The X(3872) at the Tevatron

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for the CDF and D0 collaborations

BEAUTY 2005

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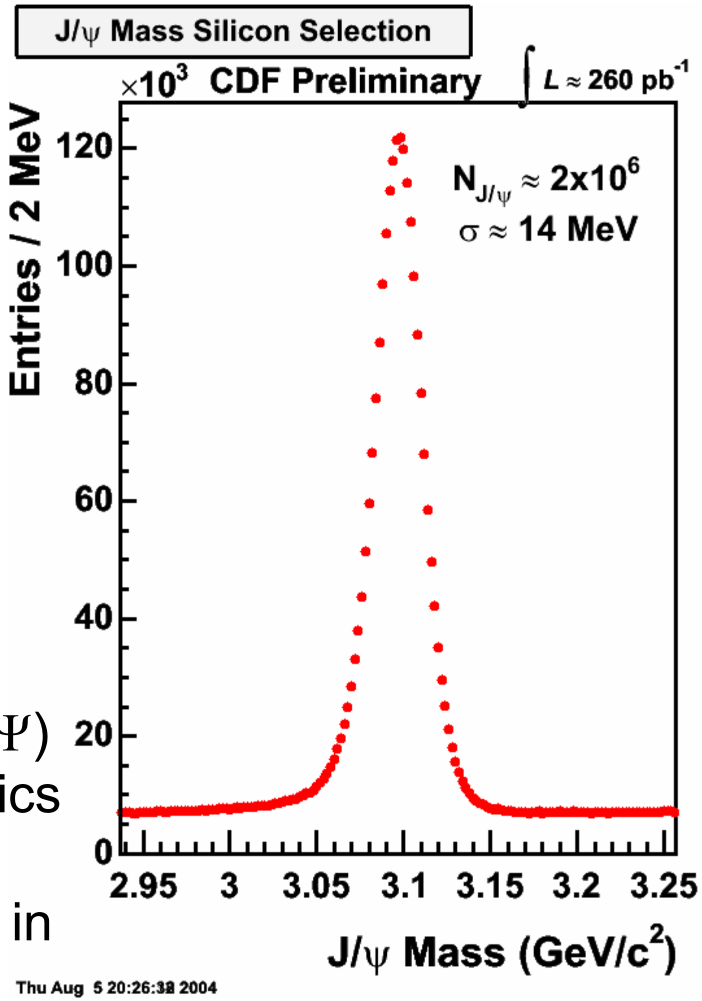
Physics at the Tevatron

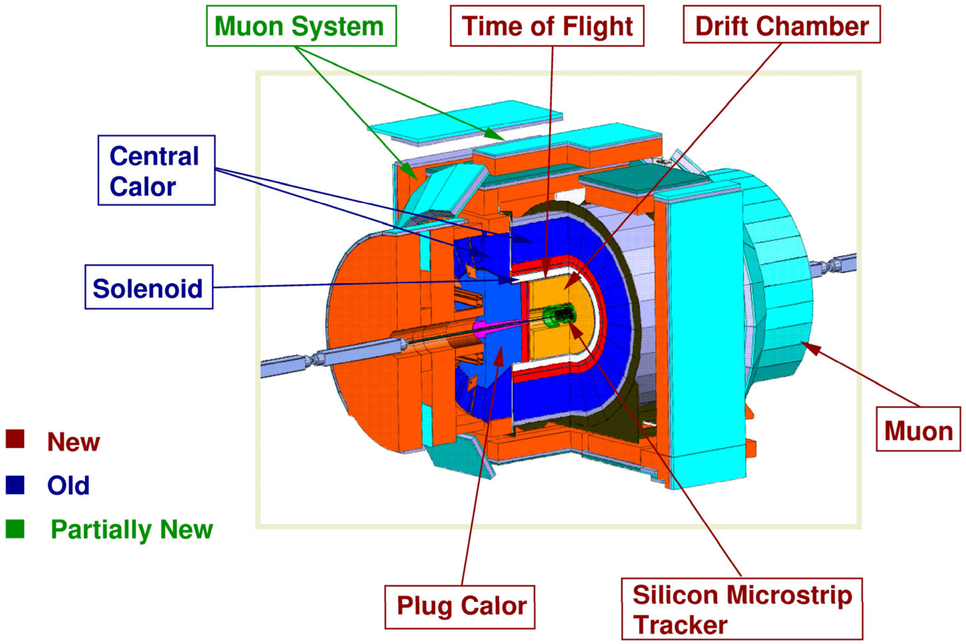
- observe $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- 1 fb^{-1} luminosity delivered early June
- huge inelastic cross-section:
  $\approx$ 5000 times bigger than for $b\bar{b}$
  $\Rightarrow$ triggers are essential!

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

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

- channel $J/\Psi \to e^+e^-$ much more challenging in hadronic environment





CDF:

- precise tracking:

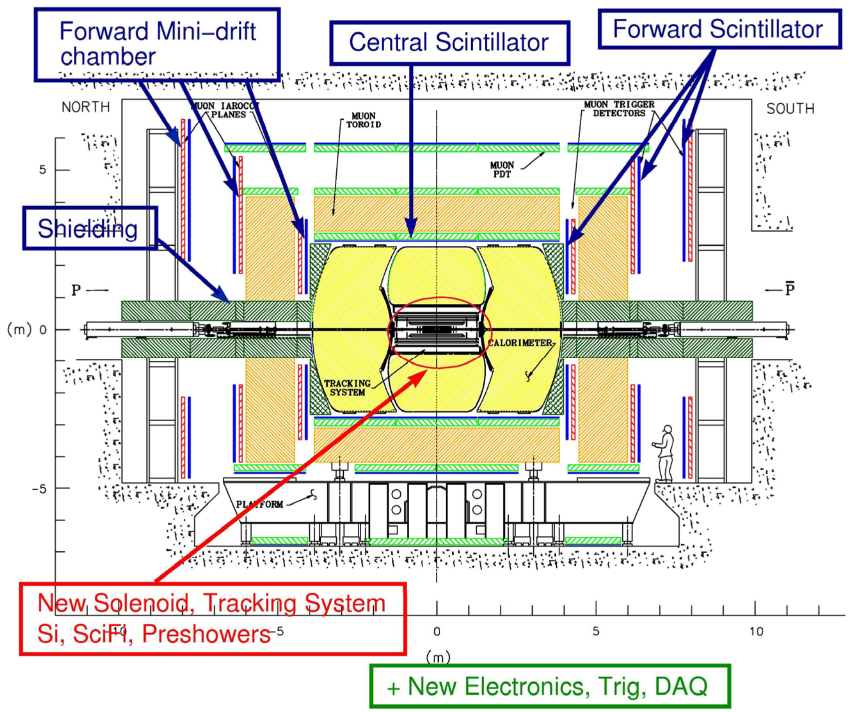
  (silicon vertex detector and drift chamber)

- important for B physics:

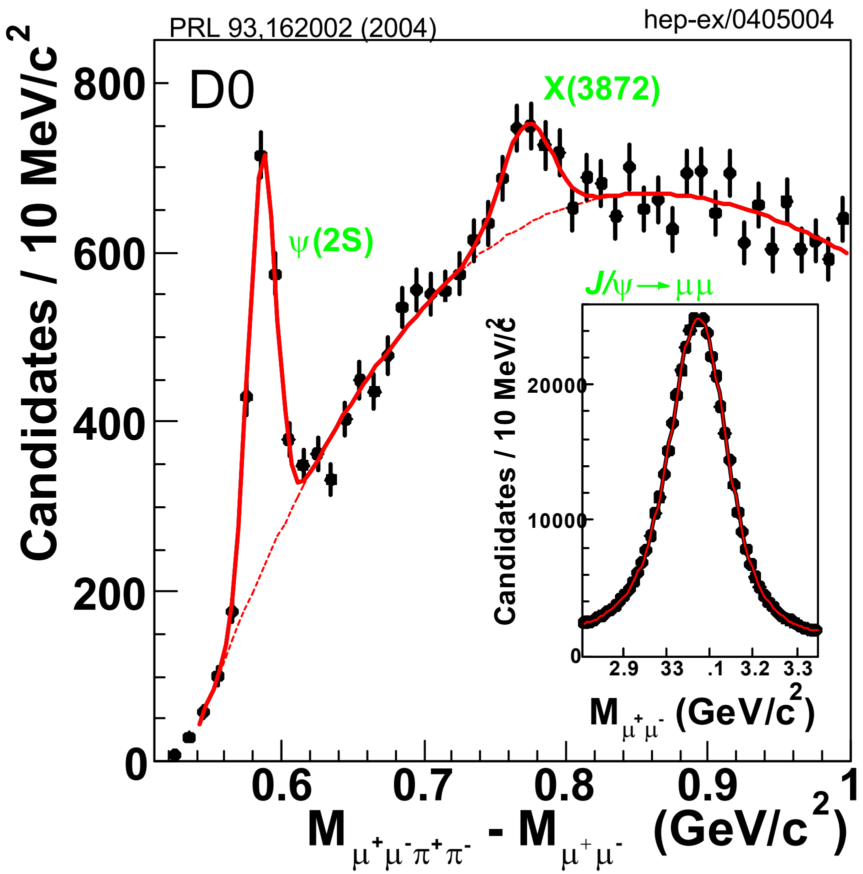
  direct trigger for displaced vertices

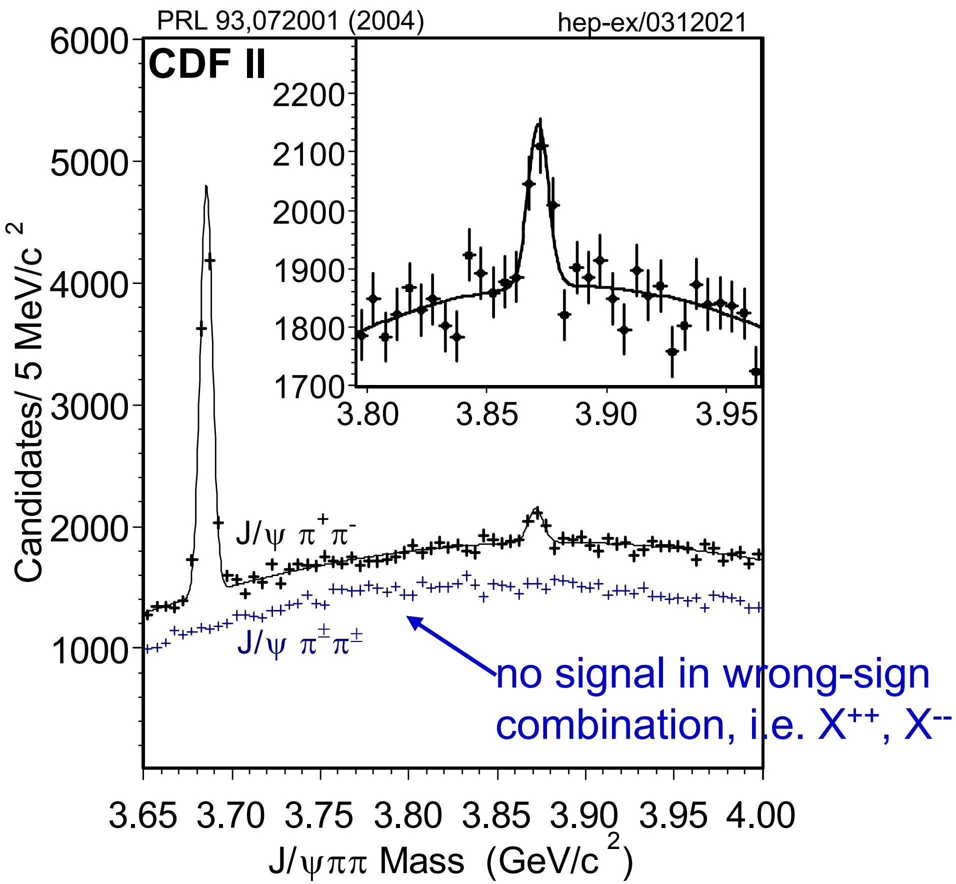
D0:

- 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





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

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

reported widths are compatible with detector resolution

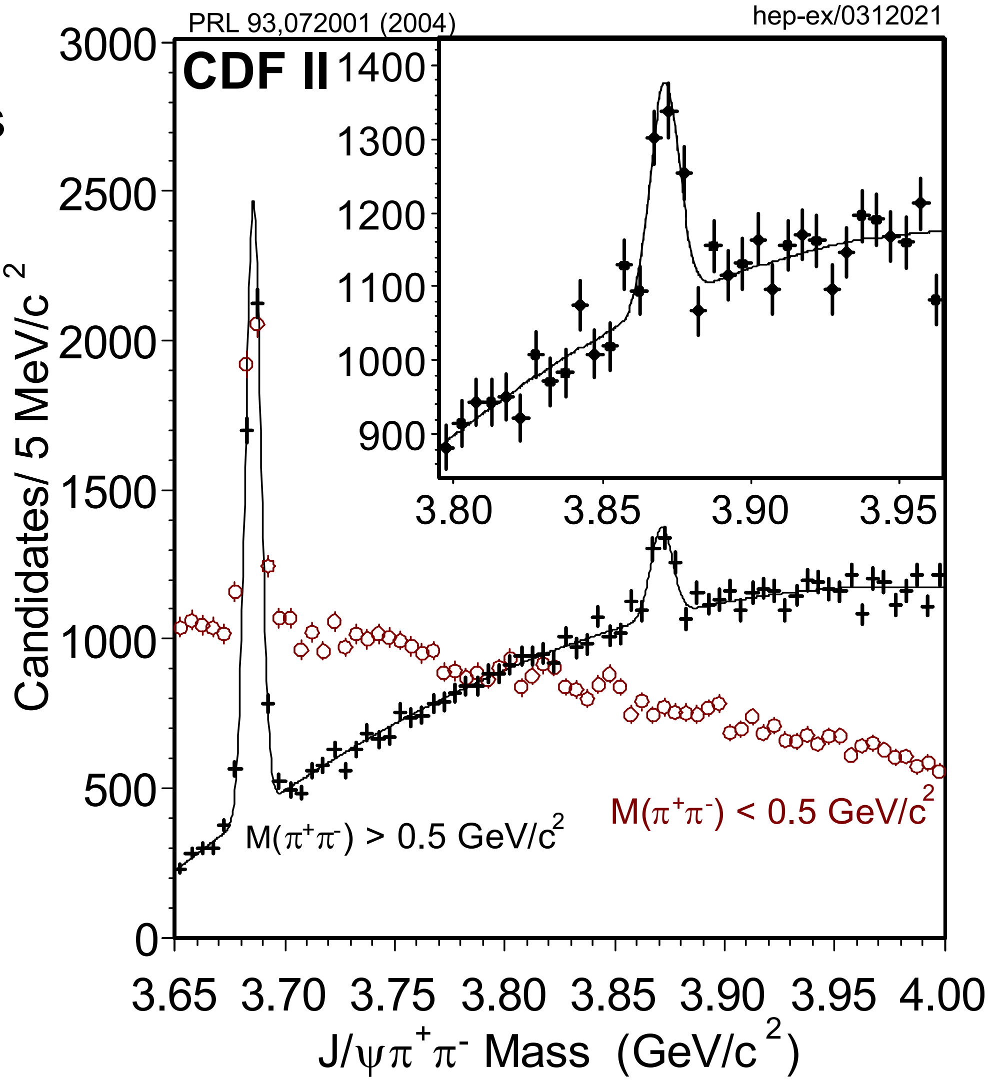
Observation of X(3872) at CDF and D0

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

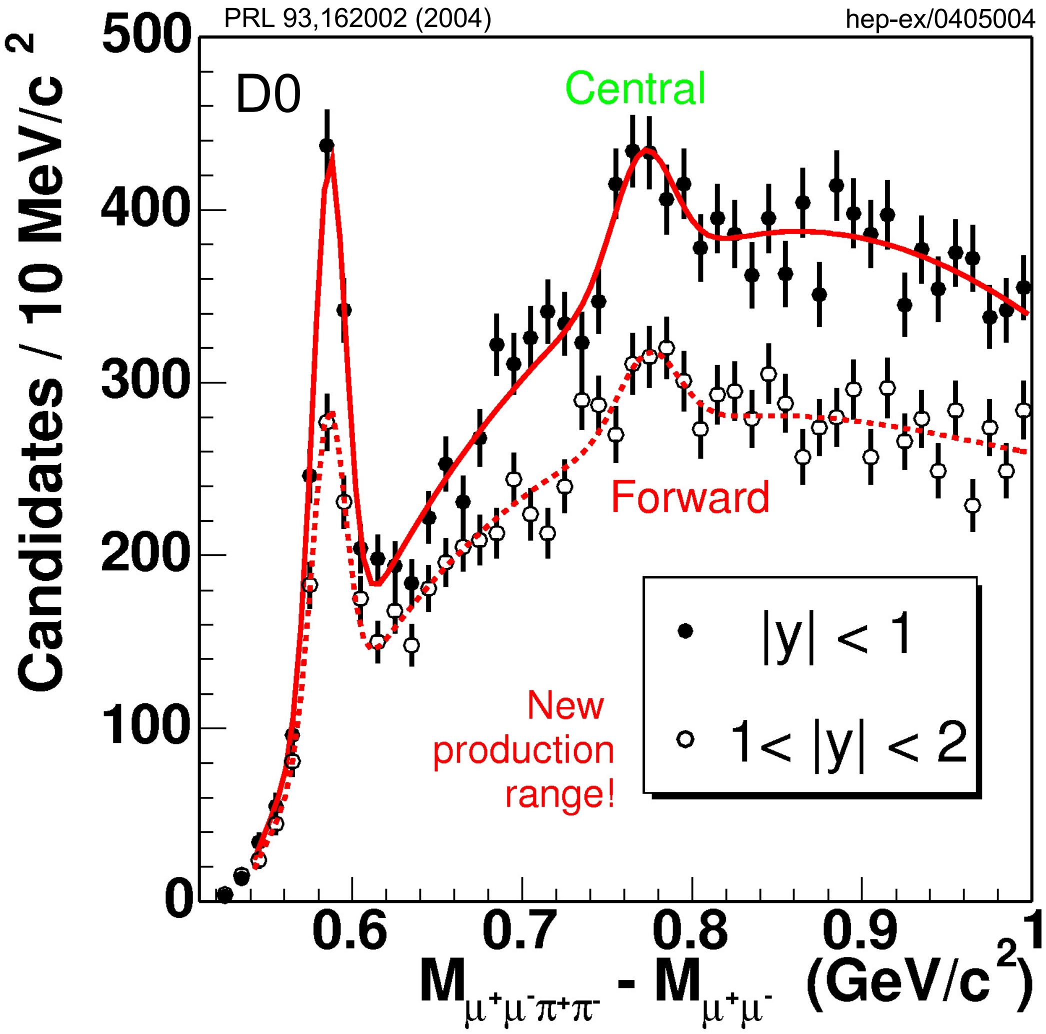
D0: demand $m(\pi^+ \pi^-) > 0.52$ GeV/c^2
as default cut

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

⇒ no apparent signal for
$m(\pi^+ \pi^-) < 0.5$ GeV/c^2



X(3872): central vs. forward



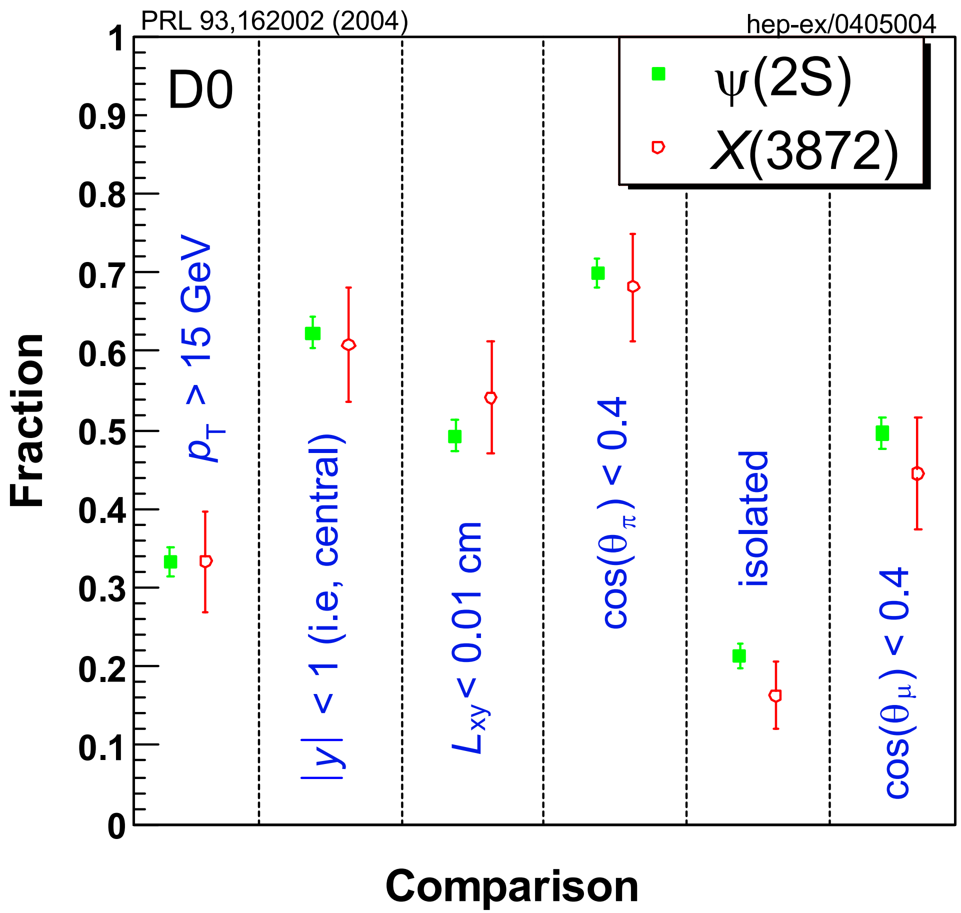
D0: large muon coverage

⇒ 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 + charged tracks in cone $\Delta R = 0.5$)

θ_π, θ_μ : boost one of the pions (muons) in dipion (dimuon) rest-frame,

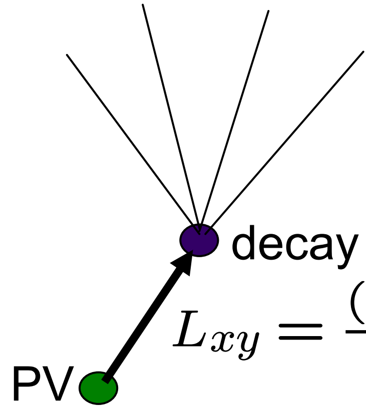
L_{xy} : distance (PV – decay vertex) * M/p_t

$\Rightarrow$ *X(3872)* behaves similarly to the $\Psi(2S)$

X(3872) production fraction from B

Define pseudo-proper decay time:

$$c\tau = \frac{M(J/\Psi\pi^+\pi^-)}{p_t(J/\Psi\pi^+\pi^-)} L_{xy}$$



$$L_{xy} = \frac{(\vec{x}_{\text{decay}} - \vec{x}_{\text{prim}}) \cdot \vec{p}_t}{|\vec{p}_t|}$$

<u>Unbinned LogL fit</u> (simultaneously for cτ and M):

- <u>Mass:</u>
  - signal: Gaussian
  - BG : 2nd order polynomial for BG
- <u>Proper time:</u>
  - signal: exponential
  - BG : 2 pos., 1 neg. exponential

  all folded with Gaussian due to resolution

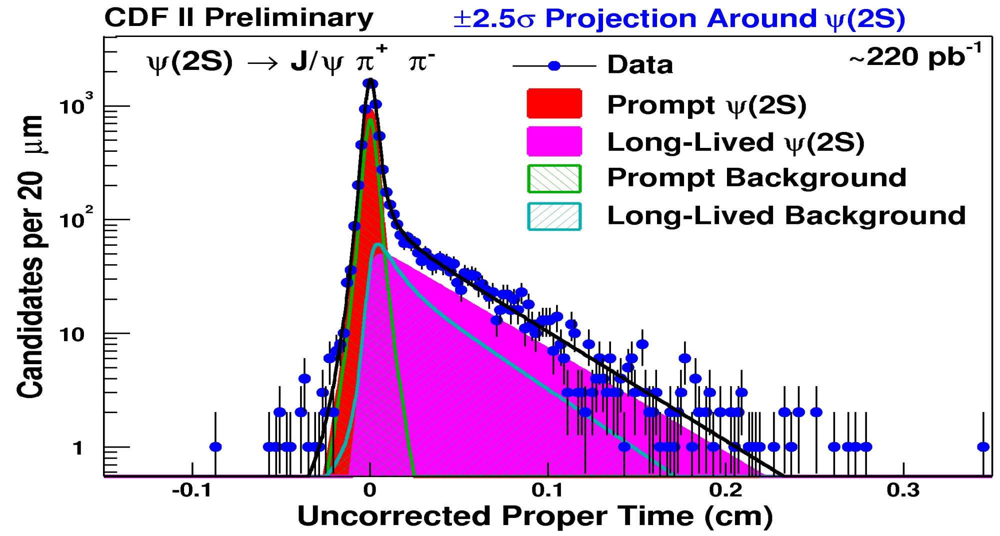
X(3872) production fraction from B

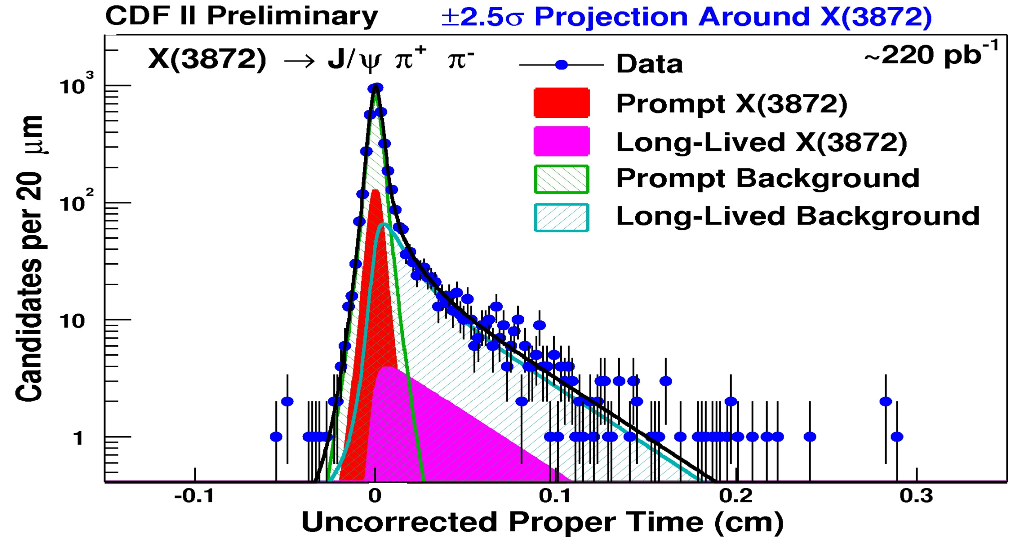
<u>fraction from B decays:</u>

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

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

⇒ X(3872) behaves similarly to the $\Psi(2S)$ (with given uncertainties)

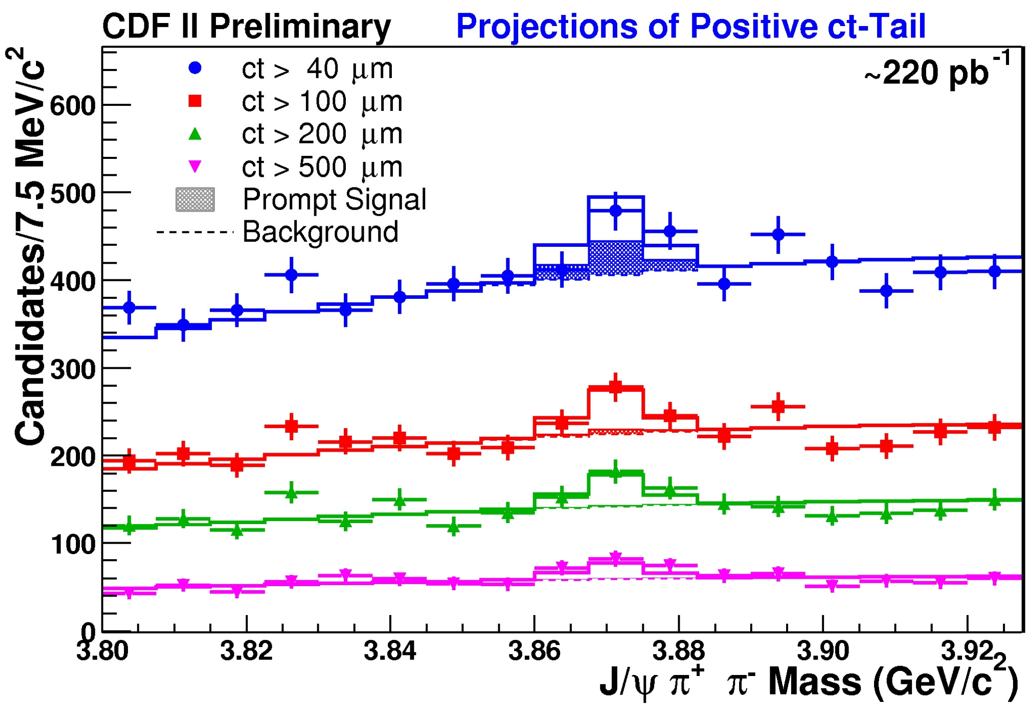




X(3872) production fraction from B

<u>Consistency check:</u>
overlay m($J/\Psi\ \pi^+\ \pi^-$) spectrum with prediction from LogL
$\Rightarrow$ data is described well

<u>N.B.</u> almost no prompt signal for $c\tau$ > 100 μm



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/Ψ ρ, $\rho \rightarrow \pi^+ \pi^-$

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

<u>for broad resonances</u> (kinematic factors vary across width)

$$\Gamma_{A\to BC} = \Gamma_{0,A\to BC}\left(\frac{k^*}{k_0^*}\right)^{2L+1}\left(\frac{f(k^*)}{f(k_0^*)}\right)^2\left(\frac{m}{m_0}\right)$$

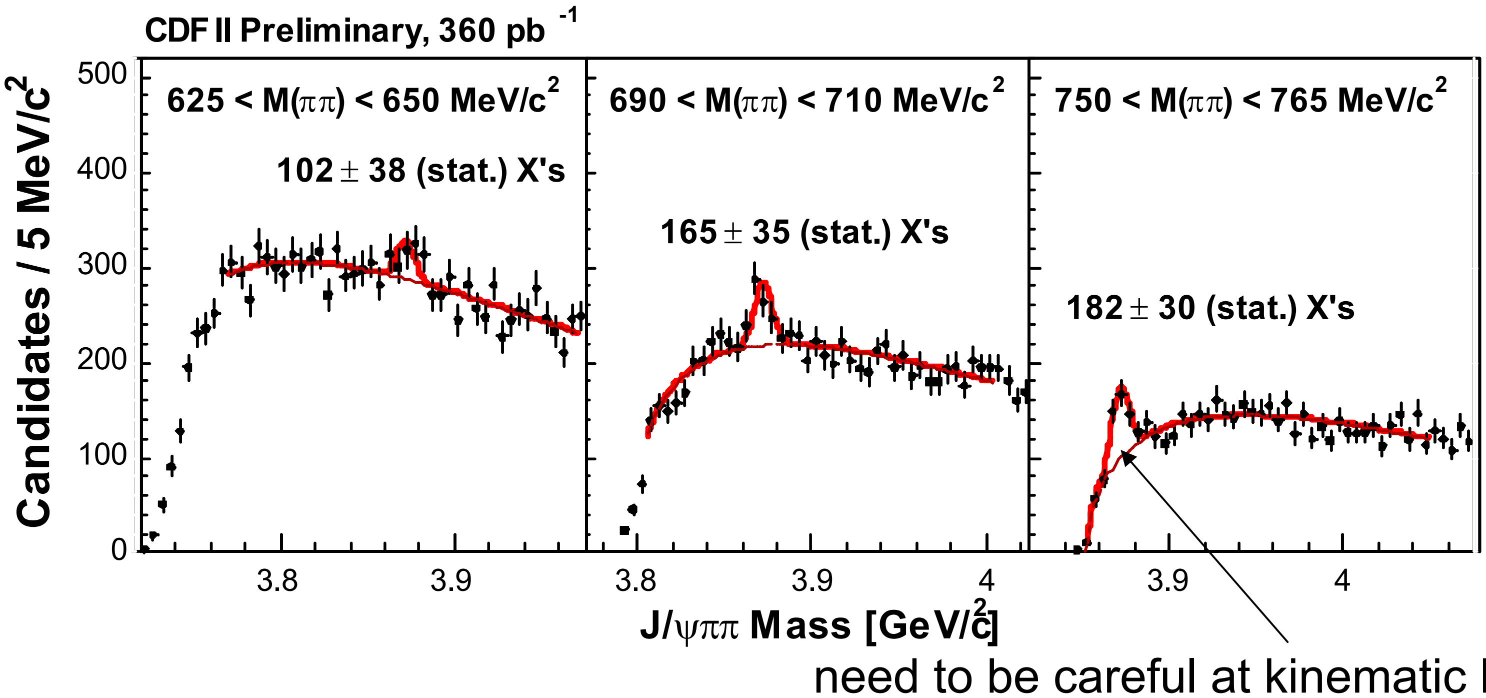
form-factor

The m(π^+ π^-) mass spectrum

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

"slicing technique"

- impose bin borders in m(π^+ π^-) as additional cuts
- fit resulting ($\pi^+\pi^-$ μ^+ μ^-) mass spectrum
- obtained yield shows variation with m(π^+ π^-)

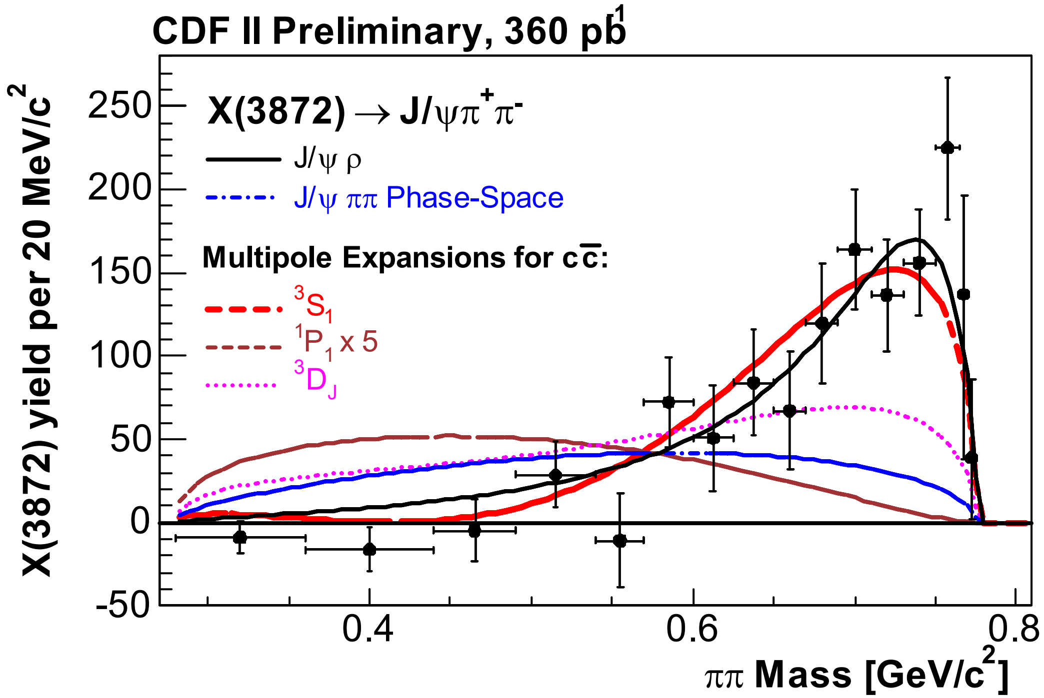


The m($\pi^+ \pi^-$) mass spectrum

<u>if ($\pi^+\pi^-$) in S-wave state:</u>
$\Rightarrow$ shape needs to be modelled
compare to multipole expansions

<u>if ($\pi^+\pi^-$) form sub-resonance:</u>
$\Rightarrow$ shape follows Breit-Wigner
e.g. decay via $\rho^0 \to \pi^+ \pi^-$
(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
  $\Rightarrow$ compatible with intermediate $\rho^0 \to \pi^+ \pi^-$ 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

  ($\Gamma(e^+e^-)B(\pi^+\pi^- J/\Psi) < 10$ eV @90% C.L.) hep-ph/0310261

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

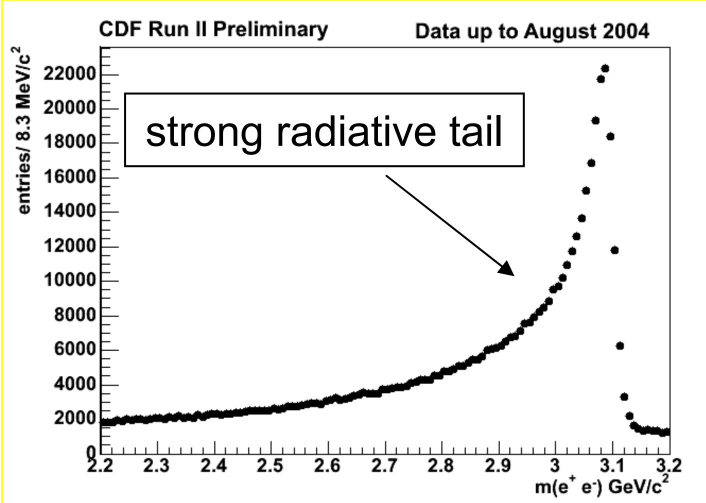
X(3872) with $J/\Psi \rightarrow e^+ e^-$

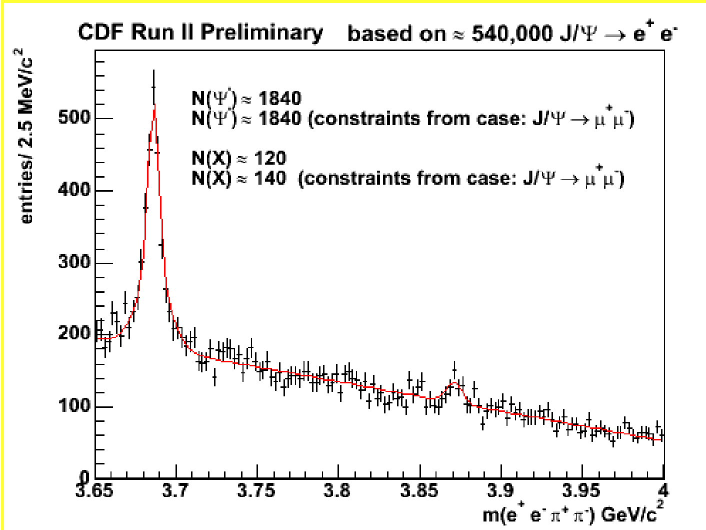
Reconstruction of $J/\Psi \rightarrow e^+e^-$ very difficult in complex hadronic environment

- dedicated $J/\Psi \rightarrow e^+e^-$ trigger
- use neural-network based approach to identify soft $e^\pm$ (p_t > 2GeV/c)
- reject $e^\pm$ from conversions based on neural network approach
- add γ at J/Ψ vertex to accommodate Bremsstrahlung
- X(3872) reconstructions follows $J/\Psi\ \pi^+\ \pi^-$ case

  (replace cut on $m(\pi^+\pi^-)$ by cut on $Q = m_X - m_{J/}\Psi - m_{\pi\pi}$)

$\Rightarrow$ able to reconstruct X(3872) in this channel!





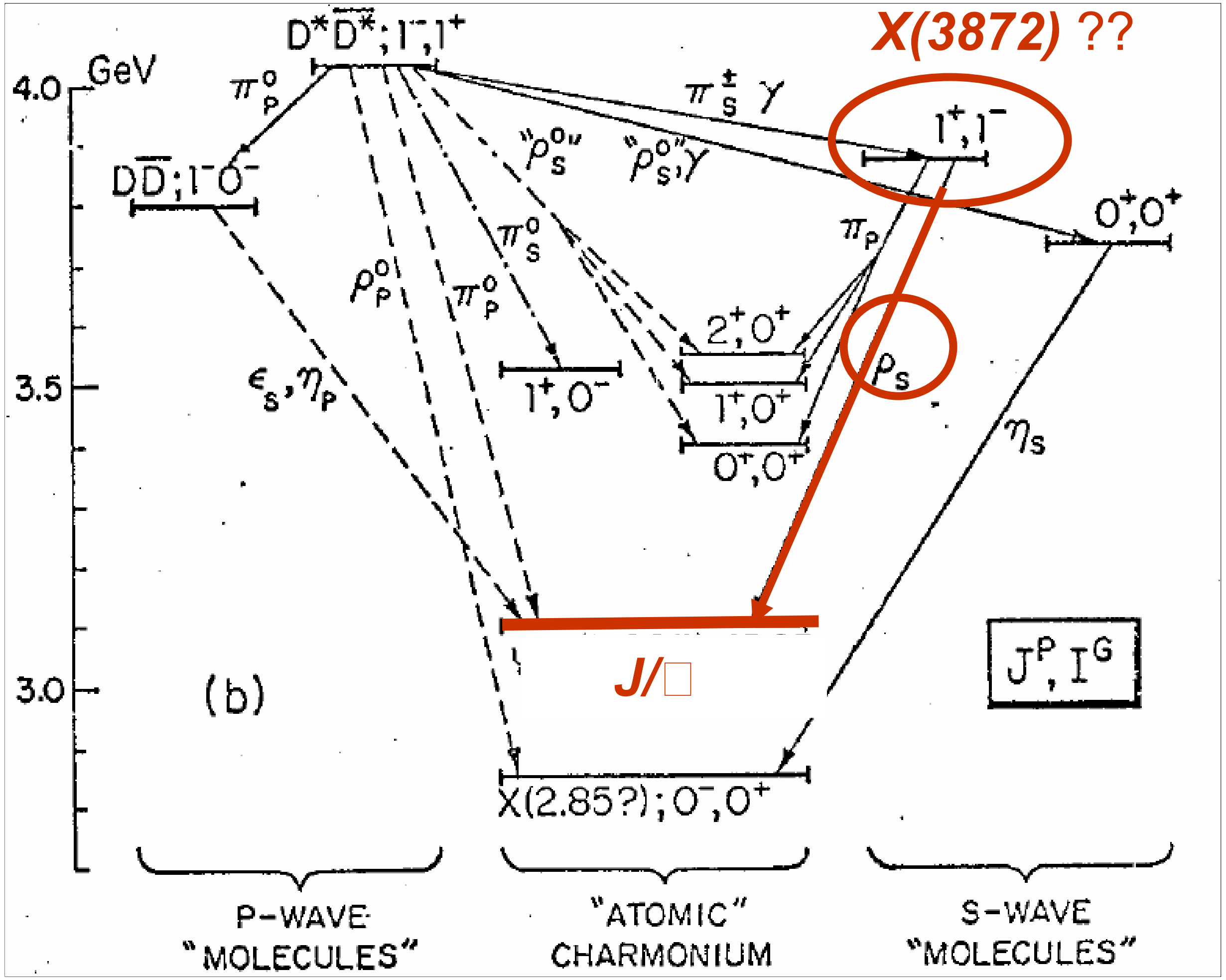
What is the X(3872) ??

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

- Charmonium ?
  - $2\ ^1P_1$, i.e. h'_c (1^{+-})
    - predicted at $\approx$ 3950 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":

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

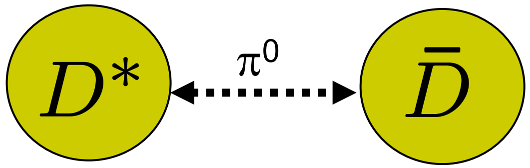
$D^*\bar{D}^*$

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

decay via:

$J/\Psi\rho^0, J/\Psi\eta$

„Deuson“ model (Törnqvist)



X(3872) similar to deuteron:

- composed of two objects
- bound by π^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 σ
  - $X \rightarrow J/\Psi\ \pi^0\ \pi^0$ forbidden

Further properties by B-factories

- **<u>BaBar:</u>** (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

C = +1

- **<u>Belle:</u>** (hep-ex/0505037)
  - 4 σ evidence for decay $X(3872) \rightarrow J/\Psi\ \gamma$
  - evidence for decay $X \rightarrow J/\Psi\ \pi^{+}\ \pi^{-}\pi^{0}$

    $\Rightarrow$ **<u>Swanson:</u>** 1^{++} $D\bar{D}^{*}$ (hep-ph/0311229)

    has contribution of $X \rightarrow J/\Psi\ \omega,\ \omega \rightarrow \pi^{+}\ \pi^{-}\pi^{0}$
  - search for $X \rightarrow \chi_{c1}\ \gamma$, $X \rightarrow \chi_{\chi 2}\ \gamma$

    $\Rightarrow$ no signal found

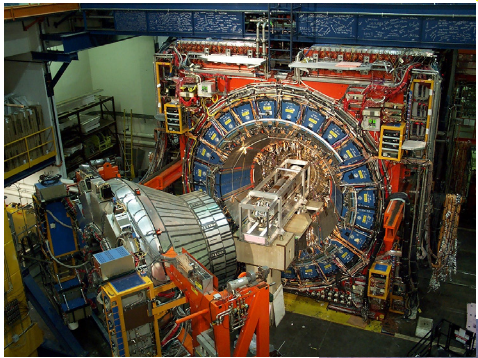
Conclusions & Outlook

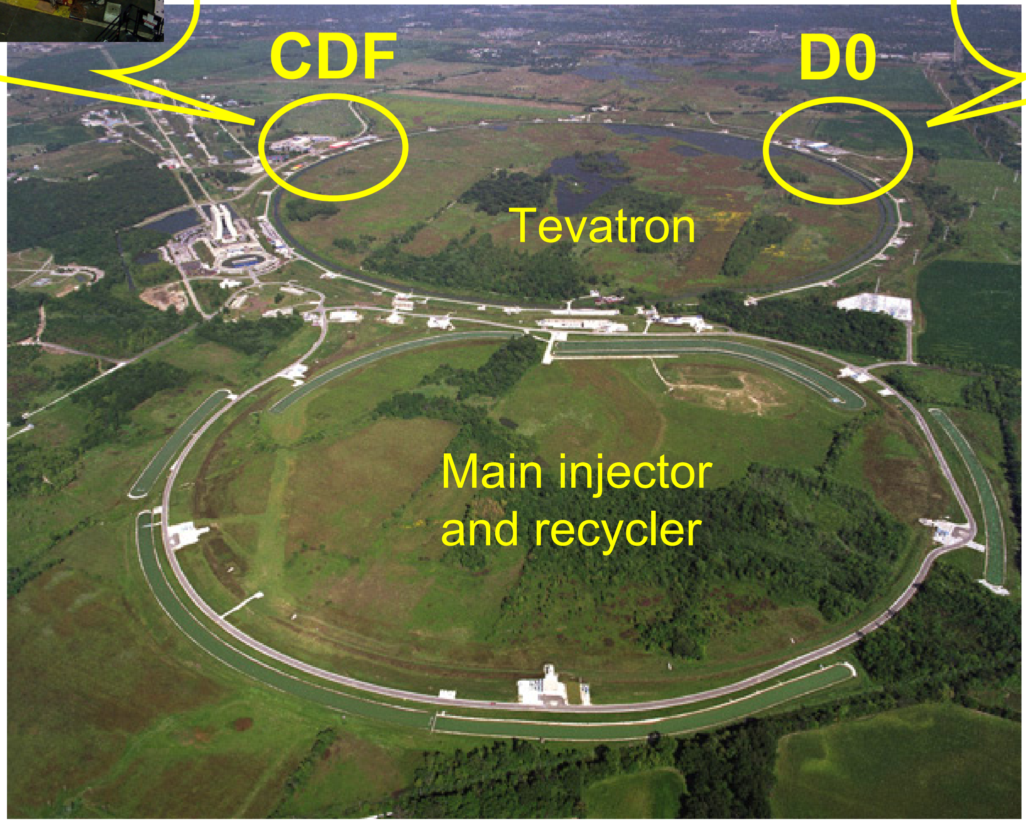
- X(3872) observed at CDF and D0 with high statistical significance
- already many properties determined:
  - behaves similar to $\Psi(2S)$: isolation, $\cos(\theta_{\pi,\mu})$, rapidity y
  - fraction from B decays
  - $\pi^+ \pi^-$ mass distribution
- experimental evidence seems to point to:
  - X(3872)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

BACKUP

The Tevatron

$p\bar{p}$ collisions



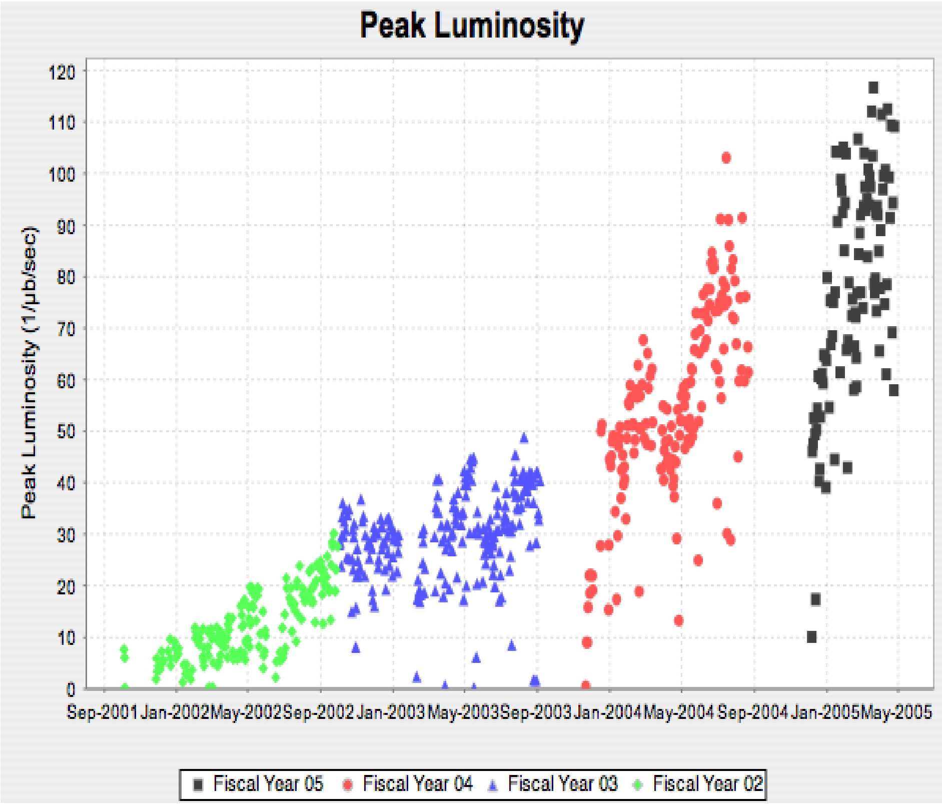


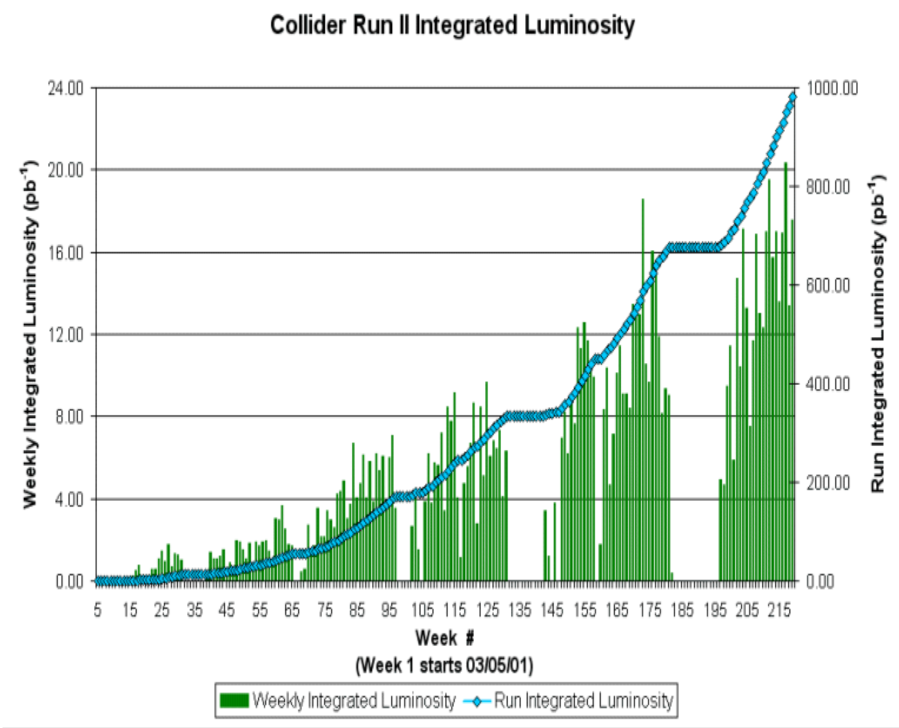
<u>RunI</u>: 1992 – 1996
data taking period
at $\sqrt{s} = 1.8\text{TeV}$

<u>RunII:</u> 2001 – 2009
major upgrades to
collider and
detectors

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

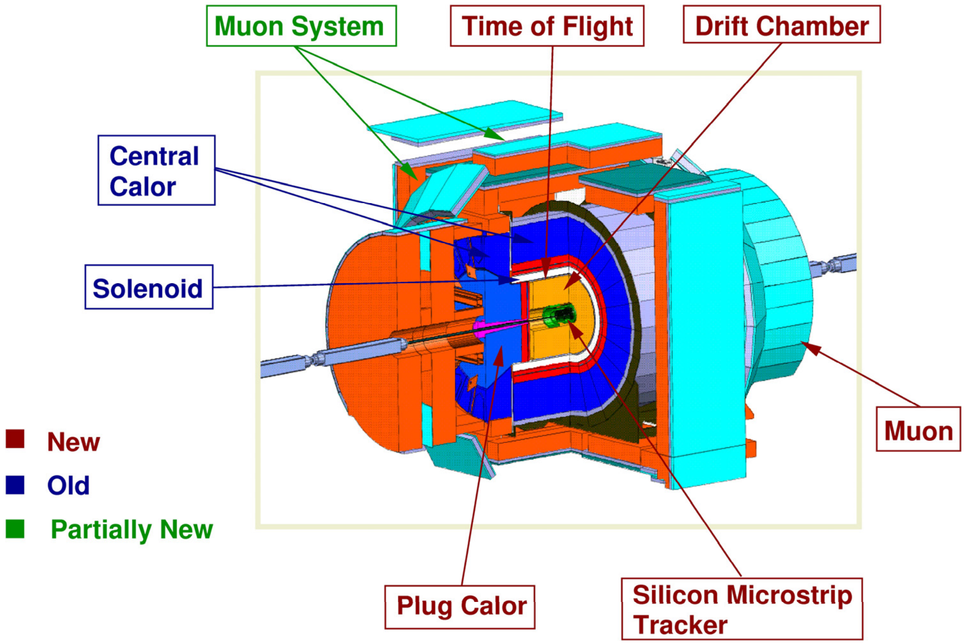
Tevatron performance





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

1 fb^{-1} delivered in beginning of June .



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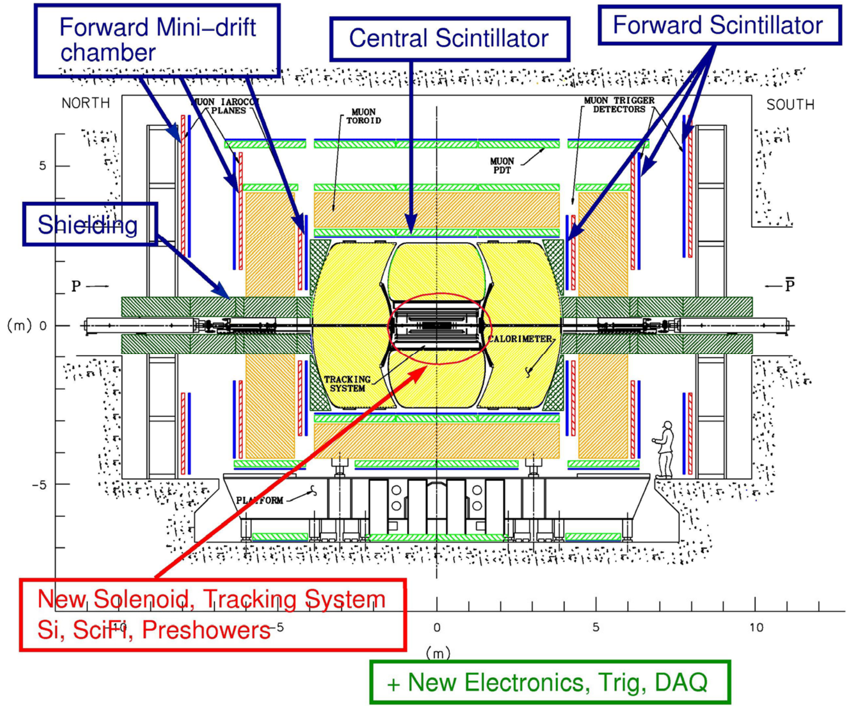


Physics at the Tevatron

- large b production rates:

  $\sigma(p\bar{p}, |\eta| < 1.0) \approx 20\mu\text{b}$

  $\Rightarrow 10^3$ times bigger than $\Upsilon(4S)$!

- spectrum quickly falling with p_t

- Heavy and excited states not produced at B factories:

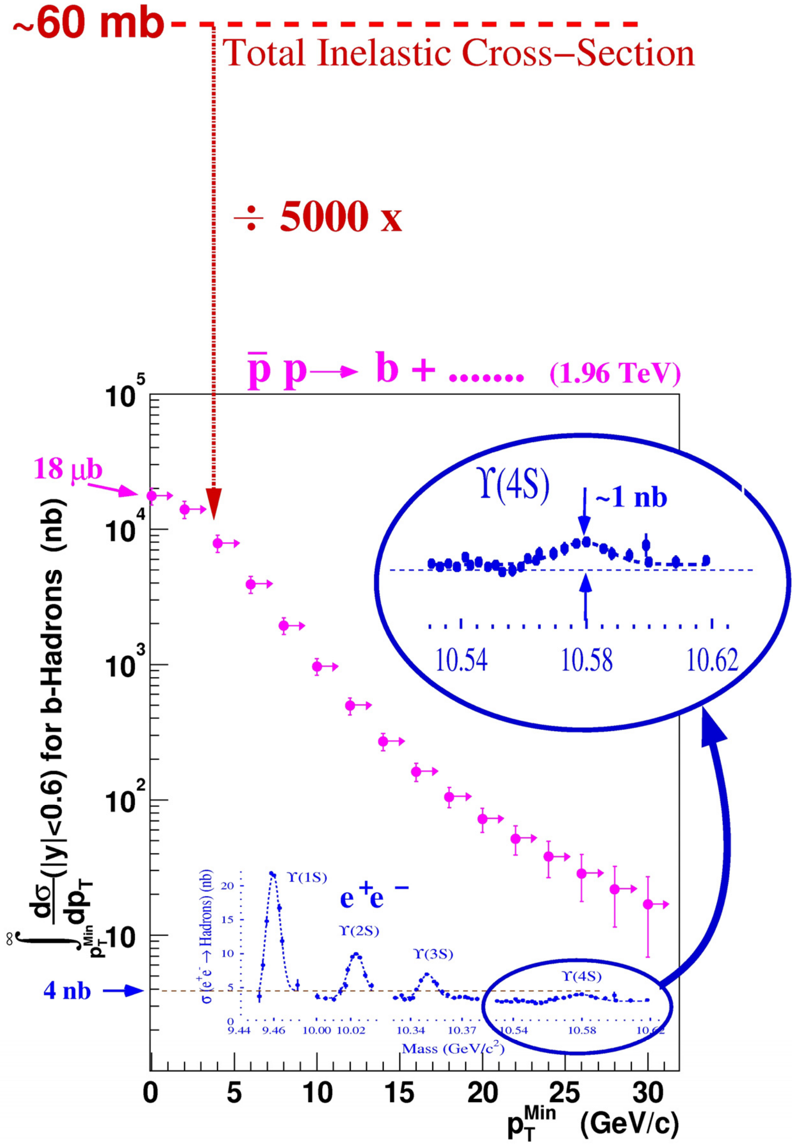
  $B_c, B_s, B^{**}, \Lambda_b, \Sigma_b, \ldots$

- enormous inelastic cross-section:

  $\Rightarrow$ triggers are essential

- events "polluted" by fragmentation tracks, underlying events

  $\Rightarrow$ need precise tracking and good resolution!

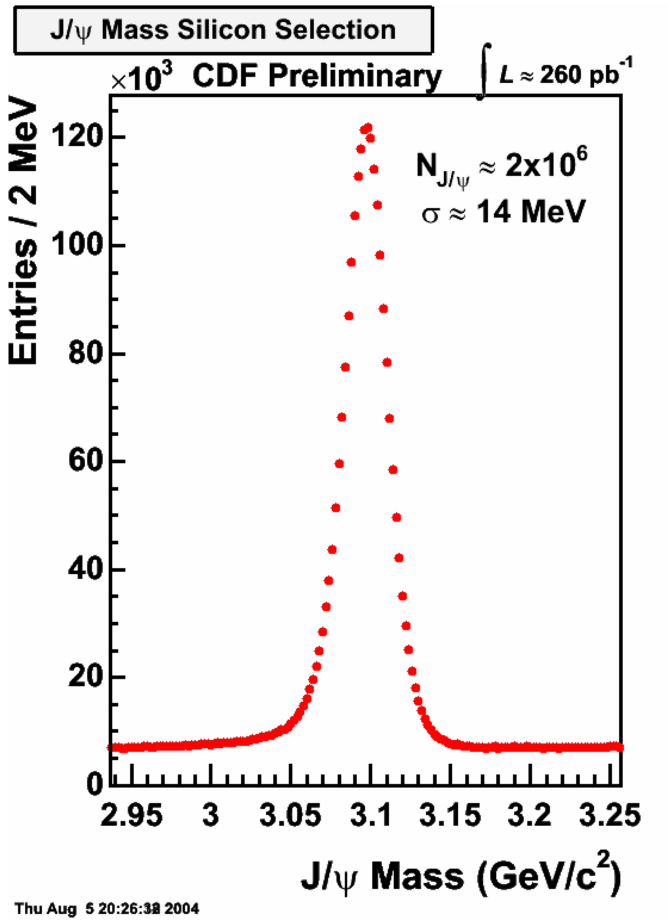


Dedicated trigger $J/\Psi \rightarrow \mu^+ \mu^-$

Evaluate muon chamber info on trigger level:

trigger events where $m(\mu^+ \mu^-)$ around $m(J/\Psi)$

- high quality J/Ψ events
- large statistics available



<u>N.B.</u> channel $J/\Psi \rightarrow e^+e^-$ much more challenging in complex hadronic environment!

Likelihood function for measuring fraction from B

define likelihood:

$$\mathcal{L} = \Pi_{i=1}^{N} \left[f_{Sig} \left((1 - f_{LL}) \mathcal{L}_P + f_{LL} \mathcal{L}_{LL} \right) + \left(1 - f_{Sig} \right) \mathcal{L}_B \right]$$

$$\mathcal{L}_i = \mathcal{F}_i(c\tau) \times \mathcal{M}_i(m)$$

composed of lifetime and mass functions

mass component:

$$\mathcal{M}_{Sig}(m) = G(m - m_0, \sigma_0)$$

Signal: Gaussian, m_0, σ_0 from full fit

$$\mathcal{M}_B(m) = a_0 + a_1(m - \bar{m}) + a_2(m - \bar{m})^2$$

Background: 2^{nd} degree polyn.

lifetime component: exponential with Gaussian resolution

$$\mathcal{F}(c\tau) = R(c\tau' - c\tau, \sigma_\tau) \otimes \exp(-c\tau'/\tau_{Sig})$$

Systematics for measuring fraction from B

- mass window
  - shift window at fixed width of 130 MeV/c^2
  - vary width of mass window: 50-250 MeV/c^2
- fit model
  - vary parameterisations, e.g. 2 Gaussians instead of 1, etc. (negligible for X(3872))
- multiple candidates (L_{xy} dominated from J/Ψ decay)
  - randomly select one candidate
  - take highest/lowest p_t candidate
  - take candidate with largest $m(\pi^+\pi^-)$
  - take candidate with smallest error on L_{xy}
  - take candidate with lowest χ^2 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

$$A\frac{(\alpha+1)(x-x_0)^\alpha}{(x_{up}-x_{low})^{\alpha+1}} \cdot \frac{\beta e^{-\beta x}}{e^{-\beta x_{low}}-e^{-\beta x_{up}}}$$

x_0 : turn-on value
x_{low}, x_{up} : fit range

with polynomial

(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