Theoretical Perspectives on CP Violation in the B System

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Fermilab

- Introduction
  - Present constraints
- Searching for New Physics
  - How can it show up? (general)
  - How can we find it? (examples)

  Most important measurements...

  and theoretical developments
- Conclusions

Thanks to: A. Falk, Y. Grossman, A. Kronfeld, Y. Nir, 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

$$\mathcal{L} = \bar{L}^i_L \, \Phi^{ij}_e \, e^j_R + \bar{Q}^i_L \, \Phi^{ij}_u \, u^j_R + \bar{Q}^i_L \, \Phi^{ij}_d \, d^j_R$$

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

In the SM:

$$\Phi^{ij}_{e,d} = \lambda^{ij}_{e,d} \, \phi \,, \qquad \Phi^{ij}_u = \lambda^{ij}_u \, (i\sigma_2 \, \phi^*) \,,$$

and ϕ is the single Higgs field of EWSB.

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

And then there are neutrinos...

Physics at ~ 5 GeV

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

- Higher dimension operators

  $\Longleftrightarrow$ exchange of heavy particles

Are all the higher dimension flavor changing operators which occur at ~ 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

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 — could be many new phases
- The observed baryon asymmetry of the Universe requires CPV beyond the SM

  (Need not imply new CPV in flavor changing processes)

$\Downarrow$

It is possible, likely, unavoidable
that the SM picture of CPV is *incomplete*

Are there new particles / interactions in the 100 GeV – 1 TeV region which couple to flavor?

If $\Lambda_{\rm CPV} \gg \Lambda_{\rm EW}$ then no observable deviation in B decays $\Rightarrow$ precision flavor measurements

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

Unitarity Triangle

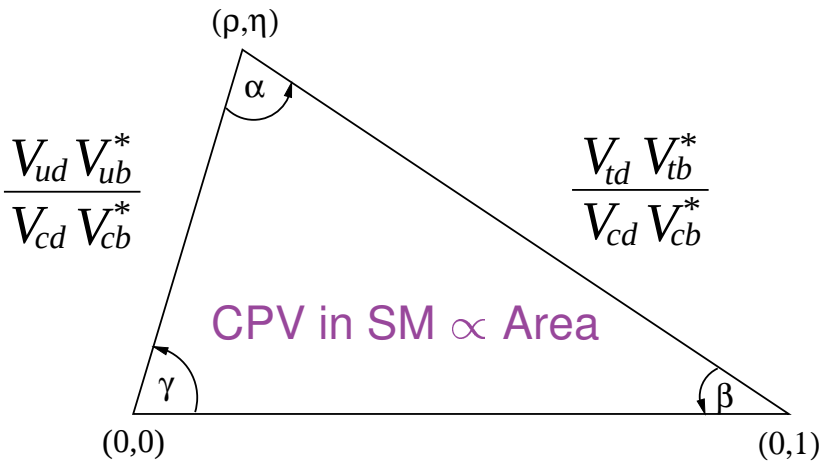
- Charged current weak interactions:

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

$\Rightarrow$ $\mathbf{V}_{\rm CKM}$ 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: $V_{ud}\,V_{ub}^* + V_{cd}\,V_{cb}^* + V_{td}\,V_{tb}^* = 0$



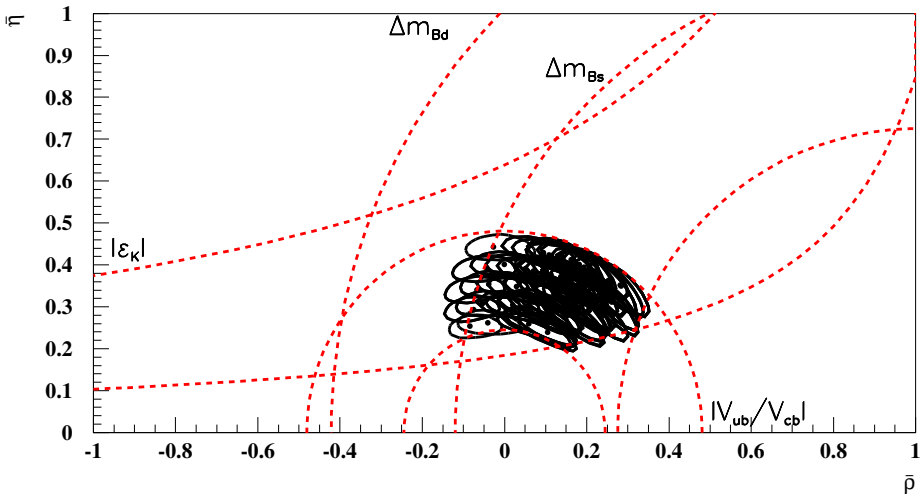
$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

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

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

The angles and sides are directly measurable

Present Constraints



The BaBar Physics Book

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

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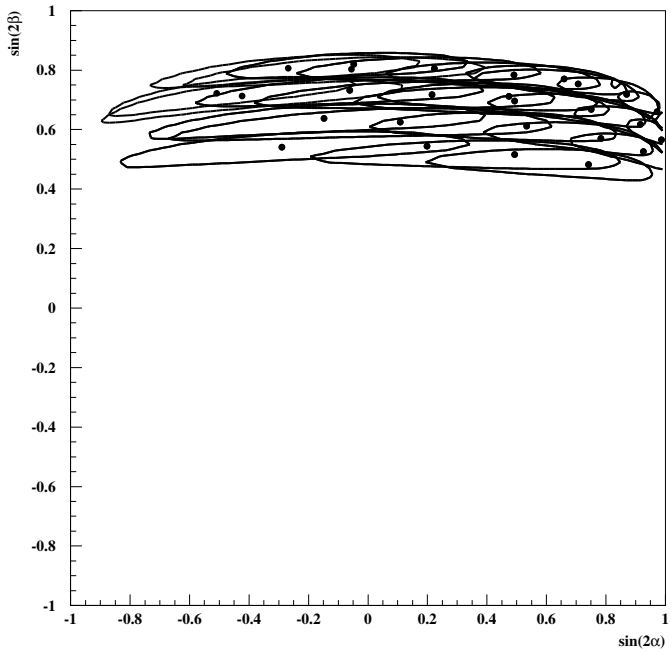
"Larger" allowed region in $\sin(2\alpha) - \sin(2\beta)$ plane:



Discrete ambiguities

⇓

Not a one-to-one map

⇓

New physics can "hide"

(assumes that B_K and B_B have the same signs)

The B System

- CP violation 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

  Measurements must be theoretically clean

In B decays we can measure:

- Magnitude of CKM elements

$$|V_{ub}|, \ |V_{cb}|, \ |V_{td}|, \ |V_{ts}|$$

- Phases — angles in Unitarity Triangle(s)

$$\alpha, \ \beta, \ \gamma$$ Probe CPV directly

Can 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: α, γ, $\pi - \beta - \gamma$, $2\beta + \gamma$...
  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 "α, β, γ" 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 $\alpha + \beta + \gamma = \pi$
$\alpha + \beta + \gamma \neq \pi$ iff $a_{CP}(B_s \to \psi\phi) \neq 0$

ii) 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" $\to$ possible)

How can NP enter?

1. Two measurements which relate to the same quantity in the SM give incompatible results — decay
2. Angles inconsistent with the sides — mixing
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

Discrete Ambiguities

$\sin 2\phi = X$ has 4 solutions:

$$\{\phi_0,\ \pi/2 - \phi_0,\ \pi + \phi_0,\ 3\pi/2 - \phi_0\}$$

SM: knowledge of sides usually selects a solution

- In many NP models new contribution to phase of $B - \bar{B}$ mixing $\Longrightarrow$ CPV in $B \to \psi K_S$ measures $\sin 2(\beta + \theta_d)$ and not $\sin 2\beta$ ("type 2, 3")

  E.g.: $\beta = 30^\circ$ and $\theta_d = 30^\circ$

  $$\sin 2\beta = \sin 2(\beta + \theta_d) = \sqrt{3}/2$$

  but: $\cos 2\beta = -\cos 2(\beta + \theta_d)$

- One should not only ask which angles can be measured, but also which functions of these

  "Impossible" methods can be useful — a sign may be enough (e.g., $B \to DD^*$ Dalitz plot analysis)

$\Rightarrow$ Resolving discrete ambiguities is looking for NP!

The sides

- NP: compare angles and sides
- Improve present constraints

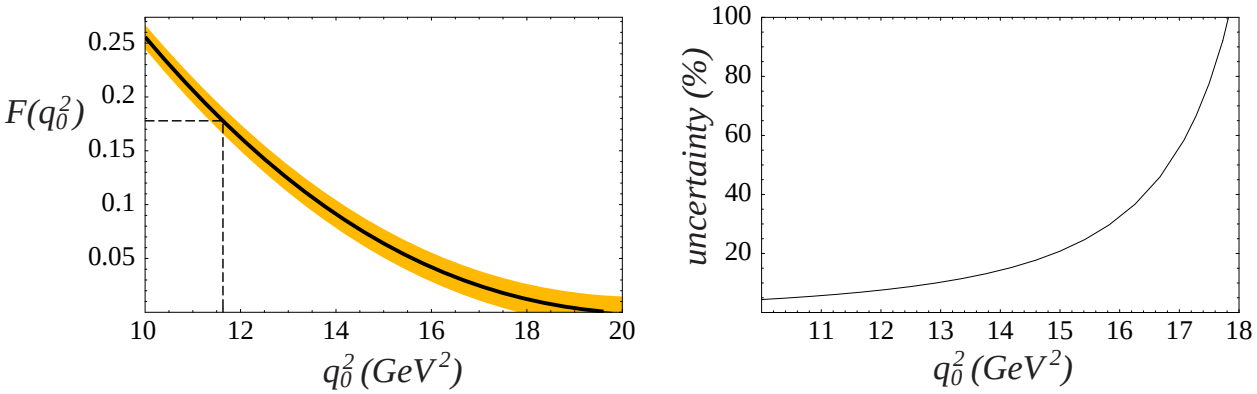
Sides: $|V_{ub}|$ and $|V_{cb}|$

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

  Exclusive: Concentrate on large q^2 — HQET relations to D and rare B decay & Lattice (unquenched)

  Inclusive: Neutrino reconstruction may be the key. Measure q^2 spectrum in $\bar{B} \to X_u \ell \bar{\nu}$

  C. Bauer, Z.L., M. Luke, hep-ph/0002161



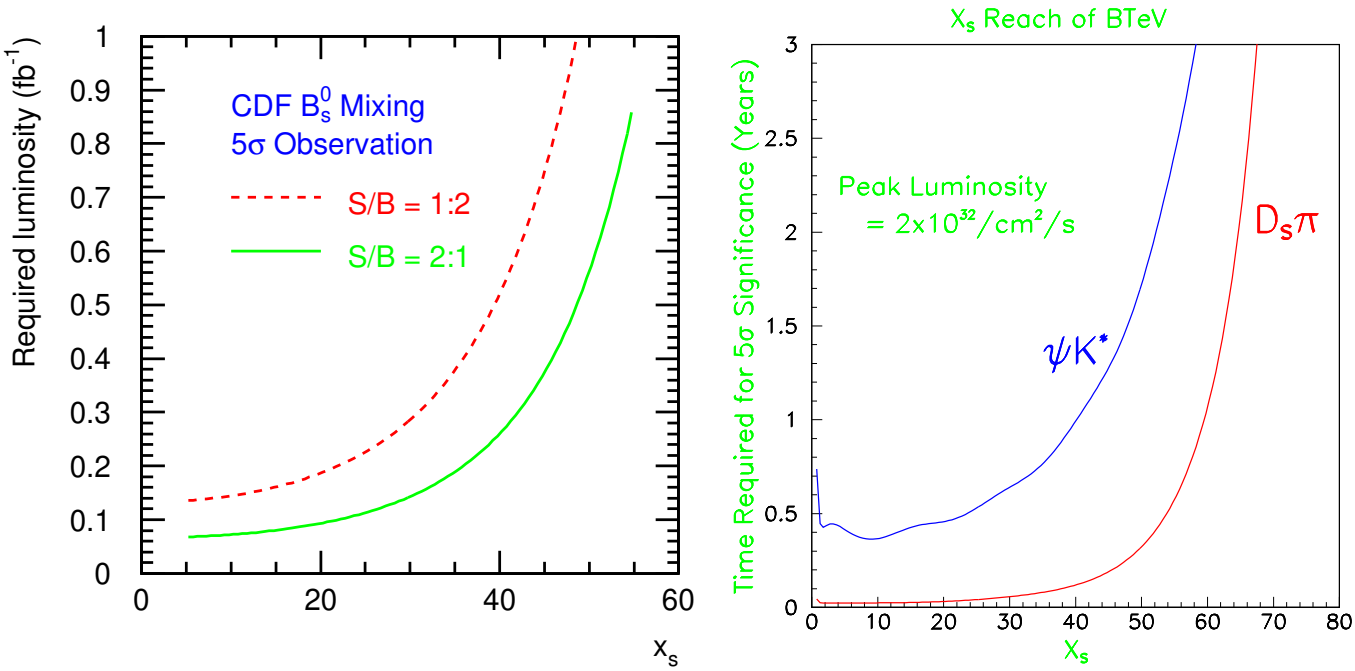
- Error in ε_K constraint — $|V_{cb}|^4$ and B_K

  To reduce $\sigma|V_{cb}|$ below 5%, need cross checks between inclusive $\bar{B} \to X_c \ell \bar{\nu}$ rate and exclusive $\bar{B} \to D^{(*)} \ell \bar{\nu}$ at zero recoil [lattice: $\mathcal{F}_{D^*} = 0.93(3)$]

$\Rightarrow$ Can get to $\sigma|V_{ub}| \sim 10\%$ and $\sigma|V_{cb}| \sim 2 - 3\%$

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

Measure B_s mixing:



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

- Need from lattice QCD: $f_B^2 B_B$ (want unquenched!)

- 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 different form factors from HQS; ultimately want unquenched lattice calculations.

- $\bar{B} \to \ell\bar{\nu}$:
  Measures $f_B|V_{ub}|$, sensitive to charged Higgs, etc.

- $\bar{B} \to X_s\gamma$ or $B \to K^*\gamma$:
  Best $m_{H^\pm}$ limits in 2HDM — in SUSY many param's

- $\bar{B} \to X_{s,d}\,\ell^+\ell^-$ or $B \to K^{(*)}\ell^+\ell^-$:
  $|V_{ts}|$, $|V_{td}|$, Higgs, right handed couplings, etc.

- $\bar{B} \to X_{s,d}\,\nu\bar{\nu}$ or $B \to K^{(*)}\nu\bar{\nu}$: (a dream...)
  Very clean — the B physics analog of $K \to \pi\nu\bar{\nu}$

- Direct CPV, e.g., in $B \to K^*\gamma$; lepton number / lepton flavor violating modes; $B_{s,d} \to \ell^+\ell^-$; etc.

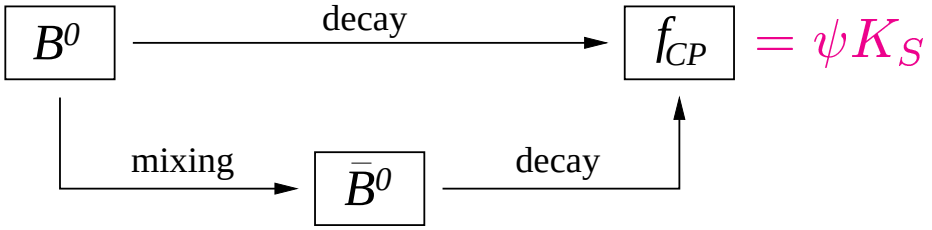
$\Rightarrow$ Richness: sensitivity to NP — applications for $|V_{ij}|$

The angles

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

Angles: β

- Interference between decay with and without mixing



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

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

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

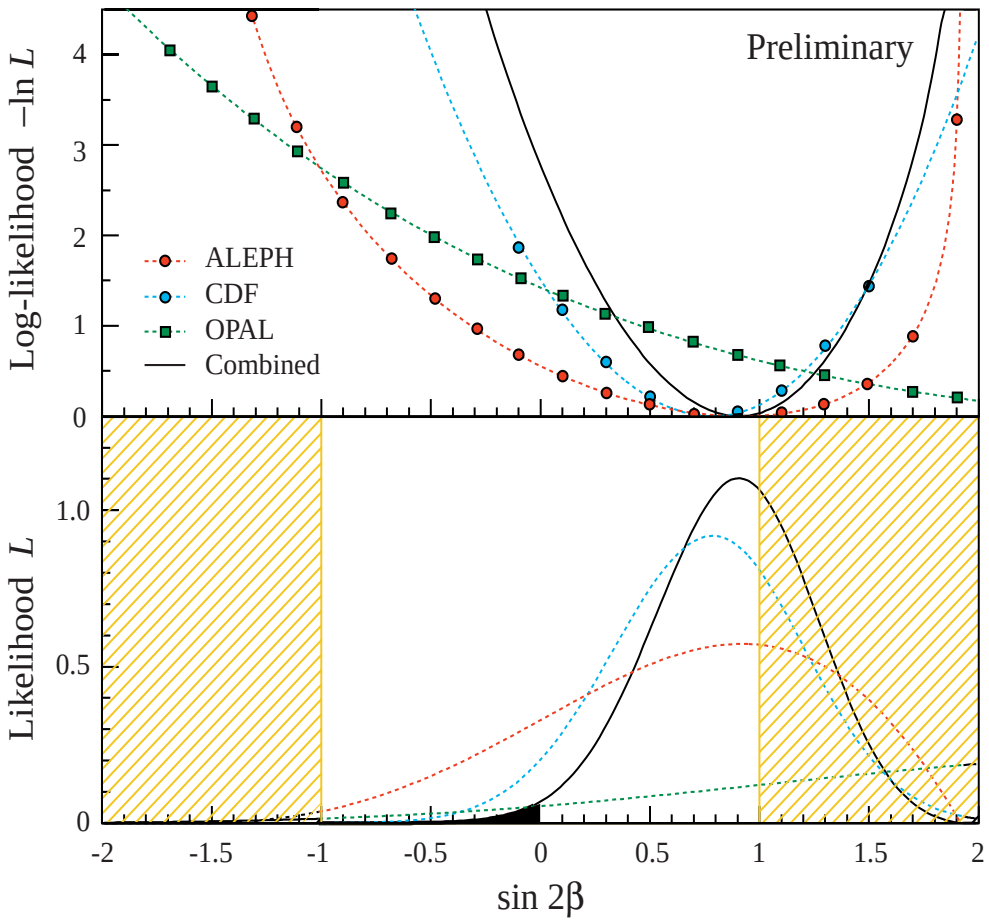
$\Rightarrow$ $\sin 2\beta$ — *Theoretically clean!*

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

measure $\sin 2\beta$. NP can enter $b \to s\bar{s}s$ penguin, and also modify 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:

$\sin(2\beta) = 0.91 \pm 0.35$

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

Angles: α

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

  Penguin only contributes to $\Delta I = 1/2$ amplitude $\Rightarrow$ 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 $Br(\pi^0\pi^0) \sim 10^{-6}$ — no current or future detector claims to be able to measure this precisely

  Not needed if P/T (incl. phase) can be computed
  (claimed by: Beneke, Buchalla, Neubert, Sachrajda)

- $B \to \rho\,\pi$: 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

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

Direct CPV: $b \to u\bar{u}d,\ u\bar{c}d$ Requires strong phase, which must be extracted from the analysis

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

- $B_s \to D_s^\pm K^\mp$ — very clean!
  Need 4 time dependent rates for $B_s, \bar{B}_s$.
  $D_s^\pm \pi^\mp$ background $\Rightarrow$ Left for BTeV / LHCB.

- $B \to K\pi$ — 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

Run II Workshops

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.

Highlights (2 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

Summary

Summary

- SM picture of CPV is:
  - unique: CPV appears only in
    1) flavor changing
    2) charged current interactions
    3) of quarks
  - predictive: all CPV observables are proportional to one parameter
  - testable: There are theoretically clean and experimentally doable measurements

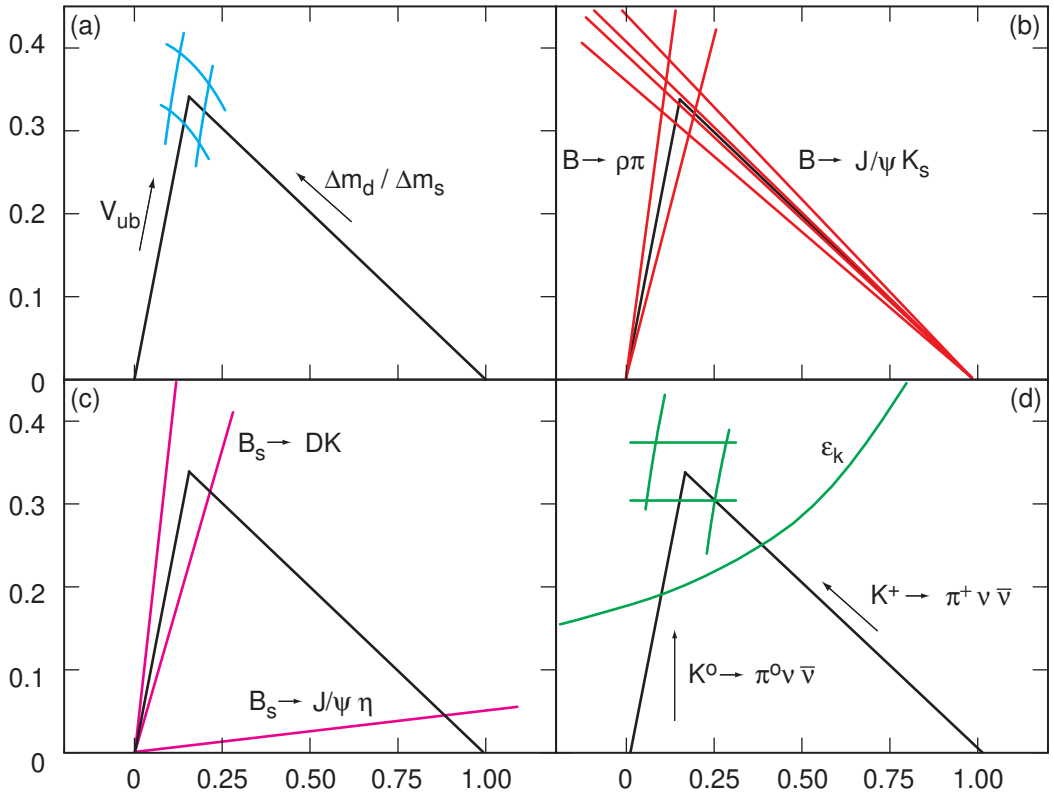
could change in the presence of NP

- If deviations from SM observed, we can hope to sort out whether NP is related to...
  - Up / down sector? Both?
  - $\Delta B = 1$ / $\Delta B = 2$ processes? Both?
  - Third generation? All generations?
  - Flavor changing / diagonal processes? Both?

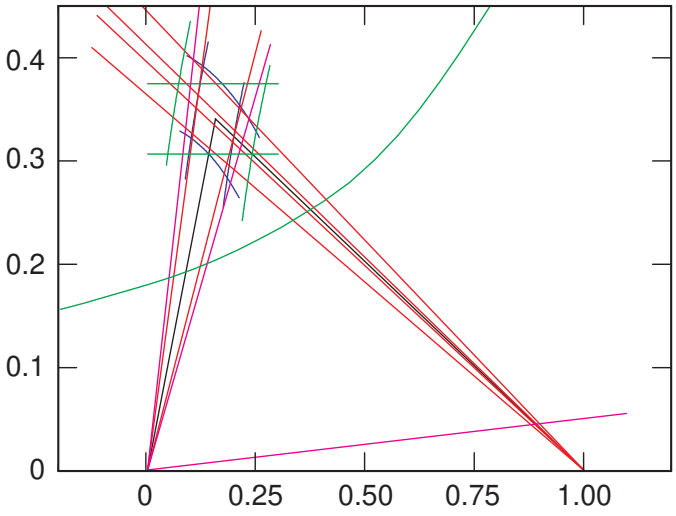
$\Rightarrow$ CPV is an excellent probe of NP

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

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To do this:

- Need high precision calculations, which are theoretically reliable and experimentally measurable

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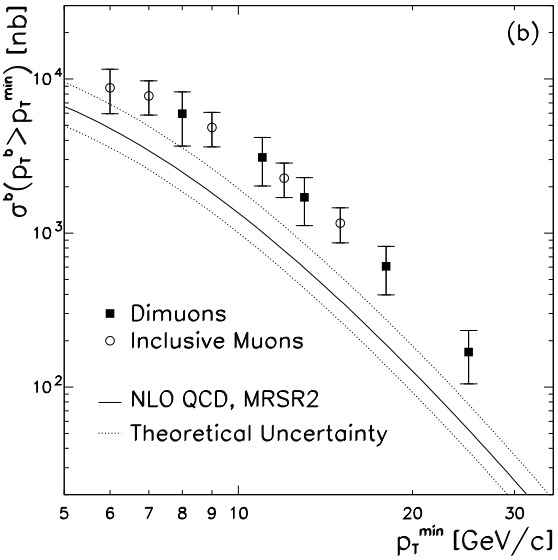
Vibrant theoretical and experimental program

$\Rightarrow$ Soon we will have a real test of CKM

$$\sin 2\beta,\ |V_{ub}/V_{cb}|,\ |V_{td}/V_{ts}|\ \ (+\varepsilon_K ?)$$

And many more later on... Hope for some luck in finding exciting and unexpected physics!

Aside: b Production @ Tevatron



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...

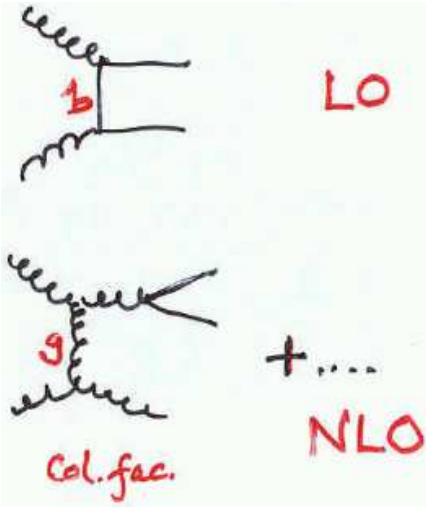
Excess of $b\bar{b}$ events is a real puzzle

We expect

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

But no reason why

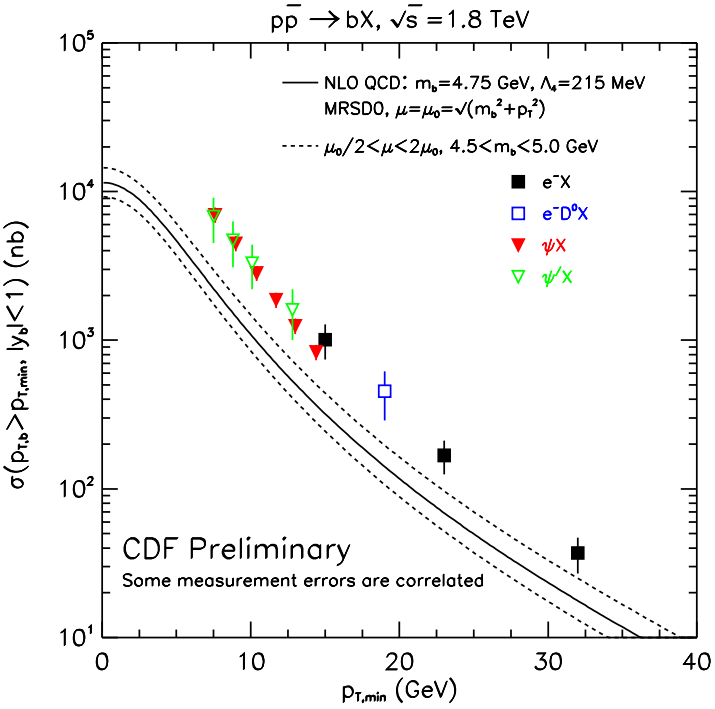
$$\frac{\text{NNLO}}{\text{NLO}}$$ is large?

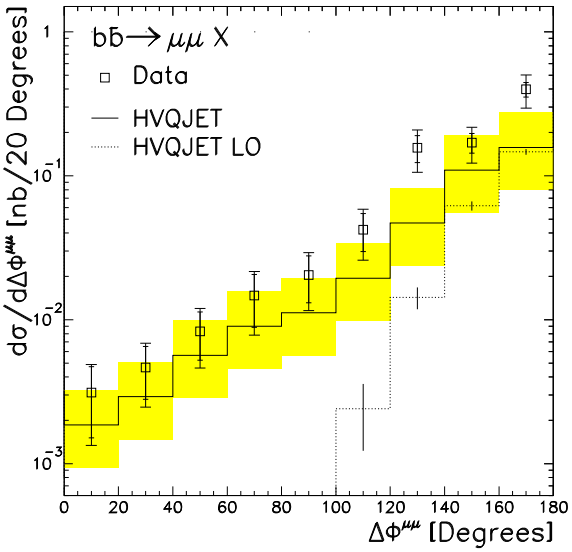


Maybe by $p_T \sim 100$ GeV, theory will work fine...

More on b Production

Plot on previous page was from D0; There is also similar data from CDF.

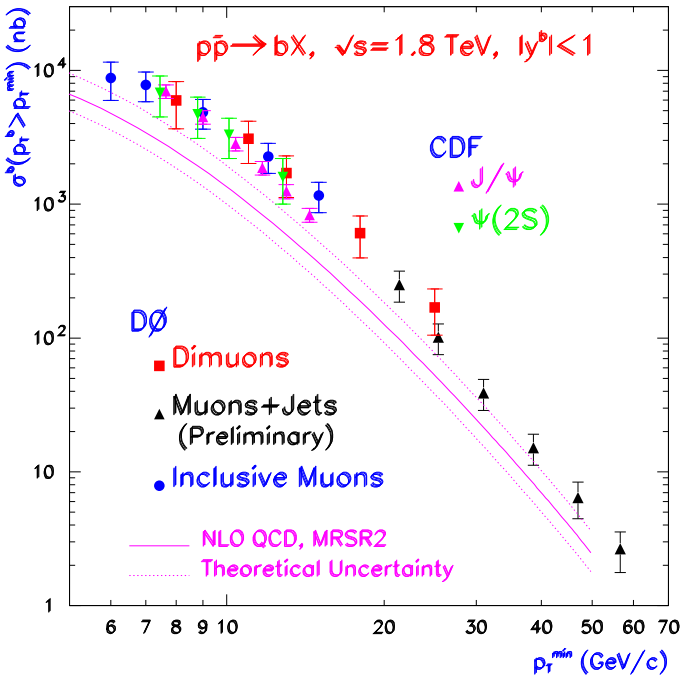




Distributions, such as angle between muons in $b\bar{b} \to \mu\mu X$, agree better than total cross section

A. Maciel, Moriond '00

(D0 – Preliminary)



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