Flavor Physics at BABAR

Jose Benitez
for the BABAR Collaboration

La Thuile
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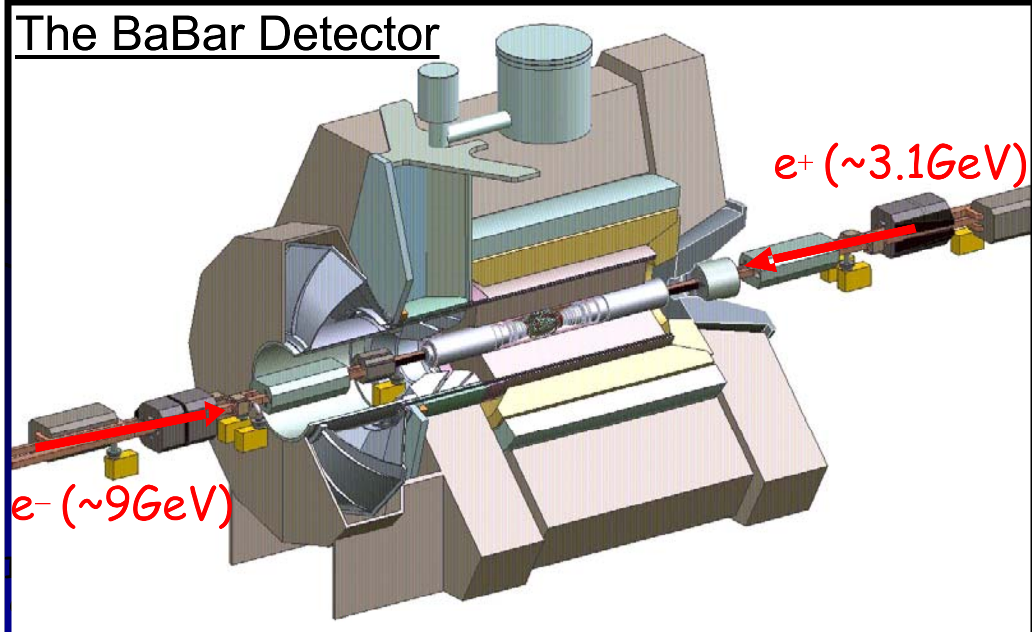
The BABAR B-factory

- The BaBar experiment operated between 1999 and 2008.
- Collected a total of 531 fb^{-1} of e^+e^- collisions at center of mass energies corresponding to
  - Υ**(4S)** : 432 fb^{-1}
  - Υ**(3S)** : 30 fb^{-1}
  - Υ**(2S)** : 14 fb^{-1}
  - Off-Peak: 54 fb^{-1}
    ~40MeV below the Υ(nS)



$e^+e^- \rightarrow$	Cross-section (nb)
$b\bar{b}$	1.10
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$u\bar{u}$	1.39
$d\bar{d}$	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	~ 40

Recent Results from BABAR

- $|V_{ub}|$ from $B^0 \to \pi^- \ell^+ \nu$
- f_{D_s} from $D_s^+ \to \tau^+\nu$ $(\tau^+ \to e^+\nu\nu)$
- D^0 Mixing using the $D^0 \to K^-\pi^+ / D^0 \to K^-K^+$ lifetime ratio
- Search for CPV in $D^0 \to K^-K^+\pi^-\pi^+$
- Search for Lepton Flavor Violation
  - $\tau^+ \to \ell^+ \gamma$
  - $\Upsilon(nS) \to \tau^- \ell^+$
- Test of Lepton Universality
  - $\Upsilon(1S) \to \tau^-\tau^+ / \Upsilon(1S) \to \mu^-\mu^+$

Measurement of $|V_{ub}|$ using $B \rightarrow \pi \ell \nu$

Motivation

- Exclusive decays of $B \to \pi \ell \nu$ provide one of the best ways to extract the CKM element V_{ub}

- The decay rate depends on the momentum transfer and is proportional to $|V_{ub}|^2$

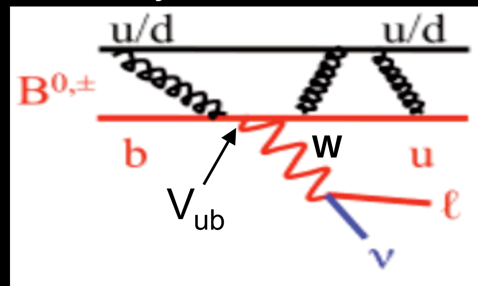
$$\frac{d\Gamma}{dq^2}(B \to \pi l \nu) = \frac{G_F^2}{24\pi^3} p_\pi^3 \, |V_{ub}|^2 |f_+(q^2)|^2$$

- The form factor $f(q^2)$ are obtained from Lattice QCD calculations

CKM Matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Decay Mechanism



$$q^2 = (p_\ell + p_\nu)^2$$

Analysis Method

- Reconstruct events by identifying a charged lepton (e,μ) and a hadron (π,ρ) in the following modes:

  $B^0 \rightarrow \pi^- \ell^+ \nu$ $B^+ \rightarrow \pi^0 \ell^+ \nu$ $B^0 \rightarrow \rho^- \ell^+ \nu$ $B^+ \rightarrow \rho^0 \ell^+ \nu$

- The ν is reconstructed as the missing 4-momentum in the event:

$$(\vec{p}_{\rm miss}, E_{\rm miss}) = (\vec{p}_{\rm beams}, E_{\rm beams}) - (\sum_i \vec{p}_i \,, \sum_i E_i)$$

- We use the difference in the B energy with respect to ½ the CM energy and the mass of the B to extract the signal yield:

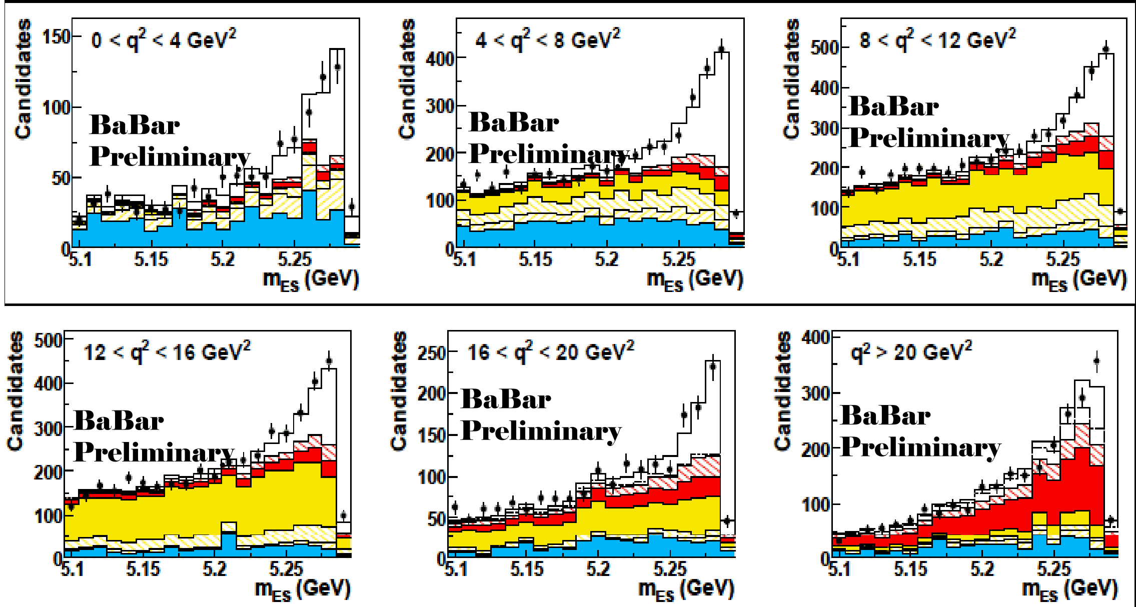
$$\Delta E = \frac{P_B \cdot P_{e^+e^-} - s/2}{\sqrt{s}}$$

$$m_{ES} = \sqrt{\frac{(s/2 + \vec{p}_B \cdot \vec{p}_{e^+e^-})^2}{E_{e^+e^-}} - \vec{p}_B^2}$$

m_{ES} distributions

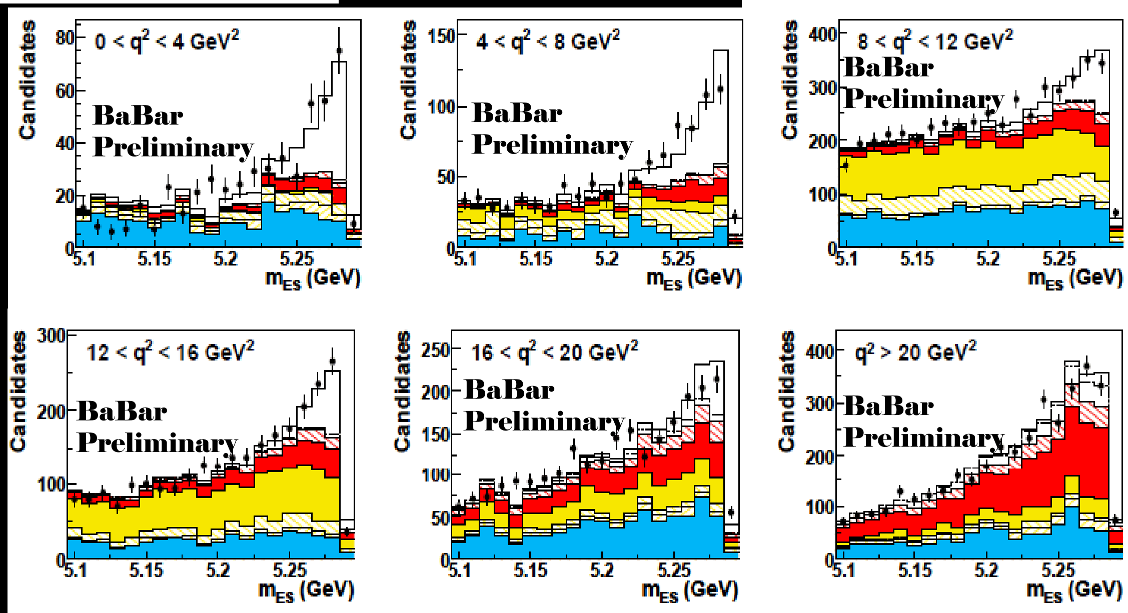
$\overline{\text{377 Million BB events}}$

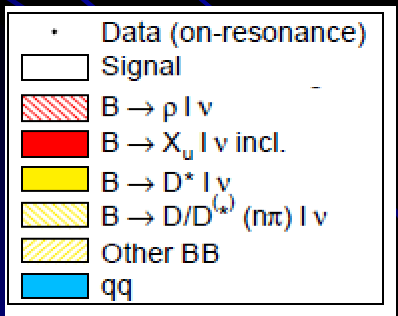
Previous analysis used only 227 Million



$B^0 \to \pi^- \ell^+ \nu$

$B^+ \to \pi^0 \ell^+ \nu$





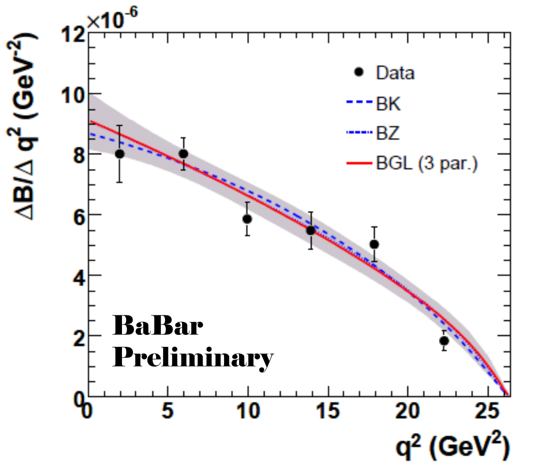
Determination of V_{ub}

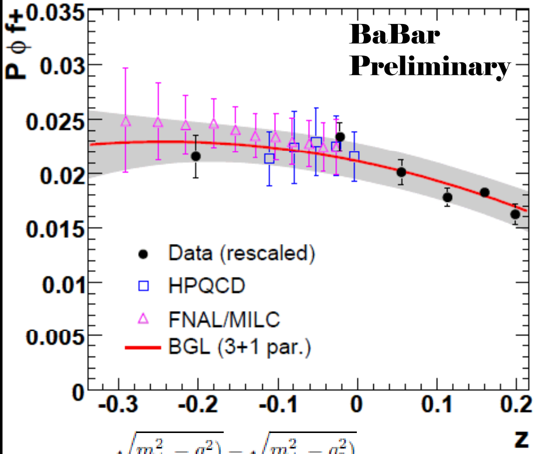
- The decay rate of $B^0 \to \pi^- \ell^+ \nu$ is extracted in a simultaneous fit to the four channels. We use isospin symmetry to constrain the decay to $\pi^0 \ell^+ \nu$ and use the $\rho \ell^+ \nu$ modes to constrain the cross-feeding backgrounds.
- The decay rate is determined as a function of q^2 and then transformed into a form factor using:

$$\frac{d\Gamma}{dq^2}(B \to \pi l \nu) = \frac{G_F^2}{24\pi^3} p_\pi^3 |V_{ub}|^2 |f_+(q^2)|^2$$

- The normalization for such a transformation is proportional to $|V_{ub}|$
- The form factor values are then required to agree with the values calculated by theory
- We obtain

$$|V_{ub}| = (3.05 \pm 0.29) \times 10^{-3}$$



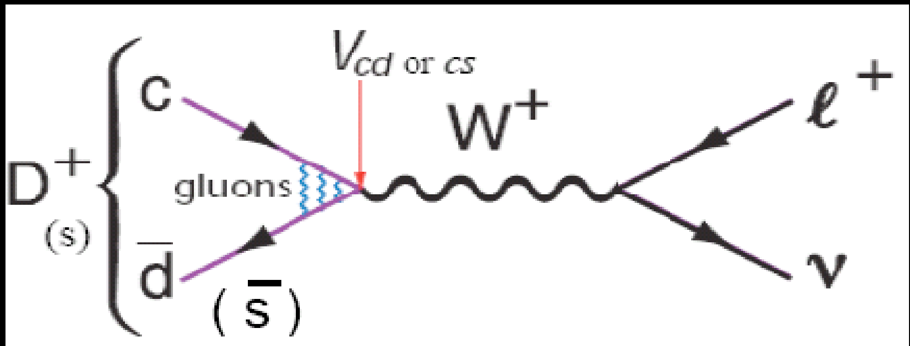


$$z(q^2, q_0^2) = \frac{\sqrt{m_+^2 - q^2} - \sqrt{m_+^2 - q_0^2}}{\sqrt{m_+^2 - q^2} + \sqrt{m_+^2 - q_0^2}}$$

Determination of f_{Ds} from $D_s^+ \rightarrow \tau^+ \nu$

Motivation

- The purely leptonic decay of charged D mesons is a clean process in the SM:



$$\Gamma(D_s^+ \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi} M_{D_s^+}^3 \left(\frac{m_\ell}{M_{D_s^+}}\right)^2 \left(1 - \frac{m_\ell^2}{M_{D_s^+}^2}\right)^2 |V_{cs}|^2 f_{D_s}^2$$

- f_{Ds} characterizes the QCD interactions.
- Currently a discrepancy of **~2.5σ** exists between theory and experiment. Theory [HPQCD+UKQCD] predicts f_{Ds}=241 ± 3 MeV while the experimental average [HFAG] is 257 ± 7 MeV.
- f_D agrees well with theory

Analysis Method

- Reconstruct events of the type

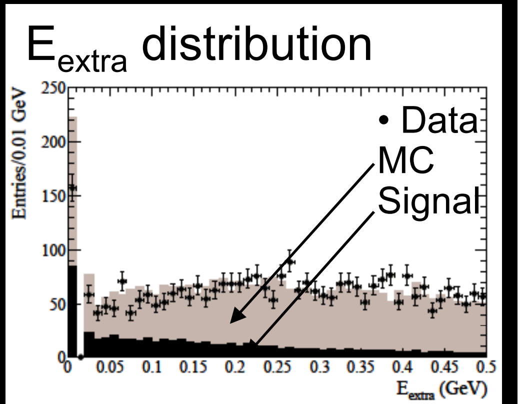
$$e^+e^- \rightarrow D_{Tag}KXD_s^*$$

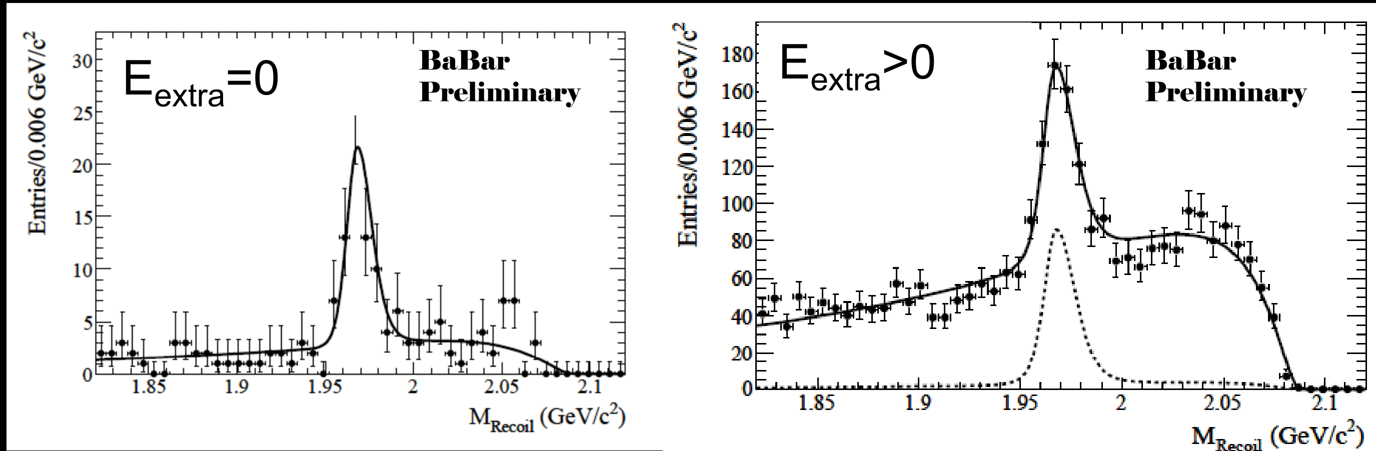
$$\text{where } D_s^* \rightarrow D_s\gamma,\ D_s \rightarrow \tau\nu \text{ and } \tau \rightarrow e\nu\nu$$

- D_{Tag} consists of 11 high yield D^0/D^+ decay channels. K consists of a K_S/K^+ to balance the quark flavor and X consists of additional reconstructed pions from fragmentation.
- Besides the DKX system, an e^+ track must be identified in signal events.
- A similar reconstruction is done for the well known decay channel $D_s^+ \rightarrow K_S K^+$ and used for normalization.

Results

- We fit for the $D_s \rightarrow \tau\nu$ signal yield using the mass recoiling against the DKXγ system and the extra neutral energy in the event.





- We obtain a total of 448 ± 36 $D_s \rightarrow \tau\nu$ events.
- Similarly extract the $D_s \rightarrow K_s K$ yield: 333 ± 28 events.
- We obtain the following value for the branching fraction:

$$B(D_s^+ \rightarrow \tau^+ \upsilon_\tau) = \frac{N_{\tau\upsilon}}{N_{K_s K}} \frac{\varepsilon_{K_s K}}{\varepsilon_{\tau\upsilon}} \frac{B(D_s^+ \rightarrow K_s^0 K^+) B(K_s^0 \rightarrow \pi^+\pi^-)}{B(\tau^+ \rightarrow e^+ \upsilon_\tau \upsilon_e)}$$

BF's from PDG

Preliminary

$$\mathcal{B}(D_s^+ \rightarrow \tau^+\nu_\tau) = (4.54 \pm 0.53^{+0.48}_{-0.33} \pm 0.28)\%$$

Errors are statistical, systematic and PDG

Result for f_{Ds}

- The decay constant is determined by inverting the formula for the partial width of $\Gamma(D_s \to \tau\nu)$ and using the PDG values for the additional parameters.
- We find a value which is consistent with the theoretical value and with the current world average.

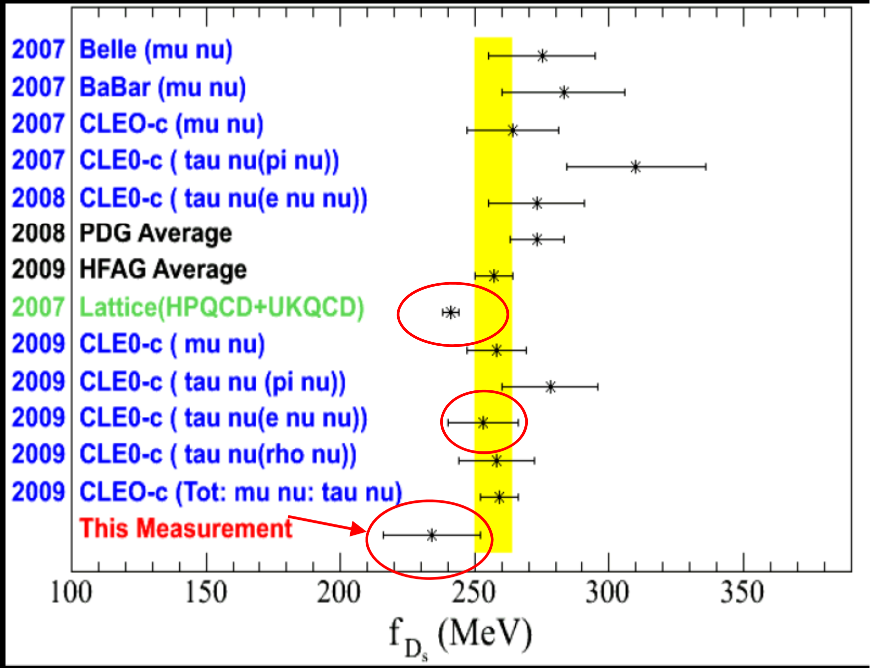
$$f_{D_s^+} = \frac{1}{G_F m_\ell \left(1 - \frac{m_\ell^2}{M_{D_s^+}^2}\right) |V_{cs}|} \sqrt{\frac{8\pi B(D_s^+ \to \ell\nu)}{M_{D_s^+}\tau_{D_s^+}}}$$

$$f_{D_s} = (233.6 \pm 13.6 \pm 10.4 \pm 7.1)\ \mathrm{MeV}$$

Errors are: statistical, systematic and PDG

Preliminary

Comparison with other measurements



Evidence of D^0 Mixing using the $D^0 \rightarrow K^-\pi^+ / D^0 \rightarrow K^-K^+$ lifetime ratio

Motivation

- D^0 mixing is characterized by a difference in masses and widths of the physical states:

$$|D_1\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle$$

$$\Delta m = m_1 - m_2$$
$$\Delta\Gamma = \Gamma_1 - \Gamma_2$$
$$\Gamma = (\Gamma_1 + \Gamma_2)/2$$

$$x \equiv \Delta m/\Gamma \text{ and } y \equiv \Delta\Gamma/2\Gamma$$

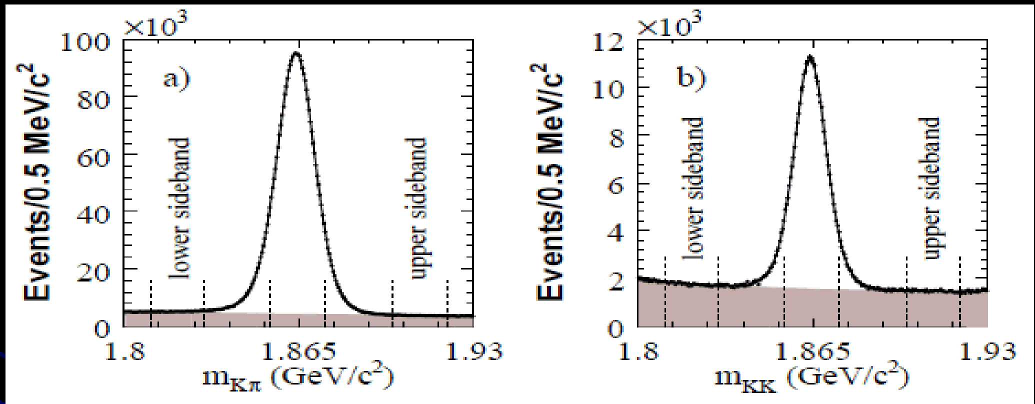
- D^0 mixing can be detected as a difference in the measured D^0 lifetime with final states of different CP:

$$y_{CP} = \frac{\langle\tau_{K\pi}\rangle}{\langle\tau_{hh}\rangle} - 1$$

- y_{cp}=y in the limit of no direct CP violation.

Analysis Method

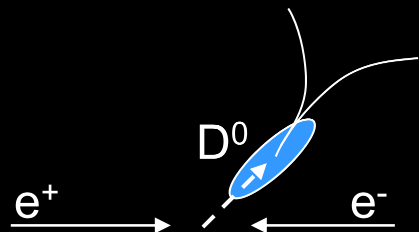
- We measure the D^0 lifetime using decays to the CP mixed final state $K^-\pi^+$ and CP even final state K^-K^+.
- No D* parent is required in order to enhance the statistical power by ~4 with respect to our previous tagged analysis.



Sample	Signal Yield (x 10^3)	Purity (%)
$K^-\pi^+$	2710.2 ± 3.4	94.2
K^+K^-	263.6 ± 1.0	80.9

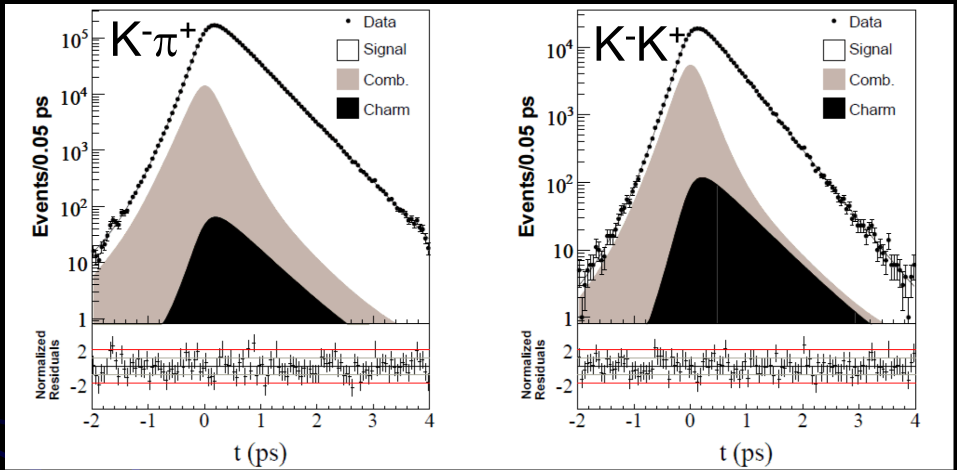
PRD 80,071103 (2009)

- We measure the D^0 decay time by measuring the displacement of D^0 decay vertex from the e^+e^- interaction point.



Results

- The decay time distribution is fitted using an exponential signal PDF convoluted with a resolution model determined from the MC simulation.



PRD 80,071103 (2009)

We obtain a $K\pi$ lifetime which is significantly larger than the KK lifetime:

$$\tau_{K\pi} = 410.39 \pm 0.38(\text{stat})\ \text{fs}$$
$$\tau_{KK} = 405.85 \pm 1.00(\text{stat})\ \text{fs}.$$

- The calculation of y_{CP} shows evidence for D^0 mixing at the level of 3.3σ:

$$y_{CP}(\text{untagged}) = [1.12 \pm 0.26(\text{stat}) \pm 0.22(\text{syst})]\%.$$

- When combined with our previous Tagged analysis we obtain a significance of 4.1σ :

$$[1.16 \pm 0.22(\text{stat}) \pm 0.18(\text{syst})]\%$$

Search for CPV in $D^0 \rightarrow K^- K^+ \pi^- \pi^+$

Motivation

- In the Standard Model CP violation in D mesons is predicted at the level of 10^{-3}; B factories are now probing the 0.5% regime
- We use the "T-odd correlation" in 4-body decays of $D^0 \rightarrow K^- K^+ \pi^- \pi^+$

$$C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$$
$$\bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$$

to search for a T-violating signal within each CP eigenstate

$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)} \qquad \overline{A_T} \equiv \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}$$

- A true CPV signal can be detected in the difference between the D^0 and $\bar{D}^0$ which is not sensitive to asymmetries due to final state interactions

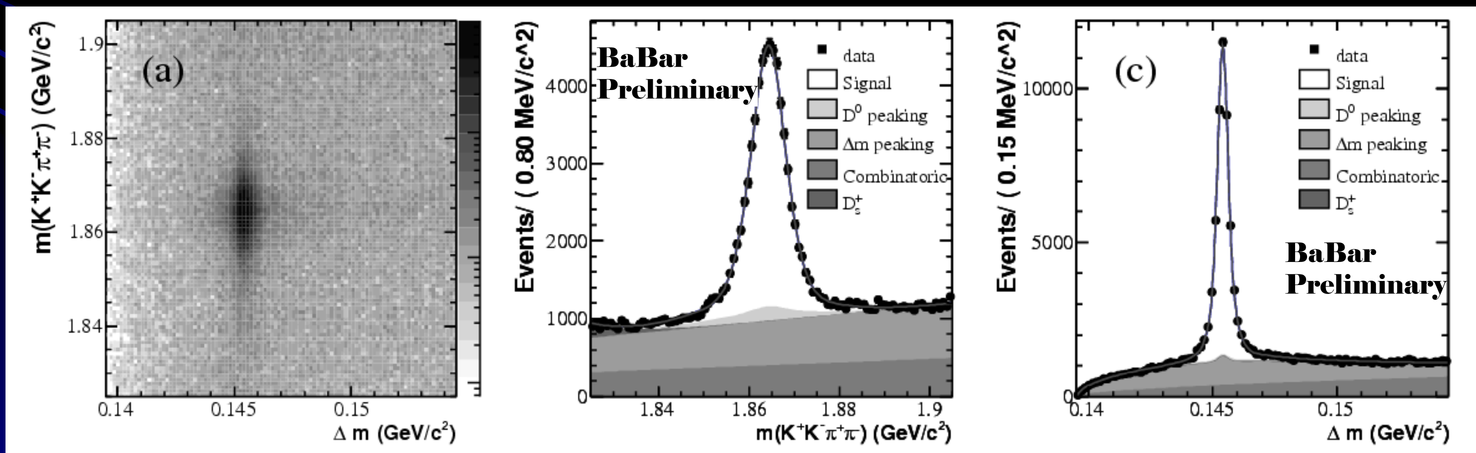
$$\mathcal{A}_T = \frac{1}{2}(A_T - \overline{A_T})$$

Analysis Method

- We reconstruct D^0's inclusively and tag the flavor using the charge of the parent D*

$$e^+e^- \rightarrow X\ D^{*+}$$
$$\hookrightarrow D^{*+} \rightarrow \pi_s^+ D^0$$
$$\hookrightarrow D^0 \rightarrow K^+K^-\pi^+\pi^-$$

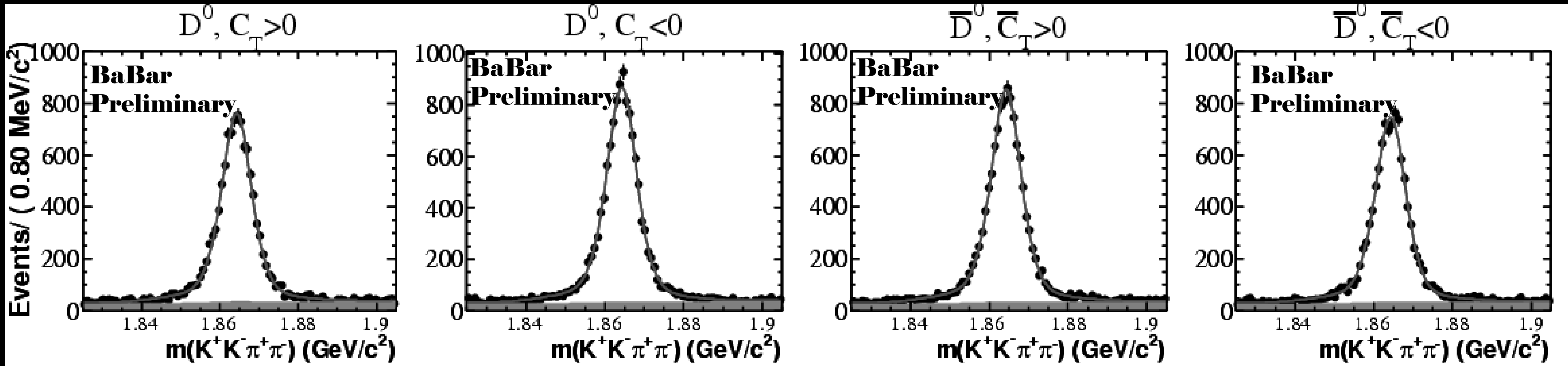
- The signal yield is extracted from a 2 dimensional fit in the D^0 mass and mass difference $m(D^0\pi^+) - m(D^0)$.



470 fb^{-1} of Data

Results

- We divide the Data into the different CP and C_T components and fit for the yield in each sample:



- The asymmetry between D^0 and $\overline{D}^0$ is consistent with zero with a sensitivity of 0.6%:

Subsample	Events
(a) D^0, $C_T > 0$	10974 ± 117
(b) D^0, $C_T < 0$	12587 ± 125
(c) $\overline{D}^0$, $\bar{C}_T > 0$	10749 ± 116
(d) $\overline{D}^0$, $\bar{C}_T < 0$	12380 ± 124

$$\mathcal{A}_T = (1.0 \pm 5.1_{\text{stat}} \pm 4.3_{\text{syst}}) \times 10^{-3}$$

Preliminary

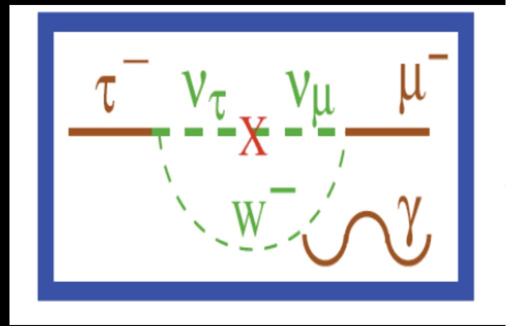
Search for Lepton Flavor Violation:

- $\tau^+ \rightarrow \ell^+ \gamma$ (ℓ=e,μ)
- Υ(nS)$\rightarrow \tau^- \ell^+$ (n=2,3 ℓ=e,μ)

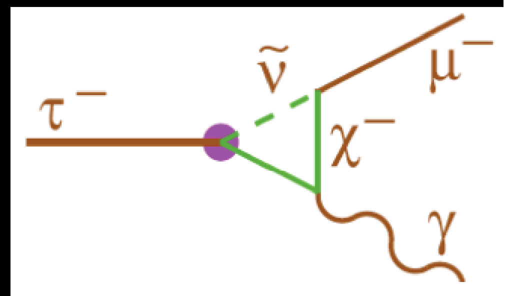
Motivation

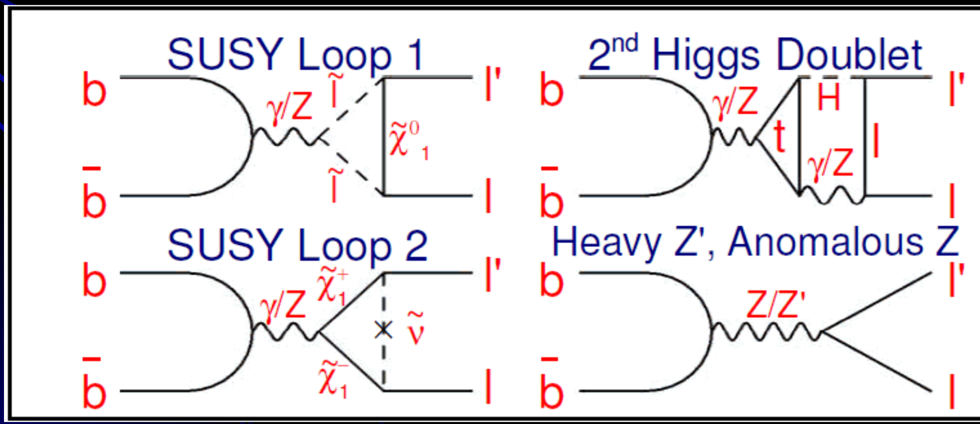
- Charged Lepton Flavor violation in the SM is unobservable
- The decays $\tau^+ \rightarrow \ell^+ \gamma$ and $\Upsilon(nS) \rightarrow \tau^- \ell^+$ are suppressed by a factor of $m_\nu^2/m_W^2 \sim 10^{-48}$
- New Physics scenarios predict rates as high as 10^{-7}

SM process ~ $O(10^{-54})$



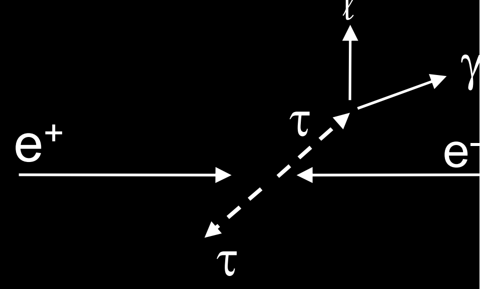
SUSY Model



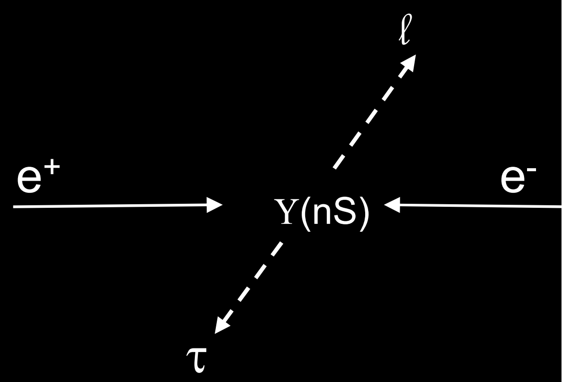


Analysis Method

- We search for $\tau^+ \rightarrow \ell^+ \gamma$ events by identifying an e^+/μ^+ track and a signal γ
  - We require the invariant mass of the $\ell^+ \gamma$ to be consistent with the τ mass and the $\ell^+ \gamma$ energy be consistent with half the beam energy
  - We also require a leptonic or hadronic τ decay on the other side of the event

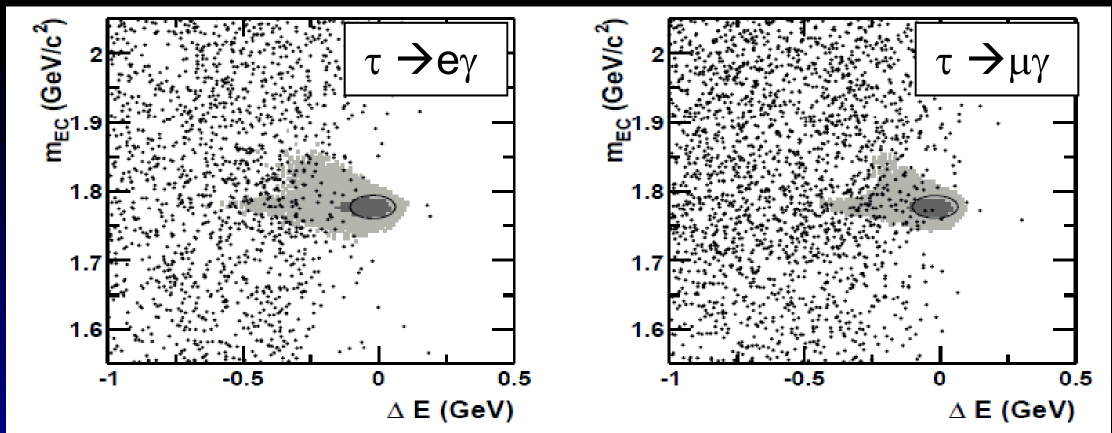


- We search for $\Upsilon(nS) \rightarrow \tau^- \ell^+$ signal events by requiring exactly two oppositely charged tracks:
  - a primary e^+/μ^+ with energy close to ½ the beam energy ($x \equiv |p_\ell|/E_B$),
  - a charged lepton or pion from the τ decay



$\tau^+ \rightarrow \ell^+ \gamma$ Search Results

- The BaBar data-set consisting of 963 Million τ decays
- The reconstruction efficiency for signal events is 4-6%
- The number of candidates found in the signal region is consistent with expected background
- Upper limits are placed at 3-4 x10^{-8} at 90% CL



Decay modes	ε (%)	UL ($\times 10^{-8}$) obs	UL ($\times 10^{-8}$) exp
$\tau^\pm \rightarrow e^\pm \gamma$	3.9±0.3	3.3	9.8
$\tau^\pm \rightarrow \mu^\pm \gamma$	6.1±0.5	4.4	8.2

PRL104, 021802 (2010)

$\Upsilon(nS) \rightarrow \tau^- \ell^+$ Search Results

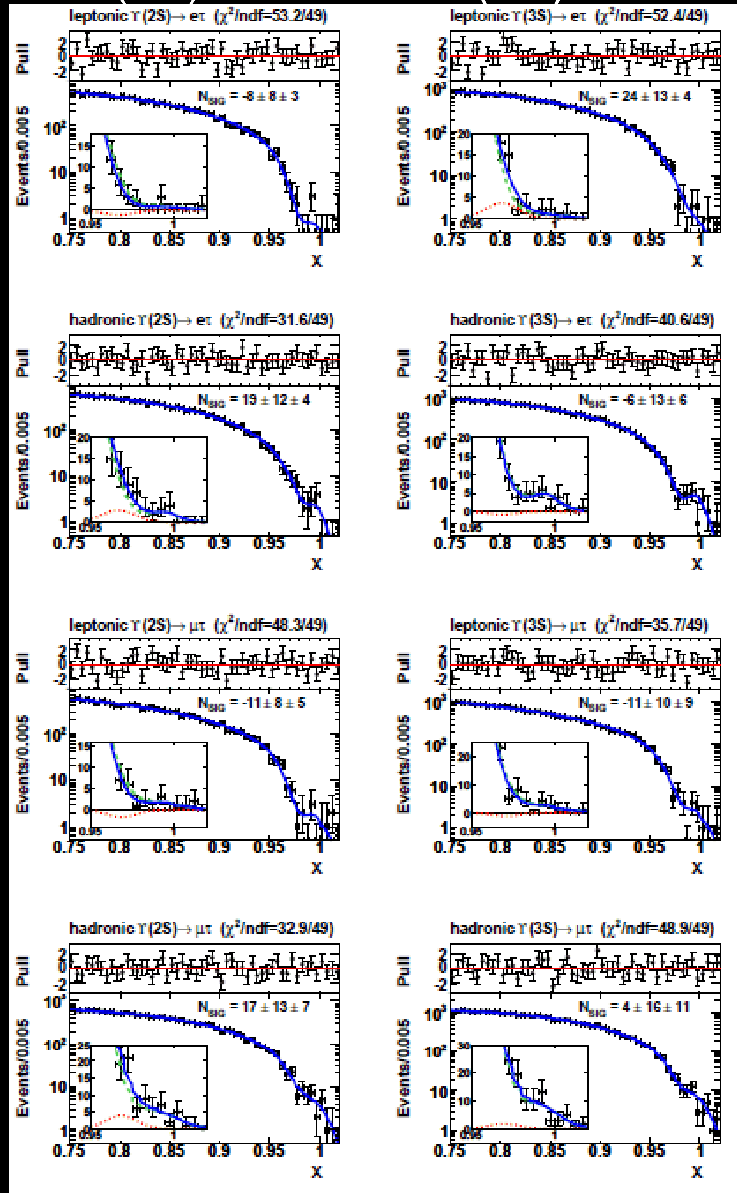
- The BaBar Data sample contains
  - 116 Million Υ(3S) events
  - 98 Million Υ(2S) events
- The reconstruction efficiency for signal is 4-6%
- We find no evidence of a signal and place upper limits at $3\text{-}4\times10^{-6}$ at 90% CL.

BaBar Preliminary

	$\mathcal{B}$ (10^{-6})	UL (10^{-6})
$\mathcal{B}(\Upsilon(2S) \to e^{\pm}\tau^{\mp})$	$0.6^{+1.5+0.5}_{-1.4-0.6}$	< 3.2
$\mathcal{B}(\Upsilon(2S) \to \mu^{\pm}\tau^{\mp})$	$0.2^{+1.5+1.0}_{-1.3-1.2}$	< 3.3
$\mathcal{B}(\Upsilon(3S) \to e^{\pm}\tau^{\mp})$	$1.8^{+1.7+0.8}_{-1.4-0.7}$	< 4.2
$\mathcal{B}(\Upsilon(3S) \to \mu^{\pm}\tau^{\mp})$	$-0.8^{+1.5+1.4}_{-1.5-1.3}$	< 3.1

arXiv:1001.1883 submitted to PRL

Υ(2S)→τℓ Υ(3S)→τℓ



Test of Lepton Universality

- $\Upsilon(1S) \rightarrow \tau^- \tau^+$ / $\Upsilon(1S) \rightarrow \mu^- \mu^+$

Motivation

• In the Standard Model the rate for decays of Y(1S) to two leptons is approximately the same for all lepton flavors:

$$\Gamma_{\Upsilon(nS)\to ll} = 4\alpha^2 Q_b^2 \frac{|R_n(0)|^2}{M_\Upsilon^2}(1+2\frac{M_l^2}{M_\Upsilon^2})\sqrt{1-4\frac{M_l^2}{M_\Upsilon^2}}$$

•The ratio of Y(1S)→ττ and Y(1S)→μμ has the following value (assuming g_τ/g_μ=1):

$$R_{\tau\mu}(\Upsilon(1S)) = \frac{\Gamma(\Upsilon(1S)\to\tau^+\tau^-)}{\Gamma(\Upsilon(1S)\to\mu^+\mu^-)} = 0.992$$

•The presence of a light scalar Higgs can cause this ratio to deviate by as much as 4% [JHEP 0901, 061 (2009)]

$$\Upsilon(1S)\to A^0\gamma\to l^+l^-\gamma$$

$$\Upsilon(1S)\to\eta_b(1S)\gamma, \eta_b(1S)\to A^0\to l^+l^-$$

Analysis Method

arXiv:1002.4358
submitted to PRL

- The analysis method uses events where

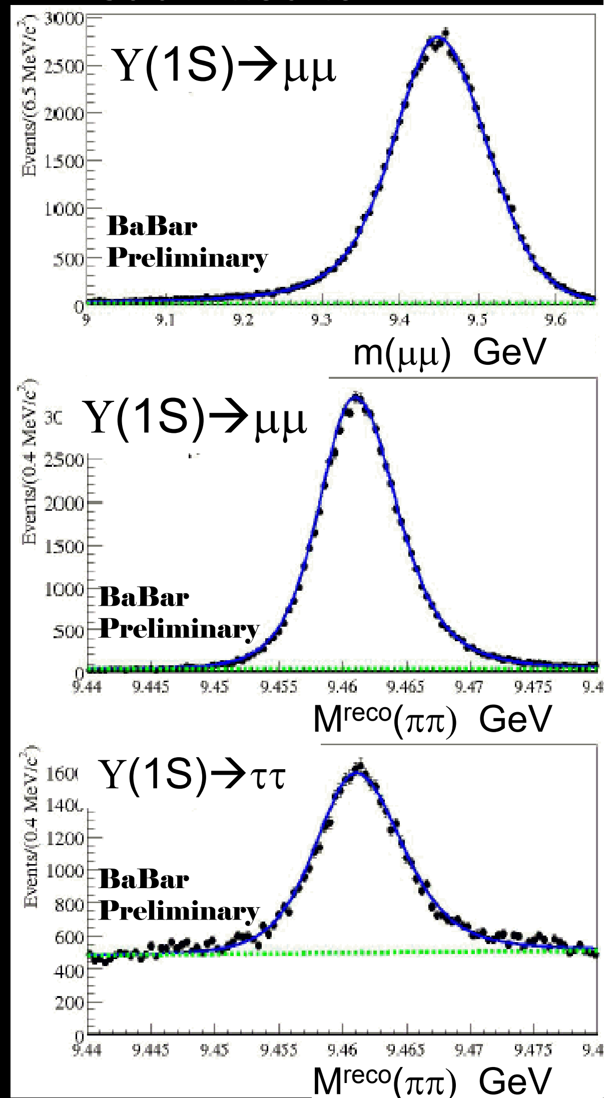
$$e^+e^- \rightarrow \Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^-$$

- We require 4 charged tracks in each event the $\pi^+\pi^-$ and two oppositely charged tracks
- The $\Upsilon(1S)$ is identified through the recoil mass against the $\pi^+\pi^-$ system:

$$M^{reco}_{\pi^+\pi^-} = \sqrt{s + M^2_{\pi\pi} - 2 \cdot \sqrt{s} \cdot E^*_{\pi\pi}},$$

- In the case of the $\Upsilon(1S) \rightarrow \mu^-\mu^+$ channel the $\mu\mu$ mass is also used
- The Signal distributions are modeled using a bifurcated Gaussian function:

$$\mathcal{F}(x) = exp\left\{ - \frac{(x-\mu)^2}{2\sigma^2_{L,R} + \alpha_{L,R}(x-\mu)^2} \right\}$$



Results

- We use 121.8±1.2 Million $\Upsilon(3S)$ events with a reconstruction efficiency of 44.6% in the $\mu^+\mu^-$ channel and 16.8% in the $\tau^+\tau^-$ channel.
- We perform a simultaneous fit to the $\mu^+\mu^-$ and $\tau^+\tau^-$ data where $R_{\tau\mu}$ is varied and obtain the following value:

Preliminary

$$R_{\tau\mu}(\Upsilon(1S)) = 1.005 \pm 0.013(stat.) \pm 0.022(syst.)$$

- This measurement is consistent with SM expectation.

Summary and Conclusions

- Using 377 Million $\bar{B}B$ events we measure $|V_{ub}|=(3.05\pm0.29)\%$ using the $B^0 \to \pi^- \ell^+ \nu$ q^2-dependent branching fraction and the LQCD predictions for the form factor.
- We measure f_{Ds} =233 ± 18 MeV using $D_s^+ \to \tau^+\nu$ decays; this measurement is consistent with the current world average.
- Our measurement of the lifetime ratio of $D^0 \to K\pi / D^0 \to KK$ shows evidence of D^0 mixing at 3.3σ; 4.1σ when combined with our previous tagged measurement.
- We have searched for CP violation using T-odd correlations in 4-body D^0 decays and find no evidence with a sensitivity of 0.6%.
- We place limits on the lepton flavor violating processes $\tau^+ \to \ell^+ \gamma$ and $\Upsilon(nS) \to \tau^+ \ell^-$ at the level of 3×10^{-8} and 3×10^{-6} respectively.
- Finally, our test of Lepton Universality is consistent with SM expectations ($R_{\tau\mu}=1.005 \pm 0.025$) with a sensitivity of 2.5% .