B Physic Results and Perspectives

What is needed: detector review

b hadron production mechanisms

lifetimes and mass measurements

CKM matrix element determination

What is needed: Introduction

B physics measurements are high precision measurements

High performances detectors

In some cases efficient triggers

Sofisticated analysis programs

Good knoledge of statistics

What is needed: detectors

Magnetic field

Tracking system

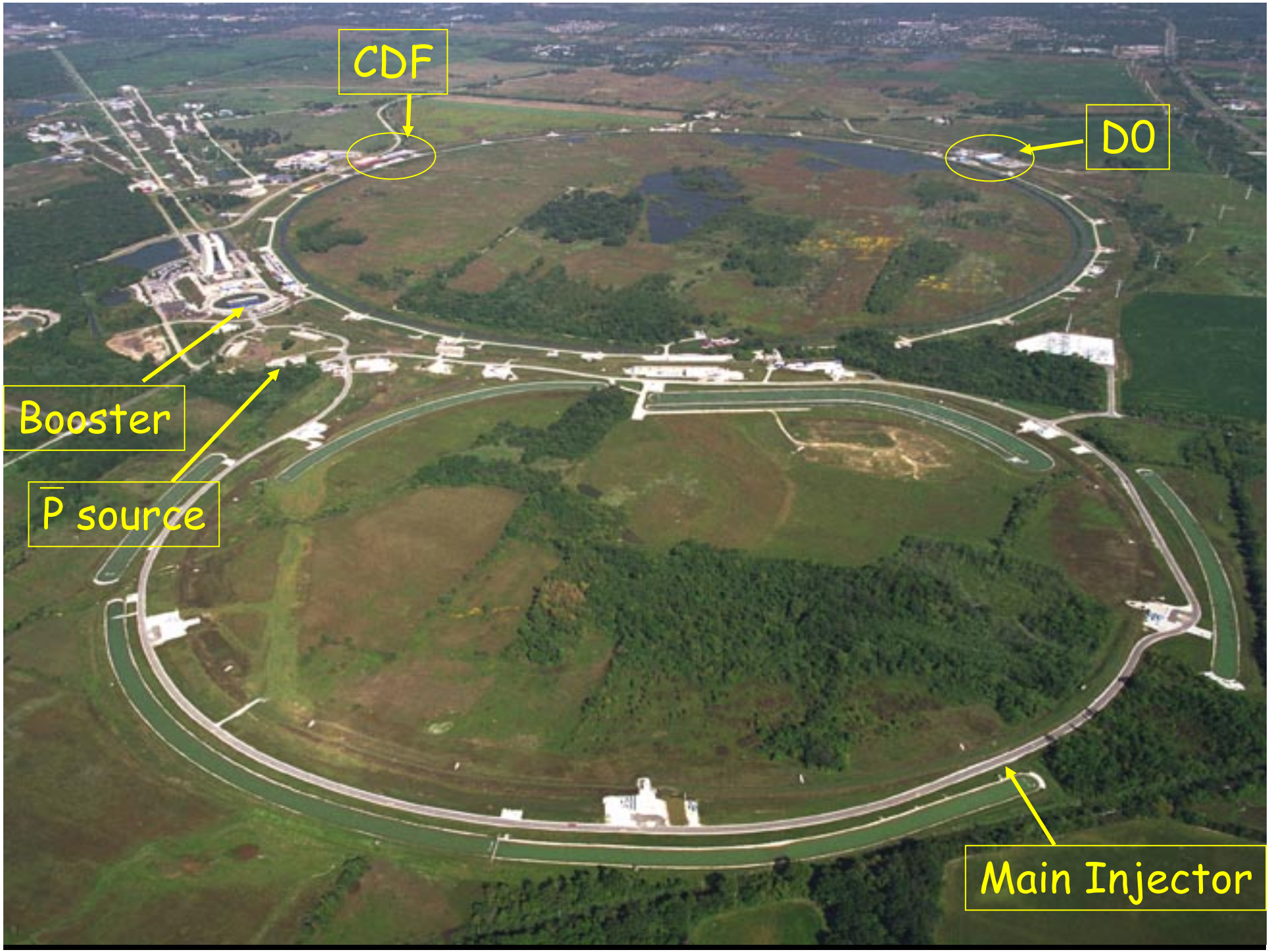
- high space resolution
- high momentum resolution

Calorimeters

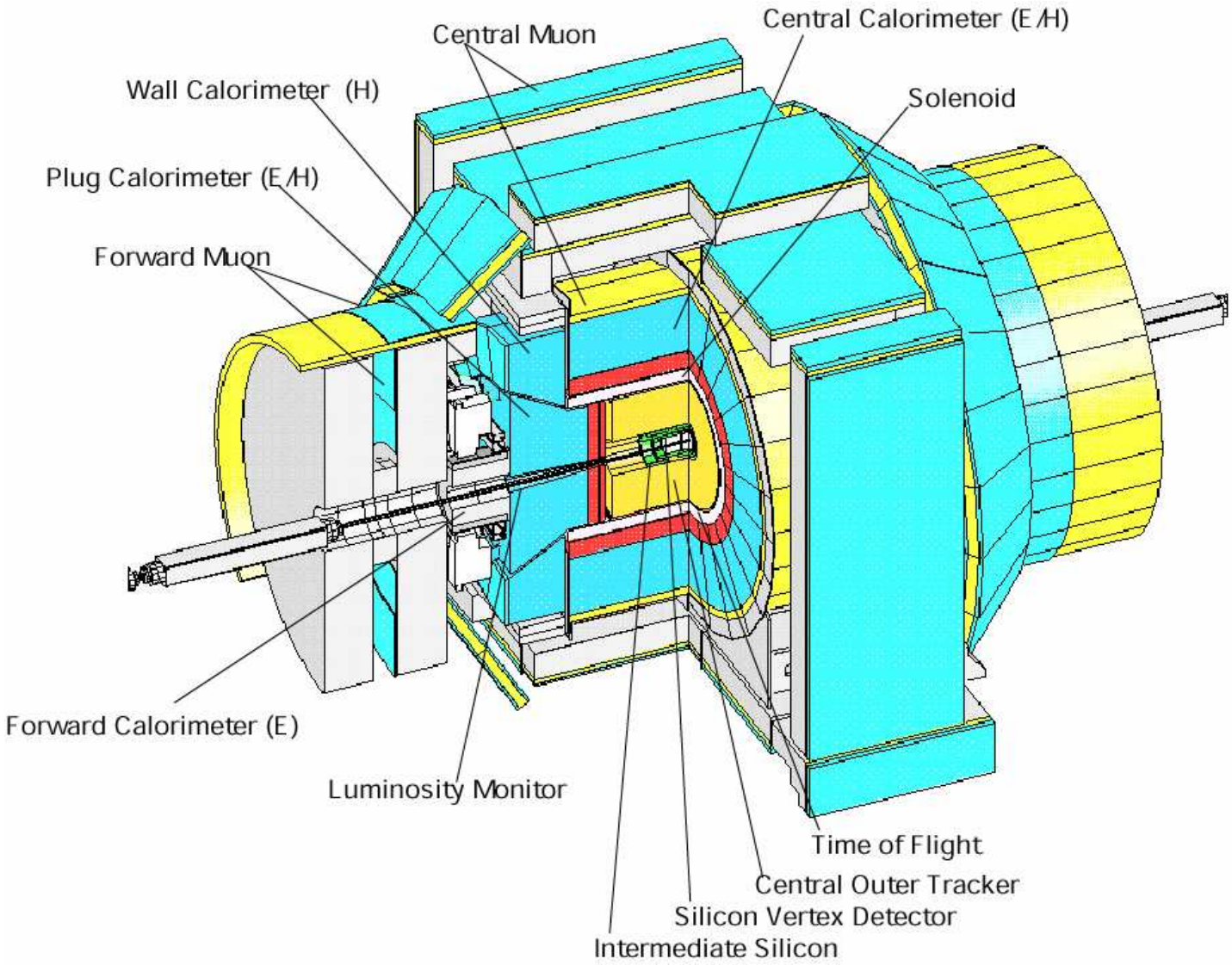
- fast and efficient to identify e
- good energy resolution to reconstruct decays as $\pi^0 \to \gamma\gamma$ or $\eta \to \gamma\gamma$

Particle identification:

- separate K from π
- identify μ and e

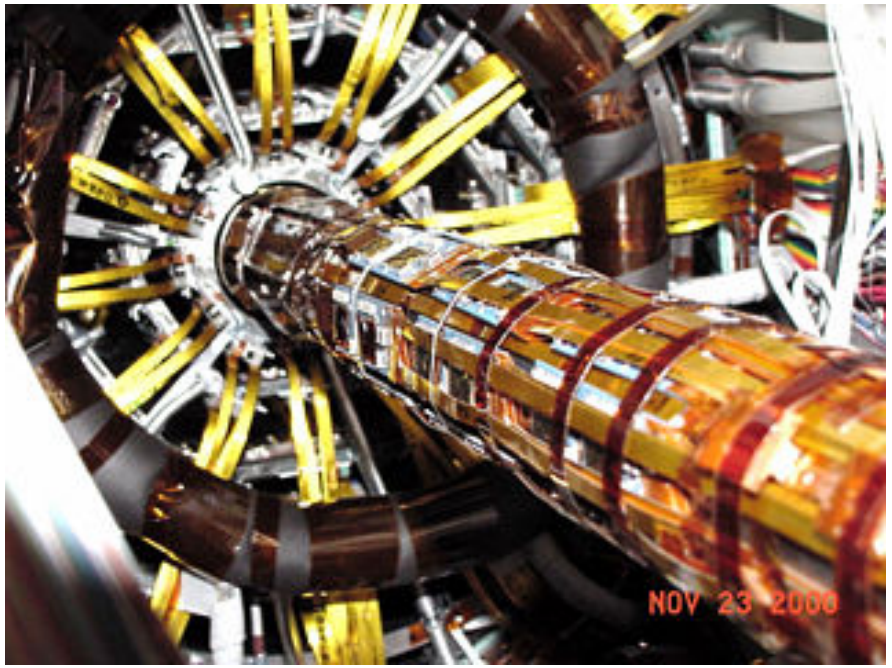

CDF
DO
Booster
$\bar{P}$ source
Main Injector

Detectors: an old one, CDF

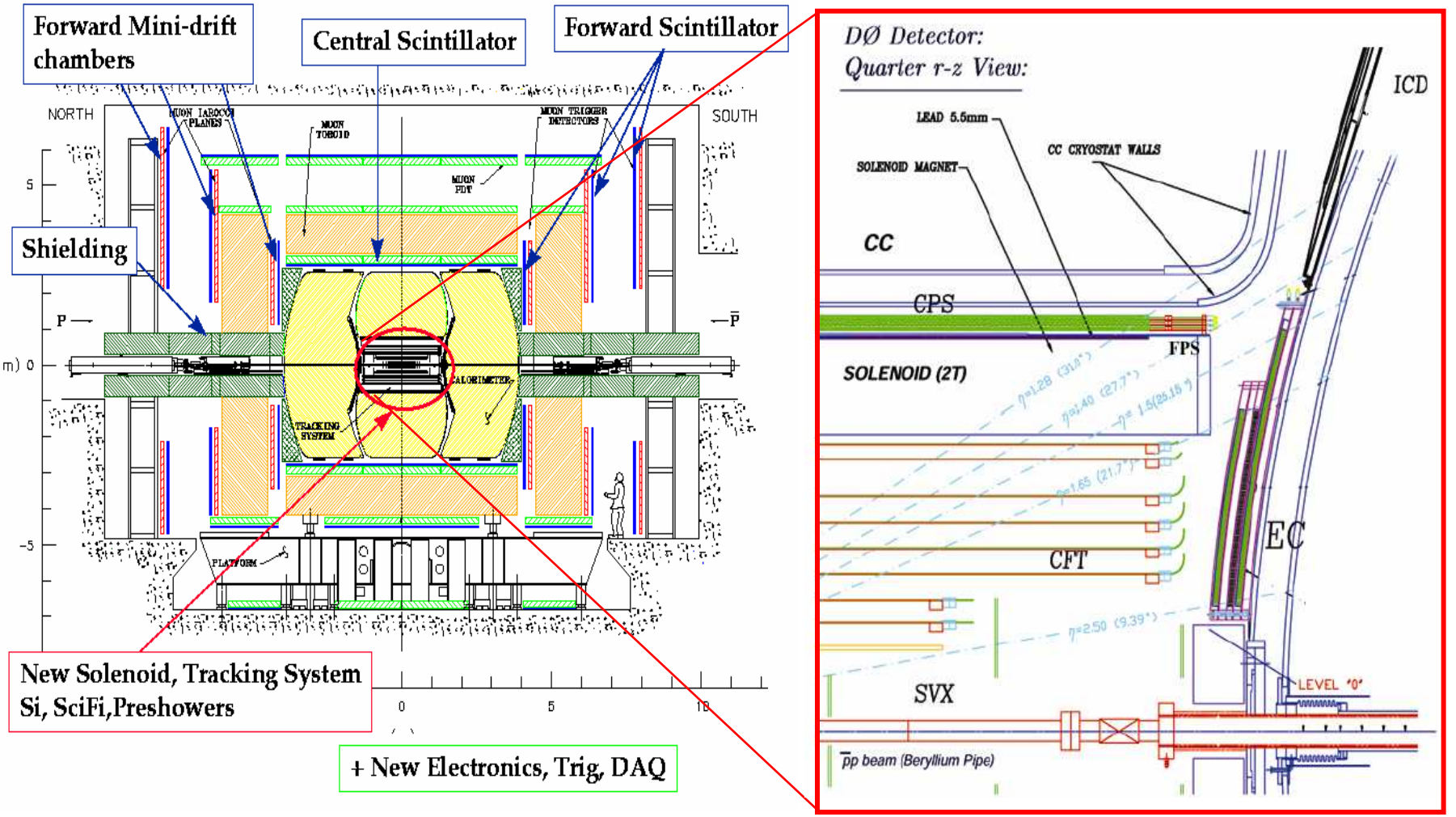


Detectors: CDF some details

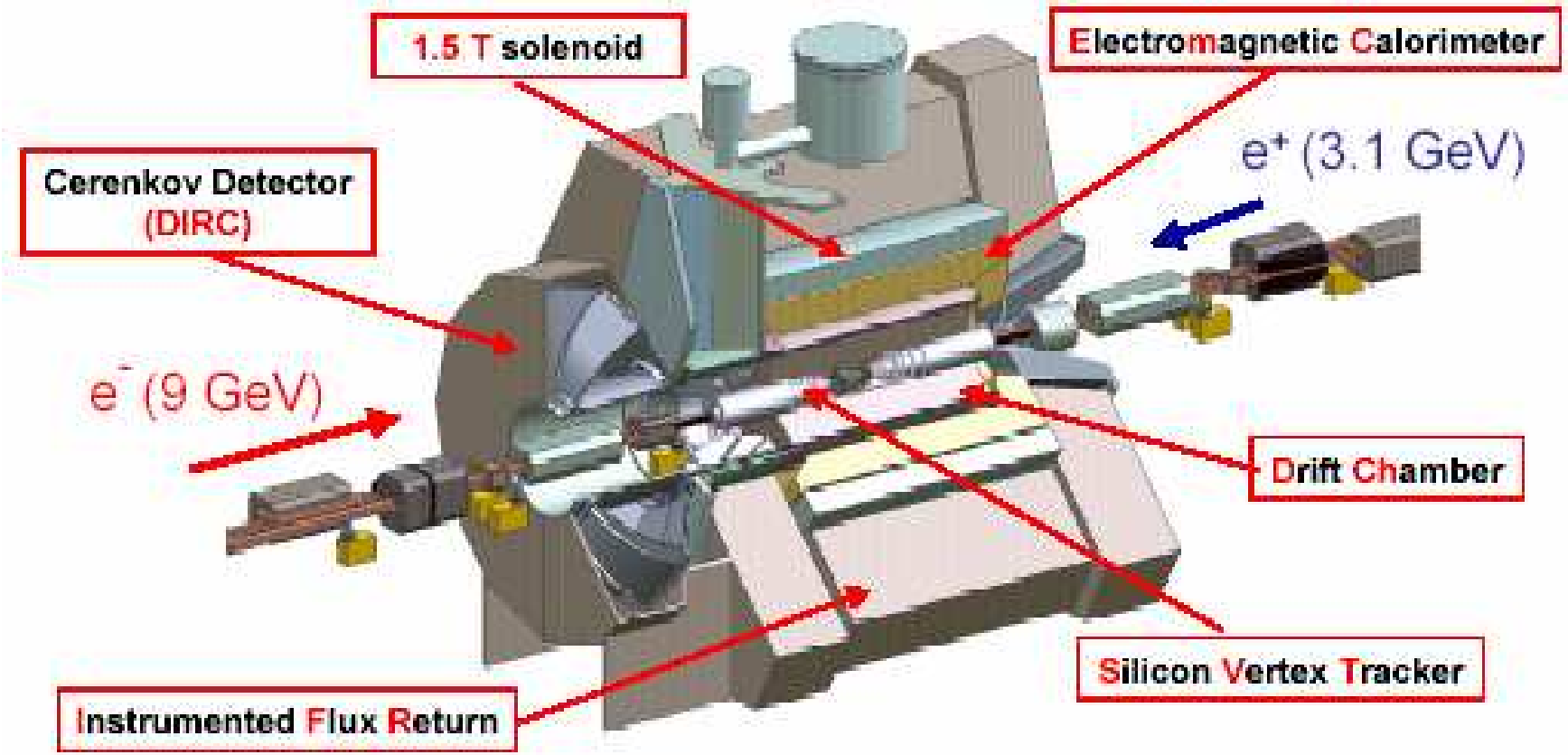
Central Outer Chamber:
96 layers
Max drift time 100 ns
Gas: Ar-Et-CF_4 (50:35:15)



Detectors: DØ



Detectors: A new one, Babar



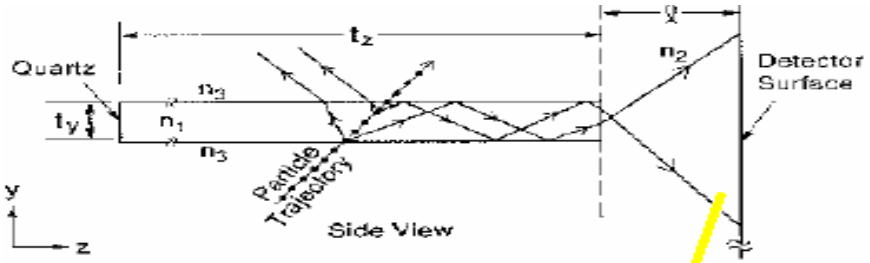
SVT: 97% efficiency, 15 μm z hit resolution (inner layers, perp. tracks)

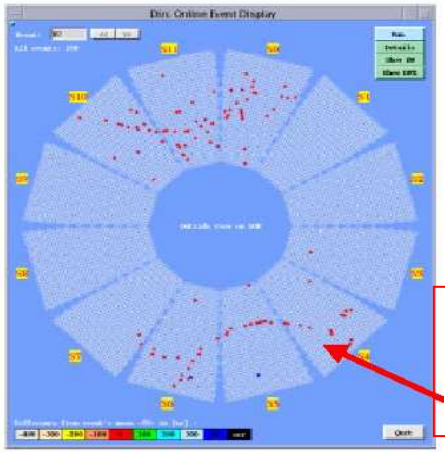
SVT+DCH: $\sigma(p_T)/p_T = 0.13\ \% \times p_T + 0.45\ \%$

DIRC: K-π separation 4.2 σ @ 3.0 GeV/c → 2.5 σ @ 4.0 GeV/c

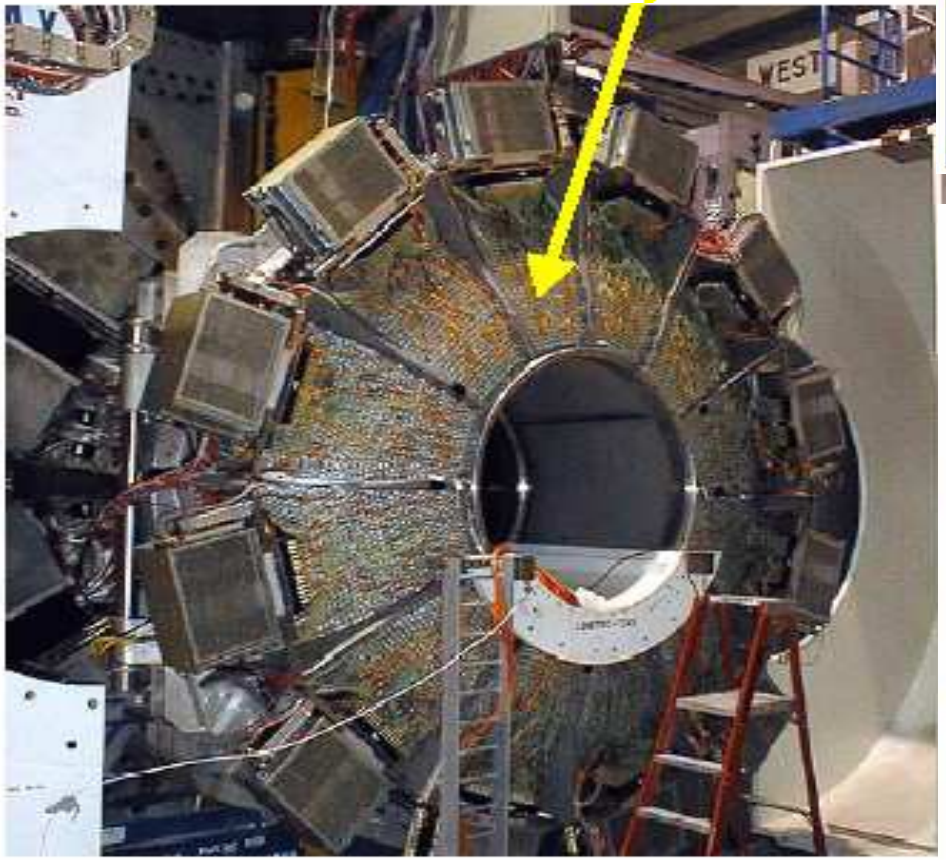
EMC: $\sigma_E/E = 2.3\ \% \cdot E^{-1/4} \oplus 1.9\ \%$

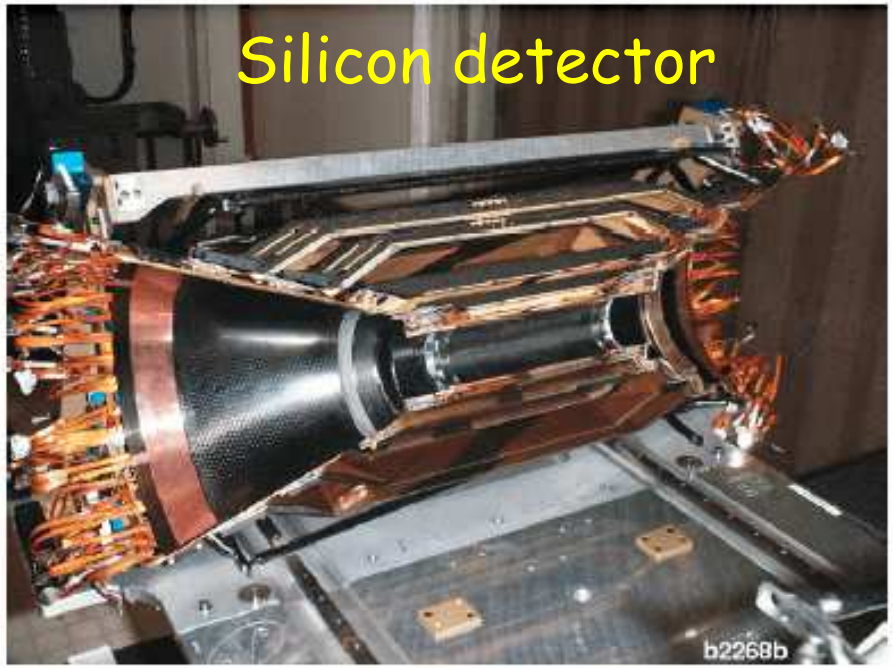
Detectors: Babar some details





Cherenkov ring



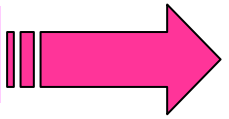


Where to produce b?

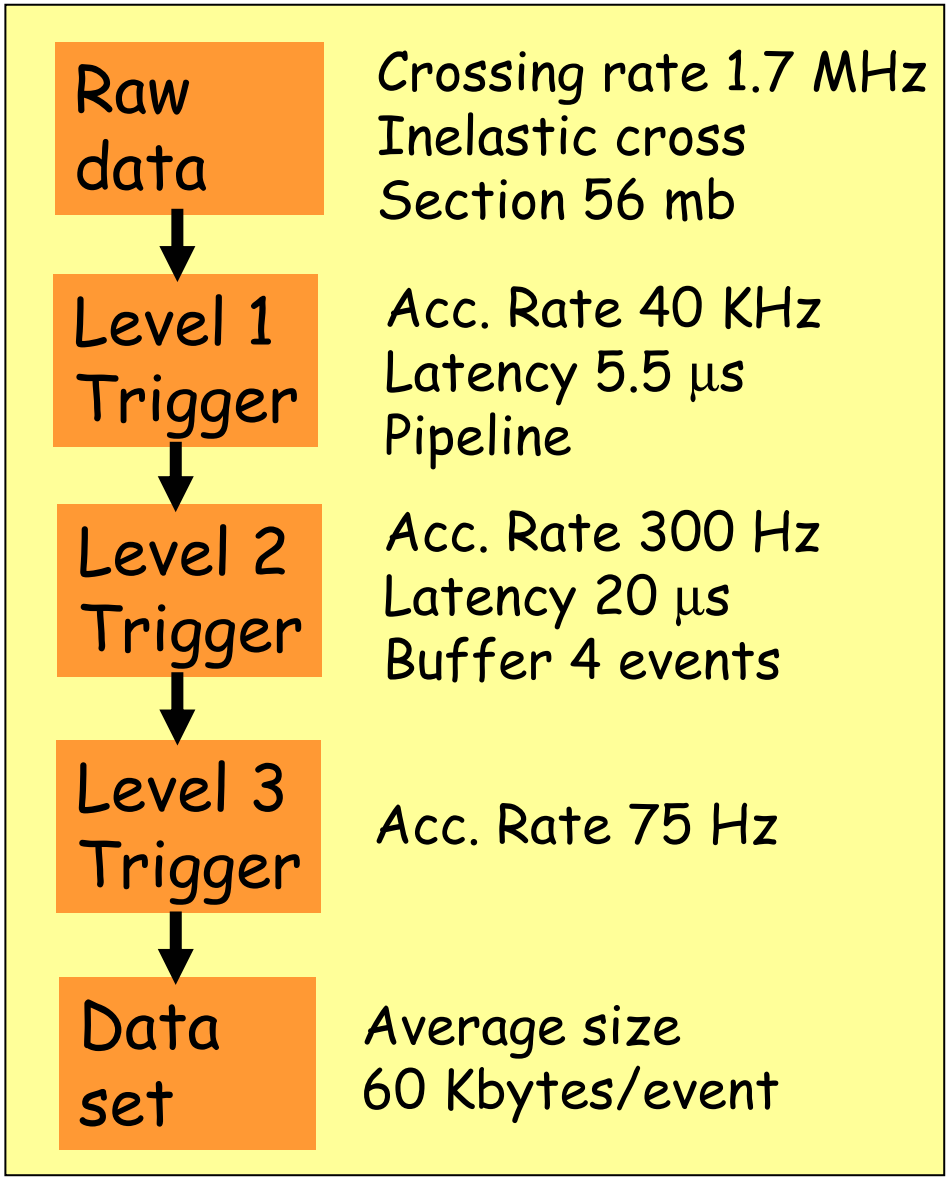
Accelerator	Beams	Species	$\sqrt{s}$(GeV)	$\sigma_{b\bar{b}}$(nb)	$\sigma_{b\bar{b}}/\sigma_{tot}$
B factories	e^+e^- $\Upsilon(4s)$	B^0 & $B^\pm$	10.5	1.15	0.25
Lep	e^+e^- Z pole	all	90	7	0.215
SpS	$p\bar{p}$	all	630	$2\cdot10^4$	$3\cdot10^{-4}$
Tevatron	$p\bar{p}$	all	1,800	$1\cdot10^5$	$6\cdot10^{-4}$
LHC	pp	all	14,000	$5\cdot10^5$	?

B factories produce only 2 species but very low background

$p\bar{p}$ interactions have all species but high background



How to select b at hadron collider ? Trigger



Level 1 Synchronous streams:

- Calorimeter
- Fast tracker
- Muons

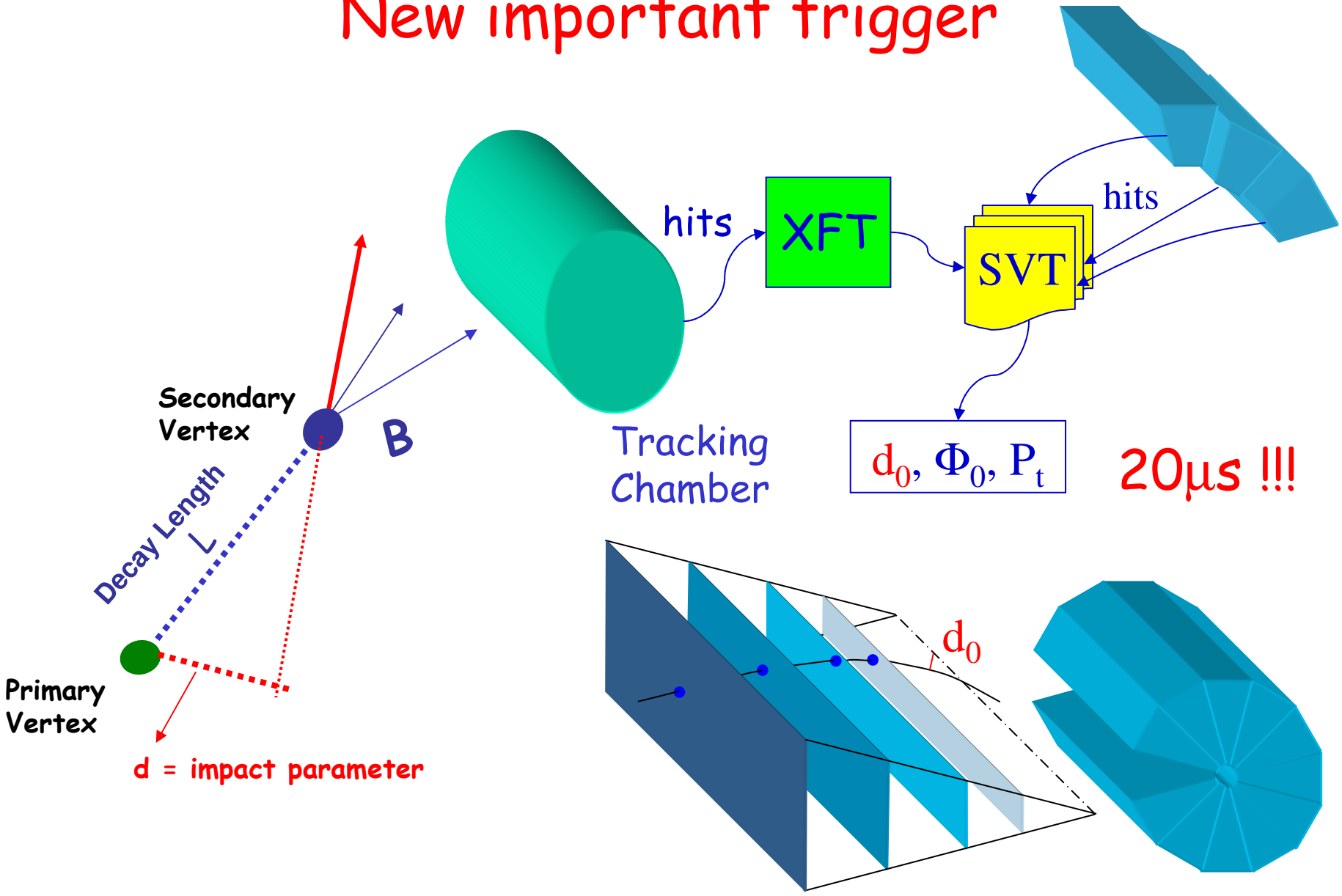
Level 2 asynchronous systems:

- Calorimeter clustering
- Track parameter available electrons

Level 3

- Offline-like

New important trigger

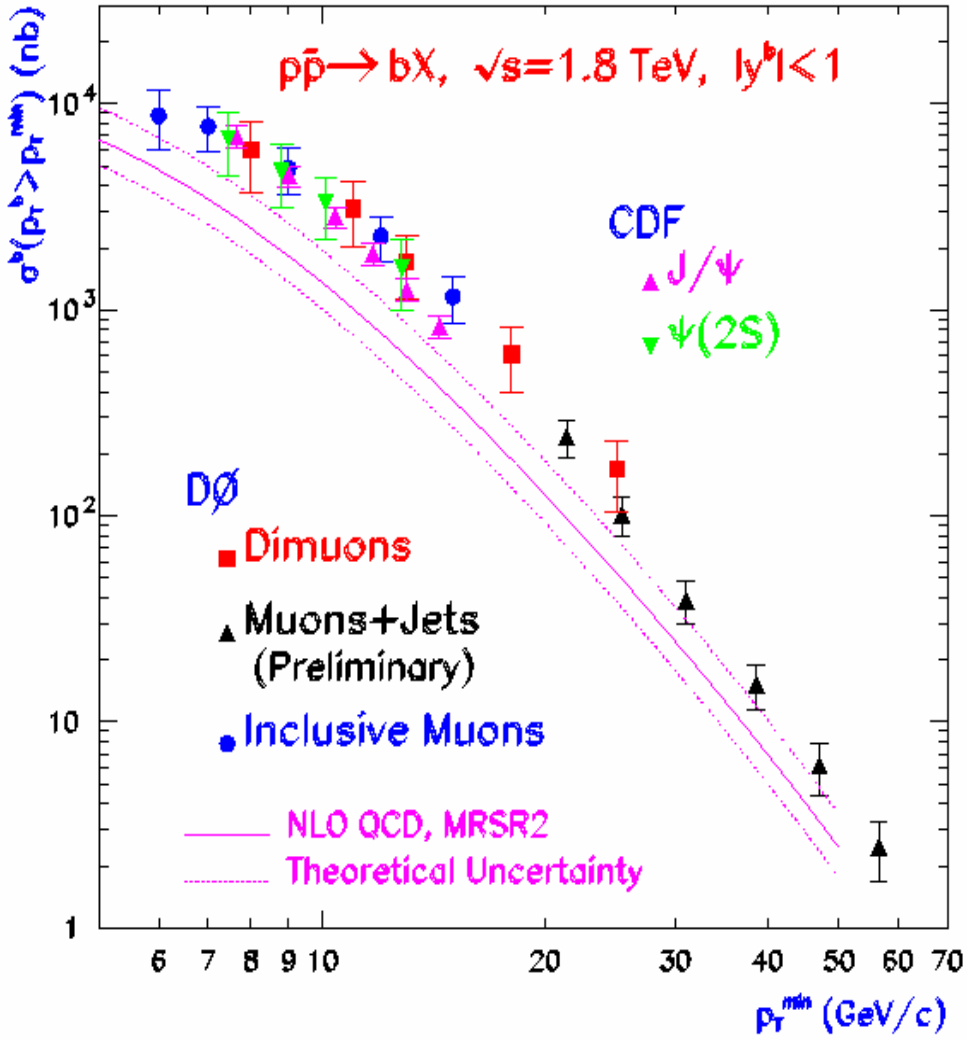


b hadron production mechanisms

- Physics objects: hadrons & leptons
  (NOT quarks & gluons)
- Quarks $\rightarrow$ hadrons: hadronization (fragmentation)
- QCD describes (well) quarks and gluons production
- Fragmentation: fenomenological models

  QCD "leading-log" Monte-Carlo models incorporate
  a. "string fragmentation" (color field collapse into string)
     PYTHIA
  b. "cluster fragmentation" (preconfinement of colour)
     HERWIG
  c. "independent fragmentation (Field & Feynman)"
     ISAJET

b hadron & B meson production cross section



CDF and D0 results with Peterson fragmentation function ε=0.006

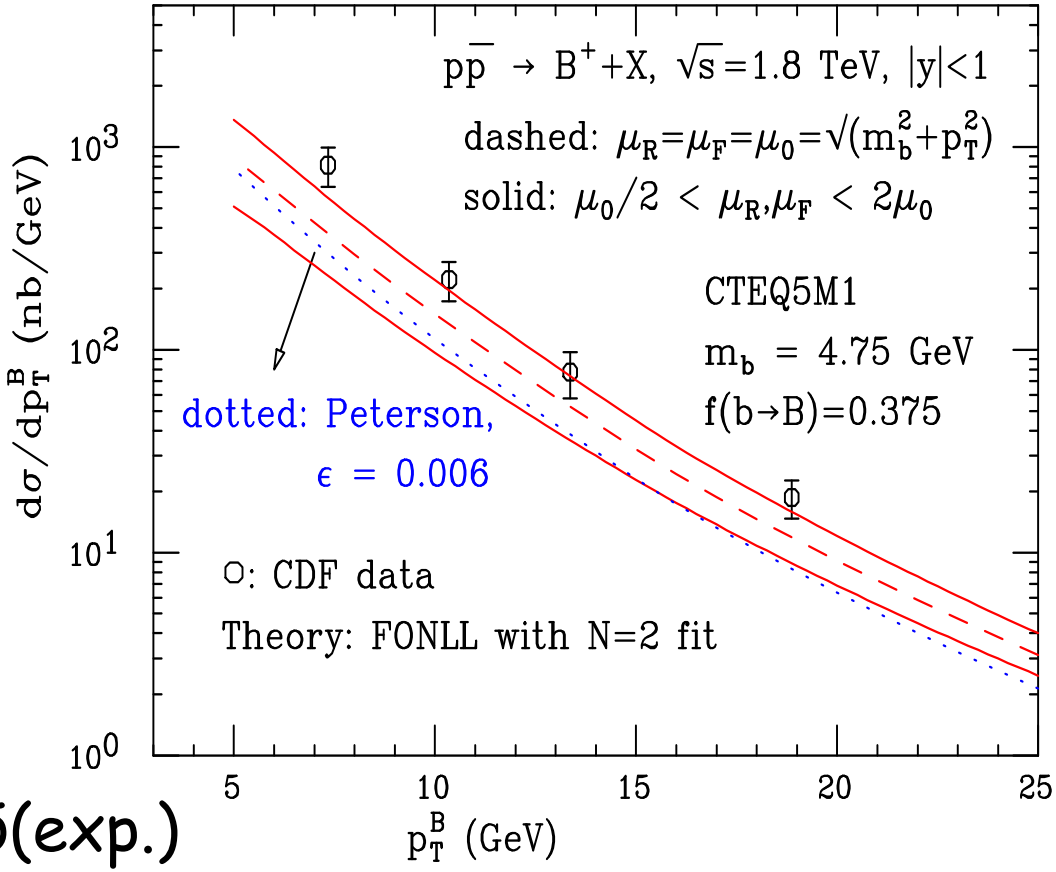
Theory:
Next to Leading Order

b hadron & B meson production cross section

Theoretical Improvements:

Resummation of next-to-leading logs and retuning of Peterson fragmentation ε=0.002

Cacciari, Nason
hep-ph/0204025



$$\frac{\text{Exp}}{\text{Theo}} = 1.7 \pm 0.5(\text{theo.}) \pm 0.5(\text{exp.})$$

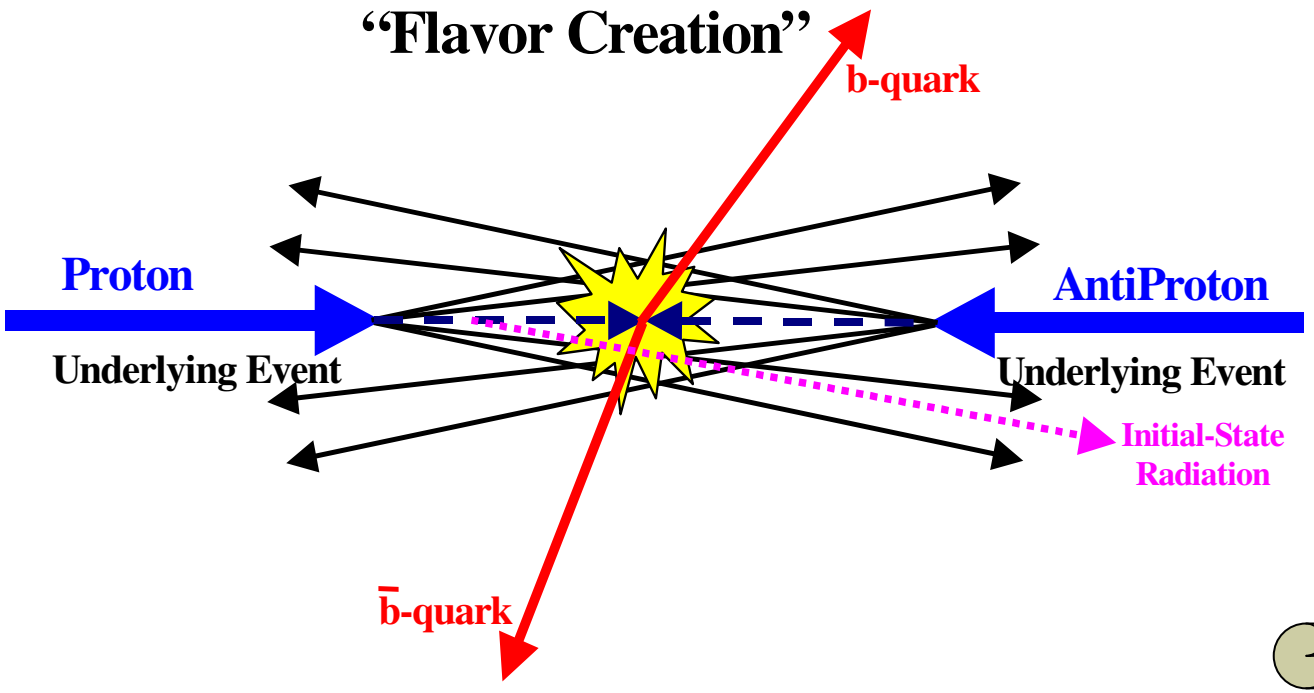
b hadron production at LO

At "leading-log" order three sources b-quarks:

"flavor creation",

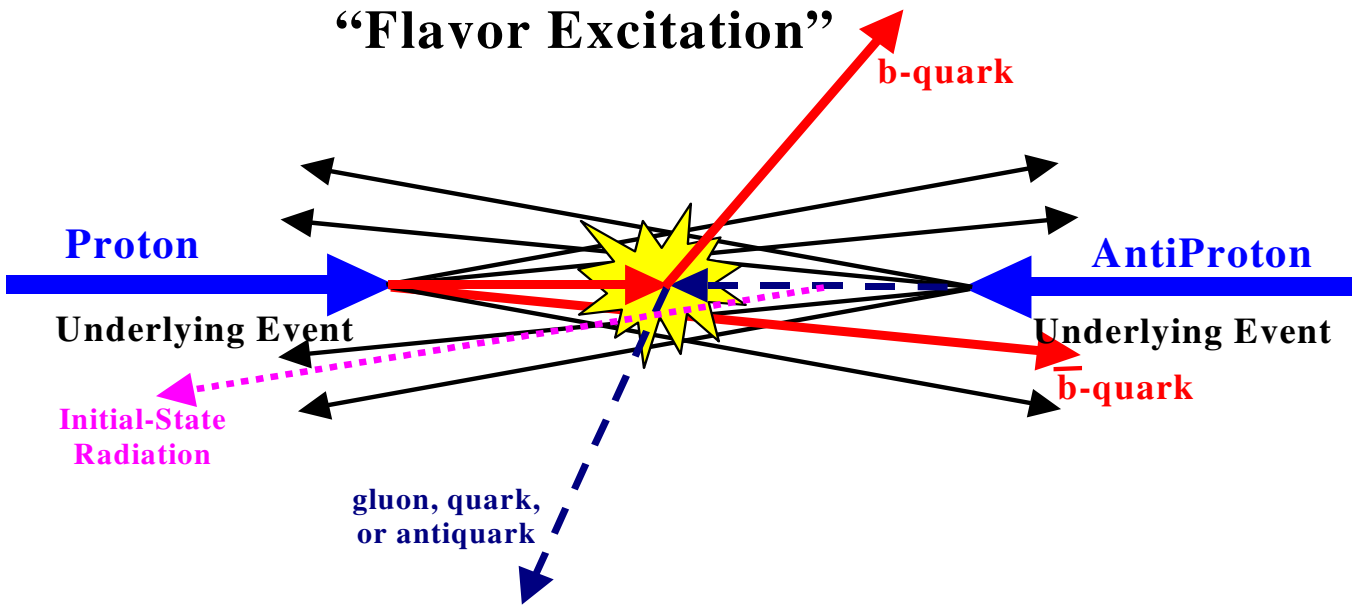
"flavor excitation",

"shower/fragmentation" (*i.e.* "gluon splitting").



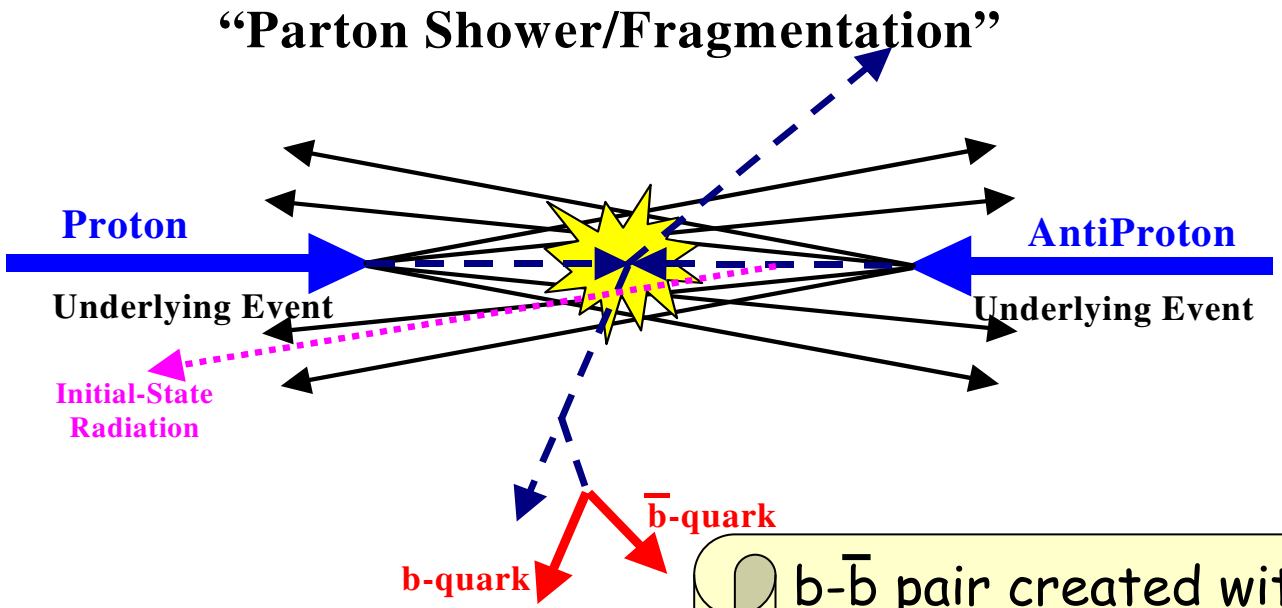
Flavor Creation: production of b-$\bar{b}$ pair by gluon fusion or by annihilation light quarks.

b hadron production at LO cont'd



Flavor Excitation :
scattering of b ($\bar{b}$)-quark out of the initial-state into the final-state by a gluon or by a light quark or antiquark.
Very sensitive to the number of b-quarks within the proton, *i.e.* the structure functions).

b hadron production at LO cont'd



b-$\bar{b}$ pair created within a parton shower or during the the fragmentation process of a gluon or a light quark or antiquark.
Here QCD hard 2-to-2 subprocess involves gluons and light quarks and antiquarks. It includes gluon splitting.

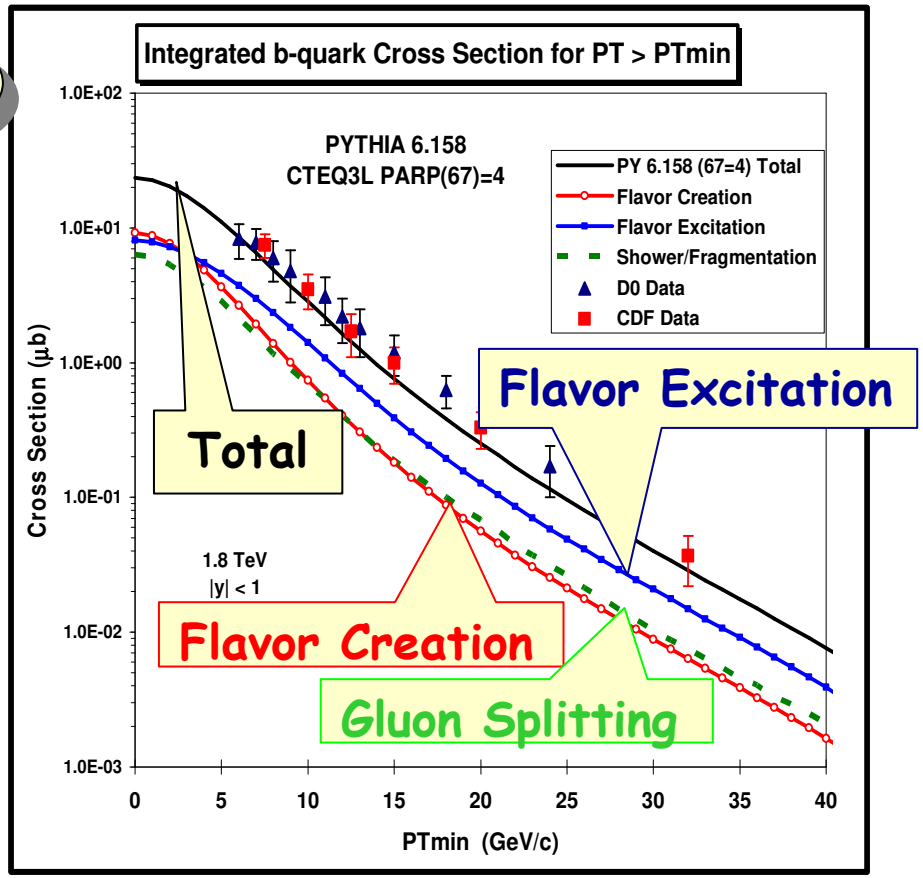
b hadron & B meson cross section:future

Merge matrix-element & parton-shower Monte Carlos to include all b production mechanisms and fragmentation

R. Field
Monte Carlo workshop
April, 30 2003

At the Tevatron:

- Precision tests of perturbative region ($p_t^2 >> mb^2$)
- Detailed exploration of non-perturbative region $d\sigma/dp_t$ ($b \rightarrow J/\psi$) down to $p_t(b)=0$

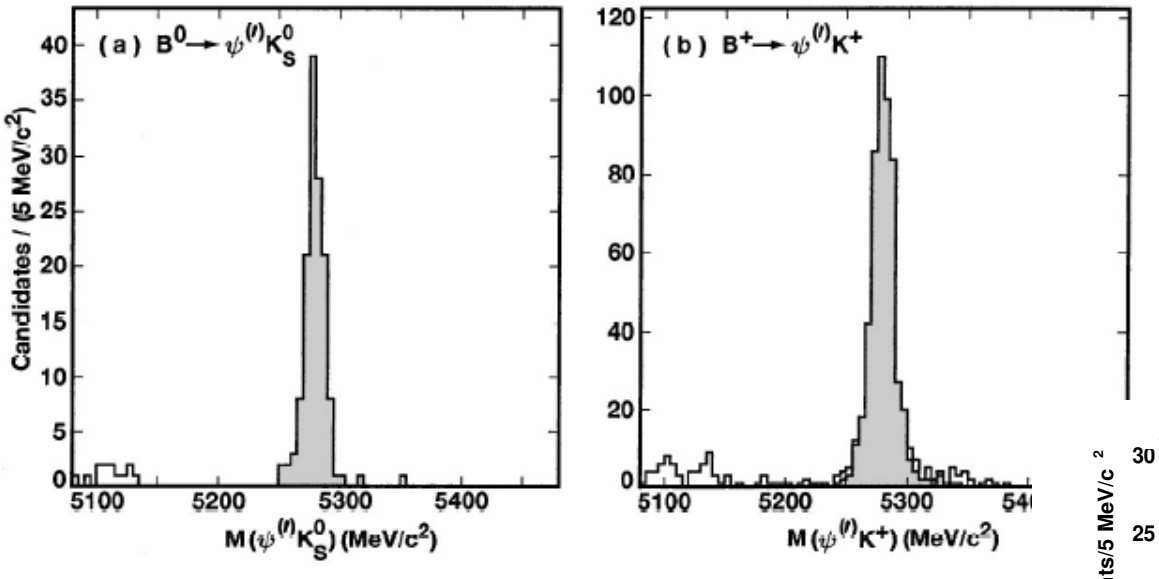


Mass Measurements

- Single heavy quark:
  described by Heavy Quark Effective Theory (HQET)
  - radiative corrections in expansions $\alpha_s(m_b)$ (perturbation theory)
  - non-perturbative corrections with an expansion in powers of Λ_{QCD}/m_b
- Two heavy quarks:
  determined by Non Relativistic Heavy Quark Effective Theory (NRHQET)

Mass Measurements

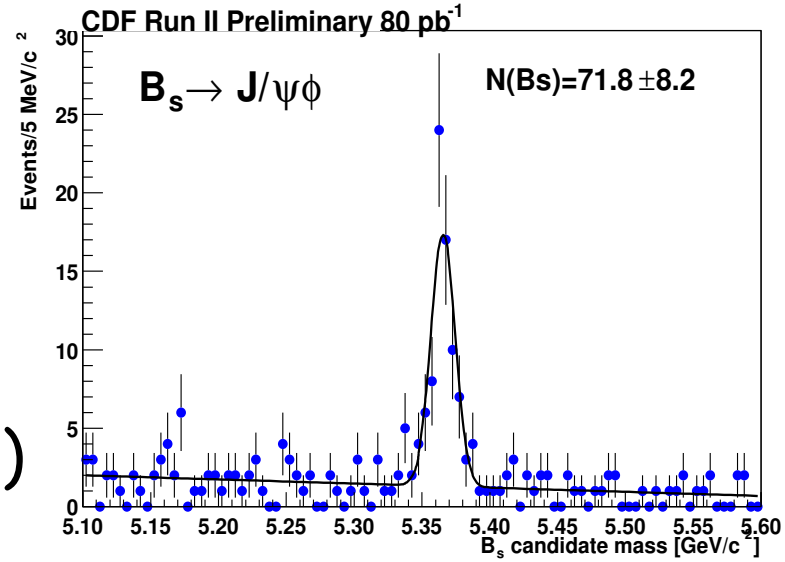
Need to fully reconstruct the decay



$B^0 \to \psi^{(\prime)} K^0_S$

$B^+ \to \psi(\prime) K^+$

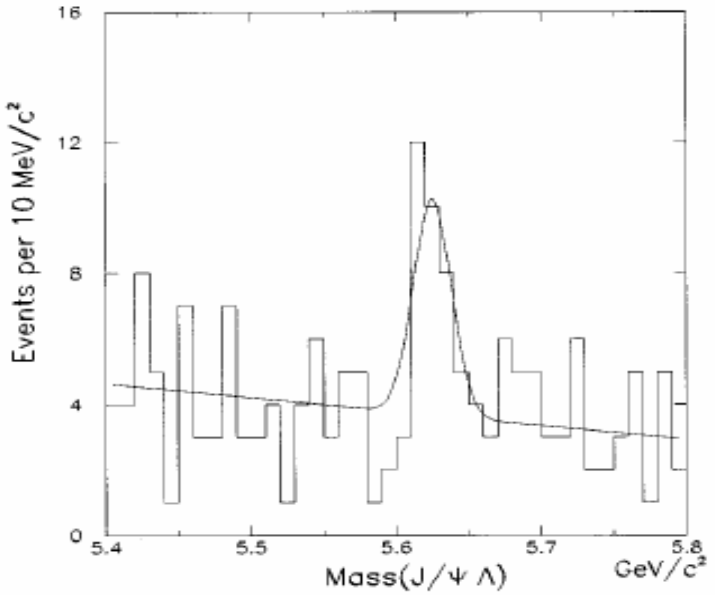
Cleo PRD61,111101



CDF $B \to J/\psi\varphi$:

$m(B_s)=5365.50 \pm 1.2(stat) \pm 0.94(syst)$

Mass Measurements



$\Lambda_b \rightarrow J/\psi\Lambda$

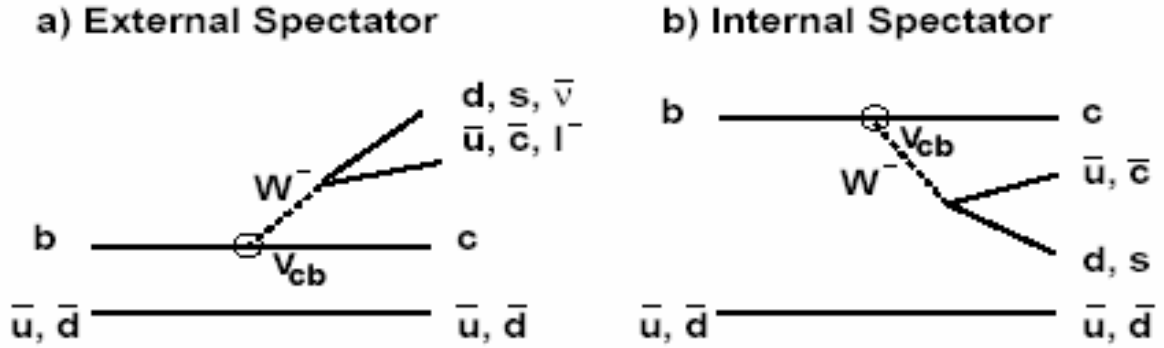
Summary

B^0	5279.4±0.5	PDG average
$B^{\pm}$	5279.0±0.5	PDG average
B^0_s	5369.6±2.4	PDG average
B_c	6.4±0.39±0.13	CDF measurement
Λ_b	5624±9	PDG average

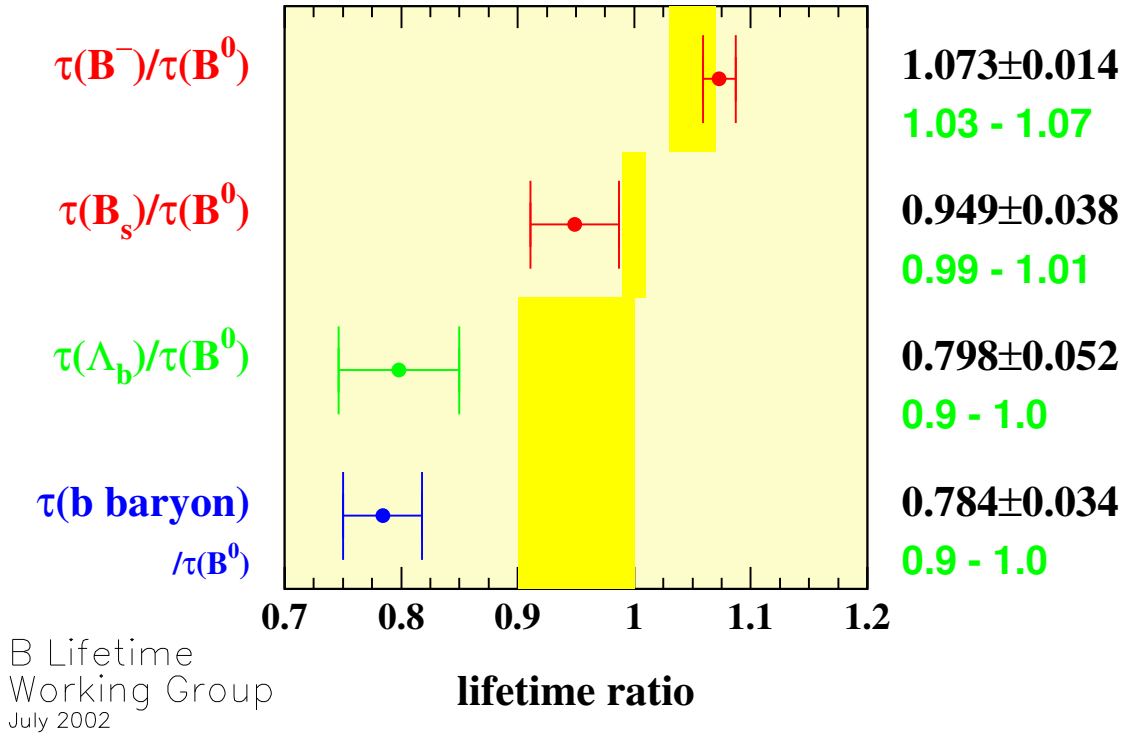
Lifetimes Determination: Theory

- Important for:
  - Mixing measurement
  - V_{cb} measurements
  - Test decay dynamics information on non perturbative QCD effects
- Described by HQET
- Leading order: spectator model

$$\tau(B_u)/\tau(B_d) = \tau(B_s)/\tau(B_d) = \tau(\Lambda_b)/\tau(B_d) = 1$$



Lifetimes Determination: Theory

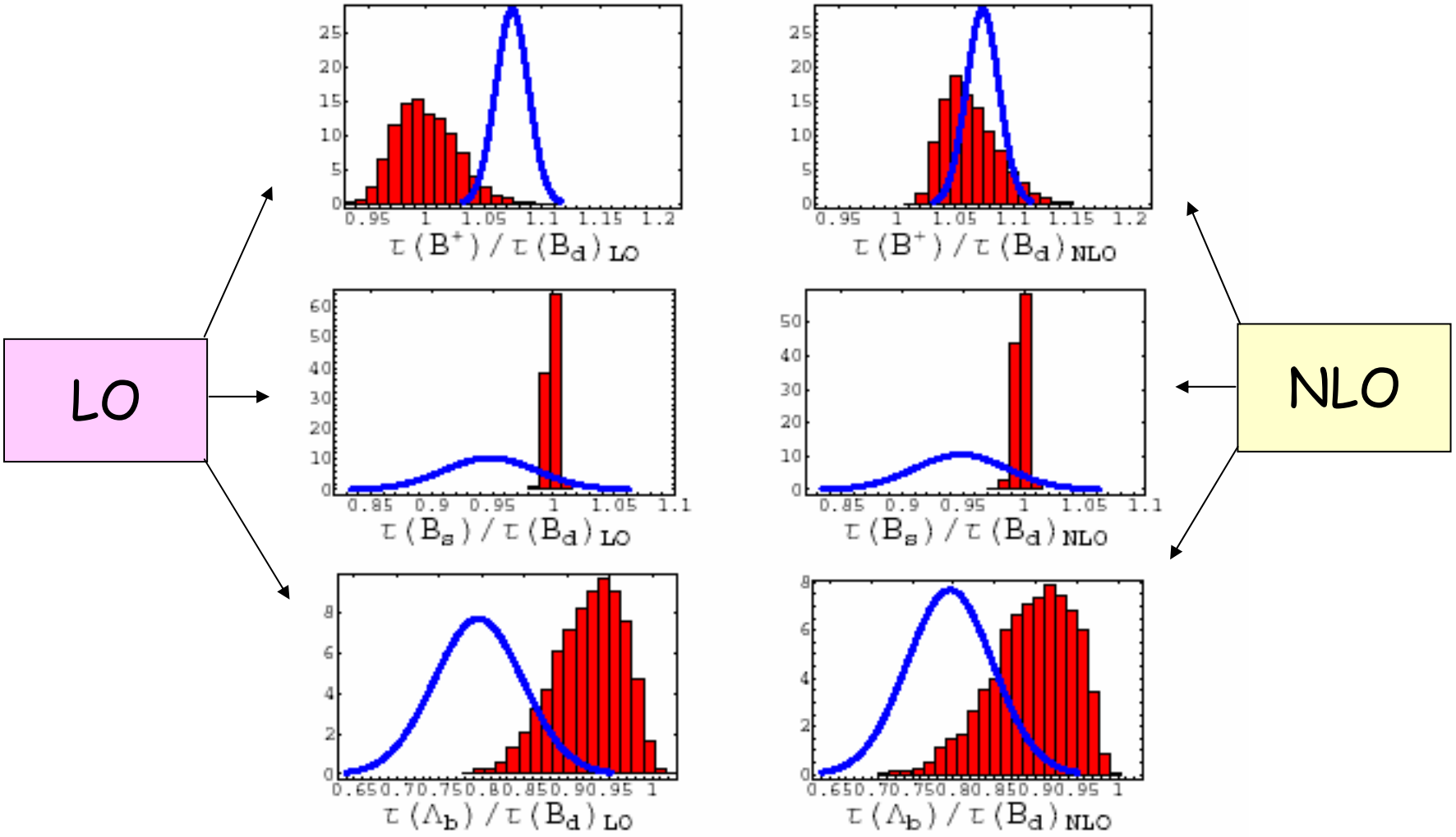


- To explain the large experimental differences hard spectator effects necessary, soft interactions contributes ≤ 2%

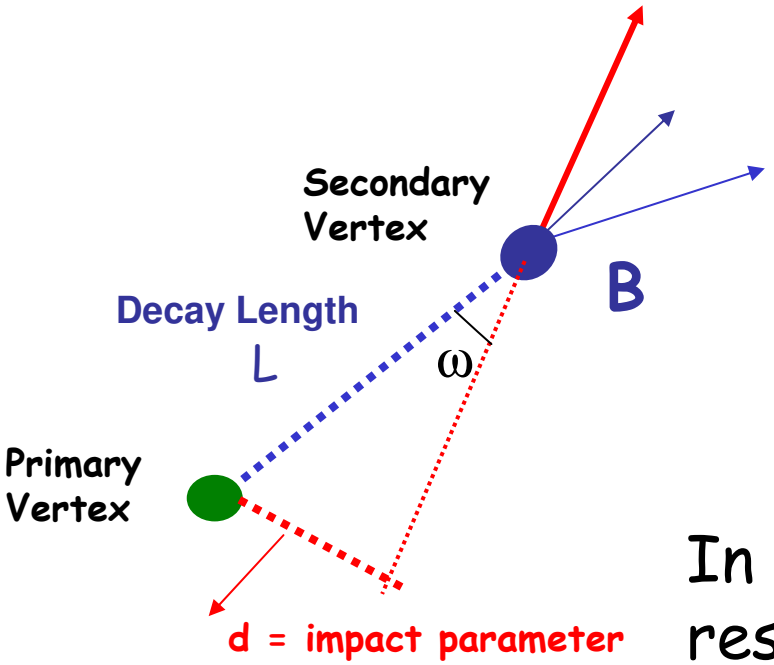
Lifetimes Determination: Theory

histogram → theory distribution

line → experimental distribution



Lifetimes: experimental techniques



Proper time

$L = \gamma\beta ct$

$\gamma\beta = p_B/m_B$

$ct = \dfrac{L \cdot m_B}{p_B}$

Needs:

1) Decay length
2) momentum

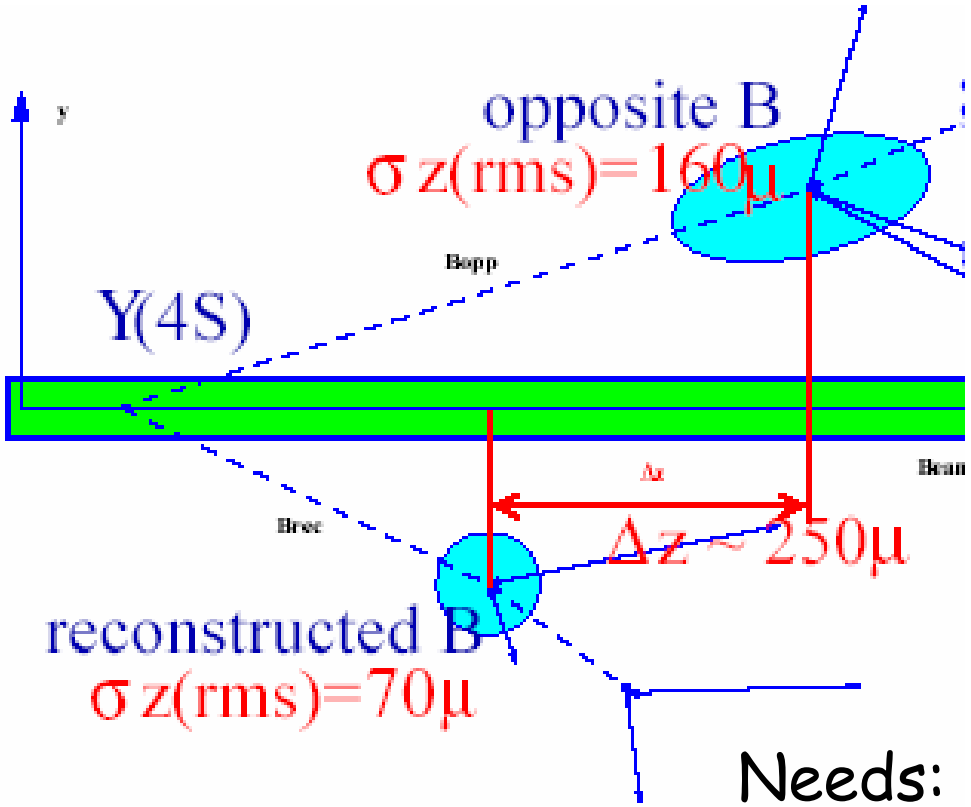
In the plane transverse respect to the beam line $ct = \dfrac{L^{xy} \cdot m_B}{p^t_B}$

First measurements done by using impact parameter:

$d^{xy} = \gamma\beta ct \cdot \sin\omega \qquad \sin\omega \sim \gamma^{-1} \qquad d^{xy} \approx ct$ (relativistic approx)

Finally fit the t distribution to extract τ_B

Lifetimes: experimental tecn. B factories



Y(4s)decays to pair of B's that travel along z axis

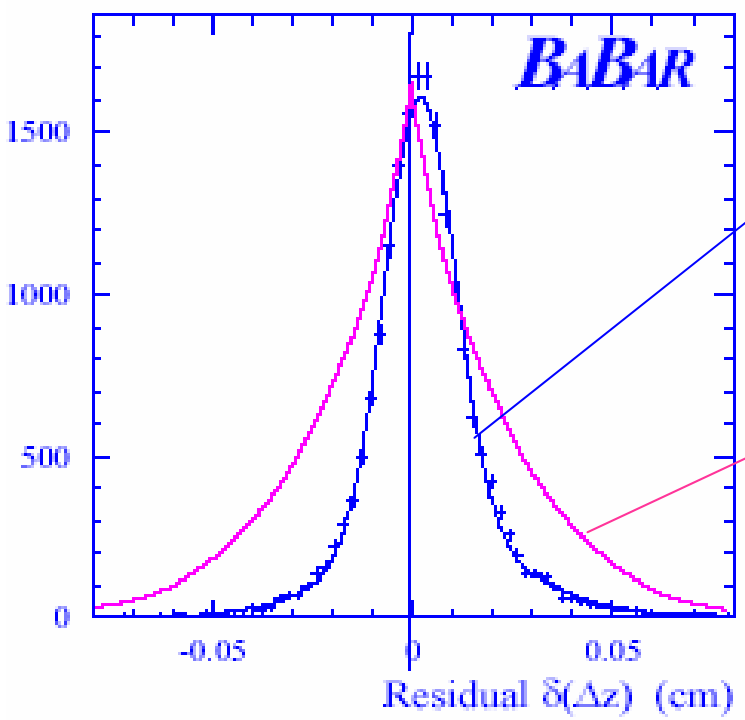
$$\Delta t = \frac{\Delta z \cdot m_B}{p_B}$$

Needs:

1. B fully reconstructed (p_B)
2. Other B partially reconstructed (i.e. one lepton to have z)

Lifetimes: experimental tecn. B factories

Main challenge: resolution factor and background



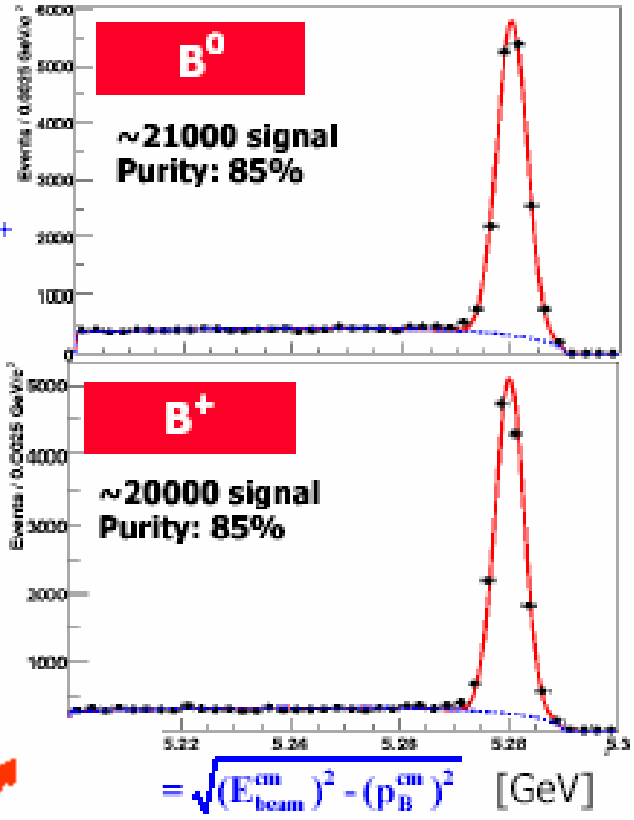
Resolution factor from Monte Carlo for fully Reconstructed hadronic B

For comparison: $\exp(\Delta z/250\mu m)$

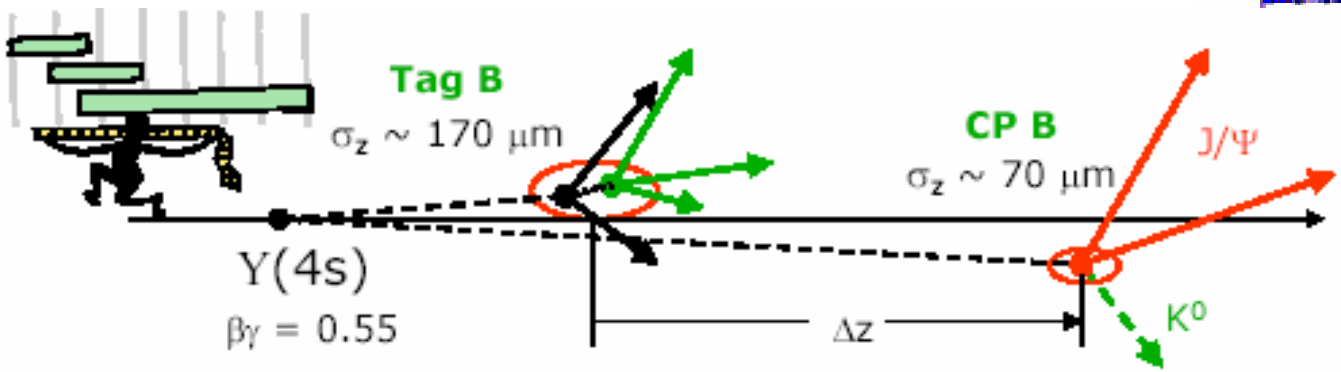
Lifetimes Measurements: exclusive

The Babar roadmap:

1. Fully reconstruct one B meson



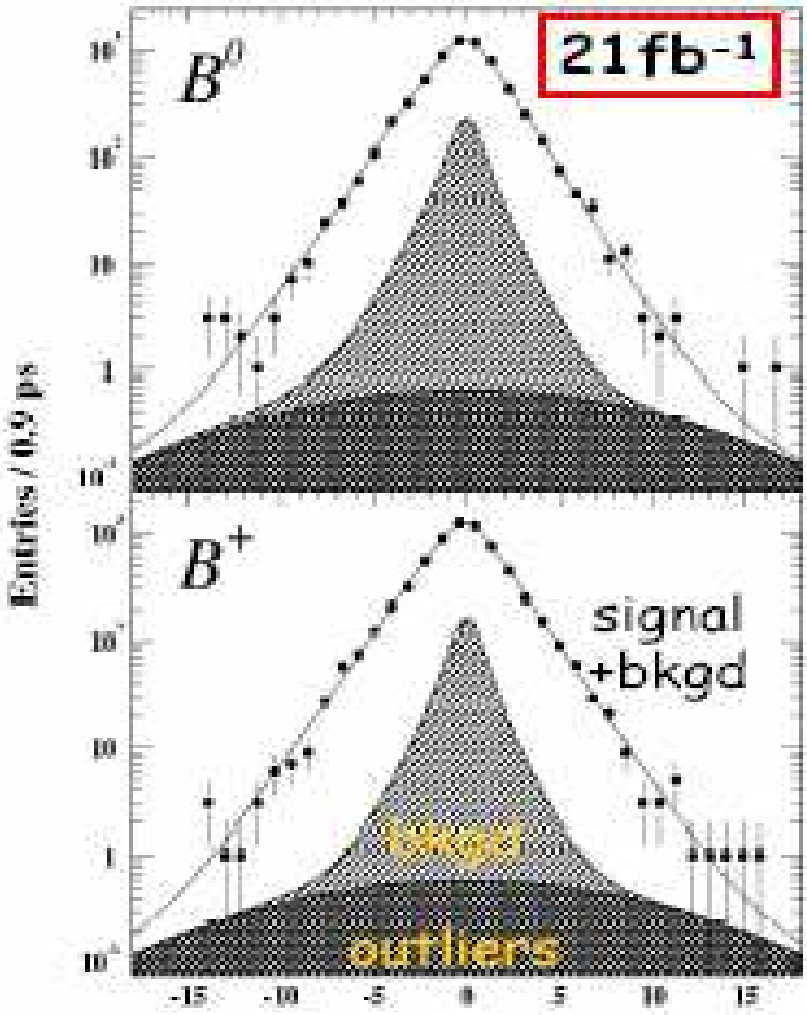
2. Reconstruct the decay vertex and the vertex of the other B



Lifetimes Measurements: exclusive

The Babar roadmap:

3. Compute the proper time difference Δt and fit the Δt spectra

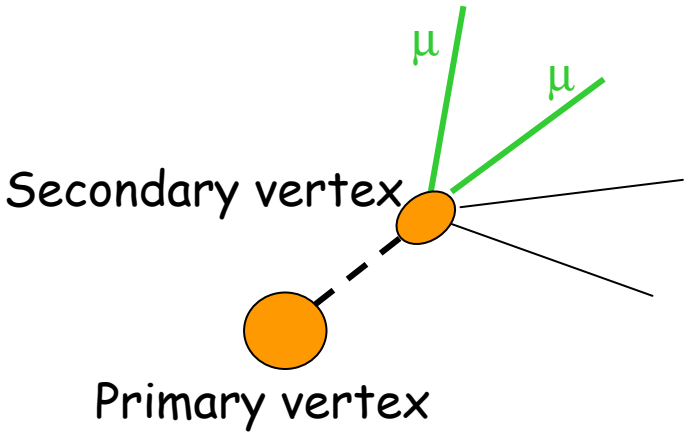


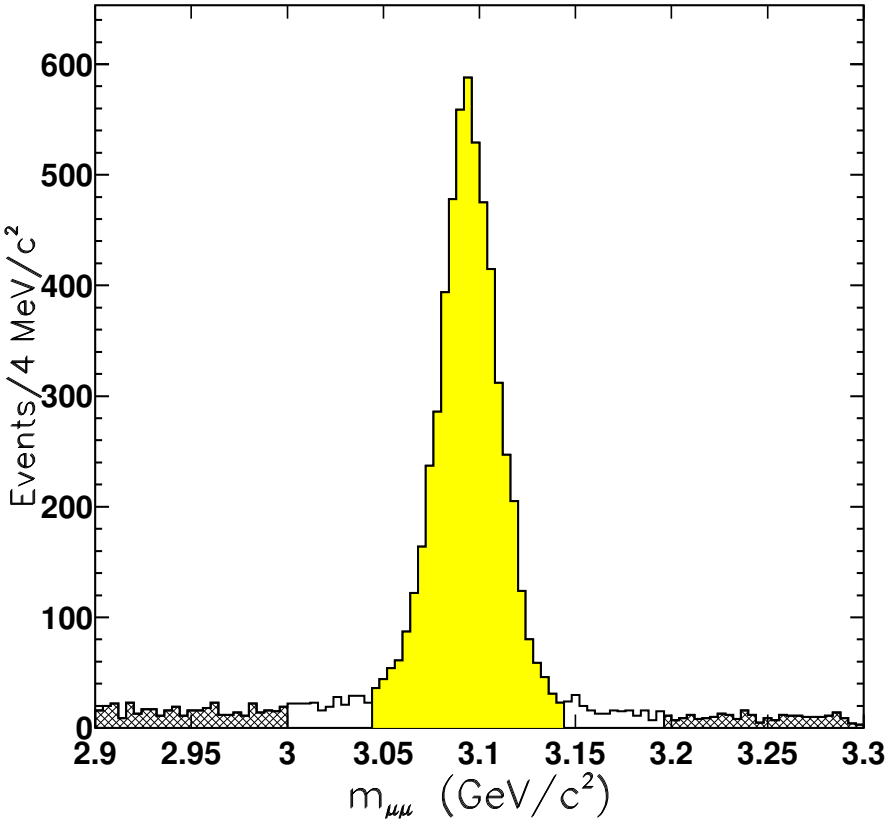
Lifetimes Measurements: inclusive

CDF roadmap:

1. Reconstruct the $J/\psi \rightarrow \mu\mu$

2. The J/ψ vertex is the B decay vertex



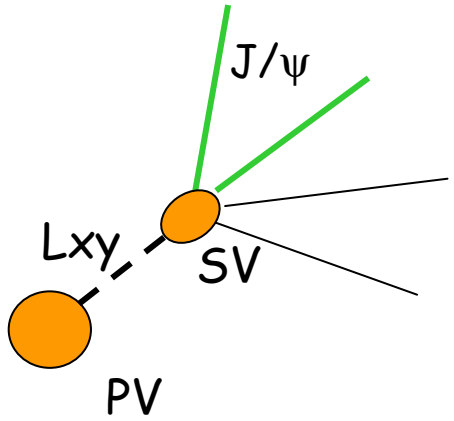


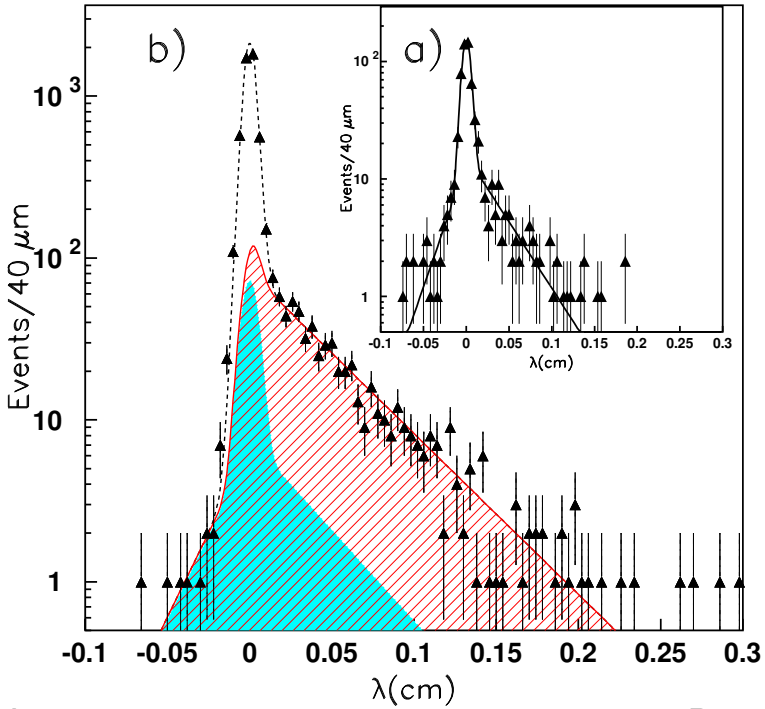
Lifetimes Measurements: inclusive

CDF roadmap:

3. $ct = \frac{Lxy\ m_B}{P_t^{J/\psi}} F^{corr}$

from Monte Carlo





4. Fit ct to extract the b lifetime

CKM Matrix Elements Introduction

- Charge currents D∈{d,s,b}, U∈{u,c,t}
- Possible transitions:

1st gen.	2nd gen.	3rd gen.	
$d \to u$	$s \to u$	$b \to u$	1st gen.
$d \to c$	$s \to c$	$b \to c$	2nd gen.
$d \to t$	$s \to t$	$b \to t$	3rd gen.

- Matrix coupling: Cabibbo-Kobayashi-Maskawa matrix

CKM Matrix Elements Introduction

- CKM matrix connects electroweak eigentstates (d', s', b') with their mass eigentstates (d, s, b)

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

- CKM matrix is unitary:

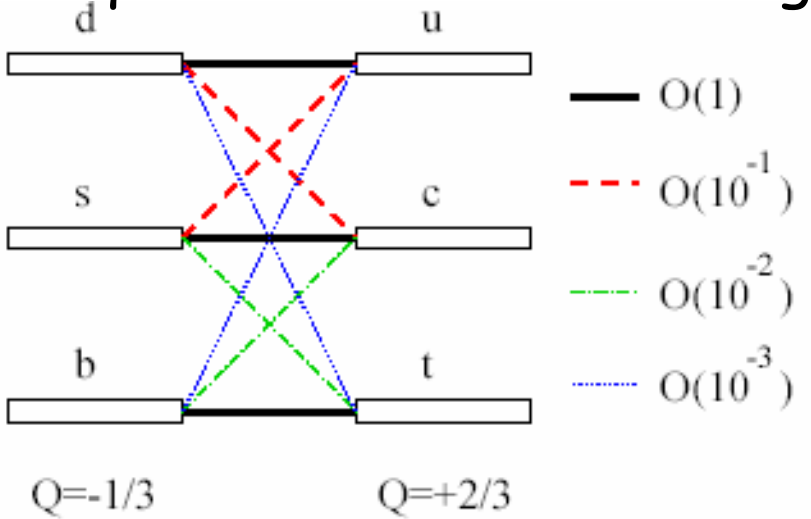
$$\hat{V}_{\mathrm{CKM}}^{\dagger} \cdot \hat{V}_{\mathrm{CKM}} = \hat{1} = \hat{V}_{\mathrm{CKM}} \cdot \hat{V}_{\mathrm{CKM}}^{\dagger}$$

- Phase structure of the CKM matrix:
  4 parameters = 3 Euler angles + 1 complex phase

CP violation

CKM Matrix: Wolfenstein Parametrization

- Hierarchy of quark transitions through charged currents



- Hierarchy explicit in the Wolfenstein parametrization

$$\hat{V}_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\,\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$\lambda \equiv |V_{us}| = 0.22$ A, η and ρ are the order 1

CKM Matrix: Unitarity triangles

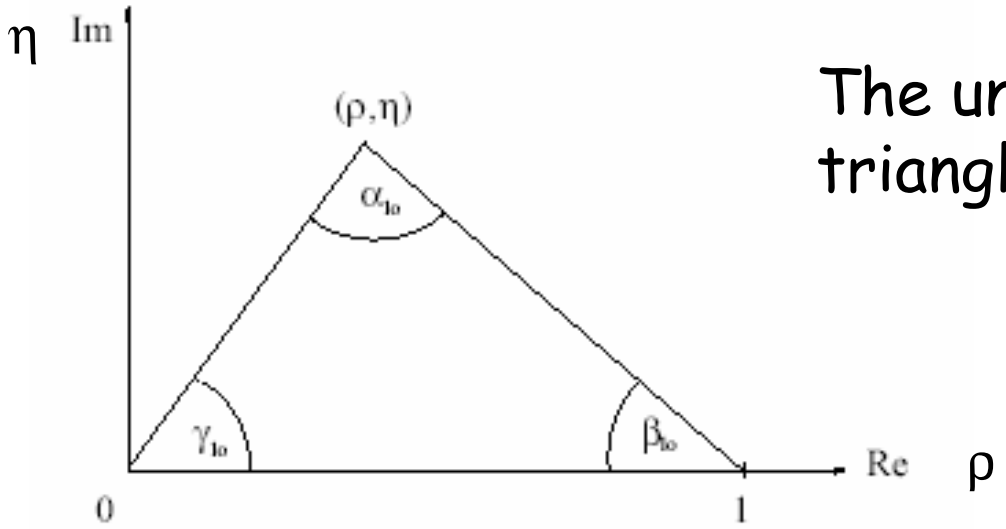
- The unitarity ⇒ 6 orthogonality relations ⇒ 6 triangles
- Triangles are very squashed, with the exception of two:

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0 \quad (1^{st} \text{ and } 3^{rd} \text{ column})$$

$$V^*_{ub}V_{tb} + V^*_{us}V_{ts} + V^*_{ud}V_{td} = 0 \quad (1^{st} \text{ and } 3^{rd} \text{ row})$$

- Two non-squashed triangles agree at leading order in λ:

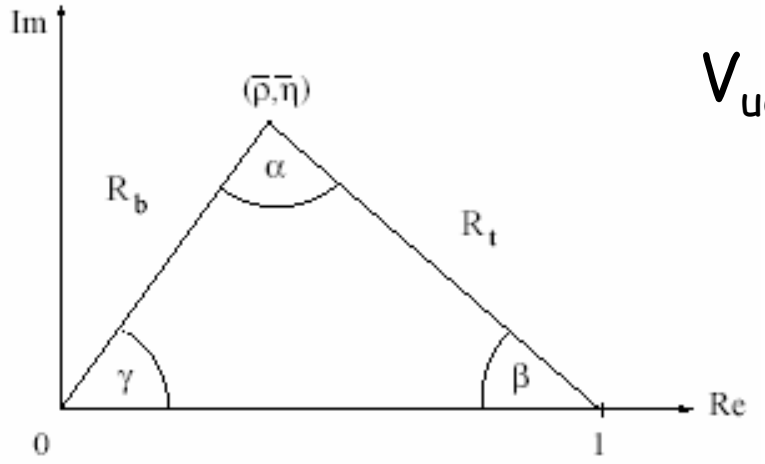
$$(\rho + i\eta)A\lambda^3 + (-A\lambda^3) + (1-\rho-i\eta)A\lambda^3 = 0$$



The unitarity triangle

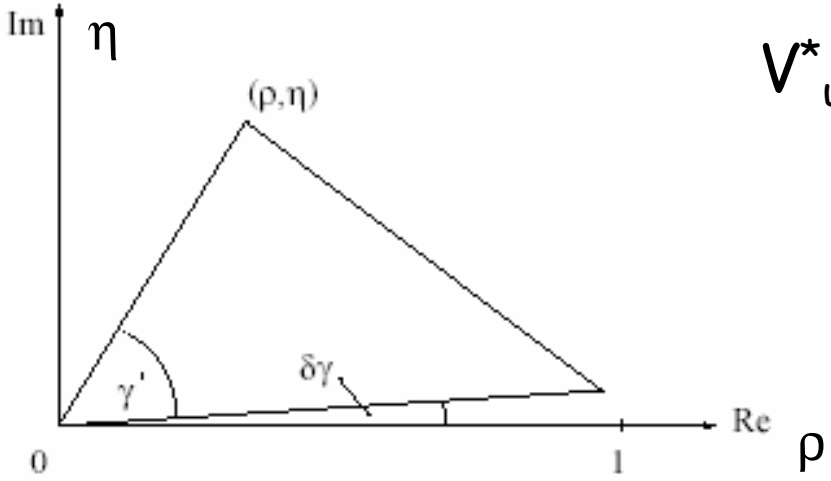
CKM Matrix: Unitarity triangles

- The unitarity triangles at next-to-leading order in λ:



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

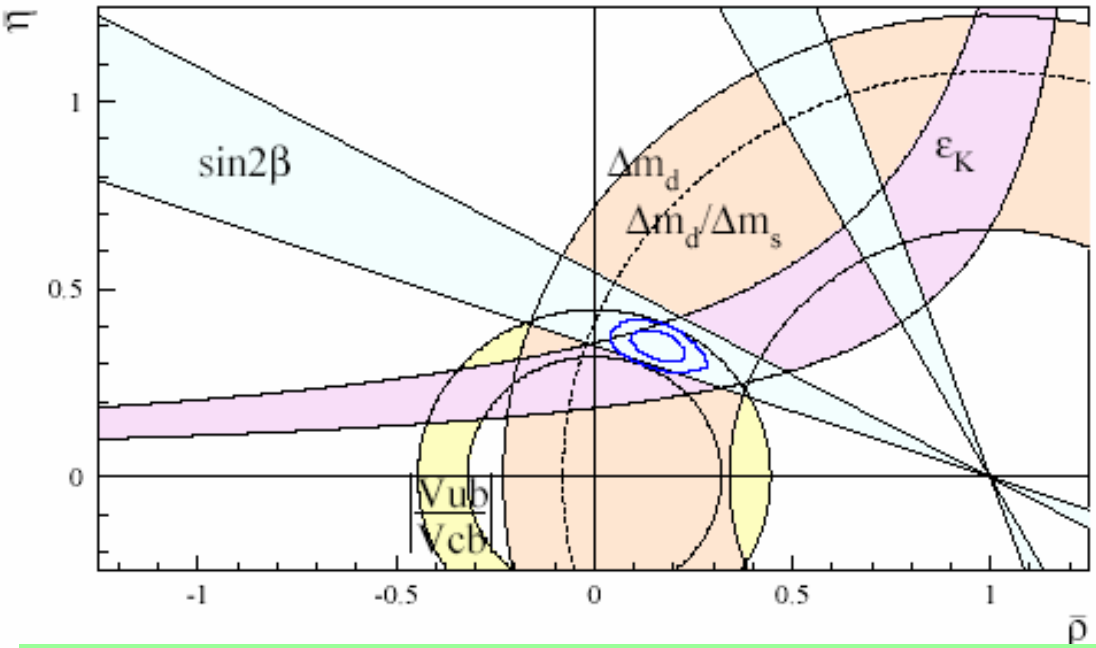
$$\bar\rho \equiv (1-\lambda^2/2)\rho$$
$$\bar\eta \equiv (1-\lambda^2/2)\eta$$



$$V^*_{ub}V_{tb} + V^*_{us}V_{ts} + V^*_{ud}V_{td} = 0$$

$$\delta\gamma = \gamma - \gamma' \qquad \delta\gamma = \lambda^2\eta = O(1^o)$$

The big picture: CKM & Standard Model



Results:

$\bar{\rho} = 0.162 \pm 0.046$

$\bar{\eta} = 0.347^{+0.029}_{-0.026}$

$\sin 2\beta = 0.705 \pm 0.035$

$\sin 2\alpha = -0.13^{+0.28}_{-0.23}$

$\gamma = 64.5^{+7.5}_{-6.5}$

Test of the CP picture of Standard Model:
$\sin 2\beta = 0.658 \pm 0.054$ (CKM fit excluding $\sin 2\beta$ and ε_K)
$\sin 2\beta = 0.734 \pm 0.055$ (direct measurement)

Δm_s predictions:
$\Delta m_s = 20.9^{+3.9}_{-4.3}$ ps^{-1}

CKM Matrix: Sides

$|V_{cb}|$ normalizzation of unitarity triangle:

- Exclusive modes: $B \to D^* l \nu_l$

HQET $\Rightarrow$ $\frac{d\Gamma}{dy} = \underbrace{K(y)}_{\text{known}} F(y)^2 |V_{cb}|^2$ $(y = v_B \cdot v_{D^*})$

Contains kinematic factors

Form factor for $B \to D^*$ transitions

$$F(1) = 1 + \mathcal{O}(\alpha_s/\pi) + \delta_{1/m_b^2} + \delta_{1/m_b^3}$$

- Inclusive modes: $B \to X_c l \nu_l$

HQE $\Rightarrow$ $\Gamma_{\rm SL} \propto |V_{cb}|^2 \left[1 + \frac{0}{m_b} + \mathcal{O}(\alpha_s^2 \beta_0) + \mathcal{O}(1/m_b^2)\right]$

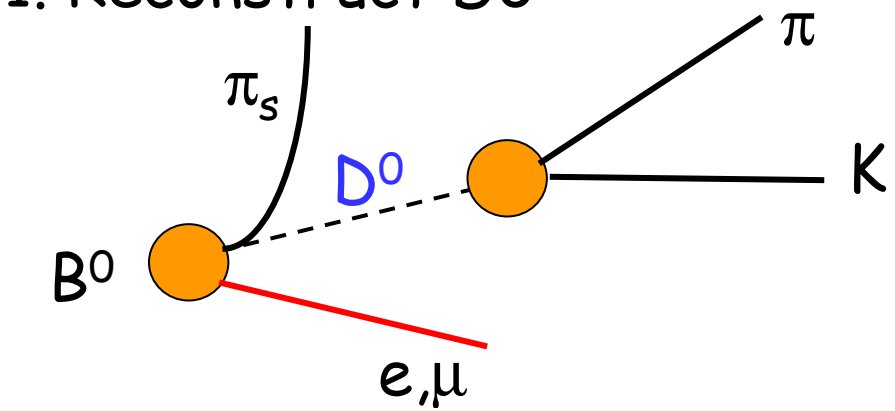
$|V_{cb}|$ measurement: exclusive decays

Plan: Measure $d\Gamma/dy$ and extrapolate to $y=1 \Rightarrow F(1)|Vcb|$

$y = v_B \cdot v_{D^*} = (m^2_B + m^2_{D^*} - q^2)/2m_B m_{D^*}$ $\quad q^2=(p_l+p_\nu)^2= (p_B - p_{D^*})^2$

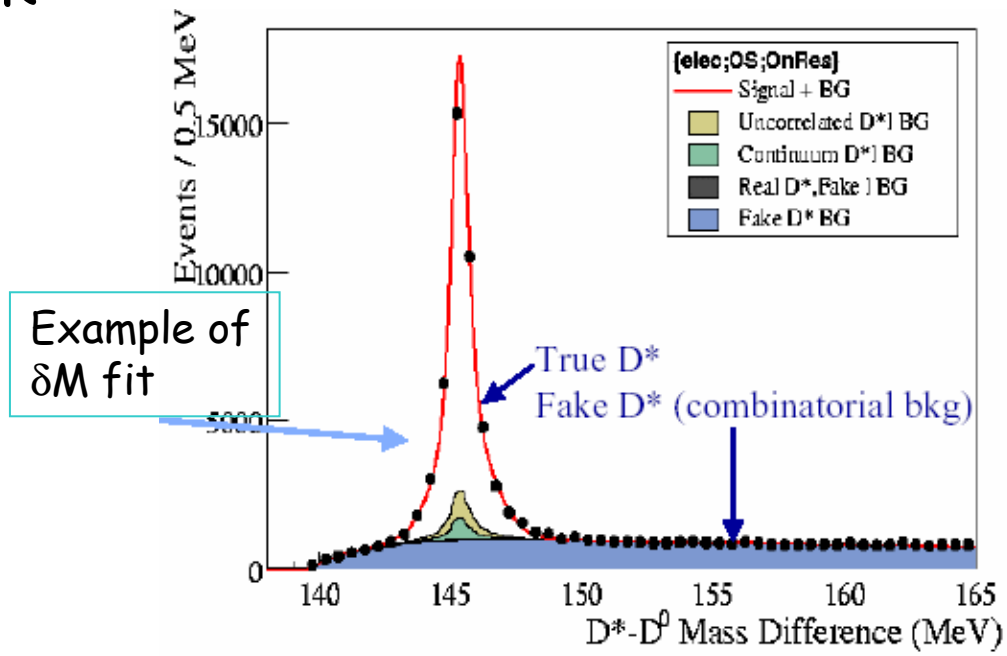
$y=1$ no D^* recoil

1. Reconstruct D0

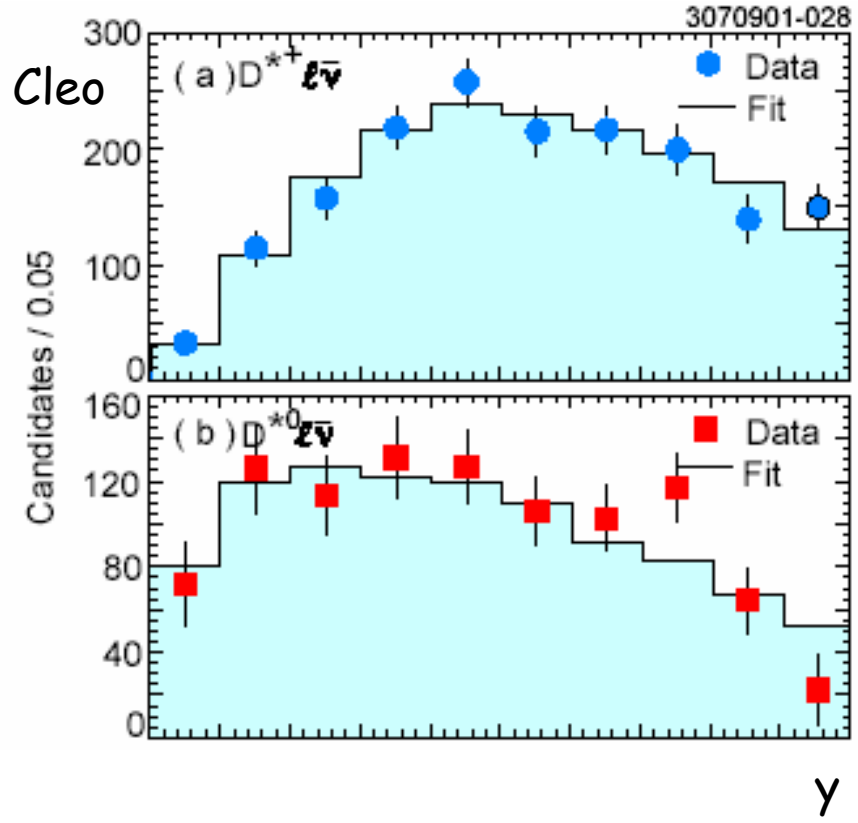


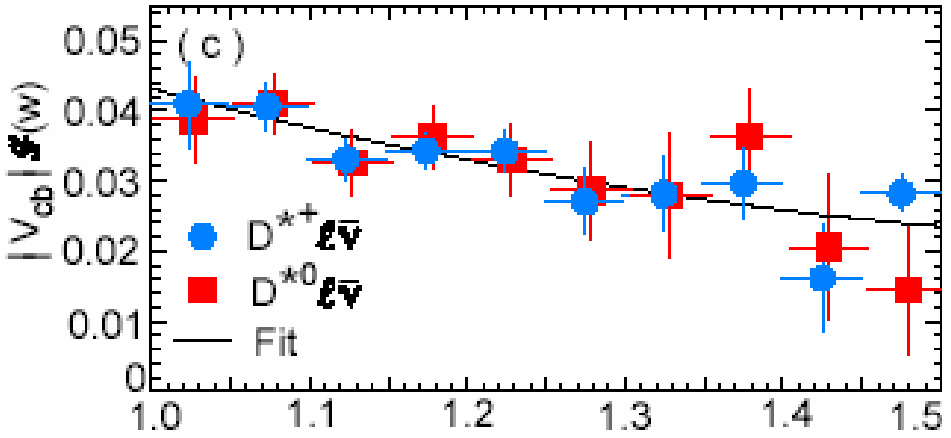
Decay mode	BR (%)
$D^{*\pm} \to D^0\pi^\pm$	67.7 ± 0.5
$D^0 \to K\pi$	3.80 ± 0.09
$D^0 \to K_s\pi\pi$	2.96 ± 0.18
$D^0 \to K\pi\pi^0$	13.1 ± 0.9
$D^0 \to K\pi\pi\pi$	7.46 ± 0.31

2. δM=M(D*)-M(D0) to fit signal and background



$|V_{cb}|$ measurement: exclusive decays





Parametrization form factor F(y) as function of the slope ρ (Caprini, Lellouch, Neubert)

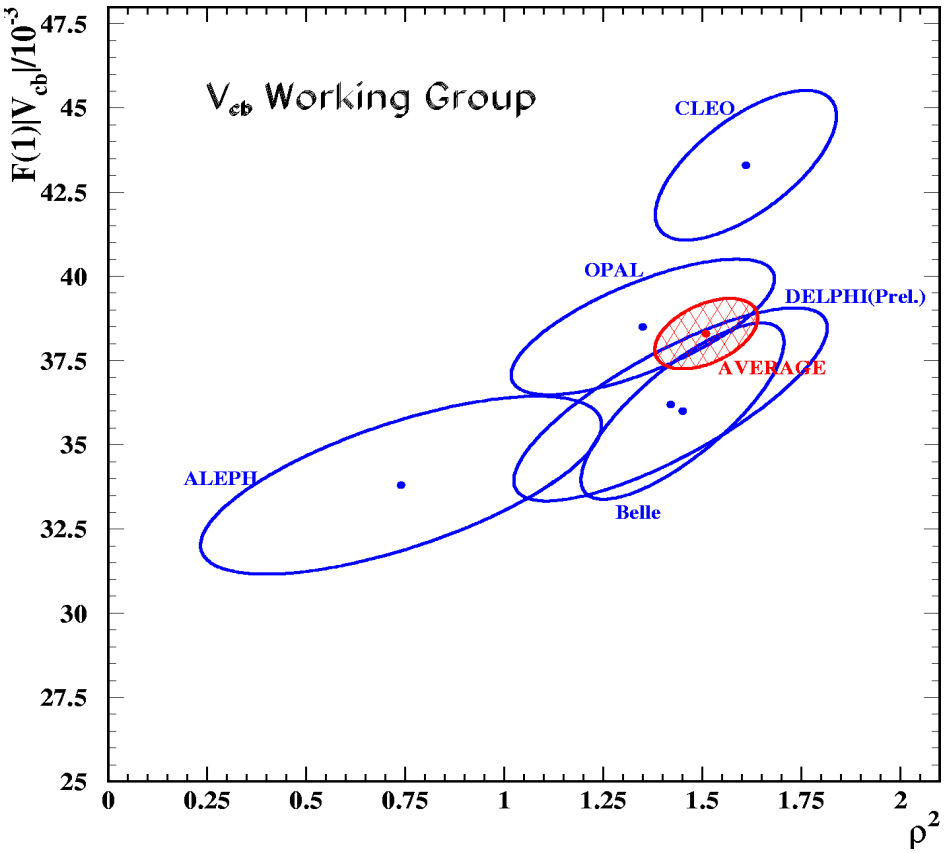
Theory: F(1) = 0.91±0.04

$F(1)|V_{cb}| = (43.1 \pm 1.3 \pm 1.8) \times 10^{-3}$ (intercept)

$\rho^2 = 1.61 \pm 0.09 \pm 0.21$ (slope at y=1)

$|V_{cb}| = (47.4 \pm 1.4 \pm 2.0 \pm 2.1) \times 10^{-3}$

$|V_{cb}|$ World average



PDG '03

$F(1)|Vcb| = (38.8 \pm 0.5_{(stat.)} \pm 0.9_{(sys.)}) \times 10^{-3}$

$\rho^2 = 1.49 \pm 0.05_{(stat.)} \pm 0.14_{(sys.)}$

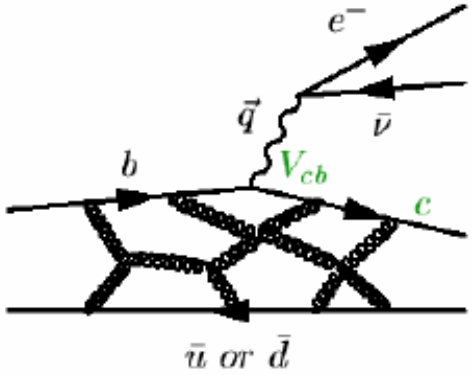
Using $F(1)=0.91 \pm 0.04$

$$|Vcb| = (42.6 \pm 0.6_{(stat)} \pm 1.0_{(sys)} \pm 2.1_{(th.)}) \times 10^{-3}$$

$|V_{cb}|$ measurement: inclusive decays

$$\sum_i \Gamma(\bar{B} \to X_c^{(i)} \ell \bar{\nu}) = \Gamma(b \to c \ell \bar{\nu}) \propto |V_{cb}|$$

Relay on theoretical assumptions



Use other observables:

- lepton energy spectrum
- hadronic recoil mass

Use theory to calculate semileptonic decay rate:

$$\Gamma_{SL} = \frac{G_F^2 |V_{cb}|^2 M_B^5}{192\pi^3} \left[\mathcal{G}_0 + \frac{1}{M_B}\mathcal{G}_1(\bar{\Lambda}) + \frac{1}{M_B^2}\mathcal{G}_2(\bar{\Lambda}, \lambda_1, \lambda_2) + \frac{1}{M_B^3}\mathcal{G}_3(\bar{\Lambda}, \lambda_1, \lambda_2 | \rho_1, \rho_2, \mathcal{T}_1, \mathcal{T}_2, \mathcal{T}_3, \mathcal{T}_4) + \mathcal{O}\left(\frac{1}{M_B^4}\right) \right]$$

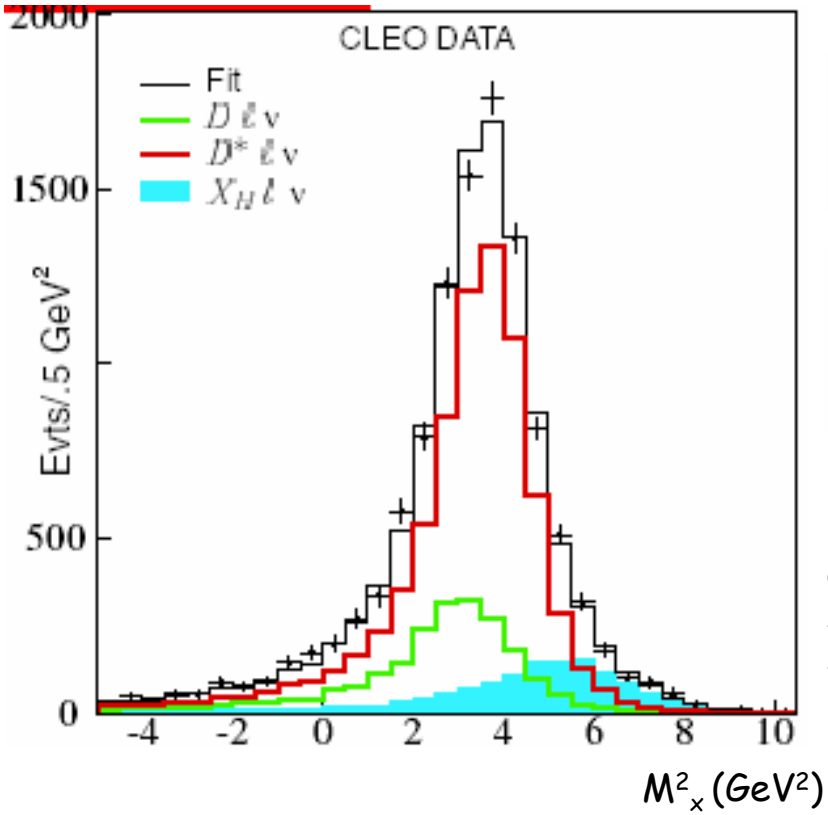
and moments of decay spectra $B \to X_c l\nu$: $\langle E_l \rangle$ $\langle E_l^2 \rangle$ $\langle M_X^2 \rangle$

$\bar{\Lambda} \approx M_B - m_b$ pole b mass λ_1 = kinetic energy of b quark in B meson Fermi motion

λ_2 = hyperfine interaction of b spin with light d.o.f.

ρ $\mathcal{T}$ other parameter less intuitive

$|V_{cb}|$ inclusive decays: M^2_X moments



$$M_X^2 = M_B^2 + M_{\ell\nu}^2 - 2E_B E_{\ell\nu} + 2|p_B||p_{\ell\nu}|\cos\theta_{\ell\nu,B}$$
$$\approx \widetilde{M_X^2} = M_B^2 + M_{\ell\nu}^2 - 2E_B E_{\ell\nu}$$

$$\langle M_X^2 - \overline{M_D}^2 \rangle = 0.251 \pm 0.023 \pm 0.062 \text{ GeV}^2$$
$$\langle (M_X^2 - \overline{M_D}^2)^2 \rangle = 0.639 \pm 0.056 \pm 0.178 \text{ GeV}^4$$

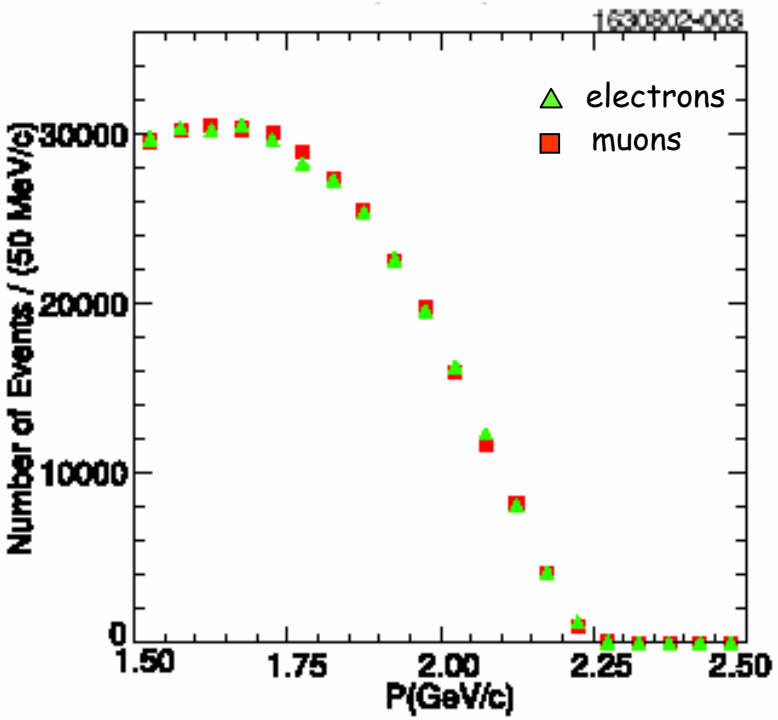
Combine $Br(B \to X_c l\nu) = (10.39 \pm 0.46)\%$ and τ_B to find
$\Gamma_{sl} = (0.427 \pm 0.020) \times 10^{-10}$ MeV

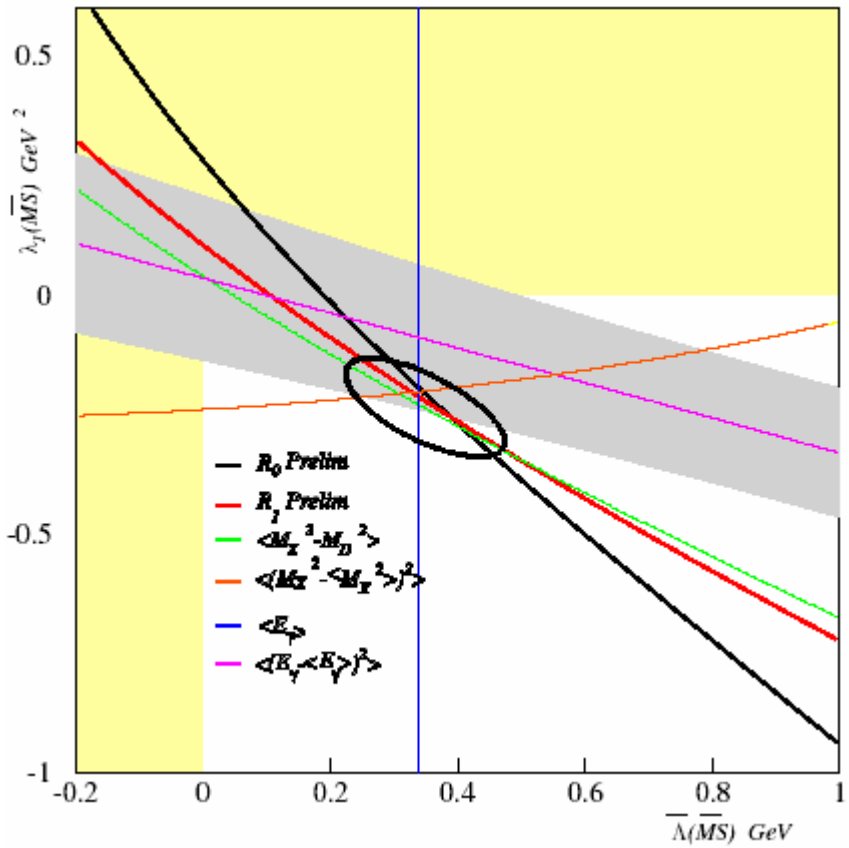
Add $\overline{\Lambda}$ and λ_1 to find:

$$|V_{cb}| = (40.4 \pm 0.5 \pm 0.9 \pm 0.8) \times 10^{-3}$$
M Γ τ

$|V_{cb}|$ inclusive decays: E_l moments

E_l sensitive to $\overline{\Lambda}$ and λ_1 Generalized energy moments R_0 and R_1





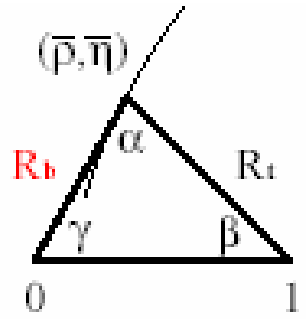
$|V_{cb}|$ Summary

Measurement	$\|V_{cb}\| \times 10^3$	$\delta_{V_{cb}}/V_{cb}$
CLEO $\bar{B} \to D^* \ell \bar{\nu}$	$(47.4 \pm 2.4 \pm 2.1)$	6.7%
$\|V_{cb}\|$ WG Average $\bar{B} \to D^* \ell \bar{\nu}$	$(42.0 \pm 1.2 \pm 1.8)$	5.2%
CLEO $\bar{B} \to X_c \ell \bar{\nu}$	$(40.4 \pm 1.0 \pm 0.8)$	3.2%

Inclusive measurements more precise but dependent on theory to determine non-perturbative parameters

CKM Matrix: Sides

$|V_{ub}|$ side R_b of triangle

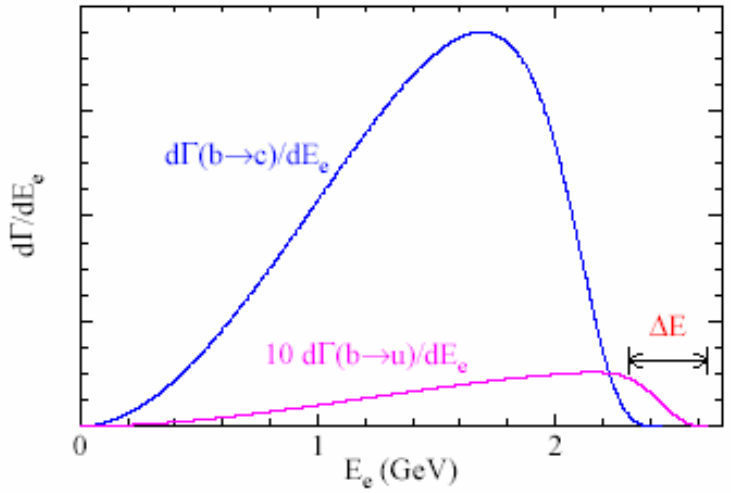


§ Exclusive modes: $B\to\pi l\nu$ $B\to\rho l\nu$

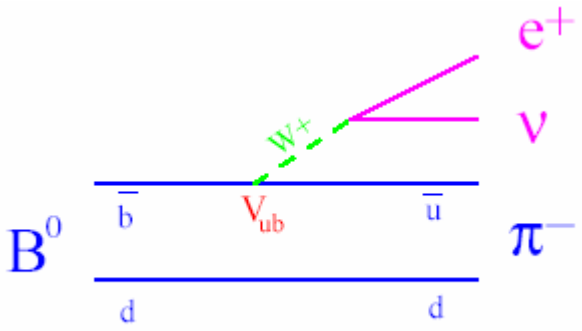
HQET does not work → form factors [→ models]

§ Inclusive modes: $B \to X_u l\, \nu_l$ (charmless B decay)

- Theoretically relatively simple
- Experimentally challenging, large background $b\to c l\nu_l$



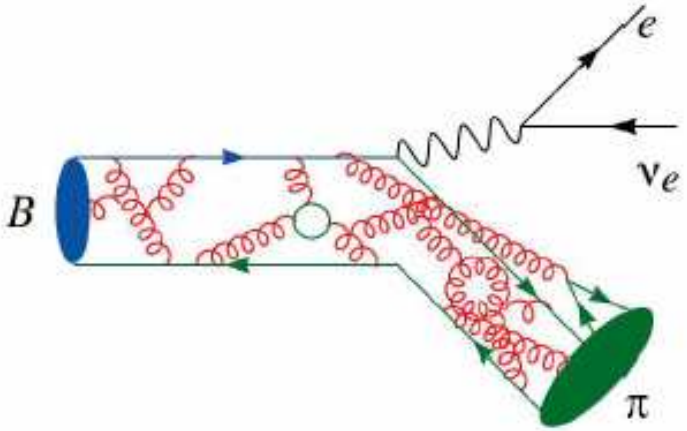
$|V_{ub}|$ measurement: exclusive decays



$$\Gamma(b \to u\ell\nu) \approx \frac{G_F^2 m_b^5}{192\pi^3}|V_{ub}|^2$$

Rate gives $|V_{ub}|^2$

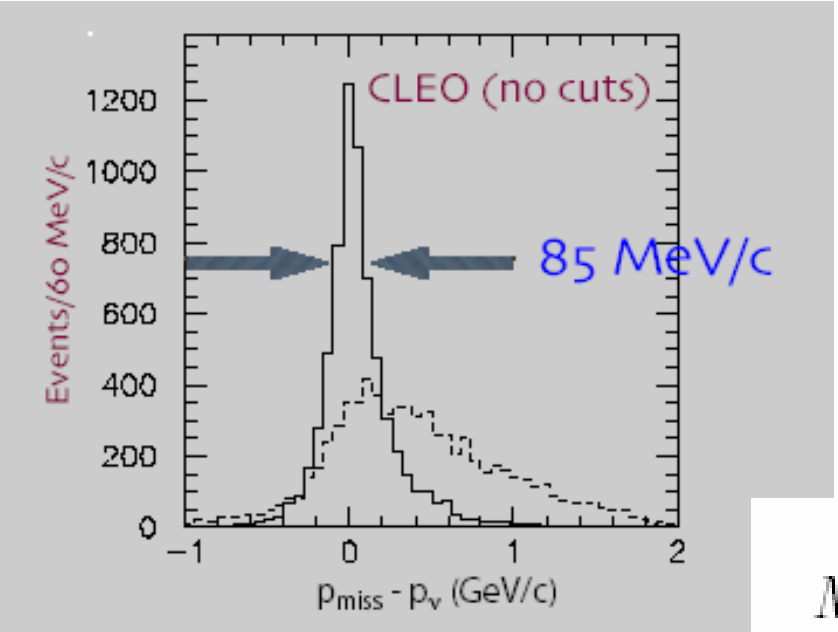
But QCD corrections are needed



$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 p_\pi^3}{24\pi^3}|f_1(q^2)|^2|V_{ub}|^2$$

$|V_{ub}|$ measurement: exclusive decays cont'd

Reconstruct $B \to l\nu + (\pi, \omega, \rho, \eta)$
Close the kinematic reconstruction the neutrino



$p_{miss} = p\Upsilon(4s) - \Sigma p_i$

$E_{miss} = E\Upsilon(4s) - \Sigma E_i$

Kinematic constraints:

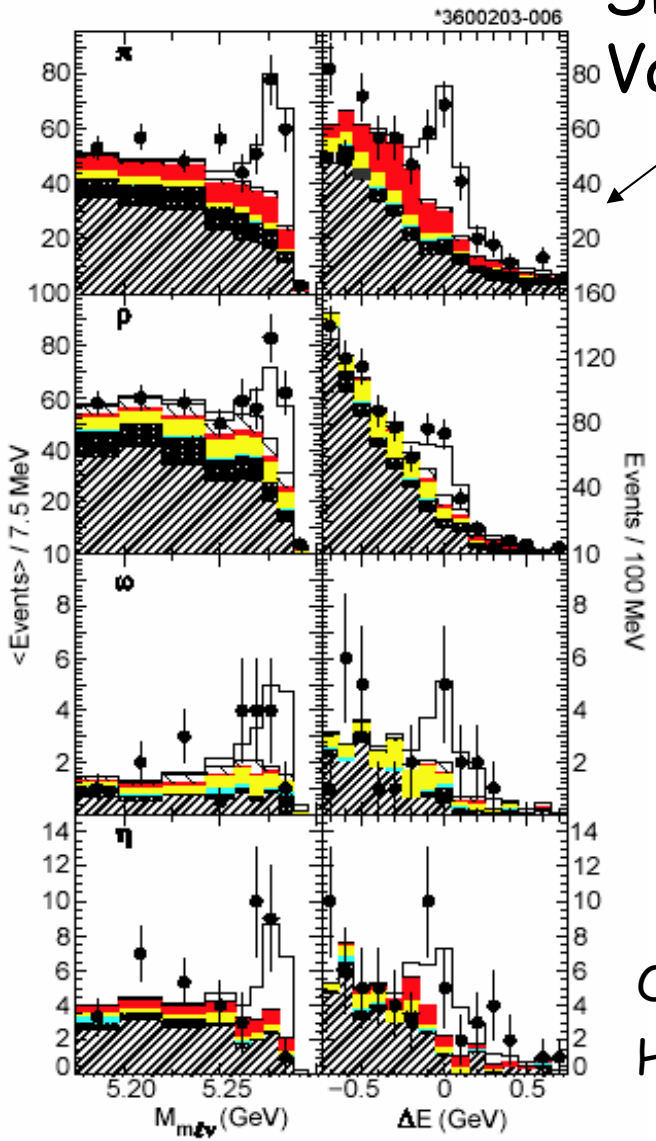
$$M_{m\ell\nu} = \sqrt{E_{\rm beam}^2 - |\alpha\vec{p}_\nu + \vec{p}_\ell + \vec{p}_m|^2}$$

$$\Delta E = (E_\nu + E_\ell + E_m) - E_{\rm beam}$$

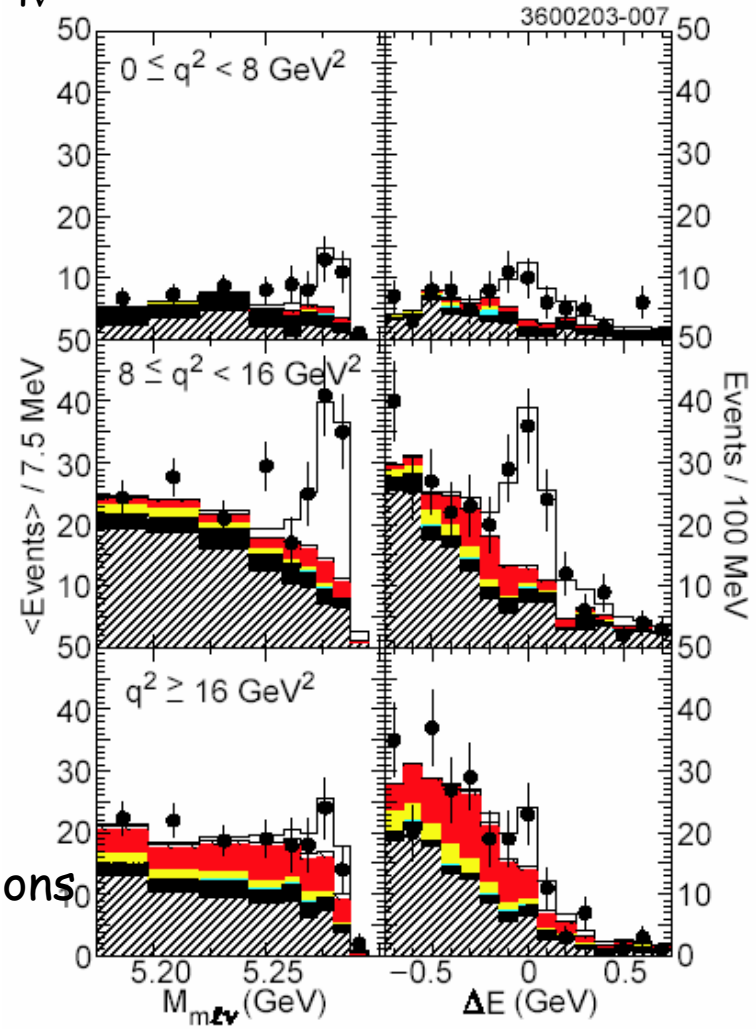
$|V_{ub}|$ measurement: exclusive decays cont'd

Simultaneous Likelihood fit

Variables, ΔE, $m_{l\nu}$



$B \to \pi l \nu$



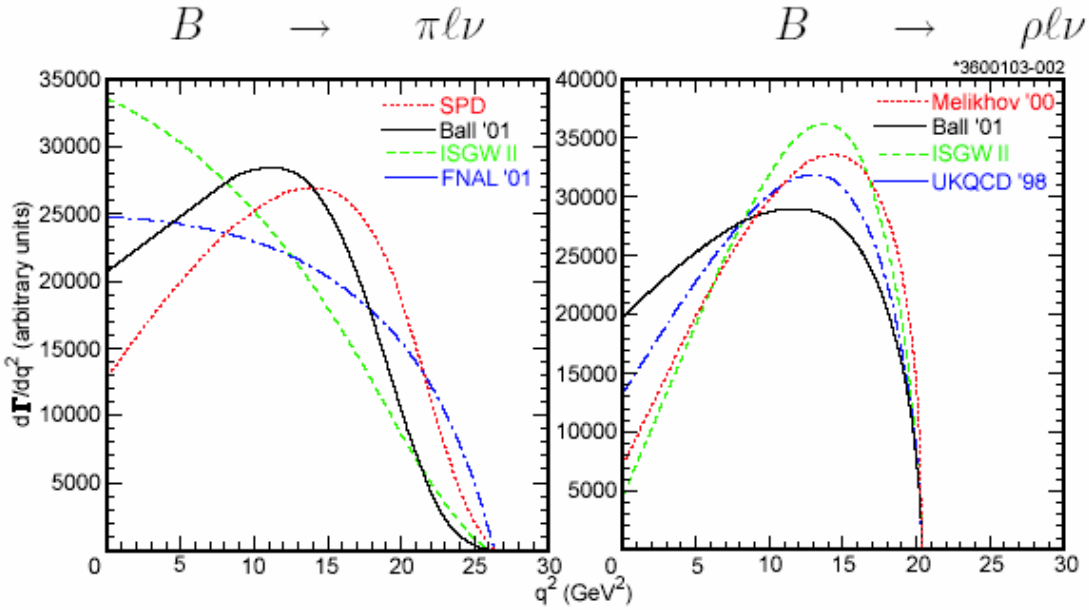
Open: all contributions

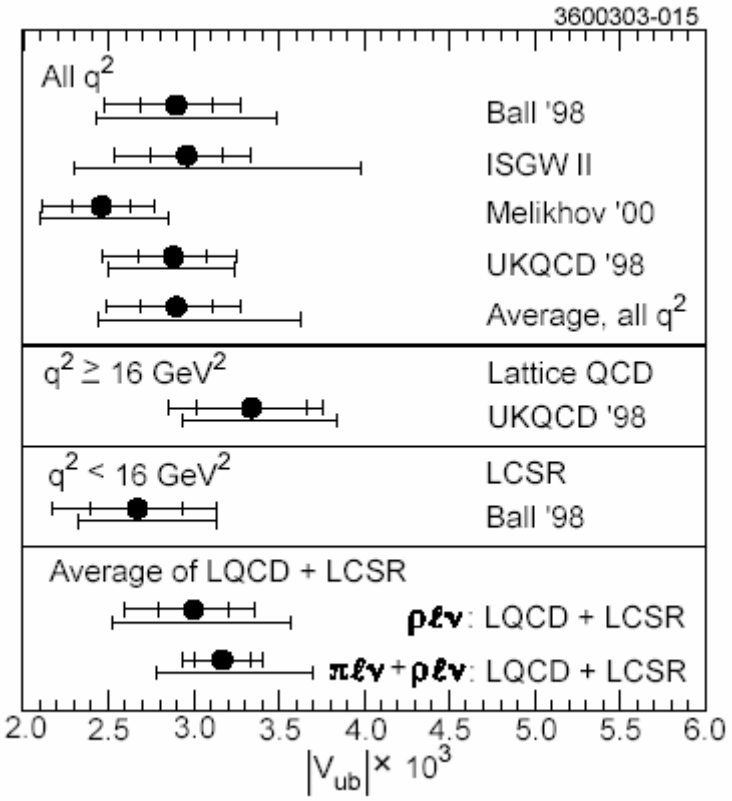
Hatched: $b \to c$

$|V_{ub}|$ measurement: exclusive decays cont'd

Fit $d\Gamma/dq^2$

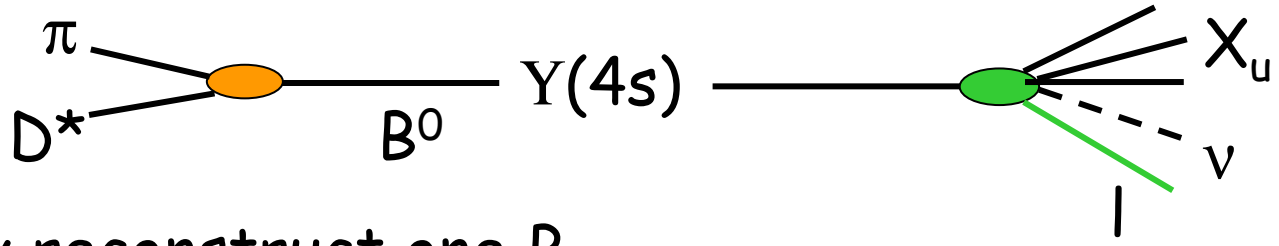
- Discriminate amongst form factors
- Extract Vub



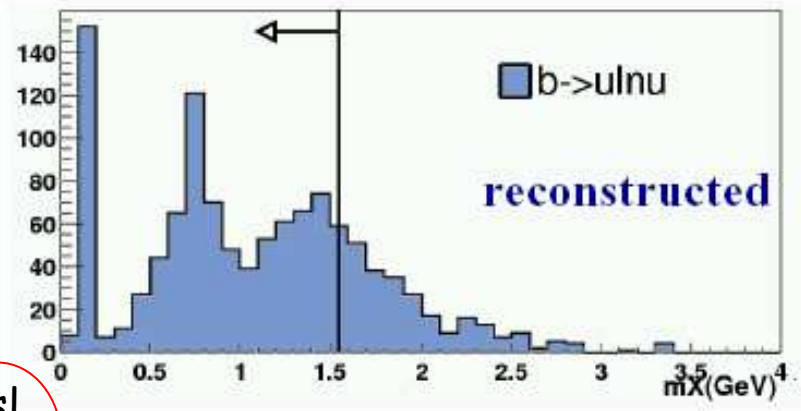


$$|V_{ub}| = (3.17 \pm 0.17\ ^{+0.16}_{-0.17}\ ^{+0.53}_{-0.39} \pm 0.03) \times 10^{-3} \qquad (\pi + \rho\ \text{LQCD+LCSR})$$

$|V_{ub}|$ measurement: inclusive decays



1. Fully reconstruct one B
2. Reconstruct the recoil B as lepton plus X
3. Cut on M_x to reject charm



4. $R_{u/sl} = \frac{Br(B \to X_u l \nu)}{Br(B \to X l \nu)} = \frac{N_u}{N_{sl}} \frac{\varepsilon_{sl}}{\varepsilon_u}$

Data

Monte Carlo

$|V_{ub}|$ measurement: inclusive decays cont'd

$$R_{u/sl} = \frac{\mathcal{B}(B \to X_u \ell \bar{\nu})}{\mathcal{B}(B \to X \ell \bar{\nu})} = 0.0197 \pm 0.0025(stat) \pm 0.0010(MC\ stat)$$

Using:

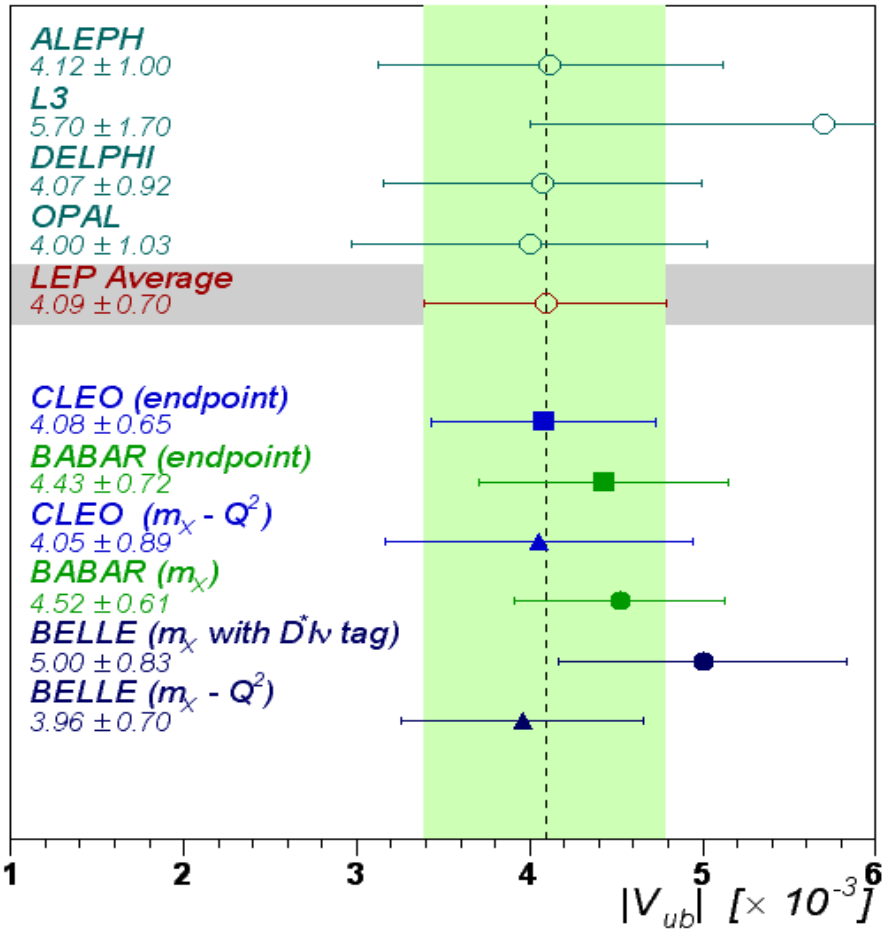
$$\mathcal{B}(B \to X_u \ell \bar{\nu}) = (2.14 \pm 0.29(stat) \pm 0.25(syst) \pm 0.37(theo)) \times 10^{-3}$$

The results:

$$|V_{ub}| = (4.52 \pm 0.31(stat) \pm 0.27(syst) \pm 0.40(theo) \pm 0.09(pert) \pm 0.24(1/m_b^3)) \times 10^{-3}$$

$|V_{ub}|$ Measurements Summary

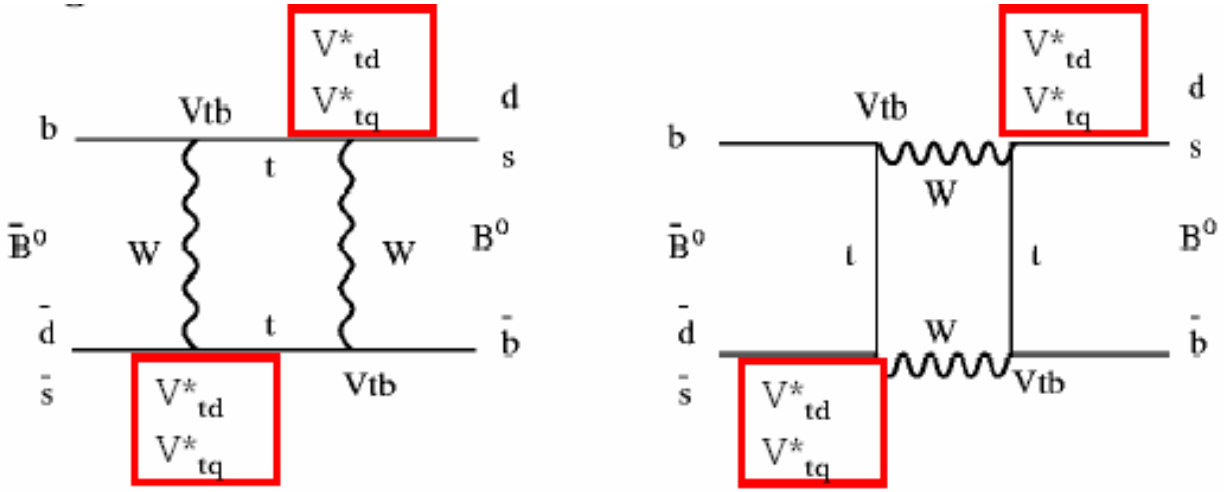
Moriond 2003



Bfactory $V_{ub} = (4.32 \pm 0.57) \times 10^{-3}$

Decay Rates of neutral B meson

- Contribution at lowest order in the standard Model:



- Time evolution:

$$i\frac{d}{dt}\begin{pmatrix}|B^0\rangle\\ |\overline{B^0}\rangle\end{pmatrix} = H\begin{pmatrix}|B^0\rangle\\ |\overline{B^0}\rangle\end{pmatrix} \qquad \text{with } H = M - i\frac{\Gamma}{2} \equiv \begin{pmatrix}M_{11} & M_{12}\\ M_{21} & M_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\ \Gamma_{21} & \Gamma_{22}\end{pmatrix}$$

Decay Rates of neutral B meson

- Mass eigenstates $|B_1\rangle$, $|B_2\rangle$ with masses $m_1^{(q)}$ $m_2^{(q)}$ and decay widths $\Gamma_1^{(q)}$, $\Gamma_2^{(q)}$:

  $\Delta m_q \equiv m_1^{(q)} - m_2^{(q)}$ $\Delta\Gamma_q \equiv \Gamma_1^{(q)} - \Gamma_2^{(q)}$ $\Gamma_q \equiv \frac{1}{2}(\Gamma_1^{(q)} + \Gamma_2^{(q)})$

$$\left|B_1^0\right\rangle = \frac{\left|B^0\right\rangle - \left|\overline{B}^0\right\rangle}{\sqrt{2}} \quad \text{and} \quad \left|B_2^0\right\rangle = \frac{\left|B^0\right\rangle + \left|\overline{B}^0\right\rangle}{\sqrt{2}}$$

- Time evolution with $\Delta\Gamma = 0$:

$$P_{B^0\to B^0}(t) = P_{\overline{B}^0\to\overline{B}^0}(t) = \frac{e^{-t/\tau}\left(1+\cos(\Delta m t)\right)}{2\tau}$$

$$P_{B^0\to\overline{B}^0}(t) = P_{\overline{B}^0\to B^0}(t) = \frac{e^{-t/\tau}\left(1-\cos(\Delta m t)\right)}{2\tau}$$

Mixing frequency

- Inside the Standard Model:

$$\Delta m_q = \frac{G_F^2}{6\pi^2}\left|V_{tb}\right|^2\left|V_{tq}\right|^2 M_W^2 M_{B_q^0} f_{B_q^0}^2 B_{B_q^0} \eta_{B_q^0} S\left(\frac{M_t^2}{M_W^2}\right)$$

non perturbative QCD

perturbative QCD

$$\frac{\Delta m_d}{\Delta m_s} = \frac{\left|V_{td}\right|^2}{\left|V_{ts}\right|^2}\frac{M_{B_d^0}}{M_{B_s^0}}\frac{\eta_{B_d^0}}{\eta_{B_s^0}}\frac{f_{B_d^0}^2 B_{B_d^0}}{f_{B_s^0}^2 B_{B_s^0}}$$

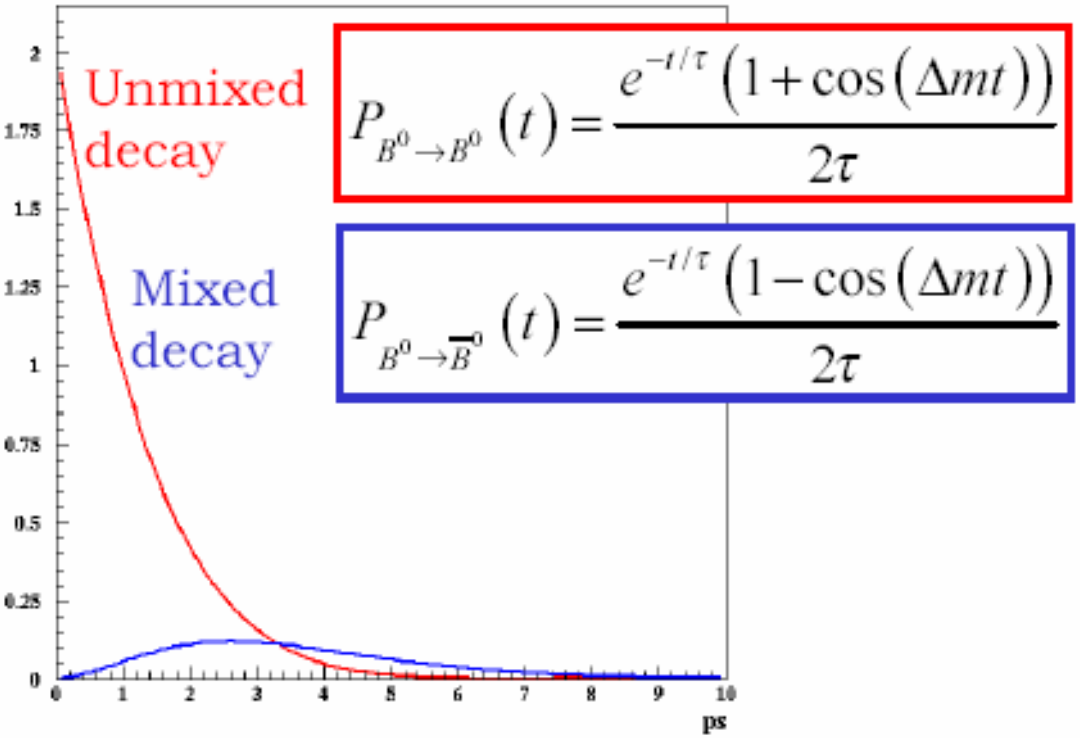
$\cong 1$

SU(3) Flavor breaking theoretical uncertainties <5%

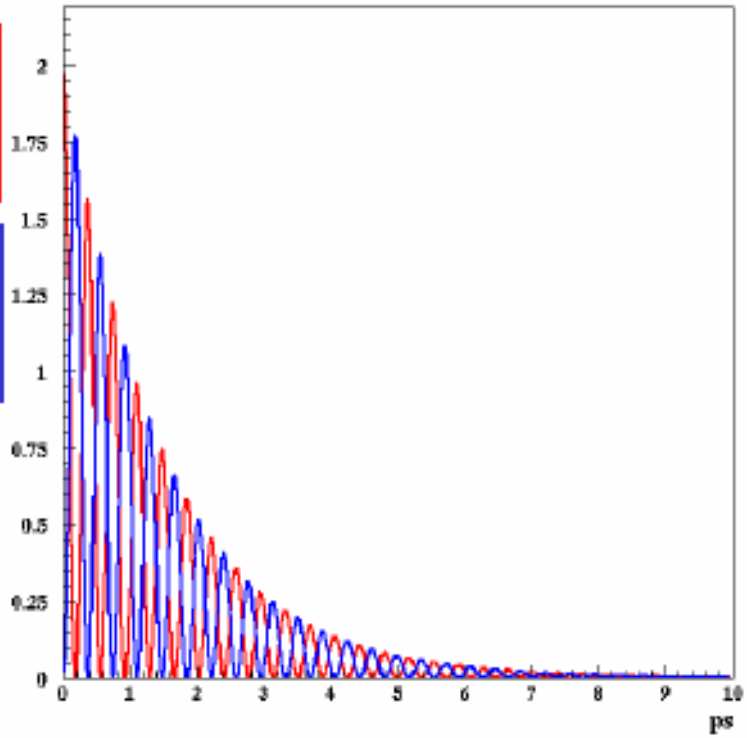
B_d and B_s Mixing differences

Due to the different size of CKM matrix elements
B_d and B_s mixing frequencies are very different

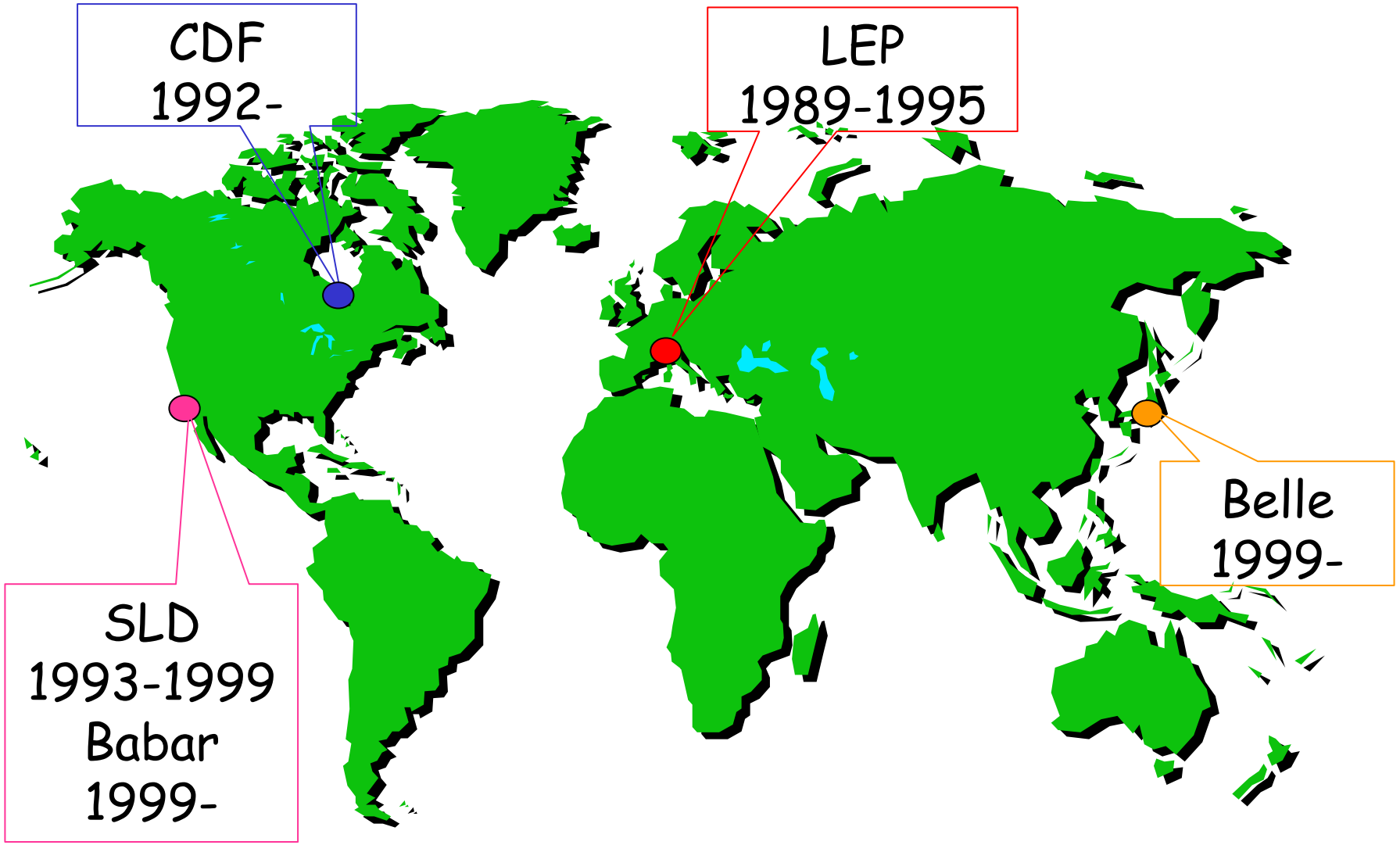
B_d Δm_d= 0.47 ps^{-1}



B_s Δm_s= 17 ps^{-1}



Where in the world?



What is needed

$$Sig(\Delta m_s) = \sqrt{\frac{N\varepsilon D^2}{2}} e^{-\frac{1}{2}(\Delta m_s \times \sigma_t)^2} \sqrt{\frac{S}{S+B}}$$

N: total number of events

εD^2: tagging effectiveness

$\varepsilon = N_{tag}/N$ efficiency

D= dilution $(N_{tag}^{R}-N_{tag}^{W})/N_{tag}$ D=1 D=0

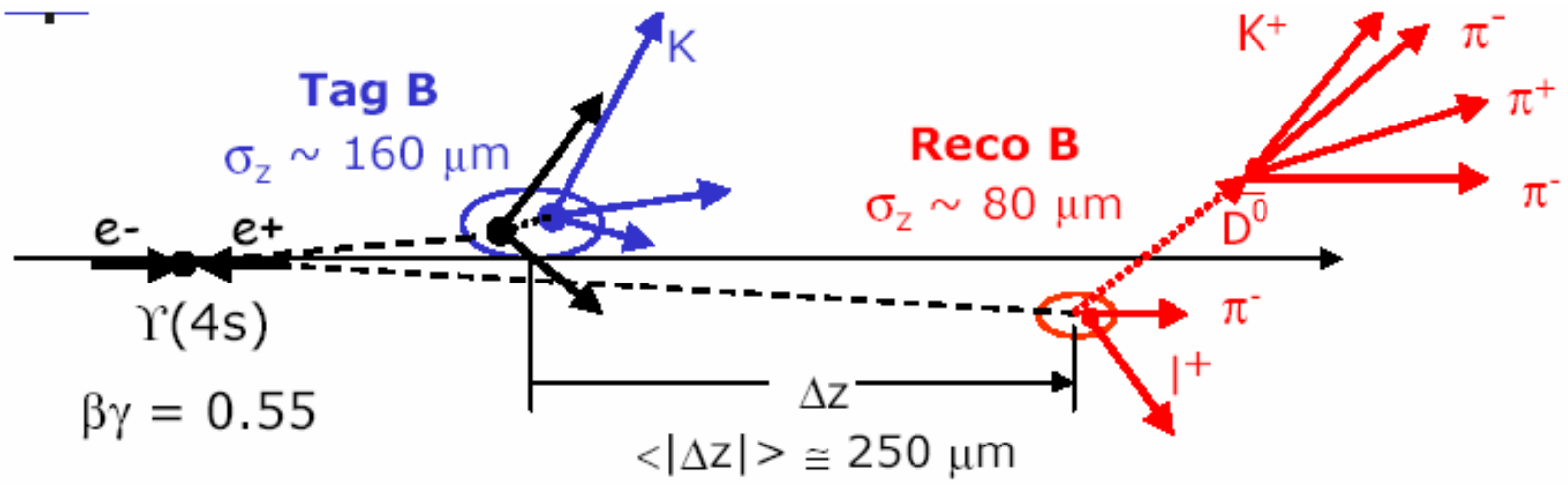
S: signal

B: background

σ_t: resolution on the proper time

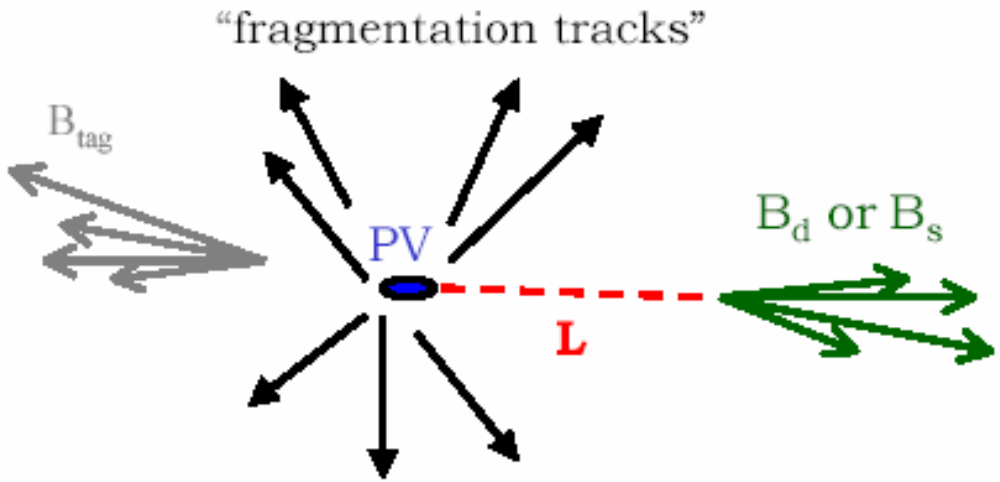
How is measured at B factories

- Only B^0_d are produced
- At t=0 coherent B^0B^0 pair production
- At t=t1 decay of one B the other starts to evolve with a frequency Δm_d
- At t=t2 decay of the other B



How is measured at LEP/SLD/CDF

- Both B^0_d and B^0_s are produced
- At t=0
  - bb production
  - hadronization of one b quark in B^0_d or B^0_s
  - other b quark hadronize in a hadron (meson or barion)
- At later time
  - B^0_d or B^0_s decays
  - b-hadron decays



Main ingredients: final state reconstruction

i.e. final state tagging

- Exclusive decays: $B^0 \to D^* \pi$ $B^0_s \to D_s \pi$
  - Low backgrounds
  - Good momentum resolution
  - Low branching fractions

Necessary for B_s

- Quasi-exclusive decays: $B^0 \to D^* l \nu$ $B^0_s \to D_s l \nu$
  - reasonable background
  - not so good momentum resolution
  - (not important for B factories)
  - Low branching fractions

Good compromise between signal and background

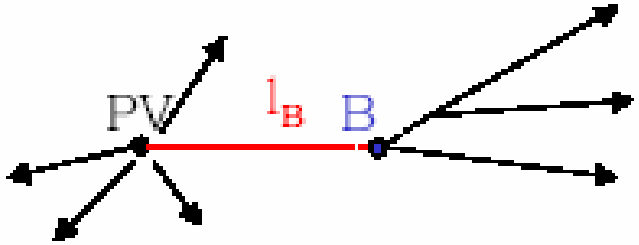
- Inclusive decays: $B^0 \to l X$ $B^0_s \to l X$
  - High background
  - worse momentum resolution
  - high statistics

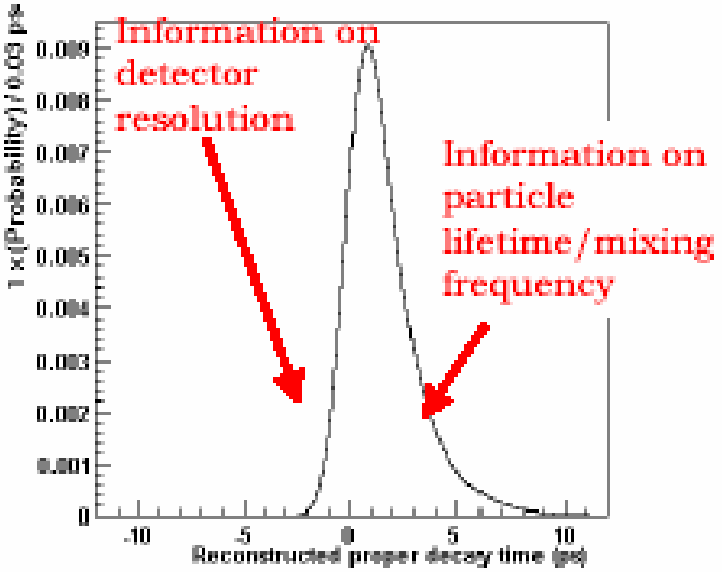
Provided first results

Main ingredients: time measurement

CDF,LEP,SLD

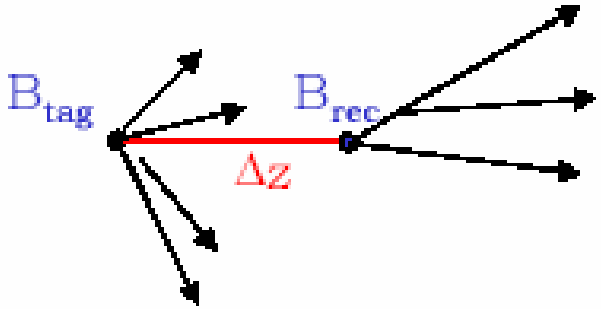
$t = l_B m_B / p_B$

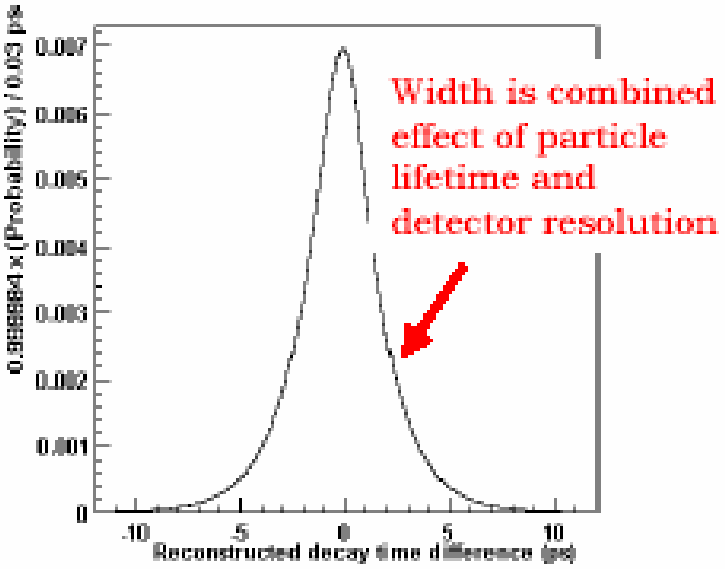




B factories

$\Delta t = \beta\gamma\Delta z$

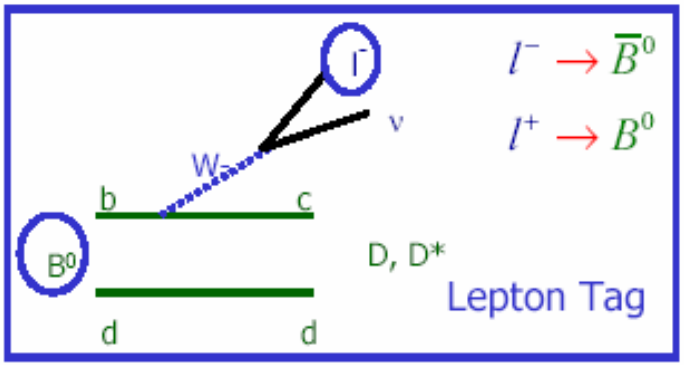




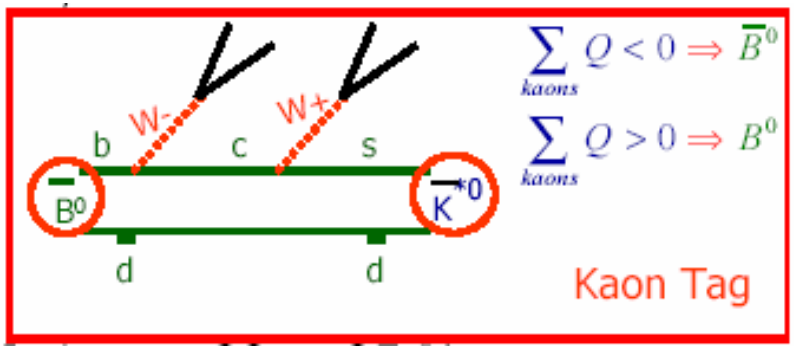
Main ingredients: Initial state tagging

Identify the flavor of the other B: opposite side tagging
$b\bar{b}$ correlated production $\Rightarrow$ infer the initial B flavor

- search for a lepton or kaon coming from B decay



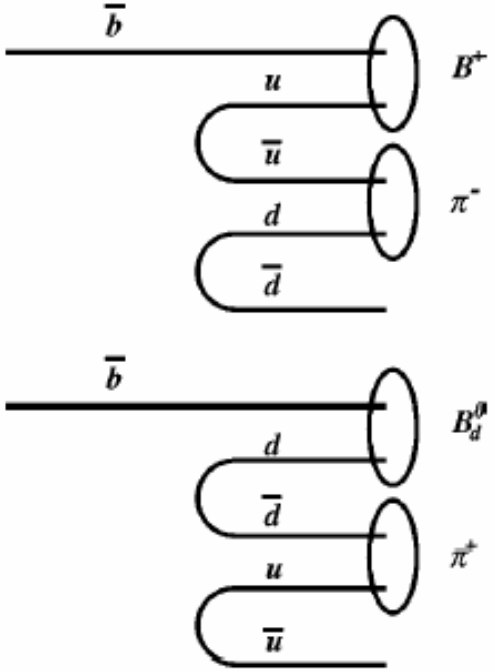
- reconstruct the "other b" charge



Main ingredients: Initial state tagging cont'd

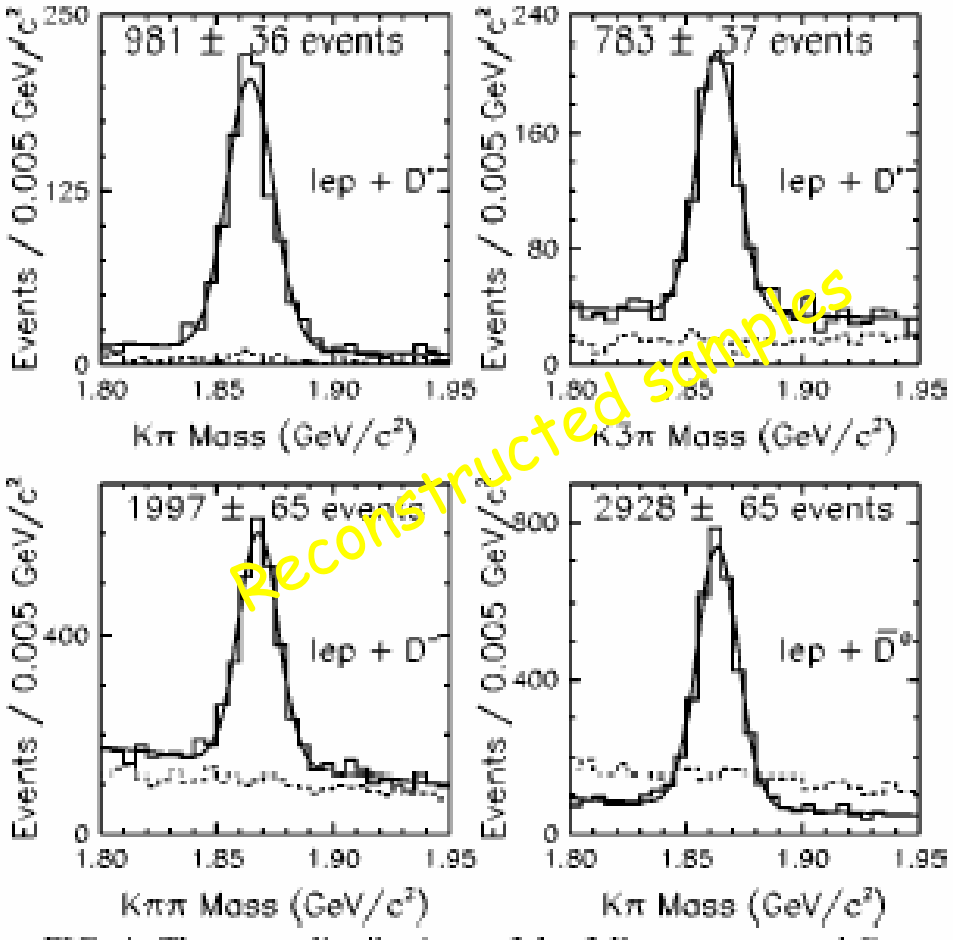
Same side tagging: infer the production B flavor from particle charge produced "close" to the B:

- fragmentation tracks
- B^{**} production and $B^{**} \rightarrow B^0\pi$

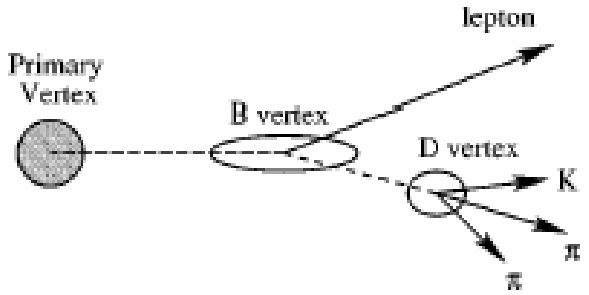


- jet charge $\sum(Q_i)>0$ for $\bar{b}$

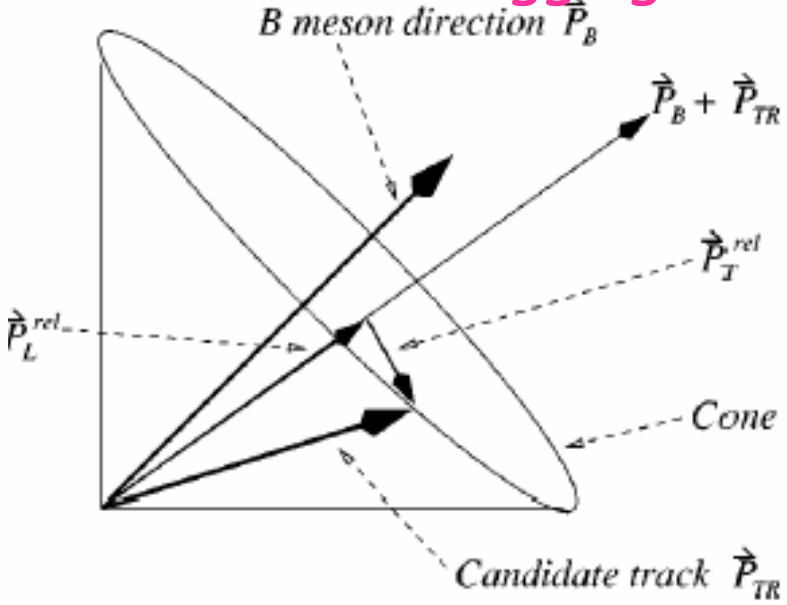
Δm_d at CDF: $B \to D^* l \nu$ + SST



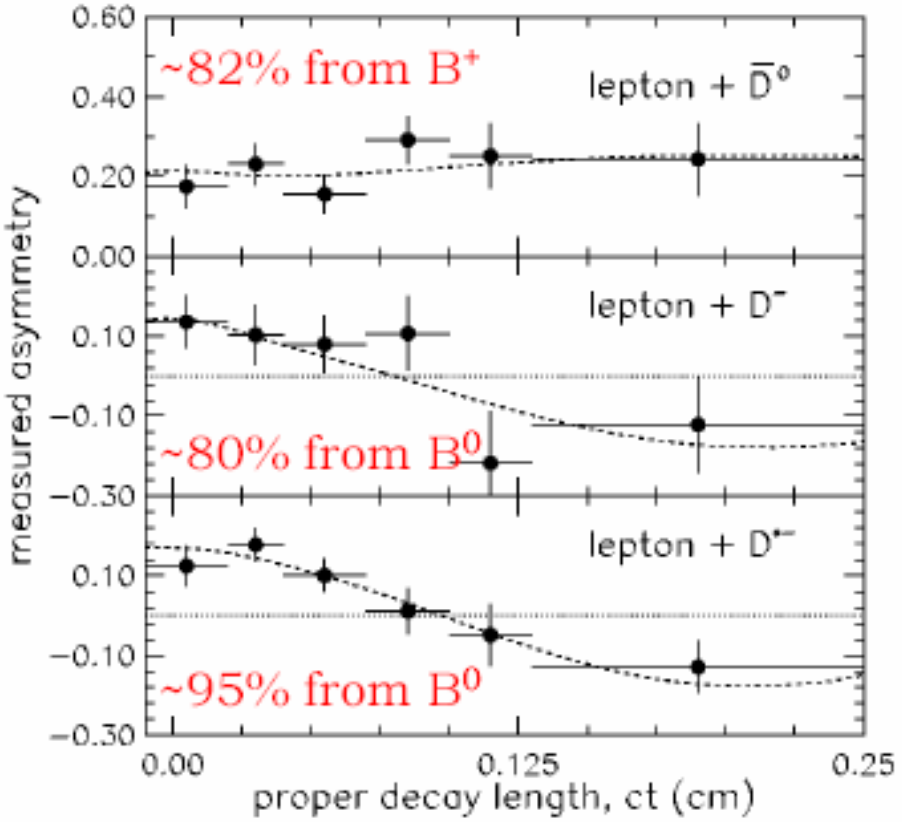
Reconstructed samples



Same Side Tagging



Δm_d at CDF: $B \to D^* l \nu$ + SST cont'd



Tagging result:

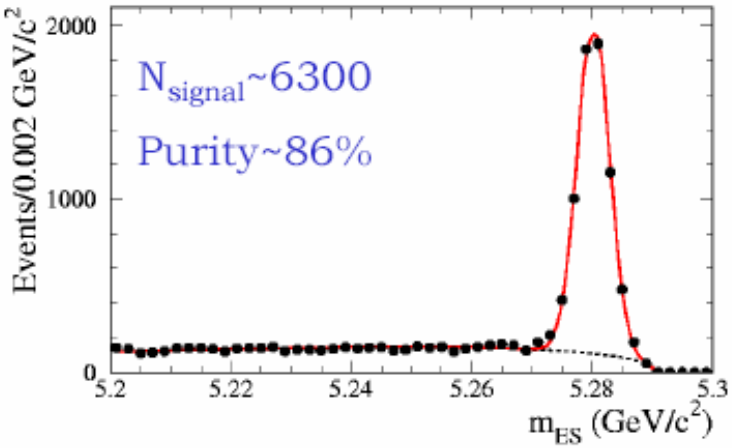
D=0.27
ε=0.71

Main systematic:
sample composition

$$\Delta m_d = 0.471^{+0.078}_{-0.068} \pm 0.034 \text{ ps}^{-1}$$

Δm_d at Babar

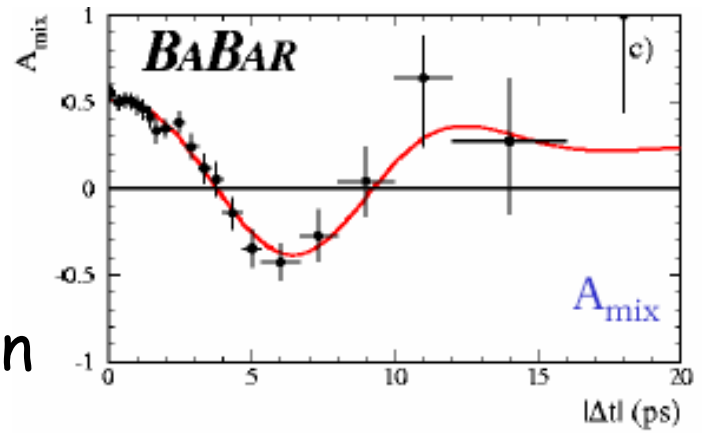
Final state:
$B \to D^{*-}\pi^+/\rho^+/a_1^+$ and $B \to J/\psi\ K^{0*}$



Initial state tagging:

- lepton D~92%
- charged kaon D~83%
- neural network D~78%

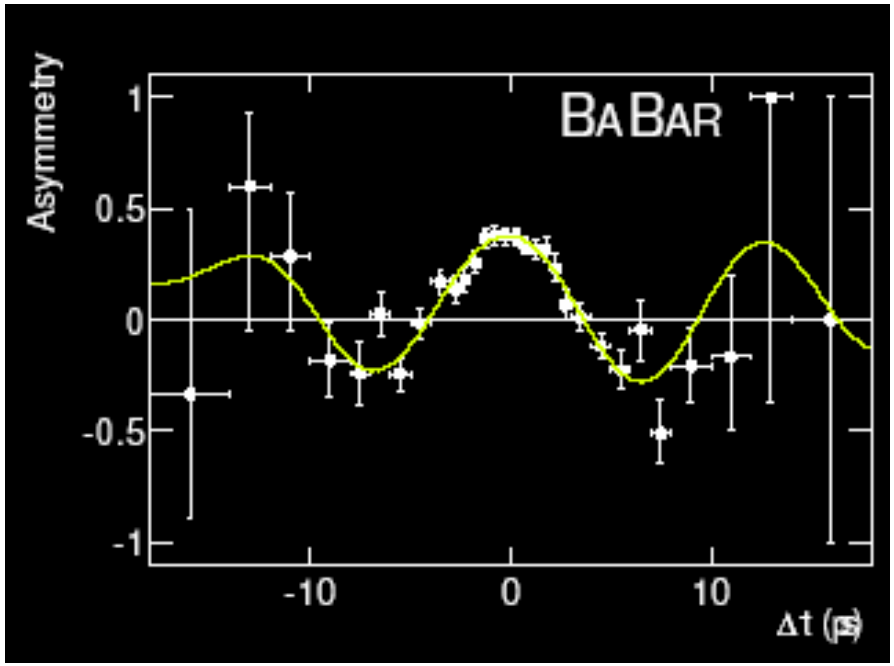
$\Delta m_d = 0.516 \pm 0.016 \pm 0.010\ ps^{-1}$



Main systematic: resolution function

Δm_d at Bfactories

Final state:
$B \rightarrow D^{*-} l \nu$



Babar 20 fb^{-1}

$\Delta m_d = 0.492 \pm 0.018 \pm 0.013\ ps^{-1}$

Belle 29 fb^{-1}

$\Delta m_d = 0.494 \pm 0.012 \pm 0.015\ ps^{-1}$

Δm_d at Bfactories

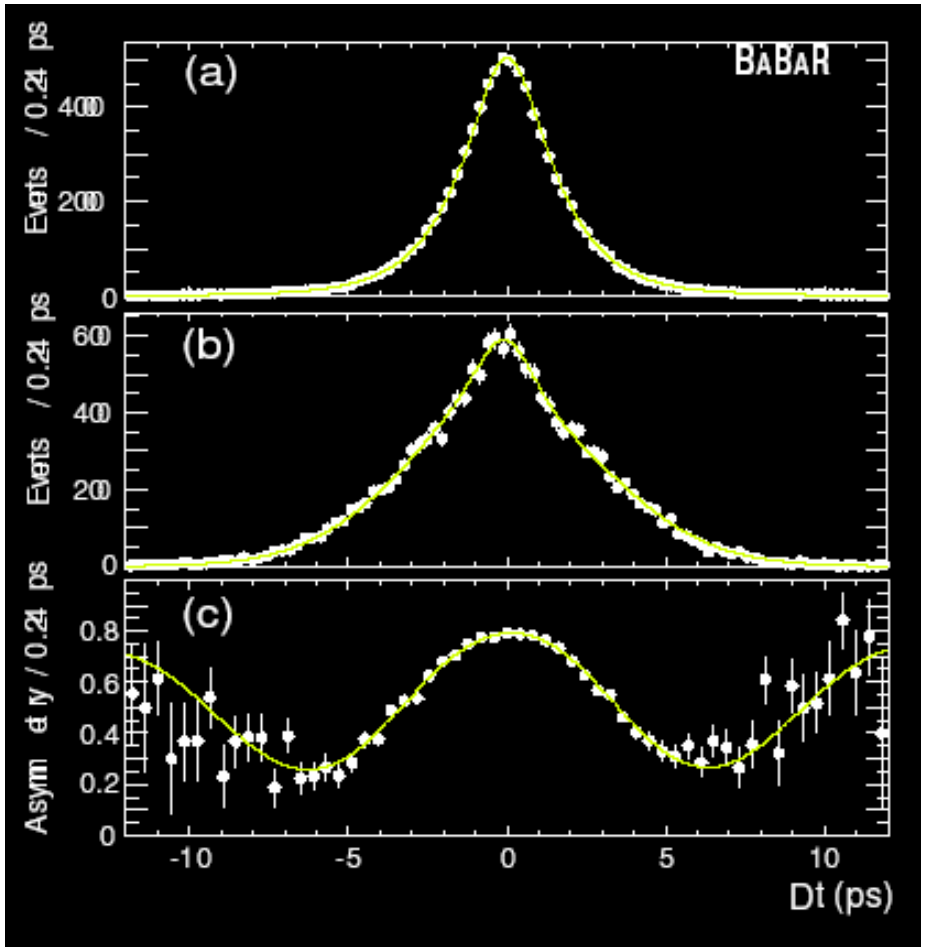
Final state:
$B \rightarrow l+X$
Tagging:
$B \rightarrow l+X$

Babar 20 fb^{-1}

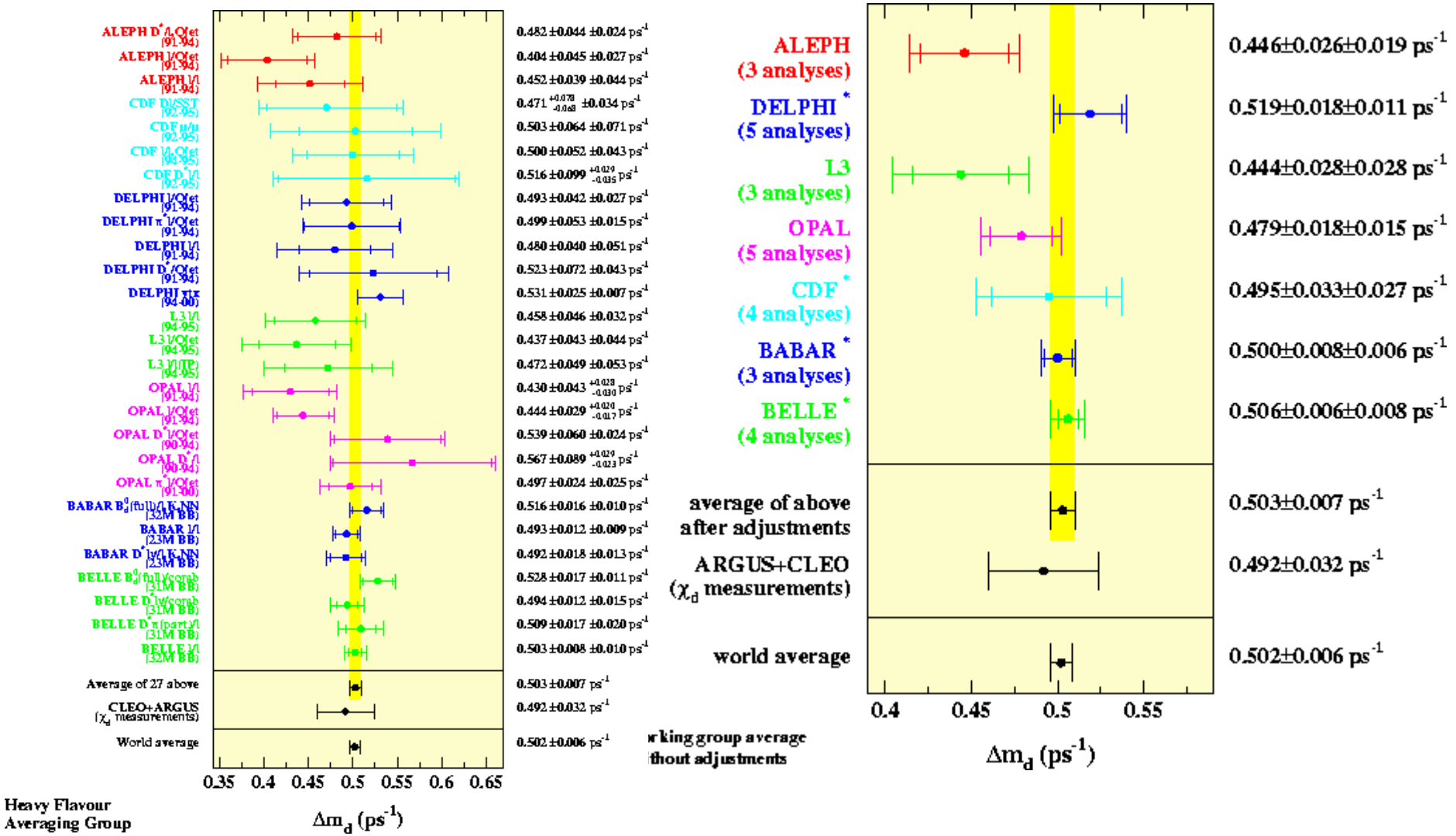
$\Delta m_d = 0.493 \pm 0.012 \pm 0.009\ ps^{-1}$

Belle 29 fb^{-1}

$\Delta m_d = 0.503 \pm 0.008 \pm 0.010\ ps^{-1}$



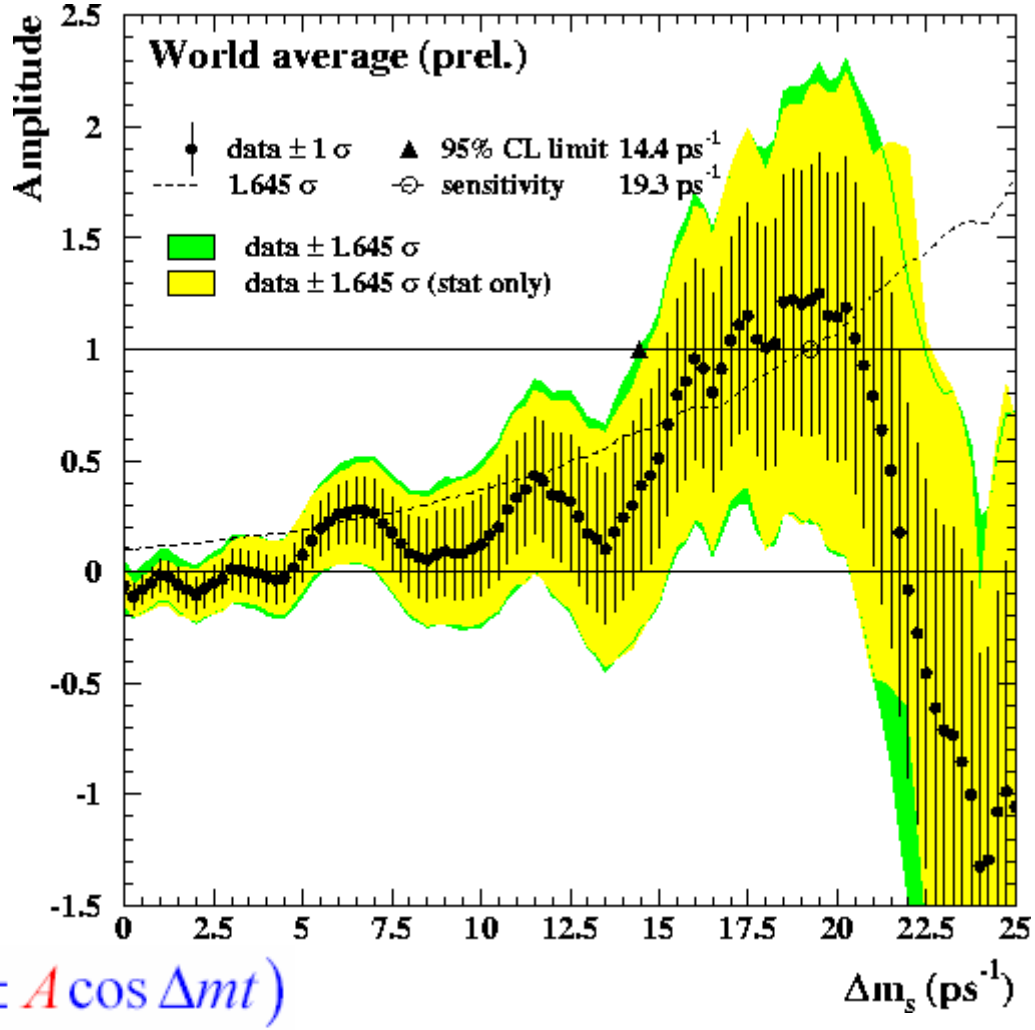
Δm_d:Summary



Δm_s:Limit

- Expected very fast oscillation
- Not measured yet
- Limit an
- Combination of limit

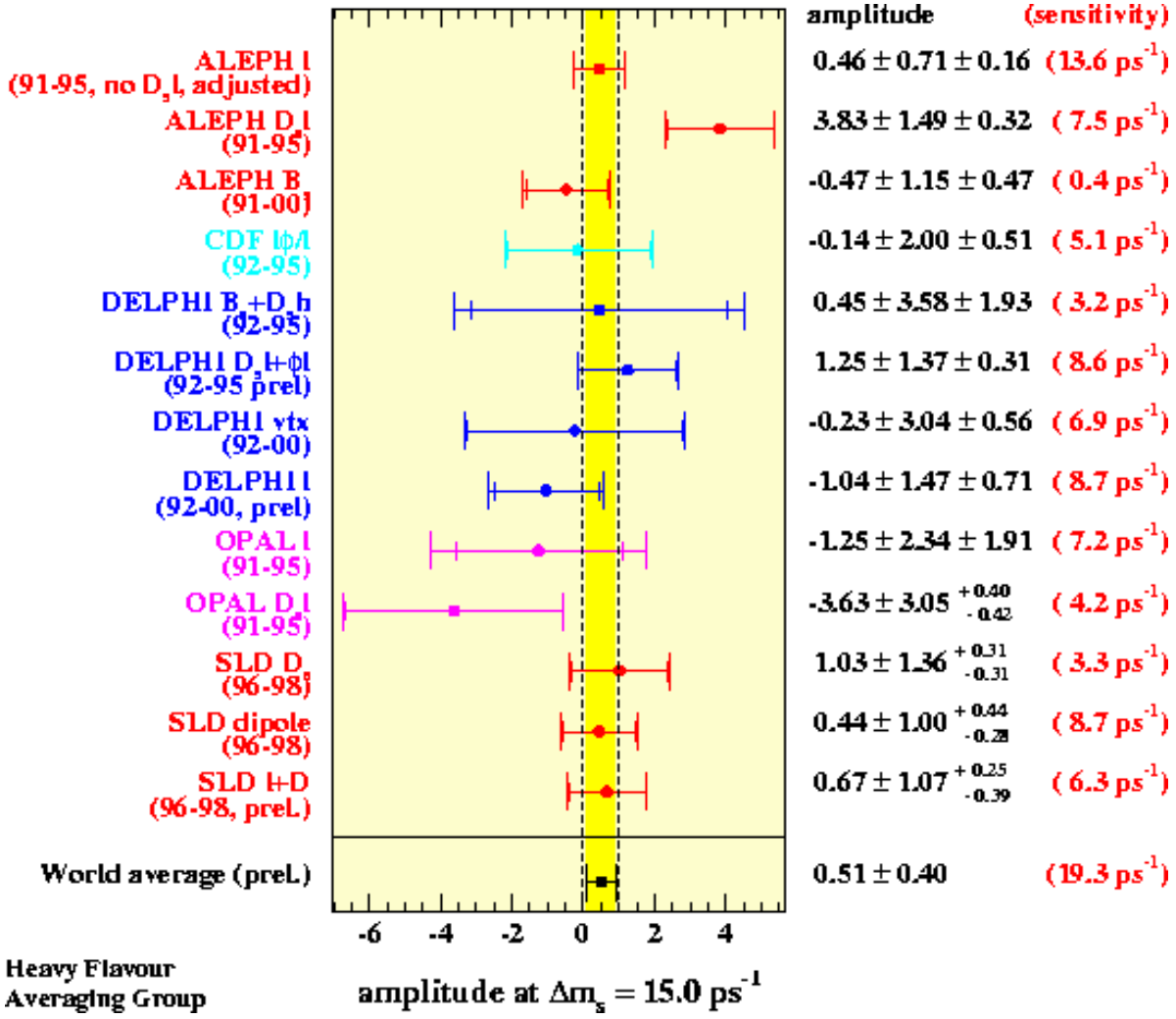
$\Delta m_s > 14.4\ ps^{-1}$ at 95% CL



Amplitude method:

$$e^{-t/\tau}\left(1 \pm \cos \Delta m t\right) \quad \rightarrow \quad e^{-t/\tau}\left(1 \pm A \cos \Delta m t\right)$$

Δm_s:sensitivity

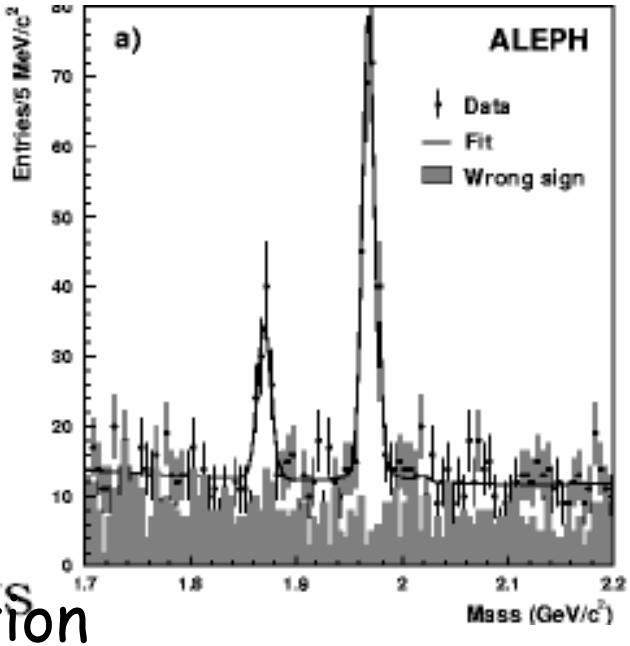


Aleph measurements

1. Exclusive reconstruction:
   small data sample
   high purity
   excellent decay length and momentum resolution

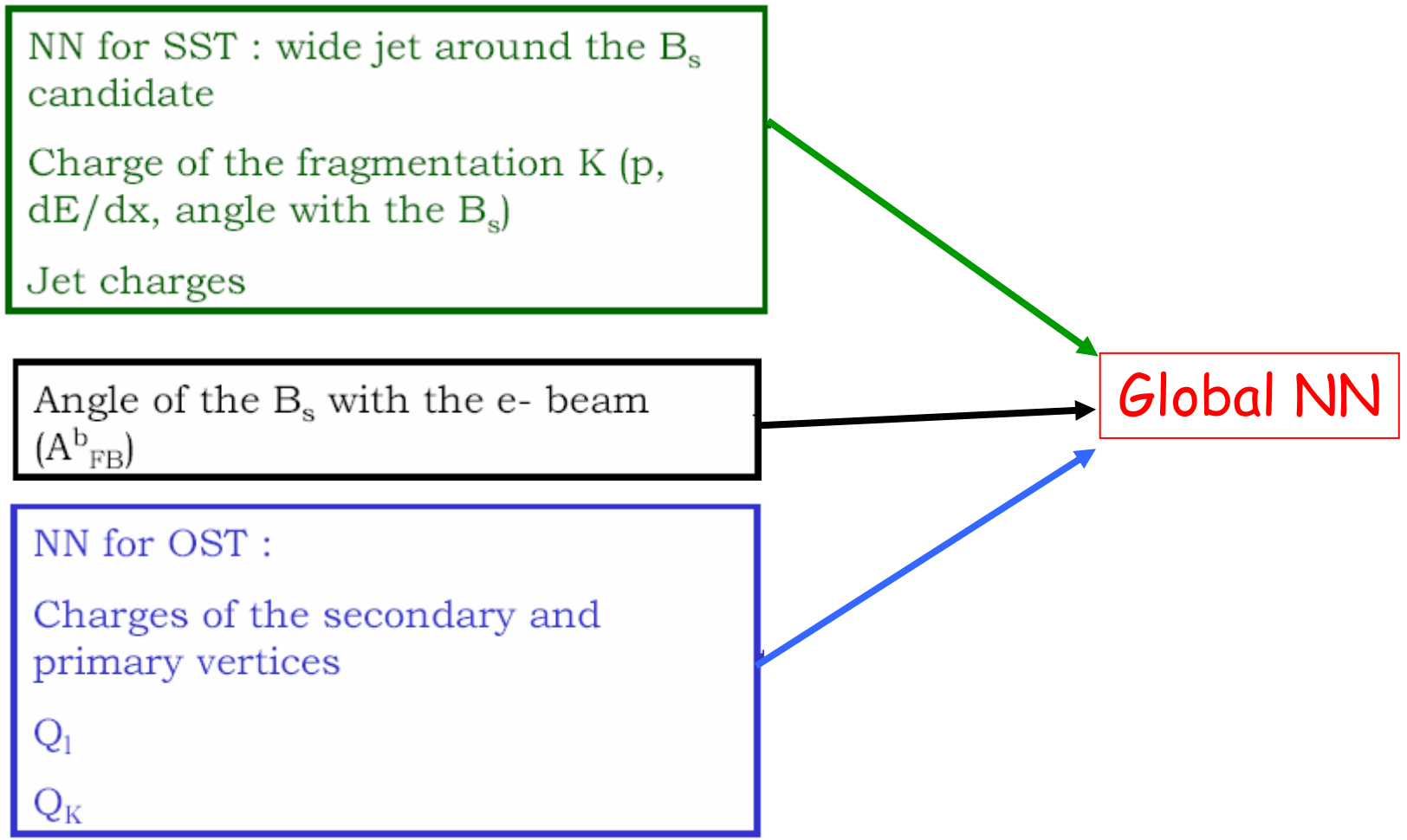
2. Semileptonic decay:
   Larger statistics
   poorer momentum resolution

3. Inclusive semileptonic B decays
   very high statistics
   compensate for poorer time resolution
   and lower purity
   Highest sensistivity to Δm_s

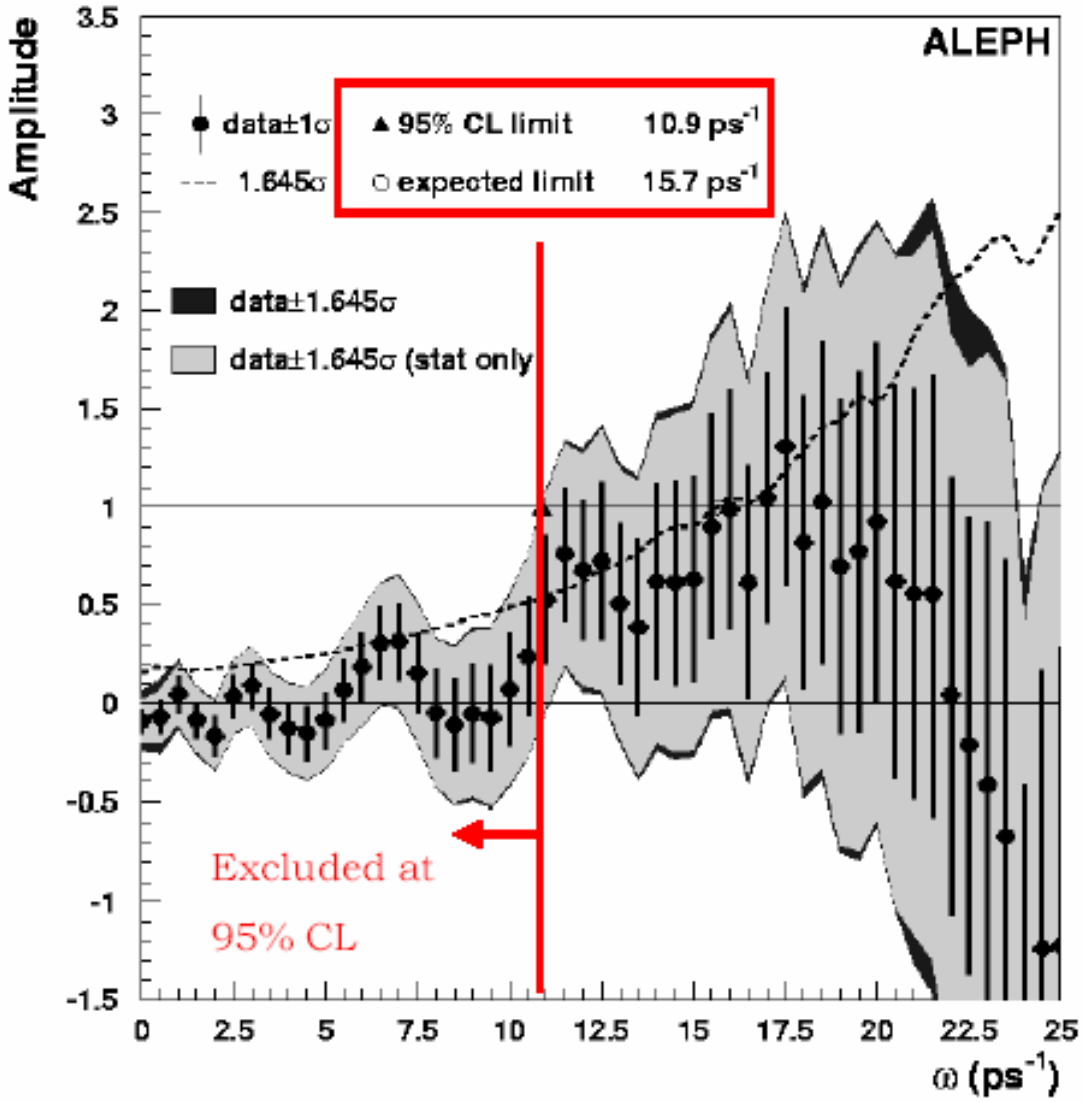


Aleph measurements cont'd

Sophisticated initial state tagging:



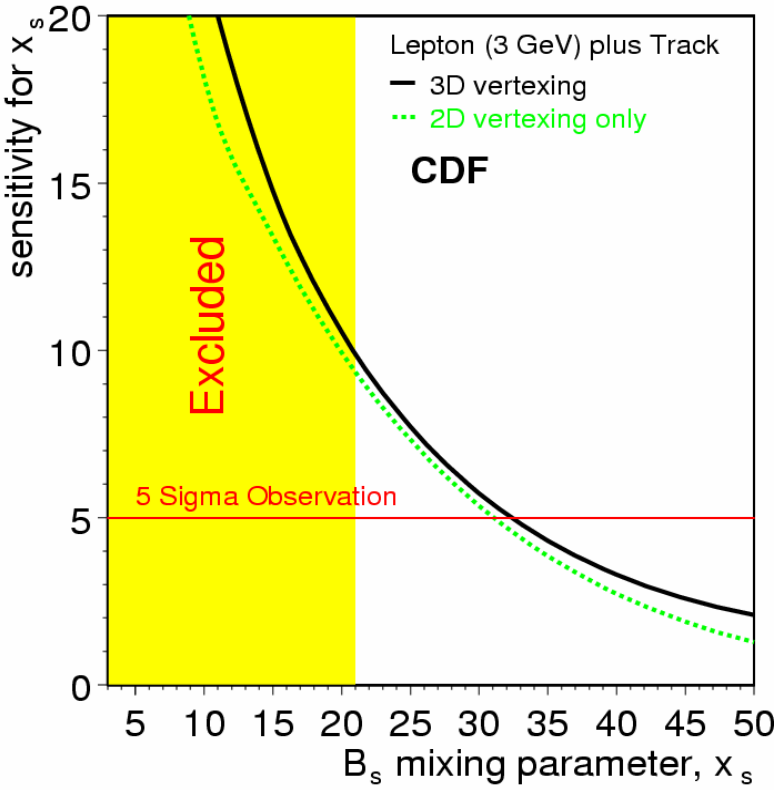
Aleph measurements cont'd



Δm_s: the future

CDF

Current limit $X_s > 20.6$



Sensitive up to $x_s \approx 30$

Decays included:

$B_s \rightarrow D_s^{\mp} l$, $D_s^{*\mp} l$

($D_s^{\mp} \rightarrow \phi\pi^{\mp}$, $K^{*0}K^{\mp}$, $\pi^-\pi^+\pi^{\mp}$)

~40K events in 2 fb^{-1}

Proper time resolution:

$$ct = \frac{L_{xy}(B_s)M(B_s)}{P_t(B_s)} = \frac{L_{xy}(B_s)M(B_s)}{P_t(l+D_s)} \times K$$

$$K = \frac{P_t(l+D_s)}{P_t(B_s)} \leftarrow \text{from Monte Carlo}$$

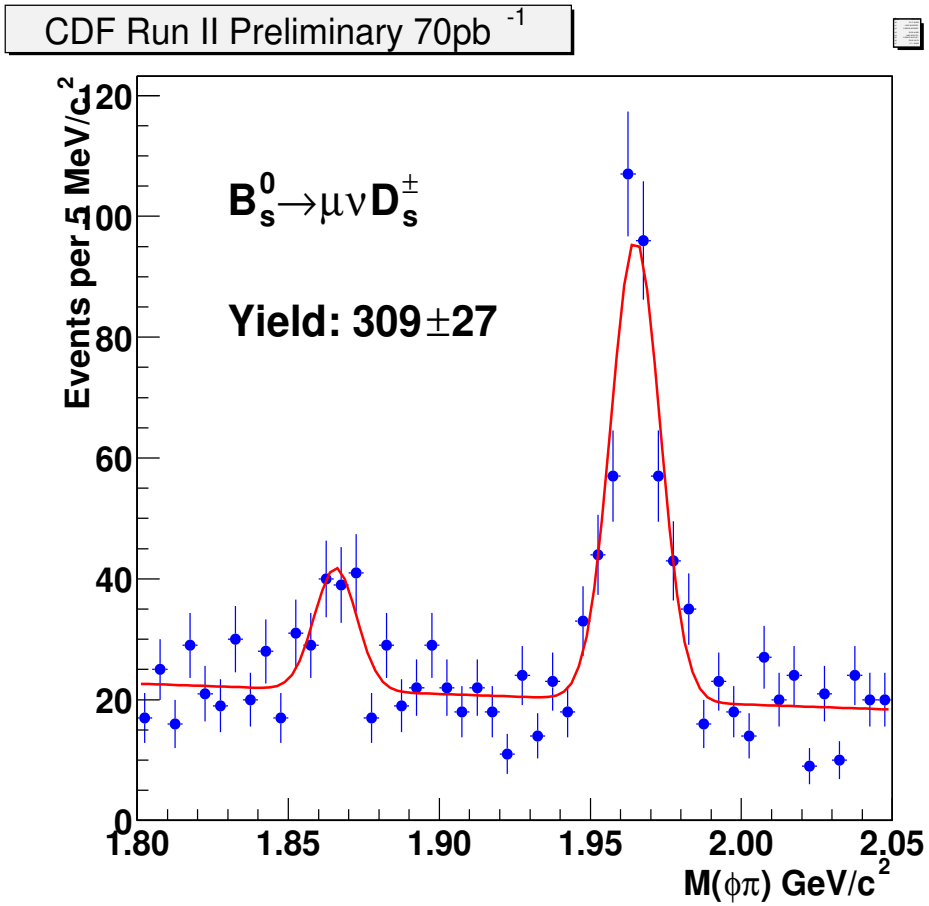
σ_t = 60 fs $\oplus$ t $\cdot$ $\sigma K/K$

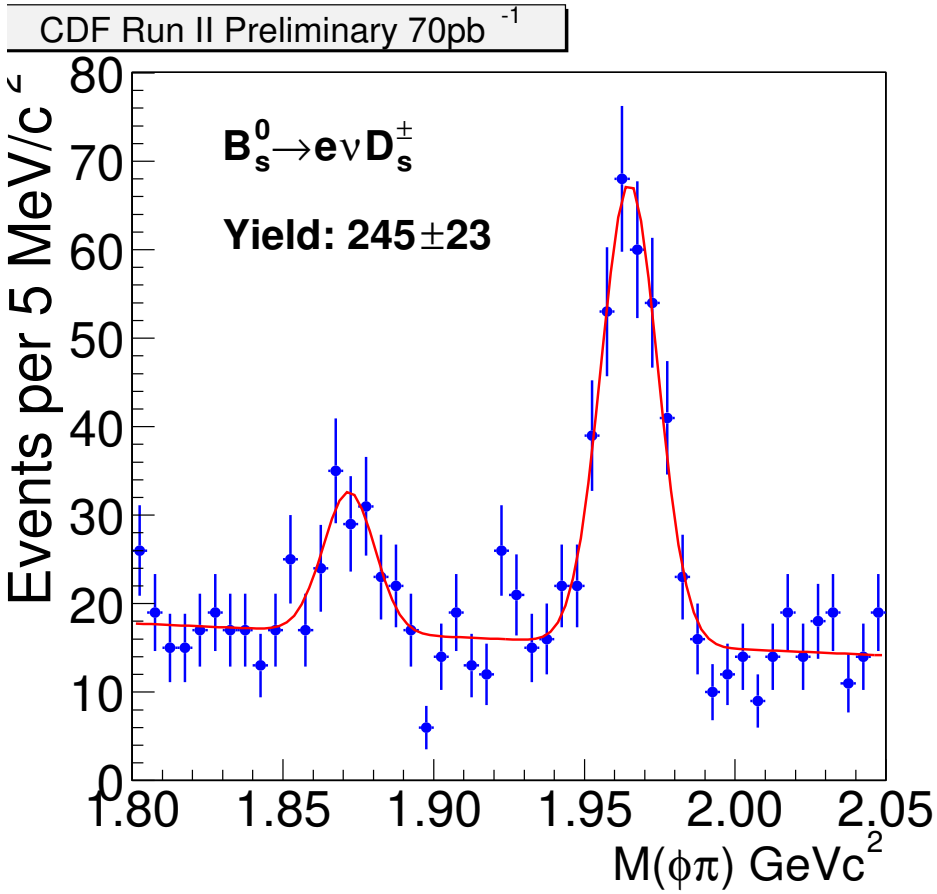
$\sigma K/K$ ~ 14%

Tagging:

εD^2 = 11.3 % (all taggers)

Δm_s: the future





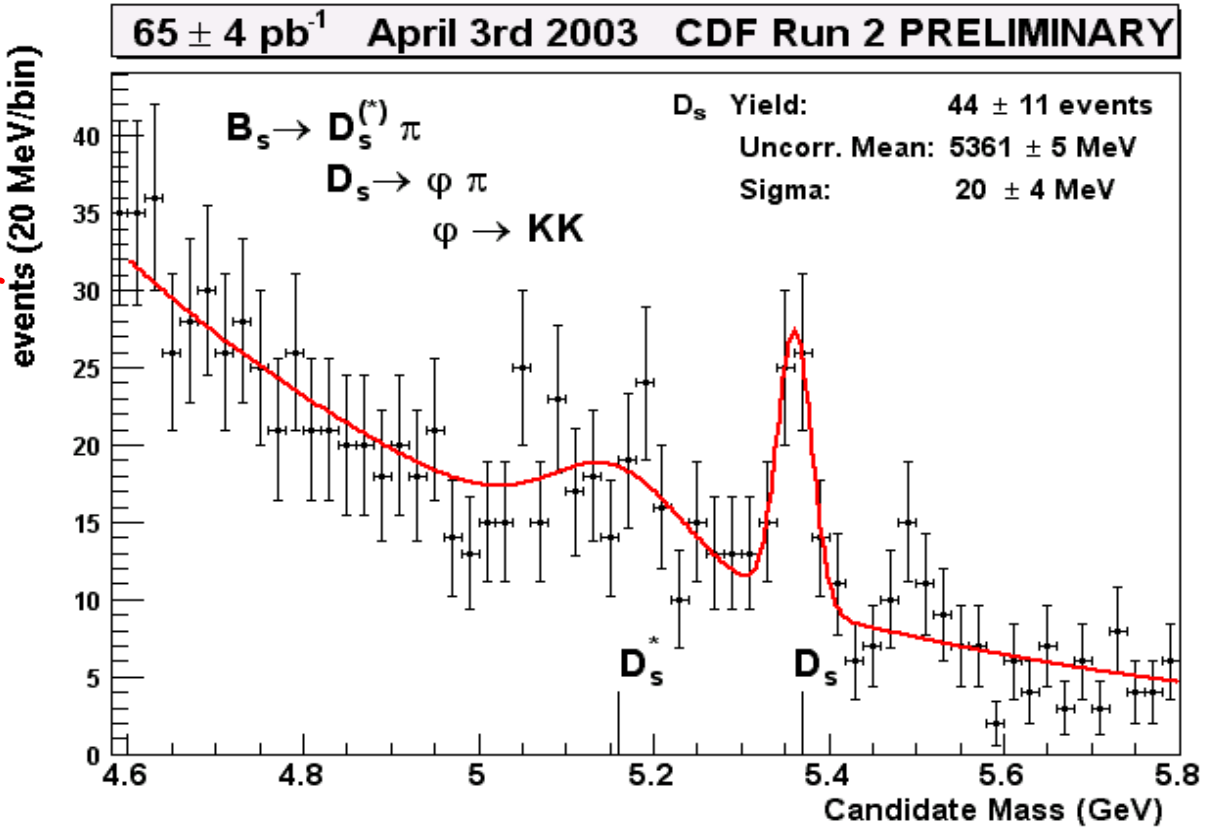
Signal to noise ratio better than expected !

Observed yield: RunI×5

Current status of CDF: Yield Study

Hadronic trigger

First observation !



$$\frac{f_s}{f_d}\frac{Br(B_s \to D_s^- \pi^+)}{Br(B_d \to D^- \pi^+)} = 0.42 \pm 0.11(stat.) \pm 0.11(Br.) \pm 0.07(syst.)$$

CP violation: introduction

$$A(\overline{B} \to \overline{f}) = e^{+i\varphi_1}|A_1|e^{i\delta_1} + e^{+i\varphi_2}|A_2|e^{i\delta_2}$$

$$A(B \to f) = e^{-i\varphi_1}|A_1|e^{i\delta_1} + e^{-i\varphi_2}|A_2|e^{i\delta_2},$$

Where

$|A_{1,2}|e^{i\delta_{1,2}}$ CP conserving strong amplitudes

$\varphi_{1,2}$ CP violating CKM phases

"Direct CP" violation:

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(B \to f) - \Gamma(\overline{B} \to \overline{f})}{\Gamma(B \to f) + \Gamma(\overline{B} \to \overline{f})} = \frac{|A(B \to f)|^2 - |A(\overline{B} \to \overline{f})|^2}{|A(B \to f)|^2 + |A(\overline{B} \to \overline{f})|^2}$$

$$= \frac{2|A_1||A_2|\sin(\delta_1 - \delta_2)\sin(\varphi_1 - \varphi_2)}{|A_1|^2 + 2|A_1||A_2|\cos(\delta_1 - \delta_2)\cos(\varphi_1 - \varphi_2) + |A_2|^2}$$

CP violation due to interference

Need to measure φ_1 - φ_2 but hadronic uncertanties

CP violation: introduction cont'd

Solution:

1. Use several amplitudes (decays) to eliminate the hadronic uncertainties

2. Use decays of neutral mesons B^0_d, B^0_s: interference effects due to mixing

Mixing induced CP violation

CP violation: mixing induced

$$\Gamma(\overset{(-)}{B}{}^0_q(t) \to f) = \left[\left| g^{(q)}_{\mp}(t) \right|^2 + \left| \xi^{(q)}_f \right|^2 \left| g^{(q)}_{\pm}(t) \right|^2 - 2\,\mathrm{Re}\left\{ \xi^{(q)}_f g^{(q)}_{\pm}(t) g^{(q)}_{\mp}(t)^* \right\} \right] \Gamma_f$$

where:

$$g^{(q)}_{+}(t)\, g^{(q)}_{-}(t)^* = \frac{1}{4}\left[e^{-\Gamma^{(q)}_{\mathrm{L}} t} - e^{-\Gamma^{(q)}_{\mathrm{H}} t} - 2\,i\, e^{-\Gamma q t} \sin(\Delta M_q t) \right]$$

$$\left| g^{(q)}_{\mp}(t) \right|^2 = \frac{1}{4}\left[e^{-\Gamma^{(q)}_{\mathrm{L}} t} + e^{-\Gamma^{(q)}_{\mathrm{H}} t} \mp 2\, e^{-\Gamma q t} \cos(\Delta M_q t) \right]$$

and Γ_f is the unevolved $B^0_q \to f$ rate

Rate for $\overset{(-)}{B}{}^0_q(t) \to \overline{f}$ follows $\quad \Gamma_f \to \Gamma_{\overline{f}}, \quad \xi^{(q)}_f \to \xi^{(q)}_{\overline{f}}$

$$\xi^{(q)}_f = e^{-i\Theta^{(q)}_{M_{12}}} \frac{A(\overline{B^0_q} \to f)}{A(B^0_q \to f)} \qquad \xi^{(q)}_{\overline{f}} = e^{-i\Theta^{(q)}_{M_{12}}} \frac{A(\overline{B^0_q} \to \overline{f})}{A(B^0_q \to \overline{f})}$$

$\Theta^{(q)}_{M_{12}}$ Is the CP violating weak phase

CP violation: mixing induced

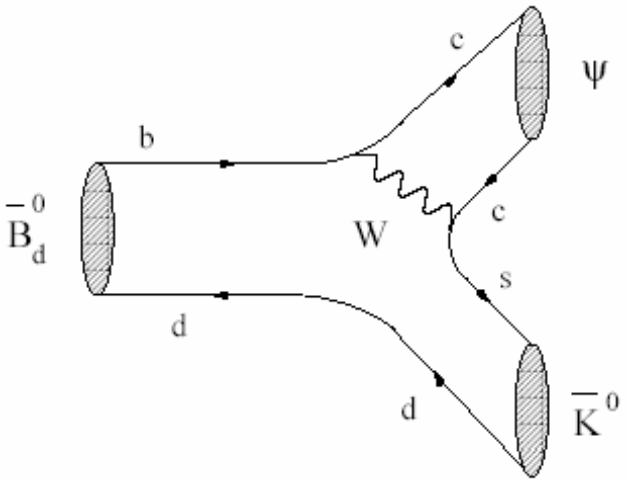
If :

- f is CP eigenstate
- the amplitude for direct CP, $\mathcal{A}_{CP}^{dir}$ =0
- the amplitude for due to $\Delta\Gamma$, $\mathcal{A}_{CP}^{\Delta\Gamma}$=0

$$a_{CP}(t) \equiv \frac{\Gamma(B_q^0(t) \to f) - \Gamma(\overline{B_q^0}(t) \to \overline{f})}{\Gamma(B_q^0(t) \to f) + \Gamma(\overline{B_q^0}(t) \to \overline{f})} = \pm \sin\phi \, \sin(\Delta M_q t)$$

"Gold-plated" mode: $B_d \to J/\psi\ K_s$

First decay where CP violation in B system has been seen
Precisely measured at B-factories



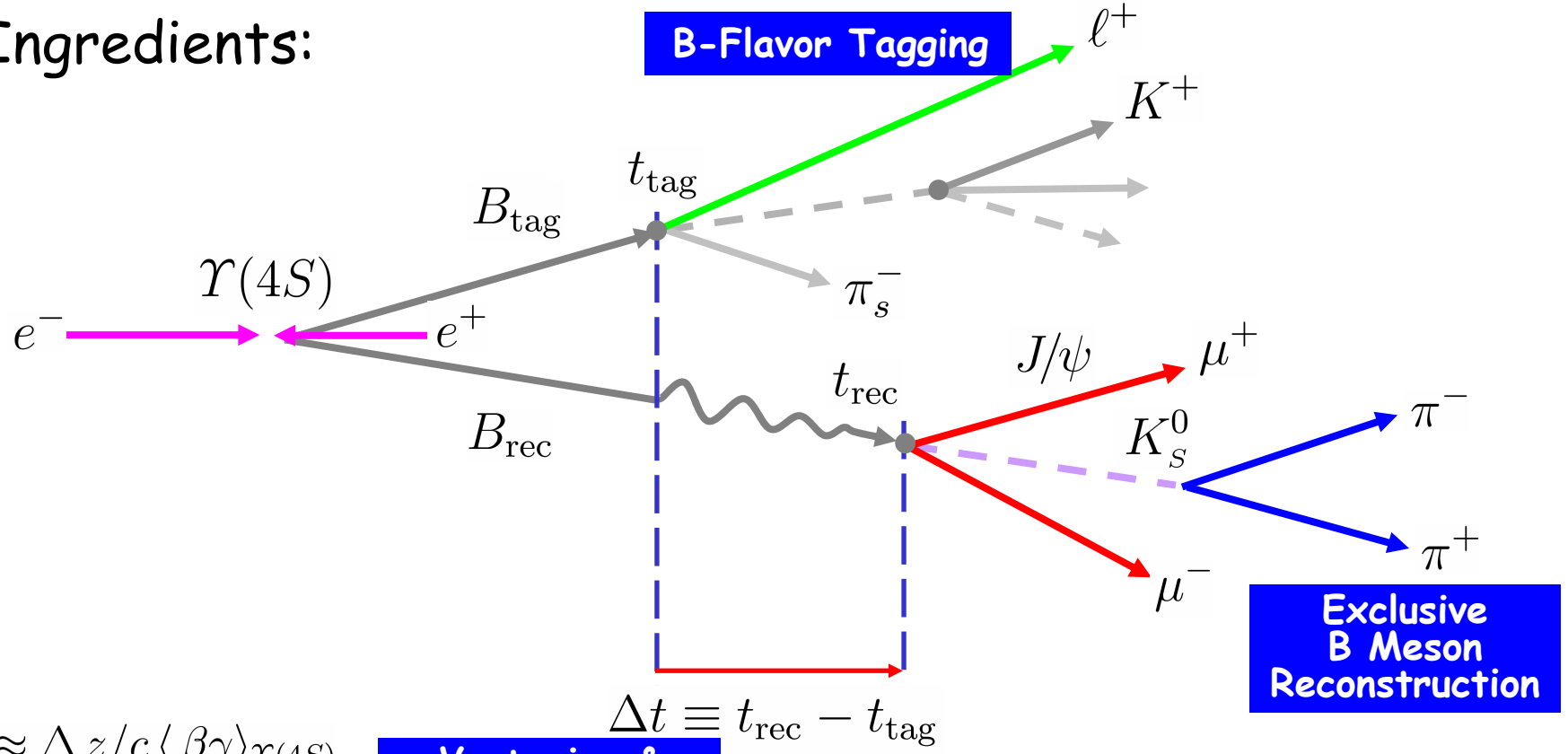
Almost no penguin contribution

$\sin\phi = -\sin 2\beta$

How to measure sin2β

$B^0 \to J/\psi K_s$ "Gold plated" other decays:
$B^0 \to J/\psi K_l$ $B^0 \to \eta_c(K_s K^+\pi^-)K_s$ $B^0 \to \chi_{c1}(J/\psi\gamma)K_s$

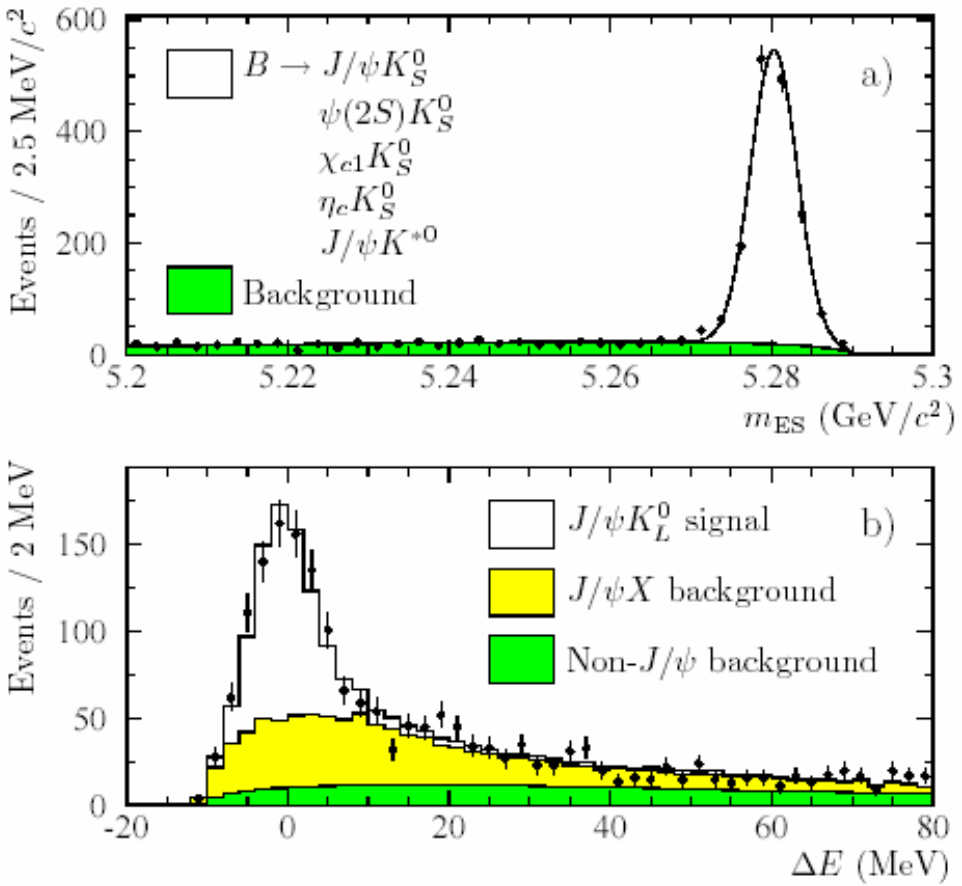
Ingredients:

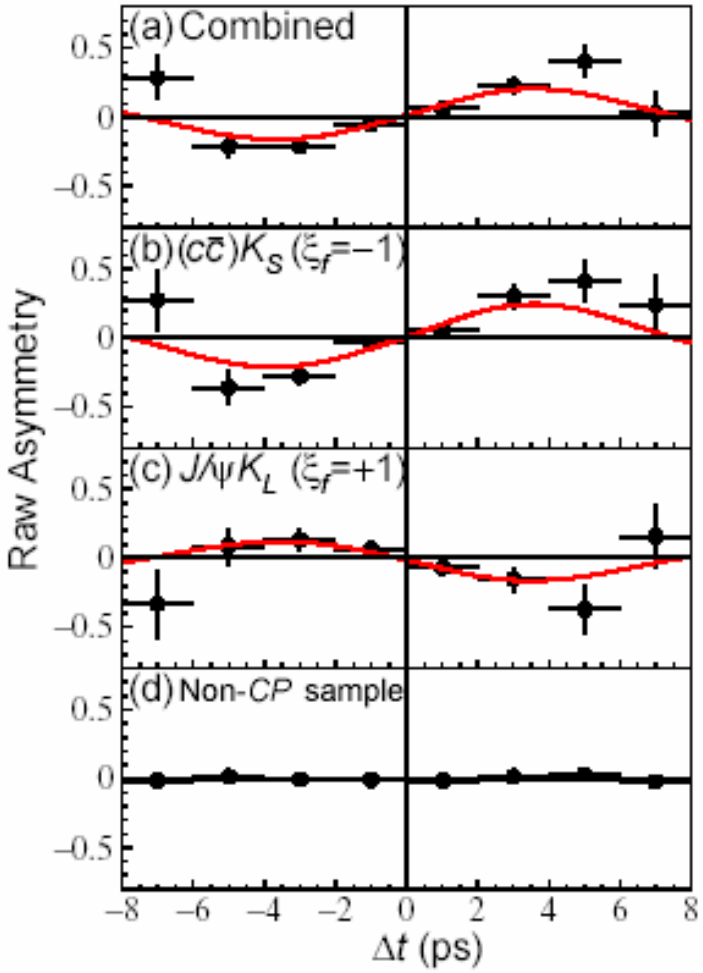


$\Delta t \approx \Delta z / c \langle \beta\gamma \rangle_{\Upsilon(4S)}$

$\langle \Delta z \rangle_{B\bar{B}} \approx 260\,\mu\text{m}$

sin2β: results





$\sin 2\beta = 0.741 \pm 0.067 \pm 0.033$ (BaBar)

$\sin 2\phi_1 = 0.719 \pm 0.074 \pm 0.035$ (Belle)

$\sin 2\beta_{WA} = 0.731 \pm 0.055$ (CL = 0.84)

sin2β: other decays

$B \to J/\psi K^* \left(K_S \pi^0 \right)$ Angular analysis, cos(2β)

$B \to J/\psi \pi^0$ Color+Cabibbo suppressed tree + penguin

$B \to \phi K_S$ b → s penguin

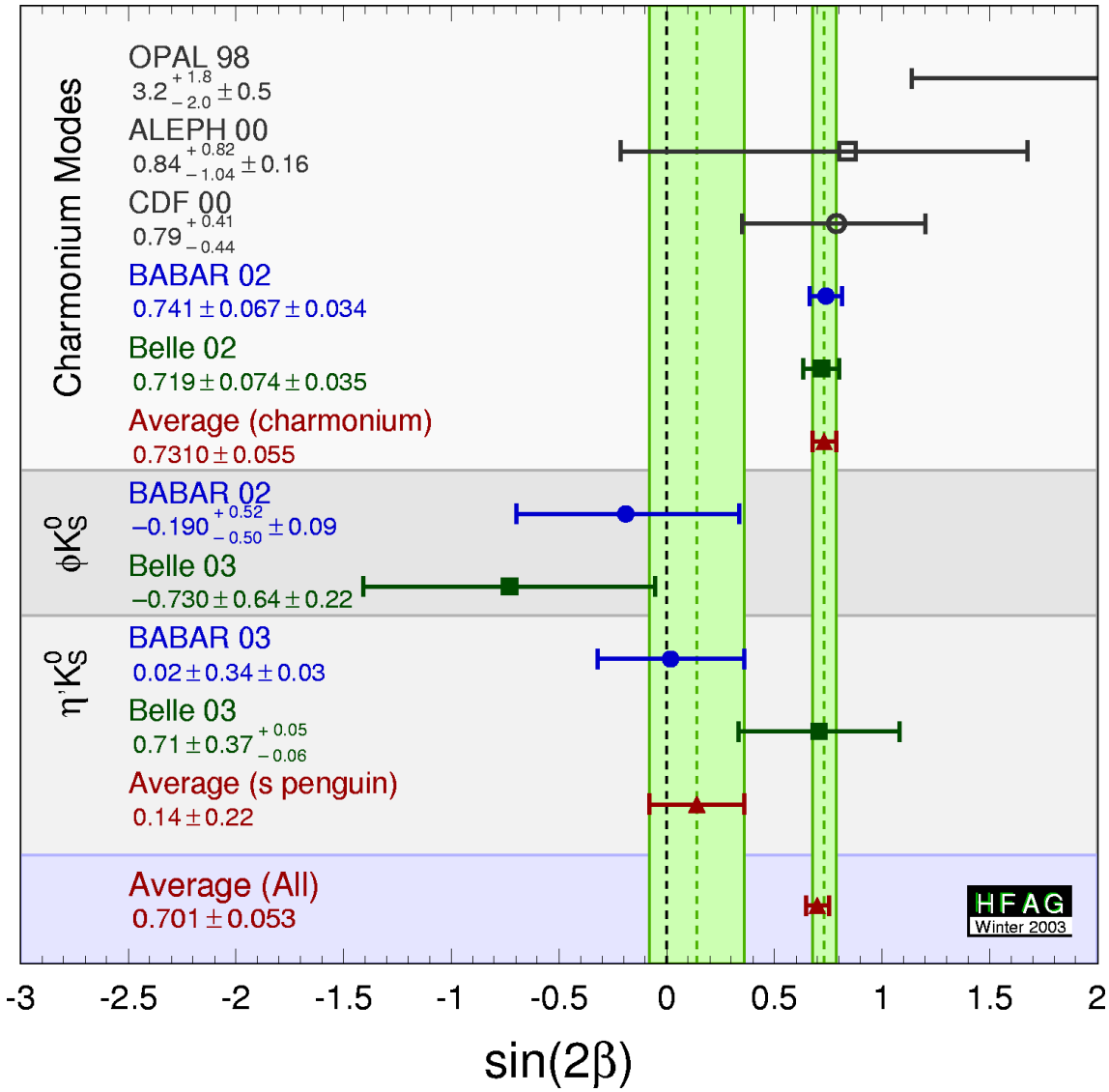
$B \to \eta' K_S$ b → s penguin + CKM suppressed tree

$B \to D^{*+} D^{*-}$ b→d Cabibbo suppressed tree + penguin, angular analysis

$B \to D^{*-} D^{+}$

$B \to D^{*+} D^{-}$ Cabibbo suppressed tree + non-CP eigenstate

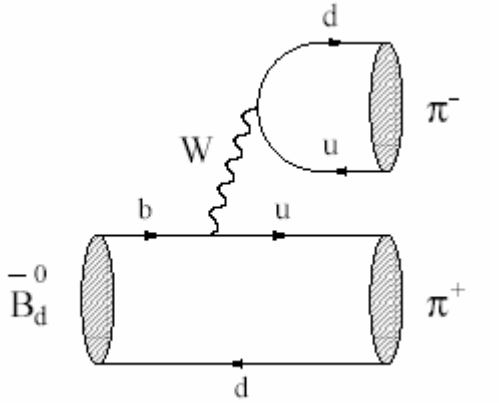
sin2β: comparison



- Time dependent CP fits @ B factories have reached maturity
- sin(2β) measurement with charmonium well established,
  - Consistent with constraint from indirect measurement
  - no longer limiting factor on CKM analysis
- Starting to explore other (rare) modes, but
  - …need more data!

How to reach sin2α

$B^0 \to \pi^+\pi^-$ more decay amplitudes:



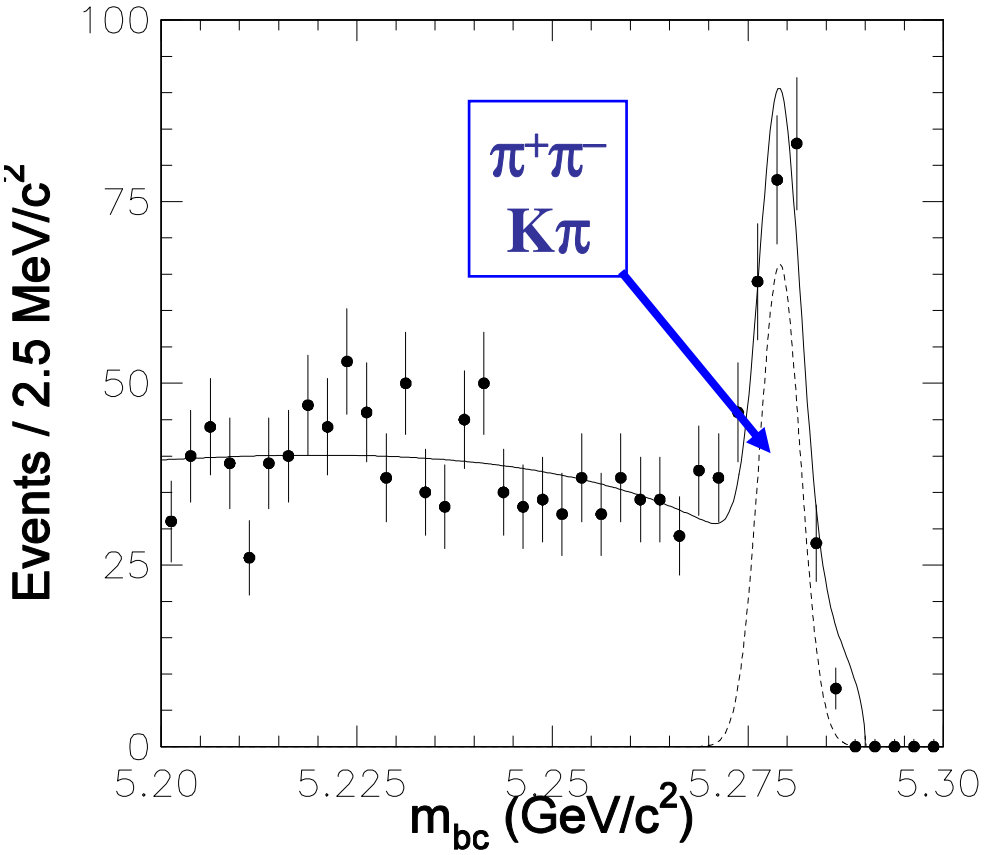
+

$$Asym(\Delta t) = \frac{N(B^0_{tag}) - N(\bar{B}^0_{tag})}{N(B^0_{tag}) + N(\bar{B}^0_{tag})}$$

$$= S_{\pi\pi} \sin(\Delta m_d \Delta t) - C_{\pi\pi} \cos(\Delta m_d \Delta t)$$

The analysis follows the previous steps

B→ππ results



Belle

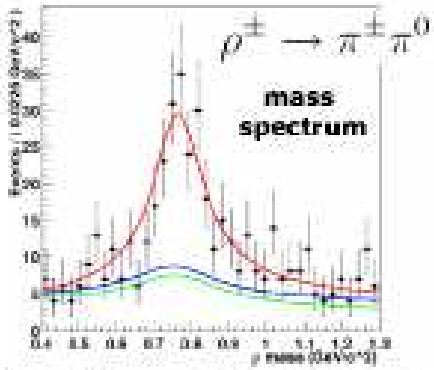
$$S_{\pi\pi} = 0.02 \pm 0.34 \pm 0.05$$
$$C_{\pi\pi} = -0.30 \pm 0.25 \pm 0.04$$

$$A_{\pi\pi} = +0.77 \pm 0.27(stat) \pm 0.08(syst) = -C_{\pi\pi}$$
$$S_{\pi\pi} = -1.23 \pm 0.41(stat)^{+0.08}_{-0.07}(syst)$$

Belle

B→ρπ and B→ρK

measure a_{CP} directly, even with penguins using full Dalitz-plot analysis

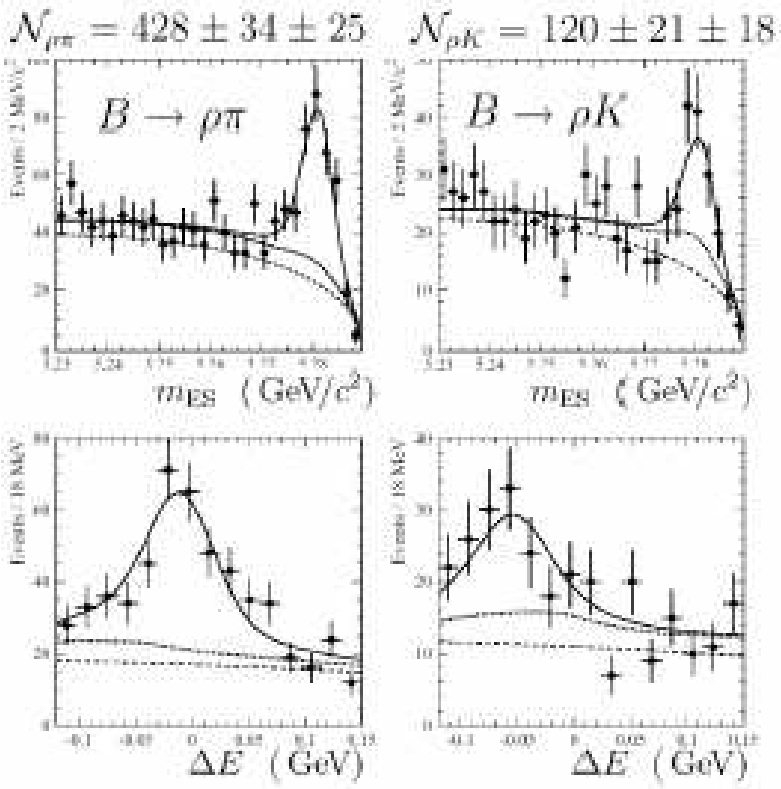


BR of ρπ and ρK

$$B(B \to \rho^{\pm}\pi^{\mp}) = (22.6 \pm 1.8 \pm 2.2) \times 10^{-6}$$

$$B(B \to \rho^{\pm}K^{\mp}) = (7.3^{+1.3}_{-1.2} \pm 1.3) \times 10^{-6}$$

$C_{\rho\pi}$ = +0.36±0.18±0.04
$S_{\rho\pi}$ = +0.19±0.24±0.03



The last angle: γ

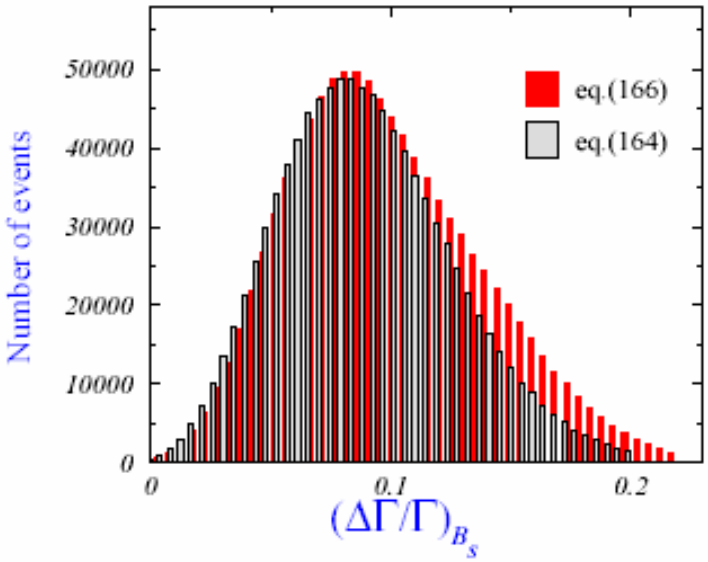
Here even more difficulties. Several decays proposed:

$B^{\pm}$	$D_{CP}{}^{0}K^{\pm}$	All Amplitudes combinations
B^{0}	$K\pi$	Rates and asymmetries
B_d	$\pi^{+}\pi^{-}$ B_s $K^{+}K^{-}$	Time dependent asymmetries
Bs	DsK-	Time dependent asymmetries
Bd	D*π+	

$B_{s,d}$ $\Delta\Gamma/\Gamma$

Definition: $1/\tau_{B_s}=\Gamma=(\Gamma_{long}+\Gamma_{short})/2 \quad \Delta\Gamma=\Gamma_{long}-\Gamma_{short}$

B_s Theoretical prediction:



B_s $\Delta\Gamma/\Gamma$

L3 Inclusive B_s lifetime

$$\tau_{Bs}^{incl} = \frac{1}{\Gamma}\frac{1}{1-(\frac{\Delta\Gamma}{2\Gamma})^2} \qquad \frac{1}{\Gamma} = 1.49 \pm 0.06 \text{ ps}$$

$\Delta\Gamma/\Gamma < 0.67$ @ 95% C.L.

CDF $B_s \rightarrow J/\psi\,\phi$ (almost CP even $\Rightarrow f_{short} \sim 1$)

$$P_{J/\psi\phi}(t) = f_{short}\Gamma^{short}\exp(-\Gamma^{short}t)+(1-f_{short})\Gamma^{short}\exp(-\Gamma^{long}t)$$

Build likelihood, $\mathscr{L}$, by using $P_{J/\psi\phi}(t)$

$f_{short} = 0.84 \pm 0.16$ $\frac{1}{\Gamma}$ constrained to τ_{Bd}

Measurement $\tau_{Bs} = 1.34^{+0.23}_{-0.19} \pm 0.05$ $\Delta\Gamma/\Gamma = 0.36^{+0.50}_{-0.42}$

B_s $\Delta\Gamma/\Gamma$

Delphi $B_s \to D_s l \nu X$

$P_{semi}(t)=(\Gamma_{long}\Gamma_{short}/(\Gamma_{long}+\Gamma_{short}))(\exp(-\Gamma^{short}t)+\exp(-\Gamma^{long}t))$

$\mathscr{L}$ scan as function $\frac{1}{\Gamma}$ constrained to τ_{B_d}, and $\Delta\Gamma/\Gamma$

$\Delta\Gamma/\Gamma < 0.47$ @ 95% C.L.

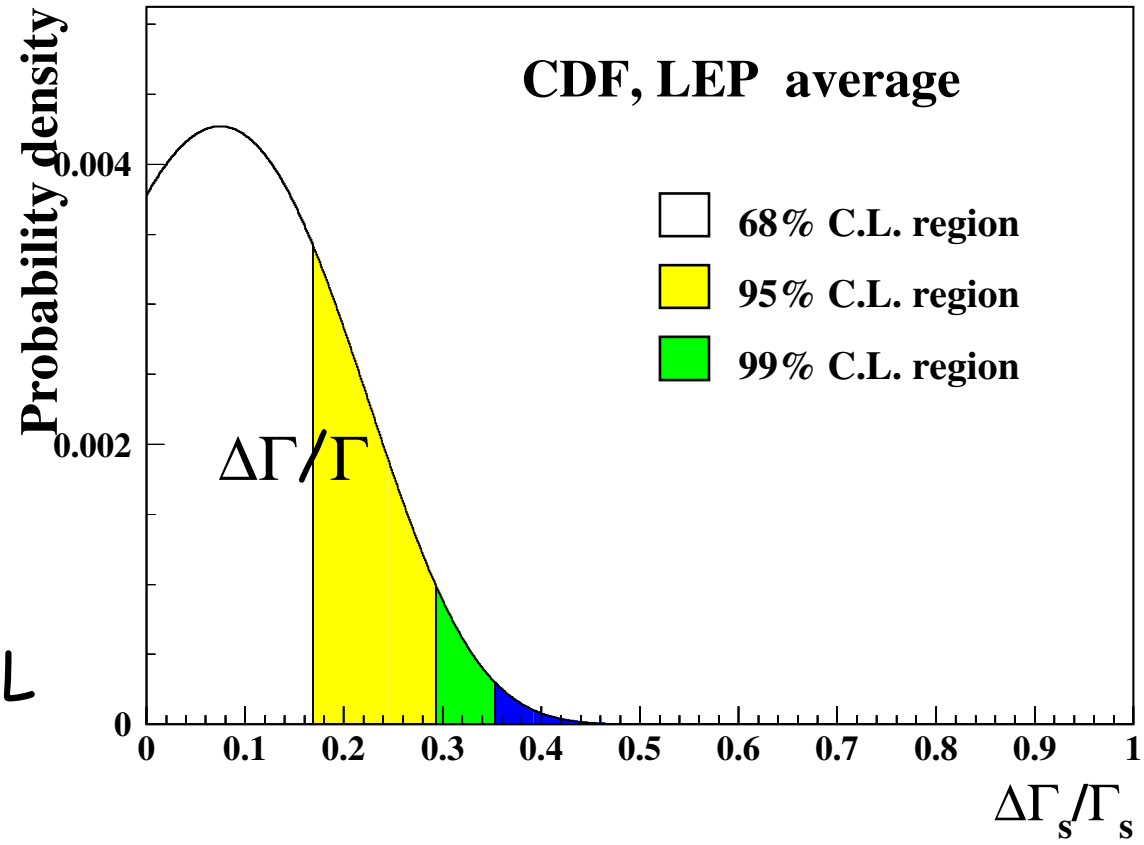
Delphi $B_s \to D_s^-$ −hadron (π,k)

$D_s^- \to \phi\pi^-$ $D_s^- \to k^{*0}k^-$ $f_{DsDs}=22\pm7\%$ (fraction of $D_s^{(*)+} D_s^{(*)-}$)

$P_{Ds-h}(t)=f_{DsDs}\Gamma_{short}\exp(-\Gamma_{short}t) + (1-f_{DsDs})P_{semi}(t)$

Scan $\mathscr{L}(1/\Gamma, \Delta\Gamma/\Gamma)$ $1/\Gamma$ const. τ_{B_d} $\Delta\Gamma/\Gamma < 0.70$ @ 95% C.L.

B_s $\Delta\Gamma/\Gamma$ Combined limit



$\Delta\Gamma/\Gamma < 0.29$ at 95% CL

$\Delta\Gamma/\Gamma = 0.07\ ^{+0.09}_{-0.07}$

B_s $\Delta\Gamma/\Gamma$ the future

CDF 2fb^{-1}:

4,000 $B_s \rightarrow J/\psi\phi$ $\sigma(\Delta\Gamma/\Gamma)=0.05$ if $CP_{even}= 0.77$
$\sigma(\Delta\Gamma/\Gamma)=0.08$ if $CP_{even}= 0.5$

75,000 $B_s \rightarrow D_s\pi$ measure $1/\Gamma$

2,500 $B_s \rightarrow D^+_s D^-_s$ CP even combined with $1/\Gamma$
$\sigma(\Delta\Gamma/\Gamma)=0.06$

More precise measurements at future experiments

B_d $\Delta\Gamma/\Gamma$

Theoretical prediction: $\Delta\Gamma_d/\Gamma_d = (3.0^{+0.9}_{-1.4}) \times 10^{-3}$

If bigger $\Rightarrow$ new physics

CP asymmetry for $B^0 \to J/\psi K_s$

$$\mathcal{A}_{CP} = \frac{\Gamma[\overline{\mathrm{B}}_d(t) \to J/\psi \mathrm{K}_S] - \Gamma[B_d(t) \to J/\psi \mathrm{K}_S]}{\Gamma[\overline{\mathrm{B}}_d(t) \to J/\psi \mathrm{K}_S] + \Gamma[B_d(t) \to J/\psi \mathrm{K}_S]} \approx \sin(\Delta M_d t)\sin(2\beta)$$

If $\Delta\Gamma \approx 0$

$$\begin{aligned}\mathcal{A}_{CP} &= \sin(\Delta M_d t)\sin(2\beta)\left[1 - \sinh\left(\frac{\Delta\Gamma_d t}{2}\right)\cos(2\beta)\right] \\ &+2\mathrm{Re}(\bar{\epsilon})\left[-1 + \sin^2(2\beta)\sin^2(\Delta M_d t) - \cos(\Delta M_d t)\right] \\ &+2\mathrm{Im}(\bar{\epsilon})\cos(2\beta)\sin(\Delta M_d t)\ .\end{aligned}$$

If $\Delta\Gamma \neq 0$

Possible constraints from B factories measurements