# Bottom Spectroscopy at CDF

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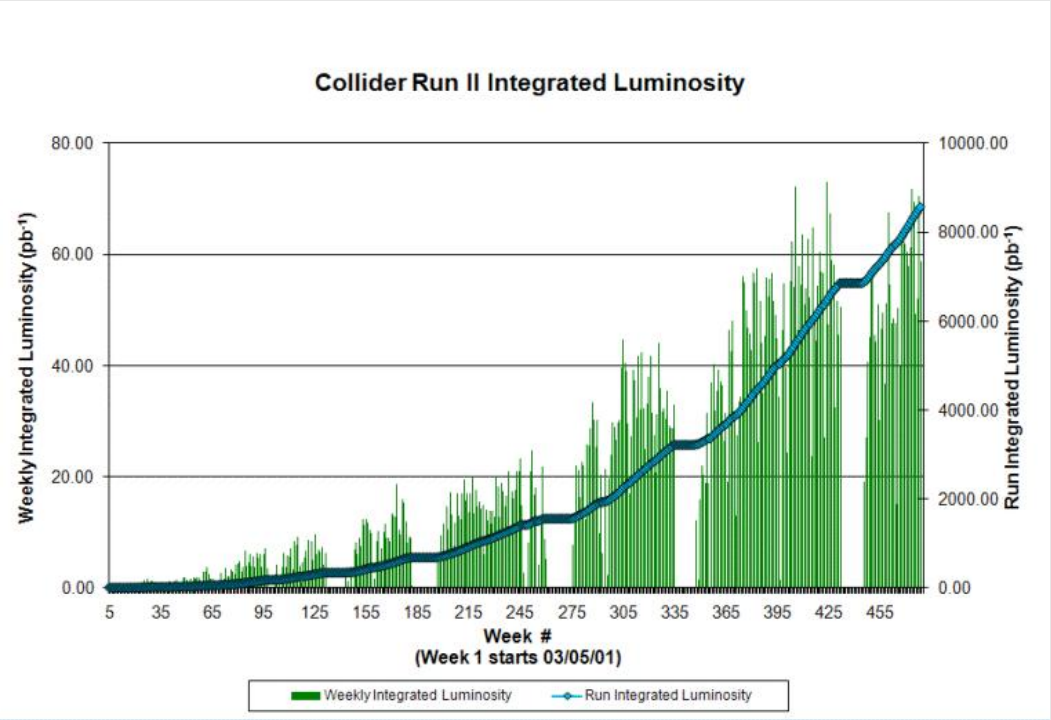
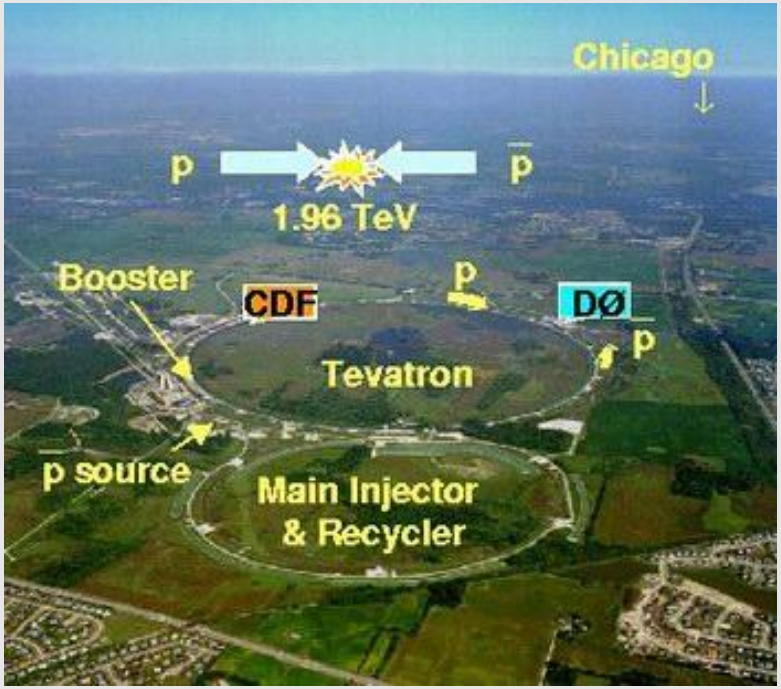
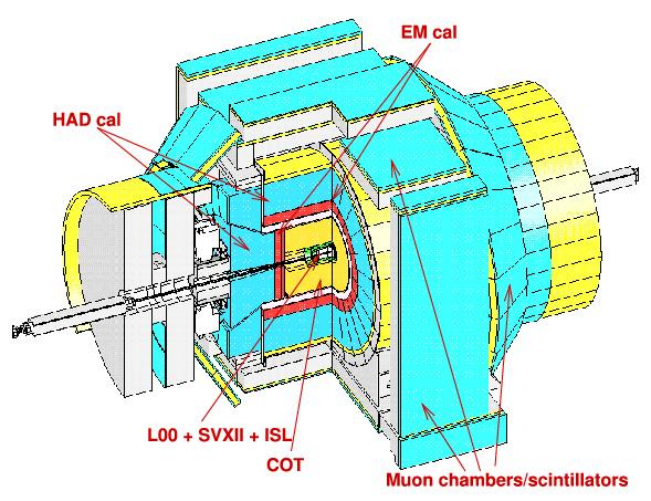
# Outline

- Motivation
- Review on heavy hadrons spectroscopy during CDF Run II
- Latest results
  - Evidence of $Y(4140)$
  - Observation of $\Xi_b^-$ and $\Omega_b^-$
  - Polarization of $\Upsilon(1S)$
- Conclusion

# Fermilab Tevatron Run II




- Delivered luminosity: $\sim 8$ fb$^{-1}$
- Acquired luminosity: $\sim 7$ fb$^{-1}$
- CDF has excellent vertex and momentum resolution

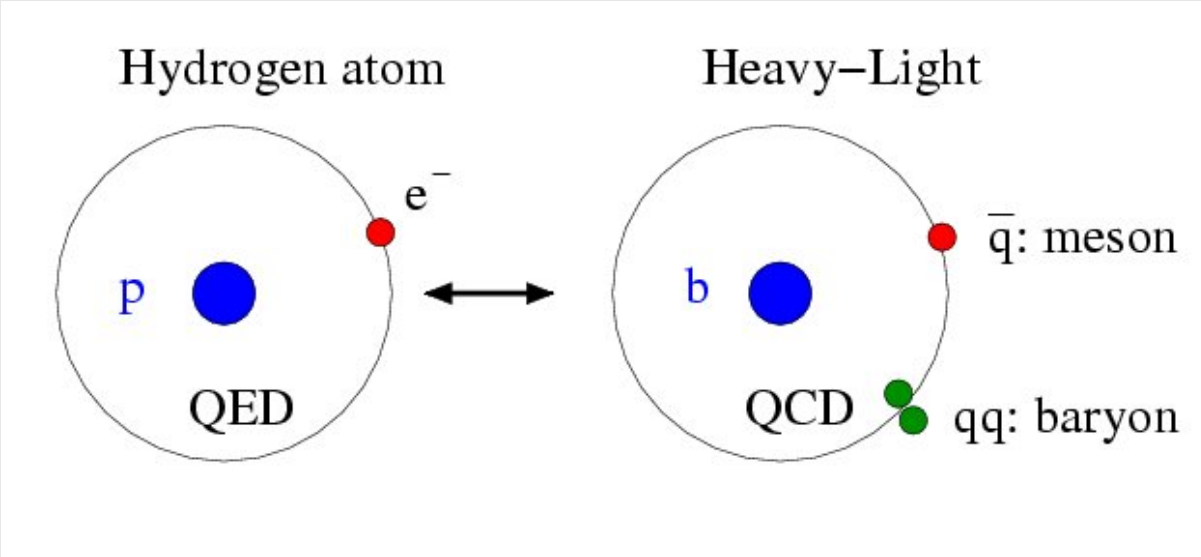
This talk: analysis covering up to 4.2 fb$^{-1}$

# Heavy Spectroscopy

## Heavy Spectroscopy it is important:

- The study of heavy spectroscopy increases our knowledge on QCD.
  - study of B hadrons = study of (non-perturbative) QCD
- Heavy quark hadrons are the hydrogen atom of QCD

B hadrons = hydrogen atom of QCD



# Bottom Spectroscopy

Tevatron is a suitable place to study bottom spectroscopy

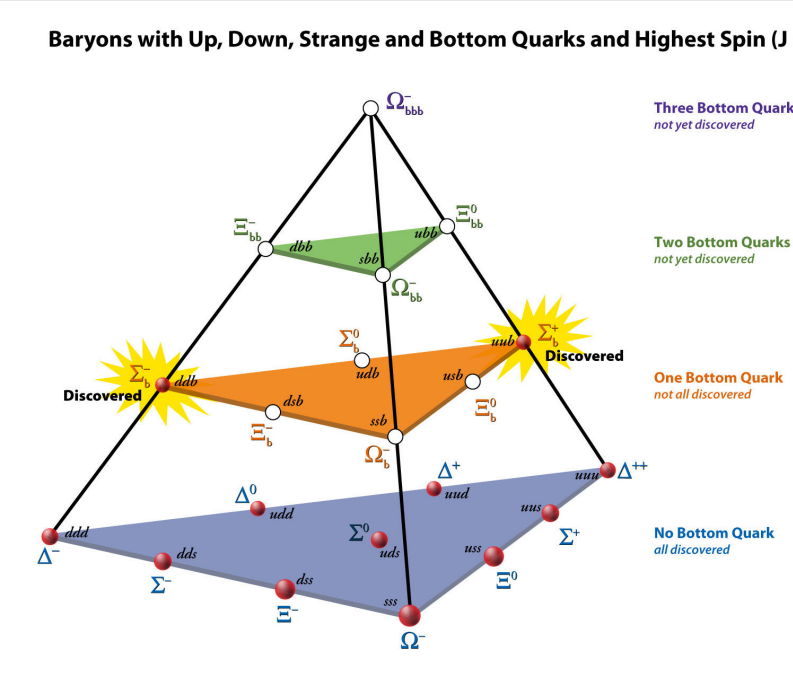
- All $B$ hadrons are copiously produced.
  - Some states are not accessible to B factories.
- They are produced boosted
  - separation between produced and decay $B$ hadron vertex is measurable.
  - low $p_T$ daughters are tracked.
- CDF has a strong program on heavy hadron spectroscopy that yielded many key results.

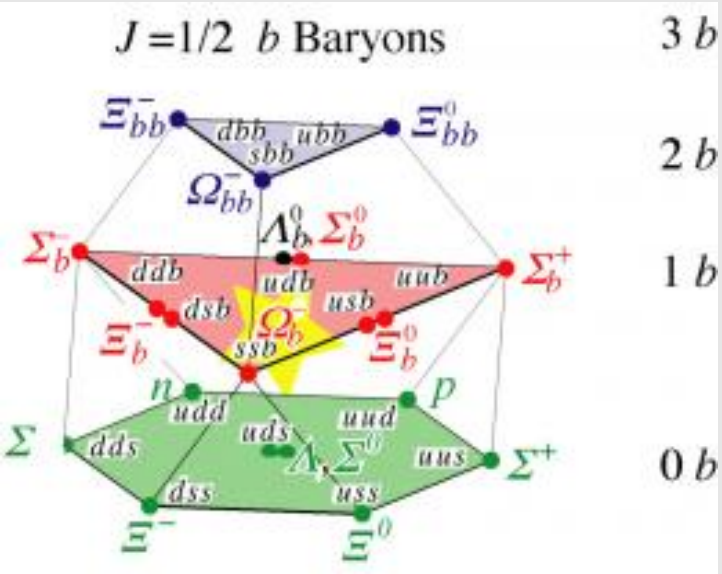
# Heavy $B$ Hadrons

Until 2006 $\Lambda_b^0 = |bdu\rangle$ was only established $B$ baryon
=> Search for
$\Sigma_b^- = |bdd\rangle$
$\Xi_b^- = |bds\rangle$, $\Omega_b^- = |bss\rangle$

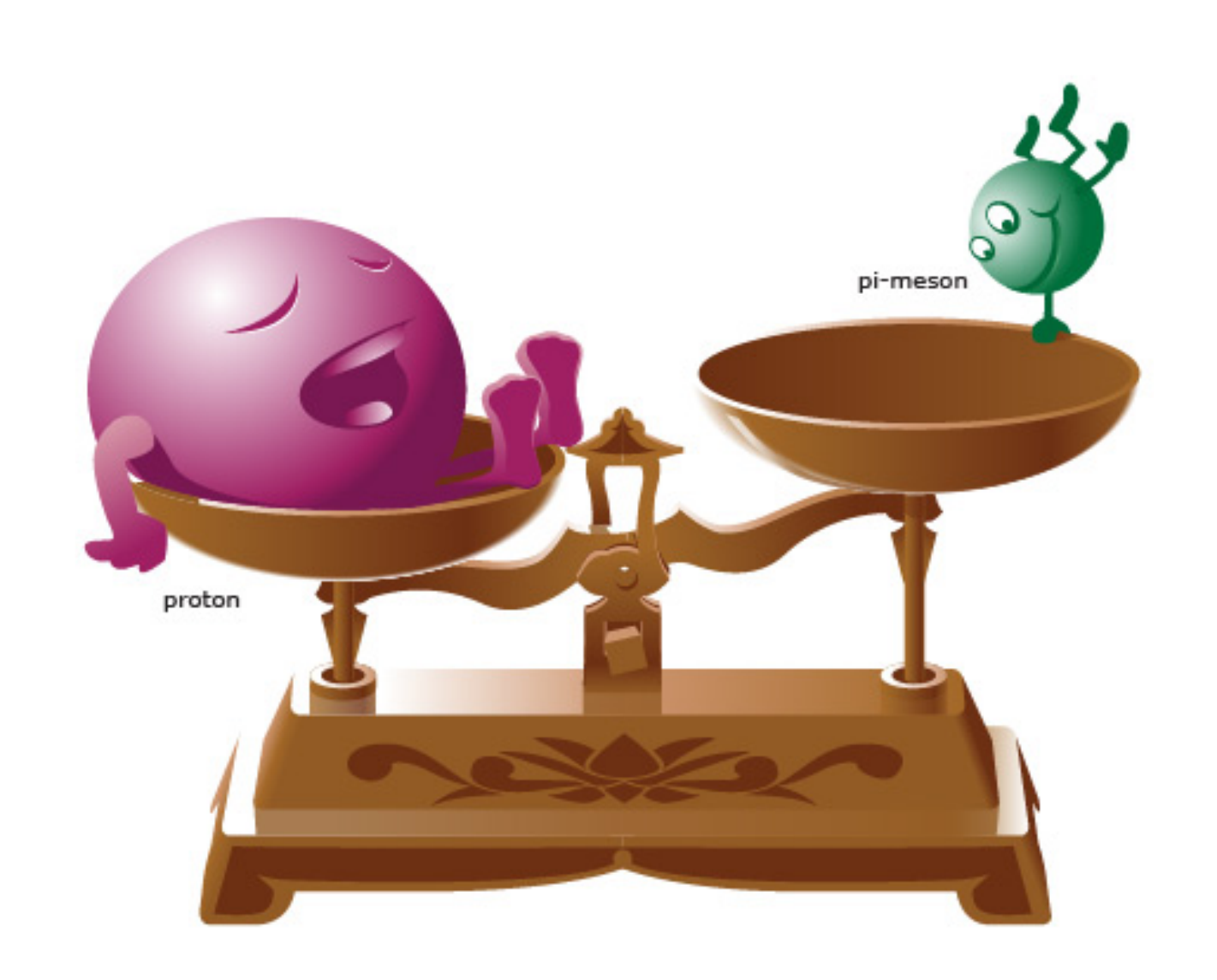
Total spin:1/2 ($X_b$) or 3/2 ($X_b^*$):
$b\{qq\}, q = u, d, s; J^P = S_Q + s_{qq}$

- $\Sigma_b^\pm$ and $\Sigma_b^{*\pm}$ discovered in 2007
- $\Xi_b^-$ discovered in 2007
- $\Omega_b^-$ discovered in 2008



# Review on CDF Charm and Bottom Results



# $\Sigma_b^{(*)\pm}$

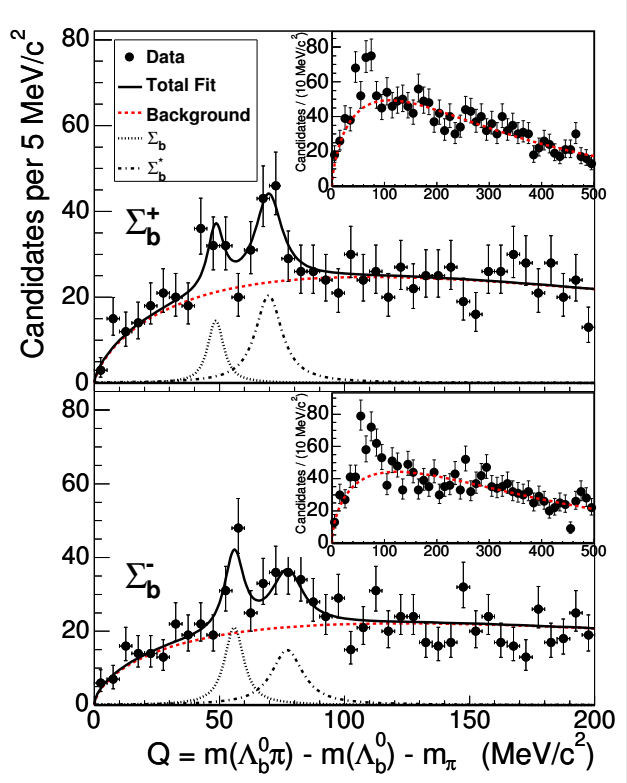
Observed by CDF in 2007:

(Phys.Rev.Lett.99:202001,2007)

$\Sigma_b^{*\pm} \to \Lambda_b^0 \pi^\pm$

$(\Lambda_b^0 \to \Lambda_c^+ \pi^-, \Lambda_c^+ \to PK^- \pi^+)$

Signals with $> 5\sigma$ significance



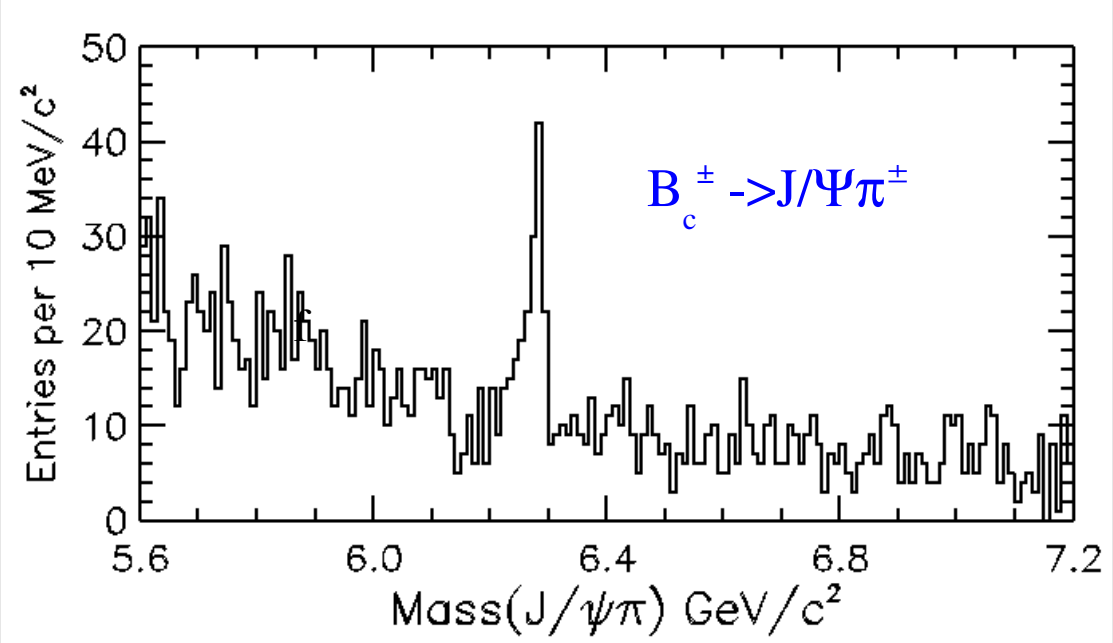

| State | Yield | Q or $\Delta_{\Sigma_b^*}$(MeV/c$^2$) | Mass (MeV/c$^2$) |
|---|---|---|---|
| $\Sigma_b^+$ | $32^{+12+5}_{-12-3}$ | $Q_{\Sigma_b^+} = 48.5^{+2.0+0.2}_{-2.2-0.3}$ | $5807.8^{+2.0}_{-2.2} \pm 1.7$ |
| $\Sigma_b^-$ | $59^{+15+9}_{-14-4}$ | $Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2$ | $5815.2 \pm 1.0 \pm 1.7$ |
| $\Sigma_b^{*+}$ | $77^{+17+10}_{-16-6}$ | $\Delta_{\Sigma_b^*} = 21.2^{2.0+0.4}_{-1.9-0.3}$ | $5829.0^{+1.6+1.7}_{-1.8-1.8}$ |
| $\Sigma_b^{*-}$ | $69^{+18+16}_{-17-5}$ | | $5836.4 \pm 2.0^{+1.8}_{-1.7}$ |

# $B_c^{\pm} \to J/\psi\,\pi^{\pm}$

$m = 6275.6 \pm 2.9\ (stat)\ \pm 2.5\ (syst)$ MeV/c$^2$
(Phys.Rev.Lett.100:182002,2008)

Theoretical expectations:

- non-relativistic potential models: $6247 - 6286$ MeV/c$^2$
- lattice QCD: $6304 \pm 12^{+18}_{-0}$ MeV/c$^2$

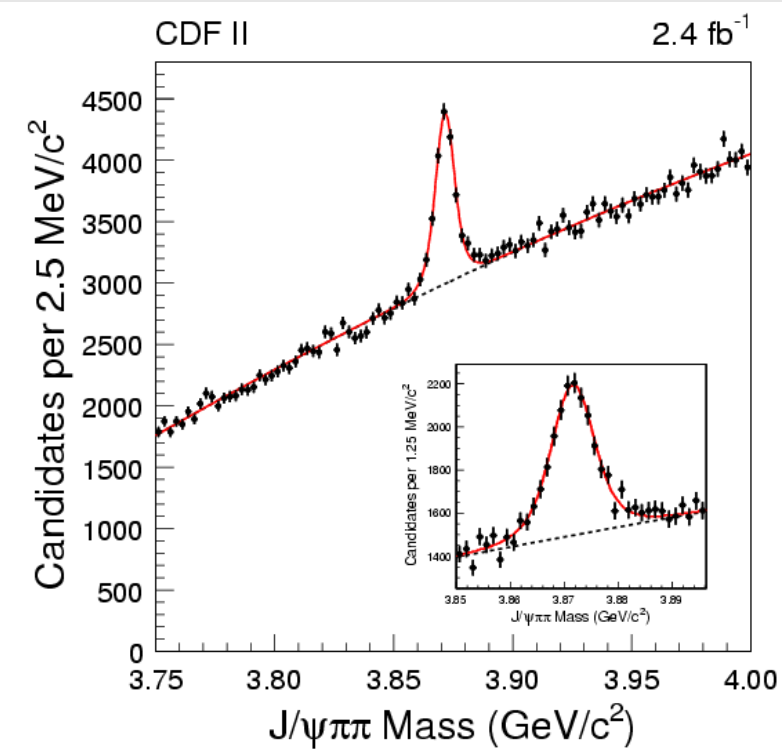


# $X(3872) \to J/\psi\,\pi^+\pi^-$

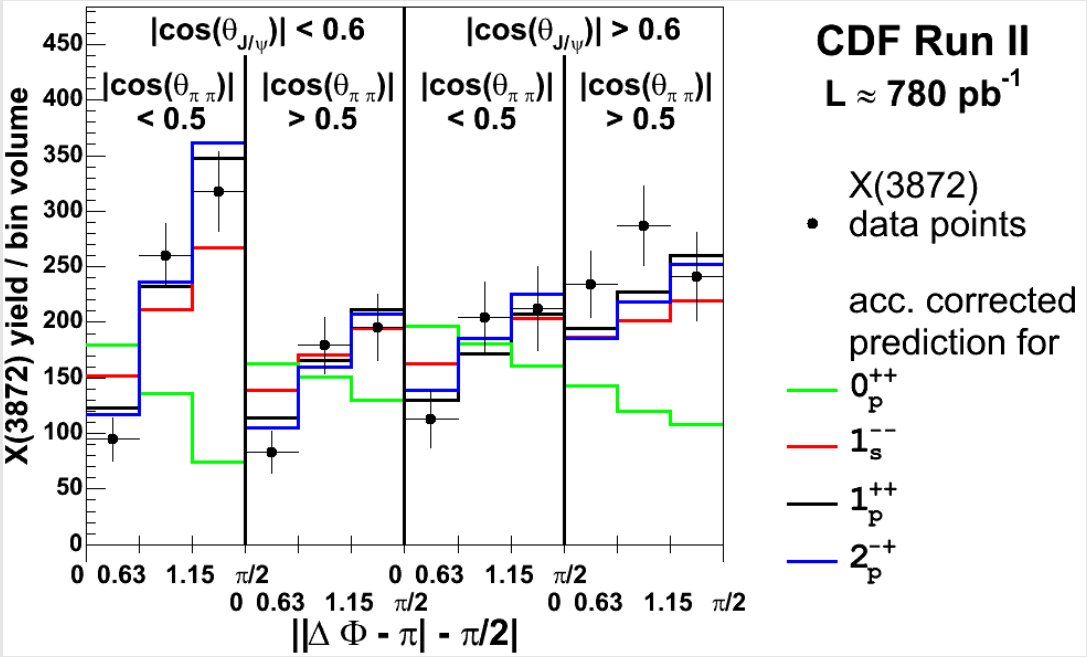
- $m(X(3872)) = 3871.61 \pm 0.16(stat) \pm 0.19(syst)$ MeV/c$^2$

(more precise measurement)

- Angular analysis $\to$ $J^{PC} = 1^{++}$ or $2^{-+}$ only assumptions compatible with data



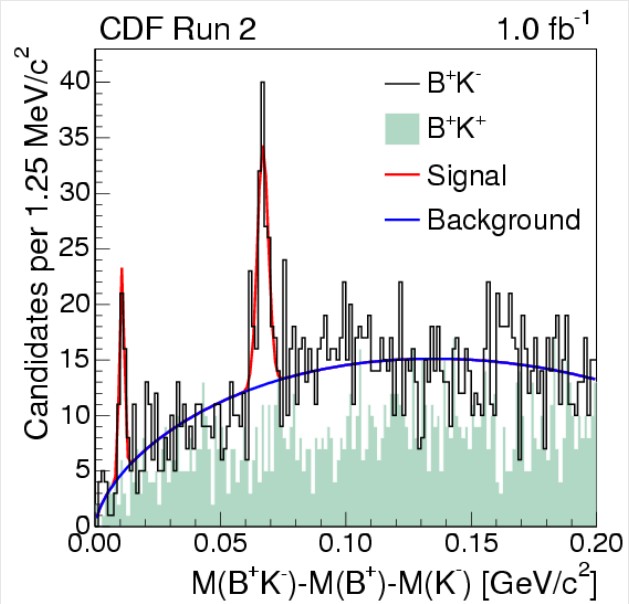

(Phys.Rev.Lett.103:152001,2009)




( Phys.Rev.Lett.98:132002,2007)

# $B_s^{**} \to B^+K^-$

$B_s^{**} \to B^+K^-$ and
$B_s^{**} \to B^{+*}K^-$ ($B^{+*} \to B^+\gamma$ , with $\gamma$ missing)




(Phys.Rev.Lett.100:082001,2008)

Two $B^+$ Decay channels explored:

- $B^+ \to J/\psi K^+$ ($J/\psi \to \mu^+\mu^-$)
- $B^+ \to D^0\pi^+$ ($D^0 \to K^-\pi^+$)

- $m(B_{s1}) = 5829.41 \pm 0.21(stat) \pm 0.14\ (syst) \pm 0.6(PDG)$ MeV/c$^2$
- $m(B_{s2}^*) = 5839.64 \pm 0.39\ (stat) \pm 0.14\ (syst) \pm 0.5\ (PDG)$ MeV/c$^2$

(first observation of $B_{s1}$)

# Latest Results

# Evidence for $Y(4140) \to J/\psi\,\Phi$

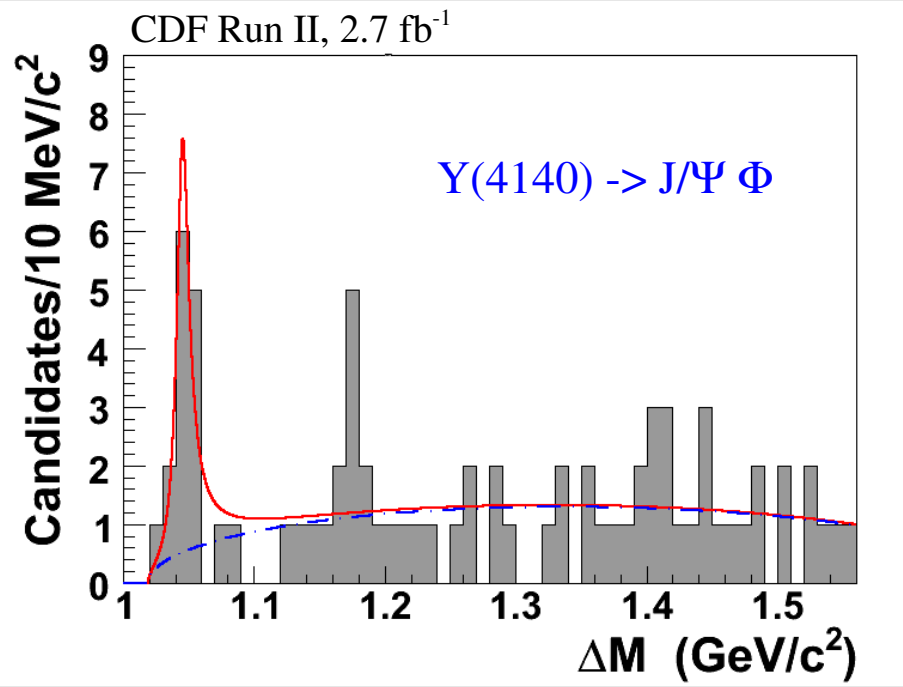
- Since the discovery of $X(3872)$ more exotic mesons with charmonium-like decay modes have been observed.
- The possible interpretations beyond standard quark model such as hybrid ($q\bar{q}g$) and four-quark states ($q\bar{q}q\bar{q}$) motivates the interest in exotic mesons in the charm sector.
- The observation of $Y(3930)$ near the $J/\psi\,\Omega^-$ threshold motivates searches for similar phenomena near the $J/\psi\,\phi$ threshold.

# Evidence for $Y(4140) \to J/\psi\,\Phi$

$B^+ \to Y(4140)K^+$; $Y(4140) \to J/\psi\,\Phi$
$(J/\psi \to \mu^+\mu^-;\ \Phi \to K^+K^-)$

- $m = 4143.0 \pm 2.9\ (stat) \pm 1.2\ (syst)$ MeV/c$^2$
- $\Gamma = 11.7^{+8.3}_{-5.0}\ (stat) \pm 3.7\ (syst)$ MeV/c$^2$
- statistical significance 3.8 $\sigma$

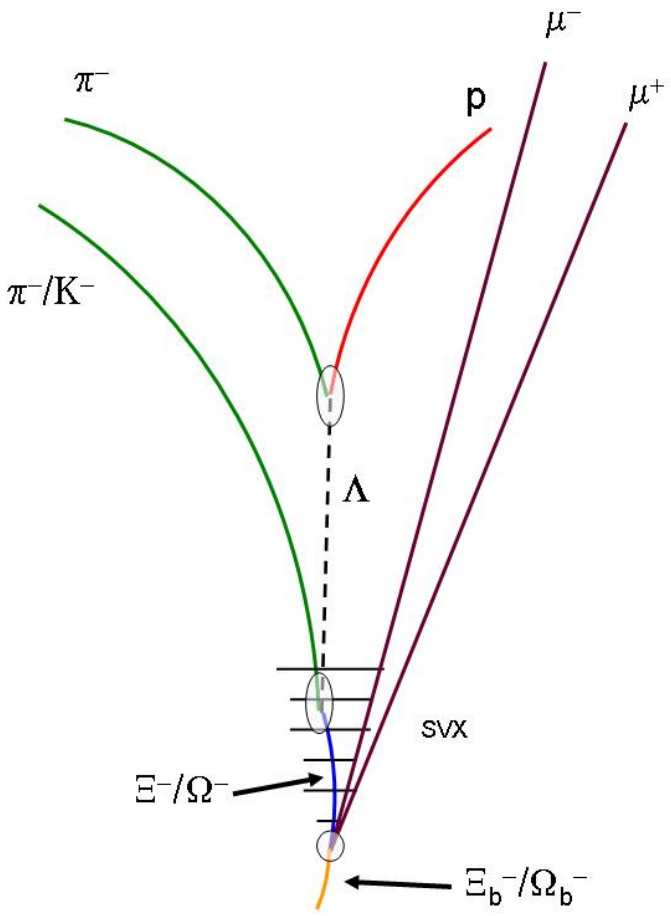
(Phys.Rev.Lett.102:242002,2009)



# $\Xi_b^-$ And $\Omega_b^-$ analysis Strategy

- $\Xi_b^- \to J/\psi \Xi^-$
  $(J/\psi \to \mu^+\mu^-, \Xi^- \to \Lambda\pi^-)$
- $\Omega_b^- \to J/\psi \Omega^-$
  $(J/\psi \to \mu^+\mu^-, \Omega^- \to \Lambda K^-)$
- $\Xi^-$ and $\Omega^-$ long lived & charged
  $(c\tau(\Xi^-) \approx 5$ cm, $c\tau(\Omega^-) \approx 2.5$ cm)
  - They are tracked in the silicon vertex detector
  - This improve significanly the purity of the samples.
- Likelihood method to extract mass, yield and significance:

$$\mathcal{L} = \prod_i^N (f_s G(m_i, m_0, s_m \sigma_i^m) + (1 - f_s) P^n(m_i))$$



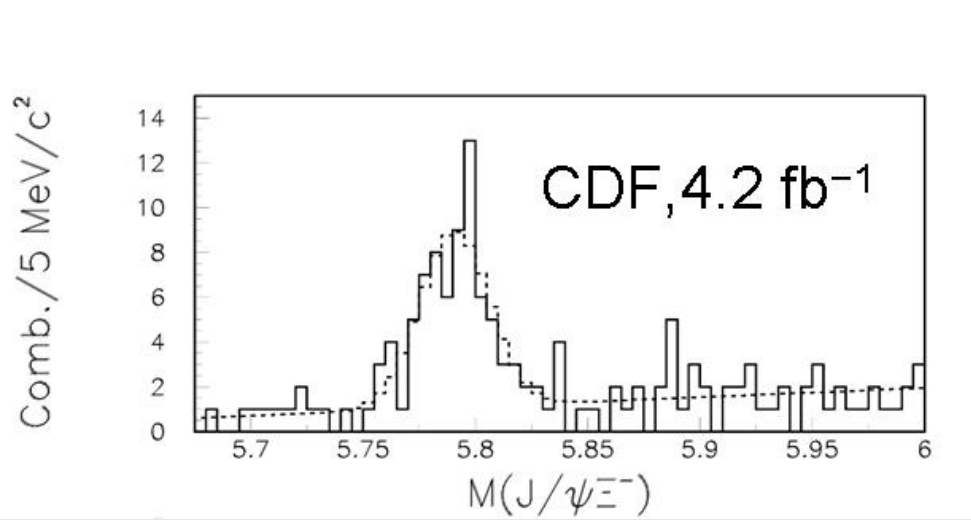
# $\Xi_b^- \ |bds\rangle$

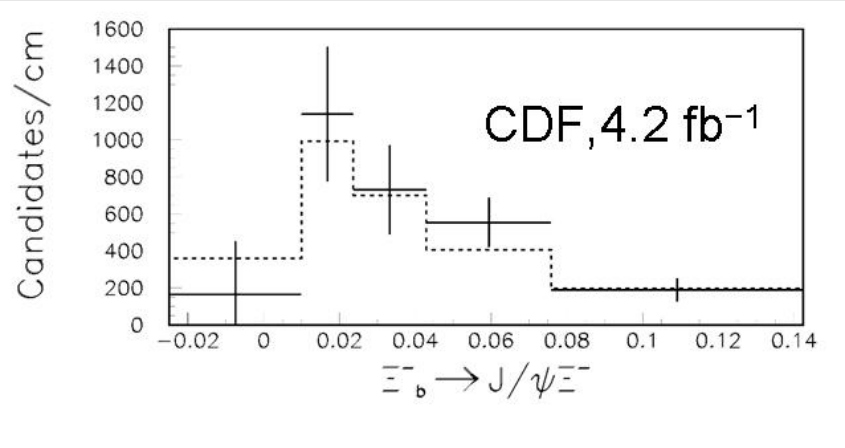
- $M(\Xi_b^-) = 5790.9 \pm 2.6(stat) \pm 0.8(syst)$ MeV/c$^2$
  (Phys.Rev.D80,072003,2009)

- Consistent with theory:
  - 5790 – 5814 MeV/c$^2$

- lifetime measurement:

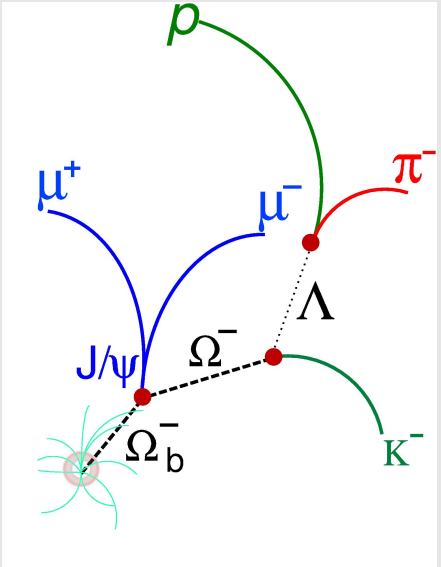
$\tau(\Xi_b^-) = 1.56^{+0.27}_{-0.25} \pm 0.02$ ps
(first exclusive $\Xi_b^-$ lifetime)



# $\Omega_b^- \ |bss\rangle$

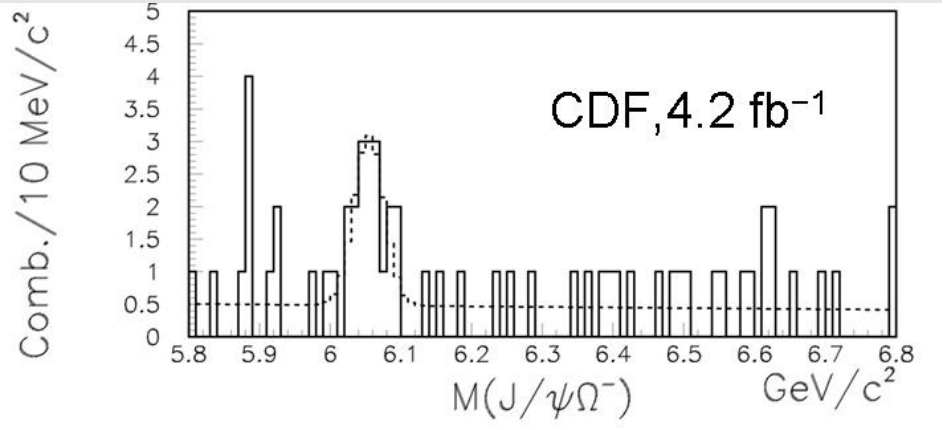
CDF observed $\Omega_b^-$ in 2009 (Phys.Rev.D80,072003,2009)

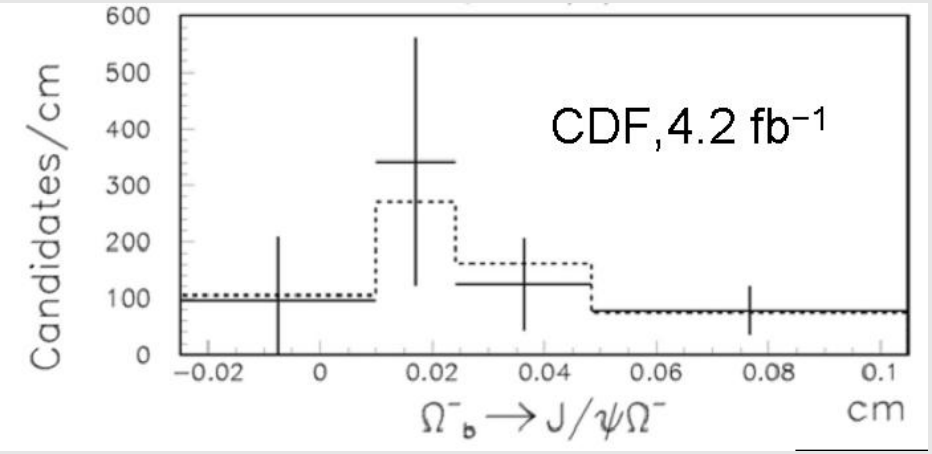



- $m(\Omega_b^-) = 6054.4 \pm 6.8(stat) \pm 0.9(syst)$ MeV/c$^2$
- $\tau(\Omega_b^-) = 1.13^{+0.53}_{-0.40} \pm 0.8$ ps (first time)

Consistent with theory:

- theory expect: 6010 – 6070 MeV/c$^2$



# $\Omega_b^-$ Discrepancy DØ - CDF

$\Omega_b^-$ first observation by DØ : $6165 \pm 10\ (stat) \pm 13\ (syst)$ MeV/c$^2$
(Phys. Rev. Lett. 101, 232002, 2008)

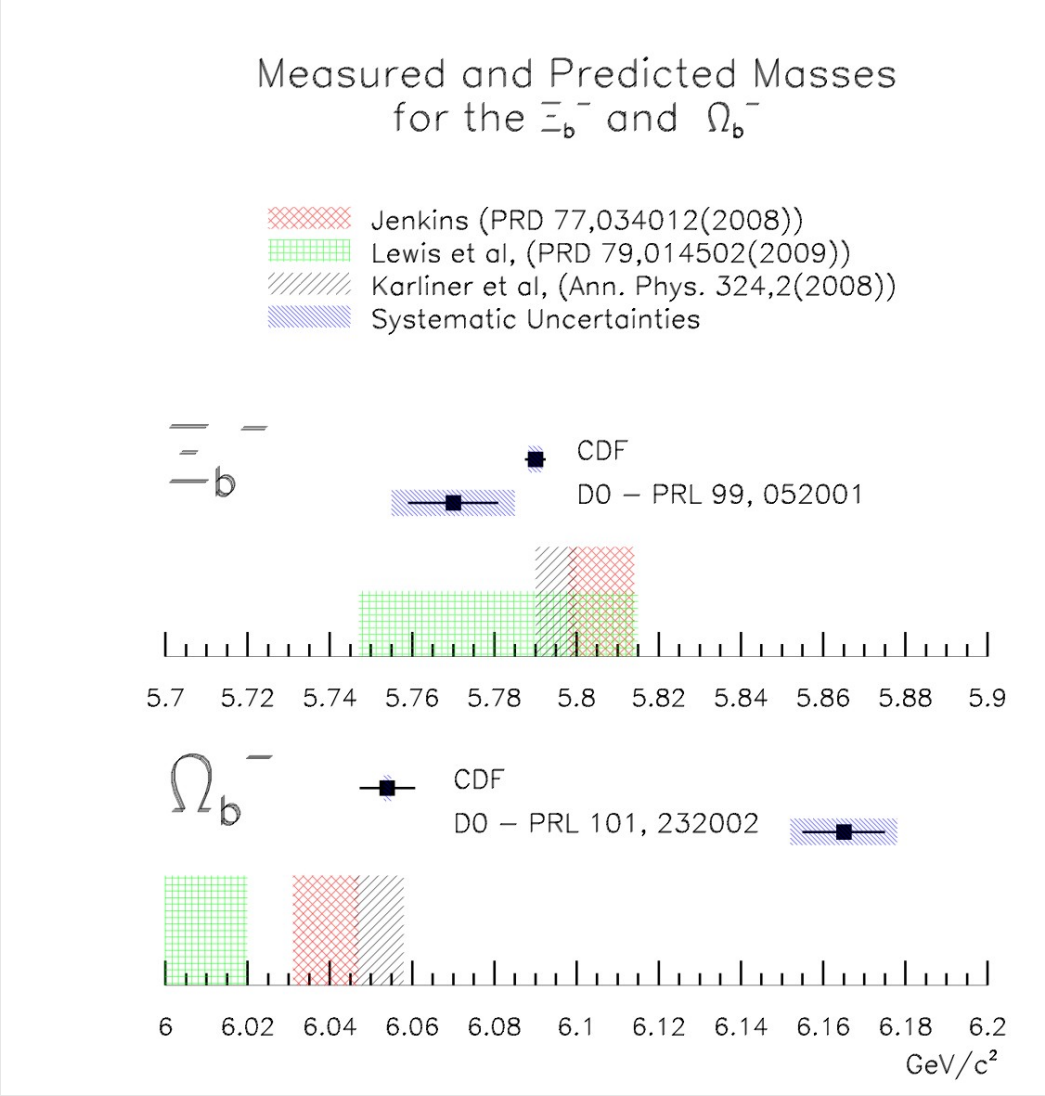
$6\sigma$ disagreement with CDF!

- $\Delta m = (111 \pm 12 \pm 14)$ MeV/c$^2$

Discrepancy also in $\Omega_b^-$ production rate:

- DØ $\frac{f(b \to \Omega_b^-)\mathcal{B}(\Omega_b^- \to J/\psi\,\Omega^-)}{f(b \to \Xi_b^-)\mathcal{B}(\Xi_b^- \to J/\psi\,\Xi^-)} =$ $0.80 \pm 0.32^{+0.14}_{-0.22}$
- CDF: $\frac{\sigma\mathcal{B}(\Omega_b^- \to J/\psi\,\Omega^-)}{\sigma\mathcal{B}(\Xi_b^- \to J/\psi\,\Xi^-)} =$ $0.27 \pm 0.12 \pm 0.01$

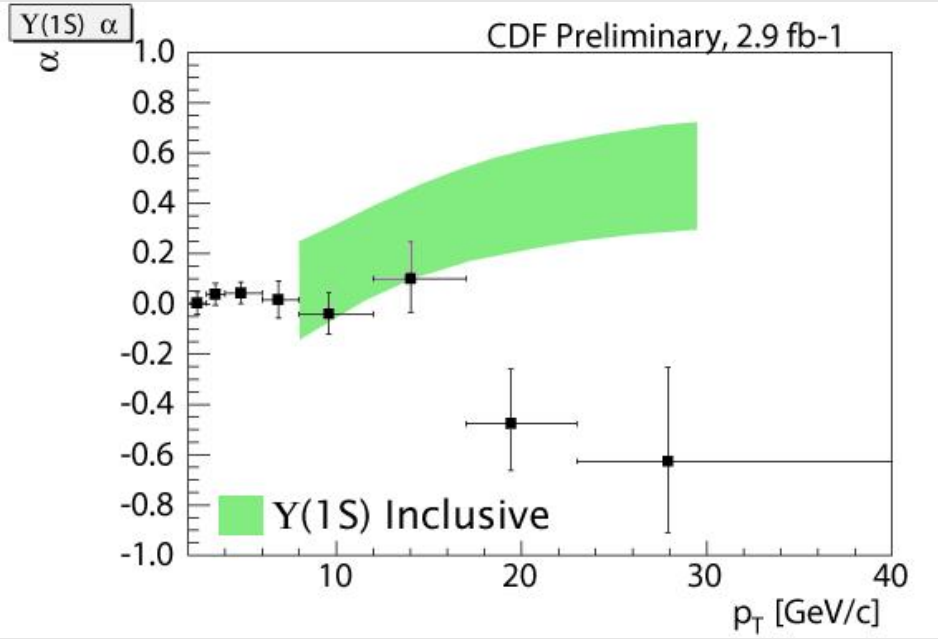
$\rightarrow$ DØ working on an update of $\Omega_b^-$ with more data

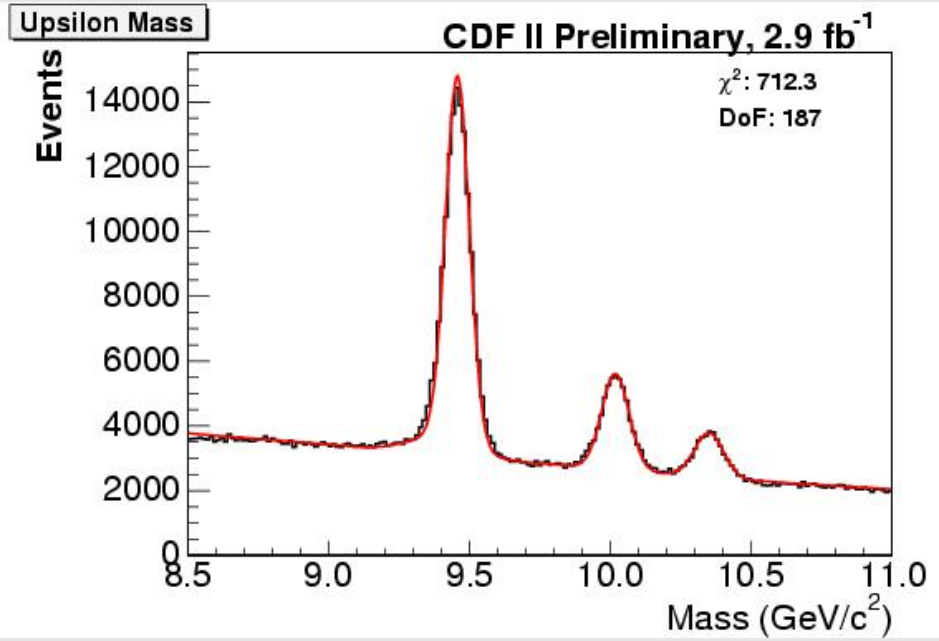


# $\Upsilon(1S)$ Polarization

- Vector meson production and polarization is discussed within the framework of non-relativistic QCD .
- Theory predicts the vector meson polarization become transverse in the perturbative regime (at large $p_T$)
  - Recent CDF measurements of polarization for $J/\psi$ and $\psi(2S)$ do not support this prediction.
- It is helpfull for our understanding test if $\Upsilon(1S)$ also is in disagreement with the theoretical predictions.

# $\Upsilon(1S)$ Polarization




- $\Upsilon(1S) \rightarrow \mu^+\mu^-$
- $|y| < 0.6$
- $2 < p_T(\Upsilon(1S)) < 40$ GeV/c

- $\frac{d\Gamma}{dcos\theta^*} \propto 1 + \alpha cos^2\theta^*$
- $\alpha = +1 \rightarrow$ fully transverse
- $\alpha = -1 \rightarrow$ fully longitudinal

$\rightarrow$ NRQCD expect transversal polarization at high $p_T$

$\rightarrow$ CDF observe longitunidal polarization at high $p_T$

$\theta^*$ is the angle between $\mu^+$ and $\Upsilon(1S)$ lab direction in $\Upsilon(1S)$ rest frame.

# Conclusions

# Conclusions

- Very rich heavy flavour program at CDF
- Many results on properties of heavy B hadrons:
  - Heavy baryons $\Sigma_b^{\pm}$, $\Sigma_b^{*\pm}$, $\Xi_b^-$ established
  - $\Omega_b^-$ observation
  - $\Upsilon(1S)$ polarization
- CDF will keep as a reference in the study of heavy hadrons next years
  - CDF accumulates more data until end of Run II

# Back Up

# $\Xi_b^- \, |bds\rangle$ Comparison DØ - CDF

CDF:

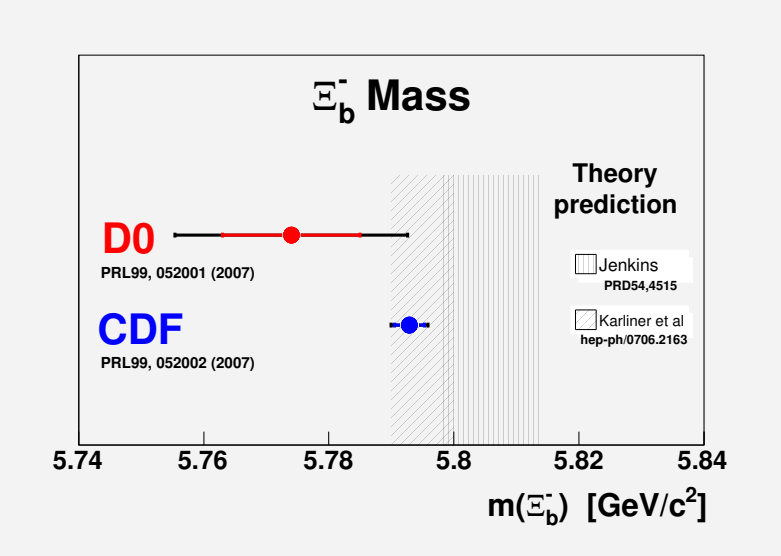
$$\frac{\sigma(\Xi_b^-)\mathcal{B}(\Xi_b^- \to J/\psi\,\Xi^-)}{\sigma(\Lambda_b^0)\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = 0.167^{+0.037}_{-0.025} \pm 0.012\text{B}$$

$$\frac{\sigma(\Omega_b^-)\mathcal{B}(\Omega_b^- \to J/\psi\,\Omega^-)}{\sigma(\Lambda_b^0)\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = 0.045^{+0.017}_{-0.012} \pm 0.004$$

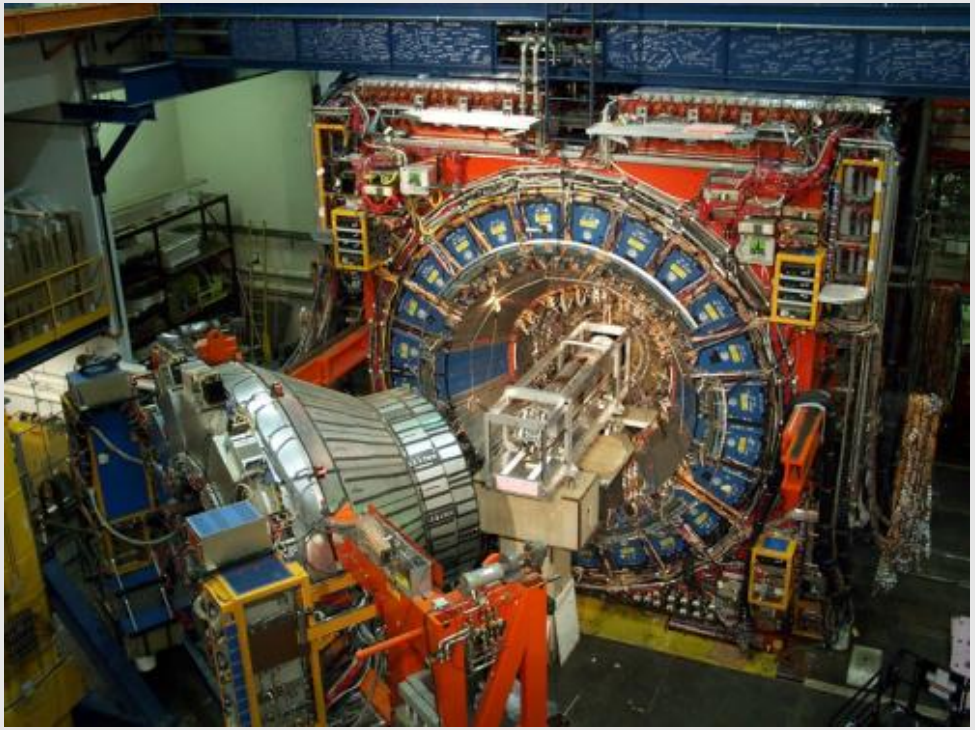
DØ :

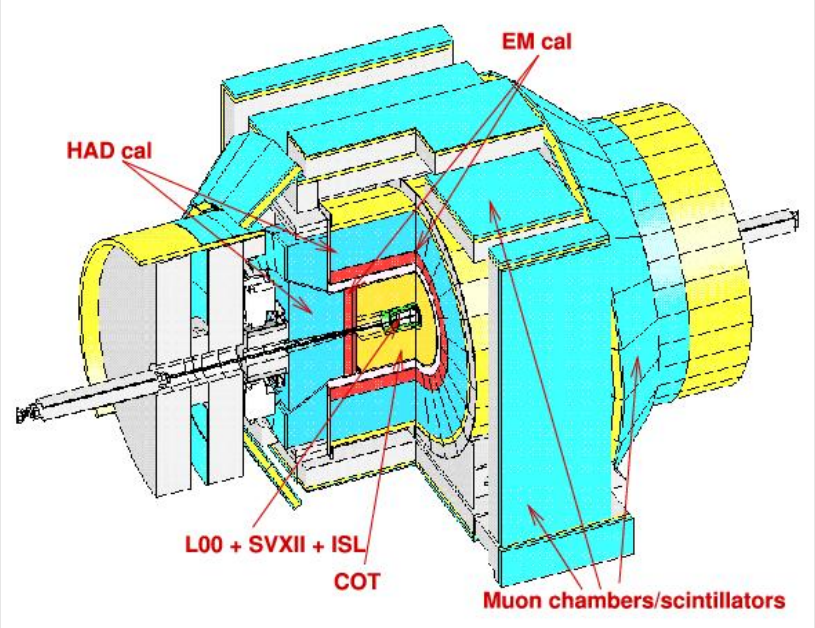
$$\frac{\sigma(\Xi_b^-)\mathcal{B}(\Xi_b^- \to J/\psi\,\Xi^-)}{\sigma(\Lambda_b^0)\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = 0.28 \pm 0.09(stat)^{+0.09}_{-0.08}(syst)$$

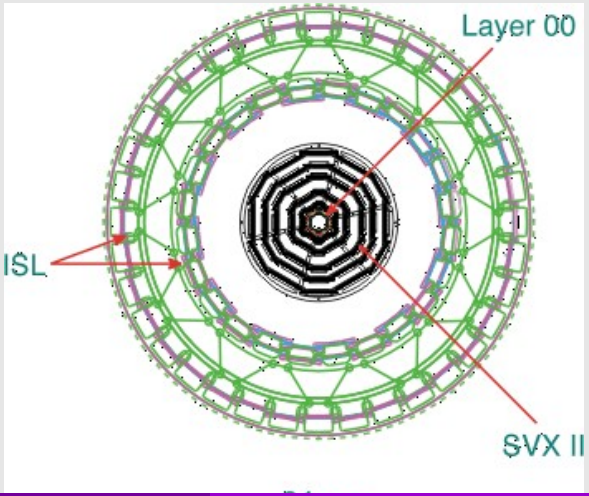
CDF, DØ results and theoretical prediction are consistent



# CDF Detector






- Excellent momentum resolution
- particle ID (TOF & dE/dx)
- Displaced track trigger and di-muon triggers