Heavy Flavor Physics at SLD

Stephane Willocq

University of Massachusetts, Amherst

- SLC/SLD
- τ_{B^+}, τ_{B^0}
- b fragm.
- K tag
- B_s mixing

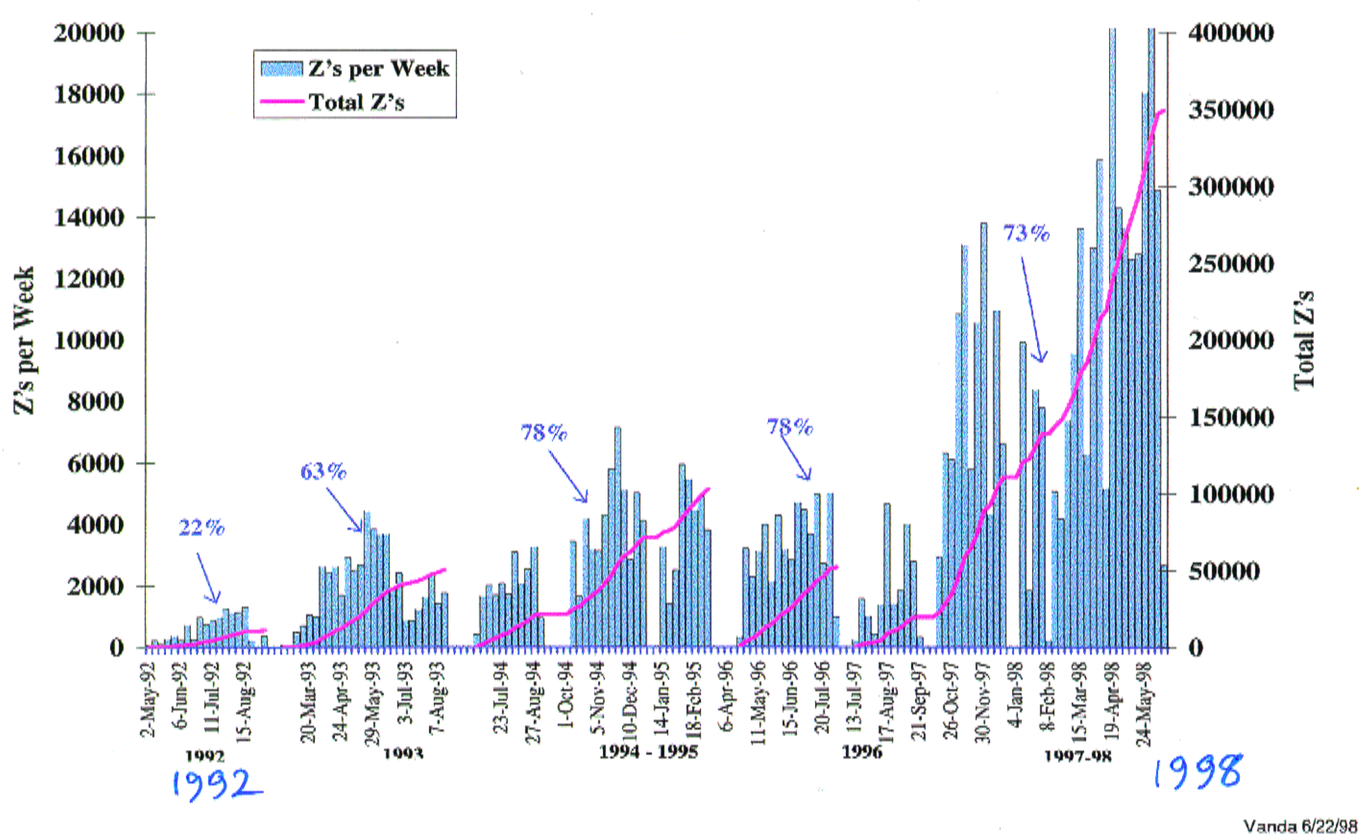
B Physics at the Tevatron Workshop

23-25 September 1999

The SLAC Linear Collider (SLC)

- *First & only linear collider* $e^+ e^- \rightarrow Z^0 \rightarrow f \bar{f}$
- *1997-98 performance* $L_{max} = 3 \times 10^{30}\ cm^{-2}\ s^{-1}$ *near design*

1992 - 1998 SLD Polarized Beam Running



- *1992-96: 200 K* $Z^0 \rightarrow q\bar{q}$
- *1997-98: 350 K* $Z^0 \rightarrow q\bar{q}$

B Physics: total # of b hadrons produced @SLD = 240 K

Compare with CLEO: 20 M, LEP: 1.7 M / expt, CDF: 600 M (before trigger)

At the Z pole: 40% B^+, 40% B^0, 12% B_s, 8% b baryons

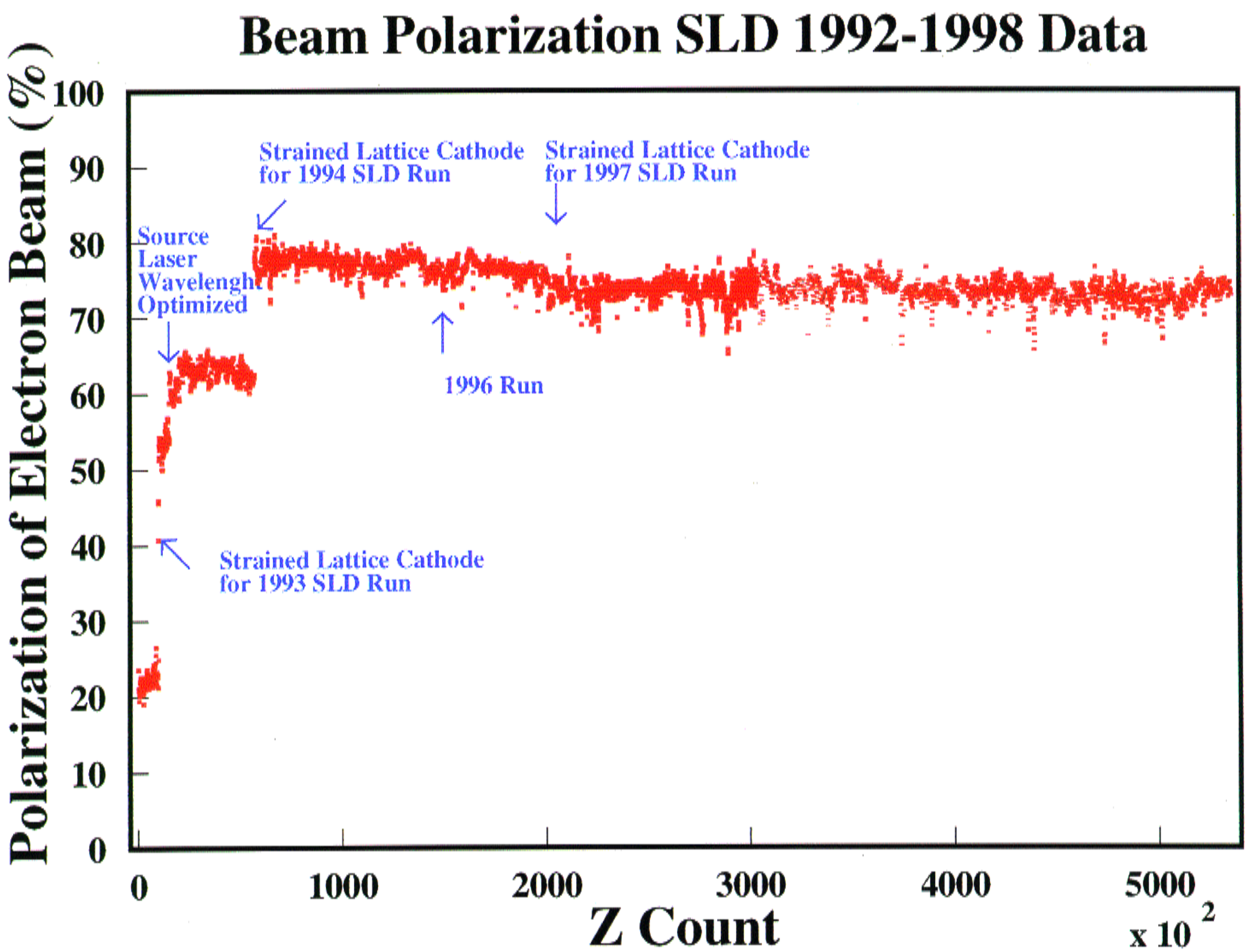
$\langle p_B \rangle = 35$ GeV/c and $\langle L \rangle = 3$ mm

Unique Characteristics of SLC/SLD Environment

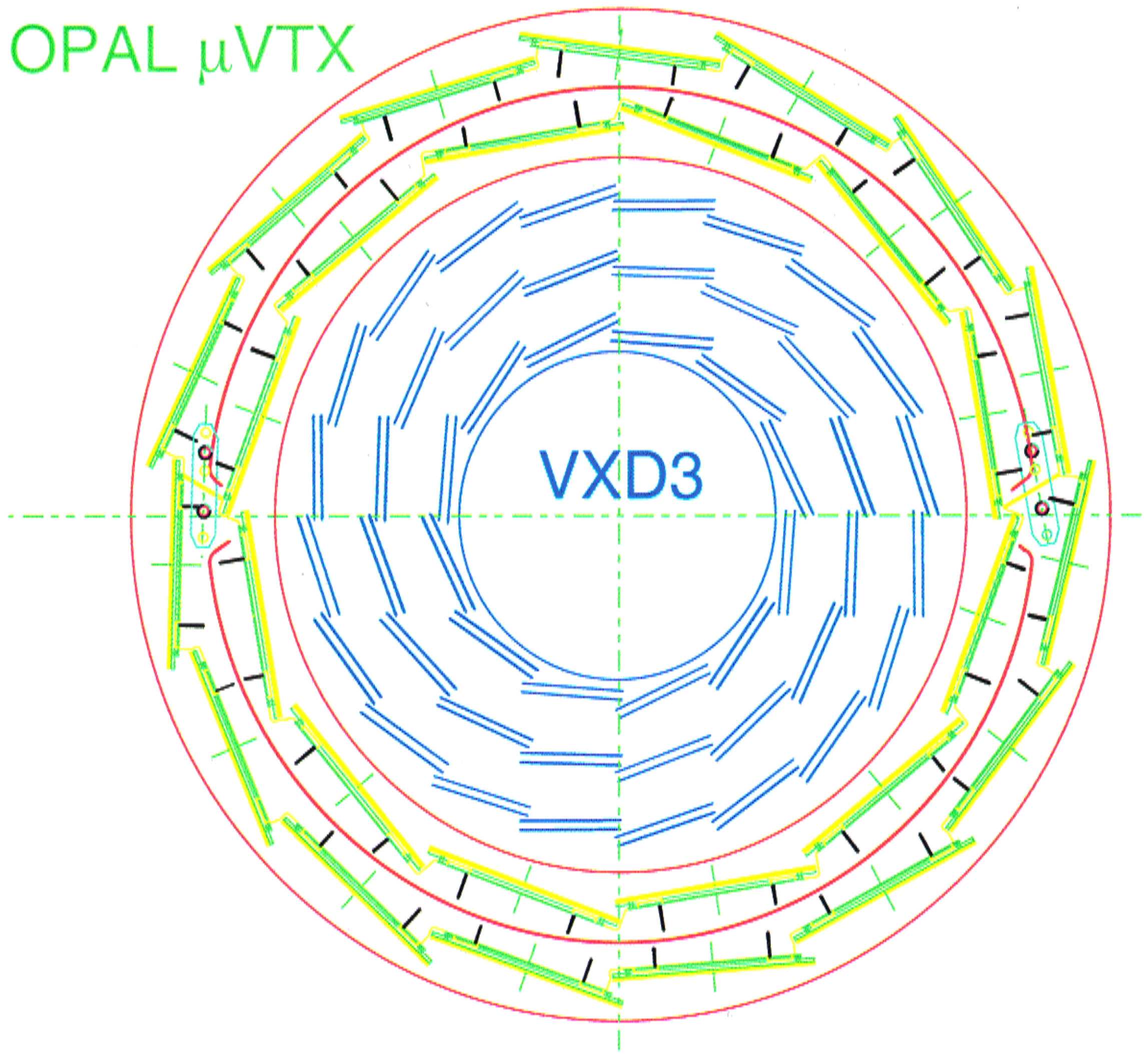
- Small and stable IP: 1.5 μm * 0.8 μm * 700 μm
  (↑ horizontal, ↑ vertical, ↑ longitudinal)

- *Electron beam polarization: avg. longitudinal pol. = 73%*

  pol. uncertainty ≈ 0.5%



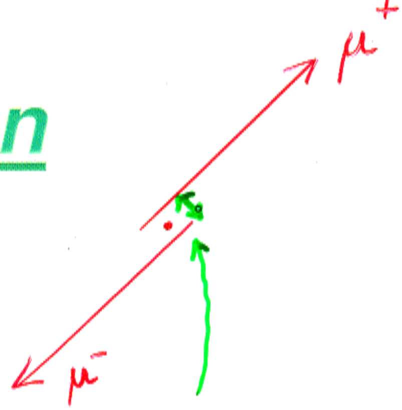
The SLD Vertex Detector (VXD3)



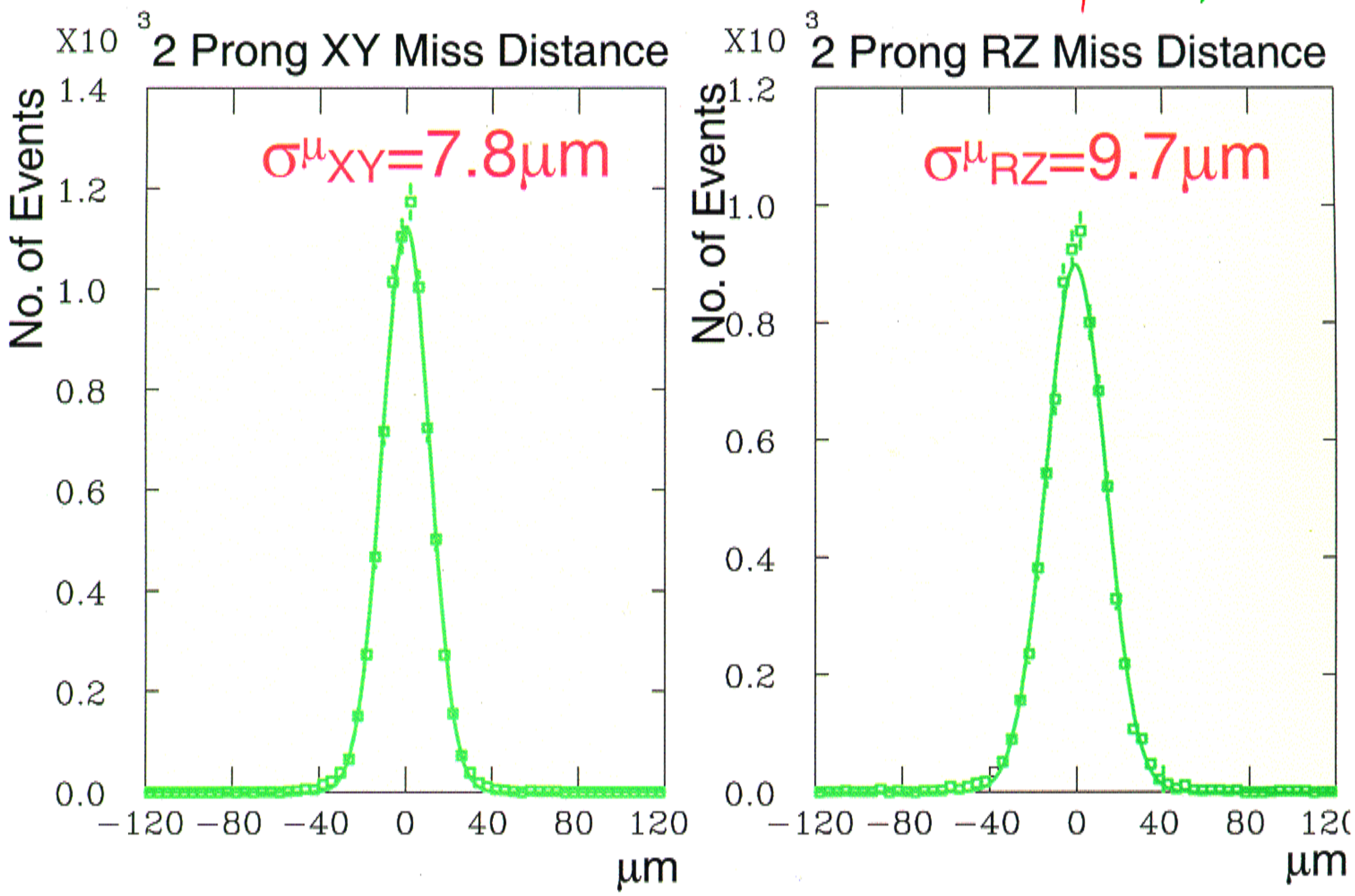
VXD3: CCD pixel vertex detector

- $\geq$ 3 space points / track (pattern recognition)
- inner radius = 2.7 cm
- max cosθ = 0.90
- X^0/layer = 0.40%
- local single-hit resolution = 3.8 μm

Tracking Resolution



Use Z → $\mu^+ \mu^-$ data

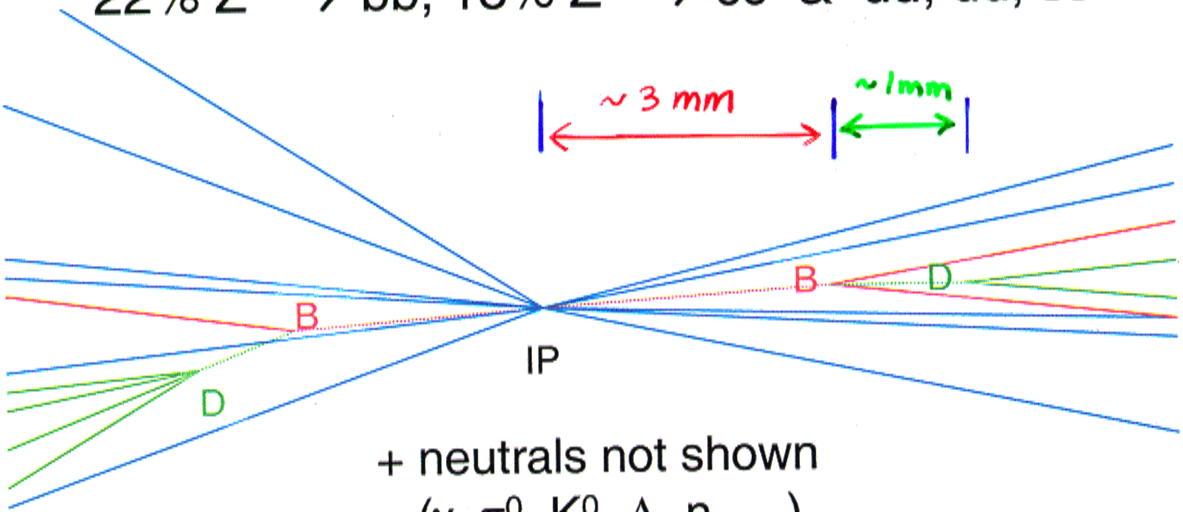


- $\sigma_{XY} = 7.8\ \mu m \oplus 33\ \mu m / p \sin^{3/2} \theta$
- $\sigma_{RZ} = 9.7\ \mu m \oplus 33\ \mu m / p \sin^{3/2} \theta$
- IP measured w/ resolution $4 \pm 2\ \mu m$ (XY view)

Experimental Procedure

- $Z \longrightarrow$ hadrons selection is pure and efficient

  22% $Z \longrightarrow b\bar{b}$, 18% $Z \longrightarrow c\bar{c}$ & $u\bar{u}$, $d\bar{d}$, $s\bar{s}$



+ neutrals not shown
(γ, π^0, K^0, Λ, n, …)

- What do we want to know?
  - $Z \rightarrow b\bar{b}$ event?
  - B decay length, momentum $\Rightarrow$ proper time
  - B or $\bar{B}$ flavor?
  - Decay mode $\Rightarrow$ B^+, B^0, Bs or b-baryon?

  Option 1: Full reconstruction of B decay

  Option 2: Partial reconstruction (full D recon)
  $\Rightarrow$ rely on kinematics and vertexing

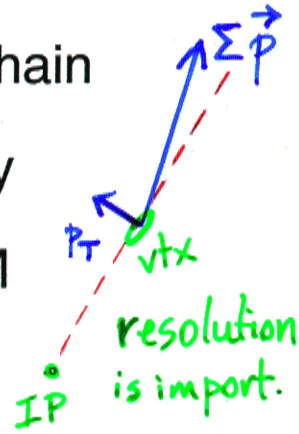
  Option 3: ***Inclusive Topological reconstruction***
  $\Rightarrow$ rely almost entirely on vertexing
  $\Rightarrow$ high efficiency but requires excellent tracking

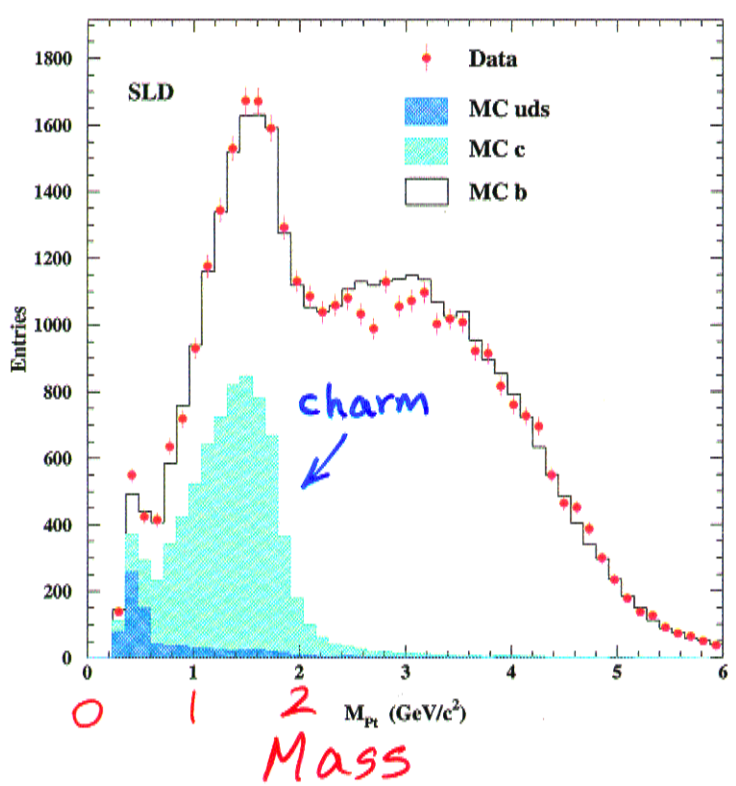
Topological Vertexing

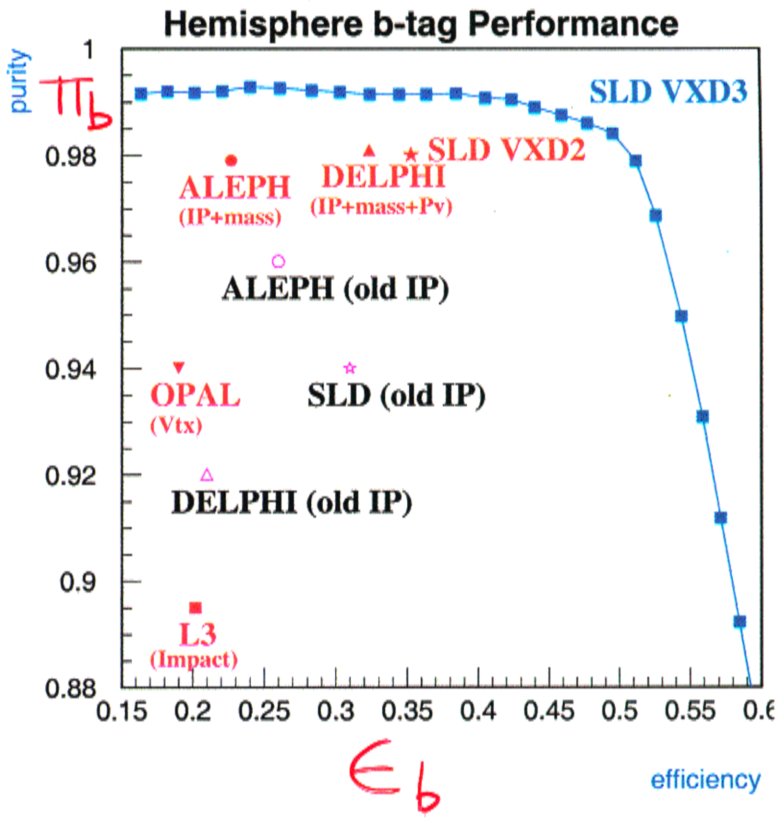
GOAL: Find all charged tracks from B decay chain

- Find 3D-regions of high track overlap density
- Compute secondary vertex invariant mass M

  & apply partial correction for missing p_T







- Pure and highly efficient ***b tag***
- For M > 2 GeV:

  Efficiency = 50% (measured from data)

  Purity = 98%

Measurement of $R_c = \Gamma(Z \to c\bar{c}) / \Gamma(Z \to \text{hadrons})$

- Select clean sample of $Z \to$ hadrons events

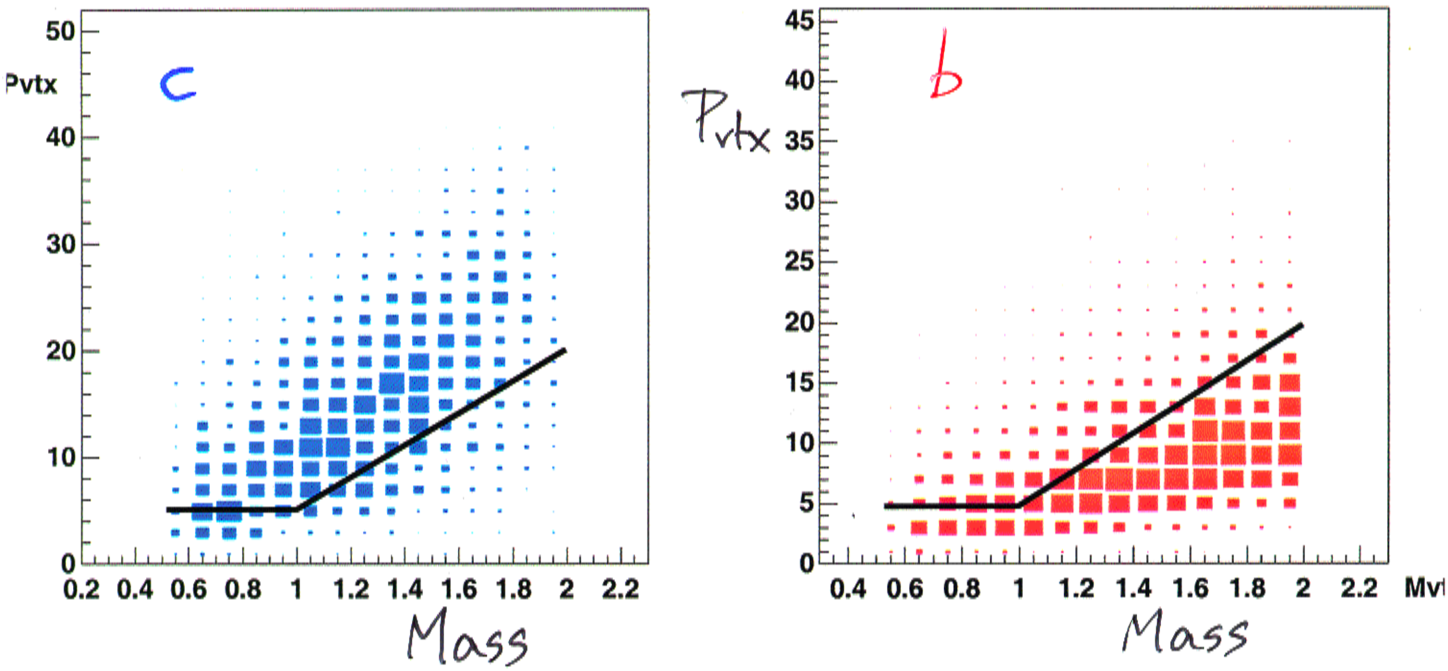
- Topological mass tag in each event hemisphere (as for R_b)

- c tag $0.55 < M < 2.0$ GeV
  b tag $M > 2.0$ GeV

- Measure rate of single c or b, double c or b, and mixed tags

  $\Rightarrow$ Determine R_b, R_c, ε_b, η_b, η_c from data

- *Improve c tag* : vertex momentum vs. mass



$\Rightarrow$ Efficiency $\eta_c = 15.4 \pm 1.3$ % and $\Pi_c = 69 \pm 2$ % from 97 data

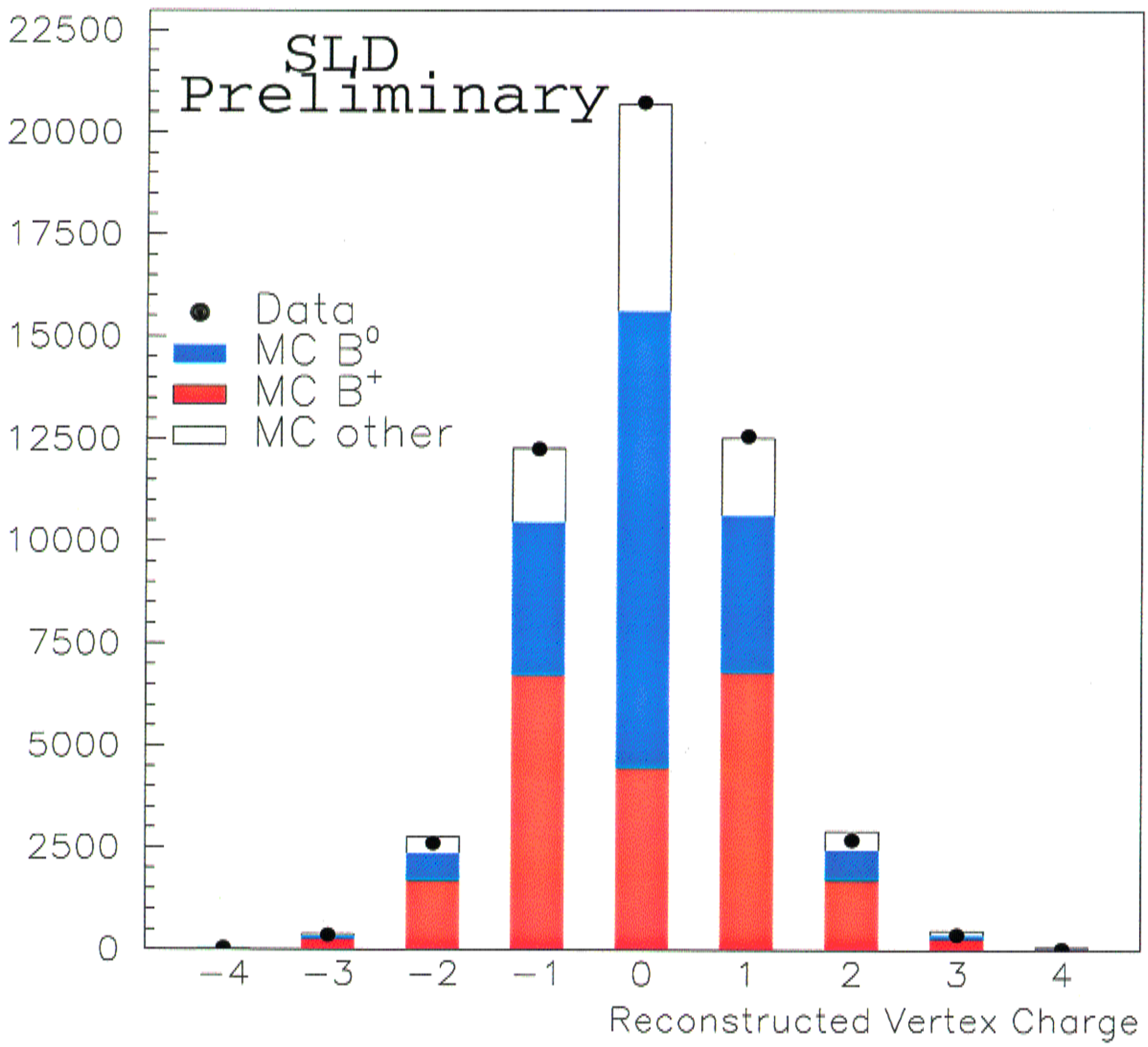
$\Rightarrow R_c = 0.1685 \pm 0.0047$ (stat) ± 0.0043 (syst) 93-98 Prelim.

• Cuts: 2.0 < M < 5.2 GeV & L > 1 mm & radius < 2.2 cm

⇒ *51,634 reconstructed vertices in 1997-98 data* (350K Z^0)

→ $B^+ : B^0$ separation directly from measured total charge

30903 charged (|Q| = 1, 2, 3) and 20731 neutral (Q = 0)



VXD3: Neutral → $B^0 : B^+ = 2.5 : 1$

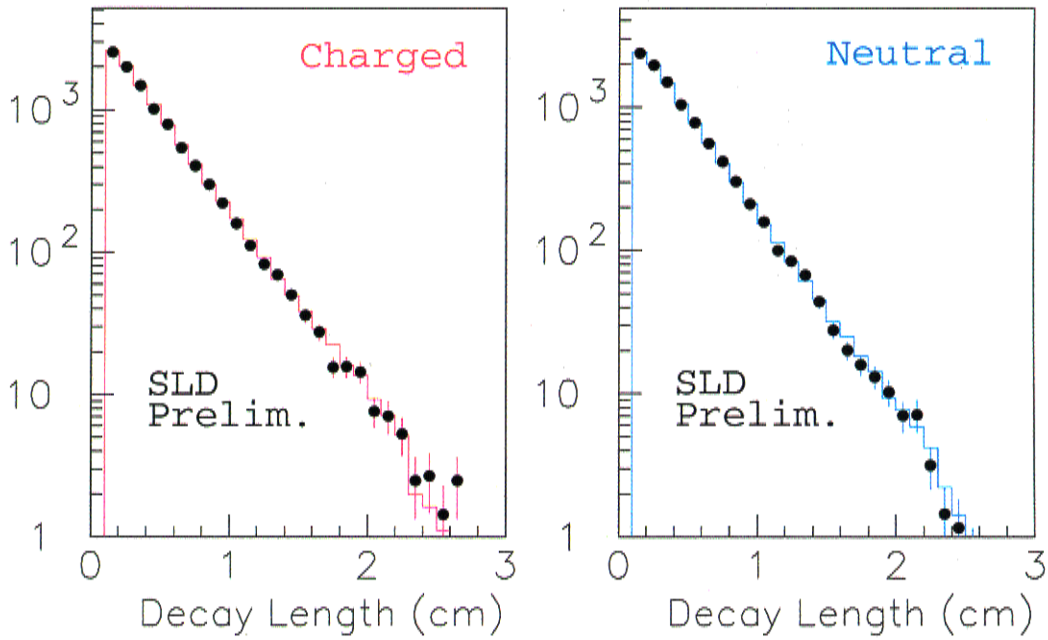
Charged → $B^+ : B^0 = 1.8 : 1$

{ enhanced by mass dependence + initial state info ⇒ ~3:1

▪ S. Willocq (UMass)

- Fit charged and neutral decay length distributions *simultaneously* using binned max likelihood

SLD 97-98 Data



Preliminary results for 1993-98 data:

$$\tau(B^+) = 1.623 \pm 0.020 \text{ (stat)} \pm 0.034 \text{ (syst) ps}$$

$$\tau(B^0) = 1.589 \pm 0.021 \text{ (stat)} \pm 0.043 \text{ (syst) ps}$$

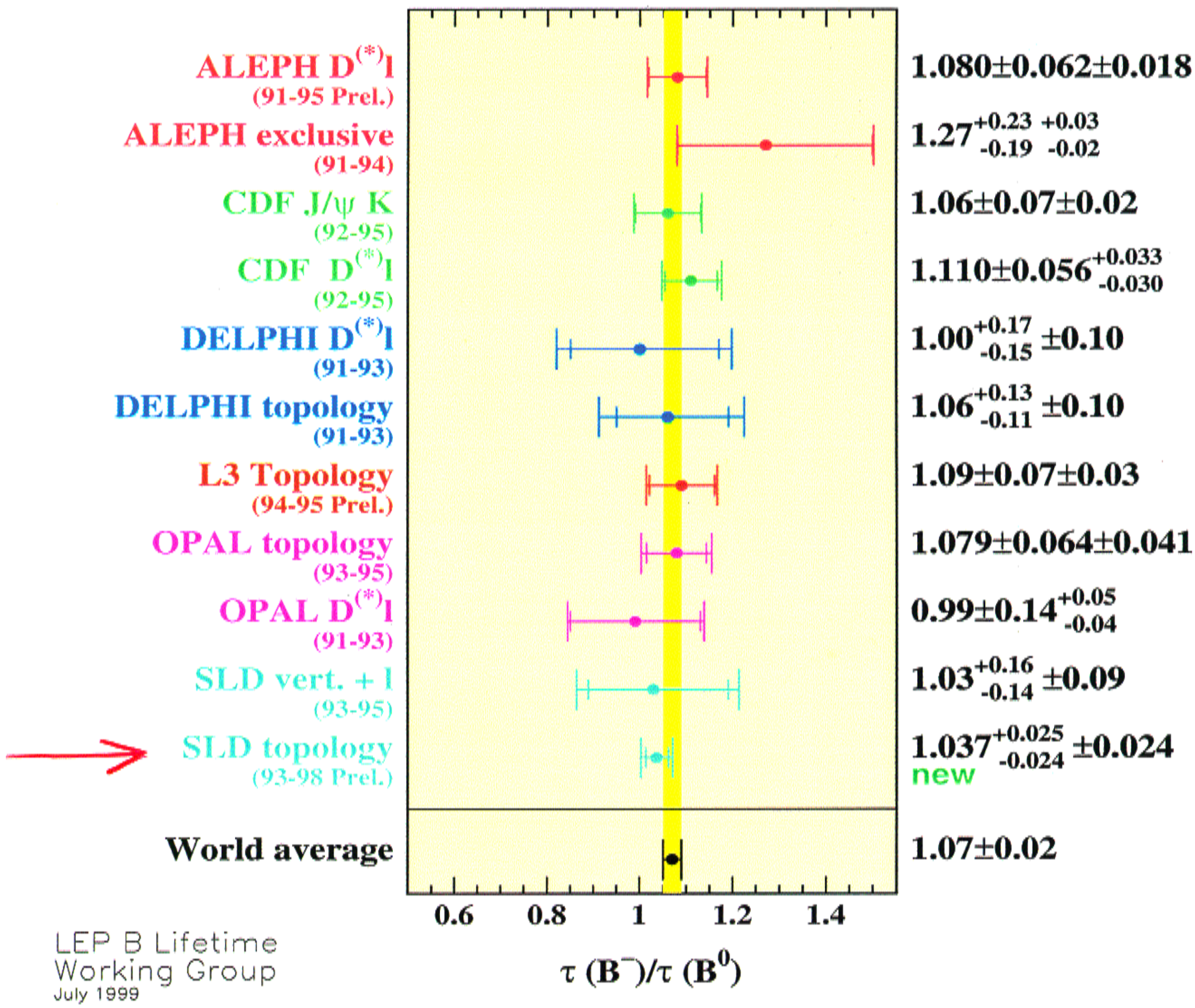
$$\tau(B^+) / \tau(B^0) = 1.037 \,^{+0.025}_{-0.024} \text{ (stat)} \pm 0.024 \text{ (syst)}$$

Main systematic uncertainties in $\tau(B^+) / \tau(B^0)$:

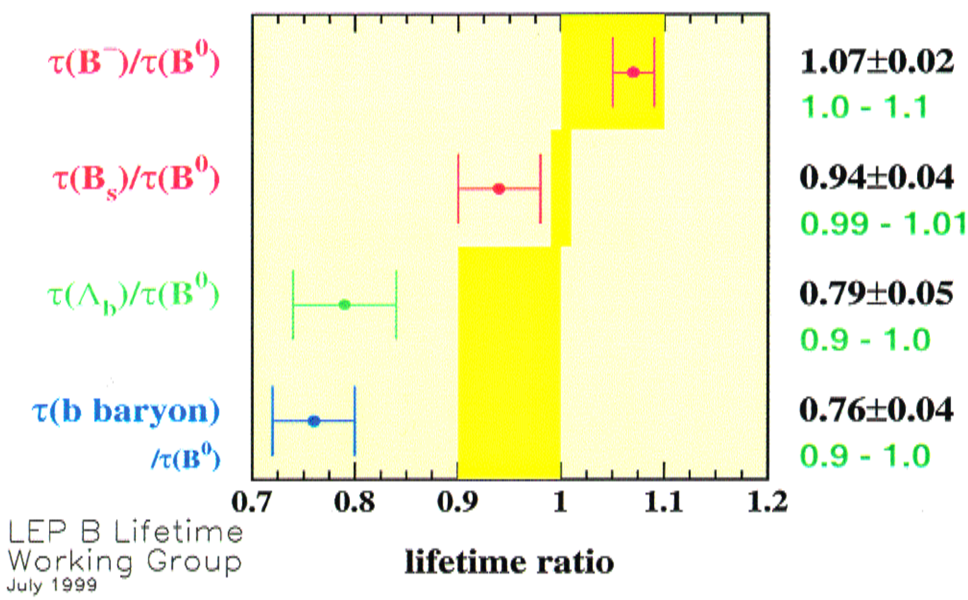
Detector	0.006
$\tau(B_s)$	0.009
f(b-baryons)	0.008
BR($B \to DX, DDX$)	0.016
D decay multiplicity	0.010
MC statistics	0.006

⇒ b fragmentation $\langle x_E \rangle = 0.714 \pm 0.008$ ⇒ $\Delta\tau = \pm 0.025$ ps

⇒ Can be reduced by measuring B momentum (proper time) or by using track *impact parameters*



ALEPH D(*)l (91-95 Prel.)
ALEPH exclusive (91-94)
CDF J/ψ K (92-95)
CDF D(*)l (92-95)
DELPHI D(*)l (91-93)
DELPHI topology (91-93)
L3 Topology (94-95 Prel.)
OPAL topology (93-95)
OPAL D(*)l (91-93)
SLD vert. + l (93-95)
SLD topology (93-98 Prel.)
World average
1.080±0.062±0.018
1.27 +0.23 -0.19 +0.03 -0.02
1.06±0.07±0.02
1.110±0.056 +0.033 -0.030
1.00 +0.17 -0.15 ±0.10
1.06 +0.13 -0.11 ±0.10
1.09±0.07±0.03
1.079±0.064±0.041
0.99±0.14 +0.05 -0.04
1.03 +0.16 -0.14 ±0.09
1.037 +0.025 -0.024 ±0.024
new
1.07±0.02
0.6
0.8
1
1.2
1.4
τ (B⁻)/τ (B⁰)
LEP B Lifetime
Working Group
July 1999

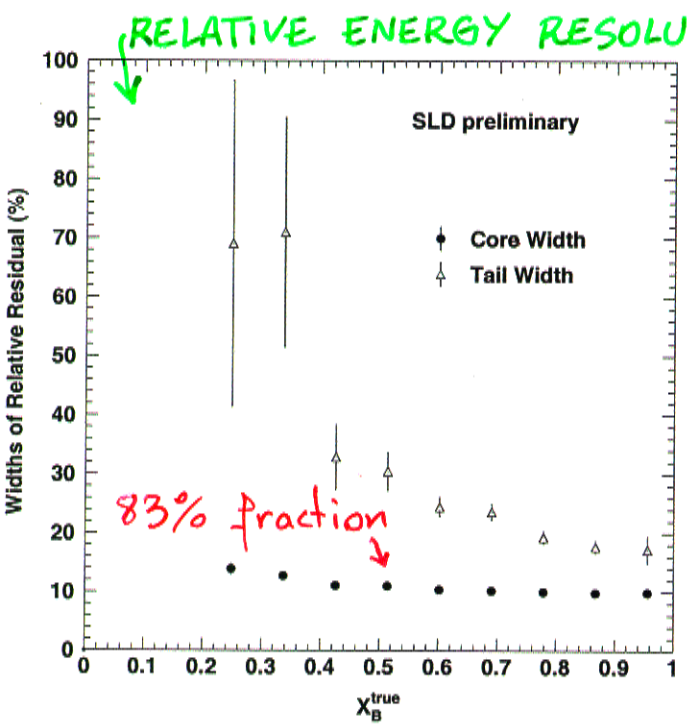


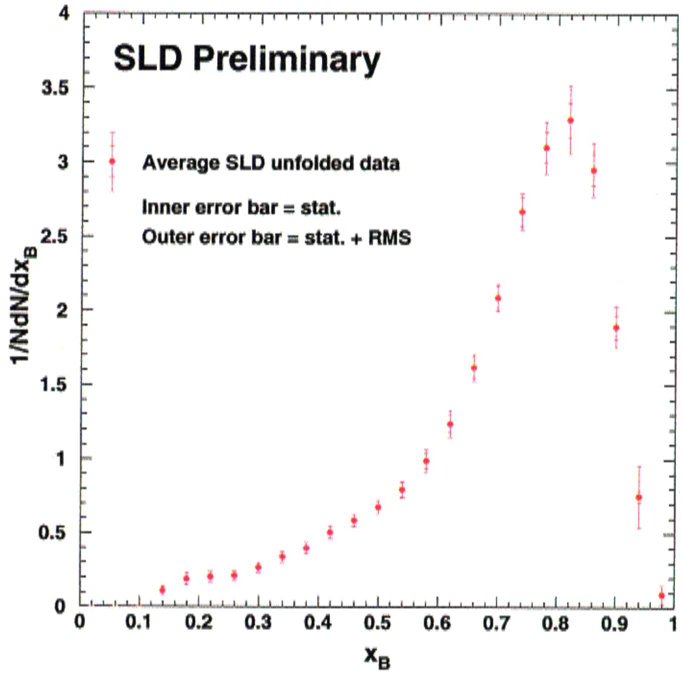
τ(B⁻)/τ(B⁰)
τ(Bs)/τ(B⁰)
τ(Λb)/τ(B⁰)
τ(b baryon) /τ(B⁰)
1.07±0.02
1.0 - 1.1
0.94±0.04
0.99 - 1.01
0.79±0.05
0.9 - 1.0
0.76±0.04
0.9 - 1.0
0.7
0.8
0.9
1
1.1
1.2
lifetime ratio
LEP B Lifetime
Working Group
July 1999

b fragmentation function

- Determine $\langle x_B \rangle$ $(x_B = E_B / E_{beam})$
  and shape of b-hadron energy distribution
- Test of QCD and fragmentation models
- Need high efficiency and good energy resolution over full energy range

⟹ Use topological vertexing and determine E_B in subsample with low missing mass (tracks only)





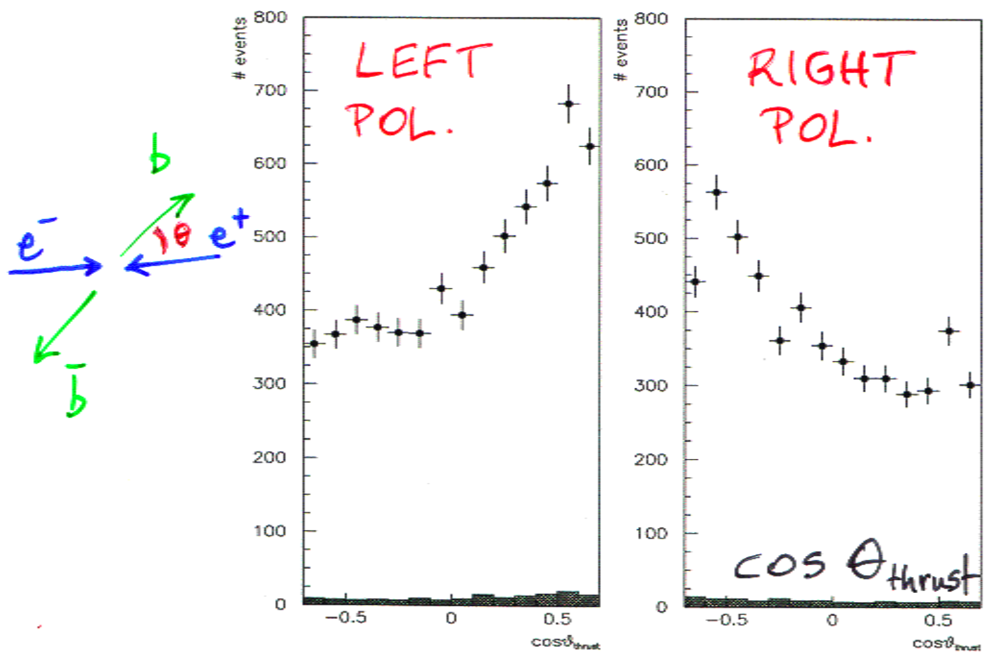
$\langle x_B \rangle = 0.714 \pm 0.005(stat) \pm 0.007(syst) \pm 0.002(model)$

Preliminary 150K Z decays (1996-97 data)

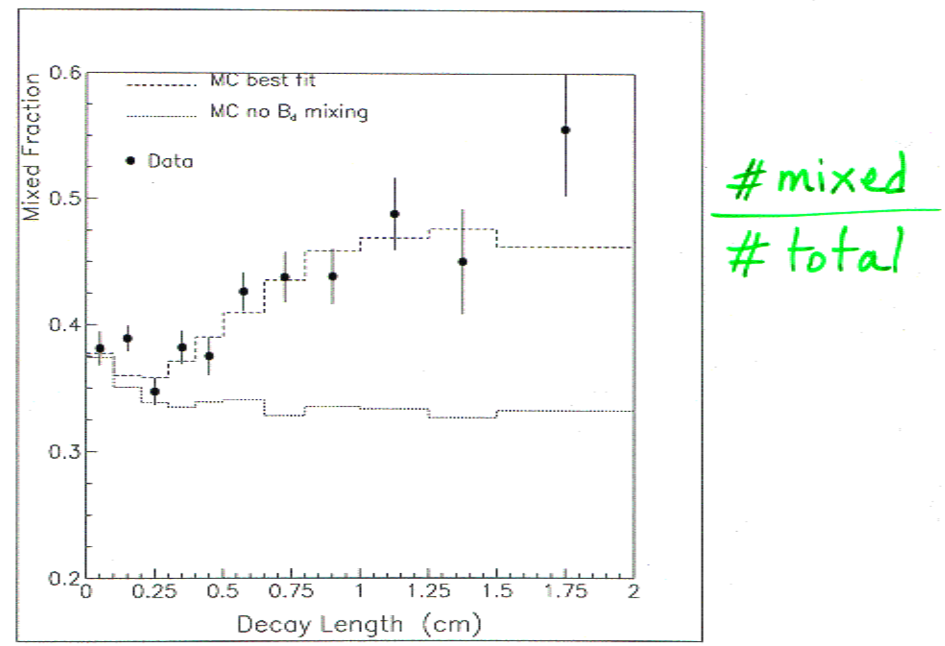
Kaon Tag Analyses

- 3D topological vertexing
- Kaon tag exploits dominant $b \rightarrow c \rightarrow s$ transition
  $\Rightarrow$ K^- tags $\overline{B^0}$ and K^+ tags B^0
- Secondary vertex tracks identified as kaons with *Cherenkov Ring Imaging Detector* (CRID)
- Kaon tag efficiency = 25-30% & correct (decay) tag probability = 77% ±2%

measured in data



Measurement of A_b



Measurement of Δm_d

→ expect $\delta(\Delta m_d) \simeq 0.029\ ps^{-1}$ (stat)

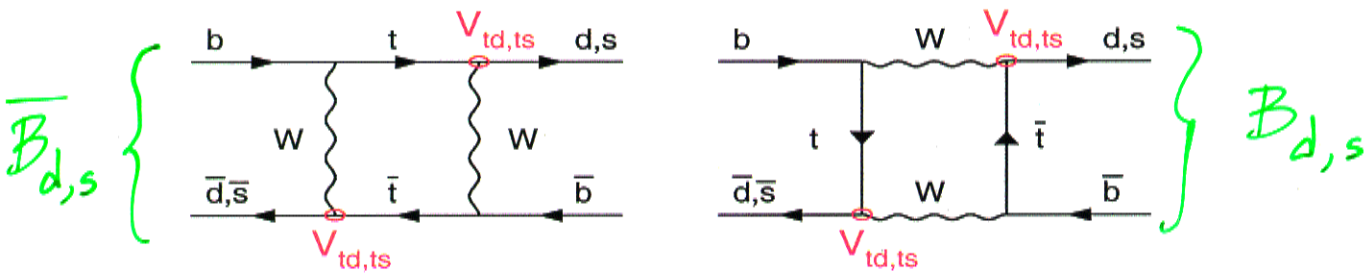
S.Willocq (UMass)

(1997-98 data)

$$A_b = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} = 0.997 \pm 0.044 \pm 0.067$$

B^0_s MIXING

- Second order weak interaction in Standard Model



$$\Delta m_d = \frac{G_F^2}{6\pi^2} M_B m_t^2 F\left(\frac{m_t^2}{m_W^2}\right) B_{Bd} f_{Bd}^2 \eta_{QCD} \left|V_{tb}^* V_{td}\right|^2$$

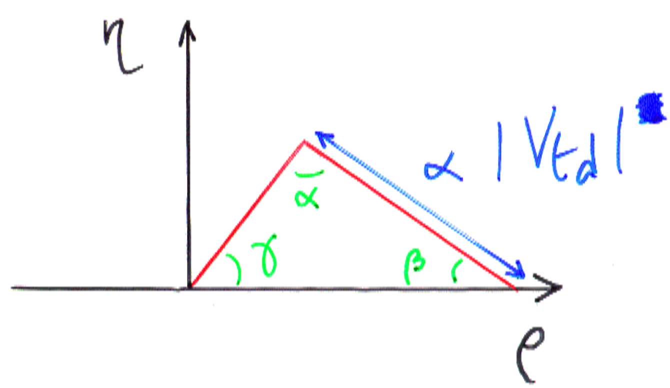
↳ large theor. uncertainty

- Measuring Δm_s and Δm_d yields most precise determination of $|V_{td}|$. Reduced theoretical uncertainties in ratio

$$\frac{\Delta m_s}{\Delta m_d} = \frac{M_{Bs}\left(f_{Bs}^2 B_{Bs}\right)}{M_{Bd}\left(f_{Bd}^2 B_{Bd}\right)} \cdot \left|\frac{V_{ts}}{V_{td}}\right|^2 = (1.15 \pm 0.05)^2 \cdot \left|\frac{V_{ts}}{V_{td}}\right|^2$$

$$\Delta m_d \propto \underbrace{A^2 \lambda^6 [(1-\rho)^2 + \eta^2]}_{|V_{td}|^2}$$

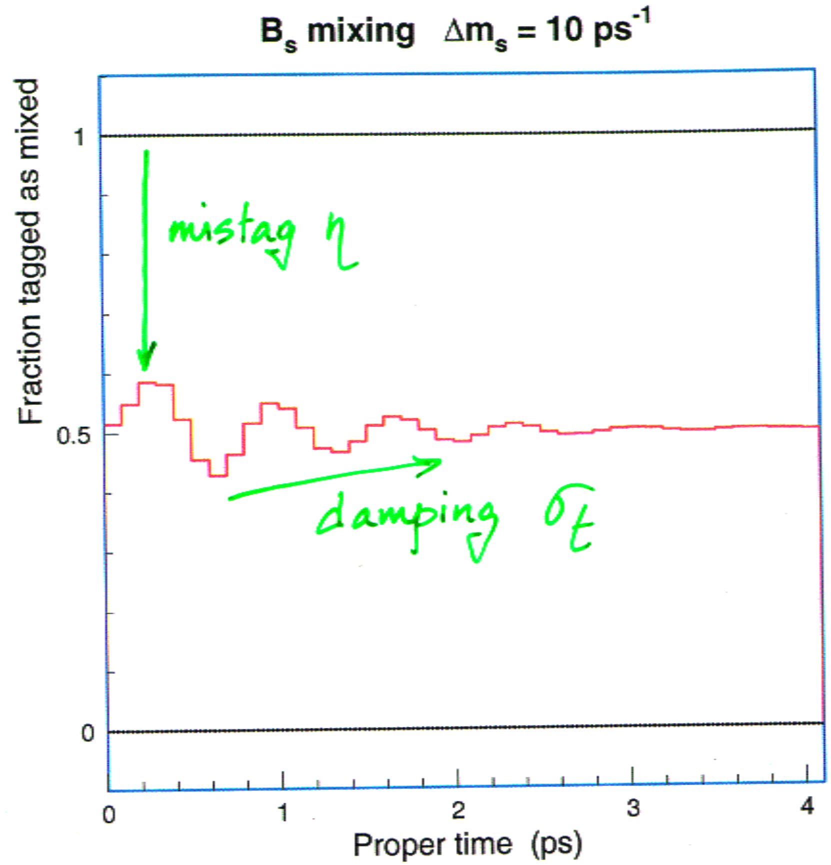
$$\Delta m_s \propto A^2 \lambda^4$$



Ingredients for B mixing study:

- B decay proper time
- Initial state (production) flavor
- Final state (decay) flavor

$\Rightarrow$ Tag event as 'mixed' or 'unmixed' if initial and final state tags disagree or agree



Observing B_s mixing is hard:

- High frequency due to $\Delta m_d \propto A^2 \lambda^6 [(1 - \rho)^2 + \eta^2]$

  $\Delta m_s \propto A^2 \lambda^4$

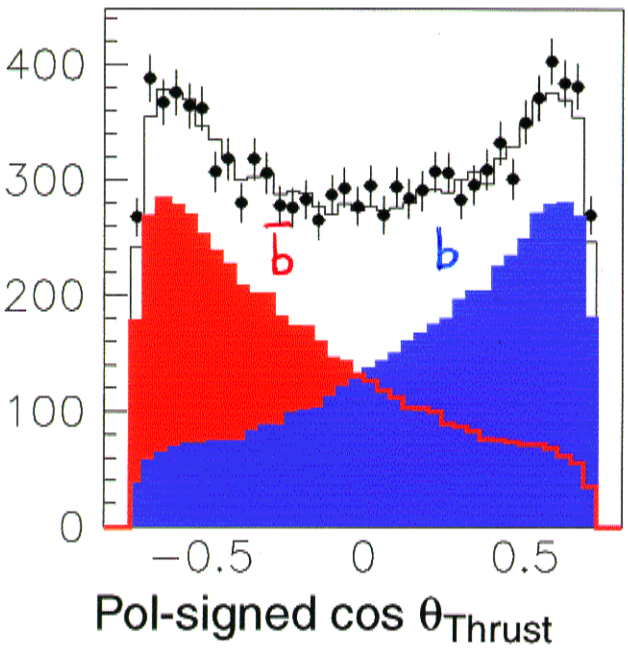
  $\Rightarrow \Delta m_s / \Delta m_d \approx 1 / \lambda^2 \approx 20$

- Signal significance $S = \sqrt{N/2}\ f(B_s)\ (1 - 2\eta)\ \exp[-(\Delta m_s \sigma_t)^2/2]$

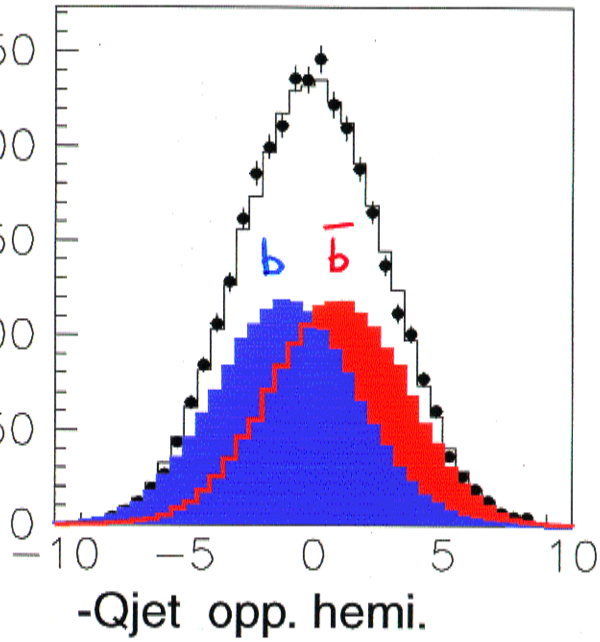
  $\Rightarrow$ need superb proper time resolution for sensitivity to high Δm_s

Initial State Tag

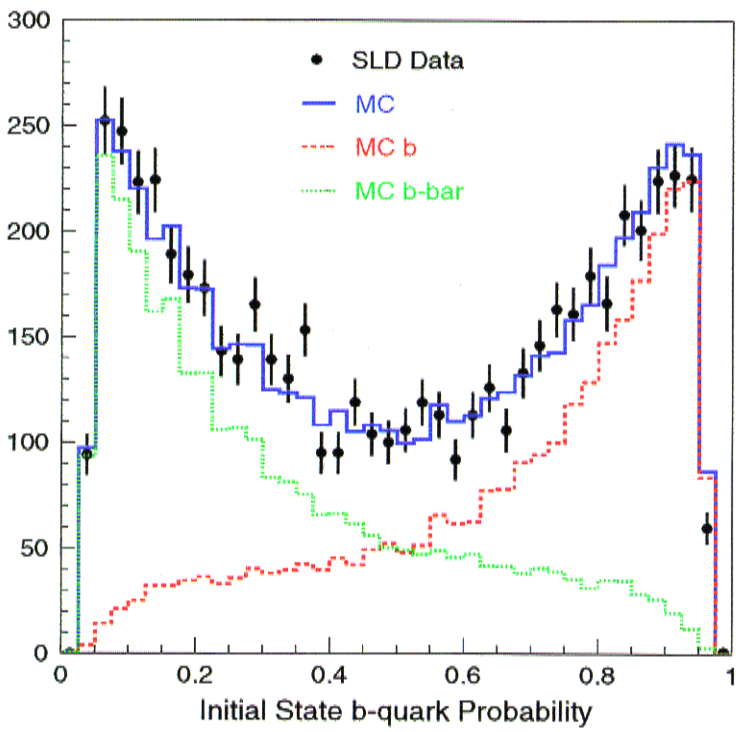
Polarized A_{FB}



Opp. Hemi. Jet Charge

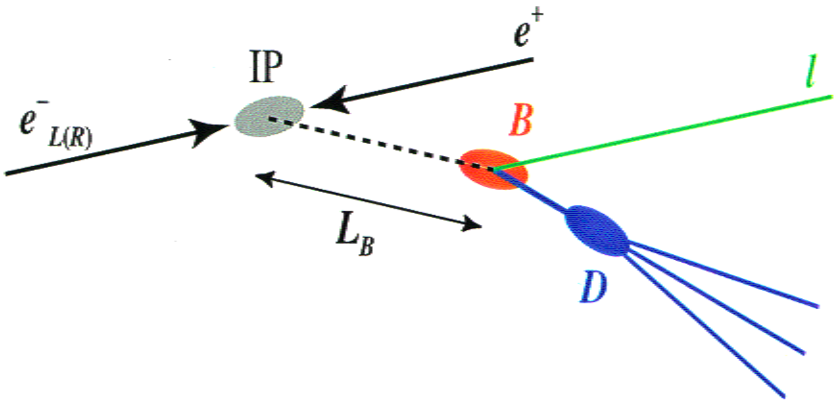


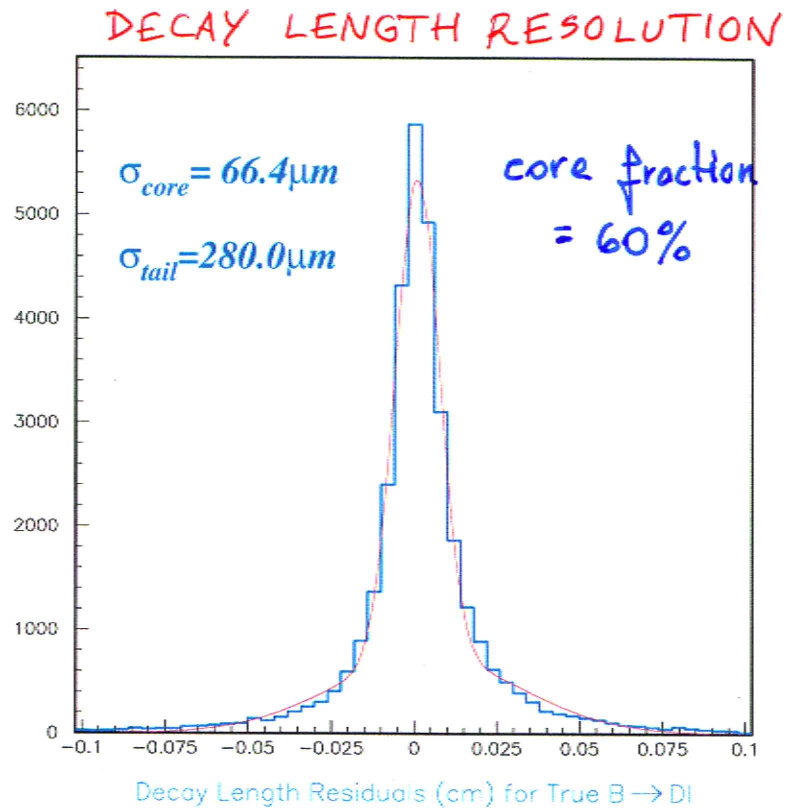
Add opposite hemisphere Vertex charge, Dipole charge, Kaon charge and Lepton charge :



⇒ *75-80% correct initial state tag* available for 100% of evts

Semileptonic Decays

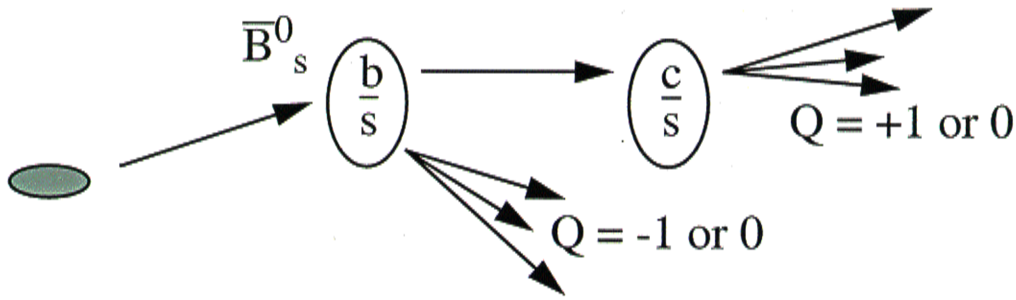




- Lepton + D vtx: topological reconstruction of D decay vertex
  - Excellent decay length resolution (66 μm core)
  - Lepton charge yields correct B/$\overline{\text{B}}$ tag probability of 92%
- Lepton + tracks: inclusive B vertex reconstruction from weighted mean of track intersections along lepton trajectory

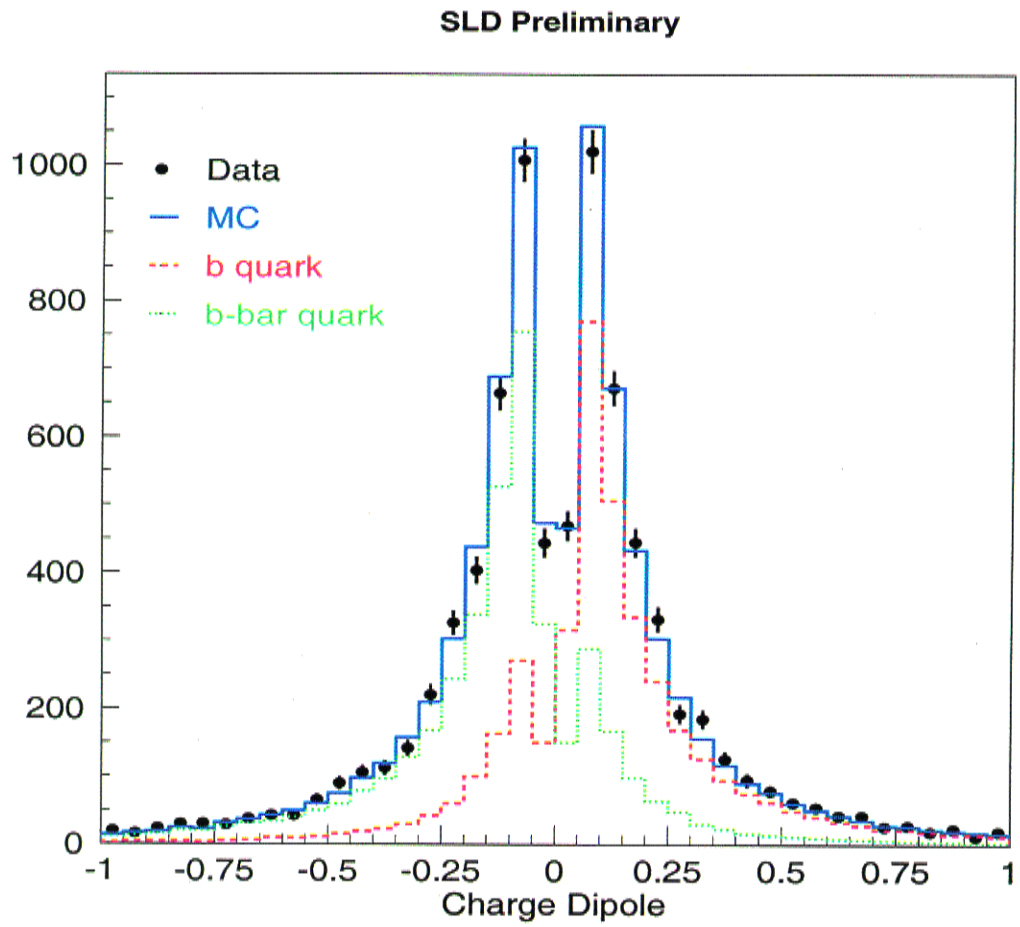
Charge Dipole Analysis

- Unique *tagging technique*
- Exploit B → D cascade charge structure



- Inclusive topological reconstruction of both secondary *and* tertiary vertices (require Qtot = 0)

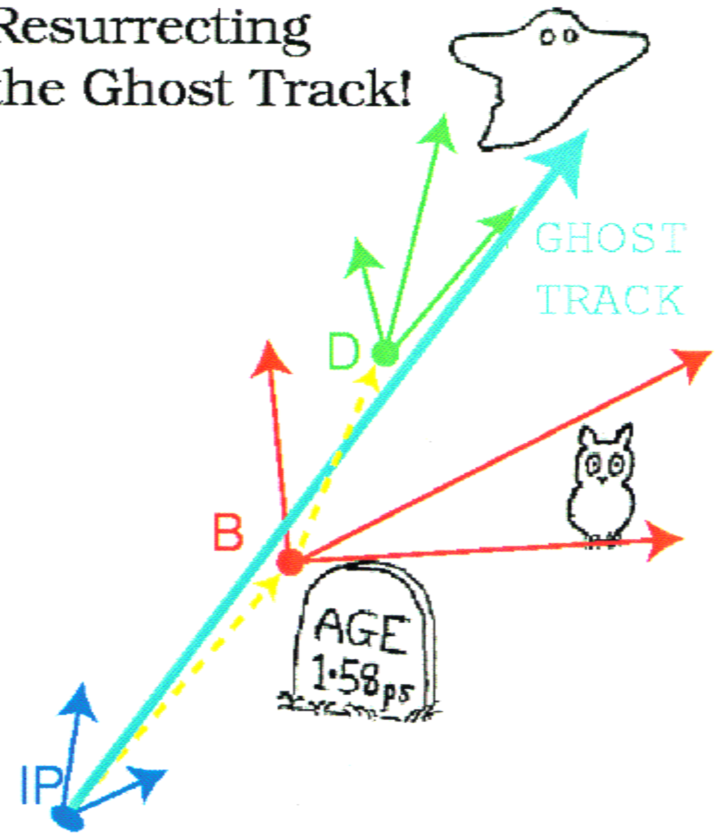
Dipole δq = Distance(B to D) * SIGN(Q_D - Q_B)



Correct $B/\overline{B}$ tag Prob=79% for B_s^0

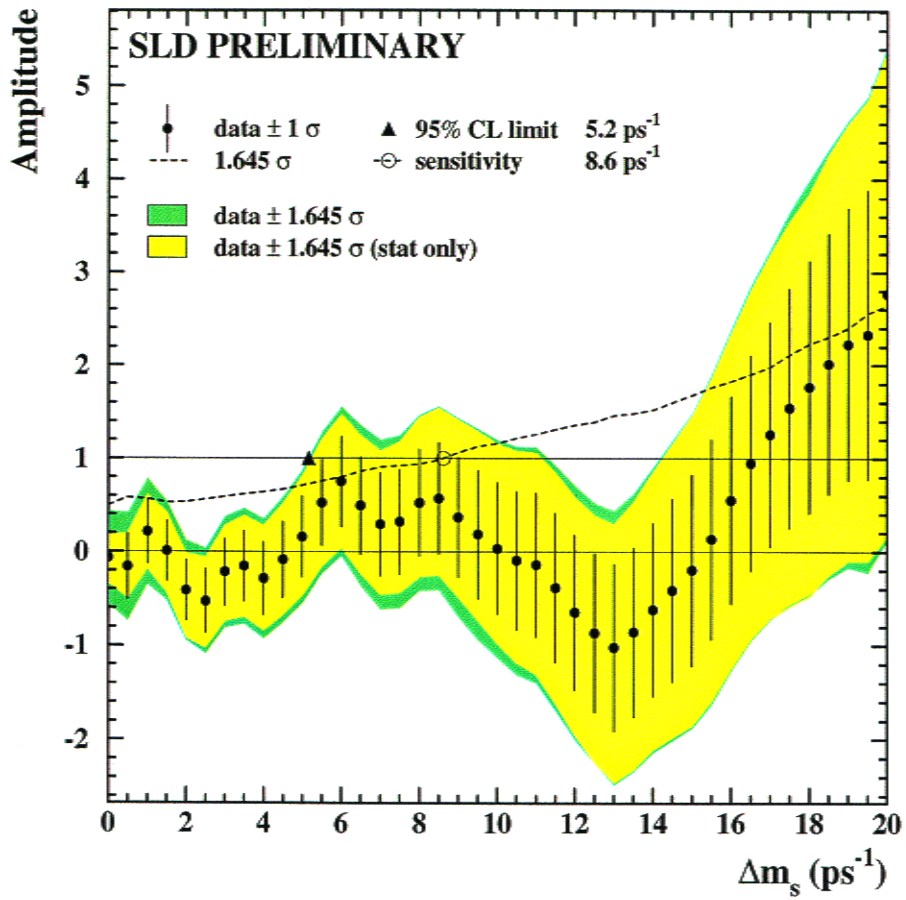
Charge Dipole Analysis: *New Topological Vertexing*

Resurrecting the Ghost Track!



- 'Ghost' track follows trajectory of $B \rightarrow D$ decay chain
- Ghost track is anchored at the IP and its direction is adjusted to minimize $\Sigma\chi^2$(ghost+jet trk)
- Vertices are restricted to lie along ghost trajectory
- 1-prong vertices can be reconstructed
- Charge dipole $B/\bar{B}$ correct tag probability = 79% for B_s
  - 91% for $B_s \rightarrow D_s X$
  - 53% for $B_s \rightarrow D \bar{D} X$

SLD Average Amplitude Lepton-Photon (Aug.99)

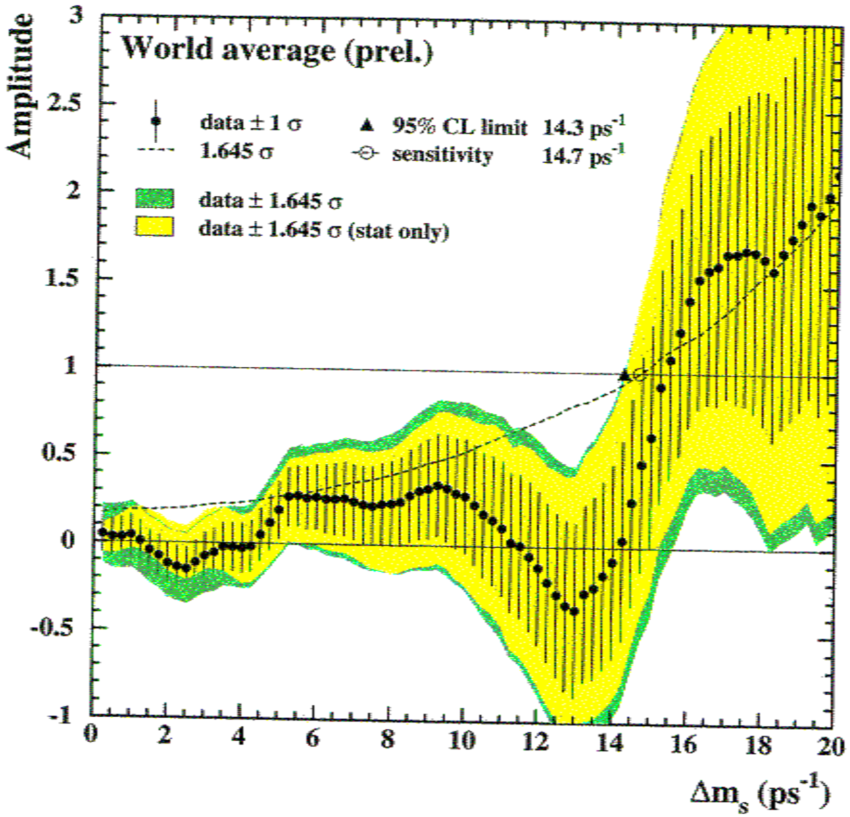


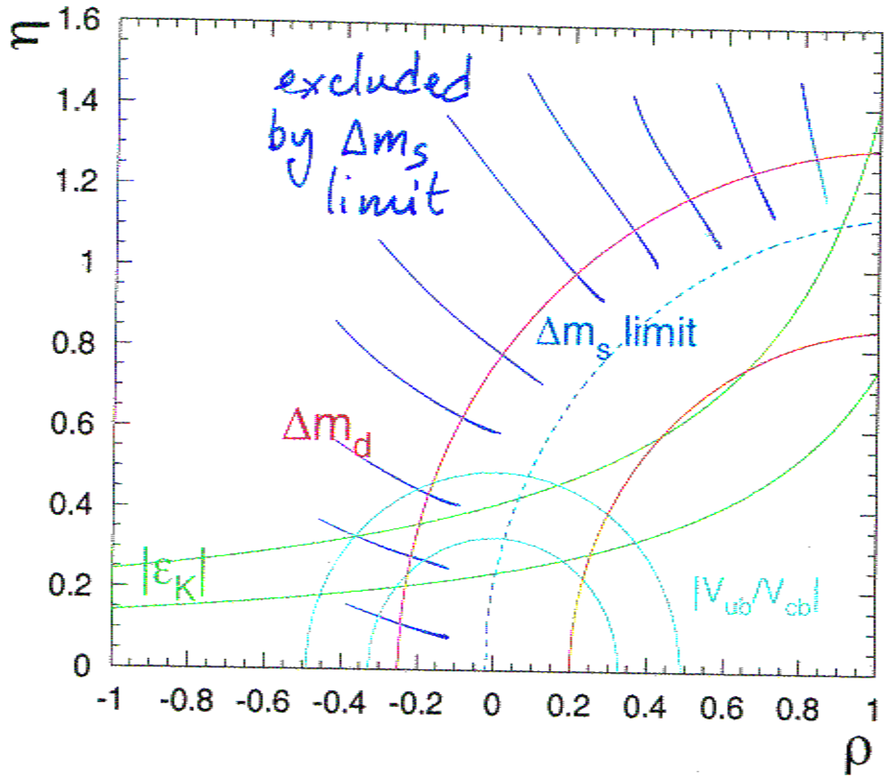
- 1997-98 data (350 K Z decays)
- 3 analyses: lepton+D, lepton+tracks, charge dipole (no overlap)
- assumed $f(B_s) = 10.8\%$
- Δm_s regions excluded at 95% C.L.:

  $\Delta m_s < 5.2\ ps^{-1}$

  $11.3 < \Delta m_s < 14.2\ ps^{-1}$

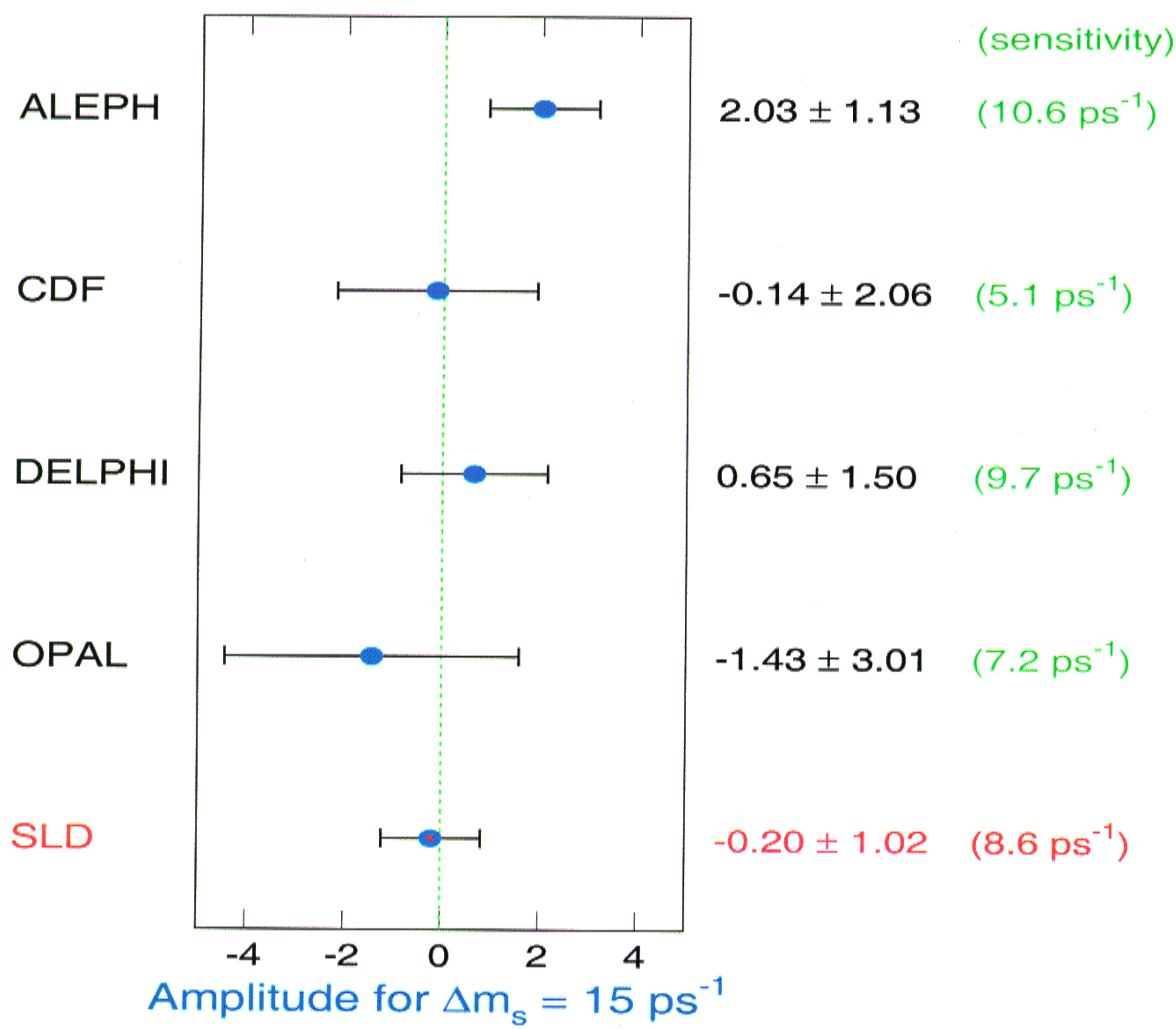
World Average Amplitude   LEPTON-PHOTON Aug.99





- Δm_s limit improves from 12.4 ps^{-1} (July 98)
  to 14.3 ps^{-1} (at 95% C.L.)
- Significant constraint on unitarity triangle apex (ρ,η)
  → complementary to measurements of sin 2β

B^0_s Mixing Amplitude Measurements (Aug 99)



SLD contributes the most at high Δm_s

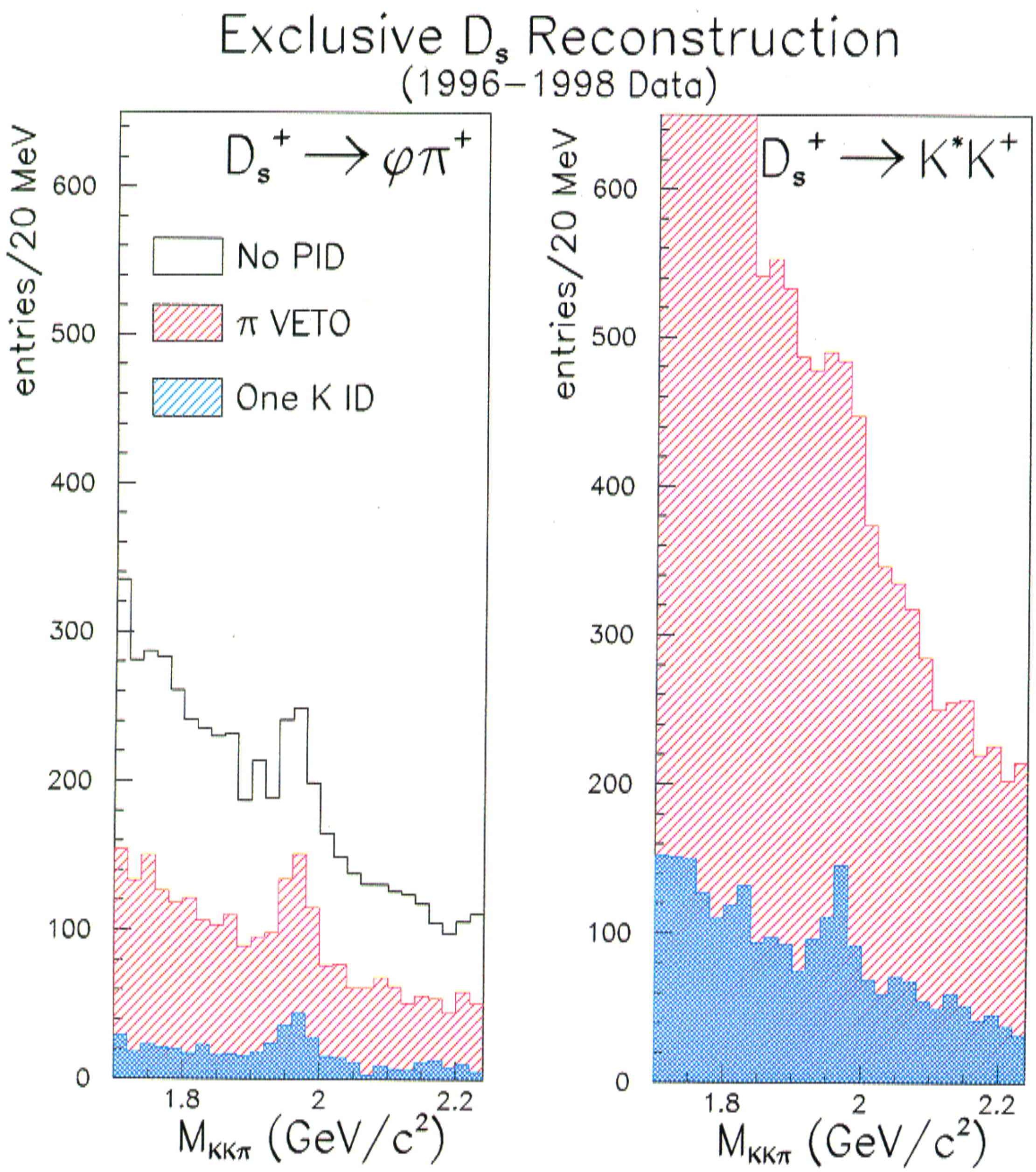
Δm_s	10 ps^{-1}	15 ps^{-1}	20 ps^{-1}
ALEPH	A= 0.33 ± 0.53	A= 2.03 ± 1.13	A= 2.07 ± 2.54
SLD	A= 0.03 ± 0.71	A=-0.20 ± 1.02	A= 2.77 ± 1.61

NEW ANALYSES: exploit CRID particle ID

- Lepton-Kaon select $B_s \to l^+ \nu \overline{D}_s^{**}$ with $\overline{D}_s^{**} \to K^- \overline{D}^0$
  $B_s \to l^+ \nu \overline{D}_s$ with $\overline{D}_s \to K^- X$

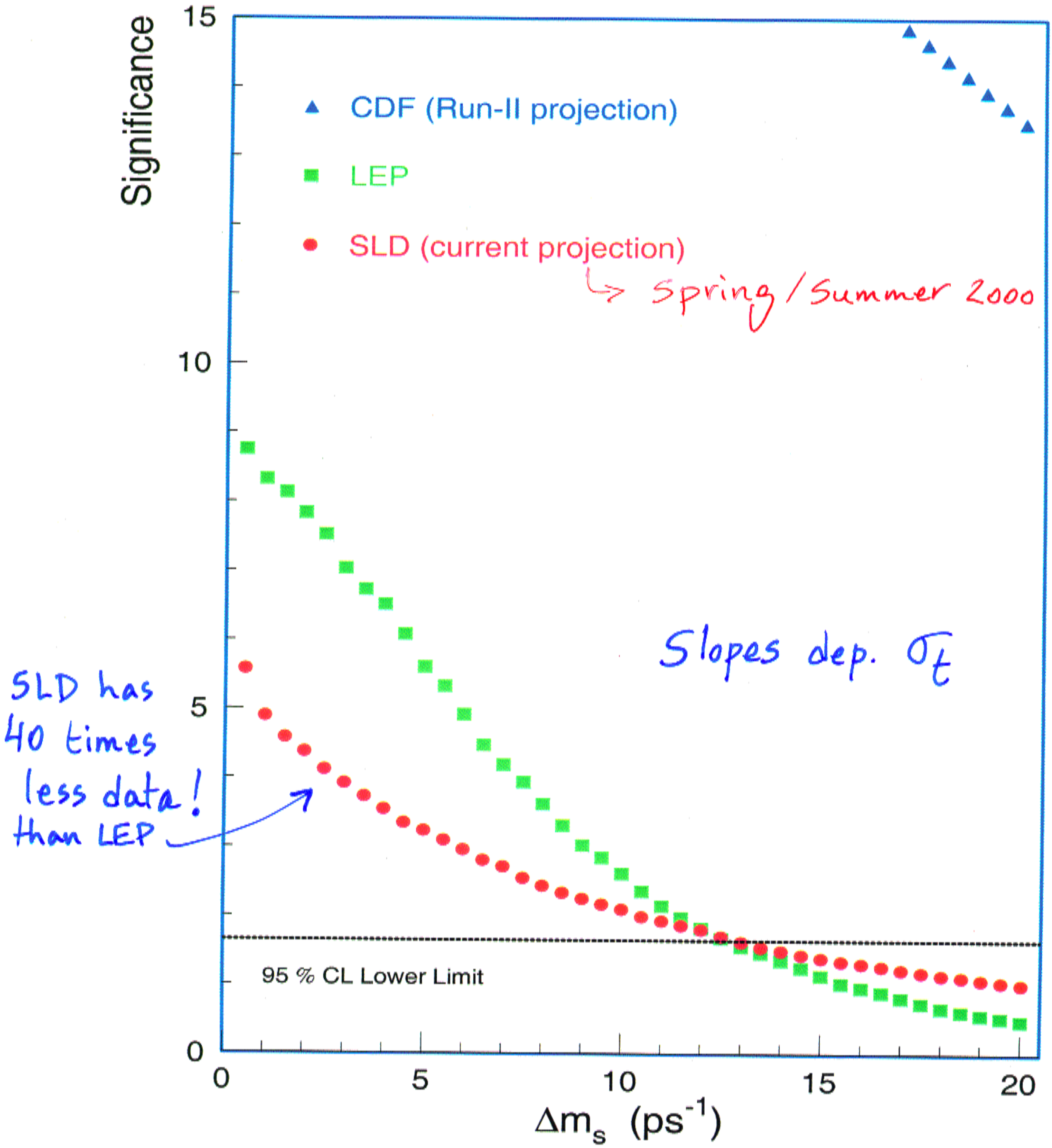
  + add lepton-ϕ combinations

- Exclusive D_s reconstruct $D_s \to \phi\pi, K^*K^+, K^*K^{*+}, K^0K^+, \phi l \nu$



⇒ Lower efficiency but very good decay length resolution (core $\sigma_L \approx 50\ \mu m$) and high B_s purity (up to 25-30%)

Significance of B_s mixing signal



Summary & Prospects

- With 1993-95 data sample of 150,000 hadronic Z decays and 1996-98 data sample of 400,000 hadronic Z decays

  SLD has produced the *most precise* B^+ and B^0 lifetime and b fragmentation function measurements, first measurements with kaon flavor tag and *very promising* B_s mixing analyses using unique techniques

  New analysis techniques take advantage of

  - polarized electrons,
  - small and stable interaction point,
  - high resolution vertex detector (VXD3),
  - particle identification (CRID)

- Improvements in B_s mixing sensitivity expected by adding two new analyses and by improving existing analyses

- Expect sensitivity comparable to LEP average ($\Delta m_s \approx 13\ ps^{-1}$)

  ⇒ SLD is sensitive to B_s mixing frequencies in region suggested by Standard Model fits to existing data

  ⇒ Significant impact on Unitarity Triangle determination and CP-violation tests