Observation of the Ξ_b^0

Patrick T. Lukens

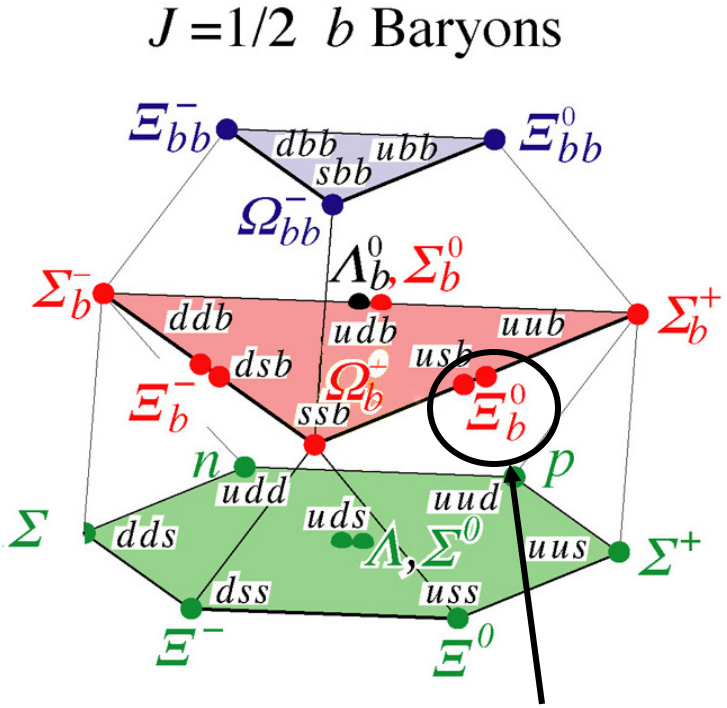
Fermilab

for the CDF Collaboration

July 2011

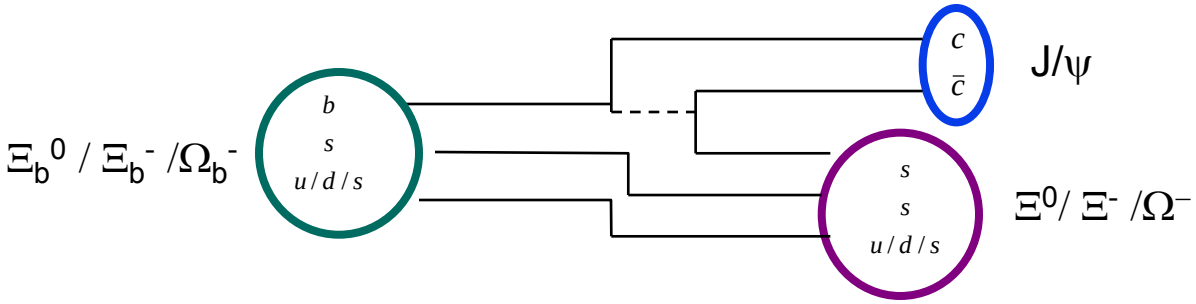
Baryon Ground States

- A reminder of the status of ground state *b* baryons
  - Λ_b, observed in 1990's
  - $\Sigma_b^{\pm}$, observed in 2007
  - Ξ_b^-, observed in 2007
  - Ω_b^-, observed in 2008,2009
    - The Ω_b^- results disagree



- Ξ_b^0, not yet observed

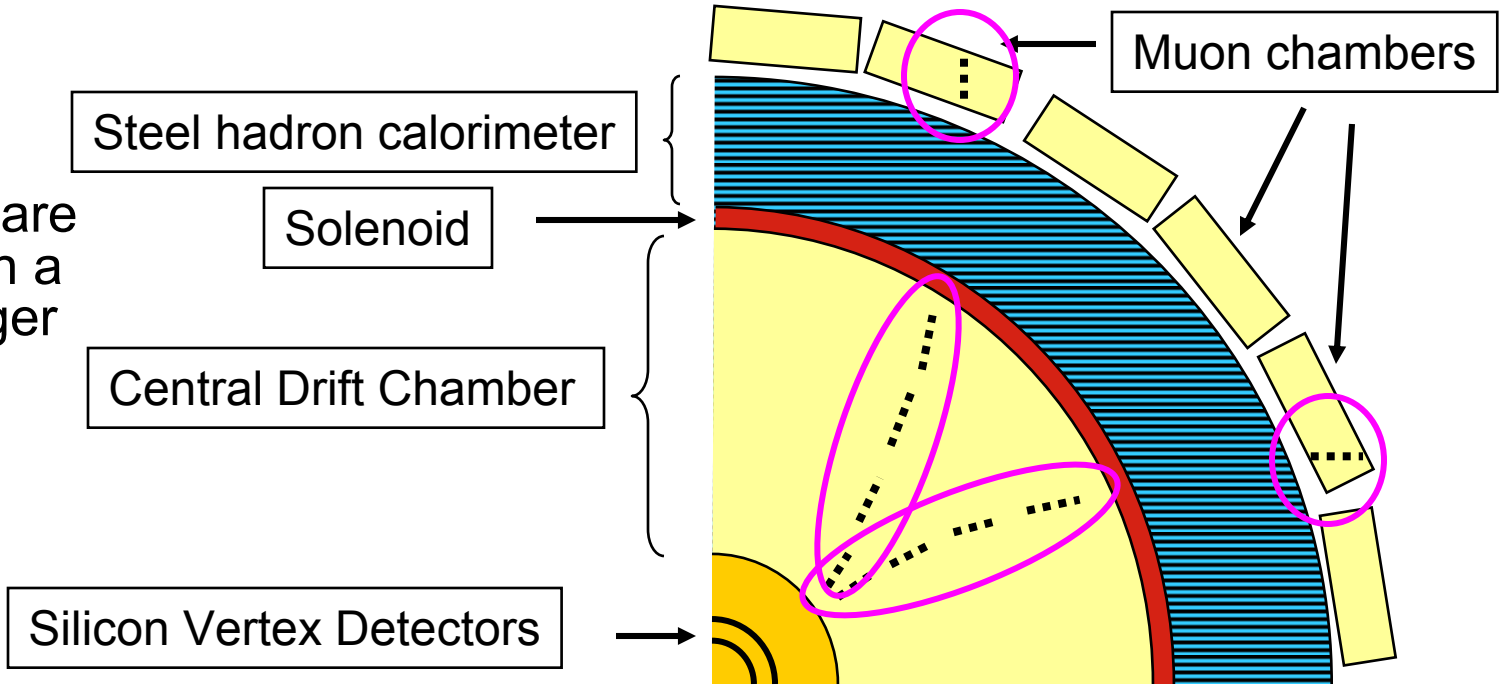
Strange, *b* Baryons with a J/ψ Final State



- So far, the Ξ_b^- and Ω_b^- have been seen through the processes
  - $\Xi_b^- \rightarrow J/\psi\ \Xi^-$, $J/\psi \rightarrow \mu^+\mu^-$, $\Xi^- \rightarrow \Lambda\pi^-$
  - $\Omega_b^- \rightarrow J/\psi\ \Omega^-$, $J/\psi \rightarrow \mu^+\mu^-$, $\Omega^- \rightarrow \Lambda K^-$
- The analogue for the Ξ_b^0 is inaccessible for CDF
  - $\Xi_b^0 \rightarrow J/\psi\ \Xi^0$, $J/\psi \rightarrow \mu^+\mu^-$, $\Xi^0 \rightarrow \Lambda\pi^0$

Collecting *b* Baryons with a J/ψ Final State

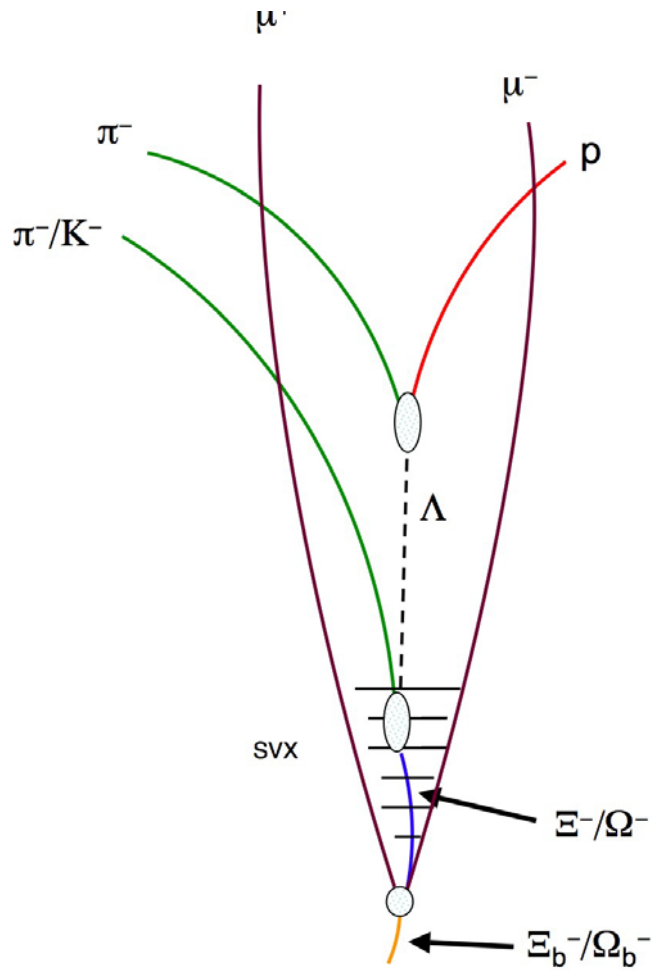
- $J/\psi \rightarrow \mu^+\mu^-$ are collected with a 2–muon trigger



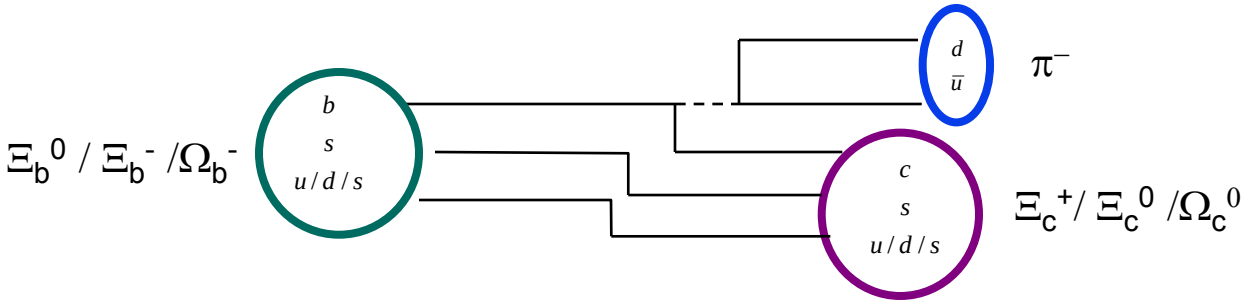
- This trigger matches central tracker and muon chamber tracks.
- A successful match will trigger acceptance of the event.

$\Xi_b^-/\Omega_b^- \to J/\psi\, X$ Reconstruction

- The muons from the J/ψ decay trigger the data collection.
- These are complicated final states
  - 5 tracks, 3 vertices
- Standard techniques are applied
  - Decay Ξ^- or Ω^- is constrained to originate from the $\mu^+\mu^-$ intersection.
  - Fit the final state.



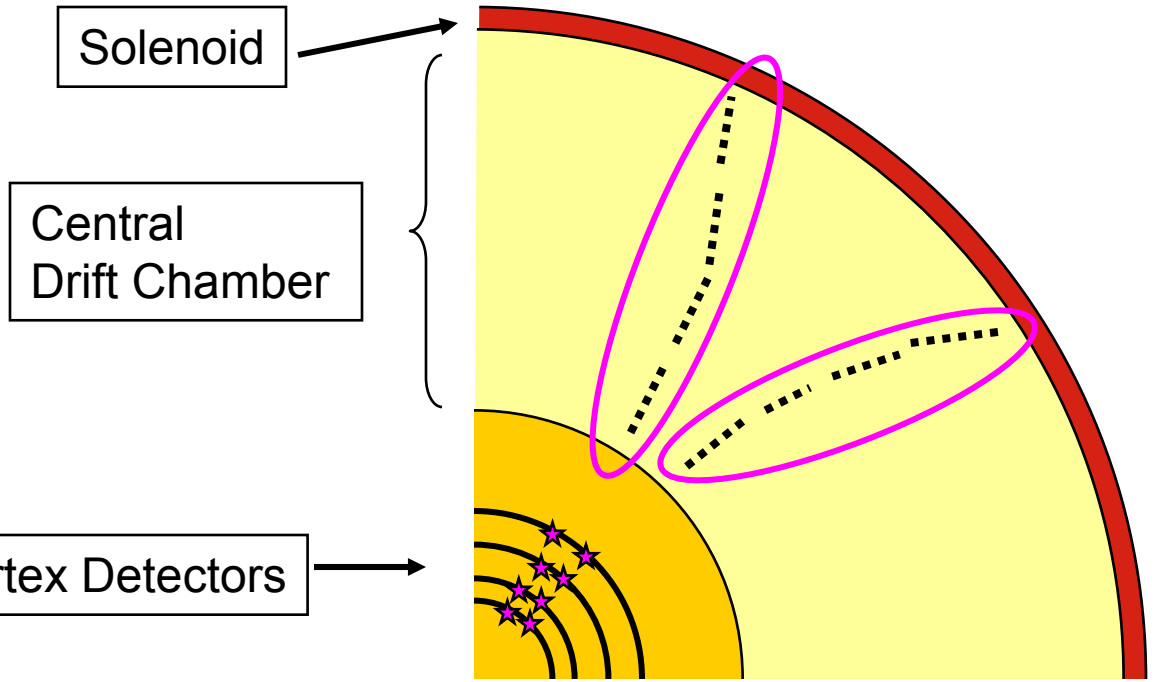
Alternative Channels



- Alternative final states with a π^- could be expected
  - $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$, $\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$
  - $\Xi_b^- \rightarrow \Xi_c^0 \pi^-$, $\Xi_c^0 \rightarrow \Xi^- \pi^+$
  - $\Omega_b^- \rightarrow \Omega_c^0 \pi^-$, $\Omega_c^0 \rightarrow \Omega^- \pi^+$
- The analogue $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ has been known for some time.
- These lack muons, so they must be found through another trigger mechanism.

CDF Two-Track Trigger

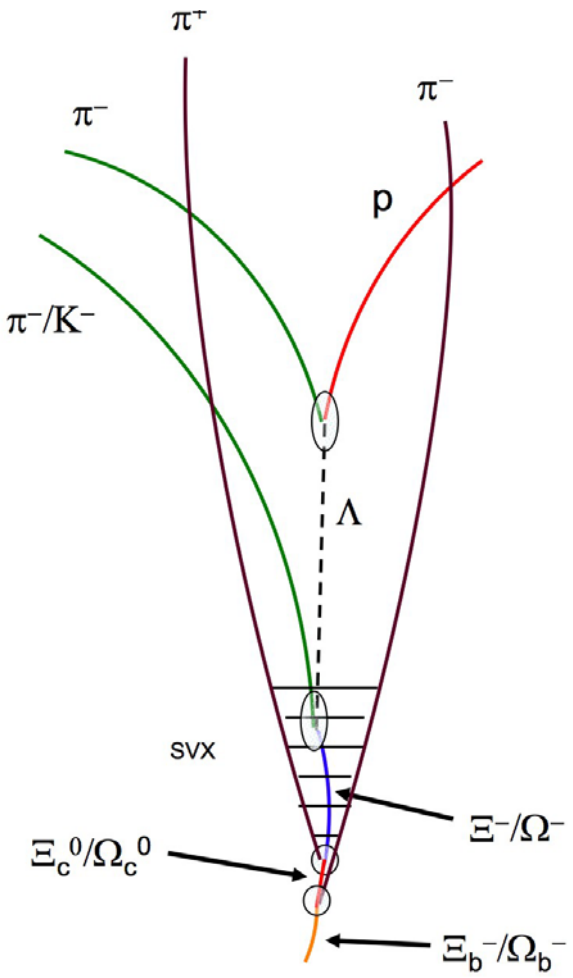
- Drift chamber tracks define "roads" into the silicon vertex detector.
  - p_T > 2 GeV/c



- Data that match prescribed patterns in the silicon triggers acceptance of the event.
- Provides purely hadronic final states - biased to heavy flavor
  - Flight from the beam > 200 μm

$\Xi_b^-/\Omega_b^- \rightarrow \Xi_c^0\pi^-/\Omega_c^0\pi^-$ Reconstruction

- The hadronic trigger opens an alternative search direction for the B baryons.
  - $\Xi_b^- \rightarrow \Xi_c^0\,\pi^-,\ \Xi_c^0 \rightarrow \Xi^-\,\pi^+$
  - The pions have trigger potential
    - One from each decay
  - Ξ^- decay products are displaced, and too low in momentum
- Reconstruction is similar to the J/ψ final states

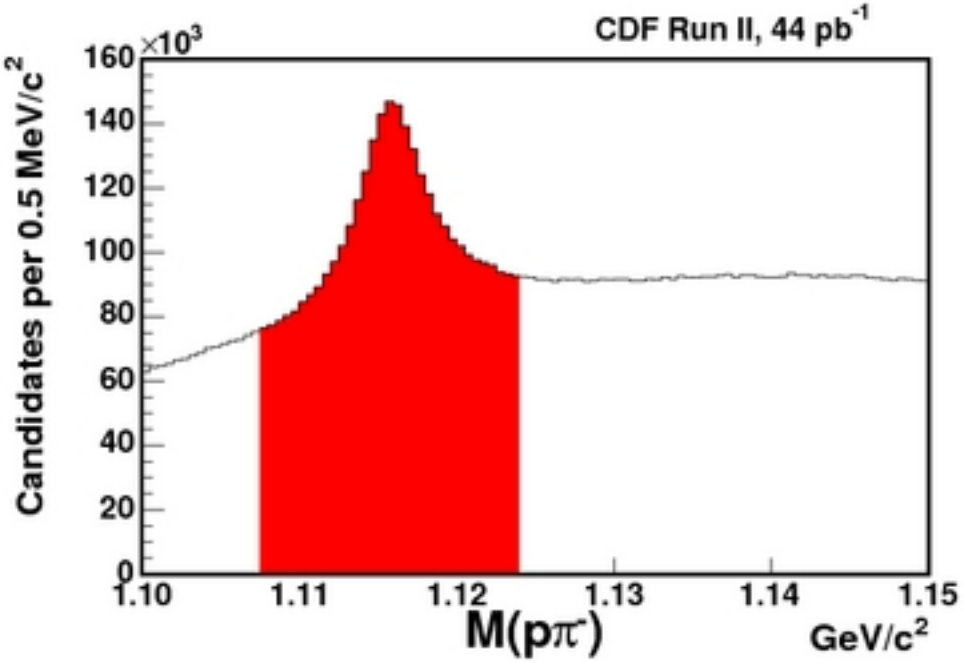


Ξ_b Reconstruction Strategy

- The approach we use is to follow the previously successful J/ψ data set analysis
  - Obvious difference with the trigger
- Selection and reconstruction as similar as possible
- The approach will be validated on the Ξ_b^-
  - By now, an established particle, but not in this decay channel
- The method will then be applied to the Ξ_b^0 search.
  - Two new final states will result
  - Begin with the final particle in the long decay chain…

Hyperon Selection

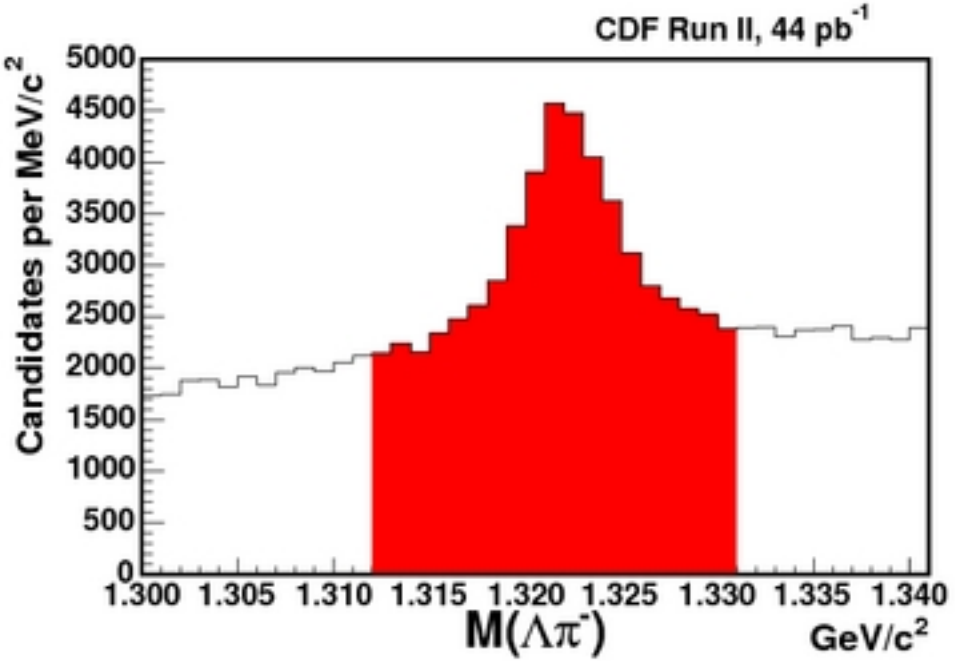
- Λ:
  - $p_T(\pi,p) > 400$ MeV
    - *p* identified as track with higher momentum
  - Flight > 1 cm
  - $P(\chi^2) > 10^{-3}$ (vertex fit)
  - M(πp) within 9 MeV of Λ



- Subset of the run
  - 44 pb^{-1}
  - Shaded area indicates signal region

Hyperon Selection

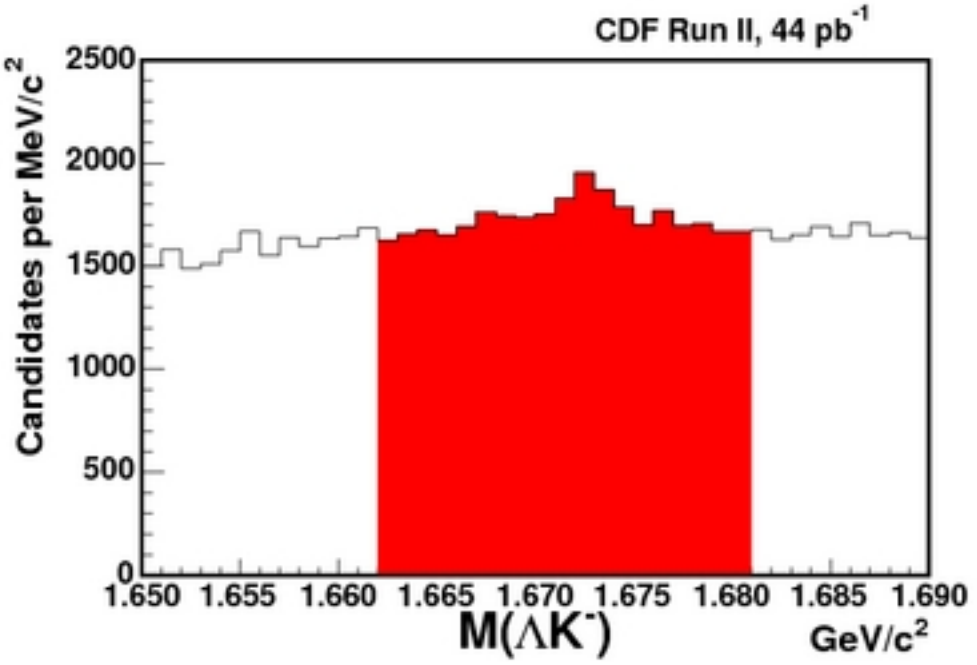
- Ξ^-
  - $p_T(\pi) > 400$ MeV
  - Flight > 1 cm
  - $P(\chi^2) > 10^{-3}$ (vertex fit and mass(Λ) constrained fit)
  - M($\Lambda\pi$) within 9 MeV of Ξ^-
  - Best vertex if ambiguities exist



- Subset of the run
  - 44 pb^{-1}
  - Shaded area indicates signal region

Hyperon Selection

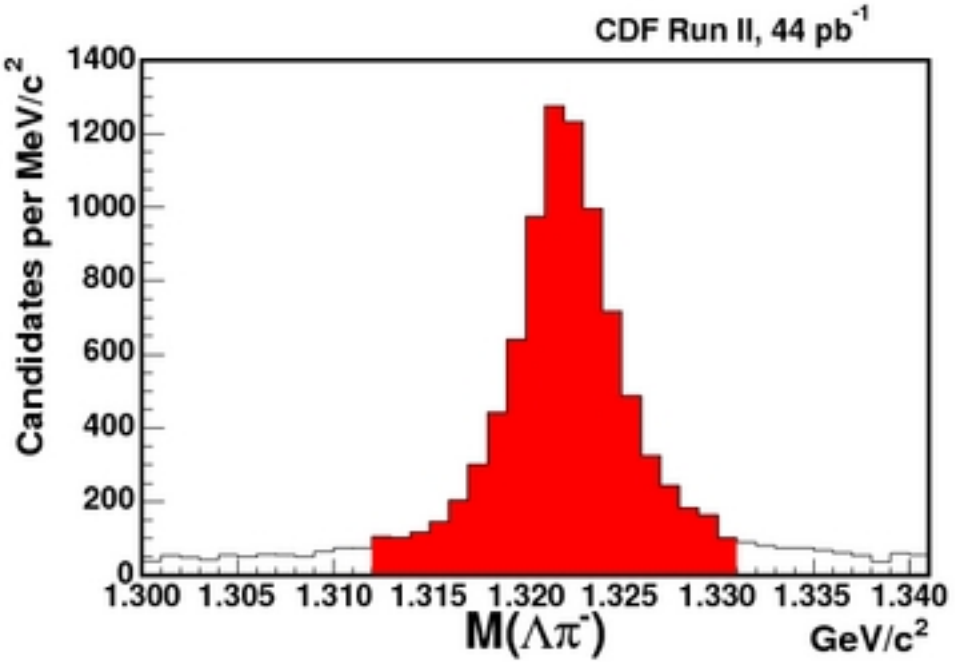
- Ω^-
  - $p_T(K) > 400$ MeV
  - Flight > 1 cm
  - $P(\chi^2) > 10^{-3}$ (vertex fit and mass(Λ) constrained fit)
  - M(ΛK) within 9 MeV of Ω^-
  - Best vertex if ambiguities exist
- Not used in the Ξ_b^0 search
  - Gives a hint at how easy the next project will be.



- Subset of the run
  - 44 pb^{-1}
  - Shaded area indicates signal region

Ξ^- Improvements

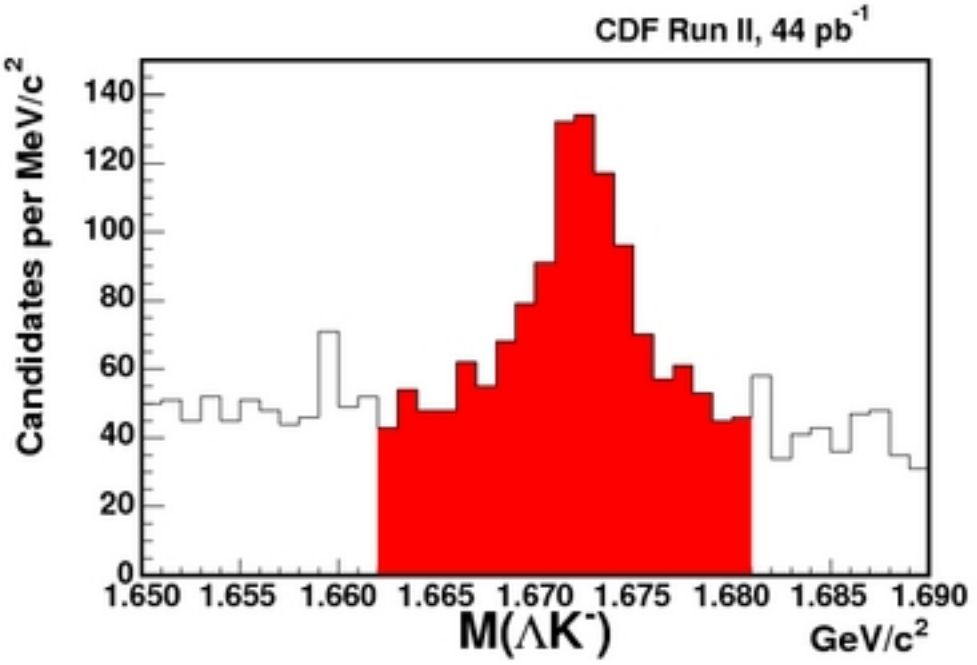
- Add silicon hits to the Ξ^- track when possible
- Require impact < 100 μm
- Leaves a very clean Ξ^- sample
  - Roughly 50-60% efficient
- This gives the Ξ^- trajectory comparable precision as any track.
  - 5 track state$\rightarrow$ 3 track state



- Subset of the run
  - 44 pb^{-1}
  - Shaded area indicates signal region

Ω^- Improvements

- Add silicon hits to the Ω^- track when possible
- Require impact < 100 μm
- Leaves a very clean Ω^- sample
- Not as efficient as for the Ξ^-
  - Shorter lifetime



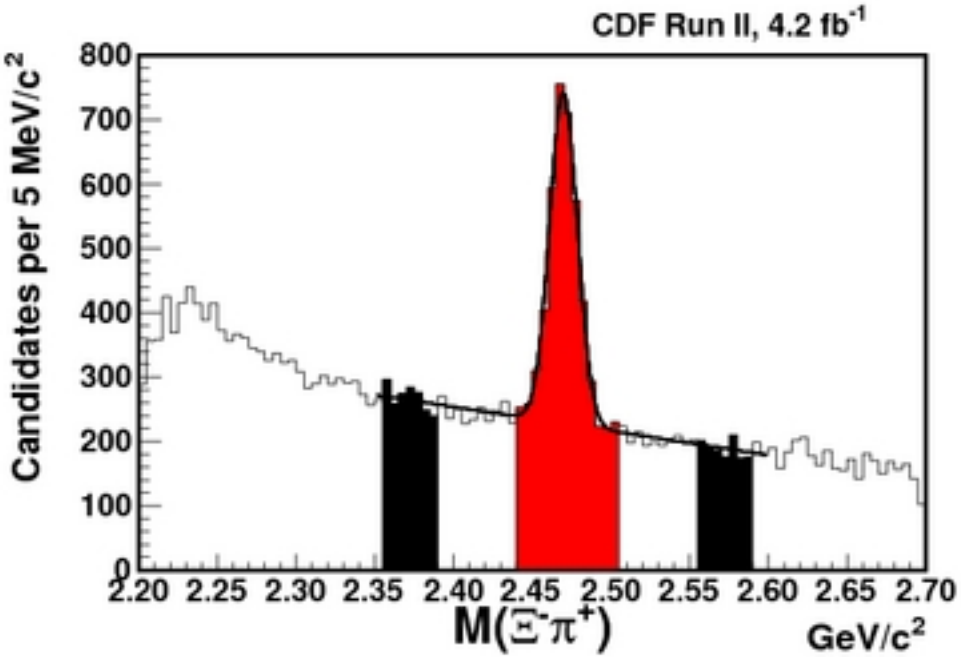
- Subset of the run
  - 44 pb^{-1}
  - Shaded area indicates signal region

$\Xi_c \to \Xi^-\pi^+(\pi^+)$ Selection

- For all:
  - $P(\chi^2) > 10^{-4}$ (vertex fit and mass(Λ/Ξ) constrained fit)
  - $p_T > 4.0$ GeV
  - SVXII hits on the Ξ^- track
  - $p_T(\pi^+) > 2.0$ GeV, $|d_0| > 100$ μm
    - Consistent with the trigger

Charmed baryons

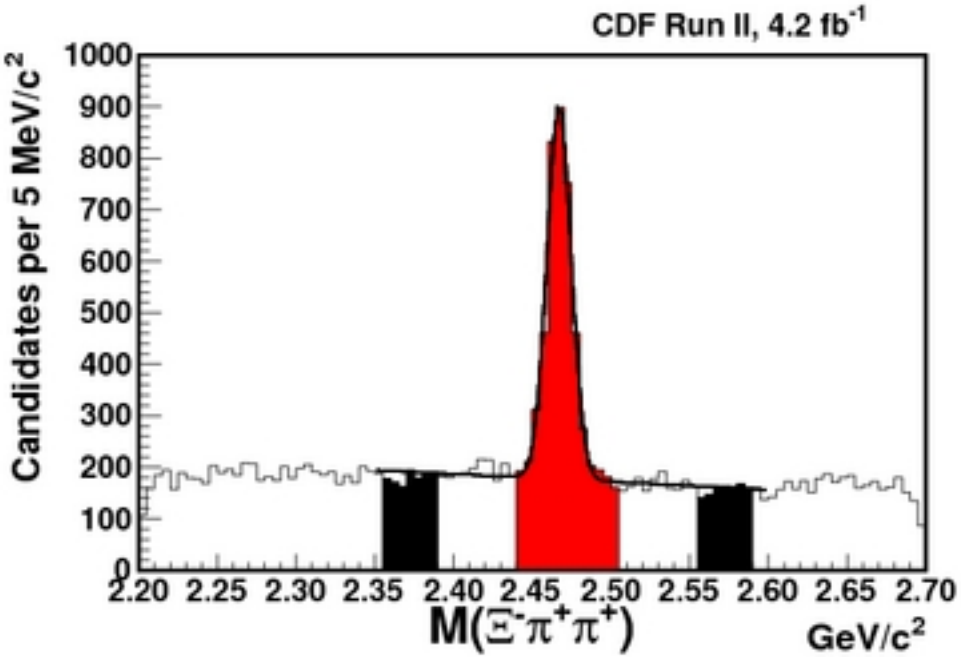
- A nice Ξ_c^0 signal can be found in the $\Xi^-\pi^+$ final state
  - ct > 100 μm
- A simple Gaussian fit was imposed on the mass distribution
  - Resolution of 9 MeV/c^2



- Red is the signal range
  - Black are sidebands used later

Charmed baryons

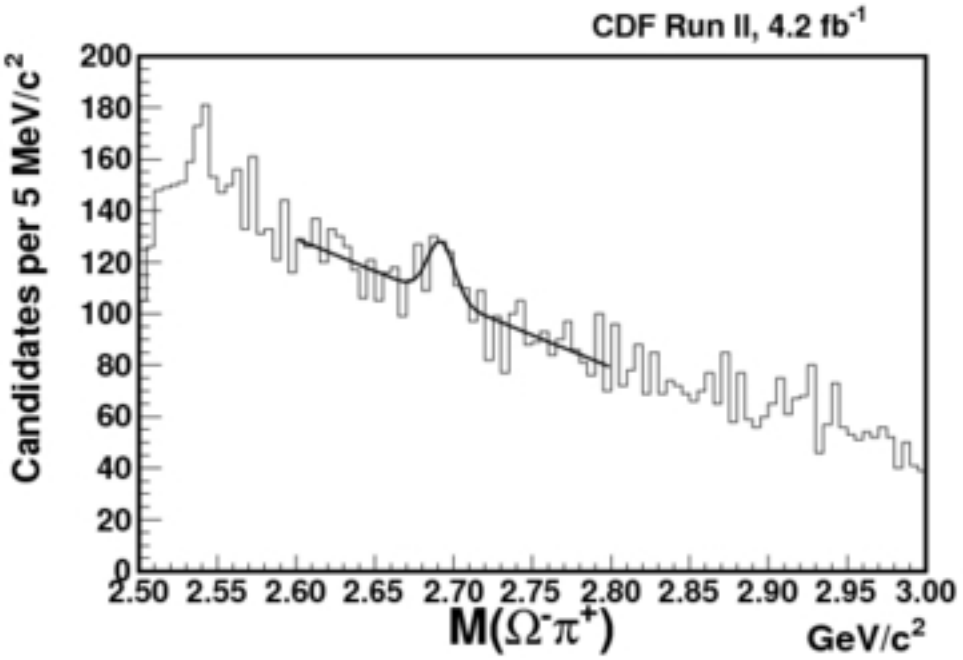
- A nice Ξ_c^+ signal can be found in the $\Xi^-\pi^+\pi^+$ final state
  - ct > 100 μm
- A simple Gaussian fit was imposed on the mass distribution
  - Resolution of 8 MeV/c^2



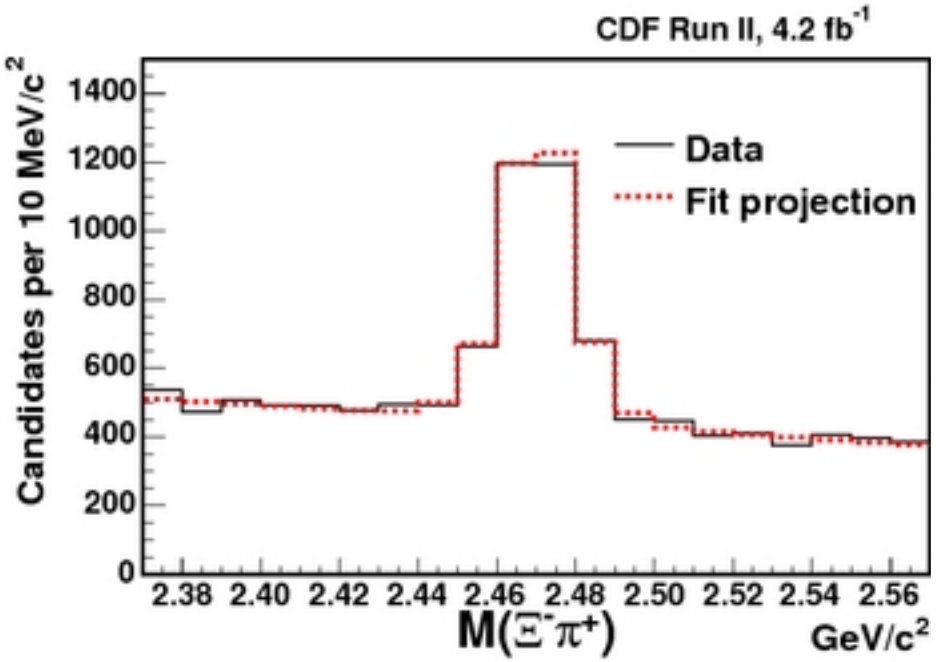
- Red is the signal range
  - Black are sidebands used later

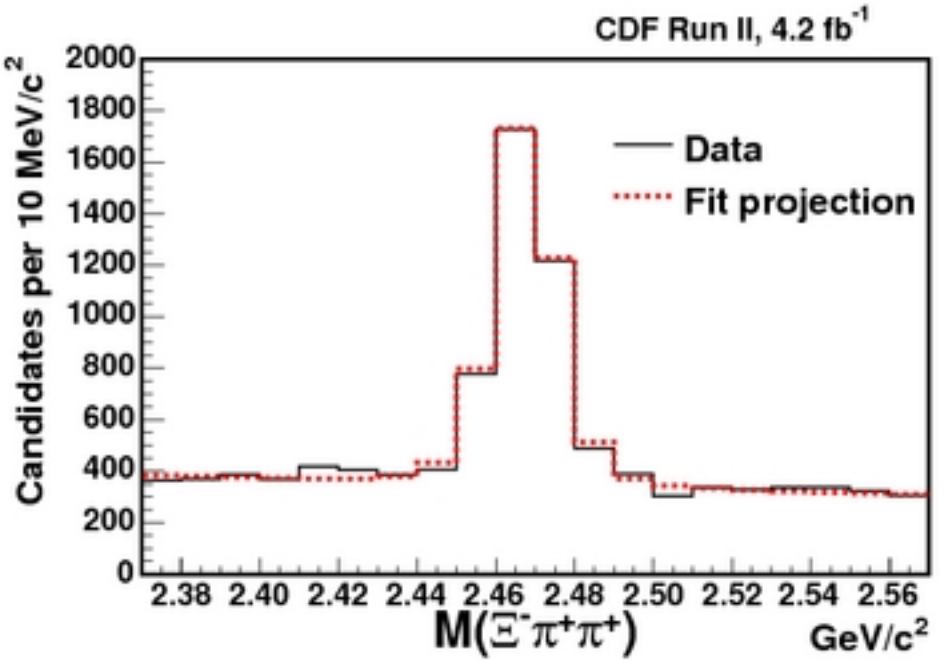
Charmed baryons

- We're not so lucky with the Ω_c^0 signal in the $\Omega^-\pi^+$ final state
- A simple Gaussian fit was imposed on the mass distribution
  - Resolution of 9 MeV/c^2
- This is last I'll say about the Ω_c^0.
  - Included for completeness.



Mass Fits of $\Xi^-\pi^+$, $\Xi^-\pi^+\pi^+$





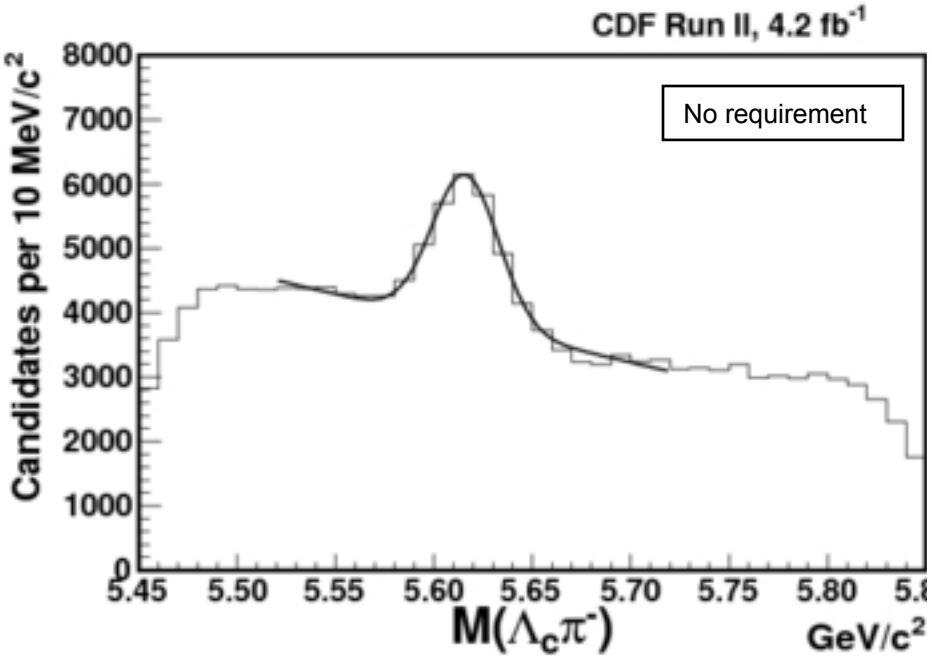
- Unbinned likelihood fits to the mass
  - Gaussian signal, linear background
  - Projections in red

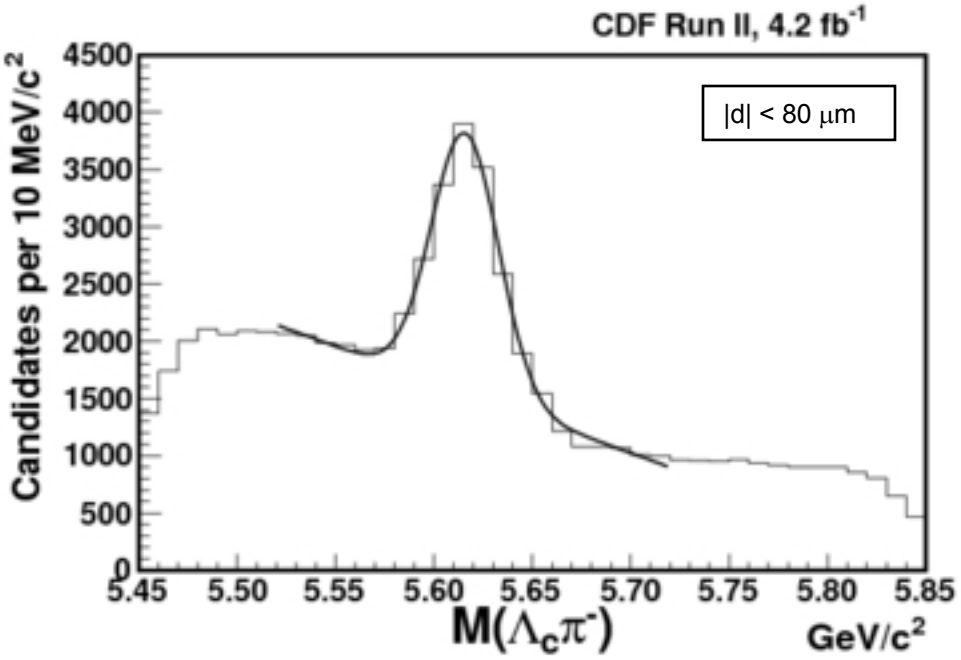
Signal	Candidates	Mass (MeV/c^2)		
		Fit Result	PDG	δM
Ξ_c^0	2110 $\pm$70	2470.4 $\pm$ 0.3	$2470.88^{+0.34}_{-0.80}$	-0.5
Ξ_c^+	3048 $\pm$ 67	2467.3 $\pm$ 0.2	$2467.8^{+0.4}_{-0.6}$	-0.5

Λ_b as a Benchmark

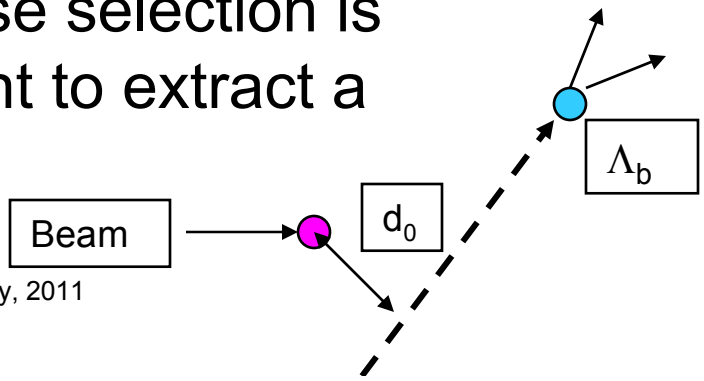
- We have few options for cross checking the $\Xi_c\pi^-$ reconstruction.
- $\Lambda_b \to \Lambda_c \pi^-$ is imperfect, but will have to do
  - Charmed baryon - π^- state
  - Collected with the two-track trigger
- These were reconstructed using the selection from the Λ_b lifetime analysis
  - (PRL 104, 102002(2010))
- The Λ_b sample is then used to cross check two selection criteria.

Impact Requirement



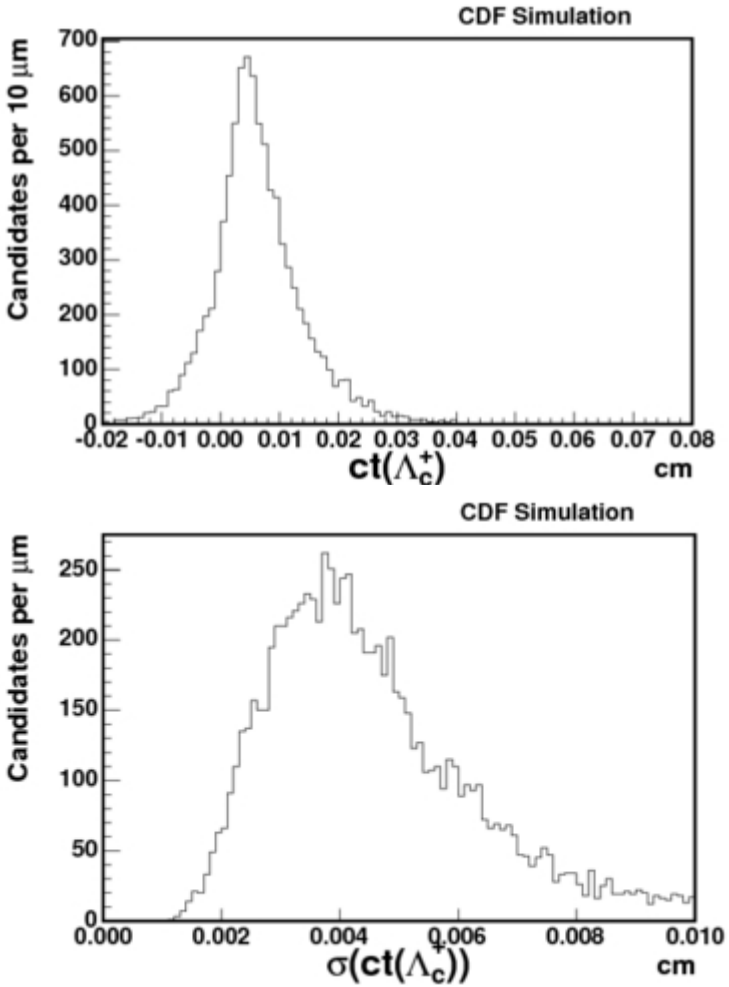


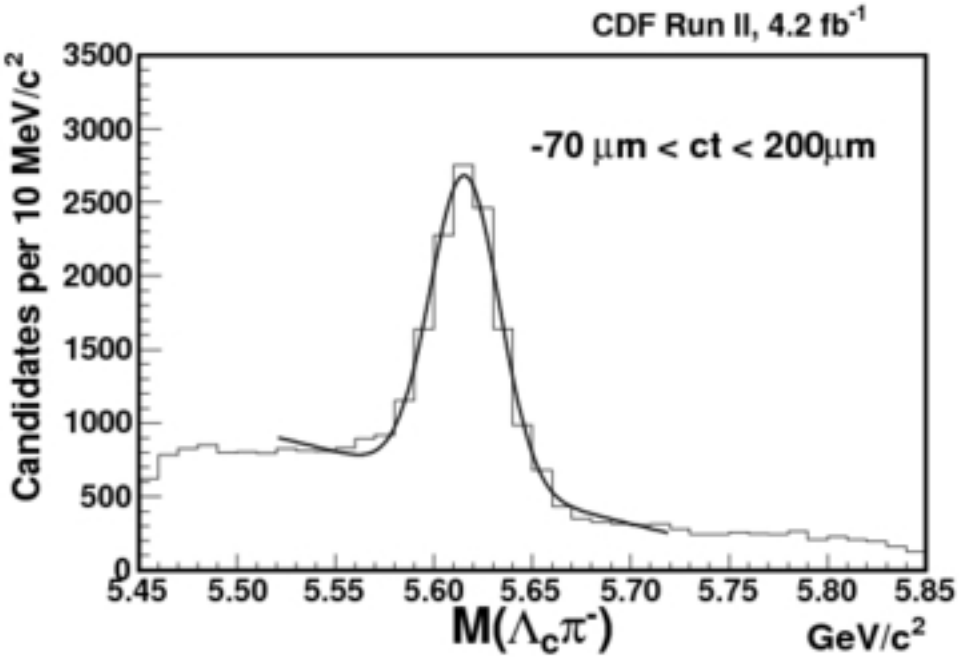
- The base selection is sufficient to extract a signal



- Impact – transverse displacement with respect to the beam
  - $|d_0| < 80$ μm
  - Used in the lifetime analysis
  - Improves the significance.

Λ_c Decay Time Requirement

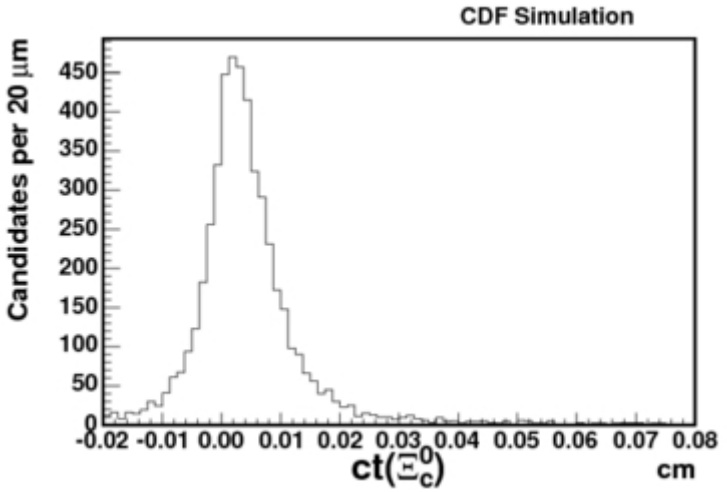


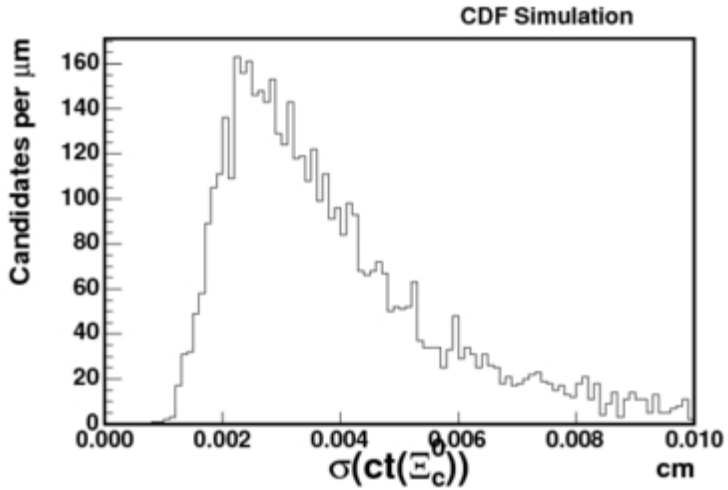


- Lifetime analysis used $-70 < ct(\Lambda_c) < 200$ μm
  - ~95% efficient, background reduced by factor of ~2

The Fickle Charmed Baryons

	$c\tau(\mu m)$
Λ_c^+	60 ± 2
Ξ_c^0	34 ± 4
Ξ_c^+	132 ± 8
Ω_c^0	21 ± 4

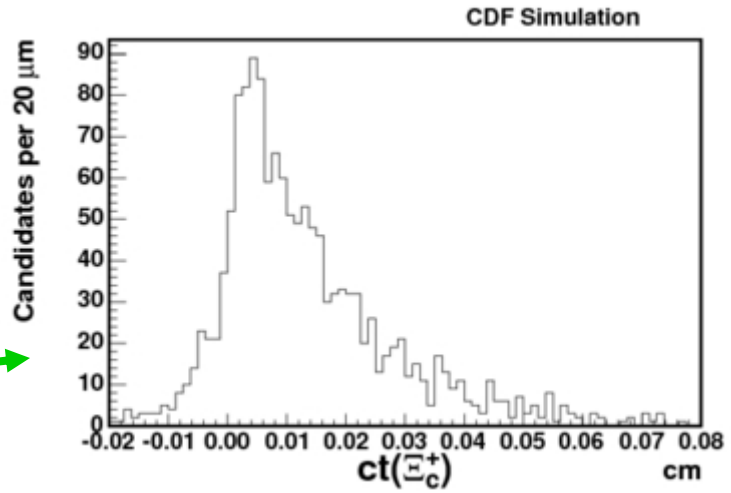


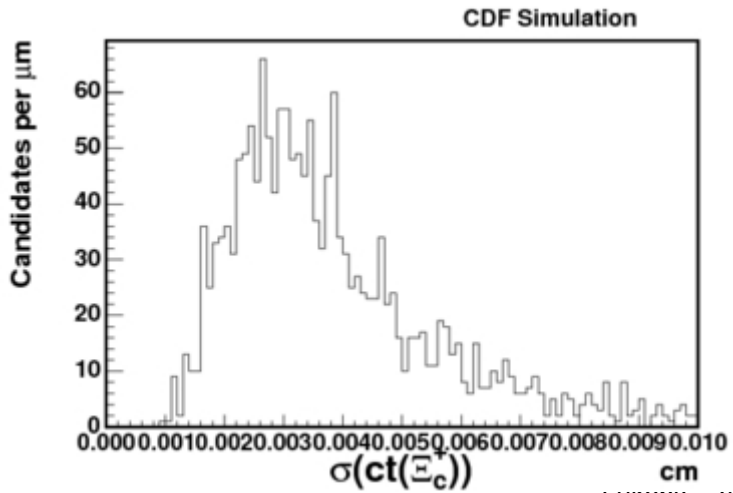


- Problem - the range of charmed baryon lifetimes is large
- Range of lifetime uncertainties is large
  - Requirement for Λ_c^+ not right for $\Xi_c^{0,+}$
- Simulated Ξ_c^0
  - $\Xi_b^- \rightarrow \Xi_c^0 \pi^-$

The Fickle Charmed Baryons

	$c\tau(\mu m)$
Λ_c^+	60 ± 2
Ξ_c^0	34 ± 4
Ξ_c^+	132 ± 8
Ω_c^0	21 ± 4



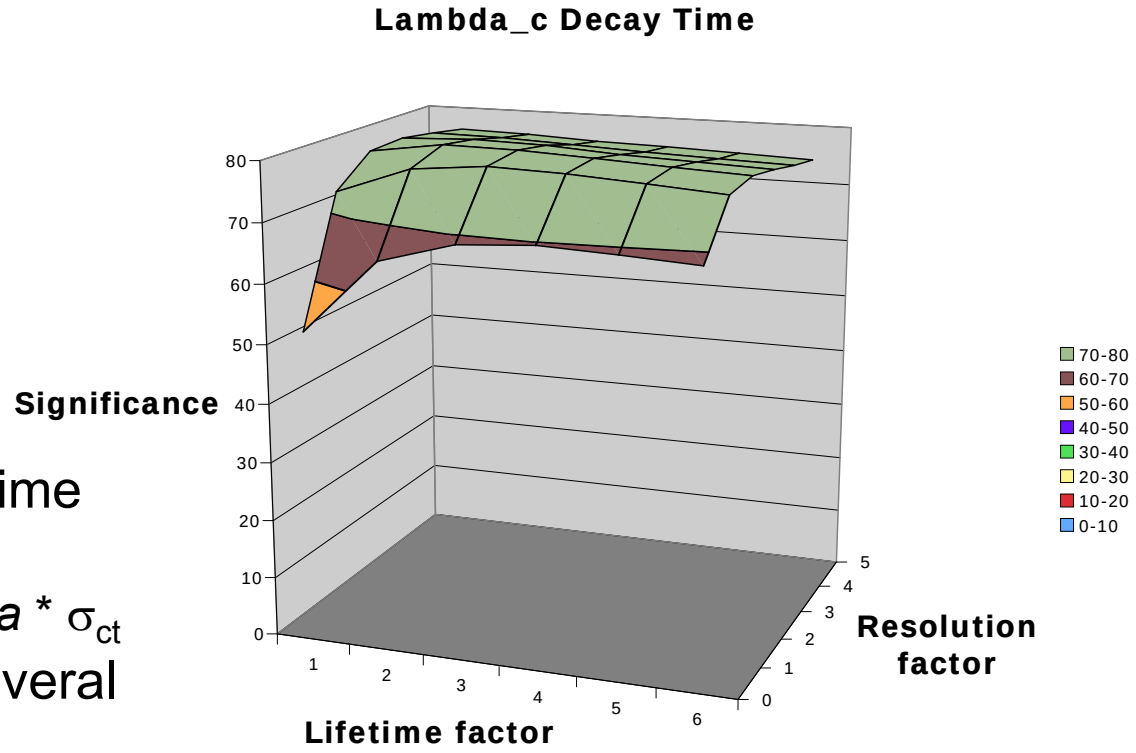


- Problem - the range of charmed baryon lifetimes is large
- Range of lifetime uncertainties is large
  - Requirement for Λ_c^+ not right for $\Xi_c^{0,+}$
- Simulated Ξ_c^+
  - $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$

Test Variations on the Λ_b

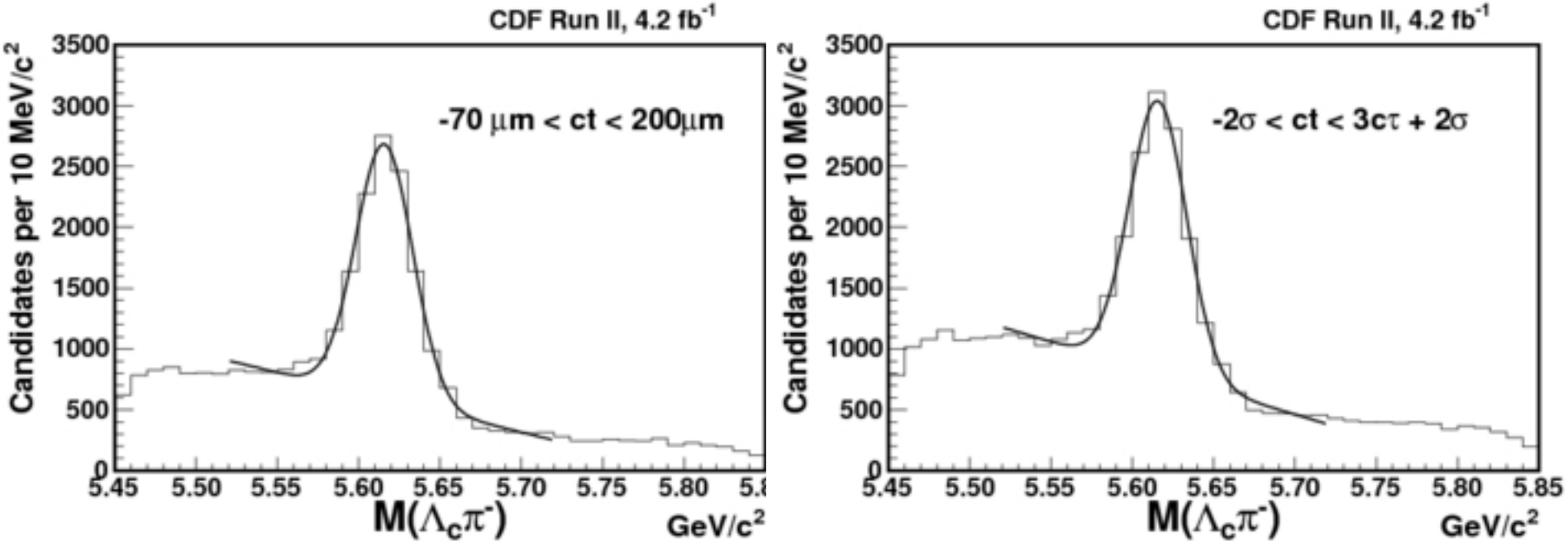
- A Ξ_c decay time requirement is needed that
  - Varies with species – factor of 4 variation
  - Depends on resolution – wide range is expected
- Small optimization study was performed on the Λ_b to choose a decay time requirement
  - Binned fit gives signal and background ($\pm 2\sigma_m$)
  - Find significance = $S/(S+B)^{0.5}$
- Significance without any ct(Λ_c) requirement is 68.4
  - Lifetime cut significance is 79.7.

Λ_b Significance Scan



- Parametrize the Λ_c decay time requirement
  - $-a * \sigma_{ct} < ct(\Lambda_c) < b*c\tau + a * \sigma_{ct}$
- Significance is found for several parameter variations
  - Will chose a=2, b=3

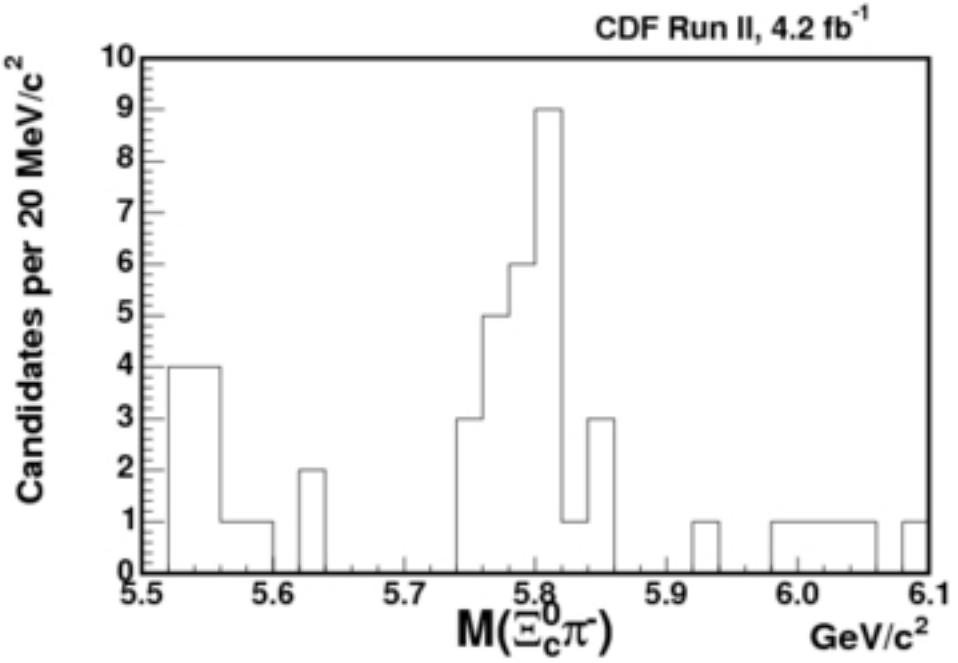
Alternative *ct* Ranges



- Very similar results to the fixed requirement
  - We will adopt this requirement for the Ξ_c channels

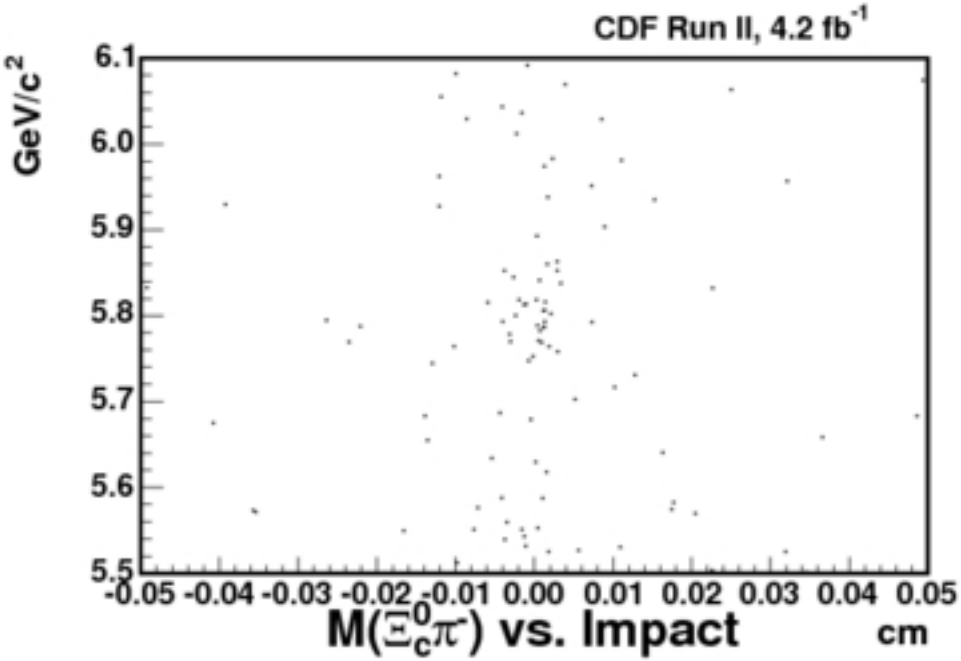
Ξ_b^- Selection

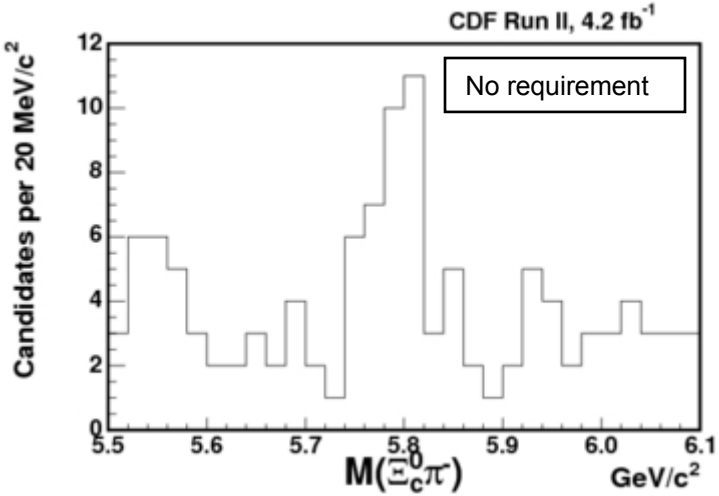
- Ξ_c^0:
  - $M(\Xi^-\pi^+)$ = 2.471 ± 0.03 GeV/c2
  - $-2\sigma_{ct} < ct < 3^*c\tau(\Xi_c^0) + 2\sigma_{ct}$
- π^-:
  - p_T > 2.0 GeV/c, $|d_0|$ > 100 μm
    - Consistent with a trigger track
  - Opposite charge from the baryon number
- $\Xi_c^0\,\pi^-$:
  - Satisfies Λ, Ξ^-, and Ξ_c^0 mass constrained and Ξ^- track fits
  - $|d_0|$ < 100 μm
    - **Transverse** displacement from the beam, or impact

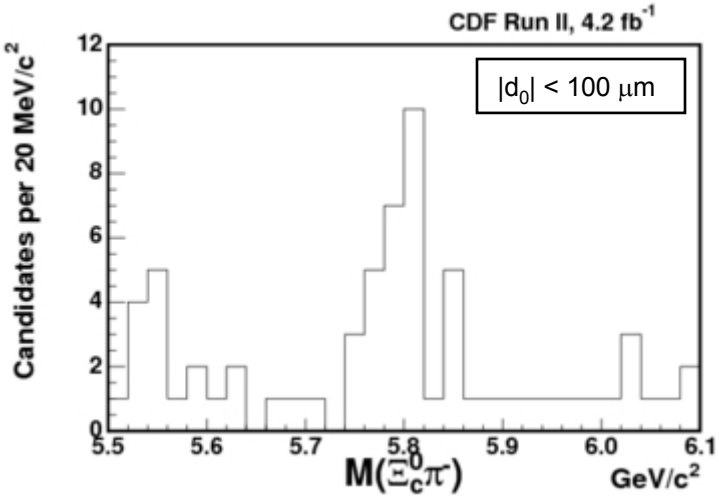


- Recall from the J/ ψΞ-, $M(\Xi_b^-)$ = 5790.9 ± 2.6 ± 0.8 MeV/c^2
- Expected resolution is 20 MeV/c^2

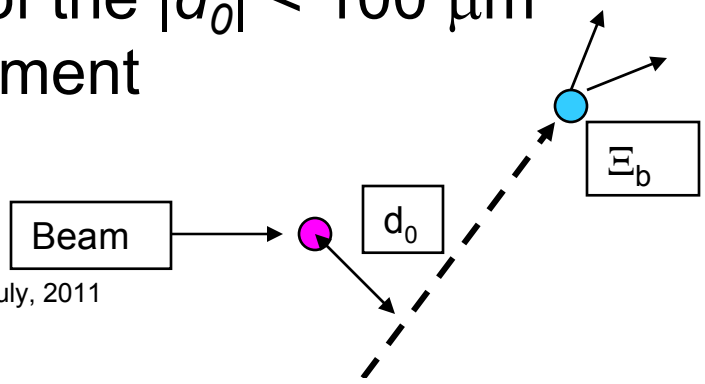
Impact of the $\Xi_c^0\pi^-$



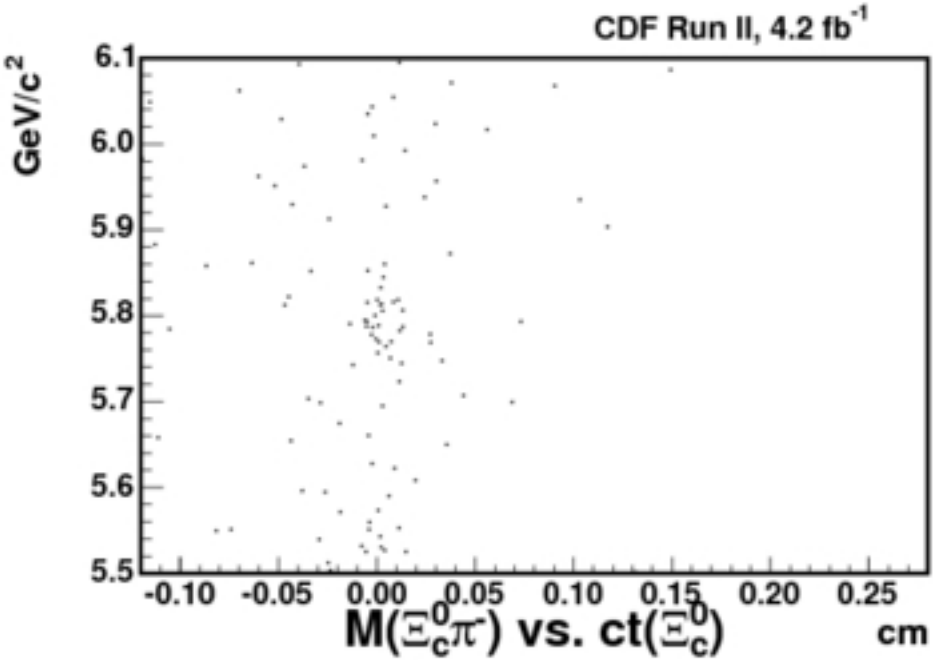


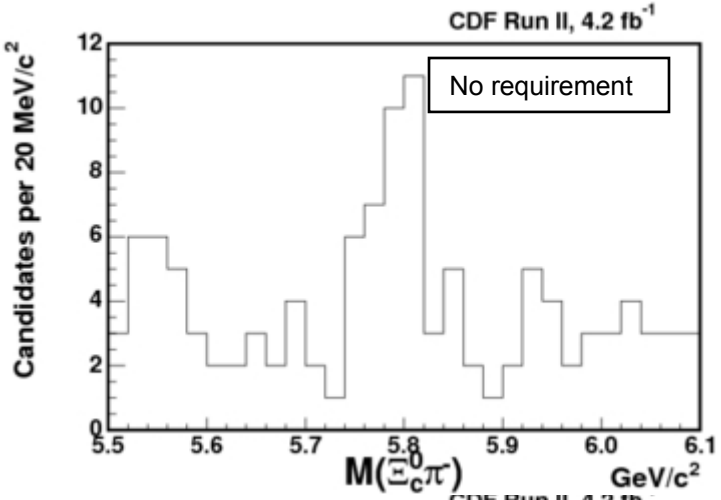


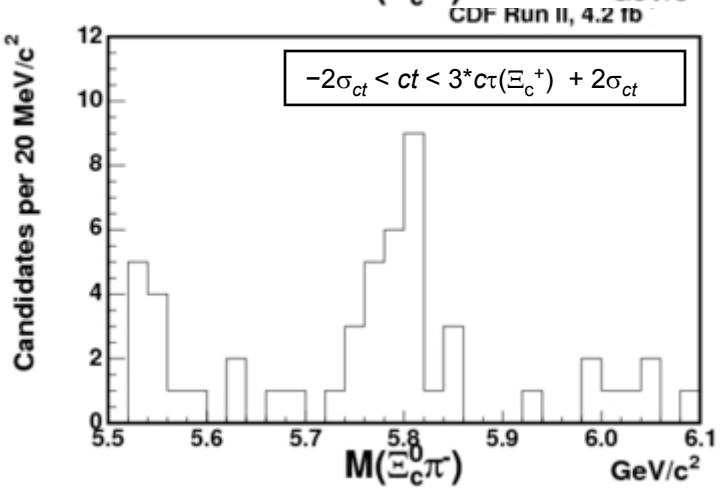
- Effect of the $|d_0|$ < 100 μm requirement



Decay time of the Ξ_c^0

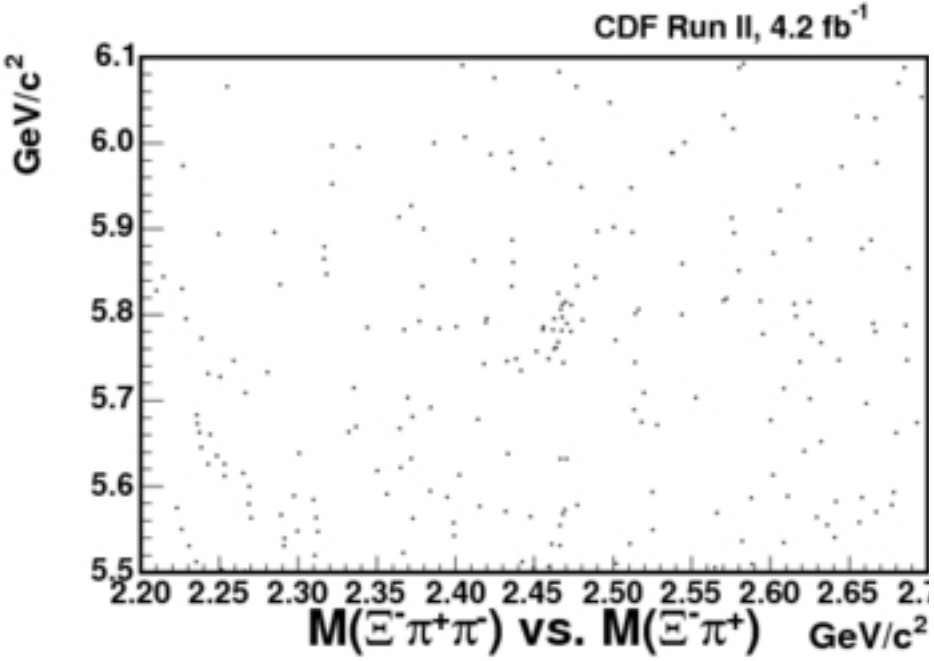


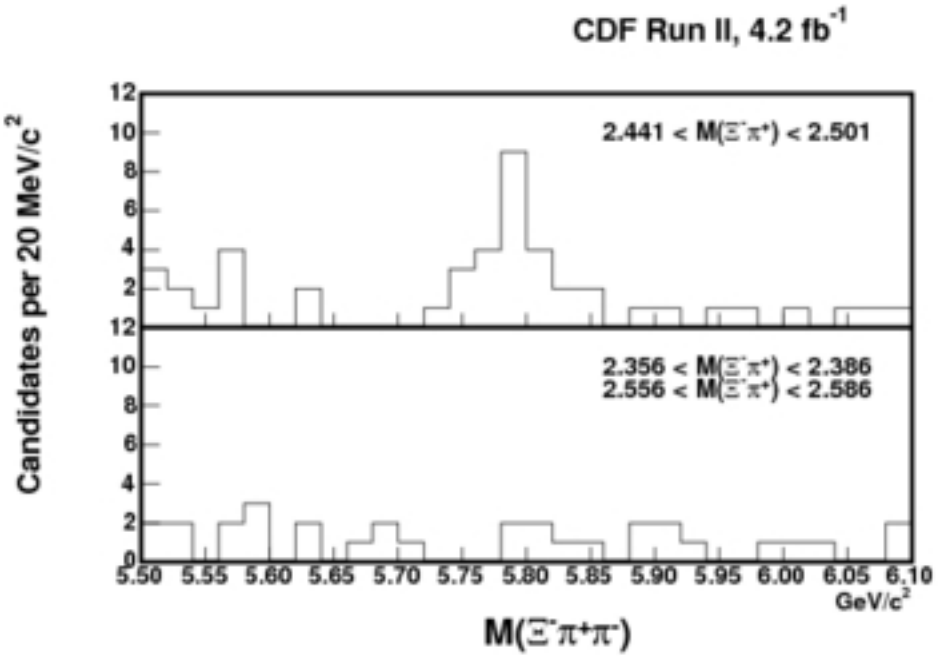




- Effect of the $-2\sigma_{ct} < ct < 3*c\tau(\Xi_c^0) + 2\sigma_{ct}$ requirement

Open the $\Xi^-\pi^+$ mass range

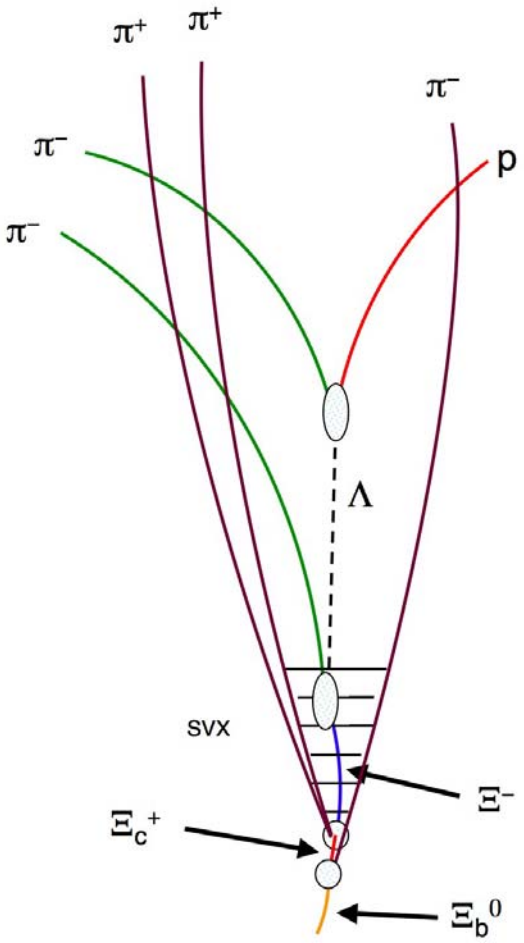




- Relax the Ξ_c^0 mass constraint and range requirements
  - Plot the Ξ^- constrained mass
- Of these, only the Ξ_c mass range is absolutely required
  - Others are improvements

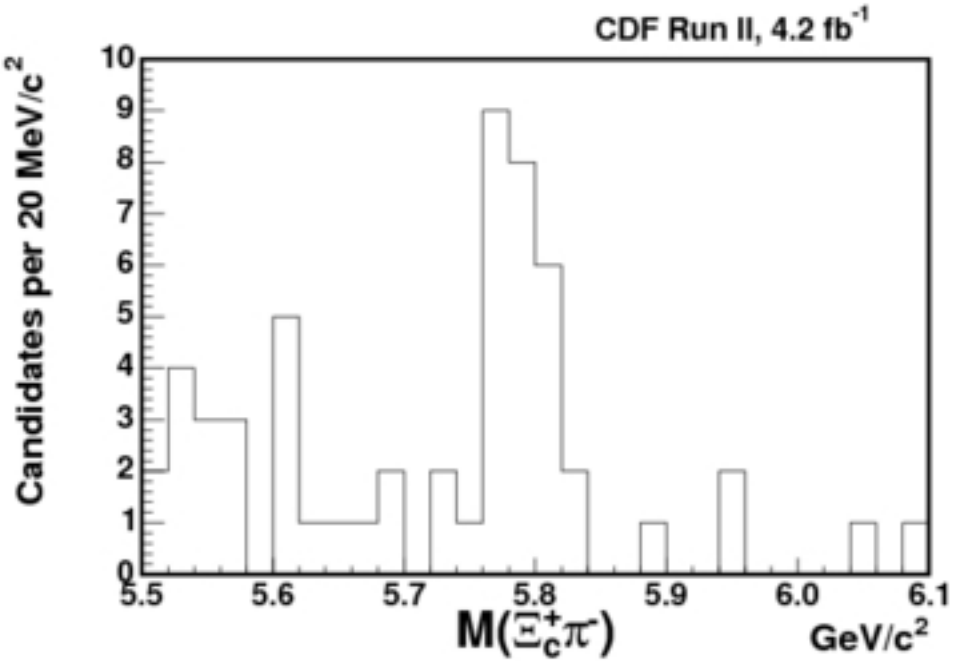
$\Xi_b^0 \to \Xi_c^+ \pi^-$ Reconstruction

- Very similar to $\Xi_b^- \to \Xi_c^0 \pi^-$
- Slightly more complicated final state
  - 6 tracks, 4 vertices
- Same techniques used for the Ξ_b^- can be employed.
- Only difference is an additional π^+ attached to the charm vertex.
- The additional track
  - Costs us in acceptance
  - But provides an additional possible trigger track



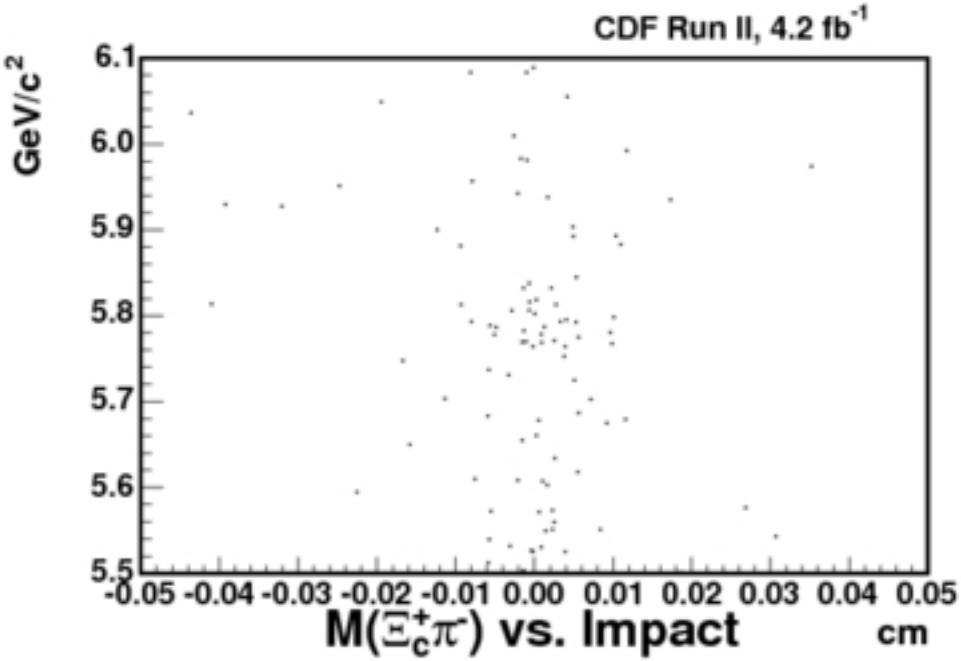
Ξ_b^0 Selection

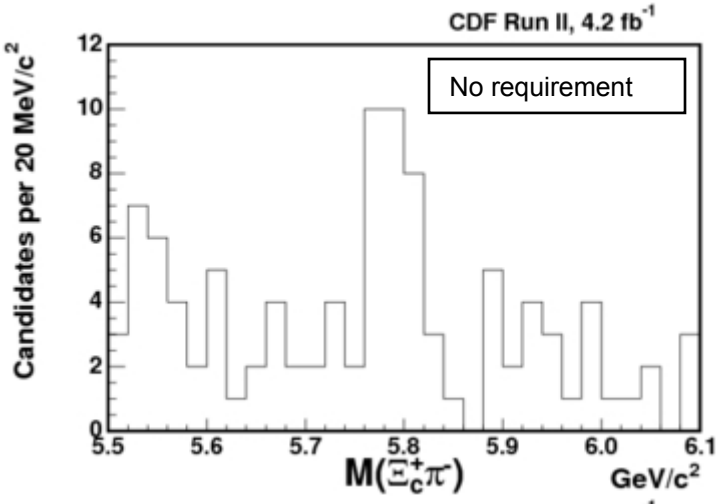
- Ξ_c^+:
  - $M(\Xi^- \pi^+ \pi^+) = 2.469 \pm 0.025$ GeV/c2
  - $-2\sigma_{ct} < ct < 3*c\tau(\Xi_c^+) + 2\sigma_{ct}$
- π^-:
  - $p_T > 2.0$ GeV/c, $|d_0| > 100$ μm
    - Consistent with a trigger track
  - Opposite charge from the baryon number
- $\Xi_c^+ \pi^-$:
  - Satisfies Λ, Ξ^-, and Ξ_c^+ mass constrained and Ξ^- track fits

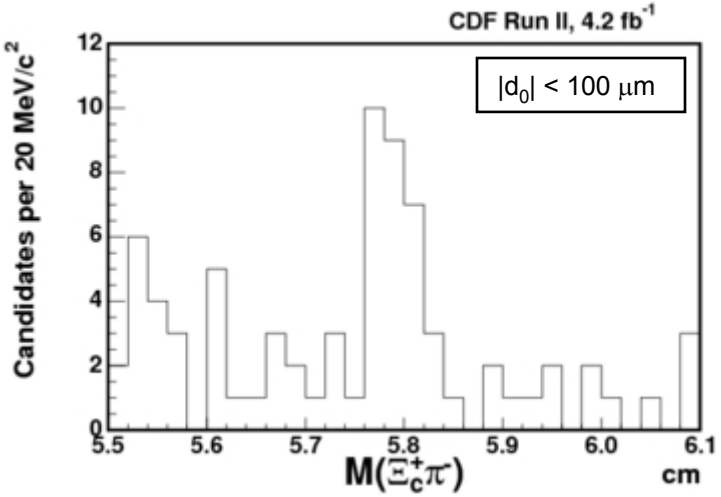


- Expected resolution is 20 MeV/c^2

Impact of the $\Xi_c^+\pi^-$

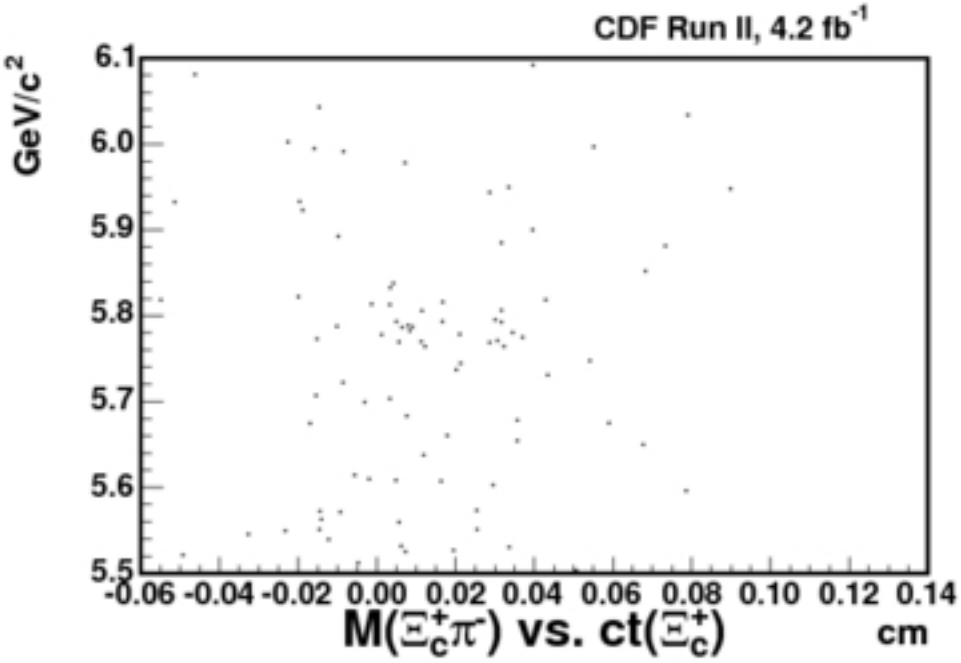


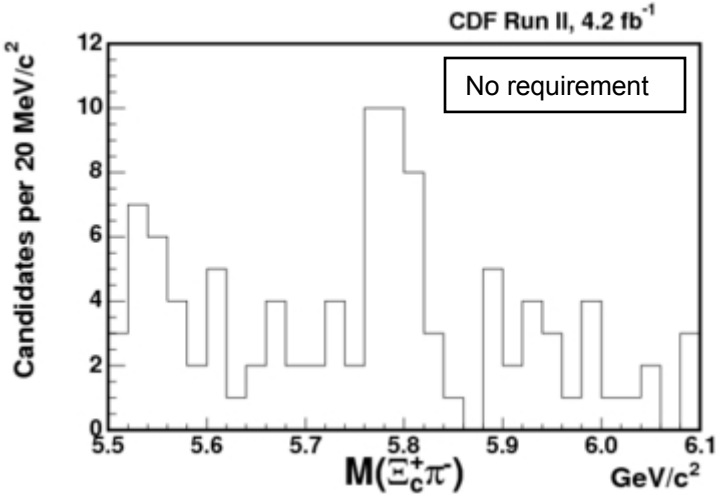


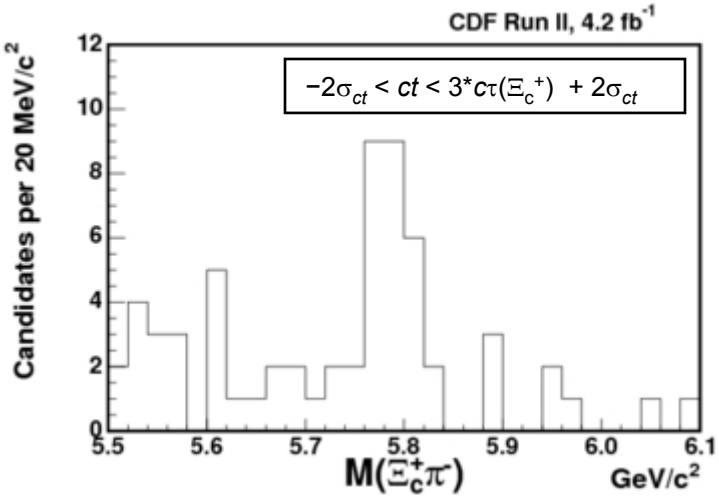


- Effect of the $|d_0| < 100$ μm requirement

Decay time of the Ξ_c^+

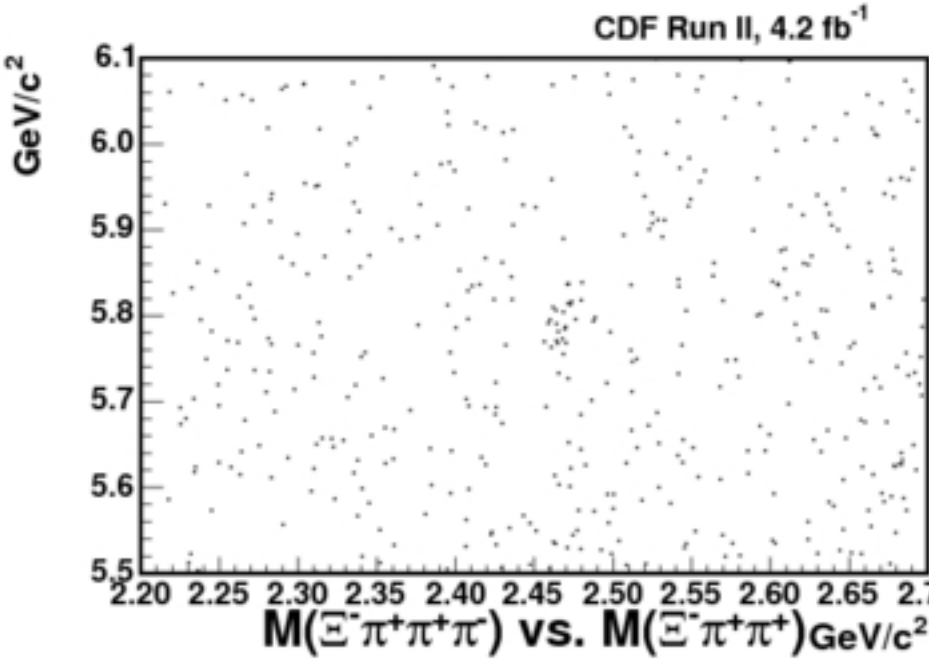


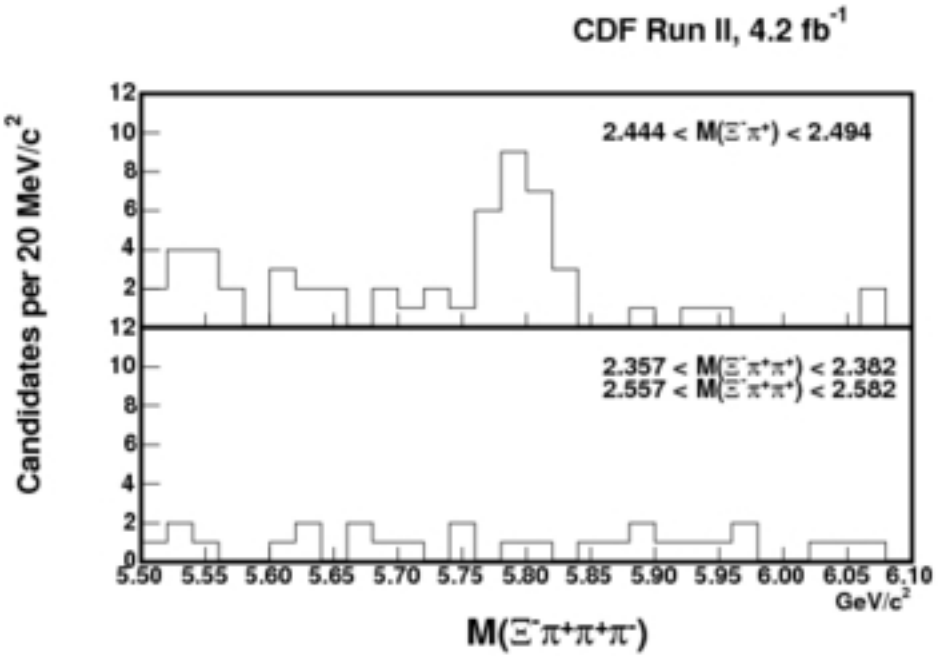




- Effect of the $-2\sigma_{ct} < ct < 3^*c\tau(\Xi_c^+) + 2\sigma_{ct}$ requirement

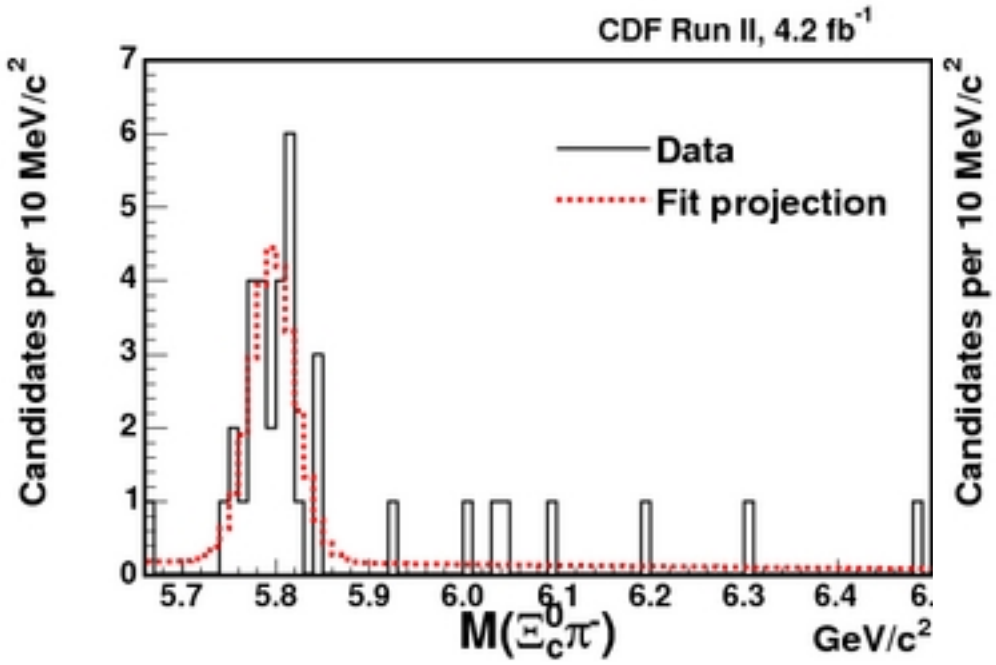
Open the $\Xi^-\pi^+\pi^+$ mass range

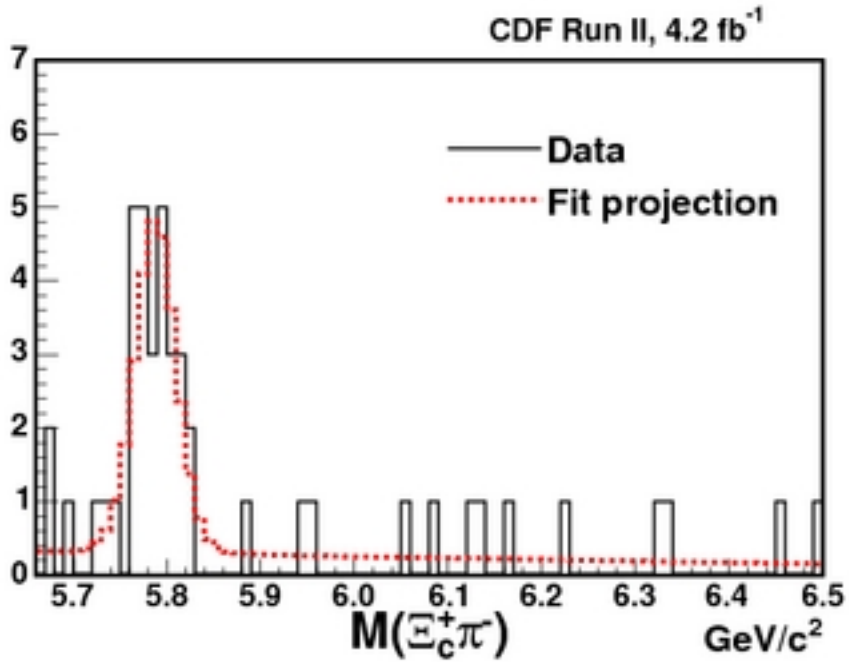




- Relax the Ξ_c^+ mass constraint and range requirements
  - Plot the Ξ^- constrained mass
- Same conclusion for the Ξ_b^0
- Ξ_c is required
  - Others are improvements

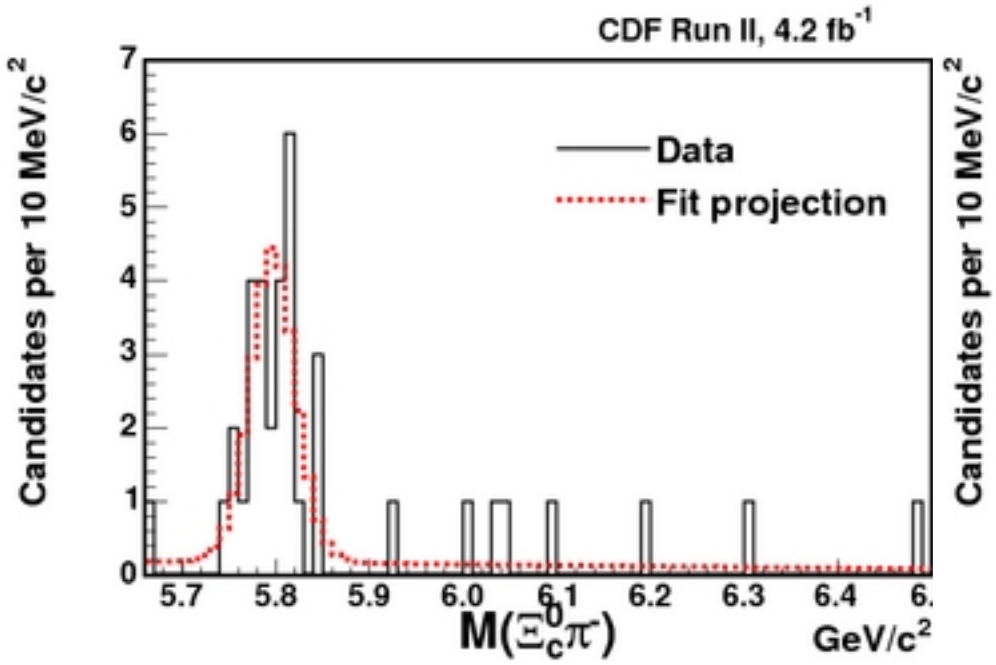
Mass Fits of the $\Xi_c^{0,+}\pi^-$

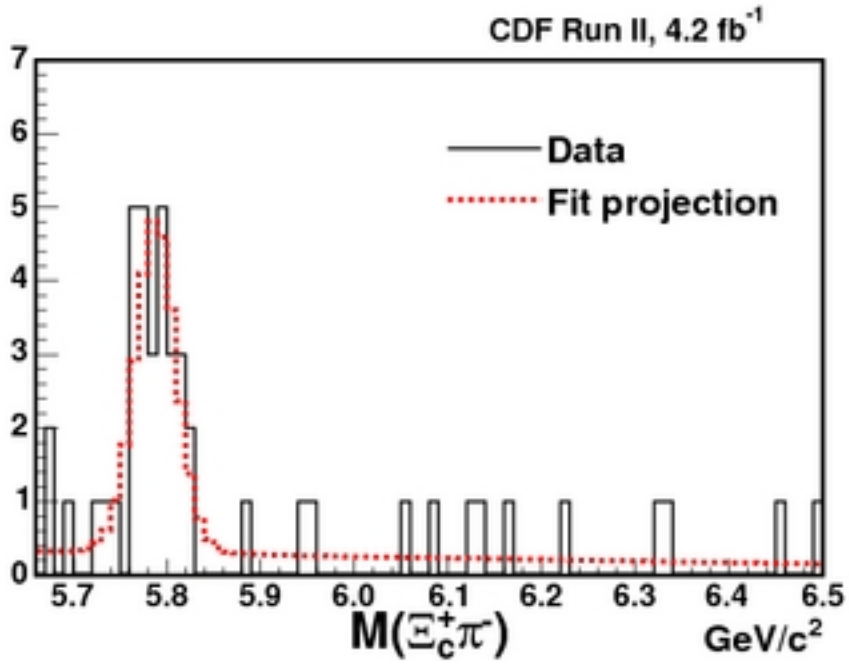




- Unbinned likelihood fits to the mass
  - Gaussian signal, linear background
  - Low edge is 5.66 GeV/c^2
    - (M(Ξ_b^-) - M(π^-))

Mass Fits of the $\Xi_c^{0,+}\pi^-$

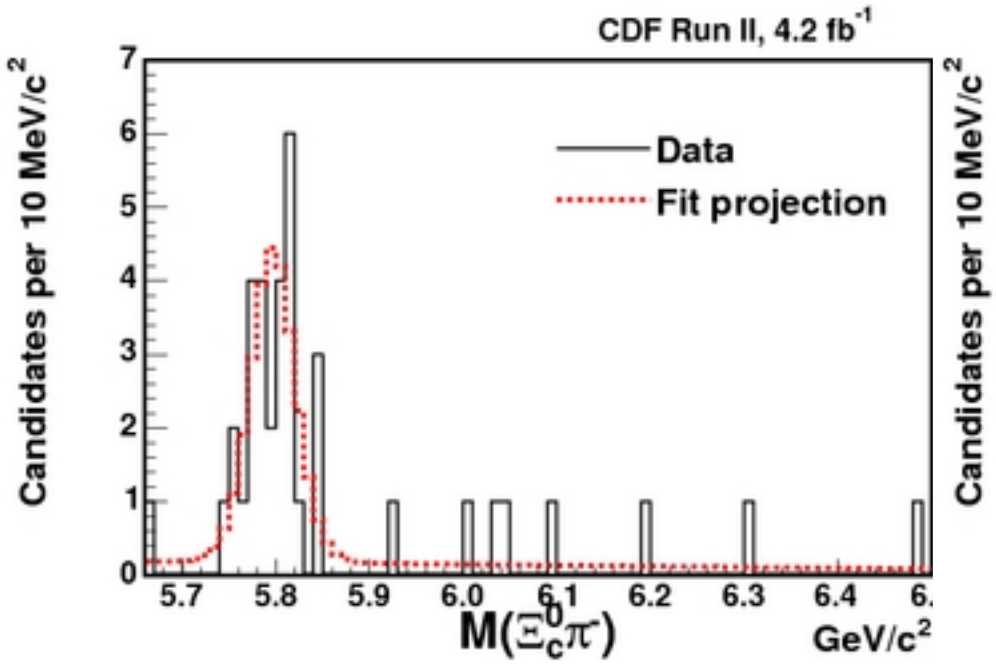


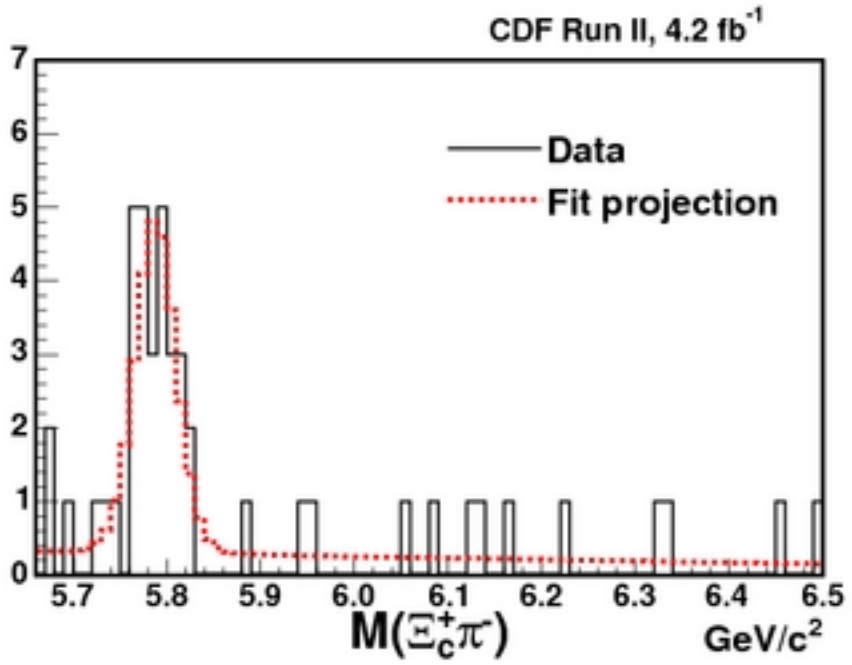


- Used for significance test
  - Fix signal=0, null hypothesis
  - Float signal, fix all other parameters
    - Mass = Ξ_b^-, Ξ_b^- + 5 MeV/c^2, Ξ_b^- - 5 MeV/c^2

- $\Delta 2\log(\mathcal{L})$ is equivalent to χ^2 test
  - 1 degree of freedom
- Null hypothesis is very unlikely
  - Ξ_b^-: 3.9×10^{-12}
  - Ξ_b^0: 3.6×10^{-12}
- Equivalent to 6.8σ

Mass Fits of the $\Xi_c^{0,+}\pi^-$





- Allow all parameters to float.

Signal	Candidates	Mass (MeV/c^2)
Ξ_b^-	$25.8^{+5.5}_{-5.2}$	5796.7 ± 5.1
Ξ_b^0	$25.3^{+5.6}_{-5.4}$	5787.8 ± 5.0

Mass Systematic Uncertainties

	Ξ_b^-	Ξ_b^0
$\Xi_c^{0,+}$ mass	0.8	0.6
Momentum Scale	0.5	0.5
Resolution Model	1	1
Total	1.4	1.3

- Quadrature sum of several effects give the systematic uncertainty on the masses.
  - Ξ_c are largest of asymmetric PDG values
  - Momentum scale is set by J/ψ and Υ.
    - Used in other CDF mass measurements
  - Resolution model is comparison between track-based predictions and observed resolutions.

Mass Difference

	$\Xi_b^-(J/\psi\Xi^-)$	Ξ_b^0
J/ψ, Ξ^-, $\Xi_c^{0,+}$ mass	0.07	0.6
Momentum Scale		
Resolution Model	0.6	1
Total	0.6	1.2
Difference Total	1.3	

- To measure the mass difference between the two states, we use our best Ξ_b^- value of $5790.9 \pm 2.6 \pm 0.8$ MeV/c^2
  - From $J/\psi\Xi^-$, PRD 80, 072003 (2009)
- Drop the momentum scale term – common to both states
- Daughter mass terms are trivial for $J/\psi\Xi^-$
- Combine in quadrature, gives

$$M(\Xi_b^-) - M(\Xi_b^0) = 3.1 \pm 5.6(stat.) \pm 1.3(syst.)$$

Results

- In conclusion, we have observed
  - $\Xi_b^- \rightarrow \Xi_c^0 \pi^-,\ \Xi_c^0 \rightarrow \Xi^- \pi^+$ $5796.7 \pm 5.1 \pm 1.4$ MeV/c^2
  - $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-,\ \Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$ $5787.8 \pm 5.0 \pm 1.3$ MeV/c^2
- Combined with the $\Xi_b^- \rightarrow J/\psi \Xi^-$ mass measurement,

$$M(\Xi_b^-) - M(\Xi_b^0) = 3.1 \pm 5.6(stat.) \pm 1.3(syst.)$$

- Mass resolution is inferior to the J/ψ final state results
  - Daughter masses are lighter
  - More momentum to measure

Conclusions

- Ξ_b^- observation is a first in this channel
  - Only the second Ξ_b^- final state observed.
  - Demonstrates the analysis technique
    - Find what's been found before, in a new way
- Ξ_b^0 observation is a first in any channel
- A nice addition to the Tevatron list of observations