

Quarkonium Spectroscopy Results at CDF

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Challenges from charmonium-like states

Quark model works pretty well so far

*however, it is **challenged** by newly discovered charmonium-like states*

these states are called X/Y/Z

Outline

CDF experimental aspects

CDF contributions to X/Y/Z before $Y(4140)$

*CDF **new contribution** to X/Y/Z: $Y(4140) \rightarrow J/\psi \phi$*

Strong Points for CDF

Heavy hadrons at Tevatron are:

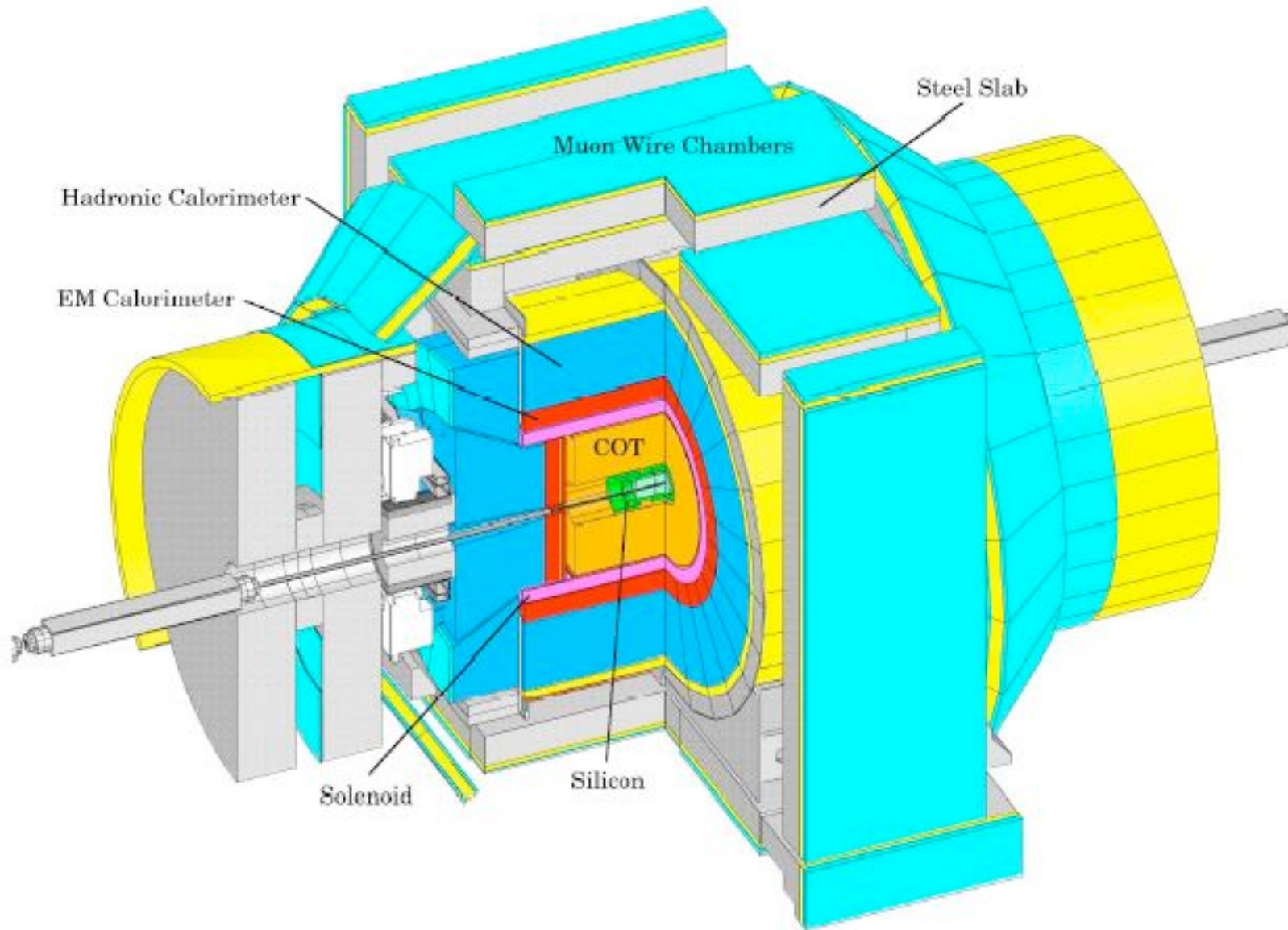
- *copiously produced*
- *boosted*
 - vertex separation
 - boost low p_T daughters

CDF has:

- excellent *mass resolution*
- excellent *vertex resolution*
- reasonable hadron *PID*

CDF detector

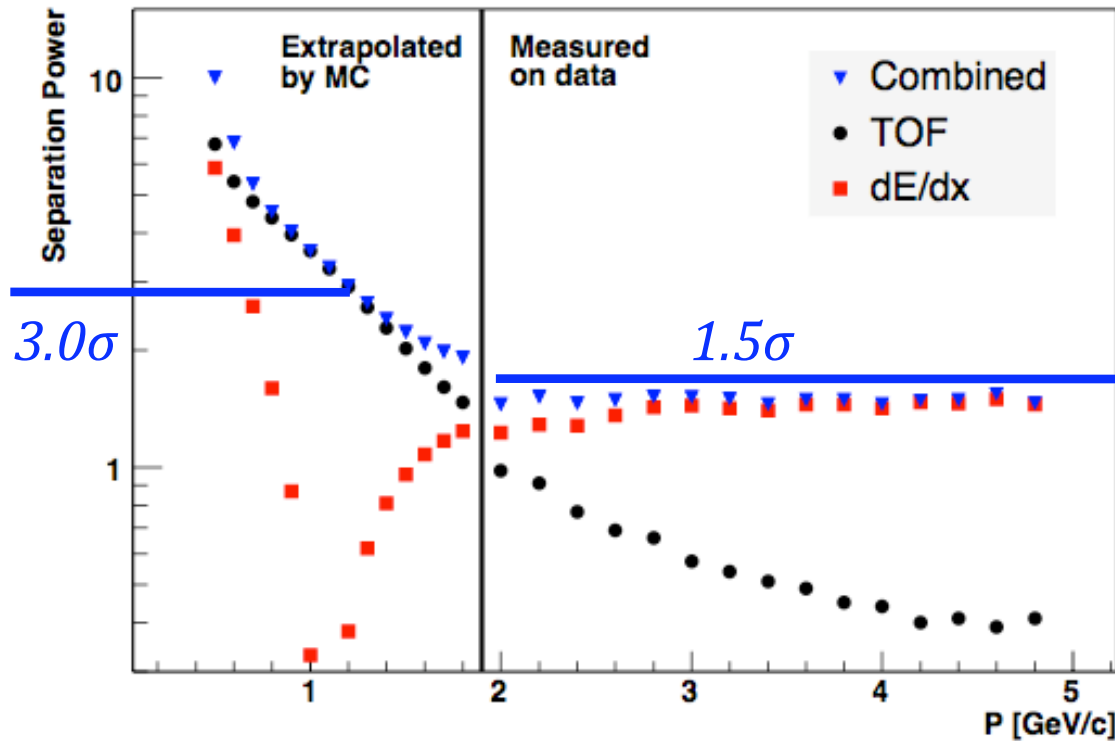
- *Muon: μ ID*
- *ToF: TOF*
- *COT: track p
 dE/dx*
- *Silicon: track p
vertex*



CDF hadron PID

CDF Run II

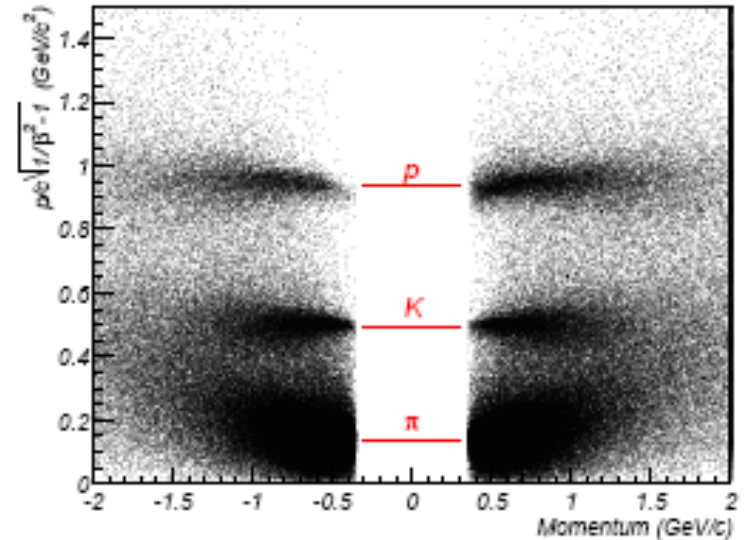
K- π separation



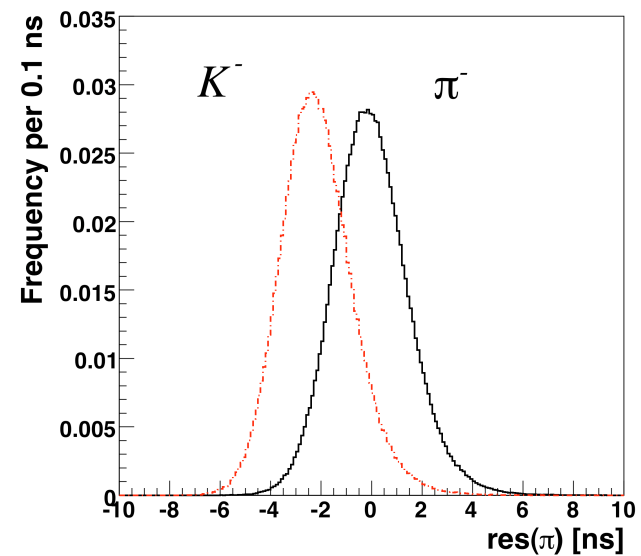
*summarizing dE/dx and ToF into a
log-likelihood ratio*

*Typical B decay daughter momentum $\sim$ GeV,
Main background: prompt pions*

CDF Time-of-flight—TOF mass



dE/dx residual



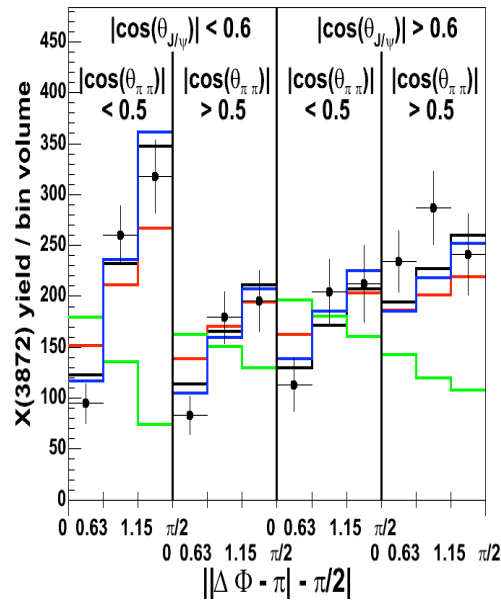
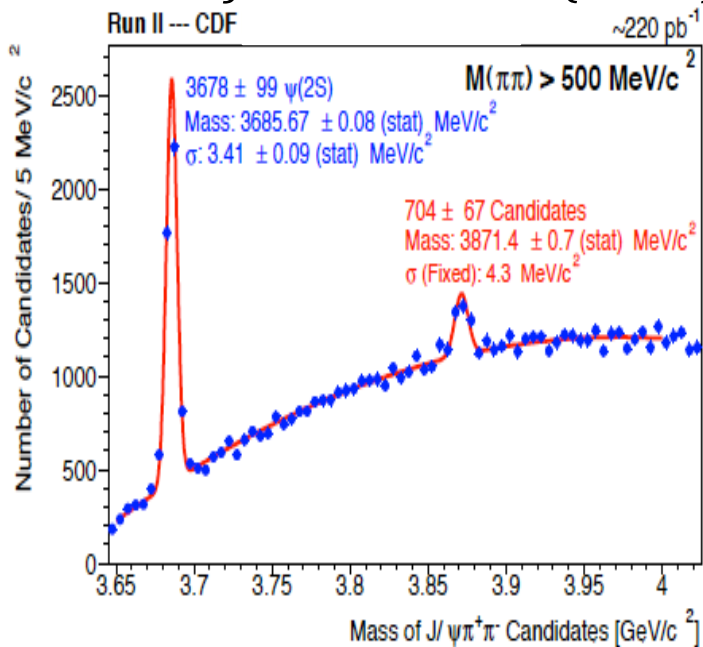
CDF recent contributions to Quarkonium Physics

PRL 93, 072001 (2004),

PRL, 98, 132002 (2007)

First confirmation of X(3872), first J^{PC} determination

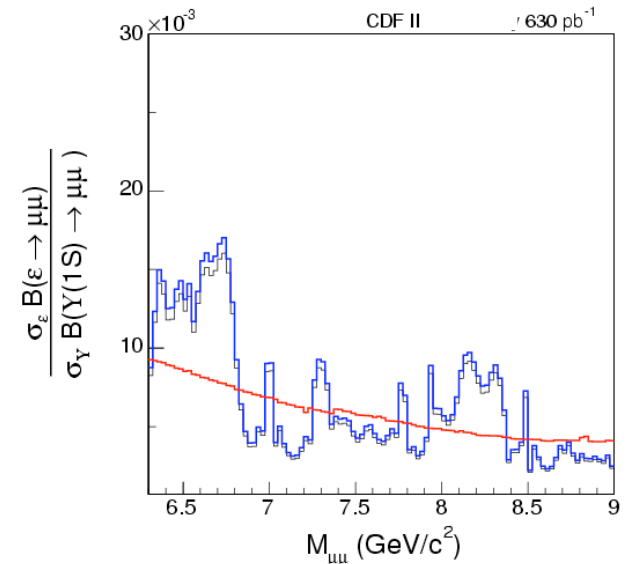
Upper limit for light dimuon resonance



CDF Run II
 $L \approx 780 \text{ pb}^{-1}$

X(3872)
• data points
acc. corrected
prediction for

0^{++}
 1^{--}
 1^{++}
 2^{+-}



Most precise mass measurement of X(3872): PRL, 103, 152001 (2009)

$m(X(3872)) = 3871.61 \pm 0.16 \text{ (stat)} \pm 0.19 \text{ (syst)} \text{ MeV}/c^2$

*What is **new** from CDF?*

*More unexplained states (cc+light quark pair) after X(3872) have been observed,
no (cc+heavy quark pair) reported before CDF's $Y(4140) \rightarrow J/\psi \phi$*

PRL 102, 242002 (2009)

Why search for $J/\psi\phi$?

- *Possibilities of four-quark states, hybrid etc have been proposed*

$J/\psi\phi$

- *extends to heavy quark*
- *reaches for four-quark states*
- *reaches for hybrid*
- *reaches for other possibilities such as nuclear-bound states etc.*

Search through exclusive B decays is experimentally more promising

$B \rightarrow J/\psi\phi K$ decays have been observed

No structure has been reported so far

Analysis strategy

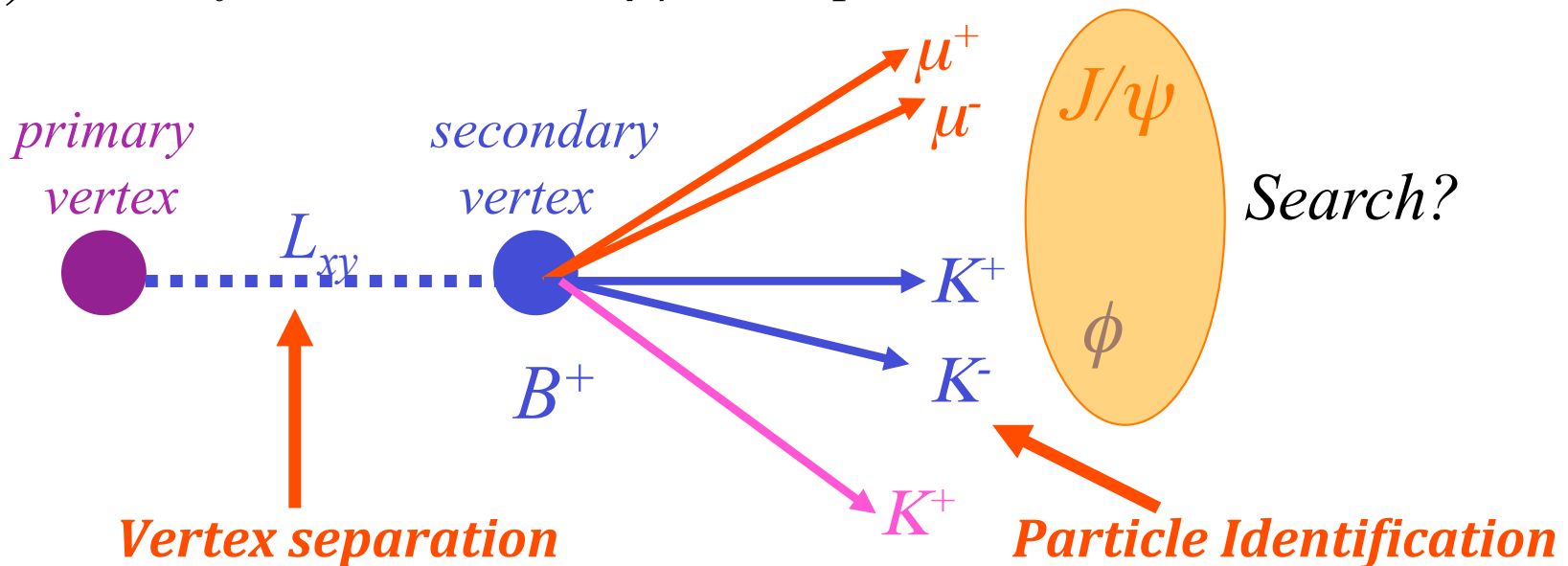
- I) Reconstruct B^+ as:

$$B^+ \rightarrow J/\psi \phi K^+$$

$$J/\psi \rightarrow \mu^+ \mu^-$$

$$\phi \rightarrow K^+ K^-$$

- II) Search for structure in $J/\psi \phi$ mass spectrum inside B^+ mass window

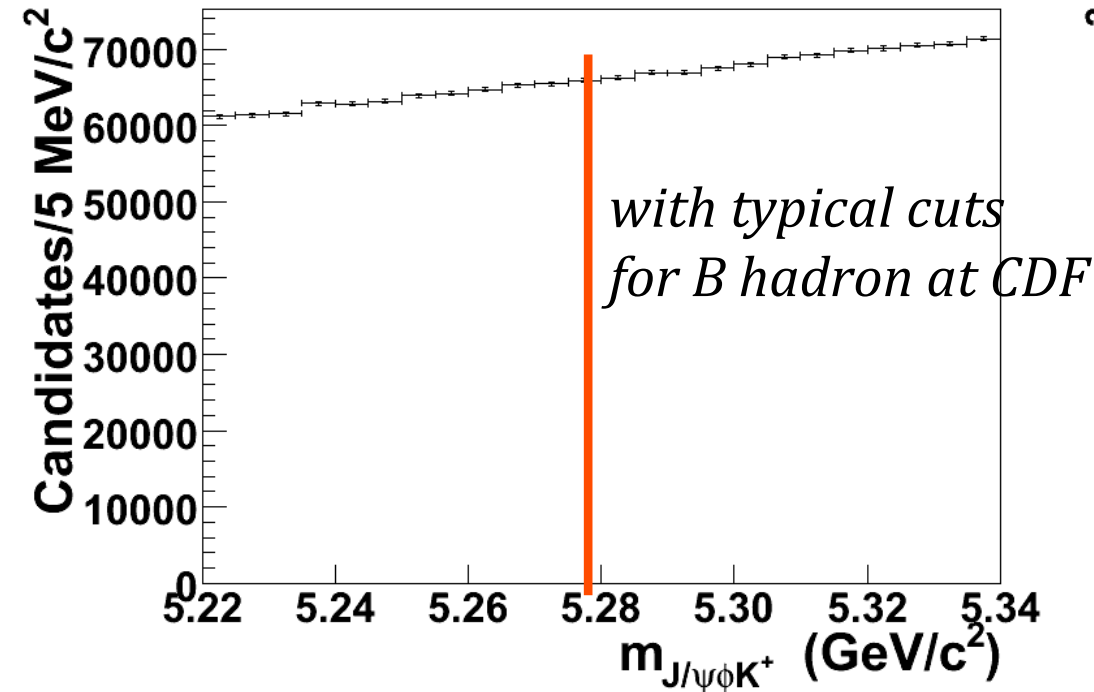


1) Reconstruct $B^+ \rightarrow J/\psi \phi K^+$

The key to reconstruct B signal

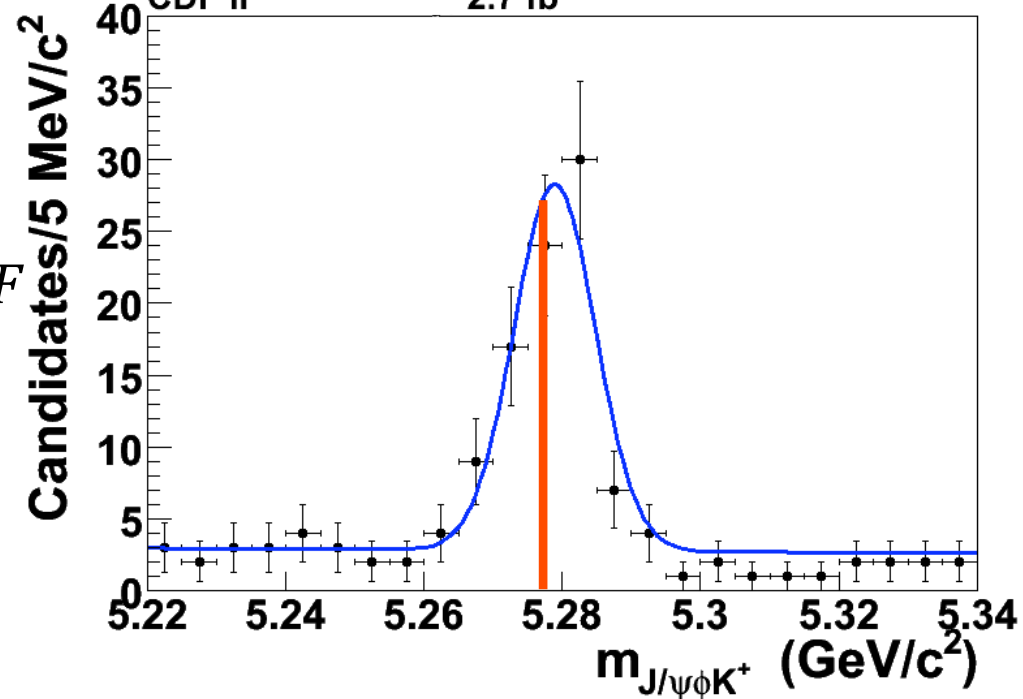
Before $L_{xy} > 500 \text{ um}$, kaon PID > 0.2

CDF II 2.7 fb^{-1}



After $L_{xy} > 500 \text{ um}$, kaon PID > 0.2

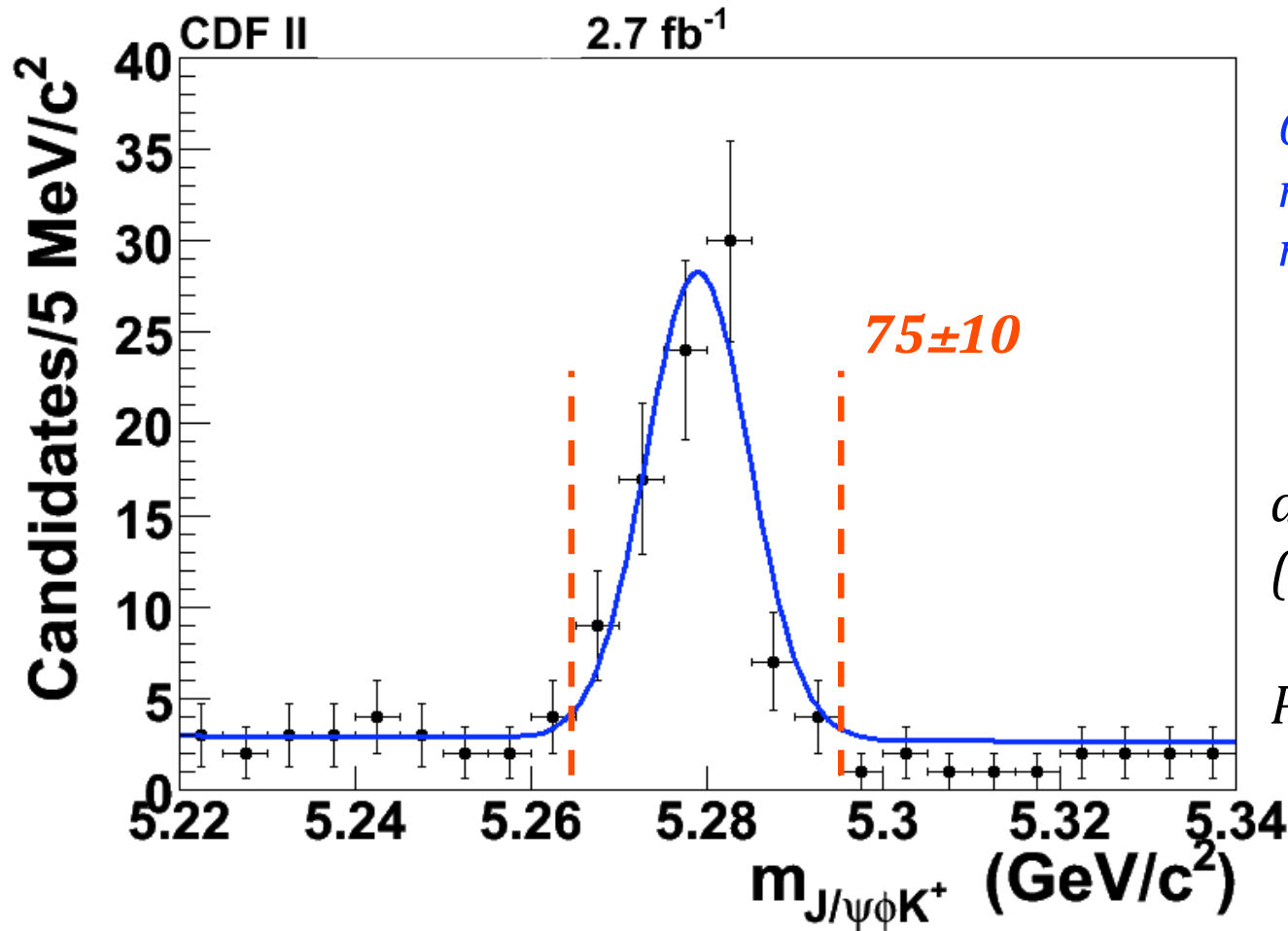
CDF II 2.7 fb^{-1}



Hard to see B signal without L_{xy} and kaon PID

*Reduce background by a factor of **20 000** by using L_{xy} and kaon PID cuts while keeping about **20%** of signal as estimated by control channels.*

Applying L_{xy} and kaon PID



Gaussian function
mean fixed to PDG
rms fixed to resolution (5.9 MeV)

define $\pm 3\sigma$ as B^+ signal region
(17.7 MeV obtained from MC)

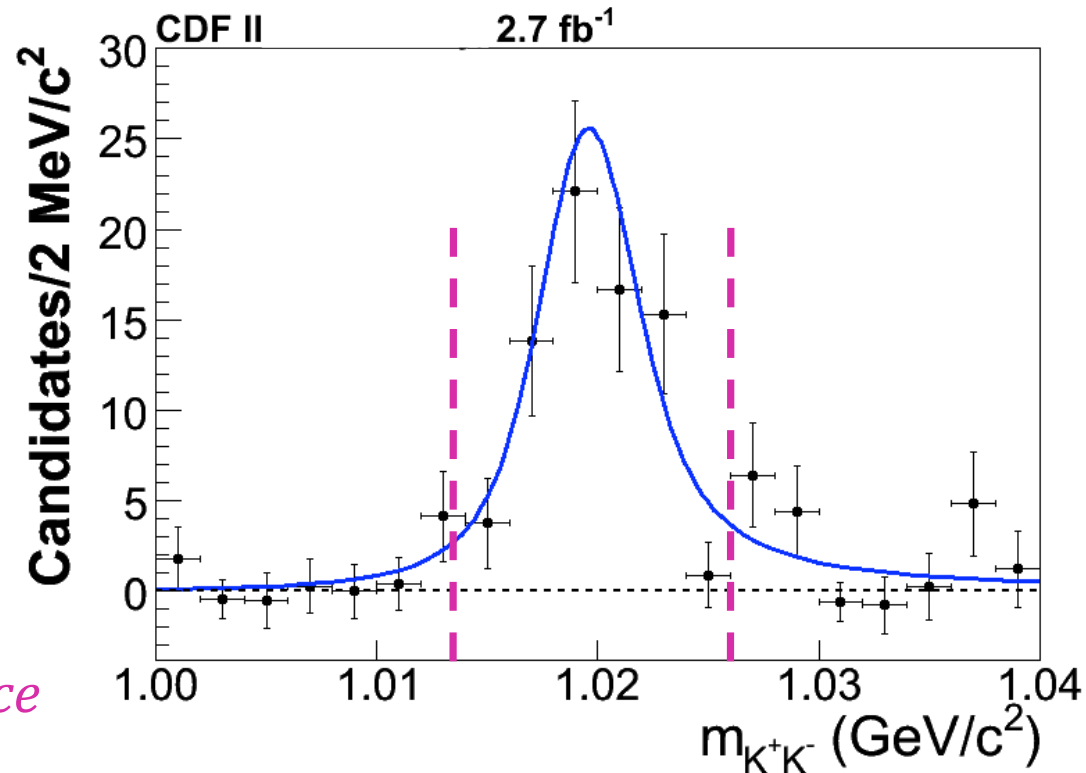
Purity ~80% in B^+ region

Is ϕ pure?

Kaon PID reduce background by a factor of ~100
clear $B^+ \rightarrow J/\psi\phi K^+$ signal

Verify $B^+ \rightarrow J/\psi \phi K^+$

- Investigate components of B^+ peak
 - relax K^+K^- mass window to:
 $[1.0, 1.04] \text{ MeV}$
 - do B^+ sideband subtraction for K^+K^-
 - fit to sideband subtracted K^+K^- mass
- A P -wave relativistic BW only fit to data with χ^2 probability 28%, no evidence for $f_0 \rightarrow K^+K^-$ or K^+K^- phase space components with our ϕ mass window



Conclusion

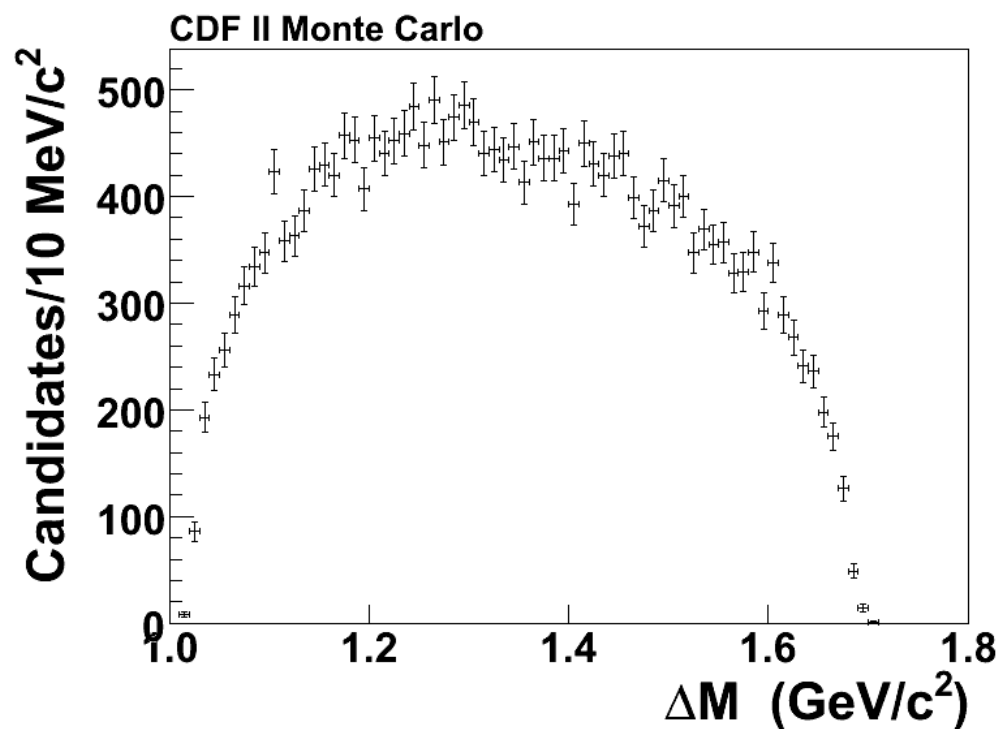
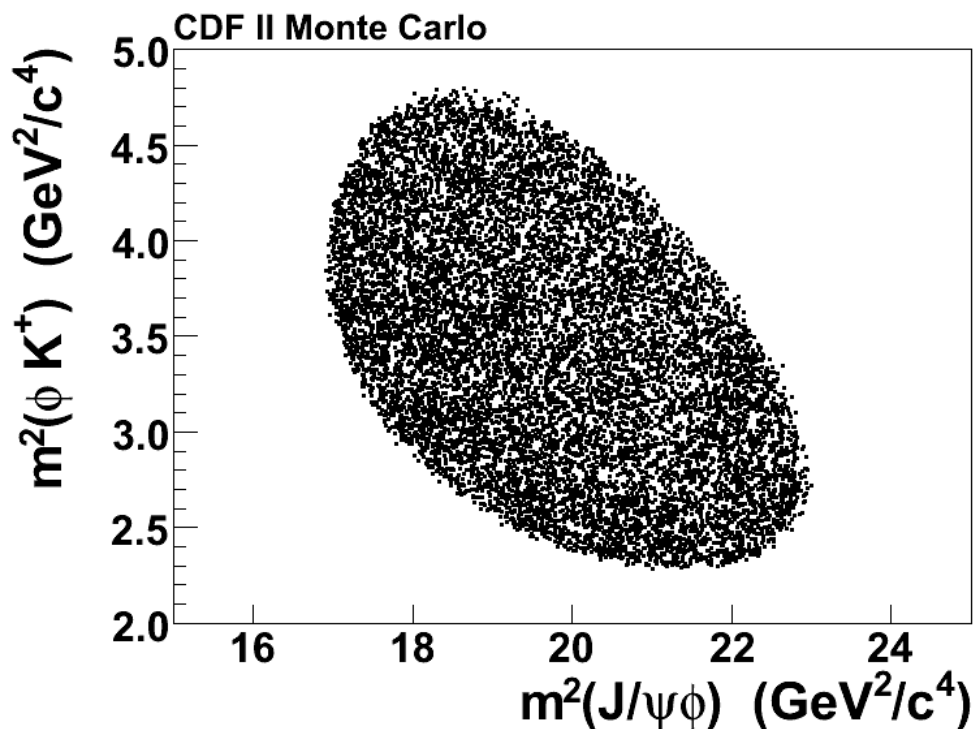
pure $B^+ \rightarrow J/\psi \phi K^+$ for B^+ peak

negligible $B^+ \rightarrow J/\psi f_0 K^+$, $J/\psi K^+ K^- K^+$ components

*II) Search for structures in
 $J/\psi\phi$ spectrum from B*

Investigate $J/\psi\phi$ mass spectrum in MC

- MC simulated phase space, full detector simulation



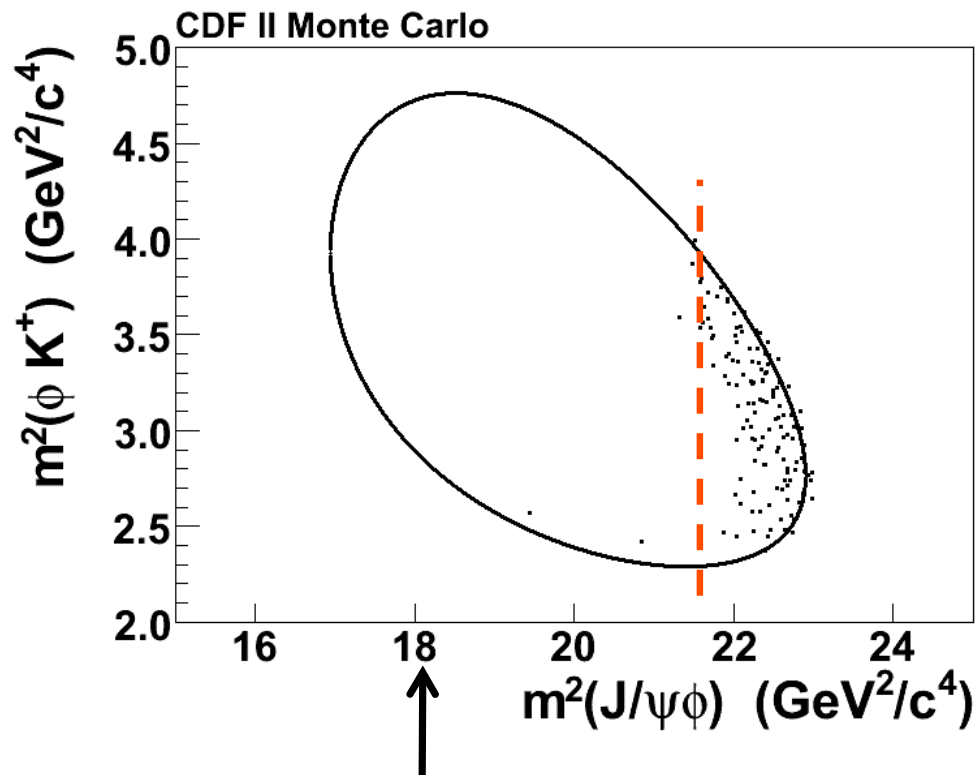
$$\Delta M = m(\mu^+ \mu^- K^+ K^-) - m(\mu^+ \mu^-)$$

- MC events smoothly distributed in Dalitz plot
- No artifacts in the $J/\psi\phi$ mass spectrum

Investigate $J/\psi\phi$ mass spectrum in MC

- We simulate generic B hadron decays with a J/ψ in the final state and we identified a contamination channel: $B_s \rightarrow \psi(2S)\phi$, $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$
PRL. 96, 231801 (2006)

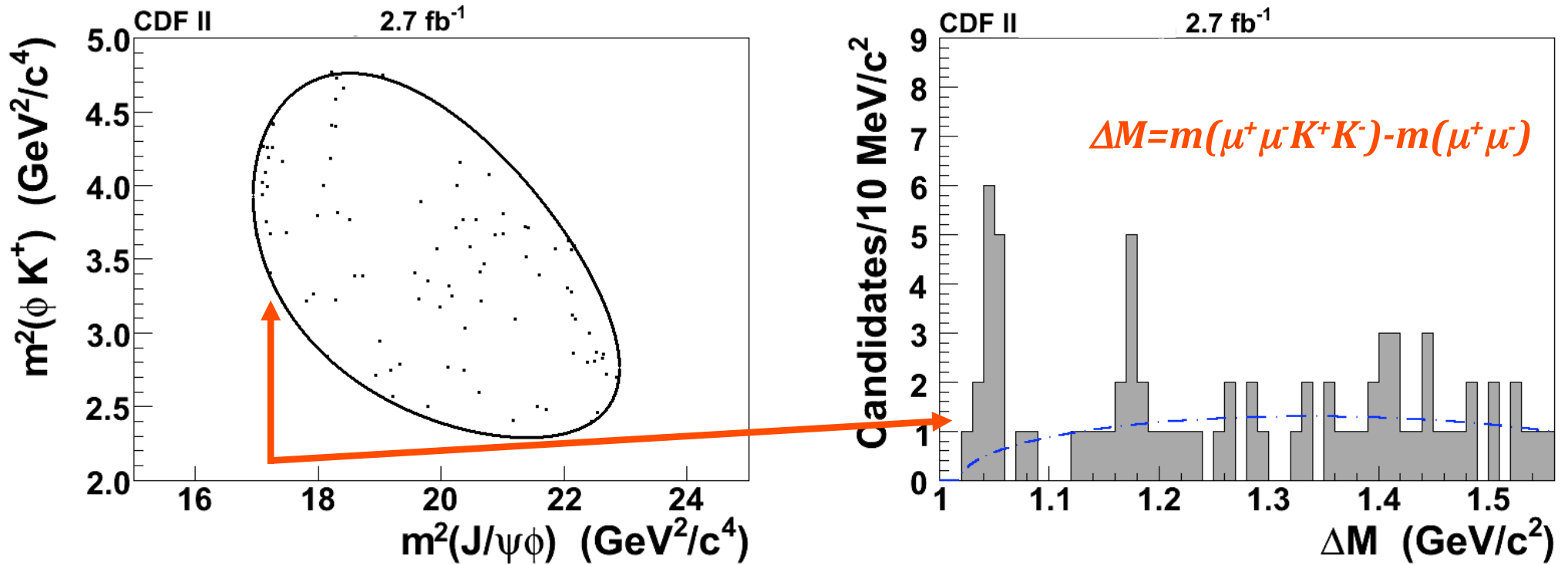
$(B_s \rightarrow \psi(2S)\phi, \psi(2S) \rightarrow J/\psi\pi^+\pi^-) \longrightarrow B^+ \rightarrow J/\psi\phi K^+$ due to kaon mis-identification



20 times Luminosity of data

- B_s contamination at $\Delta M > 1.56 \text{ GeV}$, cut it off for simplification

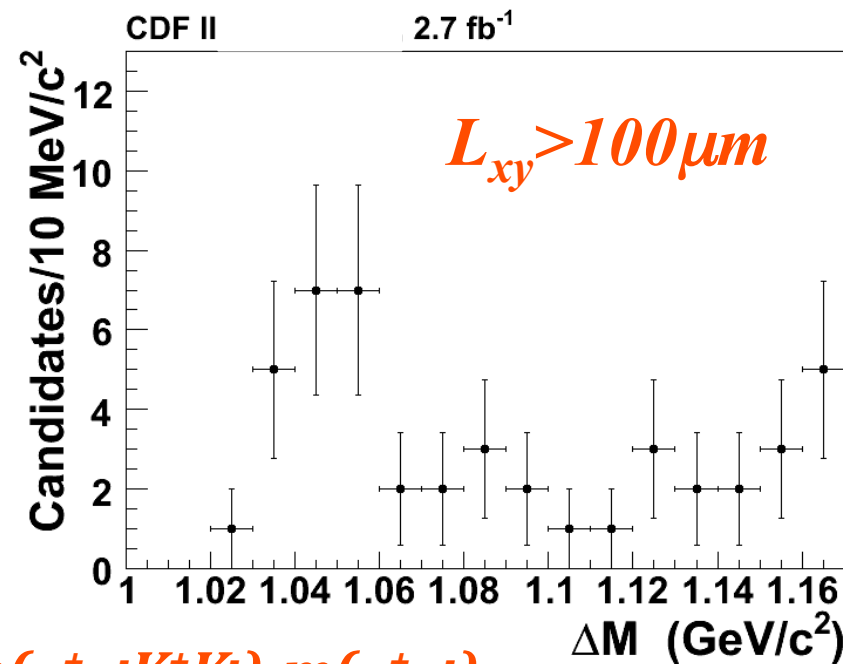
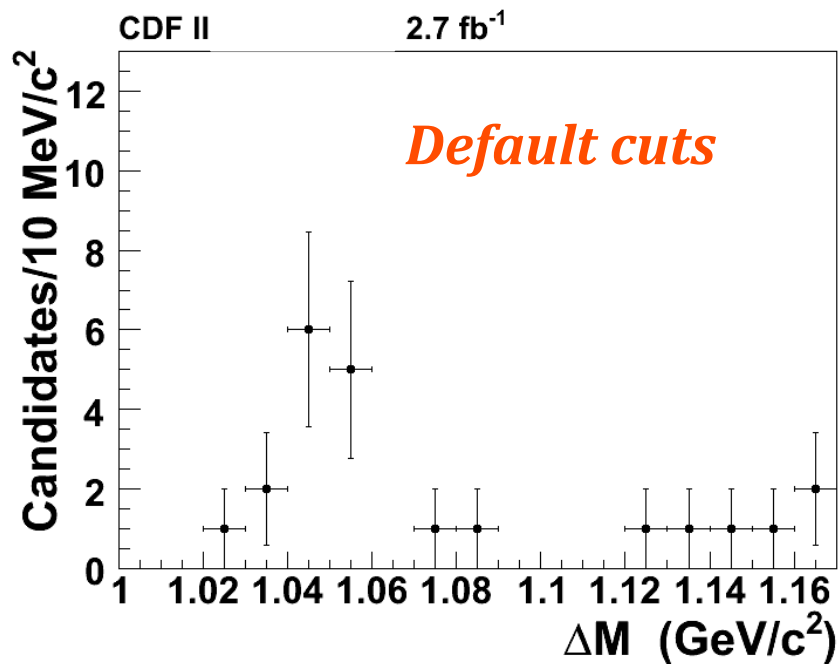
Search for structures in $J/\psi\phi$ mass--Data



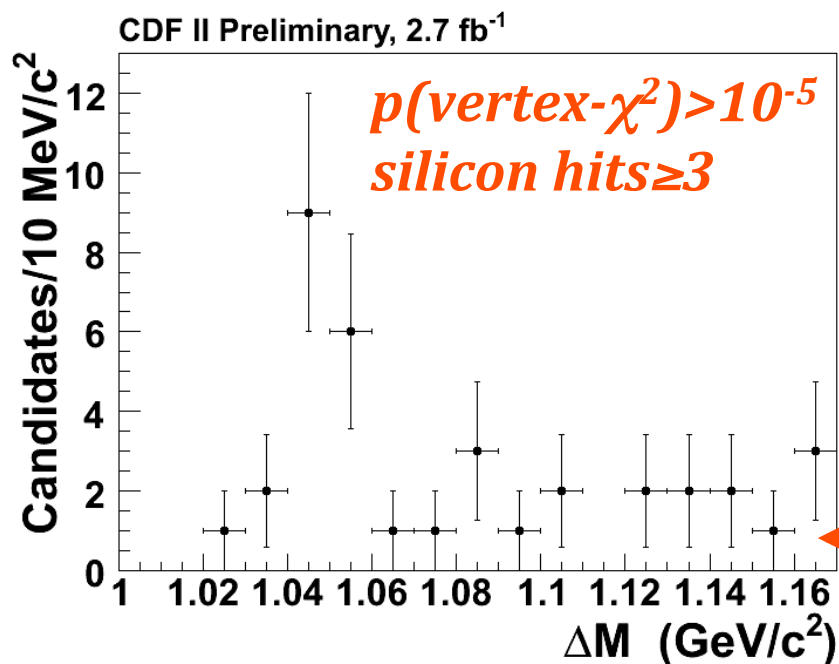
Three-body Phase Space Background shape is different from data

An near threshold enhancement is observed

Robustness test



$$\Delta M = m(\mu^+ \mu^- K^+ K^-) - m(\mu^+ \mu^-)$$

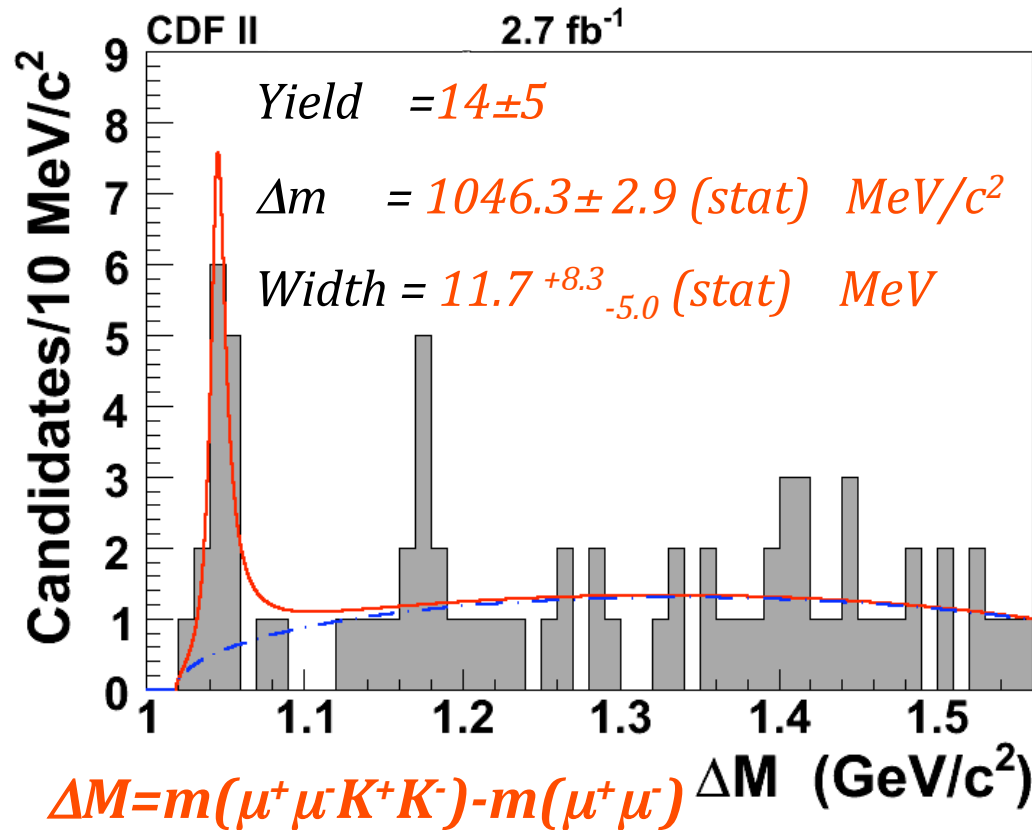


- Extensive cross checks by varying L_{xy} , kaon PID, B^+ mass window, vertex probability, # of silicon hits,...
- Robust against variations*
- More signal but with more background*

Search for structures in $J/\psi\phi$ mass--Data

- We model the Signal (S) and Background (B) as:

S : S -wave relativistic Breit-Wigner B : Three-body decay Phase Space



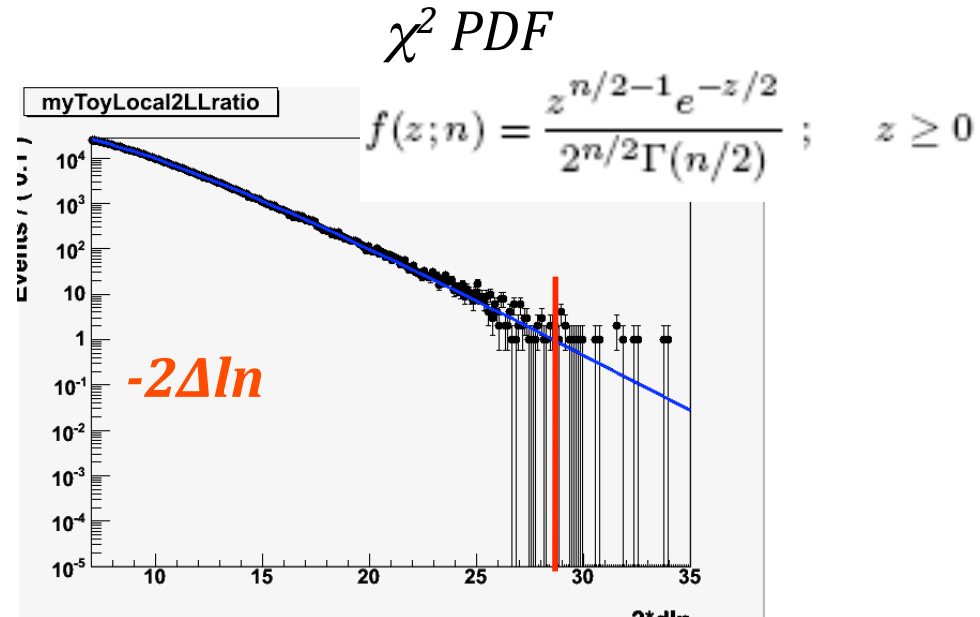
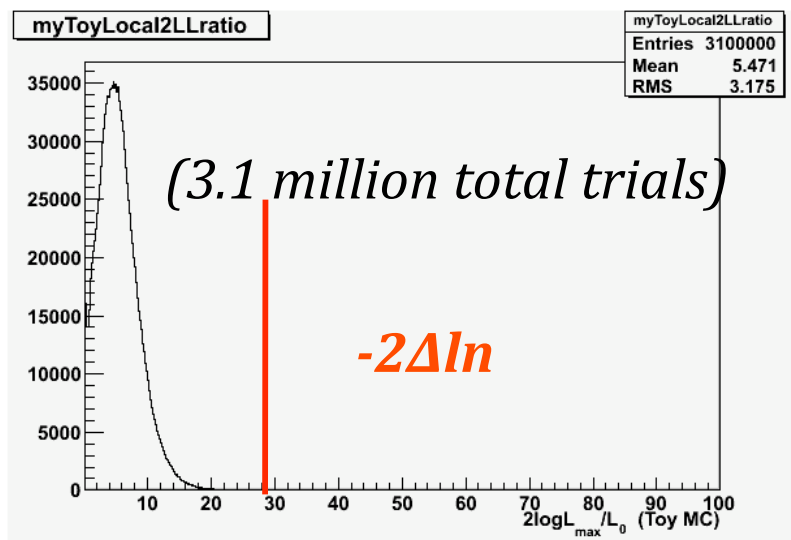
Convolved with resolution
(1.7 MeV)

Mass=:
 $4143.0 \pm 2.9 \text{ (stat)} \pm 1.2 \text{ (syst)} \text{ MeV}/c^2$
 (adding J/ψ mass)

$\sqrt{(-2\log(L_{\max}/L_0))} = 5.3$, need Toy MC to determine significance for low statistics

Significance study

- We determine significance from simulation (Toy MC):
 - Generate Δm spectrum using *Phase Space*
 - Find most significant fluctuation for each trial *anywhere* with *floating width*
 - Count it if $-2\log(L_{\max}/L_0)$ (**$-2\Delta\ln$**) $\geq$ $-2\Delta\ln$ value in data



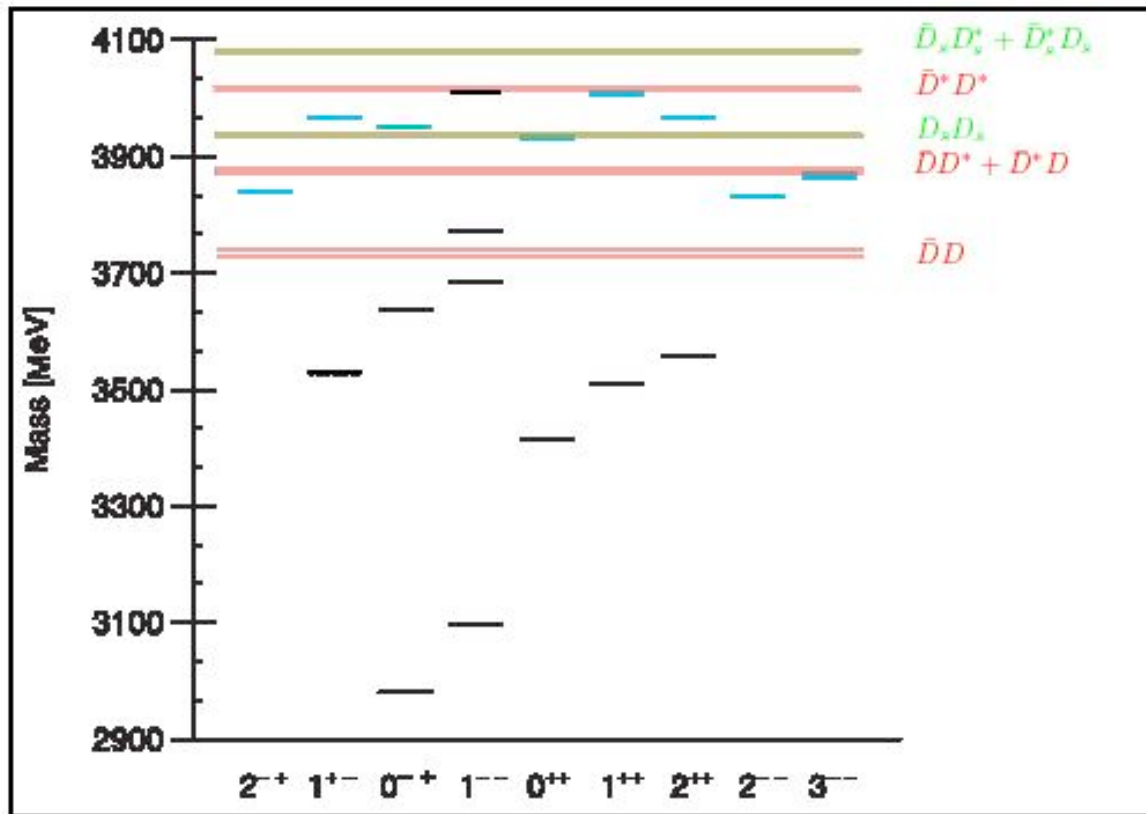
P-value: 9.3×10^{-6} , corresponding to **4.3σ**

P-value from χ^2 PDF: 6.5×10^{-6} , **4.3σ**

Most conservative: Phase Space and flat for non-B background, **3.8σ**

What is it?

Charmonium Spectrum



← **Y(4140)**

- Well **above** charm pair threshold
- Expect **tiny** BF to $J/\psi\phi$
- Does **not** fit into charmonium
- Close $J/\psi\phi$ threshold like Y(3940)

Many potential explanations

Increased **B yield** by 50-60% by adding more data (up to 5.1 fb^{-1}) and adding events from an additional trigger, cuts unchanged

large chance for Y(4140) **significance** to pass **5σ**

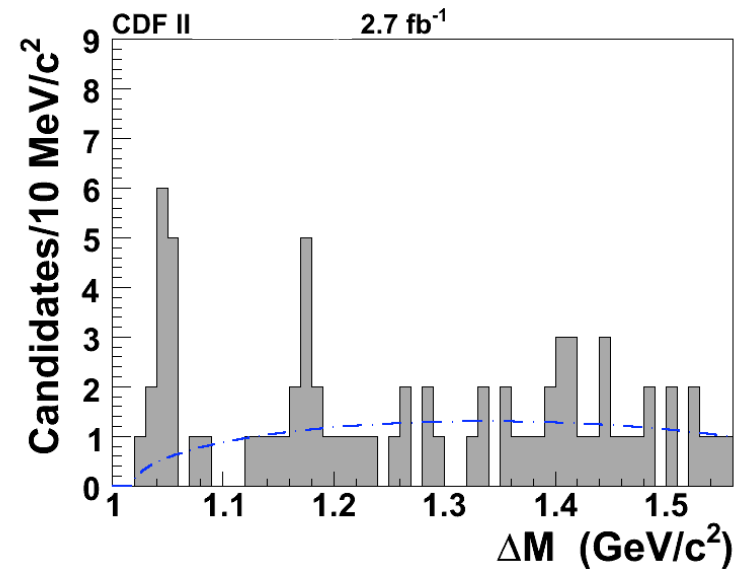
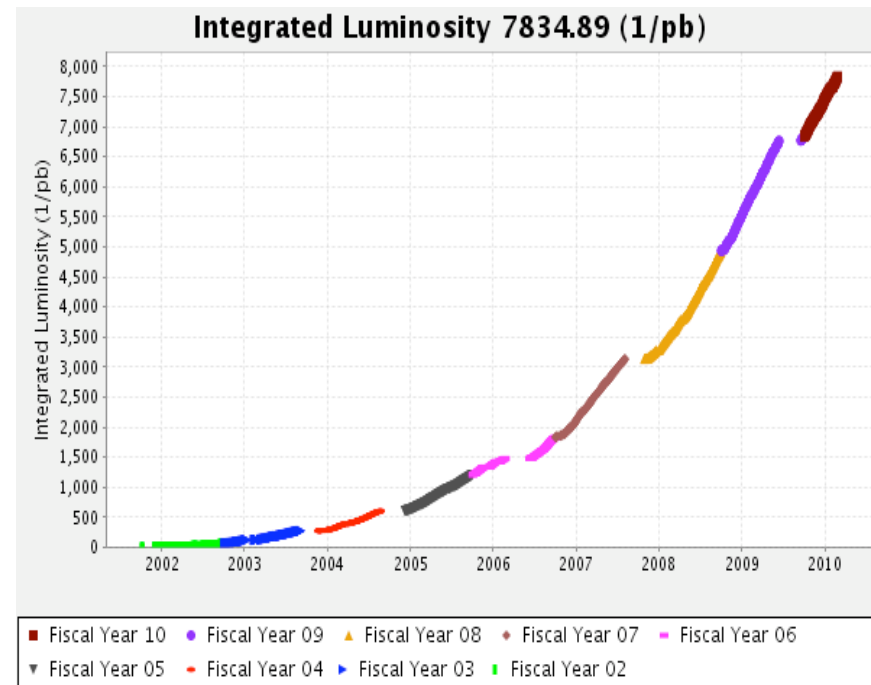
Opportunities

- **Determine J^{PC} ($C=+$)? Need statistics**
 - increase efficiency, reduce background
 - add more data, $\rightarrow 5\sigma$
 - investigate efficiencies against angles?
 - ...
- **More channels for this structure?**
 - open charm pair?

Note: Search for potential additional structures?

$B^+ \rightarrow \phi\phi K^+$, $B_s \rightarrow J/\psi\phi\phi, \dots$

$\Upsilon(nS)\phi, \dots$



Summary

CDF has been active in Quarkonium studies

--The first confirmation of $X(3872)$

--The determination of JPC , most precise mass measurement

CDF observes a new structure in $J/\psi\phi$ spectrum

Mass = 4143.0 ± 2.9 (stat) ± 1.2 (syst) MeV/c²

Width = $11.7^{+8.3}_{-5.0}$ (stat) ± 3.7 (syst) MeV

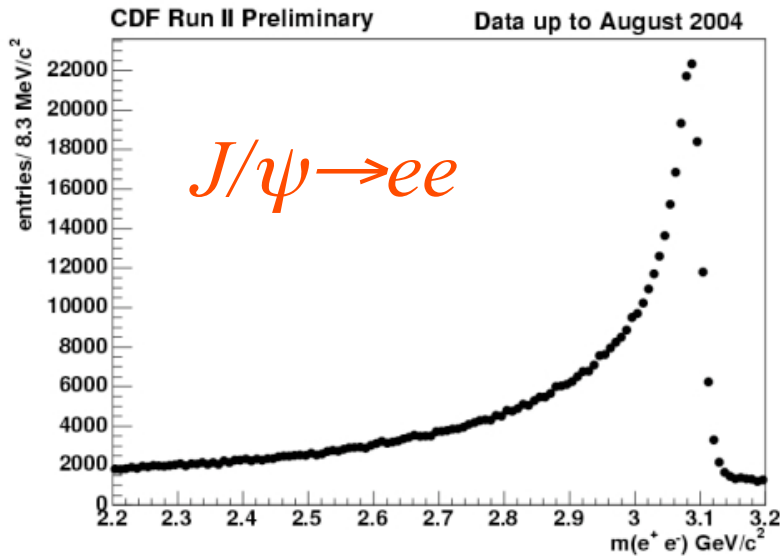
$J^{PC}=?^{?+}$ tentatively name it as $Y(4140)$

$B^+ \rightarrow Y(4140)K^+$, $Y(4140) \rightarrow J/\psi\phi$ BF estimation: $\sim (9 \pm 3.4(\text{stat}) \pm 2.9(\text{BF})) \times 10^{-6}$

About 10fb^{-1} to be recorded by CDF by the end of 2011

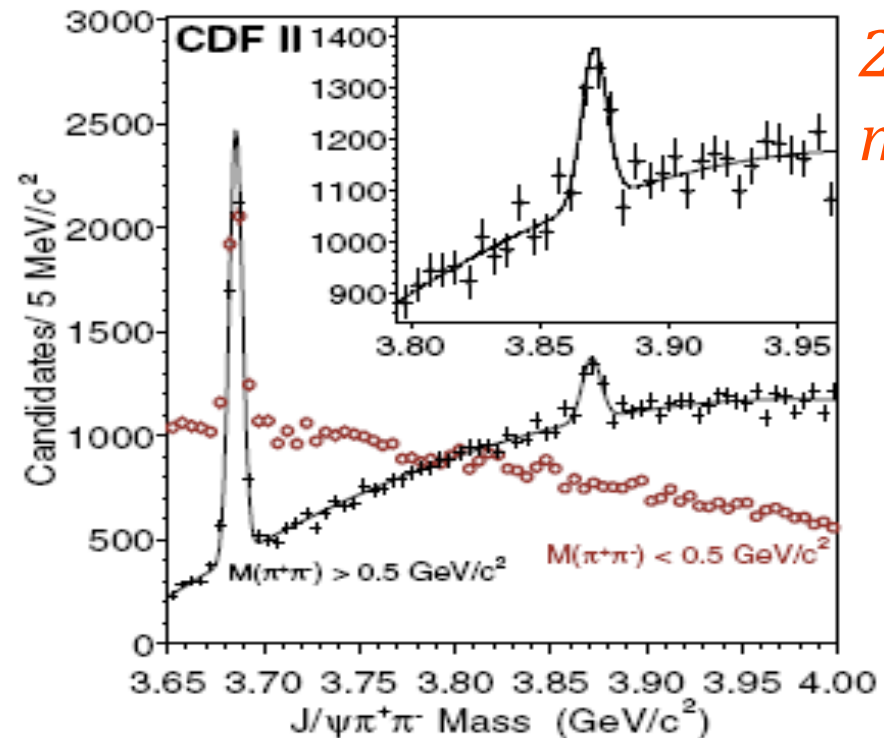
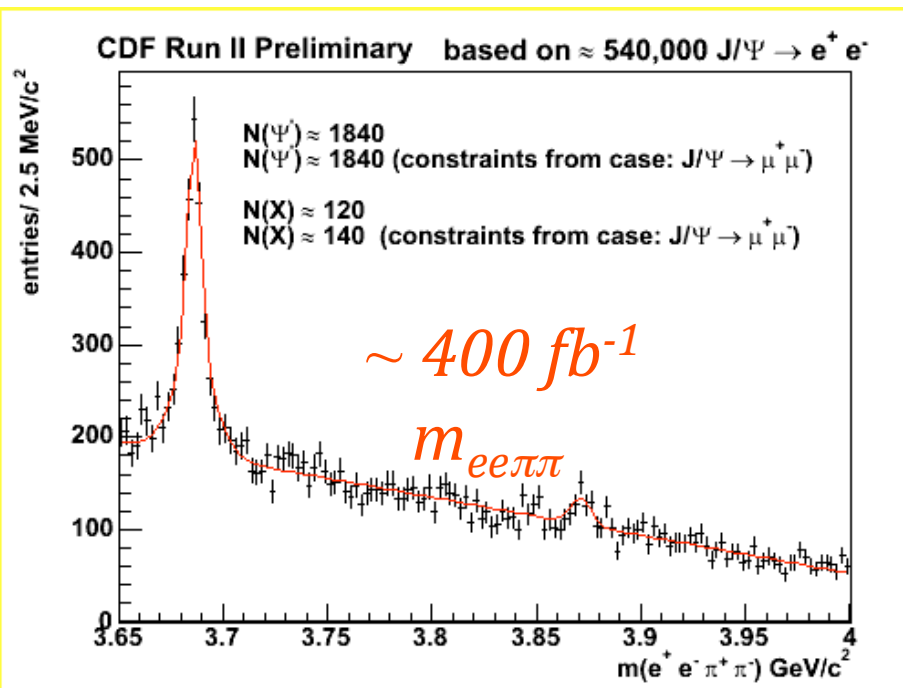
Stay tuned!

Backup 1



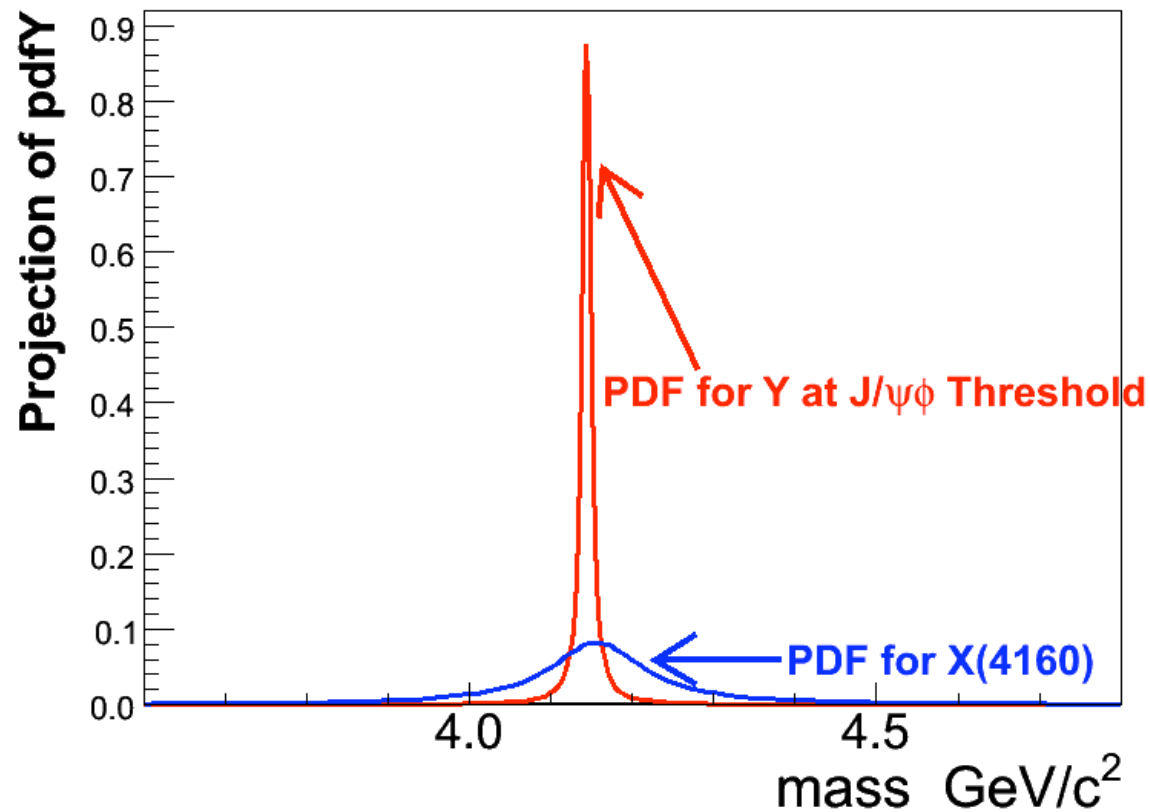
$J/\psi \rightarrow ee$ is difficult
but not impossible

Trigger is gone ☹



220 fb^{-1}
 $m_{\mu\mu\pi\pi}$

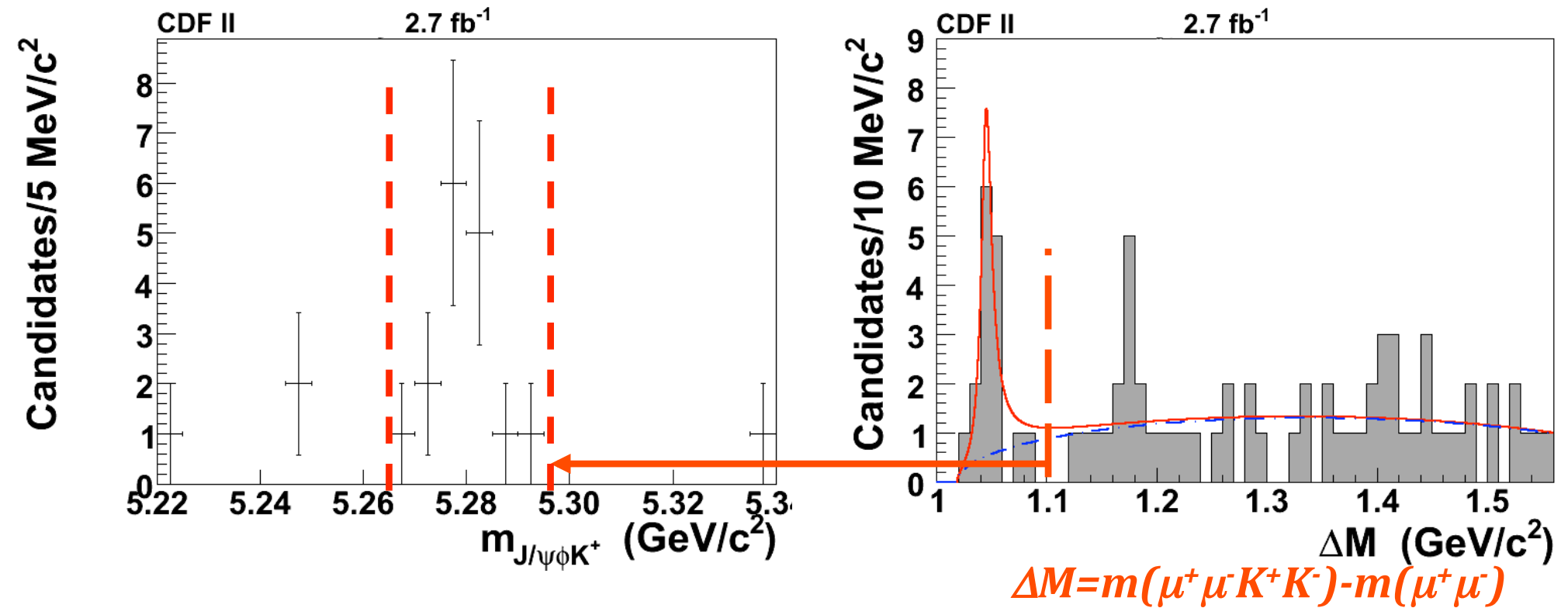
Backup 2



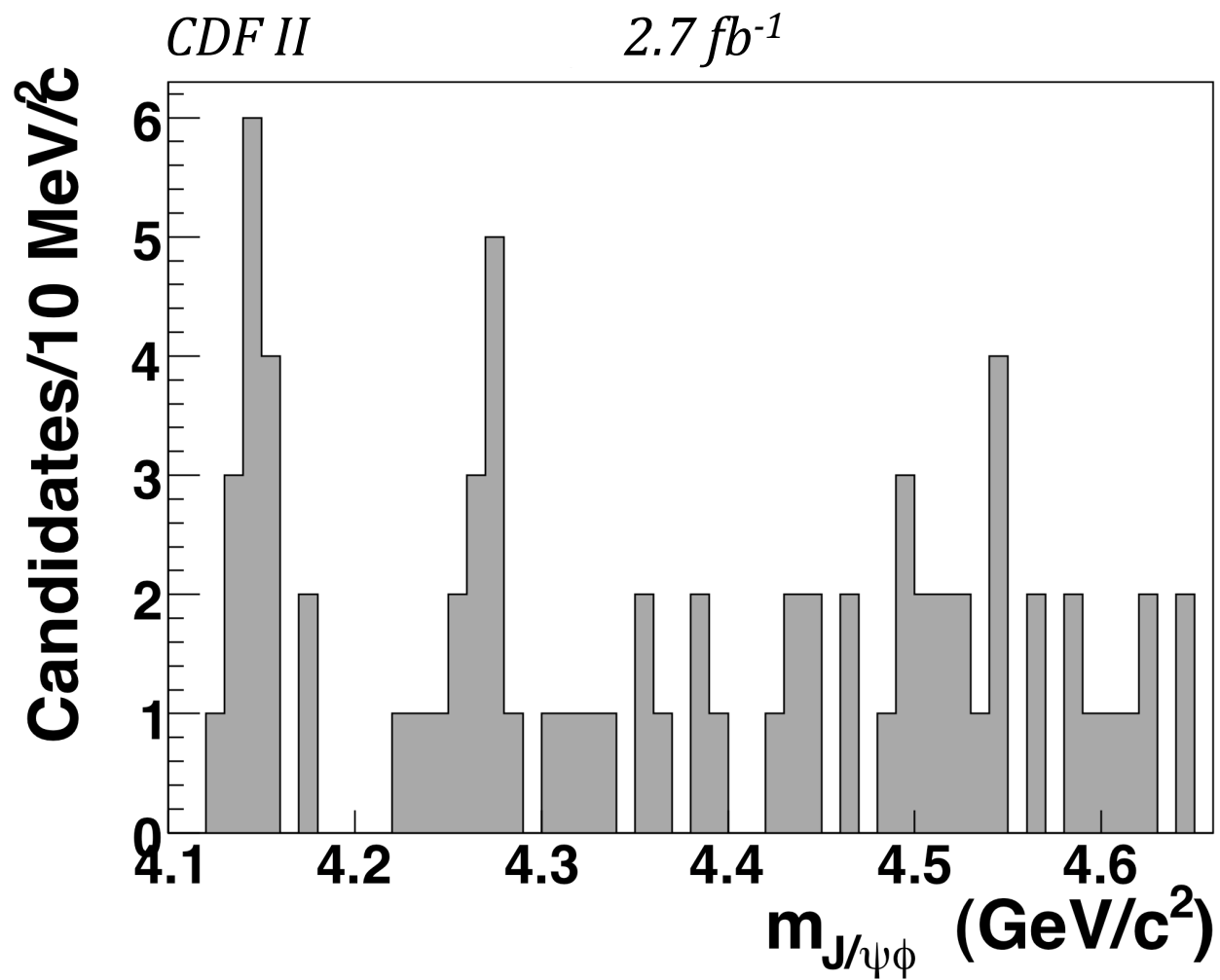
Not close from the PDF comparison although they both have $C=+$

$X(4160) \rightarrow D^* D^*$

Backup 3

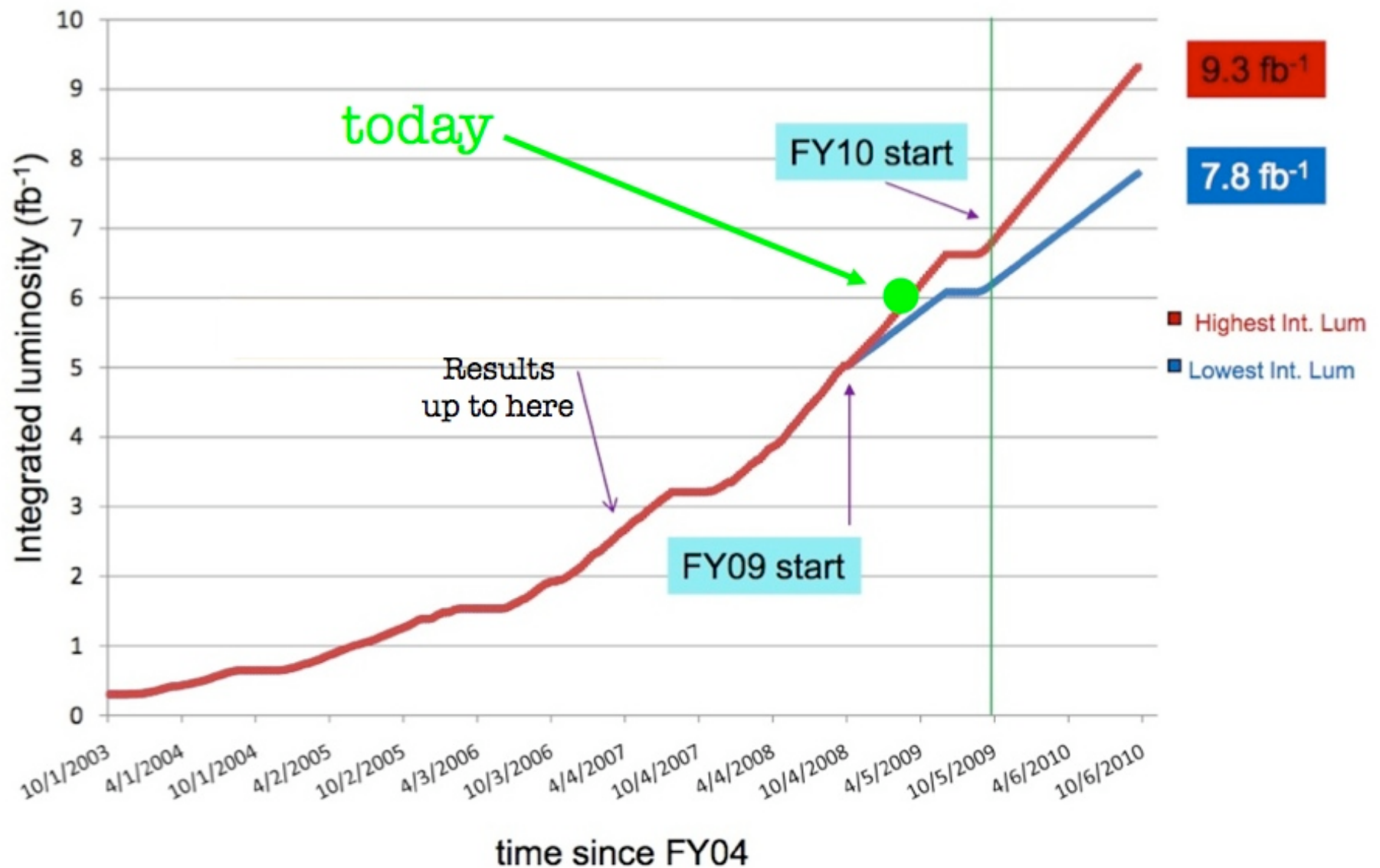


Backup 4



Tevatron

Luminosity projection curves for Run II



The challenge

- Start with typical requirements for B hadron at CDF:

-- $p(\chi^2)$ for B^+ vertex fit $> 1\%$

-- $p_T(\text{track}) > 0.4 \text{ GeV}$,

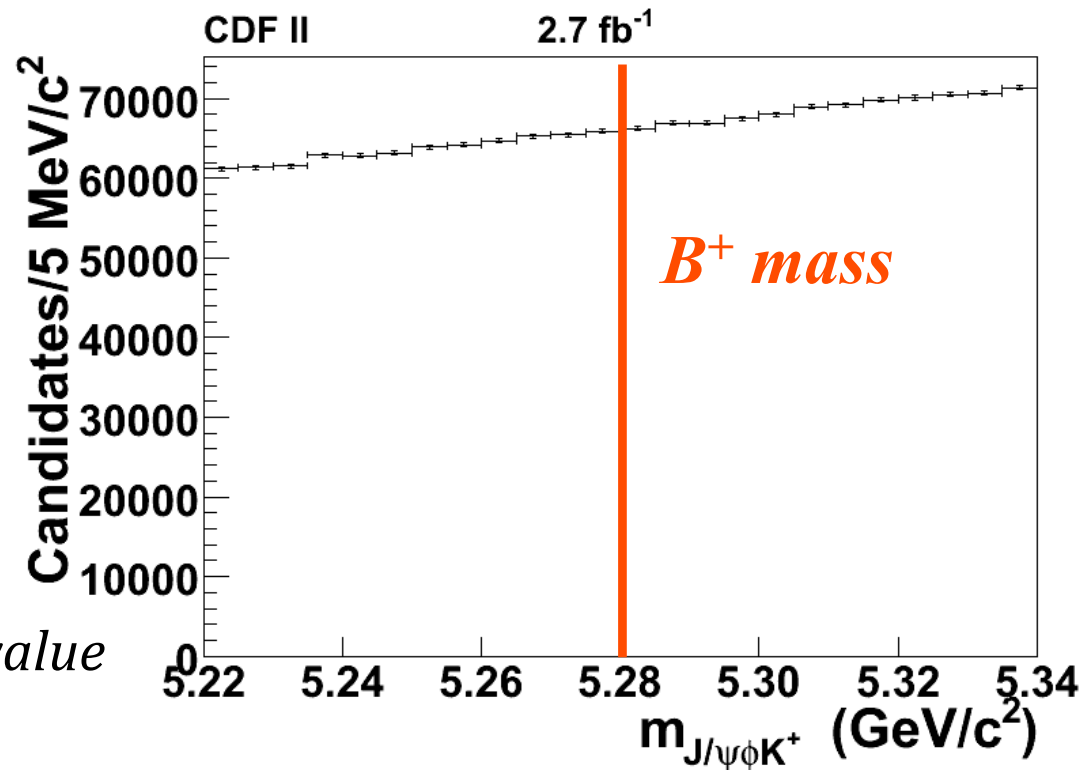
-- ≥ 4 r - ϕ silicon hits

-- $p_T(B^+) > 4 \text{ GeV}$

--mass window:

$J/\psi (\pm 50 \text{ MeV})$ and $\phi (\pm 7 \text{ MeV})$

constrain $\mu^+\mu^-$ to J/ψ PDG mass value

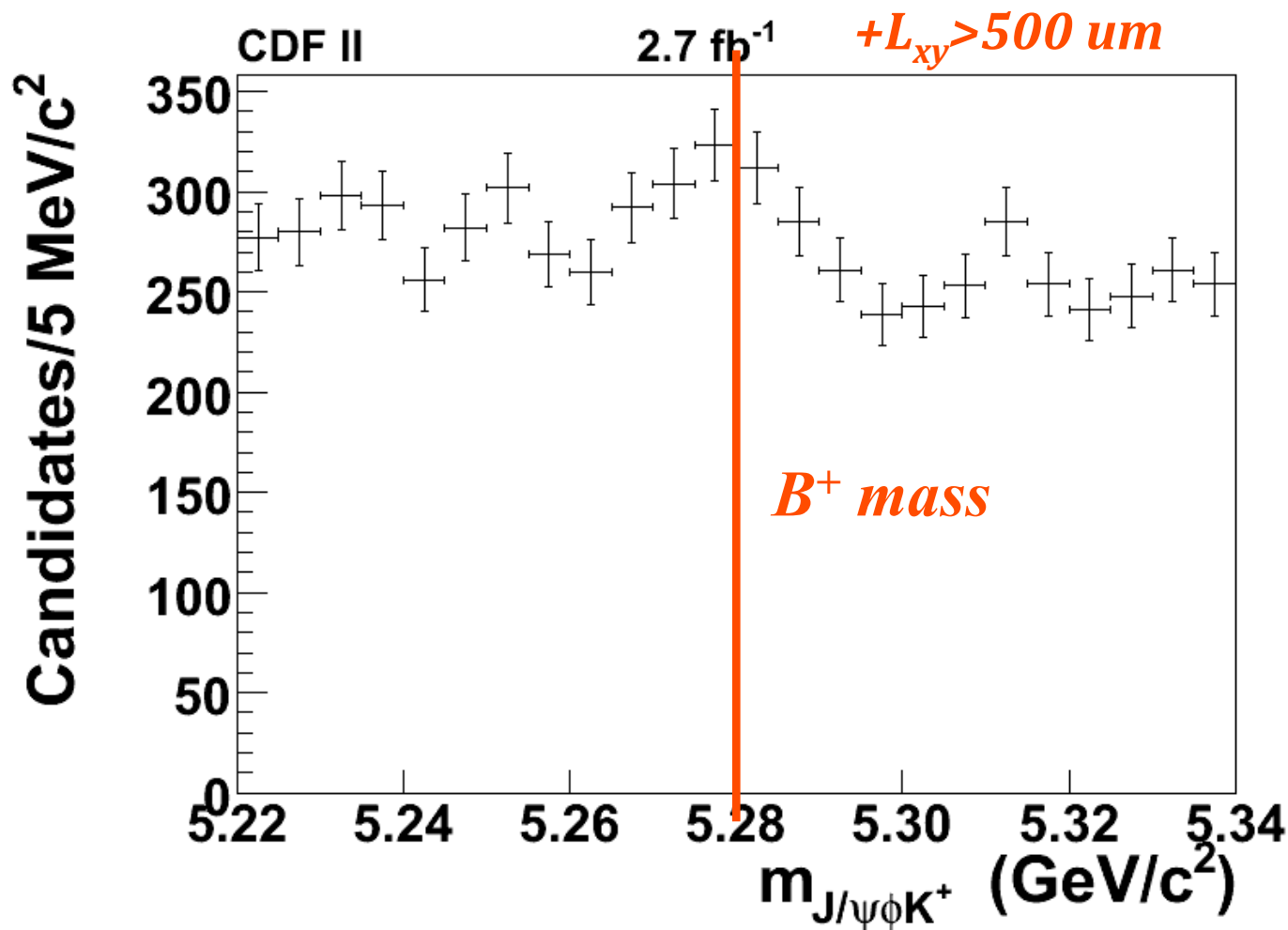


- **NOT** applied yet: L_{xy} and kaon **PID**

Typical hadron collider environment

Applying L_{xy}

- Maximize $S/\sqrt{(S+B)}$ for $B^+ \rightarrow J/\psi \phi K^+$ signal, has nothing to do with $J/\psi \phi$
- Maximized cuts: $L_{xy} > 500 \mu\text{m}$, kaon LLR > 0.2



L_{xy} Reduce background by a factor of ~ 200

Control channels

- We also reconstruct two control channels with similar cuts:

$\sim 3\,000\ B_s \rightarrow J/\psi \phi$, $\sim 50\,000\ B^+ \rightarrow J/\psi K^+$

before L_{xy} and kaon LLR cuts

- Clean control signals after L_{xy} and kaon LLR cuts
cross check and efficiency evaluation

