B Physics at the Tevatron

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Fermilab

- Introduction
  - Motivation; Status of CKM
- How to look for New Physics?
  - General issues; Examples
- Some important measurements at the Tevatron ...and elsewhere
- Conclusions

Thanks to: A. Falk, Y. Grossman, R. Jesik, R. Kutschke, A. Kronfeld, U. Nierste, Y. Nir, M. Paulini, H. Quinn

Introduction

CPV $= CP$ Violation

SM $=$ Standard Model

NP $=$ New Physics

Flavor Physics

The gauge sector of the SM is precisely tested
Additional links to short distance come from flavor

- Masses are generated by something hideous like

$$\mathcal{L} = \bar{L}_L^i \, \Phi_e^{ij} \, e_R^j + \bar{Q}_L^i \, \Phi_u^{ij} \, u_R^j + \bar{Q}_L^i \, \Phi_d^{ij} \, d_R^j$$

where $i, j =$ generations. Φ_a^{ij} are $SU(2)$ doublets and have non-zero VEV's — but this is all we know

In the SM:

$$\Phi_{e,d}^{ij} = \lambda_{e,d}^{ij} \, \phi \,, \qquad \Phi_u^{ij} = \lambda_u^{ij} \, (i\sigma_2 \, \phi^*) \,,$$

and ϕ is the single Higgs field of EWSB.

$\Rightarrow$ Masses, quark mixing, and CP violation

And then there are neutrinos...

Why B Physics?

1. Understand CP violation
2. Possibilities to observe new physics
3. Stringent tests of the Standard Model

Bits of history:

$K\bar{K}$ mixing $\Rightarrow$ GIM & charm; constrain SUSY, W_R
CP violation $\Rightarrow$ three generations, CKM
$B\bar{B}$ mixing $\Rightarrow$ heavy top

The flavor sector is one of the major problems / constraints for model building

E.g., best sensitivity to some of the particles predicted in the MSSM comes from (crudely speaking)

experiment	energy scale	best sensitivity to
Tevatron	~ 2 TeV	squarks, gluinos
LEP	~ 200 GeV	sleptons, charginos
CLEO $B \to X_s \gamma$	~ 5 GeV	charged Higgs

Y. Nir

Why is CPV interesting?

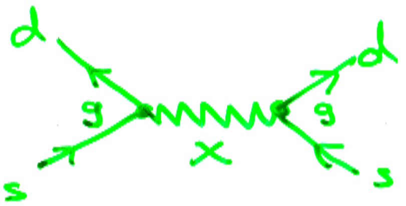
- ☆ CPV is one of the least tested aspects of the SM
- ☆ Almost any extension of the SM has new sources of CPV
- ☆ The observed baryon asymmetry of the Universe requires new CPV

⇓

It is Possible, Likely, Unavoidable that the SM picture of CPV is Incomplete

(The most recycled slide of the B workshops...)

Suppose exchange of very heavy boson X with mass M_X is responsible for a fraction f of measured value of ε



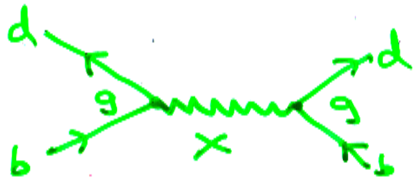
$$f|\varepsilon| \sim \left|\frac{\mathrm{Im}\, M_{12}}{\Delta m_{LS}}\right| \sim \left|\frac{g^2 \Lambda_{QCD}^3}{M_X^2\, \Delta m_{LS}}\right|$$

0.3 GeV

3.5 x 10^{-15} GeV

$$\Rightarrow M_X \sim 6\times 10^7\, (g/\sqrt{f})\ \mathrm{GeV}$$

Similarly for $B^0-\bar{B}^0$ mixing

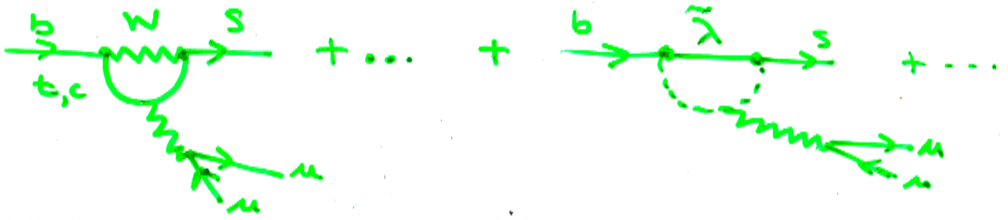


$$f\, \Delta m_{Bd} \sim \frac{g^2 \Lambda_{QCD}^3}{M_X^2}$$

3.1 x 10^{-13} GeV

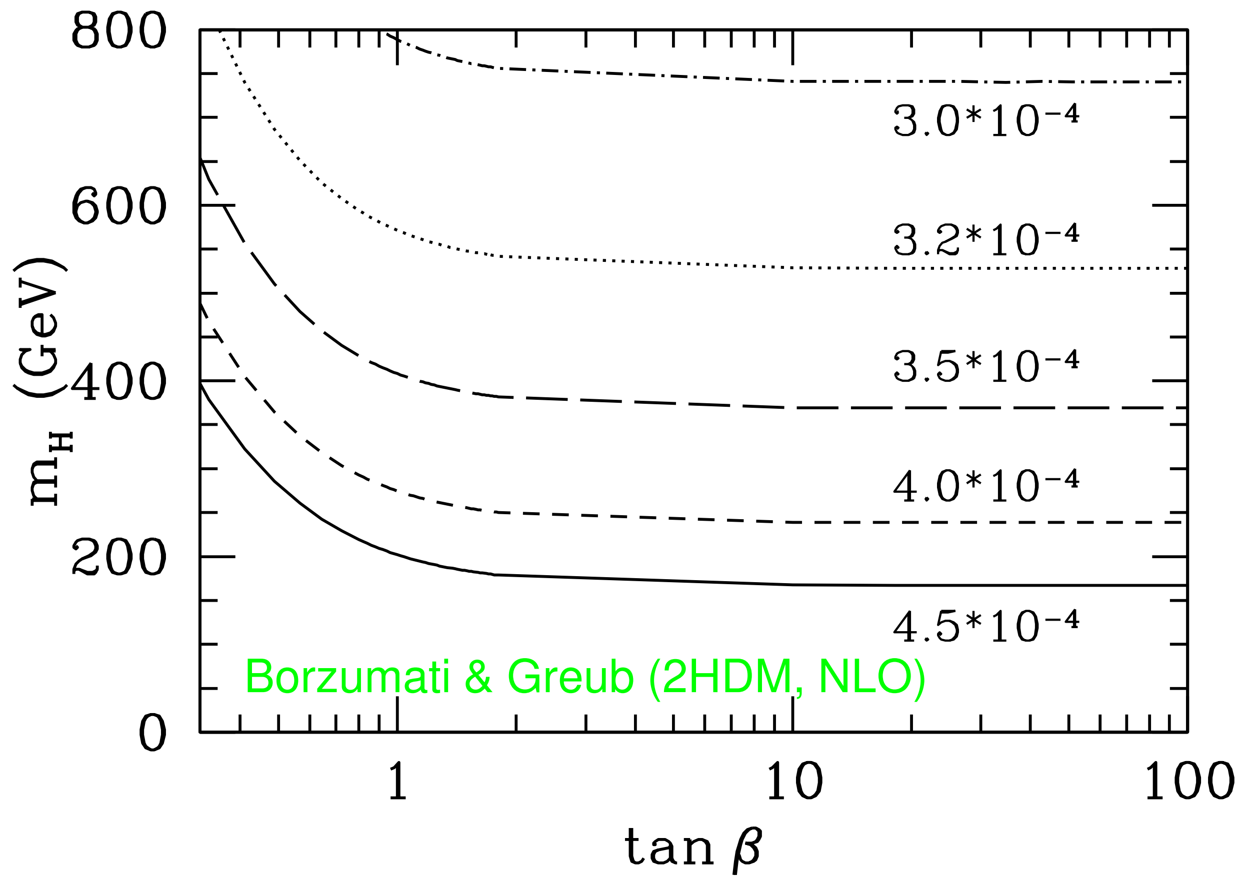
$$\Rightarrow M_X \sim 3\times 10^5\, (g/\sqrt{f})\ \mathrm{GeV}$$

Or new particles not too much heavier than W can occur in loops. Happens, for example, in low energy supersymmetry Eg. $\bar{B}\to X_s \mu^+\mu^-$



$$\boxed{B \to X_s \gamma}$$

CLEO: $Br(B \to X_s\gamma) = (2.32 \pm 0.67) \times 10^{-4}$



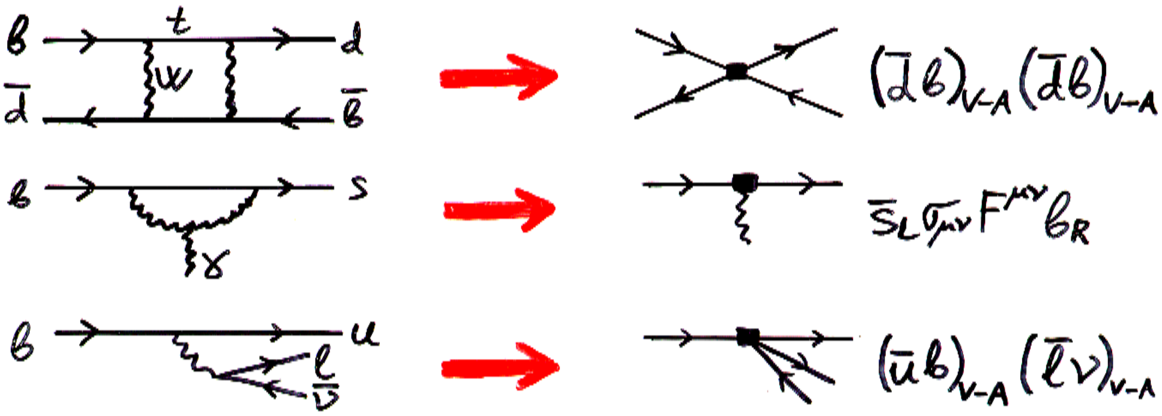
Excluded $m_{H^\pm}$ region is below the curves

Sparticle loops can weaken these bounds

Physics at $\sim 5\,$GeV

All flavor changing processes are mediated by "non-renormalizable" operators... dozens of them:

$\sim$ weak scale $\qquad\qquad$ $\sim 5\,$GeV



- Higher dimension operators

  $\Longleftrightarrow$ exchange of heavy particles

Are all the higher dimension flavor changing operators which occur at $\sim 5\,$GeV consistent with integrating out W, Z, t? At what level can we check?

$\Rightarrow$ *Right operators? Right coefficients?*

Need to understand hadronic physics from first principles

...possible for B's

Unitarity Triangle

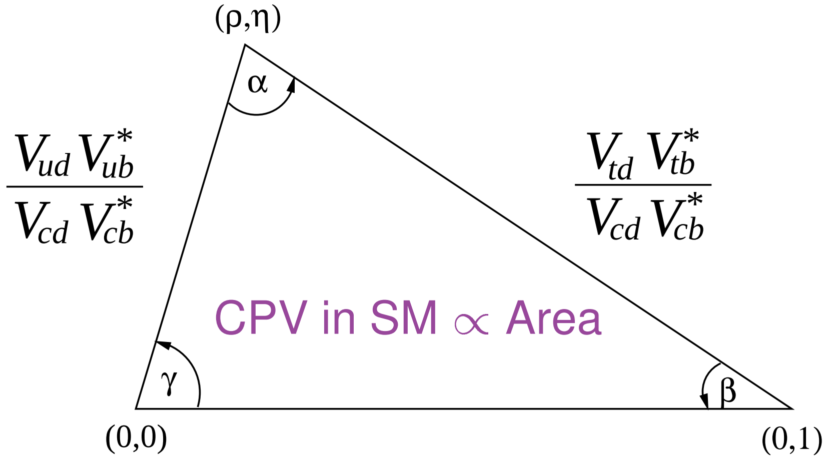
- Charged current weak interactions:

$$(u,\, c,\, t) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \qquad \begin{array}{c} \sim 1 \\ \sim \lambda \\ \sim \lambda^2 \\ \sim \lambda^3 \end{array}$$

$\Rightarrow$ $\mathbf{V}_{\rm CKM}$ is the only source of CPV in the SM

$\Rightarrow$ Elements depend on 4 real parameters in the SM (3 angles $+$ 1 CPV phase)

- Unitarity: $V_{ud}\,V_{ub}^* + V_{cd}\,V_{cb}^* + V_{td}\,V_{tb}^* = 0$



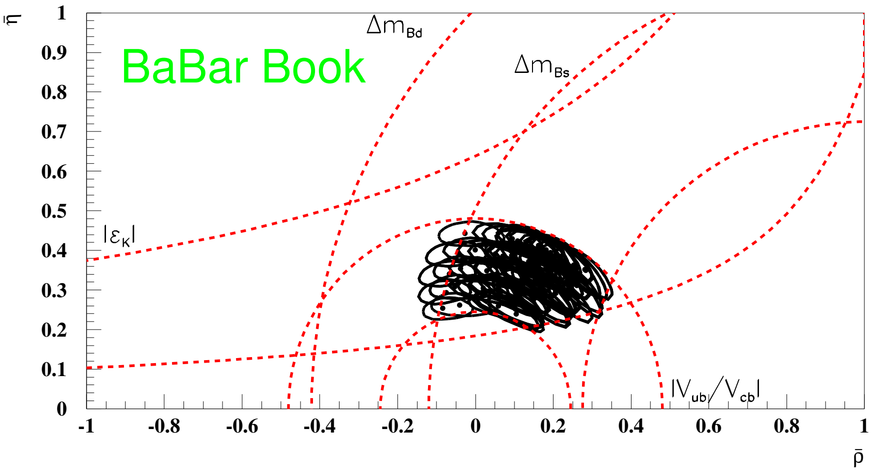
$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

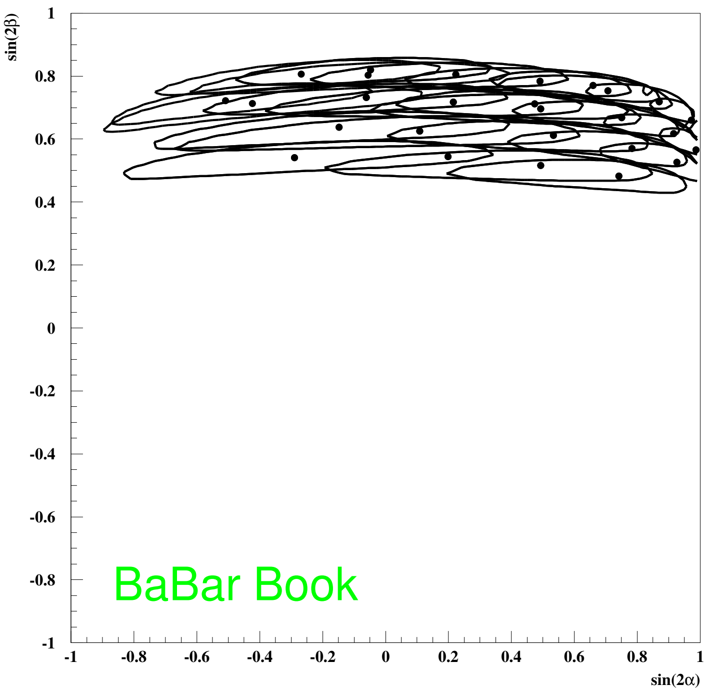
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

The angles and sides are directly measurable

Present Constraints



Observed CPV in K system is at the right level, but hadronic uncertainties preclude precision tests



Discrete ambiguities

$\Downarrow$

The allowed region is "larger" in the $\sin 2\alpha - \sin 2\beta$ plane

The B System

- While CPV is one of the least tested aspects of the SM, it is no longer a "new phenomenon"

  But... Is the SM the *only* source of CPV?

  Does the SM *fully* explain flavor physics?

  Constrain UT independently in B_d, B_s, K decay

- Are there new particles / interactions in the 100 GeV $-$ 10 TeV region which couple to flavor?

  $\Lambda_{\rm NP} \gg \Lambda_{\rm EW}$: no observable deviation in B decays $\Rightarrow$ precision flavor measurements

  $\Lambda_{\rm NP} \sim \Lambda_{\rm EW}$: dramatic effects are possible (but not guaranteed) $\Rightarrow$ detailed information on NP

- In B decays we can measure phases & magnitudes of CKM elements — must be theoretically clean!

  A few important examples...

Future

What are we after?

- In SM: Only V_{ub} and V_{td} have large phases — any large interference type CPV is a function of these

  One is "easy" to measure: β

  Second can be called: $\alpha,\ \gamma,\ \beta+\gamma,\ 2\beta+\gamma$ ...
  but this does not make any difference...

$\Rightarrow$ Independent measurements are cross checks

- Beyond SM: NP is likely to enter where SM is suppressed: 1) mixing; 2) decays which are loops in SM

  Many phases can be large and different: B_d and B_s mixing, decays. Then "$\alpha,\ \beta,\ \gamma$" is only a language.

  E.g., two "would-be" γ measurements can be sensitive to totally different NP contributions

  Do all possible measurements which have clean interpretation. Correlations narrow down type of NP

$\Rightarrow$ Independent measurements are searching for NP!

The Goal is to Find NP

Q: Big deal... Do all possible tests

A: Some tests are better than others

Q: It's trivial... Check $\alpha + \beta + \gamma = \pi$

A: This is the wrong test

i) In most NP models $\alpha + \beta + \gamma = \pi$

ii) Even if $\alpha + \beta + \gamma \neq \pi$, probably an easier test will show NP first

iii) Takes very long time and hard to do

Find the Good Tests

1. Likely to be sensitive to NP
2. Have small theoretical uncertainties
3. Easy to measure ("easy" $\rightarrow$ possible)

How can NP enter?

1. Two measurements which relate to the same quantity in the SM give incompatible results
2. Angles inconsistent with the sides
3. "Zero prediction observable" found to be large e.g., $a_{CP}(B_s \to \psi\phi)$, $a_{dir}(B \to s\gamma)$, etc.
4. Enhancement of rare decays (B, B_s, K, D)
5. B_s or D mixing incompatible with SM

- These are all easier than checking $\alpha + \beta + \gamma = \pi$ and more sensitive to NP

1.a NP cannot change things we "know"
e.g.: $a_{CP}(\psi K_S) = -a_{CP}(\psi K_L)$

1.b NP unlikely to compete with "large" SM diagrams
e.g.: $a_{CP}(\psi K_S) = -a_{CP}(D^+D^-)$

1.c NP can easily alter SM loops
e.g.: $a_{CP}(\psi K_S) = a_{CP}(\phi K_S)$

$\Rightarrow$ Goal: identify "type 1.c" cases

Workshop on
B Physics at the Tevatron
Run II and Beyond

1. CP Violation

   Conveners: Yossi Nir, Helen Quinn, Manfred Paulini (CDF), Rick Jesik (D0), Tomasz Skwarnicki (BTeV)

2. Semileptonic and Rare Decays

   Conveners: Aida El-Khadra, Mike Luke, Jonathan Lewis (CDF), Andrzej Zieminski (D0), Ron Poling (BTeV)

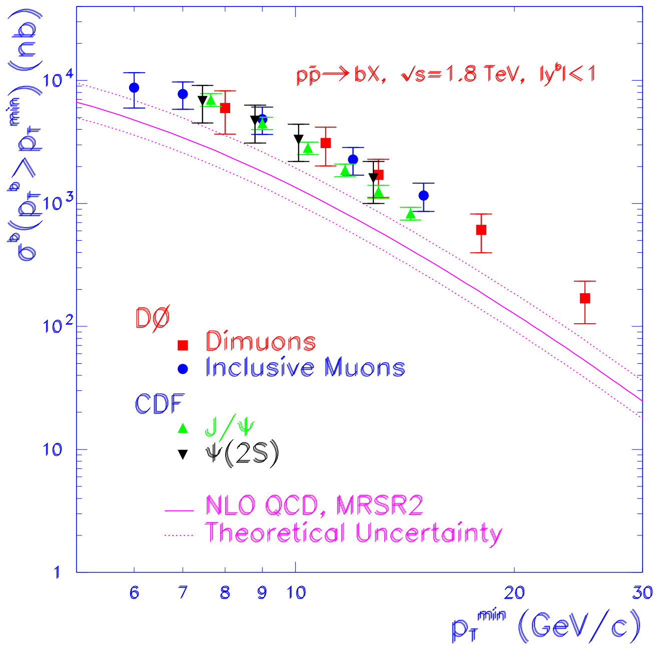
3. Mixing and Lifetimes

   Conveners: Uli Nierste, Misha Voloshin, Christoph Paus (CDF), Neal Cason (D0), Harry Cheung (BTeV)

4. Production, Fragmentation, Spectroscopy

   Conveners: Eric Braaten, Keith Ellis, Eric Laenen, William Trischuk (CDF), Rick Van Kooten (D0), Scott Menary (BTeV)

$b\,\bar{b}$ Production



The $b\,\bar{b}$ production cross section is a difficult problem in perturbative QCD

Several scales enter: m_b, p_T, and $\sqrt{s}$.

Theorists are perplexed

Good news for b physics — maybe bad for QCD...

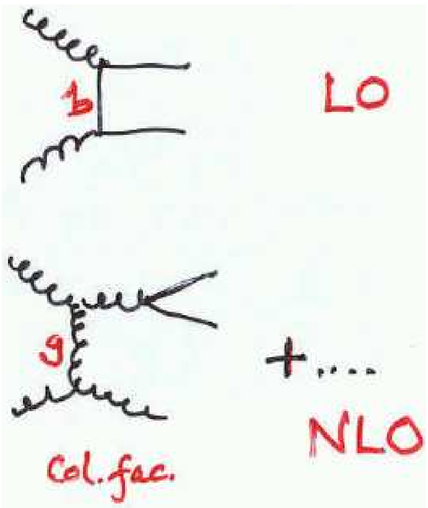
Excess of $b\,\bar{b}$ events is a puzzle

We expect

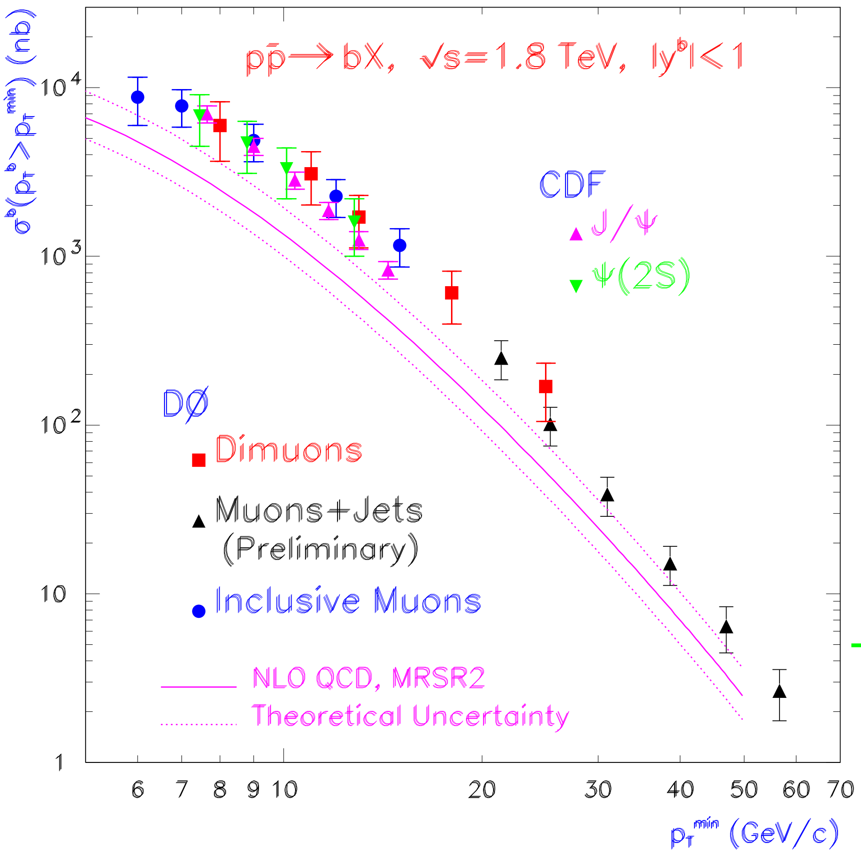
$$\frac{\text{NLO}}{\text{LO}} \text{ to be large}$$

But no reason why

$$\frac{\text{NNLO}}{\text{NLO}} \text{ is large?}$$



More on b Production

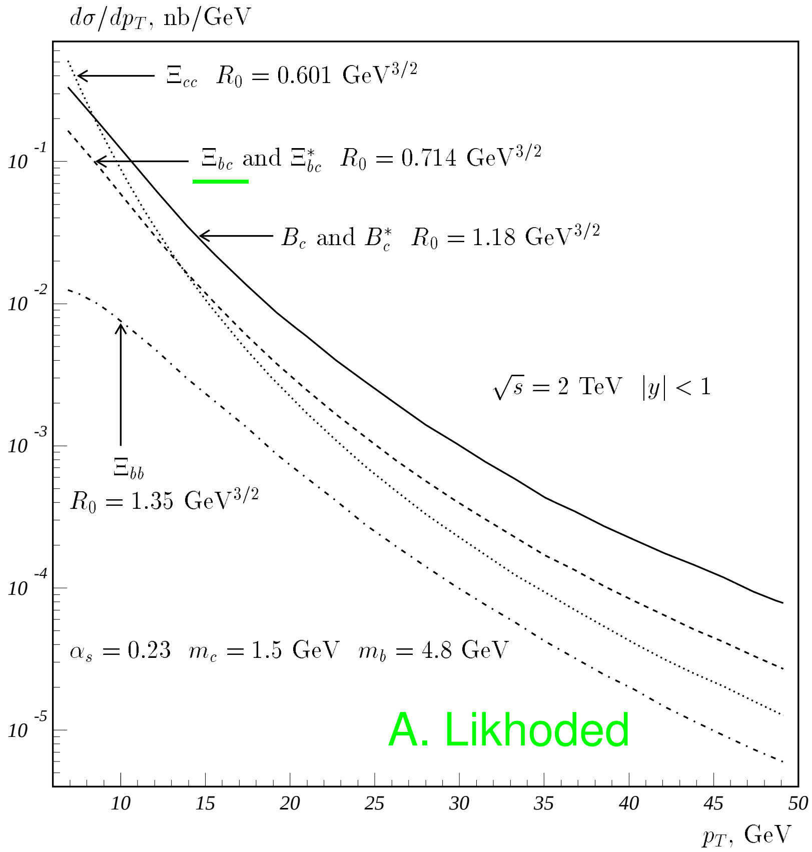


Thanks to A. Maciel

Maybe by $p_T \sim 100$ GeV, theory will work fine...

Run II will have more events at larger P_T, and more double tagged events ($\Rightarrow$ study correlations better)

Discovery of $\bar{Q}Q$ and QQq



B_c: fully reconstruct more $\Rightarrow$ better mass & lifetime

Baryons: BR's to J/ψ modes $\lesssim 10^{-6}$

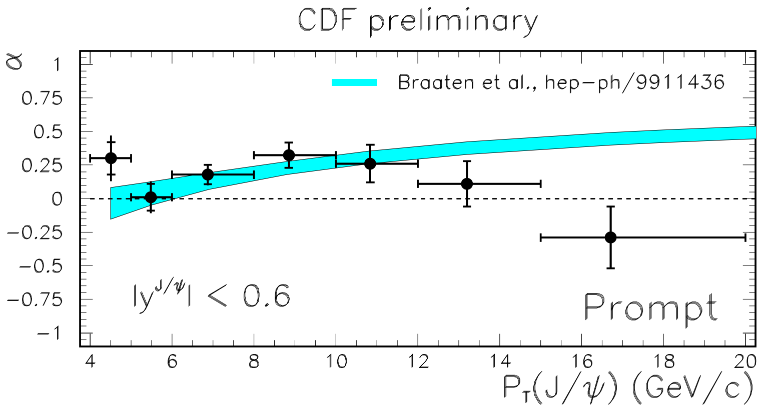
Displaced vertex trigger $\Rightarrow \sim 10^{-4}$ modes

E.g.: $\Xi^+_{bc}(ucb) \to D^{*+}\, p\, K^-$

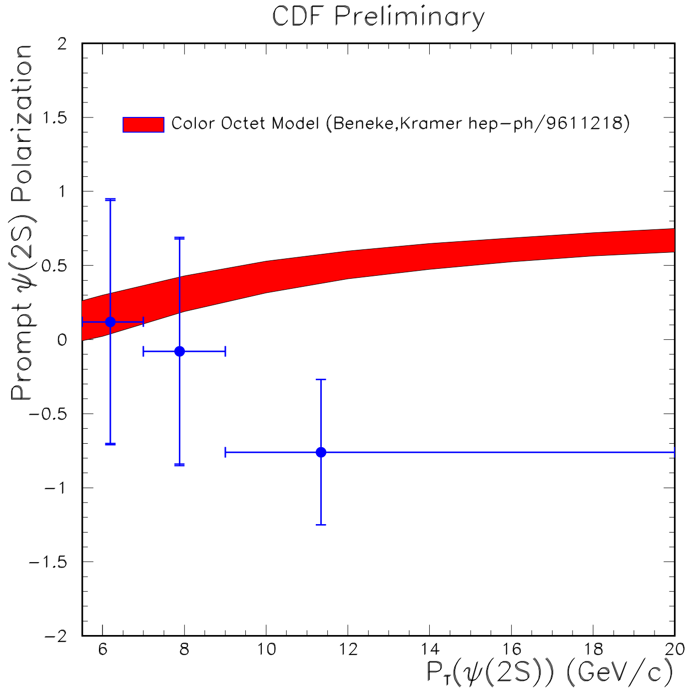
$\hookrightarrow K^-\pi^+\pi^+$

see Keith Ellis' Best Buy list on the web

Quarkonia polarization



Thanks to R. Cropp



Want: 1) clean separation of states with different quantum numbers; 2) distinguish feed-down from direct production; 3) more statistics at higher P_T

Could become a serious problem for NRQCD

Back to CKM

The sides

- NP: compare angles and sides
- Improve present constraints

Sides: $|V_{ub}|$ and $|V_{cb}|$

- Theory error of $|V_{ub}|$ dominates the SM $\sin 2\beta$ range

  Error in ε_K constraint $\sim |V_{cb}|^4$ and B_K

  $|V_{ub}|$, $|V_{cb}|$ measured in semileptonic decays — probably not affected by any new physics

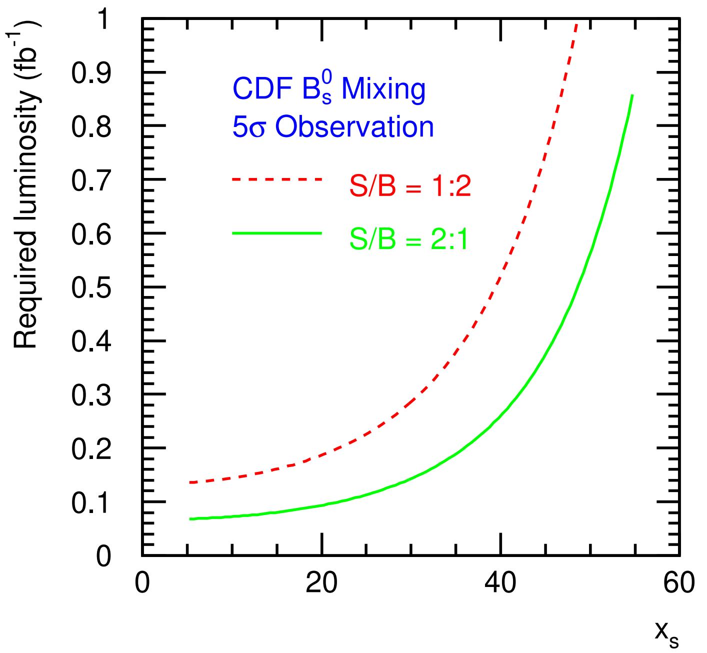
  Would love to give an entire talk on this...
  — it's likely to be left for the e^+e^- B factories

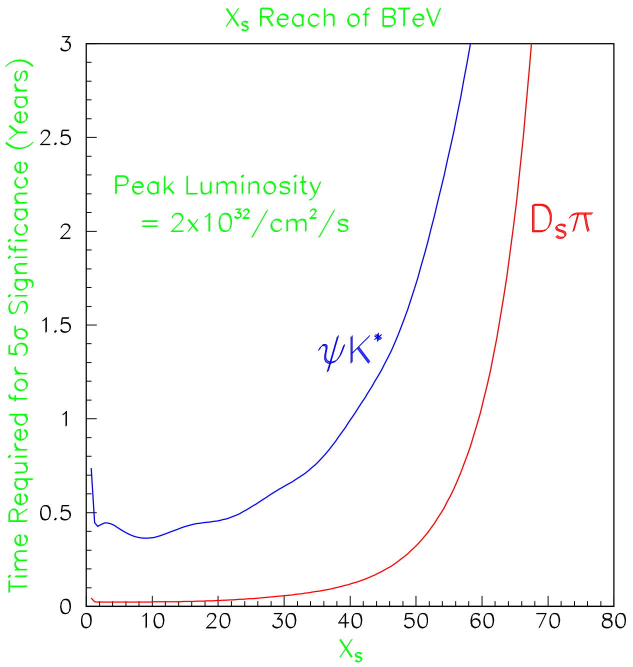
  Lattice QCD will make important impact...
  — give them more $

$\Rightarrow$ $\sigma|V_{ub}| \sim 10\%$ and $\sigma|V_{cb}| \sim 2-3\%$ seems achievable

Sides: $|V_{td}|$ and $|V_{ts}|$

Measure B_s mixing (SM: $20 - 45$)





By the time there is a 5σ observation of x_s, it is a very precise measurement

- Need from lattice QCD: $f_B^2 B_B$ and $f_{B_s}^2 B_{B_s}$

- The ratio $|V_{td}/V_{ts}|$ is easier — need: $\dfrac{f_{B_s}^2 B_{B_s}}{f_{B_d}^2 B_{B_d}}$

This is $= 1$ in $SU(3)$ limit — Chiral logs give ~ 1.3
Lattice: $[1.17(6)]^2$, need unquenched computation

Rare decays

Inclusives: under better theoretical control for now

Exclusives: need form factors (not for CPV!)

Useful relations between form factors from HQS

— ultimately want unquenched lattice calculations

- $B \to X_{s,d}\, \ell^+\ell^-$, $B \to K^{(*)}\ell^+\ell^-$, etc.:
  $|V_{ts}|$, $|V_{td}|$, Higgs, SUSY, ...
  A_{FB} — very sensitive to right handed couplings
- $B_{s,d} \to \ell^+\ell^-$: SM small; could signal NP cleanly
- $B \to X_s\gamma$, $B \to K^*\gamma$: "BaBar territory" (?)
  Room for ideas: get γ polarization from conversion?
- Direct CPV in $B \to K^*\gamma$; lepton no. violation; etc.
- $B \to X_{s,d}\, \nu\bar\nu$ or $B \to K^{(*)}\nu\bar\nu$:
  Very clean — the B physics analog of $K \to \pi\nu\bar\nu$
  (a dream... and no one knows how to measure it)

$\Rightarrow$ **There may be lots of money to be made here...!**

The angles

- NP: search for deviations from SM
- Direct probes of CPV

Angles: β

- Interference between decay with and without mixing

$$\begin{tikzcd} \boxed{B^0} \arrow[rr, "\text{decay}"] \arrow[dr, "\text{mixing}"'] & & \boxed{f_{CP}} = \psi K_S \\ & \boxed{\bar{B}^0} \arrow[ur, "\text{decay}"'] & \end{tikzcd}$$

$$\frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = 2\,\mathrm{Im}\,\lambda_f \sin(\Delta m\, t)$$

$|\lambda_{\psi K_S}| = 1$ because Penguins suppressed by λ^2

$$\arg \lambda_{\psi K_S} = \arg\,(B\,\mathrm{mix}) + 2\arg\,(\mathrm{decay}) + \arg\,(K\,\mathrm{mix})$$

$\Rightarrow$ $\sin 2\beta$ — *Theoretically clean!*

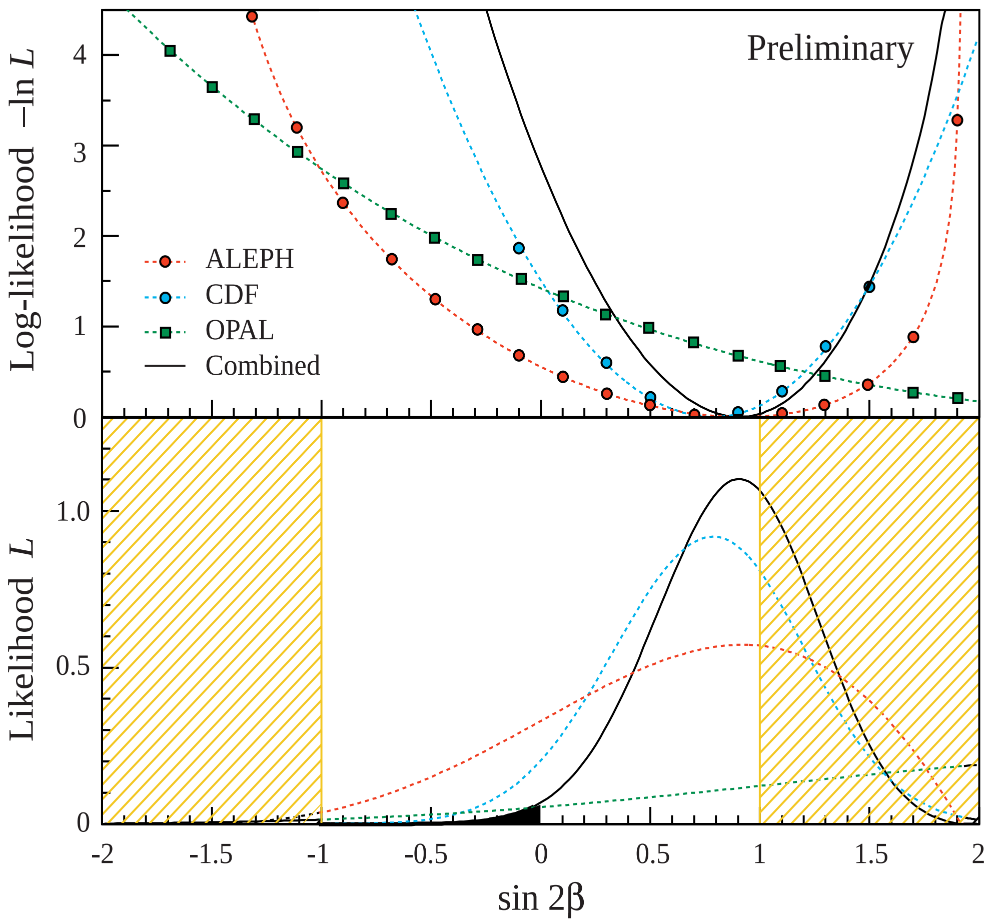
- In the SM both $\left\{ \begin{array}{ll} B \to \psi\, K_S & b \to c\bar{c}s \text{ tree} \\ B \to \phi\, K_S & b \to s\bar{s}s \text{ penguin} \end{array} \right.$

measure $\sin 2\beta$. NP can enter $b \to s\bar{s}s$ penguin, and modify other rare decay rates

$\Rightarrow$ Important to measure same angle in several modes

CP asymmetry in B ->J/Ψ K_s

ALEPH 99-099 conf 99-054



Compare/combine with CDF and OPAL:

$\sin(2\beta) = 0.91$ +- 0.35

$\sin(2\beta) > 0$ at 98.5%CL (CDF alone 93%CL)

Angles: α

- $B^0 \to \pi^+\pi^-$: Penguin / Tree is $20-50\%$ (CLEO)

  Need P/T (incl. phase) from theory.... Theorists cannot compute this reliably

  Penguin contributes to $\Delta I = 1/2$ amplitude only $\Rightarrow$ To get clean information, need $B^0 \to \pi^0\pi^0$ to isolate CP asymmetry in the clean $\Delta I = 3/2$ channel

  Expect $Br(\pi^0\pi^0) \sim 10^{-6}$ — hard, if not impossible

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- $B \to \rho\pi$: Isospin analysis is still possible (Dalitz plot), and $\pi^+\pi^-\pi^0$ final state has two charged tracks

  CLEO: $\begin{cases} Br(\rho^0\pi^+) & (1.0 \pm 0.4) \times 10^{-5} \\ Br(\rho^\pm\pi^\mp) & (3.1 \pm 0.9) \times 10^{-5} \end{cases}$

  ~ 1000 reconstructed events needed

  Takes several$\times 100\,\mathrm{fb}^{-1}$ at BaBar / Belle — similar timescale as BTeV / LHCB

Angles: γ

$$V_{ub} = |V_{ub}| \exp(-i\gamma)$$

- $B_s \to D_s^\pm K^\mp$ — very clean!
  Direct CPV: $b \to u\bar{c}s,\ c\bar{u}s$ — relative strong phase can be determined from the analysis
  Need 4 time-dependent rates for $B_s, \bar{B}_s$
  $D_s^\pm \pi^\mp$ background $\Rightarrow$ Left for BTeV / LHCB

- $B^\pm \to (D^0, \bar{D}^0) K^\pm \to f_i K^\pm \qquad (i = 1, 2)$
  Triangle construction from rates $\Rightarrow$ $\sin(\gamma \pm \delta)$
  Total Br's $\sim 10^{-7}$ — statistics?

- $B \to K\pi$ — careful!
  Combination of rates. Need some assumptions on: rescattering effects, penguins, factorization, $SU(3)$

- $B_d \to \pi^+\pi^-$ vs. $B_s \to K^+K^-$: Measure all possible $B_{d,s} \to \pi\pi, K\pi, KK$ asymmetries and rates, we'll figure out something, build a case...

$\Rightarrow$ NP could enter γ determinations very differently

Workshop Highlights

B Physics at the Tevatron: Run II and Beyond

http://www–theory.fnal.gov/people/ligeti/Brun2/

Both experiments will have 3D Si vertex detectors. D0 has wider muon coverage, CDF has a dedicated hadronic trigger and TOF. BTeV (if approved) will have excellent K/π separation and π^0 ID.

Expectations ($2\,\mathrm{fb}^{-1}$) (different timescales)

$\sigma(\sin 2\beta)$	$0.05/0.02$	CDF, D0 / BTeV
$\sigma(a_{CP}^{\pi^+\pi^-})$	0.1	CDF
$\sigma(\sin 2\alpha)$	0.1	BTeV
$\sigma(\gamma)$	$< 10^\circ$	BTeV
$N(B \to K^{(*)}l^+l^-)$	few $10^2/10^4$	CDF, D0 / BTeV
x_s	few %	CDF, BTeV
$\sigma(\Delta\Gamma_{B_s}/\Gamma_{B_s})$	$0.06/0.02$	CDF / BTeV

Complement $\Upsilon(4S)$ B factories ($\sin 2\beta$, $|V_{cb}|$, $|V_{ub}|$)

Precise measurements of α & γ left to BTeV / LHCB (& e^+e^- B factories @ $> 10^{34}$ — similar timescale)

Summary

Summary

- The Tevatron will be a major player in B physics

  The program as a whole is a lot more interesting than any single measurement

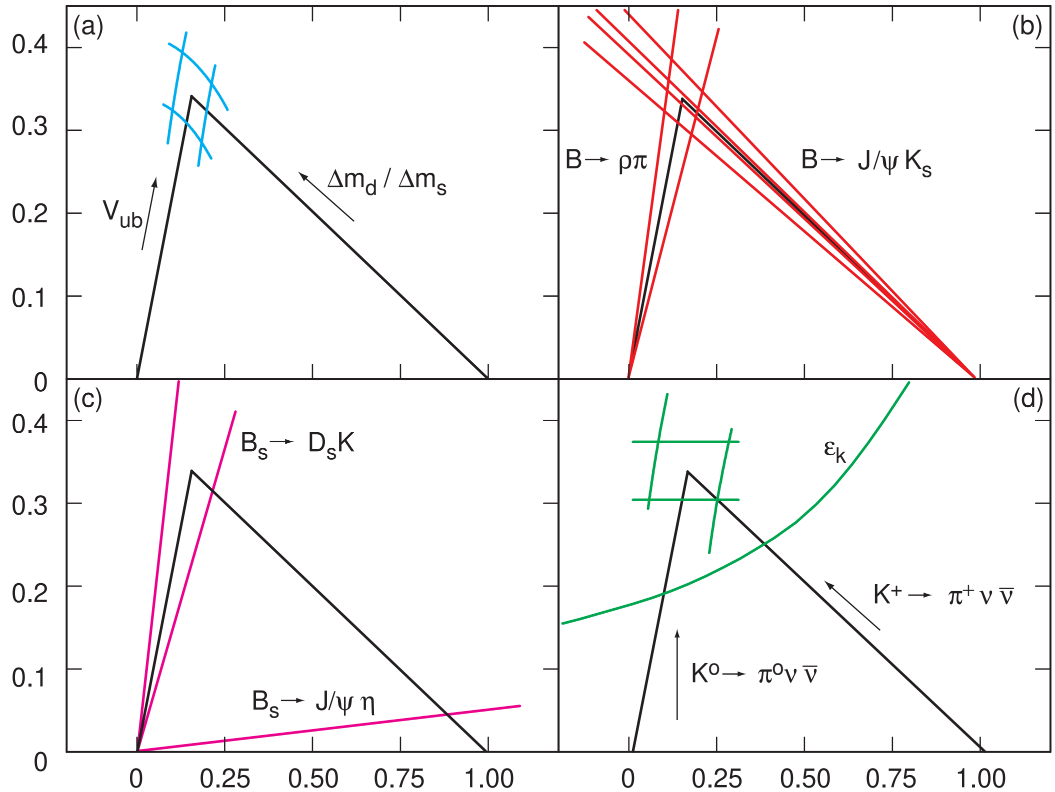
  "Gold-plated" measurements in Run IIa:

  B_s mixing
  CPV in $B_s \to \psi\phi$, $B \to \psi K_S$
  Rare decays
  Λ_b lifetime, quarkonia polarization, etc.

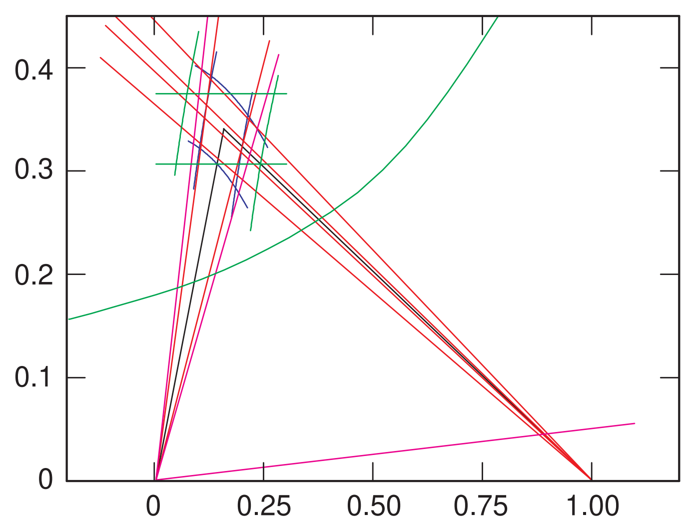
  Many more if BTeV is approved

Compare B, B_s, K Decay

M. Peskin, hep-ph/0002041



The $\$10^?$ question is...



Conclusions

- The CKM picture is predictive and testable
- The point is not only to measure the unitarity triange — but to overconstrain it and test CKM
- All possible clean measurements very important (Even if redundant in SM — correlations!)
- Need to pursue both CP violating and conserving measurements (rare decays!)
- e^+e^- and hadronic B factories are complementary

Vibrant theoretical and experimental program

Soon we'll have a precise test of CKM

$\sin 2\beta$,	$\lvert V_{ub}/V_{cb}\rvert$,	$\lvert V_{td}/V_{ts}\rvert$
(both)	(e^+e^-)	(Tevatron)

And many more later on...
Hope to find exciting and unexpected physics