Heavy quark spectroscopy at Tevatron

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On behalf of the CDF and DØ Collaborations

Outline:

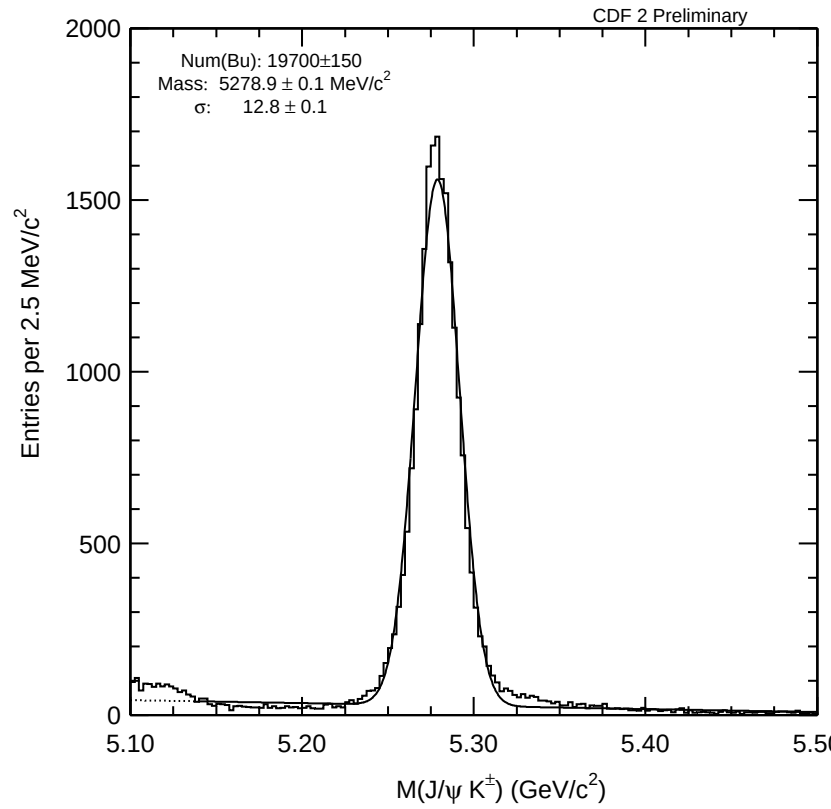
- $B_c \to J/\psi\pi$
- D_s^{**}, B^{**0} and B_s^{**}
- Σ_b, Σ_b^*
- Ξ_b^-

Introduction

- Heavy Quark mesons are QCD analog of "hydrogen atom"
  - $\longrightarrow$ Starts to be very sensitive test of various model in non-perturbative regime of QCD
  - $\longrightarrow$ Lot of information in charm sector
  - $\longrightarrow$ Bottom sector starts to speak up as well
- Heavy Quark baryon are next interesting laboratory
  - $\longrightarrow$ Heavy quark - light diquark is basic picture
  - $\longrightarrow$ Another sensitive test of models
  - $\longrightarrow$ Still many things to observe in charm sector
  - $\longrightarrow$ In bottom sector only Λ_b directly seen up to recently
- Discovery of new particles is exciting and fun
- Good practice for future discoveries

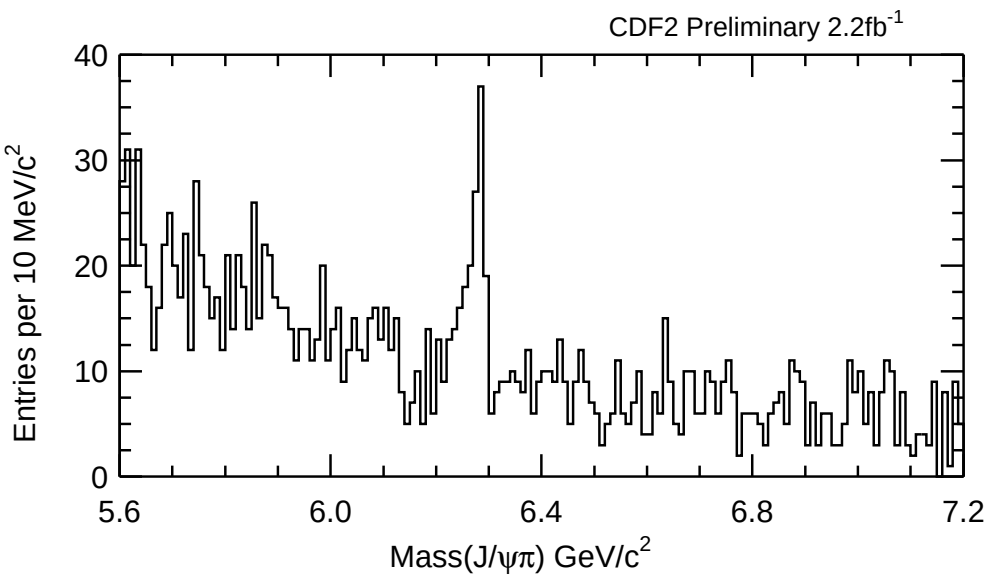
$\mathbf{B_c \to J/\psi\pi}$

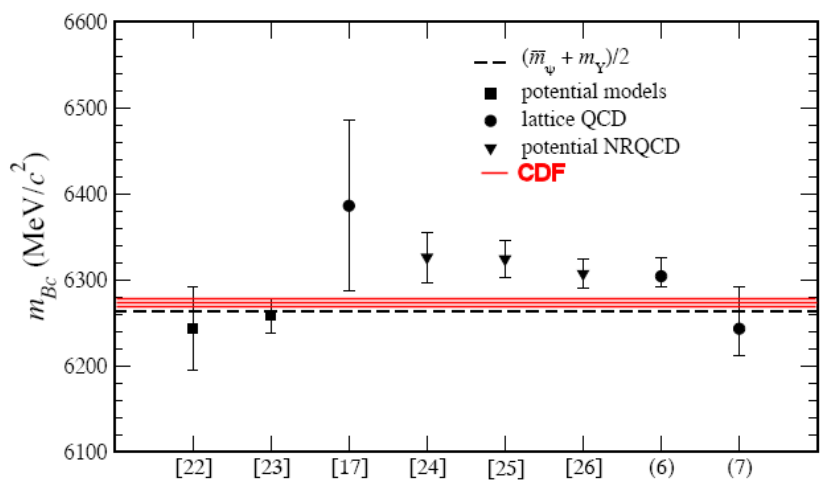
- Contains two distinct heavy quarks
- Interesting for interplay of the two heavy quark in decays
- Up to recently only seen in semileptonic decays
  $\Rightarrow$ bad mass measurement with uncertainty $\approx$ 400 MeV$/c^2$
- In May 2006, observation of decay $B_c \to J/\psi\pi$ in 1.1 fb^{-1}
  $\to$ Fully reconstructed decay
  $\Rightarrow$ Good mass resolution
- Strategy
  - Derive selection on $B^+ \to J/\psi K^+$
  - Apply same cuts to $B_c \to J/\psi\pi$
  - Wait for enough data



$\mathbf{B_c \to J/\psi\pi}$

- Update from 1.1 fb^{-1} to 2.2 fb^{-1}:
  $N_s = 87 \pm 13$ (was 45 ± 9)
  $M(B_c) = 6274.1 \pm 3.2(\text{stat}) \pm 2.6(\text{sys})$
  Significance $> 8\sigma$ (was $> 6\sigma$)
- Mass consistent with expectation
- Experiment much better than theory





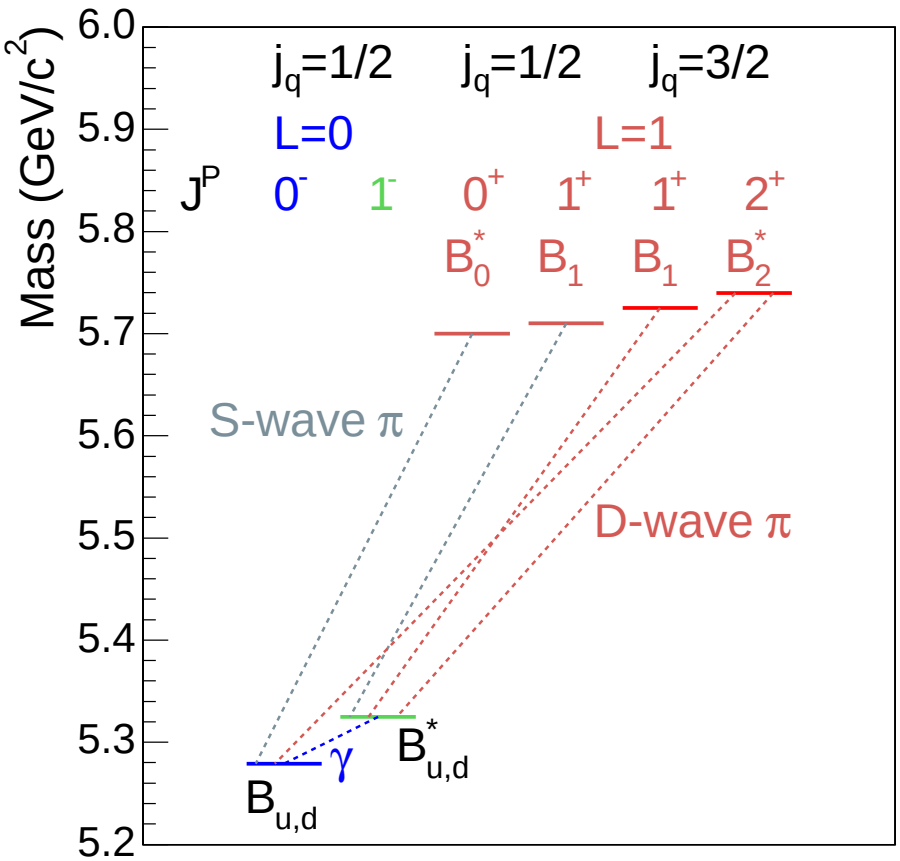
B^{**} and B_s^{**} Mesons

- Spin of heavy quark and light quark decoupled
- For $L = 1$ light quark has $j_q = 1/2$ or $j_q = 3/2$
- Combining with spin of heavy quark $\Rightarrow$ four states in two doublets

$\longrightarrow$ S-wave decay for $j_q = 1/2$

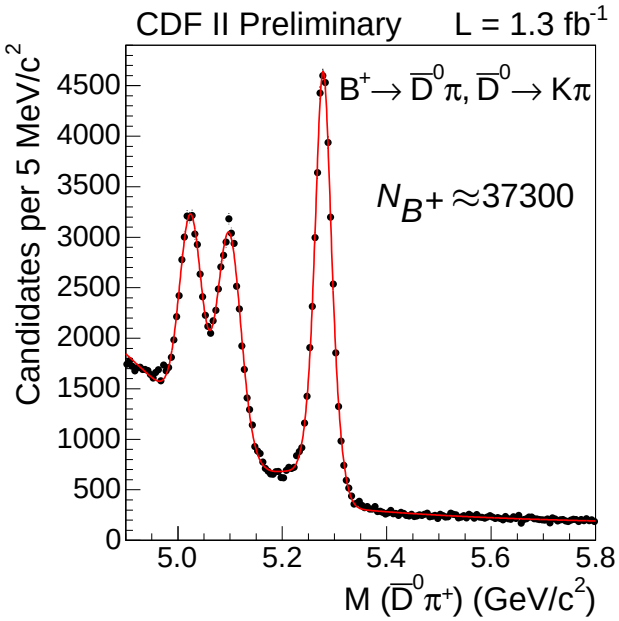
$\longrightarrow$ D-wave decay for $j_q = 3/2$

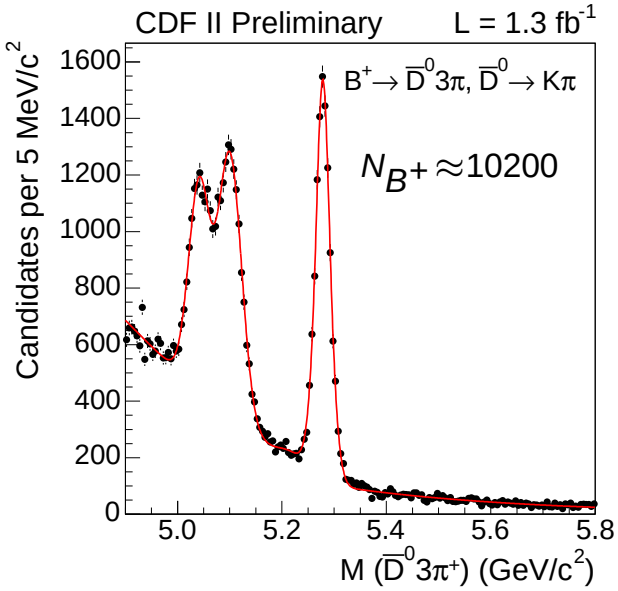
- Expect to see only states with $j_q = 3/2$
- At Tevatron also missing γ from B^* decay
- B_s^{**} analogous to B^{**} with K instead of π in decay
- $B_s^{**} \longrightarrow B_s\pi$ decay forbidden by isospin

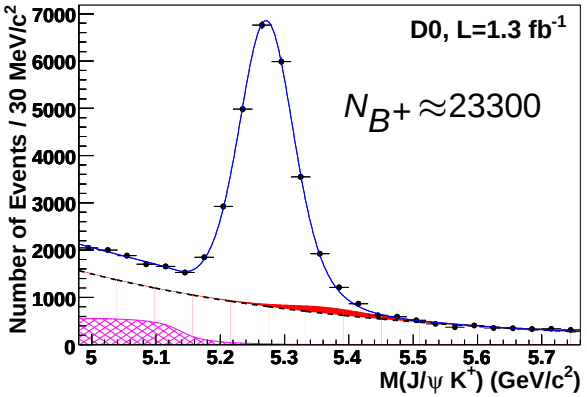


B^{**} and B_s^{**} Mesons

- Decay modes of B^+
  - $B^+ \to J/\psi K^+$ (CDF, DØ)
  - $B^+ \to \overline{D}^0 \pi^+$ (CDF)
  - $B^+ \to \overline{D}^0 3\pi^+$ (CDF, only B^{**})
- Only fully reconstructed B^+
  $\Rightarrow$ excellent mass resolution
- Combine B^+ with π^- (K^-) to form B^{**} (B_s^{**})
- Expect to see three peaks from decays
  - $B_1 \to B^{*+}\pi^-$
  - $B_2^* \to B^+\pi^-$
  - $B_2^* \to B^{*+}\pi^-$





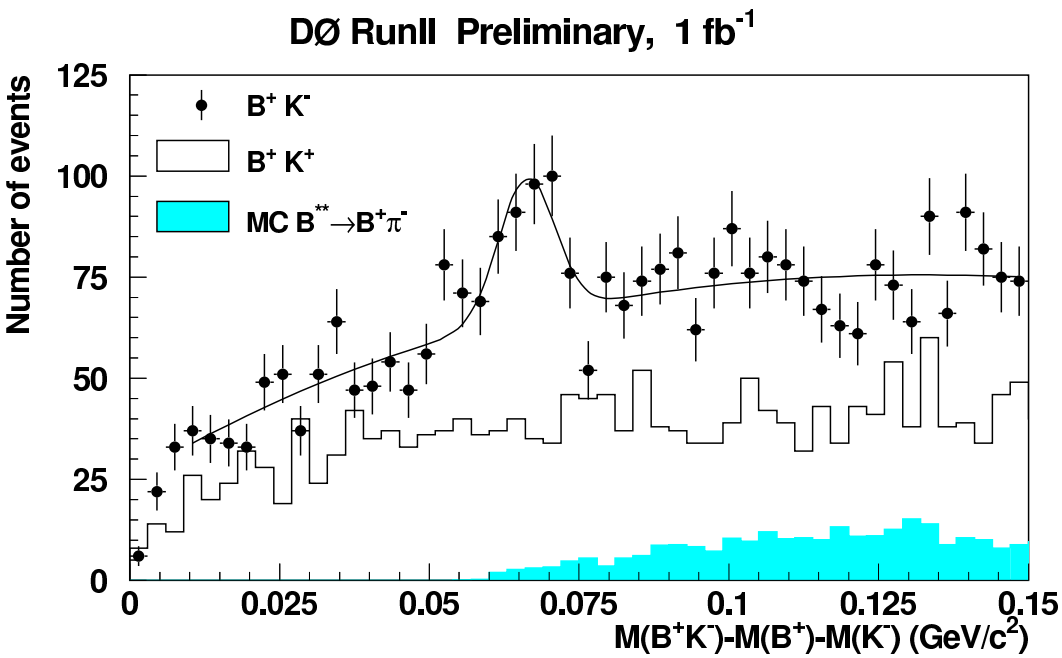


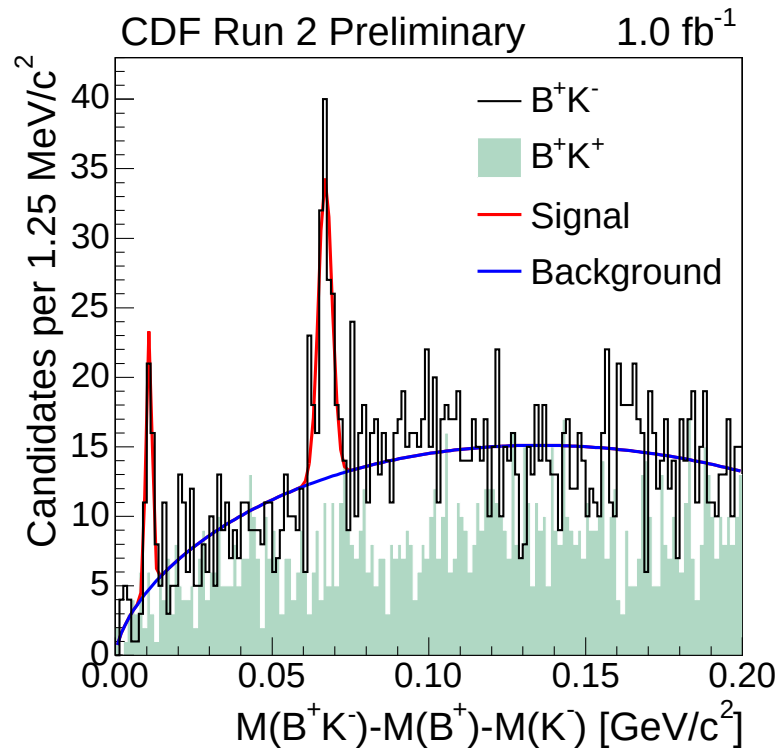
B_s^{**} Results

DØ	B_{s2}^*	$5839.1 \pm 1.4 \pm 1.5$ MeV$/c^2$
CDF	B_{s2}^*	$5839.0 \pm 0.4 \pm 0.5$ MeV$/c^2$
CDF	B_{s1}	$5829.4 \pm 0.2 \pm 0.6$ MeV$/c^2$

All observed peaks above 5σ significance

$\Rightarrow$ First observation of narrow B_s^{**}

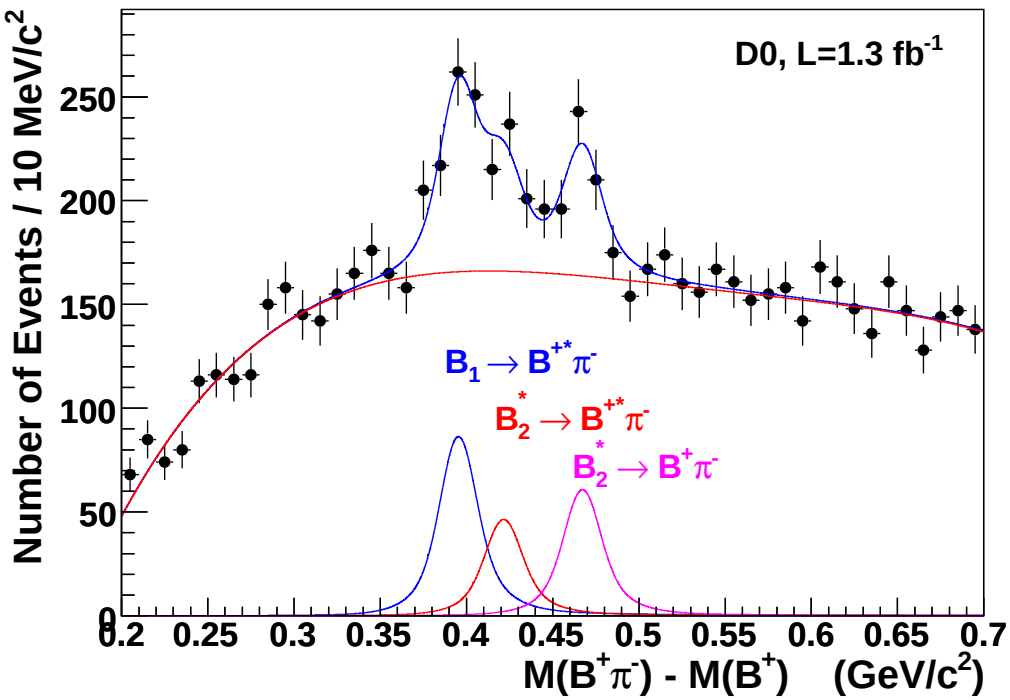


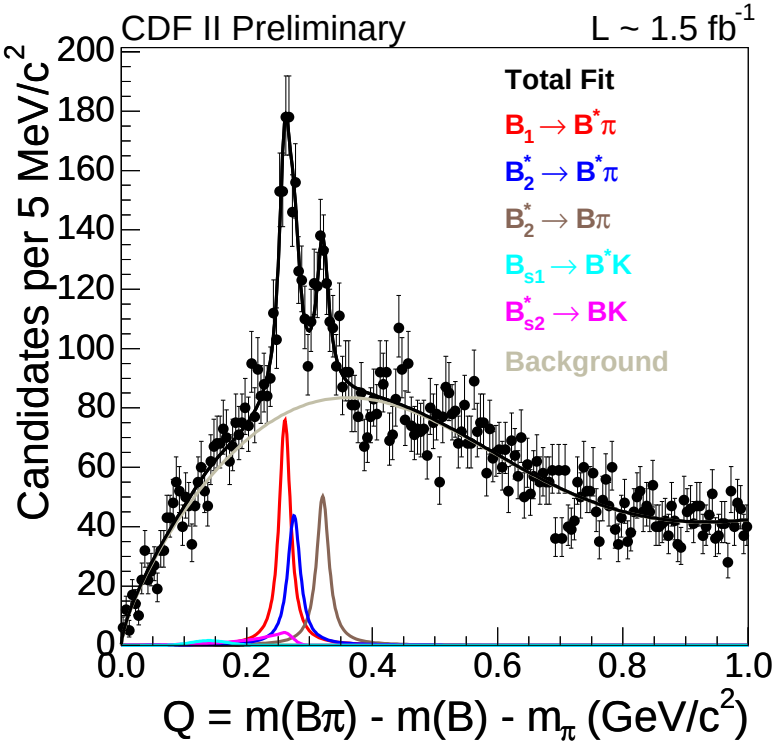


B^{**} Results

B_2^*	CDF	$5739.9^{+1.7}_{-1.8}{}^{+0.5}_{-0.6}$ MeV$/c^2$
	DØ	$5746.8 \pm 2.4 \pm 1.7$ MeV$/c^2$
B_1	CDF	$5725.3^{+1.6}_{-2.1}{}^{+0.8}_{-1.1}$ MeV$/c^2$
	DØ	$5720.6 \pm 2.4 \pm 1.4$ MeV$/c^2$

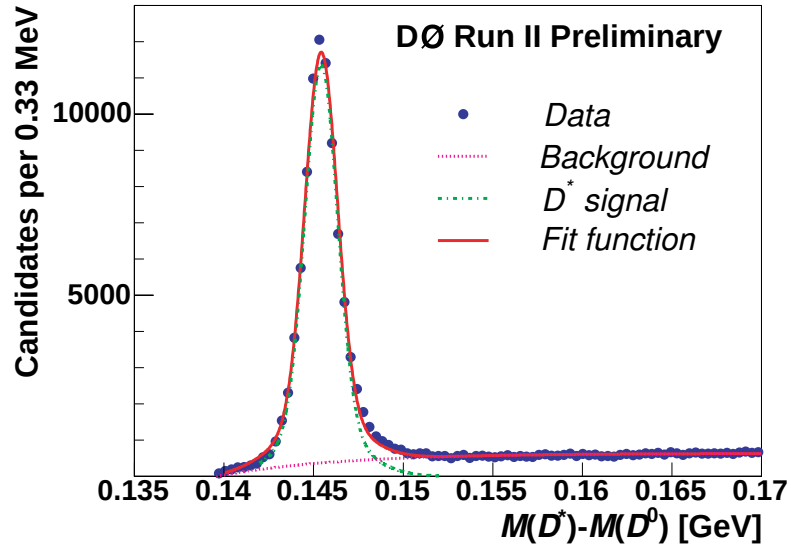
CDF also measures $\Gamma(B_2^*) = 22.1^{+3.6}_{-3.1}{}^{+3.5}_{-2.6}$ MeV

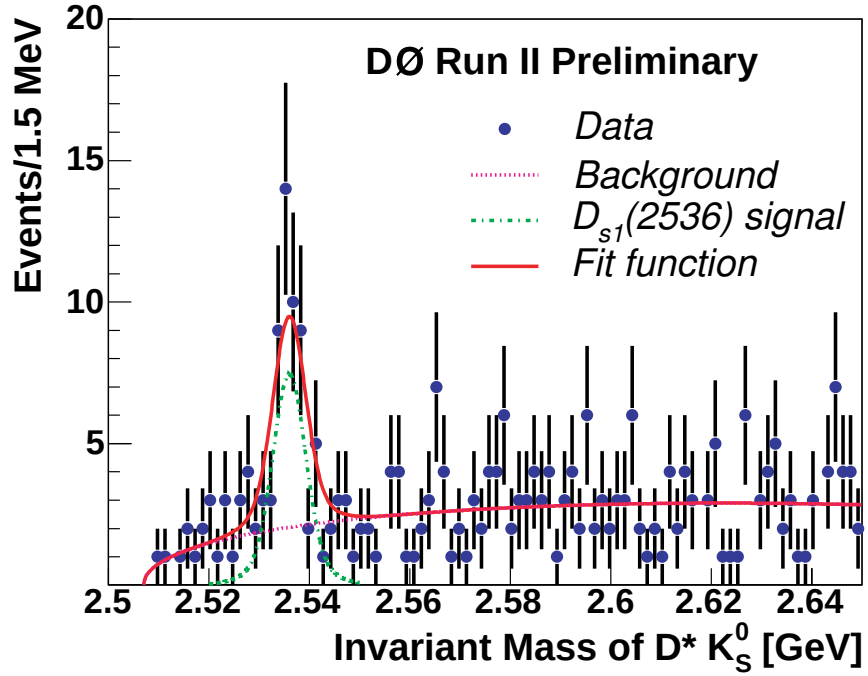




$D_{s1}(2536)$ Mass Measurement

- Measure $\mathcal{B}(B_s \to D_{s1}(2536)\mu\nu X)$
- Clean sample of $D_{s1}(2536) \to D^{*-}K_s^0$
- Observe 43.8 ± 8.3 signal events
- Measured mass $2535.7 \pm 0.6 \pm 0.5$ MeV$/c^2$
- $\mathcal{B}(B_s \to D_{s1}(2536)\mu\nu X) = (0.86 \pm 0.16 \pm 0.13 \pm 0.09)\%$





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

- Up to recently Λ_b only directly observed b-baryon
- Lack of the experimental result mainly due to the statistics
- Tevatron experiments start to have enough statistics to search for other b-baryons
- Decay via p-wave π

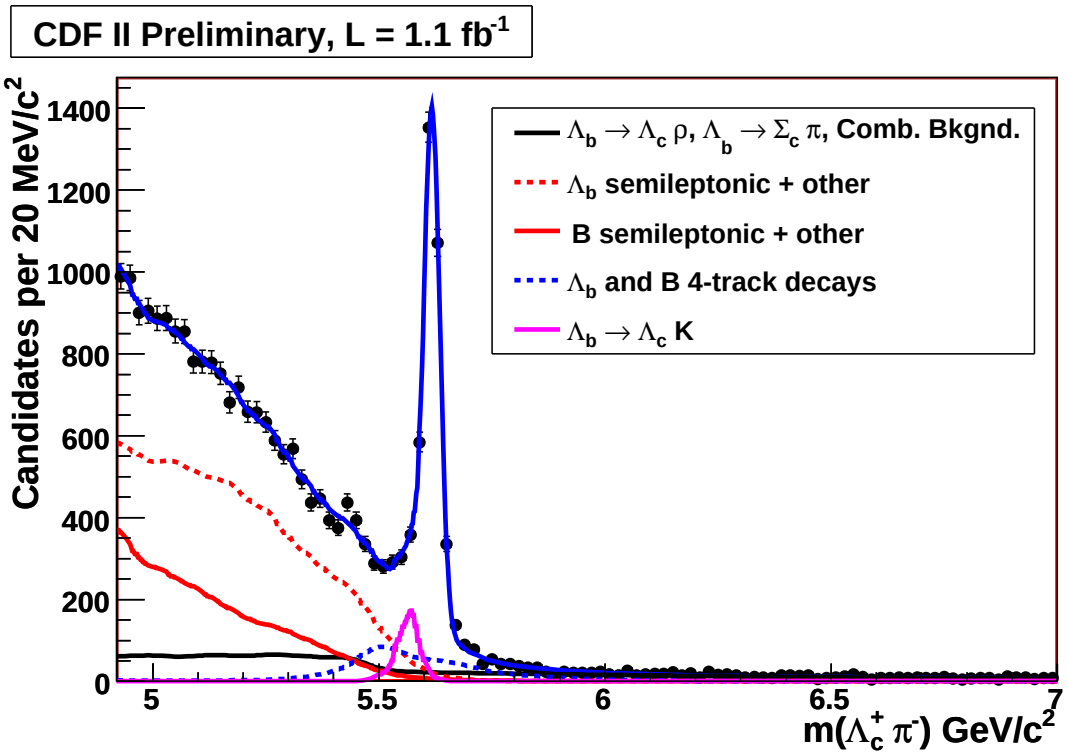
$$\Sigma_b\text{: } bqq \qquad J^P = S_Q + s_{qq} \begin{cases} \to 3/2^+ \ (\Sigma_b^*) \\ \to 1/2^+ \ (\Sigma_b) \end{cases}$$

$\Sigma_b^{(*)+}$ uub
$\Sigma_b^{(*)-}$ ddb
$\Sigma_b^{(*)0}$ udb

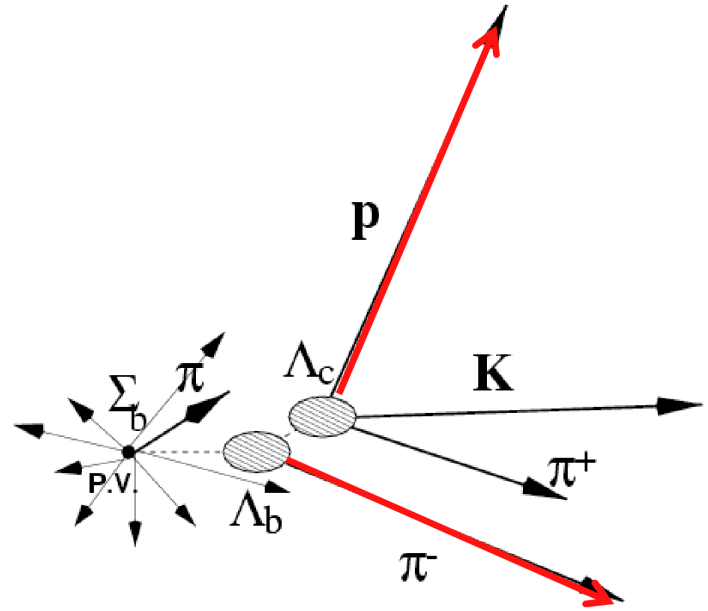
$\Sigma_b^{(*)0} \to \Lambda_b^0 \pi^0$ difficult at Tevatron

Property	Expectation (MeV/c^2)
$m(\Sigma_b) - m(\Lambda_b)$	180 — 210
$m(\Sigma_b^*) - m(\Sigma_b)$	10 — 40
$m(\Sigma_b^-) - m(\Sigma_b^+)$	5 — 7
$\Gamma(\Sigma_b)$, $\Gamma(\Sigma_b^*)$	≈ 8, ≈ 15

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



- $\Lambda_b \to \Lambda_c^+ \pi^-$, $\Lambda_c^+ \to pK^-\pi^+$
- With 1.1 fb^{-1} around 3200 $\Lambda_b \Rightarrow$ worlds largest sample
- For Σ_b search select narrow region around fully reconstructed peak

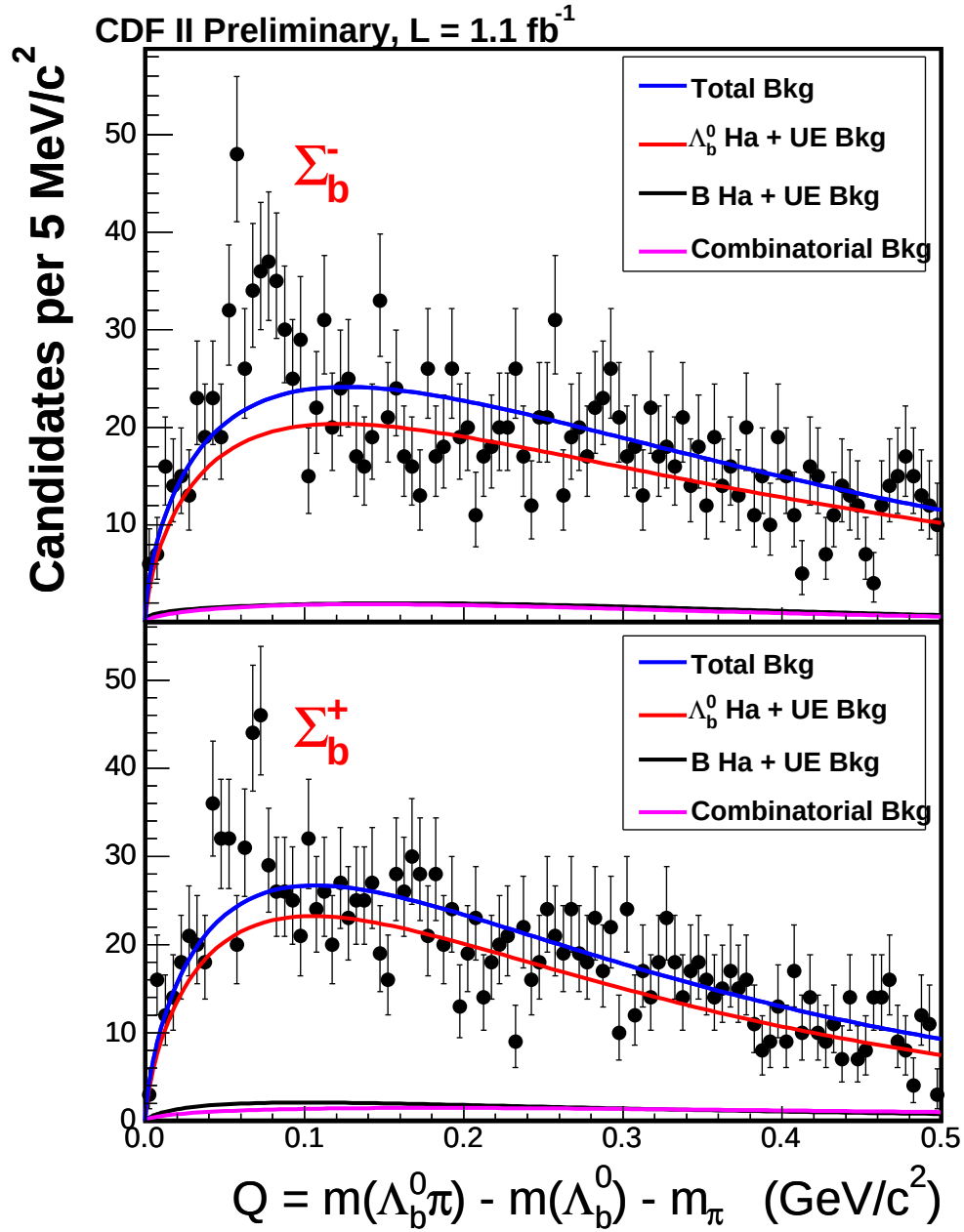


Σ_b Q-distribution

- Fixed background before looking to signal region
- Excess after unblinding

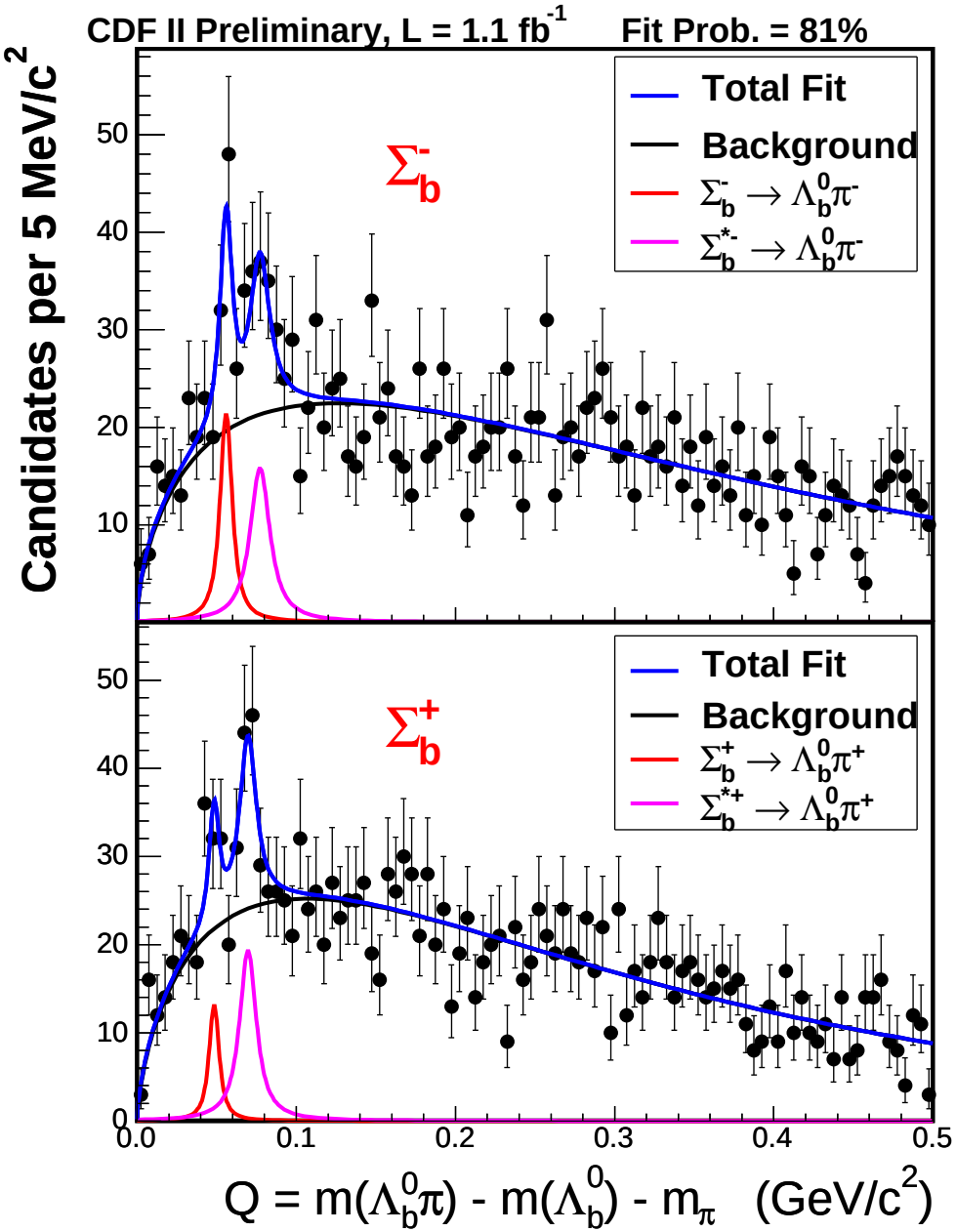
	Data	bkg	excess
$\Sigma_b^{(*)-}$	416	268	148
$\Sigma_b^{(*)+}$	406	298	108

- Data indicate two peaks for each charge
- Do unbinned maximum likelihood fit
- Fit for Q values and number of events



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

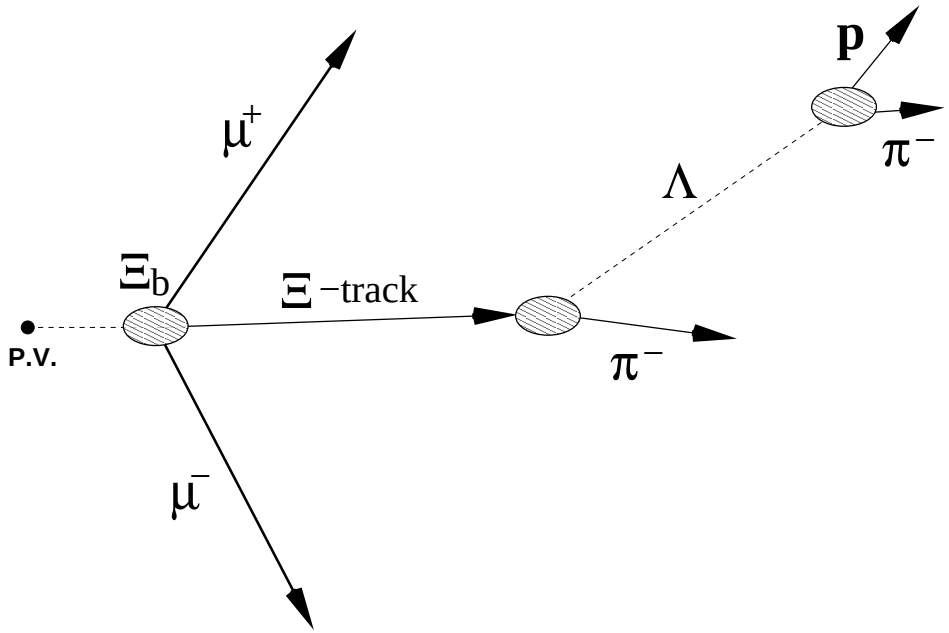
- $\to$ $m(\Sigma_b^-) - m(\Lambda_b) - m(\pi) = 55.9 \pm 1.0 \pm 0.2$ MeV$/c^2$
- $\to$ $m(\Sigma_b^+) - m(\Lambda_b) - m(\pi) = 48.5^{+2.0}_{-2.2}{}^{+0.2}_{-0.3}$ MeV$/c^2$
- $\to$ $m(\Sigma_b^*) - m(\Sigma_b) = 21.2^{+2.0}_{-1.9}{}^{+0.4}_{-0.3}$ MeV$/c^2$
- $\to$ $N(\Sigma_b^+) = 32^{+13}_{-12}{}^{+5}_{-3}$
- $\to$ $N(\Sigma_b^-) = 59^{+15}_{-14}{}^{+9}_{-4}$
- $\to$ $N(\Sigma_b^{*+}) = 77^{+17}_{-16}{}^{+10}_{-6}$
- $\to$ $N(\Sigma_b^{*-}) = 69^{+18}_{-17}{}^{+16}_{-5}$
- $\to$ Significance more than 5σ



What do we know about Ξ_b

- Quark content $bsu(\Xi_b^0)/bsd(\Xi_b^-)$
- Weak decay dominated by the b quark decay
  - Expect lifetime comparable to other b-hadrons
  - LEP experiments measure $\tau = 1.39^{+0.34}_{-0.28}$ ps from excess in $\Xi^- l^- \nu_l X$ events
- Theory expectations for mass in the range 5788–5812 MeV$/c^2$
- Possible decays useful for search
  - $\Xi_b \to J/\psi \Xi$ - good for trigger, at Tevatron only access to charged one
  - $\Xi_b \to \Xi_c \pi$
  - $\Xi_b \to D\Lambda$
  - $\Xi_b \to \Lambda_c K \pi$

Decay topology of $\Xi_b^- \to J/\psi \Xi^-$



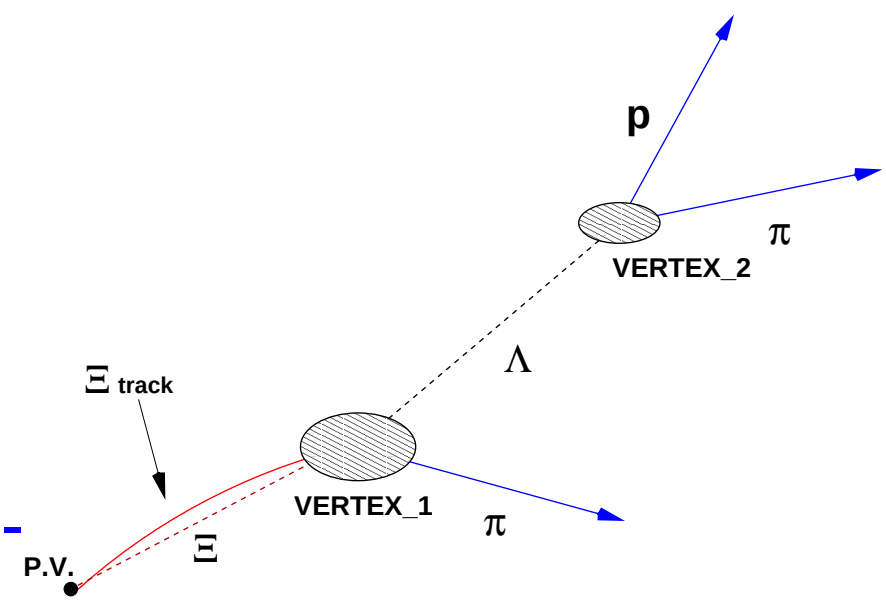
Full decay chain:

$\Xi_b^- \to J/\psi \Xi^-$

$\Xi \to \Lambda\pi$

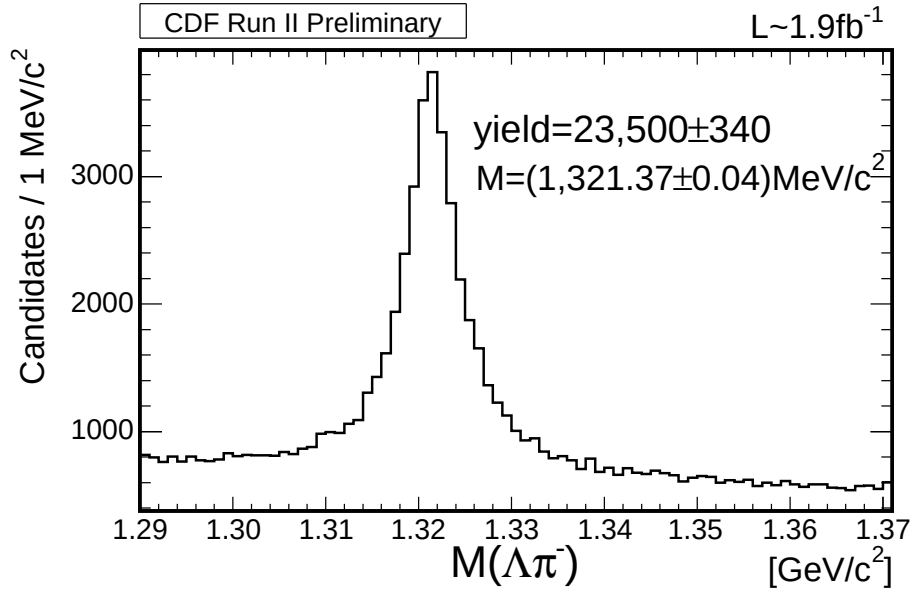
$\Lambda \to p\pi$

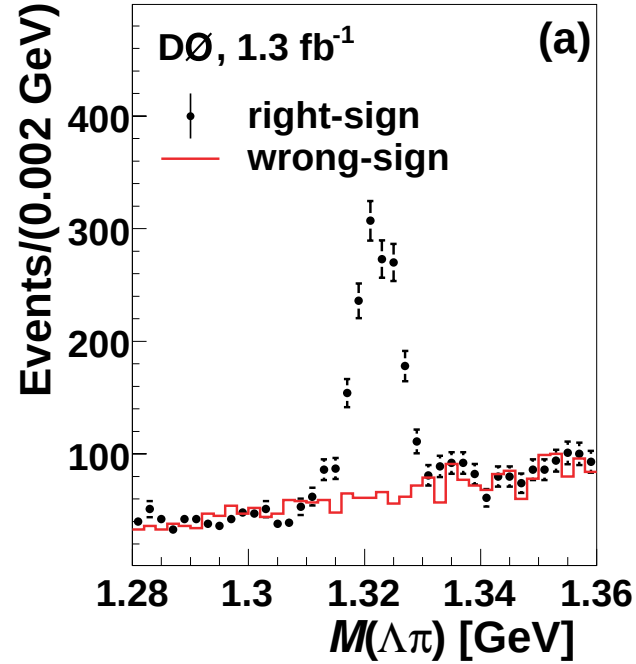
- Ξ^- is charged long lived particle
  $\Rightarrow$ challenges to work with it
  - At DØ low efficiency of default software
  - At CDF vertexting software needed modifications
- In addition, can be tracked in silicon detector (CDF)



$\Xi_b^- \to J/\psi \Xi^-$ search

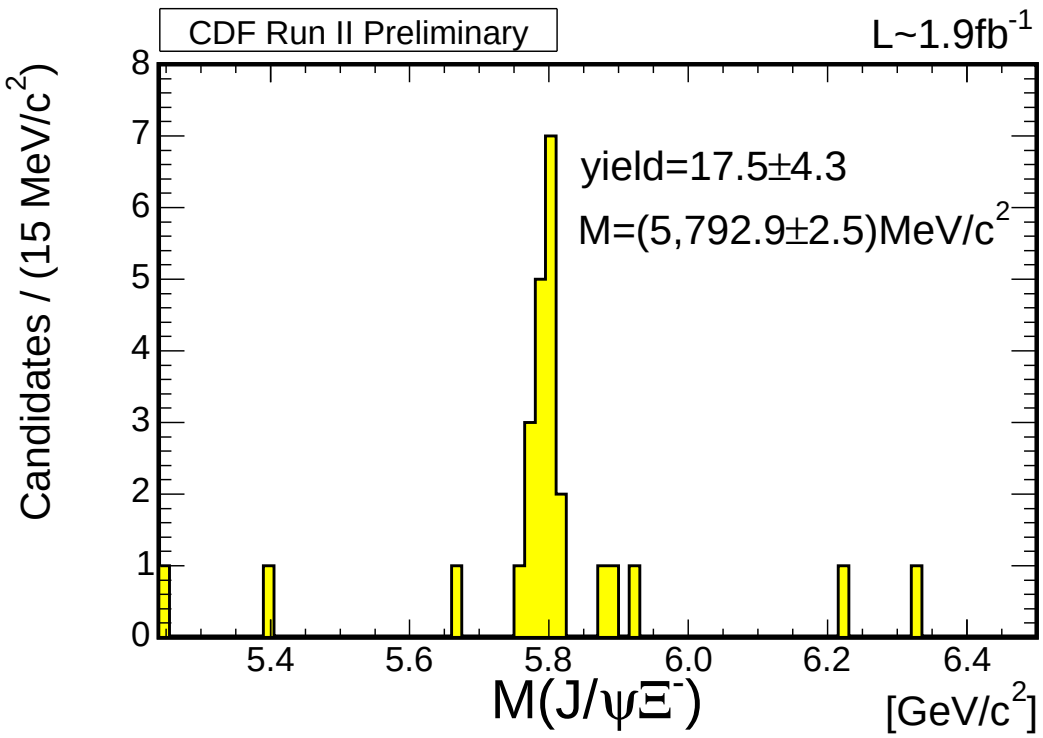
- Both experiments have clear Ξ^- signal
- Ξ^- candidates are combined with J/ψ to form Ξ_b^- candidates
- Selection
  - Main selection by momenta, vertexing quality and decay time
  - DØ develops selection based on wrong-sign data and signal MC
  - CDF reuse B^+ selection for B_c search with Ξ^- treated as track

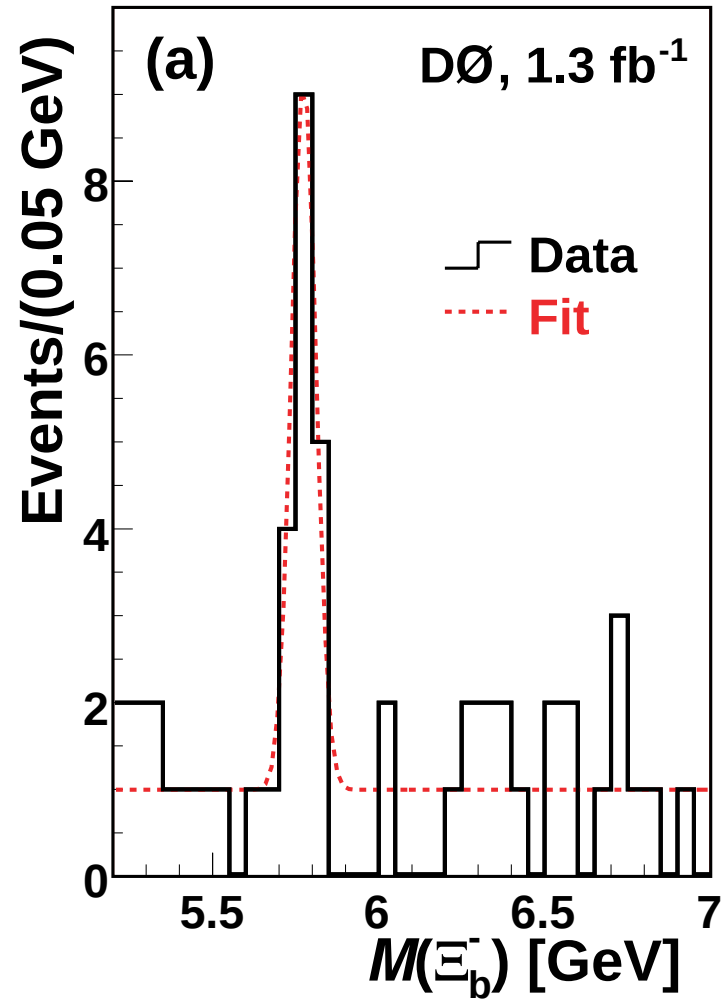




$\Xi_b^- \to J/\psi \Xi^-$ Result

$M(\Xi_b^-)$	DØ	$5774 \pm 11 \pm 15$ MeV$/c^2$
	CDF	$5792.9 \pm 2.5 \pm 1.7$ MeV$/c^2$
N_{sig}	DØ	$15.2 \pm 4.4^{+1.9}_{-0.4}$
	CDF	17.5 ± 4.3
significance	DØ	5.5σ
	CDF	7.7σ

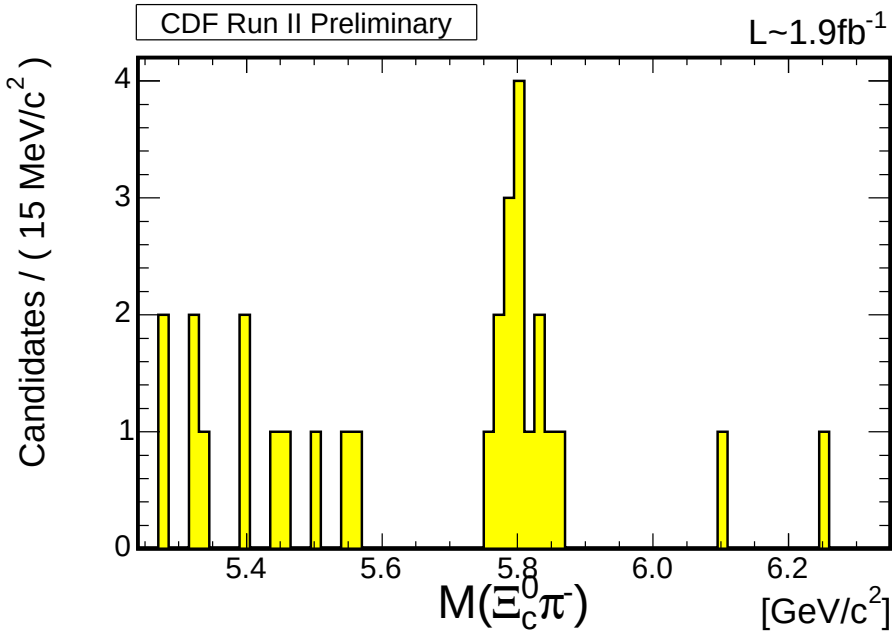


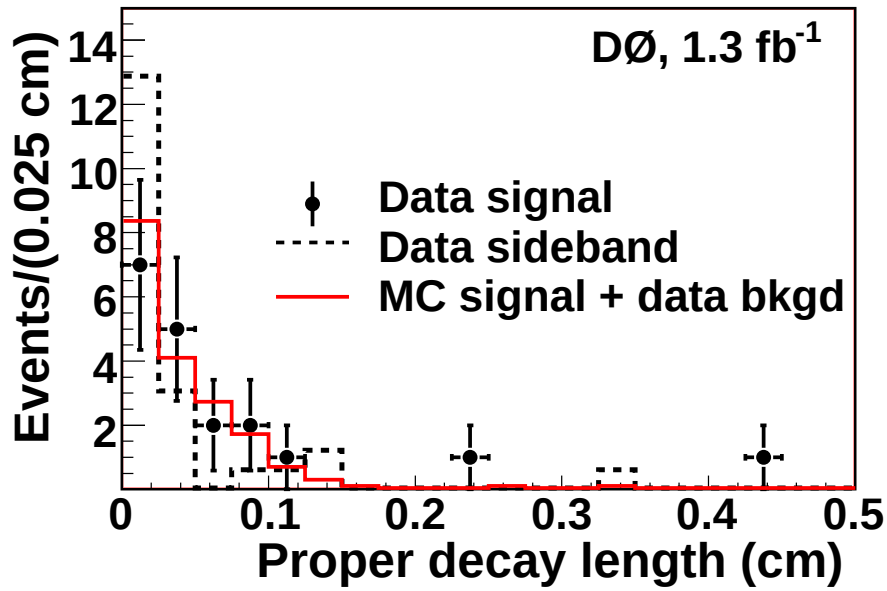


$\Xi_b^- \to J/\psi \Xi^-$ Cross-checks

- DØ made extensive check with no signal in
  - Wrong-sign $\Lambda\pi$ combinations
  - Ξ^- sidebands
  - J/ψ sidebands
- CDF has signal also in decay $\Xi_b^- \to \Xi_c^0 \pi^-$
- DØ lifetime distribution consistent with expectation

$\Rightarrow$ Signal consistent with $\Xi_b^- \to J/\psi \Xi^-$ decay





Conclusions

- Last year and half very productive in heavy quark spectroscopy
- For b-mesons
  - Observation of narrow B_s^{**}
  - Updates of B^{**} analyzes with first measurement of the $\Gamma(B_2^*)$
- For b-baryons
  - Observation of charged Σ_b, Σ_b^*
  - Observation of Ξ_b^-
- Both Tevatron experiments contribute to this enormous increase of knowledge
- Personal believe, that we can still provide some more information from spectroscopy of heavy quark hadrons

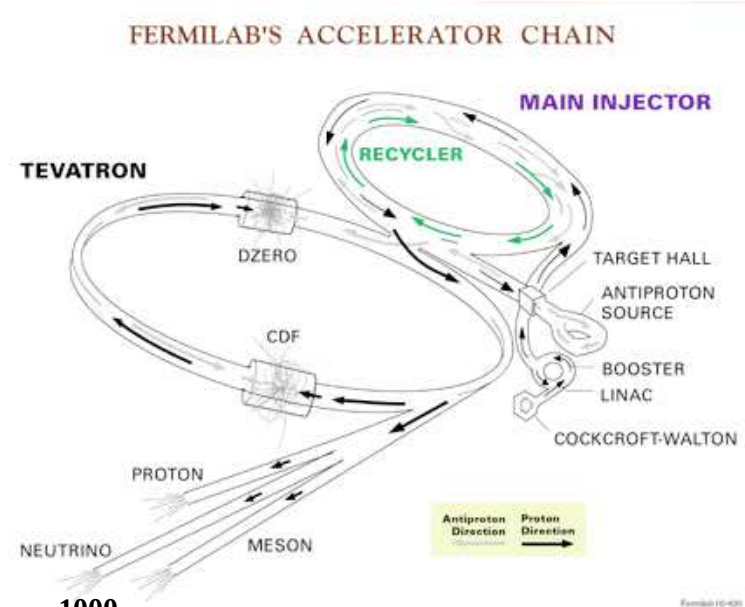
References

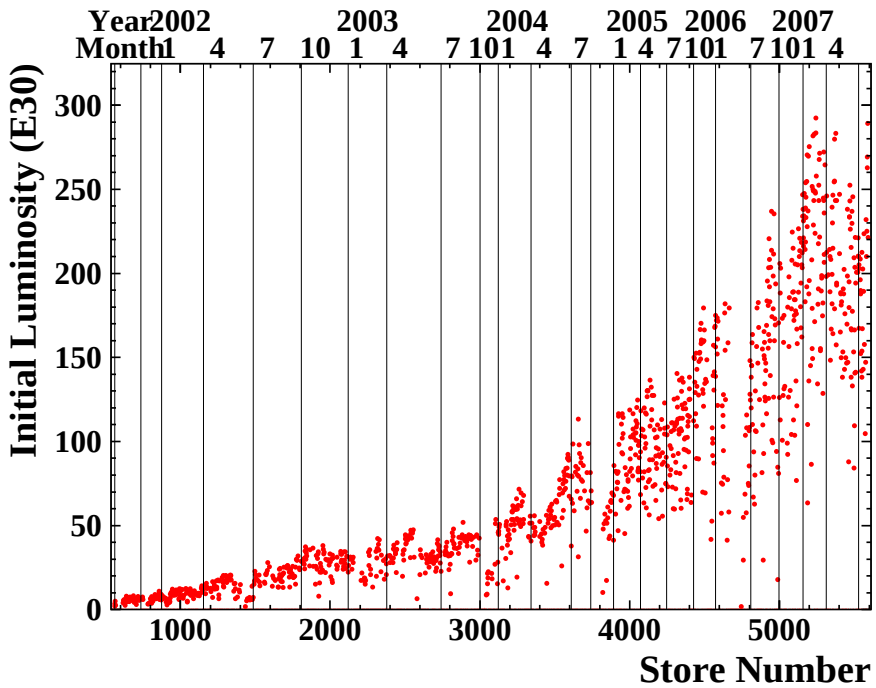
- B_c: http://www-cdf.fnal.gov/physics/new/bottom/070712.blessed-bc-mass/
- B^{**}
  - DØ: hep-ex/0705.3229
  - CDF: http://www-cdf.fnal.gov/physics/new/bottom/070726.blessed-bss/
- B_s^{**}
  - DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B31/
  - CDF: http://www-cdf.fnal.gov/physics/new/bottom/060720.blessed-BsSS_public/
- Σ_b: arXiv:0706.3868 [hep-ex]
- Ξ_b
  - DØ: Phys. Rev. Lett. 99 , 1052001 (2007)
  - CDF: Phys. Rev. Lett. 99, 052002 (2007)

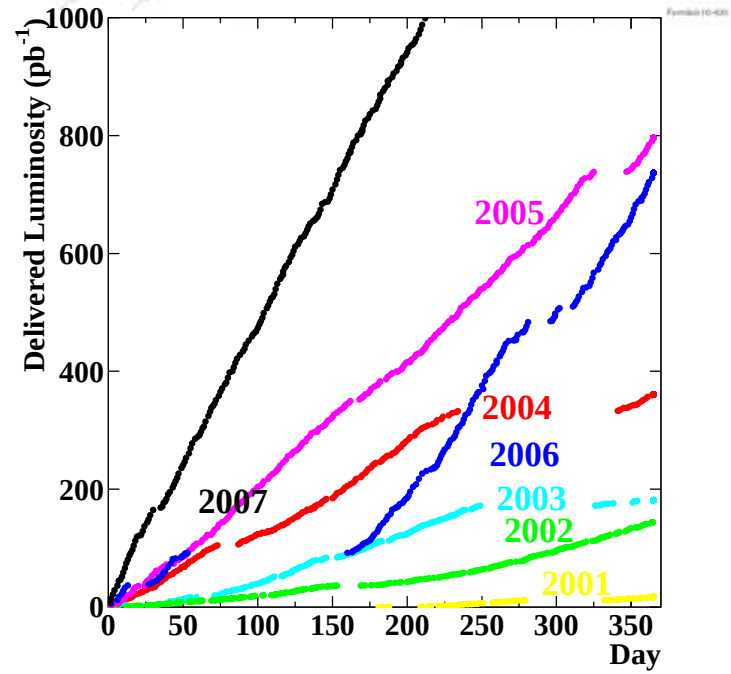
Backup

Tevatron

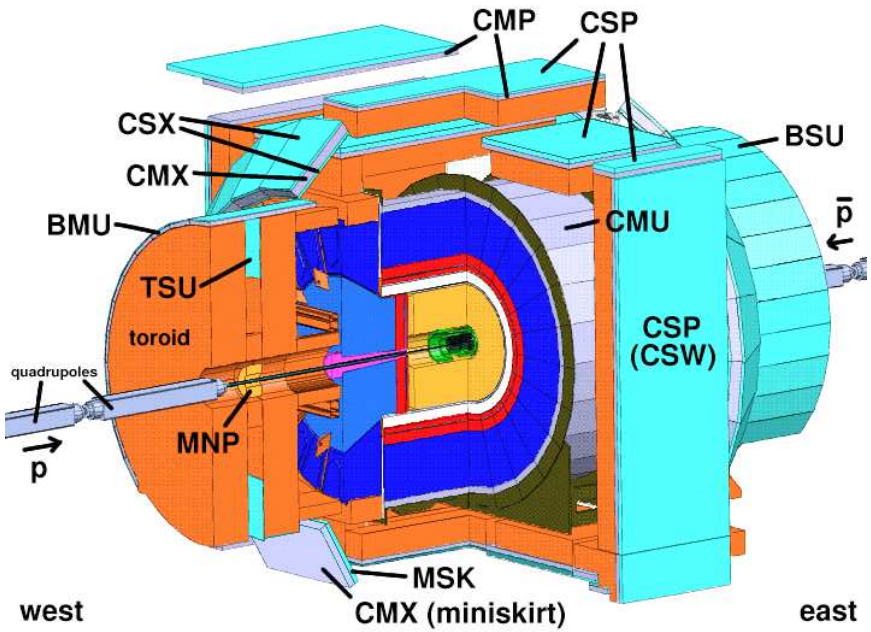
- $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\text{TeV}$
- Peak luminosity $\approx 3 \cdot 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$
- around $2.7\,\text{fb}^{-1}$ per experiment collected from around $3.2\,\text{fb}^{-1}$ delivered



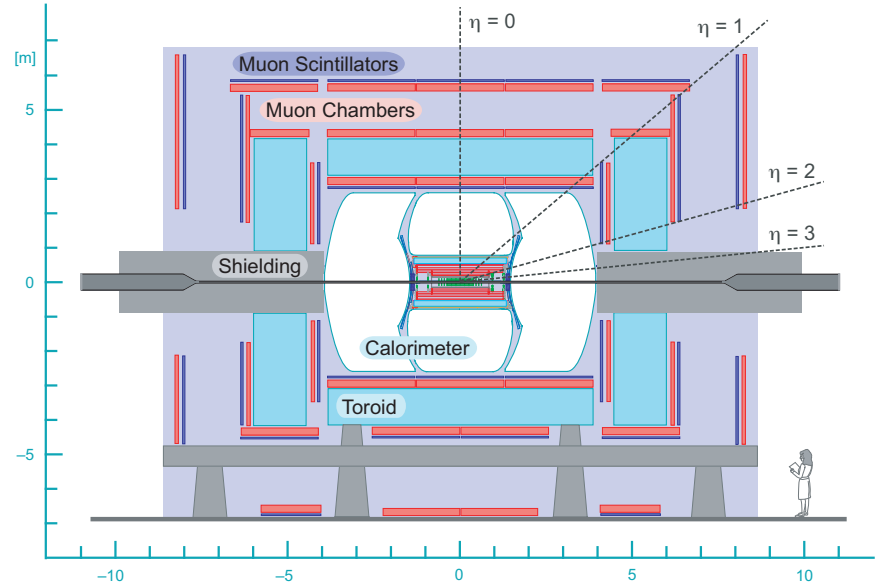




Experiments

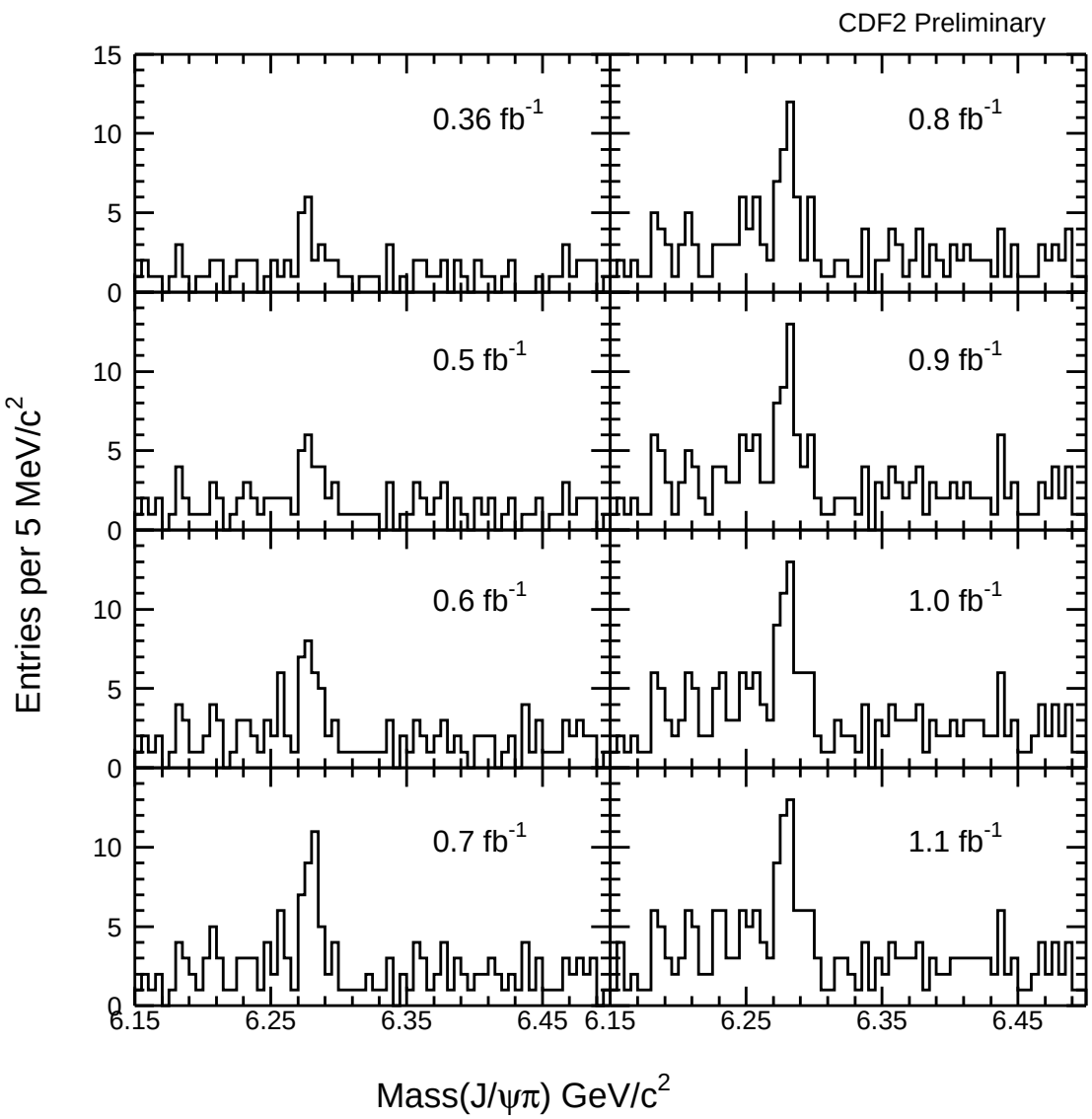


- Excellent momentum and mass resolution
- Tracking at trigger level
- Particle identification



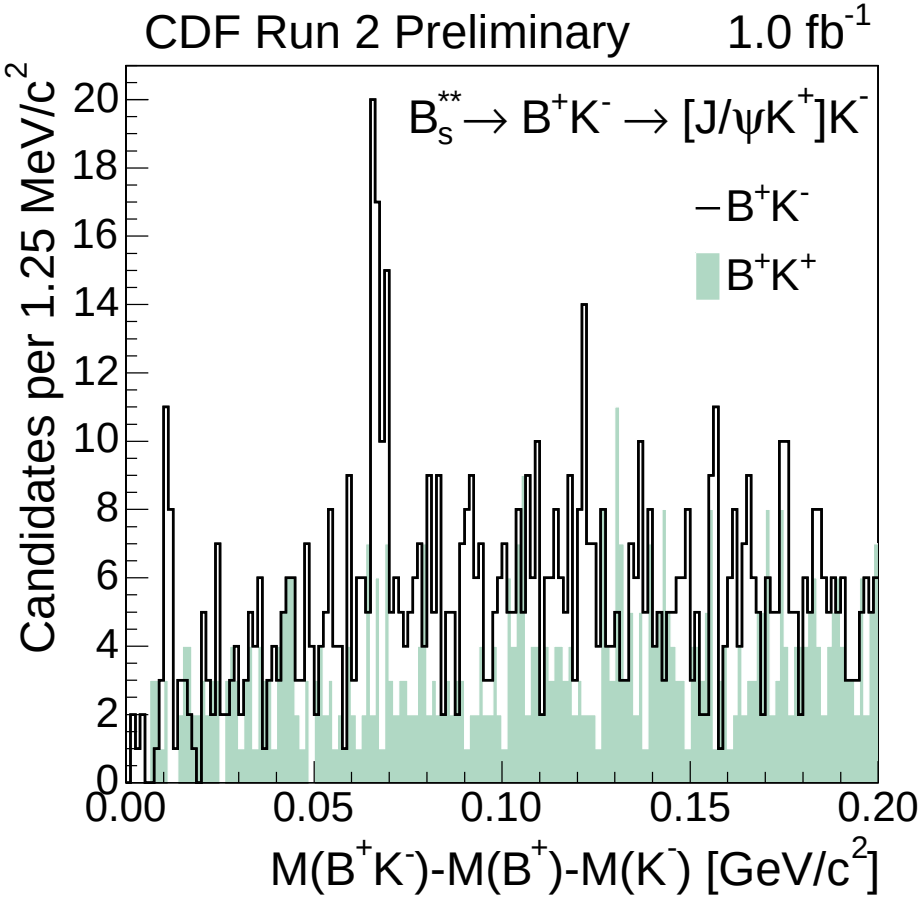
- Excellent muon coverage
- Very strong in semileptonic and J/ψ decays

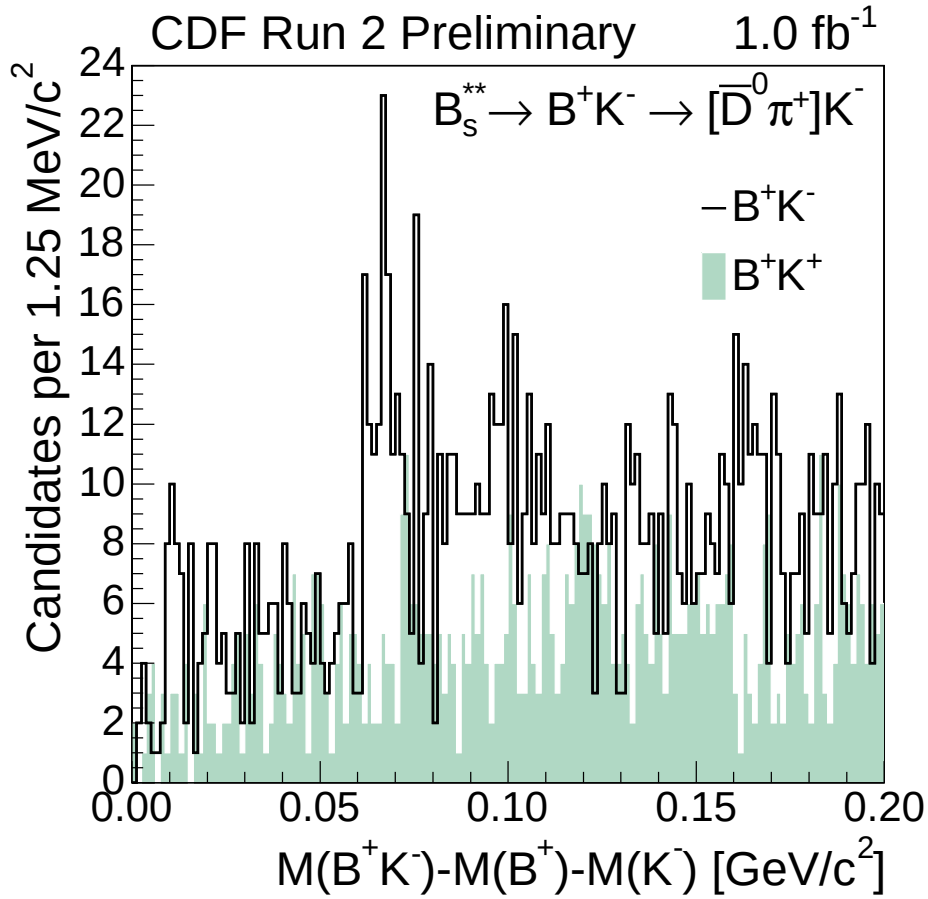
$\mathbf{B_c \to J/\psi\pi}$



- Selection derived and fix on 360 pb^{-1}
- As dataset grows, signal more significant
- Around 1 fb^{-1} enough to claim observation
- Previous result:
  $N_s = 45 \pm 9$
  $M(B_c) = 6276.5 \pm 4.0(\text{stat}) \pm 2.7(\text{sys})$
  $Significance > 6\sigma$
- Now update with doubled dataset

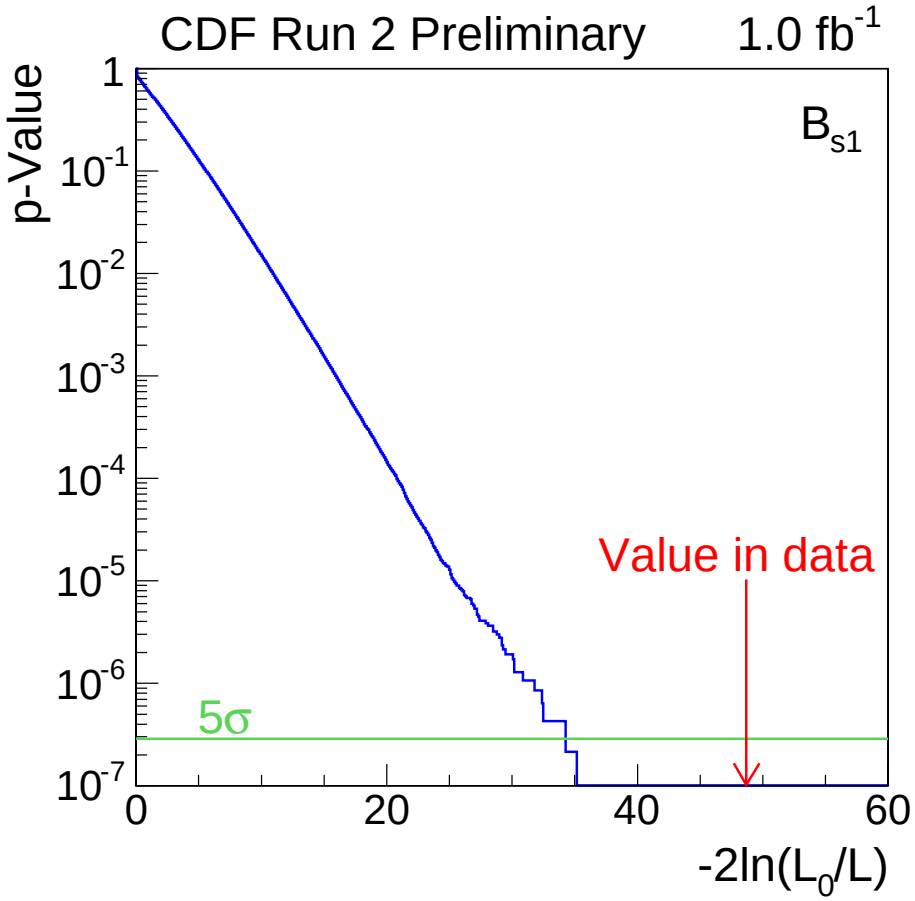
CDF B_s^{**} Q distributions

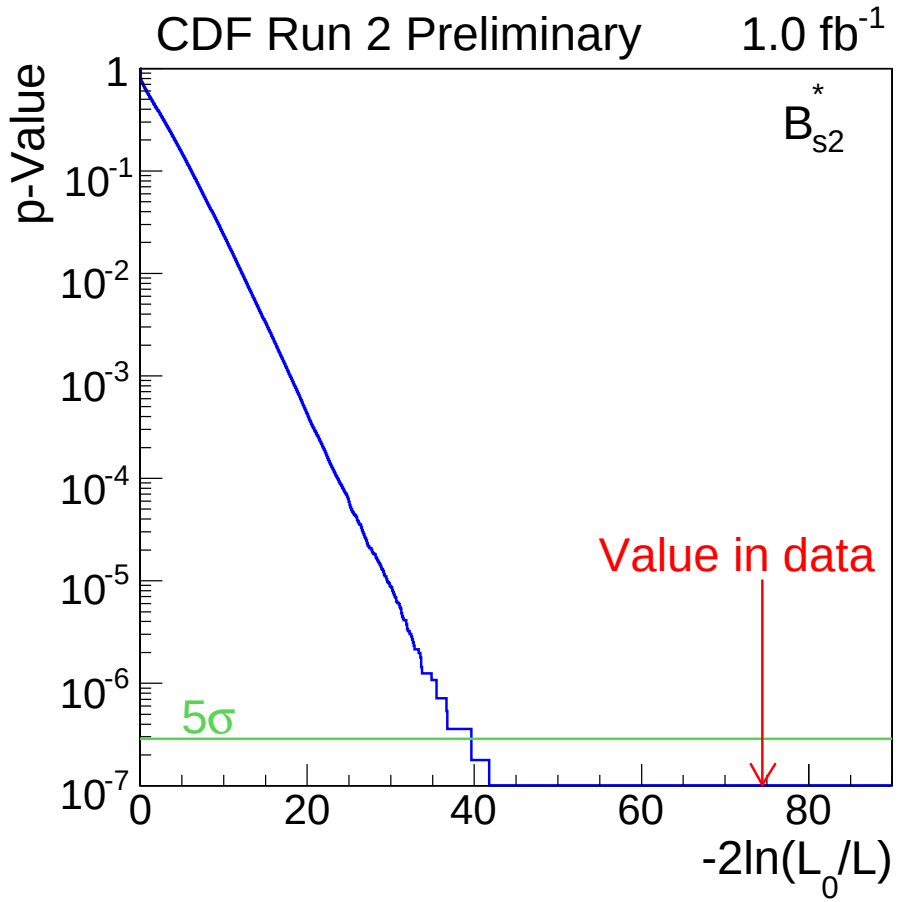




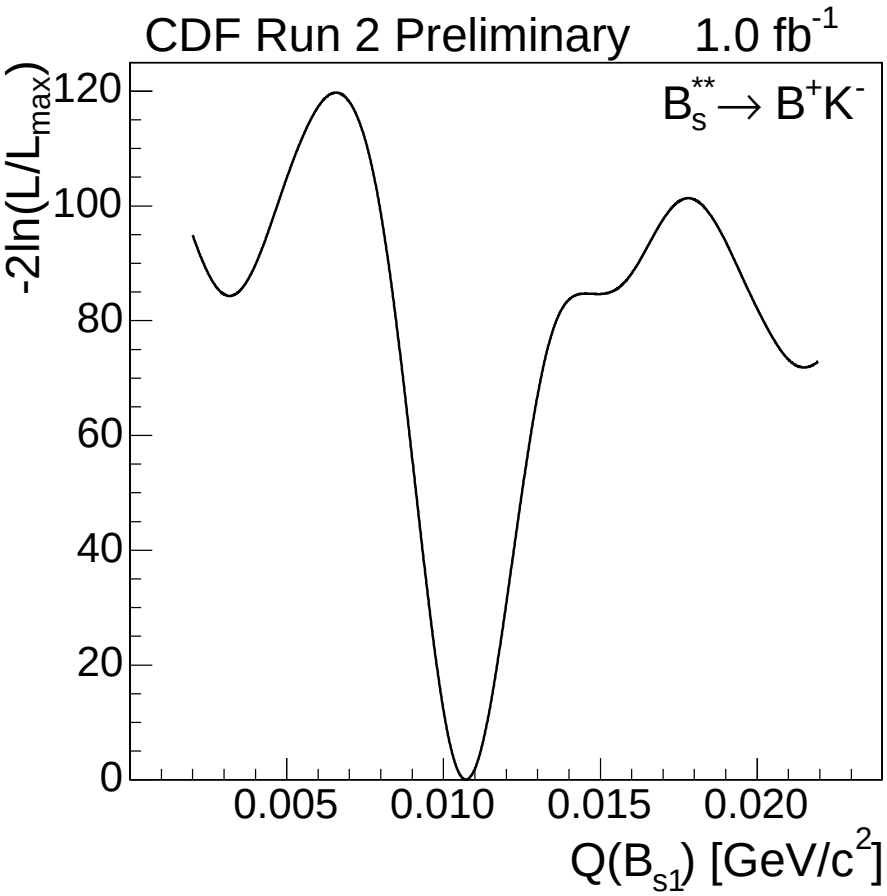
- Peak positions and width are consistent between two channels
- Background shapes are practically same

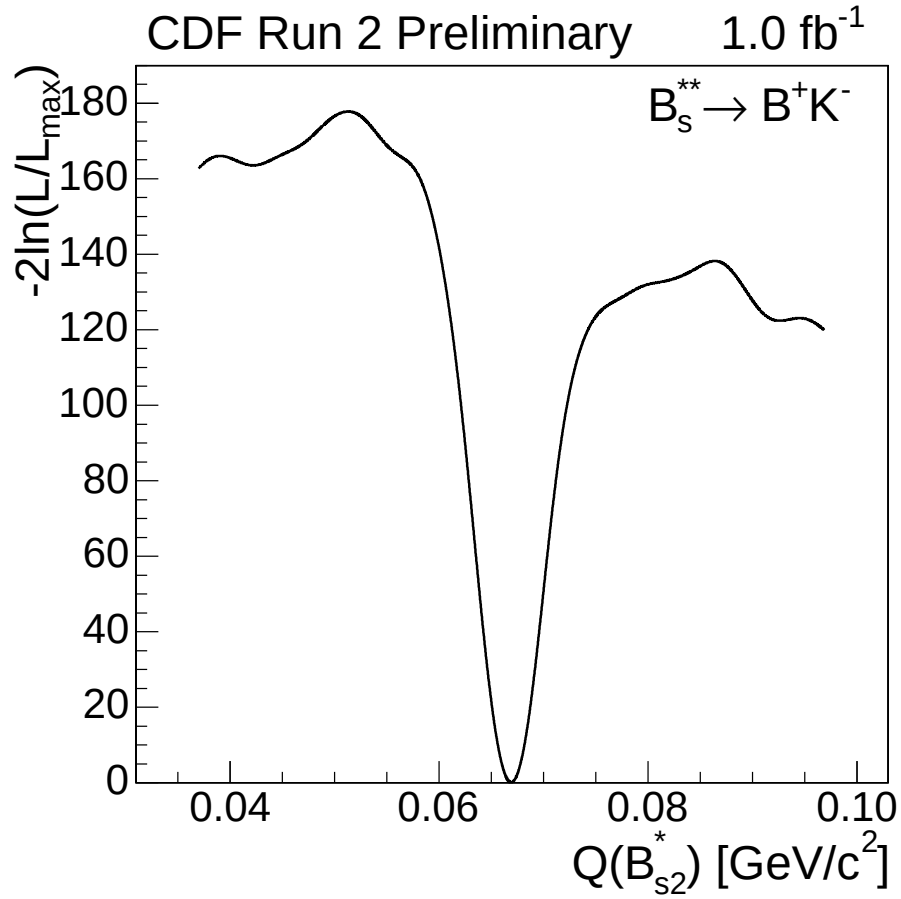
CDF B_s^{**} p-Value





CDF B_s^{**} Likelihood profiles





B^{**} in 370 pb^{-1} at CDF

New result:

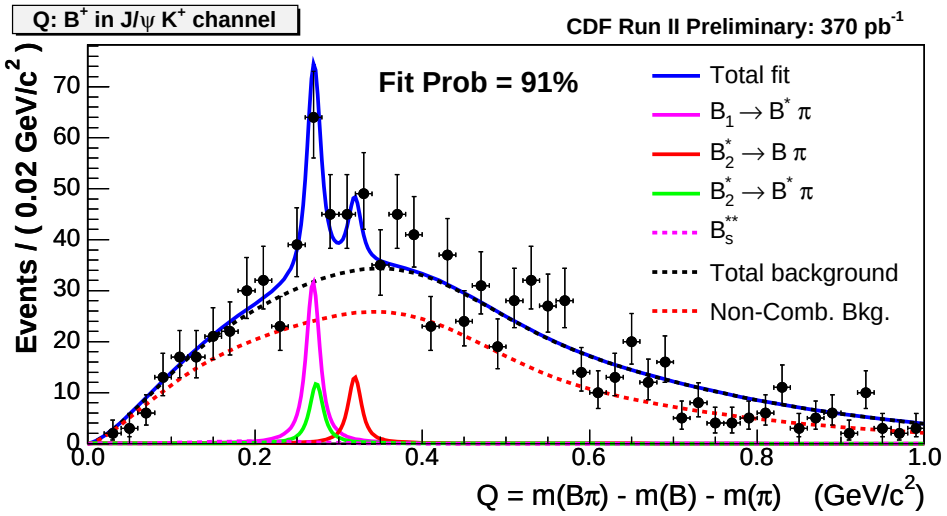
B_2^* $5739.9^{+1.7}_{-1.8}{}^{+0.5}_{-0.6}$ MeV$/c^2$

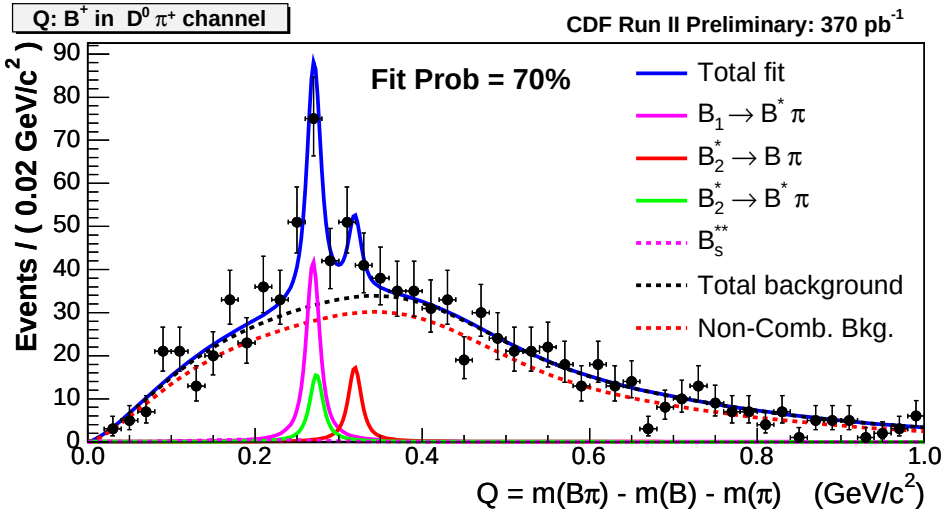
B_1 $5725.3^{+1.6}_{-2.1}{}^{+0.8}_{-1.1}$ MeV$/c^2$

Old result:

B_2^* $5738 \pm 5 \pm 1$ MeV$/c^2$

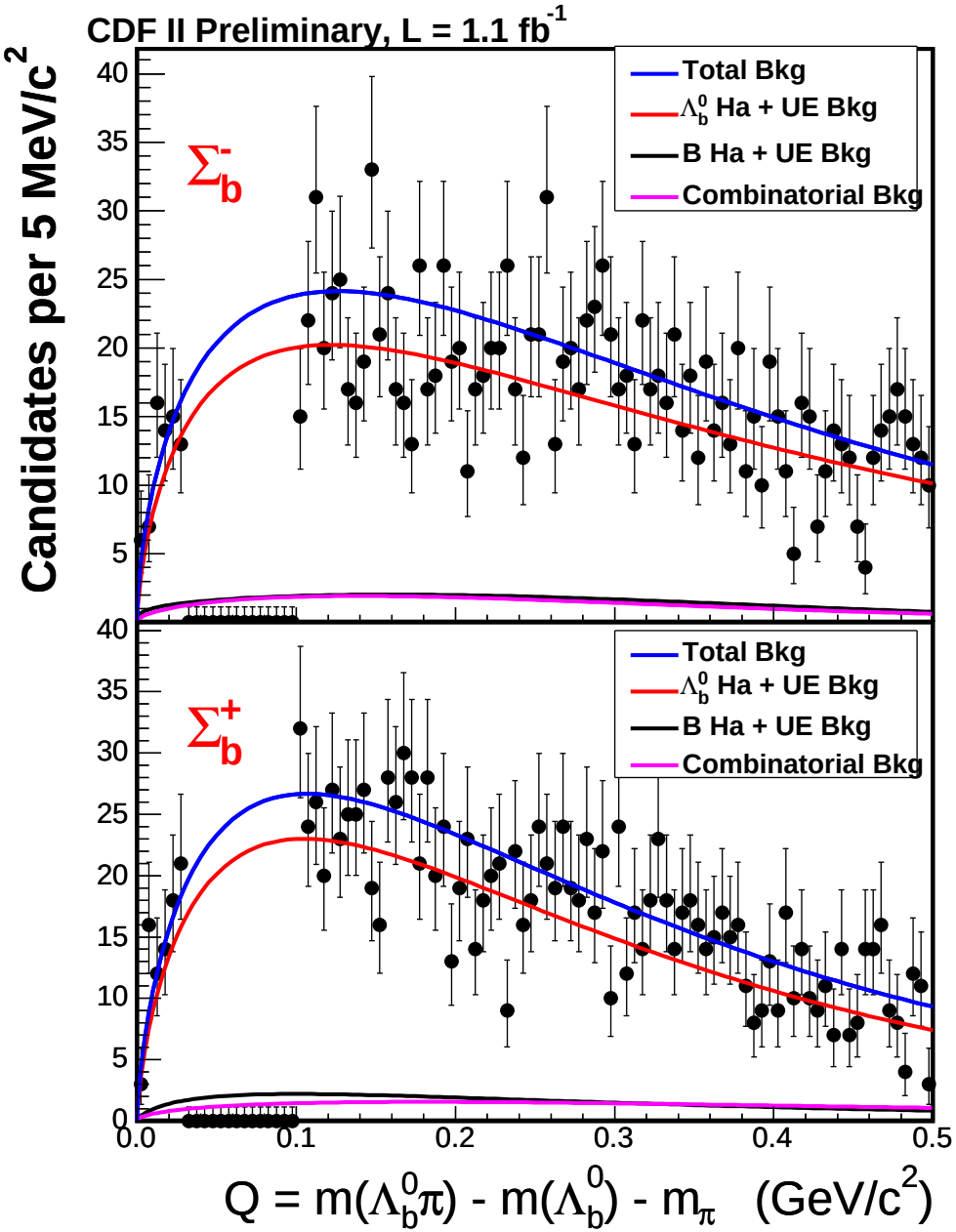
B_1 $5734 \pm 3 \pm 2$ MeV$/c^2$





Background estimation

- Do blind search
- Fix all backgrounds before looking to signal region
- Shapes
  Λ_b sideband
  PYTHIA MC
  B miss-reconstructed data
- Relative normalization according to Λ_b mass fit
- Determined background describes data well



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

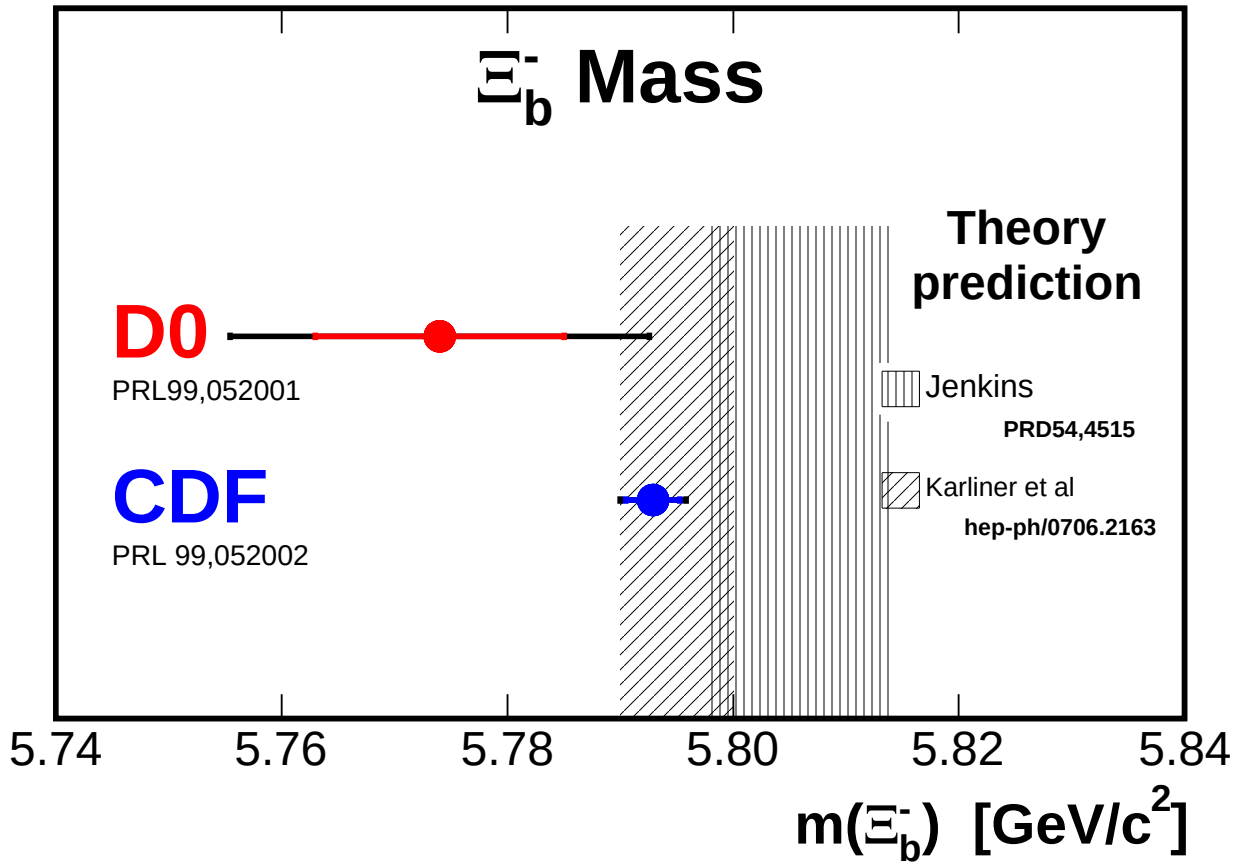
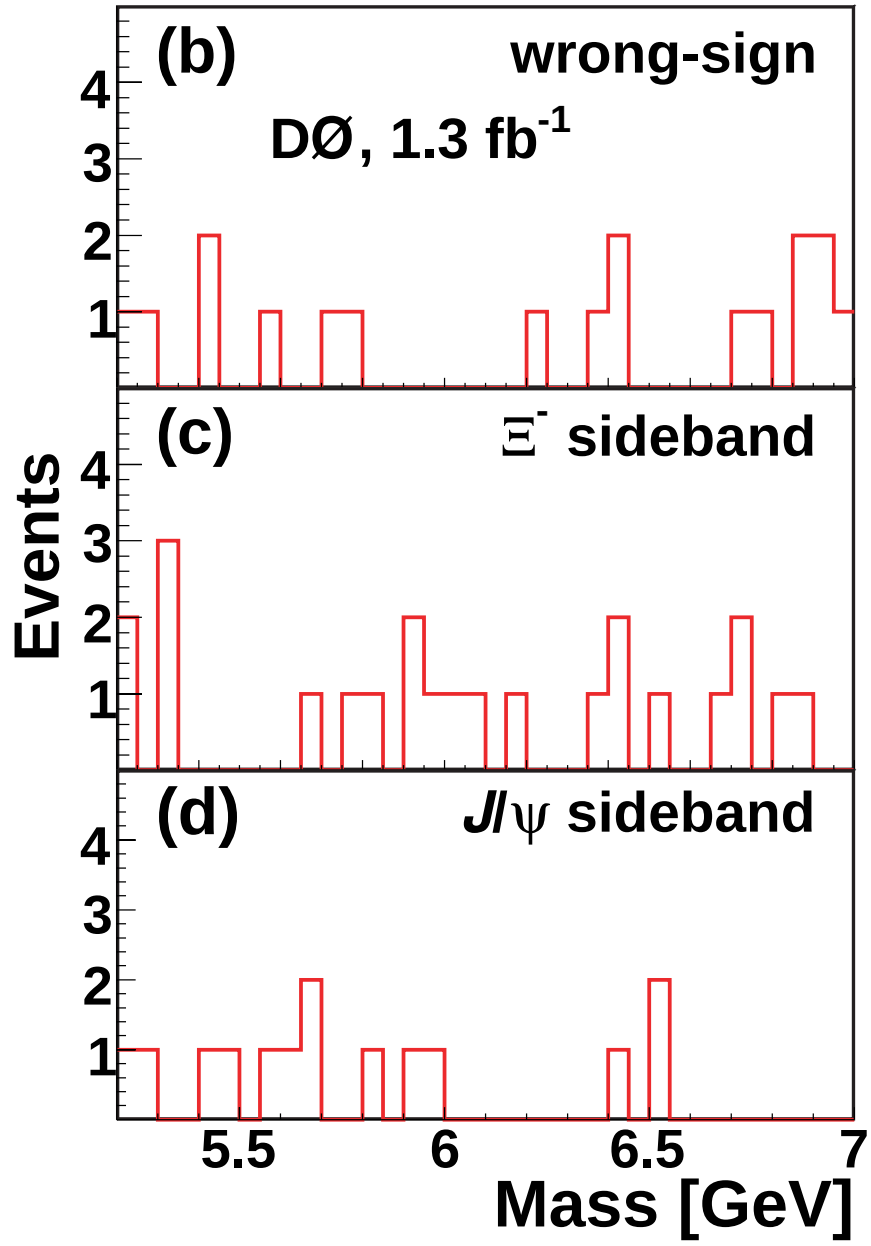
- Repeat fit with alternative hypothesis
  - Single peak left out
  - Only one peak in each charge combination
  - No peak, pure background
- Derived from $\Delta(-\ln \mathcal{L})$

	p-Value	σ		p-Value	σ
No peak	$< 8.3 \cdot 10^{-8}$	> 5.2	No Σ_b^-	$3.2 \cdot 10^{-4}$	3.4
2 peaks	$9.2 \cdot 10^{-5}$	3.7	No Σ_b^+	$9.0 \cdot 10^{-3}$	2.4
			No Σ_b^{*-}	$6.4 \cdot 10^{-4}$	3.2
			No Σ_b^{*+}	$6.0 \cdot 10^{-4}$	3.2

$\Rightarrow$ Significance more than 5σ for 4 peaks

$\Rightarrow$ Evidence for three out of four individual peaks

Ξ_b mass comparison



Ξ_b DØ checks