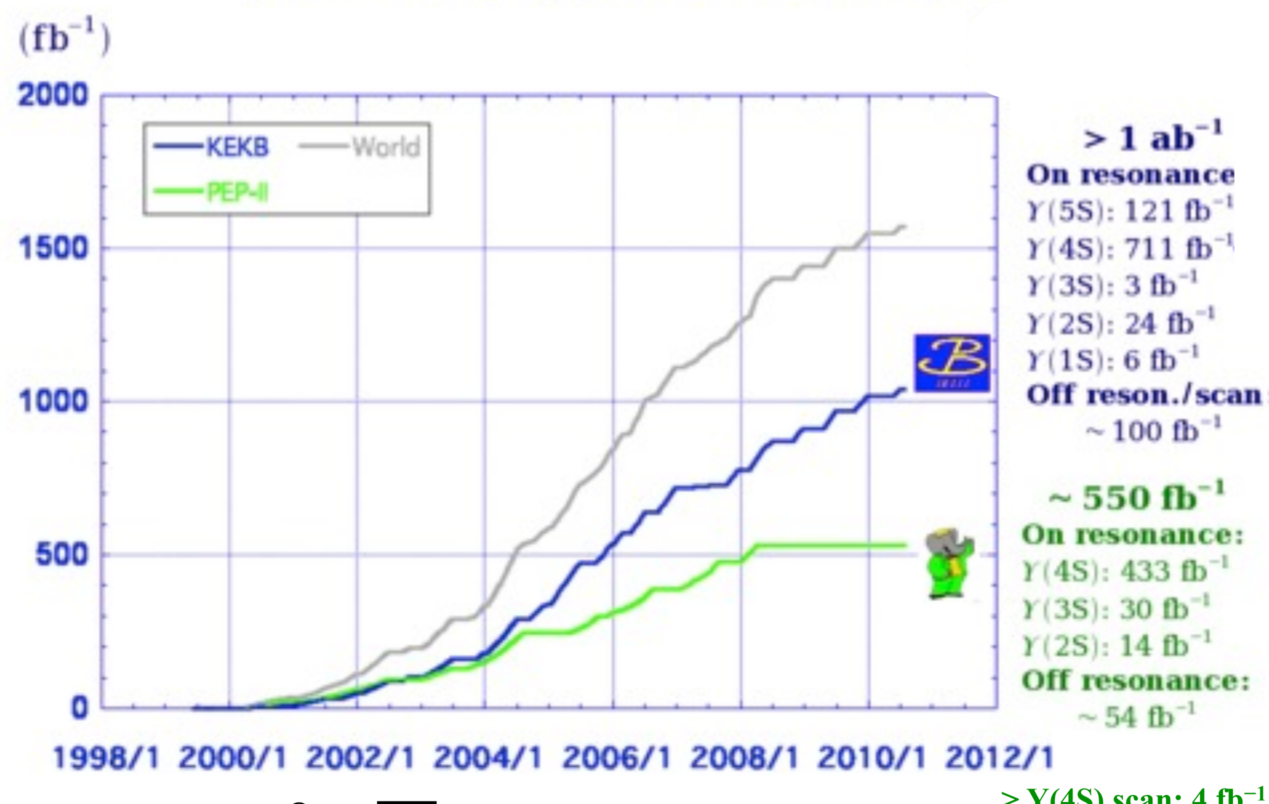








Luminosity at B factories

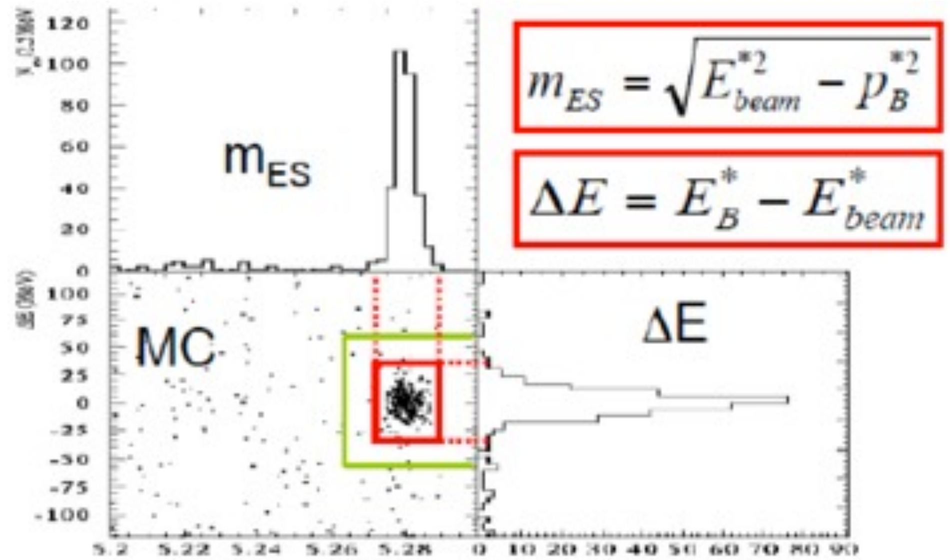


- Together *B* factories have collected $> 1.2 \times 10^9 B\overline{B}$ pairs.

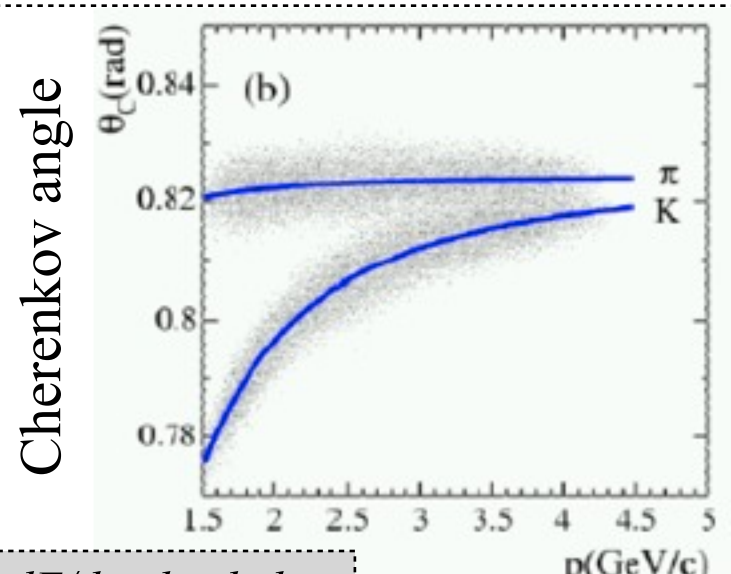
Separate signal from background

- Major background comes from continuum $e^+e^- \to q\bar{q},\ q = u, d, s, c$

Kinematics of fully reconstructed B



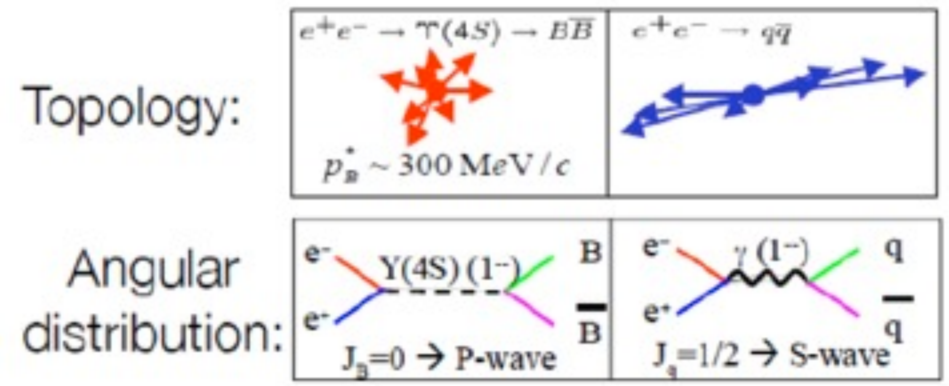
Excellent *K/π* separation power

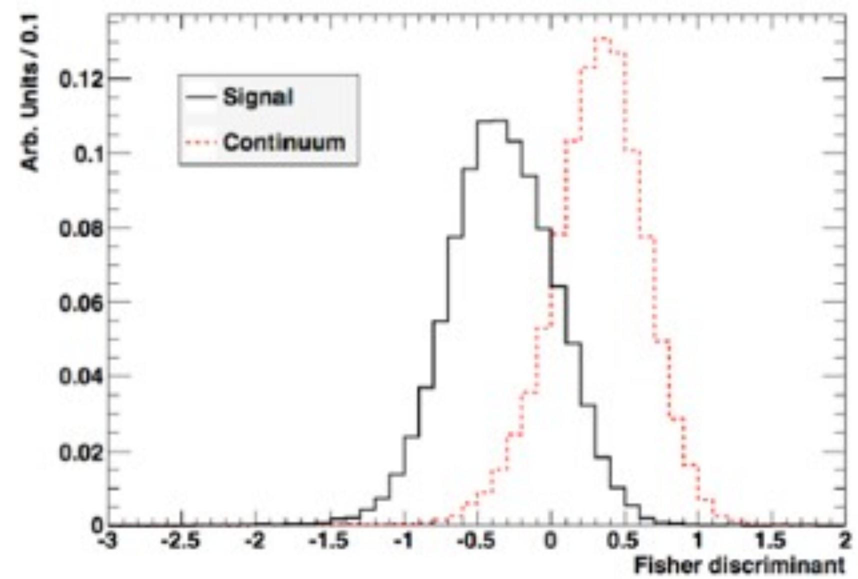


dE/dx also helps

These variables are often combined to form a grand likelihood function to increase sensitivity.

Event shape to suppress continuum

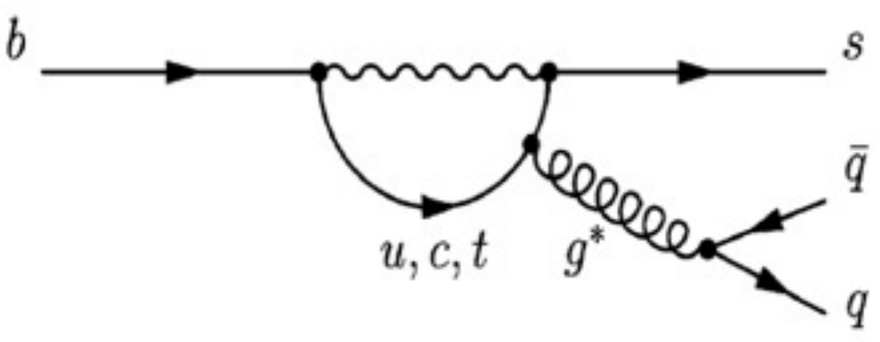




Build Fisher, NN, or other classifiers to separate background

Inclusive $B \to K^{\pm,0}$, $\pi^{\pm}$ beyond charm threshold

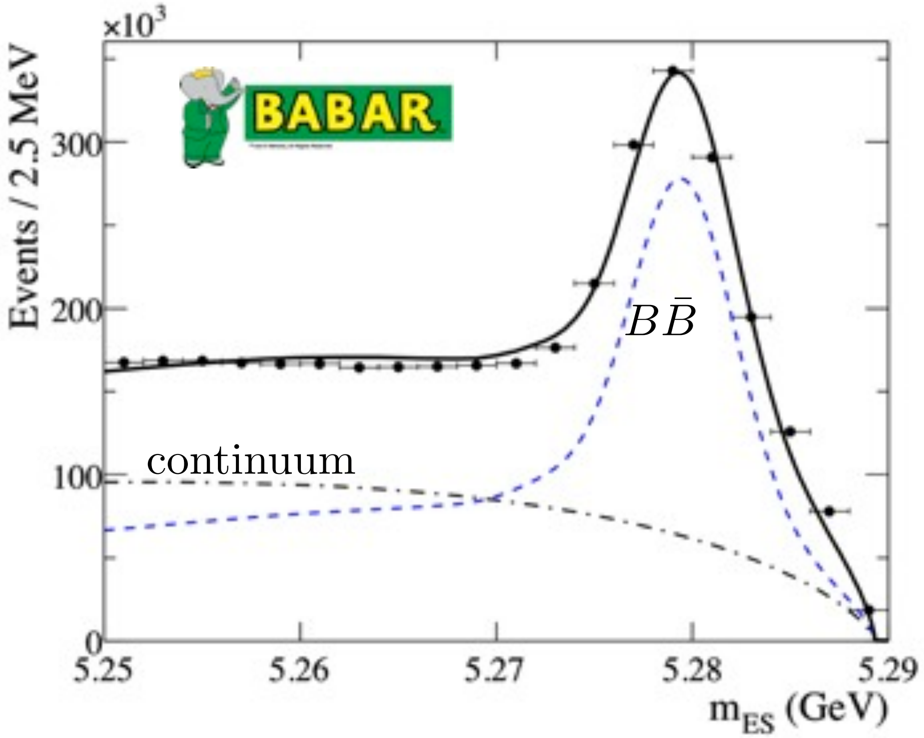
- Charmless decays have large contributions from penguin diagrams.
- New physics entering the loop could enhance the branching fraction.
  - e.g., Randall-Sundrum warped top-condensation model radion field postulation ($b \to s\phi \to sg^*$) enhances charmless BF by an order of magnitude.

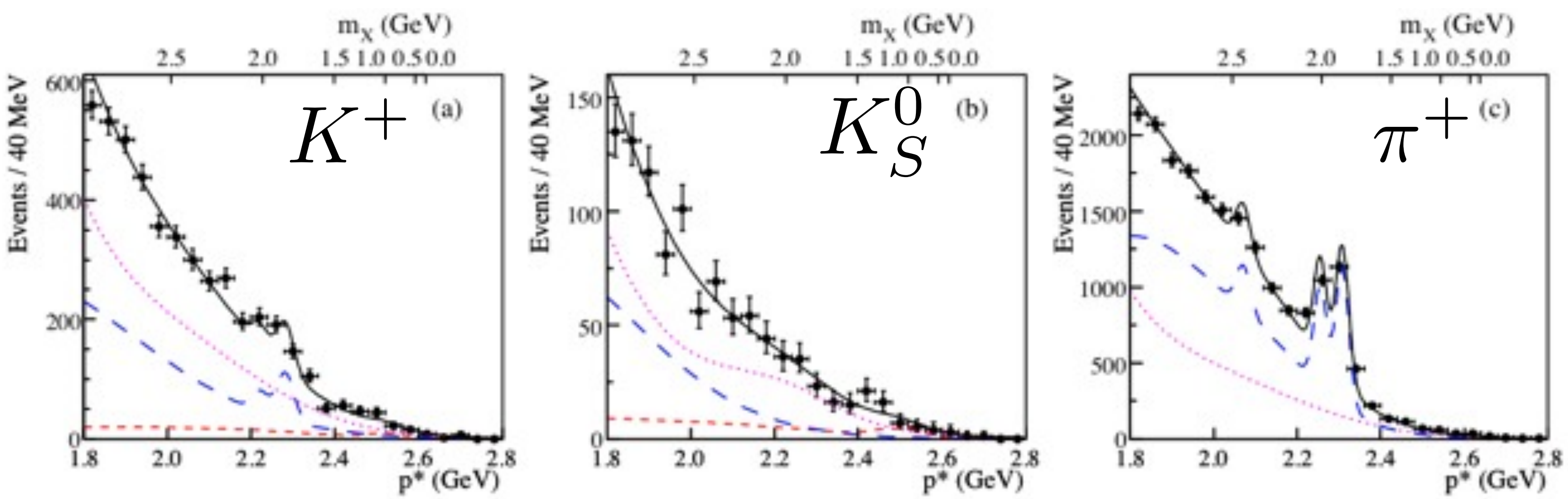


- Strategy: fully reconstruct one *B* meson through $B \to D^{(*)}X$ and measure *K* or π with momentum beyond $b \to c$ kinematic threshold in recoiled *B*.
- SM prediction of partial BF ~ 10^{-4}.
- A significant inclusive signal has *not* been observed in previous experiments.

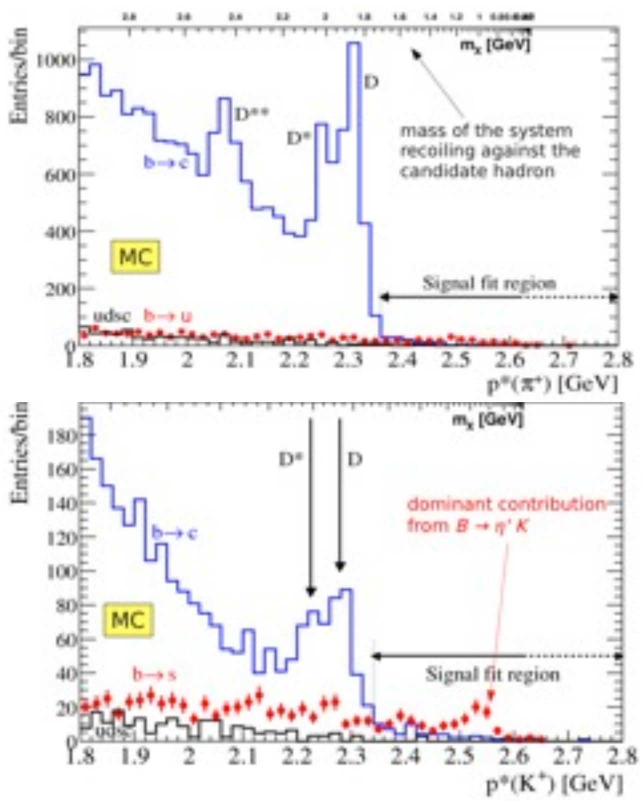
Analysis

- 2×10^6 $B\underline{B}$ events reconstructed, from 383×10^6 $B\underline{B}$ pairs.
- High p^* (momentum at recoiled frame) K and π are selected.
- Veto D^+, D^0, Ds if they can be reconstructed.
- PDF variables: m_{ES}, Fisher, p* spectrum including various charm components.

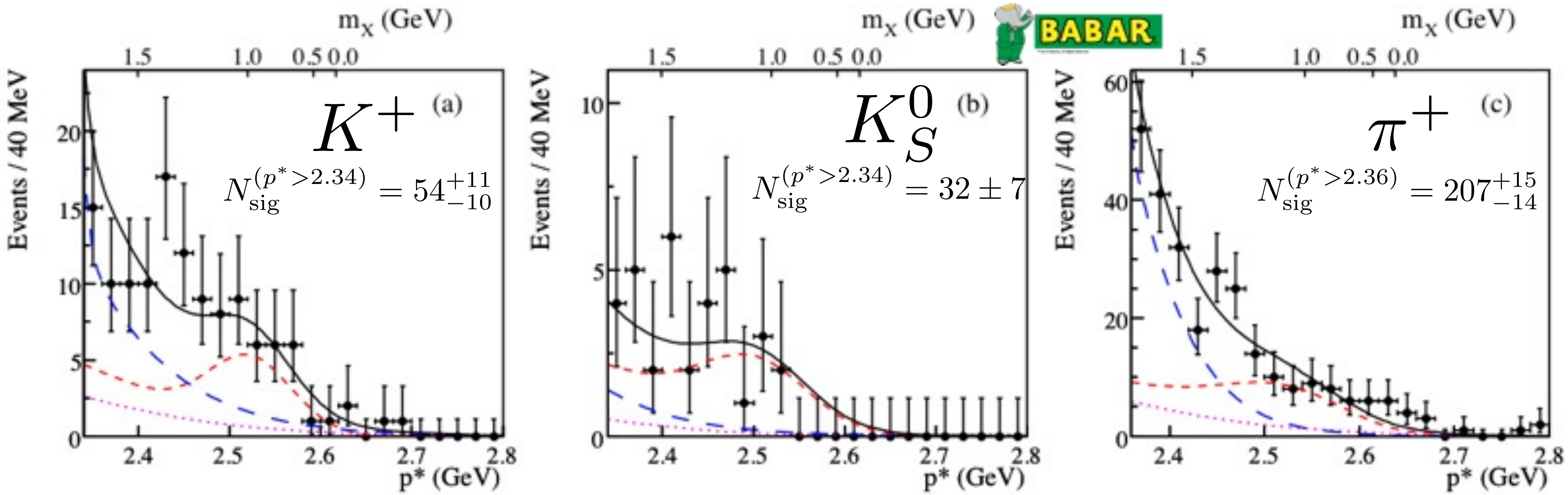




First fit p*>1.8, then the signal region p*> 2.34 (2.36)



Inclusive $B \to K^{\pm,0}$, $\pi^{\pm}$ results



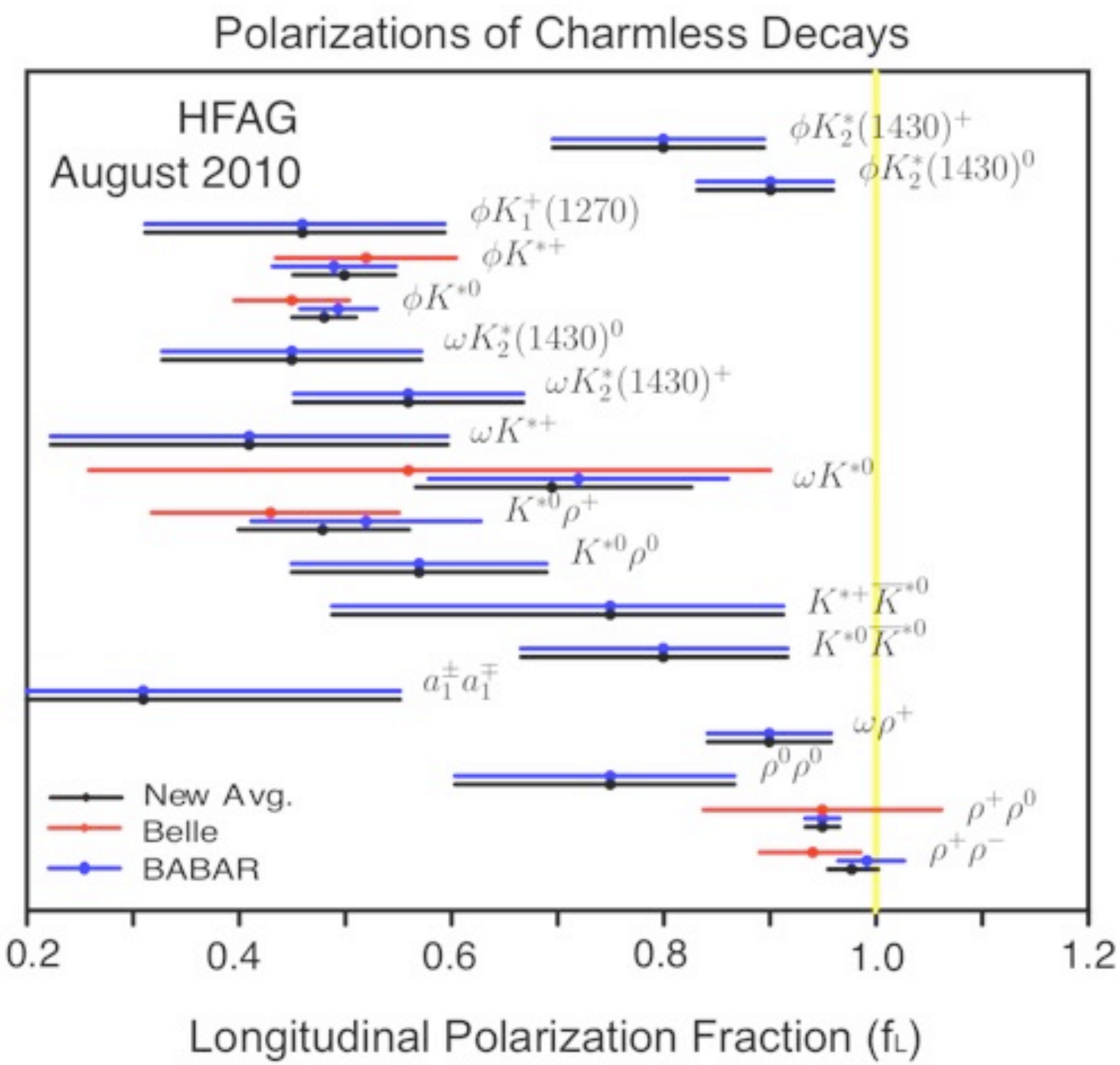
- $\mathcal{B}(B \to K^+X,\, p^* > 2.34\,\mathrm{GeV}) = (1.2 \pm 0.3 \pm 0.4) \times 10^{-4}, \quad (< 1.9 \times 10^{-4} @90\%\mathrm{C.L.}) \;\; 2.9\sigma$
  $\mathcal{B}(B \to K^0X,\, p^* > 2.34\,\mathrm{GeV}) = (1.9 \pm 0.5 \pm 0.5) \times 10^{-4}, \quad (< 2.9 \times 10^{-4} @90\%\mathrm{C.L.}) \;\; 3.8\sigma$
  $\mathcal{B}(B \to \pi^+X,\, p^* > 2.34\,\mathrm{GeV}) = (3.7 \pm 0.5 \pm 0.6) \times 10^{-4}, \quad 6.7\sigma$

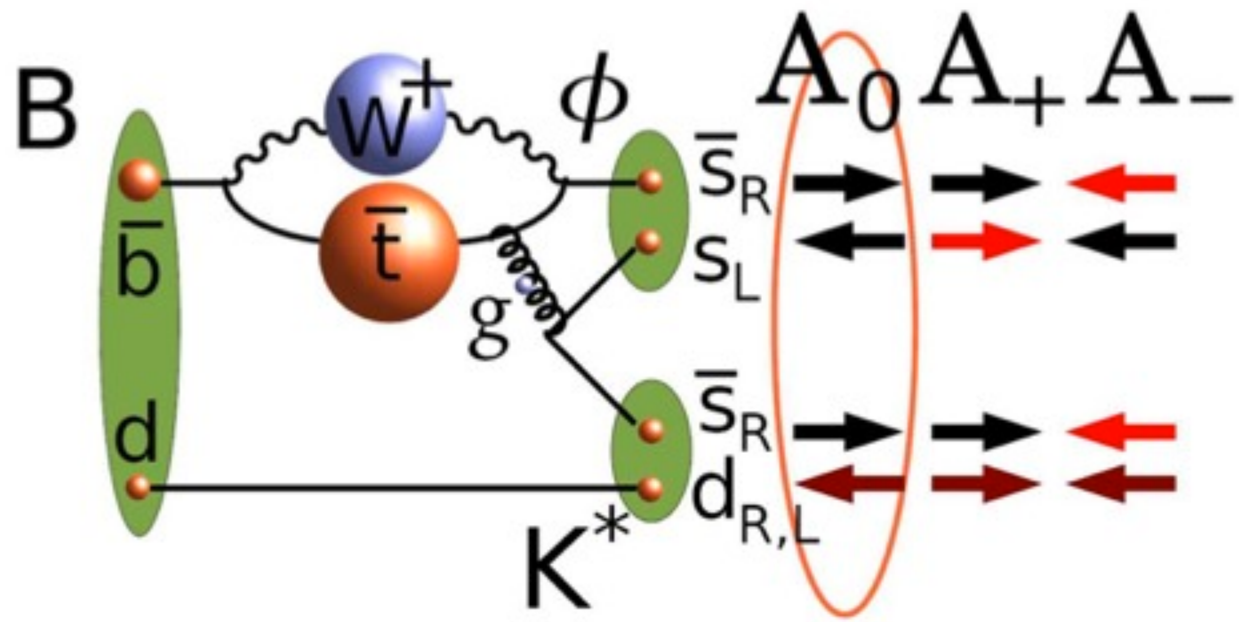
[PRD-RC 83, 031103 (2011)]

- In agreement with the Standard Model
- Exclude large enhancement from New Physics.

Polarization in $B \to Vector$-$Vector$

- Naive expectation: $f_L \sim 1$. $B \to \rho\rho$ have $f_L > 90\%$. However, $f_L \sim 50\%$ for $B \to \phi K^*$, and many other $b \to s$ penguin VV states.
- <u>$B^+ \to \rho^0 K^{*+}$</u> had not been observed yet. Expect: BF~ $(5 \pm 1) \times 10^{-6}$.





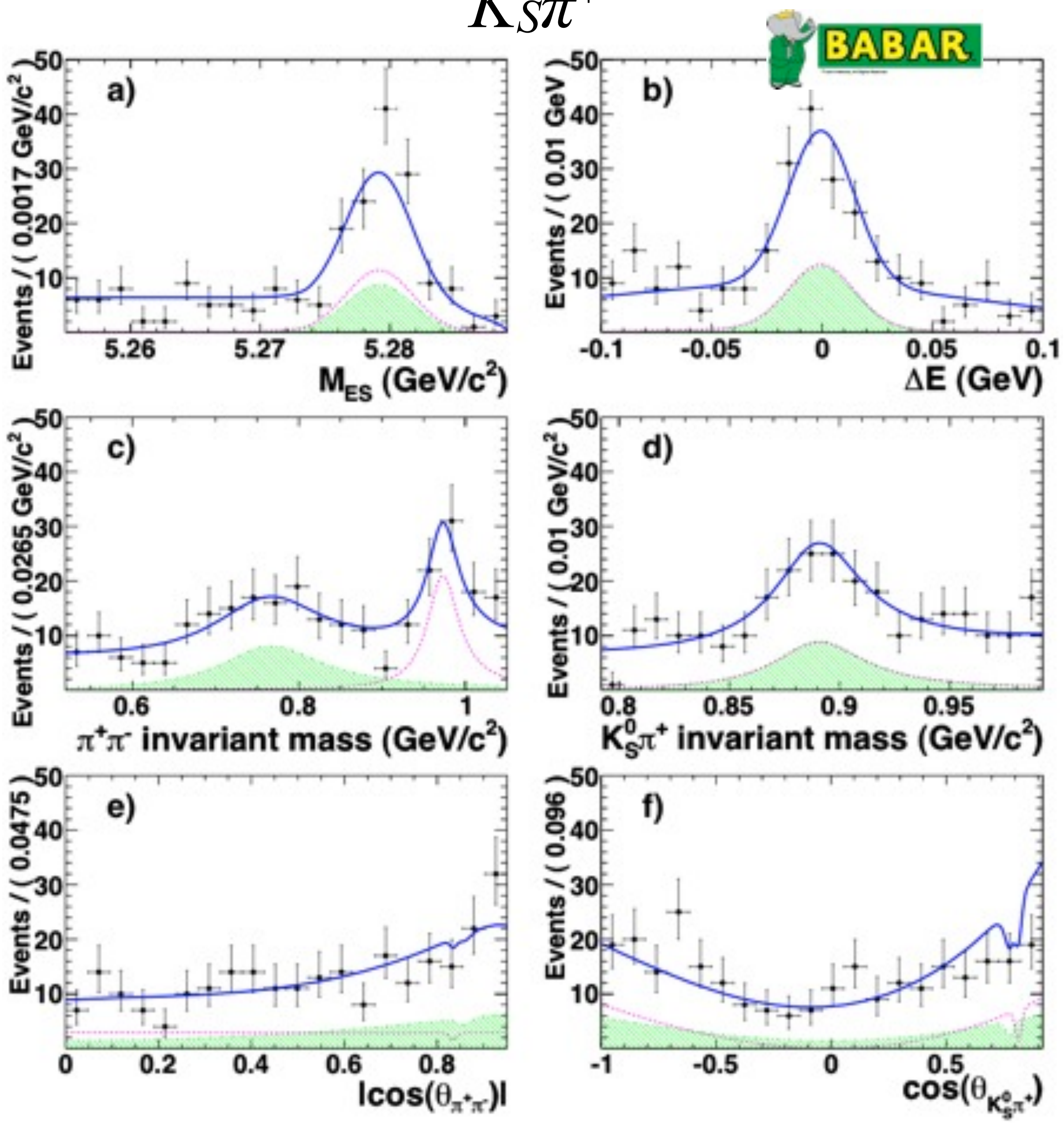
$$|A_{00}|^2 \gg |A_{++}|^2 \gg |A_{--}|^2$$

$B^+ \to \rho^0 K^{*+}$, $f_0 K^{*+}$

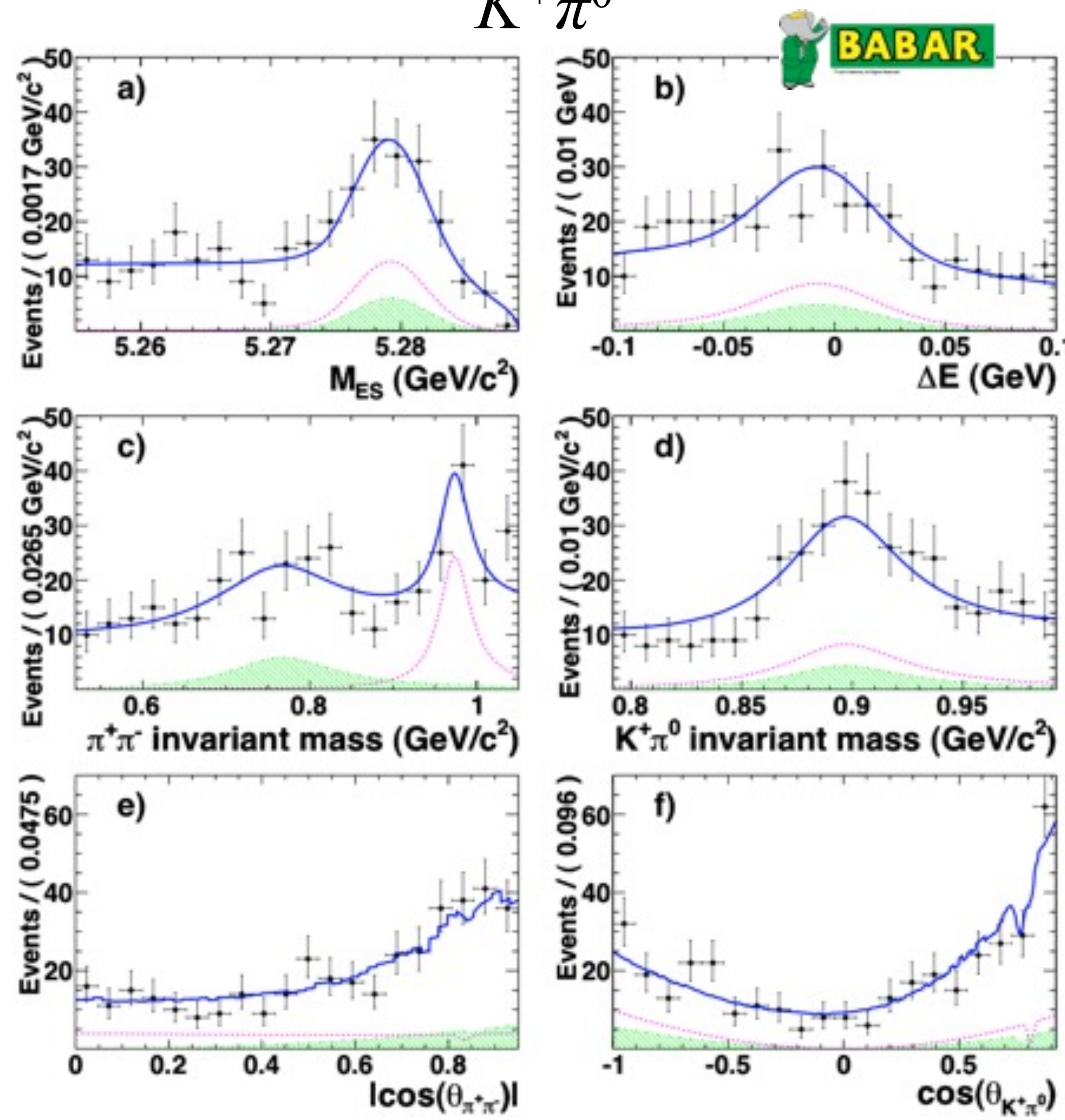
- Reconstruct: $B^+ \to \rho K^{*+}$, $f_0(980) K^{*+}$, with $\rho, f_0 \to \pi^+\pi^-$, $K^{*+} \to K^+\pi^0, K^0_S\pi^+$
- Measure: branching fraction, polarization (ρK*), direct CPV.
- Decay rate of $B \to \rho K^* \propto$ $\frac{1-f_L}{4}\sin^2\theta_{K^{*+}}\sin^2\theta_{\rho^0} + f_L\cos^2\theta_{K^{*+}}\cos^2\theta_{\rho^0}$
  - after integrating out the angle between decay planes of two vectors.
- Seven variables in PDF: $\mathcal{P}_j(x_i) = \mathcal{P}_j(m_{\mathrm{ES}\,i}) \cdot \mathcal{P}_j(\Delta E_i) \cdot \mathcal{P}_j(NN_i) \cdot \mathcal{P}_j(M_{\pi^+\pi^-\,i}) \cdot \mathcal{P}_j(M_{K\pi\,i}) \cdot \mathcal{P}_j(\cos\theta_{\pi^+\pi^-\,i}) \cdot \mathcal{P}_j(\cos\theta_{K\pi\,i})$
- 12 background components including continuum, various combination of combinatorials, higher resonances, η', and non-resonant S-wave contributions.

Projection plots of $B^+ \to \rho^0 K^{*+}$, $f_0 K^{*+}$

$K_S\pi^+$



$K^+\pi^0$



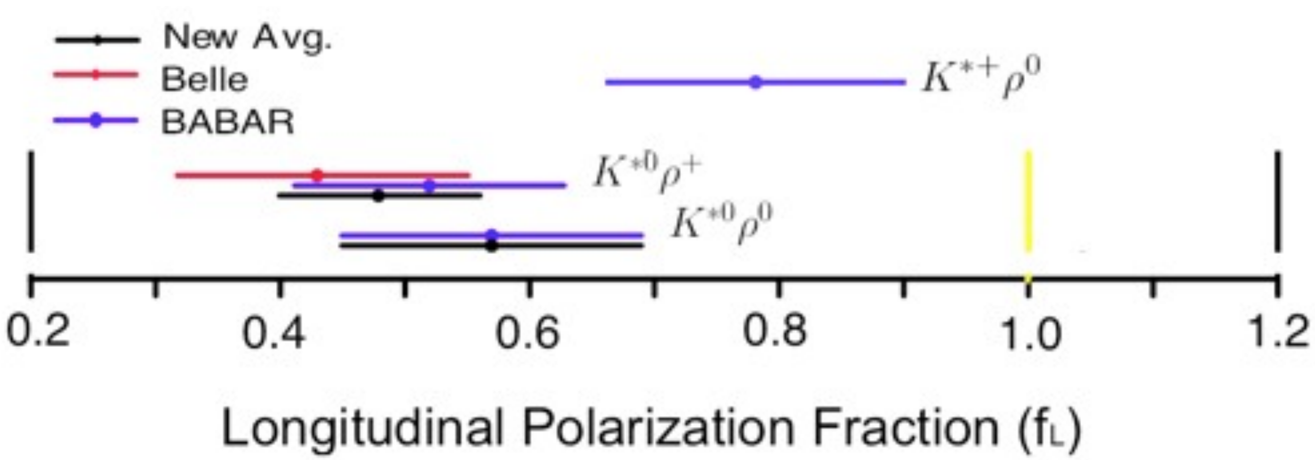
Green: ρK^*

magenta : $f_0 K^*$

	signal yield		signal yield
$B^+ \to \rho^0 K^{*+}$			
$K^{*+} \to K_S^0\ \pi^+$	85 ± 24	$K^{*+} \to K^+\ \pi^0$	67 ± 31
$B^+ \to f_0(980) K^{*+}$			
$K^{*+} \to K_S^0\ \pi^+$	69 ± 14	$K^{*+} \to K^+\ \pi^0$	91 ± 20

$B^+ \to \rho^0 K^{*+}$, $f_0 K^{*+}$ results

- Observation of $B^+ \to \rho^0 K^{*+}$ decay: $BF(B^+ \to \rho^0 K^{*+}) = (4.6 \pm 1.0 \pm 0.4) \times 10^{-6}$
- Improved $BF(B^+ \to f_0 K^{*+}) \times BF(f_0 \to \pi^+\pi^-) = (4.2 \pm 0.6 \pm 0.3) \times 10^{-6}$
- $f_L(B^+ \to \rho^0 K^{*+}) = 0.78 \pm 0.12 \pm 0.03$
  - consistent with large f_L; the other two $K^*\rho$ modes are further away.



$K^{*+}\rho^0$	BABAR	$0.78 \pm 0.12 \pm 0.03$	This result
$K^{*0}\rho^+$	BABAR	$0.52 \pm 0.10 \pm 0.04$	PRL97,201801(2006)
	Belle	$0.43 \pm 0.11^{+0.05}_{-0.02}$	PRL95,141801(2005)
$K^{*0}\rho^0$	BABAR	$0.57 \pm 0.09 \pm 0.08$	PRL97,201801(2006)

$K^{*+}\rho^0$: penguin + color-allowed $\bar{b} \to \bar{u}u\bar{s}$ tree
$K^{*0}\rho^+$: pure penguin
$K^{*0}\rho^0$: penguin + color-suppressed $\bar{b} \to \bar{u}u\bar{s}$ tree

BABAR

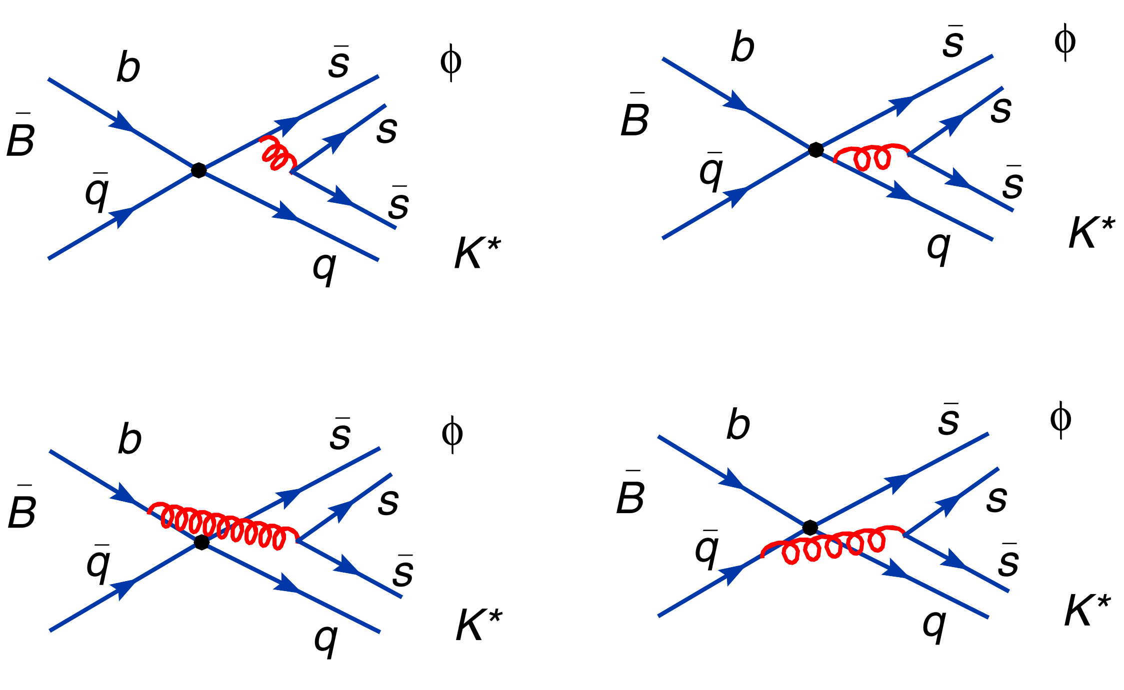
Data set: 467×10^6 $B\bar{B}$ pairs. Accepted by PRD-RC

Mode	$\mathcal{B}$ $(\times 10^{-6})$	f_L	$\mathcal{A}_{CP}$
$B^+ \to \rho^0 K^{*+}$	$4.6 \pm 1.0 \pm 0.4$	$0.78 \pm 0.12 \pm 0.03$	$0.31 \pm 0.13 \pm 0.03$
$K^{*+} \to K^0_S\,\pi^+$	$4.6 \pm 1.2 \pm 0.5$	$0.74 \pm 0.13 \pm 0.03$	$0.25 \pm 0.14 \pm 0.03$
$K^{*+} \to K^+\,\pi^0$	$4.4 \pm 2.0 \pm 0.5$	$0.94 \pm 0.27 \pm 0.03$	$0.59 \pm 0.31 \pm 0.03$
$B^+ \to f_0(980) K^{*+}$	$4.2 \pm 0.6 \pm 0.3$	-	$-0.15 \pm 0.12 \pm 0.03$
$K^{*+} \to K^0_S\,\pi^+$	$3.6 \pm 0.7 \pm 0.3$	-	$-0.34 \pm 0.16 \pm 0.03$
$K^{*+} \to K^+\,\pi^0$	$5.2 \pm 1.0 \pm 0.3$	-	$0.14 \pm 0.12 \pm 0.03$

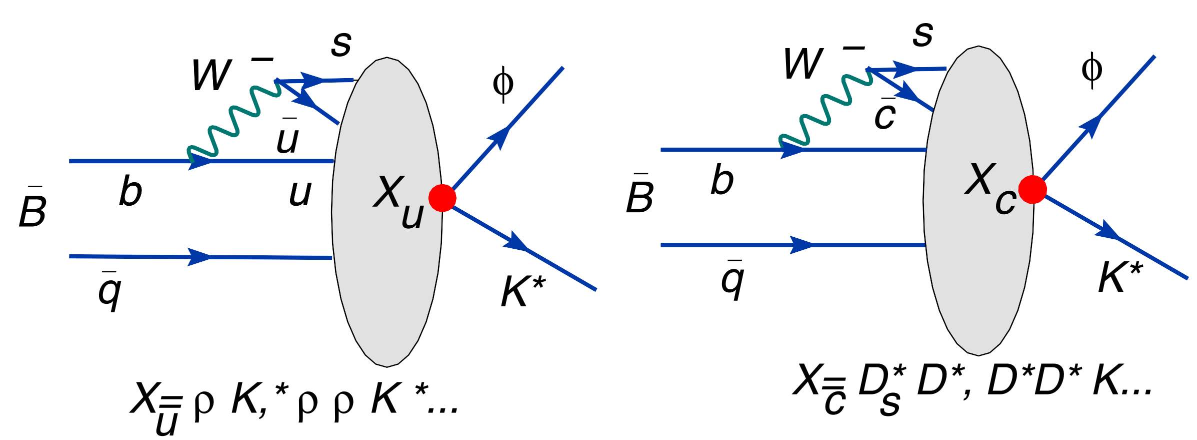
Previous results: 232M BB
$\mathcal{B}(B^+ \to \rho^0 K^{*+}) < 6.1 \times 10^{-6}$ (@90% CL)
$\mathcal{B}(B^+ \to f_0(980) K^{*+}) = (5.2 \pm 1.2 \pm 0.5)\ 10^{-6}$
PRL 97, 201801 (2006)

$B^0 \to K^{*0}\overline{K}^{*0}$ motivation

- $B \to K^{*0}\overline{K}^{*0}$ is a pure $b \to d$ penguin, and should have the same f_L as $b \to s$ under U-spin symmetry.
- Possible explanations in the SM for small f_L: large f_T contributions from penguin annihilation or rescattering.
- If a large f_T is observed, a time-dependent CP asymmetry analysis to measure phase difference between $A_T(b \to d)$ and $A_T(\bar{b} \to \bar{d})$ could distinguish the two possible contributions which have different weak phases.



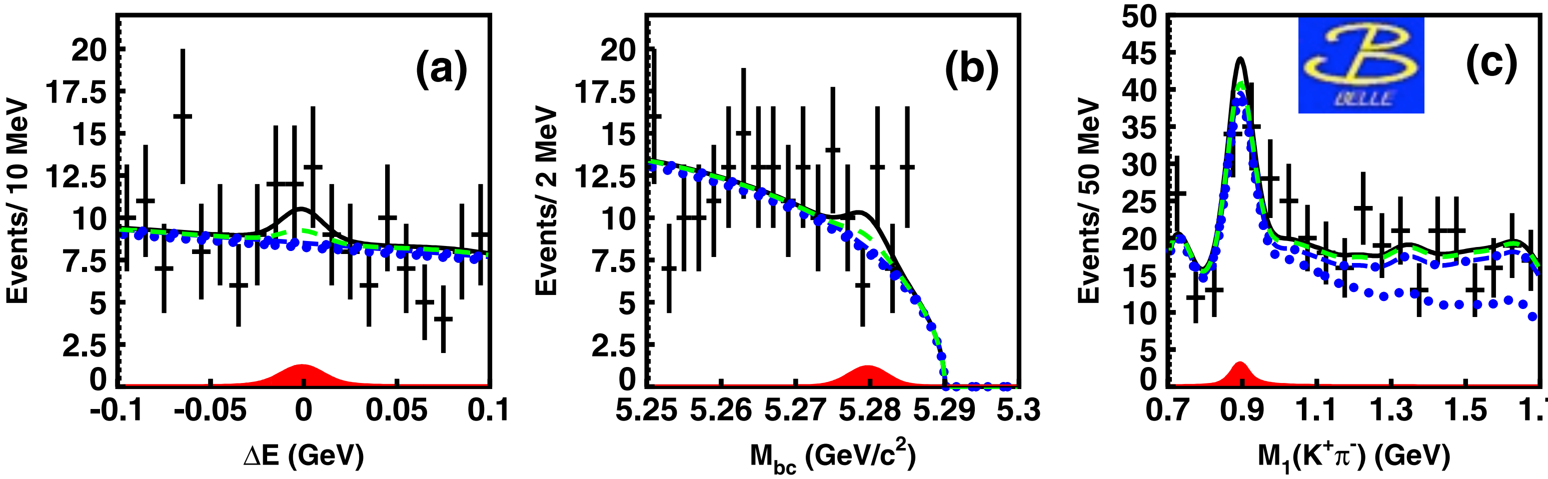
The penguin annihilation diagrams.

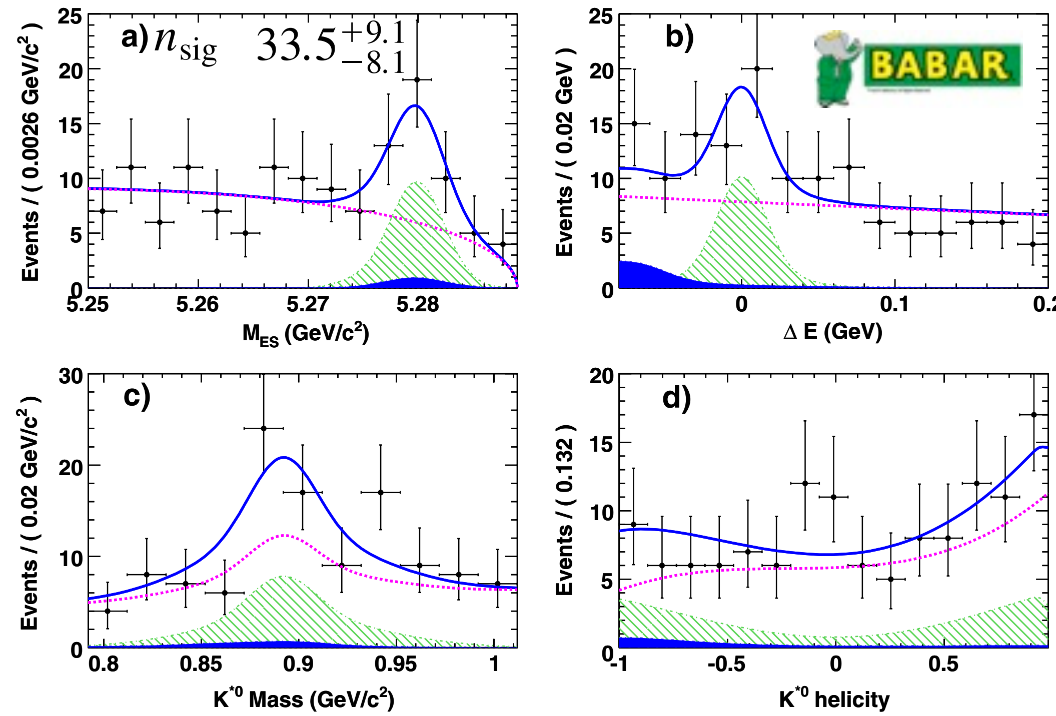


The rescattering diagrams.

Datta et al, PRD74, 034015 (2007)

$B^0 \to K^{*0}\bar{K}^{*0}$, $K^{*0}K^{*0}$ results





- Fit PDF: $m_{\rm ES}$, ΔE, $m_{K_1^*}$, $m_{K_2^*}$, (and Fisher, K^* helicity angles: (BABAR)).
- Belle fits K^*K^* and higher/non-resonances at once; BABARfits K^*K^* and subtract other contributions extrapolating from fit to higher resonance.

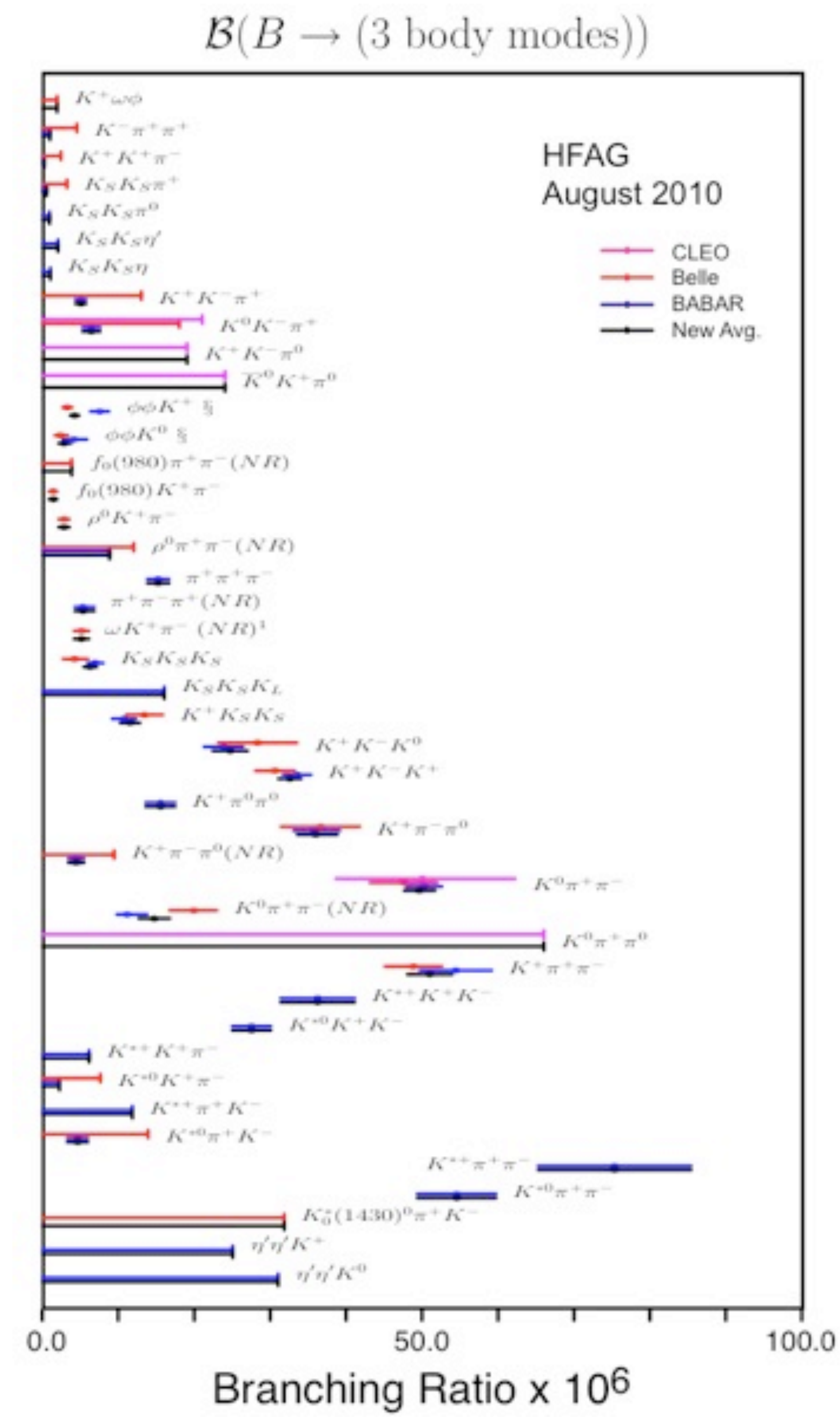
	$\mathcal{B}(K^{*0}\overline{K}^{*0})$	$f_L(K^{*0}\overline{K}^{*0})$	$\mathcal{B}(K^{*0}K^{*0})$	$N_{B\overline{B}}$ $[10^6]$	Ref.
BABAR	$1.28^{+0.35}_{-0.30} \pm 0.11$	$0.80^{+0.10}_{-0.12} \pm 0.06$	< 0.41	383	PRL100, 081801 (2008)
Belle	$0.26^{+0.33+0.10}_{-0.29-0.08}$ (< 0.8)	—	< 0.2	657	PRD81, 071101(R) (2010)

BF unit: 10^{-6}; Upper limit at 90% C.L.

$\sim 2\sigma$ discrepancy in $\mathcal{B}(K^{*0}\overline{K}^{*0})$ between the two measurements.

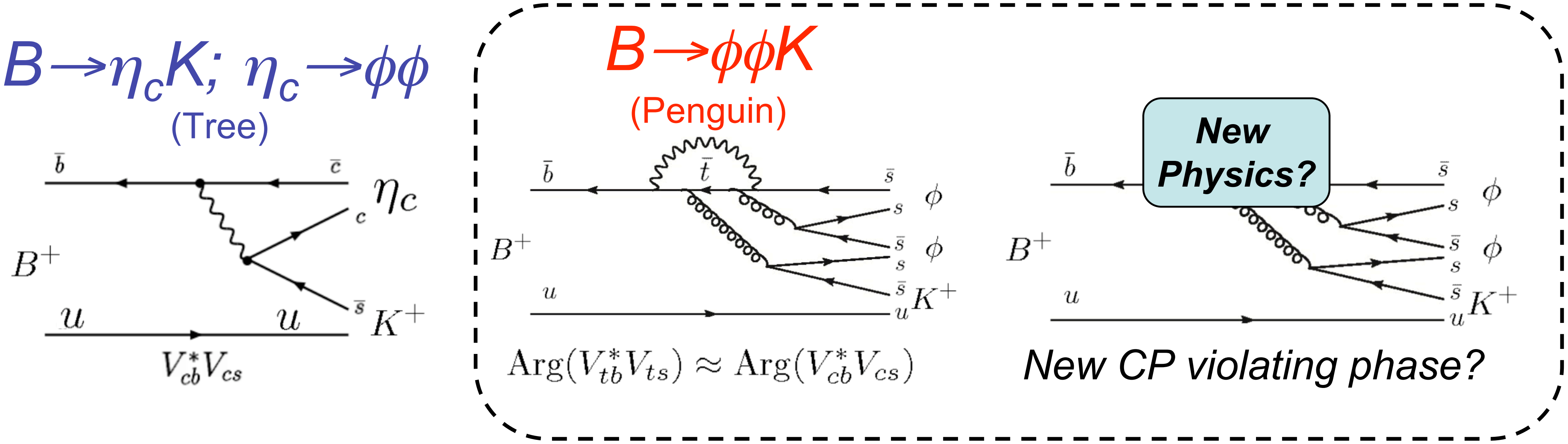
Charmless 3-body

- Search new physics in $b \to s$ or $b \to d$ penguin dominated processes.
- Typical analysis involves Dalitz plot analysis, some with time dependence, and some need to utilize isospin/SU(3) symmetry.
  - Interferences among resonances allow CKM angles and strong phases measurement.
    - Eg., $\alpha : B \to \pi\pi\pi$; $\gamma : B \to K\pi\pi$; $\beta : B \to K_S K_S K_S$
  - Search for direct CPV in components.
- Other structure in Dalitz plot.



$B \to \phi\phi K$ analysis

- Possible new physics in $b \to s$ penguin. Interference with $B \to \eta_c K$ at $\phi\phi$ mass near η_c could produce large CPV.

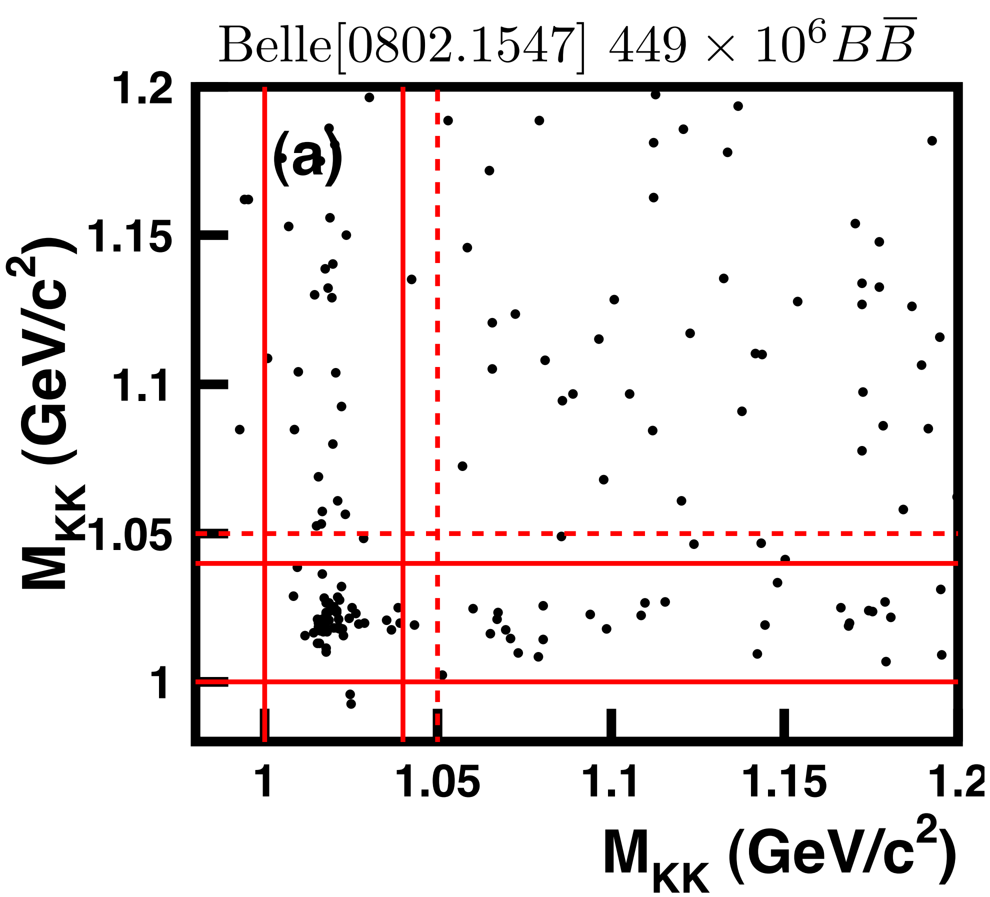


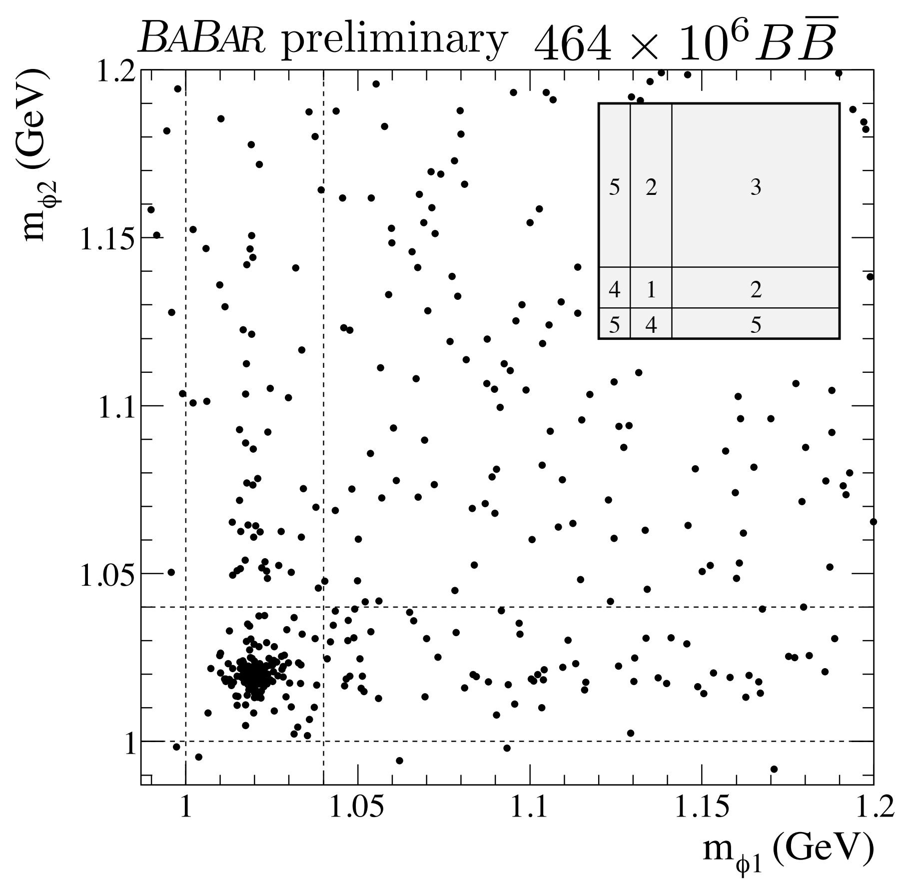
- Non-zero direct CP asymmetry would be a smoking gun for New Physics.
  - Could be as large as 40%! *(Haizumi, Phys. Lett.* ***B 583****, 285 (2004))*.

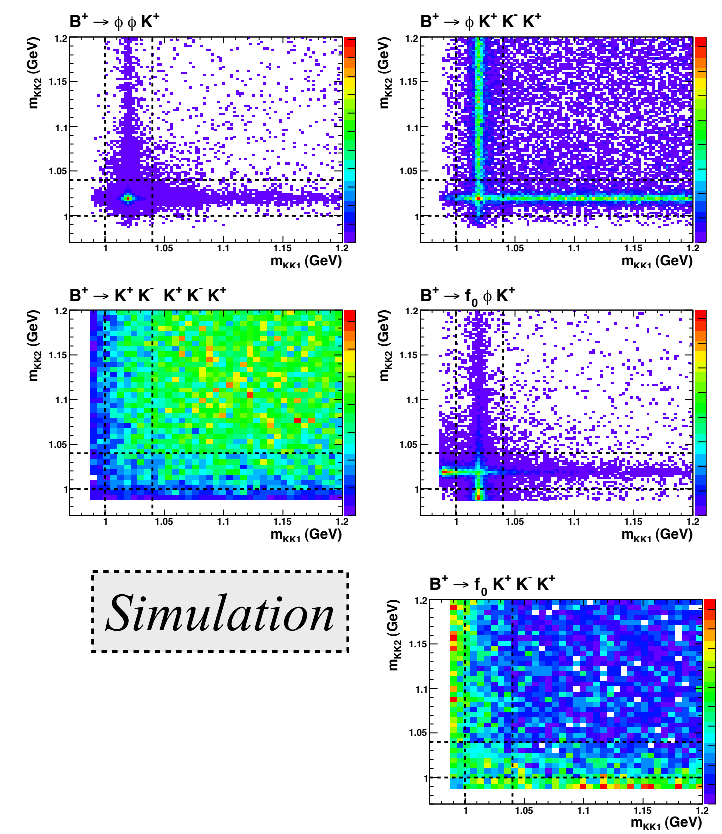
- Study spin structure of $\phi\phi$ system. Only $J^P=0^-$ component of 3-body B decay interfere with η_c.

Peaking background

- Peaking *B→5K* background occupy different zones on $m_{\phi 1}$-$m_{\phi 2}$ plane.
- Fit yields by zone and use cross-zone contributions determined by MC to estimate peaking background.



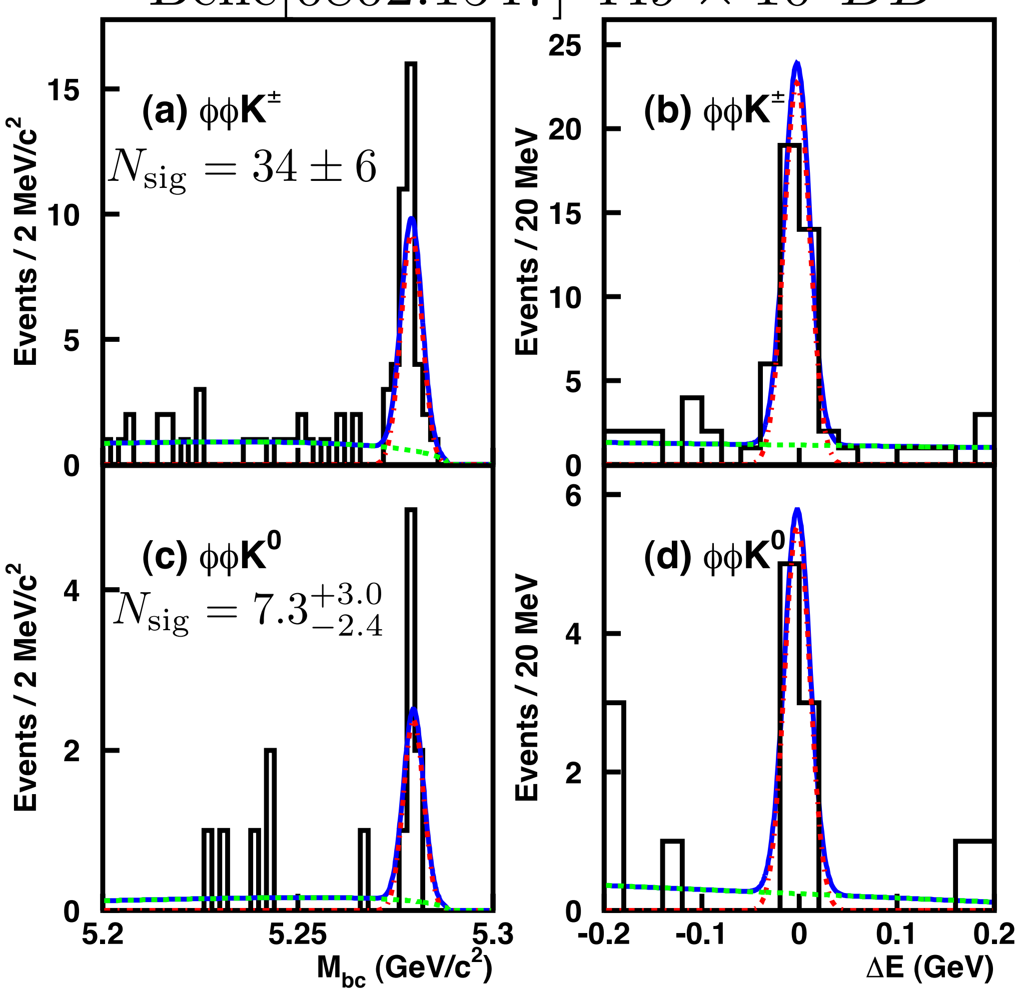




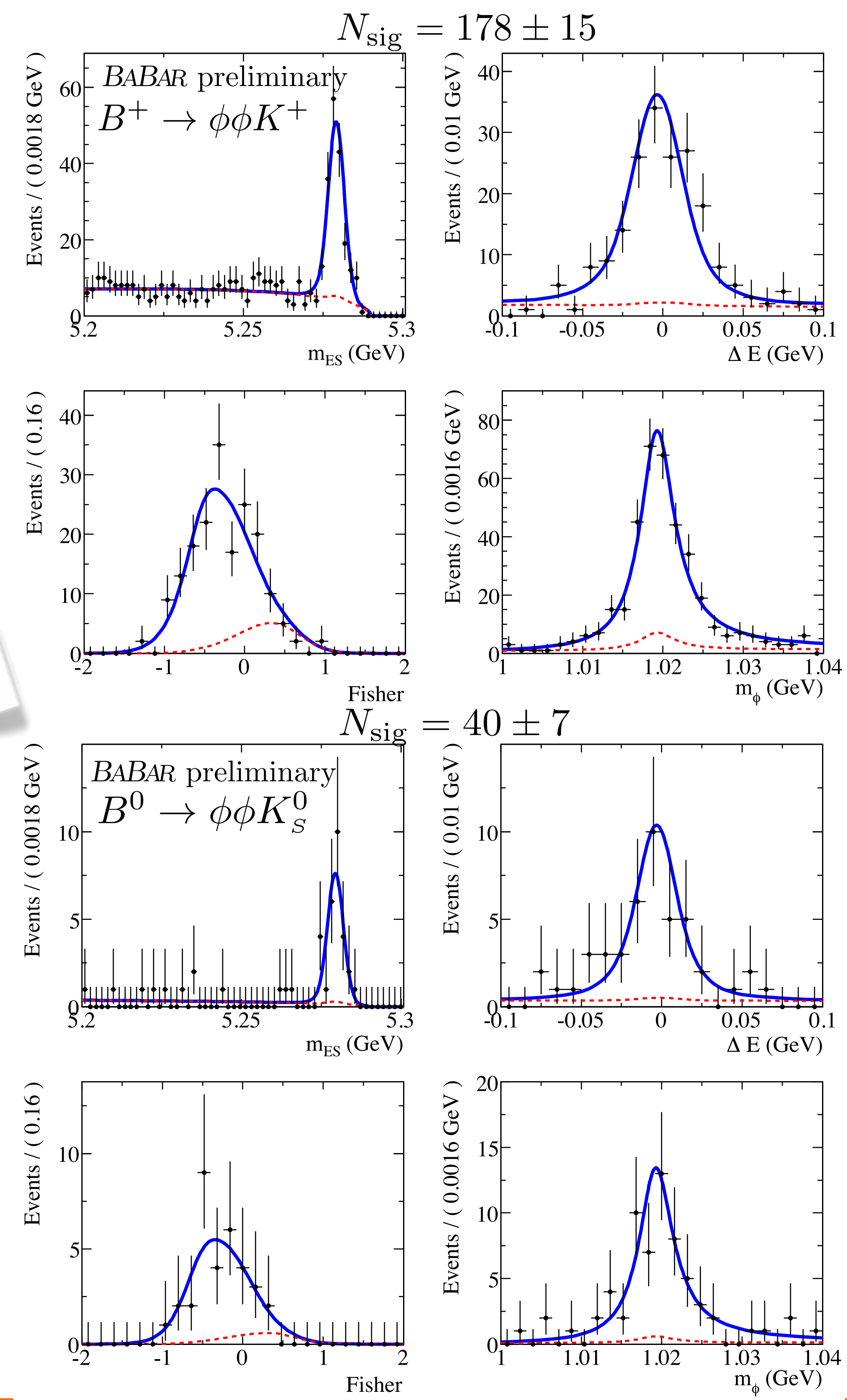
Fitting yields

- Maximum likelihood fit to m_{ES}, ΔE, Fisher, $m_{\phi 1}$, $m_{\phi 2}$ [*BABAR*].
- Cut on a likelihood of Fisher, $\cos\theta_B$, and Δz, and flavor tagging on the recoiled *B*, and then fit to m_{ES}, ΔE [Belle].

Belle[0802.1547] $449 \times 10^6 B\overline{B}$

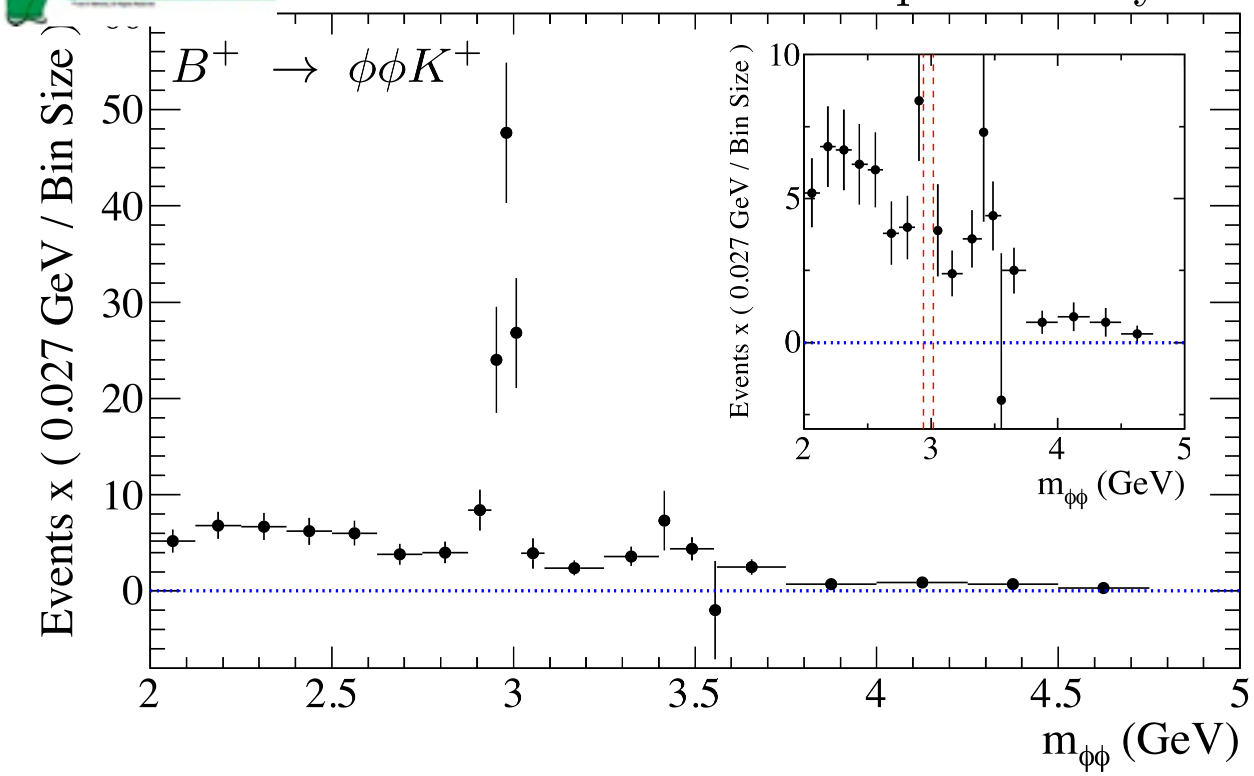


$m_{\phi\phi} < 2.85$ GeV

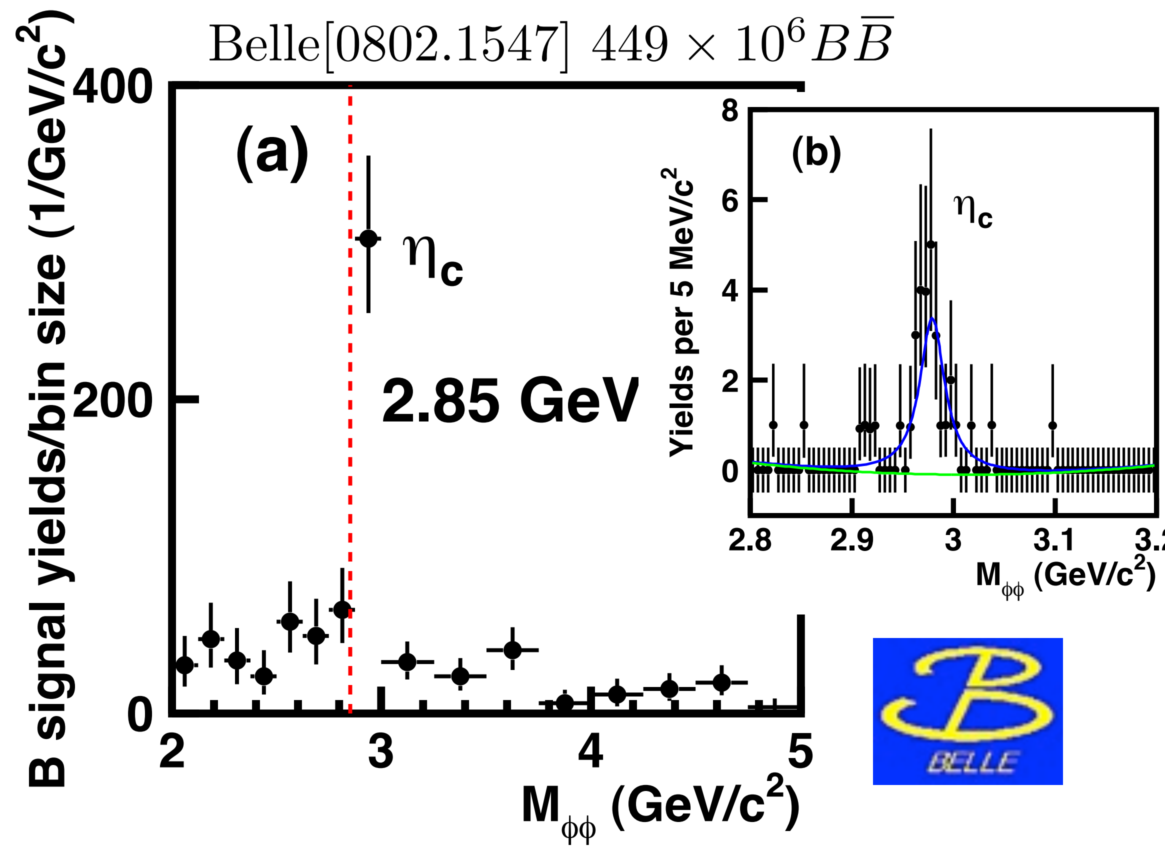


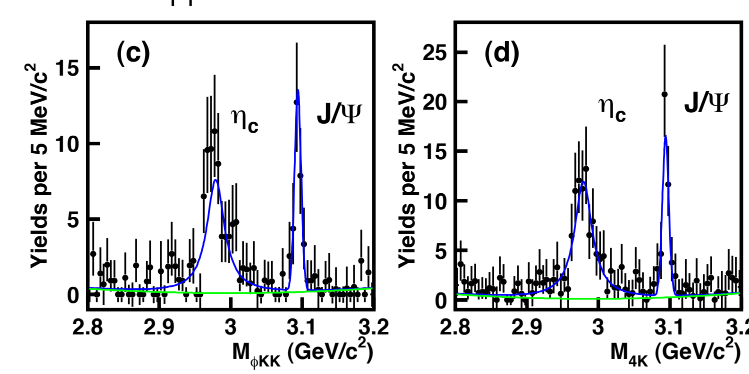
Branching fraction and A_{CP}

$464 \times 10^6 B\overline{B}$ BABAR preliminary



Belle[0802.1547] $449 \times 10^6 B\overline{B}$





Partial BF: $m_{\phi\phi} < 2.85$ GeV

(10^{-6})	$\mathcal{B}(B^+ \to \phi\phi K^+)$	$\mathcal{B}(B^0 \to \phi\phi K^0)$
BABAR	$5.6 \pm 0.5 \pm 0.3$	$4.5 \pm 0.8 \pm 0.3$
Belle	$3.2^{+0.6}_{-0.5} \pm 0.3$	$2.3^{+1.0}_{-0.7} \pm 0.2$

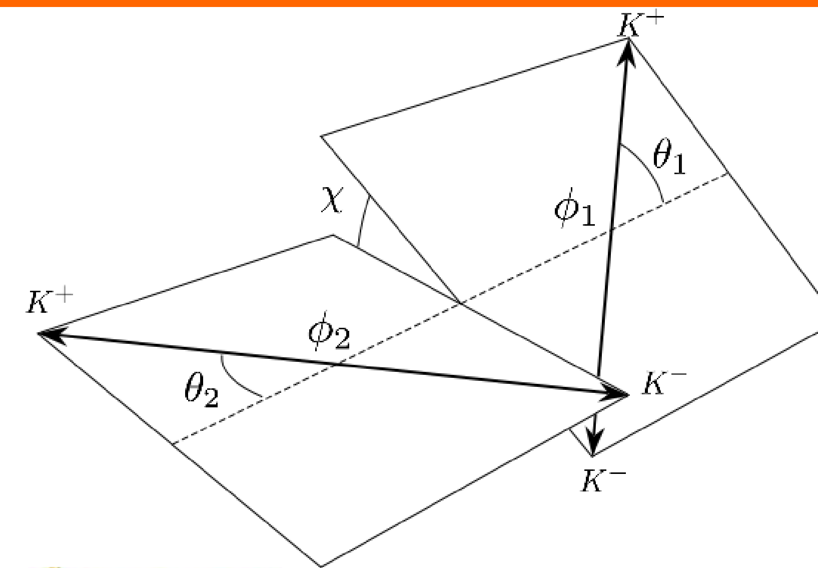
$A_{CP}(\phi\phi K^+)$ below and within η_c region, consistent with zero.

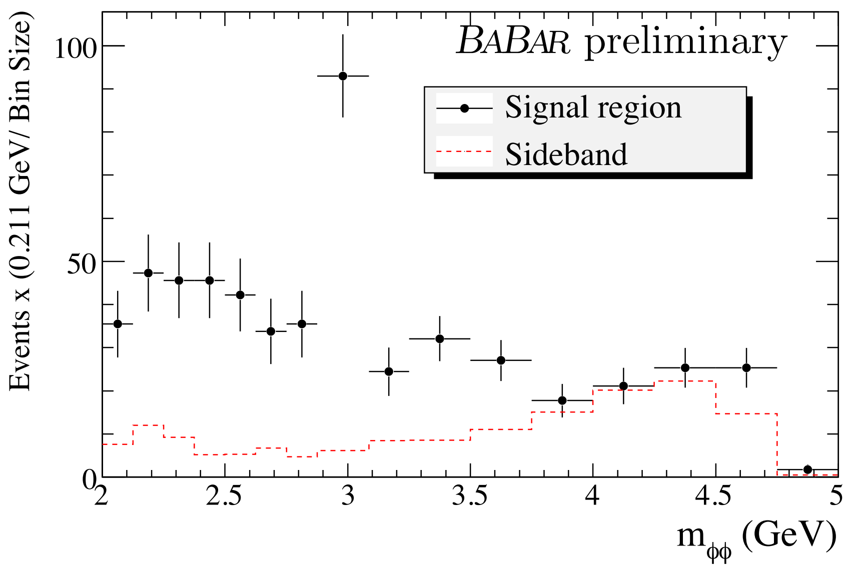
$m_{\phi\phi}$	< 2.85 GeV	2.94–2.98 GeV	2.98–3.02 GeV
BABAR	$-0.10 \pm 0.08 \pm 0.02$	$-0.10 \pm 0.15 \pm 0.02$	$-0.08 \pm 0.14 \pm 0.02$
Belle	$0.01^{+0.19}_{-0.16} \pm 0.02$	$0.15^{+0.16}_{-0.17} \pm 0.02$	

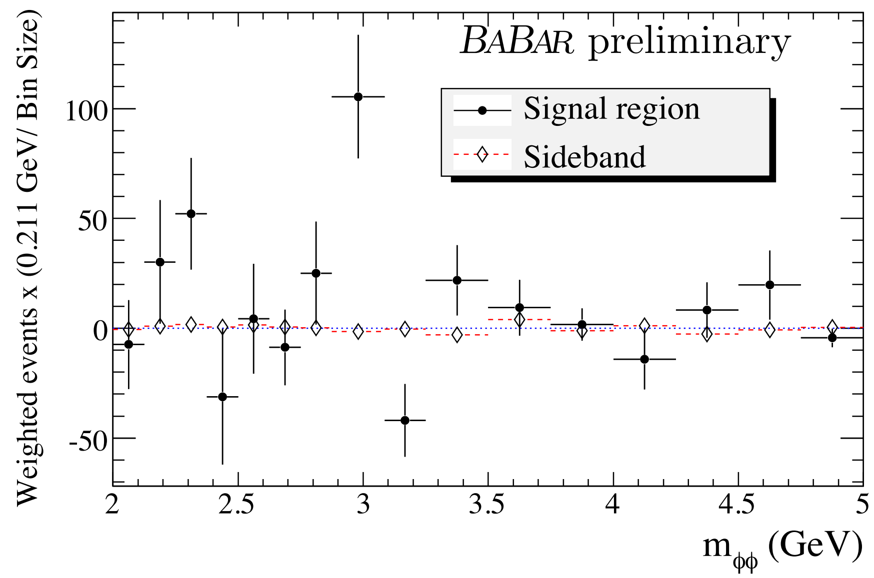
Angular study

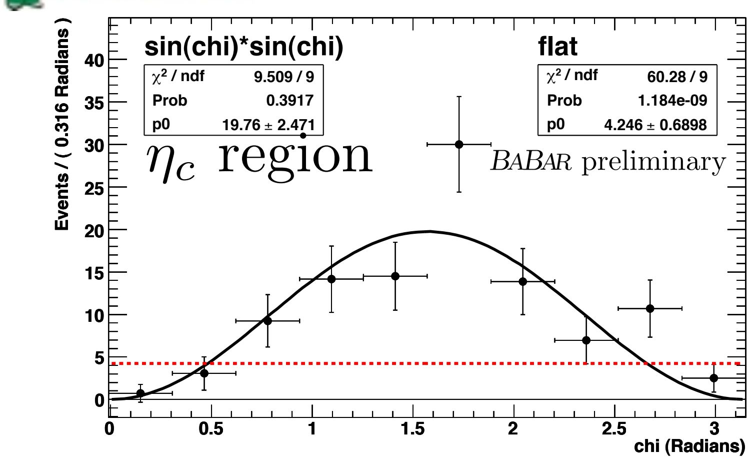
- Project J^P=0^- component by weighting $m_{\phi\phi}$ by the product of Legendre polynomial and spherical harmonic

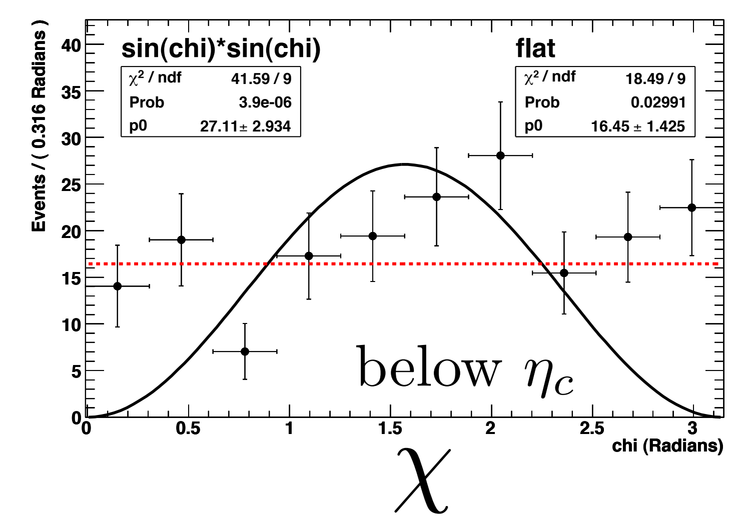
$$P_2(\cos\theta_1)\ \mathrm{Re}\left[Y_2^2(\theta_2,\chi)\right] = \frac{25}{4}\left\{3\cos^2(\theta_1)-1\right\}\sin^2(\theta_2)\cos(2\chi)$$











- η_c region is consistent with J^P=0^-.
- Below η_c region is not consistent with J^P=0^-. but consistent with J^P=0^+.

Summary

- Very rich program in hadronic charmless B decays.
- More physics still to come after shutdowns of B factories.
- Inclusive $B \to K^{\pm,0}$, $\pi^{\pm}$ beyond charm threshold:
  - Consistent with the SM, rule out large NP contribution to $b \to sg^*$.
- Observation of $B^+ \to \rho^0 K^{*+}$ and $B^0 \to K^{*0}\overline{K}^{*0}$ decays and measurement of their polarizations:
  - more pieces towards understanding $B \to VV$ polarization puzzle.
- BF, A_{CP}, and angular analysis of $B \to \phi\phi K$:
  - Clear signal, but A_{CP} consistent with zero. No large NP in the penguin.