Opportunities for $\tau$ Physics

- Overview of Tau’s at low energy

- Tau Threshold Measurements
  - Tau Mass
  - Massive Neutrino in $\tau \rightarrow \nu \nu$
  - Exotic Decays: $\tau \rightarrow eX$
  - Radiative Leptonic Decays
  - Tau Atoms

- High Statistics Measurements
  - Precision Branching Fractions
  - Hadronic structure
  - Rho Line Shape
  - CP Violation
  - Lorentz Structure
  - Neutrino Mass
Spectroscopy Is Everything
Overview of τ’s at low energy

Lowest Order Production Cross section

\[
\frac{\sigma(0)}{3s} = \frac{4p^2}{2} (3b - b^3)
\]

Radiative Effect  Beam Energy Width

CLEO-c Running Idea - no guarantee

<table>
<thead>
<tr>
<th>Ecm (GeV)</th>
<th>Lumi /fb</th>
<th>N(ττ)</th>
<th>σ (nb)</th>
<th>pτ (GeV)</th>
<th>βτ</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.557</td>
<td>0.25</td>
<td>100K</td>
<td>0.42</td>
<td>0.07</td>
<td>0.04</td>
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<tr>
<td>3.770 - ψ’’</td>
<td>3.0</td>
<td>9 M</td>
<td>2.95</td>
<td>0.63</td>
<td>0.33</td>
</tr>
<tr>
<td>4.14 - Ds</td>
<td>3.0</td>
<td>11M</td>
<td>3.56</td>
<td>1.06</td>
<td>0.51</td>
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</tbody>
</table>

Small Sample near Threshold
Larger sample with Charm background

Compare: CLEO2+3 = 15 M ττ, Belle, Babar > 100 M+ ττ
• $\tau$'s are always produced in pairs and always have $>0$ $\nu$'s

• $\tau$'s are slow – decay products are less smeared than B Factory

• Two Body $\tau \rightarrow [X] \nu$ – momentum of $[X]$ is sharp for narrow $[X]$

• $\tau \rightarrow \rho \nu$ are convenient tags in addition to $\tau \rightarrow e/\mu \nu$ tags

• Bhabha/ $\mu\mu$ bgd not a problem

• No ISR/FSR at threshold

• BUT: $\tau$ decay not jet–like

Lab Spectrum for $\tau \rightarrow \nu\nu$, $\tau \rightarrow \nu$
τ Backgrounds

• Bhabha/ (γ) not a problem
• Below charm: uds background
  • Use missing E,P cuts
  • Use 1 prong tags
  • Use sample below τ threshold to get MC right
• Charm:
  • D semileptonic, $K_L^0$ decay bgd
  • Use missing E,P cuts
  • Use 1 prong tags
  • Use tagged charm sample to get charm MC right
  • Use (uds) sample to get (uds) MC right
• τ Feed across: need to get MC right
Tau Threshold Measurements

- Tau Mass
- Massive Neutrino in $\tau \rightarrow \nu$
- Exotic Decays: $\tau \rightarrow eX$
- Radiative Leptonic Decays
- Tau Atoms
Tau Mass

This is a fundamental number in the Standard Model
   Important in precision work - eg BR(τ→lνν) vs ττ

Current best tau mass is from BES:

\[ m_\tau = 1776.96^{+0.18+0.25}_{-0.21-0.17}\text{ MeV} \]

Obtained by scanning near rapidly varying threshold
   5 pb\(^{-1}\), 2 months, narrow σ(Ebeam)

CLEO-c/BESIII can get sample > x50 greater in same time

Most of BES error was from Energy Scale from ψ, ψ’, not spread
σ(Ebeam) is 2x as large in default config compare to BESII can be made comparable at lower lumi

Look for anomalous production effects too

BESIII, CLEO-c could get σ ≈ 0.1 MeV

No one else can do this this well
Current bias: neutrinos have eV scale masses

But we have NOT looked everywhere...

\[ \tau \rightarrow \nu_X \]

2 body decay –
well defined \( p \) near threshold
Look for e, \( \mu \), tag vs

\[ m_{\nu_X} \approx 600 \text{ MeV} \]

\[ \text{BR} \approx 0.2 \% \]

\[ \int dL = 0.25/\text{fb} \]

This is best near threshold at BESIII and CLEO-c
Exotic Decays: $\tau \rightarrow e^- X$

Unique Opportunity to look for exotic bosons, eg familon

Electron signature is smeared out at higher energies - Michel Parameter measurements could miss this

$\text{PDG: BR}(\tau \rightarrow eX) < 0.2\% \ (\text{ARGUS})$
Radiative Leptonic Decays

τ→lννγ is “easy” – measured to 10%

Any deviation from expectations is very significant

No ISR/FSR at threshold

Less boost at threshold:
Greater lepton γ separation
Access to back to back lepton γ

.25 /fb at threshold should allow a 1% measurement of BR and access to “hard” kinematic regime
Tau Atoms

- $\tau^+\tau^-$ should form $^3S_1$ bound states in $e^+e^-$ collisions
  - Bohr radius $0.0003$ Angstrom $\approx a_0(\text{H})/1000$ !
  - Binding energy $= -23.7$ keV/n$^2$

- Tau atom decay via:
  - $\tau$ weak decay $\Gamma \approx 10^{-3}$ eV
  - $\tau\tau$ annihilation – S states: $ee$, hadrons ($10^{-3}$ eV), $3\gamma$ ($10^{-5}$ eV) – $2\gamma$ is not from $^3S_1$ states

- Peak production cross section huge $= 1$ millibarn
- Very narrow width $= 0.006$ eV
- $\Delta E$ beam $1$ MeV $\Rightarrow \sigma_{\text{effective}}(ee\rightarrow\tau\tau \text{ atom}) = 0.1$ nb
- If $L=10^{33}$ cm$^{-2}$s$^{-1}$, 1 tau atom every 2 minutes
• Binding Energy on the order of keV – no hope of seeing EM transition $\gamma$ between levels

• Best hope is to look for annihilation signal into $\mu\mu$ vs $ee$:
  • Signal sits on top of large $\mu$ pair and larger Bhabha background
  • Run at threshold and compare $N(\mu\mu)/N(ee)$ to off threshold running
  • $L=0.25$ fb$^{-1}$ suffices to see signal
  • Investigate $3\gamma$ annihilation – might get lucky

• Only CLEO–c and BESIII can hope to see tau
• Is there any real physics here? Could be...
High Stats Measurements

- Neutrinoless decays
- Precision Branching Fractions
- Lorentz Structure
- Hadronic structure
- Rho mass
- CP Violation
- Neutrino Mass
Neutrinoless Decays

- Current limits on neutrinoless decays are at the BR < $10^{-6}$ – $10^{-5}$ level
- In some models $\tau \rightarrow \gamma$ is more sensitive to new physics than $\mu \rightarrow e\gamma$ due to $\tau$ mass
- It is likely B factory limits will not decrease fast
- Two body neutrinoless decays should be trivial at CLEO–c and BESIII
- Sensitive to e/ / /K discrimination near 1 GeV
- CLEO–c limits conceivable at $10^{-6}$
- BESIII limits conceivable at $10^{-7}$
Precision Branching Fractions

- \( \text{BR}(\tau \rightarrow l\nu
\nu) \) has applications to lepton universality and \( R_\tau \) measurements

\[
R_\tau = \frac{\text{BR}(\tau \rightarrow e\nu\nu) - \text{BR}(\tau \rightarrow \mu\nu\nu)}{\text{BR}(\tau \rightarrow l\nu\nu)}
\]

- Absolute \( \text{BR}(\tau \rightarrow l\nu\nu, h\nu) \) currently known to \( \sigma \approx 1\% \), mostly lumi, \( \tau \) cross section systematics limited

- With \( 10^7 \) tau pairs, BESIII could match this in a global 2 track + missing energy fit

  - Use threshold \( \tau \rightarrow l\nu\nu, h\nu \) to verify trigger knowledge

<table>
<thead>
<tr>
<th>mode</th>
<th>( e\nu\nu )</th>
<th>( \nu\nu )</th>
<th>( \pi\nu )</th>
<th>( \rho\nu )</th>
<th>( K\nu )</th>
<th>( K^*\nu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR %</td>
<td>18</td>
<td>17</td>
<td>11</td>
<td>25</td>
<td>.7</td>
<td>.5</td>
</tr>
<tr>
<td>( \sigma/\text{BR} % )</td>
<td>.3</td>
<td>.4</td>
<td>1</td>
<td>.6</td>
<td>4</td>
<td>7</td>
</tr>
</tbody>
</table>
The 1 vs 1 sample has great promise for relative Branching Ratios

- Look for 1 vs 1, with both tracks $E < 0.65 E_{beam}$
- Even with NO $e$ or $\mu$ id, the almost monochromatic $\pi/K$ will stick out
- Use electron id to suppress (uds) backgrounds
- $\rho_0$ reconstruction should easily show a $\rho$
- $5/fb$ at $\psi''$ => errors much less than 1% for $h\nu, h^0\nu$ relative to $l\nu\nu$
- With some $K/\pi$ id + kinematic constraints, this should leverage into better known $\nu, \rho\nu, K\nu, K^*\nu$

Lab Spectrum for $\tau \rightarrow \nu \nu, \tau \rightarrow \nu$
Lorentz Structure

The Lorentz Structure is studied via the Michel Parameters $\rho, \eta, \xi, \delta$ in $\tau \rightarrow e/\mu \nu \nu$

$$\frac{d\mathcal{O}}{dx d\cos q} \propto x^2 \left[ h_0 + \eta h_\eta + m_l \frac{m_l}{m_\nu} + P_t \cos q (h_\eta + \eta h_\eta) \right]$$

$\eta$ multiplies lepton mass ratio

where $h_\eta = h_\eta(x)$, and $x = E_l/E_{\text{max}}$

<table>
<thead>
<tr>
<th></th>
<th>SM value</th>
<th>$\tau \rightarrow l\nu\nu$</th>
<th>$\tau \rightarrow e\nu\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>$3/4$</td>
<td>$\pm .0026$</td>
<td>$\pm .01$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$0$</td>
<td>$\pm .013$</td>
<td>$\pm .097$ ( )</td>
</tr>
<tr>
<td>$\xi$</td>
<td>$1$</td>
<td>$\pm .008$</td>
<td>$\pm .04$</td>
</tr>
<tr>
<td>$\delta$</td>
<td>$3/4$</td>
<td>$\pm .004$</td>
<td>$\pm .02$</td>
</tr>
</tbody>
</table>
• CLEO2 dominates Michel Parameter measurements:
  • Used $\tau \rightarrow \rho \nu$ vs $\tau \rightarrow \ell \nu \nu - \rho$ decay as a spin analyzer
  • Dominant errors are stat $\Rightarrow$ B factories will do much better

• $\tau$ pair spin correlations are different at lower energy $\Rightarrow$ chance for an interesting confrontation

• ISR/FSR dilutes spin correlations – interesting possibilities for threshold running
η is of particular interest at CLEO-c and BES: effect is largest for slowest ‘s

Look for 1 vs (monochromatic)

CLEO-c sensitive to η≈0.05 (currently σ_η≈0.1)

BESIII will be even more sensitive

Ecm = 3.77 GeV

Ecm = 10.58 GeV

1 M τ pairs

η=0 vs η=0.2
Hadronic structure

- For exclusive channels, BESIII/CLEO–c offer a large sample with statistics comparable to LEP/CLEO but smaller than BaBar/Belle

- Kinematic separation with monochromaticity for narrow resonances could be an important factor

- However good \( /K \) separation is key to sorting out wider resonance/interference structure

- PID also key to using the \( \tau \) as a QCD laboratory for inclusive hadronic studies

  - QCD coupling \( \alpha_s \) derived from \( \tau \) is more precise (and consistent) with that from the Z
  - \( \tau \rightarrow [X]_s=1 \nu \) key to getting strange quark mass
Rho Mass

- The $\rho$ is where $e^+e^-$ confronts the $\tau - $ see $g-2$ value

- Both the BR and line shape are problematic

- LEP: high purity, not so good at high $\omega\omega$ mass

- CLEO: very good at high $\omega\omega$ mass

- BESIII/CLEO–c: chance for low background and very good line shape

- $10^7 \tau$ will easily surpass LEP/CLEO sample sizes and bring important input to $g-2$

M. Davier hep-ex/0312065
CP Violation

- Triple product \( (P_{\text{beam}}, P_{l_1}, P_{l_2}) \) in \( \tau \to l_1 \nu \nu \) vs \( \tau \to l_2 \nu \nu \) probes CP in \( \tau \) \textbf{production} – B Factories will do this very well

- CP in \( \tau \) \textbf{decay} best probed by spin correlations in hadronic decays
  - High energy: longitudinal correlations
  - Low energy: transverse spin correlations

- CP searches at CLEO-c/BESIII probe different mechanisms than at B Factories
Neutrino Mass

- Neu mass limits come from Energy vs Mass fits to $\tau \rightarrow 5 \nu, 4 \nu$
- Current limit $\approx 18$ MeV
- Technique requires understanding MeV Scale systematics:
  - 2D correlated detector resolution ($E$ vs $M$ error)
  - Mass scale
  - underlying hadronic physics ("Spectral Function")
- ISR/FSR washes out usefulness of 1/2 of events
Neutrino Mass 2

- The 2D technique does not appear to be nicely behaved as a statistical estimator – it is more a probe of lucky events near the kinematically allowed edges – these are sensitive to detector modeling.

- At low energies, the allowed region sharpens from a triangle to a line ⇒ loose the supposed gain of the 2d method – this might be a good thing.

- At threshold – No ISR/FSR to wash out weight of events – effective factor of 2 gain in lumi.

- B Factory error ellipses are same scale as 18 MeV and 0 MeV contour differences – diminishing returns?

Allowed regions for 0, 100 MeV nu
Neutrino Mass 3

Very rough comparison of samples between CLEO98 (30 MeV limit) and 0.25/fb at CLEO-c tau threshold

<table>
<thead>
<tr>
<th>mode</th>
<th>BR</th>
<th>CLEO 98</th>
<th>&lt;CLEO-c&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>3π2π⁰</td>
<td>0.5%</td>
<td>200 events</td>
<td>100 events</td>
</tr>
<tr>
<td>5π</td>
<td>.1%</td>
<td>250 events</td>
<td>50 events</td>
</tr>
<tr>
<td>KKπ</td>
<td>.2%</td>
<td>Not used</td>
<td>65 events</td>
</tr>
</tbody>
</table>

The above assumes e/mu/pi/rho tags at CLEO-c + no charm background + perfect PID

High energy colliders cut very hard to get pure samples
Even a small threshold run can give a data sample comparable to current world’s largest samples

Again - an important opportunity for unique work at CLEO-c and especially BESIII
Neutrino Mass 4

• At BESIII/CLEO–c, expect smaller error ellipses – more discrimination near endpoint

• Running at 3.67 GeV (above $\tau$ threshold, below charm), with $\approx 10$/fb could possibly give U.L. in the MeV region

• This likely represents the limit of this technique
Conclusions

• BESIII/CLEO–c will play an important role in $\tau$ physics – no matter what BaBar/Belle do

• There are unique opportunities near threshold using the lack of ISR/FSR, and unique $\tau$ decay kinematics

• CLEO–c is not guaranteed to do any tau only running – BESIII should not miss this opportunity.
Recipe for BESIII Tau Success

1. Get a sufficient sample below tau threshold to get (uds) MC right
2. A 50 /pb scan near threshold to get the tau mass – a larger sample will allow a detailed inspection of the turn-on curve
3. 0.25 /fb at tau threshold for the threshold measurements, plus 0.25/fb 3 MeV below to get normalization for tau atom search
4. Several /fb at 3.67 GeV to for high stats measurements – use to make sure you know what you are doing above charm
5. > 10 /fb at 3.67 GeV for neutrino mass
6. All the data you can get above charm threshold
7. Goto step 1