Charmless hadronic B decays

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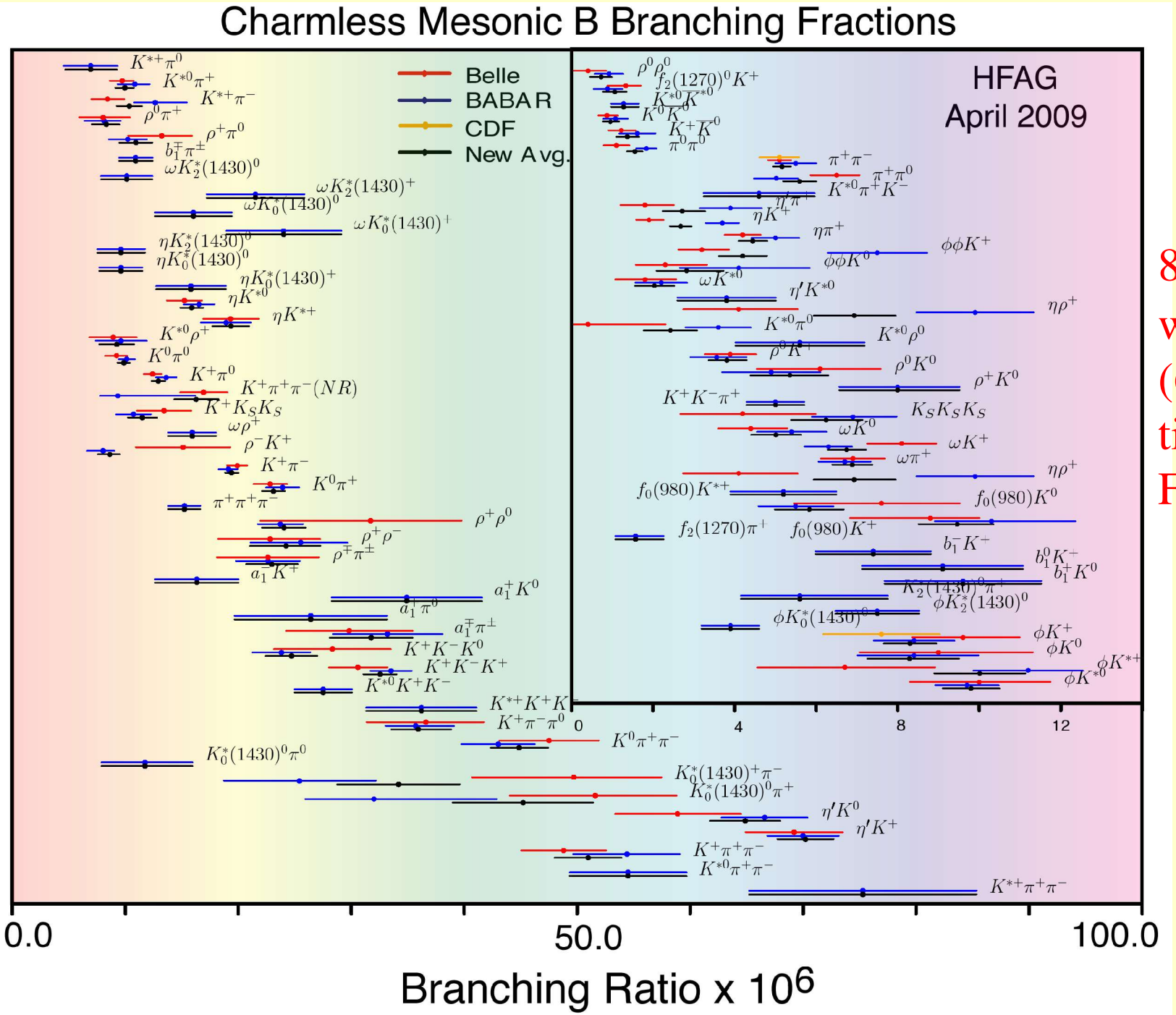
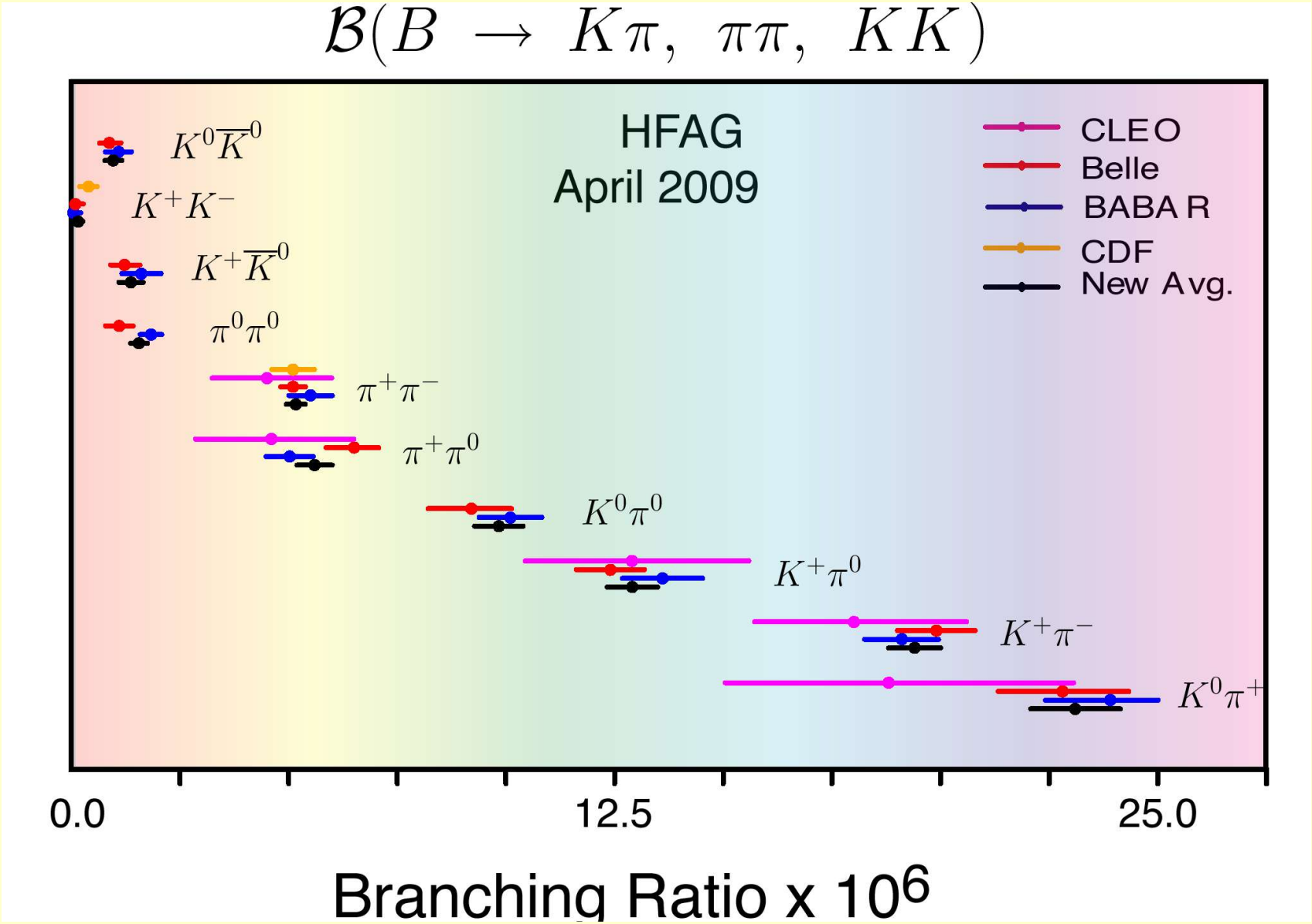
Outline

- Introduction
- Brief status of $B \to \pi\pi$, $K\pi$
- $B \to$ 3-body (Dalitz plot analyses) and Q2B
- $B \to \eta^{(\prime)}K$, $\eta^{(\prime)}\pi$, $\eta^{(\prime)}K^*$, $\eta^{(\prime)}\rho$
- $B \to VV$ decays ($\omega\rho$, ωK^*, K^*K^*)
- B decays with 0^+, 1^+, 2^+ mesons
- B decays to baryons
- Summary

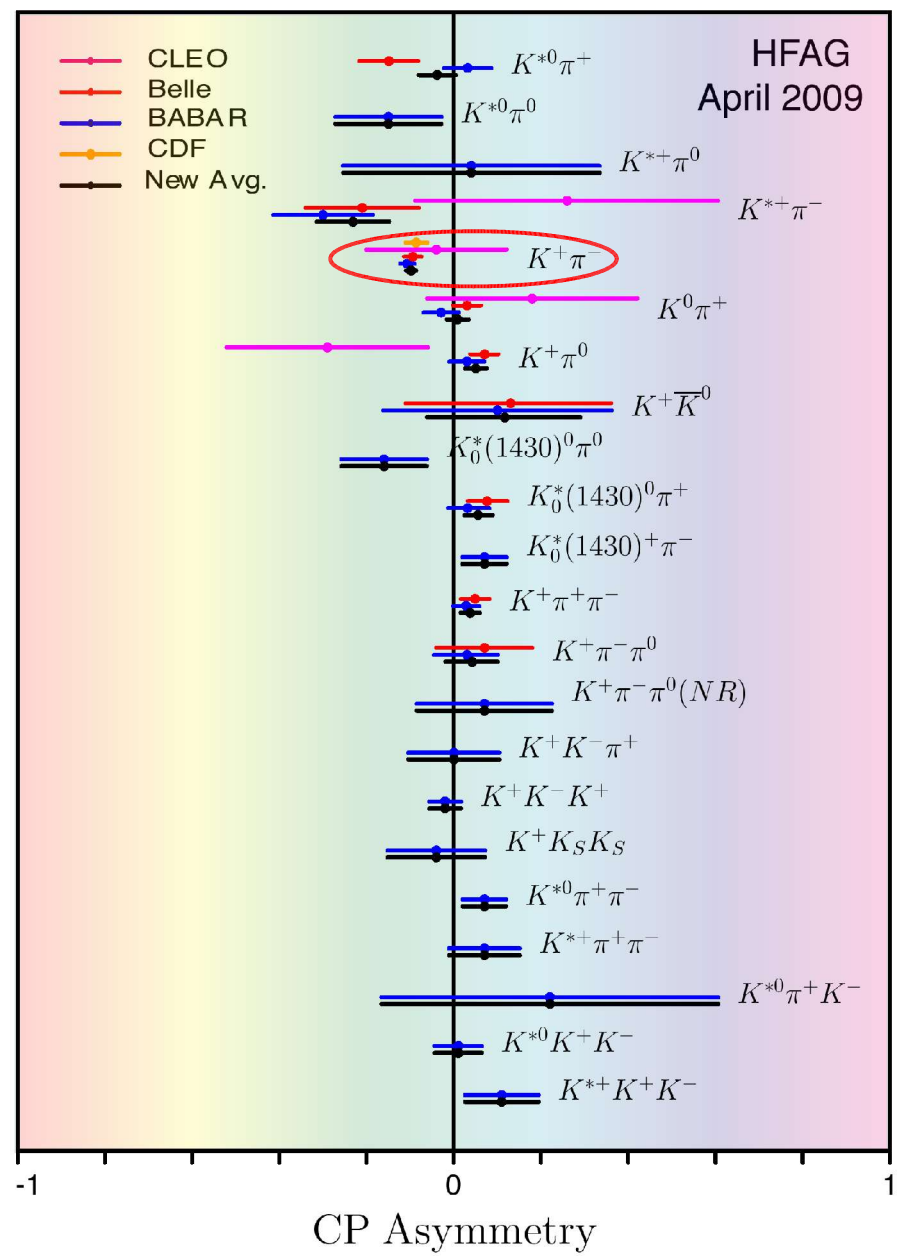


88 modes with >4σ (60 at the time of FPCP06)

Progress beyond the CLEO era



Progress beyond the CLEO era (2)



#BB events:

CLEO 15M

BABAR 467M

Belle <~657M

BABAR and Belle errors are each >10× smaller than CLEO errors. The CDF result is nearly as precise as BABAR and Belle. All are statistics limited. Does CDF have a sample with 4× as many *B*'s? Their A_{CP} measurement would be the most precise!

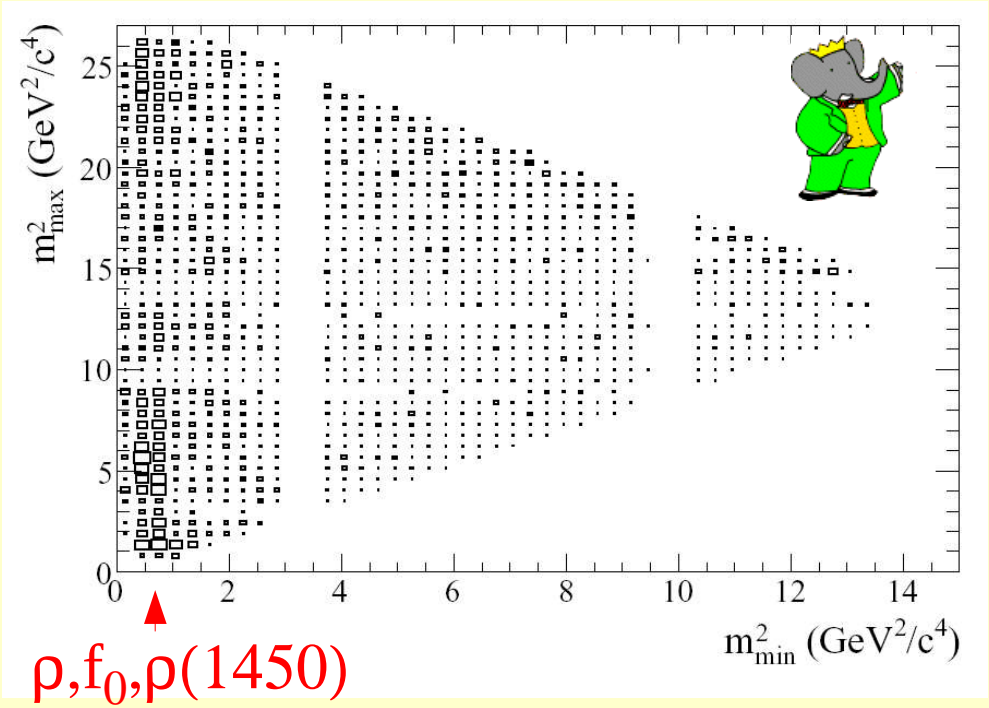
Progress of Charmless B decays in the last decade

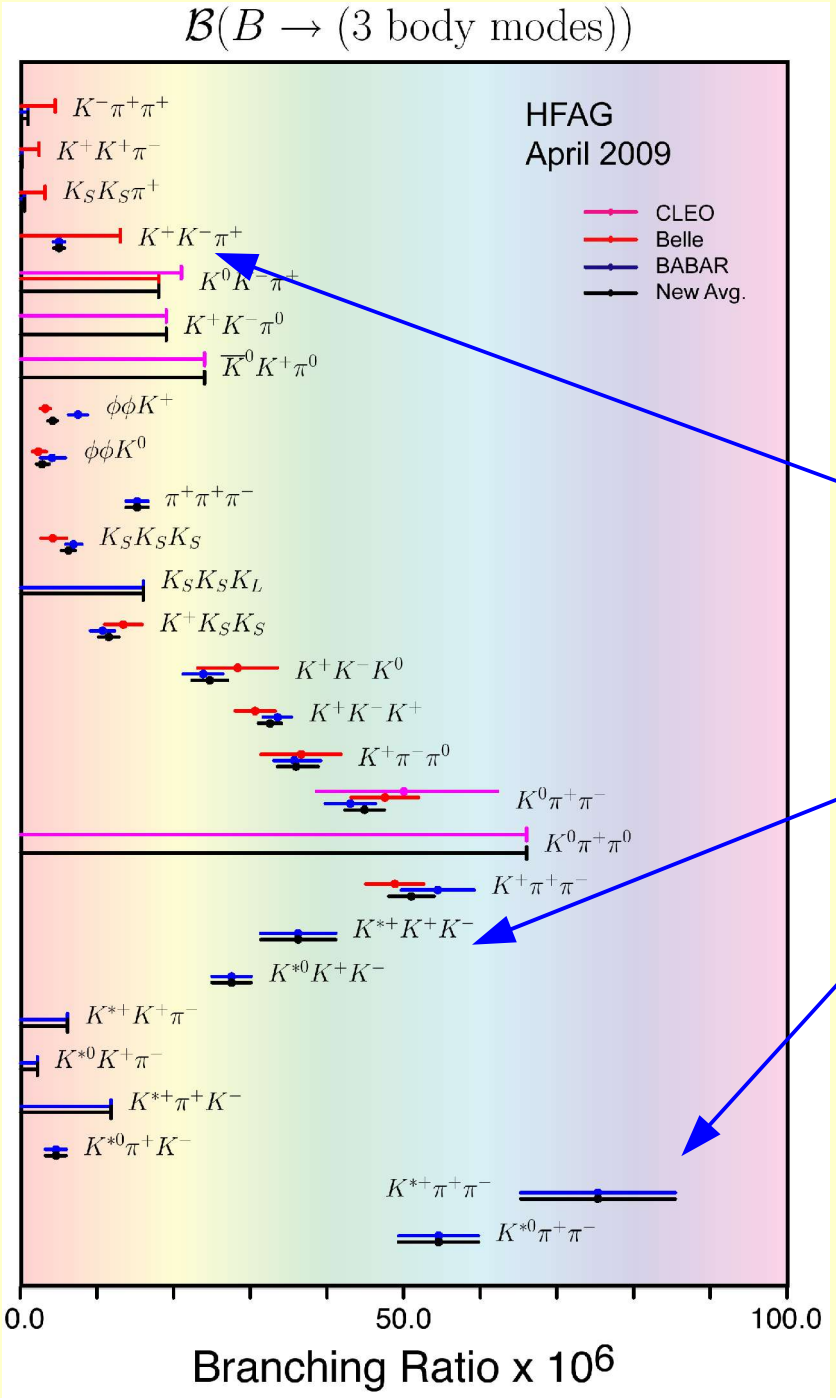
- We now have measurements of:
  - 240 branching fractions
  - 109 A_{CP}
  - 17 f_L (and $f_\perp$ etc for a few modes)
- I will cover all of this in the next 21 minutes...
- This doesn't include 120 Radiative Penguin BFs and 10 B_s BFs.

References for results presented here can be found from the rare HFAG page: http://www.slac.stanford.edu/xorg/hfag/rare/index.html

3-body *B* decays

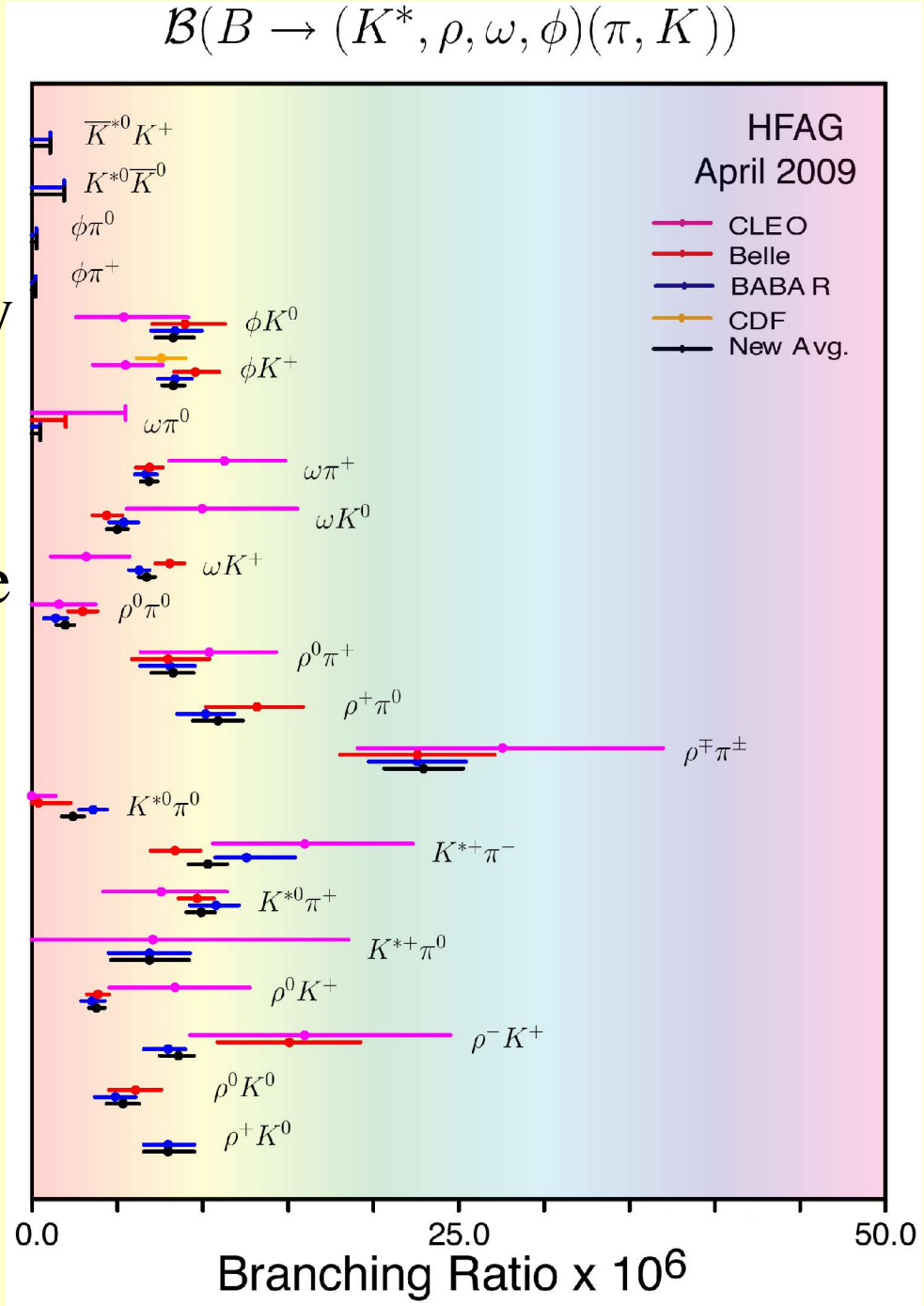
- Belle pioneered the early work but BABAR has caught up. There are now complete Dalitz analyses of 7 decays ($K\pi\pi^0$, $K^0\pi\pi$, K^0KK, $K\pi\pi$, KKK, $\pi\pi\pi$, $\pi\pi\pi^0$), most done by both experiments.
- 9 other decays have now been observed
- Most recent is $\pi\pi\pi$ from BABAR:





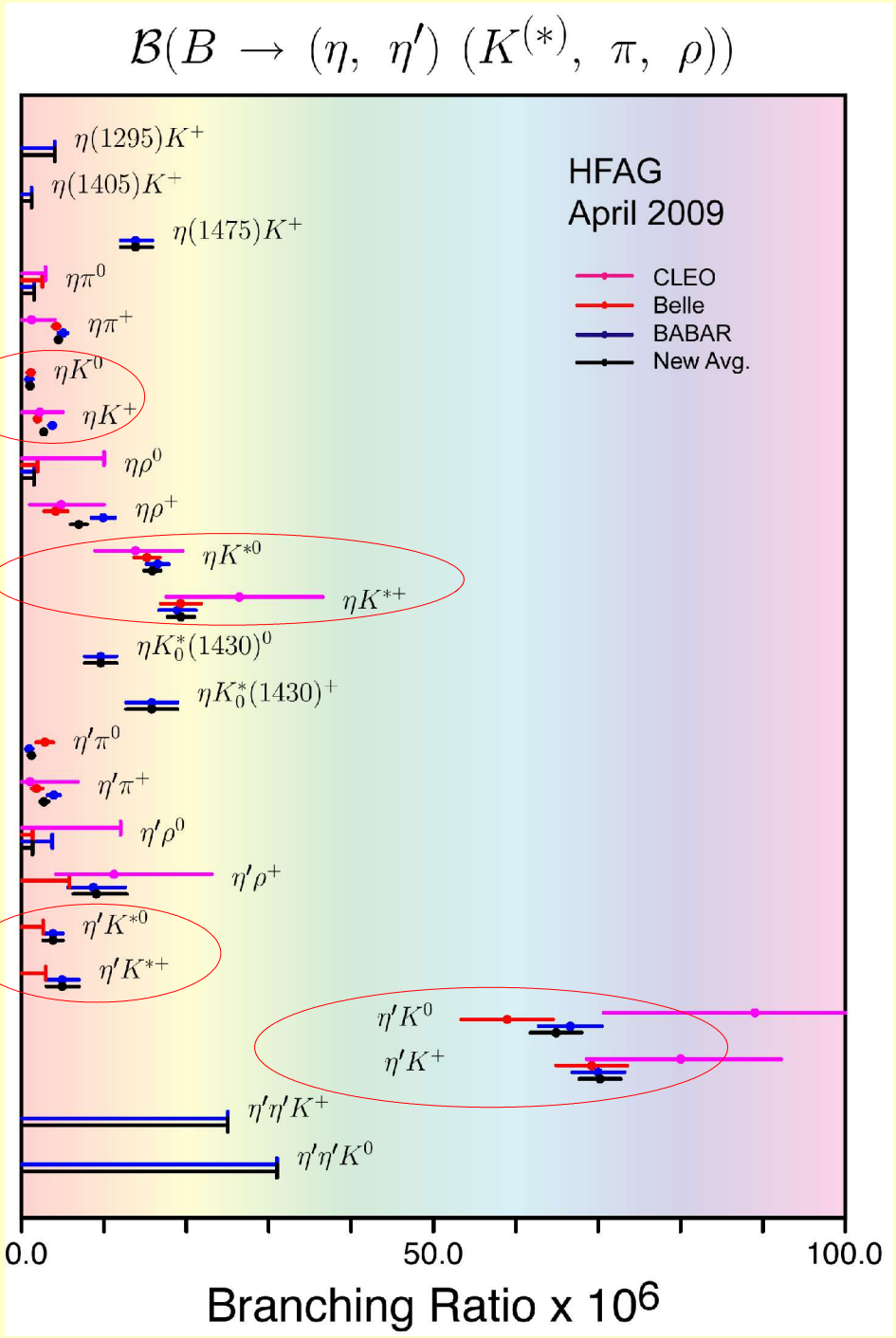
- Many modes now seen
- "New frontiers"
  - Modes with even number of kaons are unexpectedly large
  - K^*KK and $K^*\pi\pi$ have very large BRs but still pretty much unexplored both experimentally and theoretically.

- Most 3-body modes are dominated by quasi-2-body final states.
- Here we show the *PV* modes which tend to be the largest.
  - Almost all charge states of these modes are now seen!



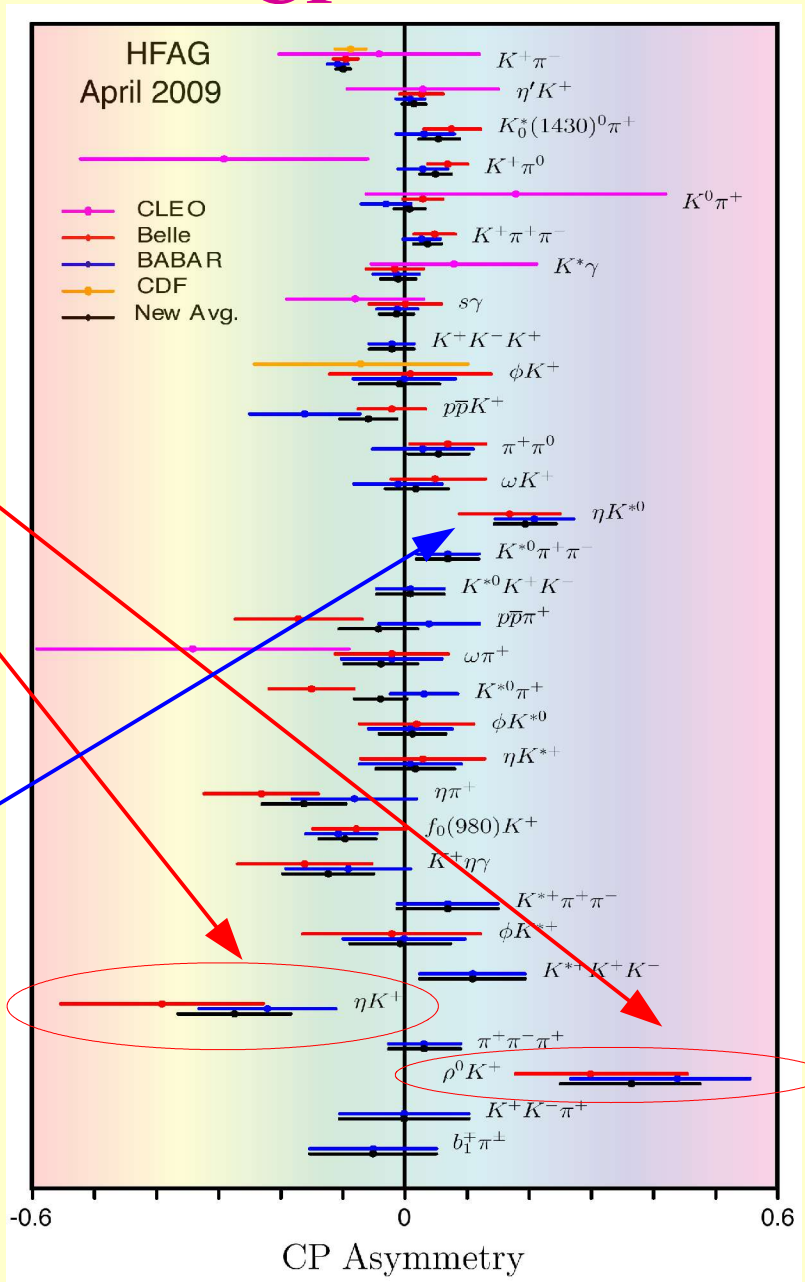
$B \to \eta^{(\prime)} K,\ \eta^{(\prime)} \pi,\ \eta^{(\prime)} K^*,\ \eta^{(\prime)} \rho$

- $B \to \eta' K$ unexpectedly large (CLEO '97)
  - Now understood? Interference between two dominant penguin diagrams (Lipkin '91) plus enhancements from m_s, form factors, higher-order in α_s [Beneke&Neubert, NPB 651, 225 (2003).]
  - Also predicts
    - $B \to \eta K^*$ large
    - $B \to \eta K$ small
    - $B \to \eta' K^*$ small
- Little new in the last year


$\mathcal{B}(B \to (\eta,\ \eta')\ (K^{(*)},\ \pi,\ \rho))$
HFAG
April 2009
CLEO
Belle
BABAR
New Avg.
$\eta(1295)K^+$
$\eta(1405)K^+$
$\eta(1475)K^+$
$\eta\pi^0$
$\eta\pi^+$
ηK^0
ηK^+
$\eta\rho^0$
$\eta\rho^+$
ηK^{*0}
ηK^{*+}
$\eta K_0^*(1430)^0$
$\eta K_0^*(1430)^+$
$\eta'\pi^0$
$\eta'\pi^+$
$\eta'\rho^0$
$\eta'\rho^+$
$\eta' K^{*0}$
$\eta' K^{*+}$
$\eta' K^0$
$\eta' K^+$
$\eta'\eta' K^+$
$\eta'\eta' K^0$
0.0
50.0
100.0
Branching Ratio x 10^6

What about A_{CP}?

- >30 measurements with a precision of 0.10 or better
- Two modes (other than $K^+\pi^-$) now 3-4σ for the WA.
  - This is expected for $B \to \eta K$ due to the small BR (tree and penguin amplitudes similar in size ⇒ large interference)
- One other mode not expected to be large – experimental fluctuation?



B→VV decays

- Helicity conservation arguments ⇒ $f_L \approx 1$
  - $f_L \approx 1 - m_V^2/m_B^2 \approx 0.98$ for ρρ
  - Expected to be true for both tree and penguins
- ρρ, ωρ are tree-dominated
- ϕK^*, ρK^*, ωK^* are penguin-dominated
  - $f_L \approx$ 0.50 for ϕK^* (Belle/BABAR uncertainty now ~0.04!)
    - Not completely understood but improving
      - Enhanced annihilation and non-factorizable contributions:

        Beneke, Rohrer, D.-S. Yang, NPB774, 64 (2007);

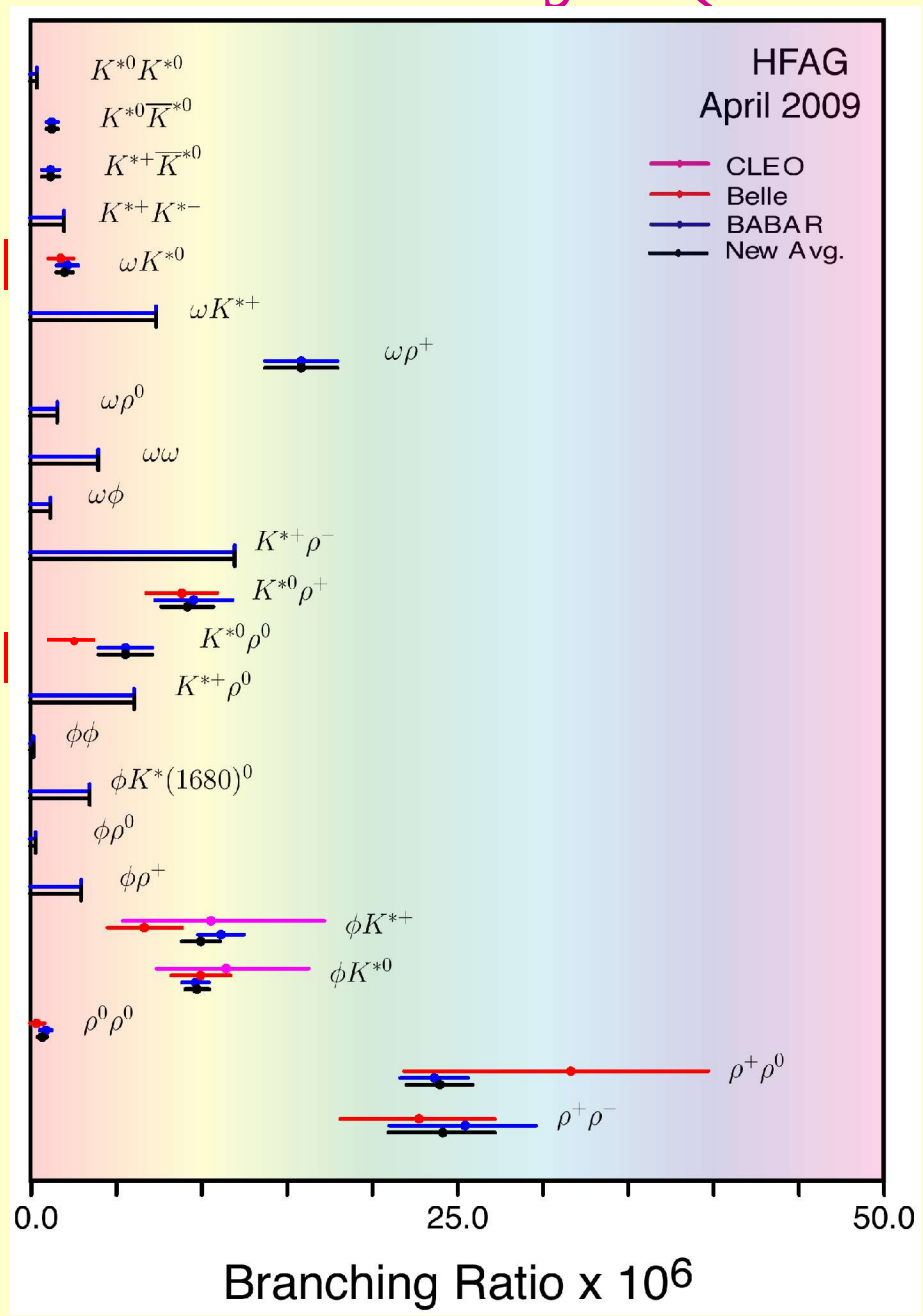
        Cheng&K.-C. Yang, PRD 78, 094001 (2008).
      - Final-state interactions
      - New physics
  - What about ρK^*, ωK^*? $f_L \approx 1$ or 0.5?

B→VV decays (cont.)

New Belle results

New BABAR results

Talk by Bill Gary yesterday



B→VV predictions

Cheng&Yang, PRD 78, 094001 (2008).

Decay	$\mathcal{B}$		f_L		$f_\perp$	
	Theory	Expt	Theory	Expt	Theory	Expt
$B^- \to \rho^- \rho^0$	$20.0^{+4.0+2.0}_{-1.9-0.9}$	18.2 ± 3.0	$0.96^{+0.02}_{-0.02}$	$0.912^{+0.044}_{-0.045}$	0.02 ± 0.01	
$\overline{B}^0 \to \rho^+ \rho^-$	$25.5^{+1.5+2.4}_{-2.6-1.5}$	$24.2^{+3.1}_{-3.2}$	$0.92^{+0.01}_{-0.02}$	$0.978^{+0.025}_{-0.022}$	$0.04^{+0.01}_{-0.00}$	
$\overline{B}^0 \to \rho^0 \rho^0$	$0.9^{+1.5+1.1}_{-0.4-0.2}$	0.68 ± 0.27	$0.92^{+0.06}_{-0.36}$	0.70 ± 0.15	$0.04^{+0.14}_{-0.03}$	
$B^- \to \rho^- \omega$	$19.2^{+3.3+1.7}_{-1.6-1.0}$	$10.6^{+2.6}_{-2.3}$	$0.96^{+0.02}_{-0.02}$	0.82 ± 0.11	0.02 ± 0.01	
$\overline{B}^0 \to \rho^0 \omega$	$0.1^{+0.1+0.4}_{-0.1-0.0}$	< 1.5	$0.55^{+0.47}_{-0.29}$		$0.22^{+0.16}_{-0.23}$	
$B^- \to \bar{K}^{*0} \rho^-$ [a]	$9.2^{+1.2+3.6}_{-1.1-5.4}$	9.2 ± 1.5	$0.48^{+0.52}_{-0.40}$	0.48 ± 0.08	$0.26^{+0.20}_{-0.26}$	
$B^- \to K^{*-} \rho^0$	$5.5^{+0.6+1.3}_{-0.5-2.5}$	< 6.1	$0.67^{+0.31}_{-0.48}$	$0.96^{+0.06}_{-0.16}$ [b]	$0.16^{+0.24}_{-0.15}$	
$\overline{B}^0 \to K^{*-} \rho^+$	$8.9^{+1.1+4.8}_{-1.0-5.5}$	< 12	$0.53^{+0.45}_{-0.32}$		$0.24^{+0.16}_{-0.22}$	
$\overline{B}^0 \to \bar{K}^{*0} \rho^0$	$4.6^{+0.6+3.5}_{-0.5-3.5}$	5.6 ± 1.6	$0.39^{+0.60}_{-0.31}$	0.57 ± 0.12	$0.30^{+0.15}_{-0.30}$	
$B^- \to K^{*-} \phi$ [c]	$10.0^{+1.4+12.3}_{-1.3-\ 6.1}$	10.0 ± 1.1	$0.49^{+0.51}_{-0.42}$	0.50 ± 0.05	$0.25^{+0.21}_{-0.25}$	0.20 ± 0.05
$\overline{B}^0 \to \bar{K}^{*0} \phi$	$9.5^{+1.3+11.9}_{-1.2-\ 5.9}$	9.5 ± 0.8	$0.50^{+0.50}_{-0.42}$	0.484 ± 0.034	$0.25^{+0.21}_{-0.25}$	0.256 ± 0.032
$B^- \to K^{*-} \omega$	$3.5^{+0.4+3.0}_{-0.4-1.7}$	< 3.4	$0.66^{+0.32}_{-0.38}$		$0.17^{+0.20}_{-0.17}$	
$\overline{B}^0 \to \bar{K}^{*0} \omega$	$3.0^{+0.5+2.9}_{-0.4-1.8}$	< 2.7	$0.57^{+0.44}_{-0.46}$		$0.21^{+0.25}_{-0.22}$	
$B^- \to K^{*0} K^{*-}$	$0.6^{+0.1+0.3}_{-0.1-0.3}$	< 71	$0.45^{+0.55}_{-0.38}$		$0.27^{+0.19}_{-0.27}$	
$\overline{B}^0 \to K^{*-} K^{*+}$	$0.1^{+0.0+0.1}_{-0.0-0.1}$	< 141	1		0	
$\overline{B}^0 \to K^{*0} \bar{K}^{*0}$	$0.6^{+0.1+0.2}_{-0.1-0.3}$	$1.28^{+0.37}_{-0.32}$	$0.52^{+0.48}_{-0.48}$	$0.80^{+0.12}_{-0.13}$	$0.24^{+0.24}_{-0.24}$	

Free parameters in the models taken from experiment

B→VV predictions

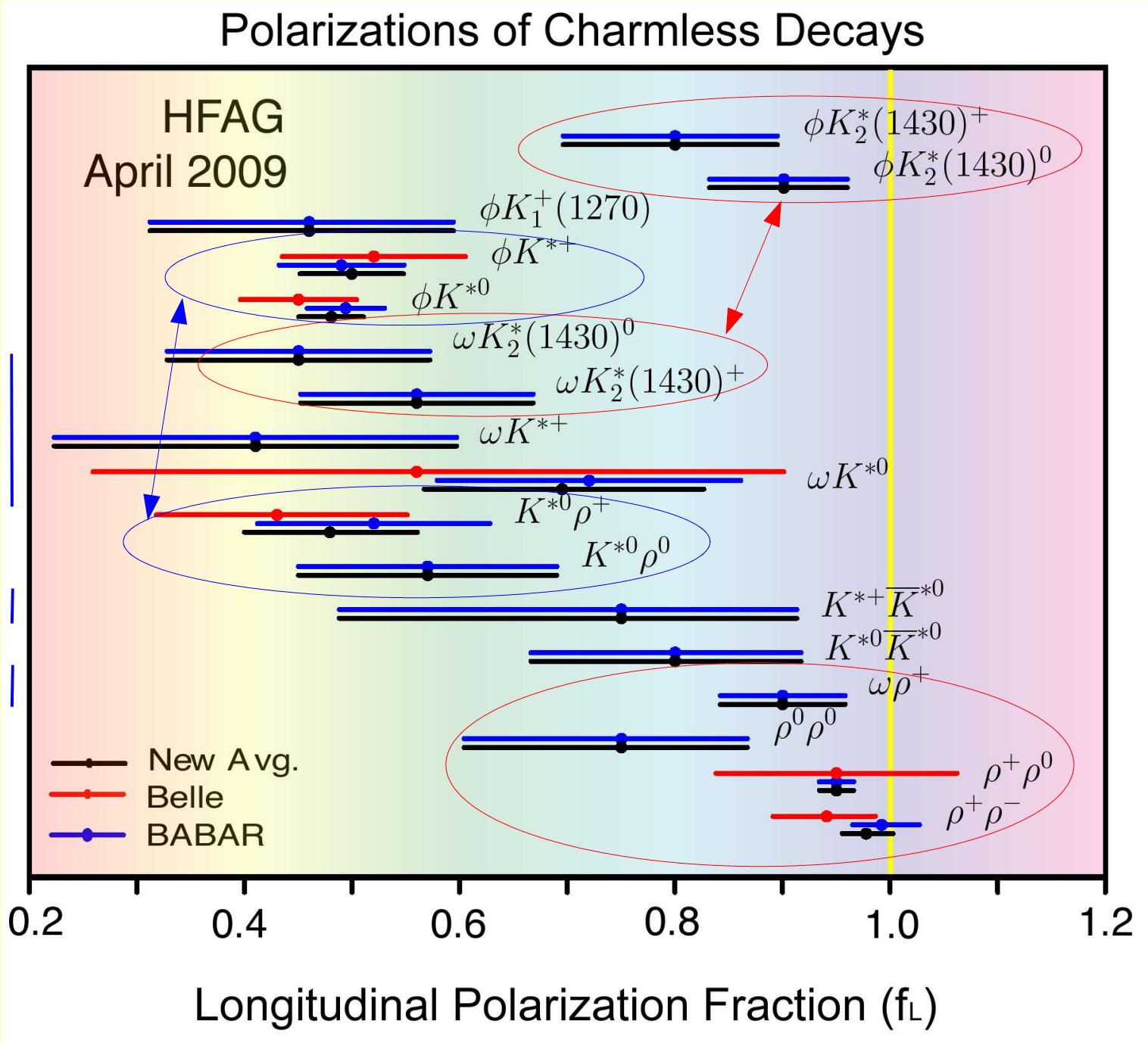
Cheng&Yang, PRD 78, 094001 (2008).

Decay	$\mathcal{B}$		f_L		$f_\perp$	
	Theory	Expt	Theory	Expt	Theory	Expt
$B^- \to \rho^- \rho^0$	$20.0^{+4.0+2.0}_{-1.9-0.9}$	24.0±2.0	$0.96^{+0.02}_{-0.02}$	0.950±0.016	0.02 ± 0.01	
$\overline{B}^0 \to \rho^+ \rho^-$	$25.5^{+1.5+2.4}_{-2.6-1.5}$	$24.2^{+3.1}_{-3.2}$	$0.92^{+0.01}_{-0.02}$	$0.978^{+0.025}_{-0.022}$	$0.04^{+0.01}_{-0.00}$	
$\overline{B}^0 \to \rho^0 \rho^0$	$0.9^{+1.5+1.1}_{-0.4-0.2}$	0.68 ± 0.27	$0.92^{+0.06}_{-0.36}$	0.70 ± 0.15	$0.04^{+0.14}_{-0.03}$	
$B^- \to \rho^- \omega$	$19.2^{+3.3+1.7}_{-1.6-1.0}$	15.9±2.1	$0.96^{+0.02}_{-0.02}$	0.90±0.06	0.02 ± 0.01	
$\overline{B}^0 \to \rho^0 \omega$	$0.1^{+0.1+0.4}_{-0.1-0.0}$	< 1.5	$0.55^{+0.47}_{-0.29}$		$0.22^{+0.16}_{-0.23}$	
$B^- \to \bar{K}^{*0} \rho^-$ [a]	$9.2^{+1.2+3.6}_{-1.1-5.4}$	9.2 ± 1.5	$0.48^{+0.52}_{-0.40}$	0.48 ± 0.08	$0.26^{+0.20}_{-0.26}$	
$B^- \to K^{*-} \rho^0$	$5.5^{+0.6+1.3}_{-0.5-2.5}$	< 6.1	$0.67^{+0.31}_{-0.48}$	$0.96^{+0.06}_{-0.16}$ [b]	$0.16^{+0.24}_{-0.15}$	
$\overline{B}^0 \to K^{*-} \rho^+$	$8.9^{+1.1+4.8}_{-1.0-5.5}$	< 12	$0.53^{+0.45}_{-0.32}$		$0.24^{+0.16}_{-0.22}$	
$\overline{B}^0 \to \bar{K}^{*0} \rho^0$	$4.6^{+0.6+3.5}_{-0.5-3.5}$	3.4±1.0	$0.39^{+0.60}_{-0.31}$	0.57 ± 0.12	$0.30^{+0.15}_{-0.30}$	
$B^- \to K^{*-} \phi$ [c]	$10.0^{+1.4+12.3}_{-1.3-\ 6.1}$	10.0 ± 1.1	$0.49^{+0.51}_{-0.42}$	0.50 ± 0.05	$0.25^{+0.21}_{-0.25}$	0.20 ± 0.05
$\overline{B}^0 \to \bar{K}^{*0} \phi$	$9.5^{+1.3+11.9}_{-1.2-\ 5.9}$	9.5 ± 0.8	$0.50^{+0.50}_{-0.42}$	0.484 ± 0.034	$0.25^{+0.21}_{-0.25}$	0.256 ± 0.032
$B^- \to K^{*-} \omega$	$3.5^{+0.4+3.0}_{-0.4-1.7}$	<7.4	$0.66^{+0.32}_{-0.38}$		$0.17^{+0.20}_{-0.17}$	
$\overline{B}^0 \to \bar{K}^{*0} \omega$	$3.0^{+0.5+2.9}_{-0.4-1.8}$	2.0±0.5	$0.57^{+0.44}_{-0.46}$	0.70±0.13	$0.21^{+0.25}_{-0.22}$	
$B^- \to K^{*0} K^{*-}$	$0.6^{+0.1+0.3}_{-0.1-0.3}$	1.2±0.5	$0.45^{+0.55}_{-0.38}$	$0.75^{+0.16}_{-0.26}$	$0.27^{+0.19}_{-0.27}$	
$\overline{B}^0 \to K^{*-} K^{*+}$	$0.1^{+0.0+0.1}_{-0.0-0.1}$	<2.0	1		0	
$\overline{B}^0 \to K^{*0} \bar{K}^{*0}$	$0.6^{+0.1+0.2}_{-0.1-0.3}$	$1.28^{+0.37}_{-0.32}$	$0.52^{+0.48}_{-0.48}$	$0.80^{+0.12}_{-0.13}$	$0.24^{+0.24}_{-0.24}$	

Free parameters in the models taken from experiment

Excellent agreement

New BABAR results



$B \to VV$ decays (cont.)

- Modes like ρK^*, ωK^* tend to $f_L \approx 0.5$ like ϕK^* ✓
- New measurements of VT modes from BABAR
  - No theory predictions!
  - f_L for $\omega K_2(1430)^*$ and $\phi K_2(1430)^*$ don't agree - why??
- Our understanding of VV decays is clearly incomplete

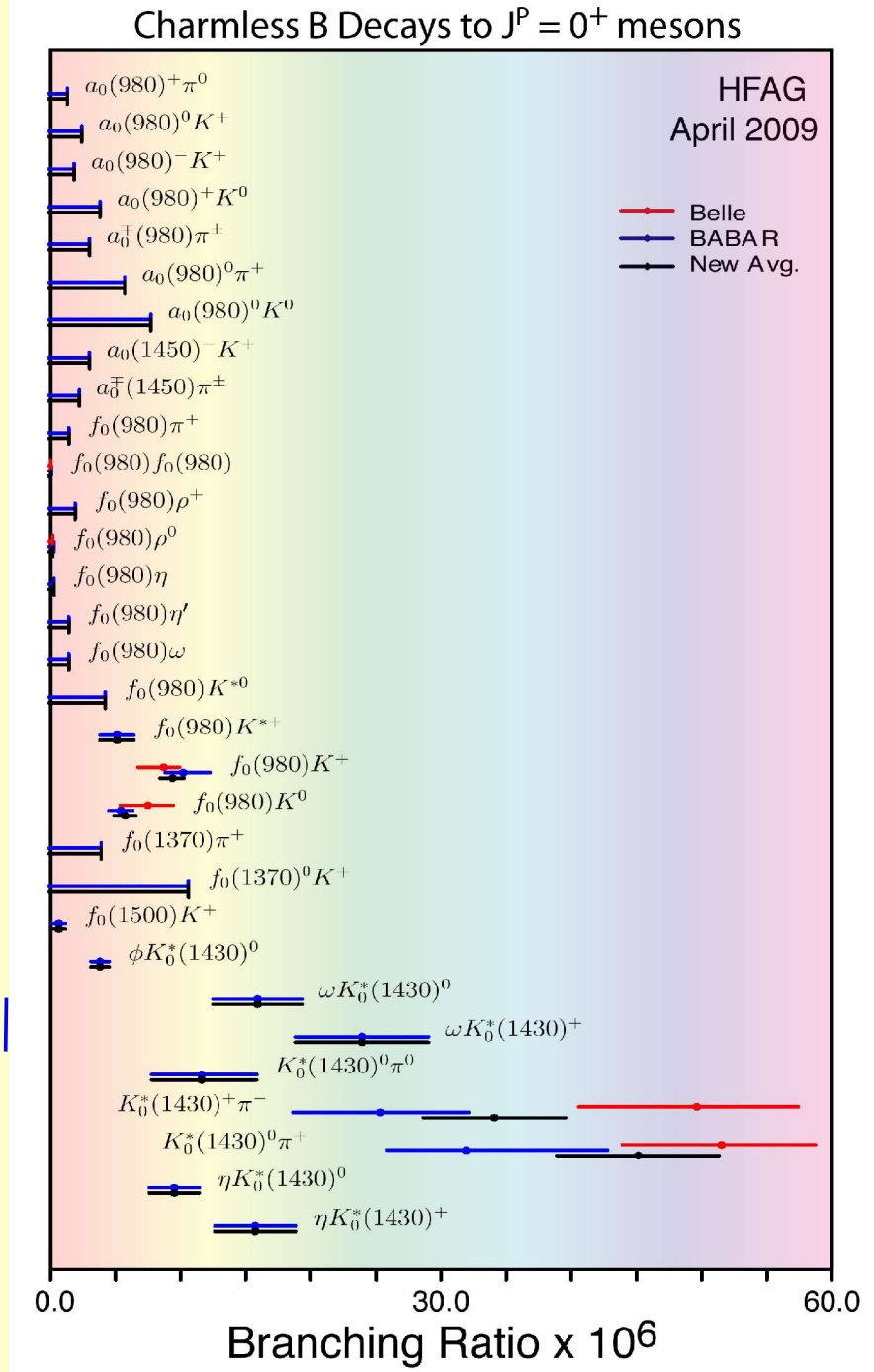
Decays involving 0^+, 1^+, 2^+ mesons

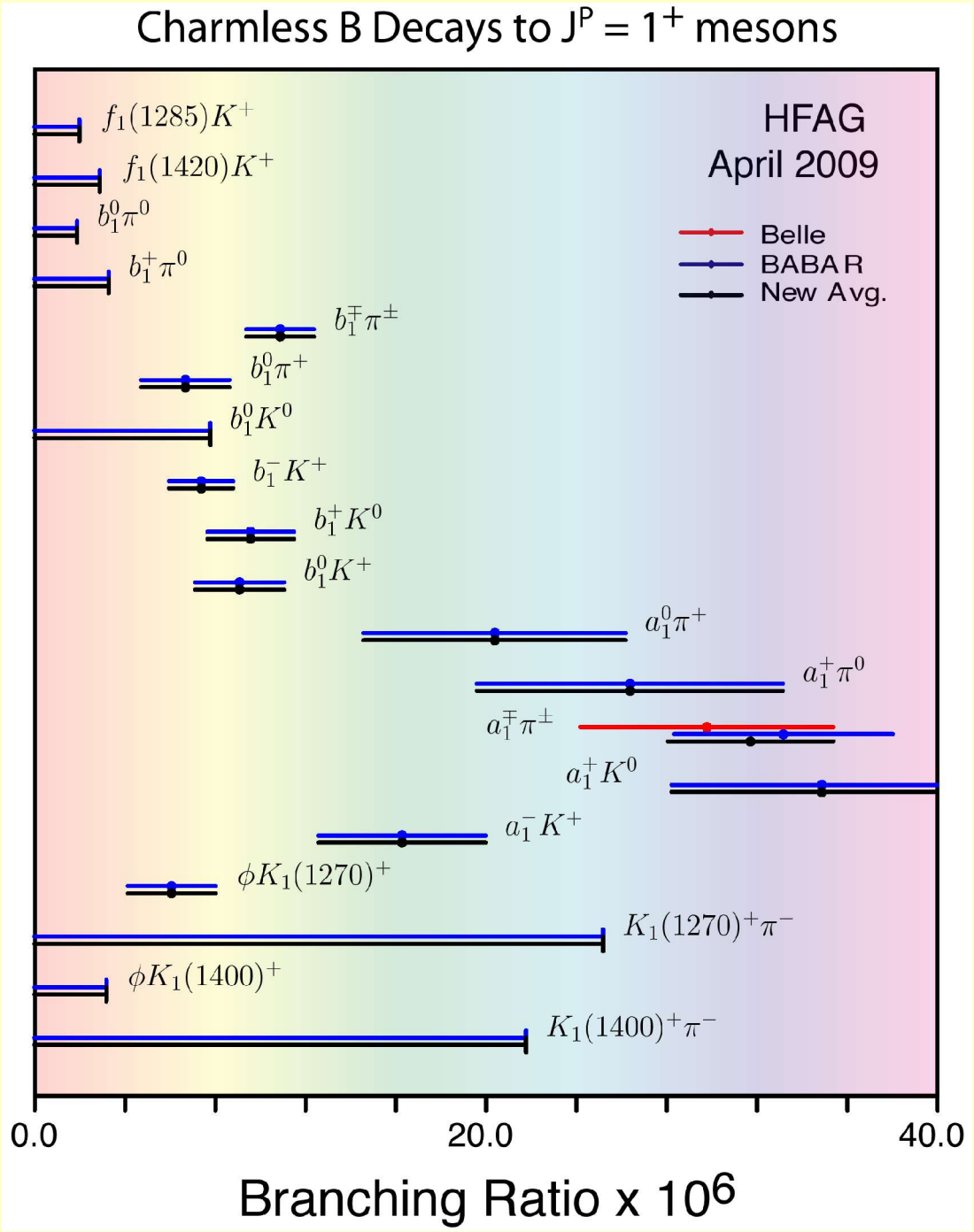
- Little is known about the scalar, axialvector, and tensor mesons: a_0, f_0, $K^*_0(1430)$, a_1, b_1, K_1, f_2, $K^*_2(1430)$
  - There have been few reliable predictions for *B* decays to such particles but this is beginning to change
  - We can learn about *B* decays and also more about these even-parity mesons
- Experimental results have exploded in the past 2-3 years, with most results coming from BABAR
  - Many branching fractions are large (10-20$\times 10^{-6}$), while some are very large (~50$\times 10^{-6}$)
- Newest addition is 5σ $B^0 \to a_1 a_1$ signal from BABAR:

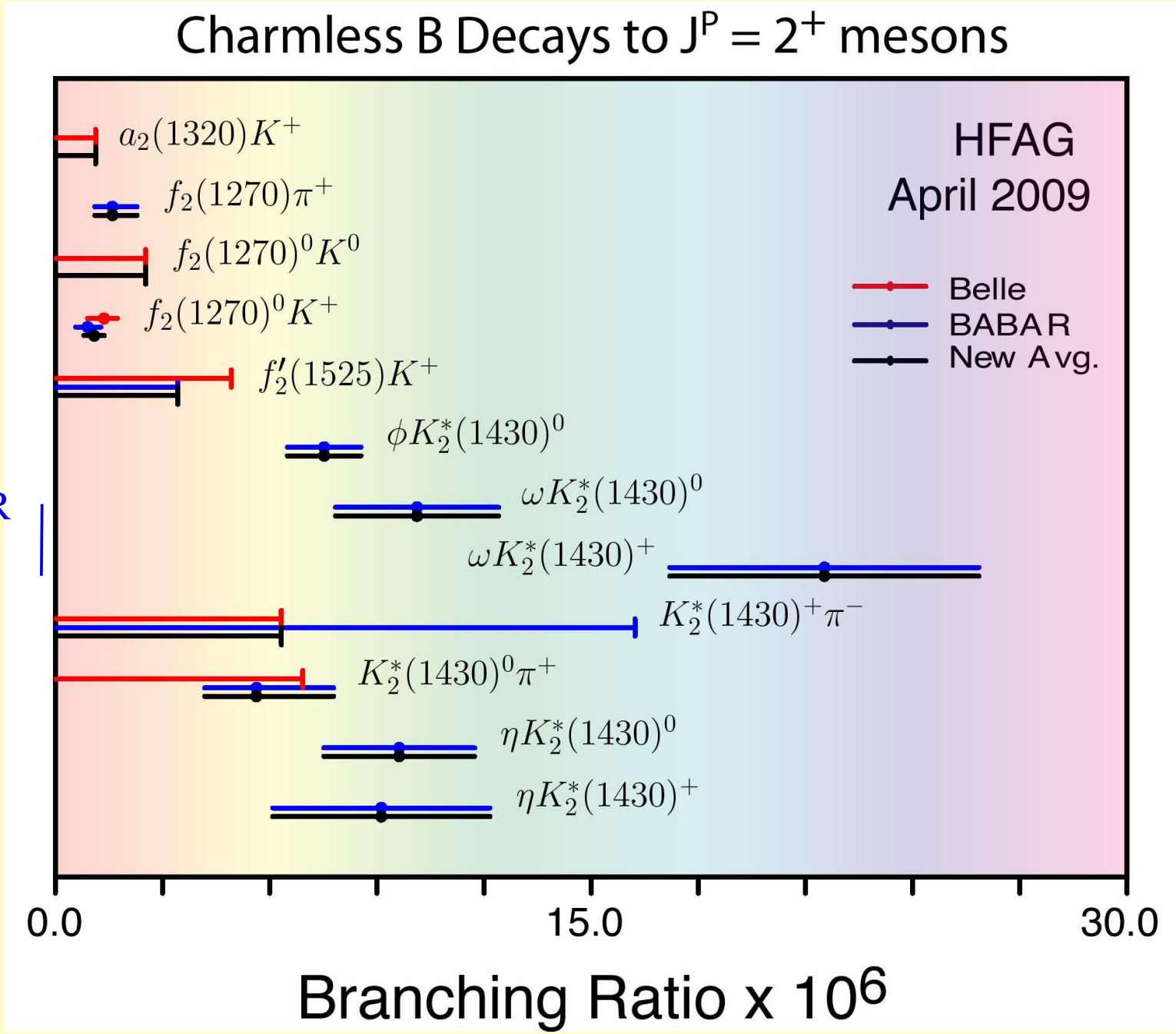
$$\mathcal{B}(B^0 \to a_1(1260)^+ \; a_1(1260)^- \;) = (47.3 \pm 10.5 \pm 6.3) \times 10^{-6}$$

Preliminary (assumes B($a_1 \to \rho\pi$)=100%)

New BABAR results




Charmless B Decays to J^P = 1^+ mesons
HFAG
April 2009
Belle
BABAR
New Avg.
$f_1(1285)K^+$
$f_1(1420)K^+$
$b_1^0\pi^0$
$b_1^+\pi^0$
$b_1^\mp\pi^\pm$
$b_1^0\pi^+$
$b_1^0K^0$
$b_1^-K^+$
$b_1^+K^0$
$b_1^0K^+$
$a_1^0\pi^+$
$a_1^+\pi^0$
$a_1^\mp\pi^\pm$
$a_1^+K^0$
$a_1^-K^+$
$\phi K_1(1270)^+$
$K_1(1270)^+\pi^-$
$\phi K_1(1400)^+$
$K_1(1400)^+\pi^-$
0.0
20.0
40.0
Branching Ratio x 10^6



New BABAR results

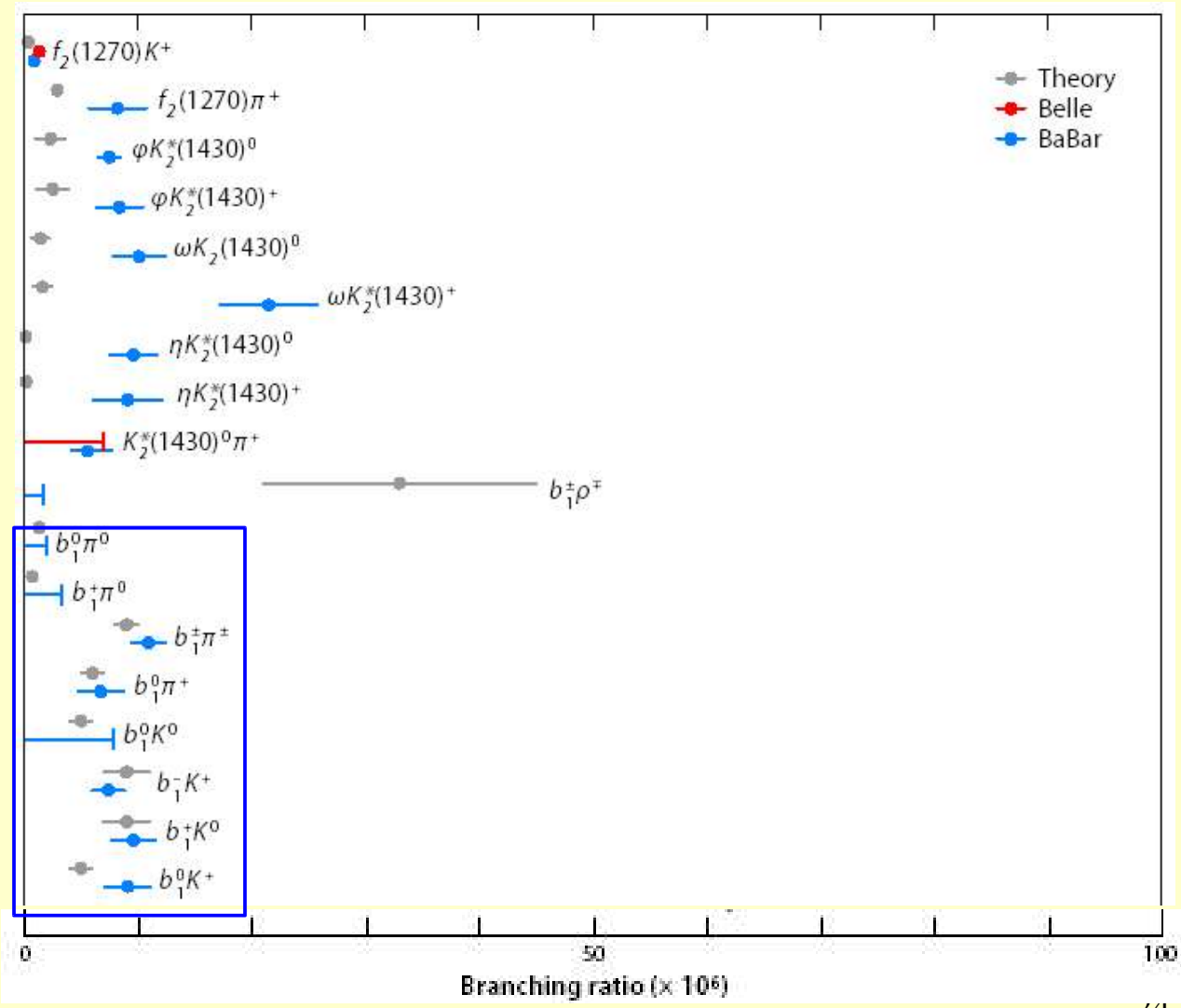
B→AV predictions

Cheng&Yang, PRD 78, 094001 (2008).

Mode	$\mathcal{B}$	f_L	Mode	$\mathcal{B}$	f_L
$\overline{B}^0 \to a_1^+\rho^-$	$23.9^{+10.5+3.2}_{-\ 9.2-0.4}$	$(0.82^{+0.05}_{-0.13})$	$\overline{B}^0 \to b_1^+\rho^-$	$32.1^{+16.5+12.0}_{-14.7-\ 4.6}$	$(0.96^{+0.01}_{-0.02})$
$\overline{B}^0 \to a_1^-\rho^+$	$36.0^{+3.5+3.5}_{-4.0-0.7}$	$(0.84^{+0.02}_{-0.06})$	$\overline{B}^0 \to b_1^-\rho^+$	$0.6^{+0.6+1.9}_{-0.3-0.2}$	$(0.98^{+0.00}_{-0.33})$
$\overline{B}^0 \to a_1^0\rho^0$	$1.2^{+2.0+5.1}_{-0.7-0.3}$	$(0.82^{+0.06}_{-0.68})$	$\overline{B}^0 \to b_1^0\rho^0$	$3.2^{+5.2+1.7}_{-2.0-0.4}$	$(0.99^{+0.00}_{-0.18})$
$B^- \to a_1^0\rho^-$	$17.8^{+10.1+3.1}_{-\ 6.4-0.2}$	$(0.91^{+0.03}_{-0.10})$	$B^- \to b_1^0\rho^-$	$29.1^{+16.2+5.4}_{-10.6-5.9}$	$(0.96^{+0.01}_{-0.06})$
$B^- \to a_1^-\rho^0$	$23.2^{+3.6+4.8}_{-2.9-0.1}$	$(0.89^{+0.11}_{-0.18})$	$B^- \to b_1^-\rho^0$	$0.9^{+1.7+2.6}_{-0.6-0.5}$	$(0.90^{+0.05}_{-0.38})$
$\overline{B}^0 \to a_1^0\omega$	$0.2^{+0.1+0.4}_{-0.1-0.0}$	$(0.75^{+0.11}_{-0.65})$	$\overline{B}^0 \to b_1^0\omega$	$0.1^{+0.2+1.6}_{-0.0-0.0}$	$(0.04^{+0.96}_{-0.00})$
$B^- \to a_1^-\omega$	$22.5^{+3.4+3.0}_{-2.7-0.7}$	$(0.88^{+0.10}_{-0.14})$	$B^- \to b_1^-\omega$	$0.8^{+1.4+3.1}_{-0.5-0.3}$	$(0.91^{+0.07}_{-0.33})$
$\overline{B}^0 \to a_1^0\phi$	$0.002^{+0.002+0.009}_{-0.001-0.000}$	$(0.94^{+0.00}_{-0.69})$	$\overline{B}^0 \to b_1^0\phi$	$0.01^{+0.01+0.01}_{-0.00-0.00}$	$(0.98^{+0.01}_{-0.33})$
$B^- \to a_1^-\phi$	$0.01^{+0.01+0.04}_{-0.00-0.00}$	$(0.94^{+0.01}_{-0.69})$	$B^- \to b_1^-\phi$	$0.02^{+0.02+0.03}_{-0.01-0.00}$	$(0.98^{+0.01}_{-0.33})$
$\overline{B}^0 \to a_1^+K^{*-}$	$10.6^{+5.7+31.7}_{-4.0-\ 8.1}$	$(0.37^{+0.39}_{-0.29})$	$\overline{B}^0 \to b_1^+K^{*-}$	$12.5^{+4.7+20.1}_{-3.7-\ 9.0}$	$(0.82^{+0.18}_{-0.41})$
$\overline{B}^0 \to a_1^0\overline{K}^{*0}$	$4.2^{+2.8+15.5}_{-1.9-4.2}$	$(0.23^{+0.45}_{-0.19})$	$\overline{B}^0 \to b_1^0\overline{K}^{*0}$	$6.4^{+2.4+8.8}_{-1.7-4.8}$	$(0.79^{+0.21}_{-0.73})$
$B^- \to a_1^-\overline{K}^{*0}$	$11.2^{+6.1+31.9}_{-4.4-\ 9.0}$	$(0.37^{+0.48}_{-0.37})$	$B^- \to b_1^-\overline{K}^{*0}$	$12.8^{+5.0+20.1}_{-3.8-\ 9.6}$	$(0.79^{+0.21}_{-0.74})$
$B^- \to a_1^0K^{*-}$	$7.8^{+3.2+16.3}_{-2.5-\ 4.3}$	$(0.52^{+0.41}_{-0.42})$	$B^- \to b_1^0K^{*-}$	$7.0^{+2.6+12.0}_{-2.0-\ 4.8}$	$(0.82^{+0.16}_{-0.26})$

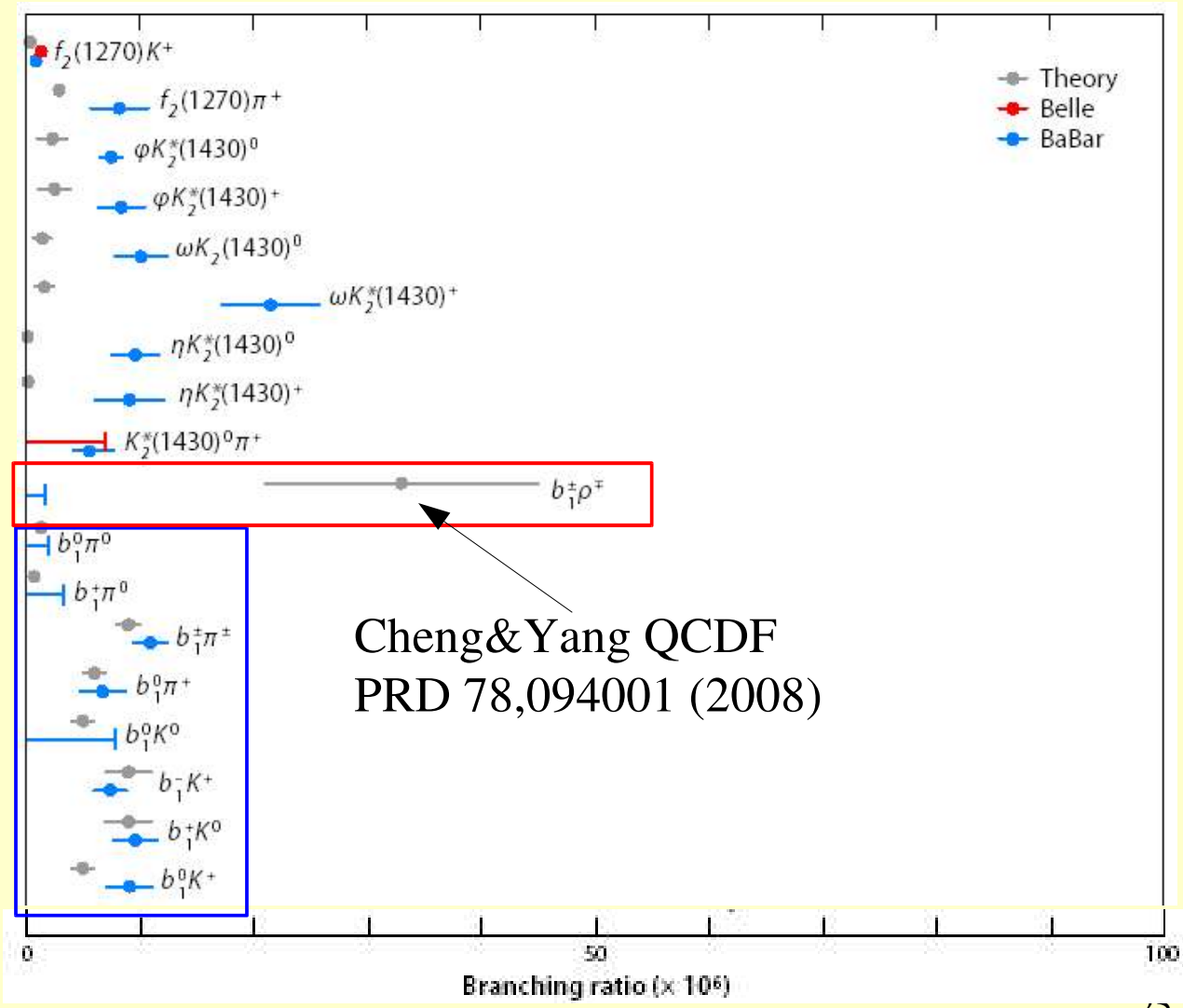
Status of modes with a b_1 meson

- Expt. and theory agree very well for $b_1\pi$ and b_1K



Status of modes with a b_1 meson

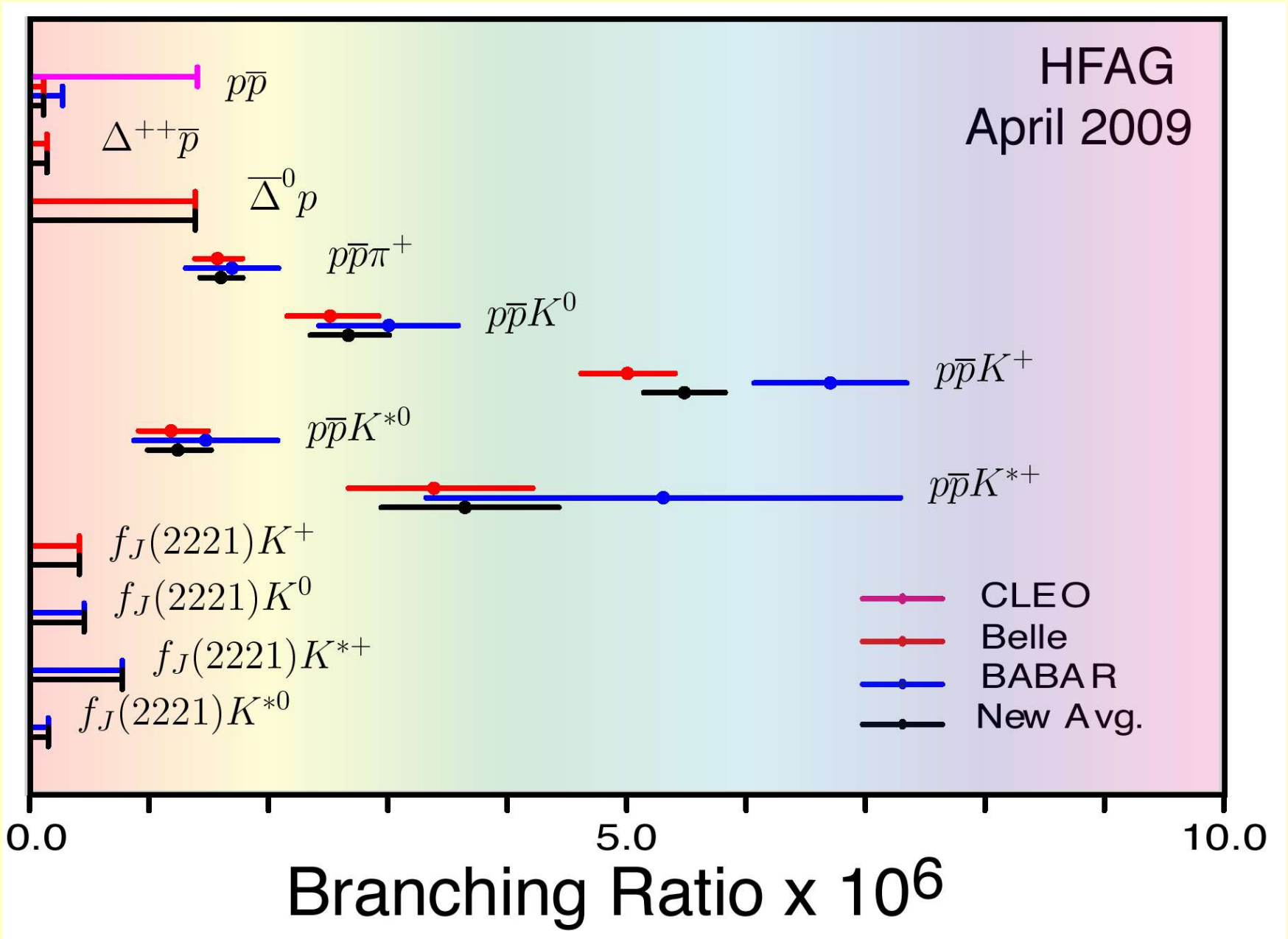
- Expt. and theory agree very well for $b_1\pi$ and b_1K but very badly for $b_1\rho$?



Decays with baryons

- Interesting field with features such as threshold enhancements, angular correlations
- Dominated by 3-body decays
  - 2-body decays $p\bar{p}$ and $\Lambda\Lambda$ not yet seen
- Belle has led the way with many results
- BABAR catching up for non-strange modes but only Belle has done most of the strange modes
- Angular correlation effects are not understood

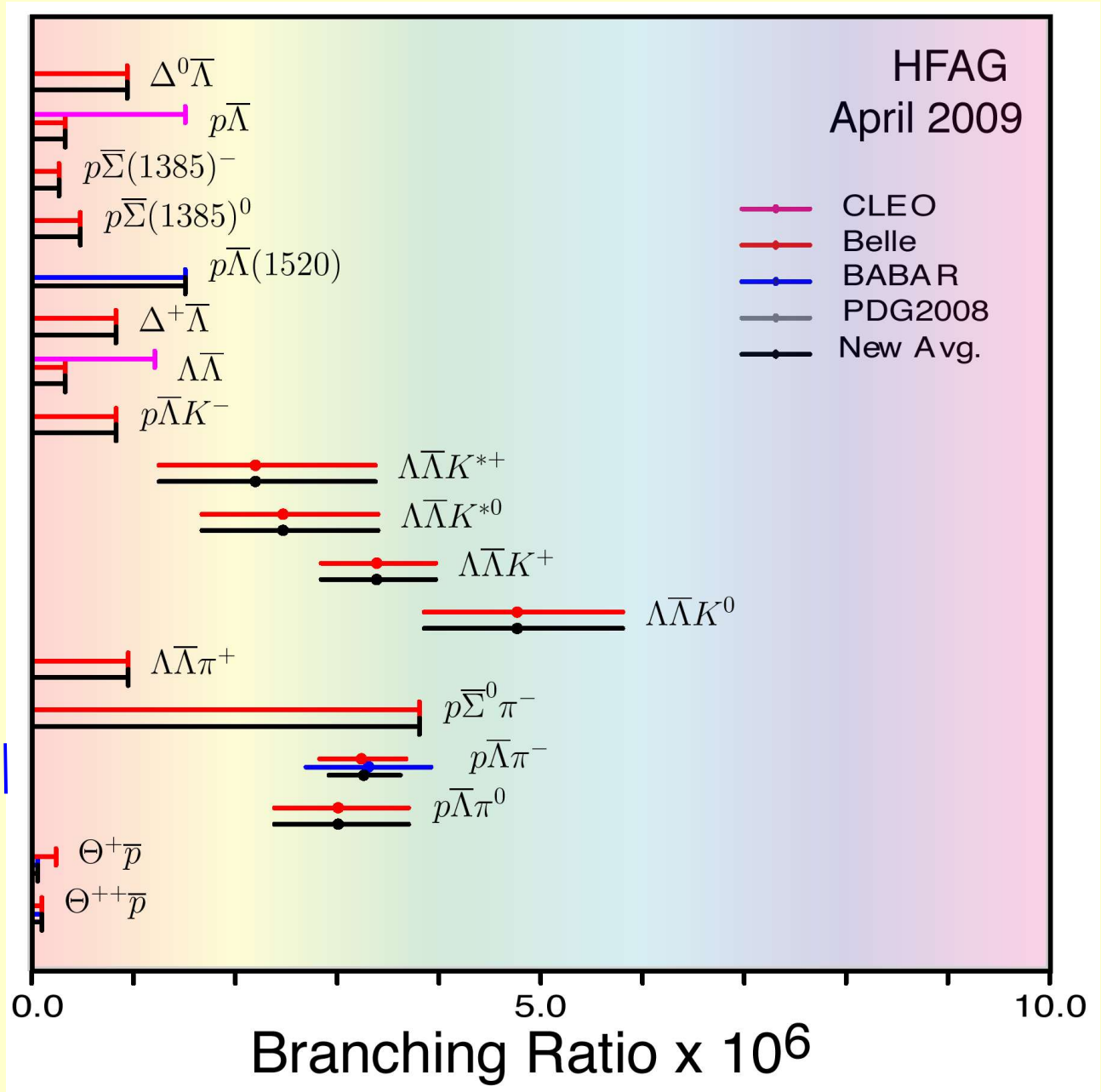
Non-strange baryonic modes



Strange baryonic modes

New Belle results

New BABAR result



Summary

- Charmless *B* decays is now a mature field
  - Many results for the full final sample from BABAR
  - Some new Belle analyses with >650M $B\bar{B}$ events
  - Little new for 2-body or $B \to \eta' K$ etc.
  - Many Dalitz plot analyses of 3-body decays
  - VV decays very interesting
    - f_L for ωK^{*0}, ρK^{*0} compatible with ϕK^* ($f_L \sim 0.5$)
    - More precise measurements needed
    - Polarization puzzle for VT decays emerging?
  - Lots of measurements with 0^+, 1^+, 2^+ mesons
    - But relatively few theoretical predictions
    - What can we learn from these decays?
  - Many measurements for baryonic decays but some unresolved issues

Backup slides