The X(3872) – mesonic molecule or conventional meson?

Group Seminar
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Outline

- Setting the scene: discovery of $X(3872)$ by Belle
- Accelerators and detectors
  - BaBar and Belle
  - Physics at the Tevatron with CDF and D0
- Experimental knowledge of the $X(3872)$
- What is the $X(3872)$?
Discovery of X(3872)

New particle discovered 2003:

B → K π⁺ π⁻ J/ψ

• 35.7 ± 6.8 events
• M = 3872.0 ± 0.5 ± 0.6 MeV/c²
• narrow resonance
• m(π⁺ π⁻) peaks at high values
• confirmed by CDF, observed also by D0, BaBar

\[ \psi(2S) \rightarrow J/\psi \pi^+ \pi^- \]

PRL 91,26001 (2003)

M(Σ/ψ) spectrum
Where does the X(3872) fit in?

states below open charm threshold identified

- (reasonably) well understood from potential models
- some new discovered states fit in well, e.g.
  - $2^1S_0$ (PRL 89 102001)
  - $2^3P_2$ (hep-ex/0507033)
  - $1^1P_1$ (hep-ex/0508037)
- others not so well, e.g. $D_s^*$
  (most likely L=1 cs meson but lighter than expected)

⇒ what about the X(3872)?
BaBar and Belle

BaBar at PEP-II
- asymmetric $e^+ e^-$ collider at Y(4S)
- 1.5 T magnetic field
- silicon tracker + drift chamber
- vertex, momentum, $dE/dx$ measurement
- DIRC Cherenkov detector for PID
- calorimeter: energy measurement

Belle at KEK-B
- asymmetric $e^+ e^-$ collider at Y(4S)
- 1.5 T magnetic field
- silicon tracker + drift chamber
- vertex, momentum, $dE/dx$
- ToF + Aerogel Cherenkov detector for PID
- calorimeter: energy measurement
The Tevatron

$p\bar{p}$ collisions

**Run I:** 1992 – 1996
data taking period
at $\sqrt{s} = 1.8$ TeV

**Run II:** 2001 – 2009
major upgrades to
 collider and
detectors

$\sqrt{s} = 1.96$ TeV
Tevatron performance

Running well - both peak luminosity and integrated luminosity before spring 2006 shutdown: ~15-20 pb\(^{-1}\) / week delivered

1 fb\(^{-1}\) delivered in beginning of June 2005.
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CDF II:
- precise tracking:
  (silicon vertex detector and drift chamber)
- important for B physics:
  direct trigger for displaced vertices

D0:
- excellent muon system and coverage
- large forward tracking coverage
- new in RunII: magnetic field
  ⇒ D0 has joined the field of B physics
Physics at the Tevatron

- large $b$ production rates:
  \[ \sigma(p\bar{p}, |\eta| < 1.0) \approx 20 \mu b \]
  \[ \Rightarrow 10^3 \text{ times bigger than } \Upsilon(4S)! \]

- spectrum quickly falling with $p_T$

- Heavy and excited states not produced at B factories:
  B factories: $B_c, B_s, B^{**}, \Lambda_b, \Sigma_b, \ldots$

- enormous inelastic cross-section:
  \[ \Rightarrow \text{triggers are essential} \]

- events “polluted” by fragmentation tracks, underlying events
  \[ \Rightarrow \text{need precise tracking and good resolution!} \]
Trigger in hadronic environment

- **Dimuon**: “easy” trigger, clean signal
  - sensitive to $\psi \rightarrow \mu^+ \mu^-$

- **Semi-leptonic B decays**
  - CDF: $(\mu, e) +$ displaced track
  - D0: single $(\mu, e)$

- **Fully hadronic B decays (CDF)**
  - $BR \approx 80\%$
  - require two displaced tracks
  - needs high precision tracking at trigger level!
Observation of X(3872) at CDF and D0

\[\Delta M = 774.9 \pm 3.1 \text{(stat)} \pm 3.0 \text{(syst.) MeV/c}^2\]
\[\sigma = 17 \pm 3 \text{ MeV/c}^2\]

\[M = 3871.3 \pm 0.7 \text{(stat)} \pm 0.4 \text{(syst.) MeV/c}^2\]
\[\sigma = 4.9 \pm 0.7 \text{ MeV/c}^2\]

reported widths are compatible with detector resolution

no signal in wrong-sign combination, i.e. X++, X--
X(3872) with $J/\psi \rightarrow e^+ e^-$?

Challenge: identify $e^\pm$ in complex hadronic environment

- >90% background from $\pi$
- Tevatron detectors originally designed for jet physics – not precision B physics

- use NeuroBayes neural network: exploit correlated information from:
  - calorimeters
  - time-of-flight
  - specific energy loss in central drift-chamber ($dE/dx$)
  - tracking (“kink” in track when $\gamma$ is emitted while traversing material) to identify electron tracks
(N.B. CDF does not have a RICH!)

typical event from $J/\psi \rightarrow e^+ e^-$ trigger

not an official CDF plot – for illustration only
X(3872) with J/Ψ → e⁺ e⁻!

- develop highly efficient electron ID with high purity
- main remaining background: conversion γ → e⁺ e⁻
  ⇒ reject with further neural network
- add γ at J/ψ vertex to accommodate Bremsstrahlung
- X(3872) reconstructions follow J/ψ → μ⁺μ⁻ case
  ⇒ able to reconstruct X(3872) in this channel!

But:
- trigger rate “explodes” with luminosity
- not one of the “lighthouses”
  → there are prices to pay at hadron machines ...
  ... this is one of them ...
X(3872) properties

compare fraction of yields w.r.t initial selection

$\Rightarrow X(3872)$ behaves similarly to the $\Psi(2S)$
Unbinned LogL fit for
• mass
• propertime

$\Psi(2S)$: 28.3 ± 1.0 (stat.) ± 0.7 (syst.) %

$X(3872)$: 16.1 ± 4.9 (stat.) ± 1.0 (syst.)%

$\Rightarrow X(3872)$ behaves similarly to the $\Psi(2S)$ (with given uncertainties)
Other decay modes

Evidence for $X(3872) \rightarrow \gamma J/\psi$
\rightarrow 13.6 \pm 4.4 events
\rightarrow 4\sigma$ significance
$\Gamma(X \rightarrow \gamma J/\psi) / \Gamma(X \rightarrow \pi^+ \pi^- J/\psi) = 0.14 \pm 0.05$
(also seen at BaBar with $3.4 \sigma$ significance hep-ex/0607050)

Evidence for $X(3872) \rightarrow \omega J/\psi$
\rightarrow 10.6 \pm 3.6 events
\rightarrow 4.3 \sigma$ significance
$\Gamma(X \rightarrow \pi^+ \pi^- \pi^0 J/\psi) / \Gamma(X \rightarrow \pi^+ \pi^- J/\psi) = 1.0 \pm 0.4 \pm 0.3$

$X(3872) \rightarrow D^0 D^0 \pi^0$ hep-ex/0606055
\rightarrow 6.4 \sigma$ significance
$M = 3875.4 \pm 0.7^{+0.4}_{-1.7} \pm 0.9$ MeV/c$^2$
$B(X \rightarrow D^0 D^0 \pi^0) / B(J/\psi \pi^+ \pi^-) = 9.4^{+3.6}_{-4.3}$
X(3872) at BaBar

observed at BaBar:
25.4 ± 8.7 events
M = 3873.4 ± 1.4 MeV/c²

difference in production mode:
\[ \mathcal{R} = \frac{B^0}{B^+} \to K^0 S X \]
\[ = 0.61 ± 0.36 ± 0.06 \]
\[ \Delta M = 2.7 ± 1.3 ± 0.2 \text{ MeV/c}^2 \]
The X(3872) so far...

• discovered 2003 by Belle in search for charmonium states
• mass: \( m = 3871.3 \pm 0.7 \pm 0.4 \text{ MeV}/c^2 \)
  CDF PRL 93,072001 (2004), width compatible with detector resolution
  \( \Gamma < 2.3 \text{ MeV}/c^2 \)
  Belle PRL 91,26001 (2003)
• No \( X^{++} \) or \( X^{--} \)
  CDF PRL 93,072001 (2004)
• No iso-partner \( X^\pm \)
  BaBar PRD 71, 031501 (2005)
• Evidence for \( X \rightarrow J/\psi \gamma, J/\psi \omega \)
  Belle hep-ex/0505037, BaBar hep-ex/0607050
• \( X \rightarrow D \bar{D} \pi^0 \)
  Belle hep-ex/0606055 (2006)

⇒ what is the X(3872)? charmonium? exotic?
→ determine quantum numbers \( J^{PC} \)
• \( m(\pi^+ \pi^-) \) sensitive to \( J^{PC} \)
• use distribution of angles between decay particles to measure \( J^{PC} \)
The $m(\pi^+ \pi^-)$ mass spectrum

Distribution of $m(\pi^+\pi^-)$ constrains quantum numbers $J^{PC}$

shape depends on:
• decay of $(\pi^+\pi^-)$ sub-system: $(\pi^+\pi^-)$ in $s$, $p$, ... wave
  (i.e. intermediate sub-resonance or not)
• relative angular momentum between $(\pi^+\pi^-)$ and $(\mu^+\mu^-)$
• (and detector acceptance, efficiency, etc.)

e.g. for decay chain: $X \rightarrow J/\psi \rho^0$; $\rho^0 \rightarrow \pi^+\pi^-$
  $\Rightarrow$ described by Breit-Wigner function
**m(ππ) analysis at Belle**

**Hypothesis testing:**
- \(m(\pi^{+}\pi^{-})\) described by \(\rho^0\), i.e.
  \[X(3872) \rightarrow J/\psi \rho^0 \rightarrow \mu^+ \mu^- \pi^+ \pi^-\]
- \(J/\psi\) and \(\rho^0\) either in:
  - **S-wave**: \(L = 0\)
  - **P-wave**: \(L = 1\) (suppressed by centrifugal barrier)

Decay via \(\rho \rightarrow \pi^+ \pi^-\) in relative \(S\) – wave with \(J/\psi\)

**but:**
- “simple” \(\rho^0\) Breit-Wigner
- \(\rho^0\) transition only

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\(\chi^2/\text{dof} = 43/39\) (CL = 28%)

\(\chi^2/\text{dof} = 71/39\) (CL = 0.1%)
The $m(\pi^+\pi^-)$ mass spectrum continued...

Distribution of $m(\pi^+\pi^-)$ constrains quantum numbers $J^{PC}$

shape depends on:
- decay of $(\pi^+\pi^-)$ sub-system: $(\pi^+\pi^-)$ in $s$, $\rho$, ... wave
  (i.e. intermediate sub-resonance or not)
- relative angular momentum between $(\pi^+\pi^-)$ and $(\mu^+\mu^-)$
- (and detector acceptance, efficiency, etc.)

e.g. for decay chain: $X \rightarrow J/\psi \rho^0; \rho^0 \rightarrow \pi^+\pi^-$

\[
\frac{d\Gamma_X}{dm_{\pi\pi}} = 2m_{\pi\pi} \frac{\Gamma_{X\rightarrow J/\psi\rho}(m_{\pi\pi}) \cdot 2m_{\rho} \Gamma_{\rho\rightarrow\pi\pi}(m_{\pi\pi})}{(m_{\pi\pi}^2 - m_{\rho}^2)^2 + m_{\rho}^2 \Gamma_{\rho}^2(m_{\pi\pi})}
\]

spectrum described by relativistic Breit – Wigner

for broad resonances such as $\rho^0$ (kinematic factors vary across width)

\[
\Gamma_{A\rightarrow BC} = \Gamma_{0,A\rightarrow BC} \left( \frac{k^*}{k^*_0} \right)^{2L+1} \left( \frac{f(k^*)}{f(k^*_0)} \right)^2 \left( \frac{m}{m_0} \right)
\]

form-factor
Challenge: Large background, rather low $X(3872)$ yield
⇒ sideband-subtraction difficult, instead:

“slicing technique”
• impose bin borders in $m(\pi^+\pi^-)$ as additional cuts
• fit resulting $(\mu^+\mu^-\pi^+\pi^-)$ mass spectrum
• obtained yield shows variation with $m(\pi^+\pi^-)$

need to be careful at kinematic borders
m(π⁺ π⁻) mass spectrum for Ψ(2S)

- Ψ(2S) in same exclusive final state
- m(π⁺π⁻) spectrum known: s-wave with small d-wave contribution
  e.g. model by Novikov-Shifman

⇒ high precision data by CDF
⇒ allows to discriminate between models
\[ m(\pi^+ \pi^-) \text{ for } X(3872) \]

Mass spectrum sensitive to \( J^{PC} \)

if \( (\pi^+\pi^-) \) in s-wave state:
shape needs to be modelled
e.g. multipole expansions for \( c\bar{c} \)

if \( (\pi^+\pi^-) \) in p-wave state:
shape follows Breit-Wigner
e.g. decay via \( \rho^0 \rightarrow \pi^+\pi^- \)

- \( m(\pi^+\pi^-) \) favours high end of mass spectrum
  \( \Rightarrow \) compatible with intermediate \( \rho^0 \rightarrow \pi^+\pi^- \) resonance
- also \( ^3S_1 \) multipole-expansion for charmonium possible
  - no charmonium candidate at that mass
  - \( ^3S_1 \) also has \( J^{PC} = 1^- \) \( \Rightarrow \) non-observation by BES

\( \Gamma(e^+e^-)B(\pi^+\pi^-J/\Psi) < 10 \text{ eV } @90\% \text{ C.L.} \) \( \text{Phys.Lett.B579:74-78 (2004)} \)
for broad resonances ($\rho^0$):
• kinematic quantities vary across width
• introduce form-factor
e.g. Blatt-Weisskopf
depends on ang. momentum L, effective range $R$
  $\Rightarrow$ affects shape for L=0, L=1

Possible $\rho^0$ - $\omega$ mixing:
• $\omega$ mass contribution far from pole position
• interference $\rho^0 \leftrightarrow \omega$ possible
  $\Rightarrow$ L=0 (S-wave) and L=1 (P-wave)
  both compatible with $m(\pi^+\pi^-)$ spectrum
  $\Rightarrow$ mixing phase of 95° (P-wave) describes data
Determination of $J^{PC}$ (1)

Distribution of angles between decay products depends on $J^{PC}$ of particles involved.
For *unpolarised* production:
- $\Delta \Phi$
- $\theta_{J/\psi}$
- $\theta_{\pi\pi}$
Determination of $J^{PC}$ (2)

- Predictions for kinematic decay quantities from helicity formalism:
  - Isobar model: decay chain as sequential 2-body decays
    \[ X(3872) \rightarrow J/\psi (\pi^+\pi^-)_{s,p} \rightarrow \mu^+ \mu^- \pi^+ \pi^- \]
  - Need:
    - One matrix element per decay vertex
    - "Propagators" to connect vertices
  - Matrix elements: angular part $D$ and kinetic part $T$
    \[ M \propto M_X \times \left( P_{J/\psi} \cdot M_{J/\psi} \right) \times \left( P_{\pi\pi} \cdot M_{\pi\pi} \right) \]
  - Using Wigner D functions
    \[ D^J_{Jz,\lambda} = e^{i\phi(J_z-\lambda)} d^J_{Jz,\lambda} \]
  - Assume state with lowest $L$ dominates, neglect others
  - Dedicated simulation for each $J^{PC}$ hypothesis (including detector effects)
  - Compare to angular distributions measured in data via $\chi^2$
Determinaton of $J^{PC}$ (3)

Simulation:
phase-space events weighted with helicity weight + detector effects:

$$w \propto \frac{1}{2J(X)+1} \sum_j J_z \left( \sum \lambda_\mu^+ \sum \lambda_\mu^- \sum \lambda_\pi^+ \sum \lambda_\pi^- \left( \sum \lambda_{J/\psi} \sum \lambda_{(\pi^+\pi^-)} \right) \mathcal{M}^2 \right)$$

- mean over initial state
- incoherent sum over final states
- coherent sum over intermediate states

$$\mathcal{M} \propto \mathcal{M}_X \times \left( P_{J/\psi} \cdot \mathcal{M}_{J/\psi} \right) \times \left( P_{\pi\pi} \cdot \mathcal{M}_{\pi\pi} \right)$$

in case of several substates:
coherent sum contains a priori unknown mixing constant $g_{LS}$

$$\left| \sum_{LS} \sum \lambda_{J/\psi} \sum \lambda_{(\pi^+\pi^-)} g_{LS} \mathcal{M} \right|^2$$
Caveats:

- no model-independent description of $\pi^+\pi^-$ in s-wave
- Breit-Wigner for $\rho^0 \rightarrow \pi^+\pi^-$ depends on form-factor details

**conservative approach:**

- fix $m_{\pi\pi}$ distribution to match the data
- analyse angular distributions only

N.B. $\rho^0$ and $\omega$ have both $J^{PC} = 1^{-+}$

$\Rightarrow$ angular distributions not affected by potential interference

- $J^{PC} = 1^+$ and $2^+$: multiple sub-states with same $L$ contribute

$$
\mathcal{M}(1^{-+}) = r_0 e^{i\phi_0} \mathcal{M}(1^-_{s=0}) + r_1 e^{i\phi_1} \mathcal{M}(1^-_{s=1}) + r_2 e^{i\phi_2} \mathcal{M}(1^-_{s=2})
$$

$$
\mathcal{M}(2^{-+}) = r_1 e^{i\phi_1} \mathcal{M}(2^-_{s=1}) + r_2 e^{i\phi_2} \mathcal{M}(2^-_{s=2})
$$

$\Rightarrow$ Can an arbitrary mixture describe the data?
Result for $\Psi(2S)$

$\psi(2S)$
- data points

acc. corrected prediction for
- $1^{++}$
- $1^{--}_s$
- $1^{--}_{Nov}$

obtain expected result:
$J^{PC} = 1^{-}$

Exploit correlations between angles via 3D fit:
- 3 bins in $\Delta \Phi$
- 2 bins in $\theta_{J/\psi}$
- 2 bins in $\theta_{\pi\pi}$
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Result for $X(3872)$

Only $J^{PC} = 1^{++}$ or $2^{-+}$ compatible with data!

All other tested hypotheses excluded by $> 3\sigma$

N.B. cannot be $1^{--}$: non-observation in $e^+e^-$ machines
Angular analysis at Belle (1)

X(3872) produced in B-decay
⇒ additional quantisation axis compared to CDF
⇒ additional angle sensitive to JPC

\[ \frac{dN}{d\cos \theta} \propto \sin^2 \theta_{K\mu} \]

\[ \chi^2/\text{dof} = 8.9/9 \]

for \( \psi(2s) \):
\[ \frac{dN}{d\cos \theta_{K\mu}} \propto \sin^2 \theta_{K\mu} \]
Angular analysis at Belle (2)

A sample of $X(3872)$ produced via $B \to K X(3872) (256 \text{ pb}^{-1})$

- $1^{++}$ looks OK
- $0^{++}$ is unlikely
- $0^{-+}$ is unlikely

<table>
<thead>
<tr>
<th>$\cos \theta_l</th>
<th>\chi^2/\text{dof} = 11/9$</th>
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<td>0.00</td>
<td>0.50</td>
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<tr>
<td>$</td>
<td>\cos \theta</td>
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</tbody>
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| $\chi^2/\text{dof} = 34/9$ |
|-----------------|-----------------|
| 0.00 | 0.50 | 1.00 |
| $|\cos \theta_{l\pi}|$ ($\rho$ frame) |

| $\chi^2/\text{dof} = 5/9$ |
|-----------------|-----------------|
| 0.00 | 0.50 | 1.00 |
| $|\cos \chi|$ |

| $\chi^2/\text{dof} = 34/9$ |
|-----------------|-----------------|
| 0.00 | 0.50 | 1.00 |
| $|\cos \psi|$ ($\rho$ frame) |

Ulrich Kerzel, University of Cambridge

X. Shen, LP2005
“Next generation” X(3872) analysis

Use sophisticated neural network “NeuroBayes”

• exploit correlations between variables → improved candidate selection

• train networks for multiple $J^{PC}$ assignments → higher significance for “good” hypotheses

• strong suppression of combinatorial BG determine if candidate is resonant signal or background

www.phi-t.de
www.neurobayes.de

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What is the $X(3872)$ (1)?

**Charmonium**

→ “natural” choice – discovered in search for charmonia states

potential candidates:

- $\chi'_c : 3P_1 (1^{++})$
- $\eta_{c_2} : 1D_2 (2^{−+})$

observation of $X(3872) \to DD\pi^0$ disfavours $J=2$ from kinematics

mass prediction from potential models:

- $^3P_1 : 3929 – 3990 \text{ MeV/c}^2$
- $^1D_2 : 3765 – 3872 \text{ MeV/c}^2$

but: author predicts $\psi(3770)$ at 3840 MeV/c²

→ predictions don’t really fit ...

→ decay via $\rho^0 \to \pi^+\pi^-$: isospin violating

⇒ is the $X(3872)$ something else?
What is the X(3872) (2) ?

curious fact: \( m(X) \approx m(D^0) + m(D^{0*}) \)
\[ m(D^+) + m(D^{*-}) \] 8.1 MeV/c^2 higher
\[ \Rightarrow \] channel closed by phase-space, large Isospin \( I = 1 \) component
\[ \rightarrow \] coincidence?

\textbf{X(3872) exotic?}

- tetraquark
  - “bag-model”: 4 interacting quarks \( \bar{c}cq\bar{q} \)
  - two di-quarks \( (cq)_3* (\bar{c}q)_3 \)
  - \( D^0 \bar{D}^{0*} \) molecule
- hybrid state, i.e. \( \bar{c}\bar{c}g \) (but expected above \( \approx 4 \) GeV/c^2)
- mainly charmonium - but interaction with \( D^0 \bar{D}^{0*} \) threshold
- something else ?

\[ \text{e.g. M. Suzuki hep-ph/0508258} \]
DeRujula, Georgi, Glashow (1977): Charmed molecules?

possible formation of 4q “molecules”:

- $D \bar{D}, D \bar{D}^*$
- $D^* \bar{D}^*$
- $D \bar{D}^{**}, D^* \bar{D}^{**}$

decay via:

- $J/\psi \rho^0$
- $J/\psi \eta$
“Deuson“ model (Törnqvist)


**X(3872) similar to deuteron:**
- composed of two objects
- bound by $\pi^0$ exchange

**Prediction:**
- $J^{PC} = 1^{++}$ (s – wave) or $0^{-+}$ (p – wave)
  (otherwise potential too weak or repulsive, mass of $D^*D^*$ molecule too high)
- small binding energy:
  $\Rightarrow$ narrow resonance, big object
- incorporates isospin breaking:
  - $X \rightarrow J/\Psi \rho^0, \rho^0 \rightarrow \pi^+\pi^-$ allowed
  - $X \rightarrow J/\Psi \sigma$ forbidden for any iso-scalar $\sigma$
  - $X \rightarrow J/\Psi \pi^0\pi^0$ forbidden
    (but very challenging to reconstruct with current experiments)
\(D^0 \bar{D}^{0*}\) molecule (Swanson)

- follows similar “spirit” to Tornqvist’s approach
- based on non-relativistic quark model, \(\pi\) and quark exchange interactions
- incorporate short-range structure: scattering of
  - \(DD^* - DD^*\)
  - \(DD^* - \omega J/\psi\)
  - \(DD^* - \rho^0 J/\psi\)
- expect \(DD^*\) in relative s-wave:
  inter-hadron forces (\(\pi\) exchange) strongest \(\Rightarrow J^{PC} = 1^{++}\)
Similar state in B-system?

if X(3872) is a molecule:
- “new“ spectroscopy with many new states?
- unique to charm sector?
  → ~20 years of discussion if $a_0/f_0$ is a conventional meson, KK* molecule, glueball, exotic other particle, ...
  ⇒ observation of a similar state in b sector would give strong hint

Törnqvist:
- expect BB, B*B bound in same way as X(3872) in $X_b \rightarrow Y(1S) \pi^+ \pi^-$ inv. mass spectrum
  → binding-energy up to ~50 MeV for b-deuson

Swanson:
- expect BB* molecule
- ... but maybe ($\pi^+ \pi^-$) dynamics very different
Search for $X_b$

even more challenging:
• much lower $Y(1S)$ yield and much more background compared to $J/\psi$

$\rightarrow$ first develop technique to suppress background in $Y(nS) \rightarrow \mu^+\mu^-$ (on candidate level)

$\Rightarrow$ expect few $X_b$ candidates in enormous comb. bg.

“benchmark mode”
$Y(2S) \rightarrow Y(1S) \pi^+\pi^-$

$\Rightarrow$ very difficult for CDF, even more so for D0
Conclusions

New particle X(3872) discovered:

- $J^{PC} = 1^{++}$ or possibly $2^{-+}$
- What is the X(3872)?
  - unusual properties: charmonium option unlikely
  - $D^0 \bar{D}^0$ molecule: fits well into experimental picture

⇒ exiting new times for spectroscopy

search for similar state in B-system ongoing

watch out for other new states, e.g.: Y(3940), Z(3930), Z(3940)
BACKUP
Hadronic vs. semi-leptonic B decays

hadronic decays
- fully reconstructed
- high $c_\tau$ resolution
- low candidate yield

semileptonic decays
- high yield
- neutrino not reconstructed
  $\Rightarrow$ worse $c_\tau$ resolution

\[ c_\tau = L_{xy} \left( \frac{M(B)}{p_t(B)} \right) \]

\[ = L_{xy} \left( \frac{M(\ell D)}{p_t(\ell D)} \right) \times K \]

from simulation
**X(3872) production fraction from B**

**Consistency check:**
overlay $m(J/\Psi \pi^\pm \pi^-)$ spectrum with prediction from LogL
⇒ data is described well

N.B. almost no prompt signal for $c\tau > 100 \mu m$
X(3872): central vs. forward

**D0**: large muon coverage

⇒ reconstruct X(3872) in **central** and **forward** part of the detector

Ψ(2S) and X(3872) behave very similar in both rapidity ranges
Observation of X(3872) at CDF and D0

Original observation by Belle: $m(\pi^+\pi^-)$ clusters at large values

D0: demand $m(\pi^+\pi^-) > 0.52$ GeV/c$^2$ as default cut

CDF: separately plot $m(J/\psi\pi^+\pi^-)$ for $m(\pi^+\pi^-) > 0.5$ GeV/c$^2$ and $m(\pi^+\pi^-) < 0.5$ GeV/c$^2$

$\Rightarrow$ no apparent signal for $m(\pi^+\pi^-) < 0.5$ GeV/c$^2$
X(3872) production fraction from B

Define pseudo-proper decay time:

\[ c\tau = \frac{M(J/\psi\pi^+\pi^-)}{p_t(J/\psi\pi^+\pi^-)} L_{xy} \]

Unbinned LogL fit (simultaneously for \( c\tau \) and \( M \)):

- **Mass:**
  - signal: Gaussian
  - BG: 2nd order polynomial for BG

- **Proper time:**
  - signal: exponential
  - BG: 2 pos., 1 neg. exponential
  all folded with Gaussian due to resolution
Helicity matrix element

$\mathcal{M} \propto D^J_{J_z,\lambda}(\theta, \phi) \cdot T(|\vec{p}|, L)$

using Wigner D functions $D^J_{J_z,\lambda} = e^{i\phi(J_z - \lambda)} d^J_{J_z,\lambda}$

assume lowest angular momentum L is dominant

$\cdot$ treat initial and final state in respective rest-frame
$\cdot$ two body decay:
  $\cdot \vec{p}_1, \vec{p}_2$ are back-to-back
  $\cdot$ common quantisation axis
  $\Rightarrow$ final state helicity $\lambda = \lambda_1 - \lambda_2$
Influence of form-factor on $m(\pi^+ \pi^-)$

use: model from Blatt-Weiskopf:
parameter “R” determines effective size, no unique choice

P-Wave $X \rightarrow J/\psi \rho$ Decay
(95° $\rho-\omega$ Phase)
Mixing phase between $\rho$ and $\omega$
Mixing phase between $\rho$ and $\omega$

Relatively small influence of $\rho^0$ form-factor radius, large effect from $X(3872)$ form-factor radius.

good fit probability found for relative phase $\Phi \ldots 95^\circ$
Effect of $\rho^0$-$\omega$ mixing

$\Rightarrow$ Neither L=0 nor L=1 can be ruled out from $m(\pi^+\pi^-)$ alone
Illustration of angular correlation

example for $J^{PC} = 1^{++}$
Sample fit for X(3872) angular analysis

CDF Run II Preliminary

$\chi^2 = 94.2 / 83$ d.o.f.

#X : $309.9 \pm 33.8$

0.0 < |cos($\theta_{J/\psi}$)| < 0.6
0.0 < |cos($\theta_{\pi\pi}$)| < 0.5
0.63 < |$|\Delta \phi - \pi - \pi/2| < 1.15

m($J/\psi\pi^+\pi$) [Gev/c$^2$]
### X(3872) fit results

<table>
<thead>
<tr>
<th>hypothesis</th>
<th>3D $\chi^2$ / 11 d.o.f.</th>
<th>$\chi^2$ prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1++</td>
<td>13.2</td>
<td>27.8%</td>
</tr>
<tr>
<td>2--</td>
<td>13.6</td>
<td>25.8%</td>
</tr>
<tr>
<td>1--</td>
<td>35.1</td>
<td>0.02%</td>
</tr>
<tr>
<td>2++</td>
<td>38.9</td>
<td>$5.5 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>1+−</td>
<td>39.8</td>
<td>$3.8 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>2−−</td>
<td>39.8</td>
<td>$3.8 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>3+-</td>
<td>39.8</td>
<td>$3.8 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>3−−</td>
<td>41.0</td>
<td>$2.4 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>2++</td>
<td>43.0</td>
<td>$1.1 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>1−+</td>
<td>45.4</td>
<td>$4.1 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>0+-</td>
<td>103.6</td>
<td>$3.5 \cdot 10^{-17}$</td>
</tr>
<tr>
<td>0−−</td>
<td>129.2</td>
<td>$&lt;1 \cdot 10^{-20}$</td>
</tr>
<tr>
<td>0++</td>
<td>163.1</td>
<td>$&lt;1 \cdot 10^{-20}$</td>
</tr>
</tbody>
</table>
Systematics for X(3872)

- Details of MC (13–17)
- Use phase-space to describe m(ππ) (12)
- Vary ρ⁰ form-factor radius (10, 11)
- Vary X(3872) mean and width (6–9)
- Vary histogram bin width (4, 5)
- Vary X(3872) fit window (2, 3)
- Default result (1)
## $\Psi(2S)$ fit results

<table>
<thead>
<tr>
<th>hypothesis</th>
<th>3D $\chi^2$ / 11 d.o.f.</th>
<th>$\chi^2$ prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^{--}_{Novikov}$</td>
<td>15.1</td>
<td>17.9%</td>
</tr>
<tr>
<td>$1^{--}_s$</td>
<td>23.5</td>
<td>1.5%</td>
</tr>
<tr>
<td>$2^{++}_p$</td>
<td>26.3</td>
<td>0.58%</td>
</tr>
<tr>
<td>$2^{+-}_s$</td>
<td>47.4</td>
<td>$1.9 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$3^{--}_s$</td>
<td>70.2</td>
<td>$1.2 \cdot 10^{-10}$</td>
</tr>
<tr>
<td>$1^{++}_p$</td>
<td>399.5</td>
<td>$&lt; 1 \cdot 10^{-20}$</td>
</tr>
<tr>
<td>$3^{+-}_s$</td>
<td>504.8</td>
<td>$&lt; 1 \cdot 10^{-20}$</td>
</tr>
<tr>
<td>$2^{--}_s$</td>
<td>504.8</td>
<td>$&lt; 1 \cdot 10^{-20}$</td>
</tr>
<tr>
<td>$1^{+-}_s$</td>
<td>504.8</td>
<td>$&lt; 1 \cdot 10^{-20}$</td>
</tr>
<tr>
<td>$2^{--}_p$</td>
<td>505.1</td>
<td>$&lt; 1 \cdot 10^{-20}$</td>
</tr>
<tr>
<td>$1^{+-}_p$</td>
<td>516.5</td>
<td>$&lt; 1 \cdot 10^{-20}$</td>
</tr>
<tr>
<td>$0^{++}_p$</td>
<td>1500.3</td>
<td>$&lt; 1 \cdot 10^{-20}$</td>
</tr>
<tr>
<td>$0^{+-}_s$</td>
<td>1847.0</td>
<td>$&lt; 1 \cdot 10^{-20}$</td>
</tr>
<tr>
<td>$0^{-+}_p$</td>
<td>3169.2</td>
<td>$&lt; 1 \cdot 10^{-20}$</td>
</tr>
</tbody>
</table>
Systematics for $\Psi(2S)$

CDF Run II Preliminary

- $1^{--}$ Nov
- $1^{--}$
- $2^{+-}$
- $3^{--}$
- $2^{++}$

systematics:
13 – 17: details of MC
6,7: vary $\Psi(2S)$ mean and width
4,5: vary histogram bin width
2,3: vary $\Psi(2S)$ fit window
1: default result

11 d.o.f. > $3\sigma$

$\chi^2$

1. Nov. 2006
Ulrich Kerzel, University of Cambridge
Detector effects

Detector acceptance, resolution and cuts affect angular variables:

ΔΦ for J^PC = 1^{++}

ΔΦ for J^PC = 1^{--}

left: 1^{++}

right: 1^{--}
$X(3872) \rightarrow \gamma J/\psi$

$B \rightarrow K \chi_{c1}; \chi_{c1} \rightarrow \gamma J/\psi$

$M(\gamma J/\psi)$

$13.6 \pm 4.4 \ X(3872) \rightarrow \gamma J/\psi$

$\text{evts (}>4\sigma \ \text{significance})$

$Bf(X \rightarrow \gamma J/\psi) = 0.14 \pm 0.05$

$Bf(X \rightarrow \pi \pi J/\psi)$

S. Olsen: FNAL Seminar May 2005

hep-ex/0505037
$X(3872) \rightarrow \pi^+\pi^-\pi^0$ J/ψ

B-meson yields vs $M(\pi^+\pi^-\pi^0)$

$\frac{\text{Br}(X \rightarrow 3\pi J/\psi)}{\text{Br}(X \rightarrow 2\pi J/\psi)} = 1.0 \pm 0.5$

1. Nov. 2006
Ulrich Kerzel, University of Cambridge
$|\cos \theta_{K\ell}|$ for $X(3872)$ events

$\chi^2/dof = 60.3/9$

fit with $\sin^2 \theta_{K\ell} + \text{bkgd}$

X(3872) is not $1^-$!

see 8 evts/bin

expect 2~3 evts/bin

background scaled from sidebands

1. Nov. 2006

Ulrich Kerzel, University of Cambridge
In the limit where $X(3872)$, $\pi\pi$, & $J/\psi$ rest frames coincide:

$$dN/d\cos\theta_{l\pi} \propto \sin^2\theta_{l\pi}$$

rule out $0^{++}$

$$\chi^2/dof = 34/9$$

$$M \propto \vec{\varepsilon}_{J/\psi} \cdot \vec{\varepsilon}_\rho$$

0++
$0^{-+} : \sin^2 \theta \sin^2 \psi$

$M \propto \vec{p}_{J/\psi} \cdot (\vec{\epsilon}_{J/\psi} \times \vec{\epsilon}_{\rho})$

$\chi^2/\text{dof} = 18/9$

$\chi^2/\text{dof} = 34/9$

safe to rule out $0^{-+}$
\[ dN / d \cos \theta d \cos \chi \propto \sin^2 \theta_l \sin^2 \chi \]

\[ M \propto |\overline{\epsilon}_\chi \times \overline{\epsilon}_{J/\psi} \times \overline{\epsilon}_{\rho}| \]

\[ \chi^2 / \text{dof} = 11/9 \]

\[ \chi^2 / \text{dof} = 5/9 \]

Compute angles in \(X(3872)\) restframe

1++ looks okay!