B Physics at the Tevatron in Run I

William Wester

Fermilab

Workshop on B Physics at the Tevatron
Run II and Beyond

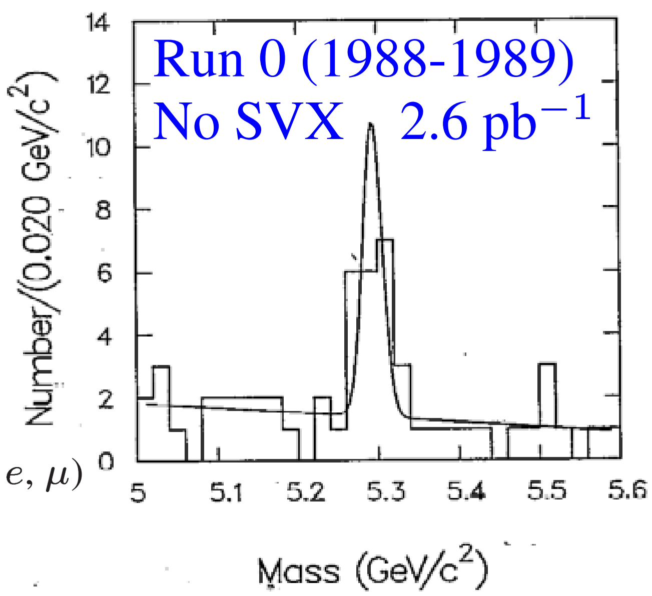
The B Physics Group at CDF

DØ B Physics

B Physics at a Hadron Collider

Advantages:

- Large $\sigma(b)$ ($\sim 50\mu$b)
- Large integrated $\mathcal{L}$ (110 pb^{-1})
- B_u, B_d, B_s, B_c, Λ_b, $(b\bar{b})$
- Triggers:($J/\psi \to \mu^+\mu^-$, $e\mu$, e, μ)
- Multipurpose detector



$B^- \to J/\psi K^-$

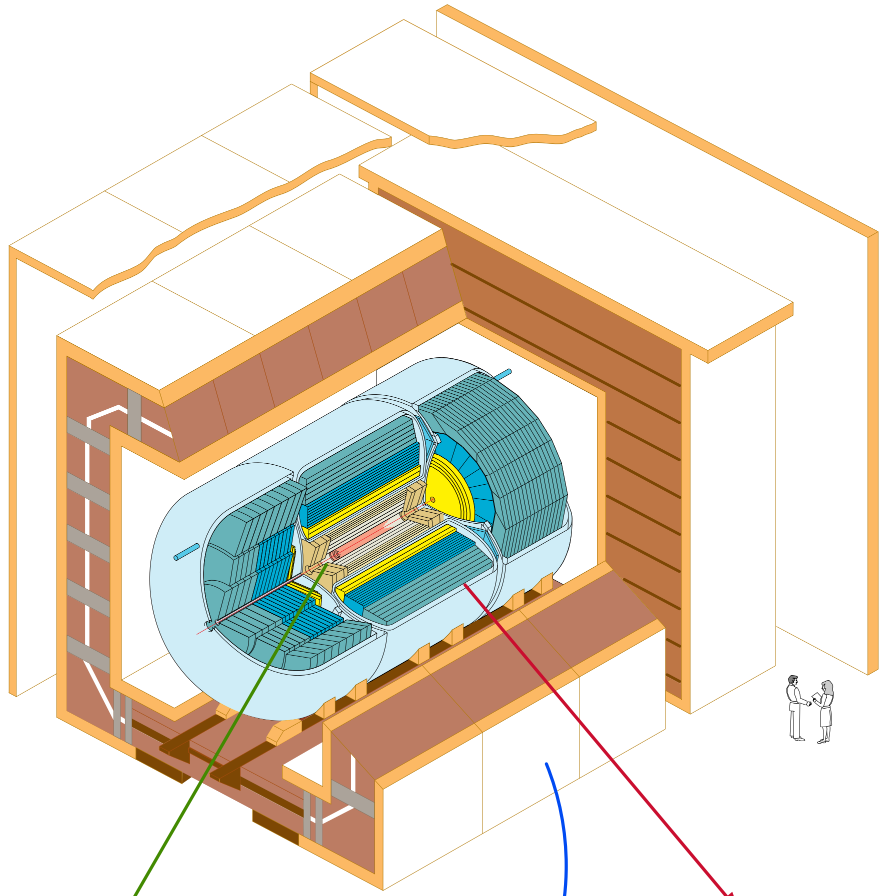
Disadvantages: *(Perceived)*

- High backgrounds
- Limited acceptance
- Small Lorentz boost
- Unknown initial state
- Soft photons difficult
- Multipurpose detector

We could trigger on B's that we could reconstruct.

Success in Run 0 led to planning for Run I!

Run I Detectors: DØ



DØ Detector

TRACKING

σ(vertex)=6 mm
$\sigma(r\phi)$ = 60 μm (VTX)
= 180 μm (CDC)
= 200 μm (FDC)

MUON

$|\eta| < 3.3$

$$\frac{\delta p}{p} = 0.2 \oplus 0.01p$$

CALORIMETRY

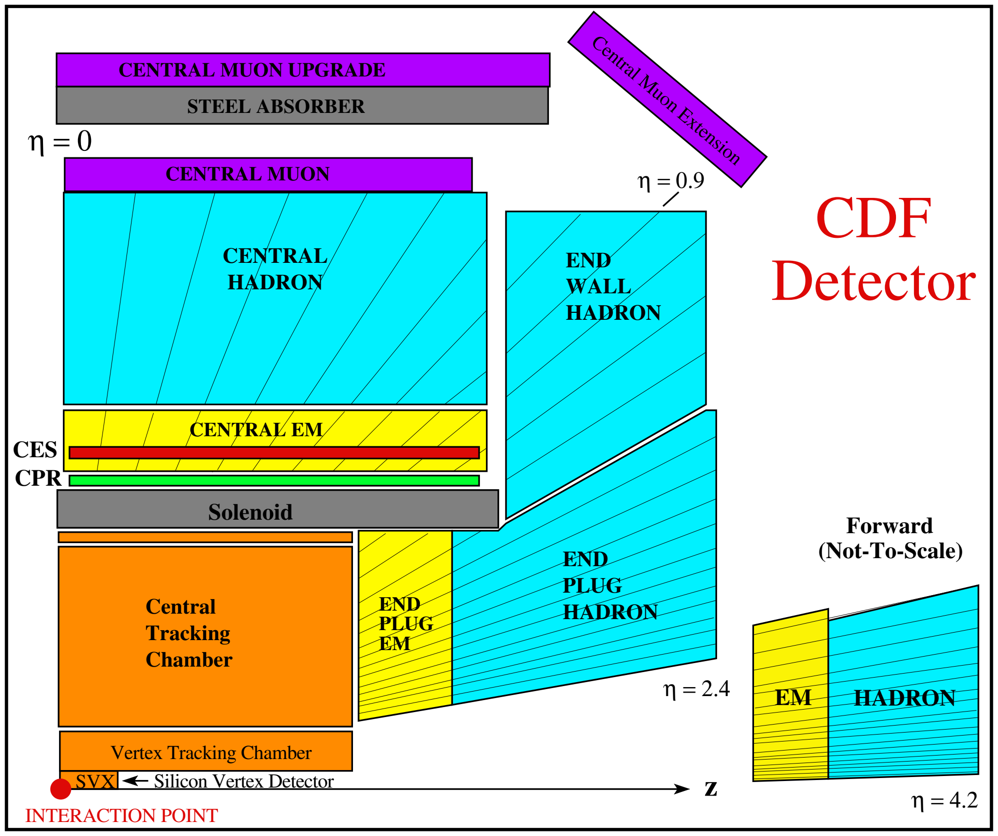
$|\eta|<4$

$\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

$\sigma(EM) = 15\% / \sqrt{E}$

$\sigma(HAD) = 50\% / \sqrt{E}$

Run I Detectors: CDF



- Silicon Vertex Detector

  impact resolution $\sigma_{d_0} \sim (13 \oplus 40/P_T)\mu$m

- Central Tracking Chamber

  $(\delta P_T/P_T)^2 = (0.0066)^2 \oplus (0.0009 \times P_T)^2$

- Muon and Calorimeter Systems

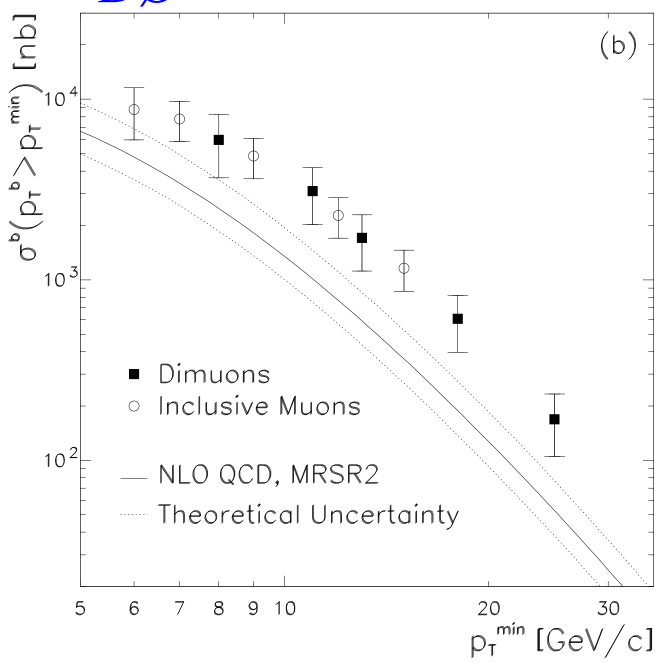
  high efficiency for e and μ trigger and offline ID

b production cross section $|\eta| < 1$

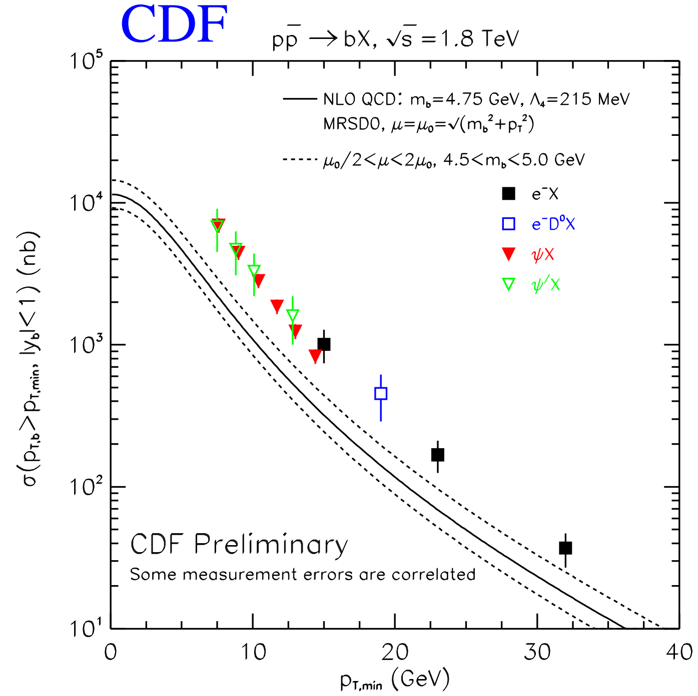
Compare measured cross section to NLO predictions

Observe data/theory $\sim$ 2-3

DØ



CDF



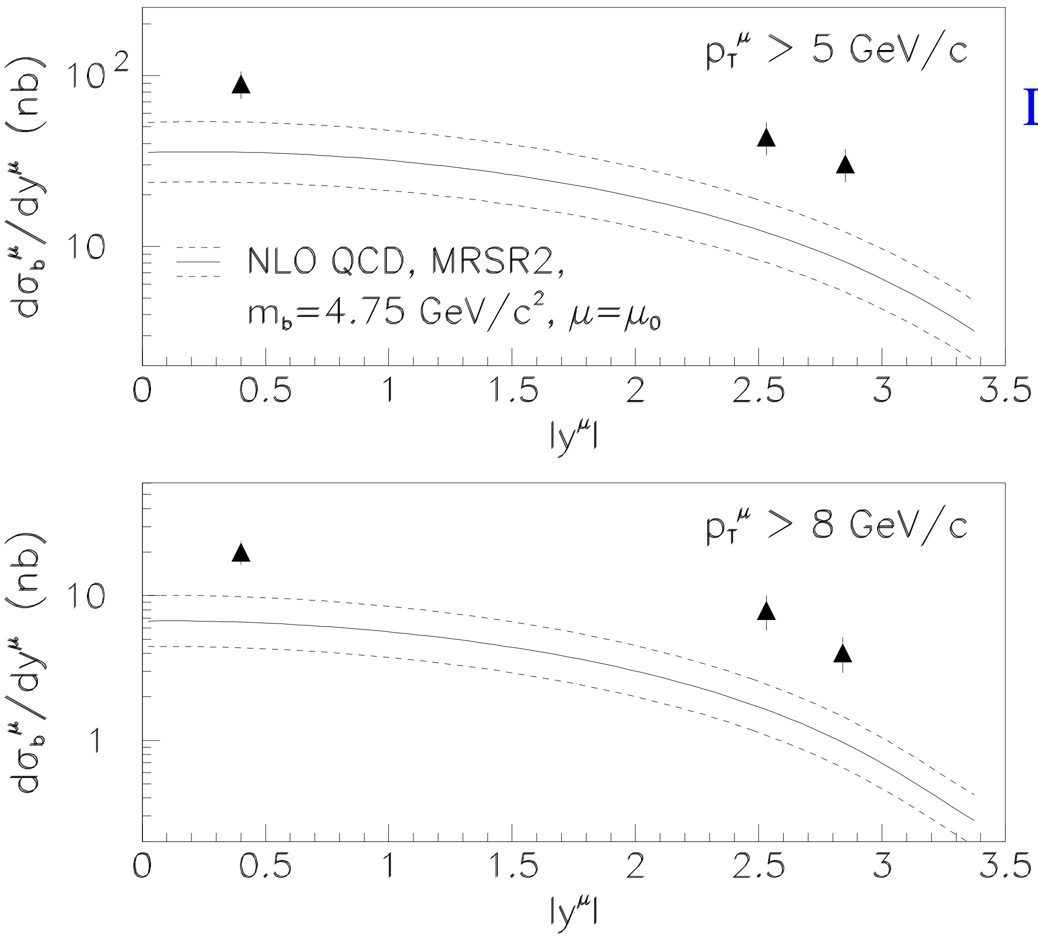
- CDF also measures the exclusive B meson cross section using fully reconstructed $B^- \to J/\psi\ K^-$ and $B^0 \to J/\psi\ K^*$ decays:

  $\sigma(p\overline{p} \to B^0\ X, P_T(B^0) > 6$ GeV/c, $|y(B^0)| < 1) =$

  2.91 $\pm$ 0.21 (stat) $\pm$ 0.41 (syst) μb (CDF Preliminary)

- CDF and DØ measure the b production cross section at $\sqrt{s} = 630$ GeV and observe a similar excess of measurement over NLO theory.

Forward b production



DØ

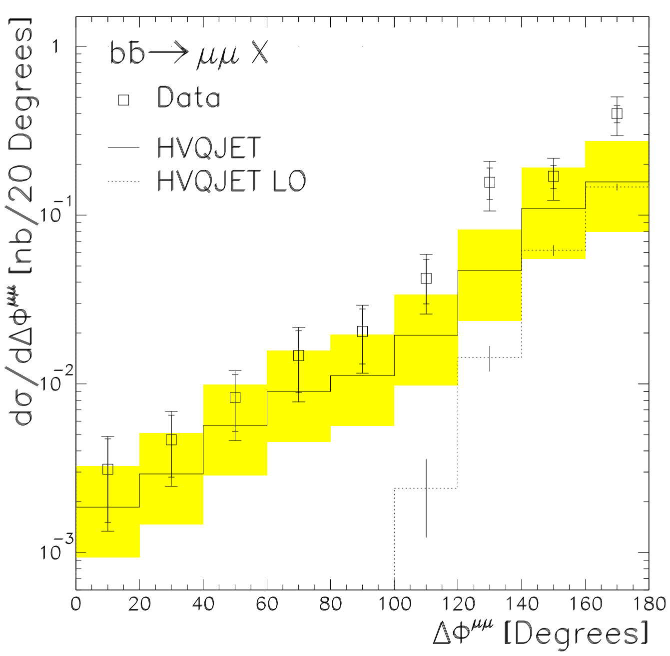
- Small angle muon system: $2.2 < |\eta^\mu| < 3.3$
- Low luminosity running $\int \mathcal{L} \sim 100\ \mathrm{nb}^{-1}$
- For $P_T(\mu) > 5$ GeV/c, data/theory:

  2.5 ± 0.4 $\quad |y(\mu)| < 0.8$

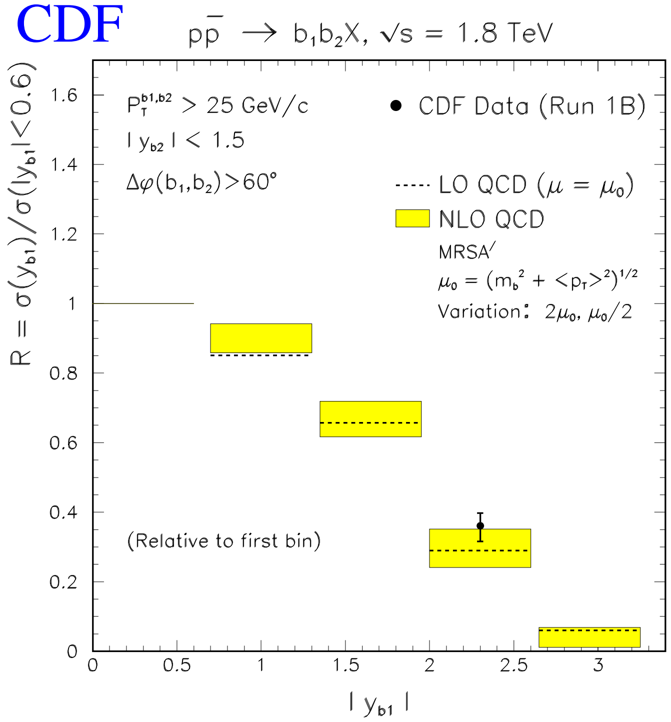
  3.6 ± 0.8 $\quad 2.4 < |y(\mu)| < 3.2$

$b\bar{b}$ correlations

DØ



CDF



- Additional tests of perturbative QCD
- $d\sigma/d\Delta\phi$ tests relative rates of NLO processes
- $d\sigma^2/dy_1 dy_2$ probes gluon distribution at large x

Onium production and polarization

Use SVX to separate "prompt" and "from B"

Study χ's for "direct" from "from χ"

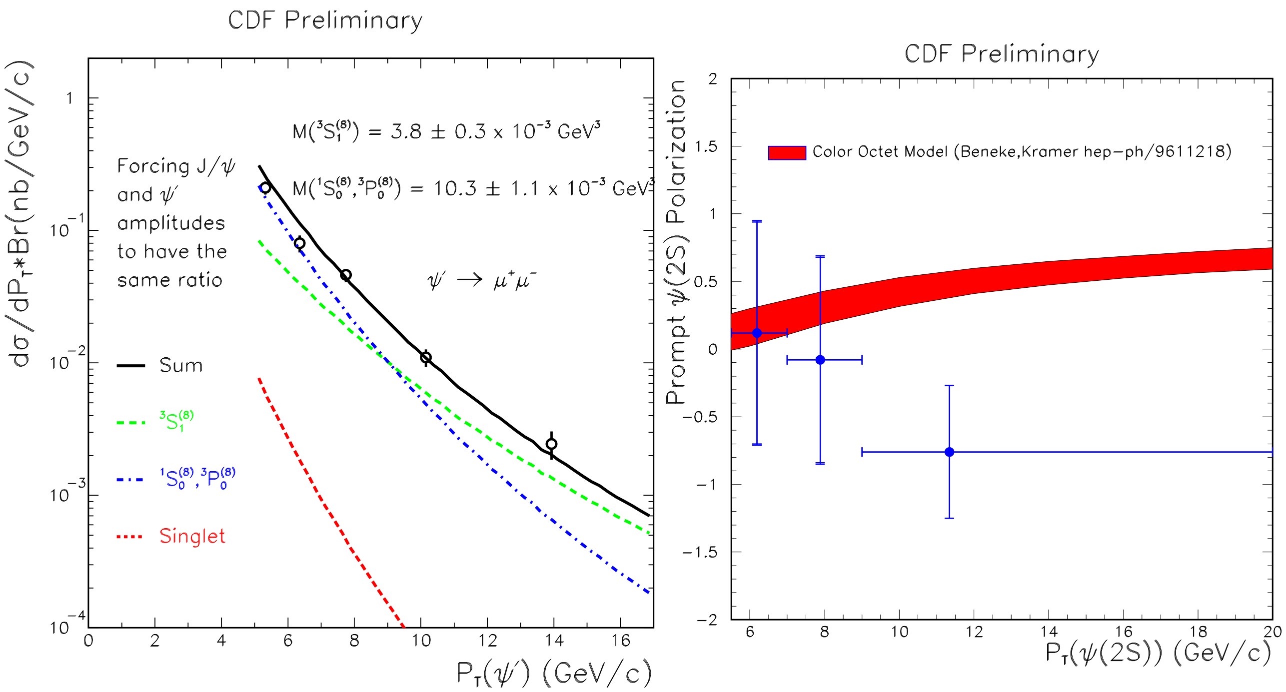
ψ(2S) does not have a feeddown source

Color Singlet Model underestimates "direct" by ~ 50

Color Octet Model predicts shape

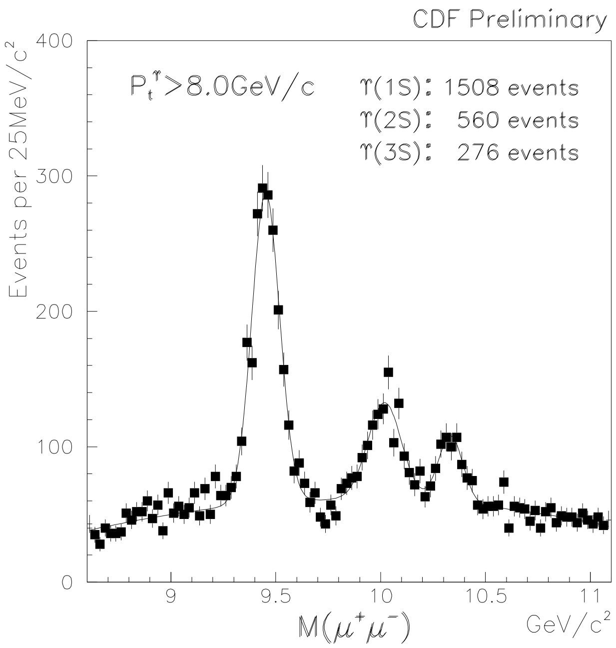
COM requires matrix elements for normalization

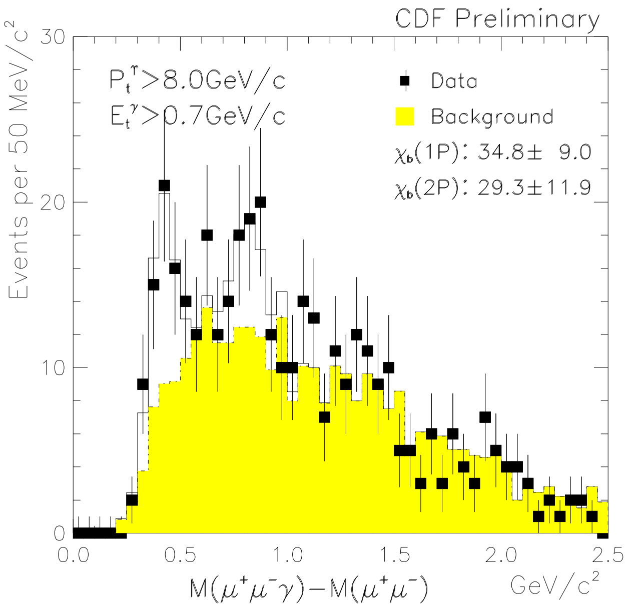
COM predicts large polarization especially at high-P_T



Prompt J/ψ and Υ also are not highly polarized

Fraction of Υ(1S) from χ_b



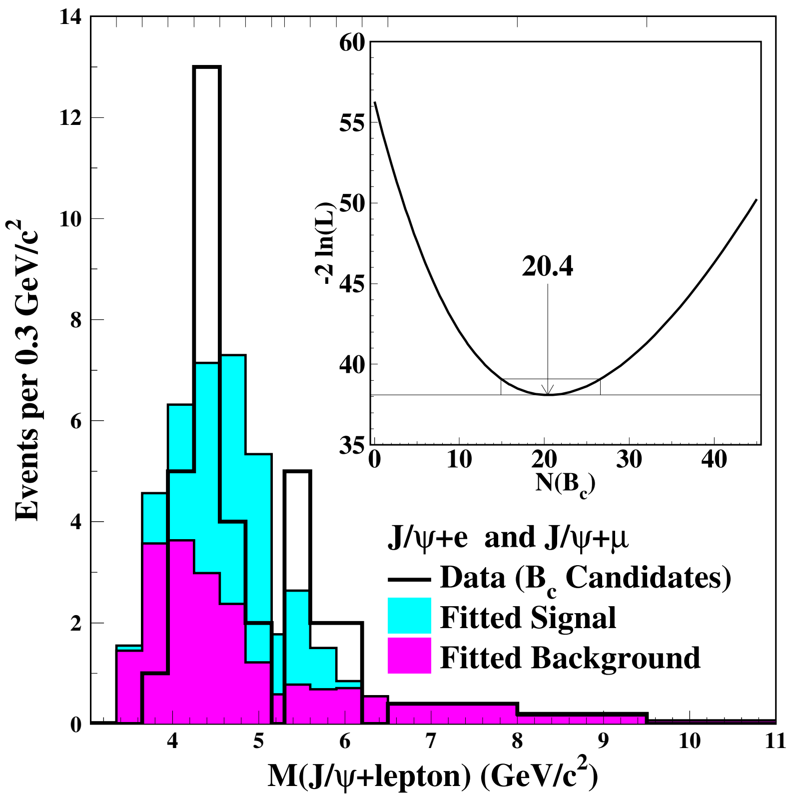


- Use high-P_T Υ(1S) to enhance boosted soft γ
- Background shape modeled using Monte Carlo and data
- Evaluate efficencies and study all feeddown mechanisms

Source of Υ(1S) (P_T > 8 GeV/c)	$27.1 \pm 6.9 \pm 4.4\%$	χ_b(1P)
	$10.5 \pm 4.4 \pm 1.4\%$	χ_b(2P)
	$< 6\%$	χ_b(3P)
	$10.7^{+7.7}_{-4.8}\%$	Υ(2S)
	$0.8^{+0.6}_{-0.4}\%$	Υ(3S)
	$50.9 \pm 8.2 \pm 9.0\%$	Direct

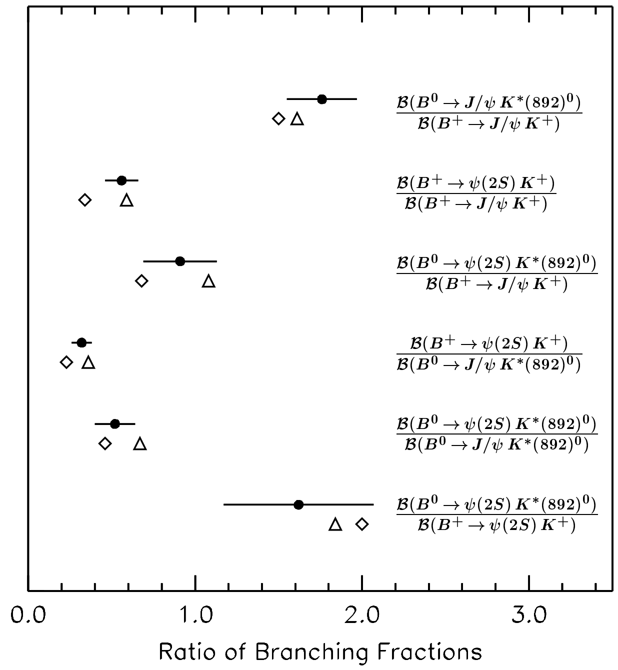
B hadron spectroscopy

	B^-	$5279.1 \pm 1.7 \pm 1.4$ MeV/c^2
B	B^0	$5281.3 \pm 2.2 \pm 1.4$ MeV/c^2
hadron	B_s^0	$5369.9 \pm 2.3 \pm 1.3$ MeV/c^2
masses	B_c^-	$6.40 \pm .39 \pm 0.13$ GeV/c^2
	Λ_b	$5621 \pm 4 \pm 14$ MeV/c^2



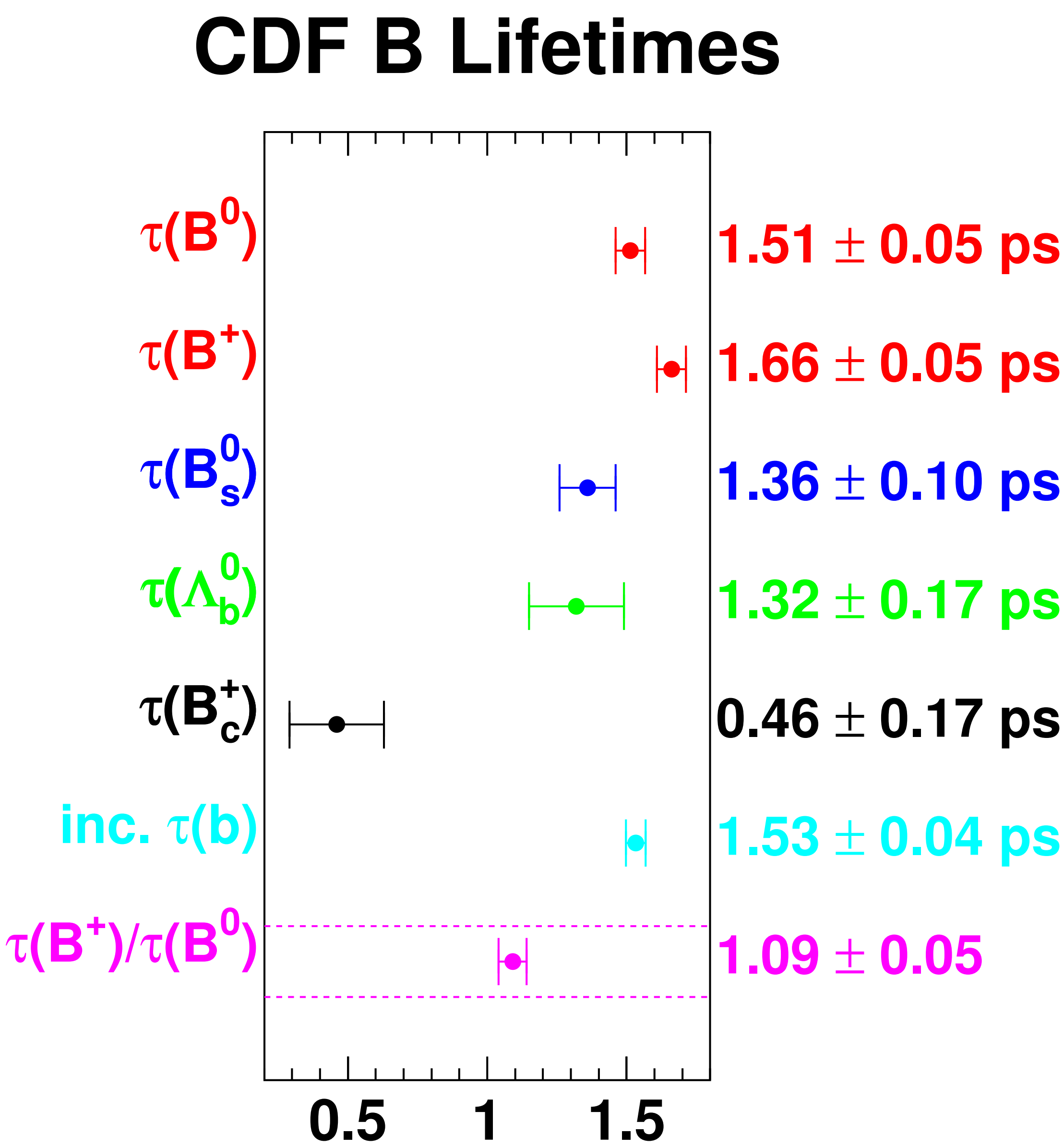
Discovery of the last meson !

Branching ratio's and fragmentation

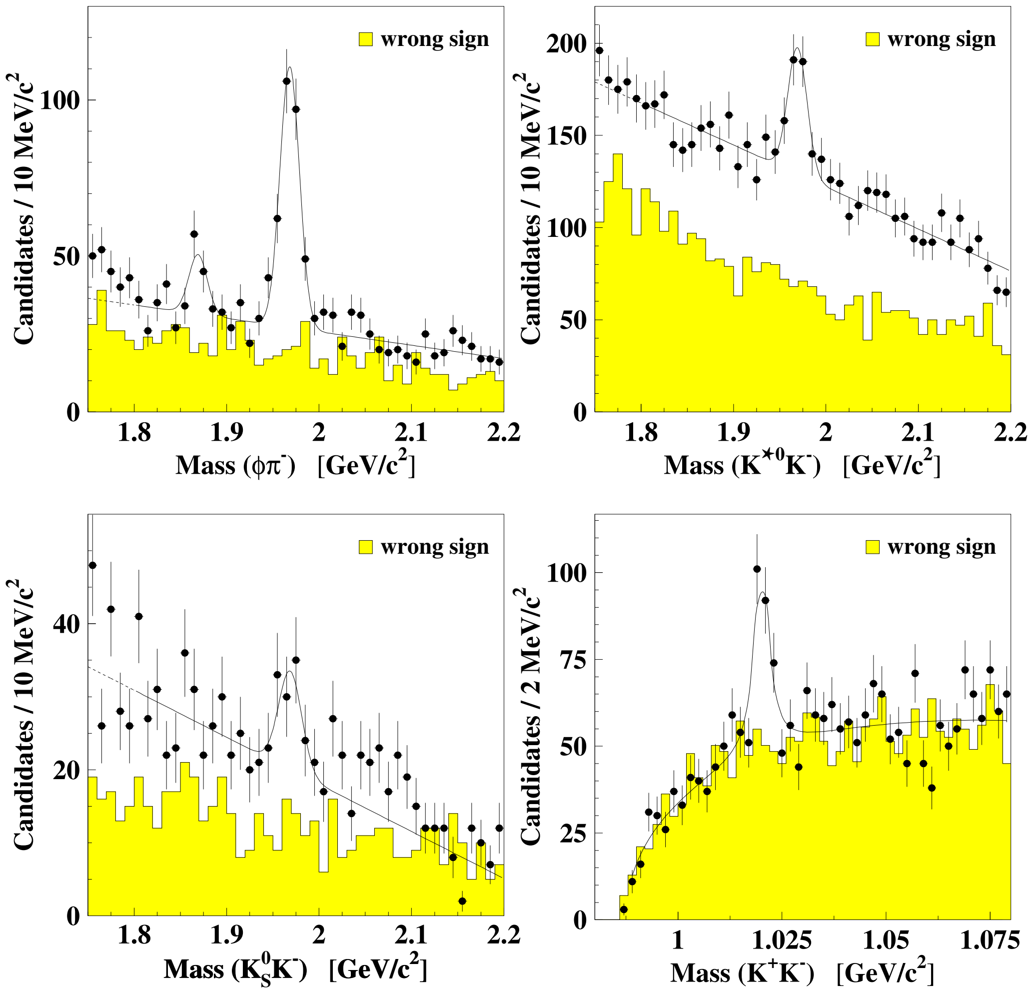


$$
\begin{array}{rl}
f_u & 0.408 \pm 0.046 \\
f_d & 0.344 \pm 0.039 \\
f_s & 0.159 \pm 0.026 \\
f_{baryon} & 0.089 \pm 0.029 \\
f^{**} & 0.26 \pm 0.06 \pm 0.03
\end{array}
$$

Lifetime results

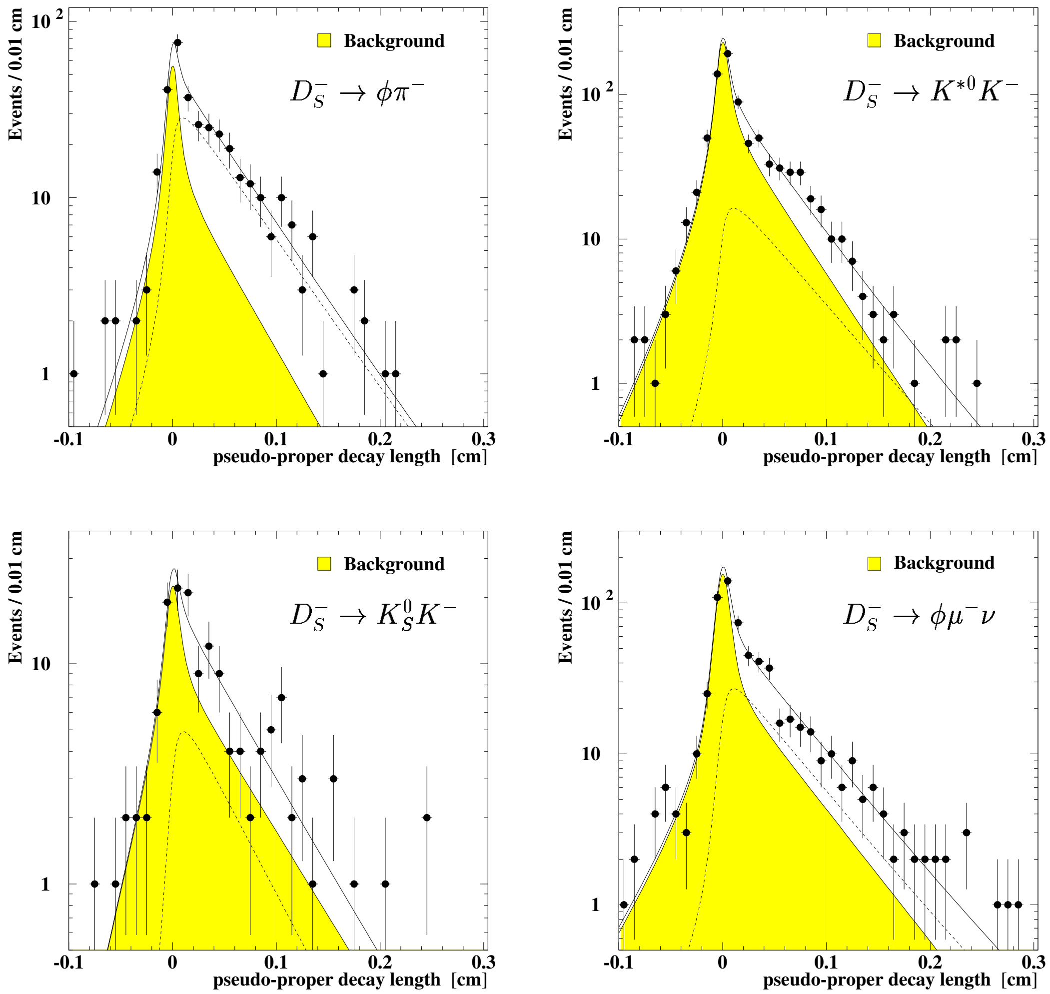


B_s^0 lifetime using $\ell\ D_s$



- Reconstruct D_s in inclusive ℓ samples
- Find $\sim$ 600 events
- Fit for lifetime of the background, then signal

B_s^0 lifetime and $\Delta\Gamma/\Gamma$

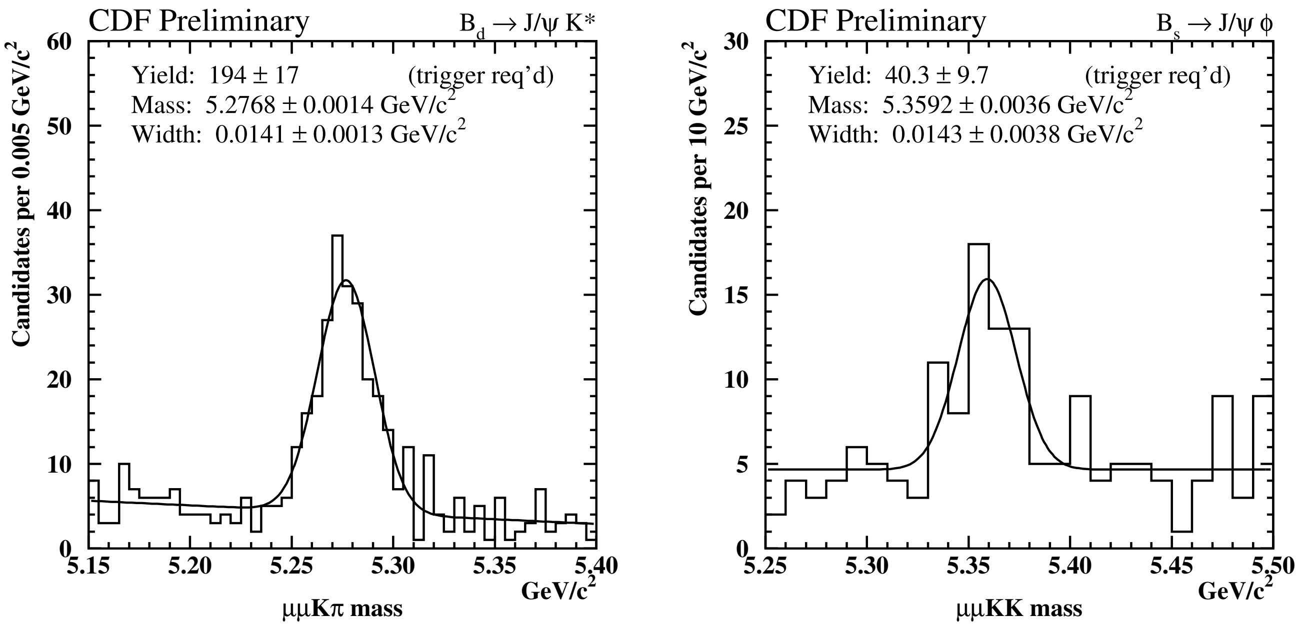


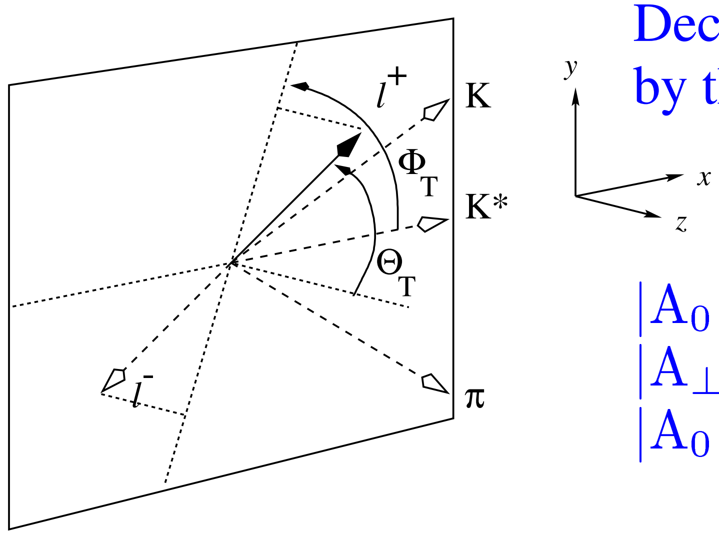
$$\boxed{\tau(B_s^0) = 1.36 \pm 0.09^{+0.06}_{-0.05}\ \text{ps}}$$

Allow for a two component fit, $\Delta\Gamma_s = \Gamma_\mathrm{L} - \Gamma_\mathrm{H}$

$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.34^{+0.31}_{-0.34}$ or $\frac{\Delta\Gamma_s}{\Gamma_s} < 0.83$ at 95% C.L.

$B \to VV$ **polarizations**

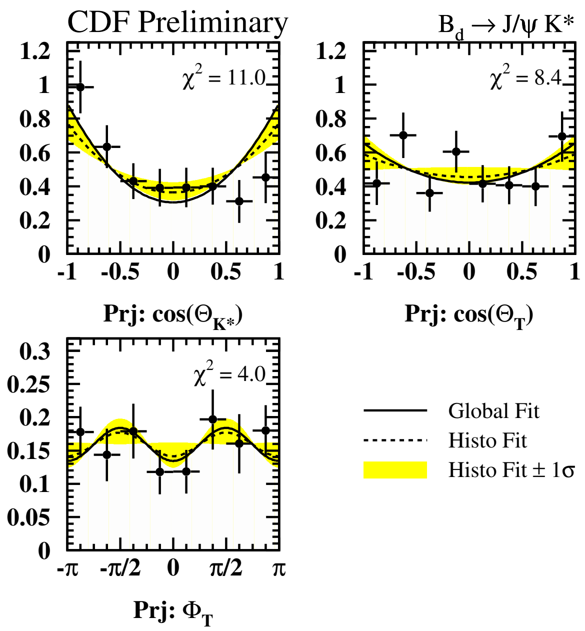




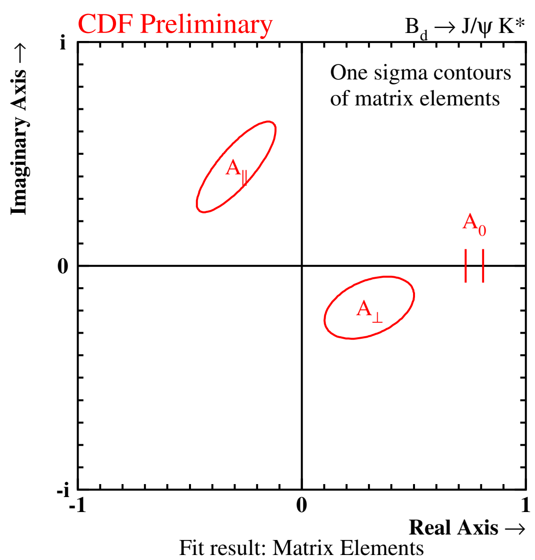
Decay distribution is described by three complex amplitudes

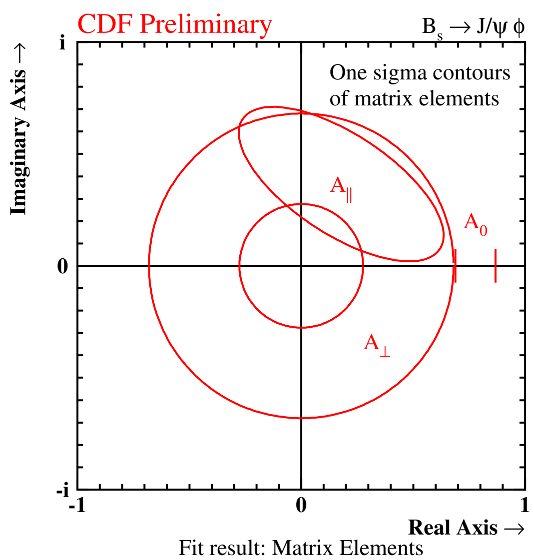
$$|A_0|^2 = \Gamma_L/\Gamma$$
$$|A_\perp|^2 = \Gamma_{odd}/\Gamma$$
$$|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2 = 1$$

$B \to VV$ polarizations

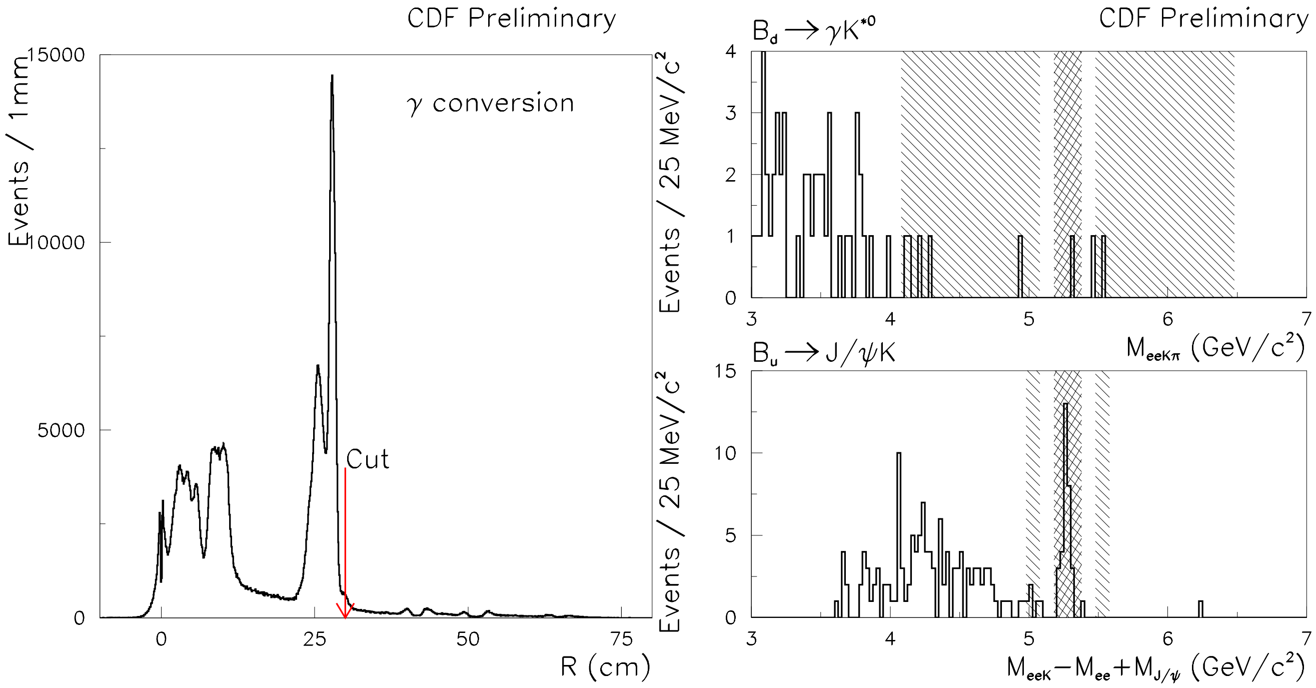


Extracted amplitudes limited by statistics. Technique will be important to separate CP-even and CP-odd components.





$B_d \to K^*\gamma$ and $B_s \to \phi\gamma$



- Identify γ using conversions, $\gamma \to e^+e^-$
- Normalize to $B^- \to J/\psi(\to e^+e^-)K^-$,
- 1 event survives $K^*\gamma$ (0.6 bkgd)
- 0 events survives $\phi\gamma$ (0.1 bkgd)

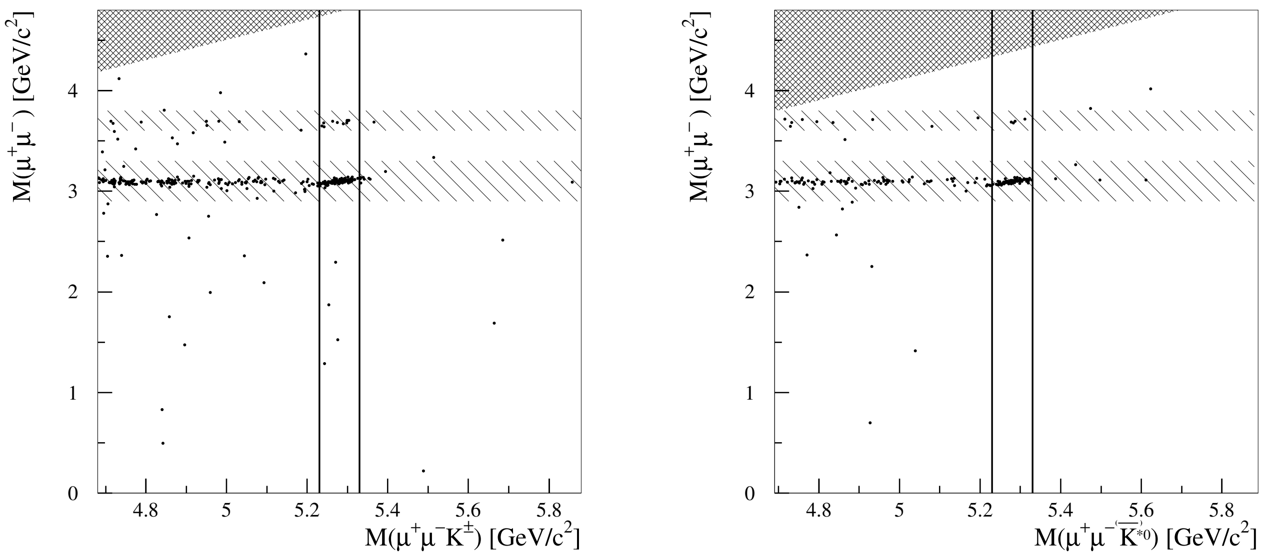
$\boxed{B(B_d \to K^*\gamma) < 1.7 \times 10^{-4} \text{ at 90\% C.L.}}$

$\boxed{B(B_s \to \phi\gamma) < 2.4 \times 10^{-4} \text{ at 90\% C.L.}}$

(assumes $\mathrm{f_s/f_u} = 0.420 \pm 0.105$)

- Using calorimeter γ gives similar result

Rare FCNC decays



$$\boxed{B(B^+ \to \mu^+\mu^- K) < 5.2 \times 10^{-6} \text{ at 90\% C.L.}}$$

$$\boxed{B(B^0 \to \mu^+\mu^- K^*) < 4.0 \times 10^{-6} \text{ at 90\% C.L.}}$$

Channel	Expt	90% C.L.	SM prediction
$B_d^0 \to \mu^+\mu^-$	CDF	8.6×10^{-7}	1.5×10^{-10}
$B_s^0 \to \mu^+\mu^-$	CDF	2.0×10^{-7}	3.5×10^{-9}
$B_{d,s}^0 \to \mu^+\mu^-$	DØ	4.0×10^{-5}	1.1×10^{-9}
$b \to X_s\mu^+\mu^-$	DØ	3.2×10^{-4}	6×10^{-6}
$B_d^0 \to e^\pm\mu^\mp$	CDF	3.5×10^{-6}	0
$B_s^0 \to e^\pm\mu^\mp$	CDF	6.1×10^{-6}	0

$\overline{B}^0 B^0$ mixing in CDF

For the B under study, we need:

flavor at production (tag)
flavor at decay

Efficiency:

$$\epsilon = \mathrm{N}_{\mathrm{tag}}/\mathrm{N}_{\mathrm{total}}$$

Dilution:

$$\mathcal{D} = \frac{\mathrm{N}_{\mathrm{RS}} - \mathrm{N}_{\mathrm{WS}}}{\mathrm{N}_{\mathrm{RS}} + \mathrm{N}_{\mathrm{WS}}} = 2\mathcal{P}_{\mathrm{RS}} - 1$$

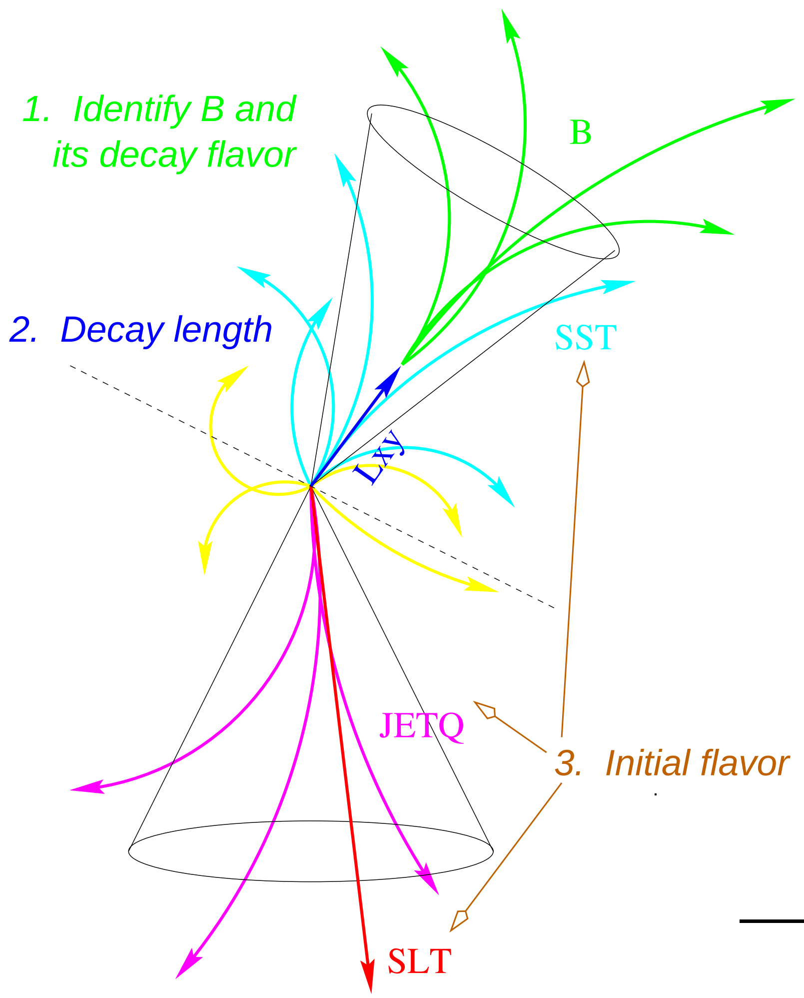
Asymmetry:

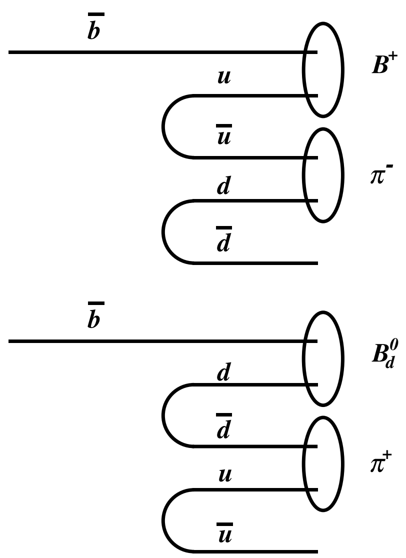
$$\mathcal{A}(t) = \frac{\mathrm{N}(t)_{\mathrm{unmixed}} - \mathrm{N}(t)_{\mathrm{mixed}}}{\mathrm{N}(t)_{\mathrm{unmixed}} + \mathrm{N}(t)_{\mathrm{mixed}}} = \mathcal{D}\cos(\Delta m_d t)$$

Statistics on $\mathcal{A}(t)$:

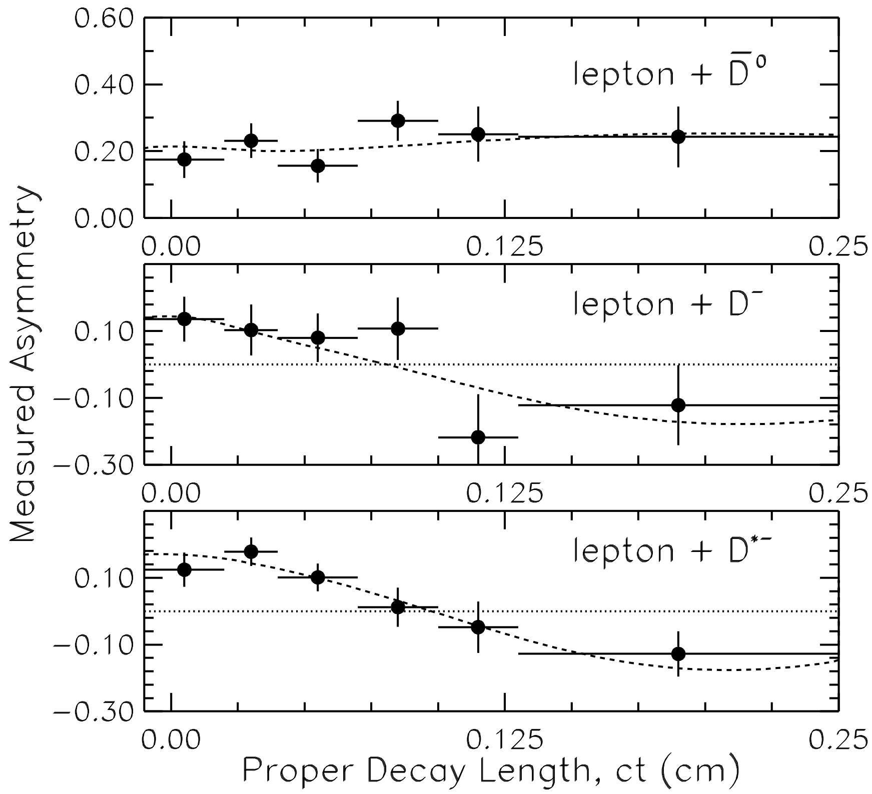
$$\textit{figure of merit} = \epsilon\mathcal{D}^2$$

Tagging algorithms





B_d^0 mixing using SST

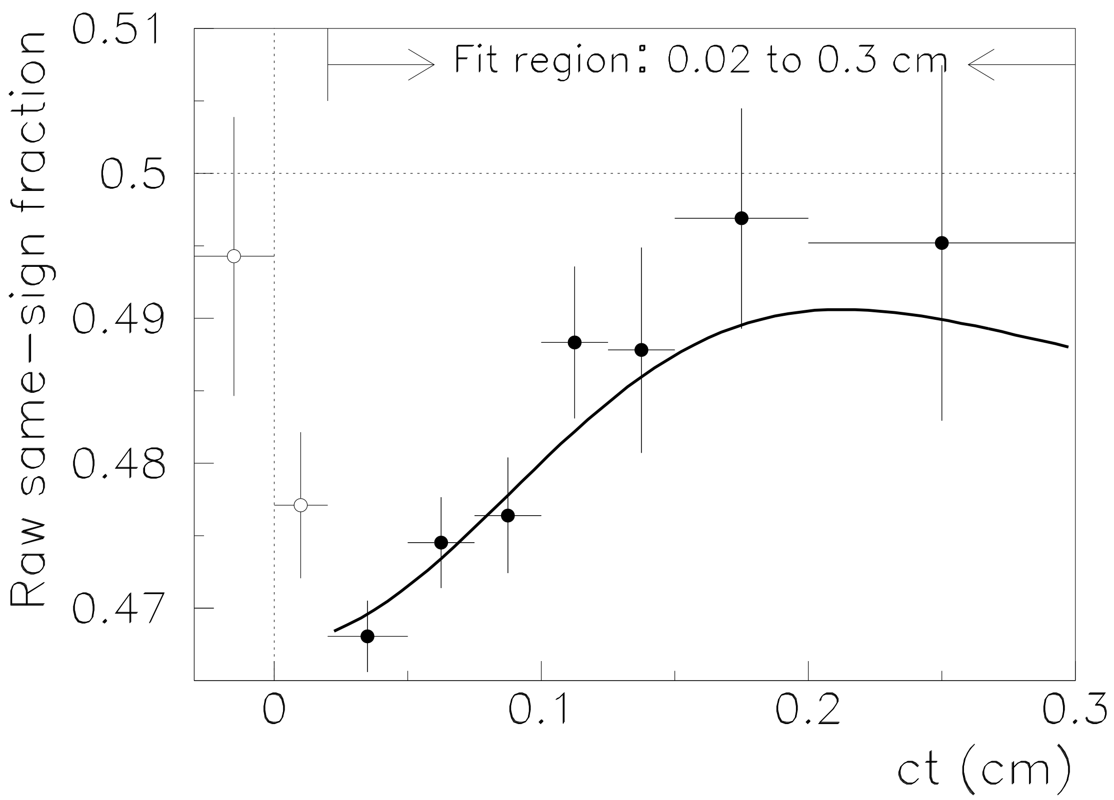


- Reconstruct $B \to D^{(*)}\ell\nu$ (3K B^-, 6K B^0)
- Form $\mathcal{A}(t)$ using SST ($\epsilon \sim 70\%$)
- Global fit: B^-/B^0, missing π, D^{**}, etc.

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

$$\boxed{\mathcal{D} = 0.181^{+0.036}_{-0.032}}$$

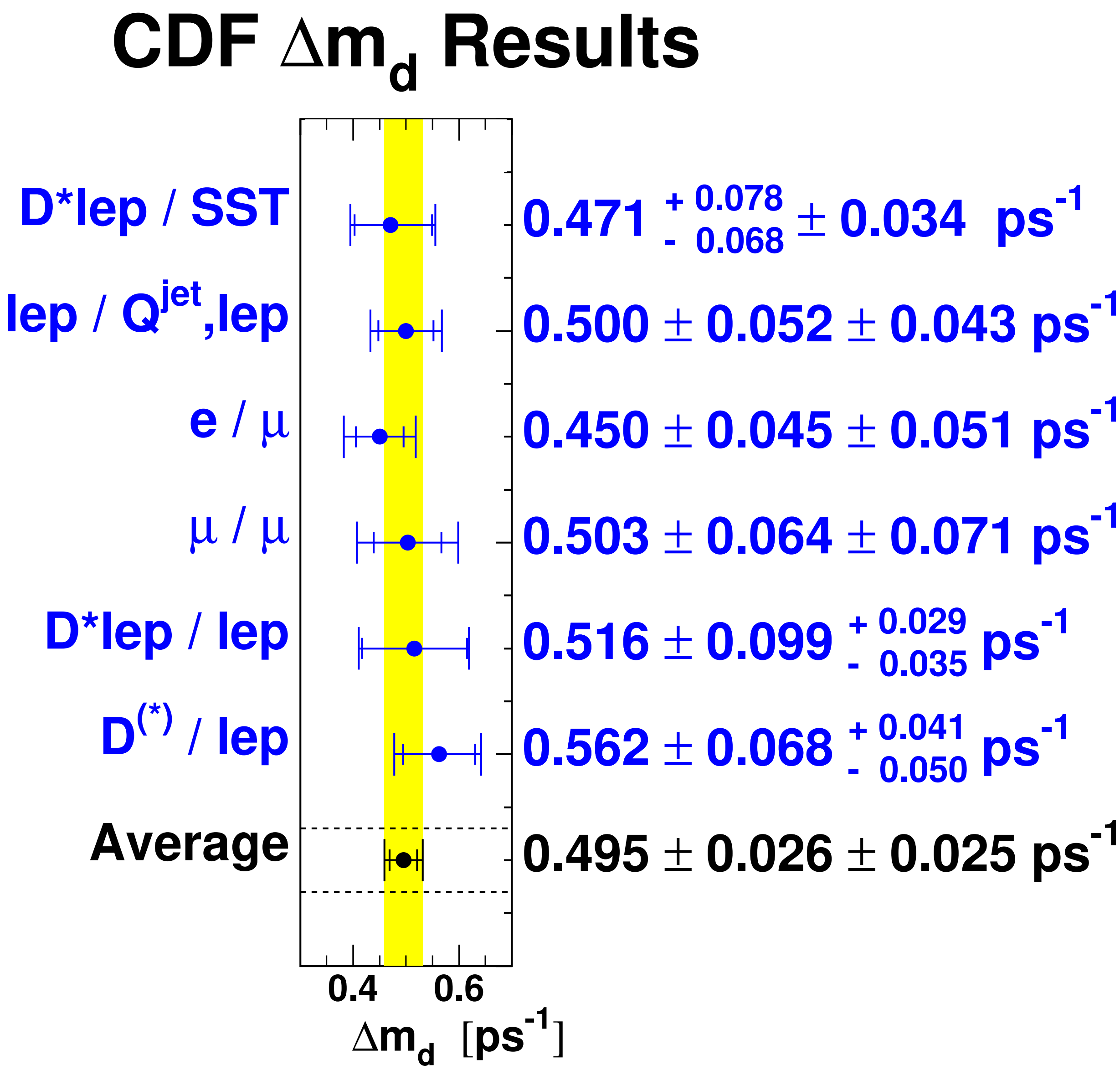
B_d^0 mixing using OST



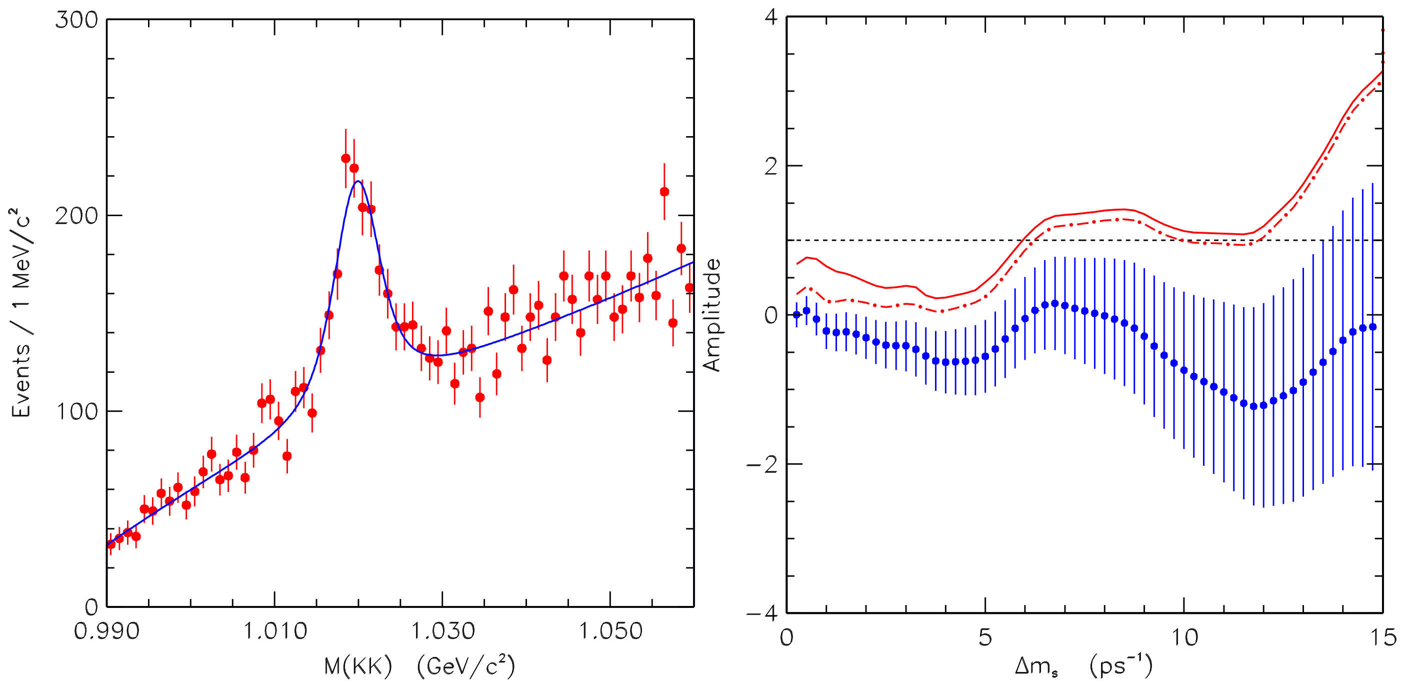
- B identified with ℓ and displaced vertex
- Soft lepton tag (SLT): high $\mathcal{D}$, low ϵ
- Jet charge tag (JetQ): higher ϵ, lower $\mathcal{D}$

$$\boxed{\Delta m_d = (0.500 \pm 0.052 \pm 0.043)\mathrm{ps}^{-1}}$$

B_d^0 mixing summary



B_s^0 mixing



Amplitude v Δm_s

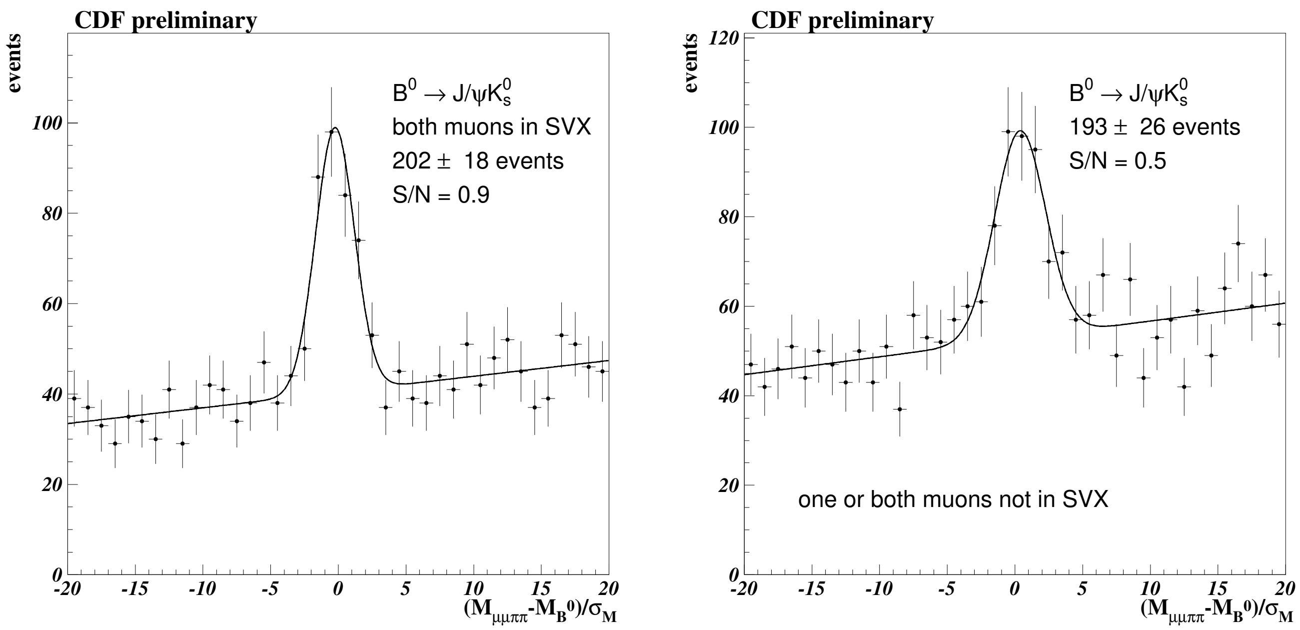
- Identify $B_s^0 \rightarrow \ell^+ \phi \mathrm{h}^- X$ decay
- 1068 ± 70 candidates, 61% pure
- Fit using the oscillation amplitude method

$\boxed{\Delta m_s > 5.8\mathrm{ps}^{-1} \text{ at } 95\% \text{ C.L.}}$

CP violation in $B_d^0 \to J/\psi K_s^0$

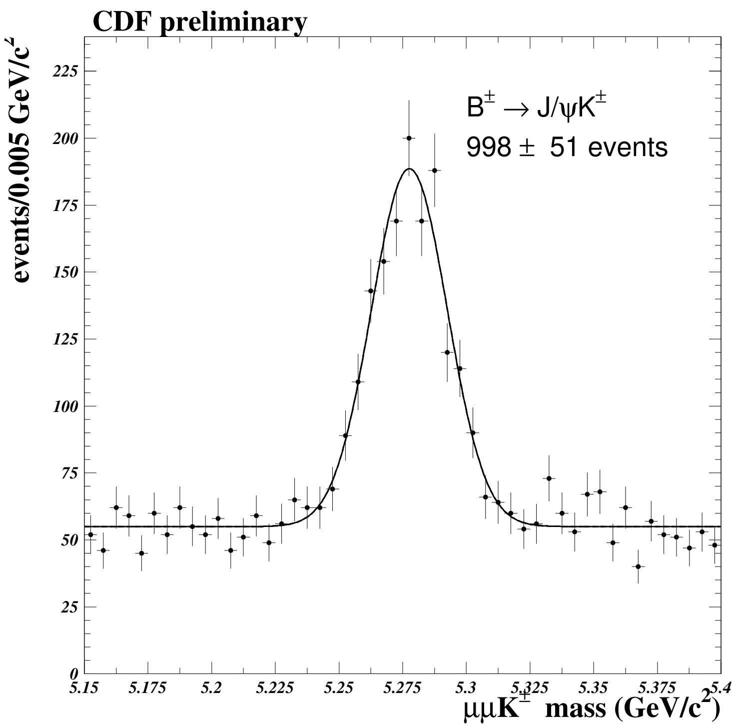
$$\mathcal{A}_{\mathrm{CP}}(\mathrm{t}) = \frac{\overline{B}^0(t) - B^0(t)}{\overline{B}^0(t) + B^0(t)} = \sin 2\beta \sin \Delta m_d t$$

$$\int \mathcal{A}_{\mathrm{CP}}(\mathrm{t}) = \frac{x_d}{1+x_d^2} \sin 2\beta \approx 0.5 \sin 2\beta$$



- use SVX events for time dependence of $\mathcal{A}_{\mathrm{CP}}(\mathrm{t})$
- also use low $c\tau$ resolution to increase statistics
- Use SST, SLT, and JetQ tagging algorithms

Summary of tagging algorithms

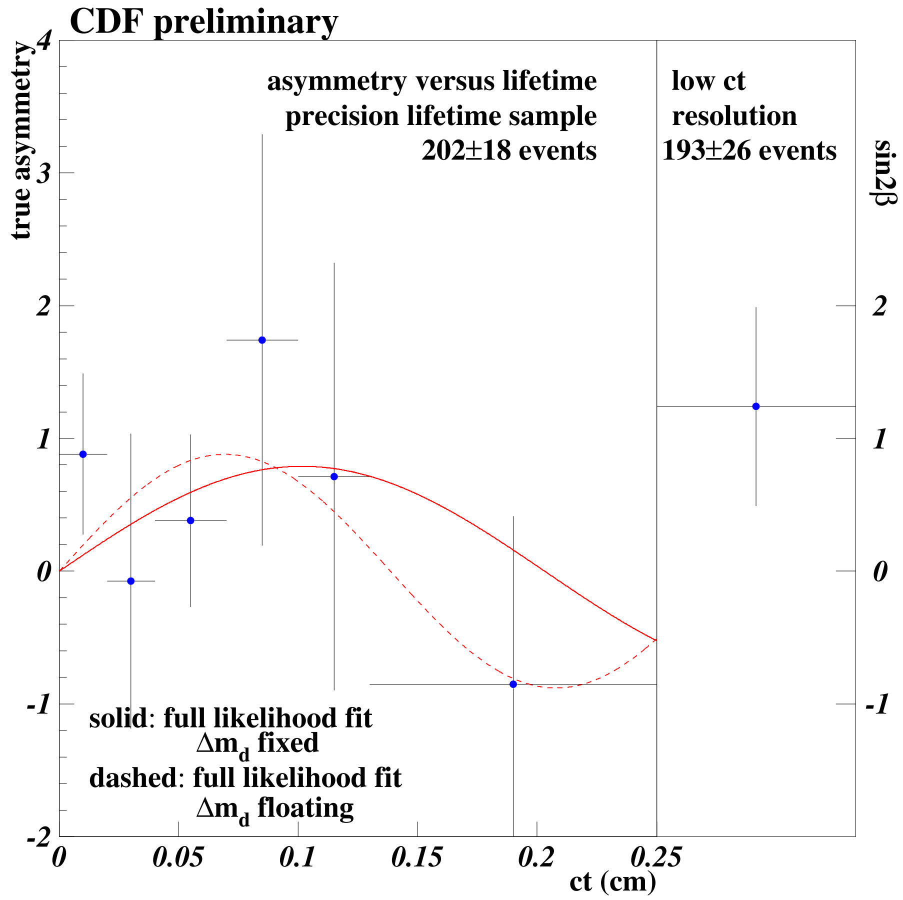


Use $B^- \rightarrow J/\psi\ K^-$ decays to calibrate OST

SST calibration uses mixing result with Monte Carlo

	ϵ	$\mathcal{D}$	$\epsilon\mathcal{D}^2$
SLT	$(5.6 \pm 1.0)\%$	$(62.5 \pm 14.6)\%$	$(2.2 \pm 1.0)\%$
Jet Q	$(40.2 \pm 2.2)\%$	$(23.5 \pm 6.6)\%$	$(2.2 \pm 1.3)\%$
SST (in silicon)	$\sim 70\%$	$(16.6 \pm 2.2)\%$	$(2.1 \pm 0.5)\%$
SST (not in silicon)		$(17.4 \pm 3.6)\%$	
combined	$\sim 80\%$		$(6.3 \pm 1.7)\%$

Results: CP violation in $B_d^0 \to J/\psi K_s^0$



$$\boxed{\sin 2\beta = 0.79^{+0.41}_{-0.44}\ \text{(stat + syst)}}$$

$$\boxed{0.0 < \sin 2\beta < 1.00\ 93\%\ \text{C.L.}}$$

(Feldman-Cousins)

Uncertainty in $\mathcal{D}$ contributes 0.16 in $\delta \sin 2\beta$

Conclusions

B physics at the Tevatron in Run I:

- Very successful

world's best (only) measurements

competitive measurements

- Broad program

tests of pQCD and non-pQCD

tests of weak interactions

- Beginning to test

non-Standard Model effects

the CKM hypothesis