B Physics at e^+e^- Colliders

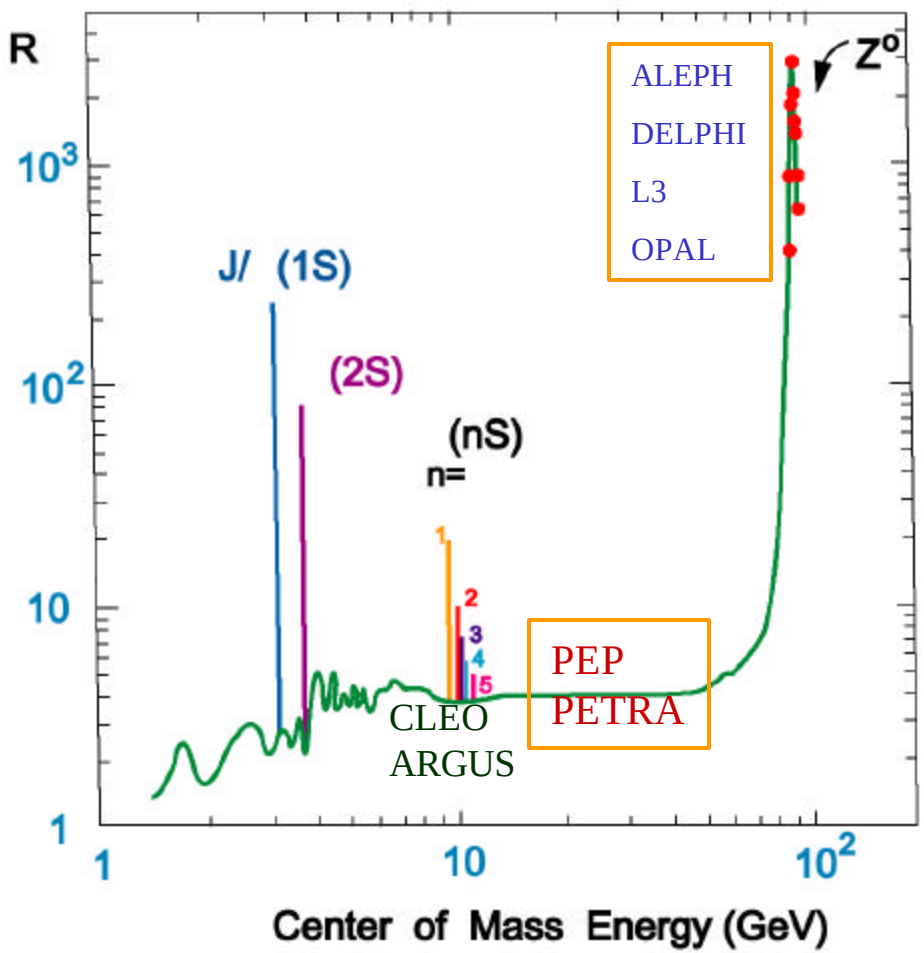
Vivek Sharma
University Of California, San Diego

Selected Results in B Decays

- A Touch of History
- Current Experiments and their environment
- B hadron Lifetimes
- CKM Elements From B Decays
  - V_{cb} from $b \to c\, l\, \nu$
  - V_{ub} from $b \to u\, l\, \nu$
  - V_{ts}/ V_{td} limits from B Oscillations
- CP Engineering Physics
  - Status of B Decays that can measure α, β and γ
- Rare B Decay
  - 2-body $b \to u$ hadronic decays and 2-Body Hadronic Penguins and CP asymm
  - $b \to s\gamma$: Decay rate and CP asymmetry
- Status of the SM Unitarity Triangle
- Near Future : The Era of B Factories has arrived !

B Physics With e^+e^- Colliders

- Scope of this talk : Measurements from the $\Upsilon(4s)$, the continuum beyond and the Z Boson resonance



Data Samples:

CLEO @ Y(4S) : About 9.7 x 10^6 $B\bar{B}$ pairs

LEP @ Z^0 : About 0.9 x 10^6 $b\bar{b}$ pairs with ALEPH, DELPHI, L3 and OPAL experiments

Three Measurements of Significance

This year marks the beginning of the era of B factories and CP asymmetry seaches the world over. It is perhaps useful to look back at the three surprising results which have paved the way towards sensitive searches for CP Violation in B Decays

1. B Lifetime (1983)
2. B Oscillation (1986)
3. $b \rightarrow u$ rate (1988)

The Large Lifetime of B Mesons

- 1983: MAC and MARKII detectors at SLAC
- Measure signed impact parameter of leptons in semileptonic b hadron decay
- Impact Parameter Resolution
  - MAC ~ 600 micron
  - MARK II ~ 200 micron
- Results
  - MAC : 1.8 +- 0.6 +- 0.4 ps
  - MARKII: 1.2+.45-.36+-.3ps
- Confirmed by TASSO & JADE @PETRA

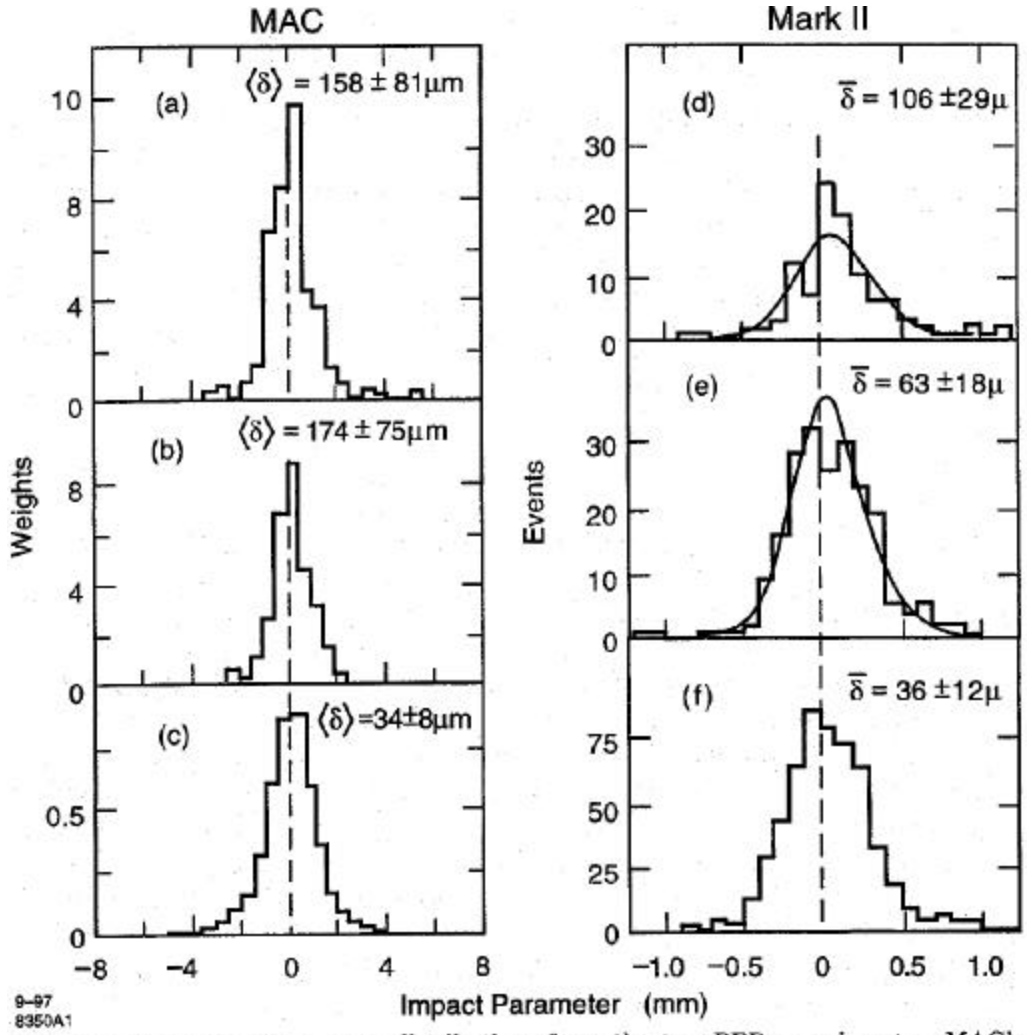
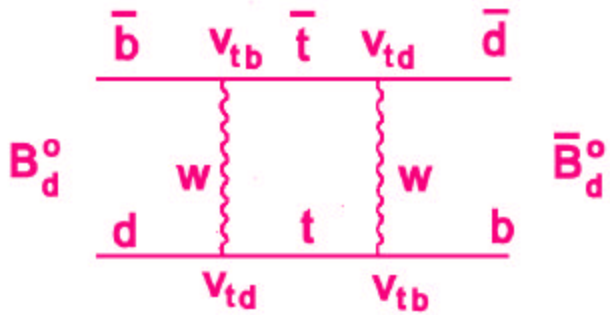
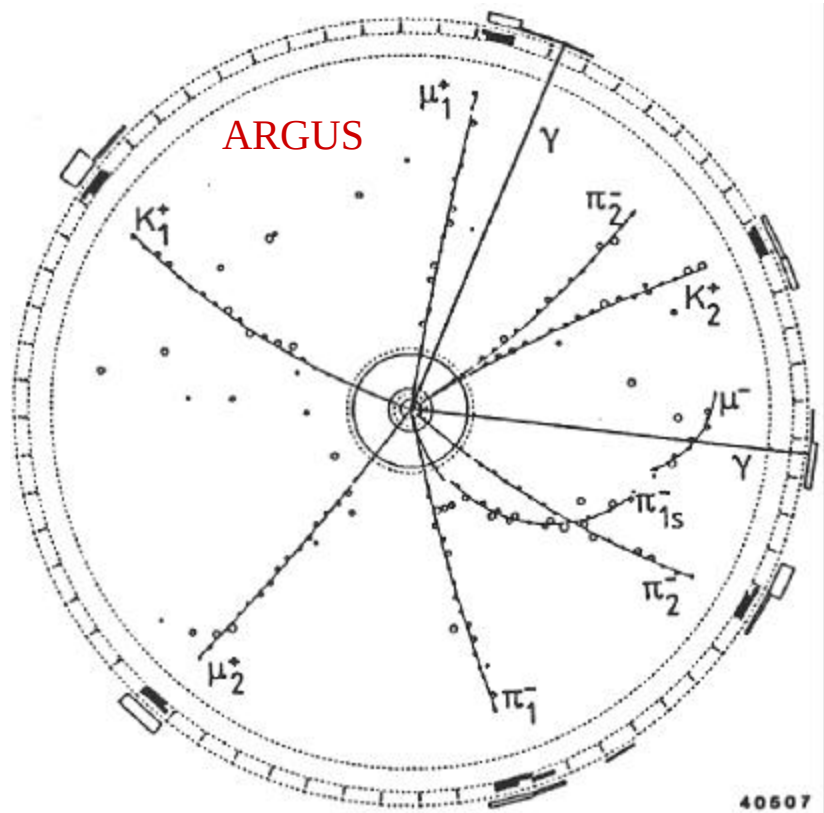


FIGURE 1. Impact parameter distributions from the two PEP experiments. MAC's results are shown for (a) muons, (b) electrons, and (c) hadrons. MARK II's results are shown for (d) "b leptons" with $p_t > 1$ GeV/c, (e) "c leptons" with $p_t < 1$ GeV/c, and (f) hadrons.

The Large B^0 Oscillation Rate



- Mixing rate depends on Top quark mass
- Inspired by PEP/PETRA non-observation of the top quark, many theorist assured as that "Top could not be heavier than 40-50 GeV..conservatively speaking" !!
- Hints from UA1, then definitive results from ARGUS(1987) showed B mixing to be large, if we could calculate better, could have shown that top quark is as heavy as it really is !



$B^0 \to D_1^{*-} \mu_1^+ \nu_1$ and $B^0 \to D_2^{*-} \mu_2^+ \nu_2$

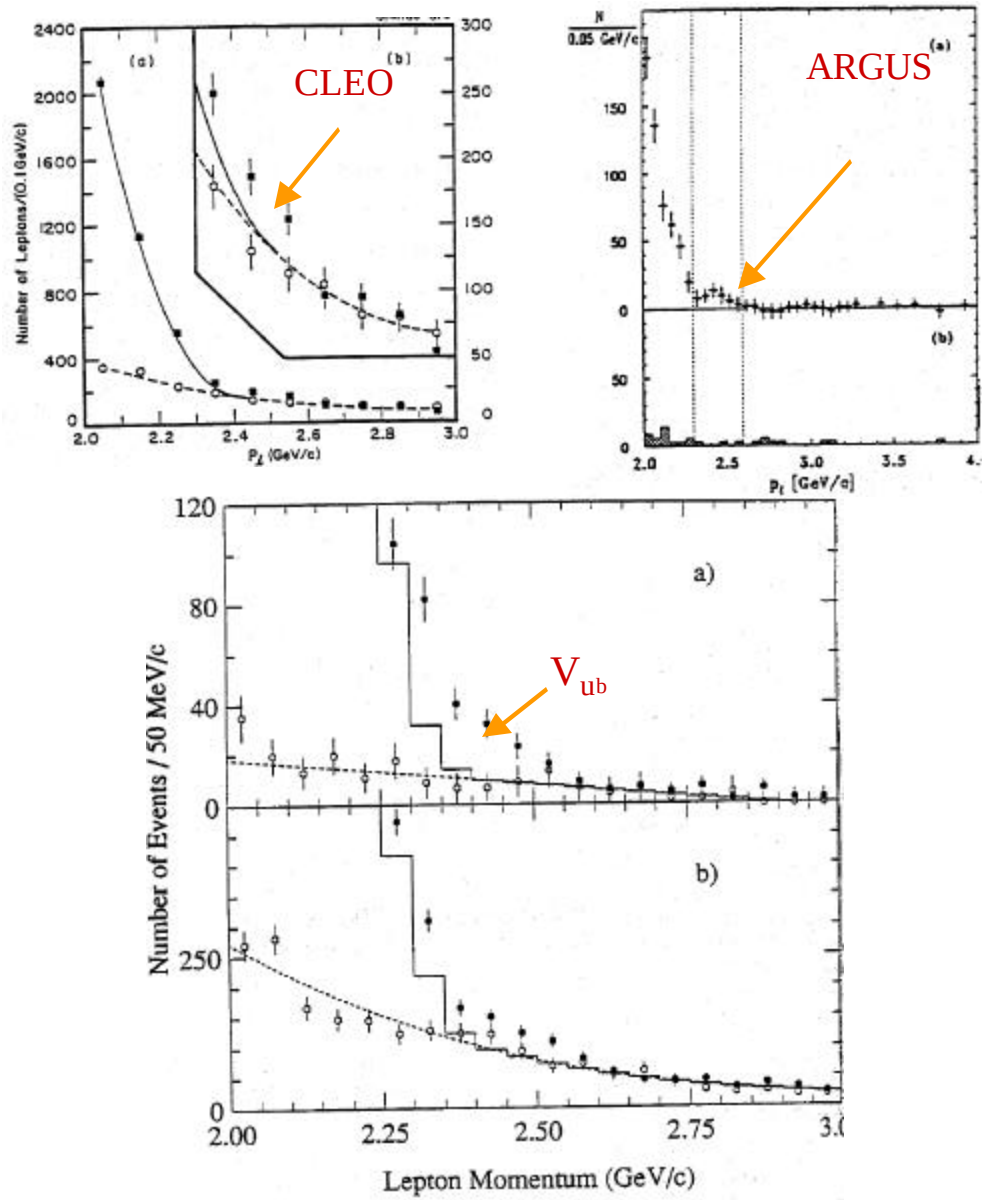
$\hookrightarrow \overline{D}^0 \pi_{1s}^-$ $\hookrightarrow D^- \pi^0$

$\hookrightarrow K_1^+ \pi_1^-$ $\hookrightarrow K_2^+ \pi_2^- \pi_2^-$

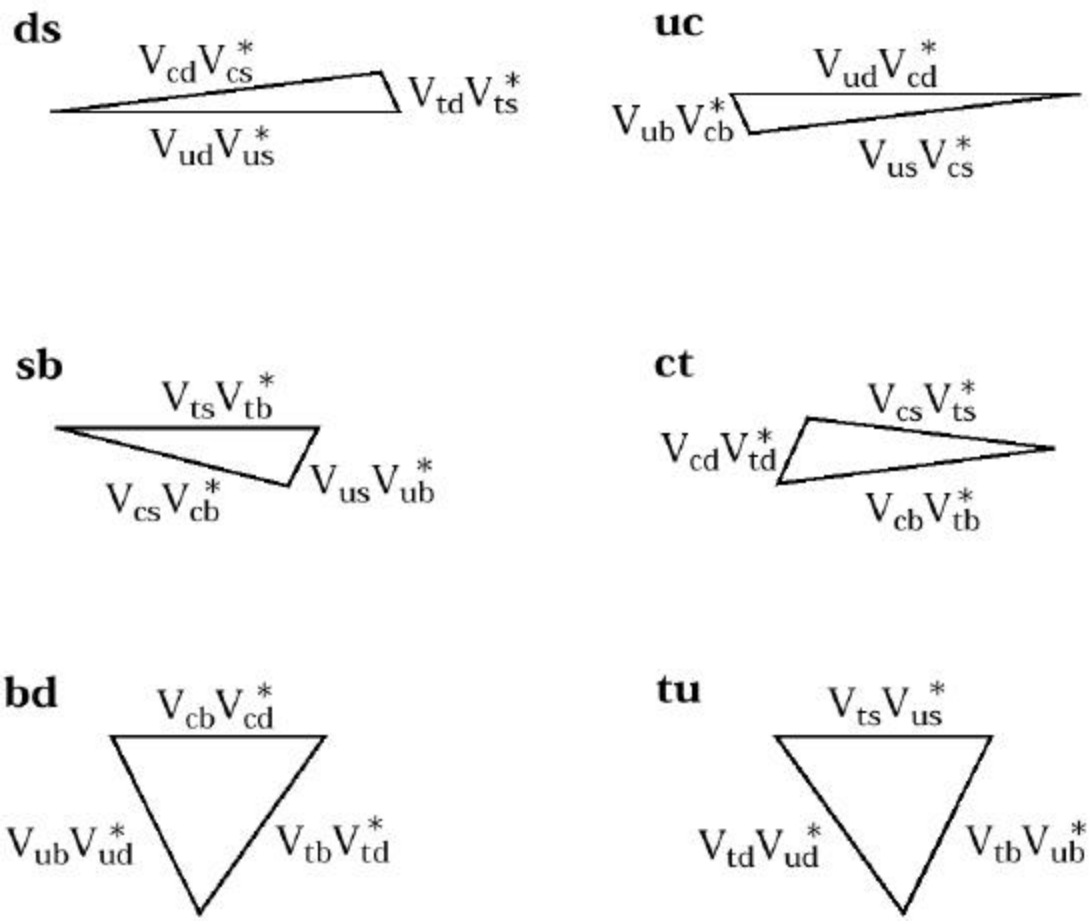
$$c_d = 0.17 \pm 0.05$$

V_{ub}: The Magnitude of b→u Transition

- Must have $V_{ub} \neq 0$ for SM with 3 generations to accommodate CP Violation seen in K^0 decays and expect CP violation in B decays
- The magnitude has too be just-right for measurable CP asymmetries in B decays
- No theory could predict the magnitude of b→u transition
- $V_{ub} \neq 0$ was proven (1988) from pure experimental (kinematic) observable.
- Interpreting the result was/is still a interplay between theory and experiment: $|V_{ub}/V_{cb}| \sim 0.08 \pm 0.02$
- Nevertheless, stage could now be set for CP violation dreams all over the world
- With the demise of SSC, CPV searches in B decays are a worldwide enterprise..(not necessarily a good thing)



Unitarity Triangles and B Decays



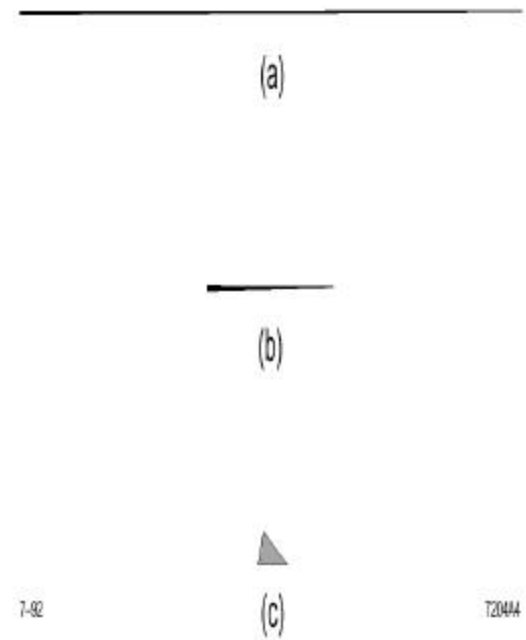


Figure 1-1. *The three unitarity triangles a) $V_{cd}V_{cs}^* = 0$, b) $V_{td}V_{ts}^* = 0$, and c) $V_{ud}V_{us}^* = 0$, drawn to a common scale.*

The three angles are large

The CKM Picture

Quark Mixing between the weak and mass eigenstates is given by 3x3 unitary matrix :

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Unitarity implies four parameters : Three real and a phase

Wolfenstein Parametrisation :

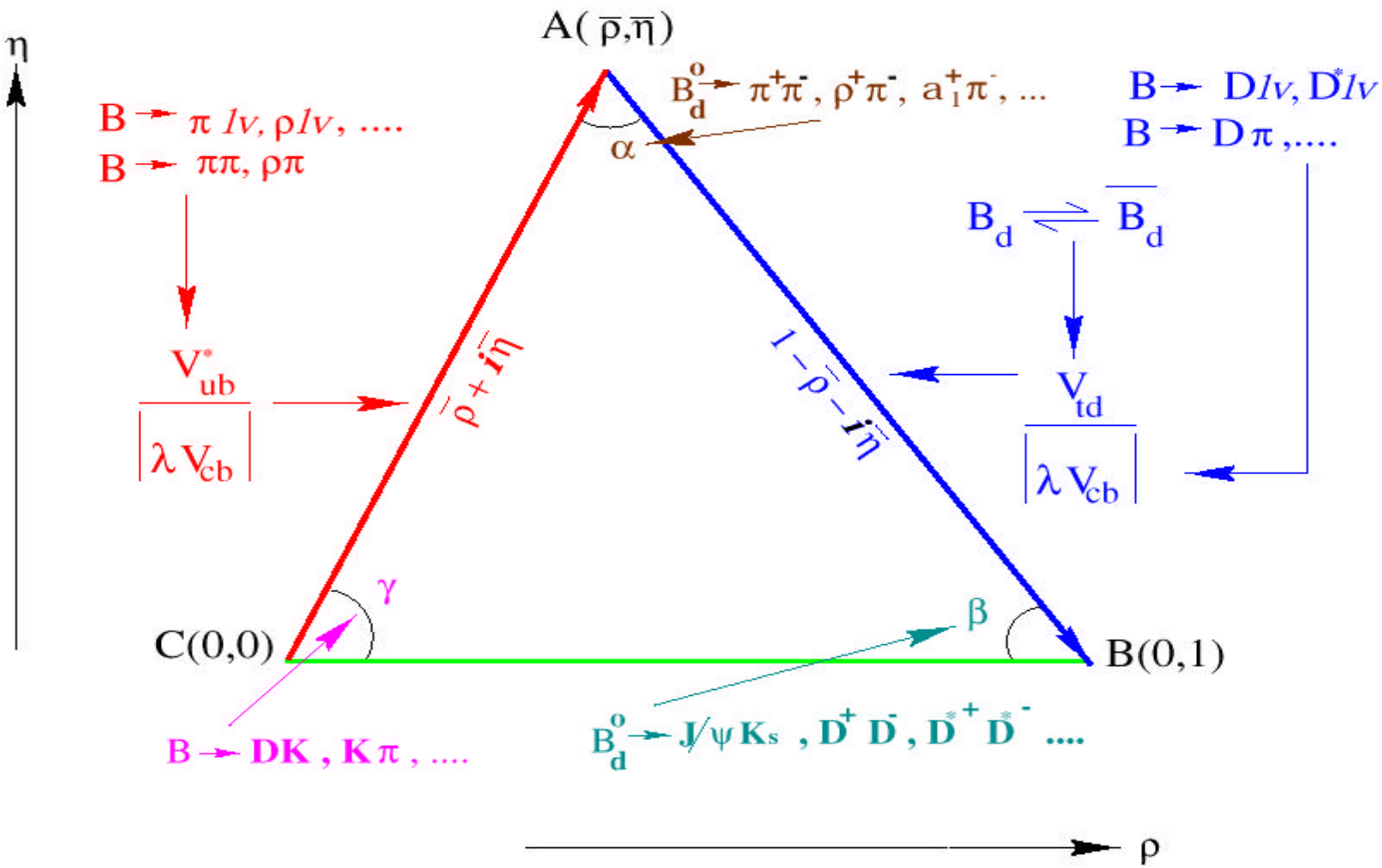
$$V \simeq \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 - iA^2\lambda^4\eta & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda \simeq \sin\theta_c \simeq 0.22$$

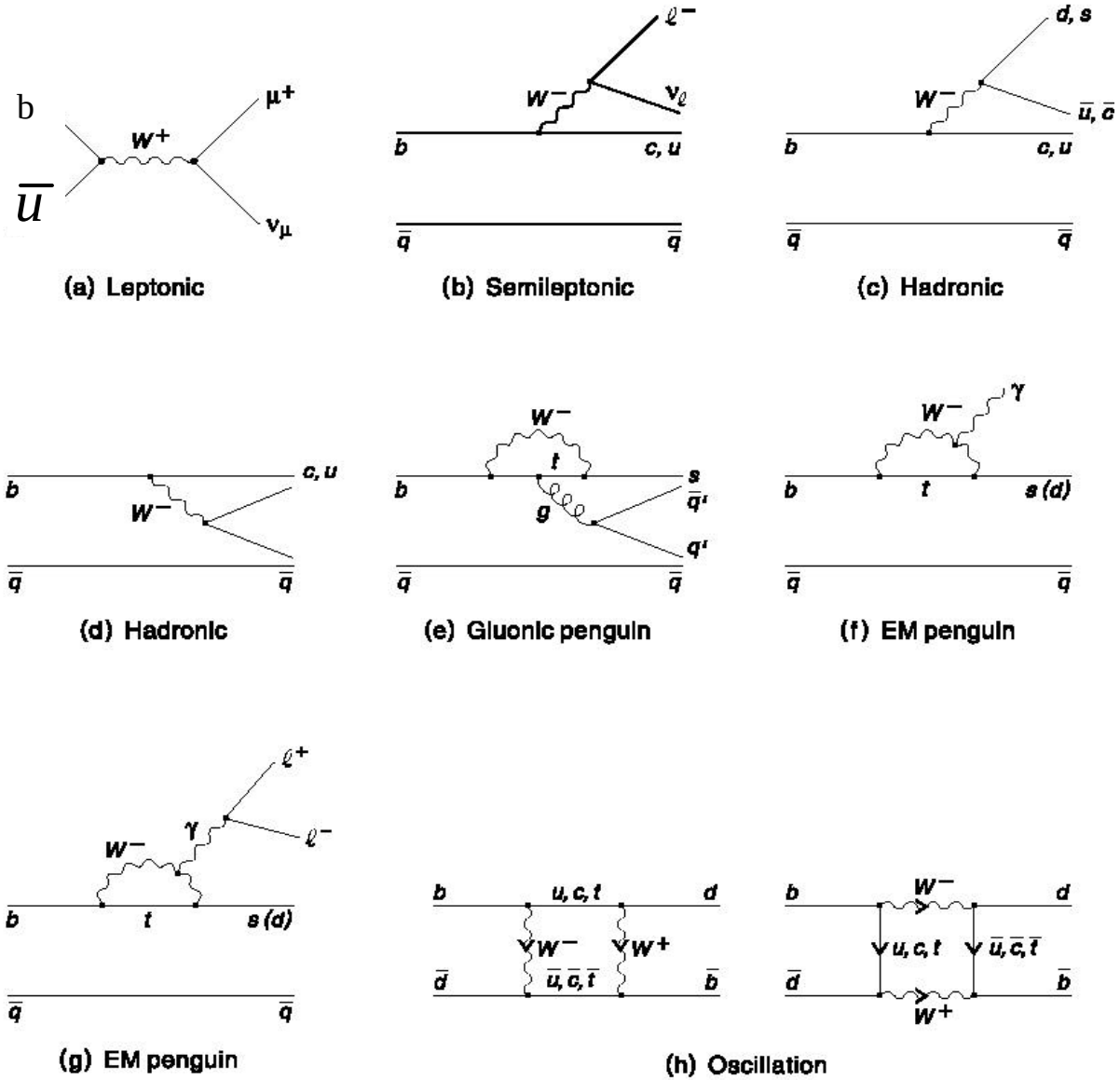
Unitarity=> $V_{ud}V_{ub}^* + V_{td}V_{tb}^* + V_{cd}V_{cb}^* = 0$

Overconstraining The Unitarity Triangle : Road Map

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

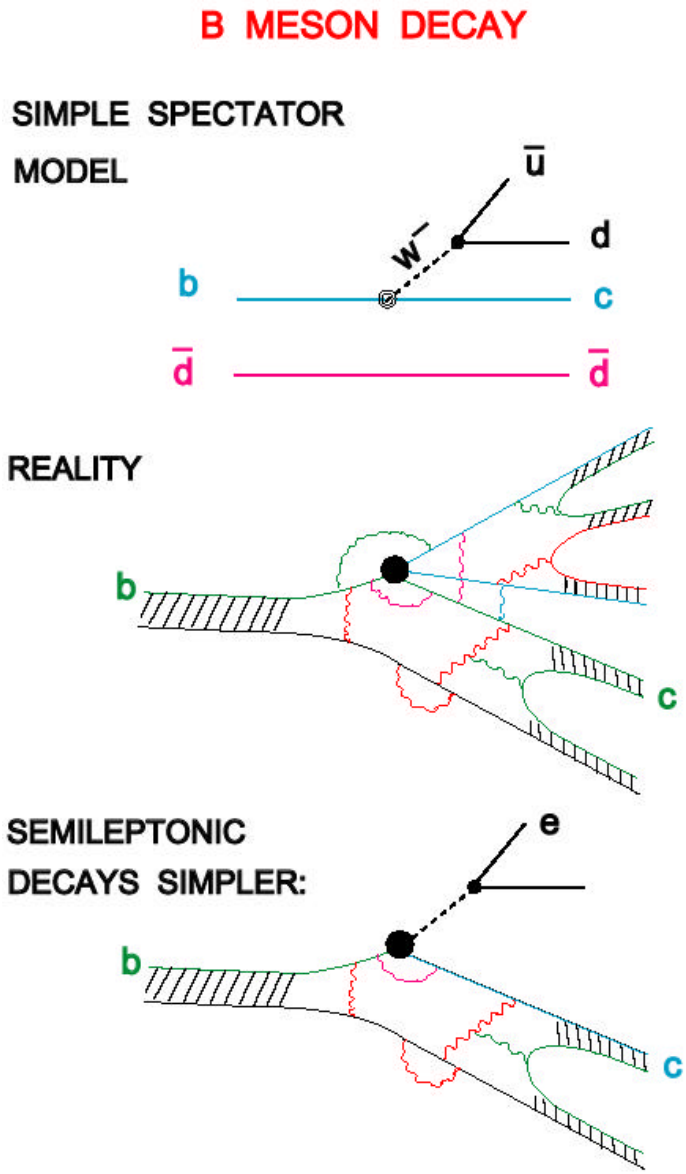


Mechanisms For B Meson Decay



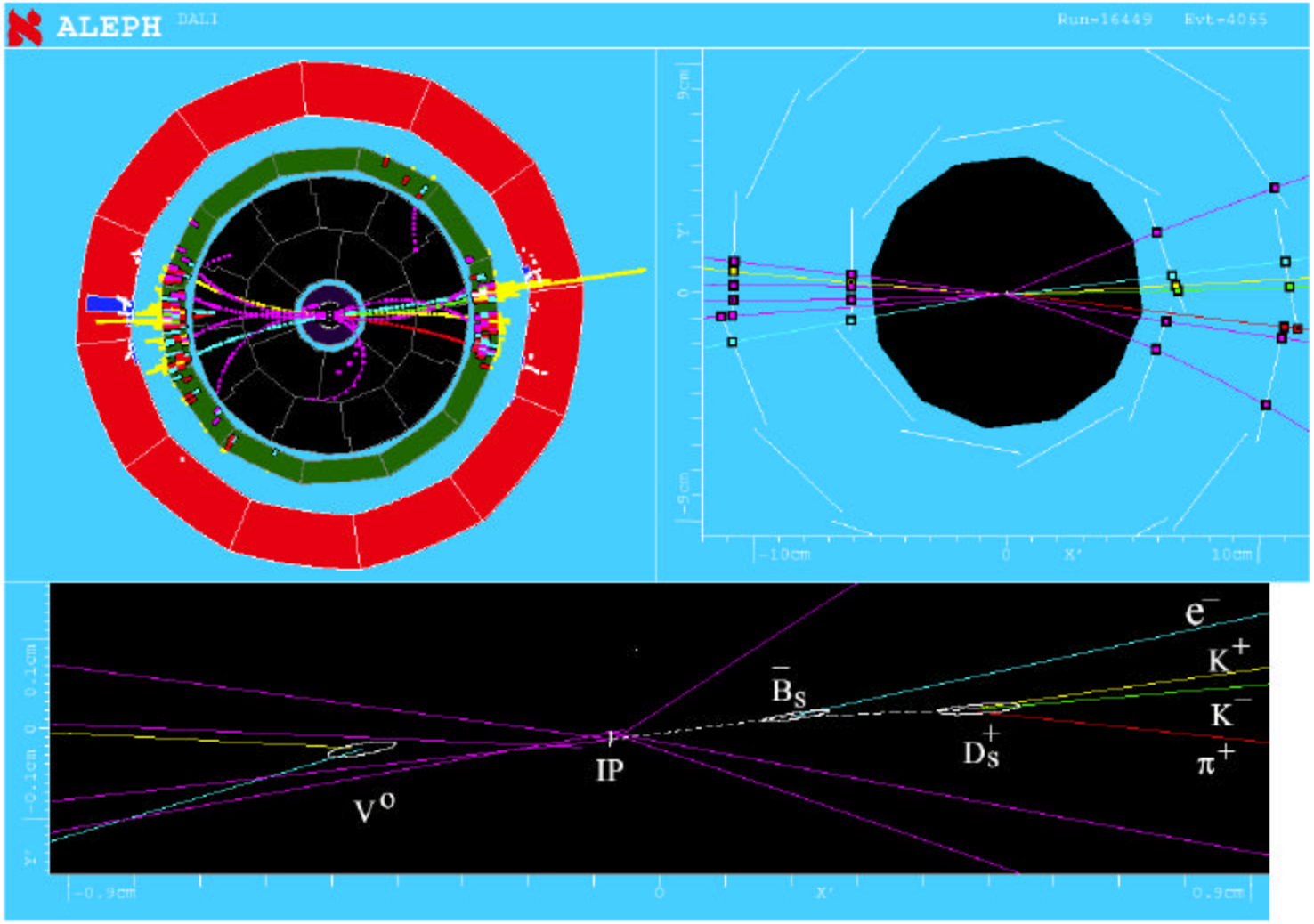
B Decays: Experimental Observables and Theory

- Extraction of CKM elements made difficult by non-perturbative QCD
- Semileptonic Decays simplest to interpret
  - b→c transition interpretation aided by HQS/HQET
  - b→u transitions more model dependent
- Hadronic B Decays interpretation model-dependent (Factorization etc)
  - Will carry over in CP studies in the future…… (unfortunately)

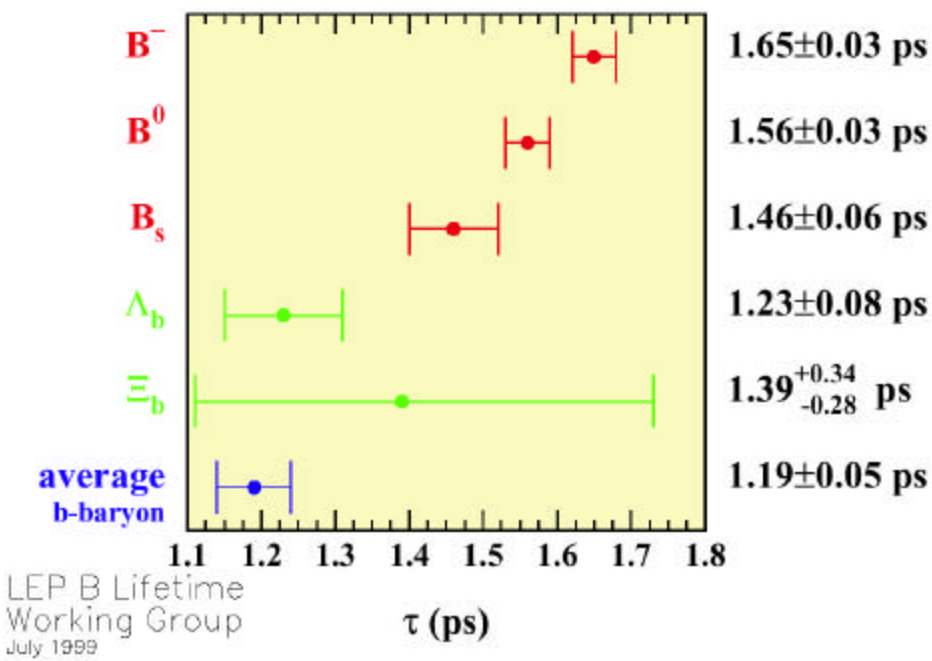


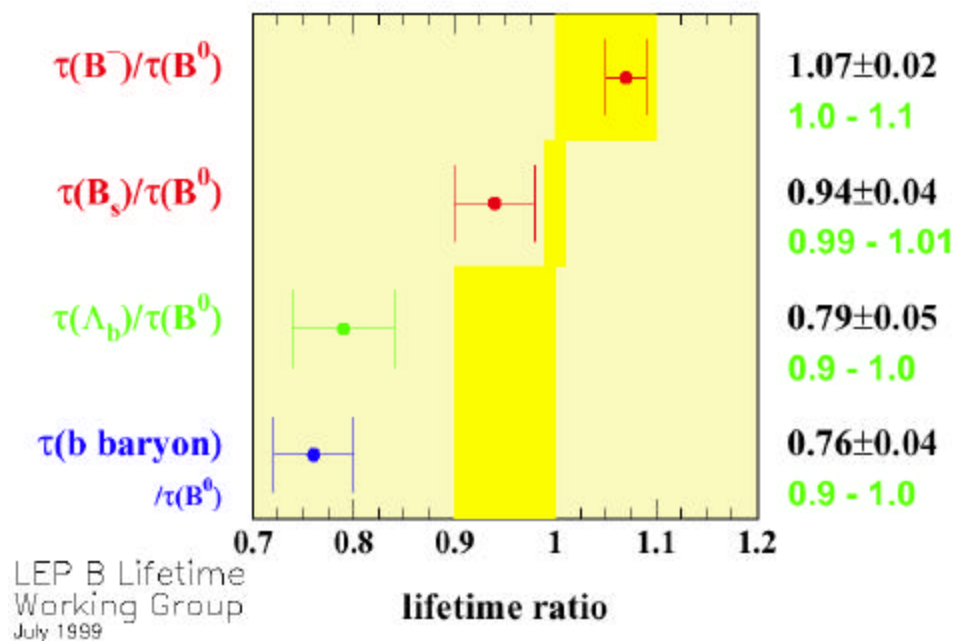
Precise Measurements of b-hadron Lifetime

Large b cross-section, large boost ($\beta\gamma$~6) and efficient silicon vertex detectors have provided precise measurements of lifetimes of all b-hadron species



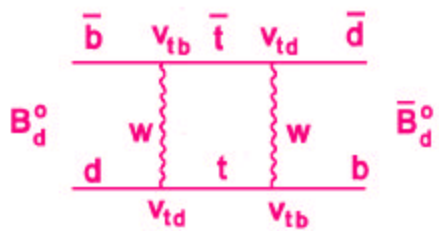
B-Hadron Lifetimes

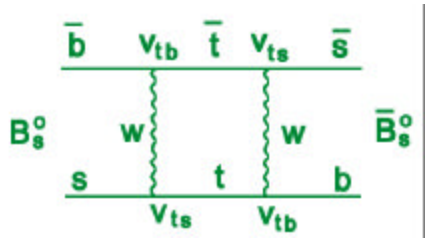




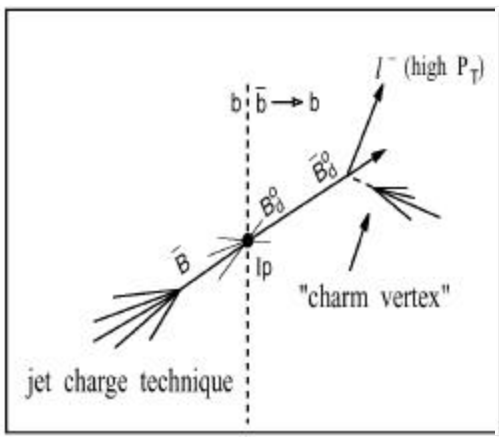
- B Meson lifetime hierarchy as expected, b-baryon lifetime smaller than predicted by QCD-based models
- CDF, in RunII will have enough exclusively reconstructed Λ_b to provide definite answers.

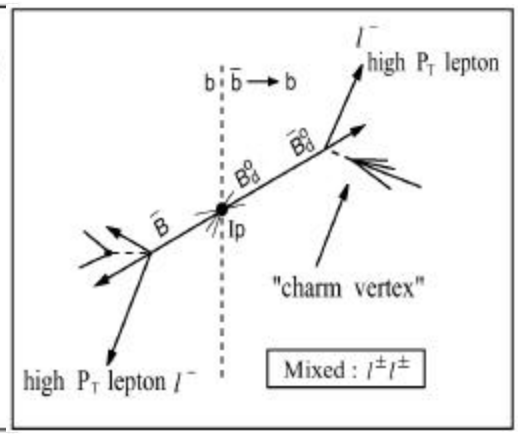
Time-dependent B^0 Oscillations

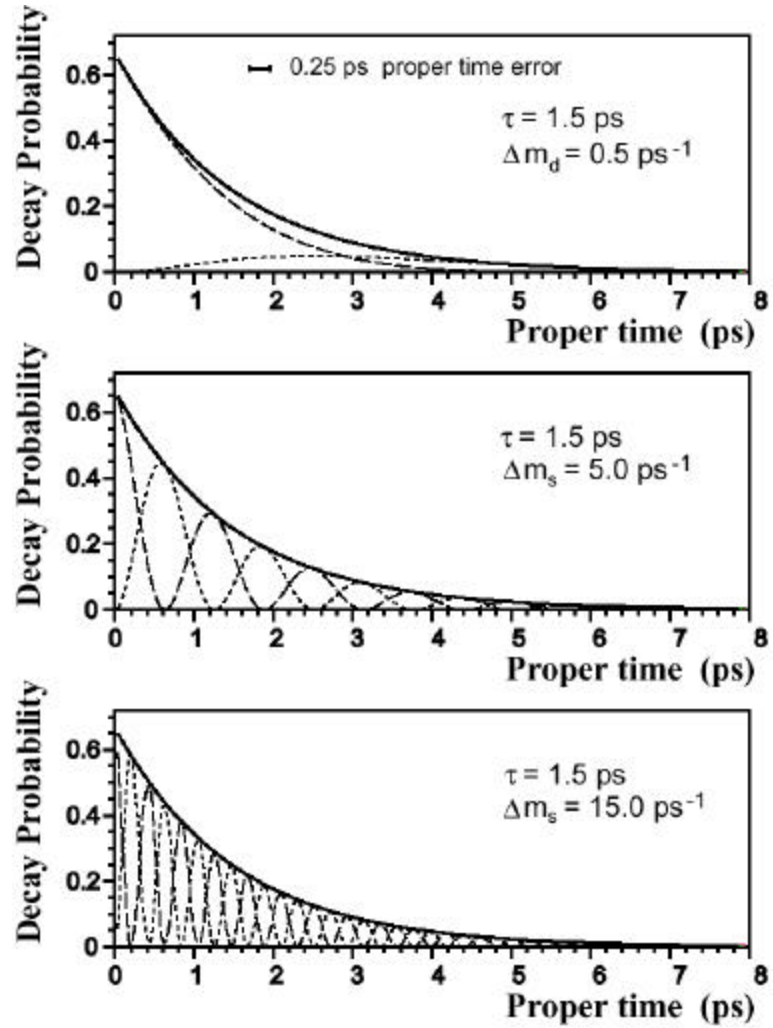




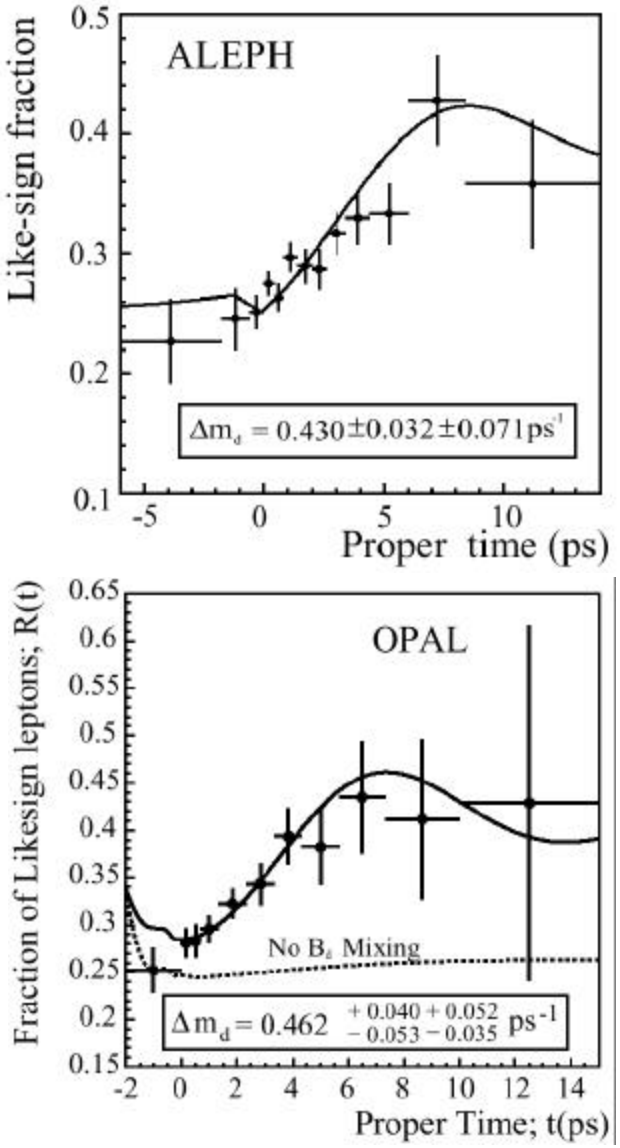
- B_d mixing frequency much larger than propertime measurement precision
  - Easily and very precisely measured using inclusive and semi-exclusive semileptonic decays

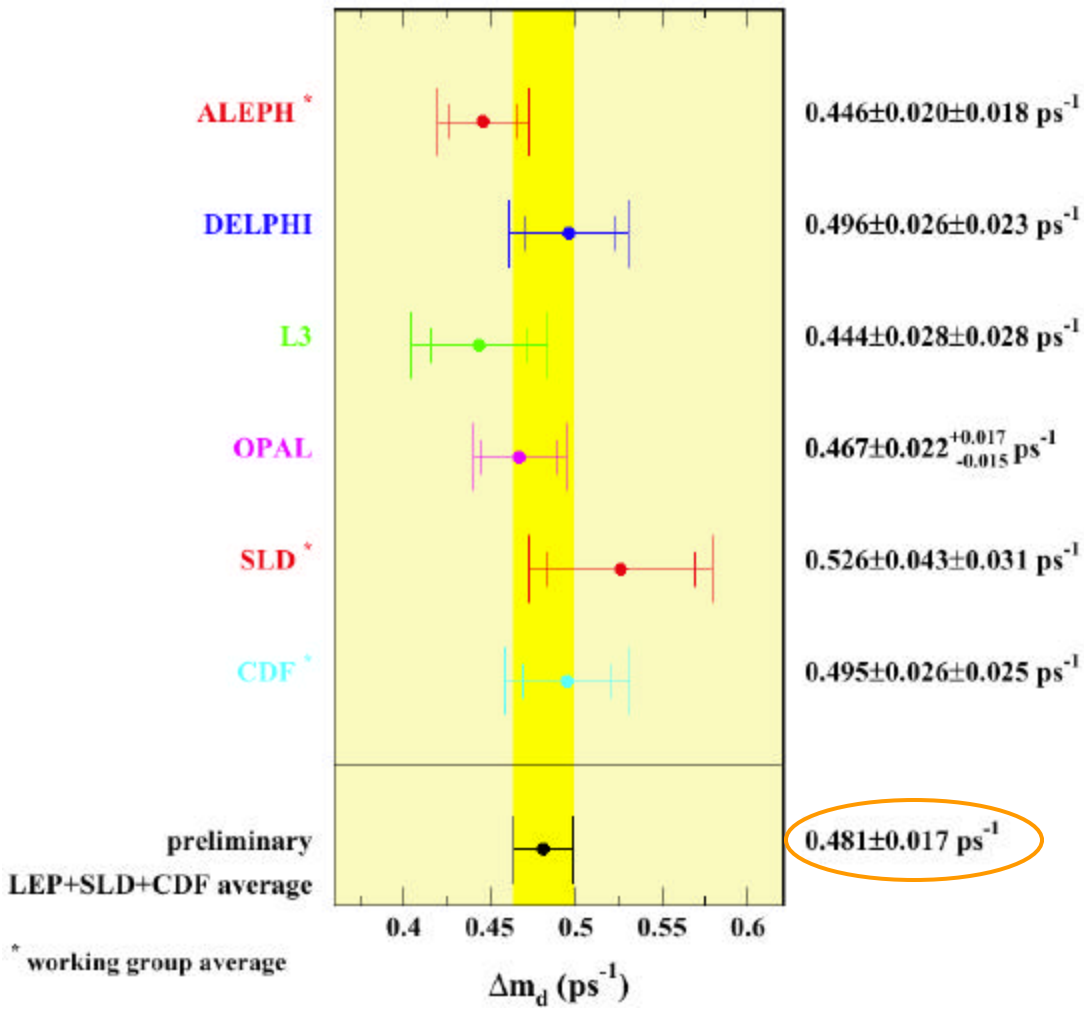




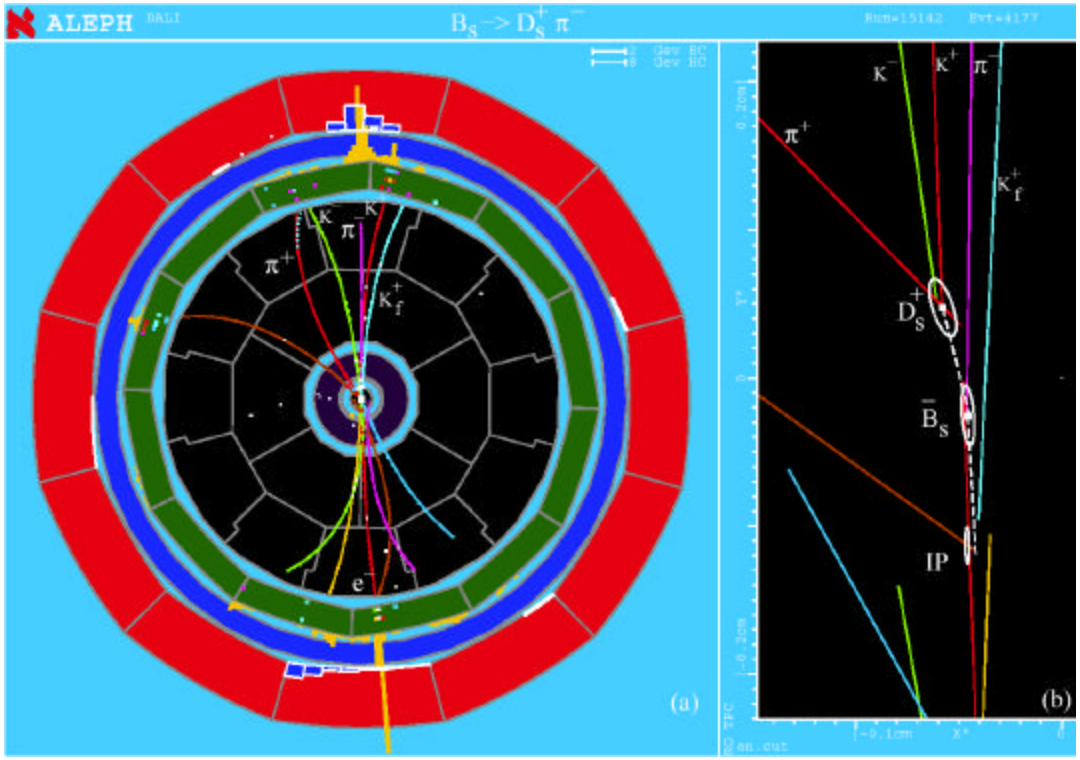


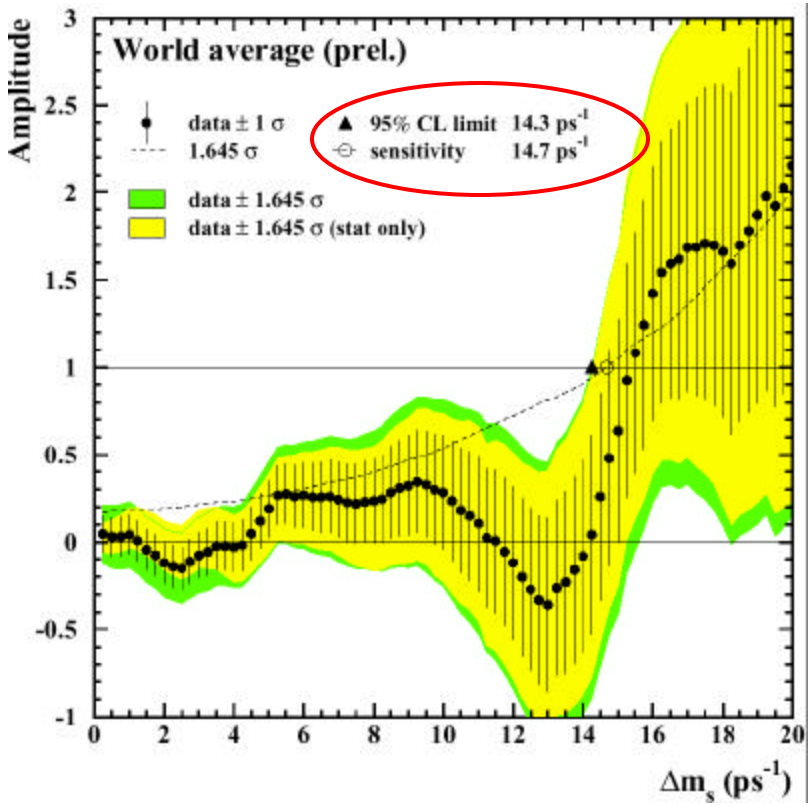
B_d Meson Mixing Measurements





Searches for B_S Mixing





- $\text{Prob}^{MIX} \sim (1\text{-}A \cos \Delta m_S t)$, A =1 if mixing is present
- Scan frequency spectrum, fit for A at every Δm_S point
- At some point the value A=1 can no longer be excluded ⇒ set limit

Heavy Quark Effective Theory

- HQET tells us that in first order when a b quark transforms to a c quark with the c going at the same velocity as the b, the form factor is 1 in first order AND the corrections to 1 can be calculated
- The form-factor therefore known to be 1-correction, at maximum q^2, called $\omega=1$, where

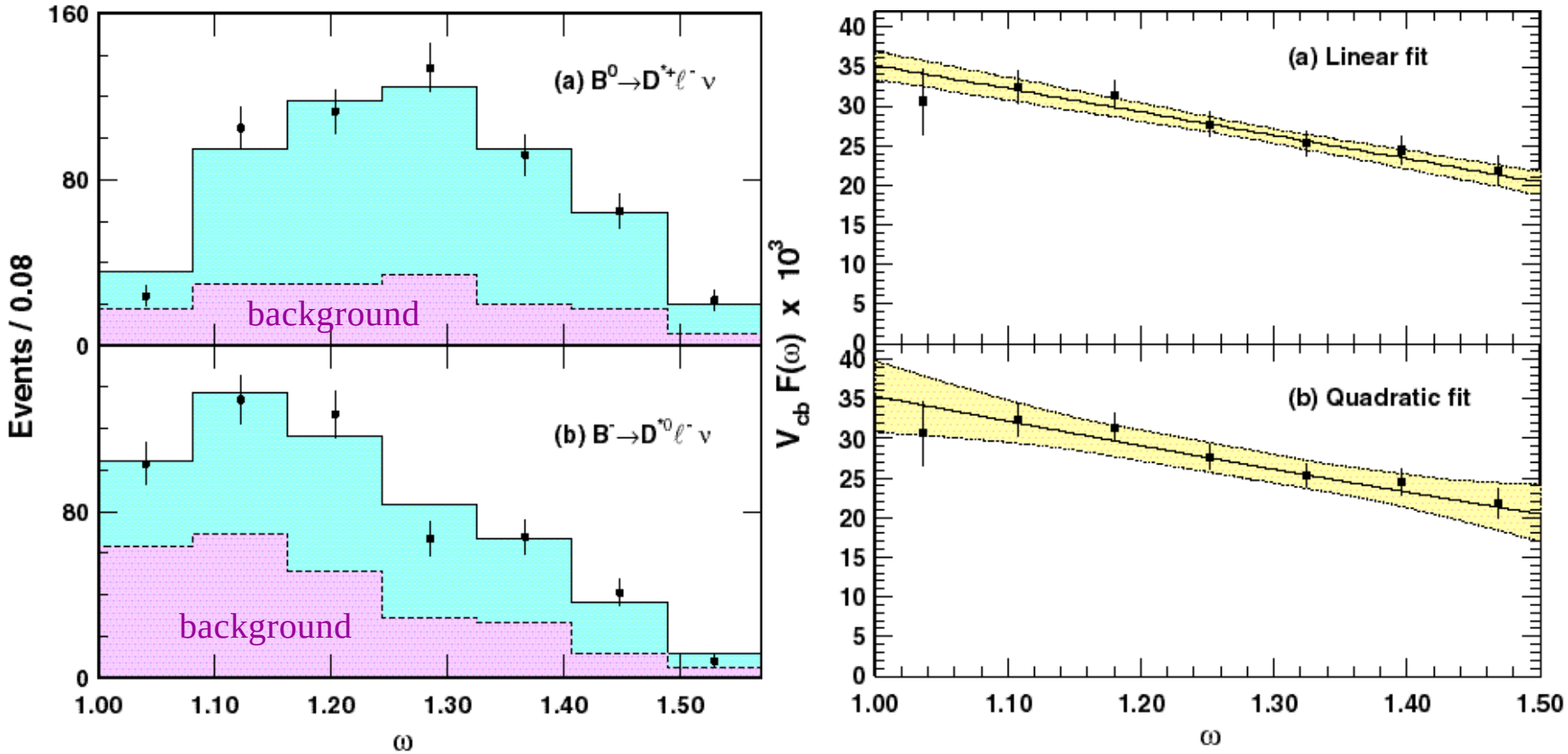
$$\omega = \frac{M_B^2 + M_{D^*}^2 - q^2}{2M_B M_{D^*}}$$

$|V_{cb}|$ from $B \to D^* \ell \nu$

- Use $B \to D^* \ell \nu$ because the decay rate is largest for and the corrections are better determined.
- In HQET there is one "universal" form-factor function, so we don't have to deal with 3 form-factors
- To find V_{cb} measure value at $\omega=1$, here D* is at rest in B rest frame

$$\frac{d\Gamma(B \to D^* \ell n)}{dw} = \frac{G_F^2}{48p^3} |V_{cb}|^2 F^2(w)(m_B - m_{D^*})^2 m_{D^*}^3 \sqrt{w^2-1} \times \left[4w(w+1) \frac{1 - 2w\frac{m_{D^*}}{m_B} + \frac{m_{D^*}^2}{m_B^2}}{\left(1 - \frac{m_{D^*}}{m_B}\right)^2} \right]$$

CLEO Measurement



V_{cb} results

- To get results fit using shape proposed by Caprini et al, or Boyd & Grinstein, or in CLEO case by Stone
- Use F(1)=0.91±0.03, from Caprini, Uraltsev…..
- Results
  - DELPHI: $(41.2\pm1.5\pm1.8\pm1.4)\times10^{-3}$
  - ALEPH: $(34.4\pm1.6\pm2.3\pm1.4)\times10^{-3}$
  - OPAL: $(36.0\pm2.1\pm2.1\pm1.2)\times10^{-3}$
  - CLEO: $(39.4\pm2.1\pm2.2\pm1.3)\times10^{-3}$

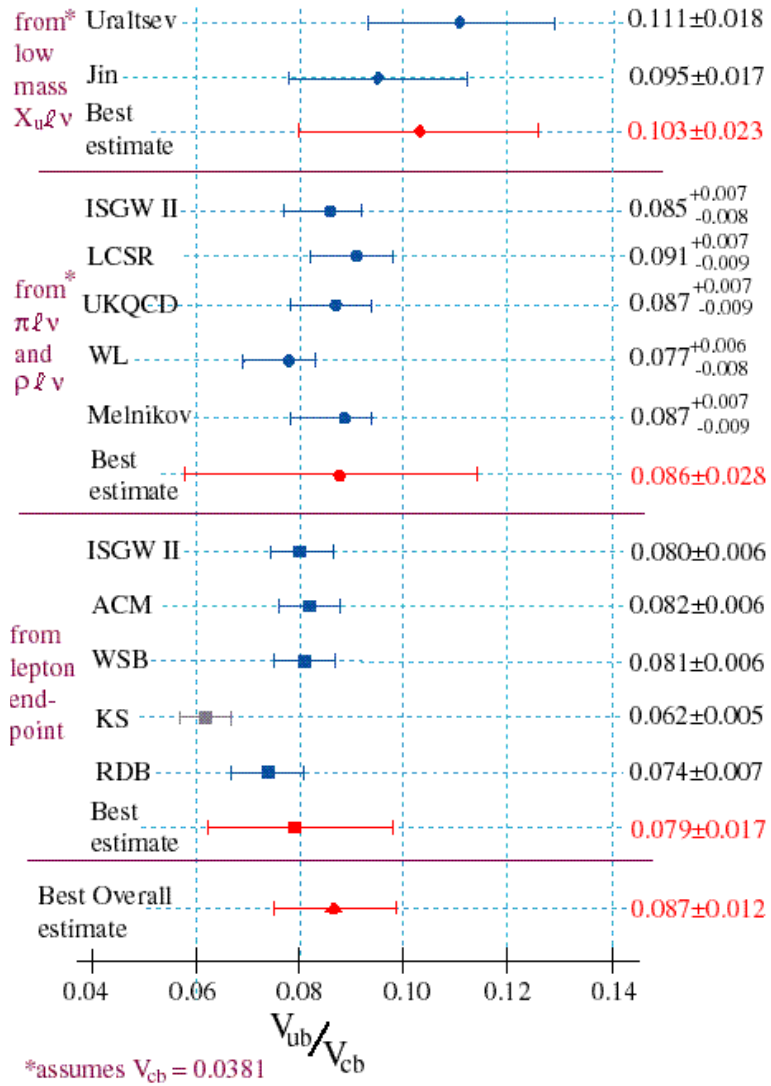
  - World Average 0.0381±0.0021 by adding theoretical error in quadrature with exp error.

Theoretical Value of F(1)

- Lim F(1) = 1 as $m_b \rightarrow \infty$,
- $F(1)=1+O(\alpha_s/\pi)+\delta_{1/m^2}+\delta_{1/m^3}$ (no $\delta_{1/m}$, Lukes thrm)
  - F(1)=0.91±0.03, from Caprini, Uraltsev…..
  - F(1)=0.89±0.06, from Bigi
  - Can we get an accurate non-quenched value from the Lattice?
  - The errors are not consistent. What do the errors mean?
- Bigi: "In stating a theoretical error, I mean that the real value can lie almost anywhere in this range with basically equal probabilty rather than follow a Gaussian distribution. Furthermore, my message is that I would be quite surprised if the real value would fall outside this range. Maybe one could call that a 90% confidence level, but I do not see any way to be more quantitative."

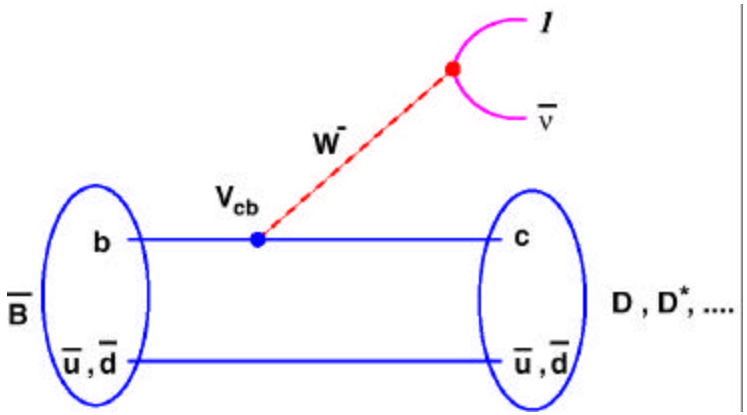
Summary of $|V_{ub}|$ Results

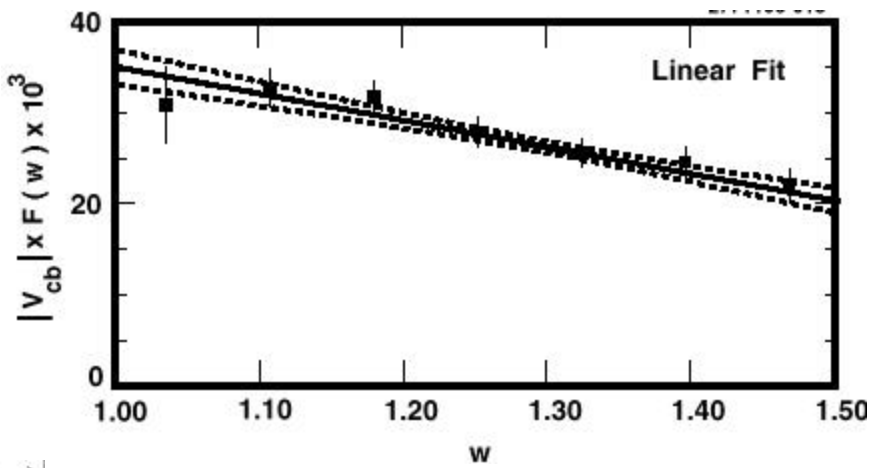
- LEP measurements use 8% theoretical error as given by Uraltsev. However Jin's similar calculation claims a 10% error but differs by 14%. I use a 14% theory error here
- Since the LEP Monte-Carlo calculations are highly correlated, I take a common 14% systematic uncertainty
- The exclusive channels rule out the Korner & Schuler (KS) model (gets the wrong V/P ratio), but have large errors
- The CLEO endpoint results have the best statistical error. Hard to estimate the theoretical error. I take 14%.



Measurements of V_{cb}

- Use HQET for extracting V_{cb} in region of zero recoil
- Fit $\overline{B} \to D^{(*)} \ell \overline{u}$ $d\Gamma / dq^2$ distribution





$$w = (M_B^2 + M_D^2 - q^2)/(2M_B M_D)$$

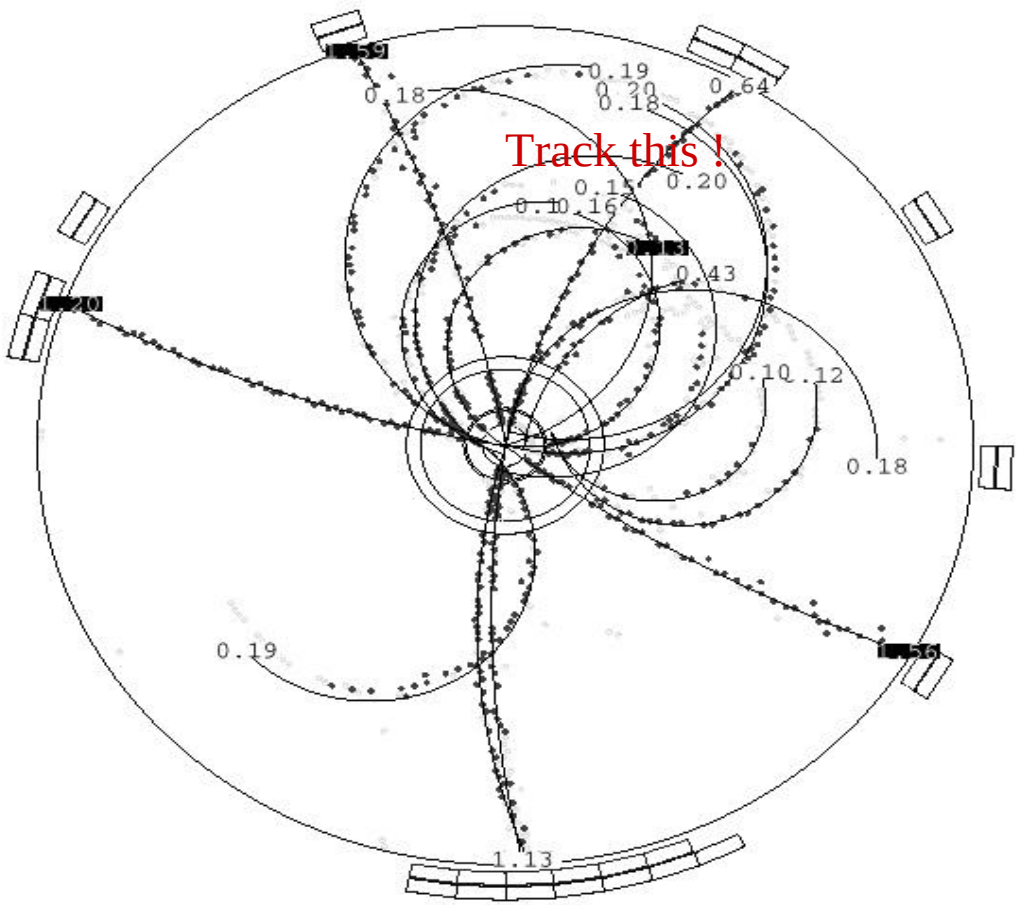
$$\mathcal{F}(w) = \mathcal{F}(1) \times (1 - \hat{\rho}^2(w-1) + c(w-1)^2 + ...)$$

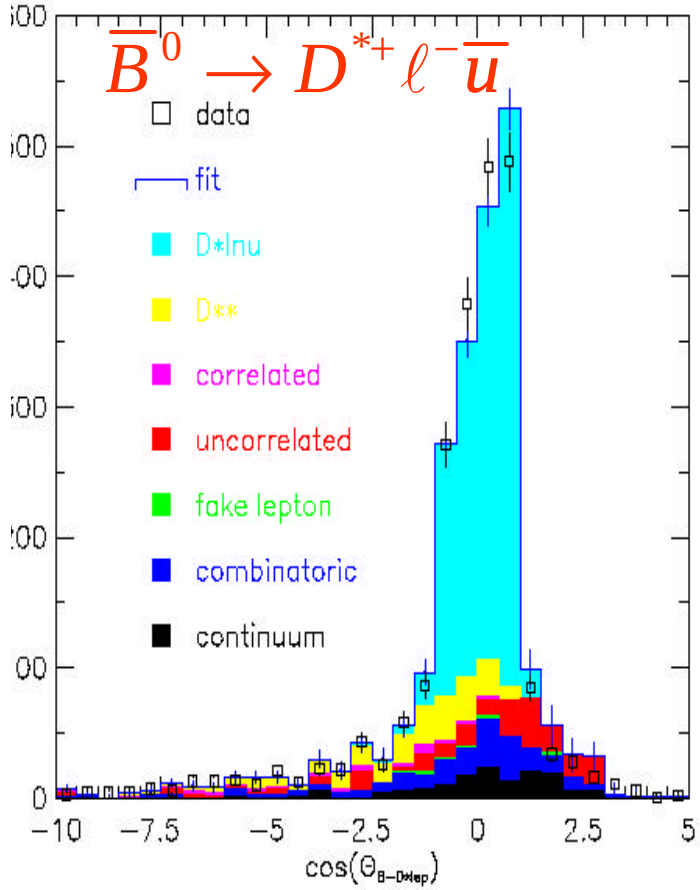
$$V_{cb}\mathcal{F}(1) = 0.0351 \pm 0.0019(stat) \pm 0.0018(syst) \pm 0.0008(\tau_B)$$

- PRD 51, 1014 (1994); 2.2 fb-1

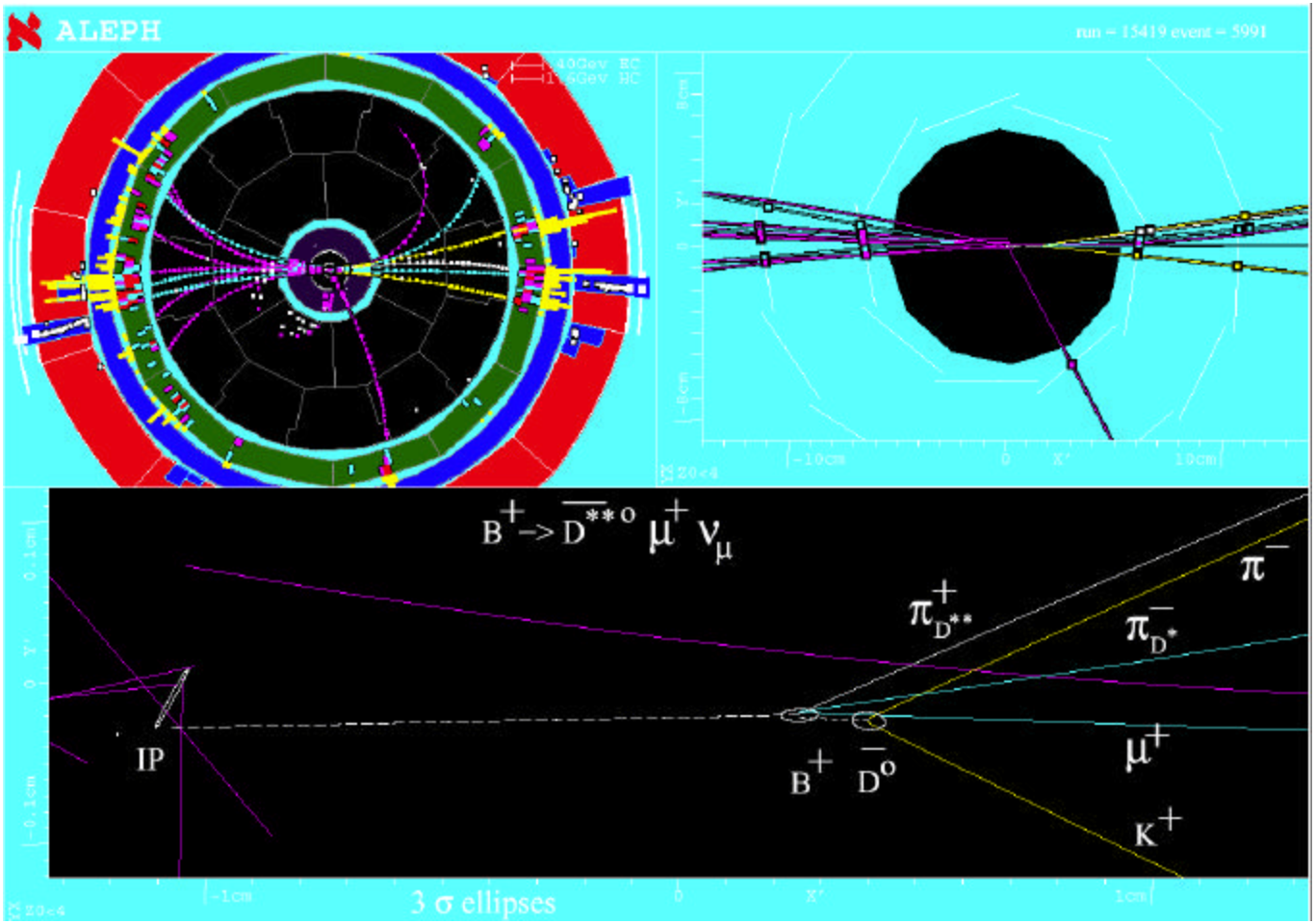
Why Is Experimental Progress SLOW!

- Absolute precision measurement, needs precise understanding of low momentum tracking efficiencies and backgrounds, comprehensive and more precise analysis in the wings



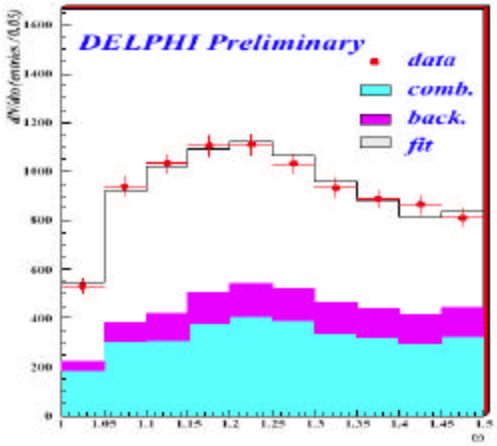


LEP Measurements of V_{cb}



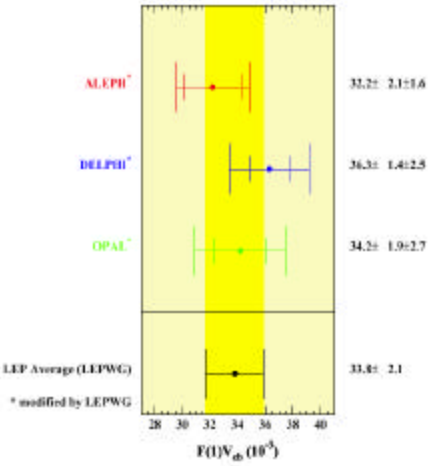
- Unlike at Y(4S), due to B boost, slow pions from D* are not that slow. Reconstruction efficiency is high
- Use B flight direction to solve for B energy, calculate q^2 and (Missing Mass)^2
- Vertex detectors help in background rejection from semileptonic decays with orbitally/radially excited D** decays

LEP Measurements of V_{cb}



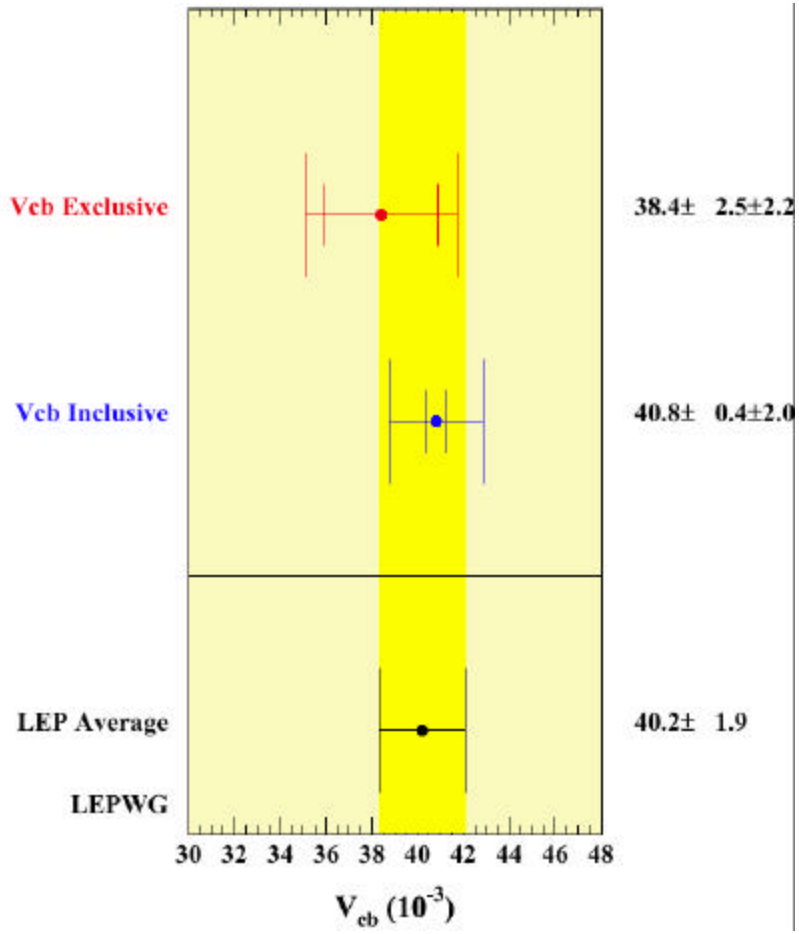
$A_1(1)\ |V_{cb}| = (37.95 \pm 1.34\ stat. \pm 1.59\ syst.) \times 10^{-3}$

$\rho^2_A = 1.39 \pm 0.12\ stat. \pm 0.18\ syst.$



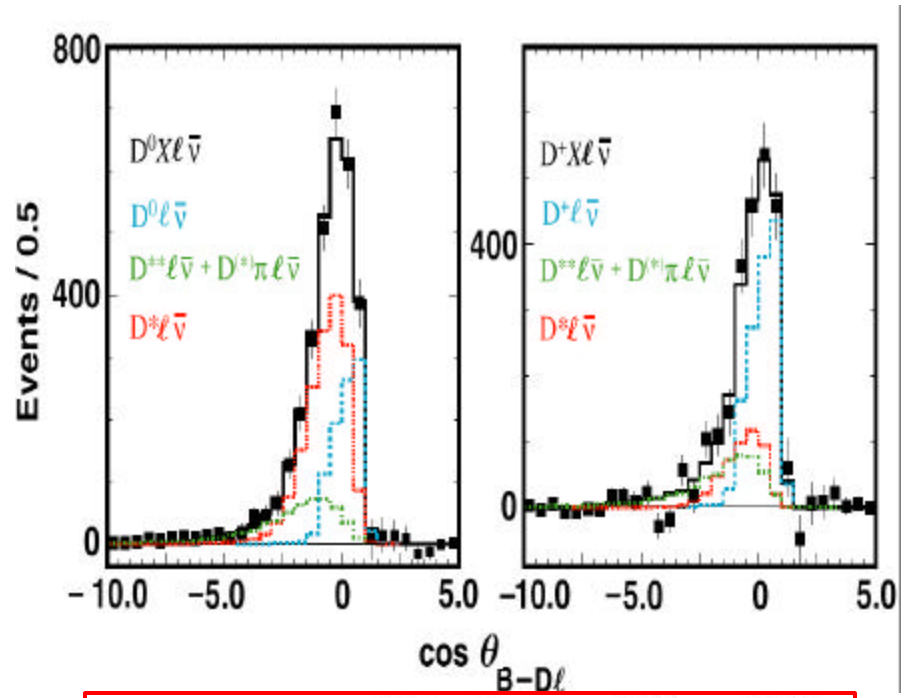
$F(1)\ |V_{cb}| = (33.8 \pm 0.9\ stat. \pm 1.9\ syst.) \times 10^{-3}$

$\rho^2_A = 1.00 \pm 0.09\ stat. \pm 0.14\ syst.$



New Result on $|V_{cb}|$ With $B \to D\ell u$

- One form factor in decay $\Rightarrow$ but corrections to 1 at zero recoil not better known than $\overline{B} \to D^{(*)}\ell\,\overline{u}$
- Experimentally :
  - Higher backgrounds (combinatorial)
  - feeddown from $\overline{B} \to (D^*, D^{**})\,\ell^-\overline{u}$
  - lower decay rate overall
  - lower rate near zero-recoil $\Rightarrow$ more extrapolation to w = 1 intercept. (systematic error)



$$\cos\theta_{B-D\ell} = \frac{2E_B E_{D\ell} - M_B^2 - M_{D\ell}^2}{2|\mathbf{p}_B||\mathbf{p}_{D\ell}|}$$

- To discriminate against background
  - calculate angle between B and (Dl) system
    - signal is bounded between [-1,1]
    - backgrounds/feeddowns (with missing mass) usually smaller (unphysical) values

Differential Decay Rate: $B \to D\ell u$

Use diff. parametrizations of form-factors

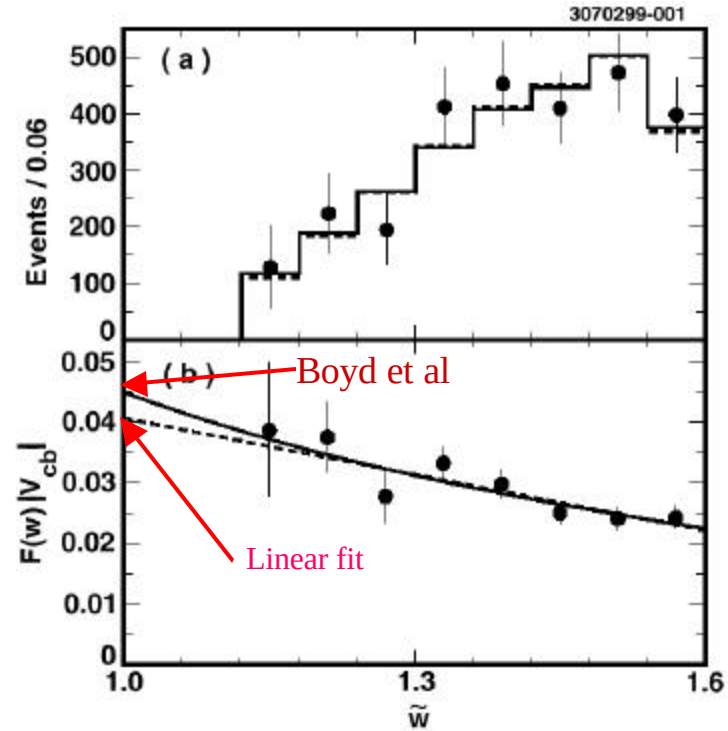
– inspired by dispersion relations

$$\frac{d\Gamma}{dw} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3}(M_B + M_D)^2 m_D^3 (w^2-1)^{3/2} F_D(w)^2$$

- As an example

$$F_D(w) = F_D(1)[1 - r_D^2(w-1) + c_D(w-1)^2 \ldots\ldots etc$$

- data support a curvature term but do not require it, physics (Boyd et al …dispersion relations) does. Diff. In extrapolation is 10%



- $$\Gamma(B \to D\ell\nu) = (13.4 \pm 0.8 \pm 1.2)\,\mathrm{ns}^{-1}$$
$$\mathcal{B}(B^- \to D^0\ell^-\bar{\nu}) = (2.21 \pm 0.13 \pm 0.19)\%,$$
$$\mathcal{B}(\bar{B}^0 \to D^+\ell^-\bar{\nu}) = (2.09 \pm 0.13 \pm 0.18)\%.$$

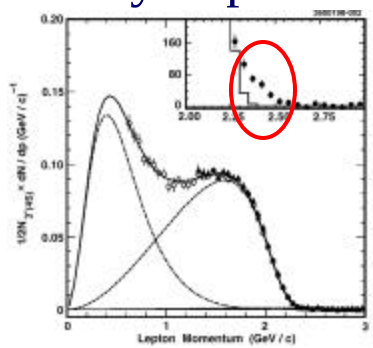
$r_D^2 = 0.76 \pm 0.16 \pm 0.08$ (*linear fit*)

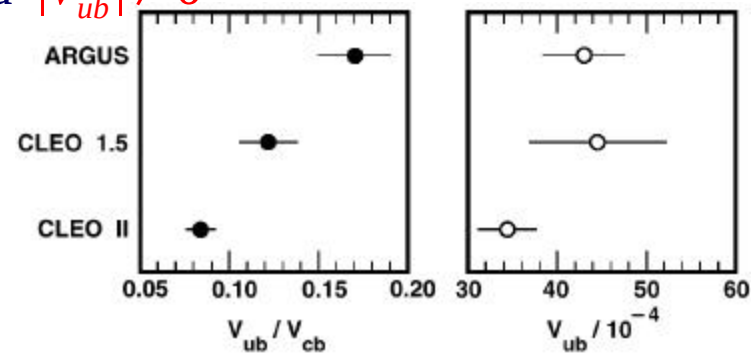
$r_D^2 = 1.30 \pm 0.27 \pm 0.14$, $C_D = 1.21 \pm 0.31 \pm 0.15$(*dispersion rel.*)

$$|V_{cb}|\,F_D(1) = [41.6 \pm 4.7 \pm 3.7] \times 10^{-3}$$

CKM Element : V_{ub}

- First measurements were inclusive semileptonic end-point rates, which were theoretically imprecise, yet showed $|V_{ub}| \neq 0$

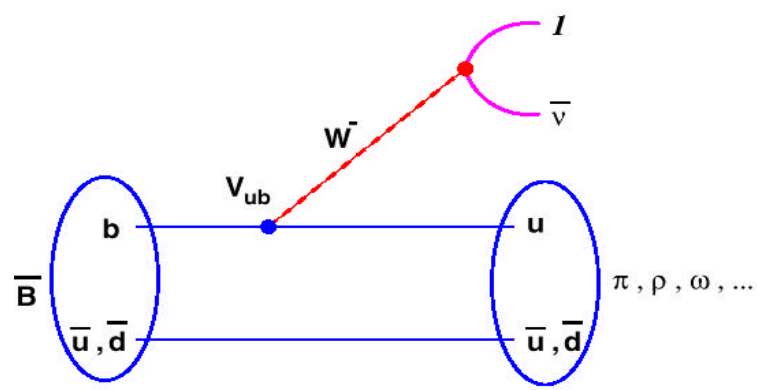




- Emphasis is now on Exclusive decays, but no "LQET" to match experimental capabilities/limitations

- CLEO measures $d\Gamma / dq^2$ and decay rate for E_l>2.3 GeV

- Bottomline: Theory not experiment is the largest source of systematic error now !



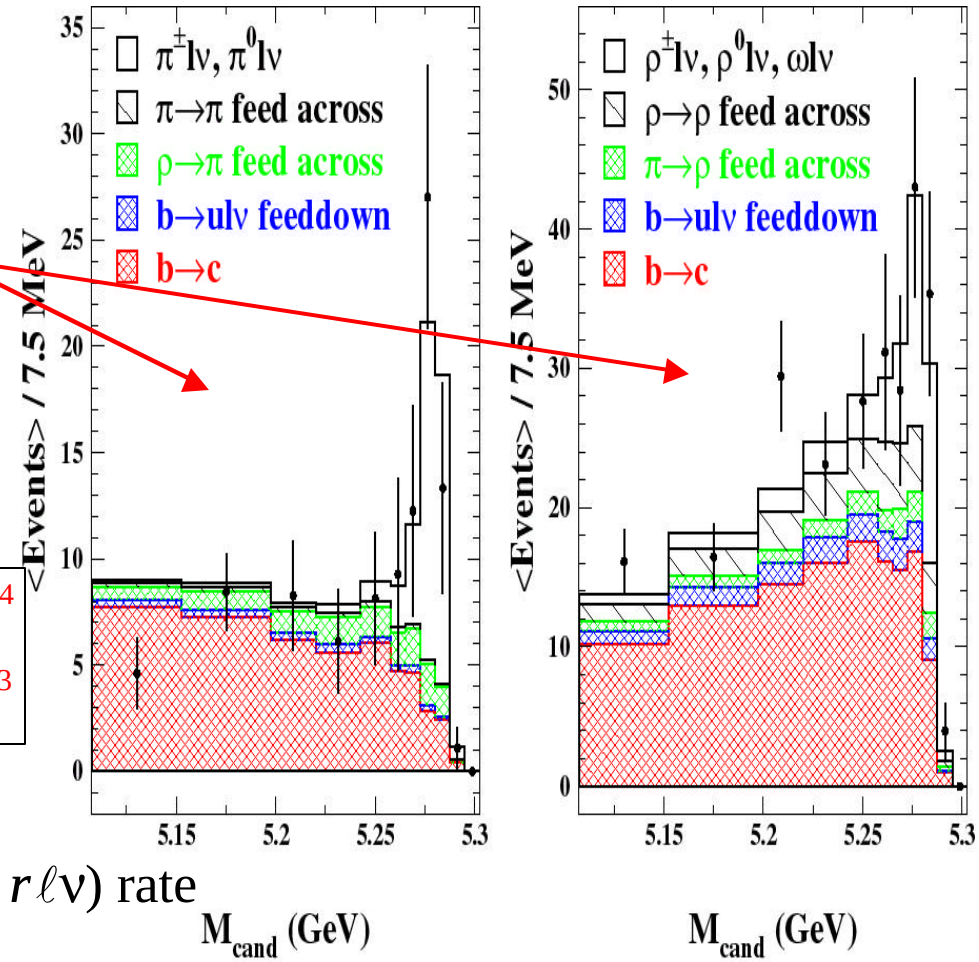
$B \to r\,\ell\,\nu$ Decay

- Rate depends on $|V_{ub}|$
- Missing momentum incorporated into full B reconstruction:
- Previously published results:

[J. P. Alexander *et al.*, Phys. Rev. Lett. **77**, 5000 (1996)]

$$used\ \vec{P}_n \approx \vec{P}_{\text{miss}} \equiv -\sum_i \vec{P}_i$$

$$\boxed{\begin{aligned} \text{Br}\left(B^0 \to r^-\ell^+ n\right) &= \left(2.5 \pm 0.4^{+0.5}_{-0.7} \pm 0.5\right)\times 10^{-4} \\ |V_{ub}| &= \left(3.3 \pm 0.2^{+0.3}_{-0.4} \pm 0.7\right)\times 10^{-3} \end{aligned}}$$

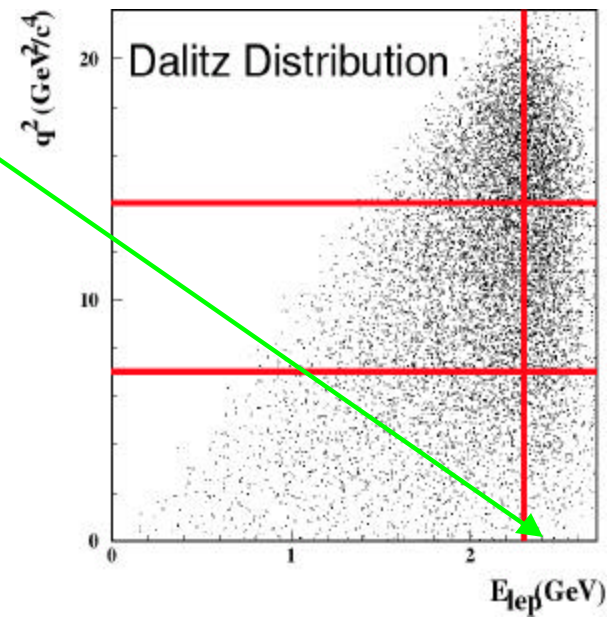


($|V_{ub}|$ value based on $B \to \pi\ell\nu$ and $B \to r\,\ell\nu$) rate

$\boxed{\sim 2.84\times 10^6\ B\bar{B}\ \text{candidates}}$

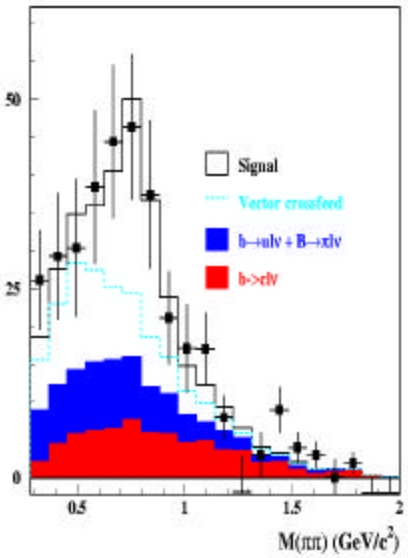
New $B \to r\ell\nu$ Decay Analysis

- Fully reconstruct r ($\pi^+\pi^0$, $\pi^+\pi^-$)/ω and ℓ candidates, infer ν energy/direction, require several kinematic consistency cuts
  - Study decay rates and $d\Gamma / dq^2$
- $b \to c\ell\nu$ backgrounds dominant
  - $b \to c\ell\nu$ suppression: final results from $P_\ell > 2.3$ GeV/c ($b \to c\ell\nu$ end point)
    - restricts sensitivity for discriminating between models
- Binned simultaneous maximum likelihood fit:
  - 3 P_ℓ bins (1.7 – 2.0, 2.0 – 2.3, >2.3 GeV/c)
  - 5 signal modes (including ω and π channels)
  - 3 kinematic variables:
    - E_ℓ
    - $\Delta E \equiv \left(E_r + E_\ell + \left|\vec{P}_{\text{miss}}\right|\right) - E_{\text{beam}}$
    - $M(\pi\,\pi\,(\pi))$
  - $b \to c$ and $b \to u$ background sources
- Significant theoretical (form-factor) dependence:
  - **shape**: extrapolation from near-end point to total rate
  - **normalization**: $|V_{ub}|$ extraction requires $\Gamma|V_{ub}|^{-2}$



$B \to r\ell\nu$ Fit Projections

$\sim 3.3\times10^6$ $B\bar{B}$ candidates

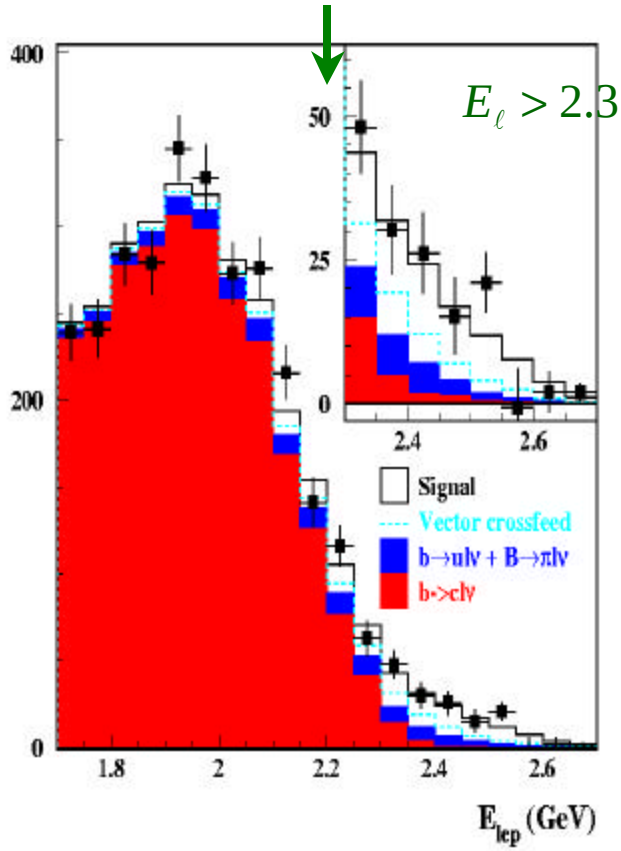


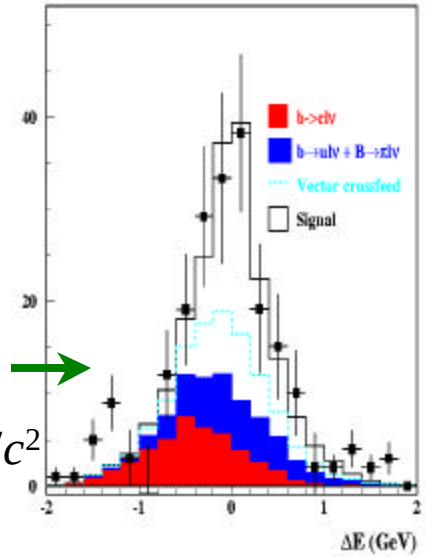
$E_\ell > 2.3$ GeV

$|\Delta E| < 0.5$ GeV

$|M(\pi\pi)-M(\rho)| < 0.15$ GeV/c^2

$|\Delta E| < 0.5$ GeV



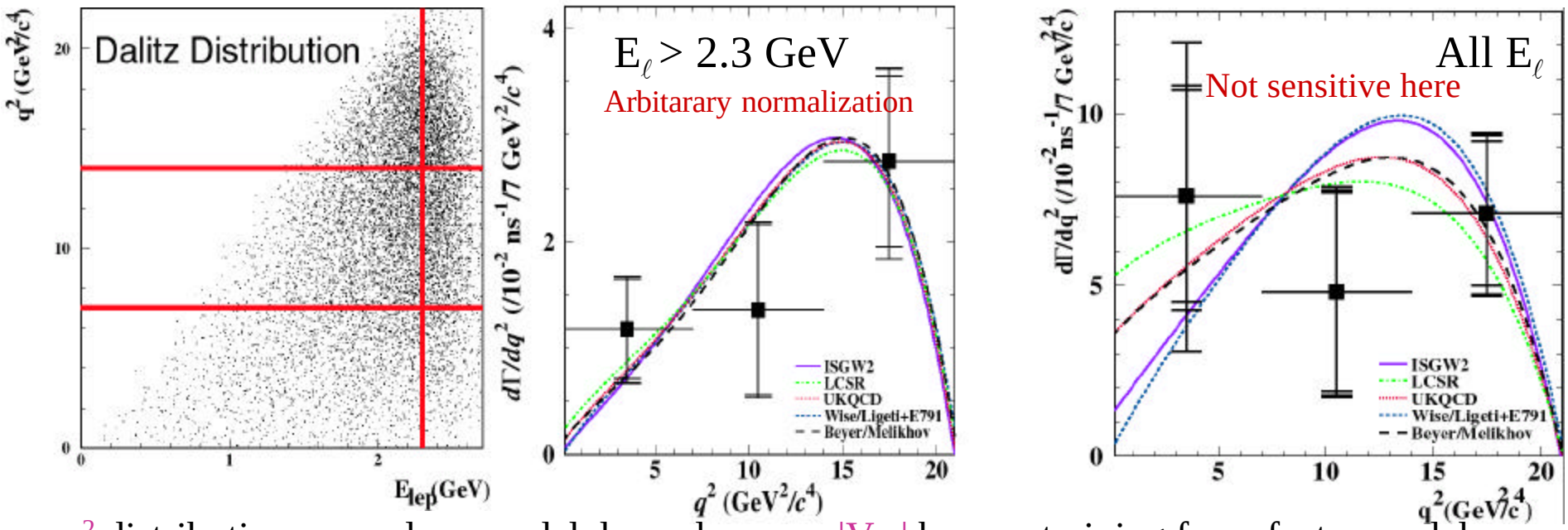


$E_\ell > 2.3$ GeV

$|M(\pi\pi)-M(\rho)| < 0.15$ GeV/c^2

$B \to r\,\ell\,\nu$ q^2 Distributions: Not yet sensitive where it matters!

~ 3.3×10^6 $B\bar{B}$ candidates



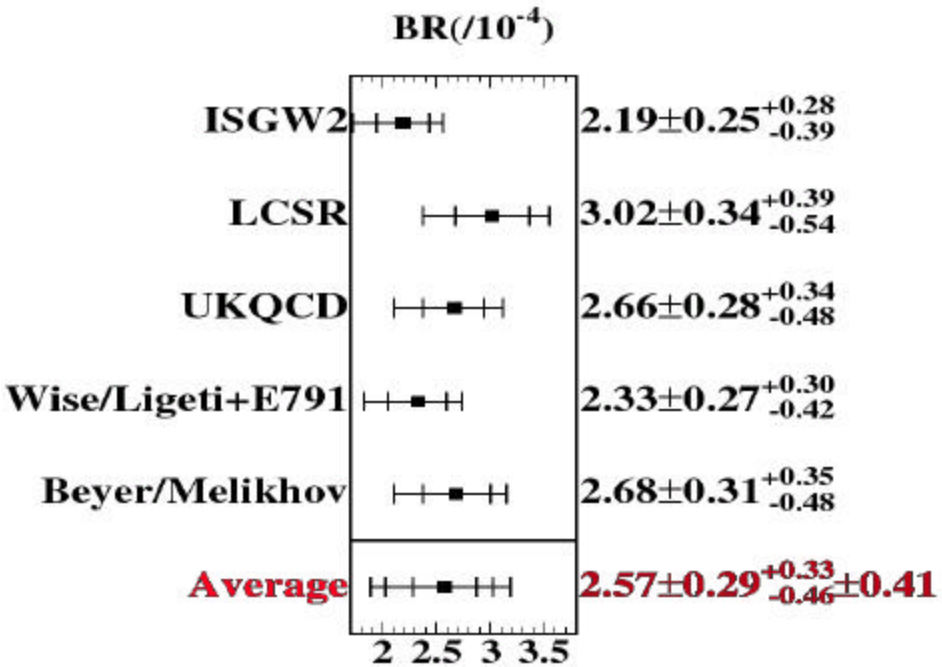
q^2 distribution can reduce model dependence on $|V_{ub}|$ by constraining form-factor models

$$\Delta\Gamma(q^2 < 7\ \mathrm{GeV}^2/c^4) = (7.6 \pm 3.0\,^{+0.9}_{-1.2} \pm 3.0) \times 10^{-2}\ \mathrm{ns}^{-1}$$
$$\Delta\Gamma(7 < q^2 < 14\ \mathrm{GeV}^2/c^4) = (4.8 \pm 2.9\,^{+0.7}_{-0.8} \pm 0.7) \times 10^{-2}\ \mathrm{ns}^{-1}$$
$$\Delta\Gamma(q^2 > 14\ \mathrm{GeV}^2/c^4) = (7.1 \pm 2.1\,^{+0.9}_{-1.1} \pm 0.6) \times 10^{-2}\ \mathrm{ns}^{-1}$$

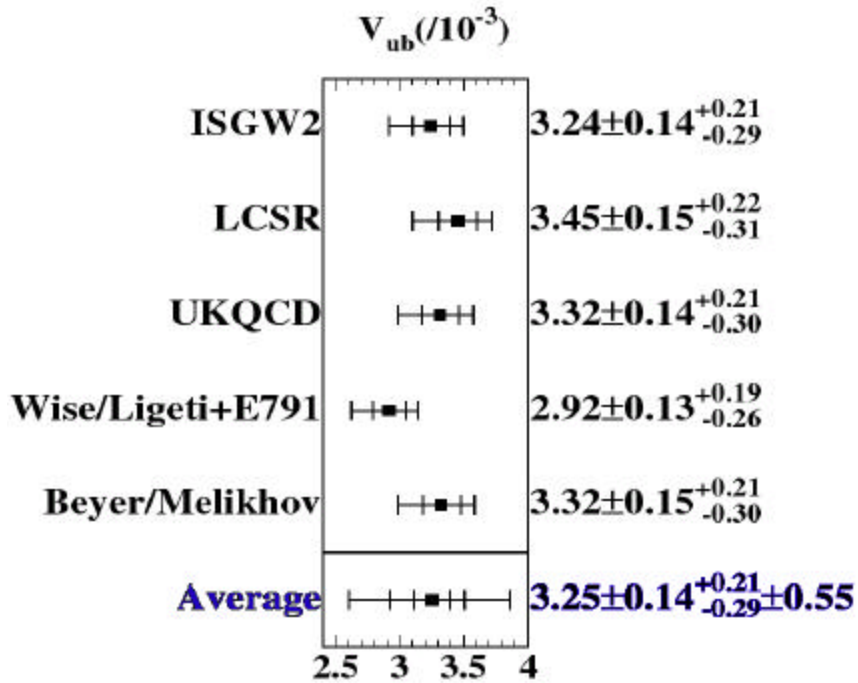
Preliminary Br ($B \to r\ell\nu$) and $|V_{ub}|$ Results

New results from this analysis, averaged with previous CLEO exclusive $b \to u\ell\nu$ results.

[J. P. Alexander *et al*., Phys. Rev. Lett. **77**, 5000 (1996)]



Branching Fraction



$|V_{ub}|$

B Decays That Measure α,β,γ

- Large selection of B decay modes with varying levels of complications (rate, theoretical control) which are useful for probing unitarity angles

Quark process	B_d^0 or B^+ Mode	*Angle*	Comment
$b \to c\bar{c}s$	$J/\psi K_S(K_l^0)$	β	Clean
	$J/\psi K^{0*}$	β	Clean, Angl.Anal
$b \to c\bar{c}d$	D^+D^-	β	Penguin Poll
	$D^{+*}D^{-*}$	β	Penguin Poll, Angl. Anal
$b \to s\bar{s}s, d\bar{d}s$	$\eta' K^0$	β	Penguin
	ϕK^0	β	Penguin Dominated
	$\phi\pi^0$	β	Penguin Dominated
$b \to u\bar{u}d, d\bar{d}d$	$\pi^+\pi^-$	α	Penguin Poll.
	$\rho^+\pi^-$	α	Penguin Poll.
	$\rho^0\pi^0$	α	Penguin Poll
$b \to u\bar{c}s, c\bar{u}s$	DK	γ	Amplitude Anal.
	$K\pi$	γ	Penguin Dominant

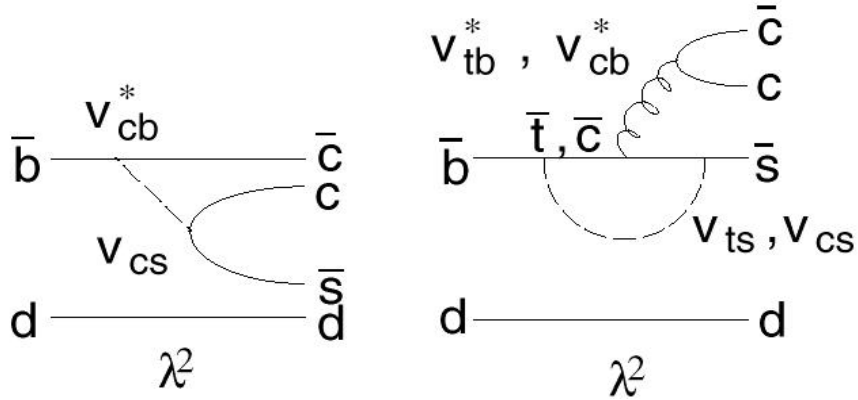
•Cleo has searched for these and many other modes and found some for the first time: Prelude to CP searches.

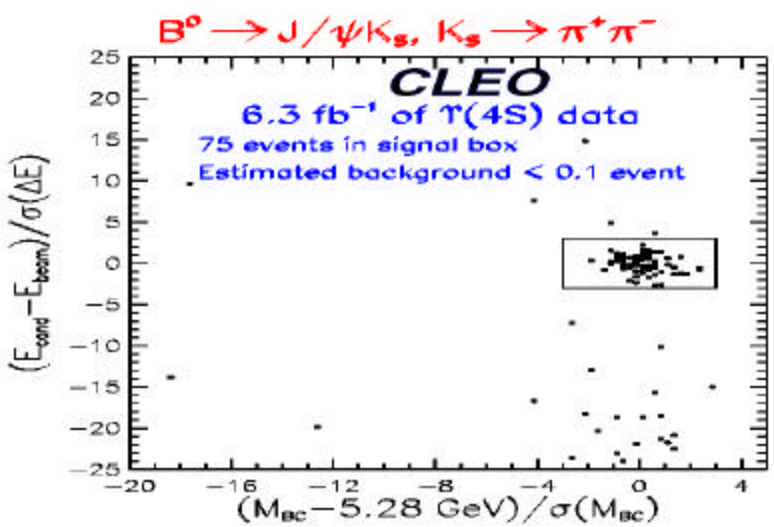
$B \to J/\psi K^0$ and Charmonium Modes

- 6.3 fb^{-1} 4S data, P_ψ >2.0 GeV
- ψ Reco Eff > 40%,
- Kinematically Fitted for better momentum resolution.

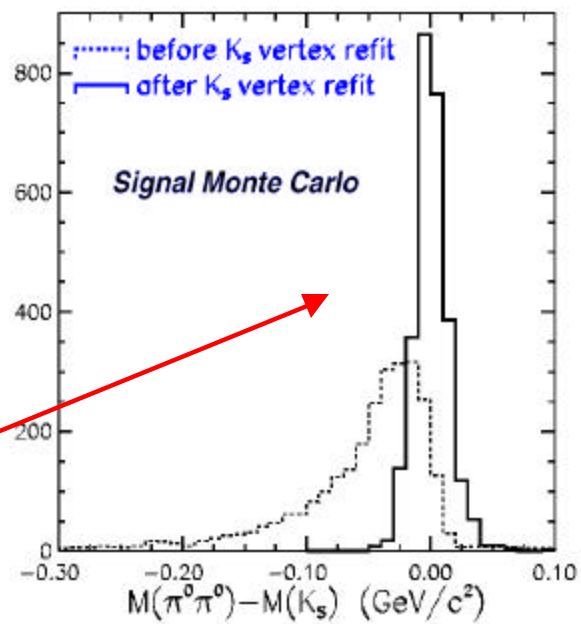
See 75 events in $B^o \to \psi K_S$, $K_S \to \pi^+ \pi^-$

$Br(B^o \to \psi K^o) = (9.2 \pm 1.6) \times 10^{-4}$

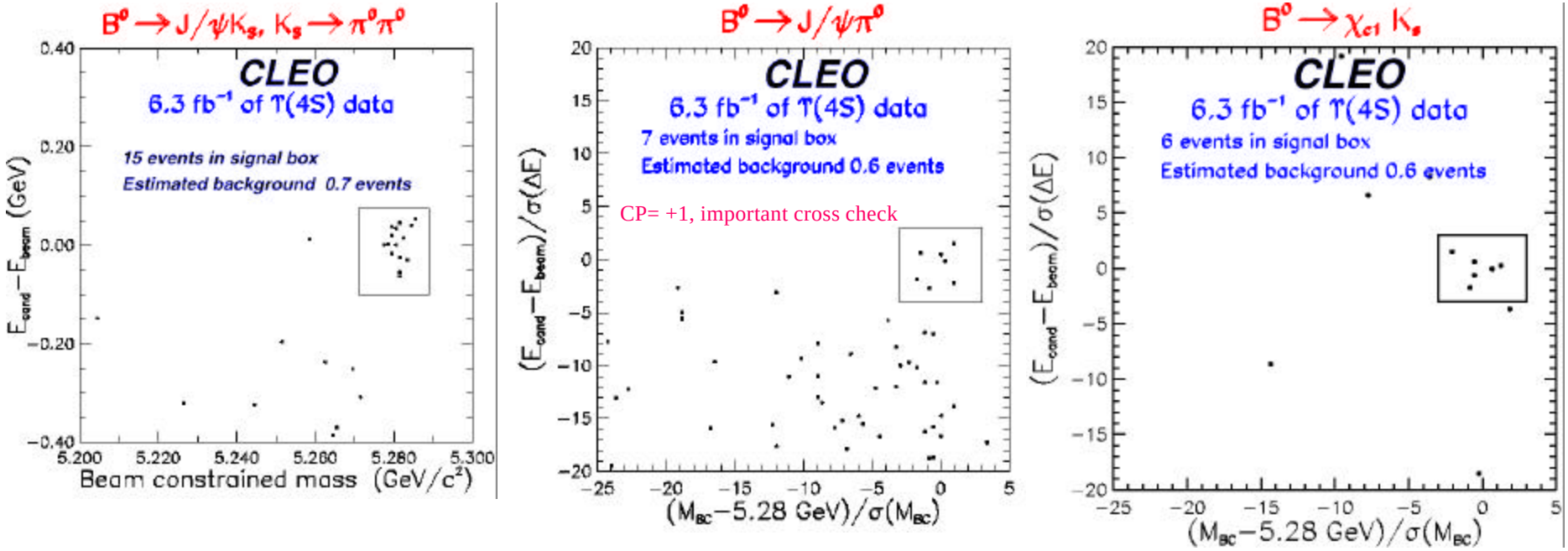


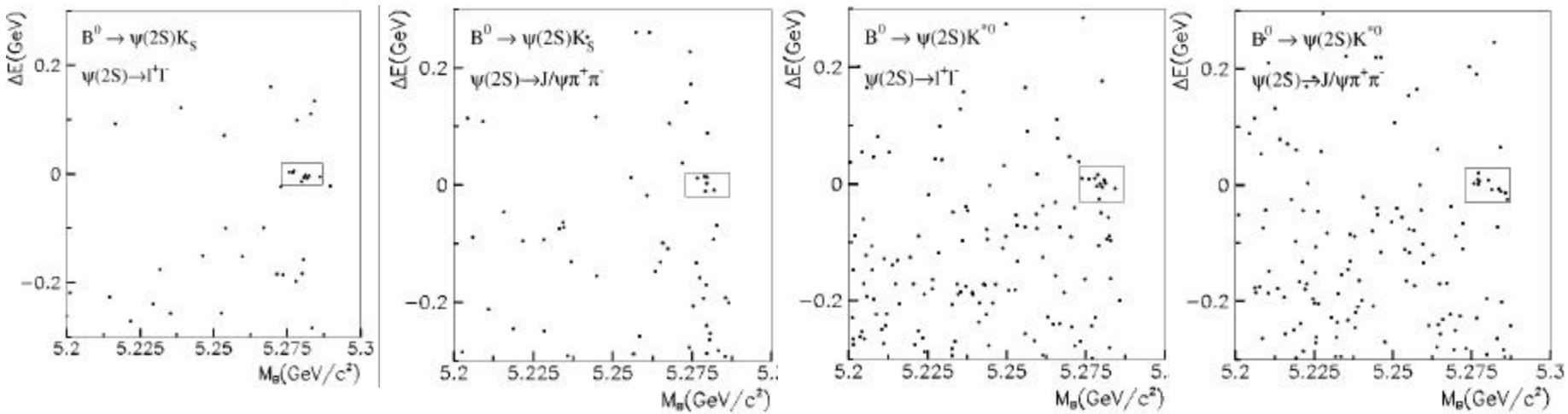


- Further, search for $K_S \to \pi^0 \pi^0$ in CsI and use 4γ directions to find and vertex the K_S flight direction,

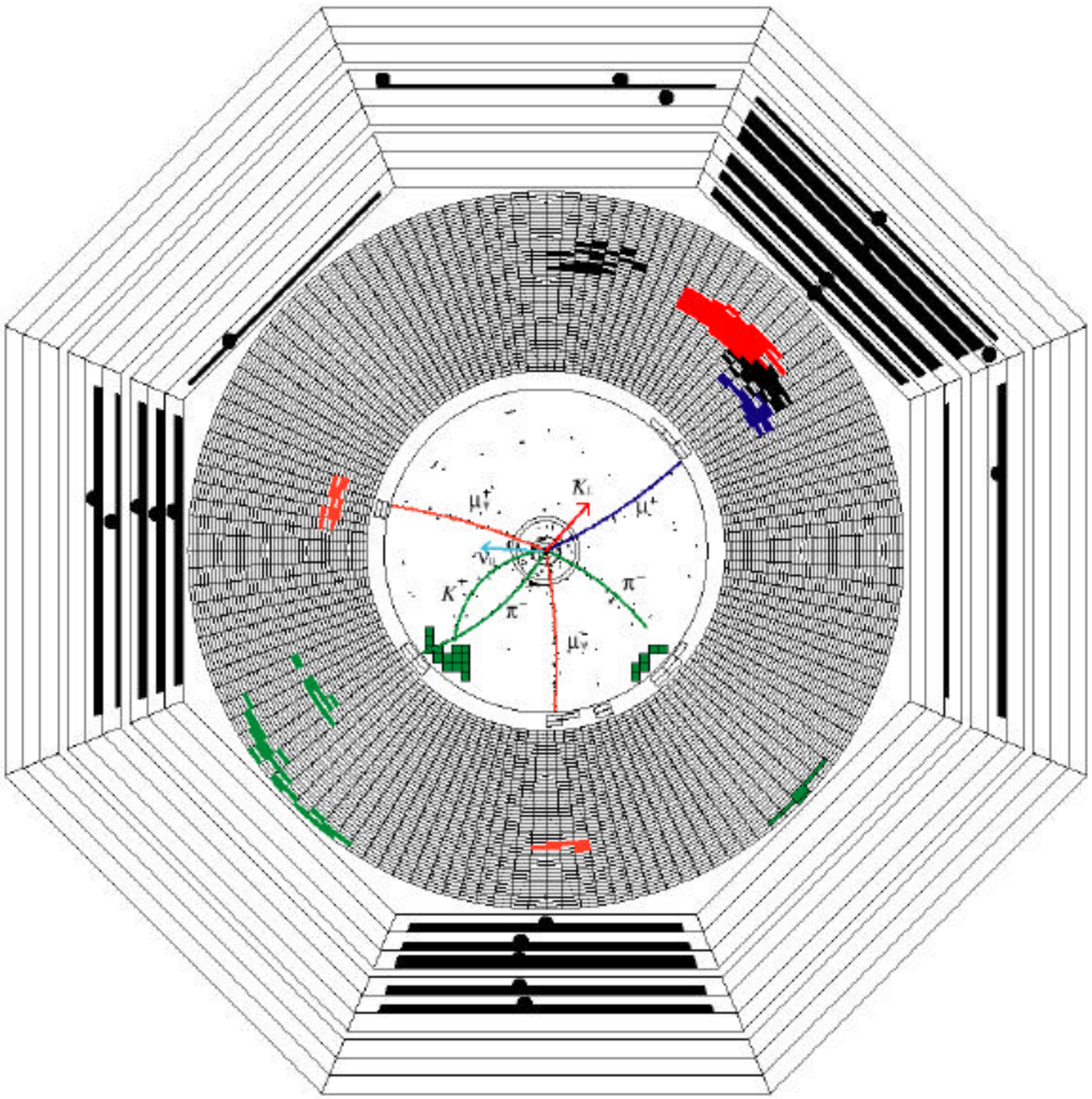


B→J/ψX and Charmonium Modes





$B \to J/\psi K_L$ Reconstruction in CsI



Fully" Reconstructed Event with a K_L and ν

$\to \psi K_L, \psi \to \mu^+\mu^-, B \to D^-\mu^+\nu, D^- \to K^+\pi^-\pi^-$

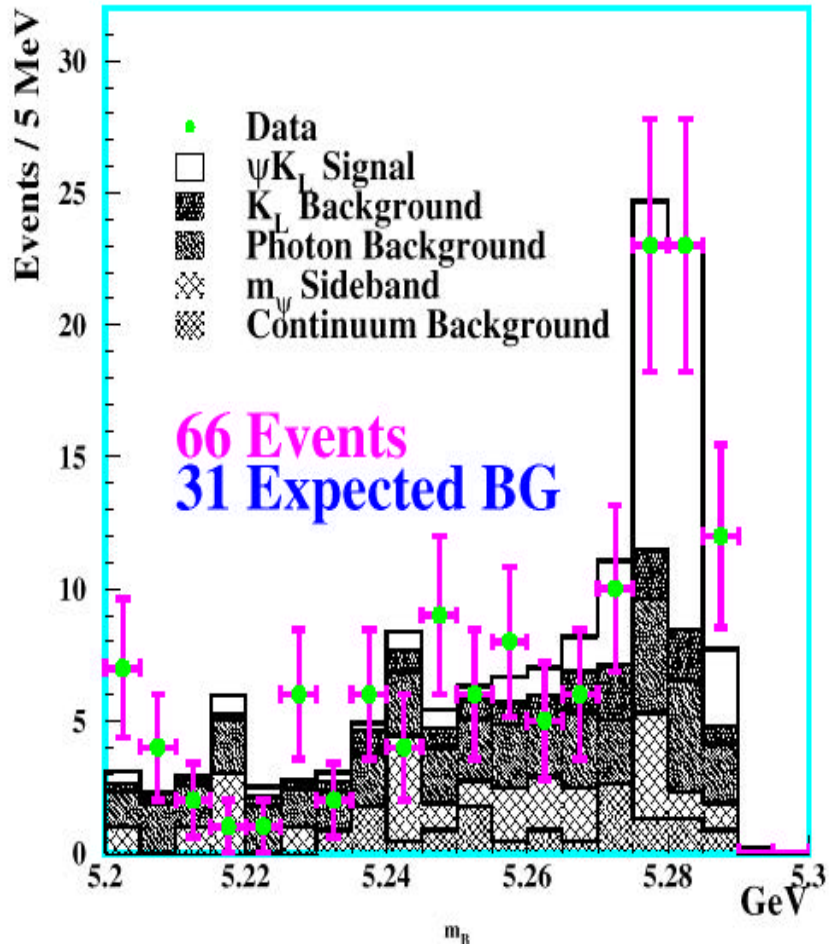
$m_{K\pi\pi} = 1855.0$ GeV, $m_{\psi K_L} = 5.281$ GeV,

$E_{miss} - |\vec{p}_{miss}| = 29$ MeV

$B \to J/\psi K_L$ Reconstruction in CsI

- Use CsI Calo.~0.81 l_{int}
  - ~ 65% K_L interact in CsI
- Reject γ showers with shower shape
- K_L Shower gives flight direction
  - combine with E_y and $\vec{P}_y$ to make B
- Veto events consistent with
  - $B^- \to y K^{(*)-}$
    $B^0 \to y\ K_S$
- Most background from photons and real K_L
- Background dilution ~10 events due to

$$B^- \to y K^{(*)0}, K^* \to K_L$$
$$B^0 \to y K_S, K_S \to p^0$$



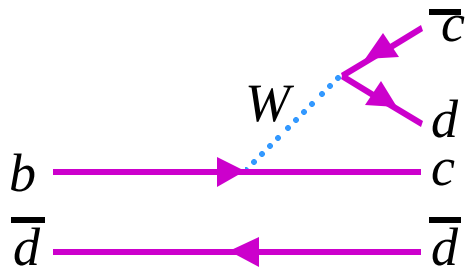
Summary Of B→ Charmonium Modes

B^0 Decay Mode	Sig Obs	Br frac $\times 10^{-4}$	CP	Comment
$B^0 \to J/\psi K_s^0$				
$K_s^0 \to \pi^+\pi^-$	75	$9.2 \pm 0.11 \pm 0.11$	-1	Clean !
$K_s^0 \to \pi^0\pi^0$	15	$12.1 \pm 0.31 \pm 0.25$		
$B^0 \to J/\psi K_L^0$	23		$+1$	$\psi K_s, \psi K^*$ bkgnd
$B^0 \to J/\psi \pi^0$	7	$0.34^{+0.17}_{-0.15} \pm 0.04$	-1	Cabibbo suppr
$B^0 \to J/\psi \eta$	0	< 0.58 90% C.L.	$+1$	$(\psi\eta) \approx \frac{1}{3}(\psi\pi^0)$
$B^0 \to \chi_{c1} K_s^0$	6	$4.5^{+2.8}_{-1.8} \pm 0.9$	-1	$\chi_{c1} \to \psi\gamma$
$B^0 \to J/\psi K^{*0}$	81.6	$13.2 \pm 1.7 \pm 1.7$	≈ -1	Transversity Anal.
$B^0 \to \psi(2S) K_s^0$	15	$5.2 \pm 1.4 \pm 0.5$	-1	$\psi(2S) \to l^+l^-$
$B^0 \to \psi(2S) K^{*0}$	21	$8.4 \pm 1.8 \pm 1.0$	≈ -1	Transversity Anal

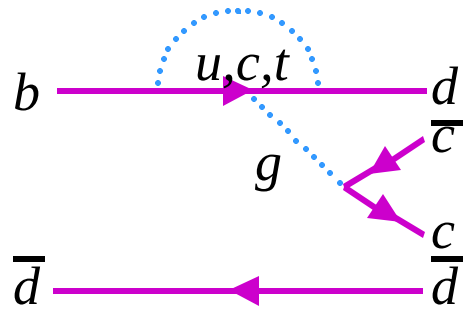
- Many more clean decay modes, can almost double the CP-sensitivity compared with $B \to J/\psi K_S$.
- First searches for Sin2β will need these "drops in the bucket"

Diagrams Contributing to $\bar{B}^0 \to D^{(*)+} D^{(*)-}$

- Decays of type: $b \to c\bar{c}d$



Tree



Strong Penguin

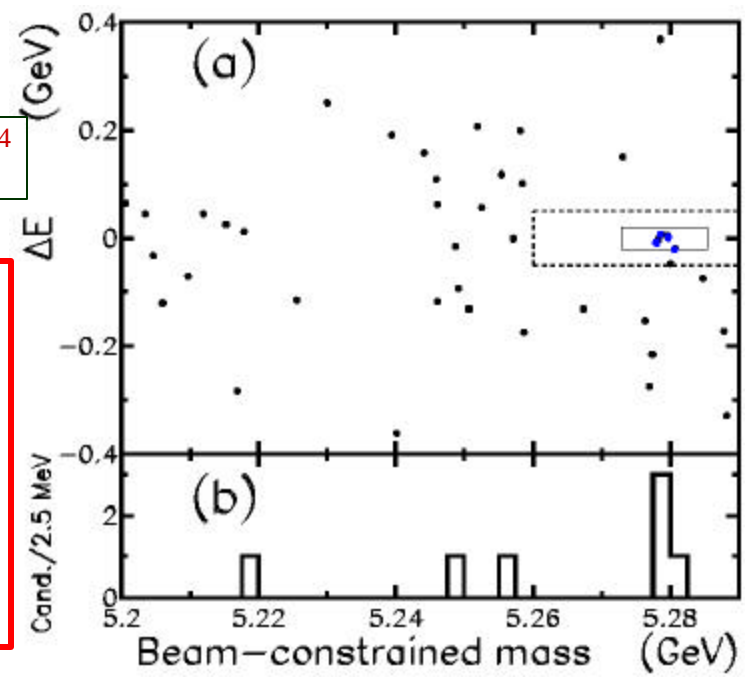
- Cabibbo-suppressed version of $B^0 \to D_S^{(*)+} D^{(*)-}$

$$Br\left(B^0 \to D^{(*)+} D^{(*)-}\right) \approx \left(\frac{f_{D^{(*)}}}{f_{D_S^{(*)}}}\right)^2 \tan^2 q_C \; Br\left(B^0 \to D_S^{(*)+} D^{(*)-}\right)$$
$$\approx (0.9)^2 (0.05) Br\left(B^0 \to D_S^{(*)+} D^{(*)-}\right)$$

First Observation of $\overline{B}^0 \to D^{*+} D^{*-}$

- P→ V V decay ⇒ s, p and d wave amplitudes contribute
- Factorization and HQET ⇒ 94% CP-Even, Penguin ~6%
- Angular analysis needed to separate amplitudes of diff. CP
- Experimental Challenge : Reco. Two slow ~100 MeV $p^{\pm}$
- See 4 events upon 0.3±0.l Background

$$Br(\overline{B}^0 \to D^{*+} D^{*-}) = [6.2^{+4.0}_{-2.9}(stat) \pm 1.0(syst)] \times 10^{-4}$$

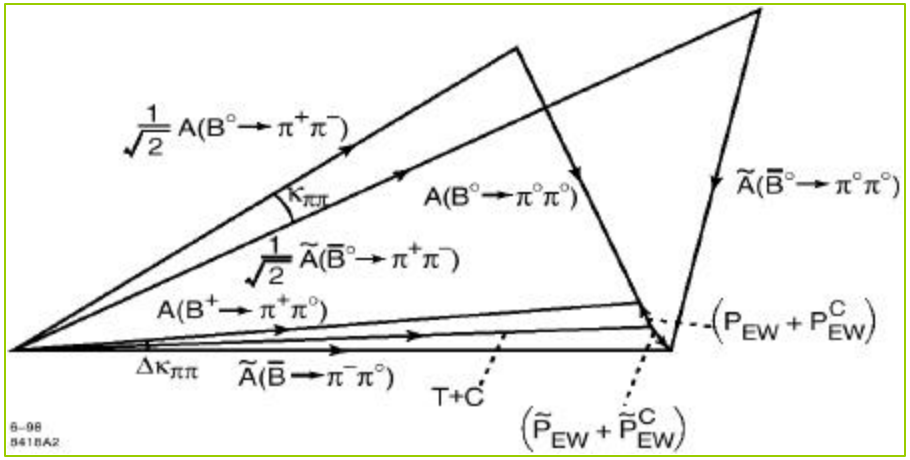


- Utility of this decay mode for CP Violation Studies requires very efficient low-momentum charged particle tracking: BaBar, Belle ! Requires "inside-out" tracking in potentially high background/high occupancy scenario.

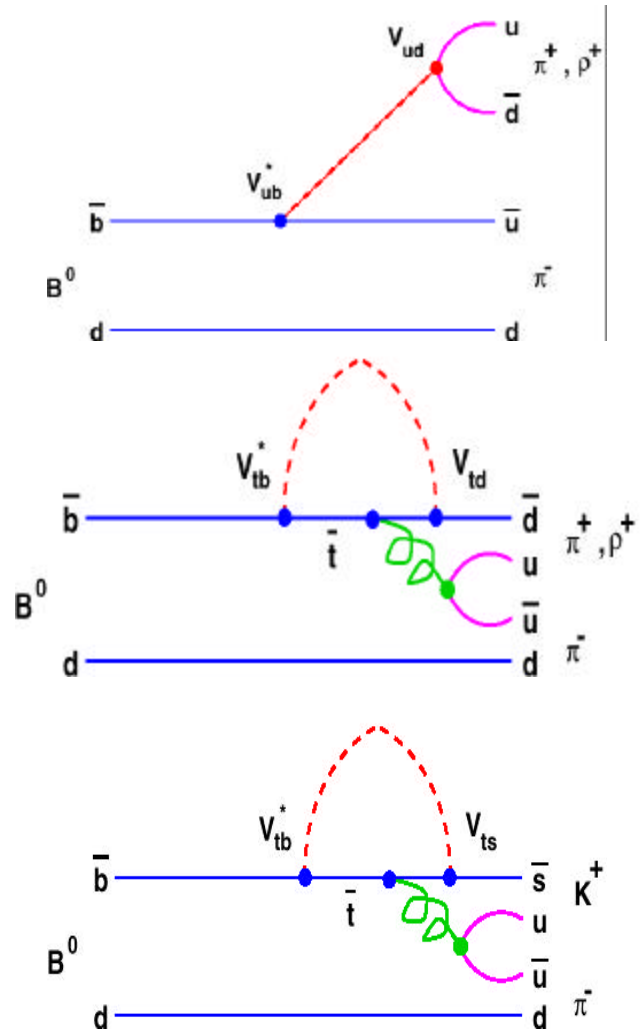
The Angle α: $\bar{B}^0 \to p^+p^-, p^+p^-p^0 etc$

Portrait of The Problem: $\bar{B} \to p^+p^-$

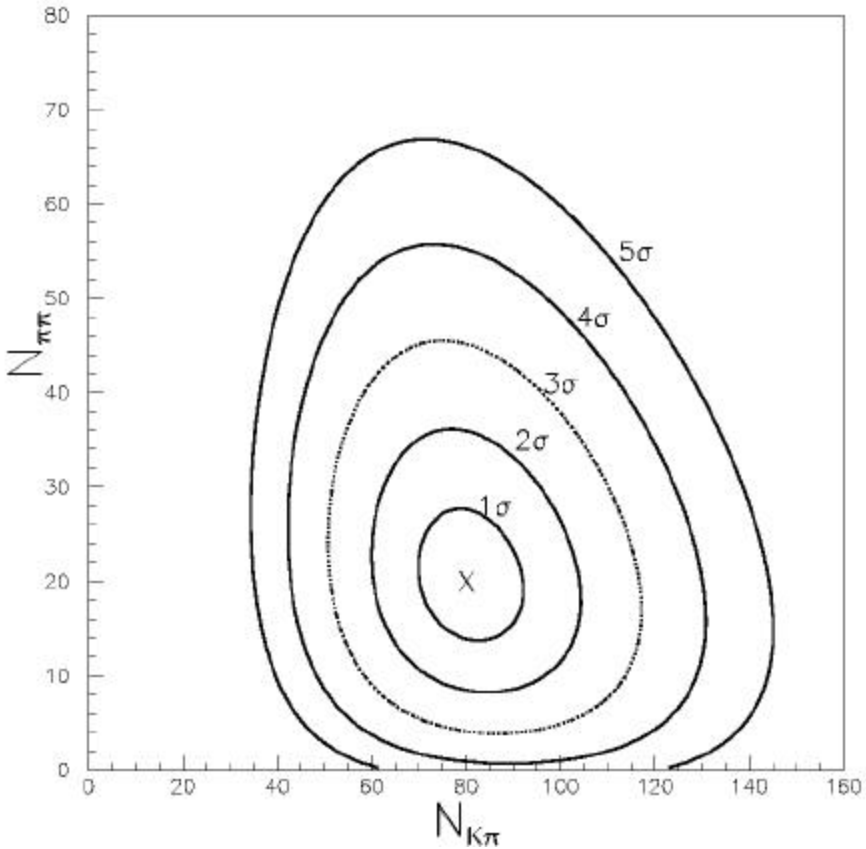
- Theory: Penguin Pollution , controllable by Isospin triangles using $\bar{B} \to p^+p^0, p^0p^0$



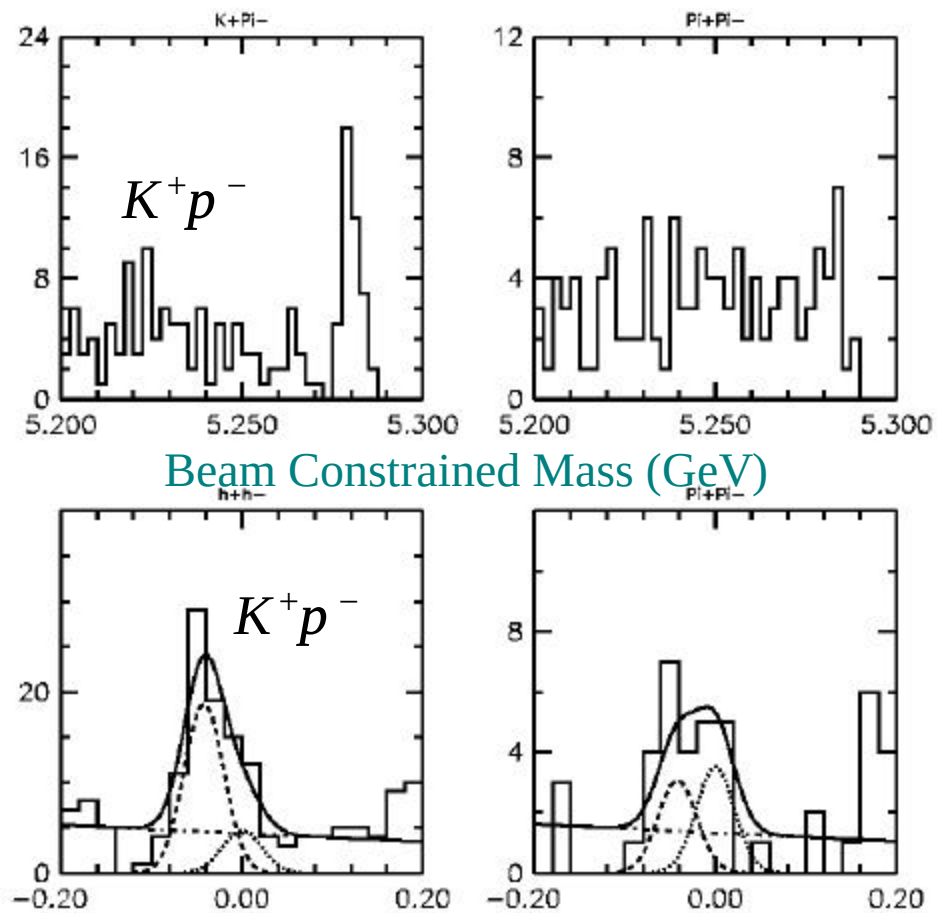
- Experimental Problem : Need to separate process from $\bar{B}^0 \to K^-p^+$ which is dominant !
- Reality: $\bar{B}^0 \to p^+p^-$ finally seen and quite smaller than expected + It aint pretty !



Likelihood Fit Results for $B^0 \to h^+ \pi^-$



After Particle ID, Mass and Fisher Shape cuts



$$\mathrm{Br}(B^0 \to K^+p^-) = (18.8^{+2.8}_{-2.6} \pm 1.3)\times 10^{-6}, 11.7s$$

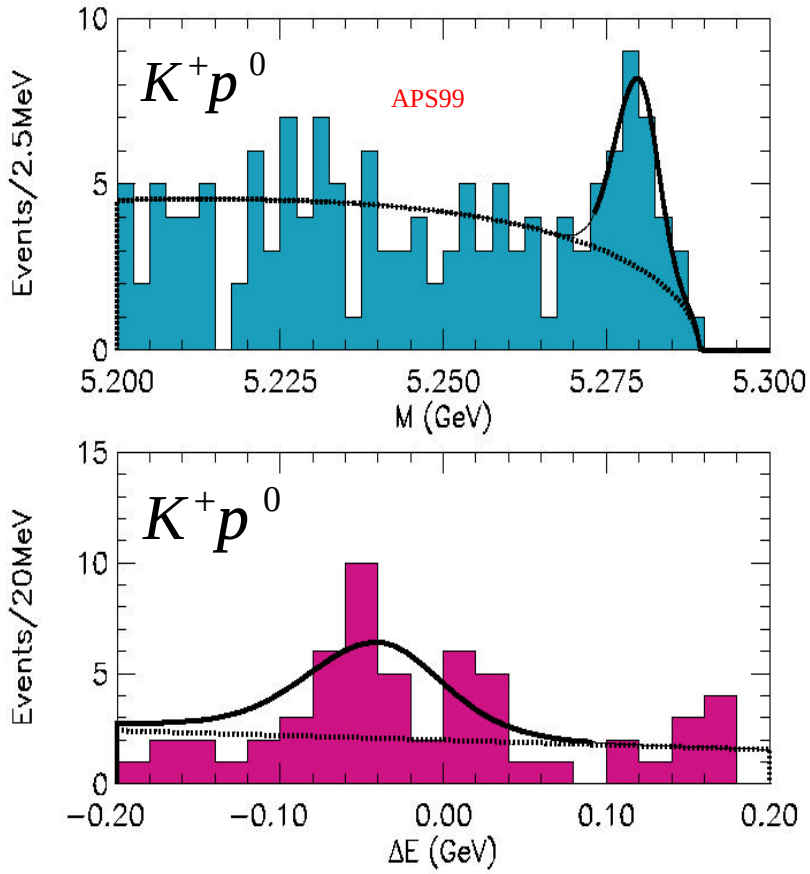
$$\mathrm{Br}(B^0 \to p^+p^-) = (4.7^{+1.8}_{-1.5} \pm 0.6)\times 10^{-6}, 4.2s$$

(assuming $f_{+-} = f_{00} = 0.5$)

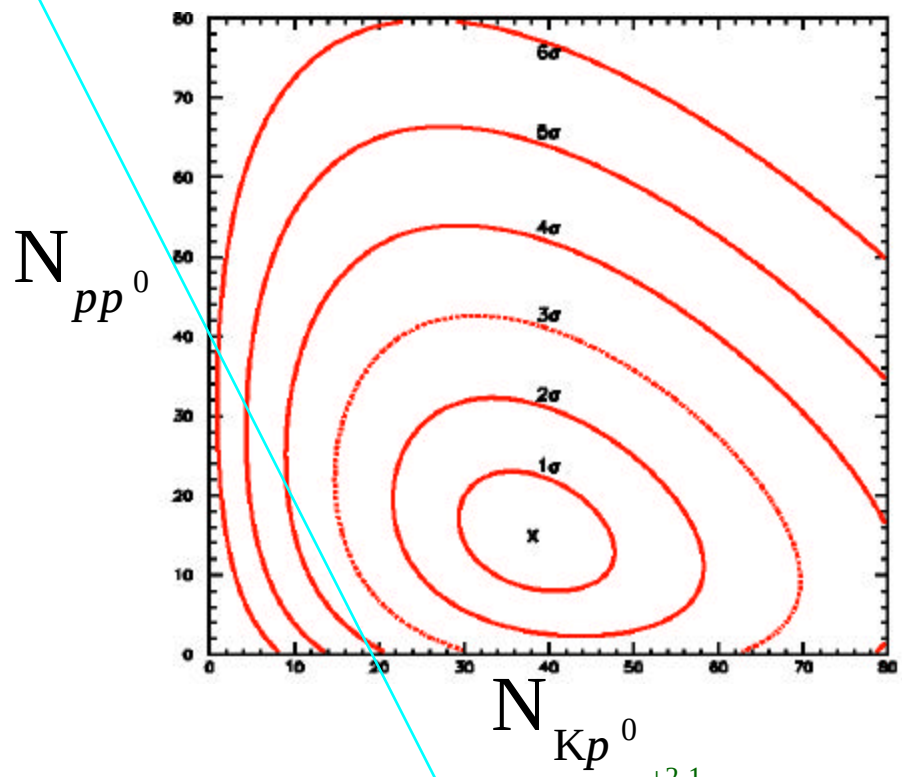
$(\Delta E \equiv E_B - E_{\mathrm{beam}})$

Likelihood Fit Results for $B^+ \to h^+\pi^0$

Measurement of α with $\overline{B} \to p^+p^-$ will be difficult



$(\Delta E \equiv E_K + E_p - E_{\text{beam}})$

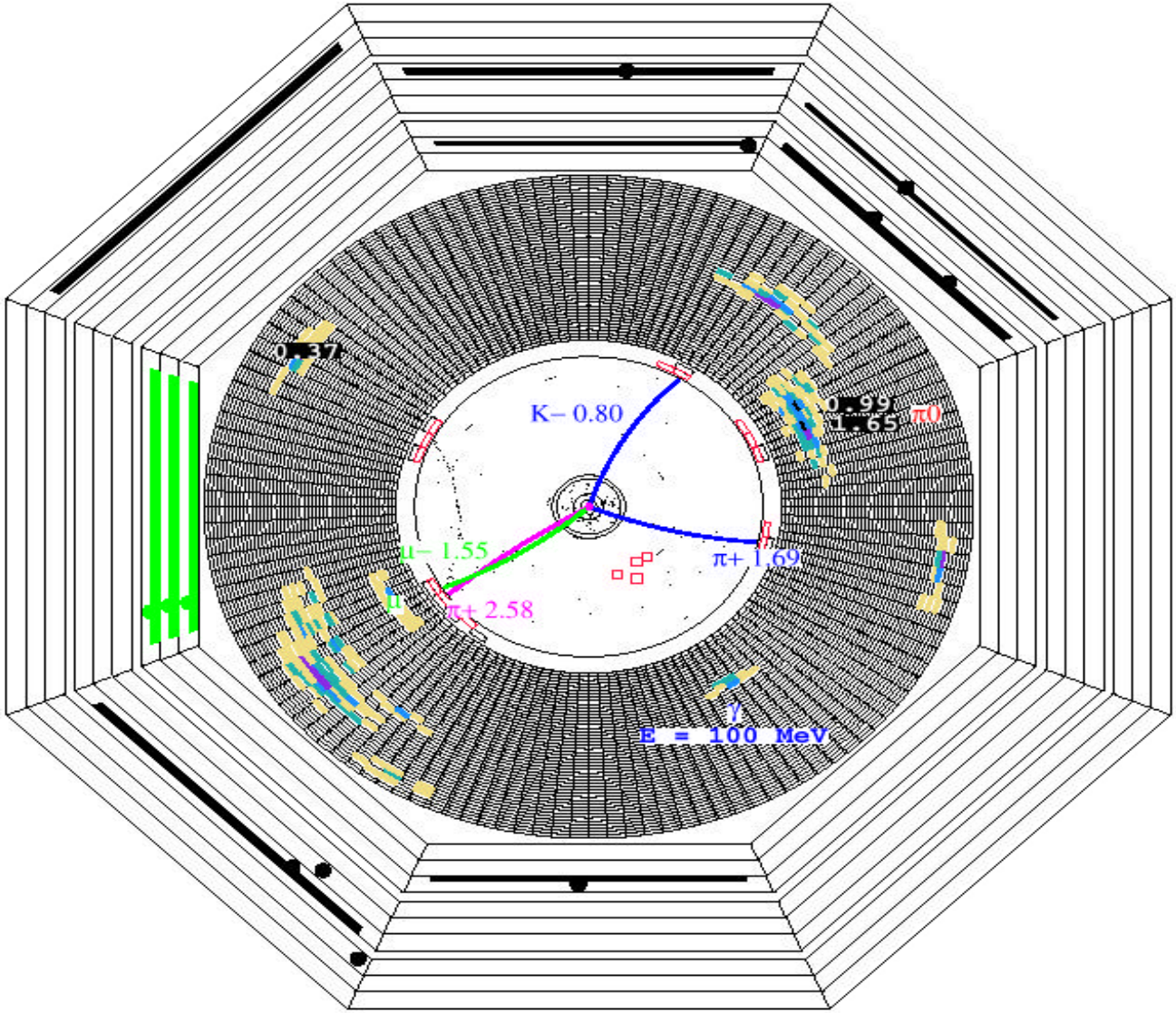


$\text{Br}(B^+ \to K^+p^0) = (12.1^{+3.0}_{-2.8}{}^{+2.1}_{-1.4}) \times 10^{-6}$

$\text{Br}(B^+ \to p^+p^0) < 12.0 \times 10^{-6}$ @90% CL

(assuming $f_{+-} = f_{00} = 0.5$)

Candidate Event : $B^0 \rightarrow K/\pi^+ \pi^0$



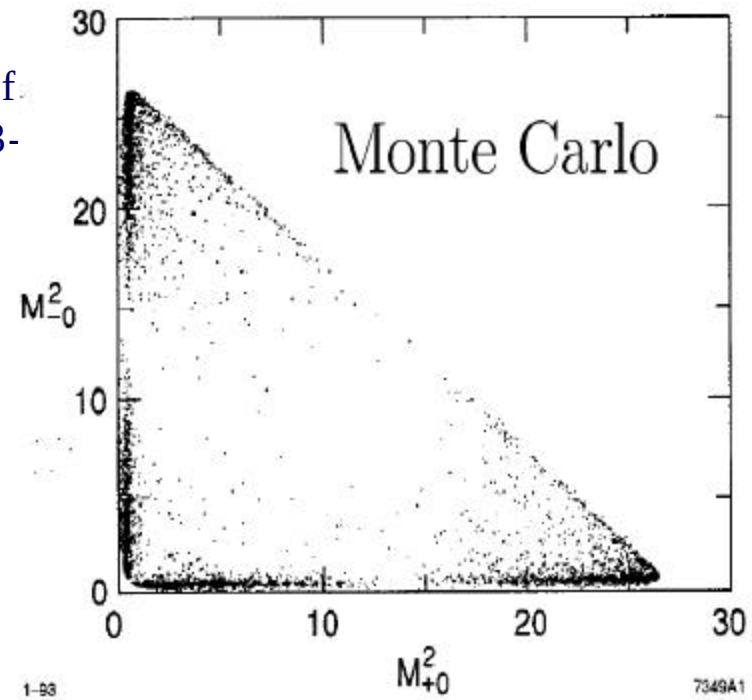
First Observation of $B^0 \to r^{\pm} p^{\mp}$

Snyder & Quinn: Decay $B^0 \to p^+ p^- p^0$ provides enough observables to determine α (in principle) even in presence of penguin contributions. Require analysis of time-dependent 3-pion Dalitz plot including interference effects between resonances.

- Assumption is that resonant contributions like $B^0 \to rp$ are dominant.
- One may worry if these rates are large enough for CP asymmetry measurements even with LARGE collected luminosity !

CLEO: $B^0 \to r^{\pm} p^{\mp}$

- Challenge : Discriminate against $B^0 \to K^{\pm} r^{\mp}$ and $B^0 \to K^{*\mp} p^{\pm}$
- Pick energetic pi0 , tight dE/dx for Kaon discrimination, ΔE, event shape variables to separate decay modes and suppress continuum
- Perform Max. Likelihood fit for $B^0 \to r^{\pm} p^{\mp}$ and $B^0 \to K^{\pm} r^{\mp}$ and continuum contribution using PDF from data and MC.



First Observation of $B^0 \to r^{\pm} p^{\mp}$

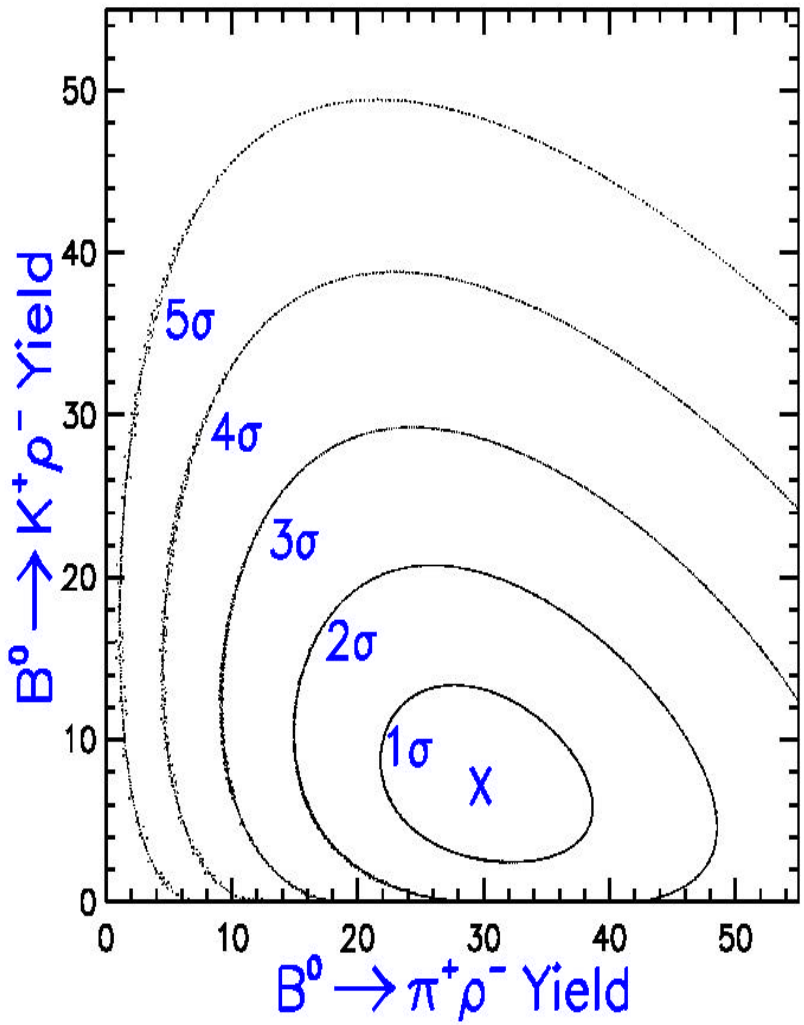
Result From 7M BBbar events :

$$Br(B^0 \to K^{\pm} r^{\mp}) < 2.5 \times 10^{-5}$$

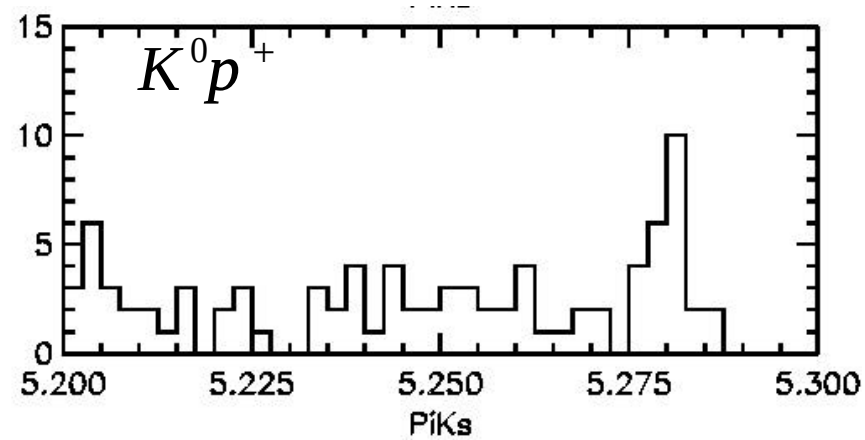
$$Br(B^0 \to p^{\pm} r^{\mp}) = [3.5^{+1.1}_{-1.0} \pm 0.5] \times 10^{-5}$$

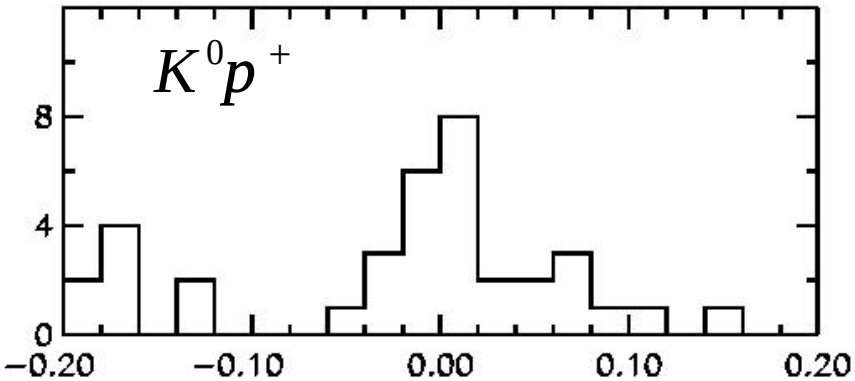
Signal ($p^{\pm} r^{\mp}$) = $29.7^{+8.9}_{-7.9}$ events

Good News for asymmetric B detectors but this is only one part of B→3π decay

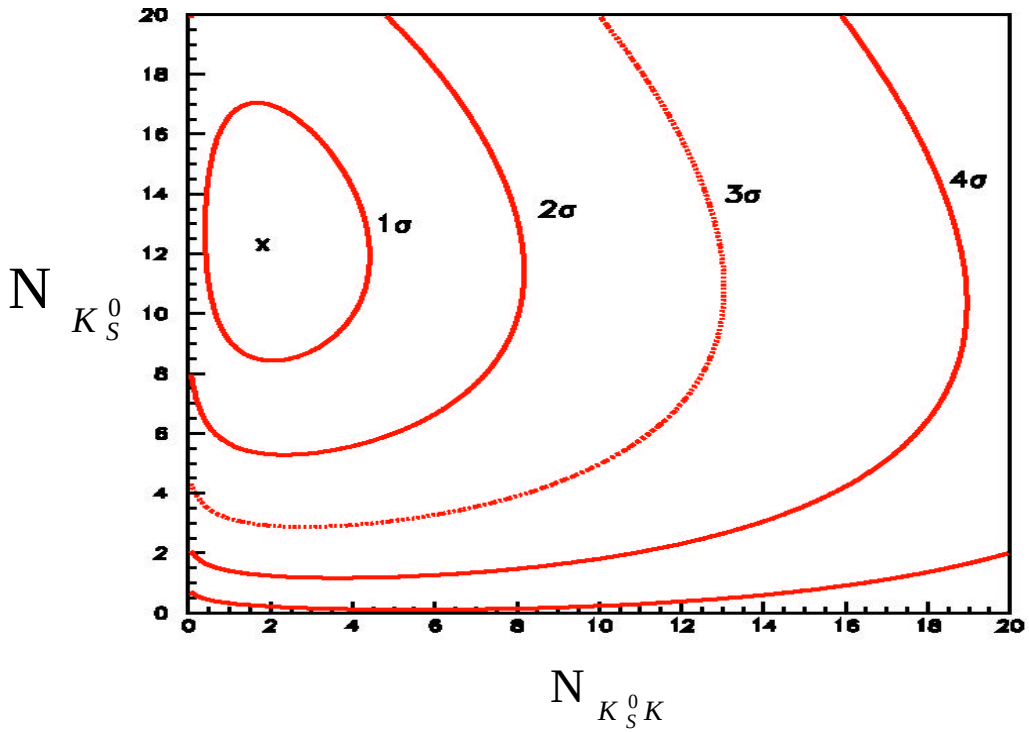


Constraints on γ: $B^0 \to K^+\pi^-$ Vs $B^+ \to K^0\pi^-$





$(\Delta E \equiv E_K + E_p - E_{\text{beam}})$



$$\mathrm{Br}(B^+ \to K^0 p^+) = (18.2^{+4.6}_{-4.0} \pm 1.6)\times 10^{-6}$$

$$\mathrm{Br}(B^+ \to K^0 K^+) < 5.1\times 10^{-6} \text{ @90\% CL}$$

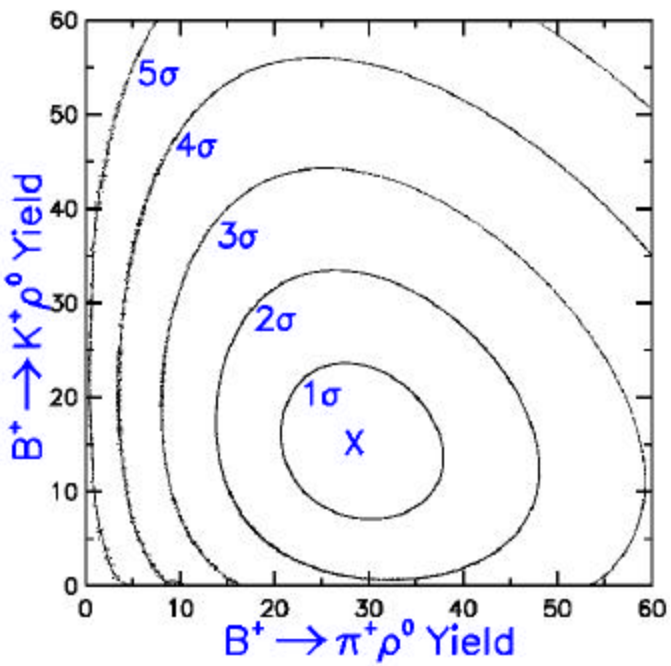
(assuming $f_{+-} = f_{00} = 0.5$)

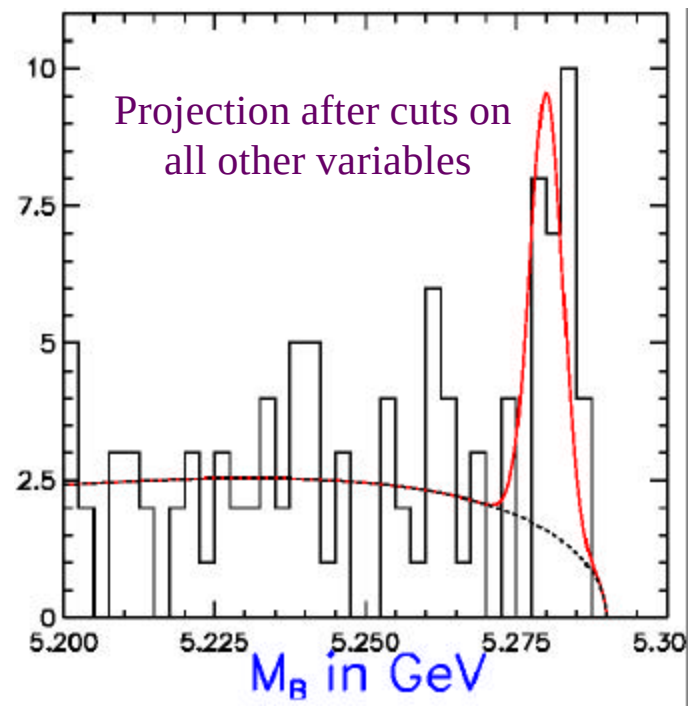
Analysis of $B^{\pm} \to VP$ via $(h^+h^-h^-)$

- Probes rare B final states $j\,h^+, r^0 h^+, K^{*0} h^+$

Bediaga et.al : Measure γ in $B^{\pm} \to p^+ p^- p^+$ dalitz amplitude anal. requires $B^{\pm} \to r^0 p^{\pm}$ be large.

- Distinguished by dE/dx, ΔE, resonance masses
- Continuum seperation by event shape requirements
- Perform ML fits , seperately for each Vector resonance





Analysis of $B^{\pm} \to VP$ via $(h^+h^-h^-)$

Cleo II+II.V Data ~ 5.8×10^6 BB events

Observation of $B^{\pm} \to r^0 p^{\pm}$

Measured Rate consistent with model predictions (Ali et. al) based on factorization

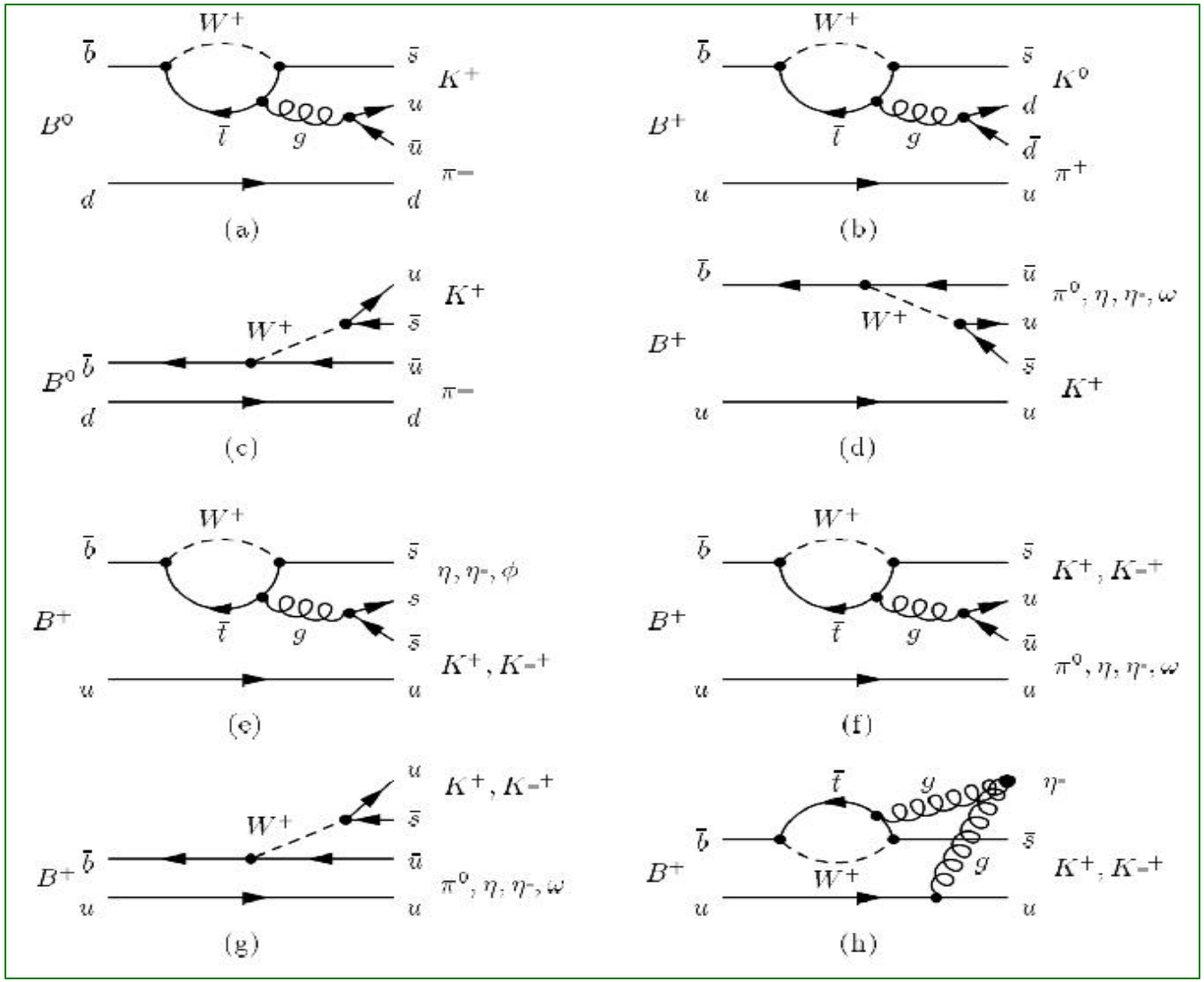
Mode	Yield	Efficiency	Branching Fraction
$r^0 p^+$	$26.1^{+9.1}_{-8.0}$	$29.6 \pm 2.6\%$	$(1.5 \pm 0.5 \pm 0.4) \times 10^{-5}$
$r^0 K^+$	< 27.5	$27.6 \pm 2.4\%$	$< 2.2 \times 10^{-5}$
$K^{*0} p^+$	< 21.0	$27.8 \pm 2.4\%$	$< 2.7 \times 10^{-5}$
$K^{*0} K^+$	< 6.5	$26.4 \pm 2.4\%$	$< 1.2 \times 10^{-5}$

Bediaga et.al : Measure γ in $B^{\pm} \to p^+ p^- p^+$ dalitz distribution , requires $B^{\pm} \to r^0 p^{\pm}$

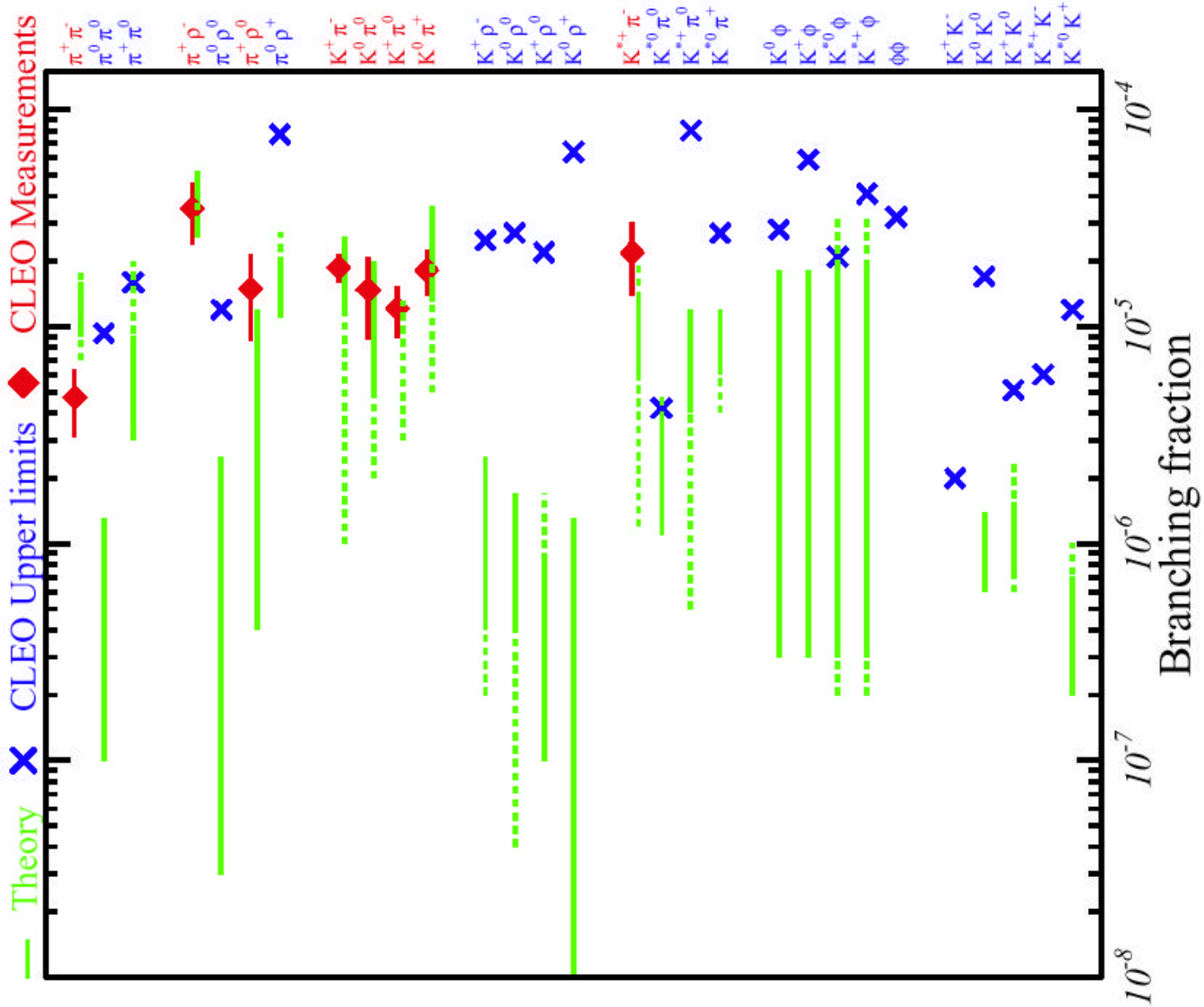
Two-Body Hadronic Penguin B Decays

- Useful for study of dynamics in Penguin decay
- Potential for observation of Indirect or Direct CP asymmetry in some modes
- Bottomline:

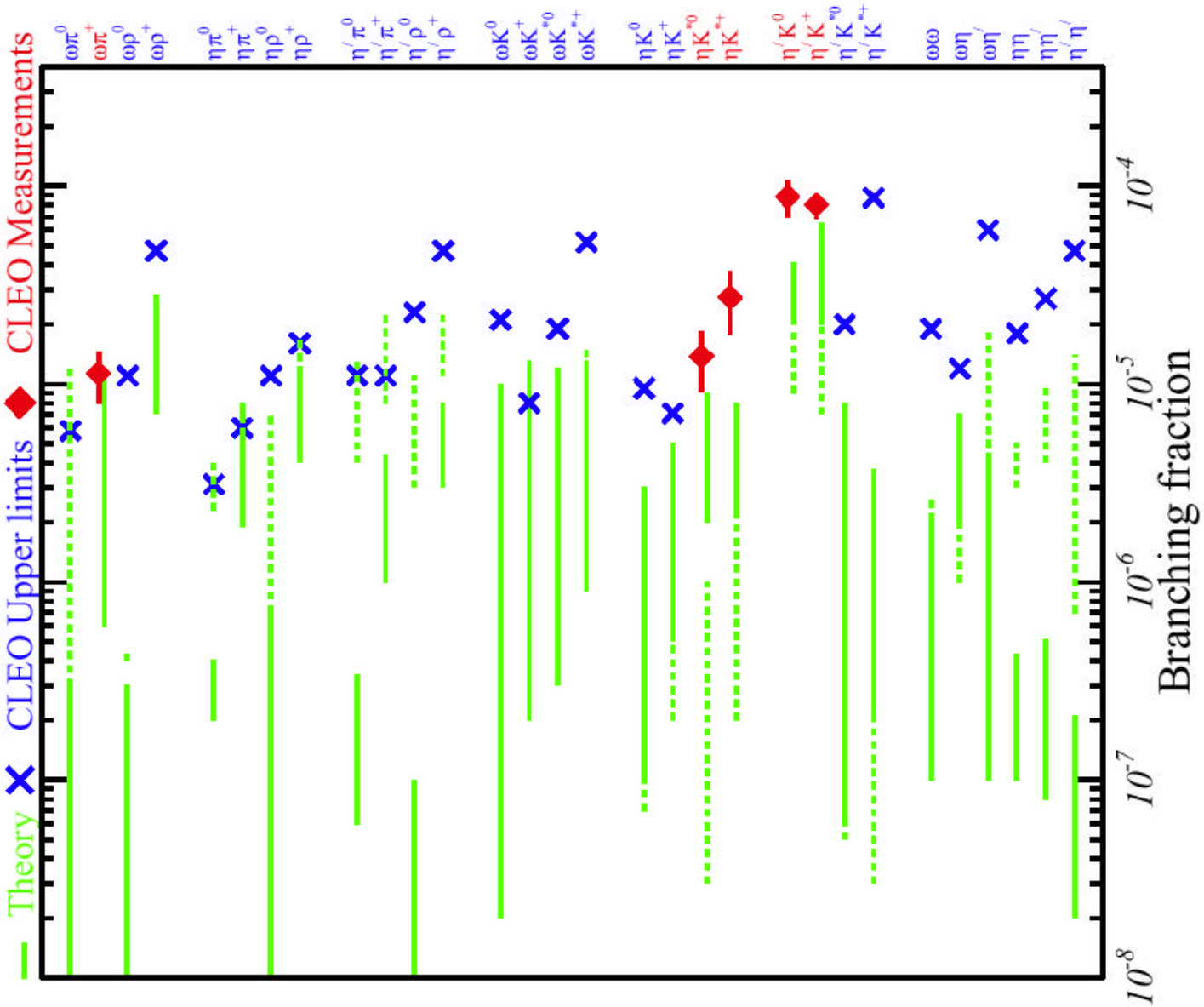
  Penguins are large !



Summary of Rare B Decays : Part I



Summary of Rare B Decays : Part II



First Searches For Direct CP Violation

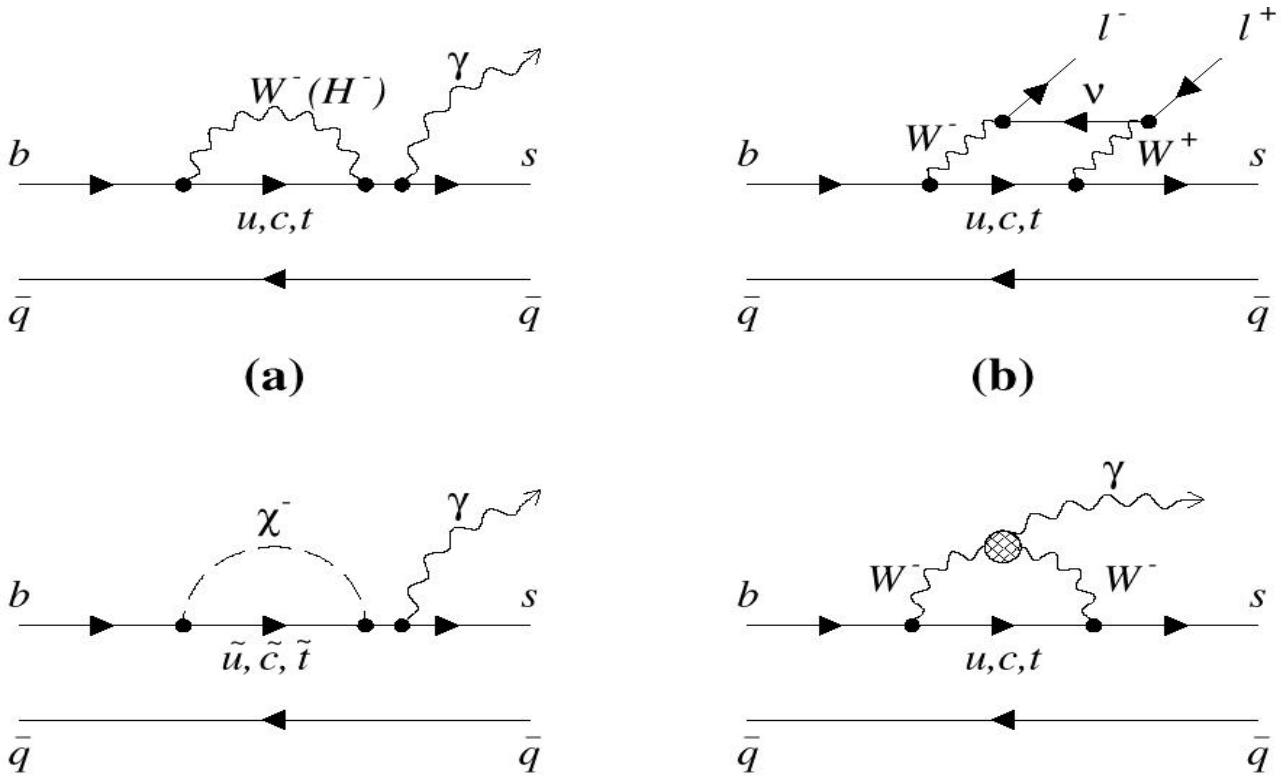
- Decay modes with contributions from Penguin and Tree term are obvious candidates for Direct CP Violation searches:

$$A_{CP} \propto Sing_{ckm}\, Sind_{strong}$$

Mode	$\mathcal{S}$	$\overline{\mathcal{S}}$	$\mathcal{A}_{CP}$	90% CL interval
$K\pi^0$	16.8 ± 7.5	28.9 ± 7.5	$-0.27 \pm 0.23 \pm 0.05$	$[-0.70, 0.16]$
$K_S^0\pi$	14.5 ± 4.4	10.2 ± 4.0	$0.17 \pm 0.24 \pm 0.05$	$[-0.27, 0.61]$
$K\pi$	$38.6^{+9.0}_{-8.1}$	$41.6^{+8.9}_{-8.0}$	$-0.04 \pm 0.16 \pm 0.05$	$[-0.35, 0.27]$
$\eta' K$	51.7 ± 9.2	48.7 ± 8.9	$0.03 \pm 0.12 \pm 0.05$	$[-0.22, 0.28]$
$\omega\pi$	$9.4^{+4.9}_{-4.0}$	$19.1^{+6.8}_{-5.9}$	$-0.34 \pm 0.25 \pm 0.05$	$[-0.80, 0.12]$

NO Sign of Direct CP Violation in B decays yet !

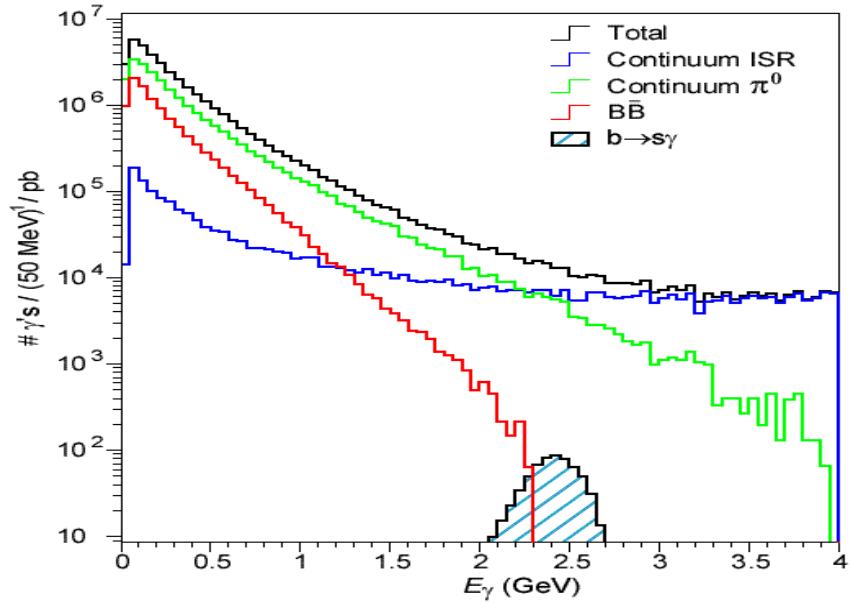
Electroweak Penguins



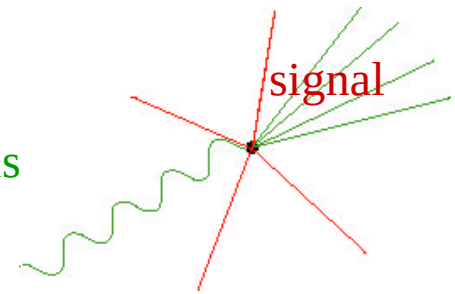
- No FCNC at tree level B decay→ gives a direct look at loops and boxes
- Sensitive to $V_{tb}V_{ts}$, New physics…
- Rate Enhanced by QCD corrections
- Recent SM NLO prediction: $\boxed{B(b \to s\gamma) = (3.28 \pm 0.33) \times 10^{-4}}$

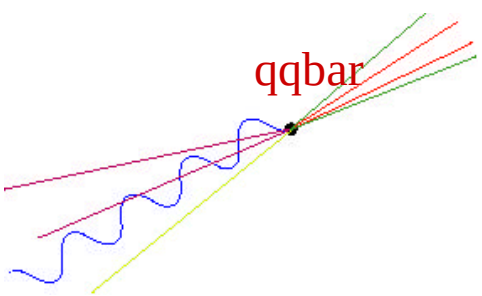
Measurement Of Inclusive $b \to s\gamma$

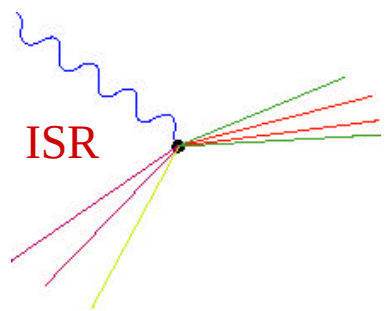
- Measure E_g spectrum for ON and OFF 4S resonance and subtract
  - Need to suppress **dominant** qqbar background to see a tiny $b \to s\gamma$ rate
- Two methods:
  - Event Shape analysis
  - Pseudo $B \to s\gamma$ reco.



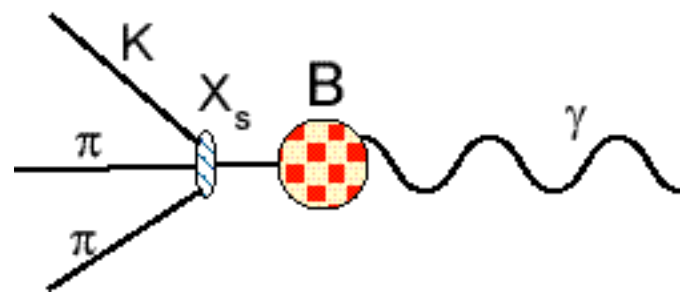
Method I:
Shape analysis







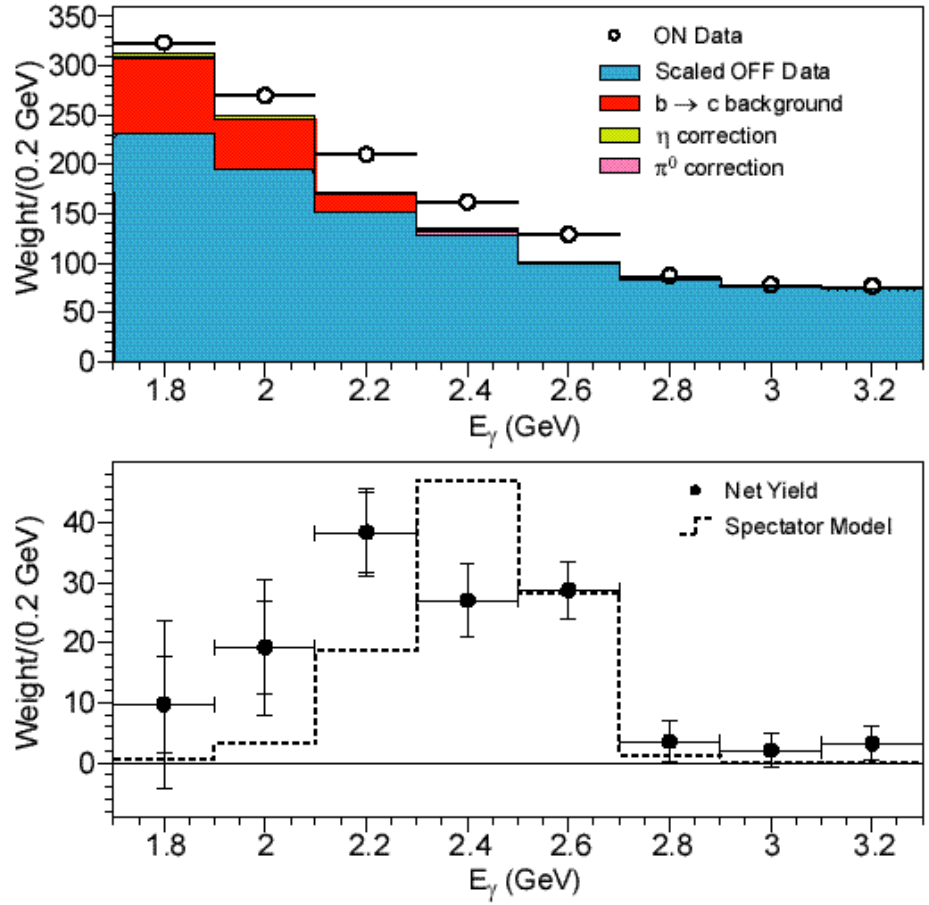
Method II: Pseudo-B Reco



Preliminary Results

- Cleo II data
  3.1 fb^{-1} ON, 1.6 fb^{-1} OFF
- *Rate* measured for
  $2.1 < E_g < 2.7\,\text{GeV}$

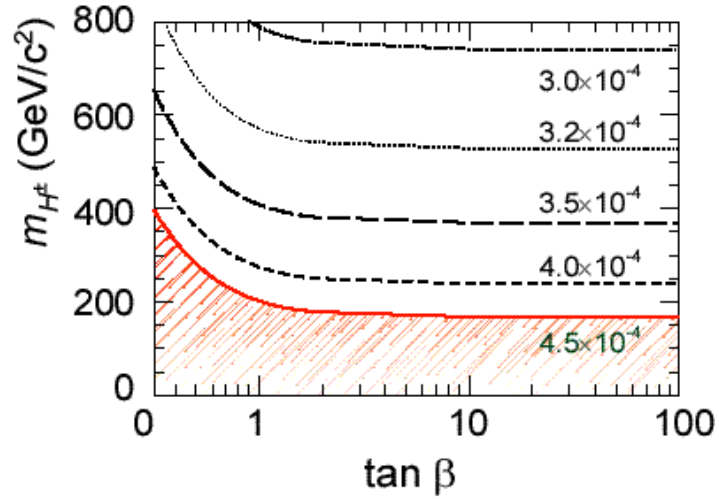
  Samples about 85% of the full spectrum
- Model systematic:
  - spectator model inputs
  - X_s hadronization
- NLO Prediction:
  $(3.28 \pm 0.33) \times 10^{-4}$
  Chetyrkin, Misiak, and Münz



$$B(b \to sg) = (3.15 \pm 0.35_{\text{stat}} \pm 0.32_{\text{sys}} \pm 0.26_{\text{model}}) \times 10^{-4}$$

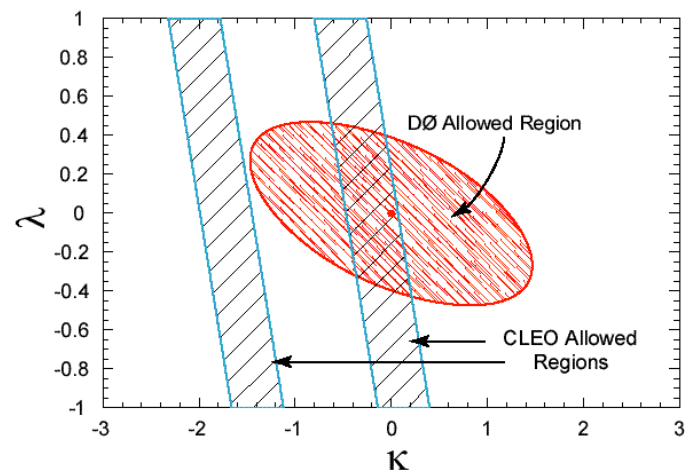
Implications

- $B(b \to s\gamma)$ $< 4.5 \times 10^{-4}$ and
  $> 2.0 \times 10^{-4}$
  each at 95% CL
- Higgs mass limits
  - Limits on Charged Higgs with model II coupling.
  - NLO calculation of Borzumati & Greub hep-ph/9802391
    Phys Rev D58 (1998).



- Anomalous WWγ couplings

$$\mathcal{L}_{WW\gamma} = -ie[(W^\dagger_{\mu\nu}W^\mu A^\nu - W^\dagger_\mu A_\mu W^{\mu\nu}) + \kappa W^\dagger_\mu W_\nu F^{\mu\nu} + \frac{\lambda}{M_W^2} W^\dagger_{\alpha\mu} W^\mu_\nu F^{\alpha\nu}]$$



CP Asymmetry in b → sγ ?

- SM says its small! Another window on new physics?

$$b \to sg = A_{sm} + A_{new} e^{iq_s} e^{iq_w}$$

$$\bar{b} \to \bar{s}g = A_{sm} + A_{new} e^{iq_s} e^{-iq_w}$$

$$\mathrm{B} = |b \to sg|^2 + |\bar{b} \to \bar{s}g|^2$$

$$\sim A_{sm}^2 (1 + 2r \cos q_s \cos q_w + r^2)$$

$$r = \frac{A_{new}}{A_{sm}}$$

New physics could appear in Asymmetry that would not alter branching ratio

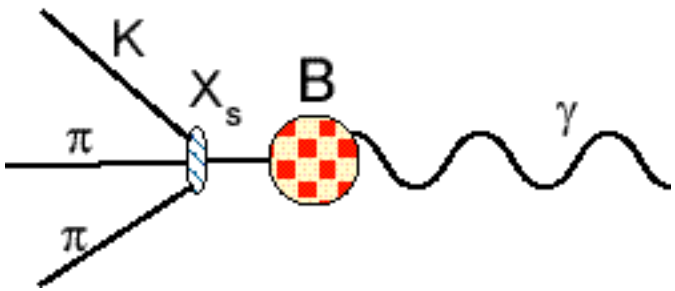
$$\mathrm{A} = \frac{|b \to sg|^2 - |\bar{b} \to \bar{s}g|^2}{|b \to sg|^2 + |\bar{b} \to \bar{s}g|^2} \sim 2r \sin q_s \sin q_w$$

- Wolfenstein, A. Kagan, M. Neubert hep-ph/9803368; Aoki, Cho, Oshimo hep-ph/9811251

B Flavor Identification and A_{CP}

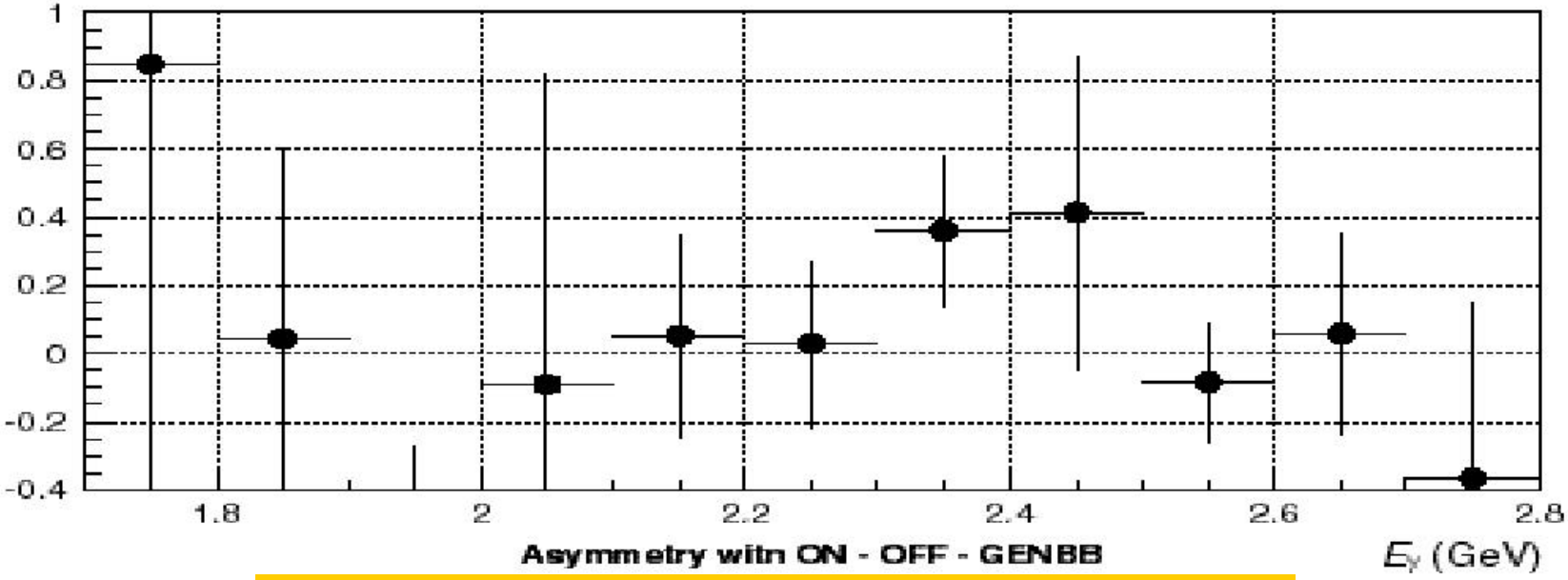
- Define $$A = \frac{\Gamma(b \to sg) - \Gamma(\bar{b} \to \bar{s}g)}{\Gamma(b \to sg) + \Gamma(\bar{b} \to \bar{s}g)}$$

- B Flavor Identification:
  - Pseudo - B reconstruction determines the particles that make up B
    $\Rightarrow$ know the b flavor !
  - minor complication :
    cannot flavor tag $\boxed{B^0 \to K_S np}$ with the pseudo- Breco.
    Such events do not contribute
  - Monte Carlo $\Rightarrow$ flavor tag effective
    - mistag rate is 8.31 ± 1.62 %
  - Worry about detector. MC asymmetries etc , use data to evaluate them all



CP Asymmetry in $b \to sg$: Preliminary

- CP asymmetry in bins of photon energy:



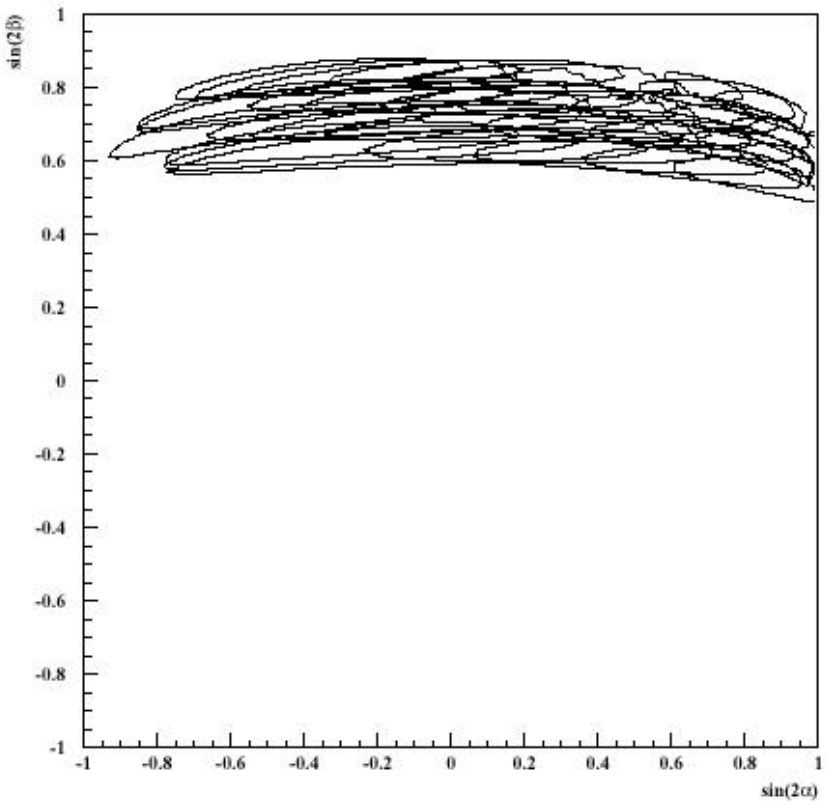
$$A = (0.16 \pm 0.14_{stat} \pm 0.05_{sys}) * (1.0 \pm 0.04_{sys})$$

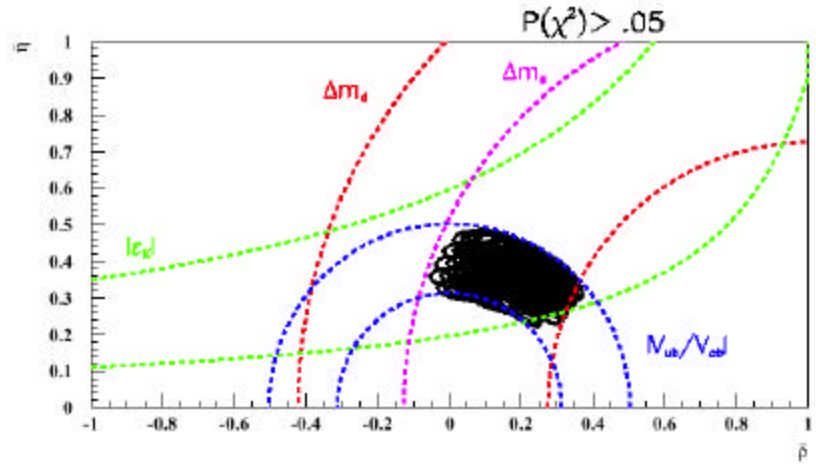
$$-0.09 < A < 0.42$$

More Sensitive Measurements Coming Soon

Status of the Unitarity Triangle

- Must be careful with the theoretical "errors"
- Prefer Buras proposal to "scan" the allowed region
- Fit results a la BaBar book : M.H.Schune & S. Plaszczynski





Experimental inputs	Theoretical scan
$\Delta m_d = 0.471 \pm 0.016$ ps^{-1}	$0.16 < f_B\sqrt{B_B} < 0.24$ GeV
$\lvert\varepsilon_K\rvert = 0.002285 \pm 1.8E{-}05$	$0.65 < B_K < 0.95$
$N_{ub}/V_{cb} = \lvert N_{ub}/V_{cb}\rvert_T \pm 0.003$	$0.075 < \lvert N_{ub}/V_{cb}\rvert_T < 0.105$
$N_{cb} = 0.04 \pm 0.002$	$1.12 < \xi_s^2 < 1.48$
$m_t = 165 \pm 6$ GeV	

$$-.05 < \bar{\rho} < .35 \ (95\%CL)$$

$$.22 < \bar{\eta} < .48 \ (95\%CL)$$

$$.55 < \sin 2\beta < .88 \ (95\%CL)$$

$$\sin 2\alpha?$$

Status of the Unitarity Triangle

Bounds

- Fleischer and Mannel:

$$\sin^2\gamma + o(corrections) \leq R \equiv \frac{\Gamma(B_d \to \pi^{\mp} K^{\pm})}{\Gamma(B^{\pm} \to \pi^{\pm} K^0)}$$

but recent CLEO measurements:

$$R = 1.07 \pm 0.45$$

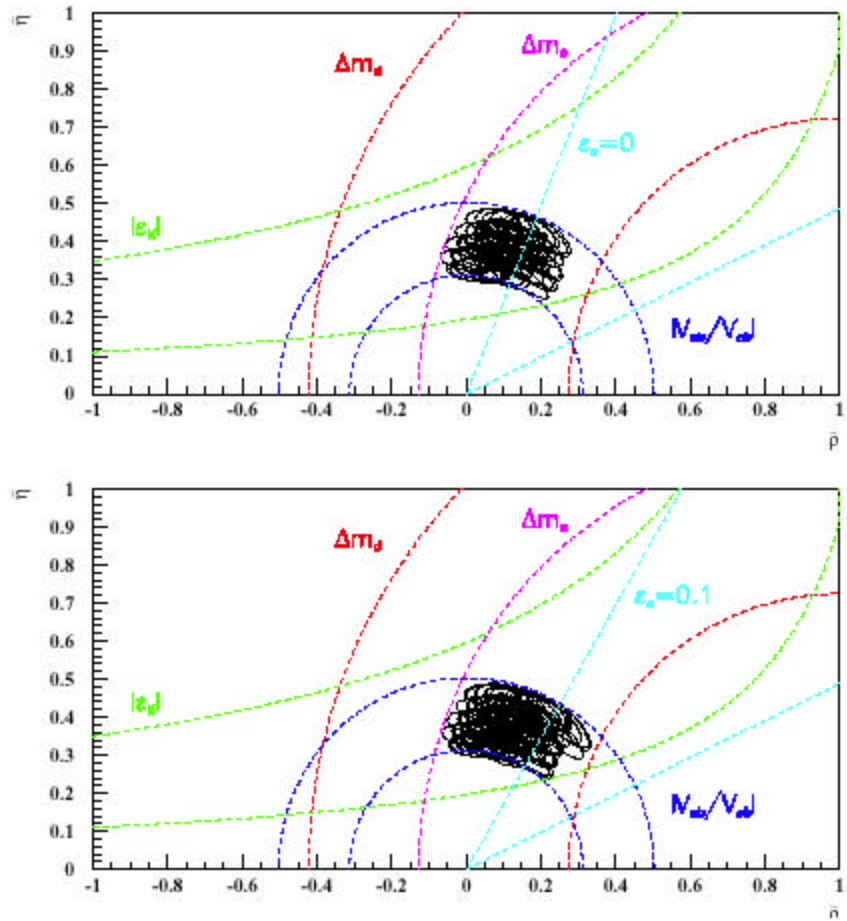
- Neubert and Rosner:

$$\mathcal{R} = \frac{1-\sqrt{R_*}}{\bar{\epsilon}_{3/2}} \leq |\delta_{EW} - \cos\gamma| + o(\bar{\epsilon}_{3/2}, \epsilon_a)$$

with

- $R_* = \frac{\Gamma(B^{\pm}\to\pi^{\pm}K^0)}{2(B^{\pm}\to\pi^0 K^{\pm})}$
- $\bar{\epsilon}_{3/2} = \sqrt{2} R_{SU(3)} \tan\theta_C \left[\frac{\Gamma(B^{\pm}\to\pi^{\pm}\pi^0)}{\Gamma(B^{\pm}\to\pi^{\pm}K^0)}\right]^{\frac{1}{2}}$
- CLEO (+ theory): $\mathcal{R} = 1.32 \pm 0.47$
- theory: $0.49 < \delta_{EW} < 0.79$

Effect on the UT

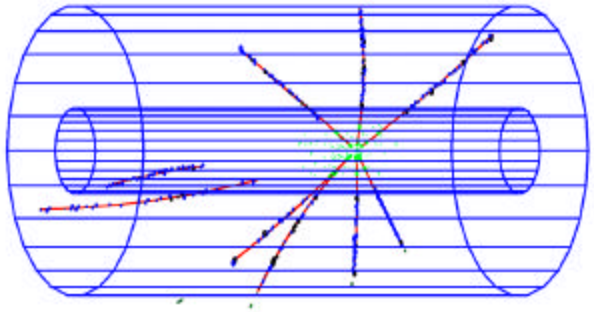


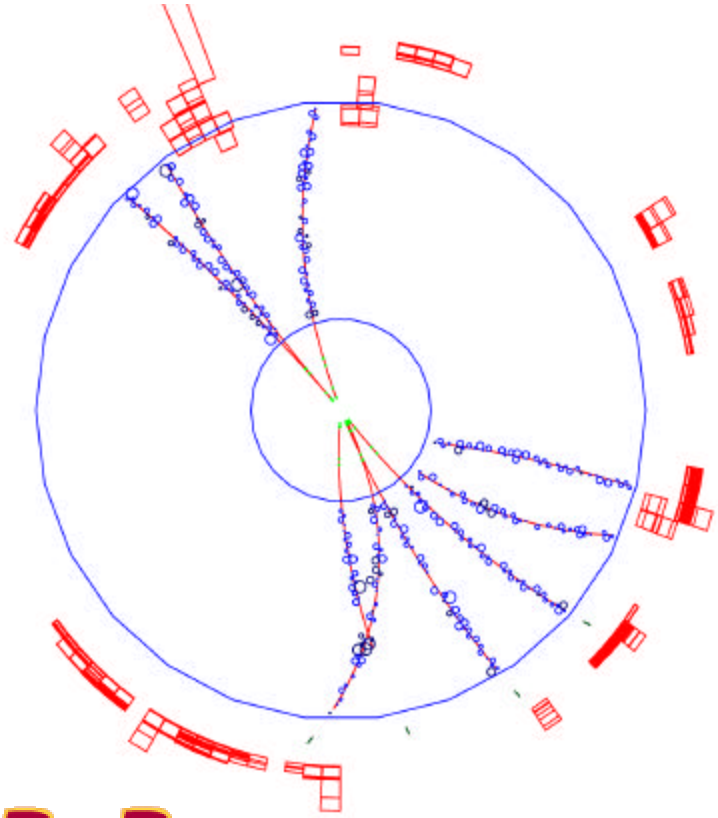
The Future

First Collisions in *BABAR*

Hadronic Event

May 26, 1999



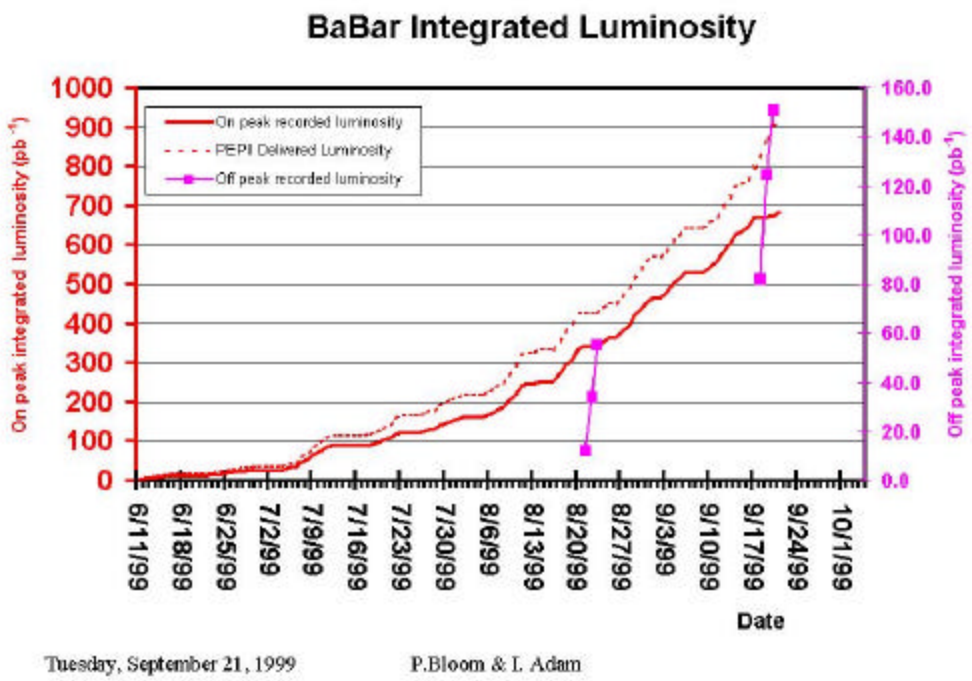


BABAR TM & L de Brunhoff

Future : B Factories are Here !

- PEP-II and KEK-B are off to an excellent start with BaBar and Belle Detectors this summer. CLEOIII (with excellent tracking and PID) installation is in progress (See Frank Wuerthwein's talk)
- PEP-II consistently delivers ~ 1.5x 10^{33} $cm^{-2}s^{-1}$ inst. Luminosity to BaBar within 4 months of startup. BaBar Datataking eff. ~ 95%
  - Anders Ryd will tell you more about the status of the B factories

•Expect about 2 fb^{-1} by end 99

•Expect about 12 fb^{-1} by july 00

•First CP results expected in 2000