The X(3872) at the Tevatron

Ulrich Kerzel, University of Karlsruhe for the CDF and D0 collaborations

BEAUTY 2005
Physics at the Tevatron

- observe $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- 1 fb$^{-1}$ luminosity delivered early June
- huge inelastic cross-section:
  $\approx 5000$ times bigger than for $b\bar{b}$
  $\Rightarrow$ triggers are essential!

- events “polluted” by fragmentation tracks, underlying events
  $\Rightarrow$ need precise tracking and good resolution

- dedicated trigger for $J/\Psi \rightarrow \mu^+ \mu^-$
  - trigger events where $m(\mu^+\mu^-)$ around $m(J/\Psi)$
  $\Rightarrow$ high quality $J/\Psi$ events with large statistics

- channel $J/\Psi \rightarrow e^+e^-$ much more challenging in hadronic environment
CDF:
- 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
Observation of X(3872) at CDF and D0

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

reported widths are compatible with detector resolution

\[ M = 3871.3 \pm 0.7 \text{ (stat)} \pm 0.4 \text{ (syst.) MeV}/c^2 \]
\[ \sigma = 4.9 \pm 0.7 \text{ MeV}/c^2 \]
Observation of X(3872) at CDF and D0

Original observation by Belle: m(π⁺ π⁻) clusters at large values

D0: demand m(π⁺ π⁻) > 0.52 GeV/c² as default cut

CDF: separately plot m(J/Ψ π⁺ π⁻) for m(π⁺ π⁻) > 0.5 GeV/c² and m(π⁺ π⁻) < 0.5 GeV/c²

⇒ no apparent signal for m(π⁺ π⁻) < 0.5 GeV/c²
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
X(3872) properties

compare fraction of yields w.r.t initial selection

isolation: $p(X) / p(X + \text{charged tracks in cone } \Delta R = 0.5)$

$\theta_{\pi}, \theta_{\mu}$: boost one of the pions (muons) in dipion (dimuon) rest-frame,

$L_{xy}$: distance (PV – decay vertex) * $M/p_t$

$\Rightarrow X(3872)$ behaves similarly to the $\Psi(2S)$
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: 2\(^{nd}\) order polynomial for BG

- **Proper time:**
  - signal: exponential
  - BG: 2 pos., 1 neg. exponential
  all folded with Gaussian due to resolution
**X(3872) production fraction from B**

fraction from B decays:

\[ \Psi(2S): \ 28.3 \pm 1.0 \text{ (stat.)} \pm 0.7 \text{ (syst.)} \% \]

\[ \text{X}(3872): \ 16.1 \pm 4.9 \text{ (stat.)} \pm 1.0 \text{ (syst.)}\% \]

⇒ \text{X}(3872) behaves similarly to the \( \Psi(2S) \)

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

N.B. almost no prompt signal for $c\tau > 100 \ \mu$m
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 $s,p,d$ wave
  (i.e. intermediate sub-resonances or not)
• relative angular momentum between $(\mu^+ \mu^-)$ and $(\pi^+ \pi^-)$
• (and detector acceptance, efficiency, etc.)

e.g. for decay chain: $X \rightarrow J/\Psi \rho$, $\rho \rightarrow \pi^+ \pi^-$

$$\frac{d\Gamma_X}{dm_{\pi\pi}} = 2m_{\pi\pi} \Gamma_{X \rightarrow J/\Psi \rho}(m_{\pi\pi}) \cdot 2m_{\rho} \Gamma_{\rho \rightarrow \pi\pi}(m_{\pi\pi})$$

for broad resonances (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
The $m(\pi^+ \pi^-)$ mass spectrum

**Challenge:** Large background, rather low $X(3872)$ yield
$\Rightarrow$ sideband-subtraction difficult, instead:

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

CDF II Preliminary, 360 pb$^{-1}$

<table>
<thead>
<tr>
<th>Mass Interval</th>
<th>Candidates</th>
<th>X's (stat.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$625 &lt; M(\pi\pi) &lt; 650$ MeV/c$^2$</td>
<td>102 ± 38</td>
<td></td>
</tr>
<tr>
<td>$690 &lt; M(\pi\pi) &lt; 710$ MeV/c$^2$</td>
<td>165 ± 35</td>
<td></td>
</tr>
<tr>
<td>$750 &lt; M(\pi\pi) &lt; 765$ MeV/c$^2$</td>
<td>182 ± 30</td>
<td></td>
</tr>
</tbody>
</table>

need to be careful at kinematic borders
The \( m(\pi^+ \pi^-) \) mass spectrum

if \((\pi^+ \pi^-)\) in S-wave state:
\[ \Rightarrow \text{shape needs to be modelled} \]
\[ \text{compare to multipole expansions} \]

if \((\pi^+ \pi^-)\) form sub-resonance:
\[ \Rightarrow \text{shape follows Breit-Wigner} \]
e.g. decay via \(\rho^0 \rightarrow \pi^+ \pi^-\)

(no kinematics, form-factor here)
\[ \frac{d\Gamma_{\rho}}{dm_{\pi\pi}} \propto \frac{\Gamma}{(m_{\pi\pi}-M_{\rho})^2 + \Gamma^2/4} \times (PS) \]

- \(m(\pi^+ \pi^-)\) favours high end of mass spectrum
\[ \Rightarrow \text{compatible with intermediate } \rho^0 \rightarrow \pi^+ \pi^- \text{ resonance} \]
- also \(^3S_1\) multipole-expansion for charmonium possible
  - no charmonium candidate at that mass
- \(^3S_1\) also has \(J^{PC} = 1^-\) \[\Rightarrow \text{non-observation by BES} \]
\[ (\Gamma(e^+e^-)B(\pi^+\pi^-J/\Psi) < 10 \text{ eV @90\% C.L.}) \]

notation: \(n^{2s+1L_J}(J^{PC})\)

CDF II Preliminary, 360 pb

\begin{align*}
X(3872) \rightarrow J/\psi \pi^+ \pi^- \\
J/\psi \rho \\
J/\psi \pi\pi \text{ Phase-Space}
\end{align*}

Multipole Expansions for \(c\bar{c}\):
- \(^3S_1\)
- \(^3P_1 \times 5\)
- \(^3D_J\)

\( X(3872) \) yield per 20 MeV/c\(^2\)

\( \pi\pi \) Mass [GeV/c\(^2\)]
X(3872) with J/Ψ → e⁺ e⁻

Reconstruction of J/Ψ → e⁺e⁻ very difficult in complex hadronic environment

- dedicated J/Ψ → e⁺e⁻ trigger
- use neural-network based approach to identify soft e± (p_t > 2GeV/c)
- reject e± from conversions based on neural network approach
- add γ at J/Ψ vertex to accommodate Bremsstrahlung
- X(3872) reconstructions follows J/Ψ π⁺ π⁻ case
  (replace cut on m(π⁺π⁻) by cut on Q = m_X - m_J/Ψ - m_ππ)

⇒ able to reconstruct X(3872) in this channel!
What is the $X(3872)$ ??

- Charmonium?
  - $2 \, ^1P_1$, i.e. $h'_c\, (1^{+-})$
    - predicted at $\approx 3950\, \text{MeV/c}^2$
    - why is the $^1P_1\, h_c$ not seen in $J/\Psi\, \pi^+\pi^-$?
    - Belle: $|\cos \theta_{J/\Psi}|$ distribution does not fit (hep-ex/0408116)
  - $1^1D_2\, (2^-)$
    - pos. C-parity
  - $1\, ^3D_2\, (2^-), 1\, ^3D_3(3^-)$
    - then also decay: $X \rightarrow \chi_{c1}\, \gamma, X \rightarrow \chi_{c2}\, \gamma$
    - $\Rightarrow$ if charmonium, very unusual properties!

- charmed molecule?
- hybrid state, i.e. $c\bar{c}g$?
- “Deuson” ?
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:
- $J^{PC} = 1^{++}$ or $0^{-+}$
  (otherwise potential too weak or repulsive)
- small binding energy:
  - narrow resonance, big object
- isospin breaking:
  - $X \rightarrow J/\Psi \, \rho^0$, $\rho^0 \rightarrow \pi^+\pi^-$ allowed
  - $X \rightarrow J/\Psi \, \sigma$ forbidden for any isoscalar $\sigma$
  - $X \rightarrow J/\Psi \, \pi^0 \, \pi^0$ forbidden
Further properties by B-factories

- **BaBar**: (hep-ex/0408083)
  - search for charged partner $X^{\pm} \rightarrow J/\Psi \rho^{\pm}$
  - expect twice the rate if $X$ is part of iso-triplett
  $\Rightarrow$ no signal found

- **Belle**: (hep-ex/0505037)
  - $4\sigma$ evidence for decay $X(3872) \rightarrow J/\Psi \gamma$
  - evidence for decay $X \rightarrow J/\Psi \pi^+ \pi^-\pi^0$
  $\Rightarrow$ **Swanson**: $1^{++} D \bar{D}^{*}$ (hep-ph/0311229)
    has contribution of $X \rightarrow J/\Psi \omega, \omega \rightarrow \pi^+ \pi^-\pi^0$
  - search for $X \rightarrow \chi_{c1} \gamma, X \rightarrow \chi_{c2} \gamma$
  $\Rightarrow$ no signal found
Conclusions & Outlook

- $X(3872)$ observed at CDF and D0 with high statistical significance
- already many properties determined:
  - behaves similar to $\Psi(2S)$: isolation, $\cos(\theta_{\pi,\mu})$, rapidity $y$
  - fraction from $B$ decays
  - $\pi^+ \pi^-$ mass distribution
- experimental evidence seems to point to:
  - $X(3872)$ has positive $C$ parity
  - $X(3872)$ compatible with ‘molecular’ interpretation
  - $\pi^+ \pi^-$ spectrum compatible with intermediate $\rho^0$ hypothesis
- yet to come: determination of $J^{PC}$ (CDF), decay modes with photons (D0), ...
The Tevatron

$pp$ collisions

RunI: 1992 – 1996
data taking period at $\sqrt{s} = 1.8\text{TeV}$

RunII: 2001 – 2009
major upgrades to collider and detectors

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

Running well - both peak luminosity and integrated luminosity
Currently ~15 pb\(^{-1}\) / week delivered

1 fb\(^{-1}\) delivered in beginning of June.
CDF:

- 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:
  $$\sigma(p\bar{p},|\eta| < 1.0) \approx 20 \mu b$$
  $$\Rightarrow 10^3$$ times bigger than $\Upsilon(4S)$!
- spectrum quickly falling with $p_t$
- Heavy and excited states not produced at B factories:
  $$B_c, B_s, B^{**}, \Lambda_b, \Sigma_b, \ldots$$
- enormous inelastic cross-section:
  $$\Rightarrow$$ triggers are essential
- events “polluted” by fragmentation tracks, underlying events
  $$\Rightarrow$$ need precise tracking and good resolution!
Dedicated trigger $J/\Psi \to \mu^+ \mu^-$

Evaluate muon chamber info on trigger level:

trigger events where $m(\mu^+ \mu^-)$ around $m(J/\Psi)$
- high quality $J/\Psi$ events
- large statistics available

N.B. channel $J/\Psi \to e^+e^-$ much more challenging in complex hadronic environment!
Likelihood function for measuring fraction from B

\[ \mathcal{L} = \prod_{i=1}^{N} [f_{\text{Sig}} \left( (1 - f_{LL}) \mathcal{L}_{P} + f_{LL} \mathcal{L}_{LL} \right) + \left( 1 - f_{\text{Sig}} \right) \mathcal{L}_{B}] \]

\[ \mathcal{L}_{i} = \mathcal{F}_{i}(c\tau) \times \mathcal{M}_{i}(m) \]

composed of lifetime and mass functions

mass component:

\[ \mathcal{M}_{\text{Sig}}(m) = G(m - m_{0}, \sigma_{0}) \]  

Signal: Gaussian, \( m_{0}, \sigma_{0} \) from full fit

\[ \mathcal{M}_{\text{B}}(m) = a_{0} + a_{1}(m - \bar{m}) + a_{2}(m - \bar{m})^{2} \]  

Background: 2\textsuperscript{nd} degree polyn.

lifetime component: exponential with Gaussian resolution

\[ \mathcal{F}(c\tau) = R(c\tau' - c\tau, \sigma_{\tau}) \otimes \exp(-c\tau'/\tau_{\text{Sig}}) \]
Systematics for measuring fraction from B

- **mass window**
  - shift window at fixed width of 130 MeV/c²
  - vary width of mass window: 50-250 MeV/c²
- **fit model**
  - vary parameterisations, e.g. 2 Gaussians instead of 1, etc. (negligible for X(3872))
- **multiple candidates** (Lₓᵧ dominated from J/Ψ decay)
  - randomly select one candidate
  - take highest/lowest pₑ candidate
  - take candidate with largest m(π⁺π⁻)
  - take candidate with smallest error on Lₓᵧ
  - take candidate with lowest χ² in vertex fit
- **fit bias**
  - generate many pseudo-experiments (Toy-MC) from original fit
  - define pulls and check for deviations from Gaussian at zero
Systematics for \( m(\pi^+\pi^-) \) measurement

- **Yield systematics:**
  - compare yield from Gaussian with counting bin entries
  - replace background parametrisation with polynomial
    \[
    A\left(\frac{\alpha+1}{x_{up}-x_{low}}\right)^\alpha \cdot \frac{\beta e^{-\beta x}}{e^{-\beta x_{low}}-e^{-\beta x_{up}}}
    \]
    \( x_0 \): turn-on value
    \( x_{low}, x_{up} \): fit range
  - (n.b. special treatment for points at kinematic boundary)
  - vary fit window size from 200 MeV/c\(^2\) to 150, 250 MeV/c\(^2\)

- **Efficiency systematics:**
  - efficiency correction determined from MC
  - measure \( p_t \) spectrum from data, vary parameters