Flavor Physics and CP Violation at LHCb

Hai-Yang Cheng (鄭海揚)

Academia Sinica, Taipei

1st **Int. Workshop on LHC Era Physics**

Nanning, Nov 15-19, 2010

LHCb is designed to search for indirect evidence of new physics beyond the standard model in the b and c sectors

Key measurements of LHCb

arXiv:0912.4179

- **Tree-level determination of γ (NP free)**
- **Charmless $B \to hh$:**
  $B_s \to hh$; $\Lambda_b \to p\pi^-$, pK^- ; $B^0 \to p\underline{p}$
- **$B_s \to J/\psi\phi$**
- **$B_s \to \mu^+ \mu^-$**
- **$B_s \to \phi\gamma$**
- **$B^0 \to K^{*0}\mu^+\mu^-$, forward-backward asymmetry**
- **CPV in charm**

Flavor physics in high luminosity (intensity) frontier is an indirect probe for NP via loop processes:

- **charm quark mass from** K^0-$\underline{K}^0$ **mixing (GIM '70)**
- **top quark mass from** B^0-$\underline{B}^0$ **mixing (ARGUS '87)**
- **Higgs mass from precision measurement of electroweak observables**

1. Null results in SM: ideal place to look for new physics in BSM

- $B_s \to \mu^+\mu^-$
- β_s
- CP violation in $B^- \to \pi^-\pi^0$
- Lepton number violation (τ decay)
- CP violation in charm meson; D^0-$\underline{D}^0$ mixing
- $\Delta\Gamma_d$
- ...

2. Take the cue form the current anomalies:

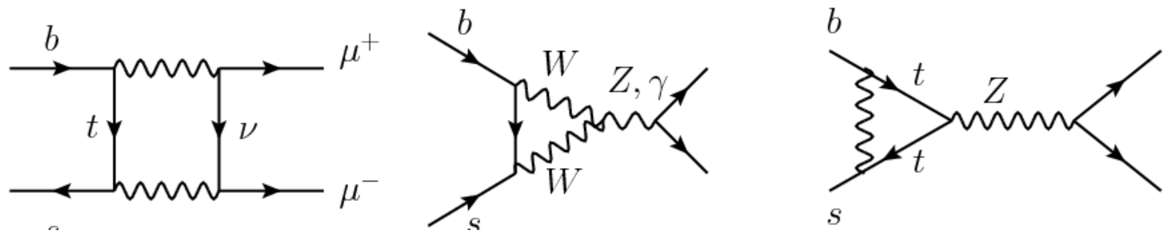
- sin2β
- B-CP puzzles, especially $\Delta A_{K\pi}$
- like-sign dimuon asymmetry
- forward-backward asymmetry in $B^0 \to K^{*0}\mu^+\mu^-$
- polarization puzzle
- ...

Flavor physics

- $B_s \to \mu^+\mu^-$
- **Forward-backward asymmetry in B**$\to K^* l^+ l^-$
- **Hadronic B decays**
- D^0 **–** $\underline{D}^0$ **mixing**

$B_s \to \mu^+ \mu^-$

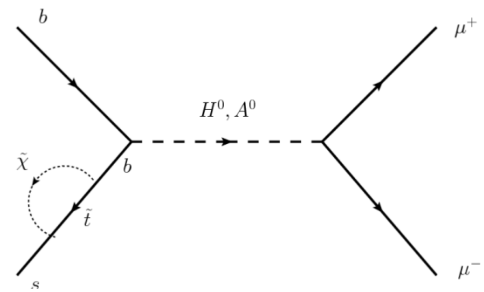
SM:



helicity & GIM suppressed

$Br(B_s \to \mu^+\mu^-) = (3.6 \pm 0.3) \times 10^{-9}$

Buras ('09)

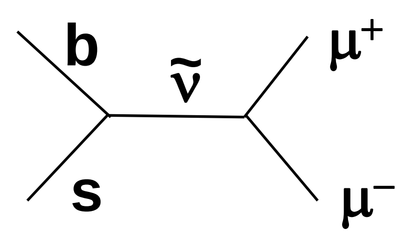


Choudhury, Gaur ('99)

NP:

(i) MSSM, $\Gamma \propto \tan\beta^6$

(ii) $\not{R}$-parity SUSY: tree-level diagram via sneutrino even for low $\tan\beta$



CDF: $<4.3\times10^{-8}$ public note 9892

D0: $<5.1\times10^{-8}$ arXiv: 1006.3469

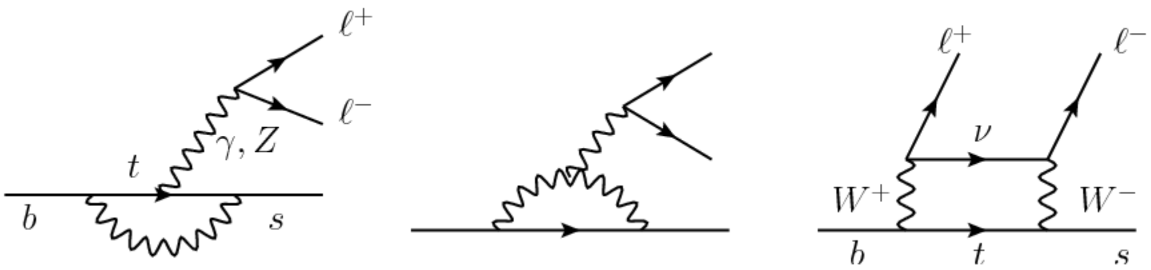
improved by LHC: $<7\times10^{-9}$

Beyond SM scenarios

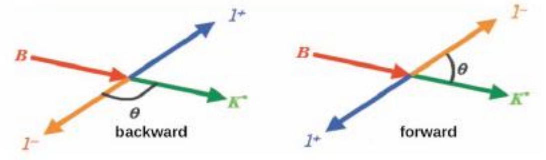
- TeV supersymmetry
- Flat extra dimension
  -- large extra dimensions
  -- universal extra dimensions
- Warped extra dimension
  -- minimal warped model
  -- Higgless model
  -- holographic composite model
- NGB Higgs
  -- little Higgs
  -- twin, folded Higgs
- New strong dynamics
  -- technicolor
  -- top seesaw
  -- quirk (iquark)
- Hidden valleys
  -- unparticle,…
- Exotic particles
  -- axigluon,…
- …

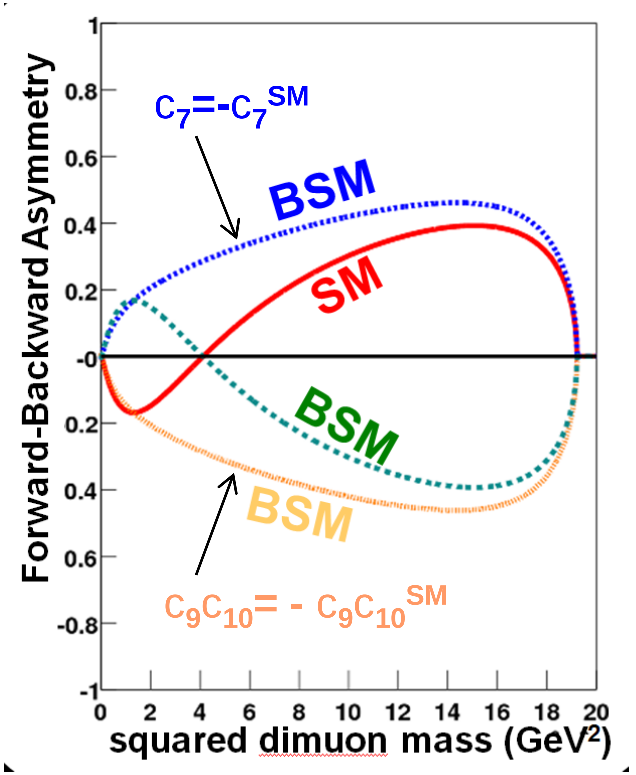
BSM=Extra xxx

Forward-backward asymmetry in B→ K*l+l-



$$A_{FB}\left(s = m^2_{\mu^+\mu^-}\right) = \frac{N_F - N_B}{N_F + N_B}$$

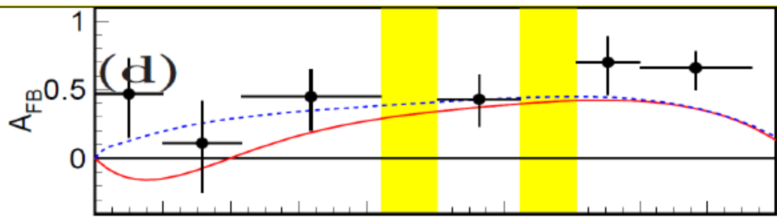




$A_{FB}(q^2) = -c^{eff}_{10}\,\xi(q^2)$ [Re$c_9^{eff}F_1 + c_7^{eff}\,F_2\,/q^2$]

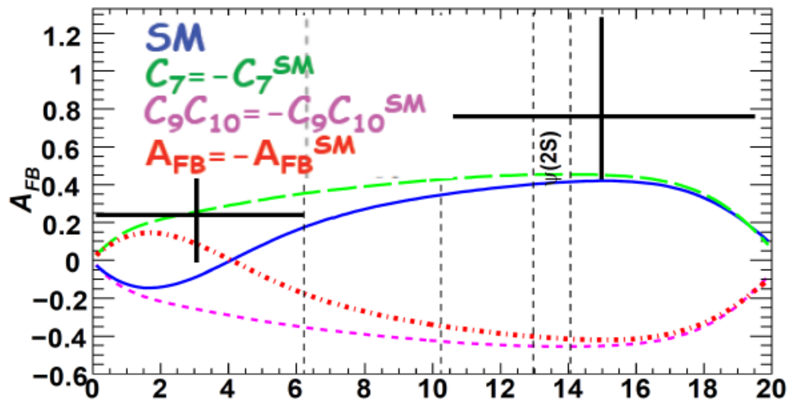
SM: $c_7^{eff} \sim -0.304$, $c_{10}^{eff} \sim -4.103$,
$c_9^{eff} \sim 4.211 + Y(q^2)$

zero of A_{FB} occurs at $q^2 = 4.36$ GeV^2



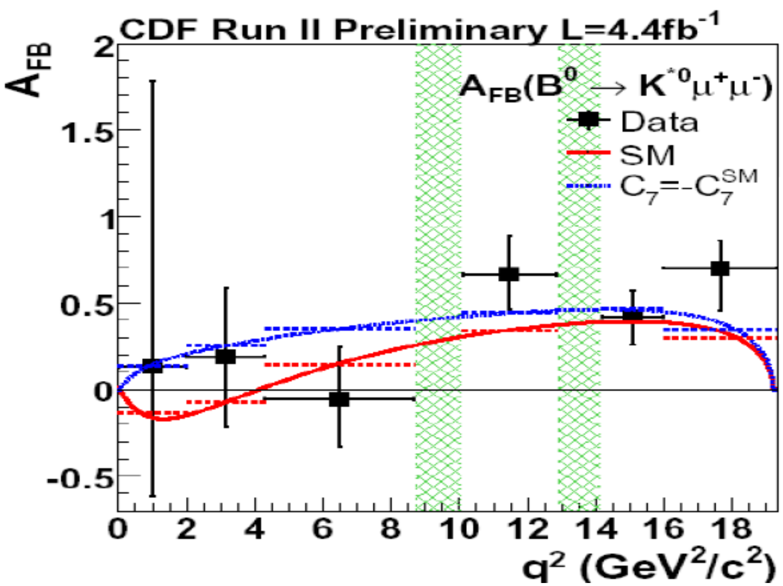
250 events

J.-T. Wei, P. Chang et al.



100 events

The present situation will be clarified by LHCb as 1400 events are expected.



100 events

$B_s \to$ PP,VP,VV decays

- **QCDF:** J.F. Sun, G.H. Zhu, D.S. Du; X.Q. Li, G.R. Lu, Y.D. Yang; F. Su, Y.L. Wu, Y.B. Yang, C. Zhung; HYC, K.C. Yang
- **pQCD:** C.H. Chen; Ali, Kramer, C.D. Lu, Y.L. Shen, W. Wang, Y.M. Wang, J. Liu, R. Zhou; J.W. Li, F.Y. You, D.Q. Guo; …
- **SCET:** Williamson, Zupan; W. Wang, D.S. Yang, C.D. Lu

- U-spin symmetry for d $\leftrightarrow$ s quarks
- Mixing-induced CP asymmetry is very small in SM
- In B_u/B_d sector, $B\to K\eta'$ has the largest rate

In B_s sector, $Br(B_s\to \eta'\eta') \sim 50\times 10^{-6}$ QCDF, SCET

$Br(B_s\to \eta\eta') \sim 35\times 10^{-6}$ pQCD

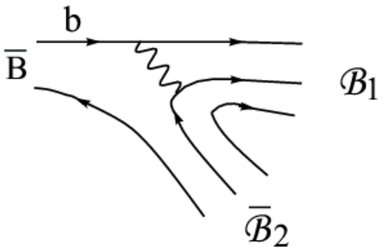
$\Lambda_b\to p\pi^-, pK^-$ (Tevatron, $Br \sim 4\times 10^{-6}$)

arXiv:0906.1479, C.D. Lu, Y.M. Wang, H. Zou, Ali, Kramer

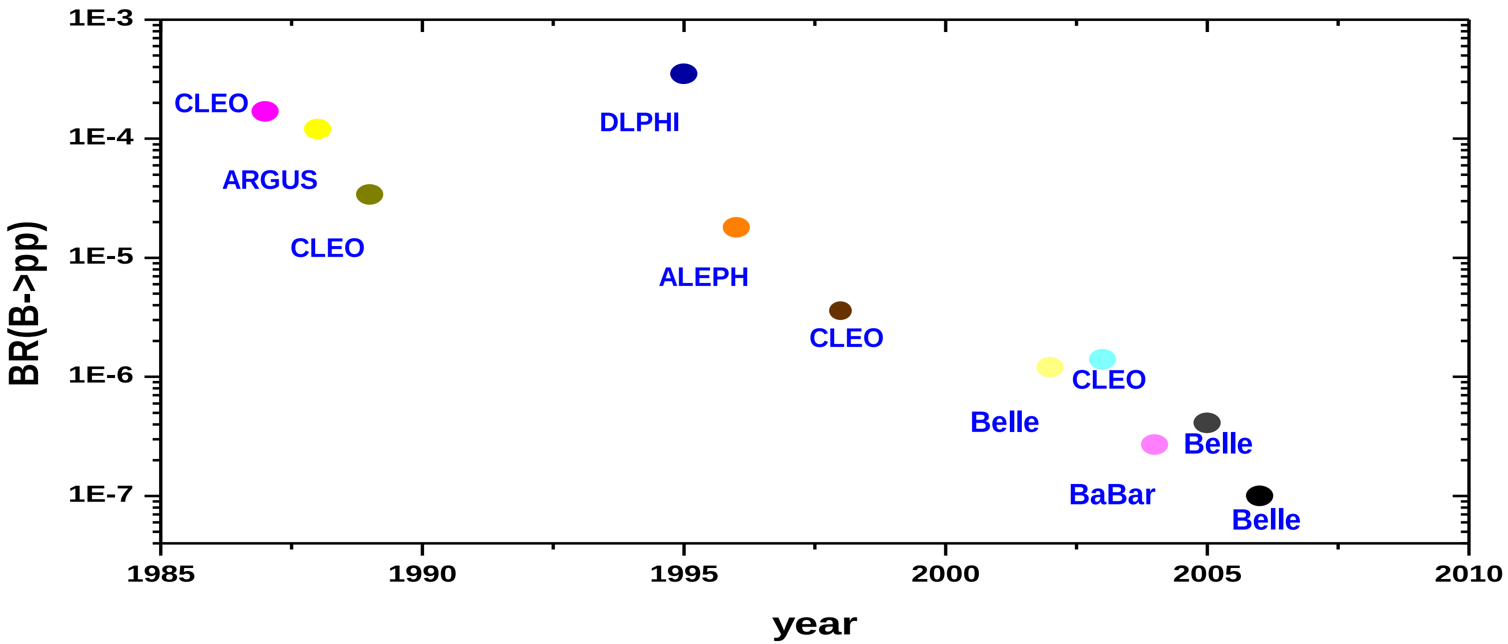
2-body baryonic B decays

charmless:

Very rare !



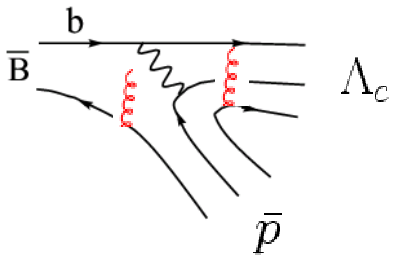
Mode	BaBar	Belle	CLEO
$\overline{B}^0 \to p\bar{p}$	$< 2.7 \times 10^{-7}$	$< 1.1 \times 10^{-7}$	$< 1.4 \times 10^{-6}$
$\overline{B}^0 \to \Lambda\bar{\Lambda}$		$< 3.2 \times 10^{-7}$	$< 1.2 \times 10^{-6}$
$B^- \to \Lambda\bar{p}$		$< 3.2 \times 10^{-7}$	$< 1.5 \times 10^{-6}$
$B^- \to \Sigma^{*0}\bar{p}$		$< 4.7 \times 10^{-7}$	
$B^- \to \Lambda\bar{\Delta}^-$		$< 8.2 \times 10^{-7}$	
$B^- \to p\bar{\Delta}^{--}$		$< 1.4 \times 10^{-7}$	
$\overline{B}^0 \to \Sigma^{*+}\bar{p}$		$< 2.6 \times 10^{-7}$	
$\overline{B}^0 \to \Lambda\bar{\Delta}^0$		$< 9.3 \times 10^{-7}$	



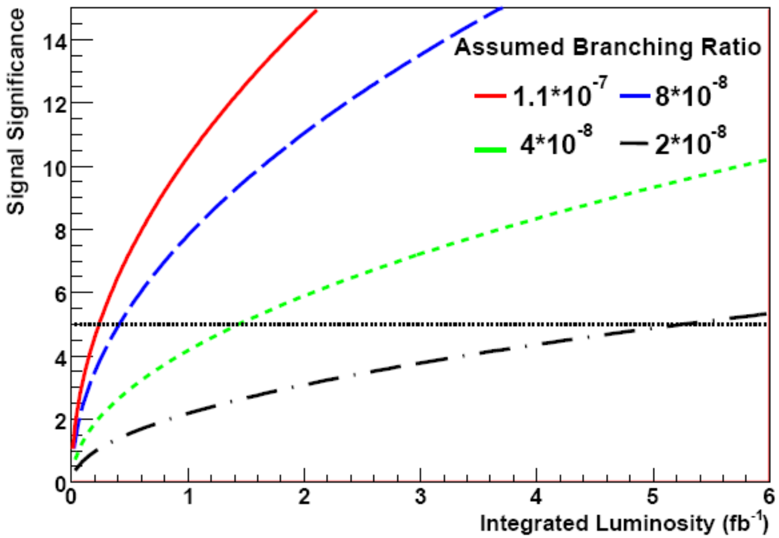
charmless 2-body baryonic B decays

	CZ	Jarfi et al.	CY	Expt.
$\overline{B}^0 \to p\bar{p}$	1.2×10^{-6}	7.0×10^{-6}	$1.1 \times 10^{-7\dagger}$	$< 1.1 \times 10^{-7}$
$\overline{B}^0 \to n\bar{n}$	3.5×10^{-7}	7.0×10^{-6}	$1.2 \times 10^{-7\dagger}$	
$B^- \to n\bar{p}$	6.9×10^{-7}	1.7×10^{-5}	5.0×10^{-7}	
$\overline{B}^0 \to \Lambda\bar{\Lambda}$		2×10^{-7}	$0^\dagger$	$< 3.2 \times 10^{-7}$
$B^- \to p\bar{\Delta}^{--}$	2.9×10^{-7}	3.2×10^{-4}	1.4×10^{-6}	$< 1.4 \times 10^{-7}$
$\overline{B}^0 \to p\bar{\Delta}^-$	7×10^{-8}	1.0×10^{-4}	1.4×10^{-7}	
$B^- \to n\bar{\Delta}^-$		1×10^{-7}	4.6×10^{-7}	
$\overline{B}^0 \to n\bar{\Delta}^0$		1.0×10^{-4}	4.3×10^{-7}	
$B^- \to \Lambda\bar{p}$	$\lesssim 3 \times 10^{-6}$		$2.2 \times 10^{-7\dagger}$	$< 3.2 \times 10^{-7}$
$\overline{B}^0 \to \Lambda\bar{n}$			$2.1 \times 10^{-7\dagger}$	
$\overline{B}^0 \to \Sigma^+\bar{p}$	6×10^{-6}		$1.8 \times 10^{-8\dagger}$	
$B^- \to \Sigma^0\bar{p}$	3×10^{-6}		$5.8 \times 10^{-8\dagger}$	
$B^- \to \Sigma^+\bar{\Delta}^{--}$	6×10^{-6}		2.0×10^{-7}	
$\overline{B}^0 \to \Sigma^+\bar{\Delta}^-$	6×10^{-6}		6.3×10^{-8}	
$B^- \to \Sigma^-\bar{\Delta}^0$	2×10^{-6}		8.7×10^{-8}	

CZ=Chernyak & Zhitnitsky ('90), CY= Cheng & Yang ('02)



Similar to the pQCD calculation of B→Λ_cp (46 Feynman diagrams) by He, T.Li, X.Q.Li, Y.M.Wang, hep-ph/0607178



LHCb can expect to make an observation (i.e. achieve a 5 significance) with 2 fb^{-1} of data, even if the true branching ratio of B→ pp is significantly below the current experimental upper limit.

Extensive studies of baryonic B decays in Taiwan both experimentally and theoretically

Expt.	Theory
Belle group at NTU (Min-Zu Wang,…)	Chen, Chua, Geng, He, Hou, Hsiao, Tsai, Yang, HYC,…

$B^- \to p\bar{p}K^-$: first observation of charmless baryonic B decay ('01)

$B \to p\bar{p}(K, K^*, \pi)$

$\to \Lambda\bar{p}(\pi, K)$

$\to \Lambda\bar{\Lambda}K$

$B \to p\bar{p}$, $\Lambda\bar{\Lambda}$, $p\bar{\Lambda}$ (stringent limits)

$B \to p\bar{\Lambda}\gamma$: first observation of $b \to s\gamma$ penguin in baryonic B decays ('04)

Publication after 2002:

13 papers (first author) so far: 7PRL, 2PLB, 4PRD

Publication after 2000: (hep-ph)

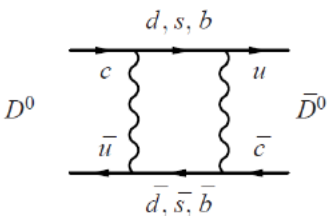
0008079, 0107110, 0108068, 0110263, 0112245, 0112294, 0201015, 0204185, 0204186, 0208185, 0210275, 0211240, 0302110, 0303079, 0306092, 0307307, 0311035, 0405283, 0503264, 0509235, 0511305, 0512335, 0603003, 0603070, 0605127, 0606036, 0606141, 0607061, 0607178, 0608328, 0609133, 0702249, PRD(05,not on hep-ph), 0707.2751, 0801.0022, 0806.1108, 0902.4295, 0902.4831

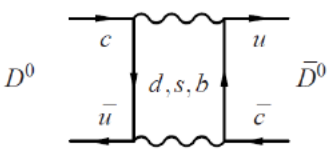
Taiwan contributes to 84% of theory papers

$D^0 - \overline{D}^0$ mixing

mass eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q\,|\overline{D}^0\rangle$

mixing parameters: $x=(m_1 - m_2)/\Gamma$, $y=(\Gamma_1-\Gamma_2)/2\Gamma$





In SM, short-distance contributions to x & y are very small, of order 10^{-6} **H.Y.C. ('82); Datta, Kumbhakar ('85)**

- **b quark contribution is negligible due to** $V_{cd}V^*_{ub}$
- **GIM cancellation**

	x (%)	y (%)	|q/p|	$\phi(^o)$
2009	$0.98^{+0.24}_{-0.20}$	0.83 ± 0.16	$0.87^{+0.17}_{-0.15}$	$-8.5^{+7.4}_{-7.0}$
FPCP2010	0.59 ± 0.20	0.80 ± 0.13	$0.91^{+0.19}_{-0.16}$	$-10.0^{+9.3}_{-8.7}$
Charm2010	$0.55^{+0.12}_{-0.13}$	0.83 ± 0.13		

BaBar('10): $x = (1.6\pm2.3\pm1.2\pm0.8)10^{-3}$
$y = (5.7\pm2.0\pm1.3\pm0.7)10^{-3}$

Theory predictions

- inclusive: $1/m_c$ expansion [Georgi; Ohl, Ricciardi, Simmons; Bigi, Uraltsev] [Lenz et al.]
- exclusive: sum over intermediate states, vanish in SU(3) limit.

  Only SU(3) effect in phase space was considered by Falk, Grossman, Lighti, Petrov ('02)

$$\Delta m = \frac{1}{m_D}\langle D^0|H_w|\overline{D}^0\rangle + \frac{1}{2m_D}\mathcal{P}\sum_n \frac{1}{\mathcal{N}}\frac{\langle D^0|H_w|n\rangle\langle n|H_w|\overline{D}^0\rangle + \langle \overline{D}^0|H_w|n\rangle\langle n|H_w|D^0\rangle}{m_D - E_n}$$

$$\Delta\Gamma = \frac{1}{2m_D}\sum_n \frac{1}{\mathcal{N}}\left[\langle D^0|H_w|n\rangle\langle n|H_w|\overline{D}^0\rangle + \langle \overline{D}^0|H_w|n\rangle\langle n|H_w|D^0\rangle\right](2\pi)\delta(m_D - E_n)$$

Δm, $\Delta\Gamma$ induced by off-shell & on-shell intermediate states

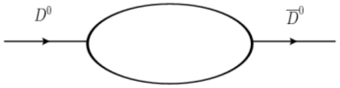
Mode	BR
PP	$\sim 10\%$
VP	$\sim 28\%$
VV	$\sim 10\%$
SP	$\sim 4.2\%$
AP	$\sim 10\%$
TP	$\sim 0.3\%$
2-body	$\sim 63\%$
hadronic	$\sim 84\%$
semileptonic	$\sim 16\%$

Approach based on 2-body decay data:

(i) Two-body decays account for 75% of hadronic rates of D mesons, (ii) PP, VP data with good precision for CF & SCS modes are available, (iii) As-yet unmeasured DCS modes are determined from topological approach

Previous attempts: Colangelo et al; Kaeding; Buccella et al.

For 2-body intermediate states



$$x \approx \frac{m_D}{4\pi} \sum_n \eta_{\rm CKM}(n)\eta_{\rm CP}(n) \cos\delta_n \sqrt{\mathcal{B}(D^0 \to n)\mathcal{B}(D^0 \to \bar{n})}\, \frac{I(m_1, m_2, \Lambda)}{p_c(n)}$$

Burdman, Shipsey

$$y \approx \sum_n \eta_{\rm CKM}(n)\eta_{\rm CP}(n) \cos\delta_n \sqrt{\mathcal{B}(D^0 \to n)\mathcal{B}(D^0 \to \bar{n})}$$

Donoghue et al; Wolfenstein

- **δ_n: strong phase between $D^0 \to$ n and $\bar{D}^0 \to$ n**
- **η_{CKM}= ±1, depending on number of s and $\bar{s}$ quarks in the final state**
- **Large cancellation of SCS with CF and DCS, perfect in SU(3) limit**

	PP	VP	VV
x(%)	0.032±0.005	0.073±0.021	
y(%)	0.086±0.041	0.269±0.253	0.037

HYC, Chiang ('10)

Assume $\cos\delta_n$=1, recalling that $\cos\delta_{K\pi}=1.03^{+0.31}_{-0.18}$ by CLEO

x_{PP+VP} = **(0.10±0.02)%**

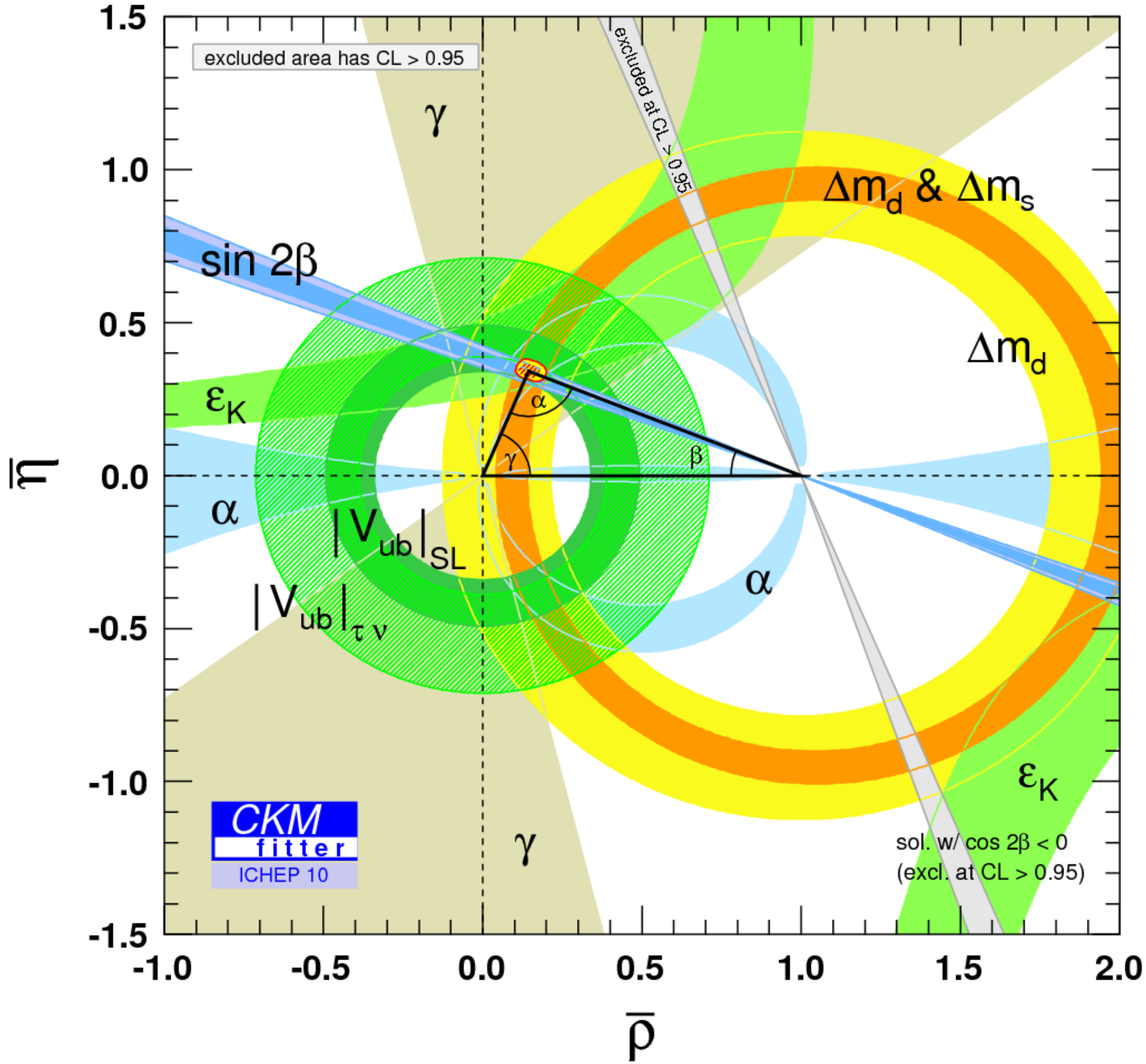
y_{PP+VP} = **(0.36±0.26)%**

x ~ (0.2-0.4)%, y ~ (0.5-0.7)%

BaBar: $\left\{ \begin{array}{l} x = (1.6\pm2.3\pm1.2\pm0.8)10^{-3} \\ y = (5.7\pm2.0\pm1.3\pm0.7)10^{-3} \end{array} \right.$

CP violation

- CP violation in charm decays
- CP violation in $B \to \pi^+\pi^-$
- dimuon asymmetry: B_s-$\underline{B}_s$ mixing angle ϕ_s
- B-CP puzzles: $\Delta A_{K\pi}$, polarization puzzle
- Mixing-induced CP asymmetries: $\Delta\sin 2\beta$



$\underline{\rho}$**=0.144±0.025**

$\underline{\eta}$=0.342$^{+0.016}_{-0.015}$

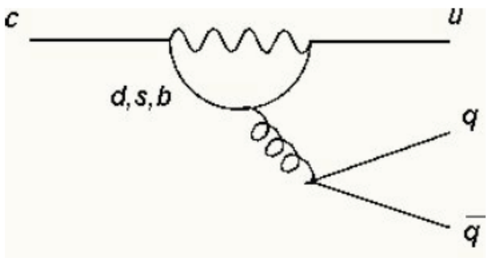
γ=(67.2±3.9)^o

Sensitivity of LHCb for γ at tree level is ~ 5^o

A comment on the size of CPV

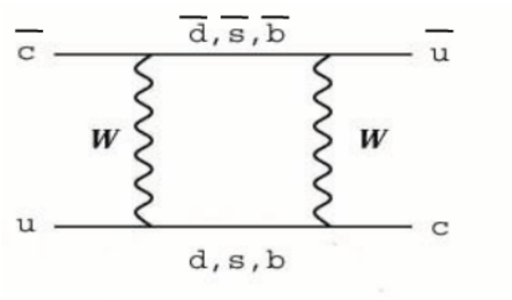
- Generic expectation is that CP-violating observables in the SM are small

Δc = 1 amplitudes



Penguin amplitude

Δc = 2 amplitudes



D-D̄ mixing

- The Unitarity Triangle for charm:

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

$$\sim\lambda \qquad \sim\lambda \qquad \sim\lambda^5$$

With b-quark contribution neglected: only 2 generations contribute
$\Rightarrow$ **real 2x2 Cabibbo matrix**

Any CP-violating signal in the SM will be small, at most $O(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim 10^{-3}$
Thus, O(1%) CP-violating signal can provide a "smoking gun" signature of New Physics

Direct CP asymmetries in D decays

SM: $A_{CP}(D^+ \to K_S \pi^+)$ = (-0.332± 0.006)%

Decay	Expt.	Asymmetry	Decay	Expt.	Asymmetry
$D^0 \to \pi^+\pi^-$	BaBar	$-0.0024 \pm 0.0052 \pm 0.0022$	$D^0 \to K^+K^-$	BaBar	$+0.0000 \pm 0.0034 \pm 0.0013$
	Belle	$+0.0043 \pm 0.0052 \pm 0.0012$		Belle	$-0.0043 \pm 0.0030 \pm 0.0011$
	CDF	$+0.0022 \pm 0.0024 \pm 0.0011$		CDF	
$D^0 \to \pi^+\pi^-\pi^0$	BaBar	$-0.0031 \pm 0.0041 \pm 0.0017$	$D^0 \to K^+K^-\pi^0$	BaBar	$+0.0100 \pm 0.0167 \pm 0.0025$
	Belle	$+0.0043 \pm 0.0130$			
$D^+ \to K_S{}^0\pi^+$	BaBar	$-0.0044 \pm 0.0013 \pm 0.0010$	$D^+ \to K_S{}^0K^+$	Belle	$0.0016 \pm 0.0058 \pm 0.0025$
	Belle	$-0.0071 \pm 0.0019 \pm 0.0020$		Focus	$+0.071 \pm 0.061 \pm 0.012$
$D_s{}^+ \to K_S{}^0\pi^+$	Belle	$+0.0545 \pm 0.0250 \pm 0.0033$	$D_s{}^+ \to K_S{}^0K^+$	Belle	$+0.0012 \pm 0.0036 \pm 0.0022$
	CLEO	$+0.27 \pm 0.11$		CLEO	$+0.049 \pm 0.021 \pm 0.009$

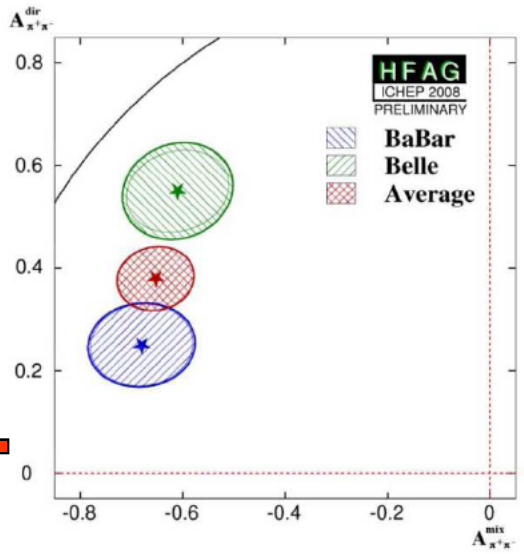
A. Petrov: at most 10^{-3} in SM; 10^{-2} is a "smoking gun" signature of NP

challenged recently by Lenz et al. (arXiv:1002.4794, see also Lenz's talk at Charm2010)

Belle-BaBar disagreement on $A_{CP}(\pi^+\pi^-)$

- Measurements with B^0 performed by B factories. 1.9σ disagreement between Belle and BaBar measurements.

Year	BaBar	Belle	Difference
2001	$-0.25 \pm 0.45 \pm 0.14$ PRD 65, 051502 (33M)		
2002	$-0.30 \pm 0.25 \pm 0.04$ PRL 89, 281802 (88M)	$-0.94^{+0.25}_{-0.31} \pm 0.09$ PRL 89, 071801 (45M)	
2003	$-0.19 \pm 0.19 \pm 0.05$ preliminary LP2003 (123M)	$-0.77 \pm 0.27 \pm 0.08$ PRD 68, 012001 (85M)	2.0σ
2004	$-0.09 \pm 0.15 \pm 0.04$ PRL 95, 151803 (227M)	$-0.58 \pm 0.15 \pm 0.07$ PRL 93, 021601 (152M)	3.2σ
2005		$-0.56 \pm 0.12 \pm 0.06$ PRL 95, 101801 (275M)	2.3σ
2006	$-0.16 \pm 0.11 \pm 0.03$ ArXiv:0607106 (347M)	$-0.55 \pm 0.08 \pm 0.05$ PRL 98, 211801 (535M)	2.3σ
2007	$-0.21 \pm 0.09 \pm 0.02$ PRL 99, 021603 (383M)		2.1σ
2008	$-0.25 \pm 0.08 \pm 0.02$ ArXiv:0807.4226 (467M)		1.9σ

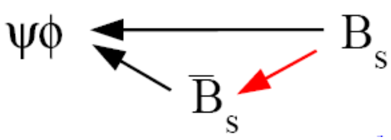


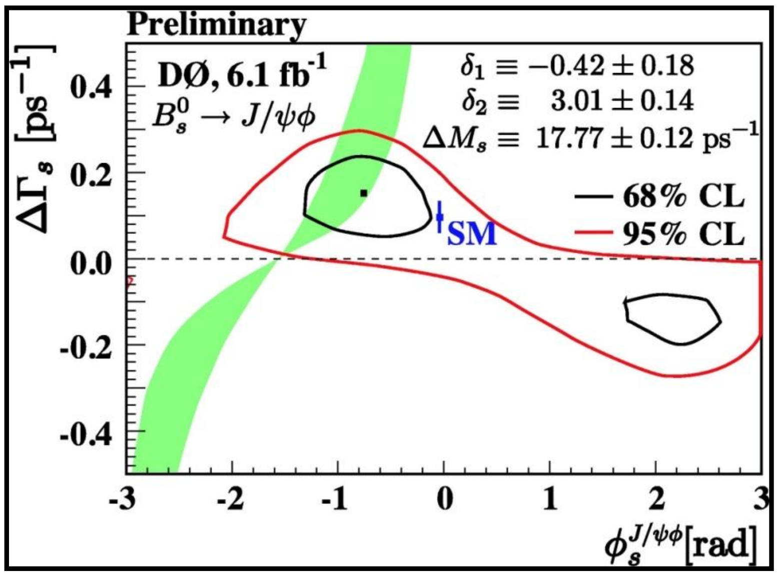
$A_{\pi\pi} = -C_{\pi\pi}$

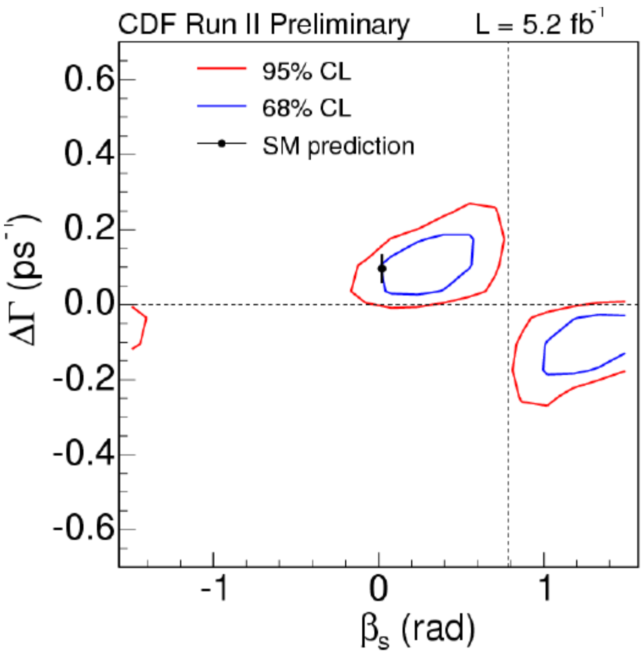
$$A_{CP}(\pi^+\pi^-) = \begin{cases} (17.0^{+4.5}_{-8.8})\% & \text{QCDF} \\ (18^{+20}_{-12})\% & \text{pQCD} \end{cases}$$

$B_s \to J/\psi\phi$

$$\phi_s^{J/\psi\varphi,SM} = -2\beta_s = 2\arg\left(-\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}\right) = -0.036 \pm 0.002$$



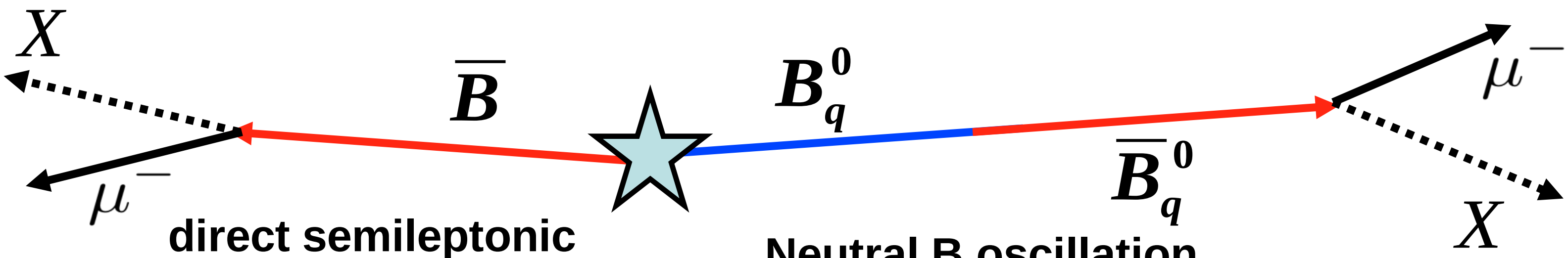




$$\phi_s^{J/\psi\varphi}(D0) = -0.76^{+0.38}_{-0.36} \pm 0.02$$

New results in $B_s \to J/\psi\varphi$ by CDF and DØ demonstrate a better consistency with the SM at ~ 1σ

Like-Sign Dimuon Asymmetry at D0



direct semileptonic decay

Neutral B oscillation followed by semileptonic decay

arXiv:1005.2757 PRD
arXiv:1007.0395 PRL
(Pub August 16, 2010)

$$A_{sl}^{b} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

$$A_{sl}^{b} = (-0.957 \pm 0.251\,(\mathrm{stat}) \pm 0.146\,(\mathrm{syst}))\%$$

D0 measurement differs from SM by 3.2σ

$$A_{sl}^{b}(SM) = -(2.3^{+0.5}_{-0.6})10^{-4}$$

Many citations: 65 as of 11/15/2010

W.S. Hou, Y.Y. Mao and C.H. Shen, arXiv:1003.4361 [hep-ph]; O. Eberhardt, A. Lenz, and J. Rohrwild, arXiv:1005.3505 [hep-ph]; A. Dighe, A. Kundu, and S. Nandi, arXiv:1005.4051 [hep-ph]; C.H. Chen and G. Faisel, arXiv:1005.4582 [hep-ph]; A.J. Buras, M.V. Carlucci, S. Gori, and G. Isidori, arXiv:1005.5310 [hep-ph]; Z. Ligeti, M. Papucci, G. Perez, and J. Zupan, arXiv:1006.0432 [hep-ph]; K.S. Babu and J. Julio, arXiv:1006.1092 [hep-ph]; Y. Li, S. Profumo, and M. Ramsey-Musolf, arXiv:1006.1440 [hep-ph]. U. Nierste, arXiv:1006.2078 [hep-ph]; B. Batell and M. Pospelov, arXiv:1006.2127 [hep-ph]; D. Choudhury and D.K. Ghosh, arXiv:1006.2171 [hep-ph]; M. Kurachi and T. Onogi, arXiv:1006.3414 [hep-ph]; A. Kostelecky and J. Tasson, arXiv:1006.4106 [gr-qc]. C.H. Chen, C.Q. Geng, and W. Wang, arXiv:1006.5216 [hep-ph]; J.K. Parry, arXiv:1006.5331 [hep-ph]; P. Ko and J.h. Park, arXiv:1006.5821 [hep-ph]; S.F. King, arXiv:1006.5895 [hep-ph]; C. Delaunay, O. Gedalia, S.J. Lee, and G. Perez, arXiv:1007.0243 [hep-ph]; C. Berger and L.M. Sehgal, arXiv:1007.2996 [hep-ph]; B. Dutta, Y. Mimura, and Y. Santoso, arXiv:1007.3696 [hep-ph]; C. Biggio and L. Calibbi, arXiv:1007.3750 [hep-ph]; M. Gronau and J.L. Rosner, arXiv:1007.4728 [hep-ph]; T. Gershon, arXiv:1007.5135 [hep-ph]; A.J. Buras, G. Isidori, and P. Paradisi, arXiv:1007.5291 [hep-ph]; A. Kostelecky and R. Van Kooten, arXiv:1007.5312 [hep-ph]; M. Kreps, arXiv:1008.0247 [hep-ex]; S. Collaboration, arXiv:1008.1541 [hep-ex].

B.A. Dobrescu, P.J. Fox, and A. Martin, Phys. Rev. Lett. **105**, 041801 (2010) [arXiv:1005.4238 [hep-ph]]; C.W. Bauer and N.D. Dunn, arXiv:1006.1629 [hep-ph]; N.G. Deshpande, X.G. He, and G. Valencia, arXiv:1006.1682 [hep-ph]; Y. Bai and A.E. Nelson, arXiv:1007.0596 [hep-ph].

J. Kubo and A. Lenz, arXiv:1007.0680 [hep-ph]. **.......**

Both B_d and B_s contribute to A^b_{sl} at Tevatron :

$$A^b_{sl} = (0.506 \pm 0.043) a^d_{sl} + (0.494 \pm 0.043) a^s_{sl}$$

a^q_{sl} is the charge asymmetry of "wrong sign" semileptonic B^0_q ($q = d,s$) decays:

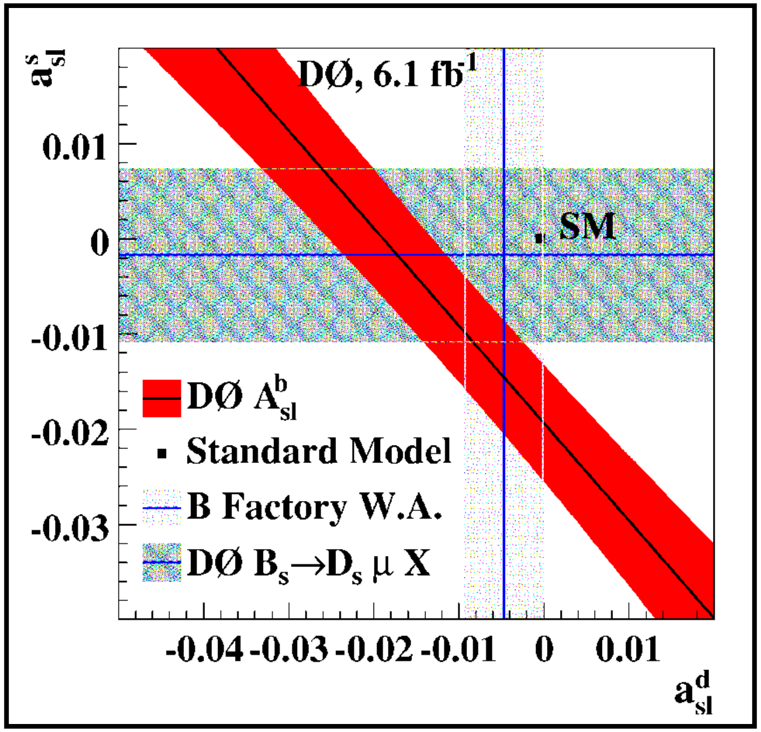
$$a^q_{sl} \equiv \frac{\Gamma(\overline{B}^0_q \to \mu^+ X) - \Gamma(B^0_q \to \mu^- X)}{\Gamma(\overline{B}^0_q \to \mu^+ X) + \Gamma(B^0_q \to \mu^- X)}; \quad q = d, s$$

requires CP violation in mixing

Using a_{sl}^d(exp) = -0.0047± 0.0046 and D0 value of A_{sl}^b leads to a_{sl}^s= -0.0146± 0.0075, much larger than $a_{sl}^s(SM)=(2.1\pm0.6)10^{-5}$

$a_{sl}^s(exp)=-(1.7\pm 9.2)10^{-3}$

$a_{sl}^s(ave) = -0.0127\pm 0.005$



$$a_{\rm sl}^s = \frac{4\left|M_s^{12}\right|\left|\Gamma_s^{12}\right|\sin\phi_s}{4\left|M_s^{12}\right|^2 + \left|\Gamma_s^{12}\right|^2} \qquad \phi_s = \arg\left(-M_s^{12}/\Gamma_s^{12}\right)$$

Since $\Delta\Gamma_s \ll \Delta M_s$ and $\left|\Gamma_s^{12}\right| \ll \left|M_s^{12}\right|$,

$$\Delta M_s \simeq 2\left|M_s^{12}\right|, \qquad \Delta\Gamma_s \simeq 2\left|\Gamma_s^{12}\right|\cos\phi_s$$

$$a_{\rm sl}^s \simeq \frac{\left|\Gamma_s^{12}\right|\sin\phi_s}{\left|M_s^{12}\right|} \simeq \frac{2\left|\Gamma_s^{12}\right|\sin\phi_s}{\Delta M_s}$$

Experimental values

$$\Delta M_s^{\rm exp} = 17.77 \pm 0.12 \ {\rm ps}^{-1}$$

$$\Delta\Gamma_s^{\rm exp} = 0.062^{+0.034}_{-0.037} \ {\rm ps}^{-1}$$

SM predictions

$$2\,M_s^{12,{\rm SM}} = 20.1(1 \pm 0.40)\, e^{-0.035i} \ {\rm ps}^{-1}$$

$$2\left|\Gamma_s^{12,{\rm SM}}\right| = 0.096 \pm 0.039 \ {\rm ps}^{-1}$$

$$\phi_s^{\rm SM} = (4.2 \pm 1.4) \times 10^{-3} = 0.24^\circ \pm 0.08^\circ$$

Lenz, Nieste;
Kubo, Lenz

See A. Lenz et al. arXiv:1008.1593 for a review of NP interpretation

- **One interesting possibility: "right sign" asymmetry**

Kostelecky, Van Kooten

$$A_{sl}^{CPT} \equiv \frac{\Gamma(\overline{B}^0 \to \mu^- X) - \Gamma(B^0 \to \mu^+ X)}{\Gamma(\overline{B}^0 \to \mu^- X) + \Gamma(B^0 \to \mu^+ X)}$$

$$A_{sl}^{b} \approx a_{sl} - A_{sl}^{CPT}$$

Assuming $a_{sl} = a_{sl}(SM) = A_{sl}^{b}(SM)$

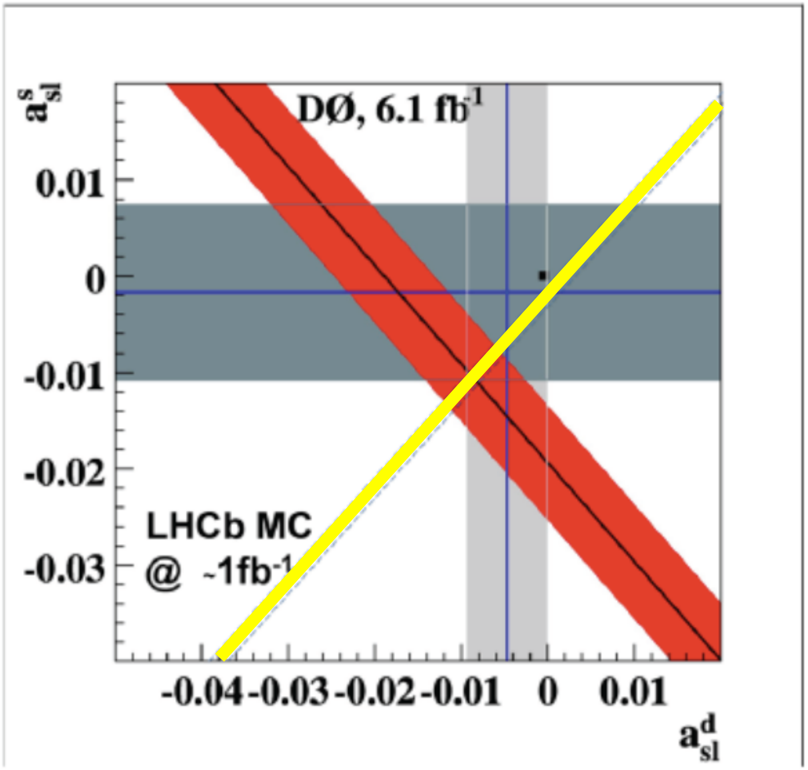
$$\Rightarrow \quad A_{sl}^{CPT} = 0.00713 \pm 0.00405$$

LHCb proposes to measure $a^s_{sl} - a^d_{sl}$

$\Delta A_{fs} = (a_{fs}(B_s) - a_{fs}(B_d)) / 2$ @ LHCb
using semileptonic decays $B_{d,s} \rightarrow D\mu\nu$

Provide constrain 'orthogonal" to DØ measurement

$\Delta A_{fs} = (2.5^{+0.5}_{-0.6})10^{-4}$ **in SM**



See talk of W. Chao on Thursday

Direct CP asymmetries

B_u/B_d	$K^-\pi^+$	$\pi^+\pi^-$	$K^-\eta$	$K^{*0}\eta$	$K^-\rho^0$	$\rho^\pm\pi^\mp$
A_{CP}(%)	$-9.8^{+1.2}_{-1.1}$	38±6	-37±9	19±5	37±11	-13±4
S	8.5σ	6.3σ	4.1σ	3.8σ	3.4σ	3.3σ

B_u/B_d	$K^{*-}\pi^+$	ρ^+K^-	$K^-\pi^0$	$\pi^-\eta$	$\pi^0\pi^0$	$\rho^-\pi^+$
A_{CP}(%)	-18±7	15±6	5.0±2.5	-13±7	43^{+25}_{-24}	11±6
S	2.6σ	2.5σ	2.0σ	1.9σ	1.8σ	1.8σ

$\Delta A_{K\pi}$
14.8±2.8
5.3σ

Belle, (16.4±3.7)% 4.4σ Nature (2008)

$\Delta A_{K\pi} \equiv A_{CP}(K^-\pi^0) - A_{CP}(K^-\pi^+)$

CDF: $A_{CP}(B_s \rightarrow K^+\pi^-) = 0.39 \pm 0.17$ **(2.3σ)**

In heavy quark limit, decay amplitude is factorizable, expressed in terms of form factors and decay constants.

Encounter several difficulties:

- **Rate deficit puzzle: BFs are too small for penguin-dominated PP,VP,VV modes and for tree-dominated decays $\pi^0\pi^0$, $\rho^0\pi^0$**

- **CP puzzle:**

  CP asymmetries for $K^-\pi^+$, $K^{*-}\pi^+$, $K^-\rho^0$, $\pi^+\pi^-$ are wrong in signs

- **Polarization puzzle:**

  f_T **in penguin-dominated $B\to VV$ decays is too small**

$\Rightarrow$ $1/m_b$ **power corrections !**

B_u/B_d	$K^-\pi^+$	$\pi^+\pi^-$	$K^-\eta$	$K^{*0}\eta$	$K^-\rho^0$	$\rho^\pm\pi^\mp$
A_{CP}(%)	$-9.8^{+1.2}_{-1.1}$	38±6	-37±9	19±5	37±11	-13±4
S	8.5σ	6.3σ	4.1σ	3.8σ	3.4σ	3.3σ
$m_b\to\infty$	×	×	√	√	×	×

B_u/B_d	$K^{*-}\pi^+$	ρ^+K^-	$K^-\pi^0$	$\pi^-\eta$	$\pi^0\pi^0$	$\rho^-\pi^+$
A_{CP}(%)	-18±7	15±6	5.0±2.5	-13±7	43^{+25}_{-24}	11±6
S	2.6σ	2.5σ	2.0σ	1.9σ	1.8σ	1.8σ
$m_b\to\infty$	×	×	√	√	√	×

B_s	$K^{*-}\pi^+$
A_{CP}(%)	-18±7
S	2.6σ
$m_b\to\infty$	×

$A(\underline{B}^0 \to K^- \pi^+) \propto \lambda_u a_1 + \lambda_c (a_4^c + r_\chi a_6^c)$

	Theory	Expt
Br	13.1×10^{-6}	$(19.4\pm0.6)\times10^{-6}$
A_{CP}	0.04	$-0.098^{+0.012}_{-0.011}$

$$A_{CP}(\overline{B}^0 \to K^- \pi^+) \propto -2 \sin\gamma \,\mathrm{Im}\, r_{FM}$$

$$r_{FM} = \left|\frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*}\right| \frac{a_1}{-\underbrace{(a_4^c + r_\chi^K a_6^c)}_{\alpha_4^c}}$$

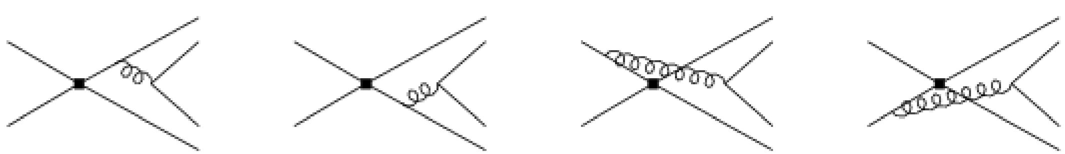
$\mathrm{Im}\,\alpha_4^c \approx 0.013 \Rightarrow$ wrong sign for A_{CP}

$$P^c = [a_4^c + r_\chi a_6^c]_{SD} + \underbrace{[a_4^c + r_\chi a_6^c]_{LD}}_{\text{charming penguin, FSI}} + \underbrace{\beta_3^c}_{\text{penguin annihilation}} + \ldots$$

charming penguin, FSI **penguin annihilation**

1/m_b **corrections**

penguin annihilation



(a) (b) (c) (d)

33

$$A_{ann} = \frac{G_F}{\sqrt{2}} f_B f_{M_1} f_{M_2} \frac{C_F}{N_c^2} \pi\alpha_s \int_0^1 dxdy \left[\Phi_{M_1}(x)\Phi_{M_2}(y)\left(\frac{1}{y(1-x\bar{y})} + \frac{1}{\bar{x}^2 y} \right) + \ldots \right]$$

has endpoint divergence: X_A and X_A^2 with $X_A \equiv \int_0^1 dy/y$

$$X_A \equiv \int_0^1 \frac{dy}{y} = \ln \frac{m_B}{\Lambda_h}\left(1 + \rho_A e^{i\varphi_A}\right)$$

BBNS

Adjust ρ_A and ϕ_A to fit BRs and A_{CP} $\Rightarrow$ $\rho_A \approx 1.10$, $\phi_A \approx -50^o$

$\mathrm{Im}(\alpha_4^c+\beta_3^c) \approx -0.039$ ($\mathrm{Im}\alpha_4^c \approx 0.013$)

New CP puzzles

	$K^-\pi^+$	$\pi^+\pi^-$	$K^-\eta$	$K^{*0}\eta$	$K^-\rho^0$	$\rho^\pm\pi^\mp$
$A_{CP}(\%)$	$-9.8^{+1.2}_{-1.1}$	38 ± 6	-37 ± 9	19 ± 5	37 ± 11	-13 ± 4
S	8.5σ	6.3σ	4.1σ	3.8σ	3.4σ	3.3σ
$m_b\to\infty$	×	×	√	√	×	×
PA	√	√	×	×	√	√

$\Delta A_{K\pi}$
14.8 ± 2.8
5.3σ
≈ 3.3
× (≈ 1.9)

	$K^{*-}\pi^+$	ρ^+K^-	$K^-\pi^0$	$\pi^-\eta$	$\pi^0\pi^0$	$\rho^-\pi^+$
$A_{CP}(\%)$	-18 ± 7	15 ± 6	5.0 ± 2.5	-13 ± 7	43^{+25}_{-24}	11 ± 6
S	2.6σ	2.5σ	2.0σ	1.9σ	1.8σ	1.8σ
$m_b\to\infty$	×	×	√	√	√	×
PA	√	√	×	×	×	√

Penguin annihilation solves CP puzzles for $K^-\pi^+, \pi^+\pi^-$,…, but in the meantime introduces new CP puzzles for $K^-\eta$, $K^{*0}\eta$, …

Also true in SCET with penguin annihilation replaced by charming penguin

All "problematic" modes receive contributions from $\lambda_u C + \lambda_c P_{EW}$

$$\rightarrow \quad A(\bar{B}^0 \to K^-\pi^+) = \lambda_u T + \lambda_c (P + \frac{2}{3} P^c_{EW} + P_A),$$

$$-\sqrt{2} A(\bar{B}^0 \to \bar{K}^0\pi^0) = -\lambda_u C + \lambda_c (P - P_{EW} - \frac{1}{3} P^c_{EW} + P_A),$$

$$A(B^- \to \bar{K}^0\pi^-) = \lambda_u A + \lambda_c (P - \frac{1}{3} P^c_{EW} + P_A),$$

$$\rightarrow \quad \sqrt{2} A(B^- \to K^-\pi^0) = \lambda_u (T + C + A) + \lambda_c (P + P_{EW} + \frac{2}{3} P^c_{EW} + P_A),$$

$\Delta A_{K\pi} \approx 0$ if C, P_{EW}, A are negligible
$\Rightarrow$ $\Delta A_{K\pi}$ puzzle

$$P_{EW} \propto (-a_7 + a_9), \; P^c_{EW} \propto (a_{10} + r_\chi a_8), \; \lambda_u = V_{ub} V^*_{us}, \; \lambda_c = V_{cb} V^*_{cs}$$

$\Delta A_{K\pi}$ puzzle can be resolved by having a large complex C ($C/T \sim 0.5 e^{-i55^o}$) or a large complex P_{EW} or the combination

Large complex C: Charng, Li, Mishima; Kim, Oh, Yu; Gronau, Rosner; …

Large complex P_{EW} needs New Physics for new strong & weak phases

Yoshikawa; Buras et al.; Baek, London; G. Hou et al.; Soni et al.; Khalil et al.

$\pi^0\pi^0$ puzzle: $A_{CP}=(43^{+25}_{-24})\%$, $Br = (1.55\pm0.19)\times10^{-6}$

The two distinct scenarios can be tested in tree-dominated modes where $\lambda'_c P_{EW} << \lambda'_u C$. CP puzzles of $\pi^-\eta$, $\pi^0\pi^0$ & large rates of $\pi^0\pi^0$, $\rho^0\pi^0$ cannot be explained by a large P_{EW}

Power corrections have been systematically studied by

- **Beneke, Neubert: S2, S4**
- **Ciuchini et al.: 0801.0341**
- **Duraisamy & Kagan: 0812.3162 (soft overlap)**
- **Li & Mishima: 0901.1272 (Glauber gluons)**

	$K^-\pi^+$	$\pi^+\pi^-$	$K^-\eta$	$K^{*0}\eta$	$K^-\rho^0$	$\rho^\pm\pi^\mp$
A_{CP}(%)	$-9.8^{+1.2}_{-1.1}$	38±6	-37±9	19±5	37±11	-13±4
S	8.5σ	6.3σ	4.1σ	3.8σ	3.4σ	3.3σ
$m_b\to\infty$	×	×	√	√	×	×
PA	√	√	×	×	√	√
large complex a_2	√	√	√	√	√	√

	$K^{*-}\pi^+$	ρ^+K^-	$K^-\pi^0$	$\pi^-\eta$	$\pi^0\pi^0$	$\rho^-\pi^+$
A_{CP}(%)	-18±7	15±6	5.0±2.5	-13±7	43^{+25}_{-24}	11±6
S	2.6σ	2.5σ	2.0σ	1.9σ	1.8σ	1.8σ
$m_b\to\infty$	×	×	√	√	√	×
PA	√	√	×	×	×	√
large complex a_2	√	√	√	√	√	√

$\Delta A_{K\pi}$
14.8±2.8
5.3σ
≈ 3.3
× (≈ 1.9)
√

All new CP puzzles can be accommodated !

No more rate deficit for $\pi^0\pi^0$ & $\pi^0\rho^0$

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

$A(B^0 \to K^-\pi^+) = A_{\pi K}(\delta_{pu}\alpha_1+\alpha_4^p+\beta_3^p)$

$\alpha_1 = a_1,\ \alpha_2 = a_2$

$\sqrt{2}\,A(B^- \to K^-\pi^0) = A_{\pi K}(\delta_{pu}\alpha_1+\alpha_4^p+\beta_3^p)+A_{K\pi}(\delta_{pu}\alpha_2+3/2\alpha_{3,EW}^p)$

In absence of C and P_{EW}, $K^-\pi^0$ and $K^-\pi^+$ have similar CP violation

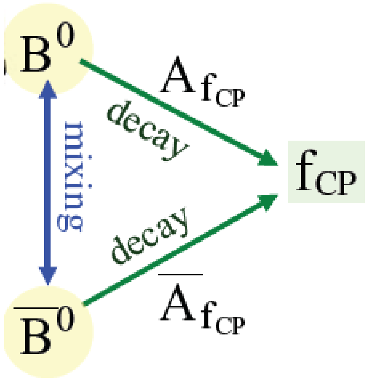
$$A_{CP}(K^-\pi^0) = -2\sin\gamma\,\mathrm{Im}\,r_{FM}/R_{FM} - 2\sin\gamma\,\mathrm{Im}\,r_C$$

$$r_{FM} = \left|\frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*}\right|\frac{a_1}{-(a_4^c+r_\chi^K a_6^c)}, \qquad r_C = \left|\frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*}\right|\frac{f_\pi F_0^{BK}(0)}{f_K F_0^{B\pi}(0)}\frac{a_2}{-(\alpha_4^c+\beta_3^c)}$$

$\arg(a_2) = -58^o$

	$m_b \to \infty$	penguin ann	large complex a_2	Expt
$A_{CP}(K\text{-}\pi^0)(\%)$	7.3	-5.5	$4.9^{+5.9}_{-5.8}$	5.0 ± 2.5
$\Delta A_{K\pi}(\%)$	3.3	1.9	$12.3^{+3.0}_{-4.8}$	14.8 ± 2.8

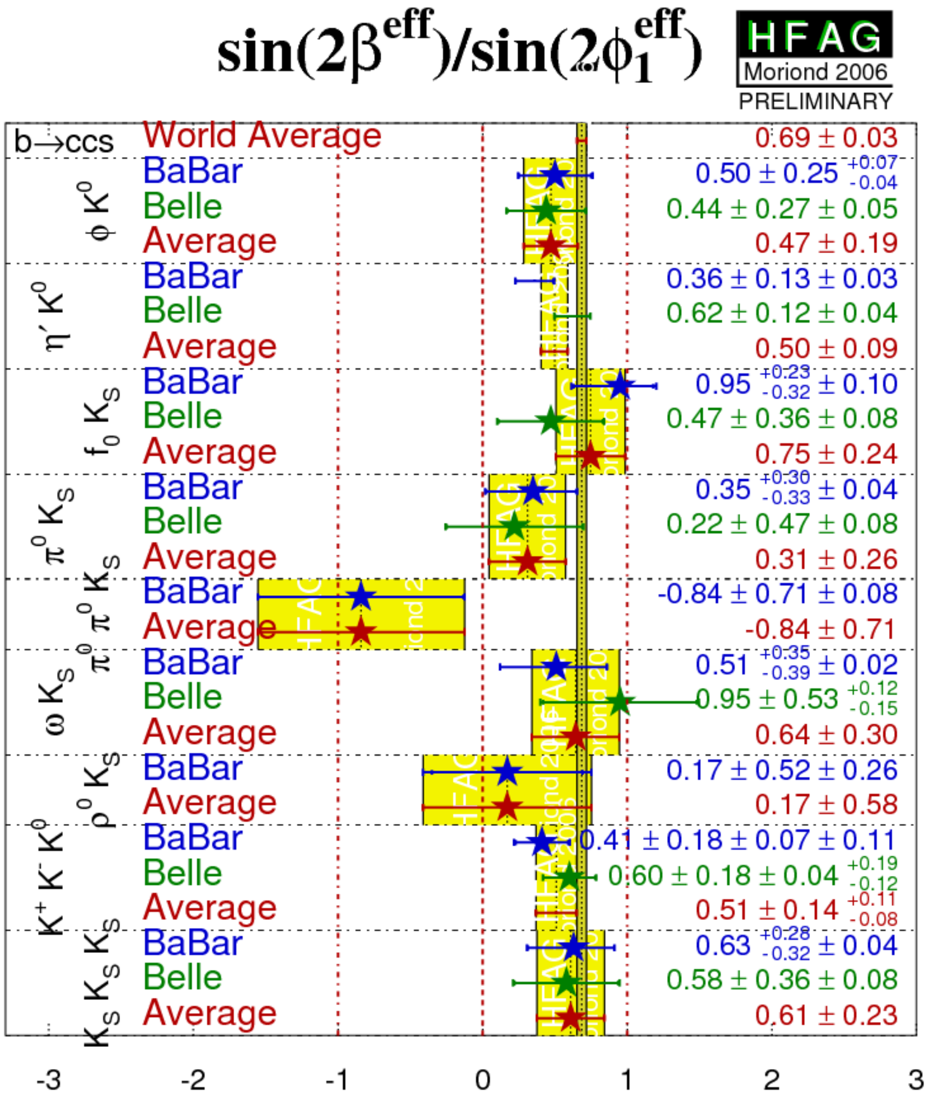
$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\overline{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = S_f \sin \Delta m t - C_f \cos \Delta m t$$

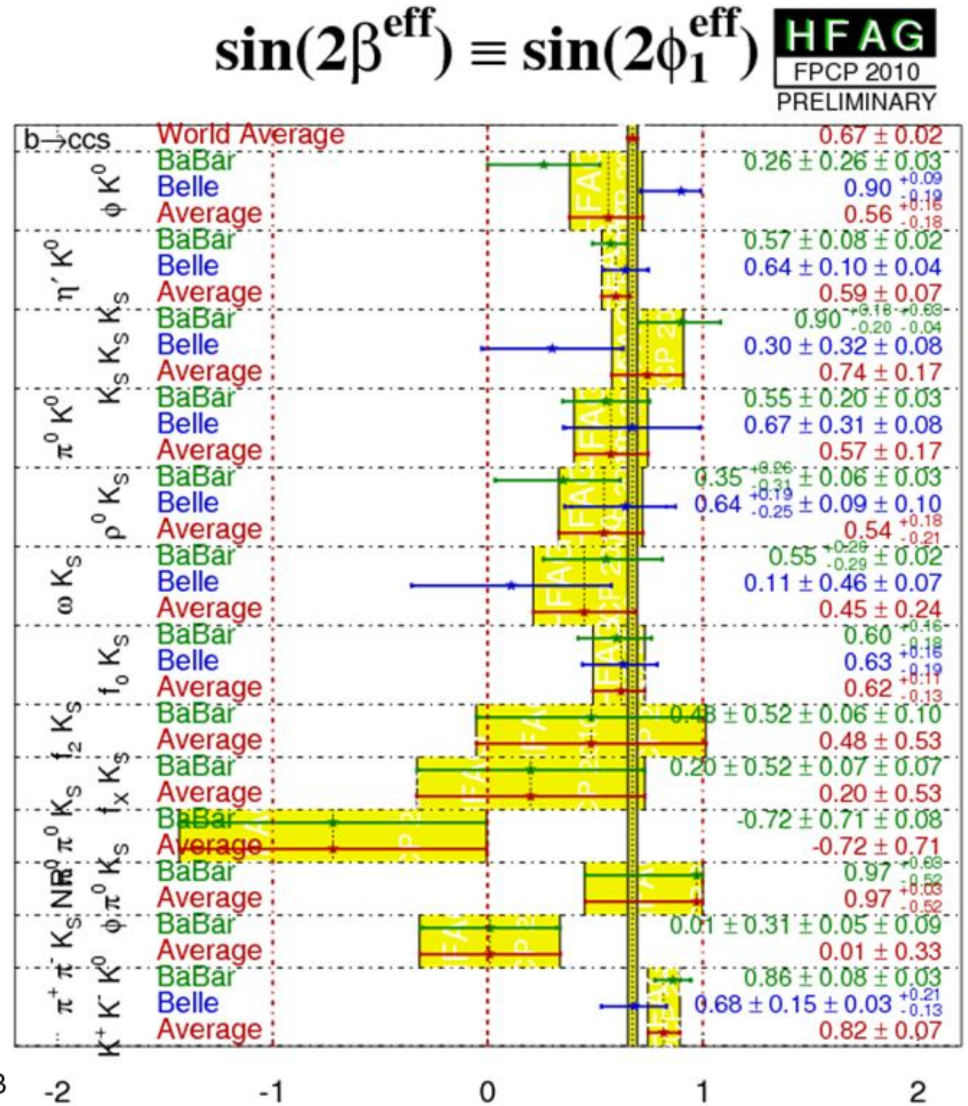


C_f (= -A_f) meaures direct CPV, S_f is related to CPV in interference between mixing & decay amplitude

In SM, $-\eta_f S_f \approx \sin 2\beta$, $C_f \approx 0$ for $b \to s$ penguin-dominated modes

$(\sin 2\beta)_{SM} = 0.867 \pm 0.048$ deviates from $(\sin 2\beta)_{expt}$ by 3.3 σ **Lunghi, Soni**





2006: $\sin 2\beta^{eff}$=0.50±0.06 from b→ qq̲s, $\sin 2\beta$=0.69±0.03 from b→ cc̲s

2010: $\sin 2\beta^{eff}$=0.64±0.04 from b→ qq̲s, $\sin 2\beta$=0.67±0.02 from b→ cc̲s

$\Delta S_f = -\eta_f S_f - \sin 2\beta$

HYC, Chua ('09)

Mode	QCDF	pQCD	Expt	Average
$\eta' K_S$	$0.00^{+0.01}_{-0.01}$	$-0.06^{+0.50}_{-0.91}$	-0.10 ± 0.08 -0.03 ± 0.11	-0.08 ± 0.07
ηK_S	$0.12^{+0.09}_{-0.08}$	$-0.07^{+0.50}_{-0.92}$	--	--
$\pi^0 K_S$	$0.12^{+0.07}_{-0.06}$	$0.06^{+0.02}_{-0.03}$	-0.12 ± 0.20 0.00 ± 0.32	-0.10 ± 0.17
ϕK_S	$0.022^{+0.044}_{-0.002}$	0.02 ± 0.01	-0.41 ± 0.26 $0.23^{+0.09}_{-0.19}$	$-0.11^{+0.16}_{-0.18}$
ωK_S	$0.17^{+0.06}_{-0.08}$	$0.15^{+0.03}_{-0.07}$	$-0.12^{+0.26}_{-0.29}$ -0.56 ± 0.47	-0.22 ± 0.24
$\rho^0 K_S$	$-0.17^{+0.09}_{-0.18}$	$-0.19^{+0.10}_{-0.06}$	$-0.32^{+0.27}_{-0.31}$ $-0.03^{+0.23}_{-0.28}$	$-0.13^{+0.18}_{-0.21}$

Except for $\rho^0 K_S$, the predicted ΔS_f tend to be positive, while they are negative experimentally

$B\to$ VV decays

■ **Polarization puzzle in charmless $\underline{B}\to$VV decays**

$$A_0 : A_- : A_+ = 1 : \frac{\Lambda_{QCD}}{m_b} : \left(\frac{\Lambda_{QCD}}{m_b}\right)^2$$

In transversity basis $A_\perp = (A^- + A^+)/\sqrt{2}, \quad A_\parallel = (A^- - A^+)/\sqrt{2}$

$$f_T \equiv f_\parallel + f_\perp = 1 - f_L = O(m_V^2/m_B^2), \qquad f_\parallel / f_\perp = 1 + O(m_V/m_B)$$

Why is f_T so sizable ~ 0.5 in $B\to K^*Á$ decays ?

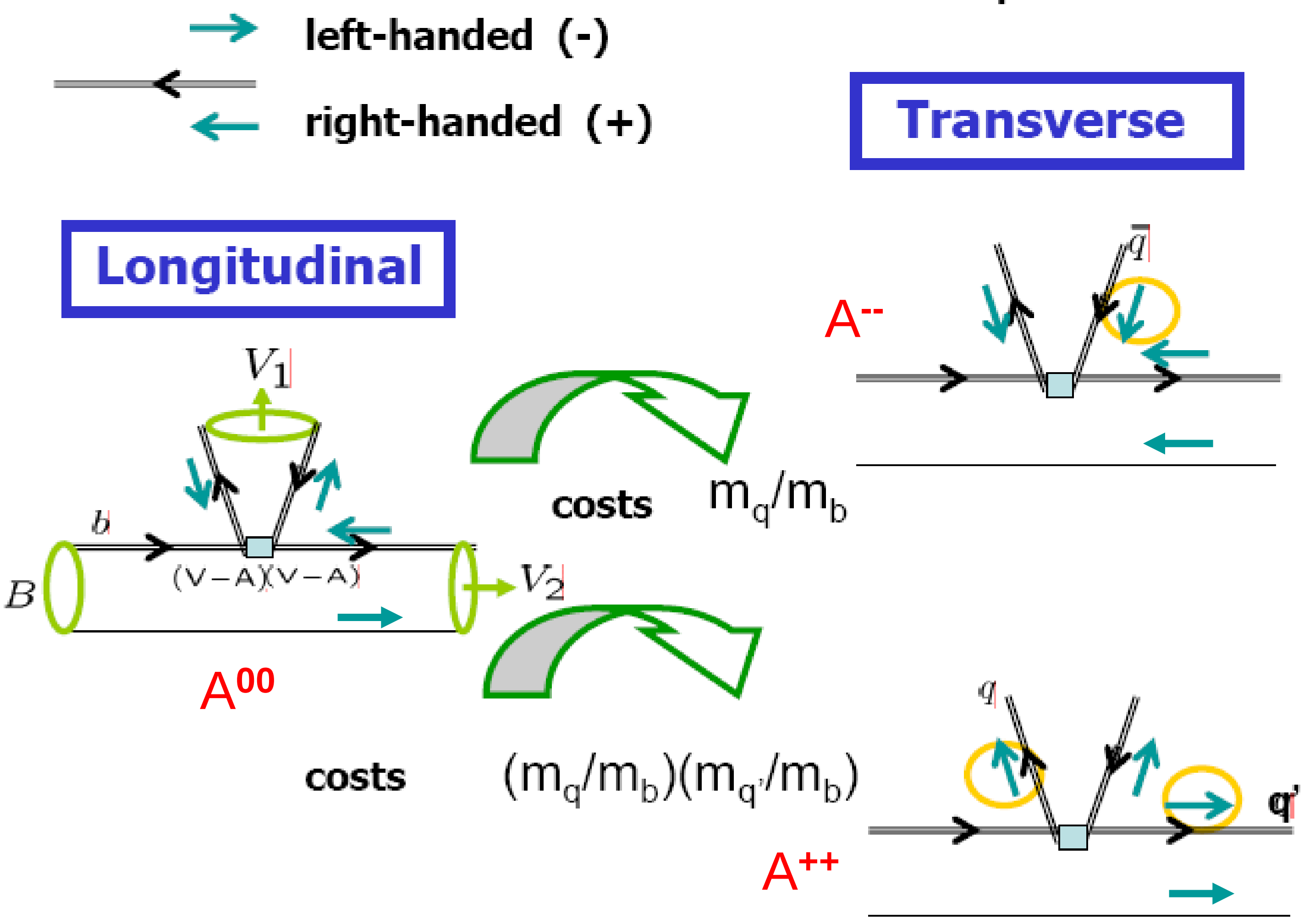
■ **NLO corrections alone can lower f_L and enhance f_T significantly !**

$$\left.\frac{\mathcal{A}^-}{\mathcal{A}^0}\right|_{\bar{B}\to\bar{K}^*\phi} \approx \left(\frac{\alpha_3^- + \alpha_4^{c,-} - \frac{1}{2}\alpha_{3,\mathrm{EW}}^-}{\alpha_3^0 + \alpha_4^{c,0} - \frac{1}{2}\alpha_{3,\mathrm{EW}}^0}\right)\left(\frac{X^-_{\bar{K}^*\phi}}{X^0_{\bar{K}^*\phi}}\right)$$

Beneke,Rohere,Yang
HYC,Yang

constructive (destructive) interference in A^- (A^0) $\Rightarrow$ f_L¼ 0.58

$\bar{B}$ -> VV polarizations

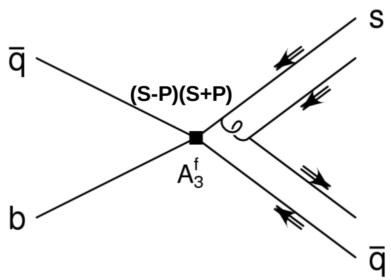


The longitudinal component dominates

$A^{00} >> A^{--} >> A^{++}$

Although f_L is reduced to 60% level, polarization puzzle is not resolved as the predicted rate, BR » 4.3£10^{-6}, is too small compared to the data, » 10£10^{-6} for B →K*Á

Kagan



(S-P)(S+P) penguin annihilation contributes to A^{--} & A^{00} with similar amount

$$A_0^{PA} : A_-^{PA} : A_+^{PA} = \left(\frac{\Lambda_{QCD}}{m_b}\ln\frac{m_b}{\Lambda_h}\right)^2 : \left(\frac{\Lambda_{QCD}}{m_b}\ln\frac{m_b}{\Lambda_h}\right)^2 : \left(\frac{\Lambda_{QCD}}{m_b}\right)^4$$

- **Br & f_L are fitted by ½$_A$=0.60, Á$_A$= -50^o**

Decay	$\mathcal{B}$		f_L		$f_\perp$	
	Theory	Expt	Theory	Expt	Theory	Expt
$B^- \to K^{*-}\phi$ [c]	$10.0^{+1.3+14.1}_{-1.1-\ 6.3}$	10.0 ± 1.1	$0.49^{+0.51}_{-0.38}$	0.50 ± 0.05	$0.25^{+0.20}_{-0.25}$	0.20 ± 0.05
$\overline{B}^0 \to \bar{K}^{*0}\phi$	$9.5^{+1.2+13.5}_{-1.1-\ 6.1}$	9.5 ± 0.8	$0.50^{+0.50}_{-0.38}$	0.484 ± 0.034	$0.25^{+0.19}_{-0.25}$	0.256 ± 0.032

$f_{||}$ ¼ $f_?$ » 0.25

Polarization puzzle in $B \to TV$

For both $B \to K^*\phi$, $K^*\omega$, $K^{*0}\rho^0$, $f_T / f_L \sim 1$

$f_L(K_2^{*+}\omega) = 0.56 \pm 0.11$, $f_L(K_2^{*0}\omega) = 0.45 \pm 0.12$,

$f_L(K_2^{*+}\phi) = 0.80 \pm 0.10$, $f_L(K_2^{*0}\phi) = 0.901^{+0.059}_{-0.069}$

BaBar

Why is $f_T / f_L \ll 1$ for $B \to K_2^*\phi$ and $f_T / f_L \sim 1$ for $B \to K_2^*\omega$?

f_L is very sensitive to the phase ϕ_A^{TV} for $B \to K_2^*\phi$, but not so sensitive to ϕ_A^{VT} for $B \to K_2^*\omega$

HYC, K.C. Yang ('10)

$f_L(K_2^*\phi) = 0.88, 0.72, 0.48$ for $\phi_A^{TV} = -30^o, -45^o, -60^o$,
$f_L(K_2^*\omega) = 0.68, 0.66, 0.64$ for $\phi_A^{VT} = -30^o, -45^o, -60^o$

Rates & polarization fractions can be accommodated by

$$\rho_A^{TV} = 0.65, \qquad \phi_A^{TV} = -33^\circ, \qquad \rho_A^{VT} = 1.20, \qquad \phi_A^{VT} = -60^\circ$$

but no dynamical explanation is offered

Conclusions

- Search for NP in the systems where null effects are predicted by SM, e.g. CP violation in D sector.

- Current B-CP puzzles & polarization anomaly do not necessarily imply NP