# Hidden Charm Spectroscopy from Tevatron

## Observation of the $Y(4140)$ in $J/\psi\,\phi$ from $B^+ \to J/\psi\,\phi\,K^+$

Felix Wick
on behalf of the CDF Collaboration

Karlsruhe Institute of Technology

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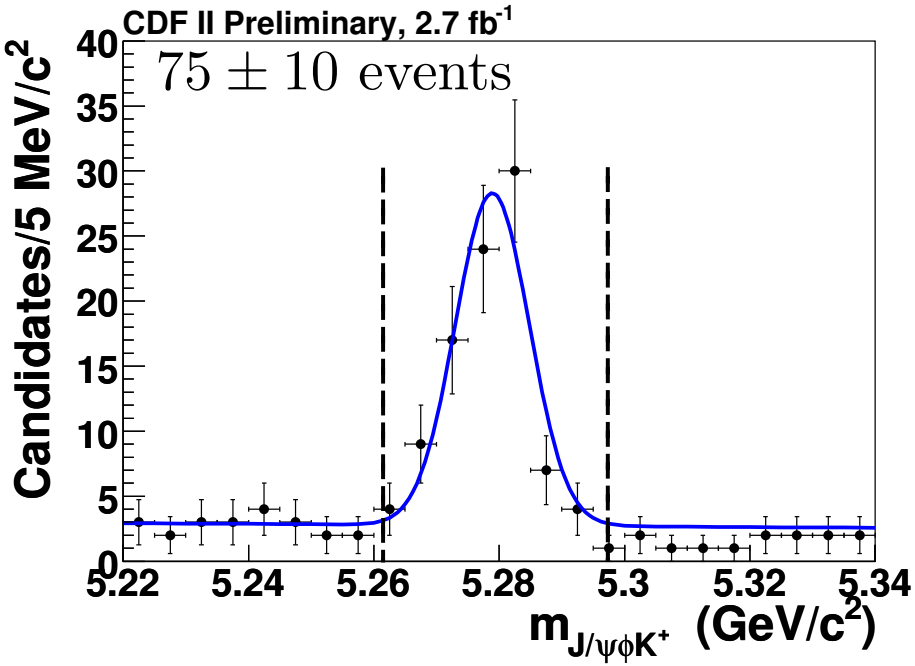
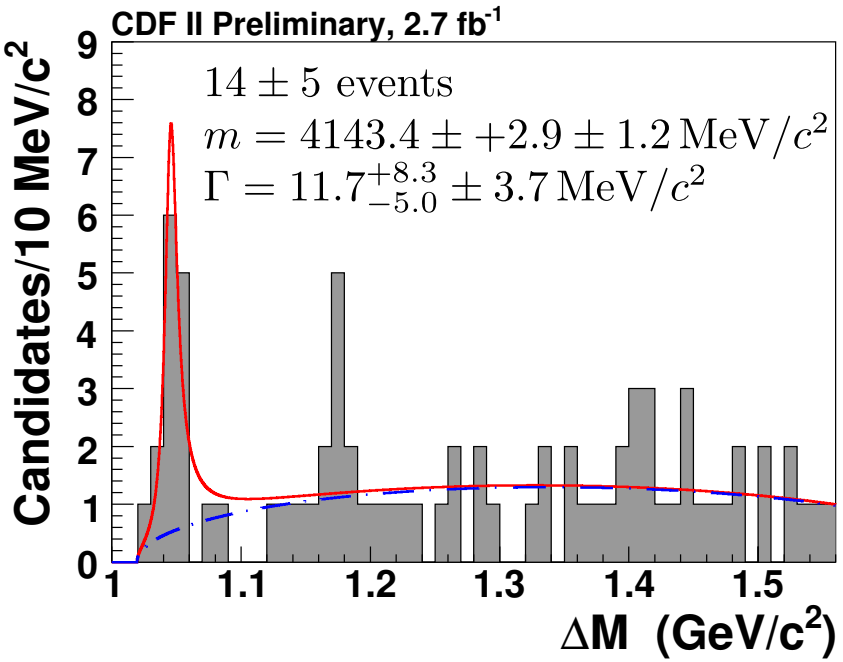
# Motivations

- discovery of several states with charmonium-like decays but unexpected properties ($XYZ$) in recent years
- possibly explained by exotic models beyond usual mesons
- CDF contributions: first confirmation of Belle's $X(3872)$ with determination of allowed quantum numbers and most precise mass measurement
- $J/\psi\,\phi$ good channel for exotic meson search
  - final state consisting of two vector mesons (positive $C$-parity)
  - invariant mass high enough for open charm decays
  - $\rightarrow$ charmonium state unlikely for narrow structure
- search near $J/\psi\,\phi$ threshold motivated by closeness of $Y(3930)$ to $J/\psi\,\omega$ threshold
- strong background reduction by using exclusive $B^+ \rightarrow J/\psi\,\phi\,K^+$ decays

# $Y(4140)$ Evidence Recap

2009: CDF evidence $(3.8\sigma)$ for narrow $J/\psi\,\phi$ structure at $4140\,\mathrm{MeV}/c^2$ in exclusive $B^+ \to J/\psi\,\phi\,K^+$ decays (PRL 102, 242002)




- no signal seen by Belle $\to$ upper limit on branching ratio:
  $\mathcal{B}(B^+ \to Y(4140)\,K^+,\, Y(4140) \to J/\psi\,\phi) < 6.0 \cdot 10^{-6}\ (90\%CL)$
- important to investigate with larger CDF data sample

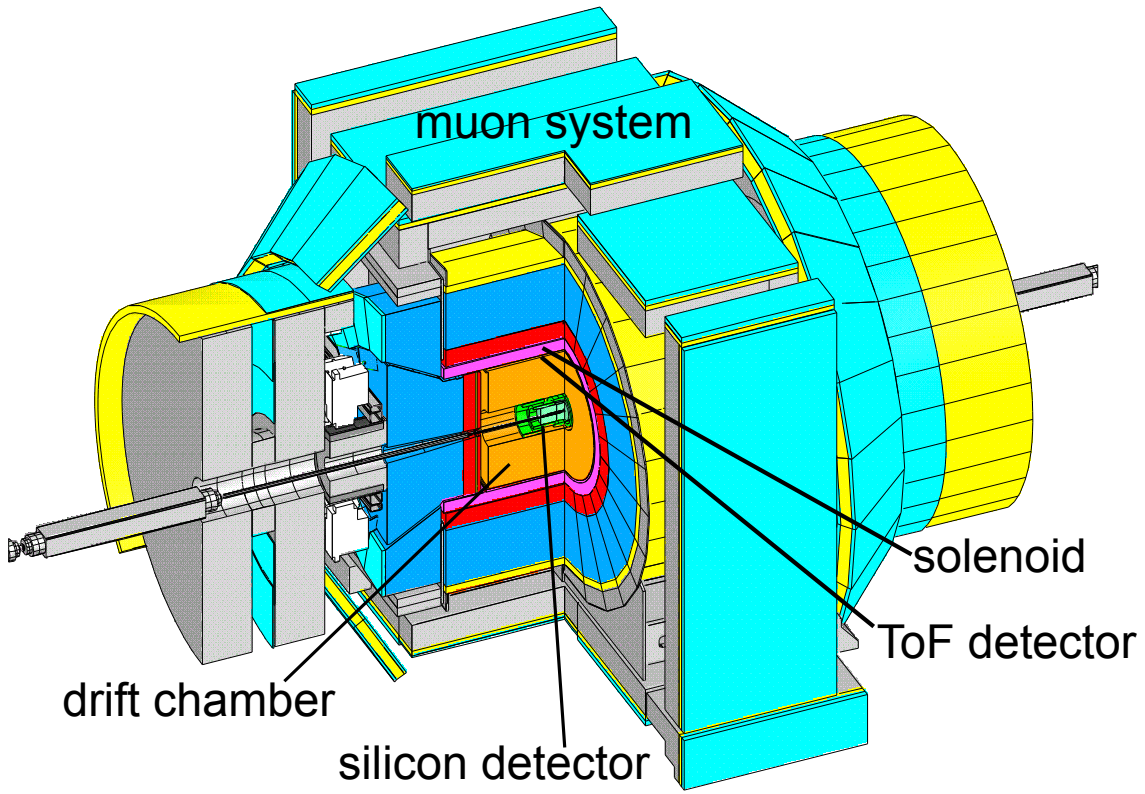
# CDF Experiment at Tevatron

## Tevatron

- $p$-$\bar{p}$ collider
- $\sqrt{s} = 1.96\,\mathrm{TeV}$

## CDF II

- multipurpose detector
- excellent tracking and mass resolution:
  $\frac{\sigma(p_T)}{p_T^2} \approx \frac{0.1\%}{\mathrm{GeV}/c}$
  $30\,\mu\mathrm{m}$ vertex resolution
- $K/\pi$ separation power $\approx 1.5\sigma$

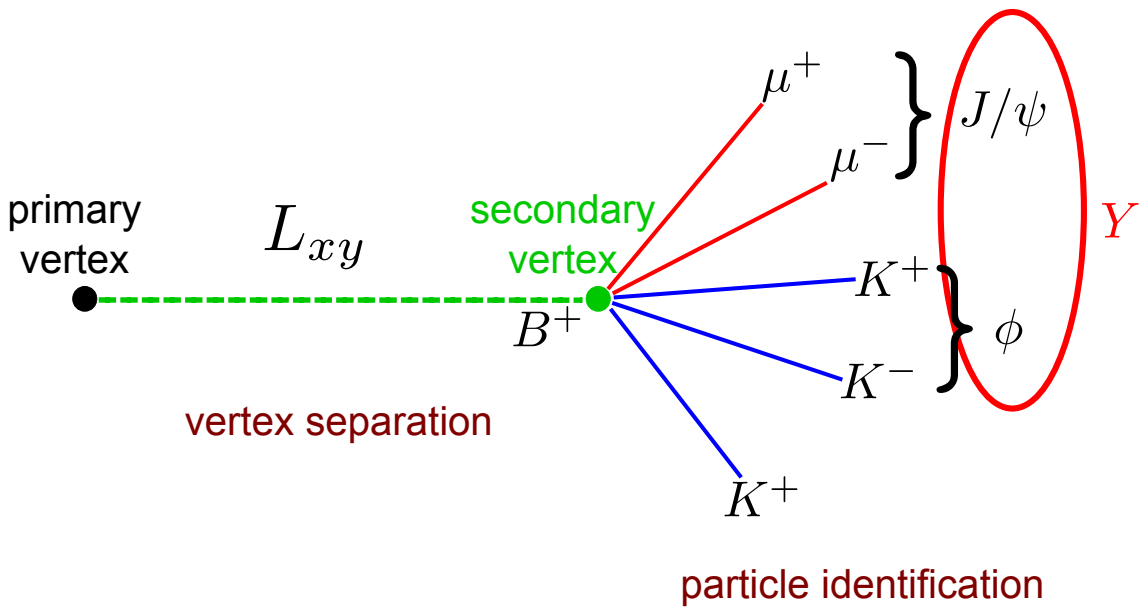


# Analysis Strategy

- Dimuon Trigger requires $\mu^+\mu^-$ pair with invariant mass $2.7\,\mathrm{GeV}/c^2 < m(\mu^+\mu^-) < 4.0\,\mathrm{GeV}/c^2$
- use integrated luminosity of $6.0\,\mathrm{fb}^{-1}$
  (no linear increase of sample size due to trigger prescales)
- $B^+$ reconstruction:
  $B^+ \to J/\psi\,\phi\,K^+$
  $J/\psi \to \mu^+\,\mu^-$
  $\phi \to K^+\,K^-$
- $\pm 50\,\mathrm{MeV}/c^2$ $J/\psi$ mass window, $\pm 7\,\mathrm{MeV}/c^2$ $\phi$ mass window
- search for structure in $J/\psi\,\phi$ spectrum inside $B^+$ mass window

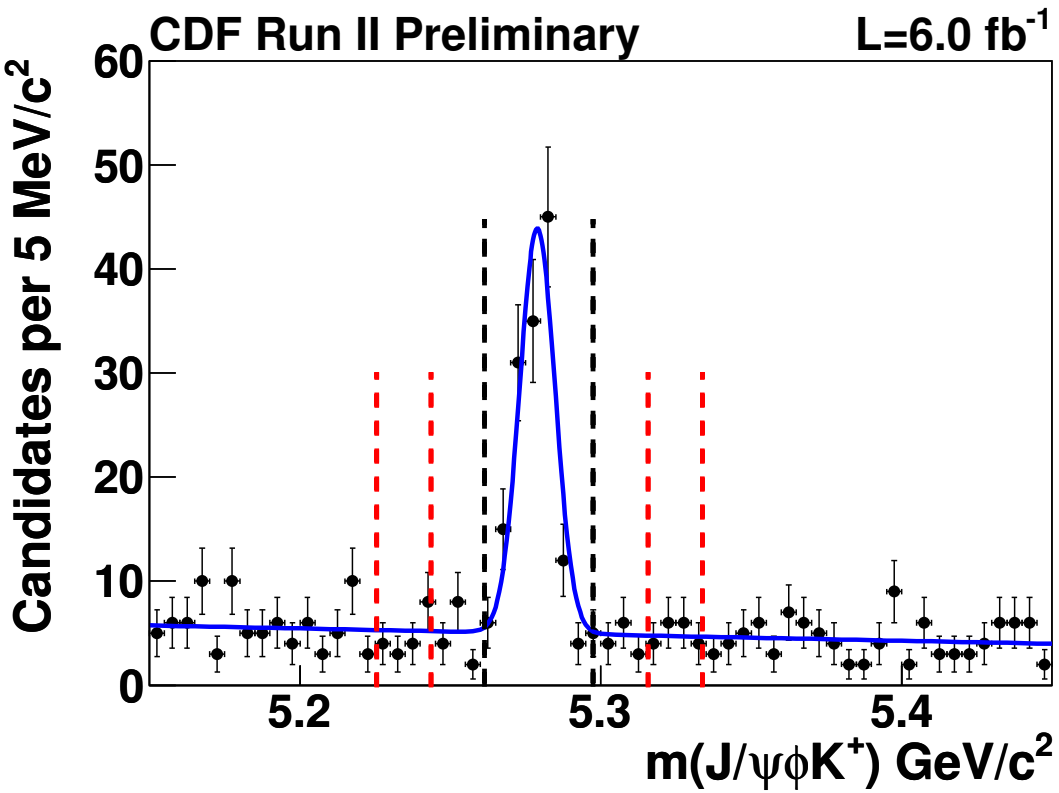
# $B^+$ Selection

- cut on transverse decay length because of long $B$-meson lifetime:
  $L_{xy}(B^+) > 500\,\mu\mathrm{m}$
  $\rightarrow$ reduction of prompt combinatorial background
- use $dE/dx$ and $ToF$ information summarized in log-likelihood ratio for kaon identification ($3$ final state kaons)
  $\rightarrow$ separation from dominant pion background
- background reduction of factor $20000$ after both cuts



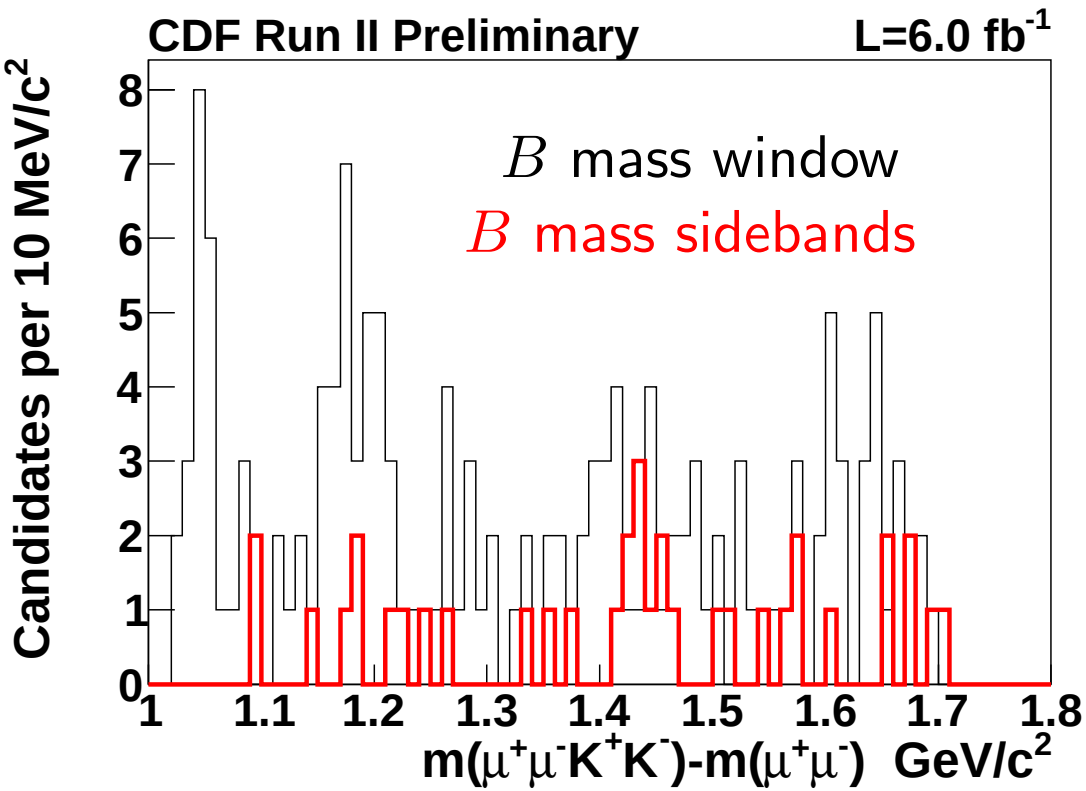
# $B^+$ Signal

- fit to data with Gaussian signal and linear background function
- $B^+$ signal of $115 \pm 12$ events ($53\%$ increase over evidence report)
- select candidates $\pm 3\sigma$ ($17.7\,\mathrm{MeV}/c^2$) around $B^+$ peak
- sideband events within $[-9,-6]\sigma$ or $[+6,+9]\sigma$ of nominal $B^+$ mass (combinatorial background)



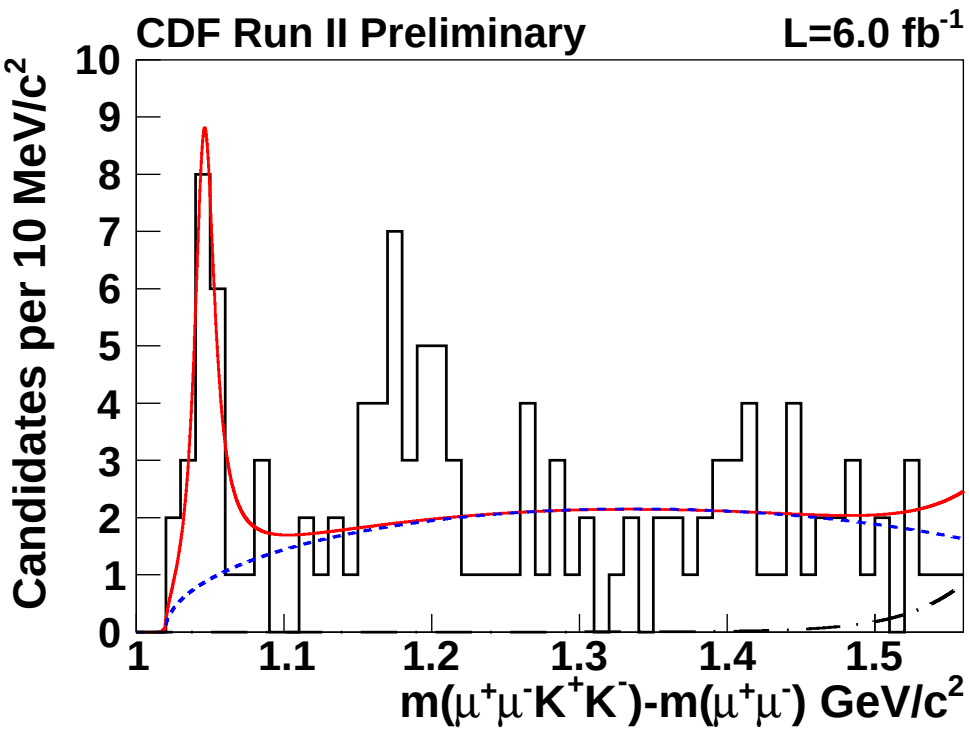
# $J/\psi\,\phi$ Spectrum

- exclude events with $m(\mu^+\,\mu^-\,K^+\,K^-) - m(K^+\,K^-) > 1.56\,\mathrm{GeV}/c^2$ to avoid combinatorial backgrounds from misidentified $B_s^0 \to \psi(2S)\,\phi \to (J/\psi\,\pi^+\,\pi^-)\,\phi$ decays
- narrow near-threshold excess in $B$ mass window
- no evidence from $B$ mass sidebands



# Fit to $J/\psi\,\phi$ Spectrum

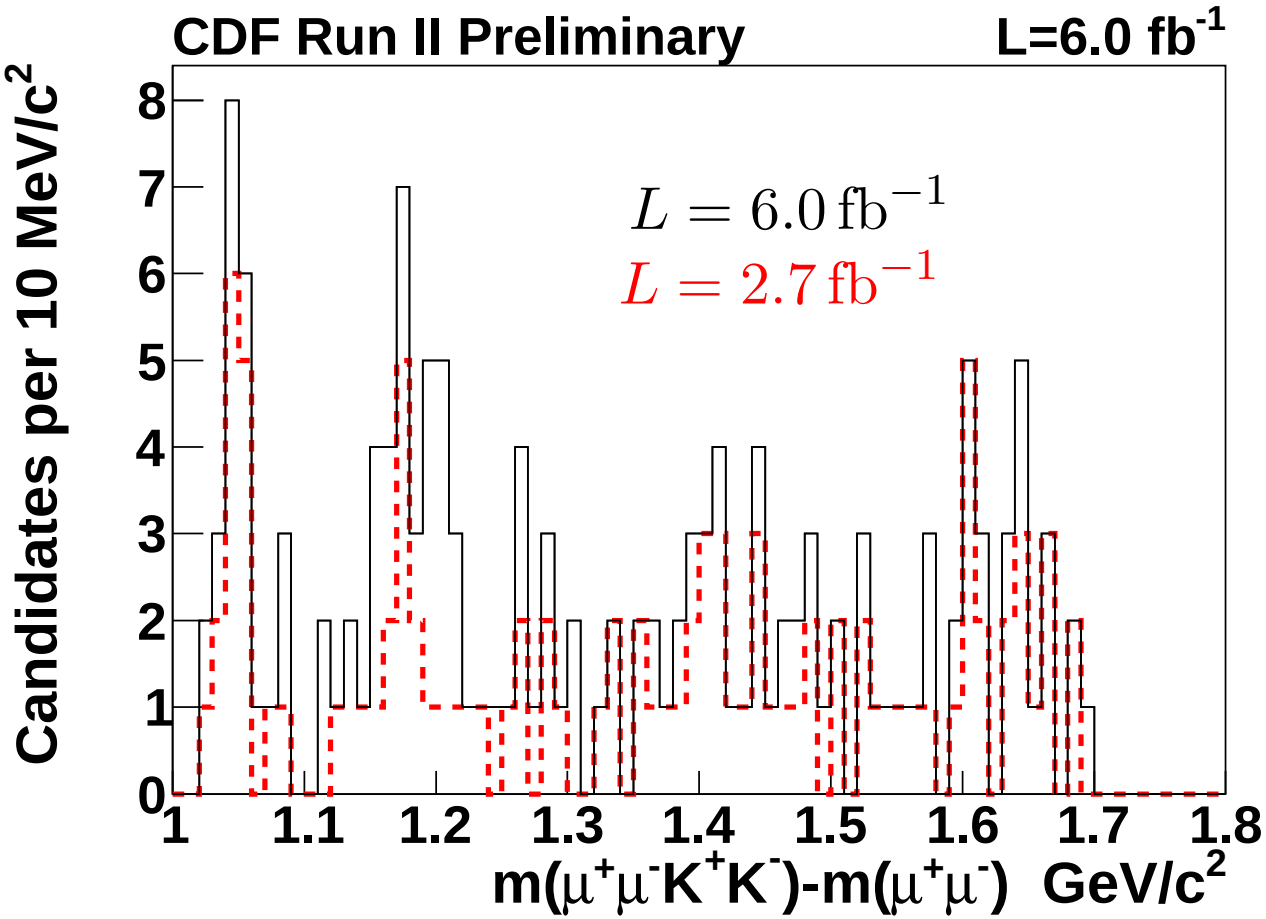
- unbinned likelihood fit
- signal: *S*-wave relativistic Breit-Wigner function convolved with Gaussian resolution ($\sigma = 1.7\,\mathrm{MeV}/c^2$ from Monte Carlo simulation)
- two background components:
  - three-body phase space (dotted blue curve)
  - fixed remaining $B_s$ contribution (dash-dotted black curve)



# Fit Results

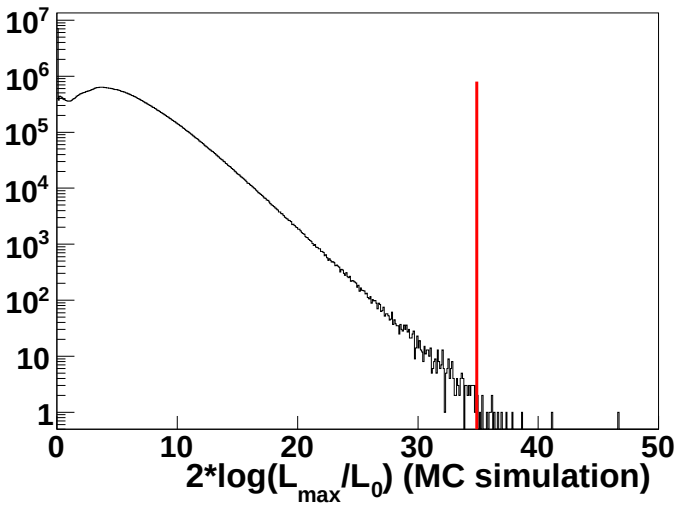
- study of systematic uncertainties by using nonrelativistic and *P*-wave relativistic Breit-Wigner signal shapes
- $19 \pm 6(\mathrm{stat}) \pm 3(\mathrm{syst})$ signal events
- mass (after including world average $J/\psi$ mass):
  $m = 4143.4^{+2.9}_{-3.0}(\mathrm{stat}) \pm 0.6(\mathrm{syst})\,\mathrm{MeV}/c^2$
- decay width: $\Gamma = 15.3^{+10.4}_{-6.1}(\mathrm{stat}) \pm 2.5(\mathrm{syst})\,\mathrm{MeV}/c^2$
  much wider than resolution $(1.7\,\mathrm{MeV}/c^2) \rightarrow$ strong decay
- relative branching fraction:
  $\frac{\mathcal{B}(B^+ \rightarrow Y(4140)\,K^+, Y(4140) \rightarrow J/\psi\,\phi)}{\mathcal{B}(B^+ \rightarrow J/\psi\,\phi\,K^+)} = 0.149 \pm 0.039(\mathrm{stat}) \pm 0.024(\mathrm{syst})$
- mass and width consistent with values from evidence report

# Comparison with $Y(4140)$ Evidence



# Significance Determination

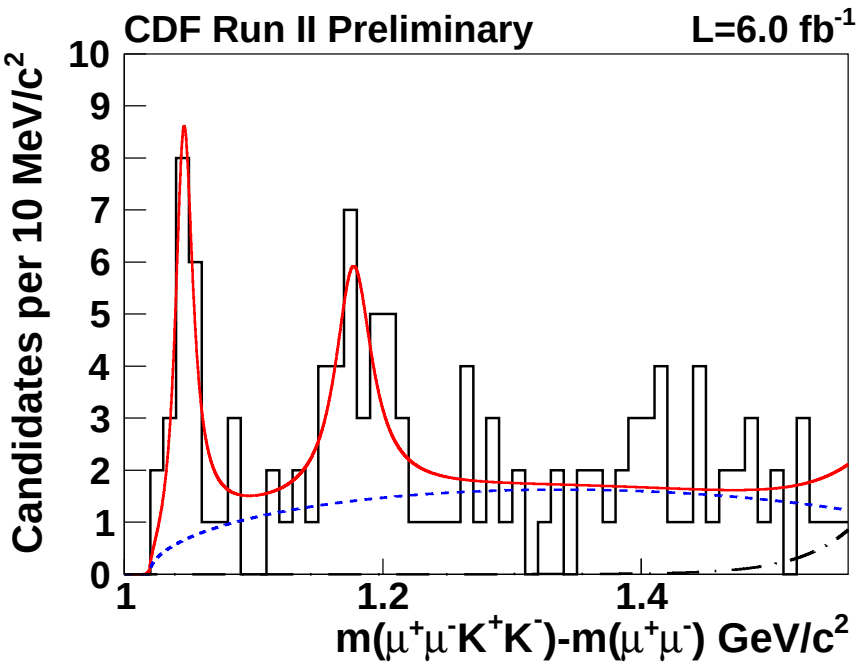
- estimate probability of background fluctuations creating such signal
- calculate log-likelihood ratio $-2\ln(\mathcal{L}_0/\mathcal{L}_{max})$ of null and signal hypothesis fits
- simulate large number of three-body phase space $B^+$ decays
- find most significant fluctuation anywhere in the mass window with $\Gamma = [1.7, 120]\,\mathrm{MeV}/c^2$




- count number of trials with $-2\ln(\mathcal{L}_0/\mathcal{L}_{max}) >$ value in data $\rightarrow$ $p$-value $= 2.3 \cdot 10^{-7}$
- corresponding to significance of $5.0\sigma$ $(n\sigma = \sqrt{2} \cdot \mathrm{erf}^{-1}(1-p))$ $\Rightarrow$ observation

# Additional Structure?

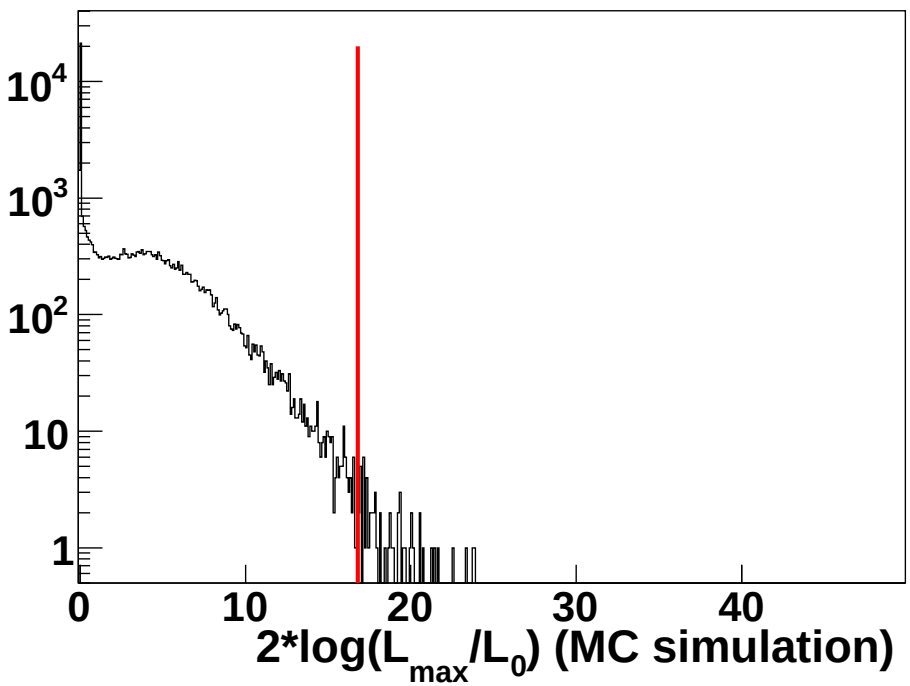
- fix $Y(4140)$ parameters
- second peak: $S$-wave relativistic Breit-Wigner function convolved with Gaussian resolution ($\sigma = 3.0\,\mathrm{MeV}/c^2$)
- two background components:
  - three-body phase space (dotted blue curve)
  - fixed remaining $B_s$ contribution (dash-dotted black curve)




- $22 \pm 8(\mathrm{stat})$ signal events
- $m = 4274.4^{+8.4}_{-6.7}(\mathrm{stat})\,\mathrm{MeV}/c^2$
- $\Gamma = 32.3^{+21.9}_{-15.3}(\mathrm{stat})\,\mathrm{MeV}/c^2$

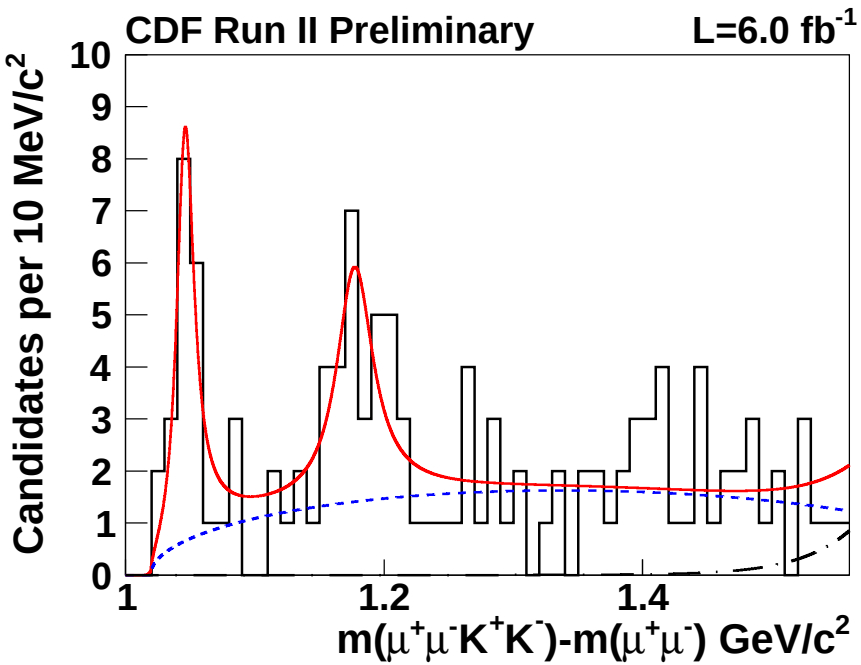
# Significance Determination of Additional Structure

- calculate log-likelihood ratio $-2\ln(\mathcal{L}_0/\mathcal{L}_{max})$ of null hypothesis fit assuming only $Y(4140)$ and signal hypothesis fit
- significance determined by simulations (same method as for $Y(4140)$)
- $p$-value $= 1.1 \cdot 10^{-3}$ corresponding to $3.1\sigma$ significance
  $\Rightarrow$ evidence



# Summary

- CDF contributes to the zoo of $XYZ$ mesons
- observation of $Y(4140)$ in $J/\psi\,\phi$ mass spectrum from $B^+ \to J/\psi\,\phi\,K^+$ decays with more than $5\sigma$ significance
- evidence $(3.1\sigma)$ for second structure at $4275\,\mathrm{MeV}/c^2$
- more data to come ...




http://www-cdf.fnal.gov/physics/new/bottom/100701.blessed-jpsiphi6.0/cdf10244_y4140_public.pdf

# Backup

# Alternative Significance Determination

- fit empirical shape to $-2\ln(\mathcal{L}_0/\mathcal{L}_{max})$ from trials
- $p$-value from integration of fitted shape $1.8 \cdot 10^{-7}$
- consistent with counting method