B Meson Physics with Jon

Michael Gronau , Technion

Jonathan Rosner Symposium

Chicago, April 1, 2011

Jon's Academic Ancestors

Jon's academic ancestors

were excellent teachers

combined theoretical and experimental work

PhD with Sam Treiman, Princeton 1965

$$\Downarrow$$

PhD with John Simpson & Enrico Fermi, Chicago 1952

A Brief History of Collaboration

- 1967 – 1969: PhD at Tel-Aviv Univ, JLR visiting lecturer

  Duality diagrams $\Rightarrow$ Veneziano formula $\Rightarrow$ String theory

- 1984 : 2 papers on heavy neutrinos
- 1988 – 2011: 4 papers on $D_{(s)}$ decays, D^0-$\bar{D}^0$ mixing

  US-Israel BSF 60 papers on B physics

  18 with Jon's PhD students & postdoc

- Jon's PhD students working on B physics:

David London	Isard Dunietz	Alex Kagan
James Amundson	Aaron Grant	Mihir Worah
Amol Dighe	Zumin Luo	Denis Suprun

Jon's Postdoc: Cheng-Wei Chiang

History & Future of Exp. B Physics

- 1980's & 1990's: CLEO at CESR, ARGUS at DESY
- 1990's & 2000's: CDF and D0 at Tevatron
- 2000's : BaBar at SLAC, Belle at KEK

1964-2000: small CPV in K, 2000-2011: large CPV in B

Theoretical progress in applying flavor symmetries & QCD to hadronic B decays, and lattice QCD to K & B parameters

Culminating in Nobel prize for Kobayashi & Maskawa

CPV in B & K decays is dominated by one phase

- Future : LHCb, ATLAS, CMS at the LHC

Super-KEKB 2014? SuperB-Frascati 2016?

Will look for small ($< 10\%$) deviations from CKM framework

Unitarity Triangle

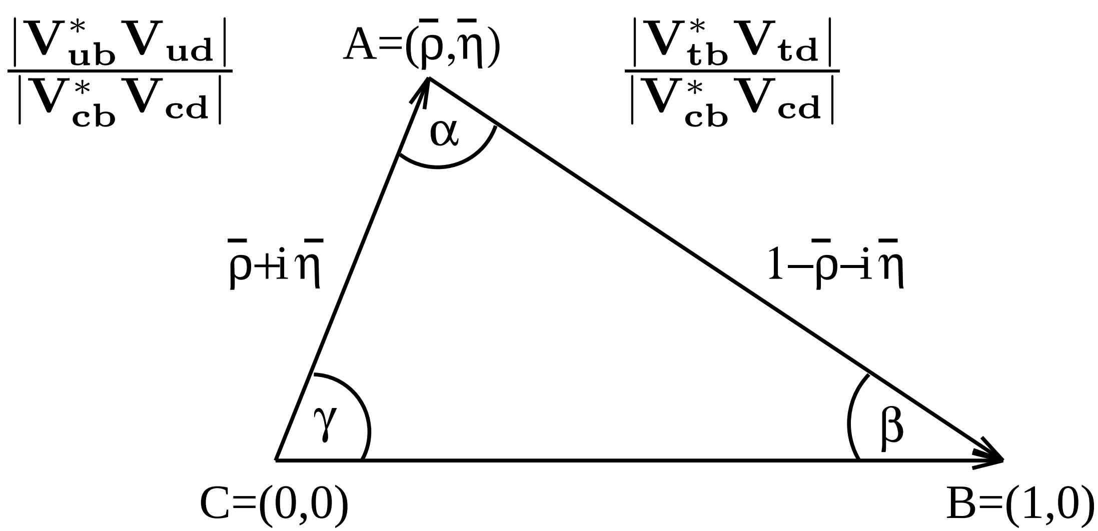
Up & down quark couplings to W are given by

$$\lambda = \sin\theta_c = 0.225$$

$$V_{\mathrm{CKM}} = \begin{array}{c|ccc} & d & s & b \\ \hline u & 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ c & -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ t & A\lambda^3(1-\bar\rho - i\bar\eta) & -A\lambda^2 & 1 \end{array}$$

Wolfenstein 1983

$$\mathbf{V^*_{ub}V_{ud}} + \mathbf{V^*_{cb}V_{cd}} + \mathbf{V^*_{tb}V_{td}} = \mathbf{0}$$ normalize by $|\mathbf{V^*_{cb}V_{cd}}| = A\lambda^3$

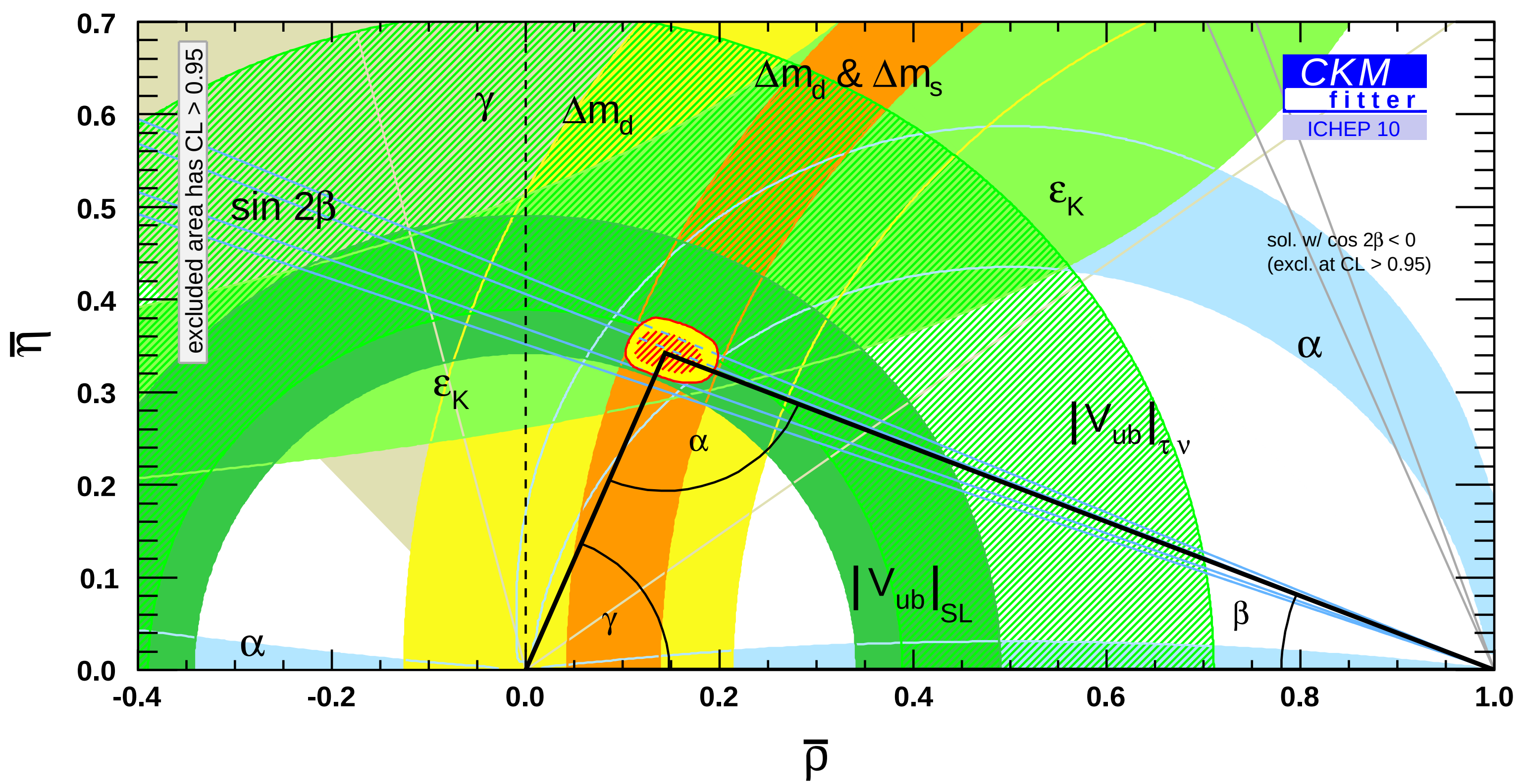


Present Status of CKM Fit

$\mathbf{A{=}0.81{\pm}0.02},\ \lambda\mathbf{{=}0.2254{\pm}0.0008},\ \bar{\rho}\mathbf{{=}0.14{\pm}0.02},\ \bar{\eta}\mathbf{{=}0.34{\pm}0.02}$

$\beta = (21.8 \pm 0.9)^\circ,\ \alpha = (91.0 \pm 3.9)^\circ, \gamma = (67.2 \pm 3.9)^\circ$

Dir. meas: $\beta = (21.1 \pm 0.9)^\circ,\ \alpha = (89.0 \pm 4.3)^\circ, \gamma = (71 \pm 23)^\circ$



CP Asymmetries in B Decays

CP asymmetries in $B_{(s)}$ *decays*

determine angles of unitarity triangles

$$A_{\mathrm{CP}}(B \to f) \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

Some asymmetries are sensitive

to physics beyond the Standard Model

Next: Five examples

B^0-$\bar{B}^0$ oscillations and decay

Golden case $\mathbf{B^0(t) \to J/\psi K_S}$ (CP eigenstate)

Interference between B^0-$\bar{B}^0$ mixing and decay

$$|B^0\rangle \to \begin{cases} |B^0\rangle \cos(\Delta m t/2) & \times A(B^0 \to \psi K_S) \\ |\bar{B}^0 > \sin(\Delta m t/2) i e^{-2i\beta} & \times A(\bar{B}^0 \to \psi K_S) \end{cases}$$

Assume single dominant weak amplitude for $b \to c\bar{c}s$

$$A(B^0 \to J/\psi K_S) = A(\bar{B}^0 \to J/\psi K_S)$$

$$\mathbf{CP\ Asym(t)} \equiv \frac{\Gamma(\bar{B}^0(t) \to \psi K_S) - \Gamma(B^0(t) \to \psi K_S)}{\Gamma(\bar{B}^0(t) \to \psi K_S) + \Gamma(B^0(t) \to \psi K_S)}$$

$$= \sin(2\beta) \sin(\Delta m t)$$

(Bigi & Sanda 1981)

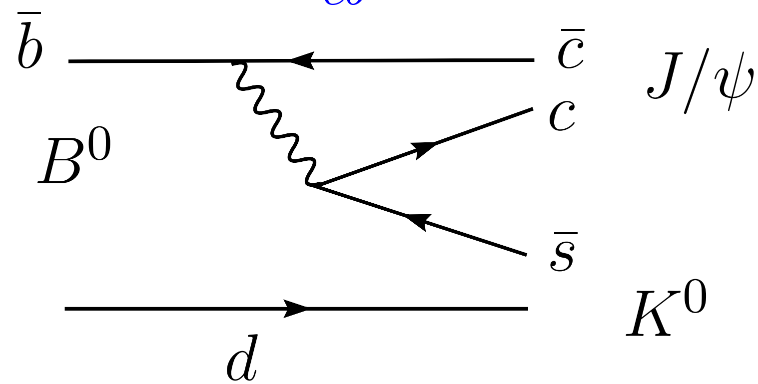
1. Th. Precision of β in $B^0 \to J/\psi K^0$ MG & JLR 2009

Dominant ("color-suppressed") tree $T \propto V_{cb}^* V_{cs}$

T includes P_{ct} using unitarity

$$V_{tb}^* V_{ts} = -V_{ub}^* V_{us} - V_{cb}^* V_{cs}$$

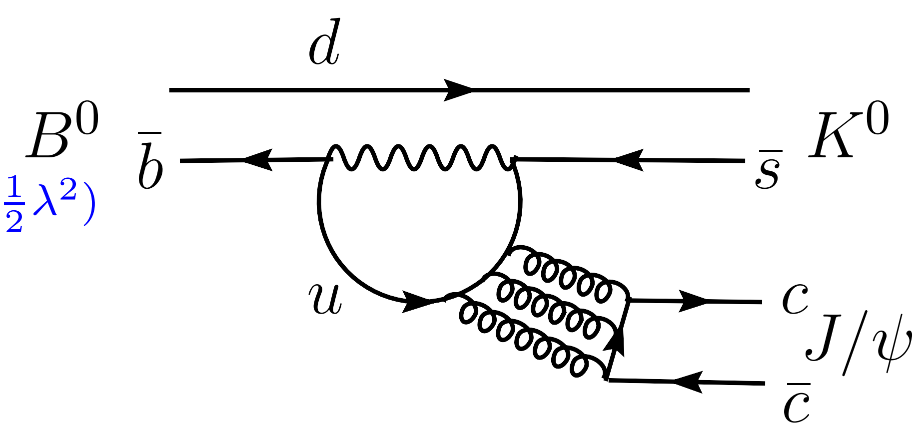
t quark integrated over



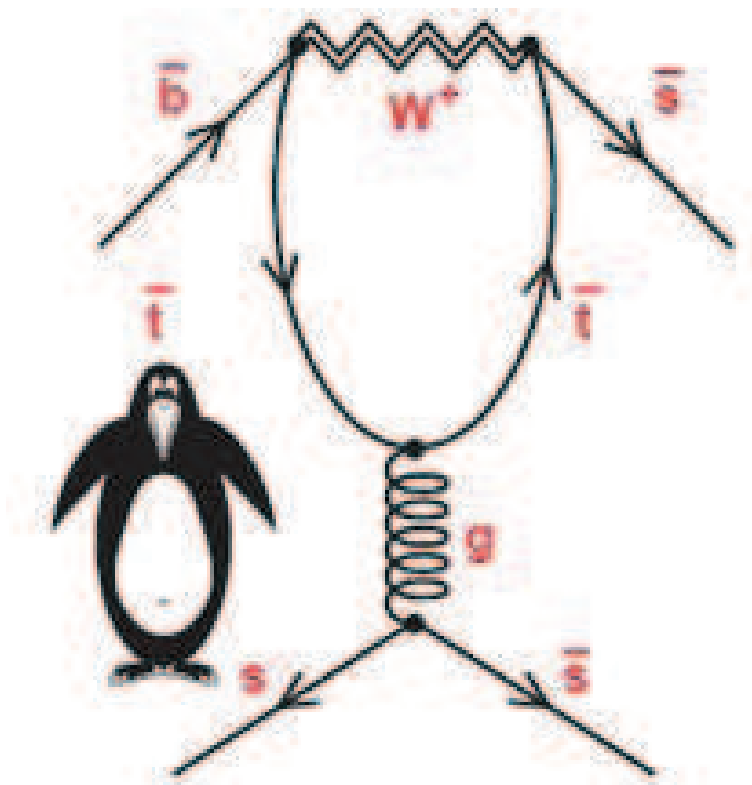
Small doubly CKM-suppressed ("penguin") $P \propto V_{ub}^* V_{us}$

3 suppressions:

- $|V_{ub}^* V_{us}|/|V_{cb}^* V_{cs}| = 0.02$ $(\sim \frac{1}{2}\lambda^2)$
- Loop factor (absorptive part)
- OZI



Artist’s work for Penguin Diagram



$\xi \equiv |P/T| = ?$

$$\mathbf{A}_{\rm CP}(\mathbf{t}) = -\mathbf{C}\cos(\mathbf{\Delta m t}) + \mathbf{S}\sin(\mathbf{\Delta m t})$$

$$\mathbf{C} = -\mathbf{2}\xi\sin\delta\sin\gamma, \quad \mathbf{S} = \sin\mathbf{2}\beta + \mathbf{2}\xi\cos\mathbf{2}\beta\cos\delta\sin\gamma$$

ξ & δ (strong phase) introduce uncertainty in $\sin 2\beta$

- Crude estimate $\xi < 10^{-2}$ (MG 1989)
- Perturbative estimates of ξ (QCDF, 2004; PQCD, 2007) rely on crude estimates of $\langle J/\psi K^0|(\bar{c}T^{\mathbf{a}}c)_V(\bar{b}T^{\mathbf{a}}s)_{V-A}|B^0\rangle$
- Absorptive part of u-quark loop (Bander, Silverman, Soni 1979) may be enhanced by long-distance rescattering
- Upper bound $\xi < 10^{-3}$ from long-distance rescattering
  Next 3 slides (MG & JLR 2009)

Bound on ξ from L-D Rescattering

- $\mathcal{S} = \mathcal{S}_0 + i\mathcal{T}$ $\quad$ $\mathcal{S}_0$: Strong interaction scattering

  $\mathcal{T} = \mathcal{T}^c\ (\propto V_{cb}^* V_{cs}) + \mathcal{T}^u\ (\propto V_{ub}^* V_{us})$: Weak interaction

- $\mathcal{S}^\dagger \mathcal{S} = 1 \qquad \mathcal{T} = \mathcal{S}_0 \mathcal{T} \mathcal{S}_0$

  Rescattering formula: $\quad$ absorptive part of u-quark loop

  $$\langle \mathbf{J/\psi K^0} | \mathcal{T}^\mathbf{u} | \mathbf{B^0} \rangle = \mathbf{\Sigma_f} \langle \mathbf{J/\psi K^0} | \mathcal{S}_\mathbf{0} | \mathbf{f} \rangle \langle \mathbf{f} | \mathcal{T}^\mathbf{u} | \mathbf{B^0} \rangle$$

  $$f(J{=}0, P{=}{-1}) = K^*\pi, \rho K, K^*\eta^{(\prime)}, (K^*\rho)_{P\,wave} \cdots (f \neq K\pi)$$

- $\mathcal{S}_0$ conserves P, T: $\quad |\langle J/\psi K^0 | \mathcal{S}_0 | f \rangle| = |\langle f | \mathcal{S}_0 | J/\psi K^0 \rangle|$

  detailed balance

  Need upper bound on $|\langle f | \mathcal{S}_0 | J/\psi K^0 \rangle|$ (OZI-suppressed)

Upper Bound on ξ (cont.)

- Apply rescattering formula to $\langle f|\mathcal{T}^c|B^0\rangle$ and saturate sum by a single $D^{*-}D_s^+$ (“charming penguin“) state:

  $|\langle f|\mathcal{T}^c|B^0\rangle| \geq |\langle f|\mathcal{S}_0|D^{*-}D_s^+\rangle||\langle D^{*-}D_s^+|\mathcal{T}^c|B^0\rangle|$ (next)

- Replace $D^{*-}D_s^+$ by $J/\psi K^0$ and use **strong inequality**

  (OZI-forb) $|\langle f|\mathcal{S}_0|J/\psi K^0\rangle| < |\langle f|\mathcal{S}_0|D^{*-}D_s^+\rangle|$ (OZI-allow)

- $|\langle|\langle J/\psi K|\mathcal{T}^c|B^0\rangle|/|D^{*-}D_s^+|\mathcal{T}^c|B^0\rangle| = \frac{1}{3}$ from decay rates

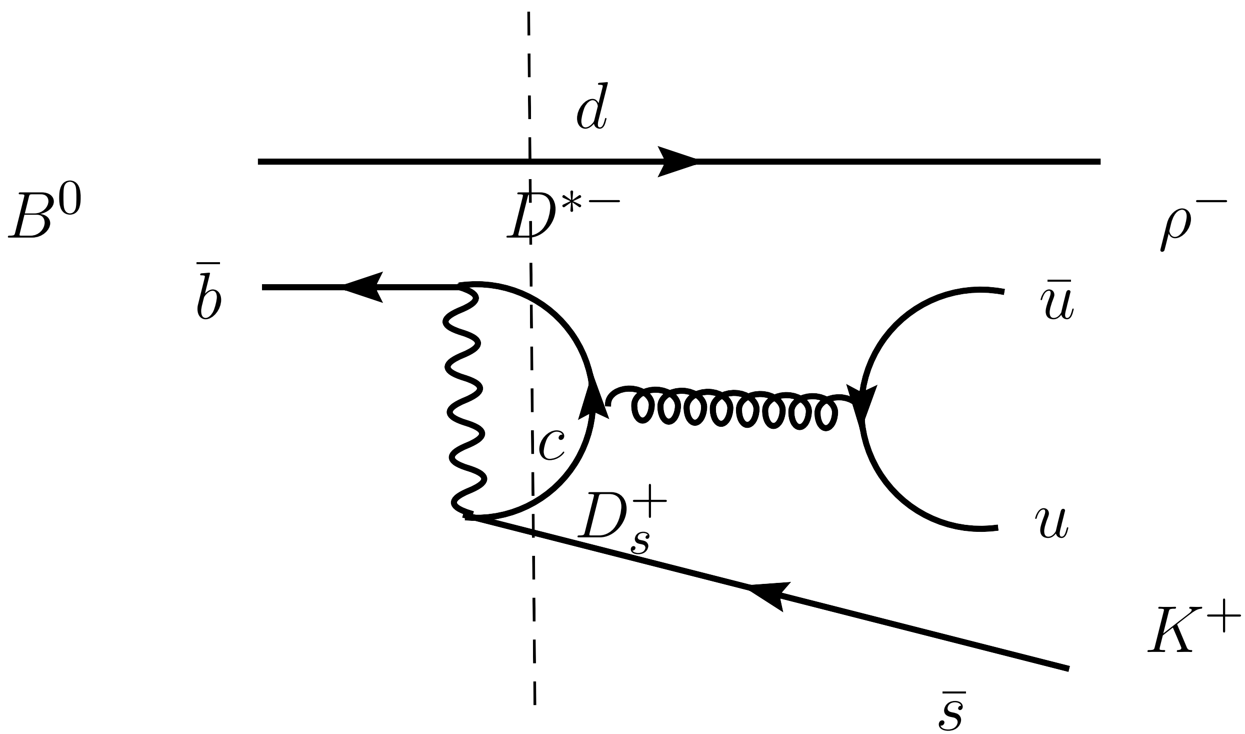
$$\boxed{\xi_f \equiv \frac{|\langle J/\psi K^0|\mathcal{S}_0|f\rangle\langle f|\mathcal{T}^u|B^0\rangle|}{|\langle J/\psi K^0|T|B^0\rangle|} \underset{\text{strong}}{<} \frac{1}{3}\frac{|\langle f|\mathcal{T}^u|B^0\rangle|}{|\langle f|\mathcal{T}^c|B^0\rangle|}\left(\frac{|\langle f|T|B^0\rangle|}{|\langle J/\psi K^0|\mathcal{T}|B^0\rangle|}\right)^2}$$

contribution of f to ξ flavor SU(3) fit, QCDF, PQCD   ratio of exp. BR

- Typically $\xi_f < 10^{-4}$

"Charming Penguin"

Example $f = \rho^- K^+$: $B^0 \to D^{*-} D_s^+ \to \rho^- K^+$



Flavor Symmetries (examples 2, 3, 4)

Isospin symmetry

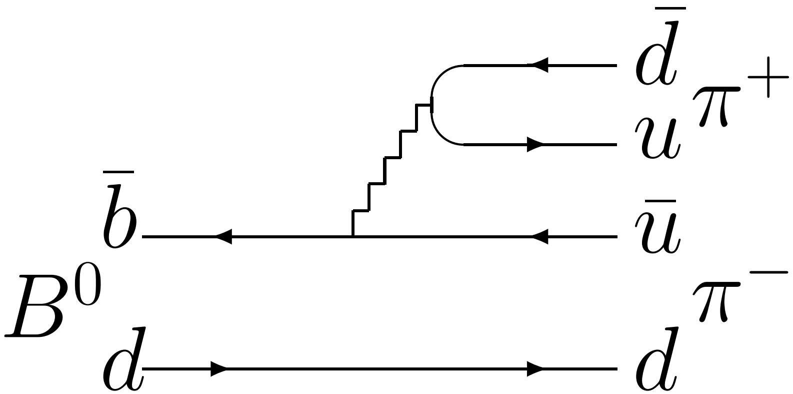
Corrections $\frac{m_d - m_u}{\Lambda_{\mathrm{QCD}}} \sim 0.02$

Flavor SU(3)

Corrections $\frac{m_s - m_d}{\Lambda_{\mathrm{QCD}}} \sim 0.3$

2. Isospin for α in $B^0 \to \pi^+\pi^-,\ \rho^+\rho^-$

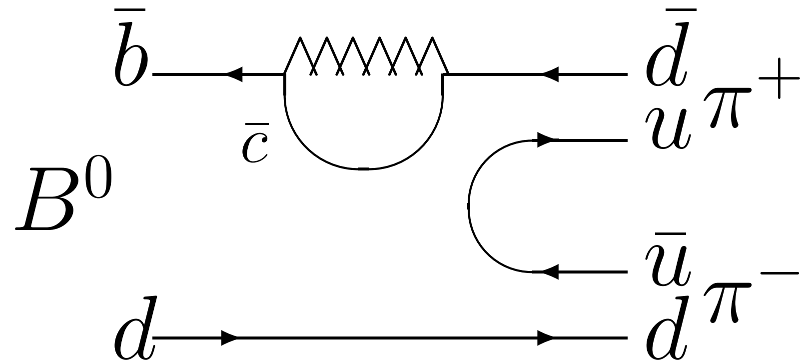
Tree $V_{ub}^* V_{ud} \sim \frac{1}{2}\lambda^3$



weak phase γ

$\Delta I = 1/2, 3/2$

Penguin $V_{cb}^* V_{cd} \sim \lambda^3$



another weak phase

$\Delta I = 1/2$

$$A(B^0 \to \pi^+\pi^-)/\sqrt{2} + A(B^0 \to \pi^0\pi^0) = A(B^+ \to \pi^+\pi^0)$$

$\Delta I = 3/2$, weak phase γ

I-triangle eliminates “penguin pollution" (MG & D. London 1990)

Same $B \to \rho\rho$ almost 100% long. polarized, f_L^{+-}=0.98 $\pm$0.02

$\alpha = 180^\circ - (\beta + \gamma) = (89.0 \pm 4.3)^\circ$ smaller theor. uncertainty

3. Isospin for New Physics in $B \to K\pi$

1. $B \to K\pi$ from $b \to s\bar{q}q$ $(q = u, d)$: $\Delta I = 0, 1$ $\quad$ ($I_{K\pi} = \frac{1}{2}, \frac{3}{2}$)

   Isospin reflection $u \leftrightarrow d$ 3 isospin amplitudes

   $$A(B^+ \to K^0\pi^+) = A_0 + A_1 \qquad -A(B^0 \to K^+\pi^-) = A_0 - A_1$$

   $$\sqrt{2}\,A(B^+ \to K^+\pi^0) = A_0 + A_1' \qquad \sqrt{2}\,A(B^0 \to K^0\pi^0) = A_0 - A_1'$$

2. Isospin quadrangle relation for amplitudes (and c.c.)

   $$A(K^0\pi^+) - A(K^+\pi^-) + \sqrt{2}A(K^+\pi^0) - \sqrt{2}A(K^0\pi^0) = 0$$

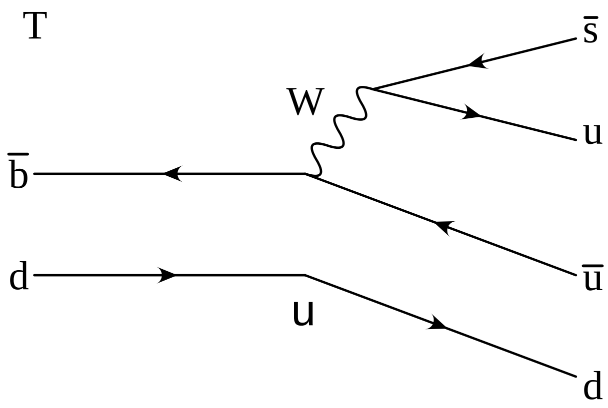
   $\Delta I = 0$ and $\Delta I = 1$ vanish separately also beyond SM

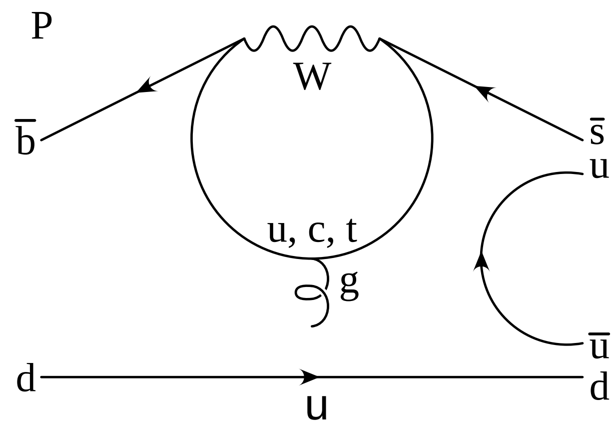
3. Peng-dominance: $P \in A_0$, $\frac{\mathrm{nonP}}{P} \leq 0.1$ [$B \to K\pi$ fit, QCDF, PQCD]

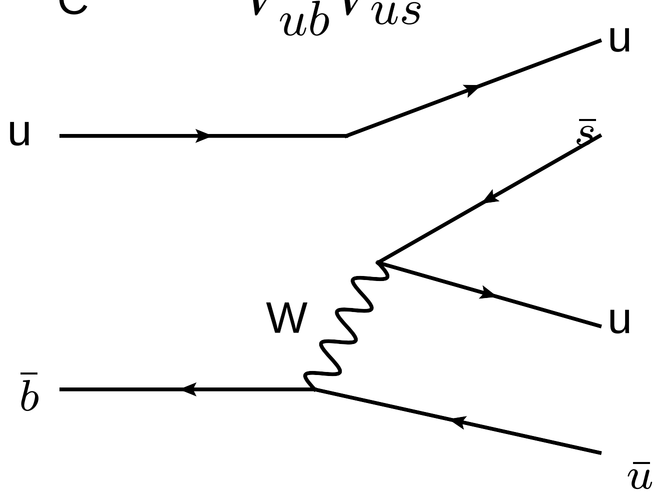
4. $2, 3 \Rightarrow$ Relation for CP Rate difference $\Delta \equiv \Gamma(\bar{K}\bar{\pi}) - \Gamma(K\pi)$

   $$\Delta(K^0\pi^+) + \Delta(K^+\pi^-) - 2\Delta(K^+\pi^0) - 2\Delta(K^0\pi^0) = \mathcal{O}\left[\left(\frac{\mathrm{nonP}}{P}\right)^2\right]$$

Penguin and Tree in $B \to K\pi$







$V_{ub}^* V_{us}$

$V_{cb}^* V_{cs}$ dominant

$$|V_{cb}^* V_{cs}|/|V_{ub}^* V_{us}| = 50 \quad (\sim 2\lambda^{-2})$$

Asymmetry Sum Rule & $B \to K\pi$ "Puzzle"

- $\Gamma(K^+\pi^-) : \Gamma(K^0\pi^+) : \Gamma(K^+\pi^0) : \Gamma(K^0\pi^0) \approx 2 : 2 : 1 : 1$

$$\boxed{A_{CP}(K^0\pi^+) + A_{CP}(K^+\pi^-) \overset{1\%}{\approx} A_{CP}(K^+\pi^0) + A_{CP}(K^0\pi^0)}$$

0.009 ± 0.025 $\quad -0.098^{+0.012}_{-0.011}$ $\quad 0.050 \pm 0.025$ $\quad -0.01 \pm 0.10$

MG & JLR, 2005 **predict** -0.14 ± 0.04

Violation of sum rule requires new $\Delta I = 1$ amplitude

- Simplifying $\underbrace{}_{}$ $\boxed{\overset{P+T}{A_{CP}(K^+\pi^-)} \approx \overset{P+T+C}{A_{CP}(K^+\pi^0)}}$ does not work

$|C| \ll |T|$ MG & JLR 1999 puzzle, Belle, Nature 03/2008

2 different asymm. require $|C/T| = O(1)$ & large $\arg(C/T)$

Difficult to accommodate in QCD (QCDF, PQCD)

large $\mathcal{B}(B \to \pi^0\pi^0)$

Consistent with flavor SU(3) fits to $B \to P_1 P_2$ $(P_i = \pi, K, \eta, \eta')$

4. Flavor SU(3) Fits to $B \to PP, VP$

Best fits, applying flavor SU(3) symmetry (including SU(3) breaking) to $\mathcal{O}(100)$ rates and asymmetries for charmless $B \to PP, VP$, have reasonable qualities ($\chi^2/\mathrm{d.o.f.} \sim 1$) and obtain values for $(\bar{\rho}, \bar{\eta})$ consistent with CKM fits

Work of MG & JLR with

D. London

diagrams $T, C, P, \ldots$ are equivalent to SU(3) amplitudes

C. W. Chiang

D. Suprun

Z. Luo

5. Anomalous Like-sign $\mu\mu$ Asymmetry

$D0$ at Tevatron $\bar{p}p$: $\frac{N^{++}-N^{--}}{N^{++}+N^{--}} = [-0.957 \pm 0.251 \ \pm 0.146]\%$

after subtracting "measured" background (kaon asym. $=5\%$)

interpreted as due to CPV in B^0–$\bar{B}^0$ or B_s–$\bar{B}_s$ mixing $\approx (A^d_{sl}+A^s_{sl})/2$

CKM: $A^b_{sl} = \mathcal{O}(10^{-4}) \Rightarrow 3.2\sigma$ anomaly D0: PRL+PRD summer 2010

D0 employed 16 systematic checks for stability of their result

All checks involved loose cuts on the muon impact parameter relative to the primary vertex

None of the tests shows origin of the asym. is neutral B decays

$\Rightarrow \quad \sim 100$ theoretical papers of great variety involving new sources of CP violation in $B_s - \bar{B}_s$ mixing:

4th family of quarks, FC neutral scalar, FC Z exchange, SUSY models, leptoquarks, warped extra dimensions, CPT violation

Background Check for Asymmetry

Propose a test for sensitivity of asymmetry to the μ impact parameter b relative to primary vertex MG & JLR, PRD 2010

Take $b \to 0$: Can D0 infer 0 asymmetry when 0 is expected?

- At Tevatron: μ's from $B_{(s)}$'s have $\langle b \rangle = 300 - 450 \mu$m (CDF)

  also calculated using $\langle p_B \rangle$ & isotropy of μ in B rest frame

- $b < b_0$: Remaining fraction of $\mu\mu$ from 2 B's$= \left(1 - e^{-\frac{b_0}{\langle b \rangle}}\right)^2$

vertex reconstruction precicion $20 - 40 \mu$m

$$\text{Fraction } (b_0 = 100 \mu\text{m}) = \begin{cases} 0.08, \langle b \rangle = 300 \mu\text{m} \\ 0.04, \langle b \rangle = 450 \mu\text{m} \end{cases}$$

100μm b-cut reduces dimuon signal relative to background

- If bkgd is subtracted correctly and if asymmetry is from B_s-$\bar{B}_s$ mixing then net asymmetry $\approx A^s_{sl}$ should increase by 2

  $(\Delta m_s \gg \Delta m_d)$

27 Years of Collaboration

- I have learned from you Jon five or six C’s:
  - Clear & Critical thinking
  - Combine methodology & efficiency
  - Care for details
  - Careful with results
  - Crisp & pedagogical writing
- Collaboration led to friendship

Wishing you Jon many years

of good health & productive research

Looking forward to continue our collaboration