Road to the discovery of Large CP Violation

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Discoveries before 1980

- 1962 Two neutrinos with mass and mixing
- 1964 CP Violation in $K \to \pi^+\pi^-$
- 1973 KM model
- 1974 J/ ψ
- 1975 Charm particles
- 1976 Υ(1S)
- 1980 Prediction of large CPV in B decays

1962 Discovery of mixing angles for two neutrinos

Without knowing about the experimental discovery of ν_μ
Maki, Sakata, and Nakagawa stated

$$\nu_1 = \nu_e \cos\delta + \nu_\mu \sin\delta$$

$$\nu_2 = -\nu_e \sin\delta + \nu_\mu \cos\delta$$

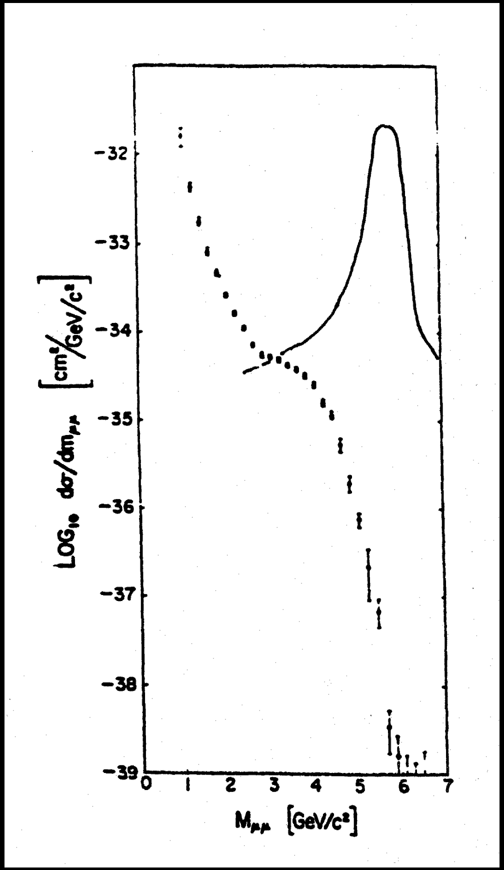
Prog. Theoretical Physics **28** 870, (1962)

before Cabibbo introduces the mixing angle for quarks

Lederman's shoulder

1970 Columbia

$$p + U \rightarrow \mu^{+}\mu^{-} + anything$$

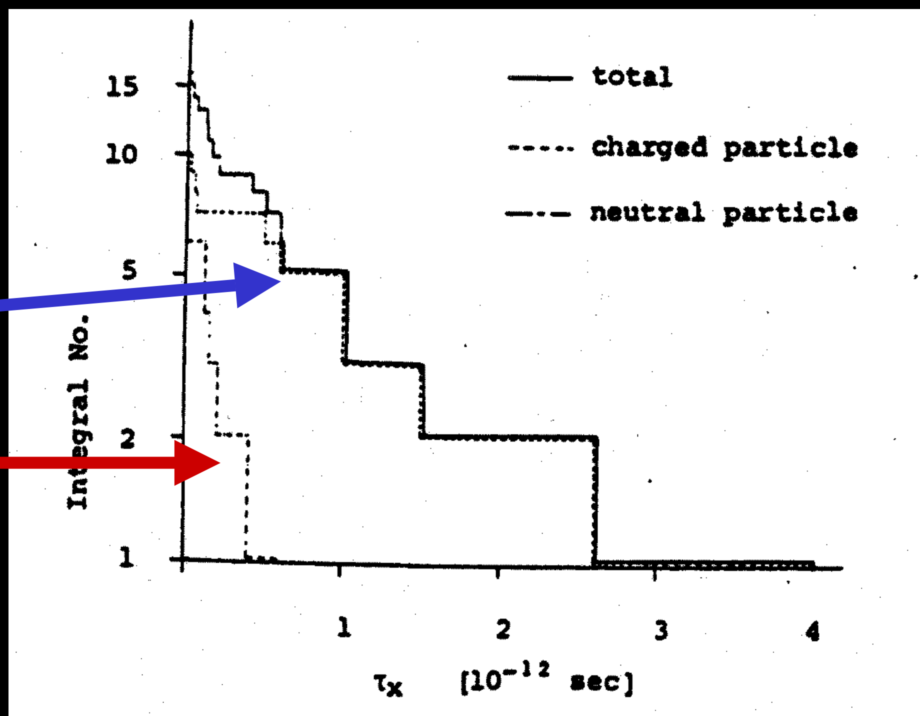


1975 Discovery of D^0 and D^+

This discovery was before G. Goldhaber et.al PRL 37, 255(1976)

D^+

D^0



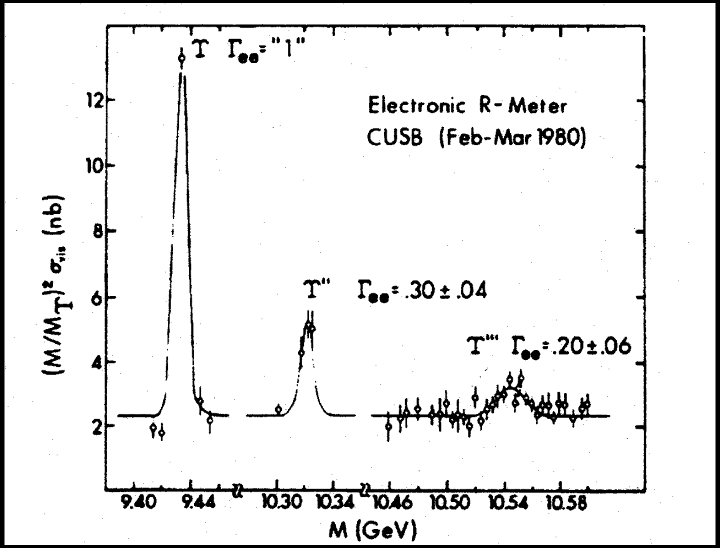
$\tau_{D^+} \ll \tau_{D^0}$

Niu et. al. 14th Int. Cosmic Ray Conf. (Munich), 7, 2442 (1975)
Nagoya Discovery

Start of B physics

- Theorists discussed B mesons since 1976
- Ellis Gaillard Nanopoulos Rudaz 1977
- Bander Silverman Soni 1979
- Cater AIS 1980
- Discovery of Υ(4S) Phys. Rev. Lett. 45, 219–221 (1980)

[Issue 4 – 28 July 1980]



Pais Seminar
Pais-Treiman paper
CP Violation in Charmed Particles

Phys.Rev.D12:2744-2750,1975

There is good news and bad news:

- Good news is that there is CP violation in heavy meson decays
- Bad news is that it is very small
- They considered wrong asymmetries

Generalization of K decays

$$\frac{\Gamma(K_L \to l^+ \nu_l \pi^-) - \Gamma(K_L \to l^- \overline{\nu}_l \pi^+)}{\Gamma(K_L \to l^+ \nu_l \pi^-) + \Gamma(K_L \to l^- \overline{\nu}_l \pi^+)} = \frac{|p_K|^2 - |q_K|^2}{|p_K|^2 + |q_K|^2}$$

$$\approx \frac{2\,\mathrm{Re}\,\varepsilon}{1+|\varepsilon|^2}$$

$$\frac{\Gamma(\overline{B}^0 \to l^+ \overline{X}) - \Gamma(B^0 \to l^- X)}{\Gamma(\overline{B}^0 \to l^+ \overline{X}) + \Gamma(B^0 \to l^- X)} = \frac{|p_B|^2 - |q_B|^2}{|p_B|^2 + |q_B|^2}$$

$$\left|B_1\right\rangle = p\left|B^0\right\rangle + q\left|\overline{B}^0\right\rangle$$

$$\left|B_2\right\rangle = p\left|B^0\right\rangle - q\left|\overline{B}^0\right\rangle$$

$$p = \frac{1+\varepsilon}{\sqrt{1+|\varepsilon|^2}}$$

$$q = \frac{1-\varepsilon}{\sqrt{1+|\varepsilon|^2}}$$

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \approx \sqrt{\frac{M_{12}^*}{M_{12}}}\sqrt{\frac{1 - \frac{i}{2}\frac{\Gamma_{12}^*}{M_{12}^*}}{1 - \frac{i}{2}\frac{\Gamma_{12}}{M_{12}}}}$$

$$\frac{\Gamma_{12}}{M_{12}} \propto \frac{m_c^2}{m_t^2}$$

$$\frac{p}{q} = \frac{1+\varepsilon}{1-\varepsilon} \approx \frac{M_{12}^*}{M_{12}}\left[1 + O\left(\frac{\Gamma_{12}}{M_{12}}\right)\right] = e^{i\delta}\left[1 + O\left(\frac{\Gamma_{12}}{M_{12}}\right)\right]$$

$$\frac{\Gamma(\bar{B}^0 \to l^+ \bar{X}) - \Gamma(B^0 \to l^- X)}{\Gamma(\bar{B}^0 \to l^+ \bar{X}) + \Gamma(B^0 \to l^- X)} = \frac{|p_B|^2 - |q_B|^2}{|p_B|^2 + |q_B|^2}$$

$$\approx O\left(\frac{\Gamma_{12}}{M_{12}}\right) \qquad \approx \frac{2\,\mathrm{Re}\,\varepsilon}{1 + |\varepsilon|^2}$$

Im ε is large!

Can we find an observable related to Im ε ?

B is definitely different from K!

When I gave a seminar at Cornell, I said ε is large and CP violation is large in B decays. But I did not have an example to show it! They asked me to come back in two months and give another seminar.

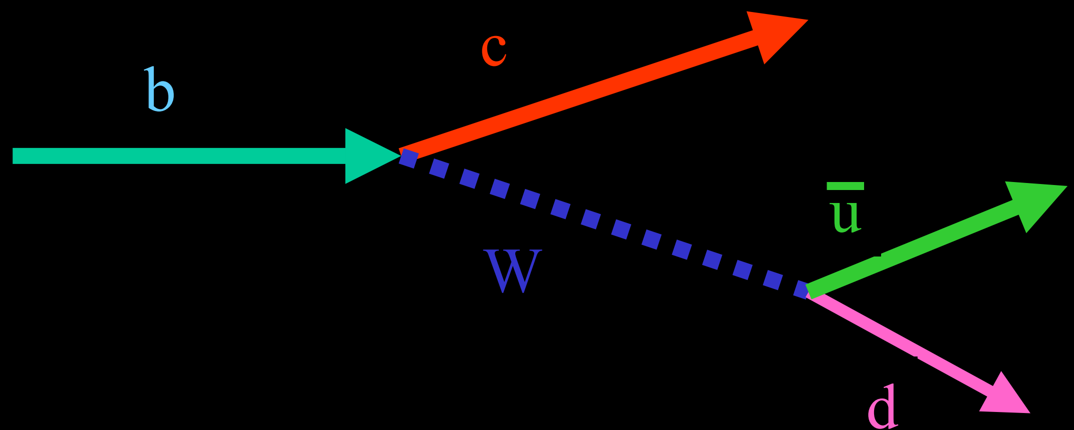
I was really desperate to discover an effect!

$$\frac{p}{q} = \frac{1+\varepsilon}{1-\varepsilon} \approx \frac{M_{12}^*}{M_{12}} = e^{i\delta}$$

How can we detect δ ?

I knew that you need 3 generations participating in CP violating decays

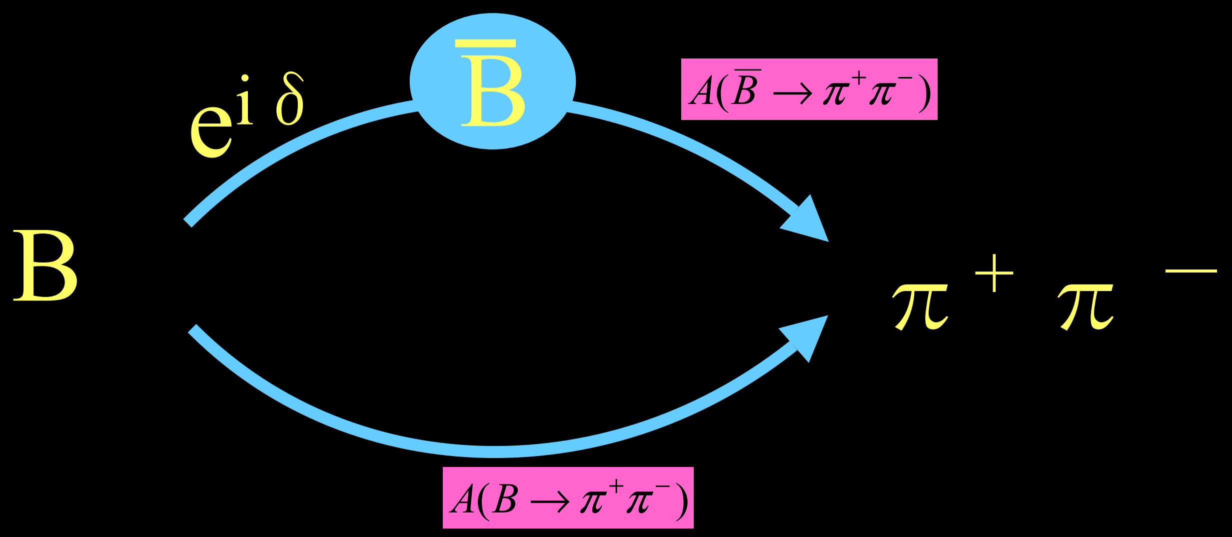
Only way for three generations to appear in K decay



For B decay, 3 generations participate in tree graph decays!

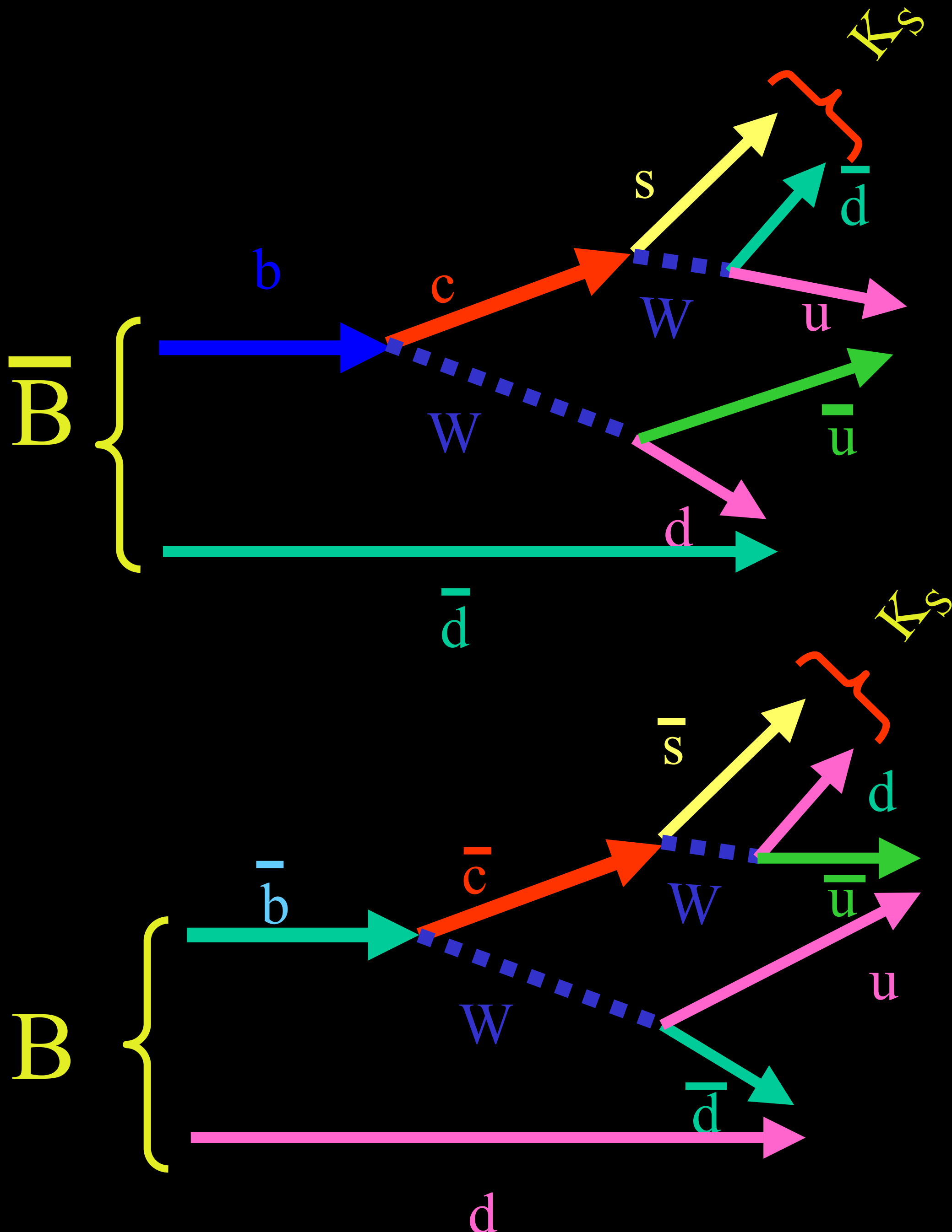
My friend and I

This came easy!



$$\frac{Br(B \to \pi^+\pi^-) - Br(\overline{B} \to \pi^+\pi^-)}{Br(B \to \pi^+\pi^-) + Br(\overline{B} \to \pi^+\pi^-)} \propto \mathrm{Im}\left[e^{i\delta} \frac{A(B \to \pi^+\pi^-)}{A(\overline{B} \to \pi^+\pi^-)} \right]$$

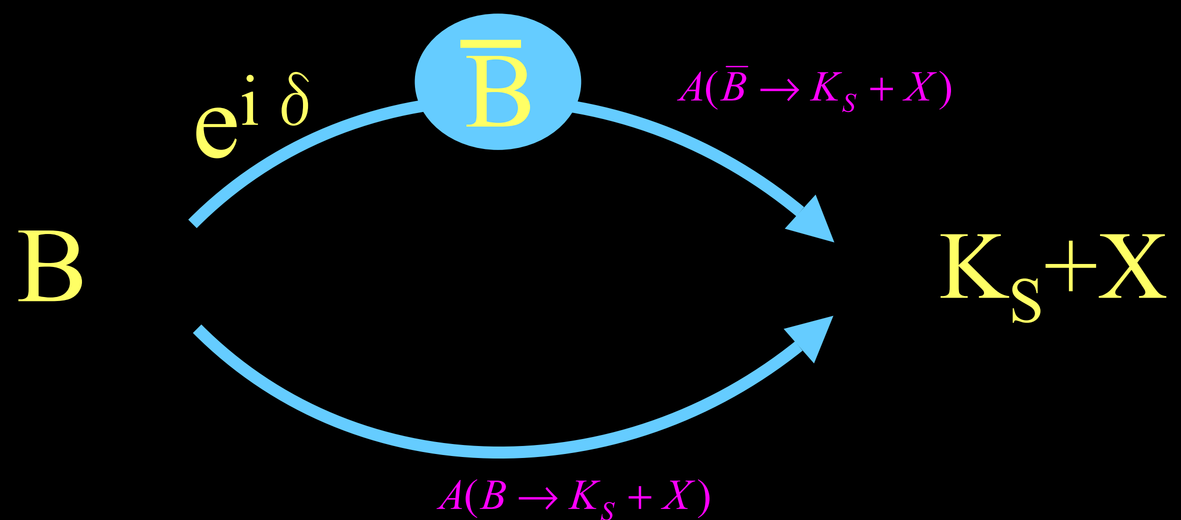
But I new CLEO will not see this decay for a long time!



Can we find large CP asymmetry in major decay modes of B?

This took 2 weeks

Final state is not CP eigenstate



Carter AIS 1980

Discovery after 1980

- 1980 $\Upsilon(4S)$
- 1981 $\Upsilon(4S) \not\to B\bar{B}^*$
- 1982 Longevity of B mesons
- 1986 B-$\bar{\text{B}}$ mixing
- 1991 b$\longrightarrow$ul ν
- 1995 b$\longrightarrow$sγ
- 1997 B$\rightarrow$$K^{\pm}\pi^{\mp}$; $K^{\pm}K^{\mp}$; $\pi^{\pm}\pi^{\mp}$;

Problem

Asymmetry vanishes for J=1 BB state

$$e^+e^- \rightarrow B(t_1)\overline{B}(t_2) \rightarrow \psi K_S$$

$$asym = \mathrm{Im}\left(\frac{q}{p}\rho\right)\sin[\Delta m(t_1 - t_2)]$$

$$\rightarrow \mu^{\pm} + X$$

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\overline{B}^* \rightarrow B\overline{B}\gamma$$

S-Wave

No photon has been detected!

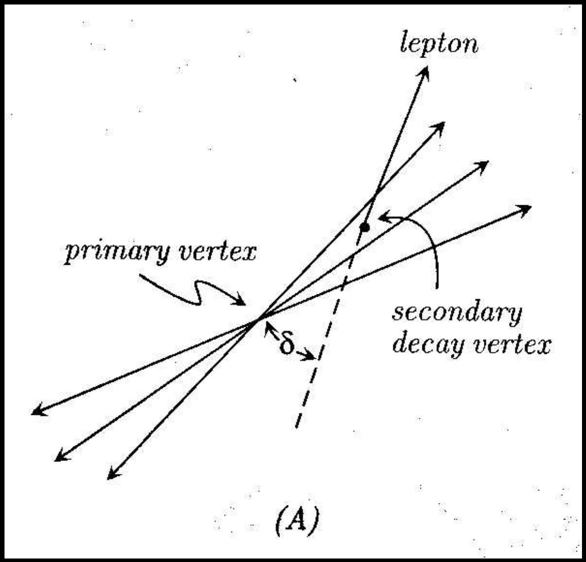
Out for CLEO

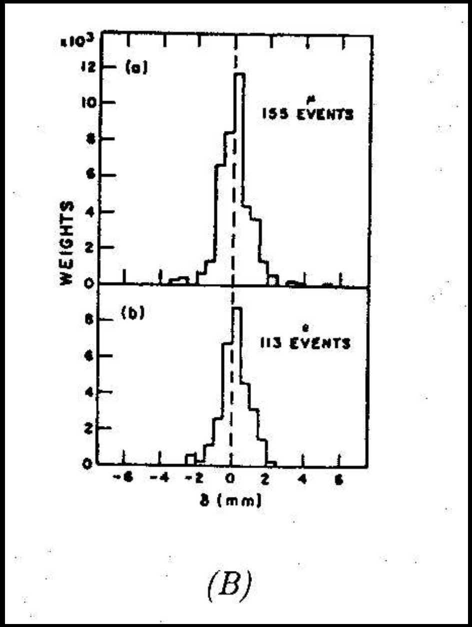
$$asym = \mathrm{Im}\left(\frac{q}{p}\rho\right)\sin[\Delta m(t_1 + t_2)]$$

1982 MAC-MARKII Discovery: Longevity of B

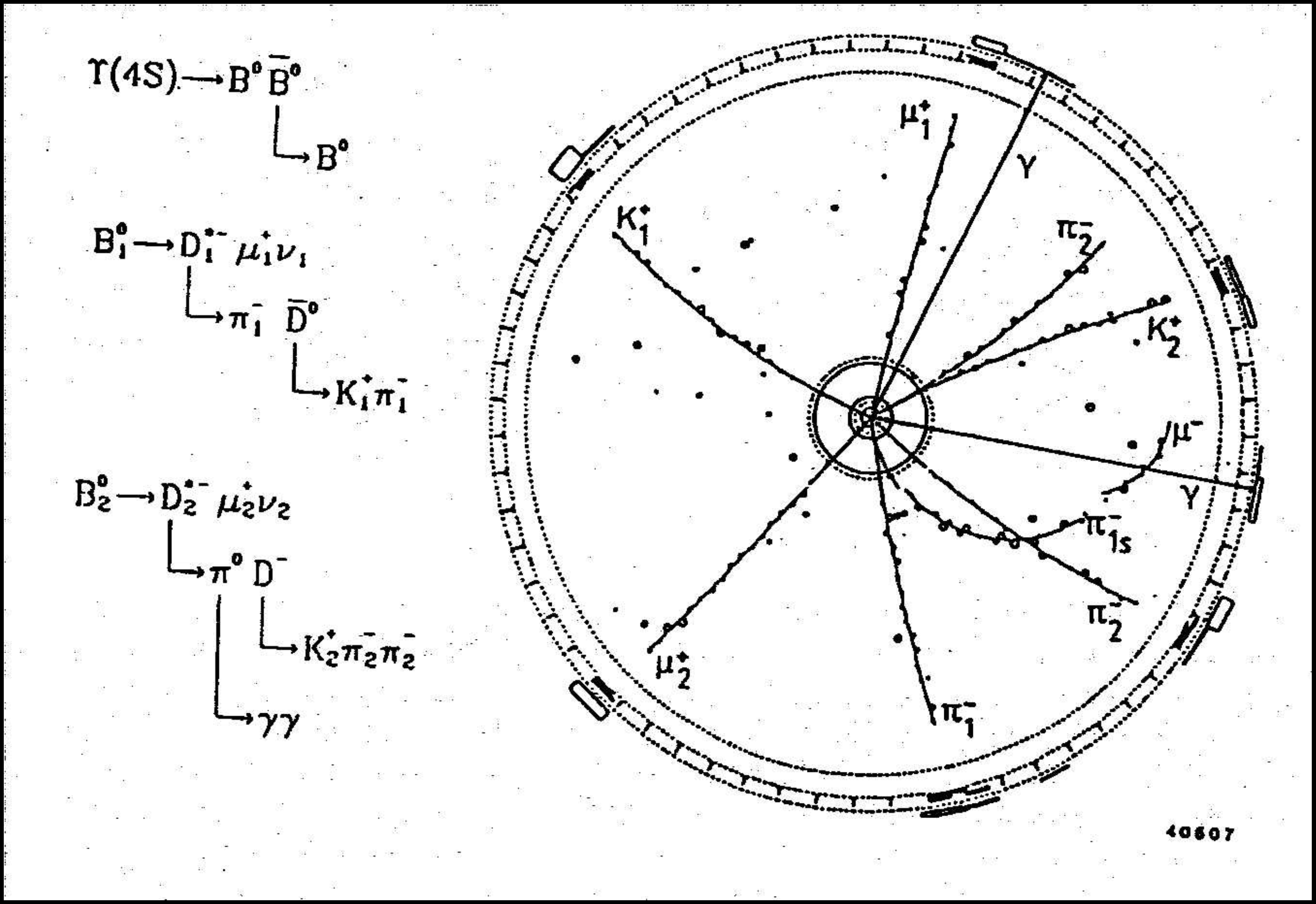
It is absolutely important for B's to live long enough to show interesting physics

$$\sin \Delta M t = \sin \frac{\Delta M}{\Gamma_B} \frac{t}{\tau_B}$$



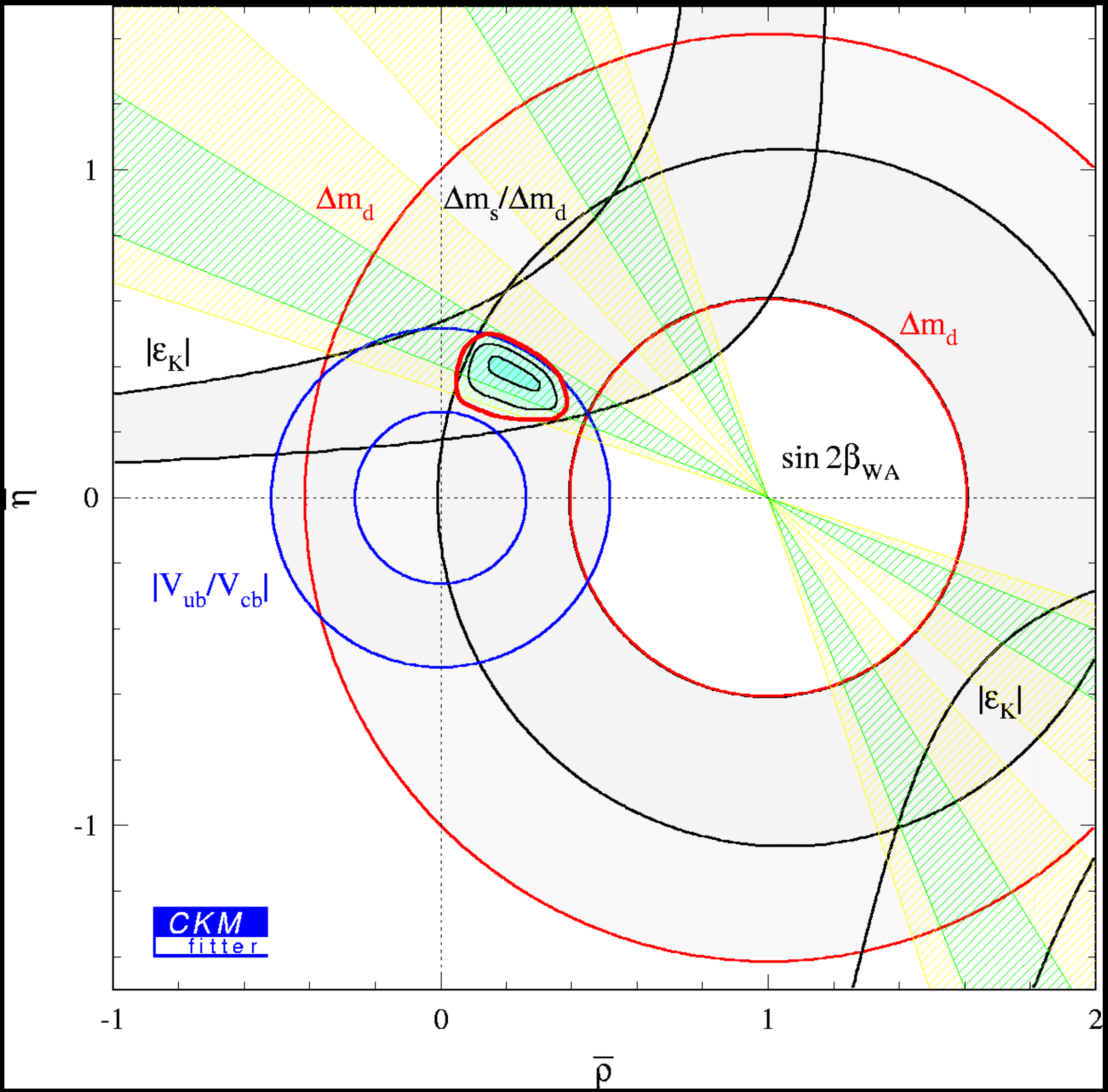


1986 Argus discovery of $B\overline{B}$ mixing

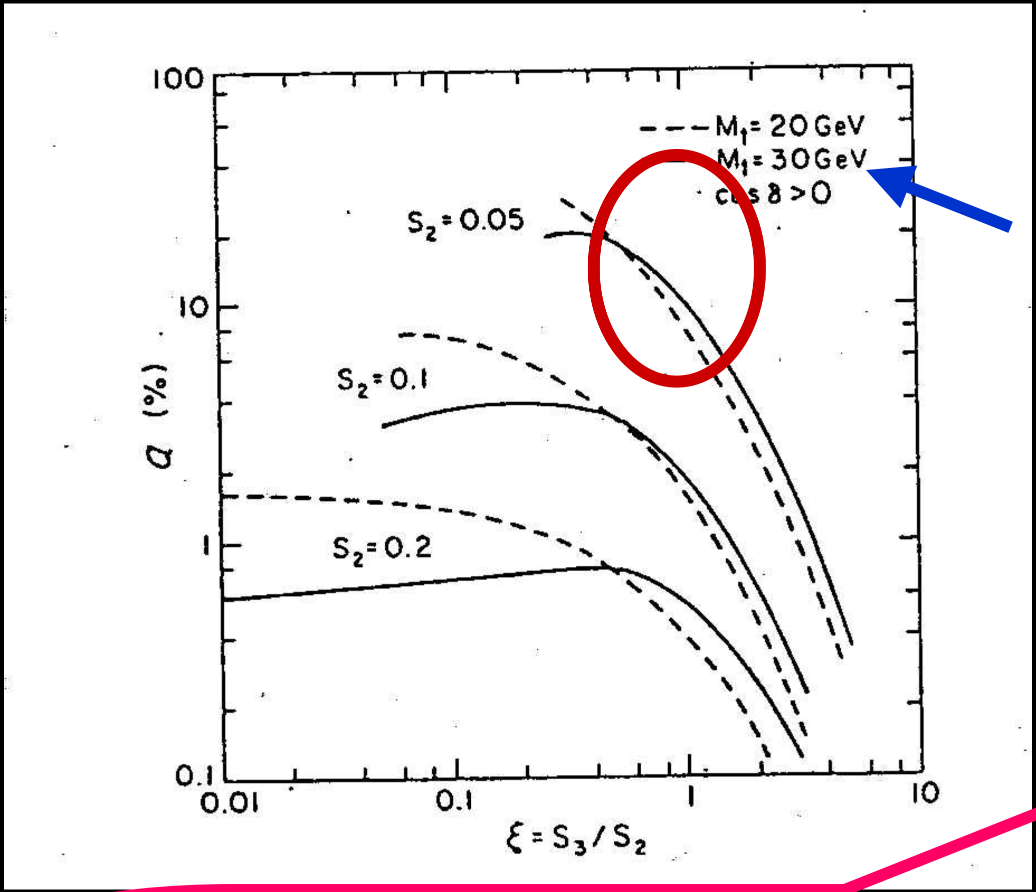


GLOBAL FIT: RESULTS

Global fit including sin2 ϕ_1:



Asymmetry in $B \to K_S + X$



Nothing was known about the KM matrix

We thought 20 GeV is almost ∞

$m_t = 174 GeV$

Carter and AIS PR D23 (1980)

Today's values

$s_3 + s_2 e^{i\delta} = V_{cb}$ $s_1 s_3 = V_{ub}$ $s_2 \approx .02$

$|V_{cb}| = A\lambda^2$ $|V_{ub}| = A\lambda^3$ $\xi \approx 1$

Small Br and big asym
or
Big Br and small asym?

$$\sigma\left(\frac{N_+ - N_-}{N_+ + N_-}\right) = \frac{\sqrt{N}}{N} \propto \frac{1}{\sqrt{Br}}$$

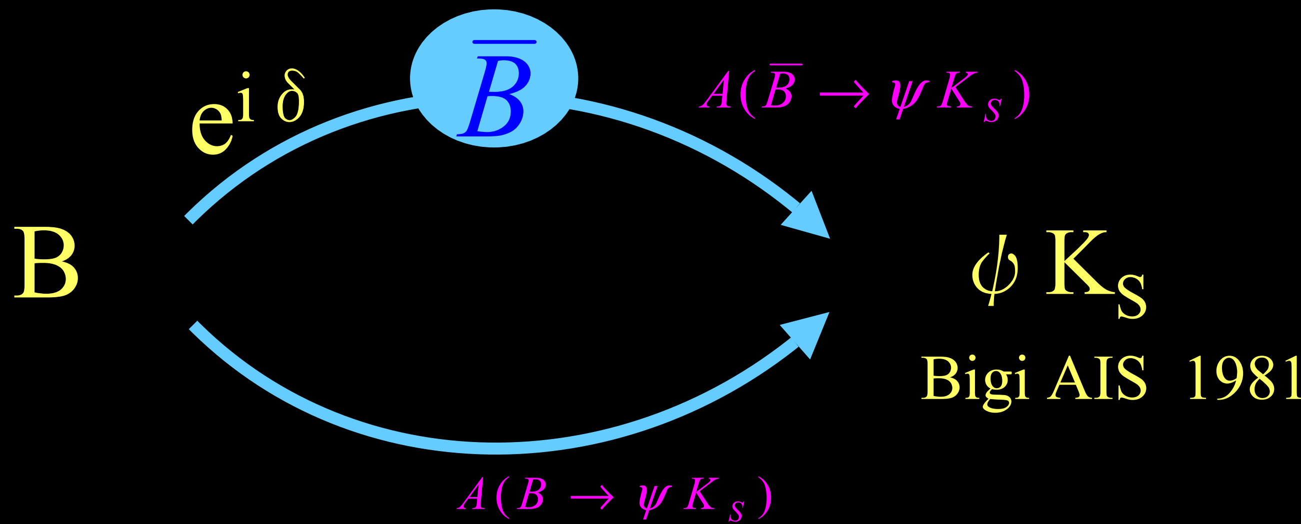
$$\frac{Asym}{\sigma} > 3$$

$$\Rightarrow Asym \times \sqrt{Br} > 3$$

Better to sacrifice events and go for larger asymmetry

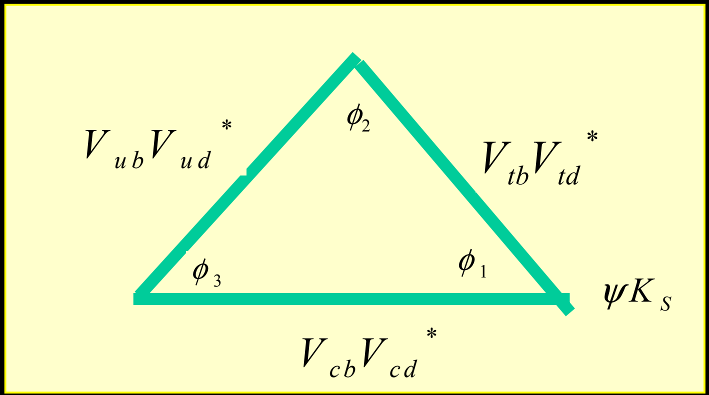
Factor of 2 increase in the asymmetry
is equivalent to a factor of 4 increase in Br

Big Asym Even Br small is better



$$asym = \frac{-x}{1+x^2}\sin 2\phi_1$$

$$\phi_1 = \tan^{-1}\frac{\eta}{1-\rho}$$



Around 1985 we gave up CLEO and started to discuss time dependence

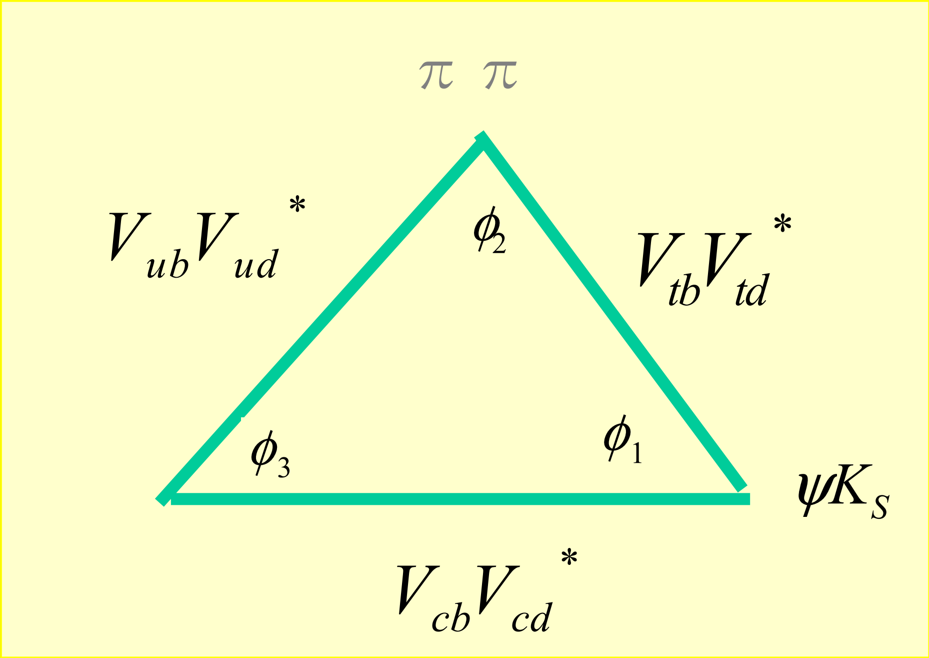
$$e^+e^- \rightarrow B(t_1)\overline{B}(t_2) \rightarrow \psi K_S$$

$$\searrow \mu^\pm + X$$

$$asym = \frac{\Gamma_- - \Gamma_+}{\Gamma_- + \Gamma_+} = \mathrm{Im}\left(\frac{q}{p}\rho\right)\sin[\Delta m(t_1 - t_2)]$$

Unitarity Triangle 1987

Bj notation
Rosner&AIS
Fermilab proeedings



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

Birth of the asymmetric collider

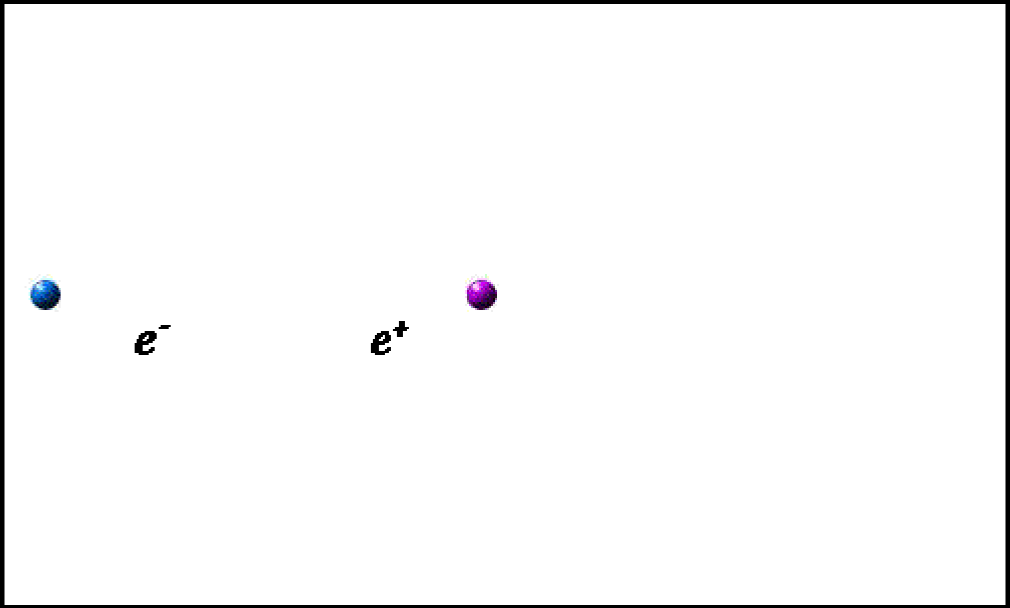
Symmetric collider

B's travel only .02mm take data in 1psec

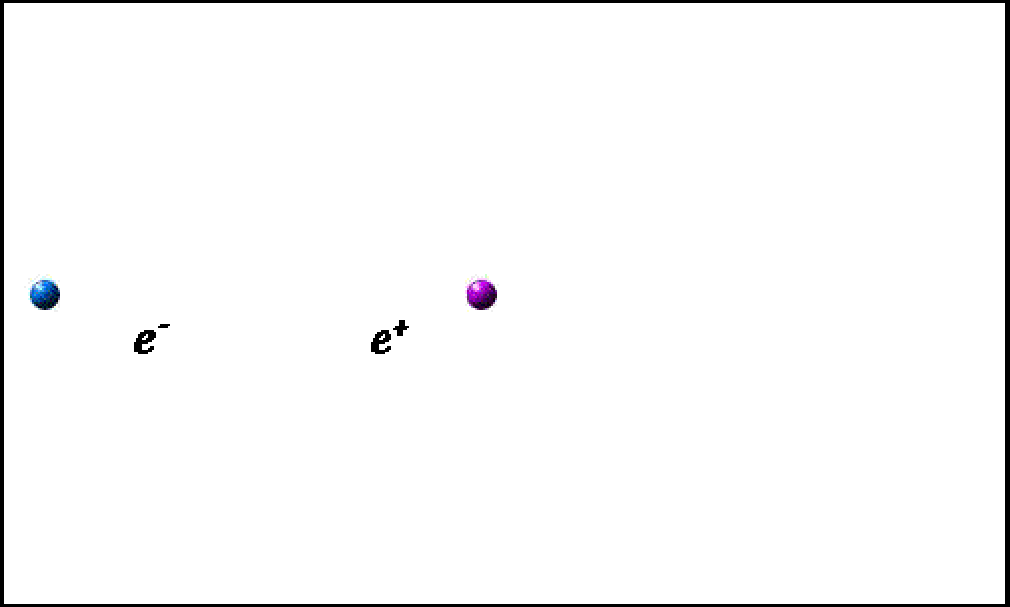
Asymmetric collider

Oddone

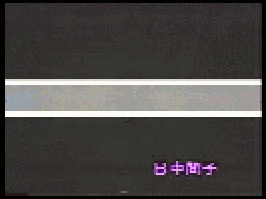
Symmetric Collider



Asymmetric Collider



Deciding on the energy Hitlin, Nakada, AIS snowmass



Looked for the best asymmetry

$$9\text{GeV} \times 3\text{GeV} \text{ is best.} \quad s \approx M_{\Upsilon}^{2}$$

$B \to \psi K_S$ asymmetries discovered

July, 2000

$$\sin 2\phi_1 = 0.82 \pm 0.12(stat) \pm 0.05(syst) \qquad Belle$$

$$\sin 2\phi_1 = 0.75 \pm 0.09(stat) \pm 0.04(syst) \qquad Babar$$

Where do we go from here?

What we know

$\mathrm{B} \to J/\psi K_S, \psi(2S) K_S, \chi_{C1} K_S, \eta_C K_S, J/\psi K^{0*}, J/\psi K_L$

$\sin 2\phi_1 = .719 \pm 0.074 \pm 0.035$

$B \to \phi K_S$ asymmetry

$-0.73 \pm 0.64 \pm 0.18$ (Belle)

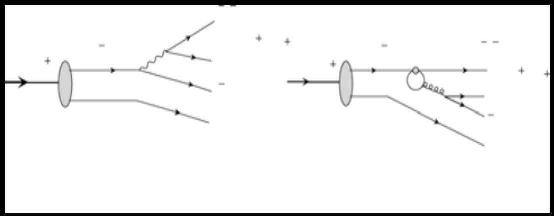
$-0.19^{+0.52}_{-0.50} \pm 0.09$ (Babar)

Very interesting! Lets wait and see.

What we have leaned

$$\frac{A(B \to f)}{A(\bar{B} \to \bar{f})} = \frac{V_T T + V_P P e^{i\delta}}{V_T^* T + V_P^* P e^{i\delta}}$$

$$\frac{A(B \to f)}{A(\bar{B} \to \bar{f})} = \frac{V_T}{V_T^*} \frac{1 + \frac{V_P P e^{i\delta}}{V_T T}}{1 + \frac{V_P^* P e^{i\delta}}{V_T^* T}}$$



Ratio is independent of strong interaction if:

1. Penguin and Tree have same KM phase
2. Penguin is absent

Penguins seems to be large in B decays

$$\frac{A(B \to K\pi)}{A(B \to \pi\pi)} = \frac{V_{ub}^* V_{us} T + V_{tb}^* V_{ts} P}{V_{ub}^* V_{ud} T + V_{tb}^* V_{td} P} = \frac{\lambda^4 T + \lambda^2 P}{\lambda^3 T + \lambda^3 P}$$

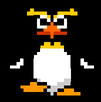
If T dominated over P, $\frac{Br(B \to K\pi)}{Br(B \to \pi\pi)} = \lambda^2 \approx \frac{1}{20}$

$$\frac{Br(B \to K\pi)}{Br(B \to \pi\pi)} > 1 \quad \Rightarrow \quad \frac{P}{T} > \lambda$$

Fat penguins

We expected $\frac{P}{T} = \frac{\alpha}{12\pi^2} \log \frac{M_W}{\mu} = O(\lambda^2)$

Exciting years of flavor physics



The end