Properties of exotic charmonium-like mesons at CDF

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(for CDF Collaboration)

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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 has been involved the first X states—X(3872) and continues to contribute to it: determine quantum number, precisely measures X(3872) mass.

CDF new contribution to X/Y/Z: Y(4140) ➔J/ΨΦ

Strong Points for CDF

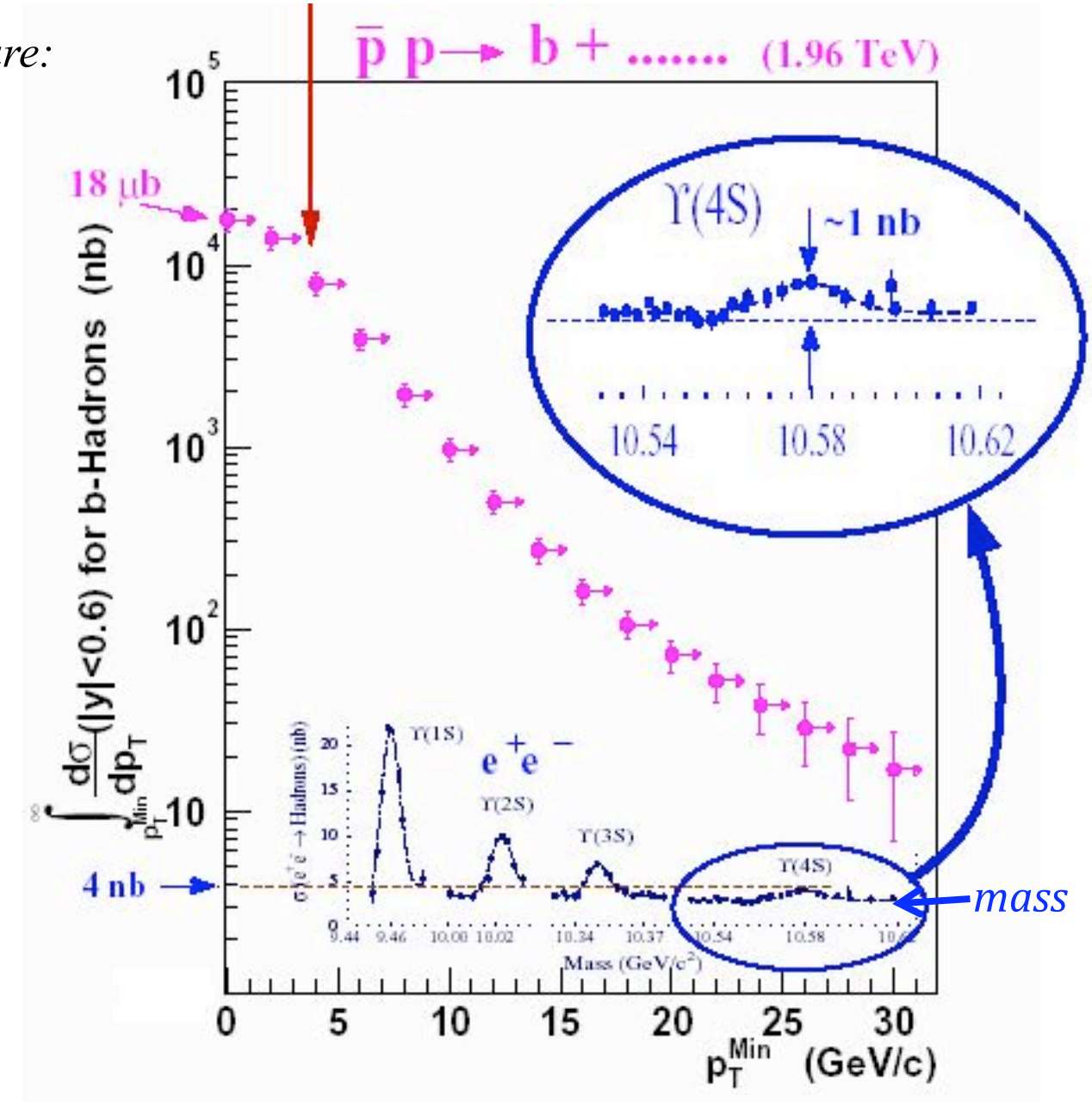
Heavy hadrons at Tevatron are:

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

CDF has:

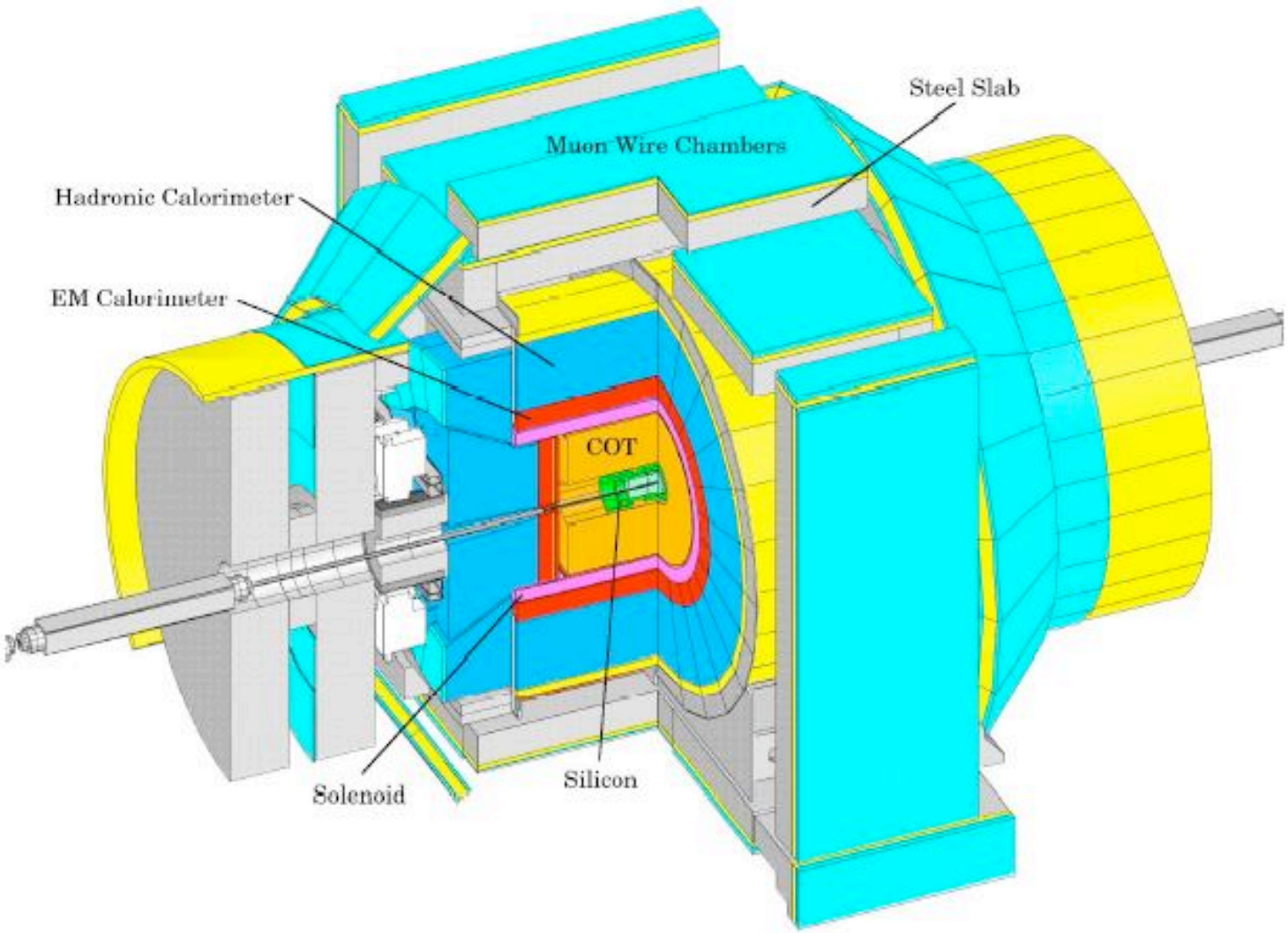
- *excellent mass resolution*
- *excellent vertex resolution*
- *reasonable hadron PID*

CDF detector

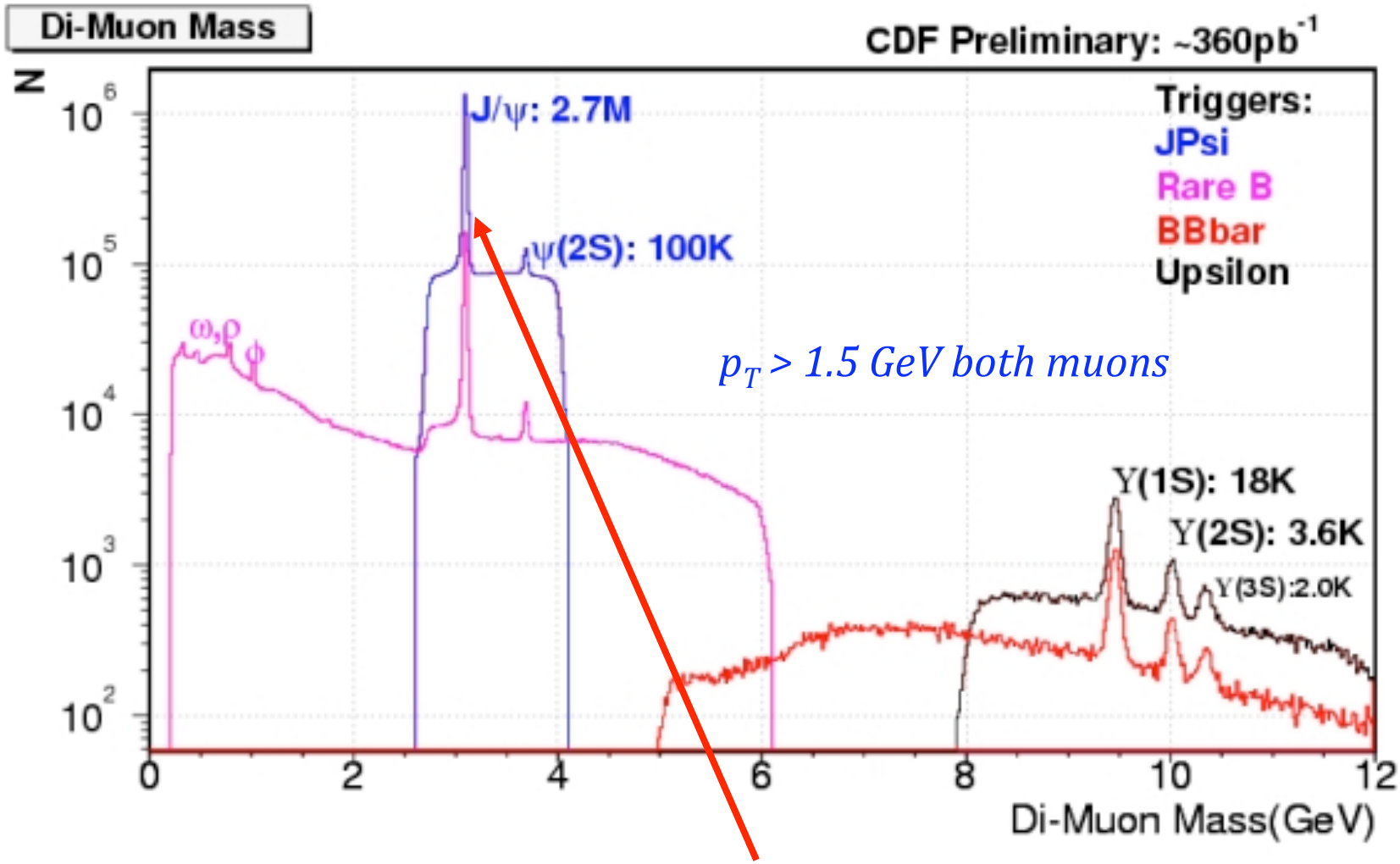


CDF detector

- ***Muon***: *μ ID*
- ***ToF***: *TOF*
- ***COT***: *track p*
  dEdx
- ***Silicon***: *track p*
  vertex



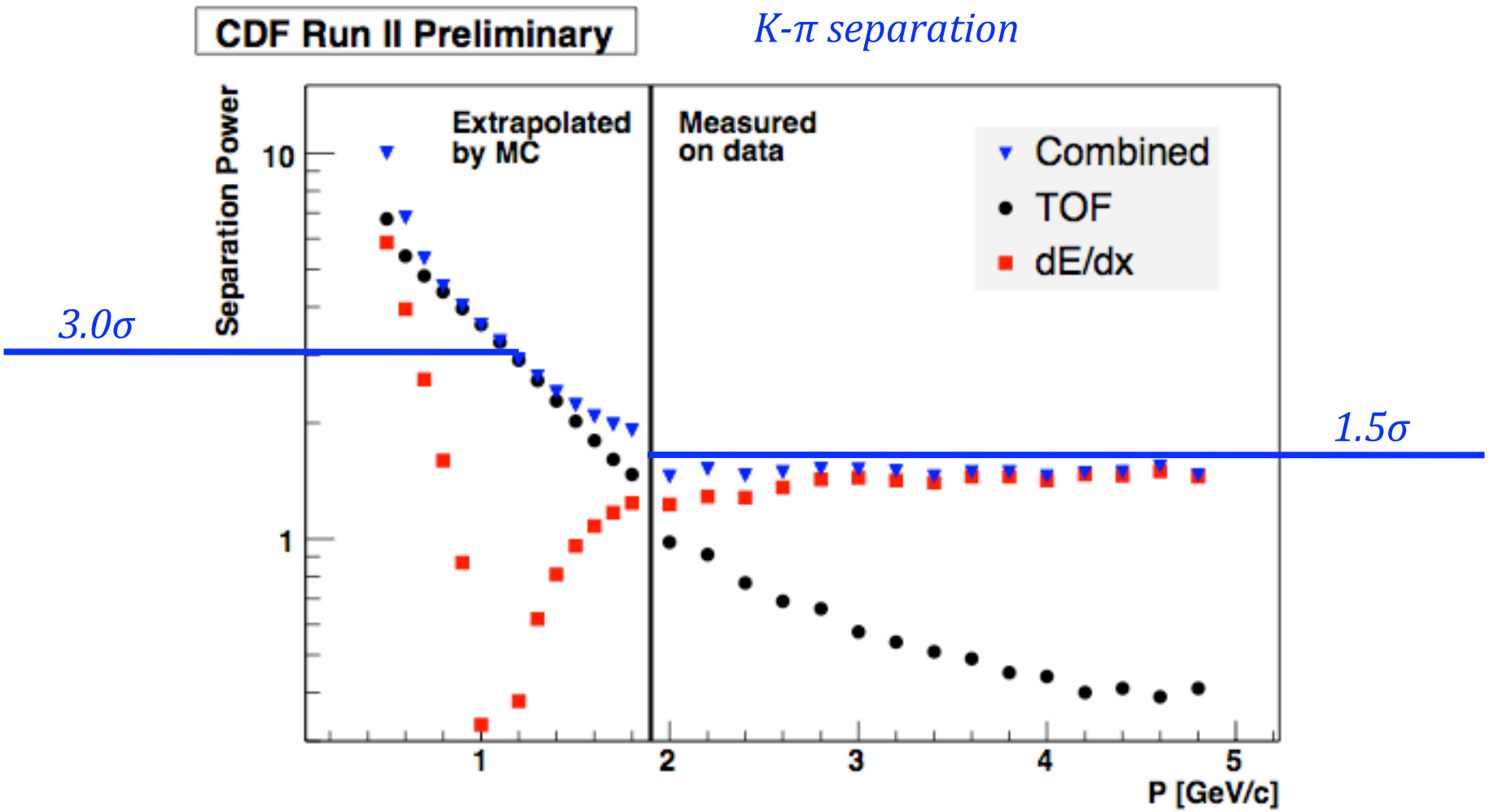
CDF Di-muon trigger



*Scale to ~2.7 fb^{-1}, ~**20M J/ψ** **with silicon hits***

~2.4 used for X(3872) mass, ~2.7 used for Y(4140)

CDF hadron PID



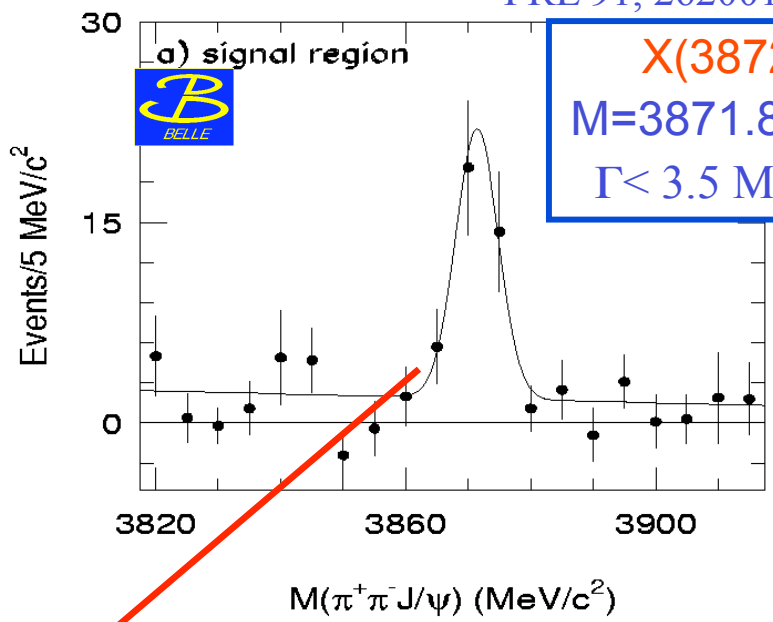
Typical B decay daughter momentum ~GeV

X(3872)--2003

$N\,^{2S+1}L_J$	J^{PC}	$u\bar{d}$, $u\bar{u}$, $d\bar{d}$ $I=1$	$u\bar{u}$, $d\bar{d}$, $s\bar{s}$ $I=0$	$c\bar{c}$ $I=0$
$1\,^1S_0$	0^{-+}	π	η, η'	$\eta_c(1S)$
$1\,^3S_1$	1^{--}	ρ	ω, ϕ	$J/\psi(1S)$
$1\,^1P_1$	1^{+-}	$b_1(1235)$	$h_1(1170)$, $h_1(1380)$	$h_c(1P)$
$1\,^3P_0$	0^{++}	$a_0(1450)^*$	$f_0(1370)^*$, $f_0(1710)^*$	$\chi_{c0}(1P)$
$1\,^3P_1$	1^{++}	$a_1(1260)$	$f_1(1285)$, $f_1(1420)$	$\chi_{c1}(1P)$
$1\,^3P_2$	2^{++}	$a_2(1320)$	$f_2(1270)$, $f_2'(1525)$	$\chi_{c2}(1P)$
$1\,^1D_2$	2^{-+}	$\pi_2(1670)$	$\eta_2(1645)$, $\eta_2(1870)$	
$1\,^3D_1$	1^{--}	$\rho(1700)$	$\omega(1650)$	$\psi(3770)$
$1\,^3D_2$	2^{--}			??
$1\,^3D_3$	3^{--}	$\rho_3(1690)$	$\omega_3(1670)$, $\phi_3(1850)$	
$1\,^3F_4$	4^{++}	$a_4(2040)$	$f_4(2050)$, $f_4(2220)$	
$2\,^1S_0$	0^{-+}	$\pi(1300)$	$\eta(1295)$, $\eta(1440)$	$\eta_c(2S)$
$2\,^3S_1$	1^{--}	$\rho(1450)$	$\omega(1420)$, $\phi(1680)$	$\psi(2S)$
$2\,^3P_2$	2^{++}	$a_2(1700)$	$f_2(1950)$, $f_2(2010)$	
$3\,^1S_0$	0^{-+}	$\pi(1800)$	$\eta(1760)$	

$c\bar{c}$

PRL 91, 262001

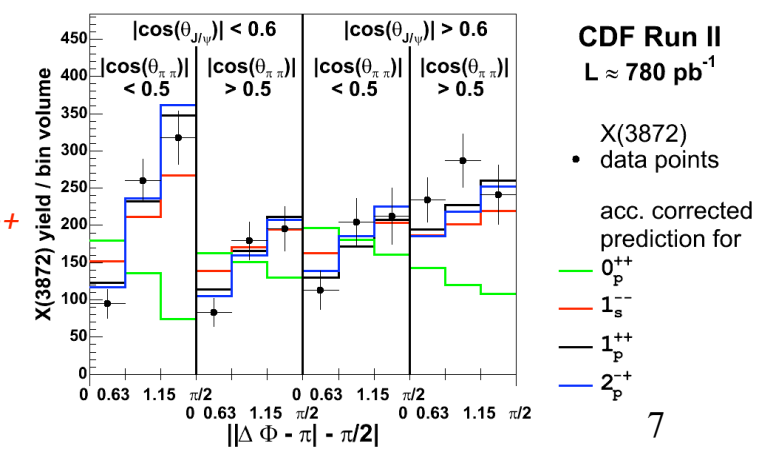


X(3872)→J/ψπ⁺π⁻
M=3871.8±0.7±0.4 MeV
Γ< 3.5 MeV @ 90% CL

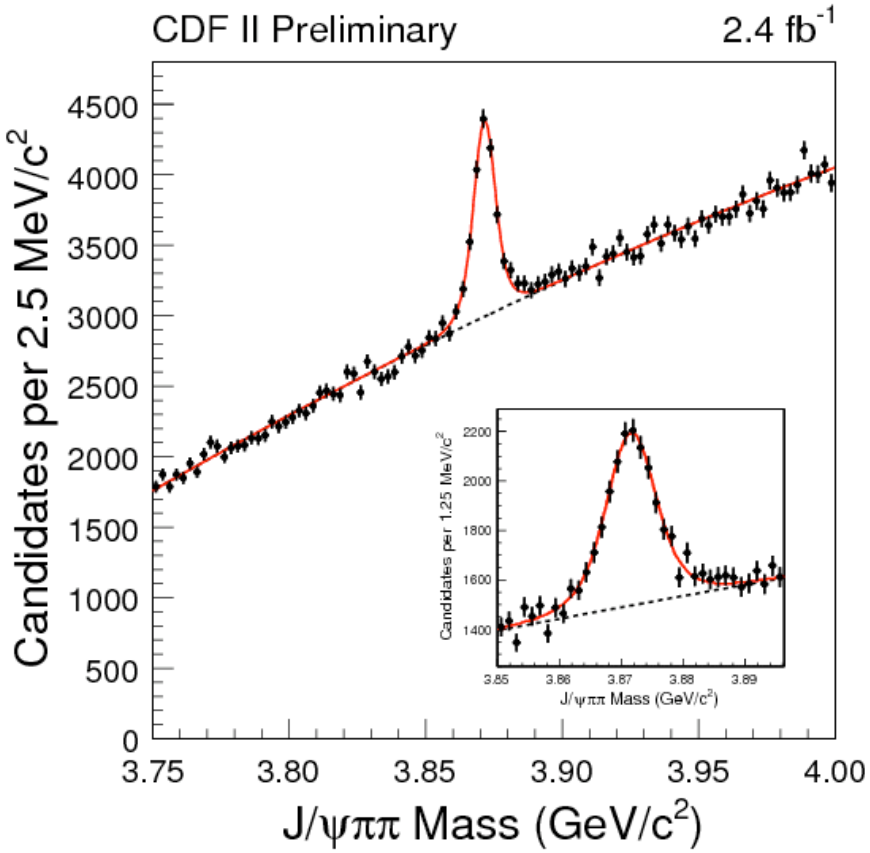
mass ~70 MeV > predictions (2003)

$\pi^+\pi^-$ peak at high value like a ρ (2003)

J^{PC} = 1^{++} or 2^{-+}



New X(3872) Mass Measurement at CDF



~6000 signals

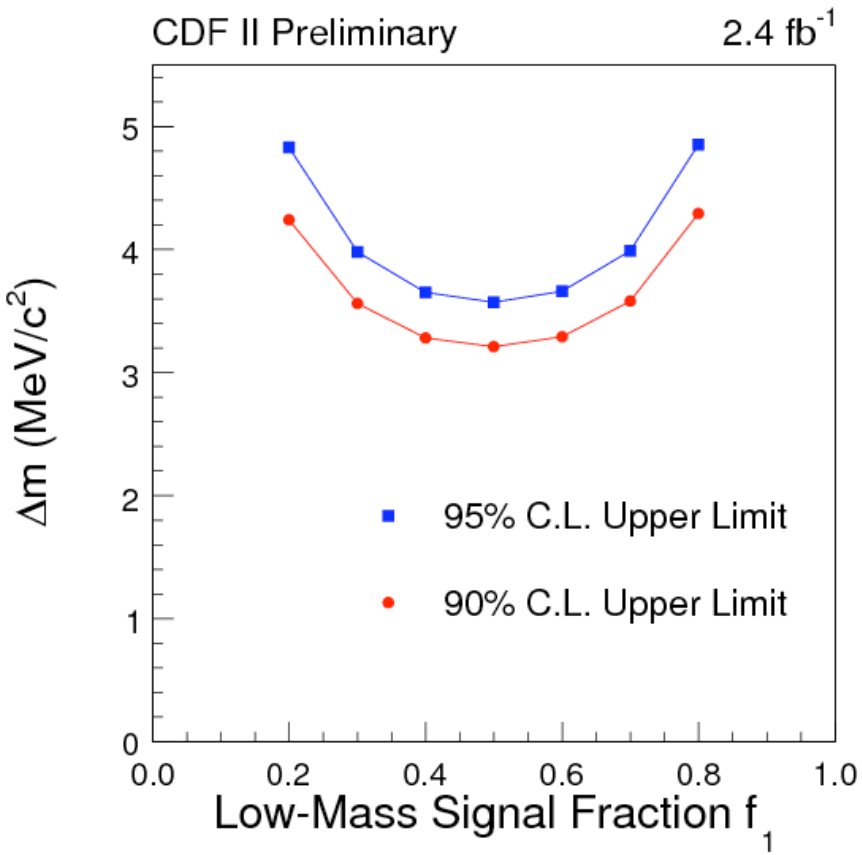
The largest sample to date

Use neural network to select

I. Test the hypothesis of:
X(3872) composed of two states?

II. Make (most) precise mass measurement
Relevant to DD molecule hypothesis*

New X(3872) Mass Measurement at CDF



Assuming different fraction for possible two states.

Breit-Wigners convoluted with resolution (assuming same width-1.34 MeV/c^2)

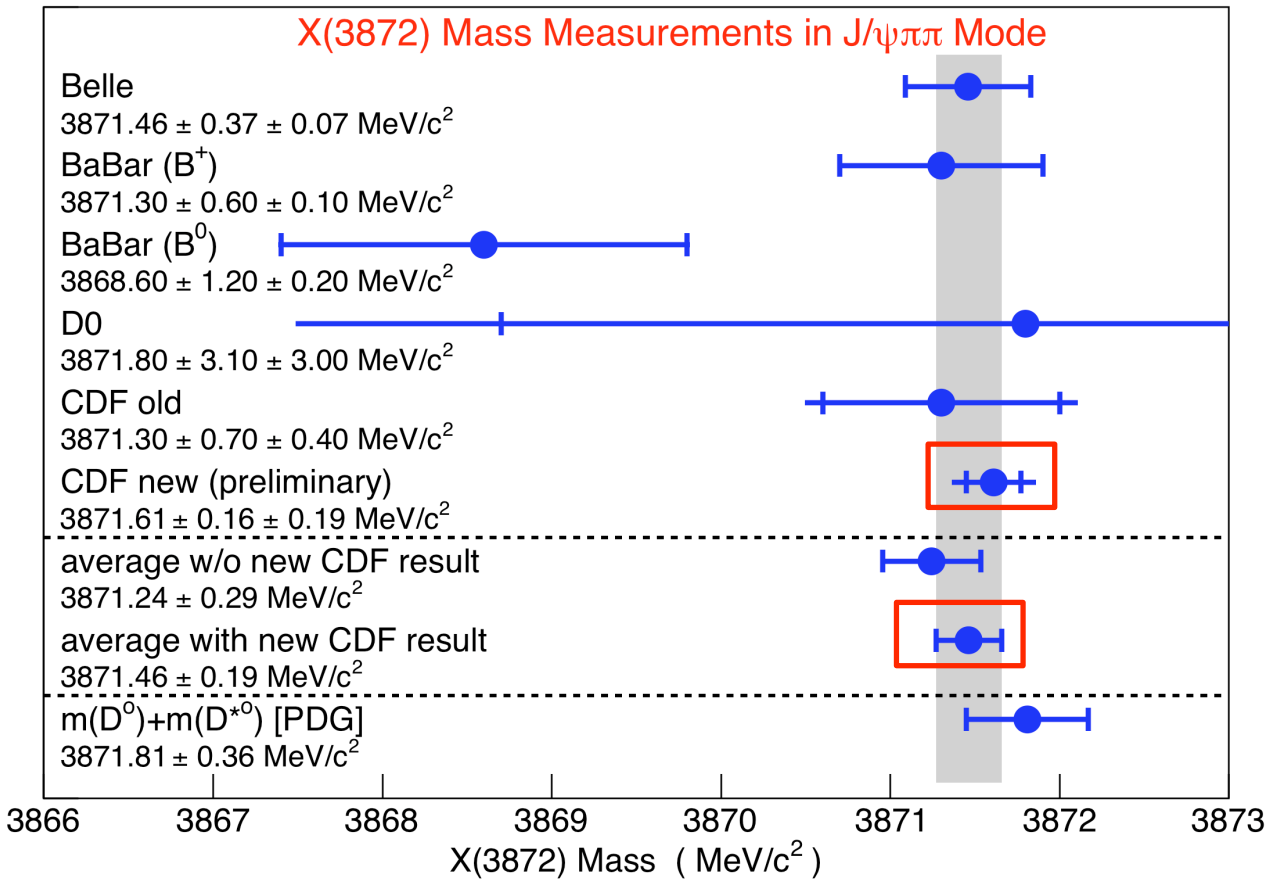
Using test statistics variable to set limit

$\Delta m < 3.2$ (3.6) MeV/c^2 at 90% (95%) C.L.

Conclusion:
Consistent with one state hypothesis.

m(X(3872)) = 3871.61 ± 0.16 (stat) ± 0.19 (syst) MeV/c^2
(assuming one state hypothesis)

New X(3872) Mass Measurement at CDF

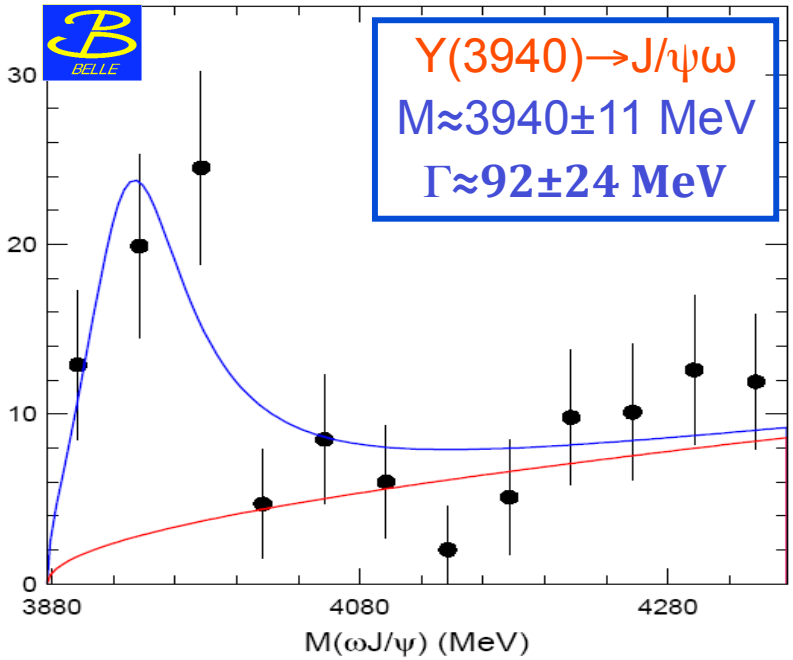


Consistent with one state hypothesis

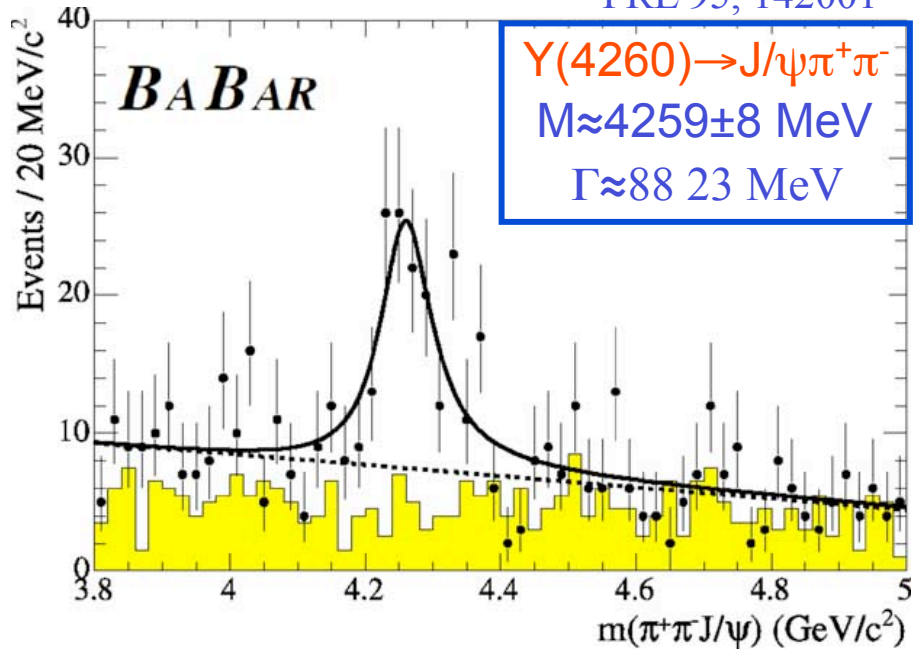
*The most precise measurement to date, still within the D*D threshold uncertainty*

Motivation to search for new state

PRL 94, 182002



PRL 95, 142001



Above DD̄ && DD̄ threshold,*
tiny Branching Fraction expected
New mass and width from BaBar:
$M \approx 3914^{+3.8}_{-3.4} \pm 2.0$, $\Gamma \approx 34^{+12}_{-8} \pm 5$ MeV
at the $J/\psi\omega$ threshold ?

Well above DD̄ && DD̄ threshold,*
tiny Branching Fraction expected
$J^{PC}=1^{--}$, plus Y(4350), Y(4660)
too many 1^{--} ?

Many more, for instance, Z(4430)+, but no heavier quark such as s involved.

Why search J/ΨΦ?

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

J/ ψφ

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

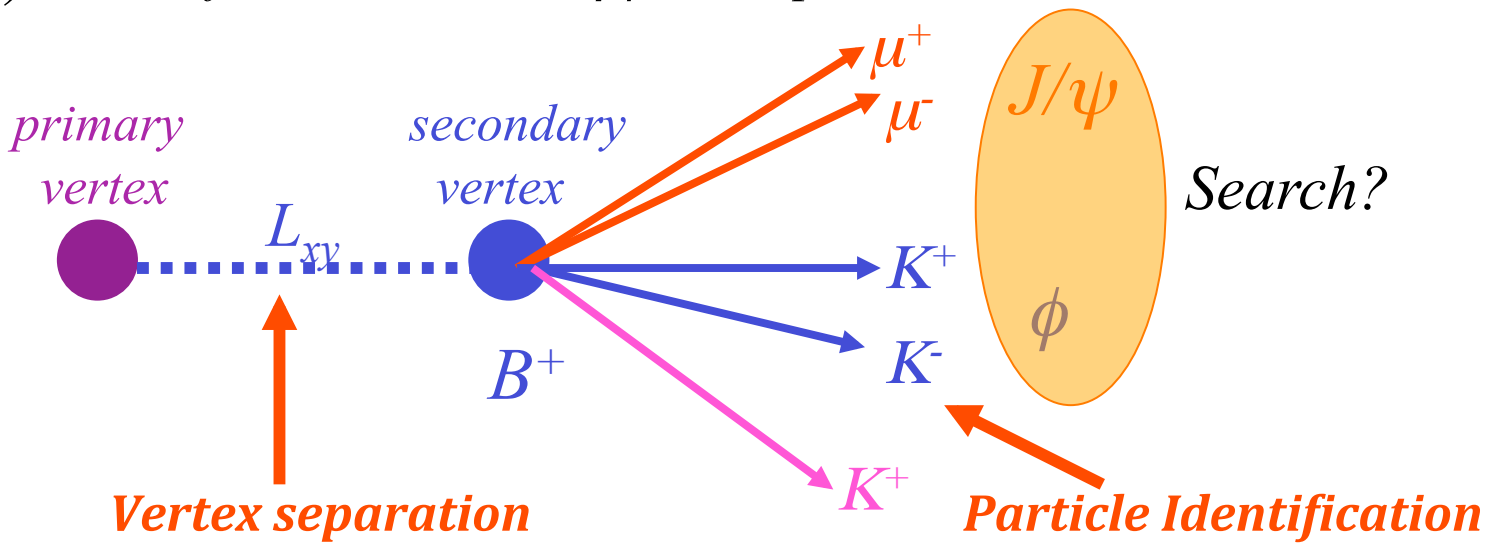
Search through exclusive B decays is experimentally easy
B➔J/ΨΦK decays have been observed
No structure has been reported so far

Analysis strategy

- *I) Reconstruct B^+ as:*

$$B^+ \rightarrow J/\psi\phi\, K^+$$
$$J/\psi \rightarrow \mu^+\mu^-$$
$$\phi \rightarrow K^+K^-$$

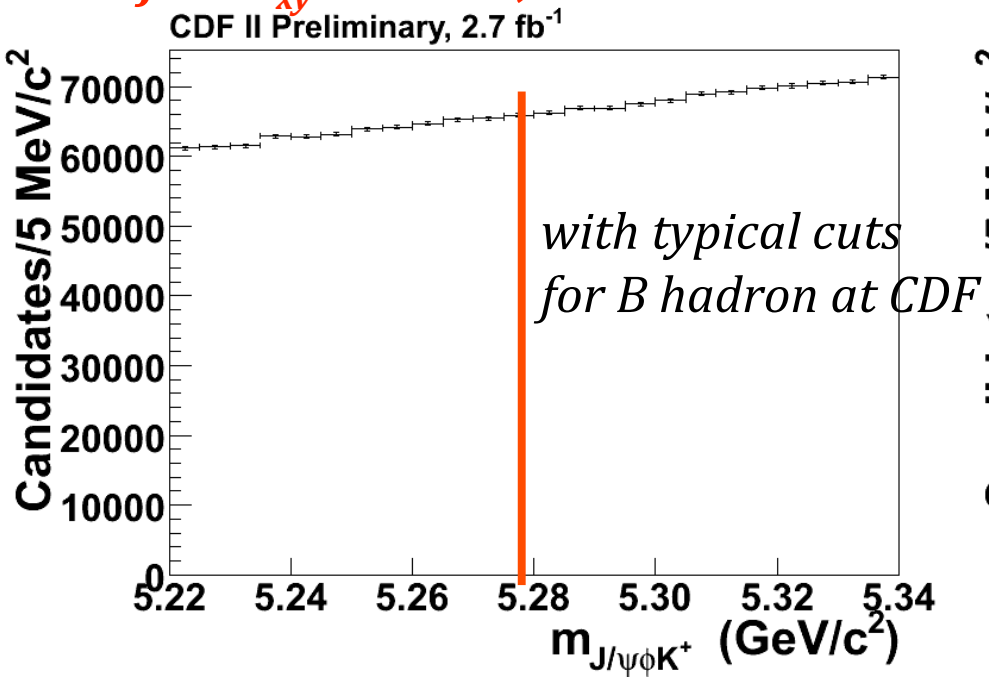
- *II) Search for structure in $J/\psi\phi$ mass spectrum inside B^+ mass window*



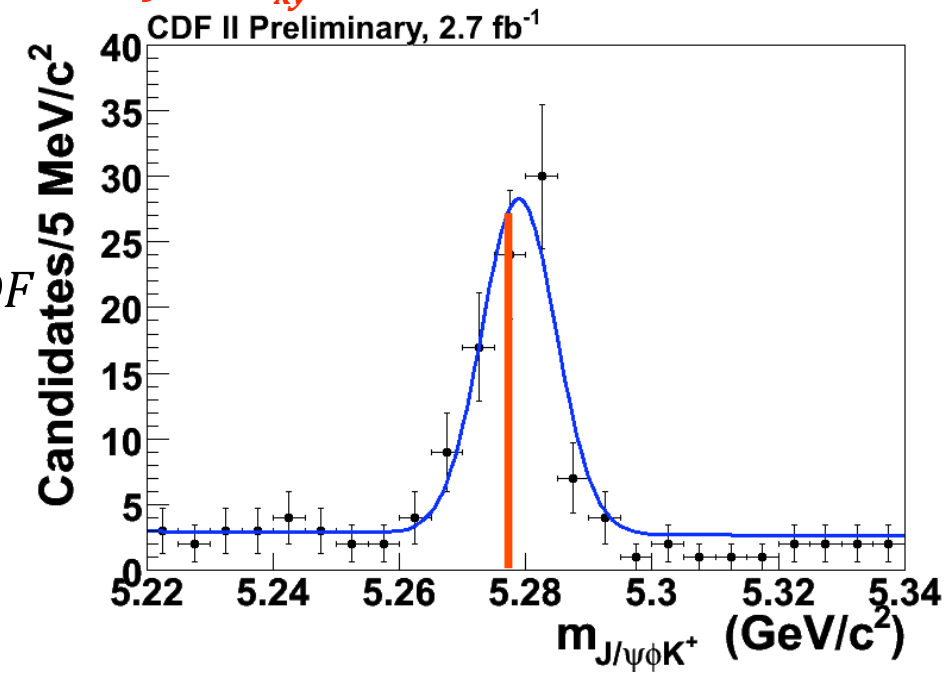
I) Reconstruct $B^+ \rightarrow J/\psi \phi K^+$

The key to reconstruct B signal

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



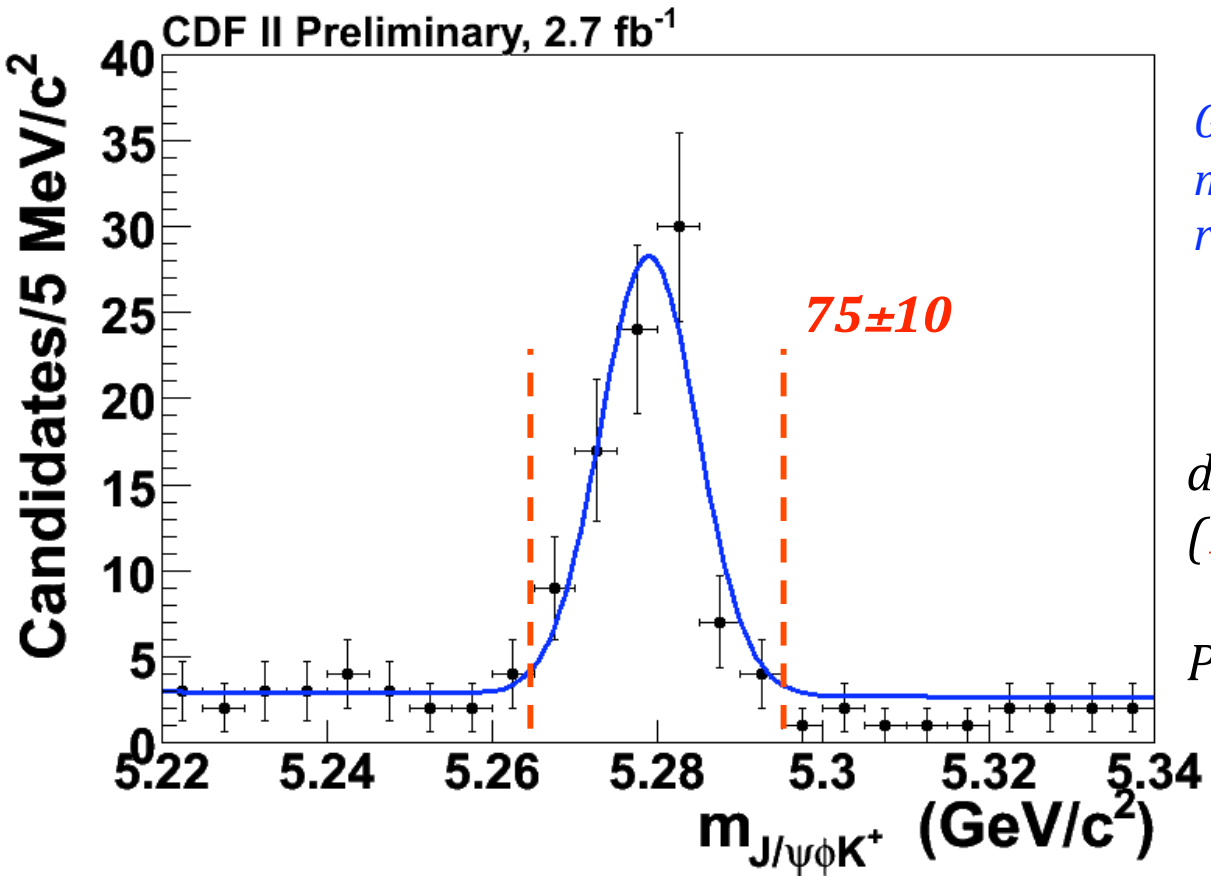
After L_{xy}>500 um, kaon PID>0.2



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 ±3σ 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*

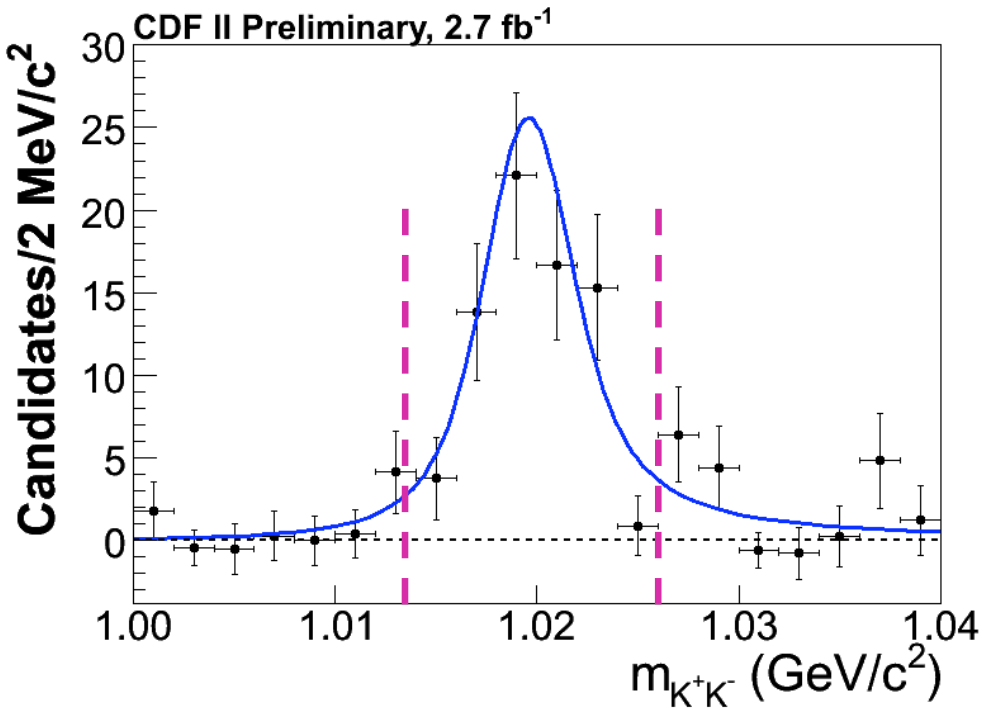
  --relax K+K- mass window to:

  [1.0,1.04] 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 $f_0 \rightarrow K^+K^-$ or K^+K^- phase space components with our ϕ mass window*



Conclusion

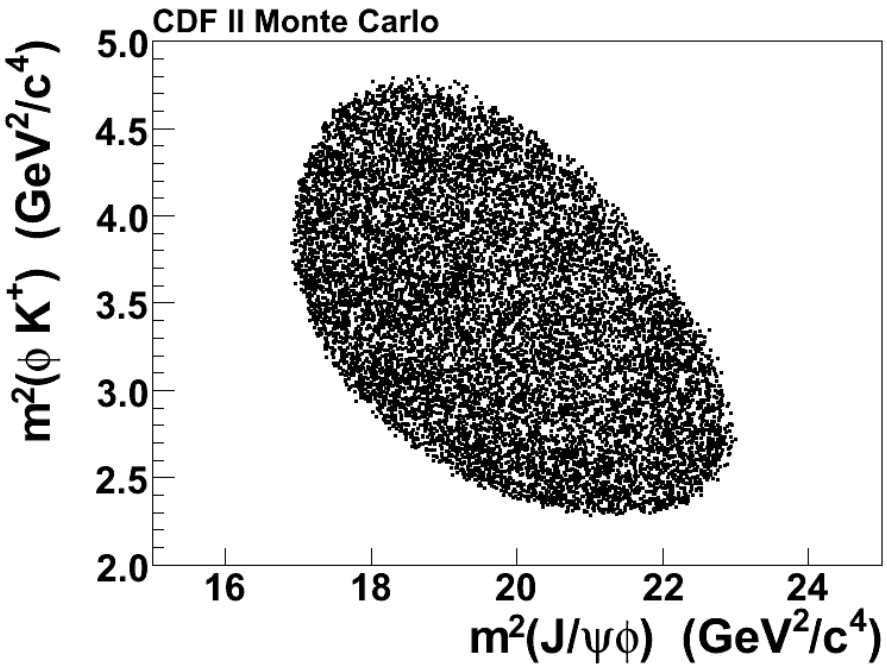
pure $B^+ \rightarrow J/\psi\phi K^+$ ***for B^+ peak***

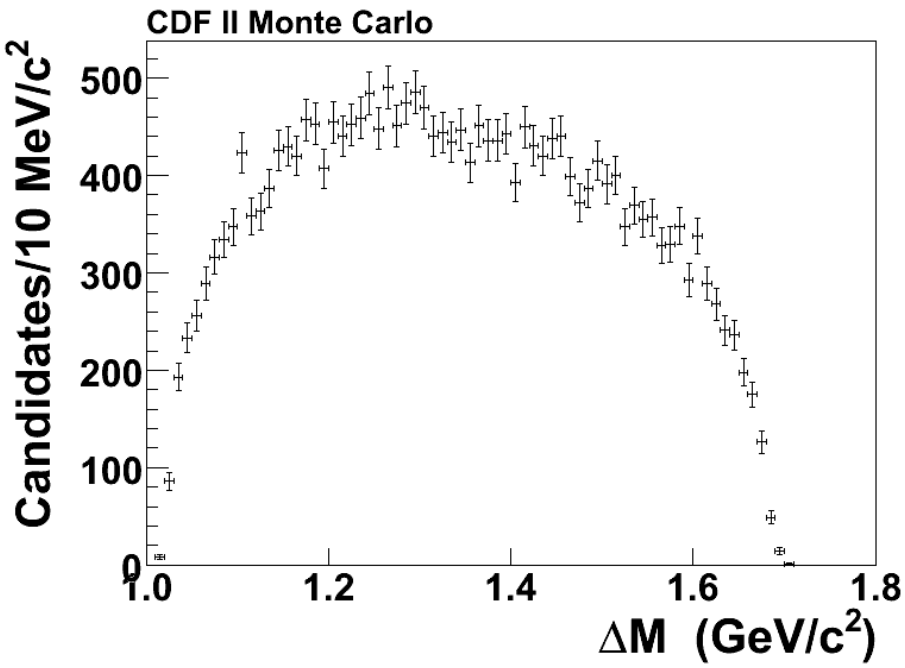
negligible $B^+ \rightarrow J/\psi f_0 K^+$, $J/\psi K^+K^- K^+$ *components*

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*

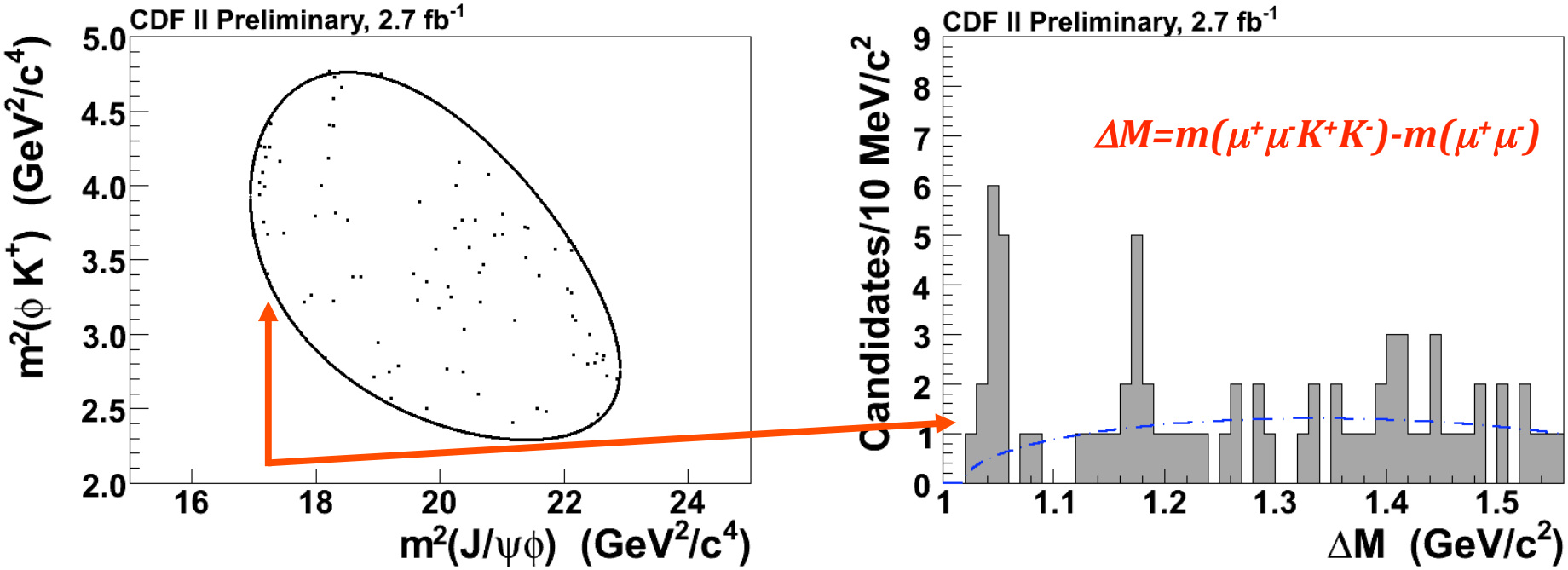




$\Delta M = m(\mu^+\mu^- K^+K^-) - m(\mu^+\mu^-)$

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

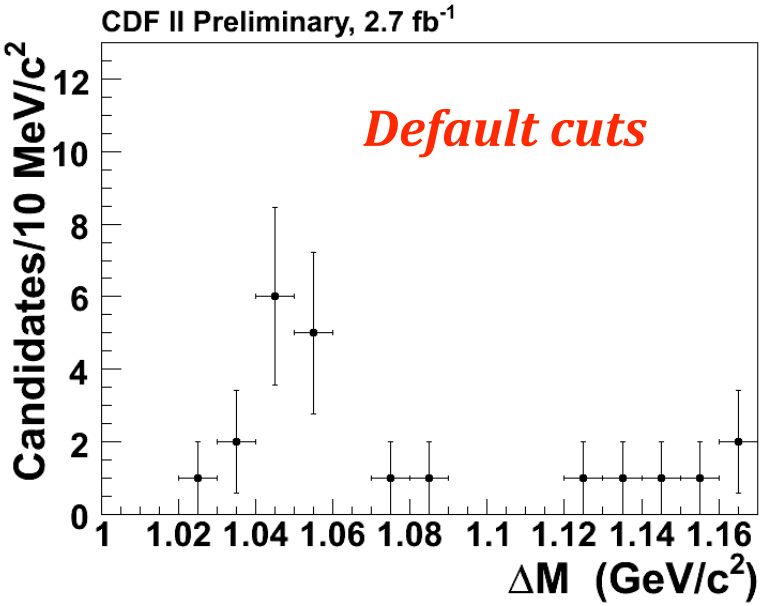
Search for structures in $J/\psi\phi$ mass--Data

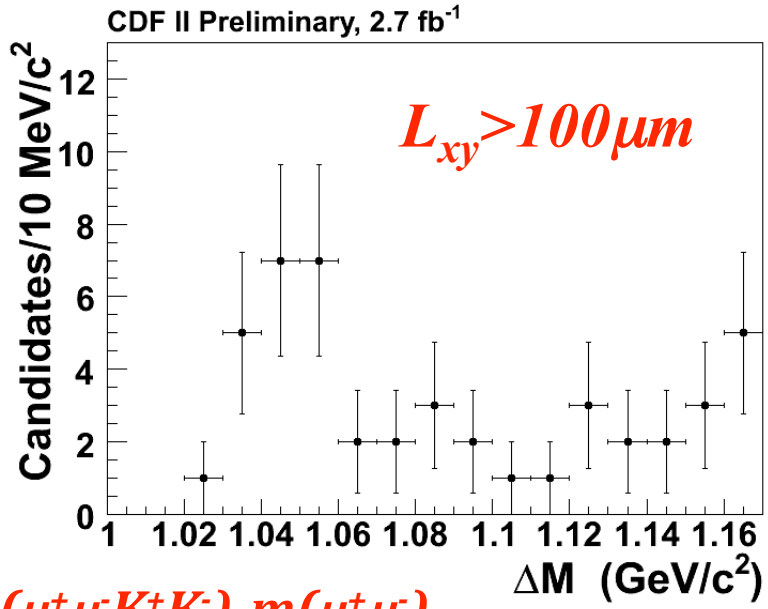


Three-body Phase Space Background shape is different from data

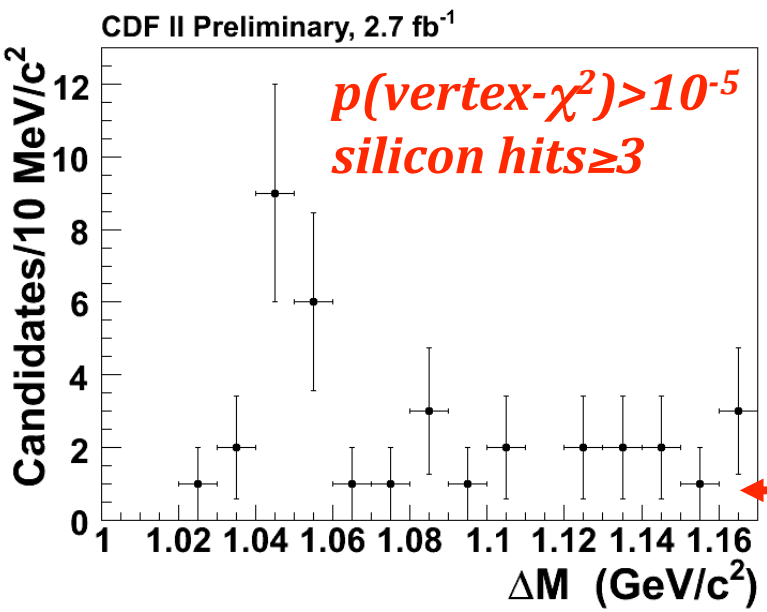
An near threshold enhancement is observed

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,…*

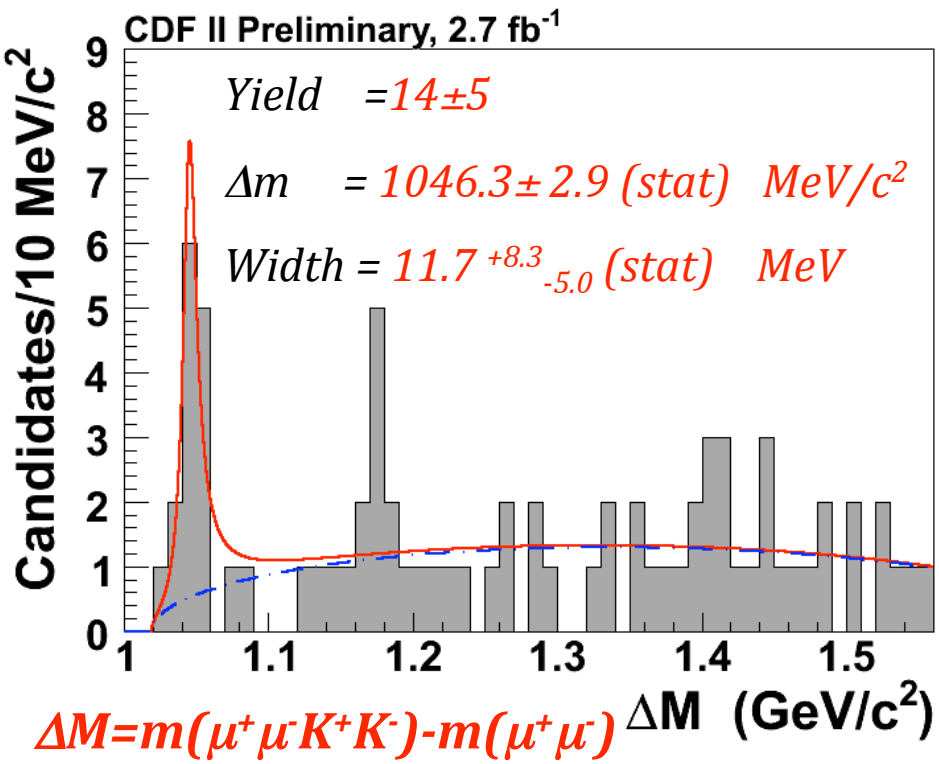
Robust against variations

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*



Convoluted with resolution (1.7 MeV)

Mass=:
4143.0 ± 2.9 (stat)± 1.2 (syst) MeV/c^2
(adding J/ψ mass in PDG)

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

Significance study

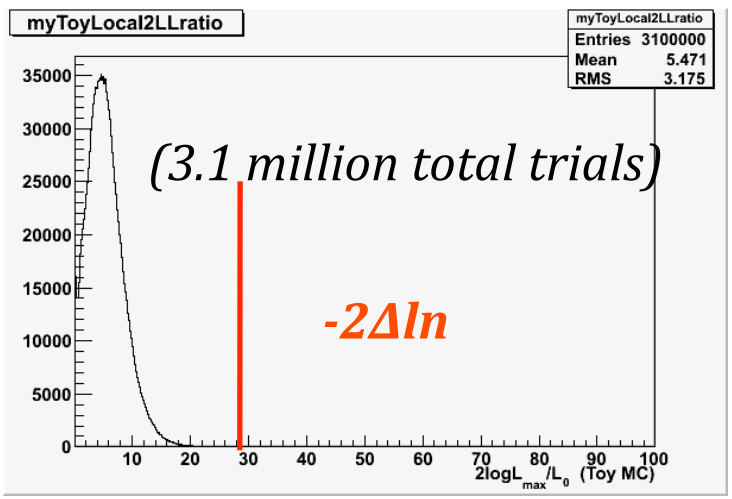
- *We determine significance from simulation (Toy MC):*

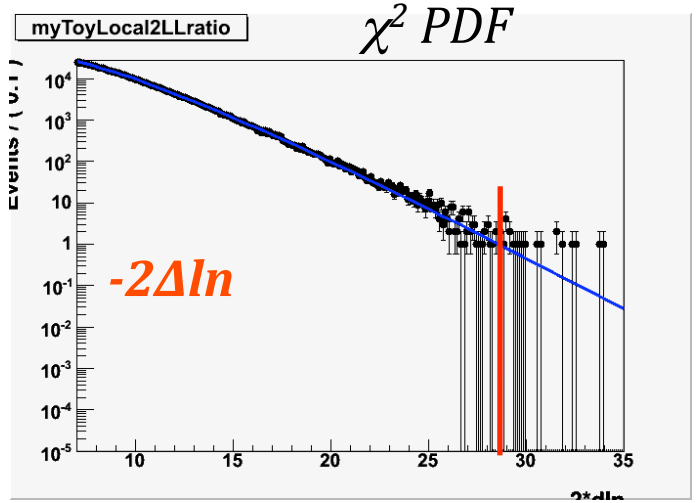
  --Generate Δm spectrum using Phase Space

  --Find most significant fluctuation for each trial anywhere in Δm

  with width in the range between 1.7(resolution) MeV and 120 MeV (10X)

  --Count it if $-2\log(L_{max}/L_0)$ (**-2Δln**) ≥ *-2Δln value in data*



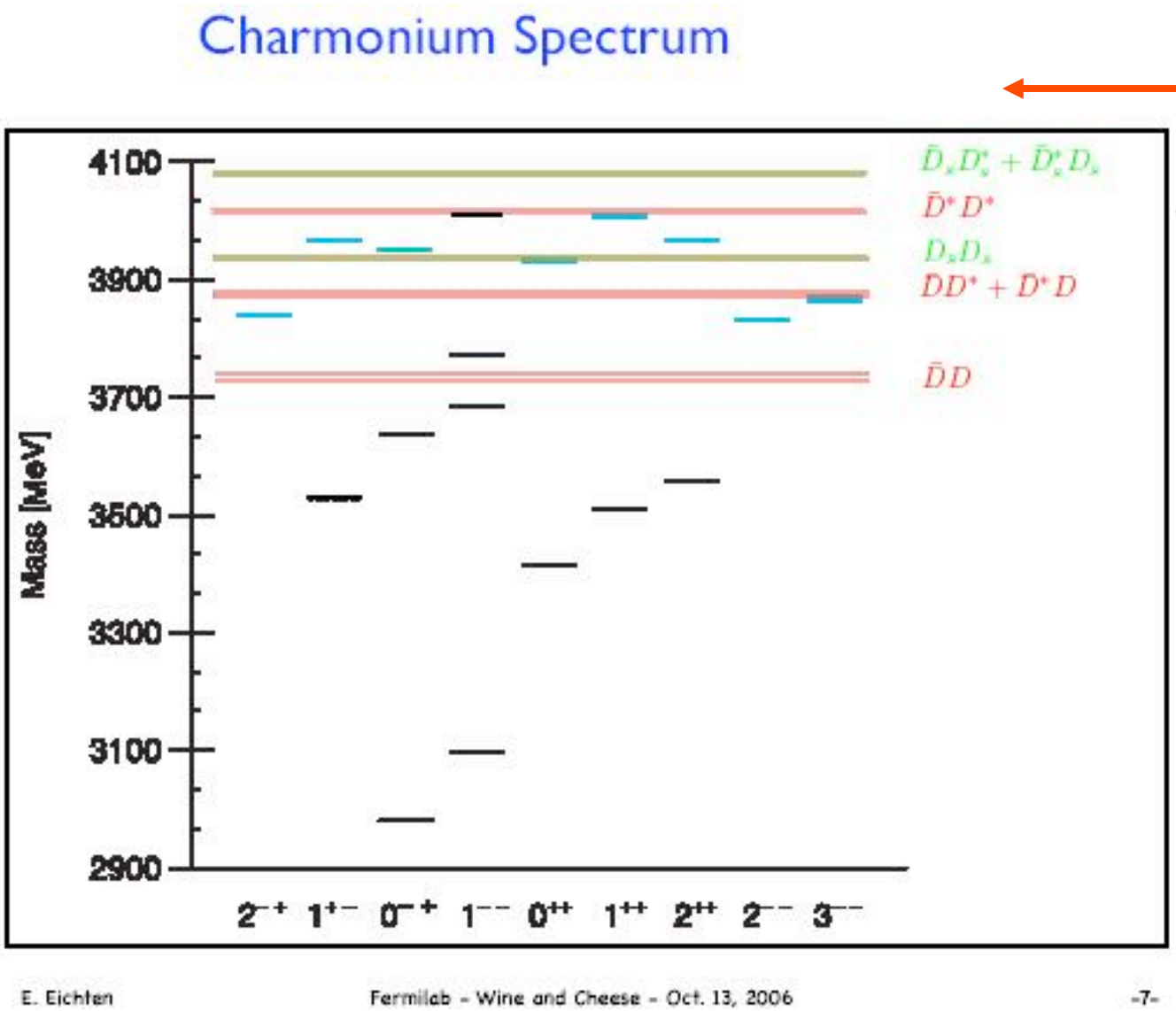


P-value: 9.3X10^{-6} ,corresponding to 4.3σ

P-value from χ^2 ***PDF**: 6.5X10^{-6}, 4.3σ*

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

What is it?



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)*

arXiv:0903.2529[hep-ph]
molecular?

Summary

I. CDF observes a new structure in $J/\psi\phi$ spectrum through B decays, at least 3.8σ

Mass = 4143.0 ± 2.9 (stat)± 1.2 (syst) MeV/c^2

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

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

II. CDF continues to contribute to X(3872):

m(X(3872)) = 3871.61 +- 0.16 (stat) +- 0.19 (syst) MeV/c^2

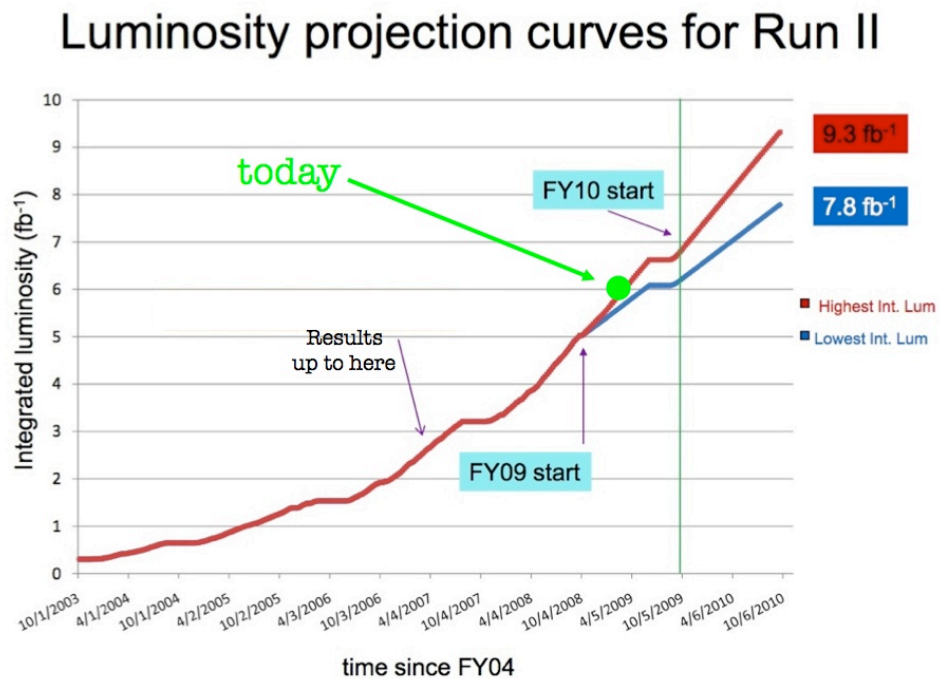
Most precise to date!

Stay tuned!

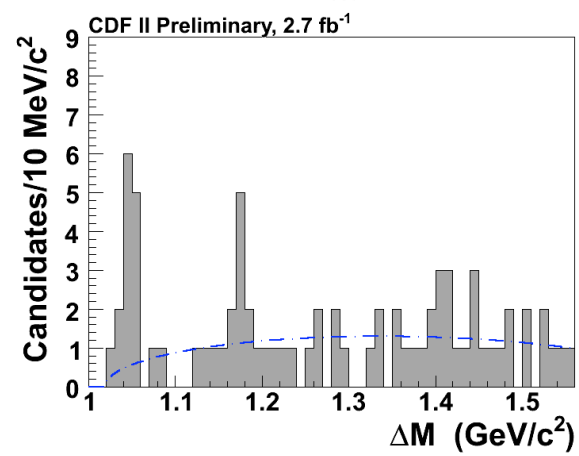
Opportunities

- ***Determine J^{PC} (C=+)? Need statistics***
  --increase efficiency, reduce background
  --add more data, ➔ 5σ
  --investigate efficiencies against angles?
  ...

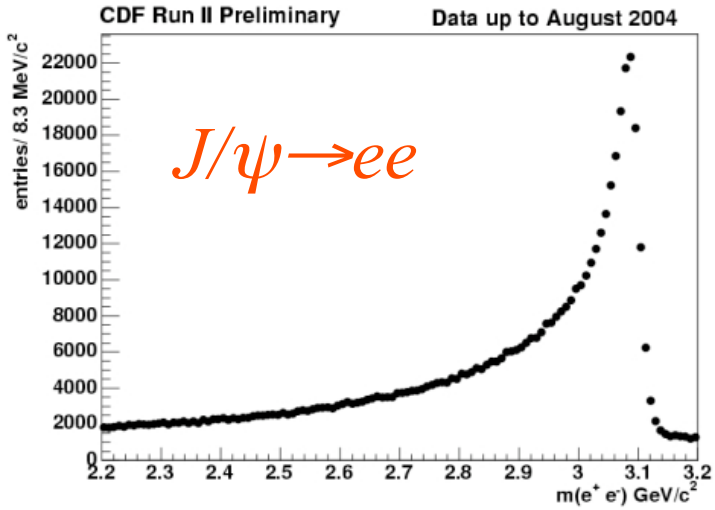
- ***More channels for this structure?***
  --open charm pair?



Note: *Search for potential more structures?*
$B^+ \to \psi(2S)\phi K^+$, $B^+ \to \phi\phi K^+$, $B_s \to J/\psi\phi\phi$
$\Upsilon(nS)\phi$, ...

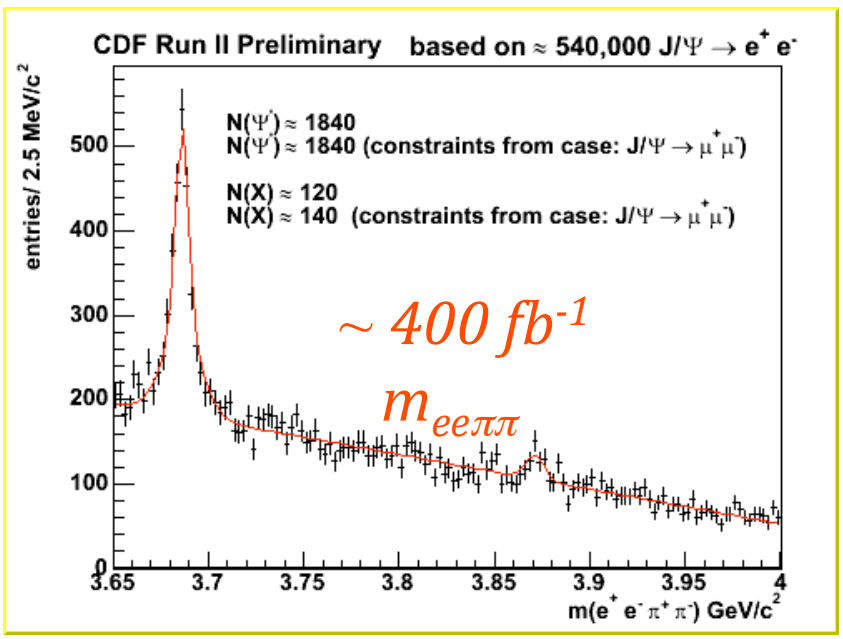


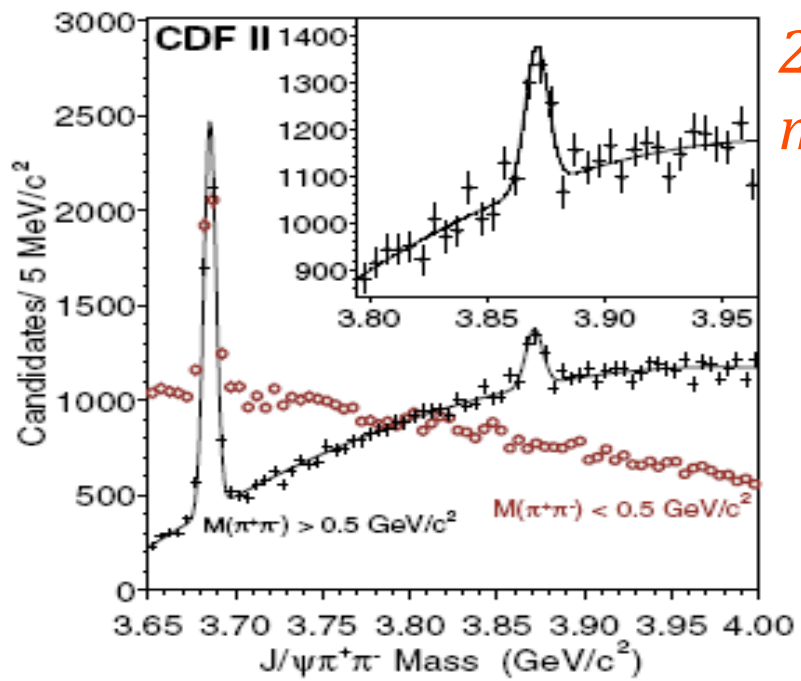
Backup 1



J/ψ→ee is difficult but not impossible

Trigger is gone ☹

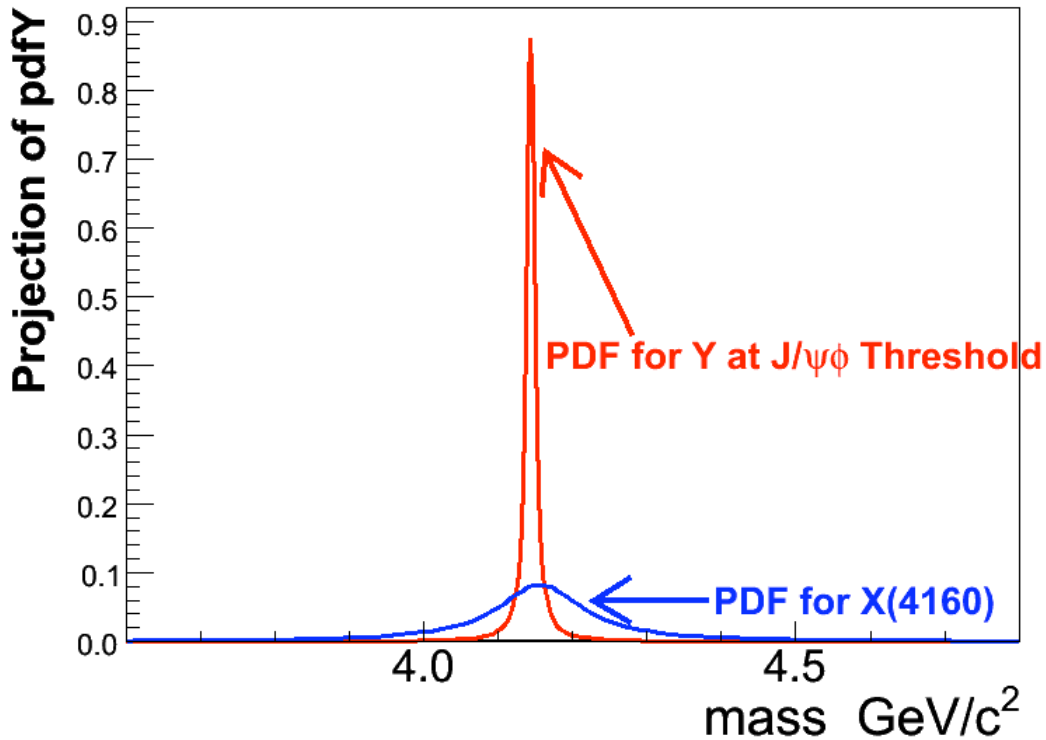




220 fb⁻¹

$m_{\mu\mu\pi\pi}$

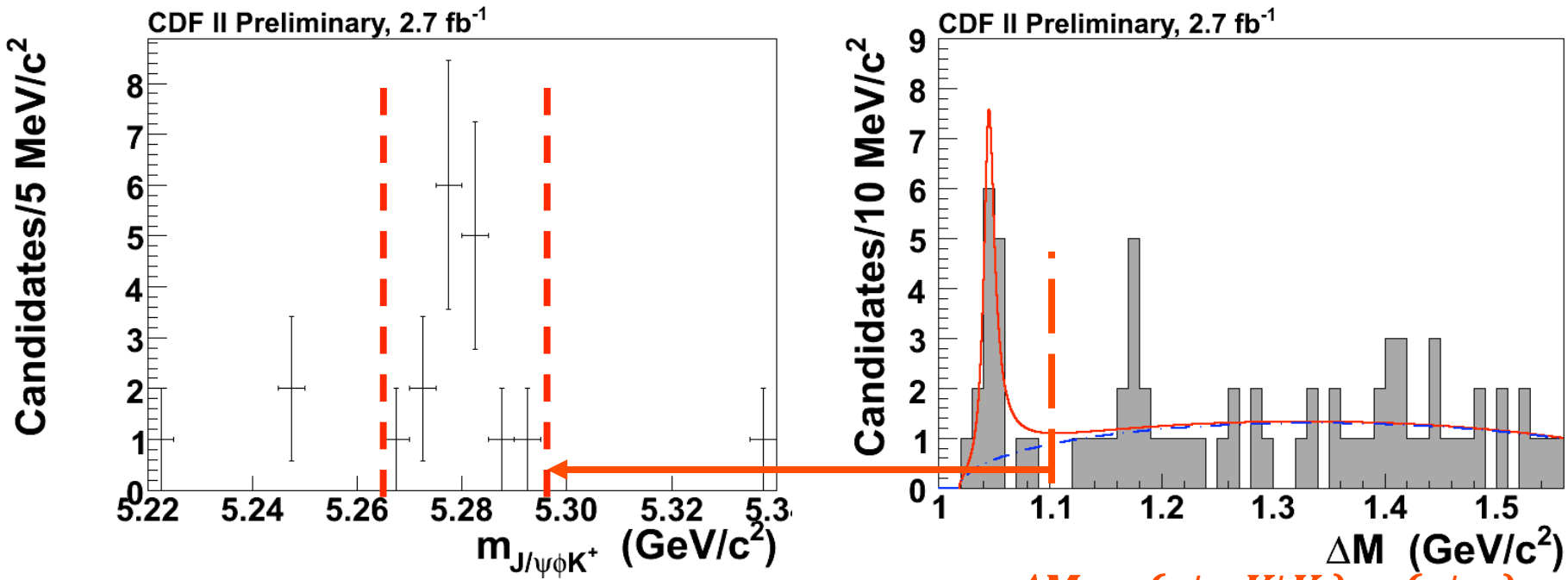
Backup 2



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

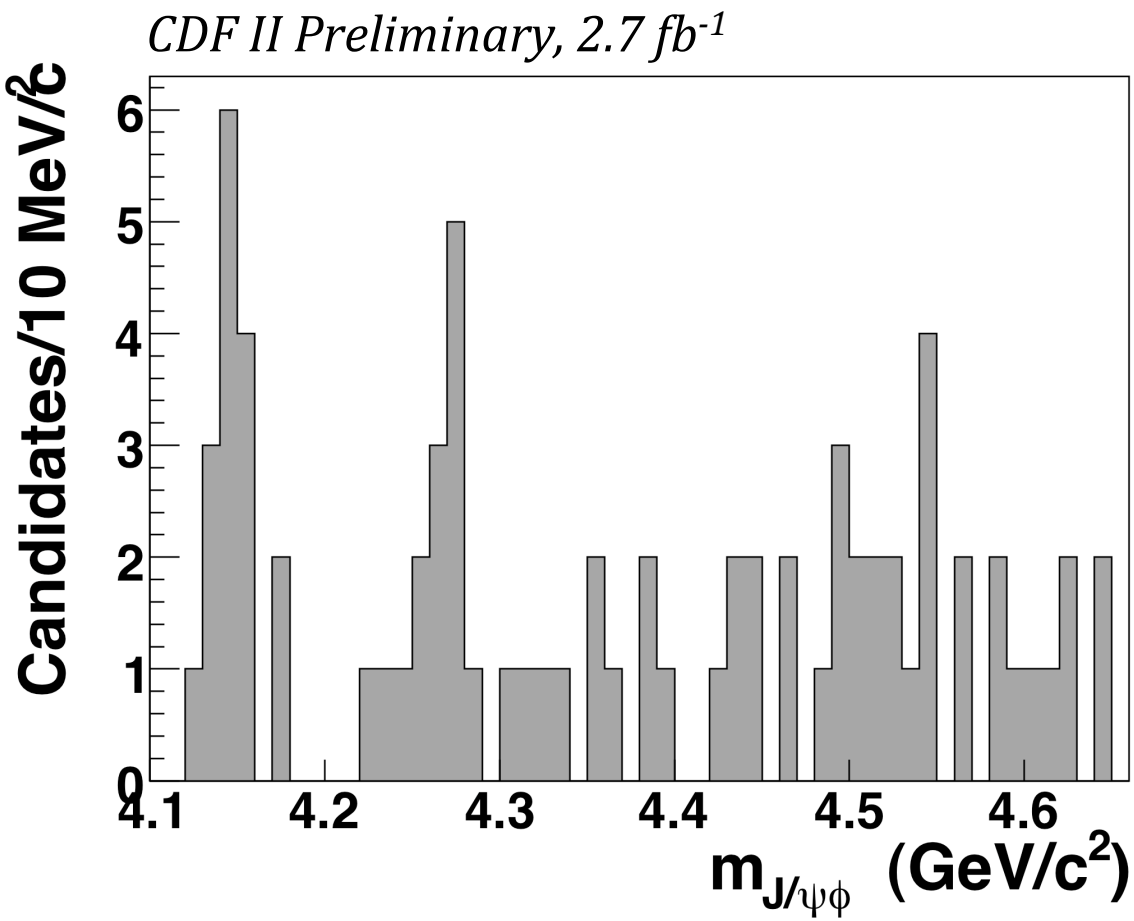
*X(4160)→D*D**

Backup 3

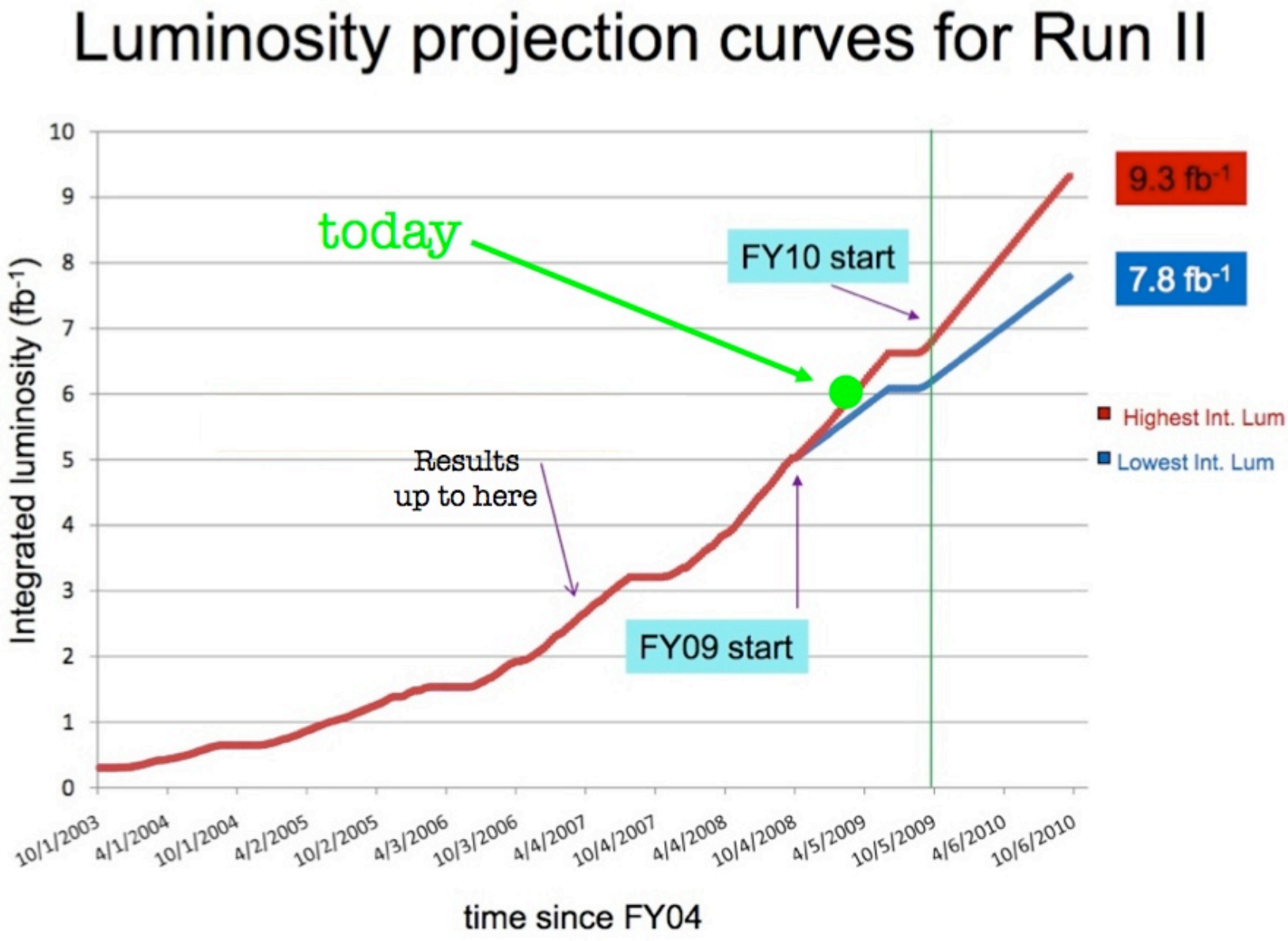


$\Delta M = m(\mu^+\mu^- K^+ K^-) - m(\mu^+\mu^-)$

Backup 4


CDF II Preliminary, 2.7 fb-1
Candidates/10 MeV/c2
0
1
2
3
4
5
6
4.1
4.2
4.3
4.4
4.5
4.6
mJ/ψφ (GeV/c2)

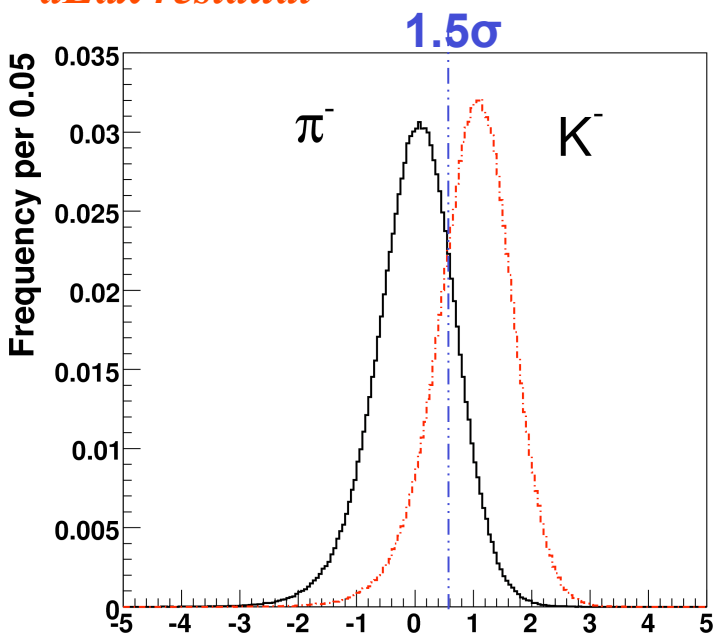
Tevatron


Luminosity projection curves for Run II
Integrated luminosity (fb-1)
10
9
8
7
6
5
4
3
2
1
0
today
FY10 start
Results
up to here
FY09 start
9.3 fb-1
7.8 fb-1
Highest Int. Lum
Lowest Int. Lum
10/1/2003
4/1/2004
10/1/2004
4/2/2005
10/2/2005
4/3/2006
10/3/2006
4/4/2007
10/4/2007
4/4/2008
10/4/2008
4/5/2009
10/5/2009
4/6/2010
10/6/2010
time since FY04

CDF hadron PID

Main background: prompt pions, need PID to suppress

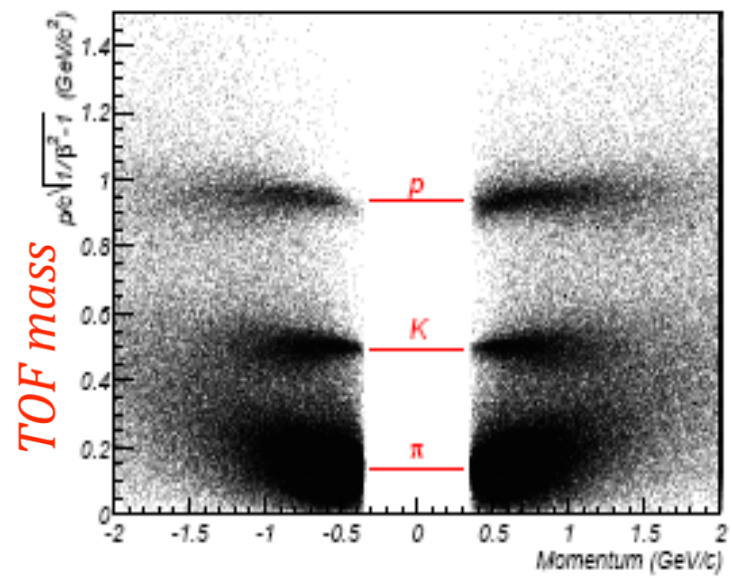
dEdx residual



dE/dx parameterized using $D^{*+(-)} \rightarrow D^0\pi^{+(-)}$ sample

dE/dx efficiency ~100%

CDF Time-of-flight: Tevatron store 860-12/23/2001



Excellent resolution

Time-of-Flight acceptance+efficiency ~60%

Make use of both dEdx and ToF for hadron PID
summarizing dEdx and ToF into a log-likelihood ratio

The challenge

- *Start with typical requirements for B hadron at CDF:*

  --p(χ2) for B^+ vertex fit>1%

  --p_T(track)>0.4 GeV,

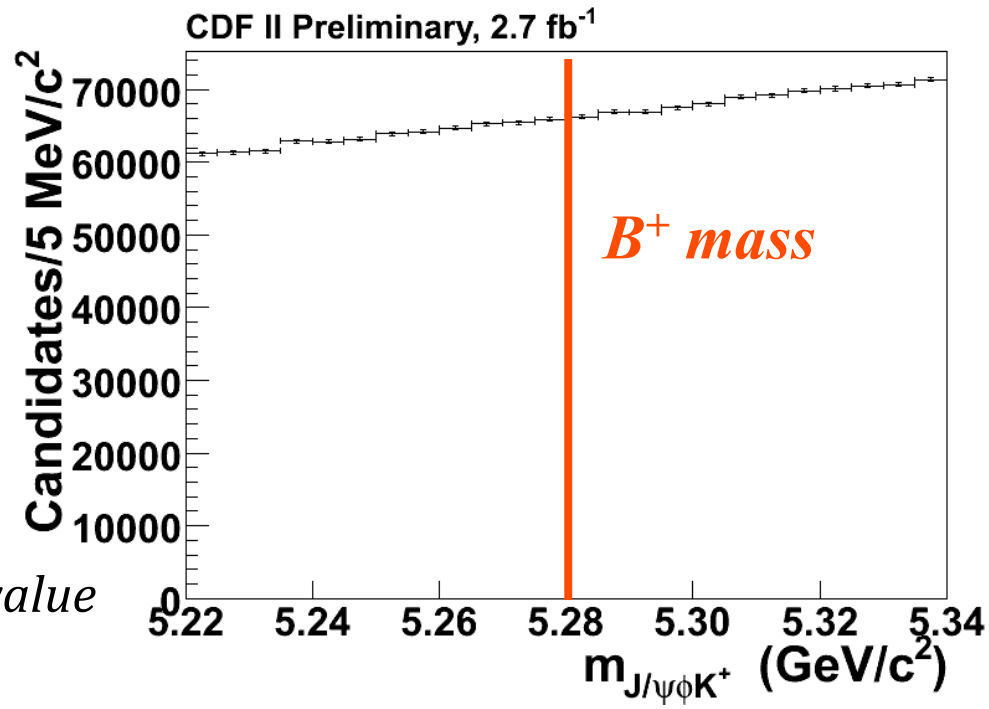
  -- >=4 r-φ silicon hits

  --$p_T(B^+)$>4 GeV

  --mass window:

  J/ψ (±50 MeV) and φ (± 7 MeV)

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

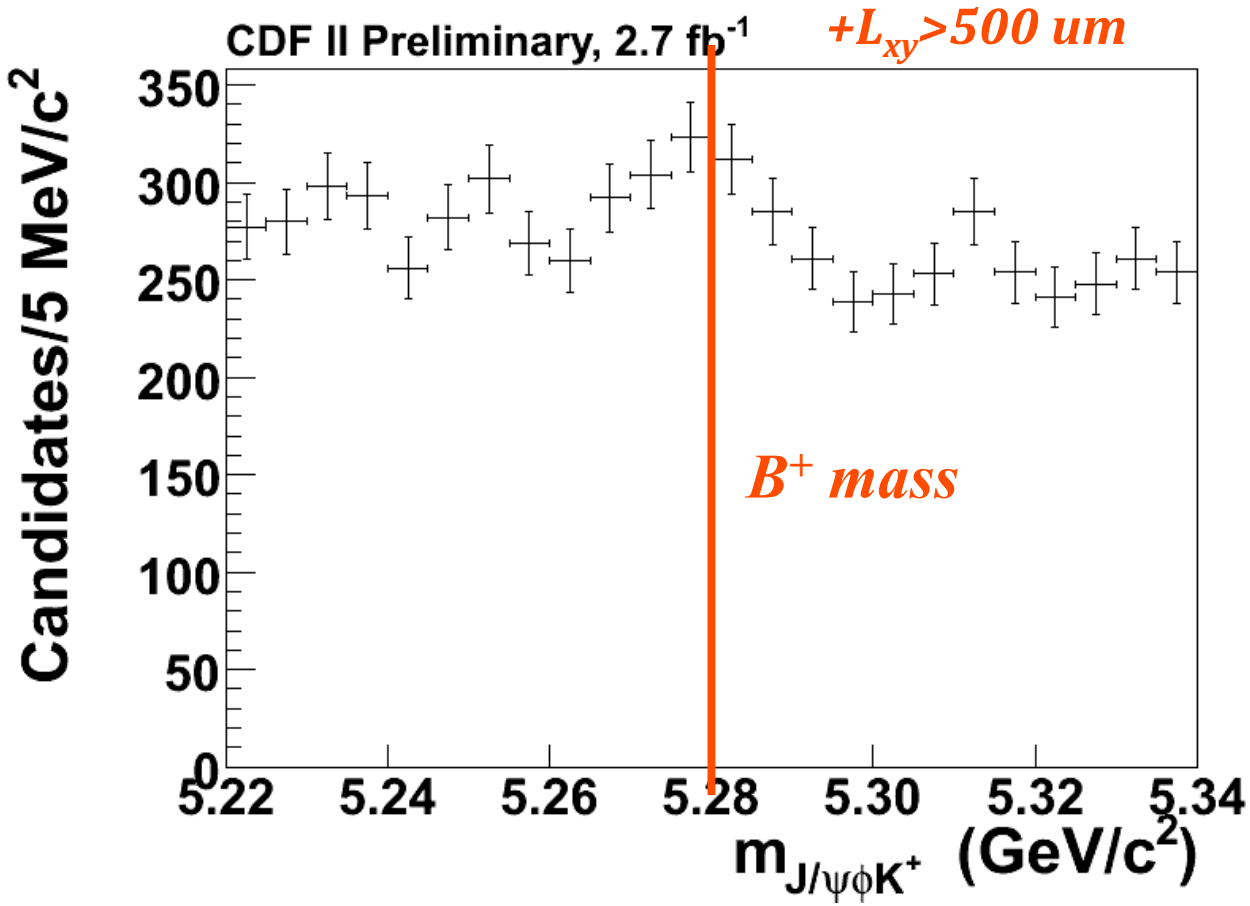


- ***NOT** applied yet: **L_{xy}** and kaon **PID***

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 μm, kaon LLR>0.2*



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

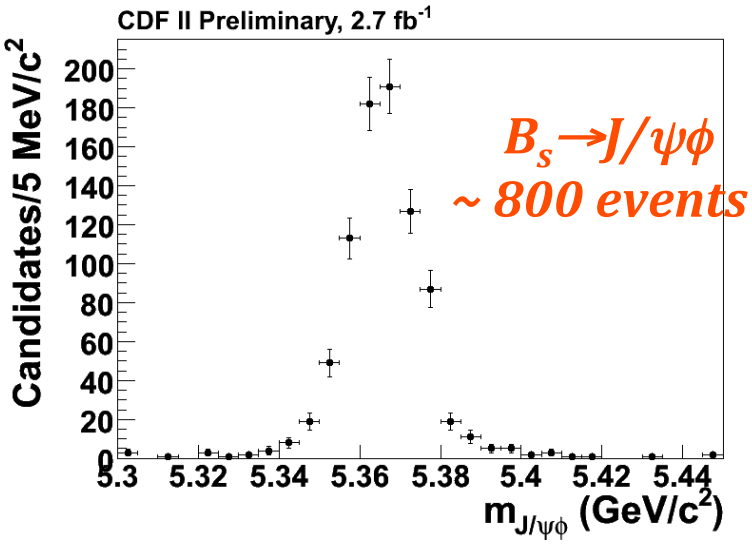
Control channels

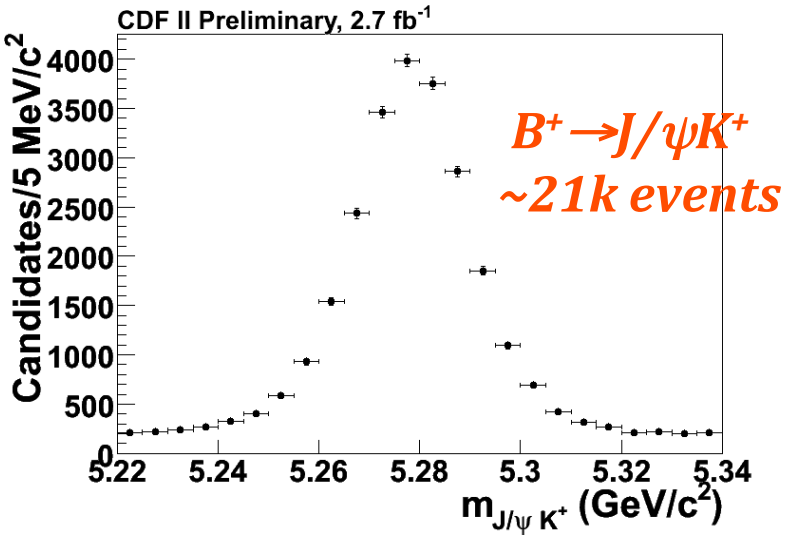
- *We also reconstruct two control channels with similar cuts:*

  ~3 000 $B_s \to J/\psi\phi$, ~50 000 $B^+ \to J/\psi K^+$

  before L_{xy} and kaon LLR cuts

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

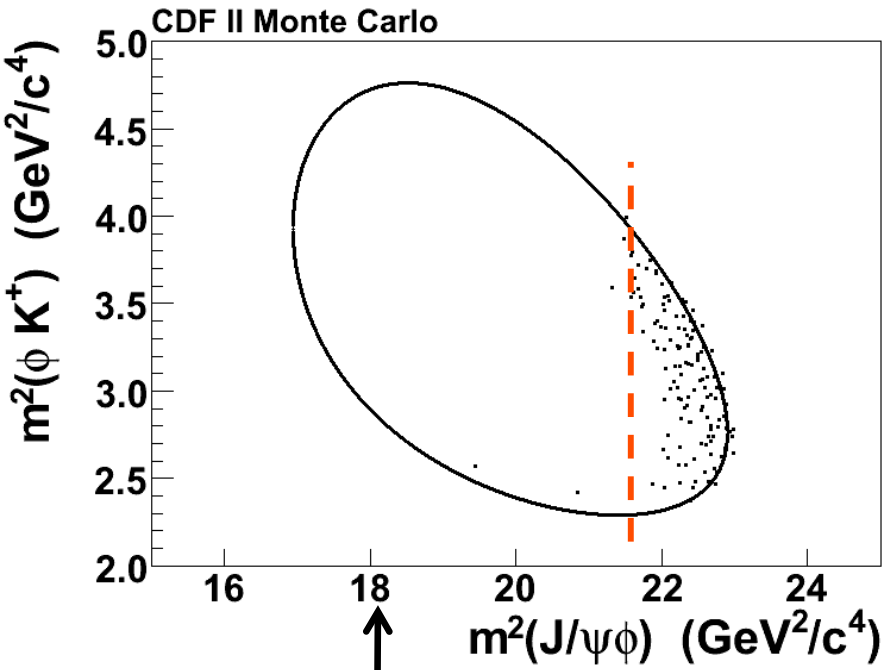




Investigate $J/\psi\phi$ mass spectrum in MC

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

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



20 times Luminosity of data

- *Bs contamination at ΔM>1.56 GeV, cut it off for simplification*