# *Experimental review on Hadron Spectroscopy*

**DPF 2009**

***Wayne State University***

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**Vaia Papadimitriou**
**Fermilab**

# OUTLINE

- **Charmonium and charmonium-like states**
  - X/Y/Z
- **Bottomonium and bottomonium-like states**
  - Yb(10890)
  - $\eta_b$
- **Heavy baryons**
  - $\Sigma_b$, $\Sigma^*{}_b$
  - $\Xi_b$
  - $\Omega_b$
- **Lighter quark spectroscopy**
  - Search for exotic pentaquarks
  - Dalitz plot analyses of B and D decays

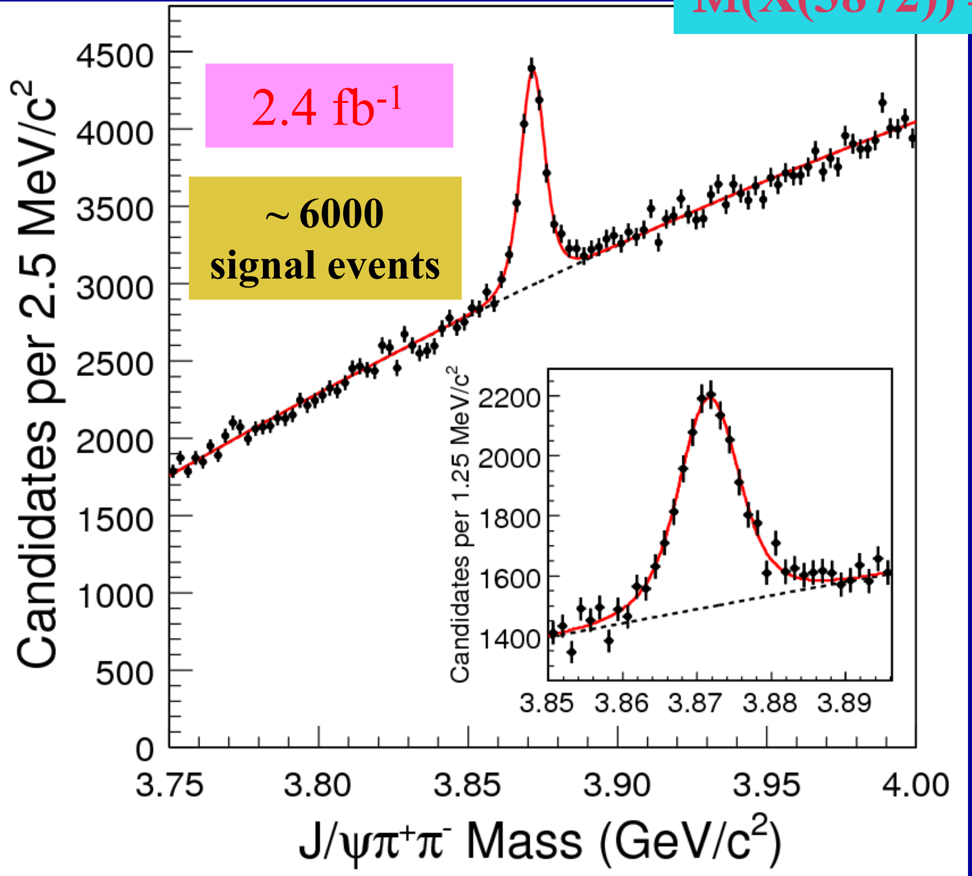
# Quarkonium and Quarkonium-like states

| State | $M$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Decay Modes | Production Modes | Observed also by |
|---|---|---|---|---|---|---|
| $Y_s(2175)$ | $2175 \pm 8$ | $58 \pm 26$ | $1^{--}$ | $\phi f_0(980)$ | $e^+e^-$ (ISR)<br>$J/\psi \to \eta Y_s(2175)$ | BaBar, BESII |
| $X(3872)$ | $3871.4 \pm 0.6$ | $< 2.3$ | $1^{++}$ | $\pi^+\pi^- J/\psi$, $\gamma J/\psi, D\bar{D}^*$ | $B \to KX(3872)$, $p\bar{p}$ | BaBar CDF, D0, |
| $X(3915)$ | $3914 \pm 4$ | $28^{+12}_{-14}$ | $0/2^{++}$ | $\omega J/\psi$ | $\gamma\gamma \to X(3915)$ | |
| $Z(3930)$ | $3929 \pm 5$ | $29 \pm 10$ | $2^{++}$ | $D\bar{D}$ | $\gamma\gamma \to$ **Z(3930)** | |
| $X(3940)$ | $3942 \pm 9$ | $37 \pm 17$ | $0^{?+}$ | $D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$) | $e^+e^- \to J/\psi X(3940)$ | |
| $Y(3940)$ | $3943 \pm 17$ | $87 \pm 34$ | $?^{?+}$ | $\omega J/\psi$ (not $D\bar{D}^*$) | $B \to KY(3940)$ | BaBar |
| $Y(4008)$ | $4008^{+82}_{-49}$ | $226^{+97}_{-80}$ | $1^{--}$ | $\pi^+\pi^- J/\psi$ | $e^+e^-$ (ISR) | |
| $X(4160)$ | $4156 \pm 29$ | $139^{+113}_{-65}$ | $0^{?+}$ | $D^*\bar{D}^*$ (not $D\bar{D}$) | $e^+e^- \to J/\psi X(4160)$ | |
| $Y(4260)$ | $4264 \pm 12$ | $83 \pm 22$ | $1^{--}$ | $\pi^+\pi^- J/\psi$ | $e^+e^-$ (ISR) | BaBar, CLEO |
| $Y(4350)$ | $4361 \pm 13$ | $74 \pm 18$ | $1^{--}$ | $\pi^+\pi^- \psi'$ | $e^+e^-$ (ISR) | BaBar |
| $X(4630)$ | $4634^{+9}_{-11}$ | $92^{+41}_{-32}$ | $1^{--}$ | $\Lambda_c^+\Lambda_c^-$ | $e^+e^-$ (ISR) | |
| $Y(4660)$ | $4664 \pm 12$ | $48 \pm 15$ | $1^{--}$ | $\pi^+\pi^- \psi'$ | $e^+e^-$ (ISR) | |
| $Z(4050)$ | $4051^{+24}_{-23}$ | $82^{+51}_{-29}$ | ? | $\pi^\pm \chi_{c1}$ | $B \to KZ^\pm(4050)$ | |
| $Z(4250)$ | $4248^{+185}_{-45}$ | $177^{+320}_{-72}$ | ? | $\pi^\pm \chi_{c1}$ | $B \to KZ^\pm(4250)$ | |
| $Z(4430)$ | $4433 \pm 5$ | $45^{+35}_{-18}$ | ? | $\pi^\pm \psi'$ | $B \to KZ^\pm(4430)$ | |
| $Y_b(10890)$ | $10,890 \pm 3$ | $55 \pm 9$ | $1^{--}$ | $\pi^+\pi^- \Upsilon(1,2,3S)$ | $e^+e^- \to Y_b$ | |
| **Y(4140)** | **4143.0±3.1** | $11.7^{+9.1}_{-6.2}$ | | **J/ψφ** | | **evidence, CDF only** |

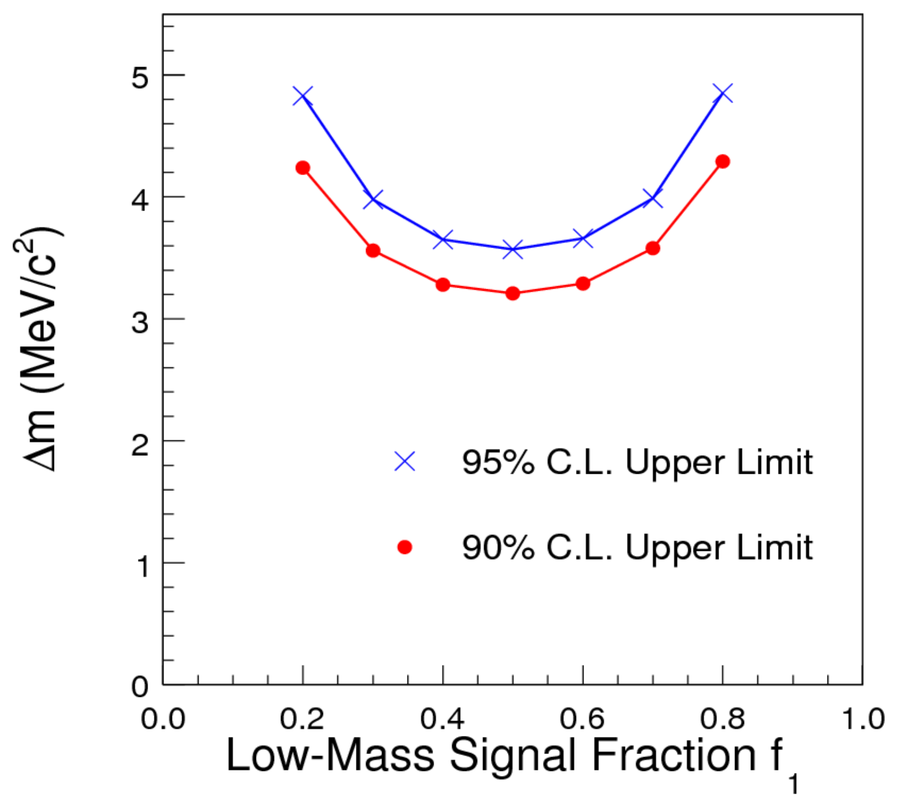
# New X(3872) mass measurement at CDF

arXiv: 0906.5218

$M(X(3872)) = 3871.61 \pm 0.16\,(stat) \pm 0.19\,(syst)\ MeV/c^2$



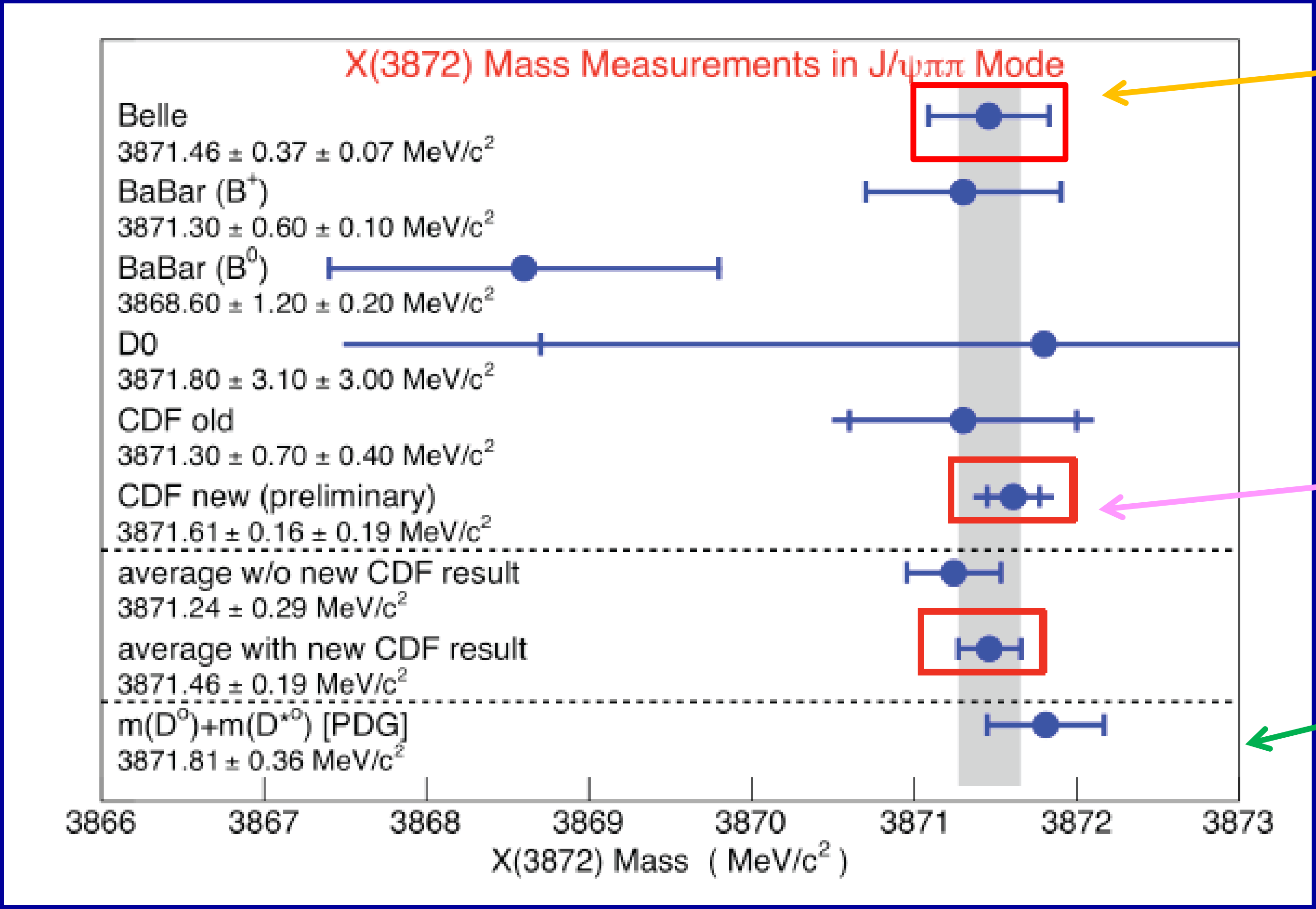

**Upper limit on the mass difference Δm between two states as a function of the fraction $f_1$ of the yield of the lower mass state**




**Four-quark state hypothesis (Maiani et al., PRD 71, 014028, 2005):**

$$\Delta m = (8 \pm 3)\ MeV/c^2$$

# X(3872) Mass




Combining $B^0$ & $B^+$

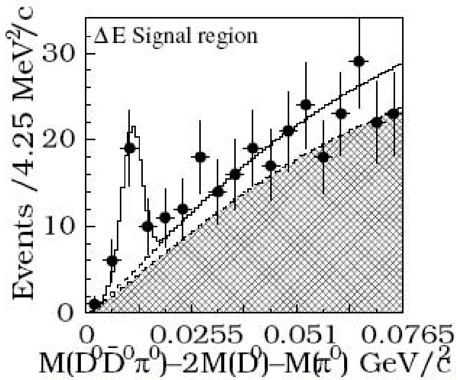
Most precise mass measurement

Molecular model still possible

# Mass of X(3872) in $D^0\overline{D}^{*0}$

Belle PRL97, 162002

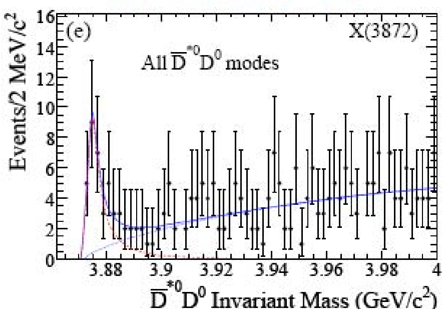
$B \to D^0\overline{D}^0\pi^0 K$




$M = 3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8$ MeV

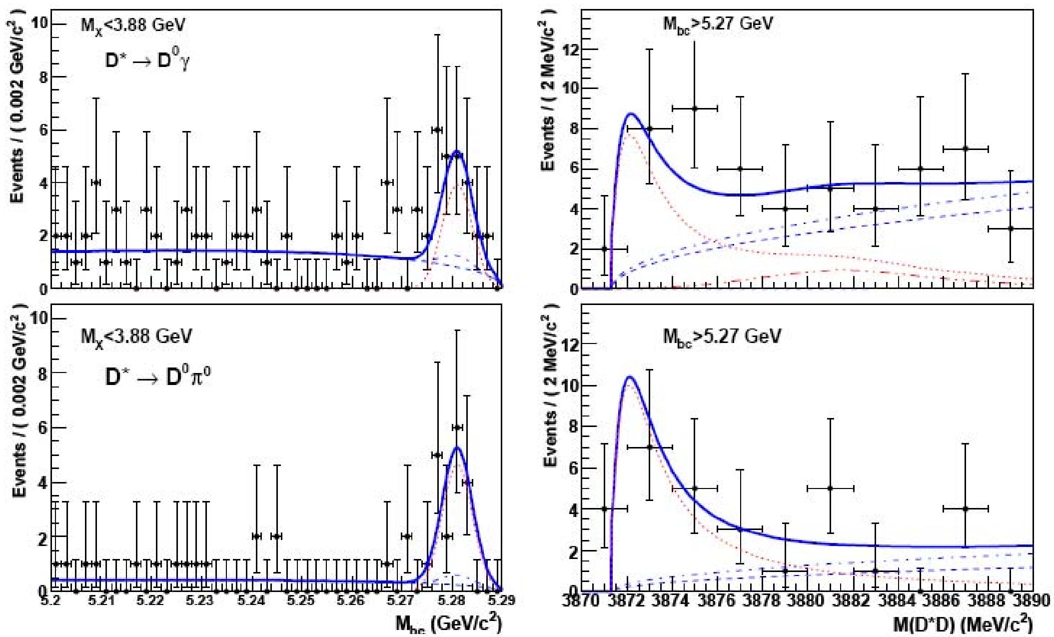
BaBar PRD77, 011102

$B \to D^0\overline{D}^{*0}K$




$M = 3875.1^{+0.7}_{-0.5} \pm 0.5$ MeV

Belle [arXiv:0810.0358]: $B \to D^0\overline{D}^{*0}K$



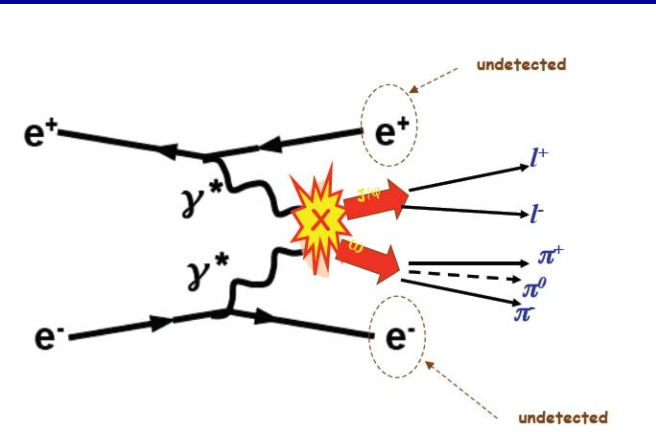

$M = (3872.6^{+0.5}_{-0.4} \pm 0.4)$ MeV

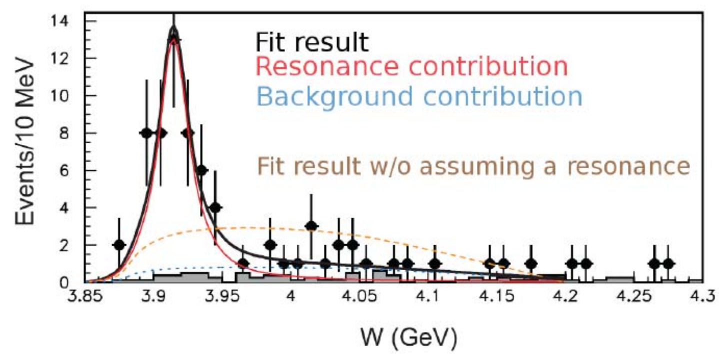
$\Gamma(BW) = 3.9^{+2.5}_{-1.3}{}^{+0.8}_{-0.3}$ MeV

$\mathcal{B}(B \to XK) \times \mathcal{B}(X \to D^0\overline{D}^{*0}) =$
$(0.73 \pm 0.17 \pm 0.08) \times 10^{-4}$

**No significant mass difference from that in $J/\psi\pi\pi$!**

# X(3915) at Belle : $\gamma\gamma \rightarrow \omega J/\psi$




**X(3915)**

$M = 3914 \pm 3 \pm 2$ MeV
$\Gamma = 23 \pm 9^{+2}_{-3}$ MeV
$N_{\mathrm{sig}} = 54 \pm 11 \pm 4$
Significance $= 7.5\sigma$

$\hookrightarrow$ consistent with $Y(3940)$ values!

**same decay mode**

Product of decay width and $\mathcal{B}$

| $J^P$ | $\Gamma_{\gamma\gamma}\mathcal{B}(X(3915) \rightarrow \omega J/\psi)$ |
|---|---|
| $0^+$ | $69 \pm 16^{+7}_{-18}$ eV |
| $2^+$ | $21 \pm 4^{+2}_{-5}$ eV |

For comparison:
$\Gamma_{\gamma\gamma}\mathcal{B}(Z(3930) \rightarrow D\bar{D})$
$= 180 \pm 50 \pm 30$ eV

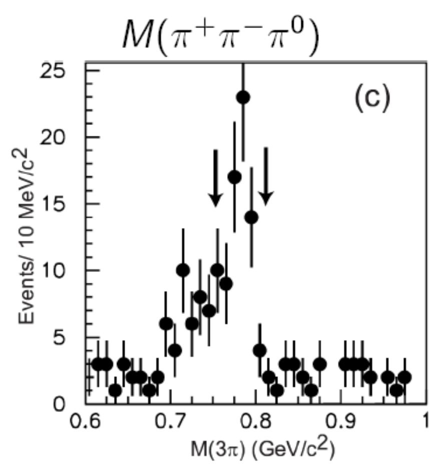
If $X(3915)=Z(3930)=\chi'_{c2}$

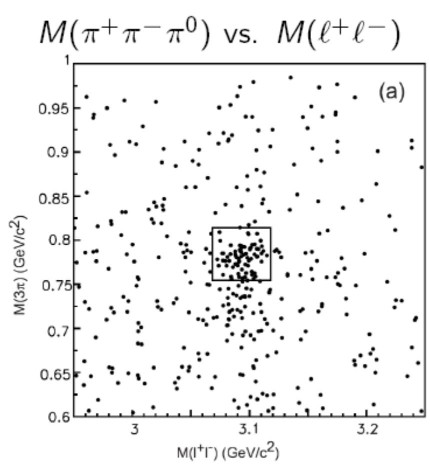
$\Downarrow$

$$\frac{\mathcal{B}(\chi'_{c2} \rightarrow \omega J/\psi)}{\mathcal{B}(\chi'_{c2} \rightarrow D\bar{D})} \geq 0.08$$

Huge for above-open-charm-threshold charmonium!

There are no good $c\bar{c}$ candidates for $X(3940)$, $Y(3940)$ and $X(3915)$.




**Seen in J/ψω**

**not seen in DD***

Belle: PRL94, 182002
$M = 3943 \pm 11 \pm 13$ MeV
$\Gamma = 87 \pm 22 \pm 26$ MeV

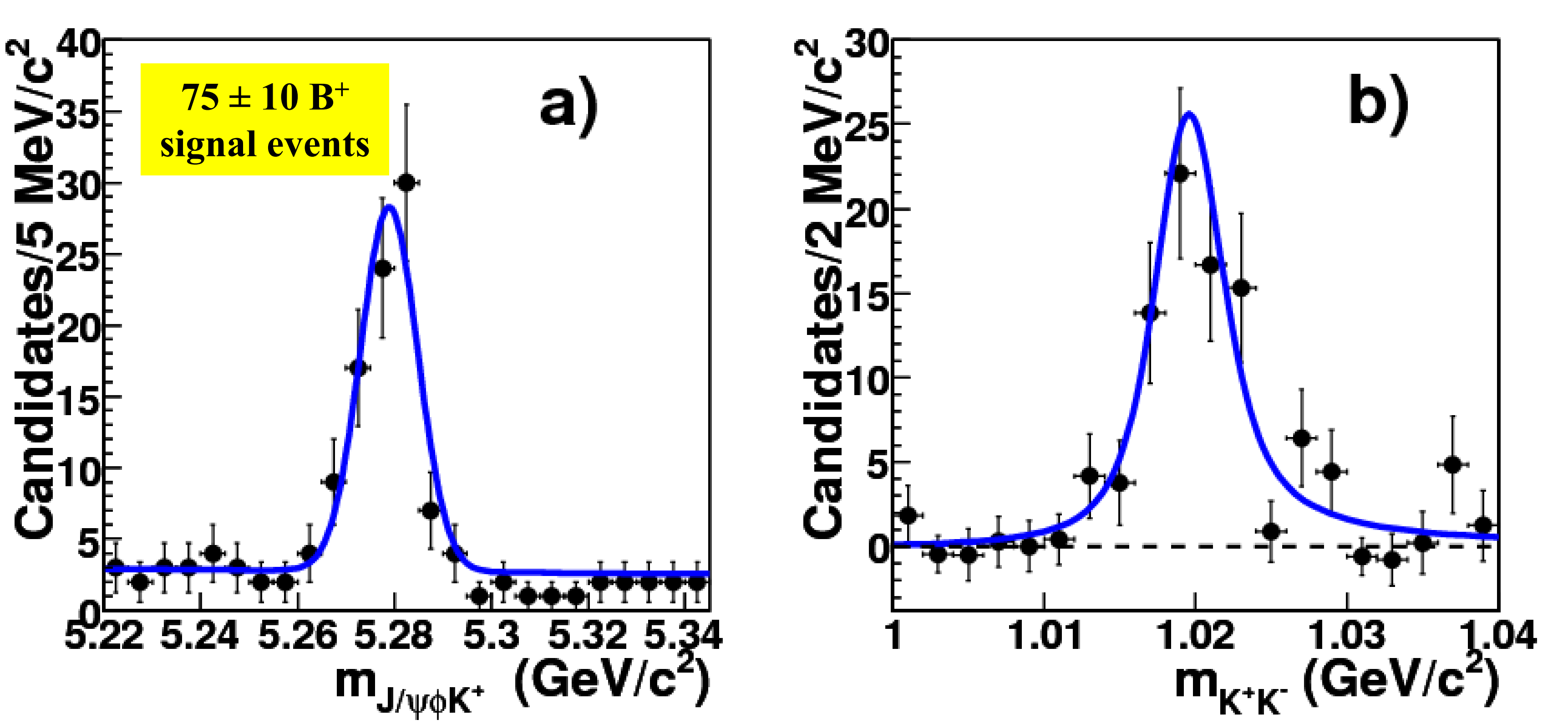
BaBar: PRL101, 082001
$M = 3914.3^{+3.8}_{-3.4} \pm 1.6$ MeV
$\Gamma = 33^{+12}_{-8} \pm 0.6$ MeV

# Evidence for a narrow near-threshold structure in the $J/\psi\phi$ mass spectrum: Y(4140)

PRL 102, 242002 (2009)

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

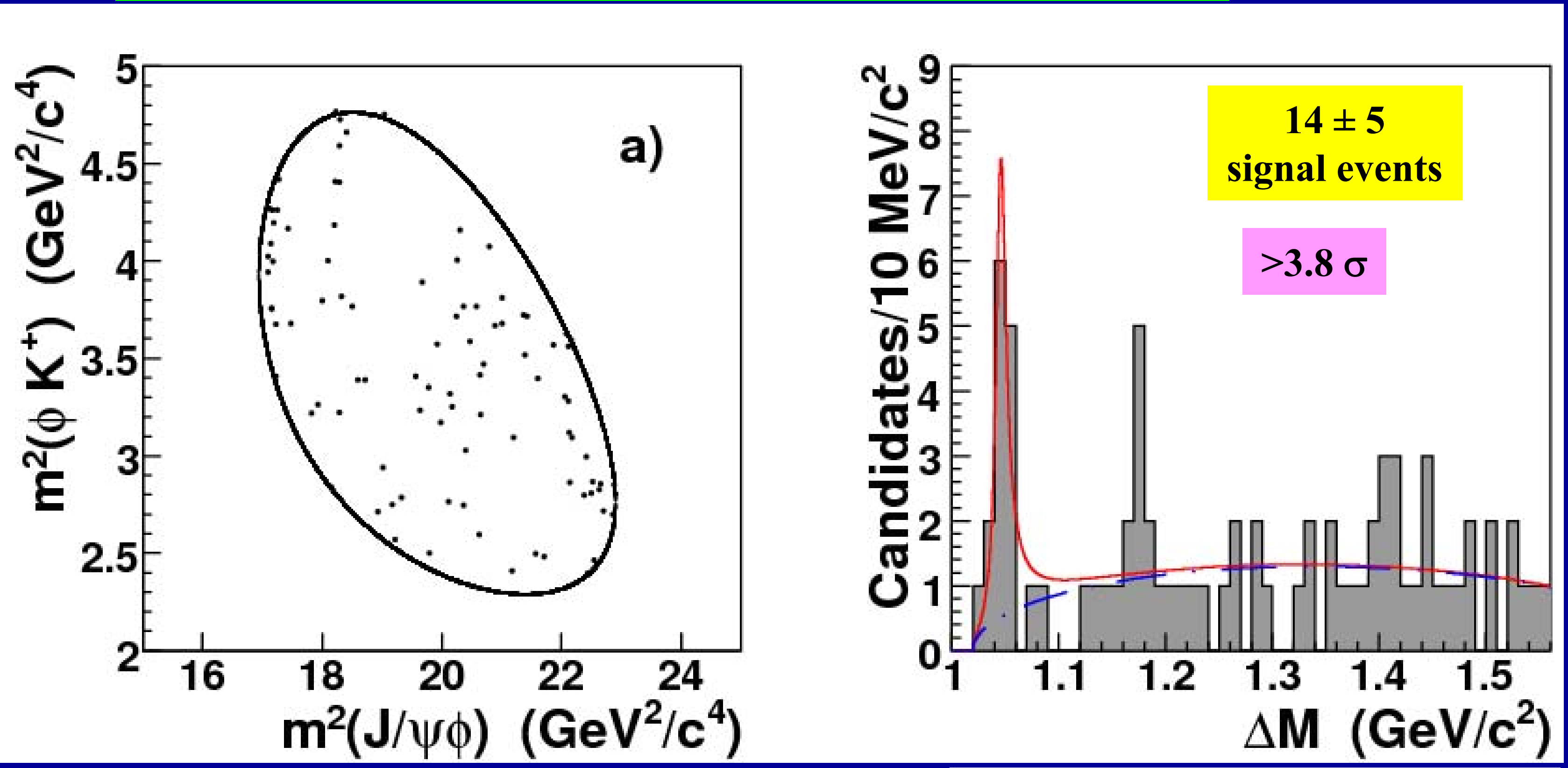
2.7 $fb^{-1}$



# Evidence for a narrow near-threshold structure in the J/ψφ mass spectrum : Y(4140)

$$m = 4143.0 \pm 2.9\,(\text{stat}) \pm 1.2\,(\text{syst})\ \text{MeV/c}^2$$

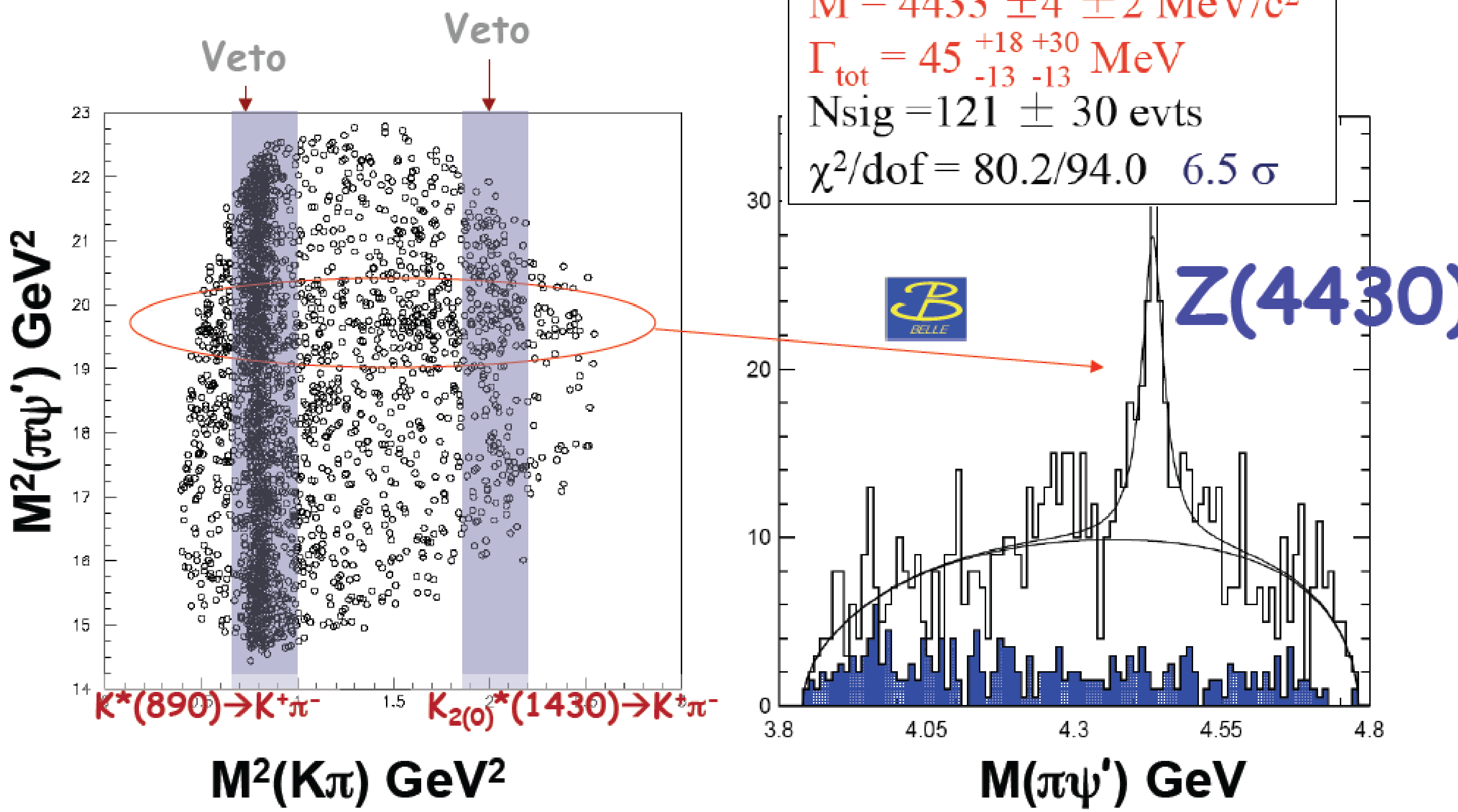
$$\Gamma = 11.7\ ^{+8.3}_{-5.0}\,(\text{stat}) \pm 3.7\,(\text{syst})\ \text{MeV/c}^2$$




$$m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$$

# $Z^{\pm}(4430)$

## $M(\pi^{\pm}\psi')$ from $B \to K \pi^{\pm} \psi'$

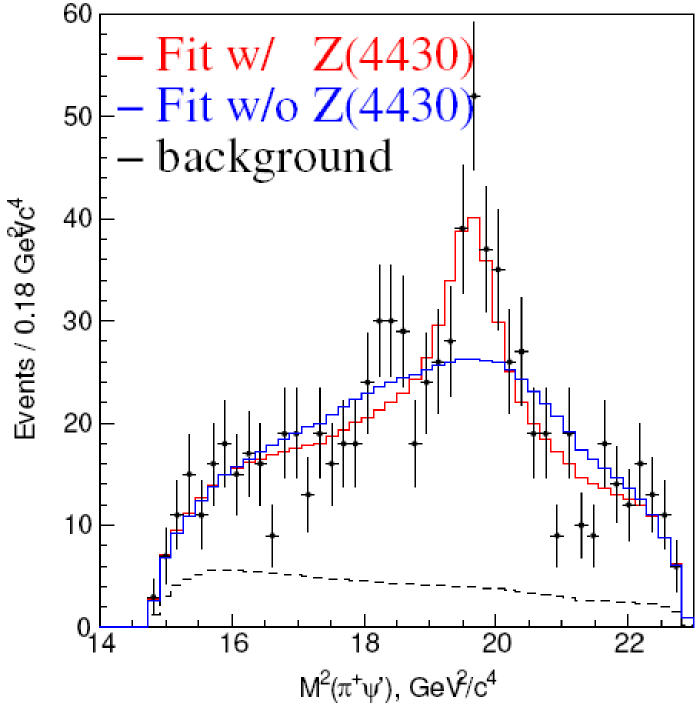



PRL 100, 142001 (2008)

$BF(B0 \to K^- Z^+) \times BF(Z^+ \to \psi(2S)\pi^+) = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$

# $Z^{\pm}(4430)$ : Full Dalitz plot analysis

**Belle confirms the original result on $Z^{\pm}(4430)$**




Belle: arxiv:0905.2869 (PRD)

Significance $= 6.4\sigma$

$$M = 4433^{+15+19}_{-12-13}\ \text{MeV}$$

$$\Gamma = 107^{+86+74}_{-43-56}\ \text{MeV}$$

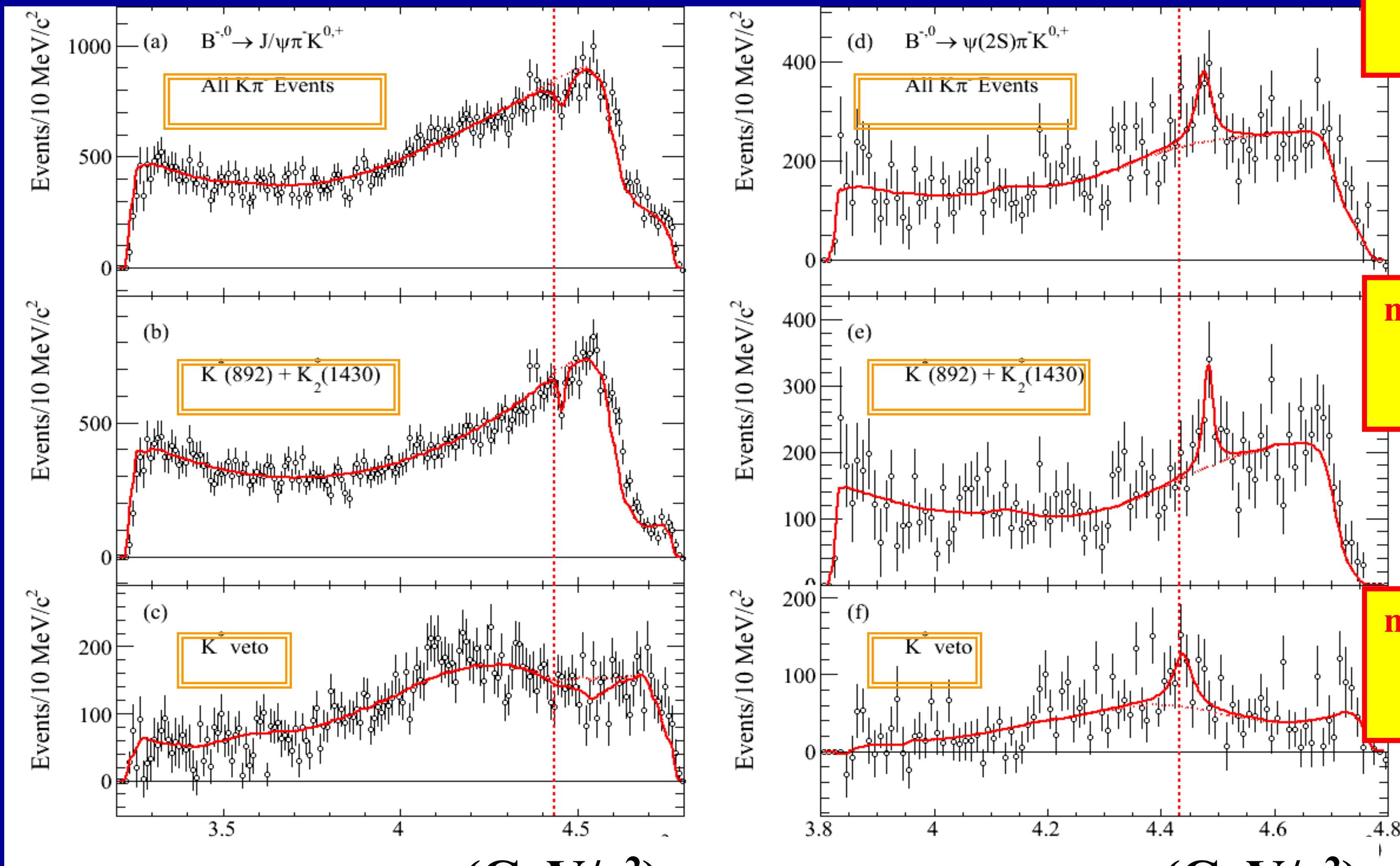
$$\mathcal{B}(B \to KZ(\psi(2S)\pi^+)) = (3.2^{+1.8+5.3}_{-0.9-1.6}) \times 10^{-5}$$

Width larger than in original analysis (45 MeV) but uncertainties are also larger.

**Systematic study: $Z^{\pm}(4430)$ significance in different fit models always $> 5.4\sigma$!**

# Fits to the corrected $m_{\psi\pi^-}$ distributions

## Four free parameters; $m_Z$, $\Gamma_Z$, $N_Z$, and $N_{K\pi^-,bkg}$




$m_{J/\psi\pi^-}$ (GeV/$c^2$)

$m_{\psi(2S)\pi^-}$ (GeV/$c^2$)

**m=4476±8**
**Γ=32±16**
**2.7σ**

**m=4483±3**
**Γ=17±12**
**2.5σ**

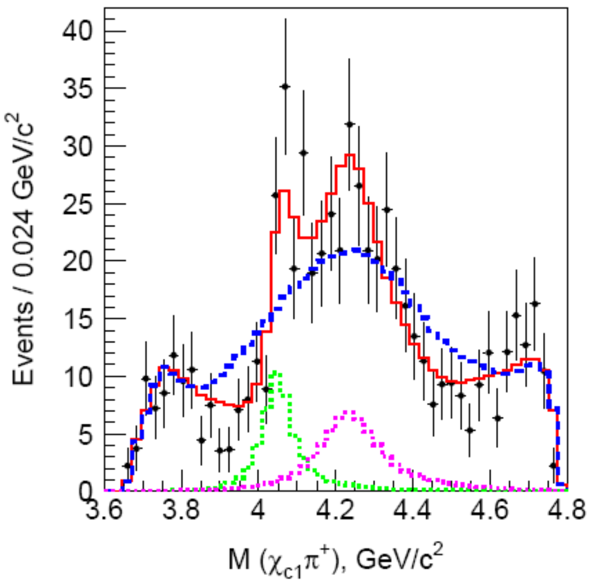
**m=4439±8**
**Γ=41±33**
**1.9σ**

BABAR

**No significant Z(4430)- signal…**

# $Z^{\pm}(4050)$ and $Z^{\pm}(4250)$ decaying to $\pi^+\chi_{c1}$

**Belle data favour fit with two new resonant structures**




– only known $K^*$ (C.L.$= 3 \times 10^{-10}$)
– $+Z(4050) + Z(4250)$ (C.L.$= 42\%$)
– $Z(4050)$ contribution
– $Z(4250)$ contribution

Belle: PRD78, 072004

| | $Z(4050)^+$ | $Z(4250)^+$ |
|---|---|---|
| $M$ [MeV] | $4051 \pm 14^{+29}_{-41}$ | $4248^{+44}_{-29}{}^{+180}_{-35}$ |
| $\Gamma$ [MeV] | $82^{+21}_{-16}{}^{+47}_{-22}$ | $177^{+54}_{-39}{}^{+316}_{-61}$ |
| $\mathcal{B}_{\overline{B^0}} \cdot \mathcal{B}_{Z^+}$ | $3.0^{+1.5}_{-0.8}{}^{+3.7}_{-1.6} \times 10^{-5}$ | $4.0^{+2.3}_{-0.9}{}^{+19.7}_{-0.5} \times 10^{-5}$ |

- **double resonant structure is distinctive (favoured over one res. at the 5.7$\sigma$)**
- spin of $Z_{1,2}$ not determined ($J = 0$ or 1 give comparable results)
- large syst. errors on $M$ and $\Gamma$ due to model uncertainties
- $\mathcal{B}$'s comparable to $Z^+(4430)$, $X(3872)$, ...

**$Z^+(4050)$ and $Z^+(4250)$ join $Z^+(4430)$ as charged charmonium-like exotics**

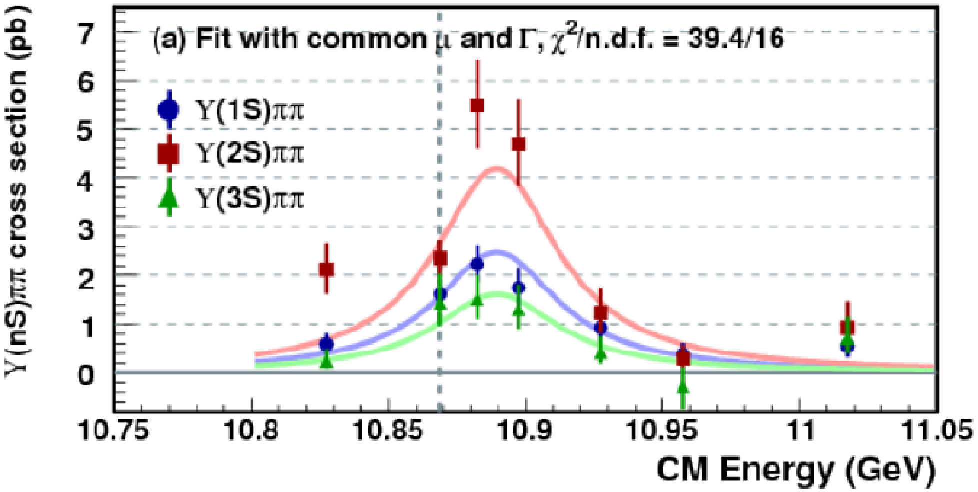
# Bottomonium and bottomonium-like states

***Bottomonium and bottomonium-like states***

# Υ(nS)ππ production: Observation of Yb(10890)

**Energy scan: 7/fb collected between $\Upsilon(5S)$ and $\Upsilon(6S)$**

preliminary




Fit all three cross-sections with the same BW:

| | $\pi\pi\Upsilon(1S)$ | $\pi\pi\Upsilon(2S)$ | $\pi\pi\Upsilon(3S)$ |
|---|---|---|---|
| peak [pb] | $2.46^{+0.27}_{-0.25} \pm 0.18$ | $4.18^{+0.49}_{-0.46} \pm 0.55$ | $1.61^{+0.31}_{-0.28} \pm 0.21$ |
| $M$ [MeV] | $10889.6 \pm 1.8 \pm 1.6$ | | |
| $\Gamma$ [MeV] | $54.7^{+8.5}_{-7.2} \pm 2.5$ | | |

The structure is different from known $\Upsilon(5S)/10860$

- Mean is $\sim$ 20 MeV higher
- Width is two times smaller

Is it a bottomonium counterpart to $1^{--}$ states seen in $c$-quarks sector?
W.S. Hou PRD74, 017504

# The Inclusive Photon Spectrum in Υ(3S) Data

## Observation of the $\eta_b$

**Peaking background components (1):**

$\Upsilon(3S) \to \chi_{b0}(2P)\,\gamma^{soft}$ $E(\gamma^{soft}) = 122$ MeV
↳ $\Upsilon(1S)\,\gamma^{hard}$ $E(\gamma^{hard}) = 743$ MeV

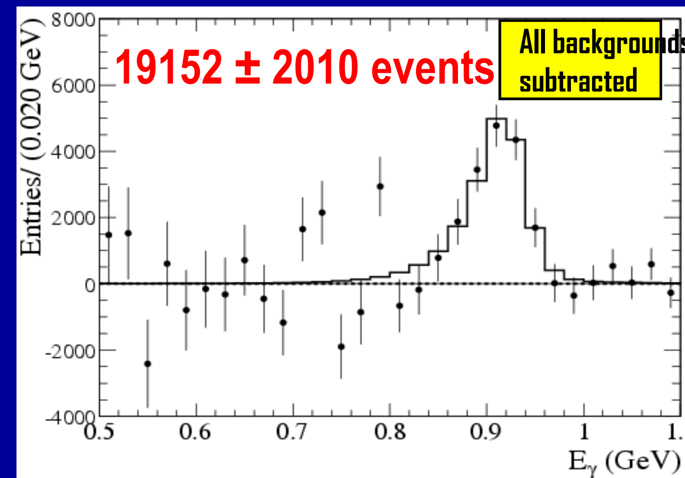
$\Upsilon(3S) \to \chi_{b1}(2P)\,\gamma^{soft}$ $E(\gamma^{soft}) = 99$ MeV
↳ $\Upsilon(1S)\,\gamma^{hard}$ $E(\gamma^{hard}) = 764$ MeV

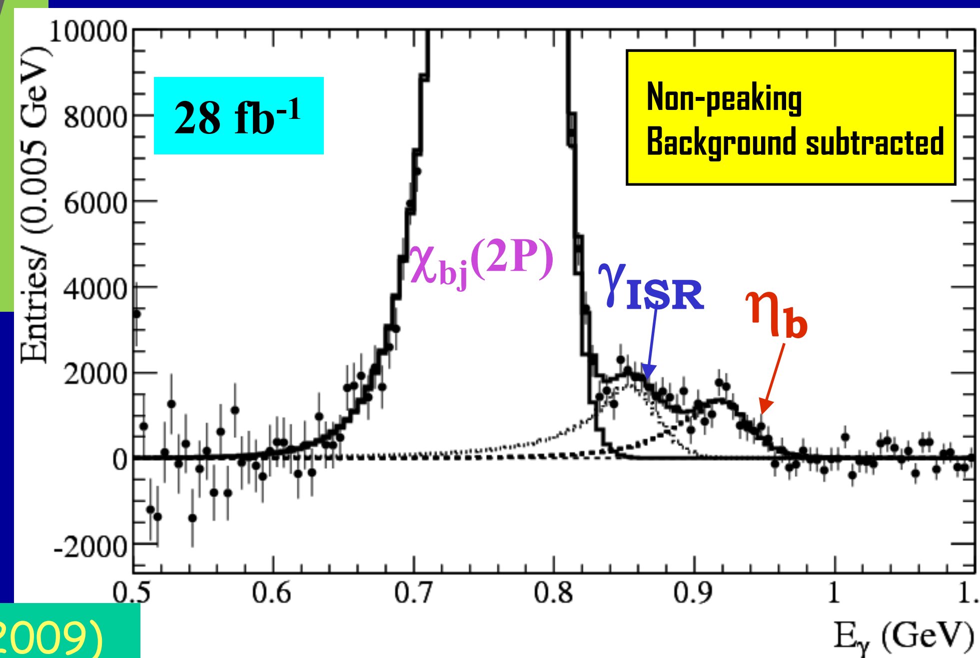
$\Upsilon(3S) \to \chi_{b2}(2P)\,\gamma^{soft}$ $E(\gamma^{soft}) = 86$ MeV
↳ $\Upsilon(1S)\,\gamma^{hard}$ $E(\gamma^{hard}) = 777$ MeV

$\Upsilon(3S) \to \chi_{bJ}(2P)\,\gamma^{soft}$
(J=0,1,2) ↳ $\Upsilon(1S)\,\gamma^{hard}$

**Peaking background component (2):**

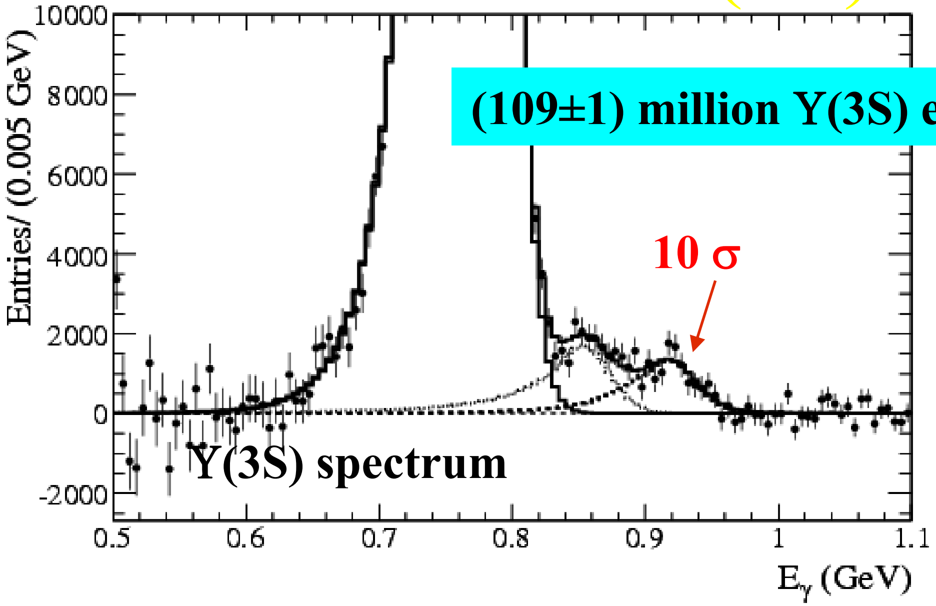
**Radiative return from Υ(3S) to Υ(1S):** $e^+e^- \to \gamma_{ISR}\,\Upsilon(1S)$

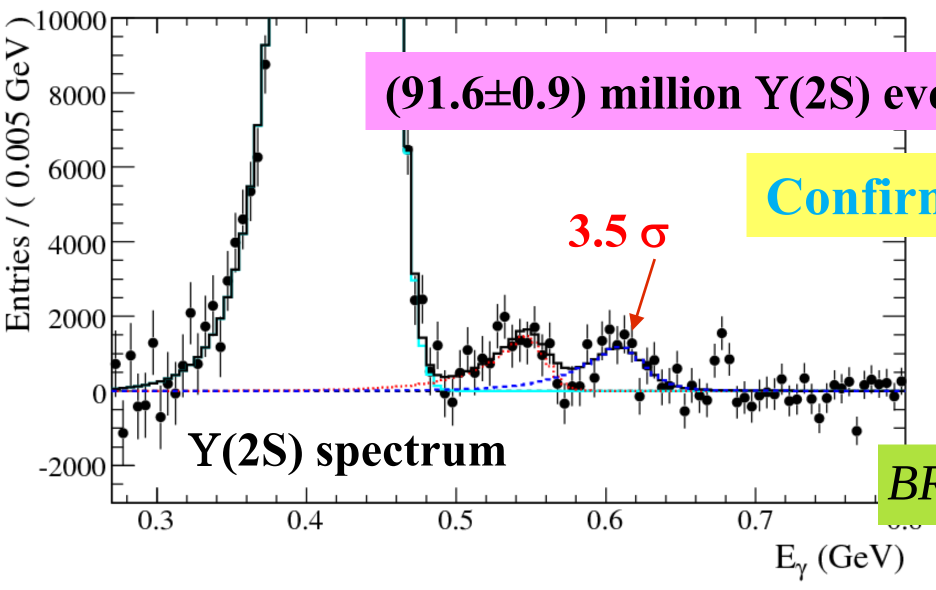



PRL 101, 071801 (2008), PRL 102, 029901 E (2009)

# Comparison of Eγ Spectra Υ(3S) and Υ(2S)




**Non-peaking Background subtracted**

**Comparison with Υ(3S) → γ $\eta_b$ Analysis:**

- ☛ **Better photon energy resolution at lower energy**
  - ➔ **better separation between peaks**
- ☛ **More random photon background at lower energy**
  - ➔ **less significance at similar BF**

**Confirmation with the Υ(2S) analysis**

$$BR(\Upsilon(3S)\rightarrow\gamma\eta_b)=(4.8\pm0.5\pm0.6)\mathrm{x}10^{-4}$$

$$BR(\Upsilon(2S)\rightarrow\gamma\eta_b)=(4.2^{+1.1}_{-1.0}\pm0.9)\mathrm{x}10^{-4}$$

$$BR(\Upsilon(2S)\rightarrow\gamma\eta_b)/BR(\Upsilon(3S)\rightarrow\gamma\eta_b)=0.89^{+0.25+0.12}_{-0.23-0.16}$$

**Theory: 0.3-0.7**

# Summary of $\eta_b$ Results

- $\eta_b$ mass:

$$\Upsilon(3S) \quad \text{analysis} \;: \qquad m(\eta_b) = 9388.9^{+3.1}_{-2.3} \pm 2.7 \;\; \text{MeV}/c^2$$

PRL 101, 071801 (2008)

$$\Upsilon(2S) \quad \text{analysis} \;: \qquad m(\eta_b) = 9392.9^{+4.6}_{-4.8} \pm 1.8 \;\; \text{MeV}/c^2$$

arXiv : 0903.1124 (submitted to PRL)

- Hyperfine splitting:

$$\Upsilon(3S) \quad \text{analysis} \;: \qquad m(\Upsilon(1S)) - m(\eta_b) = 71.4^{+2.3}_{-3.1} \pm 2.7 \;\; \text{MeV}/c^2$$

$$\Upsilon(2S) \quad \text{analysis} \;: \qquad m(\Upsilon(1S)) - m(\eta_b) = 67.4^{+4.8}_{-4.6} \pm 1.9 \;\; \text{MeV}/c^2$$

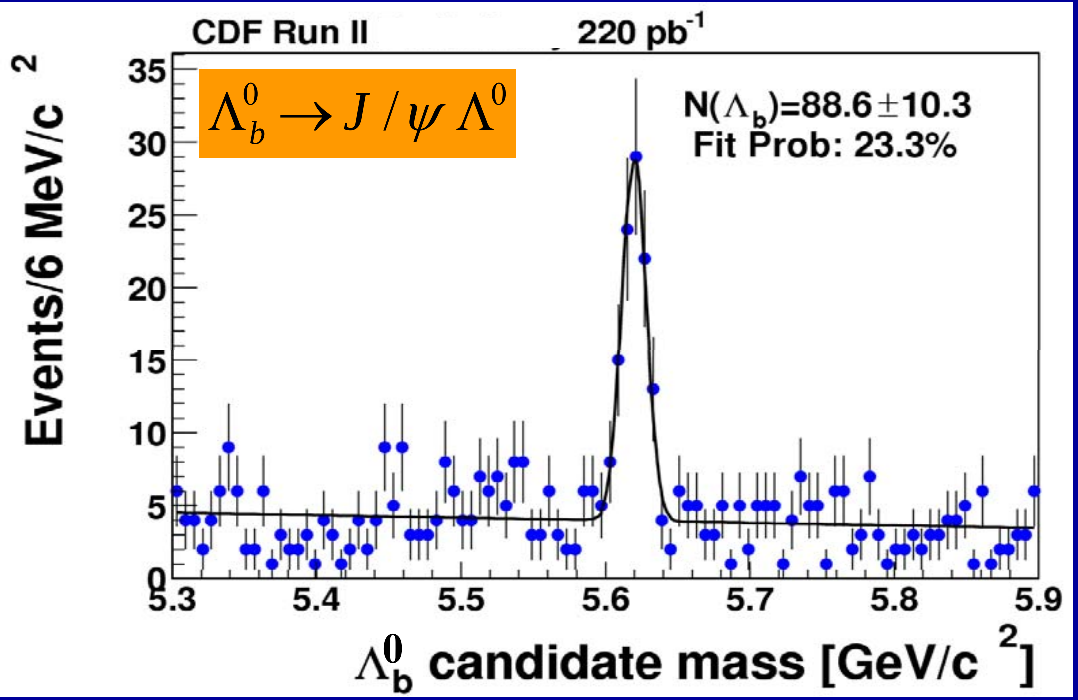
- **Combined mass is $m(\eta_b(1S)) = 9390.4 \pm 3.1$ MeV/$c^2$ resulting in a hyperfine splitting of $69.9 \pm 3.1$ MeV/$c^2$**

# b-Baryons

***b - Baryons***

# $\Lambda^0_b$ mass

PRL 96, 202001 2006




$$M(\Lambda_b^0) = 5619.7 \pm 1.2(stat) \pm 1.2(syst)\ \mathrm{MeV/c^2}$$

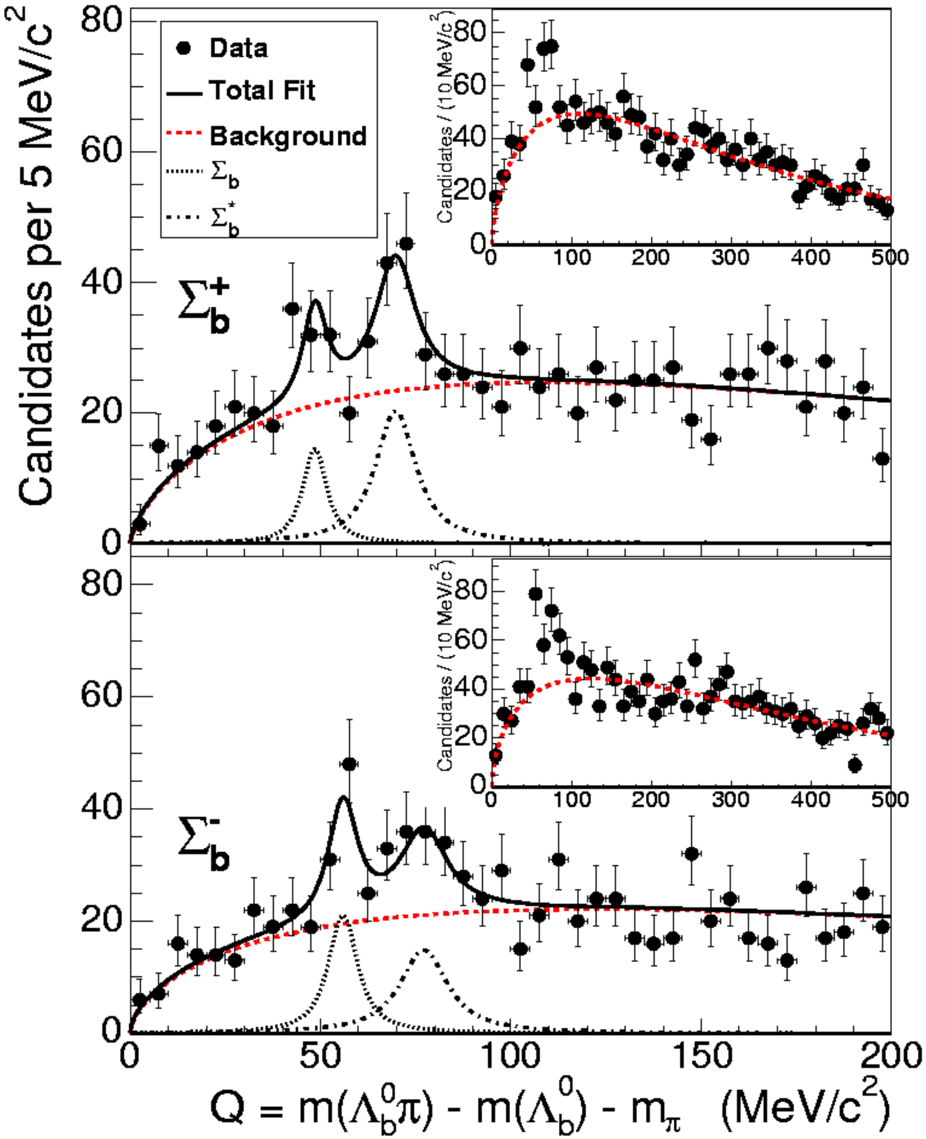
**$\Lambda^0_b$ mass : PDG 2008 average** **$5620.2 \pm 1.6\ \mathrm{MeV/c^2}$**

# Observation of $\Sigma_b$ at CDF

~ 1.1 fb$^{-1}$

$$\Sigma_b^{(*)\pm} \rightarrow \Lambda_b \pi^{\pm}; \Lambda_b \rightarrow \Lambda_c^+ \pi^-, \Lambda_c^+ \rightarrow p K^- \pi^+$$

**3180±60 (stat)** $\Lambda_b^0 \rightarrow \Lambda_c^+ K^-$ **cand.**




| State | Yield | Mass (MeV/c²) |
|---|---|---|
| $\Sigma_b^+$ | $32^{+13+5}_{-12-3}$ | $5807.8^{+2.0}_{-2.2} \pm 1.7$ |
| $\Sigma_b^-$ | $59^{+15+9}_{-14-4}$ | $5815.2 \pm 1.0 \pm 1.7$ |
| $\Sigma_b^{*+}$ | $77^{+17+10}_{-16-6}$ | $5829.0^{+1.6+1.7}_{-1.8-1.8}$ |
| $\Sigma_b^{*-}$ | $69^{+18+16}_{-17-5}$ | $5836.4 \pm 2.0^{+1.8}_{-1.7}$ |

$$Q_{\Sigma_b^+} = 48.5^{+2.0+0.2}_{-2.2-0.3}\ MeV/c^2$$

$$Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2\ MeV/c^2$$

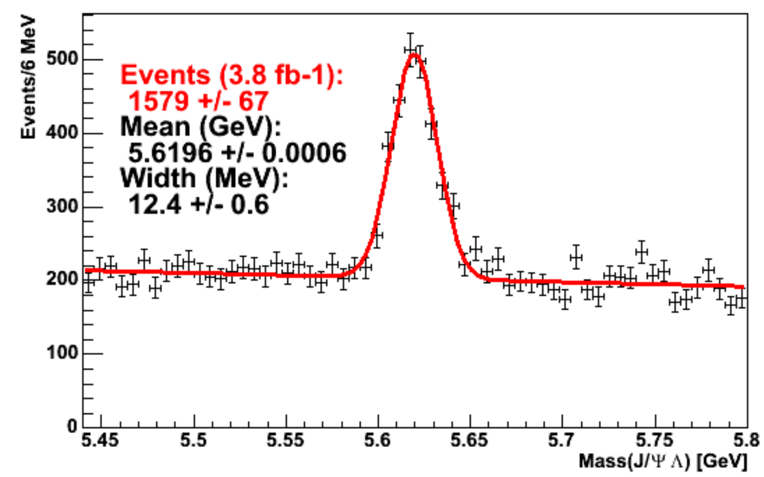
$$M(\Sigma_b^*) - M(\Sigma_b) = 21.2^{+2.0+0.4}_{-1.9-0.3}\ MeV/c^2$$

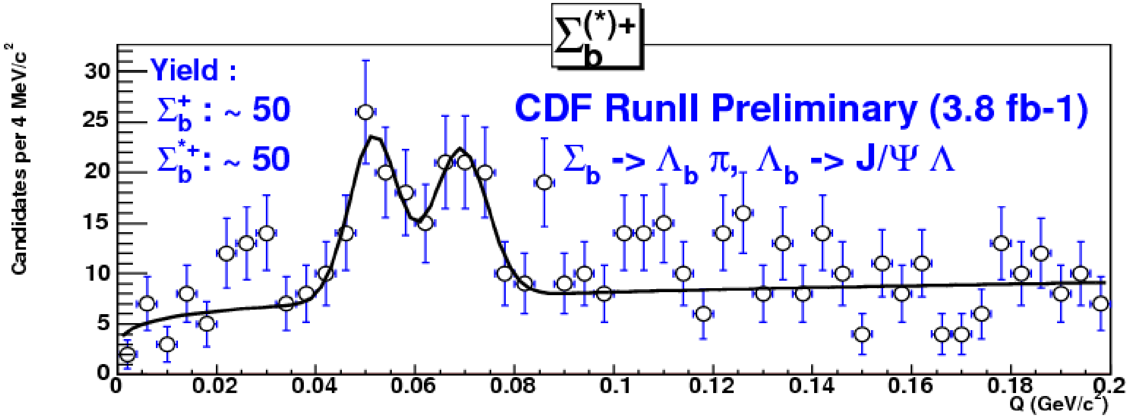
**PRL 99, 202001 2007**

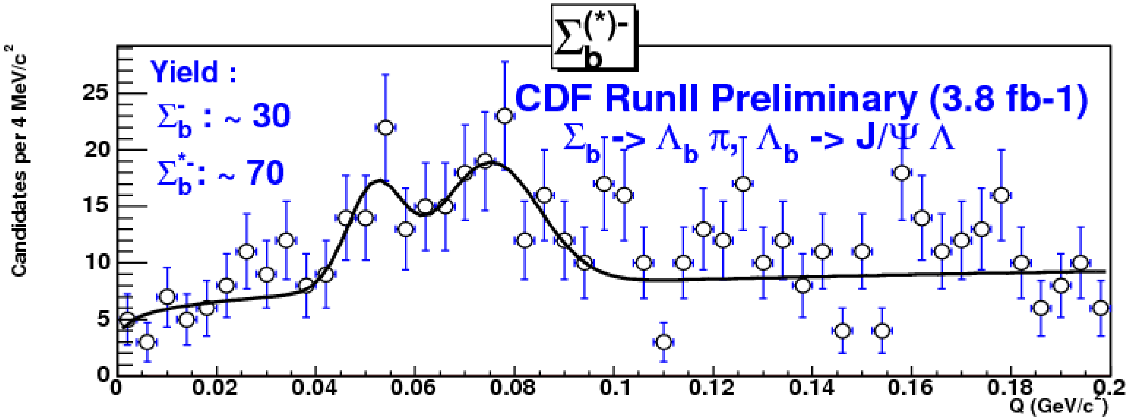
# Observation of $\Sigma_b$ at CDF

~ 3.8 fb$^{-1}$

$$\Sigma_b^{(*)\pm} \rightarrow \Lambda_b \pi^{\pm}; \Lambda_b \rightarrow J/\psi\, \Lambda$$



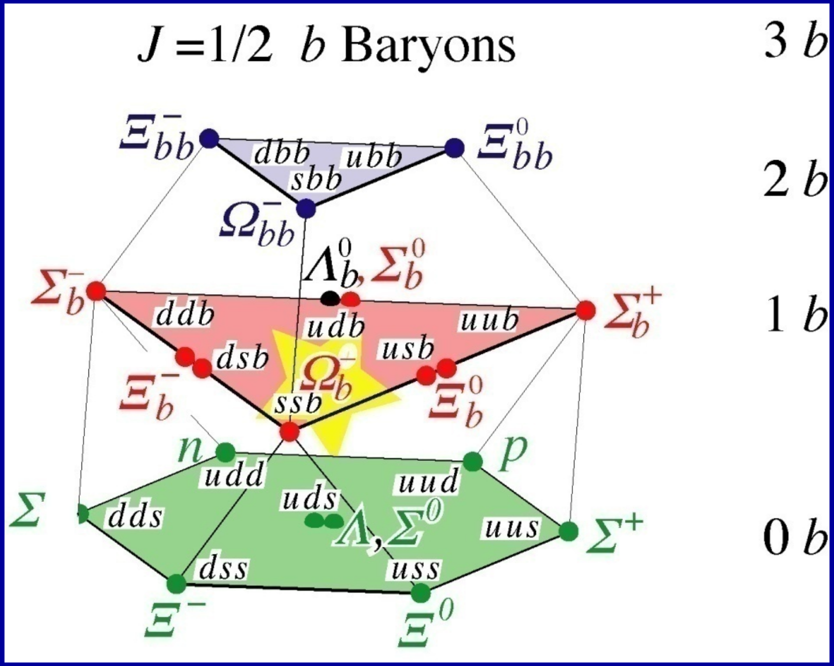



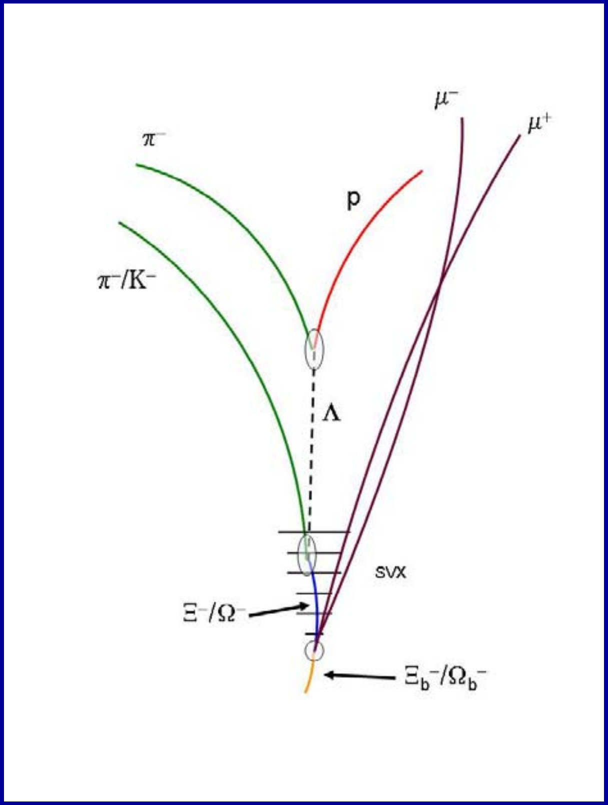



# Observation of $\Xi_b$ and $\Omega_b$ by CDF and D0

$$\Xi_b^- \to J/\psi\,\Xi^-; J/\psi \to \mu^+\mu^-, \Xi^- \to \Lambda^0\pi^-, \Lambda^0 \to p\pi^-$$

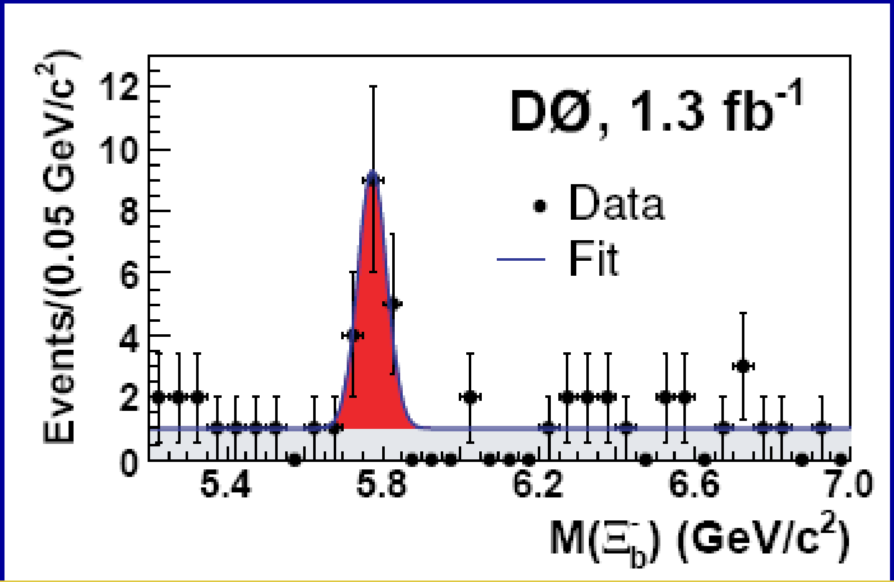
$$\Omega_b^- \to J/\psi\,\Omega^-; J/\psi \to \mu^+\mu^-, \Omega^- \to \Lambda^0 K^-, \Lambda^0 \to p\pi^-$$



# Mass measurements of $\Xi_b$ and $\Omega_b$ by D0

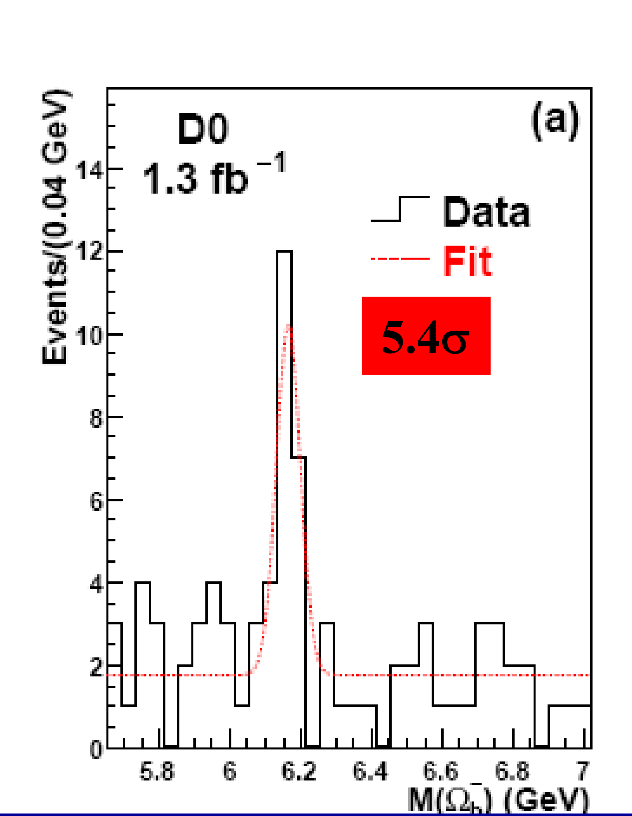
PRL 99, 052001 2007




$15.2 \pm 4.4\,(stat)\,^{+1.9}_{-0.4}(syst)$ signal events

$$M(\Xi_b^-) = 5.774 \pm 0.011(stat) \pm 0.015(syst)\ \mathrm{GeV/c^2}$$

PRL 101, 232002 2008




$17.8 \pm 4.9\,(stat) \pm 0.8(syst)$ signal events

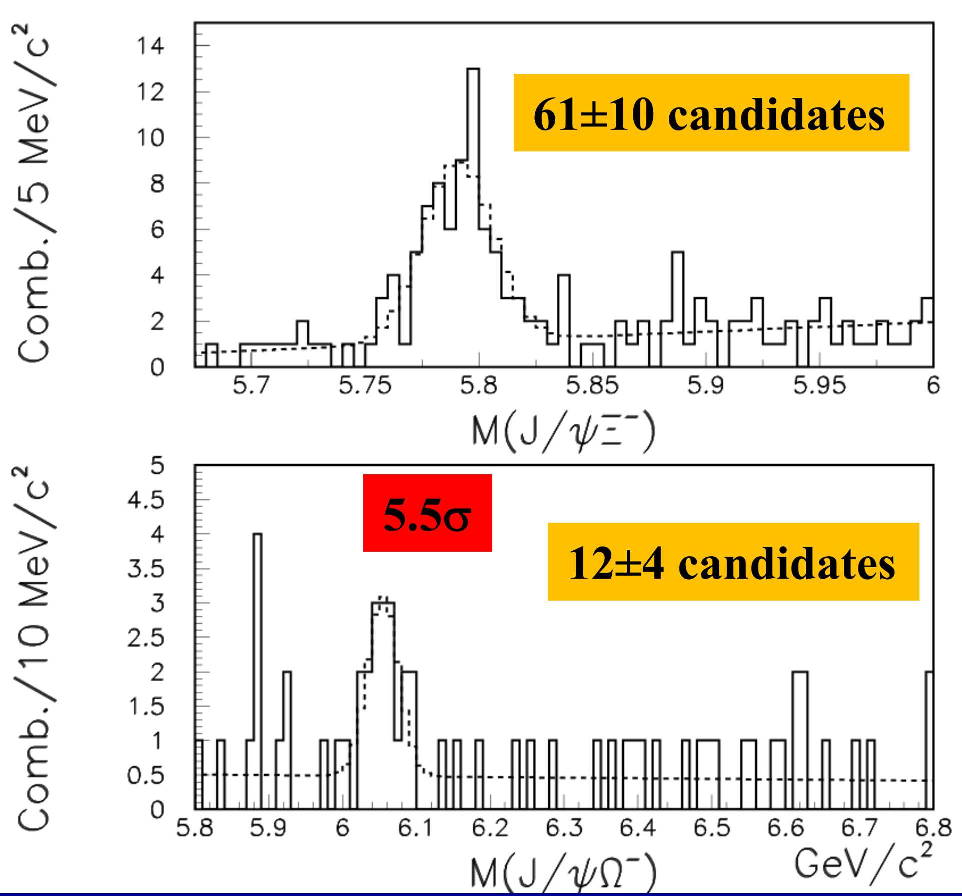
$$M(\Omega_b^-) = 6.165 \pm 0.010\,(stat) \pm 0.013\,(syst)\ \mathrm{GeV/c^2}$$

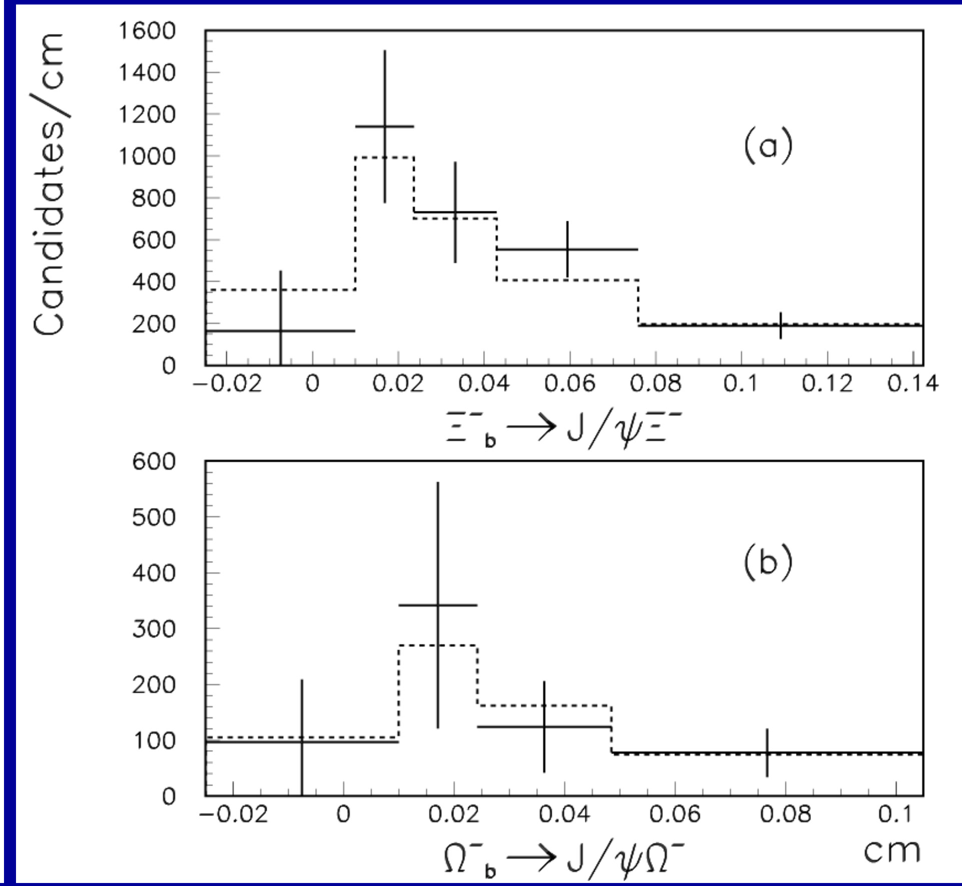
# Mass and lifetime measurement of $\Xi_b$ and $\Omega_b$ by CDF

**arXiv:0905.3123**

$4.2\ fb^{-1}$

**ct > 100 μm**



# Mass, Lifetime and Branching Ratio Results

- CDF measures *b*-baryon masses:
  - $\Xi_b^-$: 5790.9 ± 2.6(stat.) ± 0.8(syst.) MeV/$c^2$
  - $\Omega_b^-$: 6054.4 ± 6.8(stat.) ± 0.9(syst.) MeV/$c^2$
- CDF measures b-baryon lifetimes
  - $\Xi_b^-$: $1.56^{+0.27}_{-0.25}$(stat.) ± 0.02(syst.) ps
    - First in a fully reconstructed state.
  - $\Omega_b^-$: $1.13^{+0.53}_{-0.40}$(stat.) ± 0.02(syst.) ps
    - First ever

- 2.0 MeV/$c^2$ shift in $\Xi_b^-$ from the 1.9 $fb^{-1}$ measurement - PRL 99,052002(2007)

| | Mass (MeV/$c^2$) | $\tau_0$(ps) | $\sigma B/\sigma B(\Lambda_b^0)$ |
|---|---|---|---|
| $\Xi_b^-$ | 5790.9 ± 2.6 ± 0.9 | $1.56^{+0.27}_{-0.25}$ ± 0.02 | $0.167^{+0.037}_{-0.025}$ ± 0.012 |
| $\Omega_b^-$ | 6054.4 ± 6.8 ± 0.9 | $1.13^{+0.53}_{-0.40}$ ± 0.02 | $0.045^{0.017}_{-0.012}$ ± 0.004 |

# $\Omega_b^-$ Measurement Comparisons between CDF and D0

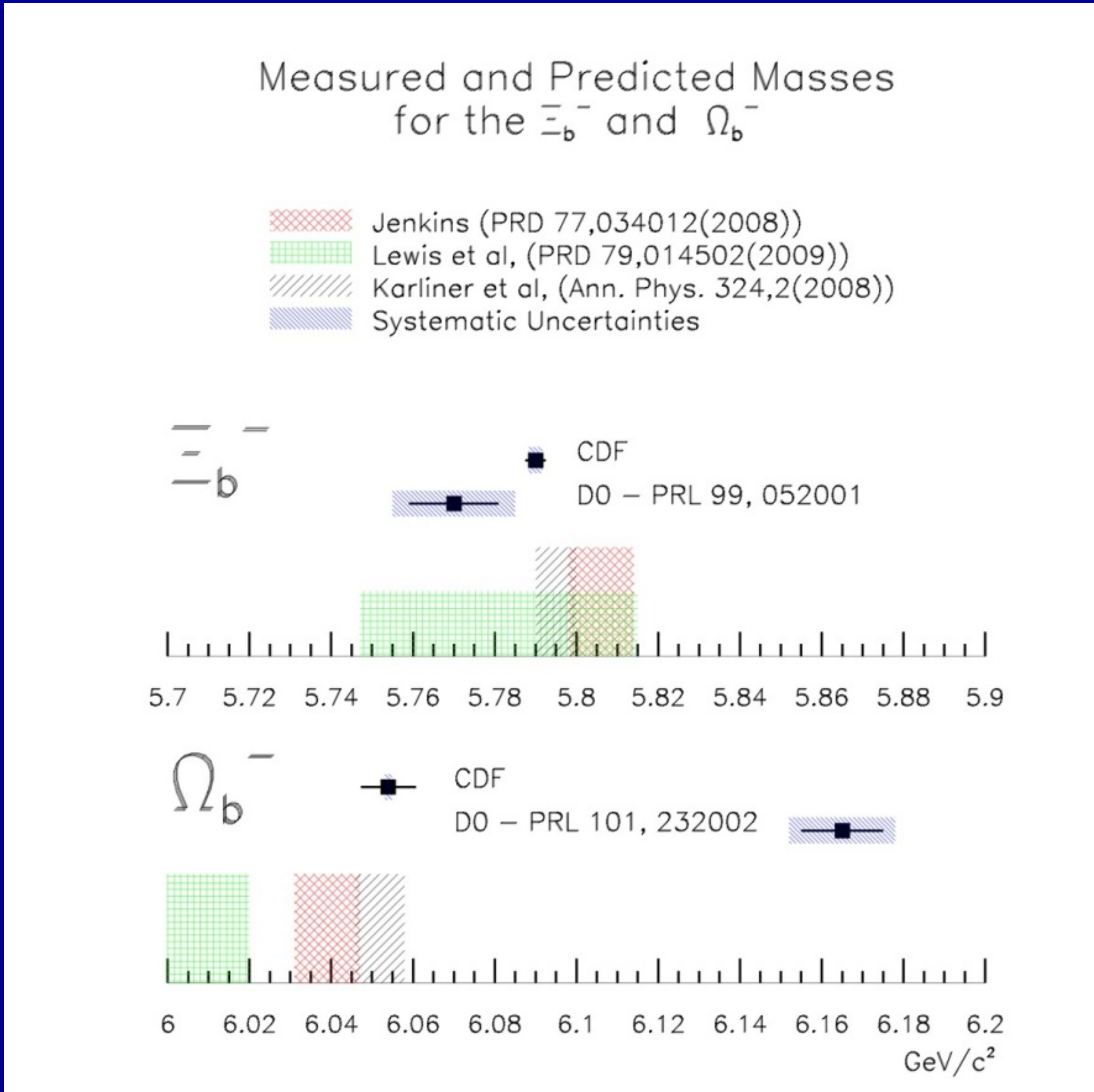
- D0 finds $M(\Omega_b^-)=6165\pm10(\text{stat.})\pm13(\text{syst.})\ \text{MeV}/c^2$
  - PRL 101, 232002(2008)
- CDF finds $M(\Omega_b^-)=6054.4\pm6.8(\text{stat.})\pm0.9(\text{syst.})\ \text{MeV}/c^2$
  - arXiv:0905.3123
- CDF calculates $M(\Omega_b)_{D0} - M(\Omega_b)_{CDF} = 111\pm12(\text{stat.})\pm14(\text{syst.})\ \text{MeV}/c^2$
  - Significant disagreement
- D0 finds

$$\frac{f(b\to\Omega_b^-)B(\Omega_b^-\to J/\psi\Omega^-)}{f(b\to\Xi_b^-)B(\Xi_b^-\to J/\psi\Xi^-)} = 0.80\pm0.32^{+0.14}_{-0.22}$$

- CDF finds

$$\frac{\sigma B(\Omega_b^-\to J/\psi\Omega^-)}{\sigma B(\Xi_b^-\to J/\psi\Xi^-)} = 0.27\pm0.12\pm0.01$$

# Summary of Results



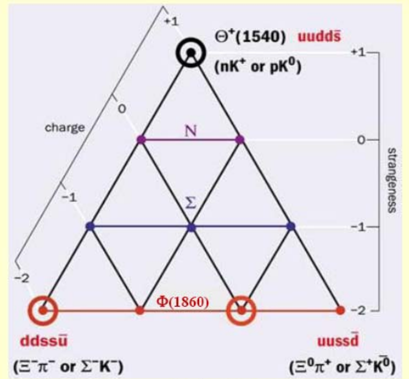
# Light-quark spectroscopy

***Light-quark Spectroscopy***

# Search for the $\Phi^{--}(1860)$ pentaquark state with CLAS (photoproduction on deuterium target)

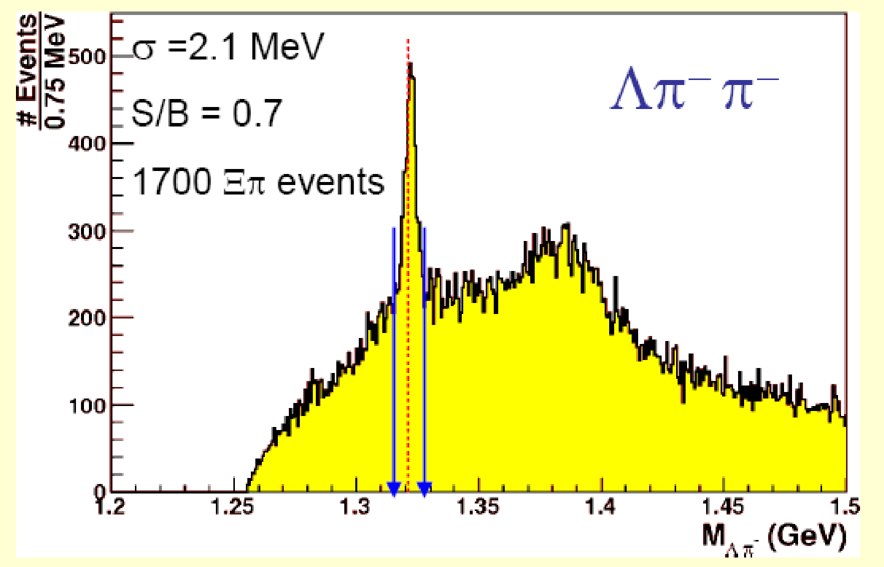
$$\gamma d \to \Phi^{--} X$$

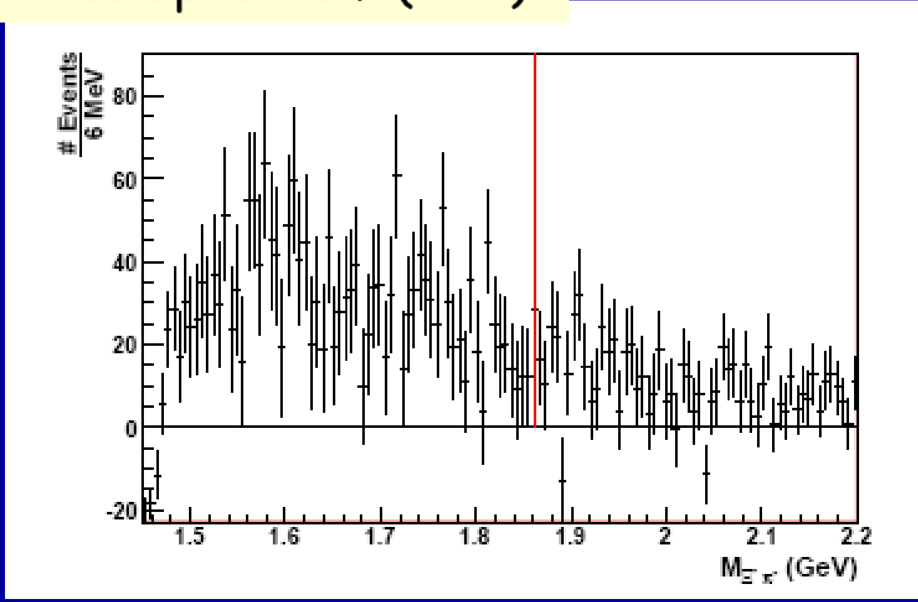
$$\Phi^{--} \to \pi^- \Xi^-(1321) \to \pi^-(\pi^-\Lambda) \to \pi^-\pi^-(\pi^- p)$$



Pentaquark Antidecuplet

Side-band subtraction
Mass spectrum ($\Xi^-\pi^-$)




**90% C.L. upper limit on inclusive production of $\Phi^{--} < 0.62$ nb**

# Dalitz plot analyses of B and D decays and light hadron spectroscopy



- $B^- \to D^+\pi^-\pi^-$:
  - Total $\mathcal{B}(B^- \to D^+\pi^-\pi^-) = (1.08 \pm 0.03(\text{stat}) \pm 0.05(\text{syst})) \times 10^{-3}$
  - $m_{D_2^*} = (2460.4 \pm 1.2 \pm 1.2 \pm 1.9)\text{MeV/c}^2$; $\Gamma_{D_2^*} = (41.8 \pm 2.5 \pm 2.5 \pm 2.0)\text{MeV}$
  - $m_{D_0^*} = (2297 \pm 8 \pm 5 \pm 19)\text{MeV/c}^2$, $\Gamma_{D_0^*} = (273 \pm 12 \pm 17 \pm 45)$ MeV
  - $\mathcal{B}(B^- \to D_2^*\pi^-) \times \mathcal{B}(D_2^* \to D^+\pi^-) = (3.5 \pm 0.2 \pm 0.3 \pm 0.4) \times 10^{-4}$
  - $\mathcal{B}(B^- \to D_0^*\pi^-) \times \mathcal{B}(D_0^* \to D^+\pi^-) = (6.8 \pm 0.3 \pm 0.4 \pm 2.0) \times 10^{-4}$
- $B^+ \to \pi^+\pi^-\pi^+$
  - Total $\mathcal{B}(B^\pm \to \pi^\pm\pi^\mp\pi^\pm) = (15.2 \pm 0.6 \pm 1.2 \pm 0.4) \times 10^{-6}$
  - $\mathcal{B}(B^\pm \to \pi^\pm\pi^\mp\pi^\pm \text{ nonresonant}) = (5.3 \pm 0.7 \pm 0.6^{+1.1}_{-0.5}) \times 10^{-6}$
  - $\mathcal{B}(B^\pm \to \rho^0(770)\pi^\pm) = (8.1 \pm 0.7 \pm 1.2^{+0.4}_{-1.1}) \times 10^{-6}$
  - $m_{f_0(1370)} = 1400 \pm 40\,\text{MeV}/c^2$ and $\Gamma_{f_0(1370)} = 300 \pm 80_{sta}$ MeV
  - $\mathcal{B}(B^\pm \to f_2(1270)\pi^\pm) = (1.57 \pm 0.42 \pm 0.16\,^{+0.53}_{-0.19}) \times 10^{-6}$
- $D_S^+ \to \pi^+\pi^-\pi^+$
  - $B(D_S^+ \to \pi^+\pi^-\pi^+)/B(D_S^+ \to K^+K^-\pi^+) = 0.199 \pm 0.004 \pm 0.009$
  - Amplitude and phase of the $\pi^+\pi^-$ $\mathcal{S}$-wave is extracted in a model-independent way for the first time

# Conclusions

- Many new results in Hadron Sprectroscopy.
- It would be very helpful to cross check some of the results among different experiments.
- A lot of answers and surprises awaiting!!

# Acknowledgments

❖ I would like to thank S. Behari, L. Dong, H. Egiyan, K. Yi and A. Zupanc for providing information for this review.