SLAC Summer Institute 2002
HF @ Tevatron

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MIT/CDF

Discovering anything virtual

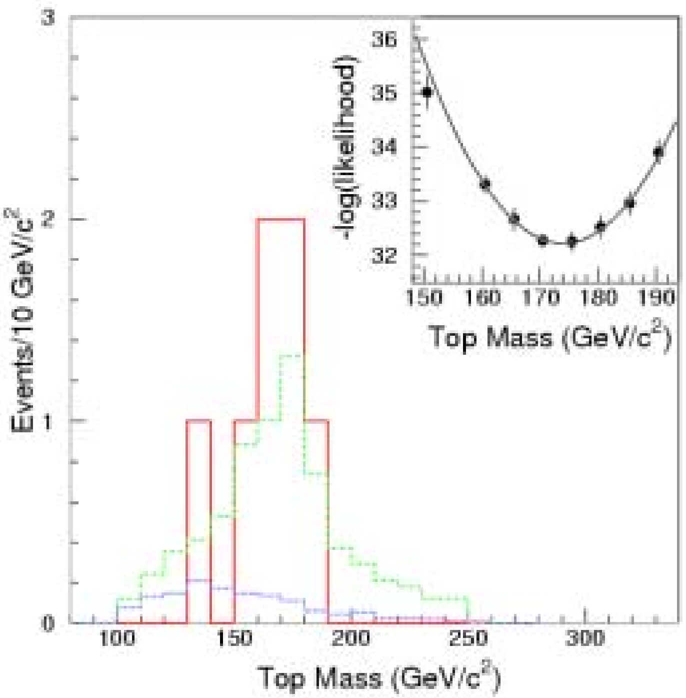
Overview of Lecture 3

- New Physics vs Old Physics

  $\Rightarrow$ B decays as a probe for the **Unknown**

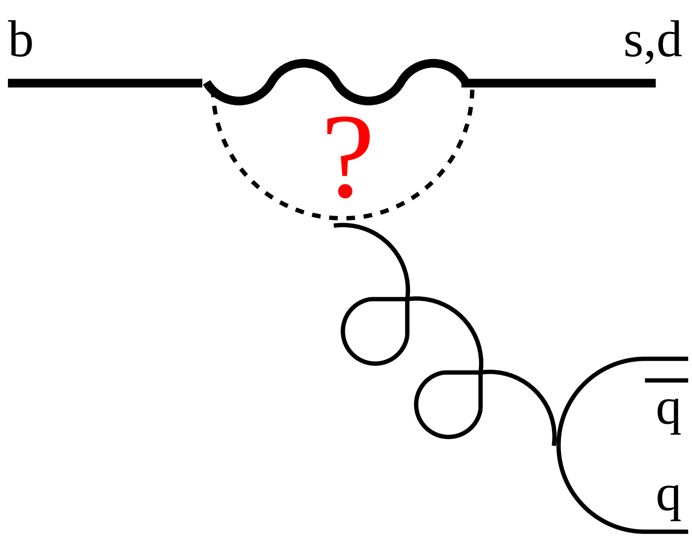
- B_s mixing @ CDF
- Measuring γ @ CDF
- Measuring CP viol. phase of a penguin

New Physics via Observation of New Particle



$\longrightarrow$ Highest energies, low precision

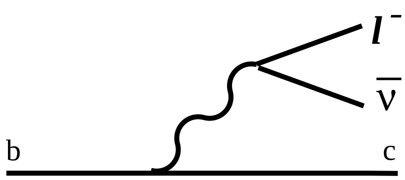
New Physics via Virtual Intermediate States

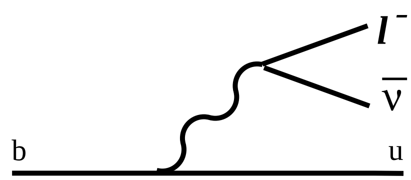


$\longrightarrow$ Highest precision, low energy

Impact of New Physics in *B* Decays

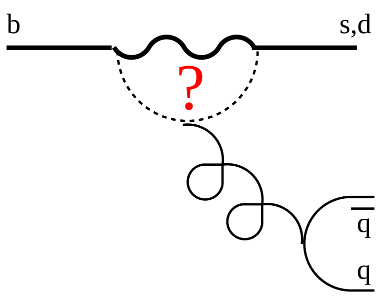
(Largely) independent of NP:

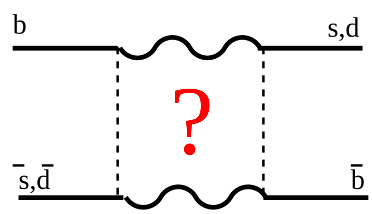


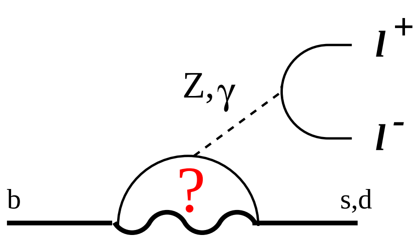


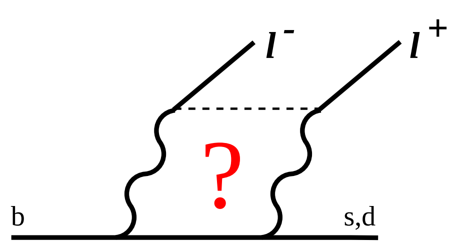
$|V_{cb}|$ $|V_{ub}|$ $e^{-i\gamma}$

Strikingly sensitive to NP:









Excellent Review of NP effects: Y.Nir hep-ph/9911321
e.g. SUSY, LR-symmetry, Multi-Higgs, new fermions, etc.

Rehash of CKM Matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_x c_z & s_x c_z & s_z e^{-i\phi} \\ -s_x c_y - c_x s_y s_z e^{i\phi} & c_x c_y - s_x s_y s_z e^{i\phi} & s_y c_z \\ s_x s_y - c_x c_y s_z e^{i\phi} & -c_x s_y - s_x c_y s_z e^{i\phi} & c_y c_z \end{pmatrix}$$

Subscript x, y, z are the three Euler angles.
s, c stands for $\sin, \cos$.

$$s_x = \lambda,\ s_y = A\lambda^2,\ s_z = O(\lambda^3) \quad \lambda = 0.22,\ A = 0.8$$

Phase shows up at $O(\lambda^3), O(\lambda^4), O(\lambda^5), O(\lambda^6)$

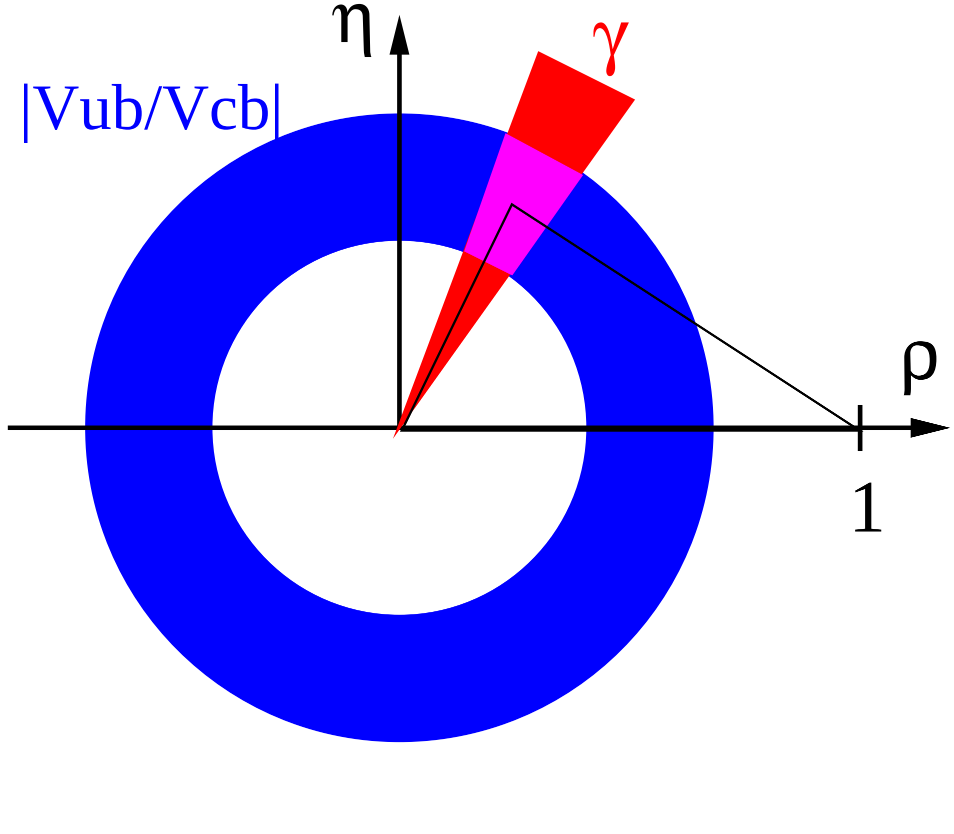
Guiding principle for phase convention:
Dominant processes are chosen to have zero phase !

Note: KM originally chose convention that gives zero phase to first row and column.

B Decays within the SM

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & |V_{ub}|\times e^{-i\gamma} \\ -\lambda & 1-\frac{1}{2}\lambda^2 & |V_{cb}| \\ \lambda|V_{cb}|-|V_{ub}|\times e^{+i\gamma} & -|V_{cb}| & 1 \end{pmatrix} + O(\lambda^4)$$

Measurements free of New Physics in loops:



Roadmap towards anything Virtual

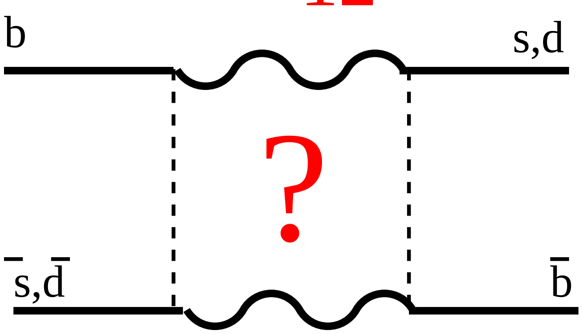
- Measure $\lambda, |V_{cb}|, |V_{ub}|, \gamma$ in tree level processes.
- Use theory to predict loop processes.
- Measure loop processes and compare with theory predictions.

Example: Meson Mixing

$$i\frac{d}{dt}\begin{pmatrix} a \\ b \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} a \\ b \end{pmatrix}$$

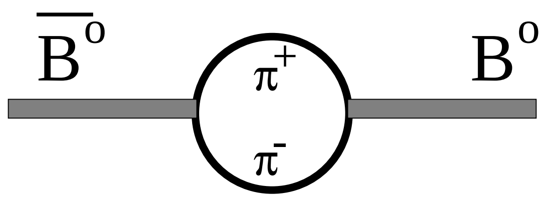
$$|B(t)\rangle = a|B^0\rangle + b|\bar{B}^0\rangle$$

M_{12}



off shell
intermediate state

Γ_{12}



on shell
intermediate state

$$|M_{12}| \gg |\Gamma_{12}|$$

Physical Observables in B_d Mixing

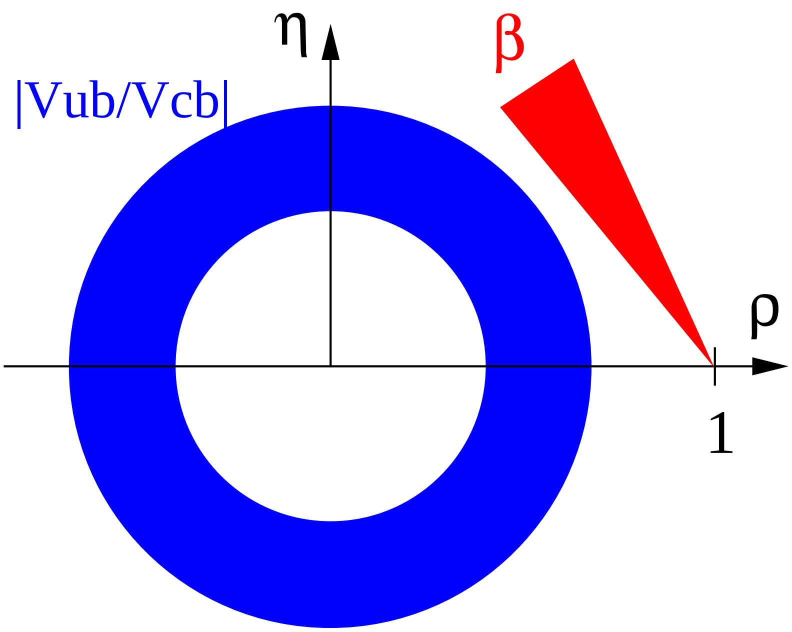
$$
\begin{aligned}
\Delta m &= 2|M_{12}| \\
\Delta\Gamma &= 2Re(M_{12}\Gamma_{12}^*)/|M_{12}| \quad \propto \cos 2\beta \\
A_{cp}^{mix}(t) &= \pm Im\left(\frac{M_{12}^*\bar{A}}{|M_{12}|A}\right) \times \sin\Delta m t \quad \propto \sin 2(\beta+\theta)
\end{aligned}
$$

$$
\begin{aligned}
2\beta &:= Arg(M_{12}) \\
2\theta &:= Arg\left(\frac{\bar{A}}{A}\right)
\end{aligned}
$$

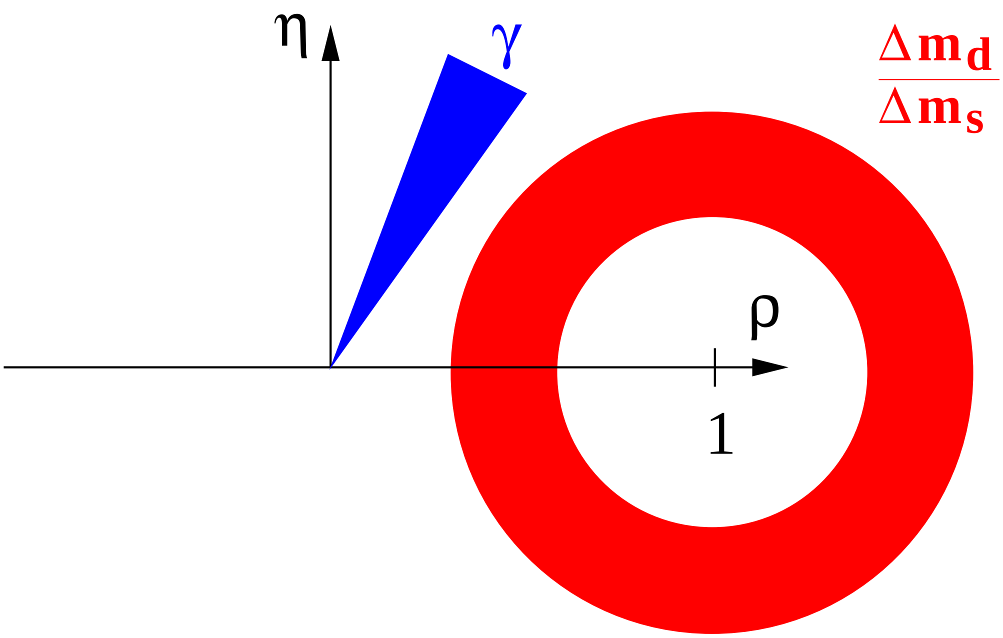
$$
\begin{aligned}
b \to c &\to \theta = 0 \quad \text{by definition} \\
b \to u &\to \theta = \gamma
\end{aligned}
$$

We measure β via $A_{cp}^{mix}(t)$ in $b \to c$ and γ via comparison with $A_{cp}^{mix}(t)$ in $b \to u$.

Observing New Physics in M_{12}



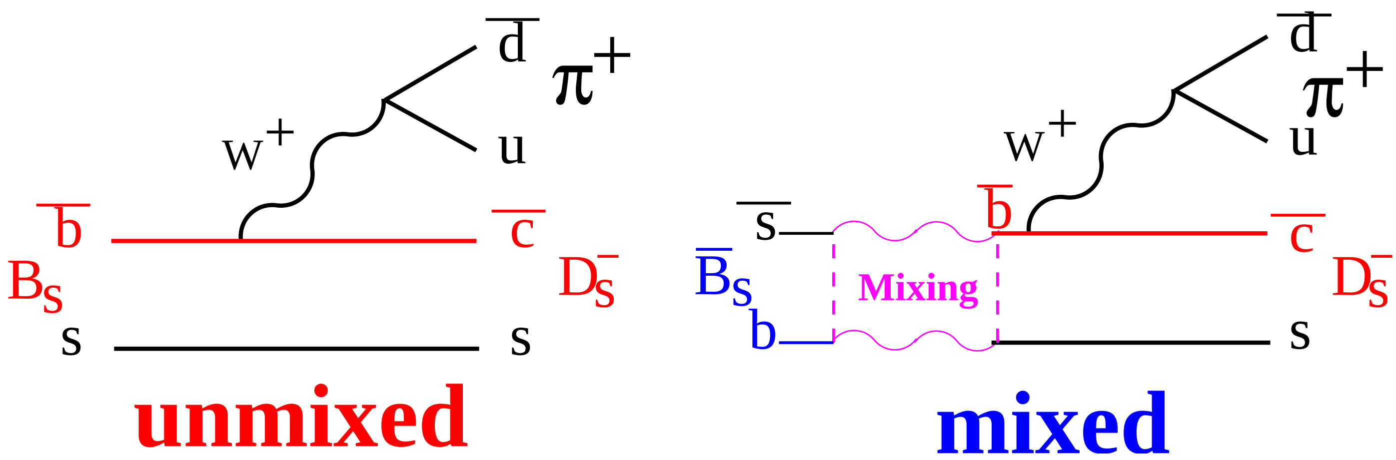
CP violating New Physics in mixing



CP conserving New Physics in mixing

B_s Mixing

Measuring B_s mixing



- Trigger on & reconstruct the signal
- suppress bkg
- measure the flavor @ production
- measure flight distance
- measure B_s momentum

Meson Mixing

$$A_{mix} = \frac{N_{unmixed}-N_{mixed}}{N_{unmixed}+N_{mixed}}$$

$$= D \ \cos \Delta mt$$

$$D = 2P_{tag} - 1$$

$$Sig(\Delta m) = \sqrt{\frac{N\epsilon D^2}{2}} e^{-(\Delta m\sigma_t)^2/2} \sqrt{\frac{S}{S+bkg}}$$

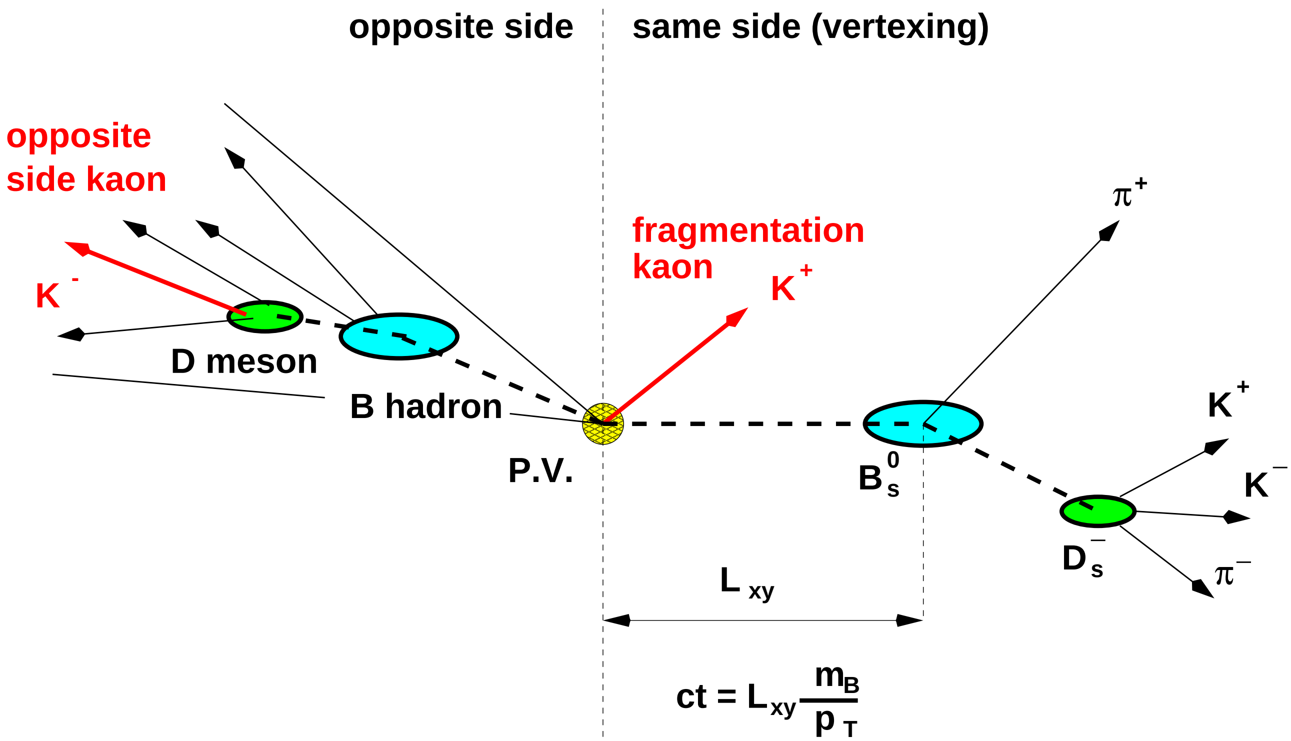
Note: $\Delta m\sigma_t < 1$ for $\Delta m/\Gamma < 33(25)$ with(without) L00

Trigger & reconstruct the Signal

$B_s \to D_s^{\pm}\pi^{\mp}$	$D_s \to \phi\pi$	$16k$
	$D_s \to K^{*0}K^{-}$	$15k$
	$D_s \to \pi^{+}\pi^{-}\pi^{+}$	$5.5k$
$B_s \to D_s^{\pm}\pi^{\mp}$	all	$37k$
$B_s \to D_s^{\pm}\pi^{+}\pi^{-}\pi^{\mp}$	$D_s \to \phi\pi$	$15k$
	$D_s \to K^{*0}K^{-}$	$17k$
	$D_s \to \pi^{+}\pi^{-}\pi^{+}$	$6k$
$B_s \to D_s^{\pm}\pi^{+}\pi^{-}\pi^{\mp}$	all	$38k$

Note: This is official CDF PR. It includes only trigger & tracking acceptance.

Flavor Tagging at CDF



	Run1	Run2
Same-Side	1.0	4.2
Soft Lepton	1.7	1.7
Jet Charge	3.0	3.0
Opposite Kaon	0.0	2.4
Total	5.7	11.3

Table 1: ϵD^2 in % , Fermilab Proposal 909, 1998.

$\Upsilon(4s)$ vs Hadron Collider

$\Upsilon(4s)$

- coherent $B^0 - \overline{B^0}$ production.

  $\Rightarrow$ the other $b-$quark ALWAYS tags the flavor.

- Geometric Acceptance $95 - 98\%$ of 4π.

  $\Rightarrow$ ϵD^2 is large ($\sim 30\%$)

Hadron Colliders

- the other $b-$quark hadronizes as B^0, B^+, B_s, Λ_b, etc.

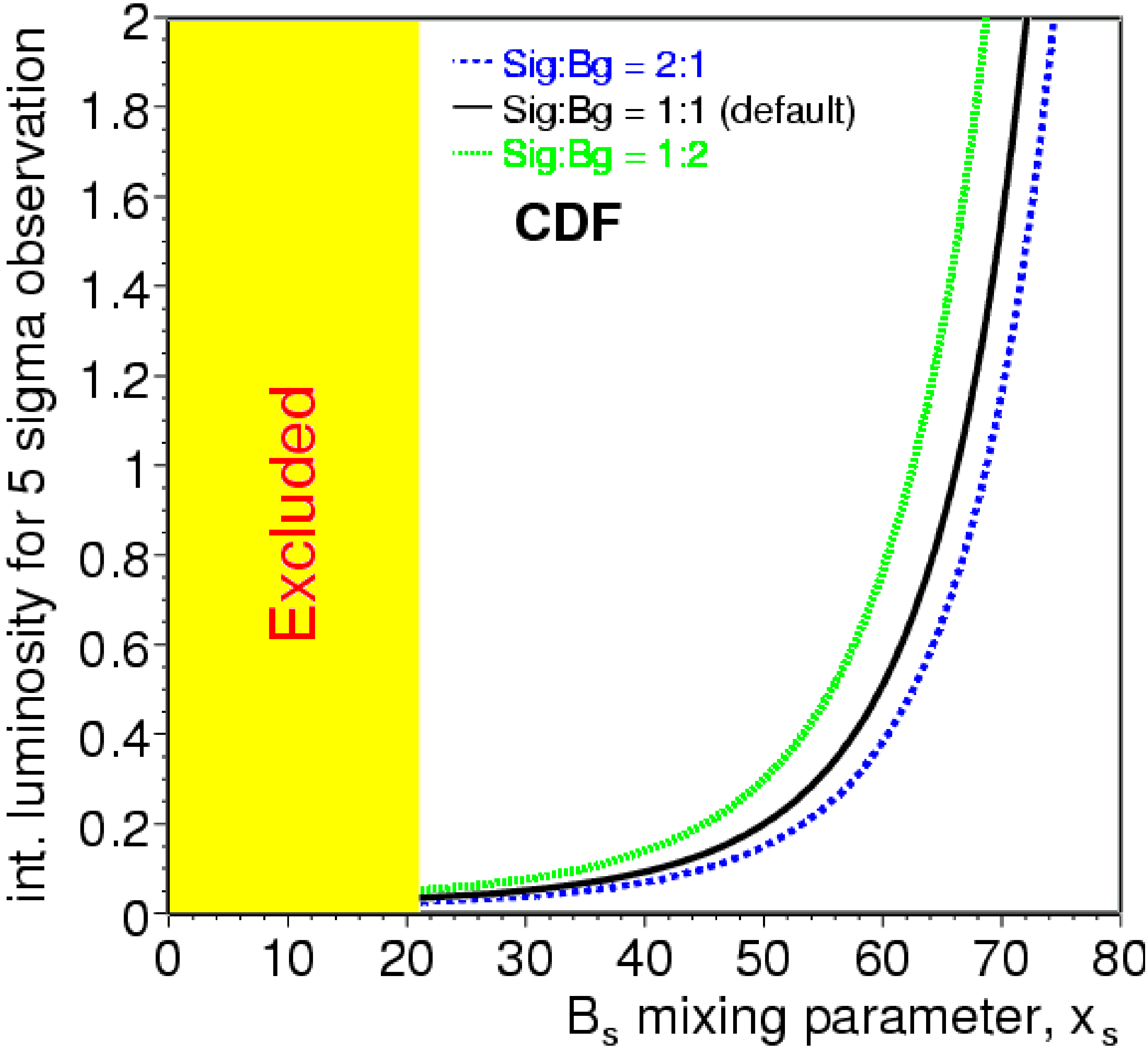
  $\Rightarrow$ D is decreased by mixing:

$$
\begin{aligned}
D_{max} &= 2P_{max} - 1 \\
&= 2(1 - f_d \cdot \chi_d - f_s \chi_s) - 1 \\
&\sim 0.7
\end{aligned}
$$

- Geometric Acceptance is far from complete because of production characteristics.

- inferior Kaon particle ID

PR: Mixing Reach in Hadronic Decays



“Conservative” Perspective

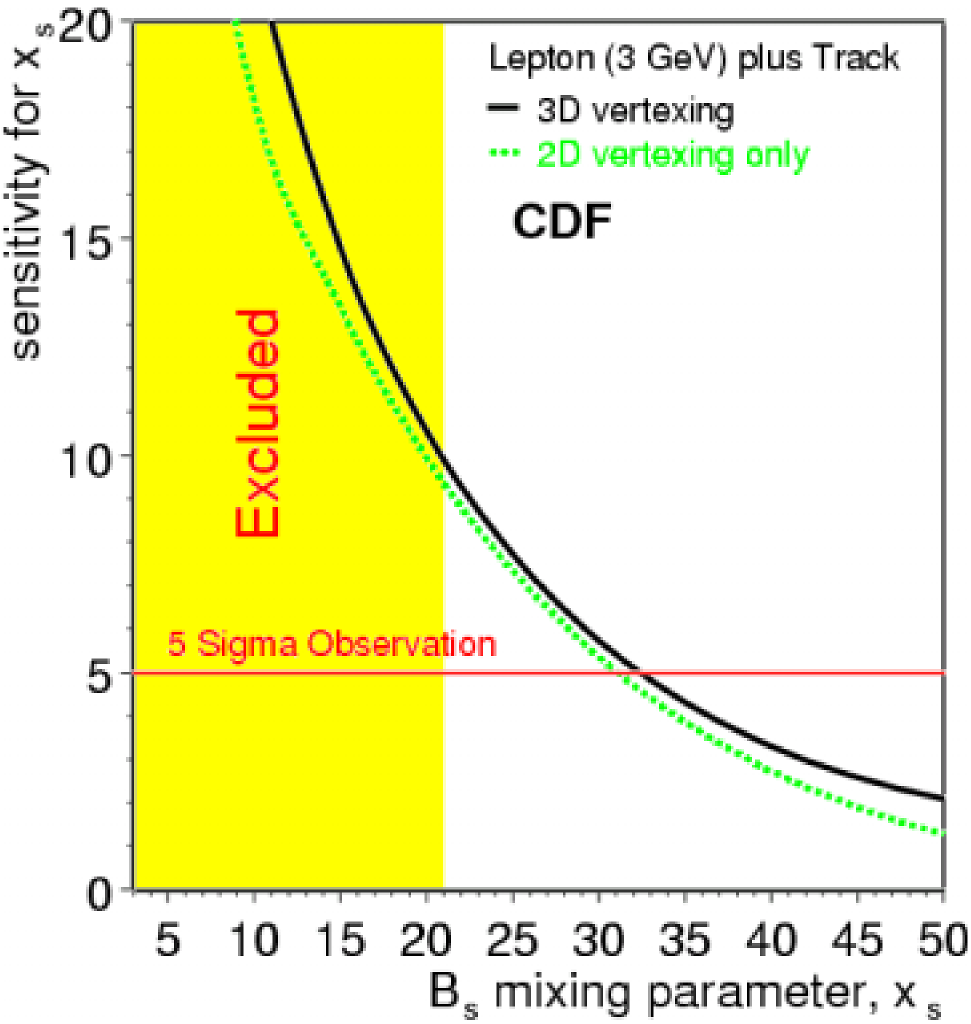
Analysis cuts	$\times$	2
$B_s \to D_s\pi$ only	$\times$	2
no L00	$\times$	1.5 @ $x_s = 25$
svx & svt ineff.	$\times$	2.4
Run1 ϵD^2	$\times$	2.0

Take your pick on these factors and multiply y-axis on previous page by it to arrive at **your own** best guess as to how mu8ch lumi is required to measure x_s.

Aside: Mixing via semi-leptonic decays

Proper time resolution

$$
\begin{aligned}
ct &= \frac{L_{xy} m_{B_s}}{p_T(lD_s)} \times \kappa \\
\sigma_t &= \sqrt{\sigma_{t0}^2 + (t\frac{\sigma_\kappa}{\kappa})^2} \\
&\sim \sqrt{(60fs)^2 + (0.14\ t)^2}
\end{aligned}
$$



Measuring γ

Measuring γ — the principle

$$\gamma = Arg\,(V_{ub}^*\, V_{ud}\, V_{cb}\, V_{cd}^*)$$
$$= Arg(V_{ub}^*) + O(\lambda^5) \text{ (standard phase conv.)}$$

BTeV expectations: $B_s \to D_s K, B_d \to DK$ results in $\sigma_\gamma \sim 5 - 10°$ after two years of running, i.e. $\sim 2008 - 2010$.

Measuring γ is very difficult !!!

Fertile ground for new ideas !!!

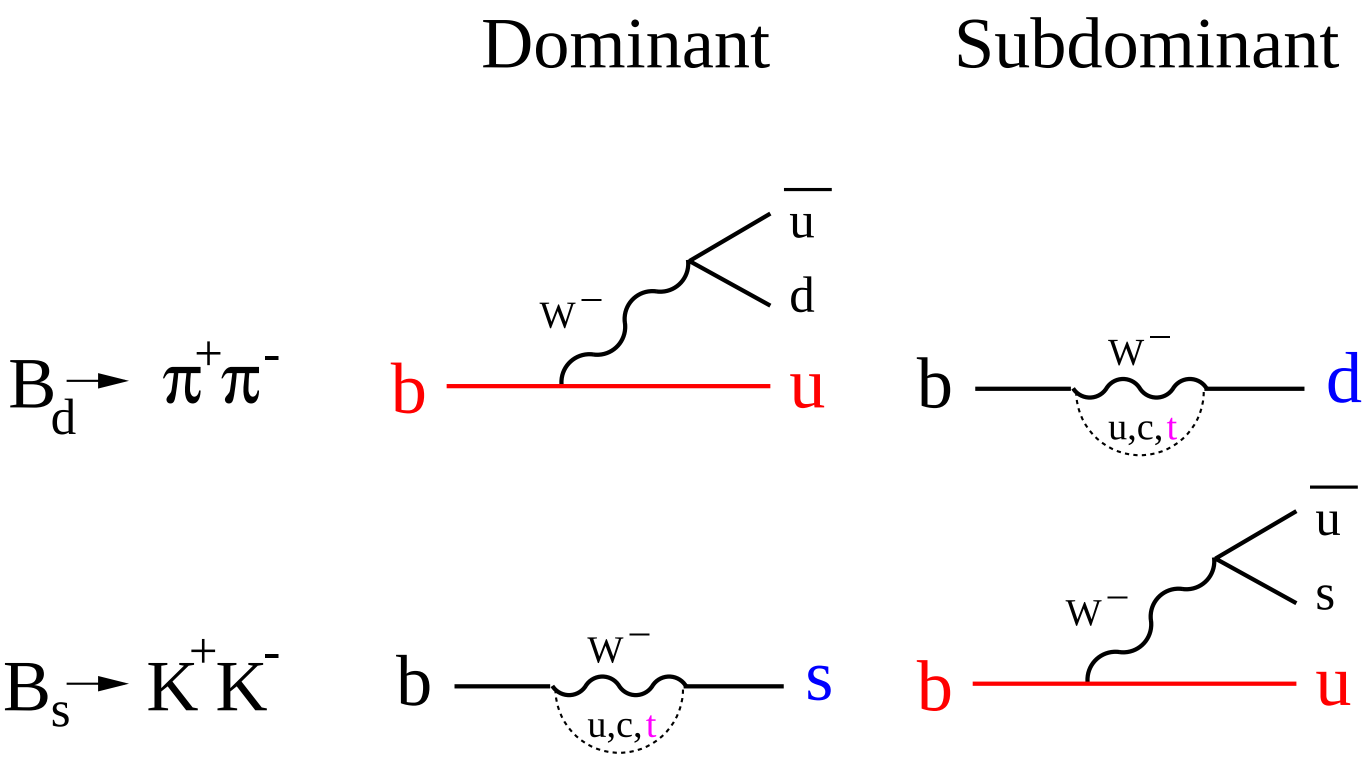
Measuring γ — an alternative approach

If Penguins didn't exist:

	$Im(\frac{\bar{A}M_{12}^*}{A\|M_{12}\|})$
$B_d \to \pi^+\pi^-$	$\sin 2(\gamma + \beta)$
$B_d \to J/\psi K_s$	$\sin 2\beta$

but nature's not this simple ...

"Penguin Pollution"



$$\frac{\text{Subdominant}}{\text{Dominant}} \sim 0.2 - 0.4$$

Penguin cleanup by relating CP asymmetries in $B_d \to \pi^+\pi^-$ to $B_s \to K^+K^-$ via SU(3) flavor.

Measuring γ @ CDF

CP Violation in $B_d \to \pi^+\pi^-$, $B_s \to K^+K^-$

$$A_{CP}(t) = A_{dir}\cos\Delta mt + A_{mix}\sin\Delta mt$$

Combined fit to $B_d \to \pi^+\pi^-$, $B_s \to K^+K^-$

- Measure $A^{\pi\pi}_{dir}$, $A^{\pi\pi}_{mix}$, A^{KK}_{dir}, A^{KK}_{mix}.
- UT triangle fixes β
- **extract weak phase γ**
- **extract strong phase and modulus of penguin/tree ratio**

Aside: Details in Tevatron Run II B-workshop write-up.

Measuring γ — the details

(R.Fleischer PLB459 (1999) 306)

χ^2 fit to 5 experimental results

Four unknowns:

- d = ratio of hadronic matrix elements $''P/T'' \sim 0.3$
- θ = strong phase of ratio of hadronic matrix elements $\sim 0???$
- γ, β = weak phases

Five observables:

$$A_{cp}(t) = A_{cp}^{dir} \times \cos\Delta mt + A_{cp}^{mix} \times \sin\Delta mt$$

$$A_{cp}^{dir}(\pi^+\pi^-) = -2d\sin\theta\sin\gamma + O(d^2)$$

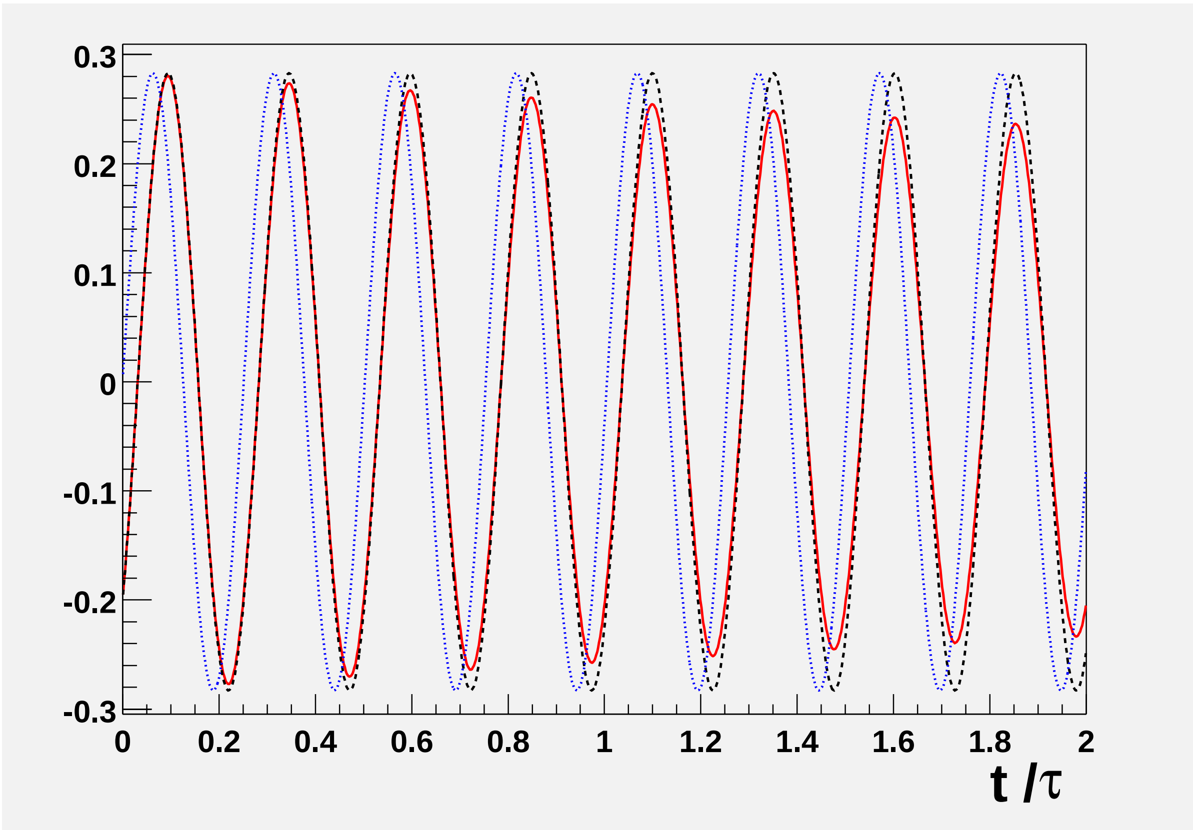
$$A_{cp}^{dir}(K^+K^-) = \frac{2\lambda^2}{d(1-\lambda^2)}\sin\theta\sin\gamma + O((\frac{\lambda^2}{d})^2)$$

$$A_{cp}^{mix}(K^+K^-) = \frac{2\lambda^2}{d(1-\lambda^2)}\cos\theta\sin\gamma + O((\frac{\lambda^2}{d})^2)$$

$$A_{cp}^{mix}(\pi^+\pi^-) = \sin 2(\beta+\gamma) + 2d\cos\theta \times (\cos\gamma\sin 2(\beta+\gamma) - \sin(2\beta+\gamma)) + O(d^2)$$

$$A_{cp}^{mix}(J/\psi K_s) = \sin 2\beta$$

CP Violation in $B_s \to K^+K^-$



blue: $A_{dir} = \Delta\Gamma = 0$

black: $\Delta\Gamma = 0$

red: $A_{dir}, A_{mix}, \Delta\Gamma$ non-zero

$$\frac{\Gamma-\bar{\Gamma}}{\Gamma+\bar{\Gamma}} = \frac{2e^{-\langle\Gamma\rangle t}}{e^{-\Gamma_H t}+e^{-\Gamma_L t}+A_{\Delta\Gamma}(e^{-\Gamma_H t}-e^{-\Gamma_L t})} \times$$

$$(A_{mix}\sin(\Delta mt) + A_{dir}\cos(\Delta mt))$$

Yields and Expected errors

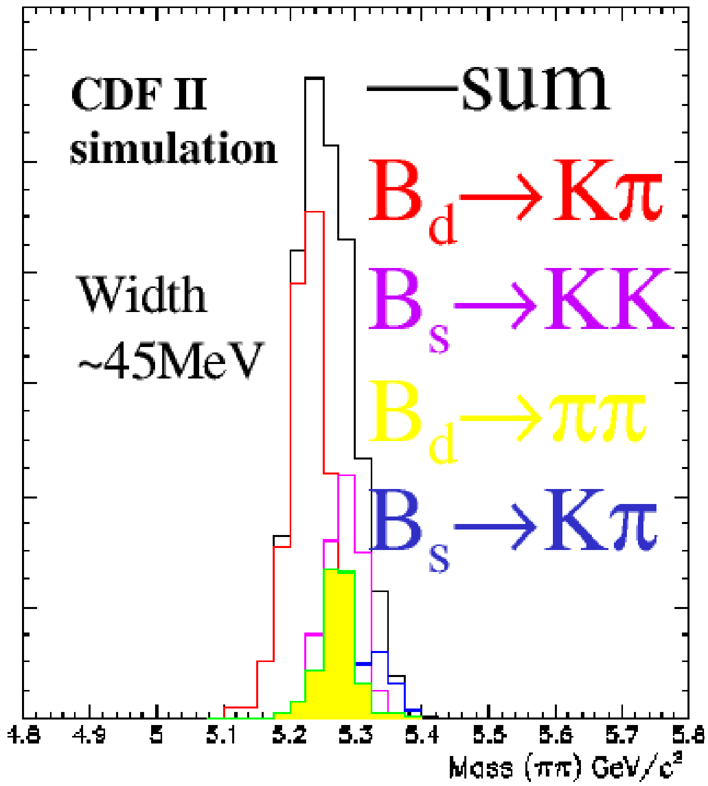
Assume SU(3) and B_d/B_s **production** ~ 2.5

$B_d \to \pi^+\pi^-$	$B_d \to K^+\pi^-$	$B_s \to \pi^+K^-$	$B_s \to K^+K^-$
1	4	0.5	2
5-10k	20-40k	2.5-5k	10-20k

Experimental Errors for “nominal assumptions”:

$\sigma_{Acp} \sim 0.08$ for $B_s \to K^+K^-$
$\sigma_{Acp} \sim 0.14$ for $B_d \to \pi^+\pi^-$

Distinguishing $\pi\pi, K\pi, KK$

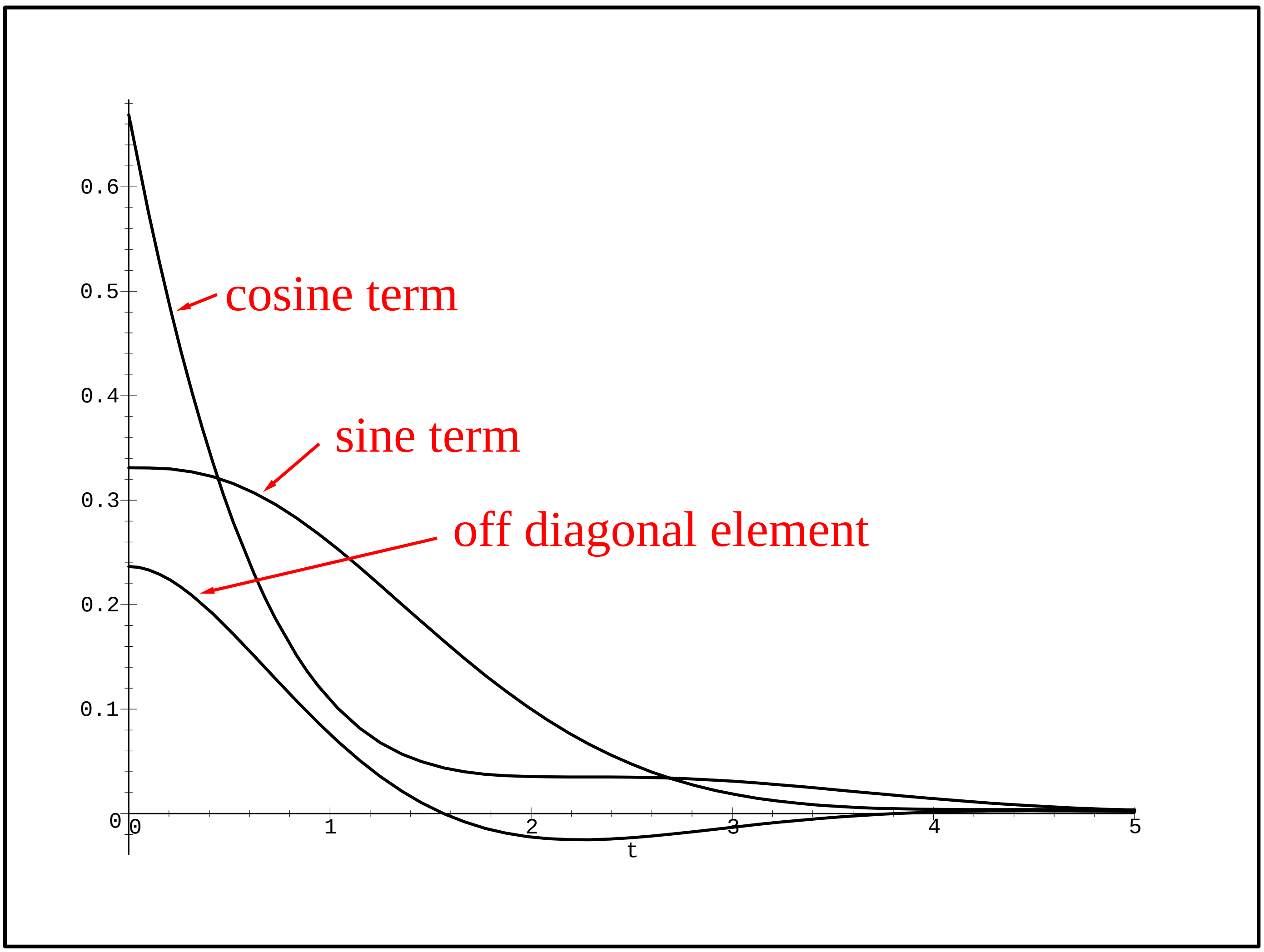


	$K\pi$	$\pi\pi$	KK
B_d	20k	5k	0
σ	0.95%	2.8%	-
B_s	2.5k	0	10k
σ	4.8%	-	1.6%
bkg	14k	28k	14k
	"Effective" S/bkg		
B_s:	0.21	-	0.64
B_d:	1.24	0.34	-

Sensitivity for A_{cp} — analytical expressions

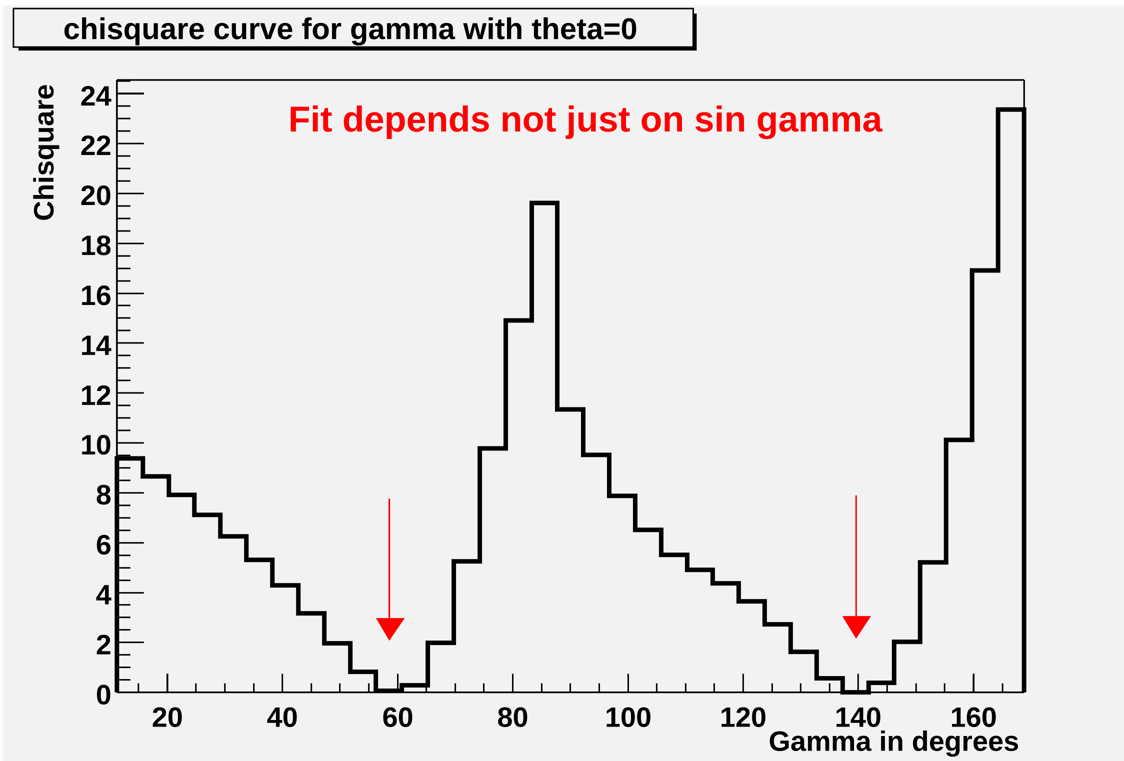
$$A_{cp} = A_{cp}^{dir} \times \cos xt + A_{cp}^{mix} \times \sin xt$$

G = inverse of cov. matrix for $A_{cp}^{dir}, A_{cp}^{mix}$



Expected Reach in Run IIa

χ^2 fit for γ:



$\sigma_\gamma =^{+5.4}_{-6.8} \pm 3$ degrees

Systematic Error due to SU(3) breaking of 20%:
$\sim 1/2$ the expected experimental error !!!

Aside: Comparable to BTeV reach in $B_s \to D_s K$ by 2008-2010.

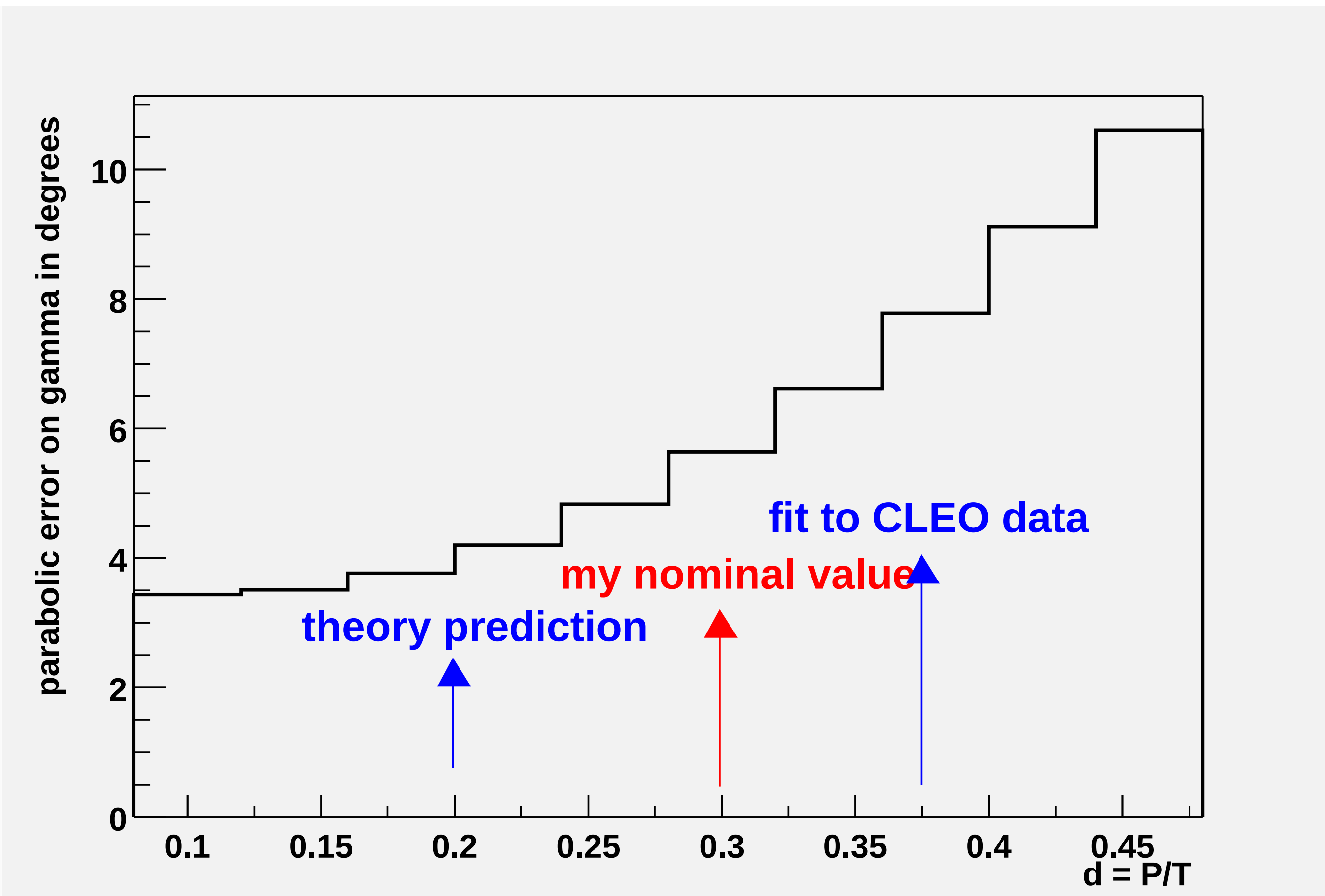
A word about theory systematics ...

- $B_d \to \pi^+\pi^-$ measures $\sin 2(\beta+\gamma)$ up to $\sim 30\%$ "penguin pollution".
- "penguin pollution" cleaned up by $B_s \to K^+K^-$ up to $\sim 20\%$ SU(3) breaking.

SU(3) symmetry breaking is a "2nd order" effect on the measurement of γ.

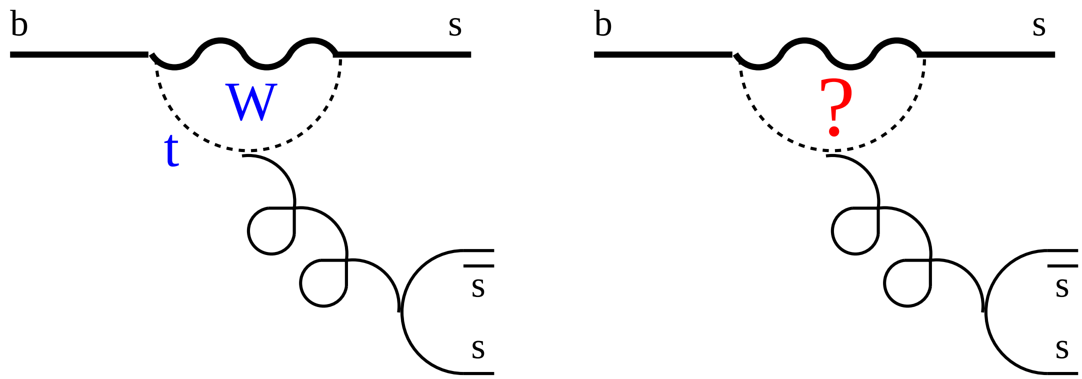
Aside: SU(3) breaking tends to cancel in rate ratios like CP asymmetries. To be conservative, we ignored this fact.

Dependence on "Nature's choice"



Large Penguin Correction to untangle $\Leftrightarrow$ Large error on γ

Chasing SUSY with Penguins



$$A_{SM} \propto \lambda^2 \frac{\alpha_s}{4\pi} \qquad A_{NP} \propto \frac{M_W^2}{M_{NP}^2}$$

$$\frac{A_{NP}}{A_{SM}} \sim O(1) \quad \Leftrightarrow \quad M_{NP} \sim 3\ TeV$$

SUSY may lead to $A_{CP}(B^{\pm} \to \phi K^{\pm}) \sim 30\%$ **(PRD63 (2001) 015003)**

Expect $1.4 - 1.9$**k events @ BR=5.5e-6** $(\sim 1000 fb^{-1}$**@**$\Upsilon(4S))$

$> 4\sigma$ **"observation" up to S/bkg** $\sim 1/4$

Other beautiful Physics

- $\Delta\Gamma$ & $Arg(M_{12})$ using $B_s \rightarrow J/\psi\phi$; CDF(BTeV) expects 4000(20,000) events/2fb^{-1}
- Measure $\beta + \gamma$ using $B_d \rightarrow \pi^+\pi^-\pi^0$; BTeV expect $\epsilon D^2 \times$ yield = 500 events.

3 Lectures Conclusion

- D0 & CDF Run2 physics program are finally starting.
- Likely to start being competitive with BaBelle by Summer 2003 on a number of charm- and B-physics topics.
- Unique opportunities: $\Delta m_s, \gamma$