Heavy Flavor Baryon States at the Tevatron

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Studies by CDF and D0 at Fermilab

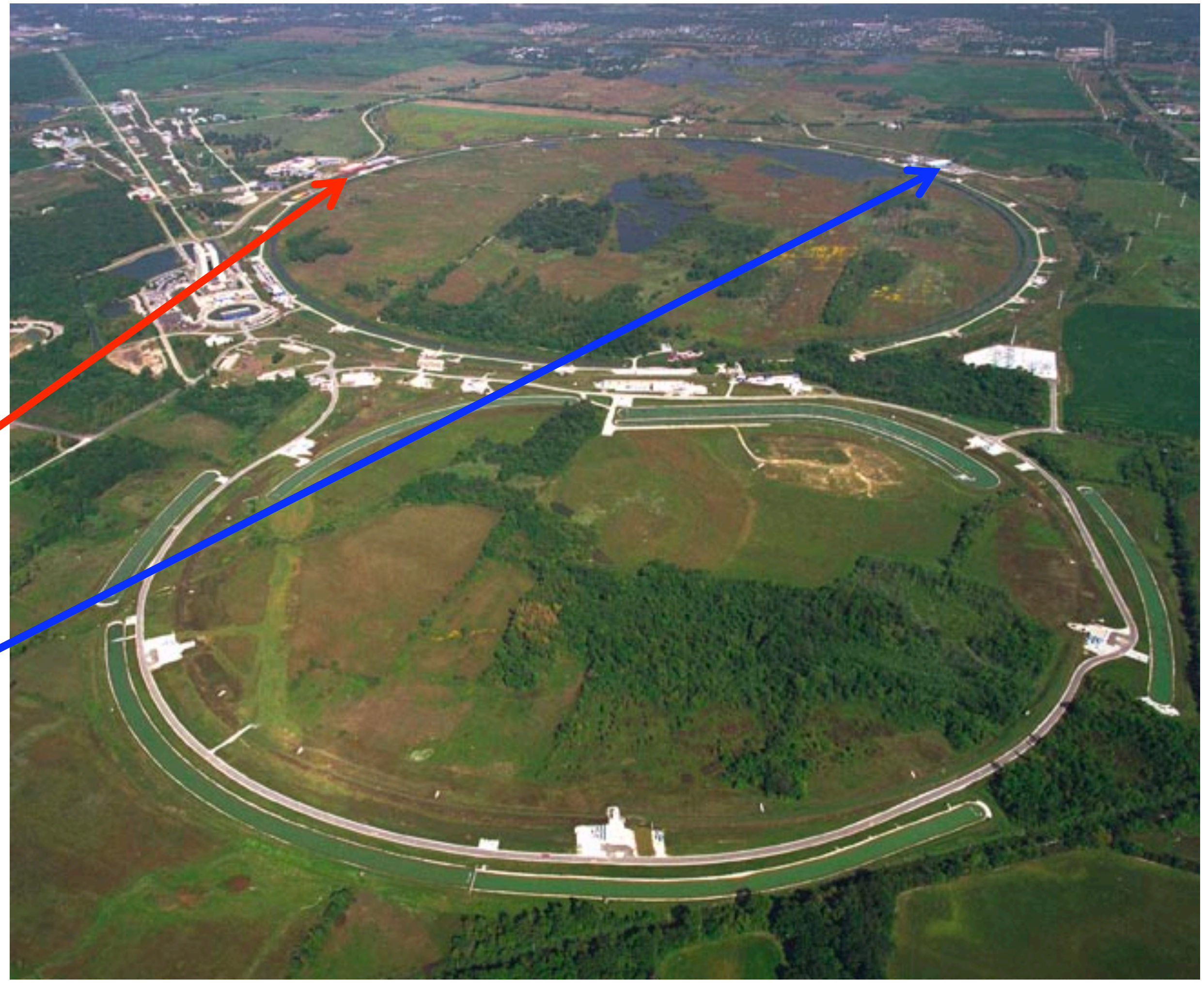
- A record of discoveries and other breakthrough measurements, including first observations of the Ξ_b, Σ_b, and Ω_b, measurements of the Λ_b lifetime, and studies of rare Λ_b decays.
- Charm baryon spectroscopy: the properties of $\Lambda_c(2595)$, $\Lambda_c(2625)$, $\Sigma_c(2455)$, and $\Sigma_c(2520)$.
- Precision measurement of the widths and masses of bottom baryon resonances Σ_b and Σ_b^*.
- A new result on Λ_b production.

The Tevatron proton-antiproton collider at Fermilab

- Center-of-mass energy: 1.96 TeV
- Collecting Run II data since 2002

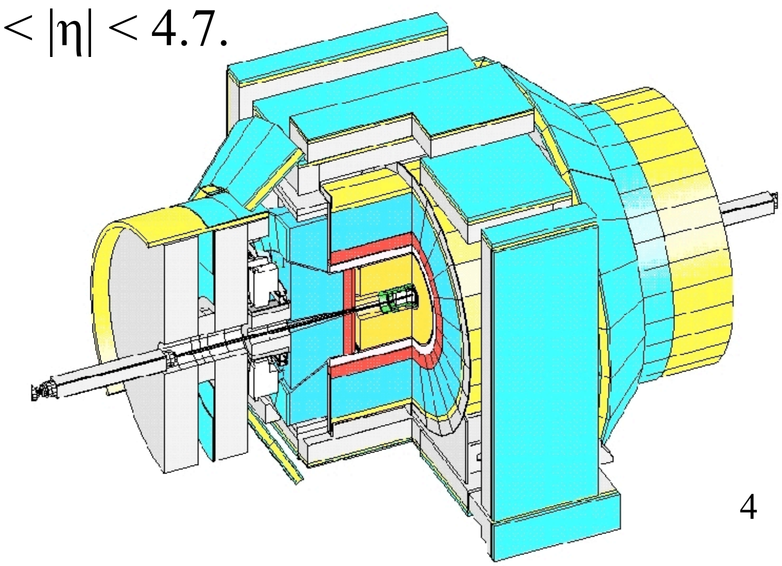
CDF

D0



The CDF Detector

- *silicon vertex detector* (L00+SVXII +ISL): 8 layers at radii from 1.5cm to 28cm. Resolution on d_0: 40 μm. Resolution on z_0: 70 μm. Resolution on vertex: 15μm.
- *central outer tracker* (COT): Ar-C_2H_6 open cell multiwire drift chamber with 8 superlayers (96 measurement layers) at radii from 40 to 140 cm, alternately stereo (±2°) and axial. Radii from 40 to 137 cm, length 3.1 m. $|\eta| \leq 1$. Position resolution: 140 μm. $\sigma(p_T)/p_T^2$=0.0015 $(\mathrm{GeV}/c)^{-1}$.
- scintillator + PMT *TOF*: 115 ps resolution. K/π separation ≥ 2σ for p < 1.6 GeV/c.
- 1.4 T *superconducting solenoid* (1.5m radius × 4.8m length).
- EM (Pb/scint) and HAD (Fe/scint) *calorimeters* cover $|\eta| < 3.64$: 5.5 int. lengths. Resolutions $13.5\%/\sqrt{E_T} \oplus 2\%$ (CEM) and $75\%/\sqrt{E_T} \oplus 3\%$ (CHA).
- *muon detection*: 8 layers, scintillators and proportional chambers to $|\eta| < 1.5$, detect muons with $p_T > 1.4$ GeV/c (CMU) or > 2.0 GeV/c (CMP).
- gas Cherenkov *luminosity counters* at $3.7 < |\eta| < 4.7$.

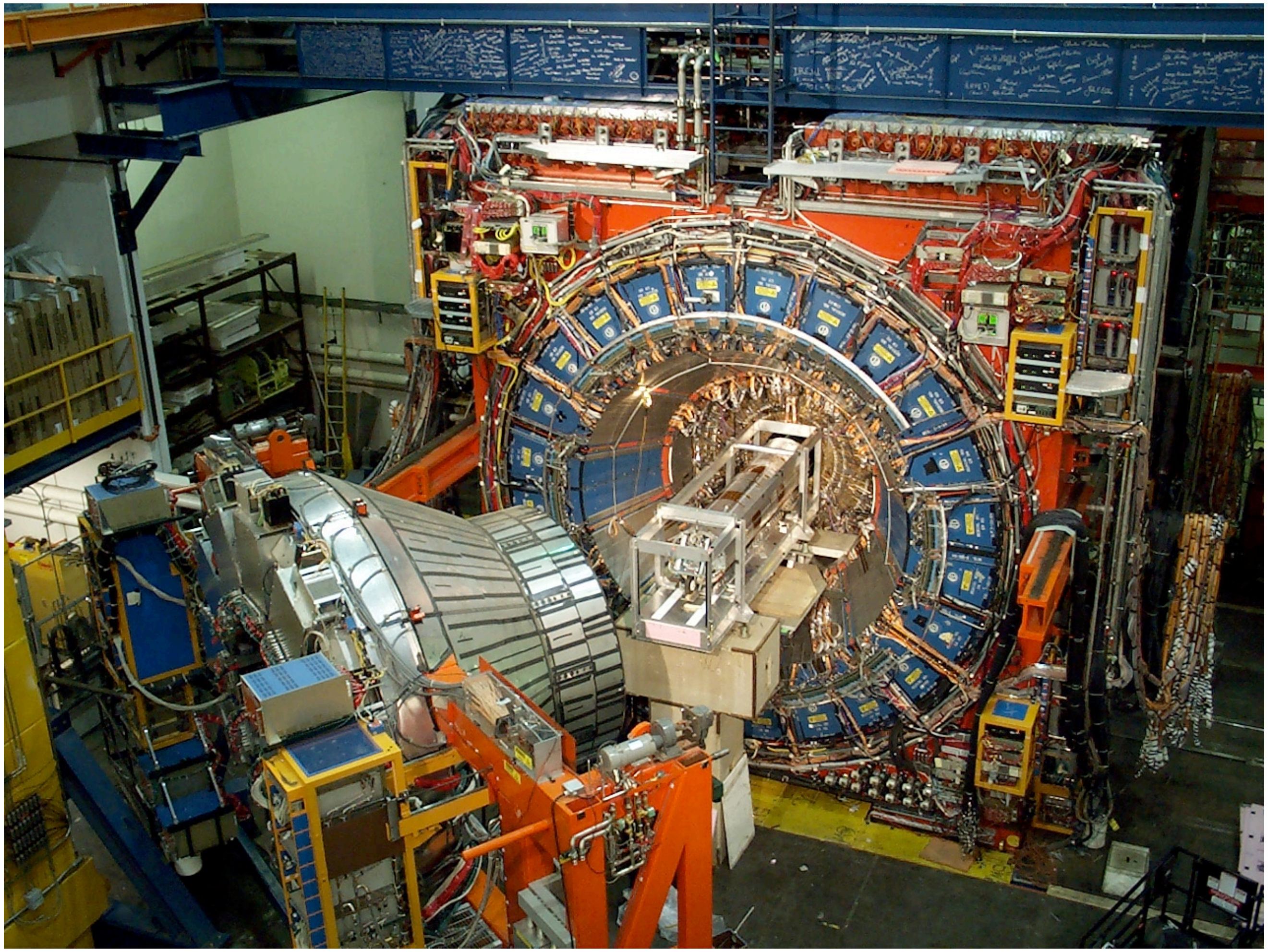


The CDF Trigger System

- *Level 1, the 'extremely fast tracker':* identifies charged particles from the COT, measures their p_T and azimuthal angles. Requires 2 charged particles with p_T>2 GeV.

- *Level 2, the Silicon Vertex Trigger:* adds Si hit information, allowing precise measurement of impact parameters d_0. Requires the 2 L1 tracks have $0.1 < d_0 < 1$ mm and a common vertex displaced from the interaction point by >100 μm to beamline.

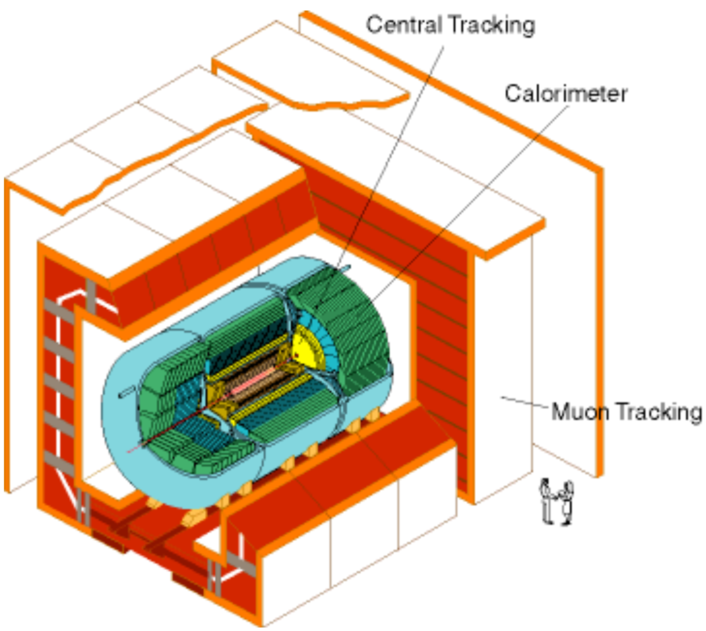
- *Level 3*: software confirmation of L1 and L2 with improved reconstruction. High efficiency for collection of long-lived heavy hadrons with the "Two Track Trigger."



The D0 Detector

- *silicon microstrip tracker* (SMT): 800k strips with pitch 50-80 μm for tracking and vertexing to $|\eta| < 2.5$. 6 barrels, each with 4 layers, plus 16 radial disks. Resolution on rφ ~10μm.

- *central fiber tracker* (CFT): 8 thin coaxial barrels, each with 2 doublets of 0.835 mm ±3° stereo scintillating fibers connected to solid state photon counters (VLPC's).



- 2 T *superconducting solenoid magnet,* length 2.73m, diameter 1.42m.

- *preshower detectors*: outside solenoid. Pb preradiator. Extruded triangular scintillator strips read out by wavelength shifting fibers + VLPCs.

- *calorimeter:* (LAr + U) covers $|\eta| < 4.2$. Central and endcap regions are separated by shower sampling scintillators through $1.1 < |\eta| < 1.4$.

- *muon detection*: tracking detectors + scint. trigger counters in front of and behind 1.8T toroids. 10 cm wide drift tubes at $|\eta| < 1$, 1 cm mini-drift tubes at $1 < |\eta| < 2$.

- plastic scintillator *luminosity counters* at $2.7 < |\eta| < 4.7$. Also 18 Roman pots adjacent to the IR.

The D0 triggers

Level 1: 2 kHz output

Level 2: 1 kHz; Levels 1 and 2 use calorimeter, preshower, fiber tracker, and muon detectors. Level 2 uses calorimeter clustering and matching of objects between subdetectors.

Level 3: 100 Hz to storage. Level 3 partially reconstructs event data within 50 msec.

Tevatron experiments: a rich history of contributions to heavy baryon studies

- Measurement of the Λ_b lifetime in $\Lambda_b \to J/\psi\Lambda^0$(2006) and in $\Lambda_b \to \Lambda_c\pi^-$ (2009): each was the single most precise measurement of $\tau(\Lambda_b)$ at its time (CDF).

- Measurement of Λ_b cross sections and branching ratios $\sigma\left(\Lambda_b^0 \to \Lambda_c^+\pi^-\right)$(2006), $B(\Lambda_b \to \Lambda_c\pi^-\pi^+\pi^-)$(2009), and $B\left(\Lambda_b \to \Lambda_c\mu\nu\right)$(2009): first measurements (CDF).

- Discovery of the Ξ_b^- (2007, D0 and CDF) and $\Sigma_b^{(*)}$ (2007) (CDF).

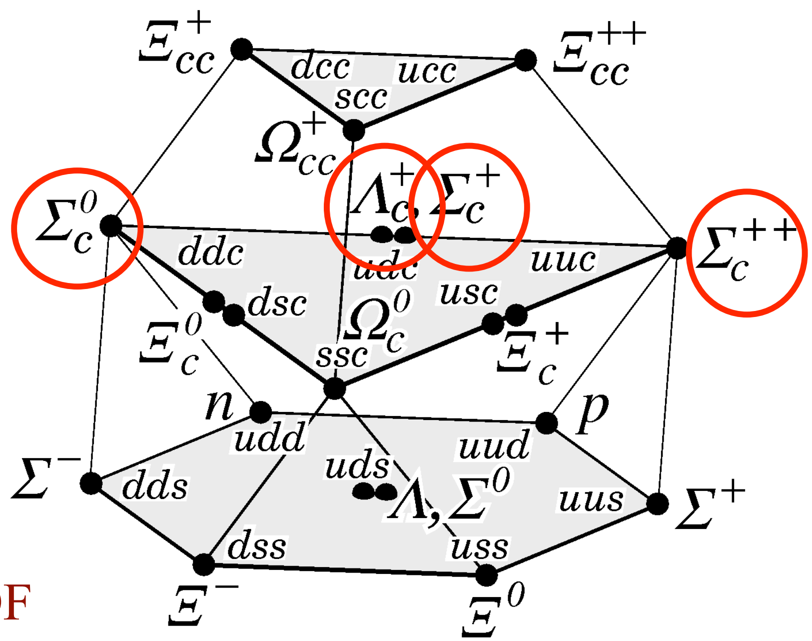
- Observation of the Ω_b (2008, D0) and measurement of its relative production rate and lifetime (2009, CDF).

- Measurement of Λ_b relative production cross section × BR($\Lambda_b^0 \to \Lambda_c^+\pi^-$) : test of HQET and opportunity to extract CKM matrix elements (2006, CDF).

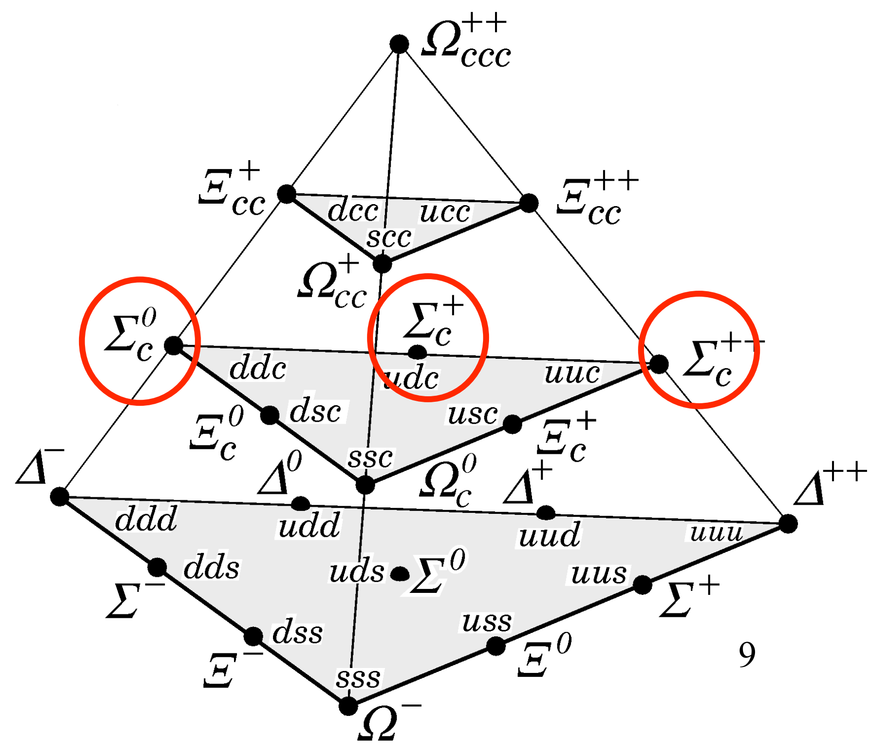
- Observation of charmless Λ_b decays: measurement of CP violation, sensitive to V_{ub} and new physics (2008, CDF).

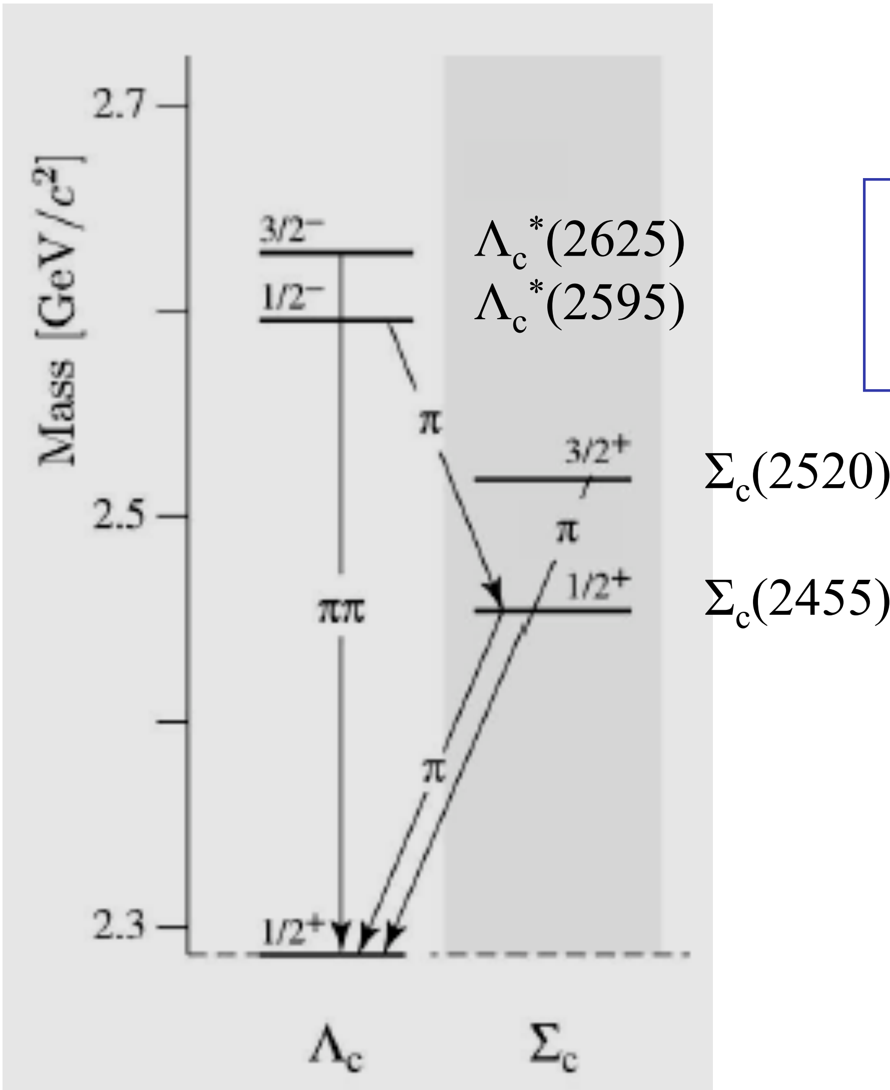
The Properties of $\Lambda_c(2595)$, $\Lambda_c(2625)$, $\Sigma_c(2455)$, and $\Sigma_c(2520)$

Motivation: Predicting the mass spectrum and spin splittings in this regime of small momentum transfer requires non-perturbative strong interaction calculations. Mass predictions come from QCD sum rules, lattice, quark model, and bag model.   Data can drive theoretical development.



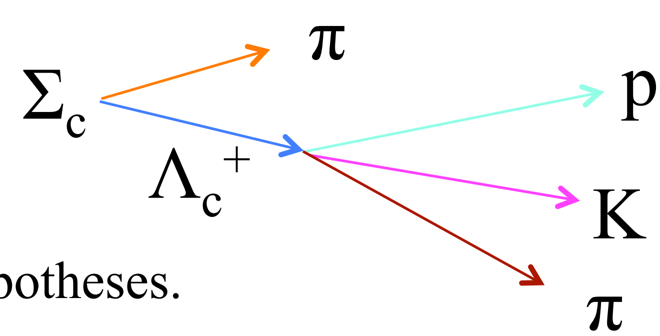
CDF





These are all accessible through their strong decays to Λ_c + 1 or 2 pions.

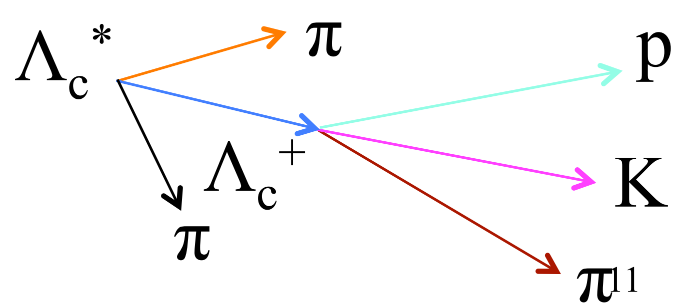
The dataset: 5.2 fb^{-1} acquired Feb 2002-June 2009.



Overview of the method:

- Find the right particles: fit tracks to K, π, and p hypotheses.
- Form pKπ vertex: Λ_c candidate.
- Consistency check: require p and π candidates to have same charge, and total charge is ±1.
- Form $\Sigma_c(2455)$ and $\Sigma_c(2520)$ candidates: Λ_c+1π in a common vertex.
- Form $\Lambda_c(2595)$ and $\Lambda_c(2625)$ candidates: Λ_c+ all possible oppositely charged ππ pairs in common vertex.

This signal extraction uses a neural network.



Detailed procedure:

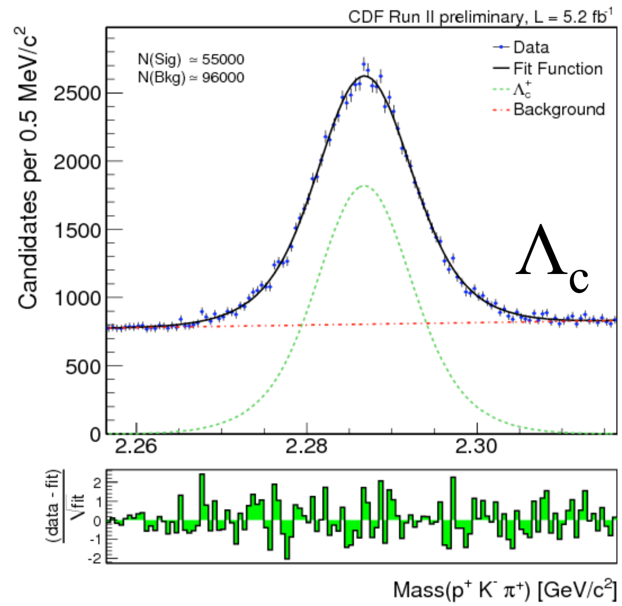
- Quality cuts (e.g., # of hits in the tracker, etc.)

- Split dataset into 2 parts: half for network training, half for analysis.

- On the training sample: Fit distribution to Gaussian + linear background---produce the Probability Density Function. Assign a weight to each training event, as likelihood of being signal or background, based on event mass proximity to Gaussian mean. This is the sPlot technique.*

- Train neural network to search for Λ_c using Λ_c events with displaced secondary vertex, high track p_T, and correct particle ID's from TOF and dE/dx. *Train on data exclusively*.

- Apply trained neural network to analysis sample. Select Λ_c events based on track opening angles, impact parameter significance ($d/\sigma(d_0)$), track p_T, track identity likelihood, quality of vertex reconstruction, secondary vertex displacement.



*M. Pivk and F.R.Le Diberder, NIM A555, 356 (2005).

Procedure, continued

- Σ_c and Λ_c^* selection based on:
  - Λ_c signal probability from network
  - pion p_T
  - pion impact parameter
  - Λ_c within mass window

- In the Σ_c and Λ_c^* network training samples, weight events as signal or bkg based on their mass difference ΔM relative to Gaussian mean. Training includes only $\Sigma_c(2455)$ and $\Lambda_c^*(2595)$ but networks are applied to the higher mass states as well. Train on data exclusively.

- Σ_c (Λ_c^*) network inputs:
  - Σ_c (Λ_c) proper decay time
  - Σ_c (Λ_c) quality of fit (χ^2)
  - Λ_c signal likelihood from Λ_c network
  - For Σ_c: Σ_c transverse impact parameter uncertainty $\sigma(d_0)$
  - For Σ_c: Transverse impact parameter of π from Σ_c decay
  - For Λ_c^*: uncertainty on impact parameter of $\pi\pi$ pair

- Independent networks for charged and neutral Σ_c's.
- choose network output threshold to maximize $S/\sqrt{(S+B)}$.

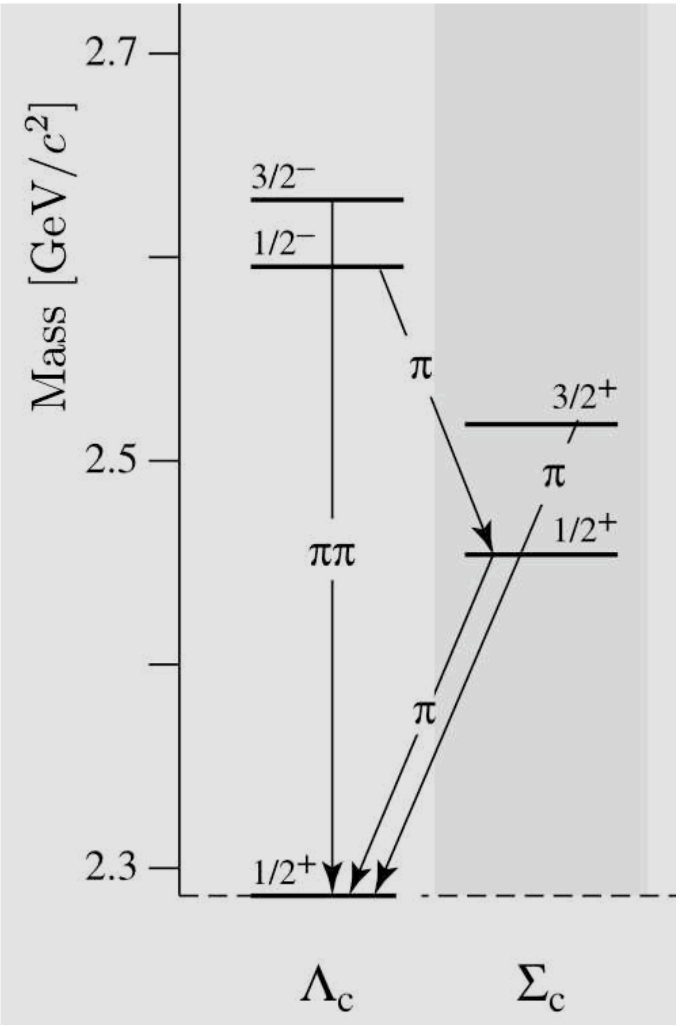
- To remove the Λ_c mass systematic, observe the Λ_c^* and Σ_c through mass difference plots:
  - $m(\Lambda_c^+ \pi^-) - m(\Lambda_c^+)$
  - $m(\Lambda_c^+ \pi^+) - m(\Lambda_c^+)$
  - $m(\Lambda_c^+ \pi^+ \pi^-) - m(\Lambda_c^+)$

- Fit function: nonrelativistic Breit-Wigner + triple Gaussian detector resolution from Monte Carlo.

- ***Λ_c(2595) requires special treatment.*** The kinematic threshold is non-negligible for Λ_c(2595) because it decays dominantly through $\Sigma_c(2455)^{0+}\pi^{+-}$ channels: use mass *dependent* Breit-Wigner for this one.

Λ_c(2595) fits include contributions from 3 final states:

1. $\Sigma_c(2455)^0 \pi^+$
2. $\Sigma_c(2455)^{++} \pi^-$
3. $\Sigma_c(2455)^+\pi^0$



The process of separating the signal final state ($\Lambda_c^+ \pi\pi$) requires fitting simultaneously to all possible intermediate Σ_c channels. From this, ***the pion coupling h_2 can be extracted,*** as it enters each amplitude through the Σ_c-π vertex.

Backgrounds:

1. Combinatorial without real Λ_c
2. Real Λ_c or Σ_c + random tracks
3. Feed-down from other Λ_c^*'s into the Σ_c spectrum

Systematics:

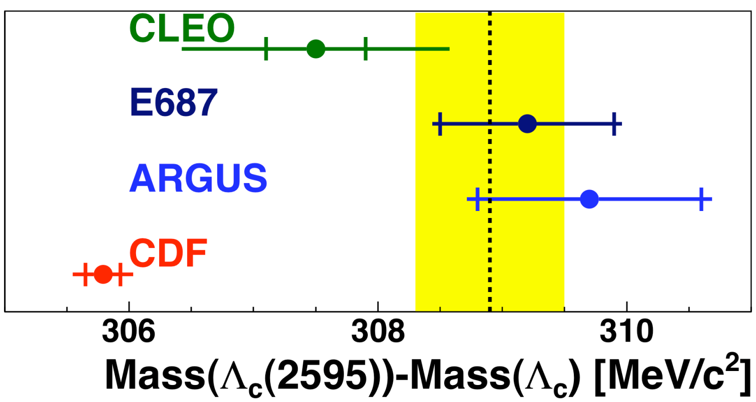
- detector resolution
- mass scale (B field)
- fit model
- uncertainty on Σ_c PDG value

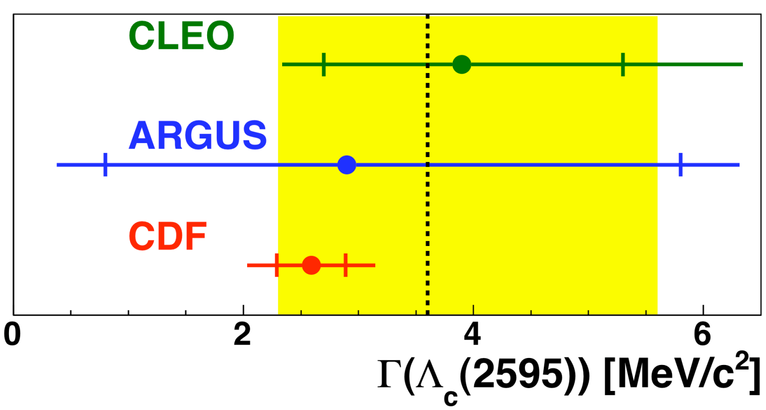
Resolution is estimated with Monte Carlo and validated by data in the kinematically analogous channels $D^*(2010)^+ \rightarrow D^0\pi^+$ and $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$.

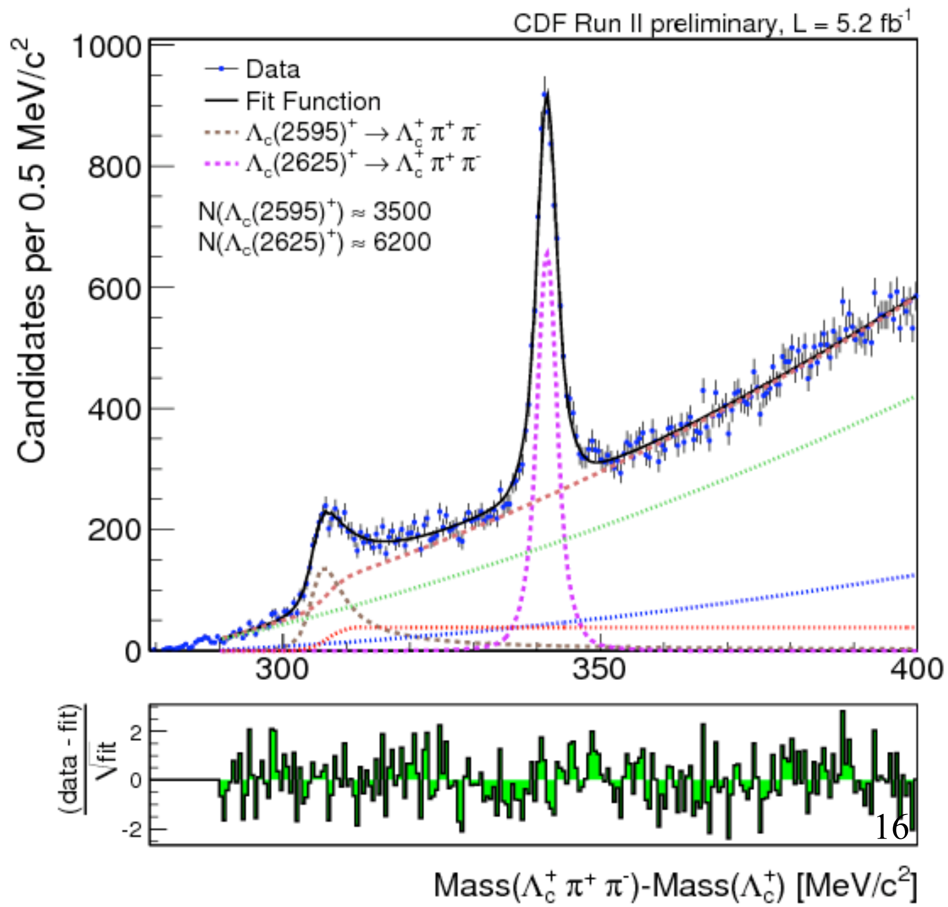
$\Lambda_c(2595)^+$ Results

Mass = 2592.25 ± 0.24 ± 0.14 MeV/c^2
h_2^2 = 0.36 ± 0.04 ± 0.07
3.5k signal events

This mass result is 3.1 MeV lower than previous measurements because of the inclusion of the threshold effects.

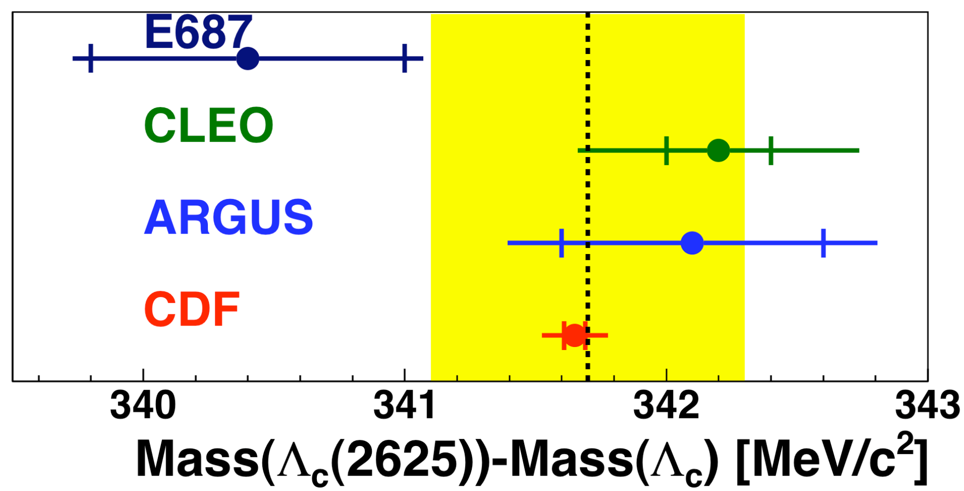






$\Lambda_c\ (2625)^+$ Results

Mass 2628.11 ± 0.13 ± 0.14 MeV/c^2
Width consistent with zero;
$\Gamma < 0.97$ MeV/c^2 @ 90% C.L.
6.2k signal events



Consistent with previous measurements; significant improvement in precision.

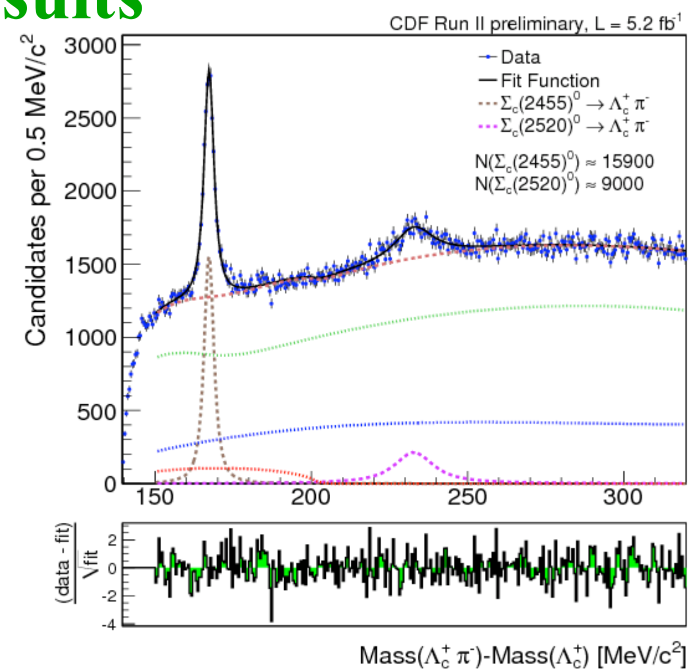
Σ_c Results

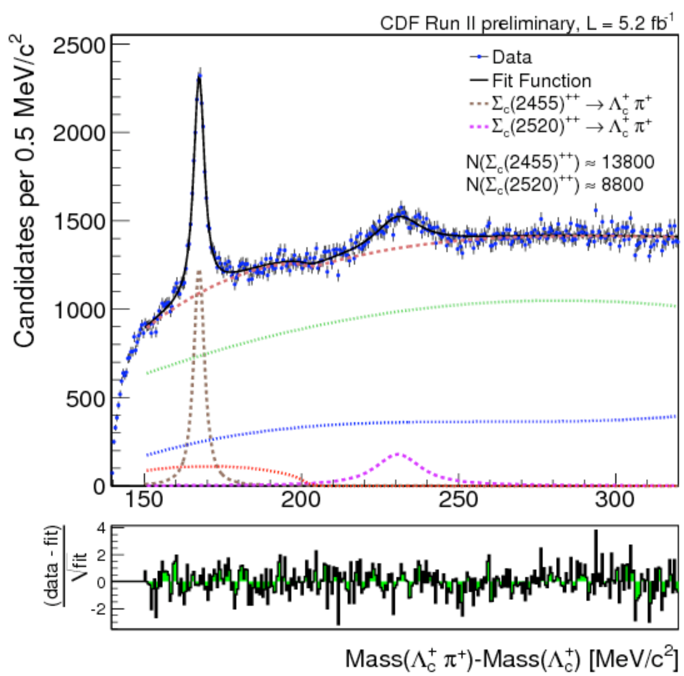
$\Sigma_c(2455)^0$
Mass = 2453.74 ± 0.12 ± 0.14 MeV/c^2
Width=1.65 ± 0.11 ± 0.49
15.6k signal events

$\Sigma_c(2520)^0$
Mass = 2519.34 ± 0.58 ± 0.14 MeV/c^2
Width 12.51 ± 1.82 ± 1.37 MeV/c^2
9k signal events

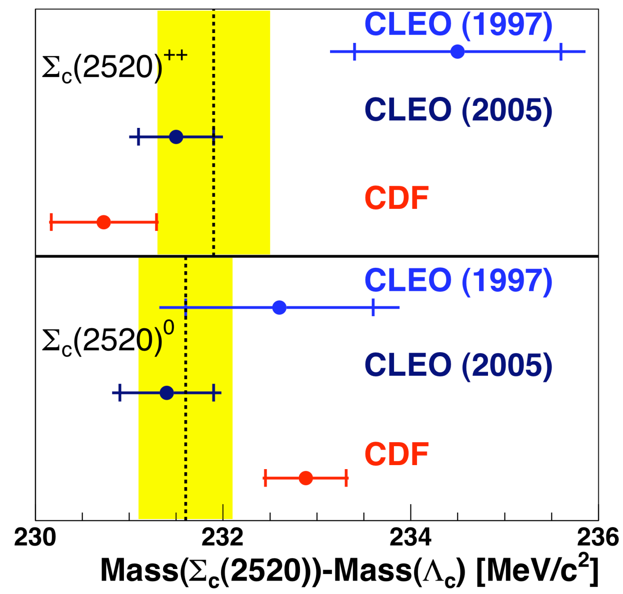
$\Sigma_c(2455)^{++}$
Mass = 2453.90 ±0.13 ± 0.14 MeV/c^2
Width 2.34 ± 0.13 ± 0.45 MeV/c^2
13.8k signal events

$\Sigma_c(2520)^{++}$
Mass = 2517.19 ± 0.46 ± 0.14 MeV/c^2
Width 15.03 ± 2.12 ± 1.36 MeV/c^2
8.8k signal events

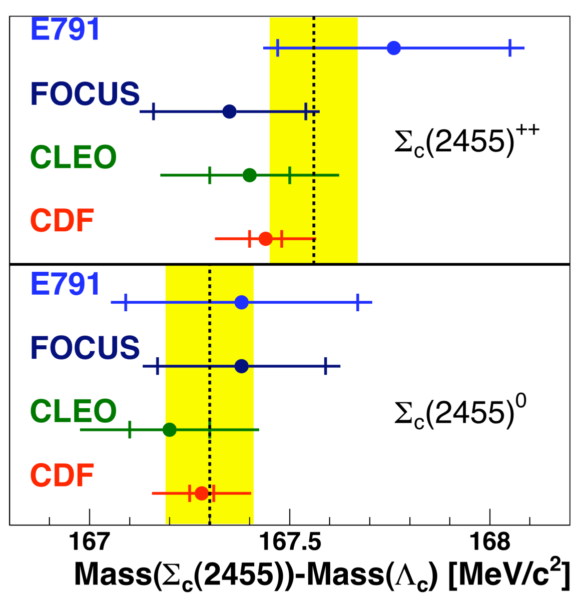


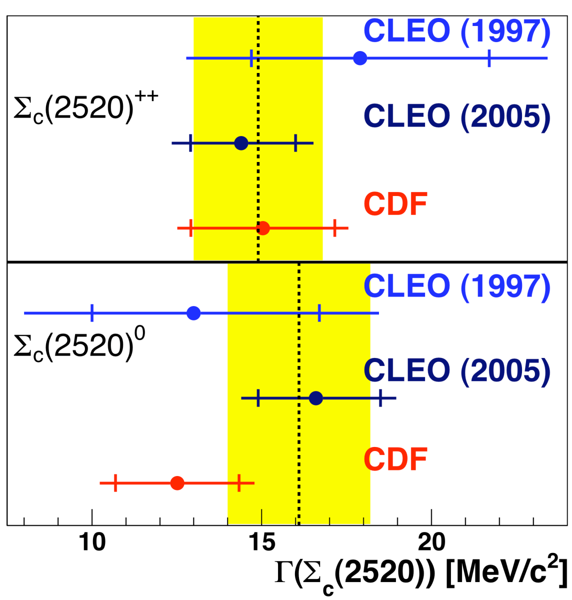


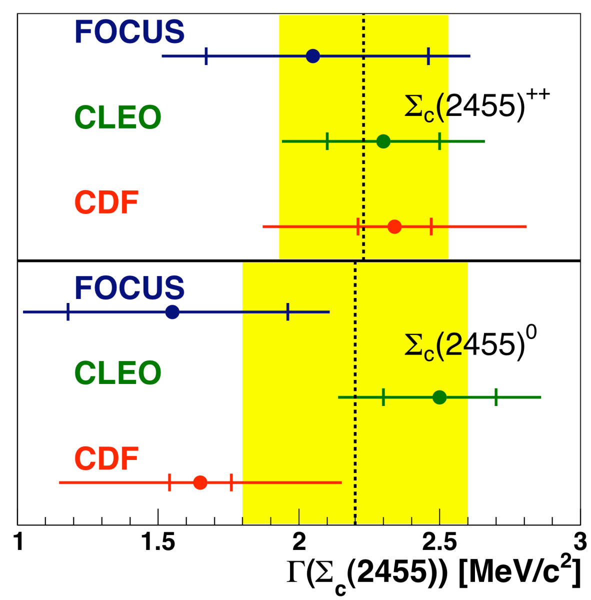
Of the two previous measurements of $\Sigma_c(2520)^{++}$ mass by CLEO, the lower, earlier value is favored:



$\Sigma_c(2455)^+$, $\Sigma_c(2520)^0$, and $\Sigma_c(2455)^0$ are all consistent with previous studies.

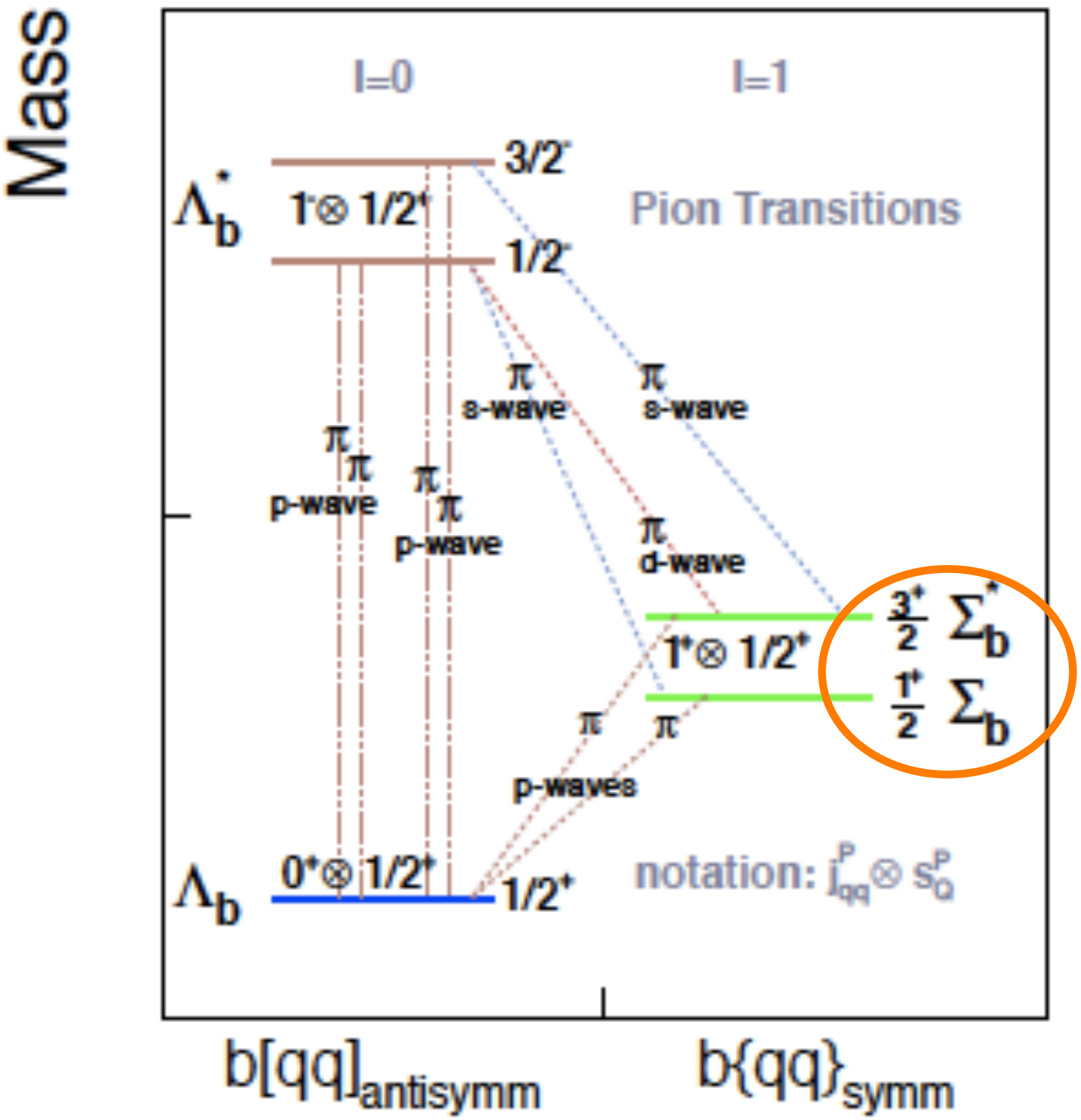






Measurement of the Bottom Baryon Resonances Σ_b and Σ_b^*

Motivation: with quark content udb, these are the "helium atoms of QCD": a "nucleus" of one heavy quark + two orbiting light constituents. This probes non-perturbative QCD in a new regime. Mass spectra for this family are predicted by Heavy Quark Effective Theory, potential models, and lattice calculations. Mass splittings (first measurement here!) are expected to be driven by the u-d mass difference. Resonance widths (first measurement too!) are challenging to predict.



These states, discovered by CDF in 2007, are reconstructed through their common decay to Λ_b.

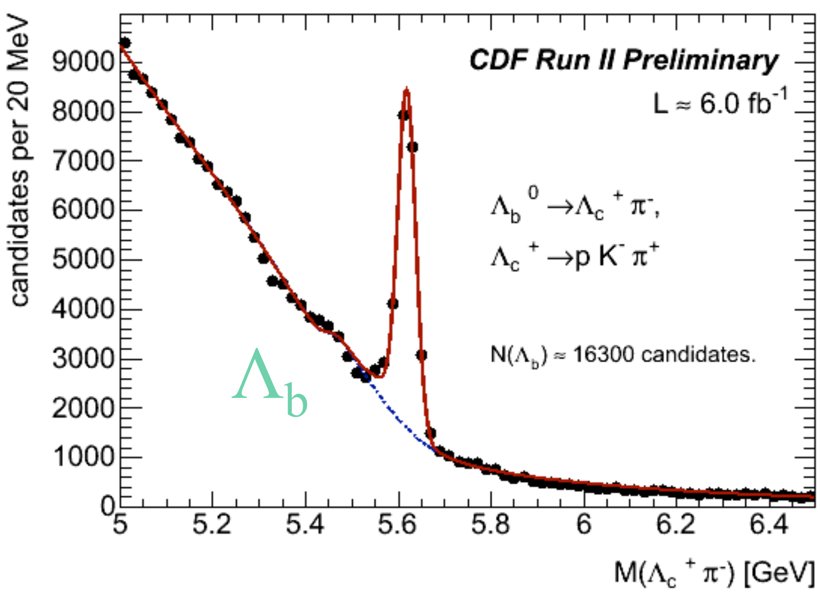
Method:

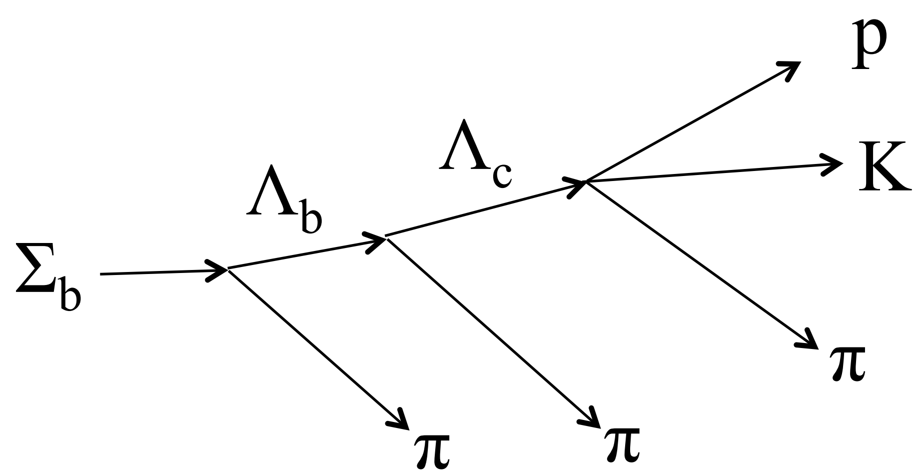
- *Dataset: 6.0 fb^{-1} collected from March 2002 to Feb 2010.*

- Apply quality cuts to all tracks.

- Fit 3 tracks to common vertex (Λ_c)--- *no particle ID.* Constrain to PDG Λ_c mass.

- Add a π to the vertex and constrain to PDG Λ_b mass.





- Clean up combinatorial background: cut on tracks' p_T, η. Require impact parameter d_0 small.

- Consistency: require $\geq$ 2 of the tracks included in the Silicon Vertex Trigger: 2 displaced tracks.

- Λ_b decay vertex displaced ($c\tau$) from primary vertex. Λ_b points back to the primary vertex.

- Add a π to the Λ_b vertex.

Λ_b reconstruction:

- All requirements are taken from data optimizing S/√(S+B) with a binned fit.
- 16.3k candidates
- Backgrounds: combinatorics, partially and fully reconstructed B mesons producing $\Lambda_c\pi$, partially reconstructed Λ_b decays, fully reconstructed Λ_b. decays to other channels (e.g., misidentified $\Lambda_b \rightarrow \Lambda^0 K^-$).

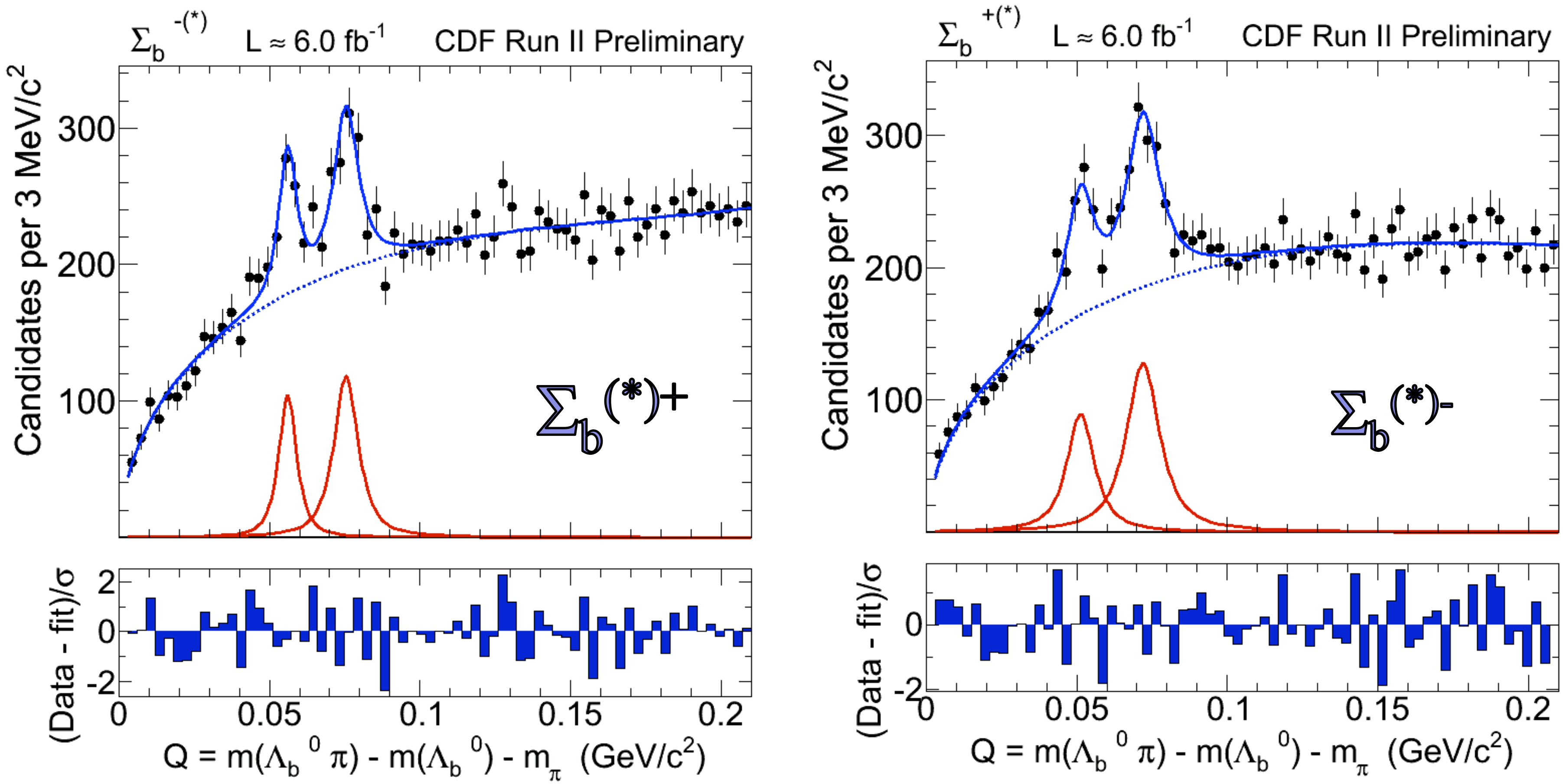
Σ_b reconstruction:

- To remove systematics on the Λ_b mass resolution, fit the mass difference

$$Q \equiv m(\Lambda_b \pi) - m(\Lambda_c \pi) - m_\pi^{PDG}.$$

- The fit:
  - Signal: unbinned non-relativistic Breit-Wigner lineshape, width broadened to reflect pion's p-wave structure, convoluted with double Gaussian resolution function.
  - Bkg: second-order polynomial x square-root (i.e. combinatoric) kinematic threshold.
- Separate negative log likelihood functions are constructed for $(\Sigma_b, \Sigma_b^*)^+$ and $(\Sigma_b, \Sigma_b^*)^-$.

Results



Significance > 7.0σ for each of the 4 peaks.

Systematic uncertainties:

- Tracker momentum scale---dominates mass measurements
- Two-Gaussian resolution model---dominates width measurements
- background model
- fitting algorithm for Monte Carlo events

Uncertainties are validated by comparison with analogous charm decays in data.

The final numbers on $\Sigma_b^{(*)}$:

Combining these new mass differences with the CDF measurement of the Λ_b mass ($5609.7 \pm 1.2 \pm 1.2$ MeV/c^2) yields masses

$$m(\Sigma_b^+) = 5811.2^{+0.9}_{-0.8}(stat.) \pm 1.7(syst.) \text{ MeV/c}^2$$
$$m(\Sigma_b^-) = 5815.5^{+0.6}_{-0.5}(stat.) \pm 1.7(syst.) \text{ MeV/c}^2$$
$$m(\Sigma_b^{*+}) = 5832.0 \pm 0.7(stat.) \pm 1.8(syst.) \text{ MeV/c}^2$$
$$m(\Sigma_b^{*-}) = 5835.0 \pm 0.6(stat.) \pm 1.8(syst.) \text{ MeV/c}^2$$

and the first measurement of the widths:

$$\Gamma(\Sigma_b^+) = 9.2^{+3.8}_{-2.9}(stat.)^{+1.0}_{-1.1}(syst.) \text{ MeV/c}^2$$
$$\Gamma(\Sigma_b^-) = 4.3^{+3.1}_{-2.1}(stat.)^{+1.0}_{-1.1}(syst.) \text{ MeV/c}^2$$
$$\Gamma(\Sigma_b^{+*}) = 10.4^{+2.7}_{-2.2}(stat.)^{+0.8}_{-1.2}(syst.) \text{ MeV/c}^2$$
$$\Gamma(\Sigma_b^{*-}) = 6.4^{+2.2}_{-1.8}(stat.)^{+0.7}_{-1.1}(syst.) \text{ MeV/c}^2$$

$\Sigma_b^{(*)}$ Conclusions

- All 4 $\Sigma_b^{(*)}$ states are confirmed at significance > 7σ.
- Mass difference measurements improve upon previous results by > factor of 2.
- Isospin mass splittings available for the first time, at precision comparable to that for charm.
- Negative isospin states have mass slightly higher than positive ones, contrary to the charm case. A theoretical model for this exists.[§]
- The natural widths have been measured for the first time and are in agreement with theoretical expectations.

[§] F.K. Guo et al., JHEP 0809, 136 (2008) and arXiv:0809.2359.

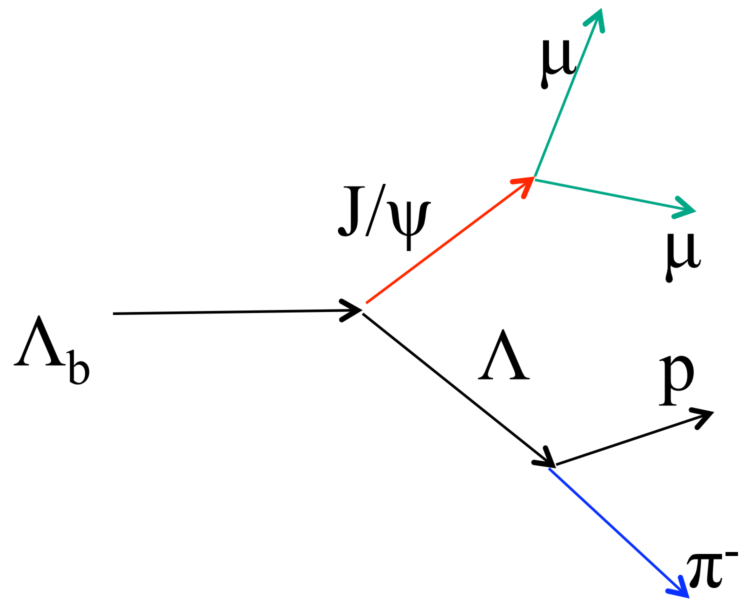
Measurement of the Production Fraction Times Branching Fraction $f(b \to \Lambda_b) \cdot B(\Lambda_b \to J/\psi\Lambda)$

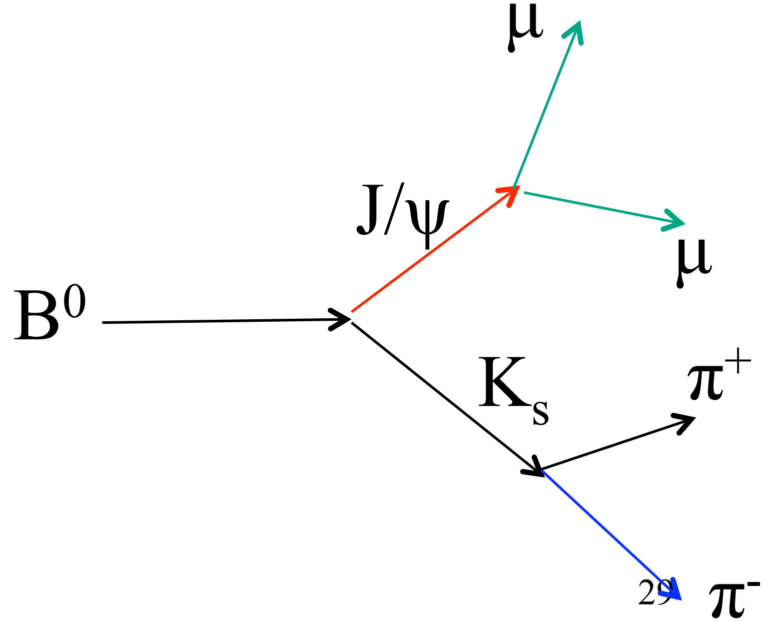
Motivation: Decays of b hadrons may be a window onto physics beyond the Standard Model. Few measurements of b baryons are available, and uncertainties on branching fractions are typically 30-60% or more. Improved experimental precision can be input to PQCD and relativistic and non-relativistic quark models.

Dataset: 6.1 fb^{-1} recorded during 2002-2009

Overview:

Reconstruct 2 kinematically similar channels. In the ratio of their production fractions × branching ratios, *systematics on quark production, luminosity, trigger efficiencies, and selection efficiencies cancel.*





Method

- Quality cuts: require ≥ 1 $p\bar{p}$ interaction, minimum # hits in tracking, etc., limit # hits between primary and secondary vertices.

- Trigger on 1 or 2 μ's. Reconstruct μ's with track segments that match central tracking to muon detectors. Select on track p_T and central η. One μ must be observed both inside and outside toroid.

- Vertex 2 μ's: find J/ψ candidates in mass range $2.8 < M_{\mu\mu} < 3.35$ GeV/c^2.

- In events that pass the J/ψ cut: vertex all pairs of oppositely charged tracks, select from these $\Lambda(K_s)$ within mass window $1.102(0.466) < M < 1.130(0.530)$ GeV/c^2.

- Require minimum impact parameters on $\Lambda(K_s)$ tracks.

- Cut on angle (Λ p_T, Λ track vector) to remove feed-down.

- Constrain μμ pair to J/ψ mass (3.097 GeV/c^2).

Method, continued

- Form $\Lambda_b(B^0)$ candidate: form vertex of $\Lambda(K_s)$ and μμ pair.

- Cut on candidate minimum p_T.

- Require $5.0(4.8) < M < 6.2(5.8)$ GeV/c^2 for $\Lambda_b(B^0)$.

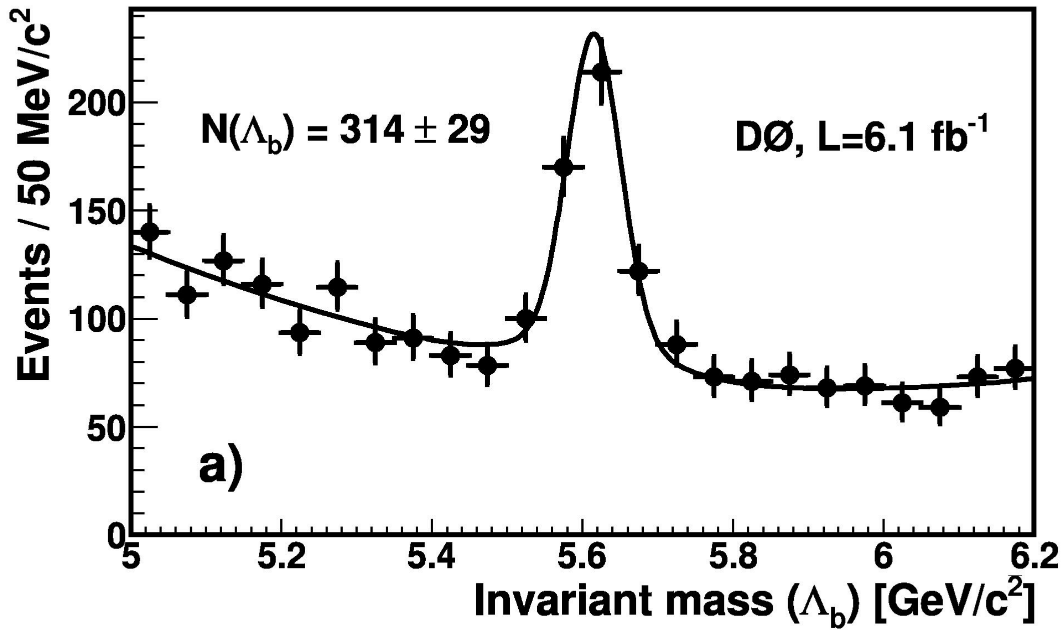
- Predict N_{bkg} from data sidebands. Predict N_{signal} (Λ_b or B^0) from Monte Carlo. Maximize $N_{signal} / \sqrt{N_{signal} + N_{bkg}}$ with requirements on p_T, transverse decay length and its significance, proper decay length significance, and vertex quality.

- Resolve ambiguities: If both Λ and K_s are found in same event: choose the one with best vertex if they are formed from different tracks, and remove event if they are formed from same tracks.

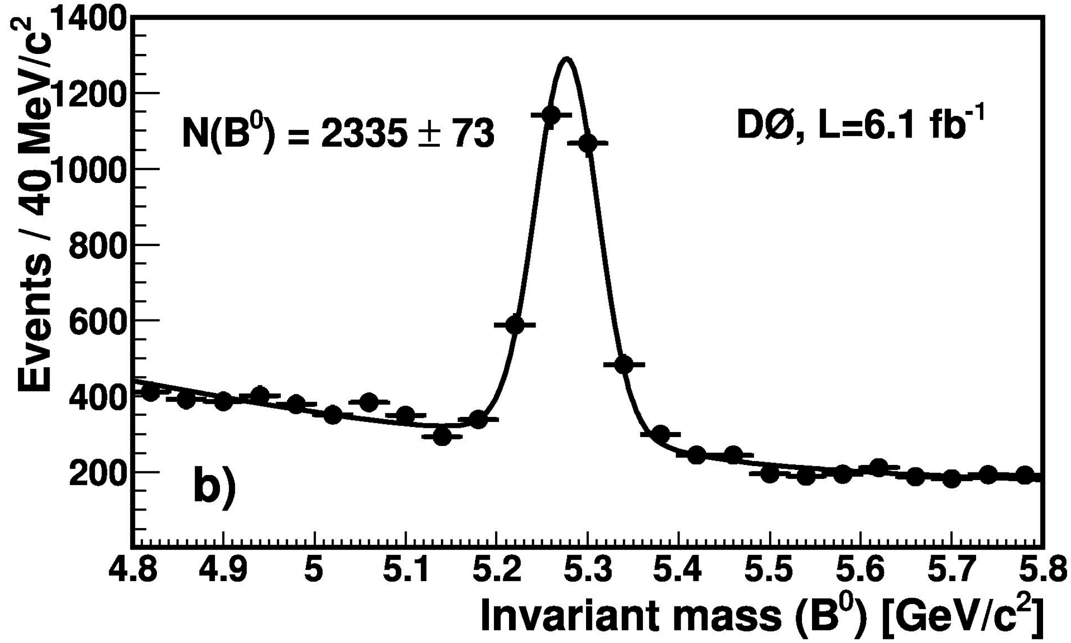
- Extract # events by using unbinned fits to double Gaussian + second order polynomial.

Observed yields:

$$N_{\Lambda_b \to J/\psi\Lambda} = 314 \pm 29$$



$$N_{B^0 \to J/\psi K_s^0} = 2335 \pm 73$$



Input these yields to :

$$\sigma_{rel} \equiv \frac{f(b \to \Lambda_b) \cdot B(\Lambda_b \to J/\psi\Lambda)}{f(b \to B^0) \cdot B(B^0 \to J/\psi K_s^0)} = \frac{N_{\Lambda_b \to J/\psi\Lambda}}{N_{B^0 \to J/\psi K_s^0}} \cdot \frac{B(K_s^0 \to \pi^+\pi^-)}{B(\Lambda \to p\pi^-)} \cdot \varepsilon$$

Using:

$$\varepsilon \equiv \frac{\varepsilon_{B^0 \to J/\psi K_s^0}}{\varepsilon_{\Lambda_b \to J/\psi\Lambda}} = 2.37 \pm 0.05 \text{ (MC stat.)}$$

$$B(K_s^0 \to \pi^+\pi^-) = 0.6920 \pm 0.0005(PDG)$$

$$B(\Lambda \to p\pi^-) = 0.639 \pm 0.005(PDG)$$

Uncertainties:

- Λ_b, B^0 yields - 5.5%
- simulation model contribution to ε - 2%
- contamination of Λ_b by B^0 and B^0 by Λ_b – 2.3%
- Λ_b polarization effects upon Λ emission – 7.2%

Combined uncertainty: 9.6%

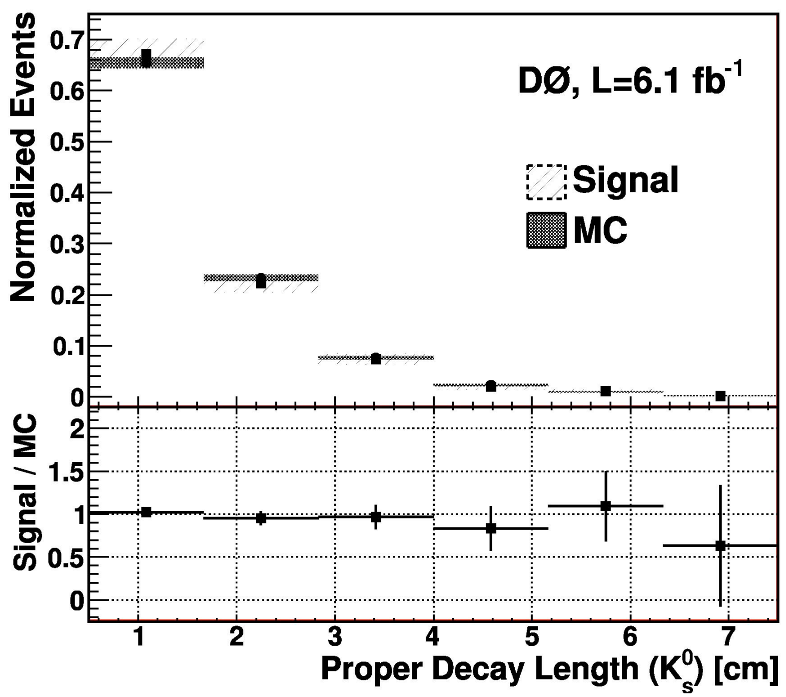
Result:

$$\sigma_{rel} = 0.345 \pm 0.034(stat.) \pm 0.033(syst.) \pm 0.003(PDG)$$

Cross checks and stability studies:

- No variation observed correlated with temporal selection, η, p_T, decay lengths, etc.

- Monte Carlo compared to and confirmed by data for decay length distributions, vertex χ^2 distributions, and Λ and K_s lifetime measurement.

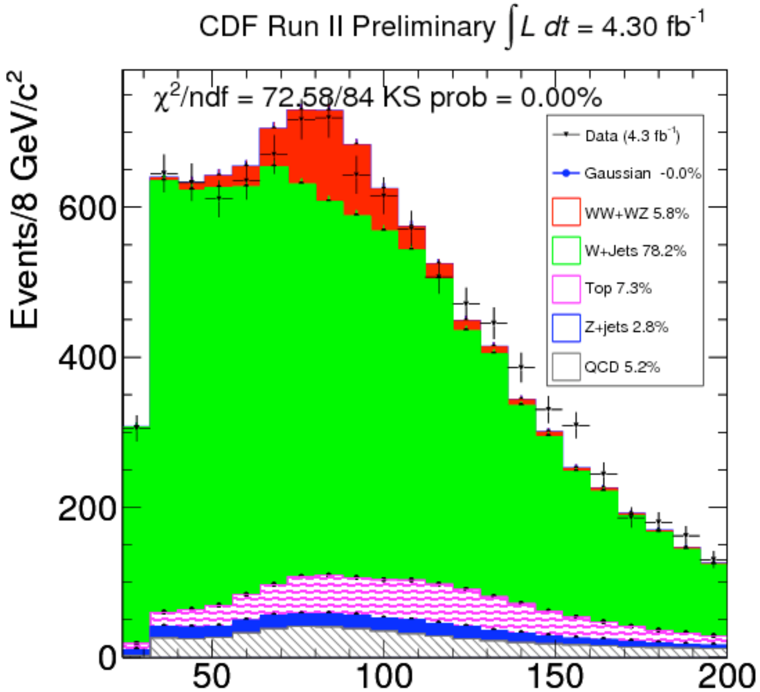


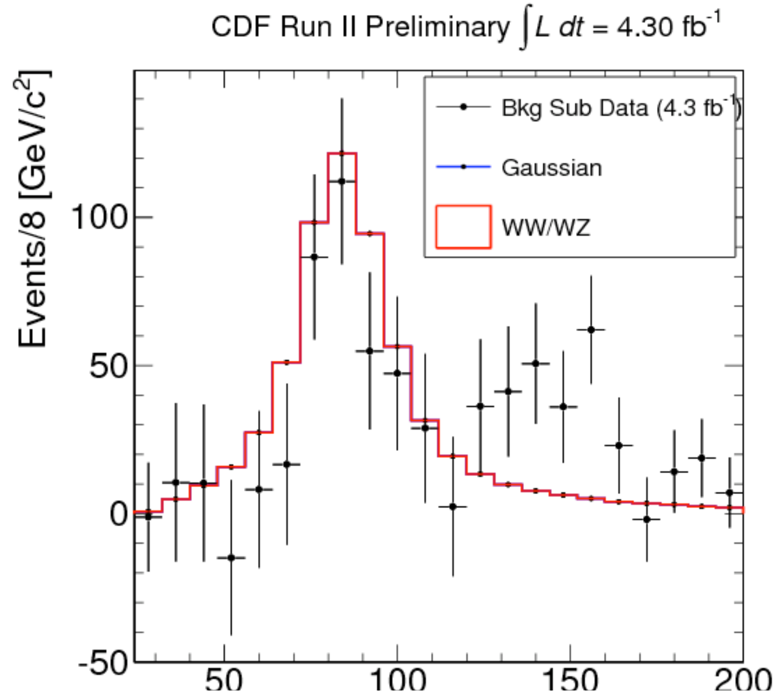
Summary

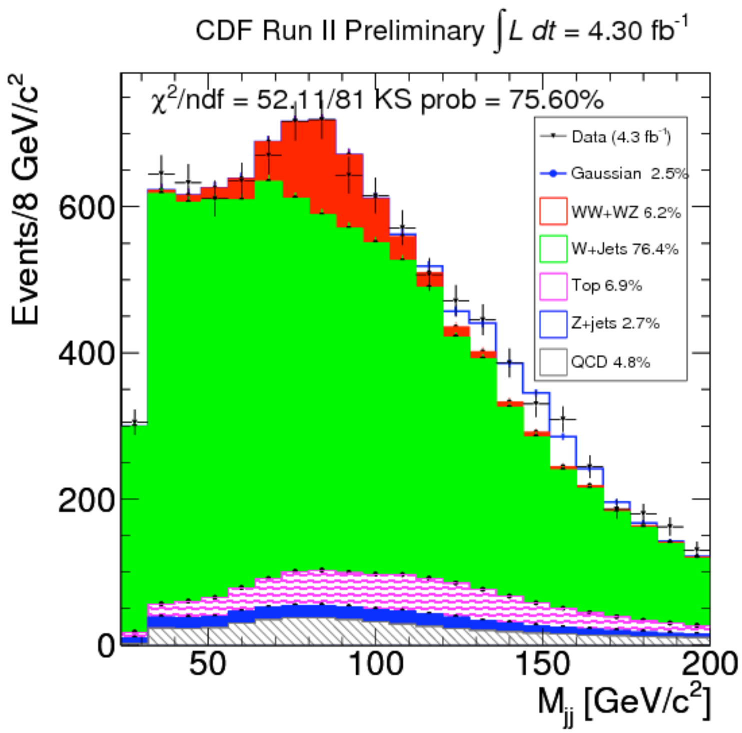
Recent measurements by CDF and D0 of heavy baryons at the Tevatron are presented.

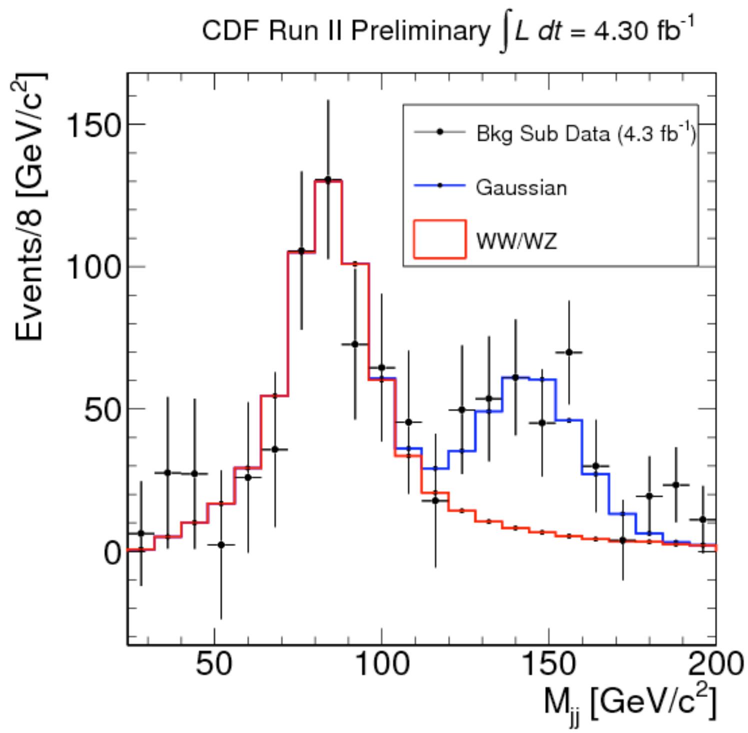
- $\Lambda_c(2595)$, $\Lambda_c(2625)$, $\Sigma_c(2455)$, and $\Sigma_c(2520)$ masses and widths have been measured to generally improved precision and, for $\Lambda_c(2595)^+$, a significant revision in the world average mass.
- The pion coupling h_2 is obtained.
- All four $\Sigma_b^{(*)}$ states are reconfirmed at significance $>7\sigma$, and the precision on their masses is improved by more than a factor of 2.
- Widths and isospin mass splittings of the four $\Sigma_b^{(*)}$ states have been measured for the first time.
- The Λ_b production cross section relative to B^0, times branching fractions to kinematically similar final states, has been measured.

backup


CDF Run II Preliminary ∫L dt = 4.30 fb-1
χ2/ndf = 72.58/84 KS prob = 0.00%
Data (4.3 fb-1)
Gaussian -0.0%
WW+WZ 5.8%
W+Jets 78.2%
Top 7.3%
Z+jets 2.8%
QCD 5.2%
Events/8 GeV/c2
0
200
400
600
50
100
150
200


CDF Run II Preliminary ∫L dt = 4.30 fb-1
Bkg Sub Data (4.3 fb-1)
Gaussian
WW/WZ
Events/8 [GeV/c2]
-50
0
50
100
50
100
150
200


CDF Run II Preliminary ∫L dt = 4.30 fb-1
χ2/ndf = 52.11/81 KS prob = 75.60%
Data (4.3 fb-1)
Gaussian 2.5%
WW+WZ 6.2%
W+Jets 76.4%
Top 6.9%
Z+jets 2.7%
QCD 4.8%
Events/8 GeV/c2
0
200
400
600
50
100
150
200
Mjj [GeV/c2]


CDF Run II Preliminary ∫L dt = 4.30 fb-1
Bkg Sub Data (4.3 fb-1)
Gaussian
WW/WZ
Events/8 [GeV/c2]
0
50
100
150
50
100
150
200
Mjj [GeV/c2]