Heavy quark meson spectroscopy at CDF

X(3872) mass and evidence for Y(4140)

Felix Wick
(University of Karlsruhe)

on behalf of the CDF collaboration

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Motivation and Overview

- discovery of several states with charmonium-like decays but inappropriate properties (XYZ) in recent years
- possibly explained by exotic models beyond usual mesons

- Precision Measurement of the X(3872) Mass in $J/\psi\pi^+\pi^-$ Decays

  `arXiv:0906.5218v1 [hep-ex]`, submitted to PRL

- Evidence for a Narrow Near-Threshold Structure in the $J/\psi\phi$ Mass Spectrum in $B^+ \to J/\psi\phi K^+$ Decays

  `Phys. Rev. Lett. 102, 242002 (2009)`

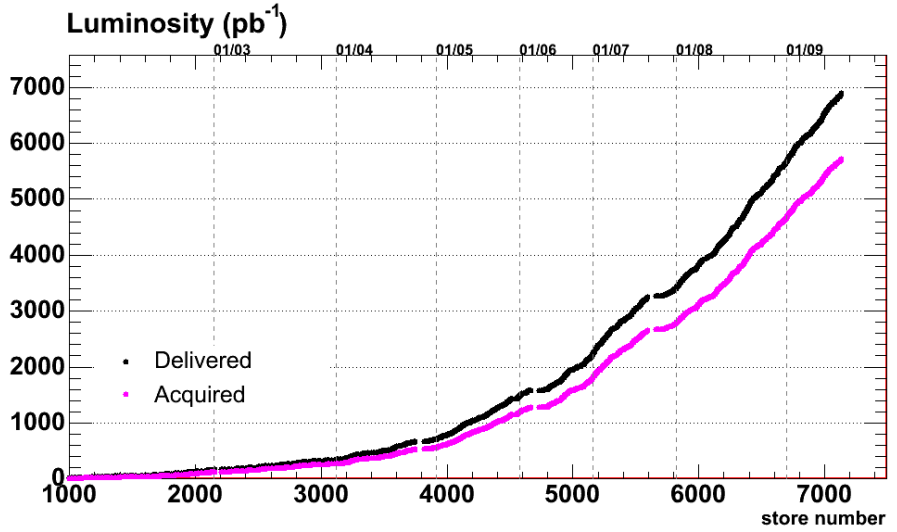
Tevatron and CDF at Fermilab

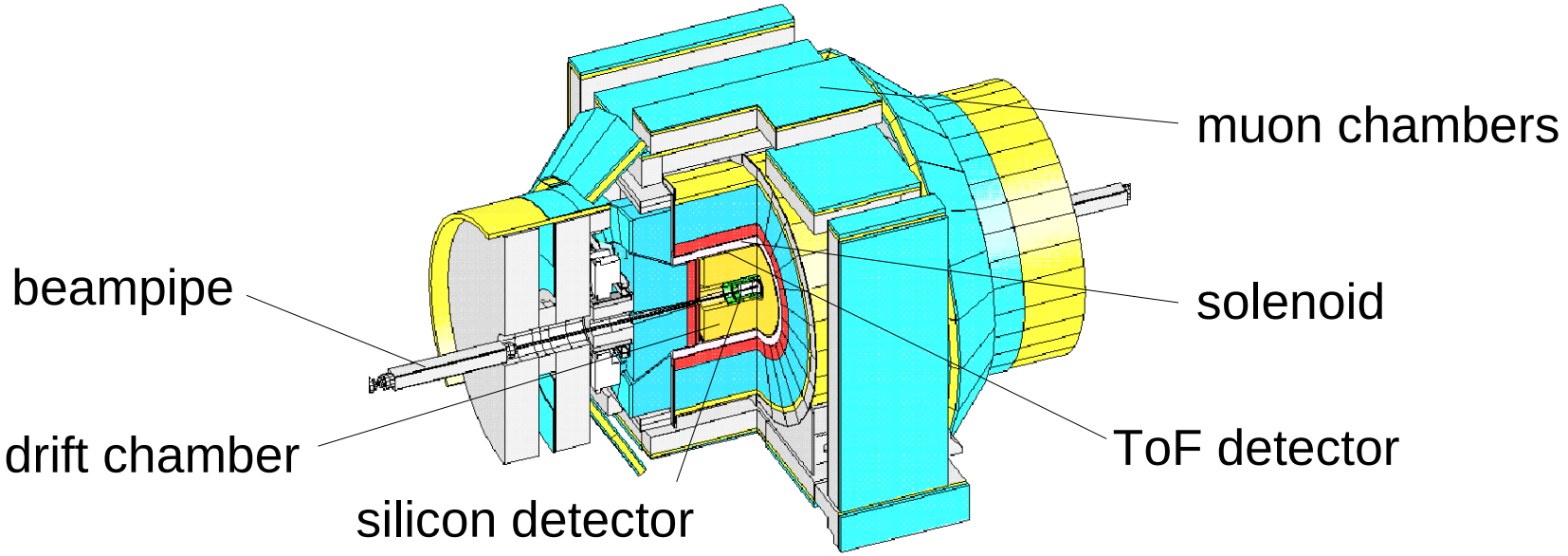
Tevatron:

- proton-antiproton collider
- $\sqrt{s} = 1.96\,\mathrm{TeV}$

CDF II:

- multipurpose detector
- excellent tracking and mass resolution

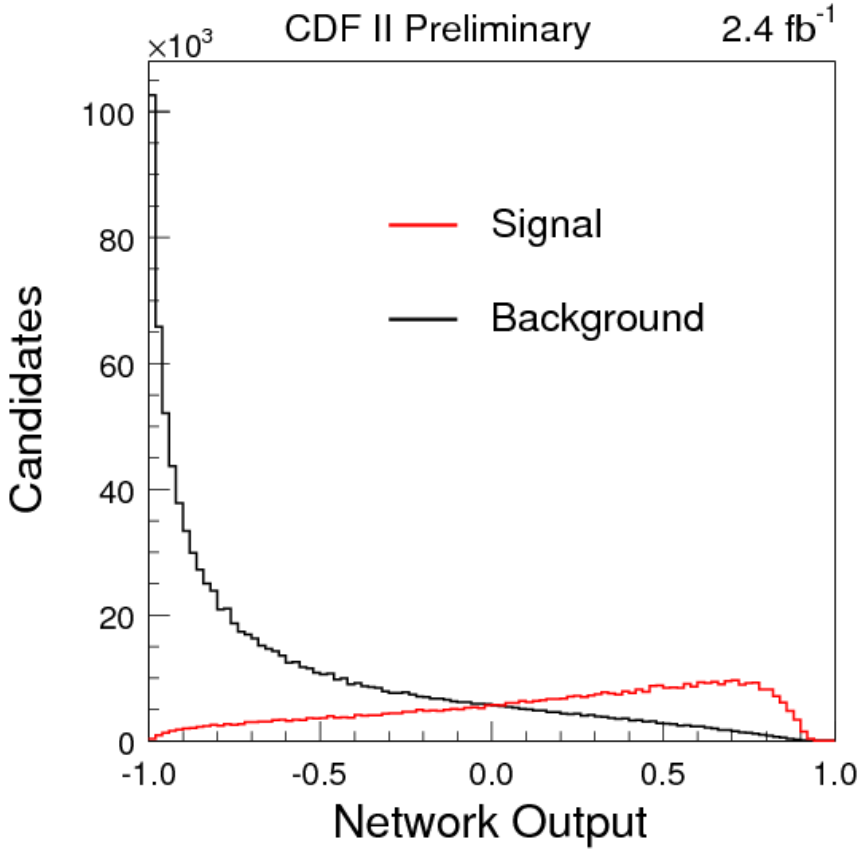




X(3872)

- nature of X(3872) state still unclear
- does not fit properly in charmonium spectrum
- several possible exotic explanations
- mass analysis can test two different hypotheses
  - four-quark state (model of Maiani et al.)
    prediction: X(3872) mass structure consists of two separate states
    Phys. Rev. D **71,** 014028 (2005)
  - molecular state composed by D^0 and D^{0*} mesons
    test by comparison of X(3872) mass with sum of meson constituent masses
    Phys. Lett. B **590,** 209 (2004)
    Phys. Lett. B **588,** 189 (2004)

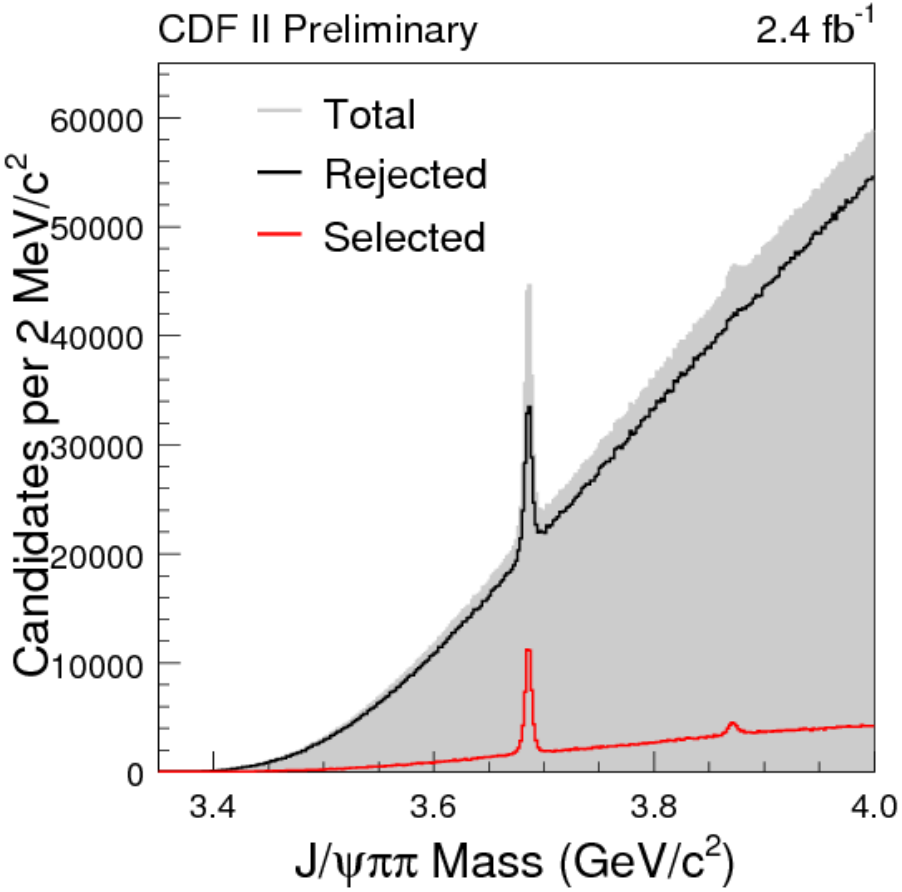
$X(3872) \to J/\psi\pi^+\pi^-$ Neural Network



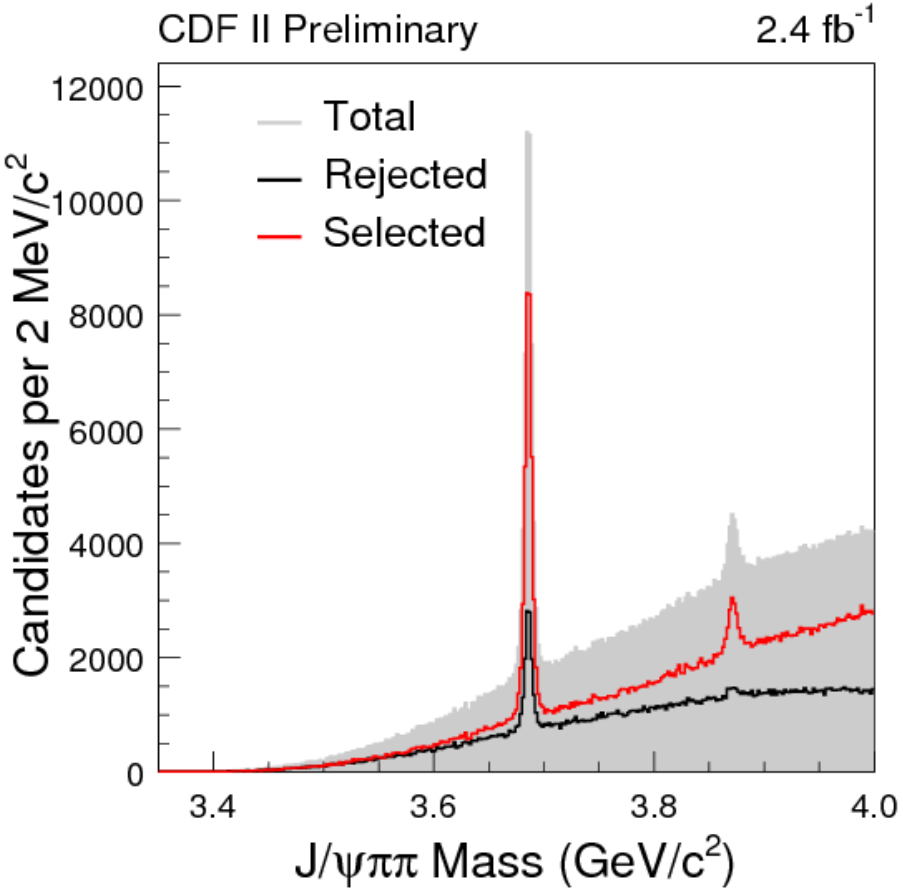
- multivariate technique to separate signal and background
- training samples
  - signal: simulated events
  - background: sidebands in data mass spectrum
- most important input quantities
  - Q value of the decay
  - transverse pion momenta
  - kinematic fit quality
  - muon identification quantities
- select candidates with network output > 0.25

Selection Cuts

cut on neural network output

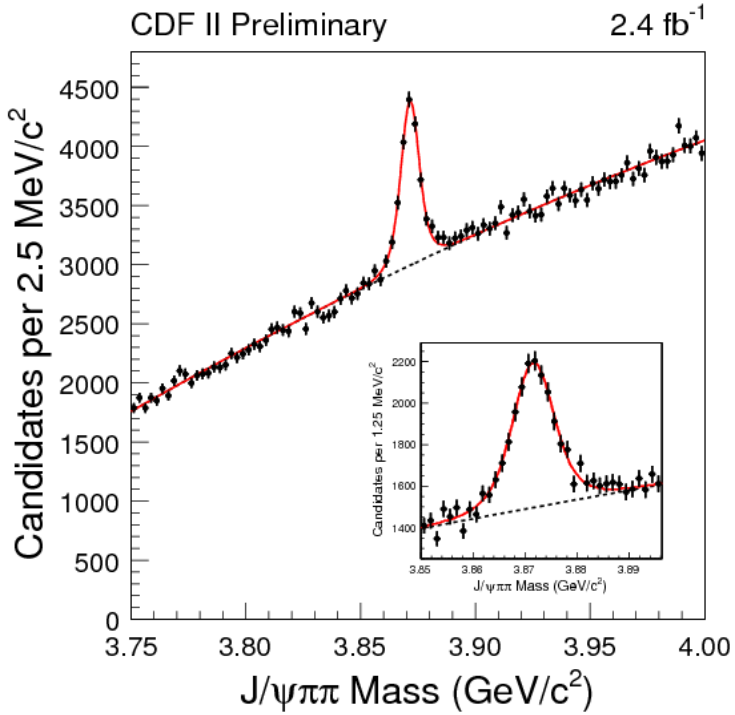


number of candidates per event <= 3

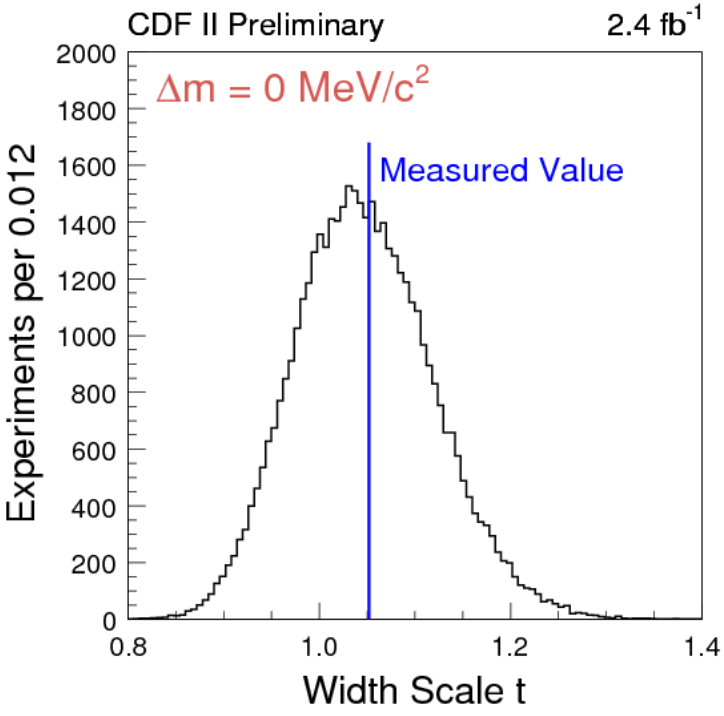


select around 34500 $\psi(2S)$ and 6000 X(3872) signal events

Mass Shape Study



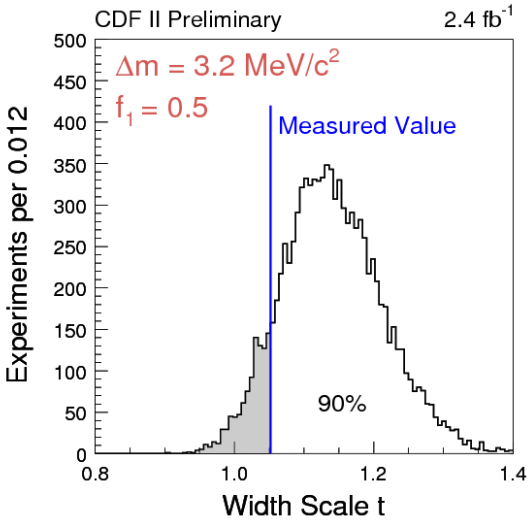
- mass shape described by BW function convolved with Gaussian resolution (BW width and resolution fixed)
- signal width scaling parameter t as free parameter in the fit

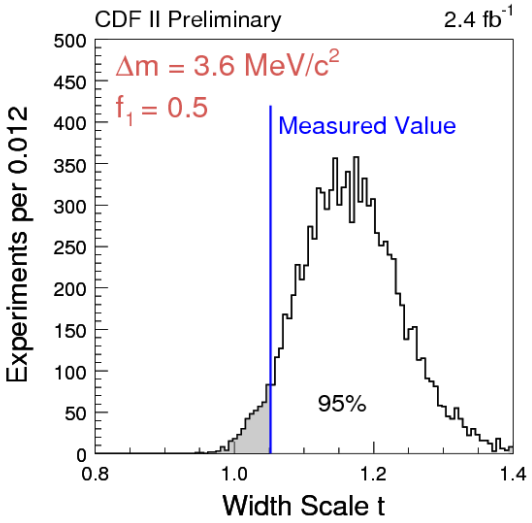


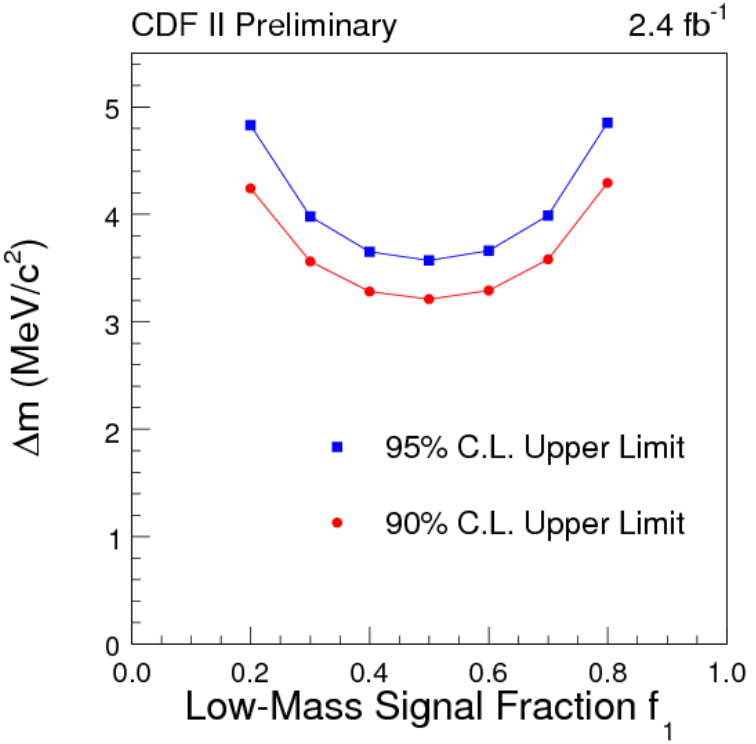
- compare with ensemble of simulated experiments assuming single state
- no evidence for two states
  → limit on maximum mass difference
- data compatible with single state
  → mass measurement

Limit on Maximum Mass Difference

limit determination by means of simulated ensembles with various mass differences Δm between two possible states





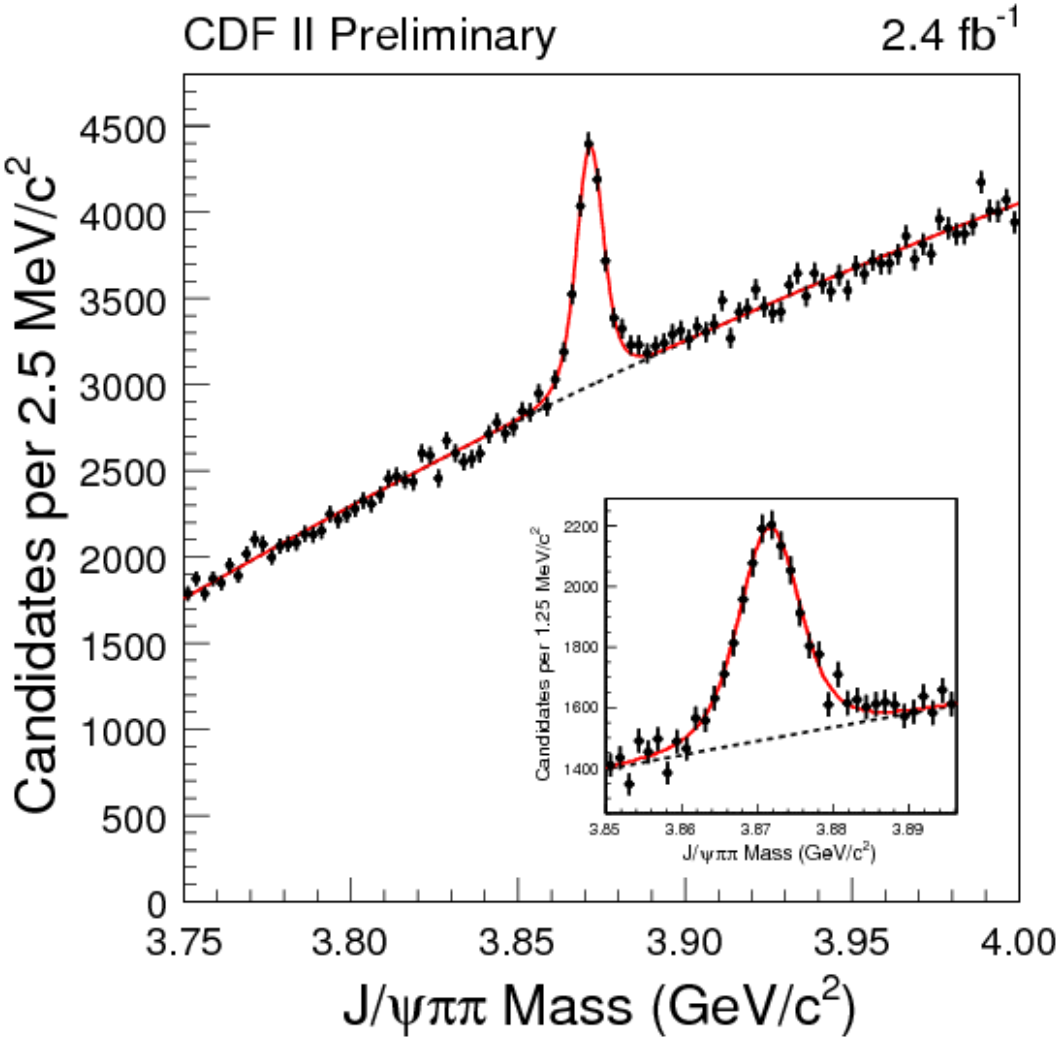


four-quark state hypothesis (model of Maiani et al.):

$$\Delta m = (8 \pm 3)\,\mathrm{MeV/c^2}$$

Mass Measurement

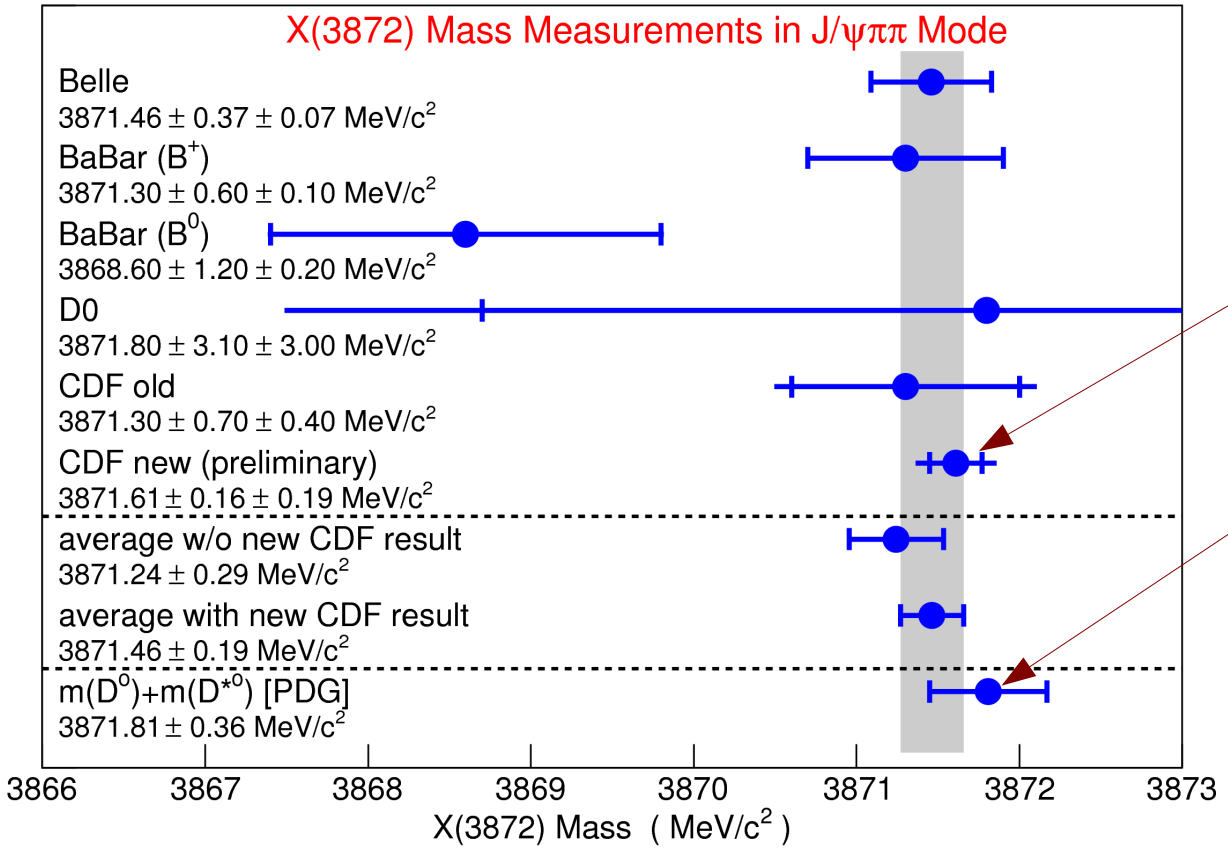
select around 6000 X(3872) signal events in $J/\psi\pi^+\pi^-$ mass spectrum



- unbinned maximum likelihood fit
- signal:
  non-relativistic BW function (width fixed to average value from Babar and Belle) convolved with Gaussian resolution (obtained from simulation)
- background:
  second order polynomial

X(3872) Mass

- momentum scale uncertainty as main source of systematic errors can be estimated by means of $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$
- $m(X(3872)) = 3871.16 \pm 0.16(\mathrm{stat}) \pm 0.19(\mathrm{sys})\,\mathrm{MeV/c^2}$



- most precise mass measurement
- molecular model still possible

Y(4140)

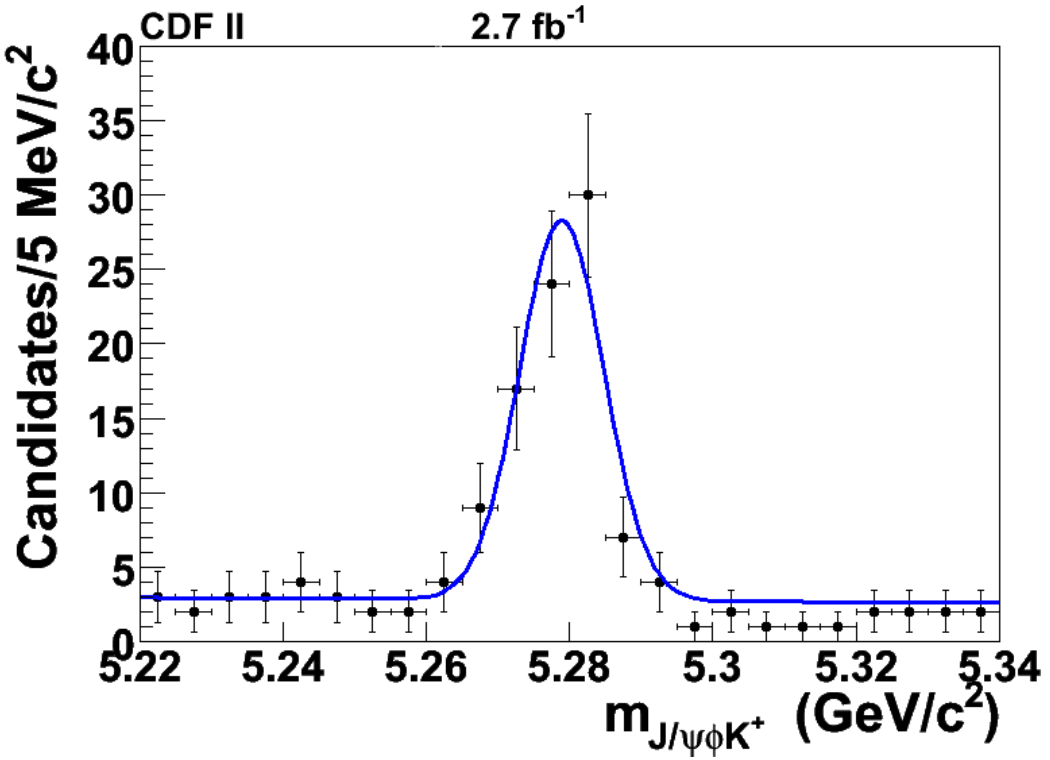
- $J/\psi\phi$ good channel for exotic meson search
  - final state consisting of two vector mesons (like $X(3872) \to J/\psi\rho(\omega)$ and $Y(3930) \to J/\psi\omega$)
  - invariant mass high enough for open charm decays $\longrightarrow$ charmonium state unlikely

- search near $J/\psi\phi$ threshold motivated by closeness of Y(3930) to $J/\psi\omega$ threshold

- strong background reduction by using exclusive B^+ decays to $J/\psi\phi K^+$

$B^+ \to J/\psi\phi K^+$ Selection

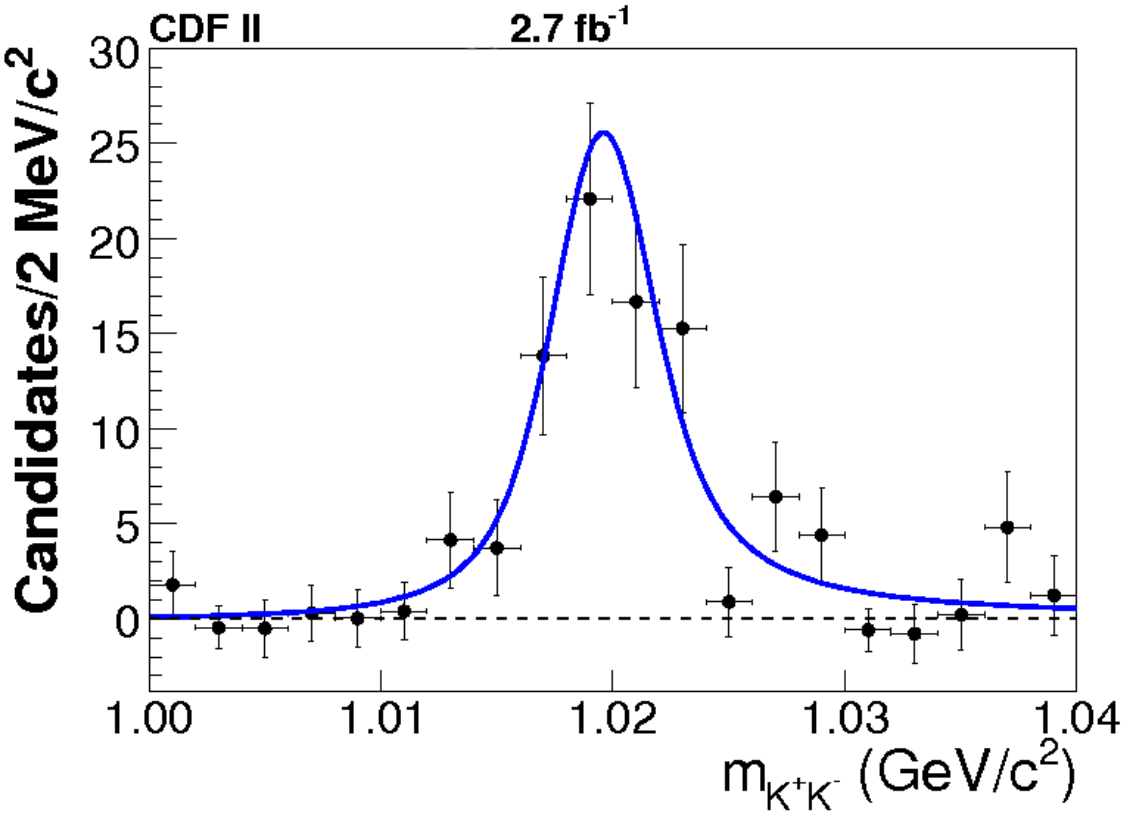
- reconstruct $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$, additional kaon track
- cut on decay length in the transverse plane because of long *B*-meson lifetime: $L_{xy}(B^+) > 500\,\mu\mathrm{m}$
- use *dE/dx* and ToF information summarized in log-likelihood ratio for kaon identification



- fit to data with Gaussian signal and linear background function
- B^+ signal of 75±10 events is largest sample to date
- select candidates ±3σ (17.7 MeV/c^2) around B^+ peak

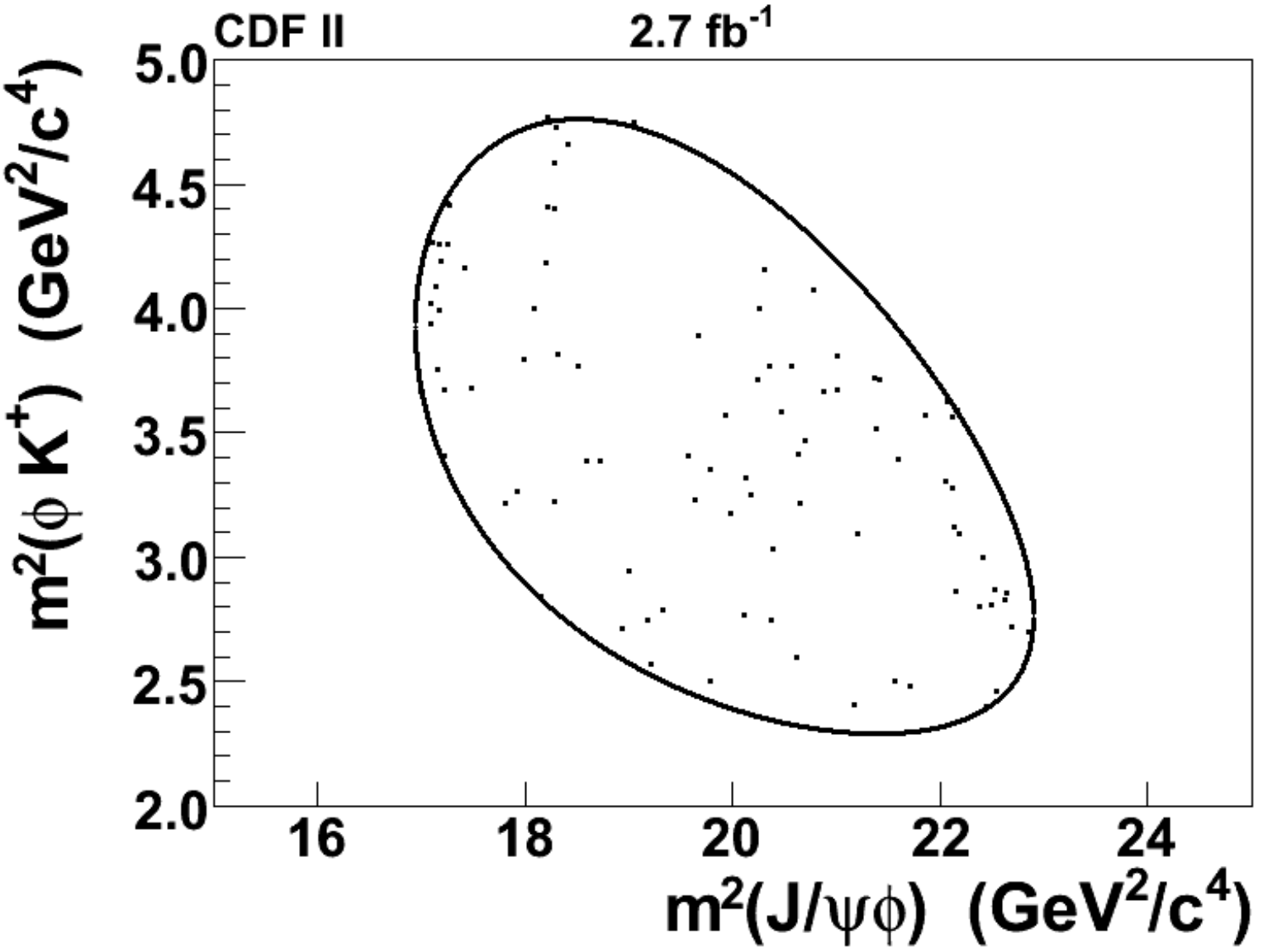
ϕ Mass Spectrum

- B^+ sideband-subtracted without ϕ mass window requirement
- fit function is *P*-wave relativistic BW convolved with Gaussian resolution (obtained from simulation)



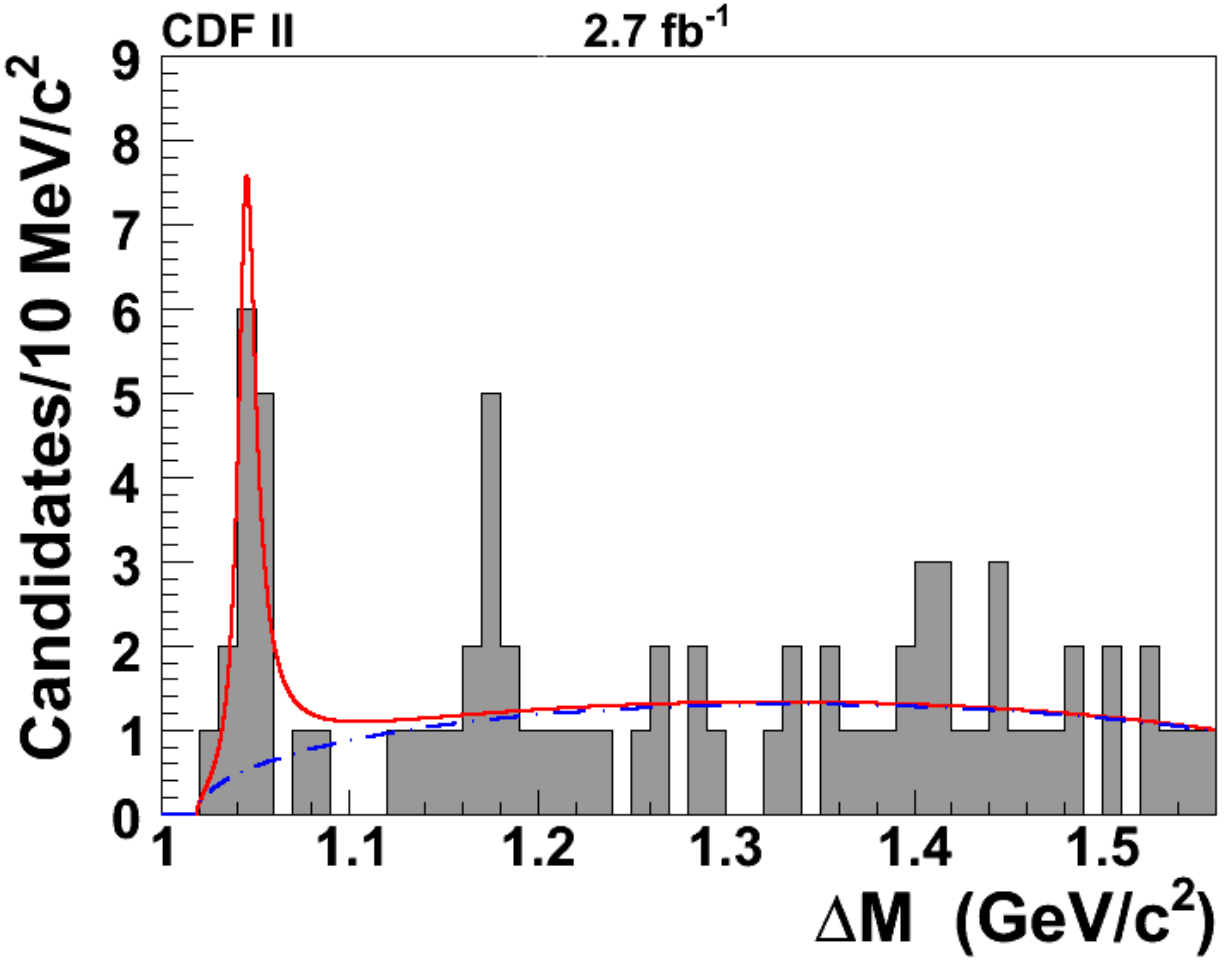
$\longrightarrow$ $B^+ \to J/\psi K^+ K^- K^+$ final state well described as $J/\psi \phi K^+$

Dalitz Plot


CDF II
2.7 fb-1
5.0
4.5
4.0
3.5
3.0
2.5
2.0
m2(φ K+) (GeV2/c4)
16
18
20
22
24
m2(J/ψφ) (GeV2/c4)

$J/\psi\phi$ Mass Spectrum

- $\Delta M = m(\mu^+\mu^- K^+ K^-) - m(\mu^+\mu^-)$
- 73 events with ΔM < 1.56 GeV/c^2



- unbinned likelihood fit
- signal:
  S-wave relativistic BW convolved with Gaussian resolution (fixed to 1.7 MeV/c^2 from MC simulation)
- background:
  three-body phase space
- 14±5 signal events

Evidence for new Structure

- calculate log-likelihood ratio $-2\ln(\mathcal{L}_0/\mathcal{L}_{max})$ of null hypothesis fit and signal hypothesis fit by using pure three-body phase space background
- modeling combinatorial background in B^+ mass window separately as flat spectrum decreases this value
- MC simulations to estimate probability of background fluctuations creating such signal anywhere in the mass window $\longrightarrow$ significance of 3.8σ
- systematic uncertainties estimated by varying the fit model
- $m = 4143.0 \pm 2.9(\mathrm{stat}) \pm 1.2(\mathrm{sys})\,\mathrm{MeV/c^2}$

  using world-average J/ψ mass
- $\Gamma = 11.7^{+8.3}_{-5.0}(\mathrm{stat}) \pm 3.7(\mathrm{sys})\,\mathrm{MeV/c^2}$

Summary

- X(3872) mass shape studies
  - no evidence for two-state hypothesis proposed by four-quark model
  - most precise mass measurement still consistent with model of molecular bound state consisting of $D^0 D^{0*}$ mesons

- evidence for an exotic charmonium-like state $Y(4140) \rightarrow J/\psi\phi$
  - $m = 4143.0 \pm 2.9(\mathrm{stat}) \pm 1.2(\mathrm{sys})\,\mathrm{MeV/c^2}$
  - $\Gamma = 11.7^{+8.3}_{-5.0}(\mathrm{stat}) \pm 3.7(\mathrm{sys})\,\mathrm{MeV/c^2}$